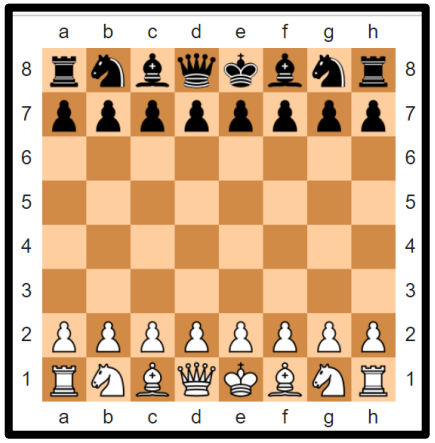
Nuclear Theory



Protons

Neutrons

Binding Energy per Nucleon [MeV]

7.5 8.2 8.8

The colorful chart of nuclei

Pablo G.

giulianp@frib.msu.edu

Kyle G.

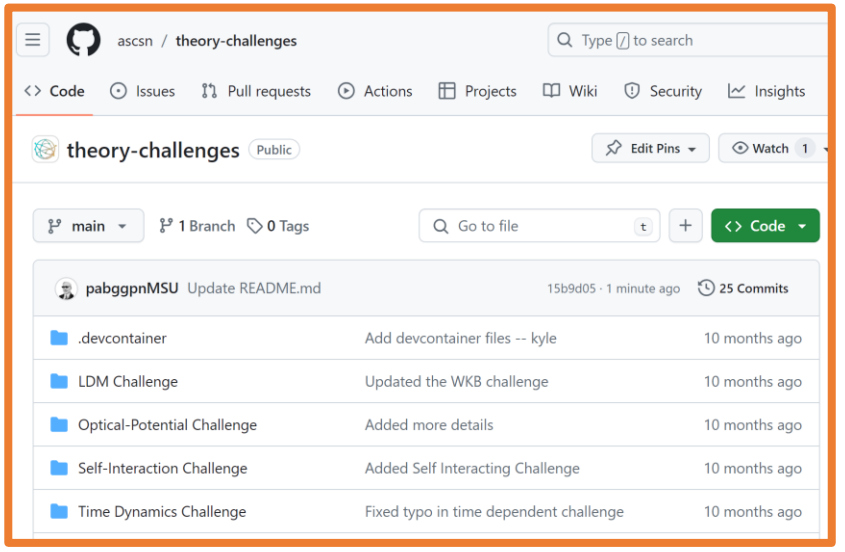
godbey@frib.msu.edu

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

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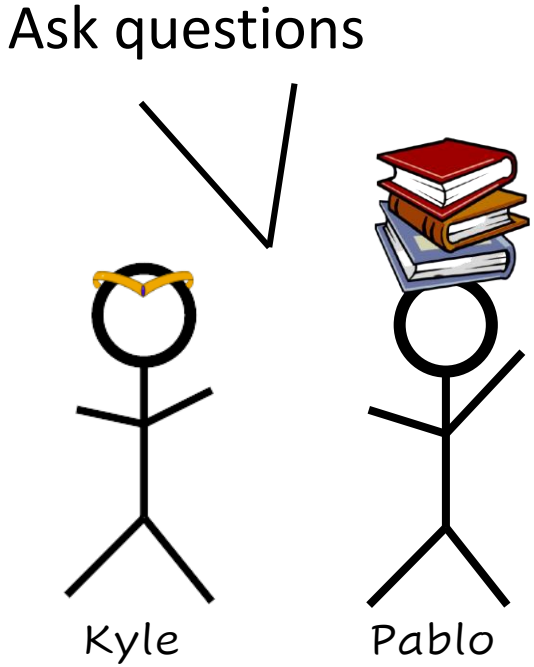
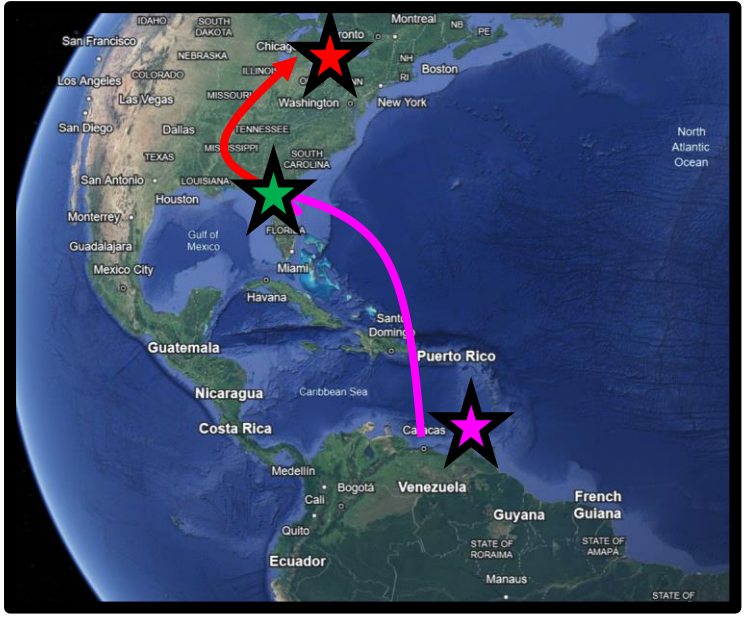
Challenges (Hands-On Session)



Me

Me

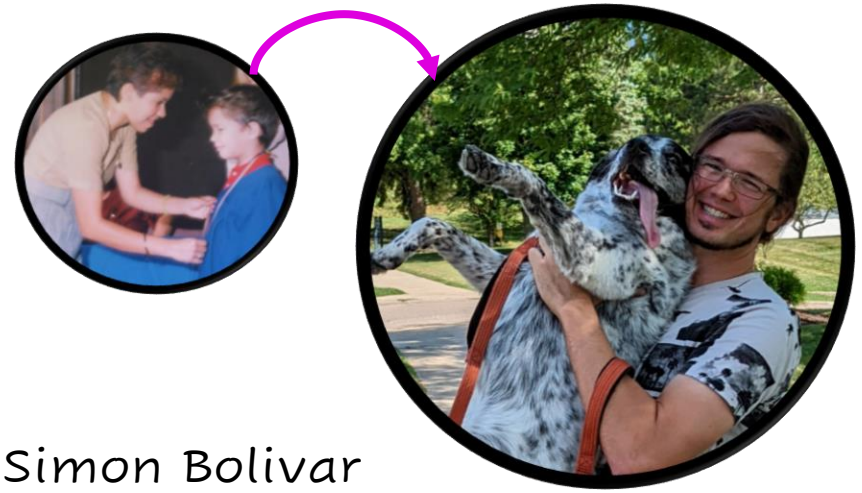


★ Undegrad

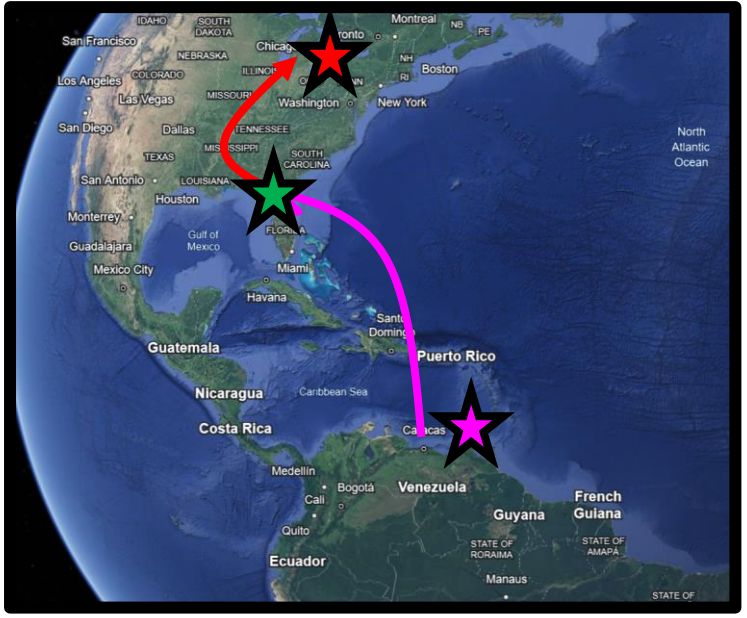
★ PhD

★ Postdoc

Me



Universidad Simon Bolivar



Venezuela

Undegrad

PhD

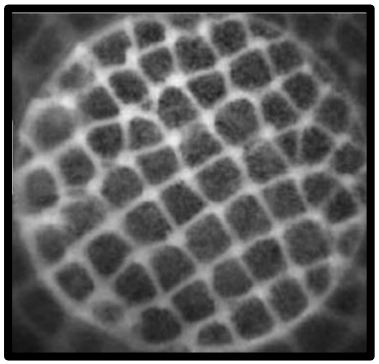
Postdoc

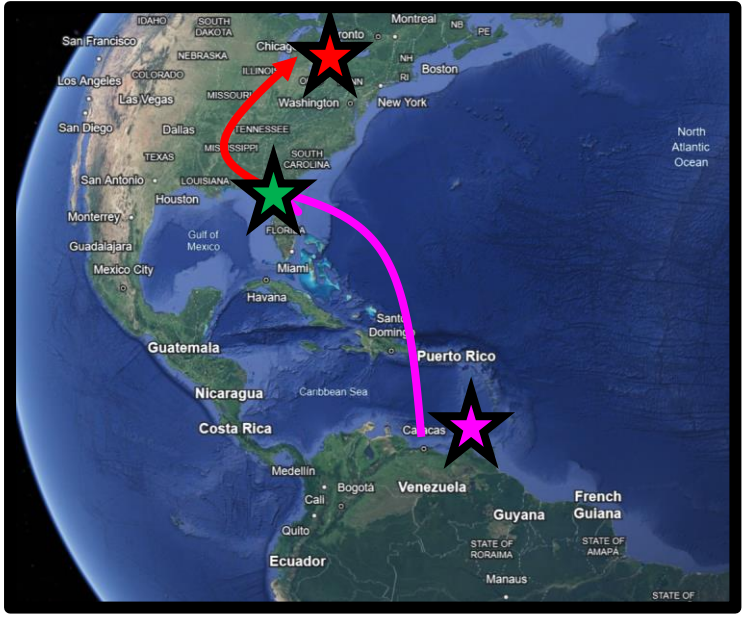
Florida State University

Michigan

Me

Pattern formation
in vibrated sand





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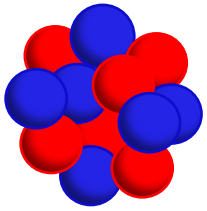
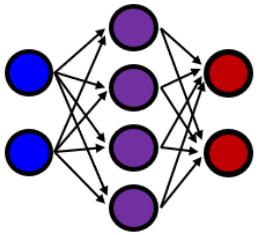
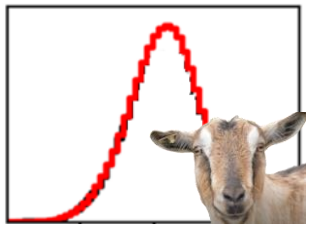


Nuclear
Physics



Machine
Learning



Bayesian
Statistics

Me

Pattern formation
in vibrated sand

Education

Outreach

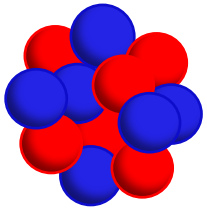
Community

Undegrad

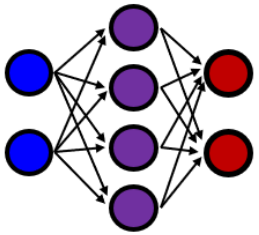
PhD

Postdoc

Venezuela



Nuclear
Physics



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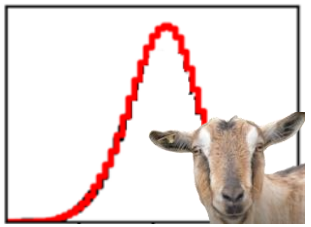

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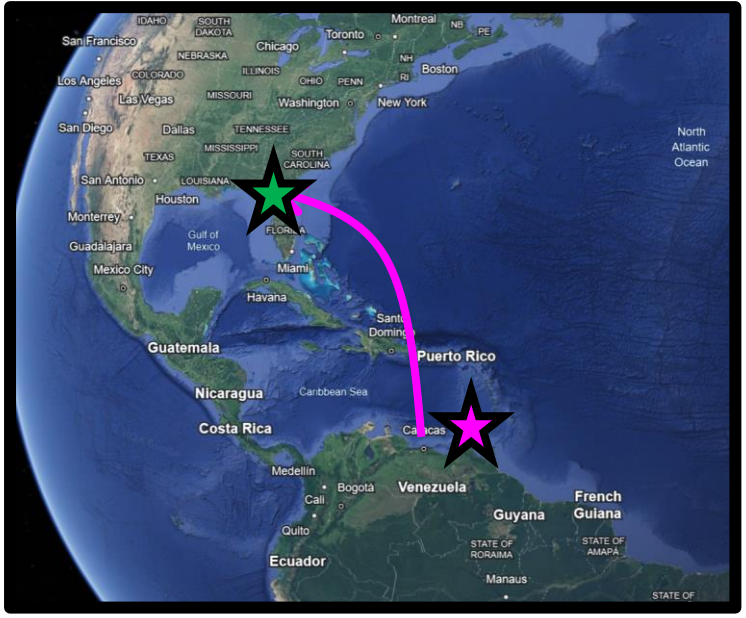


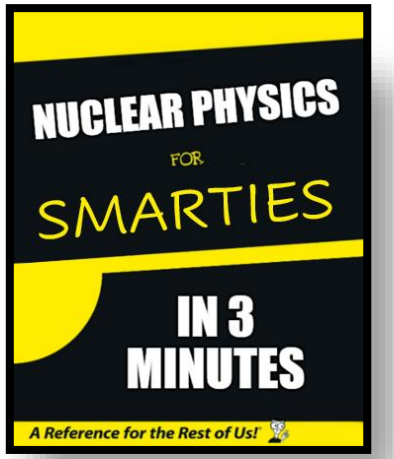
Undegrad

PhD

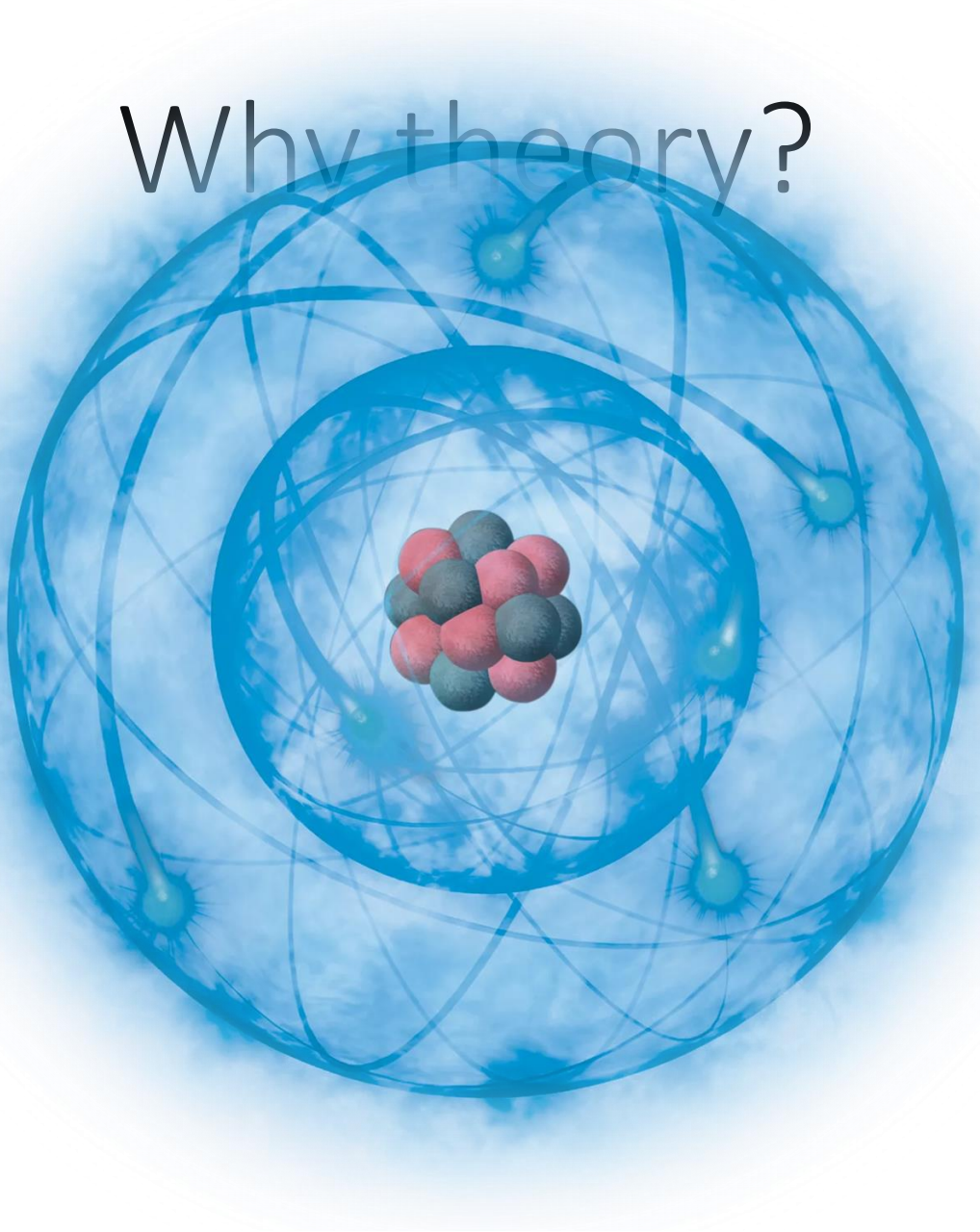
FSU video

Why theory?

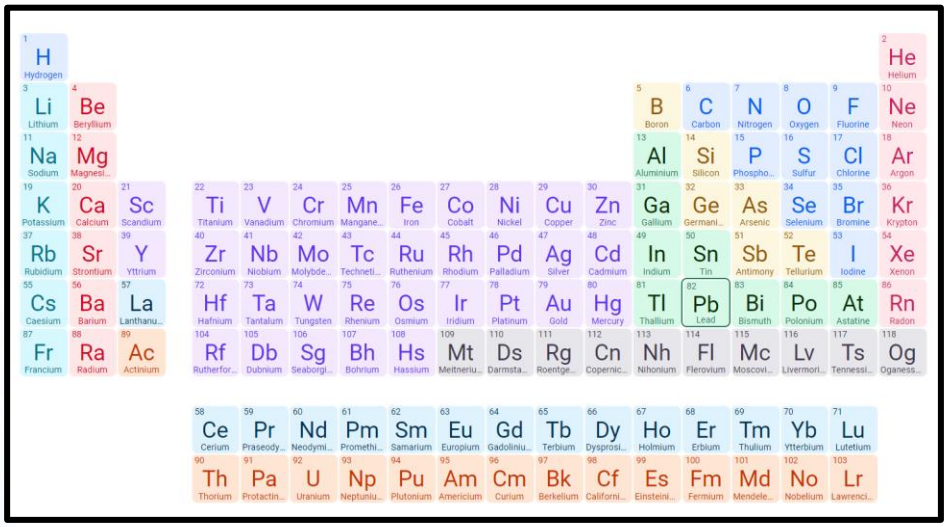
Why theory?


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

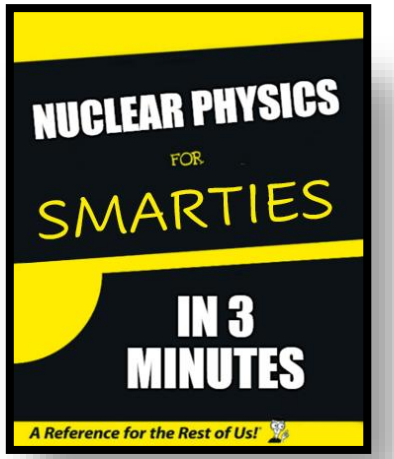
Why theory?



Chemical Periodic Table



An atom



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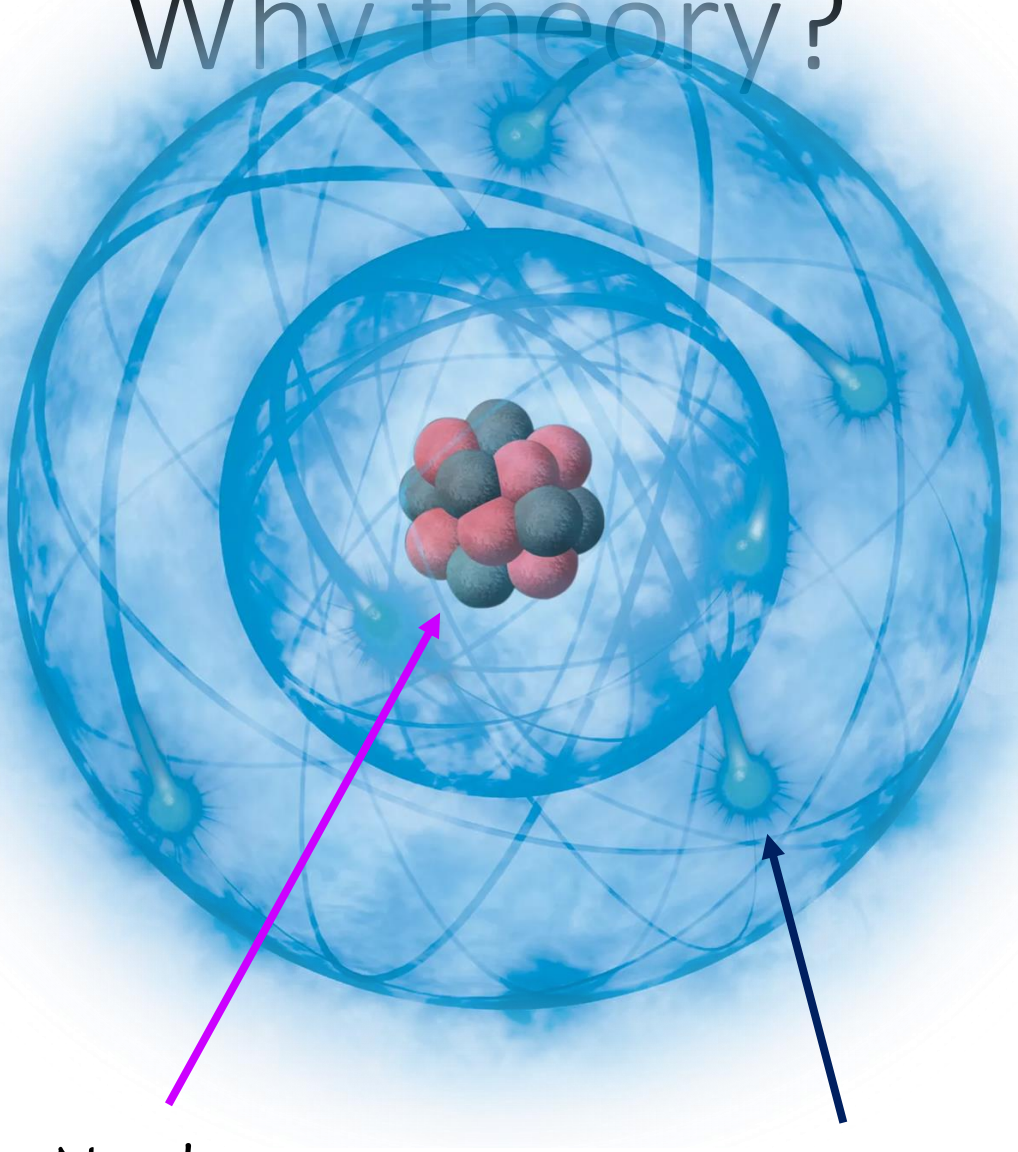

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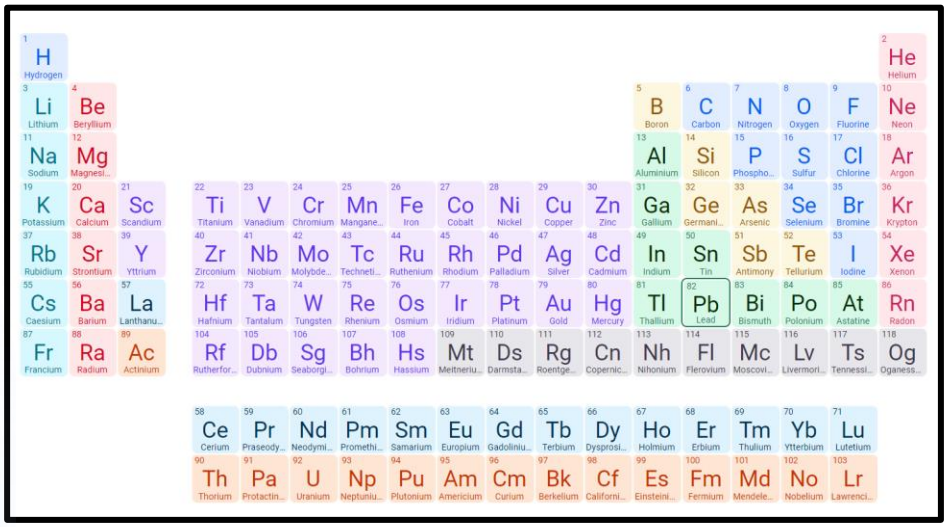

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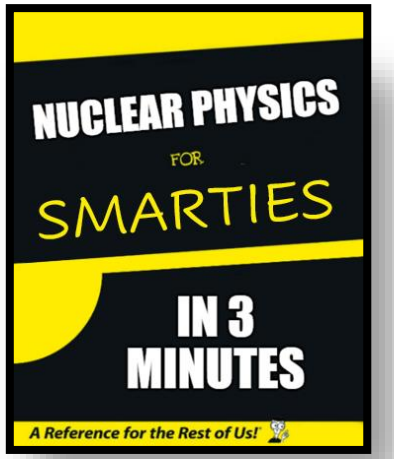
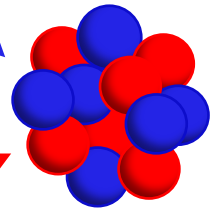


Why theory?

Neutrons

N

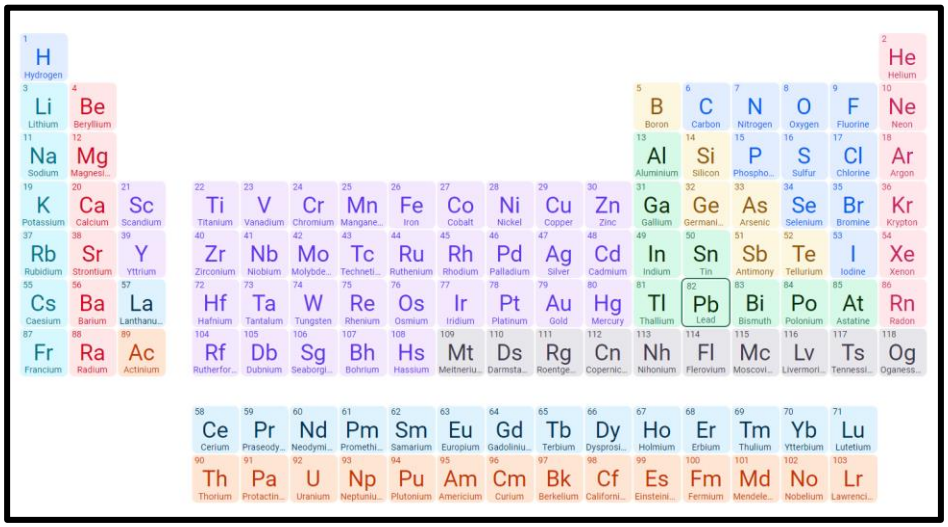


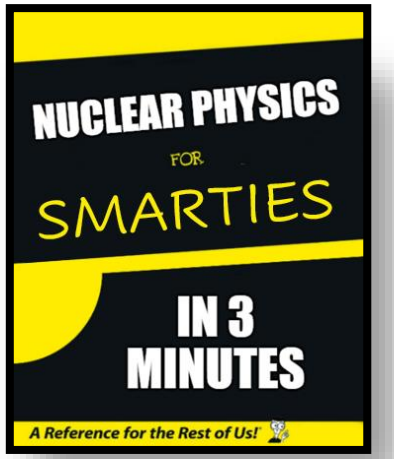
A nucleus

Protons

Z

Chemical Periodic Table





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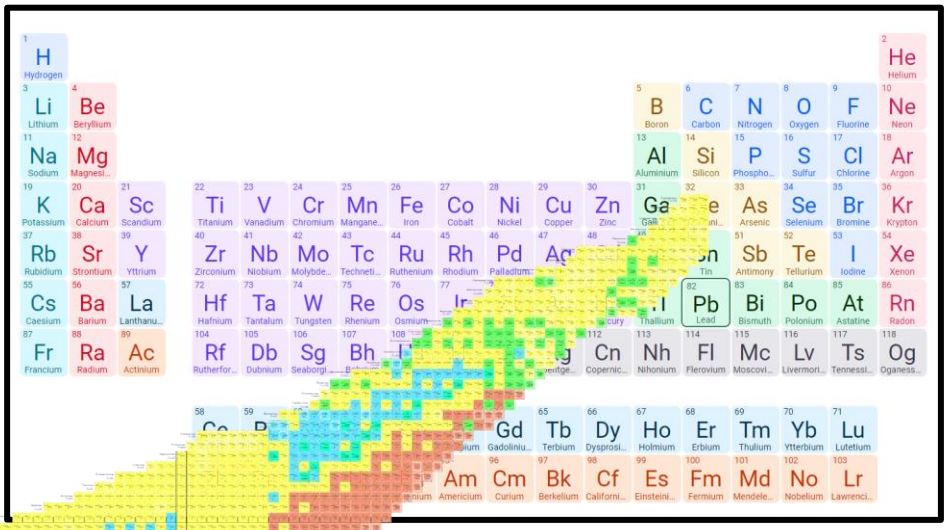
Chemical Periodic Table



Neutrons

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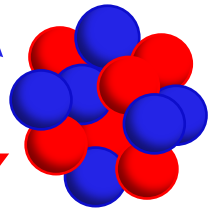

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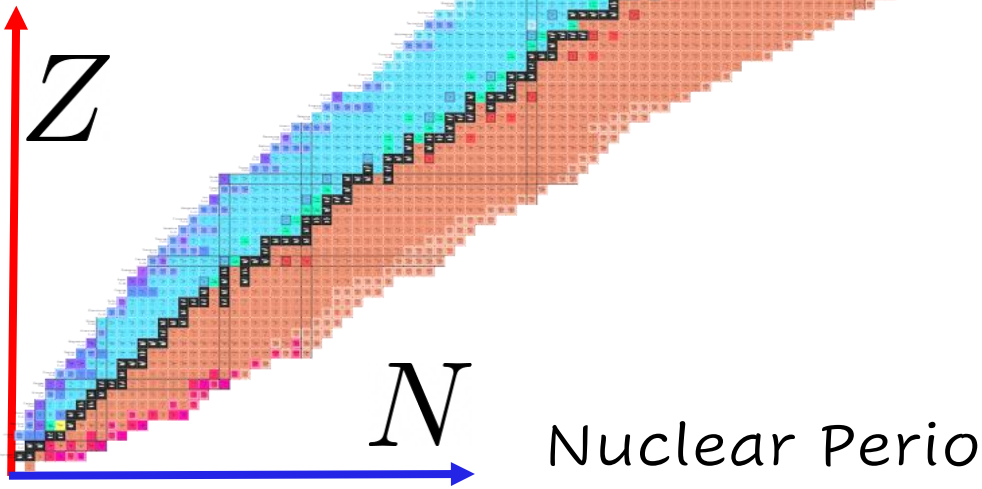


Nuclear Periodic Table

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

Why theory?

^{12}C

Neutrons

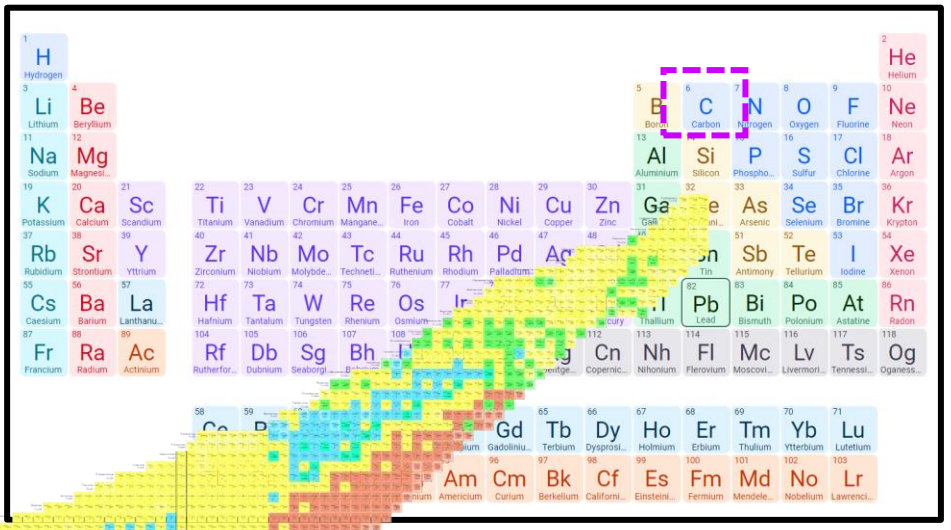
N

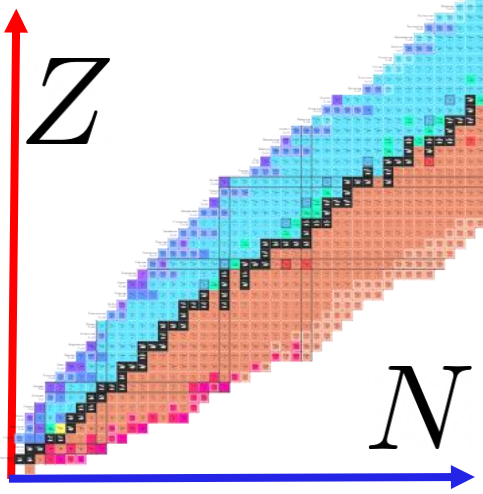
Protons

Z

A nucleus

Chemical Periodic Table





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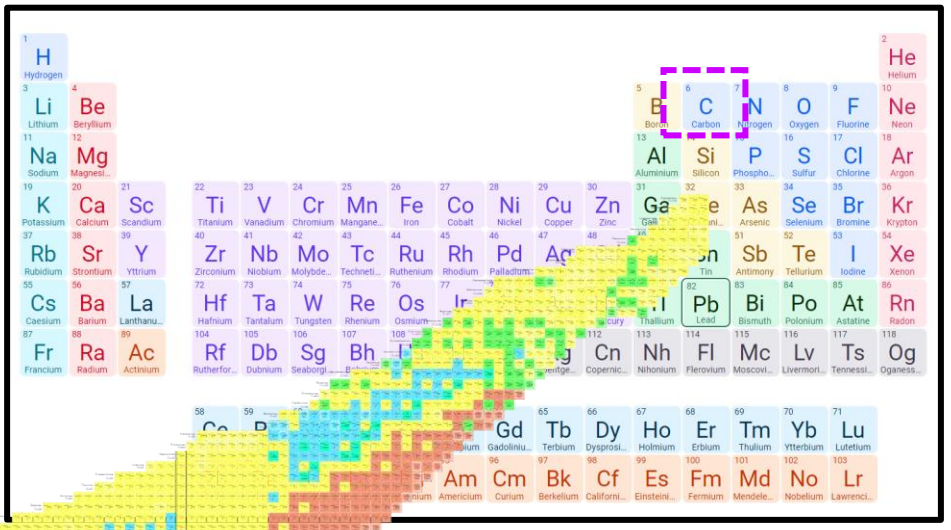

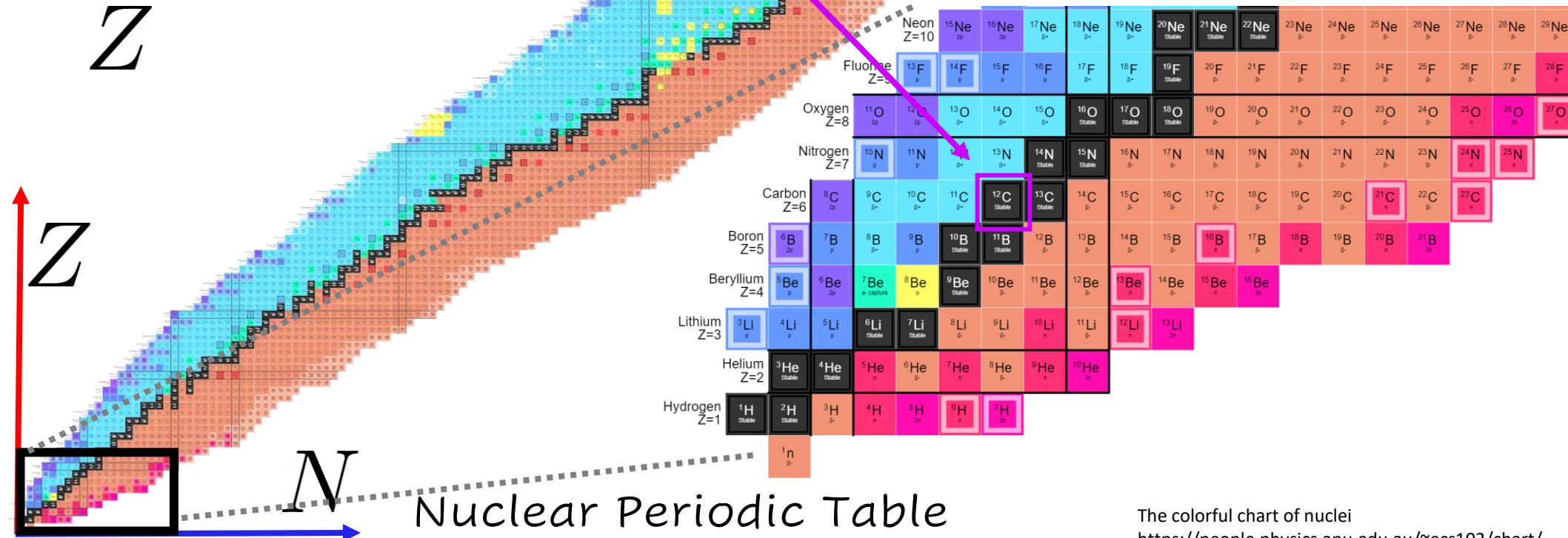

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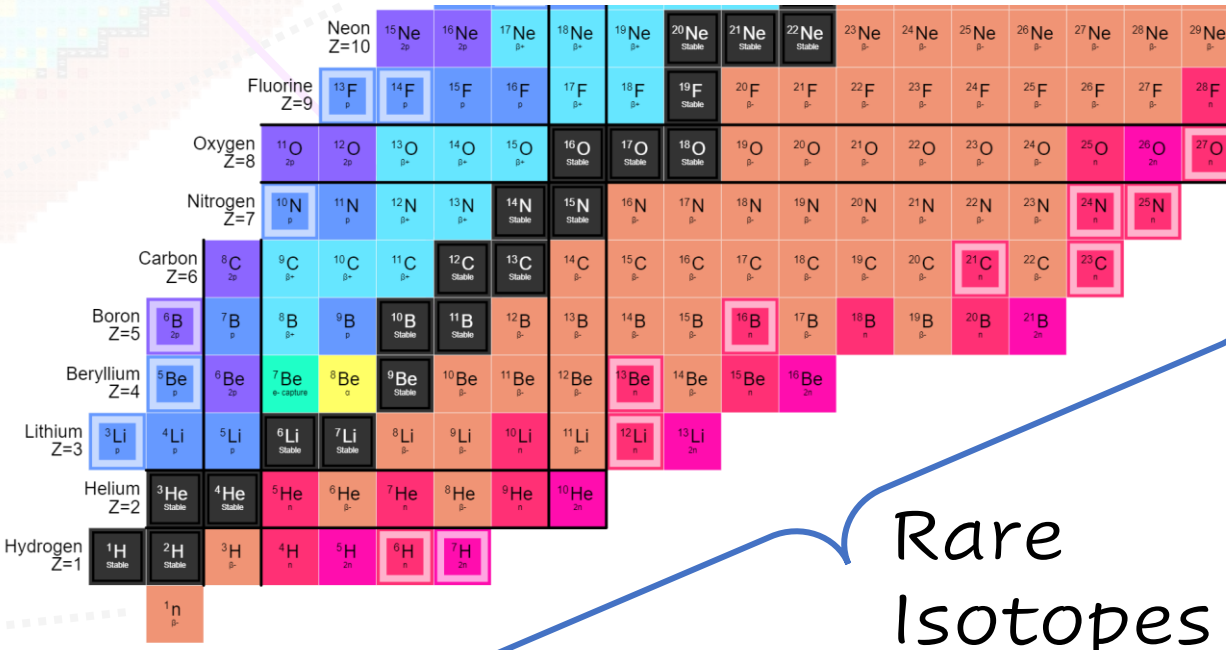

Rare Isotopes

Z

N

Nuclear Periodic Table

The colorful chart of nuclei

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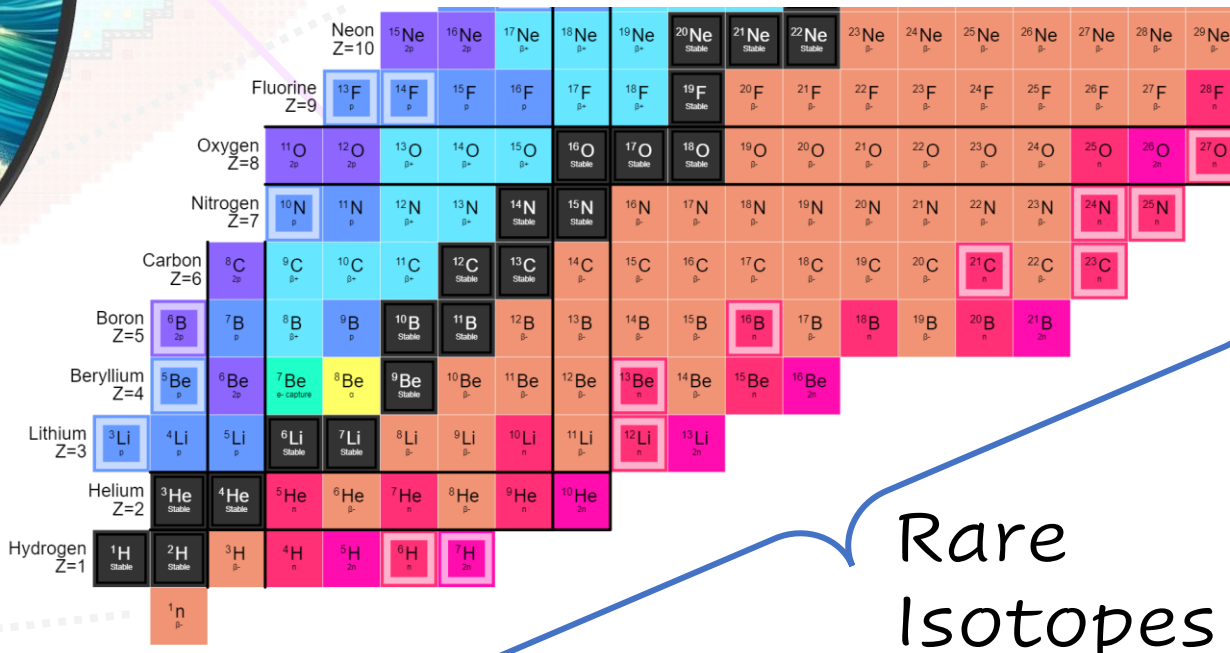
Why theory?

