Neutron—Mirror-Neutron Oscillations

Exploring new avenues for Dark Matter searches

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on behalf of N-N' Collaboration

History of Mirror Matter Theory

- Left-Right symmetry can be restored in nature

  Lee&Yang (1956)

- Mirror fermions can not have common E-M, Weak and Strong Interactions but only common Gravity

  Kobzarev, Okun, Pomeranchuk (1966)

- MM as a viable candidate for DM if $T'/T \ll 1$

  Berezhiani, Comelli, Vilante (2001)

- Mirror Dark Matter: cosmology, galaxy structure and direct detection

  Foot (2014)

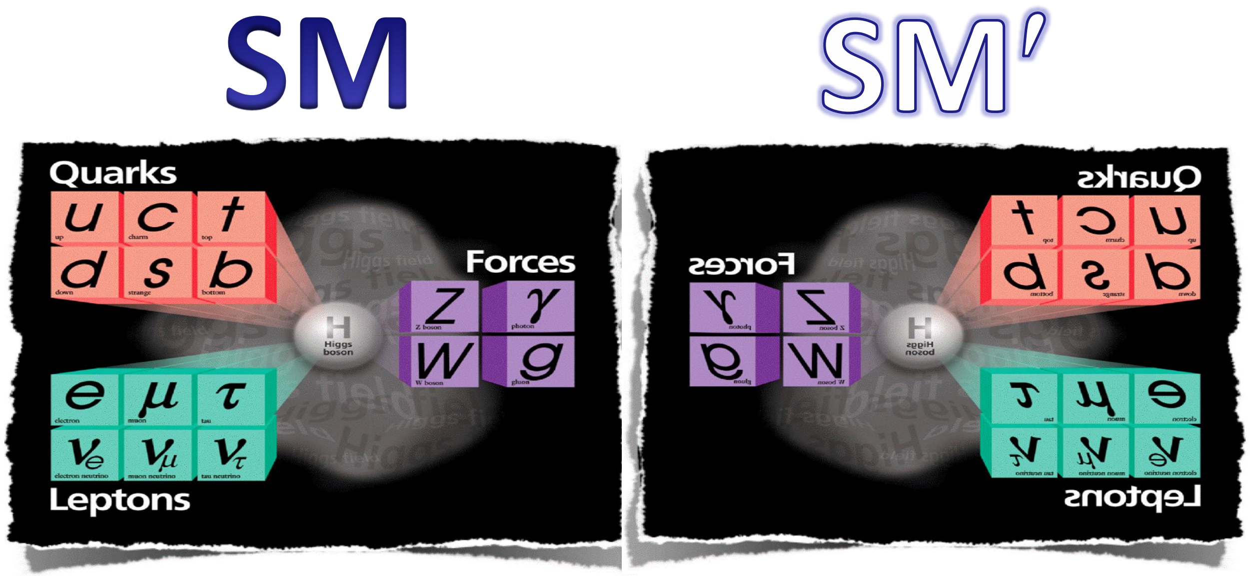
- Neutron Mirror-Neutron Oscillation

  Berezhiani (2006-2014)

Review: "Mirror particles and mirror matter: 50 years of speculations and search." by L.B. Okun, (Moscow, ITEP), 2006, http://arxiv.org/abs/hep-ph/0606202 (contains all references before 2006)

Features of Dark Matter within Mirror Matter Paradigm

- **Rich Dark Sector**
  - MM can explain part or whole of Dark Matter
  - MM is self-interacting, collision-less, long-lived
  - Spectrum of particles mass (like in Standard Model)
  - $\mathcal{L}=\mathcal{L}_{SM}+\mathcal{L}_{SM'}+\mathcal{L}_{mix}$ New physics in $\mathcal{L}_{mix}$
- **MM and OM cosmology not equivalent**
  - T'/T << 1: $\Omega_B > \Omega_{B'}$
  - MM abundance of He is higher than H
  - Mirror stars are older than ordinary stars
  - MM predicts small scale structure of DM



Portals to the mirror world

$\mathcal{L}_{\text{mix}}$

<u>All neutrals:</u>

(a) Neutrinos
(b) Neutrons
(c) Photons

+ Heavy neutral messenger particles

Neutron-Mirror Neutron Oscillation

Hamiltonian of free neutron in the presence of a magnetic field

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

Berezhiani, Bento
Phys.Rev.Lett. 96 (2006) 081801

Probability to oscillate from neutron to mirror neutron.

