Searches for n→n'→n at HFIR, ORNL

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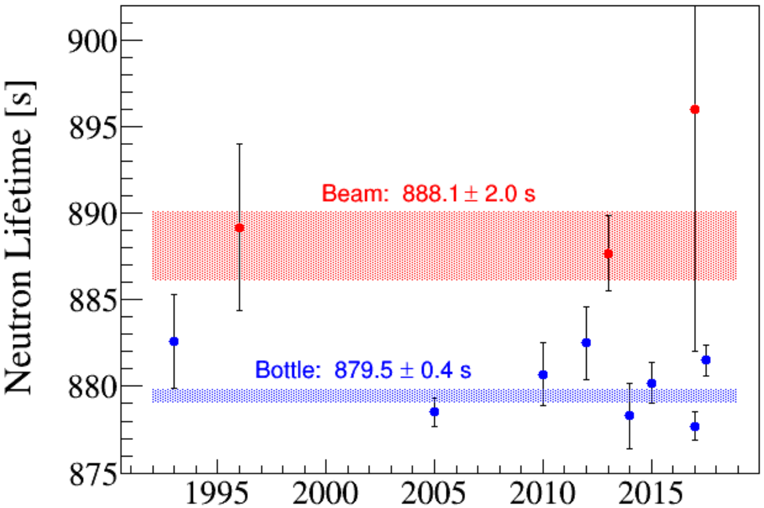
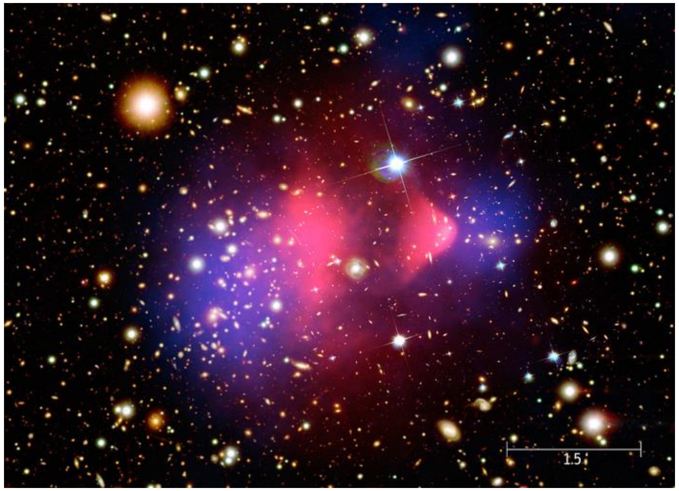
Particle Physics with Neutrons at the ESS, December 10-14, 2018

"Stockholm skyline at night" (CC BY 2.0) by Giuseppe Milo

Why neutron oscillations

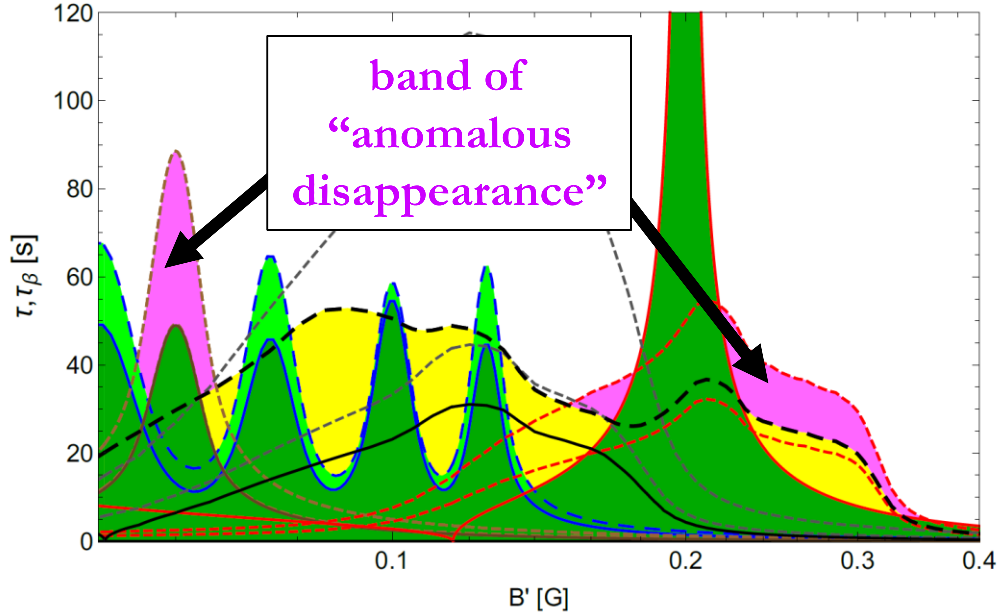
- Neutron lifetime discrepancy: ~ 4 σ
- Dark matter: particle nature unknown, new avenues for discovery may be needed to solve puzzle
- Neutron oscillations one of a few possible dark portals





Where to search for oscillations

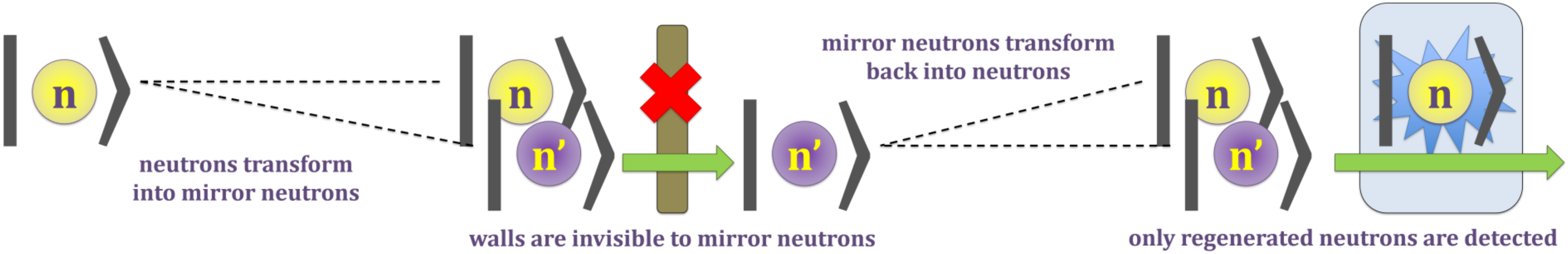
- Resonance at low B: (Biondi, Kirch talks) anomalous signal reported
- New ideas
  - Spin precession (Young talk)
  - Mass splitting (high B) (Berezhiani talk)
  - Transition Magnetic Moment (Kamyshkov talk)
  - $n \rightarrow n' \rightarrow \bar{n}$ and more (Barrow talk)



