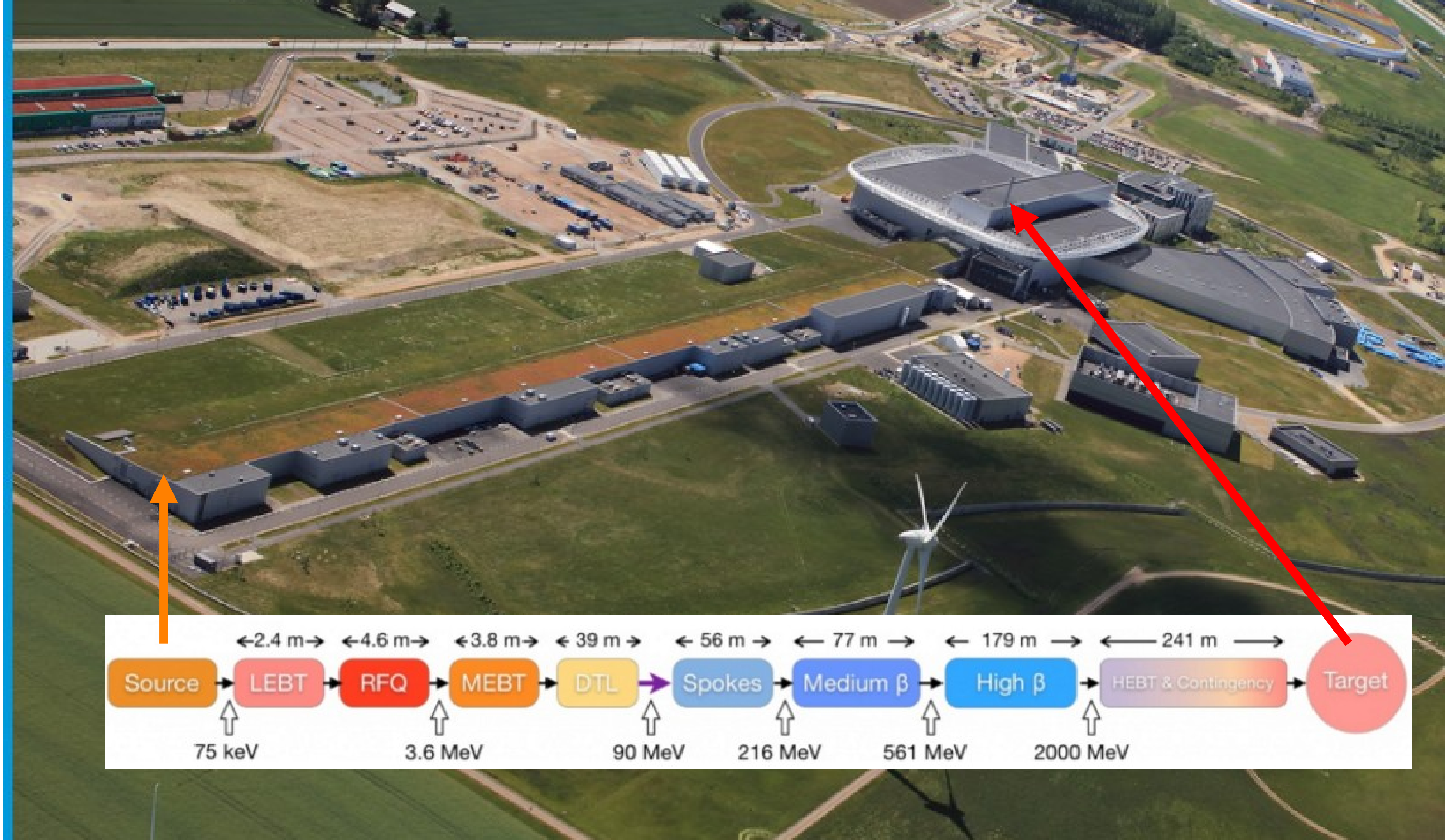
# Search for Baryon Number Violation (BNV) with cold neutrons

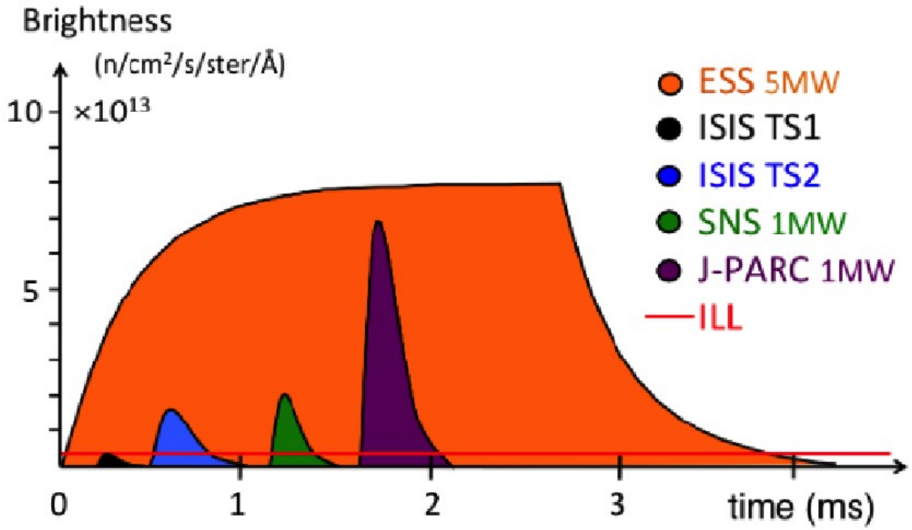


←2.4 m→
←4.6 m→
←3.8 m→
← 39 m →
← 56 m →
← 77 m →
← 179 m →
← 241 m →
Source
LEBT
RFQ
MEBT
DTL
Spokes
Medium β
High β
HEBT & Contingency
Target
75 keV
3.6 MeV
90 MeV
216 MeV
561 MeV
2000 MeV

