n-n′ Oscillations
Signals and Constraints

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THE SCIENTIFIC RESEARCH SOCIETY

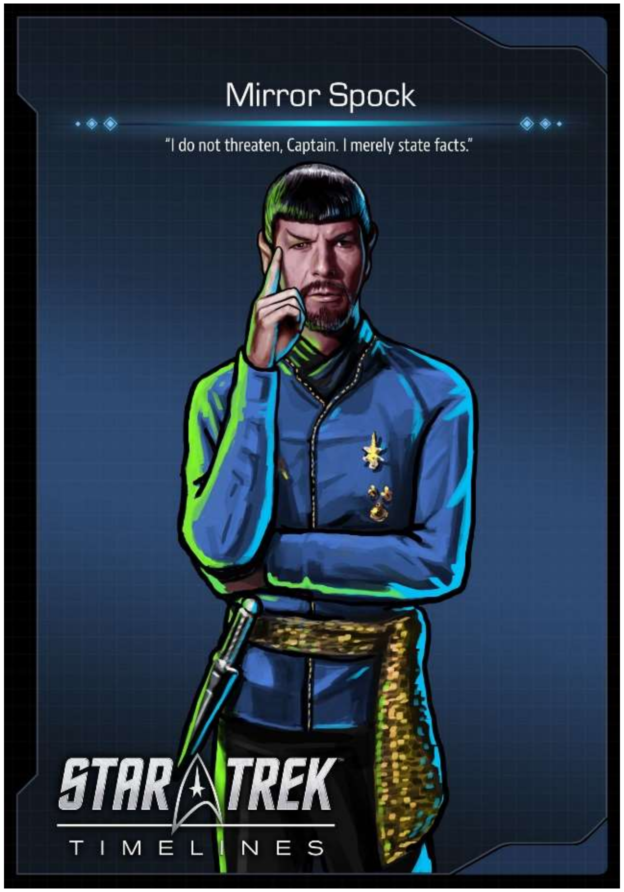
Overview

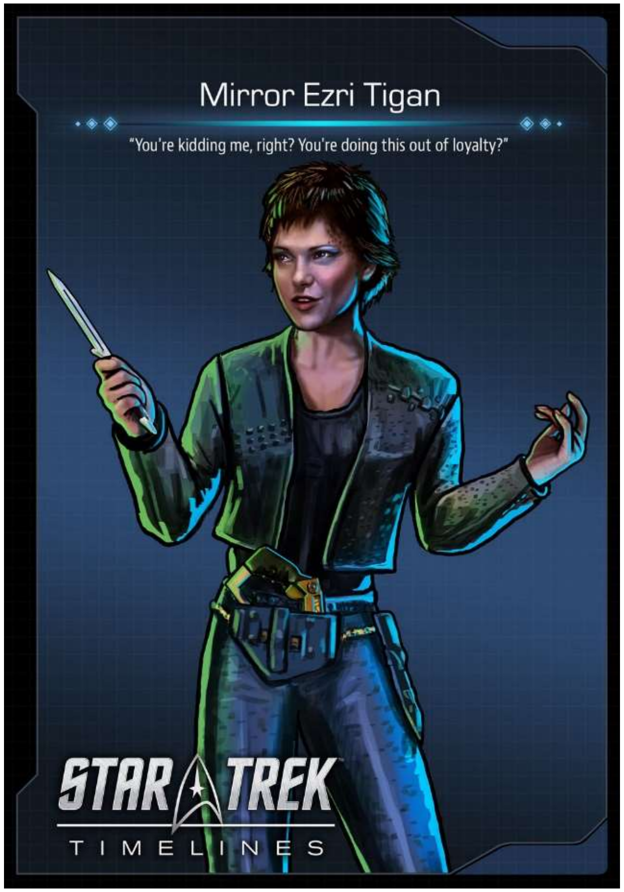
Motivation | Measurements | Summary

1. Motivation
2. Apparatus
3. Measurements
4. Data Analysis
5. Summary

Art from: *New Scientist* **242**, 34 (2019)

§1 **Mirror Realm in Sci-Fi**





Art from: ST Fandom, Capt. Jello

§1 Mirror Realm

<u>Parity Violation (PV) in β–decay:</u>

Lee & Yang's

PRL 104, 254 (1956)

<u>Introduce Mirror realm hidden from standard model particles</u> → No global PV in weak interactions

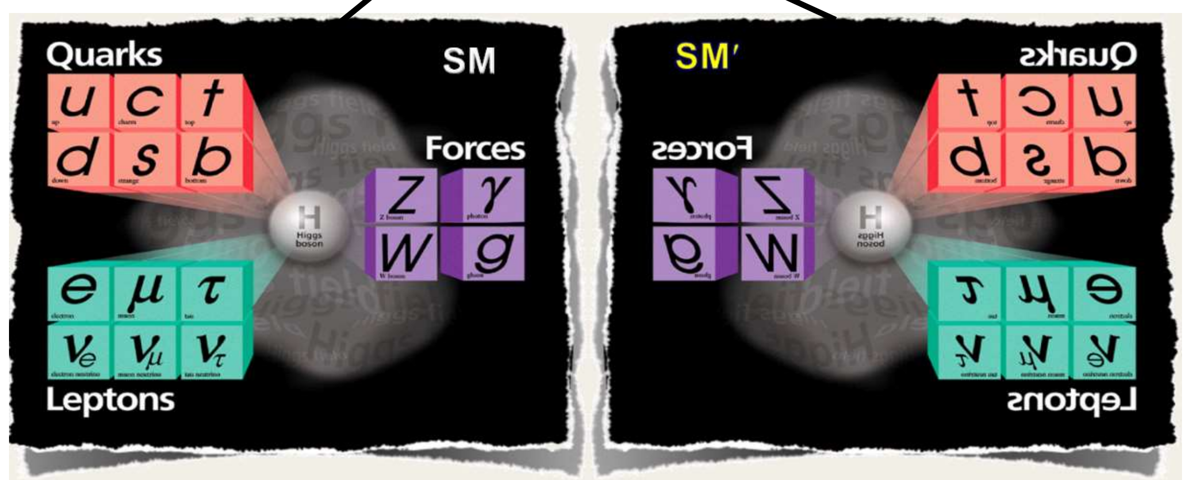
SM , SM'

Standard Model Particles

,

Mirror Realm Particles

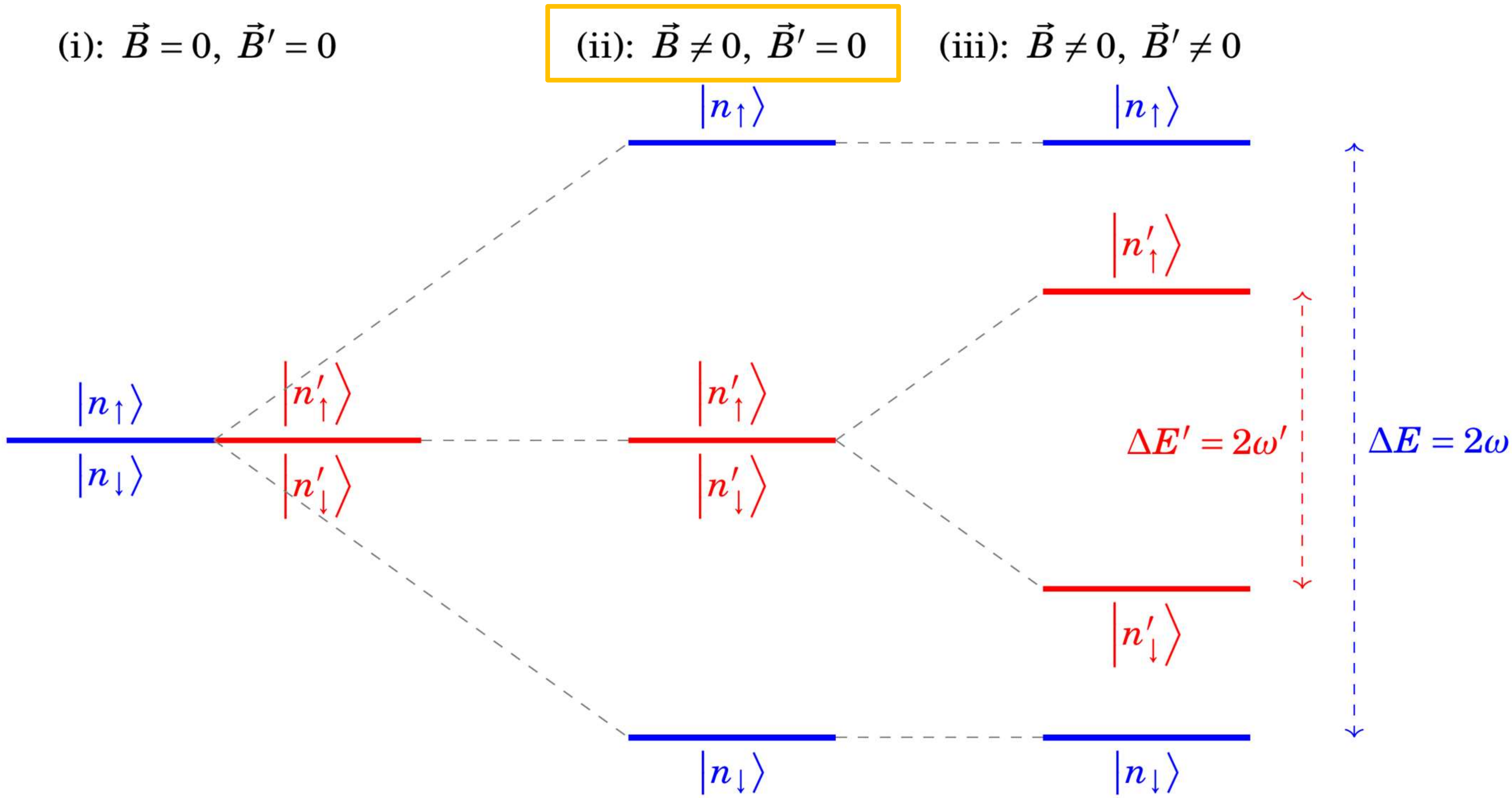
$$\mathcal{L}_{total} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{Mixing}$$



