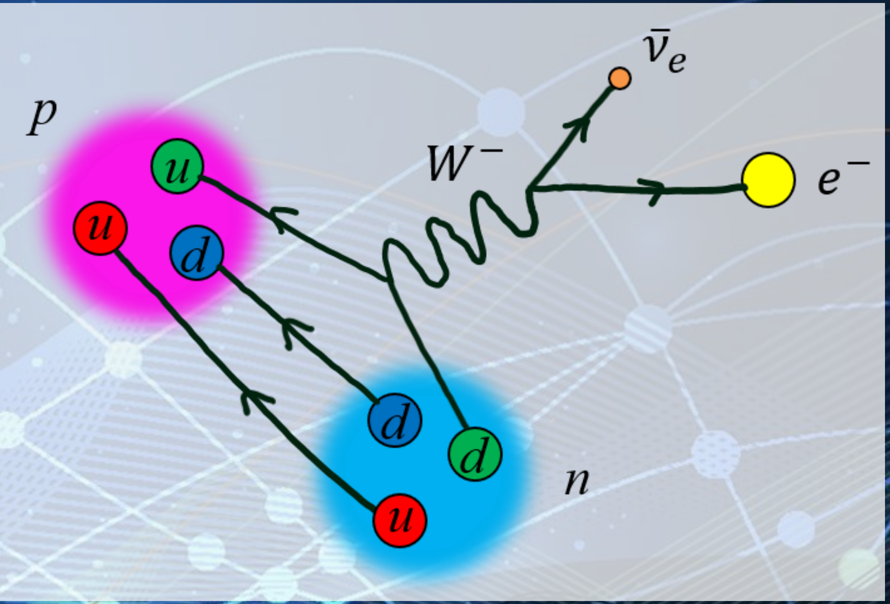
Fundamental Neutron Physics at NIST



Shannon Hoogerheide

NCNR Summer School

Feb 11, 2022

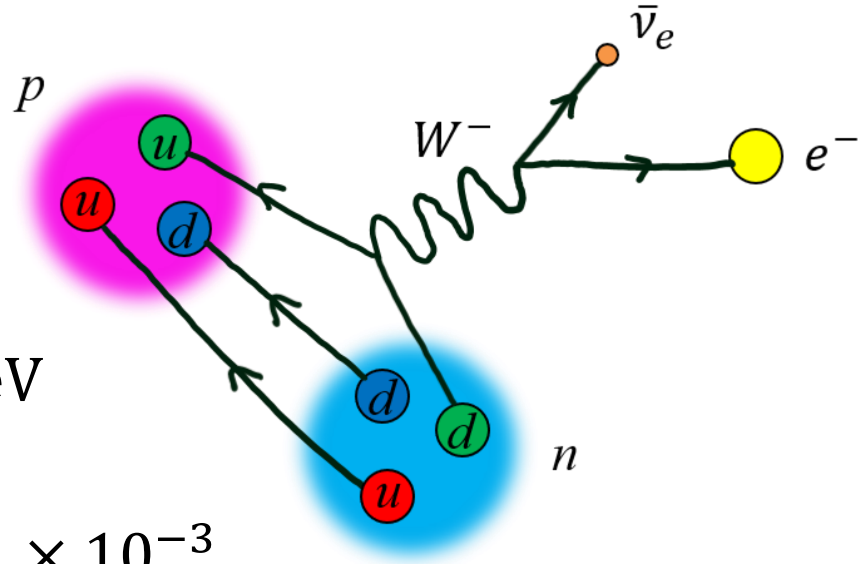
Neutron Beta Decay Basics

NIST

- Free neutron is unstable: $\tau_n \approx$ 15 min

- Main decay channel: $n \rightarrow p + e^- + \bar{\nu}_e$

  $0 < E_e < 783\ \text{keV} \quad 0 < E_p < 751\ \text{eV}$



- Other decay modes

  $n \rightarrow p + e^- + \bar{\nu}_e + \gamma$ BR(>14keV) $\approx 3 \times 10^{-3}$

  $n \rightarrow H + \bar{\nu}_e$ BR $\approx 4 \times 10^{-6}$

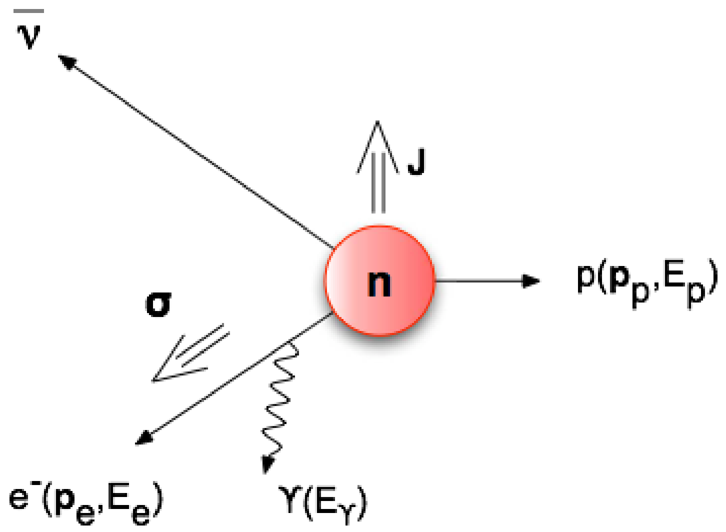
  $E_{\bar{\nu}} = 783$ keV E_H =326.5 eV

- Exotic Decay Modes?

  $n \rightarrow X$

Fundamental Neutron Physics

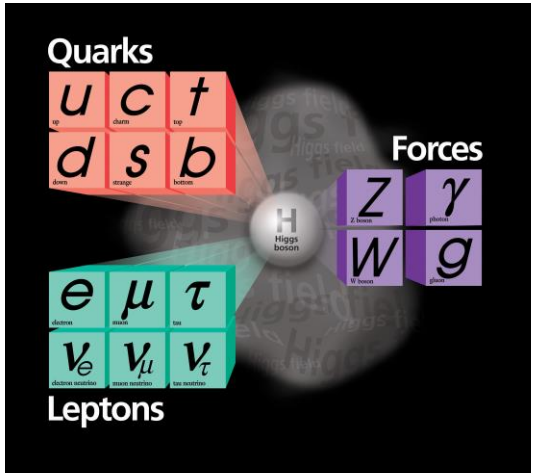
$$dW \propto \frac{1}{\tau} F(E_e) \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\upsilon}{E_e E_\upsilon} + A \frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + B \frac{\vec{\sigma}_n \cdot \vec{p}_\upsilon}{E_\upsilon} + D \frac{\vec{\sigma}_n \cdot (\vec{p}_e \times \vec{p}_\upsilon)}{E_e E_\upsilon} + b \frac{m_e}{E_e} \right]$$

