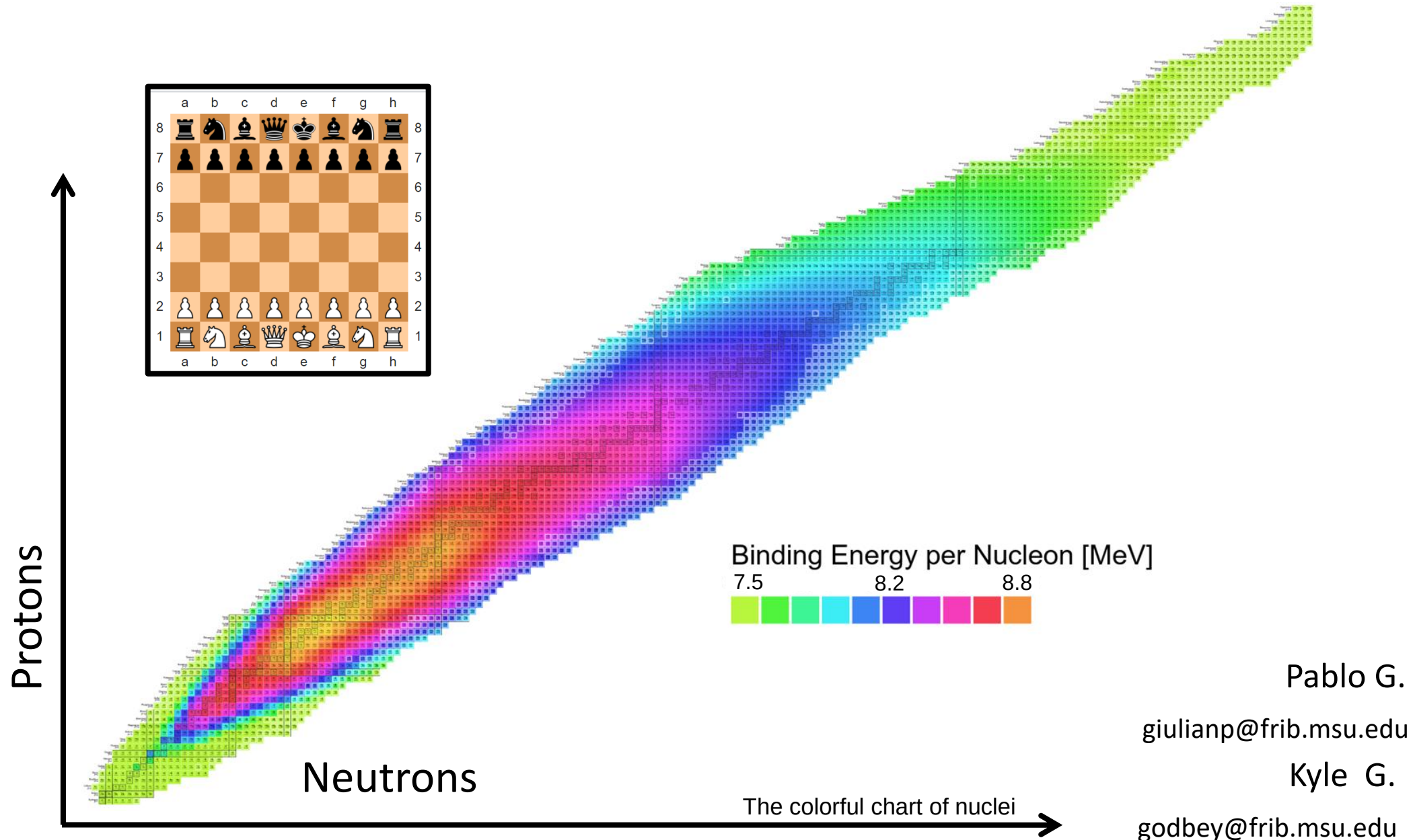


Nuclear Theory



Pablo G.

giulianp@frib.msu.edu

Kyle G.

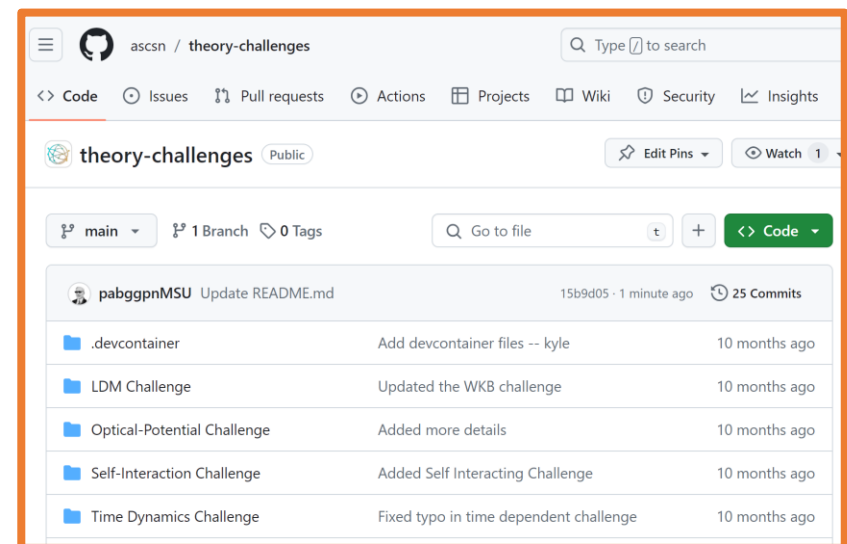
godbey@frib.msu.edu

Hand-on session set-up



ASCSN

Advanced Scientific Computing and Statistics Network



<https://github.com/ascsn/theory-challenges>

For today

Who am I?

Why theory?

Building models

Building a (simple) nuclear model

Quantum mechanics

Building (better) nuclear models

Challenges (Hands-On Session)

For today

Who am I?

Why theory?

Building models

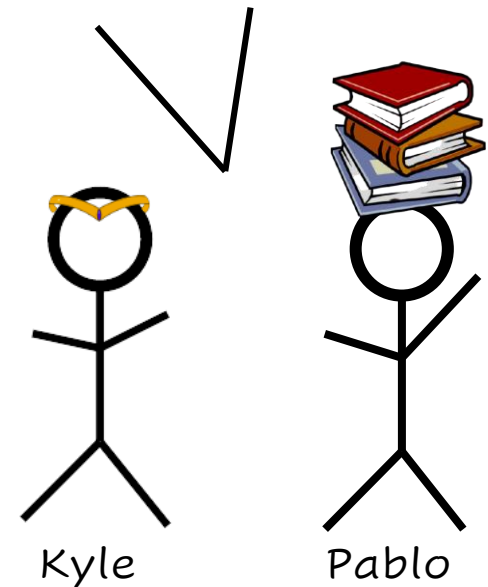
Building a (simple) nuclear model

Quantum mechanics

Building (better) nuclear models

Challenges (Hands-On Session)

Ask questions



Me



Me



Undegrad



PhD



Postdoc



Me



Universidad Simon Bolivar



- ★ Undegrad
- ★ PhD
- ★ Postdoc



Venezuela



Michigan

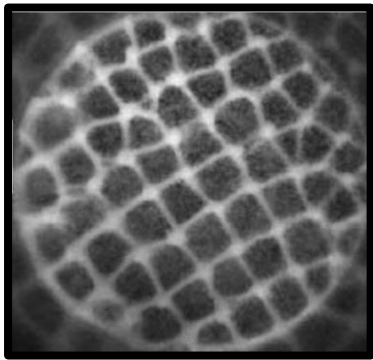
Florida State University



Me



Pattern formation
in vibrated sand



Undegrad



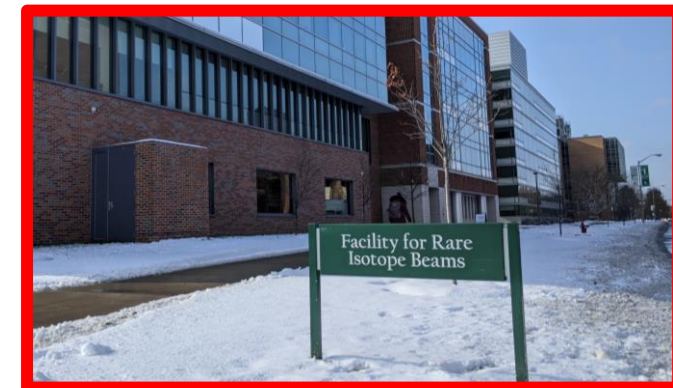
PhD



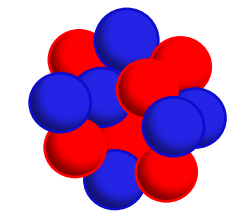
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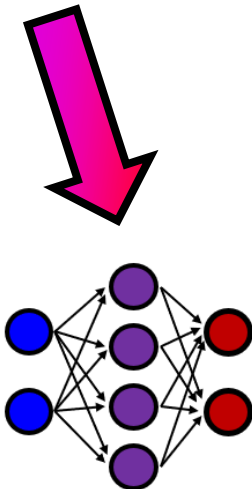
Venezuela



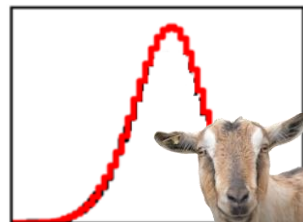
Michigan



Nuclear
Physics



Machine
Learning

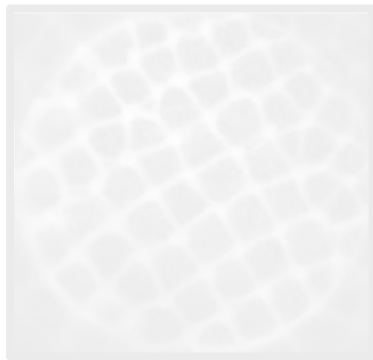


Bayesian
Statistics

Me



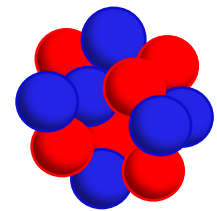
Pattern formation
in vibrated sand



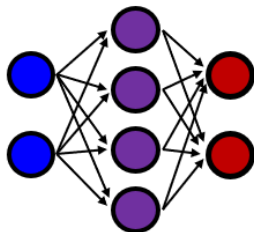
Education

Outreach

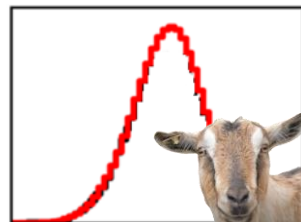
Community



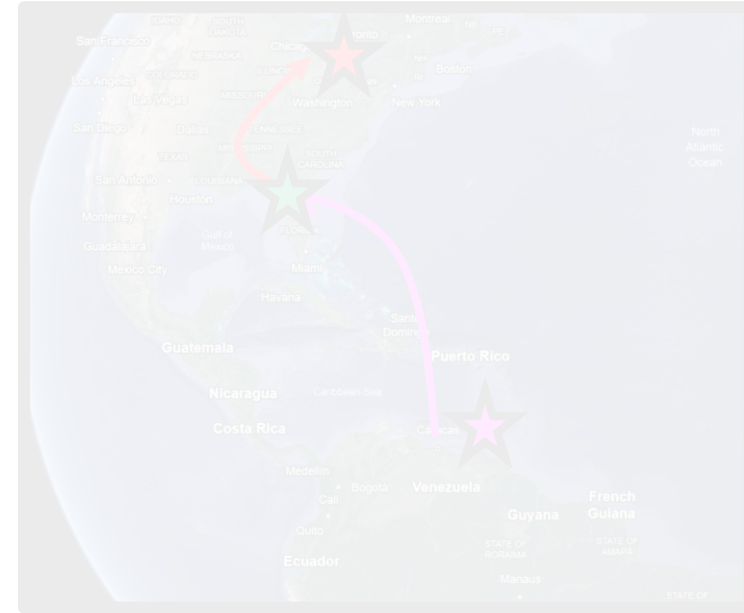
Nuclear
Physics



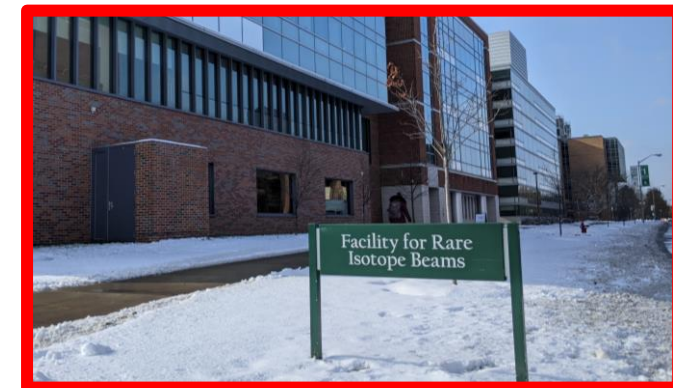
Machine
Learning



Bayesian
Statistics



Venezuela



Michigan

Me



★ Undegrad

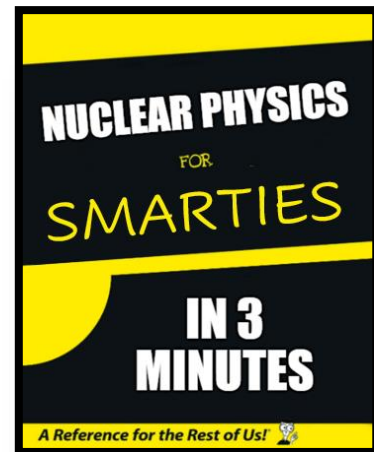
★ PhD

FSU video

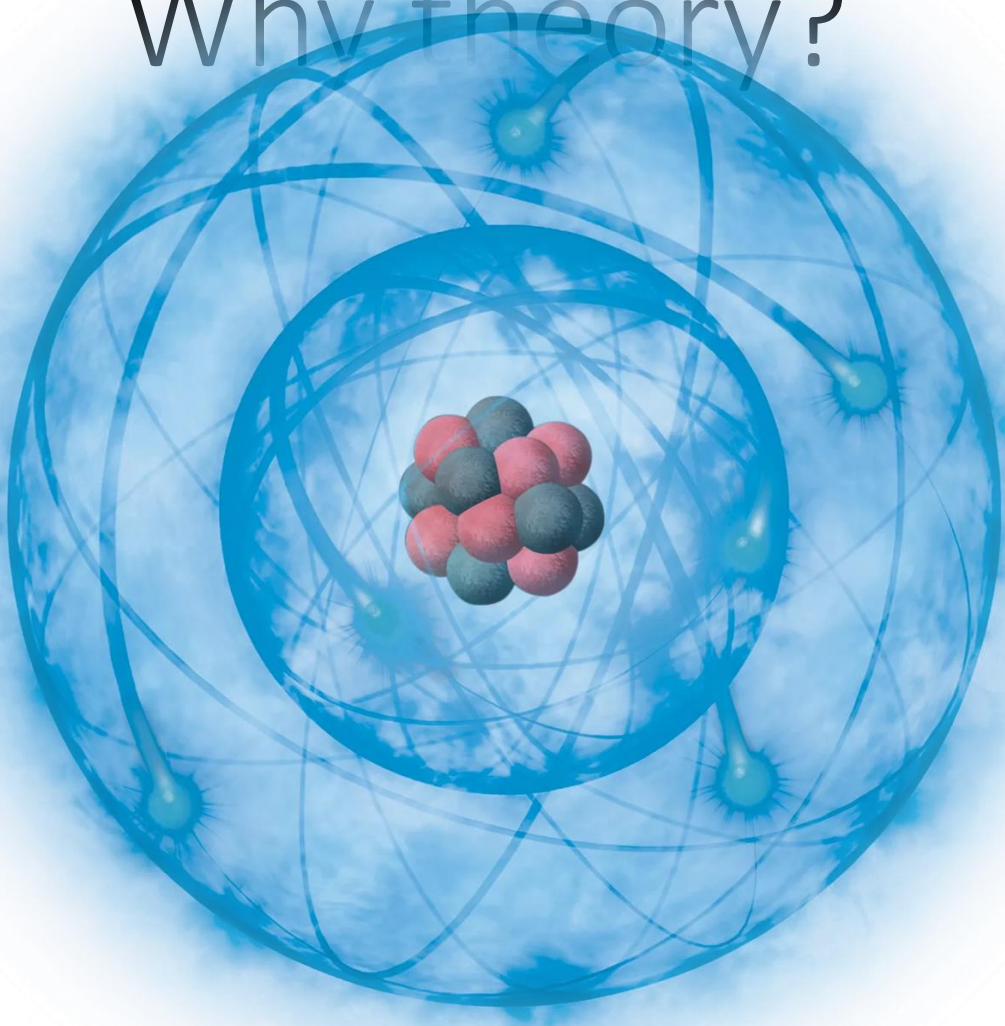


Why theory?

Why theory?



Why theory?



Chemical Periodic Table

1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
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37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Caesium	56 Ba Barium	57 La Lanthanum	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89 Ac Actinium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson
58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium				
90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium				

An atom

NUCLEAR PHYSICS
FOR
SMARTIES
IN 3
MINUTES
A Reference for the Rest of Us!

Why theory?

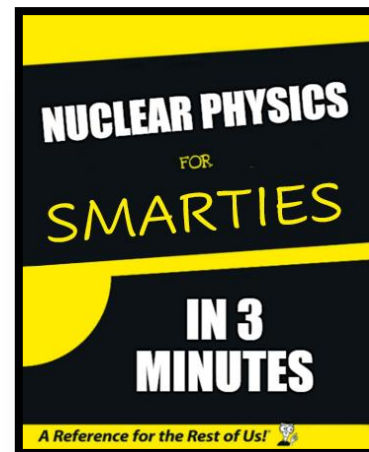
Chemical Periodic Table

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37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
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90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium				

An atom

Nucleus

Electrons



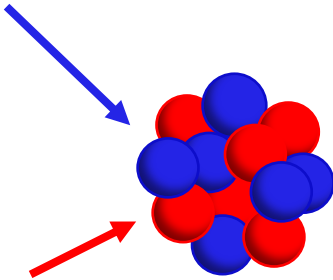
Why theory?

Neutrons

N

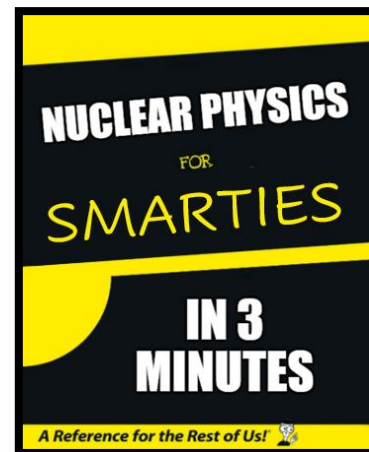
Protons

Z



} A nucleus

Chemical Periodic Table



Why theory?

Chemical Periodic Table

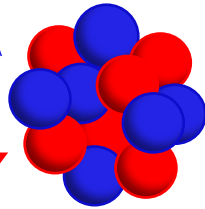
1 H Hydrogen																	2 He Helium
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Neutrons

N

Protons

Z

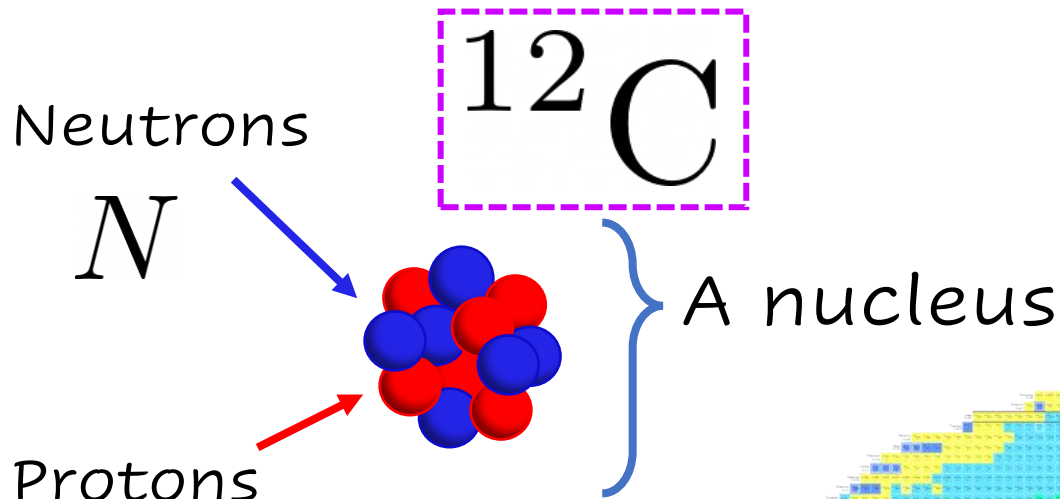


A nucleus

N

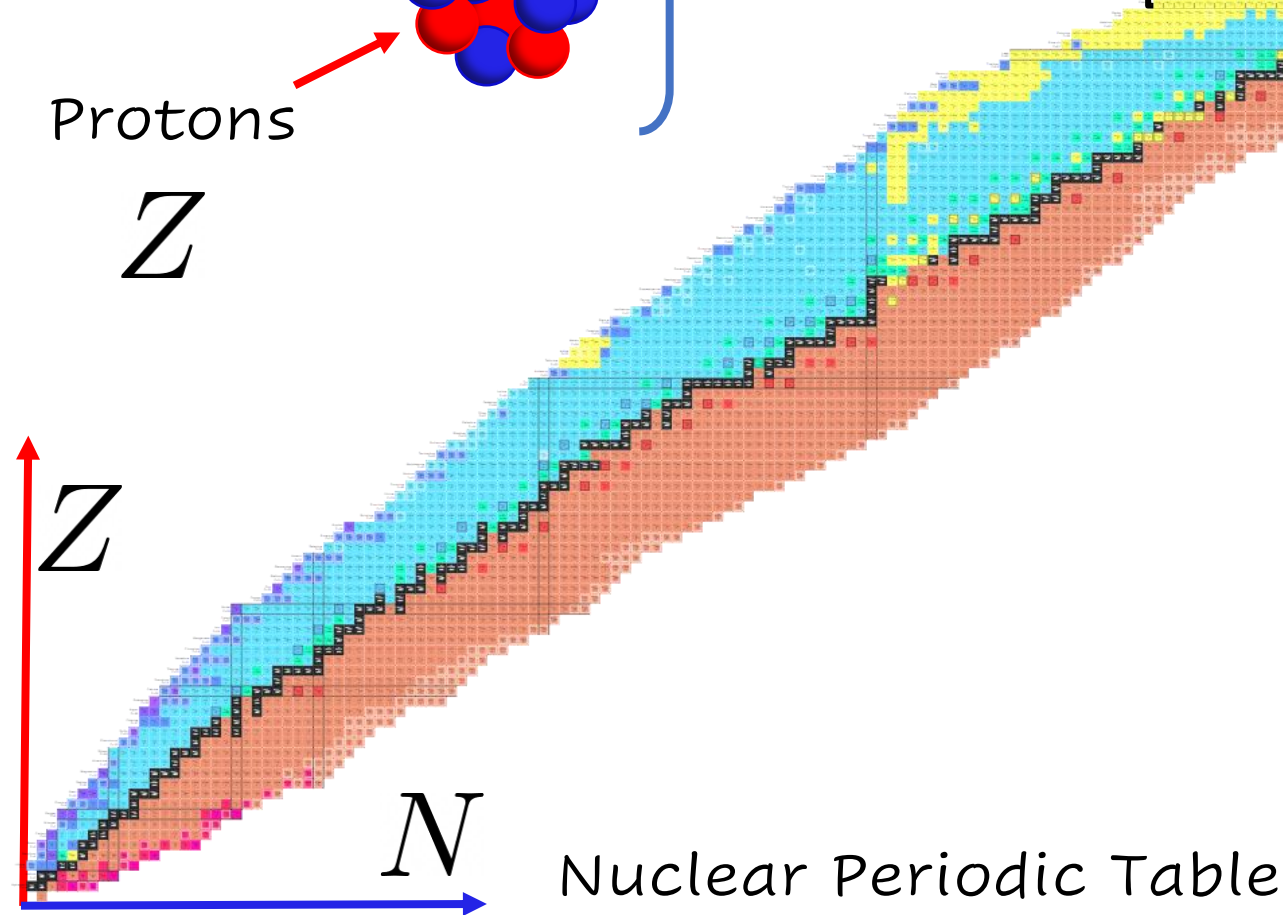
Nuclear Periodic Table

Why theory?



Chemical Periodic Table

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Why theory?

Chemical Periodic Table

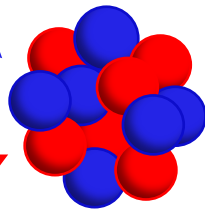
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37	Rb Rubidium	38	Sr Strontium	39	Y Yttrium	40	Zr Zirconium	41	Nb Niobium	42	Mo Molybdenum	43	Tc Technetium	44	Ru Ruthenium	45	Rh Rhodium	46	Pd Palladium	47	Ag Silver	48	Cd Cadmium	49	In Indium	50	Sn Tin	51	Sb Antimony	52	Te Tellurium	53	I Iodine	54	Xe Xenon
55	Cs Caesium	56	Ba Barium	57	La Lanthanum	58	Hf Hafnium	59	Ta Tantalum	60	W Tungsten	61	Re Rhenium	62	Os Osmium	63	Ir Iridium	64	Pt Platinum	65	Au Gold	66	Hg Mercury	67	Tl Thallium	68	Pb Lead	69	Bi Bismuth	70	Po Polonium	71	At Astatine	72	Rn Radon
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Neutrons

N

Protons

Z



^{12}C

A nucleus

Z

N

Nuclear Periodic Table

Hydrogen $Z=1$	^1H Stable	^2H Stable	^3H β^-	^4H n	^5H $2n$	^6H n	^7H $2n$											
Helium $Z=2$	^3He Stable	^4He Stable	^5He n	^6He β^-	^7He β^-	^8He β^-	^9He n	^{10}He $2n$										
Lithium $Z=3$	^3Li β^-	^4Li β^-	^5Li Stable	^6Li Stable	^7Li Stable	^8Li β^-	^9Li n	^{10}Li n	^{11}Li n	^{12}Li n	^{13}Li $2n$							
Beryllium $Z=4$	^5Be β^-	^6Be β^-	^7Be β^-	^8Be α	^9Be Stable	^{10}Be β^-	^{11}Be β^-	^{12}Be β^-	^{13}Be n	^{14}Be β^-	^{15}Be n	^{16}Be $2n$						
Boron $Z=5$	^6B β^-	^7B β^-	^8B β^-	^9B β^-	^{10}B Stable	^{11}B Stable	^{12}B β^-	^{13}B β^-	^{14}B β^-	^{15}B β^-	^{16}B n	^{17}B β^-	^{18}B β^-	^{19}B β^-	^{20}B β^-	^{21}B $2n$		
Carbon $Z=6$	^8C β^-	^9C β^-	^{10}C β^-	^{11}C β^-	^{12}C Stable	^{13}C Stable	^{14}C β^-	^{15}C β^-	^{16}C β^-	^{17}C β^-	^{18}C β^-	^{19}C β^-	^{20}C β^-	^{21}C β^-	^{22}C n	^{23}C n		
Nitrogen $Z=7$	^{10}N β^-	^{11}N β^-	^{12}N β^-	^{13}N β^-	^{14}N Stable	^{15}N Stable	^{16}N β^-	^{17}N β^-	^{18}N β^-	^{19}N β^-	^{20}N β^-	^{21}N β^-	^{22}N β^-	^{23}N β^-	^{24}N n	^{25}N n		
Oxygen $Z=8$	^{11}O β^-	^{12}O β^-	^{13}O β^-	^{14}O β^-	^{15}O β^-	^{16}O Stable	^{17}O Stable	^{18}O Stable	^{19}O β^-	^{20}O β^-	^{21}O β^-	^{22}O β^-	^{23}O β^-	^{24}O β^-	^{25}O β^-	^{26}O n	^{27}O n	^{28}O n
Fluorine $Z=9$	^{13}F β^-	^{14}F β^-	^{15}F β^-	^{16}F β^-	^{17}F β^-	^{18}F β^-	^{19}F Stable	^{20}F β^-	^{21}F β^-	^{22}F β^-	^{23}F β^-	^{24}F β^-	^{25}F β^-	^{26}F β^-	^{27}F β^-	^{28}F n		
Neon $Z=10$	^{15}Ne β^-	^{16}Ne β^-	^{17}Ne β^-	^{18}Ne β^-	^{19}Ne β^-	^{20}Ne Stable	^{21}Ne Stable	^{22}Ne Stable	^{23}Ne β^-	^{24}Ne β^-	^{25}Ne β^-	^{26}Ne β^-	^{27}Ne β^-	^{28}Ne β^-	^{29}Ne β^-			

Rare Isotopes

Rare Isotopes

Why theory?

Chemical Periodic Table



A standard chemical periodic table with elements color-coded by groups. The FRIB logo, featuring a stylized atom and human figures, is overlaid on the right side of the table.

FRIB

Facility for Rare Isotope Beams



A nuclear periodic table showing isotopes of elements from Hydrogen (Z=1) to Neon (Z=10). The table is color-coded by the number of protons (Z) and neutrons (N). Stable isotopes are shown in black, while unstable ones are in various colors. The table is labeled with 'Z' for atomic number and 'N' for neutron number.

Neon Z=10	¹⁵ Ne	¹⁶ Ne	¹⁷ Ne	¹⁸ Ne	¹⁹ Ne	²⁰ Ne	²¹ Ne	²² Ne	²³ Ne	²⁴ Ne	²⁵ Ne	²⁶ Ne	²⁷ Ne	²⁸ Ne	²⁹ Ne		
Fluorine Z=9	¹³ F	¹⁴ F	¹⁵ F	¹⁶ F	¹⁷ F	¹⁸ F	¹⁹ F	²⁰ F	²¹ F	²² F	²³ F	²⁴ F	²⁵ F	²⁶ F	²⁷ F	²⁸ F	
Oxygen Z=8	¹¹ O	¹² O	¹³ O	¹⁴ O	¹⁵ O	¹⁶ O	¹⁷ O	¹⁸ O	¹⁹ O	²⁰ O	²¹ O	²² O	²³ O	²⁴ O	²⁵ O	²⁶ O	²⁷ O
Nitrogen Z=7	¹⁰ N	¹¹ N	¹² N	¹³ N	¹⁴ N	¹⁵ N	¹⁶ N	¹⁷ N	¹⁸ N	¹⁹ N	²⁰ N	²¹ N	²² N	²³ N	²⁴ N	²⁵ N	
Carbon Z=6	⁸ C	⁹ C	¹⁰ C	¹¹ C	¹² C	¹³ C	¹⁴ C	¹⁵ C	¹⁶ C	¹⁷ C	¹⁸ C	¹⁹ C	²⁰ C	²¹ C	²² C	²³ C	
Boron Z=5	⁶ B	⁷ B	⁸ B	⁹ B	¹⁰ B	¹¹ B	¹² B	¹³ B	¹⁴ B	¹⁵ B	¹⁶ B	¹⁷ B	¹⁸ B	¹⁹ B	²⁰ B	²¹ B	
Beryllium Z=4	⁵ Be	⁶ Be	⁷ Be	⁸ Be	⁹ Be	¹⁰ Be	¹¹ Be	¹² Be	¹³ Be	¹⁴ Be	¹⁵ Be	¹⁶ Be					
Lithium Z=3	³ Li	⁴ Li	⁵ Li	⁶ Li	⁷ Li	⁸ Li	⁹ Li	¹⁰ Li	¹¹ Li	¹² Li	¹³ Li						
Helium Z=2	³ He	⁴ He	⁵ He	⁶ He	⁷ He	⁸ He	⁹ He	¹⁰ He									
Hydrogen Z=1	¹ H	² H	³ H	⁴ H	⁵ H	⁶ H	⁷ H										
	¹ n																

Rare Isotopes

Rare Isotopes

Nuclear Periodic Table

The colorful chart of nuclei
<https://people.physics.anu.edu.au/~ecs103/chart/>

A circular illustration of a wooden sailing ship with blue and white striped sails, navigating through a turbulent sea with large, white-capped waves. In the background, there are mountains and a small island with a tree under a blue sky with clouds.

Premiering 2024



Teaser

Thanks
Agnes
Mocsy!



FRIB

Facility for Rare Isotope Beams

Neon Z=10

Fluorine Z=9

Oxygen Z=8

Nitrogen Z=7

Carbon Z=6

Boron Z=5

Beryllium Z=4

Lithium Z=3

Helium Z=2

Hydrogen Z=1

Rare Isotopes

Rare Isotopes

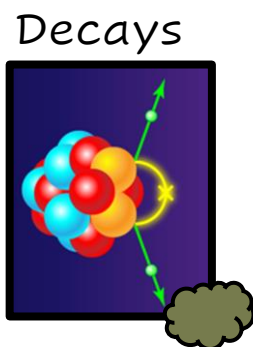
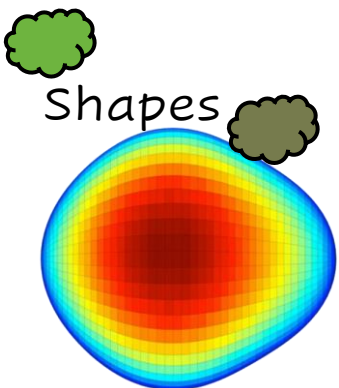
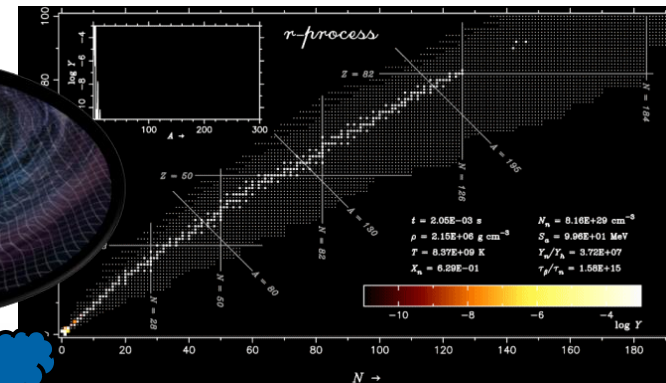
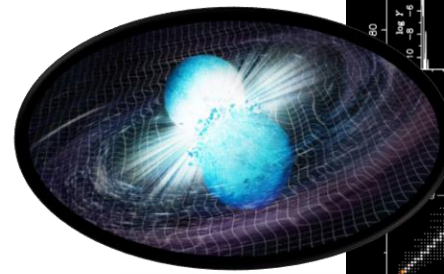
We have fun



[Teaser](#)



Big questions



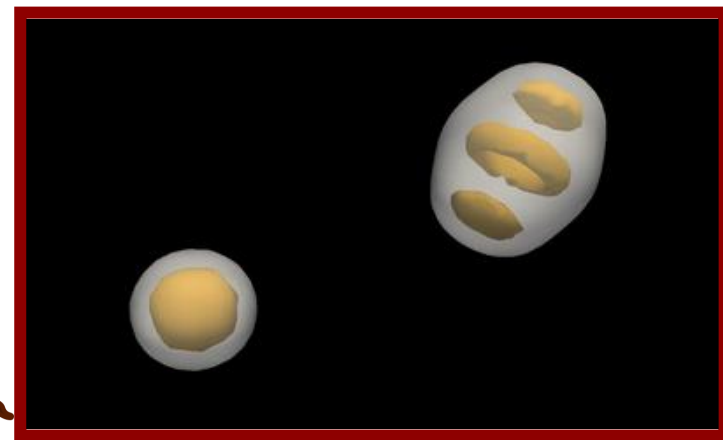
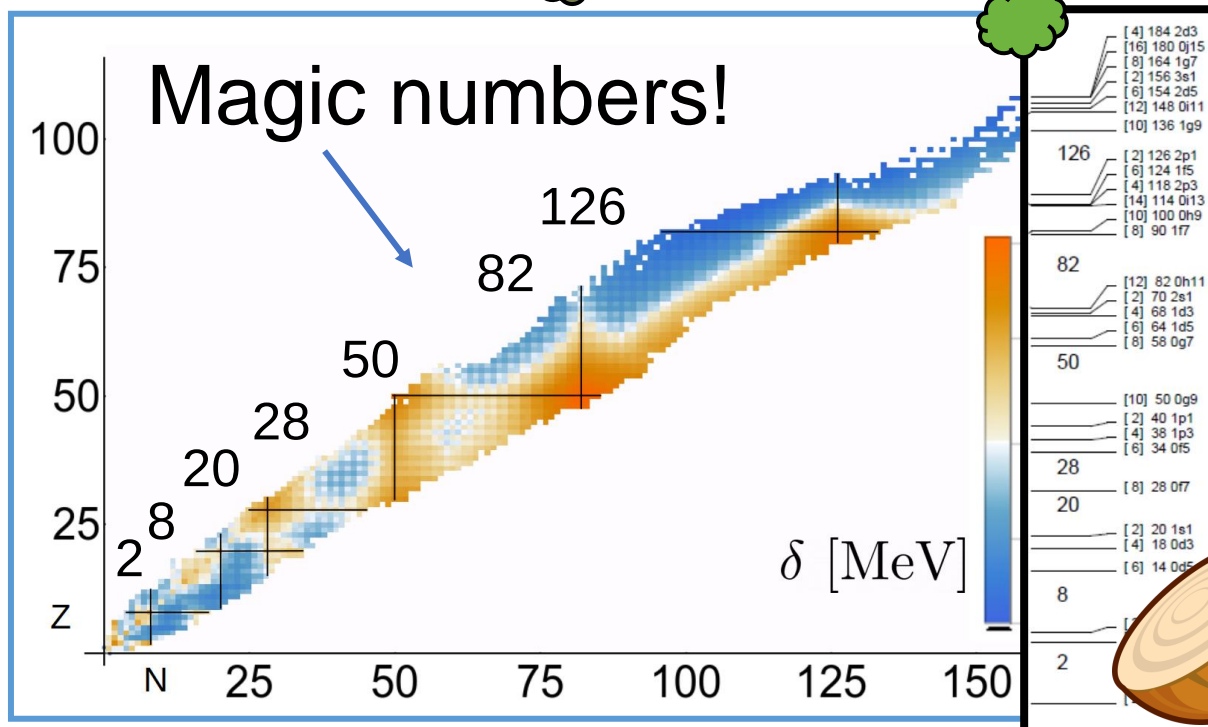
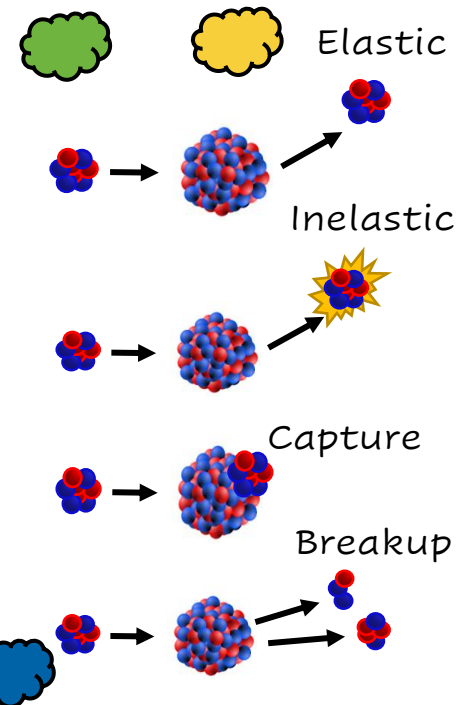
Structure

Astrophysics



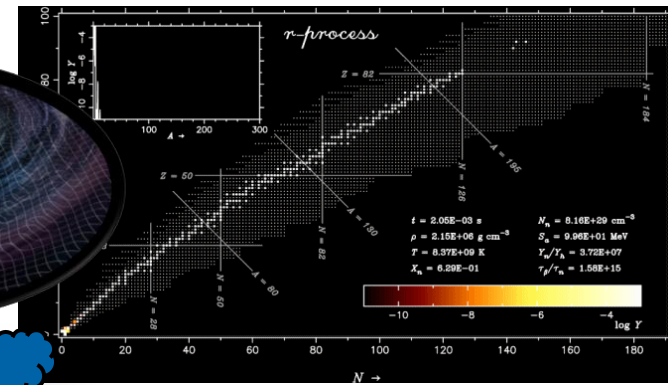
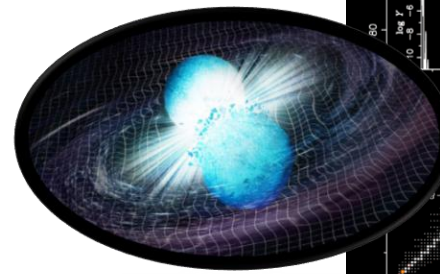
Applications

Symmetries



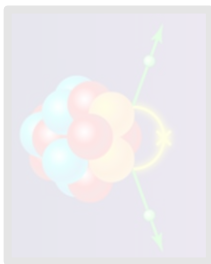
Big questions

Where do heavy elements come from?



Shapes

Decays



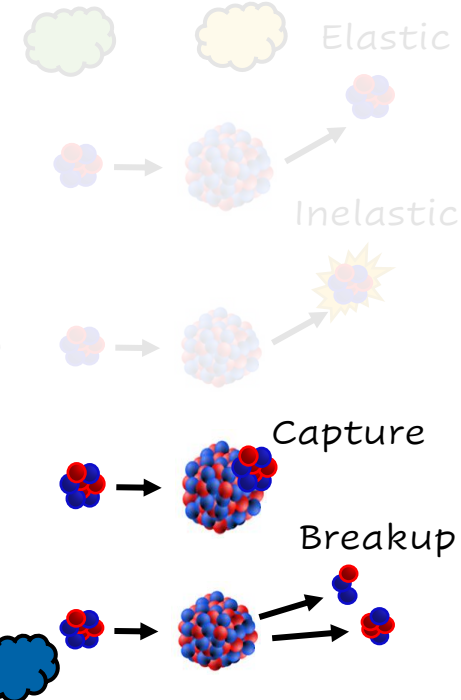
Structure

Astrophysics

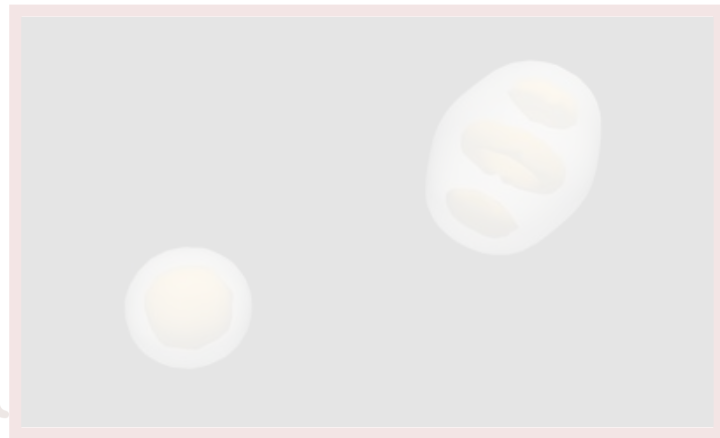
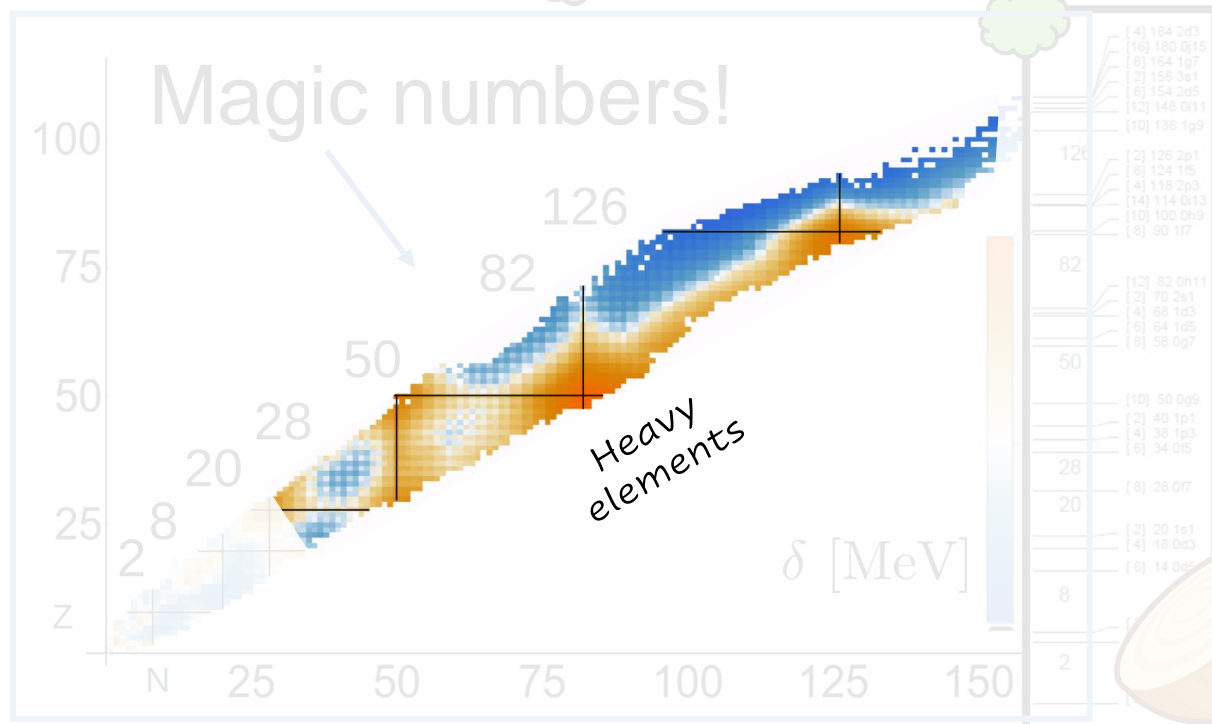


Applications

Symmetries



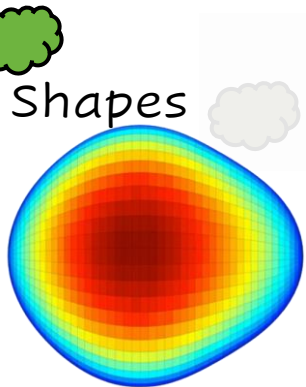
Power



Big questions

What structures form at the extremes?

Where do heavy elements come from?



Decays



Structure

Astrophysics

FRIB

Applications

Symmetries



Power

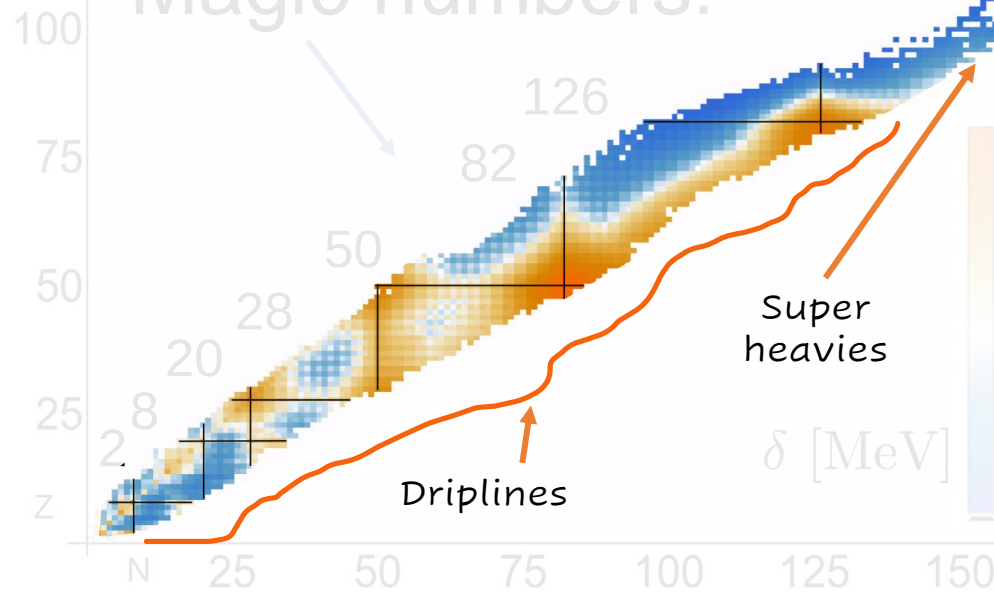
Elastic

Inelastic

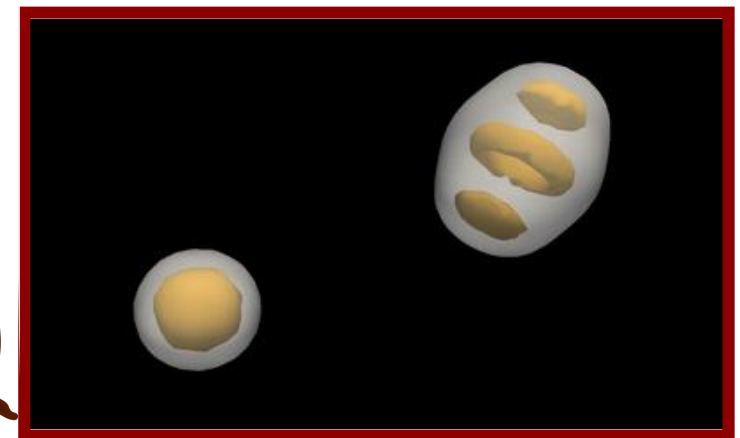
Capture

Breakup

Magic numbers!