NIMA **611** (2009) 137, PRD **80** (2009) 032003, EPJC **72** (2012) 1974, EPJC **78** (2018) 717, arXiv:1807.07906

Complementary approaches

- Ultracold neutrons
  - "Bottle": measure lifetime and look for anomaly under certain conditions (e.g. at specific magnetic field)
  - Distinguish anomaly from other systematic loss?
- Independent approach: cold neutron regeneration
  - High intensity "beam": second order effect

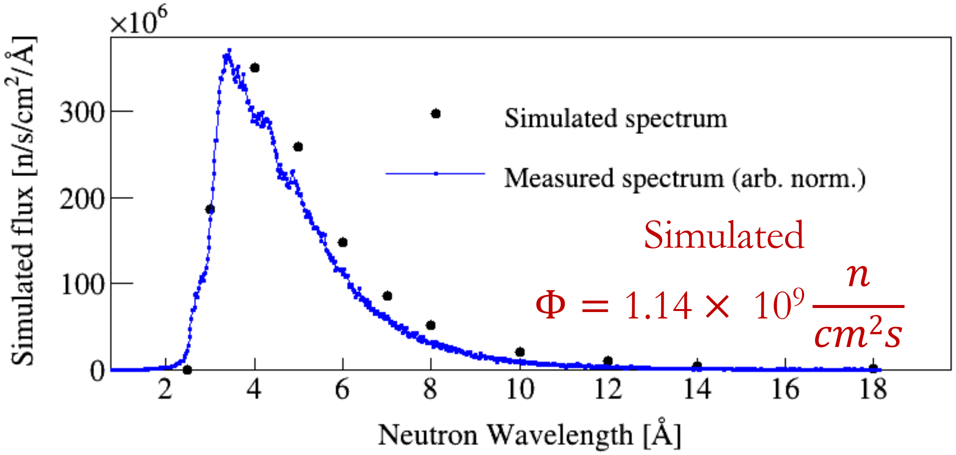


HFIR and GP-SANS

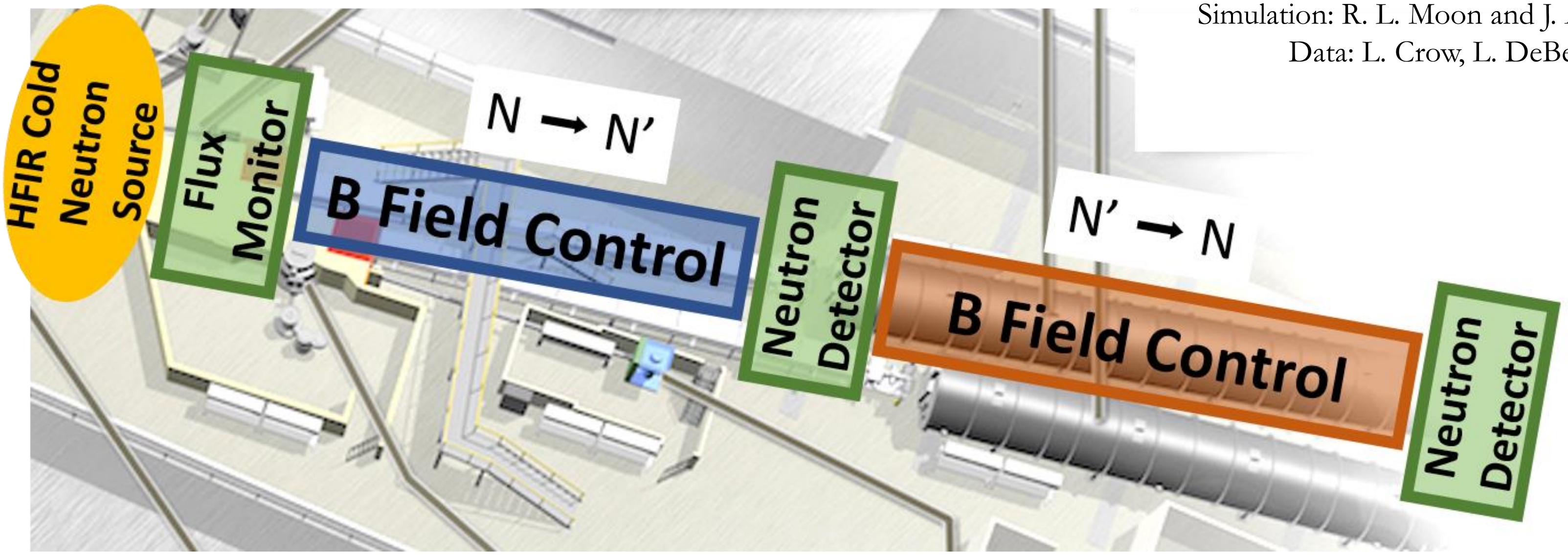
- 85 MW High Flux Isotope Reactor: highest reactor-based source of neutrons for research in US
- General Purpose: Small Angle Neutron Scattering Instrument
- Developed n→n' program with GP-SANS instrument scientist team

