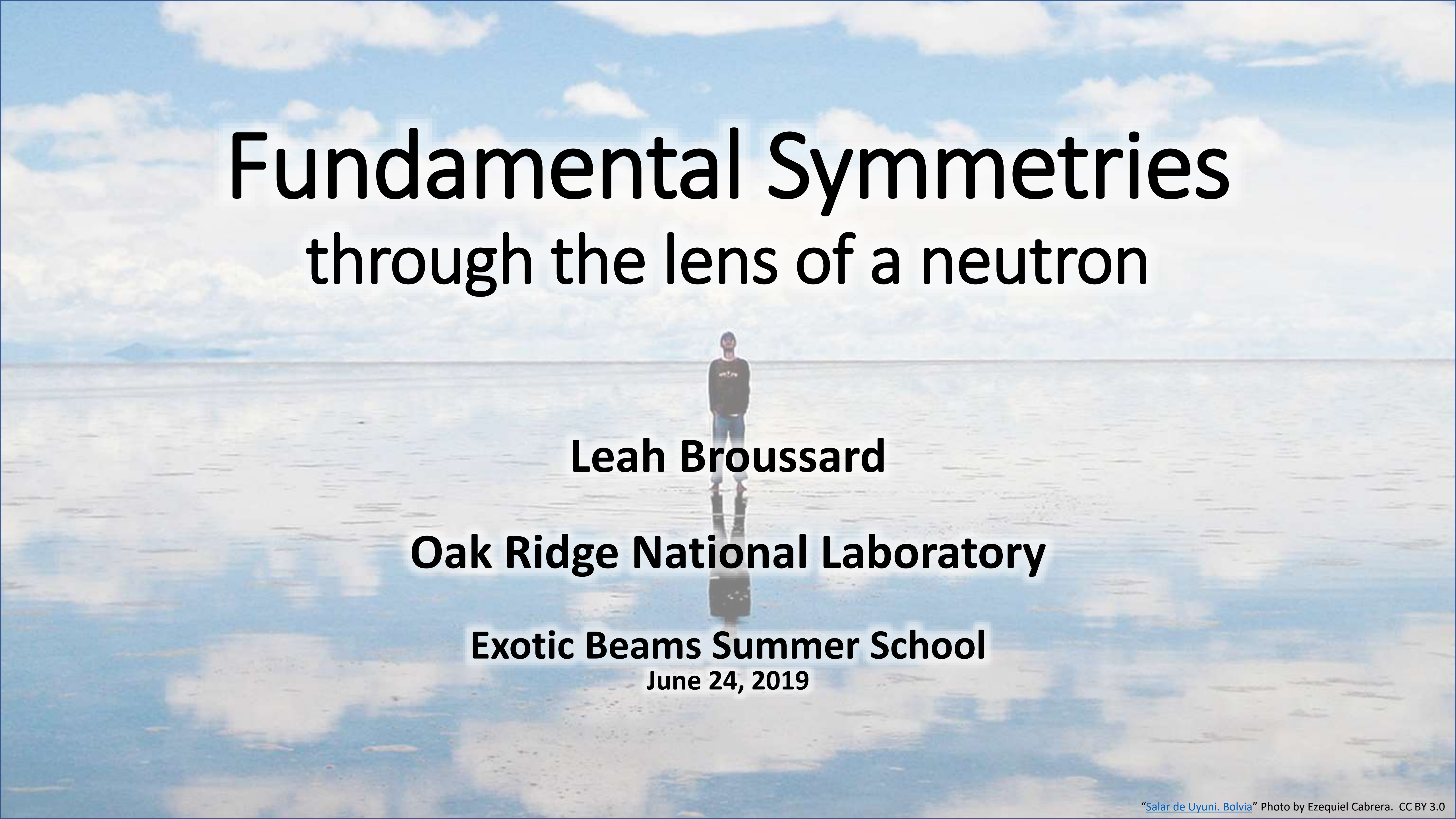


Fundamental Symmetries

through the lens of a neutron

Leah Broussard

Oak Ridge National Laboratory

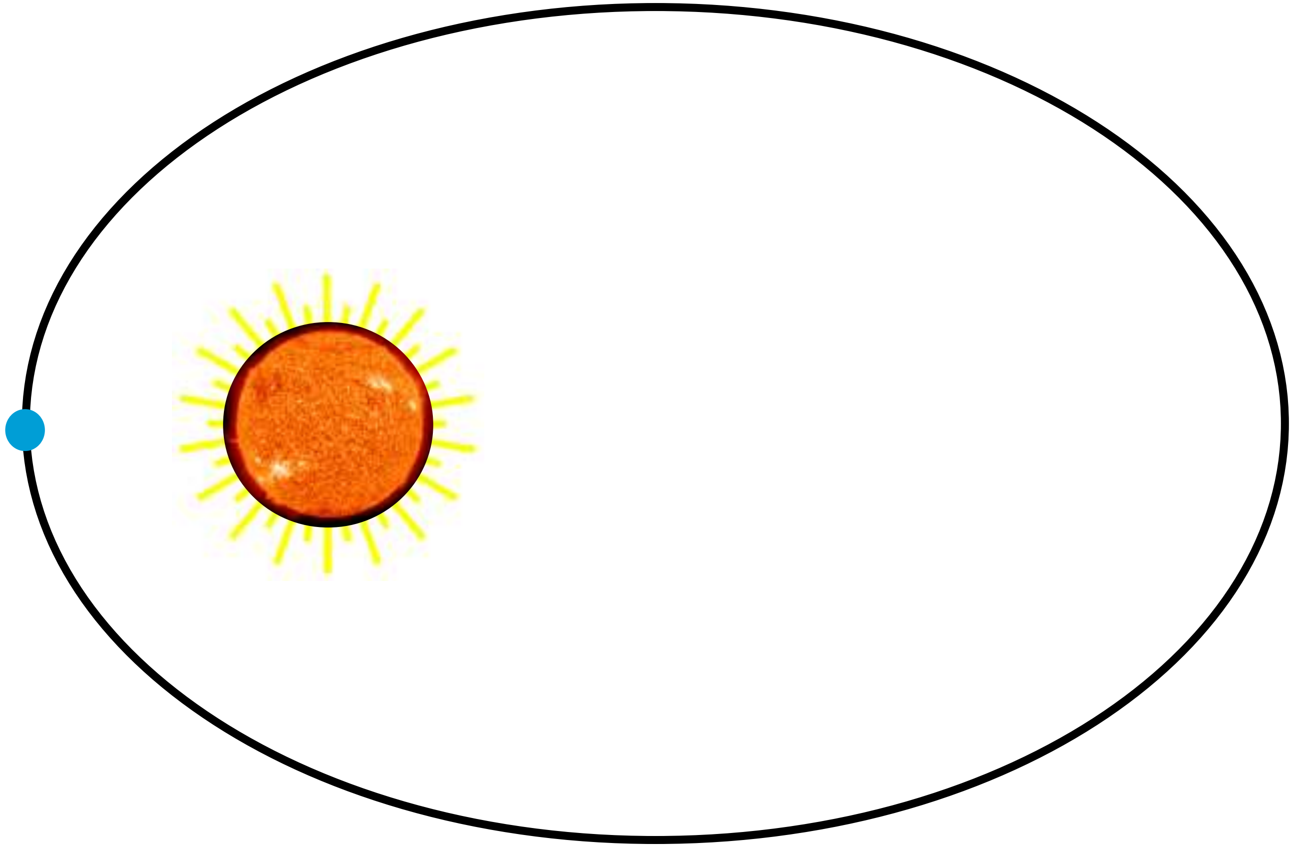
Exotic Beams Summer School

June 24, 2019

“Salar de Uyuni. Bolvia” Photo by Ezequiel Cabrera.

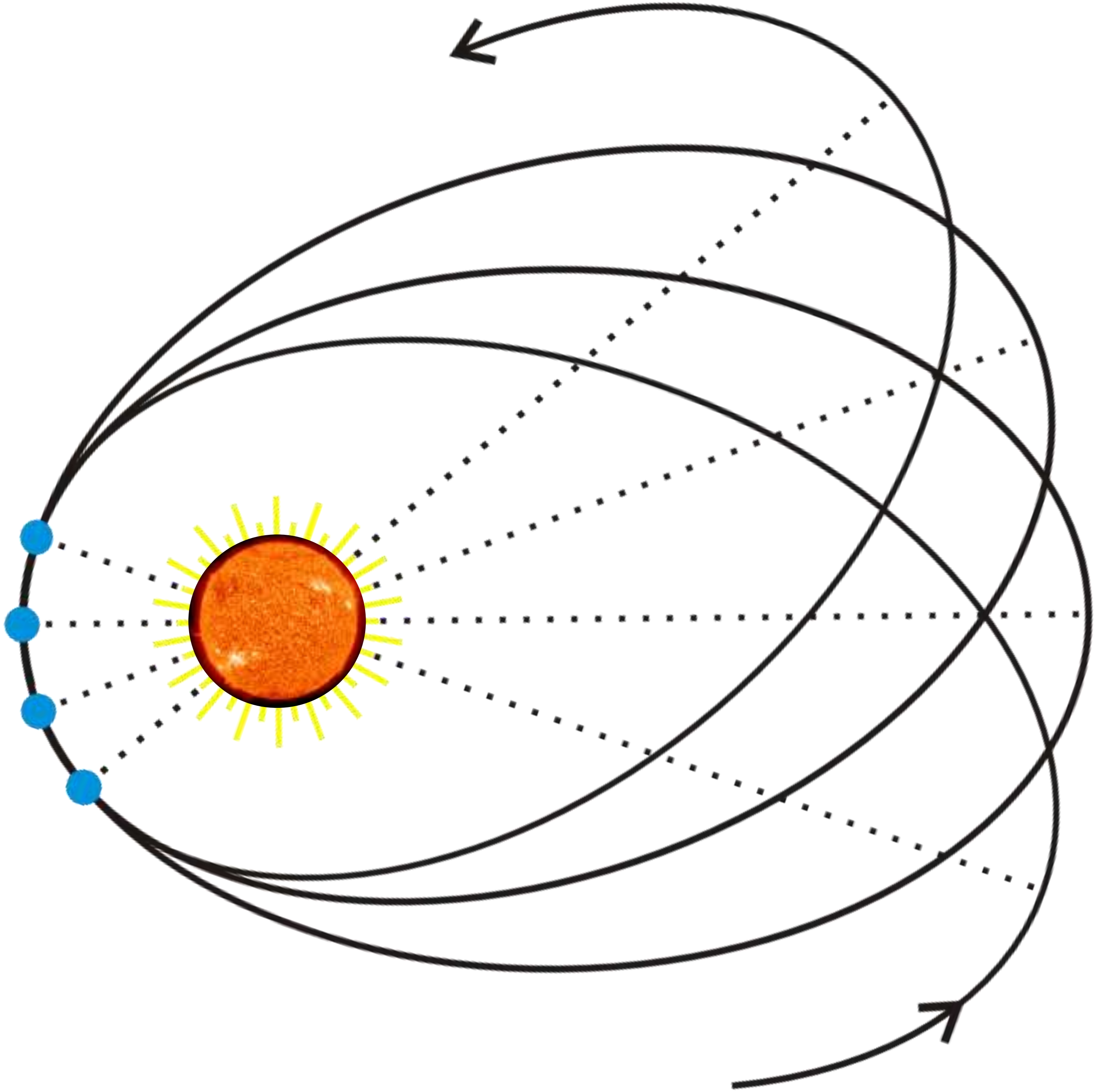
Planetary orbits

- 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...

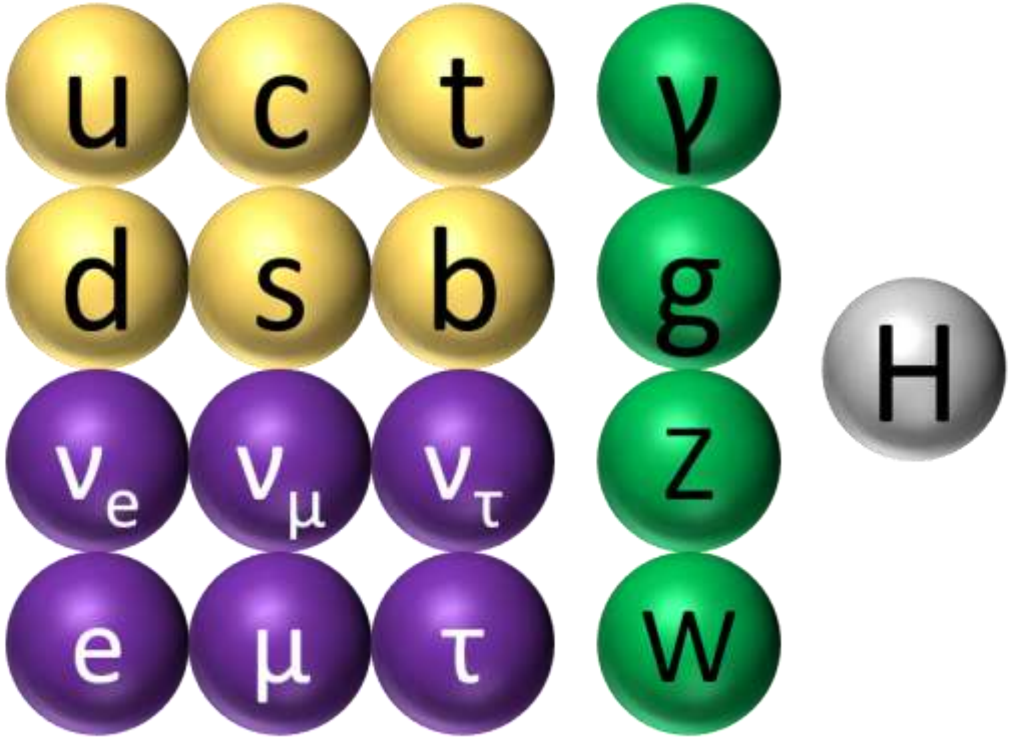


Planetary orbits

- Precession of Mercury's orbit
  - 565" per earth century observed
  - Outer planets explained 527" per earth century
- New particle? Planet Vulcan?
- New model? **General relativity**
- Use symmetry to find new physics!



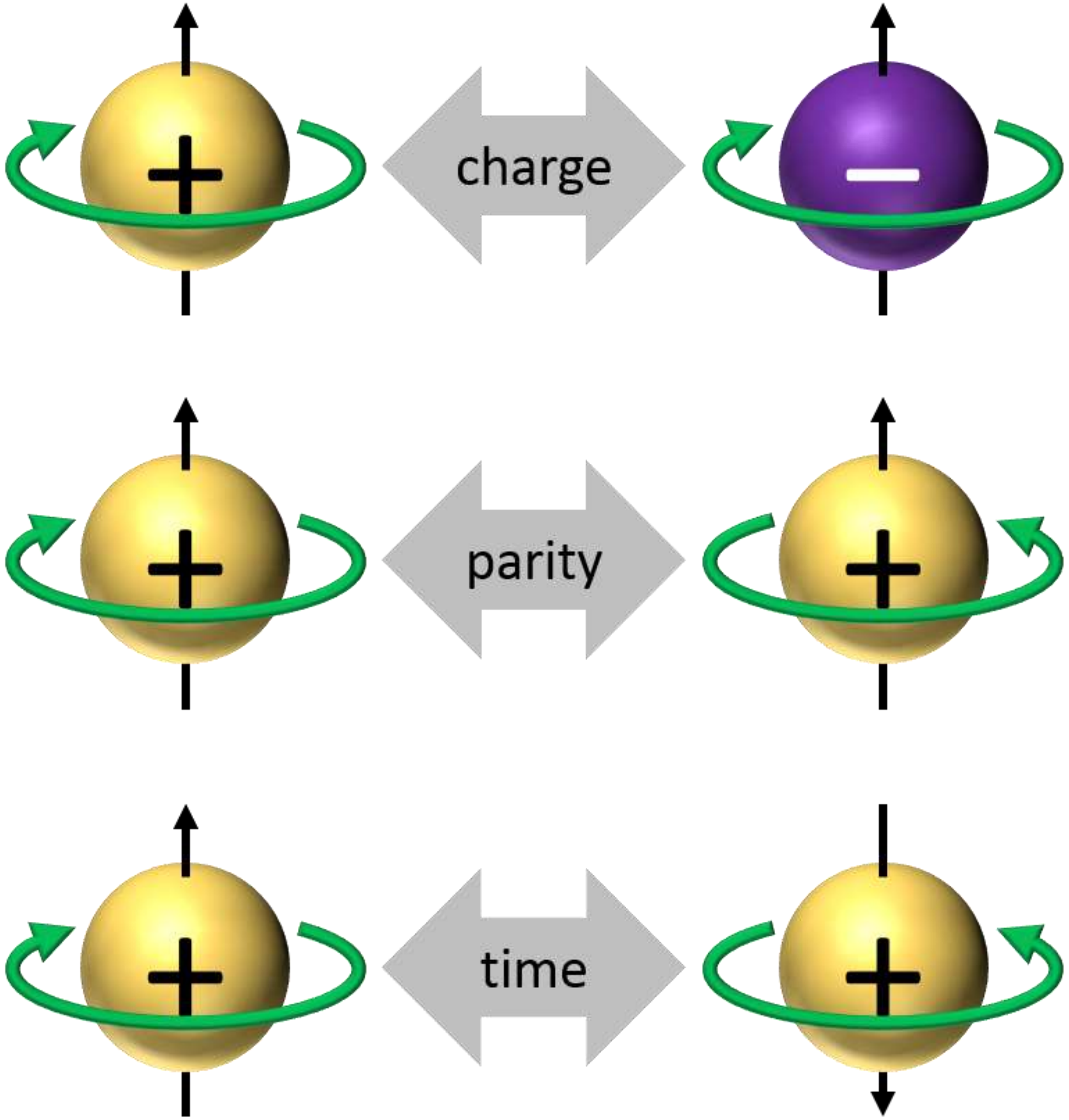
Standard Model of Particle Physics



- Many questions: gravity? dark matter? missing antimatter? fine-tuning? 26 free parameters?
- We haven't seen new particles at the LHC (yet)…
- Is there an underlying framework?
- Is there an underlying symmetry?

Symmetries in nature

- Spacetime symmetries
  - Time, Space, Rotations
- Permutation symmetries
  - Fermi-Dirac/Bose-Einstein statistics
- Internal symmetries
  - Charge, Lepton #, Baryon #, ...
- Discrete symmetries
  - Charge, Parity, Time

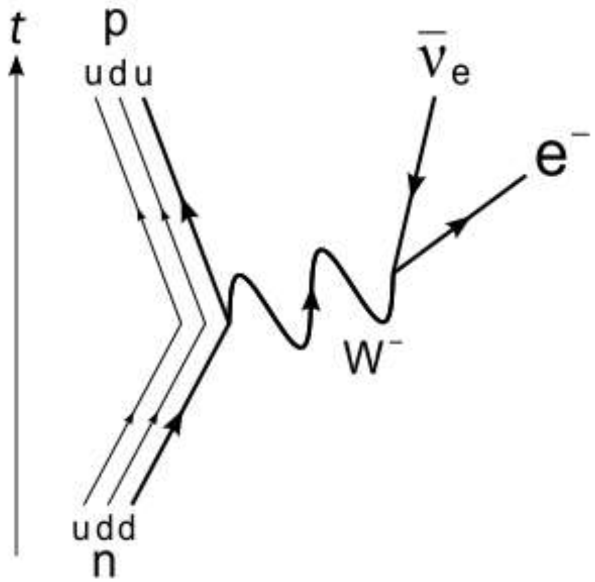


Outline

- P-violation and the weak interaction
- CP-violation and the electric dipole moment
- B-violation and oscillations

Neutron beta decay

- Weak interaction mixes quarks
  - "beta" = electron/positron emitted to conserve charge, along with (anti-)neutrino
- Neutron is simplest "nucleus" to beta decay
- CKM Unitarity test
  - If you rotate, and unrotate, you should get back where you started
  - As you rotate, your yardstick shouldn't change length



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

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Failure means some new physics is missing…

The electroweak interaction

- General interaction vertex

Scalar	$\bar{\psi}\phi$
Pseudoscalar	$\bar{\psi}\phi$
Vector	$\bar{\psi}\gamma^{\mu}\phi$
Axial Vector	$\bar{\psi}\gamma^{\mu}\gamma^{5}\phi$
Tensor	$\bar{\psi}(\gamma^{\mu}\gamma^{\nu}-\gamma^{\nu}\gamma^{\mu})\phi$

- Could other currents be participating?

