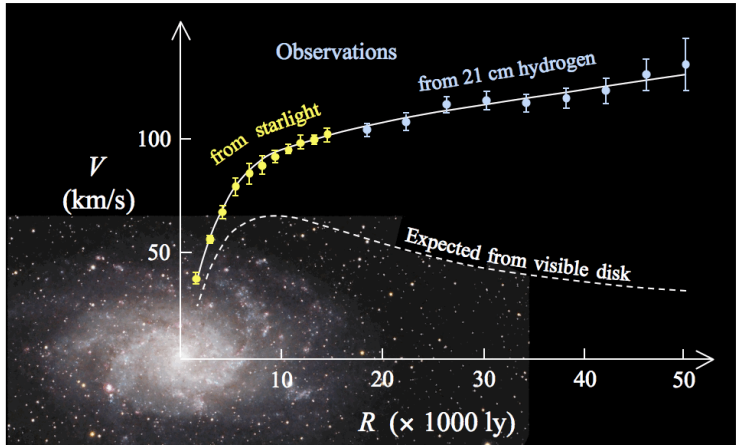
Fundamental Symmetries through the lens of a neutron

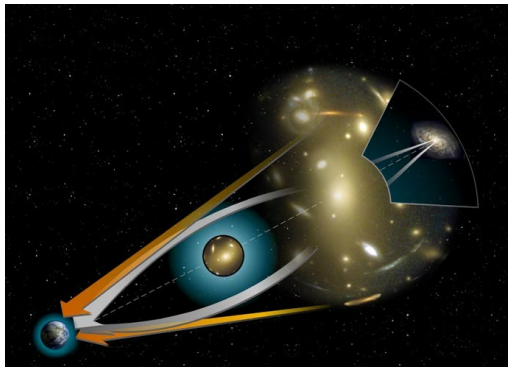
Leah Broussard
Oak Ridge National Laboratory

Nuclear Physics summEr school for undEr Represented Students
DillardUniversity, New Orleans LA
June 13, 2024

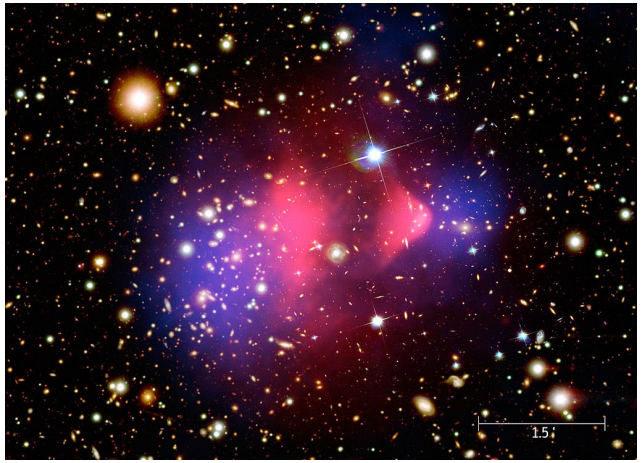
The neutron, symmetry, and our universe

- **A quest to understand our universe**
- The neutron as a laboratory
- How well do we understand the weak interaction?
- Can our matter turn into antimatter (or dark matter)?
- Concluding remarks

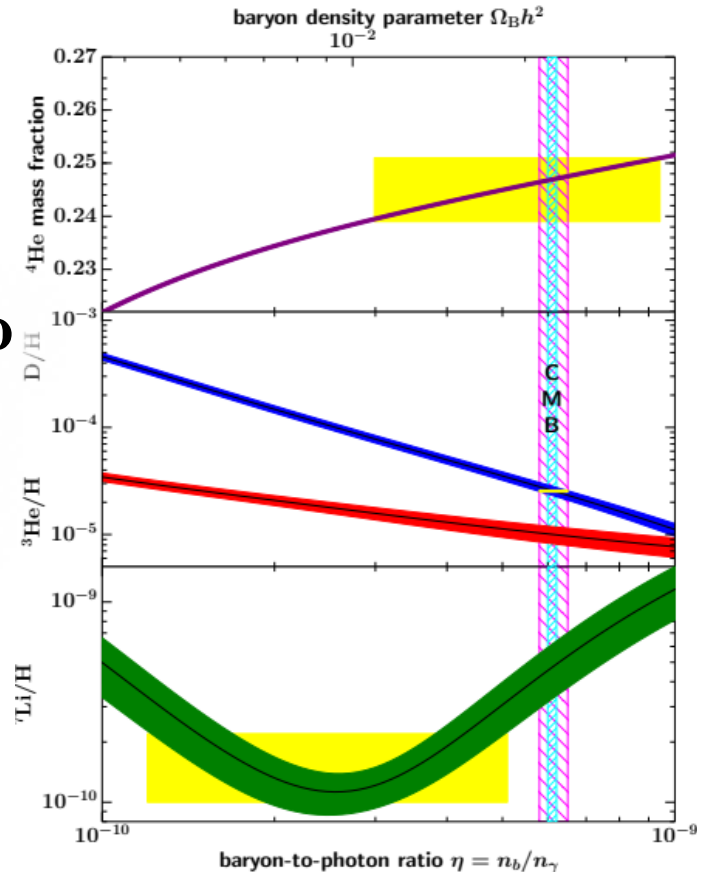




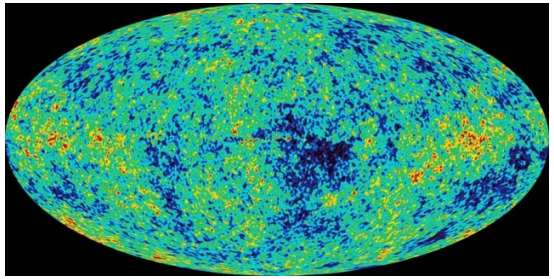
What makes up 85% of matter in the universe?



Why is there no antimatter in the universe?