[4] 184 2d3	[2] 126 2p1
[16] 180 0i15	[6] 124 1f5
[8] 164 1g7	[4] 118 2p3
[2] 156 3e1	[14] 114 0i13
[6] 154 2d5	[10] 100 0h9
[12] 148 0i11	[8] 90 1i7
[10] 136 1g9	
126	
[2] 126 2p1	[12] 82 0h11
[6] 124 1f5	[2] 70 2e1
[4] 118 2p3	[4] 68 1d3
[14] 114 0i13	[6] 64 1d5
[10] 100 0h9	[8] 58 0g7
[8] 90 1i7	
	82
	[10] 50 0g9
	[2] 40 1p1
	[4] 38 1p3
	[6] 34 0f5
	50
	[8] 28 0f7
	28
	[2] 20 1e1
	[4] 16 0d3
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	20
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	8
	2

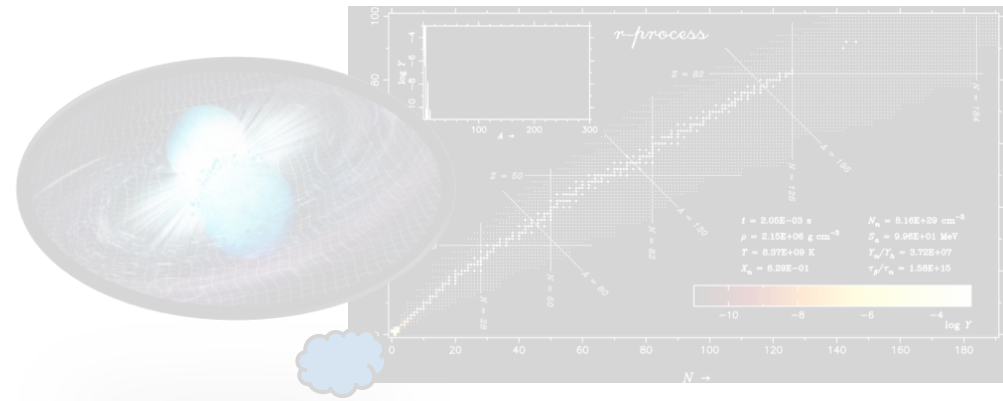


Big questions

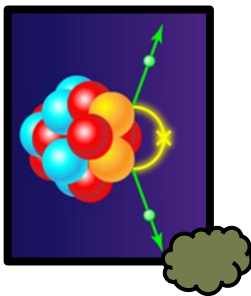
What structures form at the extremes?

Where do heavy elements come from?

What's up with neutrinos?



Decays



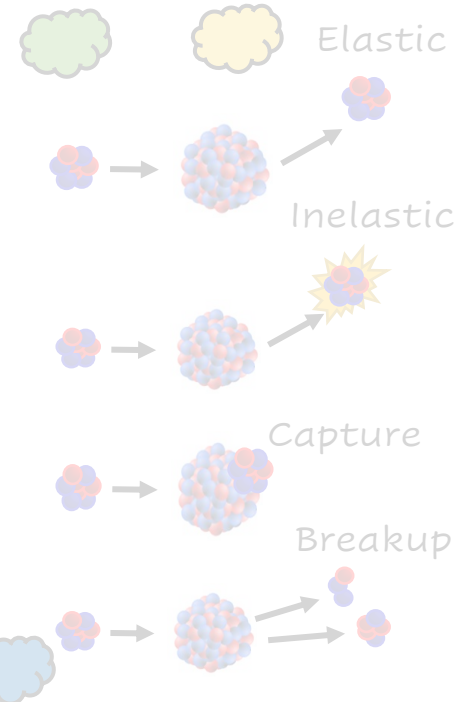
Structure

Astrophysics

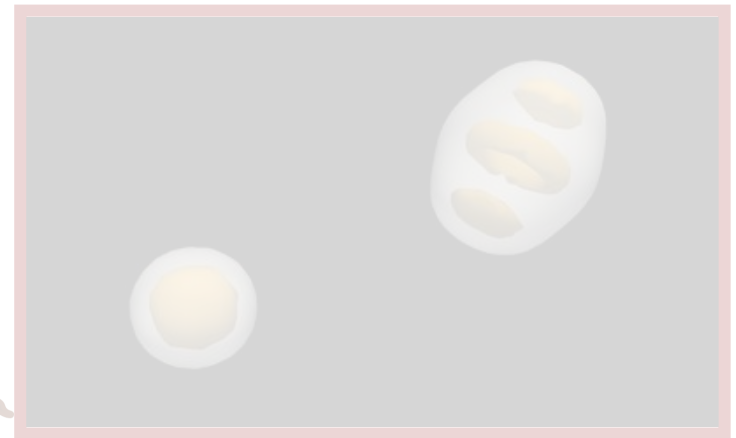
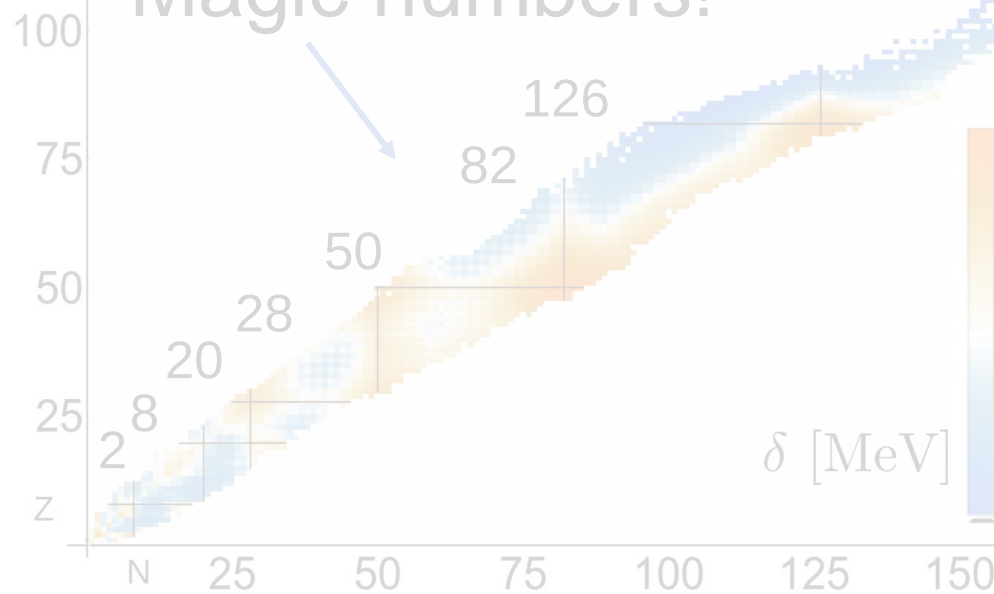
FRIB

Applications

Symmetries



Magic numbers!



Big questions

What structures form at the extremes?

Can we make useful things?

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Applications

Symmetries

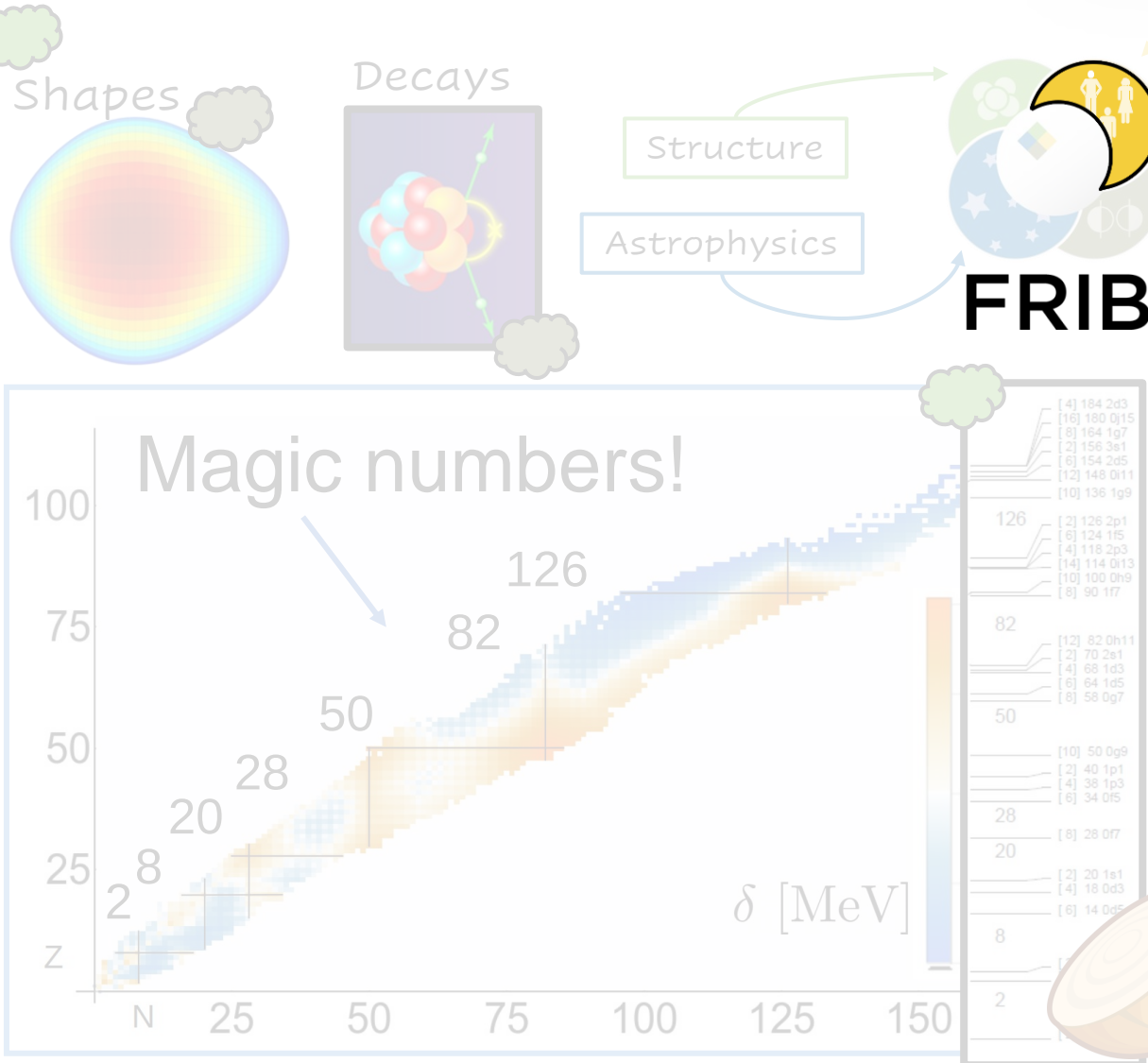
Elastic

Inelastic

Capture

Breakup

Power



Big questions

All of this is really,
really hard to study

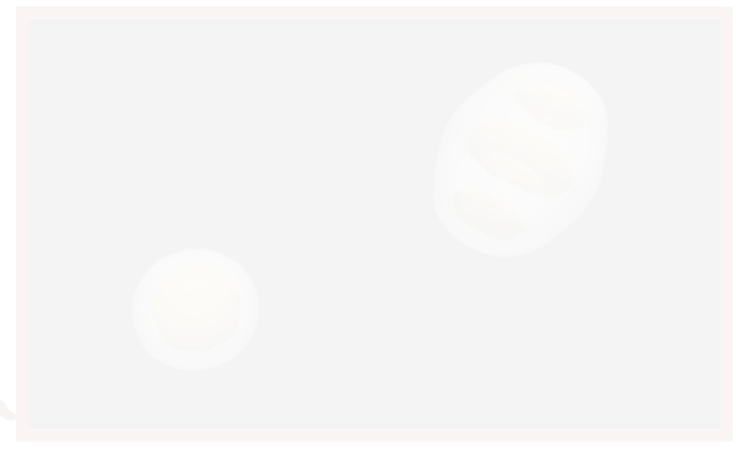
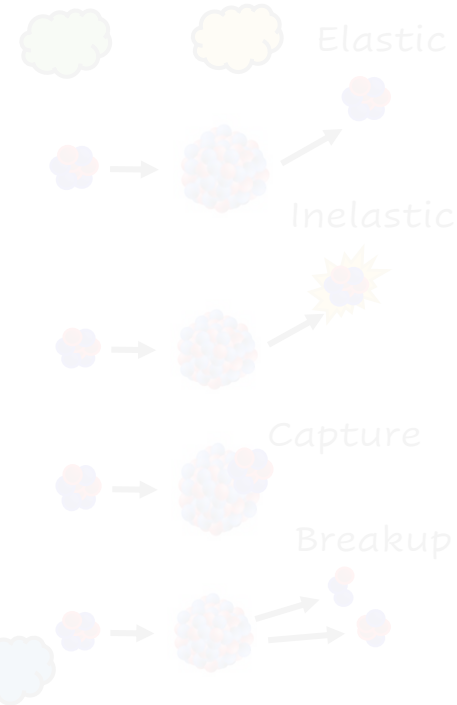


Structure
Astrophysics



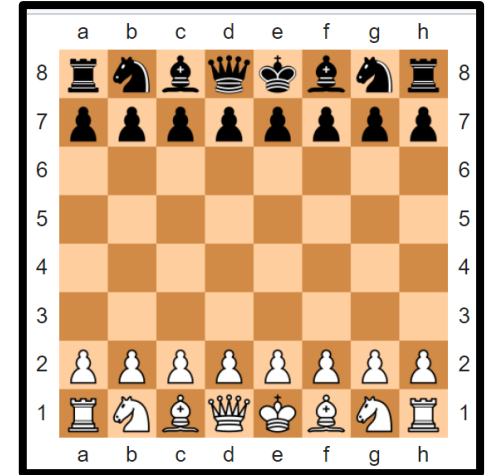
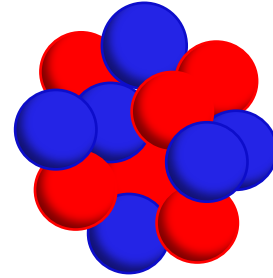
Applications

Symmetries



The Challenge

All of this is really,
really hard to study

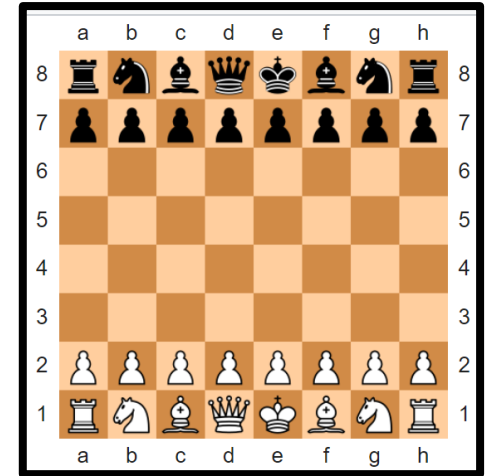
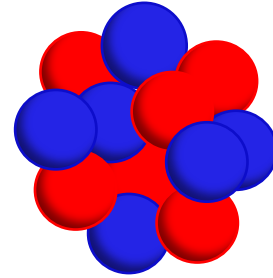


1) Rules are unclear

$$\mathcal{H}|\psi(x, t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(x, t)\rangle$$

The Challenge

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really hard to study



1) Rules are unclear



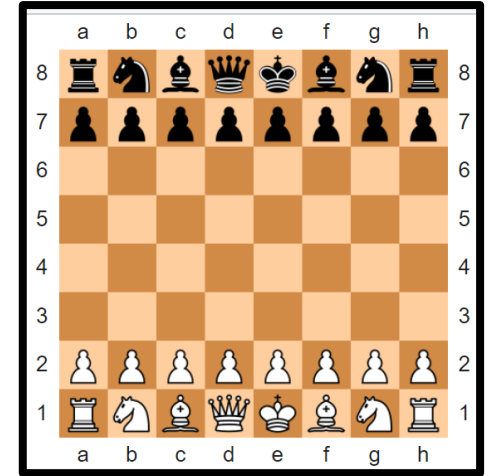
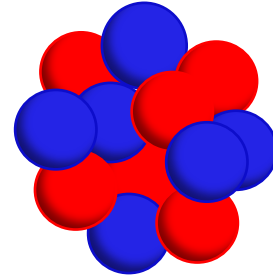
You can watch

... from far
away

$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

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You can watch

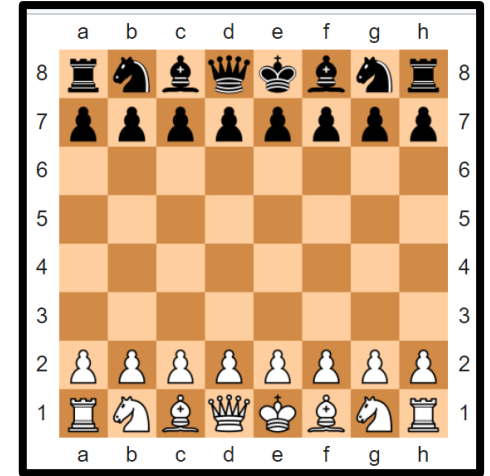
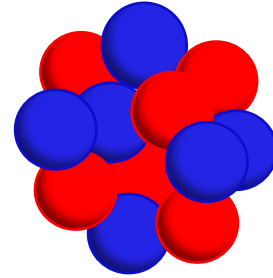
... from far
away

...and is dark

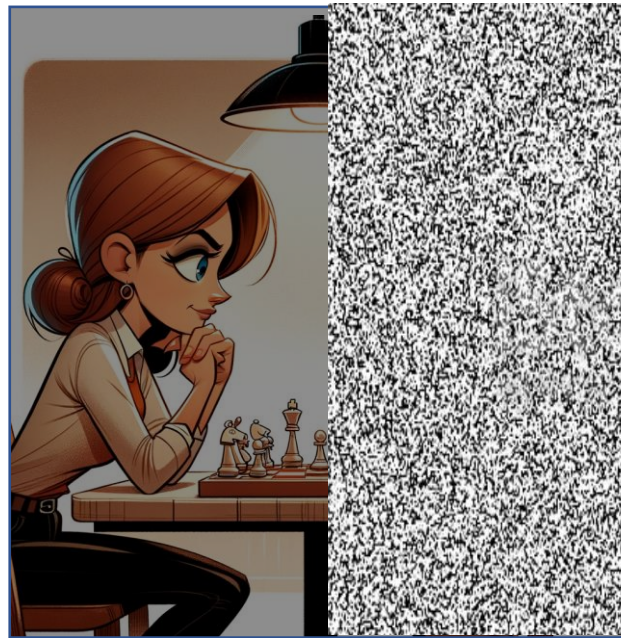
$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

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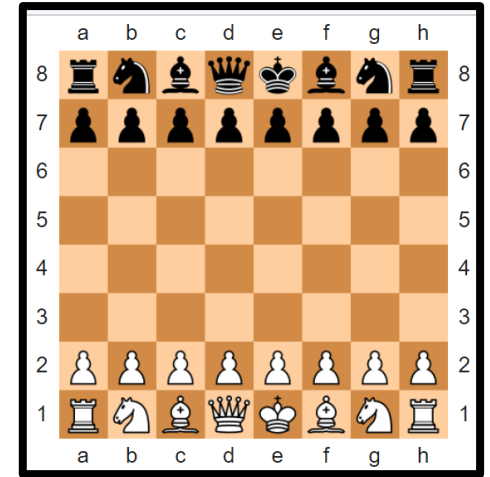
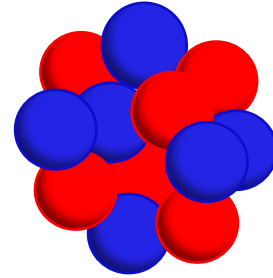
...and is dark

...and half the
screen is broken

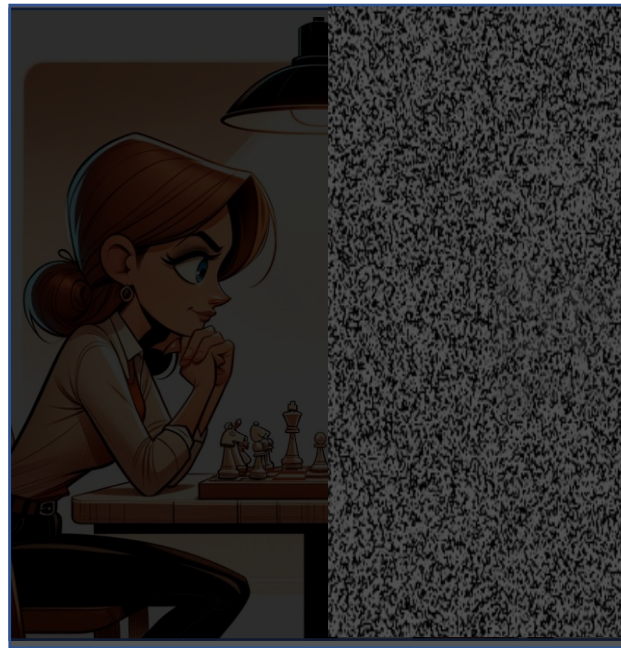
$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

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You can watch

... from far
away

...and is dark

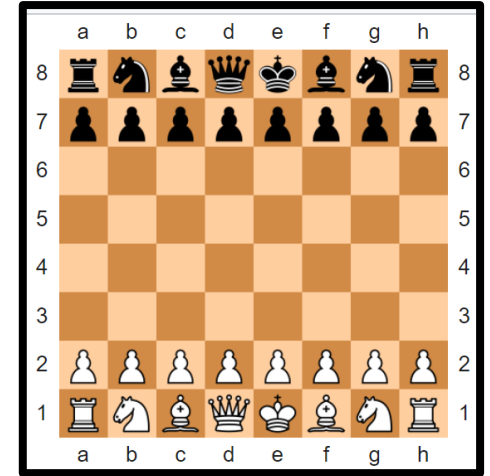
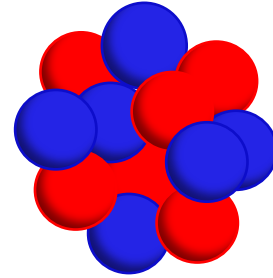
...and half the
screen is broken

...and you are
wearing sunglasses

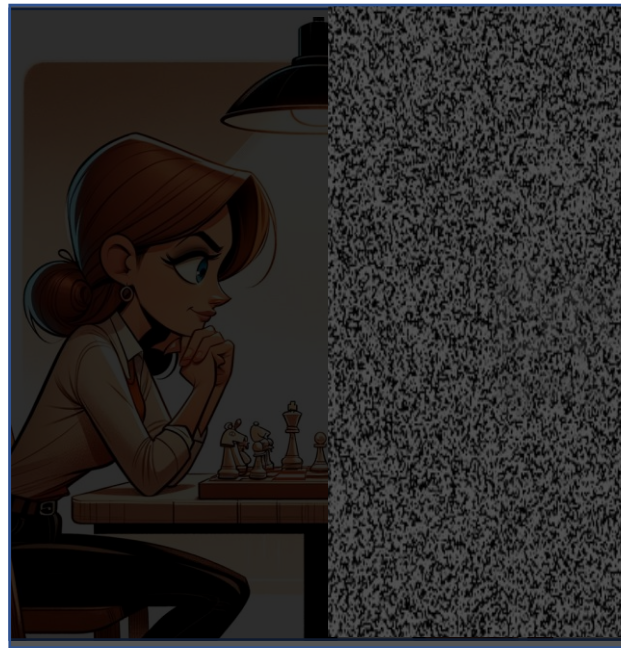
$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

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You can watch


... from far
away

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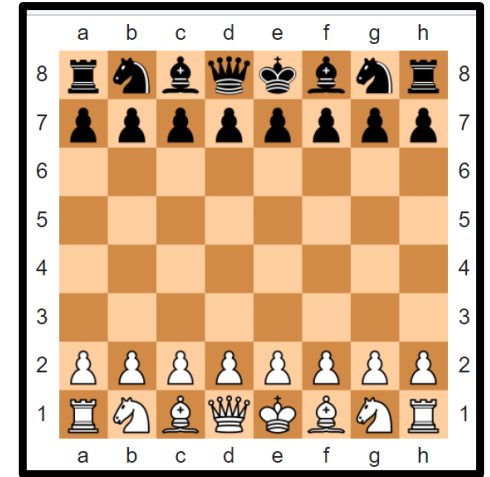
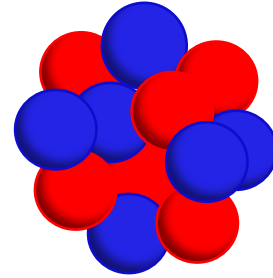
...and you are
wearing sunglasses

... and only one
instant at a time

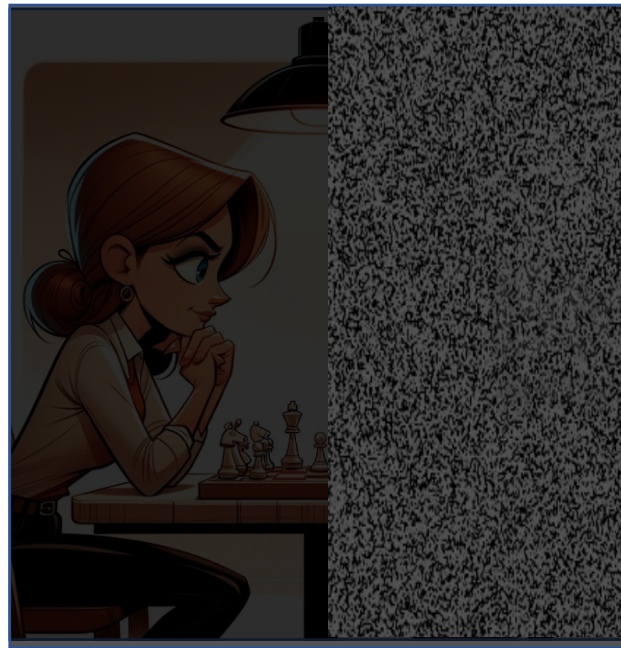
$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$


The Challenge

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You can watch

... from far
away

...and is dark

...and half the
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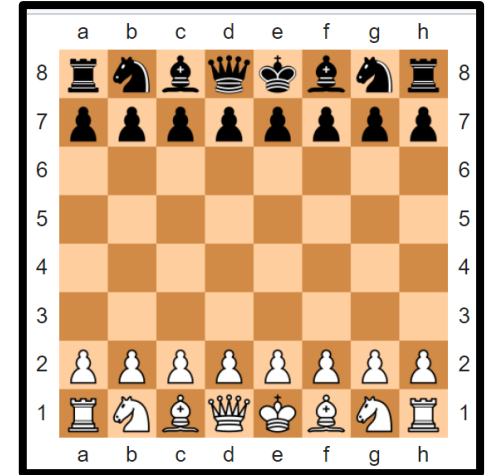
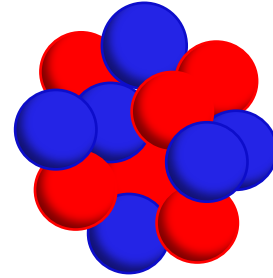
...and you are
wearing sunglasses

Experiment! $\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$

... and only one
instant at a time

The Challenge

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really hard to study

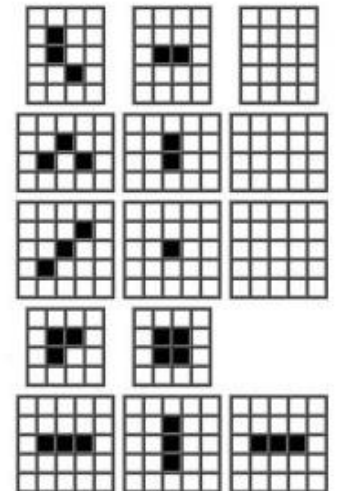


1) Rules are unclear

2) Emergent complexity

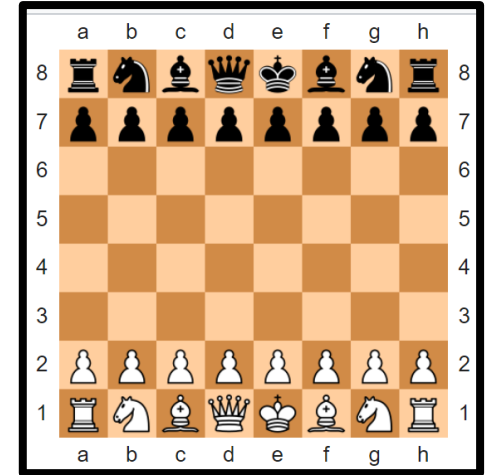
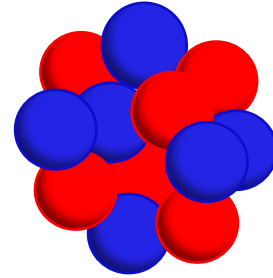
Game of Life

- Each cell has 8 neighbors
 - Survival: 2-3 neighbors
 - Death: 0-1 neighbors (isolation), ≥ 4 neighbors (overcrowding)
 - Births: empty cell with exactly 3 neighbors



The Challenge

All of this is really,
really hard to study



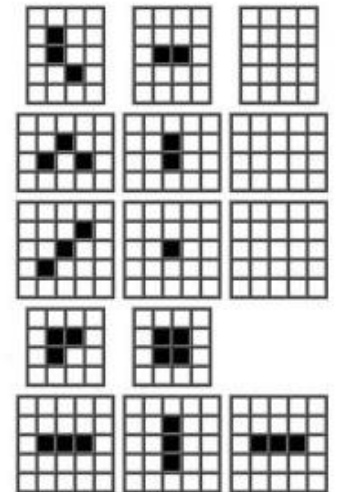
1) Rules are unclear

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Game of Life

- Each cell has 8 neighbors
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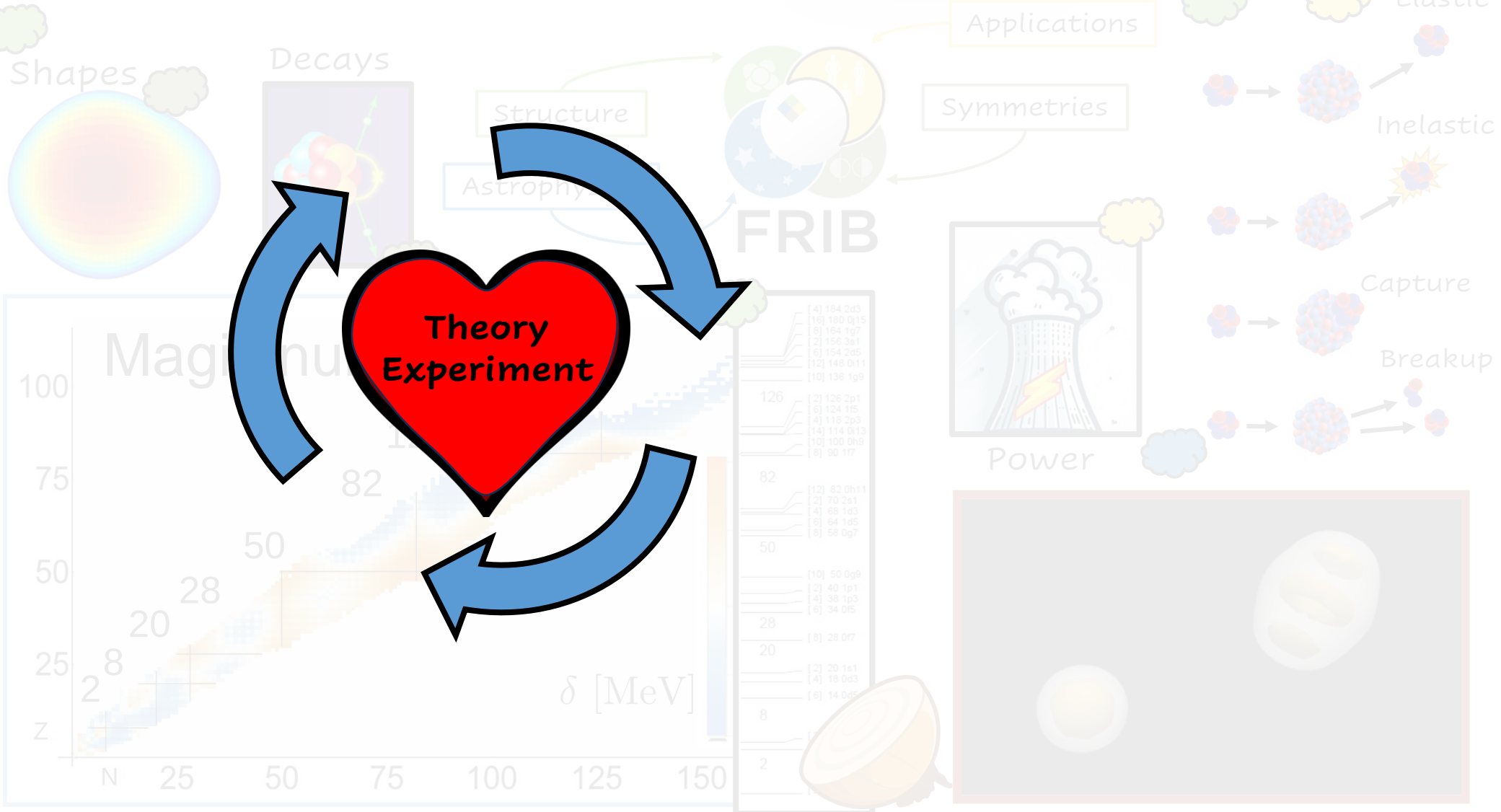
We need theory

What structures form at the extremes?

Can we make useful things?

Where do heavy elements come from?

What's up with neutrinos?



We need theory

What structures form at the extremes?

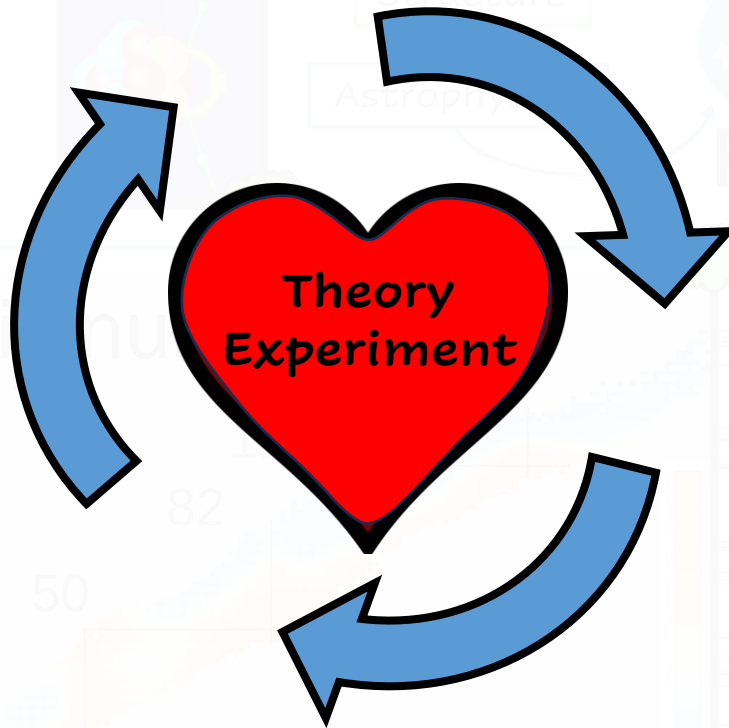
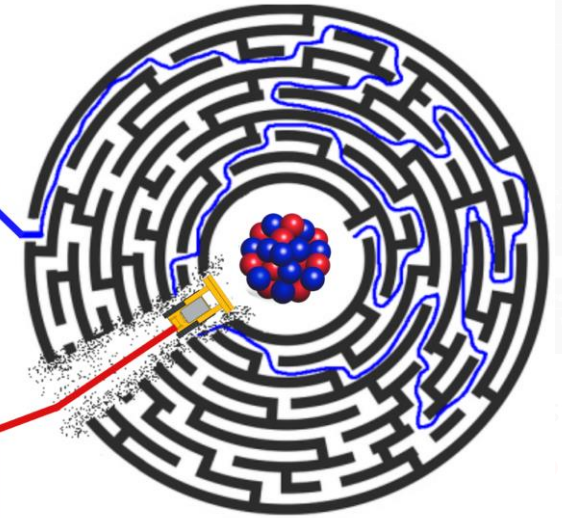
Can we make useful things?

Where do heavy elements come from?

What's up with neutrinos?

Traditional approaches

Dimensionality reduction



[Video of me talking](#)

My research is to use machine learning and statistics to propel this cycle



For today

Who am I?

Why theory?

Building models



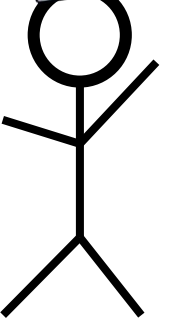
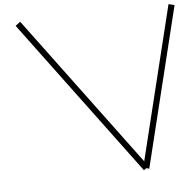
Building a (simple) nuclear model

Quantum mechanics

Building (better) nuclear models

Challenges (Hands-On Session)

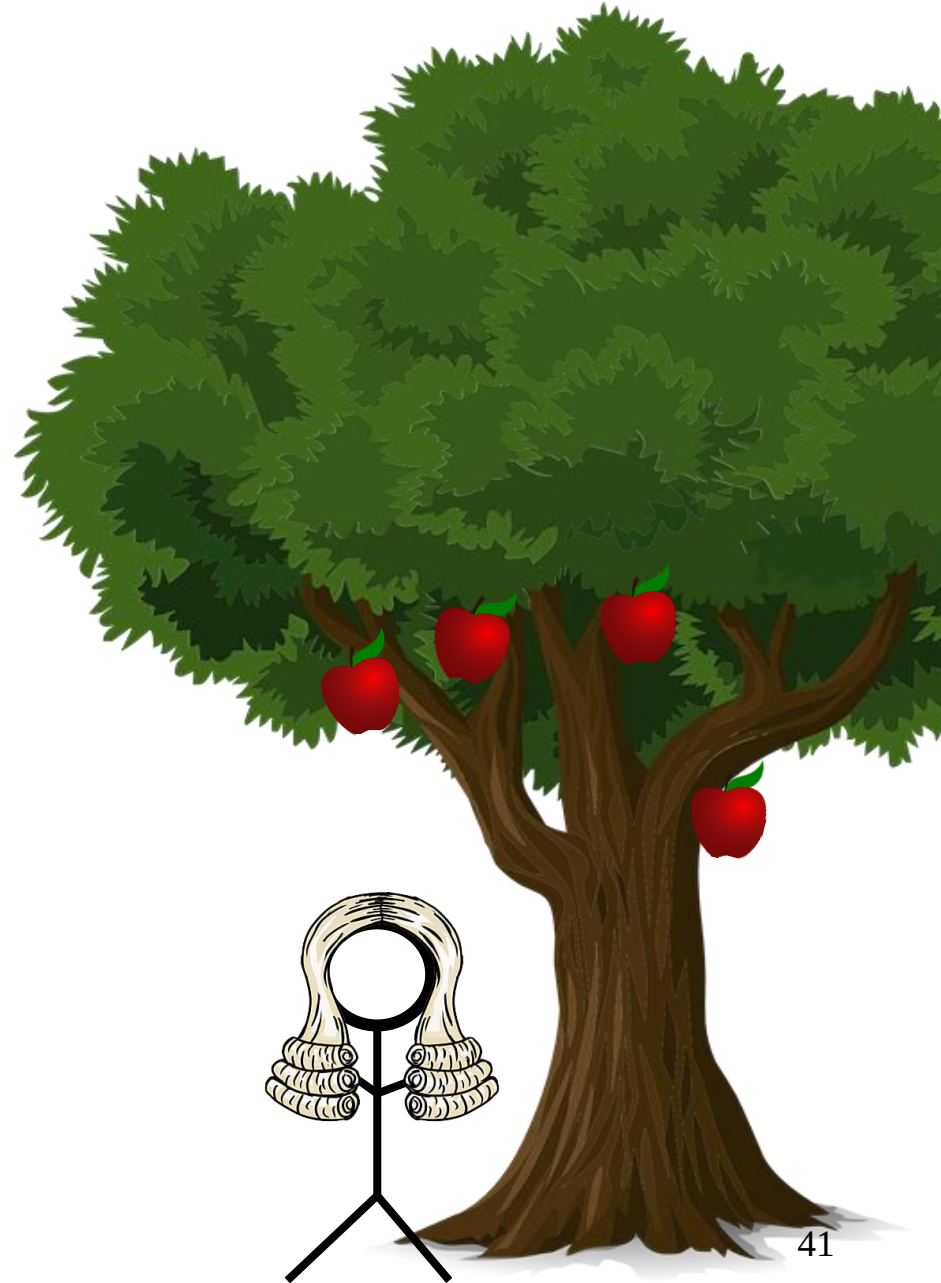
Questions?