GP-SANS as a n→n' probe: Neutron flux

- 2×10^{10} n/s white neutron beam between 2–15 Å when velocity selector removed

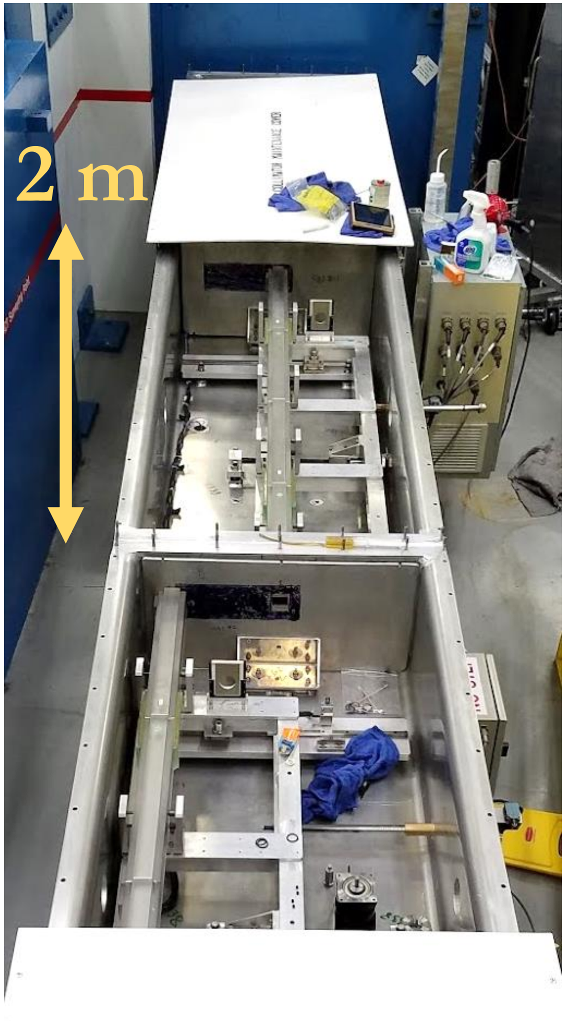


Simulation: R. L. Moon and J. A. Bucholz
Data: L. Crow, L. DeBeer-Schmitt



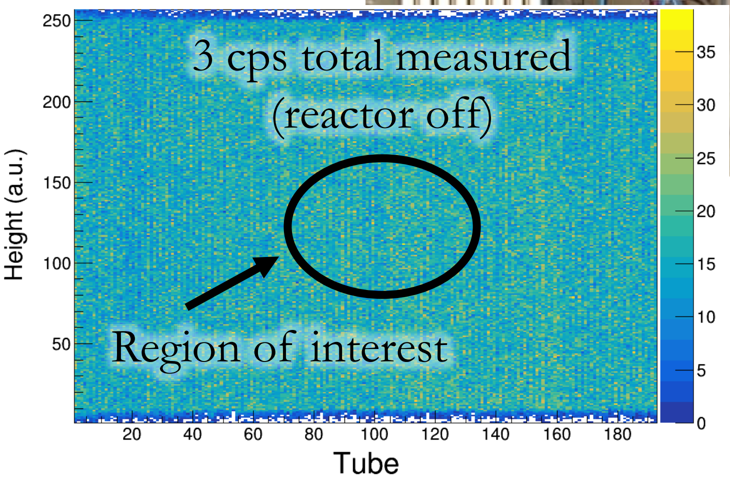
GP-SANS as a n→n' probe: Beam guides

- Primary flight path ~15 m long
  - Typically used for collimation
- Fall 2019 upgrade
  - Simplify installation
  - Room for 20 cm diameter beam guides
  - Magnetic material removable
- Secondary flight path (detector tank) ~20 m long, ~1.5 m diameter
- Not too distant future: x6 more neutrons from upgrade of upstream optics (now m=1)



GP-SANS as a n→n' probe: Detector

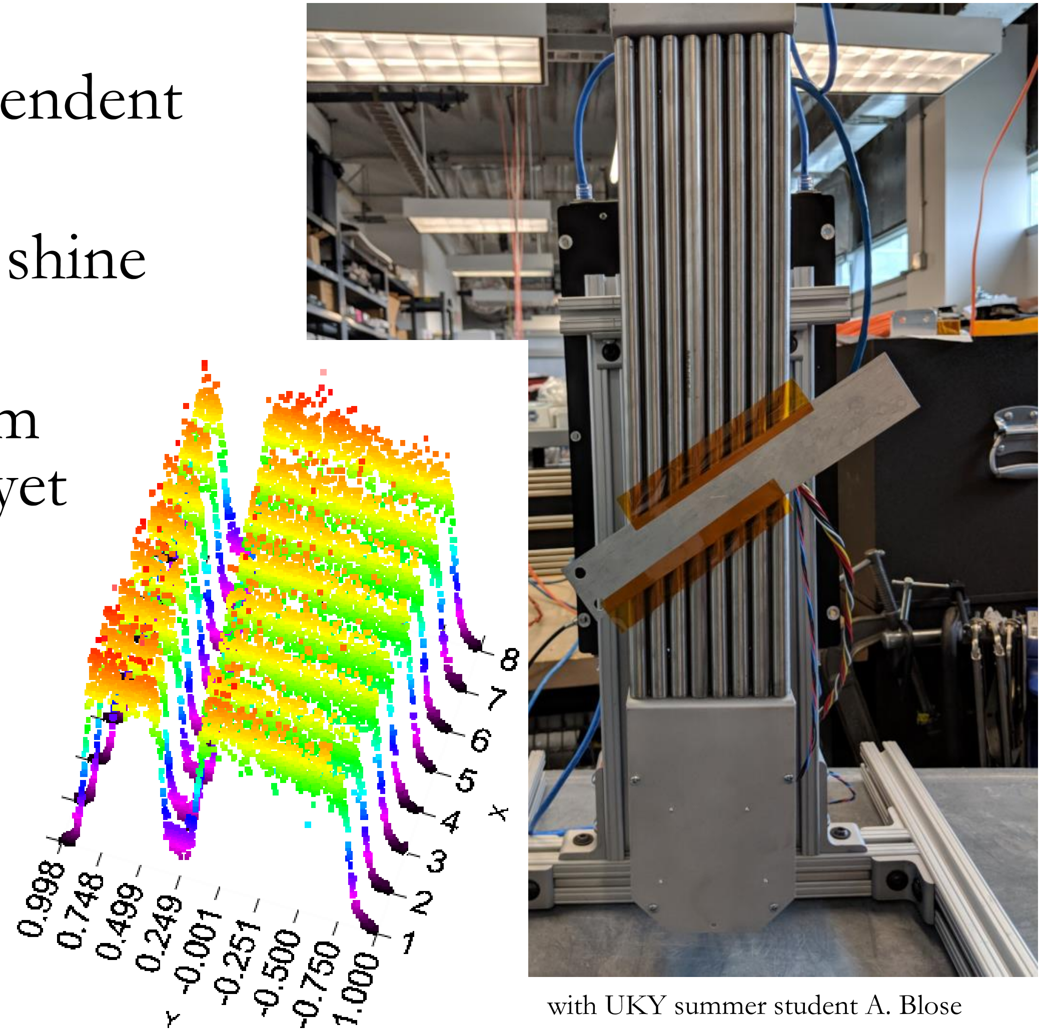
- 1 m^2 of 192 ^3He tubes
  - $n+{}^3He \rightarrow t+p$
  - Large signal, well defined amplitude, insensitive to gamma radiation
  - 5 mm x 5 mm position resolution: in situ background measurement outside ROI
- Cd-shielded detector tank with sapphire vacuum window
- 3×10^{-4} cps/cm^2 background from cosmogenic neutrons
- Detector movable: 1.5 – 20 m from tank entrance