Chemical Periodic Table

FRIB

Facility for Rare Isotope Beams



Rare Isotopes

Z

N

Nuclear Periodic Table

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

"It is a big device, but without the people around it, its nothing"

Rare Connections

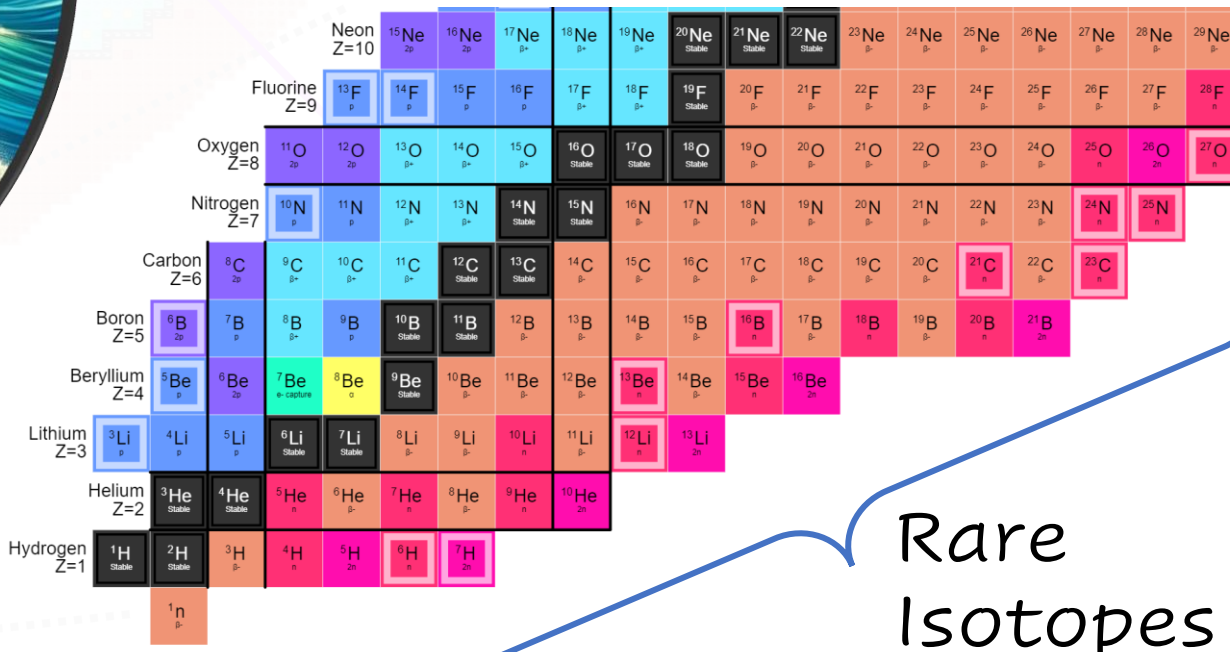
Premiering 2024

Teaser

Thanks Agnes Mocsy!

FRIB

Facility for Rare Isotope Beams



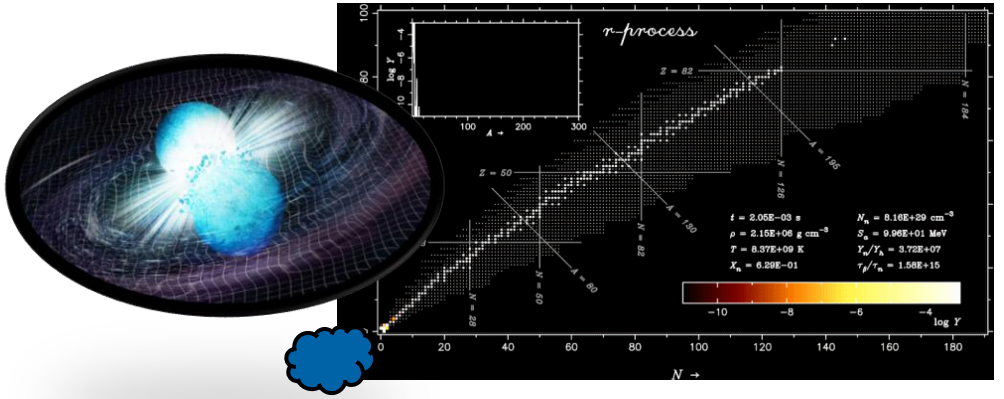
Rare Isotopes

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

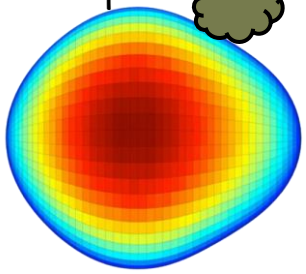
We have fun

Teaser

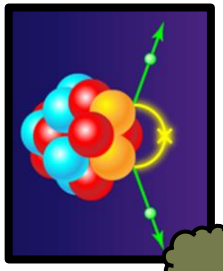
Big questions



Shapes



Decays



Structure

Astrophysics

Applications

Symmetries

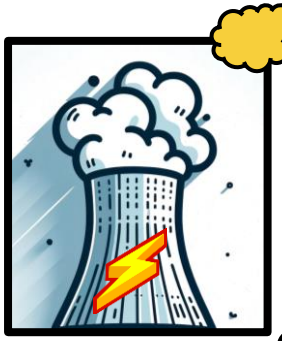
FRIB

Elastic

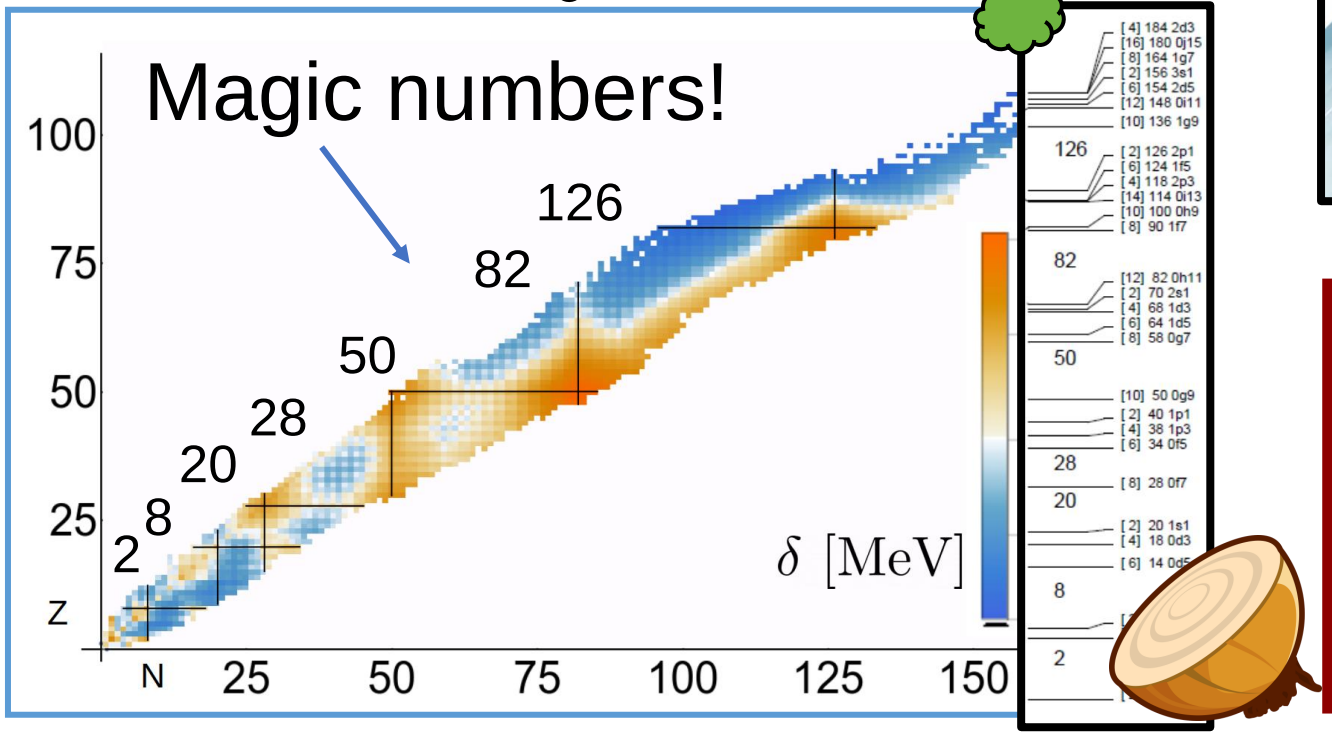
Inelastic

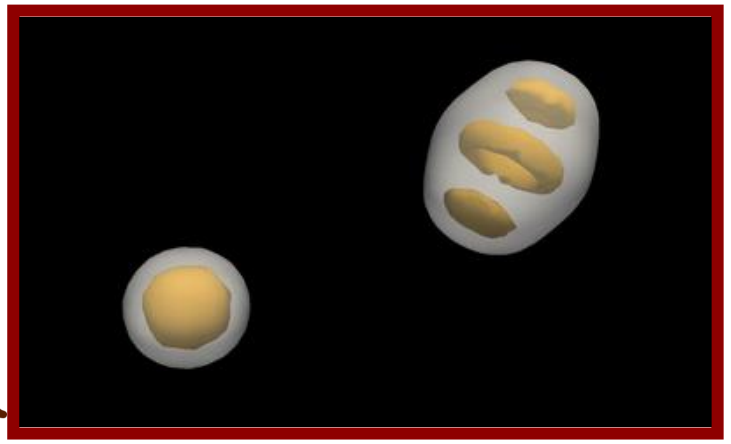
Capture

Breakup

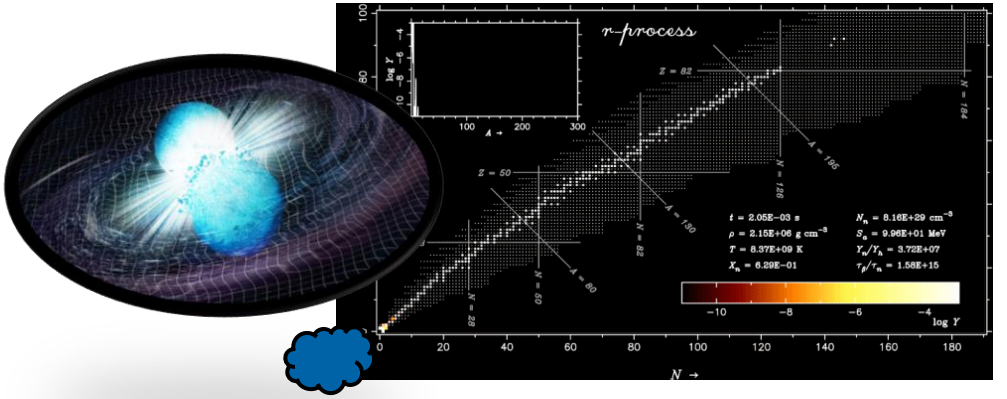


Power





Big questions



Where do heavy elements come from?

Shapes

Decays

Structure

Astrophysics

FRIB

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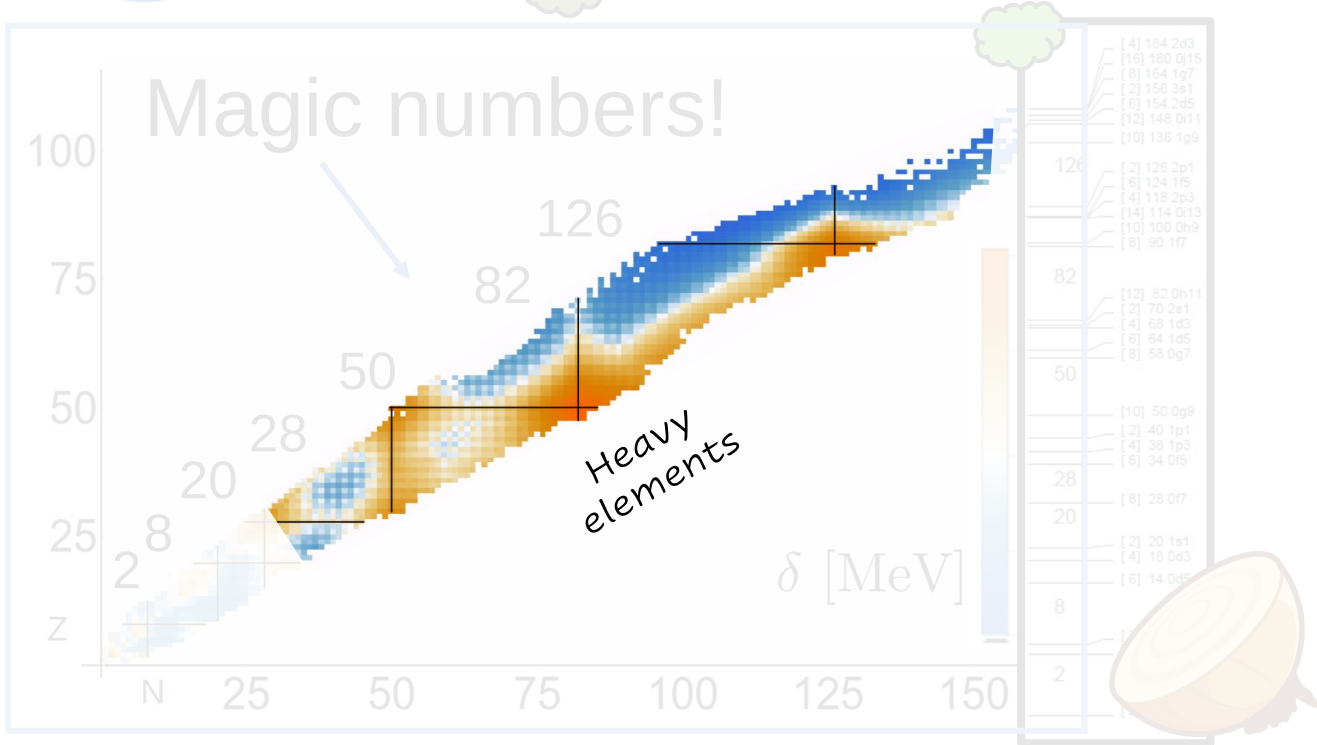
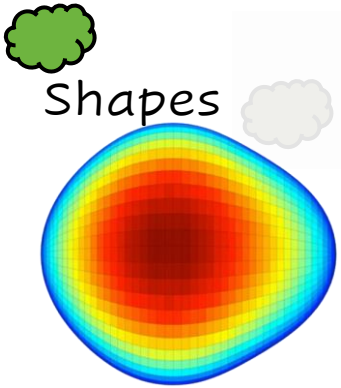


Big questions

What structures form at the extremes?

Where do heavy elements come from?



Structure

Applications

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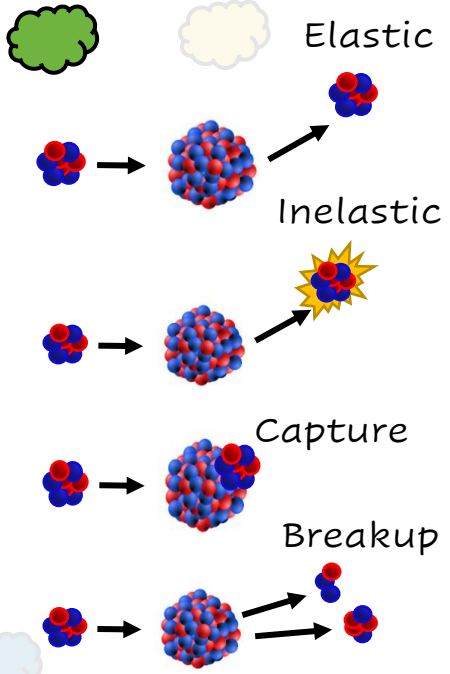
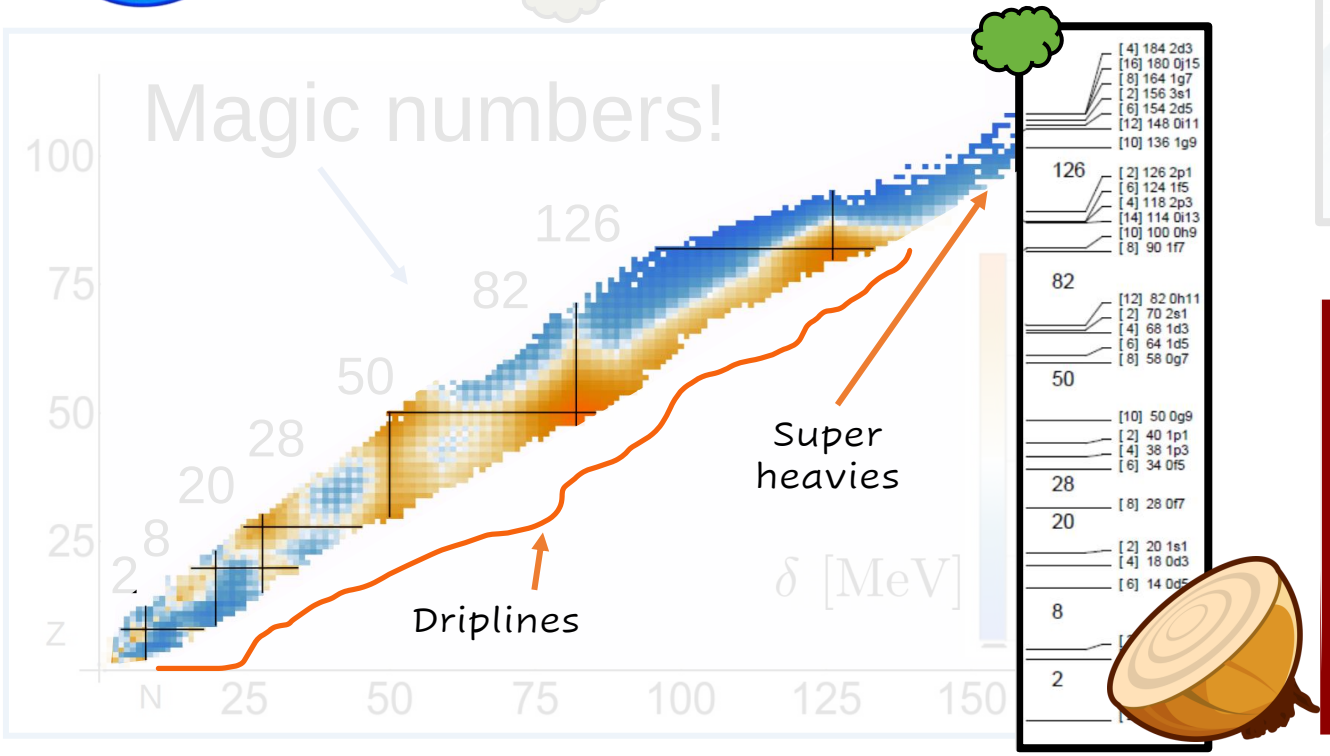
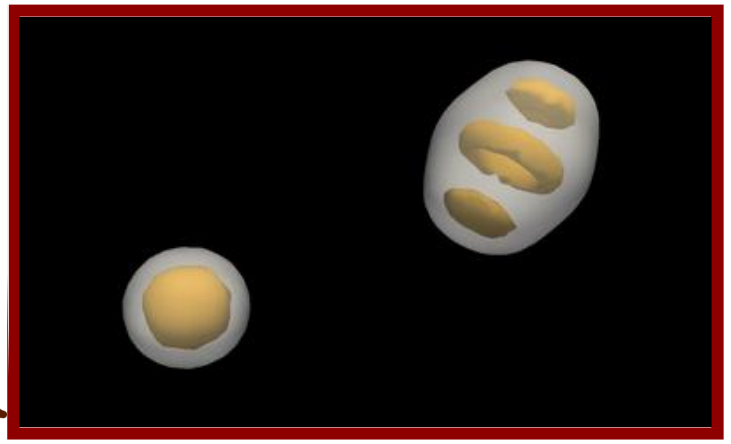
FRIB







Big questions

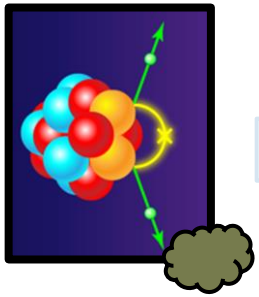
What structures form at the extremes?

Where do heavy elements come from?

What's up with neutrinos?

Shapes

Decays



Structure

Astrophysics

FRIB

Applications

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Inelastic

Capture

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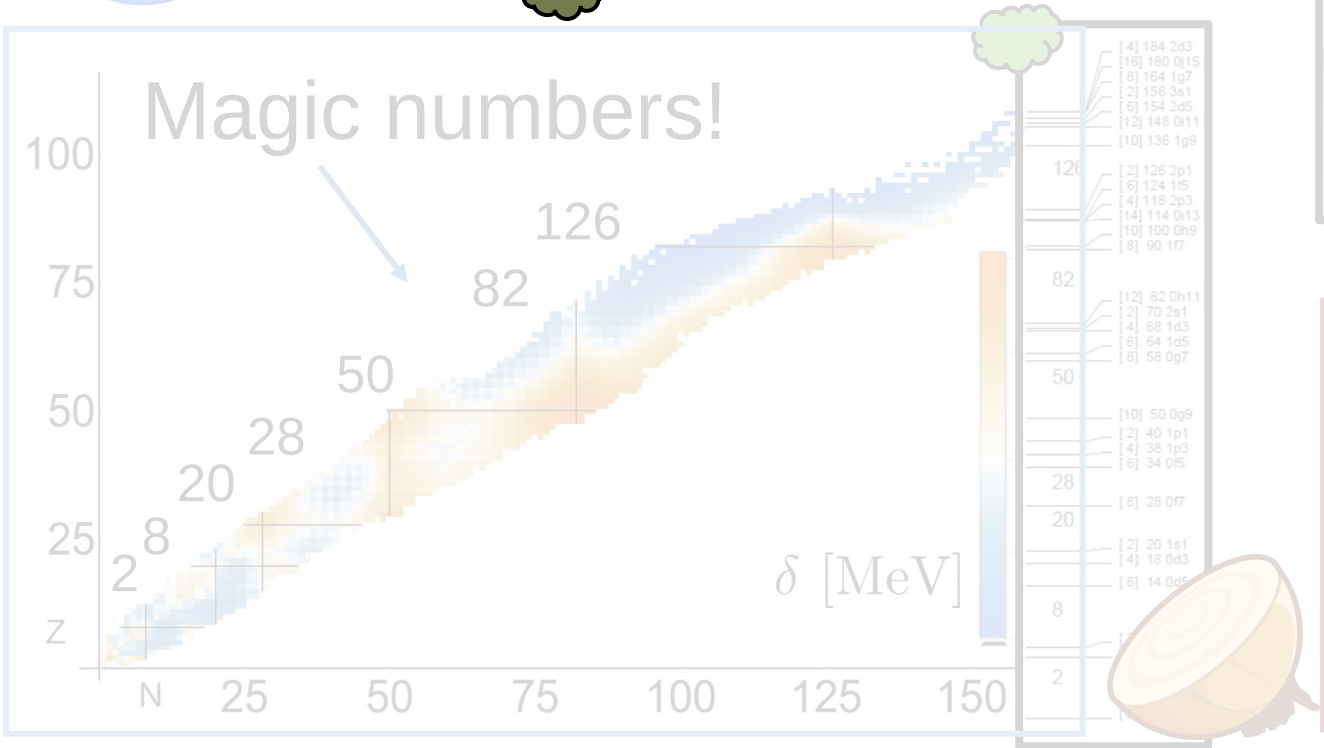
Power



Big questions

What structures form at the extremes?

Can we make useful things?

Where do heavy elements come from?

What's up with neutrinos?

Shapes

Decays

Structure

Astrophysics

Applications

Symmetries

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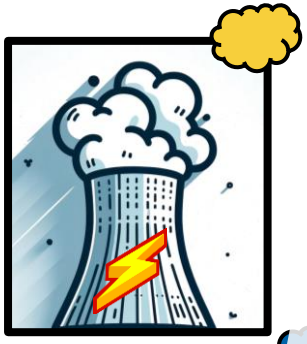

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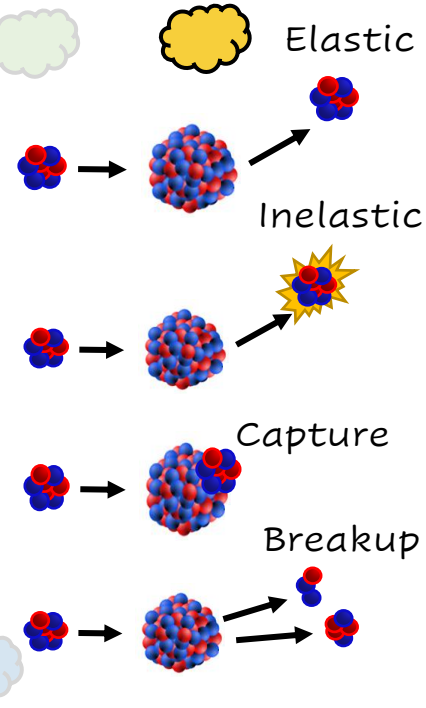
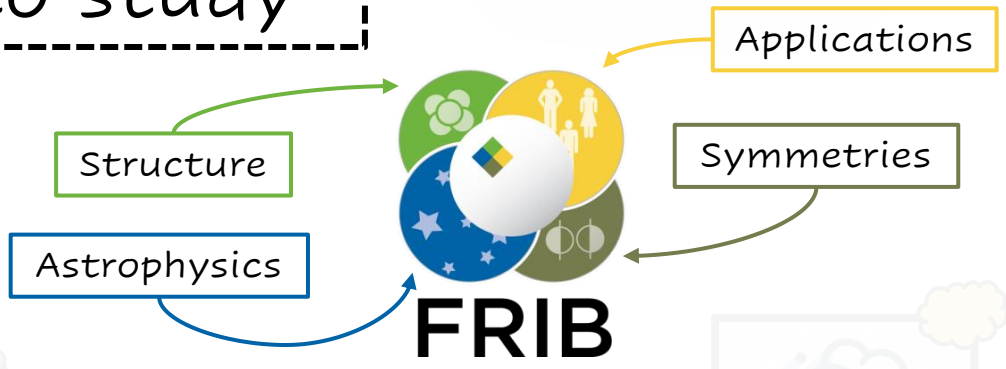


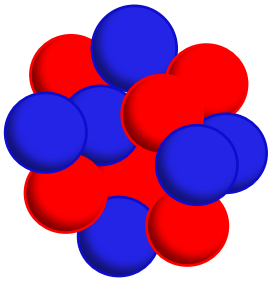
Big questions

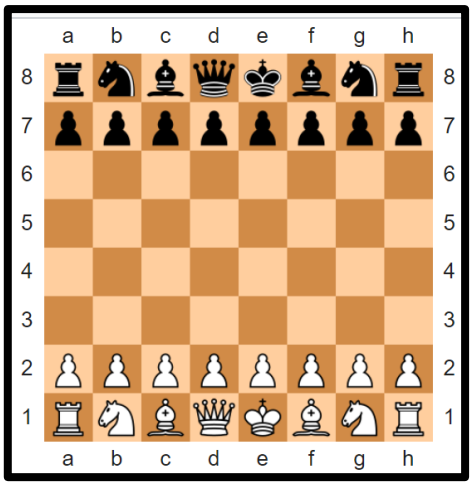
All of this is really, really hard to study



The Challenge

All of this is really, really hard to study





1) Rules are unclear

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

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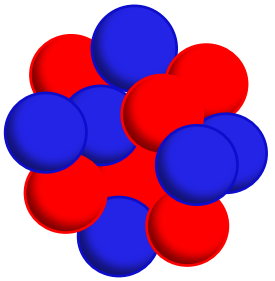

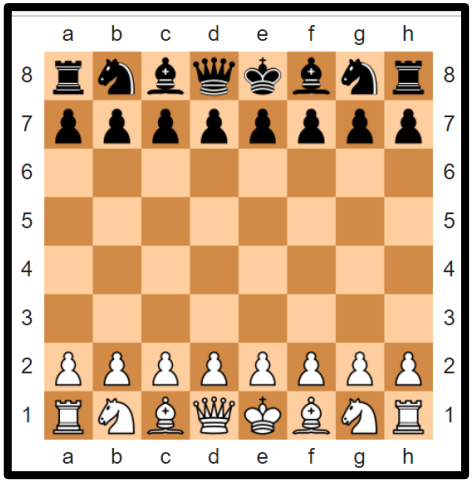

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You can watch

... from far away

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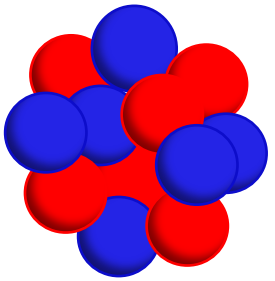

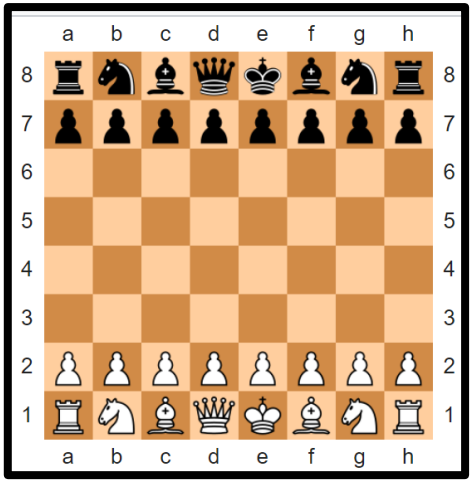

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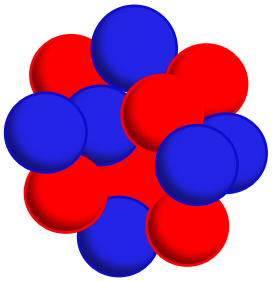

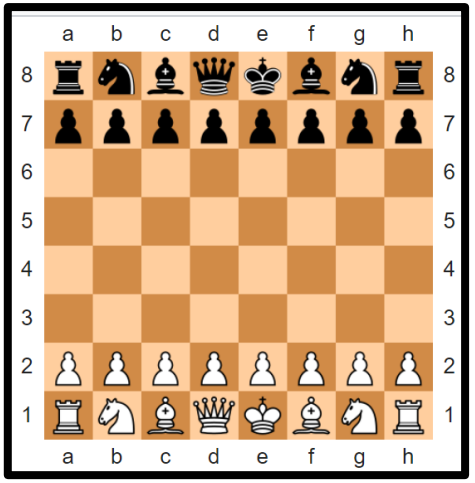

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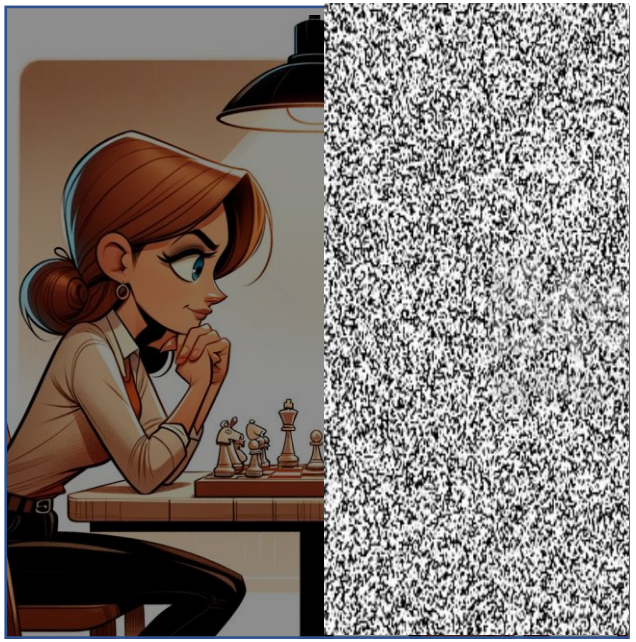

You can watch

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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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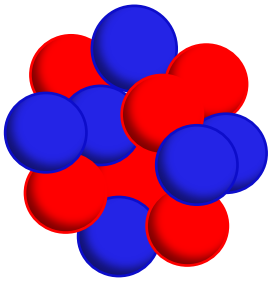

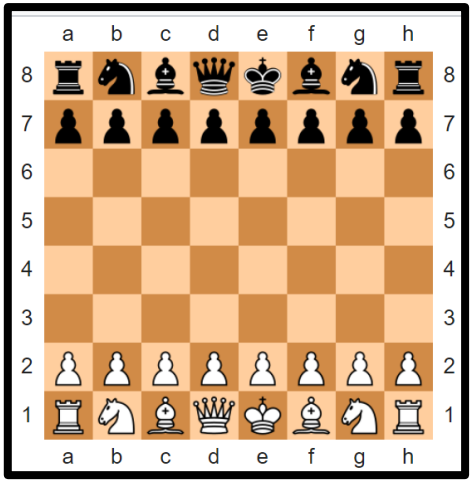

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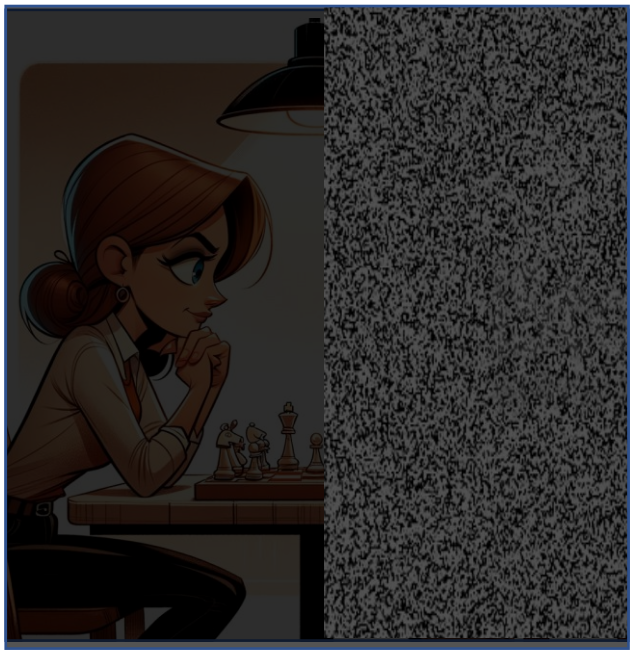

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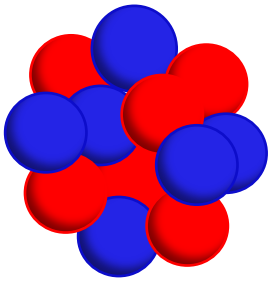

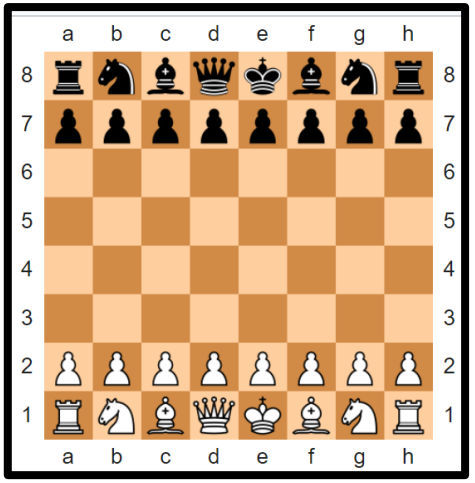

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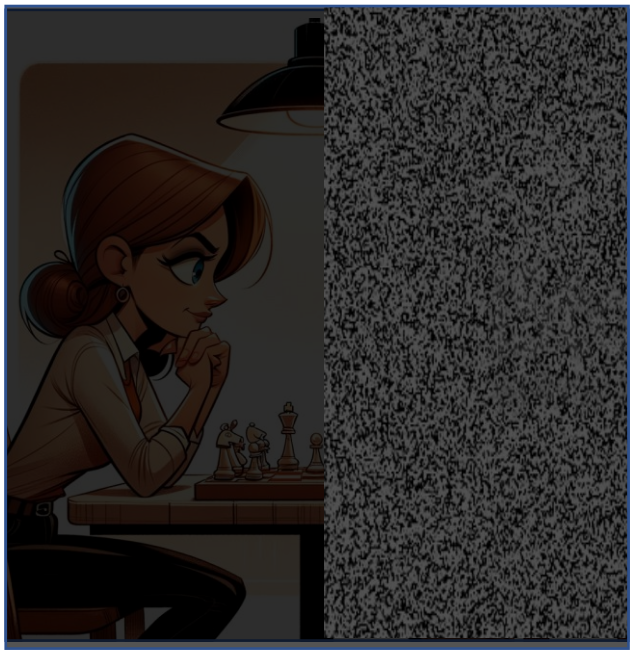

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...and you are wearing sunglasses

... and only one instant at a time

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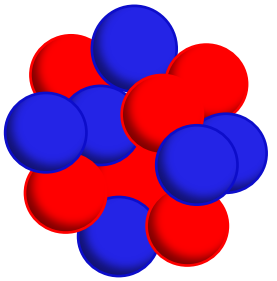

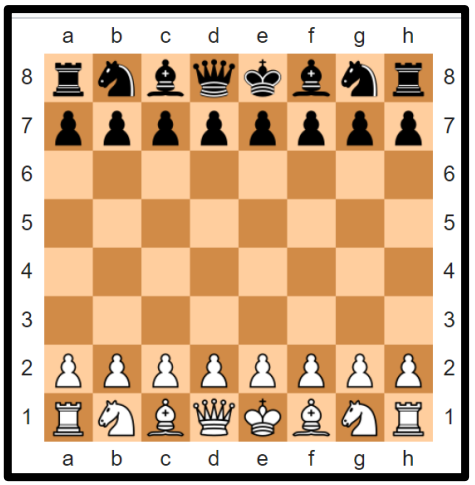

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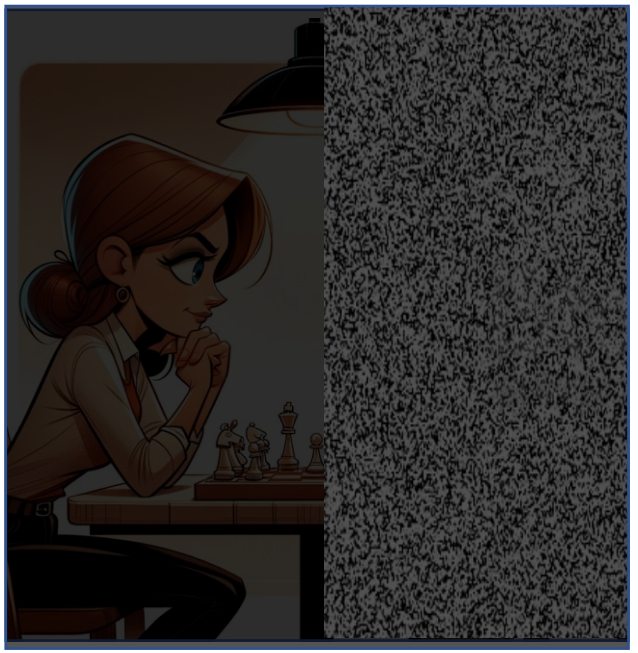

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Experiment! $\mathcal{H}|\psi(x,t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(x,t)\rangle$

The Challenge

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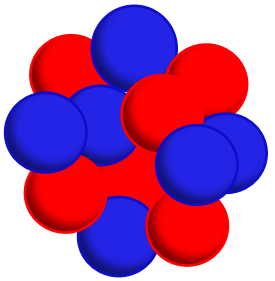
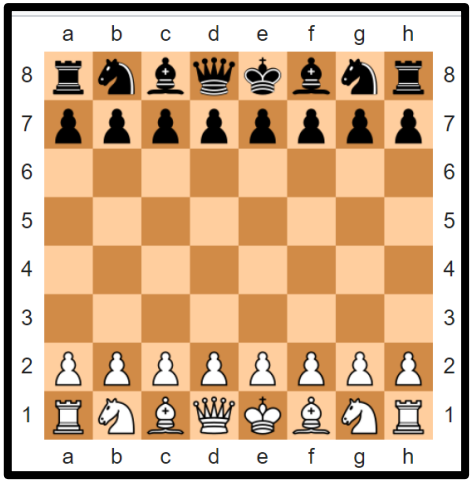


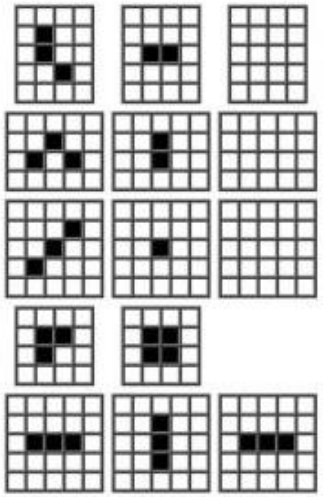


1) Rules are unclear

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



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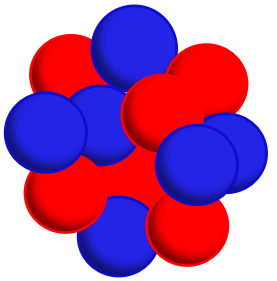

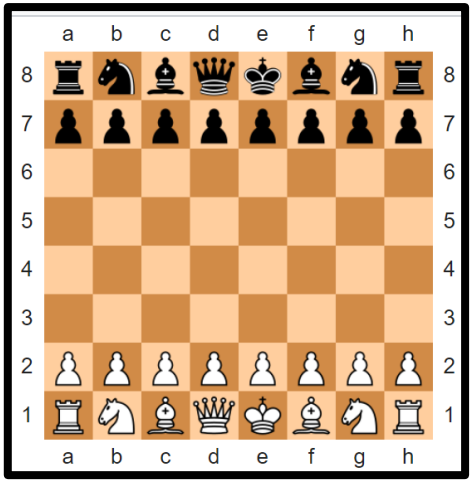

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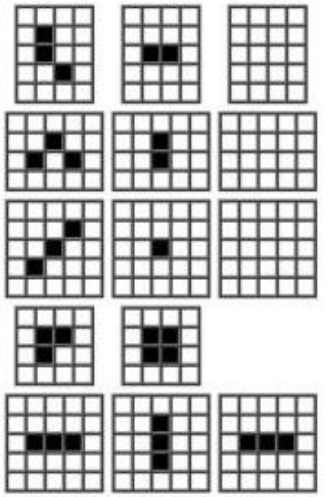


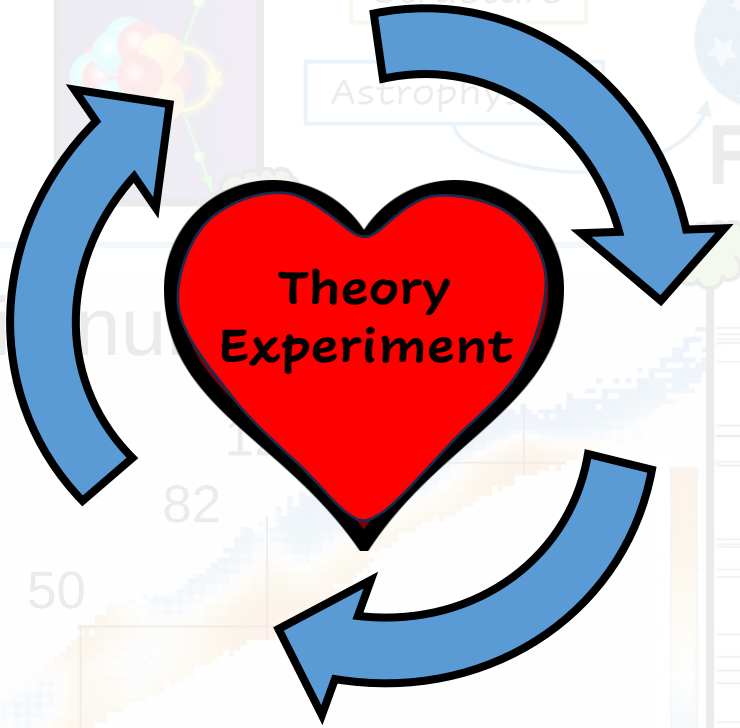
We need theory

What structures form at the extremes?

Can we make useful things?

Where do heavy elements come from?

What's up with neutrinos?



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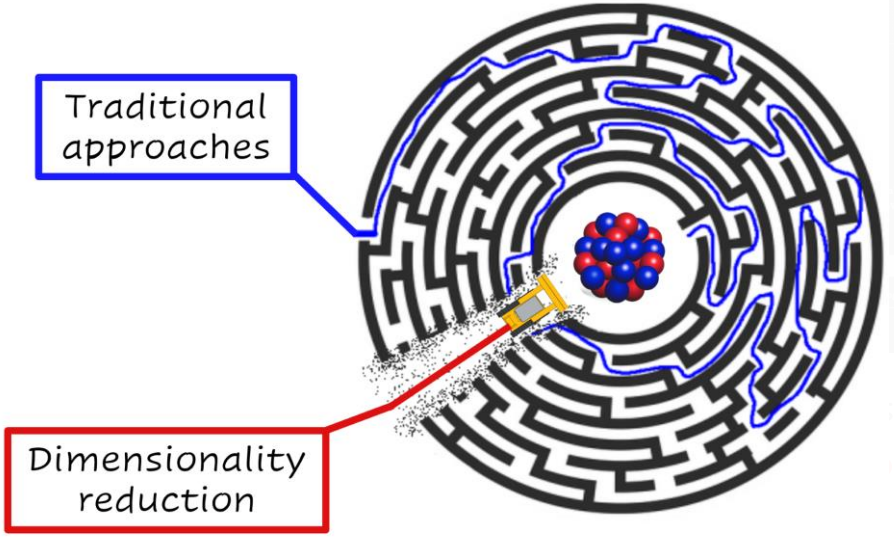
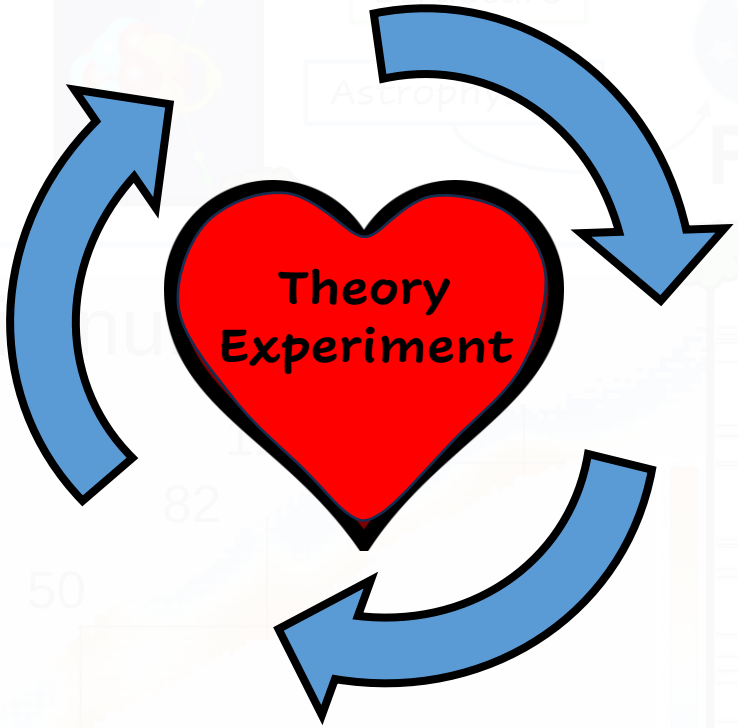
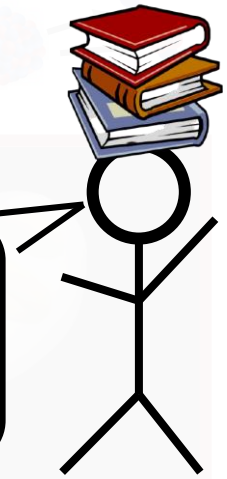




Video of me talking

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



For today

Who am I?

