New searches for neutron oscillations at ORNL

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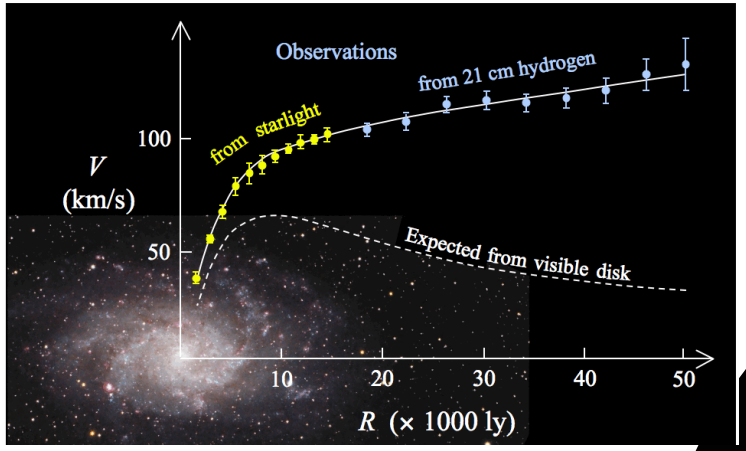
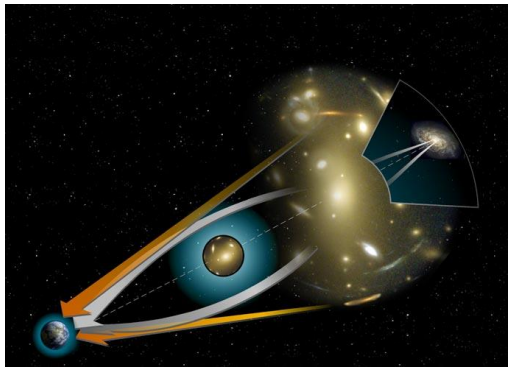
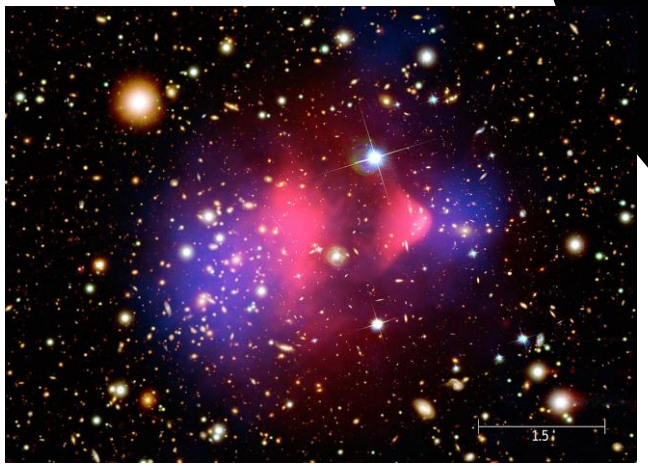
Oak Ridge National Laboratory

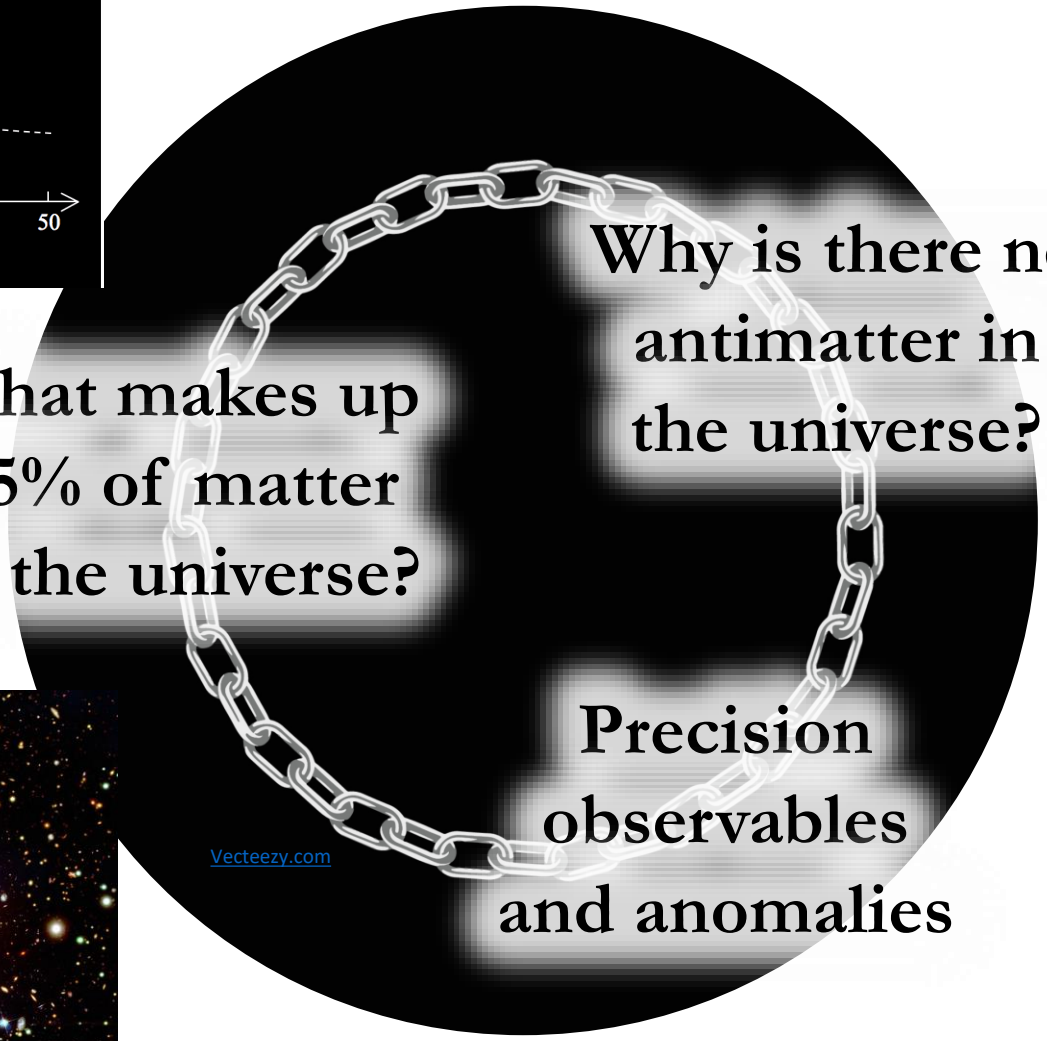
Physics of fundamental Symmetries and Interactions
October 16 – 21, 2022







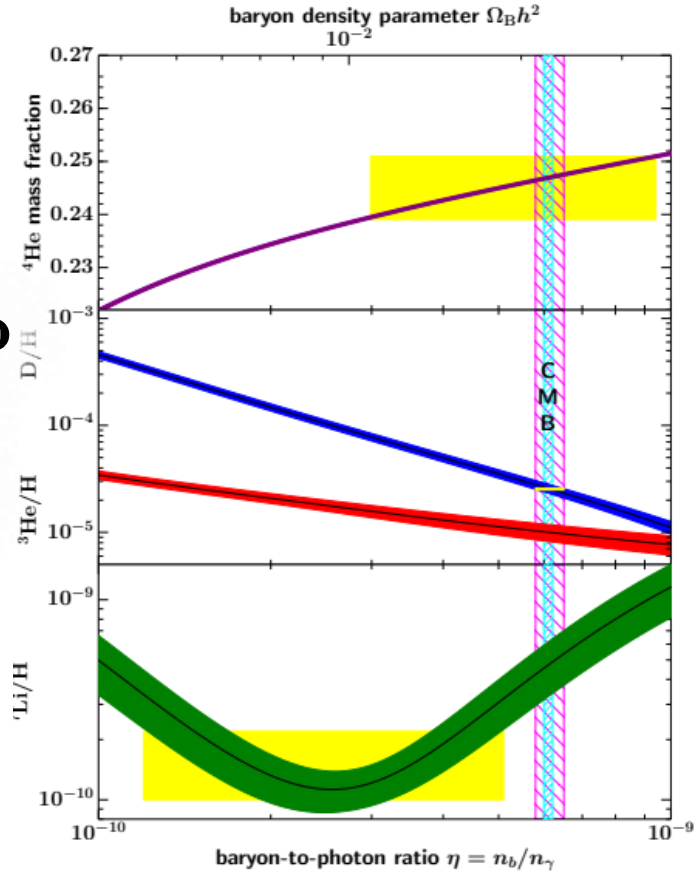
What makes up 85% of matter in the universe?

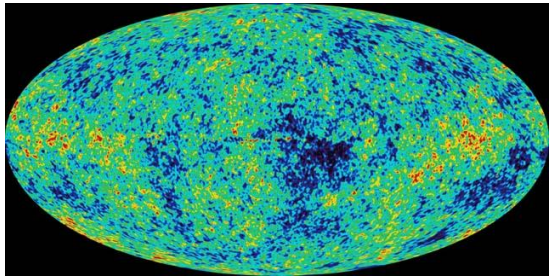


Why is there no antimatter in the universe?

Precision observables and anomalies

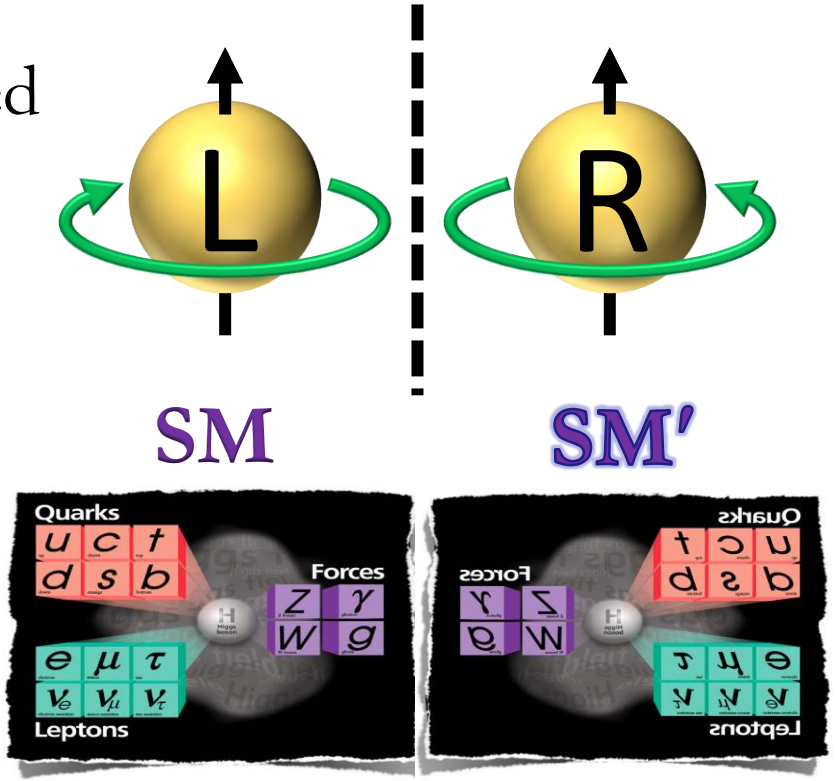
Vecteezy.com





Mirror matter and mirror neutrons

- Decades of searches for dark matter: no confirmed detection. New avenues needed!
- Mirror Matter: identical particles/forces, opposite parity [Phys.Usp. **50** (2007) 380-389, From Fields to Strings **3** (2015) 2147, Phys.Rev. **104** (1956) 254-258]
- Only interacts with known particles via gravity [Sov.J.Nucl.Phys. **3** (1966) 6]
- A "hidden sector" which could help explain dark matter [PLB **503** (2001) 362, IJMPA **29** (2014) 1430013]
- **Experimental observable**: predictions of neutron oscillations in Mirror Matter models PRL 96 081801 (2006); possibly related to cobaryogenesis IJMP **33** 1844034 (2018) [Z. Berezhiani talk]
- Neutron could be one of a few portals to a dark sector!



Neutron oscillations $n \to n'$

- Consider the neutron, and its ~~evil~~ mirror twin

$$H_n = m_n + \frac{p^2}{2m_n} + \mu_n(\vec{\sigma} \cdot \vec{B}) + V - i\,W - \frac{i}{2\tau_n}$$

Different Higgs VEV between n, n'

Local matter/mirror matter

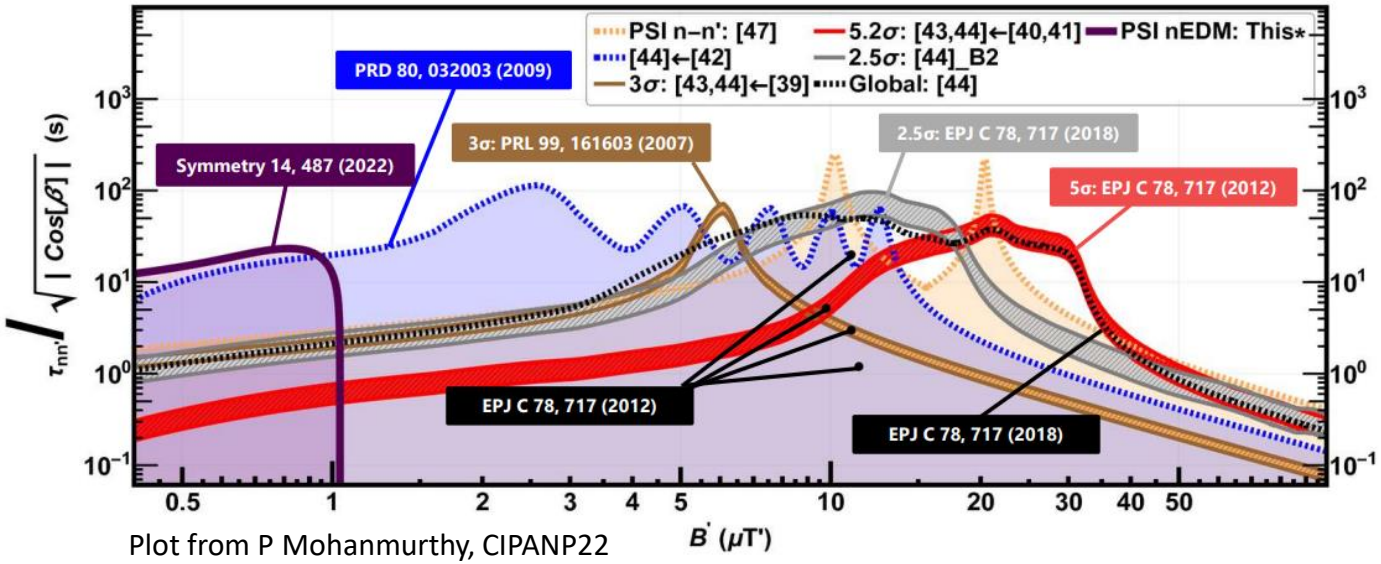
- Two-state mixing Hamiltonian can be written as [Z. Berezhiani talk]

$$i\frac{d}{dt}|\Psi(t)\rangle = \begin{pmatrix} \Delta E(\Delta m, B - B', \dots) & \epsilon_{nn'} \\ \epsilon_{nn'} & 0 \end{pmatrix} |\Psi(t)\rangle$$