- Weak interaction has experimentally observed form:

$$J^{\mu}_{had} = V_{ud}\bar{u}\left(\gamma^{\mu}-\gamma^{\mu}\gamma^{5}\right)d$$
$$J^{\mu}_{lep} = \bar{e}\left(\gamma^{\mu}-\gamma^{\mu}\gamma^{5}\right)\upsilon_{e}$$

- Helicity operator $1-\gamma^{5}$ projects out left-handed particles/right-handed antiparticles
- Weak interaction **V-A** is **maximally parity-violating**

Nuclear beta decay

- $0^+ \rightarrow 0^+$ Fermi decays:

  $ft =$ K

- Nuclear mirror decays:

  K $\mathcal{}_T|^2)$

- Define … remov…

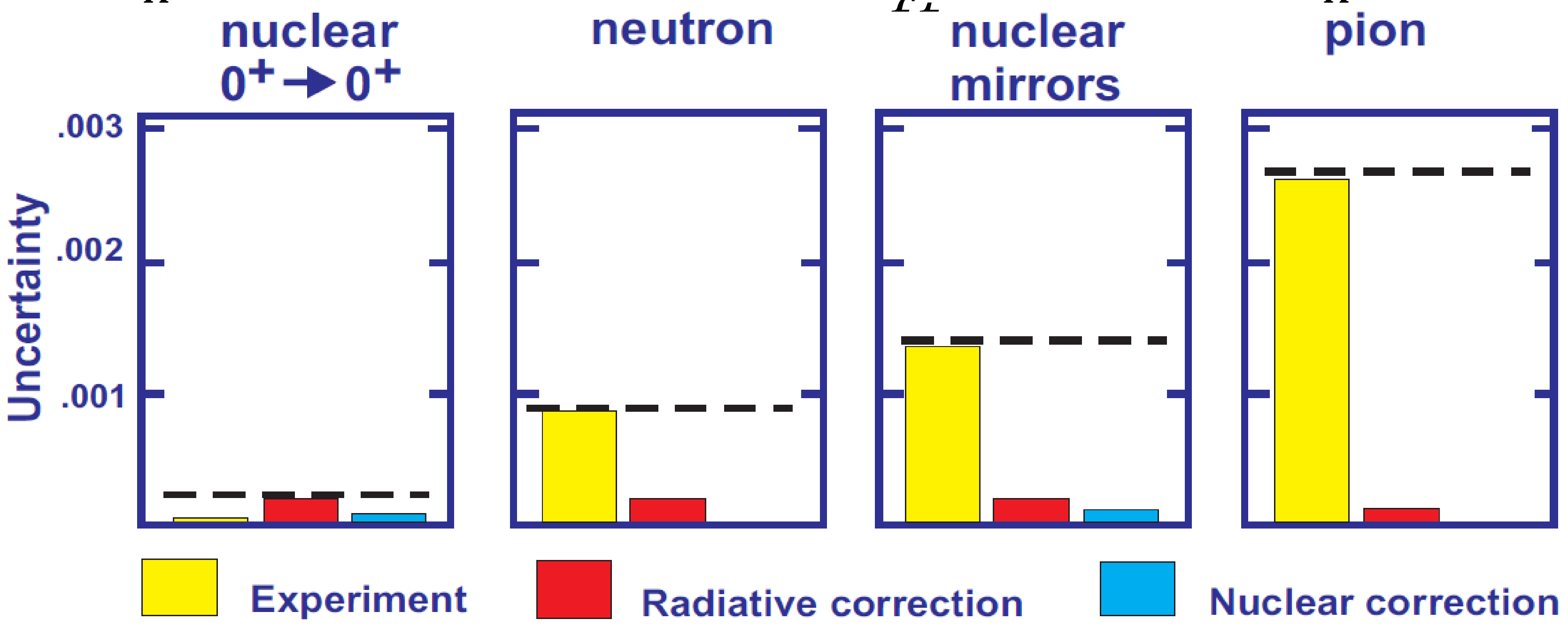
  $\mathcal{F}t =$

  $= \frac{}{(G_I}$

  …wn:

  $$\frac{g_A^2|M_{GT}^0|^2}{g_V^2|M_F^0|^2}$$

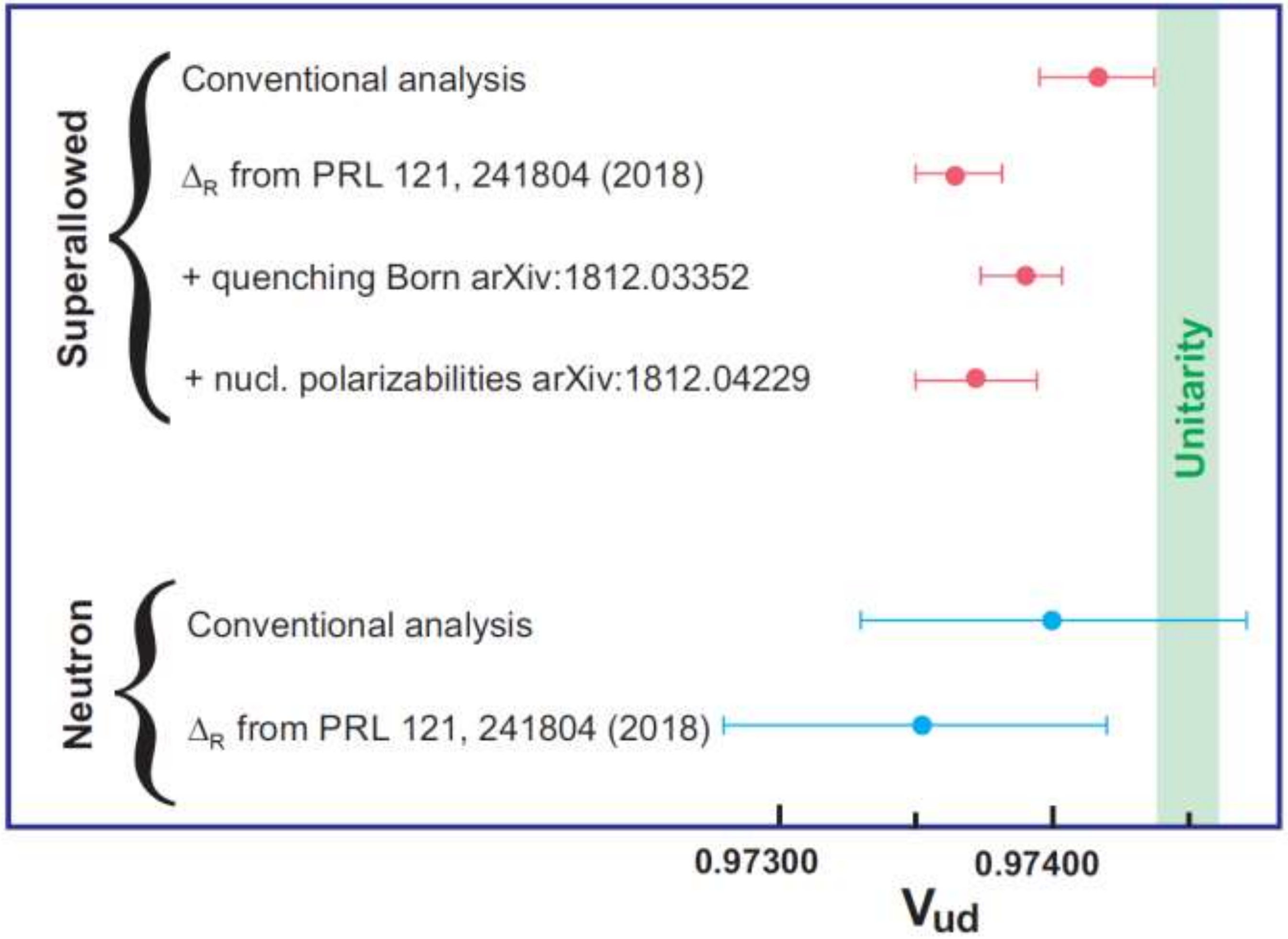
  $$+\frac{f_A}{f_V}\Big)\rho^2$$



Hardy, ACFI 1st Row CKM 2019

Unitarity status

- CKM unitarity appeared valid until 2018
- Reanalysis of Δ_R^V: improved uncertainty and dramatically shifted value of V_{ud} from $0^+ \rightarrow 0^+$ superallowed decays
  - 3 σ violation!
- Strong motivation for new complementary measurements



Hardy, ACFI 1st Row CKM 2019

C.-Y. Seng et al, Phys. Rev. Lett. 121 241804 (2018)
C.-Y. Seng et al, arXiv:1812.03352 (2019)
M. Gorchtein et al, arXiv:1812.04229

Measurables in neutron decay

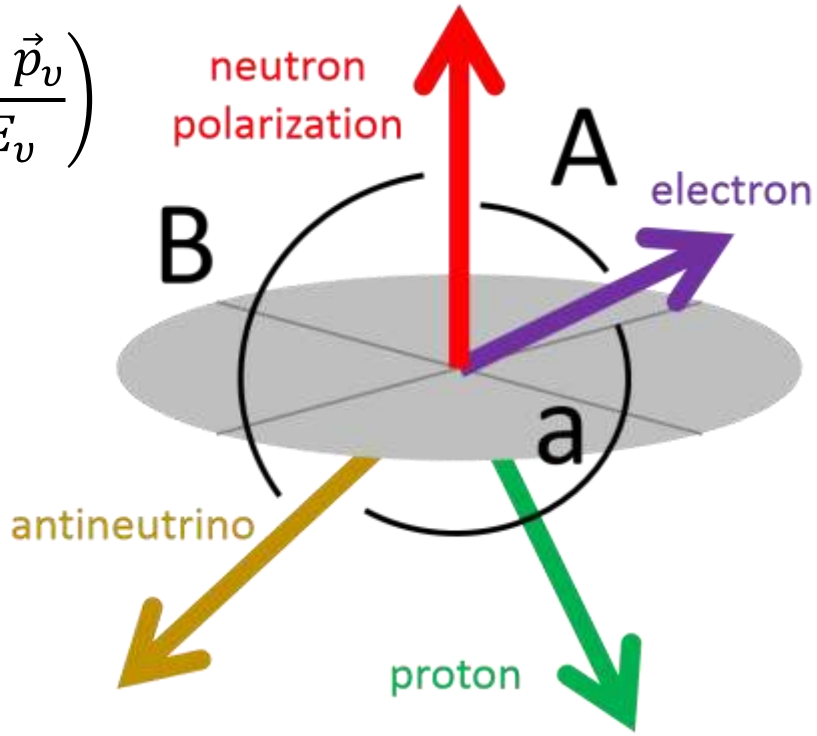
- Angular correlations

$$\mathrm{dW} \propto 1 + \boldsymbol{a}\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \boldsymbol{b}\frac{m_e}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left(\boldsymbol{A}\frac{\vec{p}_e}{E_e} + \boldsymbol{B}\frac{\vec{p}_\nu}{E_\nu} + \boldsymbol{D}\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)$$

  - **A**, **a** sensitive to **A, V** interactions
  - $\boldsymbol{A} = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}$ $\quad \boldsymbol{a} = \frac{1-\lambda^2}{1+3\lambda^2}$ $\quad \boldsymbol{\lambda = \frac{g_A}{g_V}}$
  - **B**, **b** sensitive to **S, T**
- Decay lifetime

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

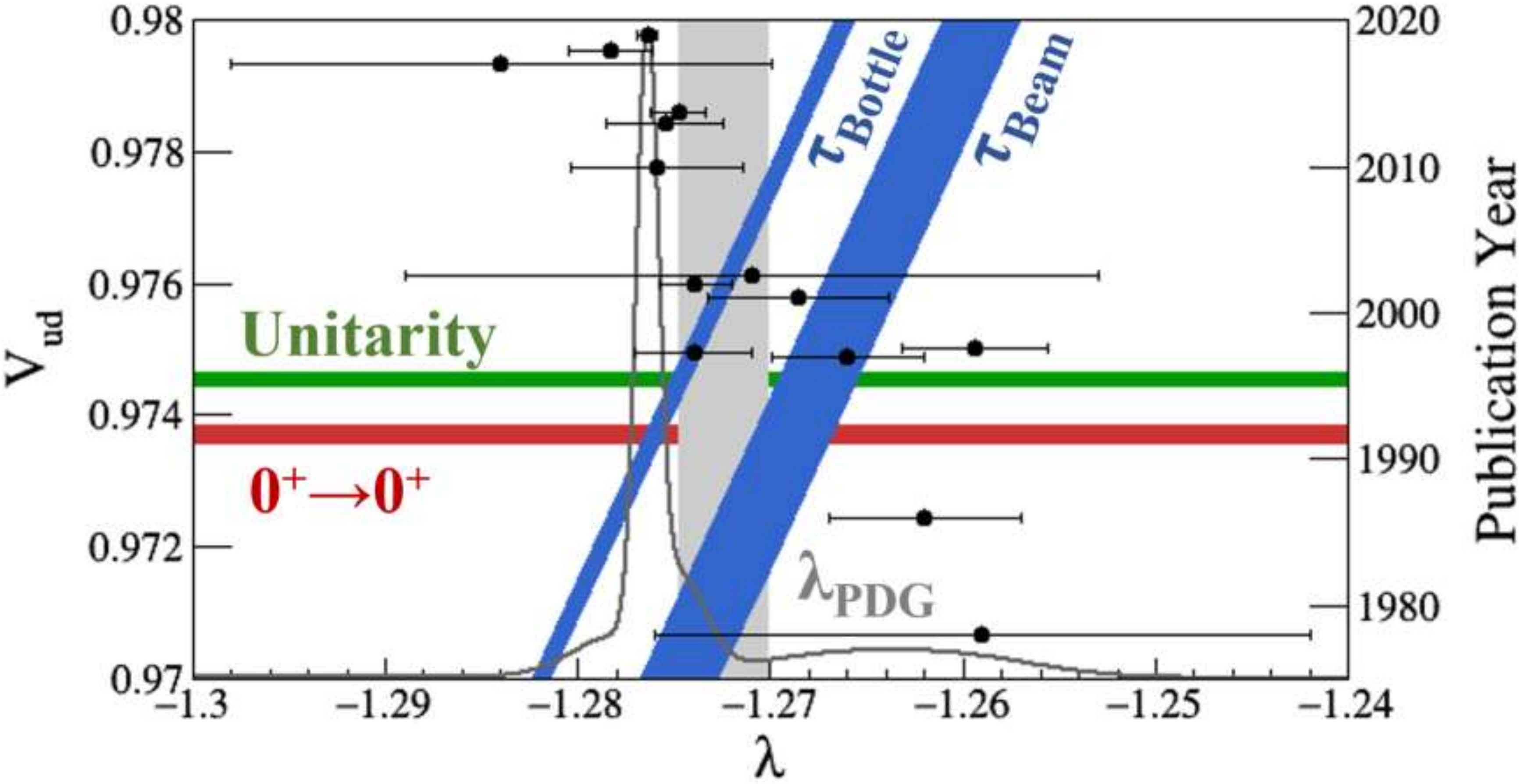
  - 2 **unknowns** = 2 **observables**
- Improved LQCD calcs of g_A, g_S, g_T



Chang et al, Nature 558 (2018) 91-94
Gupta et al, PRD 98 (2018) 034503

Vud from neutron decay

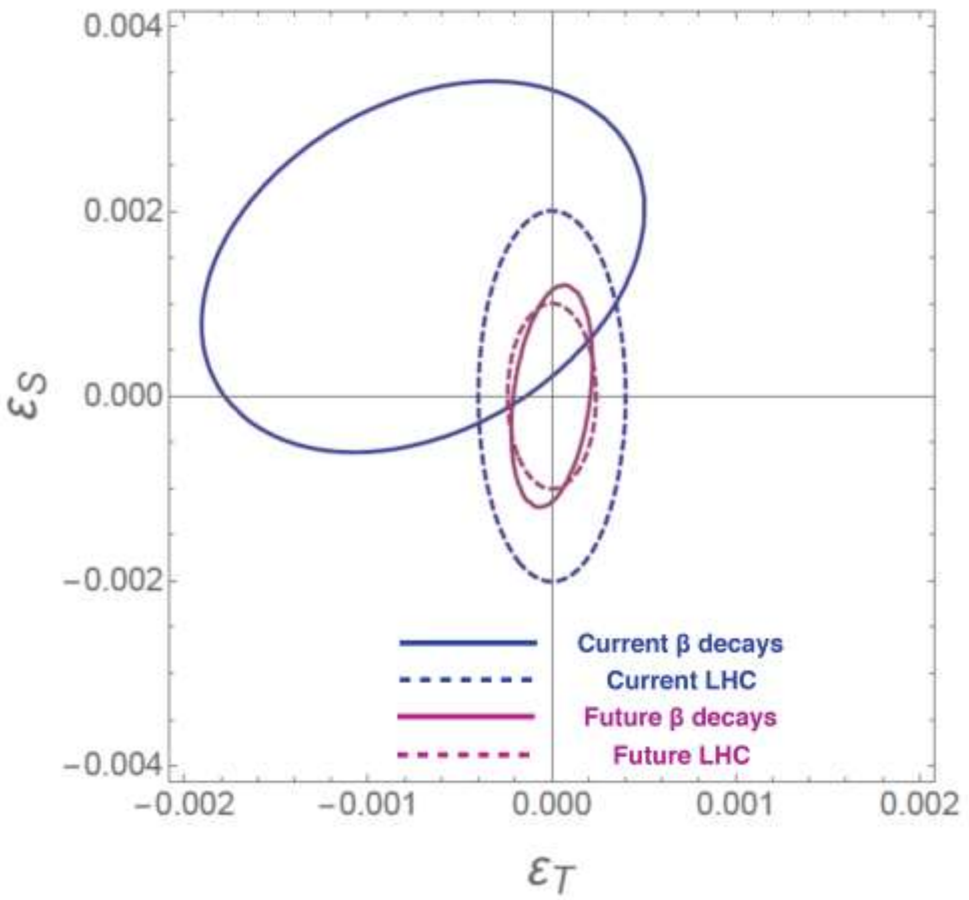
New goals:
neutron decay
dA/A or da/a
~ **0.05%** and
dτ ~ 0.13 s



Sensitivity to Scalars and Tensors currents

- Asymmetries: $\alpha_{\text{meas}}(E_e) = \frac{\alpha(E_e)}{1+b m_e/E_e}$
- Spectral measurement: $1 + b\, m_e/E_e$ distortion to decay rate

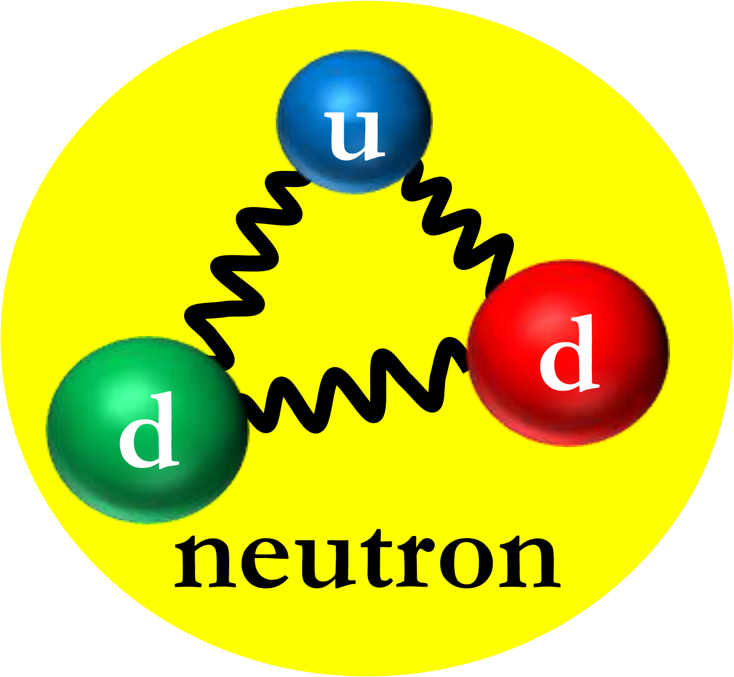
- **B** (b_ν), **b** linear sensitivity to BSM **S**,**T**:
  - $b^{BSM} = \frac{2}{1+3\lambda^2}[g_S\epsilon_S - 12\lambda g_T\epsilon_T]$
  - $b_\nu^{BSM} = \frac{2}{1+3\lambda^2}[\lambda g_S\epsilon_S - 4 g_T\epsilon_T(1+2\lambda)]$



Gupta et al, PRD 98 (2018) 034503

The neutron

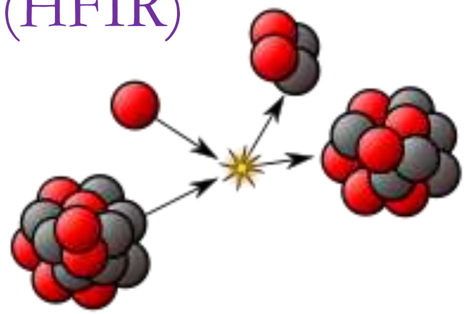
- Source: Freed from atoms
- Mass: 1.0087 a.m.u. (Proton: 1.0073 a.m.u)
- Spin: ½
- **Gravity**: 100 neV per m
- **Electromagnetism**: Electric charge: 0
  Magnetic dipole moment: 60 neV per 1 T
  Electric dipole moment: 0 e-cm (?)
- **Weak**: beta decay lifetime of about 15 minutes
- **Strong**: neutrons can interact with matter



Making free neutrons

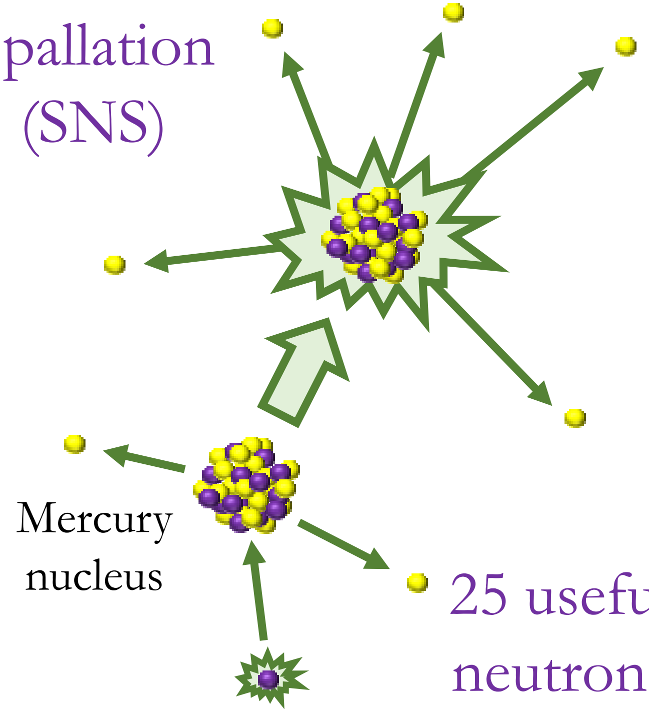
- Lots of energy required (MeV scale) to free neutrons from atom

Nuclear fission (HFIR)



2-3 useful neutrons produced

Spallation (SNS)



25 useful neutrons produced

- Experiments need slow neutrons
  - Longer wavelengths = easier to guide
  - Slower = more decays in your experiment

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

“Nuclear Reactions” by Kjerish [CC BY-SA 4.0]