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

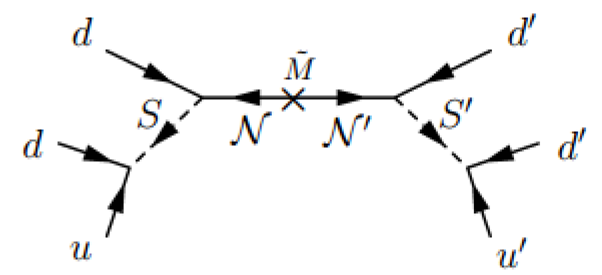


Diagram inducing neutron - mirror neutron mixing.

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

t is determined by neutron velocity and free path length.

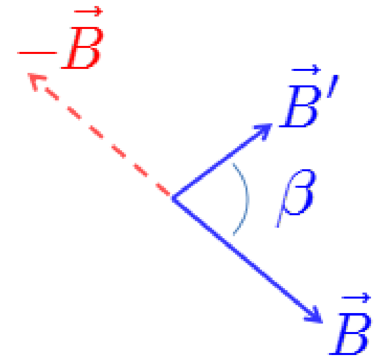
$\tau, \beta, and\ \omega'$ are unknown

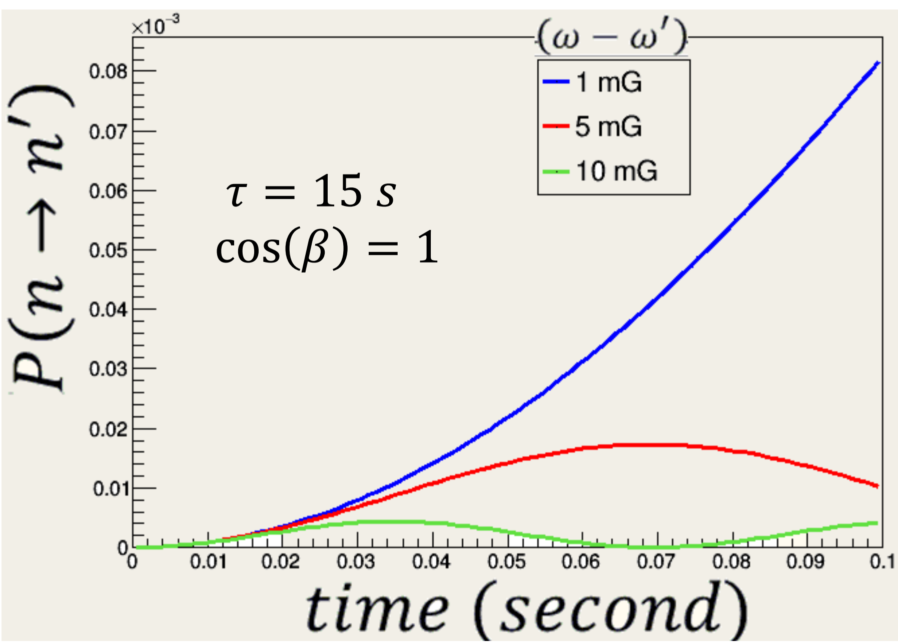
Resonance occurs when $\omega = \omega'$ and is maximized when $\cos\beta = 1$

$$P(n \to n') = \frac{\sin^2[(\omega - \omega')t]}{\tau^2[(\omega - \omega')]^2} \propto \frac{t^2}{\tau^2}$$

Probability of oscillation grows with t^2

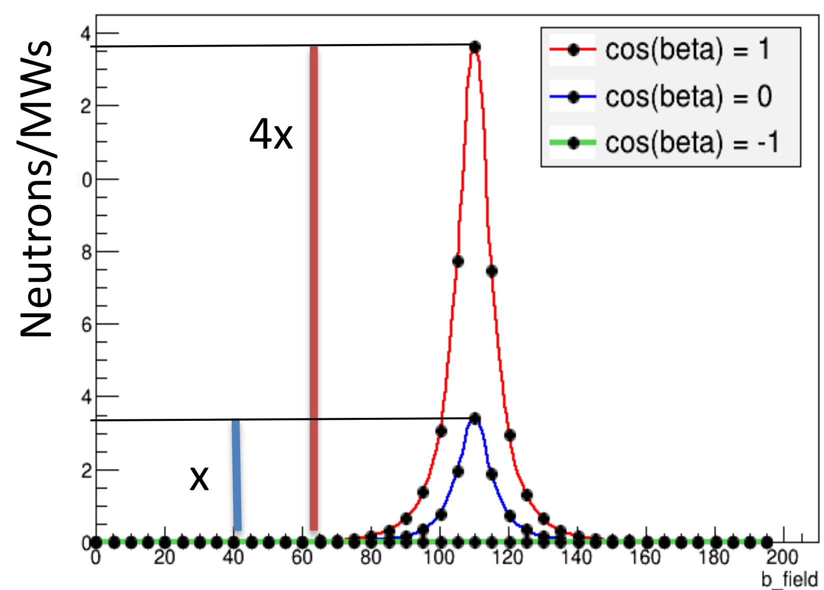
$$\Delta\omega = \sqrt{(\omega - \omega')^2 + \epsilon^2}$$