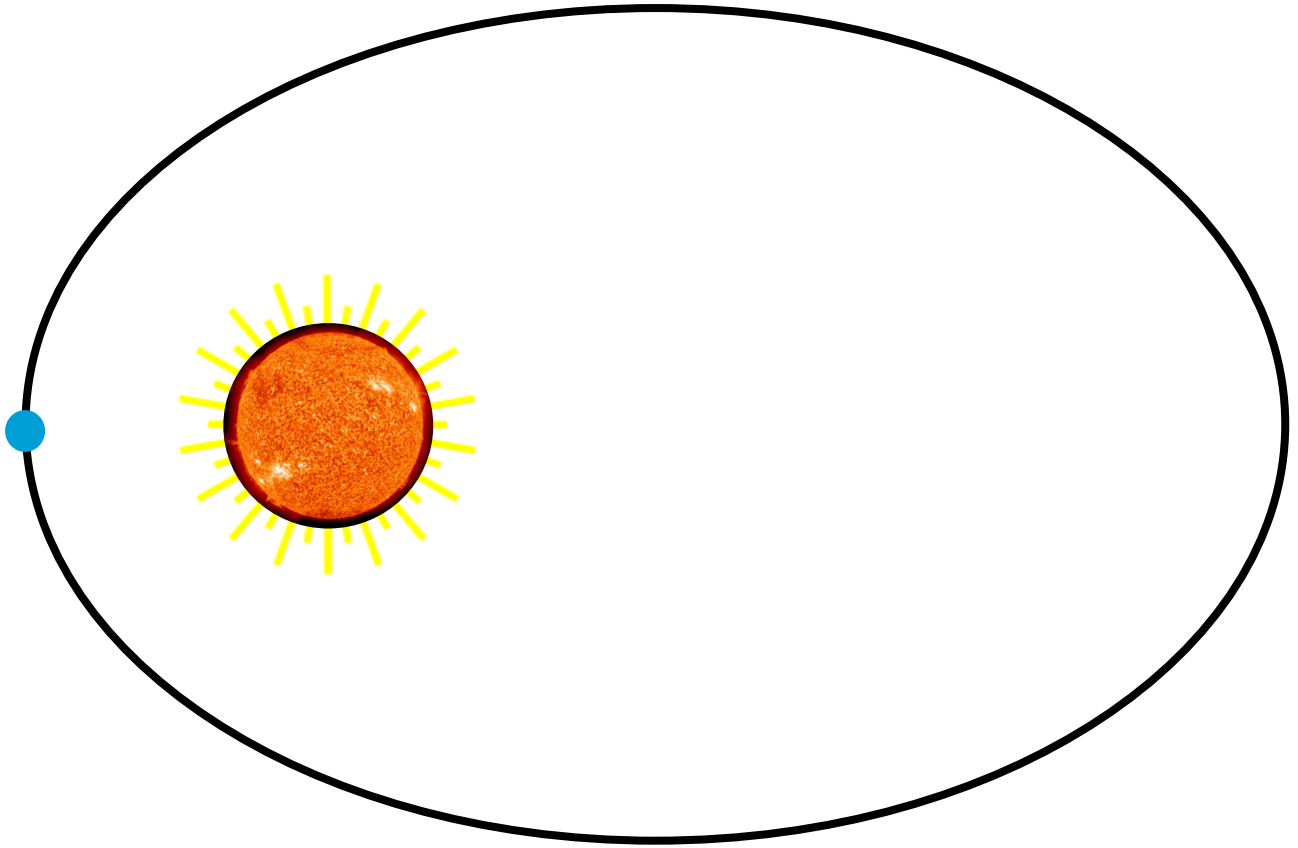


Precision observables and anomalies



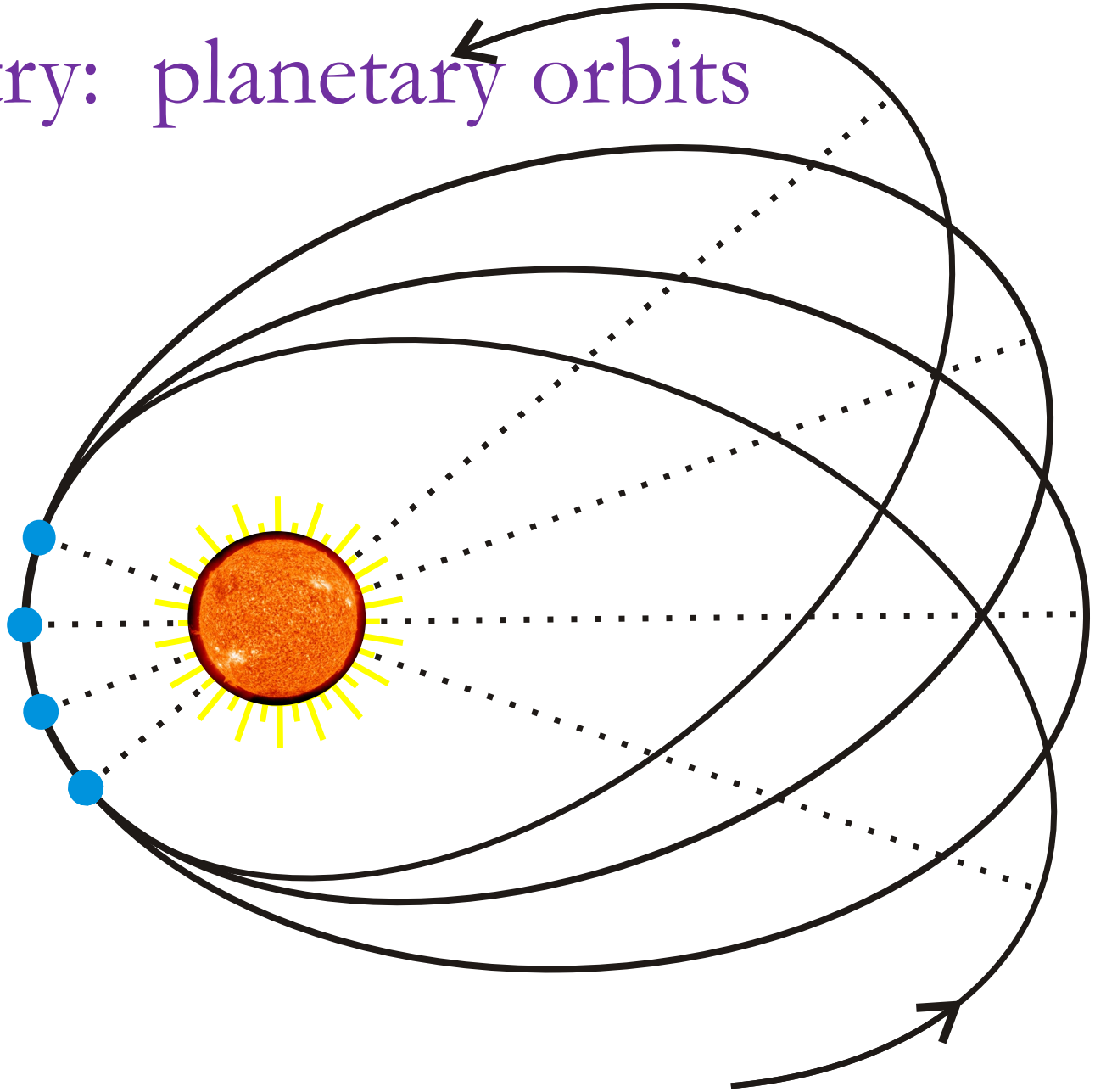
The power of symmetry: planetary orbits

- Kepler's first law of planetary motion: the orbit is an ellipse with the sun at one focus
- Symmetry: the long axis can point in any direction
- Broken symmetry: at any given time, the long axis points in a specific direction
  - Sensitive to perturbations...

