Particle physics opportunities at ESS

Bernhard Meirose

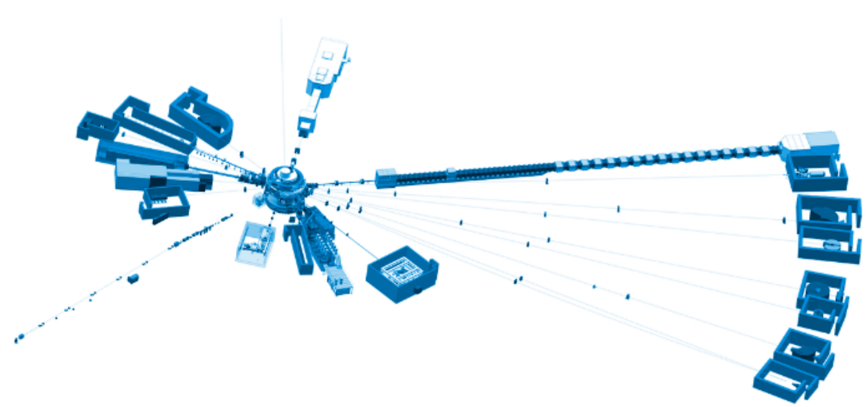
ESS timeline

ESS Timeline	GROUNDBREAKING	INITIAL OPERATIONS	INSTRUMENT COMMISSIONING BEGINS	USER PROGRAMME BEGINS	PROJECT COMPLETION STATUS
	2014	2019	2022	2023	73%

ESS and particles

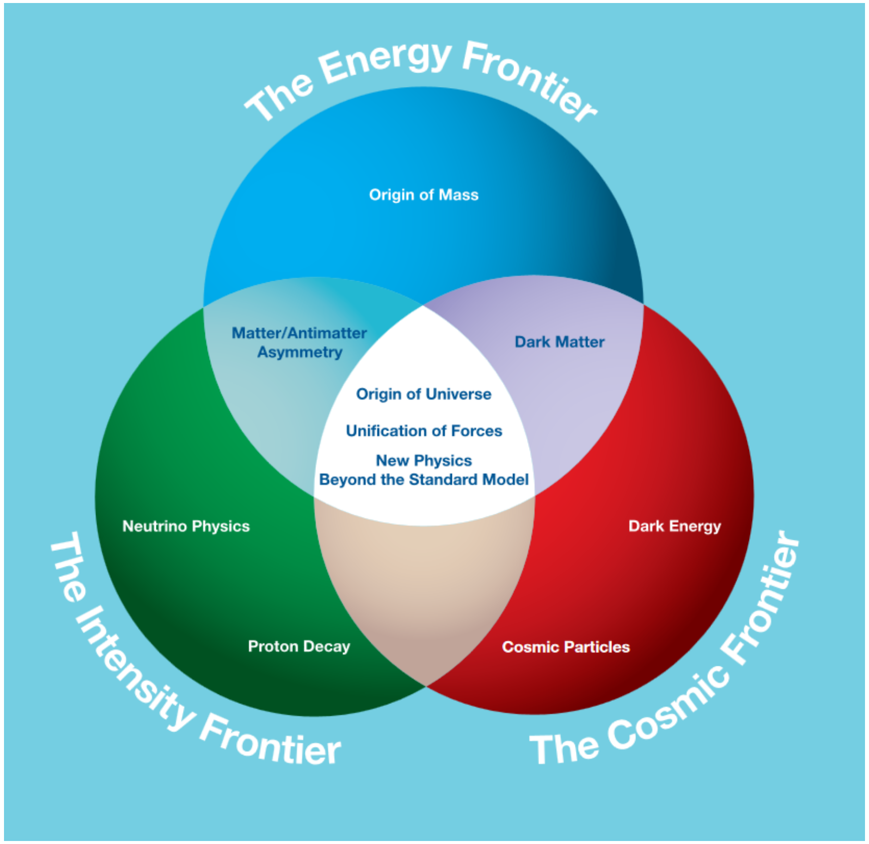
- Primarily a neutron scattering/materials science experiments facility
- But particle physics entering “the menu”
- 22 instruments planned
- First 15 will be brought on-line by the end of 2025
- Instruments 16-22 - document from ESS has analysed the capability gaps
- Result of this analysis: **particle physics community clearly missing!**
- **Therefore filling this capability gap is given the highest priority.**

The ESS instrument suite – a capability gap analysis



ESS – at the intensity frontier

- Low-energy, high-precision frontier complementary to high energy experiments
- Search for rare phenomena
- Sensitive to scales of new physics substantially in excess w.r.t colliders
- High neutron intensity of ESS a crucial element



European Strategy of particle physics

- European Strategy for Particle Physics emphasises the need for a more diverse program beyond that at CERN: “ Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported. ”

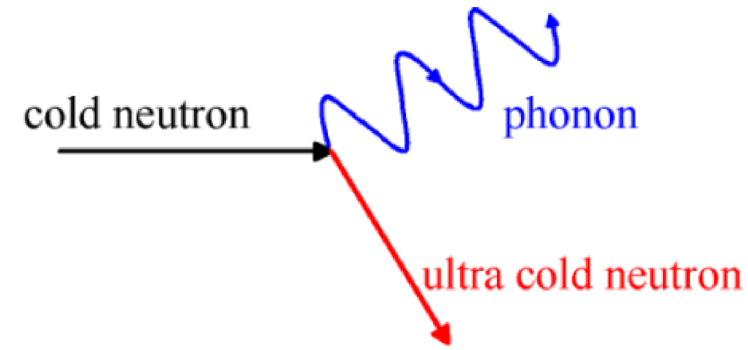
- Strategy refers to “laboratories” and not “national laboratories” as in earlier updates, to take account a fundamental physics program at the ESS

Fundamental physics at ESS (planned)

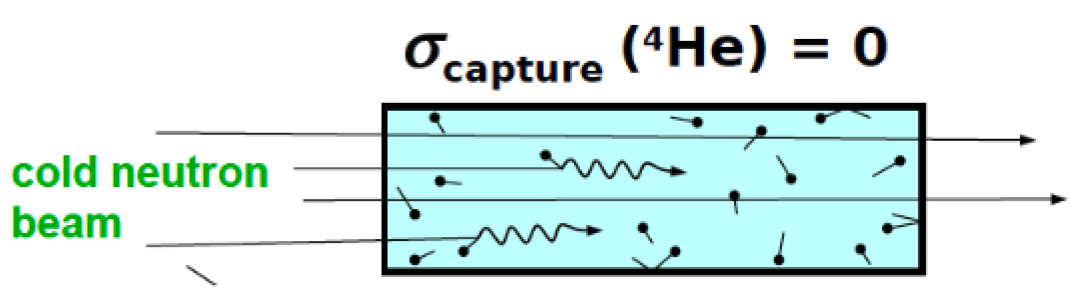
- **Neutron Beamlines:**
- HIBEAM-NNbar
  Ultra-cold neutrons (UCN) source
  ANNI (cold neutron source)

- **Neutrino experiments:**
- ESS neutrino Super Beam (ESSnuSB)
- Coherent Elastic Neutrino-Nucleus Scattering