Neutrons and matter

- Coherent scattering from many nuclei $\psi_n(r) = e^{ikz} + b\frac{e^{ikr}}{r}$
- Neutron wavefunction satisfies wave equation

$$(\nabla^2 + k^2)\psi_n(r) = 4\,\pi N\, b(r)\,\psi_n(r)$$

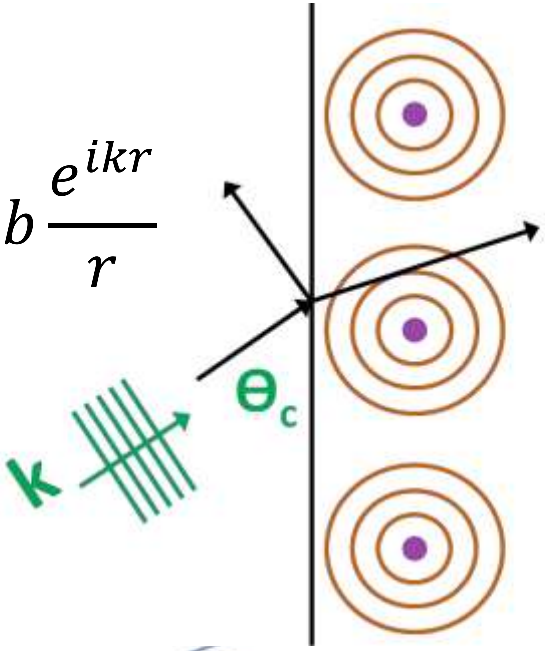
- Snell's Law = neutron guides $n = \sqrt{1 - {4\pi Nb}/{k^2}}$

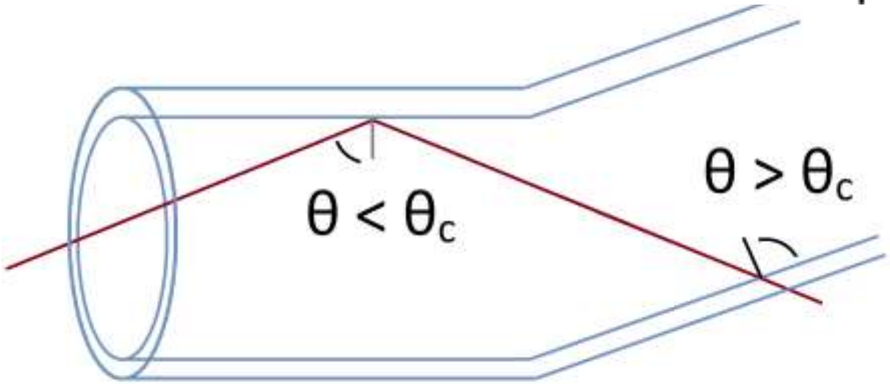
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\theta_c = \lambda\sqrt{Nb/\pi}$$

$$\lambda_c = \sqrt{\pi/Nb} > 500\ \text{Å}$$

- Ultracold neutrons have $\theta_c = 90°$

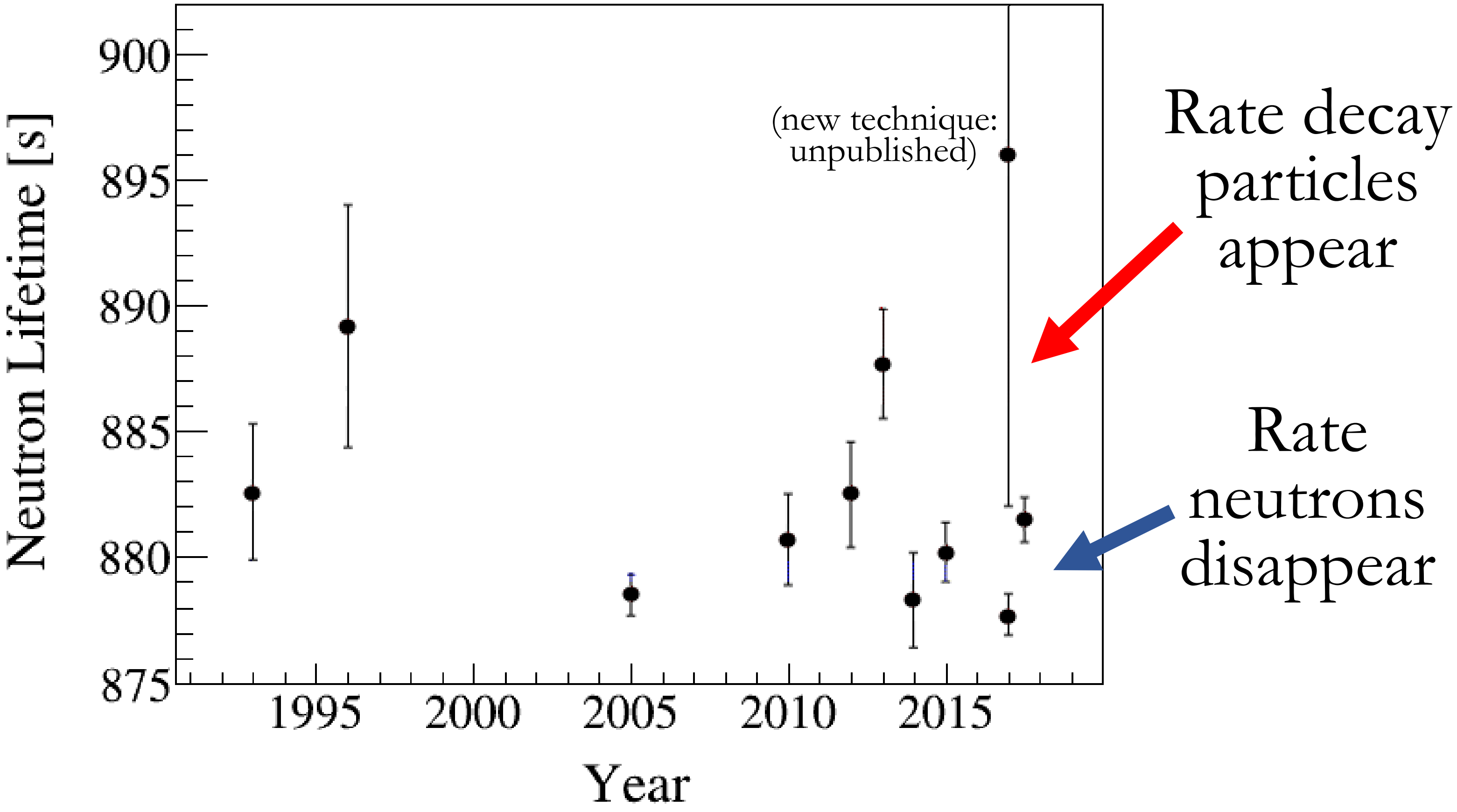





Please
Ingress & Egress by ladder
only No climbing
One person at a time on
Scaffolder Platform

Neutron Lifetime

- "Beam" technique: count the dying
- "Bottle" technique: count the survivors
- 8.6 s (~4 σ) discrepancy between methods!



Rate decay particles appear

Rate neutrons disappear

Neutron beta decay

- Understanding this process is critical to many other applications:

Primordial element formation

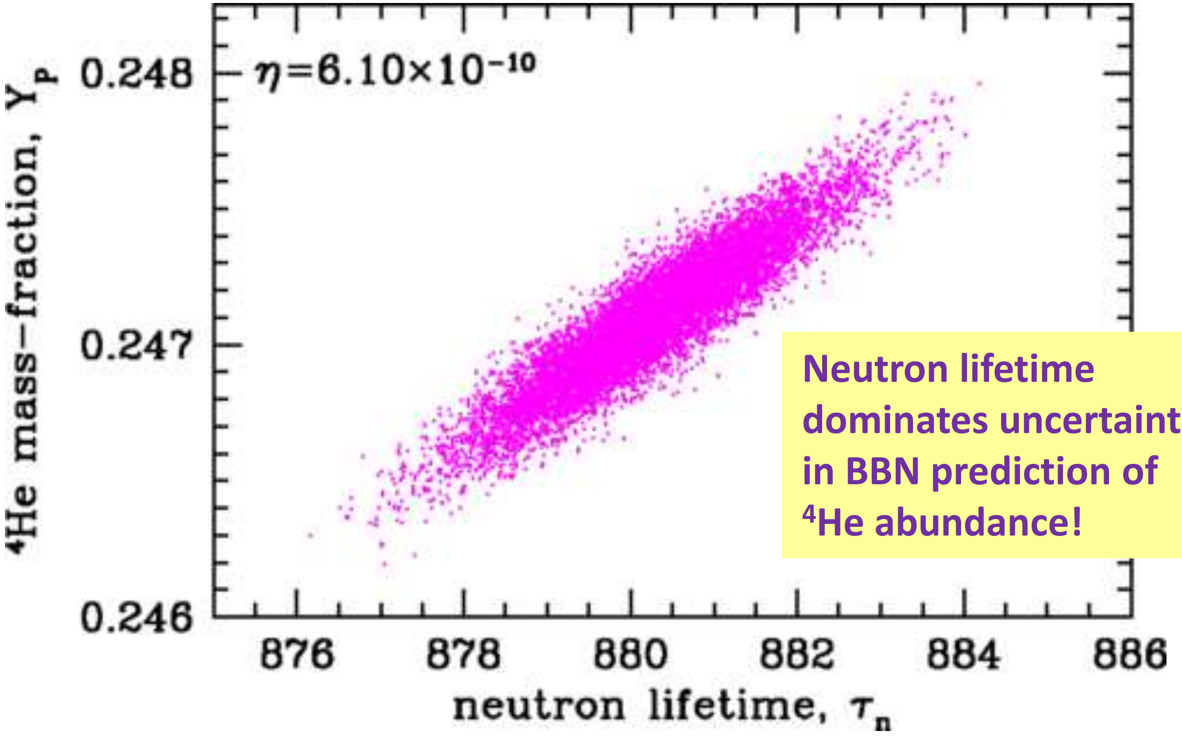
Solar cycle

Neutron star formation

Pion decay

Neutrino detection

Neutrino scattering



Neutron lifetime dominates uncertainty in BBN prediction of ^{4}He abundance!

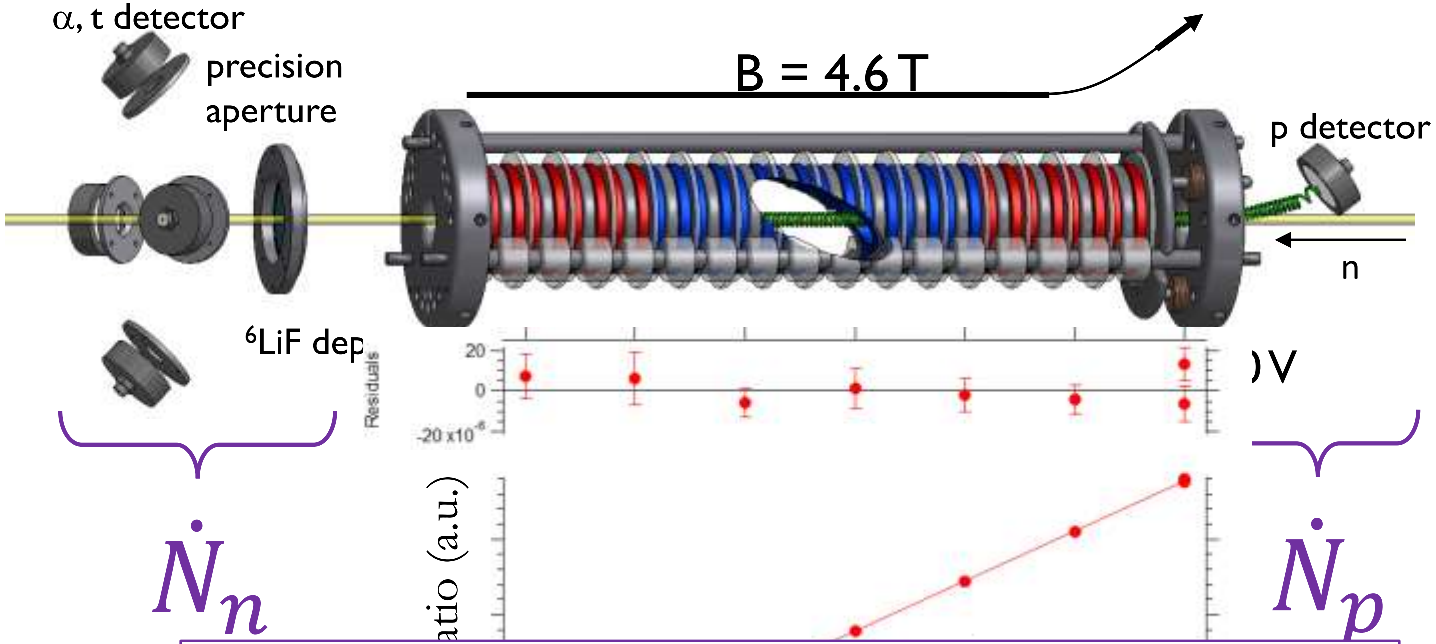
Beam Lifetime Experiments: BL2

- Measure neutron flux and proton decay rate:

$$\dot{N}_p = \epsilon_p \frac{A\,L}{\tau_\beta} \int \frac{\varphi(v)}{v} dv$$

$$\dot{N}_n = \epsilon_n A v_n \int \frac{\varphi(v)}{v} dv$$

$$\dot{N}_p = \dot{N}_n \left(\frac{L}{\tau_\beta}\right) \frac{\epsilon_p}{\epsilon_n v_n}$$



BL1: $\tau_n = 887.7 \pm 1.2_{stat} \pm 3.4_{stat}\ s$

BL2 data-taking concluding in 2019
projected uncertainty: < 1 s

Slide adapted from S. Hoogerheide, PPNS2018
A. Yue et al, Phys. Rev. Lett. **111** 222501 (2013)

Bottle lifetime experiments

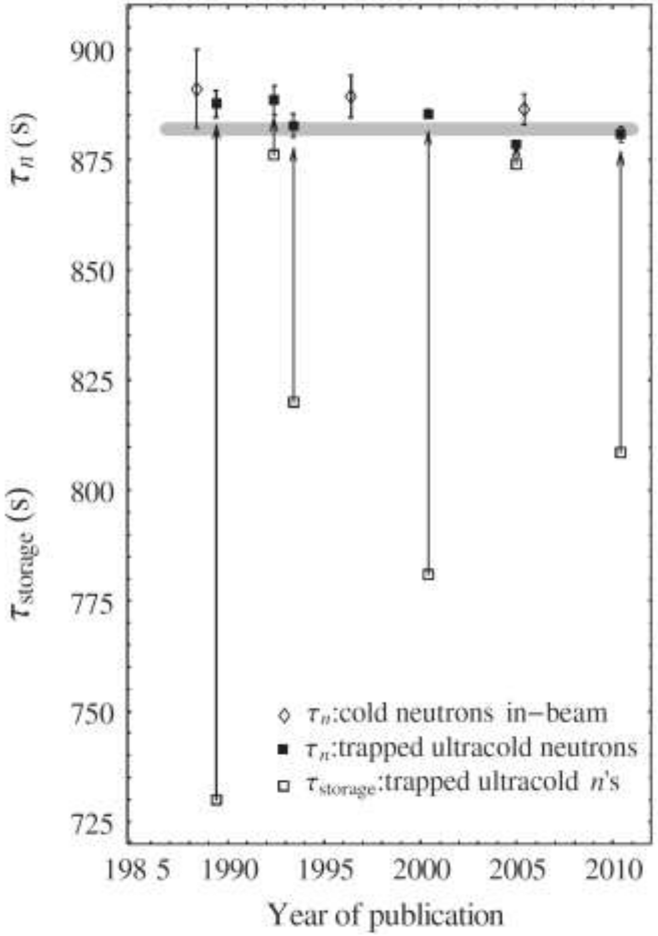
- Measure neutrons remaining after storage:

$$N(\Delta t) = N_0 e^{-\Delta t/\tau_s}$$

$$\frac{1}{\tau_s} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{other}}$$

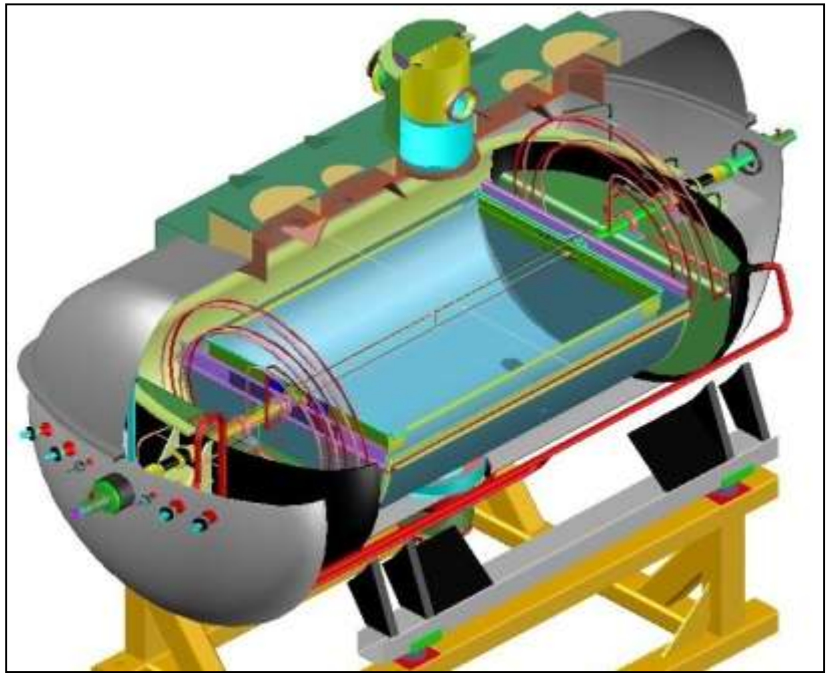
- Loss mechanisms: upscattering on walls, capture on walls, gaps in walls, quasibound escape, depolarization, residual gas...
- Wall losses depend on velocity, collision rate, loss factor:

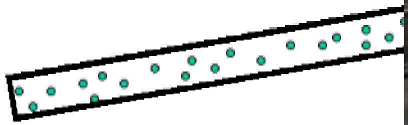
$$\tau_i^{-1} = \gamma(v)\mu_i(v)$$

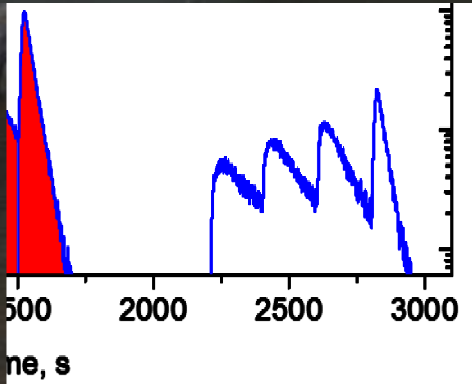


Dubbers and Schmidt, *RMP* **83** 1111 (2011)

Material Bottle: Gravitrap II



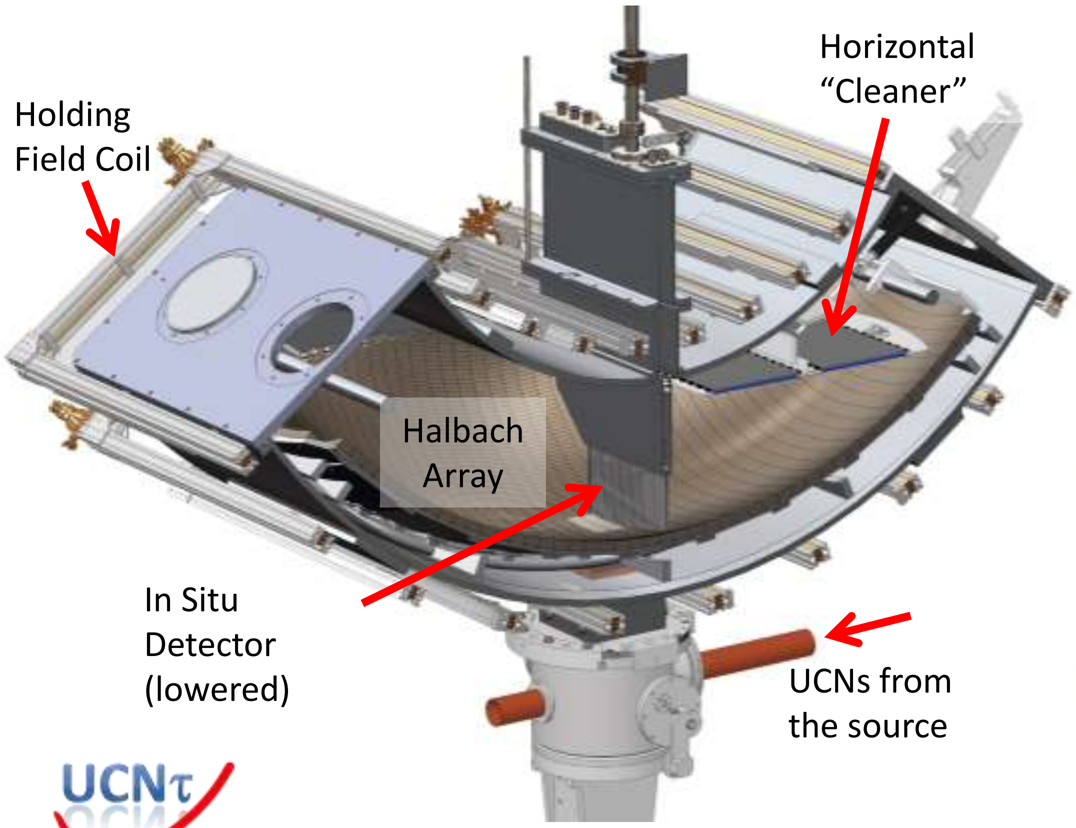




$.7_{stat} \pm 0.6_{syst}\ s$

Slide adapted from A. Serebrov, PPNS2018
A. P. Serebrov et al, JETP Lett. **106** 623 (2018)