Effect of misalignment of B and B'

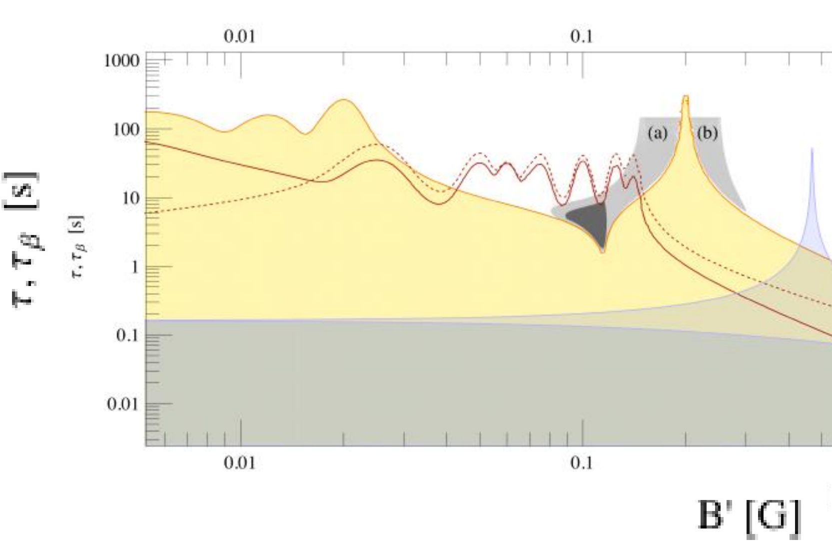
Example: $\tau = 3$, B' = 110 mG



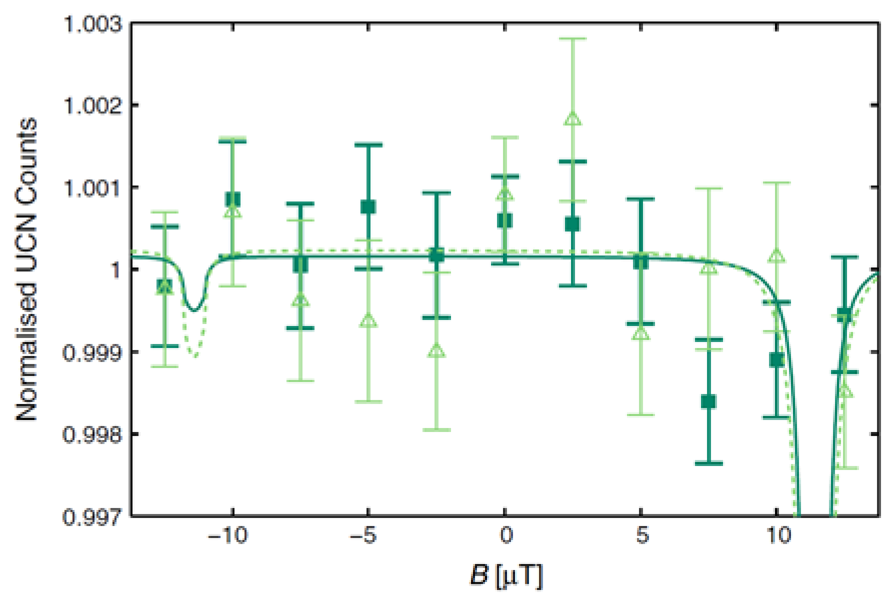
Controversial Results of two UCN experiments (see PDG)

1. Experiment: Serebrov et al., Analysis: Berezhiani et al. **5.2σ** effect consistent with $\tau \cdot cos\beta \in (2 - 10)\ s$; and $B' \in (90 - 120)$ mG

2. Experiment and Analysis: Altarev et al. **no effect** at 95% CL. $\rightarrow$ τ >12 s for $B' \in (0 - 125)$ mG



Measured ⥮ asymmetry → ~ (7±1.4)×10^{-4} (~5σ)



Best Fit Parameters :

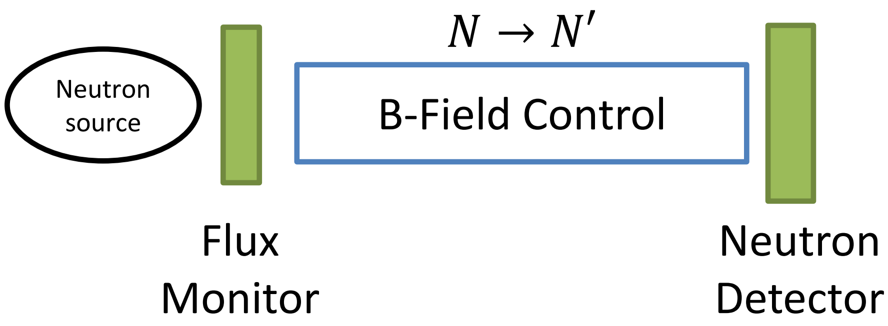
$\tau = 21.9\ s,\ \beta = 25.3°, B' = 11.4\ \mu T$