# ESS cold neutron source

- Average beam current: 62mA
- Peak power:   125 MW
- Average power: 5 MW

  (right now committed to 2MW)
- Pulse length: 2.9 ms

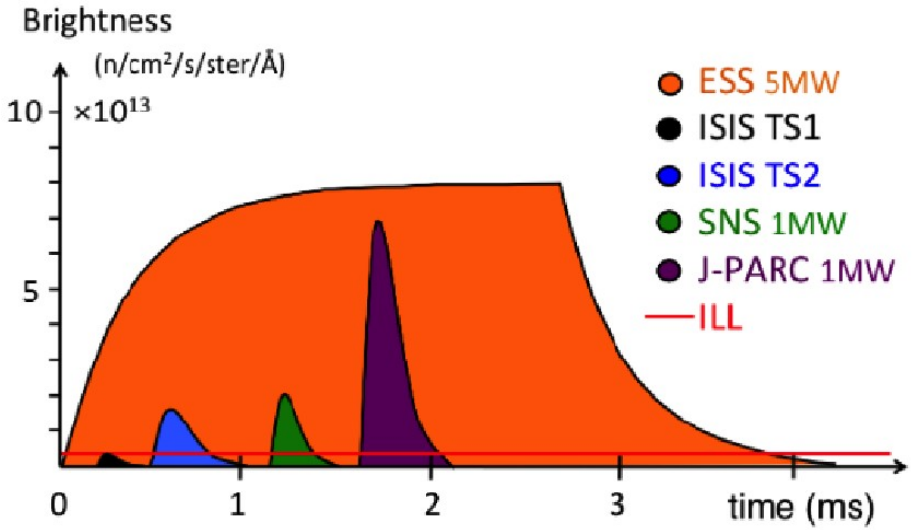


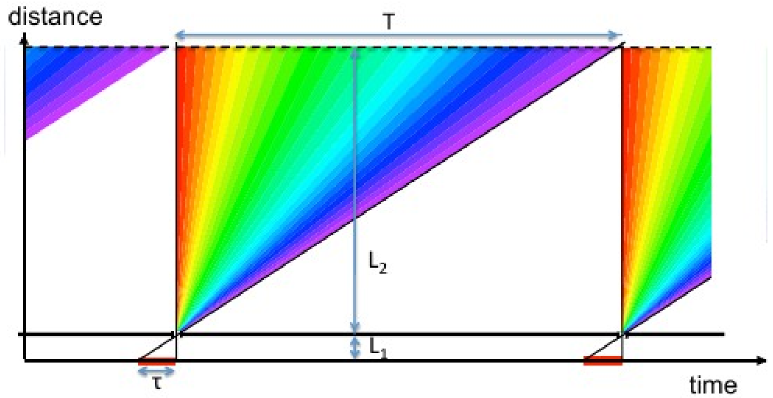
# ESS future cold neutron source

- Average beam current: 62mA
- Peak power:   125 MW
- Average power: 5 MW

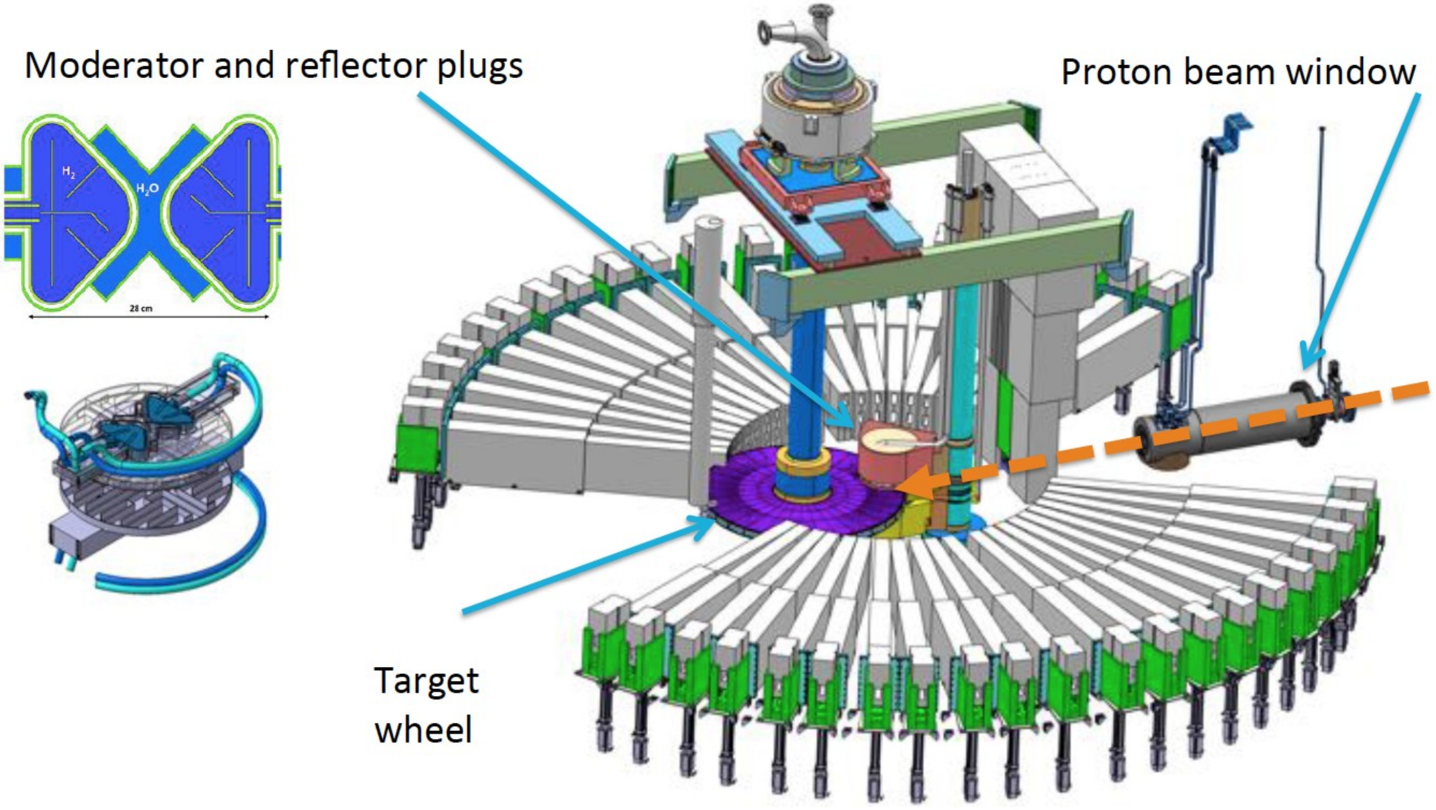
  (right now committed to 2MW)
- Pulse length: 2.9 ms
- Repetition rate: 14 Hz
- Number of beam ports: 48