Ultra cold neutron (UCN) source

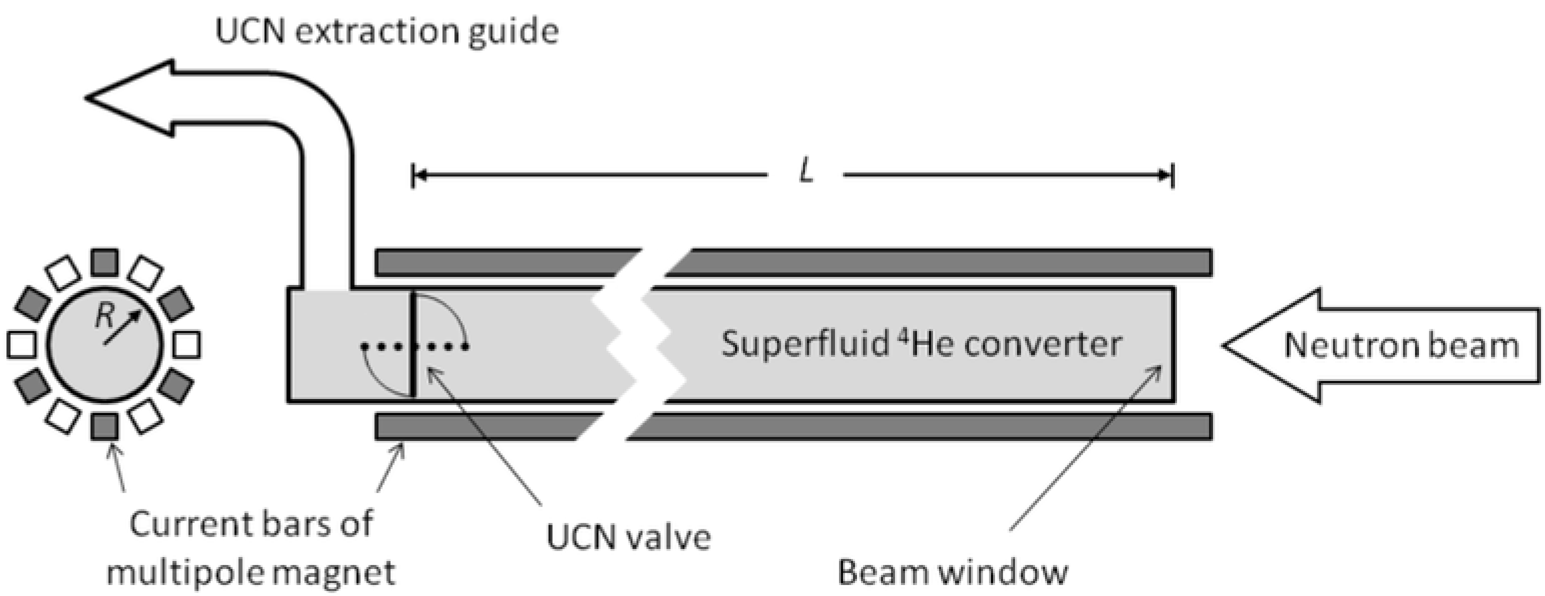


- UCN energy in neV range
- Very slow
  → de Broglie-wavelength >> interatomic distances of matter
  → Totally reflected under any angle of incidence
- Can be stored them in ”neutron bottles” made of suitable materials with small cross sections for neutron capture
- UCN production mostly based on superfluid 4He
  1 meV neutrons lose energy in single scattering events



UCN beamline experiments

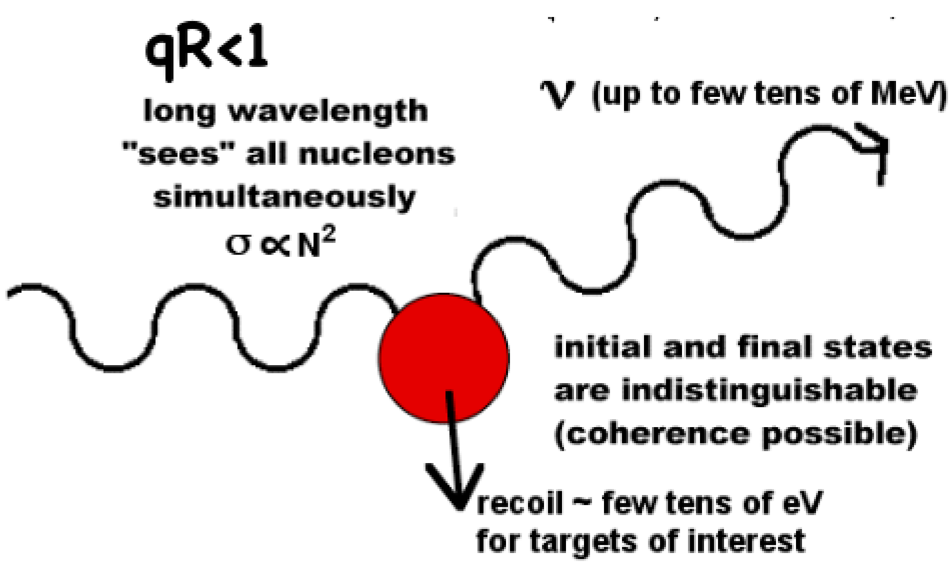
- Gravity resonance spectroscopy
- Neutron interferometry
- Neutron beta decay