$Best\ Fit\ \frac{\chi^2}{dof} = \frac{17.86}{17};\ \ Linear\ Fit: \frac{\chi^2}{dof} = 22.72/21$

Resolve controversy using an inexpensive neutron beam experiment

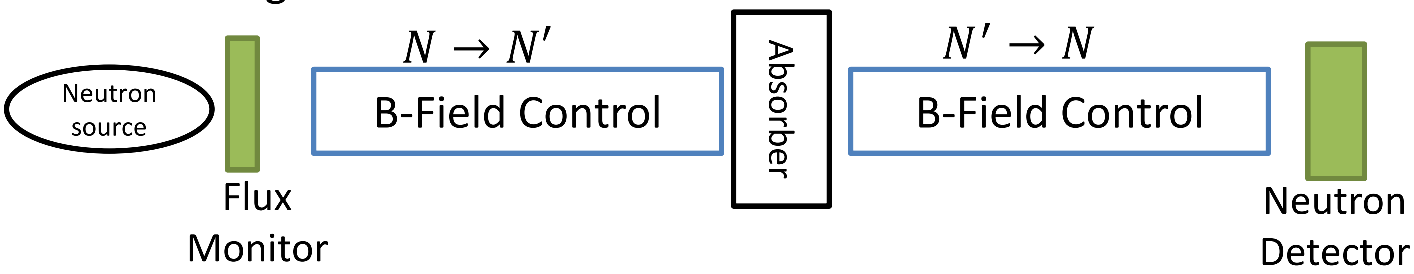
Disappearance Mode

Oscillation signal is a disappearance of neutrons at detector as function of B-Field



Regeneration Mode

Oscillation signal is an increase in neutrons at detector as function of B-Field



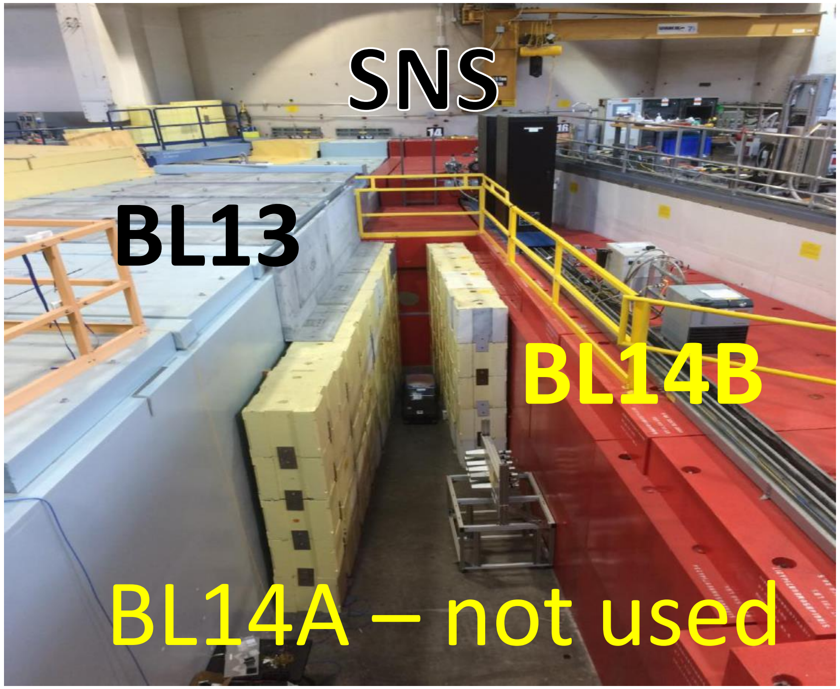
Regeneration and Disappearance Modes can be run concurrently and can be run parasitically with other cold neutron experiments