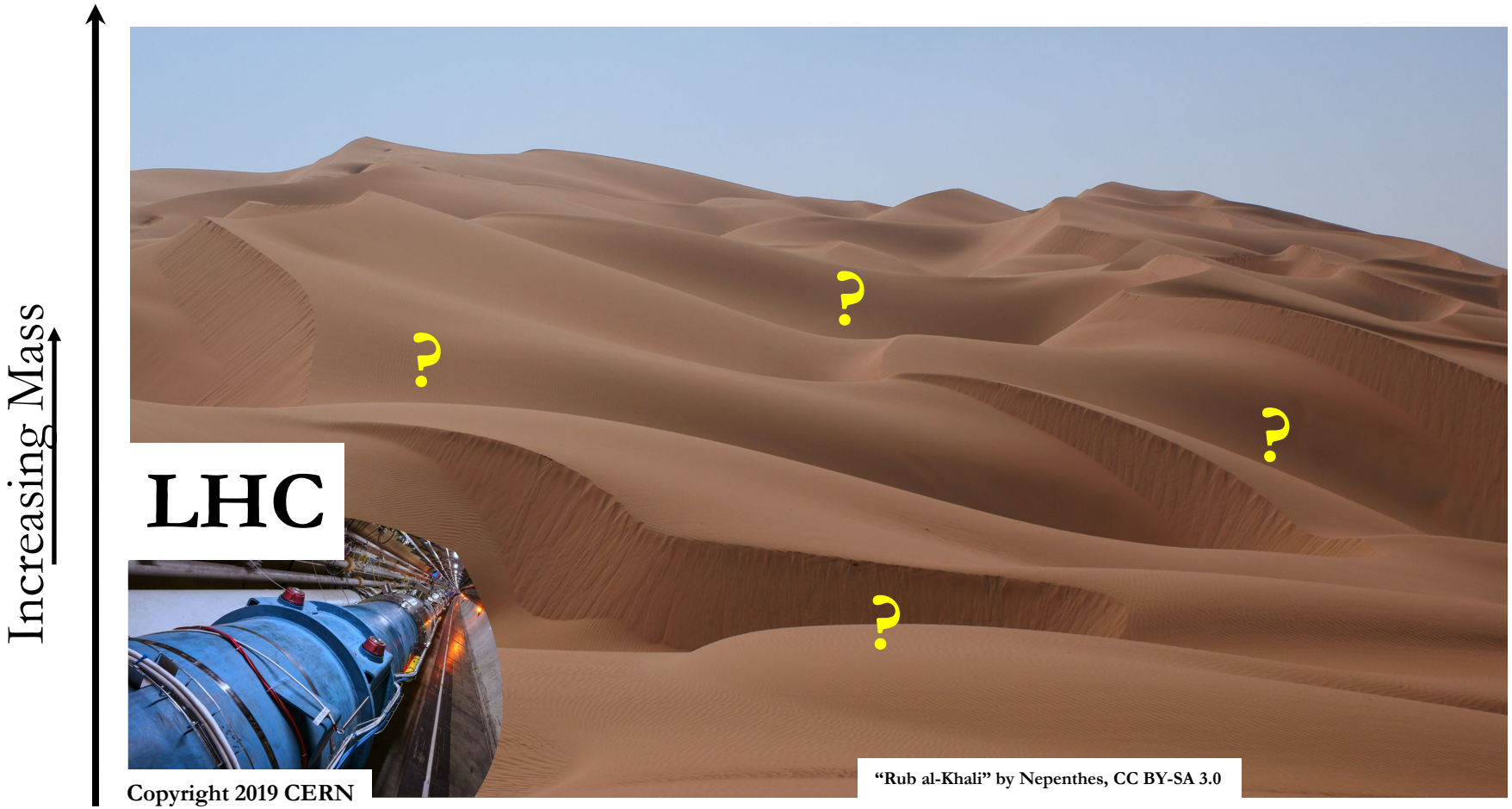


The power of symmetry: planetary orbits

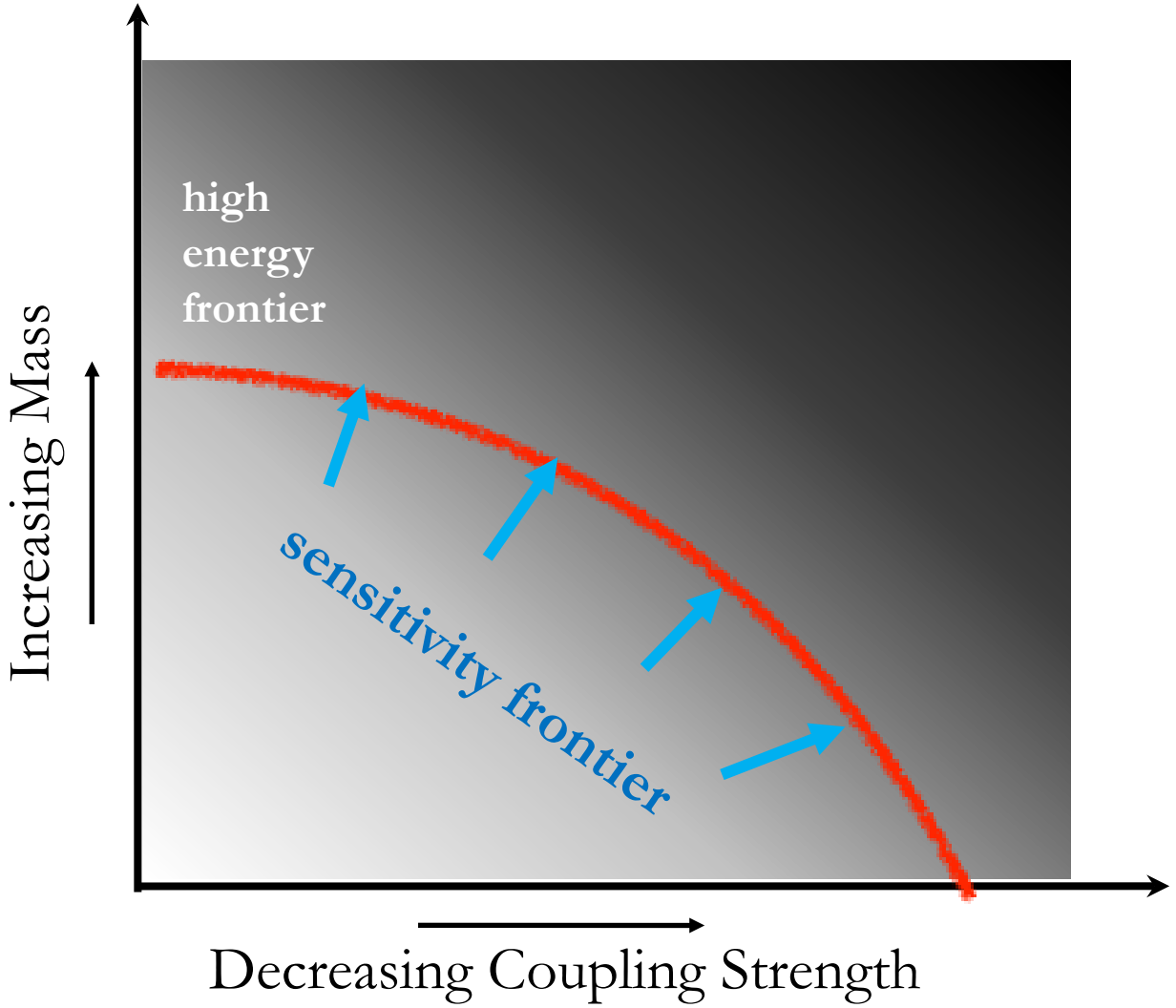
- Precession of Mercury's orbit
  - 574" per earth century observed
  - Outer planets explained 531" per earth century
- New particle? Planet Vulcan?
- New model? **General relativity**
- Use symmetry to find new physics!



What would "new physics" look like?



What would "new physics" look like?

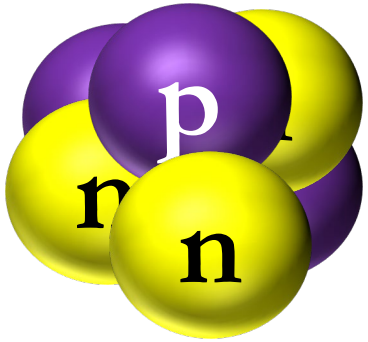


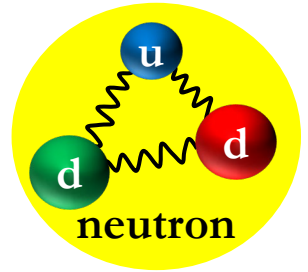
The neutron, symmetry, and our universe

- Symmetries and precision measurements are powerful tools to search for hints of new physics which can explain some of the biggest mysteries in science
- **The neutron as a laboratory**
- How well do we understand the weak interaction?
- Can our matter turn into antimatter (or dark matter)?
- Concluding remarks

The neutron

- Baryon (3 quarks): up + down + down
- Mass: 1.0087 a.m.u. or 940 MeV
  (Proton: 1.0073 a.m.u or 938 MeV)
- Spin: ½
- Charge = 0



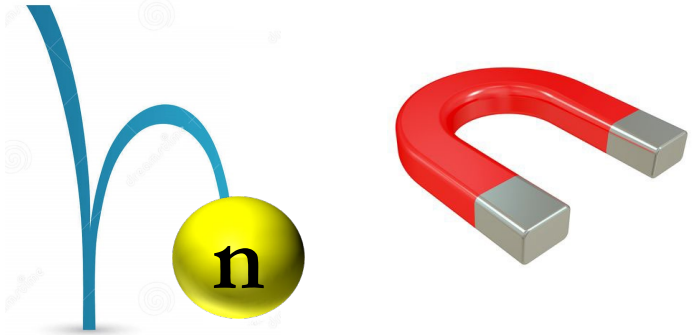


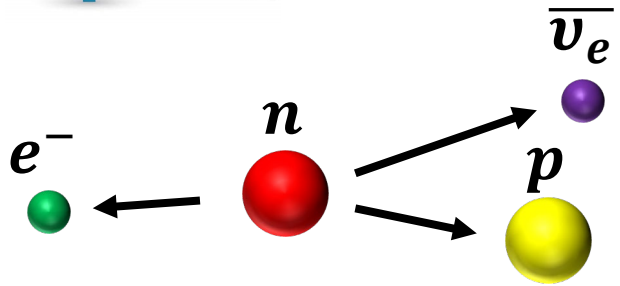
- Important for stabilizing atoms!
- Lots of energy required (MeV scale) to free neutrons from atom
- Experiments need slow neutrons

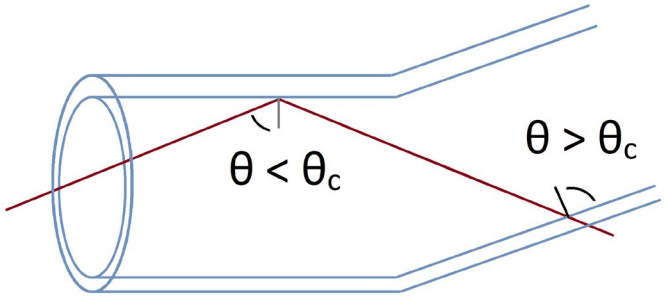
Class	Energy	Source
Fast	> 1 MeV	Fission / spallation
Slow	eV – keV	Moderation
Thermal	0.025 eV	Thermal equilibrium
Cold	μeV – meV	Cold moderation
Ultracold	< 300 neV	Superthermal process

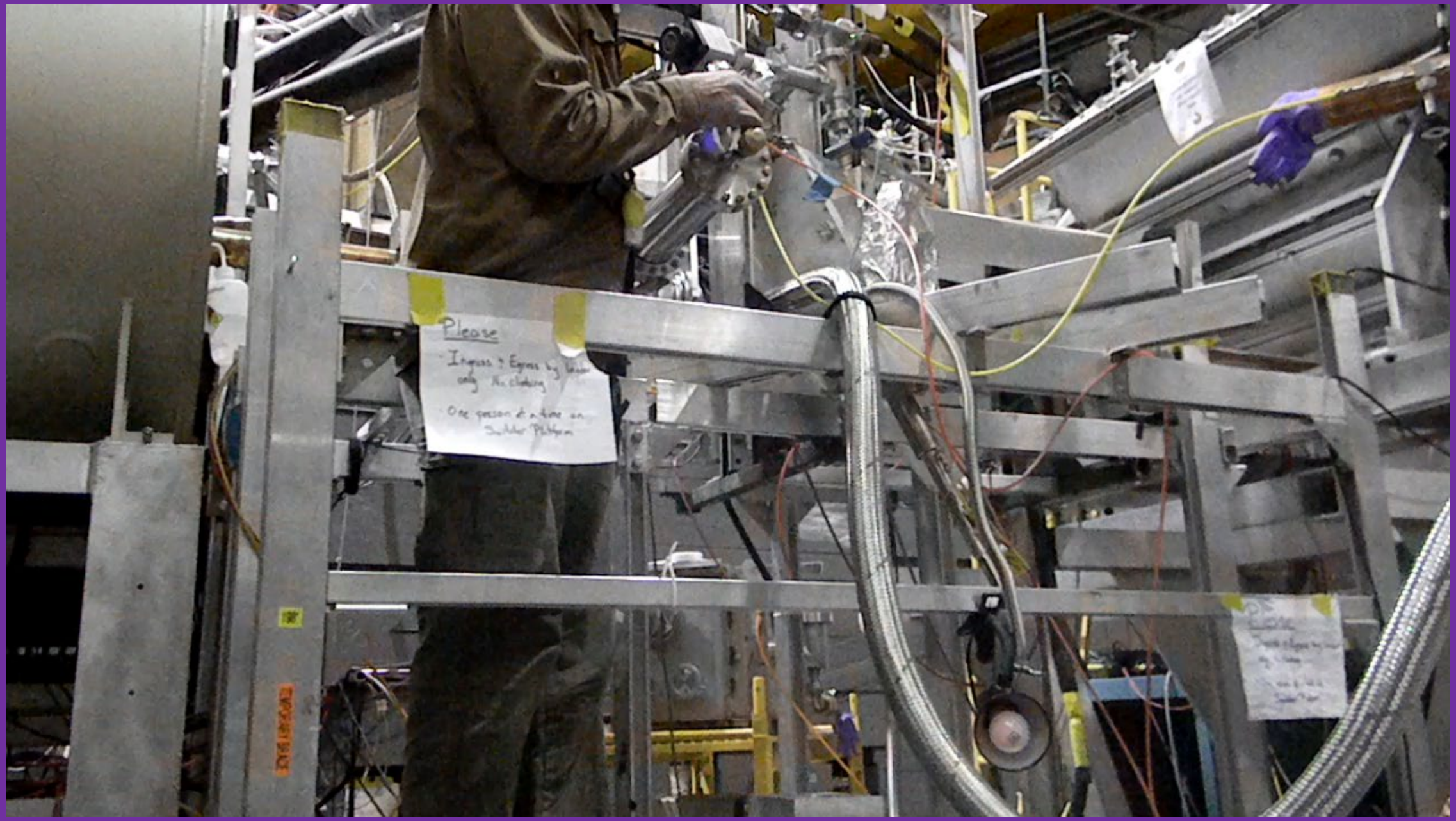
The free neutron and its interactions

- Influence of all 4 forces are important to cold neutrons
- **Gravity**: ~100 neV per m
- **Electromagnetism**:
  - Magnetic dipole moment: 60 neV per 10,000 G (Earth field is ~0.5 G)
  - Electric dipole moment: 0 e-cm (?)
- **Weak**: beta-decays into a proton
- **Strong**: colds neutrons have an index of refraction, reflect from material walls
  - Ultracold neutrons are totally internally reflecting $\theta_c = 90°$