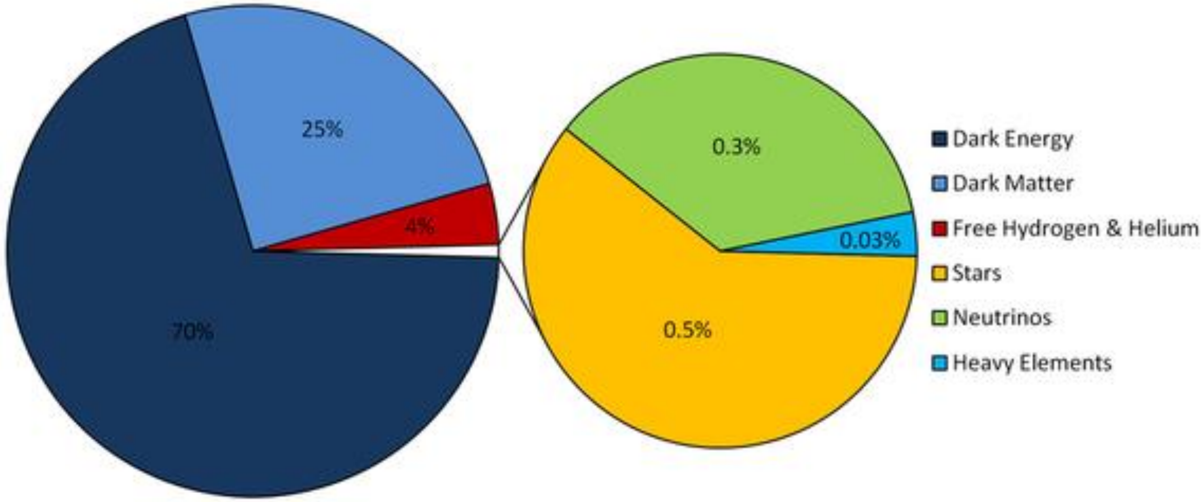


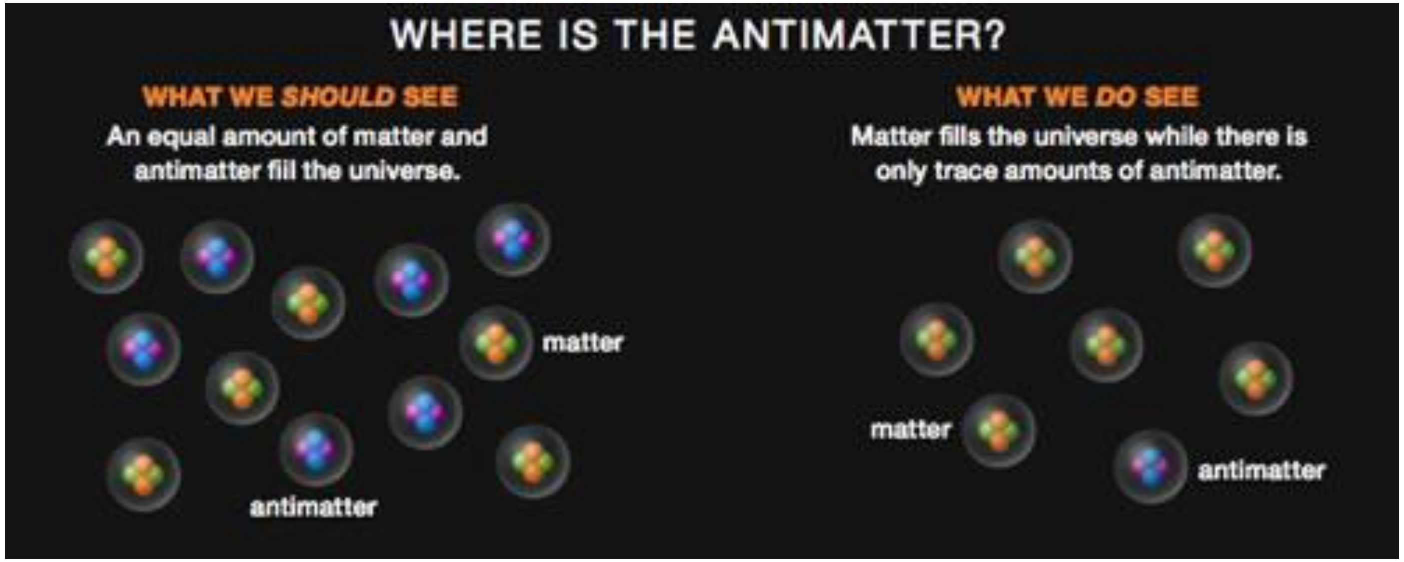
- Neutron lifetime
- Angular correlations (*a, A, b, B, D, ...*)
- Hadronic Parity Violation

Big Bang Nucleosynthesis
CKM Unitarity; V_{ud}
$\lambda = g_A/g_V$
Beyond Standard Model physics
T-violation
Matter/anti-matter asymmetry
Search for 5^{th} forces (new physics)

Why Look for Physics Beyond the Standard Model of Particle Physics?



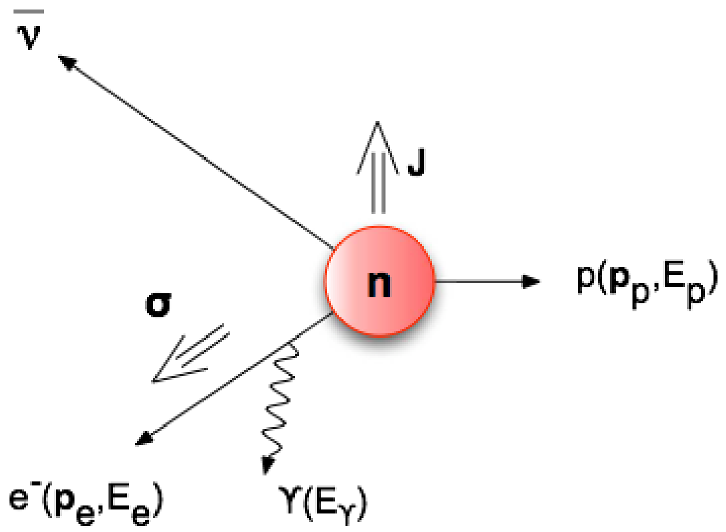




SI

Fundamental Neutron Physics: Challenges

$$dW \propto \frac{1}{\tau} F(E_e)\left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\upsilon}{E_e E_\upsilon} + A\frac{\vec{\sigma}_n\cdot\vec{p}_e}{E_e} + B\frac{\vec{\sigma}_n\cdot\vec{p}_\upsilon}{E_\upsilon} + D\frac{\vec{\sigma}_n\cdot(\vec{p}_e\times\vec{p}_\upsilon)}{E_e E_\upsilon} + b\frac{m_e}{E_e}\right]$$

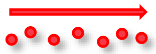


Challenges:
- Lifetime is too long
- Neutrons are hard to manipulate
- Decay antineutrino is unobservable
- Decay proton endpoint energy only 751 eV

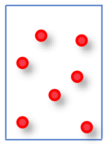
→We need a lot of cold neutrons!

Solution: NG-C Fundamental Physics Beamline

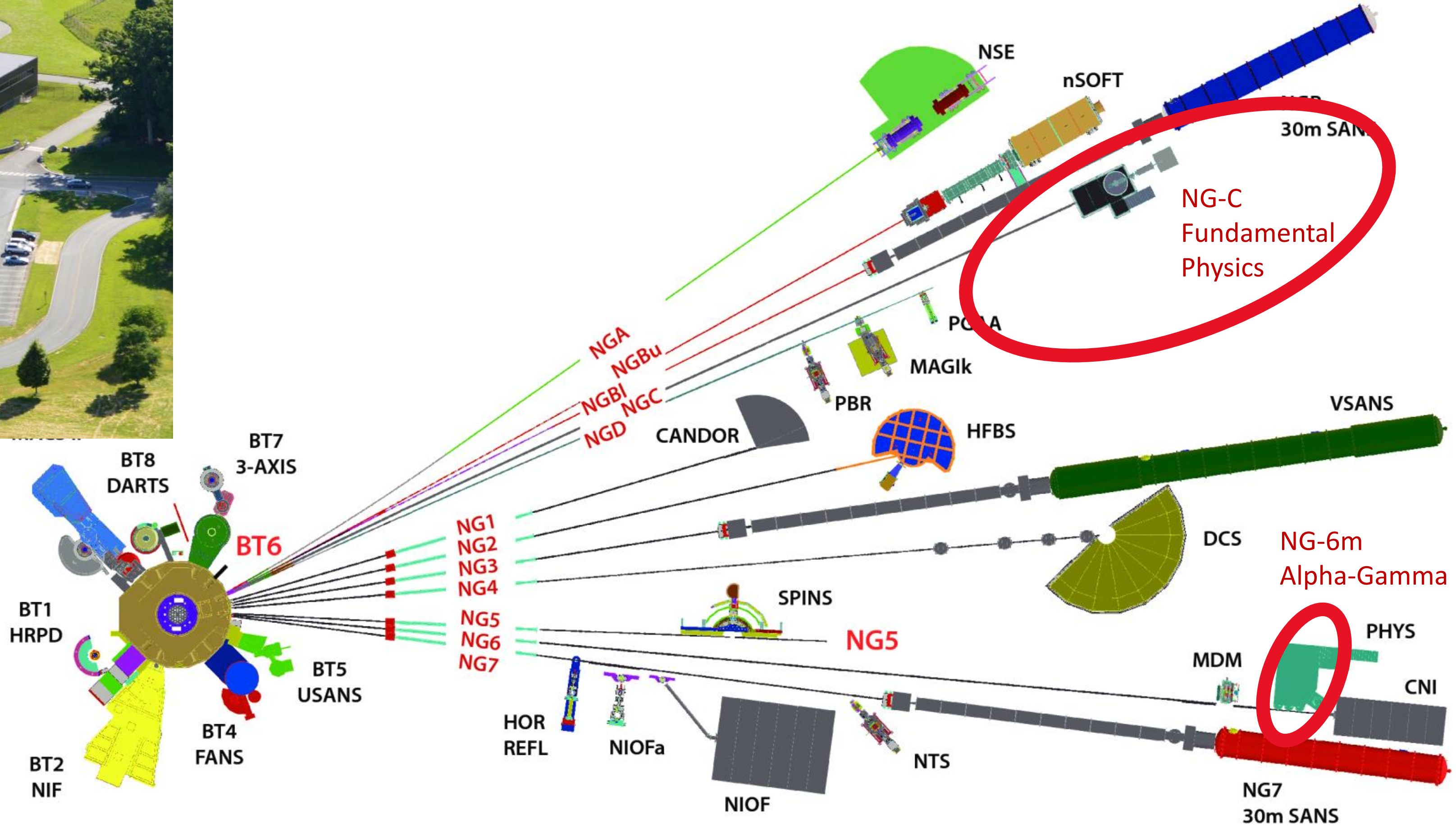
Cold neutrons:
- Moderated by, eg. liquid H or liquid D
- Energy < 5 meV
- Temperature < 60 K
- velocity < 1000 m/s