Pablo

Building models (planets)

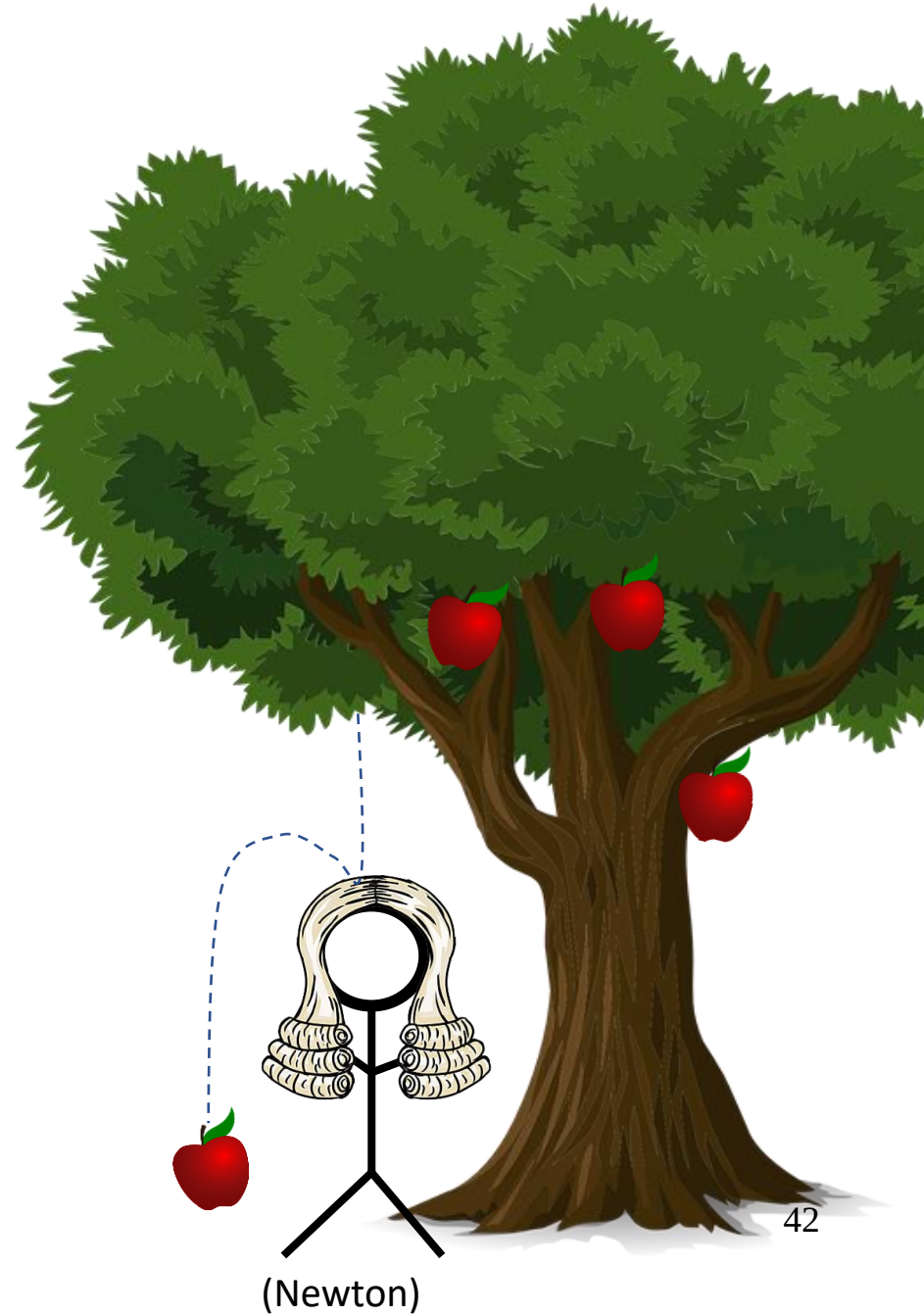
XVII century



(Newton)

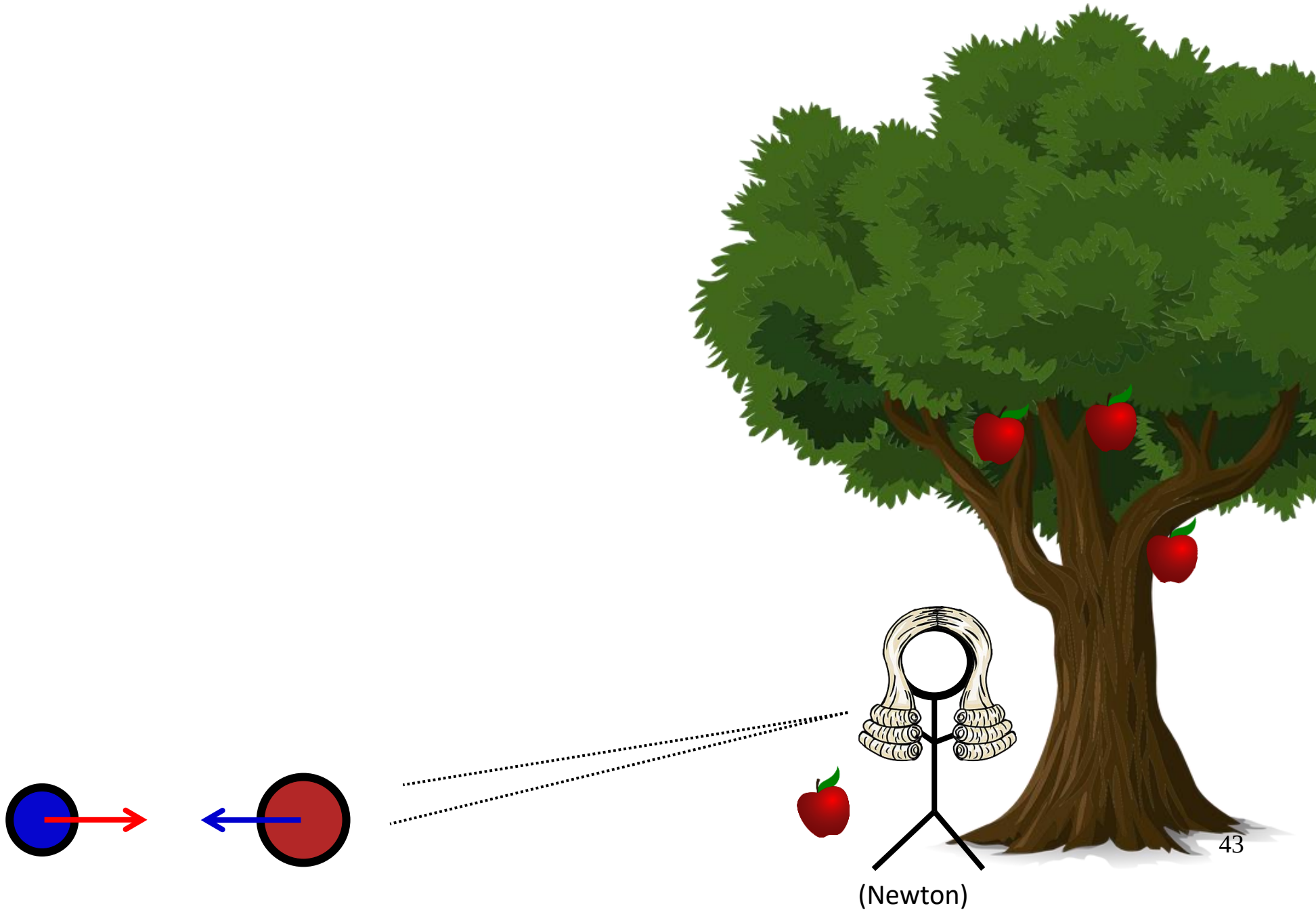
Building models (planets)

XVII century



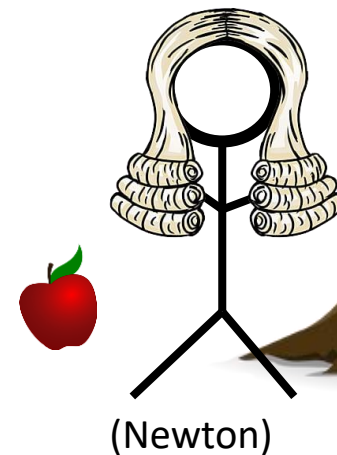
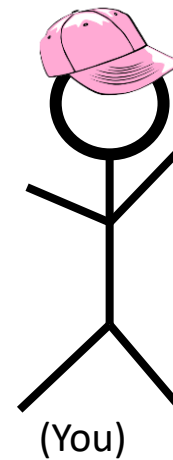
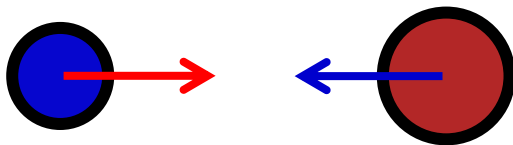
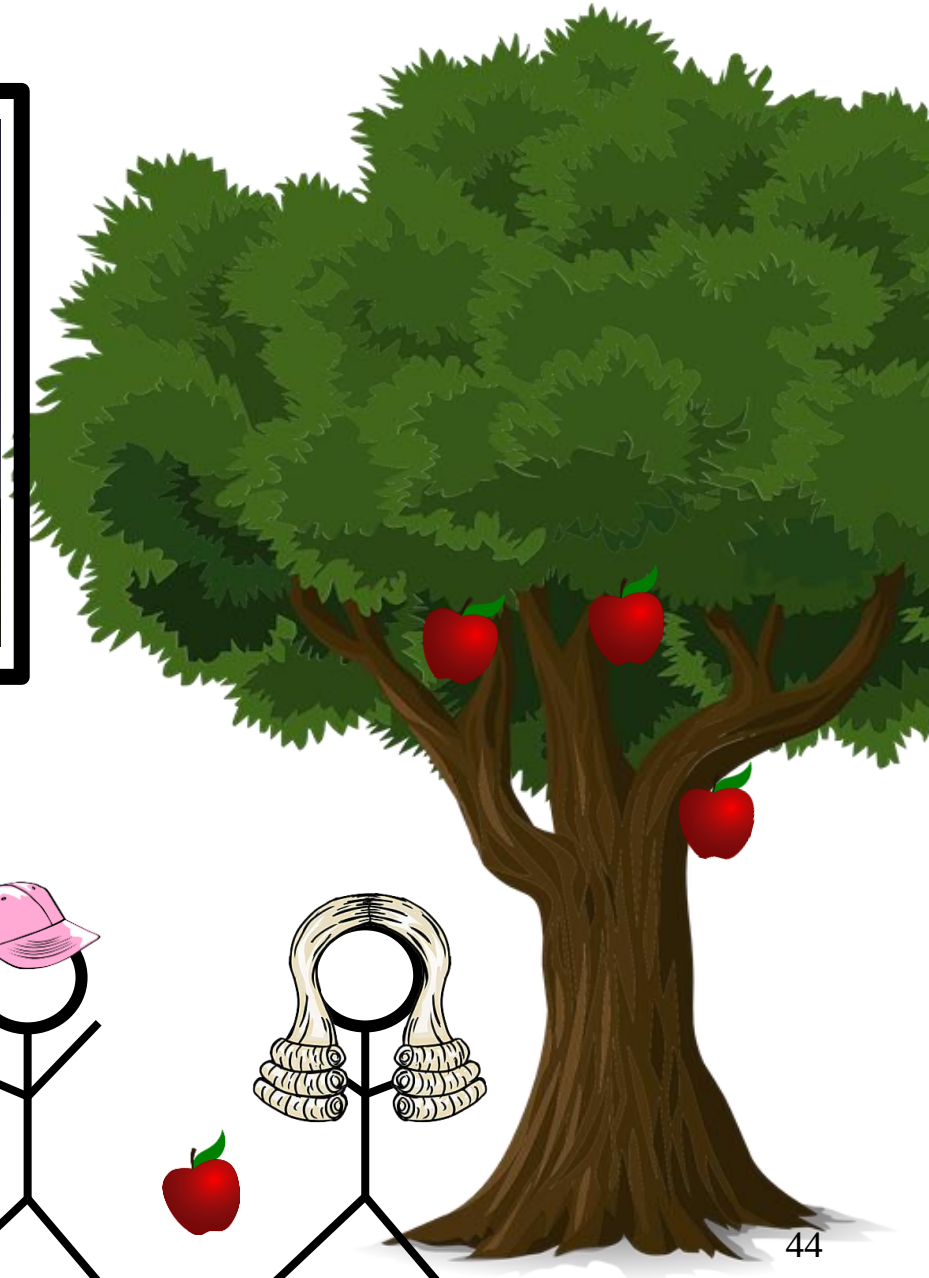
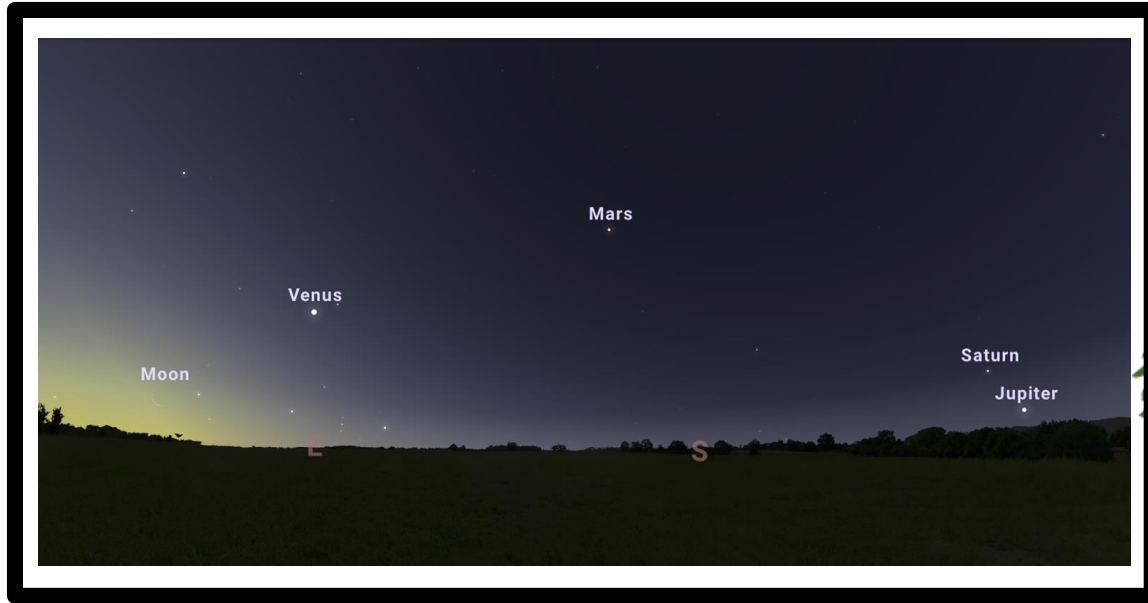
Building models (planets)

XVII century



Building models (planets)

XVII century

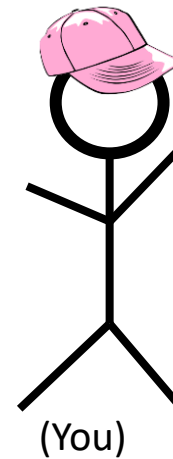
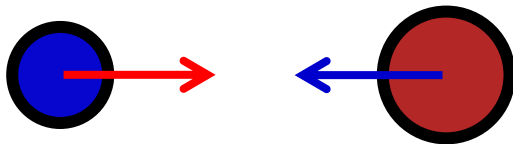


Building models (planets)

XVII century

Behaviors:

.Trajectories

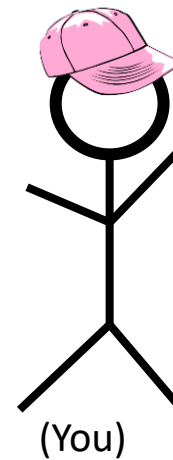
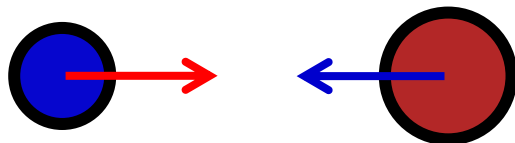


Building models (planets)

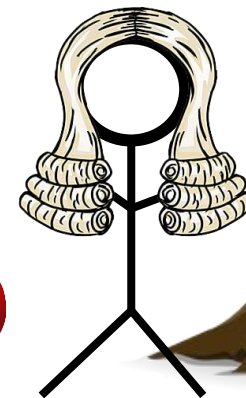
XVII century

Behaviors:

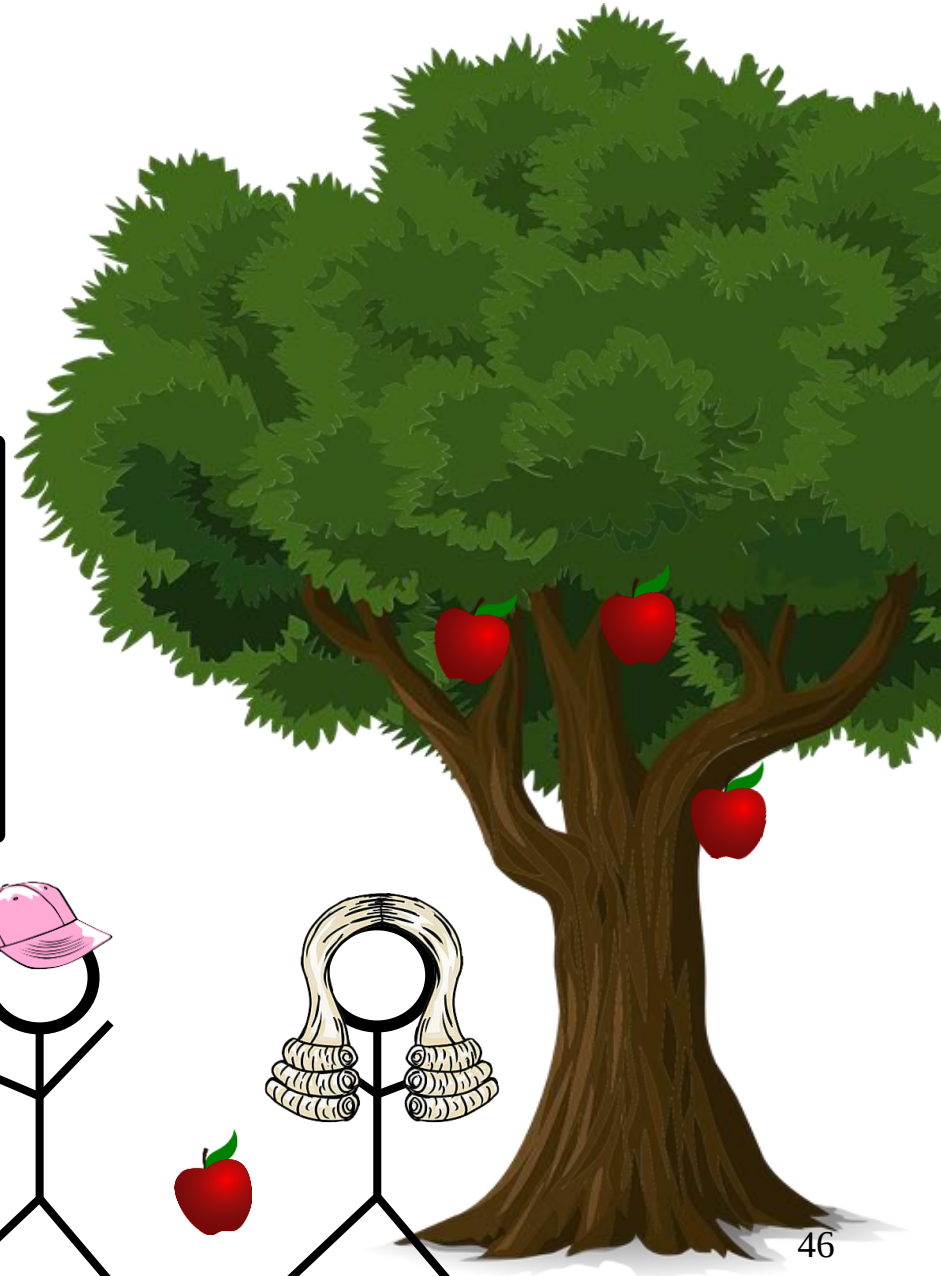
- .Trajectories
- .Structure



(You)



(Newton)

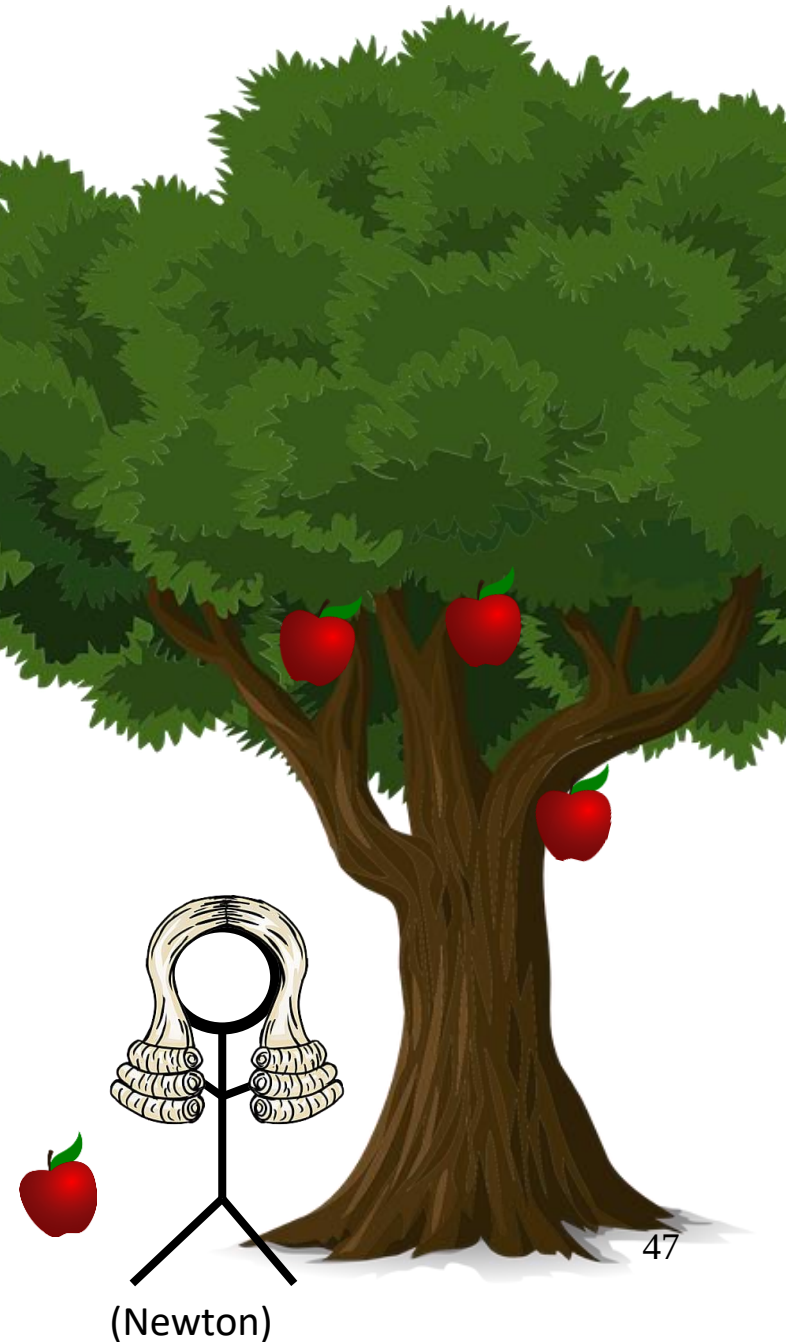
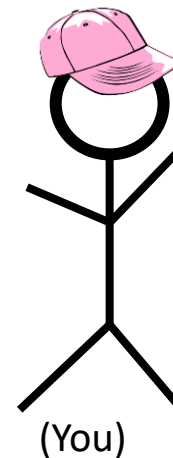
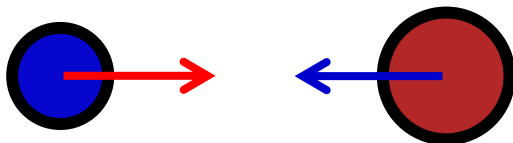


Building models (planets)

XVII century

Behaviors:

- .Trajectories
- .Structure
- .Brightness



Building models (planets)

XVII century

Behaviors:

- .Trajectories
- .Structure
- .Brightness

?



Building models (planets)

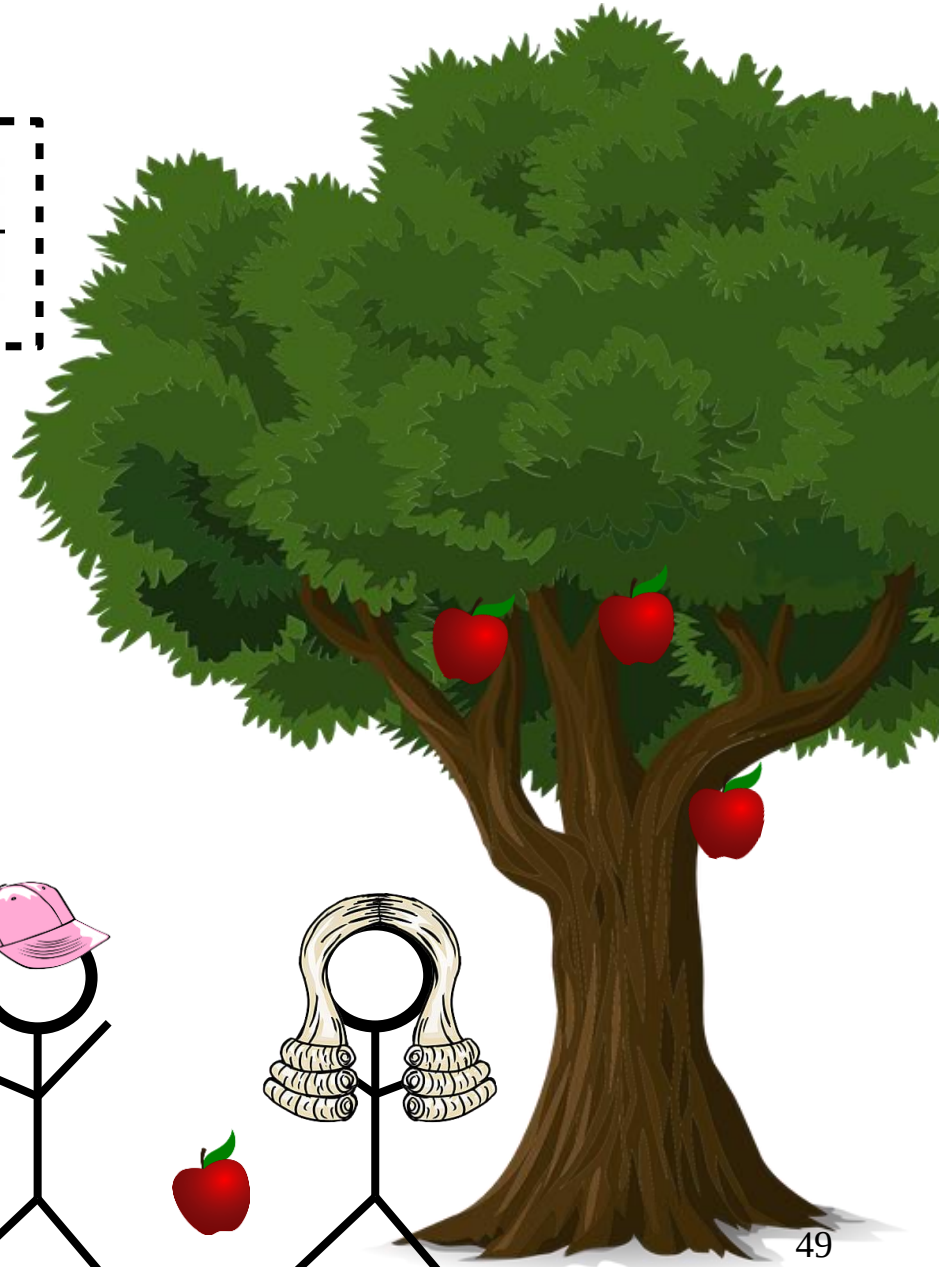
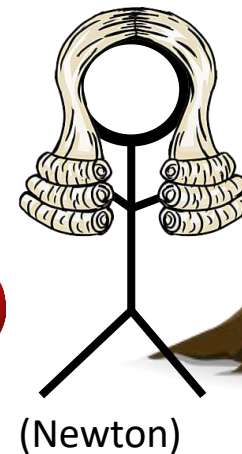
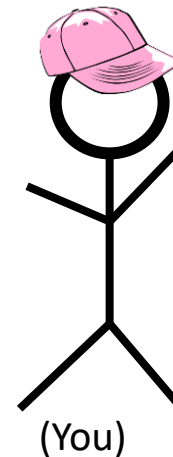
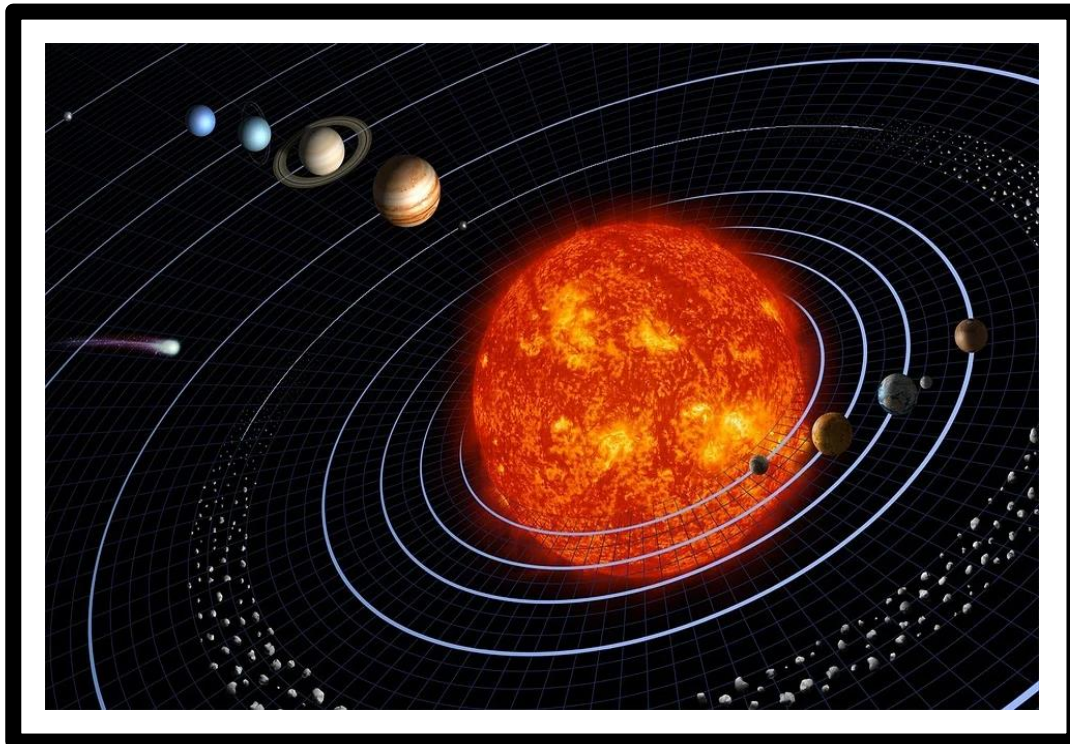
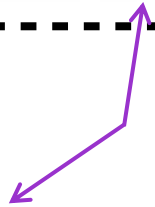
XVII century

Behaviors:

- .Trajectories
- .Structure
- .Brightness

$$F = G \frac{m_1 m_2}{r^2}$$

model



Building models (planets)

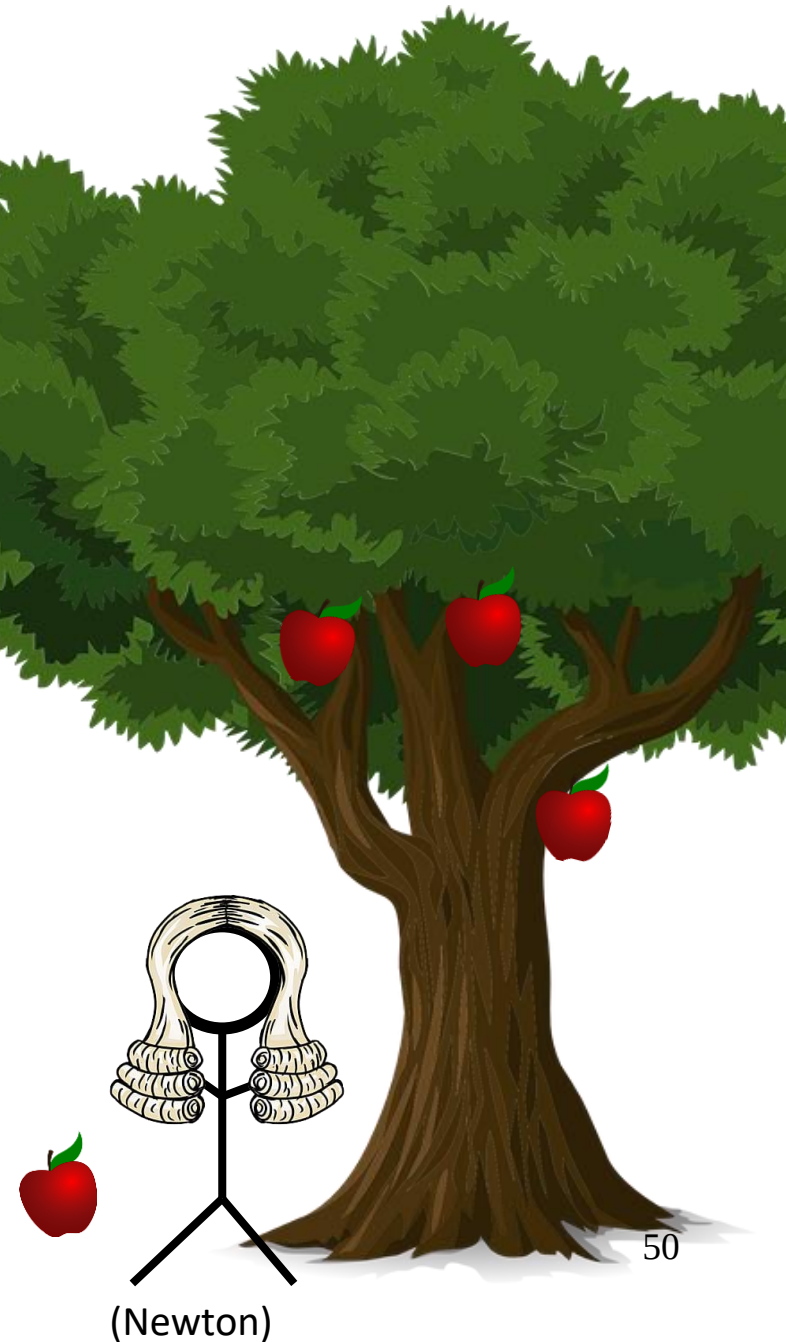
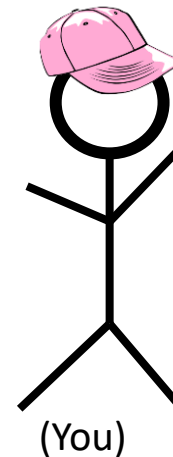
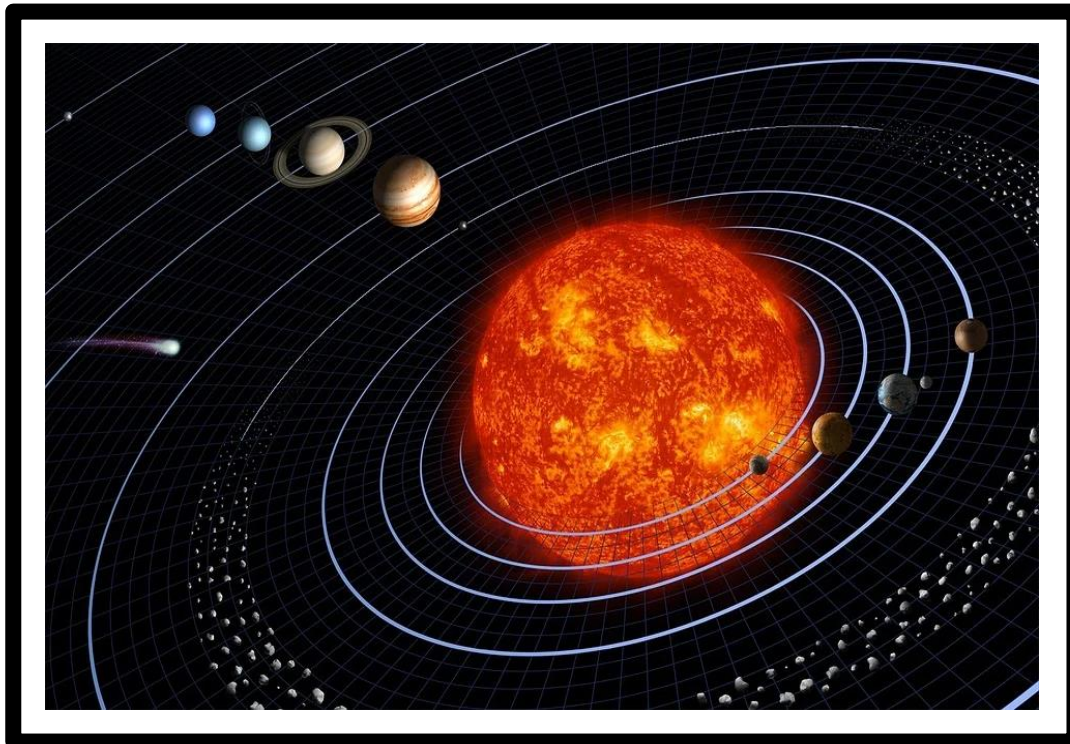
XVII century

Behaviors:

- ✓ .Trajectories
- ✓ .Structure
- ✓ .Brightness

$$F = G \frac{m_1 m_2}{r^2}$$

Good model



Building models (planets)

Good model

↓
Explain

Predict

Build



“Retrograde”



Halley's comet



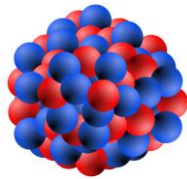
Space shuttle

Building models (nuclear)

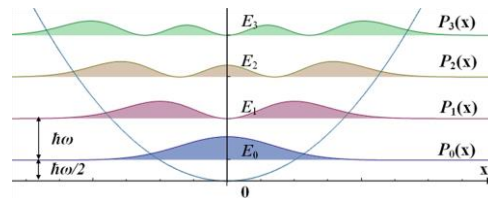
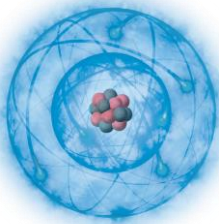
XXI century

Behaviors:

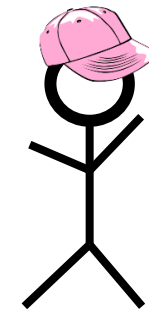
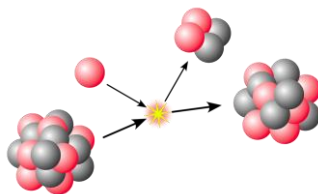
.Binding energy (energy “debt”)



.Structure (arrangement of nucleons)



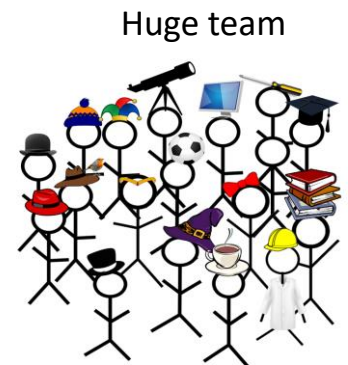
.Reactions (smashing nuclei)



(You)



(Pablo)



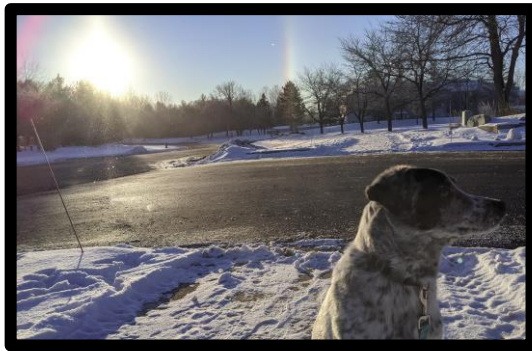
Building models (nuclear)

Good models

↓
Explain

Predict

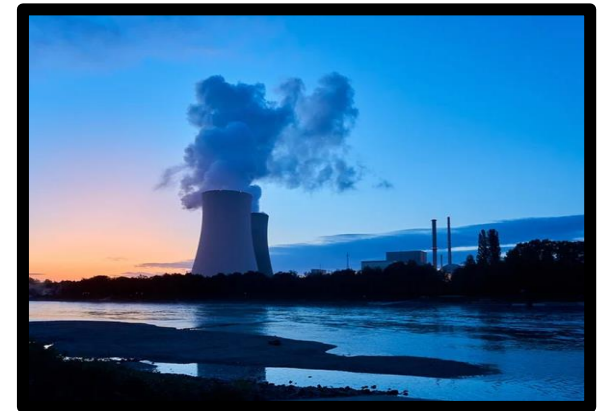
Build



Burning Sun



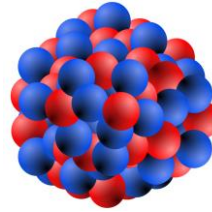
Kilonova after merger



Nuclear energy

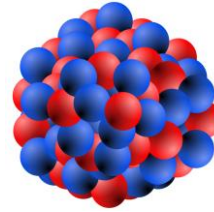
Binding energy \longrightarrow Energy needed to break it apart

$$m = Zm_p + Nm_n - \frac{BE}{c^2}$$

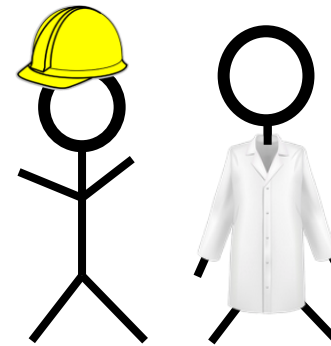
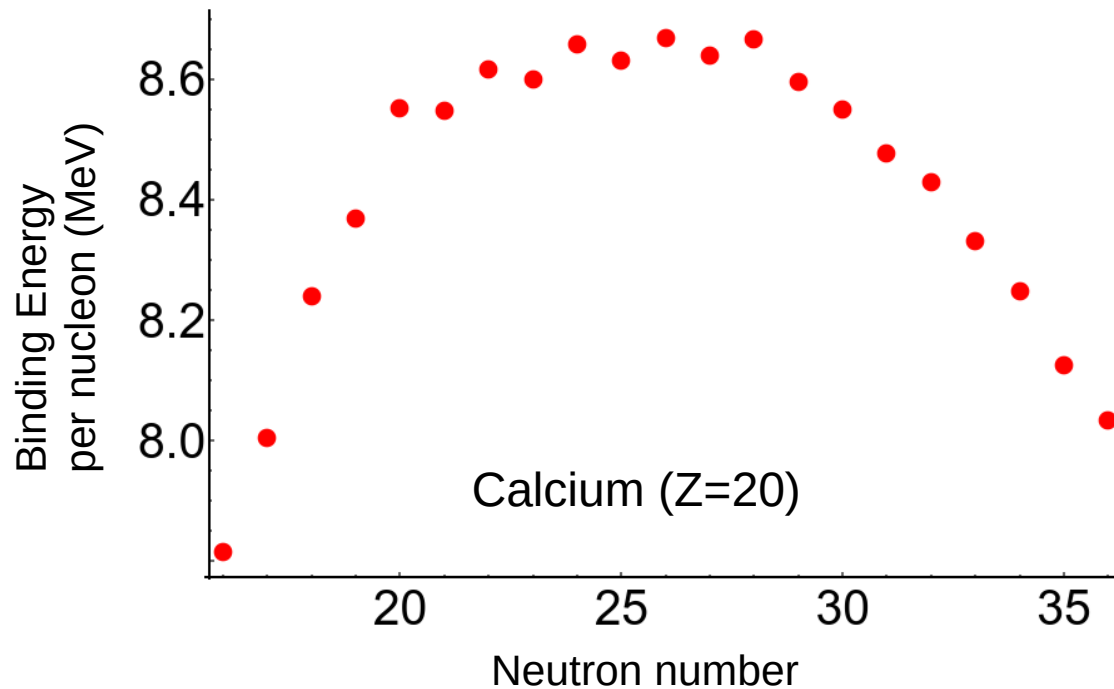


Binding energy \longrightarrow Energy needed to break it apart

$$m = Zm_p + Nm_n - \frac{BE}{c^2}$$



Behavior:

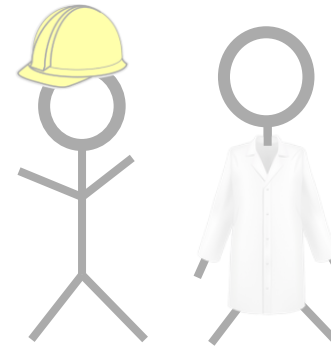
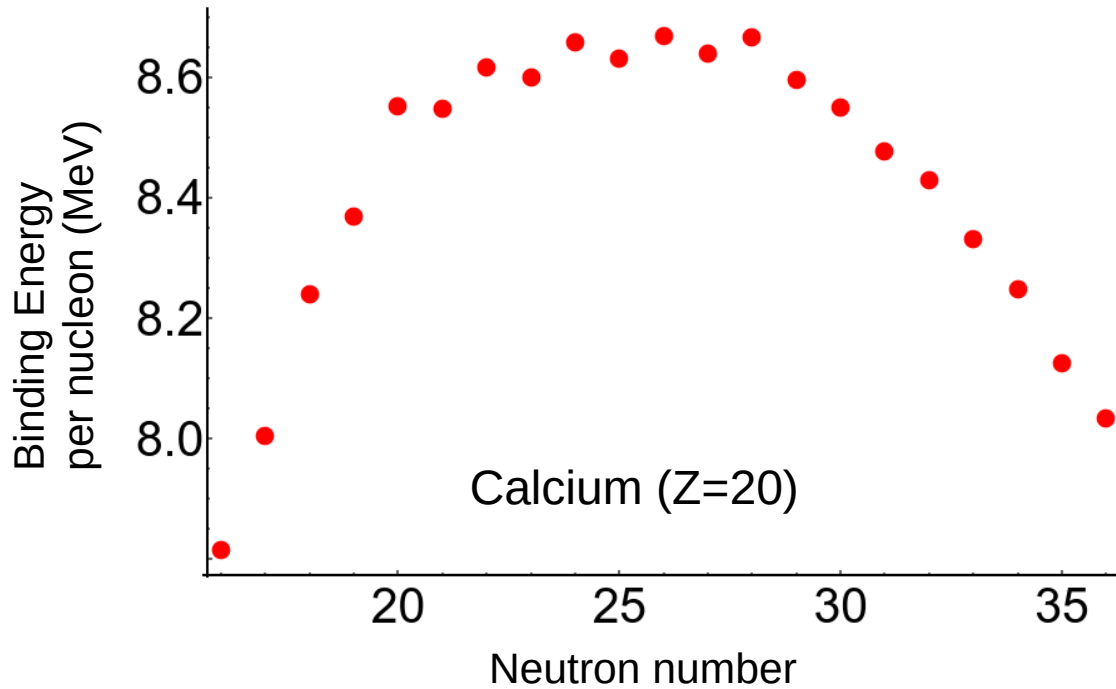
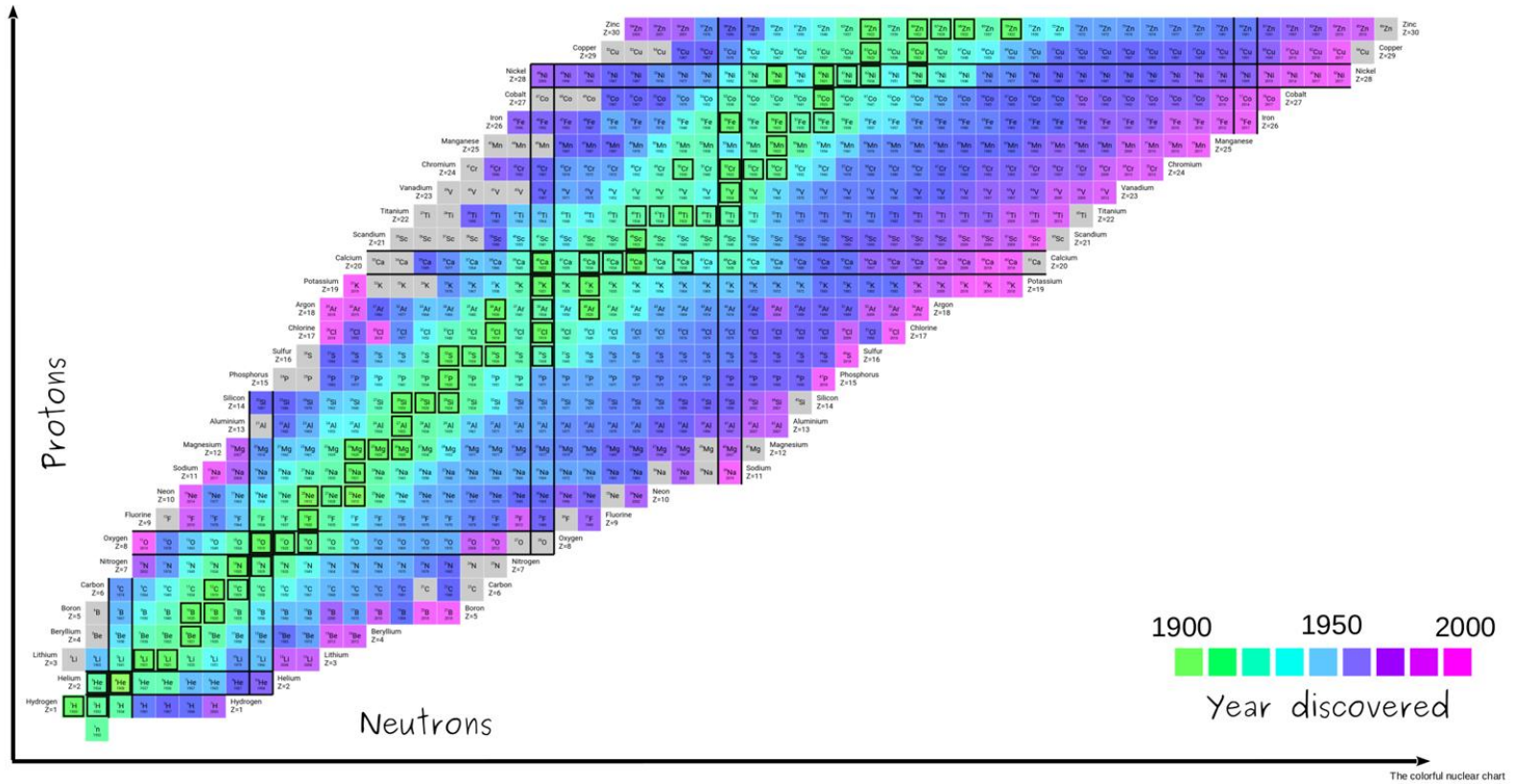


(Exp Friends)

Binding

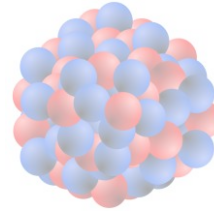
$$m = Zm_p$$

Behavior:



(Exp Friends)

Binding energy \longrightarrow Energy needed to break it apart



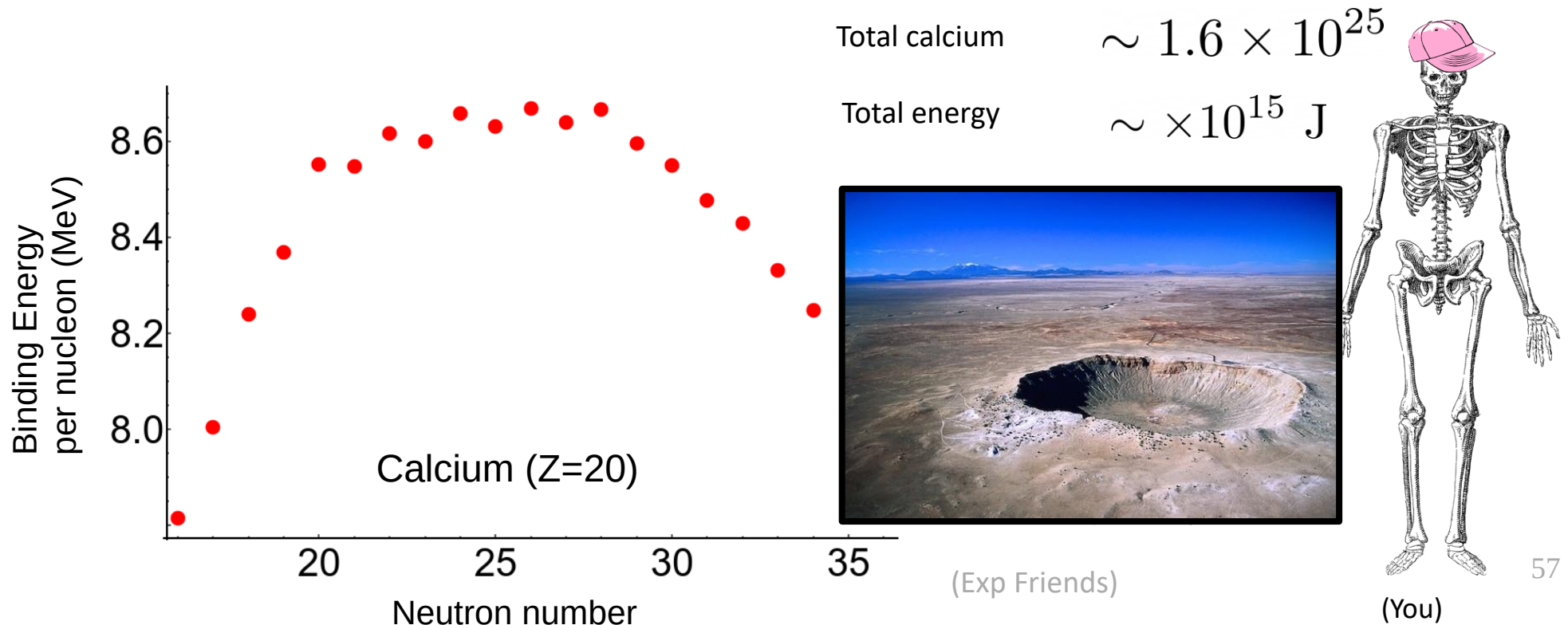
$$m = Zm_p + Nm_n - \frac{BE}{c^2}$$

Comparisons as energy

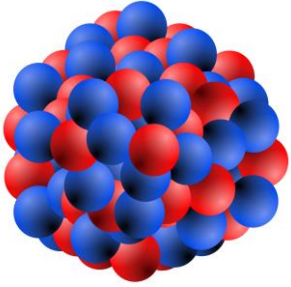
$\approx (0.09 \approx 1/11) \times$ impact energy forming Meteor Crater, Arizona ($\approx 1 \times 10^{16}$ J)

\approx energy released by a hurricane in 1 second ($\approx 6 \times 10^{14}$ J)

Behavior.