K. D. Berry *et al*, *NIMA* **693** (2012) 179

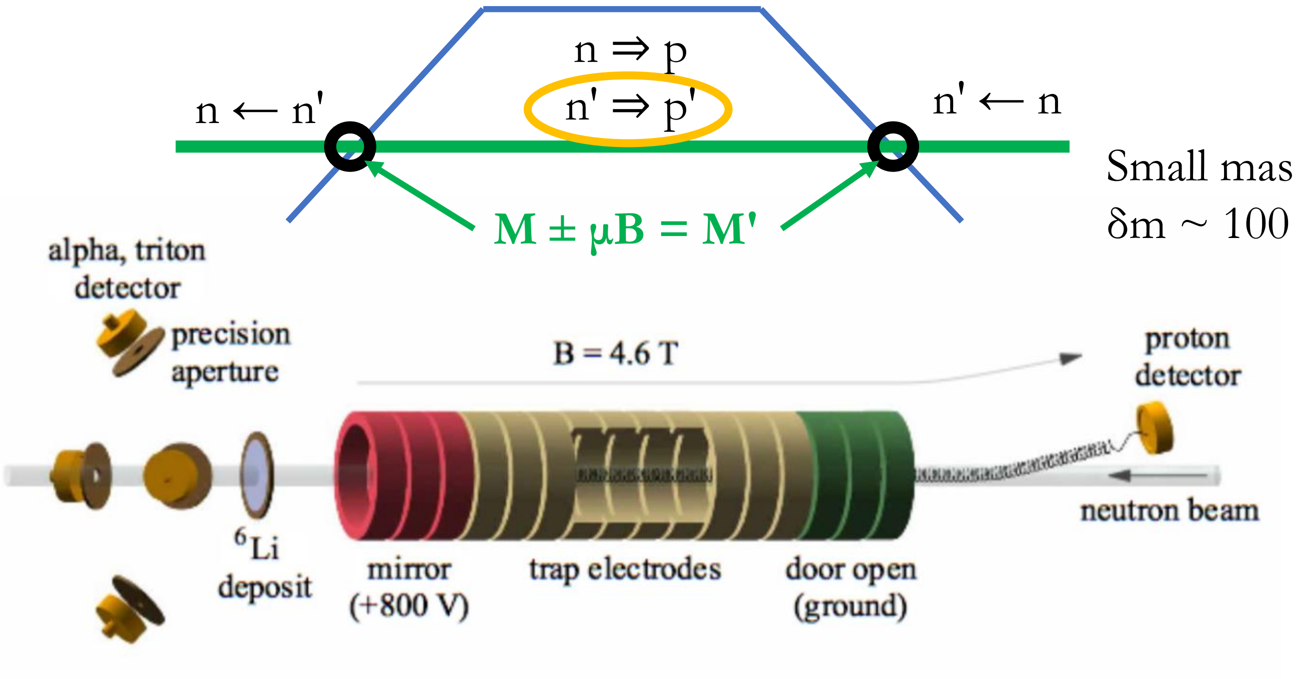
GP-SANS as a n→n' probe: Backgrounds

- Position- and time-dependent backgrounds
- Cosmogenic neutrons: shine from concrete floor
- Neutron scattering from other instruments not yet well characterized
- "Mini GP-SANS" detector installed outside detector tank
- Study optimization of extra shielding



with UKY summer student A. Blose

Explain CN lifetime by n→n'?

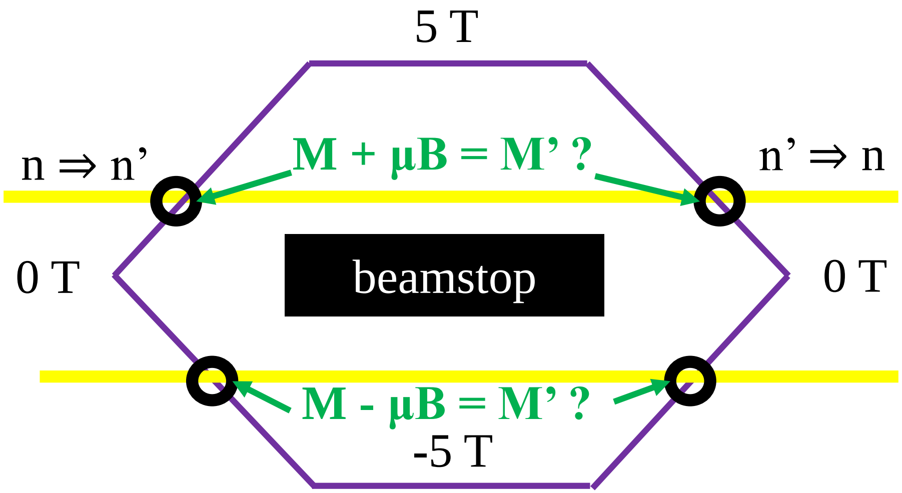


Small mass splitting
$\delta m \sim 100$ neV

- ~1% transformation explains anomaly
- Study in NIST Beam Lifetime:
    - Lifetime, proton efficiency, neutron flux vs. B, polarization