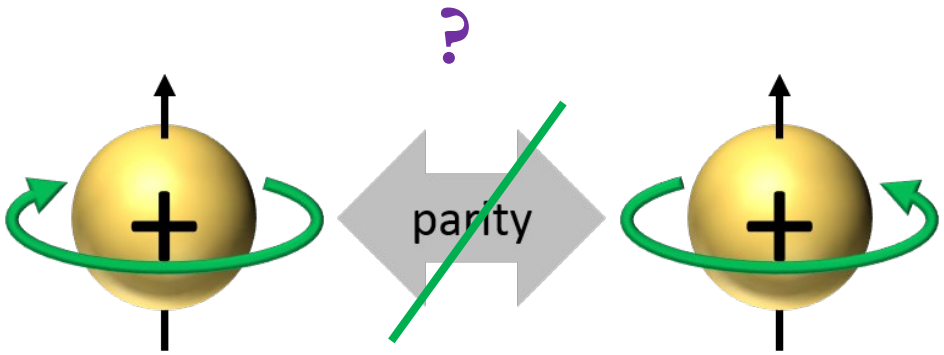

Please

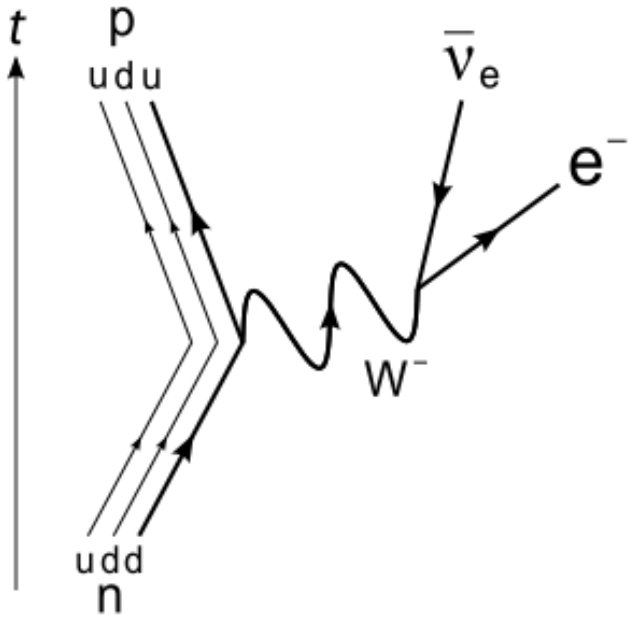
The neutron, symmetry, and our universe

- Symmetries and precision measurements are powerful tools to search for hints of new physics which can explain some of the biggest mysteries in science
- The neutron's unique properties make it an ideal laboratory for these sensitive studies
- **How well do we understand the weak interaction?**
- Can our matter turn into antimatter (or dark matter)?
- Concluding remarks

The Weak Interaction

- Weak interaction is the only one that violates **Parity symmetry**
  - Only couples to Left-Handed particles
  - (We don't understand why)
- Weak interaction is the only one that can change quark / lepton flavor
- Beta decay a type of weak interaction
- Neutron is simplest "nucleus" to undergo beta decay





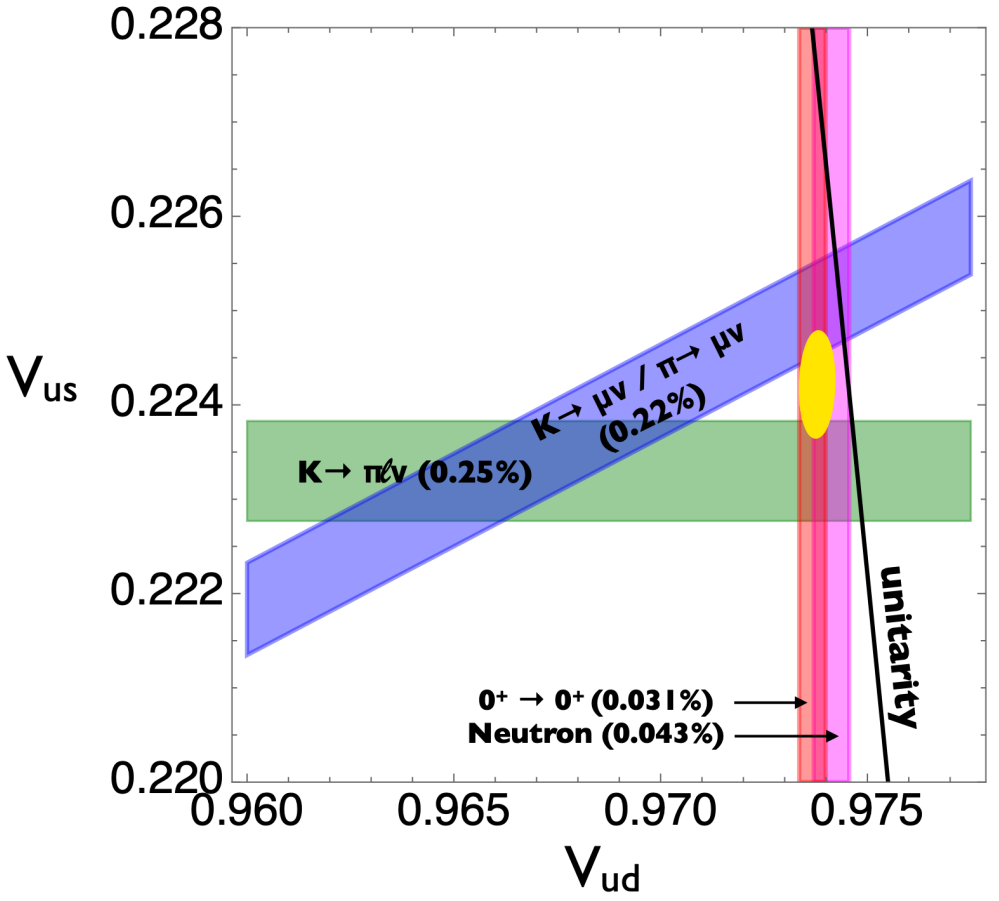
Quark Mixing in the Weak Interaction

- Cabibbo – Kobayashi – Maskawa CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \text{new physics}$$

- Should behave like a rotation matrix (we call it "unitarity")
- Powerful broadband test: failure is an indicator of missing physics.



$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1\text{-}\mathbf{15(5)} \times \mathbf{10^{-4}}$$