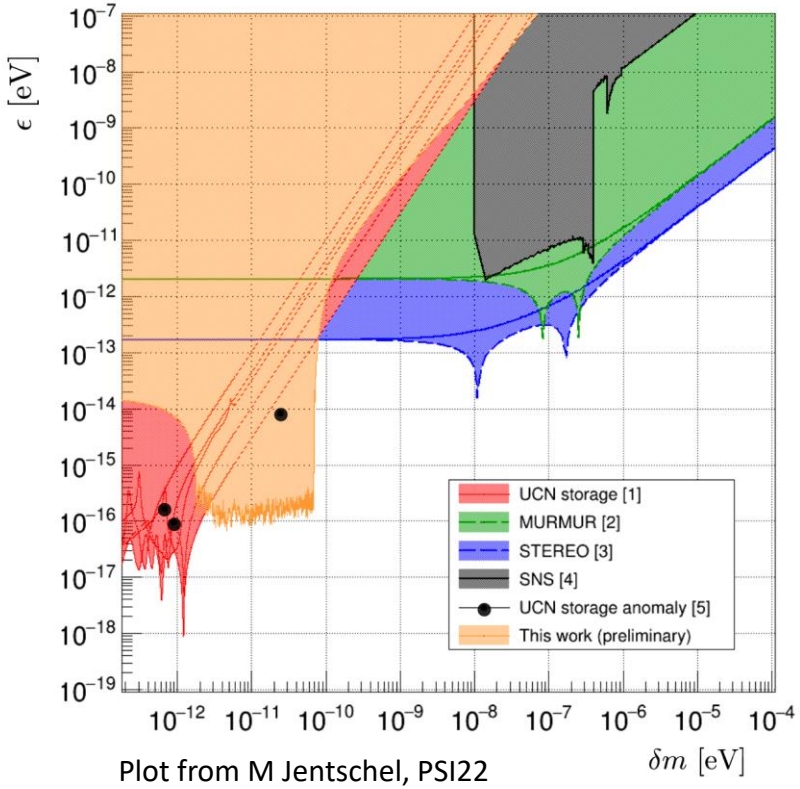
- As $\Delta E \to 0$, probability for oscillation resonantly enhanced
  - Tune B or V to look for evidence of Δm, B', $\epsilon_{nn'} \dots$

Prior/ongoing searches for mirror neutrons

- Strong limits from B dependence of stored UCN
  - $\tau_{nn'} > 448$ s (90% CL) assuming ΔE=0 (e.g. no mirror field B') NIMA **611** (2008) 137
  - Anomalies manifest on reanalysis when relaxing $B' \neq 0$ EPJC **72** (2012) 1974, EPJC 78 (2018) 717, data of PRL 99 (2007) 161603
- Exclusions from recent searches [I. Rienacker talk], also PRD 80 (2009) 032003, PLB 812 (2021) 135993, Sym 14 (2022) 487
- Similar: exclusions of hidden neutrons [M. Jentschel talk]



Plot from P Mohanmurthy, CIPANP22



Plot from M Jentschel, PSI22

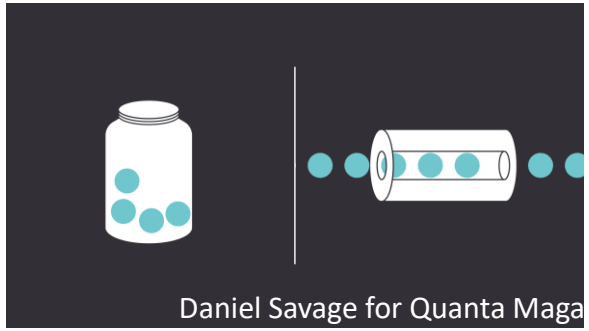
Can $n - n'$ explain n lifetime anomaly?

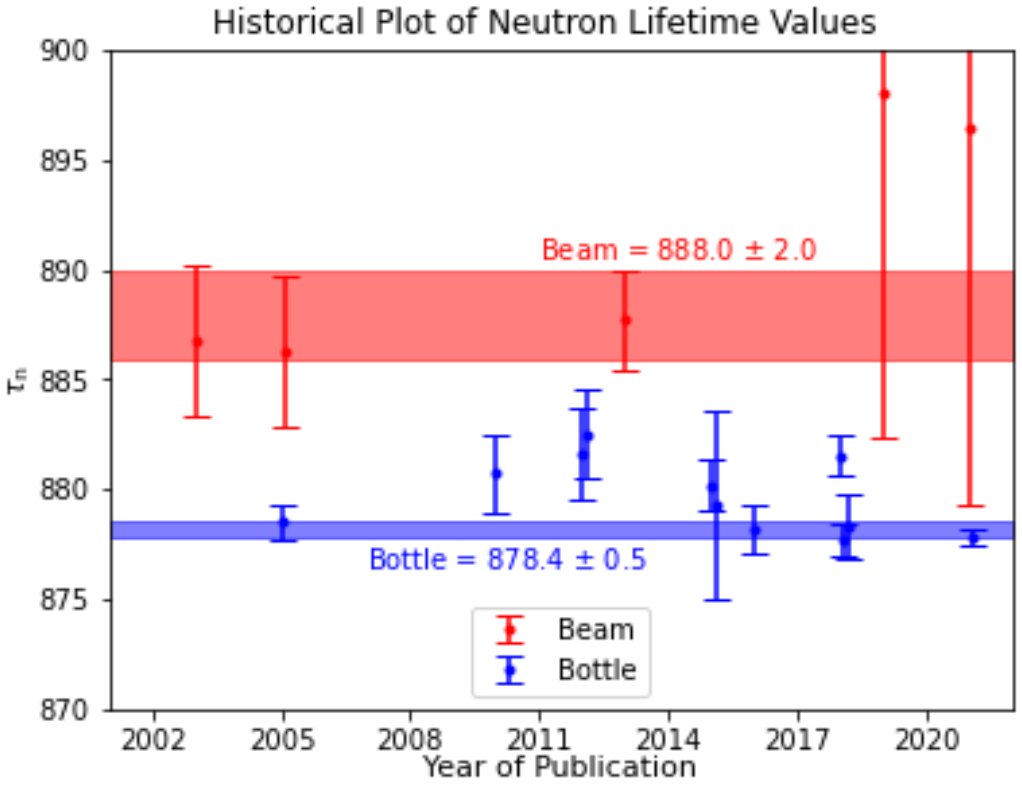
- "Bottle" technique:: use a bottle of ultra-cold neutrons, observe surviving neutrons
- "Beam" technique: use a beam of cold neutrons, count decays into protons
- 4σ discrepancy persists between "beam" and "bottle" measurements Atoms 6 (2018) 4

[C.-Y. Liu talk]

[Z. Berezhiani talk]

[F. Wietfeldt talk]





- Do neutrons disappear into something other than protons?

$n \to n'$ in the NIST Beam Lifetime experiment

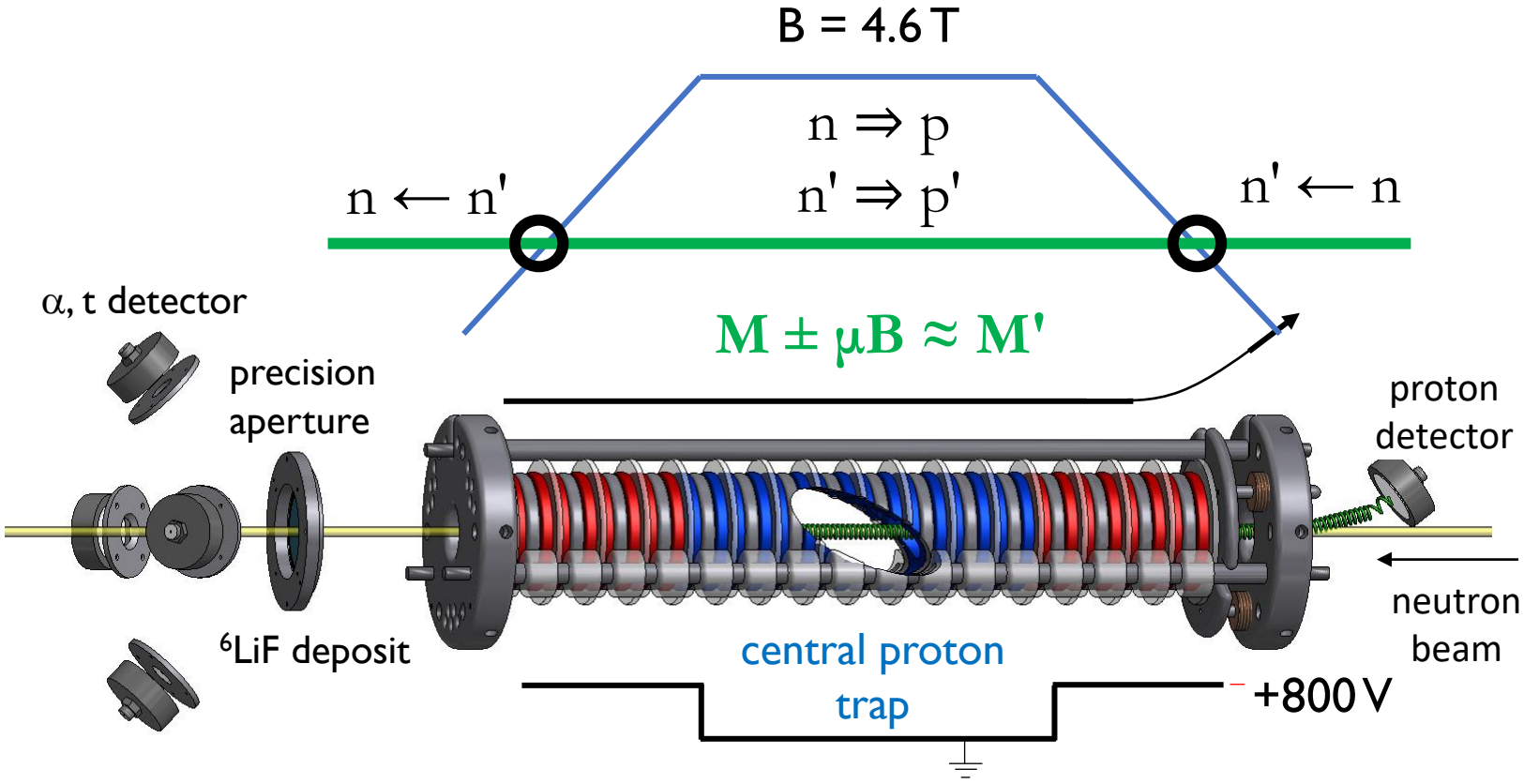
Measure neutron flux and proton decay rate:

[F. Wietfeldt talk]

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

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

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



Landau-Zener transition: enhanced transition probability for non-adiabatic zero-crossing of energy difference

PRC 71 (2005) 055502, PRL 111 (2013) 222501

EPJC 79 (2019) 484

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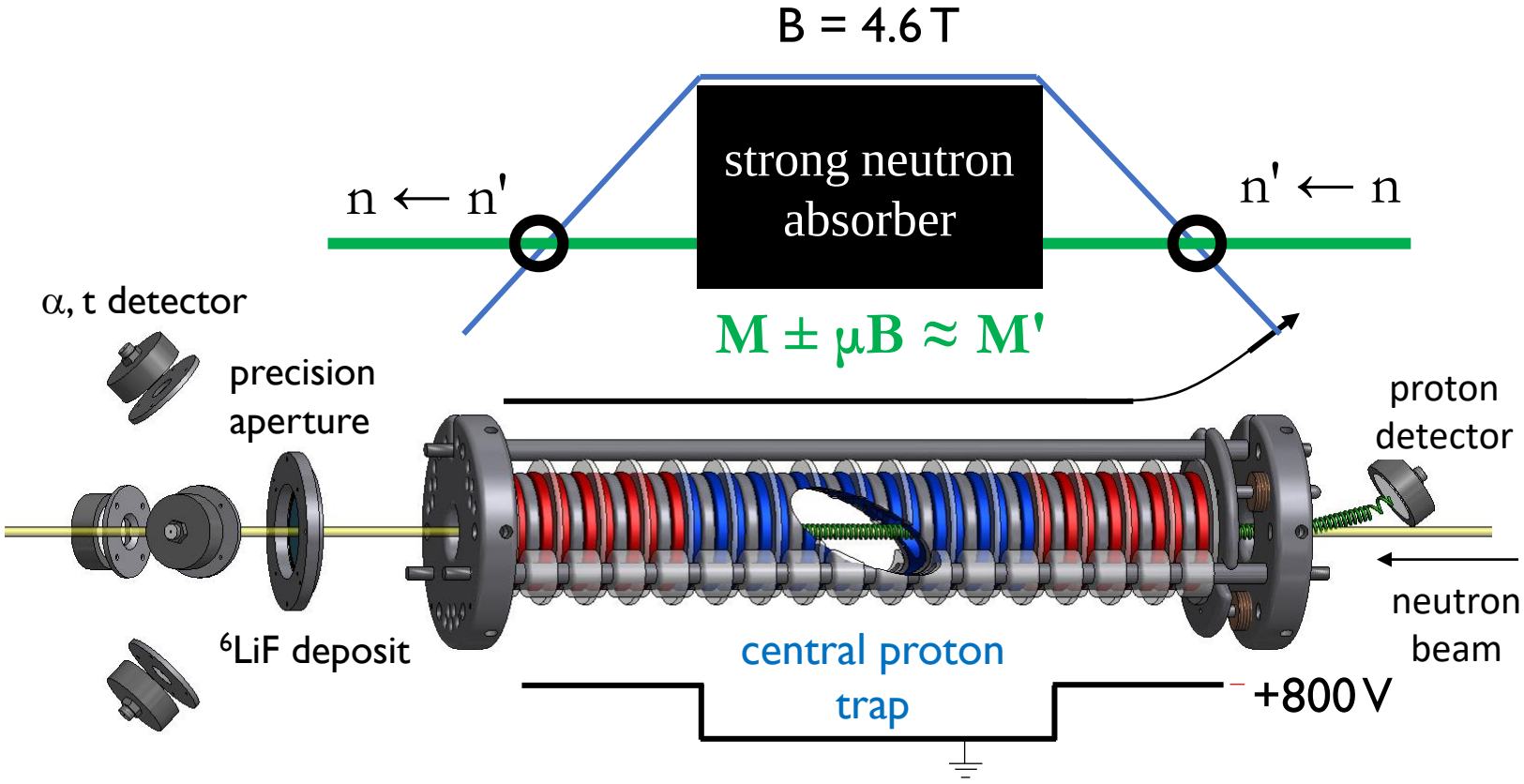