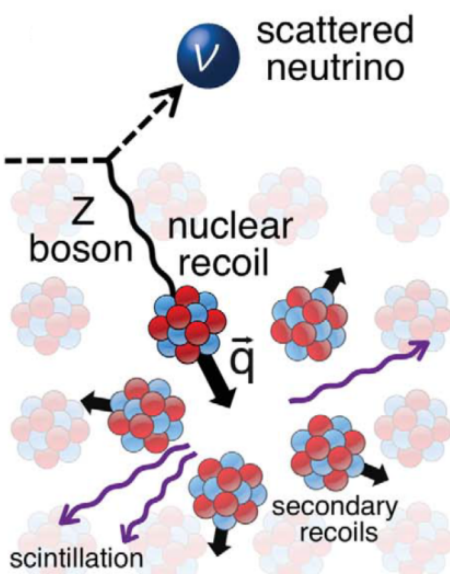


Neutrino experiments at ESS

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

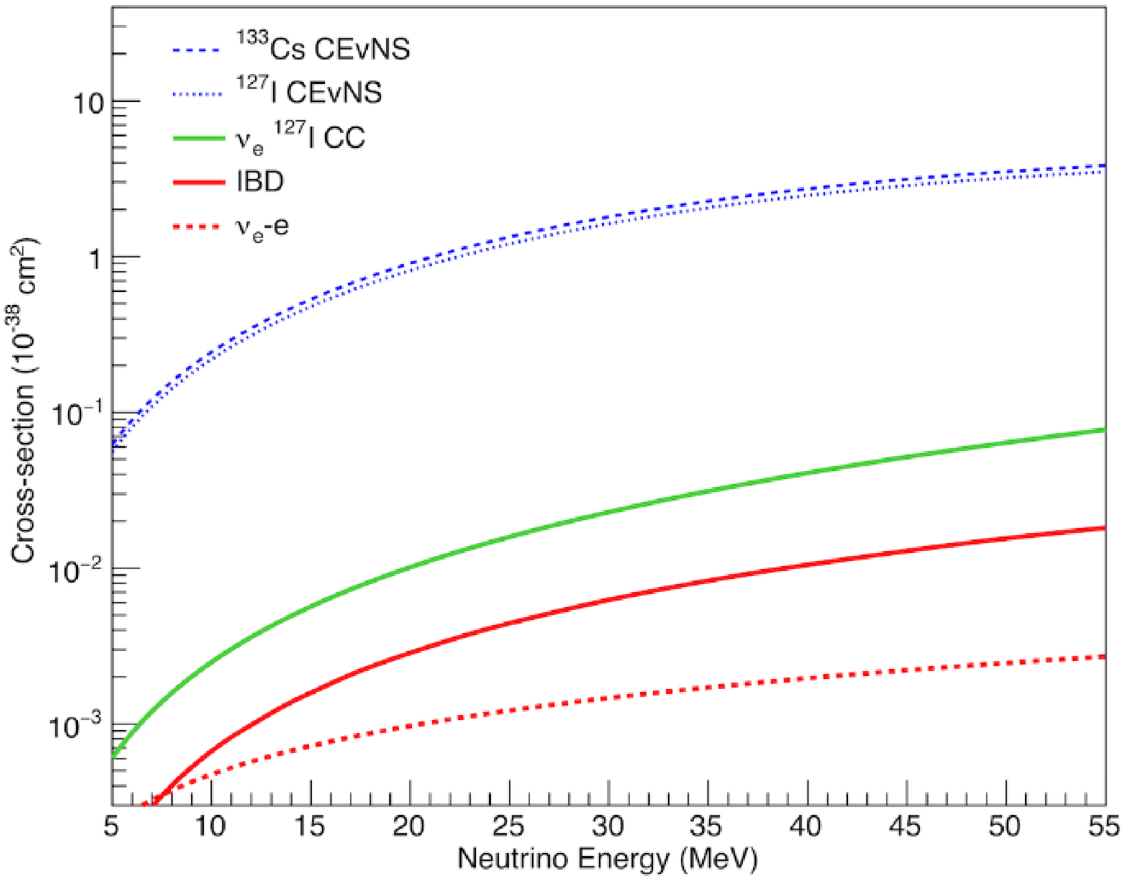
- 1973 - Weak neutral current in neutrino-nucleus interactions by Gargamelle collaboration at CERN
- 1974 - D. Z. Freedman → first theoretical description of CEvNS as SM process
- When neutrino scatters off a nucleus interaction depends on the non-trivial interplay between neutrino and the individual nucleons
- BUT, if long wavelength will see nucleus a a whole





CEvNS cross section

- Largest ν x-section
- But only low energy NRs detectable



Observed in 2017 at ORNL

SNS
SPALLATION NEUTRON SOURCE

REPORT

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], ...
+ See all authors and affiliations

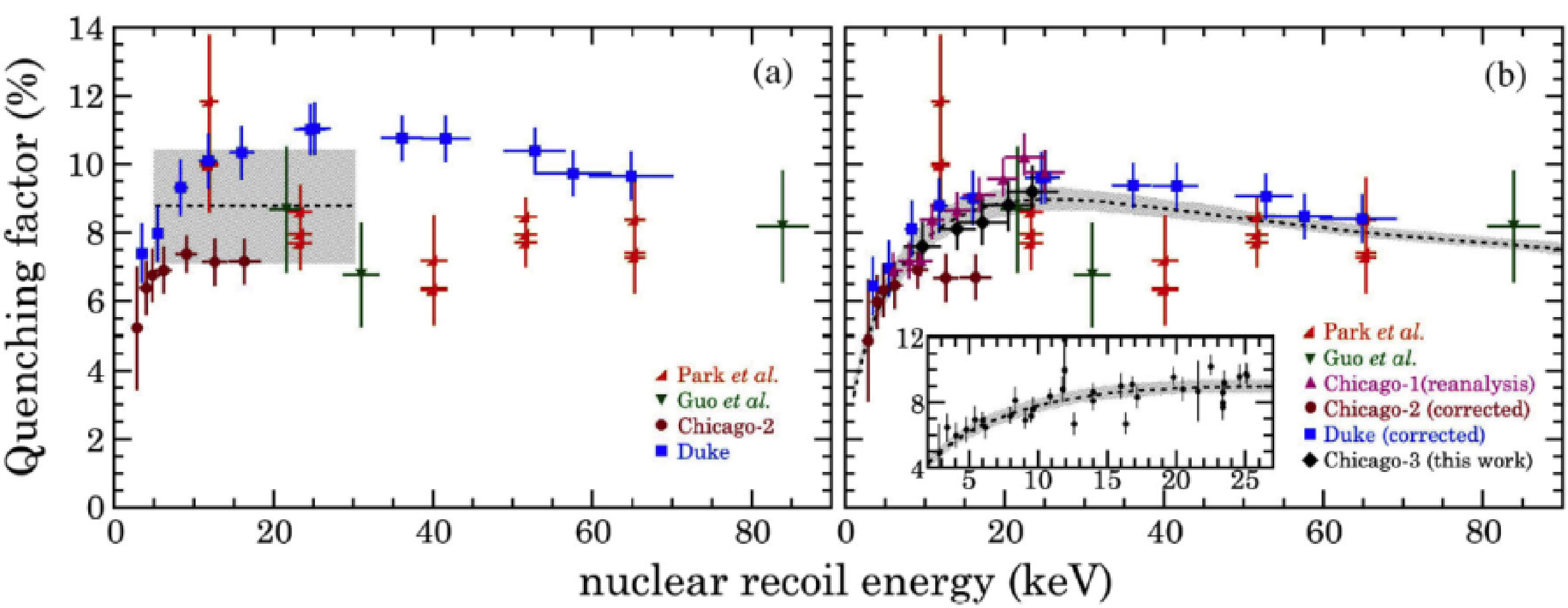
Science 15 Sep 2017:
Vol. 357, Issue 6356, pp. 1123-1126
DOI: 10.1126/science.aao0990

→ If x-sec is so large – why after 43 years??

CEvNS Detectors

- Neutral-current process → signature is nuclear recoil
- Energies of few eV to keV
- Conventional radiation detectors → small fraction of total energy carried by nuclear recoil is converted into detectable scintillation and ionization signal
- Quenching factor = Fraction between detectable and total energy (typically on the order of a few to a few ten percent)

PHYSICAL REVIEW D 100, 033003 (2019)



QF is the main systematic affecting CEvNS sensitivity to new physics.

Progress is possible...

Why at ESS and what can we learn?

- **Spallation sources:**

Generation of nuclear recoils as energetic as allowed by the coherence condition, facilitating detection

Pulsed beam timing reduces the impact of steady-state backgrounds able to mask the signal