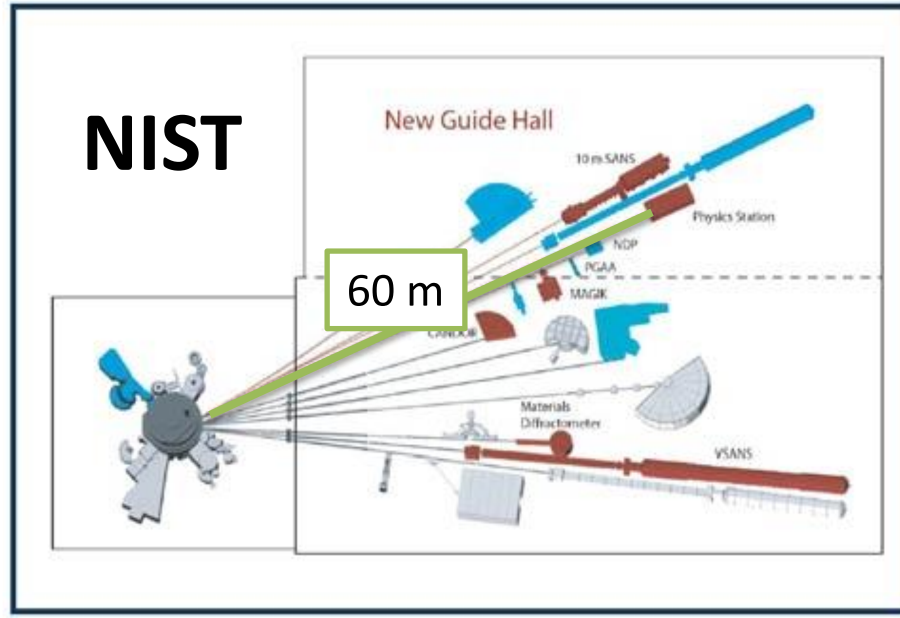
Requirements for Mirror-Neutron Oscillation Experiment

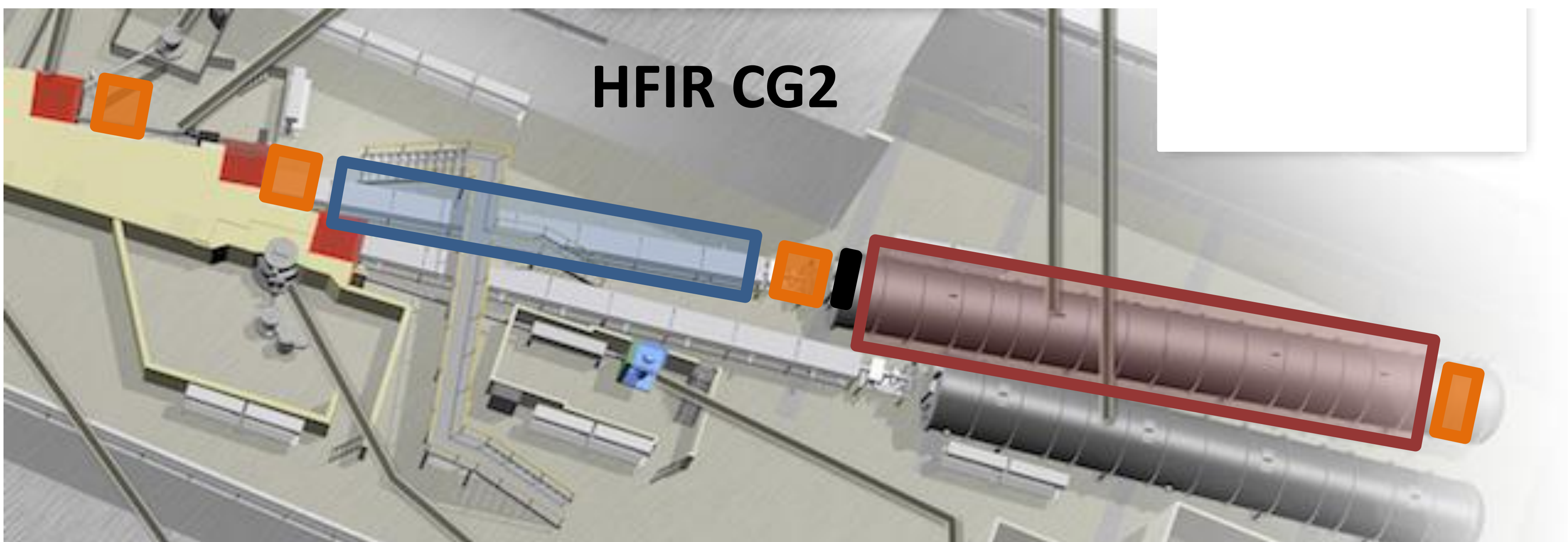
- **Neutron Source** with free flight path > 20 m
  - only a few available in US
- **Magnetic Field control** - Helmholtz coils or cos(theta) coil
- Neutron Absorber
- Neutron Detectors:
  - flux monitor,
  - 3He current mode detector for disappearance
  - 3He counting mode for regeneration

"Neutron Disappearance and Regeneration from Mirror State" arXiv:1703.06735

Source	Mirror Neutrons per second $\tau = 3;\ \Delta b = 1\ mG; \cos(\beta) = 1$	Neutrons Regenerated (cps) $\tau = 3;\ \Delta b = 1\ mG; \cos(\beta) = 1$
SNS: 14a	4.8×10^5	20
HFIR:CG2	1.4×10^6	140
NIST	3.6×10^7	35