Berezhiani, arXiv:1807.07906

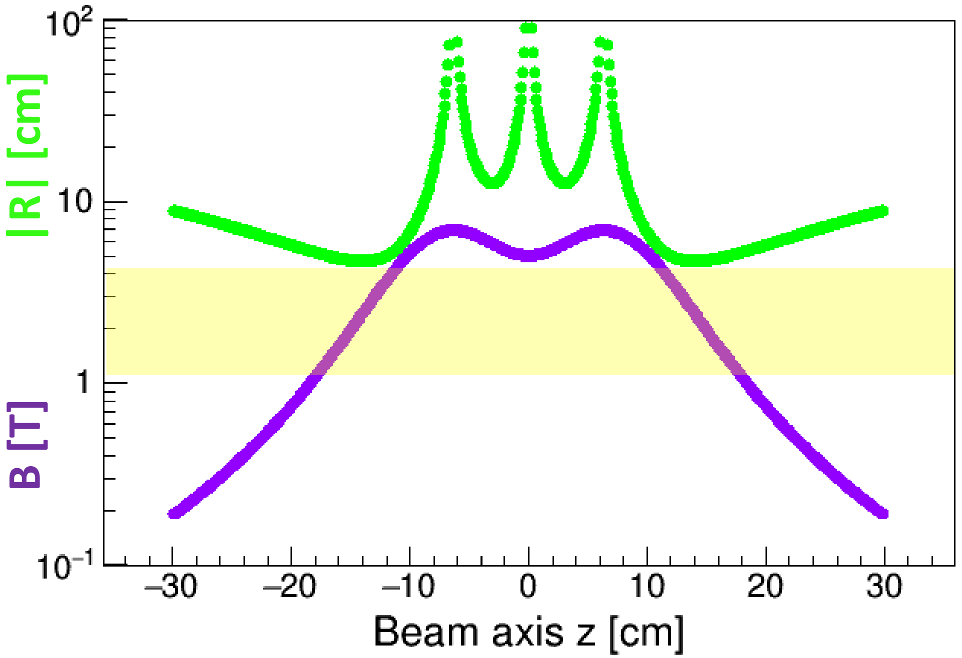
Search for $\delta m_{nn'}$ at GP-SANS



- Use regeneration technique
- Transformation depends on adiabaticity parameter ξ
    - e.g. non-adiabatic case (Landau Zener conversion):
      $P_{nn'} \approx \xi \approx \frac{\Delta E \cdot \Delta t}{\hbar} = \delta m \, \sin 2\theta_0 \frac{R(z)}{\hbar v}$ (Eq. 20 of arXiv:1807.07906)
      Resonance length scale $R(z) = \frac{d(\ln B(z))}{dz}$

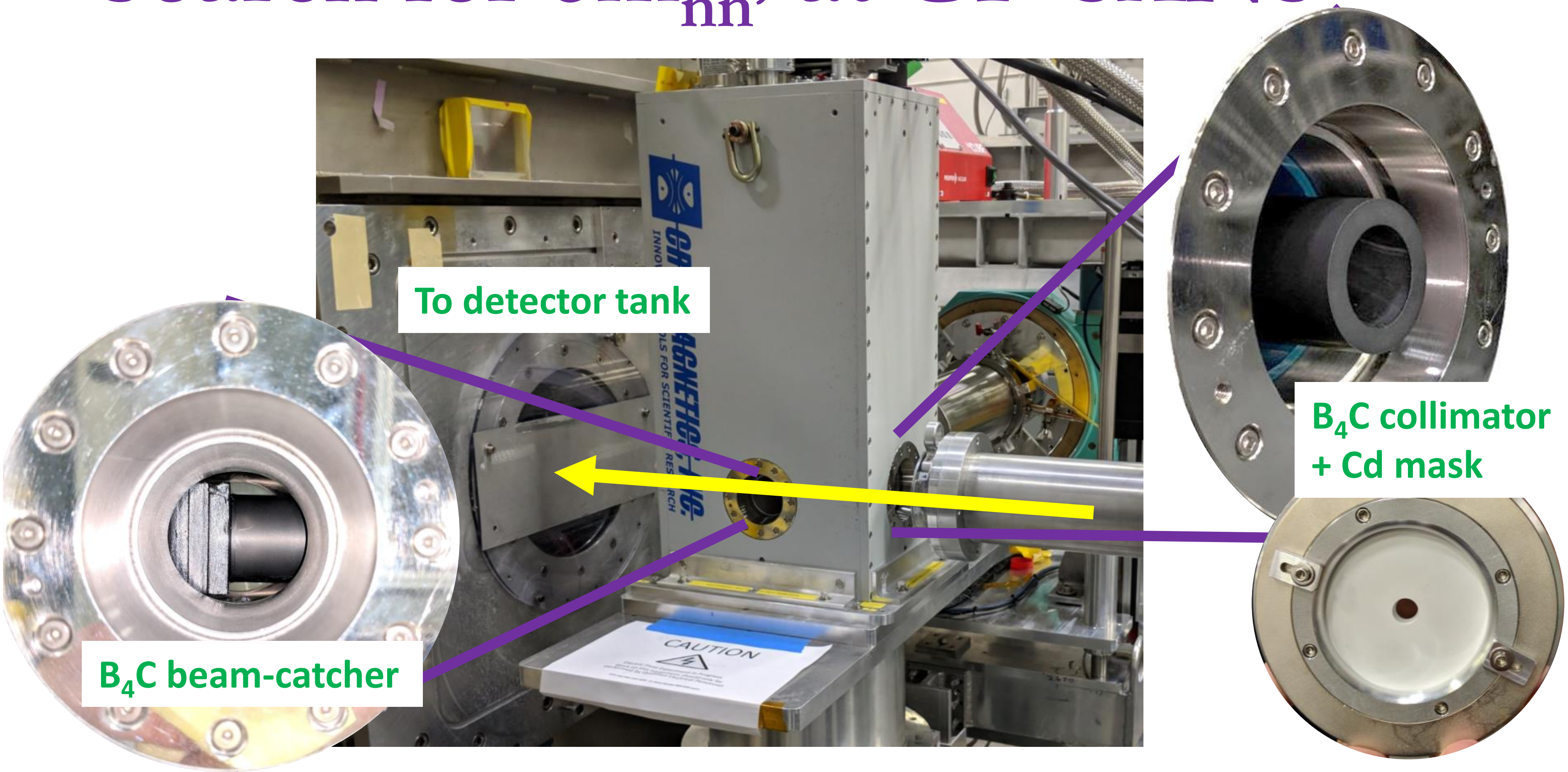
Search for $\delta m_{nn'}$ at GP-SANS

- Interesting region for lifetime anomaly: ~1–4 T
- e.g. if δm=120 neV, B = 2 T, θ_0=10^{-3}, monochromatic 4.75 Å
  - $\xi \approx 0.04$ and $P_{nn'}(0) \approx 3\%$



- Dramatic effect to explain lifetime anomaly at GP-SANS (expect 10^7 n/s for collimated 4.75 Å beam):
  - **10^4 n→n'→n/s** when magnet is ramped up