Binding energy

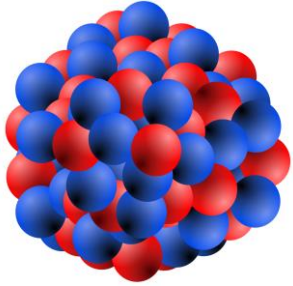


Liquid drop model



$$BE(N, Z) =$$

Binding energy

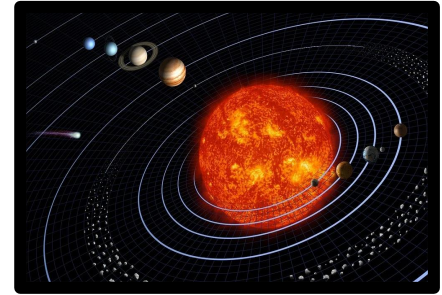


Liquid drop model

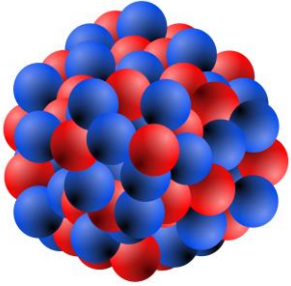


$$\text{BE}(N, Z) =$$

$$F = G \frac{m_1 m_2}{r^2}$$



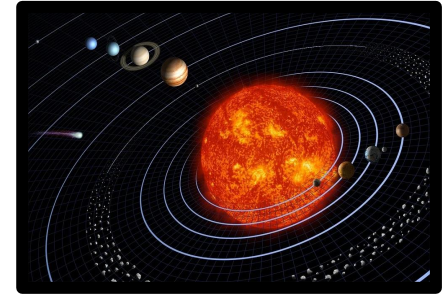
Binding energy



Liquid drop model

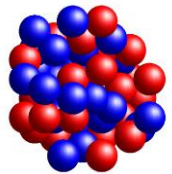


$$F = G \frac{m_1 m_2}{r^2}$$



$$BE(N, Z) =$$

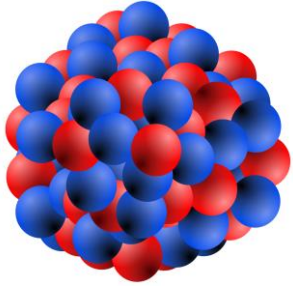
More nucleons



BE



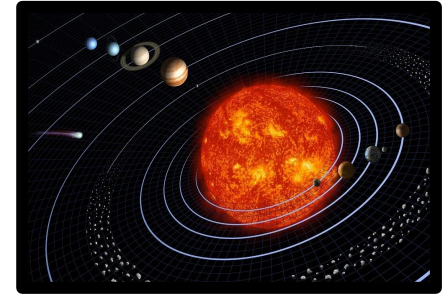
Binding energy



Liquid drop model

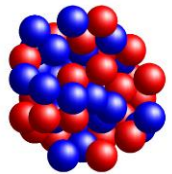


$$F = G \frac{m_1 m_2}{r^2}$$



$$BE(N, Z) = a_V(N + Z)$$

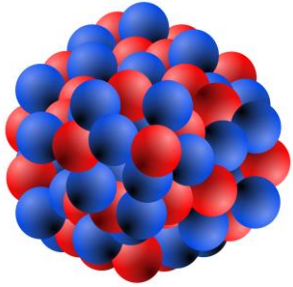
More nucleons



BE



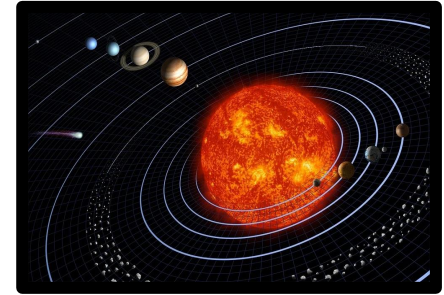
Binding energy



Liquid drop model

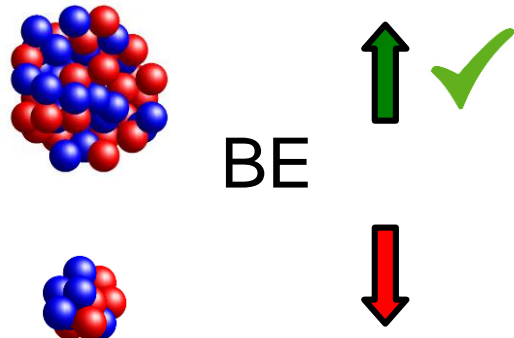


$$F = G \frac{m_1 m_2}{r^2}$$

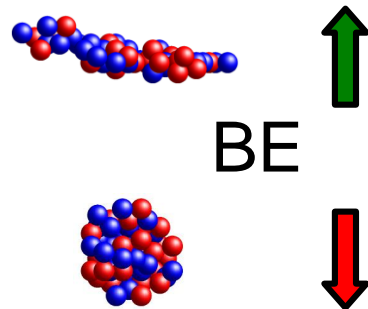


$$BE(N, Z) = a_V(N + Z)$$

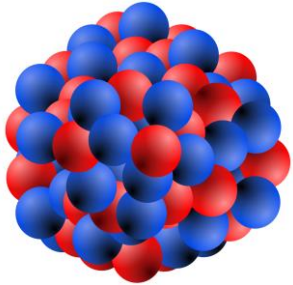
More nucleons



More surface



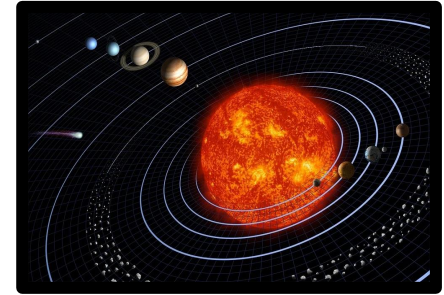
Binding energy



Liquid drop model



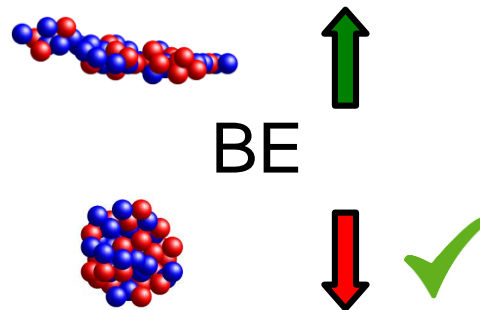
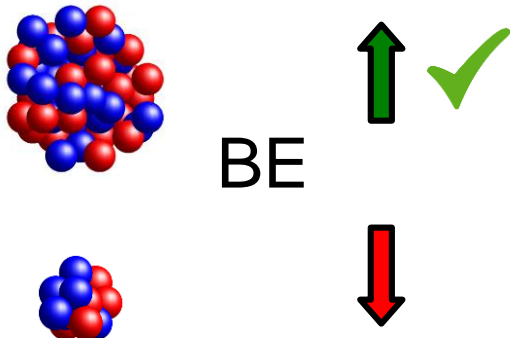
$$F = G \frac{m_1 m_2}{r^2}$$



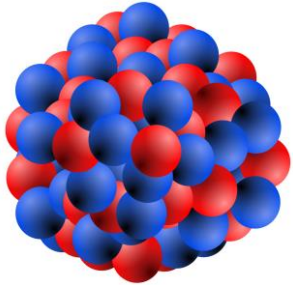
$$BE(N, Z) = a_V(N + Z) - a_S(N + Z)^{2/3}$$

More nucleons

More surface



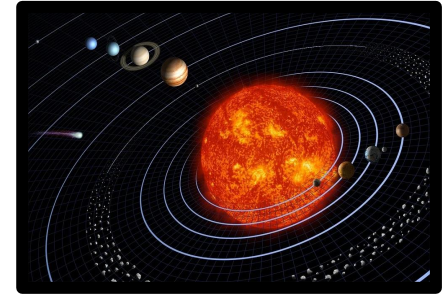
Binding energy



Liquid drop model

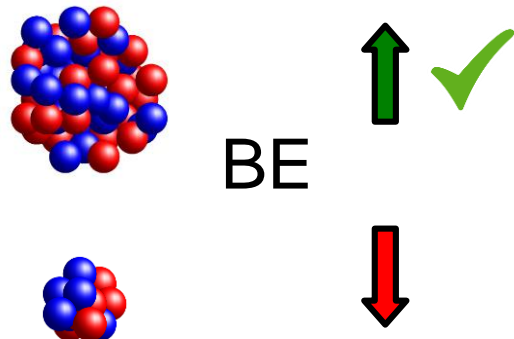


$$F = G \frac{m_1 m_2}{r^2}$$

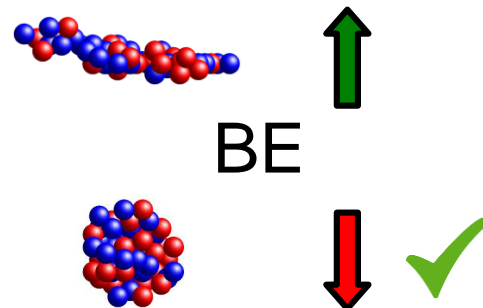


$$BE(N, Z) = a_V(N + Z) - a_S(N + Z)^{2/3}$$

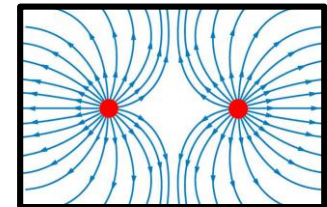
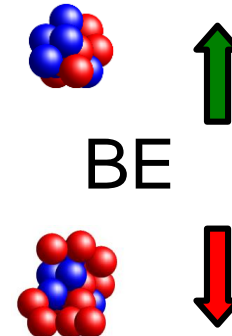
More nucleons



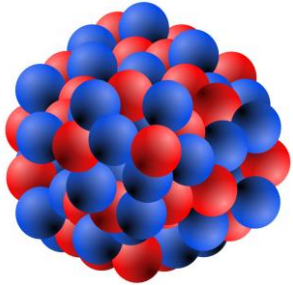
More surface



More protons



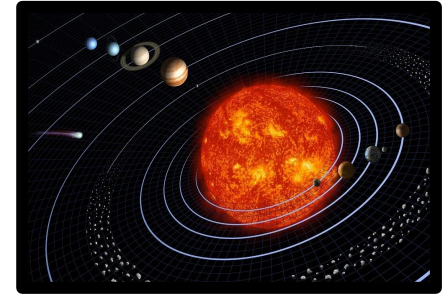
Binding energy



Liquid drop model

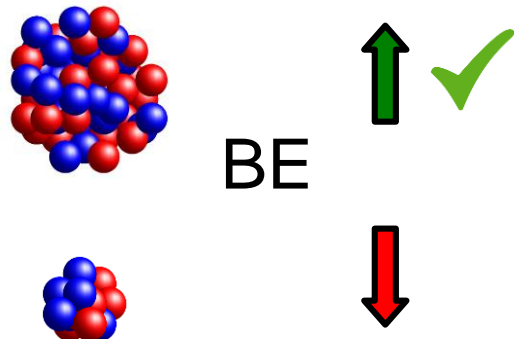


$$F = G \frac{m_1 m_2}{r^2}$$

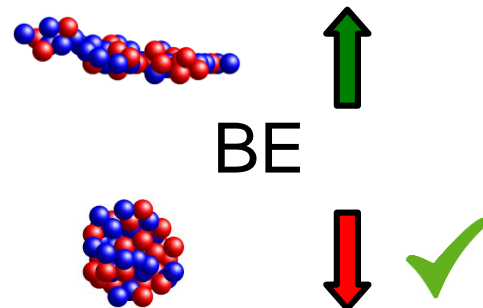


$$BE(N, Z) = a_V(N + Z) - a_S(N + Z)^{2/3} - a_C \frac{Z^2}{(N + Z)^{1/3}}$$

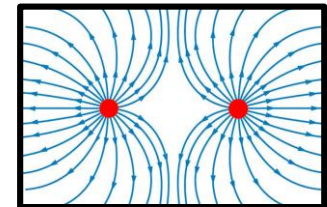
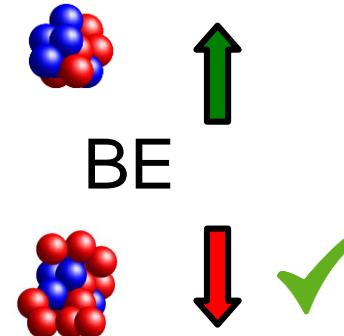
More nucleons



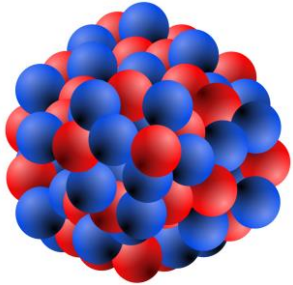
More surface



More protons



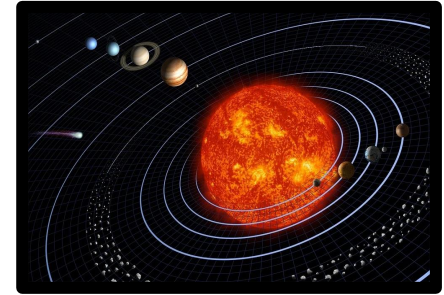
Binding energy



Liquid drop model

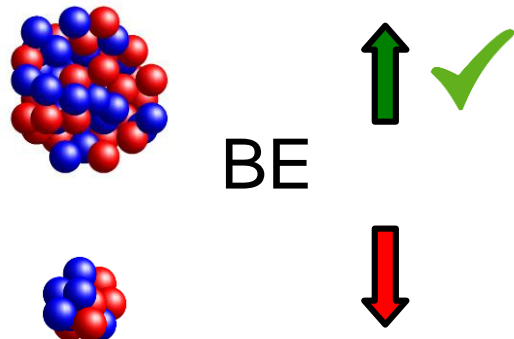


$$F = G \frac{m_1 m_2}{r^2}$$

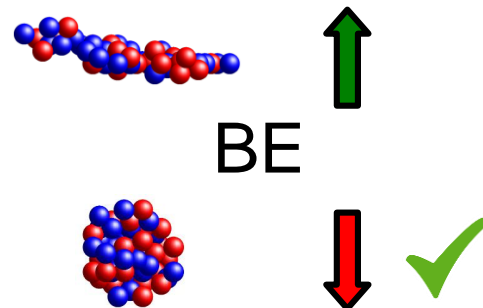


$$BE(N, Z) = a_V(N + Z) - a_S(N + Z)^{2/3} - a_C \frac{Z^2}{(N + Z)^{1/3}}$$

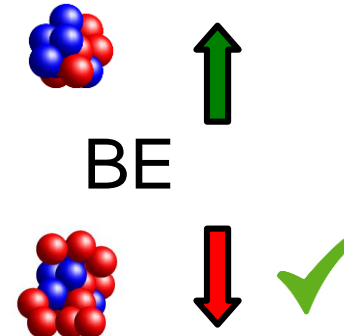
More nucleons



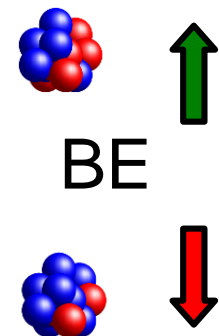
More surface



More protons

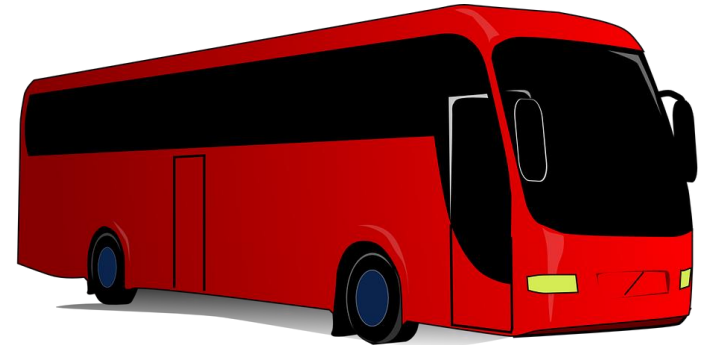


More asymmetry



Binding energy (Asymmetry parenthesis)

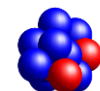
Protons	Neutrons	
<input type="text"/>	<input type="text"/>	120 \$
<input type="text"/>	<input type="text"/>	50 \$
<input type="text"/>	<input type="text"/>	25 \$
<input type="text"/>	<input type="text"/>	15 \$
<input type="text"/>	<input type="text"/>	10 \$



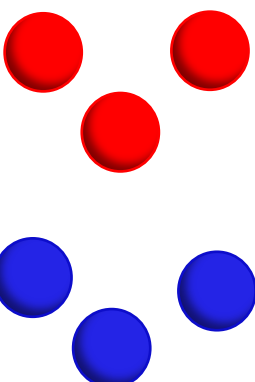
More asymmetry

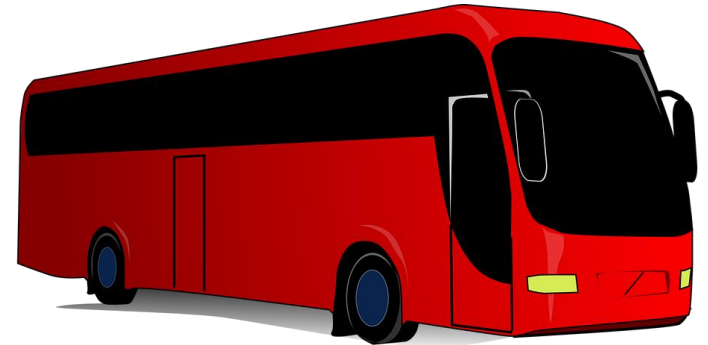


BE



Binding energy (Asymmetry parenthesis)

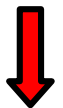
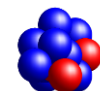
	Protons	Neutrons	
	<input type="text"/>	<input type="text"/>	120 \$
	<input type="text"/>	<input type="text"/>	50 \$
	<input type="text"/>	<input type="text"/>	25 \$
	<input type="text"/>	<input type="text"/>	15 \$
	<input type="text"/>	<input type="text"/>	10 \$









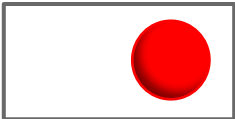
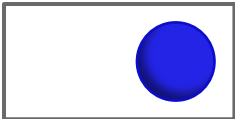
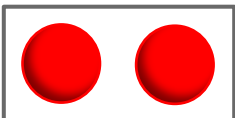
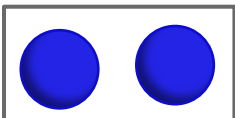
More asymmetry

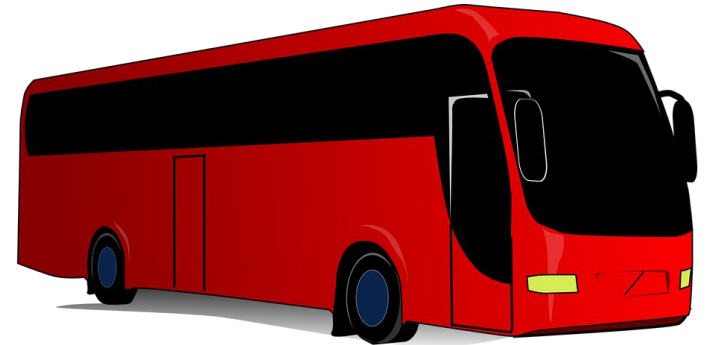


BE

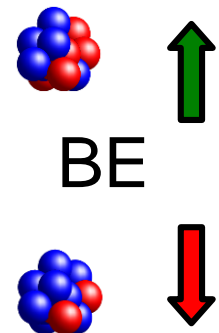


Binding energy (Asymmetry parenthesis)







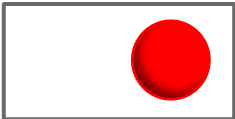
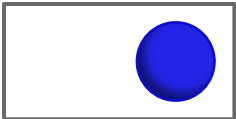
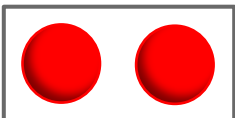
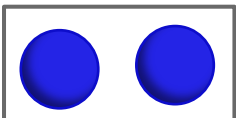
Protons	Neutrons	
		120 \$
		50 \$
		25 \$
		15 \$
		10 \$



More asymmetry



Binding energy (Asymmetry parenthesis)

Protons	Neutrons
	
	
	
	
	

120 \$

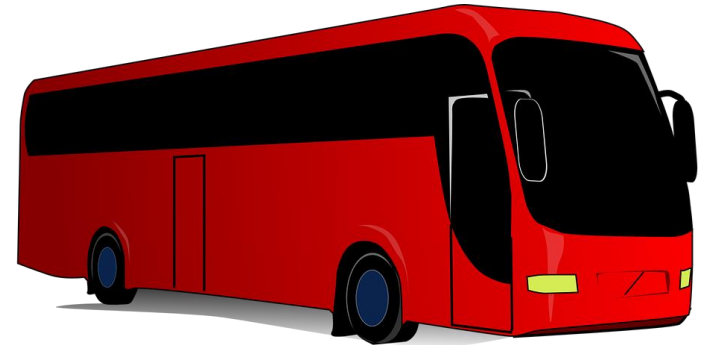
50 \$

25 \$

15 \$

10 \$

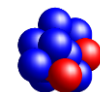
Total = 70 \$



More asymmetry

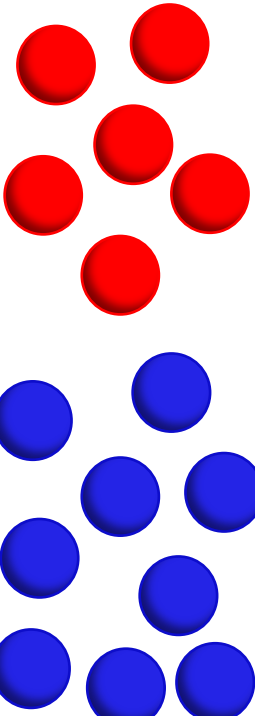
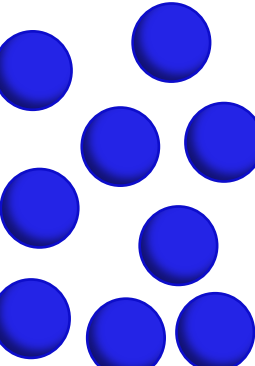


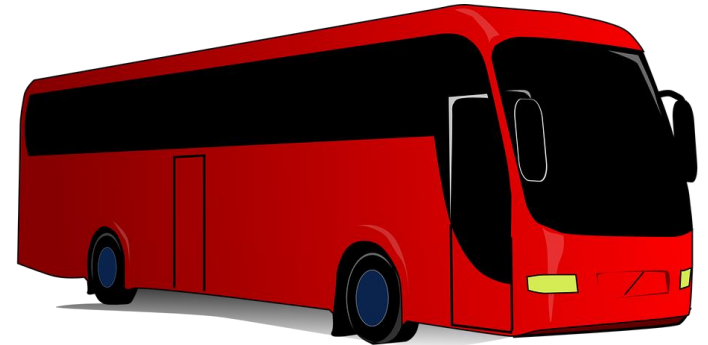
BE



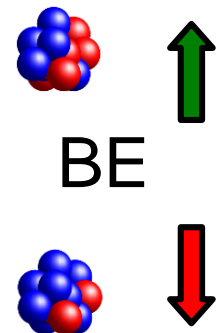
70

Binding energy (Asymmetry parenthesis)


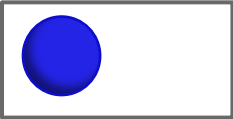

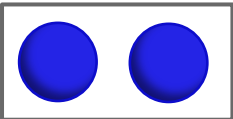
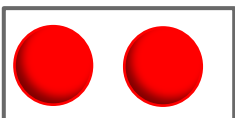
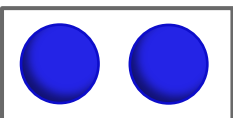
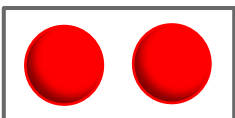
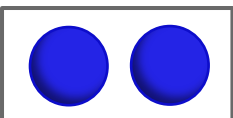
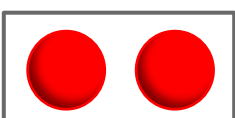
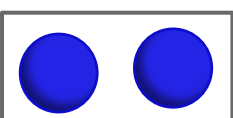
	Protons	Neutrons	
	<input type="text"/>	<input type="text"/>	120 \$
	<input type="text"/>	<input type="text"/>	50 \$
	<input type="text"/>	<input type="text"/>	25 \$
	<input type="text"/>	<input type="text"/>	15 \$
	<input type="text"/>	<input type="text"/>	10 \$
	<input type="text"/>	<input type="text"/>	

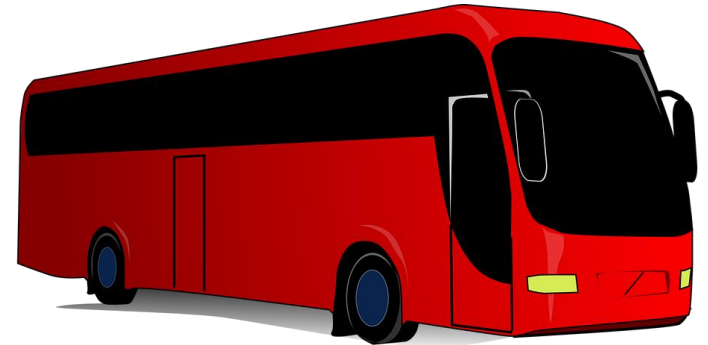


More asymmetry



Binding energy (Asymmetry parenthesis)

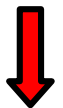
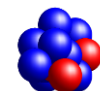
Protons	Neutrons	
		120 \$
		50 \$
		25 \$
		15 \$
		10 \$




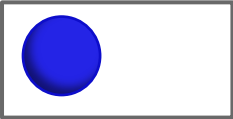

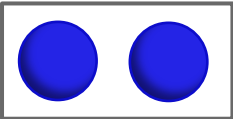
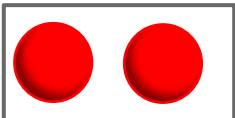
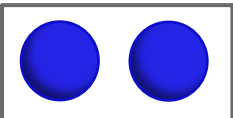
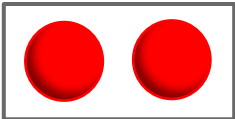
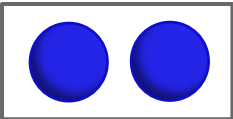
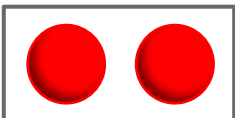
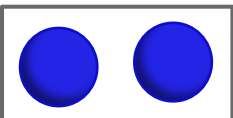
More asymmetry

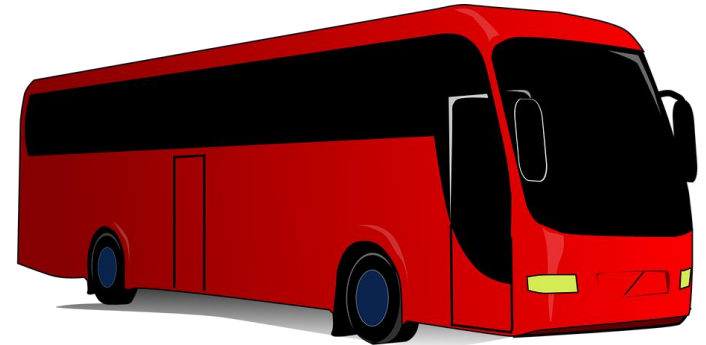


BE



Binding energy (Asymmetry parenthesis)

Protons	Neutrons	
		120 \$
		50 \$
		25 \$
		15 \$
		10 \$
		Total = 420 \$



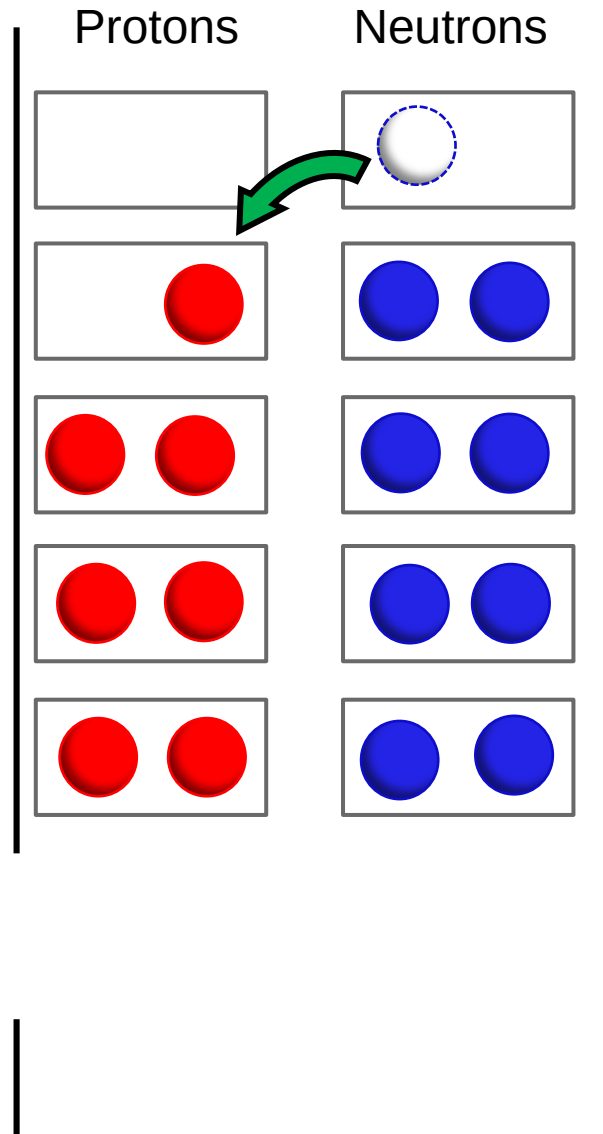
More asymmetry



BE



Binding energy (Asymmetry parenthesis)



120 \$

50 \$

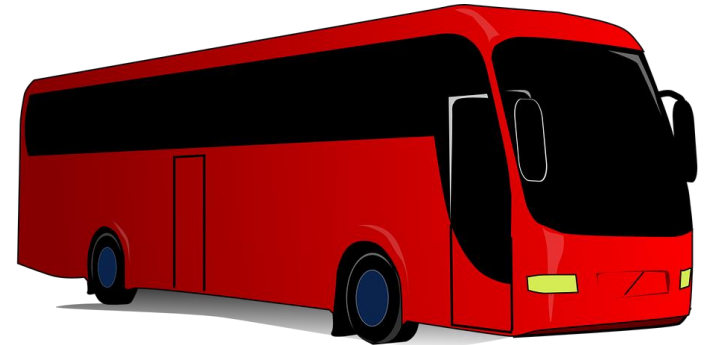
25 \$

15 \$

10 \$

~~Total = 420 \$~~

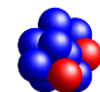
Total = 350 \$



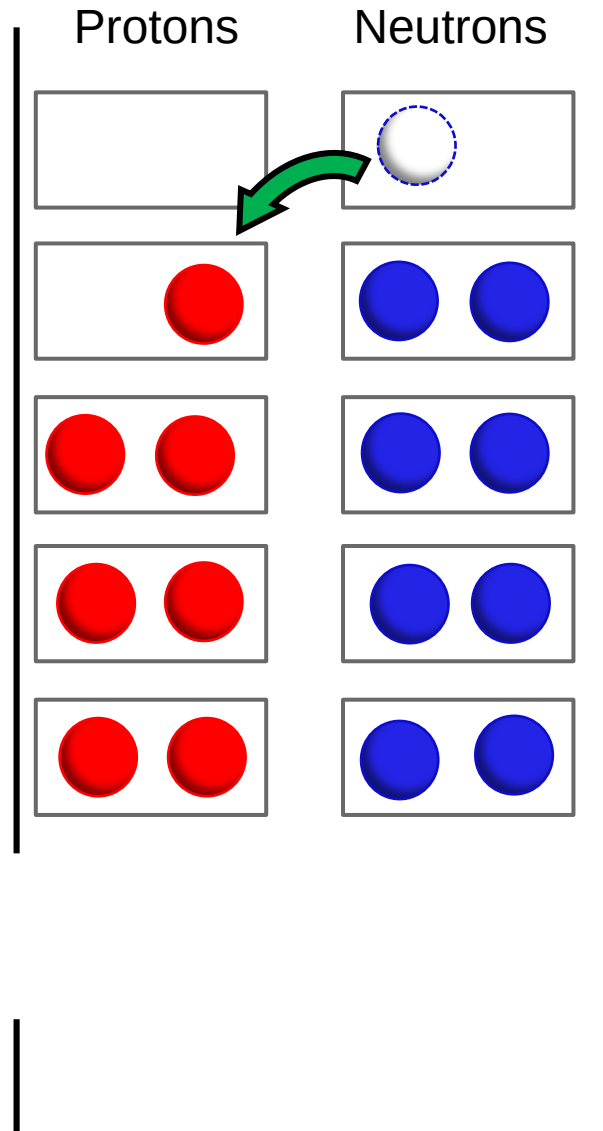
More asymmetry



BE



Binding energy (Asymmetry parenthesis)



120 \$

50 \$

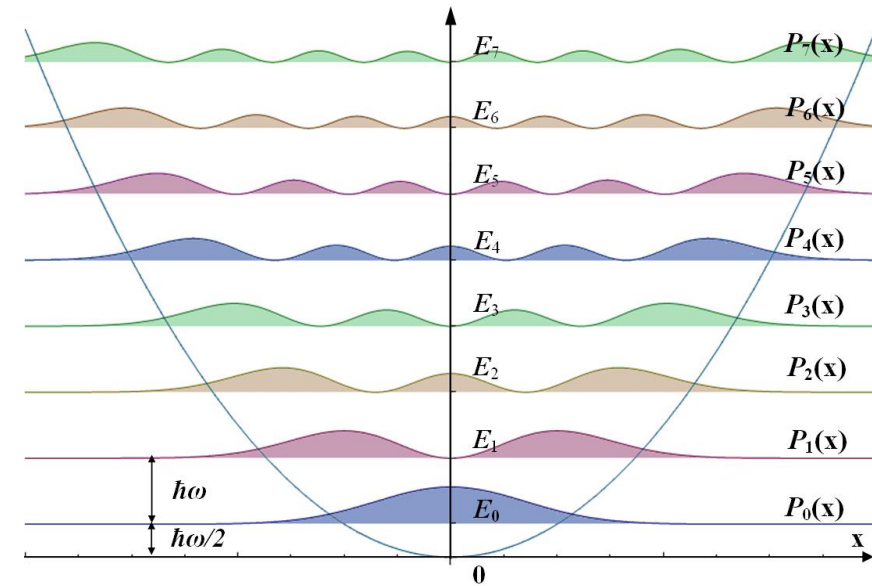
25 \$

15 \$

10 \$

~~Total = 420 \$~~

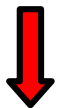
Total = 350 \$



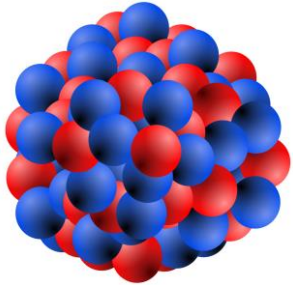
More asymmetry



BE



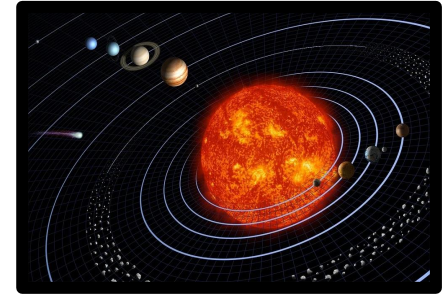
Binding energy



Liquid drop model

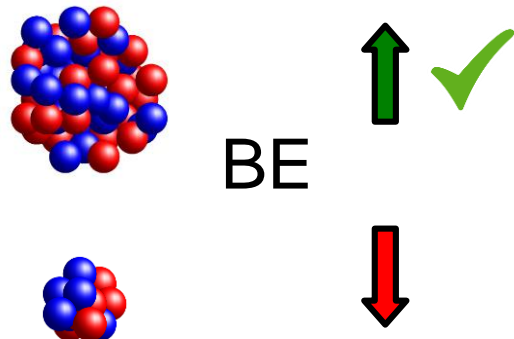


$$F = G \frac{m_1 m_2}{r^2}$$

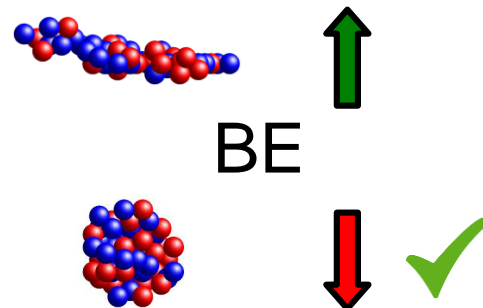


$$BE(N, Z) = a_V(N + Z) - a_S(N + Z)^{2/3} - a_C \frac{Z^2}{(N + Z)^{1/3}} - a_A \frac{(N - Z)^2}{N + Z}$$

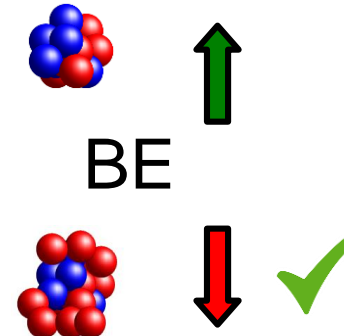
More nucleons



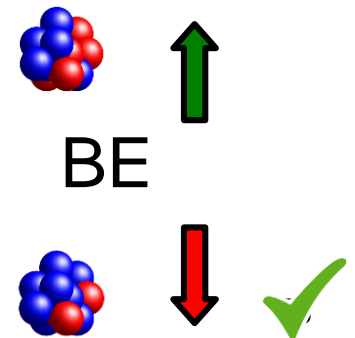
More surface



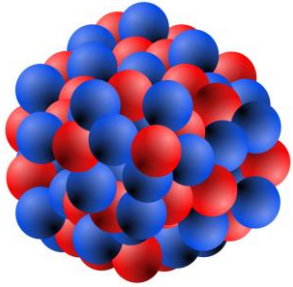
More protons



More asymmetry



Binding energy



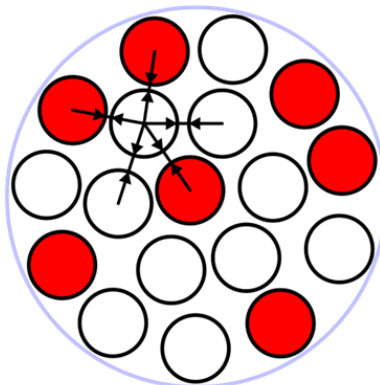
Liquid drop model



$$F = G \frac{m_1 m_2}{r^2}$$

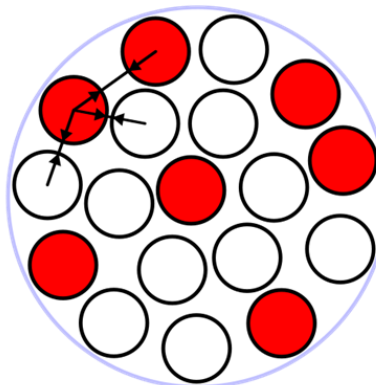
$$BE(N, Z) = a_V(N + Z) - a_S(N + Z)^{2/3} - a_C \frac{Z^2}{(N + Z)^{1/3}} - a_A \frac{(N - Z)^2}{N + Z}$$

More nucleons



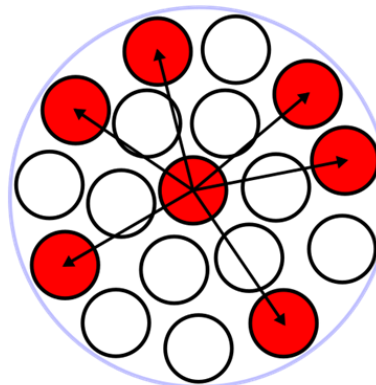
Volume

More surface



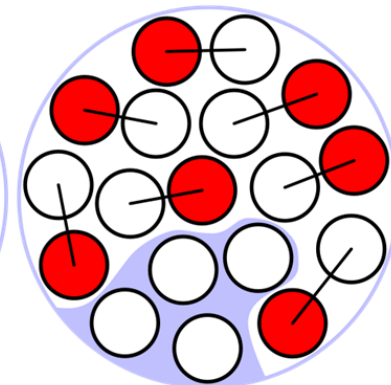
Surface

More protons



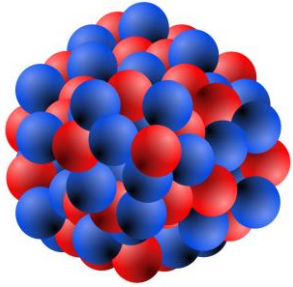
Coulomb

More asymmetry



Asymmetry

Binding energy



Liquid drop model

Mean squared error: 0.02
Variance score: 0.96
Mean absolute error: 0.07

[14.01172846 13.28609536 0.57346032 16.98655754]

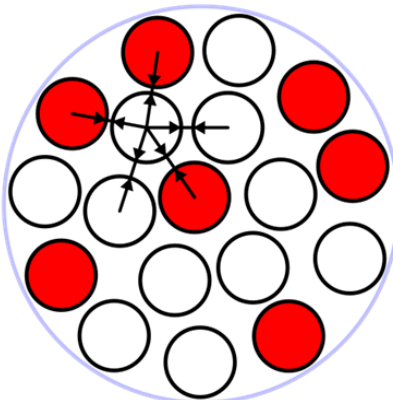
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More nucleons

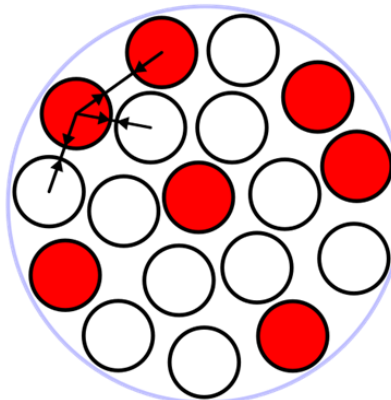
More surface

More protons

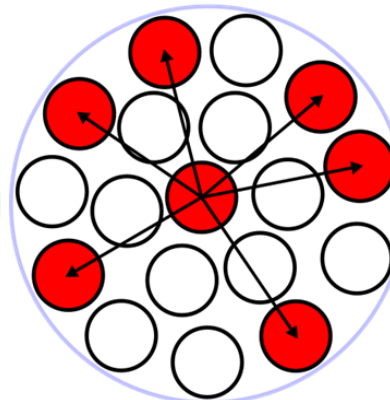
More asymmetry



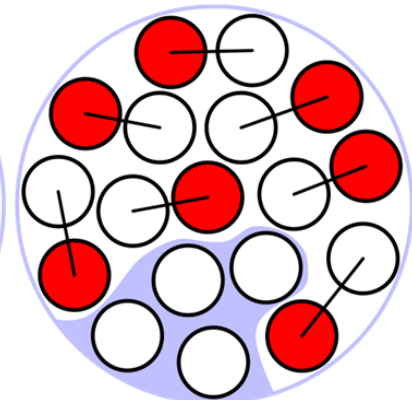
Volume



Surface

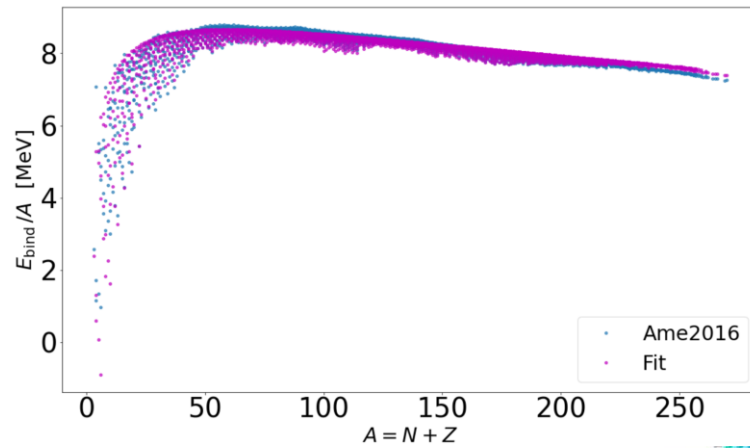


Coulomb



Asymmetry

Binding energy



Protons

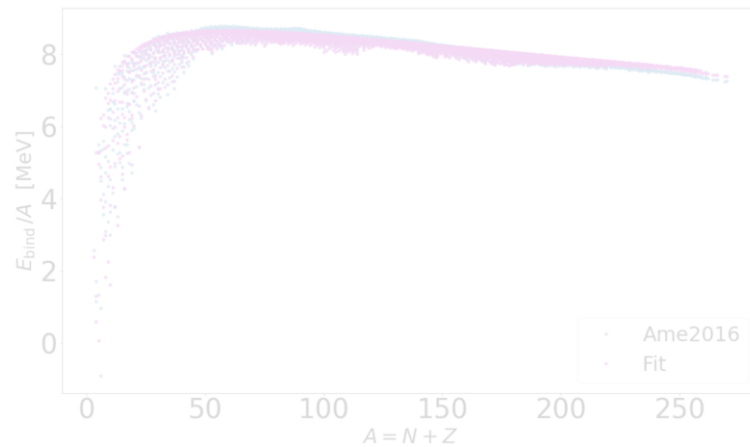
Binding Energy per Nucleon [MeV]



Neutrons

The colorful chart of nuclei

Binding energy



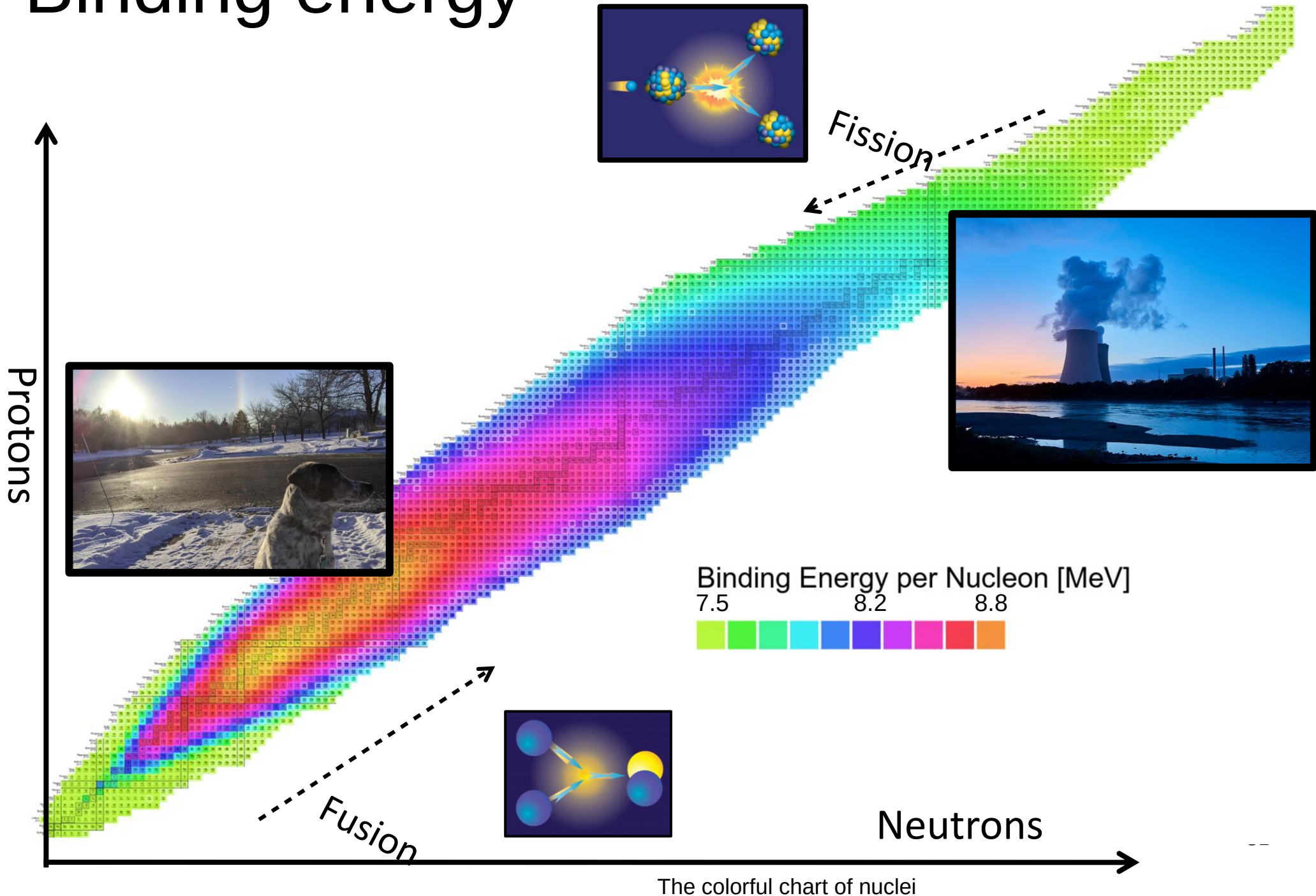
3D Chart!