Magnetic Bottle: UCNτ



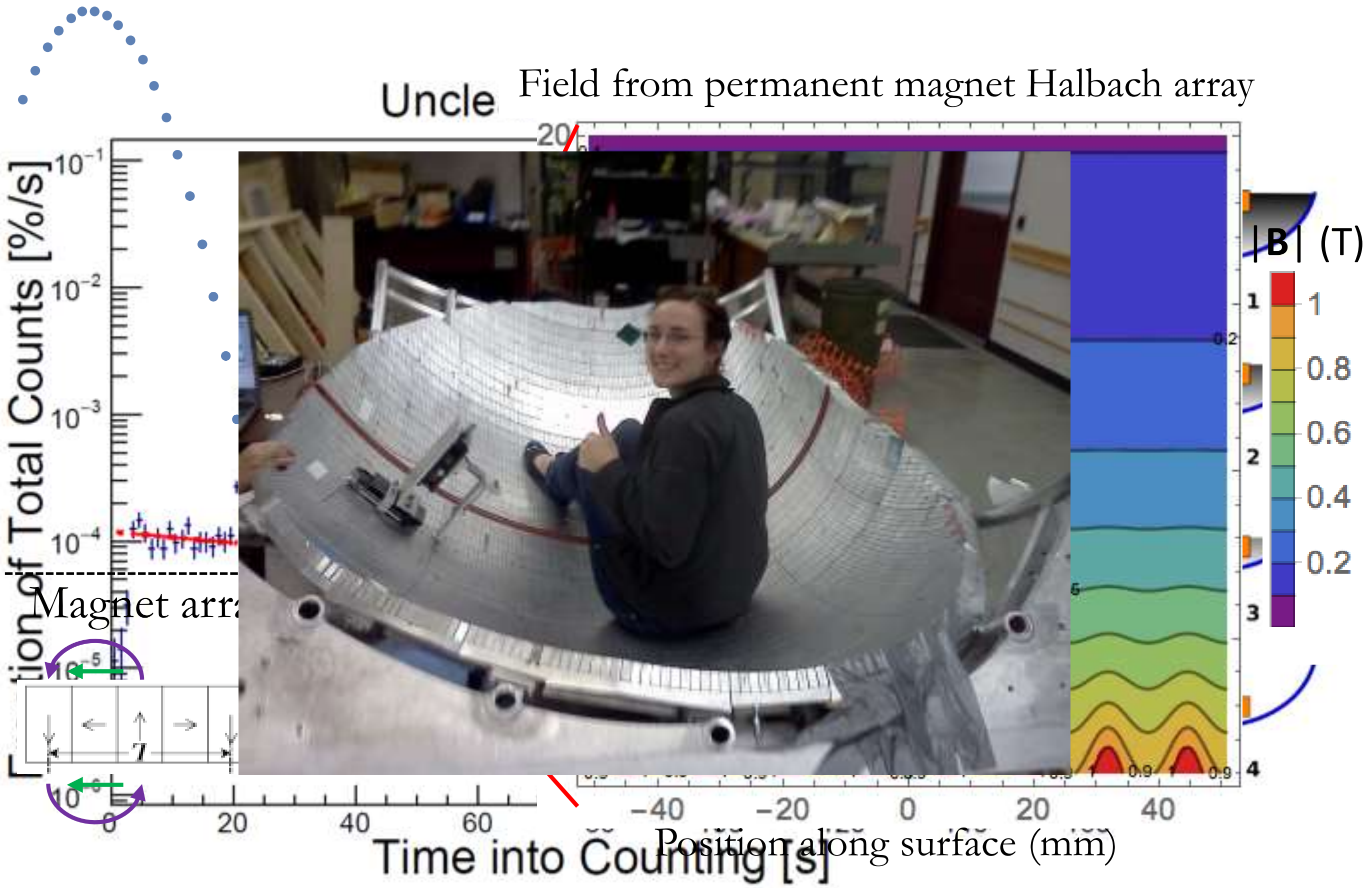
Holding Field Coil

Horizontal "Cleaner"

Halbach Array

In Situ Detector (lowered)

UCNs from the source



$$\tau_n = 877.7 \pm 0.7_{stat} \pm^{0.4}_{0.2}\ {}_{syst}\ s$$

Slide adapted from S. Clayton, FNPSS2018

R. W. Pattie Jr et al, Science **360** 627 (2018)

The β Asymmetry: UCNA

- $W \propto 1 + \frac{v}{c}\langle P\rangle A(E)\cos\theta$
- Magnetic spectrometer: $\langle\cos\theta\rangle = \pm\frac{1}{2}$
- Measure asymmetry: 2 detectors, 2 spin directions

$$A_{exp} = \frac{N^+ - N^-}{N^+ + N^-} = \frac{1}{2}\frac{v}{c}PA$$

- Cancel systematics with Super-Ratio

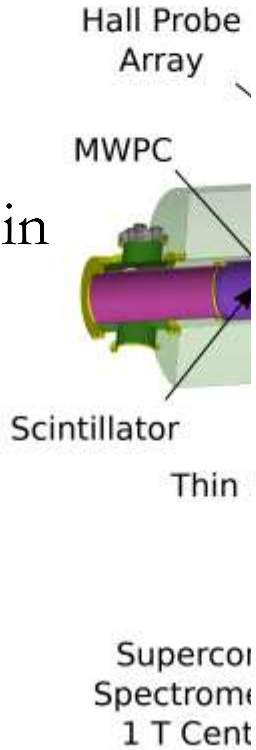
$$R(E) = \frac{N(E)_1^+ N(E)_2^-}{N(E)_1^- N(E)_2^+}$$

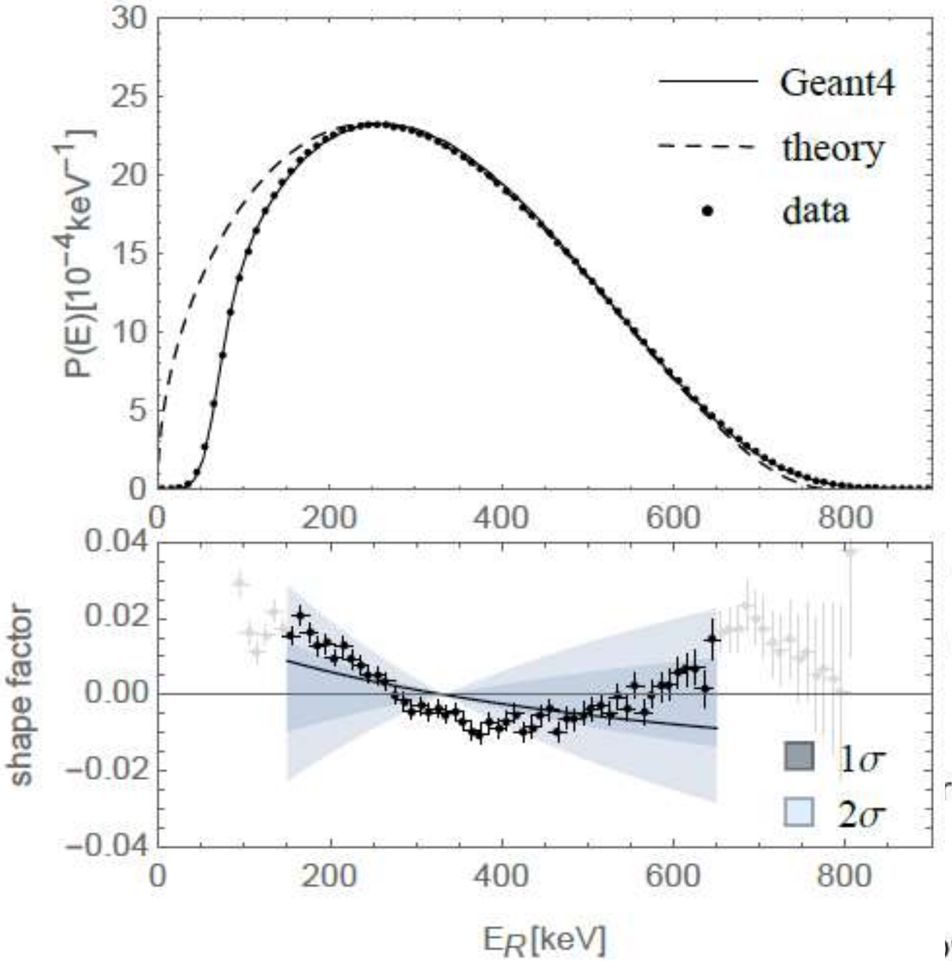
$$A_{SR} = \frac{1-\sqrt{R}}{1+\sqrt{R}} = \frac{v}{c}\langle P\rangle A(E)\cos\theta$$

- "Super-sum" removes distortion from **A**

$$\Sigma = \frac{1}{2}\sqrt{N(E)_1^+ N(E)_2^-} + \frac{1}{2}\sqrt{N(E)_1^- N(E)_2^+}$$

Brown et al, PRC 97 035505 (2018)
Hickerson et al, PRC 96 (2017) 042501





Hickerson et al., PRC 96 (2017) 042501

w during
beta-decay
easurement

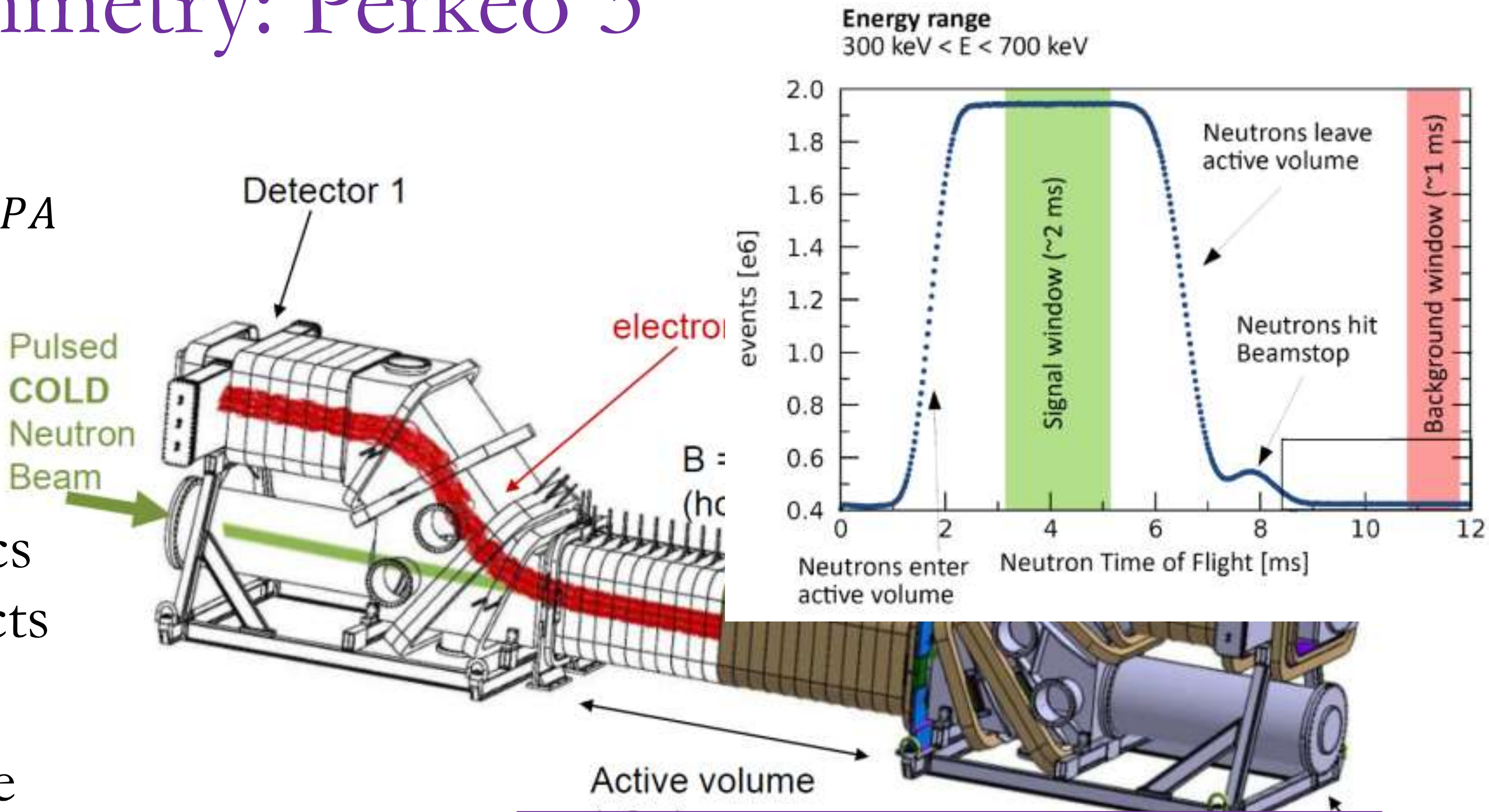
$b_n = 0.067 \pm 0.005_{stat}\ {}^{+0.090}_{-0.061}\ {}_{sys}$

Most recent dataset: $b_n = x.xx \pm 0.03$

The β Asymmetry: Perkeo 3

$$A_{exp} = \frac{N^+ - N^-}{N^+ + N^-} = \frac{1}{2}\frac{v}{c}PA$$

- Pulsed cold neutron beam avoids systematics due to edge effects
- Most precise λ extraction to date



$$A_0 = -0.11985 \pm 0.00017_{stat} \pm 0.00012_{sys}$$

$$\lambda = -1.27641 \pm 0.00045_{stat} \pm 0.00033_{sys}$$

Slide content from B. Maerkisch
Maerkisch et al, Phyr. Rev. Lett. 122 242501 (2019)

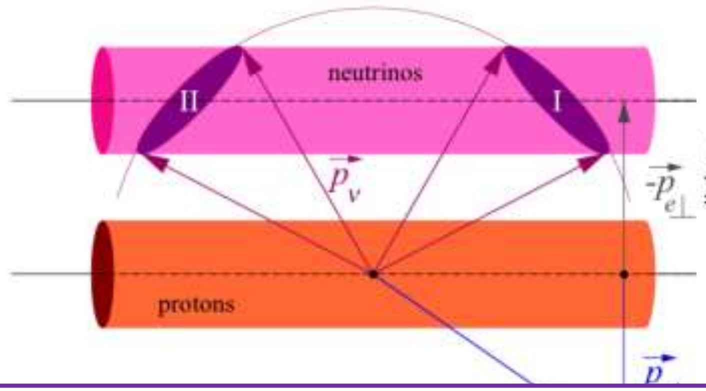
The β-ν Correlation: aCORN

- Kinematic slice + E, p conservation →

"Wishbone asymmetry"

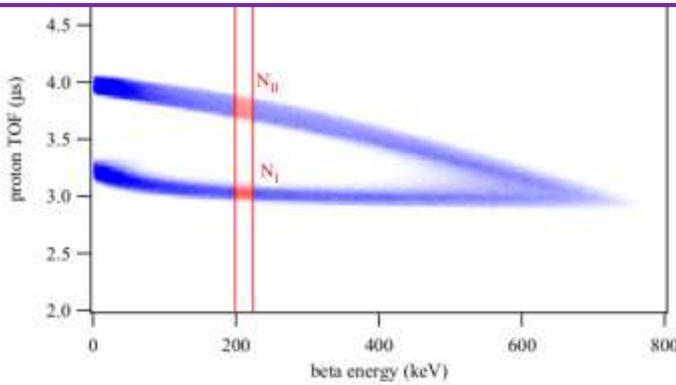
$$X(E) = \frac{N_I - N_{II}}{N_I + N_{II}} = af_a(E)$$

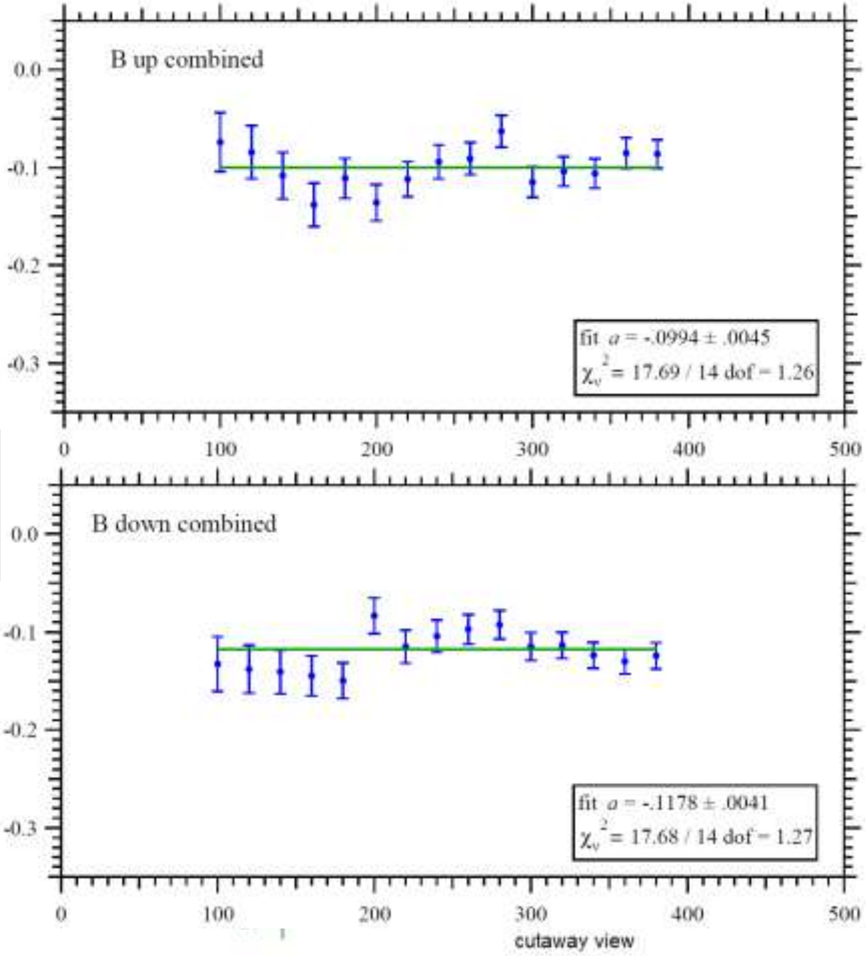
- $f_a(E)$ = ave. angle between $\overrightarrow{p_e}, \overrightarrow{p_\nu}$
  - depends on collimation, B field strength, neutron density distribution



$$a = -0.1090 \pm 0.0030_{stat} \pm 0.0028_{sys}$$

Most recent dataset: $\Delta a < 2\%$





Slides adapted from F. E. Wietfeldt
G. Darius et al, Phys. Rev. Lett. 119 042502 (2017)

The β-ν Correlation: Nab at the SNS

- 4π acceptance of β's: "tear-drop" phase space

Conservation of momentum:

$$p_p^2 = p_e^2 + 2p_e p_\upsilon \cos\theta_{e\nu} + p_\nu^2$$

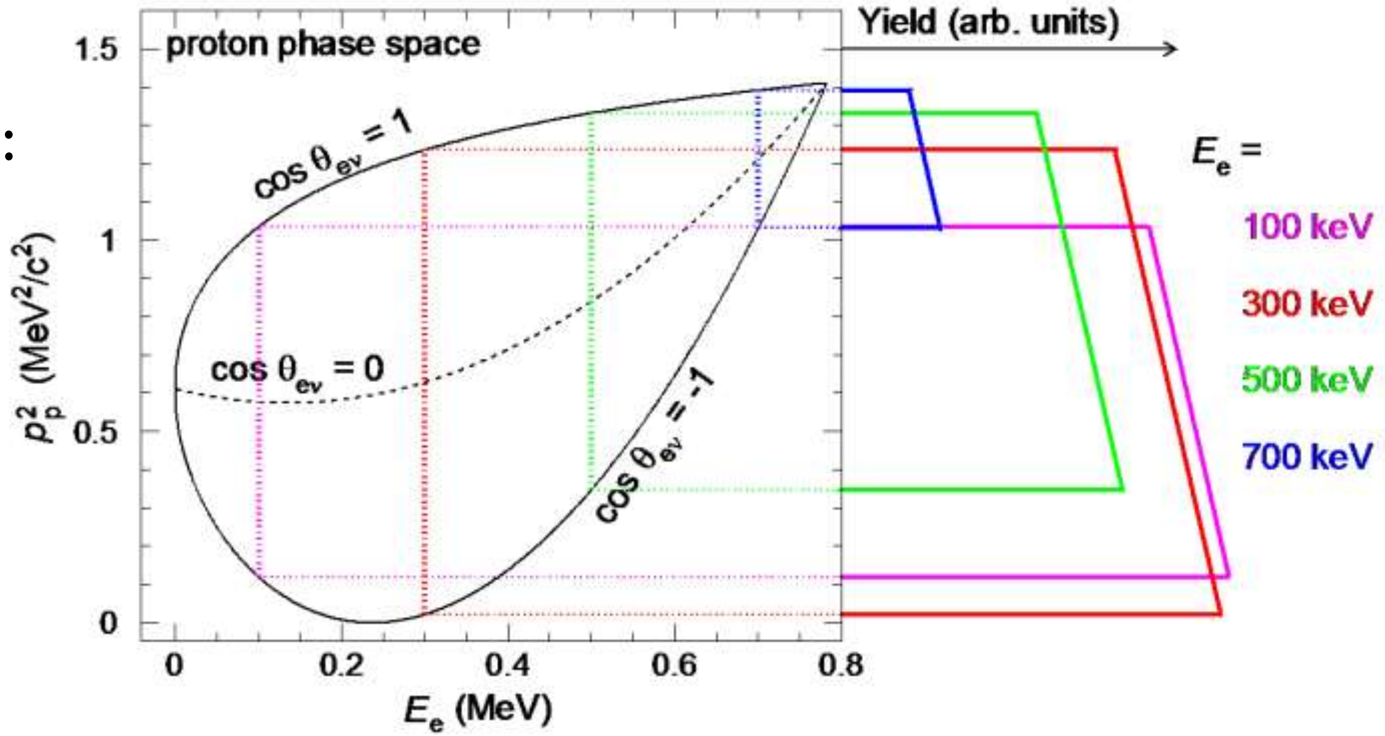
$$(\, p_\upsilon \sim E_0 - E_e \,)$$

Edges:

$$(p_e - p_\upsilon)^2 < p_p^2 < (p_e + p_\upsilon)^2$$

Yield: $\propto 1 + \boldsymbol{a}\frac{p_e}{E_e}\cos\theta_{e\nu}$

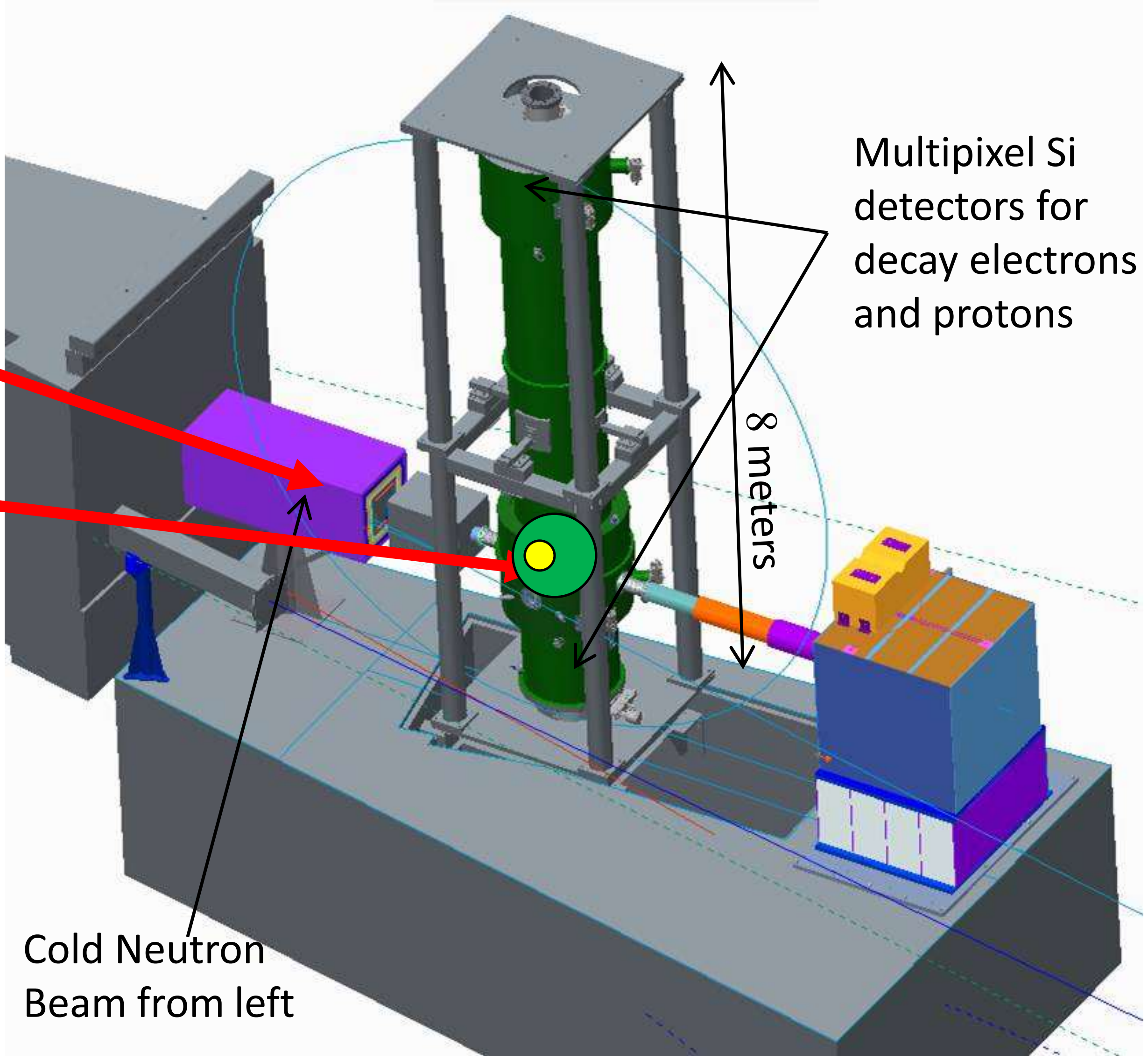
Goal: **Δa/a**~10^{-3} and **Δb**~3×10^{-3}