Why theory?

Building models

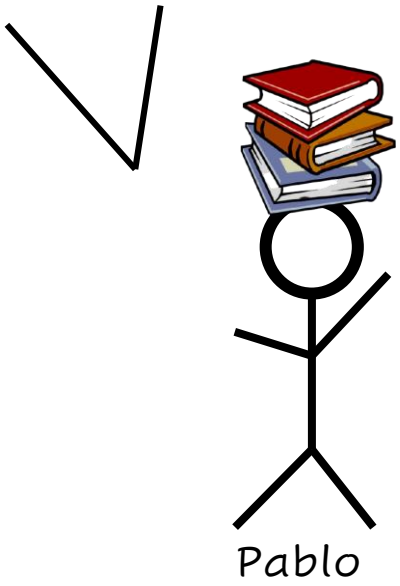
Building a (simple) nuclear model

Quantum mechanics

Building (better) nuclear models

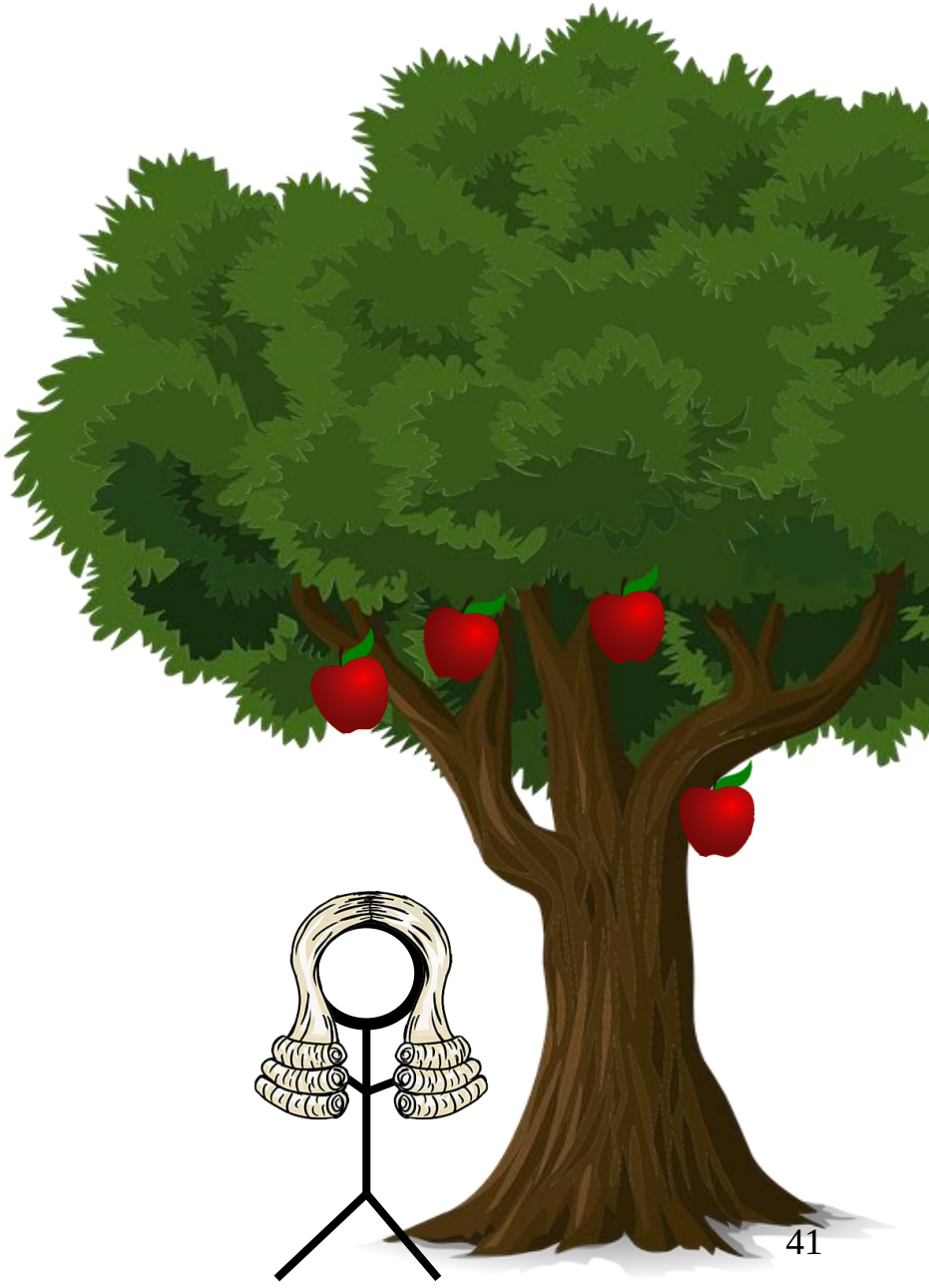
Challenges (Hands-On Session)

Questions?



Building models (planets)

XVII century



(Newton)

Building models (planets)

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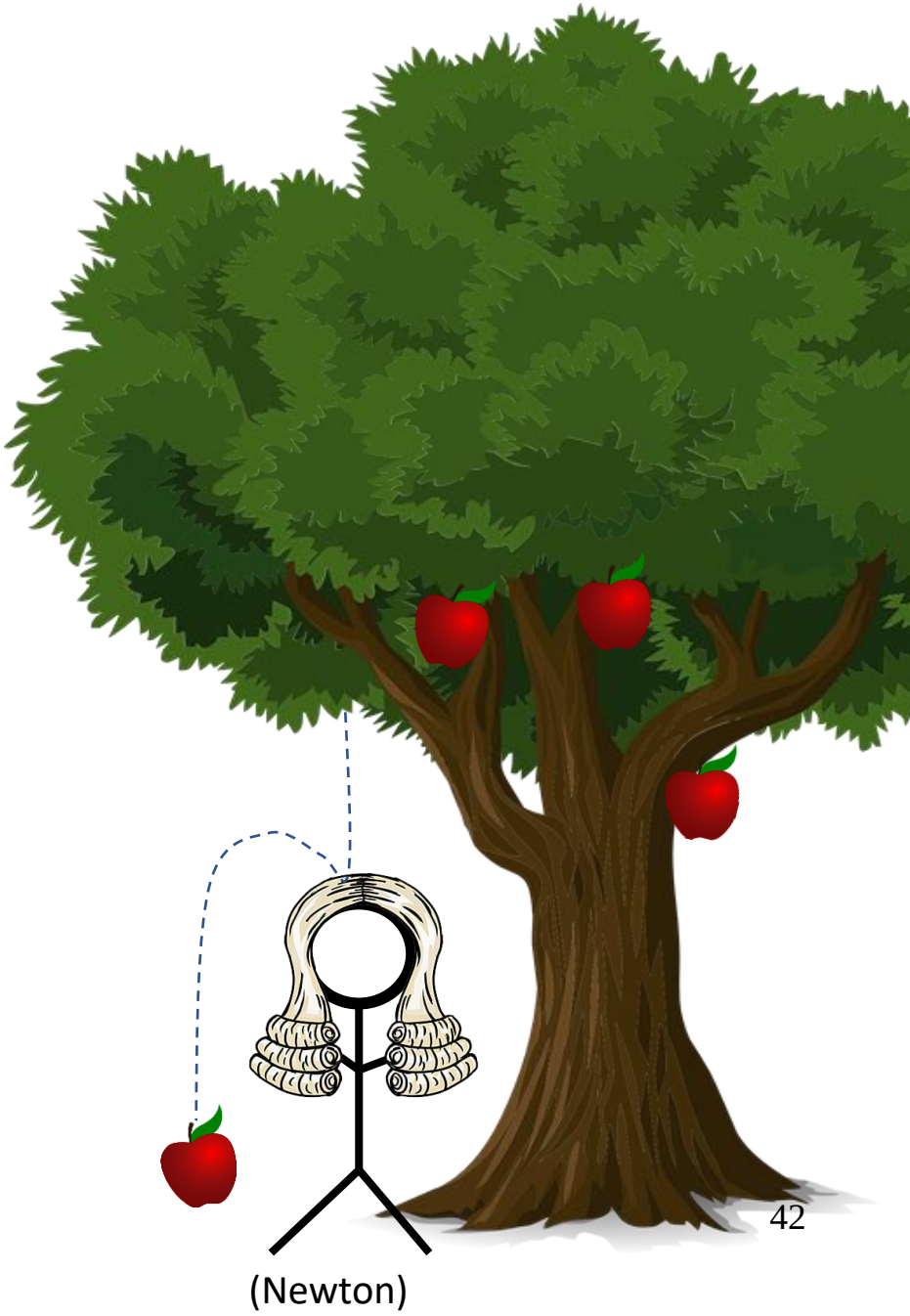

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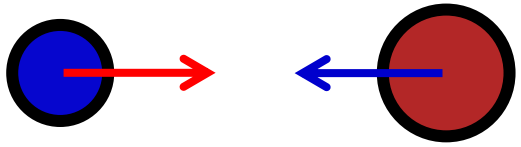

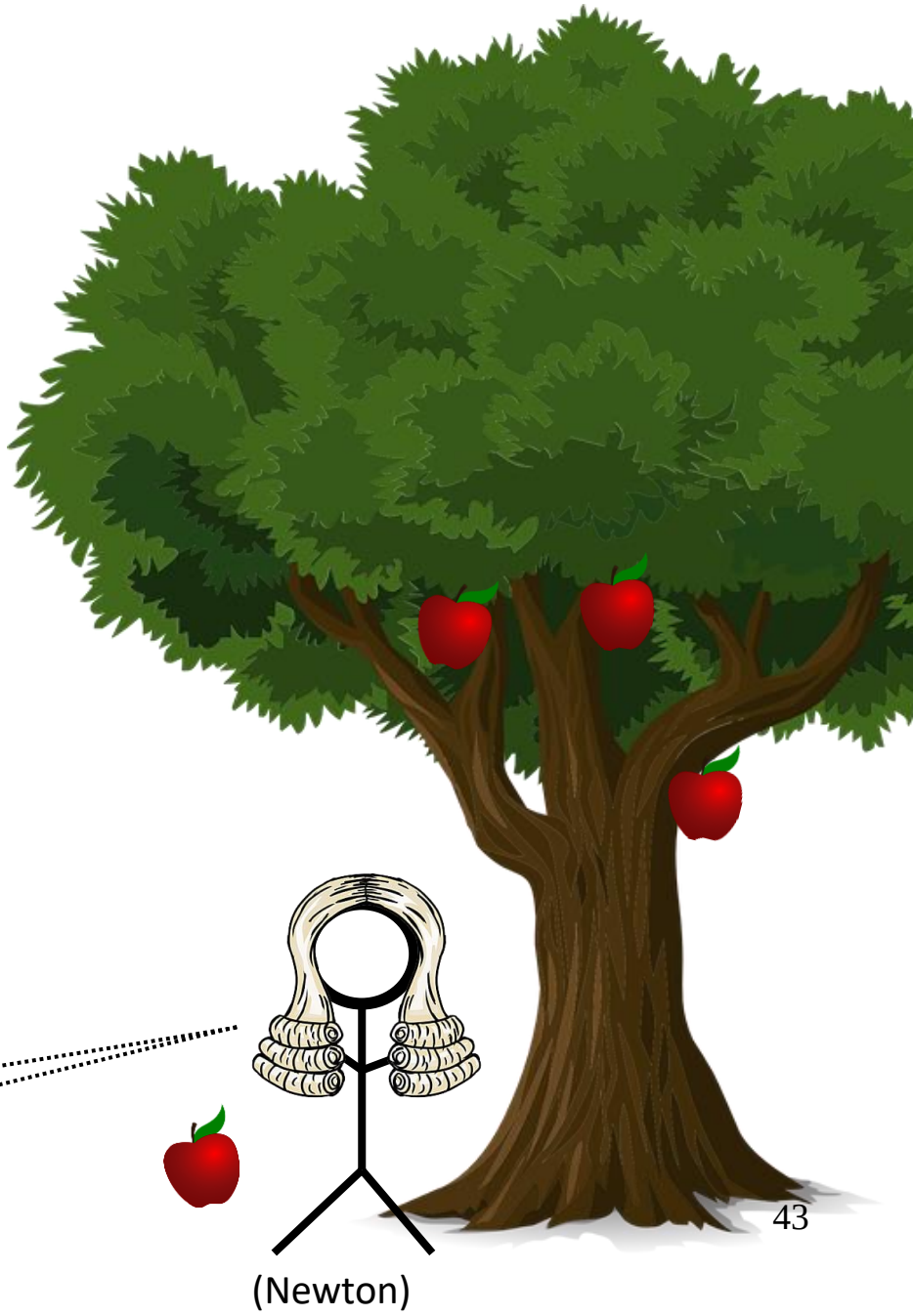

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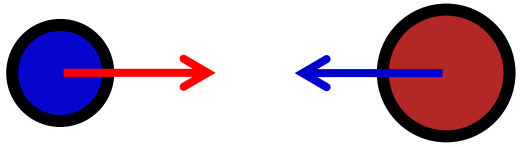
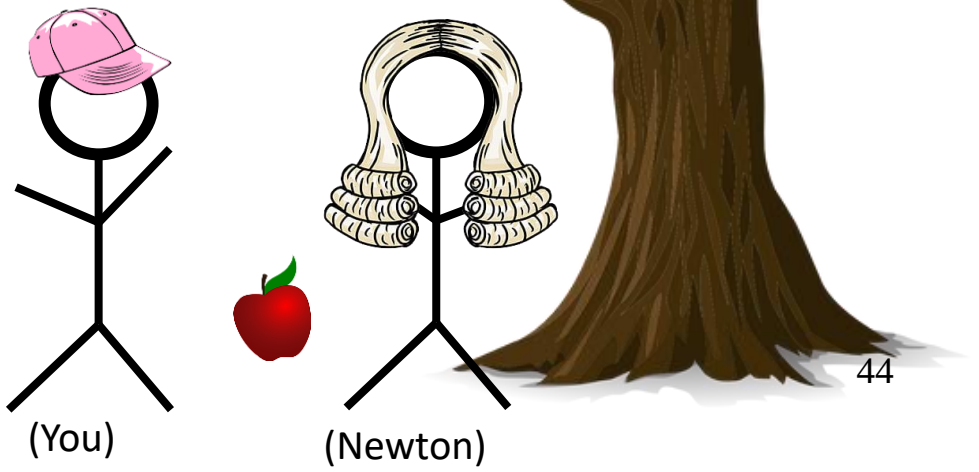


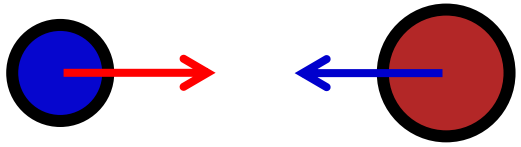


Building models (planets)

XVII century

Behaviors:

- Trajectories

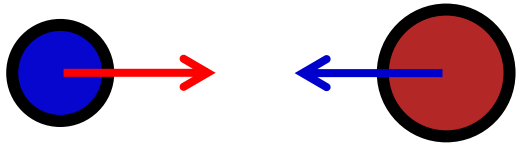


Building models (planets)

XVII century

Behaviors:

- Trajectories
- Structure

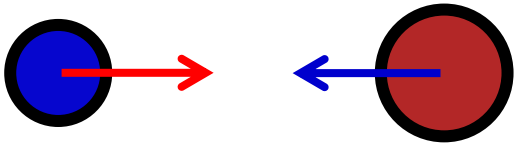


Building models (planets)

XVII century

Behaviors:

- Trajectories
- Structure
- Brightness



Building models (planets)

XVII century

Behaviors:

- Trajectories
- Structure
- Brightness

?

Building models (planets)

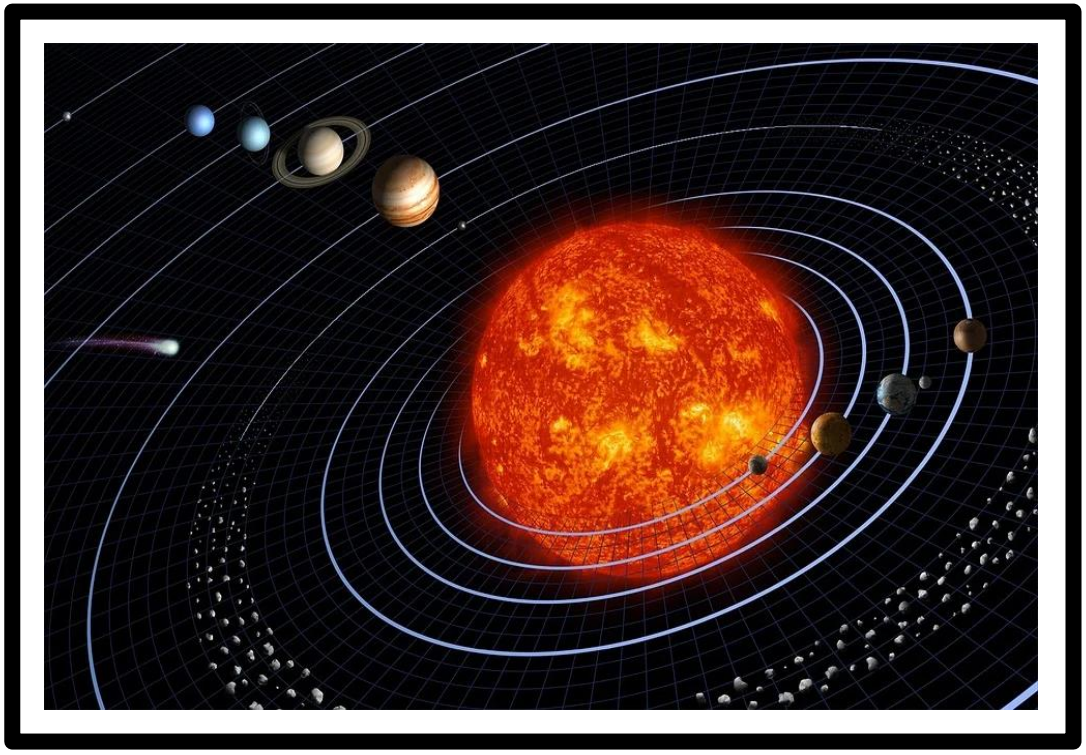
XVII century

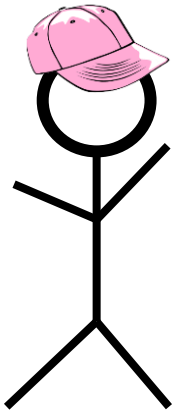
Behaviors:

- Trajectories
- Structure
- Brightness

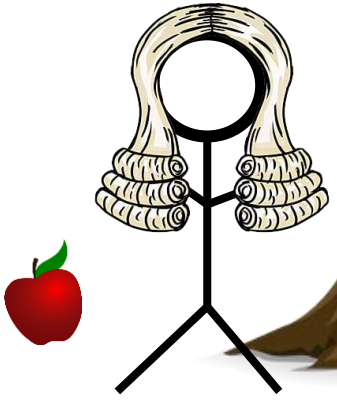
$$F = G\frac{m_1 m_2}{r^2}$$

model





(You)



(Newton)

Building models (planets)

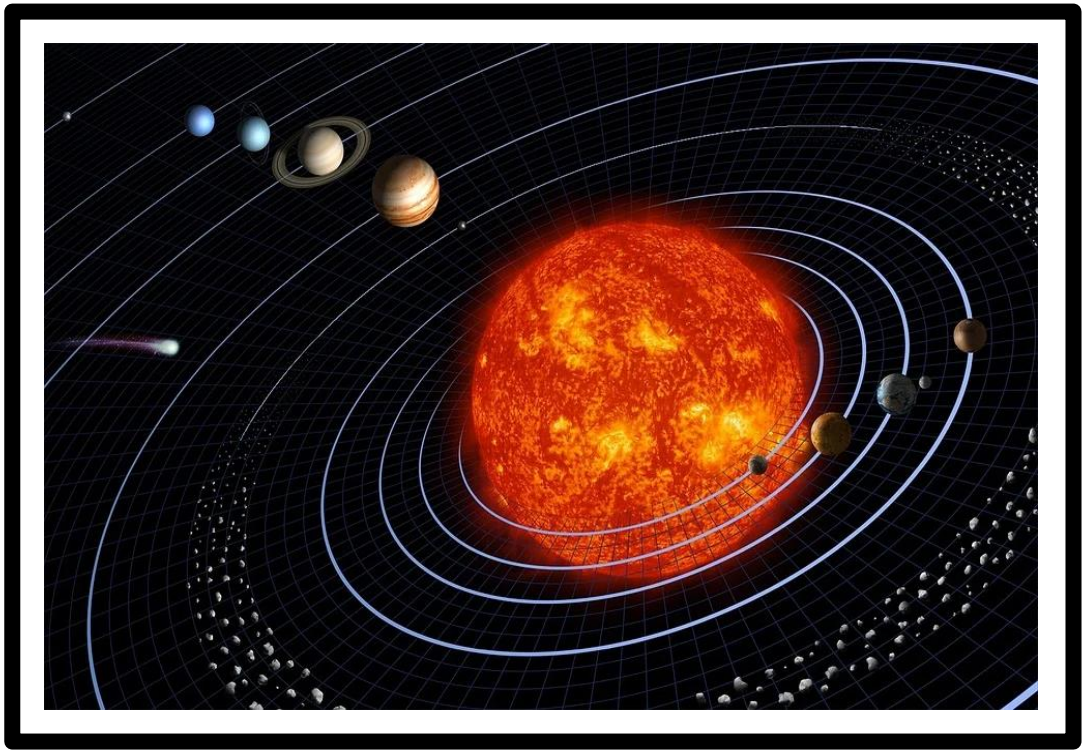
XVII century

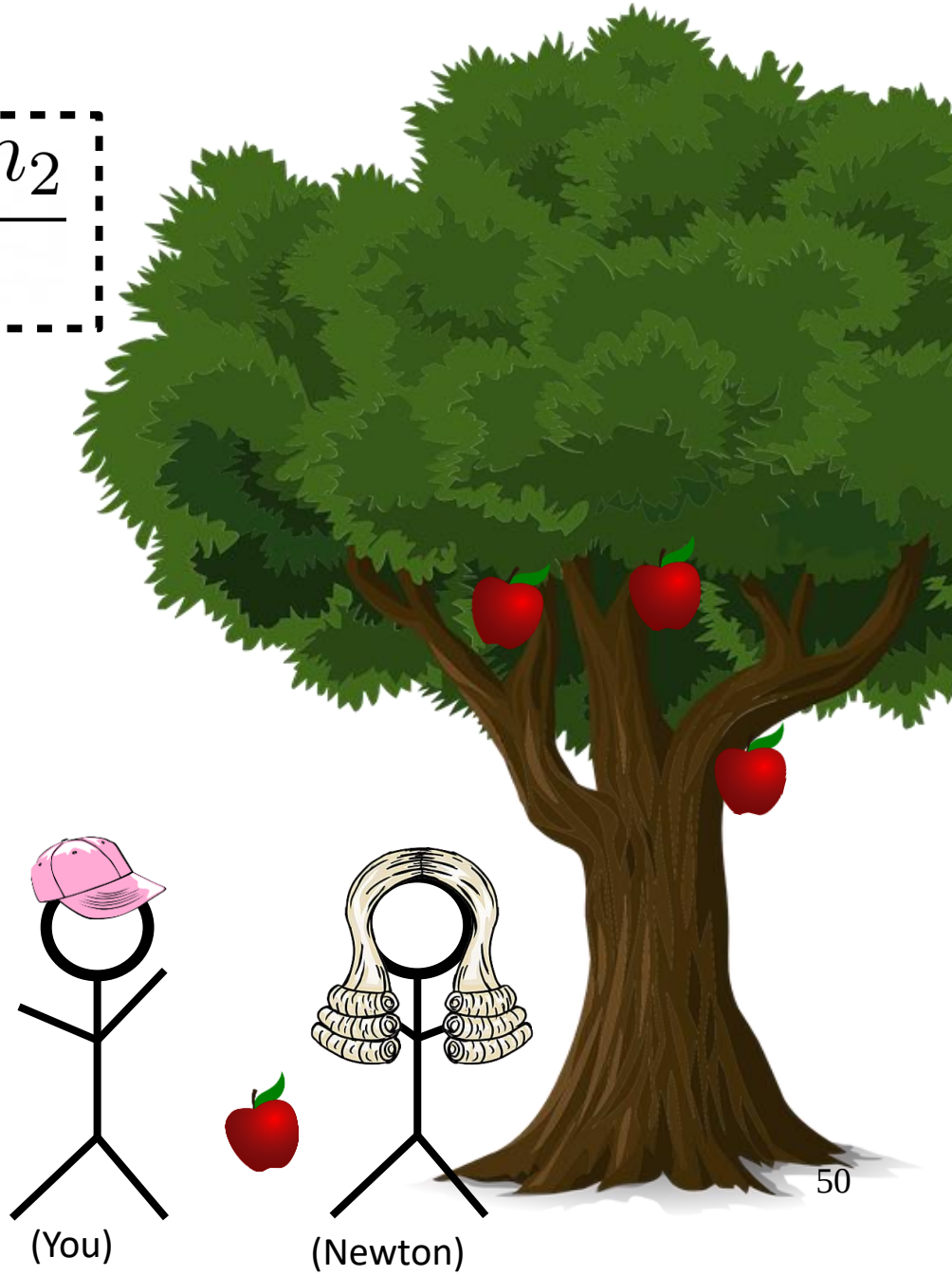
Behaviors:

- ✓ 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

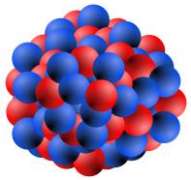
Space shuttle

Building models (nuclear)

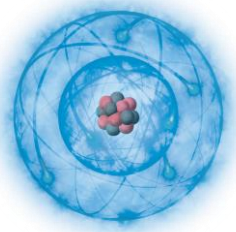
XXI century

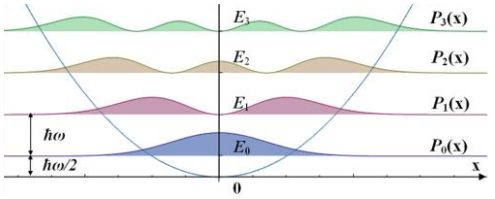
Behaviors:

- Binding energy (energy “debt”)

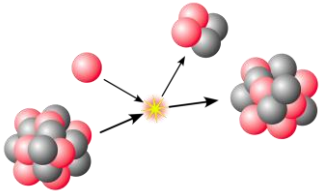


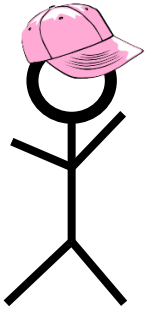
- Structure (arrangement of nucleons)





- Reactions (smashing nuclei)

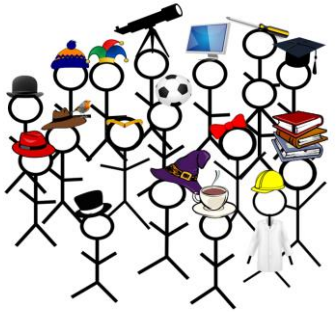




(You)

(Pablo)

Huge team



Building models (nuclear)

Good models

Explain

Predict

Build

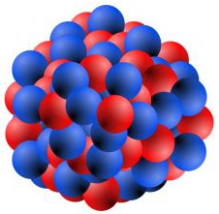
Burning Sun

Kilonova after merger

Nuclear energy

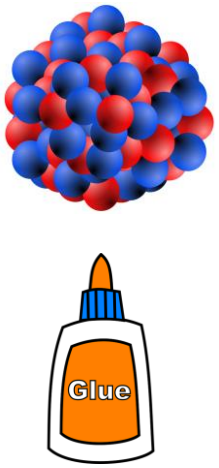
Binding energy ⟶ Energy needed to break it apart

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

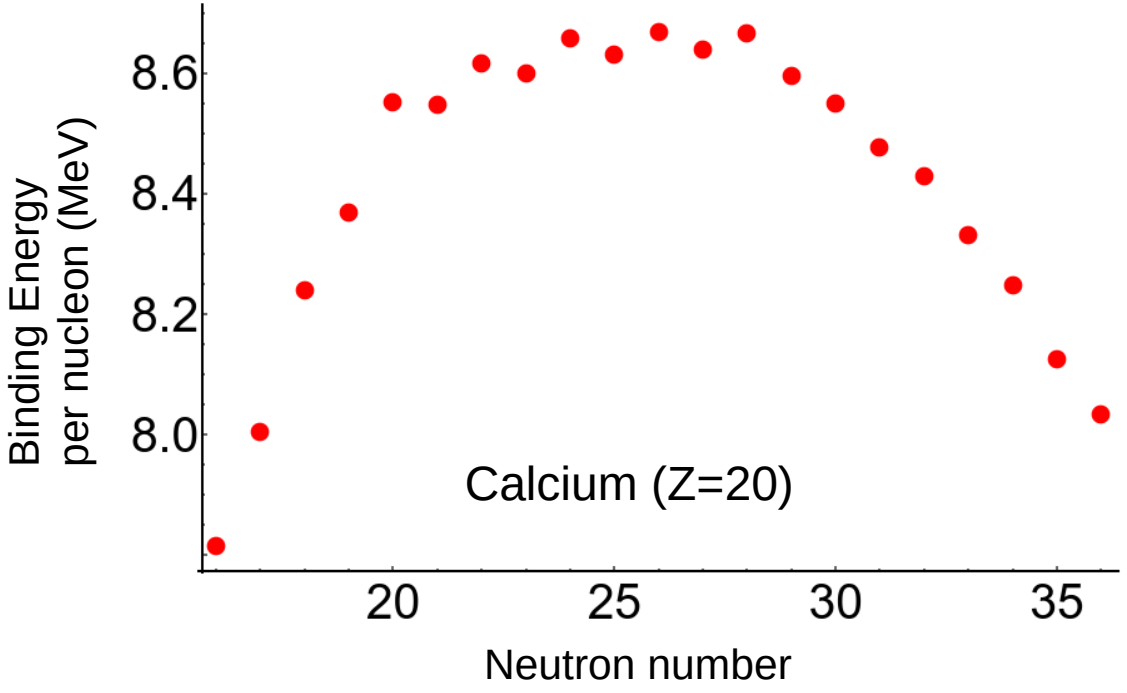


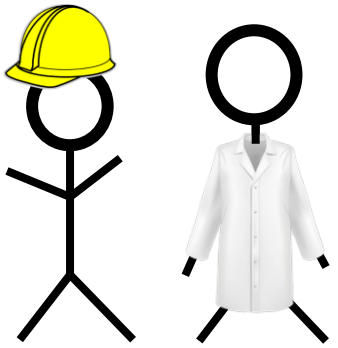
Binding energy ⟶ Energy needed to break it apart

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



Behavior:



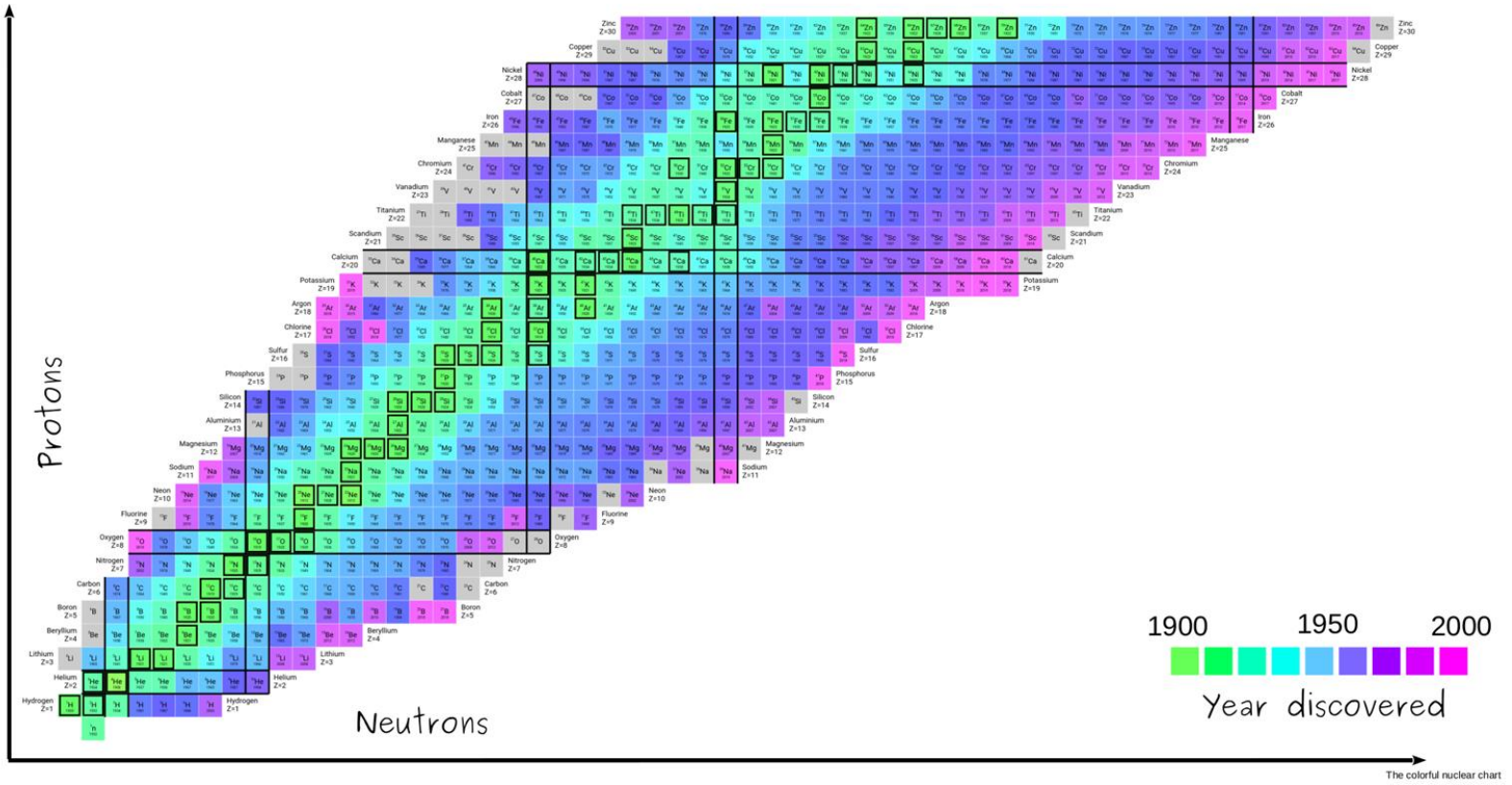


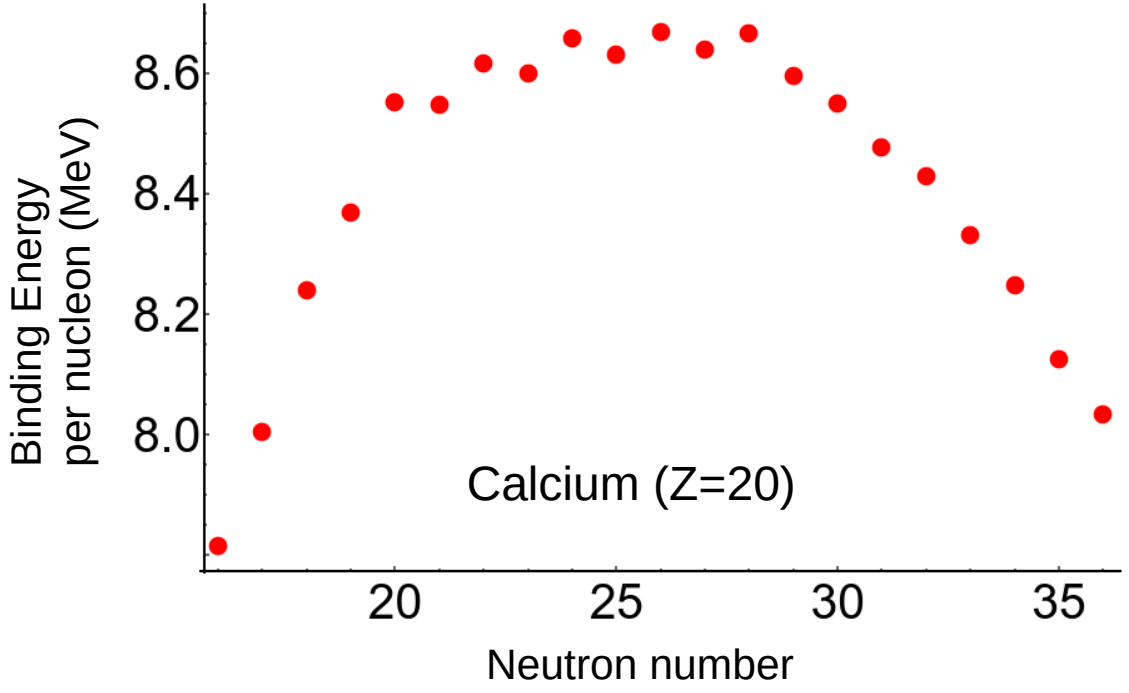
(Exp Friends)

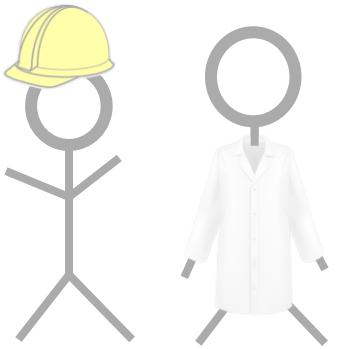
Binding

$$m = Zm_p$$

Behavior:

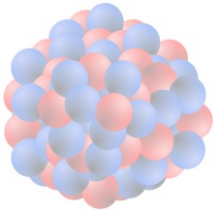






(Exp Friends)

Binding energy ⟶ Energy needed to break it apart



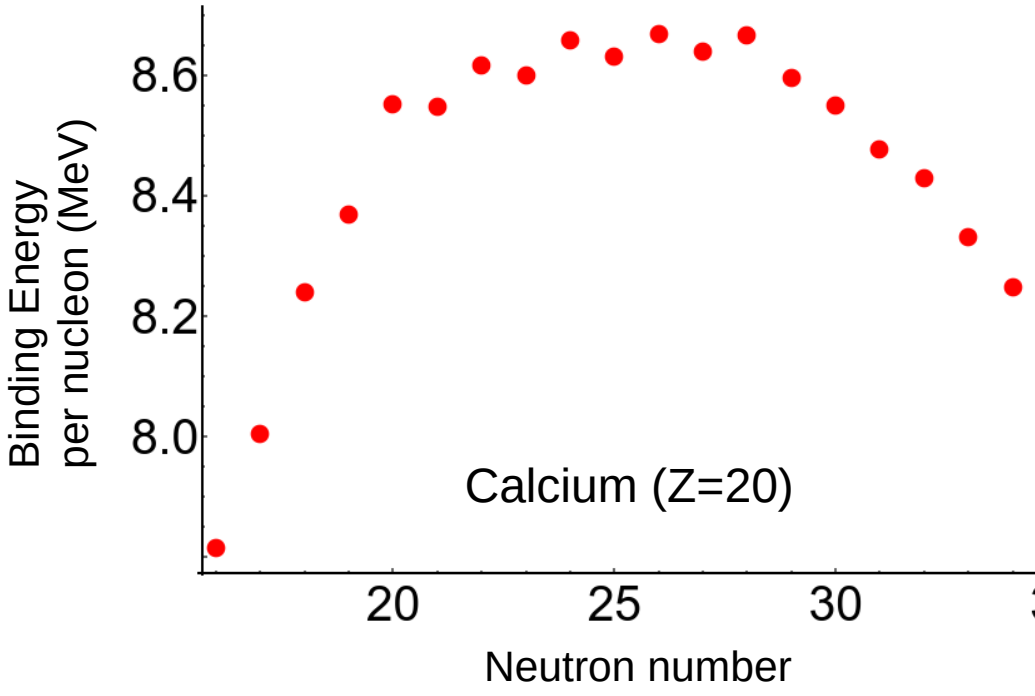
$$m = Zm_p + Nm_n - \frac{BE}{c^2}$$

Comparisons as energy

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

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

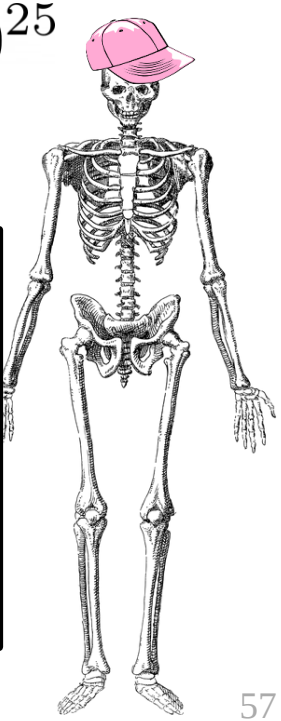
Behavior?