- **Physics potential**

New tool for the study of fundamental neutrino properties

Measure potential non-standard neutrino interactions

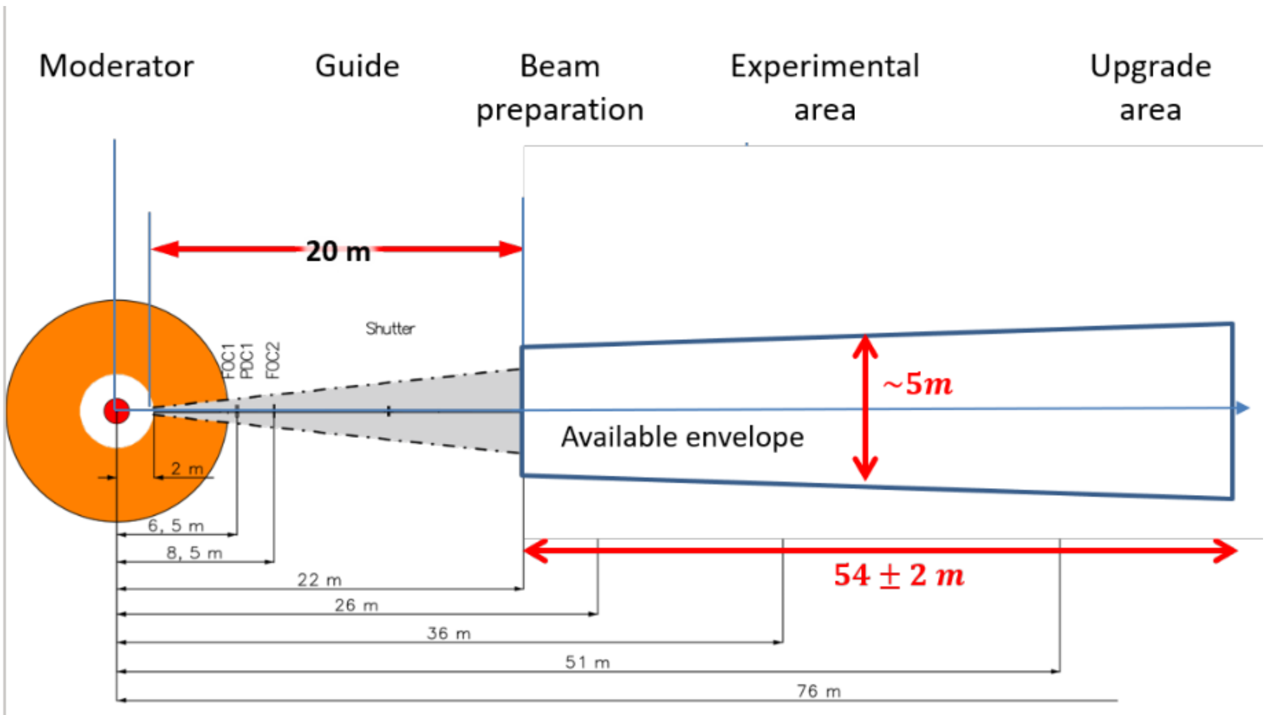
Measure weak mixing angle at low energies with increased precision

Search for sterile neutrinos or new types of dark matter particles

ANNI - A pulsed cold neutron beam facility for particle physics at the ESS

ANNI

- ANNI: possible fundamental physics beamline at ESS
- Uses curved guide: only cold (slow/meV) neutrons get trough
- Use pulsed neutron beams
- A facility with different applications



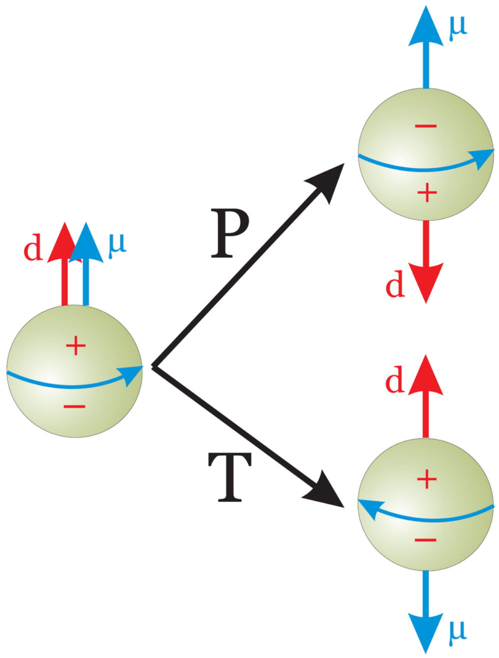
ANNI – possible experiments

- Neutron beta decay
- Hadronic parity violation
- Neutron Electric Dipole Moment (EDM)
- HIBEAM (first stage of NNbar)

ESS Instrument Construction Proposal
ANNI – a cold neutron beam facility for Particle Physics

Neutron electric dipole moment

- Searches address strong CP problem and are highly sensitive to new physics processes in which CP-violation occurs



- No-zero nEDM violates both C and T symmetries
- If T is violated and CPT preserved, CP violated

Non-Relativistic Hamiltonian

$$H = \vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

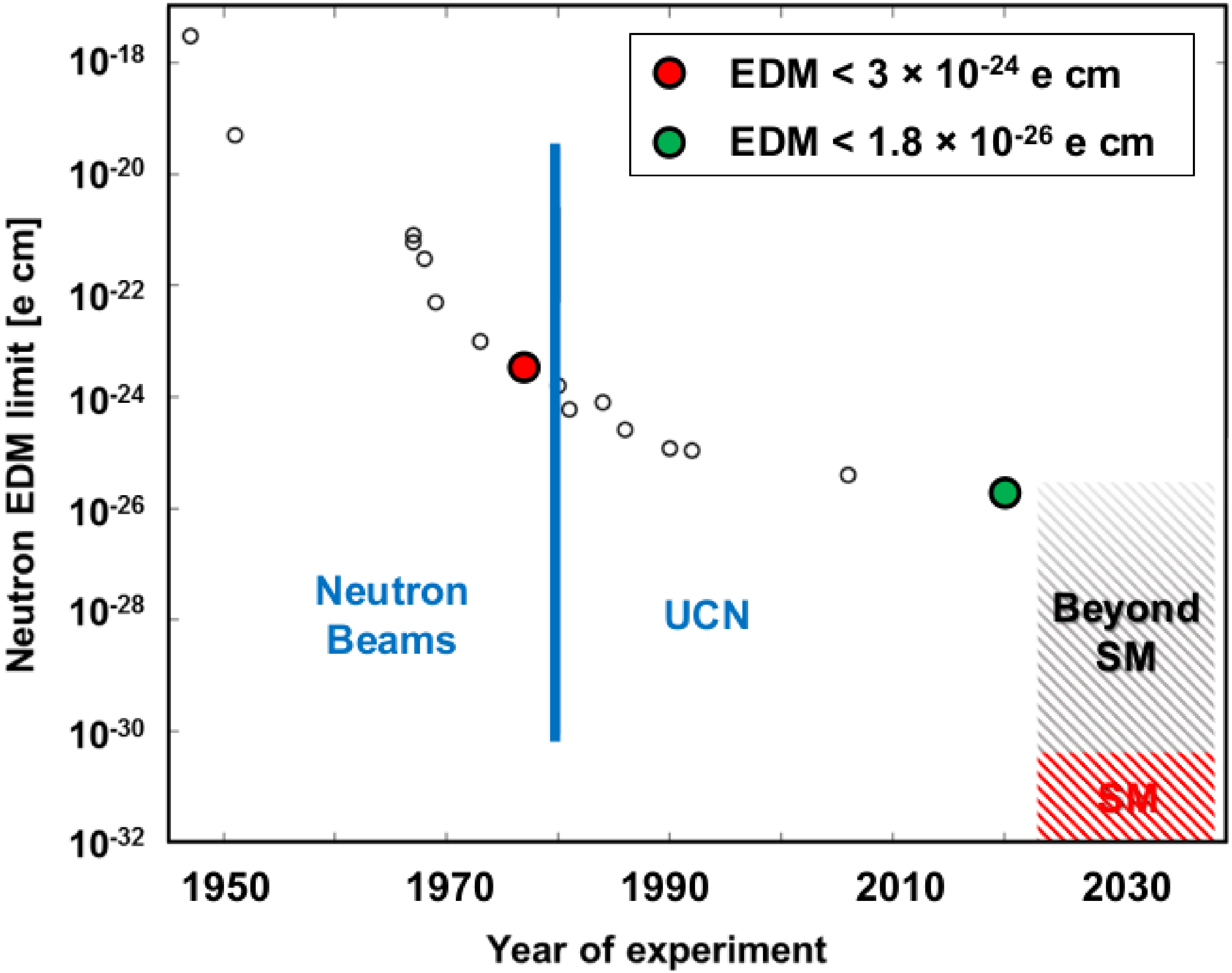
$\vec{\mu} \cdot \vec{B}$	$\vec{d} \cdot \vec{E}$
C-even	C-even
P-even	P-odd
T-even	T-odd