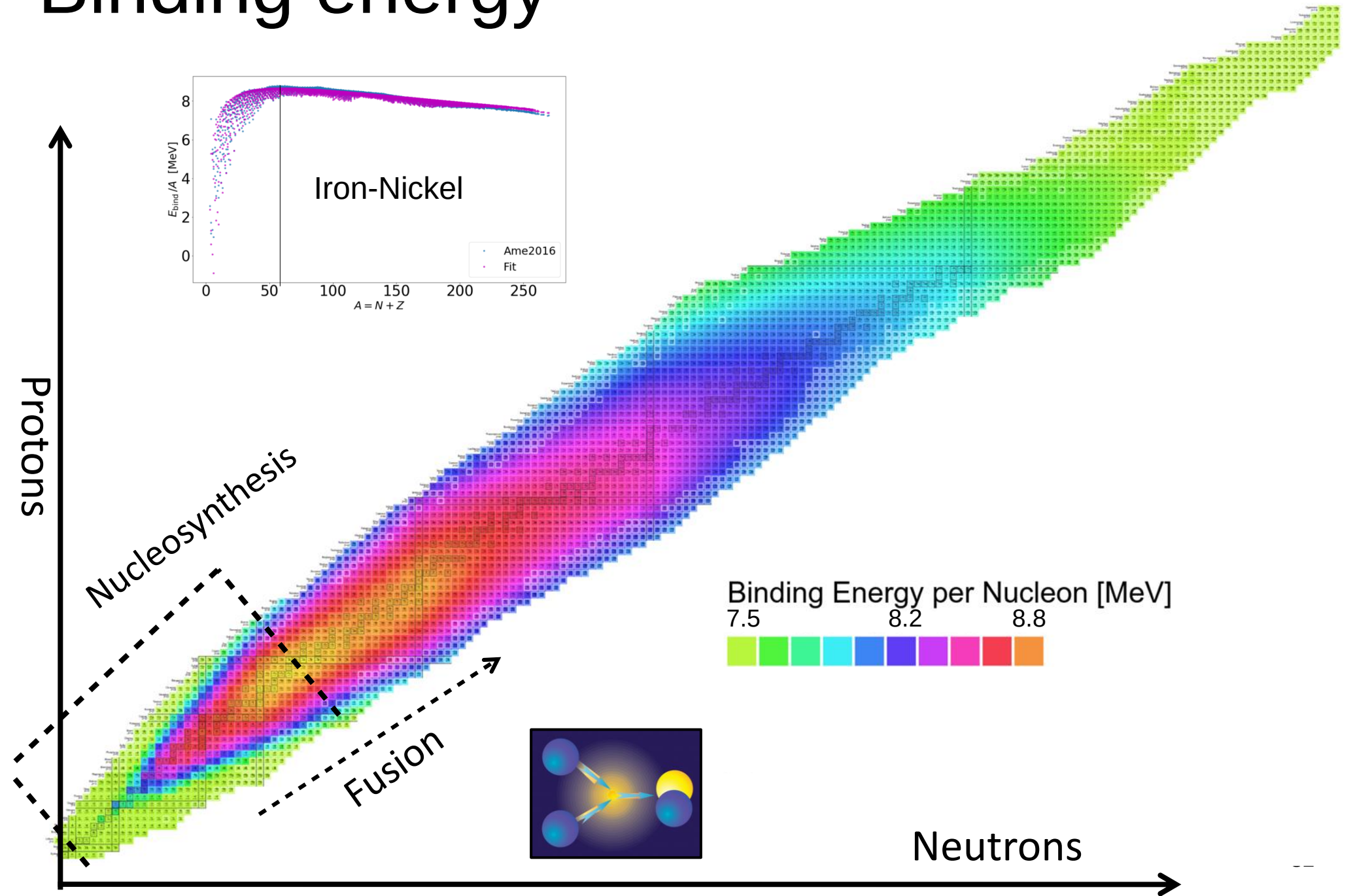
Neutrons

The colorful chart of nuclei

Binding energy

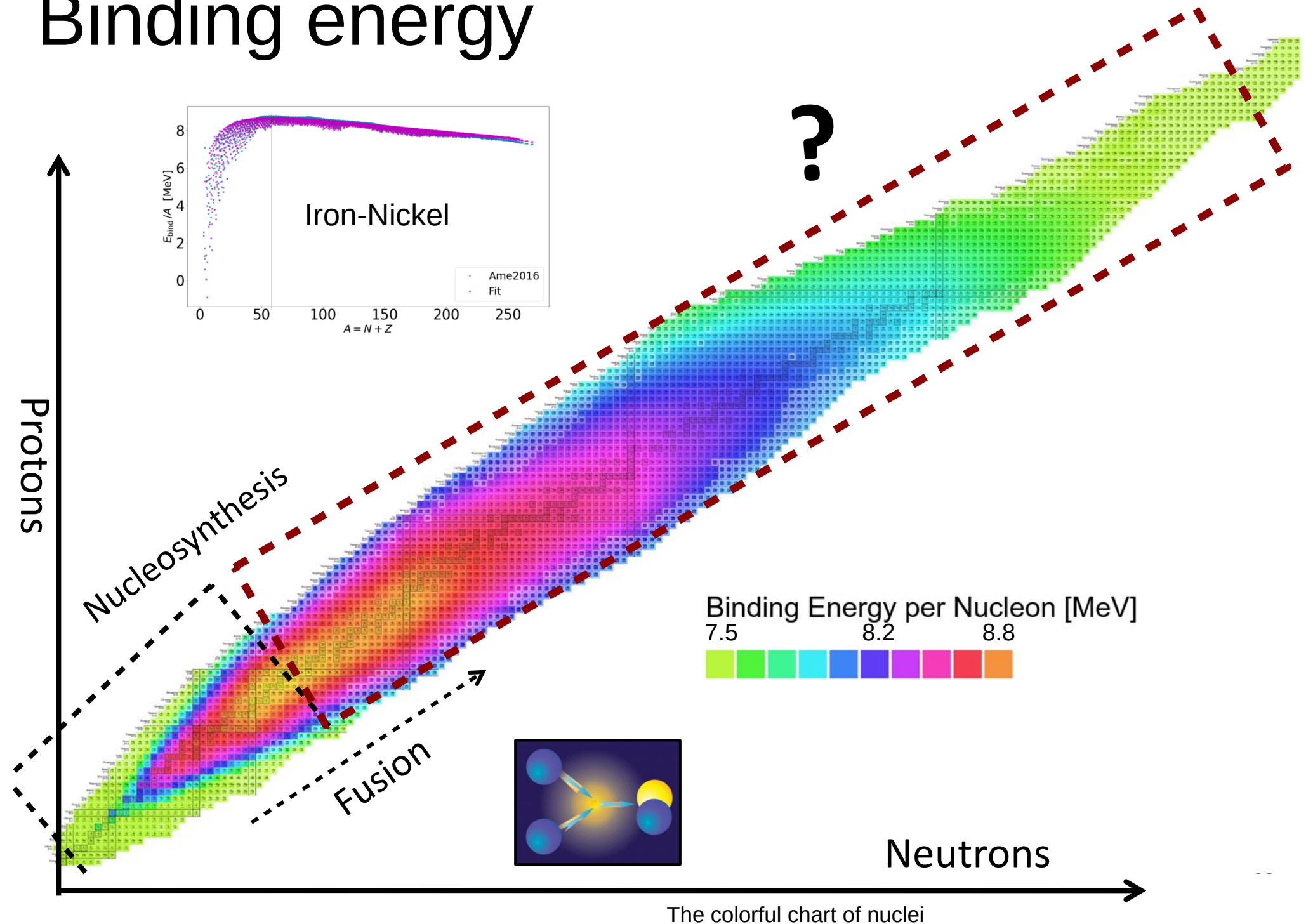


Binding energy



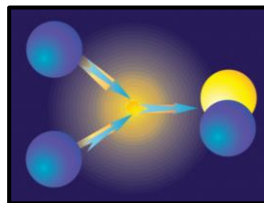
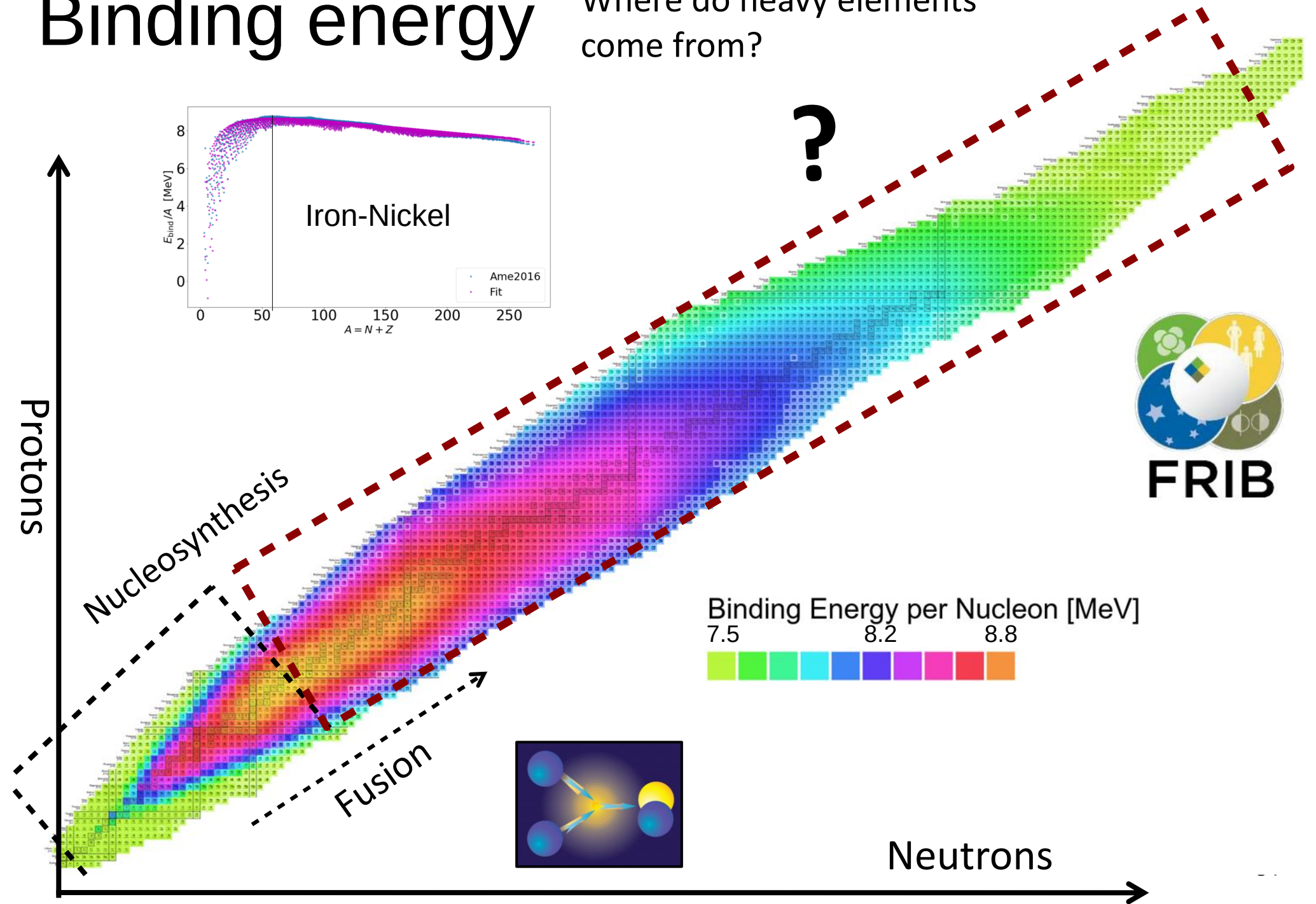
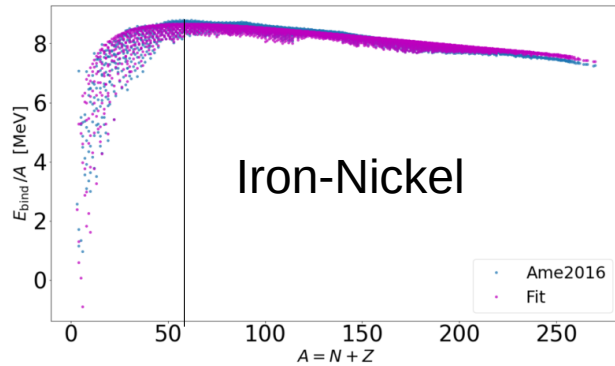
The colorful chart of nuclei

Binding energy



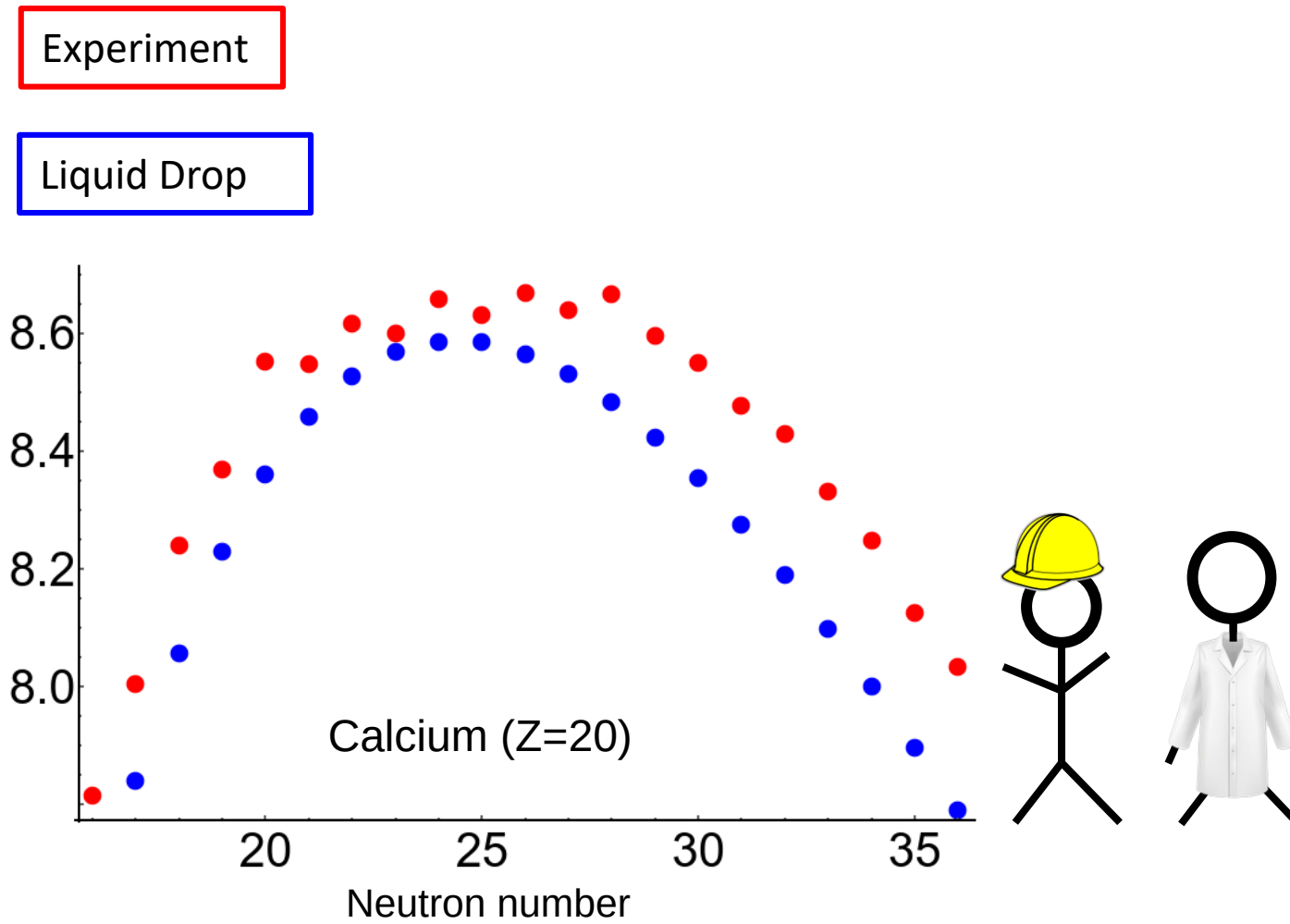
Binding energy

Where do heavy elements come from?



The colorful chart of nuclei

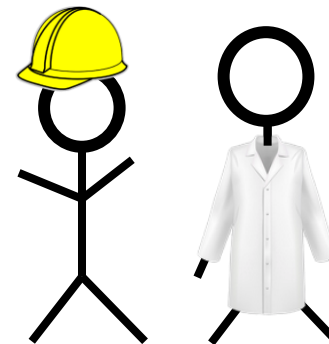
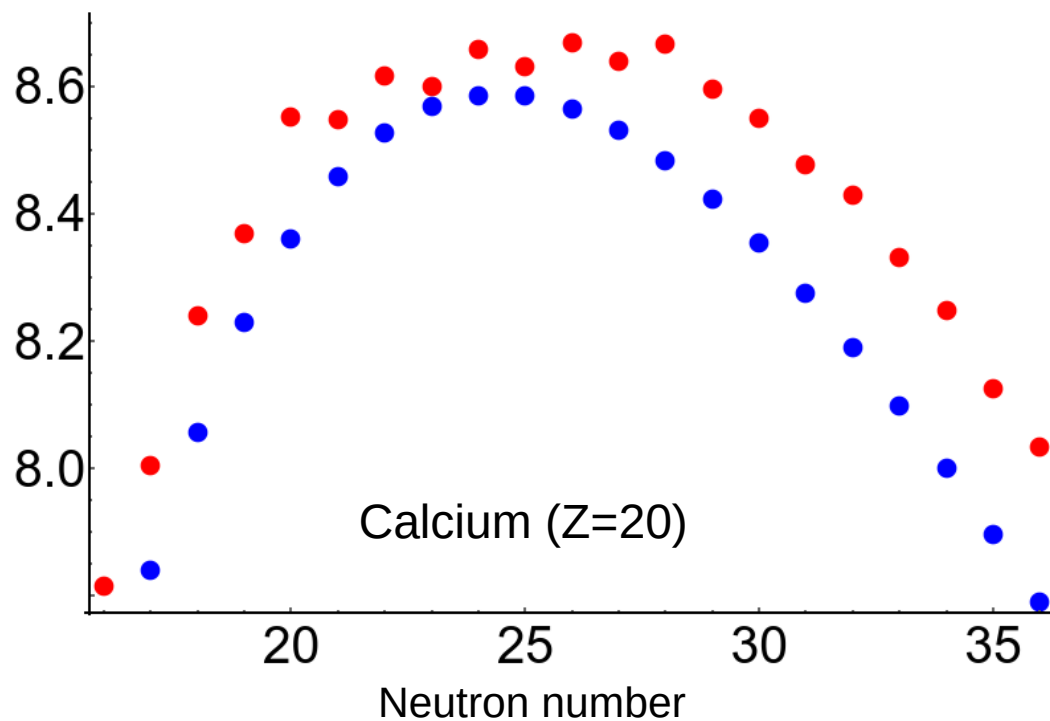
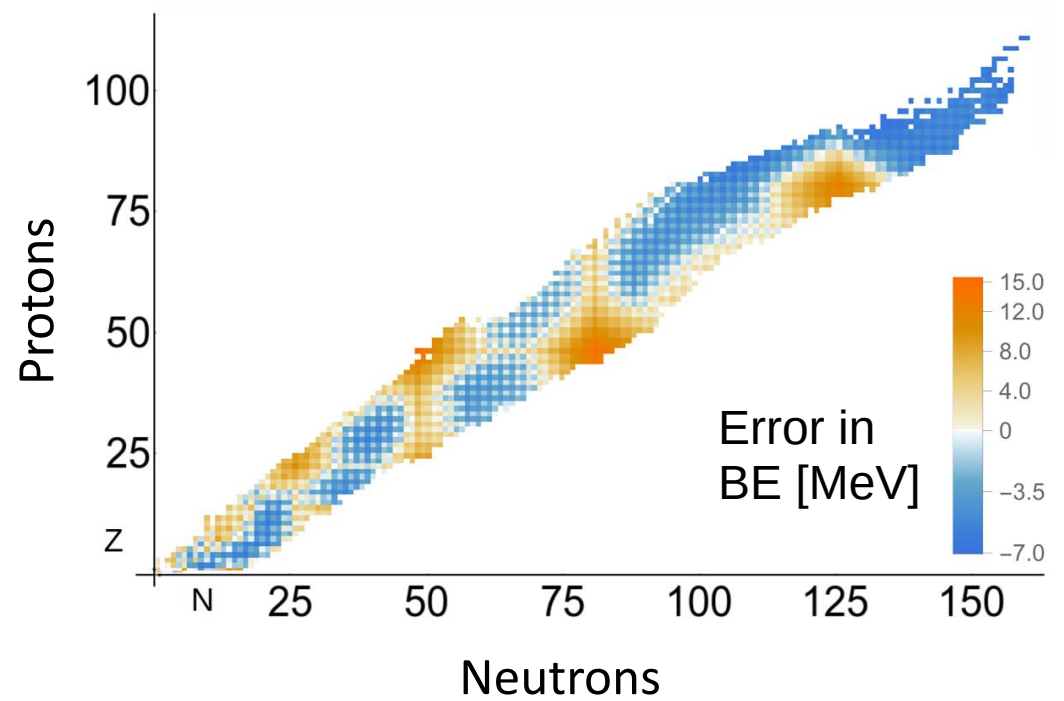
Binding energy



Binding energy

Experiment

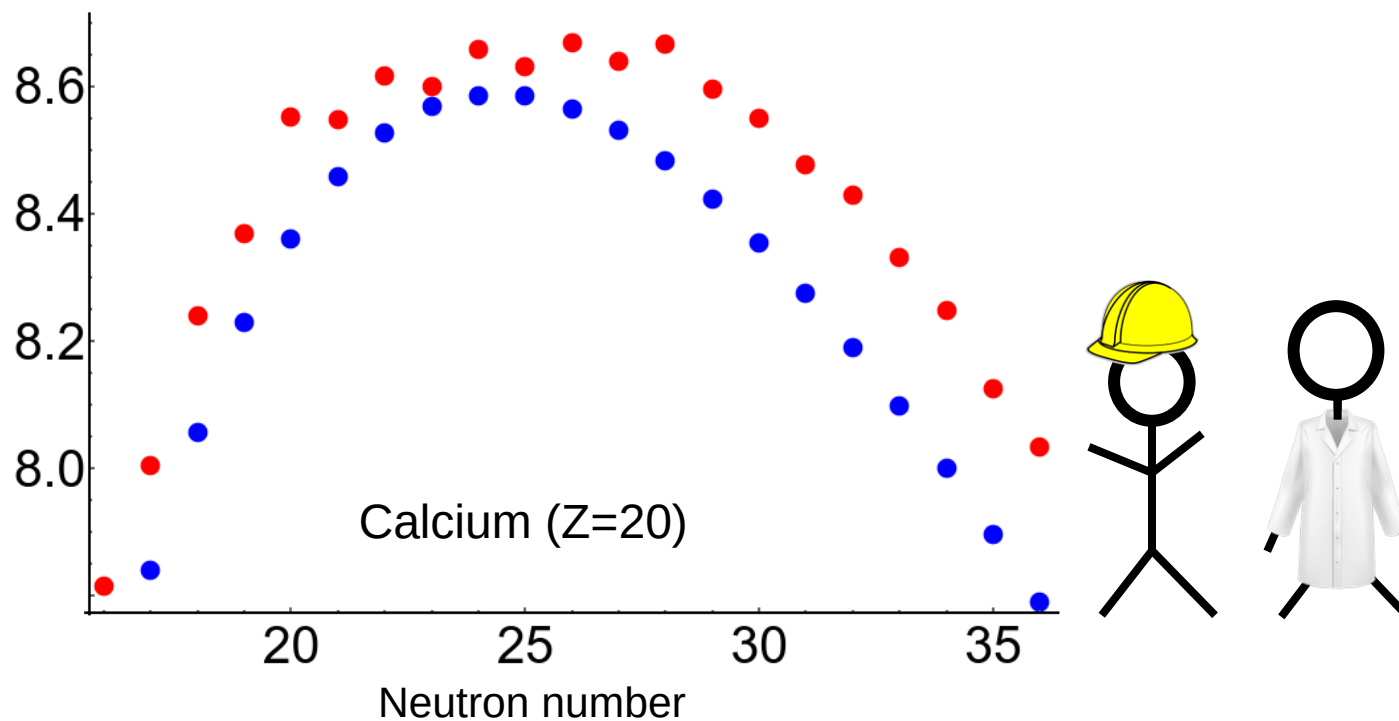
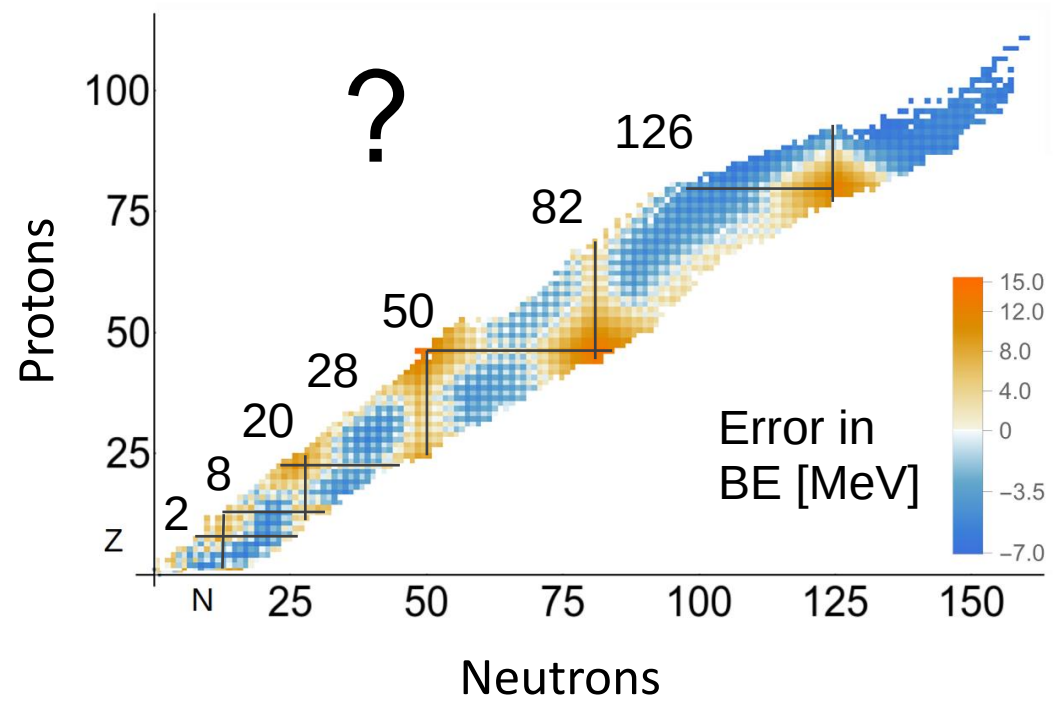
Liquid Drop



Binding energy

Experiment

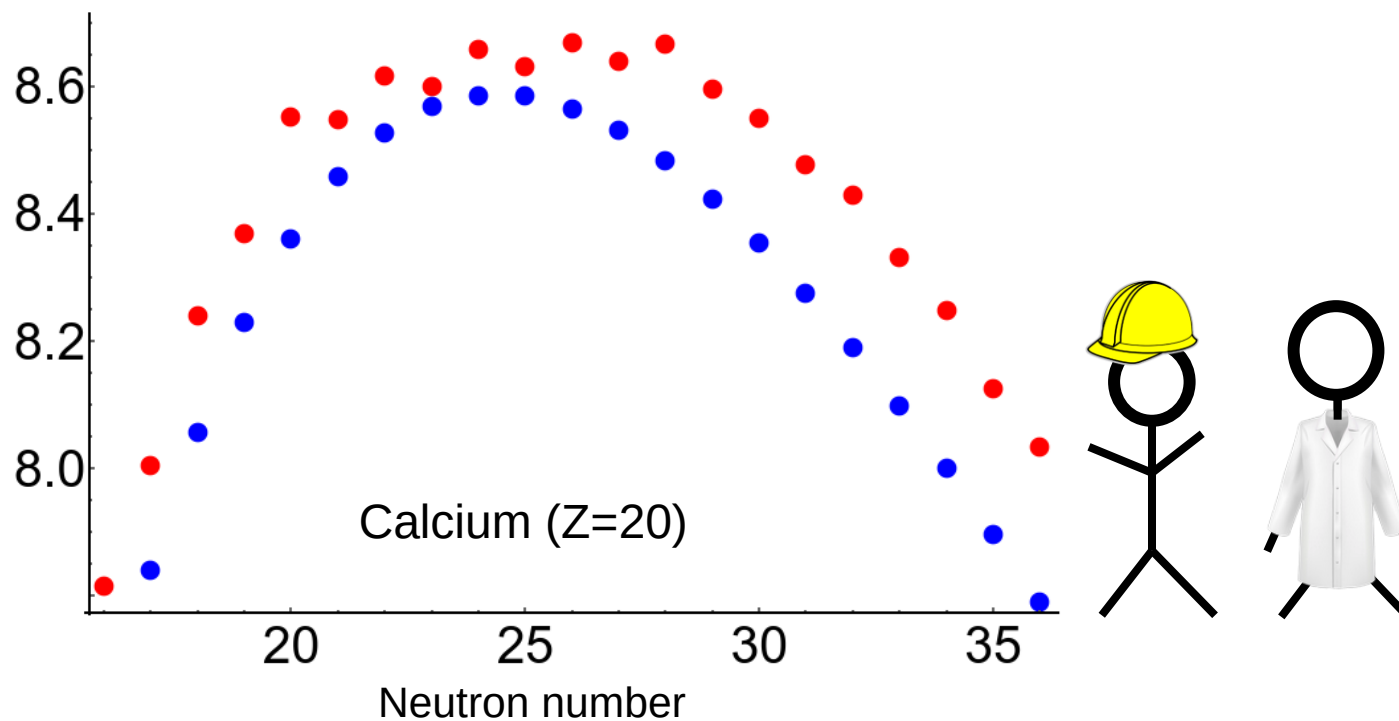
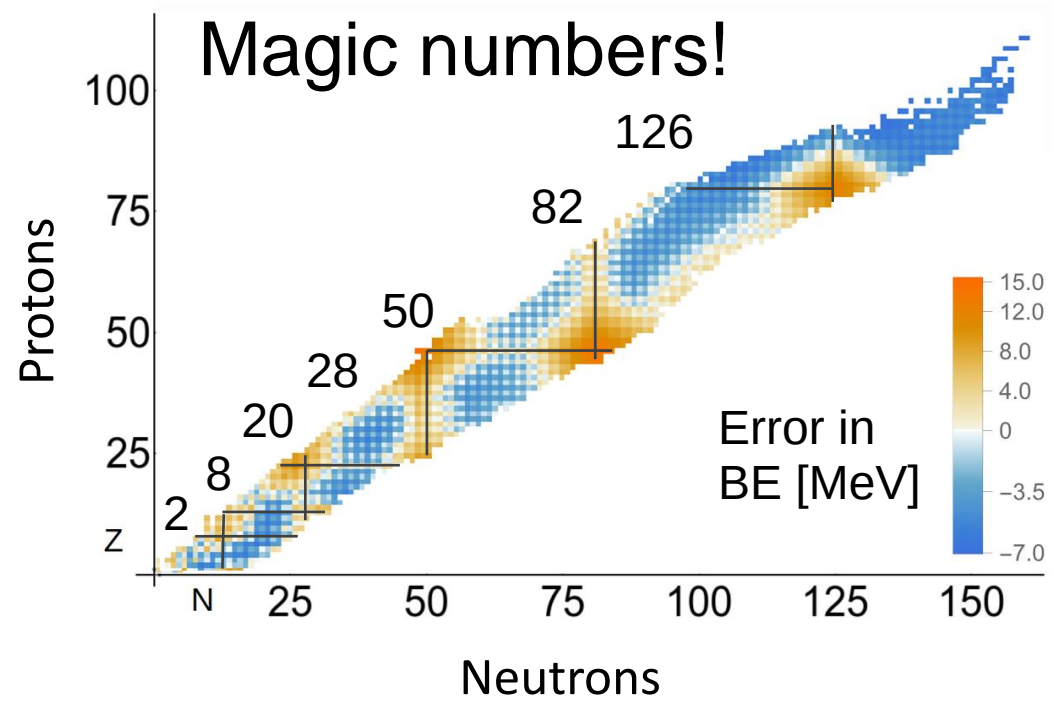
Liquid Drop



Binding energy

Experiment

Liquid Drop



For today

Who am I?

Why theory?

Building models

Building a (simple) nuclear model

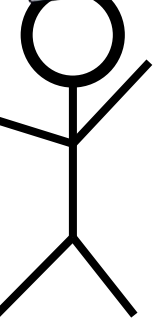
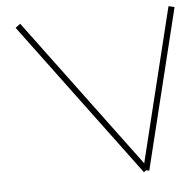
Quantum mechanics



Building (better) nuclear models

Challenges (Hands-On Session)

Questions?



Pablo

Quantum mechanics

*"I think I can safely say
that nobody understands
quantum mechanics."*



Richard Feynman

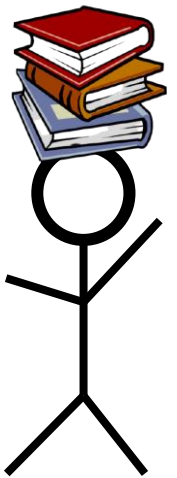
Quantum mechanics

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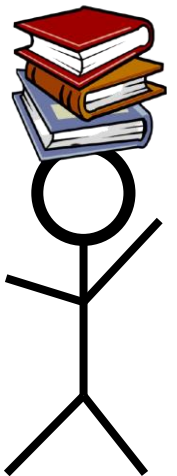
two things we need today



Quantum mechanics

1) Everything comes in “quanta”

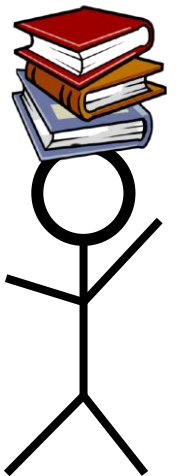
two things we need today



Quantum mechanics

- 1) Everything comes in “quanta”
- 2) Schrodinger equation* describes the dynamics of the system

two things we need today

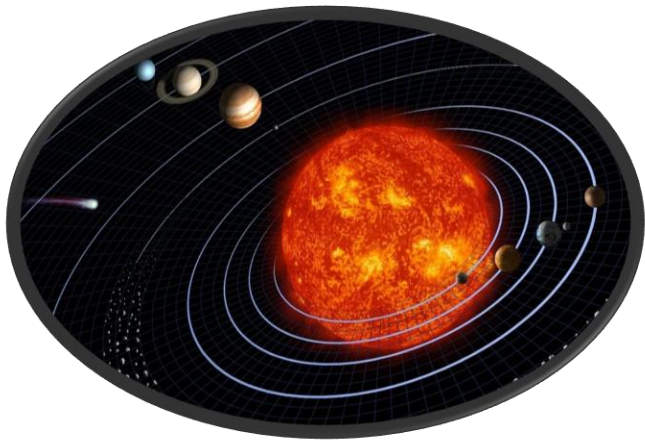


*For things moving very fast: Dirac Eq.

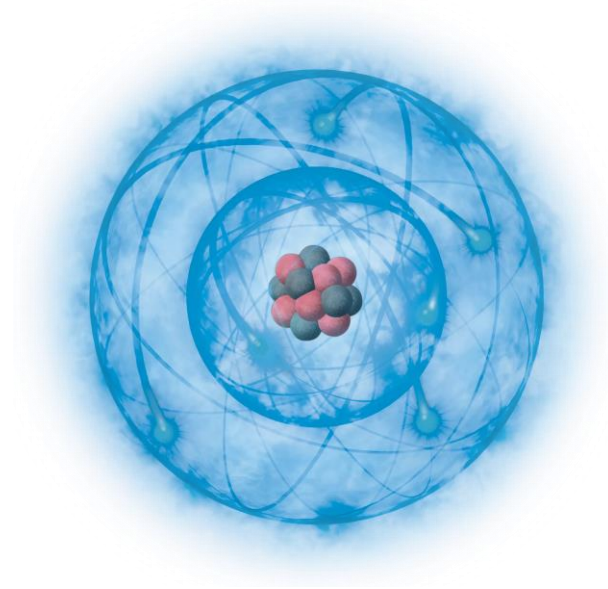
Quantum mechanics

1) Everything comes in “quanta”

2) Schrodinger equation* describes the dynamics of the system



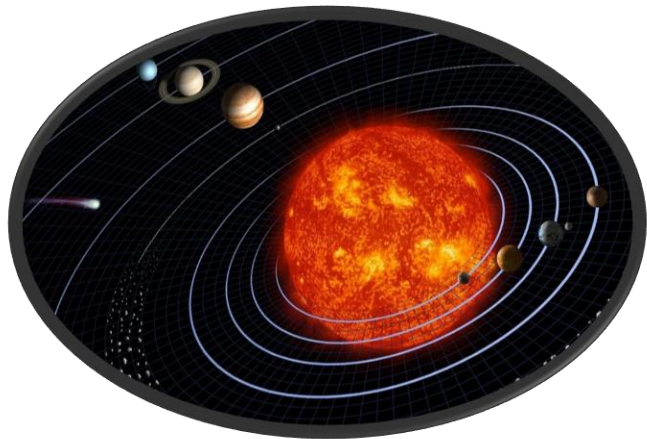
VS



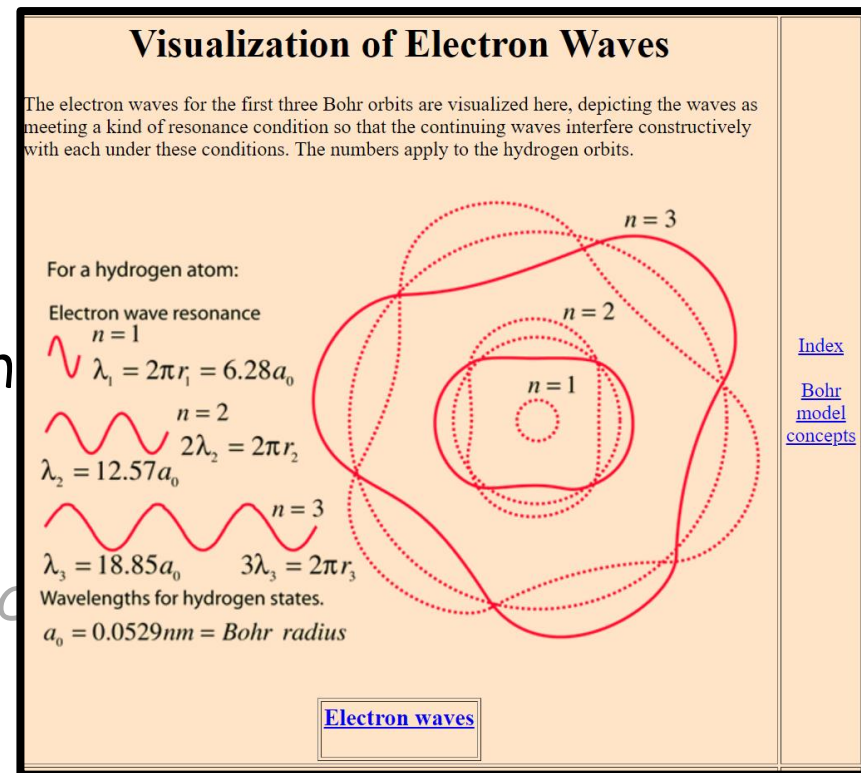
Quantum mechanics

1) Everything comes in “quantum”

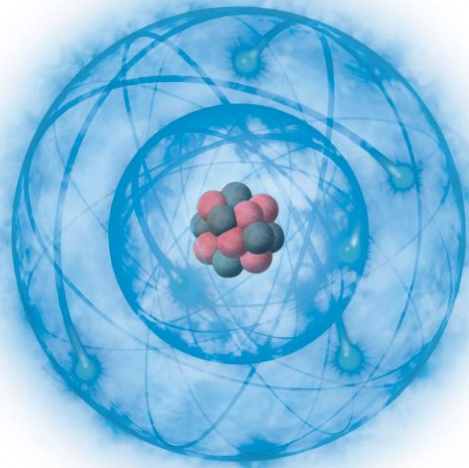
2) Schrodinger equation* describes the dynamics of the system



VS



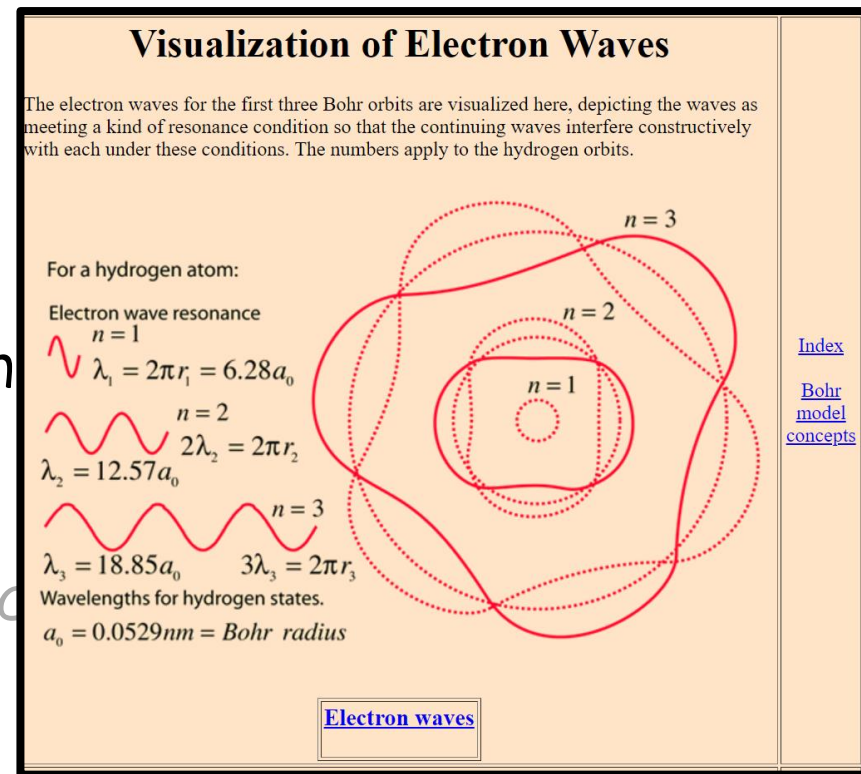
<http://hyperphysics.phy-astr.gsu.edu/hbase/ewav.html>



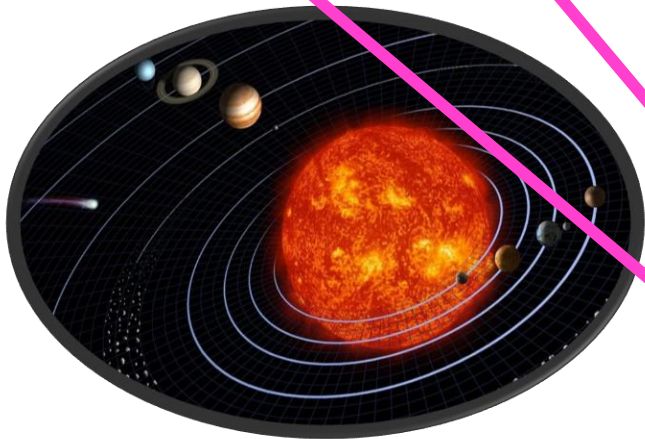
Quantum mechanics

1) Everything comes in “quantum”

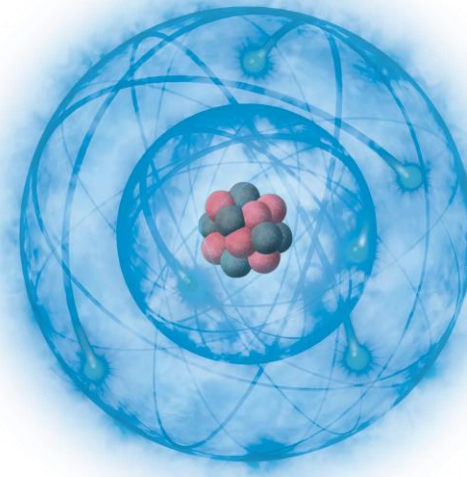
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<http://hyperphysics.phy-astr.gsu.edu/hbase/ewav.html>

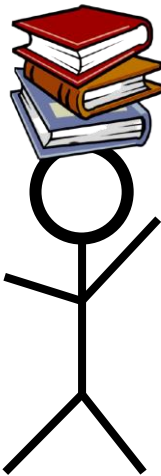


VS



Pablo: don't forget the rope

Thanks Tibor for the rope!!



Quantum mechanics

Visualization of Electron Waves

The electron waves for the first three Bohr orbits are visualized here, depicting the waves as meeting a kind of resonance condition so that the continuing waves interfere constructively with each other under these conditions. The numbers apply to the hydrogen orbits.

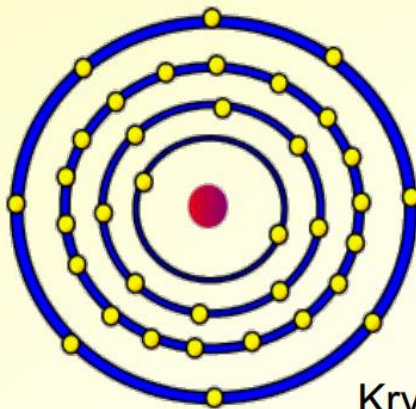
1912



Nobel Prize 1922

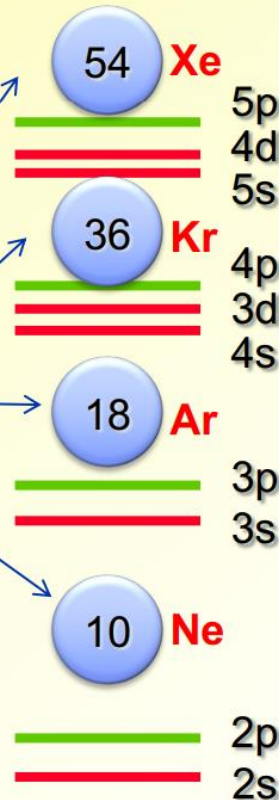
Bohr's picture still serves as an elucidation of the physical and chemical properties of the elements.

noble gases
(closed shells)



Krypton Atom

electronic
shells of
the atom



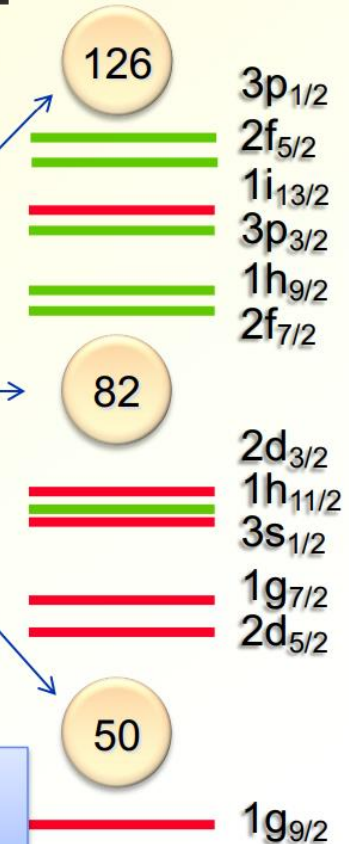
1949



Nobel Prize 1963

nucleonic
shells of
the nucleus

magic nuclei
(closed shells)

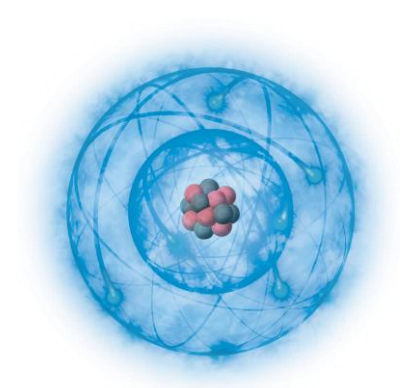


We know now that
this picture is **very**
incomplete...