Total calcium $\sim 1.6 \times 10^{25}$

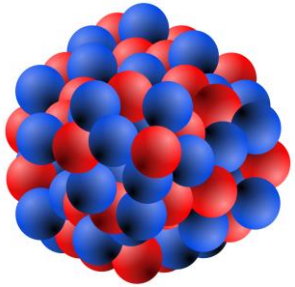
Total energy $\sim \times 10^{15}$ J

(Exp Friends)



(You)

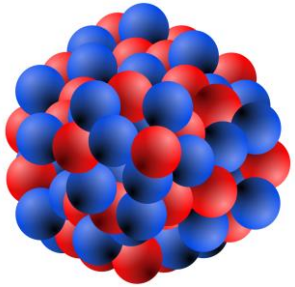
Binding energy



Liquid drop model

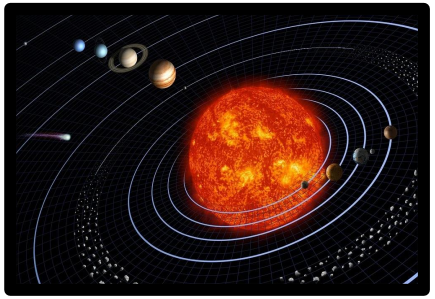
$$\mathrm{BE}(N,Z) =$$

Binding energy



Liquid drop model

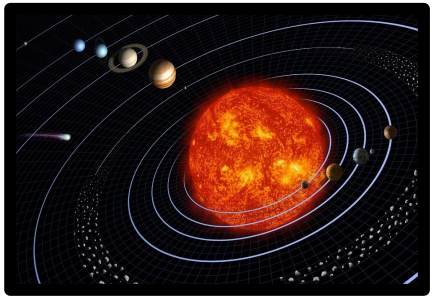
$$F = G\frac{m_1 m_2}{r^2}$$

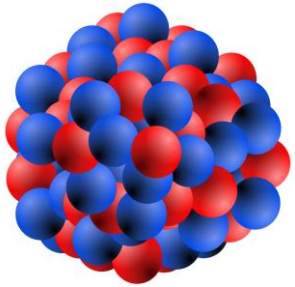


$$\mathrm{BE}(N,Z) =$$

Binding energy

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

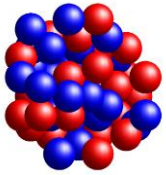




Liquid drop model

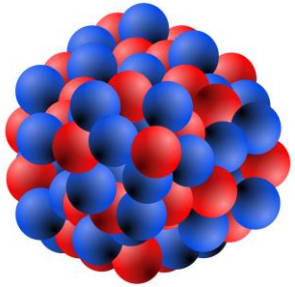
$$\mathrm{BE}(N,Z) =$$

More nucleons



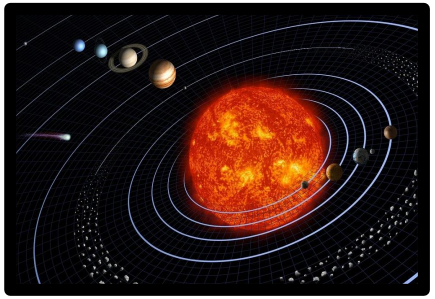
BE

Binding energy



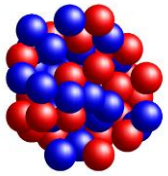
Liquid drop model

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



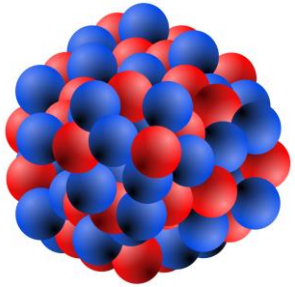
$$\mathrm{BE}(N,Z) = a_V(N+Z)$$

More nucleons



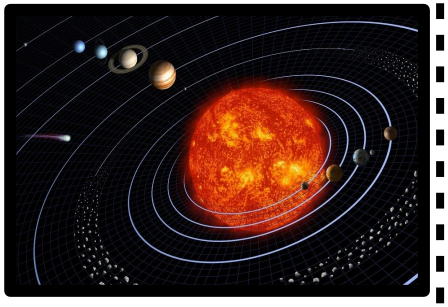
BE

Binding energy



Liquid drop model

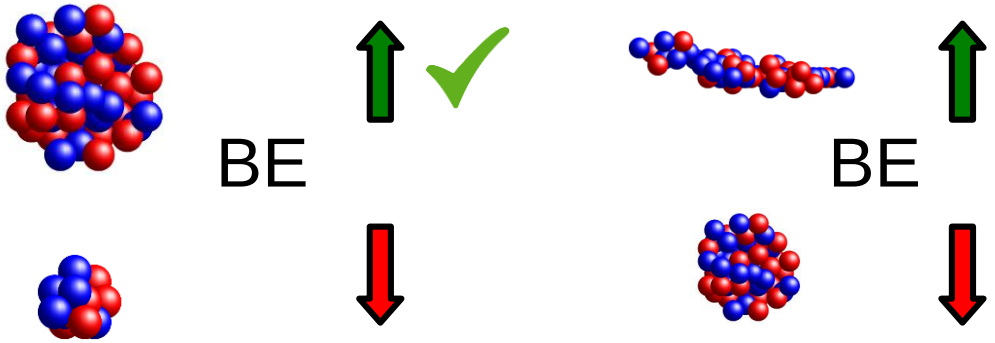
$$F = G\frac{m_1 m_2}{r^2}$$



$$\mathrm{BE}(N,Z) = a_V(N+Z)$$

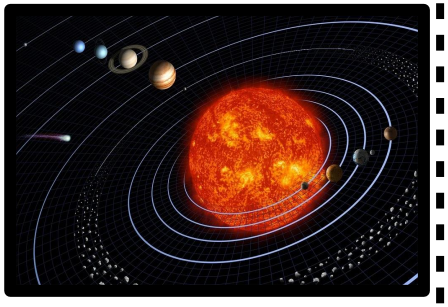
More nucleons

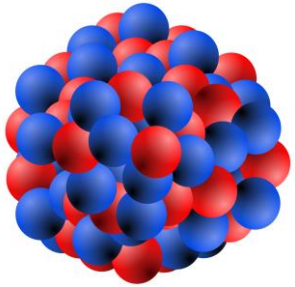
More surface



Binding energy

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



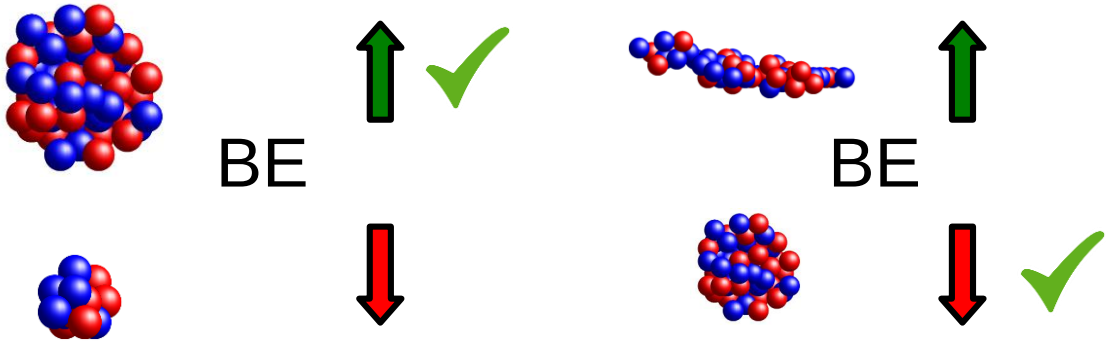


Liquid drop model

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

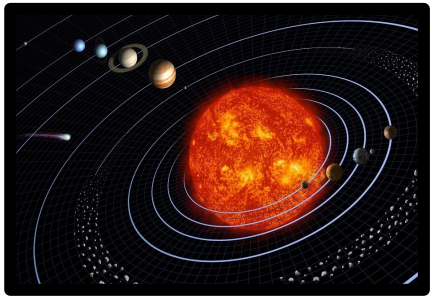
More nucleons

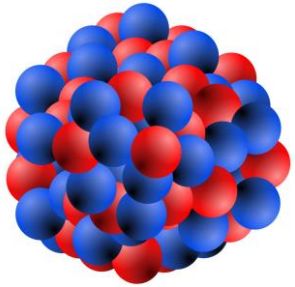
More surface



Binding energy

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





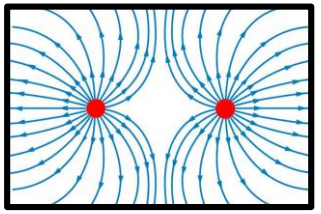
Liquid drop model

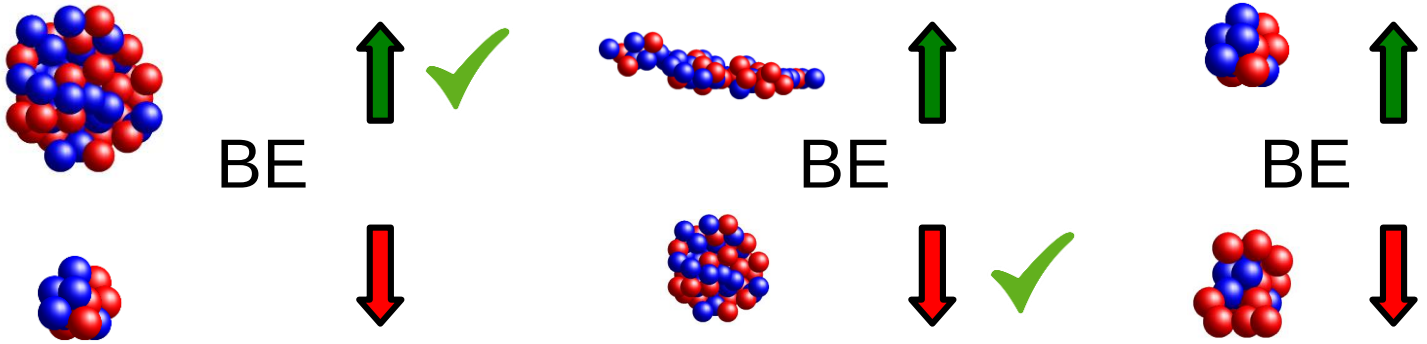
$$\mathrm{BE}(N,Z) = a_V(N+Z) - a_S(N+Z)^{2/3}$$

More nucleons

More surface

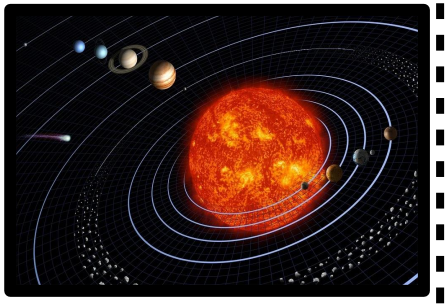
More protons

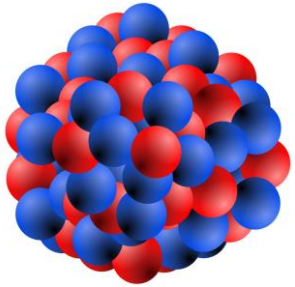




Binding energy

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





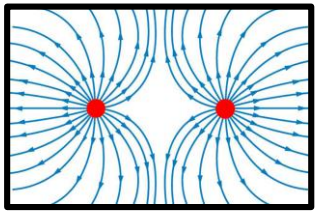
Liquid drop model

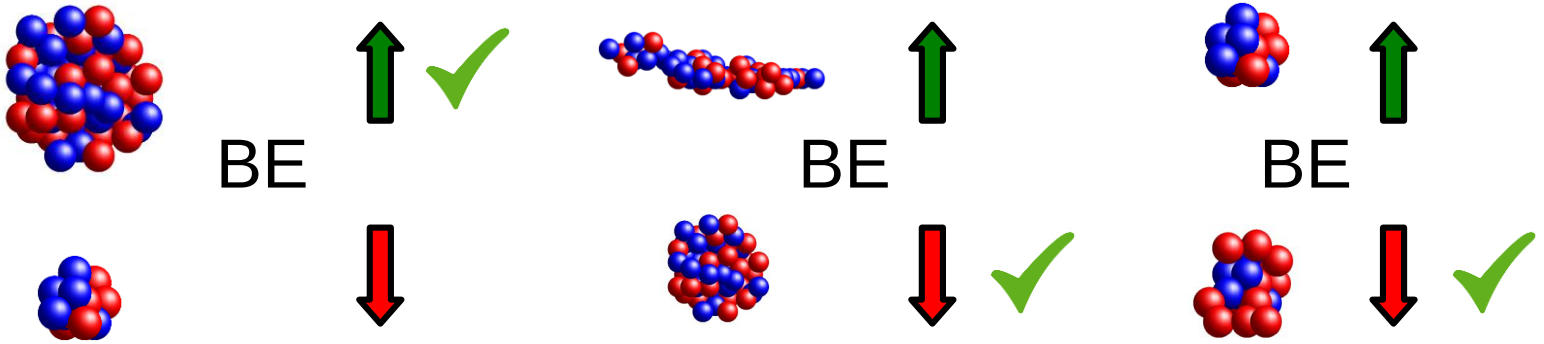
$$\mathrm{BE}(N,Z) = a_V(N+Z) - a_S(N+Z)^{2/3} - a_C\frac{Z^2}{(N+Z)^{1/3}}$$

More nucleons

More surface

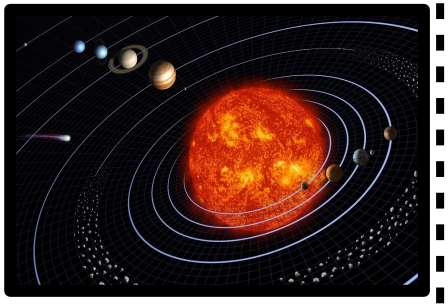
More protons

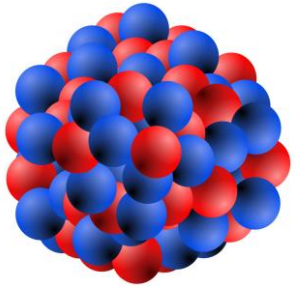




Binding energy

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

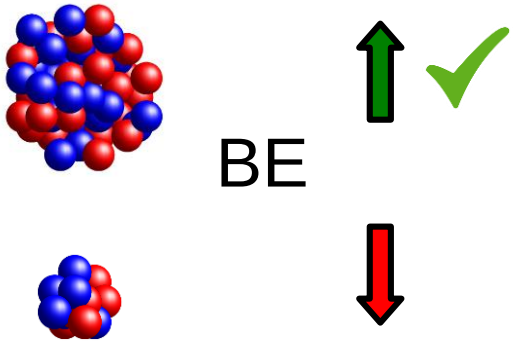




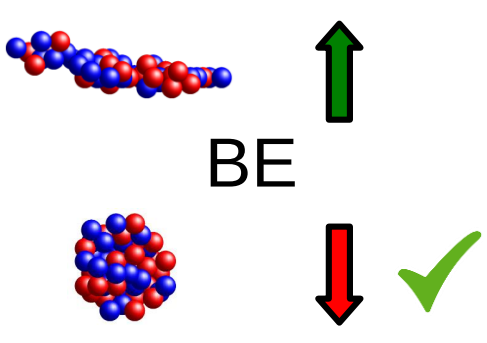
Liquid drop model

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

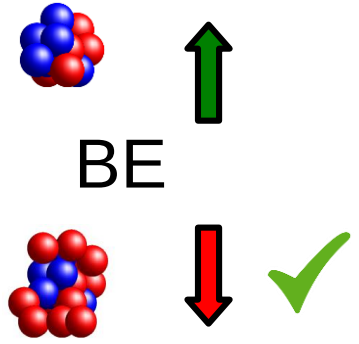
More nucleons



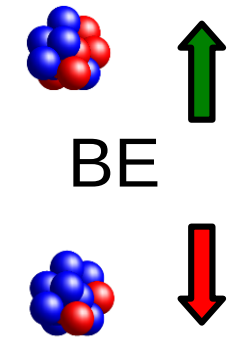
More surface



More protons



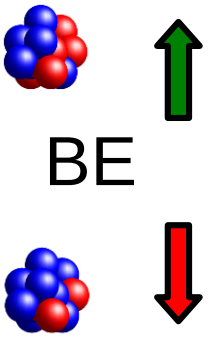
More asymmetry



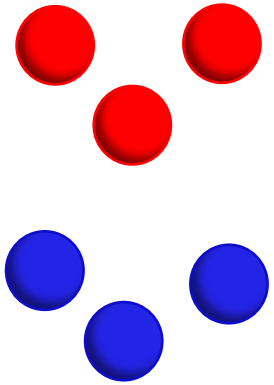
Binding energy (Asymmetry parenthesis)

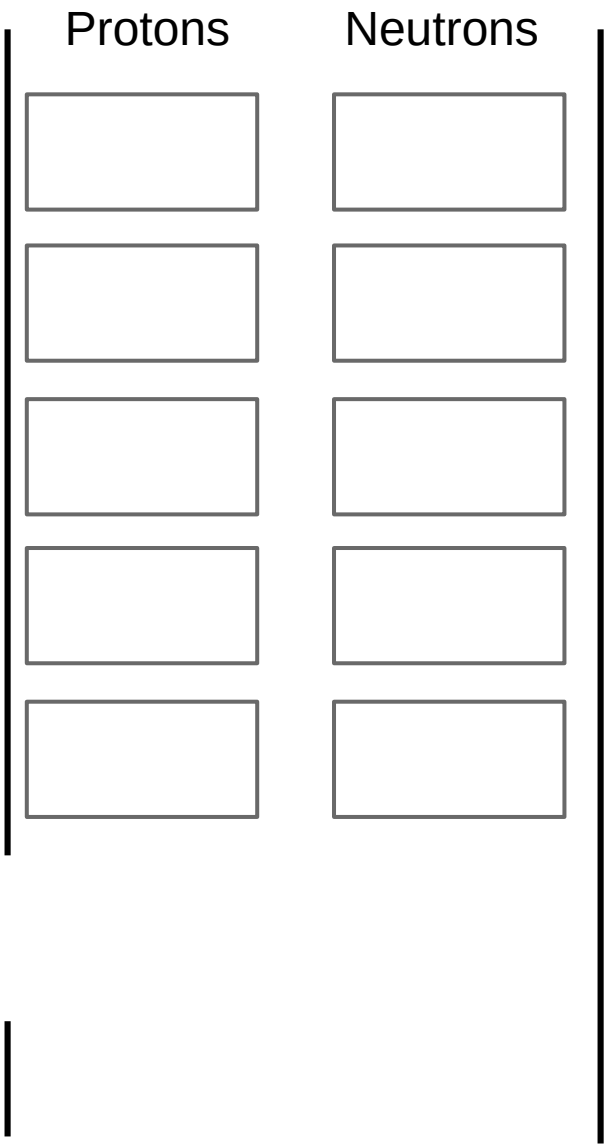
Protons	Neutrons	
		120 $
		50 $
		25 $
		15 $
		10 $

More asymmetry



Binding energy (Asymmetry parenthesis)





120 $

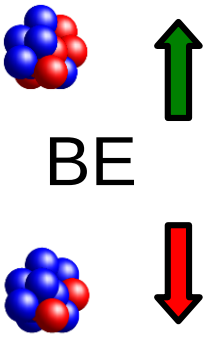
50 $

25 $

15 $

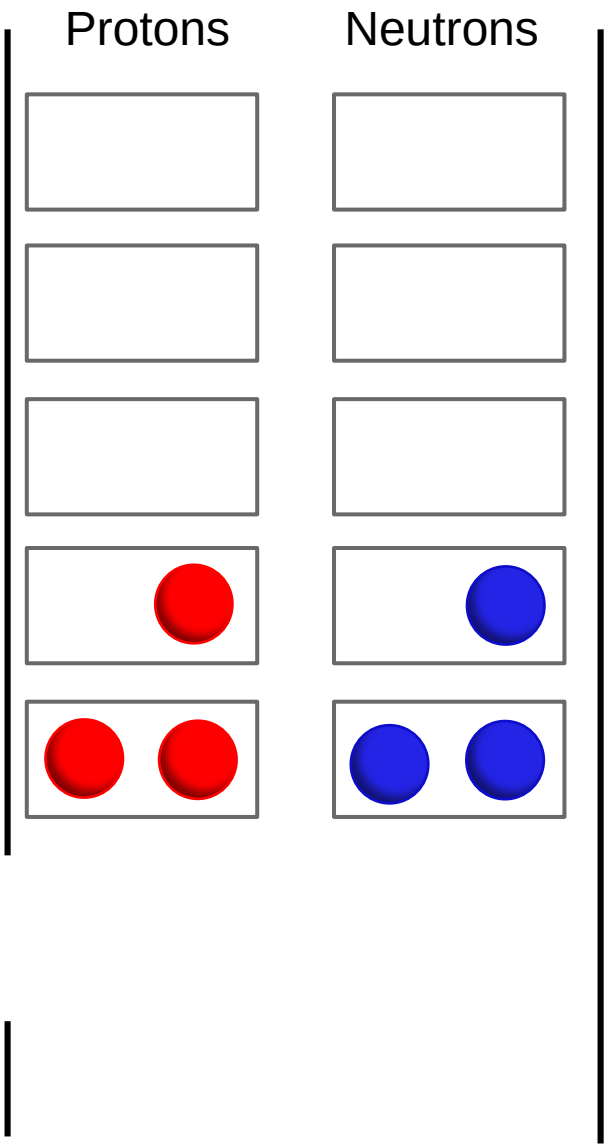
10 $

More asymmetry



BE

Binding energy (Asymmetry parenthesis)



120 $

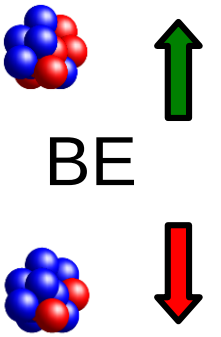
50 $

25 $

15 $

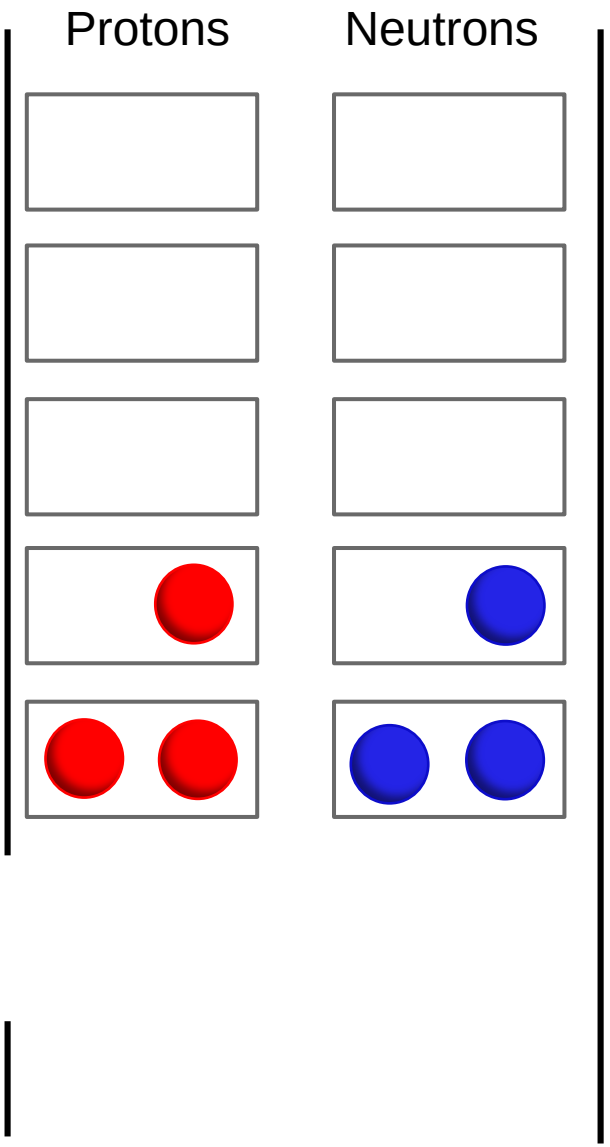
10 $

More asymmetry



BE

Binding energy (Asymmetry parenthesis)



120 $

50 $

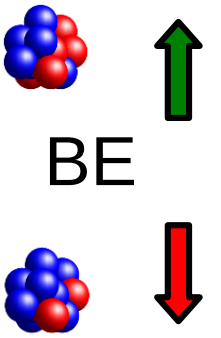
25 $

15 $

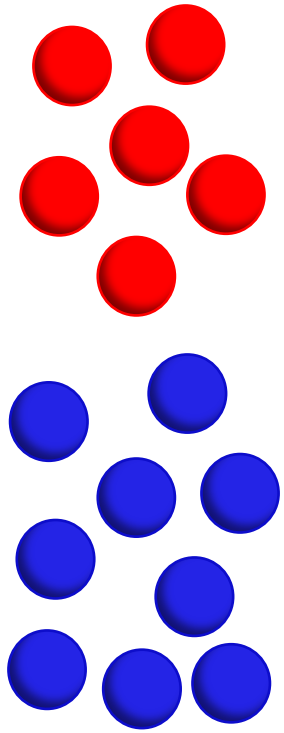
10 $

Total = 70 $

More asymmetry

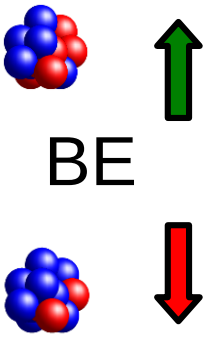


Binding energy (Asymmetry parenthesis)

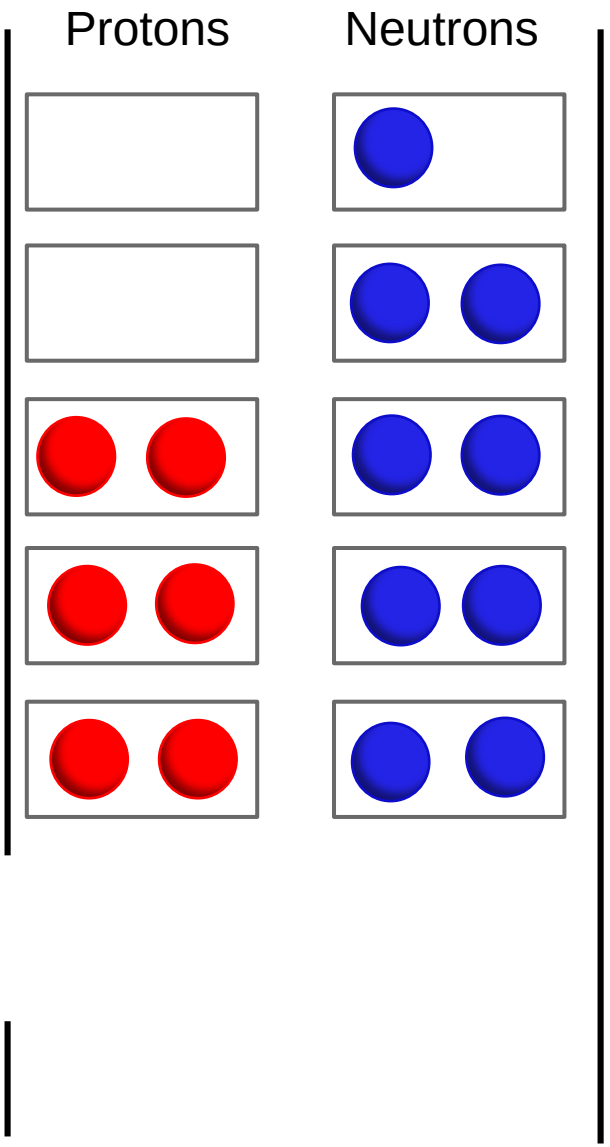


Protons	Neutrons	
		120 $
		50 $
		25 $
		15 $
		10 $

More asymmetry



Binding energy (Asymmetry parenthesis)



120 $

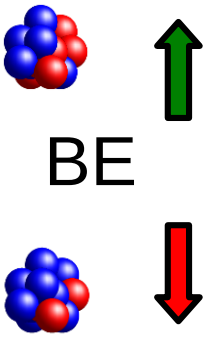
50 $

25 $

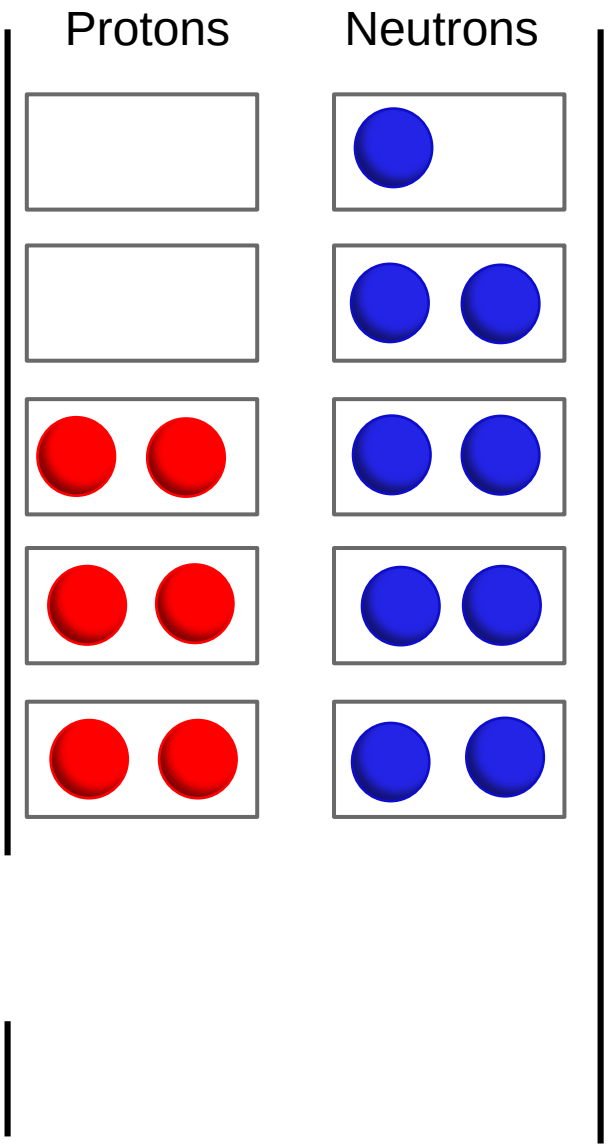
15 $

10 $

More asymmetry



Binding energy (Asymmetry parenthesis)



120 $

50 $

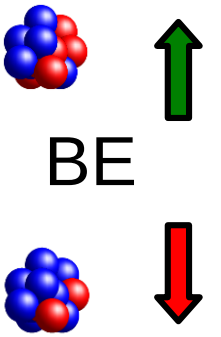
25 $

15 $

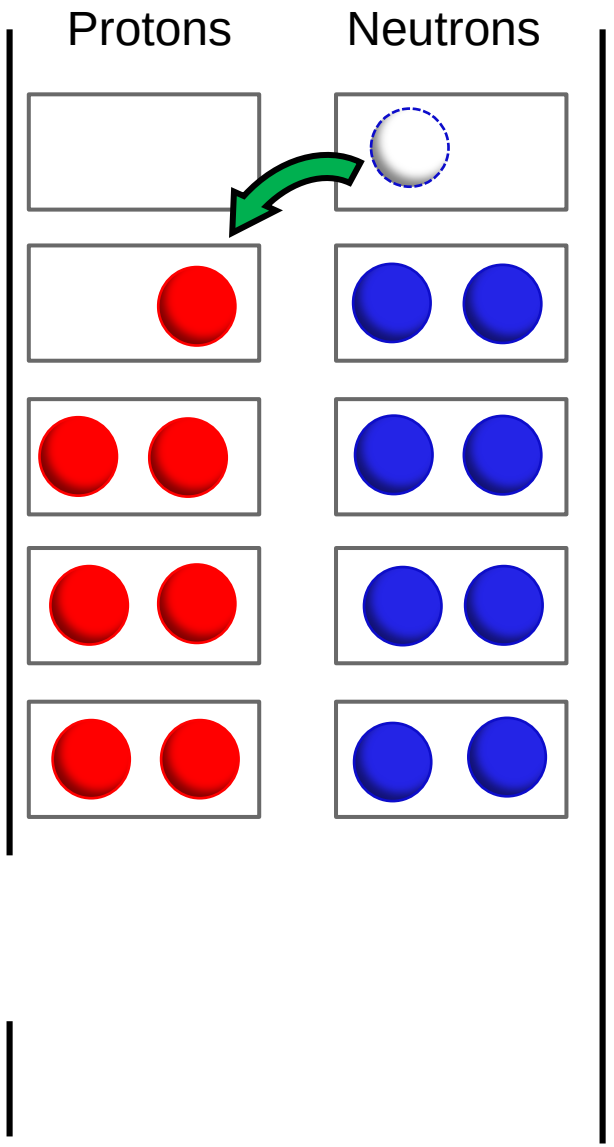
10 $

Total = 420 $

More asymmetry



Binding energy (Asymmetry parenthesis)



120 $

50 $

25 $

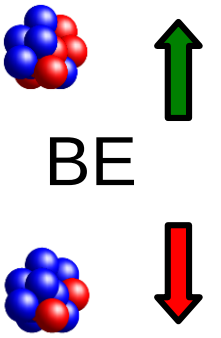
15 $

10 $

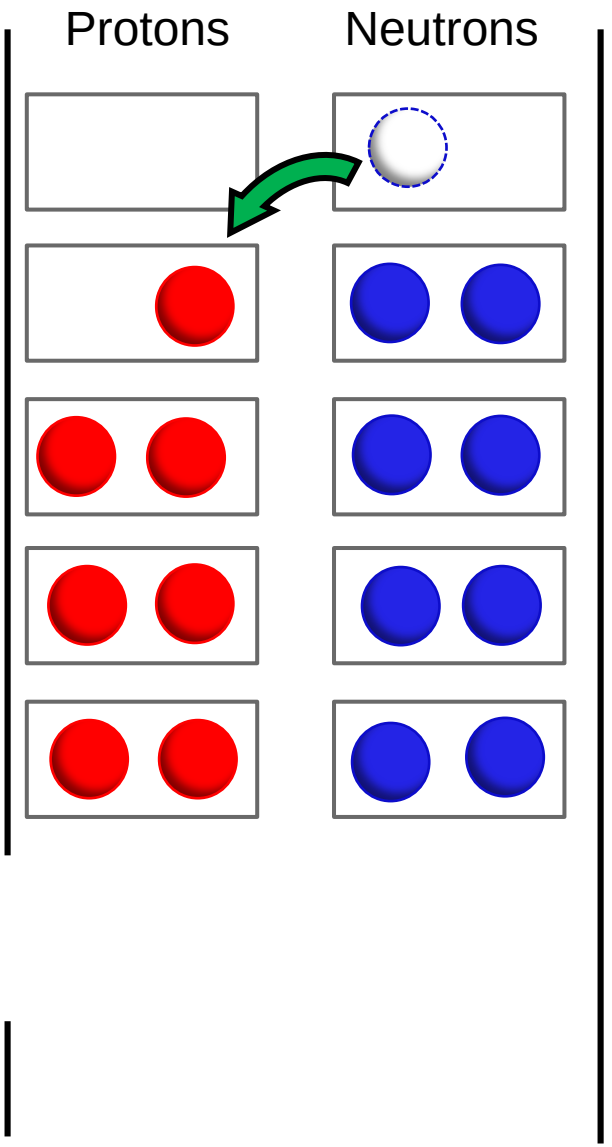
More asymmetry

Total = 420 $

Total = 350 $



Binding energy (Asymmetry parenthesis)



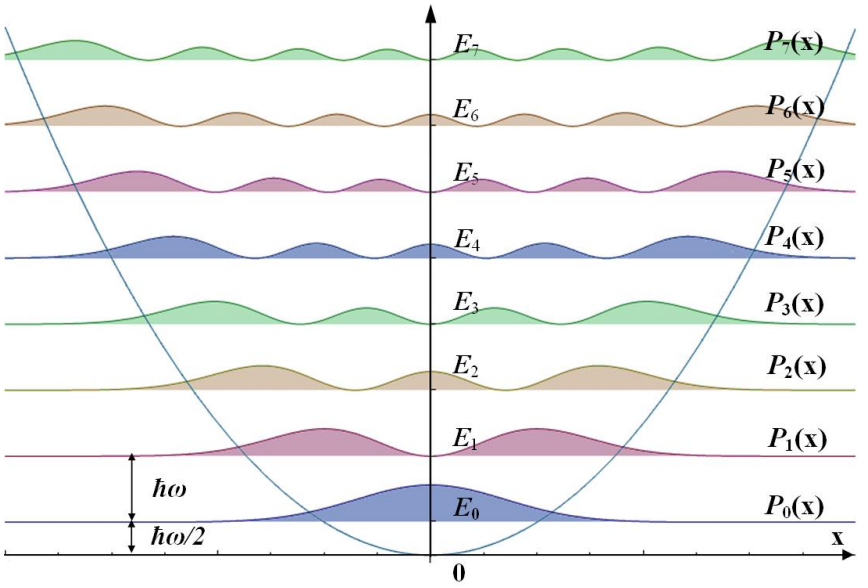
120 $

50 $

25 $

15 $

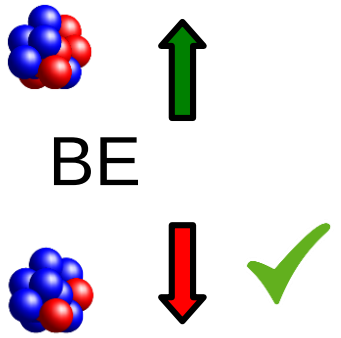
10 $



More asymmetry

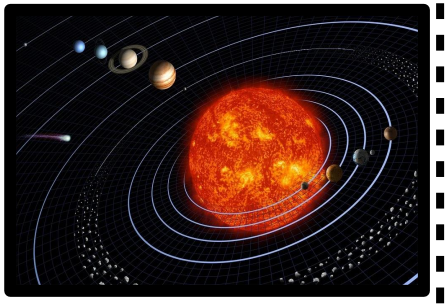
~~Total = 420 $~~

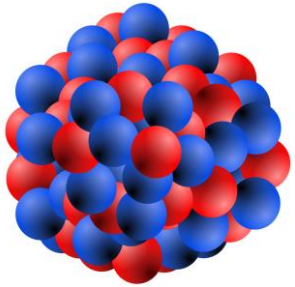
Total = 350 $



Binding energy

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

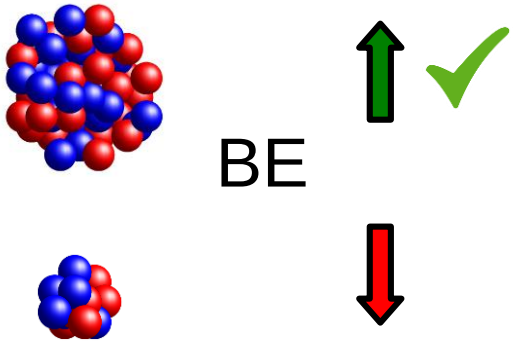




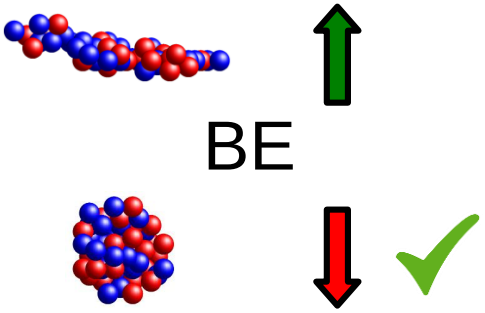
Liquid drop model

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

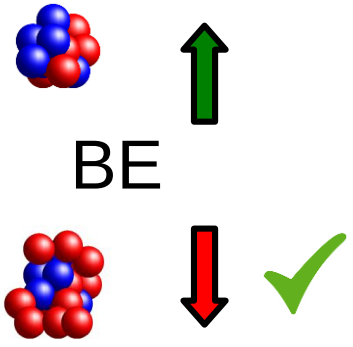
More nucleons



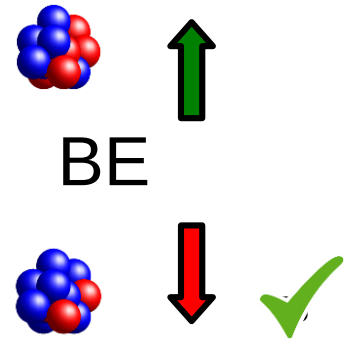
More surface



More protons

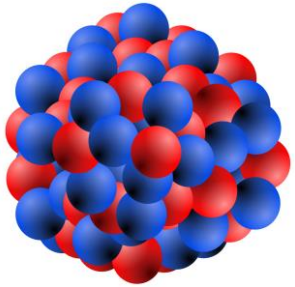


More asymmetry

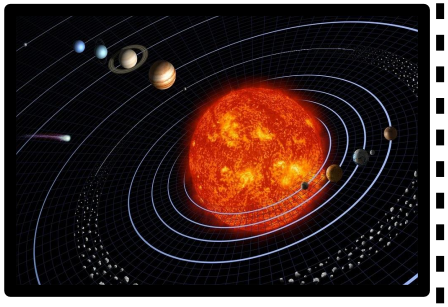


Binding energy

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



Liquid drop model



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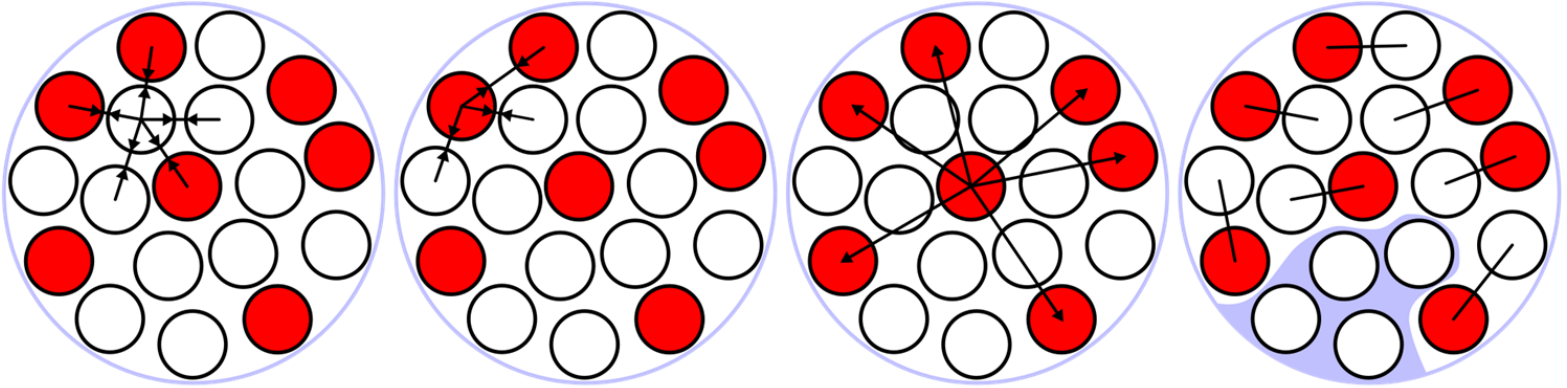
More nucleons