Non-zero d violates T and CP

(Field Theories generally preserve CPT)

EDM limits

Courtesy of Florian Piegsa



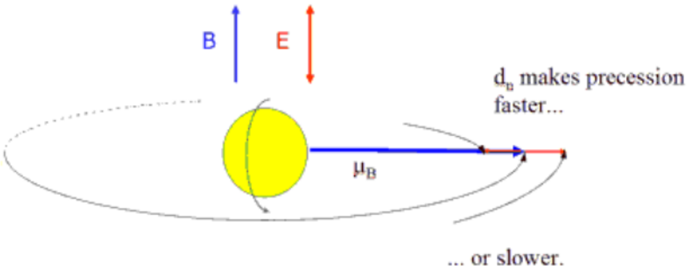
EDM(SM) ~ 10^{-32} e cm

EDM@ESS < 10^{-27} e cm (10^{-28} "quite challenging")

Quick theoretical fundamentals

- If nEDM non-zero, then a shift in the Larmor frequency should be observed
- If B and E are static and aligned with z axis, neutron spin precesses around z at Larmor angular frequency:

$$\hbar\omega_n = -2\mu_n B - 2d_n E$$



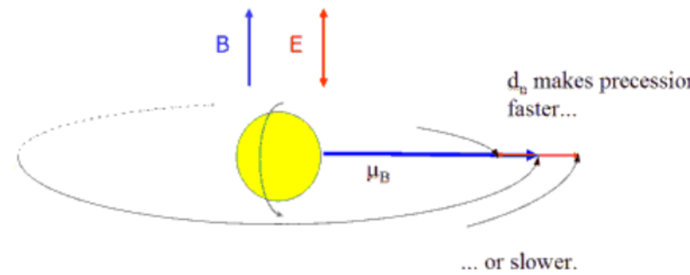
- Note:
- If **B = 1 μT** , magnetic precession frequency **$|\omega_n / 2\pi|$ = 29 Hz**,
- whereas for
- **d_n = 10^{-26} e cm** and **E = 20 kV/cm**,
- the electric precession frequency is only **10^{-7} Hz**!

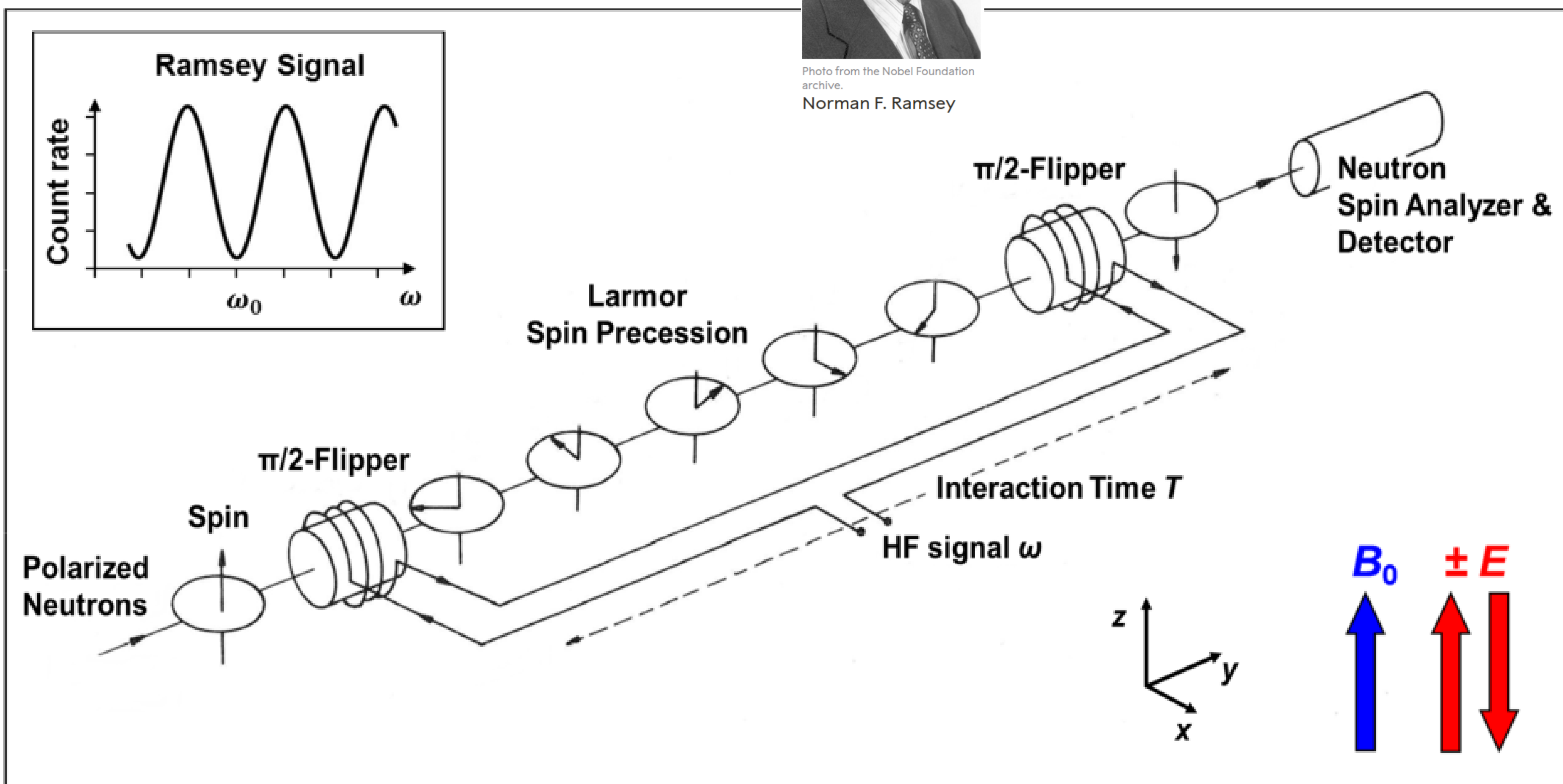
Measurement principle

- Measure precisely Larmor frequency in the two polarities of the E (parallel and antiparallel to B). Extract EDM as:

$$d_n = -\hbar \Delta\omega_n / 4E$$


Photo from the Nobel Foundation archive.
Norman F. Ramsey





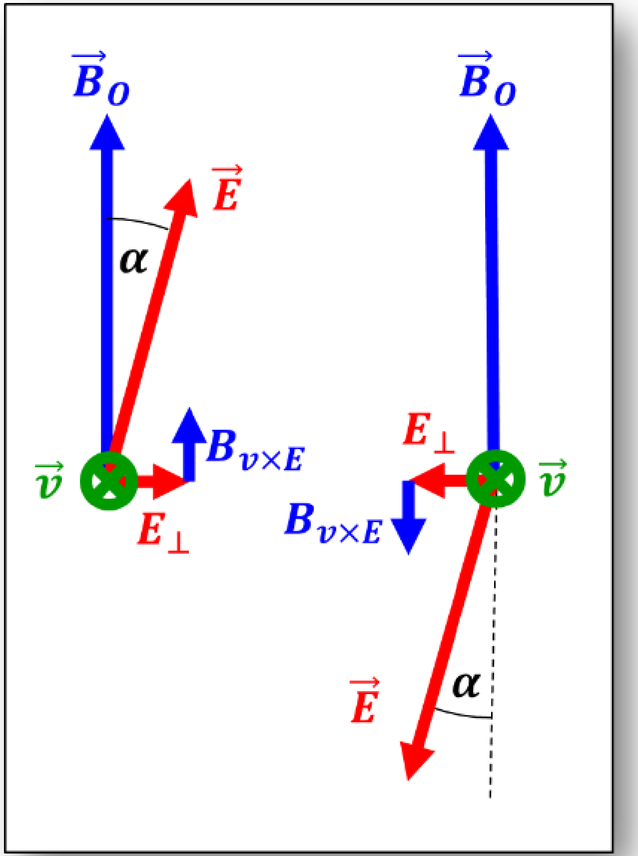
Why were Beam EDM Experiments abandoned?