  (15 under construction now)
- First beam on target: end of 2025



# Beam ports available




 Courtesy of Valentina Santoro

# Large Beam Port
# Installed in the Target Monolith
# Dedicated to $n\bar{n}$ oscillations

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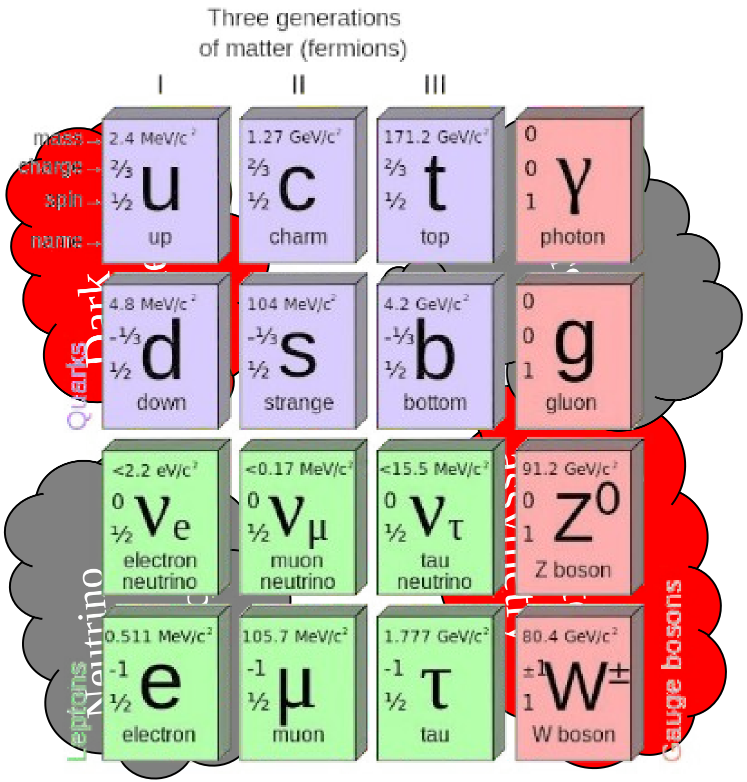
# Installed in the Target Monolith
# Dedicated to $n\bar{n}$ oscillations

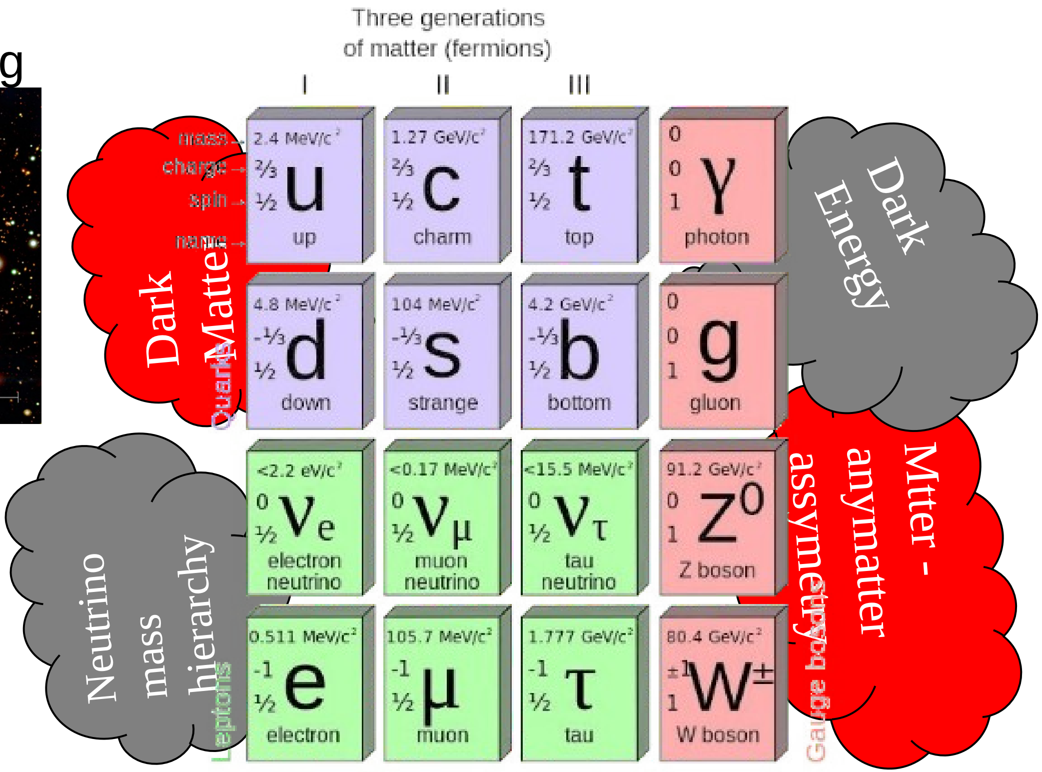

NNBAR Large Beam Port has been constructed to provide sufficient intensity of **$1.5\text{x}10^{15}$ n/s**
there is no beamline **<u>currently available or planned at any other facility that could reach a flux even close to this number</u>**