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$n \to n'$ in the NIST Beam Lifetime experiment

- Calculated evolution through NIST beam lifetime B profile PRC 71 (2005) 055502

$$\frac{\partial}{\partial t}\hat{\rho} = -i[\hat{H}\cdot\hat{\rho}] = -i\hat{H}\hat{\rho} + i\hat{\rho}\hat{H}^{\dagger}$$

Liouville–von Neumann equation

$$\hat{H} = \begin{pmatrix} \Delta m + V - iW \pm \mu B & \epsilon \\ \epsilon & 0 \end{pmatrix}$$

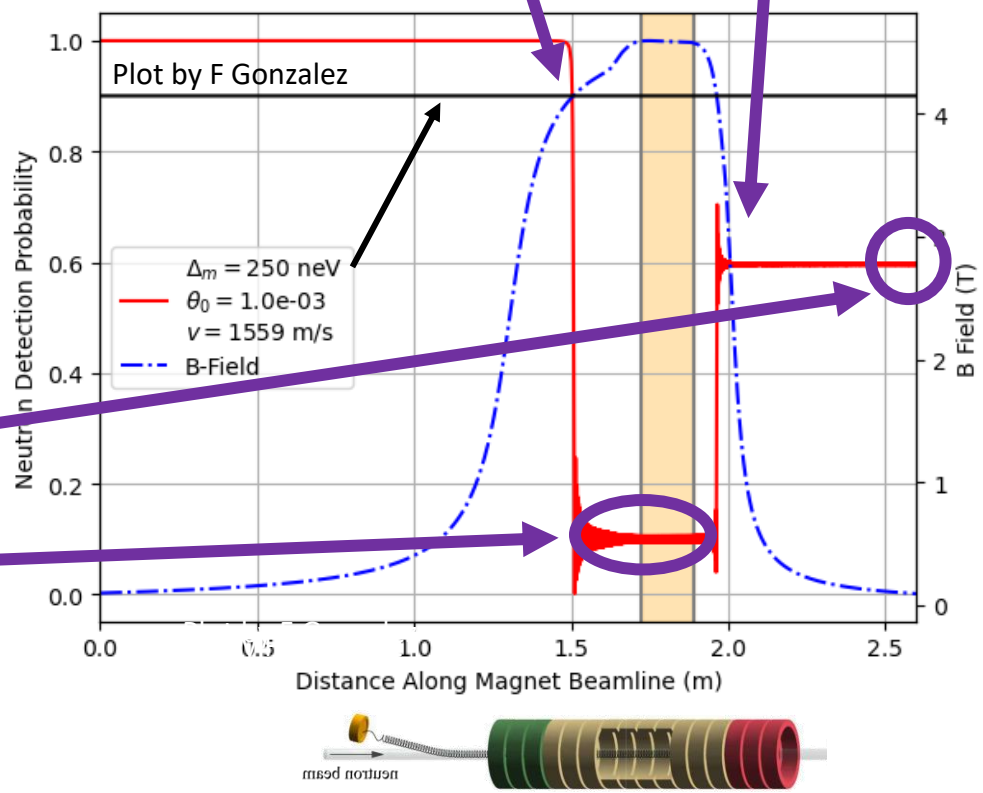
$$\hat{\rho}(0) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} = n$$

- Combine calculated shift in $\dot{N}_p$, $\dot{N}_n$ to find a lifetime shift

$$\tau_{meas} = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

- Region of interest for $n \to n'$:
  - When $\delta\tau_{meas}/\tau_n \sim 1\%$

Landau-Zener transition when ΔE =0



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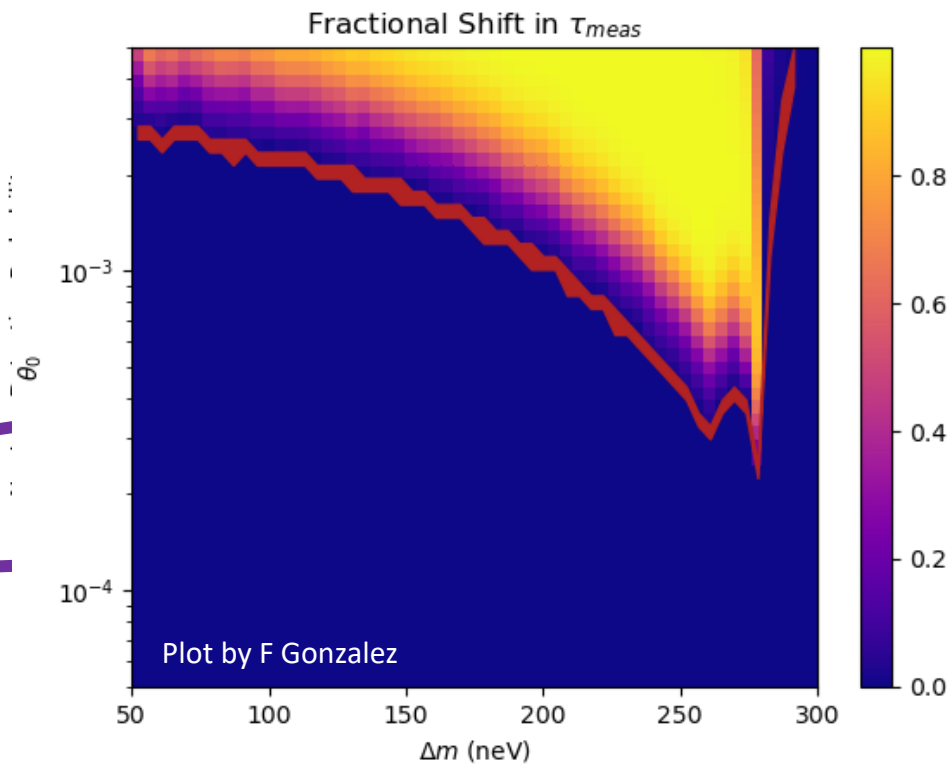
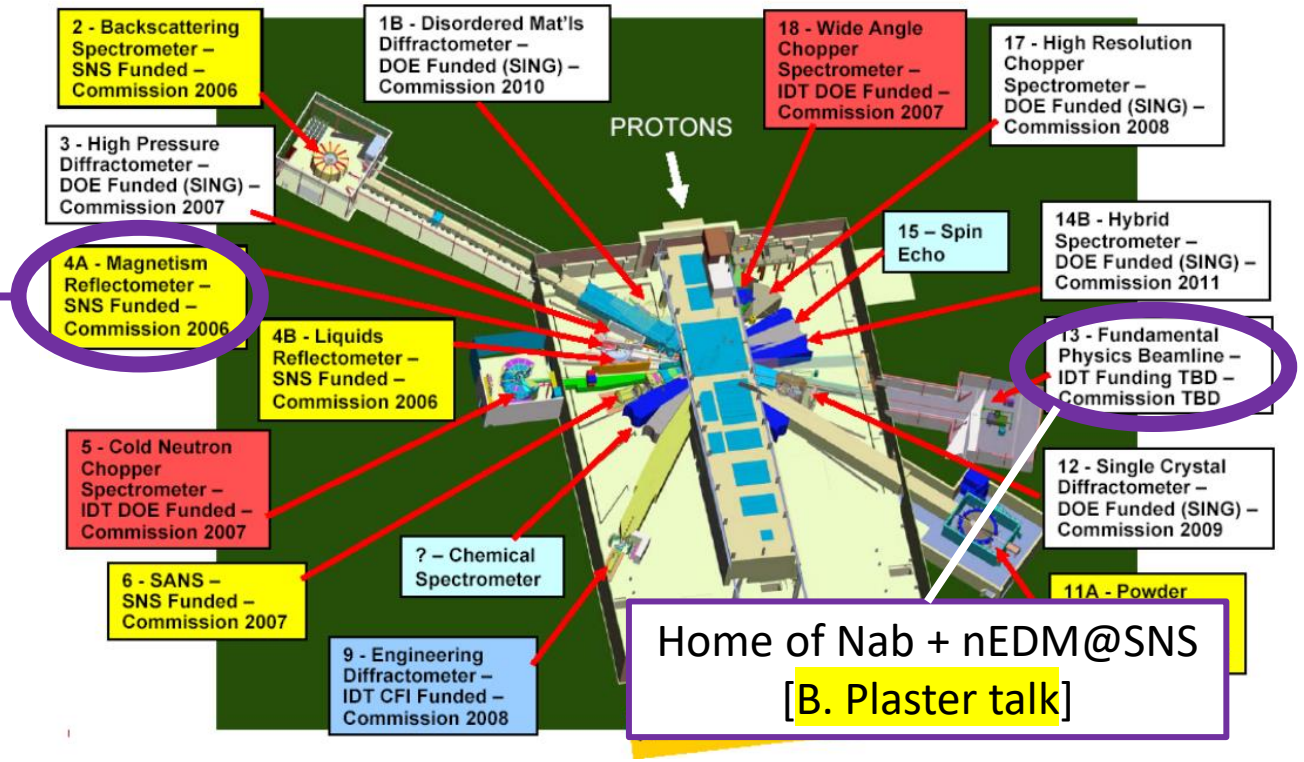
Landau-Zener transition when $\Delta E = 0$



The Magnetism Reflectometer instrument at ORNL's Spallation Neutron Source

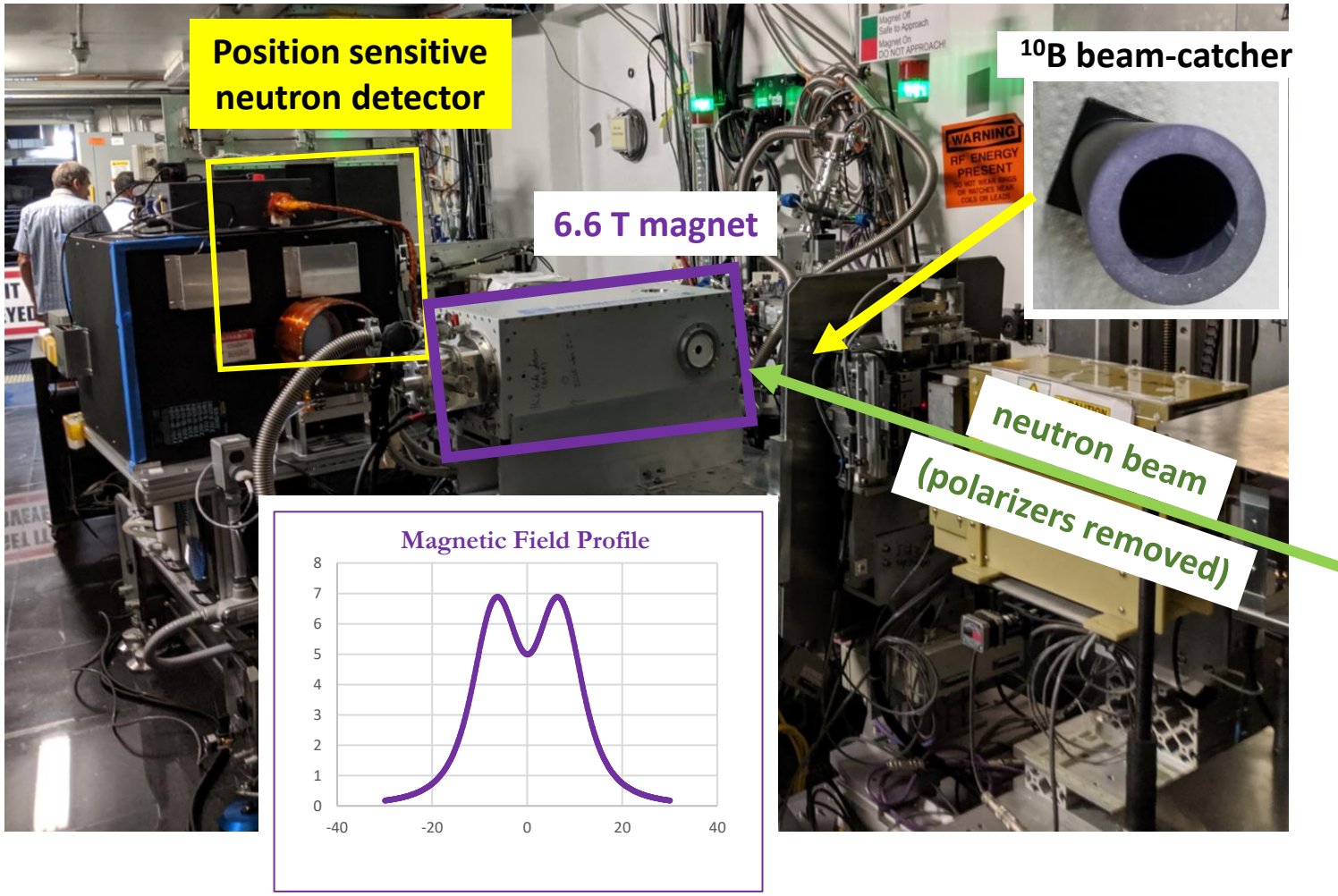
- 1.4 MW, 1 GeV, 60 Hz proton beam → spallation → neutrons
- 20 K liquid H moderator

- Magnetism Reflectometer: polarized neutrons for GI-SANS, study magnetism in materials
- 20×20 cm^2 position sensitive detector