Courtesy of Florian Piegsa

- v×E – effect: $\vec{B}_{v\times E} = -\frac{\vec{v}\times\vec{E}}{c^2}$
- This can cause a false EDM signal:

$$d_{\text{false}} \approx 10^{-20}\ \text{e cm}\cdot\sin\alpha \quad \text{for: } v = 100\ \text{m/s}$$

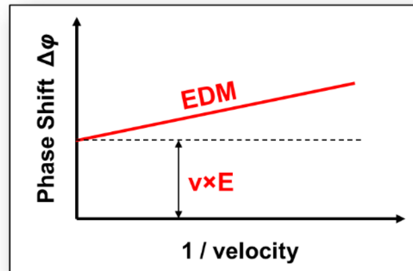
- The false effect is velocity-dependent, however, a real EDM signal is not !



Novel EDM experiment

- Measure nEDM with **cold pulsed neutron beam** instead of stored ultracold neutrons
- Directly measure **v × E-effect via neutron TOF → ESS!!**

See: Piegsa, PRC 88,045502(2013)

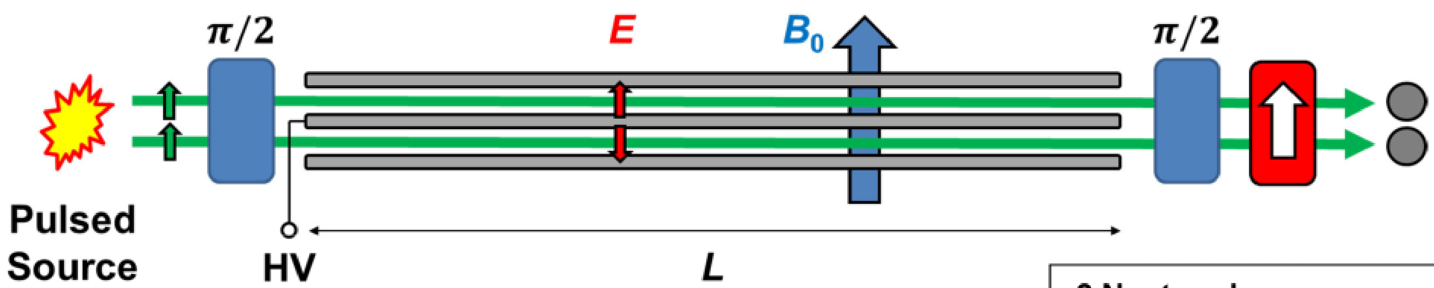


Length of experiment

$$\Delta\varphi = \frac{8d_n E}{\hbar}T + \frac{4\gamma_n E L}{c^2}\sin\alpha$$

slope = EDM   offset = v×E

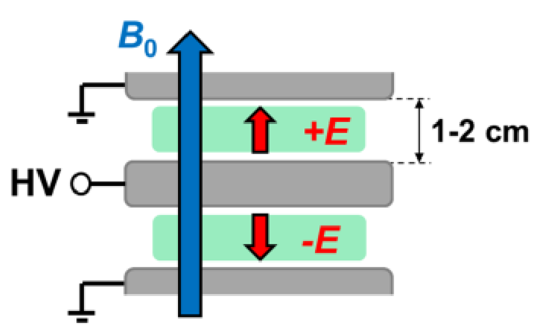
SIDE VIEW

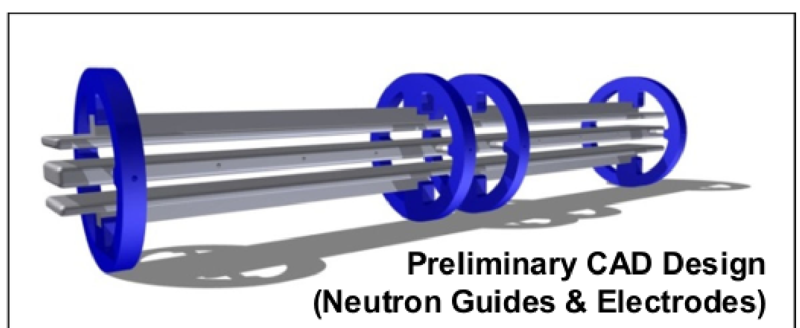


Courtesy of Florian Piegsa

2 Neutron beams
E > 50 kV/cm
B_0 = 200 μT
L = 5 m (proof-of-prin.)
L = 50 m (full-scale)

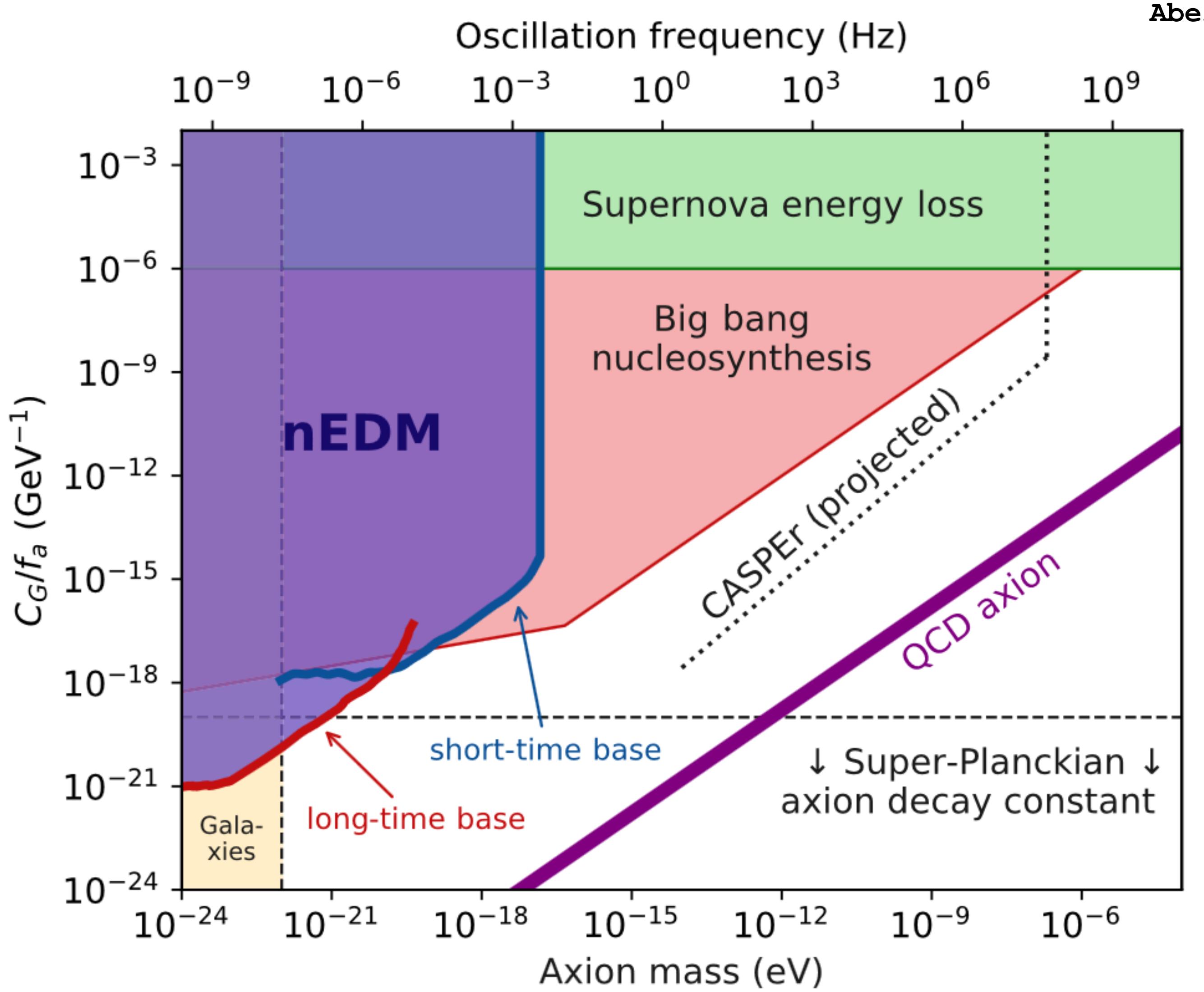
CROSS SECTION





nEDM search for ultra-light axion dark matter

Abel et al., PRX7(2017)041034



Limits on the interactions of an axion with the gluons, assuming axions saturate ocal cold DM content. The regions above the thick blue and red lines correspond to the regions of parameters excluded by the article at 95% CL.

ESS neutrino superbeam (ESSnuSB)

Motivation for ESSnuSB

- CP violation in the weak interactions of quarks established since 1964
- Sakharov condition to explain imbalance of matter and antimatter abundance in the Universe
- CP violation in quarks is too small to support explanation