# Standard Model



# Standard Model and its problems

Gravitational lensing




Sacharov conditions:
- Time Reversal Violation
- Departure from equilibrium
- Baryon Number Violation

# NNBAR: $n \rightarrow \bar{n}$ oscillations

$$H = \begin{pmatrix} E_n & \varepsilon_{n\bar{n}} \\ \varepsilon_{n\bar{n}} & E_{\bar{n}} \end{pmatrix}$$

Mass mixing term
(very small)

$n\,\bar{n}$ potential energy difference
can be large

Probability to find an antineutron at time *t* is given by:

$$P_{n\bar{n}}(t) = \frac{\varepsilon_{n\bar{n}}^2}{(\Delta E/2)^2 + \varepsilon_{n\bar{n}}^2} \sin^2\left(t\sqrt{(\Delta E/2)^2 + \varepsilon_{n\bar{n}}^2}\right) e^{-t/\tau_n}$$

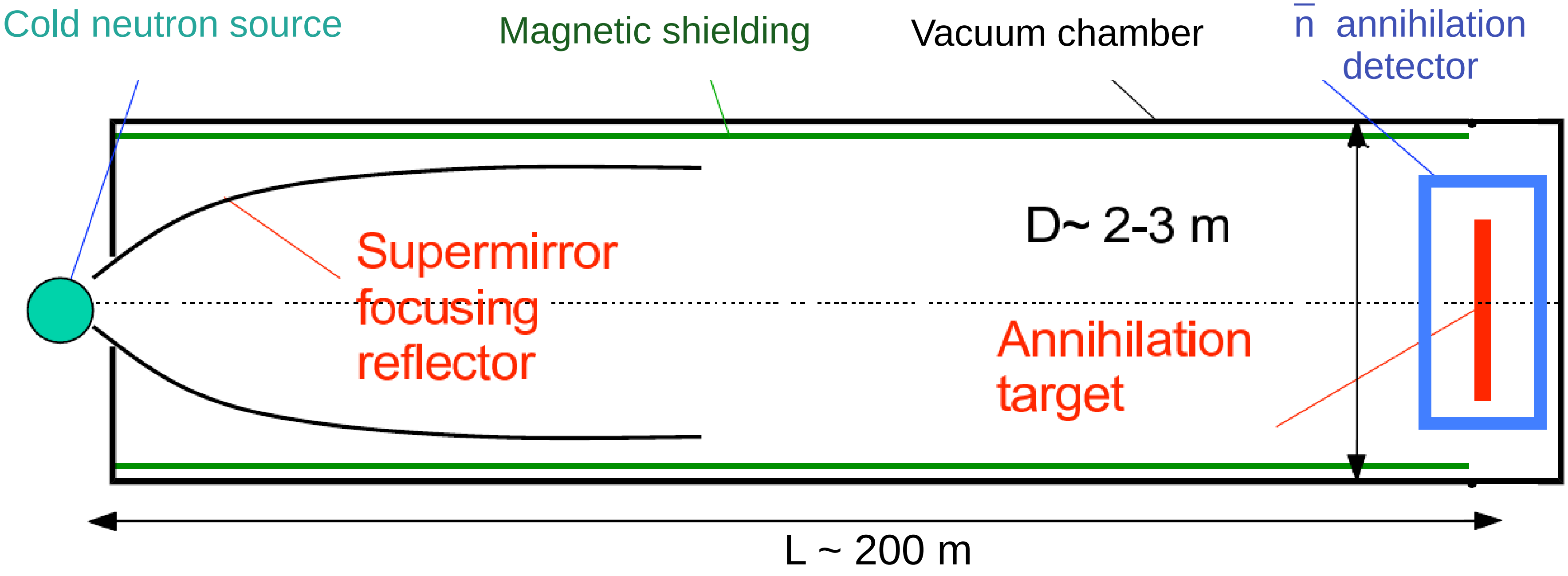
$n\,\bar{n}$ oscillation suppression factor
can be huge

Best experimental limits for $n\,\bar{n}$ oscillation :

- Super-Kamiokande, K.Abe *et al.* Phys. Rev. D91 (2015) 072006: $\tau_{n\bar{n}} > 2.7 \cdot 10^8$ s , but…
- ILL, Baldo-Ceolin *et al.* Z.Phys. C63 (1994) 409 : $\tau_{n\bar{n}} > 0.86 \cdot 10^8$ s ,