Ultracold neutrons:
- Slowing, selection, or down-conversion from cold neutron population
- Energy < 200 neV
- Temperature < 2 mK
- velocity < 6 m/s

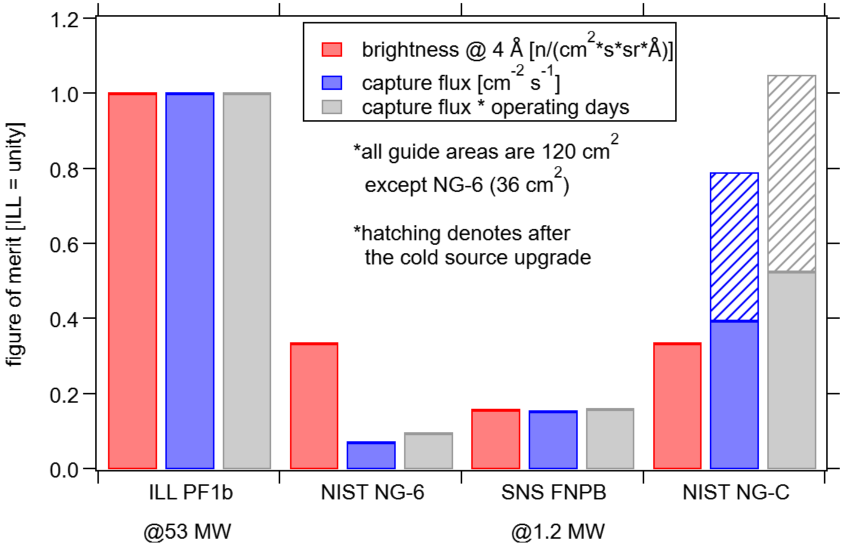


NG-C Beamline at the NCNR

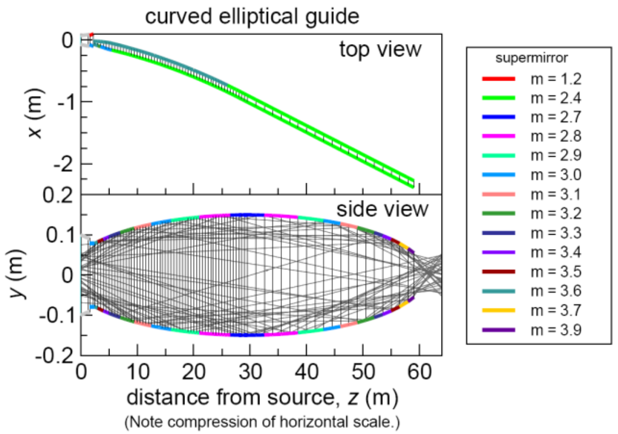


NG-C: The Fundamental Physics Beamline

- **Highest flux cold neutron beam in the US** for fundamental physics
  - 2023 Cold Source upgrade -> comparable to best in the world
- National Resource operated in service to the Physics Community
- Proposed experiments are selected to run by external Beam Time Allocation Committee (BTAC)

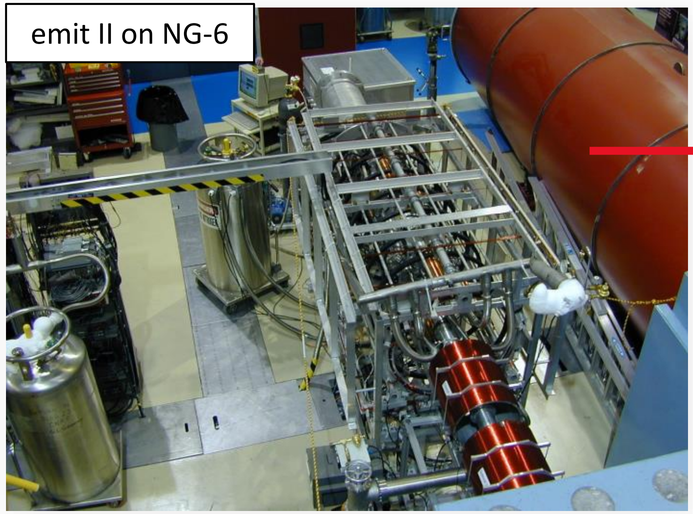


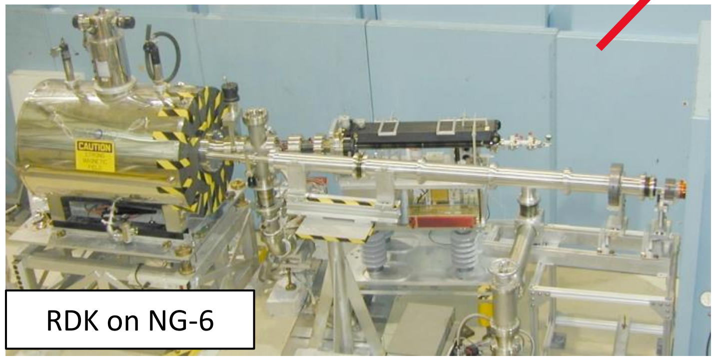
- Constructed as part of the new guide hall expansion
- Replaced NG-6 in 2015 as the Fundamental Physics Beamline
- Polychromatic beamline
- Curved ballistic supermirror guide
  - Very low fast neutron and gamma backgrounds
- 11 cm x 11 cm beam exit
  - Computer-controlled aperture with 4 independent blades made of ¼" thick borated Al
- Large-area, high-uniformity supermirror polarizer available
- 2.4 m deep pit at end of guide
- Local LHe reliquifier available (15 L/day); Building-wide LHe recovery system under construction



A conceptual design for guide NG-C is shown above. Also shown is a random selection of transmitted 4 Å wavelength neutron trajectories making at least one reflection from the top or bottom surface. (Straight through trajectories are omitted for clarity.)

Notable Results in Fundamentalism:

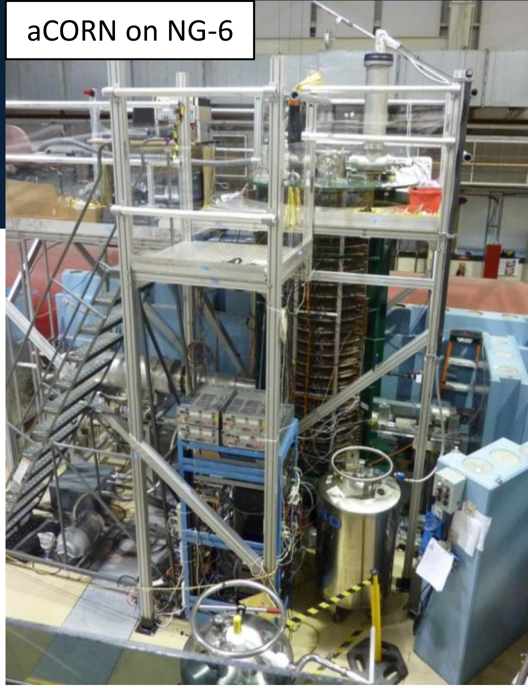




NEUTRONS (NG-6 and NG-C):