- CP violation not yet observed in non-quark elementary particle systems.
- CP violation in leptons could generate matter–antimatter disparity through leptogenesis
- Leptonic mixing, which appears in SM, provides potential source of CP violation
- Acomplished through a complex phase δ_{CP}
- CP violation can be measured in $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ muon and $\boldsymbol{\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu}$ oscillations
- The current best-fit value of δ_{CP} is around -90° from T2K and NOvA
- One of the main goals of ESSnuSB is to measure δ_{CP} more precisely

ESS neutrino superbeam (ESSnuSB)

- ESSnuSB aim – use ESS linac to produce intense neutrino beam
- **Main goal is to observe CP violation in leptonic sector**
- ESS linac would need to be modified – 5 MW → 10 MW (and more)
- Megaton water Cherenkov detector several hundred kilometers away

The plan:

1. Run with ν_μ and look at ν_e appearance, then
2. Run with $\overline{\nu}_\mu$ and look at $\overline{\nu}_e$ appearance

probability of oscillation

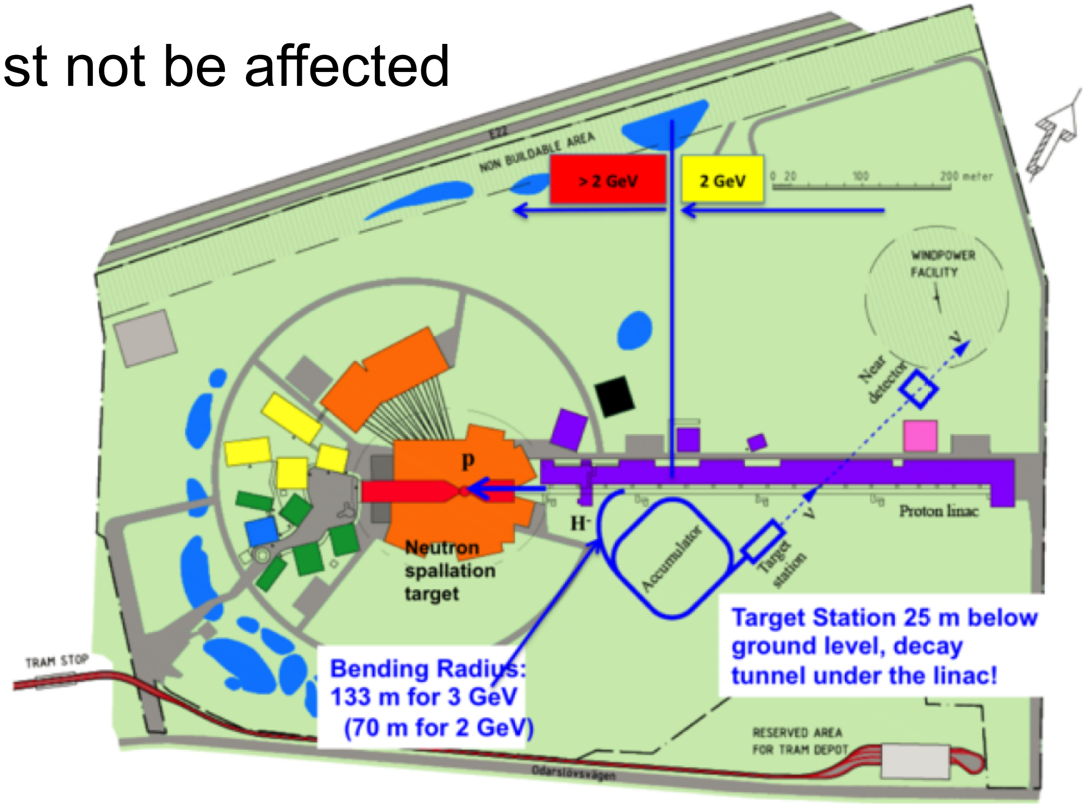
$$P_{\alpha\to\beta} \neq P_{\overline{\alpha}\to\overline{\beta}}$$

neutrino flavour at production

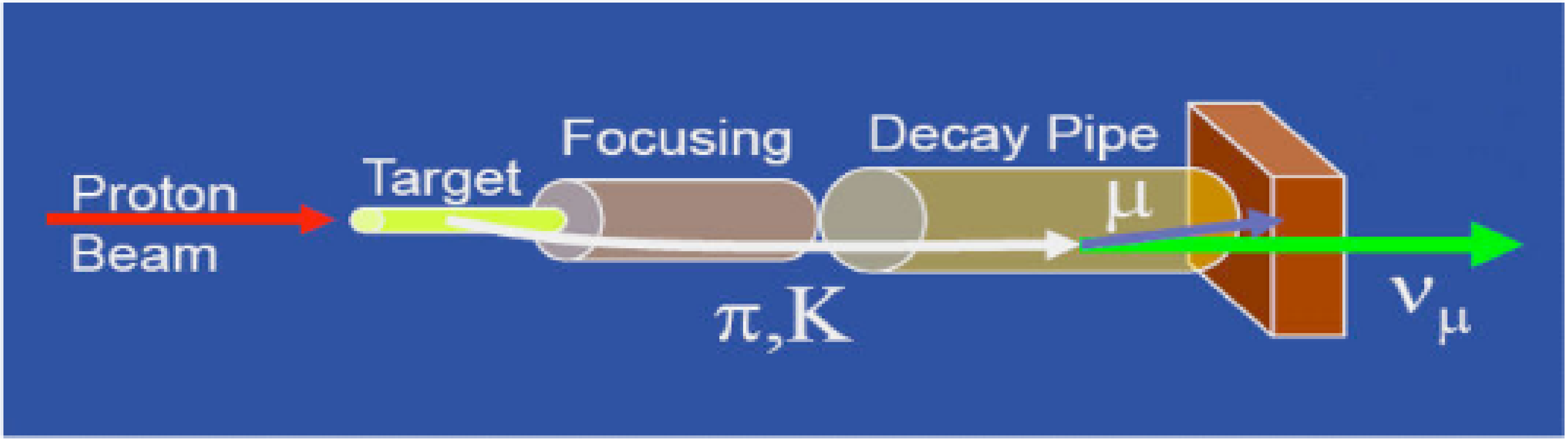
neutrino flavour at detection

Modifications to ESS linac to produce neutrinos

- Neutrino optimized target station
- Underground near detector
- Double linac rate rate (14 Hz → 28 Hz)
- ESS proton pulse too long for conventional magnetic horn (would melt)
- Accumulator (C~400 m) → compress to few μs the 2.86 ms proton pulses
- The neutron program must not be affected