$\mathcal{L}_{Mixing}$, Neutral particle mixing (SM ↔ SM'): <u>n ↔ n'</u>, γ ↔ γ', ν ↔ ν'

For Mirror Matter Review: L. B. Okun, Phys. Usp. **50** 380-389 (2006)

§1 Theory of nn′ Oscillations



Typical 2−level system for (ii): $\boldsymbol{P_{n\to n'}(t)} = \dfrac{\mathbf{1}}{\boldsymbol{\omega^2\tau_{nn'}^2} + \mathbf{1}}\boldsymbol{sin^2}\left[\boldsymbol{t}\sqrt{\boldsymbol{\omega^2} + \mathbf{1}/\boldsymbol{\tau_{nn'}^2}}\right]$, $\boldsymbol{\omega^{(\prime)}}$=45 Hz/$\mu$T · $\boldsymbol{B^{(\prime)}}$

Z. Berezhiani, *Euro. Phys. J. C* **64**, 421 (2009).

§1 Searches assuming B' = 0

When, $B' = 0$: Most older experiments…

Ratio

$$E_B(t_s) = \frac{n_0(t_s)}{n_B(t_s)} - 1$$
$$= m_s \Delta_0$$
$$= \frac{t_s}{\langle t_f \rangle} \frac{\langle t_f^2 \rangle}{\tau_{nn'}^2}$$

$$m_s = t_s / \langle t_f \rangle$$
$$\eta = B/B'$$

$\vec{B}$: magnetic field seen by SM particles, $\vec{B'}$: … (SM') particles,
β: angle between $\vec{B}$ & $\vec{B'}$, η: ratio between $\vec{B}$ & $\vec{B'}$
m_s: number of times neutrons bounced off the walls

Z. Bereziani, *Euro. Phys. J. C* **64**: 421-431 (2009)

§1 Searches assuming B′ ≠ 0

Relax the condition, $B' \neq 0$: There are 2 channels of analysis

Ratio	Asymmetry
$E_B(t_s) = \frac{n_0(t_s)}{n_B(t_s)} - 1 = m_s \Delta_B = \frac{t_s}{\langle t_f \rangle} \frac{\eta^2(3-\eta^2)}{2\omega'^2 \tau_{nn'}^2 (1-\eta^2)^2}$	$A_B(t_s) = \frac{n_B(t_s) - n_{-B}(t_s)}{n_B(t_s) + n_{-B}(t_s)} = -m_s D_B Cos(\beta) = -\frac{t_s}{\langle t_f \rangle} \frac{\eta^3 Cos\beta}{\omega^2 \tau_{nn'}^2 (1-\eta^2)^2}$

$$m_s = t_s / \langle t_f \rangle$$

$$\eta = B/B'$$

$\vec{B}$: magnetic field seen by SM particles, $\overrightarrow{B'}$: … (SM') particles,
β: angle between $\vec{B}$ & $\overrightarrow{B'}$, η: ratio between $\vec{B}$ & $\overrightarrow{B'}$
m_s: number of times neutrons bounced off the walls

Z. Bereziani, *Euro. Phys. J. C* **64**: 421-431 (2009)

§1 General Techniques

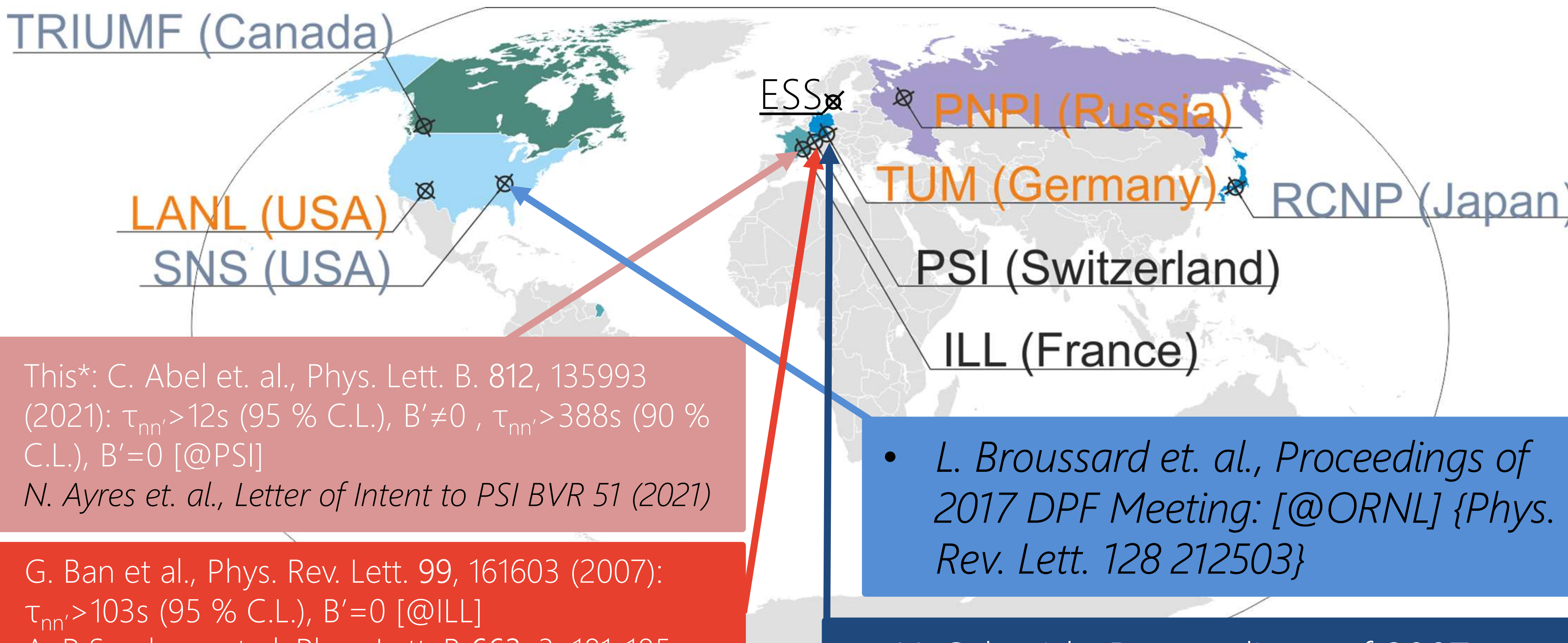
UCN Storage Experiment:

Store UCNs, apply 0 and >0 magnetic fields, check if some neutrons vanished (into mirror realm)?

Regeneration Experiment (“Particle Through a Wall” kind of experiment):

Shoot cold neutrons through a magnetic field onto a wall, check if neutrons can be detected on the other side of the wall under magnetic field?