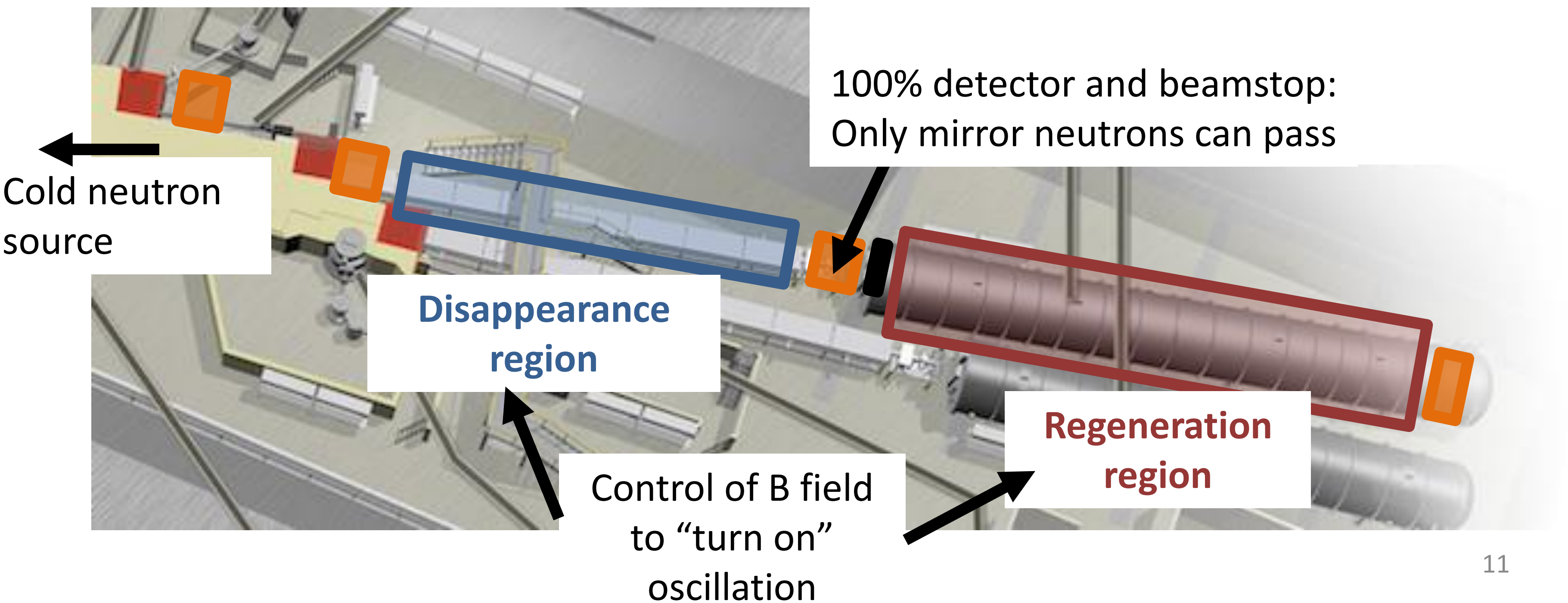

SNS
BL13
BL14B
BL14A – not used


NIST
New Guide Hall
10 m SANS
Physics Station
NDP
PGAA
MAGIK
60 m
Materials Diffractometer
VSANS