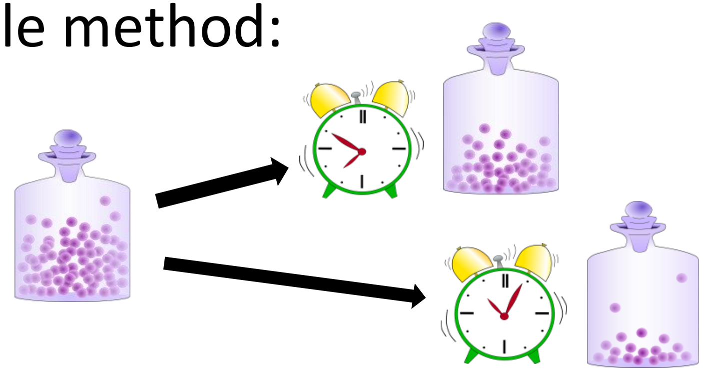
- Time Reversal Asymmetry (D) – emiT I and II
  - Lising et al., PRC 2000
  - Mumm et al., PRL 2011
- Magnetic Trapping of Ultracold Neutrons
  - Huffman et al., Nature 2000
- Beam Neutron Lifetime
  - Dewey et al., PRL 2003
  - Yue et al., PRL 2013
- Neutron Radiative Decay - RDK I and II
  - Nico et al., Nature 2006
  - Bales et al., PRL 2016
- Parity Violating Neutron Spin Rotation
  - Snow et al., PRC 2011
  - Swanson et al., PRC 2019
- Electron-Antineutron Correlation (aCORN)
  - Darius et al., PRL 2017
  - Hassan et al., PRC 2021

Publication since 2015



Neutron Lifetime τ_n: $N(t) = N_0 e^{-t/\tau_n}$

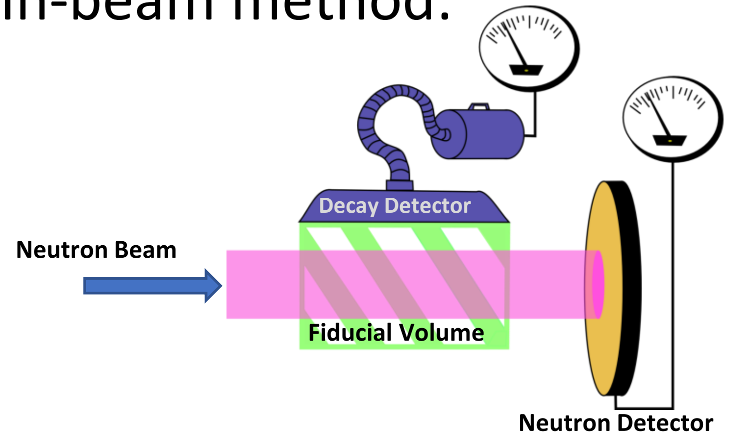
Bottle method:



$$\frac{N(t_1)}{N(t_2)} = e^{-(t_1 - t_2)/\tau_n}$$

"count the living"

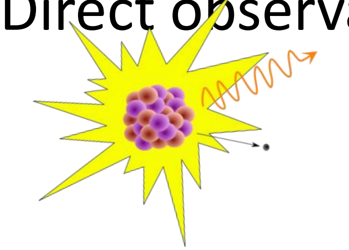
In-beam method:



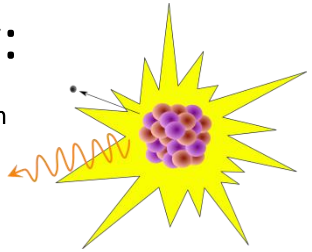
$$\frac{\partial N(t)}{\partial t} = -N/\tau_n$$

"count the dead"

Direct observation of decay:



Similar in principle to Freshman Physics Majors measuring radionuclide half lives
-- only a lot harder.

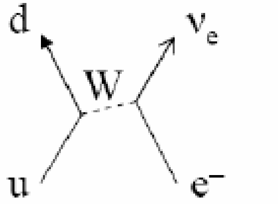
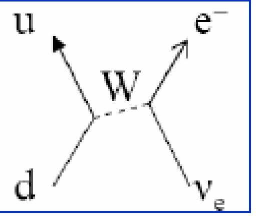
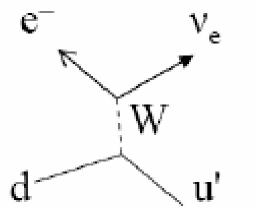


$$\ln\left(\frac{\partial N(t)}{\partial t}\right) \text{ is } -1/\tau_n$$

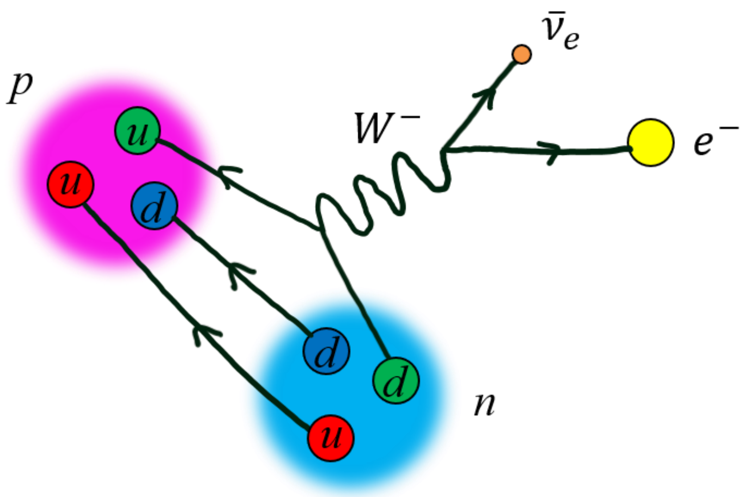
"watch them die"

Neutron Lifetime Motivation

Neutron lifetime sets weak interaction rates which govern many processes:

Cosmology	Primordial element formation	$n + e^+ \rightarrow p + \nu'_e$	$\sigma_\nu \sim 1/\tau$	
	(^{2}H, ^{3}He, ^{4}He, ^{7}Li, …)	$p + e^- \rightarrow n + \nu_e$	$\sigma_\nu \sim 1/\tau$	
		$n \rightarrow p + e^- + \nu'_e$	τ	
Astronomy	Solar cycle	$p + p \rightarrow {}^2H + e^+ + \nu_e$		
		$p + p + e^- \rightarrow {}^2H + \nu_e$ etc.	$\sim (g_A/g_V)^5$	
	Neutron star formation	$p + e^- \rightarrow n + \nu_e$		
Particle Physics	Pion decay	$\pi^- \rightarrow \pi^0 + e^- + \nu'_e$		
	Neutrino detectors	$\nu'_e + p \rightarrow e^+ + n$		
	Neutrino forward scattering	$\nu_e + n \rightarrow e^- + p$ etc.		
	W and Z production	$u' + d \rightarrow W^- \rightarrow e^- + \nu'_e$ etc.		

from D. Dubbers



Big Bang Nucleosynthesis

NIST

1ms

Thermal equilibrium
(T > 1 MeV)

$$\frac{n}{p} \propto e^{-Q/T}$$

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$$n + \nu_e \leftrightarrow p + e^-$$