§1 Existing Efforts



- This*: C. Abel et. al., Phys. Lett. B. 812, 135993 (2021): $\tau_{nn'}$>12s (95 % C.L.), B′≠0 , $\tau_{nn'}$>388s (90 % C.L.), B′=0 [@PSI]
- *N. Ayres et. al., Letter of Intent to PSI BVR 51 (2021)*

- G. Ban et al., Phys. Rev. Lett. 99, 161603 (2007): $\tau_{nn'}$>103s (95 % C.L.), B′=0 [@ILL]
- A. P. Serebrov et al. Phys. Lett. B 663, 3, 181-185 (2008): $\tau_{nn'}$>448s (90 % C.L.), B′=0 [@ILL]
- I. Altarev et al., Phys. Rev. D 80, 032003 (2009): $\tau_{nn'}$>12s (95 % C.L.), B′≠0 [@ILL]

UCN Storage Experiments

- *L. Broussard et. al., Proceedings of 2017 DPF Meeting: [@ORNL] {Phys. Rev. Lett. 128 212503}*

- U. Schmidt, Proceedings of 2007 BLNV Workshop: $\tau_{nn'}$>2.7s (90 % C.L.), B′=0 [@FRM-II]

Regeneration Experiments

§1 Existing Efforts

Dominated by: Disappearance Experiments

Look for magnetic field dependence of number of neutrons stored for time: t_s

Ratio

$\mathbf{B' = 0}$

PDG

$$E_B\,(t_s) = \frac{n_0(t_s)}{n_B(t_s)} - 1$$

$$= \frac{t_s}{\langle t_f \rangle} \frac{\langle t_f^2 \rangle}{\tau_{nn'}^2}$$

VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>352	95	[1] ABEL	21	CNTR	UCN, scan of *B* field
>448	90	SEREBROV	09A	CNTR	Assumes $B' < 100$ nT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 17	95	[2] BEREZHIANI	18	CNTR	UCN, scan of *B* field
> 12	95	[3] ALTAREV	09A	CNTR	UCN, scan $0 \le B \le 12.5\ \mu$T
>414	90	SEREBROV	08	CNTR	UCN, *B* field on & off
>103	95	BAN	07	CNTR	UCN, *B* field on & off

Z. Berezhiani, *Euro. Phys. J. C* **64**, 421 (2009).

§1 !!!SIGNALS!!!

Further analysis by Berezhiani et al., of storage type experiments:

Δ_B: Ratio Channel ; $\boldsymbol{D_B}$: Asymmetry Channel

PNPI@ILL

Z. Berezhiani, F. Nesti, *Euro. Phys. J. C* **72**, 1974 (2012)

$$D_{B=20\mu}\ Cos(\beta) = -(16.0 \pm 3.2) \times 10^{-8}$$

"5σ"

Z. Berezhiani et al., *Euro. Phys. J. C* **78**, 717 (2018)

$$D_{B=12\mu}\ Cos(\beta) = (16.6 \pm 6.7) \times 10^{-8}$$

"2σ"

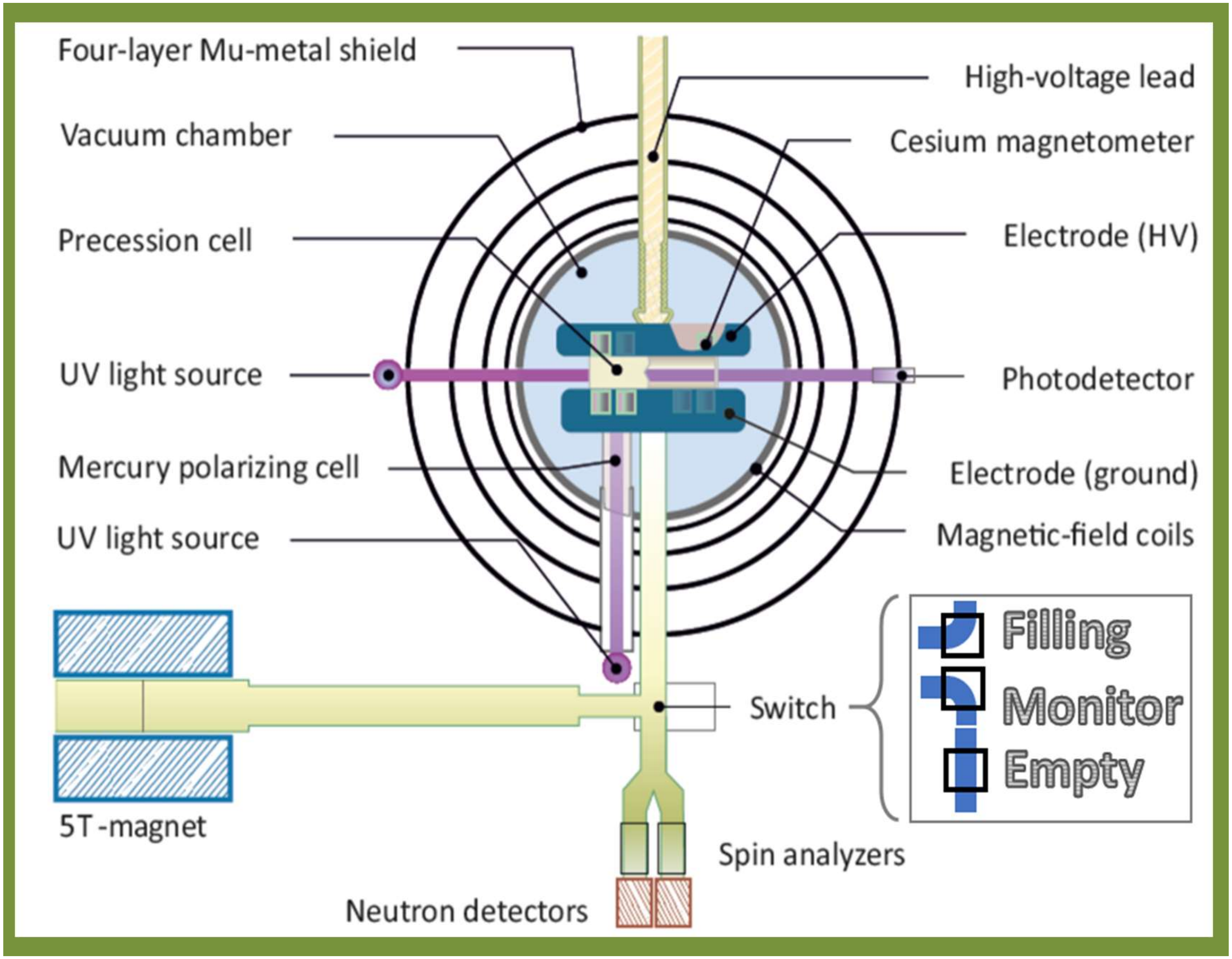
PSI et al.@ILL

Berezhiani et al.'s further analysis of data from
G. Ban et al., *Phys. Rev. Lett.* **99**, 161603 (2007)

$$D_{B=6\mu T} Cos(\beta) = (6.2 \pm 2.0) \times 10^{-7}$$

"3σ"

§2 nEDM@PSI Apparatus



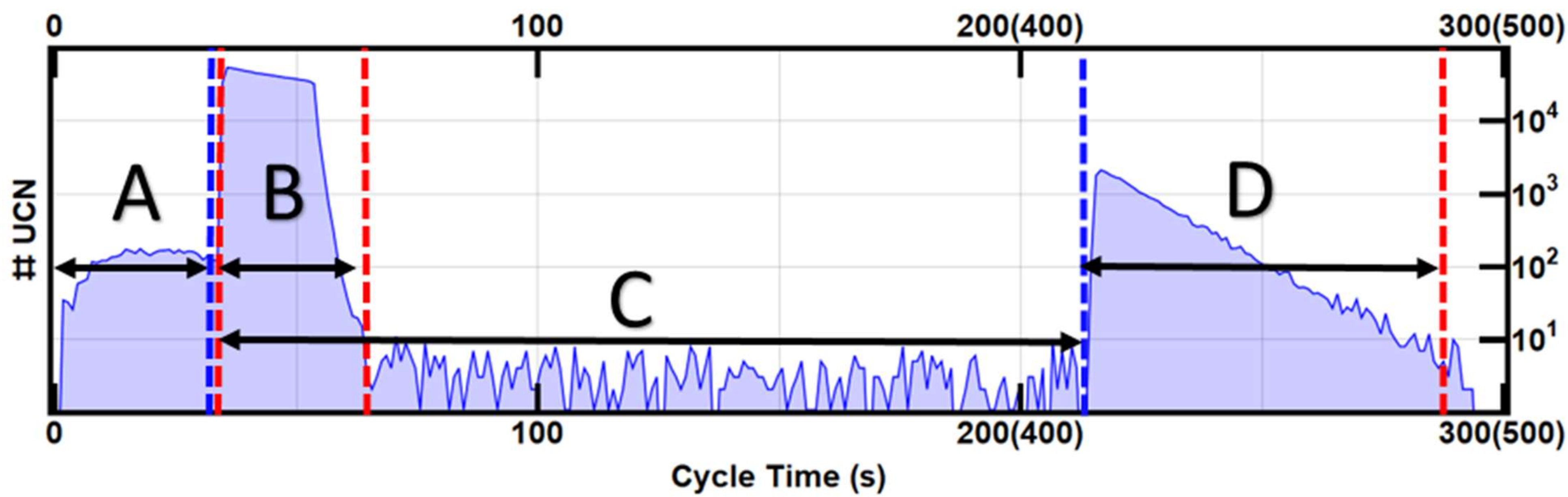
Courtesy: C. Abel et al., *PPNS 2018 (2019): arXiv [1811.04012].*

§3 Data Collection Scheme

Data collected in runs (table), each runs is made up of many cycles (bottom).