HFIR CG2

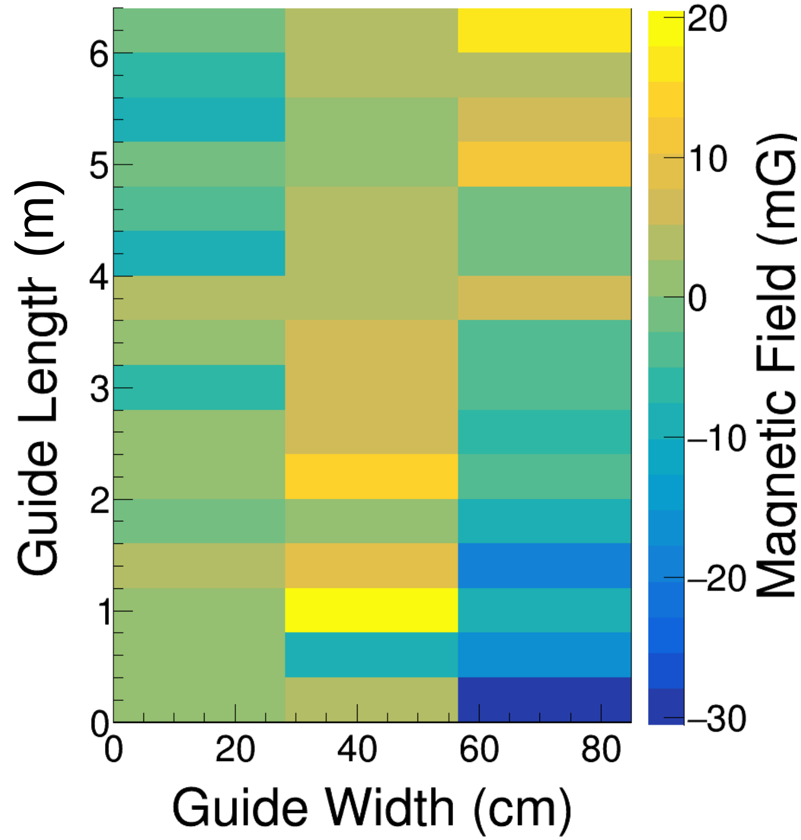
Search for Mirror Neutrons at HFIR

- Existing instrument GP-SANS well suited:
  - Long & large area guides, shielded large area detector, spacious
  - Improvements required are modest
  - Minimal impact on SANS research program



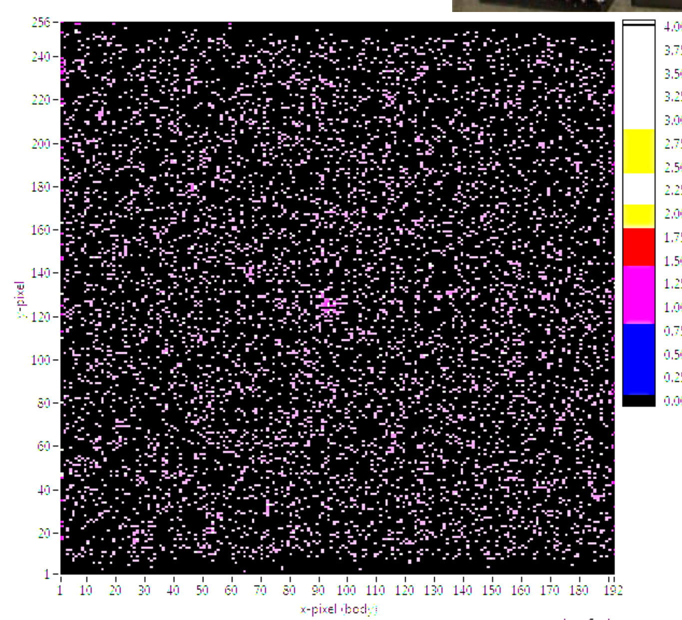
HFIR B field control

- Preliminary scan ~ 20 mG nonuniformity + some hot spots
- Desired uniformity ~ few mG very reasonable with B control coils + shielding
- Guide upgrade in 2018: include considerations for B field uniformity/control
- Developing prototype mapping/control systems



HFIR Background

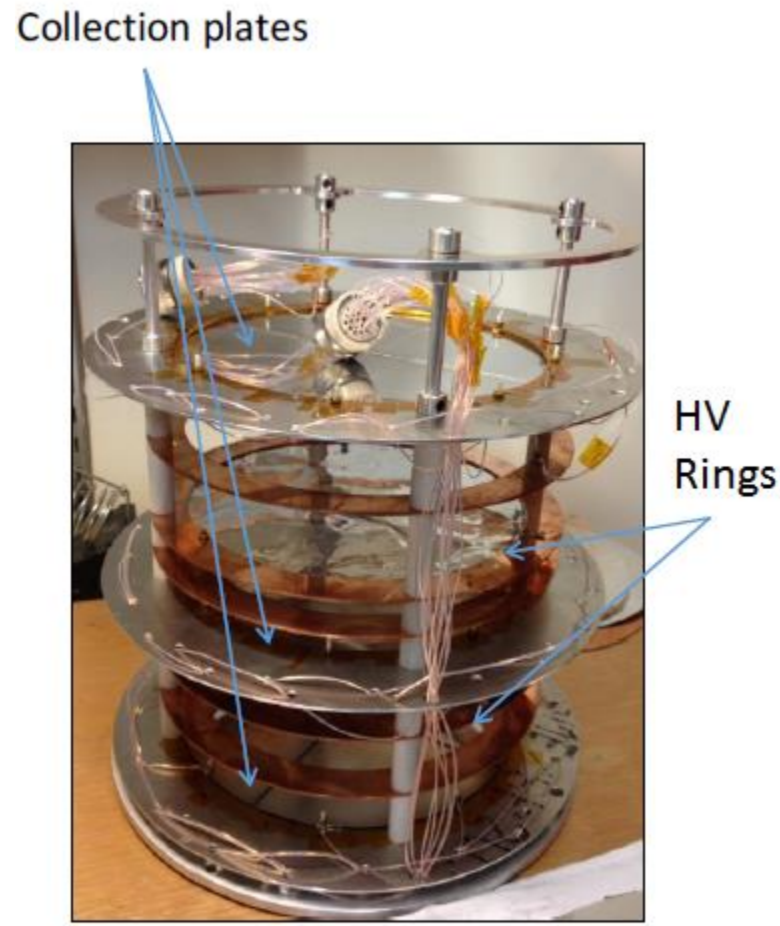
- Regeneration sensitivity depends on Signal : Background
  - Goal ≤ 0.05 cps
- 1mx1m ^{3}He position sensitive detector[1]
  - ~5 mm position resolution
- Measured background with minimal shielding: ~2 cps
  - Goal: 0.05 cps with further shielding, position cuts
  - Measurements with add'l shielding after detector upgrade later this spring