[Index](#)
[Bohr](#)
[model](#)
[concepts](#)

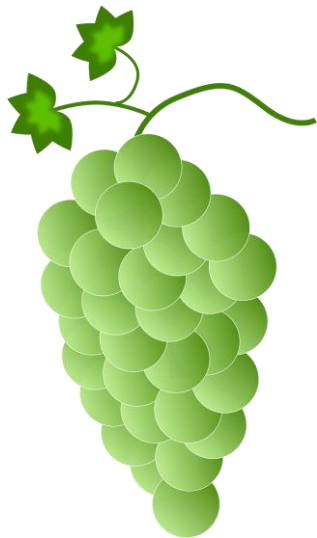
wav.html

Quantum mechanics



1) Everything comes in “quanta”

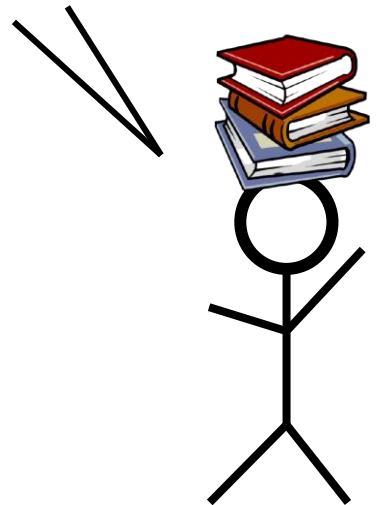
2) Schrodinger equation* describes the dynamics of the system



Not-nucleus

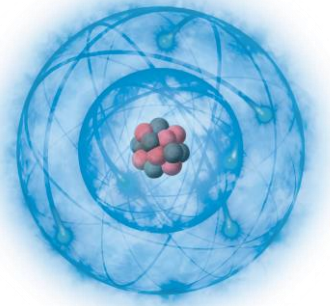


Nuclei looks more like an onion than like grapes



Nucleus

Quantum mechanics



1) Everything comes in “quanta”

2) Schrodinger equation* describes the dynamics of the system

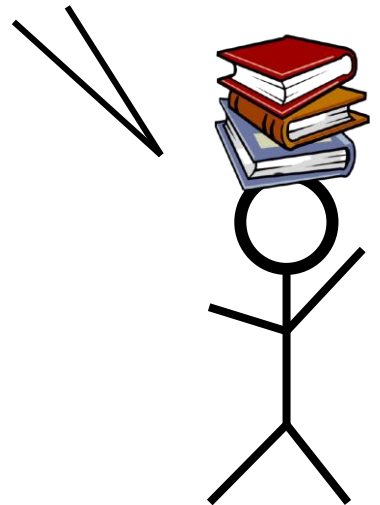


Not-nucleus

Nuclei looks more like an onion than like grapes



Nucleus



Nuclei are like ogres



Quantum mechanics

1) Everything comes in “quanta”

2) Schrodinger equation* describes the dynamics of the system

$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

Quantum mechanics

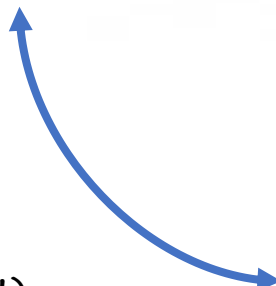
1) Everything comes in “quanta”

2) Schrodinger equation* describes the dynamics of the system

(quantum)

$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

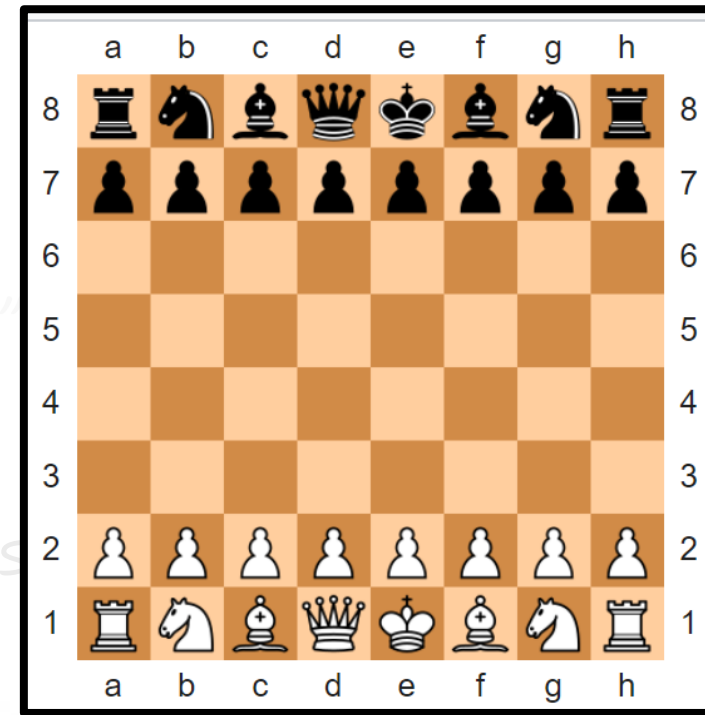
(classical)

$$\vec{F} = m\vec{a}$$


Quantum mechanics

1) Everything comes in “quantum”

2) Schrodinger equation* describes dynamics of the system



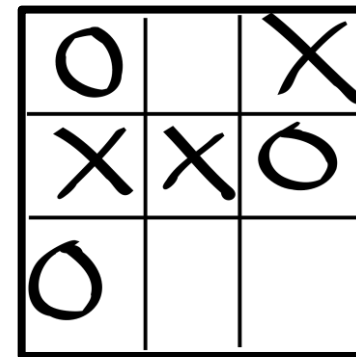
Chess

(quantum)

$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

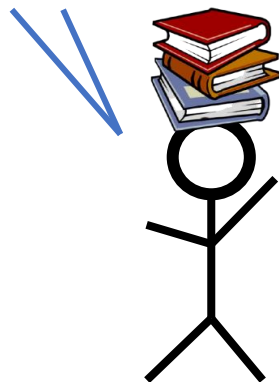
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$$\vec{F} = m\vec{a}$$



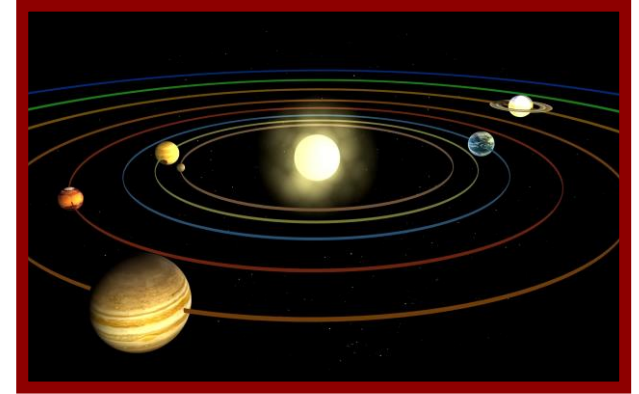
Tic tac toe

Think of it as the rules of the game



Quantum mechanics

Solar System Video - The Best Planet
Video for Educational Purposes



$$F = G \frac{m_1 m_2}{r^2}$$

1) Everything comes in "quantum"

2) Schrodinger equation* describes the dynamics of the system

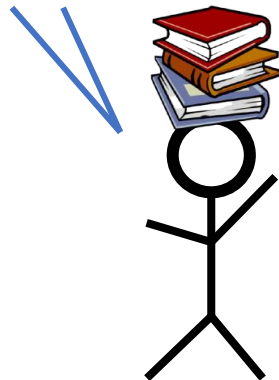
(quantum)

$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

(classical)

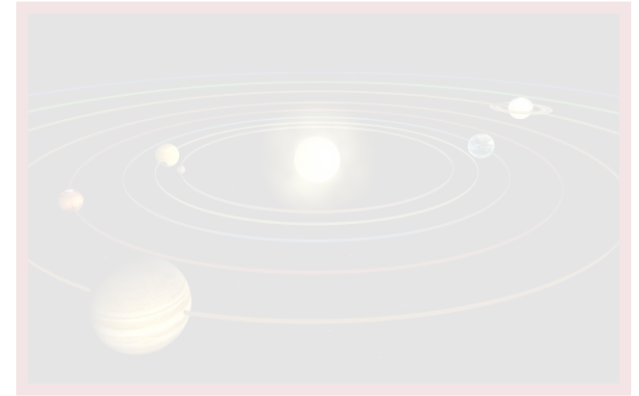
$$\vec{F} = m\vec{a}$$

Think of it as the
rules of the game



Quantum mechanics

Solar System Video - The Best Planet
Video for Educational Purposes



$$F = G \frac{m_1 m_2}{r^2}$$

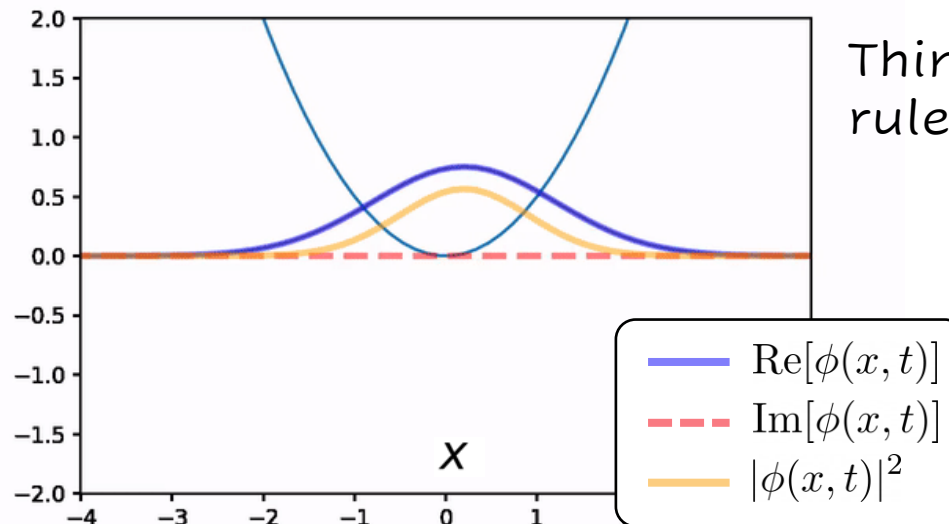
2) Schrodinger equation* describes the dynamics of the system

(quantum)

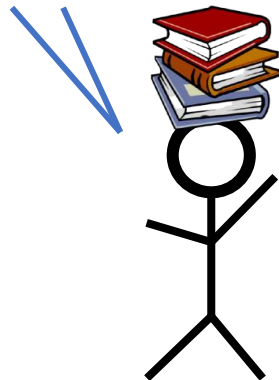
$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

$$\mathcal{H} = -\frac{\partial^2}{\partial x^2} + \omega^2 x^2$$

Harmonic
Oscillator



Think of it as the
rules of the game



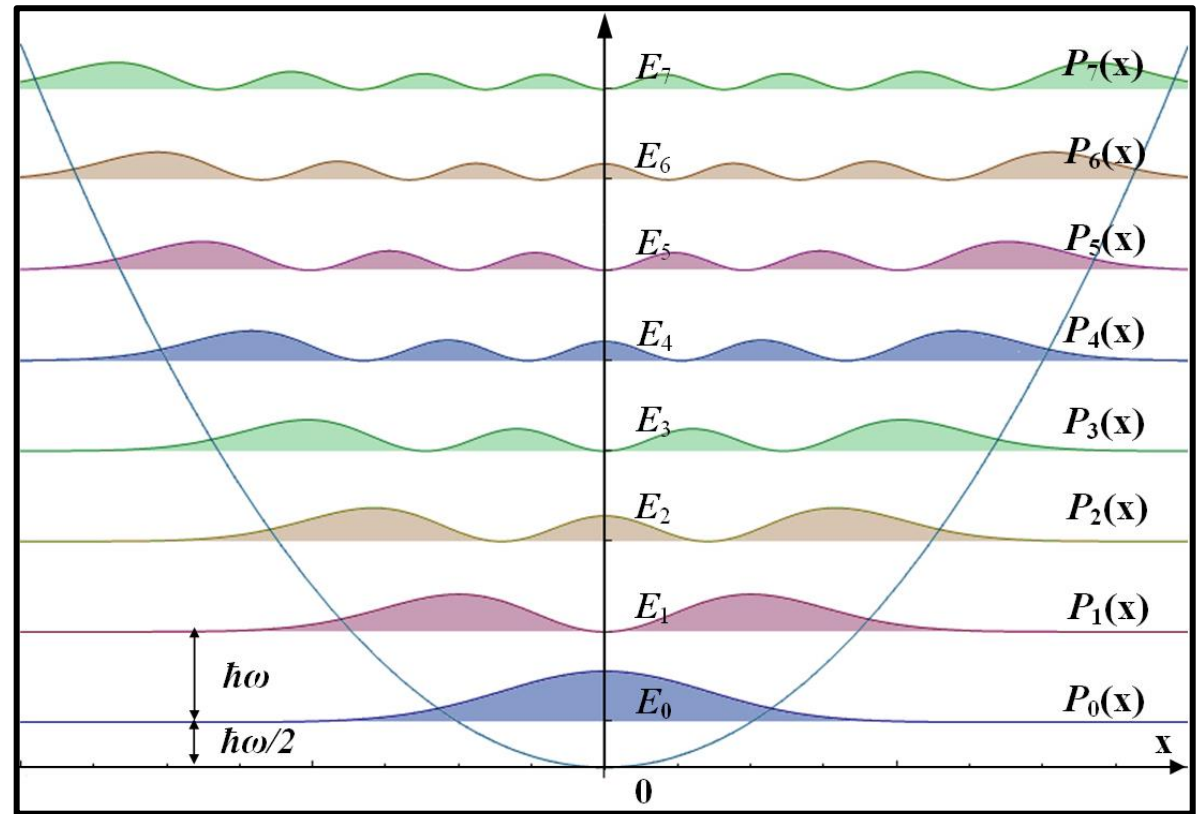
Quantum mechanics

Spectrum

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

$$\mathcal{H} = -\frac{\partial^2}{\partial x^2} + \omega^2 x^2$$

Harmonic
Oscillator

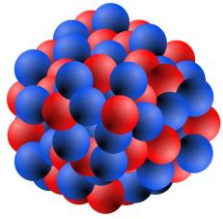


Time-independent

$$\mathcal{H}|\psi(x)\rangle = E|\psi(x)\rangle$$

Quantum mechanics

Can we model the nucleus with this?

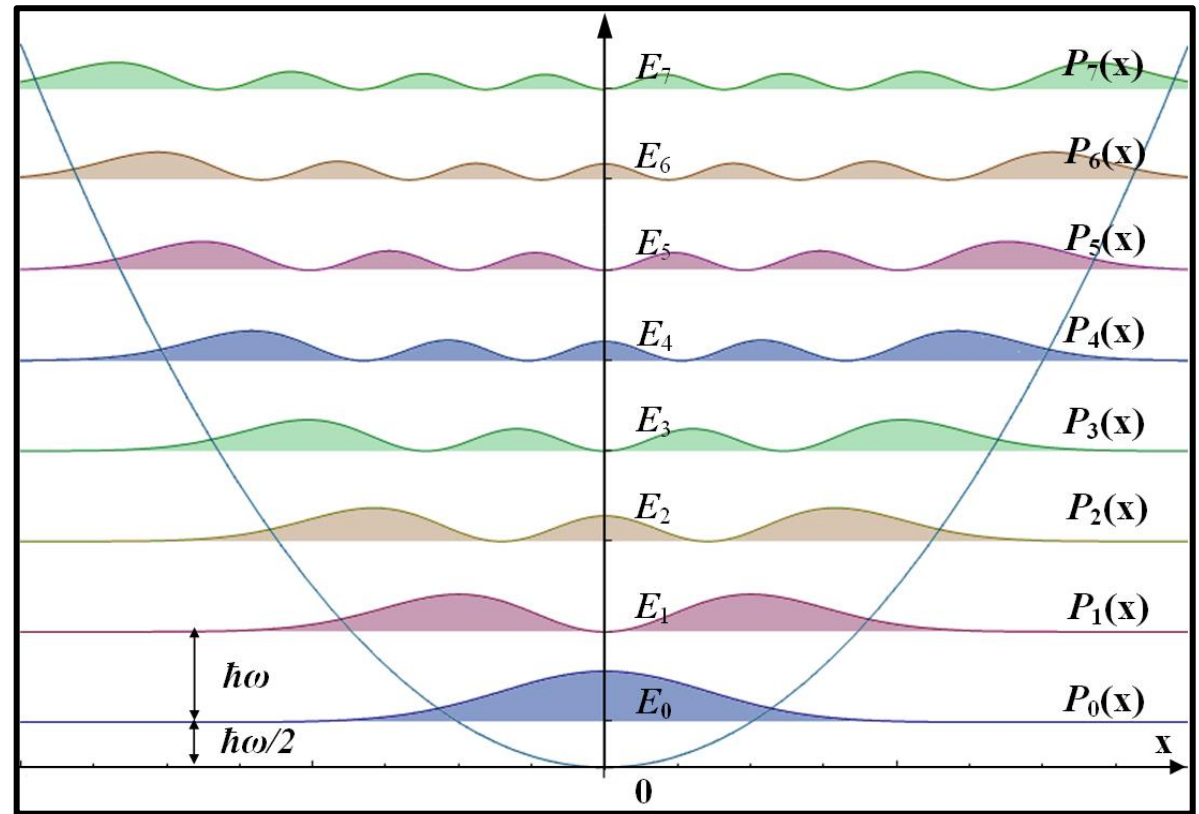


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Harmonic
Oscillator

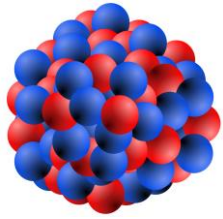


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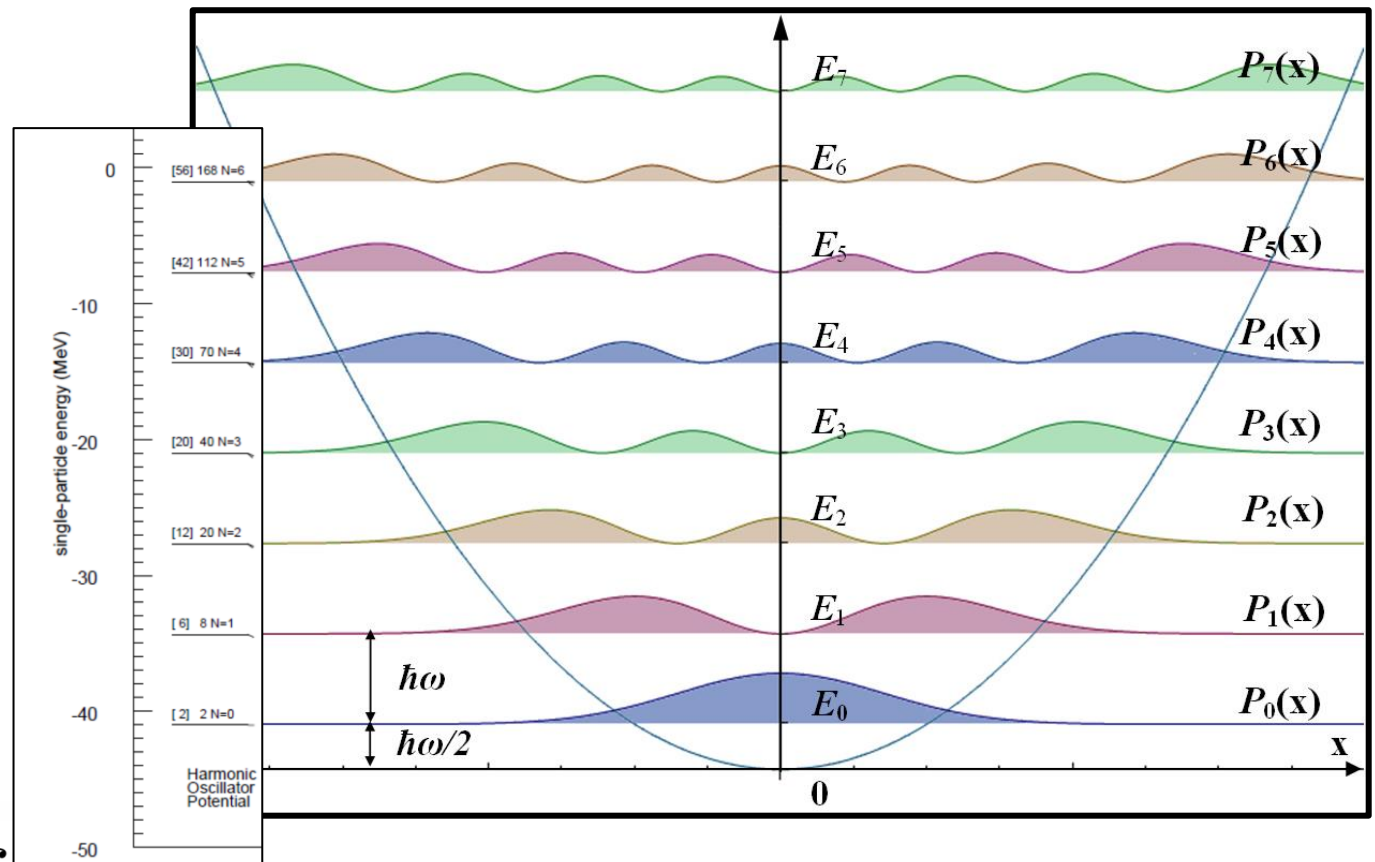


Spectrum

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Harmonic
Oscillator

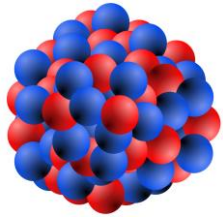


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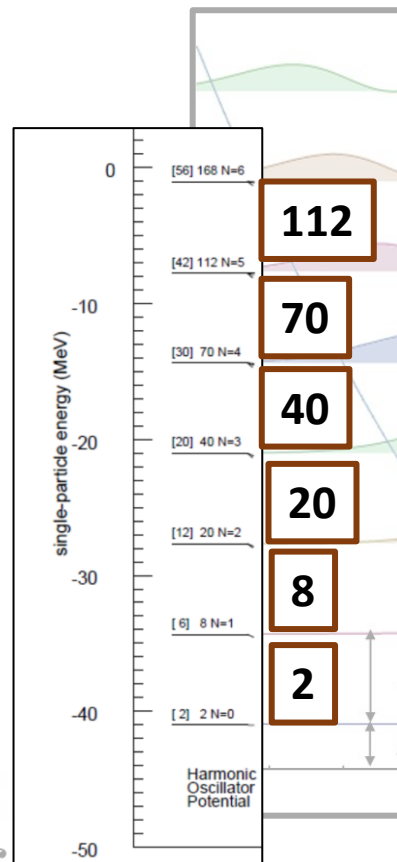


Spectrum

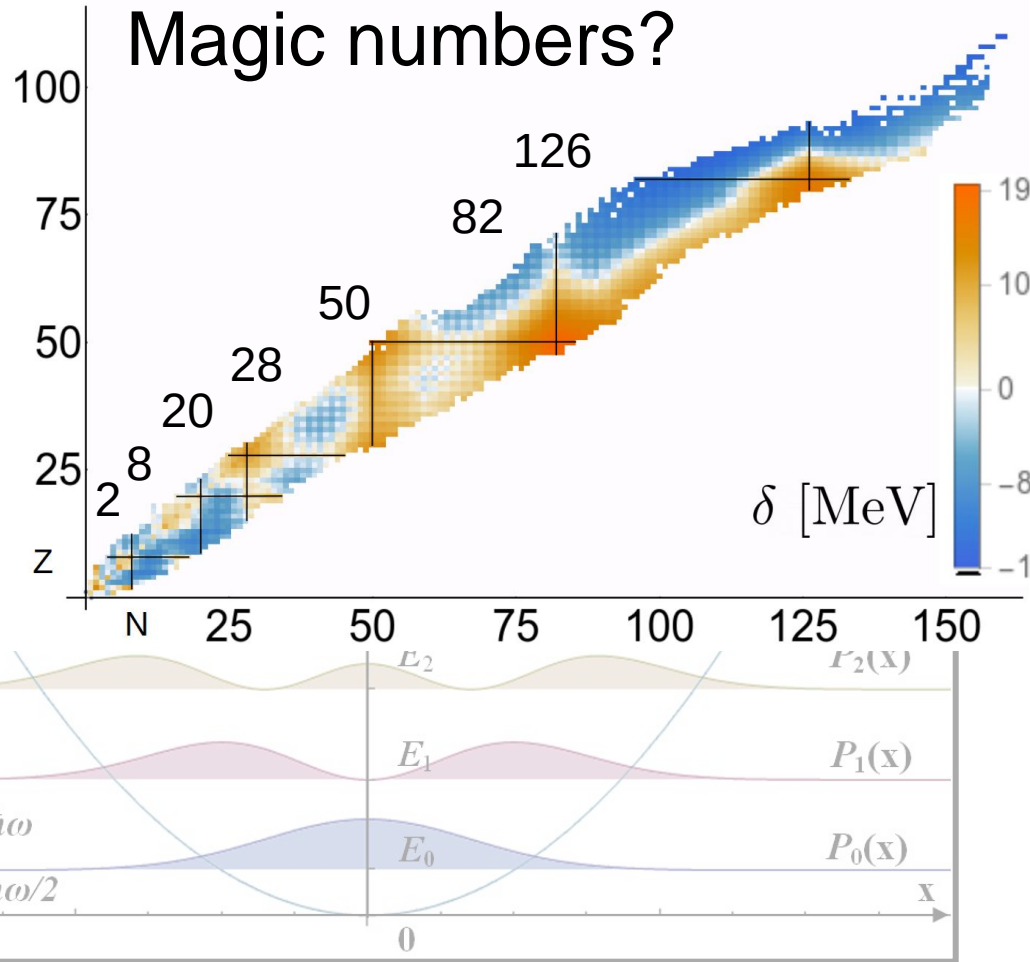
$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

$$\mathcal{H} = -\frac{\partial^2}{\partial x^2} + \omega^2 x$$

Harmonic Oscillator



Magic numbers?

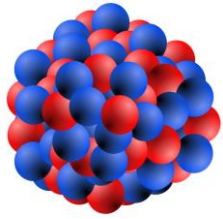


Time-independent

$$\mathcal{H}|\psi(x)\rangle = E|\psi(x)\rangle$$

Quantum mechanics

Can we model the nucleus with this?



Not really...

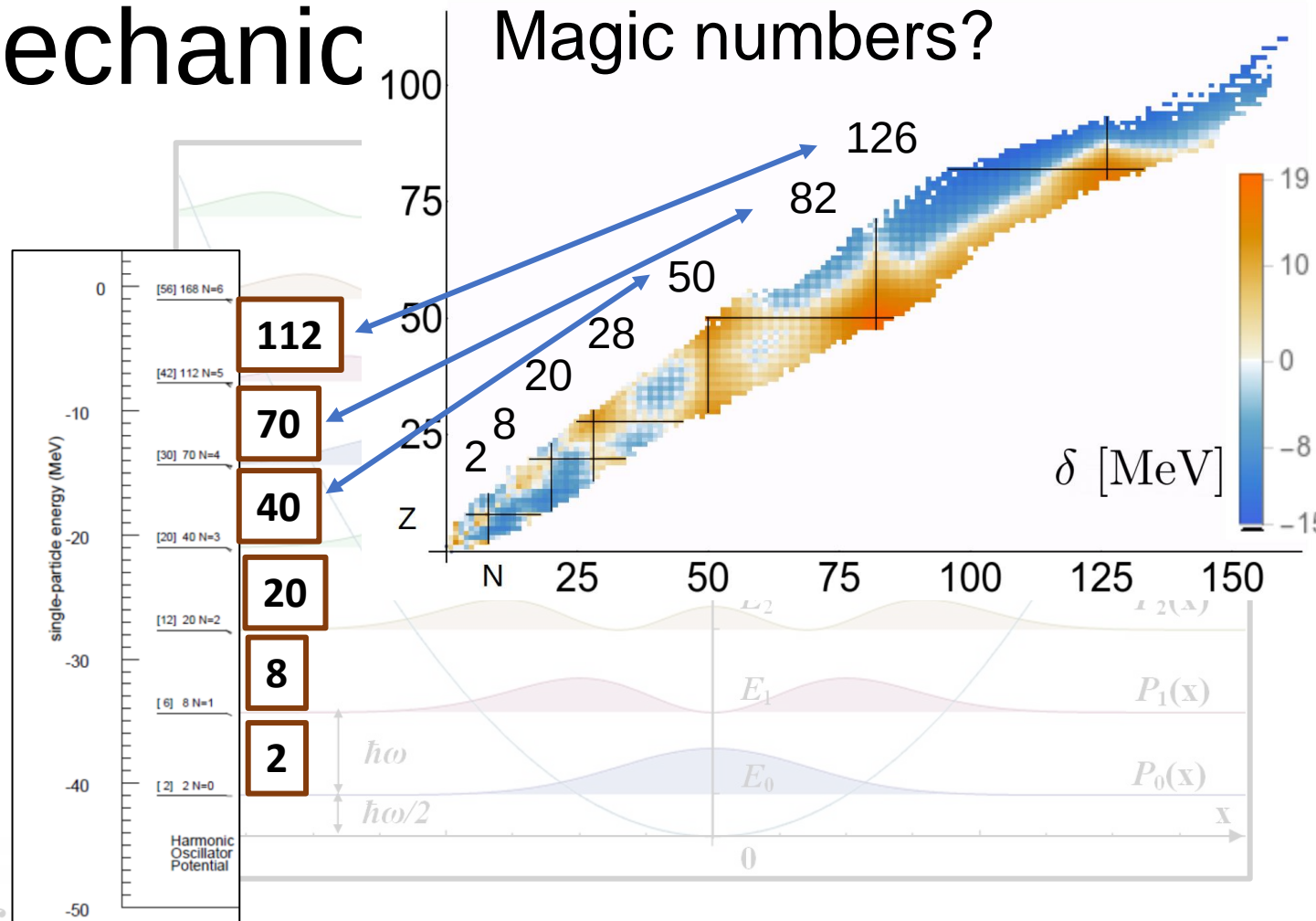
Spectrum

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

$$\mathcal{H} = -\frac{\partial^2}{\partial x^2} + \omega^2 x$$

Harmonic Oscillator

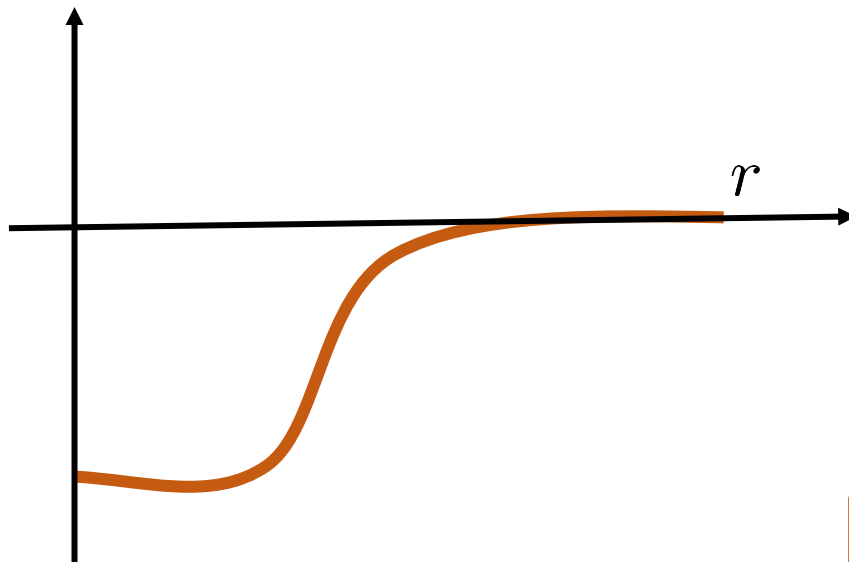
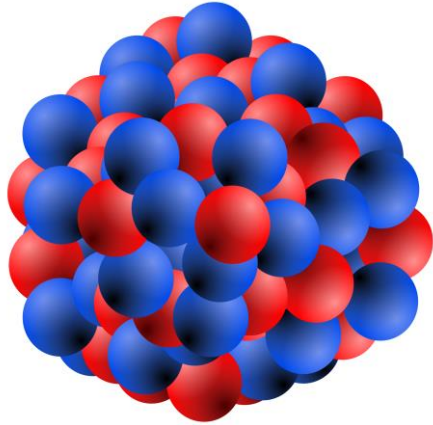
Magic numbers?



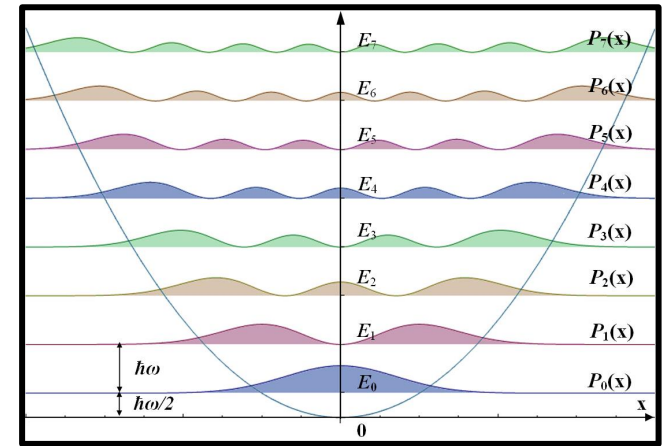
Time-independent

$$\mathcal{H}|\psi(x)\rangle = E|\psi(x)\rangle$$

Quantum mechanics



Woods-Saxon potential



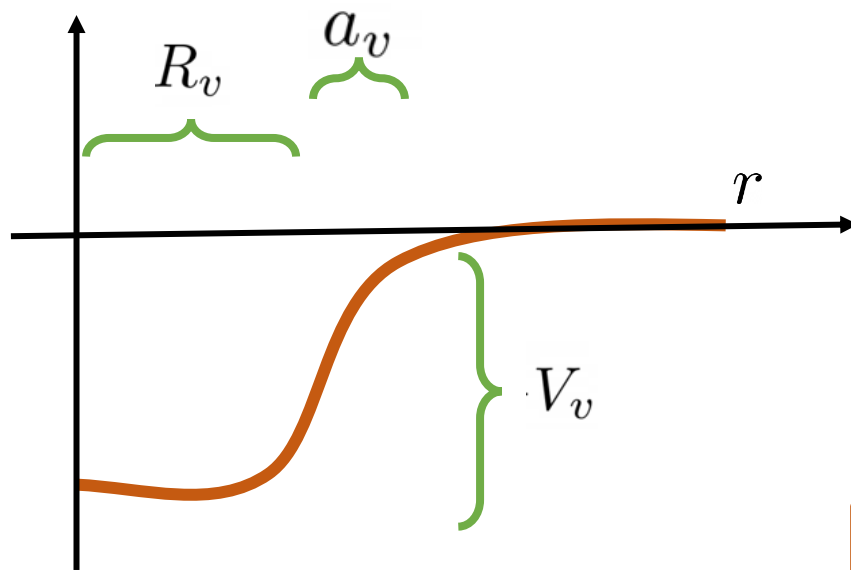
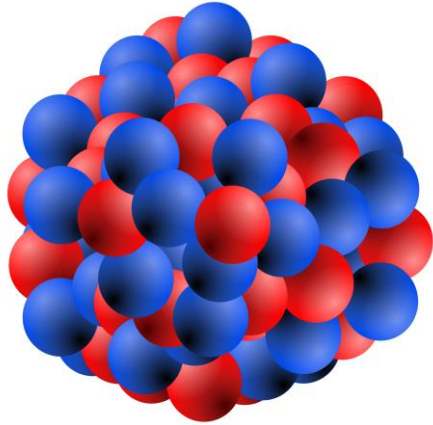
$$\mathcal{H} = -\frac{\partial^2}{\partial x^2} + \cancel{\omega^2 x^2}$$

↓

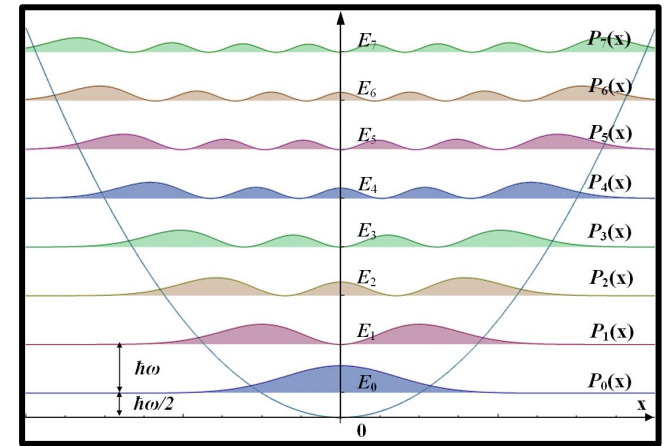
$$\mathcal{H} = -\frac{\partial^2}{\partial x^2} + V(r)$$

$$-V_v \left[1 + \exp\left(\frac{r - R_v}{a_v}\right) \right]$$

Quantum mechanics



Woods-Saxon potential



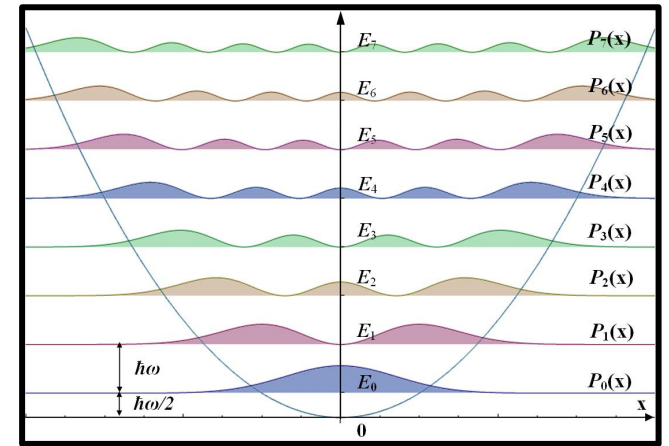
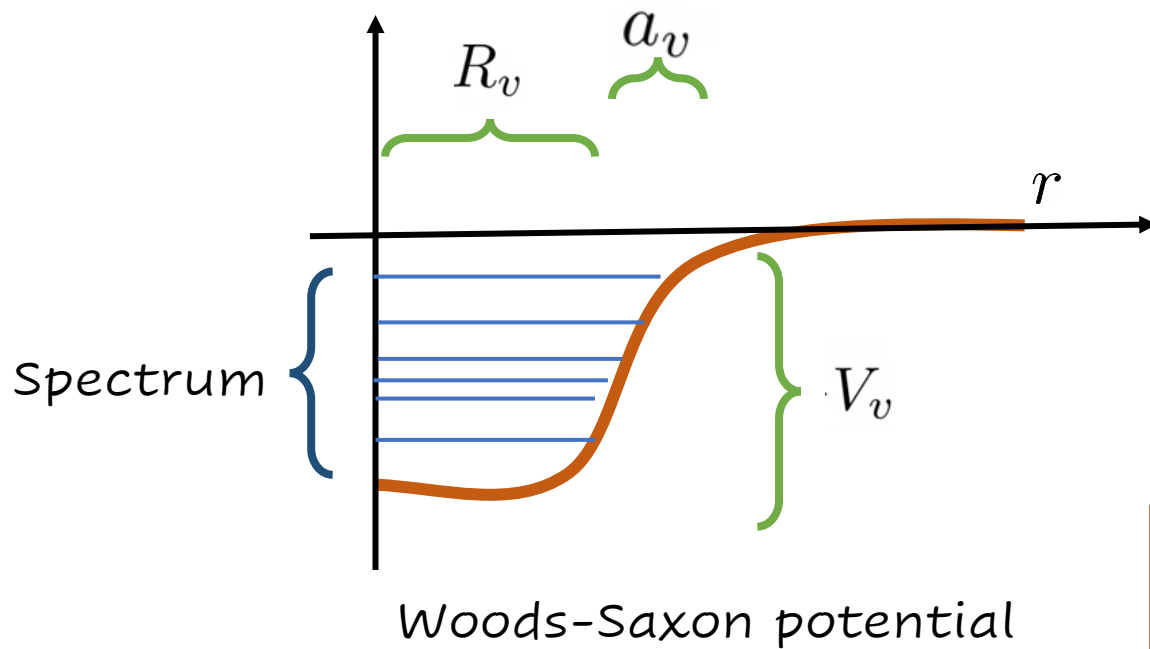
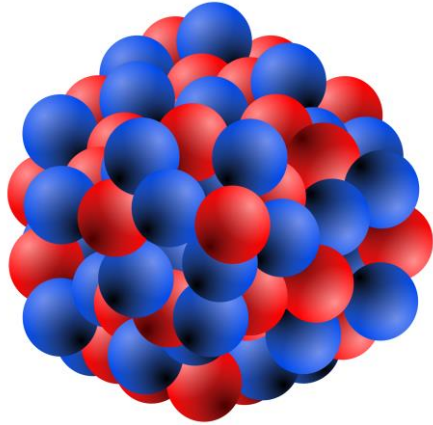
$$\mathcal{H} = -\frac{\partial^2}{\partial x^2} + \cancel{\omega^2 x^2}$$

↓

$$\mathcal{H} = -\frac{\partial^2}{\partial x^2} + V(r)$$

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Quantum mechanics



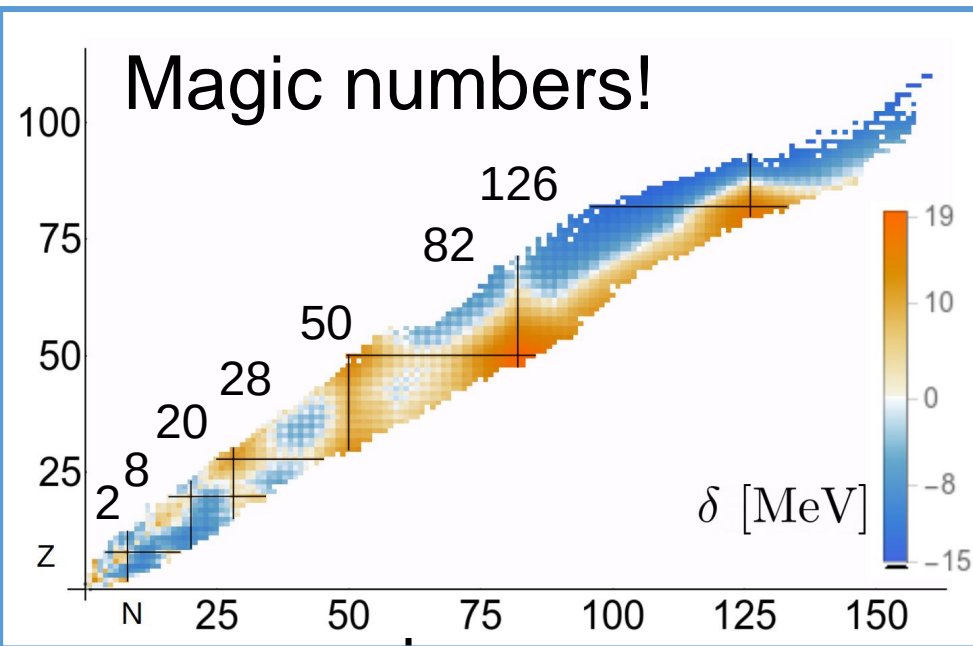
$$\mathcal{H} = -\frac{\partial^2}{\partial x^2} + \cancel{\omega^2 x^2}$$

↓

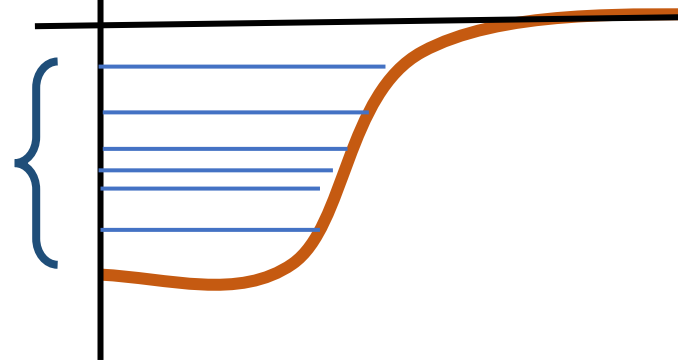
$$\mathcal{H} = -\frac{\partial^2}{\partial x^2} + V(r)$$

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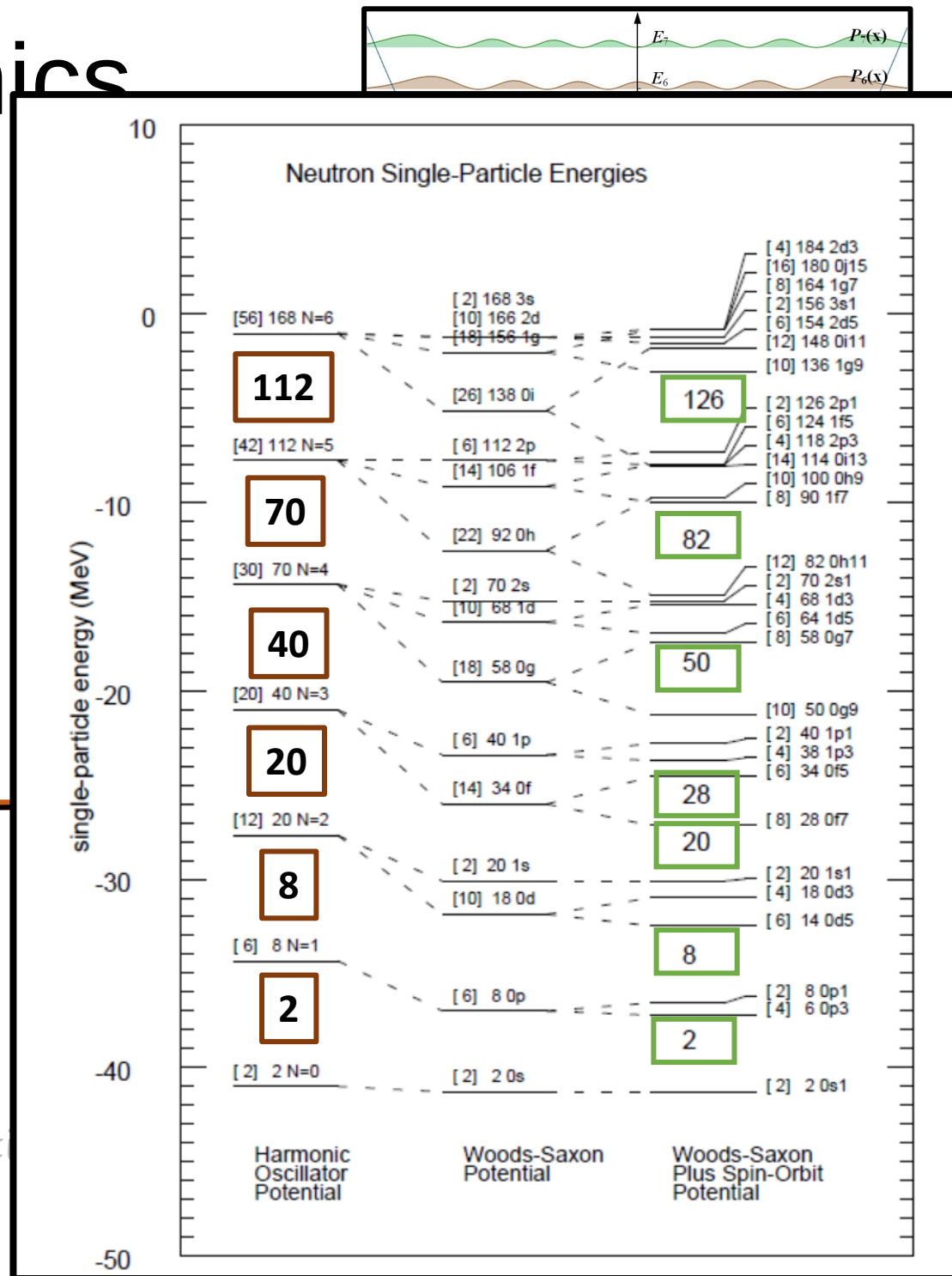
Quantum mechanics