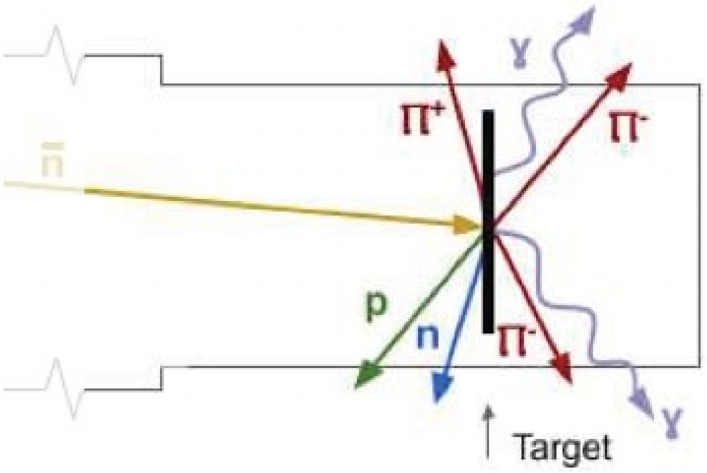
# NNBAR/HIBEAM $n\text{-}\bar{n}$ oscillations measurement principle

$$FoM \propto n \cdot t^2$$ ← Free flight time

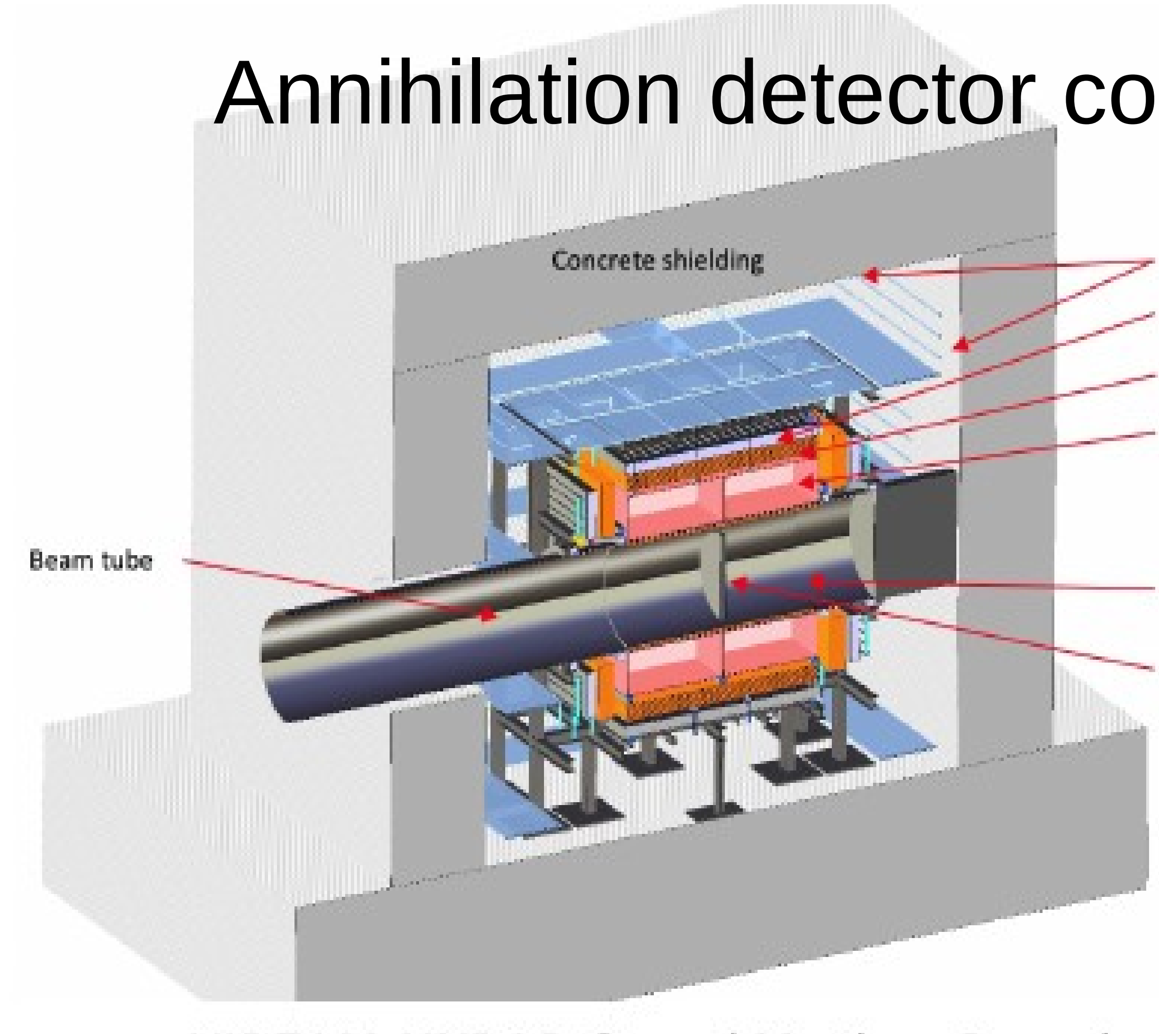


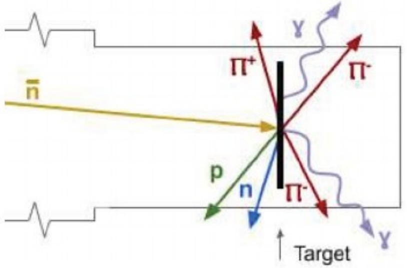
# Annihilation event signature - extremely strong

- Huge energy release ~1800 MeV
- On average 4-5 pions (neutral or charged)
- Light fragments from carbon nuclei
- All tracks from common vertex
- Gammas from $\pi^0$ decay
- Process at rest (well isotropic)
- Can not be mimicked by cold neutron capture events (however they must be considered as load in detectors)
- Cosmic background must be suppressed