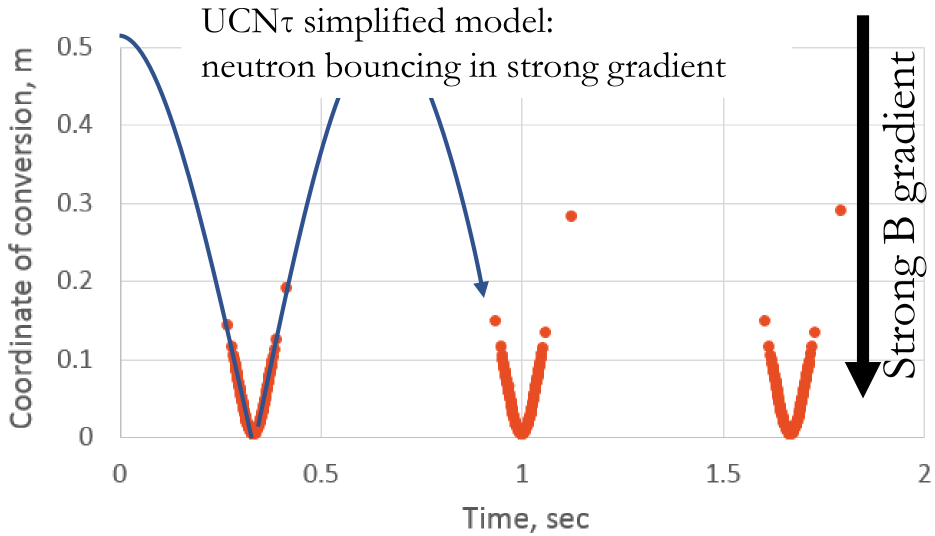
Search for $\delta m_{nn'}$ at GP-SANS



- Experiment approved to run in November at HFIR
  - Reactor cycle postponed: we are installed and ready for next restart
- Important baby step for working with GP-SANS team

Explain UCN lifetime by n→n'?

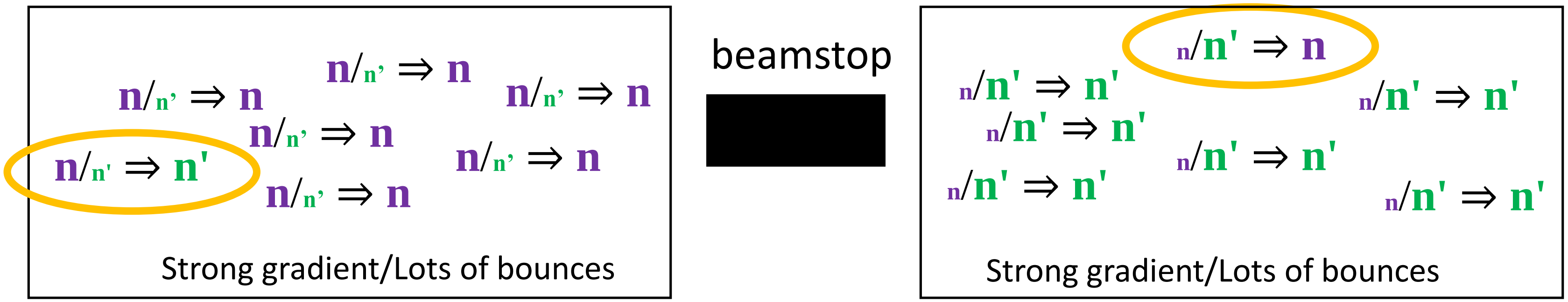
- Transition magnetic moment η: independent of time, magnetic field
- Decoherence if:
  - n hits wall, n' goes through
  - n feels force of B gradient, n' doesn't
- To explain discrepancy:
  - $P_{nn'} \approx \frac{2\eta^2}{\mu^2} \sim 10^{-7} - 10^{-9}$
- Explore in UCNτ:
  - Measure lifetime vs UCN spectrum, plus other ideas



Kamyshkov, UTK

Kamyshkov, Berezhiani, Varrano, in prep

Search for TMM η at GP-SANS



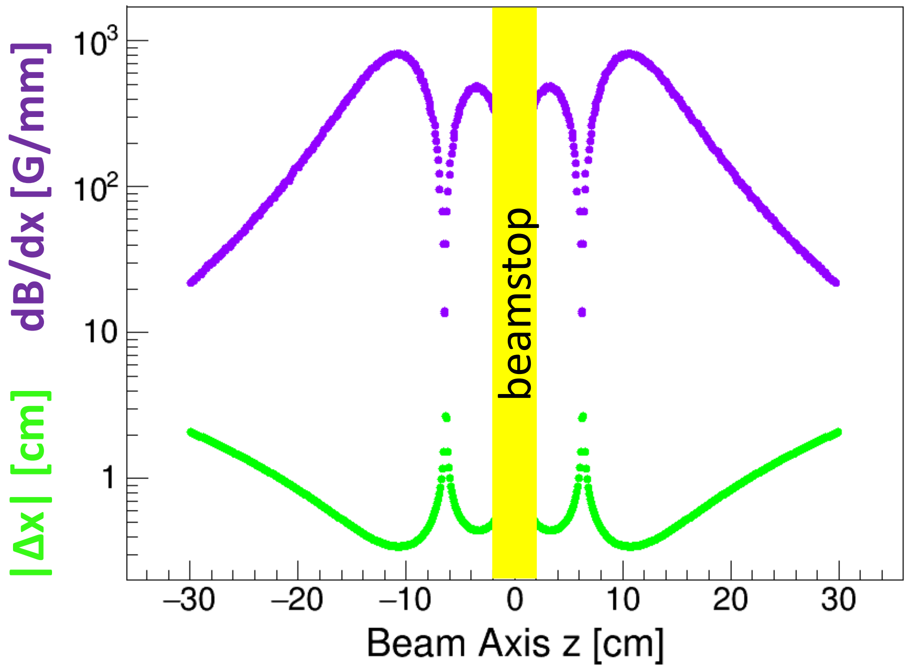
- Gradient specifies separation resulting in decoherence

$$\mu \Delta B = \Delta E > \frac{\hbar}{\Delta t} = \frac{\hbar v}{\Delta x} \quad \rightarrow \quad \frac{dB}{dx} > \frac{\hbar v}{\mu \Delta x^2}$$

- Regeneration approach avoids ambiguity of UCN storage loss systematics
- Requires high suppression beam-catcher

Search for TMM η at GP-SANS

- Using same experiment configuration: ~450 **n**/n' breakpoints before and after beamstop
- $\frac{\eta}{\mu} < \sim 2 \times 10^{-4}$ (95% C.L.) achievable in 1 day using 4.75 Å beam (depending on backgrounds)



- With 10^{10} n/s intensity from white beam: $\frac{\eta}{\mu} < \sim 8 \times 10^{-5}$ (95% C.L.) in 1 day