1s

After freezeout (T ~ 0.8 MeV)
n/p decreases due to
neutron decay

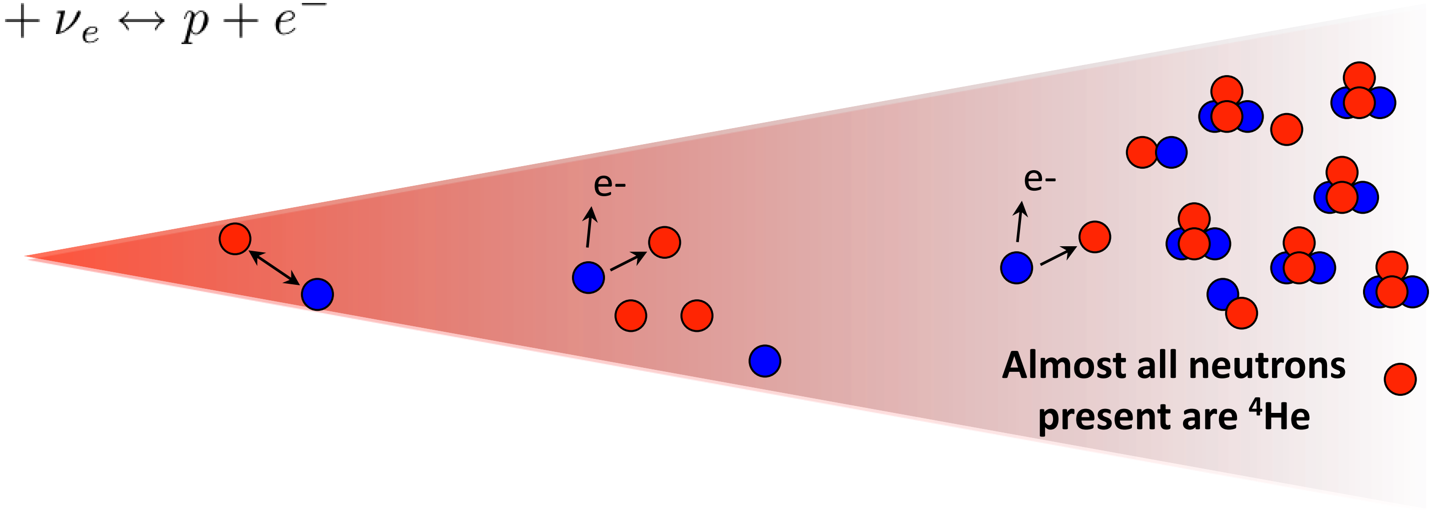
$$n \rightarrow p + e^- + \bar{\nu}_e$$

100s

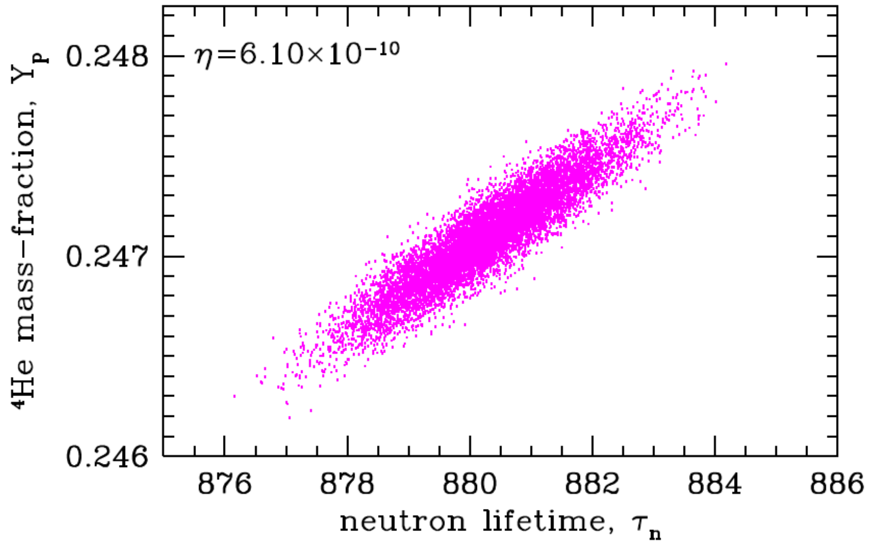
Nucleosynthesis (T~0.1 MeV)
Light elements are formed

$$p + n \rightarrow d + \gamma$$

$$d + d \rightarrow {}^4\text{He} + \gamma$$

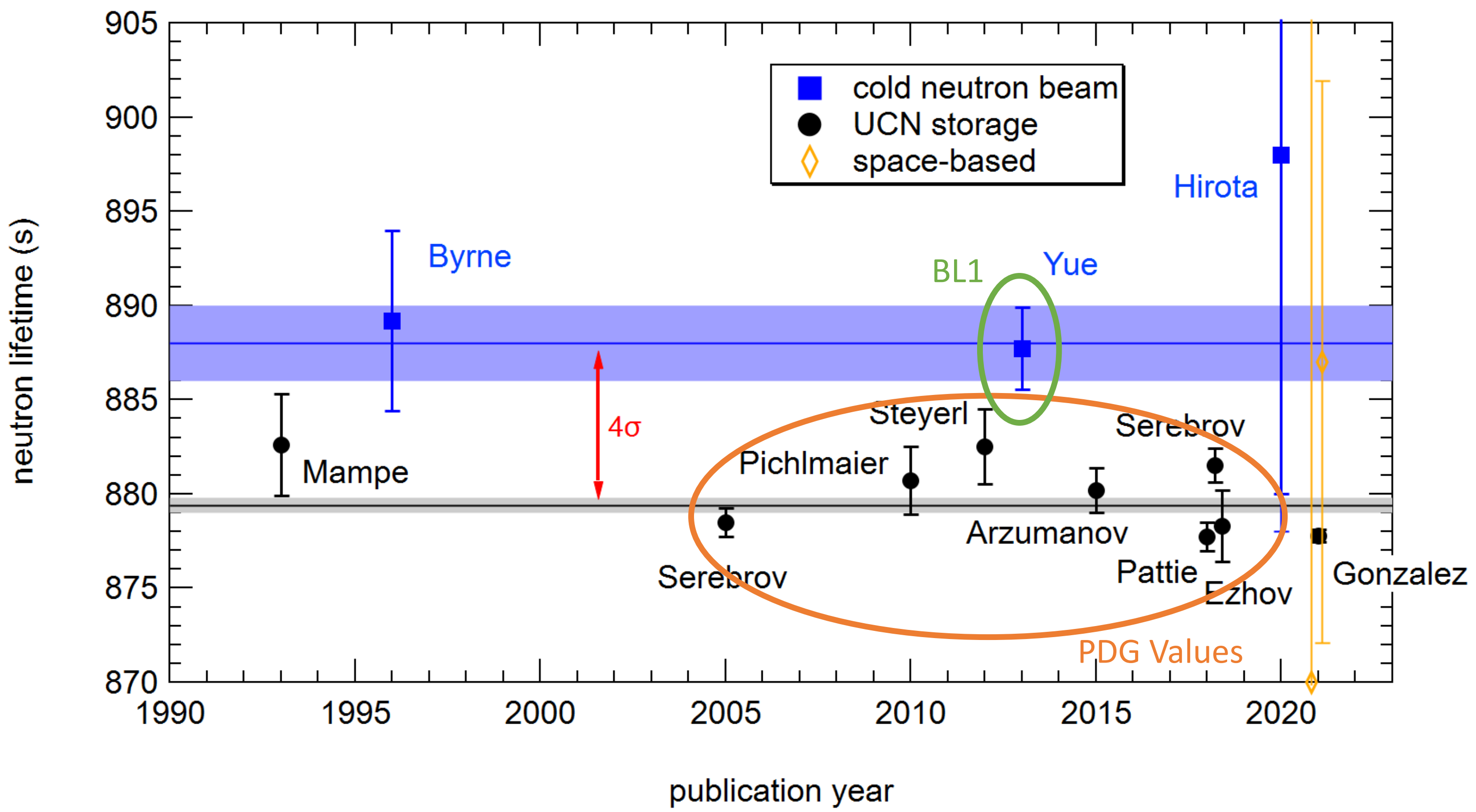


Rev. Mod. Phys. 88, 015004 (2016)



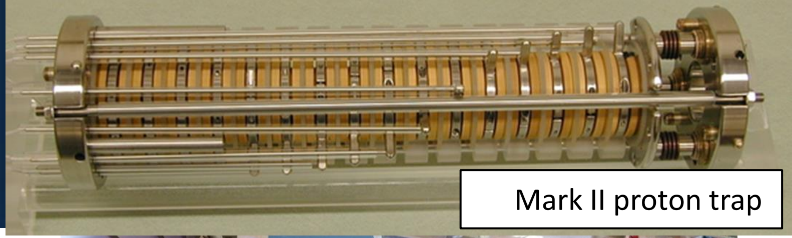
Neutron lifetime dominates the theoretical uncertainty of ^{4}He abundance.