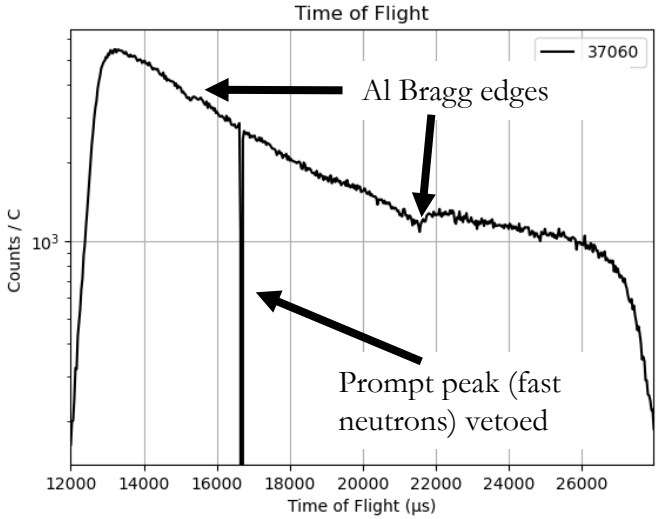
$n \to n'$@SNS experiment approach

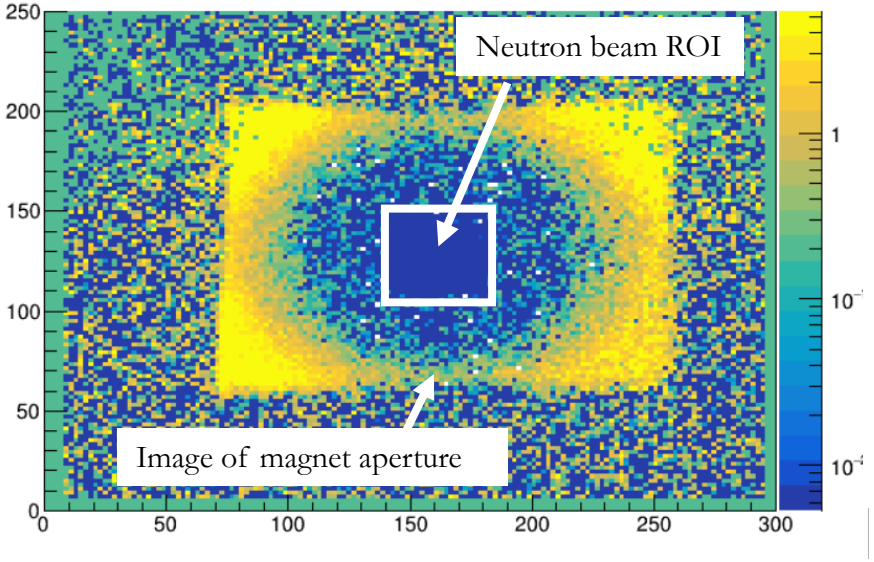
- Technique of cold neutron regeneration
  $$n \to n' \to n$$
- Thick $^{10}B_4C$ beam-catcher: n blocked, n' pass
- Compare transmission through superconducting "split coil" magnet 6.6 T vs 0 T
- 2 short beamtimes in July and August 2019

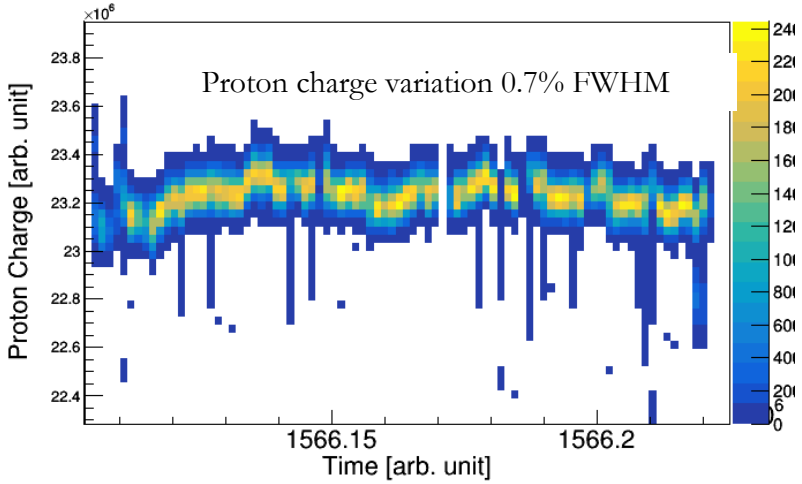


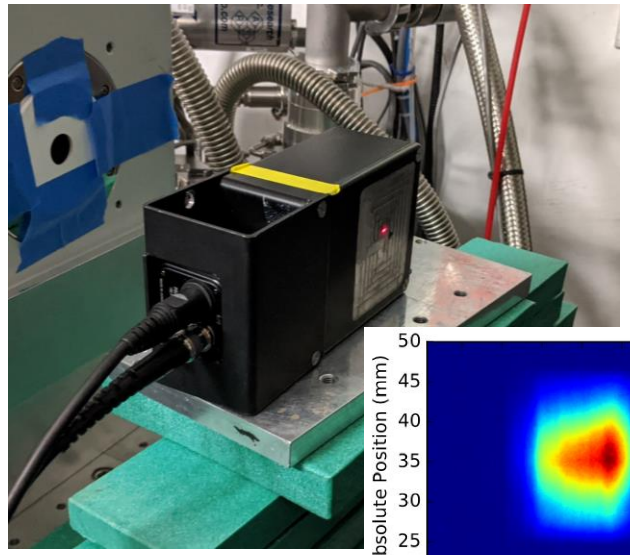
Neutron beam characterizations

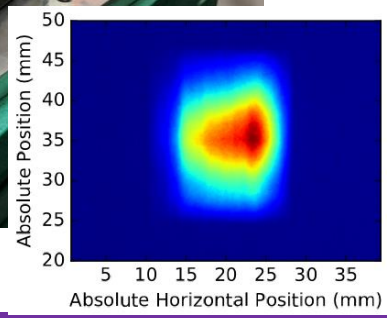
- Neutron beam extent/divergence inside magnet characterization important for sensitivity
- Proton charge used for normalization. Beam stability excellent but linearity of neutron production poor
- Spectral intensity calibration, TOF:λ calibration





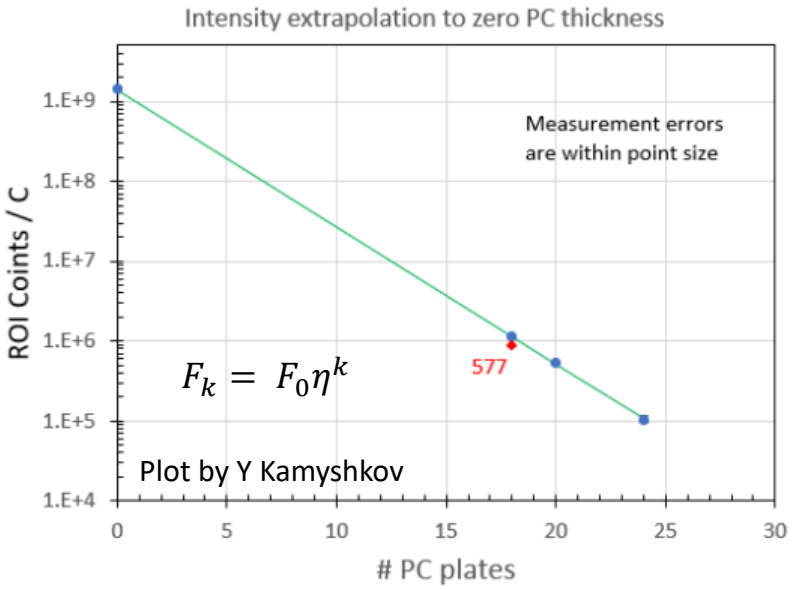


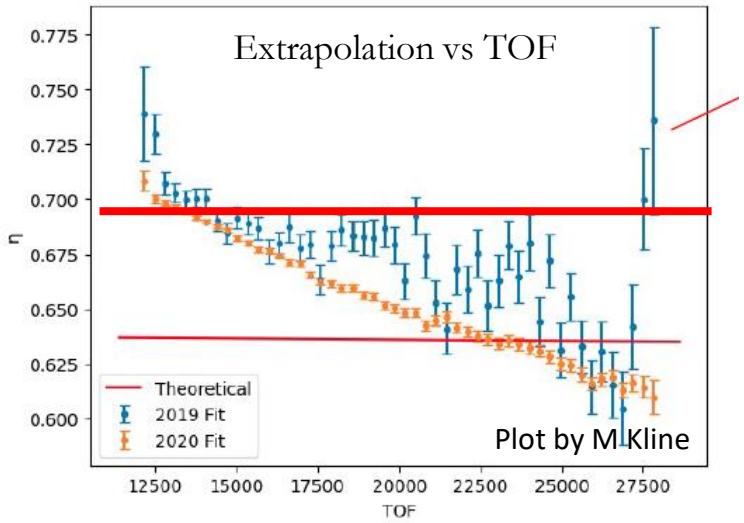


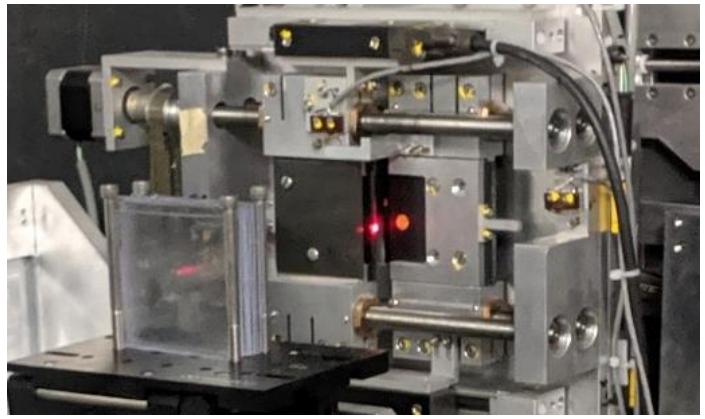


Neutron beam intensity

- Challenge: main detector unable to accept full beam intensity & calibrated neutron monitor unavailable
- Attenuate beam: $(C_{16}O_3H_{14})_n$ polycarbonate sheets
- $F_0 = (1.35 \pm 0.31) \times 10^9$ n/C between 2.2Å – 5.1Å
  - reduced by 78 ± 2% to $(1.05 \pm 0.31) \times 10^9$ n/C





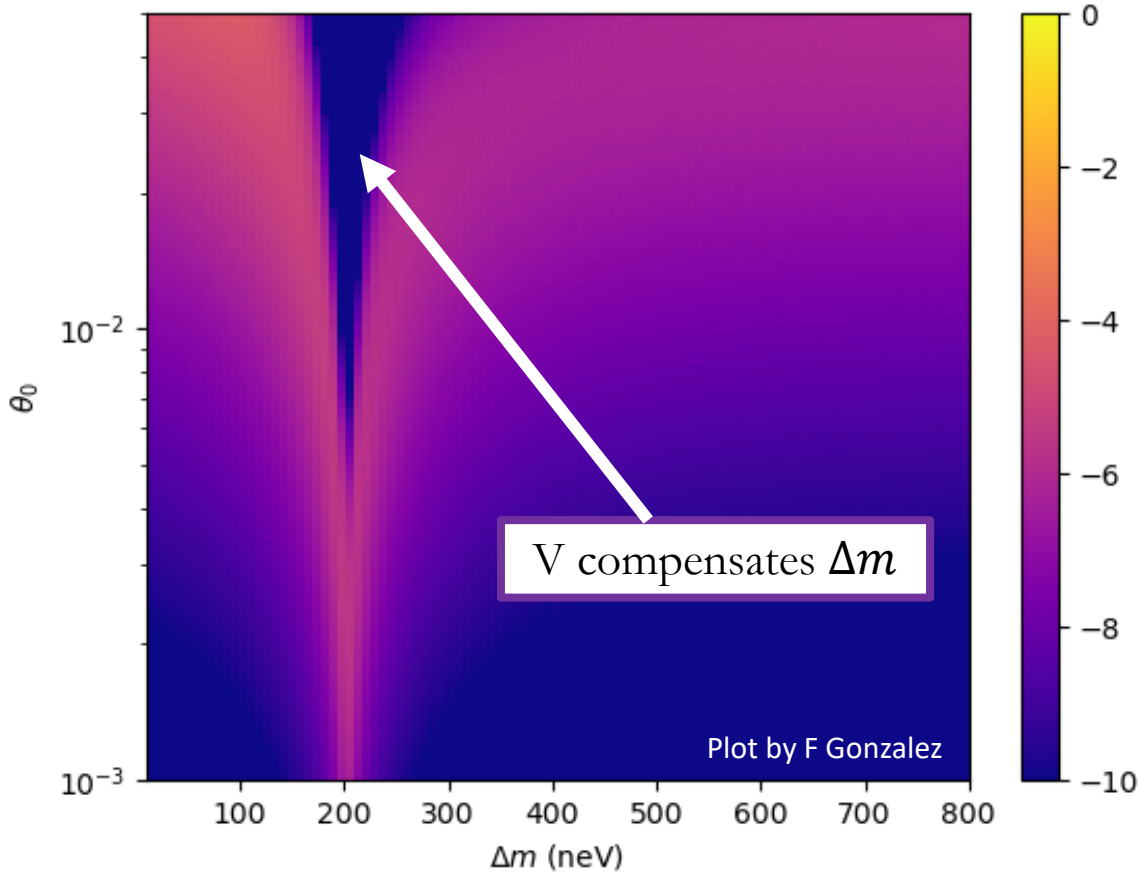


Thickness: 1.270 mm ± 0.0173 mm
Density: 1.1947 ± 0.0085 g/cm^3
Cross sections from NIST
$\eta_{calc} = 0.6790 \pm 0.0036$
$\eta_{meas} = 0.675 \pm 0.008$

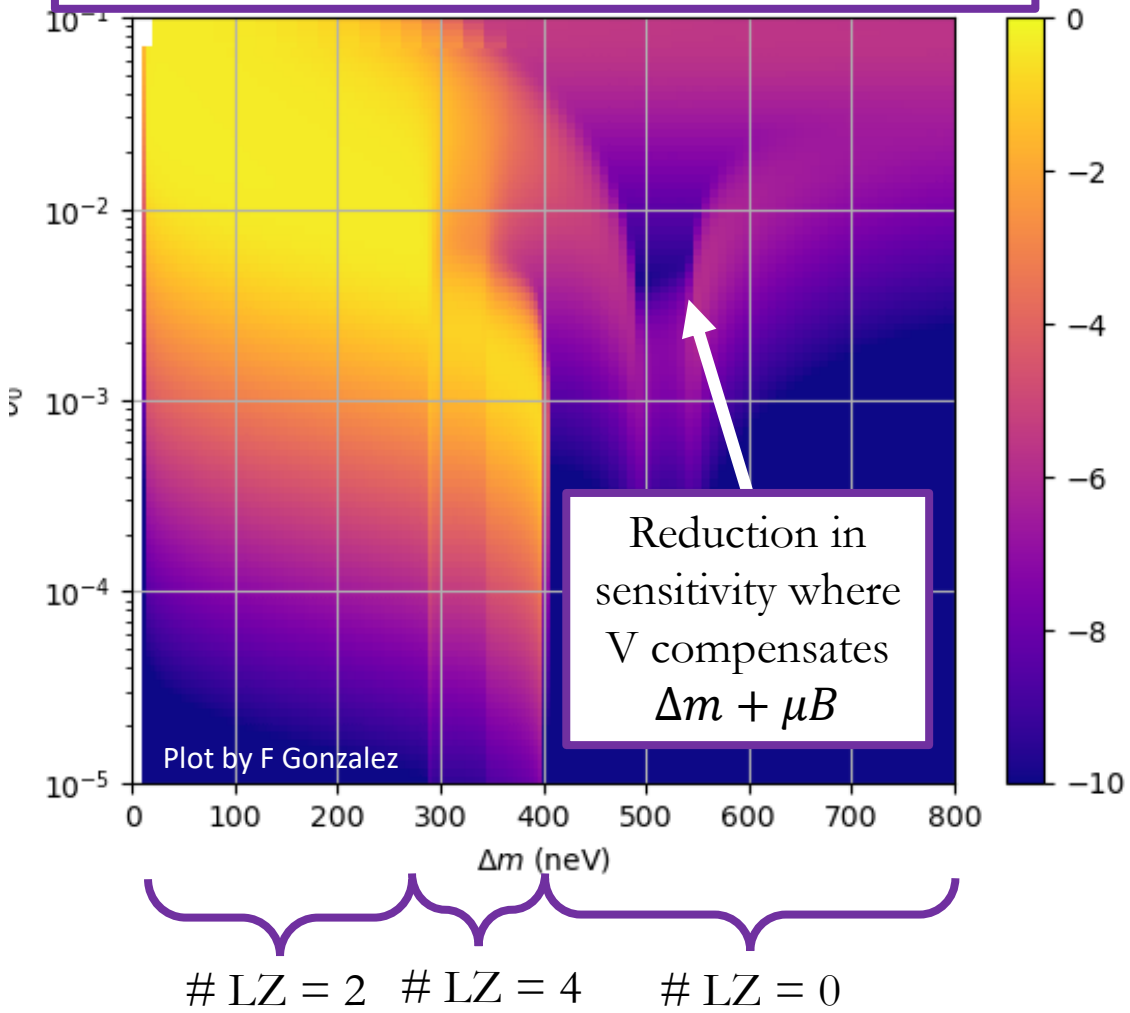
PHITs simulations and later comparison studies suggest extrapolation approach underestimates intensity.