Search for TMM η at GP-SANS

- Best path to increase sensitivity: increase breakpoints
  - Solenoid: large gradients, but very short distance
  - Add smaller gradients over longer distance
- Series of coils with alternating currents (100 G/m):
  - +500 breakpoints over each 15 m length
  - Modest improvement to $\frac{\eta}{\mu} < \sim 5 \times 10^{-5}$ (95% C.L.) in 1 day
- Cylindrical Halbach array (kG/cm):
  - +20k breakpoints over 15 m; but only upstream feasible
  - Reach $\frac{\eta}{\mu} < \sim 2 \times 10^{-5}$ (95% C.L.) in 1 day
  - See also Barrow talk next

Search for Low B resonance

$$\hat{H} = \begin{pmatrix} m - i\Gamma/2 + \mu(\vec{B}\cdot\vec{\sigma}) & \varepsilon \\ \varepsilon & m' - i\Gamma'/2 + \mu'(\vec{B}'\cdot\vec{\sigma}) \end{pmatrix}$$

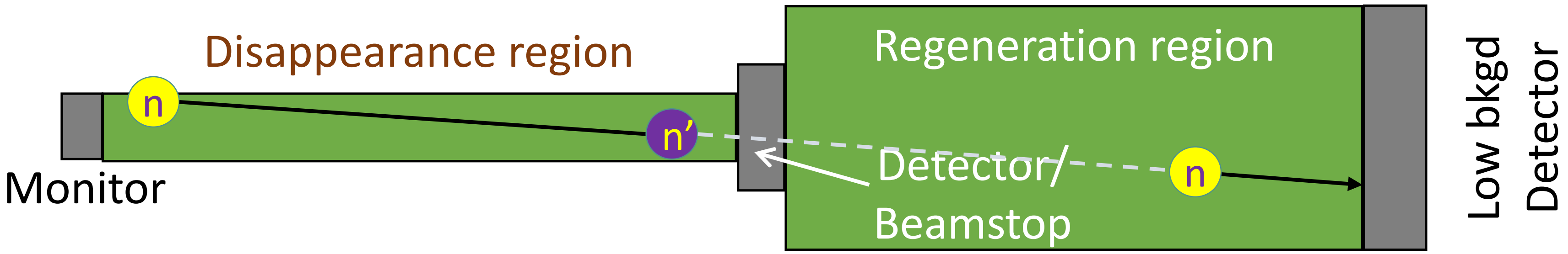
$$\mathrm{P}(n \rightarrow n') = \frac{\sin^2[(\omega - \omega')t]}{[(\omega - \omega')]^2 2\tau^2} + \frac{\sin^2[(\omega + \omega')t]}{(\omega + \omega')^2 2\tau^2} + \cos\beta\left[\frac{\sin^2[(\omega-\omega')t]}{(\omega-\omega')^2 2\tau^2} - \frac{\sin^2[(\omega+\omega')t]}{(\omega+\omega')^2 2\tau^2}\right]$$

$\omega = \frac{1}{2}|\mu B|$, $\omega' = \frac{1}{2}|\mu' B'|$, $\mu = \mu'$ and $\tau = \frac{1}{\varepsilon}$

- Scales as t^2/τ^2
- Resonance as **B→B'**

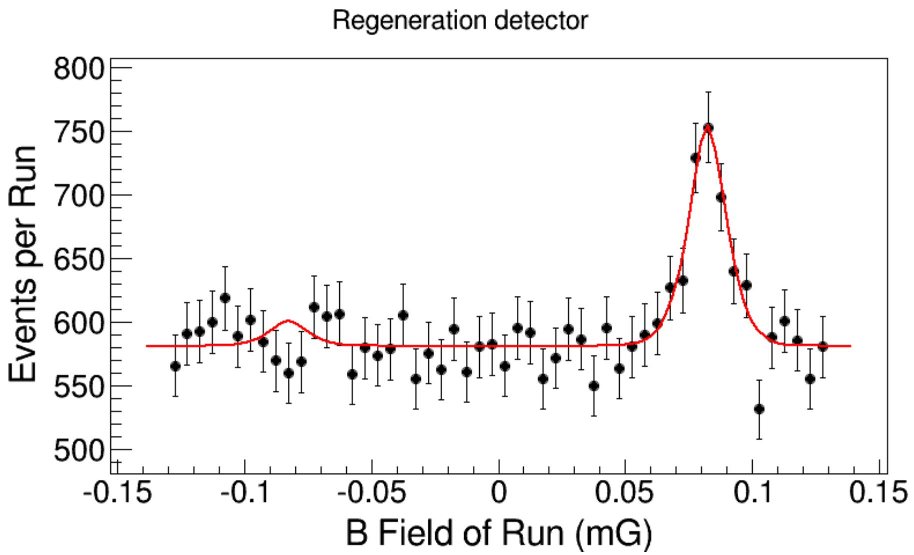
Berezhiani and Bento, PRL **96** (2006) 081801
Berezhiani and Nesti Eur Phys J **C72** (2012) 1974

Low B resonance at GP-SANS



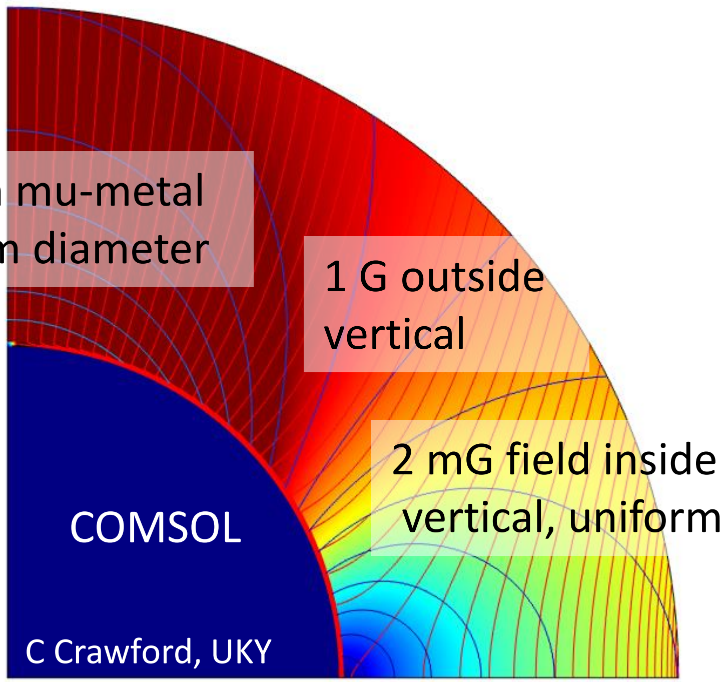
- CN complementary to UCN: Bump hunt
- Requires: high flux, B control/uniformity, low background detector
- Example: $\tau = 14$ s, B' = 0.08 G