State of the Neutron Lifetime



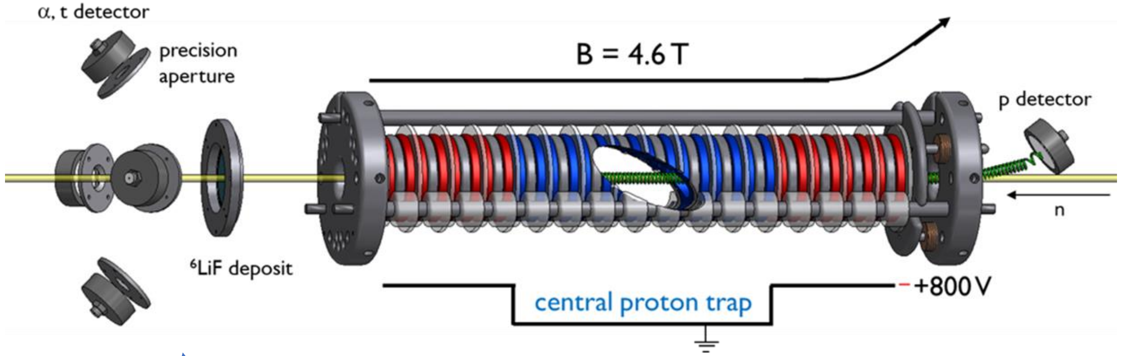
- Competitive determination of V_{ud} requires τ_n precision of order 0.1 s
- Important for Big Bang Nucleosynthesis
- More beam measurements are necessary to understand the discrepancy and improve precision

Currently Running on NG-C: BL2



Measurement of neutron lifetime, τ_n, with a cold neutron beam

Beam Method:

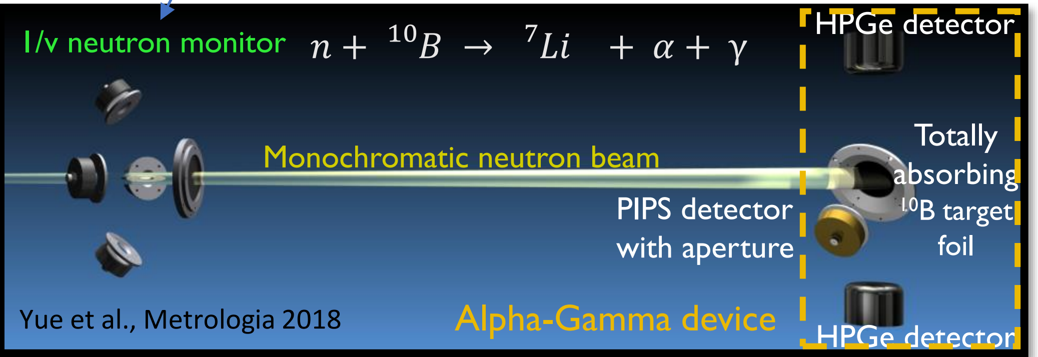


$$\tau_n = \dot{N}_{\alpha+t}\left(\frac{L}{\dot{N}_p}\right)\frac{\epsilon_p}{\epsilon_0 v_0}$$

Requires two absolute measurements:

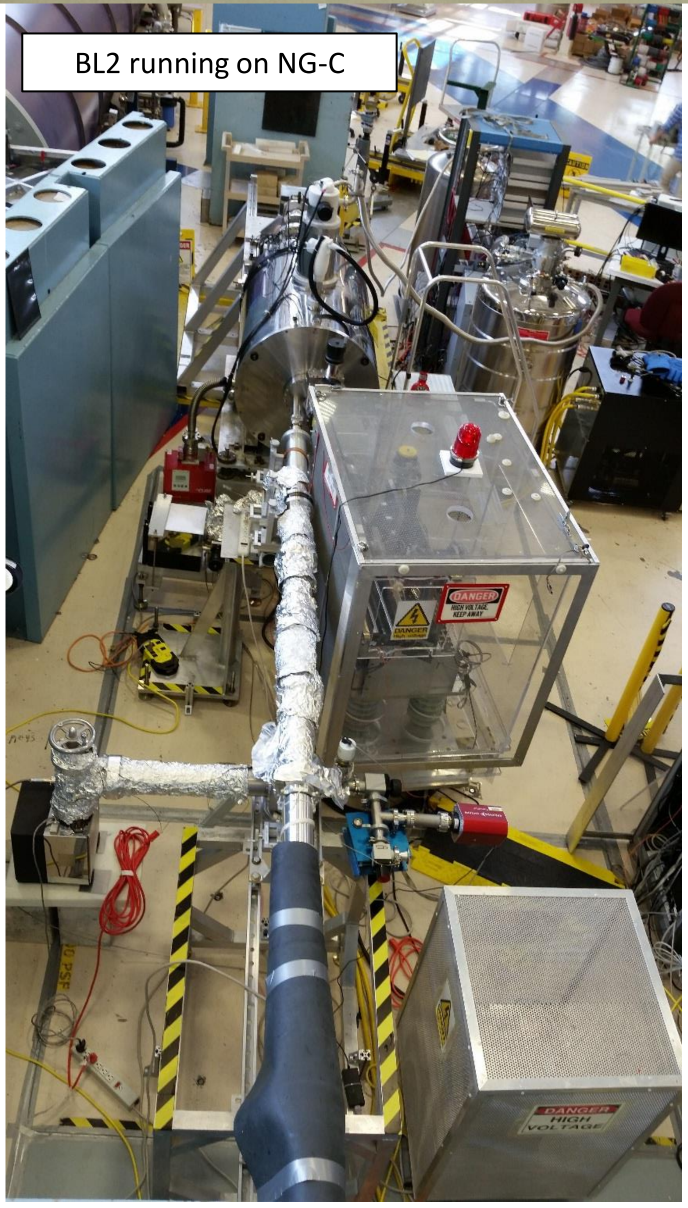
- Density of neutrons in the beam ($N_{\alpha+t}$)
- Number of decay products (N_p)

Neutron monitor calibrated using Alpha-Gamma device



<u>Alpha-Gamma:</u>

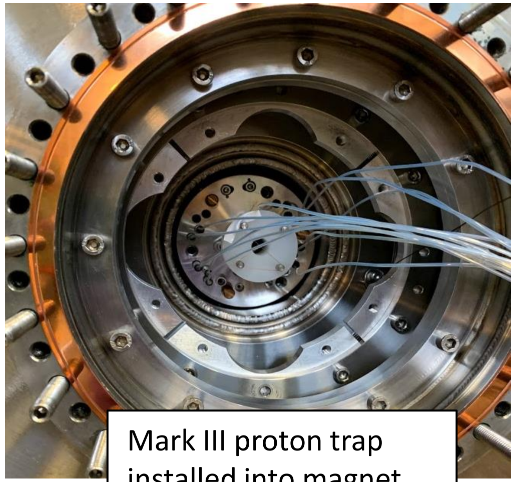
- Determines neutron fluence to precision of 0.06% (best in world)
- Synergy between fundamental and calibrations and applied work

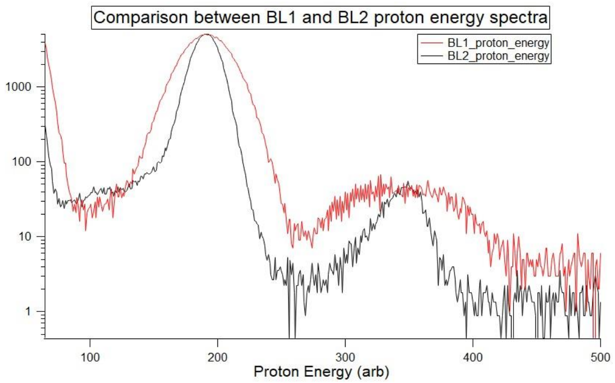


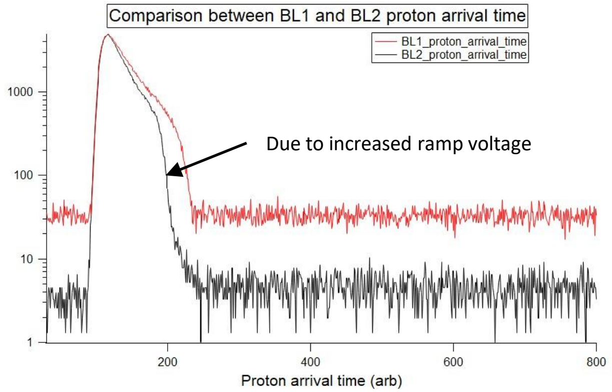
Currently Running on NG-C: BL2

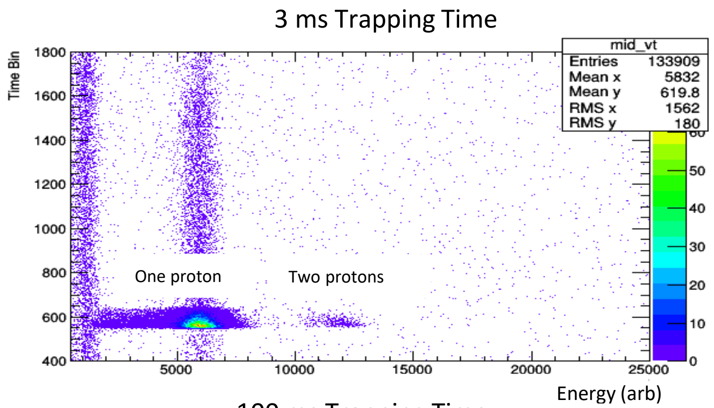
- Running on NG-C in production mode since 2018
- Significantly larger parameter space than BL1 (e.g. 3 ms – 100 ms trapping time range)
- Improvements in simulation, proton counting, neutron counting
- Focus on systematic tests and cross-checks
- Planned running through 2022 (reactor shutdown for cold source upgrade)