More surface

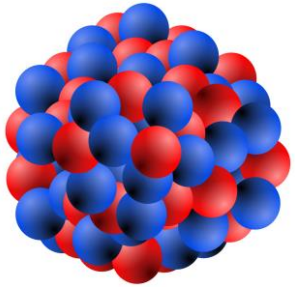
More protons

More asymmetry



https://en.wikipedia.org/wiki/Semi-empirical_mass_formula

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]
```

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

More nucleons

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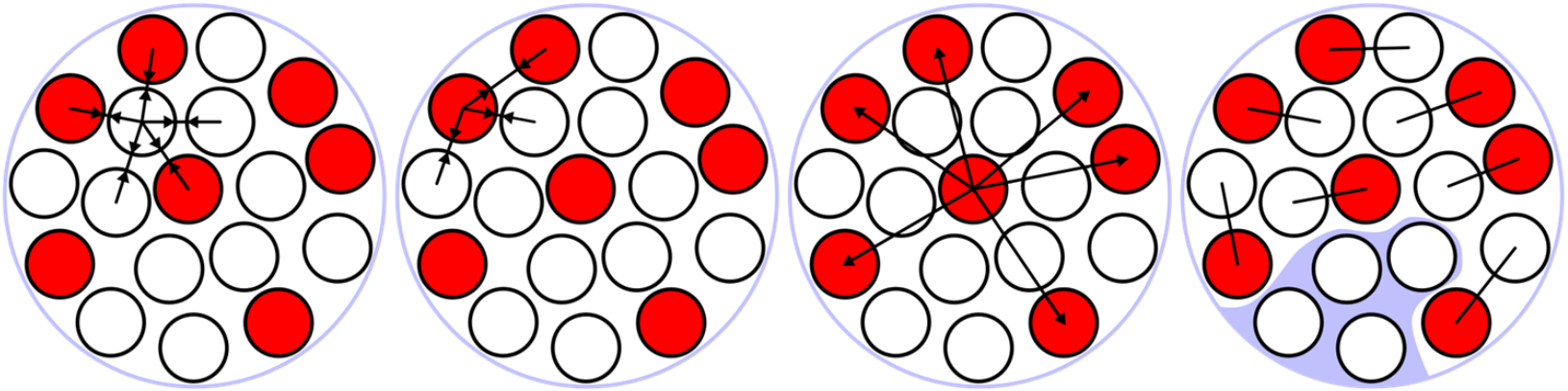
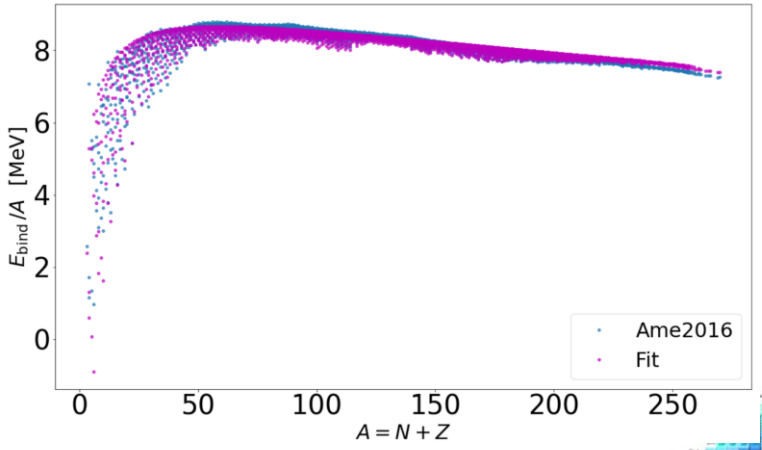


Binding energy



Protons

Neutrons

Binding Energy per Nucleon [MeV]

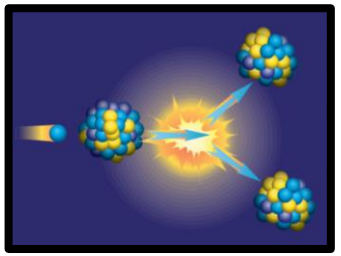
7.5 8.2 8.8

The colorful chart of nuclei

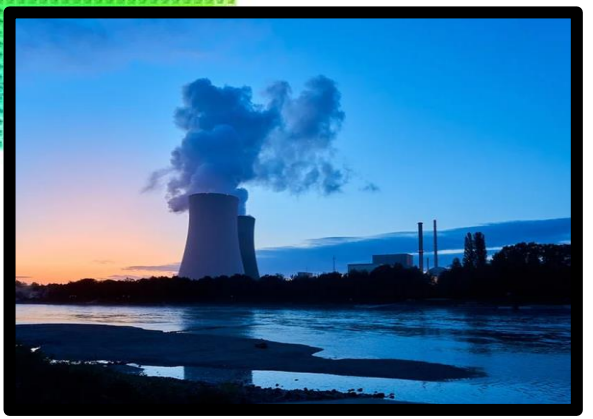
Binding energy

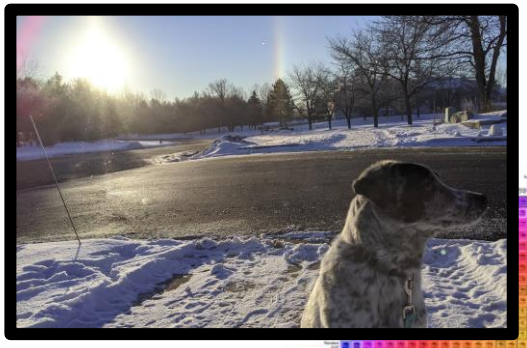
[3D Chart!]

Binding energy



Fission

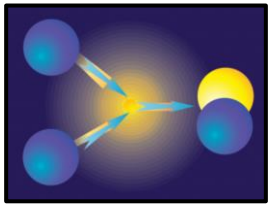




Protons

Binding Energy per Nucleon [MeV]

7.5 8.2 8.8

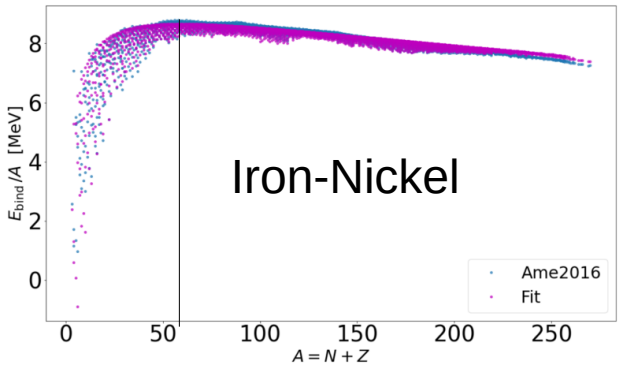


Fusion

Neutrons

The colorful chart of nuclei

Binding energy



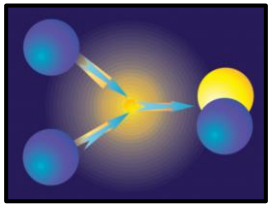
Protons

Nucleosynthesis

Fusion

Binding Energy per Nucleon [MeV]

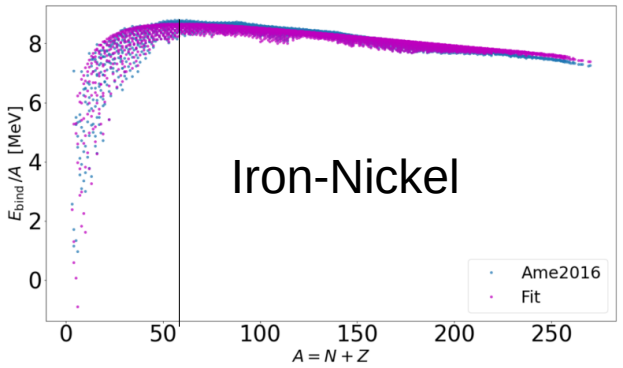
7.5 8.2 8.8



Neutrons

The colorful chart of nuclei

Binding energy



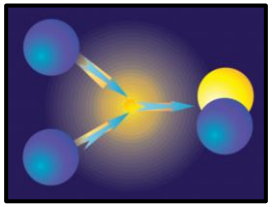
?

Protons

Nucleosynthesis

Fusion

Binding Energy per Nucleon [MeV]
7.5 8.2 8.8

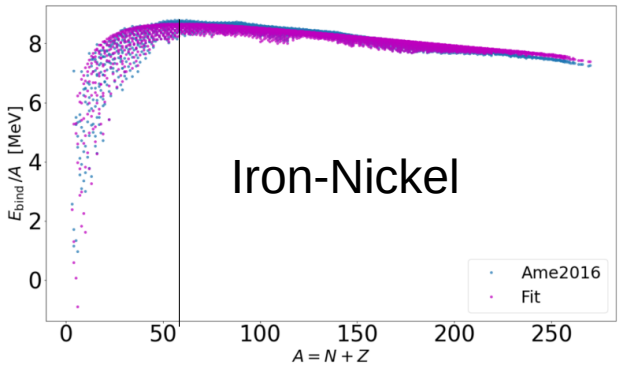


Neutrons

The colorful chart of nuclei

Binding energy

Where do heavy elements come from?

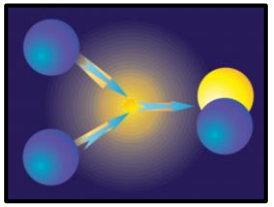


?

Protons

Nucleosynthesis

Fusion



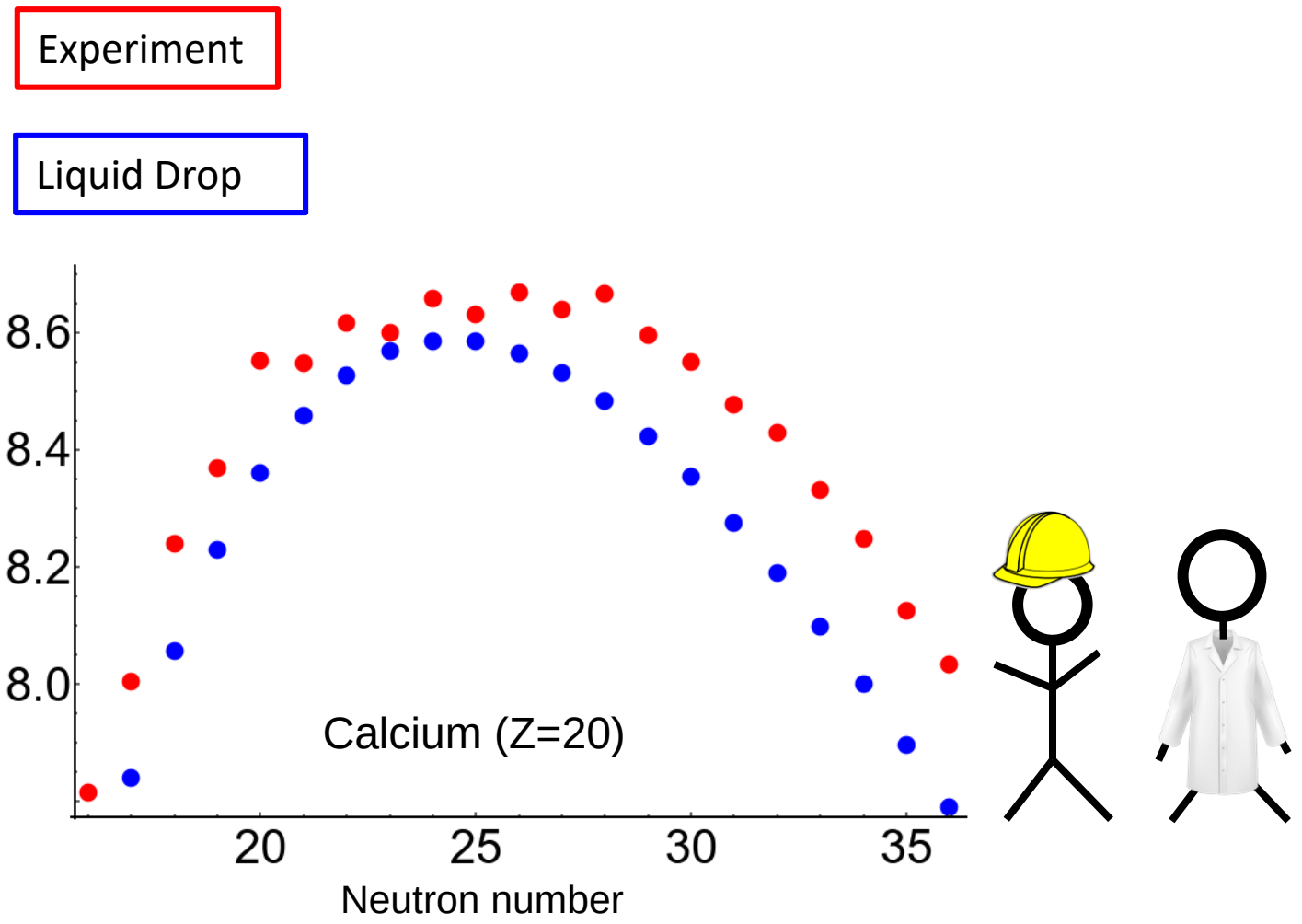
Binding Energy per Nucleon [MeV]
7.5 8.2 8.8

Neutrons

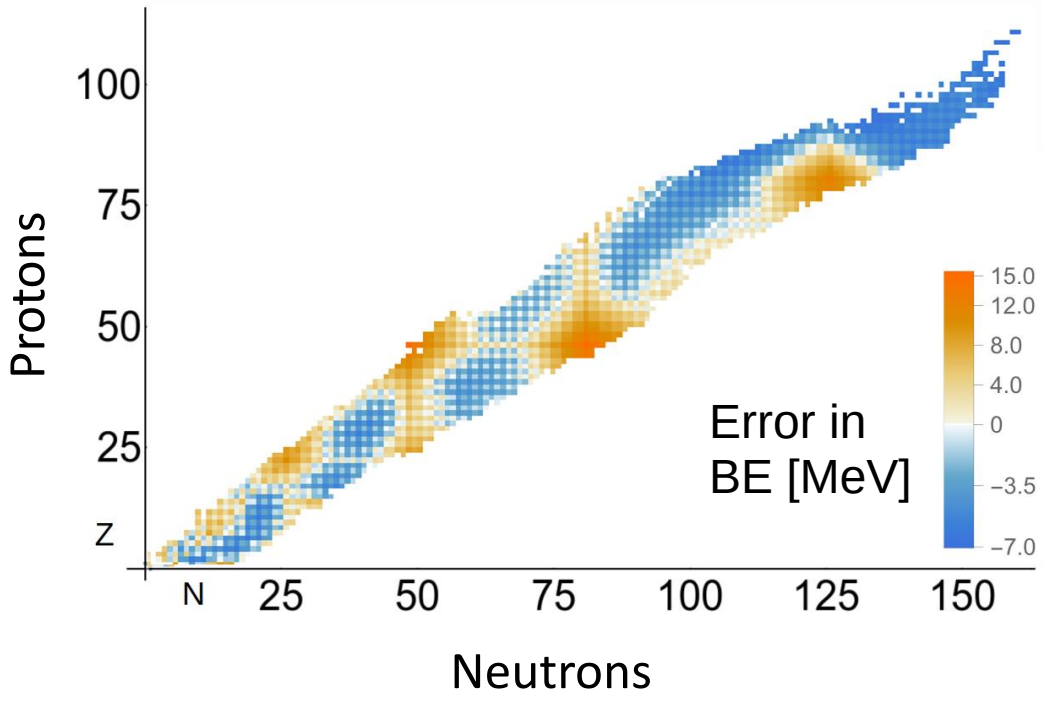
The colorful chart of nuclei

FRIB

Binding energy

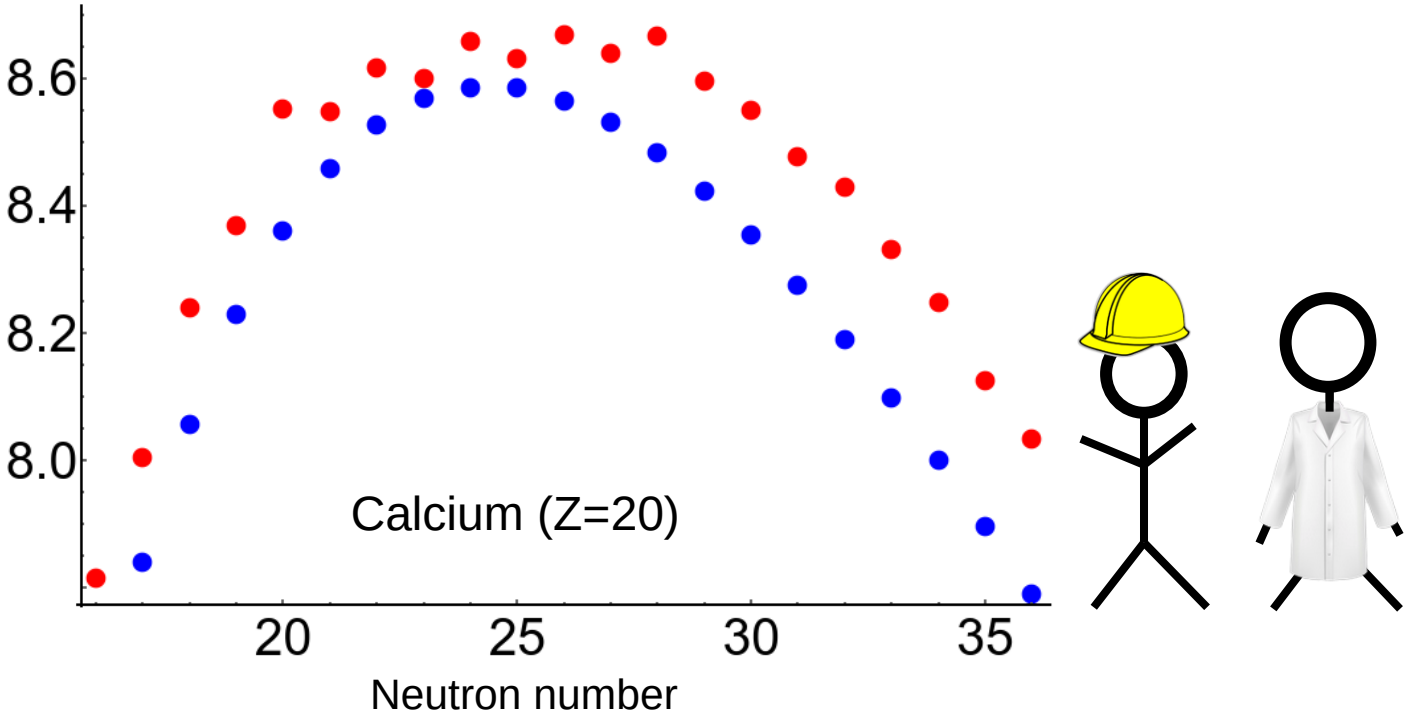


Binding energy

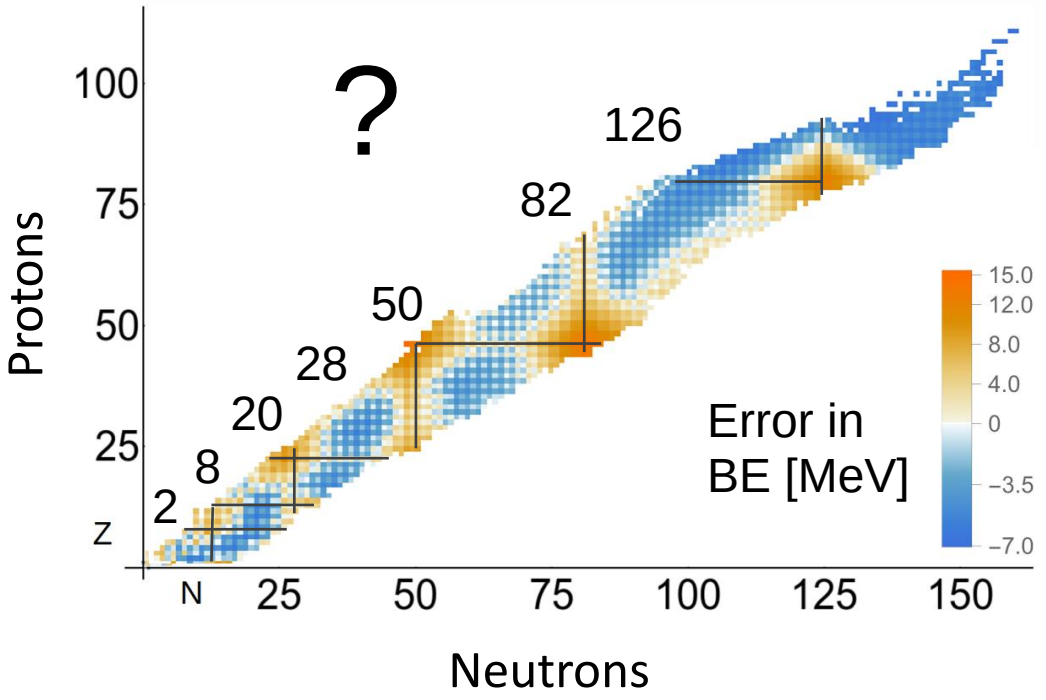


Experiment

Liquid Drop

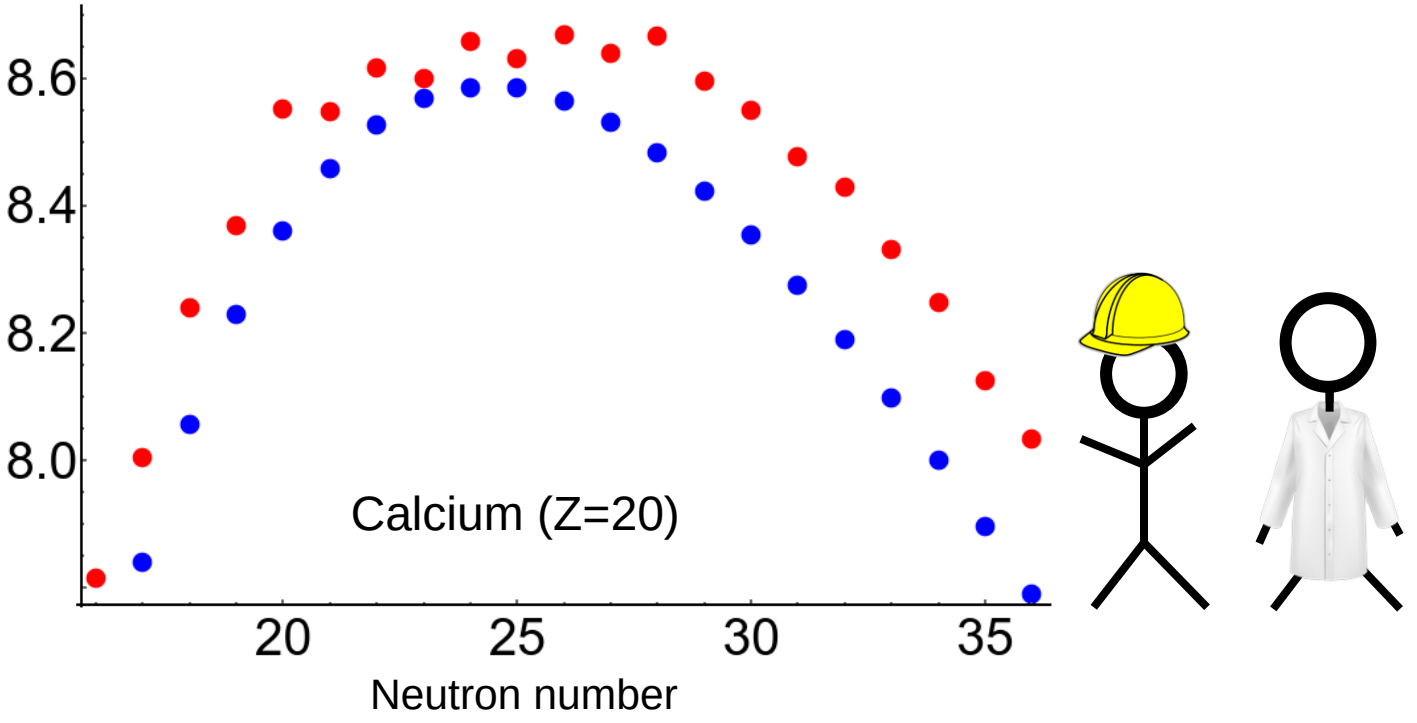


Binding energy

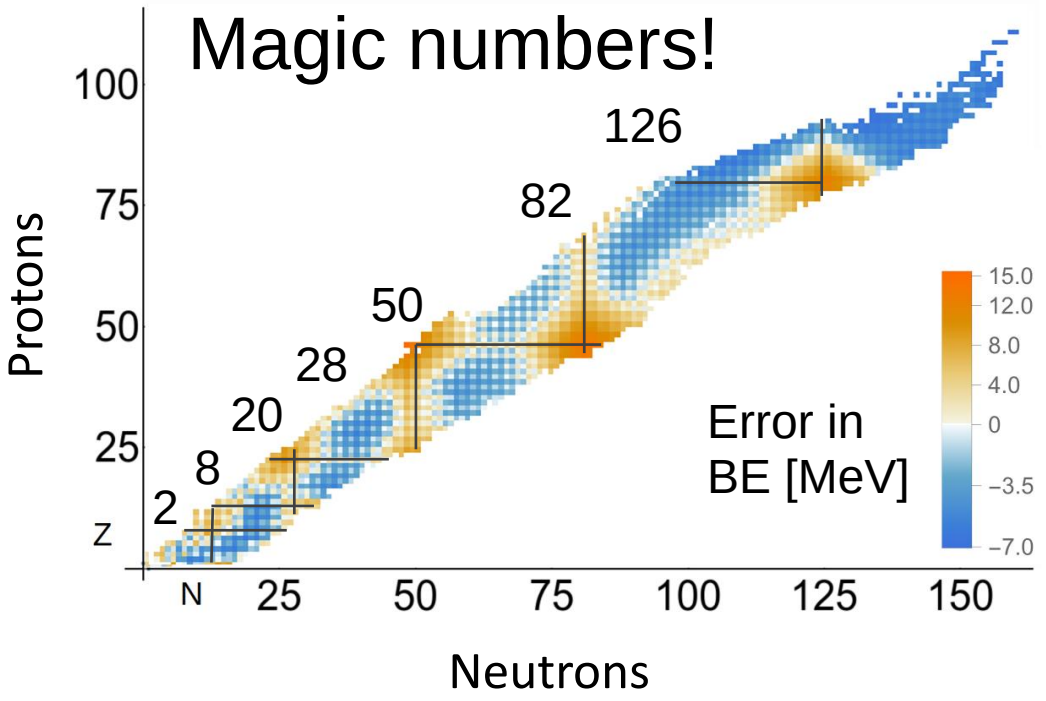


Experiment

Liquid Drop

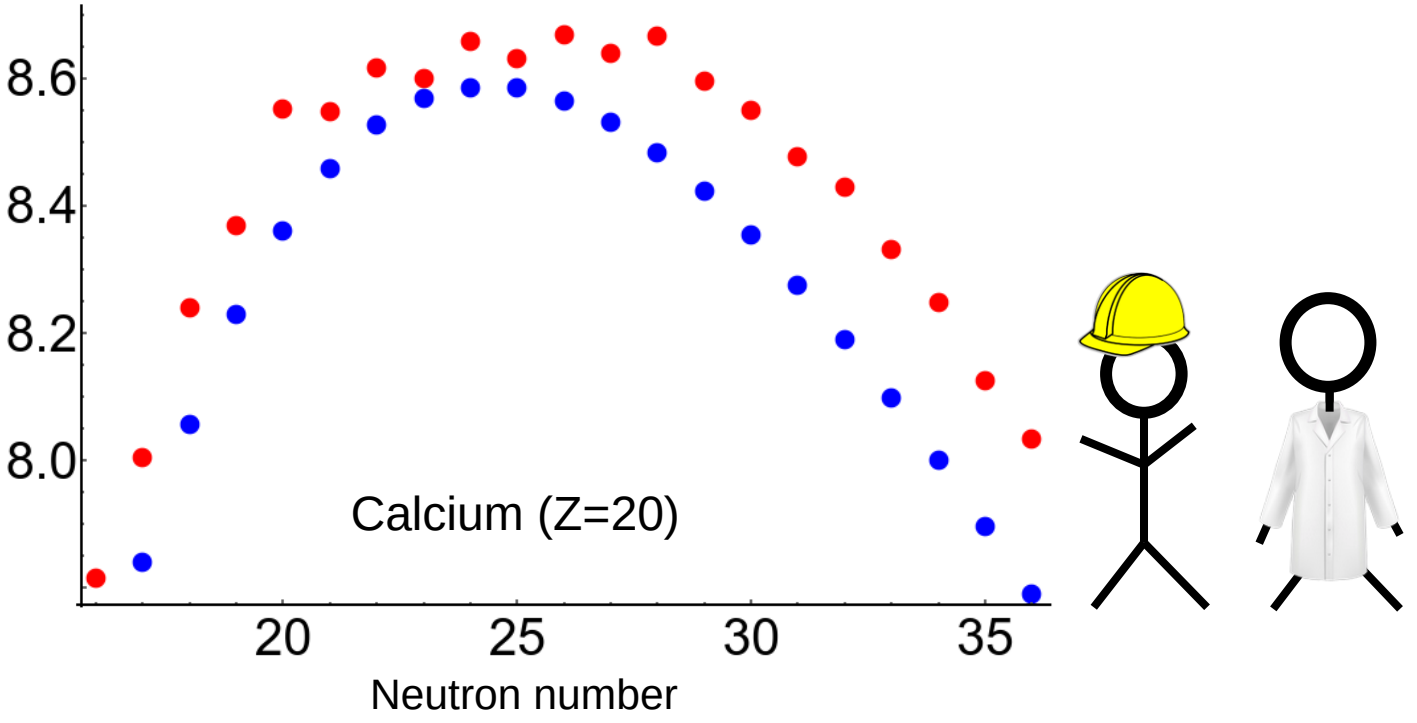


Binding energy



Experiment

Liquid Drop



For today

Who am I?

Why theory?

Building models

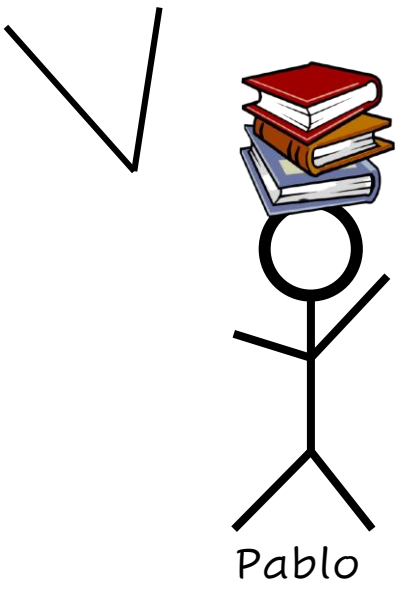
Building a (simple) nuclear model

Quantum mechanics

Building (better) nuclear models

Challenges (Hands-On Session)

Questions?



Quantum mechanics

“I think I can safely say that nobody understands quantum mechanics.”

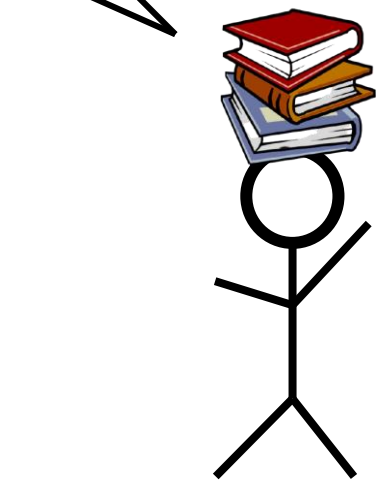
Richard Feynman

Quantum mechanics

“I think I can safely say that nobody understands quantum mechanics.”

Richard Feynman

two things we need today



Quantum mechanics

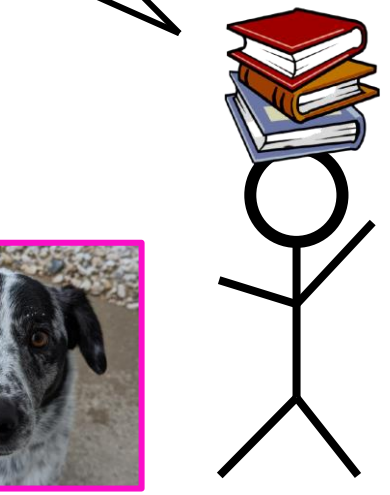
1) Everything comes in "quanta"

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"

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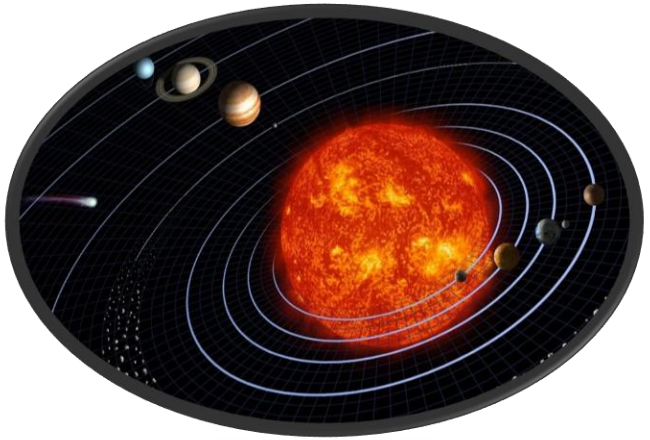
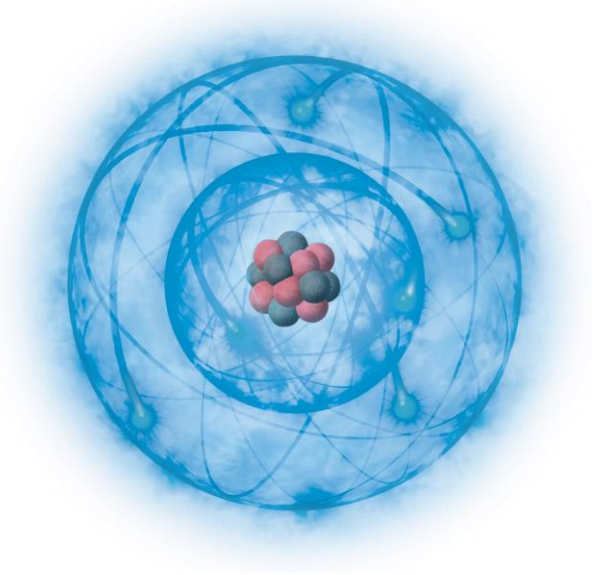


VS



Quantum mechanics

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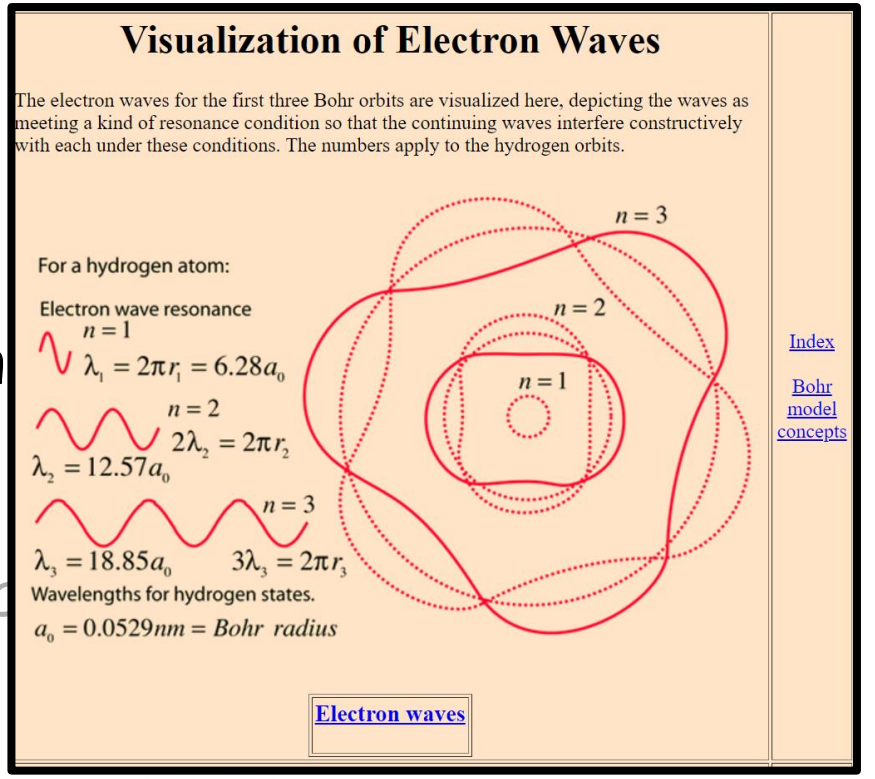
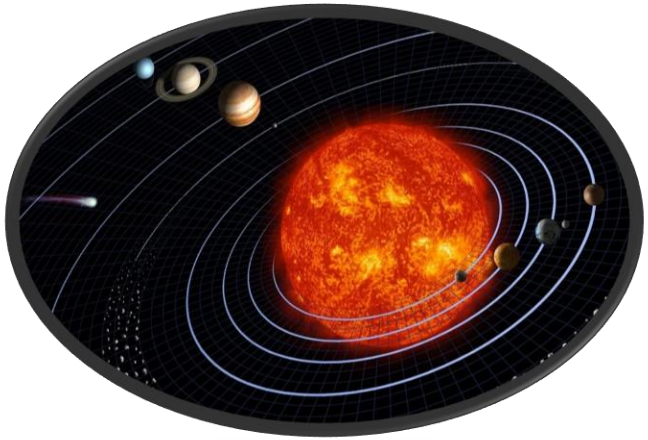
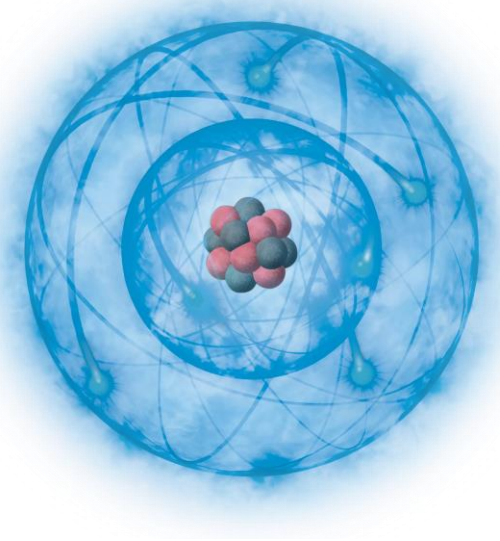


http://hyperphysics.phy-astr.gsu.edu/hbase/ewav.html



VS



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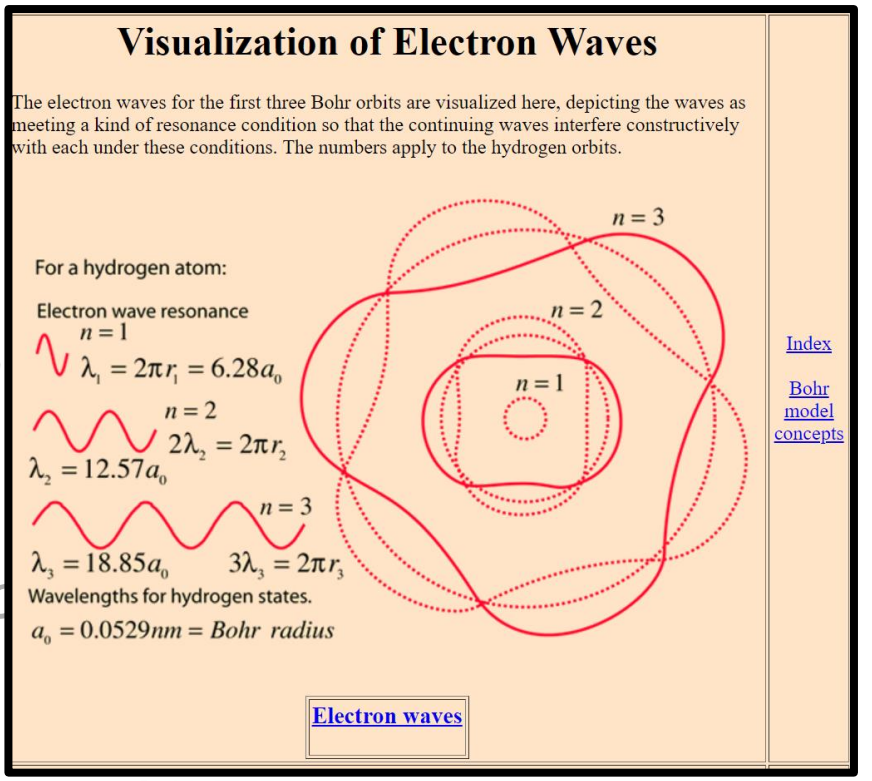
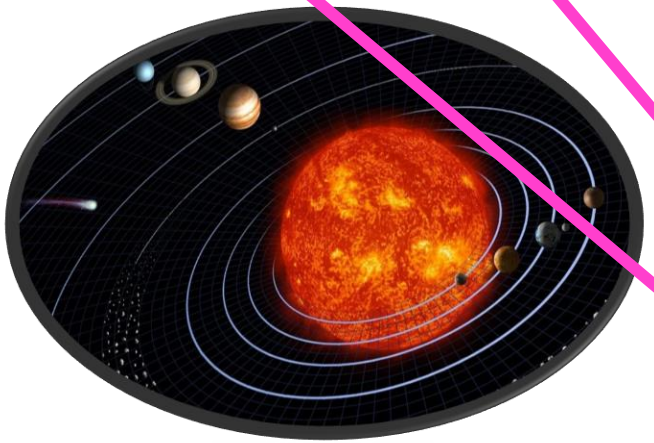
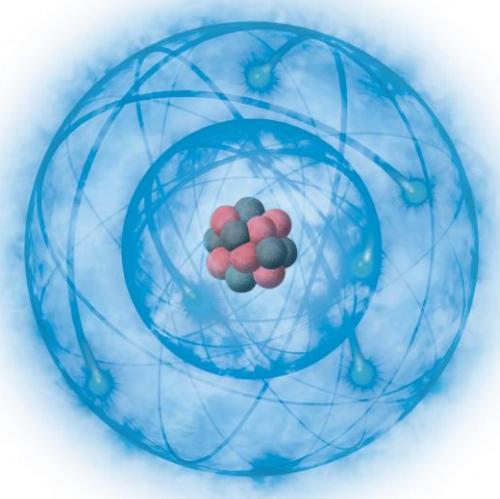


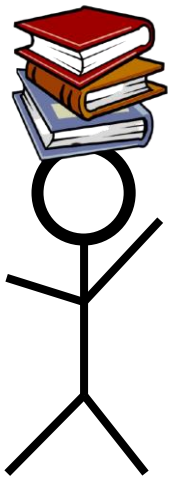
http://hyperphysics.phy-astr.gsu.edu/hbase/ewav.html



vs

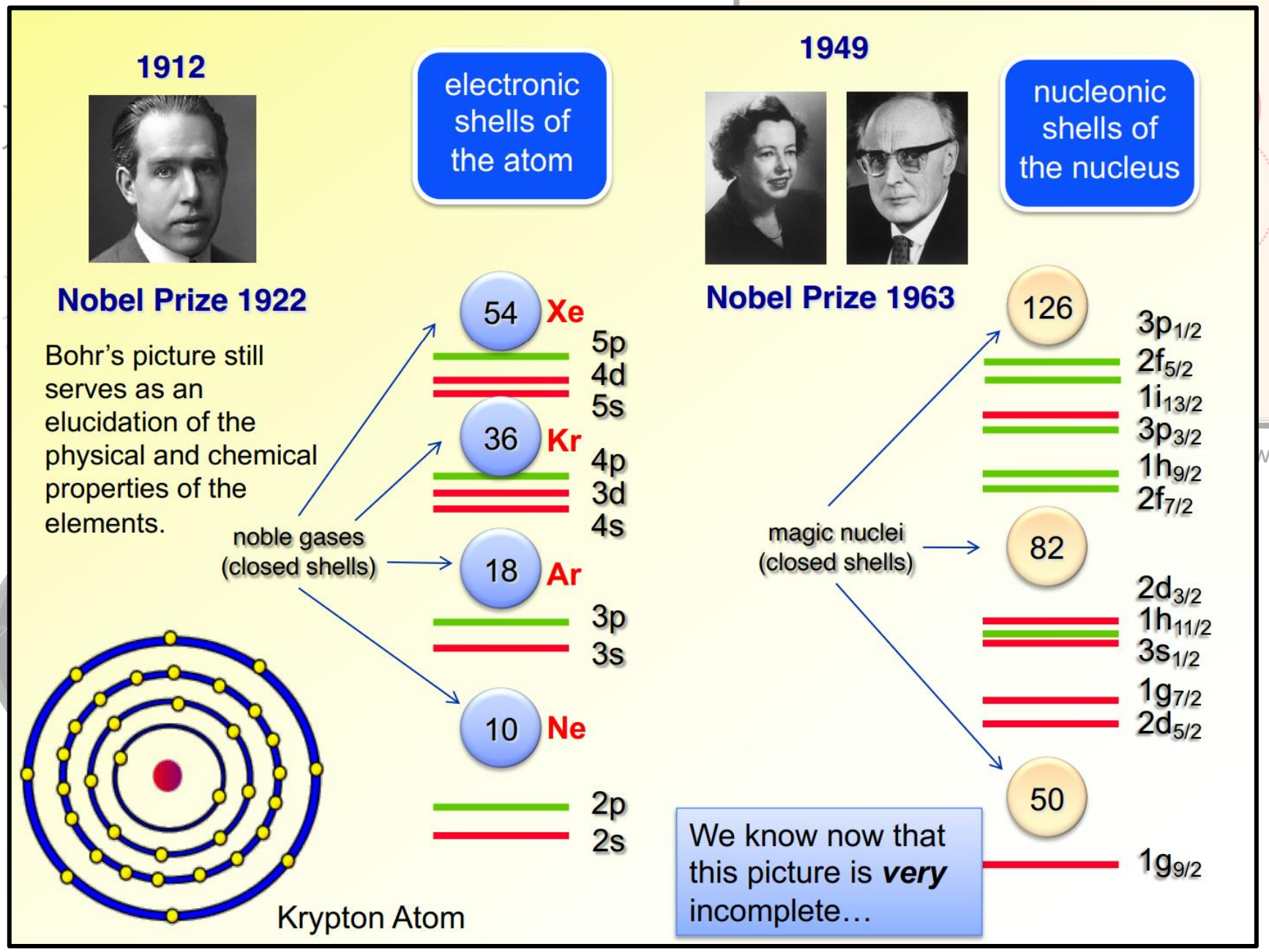


Pablo: don't forget the rope



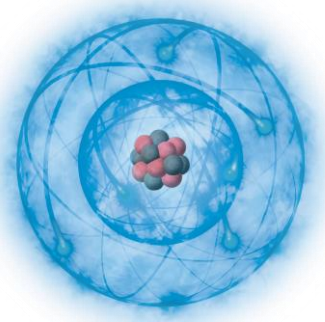
Thanks Tibor for the rope!!

Quantum mechanics



Slide made by Witek Nazarewicz

Quantum mechanics



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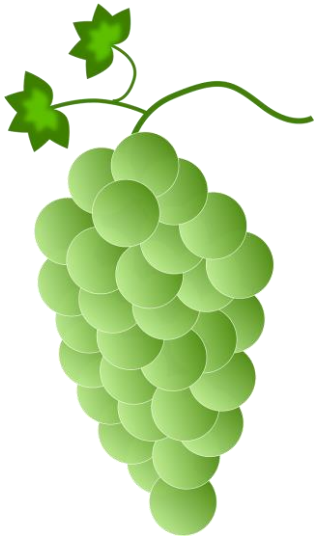
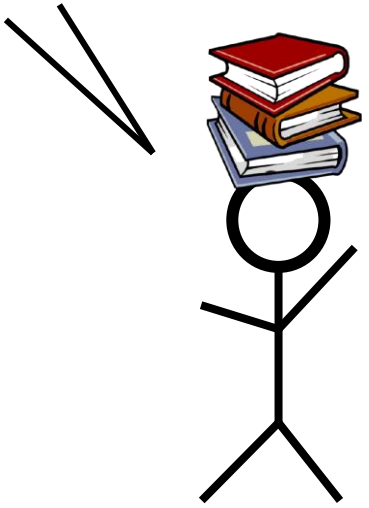


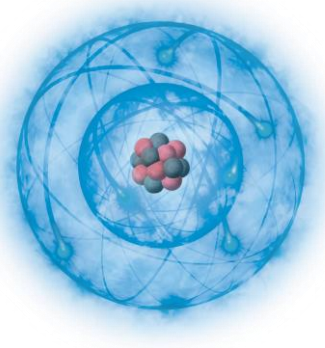
Not-nucleus

Nuclei looks more like an onion than like grapes

Nucleus



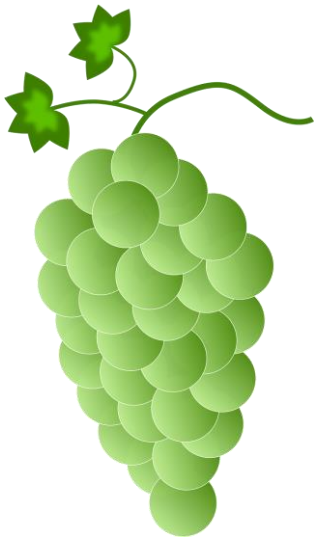
Quantum mechanics



1) Everything comes in "quanta"

2) Schrodinger equation* describes the dynamics of the system

Nuclei are like ogres