$n \to n'$@SNS sensitivity

Probability for neutron regeneration, B=0, absorber only



Probability for neutron regeneration at max field

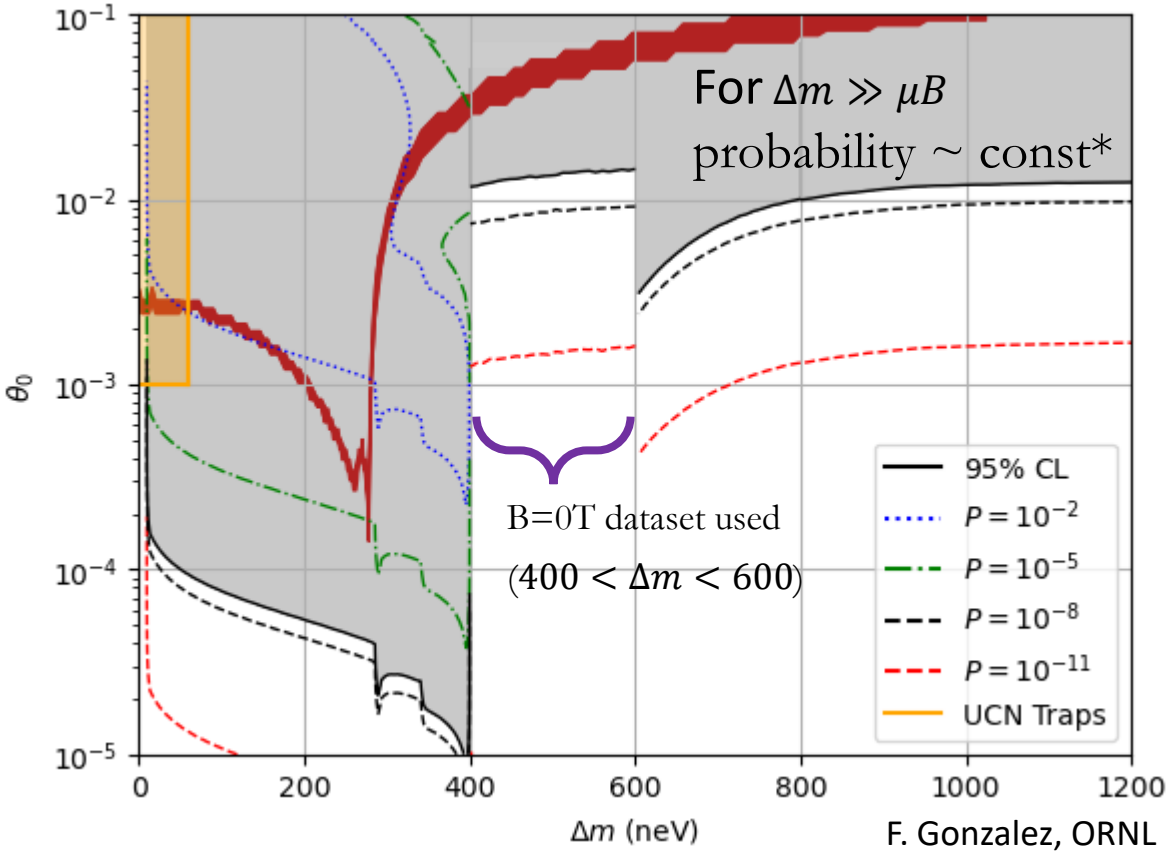


Neutron oscillations in matter Sym 14 (2022) 230

Impact for neutron lifetime anomaly

B Field at B4C	B4C Position	Total Cts in ROI	Charge	Cts / 5C
+4.8 T	center	7748 ± 88	13.8 C	2805 ± 32
-4.8 T	center	4976 ± 70	8.8 C	2823 ± 40
0 T	center	6631 ± 81	11.9 C	2791 ± 34
3.33 T	center	1017 ± 32	1.8 C	2817 ± 88
+6.6 T	peak B	1010 ± 32	1.8 C	2804 ± 88
-6.6 T	peak B	1120 ± 33	2.0 C	2863 ± 86
0 T	peak B	4916 ± 70	8.7 C	2815 ± 40

- Excluded transmission < 2.5 x 10^{-8} (95 C.L.) (grey region)
- **Conclusion**: this exotic process does not explain neutron lifetime anomaly
  PRL 128 (2022) 212503

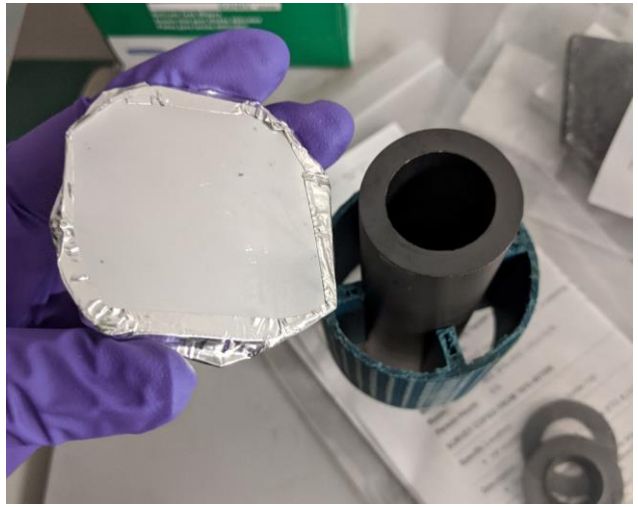


Gray – Excluded region from our experiment (95% CL)
Red – 1% ± 0.2% difference in neutron lifetime
Dashed – Probability bands

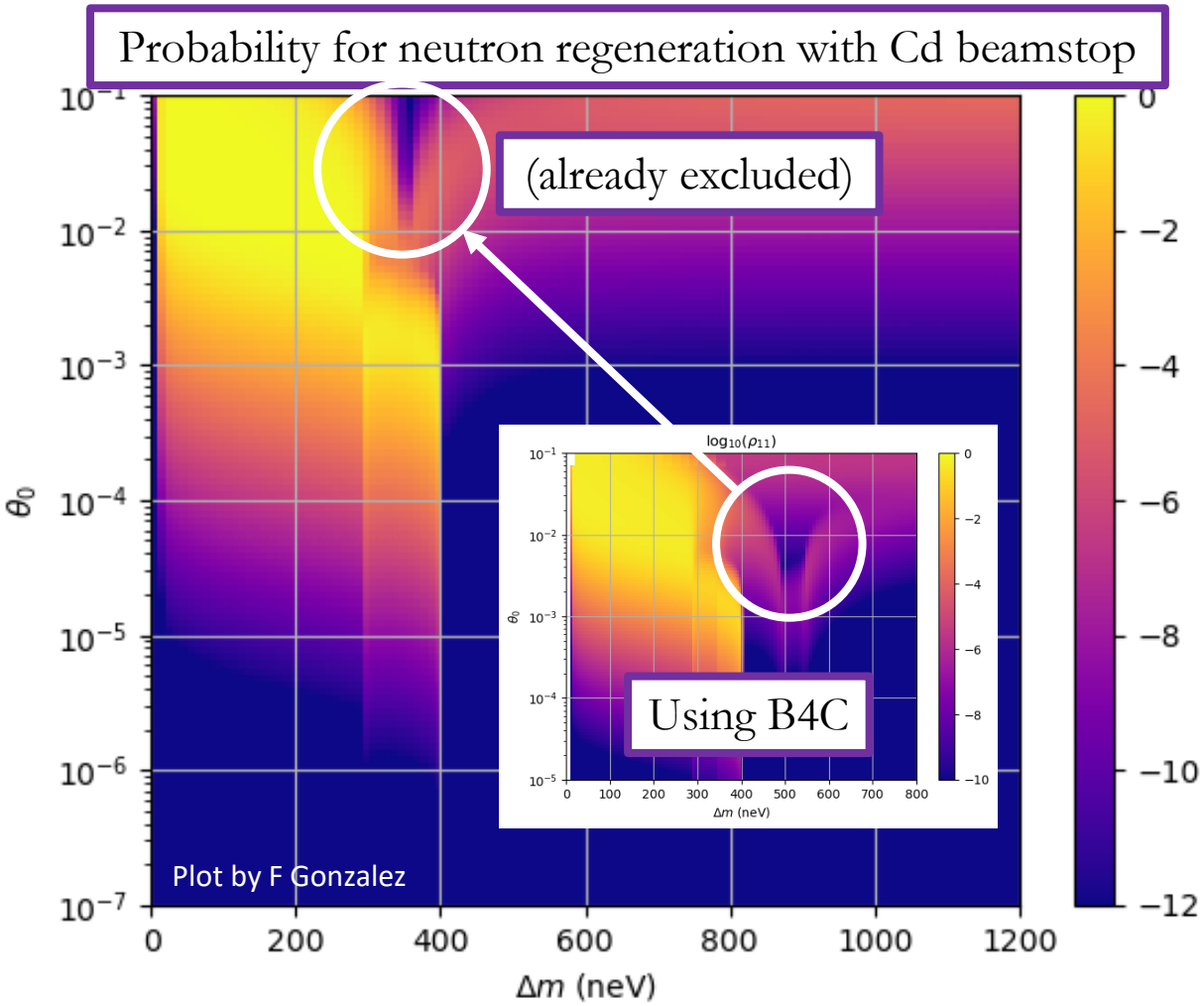
*Caveat: see [Z. Berezhiani talk]

Improved search for $n \to n'$@ SNS

- 32 mm thick B_4C: overall reduction in sensitivity due to n' attenuation inside absorber; void near compensating V_F
  Sym 14 (2022) 230
  - Important for comparing limits to STEREO
- Minimize impact → 1.27 mm thick Cd beamstop