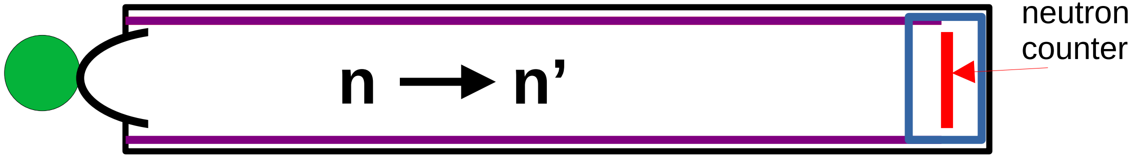
# Annihilation detector components

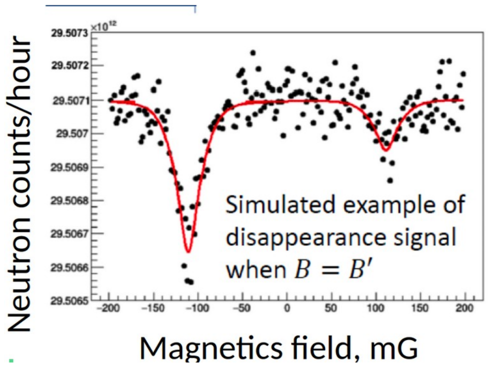


# HIBEAM and Dark Matter sector

- Neutron disappearance - conversion to ‘sterile neutron’, ΔB=1



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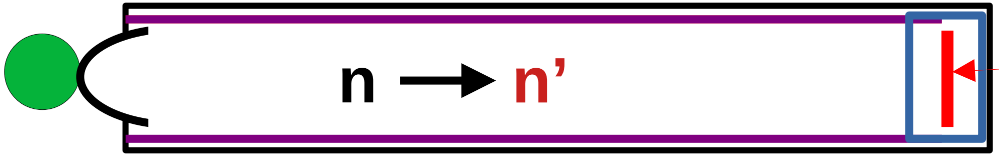
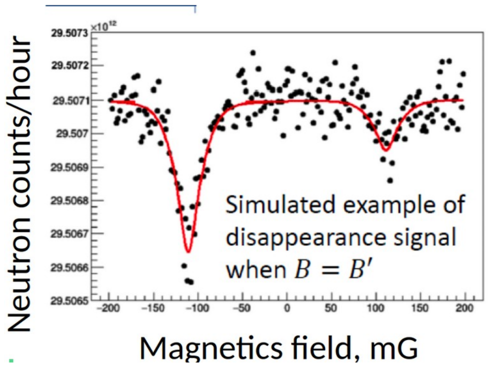
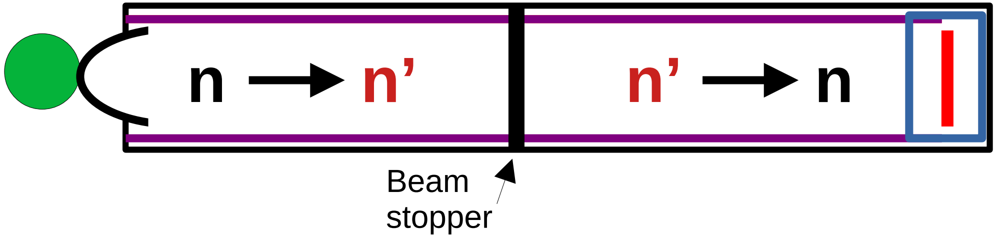
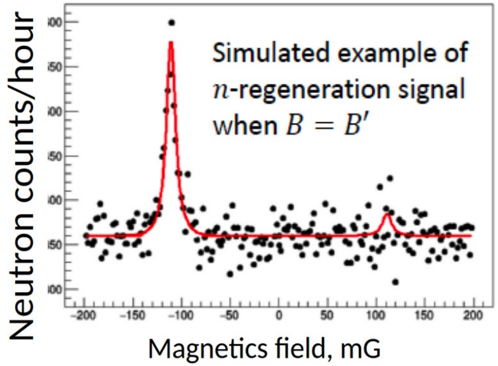



- Neutron regeneration by conversion from ‘sterile neutron’, ΔB=1



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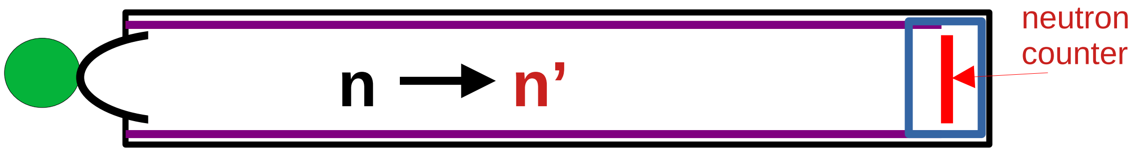