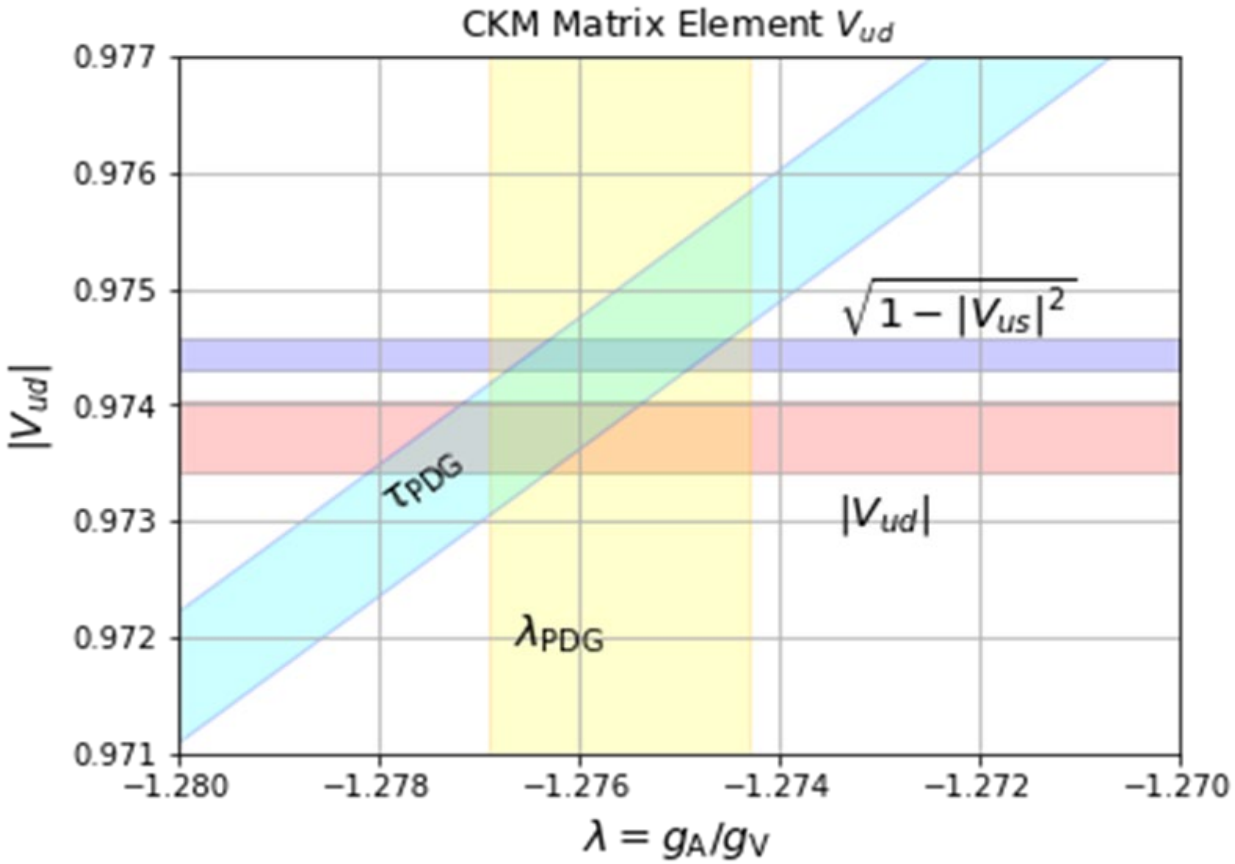
arXiv:2208.11707 and references therein

V_{ud} from neutron beta decay

- Nuclear decays give most precise value, but sensitive to nucleus-dependent corrections
- Is 3σ anomaly New Physics? We need a cross-check from the neutron system
- Neutron decay requires 2 measurements to fix 2 unknowns

$$\tau^{-1} \propto (V_{ud})^2(1 + 3(\lambda)^2)$$

  - Decay lifetime
  - Decay correlations
- Need experimental improvements in both to provide competitive determination



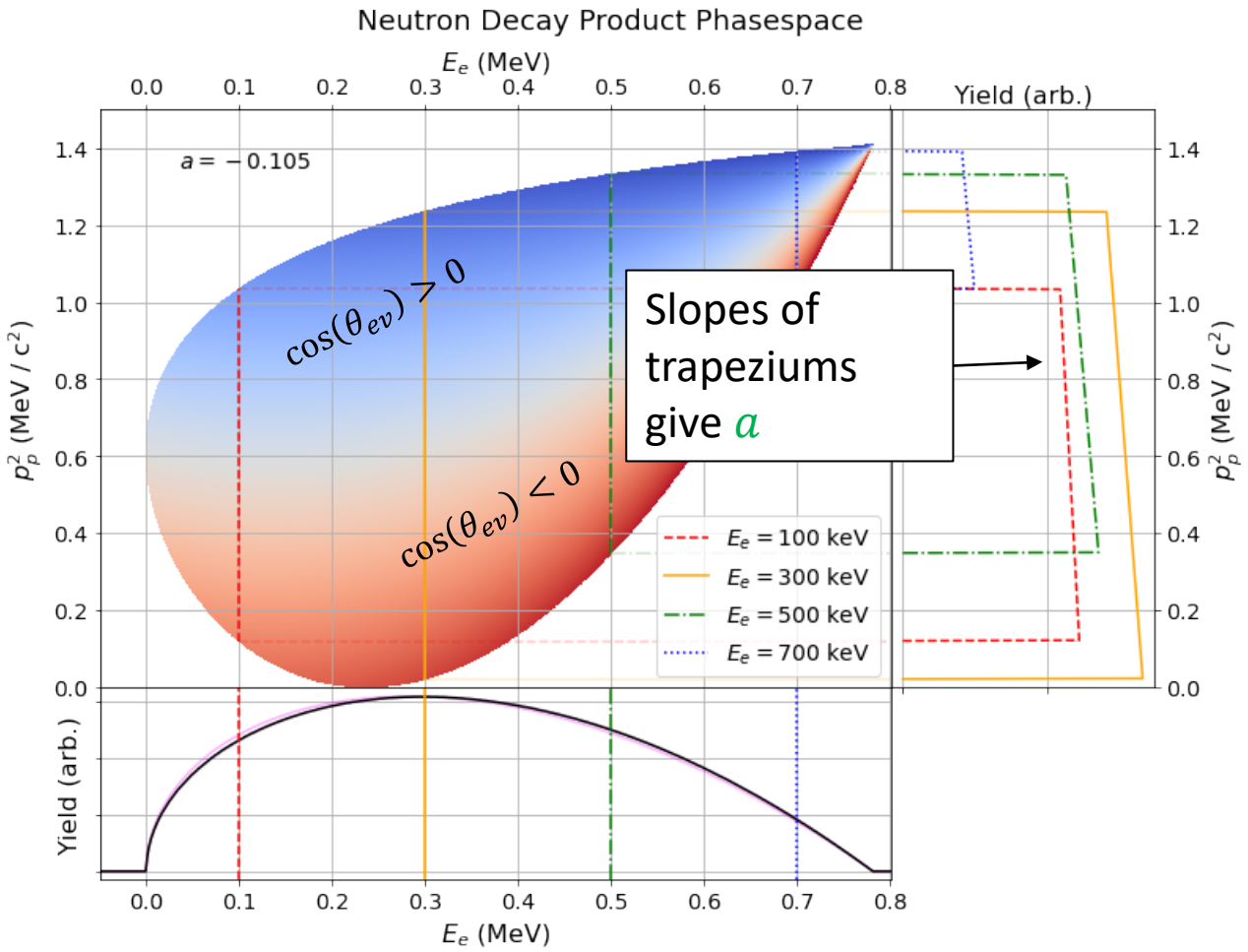
Plot from: F. Gonzalez (ORNL) Data from:
Workman, R. L. *et al*, Particle Data Group (2022)

Accessing λ via neutron decay correlations

- $\lambda = g_A/g_V$: left-handed weak interaction in the background of the strong interaction
- Decay rate is modified, e.g.:

$$dW \propto 1 + a\frac{|\vec{p_e}|\,|\vec{p_\nu}|}{E_e E_\nu}\cos(\theta_{e\nu})$$

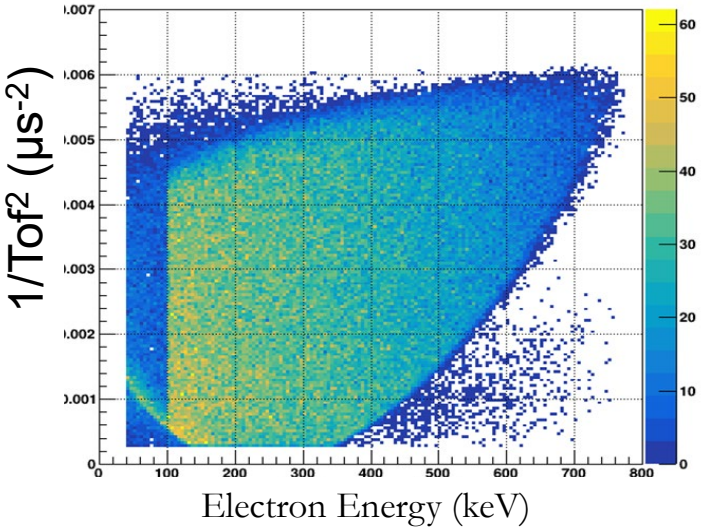
- Neutrino not detected; can relate to proton + electron using conservation of energy + momentum
- If we can reconstruct E_e, p_p^2 for each decay, we can extract a



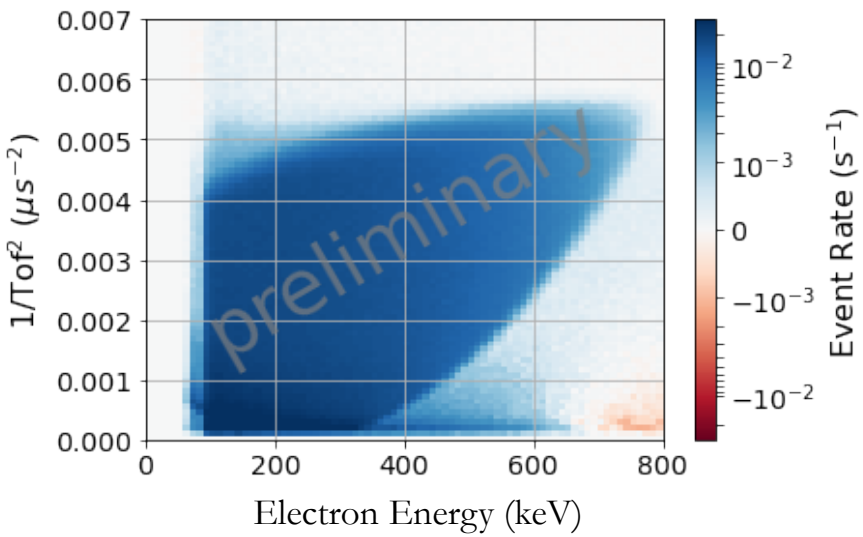
The Nab experiment

- Electron energy is detected directly
- Proton momentum determined by time-of-flight (TOF) relative to "instant" electron
  - Magnetic filter only permits protons moving straight up
- First "teardrop" data taken in 2023