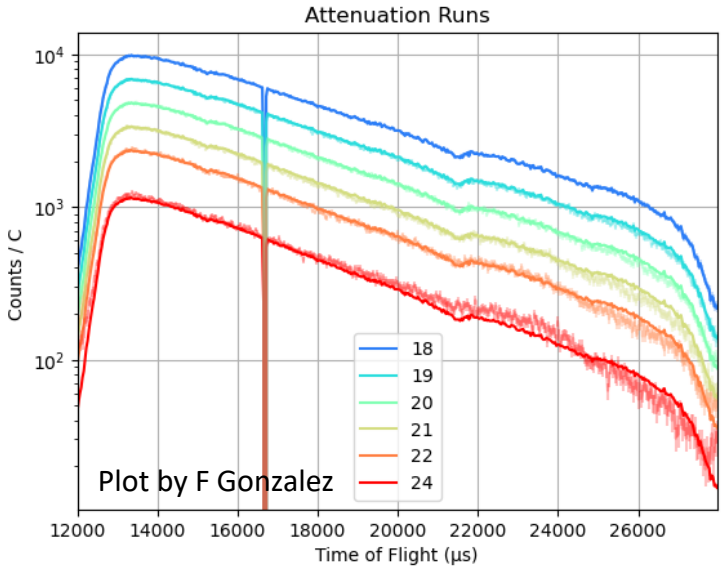


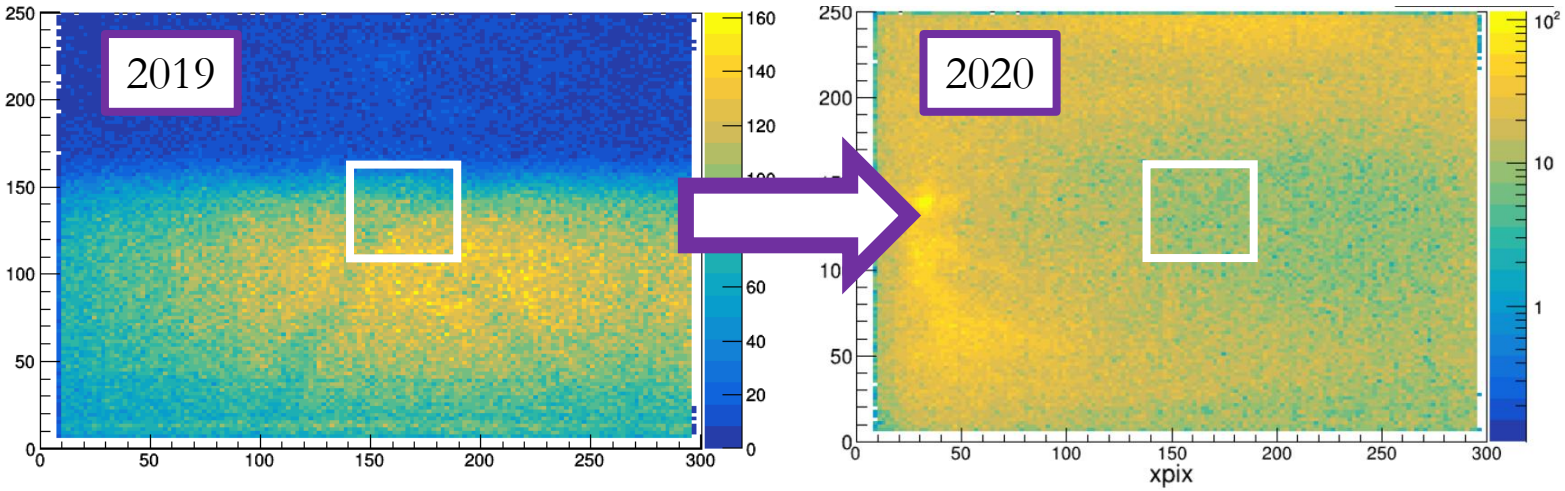
- November 2020 beamtime: 8× statistics

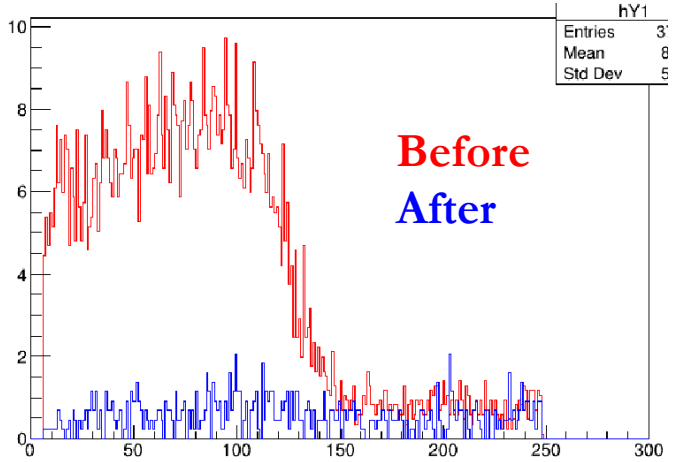


Improved search for $n \to n'$@ SNS

- Higher intensity after optimizing beamline, improved understanding of scattering backgrounds: $(2.95 \pm 0.10) \times 10^9$ n/C (+ add'l correction TBD)
- Improved shielding for 10x reduction in detector background count rate
- Improved sensitivity – uniformity and time dependence become important

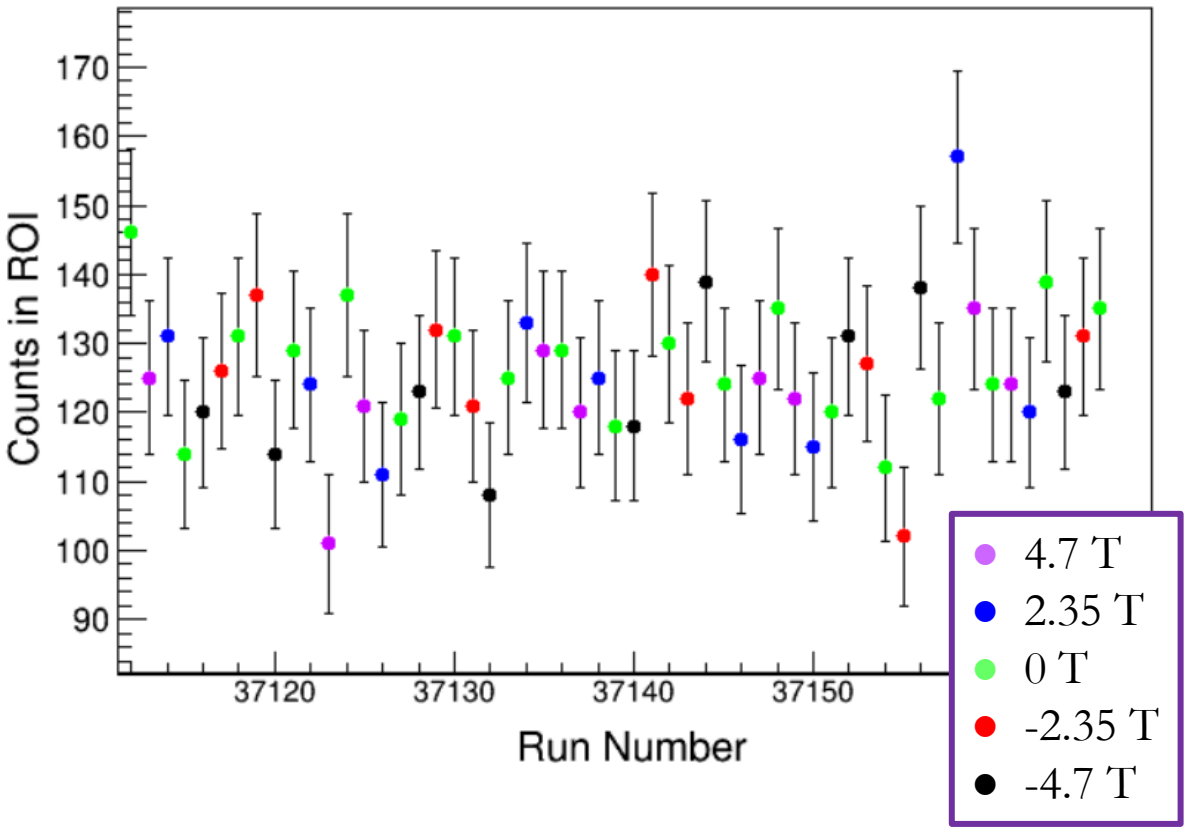


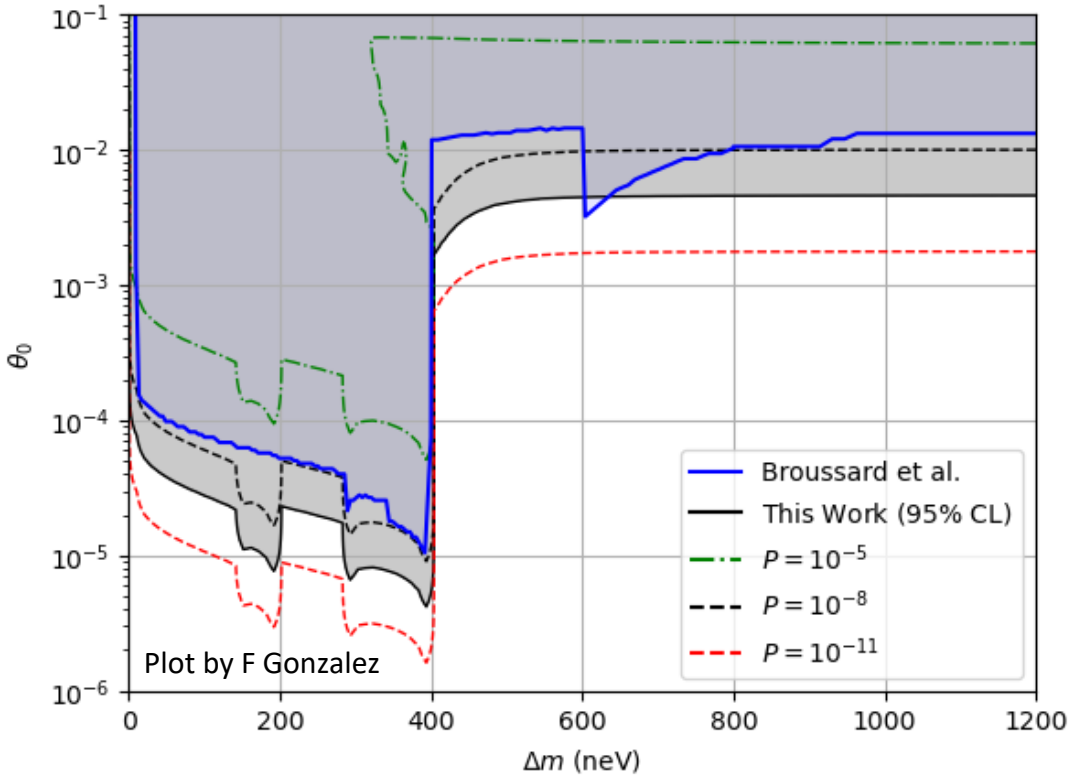




Improved search for $n \rightarrow n'$@ SNS

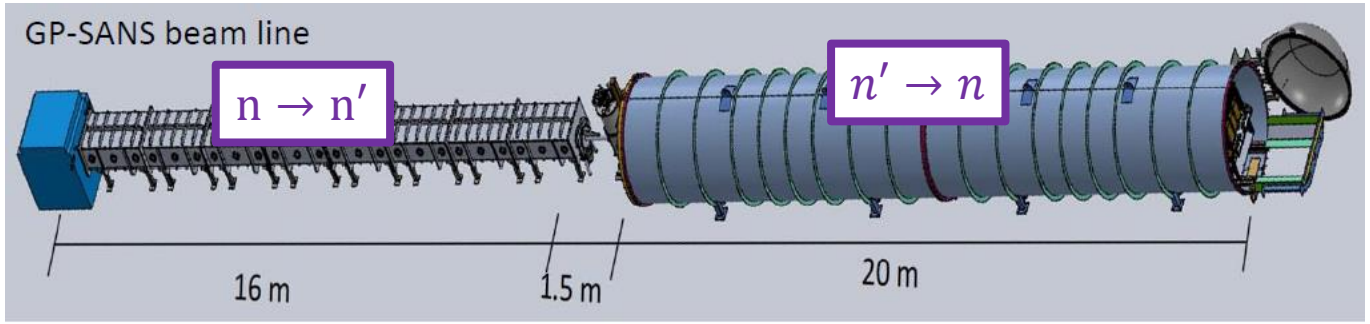
- Statistics only limit on transmission < 4.35 x 10^{-10} (95% C.L.)

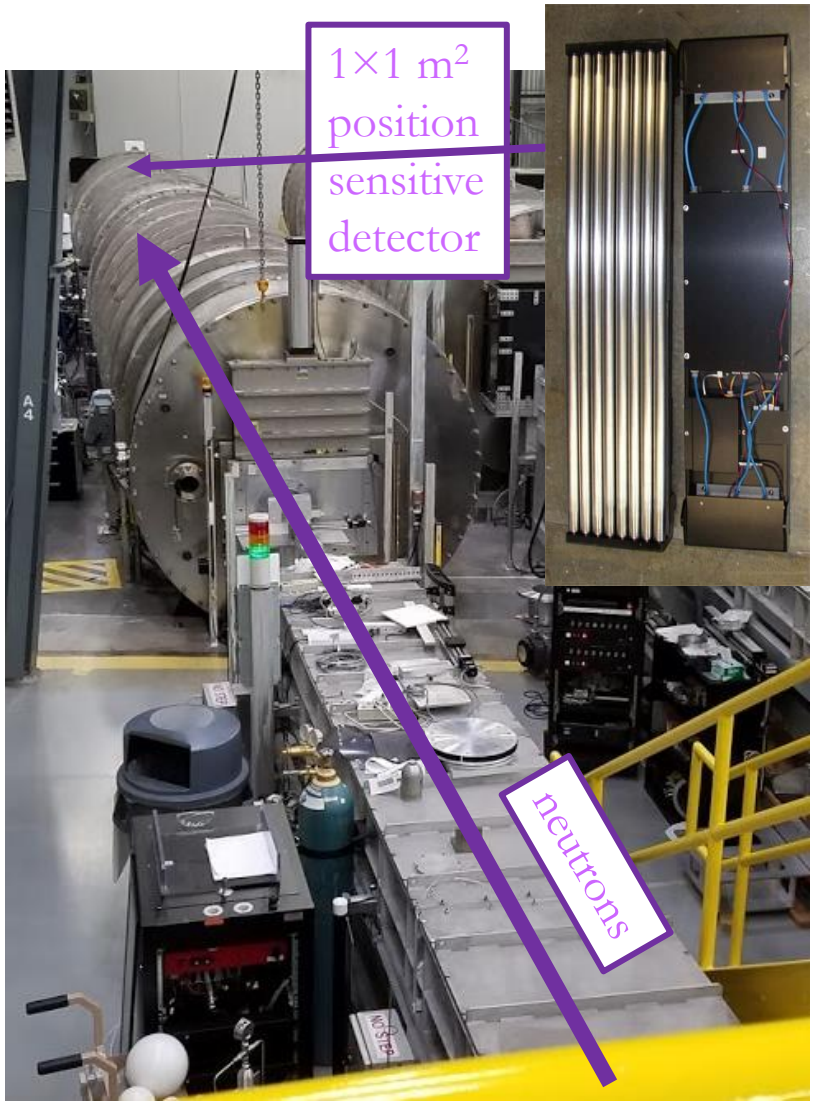




Next: searches for $n \to n'$@ HFIR

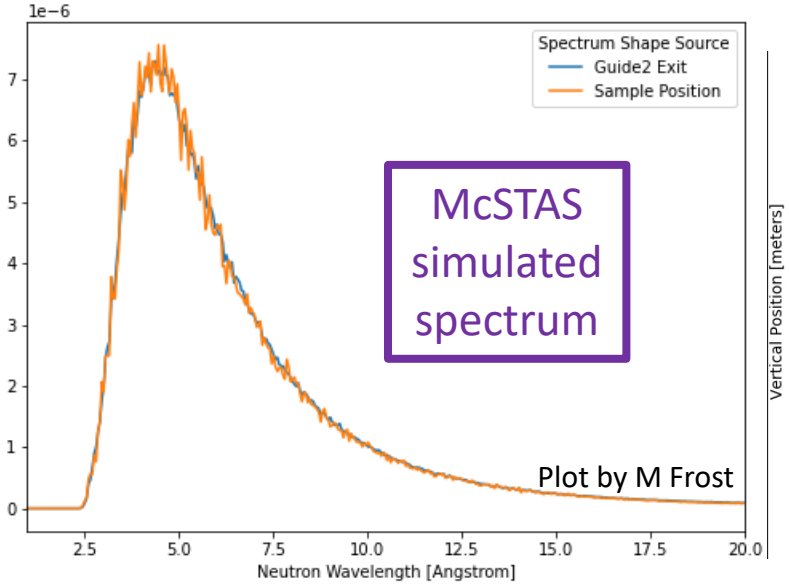
- High Flux Isotope Reactor - 85 MW: highest reactor-based source of neutrons for research in US
- New program of searches using General-Purpose Small Angle Neutron Scattering instrument
- ~10,000× more neutron intensity than SNS Mag Ref
- Lower backgrounds: ^{3}He neutron detector in Cd shielded tank
- 15 m and 20 m long beamguides for "disappearance" and "regeneration"