Bowman, J Res NIST 110 40 (2005)
Pocanic et al, NIMA 611 211 (2009)
Baessler et al, J Phys G 41 114003 (2014)

Nab at the SNS

1. Unpolarized neutrons enter experiment region
2. Neutrons decay, charged particles are trapped by magnetic fields
3. Electrons and protons are guided along magnetic field lines to detectors
4. Detectors determine electron energy and proton time of flight

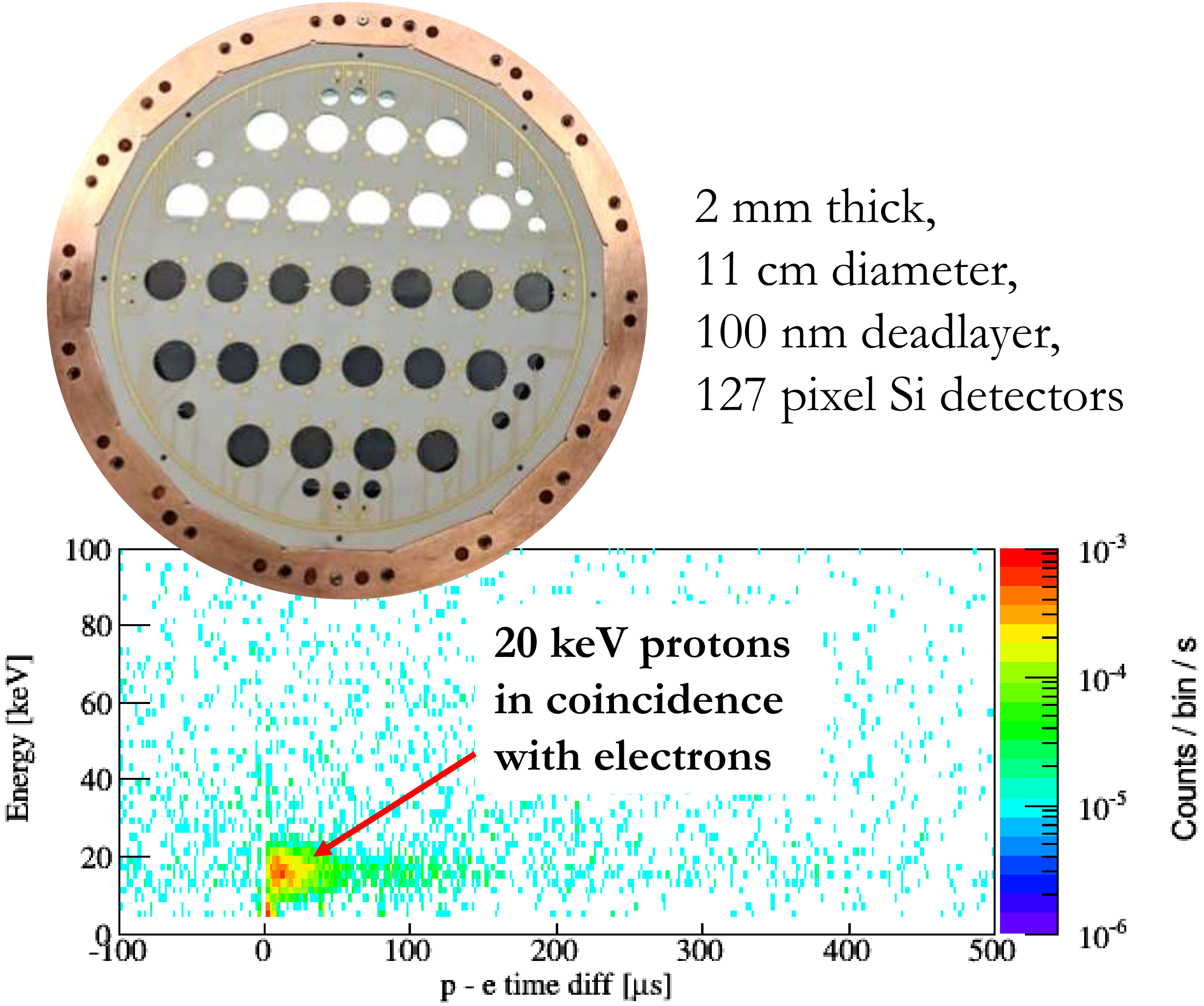


Multipixel Si detectors for decay electrons and protons

Cold Neutron Beam from left

Nab detectors

- Challenge to detect both:
  protons ~ 0.8 keV (requires accelerating voltage of -30 kV)
  electrons ~ 800 keV
- Demonstrated with UCN!
- Fully instrumented system acceptance testing nearly complete at LANL
- Precision characterizations next: deadlayer, charge collection profile, calibration, cross-talk...



2 mm thick,
11 cm diameter,
100 nm deadlayer,
127 pixel Si detectors

20 keV protons in coincidence with electrons

Salas-Bacci et al, NIMA 735 (2014) 408; Sjue et al, RSI 86 (2015) 023102; LJB et al, NIMA 849 (2017) 83; LJB et al, J. Phys: Conf Ser. 876 012005 (2017) LJB et al, Hyp. Int. 240 1 (2019)

Nab magnetic spectrometer

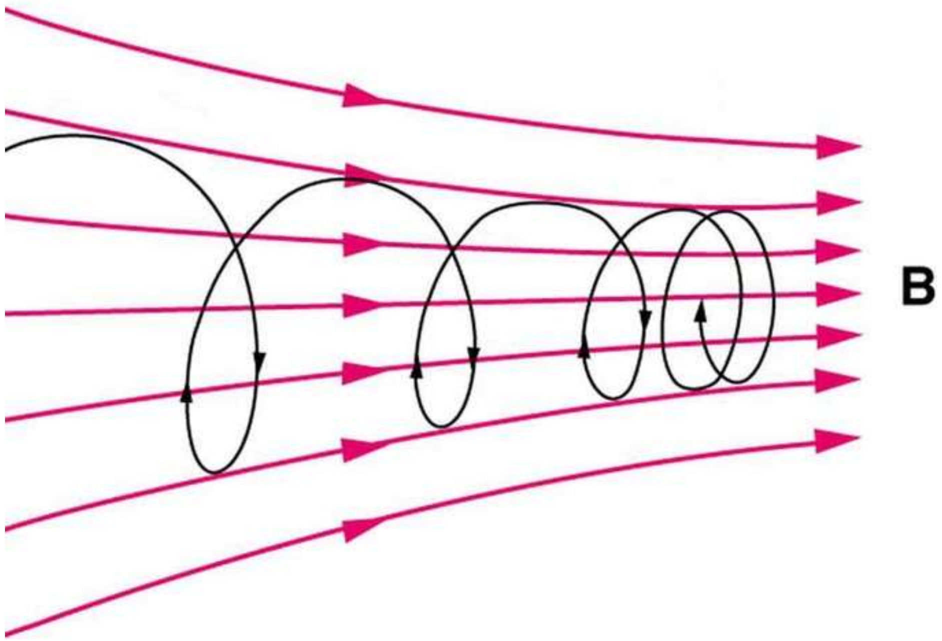
- Charged particles spiral along B field lines:

$$qv_\perp B = \frac{mv_\perp^2}{r}$$

- Magnetic moment is an adiabatic invariant:

$$\mu = \frac{mv_{1,\perp}^2/2}{B_1} = \frac{mv_{2,\perp}^2/2}{B_2}$$

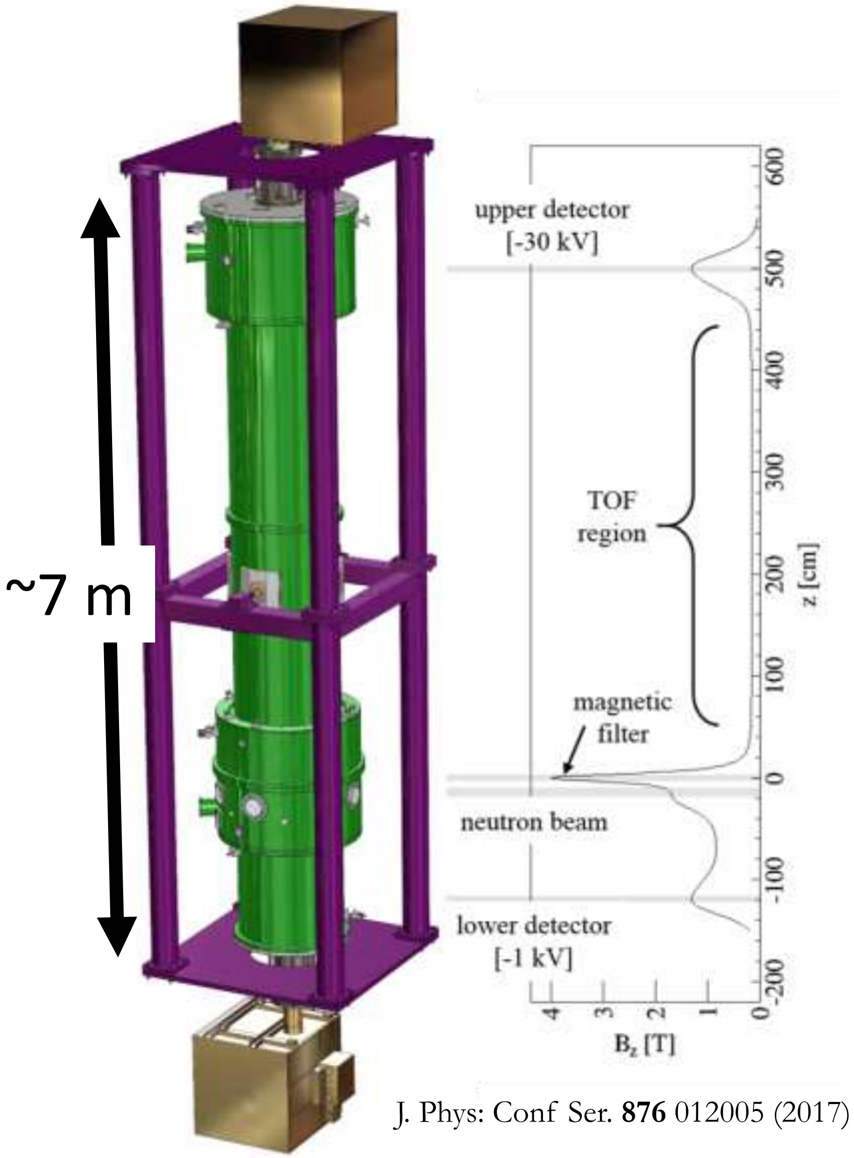
- Conservation of energy: transform $v_\perp$ to $v_\parallel$
- Increase B: decrease $v_\parallel$ (particle reflects)
- Decrease B: motion becomes parallel to field…



Nab magnetic spectrometer

- 4 T magnetic mirror (filter): reflect/ignore protons with small $v_{\parallel}$
- 0.2 T TOF region: proton motion nearly parallel to B = spectrometer axis
- Relate time of flight (measured) to proton momentum (desired):

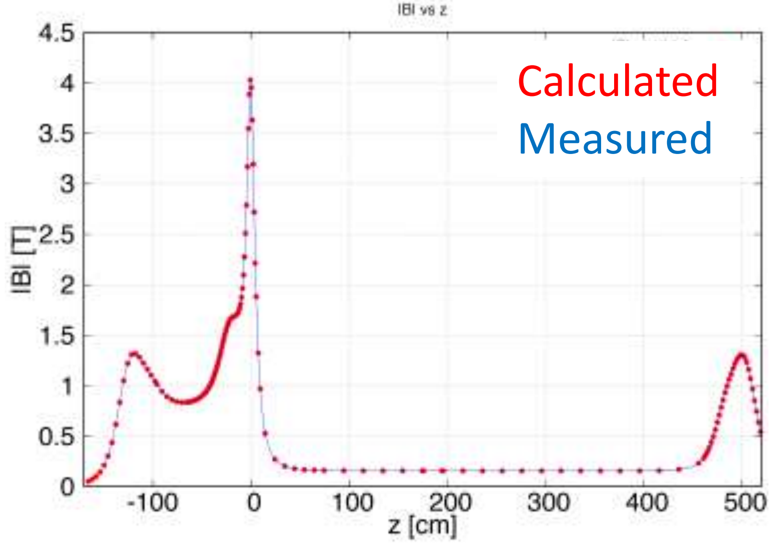
$$t_p = L\frac{m_p}{p_p} = \frac{f(\cos\theta)}{p_p}$$



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

Nab spectrometer now commissioning

- Performance success—excellent agreement with calculations
- Precision mapping to be completed *imminently*



Check out beamline 13 on your SNS tour!

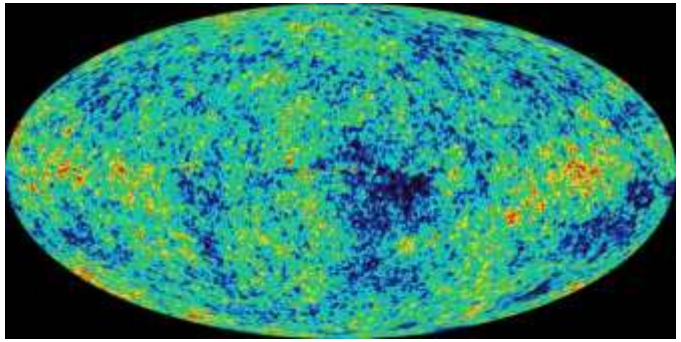
Outline

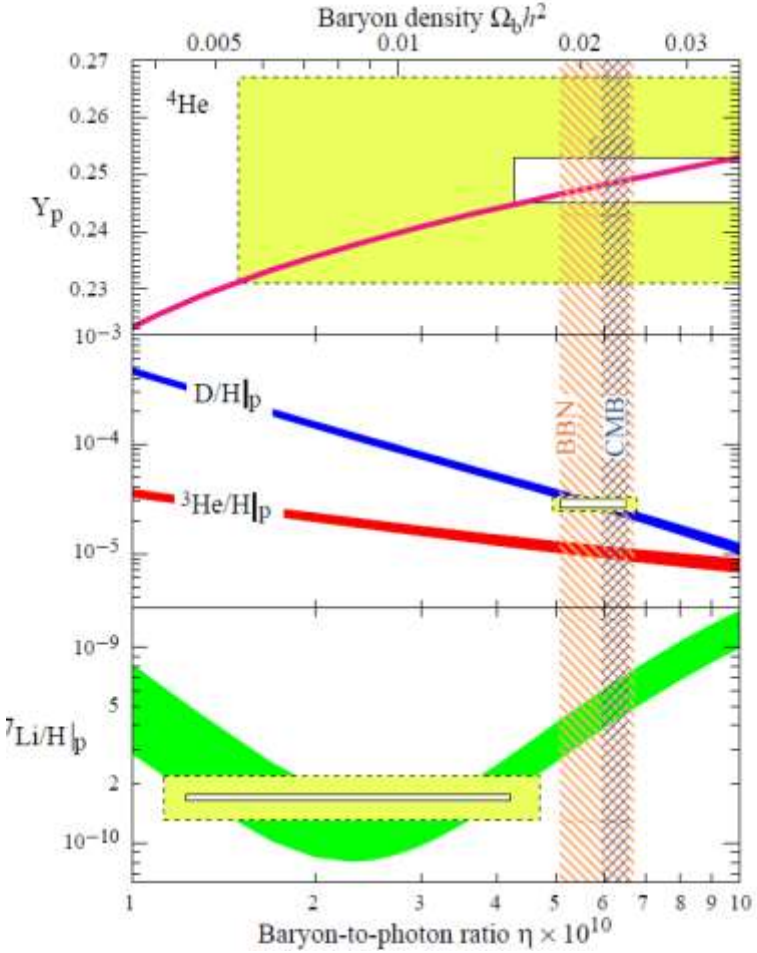
- P-violation and the weak interaction
- CP-violation and the electric dipole moment
- B-violation and oscillations

The early universe

- Big Bang Nucleosynthesis calculations: how light elements were formed
- Cosmic Microwave Background: “Big Bang’s echo”
- Where’s the antimatter?
  - Cosmic rays?
  - Antimatter galaxies?
  - BBN, CMB agree:

$$\boxed{\eta \equiv \frac{n_B - n_{\bar{B}}}{s} \sim 10^{-10}}$$





Look for clues in symmetries

- Internal symmetry: **Baryon number B**
  - Quarks: **B = +⅓**
  - Antiquarks: **B = -⅓**
- Big Bang should have produced matter = antimatter → **B = 0**
- **First condition**: we must have a process that does not conserve **B** to create an excess
  - X + Y → **B**
  - Has not been observed…

Andrei Sakharov

Look for clues in symmetries

- **Second Condition:** Production of matter must be favored over antimatter
- C-symmetry must be broken

$$X + Y \to B > \bar{X} \to \bar{Y} + \bar{B}$$

- CP-symmetry must be broken

(CP – conjugates)

$$\begin{array}{l} X \to B_L + X \to B_R > \\ \bar{X} \to \bar{B}_L + \bar{X} \to \bar{B}_R \end{array}$$

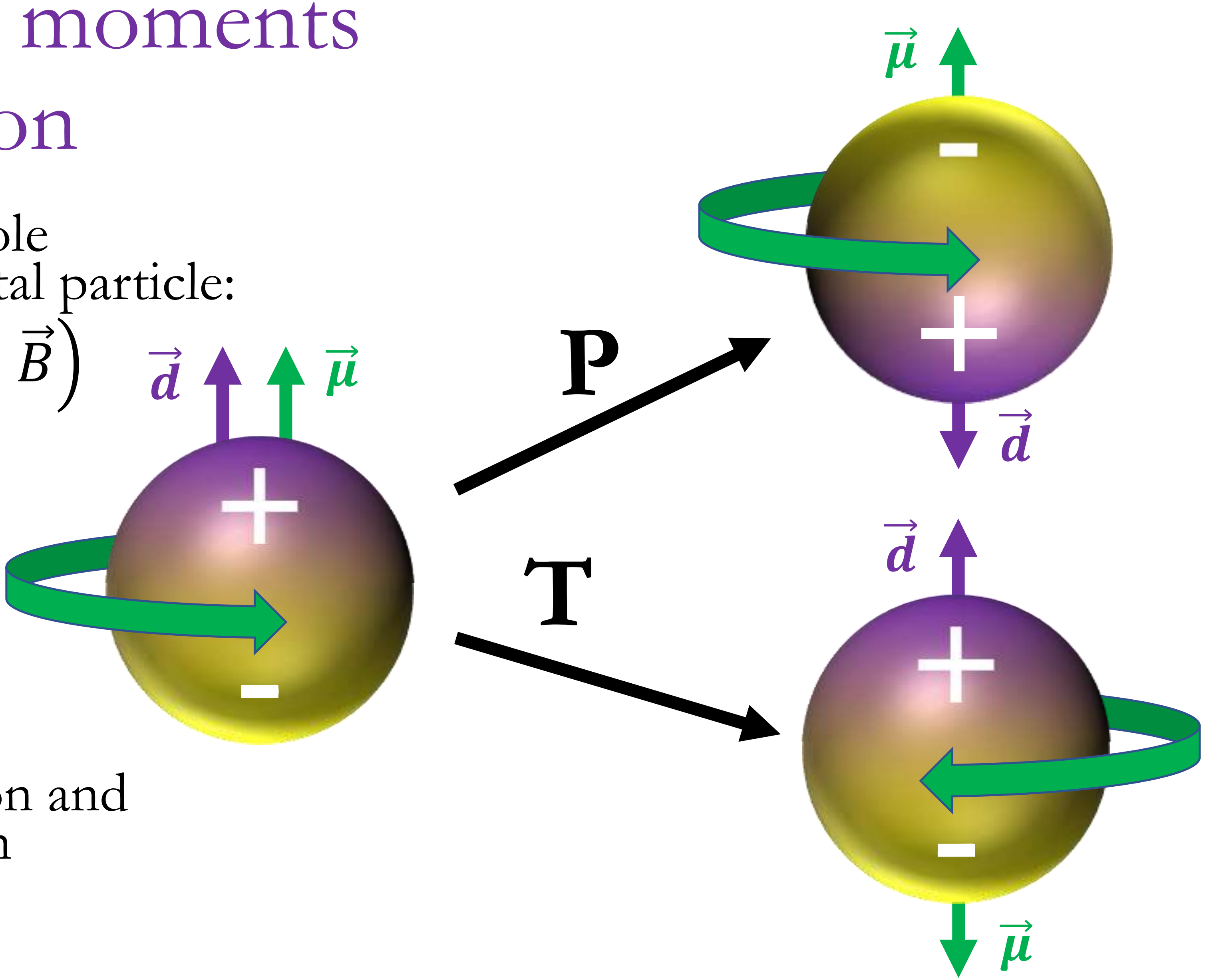
- **Third Condition:** Excess B shouldn't be washed out – need this process to occur out of thermal equilibrium