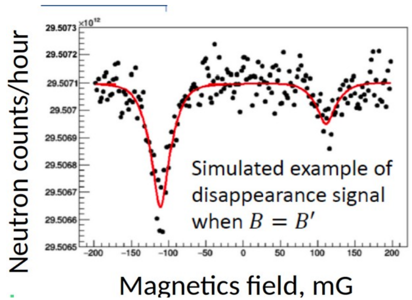


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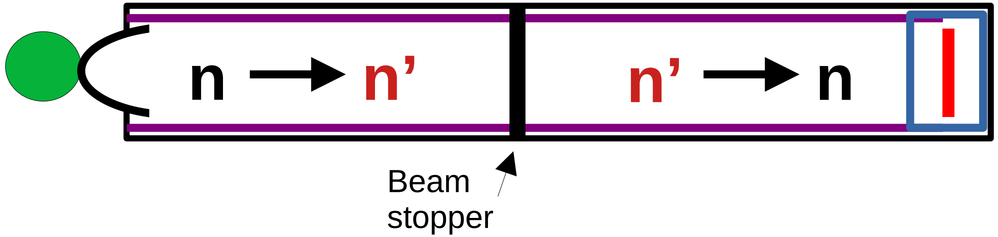
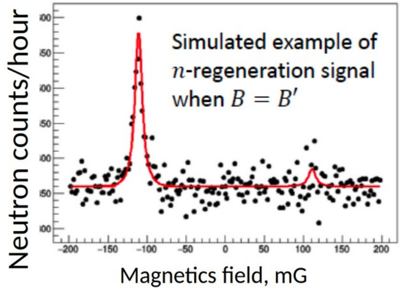
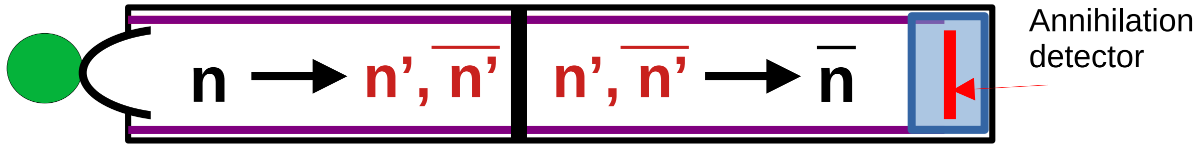
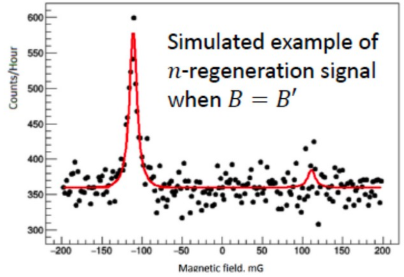



- Neutron conversion to antineutron via sterile world, ΔB=2



# HIBEAM and axions or ALPs

- 1978: Peccei-Quinn proposed scalar field to solve Strong CP-problem
- 1979: Weinberg-Wilczek axion - associated with this field pseudoscalar bozon
- 1983: axion-like particles (ALPs) can also account for Dark Mater problem

Axion-gluon coupling: $$\mathcal{L}_g = \frac{C_G}{f_a}\frac{g^2}{32\pi^2}\, a\, G^b_{\mu\nu}\tilde{G}^{b\mu\nu}$$

Axion-nucleon coupling: $$\mathcal{L}_N = \frac{C_N}{2f_a}\, \delta_\mu\, a\, \tilde{N}\gamma^\mu\gamma^5 N$$

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$$H_a(t) = \frac{C_N\, a_0}{2f_a}\sin(m_a t)\,\boldsymbol{\sigma}_N\cdot\boldsymbol{p}_a$$

Precession of $\boldsymbol{\sigma}_N$ around direction of ALP "wind" $\boldsymbol{p}_a$

Indistinguishable from Larmor precession around magnetic field lines:

$$H_m(t) = -\gamma\, \boldsymbol{\sigma}_N\cdot\boldsymbol{B}$$

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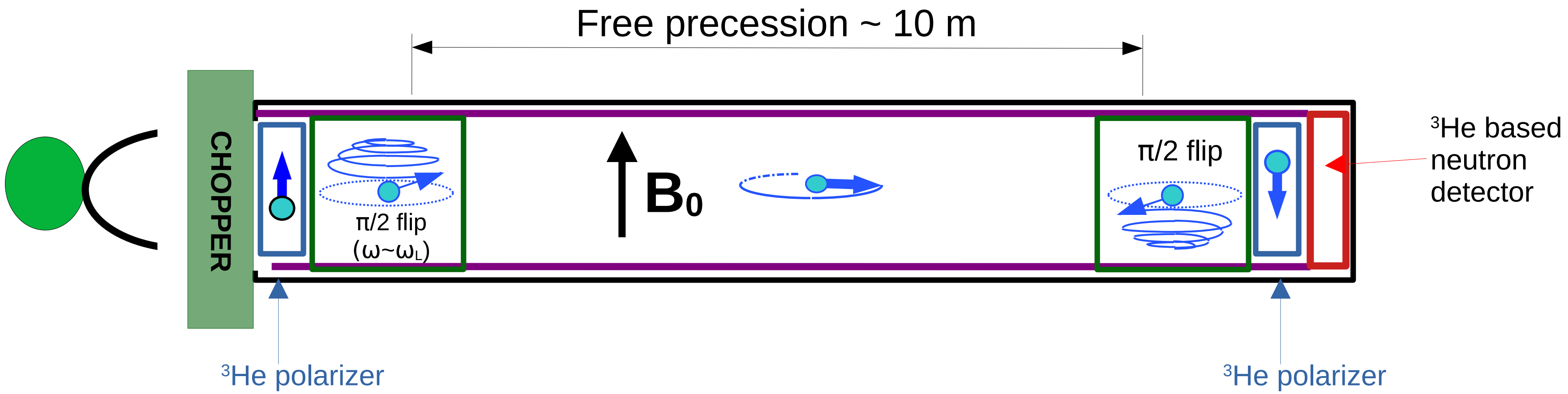