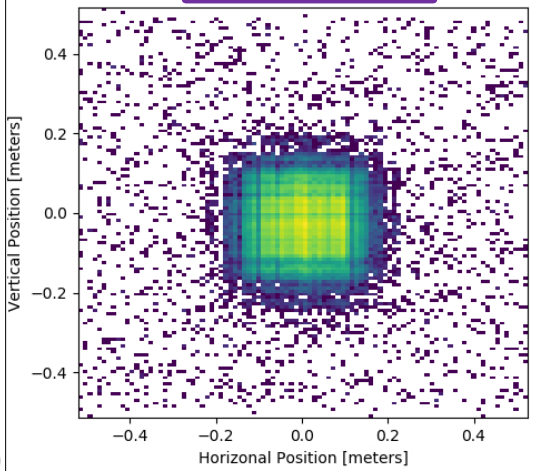
First search for $n \rightarrow n'$@ HFIR

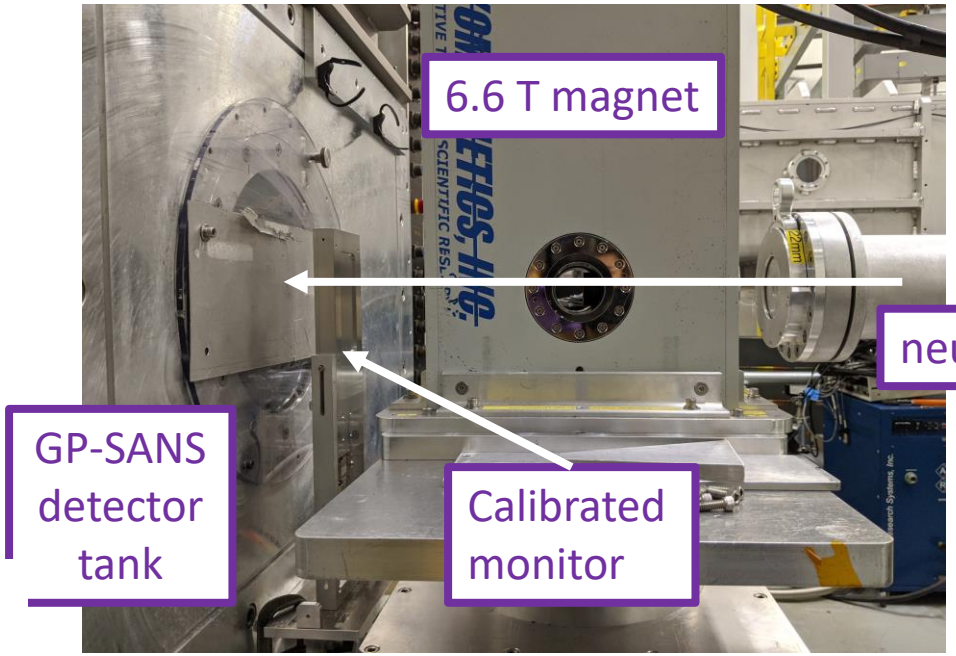
- 2020-2022: Short beamtimes to study how to improve limit on $n \rightarrow n'$ with small Δm
- Intensity for collimated beam
  - **Calibrated monitor: 9.93 x 10^8 n/s**
  - **Au Foil: 7.4 x 10^8 n/s**
  - **Reactor off background: 3 cps / m^2**

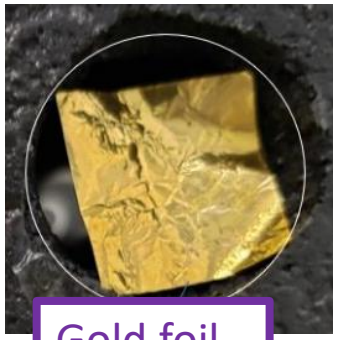


McSTAS simulated spectrum

Signal ROI





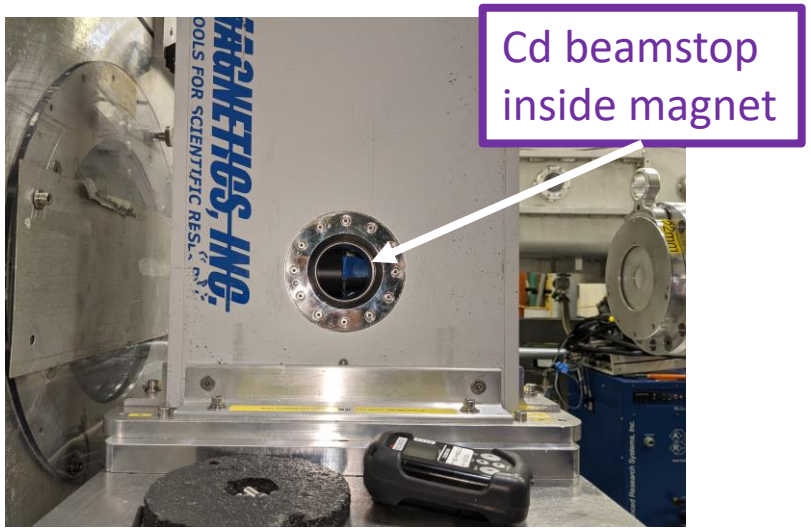


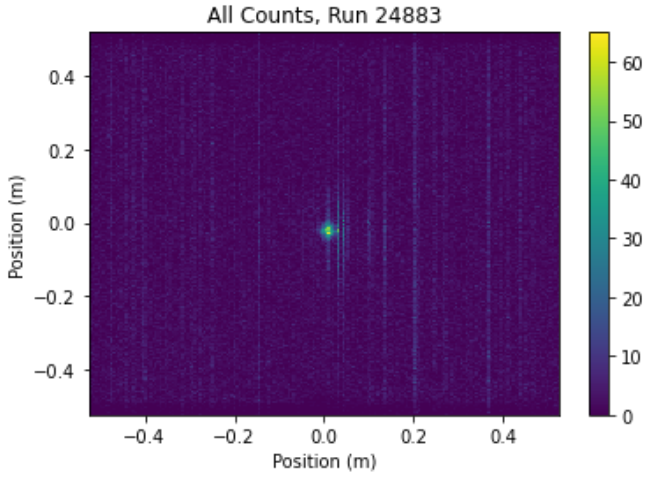
Gold foil activation

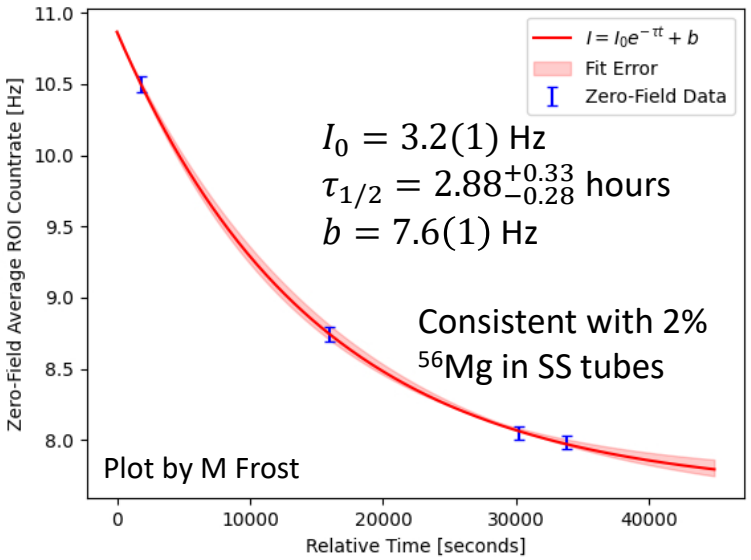
Attenuator scan

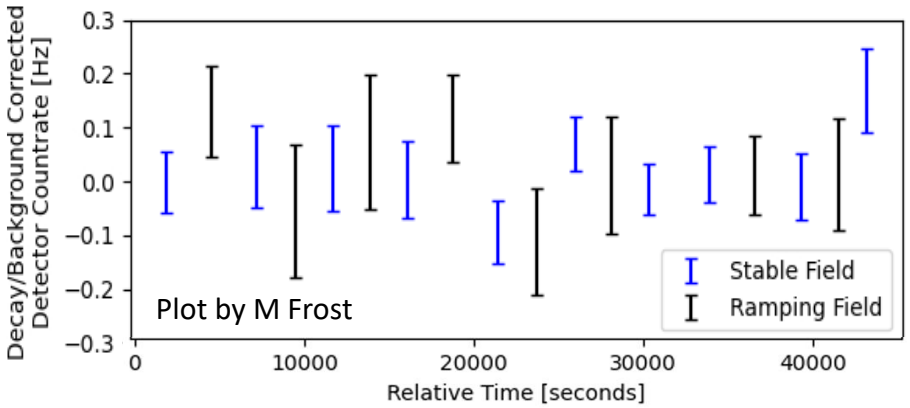
First search for $n \rightarrow n'$@ HFIR

- July 2021: First beamtime to search for $n \rightarrow n'$
- First use of "white beam" (no velocity selector)
- Intensity studies introduced activation background – limited sensitivity to physics
  - 2022: optimized hardware thresholds (n vs γ) reduces effect





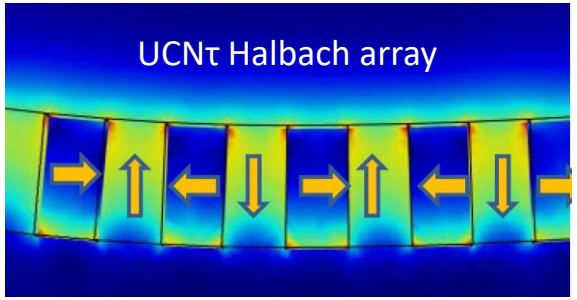


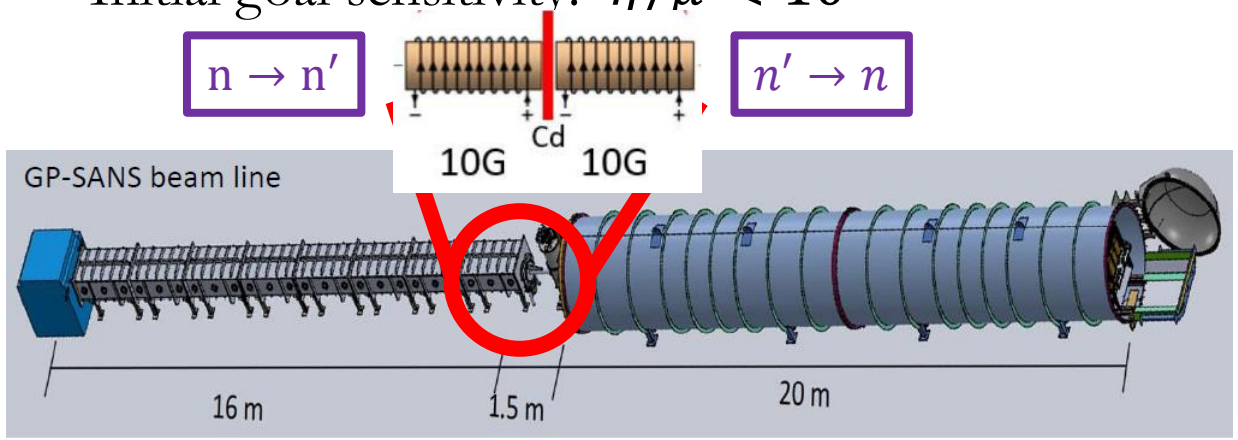


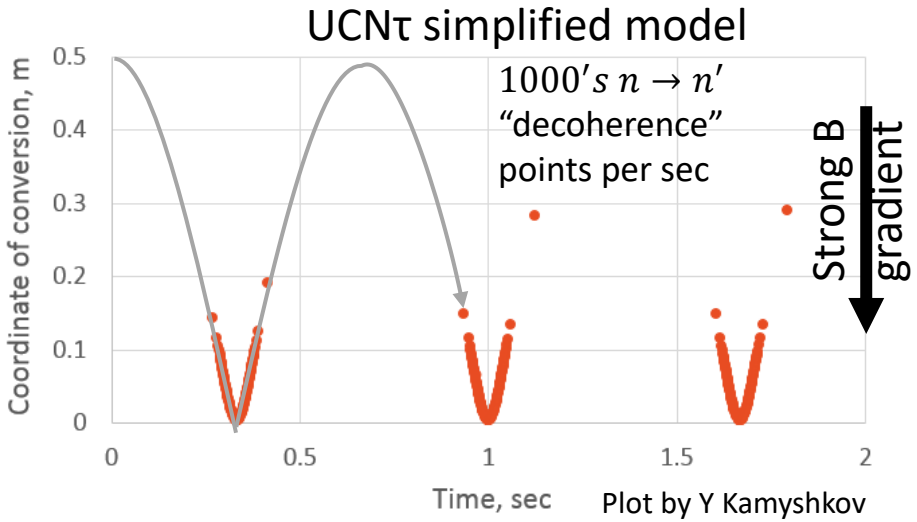
Background rate ~ 0.1 Hz / ROI achievable

Upcoming at HFIR

- Beamtime proposal for $n \to n'$ search with small Δm at HFIR, goal 2023
- Next stage: Search for Transition Magnetic Moment MDPI Phys, 1 (2019) 271-289 using (1) split coil magnet [ref] and (2) custom coil assembly
  - $\hat{H} = \begin{pmatrix} \Delta E(\Delta m_n, \vec{B}, V) & \epsilon_{nn'} + \eta\, \vec{\sigma} \cdot \vec{B} \\ \epsilon_{nn'} + \eta\, \vec{\sigma} \cdot \vec{B} & 0 \end{pmatrix}$ [Z. Berezhiani talk]
  - Explain bottle lifetime discrepancy: $\eta/\mu \sim 10^{-4} - 10^{-5}$
  - Initial goal sensitivity: $\eta/\mu < 10^{-4}$