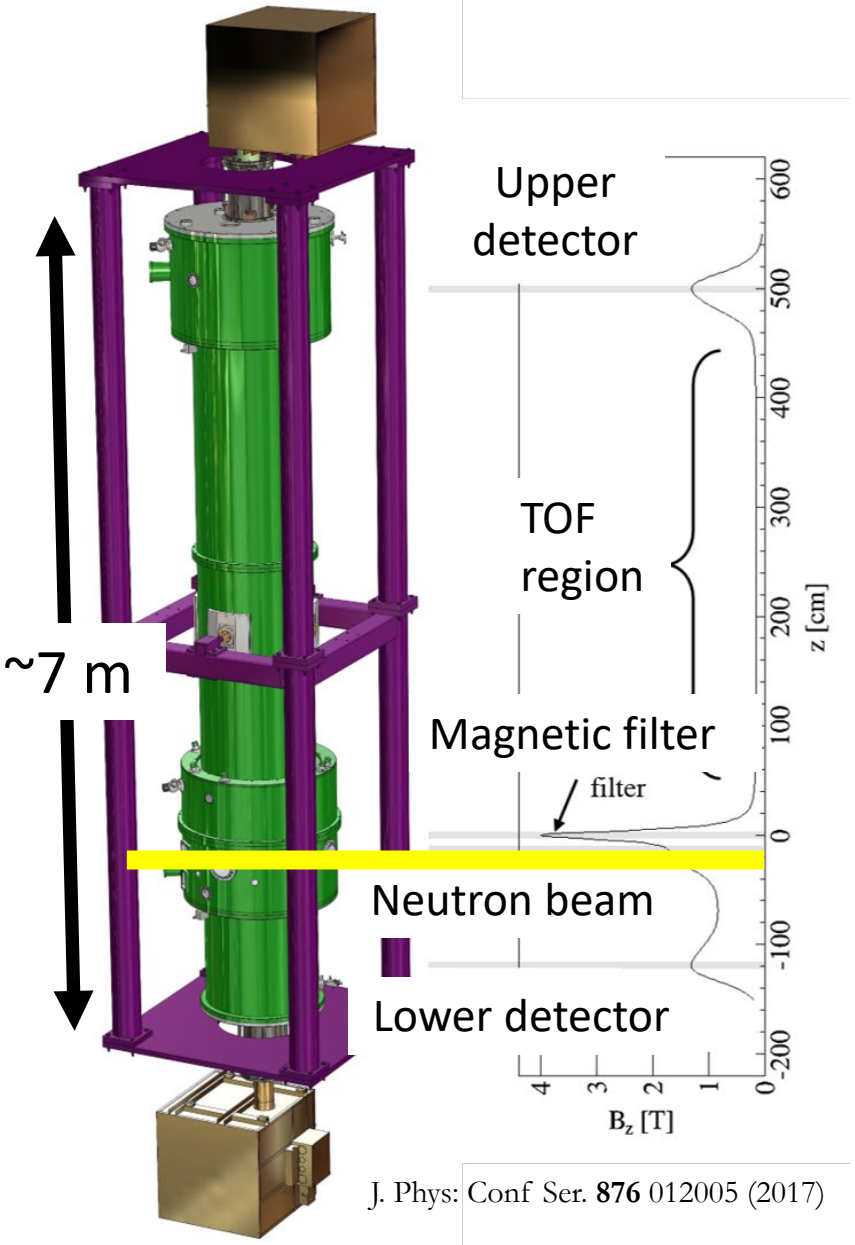
Simulated



Measured



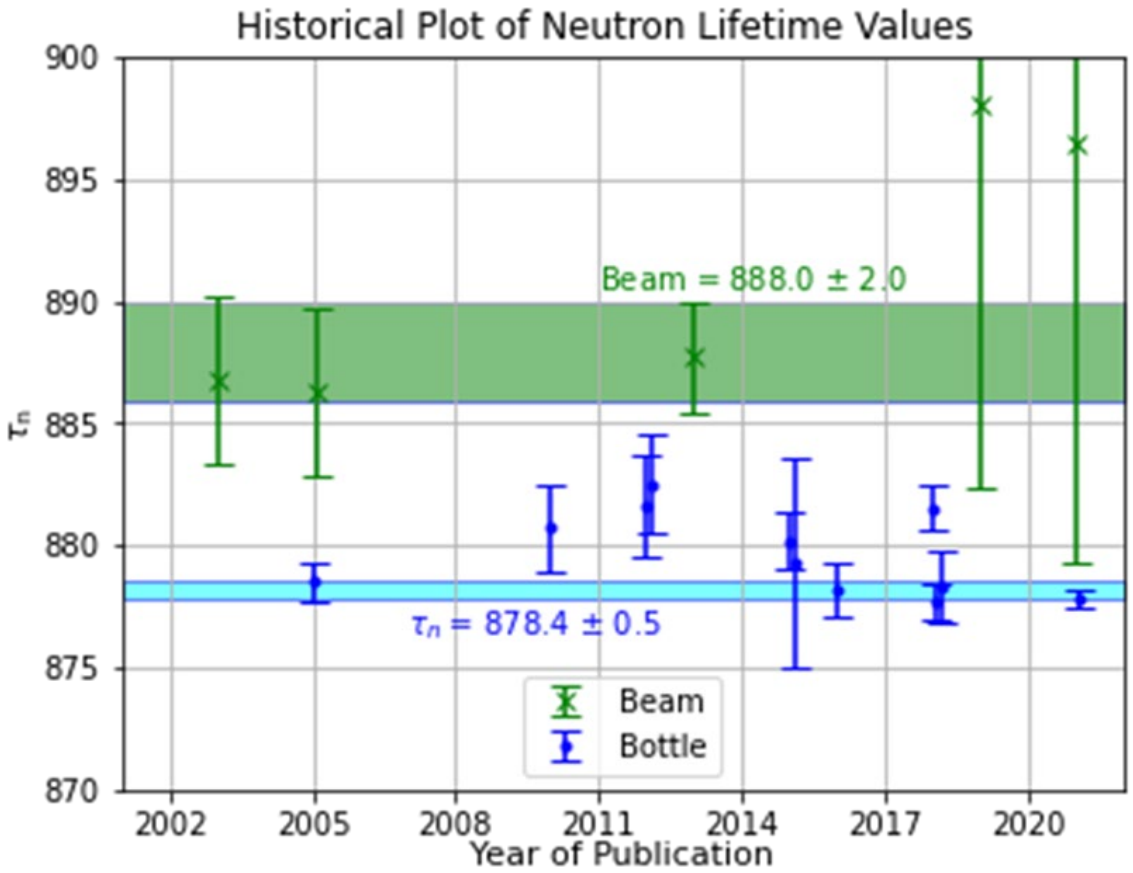
Plots from: F. Gonzalez (ORNL



J. Phys: Conf Ser. **876** 012005 (2017)

Neutron decay lifetime: a puzzle

- "Bottle" technique: use a bottle of ultracold neutrons, observe surviving neutrons
- "Beam" technique: use a beam of cold neutrons, count decays into protons
- 4σ discrepancy persists between "beam" and "bottle" measurements Atoms 6 (2018) 4



- Do neutrons disappear into something other than protons?

Plot from: F. Gonzalez (ORNL) Data from:
Workman, R. L. *et al*, Particle Data Group (2022)

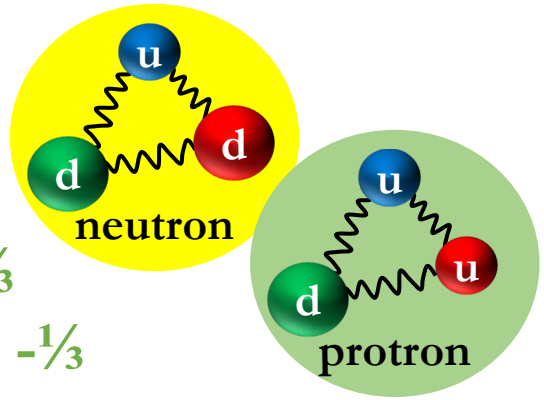
The neutron, symmetry, and our universe

- Symmetries and precision measurements are powerful tools to search for hints of new physics which can explain some of the biggest mysteries in science
- The neutron's unique properties make it an ideal laboratory for these sensitive studies
- We can characterize the weak interaction in exceptional detail, and very broadly search for new physics, in upcoming experiments.
- **Can our matter turn into antimatter (or dark matter)?**
- Concluding remarks

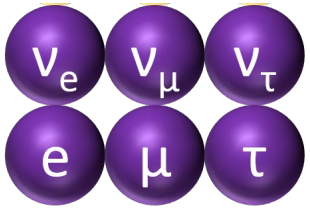
How to create a universe made of matter?

- Natural to expect that Big Bang should have produced matter = antimatter → total baryon number **B** = 0
- Sakharov: We must have a process that does not conserve **B** to create an excess of matter in the universe

Andrei Sakharov



Quarks: **B** = +⅓
Antiquarks: **B** = -⅓



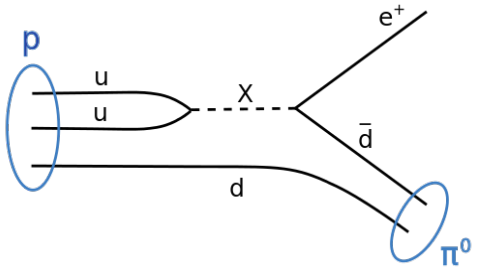
Electrons/
Neutrinos: **L** = +1
Anti-electrons/
Anti-neutrinos: **L** = -1

- It's actually strange that **B** and **L** always seem to be conserved!