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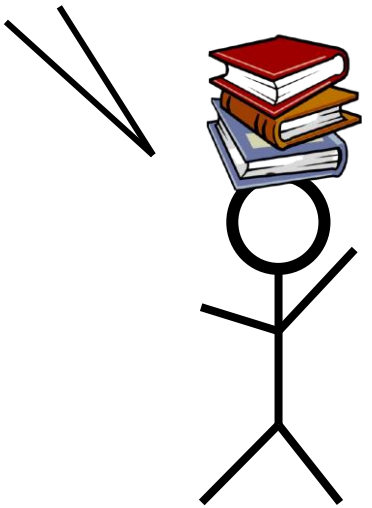
Nucleus



Quantum mechanics

1) Everything comes in "quanta"

2) Schrodinger equation* describes the dynamics of the system

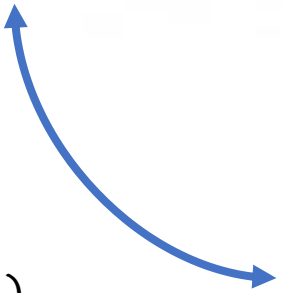
$$\mathcal{H}|\psi(x,t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(x,t)\rangle$$

Quantum mechanics

1) Everything comes in "quanta"

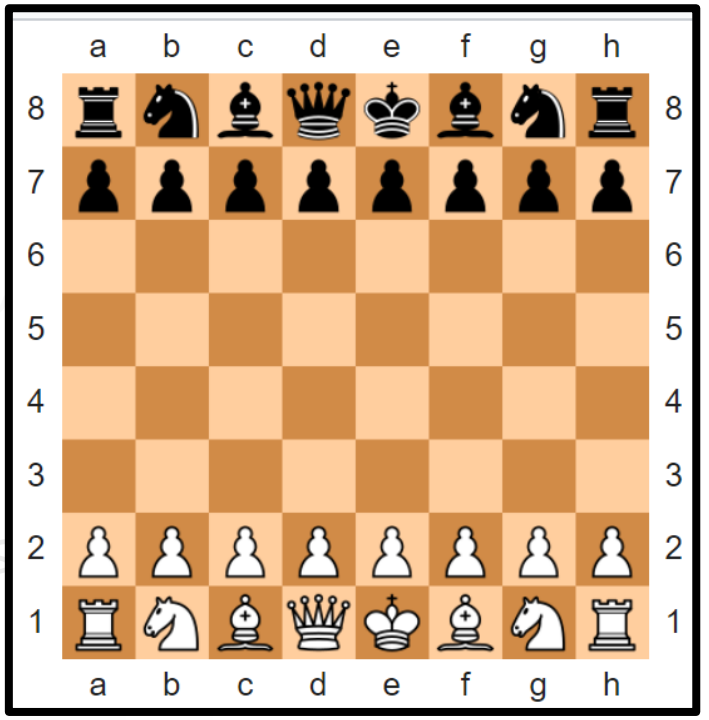
2) Schrodinger equation* describes the dynamics of the system

(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



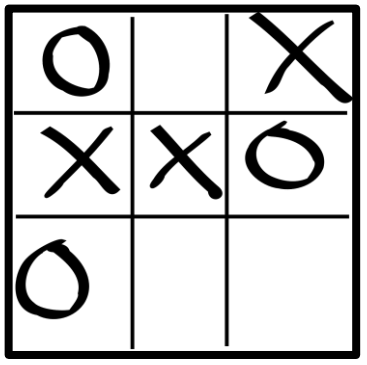
Chess

1) Everything comes in "quantum"

2) Schrodinger equation* describes dynamics of the system

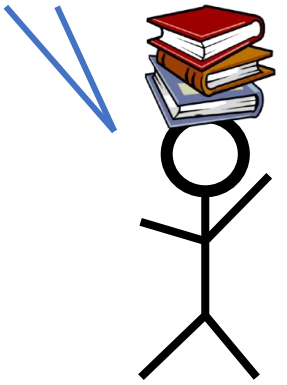
(quantum) $\mathcal{H}|\psi(x,t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(x,t)\rangle$

(classical) $\vec{F} = m\vec{a}$



Tic tac toe

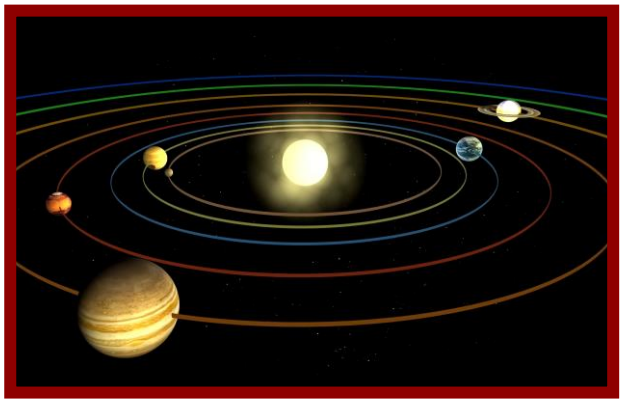
Think of it as the rules of the game



Quantum mechanics

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

Solar System Video - The Best Planet Video for Educational Purposes



1) Everything comes in "quantum"

2) Schrodinger equation* describes the dynamics of the system

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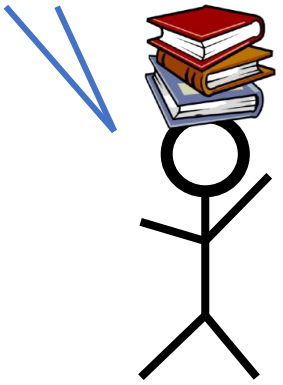

Quantum mechanics

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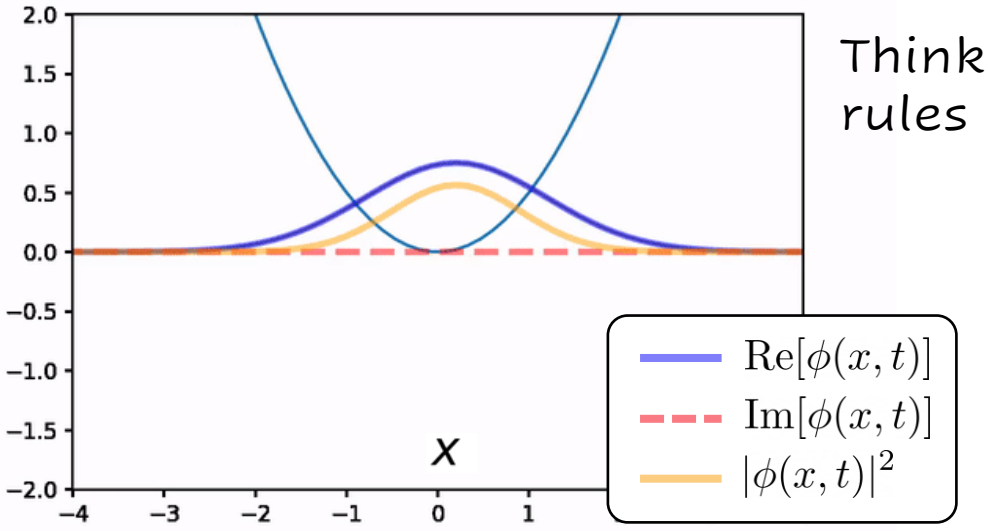
Harmonic Oscillator



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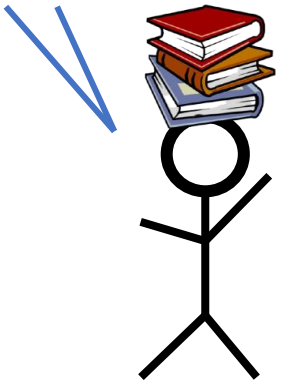
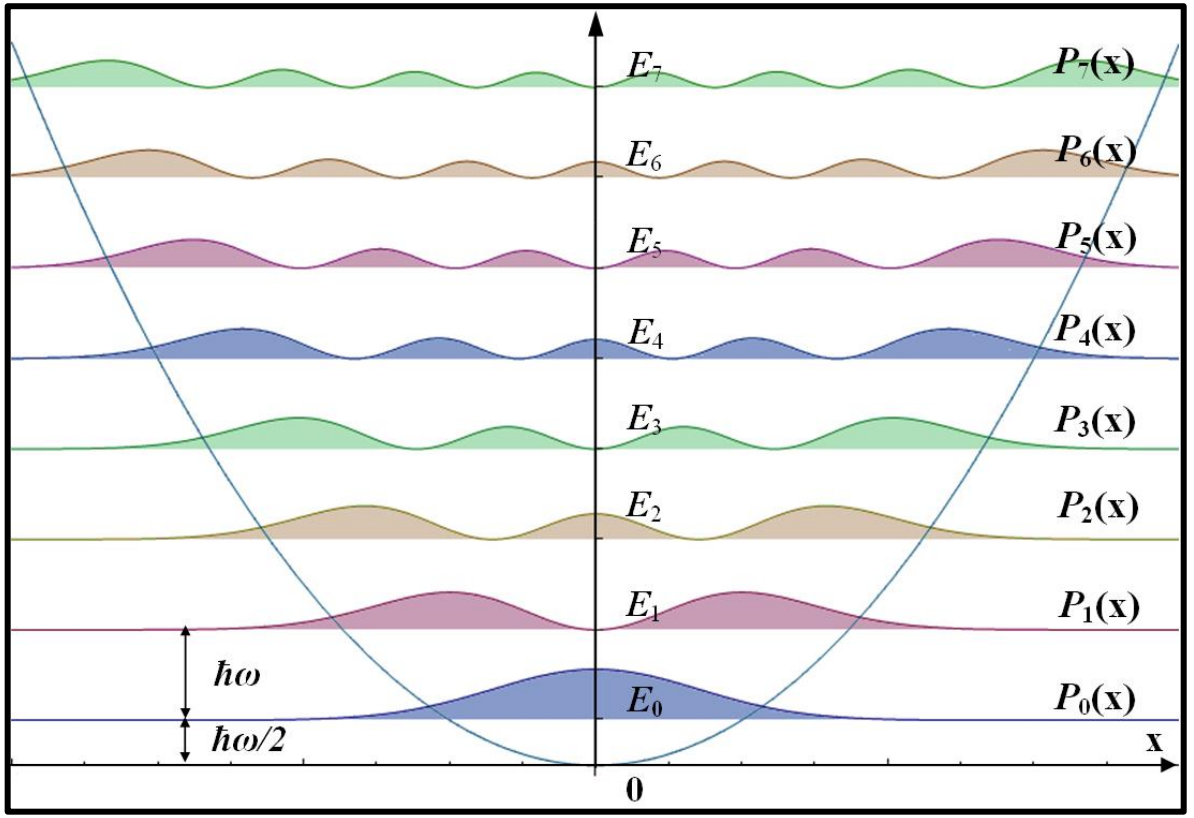


Quantum mechanics



Spectrum

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

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Harmonic Oscillator

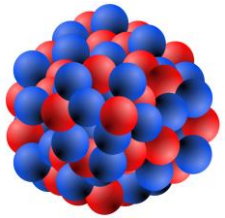
Time-independent

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

https://en.wikipedia.org/wiki/Quantum_harmonic_oscillator

Quantum mechanics

Can we model the nucleus with this?



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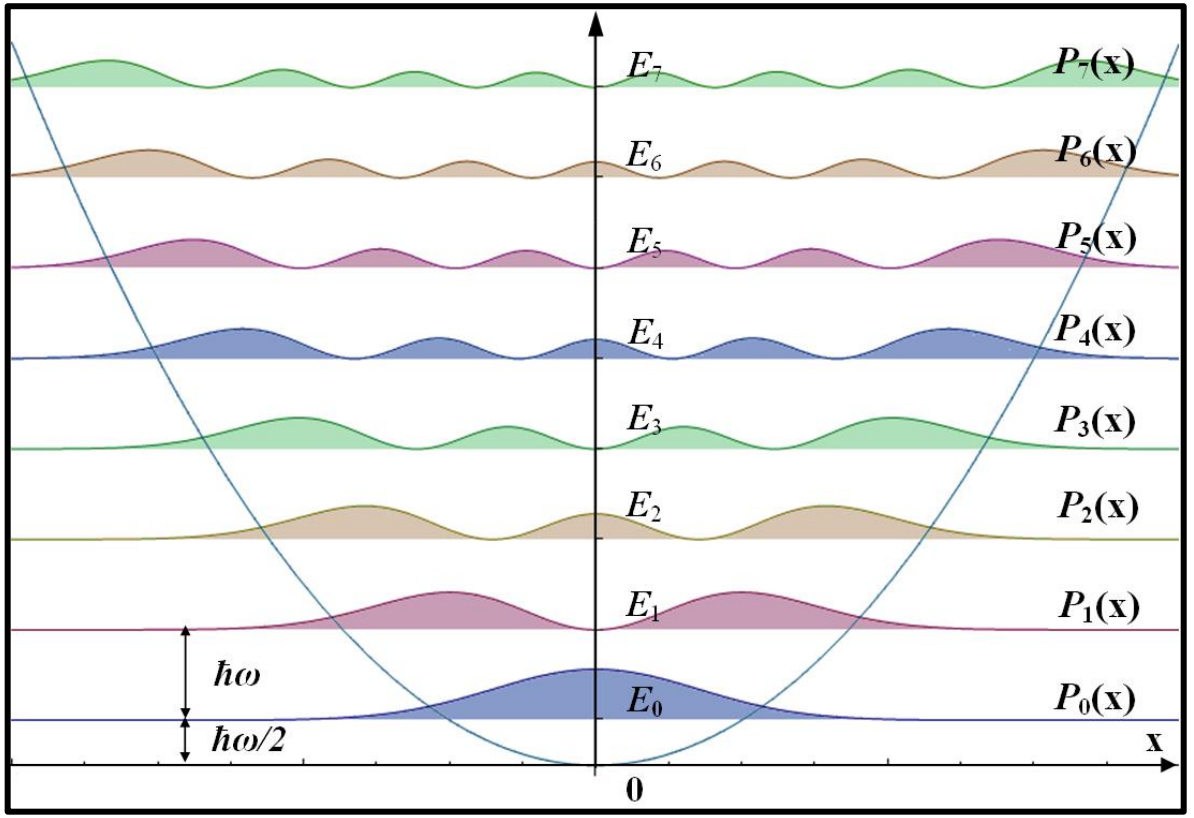

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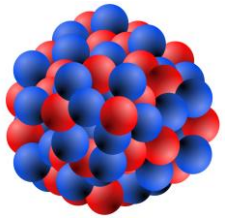

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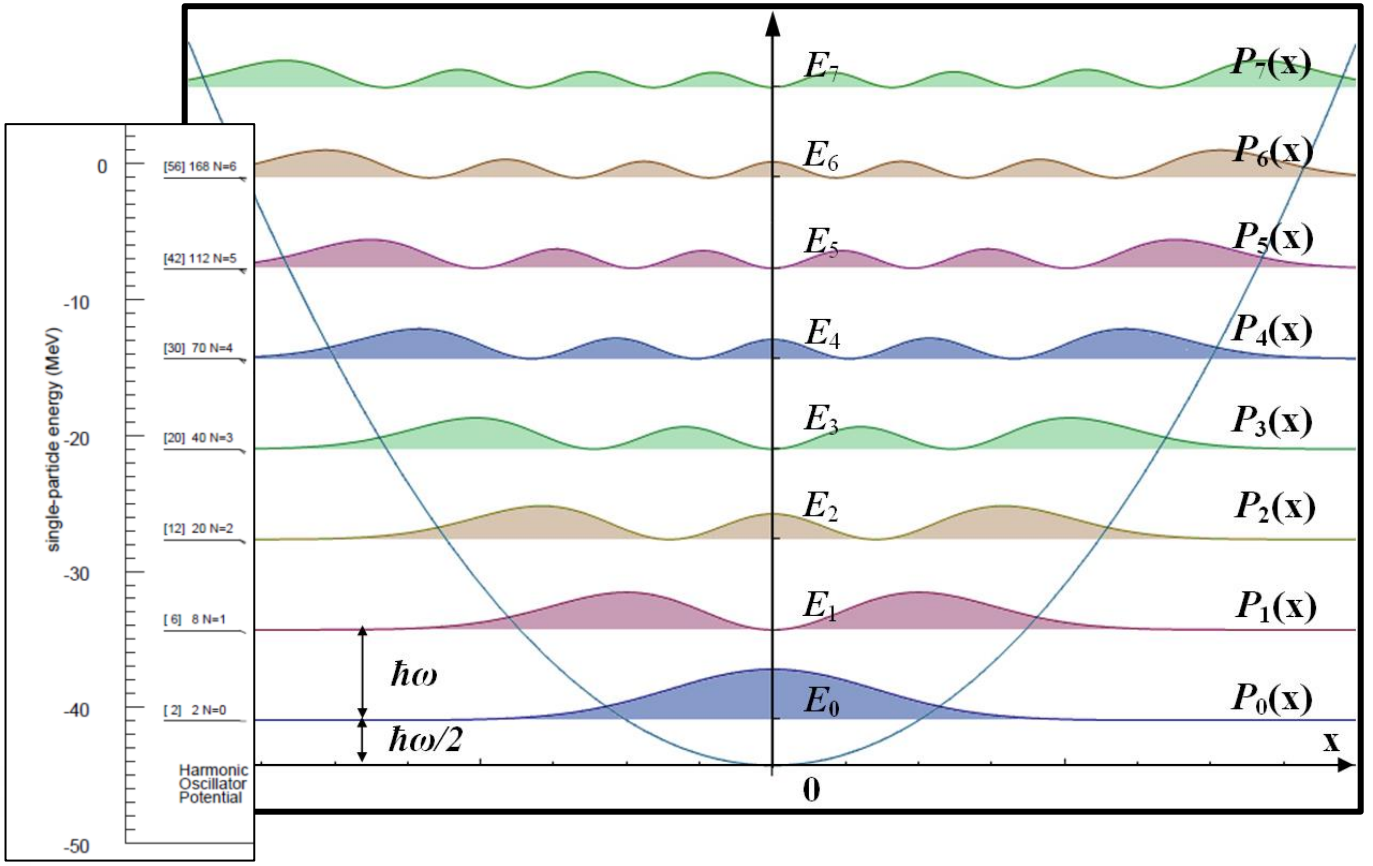

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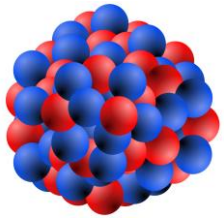

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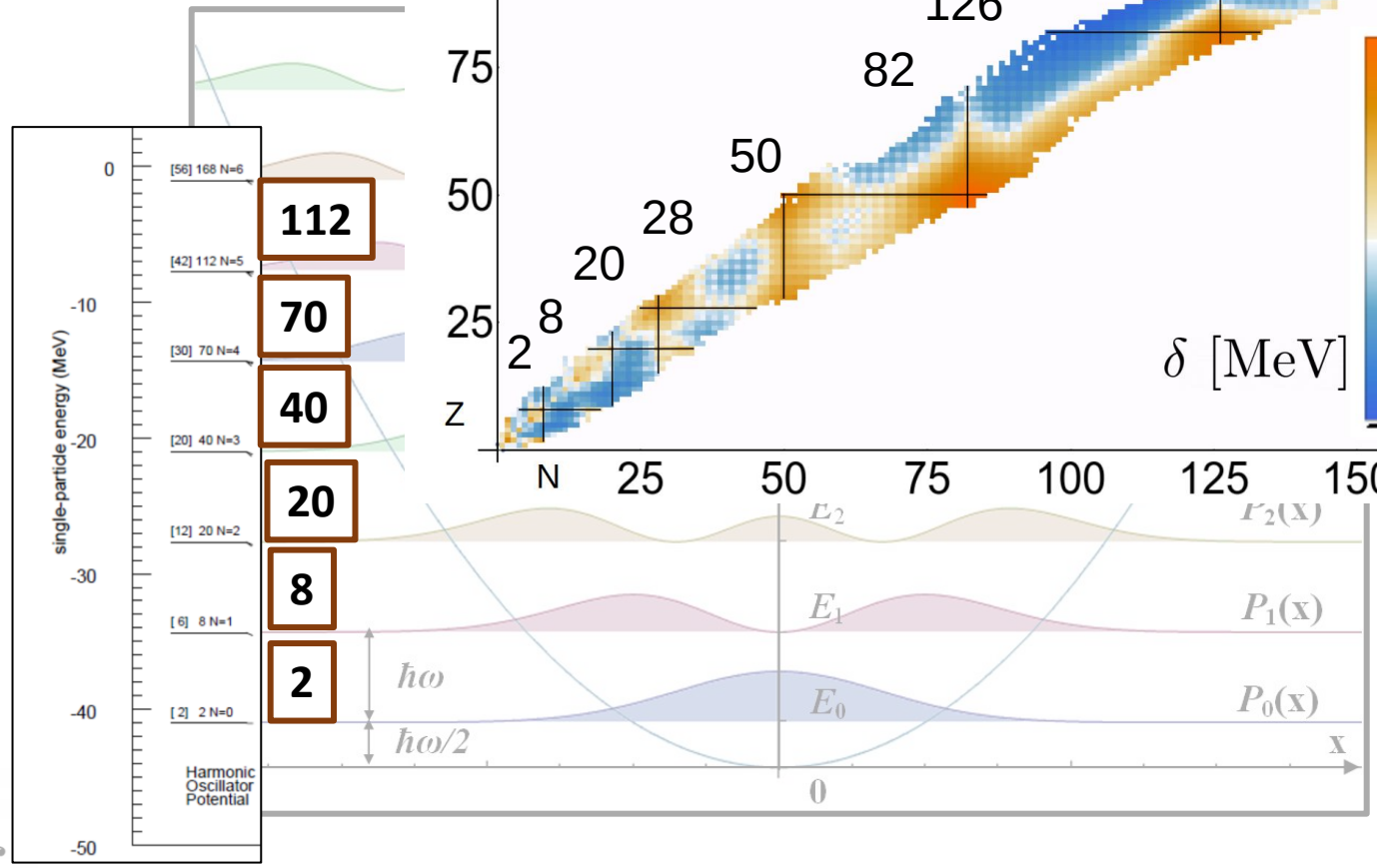

Magic numbers?

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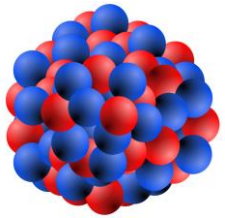

Not really...

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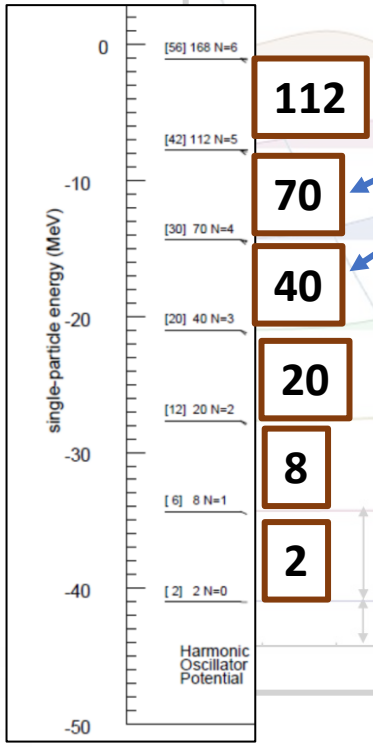

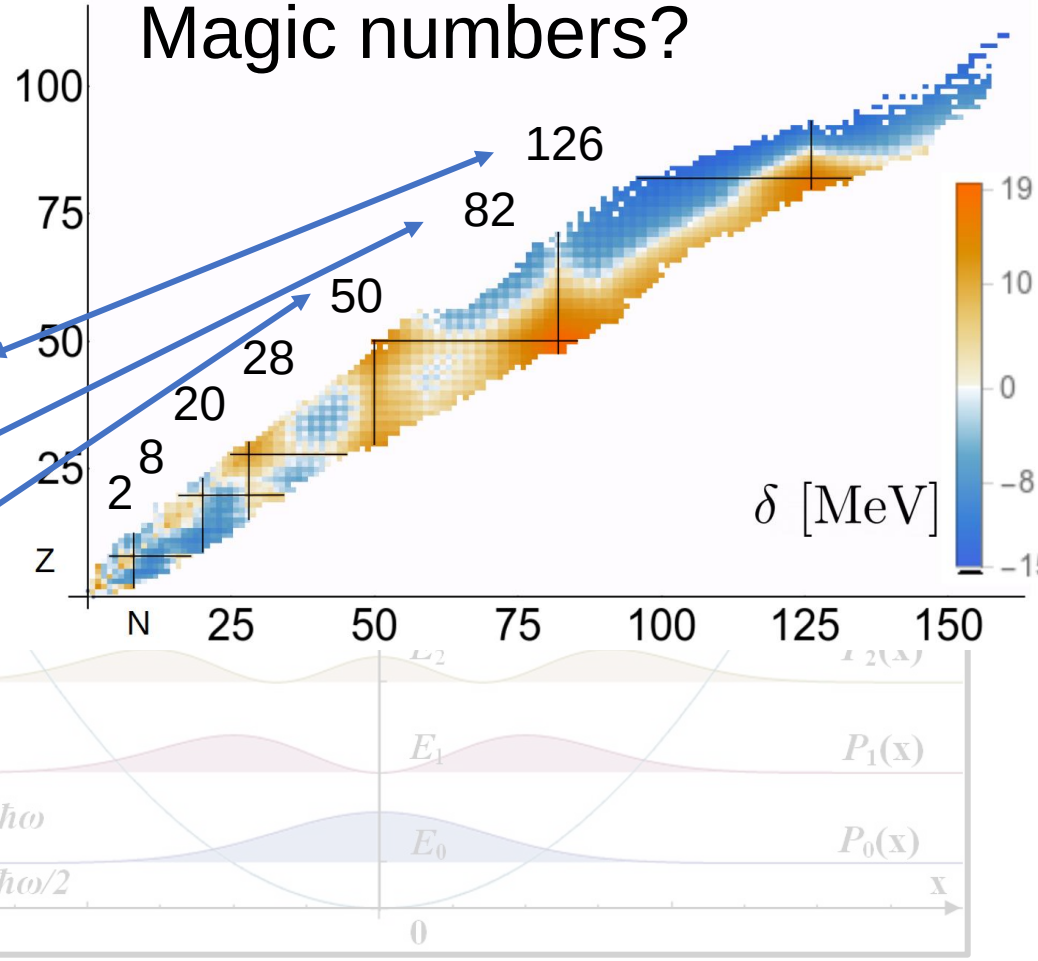

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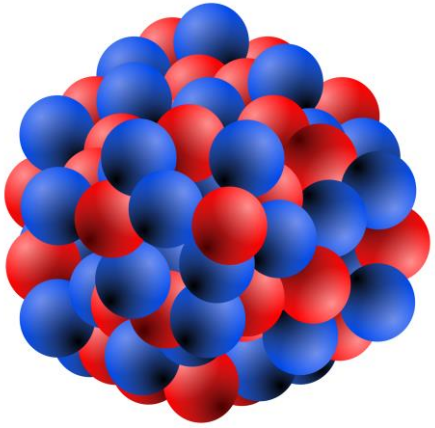

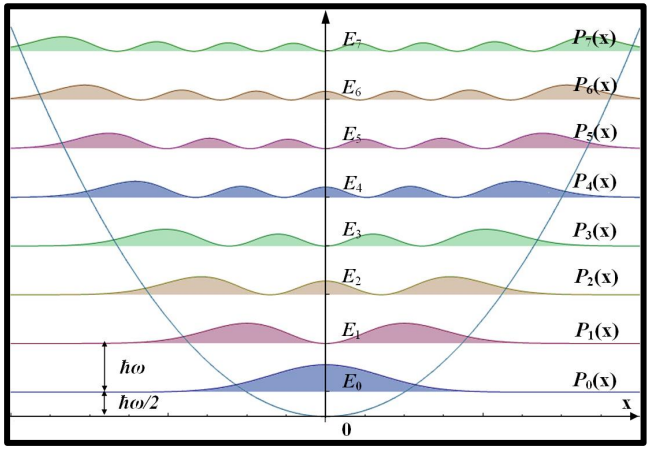

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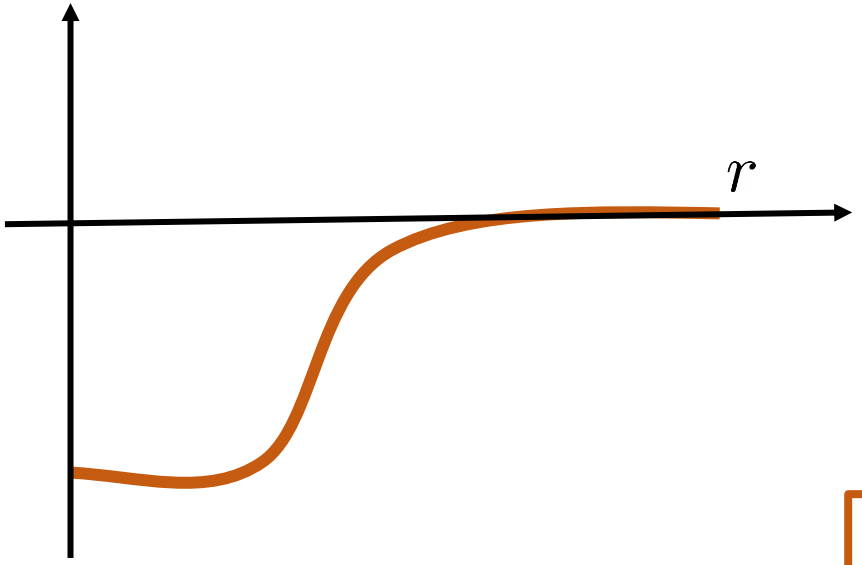
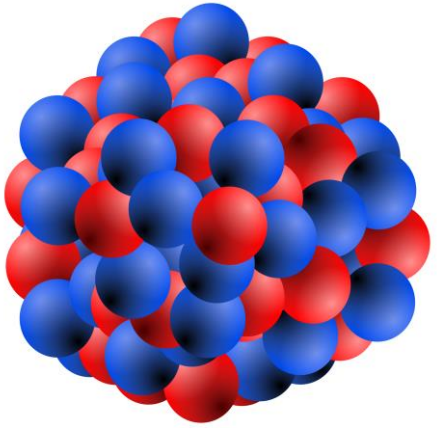
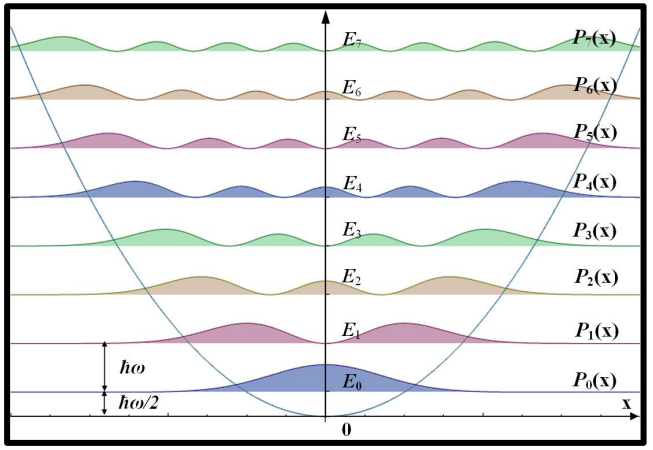


Woods-Saxon potential

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

Quantum mechanics





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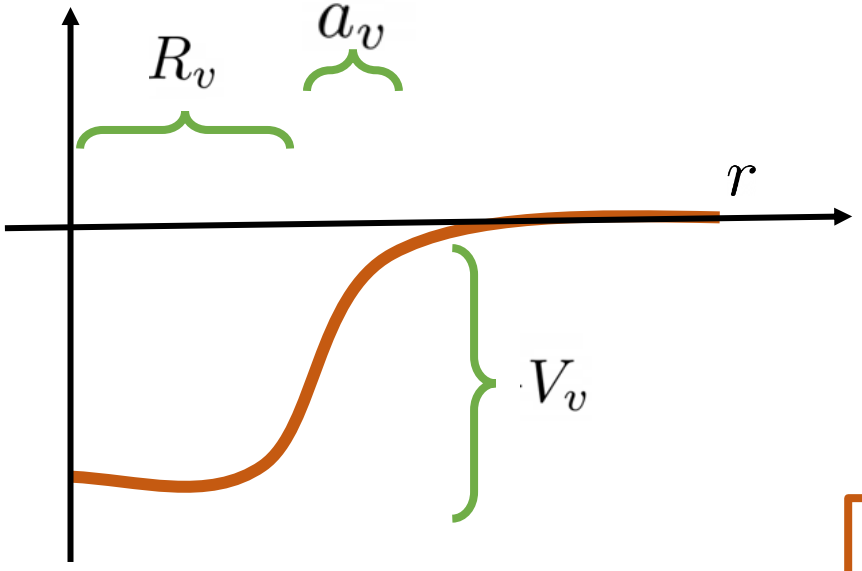

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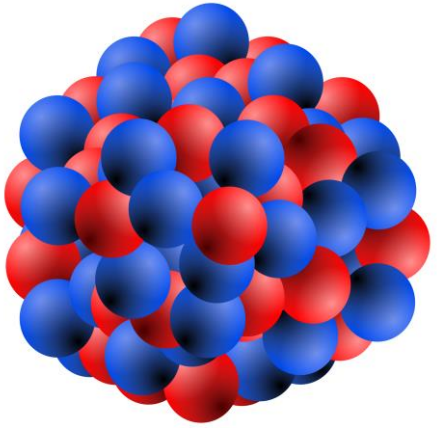

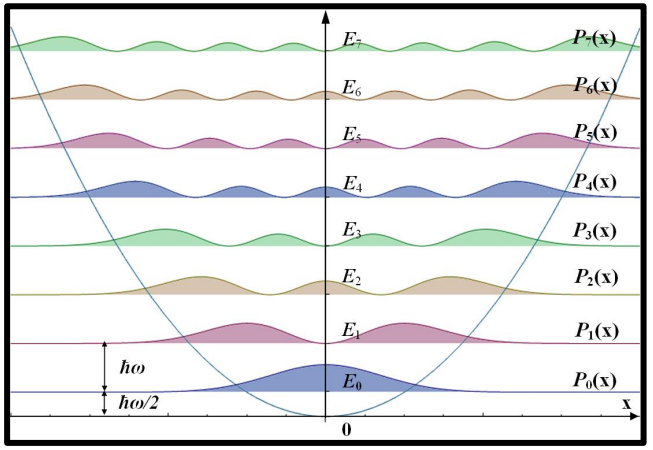

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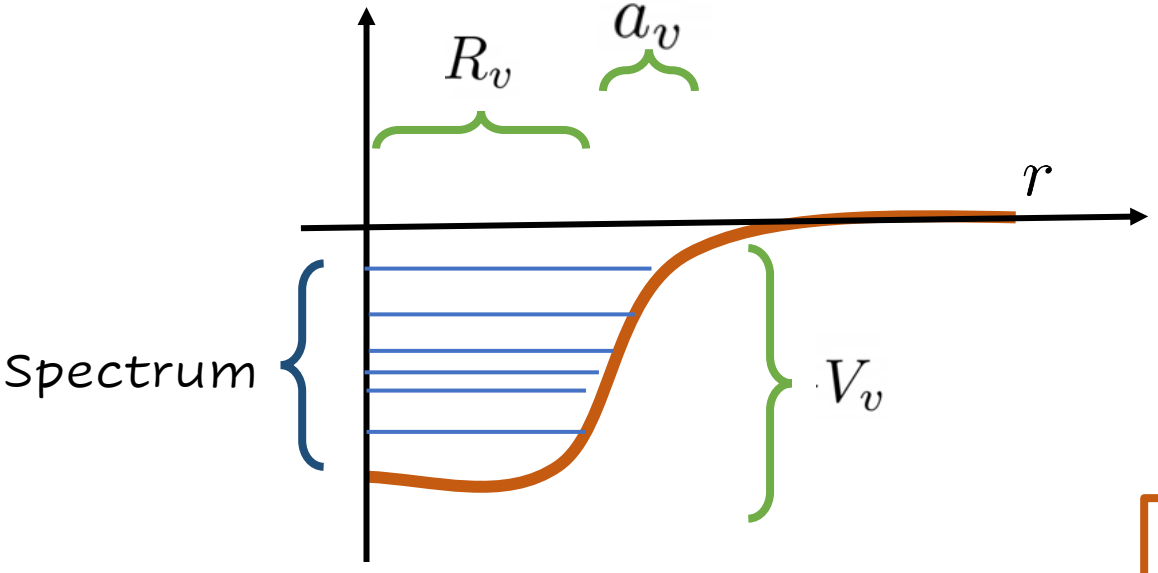

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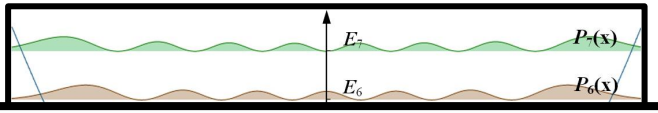
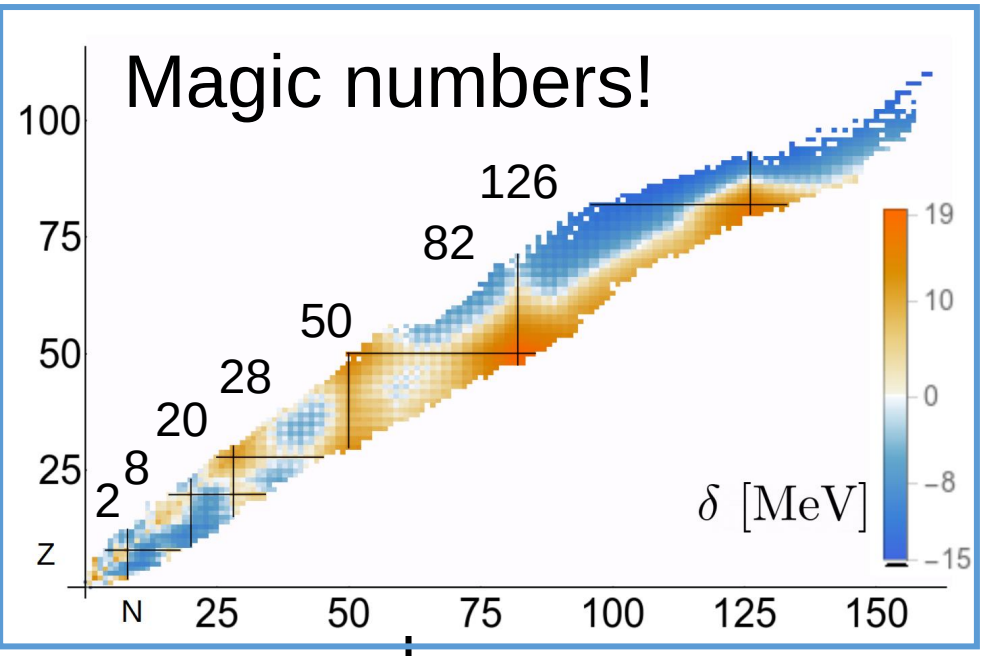
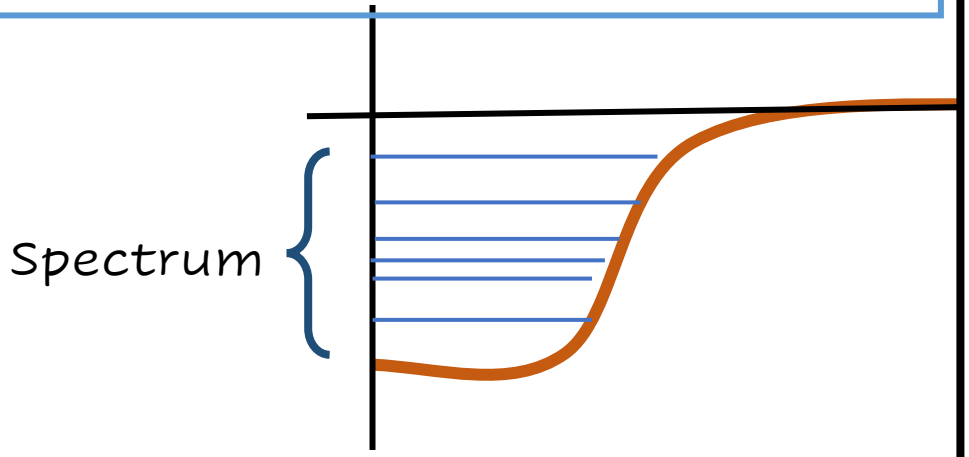
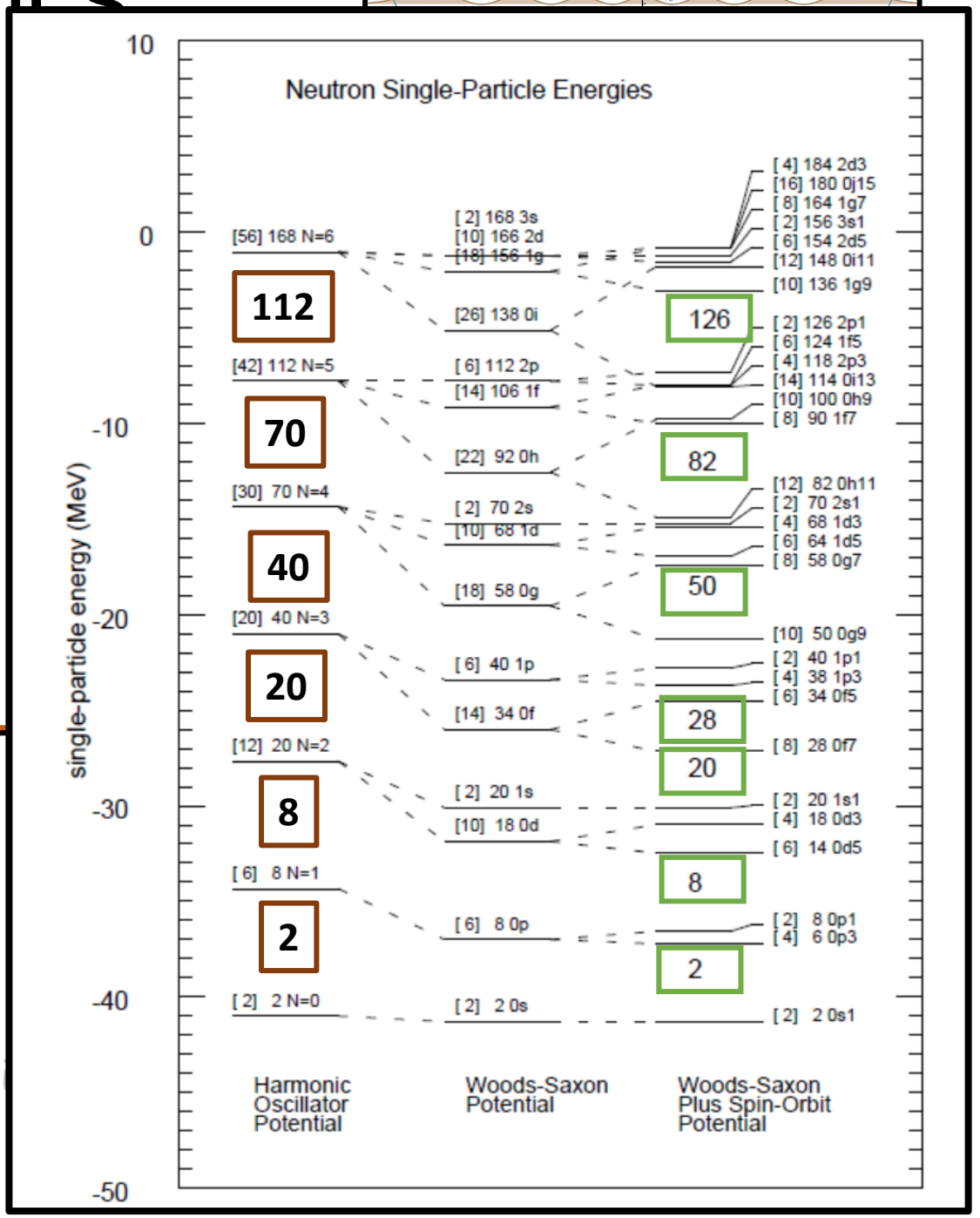






Woods-Saxon potenti



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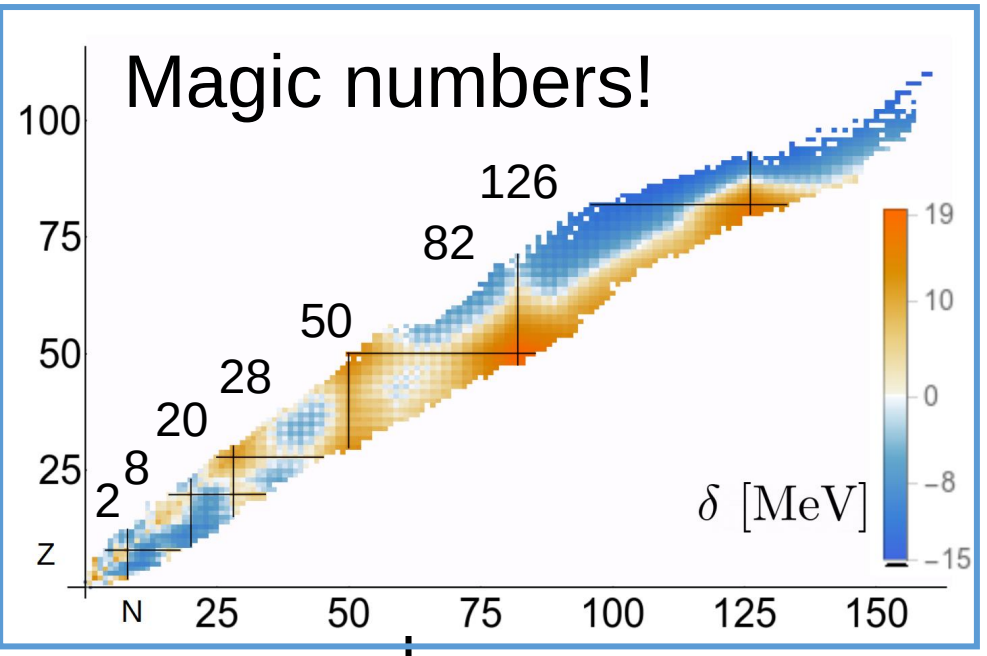
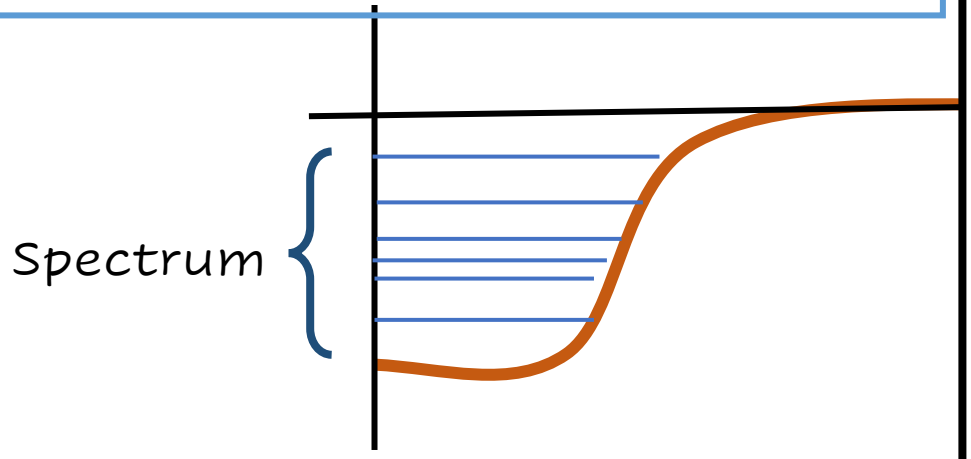
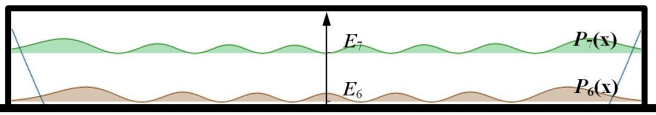
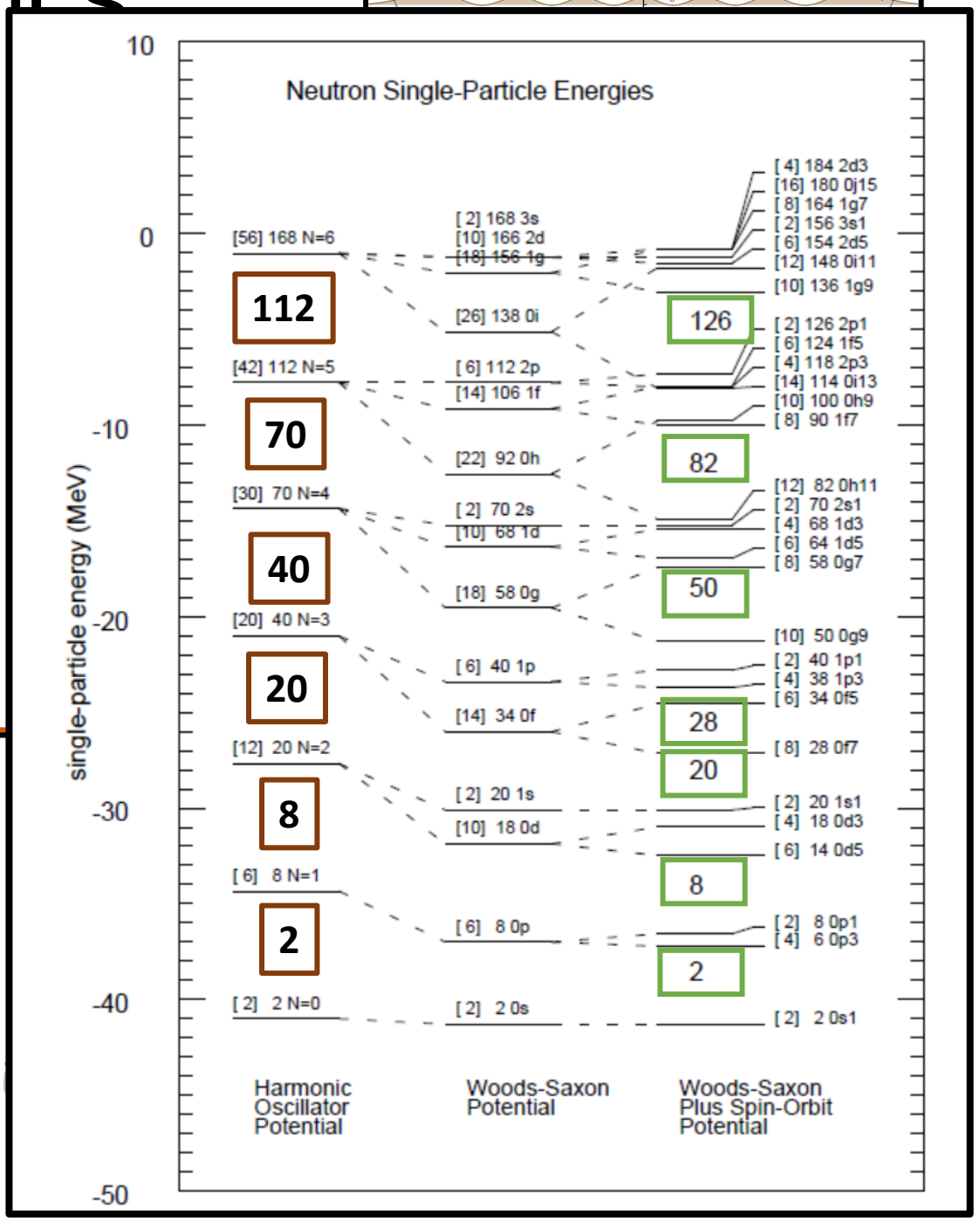




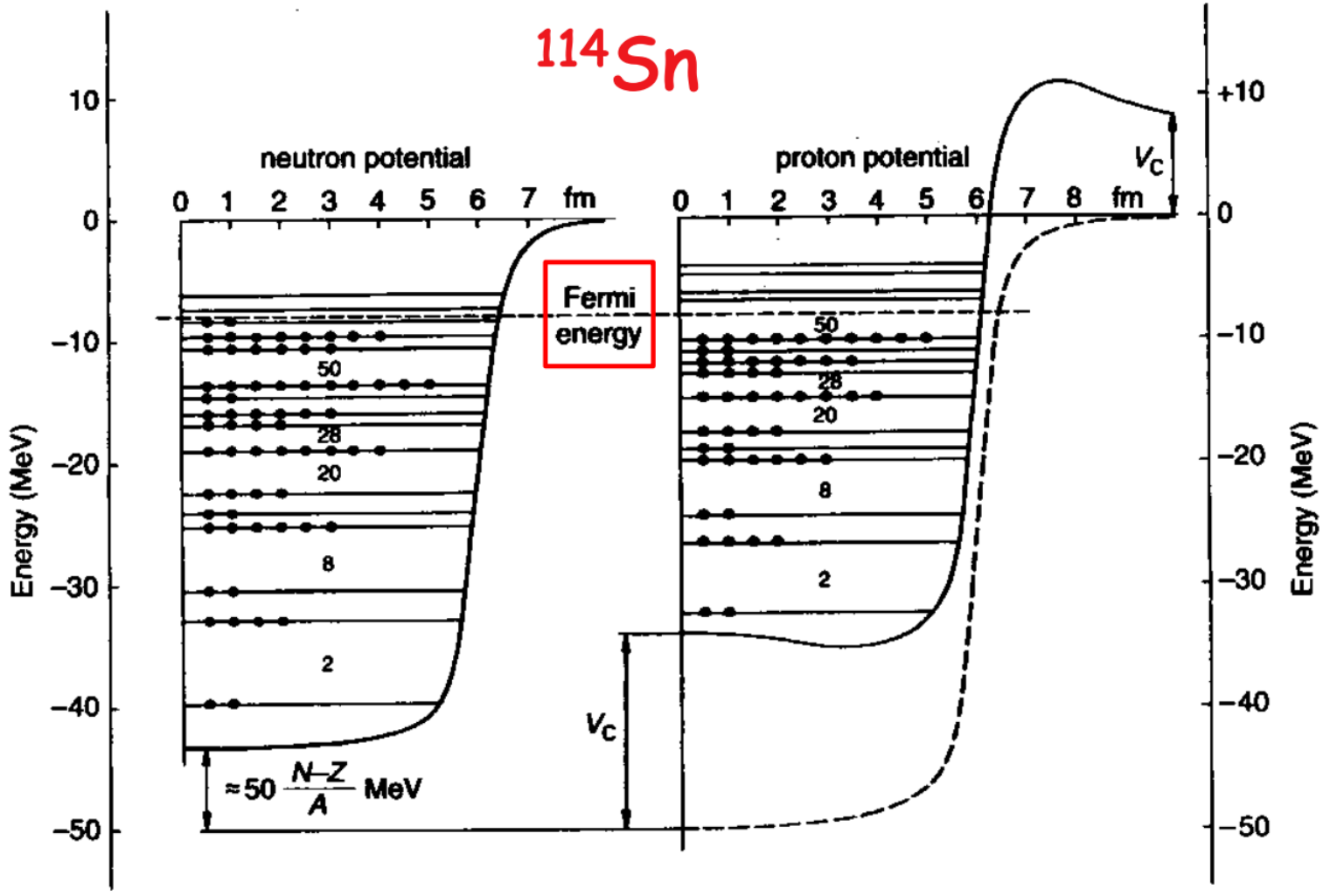
Woods-Saxon potenti

Shell Model





Nuclear shell model potential