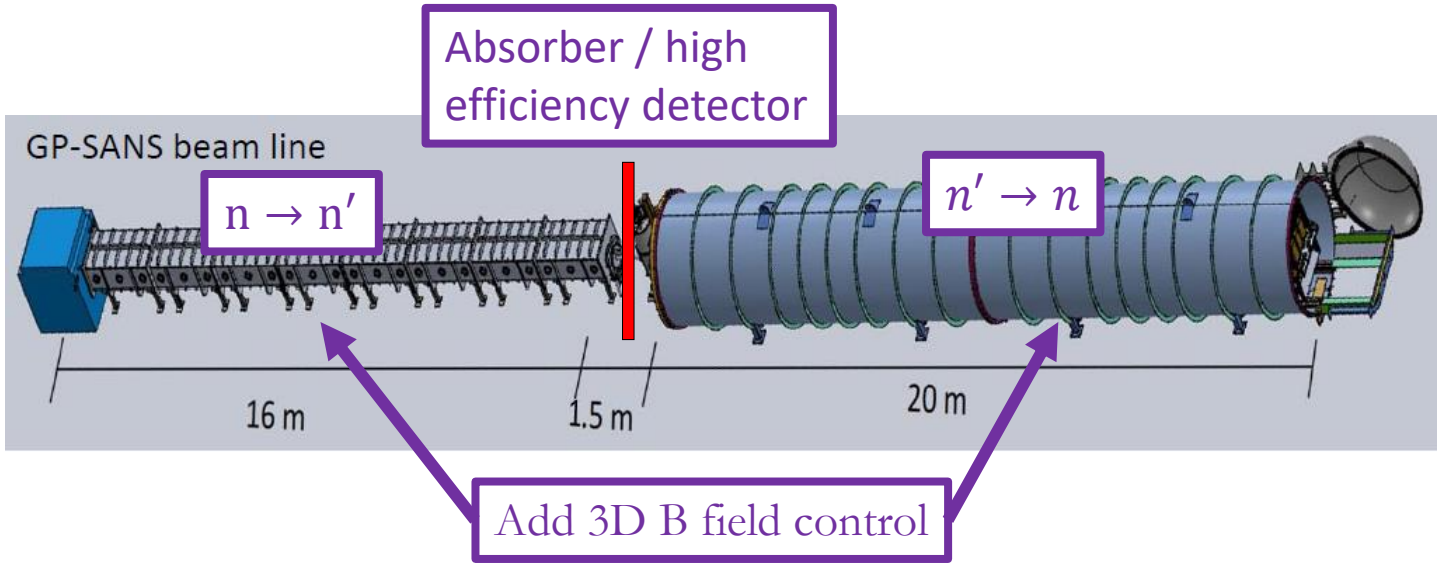


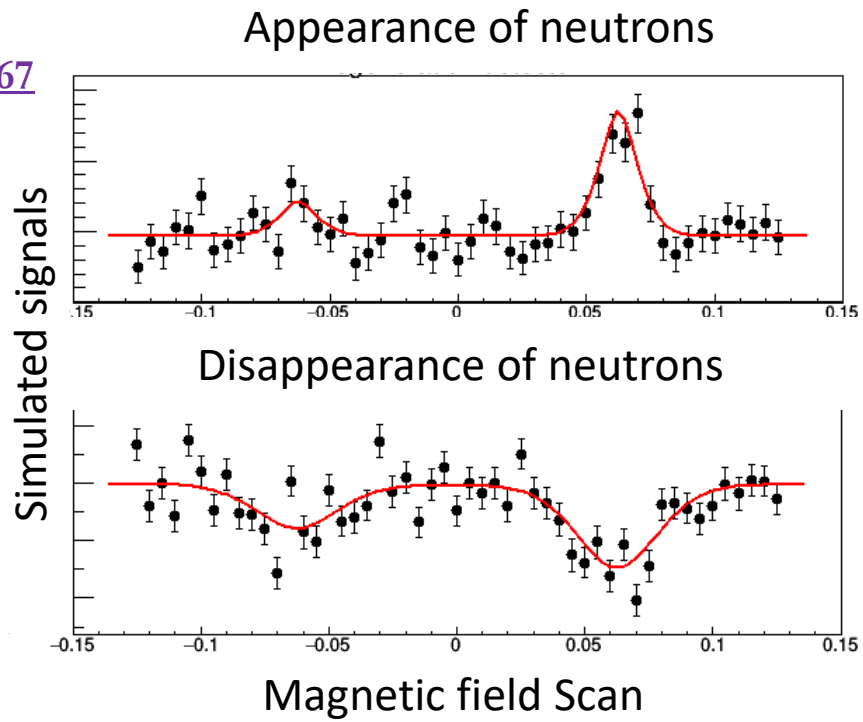




Upcoming at HFIR

- Back to the beginning – anomalies observed in UCN searches based on tuning $B \sim B'$ to achieve $\Delta E \rightarrow 0$ and $\mathrm{P}(n \rightarrow n') \propto \left(\epsilon_{nn'} t_{free}\right)^2$
- Cold neutron regeneration complementary, robust approach
  PRD **96** 035039 (2017)
- Leverage the full GP-SANS instrument arXiv:1710.00767



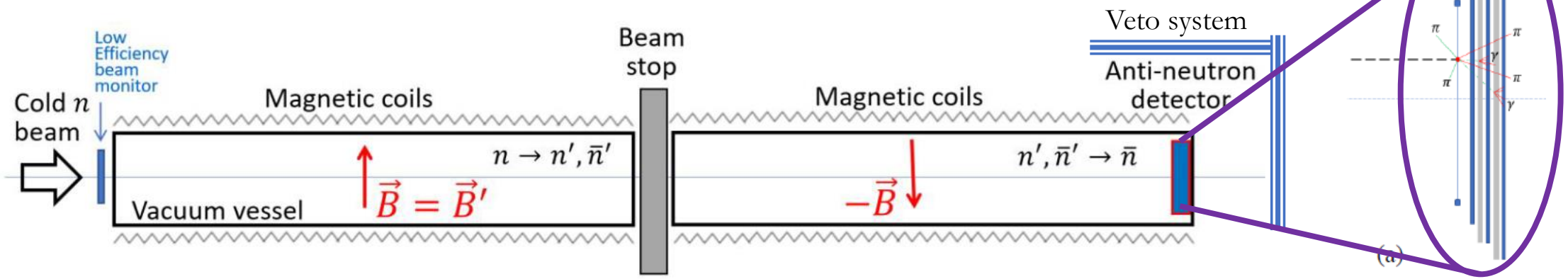


Mirror neutrons and antineutrons

$$|\phi_n\rangle = \begin{vmatrix} n \\ n' \\ \bar{n}' \\ \bar{n} \end{vmatrix}$$

- Straightforward extension of formalism to consider $n \to \bar{n}, n', \bar{n}'$
- Shortcut for neutron-antineutron oscillations
  EPJC 81 (2021) 33
- New Avenue for search for baryon number violation
- Connection to cobaryogenesis
  IJMP **33** 1844034 (2018)

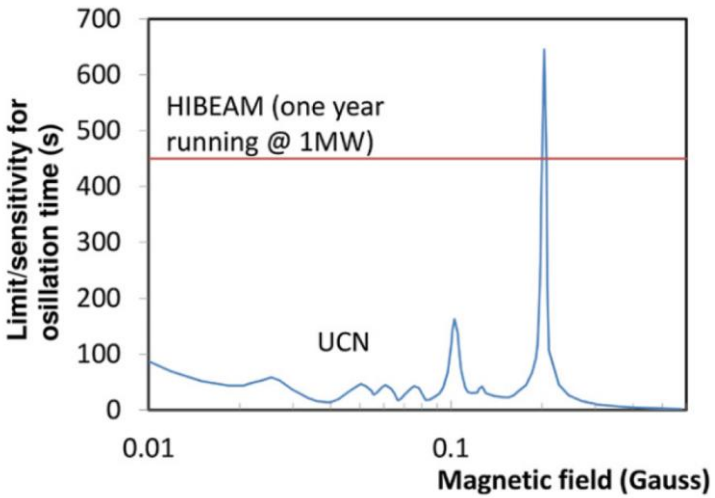
$$\mathcal{H}_{int} = \begin{pmatrix} m + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \delta_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m - \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \delta_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \delta_{n\bar{n}'} & m' + \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' & \varepsilon_{n\bar{n}} \\ \delta_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n\bar{n}} & m' - \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' \end{pmatrix}$$

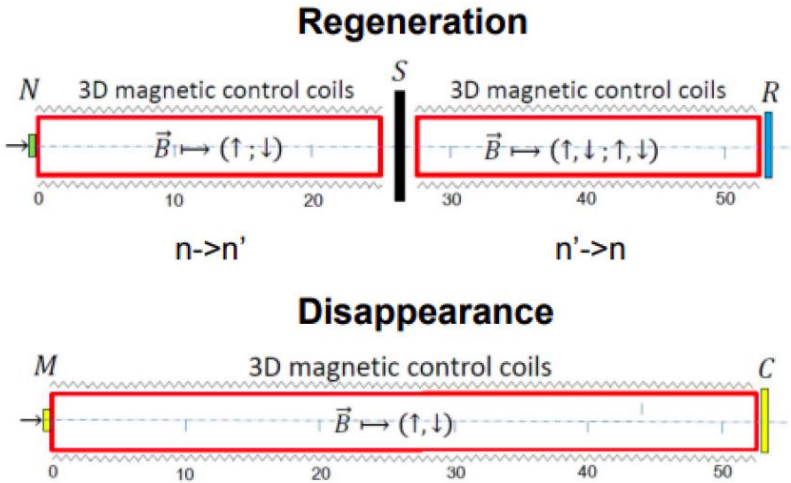


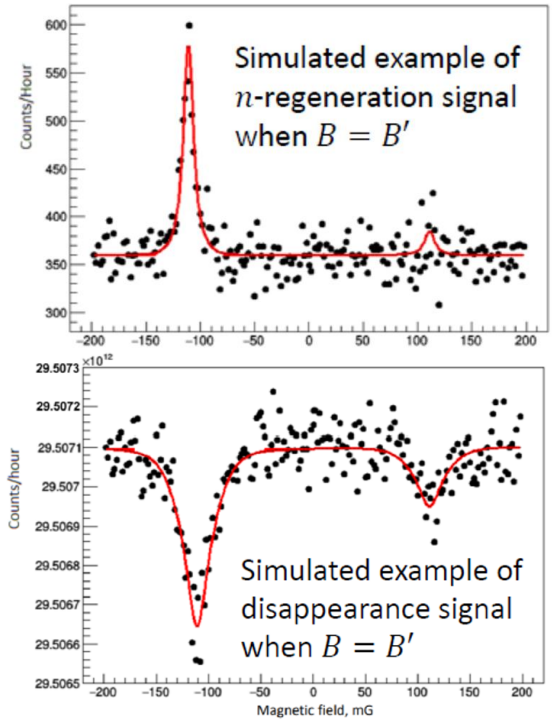
- Bonus: R&D for a high sensitivity $n \to \bar{n}$ search NNBAR [R. Wagner Friday]

HIBEAM sensitivity to $n \to n'$

- ESS: World's most powerful spallation source
- Assume ESS@1MW, 50m, 1 year operation, 1 n/s bkgd, 2 m detector
- Searches: $n \to n' \to n$, $n \to n' \to \bar{n}$







B. Meirose, COSMO22

Summary

- Searches for dark matter and baryon number violation strongly motivated
  - Neutrons are under-explored territory in worldwide BLV/dark matter programs
- We have performed a search for neutron oscillations with small mass splitting; excluded the possibility that $n - n'$ causes the neutron lifetime anomaly in NIST Beam Lifetime
- Future searches leverage ORNL's High Flux Isotope Reactor for this and other mechanisms for neutron oscillations, higher sensitivity comes from dedicated instrument at ESS
  - Searches for $n \to n' \to \bar{n}$ enable unique opportunity for early R&D for future high sensitivity search for $n \to \bar{n}$

I gratefully acknowledge support from the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U. S. Department of Energy [project number 8215] and the U.S. Department of Energy, Office of Science, Office of Nuclear Physics [DE-AC05-00OR22725]. This research used resources at the Spallation Neutron Source and the High Flux Isotope Reactor, DOE Office of Science User Facilities operated by the Oak Ridge National Laboratory.

Parallel universe breakthrough: Scientists begin work on finding a 'mirrorverse'

SCIENTISTS are hoping to open a portal ... undoubtedly be the biggest ...

By SEAN MA...

P-magazine, Belgium

TL;DR

...rallel universe breakthrough: ...ists begin work on finding a ...

1 minute read

Naukowcy próbują odnaleźć lustrzane uniwersa rodem ze Star Treka

...R, MIRROR"

Two Experiments Might Soon Show If So-Called Mirror Matter Exists

...ists Are Trying to Find A Mirror Universe - Like in Star Trek

BY CRAIG ELVY – ON JUL 04, 2019 IN TV NEWS

...TARÁN

Science › Physics

Scientists are trying to open a portal to a Stranger Things-style MIRRORVERSE

Scientists believe there could be a parallel universe as real as our own, but almost completely cut off from us

www.mirror.co.uk

amedpost.co...

http://inetgreen.club

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screenrant.com/

Natalia Bogucka 04.07.19 (11:38)

www.o2.pl

Naukowcy próbują otworzyć portal do równoległe... ...ochświata

Choć brzmi to jak historia z film... Laboratory w Tennessee wierz... odzwierciedleniem naszego ... portal, który ich do niego prze...

Demogorgons, Spock with a goatee, you know the rest

July 3, 2019 9:11 AM Subscribe

Leah Broussard, Oak Ridge National Laboratory, and the search for "mirror matter". In a series of experiments she plans to run at Oak Ridge this summer, Broussard will send a beam of subatomic particles down a 50-foot tunnel, past a powerful magnet and into an impenetrable wall. If the setup is just right — and if the universe cooperates — some of those particles will transform into mirror-image versions of themselves, allowing them to tunnel right through the wall. And if that happens, Broussard will have uncovered the first evidence of a mirror world right alongside our own.

...de EE UU intentarán abrir un portal ...elo

...el equipo y física **Leah Broussard** a la cadena ...

...e existence of a mirror universe is ...t will be in Tennessee

...hursday, July 4th 2019

fox17.com/

Bonus

- About 100 (mostly clickbait) stories on the experiment
- Hundreds of thousands of tweets/other social media
- 2 posted letters
- 1 piece of art
- Response from the public
  - 1/3 enthusiastic public
  - 1/3 "alternative physicists"
  - 1/3 *volunteers to go through the portal*

I have a Google new alert setup for @leahjbroussard and every time it goes off I am excited and scared all at the same time.
Did she do it??
Did she do it and now we are all going to die??

@leahjbroussard have you considered what might come through the portal?... regardless, please proceed.

@leahjbroussard Not that I don't doubt you'll make excellent progress with your experiment, but I hope that you'll be taking every precaution should 'something' try to follow the particles back. Be really cautious and have failsafes to shut it down if need be.

I'm an excited hobbyist (sharing with my 6 year old son and 4 year old daughter) and wish you the best.

Hello Goodmorning, I saw your experiment recently and just wanted to let you know if you ever reach a point you want to see if you can mirror humans. I volunteer as a guinea pig.

Find us a better timeline! You're our only hope @leahjbroussard

I really encourage you and your team to watch Stranger Things before attempting to open the gate to a mirror universe.
Sent from my iPhone

Thank you!