Searches for Violation of B and L

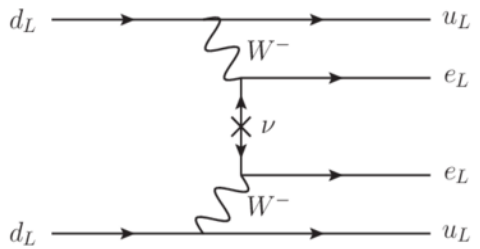
- **Conservation of charge** cannot be violated
- **Proton Decay**: Originally motivated massive detectors!
  - But limit is now > 10^{34} years
  - Universe is 10^{10} years old

$$p \rightarrow e^+ + \pi^0$$
$$\Delta B \neq 0, \Delta L \neq 0$$
$$\Delta[B - L] = 0$$



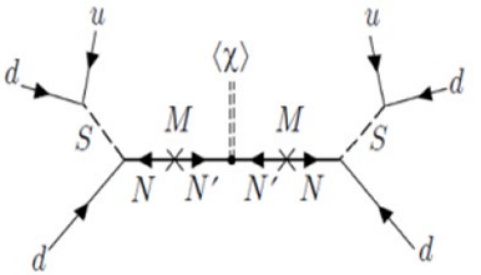
- **Neutrinoless double-beta decay**: vibrant worldwide program already ongoing!

$$0\nu2\beta$$
$$\Delta B = 0, \Delta L \neq 0$$
$$\Delta[B - L] \neq 0$$



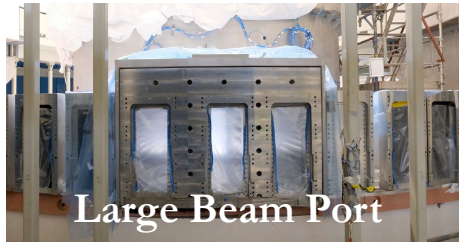
- Complementary approach: **Neutron – antineutron oscillations**

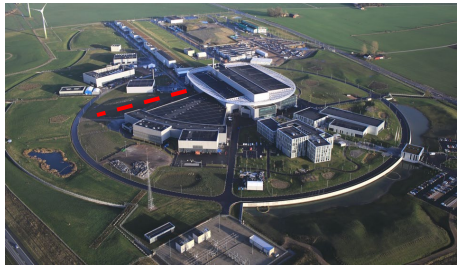
$$n \rightarrow \bar{n}$$
$$\Delta B = 2, \Delta L = 0$$
$$\Delta[B - L] \neq 0$$

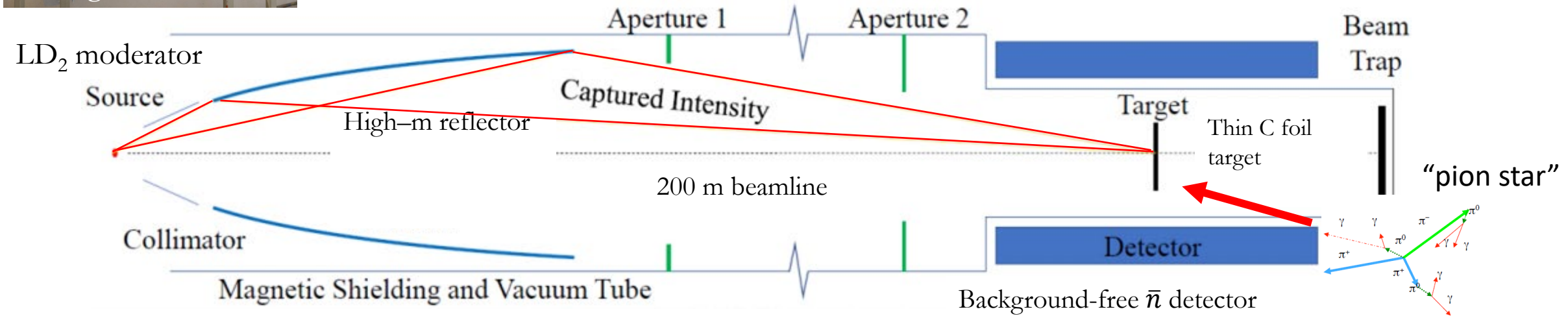


The NNBAR Experiment

- NNBAR at ESS: Leverage 3 decades of advances: moderator design, neutronics, detection, reconstruction techniques ×**1000** sensitivity of ILL [J Phys G 48 070501 (2021)]

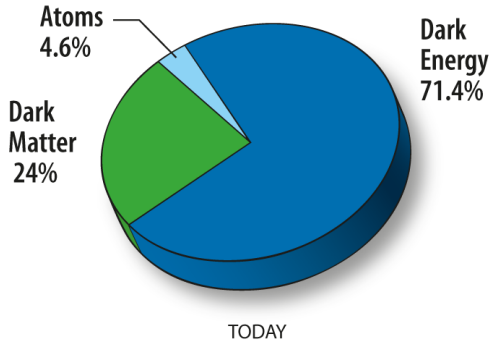




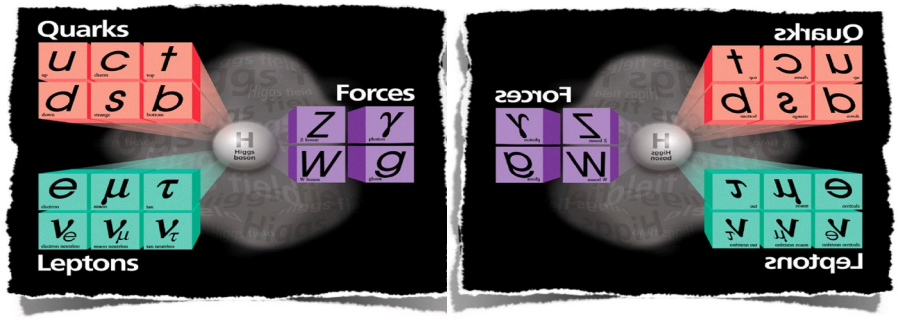


Neutron – Mirror Neutron Oscillations

- Violation of **Baryon Number** closely tied to **matter – antimatter** puzzle
- Could it also be linked to **dark matter**?
  - After decades of searches, we still don't know what particles make up dark matter
- Mirror matter[1]: identical copy of Standard Model with opposite **Parity**
  - Right-handed Mirror Universe
- Prediction: oscillations between neutrons and mirror partners[2]
  - Experimentally testable!



SM **SM′**

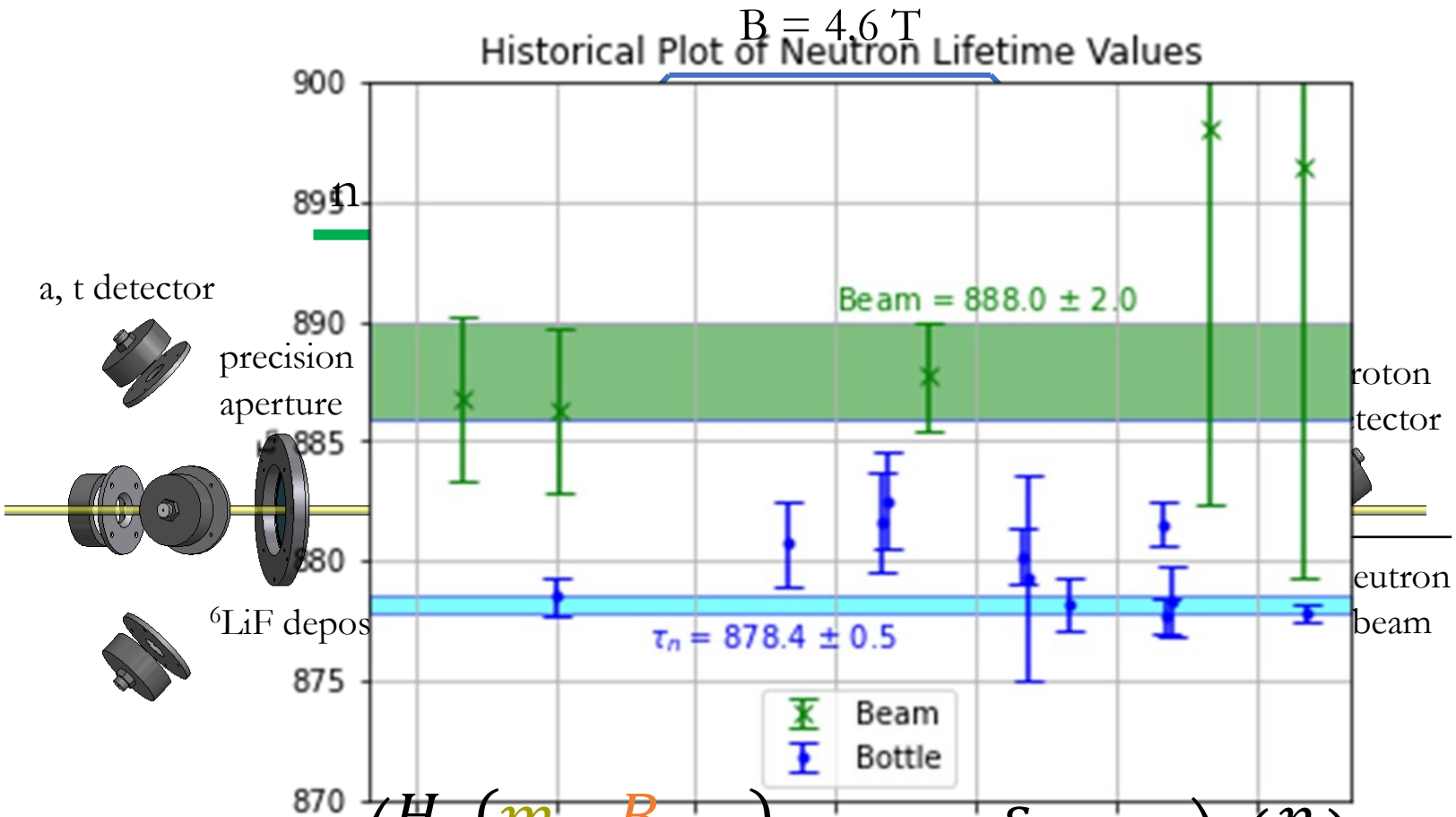


$$\hat{H}\psi = \begin{pmatrix} H_n & \varepsilon \\ \varepsilon & H_{n'} \end{pmatrix} \begin{pmatrix} n \\ n' \end{pmatrix}$$