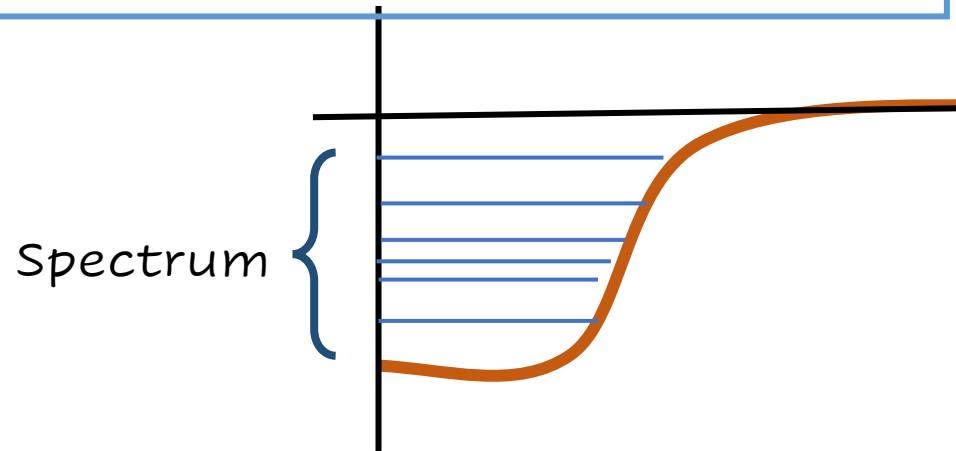


Spectrum

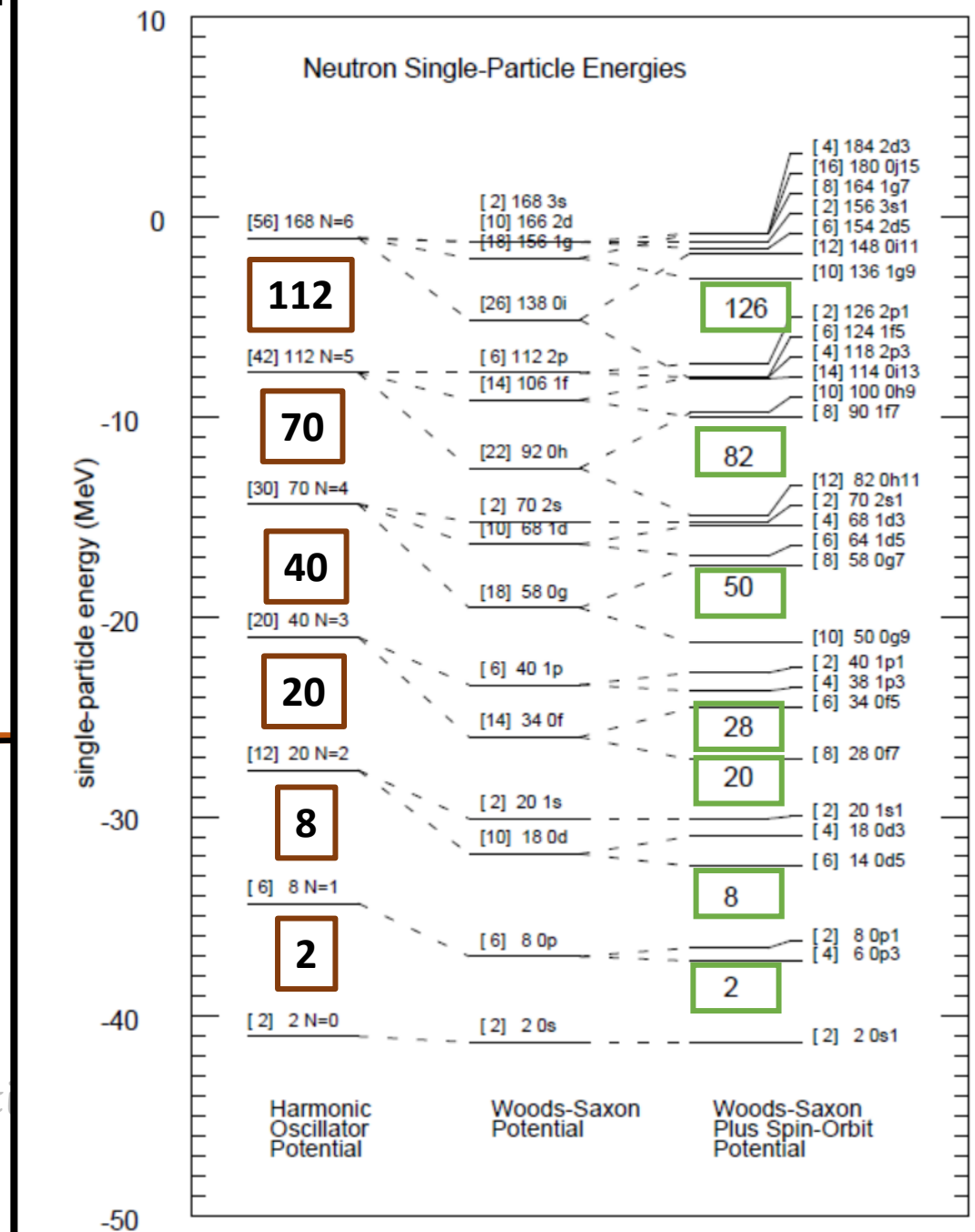


Woods-Saxon potent

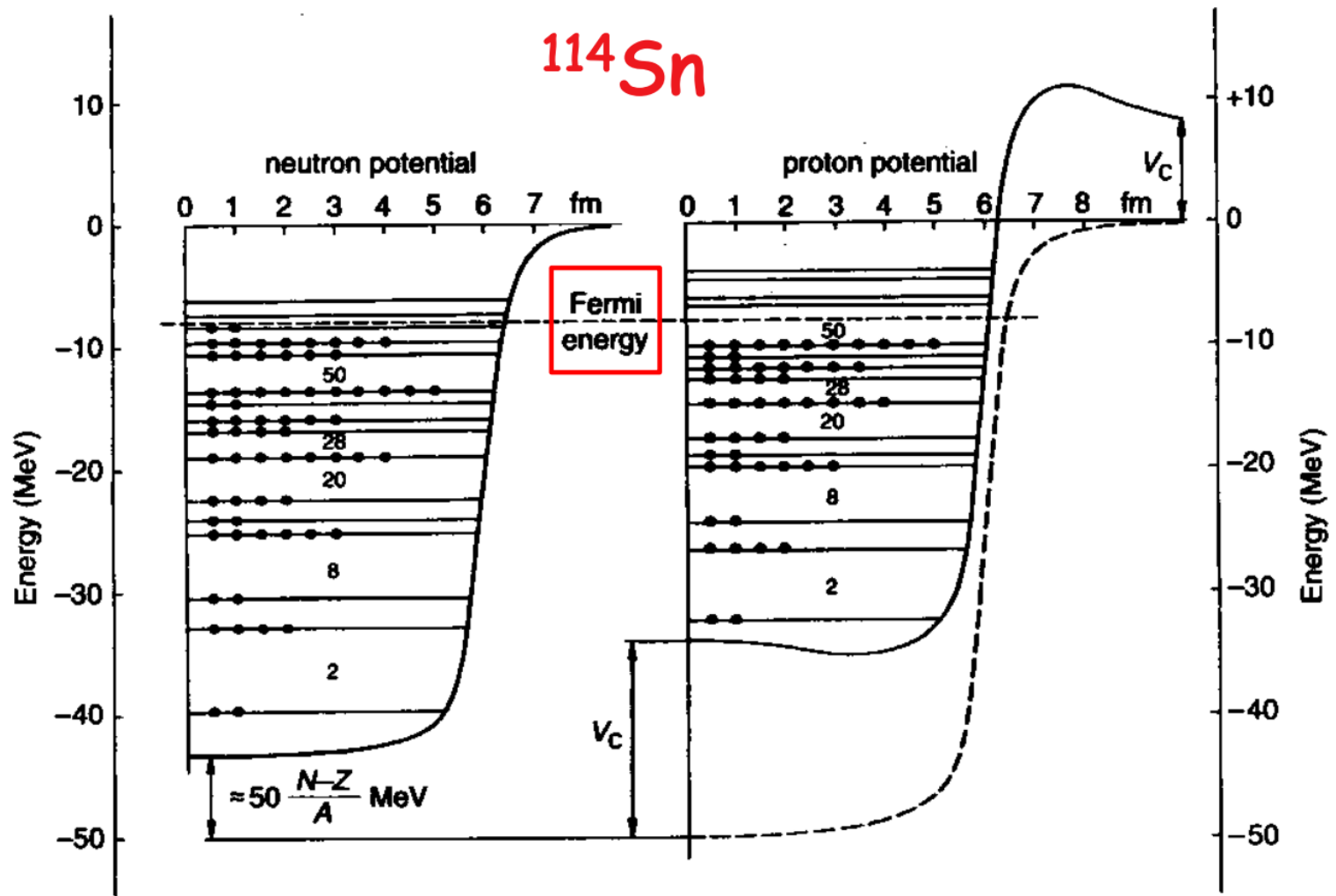




Shell Model



Nuclear shell model potential



Shell Model

Harmonic
Oscillator
Potential

Woods-Saxon
Potential

Woods-Saxon
Plus Spin-Orbit
Potential

Building better models

$$\mathcal{H}|\psi(x, t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(x, t)\rangle$$

Building better models

Rules of the game
(we don't have
them)



$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

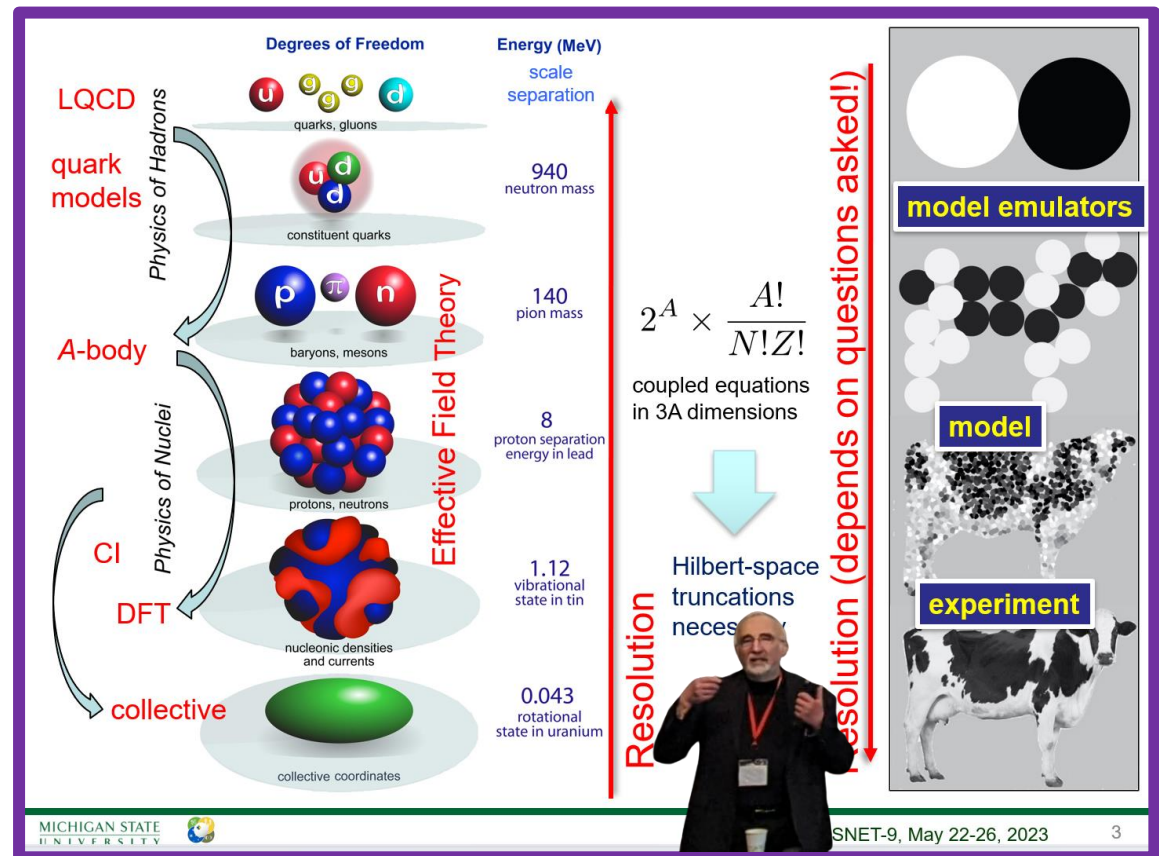


Building better models

Rules of the game
(we don't have them)

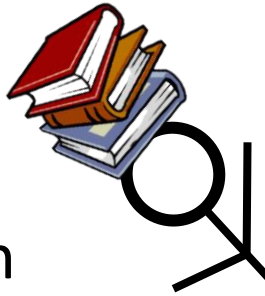


$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$



Building better models

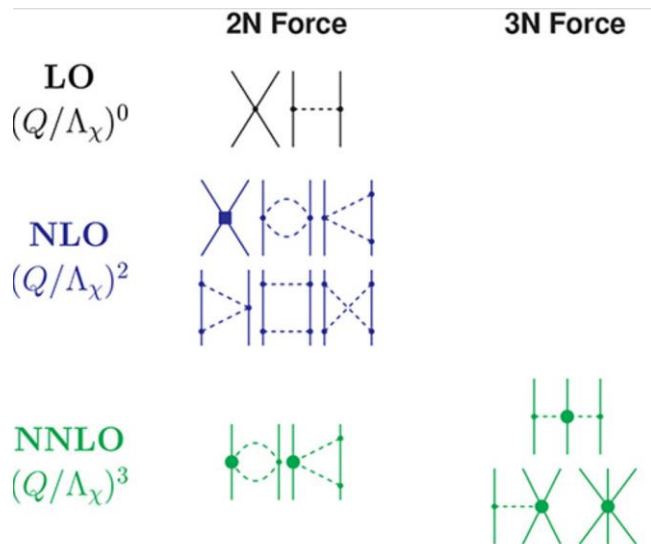
Each model
is a new set of
guessed rules



$$\boxed{\mathcal{H}} |\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$

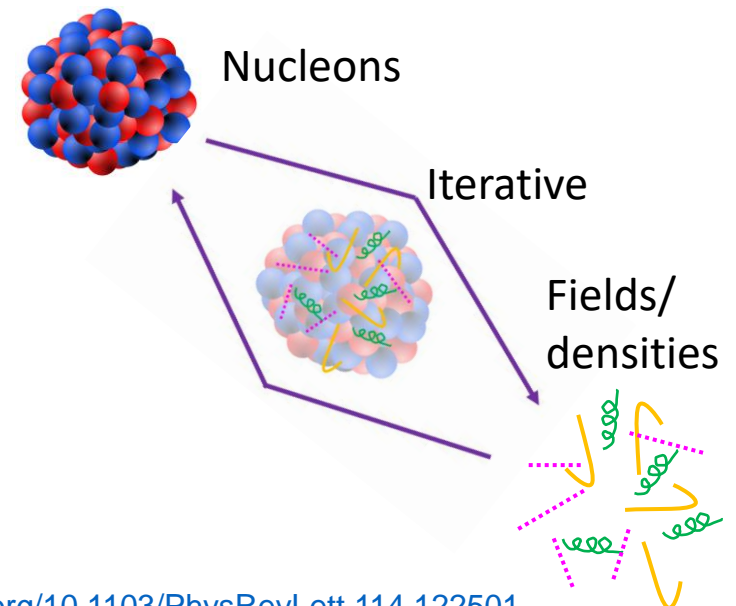
Explain
Predict
Build

Chiral Effective Field Theory



<https://doi.org/10.3389/fphy.2020.00057>

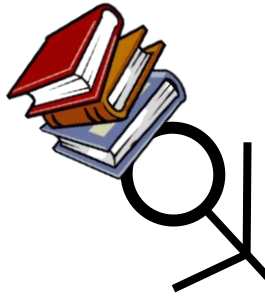
Density Functional Theory



<https://doi.org/10.1103/PhysRevLett.114.122501>

Building better models

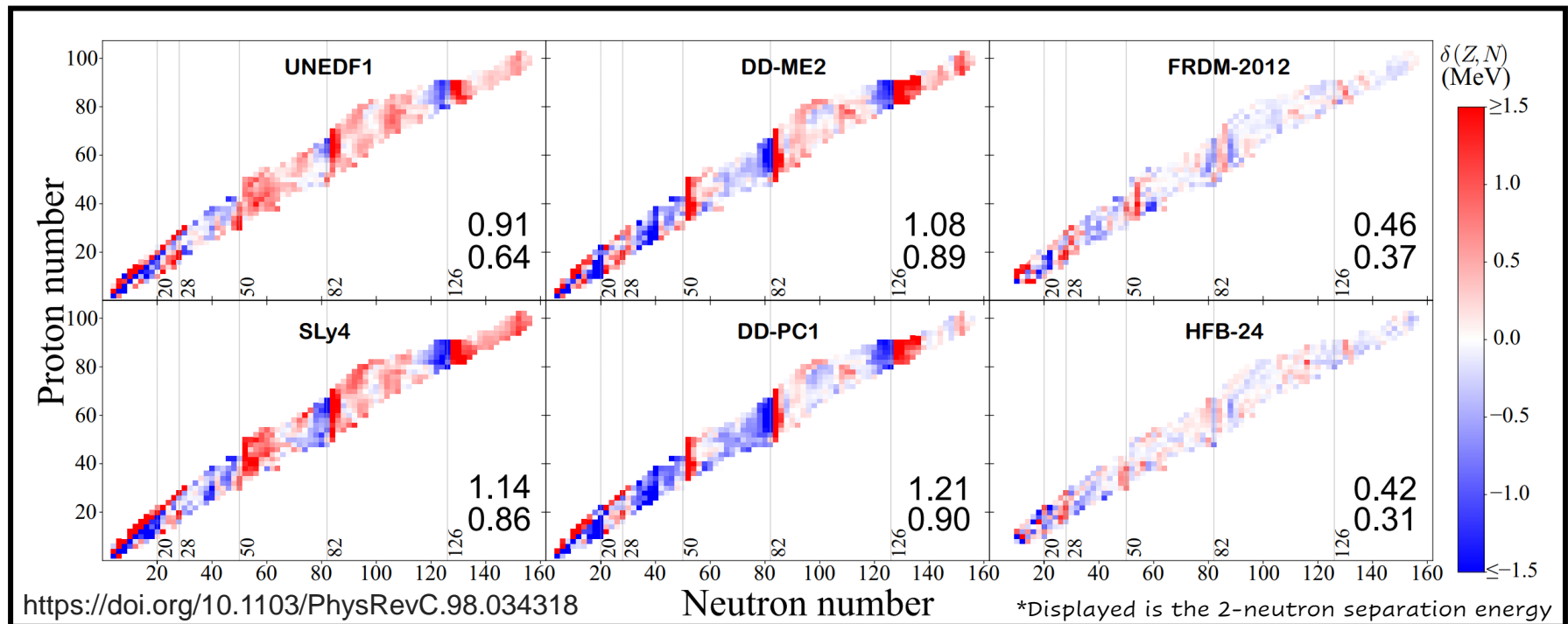
Each model
is a new set of
guessed rules



Nuclear
Masses*

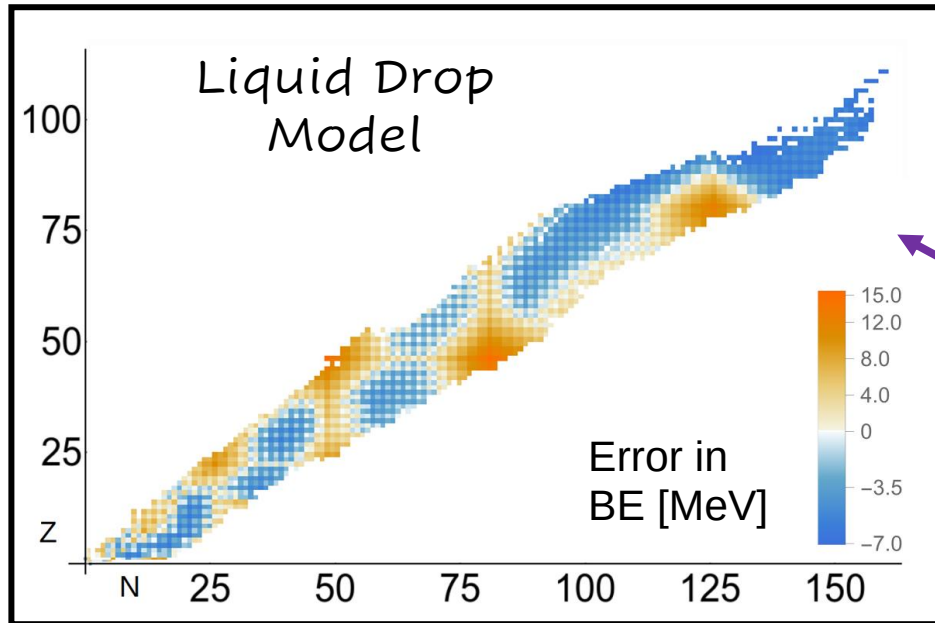
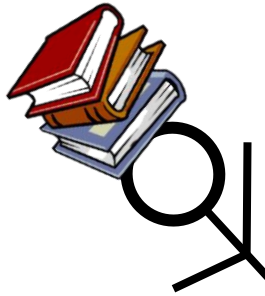


Modern Models



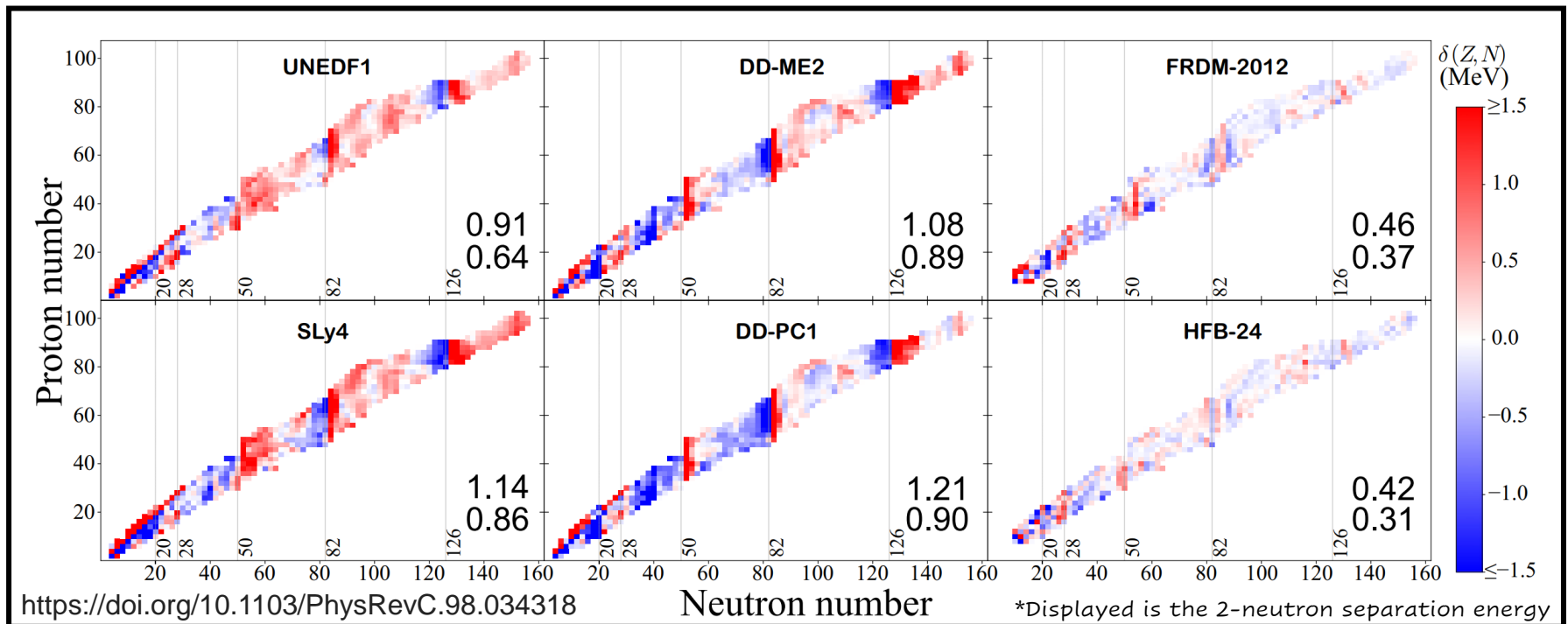
Building better models

Each model
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guessed rules

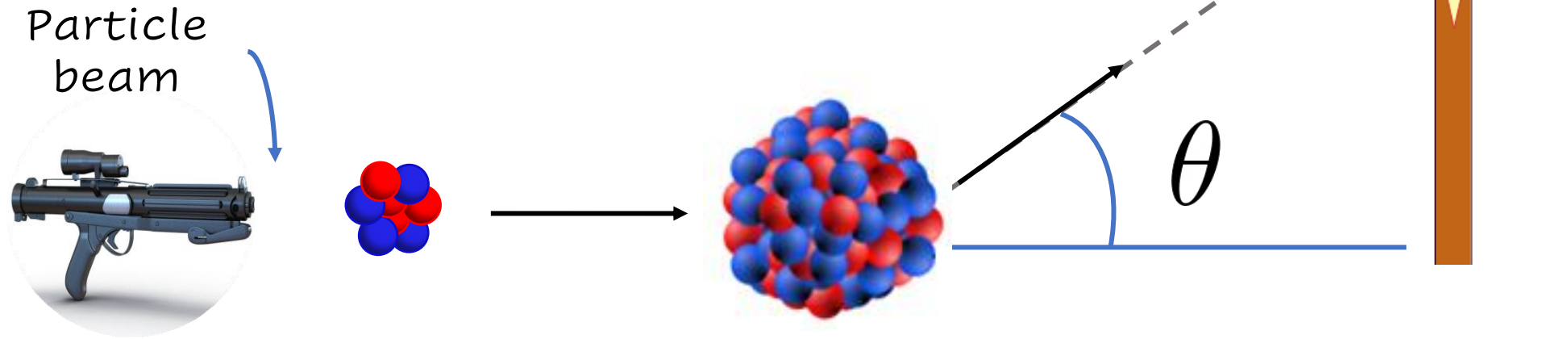


Nuclear
Masses*

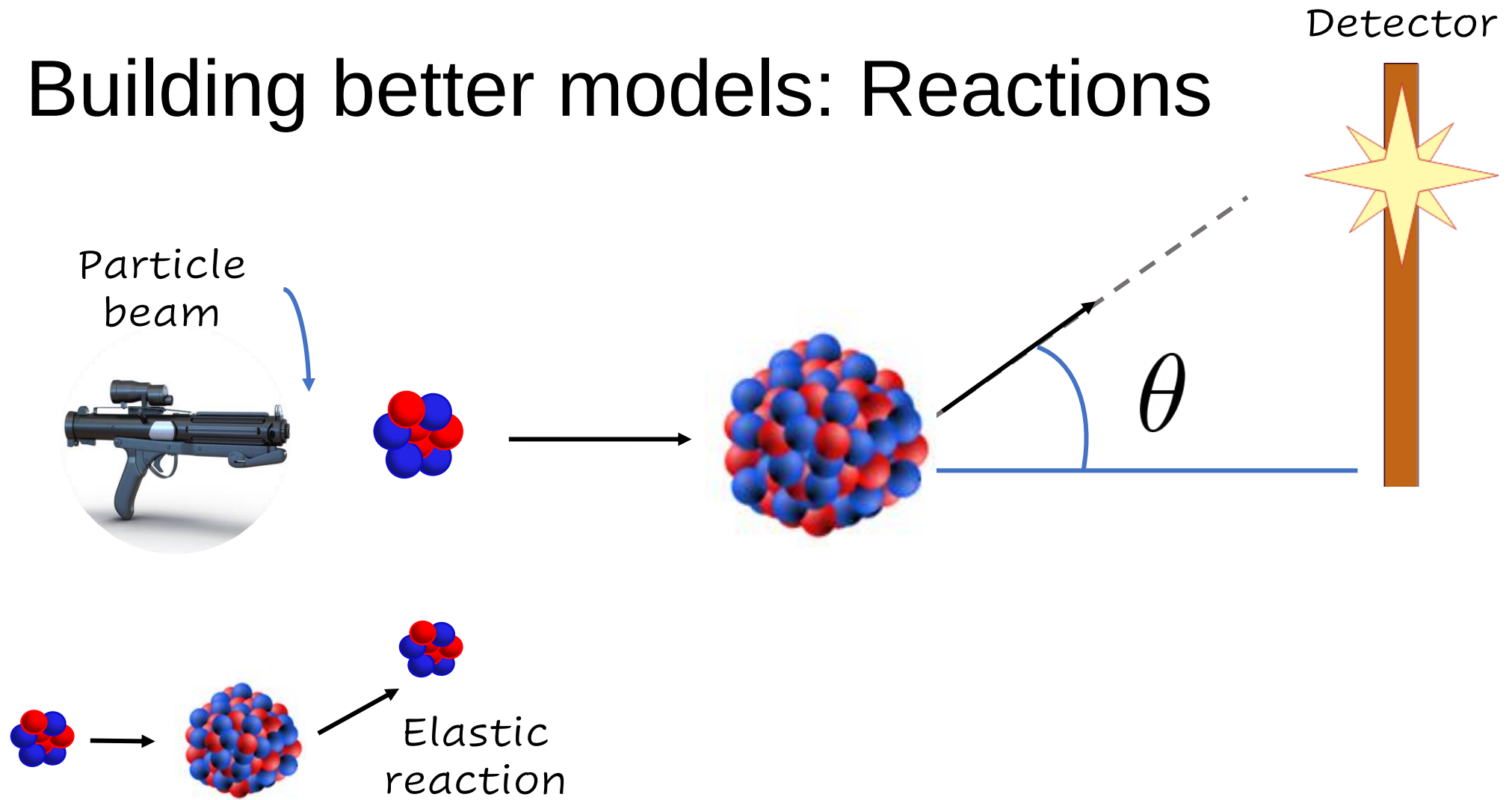
Modern Models



Building better models: Reactions

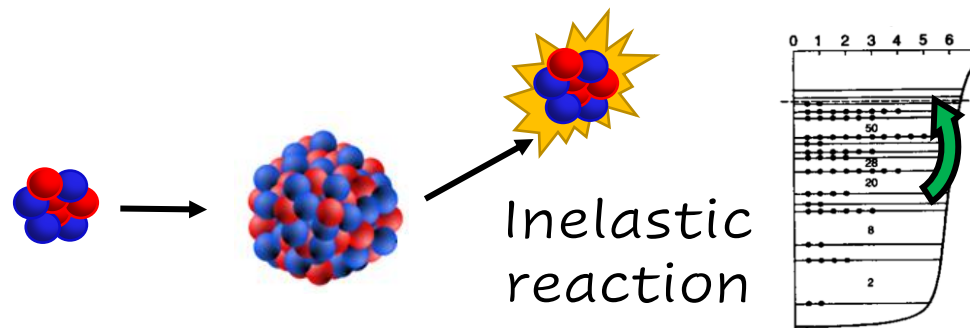
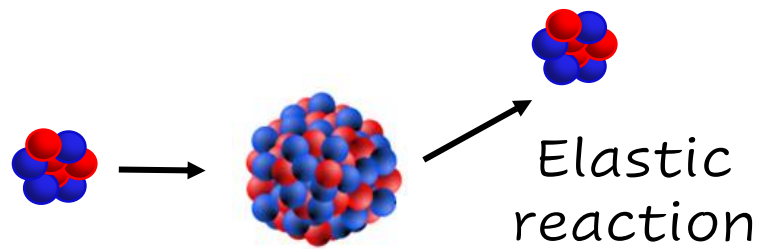
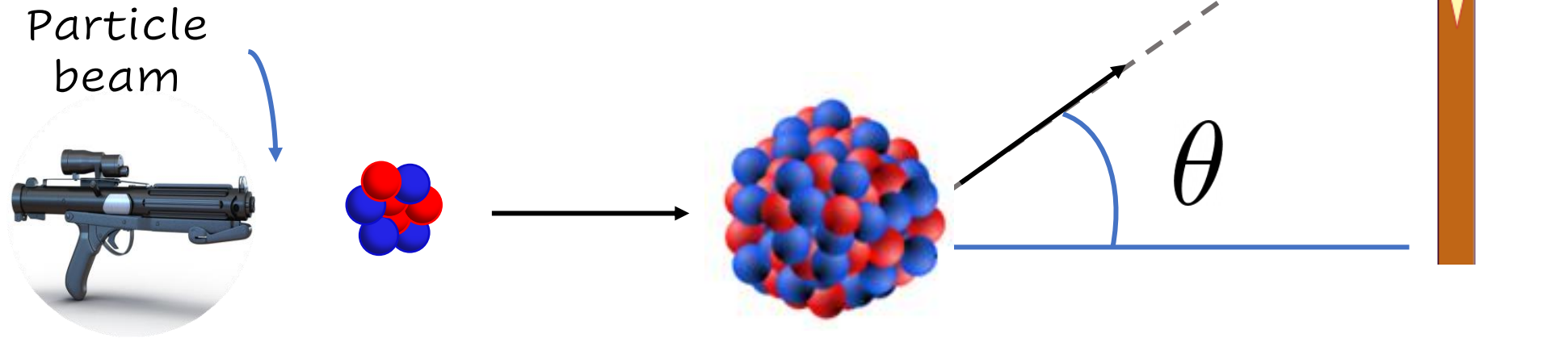


Building better models: Reactions

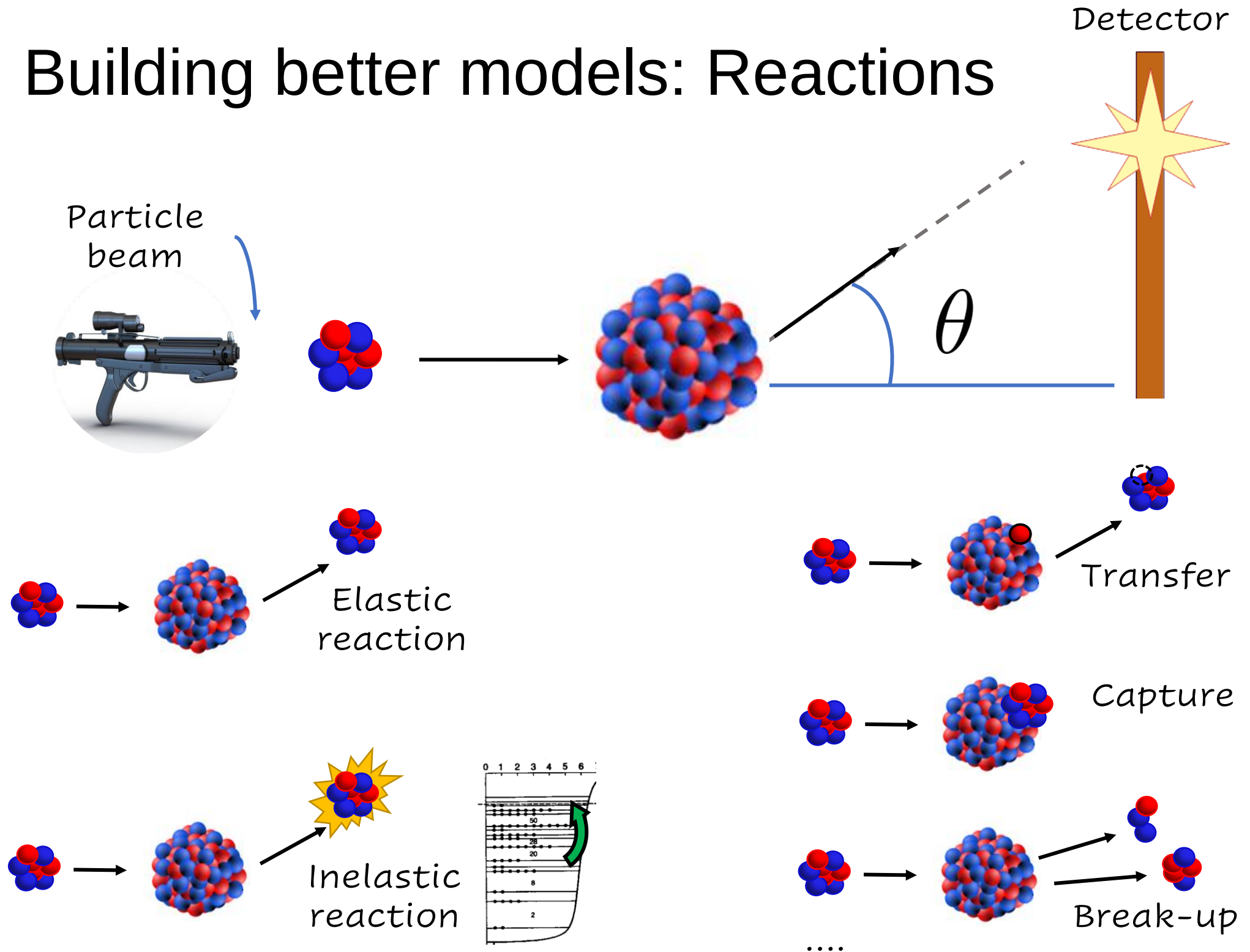


Building better models: Reactions

Detector



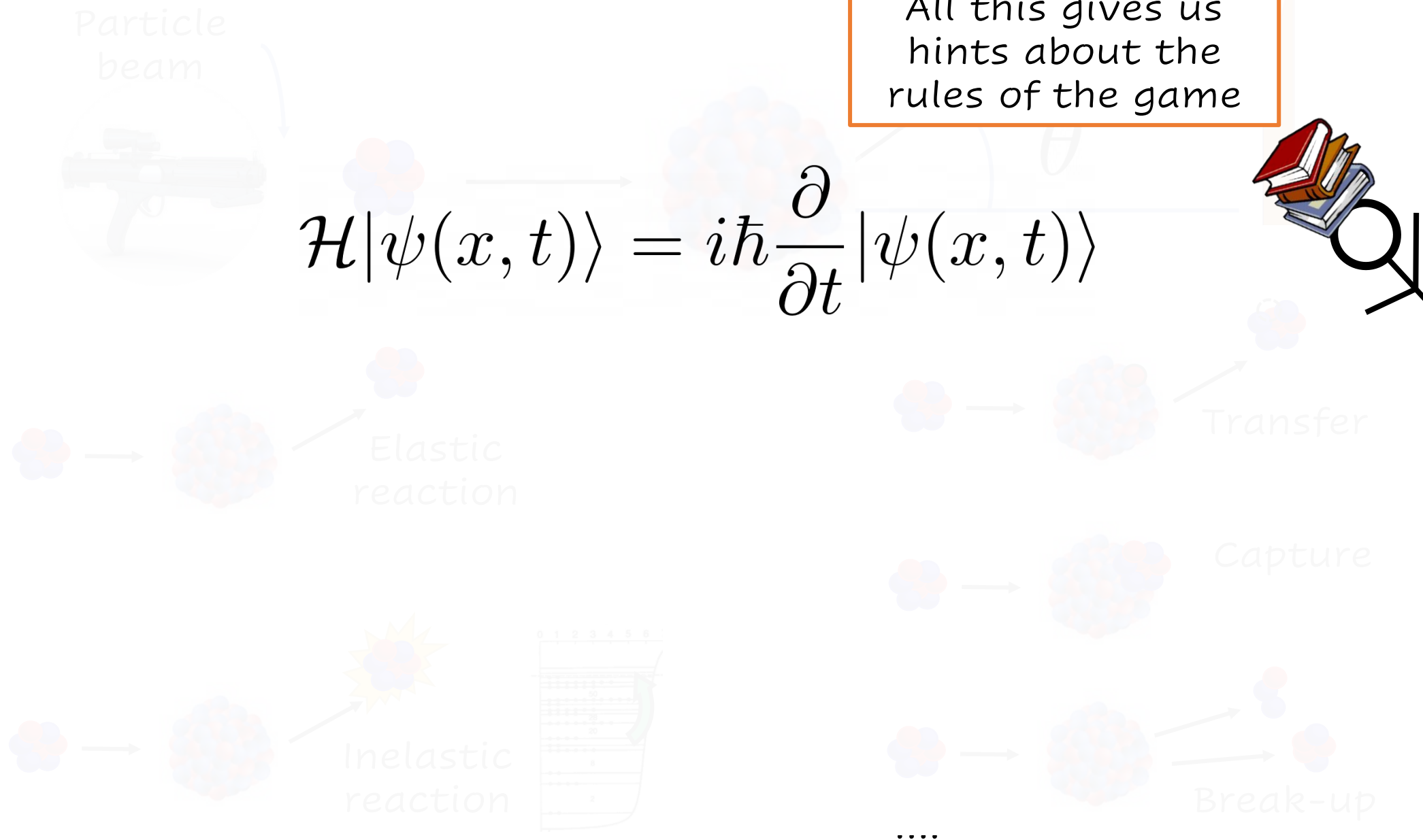
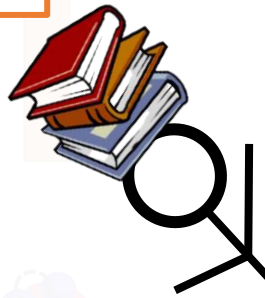
Building better models: Reactions



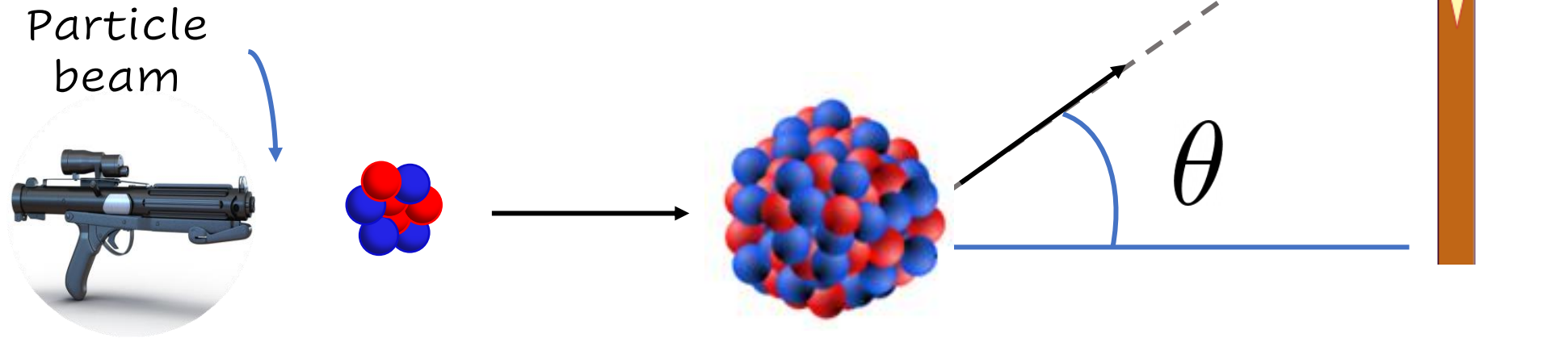
Building better models: Reactions

All this gives us
hints about the
rules of the game

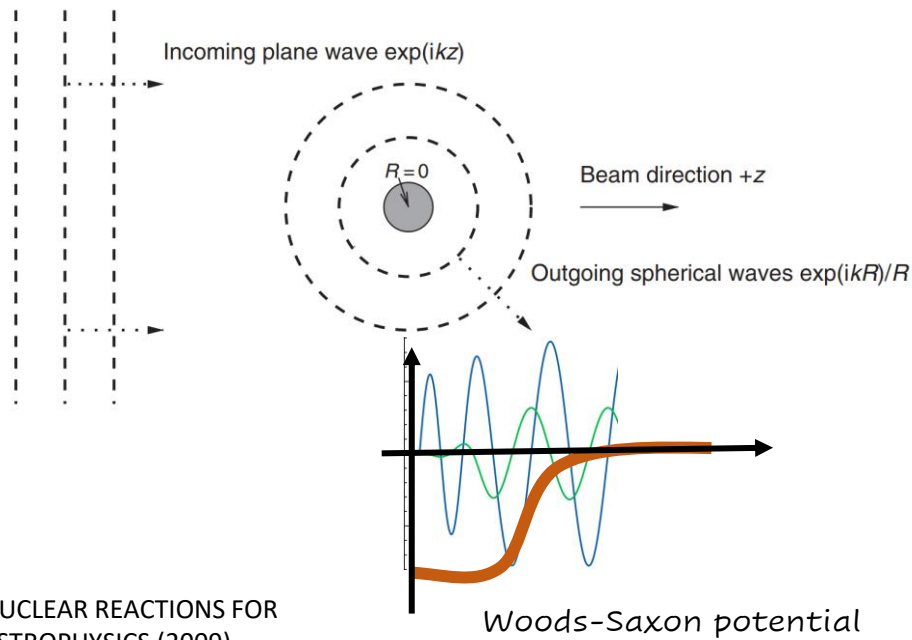
$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$



Building better models: Reactions

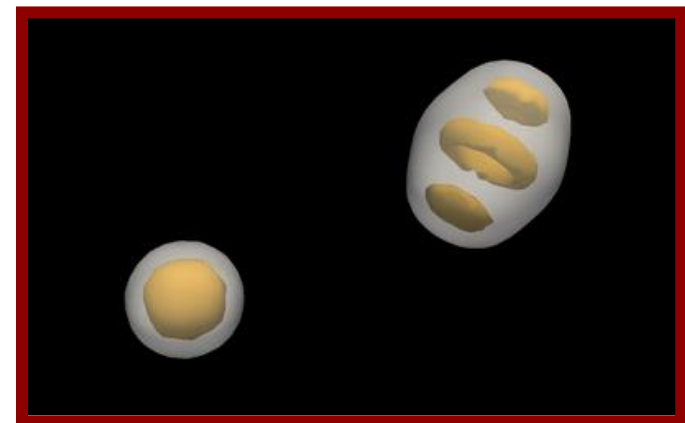


Optical Potentials



Time-dependent Density Functional Theory

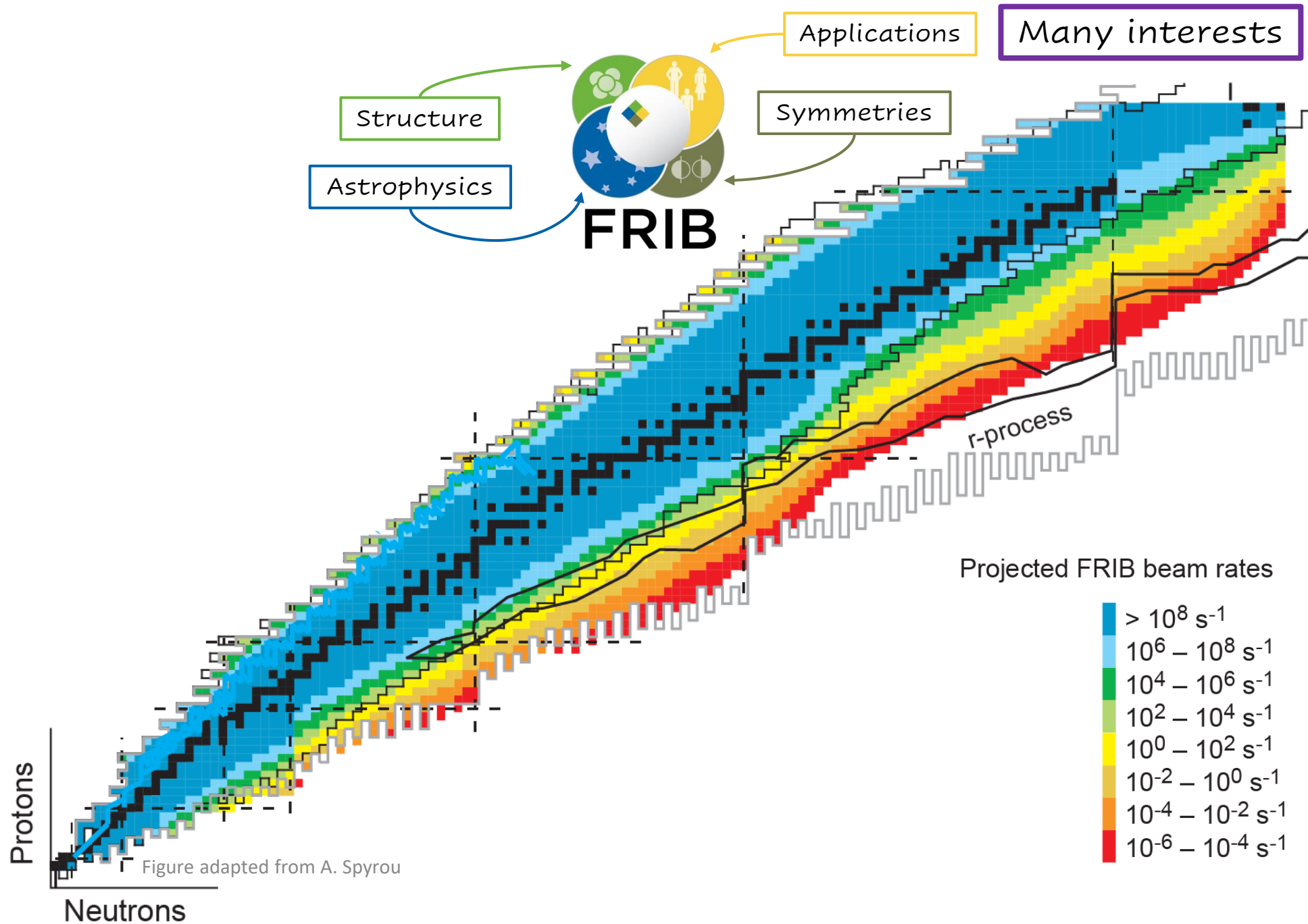
$$\mathcal{H}|\psi(x, t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(x, t)\rangle$$



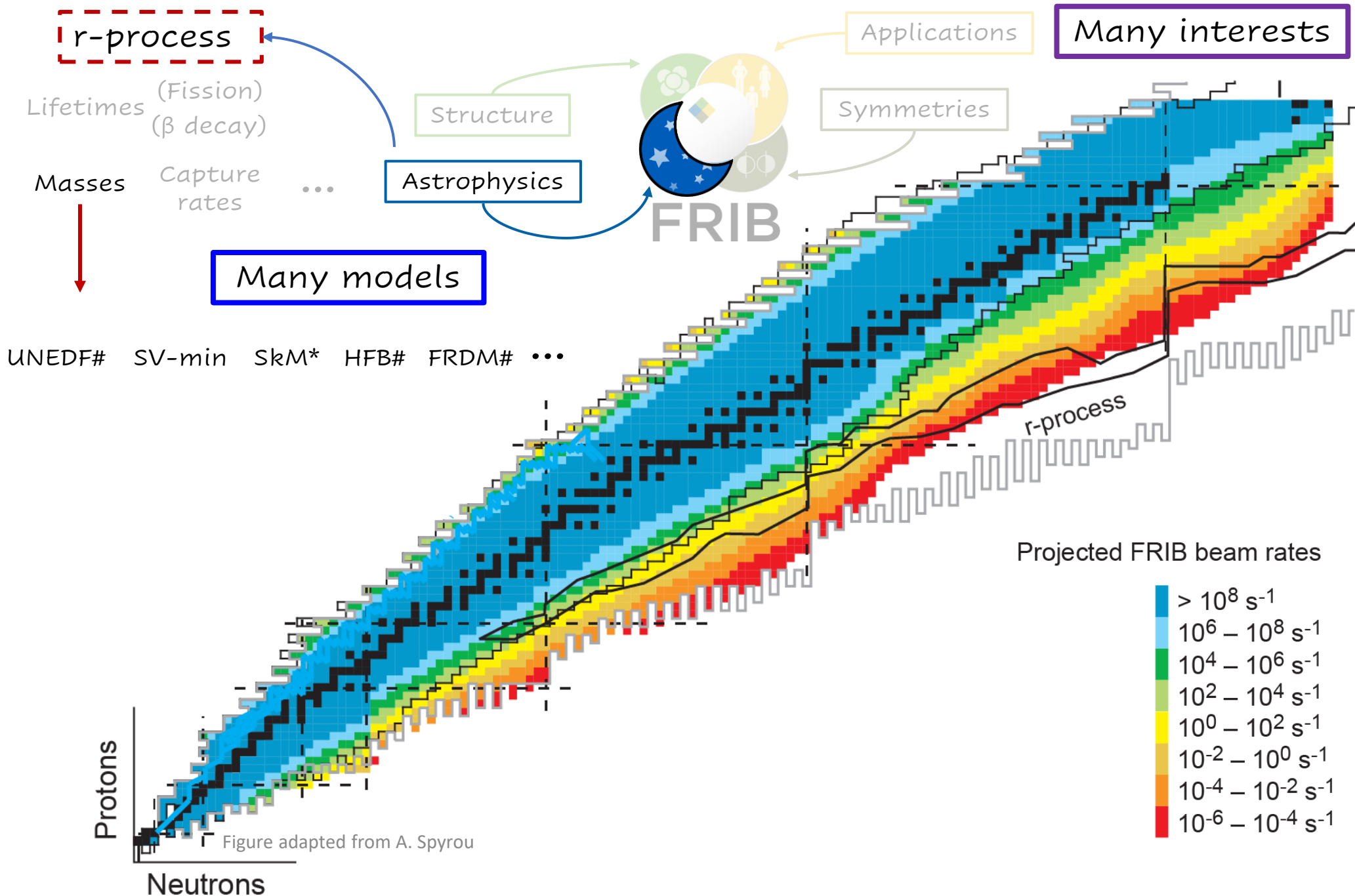
Made by Kyle Godbey



Theory-Experiment Cycle



Theory-Experiment Cycle



Theory-Experiment Cycle

r-process

Lifetimes (Fission)
(β decay)

Masses Capture rates ...