Shell Model

Building better models

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Building better models

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

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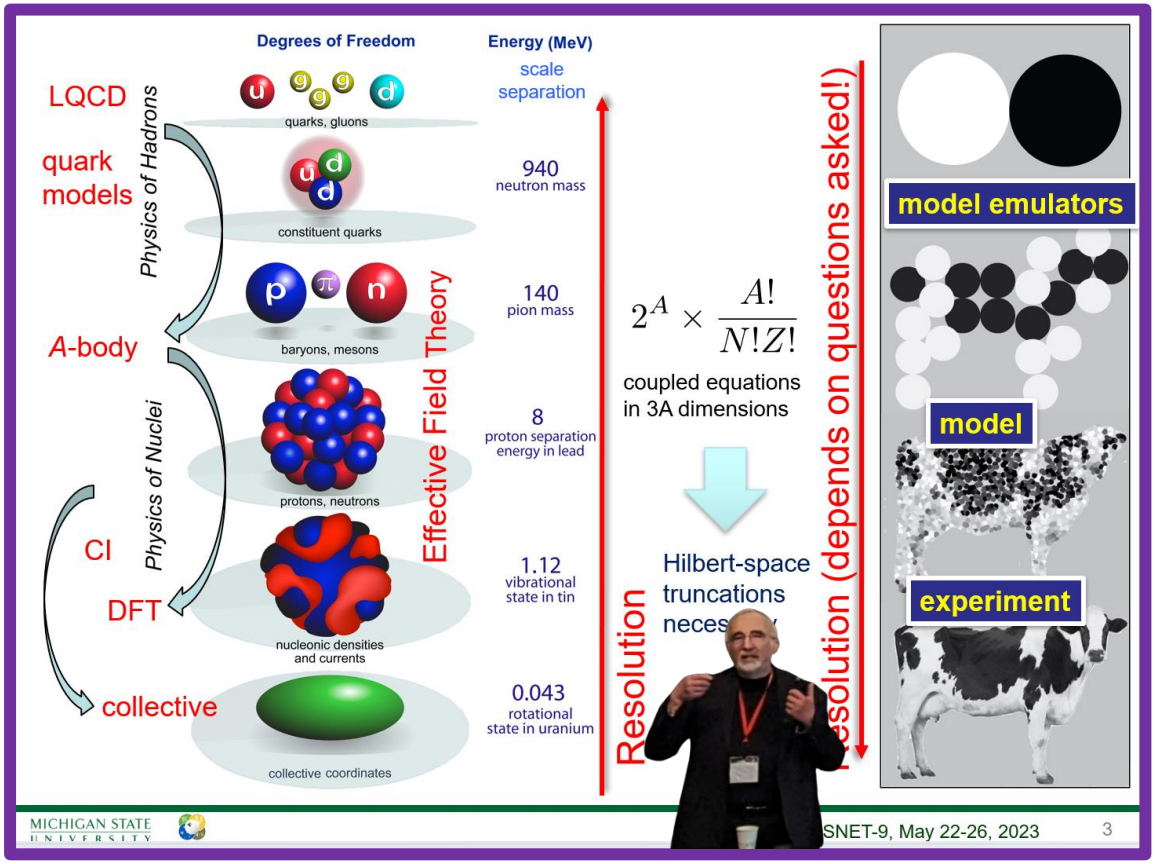
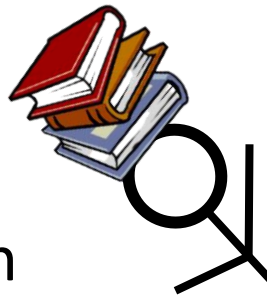


Witek Nazarewicz

Building better models

Each model is a new set of guessed rules



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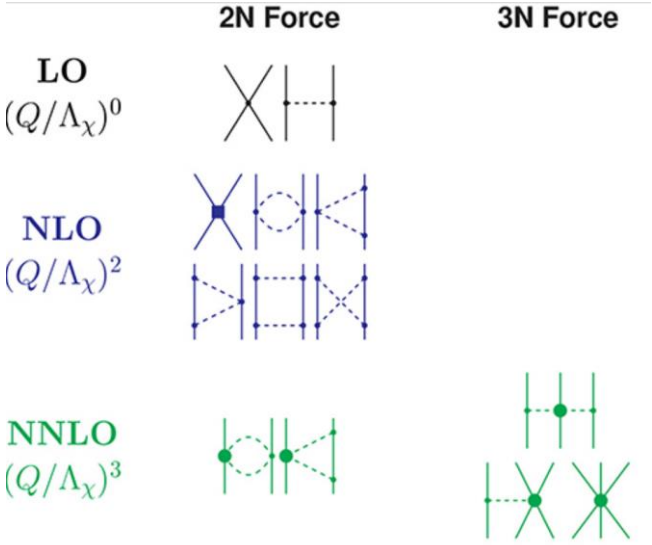
Explain

Predict

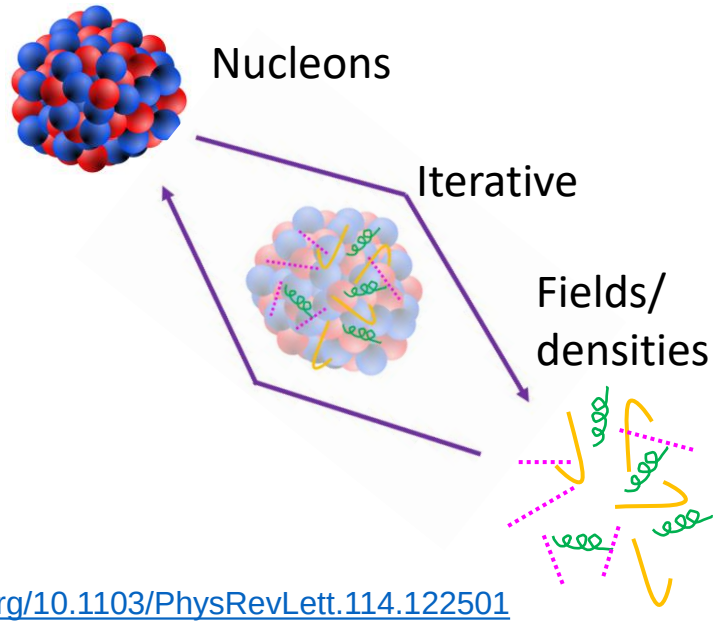
Build

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

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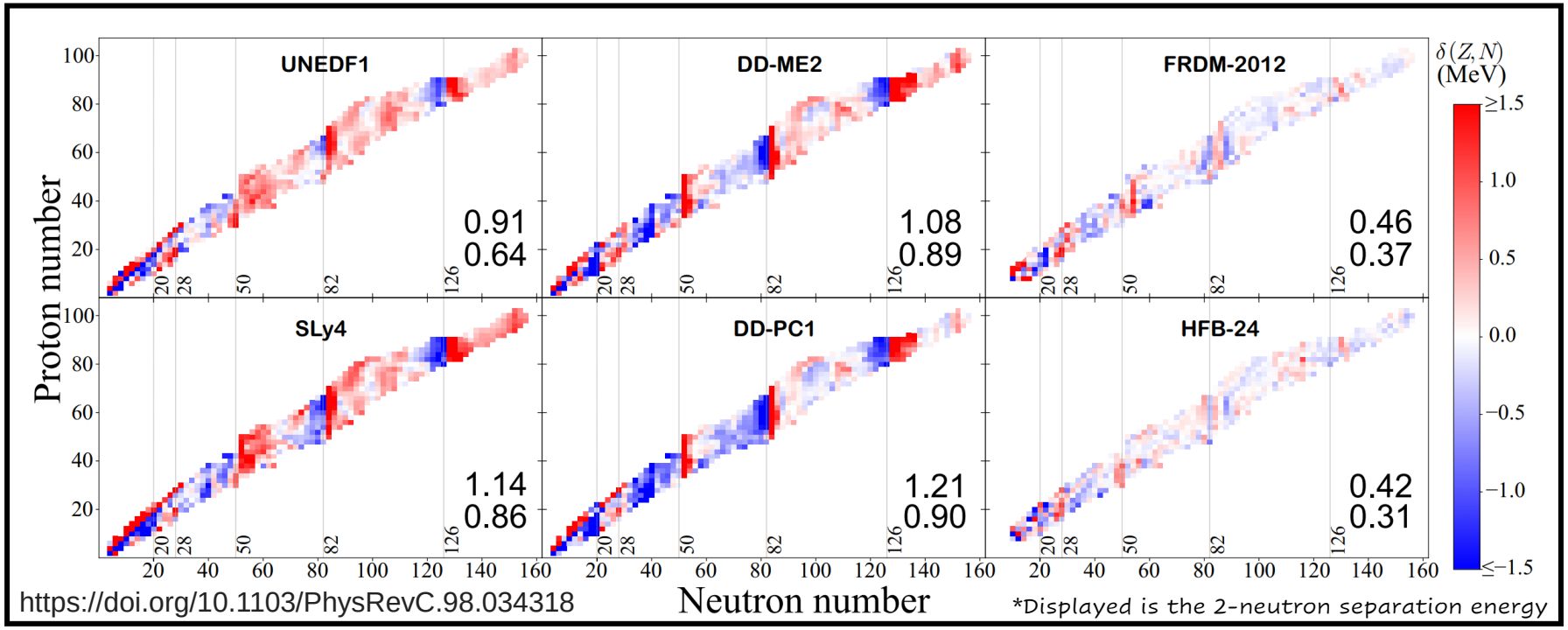
Nuclear Masses*

Modern Models



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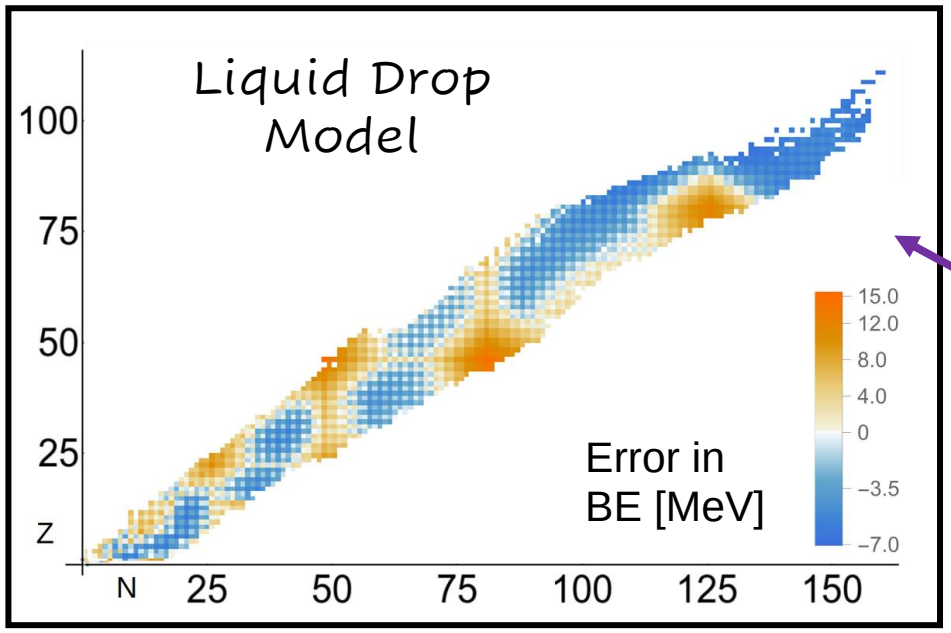

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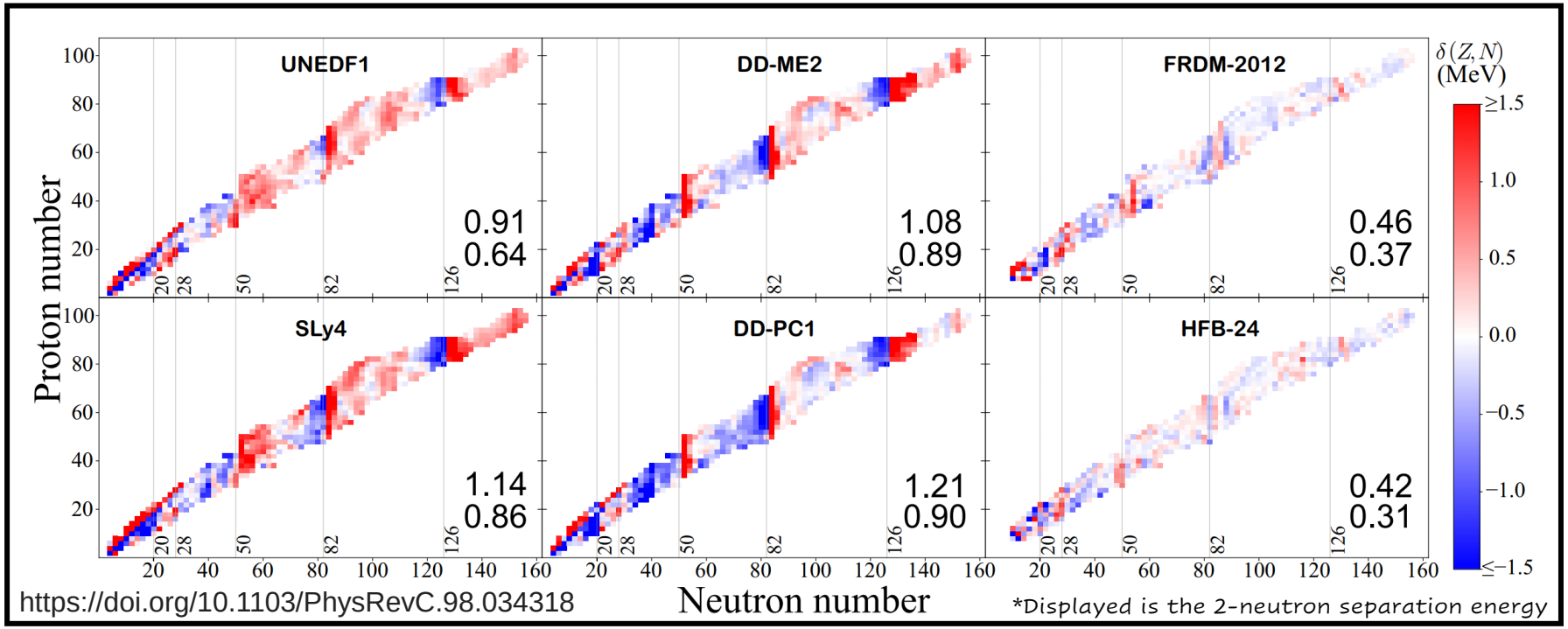
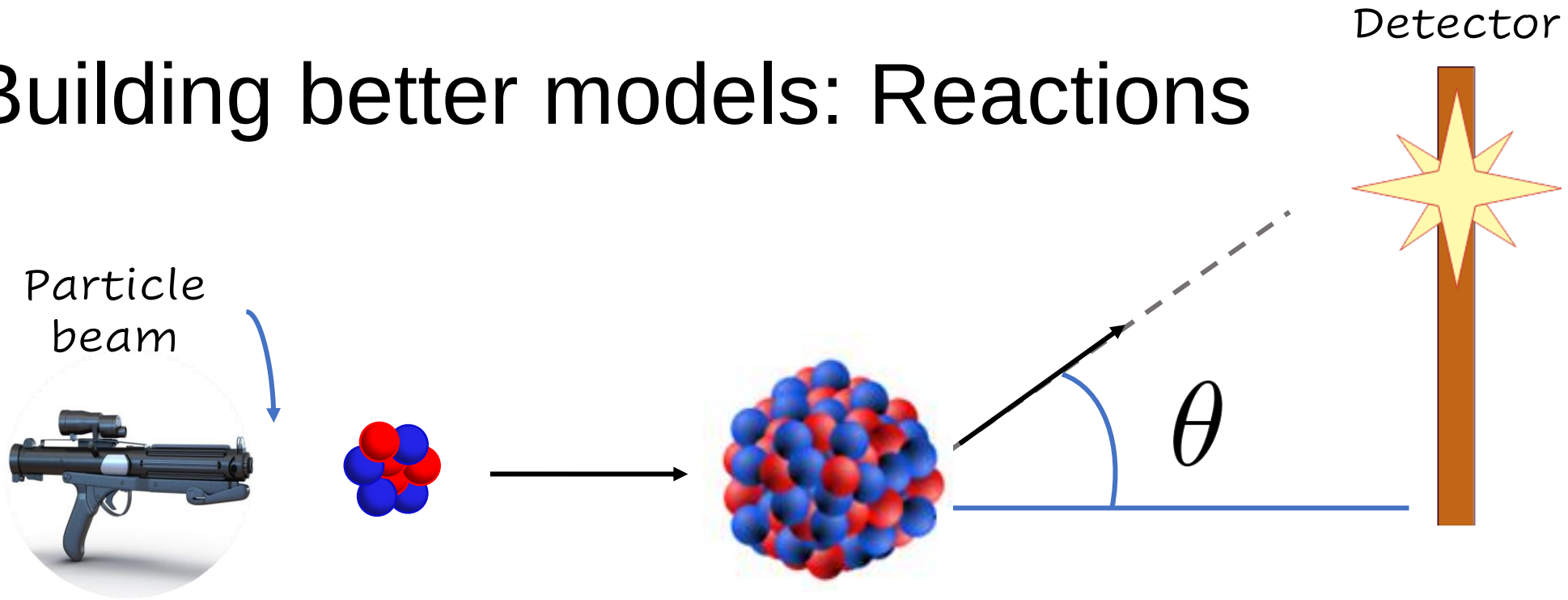


https://doi.org/10.1103/PhysRevC.98.034318

*Displayed is the 2-neutron separation energy

Building better models: Reactions



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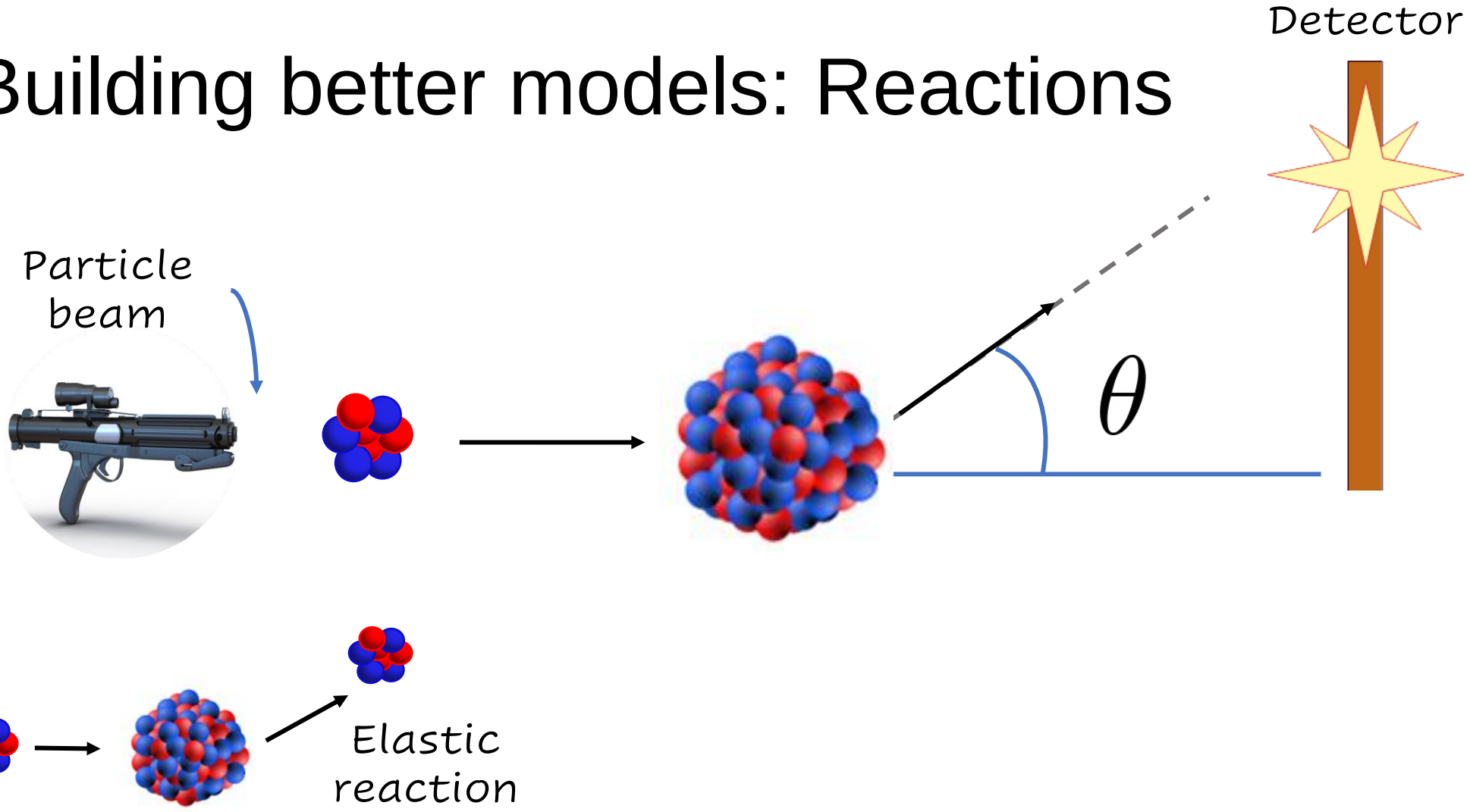

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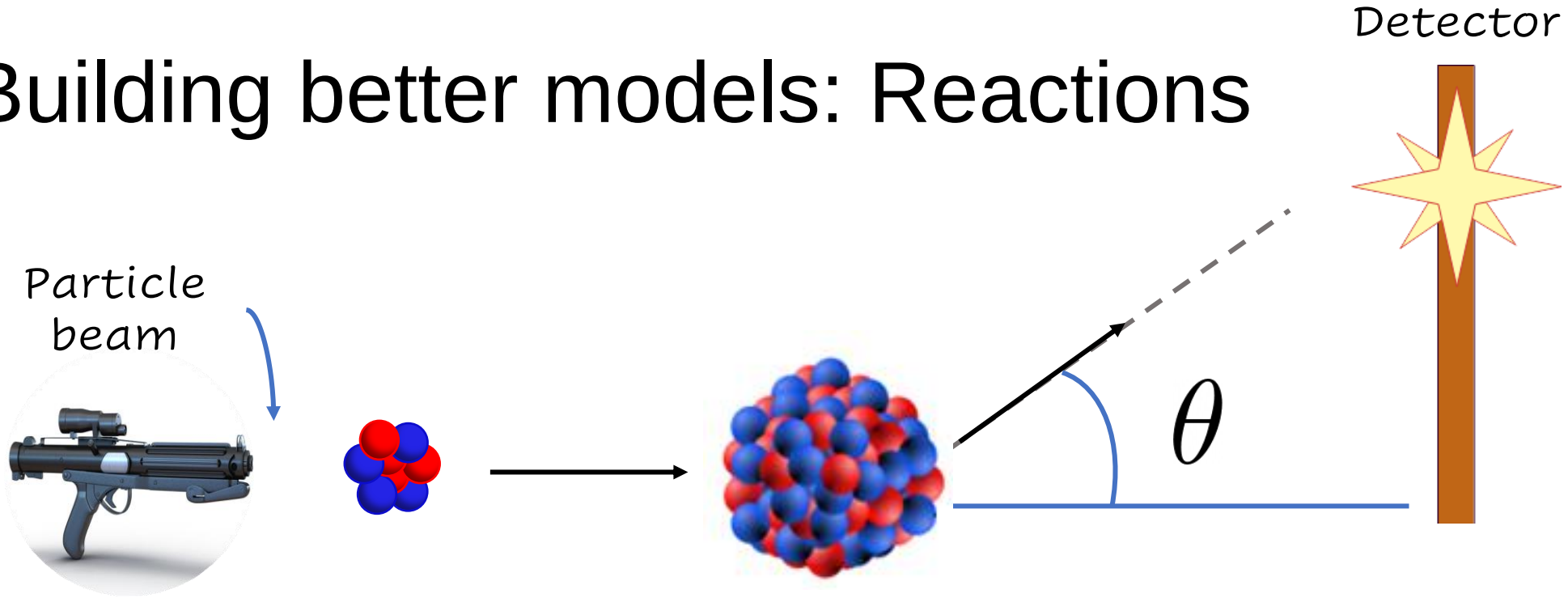

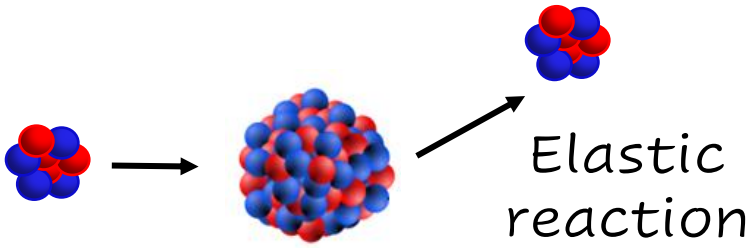

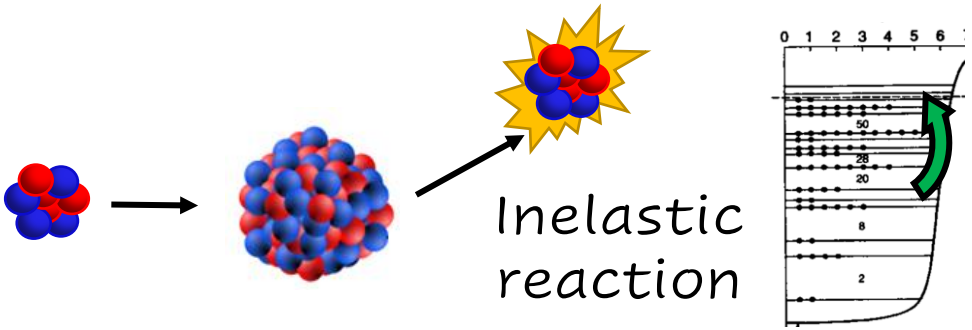

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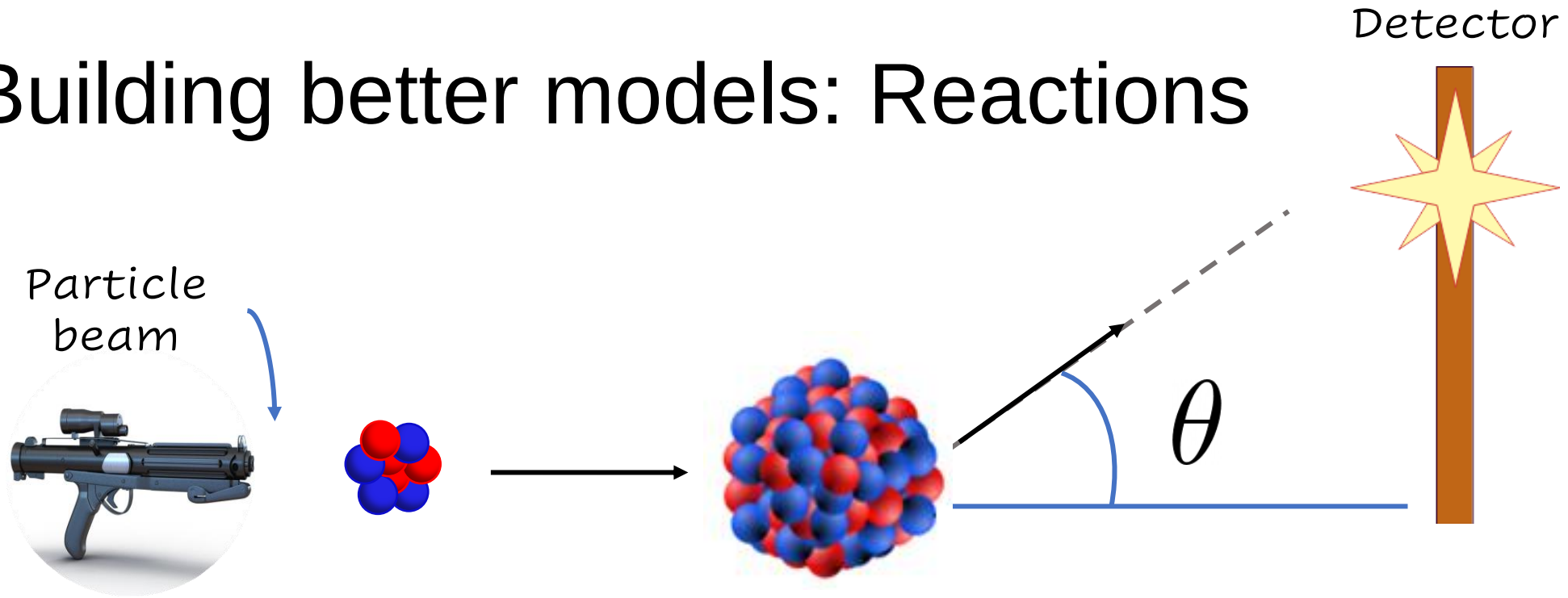
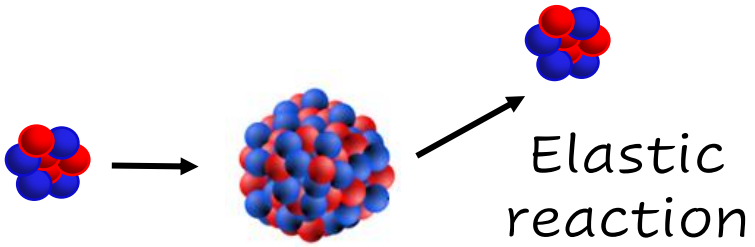
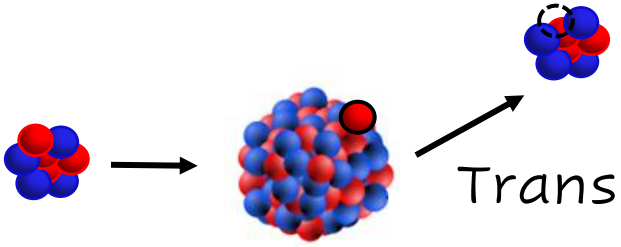
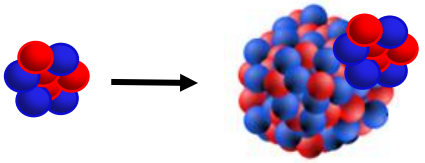
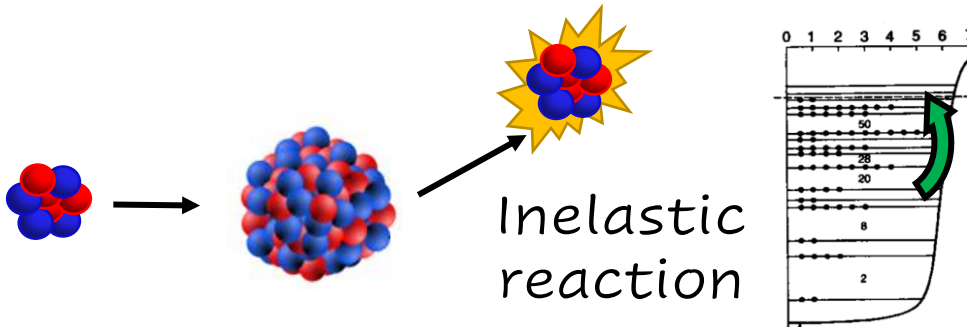
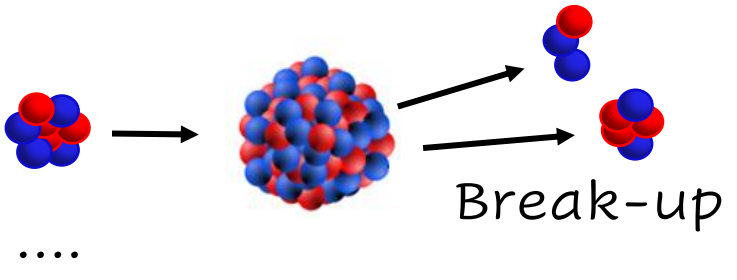






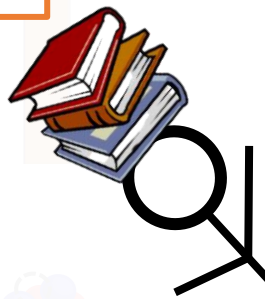






Building better models: Reactions

All this gives us hints about the rules of the game



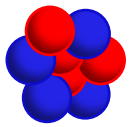
$$\mathcal{H}|\psi(x,t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(x,t)\rangle$$

....

Building better models: Reactions

Detector

Particle beam



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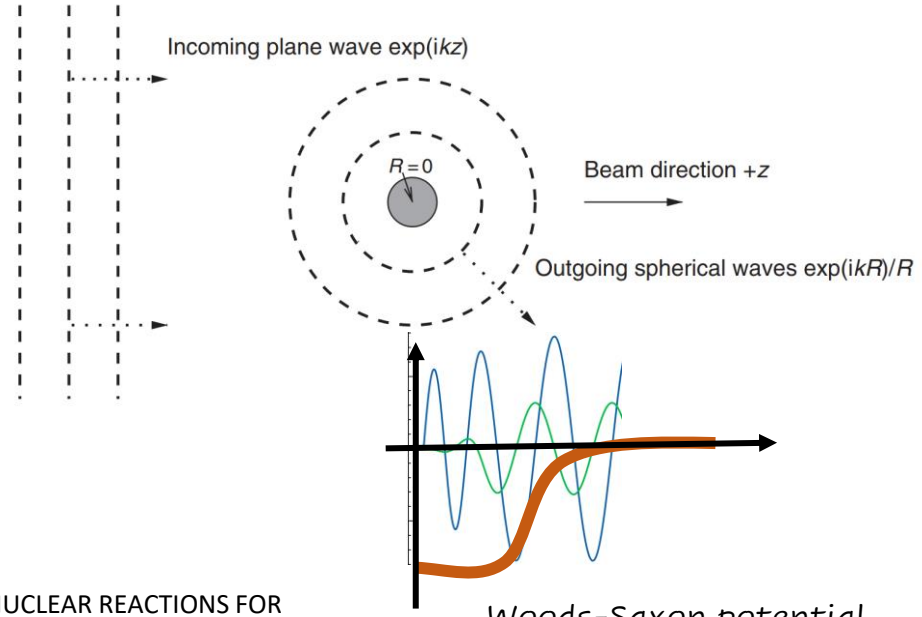
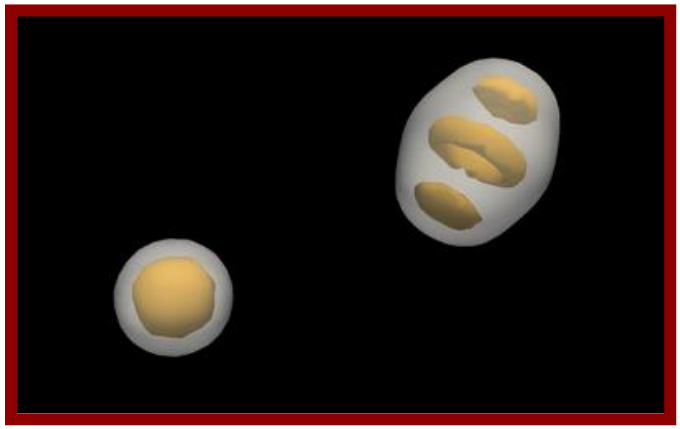
Optical Potentials



Woods-Saxon potential

Time-dependent Density Functional Theory

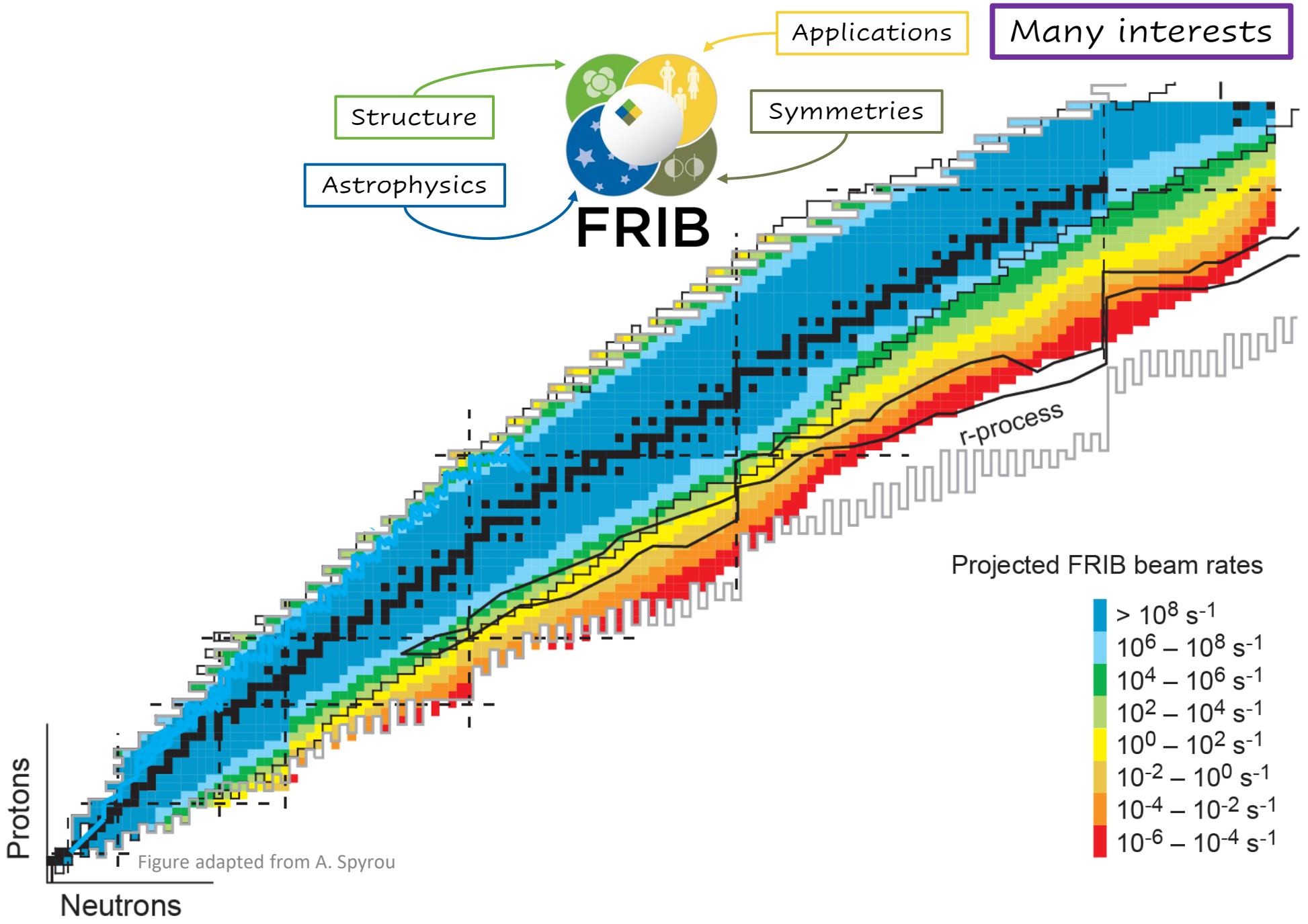
$$\mathcal{H}|\psi(x,t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(x,t)\rangle$$



NUCLEAR REACTIONS FOR ASTROPHYSICS (2009)

Made by Kyle Godbey

Theory-Experiment Cycle



Theory-Experiment Cycle

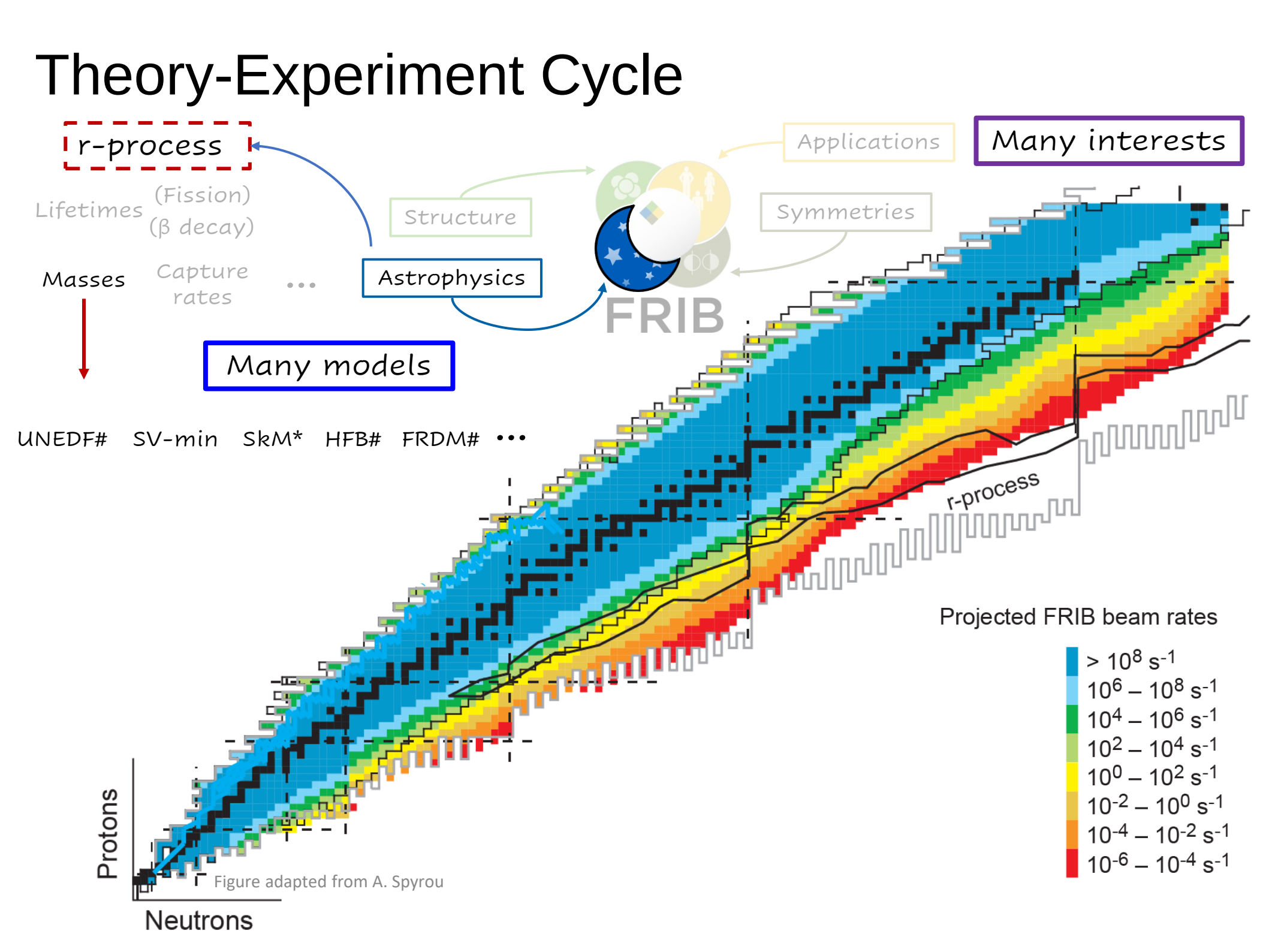


Figure adapted from A. Spyrou

Theory-Experiment Cycle

r-process

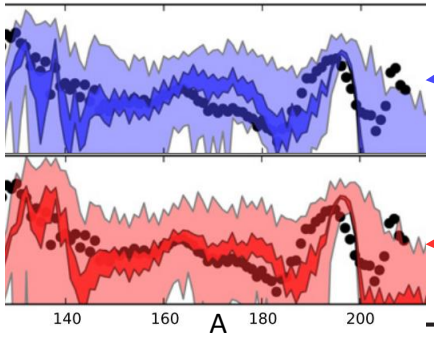
Lifetimes (Fission) (β decay)

Masses Capture rates ...

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)**

Astrophysics

Structure

Applications

Symmetries

Many interests

FRIB

r-process

Projected FRIB beam rates

- > 10^{8} s^{-1}
- 10^{6} – 10^{8} s^{-1}
- 10^{4} – 10^{6} s^{-1}
- 10^{2} – 10^{4} s^{-1}
- 10^{0} – 10^{2} s^{-1}
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Protons

Neutrons

Figure adapted from A. Spyrou

Theory-Experiment Cycle

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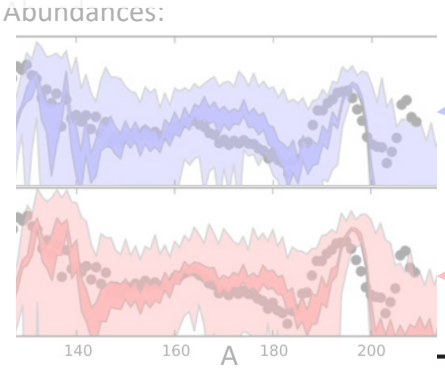
UNEDF# SV-min SkM* HFB# FRDM# •••



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r-process

Projected FRIB beam rates

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Many experiments, many nuclei

Charge Exchange
Transfer, surrogate (n,γ)

β-Oslo – (n,γ)

TAS, mass measurements
Discrete γ spectroscopy

βn - measurements

Half-life, ToF mass

Protons

Neutrons

Figure adapted from A. Spyrou

Theory-Experiment Cycle

r-process

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Astroph

Structu

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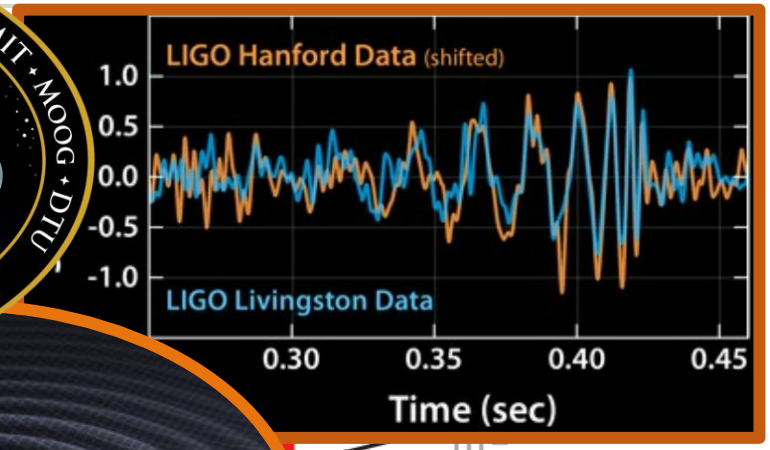
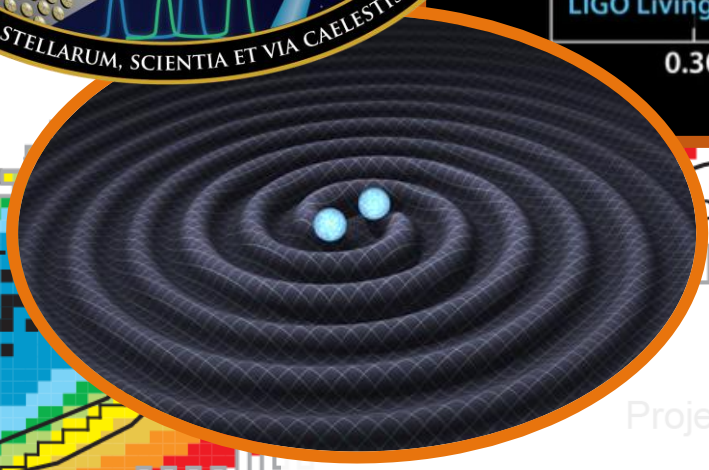
Many interests

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

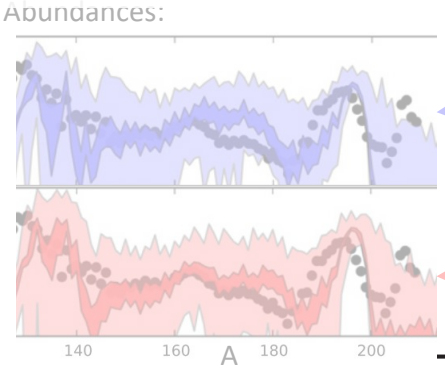


Many models