B - Pattern	t^*_s (t_t)/s	B_{max}/μT	# Cycles
0↑0↓0↓0↑0↓0↑0↑0↓0	180 (300)	10	1616
0↑0↓0↓0↑0↓0↑0↑0↓0	380 (500)	10	2908
0↑0↓0↓0↑0↓0↑0↑0↓0	180 (300)	20	1296
0↑0↓0↓0↑0↓0↑0↑0↓0	380 (500)	20	1992

Cycle Time:
A: filling phase
B: monitor phase
C: storage phase, and
D: emptying phase



§3 Mean Time of Flight

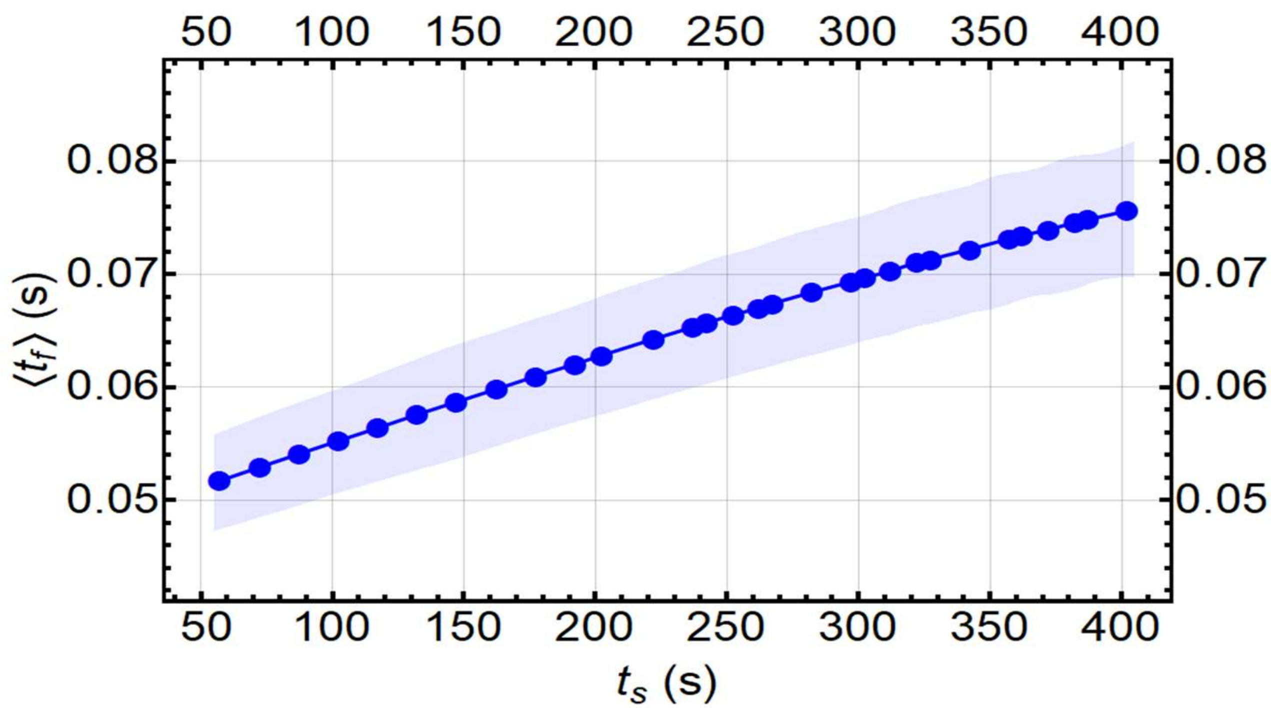
<t_f> is dependent on the energy spectra of the UCNs.

- Energy spectra from a fit of a loss model to the measured storage curve.

Simulate energy distribution and obtain <t_f> distributions → Obtain E_B or A_B UCN counting distributions → Combine data to generate constraints upon: $\tau_{nn'}$

$$E_B\,(t_s) = \frac{n_0(t_s)}{n_B(t_s)} - 1$$
$$= \frac{t_s}{\langle t_f \rangle} \frac{\eta^2(3-\eta^2)}{2\omega'^2\tau_{nn'}^2(1-\eta^2)^2}$$

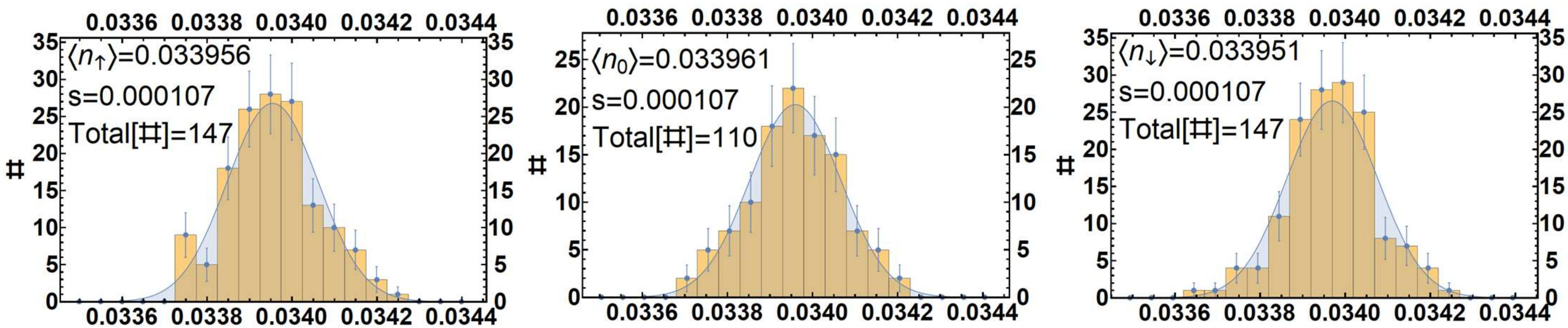
- Eg. the formula above uses averaged value of t_f: <t_f>
- The plot here shows <t_f> and the error bar is the smearing introduced by the uncertainty in energy spectra of UCNs.
- <t_f> changes with storage time.



§4 UCN Counting Statistics

Simulate energy distribution and obtain $\langle t_f \rangle$ distributions → Obtain E_B or A_B UCN counting distributions → Combine data to generate constraints upon: $\tau_{nn'}$

- **Each run has a characteristic {~ B_{max}/μT, t^*_s/s } setting.**
- **The normalized emptying counts are histogrammed for each run.**
- **Eg. here the run corresponds to {~ B_{max}, t^*_s} = {10 μT, 180 s}.**



$n_{\uparrow}\{B=10\ \mu T, t_s^*=180\ s\}$ $n_0\{B=0\ \mu T, t_s^*=180\ s\}$ $n_{\downarrow}\{B=10\ \mu T, t_s^*=180\ s\}$

$$\langle E_B \rangle = \frac{2\langle n_0 \rangle}{\langle n_\uparrow \rangle + \langle n_\downarrow \rangle} - 1$$

$$\langle A_B \rangle = \frac{\langle n_\uparrow \rangle - \langle n_\downarrow \rangle}{\langle n_\uparrow \rangle + \langle n_\downarrow \rangle}$$