Andrei Sakharov

Electric dipole moments and CP violation

- Non-zero electric dipole moment in fundamental particle:

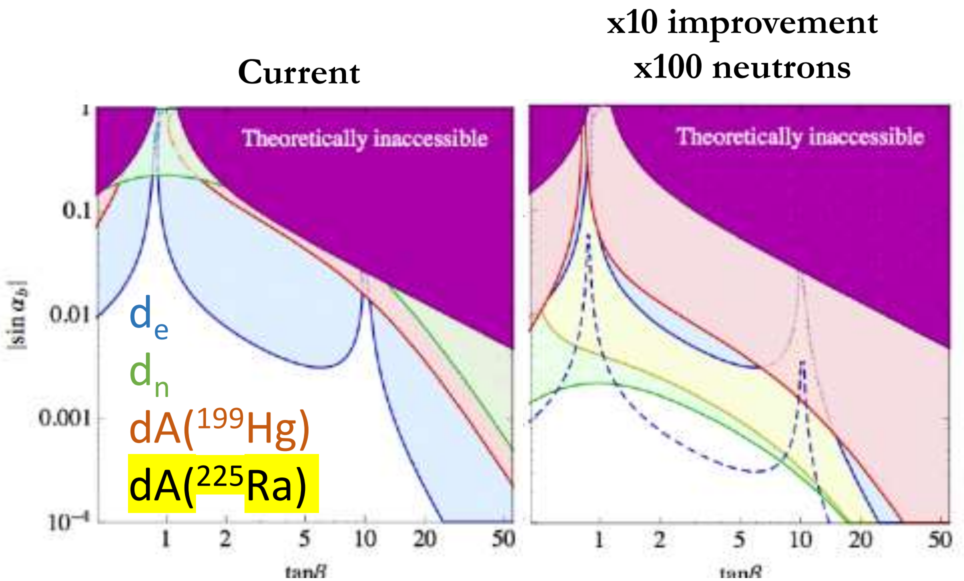
$$H = -\frac{1}{2}\left(\vec{d} \cdot \vec{E} + \vec{\mu} \cdot \vec{B}\right)$$



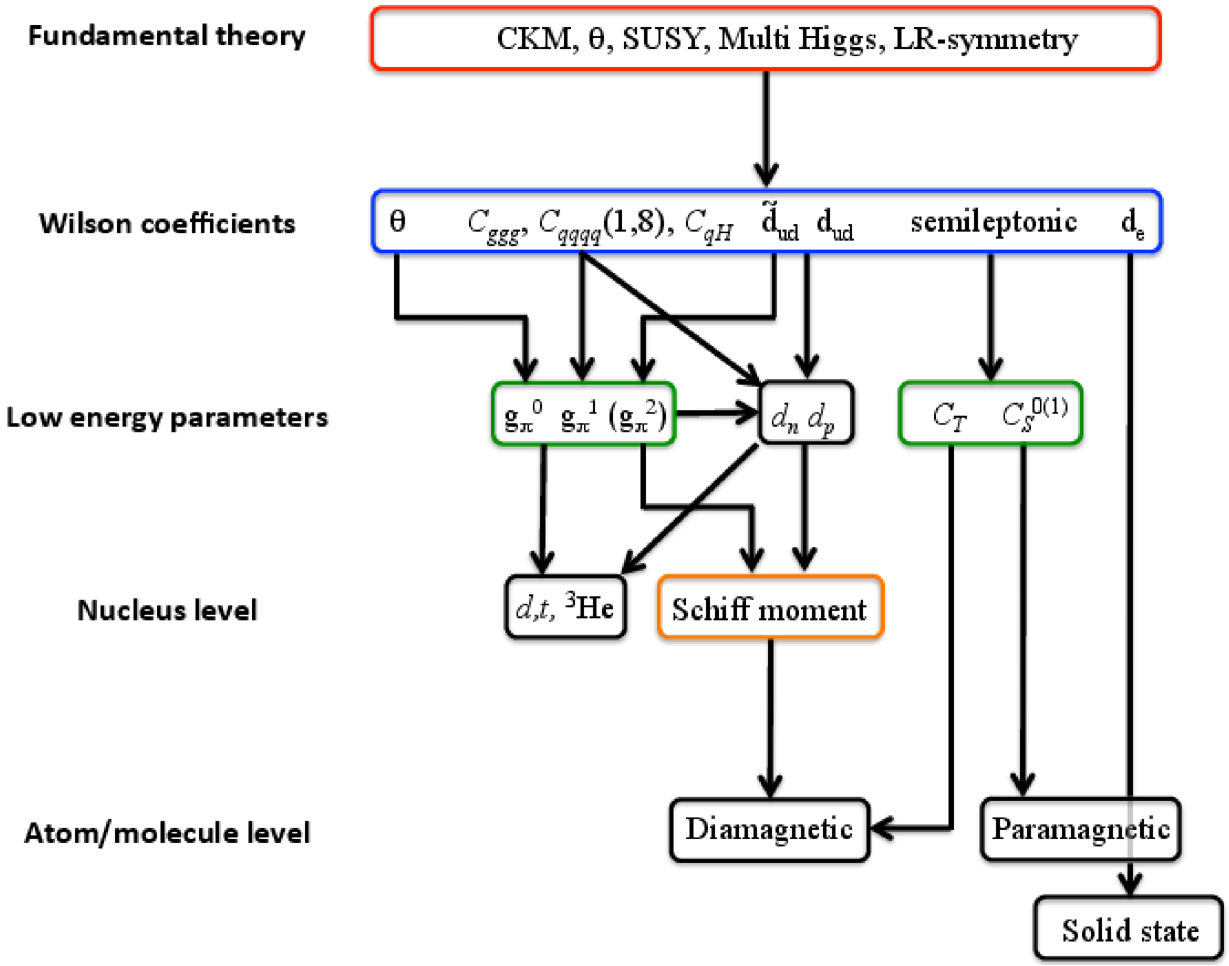
- **P**-violation, **T**-violation and therefore **CP**-violation

Electric dipole moments

- Need many experiments to sort out the source of CP-violation…



Constraints on Two-Higgs Doublet model



Chupp, Fierlinger, Ramsey-Musolf, and Singh, Rev. Mod. Phys. 91 1 (2019)

Neutron electric dipole moment

- Neutron has magnetic dipole moment: feels torque perpendicular to magnetic field
- Spin precesses with frequency

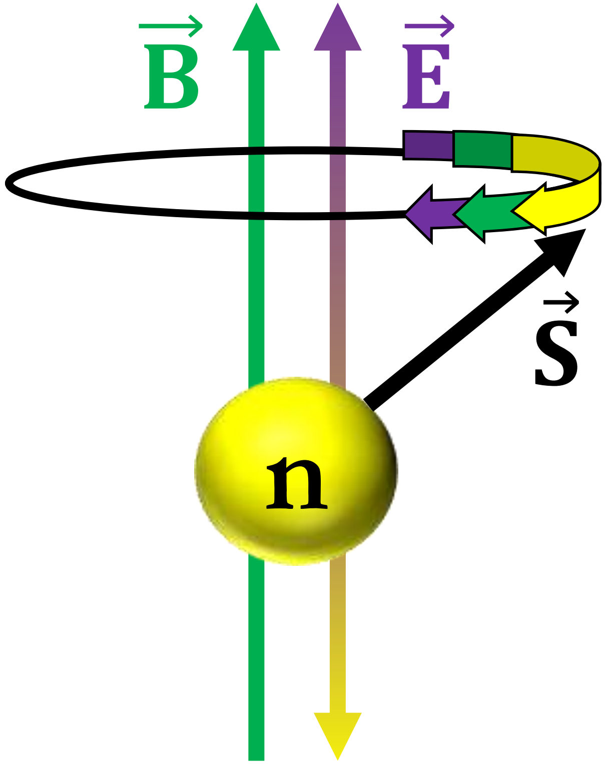
$$\mathbf{h\nu = 2\mu_n B}$$

- If neutron had an EDM, spin precesses around electric field:

$$\mathbf{h\nu = 2d_n E}$$

- Tactic: compare frequency with electric/magnetic fields parallel/antiparallel

$$\mathbf{h\nu_{\pm} = 2\mu_n B \pm 2d_n E} \qquad \mathbf{\Delta\nu = \frac{4d_n E}{h}}$$



$\Delta\nu$=7.5 nHz for $d_n=10^{-28}$ e-cm, E=75 kV/cm

Limit on the neutron EDM

Vol. 3—No. 13

OAK RIDGE, TENNESSEE

Harvard University Conducts Important Research at ORNL

The growing importance of Oak Ridge National Laboratory as a research center is manifested particularly in its assistance to universities and technical schools on various projects in which nuclear research is involved. An example
of such relati
collaboration
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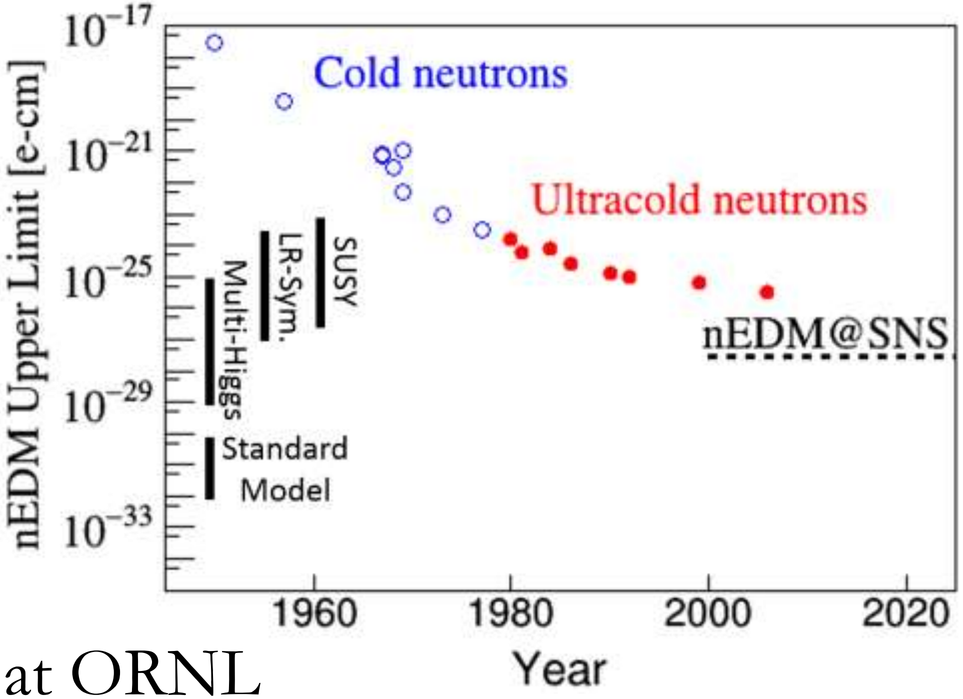
HARVARD UNIVERSITY SPONSORS PROGRAM HERE — James H. Smith, Harvard University graduate student in physics, is shown as he adjusts a neutron beam apparatus at the south face of the Oak Ridge Pile. Using the Pile as a source of neutrons, Mr. Smith is engaged in a project jointly sponsored by Harvard University and Oak Ridge National Laboratory for the purpose of determining if neutrons have permanent electric dipole moments.

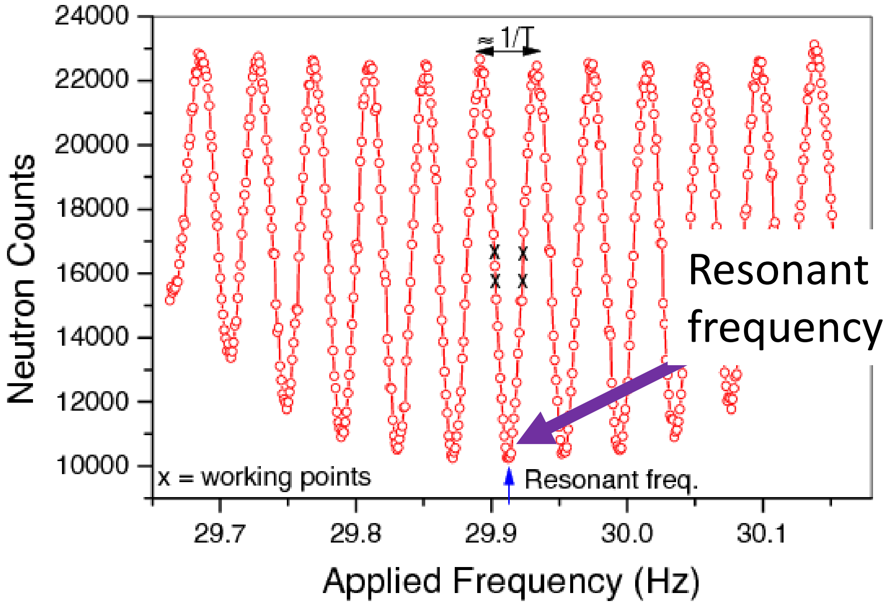


- First measured by Smith, Purcell and Ramsey at ORNL
  - Studying parity violation in neutron scattering
- Neutron EDM extremely small: “Strong CP problem” in QCD Langrangian
- Motivates “axions” (dark matter candidate)

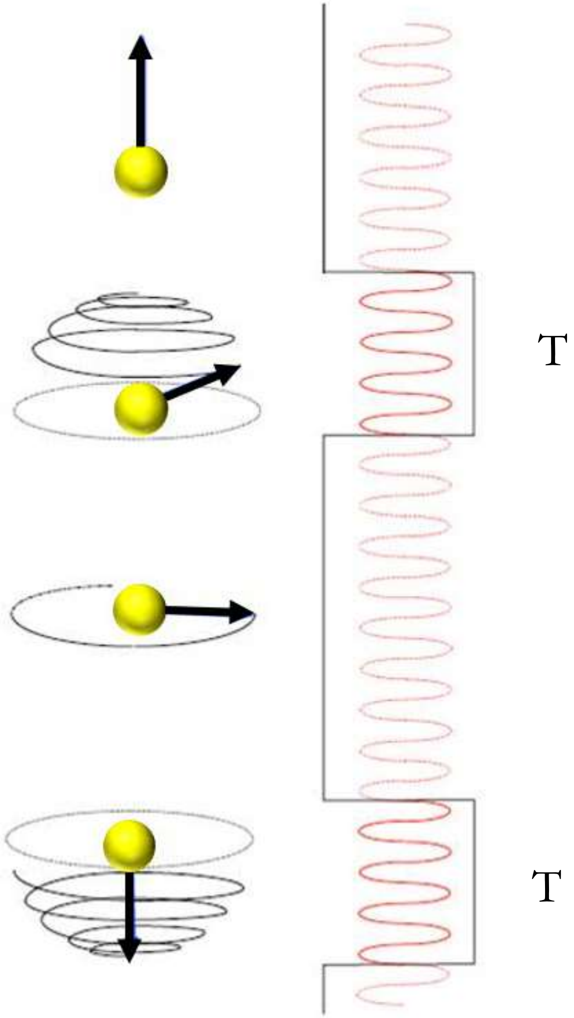
Smith, Purcell, and Ramsey, Phys Rev 108 120 (1957)

Ramsey's Method of Separated Oscillating Fields

1. Prepare "spin up" neutron
2. Apply 90° spin flip
3. Spin freely precesses by ωΔt
4. Apply 90° spin flip (to "spin down")
5. Measure "spin up" vs "spin down"

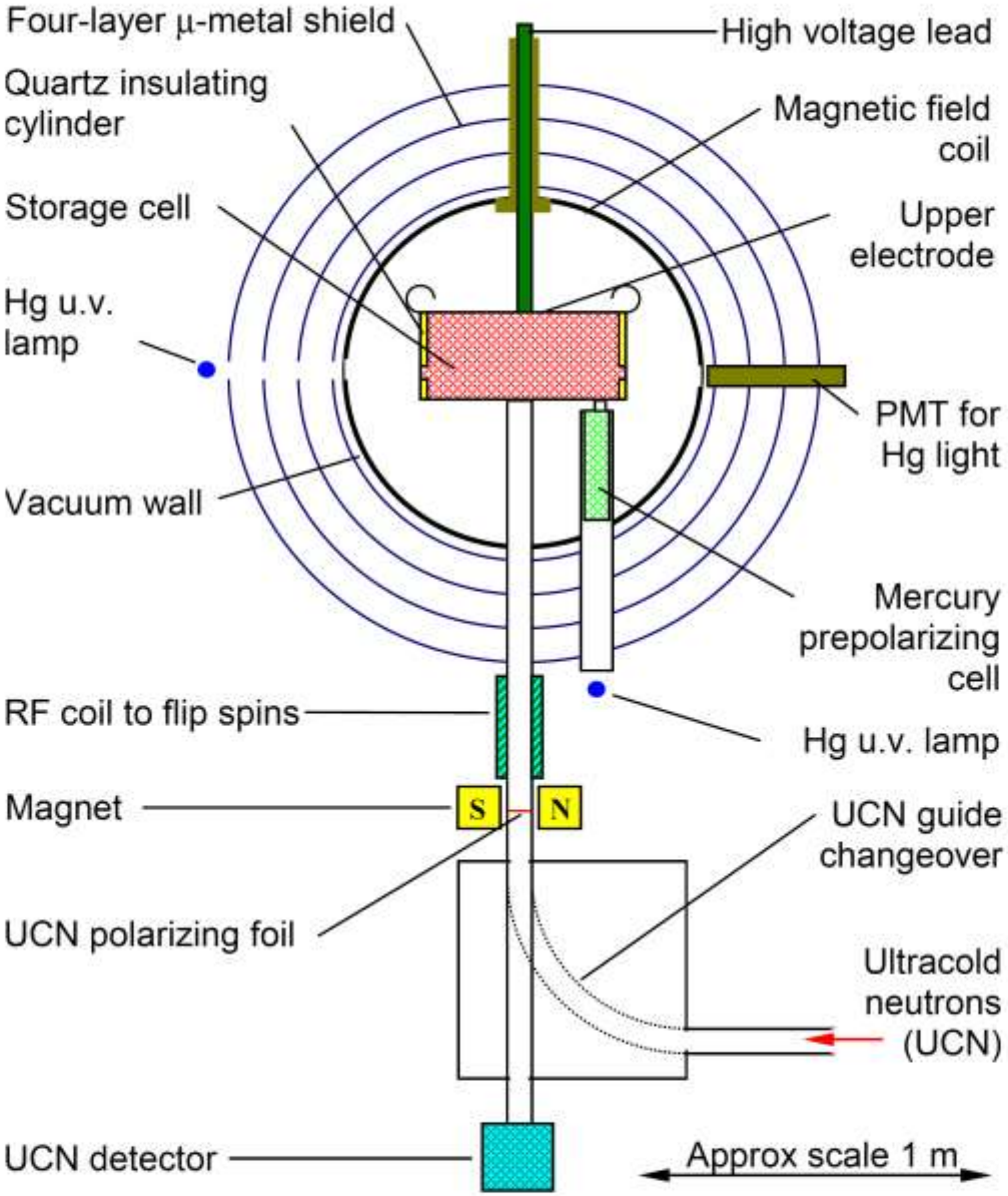


Resonant frequency



Baker et al, NIMA 736 184 (2014)

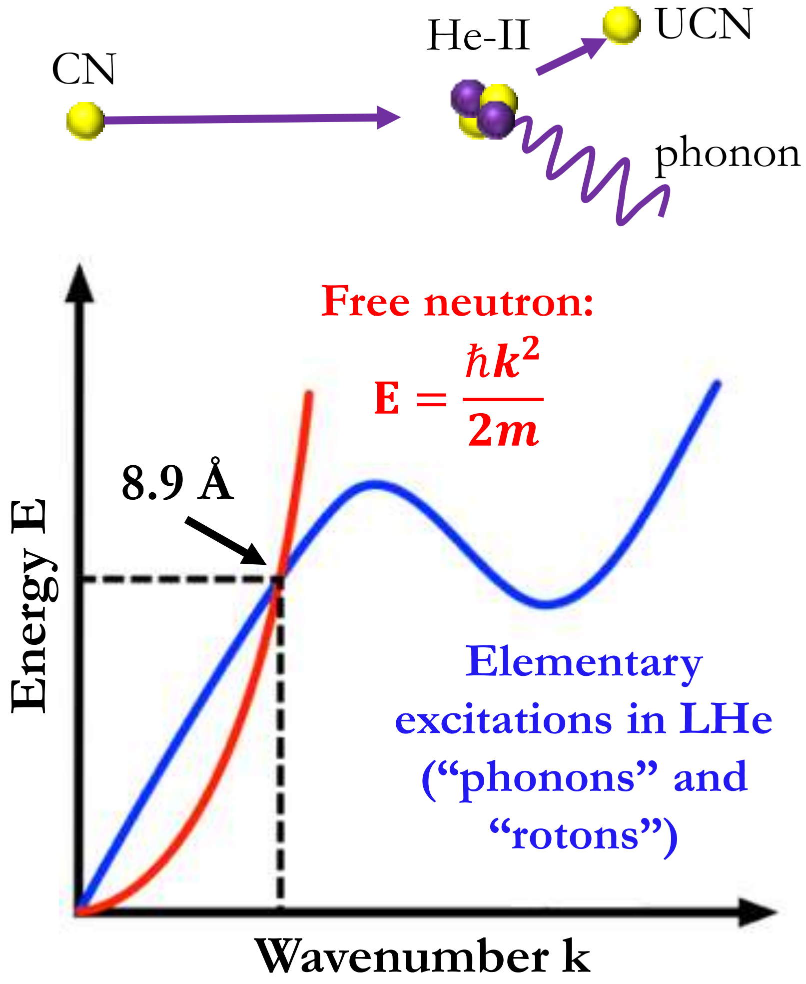
Present best nEDM limit



- Trapped 0.5 UCN/cc, stored for ~100 s
- E ~ 10 kV/cm
- Result: $d_n = -0.21 \pm 1.82 \times 10^{-26}$ e-cm