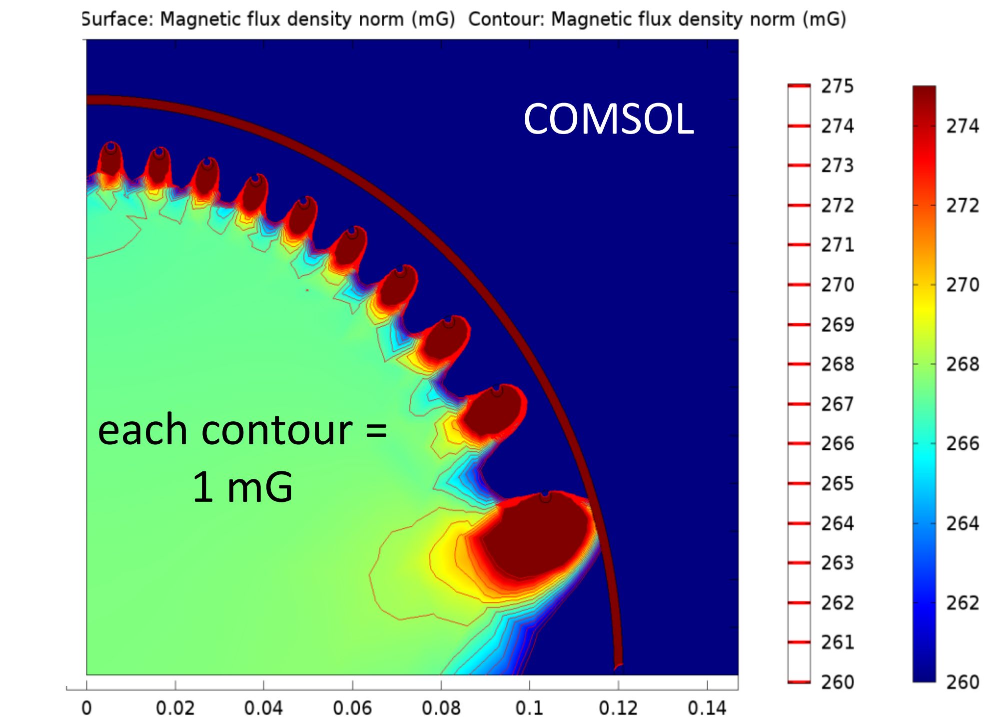
$$P(n \to n' \to n) \propto \left(\frac{t_{Dis}}{\tau}\right)^2 \left(\frac{t_{Reg}}{\tau}\right)^2$$



Magnetic field uniformity

- ~mG level uniformity requirement achievable using Solenoid/Cos-θ coils
- Build in 2 m sections: can neglect effect of joints[1]

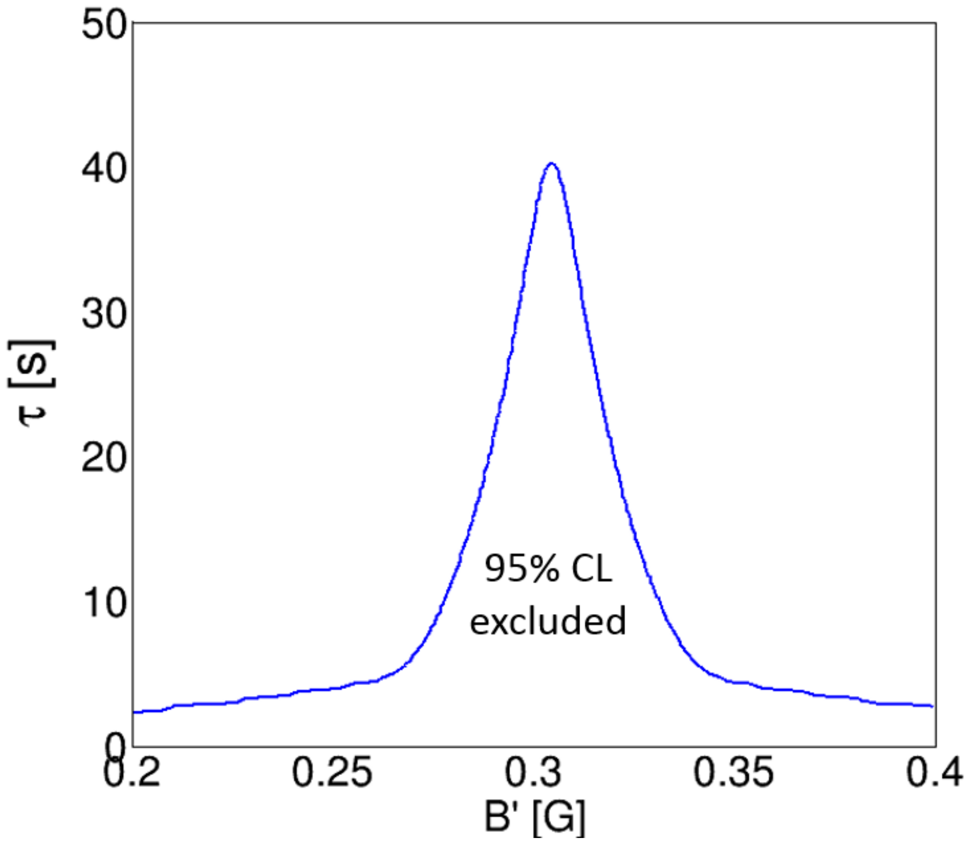




[1]Davis and Young, PRD **95** 036004 (2017)

Low B resonance at GP-SANS

- Sensitivity limited compared to PSI UCN search in bump search
  - Single point search can explore anomaly if observed
- Improve with planned future beamline optics upgrades/better detector shielding



Summary

- CN searches for $n \rightarrow n'$ can explore a diversity of ideas, complementary to UCN searches
- Staged program at GP-SANS minimizes risk to instrument while enabling science at each step
- $\delta m_{nn'}$ search to be performed in next HFIR cycle
- TMM search in several stages to follow, allows staging for ideas for ANNI
- Low B resonance search can be powerful cross-check of UCN anomalies
- Upcoming GP-SANS upgrades will enable more flexibility and higher sensitivity

The nn’ Collaboration

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