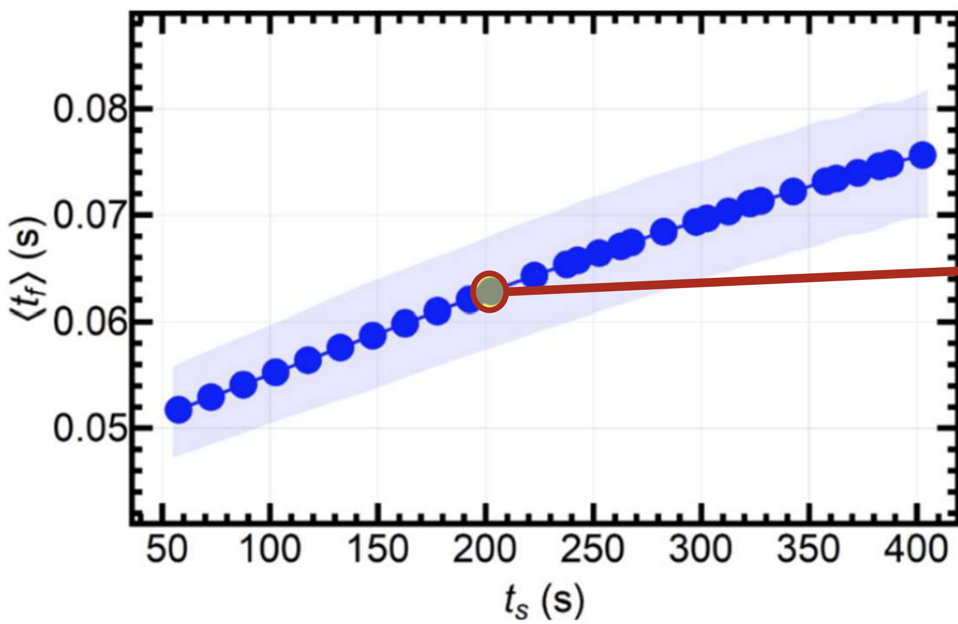
§4 Combine Counting Data with <t_f>

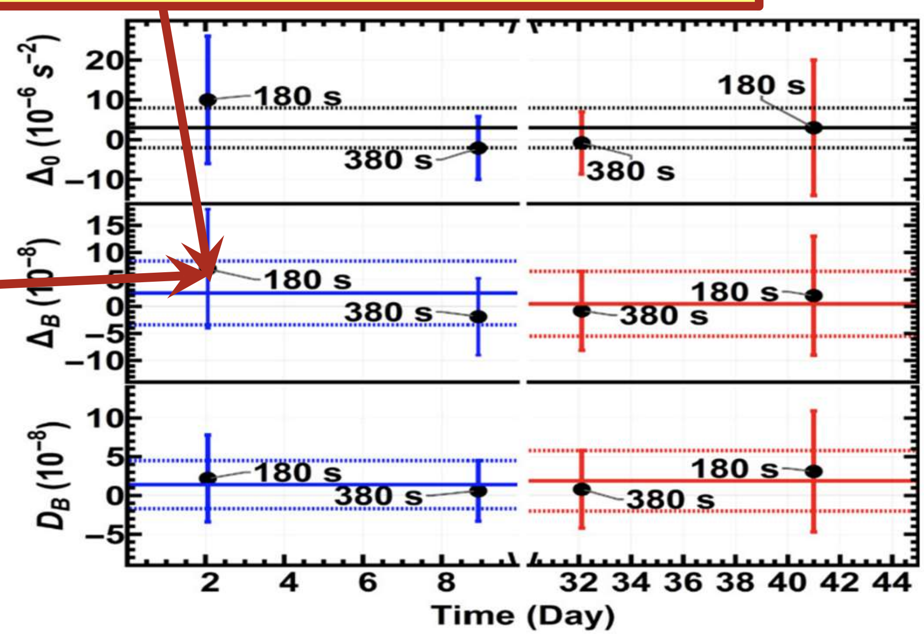
Simulate energy distribution and obtain <t_f> distributions

Obtain E_B or A_B UCN counting distributions

Combine data to generate constraints upon: $\tau_{nn'}$

$\{\sim B_{\max}/\mu\mathrm{T}, t_s^*/s\}$	$arg(B)$	$\langle n_B \rangle$	$\langle E_B \rangle (\times 10^{-4})$	$\langle A_B \rangle (\times 10^{-4})$
	↑	0.033956(88)		
$\{10, 180\}$	0	0.033961(102)	$(+2.2 \pm 3.4)$	$(+0.7 \pm 1.8)$
	↓	0.033951(88)		





C. Abel et al., *Phys. Lett. B.* **812**, 135993 (2021).

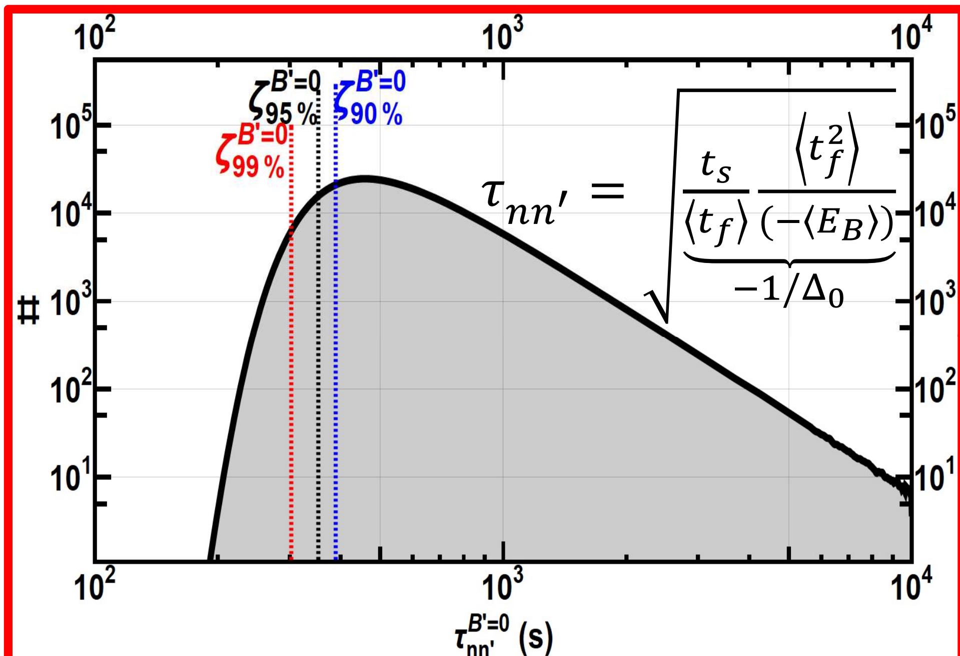
§4 nn′ Oscillation Assuming B′=0

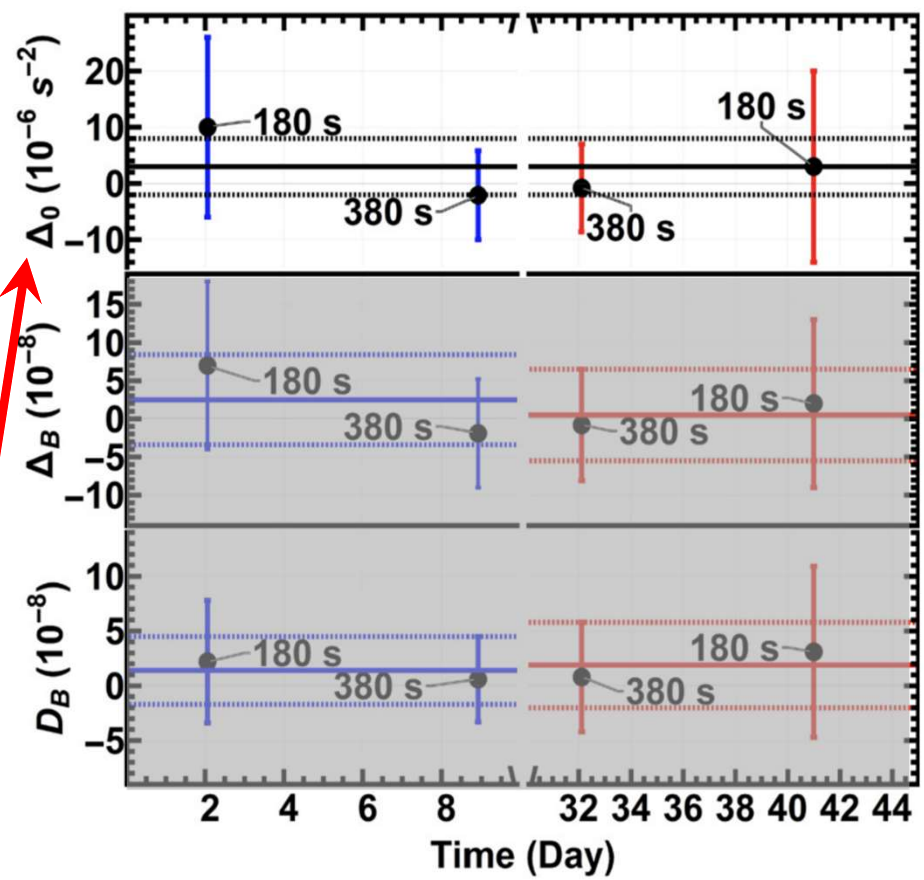
Simulate energy distribution and obtain $\langle t_f \rangle$ distributions