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

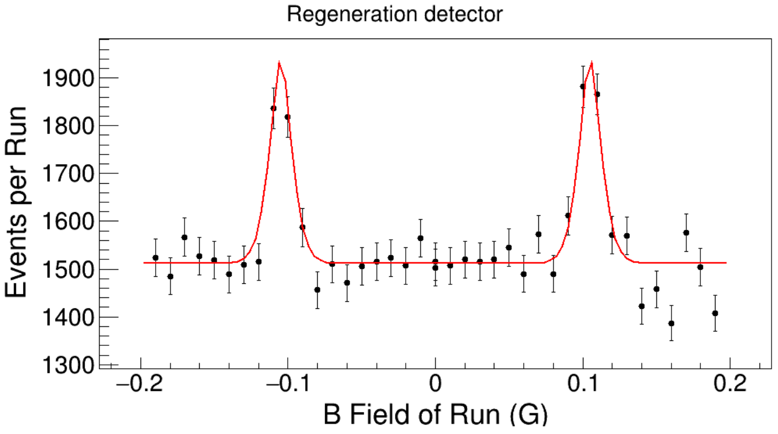
Disappearance Detector

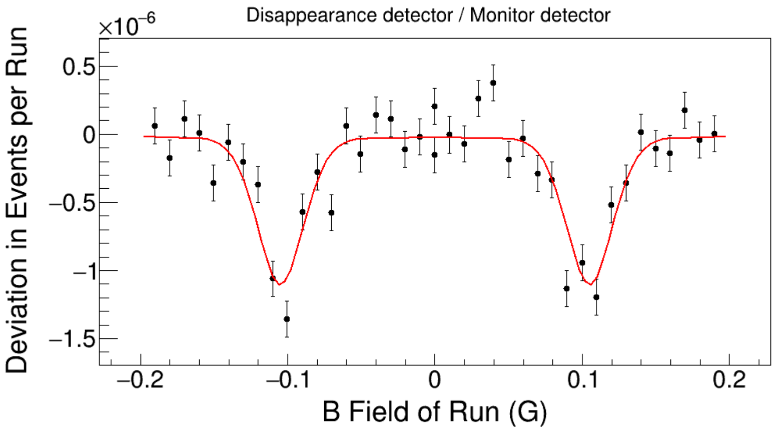
- Require 10^{-6} level or better monitoring for neutron flux
- Use detector provided by n-^{3}He experiment
  - $n+^3He \rightarrow t+p$
- Flux monitoring should be statistics limited



Expected sensitivity @ HFIR

- Neutron flux ~ 10^9 n/s[1]
- Phase 1: Disappearance
  - 2 years R&D/implementation
  - Limit of $\tau > 15$ s ($2\ \sigma$) in 2 weeks (with statistics-limited monitor)
- Phase 2: Regeneration
  - 1 year R&D/implementation (req. coordination with BES)
  - Limit of $\tau > 15$ s ($2\ \sigma$) in 2 weeks (with 0.05 cps bkgd)
- Project funds < $0.5M





Simulated positive signal at $\tau = 10$ s, 14 days beam time, 10 mG step size (0.05 Hz bkgd, stats-limited n detectors)

[1]L. Crow et al, *NIMA* **634** (2011) S71

Conclusion

- Mirror Matter is a viable candidate for Dark Matter with testable predictions in n-n' oscillations.
- New search using GP-SANS: small, low cost, short beamtime, large potential impact
  - Controversy in UCN storage experiments will be resolved
  - Pursuing ORNL partial support through LDRD program
- Stepping stone to future parasitic experiment at SNS Second Target Station or ESS

Dark Sectors 2016 Workshop: Community Report

B. Exploring Rich Dark Sectors

new milli-charged particles [245]. Opportunities to implement relatively low cost, parasitic experiments at existing facilities should be explored further.

Collaboration

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