Structure

Astrophysics

Applications

Many interests

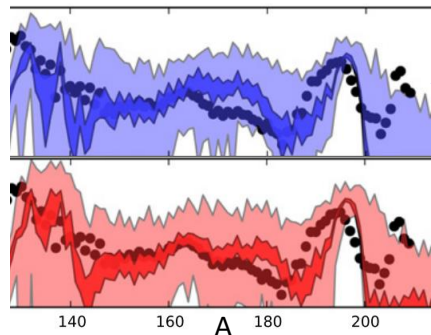
Symmetries

FRIB

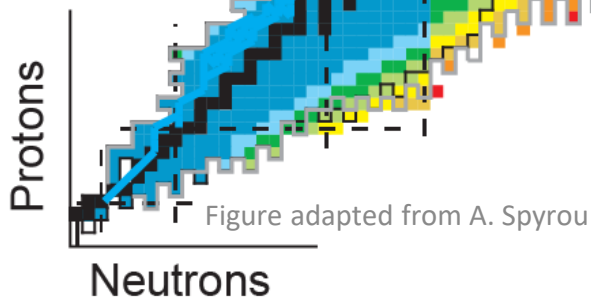
Many models

UNEDF# SV-min SkM* HFB# FRDM# ...

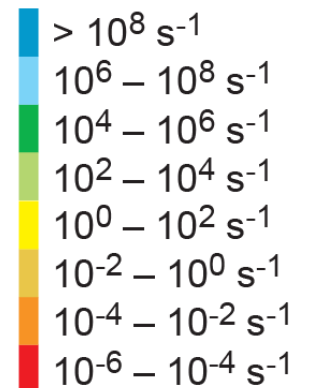
Abundances:



Adapted from: The impact of individual nuclear properties on r-process nucleosynthesis, **Mumpower et al, (2016)**



Projected FRIB beam rates



Theory-Experiment Cycle

r-process

Lifetimes (Fission)
(β decay)

Masses Capture rates ...

Structure

Astrophysics

Many models

Applications

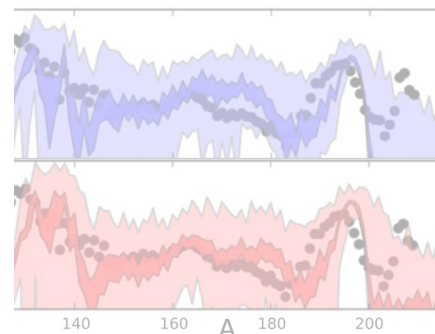
Many interests

Symmetries

FRIB

UNEDF# SV-min SkM* HFB# FRDM# ...

Abundances:



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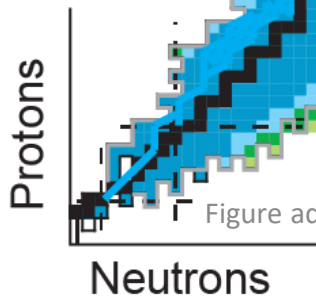


Figure adapted from A. Spyrou

Many experiments,
many nuclei

Projected FRIB beam rates

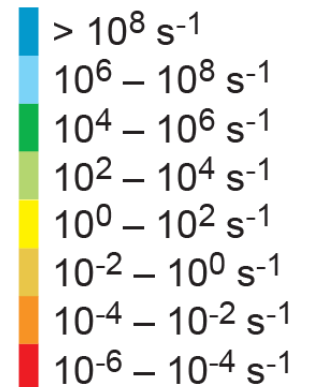
Charge Exchange
Transfer, surrogate (n, γ)

β -Oslo - (n, γ)

TAS, mass measurements
Discrete γ spectroscopy

βn - measurements

Half-life, ToF mass



Theory-Experiment Cycle

r-process

Lifetimes (Fission)
(β decay)

Masses Capture rates ...

Many models

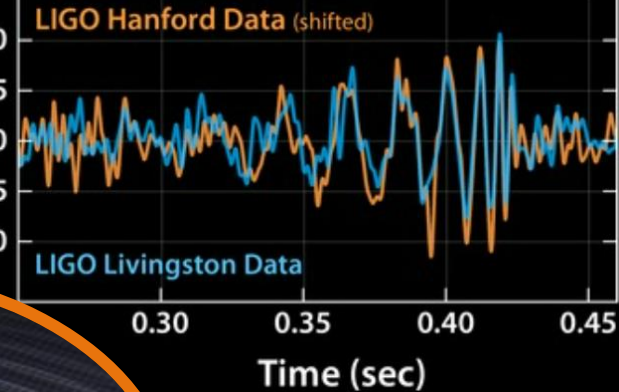
Structure

Astroph

Applications

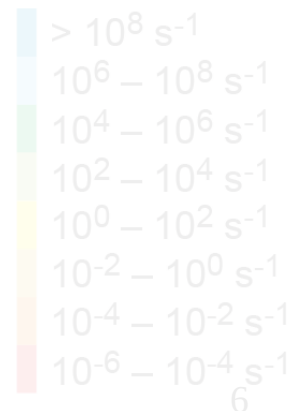
Many interests

<https://www.ligo.caltech.edu/image/ligo20160211a>



Many observations

Projected FRIB beam rates



Charge Exchange
Transfer, surrogate (n, γ)

β -Oslo - (n, γ)

TAS, mass measurements
Discrete γ spectroscopy

βn - measurements

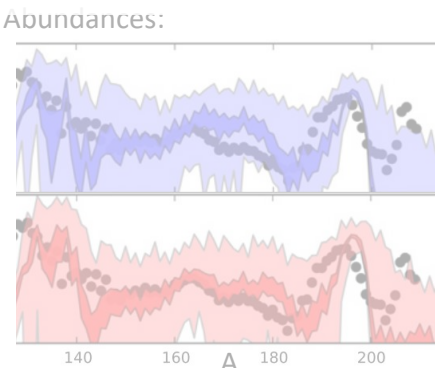
Half-life, ToF mass

Many experiments,
many nuclei

Protons
Neutrons

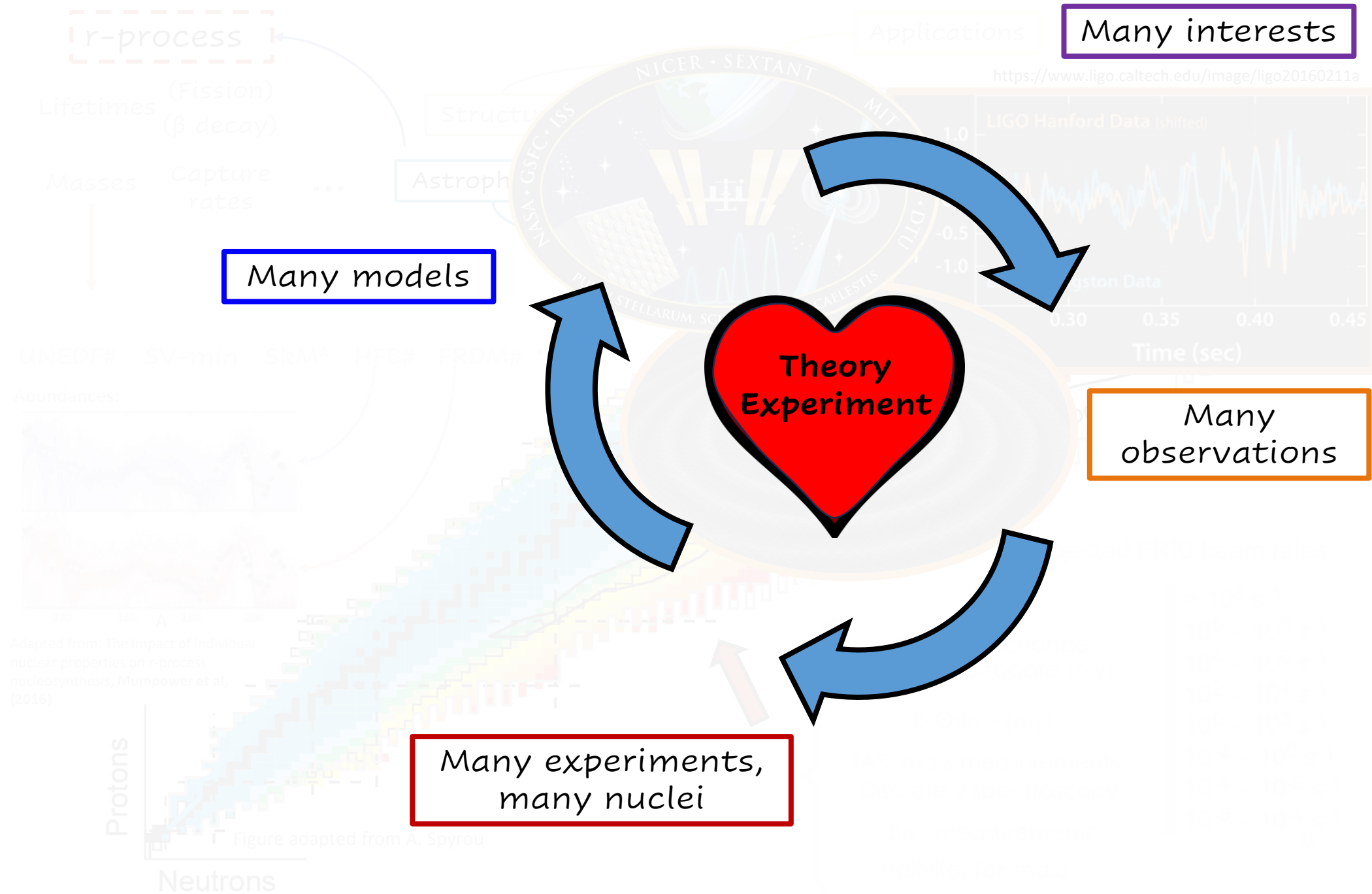
Figure adapted from A. Spyrou

UNEDF# SV-min SkM* HFB# FRDM# ...

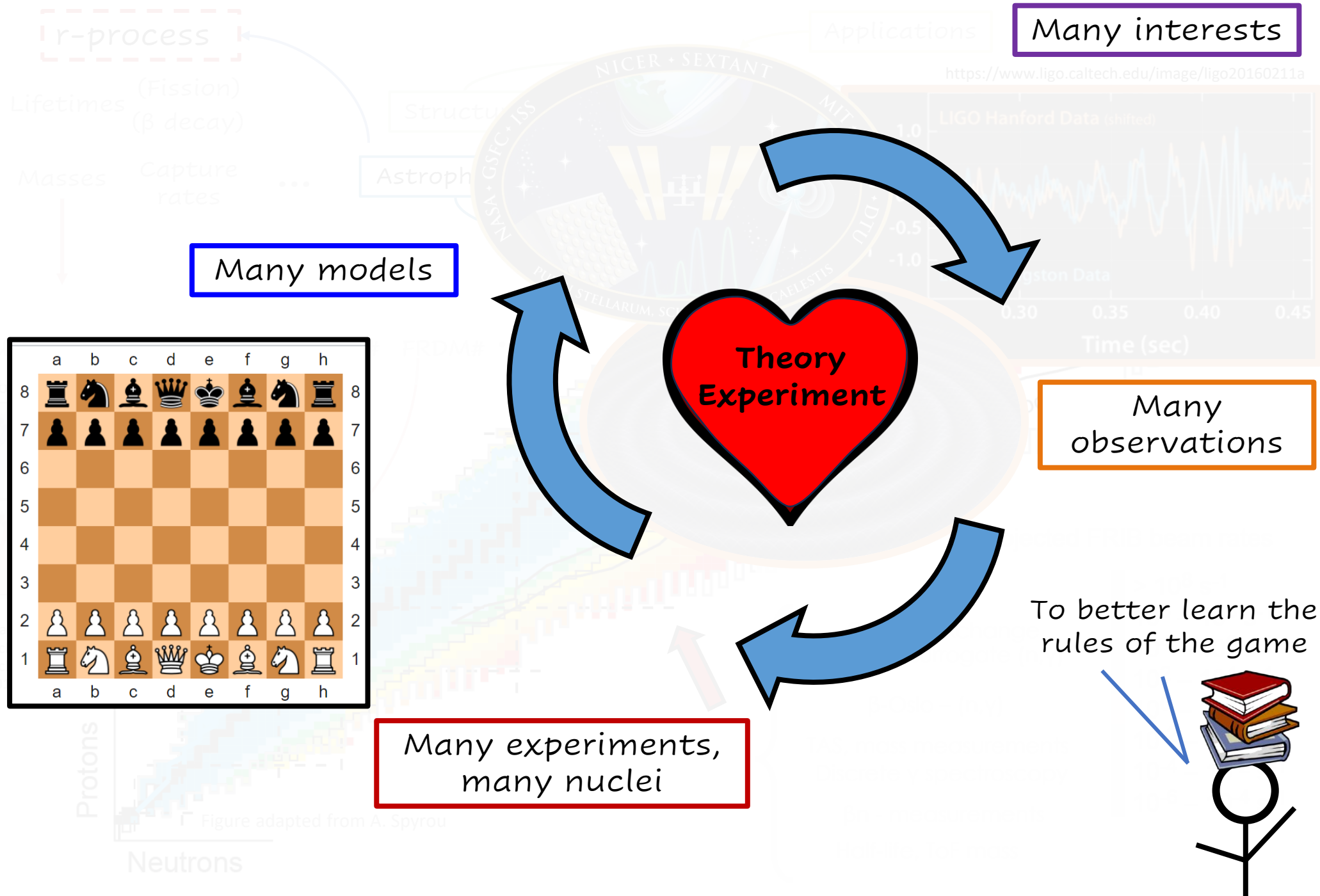


Adapted from: The impact of individual nuclear properties on r-process nucleosynthesis, *Mumpower et al, (2016)*

Theory-Experiment Cycle



Theory-Experiment Cycle



For today

Who am I?

Why theory?

Building models

Building a (simple) nuclear model

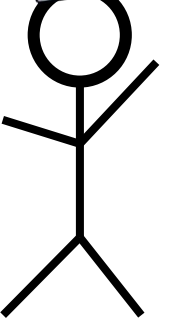
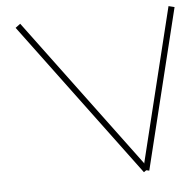
Quantum mechanics

Building (better) nuclear models

Challenges (Hands-On Session)



Questions?



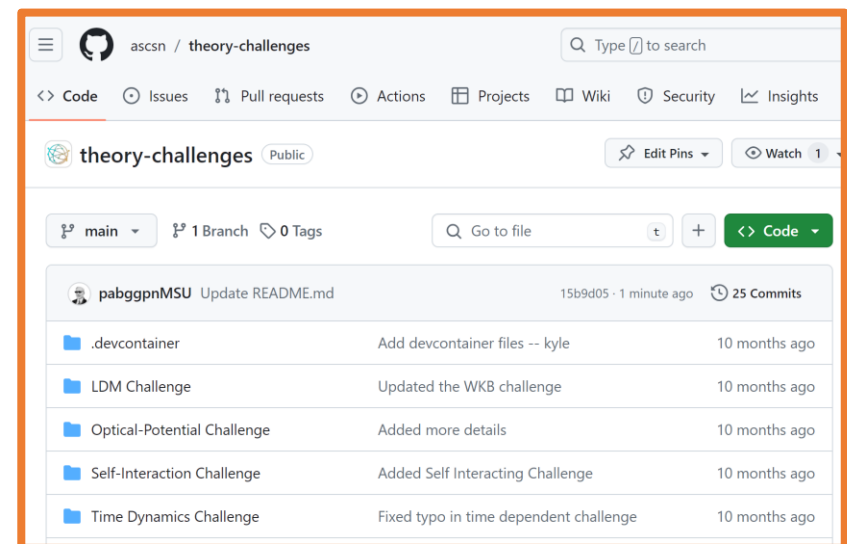
Pablo

Hand-on session set-up



ASCSN

Advanced Scientific Computing and Statistics Network



<https://github.com/ascsn/theory-challenges>

Starting up with Python



[Link to the videos](#)

main 2 Branches 0 Tags

Go to file Add file Code

pabggpnMSU Add files via upload 33ebaa9 · 2 days ago 35 Commits

ClassicalMechanics	Create About.txt	4 days ago
Coding	Moving more things around	4 days ago
Math	Add files via upload	2 days ago
QuantumMechanics	Create About.txt	4 days ago
.gitignore	cleared outputs on notebook; added .gitignore	3 weeks ago
README.md	Update README.md	2 days ago

README

online-guides

Compilation of the online guides for the coming up to speed course (<https://forum.ascsn.net/t/2024-coming-up-to-speed-summer-course-introductions/234>)

Recorded lectures:

- [Lecture 1: Introduction, Derivatives and Integrals](#)

Check out these videos on how to start playing with python:

- [Python tutorial 1: Setting up online coding enviroment, using lists, loops, and functions](#)
- [Python tutorial 2: Importing packages like numpy, plotting and visualization](#)

Online guides with video-lectures and
python notebooks!

Math
Python

Classical Mechanics
Quantum Mechanics



FRIB



ASCSN

Hand-on session time

★ Difficulty

Liquid Drop Model ★ ★

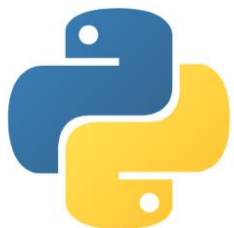
Reaction cross sections ★ ★ ★

Time Dynamics ★

Self Interaction ★ ★

Proton emitters lifetimes ★ ★

Single particle spectrum ★ ★ ★



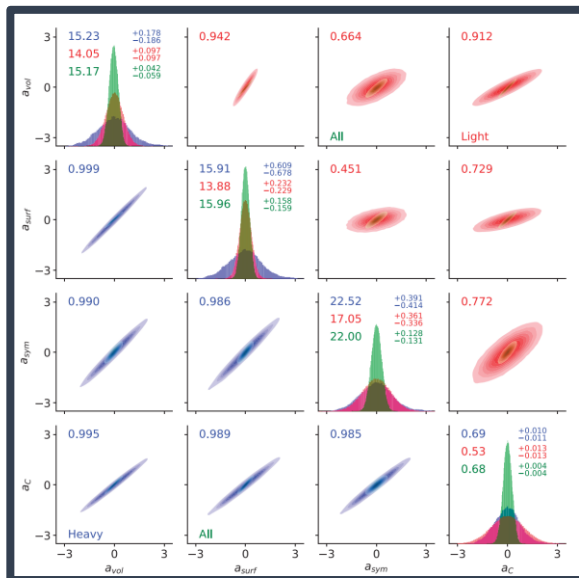
Hand-on session time

Calibrating the Liquid Drop Model Challenge ★ ★

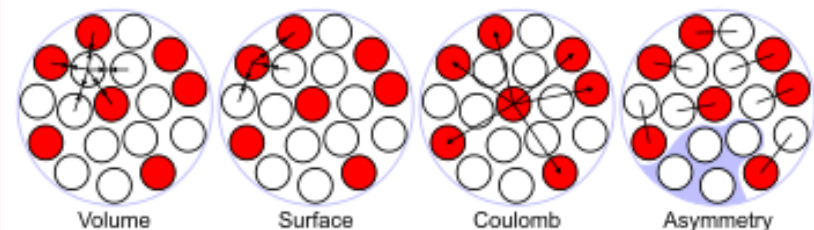
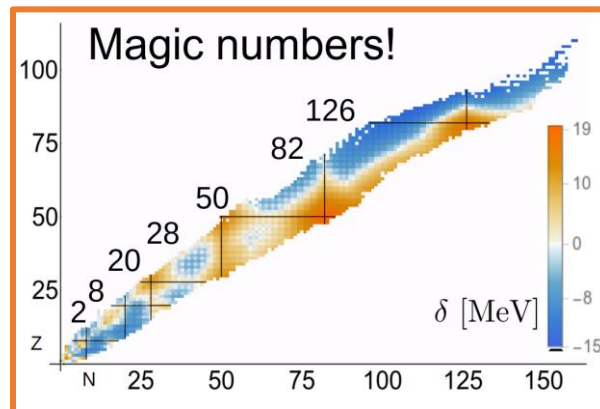
The purpose of this challenge is for you to calibrate the Liquid Drop Model https://en.wikipedia.org/wiki/Semi-empirical_mass_formula and compare the results of a "black box" calibration vs a principled Bayesian one.

Your task is to:

- Import the data from the AME 2016 table (included in the github). We are only using nuclei above $A=16$ to avoid light nuclei where the LDM fails particularly. Perform a curve fit using the built in functions from python (https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.curve_fit.html) and take note of the reported uncertainties in the parameters.
- Make a plot of the residuals and estimate the model error on its best fit.
- Make a model calibration using the Bayesian formalism that is defined in the accompanying file "# Guided Example Bayesian calibration". For the error, use your estimation from the previous point (the model error in this case is much smaller than the actual experimental uncertainties).
- Plot the corner plot posterior as well as the model values on the Binding Energy per nucleon for the Calcium chain up to 60Ca including the available experimental data.
- What would be the results if you have used in the calibration the Binding Energy per nucleon instead of the total Binding Energy?
- Bonus: Find the experimental error in the masses and repeat the calibration using only experimental errors. This should give a good demonstration on the dangers of not taking into account model errors.



$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(N-Z)^2}{A}$$



Hand-on session time

Reaction Cross Section Challenge ★★

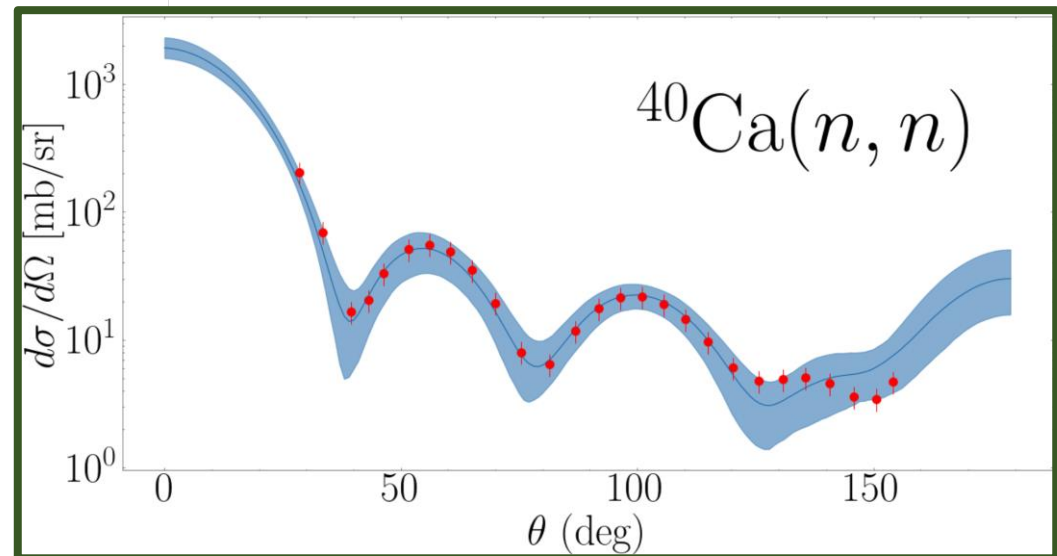
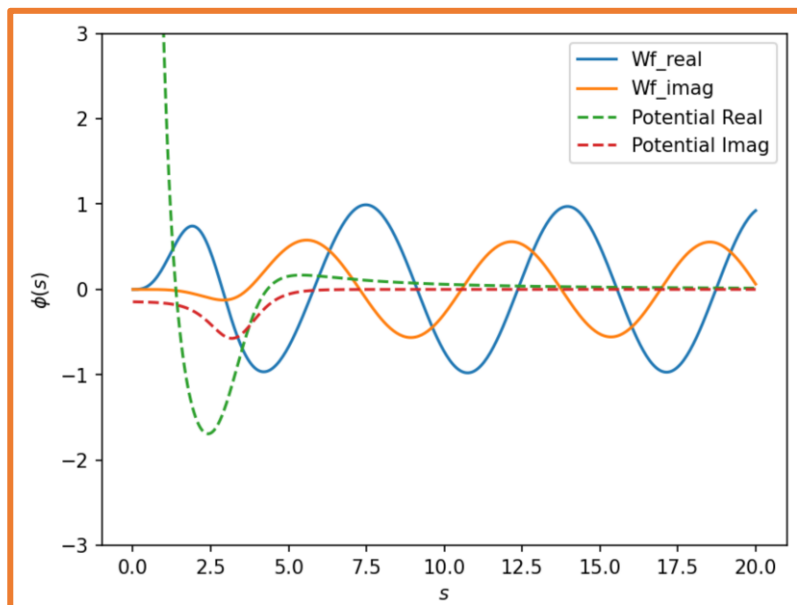
Notebook adapted from the ROSE challenges made by Daniel Odell and Pablo Giuliani:

<https://indico.cern.ch/event/1223721/contributions/5394829/>. Functions for calculating the wave-function solutions and phaseshifts adapted from the ROSE github: <https://github.com/odell/rose>

The purpose of this challenge is to extract information of a nucleus through the scattering cross section of particles that interact with it (in this case, neutrons). We will use an optical potential to model such interaction.

The accompanying re-scaled Schrodinger equation is:

$$\left[-\frac{d^2}{ds^2} + \frac{\ell(\ell+1)}{s^2} + U(s, \omega, k) - 1 \right] \phi(s) = 0 ,$$



Hand-on session time

Time Dynamics Challenge ★

This challenge is about computing the time evolution of a quantum system. We will focus on the harmonic oscillator for this first exploration (you could try a self interacting particle after you finish this challenge). Our Hamiltonian is:

$$H = -\frac{\partial^2}{\partial x^2} + \alpha x^2$$

Let us drop the numerical constants to simplify notation ($\hbar = 1$).

The evolution of a quantum mechanical wave function is [described through Schrodinger equation as](#):

$$H |\phi(t, x)\rangle = i \frac{\partial}{\partial t} |\phi(t, x)\rangle,$$

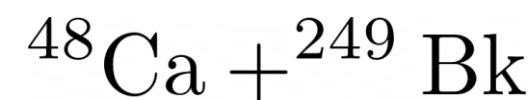
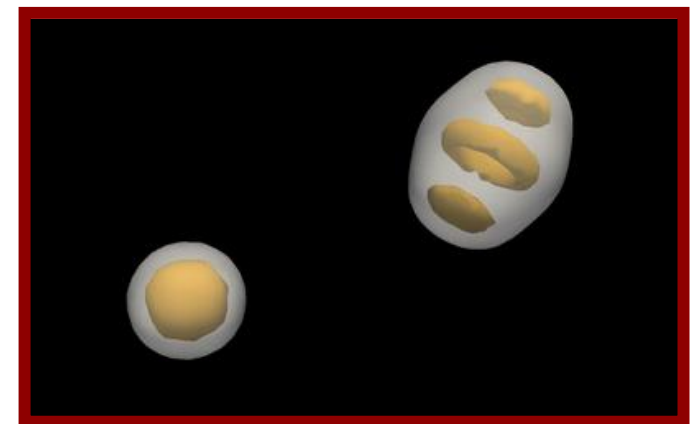
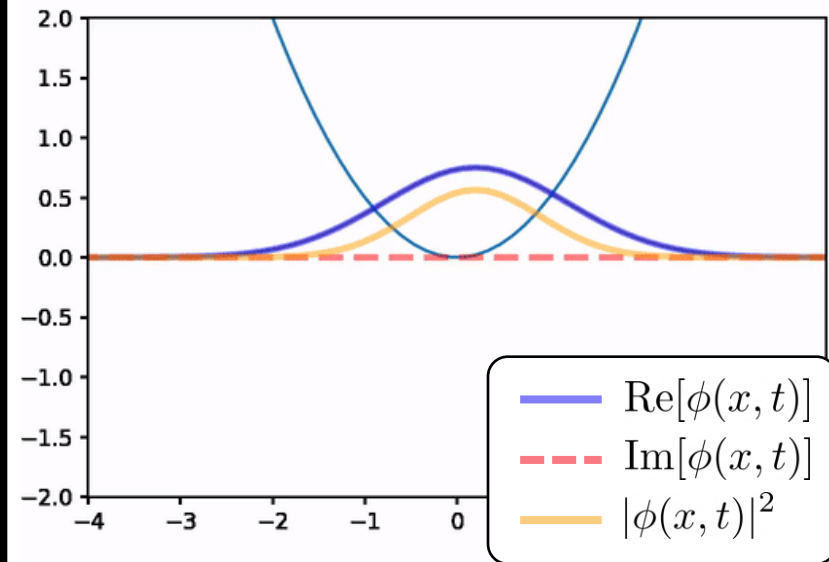
which results in the evolution operator from an initial state:

$$|\phi(t, x)\rangle = e^{-iHt} |\phi(0, x)\rangle.$$

To solve the problem numerically, the evolution operator is usually expanded in its Taylor approximation and a finite time step Δt is taken:

$$|\phi(\Delta t, x)\rangle \approx \left(1 + (-iH\Delta t) + \frac{1}{2}(-iH\Delta t)^2 + \dots\right) |\phi(0, x)\rangle.$$

By taking small steps Δt , we can leave the expansion up to a small order (even linear in Δt) and arrive at the final time by succesively applying the approximated evolution operator.



Hand-on session time

Self Interaction challenge ★

The purpose of this challenge is for you to build a solver for a self interacting particle:

$$H\phi(x) = \lambda\phi(x),$$

with

$$H = -\frac{\partial^2}{\partial x^2} + \kappa x^2 + q\rho(x),$$

where the density is defined as:

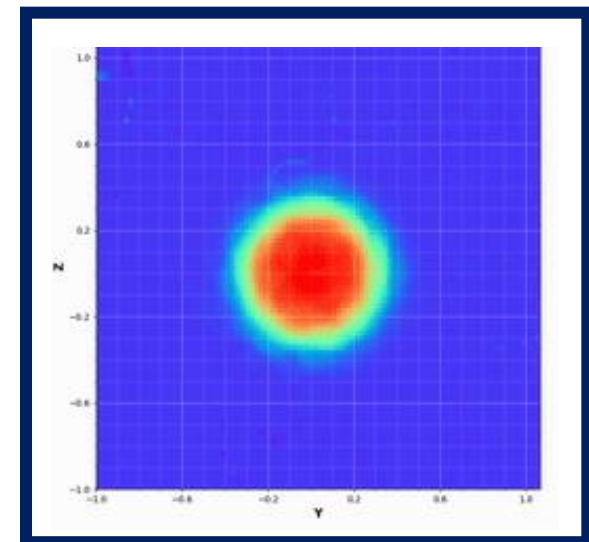
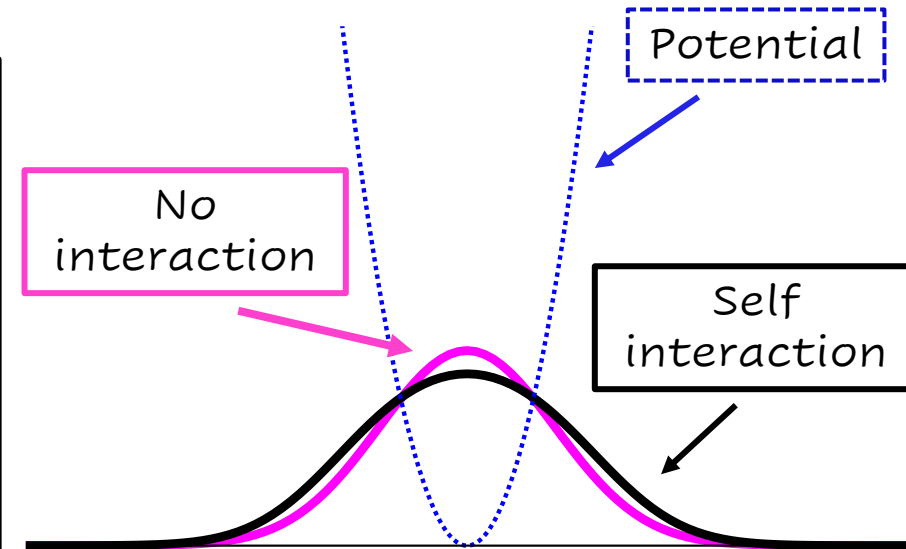
$$\rho(x) = |\phi(x)|^2,$$

and the wave-function is normalized:

$$\int |\phi(x)|^2 dx = 1$$

With parameters $\alpha = \{\kappa, q\}$. This is the 1D Gross-Pitaevskii equation describing approximately the low-energy properties of dilute Bose-Einstein condensates. We will use it as a proxy for the non-linear Density Functional Theory equations. Check out <https://journals.aps.org/prc/abstract/10.1103/PhysRevC.106.054322> for a cool emulator on it.

Note that H depends on ϕ , this is a tricky problem to solve. One approach is to solve it first for $q = 0$ (no self-interaction), obtain the wave function ϕ , create the density $\rho(x)$, plug it back into H and solve it again, repeating until the system converges. One recommendation is to mix the new solutions slowly to avoid instabilities: when updating the new density $\rho(x)$ to mix it with the previous one, around 85% and 15% old with new.



40Ca nucleus vibrating

Hand-on session time

Calculating life time of proton emitters ★ ★

The purpose of this challenge is for you to calculate, and compare with experimental data, the life time of proton decays for several proton emitter nuclei. We will follow the directions of the accompanying file: "WKB-protons.pdf" prepared by Witek Nazarewicz as part of his nuclear structure class.

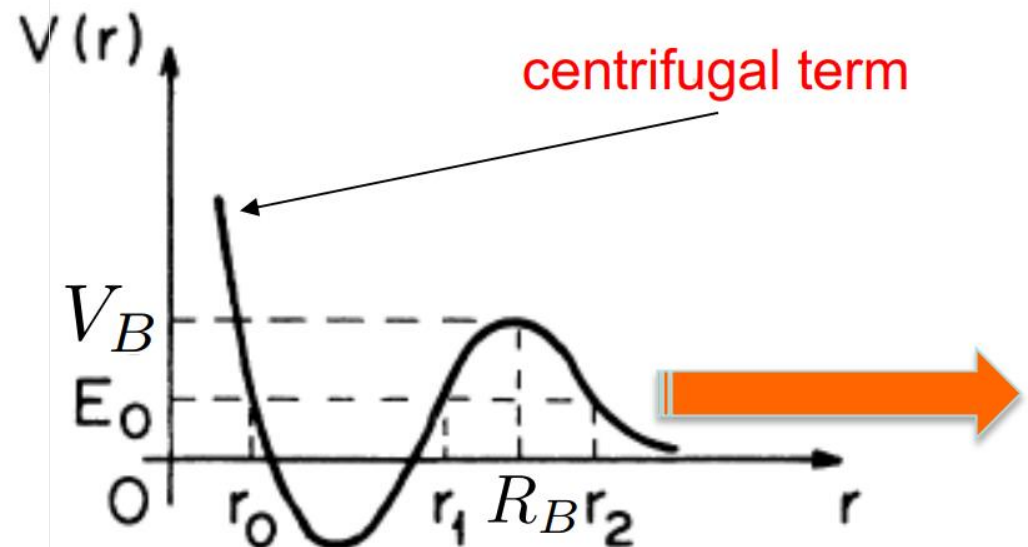
Your task is to:

- Solve questions 1 and 2 of the attached pdf. Consider that making integrals is easy if you discretize the "x" space and replace them by dot products (ask for help if you don't know how to do this)

Lifetimes

Nucleus	Q_p (keV)	Orbit	$t_{1/2}^{\text{exp}}$
$^{109}_{53}\text{I}_{56}$	829 ± 4	$1d_{5/2}$	$(100 \pm 5) \mu\text{s}$
$^{112}_{55}\text{Cs}_{57}$	823 ± 7	$1d_{5/2}$	$(500 \pm 100) \mu\text{s}$
$^{113}_{55}\text{Cs}_{58}$	977 ± 4	$1d_{5/2}$	$(17 \pm 2) \mu\text{s}$
$^{146}_{69}\text{Tm}_{77}$	1140 ± 5	$0h_{11/2}$	$(235 \pm 27) \text{ms}$
	1210 ± 5	$0h_{11/2}$	$(72 \pm 23) \text{ms}$
$^{147}_{69}\text{Tm}_{78}$	1071 ± 3	$0h_{11/2}$	$(2.7^{+2.4}_{-0.9}) \text{s}$
	1132 ± 4	$1d_{3/2}$	$(360 \pm 40) \mu\text{s}$
$^{150}_{71}\text{Lu}_{79}$	1283 ± 4	$0h_{11/2}$	$(40^{+30}_{-20}) \text{ms}$

$$\Gamma = S_p \mathcal{N} \frac{\hbar^2}{4\mu} \exp \left\{ -2 \int_{r_1}^{r_2} |k(r)| dr \right\}$$



Hand-on session time

Woods-Saxon spectrum challenge



The purpose of this challenge is for you to build the single particle spectrum of a Woods-Saxon potential with a spin-orbit term. Our Hamiltonian is:

$$\left[-\frac{\hbar^2}{2m} \frac{d^2}{dr^2} + \frac{\hbar^2}{2m} \frac{\ell(\ell+1)}{r^2} + V_{\text{eff}}(r, \alpha) - E \right] \phi(r) = 0,$$

where the effective potential is:

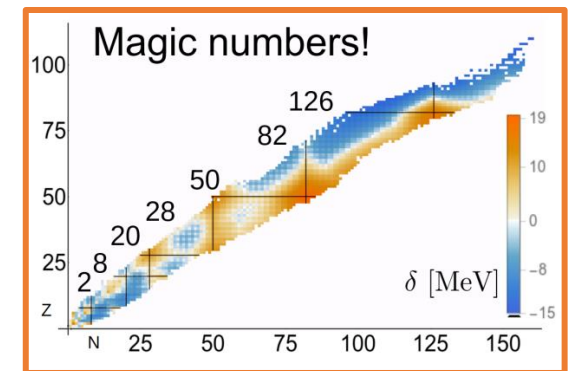
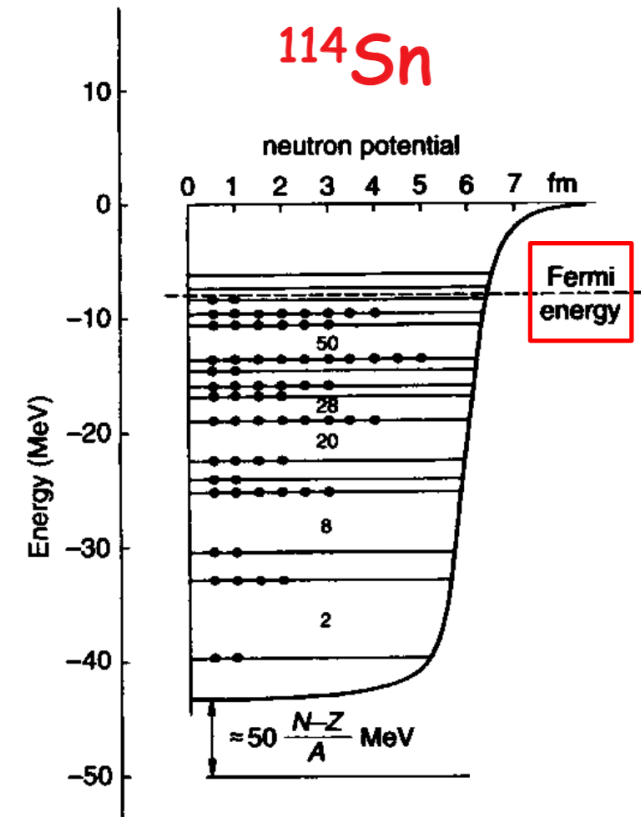
$$V_{\text{eff}}(r, \alpha) = V_{\text{WS}}(r) + (\vec{\ell} \cdot \vec{s}) V_{\text{SO}}(r)$$

where the Woods-Saxon term is defined as:

$$V_{\text{WS}}(r, \alpha) = V \left[1 + \exp\left(\frac{r-R}{a}\right) \right]^{-1},$$

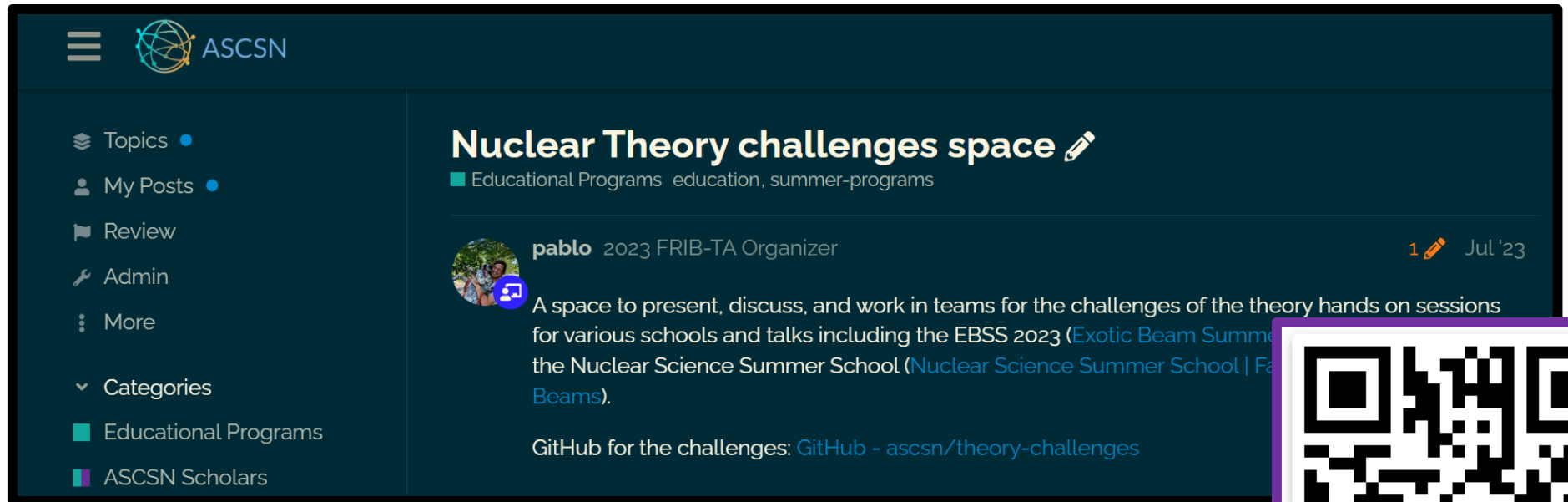
and the spin orbit is:

$$V_{\text{SO}}(r, \alpha) = V_{\text{SO}} r_0^2 \frac{1}{r} \frac{d}{dr} \left[1 + \exp\left(\frac{r-R}{a}\right) \right]^{-1},$$



Hand-on session time

<https://forum.ascsn.net/>



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ASCSCN

Advanced Scientific Computing and Statistics Network

<https://github.com/ascscn/theory-challenges>