Obtain E_B or A_B UCN counting distributions

Combine data to <u>generate constraints</u> upon: $\tau_{nn'}$

$$\tau_{nn'}^{(B'=0)} > 352\ s\ (95\%\ \mathrm{C.L.})$$





C. Abel et al., *Phys. Lett. B.* **812**, 135993 (2021).

§4 nn′ Oscillation Assuming B′≠0

Simulate energy distribution and obtain $\langle t_f \rangle$ distributions

Obtain E_B or A_B UCN counting distributions

Combine data to generate constraints upon: $\tau_{nn'}$

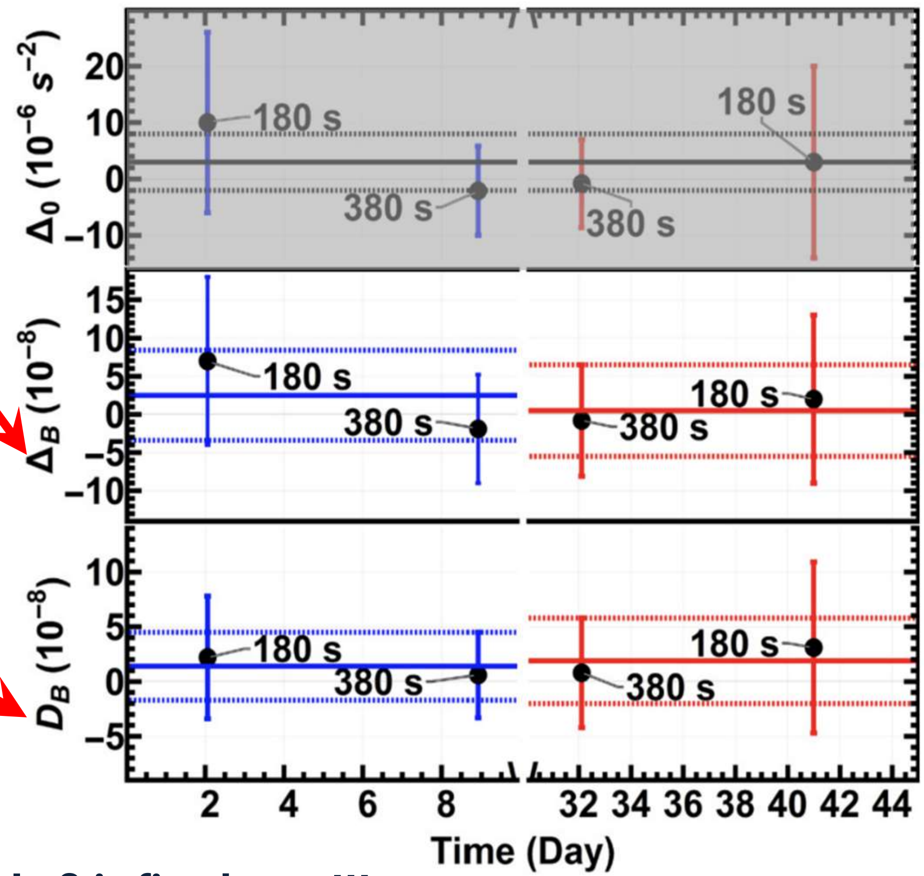
$$\tau_{nn'}^{B'\neq 0,E_B} = \sqrt{\underbrace{\frac{t_s}{\langle t_f\rangle}\frac{1}{\langle E_B\rangle}}_{1/\Delta_B}\underbrace{\frac{\eta^2(3-\eta^2)}{2\omega'^2(1-\eta^2)^2}}_{f_{E_B}(\eta)}}$$

Ratio

$$\eta = B/B'$$

$$\frac{\tau_{nn'}^{B'\neq 0,A_B}}{\sqrt{\cos\beta}} = \sqrt{\underbrace{\frac{t_s}{\langle t_f\rangle}\frac{1}{\langle A_B\rangle}}_{1/D_B}\underbrace{\frac{\eta^3}{\omega^2(1-\eta^2)^2}}_{f_{A_B}(\eta)}}$$

Asymmetry



!!!>>> Assuming the angle β is fixed <<<!!!

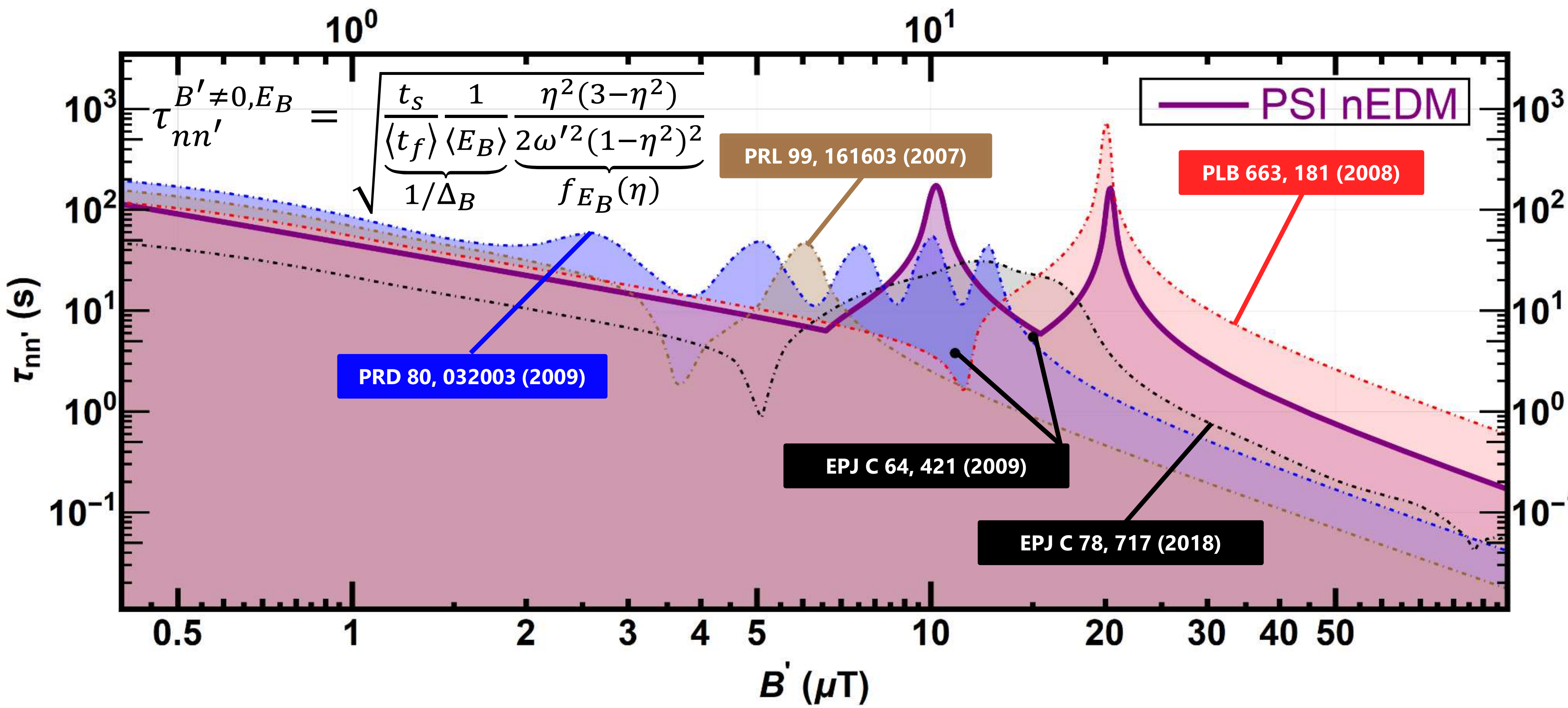
C. Abel et al., *Phys. Lett. B.* **812**, 135993 (2021).

§4 Constraints in Ratio Channel

Combining the scaling function, $f_{E_B}(\eta)$, with constraints on $\tau_{nn'}^{B'\neq 0,E_B} / \sqrt{|f_{E_B}(\eta)|}$ in appropriate range of B'

Dashed constraint for PSI nEDM neglects errors from uncertainty in energy spectra (like all the other constraints)

95% C.L. constraints



!!!>>> Assuming the angle β is fixed <<<!!!