UCN from superfluid He (He-II)

- UCN production via "superthermal process"
- 8.9 Å (1 meV/11 K) cold neutron emits phonon in He-II, becomes UCN (500 Å/300 neV/3.5 mK)
- He-II cooled to ~1 K: Reverse process is suppressed by Boltzmann factor $e^{-E/k_B T}$



nEDM at the SNS

- Use helium to improve statistical precision
  - E: LHe = high voltage insulator, >85 kV/cm achieved
  - N: Higher densities using He-II
  - t: temp < 0.5 K allows storage times of ~1000 s

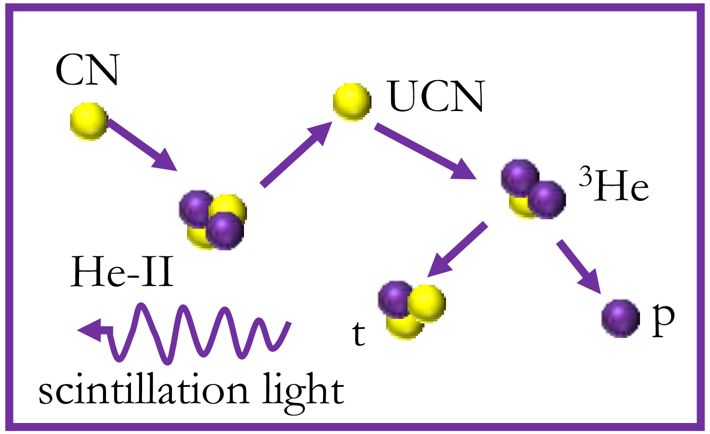
$$\sigma(d_n) \propto \frac{1}{Et\sqrt{N}}$$

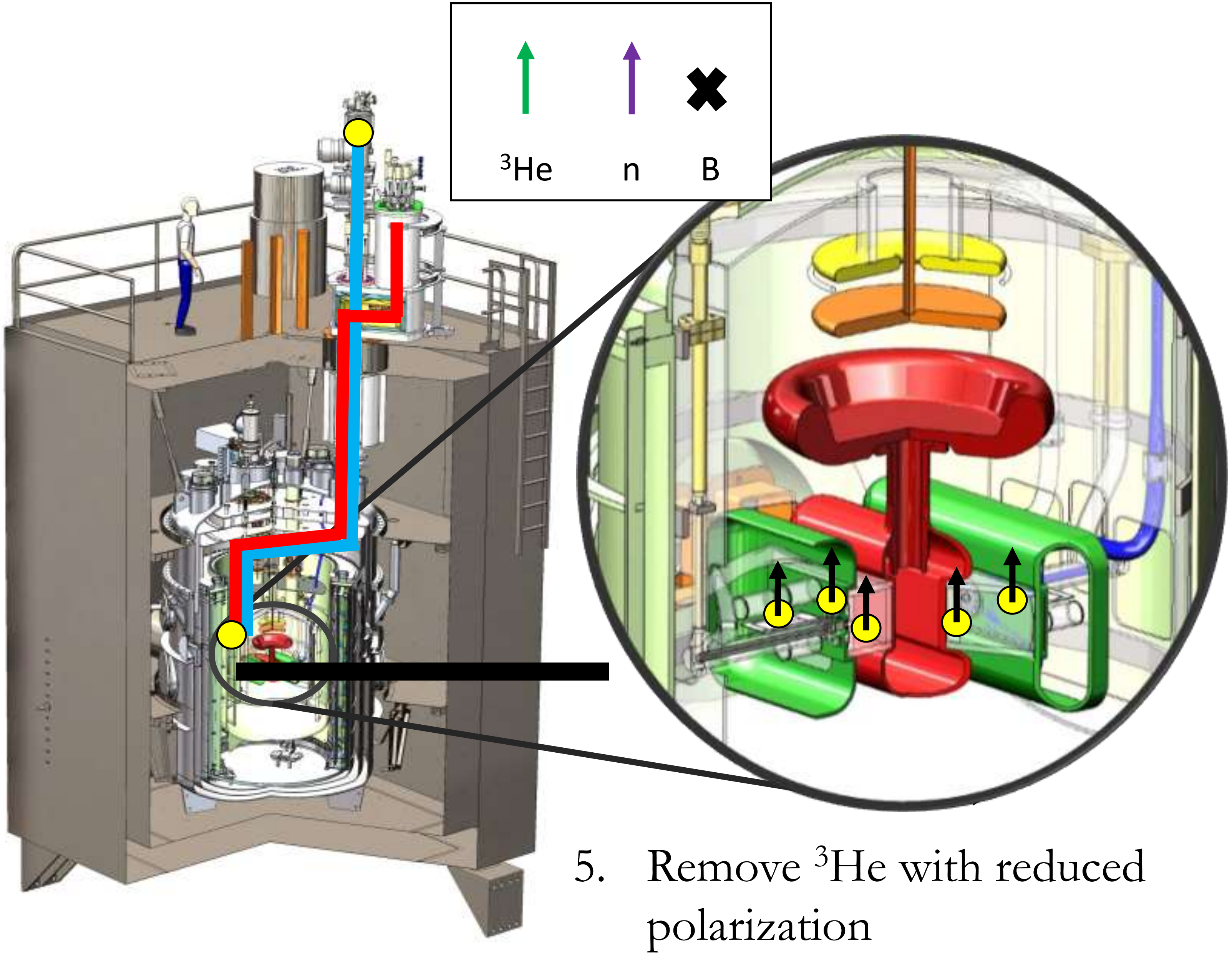
- and reduce systematic uncertainty
  - **“Geometric phase”: interaction of $\vec{\boldsymbol{v}} \times \vec{\boldsymbol{E}} = \vec{\boldsymbol{B}}_{\boldsymbol{E}}$ and magnetic gradients**
  - Limit leakage currents from electric field (which may produce magnetic fields)
  - Multiple measurement cells with opposite $\vec{E} \cdot \vec{B}$
  - Multiple measurement techniques

Golub and Lamoreaux, Phys Rep 237 1 (1994)
Ito et al, Rev Sci Instrum 87 045113 (2016)

SNS nEDM

- He-II is UCN source
- ^{3}He captures neutrons with strong spin-dependence
- He-II acts as a scintillator
- ^{3}He (95% polarized) used as a co-magnetometer





5. Remove ^{3}He with reduced polarization

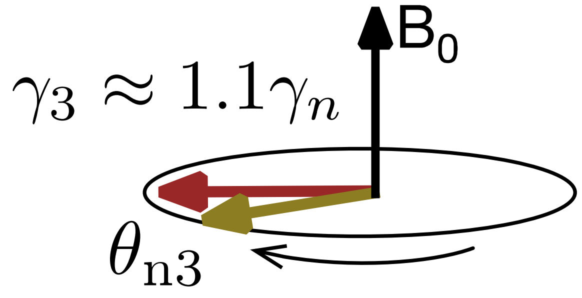
Extracting the nEDM

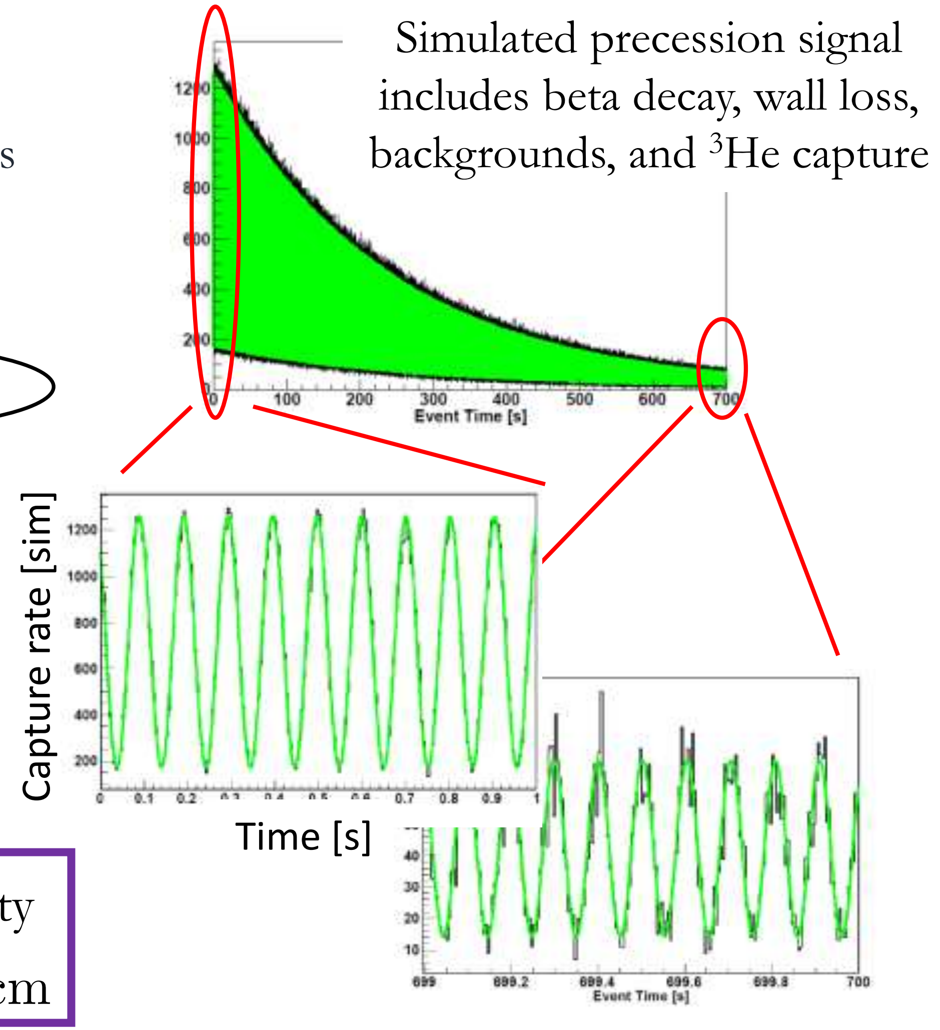
- ^{3}He capture is strongly spin-dependent
  - 69 kb if spins anti-aligned
  - 11 b if spins aligned
- Time evolution of angle:

$$\theta_{\mathrm{n3}} = |\gamma_n - \gamma_3| B_0 t \pm \frac{e d_n |E|}{\hbar} t$$

  - $\cos(\omega_n - \omega_3)$ variation in reaction rate
  - Beat frequency: 9 Hz @ 30 mG
- ^{3}He as co-magnetometer
  - ^{3}He shielded by atomic electrons
  - ^{3}He precession measured directly by SQUID pickup

Precession of both species

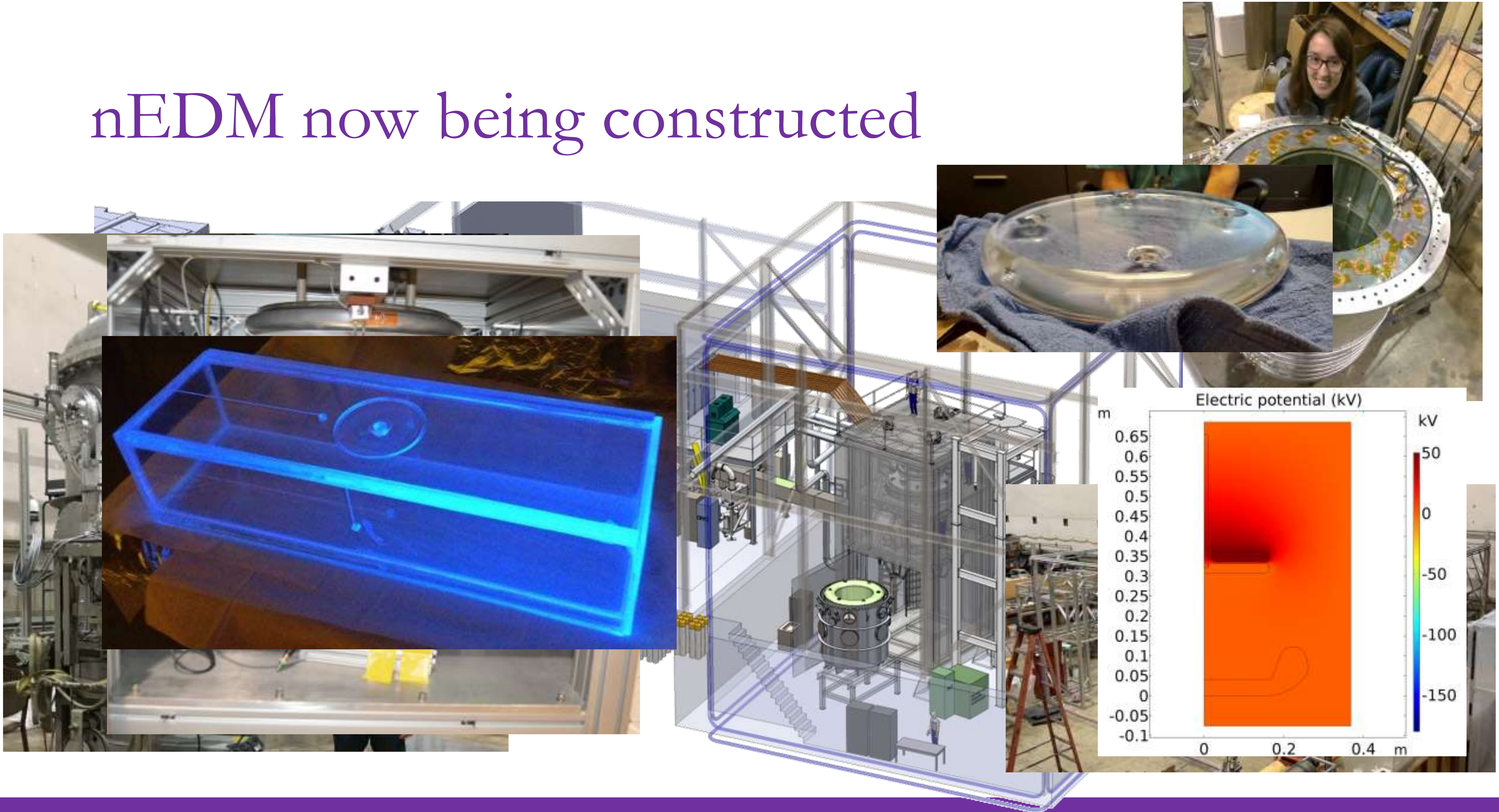




Simulated precession signal includes beta decay, wall loss, backgrounds, and ^{3}He capture

Expected sensitivity $\approx \pm 5 \times 10^{-28}\, e.\mathrm{cm}$

nEDM now being constructed

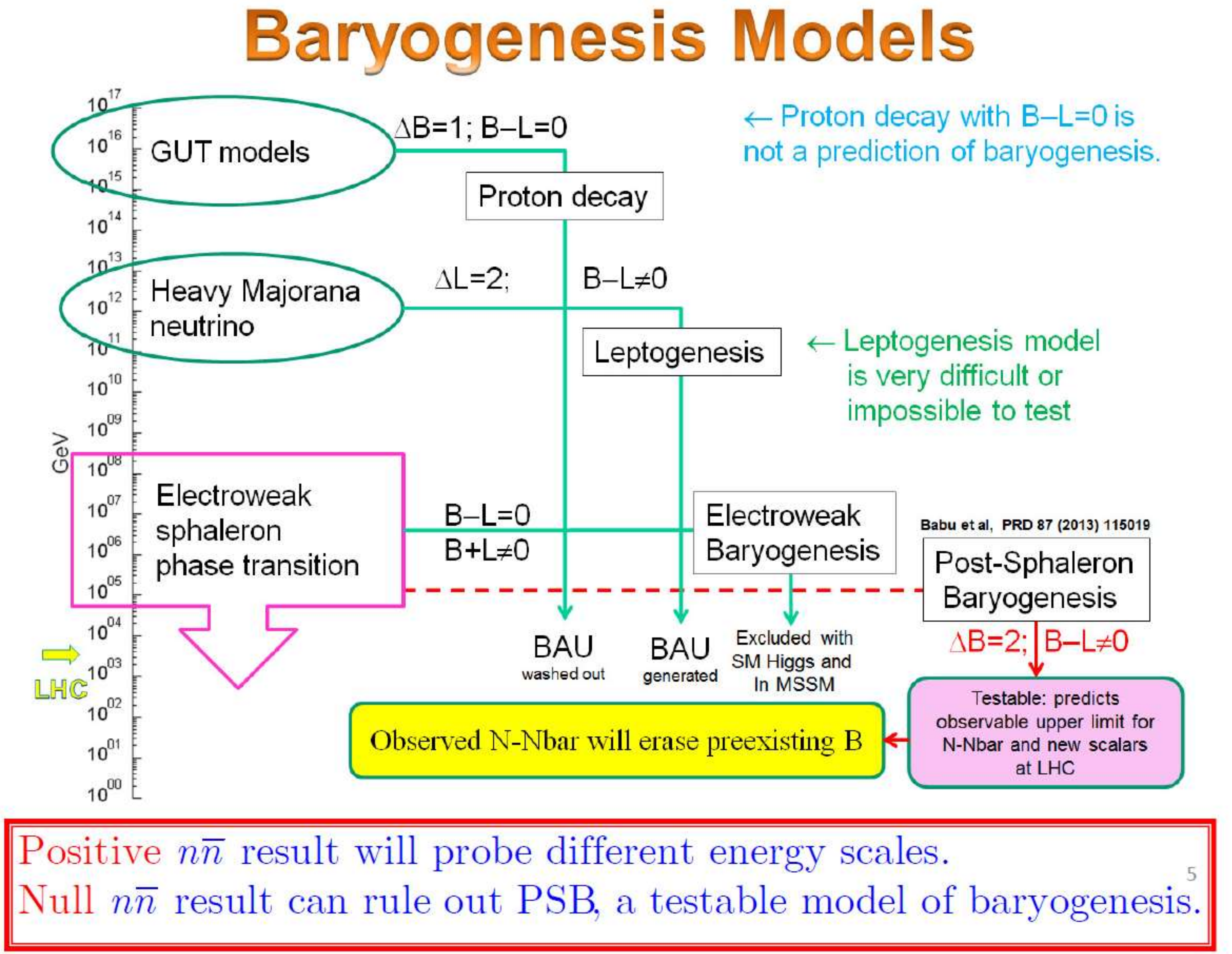


Outline

- P-violation and the weak interaction
- CP-violation and the electric dipole moment
- B-violation and oscillations

Baryo

- BNV per nonpertu process i phase tra which co
- Regimes
  - Leptog Lepton Baryon
  - Electr violatio asymm
  - Post-s BNV p transiti



Baryogenesis Models

GUT models

ΔB=1; B−L=0

Proton decay

← Proton decay with B−L=0 is not a prediction of baryogenesis.