[1][Phys.Usp. **50** (2007) 380-389, From Fields to Strings **3** (2015) 2147, Phys.Rev. **104** (1956) 254-258] [2]PRL 96 081801 (2006)

Neutron Lifetime Puzzle

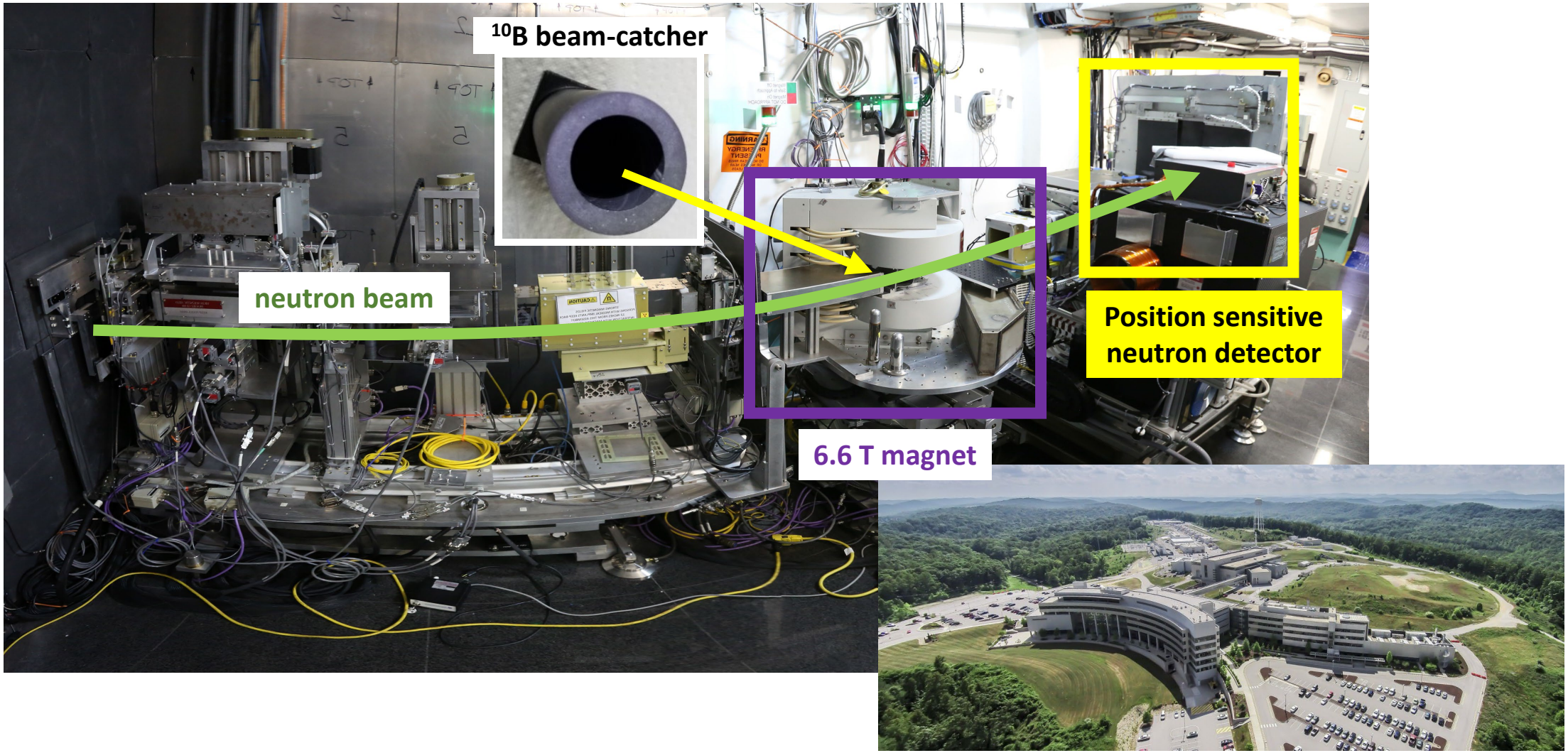
- Beam Lifetime: proton rate too low?
- n, n' mass splitting compensated by B
- Landau-Zener transition: jump into opposite state at energy-crossing
- n' decays into undetectable p'
- Let's test that…



$$\hat{H}\psi = \begin{pmatrix} H_n(m_n, B, \ldots) & \varepsilon \\ \varepsilon & H_{n'}(m_{n'}, \ldots) \end{pmatrix} \begin{pmatrix} n \\ n' \end{pmatrix}$$

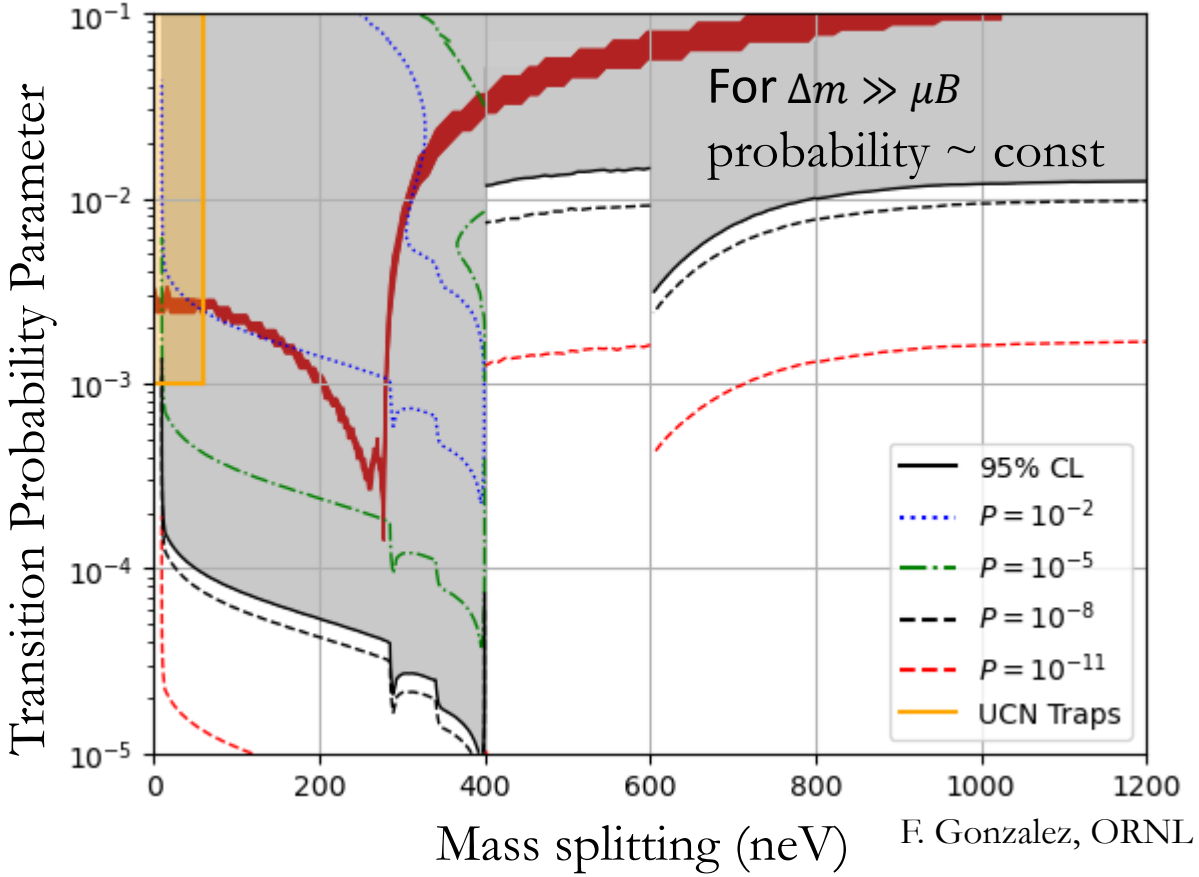
EPJC 79 (2019) 484

$n \to n' \to n$ @ SNS experiment approach



Does $n \to n'$ explain neutron lifetime anomaly?

- No signal found above background
- Compare to expectation in NIST Beam Lifetime magnet
  - Red = these values would explain lifetime discrepancy
  - Gray = we ruled these values out!
- **Conclusion**: this exotic process does NOT explain neutron lifetime anomaly
- Experimental limits recently improved further! (arXiv:2402.15981)



Gray – Excluded transmission < 2.5 x 10^{-8} (95% C.L.)
Red – 1% ± 0.2% difference in neutron lifetime
Dashed – Probability bands

PRL 128 (2022) 212503

Summary

- Symmetries and precision measurements are powerful tools to search for hints of new physics which can explain some of the biggest mysteries in science
- The neutron's unique properties make it an ideal laboratory for these sensitive studies
- We can characterize the weak interaction in exceptional detail, and very broadly search for new physics, in upcoming neutron experiments.
- New searches for B-violation are strongly motivated! Neutron oscillations are under-explored with significant improvements on the horizon