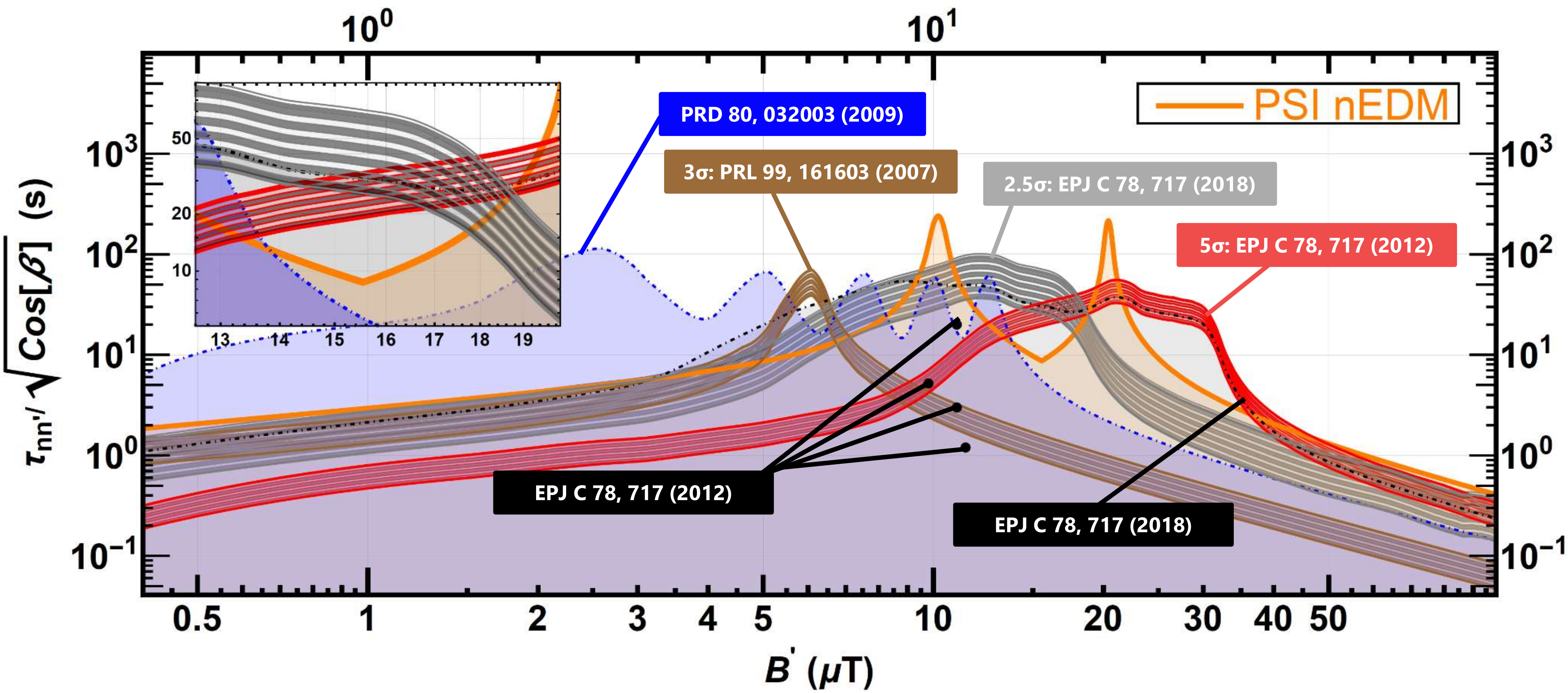
C. Abel et al., *Phys. Lett. B.* **812**, 135993 (2021).

§4 Constraints in Asymmetry Channel

The signals shown here from further analysis of the data indicated in the papers shown in the legend by Berezhiani et al. in 2018

$$\frac{\tau_{nn'}^{B'\neq 0, A_B}}{\sqrt{\cos\beta}} = \sqrt{\underbrace{\frac{t_s}{\langle t_f \rangle}\frac{1}{\langle A_B \rangle}}_{1/D_B}\underbrace{\frac{\eta^3}{\omega^2(1-\eta^2)^2}}_{f_{A_B}(\eta)}}$$

95% C.L./C.I.



!!!>>> Assuming the angle β is fixed <<<!!!

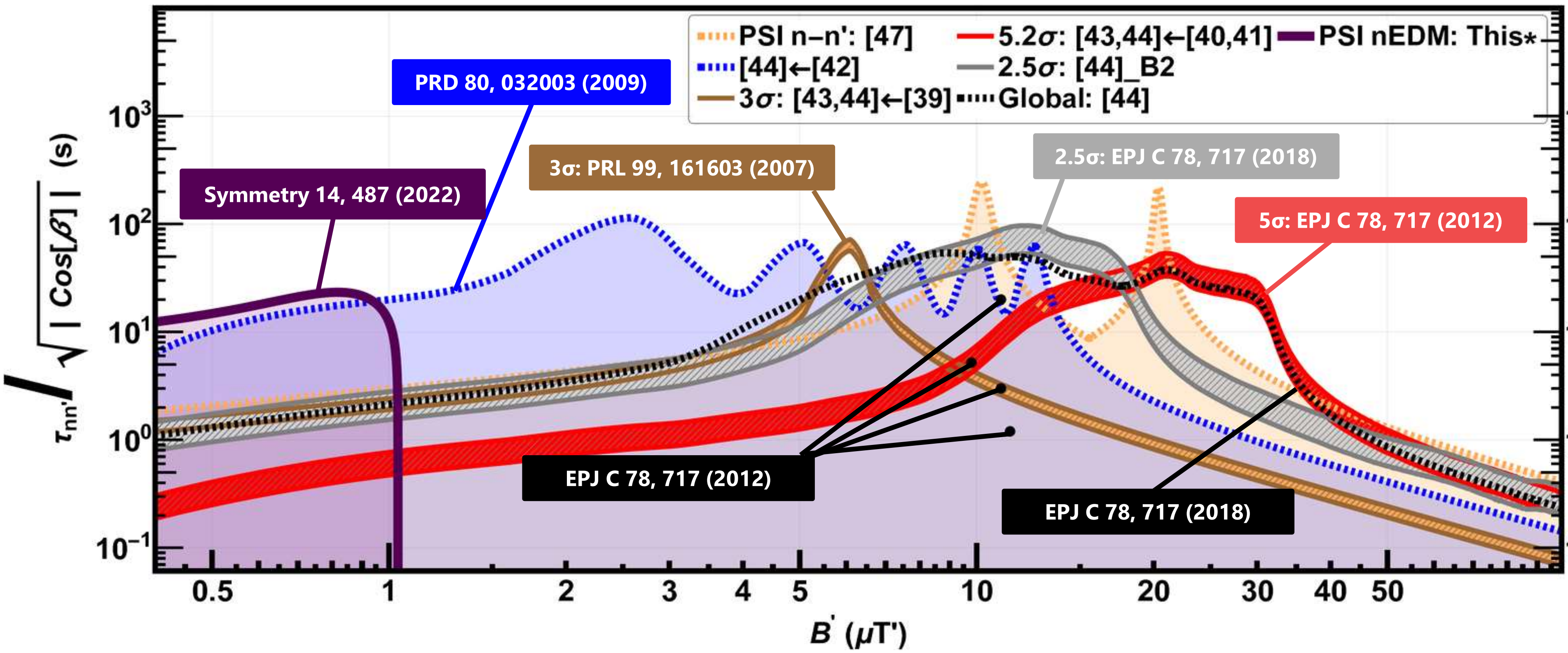
C. Abel et al., *Phys. Lett. B.* **812**, 135993 (2021).

§4 Constraints in Asymmetry Channel

New constraint uses precession frequency of neutrons in {B, -B}

$$\frac{\tau_{nn'}^{B'\neq 0,nEDM}}{\sqrt{\cos\beta}} = \sqrt{\frac{\delta\omega}{\omega}\cdot\underbrace{\frac{1}{\omega'^2\eta(\eta^2-1)}}_{f_d(\eta)}}$$

95% C.L./C.I.

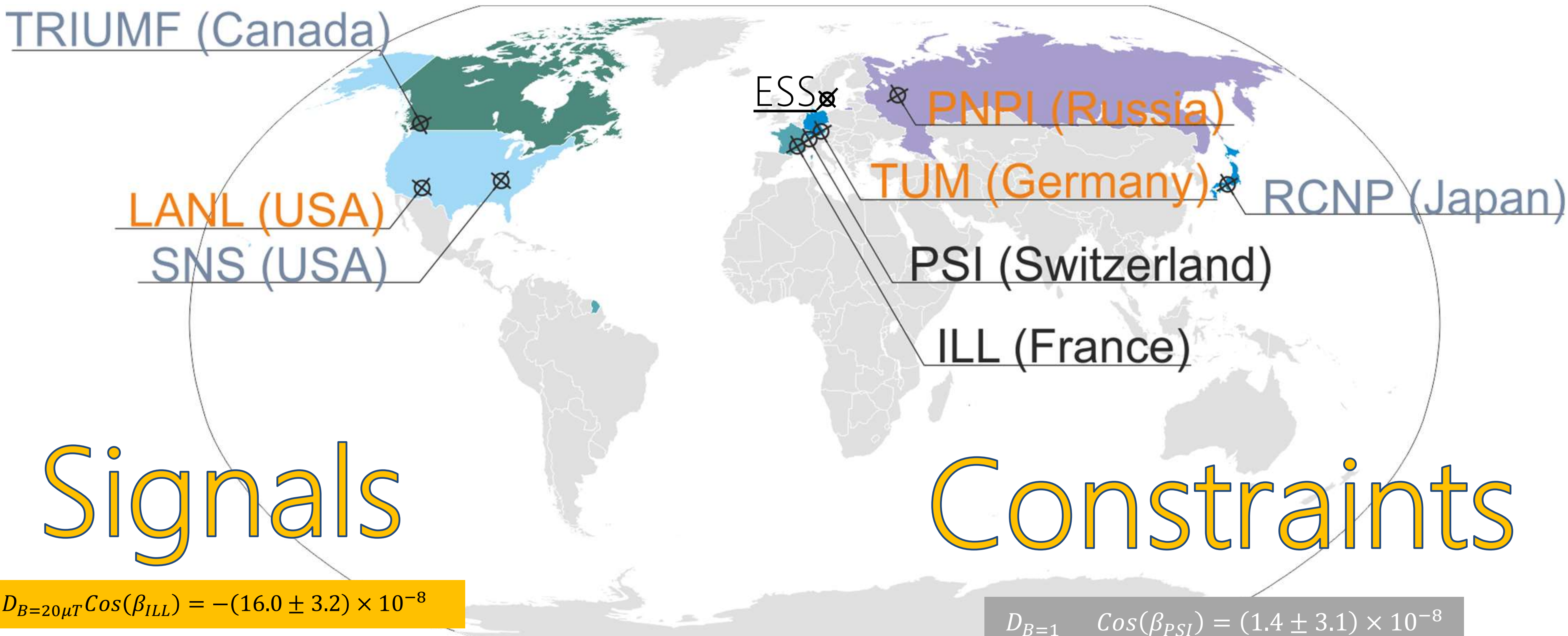


!!!>>> Assuming the angle β is fixed <<<!!!