Heavy Majorana neutrino

ΔL=2; B−L≠0

Leptogenesis

← Leptogenesis model is very difficult or impossible to test

Electroweak sphaleron phase transition

B−L=0
B+L≠0

Electroweak Baryogenesis

Babu et al, PRD 87 (2013) 115019

Post-Sphaleron Baryogenesis

BAU washed out

BAU generated

Excluded with SM Higgs and In MSSM

ΔB=2; B−L≠0

Testable: predicts observable upper limit for N-Nbar and new scalars at LHC

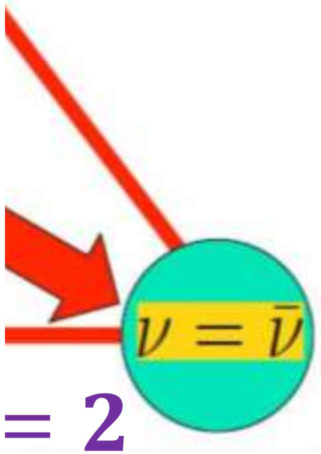
Observed N-Nbar will erase preexisting B

Positive $n\bar{n}$ result will probe different energy scales.
Null $n\bar{n}$ result can rule out PSB, a testable model of baryogenesis.

le:

$\Delta B = 1$

$\Delta L = 1$



$= 2$

Slide content from R. Mohapatra

Neutron anti-neutron oscillations

$$\hat{H} = \begin{pmatrix} m + \vec{\mu}(\vec{B} \cdot \vec{\sigma}) & \varepsilon \\ \varepsilon & m - \vec{\mu}(\vec{B} \cdot \vec{\sigma}) \end{pmatrix}$$

- Magnetic fields can suppress oscillations:
  Mass splitting from any nonzero B >> off-diagonal term

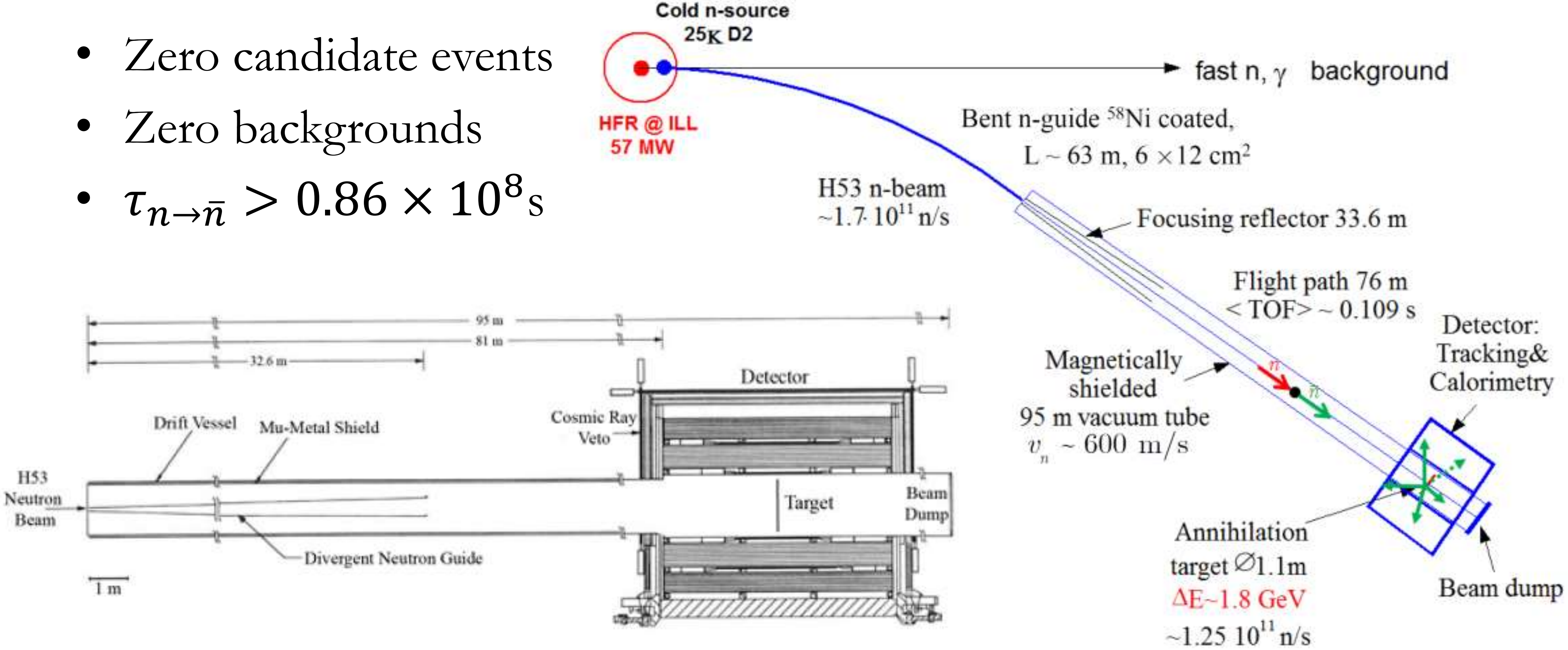
$$\Delta E = E_n - E_{\bar{n}} = 2\mu B$$

$$\Delta E(1\,nT) \sim 10^{-22}\ \text{MeV} \qquad \varepsilon < 10^{-29}\ \text{MeV}$$

- Need "Quasi-free limit": Uncertainty principle = $\Delta E \Delta t \ll \hbar$
  - ILL: neutron TOF ~ 0.1 s, B~10 nT
- In this limit $P_{n\rightarrow\bar{n}}(t) = \left(\frac{t_{free}}{\tau_{n\rightarrow\bar{n}}}\right)^2$

Free $n \rightarrow \bar{n}$ Search at ILL

- Zero candidate events
- Zero backgrounds
- $\tau_{n\rightarrow\bar{n}} > 0.86 \times 10^{8}\text{s}$



Baldo-Ceolin et al, ZPC 63 409-416 (1994)

Improving limits on $n \rightarrow \bar{n}$: European Spallation Source

- Similar time-averaged brightness to ILL
  - Pulsed = bkgd rejection
- >200 m beamguides possible
- Moderator, neutron optics, detector design study
  - ~1000x ILL possible

Moderator configuration	Sensitivity Nt^2 in ILL units/yr
ESS TDR 2013	250
Option of large LD_2 source	550
Flat "pancake" with h = 3 cm	200
ANNI with BF1 Source	0.8

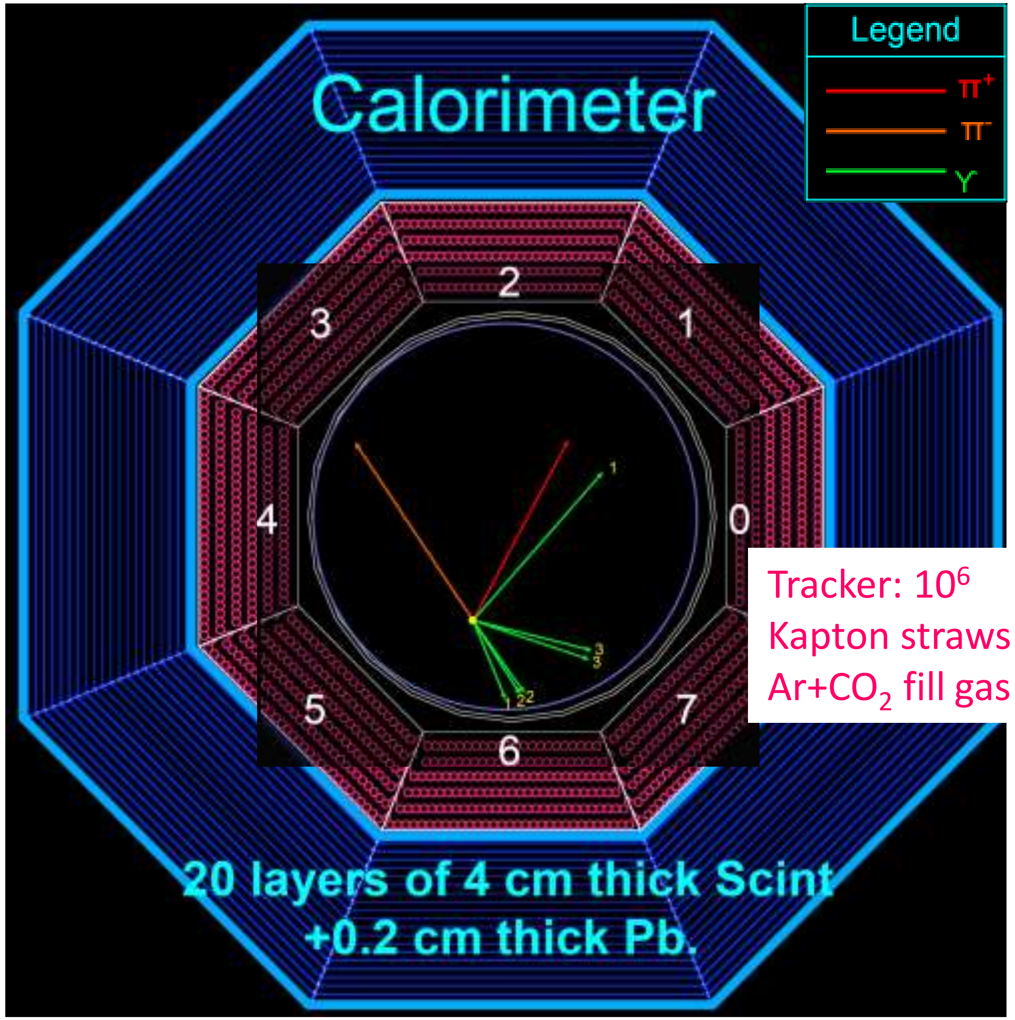
Adapted from M. Frost, INT 17-69W

$\bar{n}$ annihilation detection

- Maintain "background free", improve efficiency
- Example "pion star"

$$\bar{n} + {}^{12}C \rightarrow {}^{11}C$$
$$+3\pi^0 + \pi^+ + \pi^-$$

- Goal background suppression $< 10^{-8}$ Hz
- Key backgrounds:
    - Gamma backgrounds
        - Neutron capture
    - High energy n,p
    - Beta delayed n
    - Cosmic rays
        - Dominant, scales with size



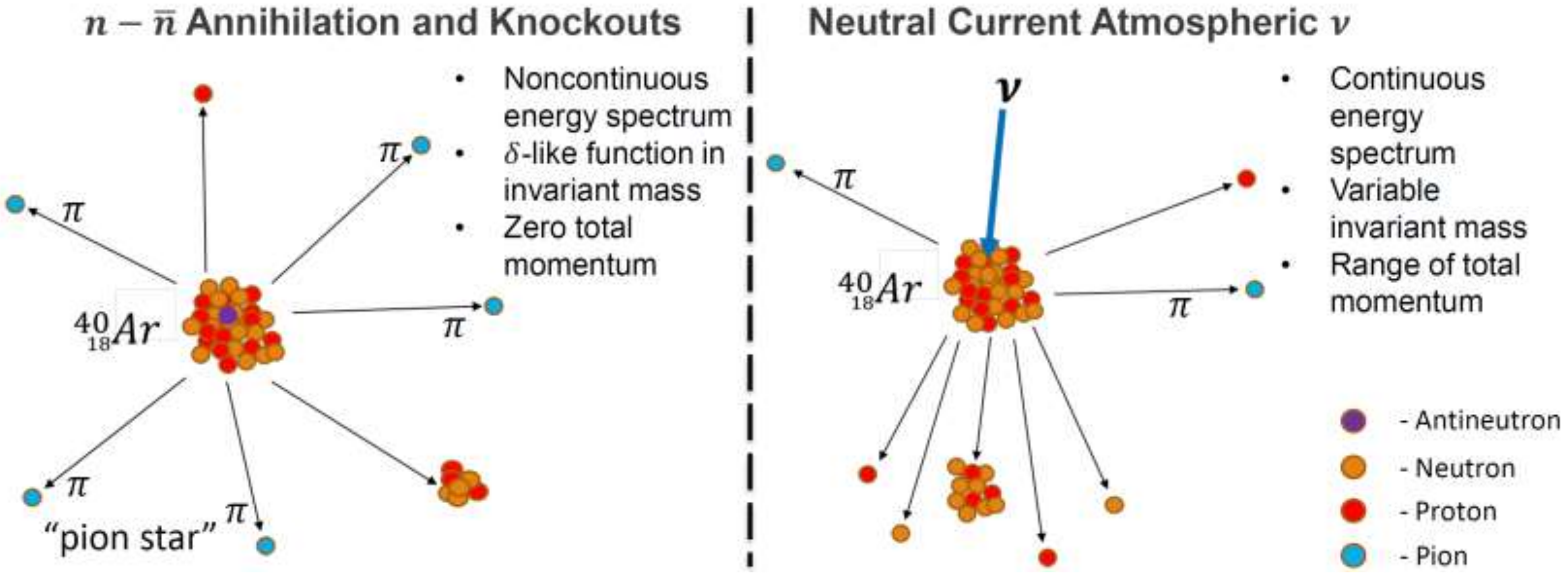
Tracker: 10^6 Kapton straws $Ar+CO_2$ fill gas

Detector study by A.R. Young, R.W. Pattie Jr, D.G. Phillips II

Adapted from A. R. Young, INT 17-69W

$n \rightarrow \bar{n}$ in Nuclei

- $n, \bar{n}$ have different interactions in nuclei → intranuclear searches: suppression factor R~5x10^{22} s^{-1} (for ^{16}O)
- Distinguish $\bar{n}$ signal from ν_{atm} background

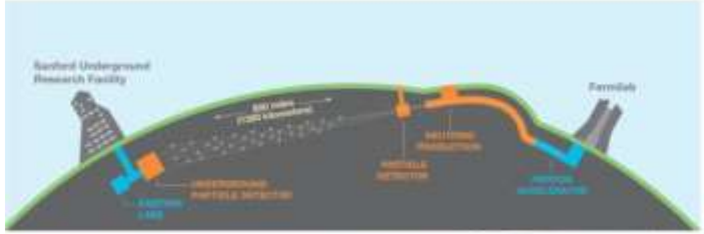


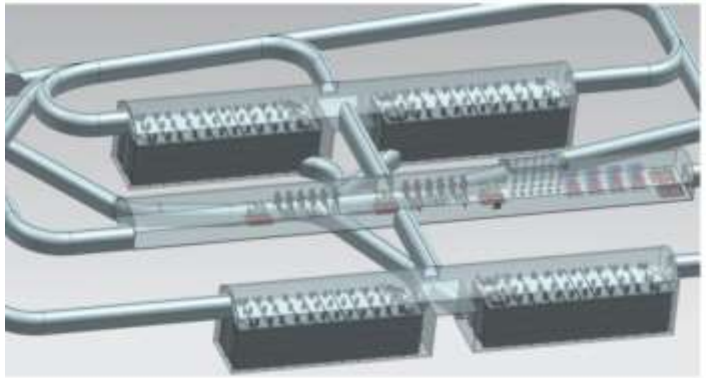
- Best limits from SuperKamiokande: $\tau_{n\rightarrow\bar{n}} > 2.7 \times 10^{8}$s

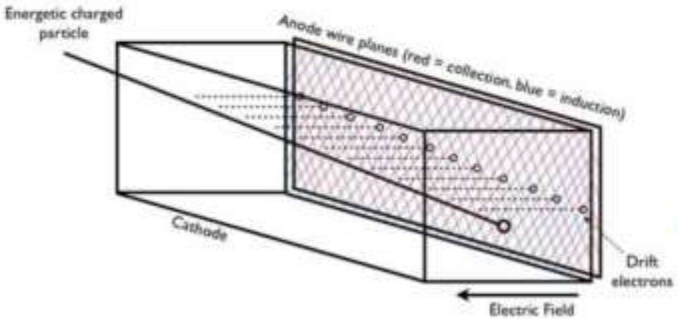
24 candidates, 24.1 expected backgrounds

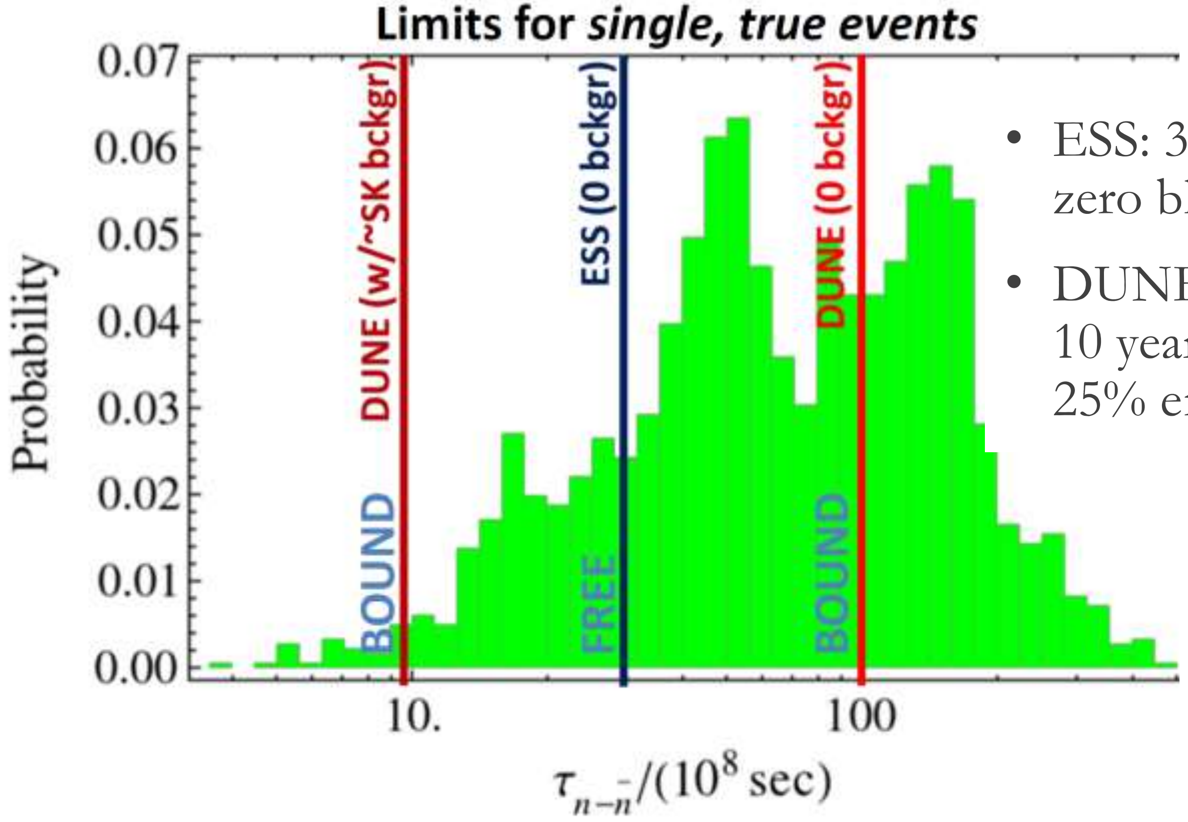
Adapted from J. Barrow, BLV 2017
Abe et al, PRD 91 072006 (2015)

The Deep Underground Neutrino Experiment and Proposed $n — \bar{n}$ Search









- ESS: 3-5 years, zero bkgd
- DUNE detector: 10 years, 0 bkgd, 25% efficiency

BLV 2017 7

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Adapted from J. Barrow, BLV 2017
Babu, Dev, Fortes, and Mohapatra- DOI:10.1103/PhysRevD.87.115019

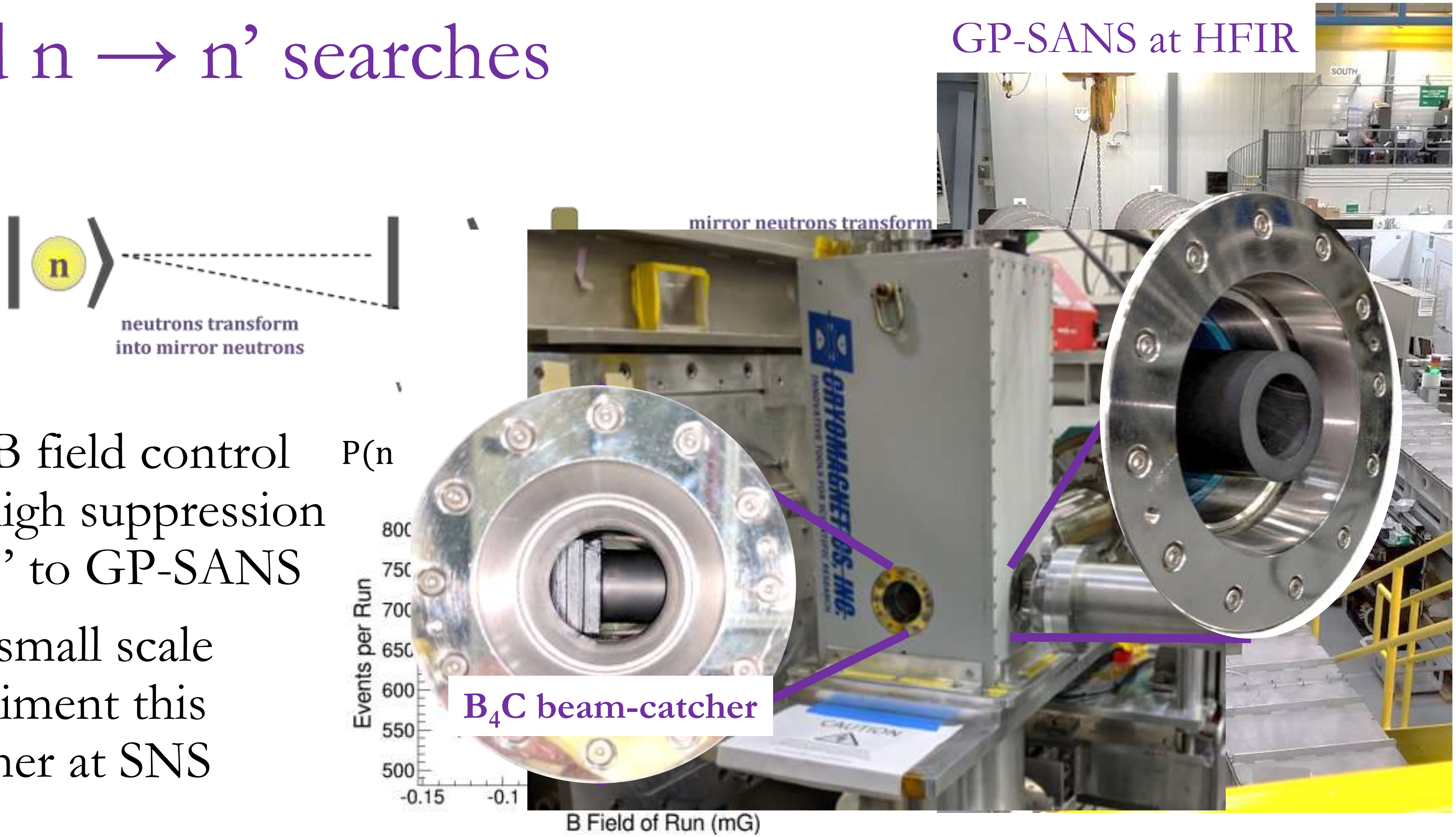
Mirror neutron oscillations

- “Mirror matter”: hidden sector dark matter candidate
- Multiple Baryon Numbers, with overall conservation of $B_{tot} = B + B'$
- Experimental signature: oscillation into invisible “mirror neutrons”
  - All previous searches performed in ultracold neutron bottle experiments
- Various mechanisms to induce oscillations, using magnetic fields
  - some suggested to explain the neutron lifetime discrepancy
  - can consider mixing with antineutrons

$$\mathcal{H}_{int} = \begin{pmatrix} m + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \eta\boldsymbol{\sigma}\cdot[\boldsymbol{B} \pm \boldsymbol{B}'] + \varepsilon \\ \eta\boldsymbol{\sigma}\cdot[\boldsymbol{B} \pm \boldsymbol{B}'] + \varepsilon & m' + \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' \end{pmatrix}$$

Cold n → n’ searches

- Add B field control and high suppression “wall” to GP-SANS
- First small scale experiment this summer at SNS



Broussard et al, EPJC 2019

Summary

- Tremendous opportunity to search for influence of new physics using low energy precision tests of fundamental symmetries
- Violation of CKM unitarity by 3 σ demands new precision measurements using independent approaches
  - New precision neutron measurements on the horizon including Nab at SNS
- Matter asymmetry in universe remains one of the most important questions in science
  - Electric dipole moment searches such as nEDM at SNS will probe interesting parameter space for theories predicting CP-violation
  - Observation of neutron oscillations would demonstrate baryon number violating process
- Lots of exciting developments in neutrons and nuclei.... stay tuned!