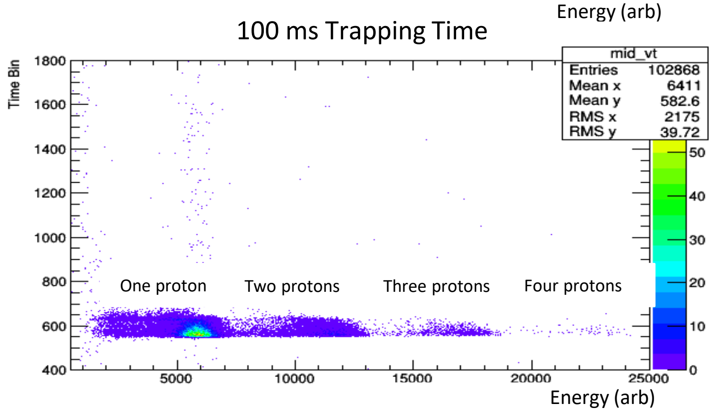

Mark III proton trap


Mark III proton trap installed into magnet bore, shown with alignment crosshairs



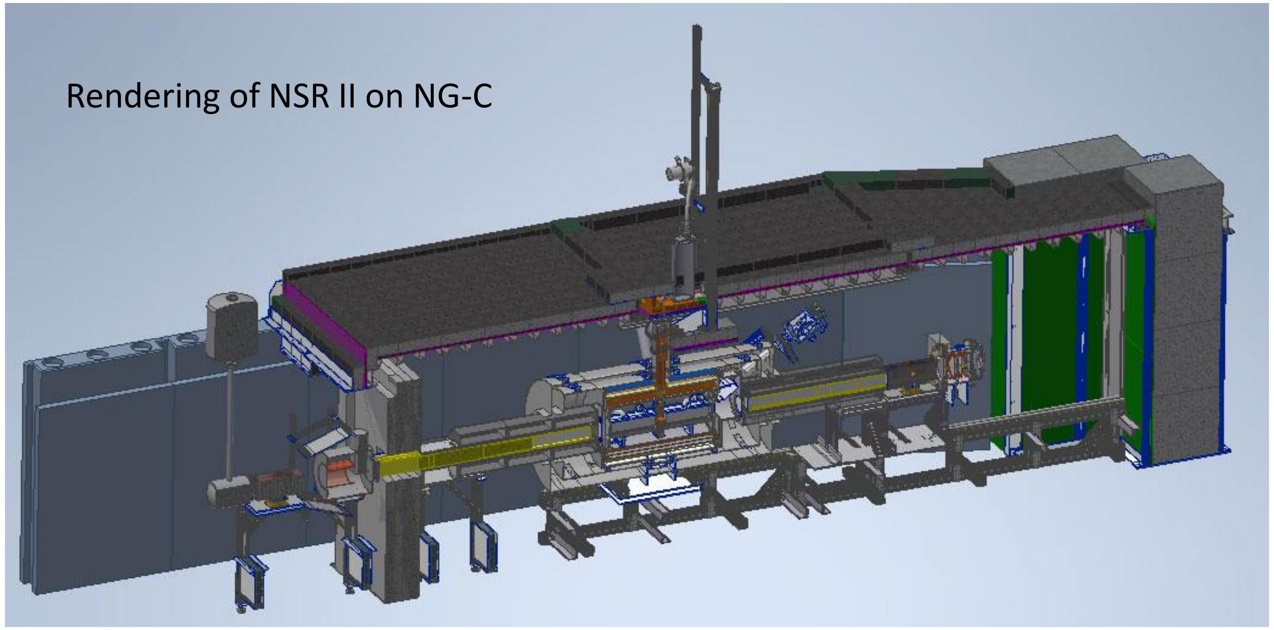






- Mark III proton trap installed in January 2021
- Designed for improved pumping and metrology
- Electrode length to be used as experimental blind
- Tested electrically without neutrons
- Current extended (unplanned) reactor shutdown began prior to testing with neutrons

Preparing to Run on NG-C: Neutron Spin Rotation II



- First experiment designed to take the full beam at NG-C
  - Requires full shielding enclosure
- Planned swap-over during 2023 reactor shutdown/cold source upgrade
- Uses parity violation to probe nucleon-nucleon weak interactions
- Two experimental objectives with two different targets.

1st Goal

- Hadronic parity violation with liquid helium target. Current limit of $d\phi/dz \approx 9 \times 10^{-7}$ rad/m, from 2008 (Swanson et al. PRC 2019)

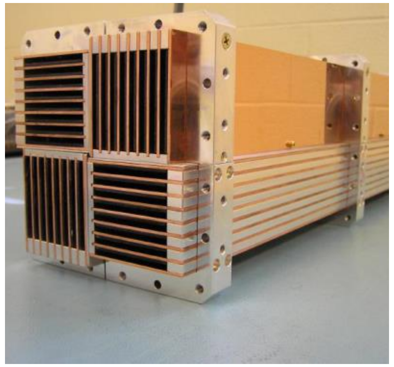
• Result was statistics limited. Can achieve significant flux increases from moving to NC-C and using the full guide flux.

• Goal is to improve the limit to the level $d\phi/dz = 2 \times 10^{-7}$ rad/m to improve knowledge of NN weak amplitudes and test new theoretical predications (e.g., Garder, Haxton, and Holstein, ARNPS 2017)

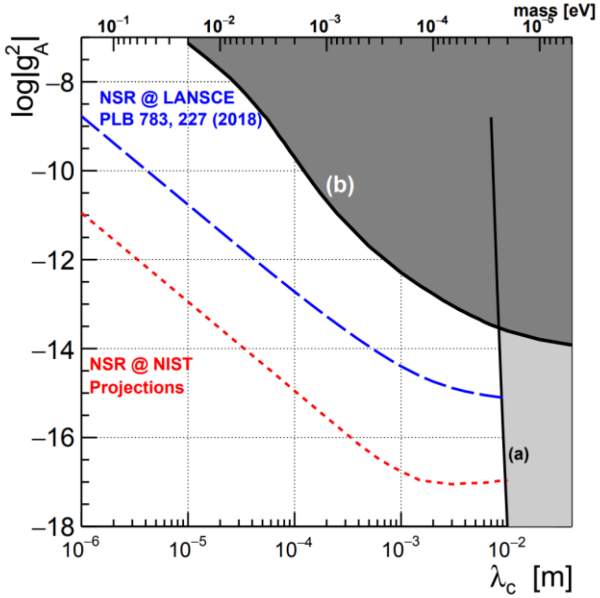
2nd Goal

• Explore the existence of a new possible long-range spin-dependent interaction in the mesoscopic scale (mm to um).
• Result for g_A^2 at first run at LANSCE was statistics limited

$$V_5 = \frac{g_A^2}{4\pi m}\frac{e^{-m_0 r}}{r}\left(\frac{1}{r}+\frac{1}{\lambda_c}\right)\vec{\sigma}\cdot(\vec{v}\times\hat{r})$$

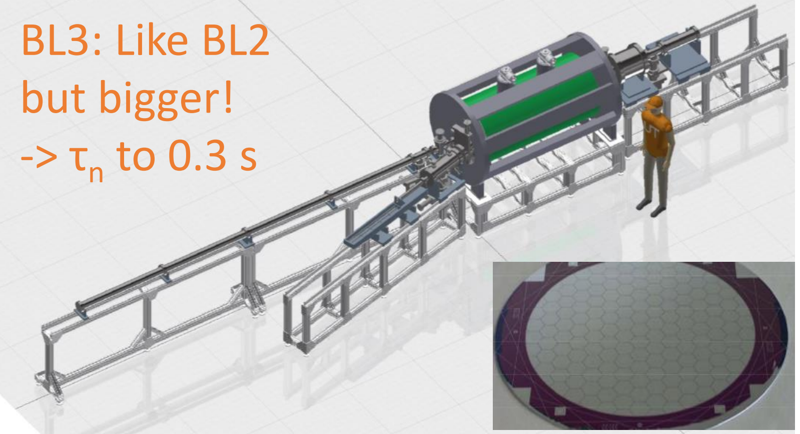


Cu/glass target



Future Possibilities

NIST



BL3: Like BL2 but bigger!