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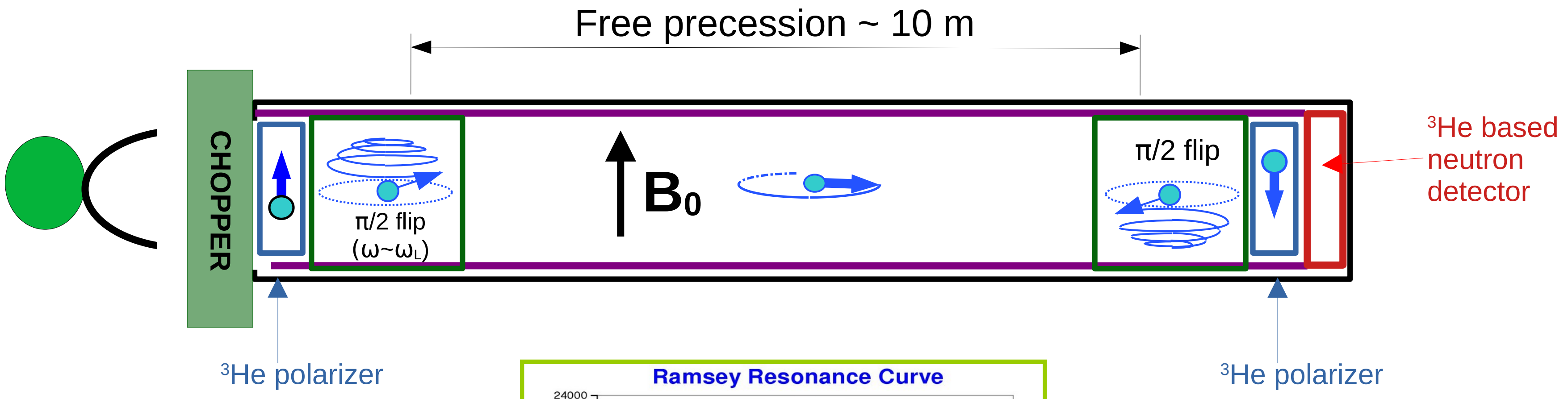
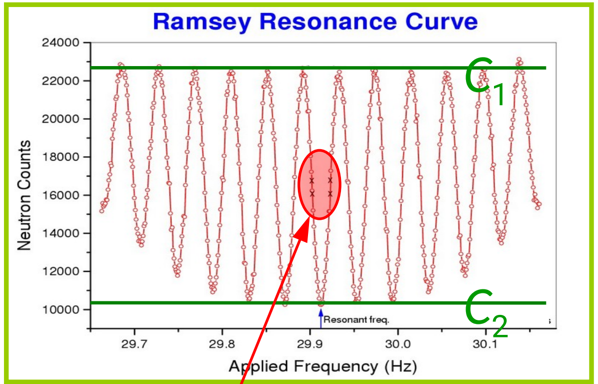



Experimental precision:

$$\Delta f \propto (\alpha T \sqrt{N})^{-1}$$

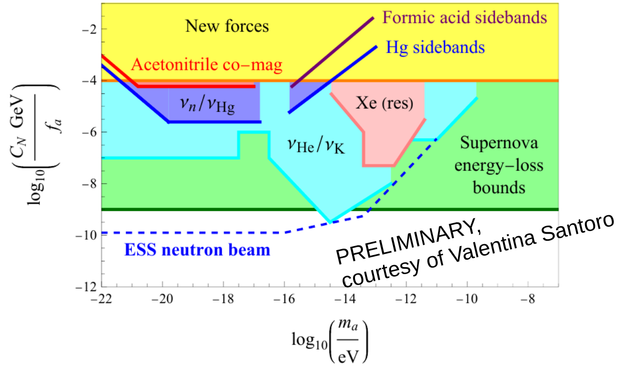
where $T$ is free precession time, $N$ number of neutrons and $\alpha$ is the resonance visibility:

$$\alpha = \frac{(C_1 - C_2)}{(C_1 + C_2)}$$



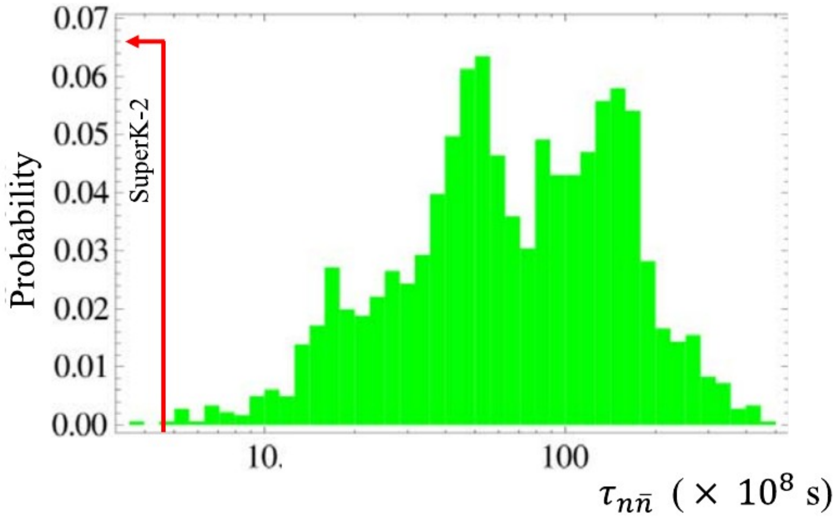

**X** – 4 working points
ω close to Larmor freq.

Up to 3 orders of magnitude
Improvement of current limits




# Thank you

Likelihood distribution for neutron–antineutron oscillation time for a Post-Sphaleron Baryogenesis (PSB) scenario




Adapted from K.S. Babu at al. Phys. Rev. **D 87**(11) (2013)

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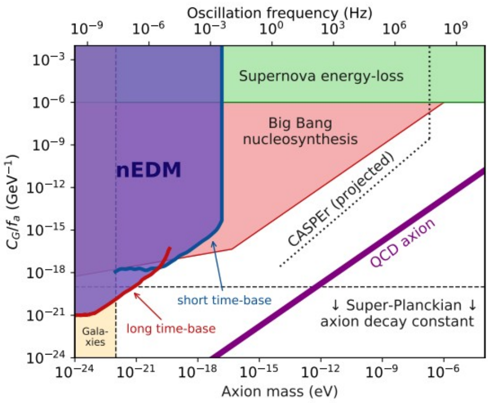


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