P. Mohanmurthy et al., *Symmetry* **14**, 487 (2022)

§4 Constraints on fixed angle - β

There have been measurements at ILL and PSI. If β was a fixed value, then it would be different at PSI and at ILL. We can constrain β using measurements from the 2 locations, under the assumption that the angle - β is fixed to the reference frame of the Earth



Signals

$D_{B=20\mu T} Cos(\beta_{ILL}) = -(16.0 \pm 3.2) \times 10^{-8}$

$D_{B=6\mu T} Cos(\beta_{ILL}) = (6.2 \pm 2.0) \times 10^{-7}$

$D_{B=12\mu T} Cos(\beta_{ILL}) = (16.6 \pm 6.7) \times 10^{-8}$

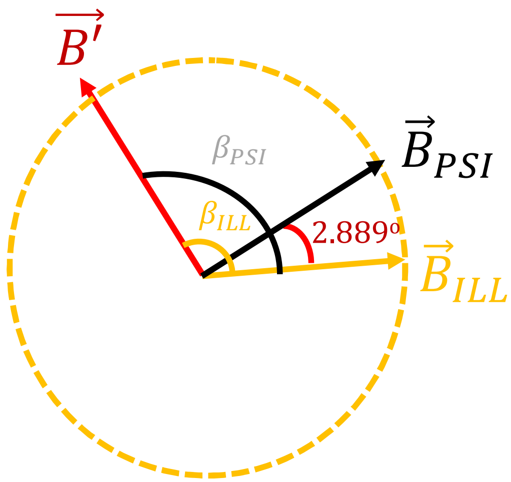
Constraints

$D_{B=1} \quad Cos(\beta_{PSI}) = (1.4 \pm 3.1) \times 10^{-8}$

$D_{B=20\mu T} Cos(\beta_{PSI}) = (1.9 \pm 3.9) \times 10^{-8}$

§4 Constraints on fixed angle - β

Allowed regions



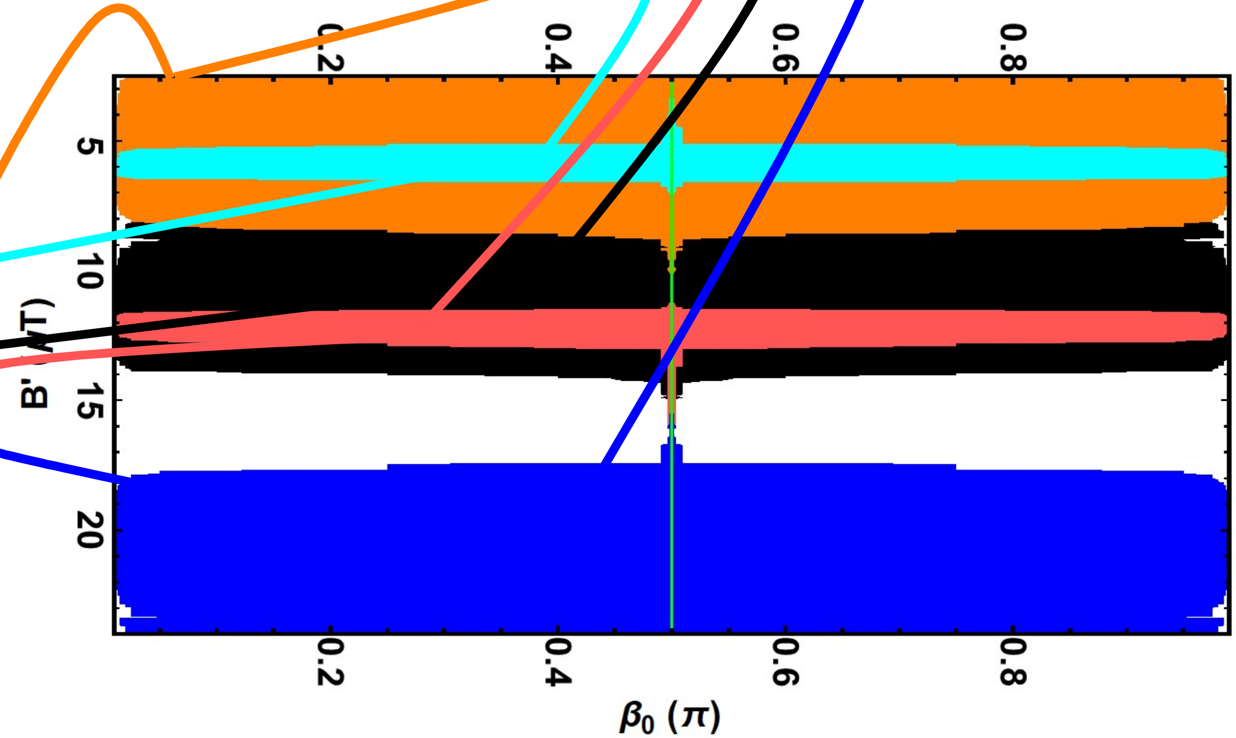
$D_{B=10\mu T} Cos(\beta_{PSI}) = (1.4 \pm 3.1) \times 10^{-8}$

$D_{B=20\mu T} Cos(\beta_{PSI}) = (1.9 \pm 3.9) \times 10^{-8}$

$D_{B=6\mu T} Cos(\beta_{ILL}) = (6.2 \pm 2.0) \times 10^{-7}$

$D_{B=12\mu T} Cos(\beta_{ILL}) = (16.6 \pm 6.7) \times 10^{-8}$

$D_{B=20\mu T} Cos(\beta_{ILL}) = -(16.0 \pm 3.2) \times 10^{-8}$



!!!>>> Assuming the angle β is fixed <<<!!!

Assuming all the vectors lie in the same plane

§5 Summary

[A] C. Abel et al., *Phys. Lett. B.* **812**, 135993 (2021).
[B] P. Mohanmurthy et al., *Symmetry* **14**, 487 (2022)

$$\tau_{nn'}^{E_{B'=0}} > 352\ s\ @\ 95\ \%\ C.L.$$

$$\tau_{nn'}^{E_B} > 6\ s\ \forall\ B' \in (0.38, 25.66)\ \mu T\ @\ 95\ \%\ C.L.$$

$$\tau_{nn'}^{A_B} > 9\ s\ \forall\ B' \in (5.04, 25.39)\ \mu T\ @\ 95\ \%\ C.L.$$
$$\tau_{nn'}^{A_B^{\Omega\oplus}} > 7\ s\ \forall\ B' \in (4.40, 24.43)\ \mu T\ @\ 95\ \%\ C.L.$$
$$\tau_{nn'}^{d_n} > 5.7\ s\ \forall\ B' \in (0.36, 1.01)\ \mu T\ @\ 95\ \%\ C.L.$$

Relevant Result Papers:
[1] G. Ban et al., Phys. Rev. Lett. 99 (2007) 161603.
[2] A. P. Serebrov et al., NIMA 611, 137–140 (2009); Phys. Lett. B 663, 181 (2008).
[3] I. Altarev et al., Phys. Rev. D 80, 032003 (2009).
[4] Z. Berezhiani, EPJ C 64 (2009) 421.
[5] Z. Berezhiani and F. Nesti, EPJ C 72, 1974 (2012).
[6] Z. Berezhiani et al., EPJ C 78, 717 (2018).

✓ First reported detailed annual and sidereal modulation study

✓ **Best constraints around B' ~ 10 µT, and also in the range of B'<1.5µT and B'>37 µT**

✓ We excluded 3/5 portions where at least 2 signals overlap

! Need further tests of these signals in the range of B' ∈ (4, 37) µT