-> τ_n to 0.3 s

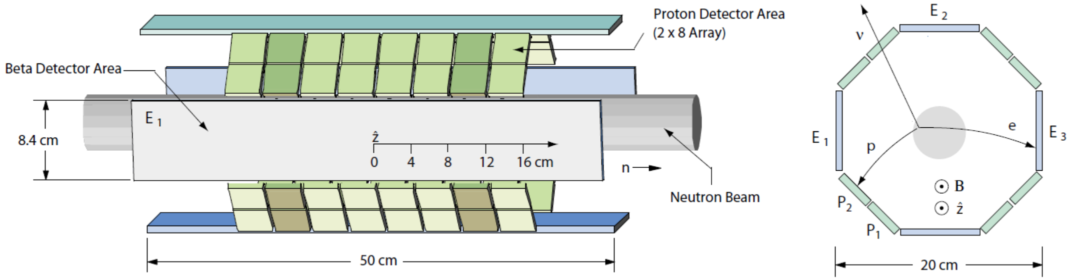
Currently in the design and funding proposal stage

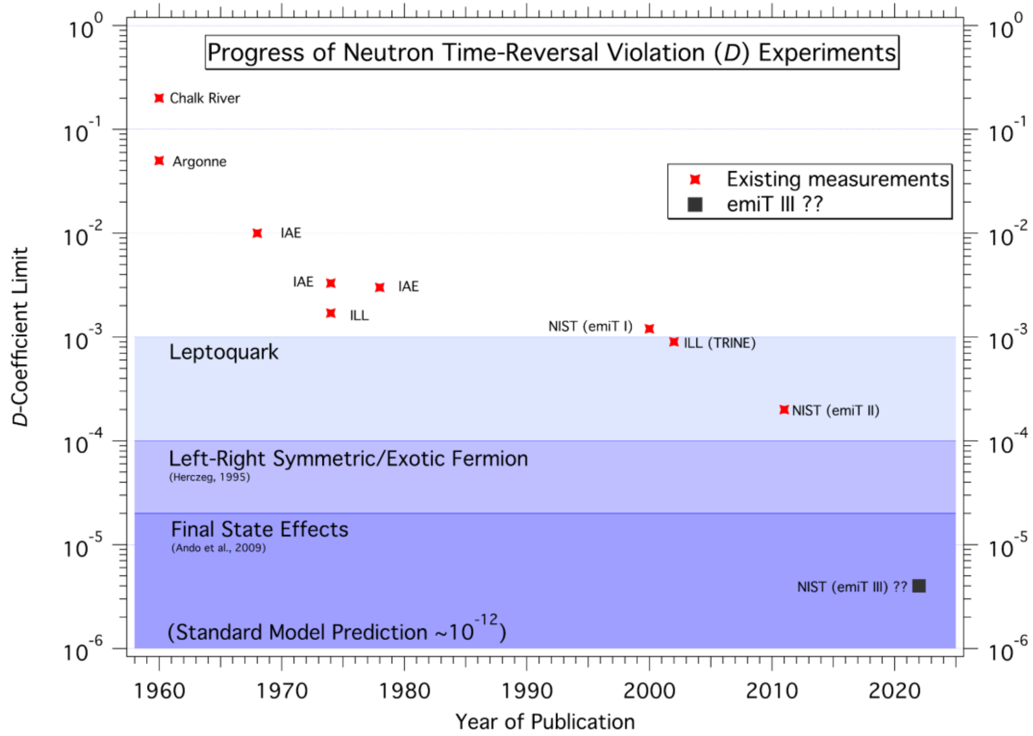
<u>Other possibilities (NGC):</u>

- Nab (after nEDM takes over FNPB)
- Mirror Neutron Oscillations
- NextGen Hadronic Parity Violation
- aCORN "B"
- Neutron Decay into Hydrogen
- "Project 8"-style measurements of neutron decay
- …

emit III: Measure D to 10^{-5}, measure final state effects

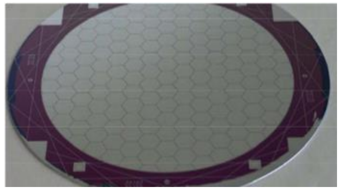
-> requires improved detectors (next page)





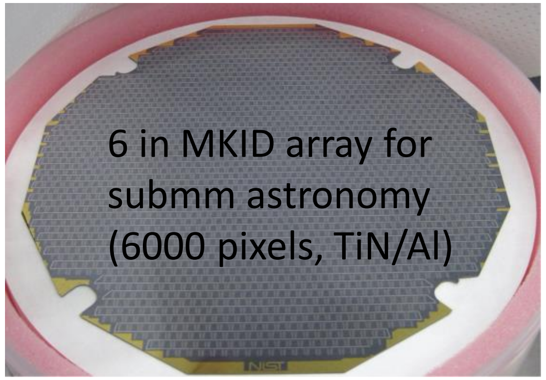
Future Possibilities: Cryogenic Detectors

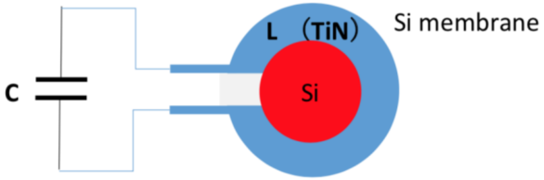
State of the art Si detector (Nab, BL3):

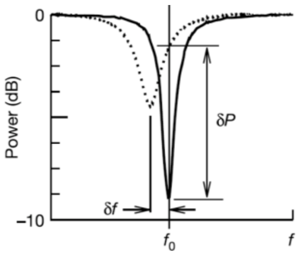


- Active area ~ 100 cm^2
- Energy resolution of 3 keV
- Energy threshold of 6 keV
- proton acceleration ~15 kV
- $40k per detector

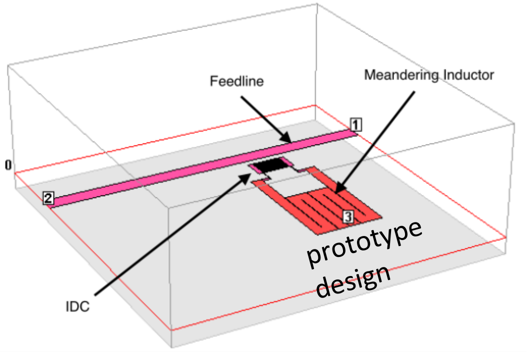
Cryogenic Superconducting Detectors have demonstrated energy resolutions of tens of eV or better for low energy radiation and can be multiplexed to large arrays **but have never been used with charged particles**







Potential for use well beyond fundamental neutron physics



Collaboration between NPG and Quantum Sensors Group
E. M. Scott (postdoc), C. Heikes (postdoc), J. Gao, M. Vissers, J. Wheeler (postdoc), J. Ullom

Current focus is prototyping a large area (~1 cm^2) TKID:

- Simulating performance and optimizing design
- Fabrication and initial testing done at NIST Boulder
- Charged particle testing to be done at NCNR with monoenergetic beta sources

Summary

NIST

- NG-C Beamline is the best resource in the US for doing fundamental research with cold neutrons. The NCNR cold source upgrade in 2023 will make it comparable to the best in the world.
- The Neutron Physics Group has a long and successful history of leading and supporting experiments both at the NCNR and at other facilities
  - best precision on several fundamental properties of the neutron
  - development of the highest precision technique for absolute neutron counting
  - Training ground for many undergraduate students, graduate students, and postdocs
  - Numerous projects are in the pipeline for the future
- Advancement in basic research fuels advancement of NIST priorities:
  - validating the underpinnings of SI units
  - determining fundamental constants of nature
  - improving methods in standards and metrology
  - developing novel applied technologies for commerce

Questions?