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



Many observations



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

Figure adapted from A. Spyrou

Many experiments, many nuclei

Projected FRIB beam rates

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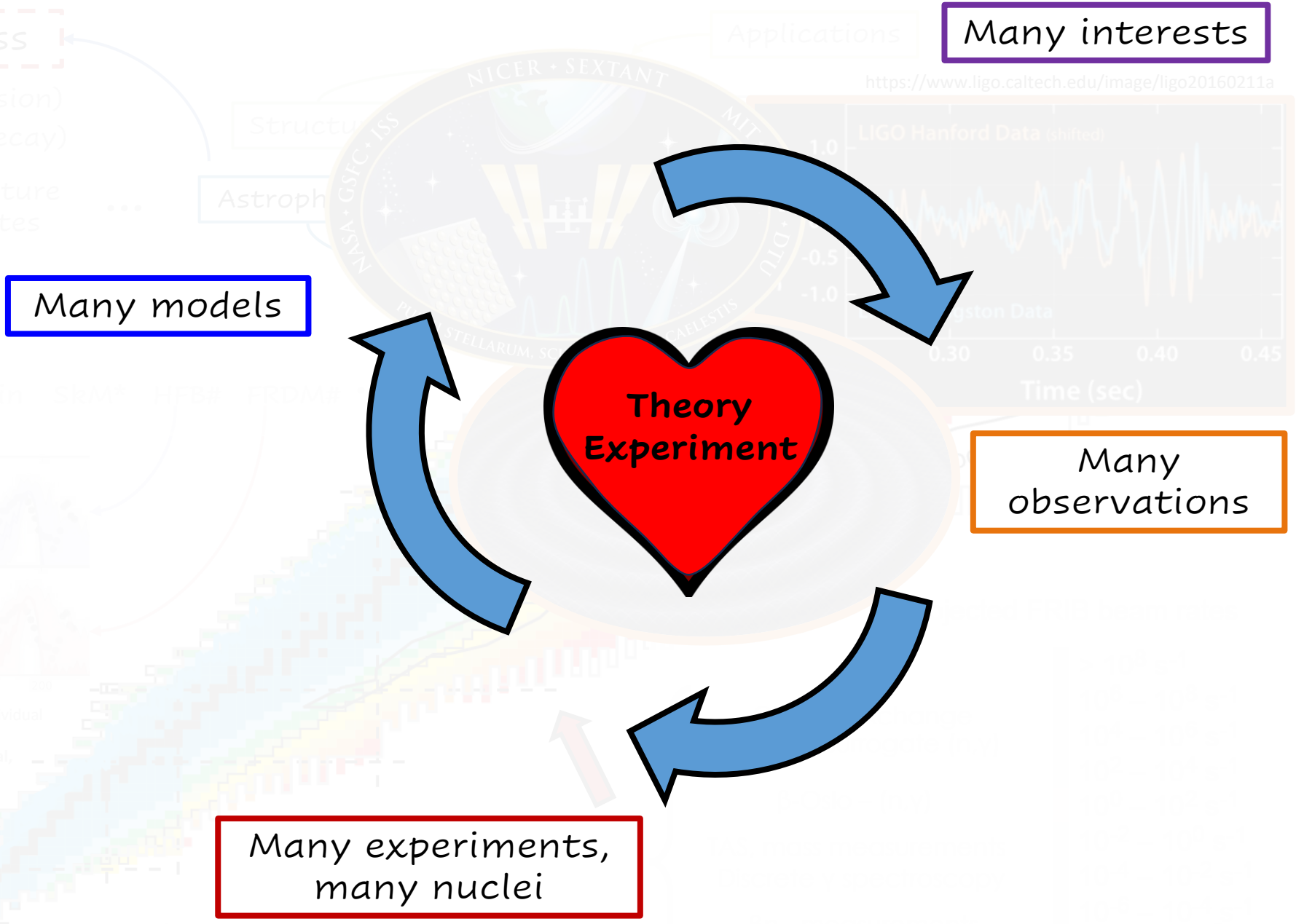
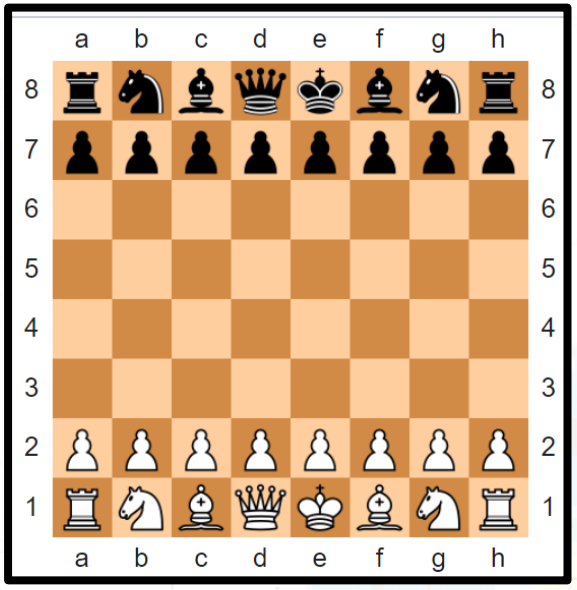
Theory-Experiment Cycle

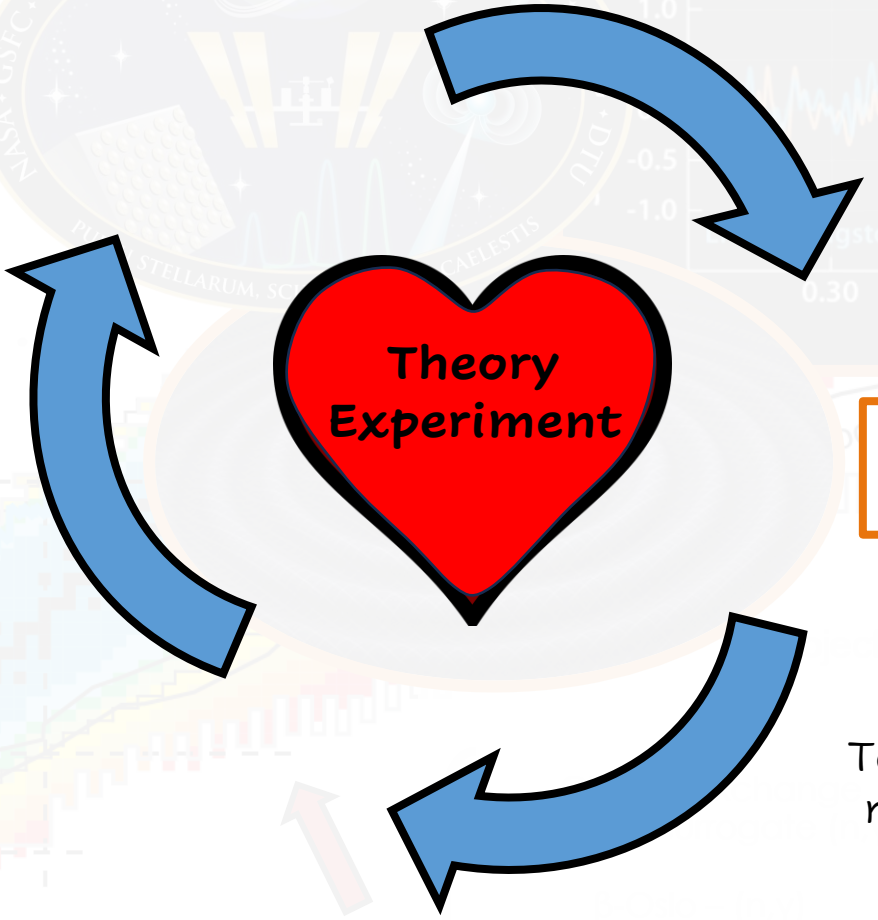


Theory-Experiment Cycle

Many interests

Many models

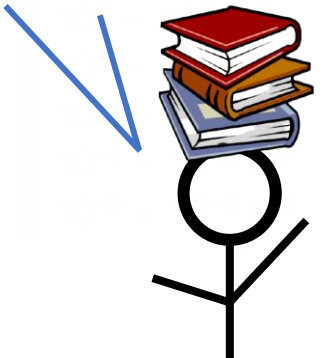




Many observations

Many experiments, many nuclei

To better learn the rules of the game



For today

Who am I?

Why theory?

Building models

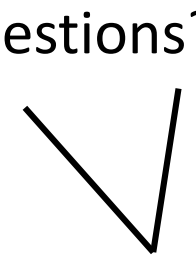
Building a (simple) nuclear model

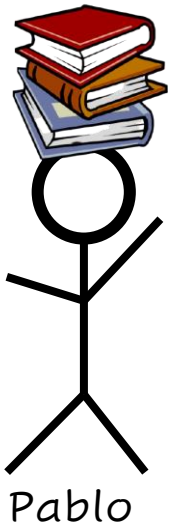
Quantum mechanics

Building (better) nuclear models

Challenges (Hands-On Session)

Questions?



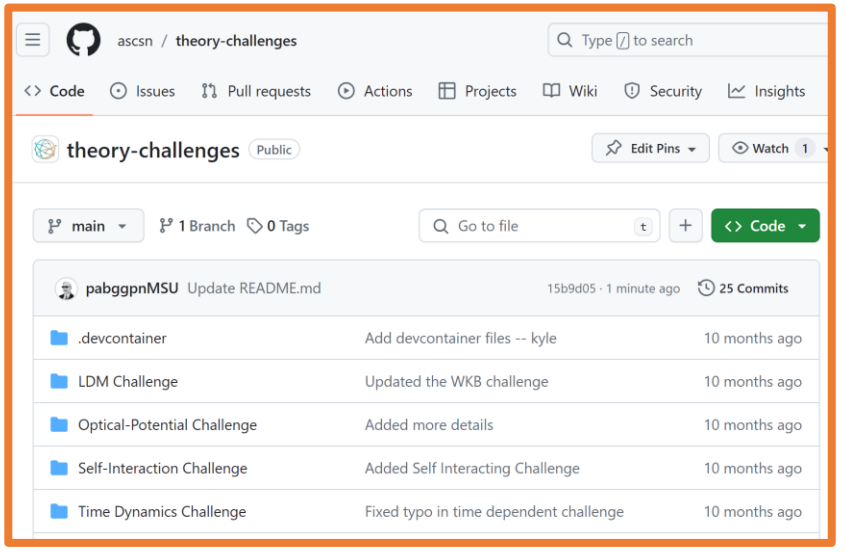


Hand-on session set-up

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 ★★★

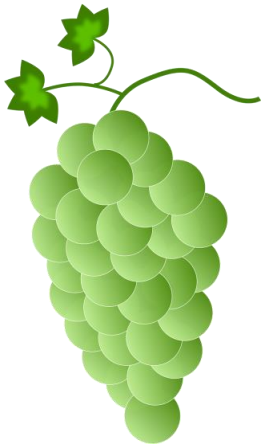
Hand-on session time

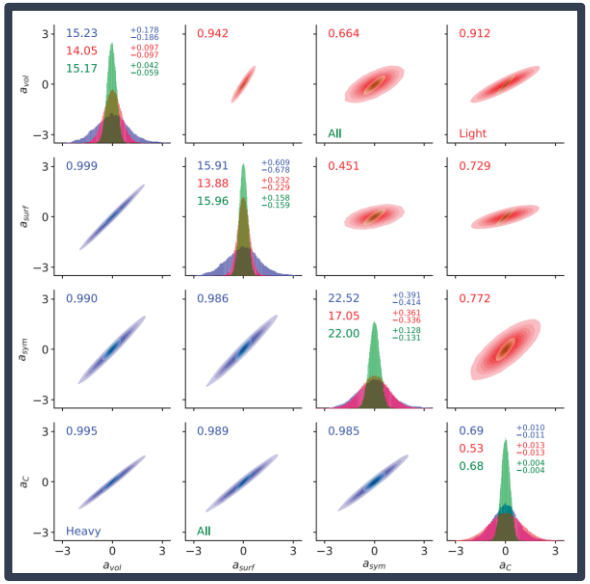
Calibrating the Liquid Drop Model Challenge ★ ★

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.

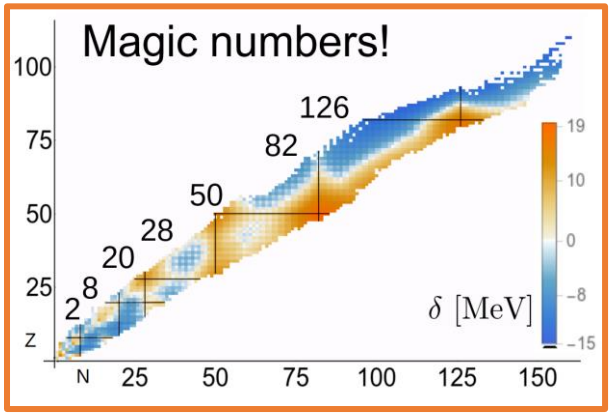
Your task is to:

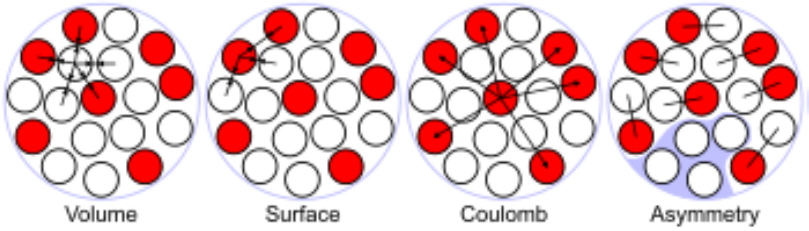
- Import the data from the AME 2016 table (included in the github). We are only using nuclei above A=16 to avoid light nuclei where the LDM fails particularly. Perform a curve fit using the built in functions from python (https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.curve_fit.html) 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 acompaning 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.





$$E_{\mathrm{B}} = a_{\mathrm{V}} A - a_{\mathrm{S}} A^{2/3} - a_{\mathrm{C}} \frac{Z(Z-1)}{A^{1/3}} - a_{\mathrm{A}} \frac{(N-Z)^2}{A}$$





Hand-on session time

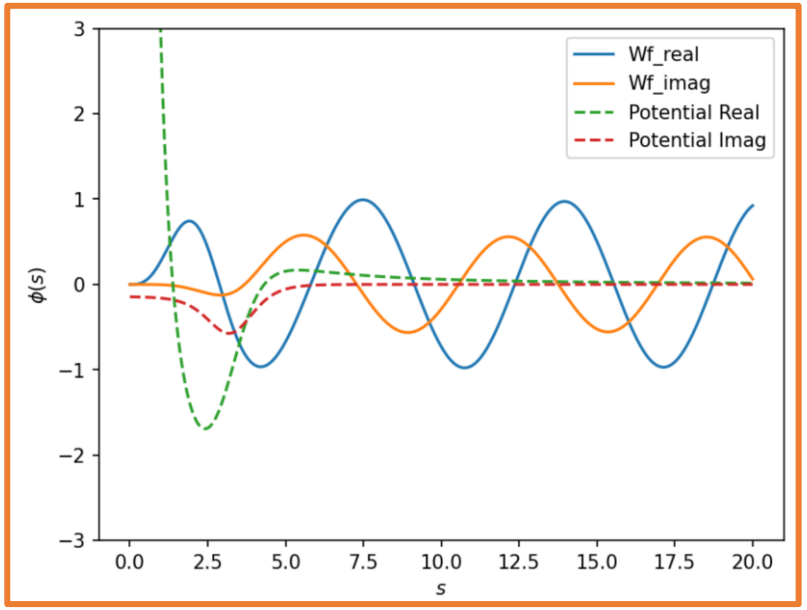
Reaction Cross Section Challenge ★★★

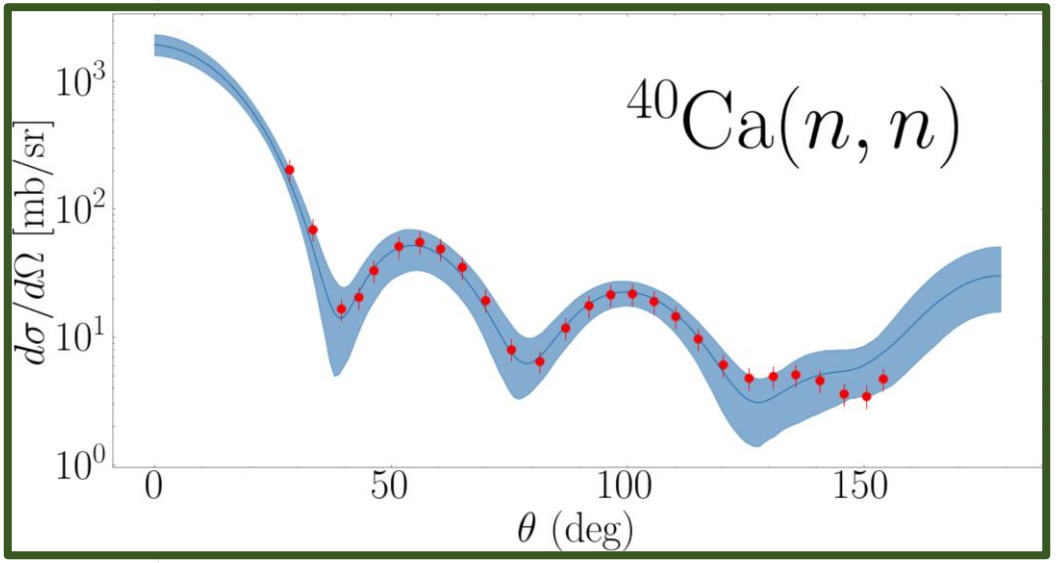
Notebook adapted from the ROSE challenges made by Daniel Odell and Pablo Giuliani: https://indico.cern.ch/event/1223721/contributions/5394829/. Functions for calculating the wave-function solutions and phaseshifts adapted from the ROSE github: https://github.com/odell/rose

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 acompanying 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:

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

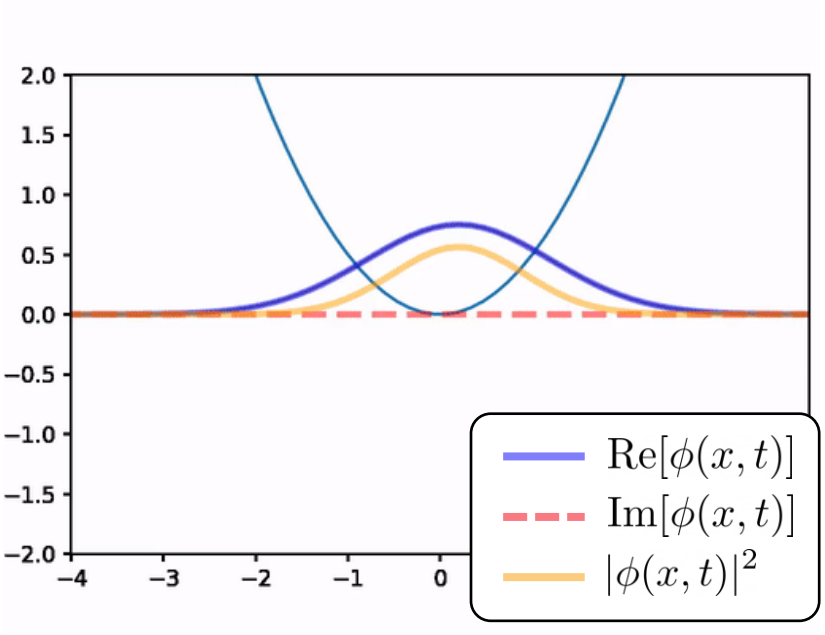
which results in the evolution operator from an initial state:

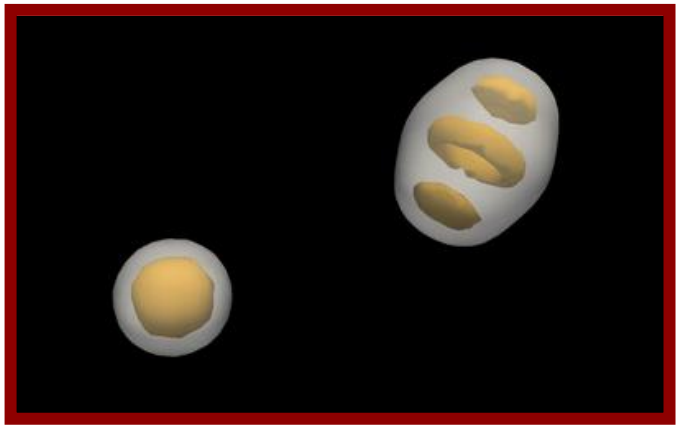
$$|\phi(t,x)\rangle = e^{-iHt}|\phi(0,x)\rangle.$$

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

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

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.





$^{48}\mathrm{Ca} + ^{249}\mathrm{Bk}$

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:

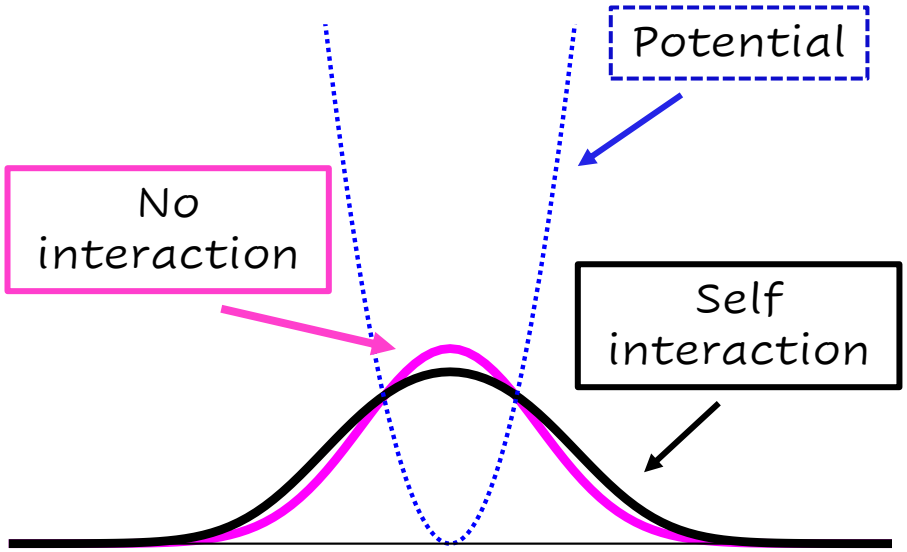
$$\rho(x) = |\phi(x)|^2,$$

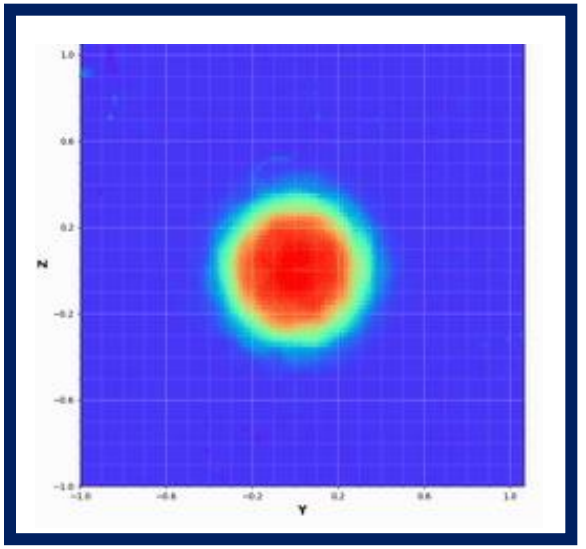
and the wave-function is normalized:

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

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 recomendation 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.

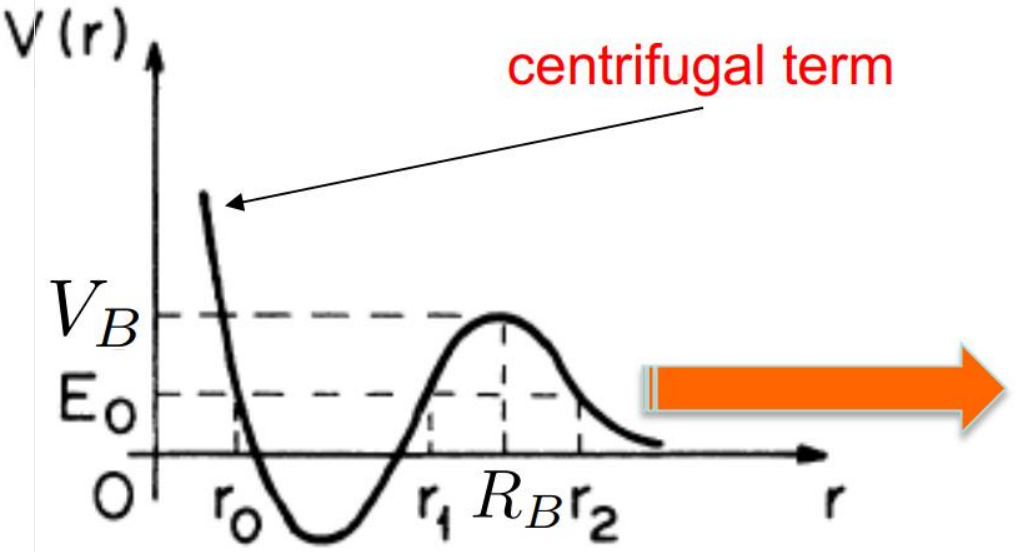
Your task is to:

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

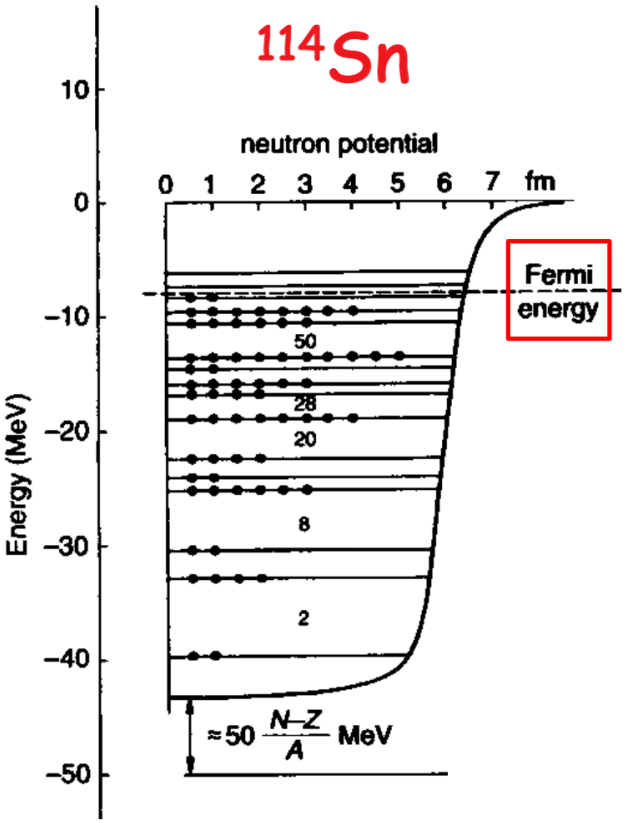
$$V_{\text{eff}}(r,\alpha)=V_{\text{WS}}(r)+(\vec{\ell}\cdot\ \vec{s})V_{\text{SO}}(r)$$

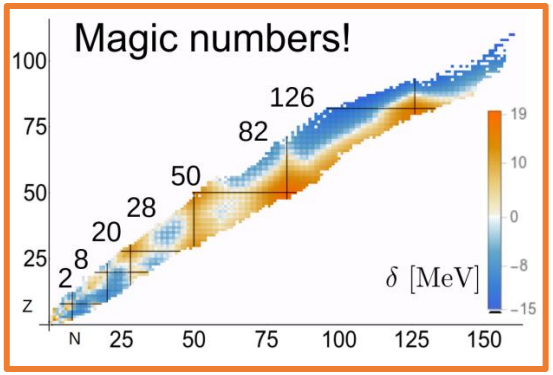
where the Woods-Saxon term is defined as:

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

and the spin orbit is:

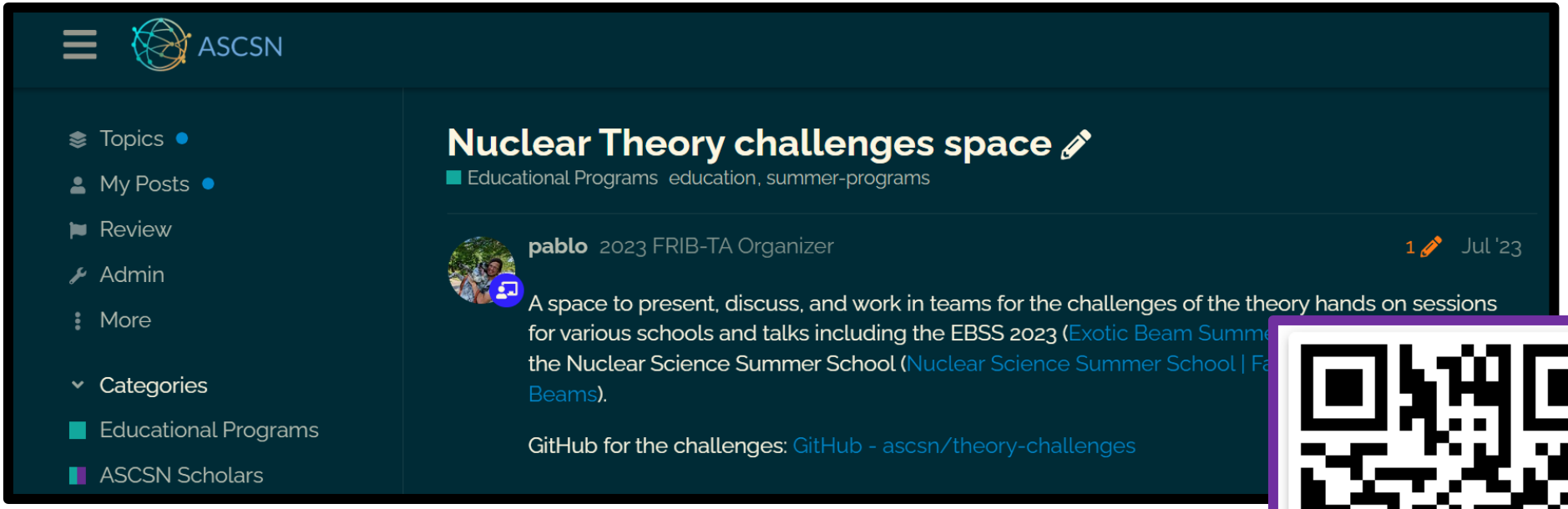
$$V_{\text{SO}}(r,\alpha)=V_{\text{SO}}r_0^2\frac{1}{r}\frac{d}{dr}\left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1},$$





Hand-on session time

https://forum.ascsn.net/



Register on the forum

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

ASCSN

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