Neutrino beam production



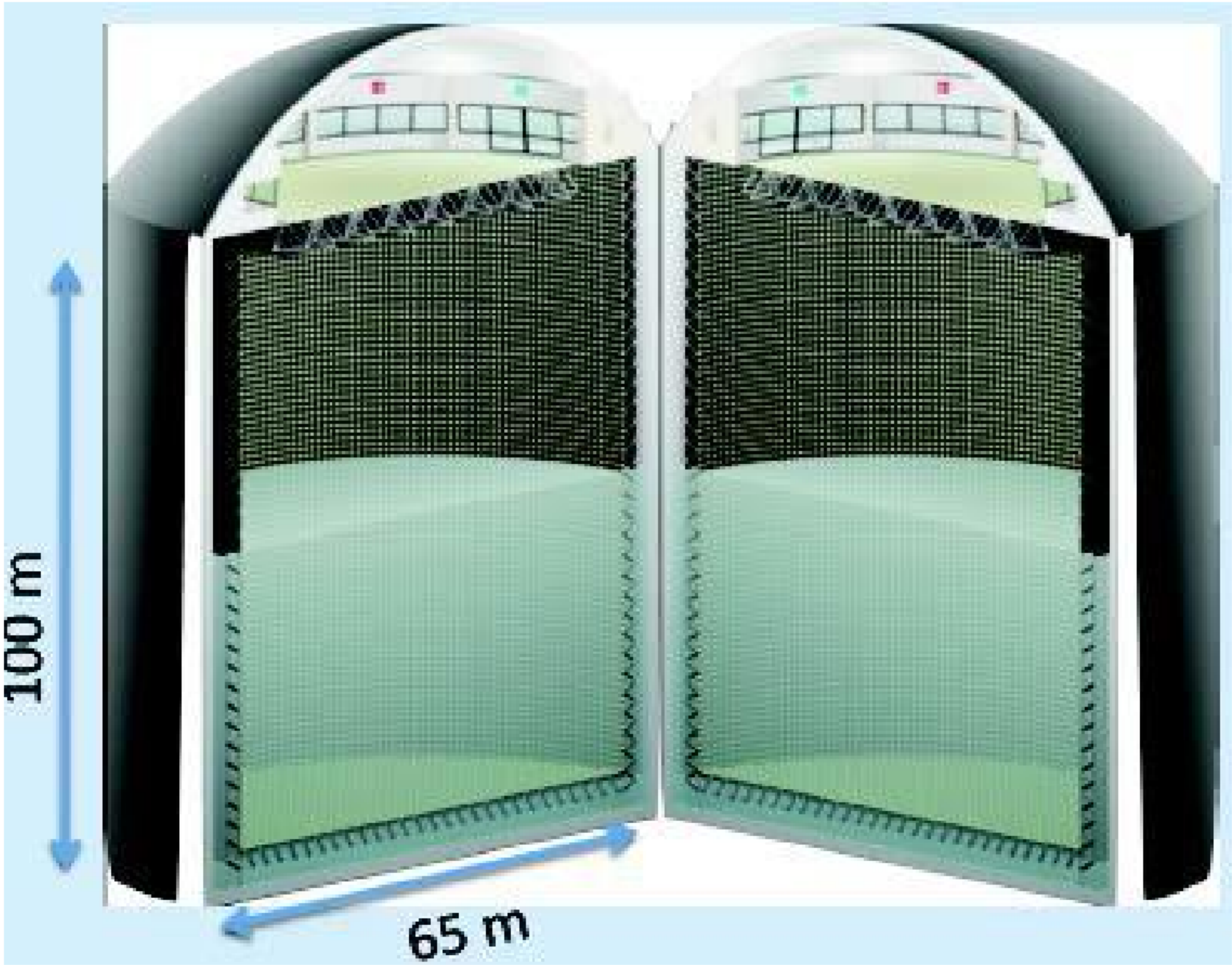
Neutrino production.
Credit: Fermilab

ESSnuSB Far detector

MEMPHYS like Cherenkov detector(MEgaton Mass PHYSics)

- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8” PMTs
- 30% optical coverage

(arXiv: hep-ex/0607026)



δ_{CP} and second oscillation maximum

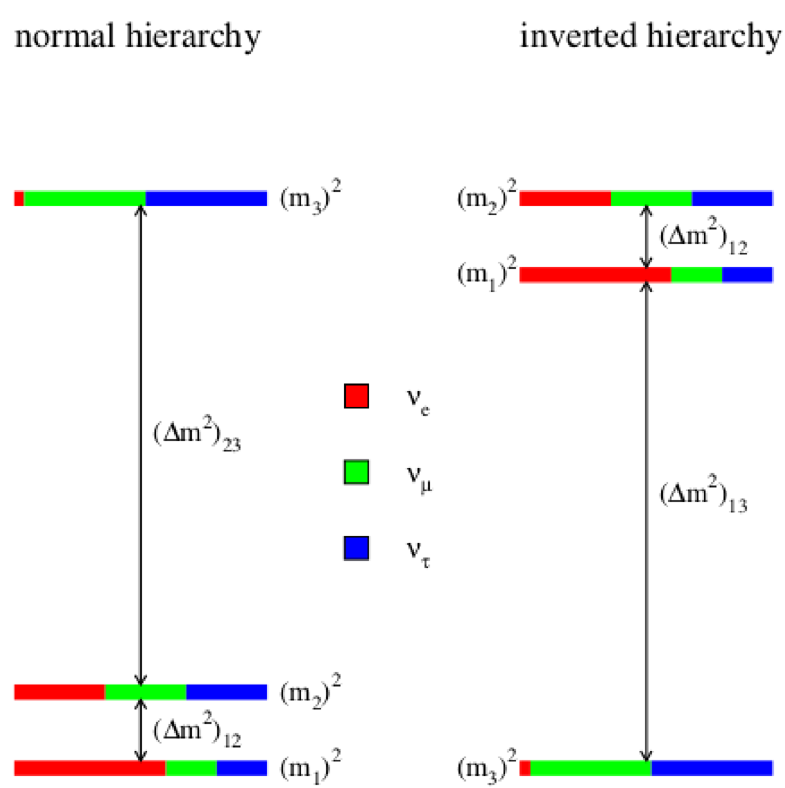
- δ_{CP} still undetermined: range from −180° to +180° allowed at 3σ C.L.
- Octant in which atmospheric mixing angle lies is unknown: $\theta_{23} < 45^\circ$ ($\theta_{23} > 45^\circ$)

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

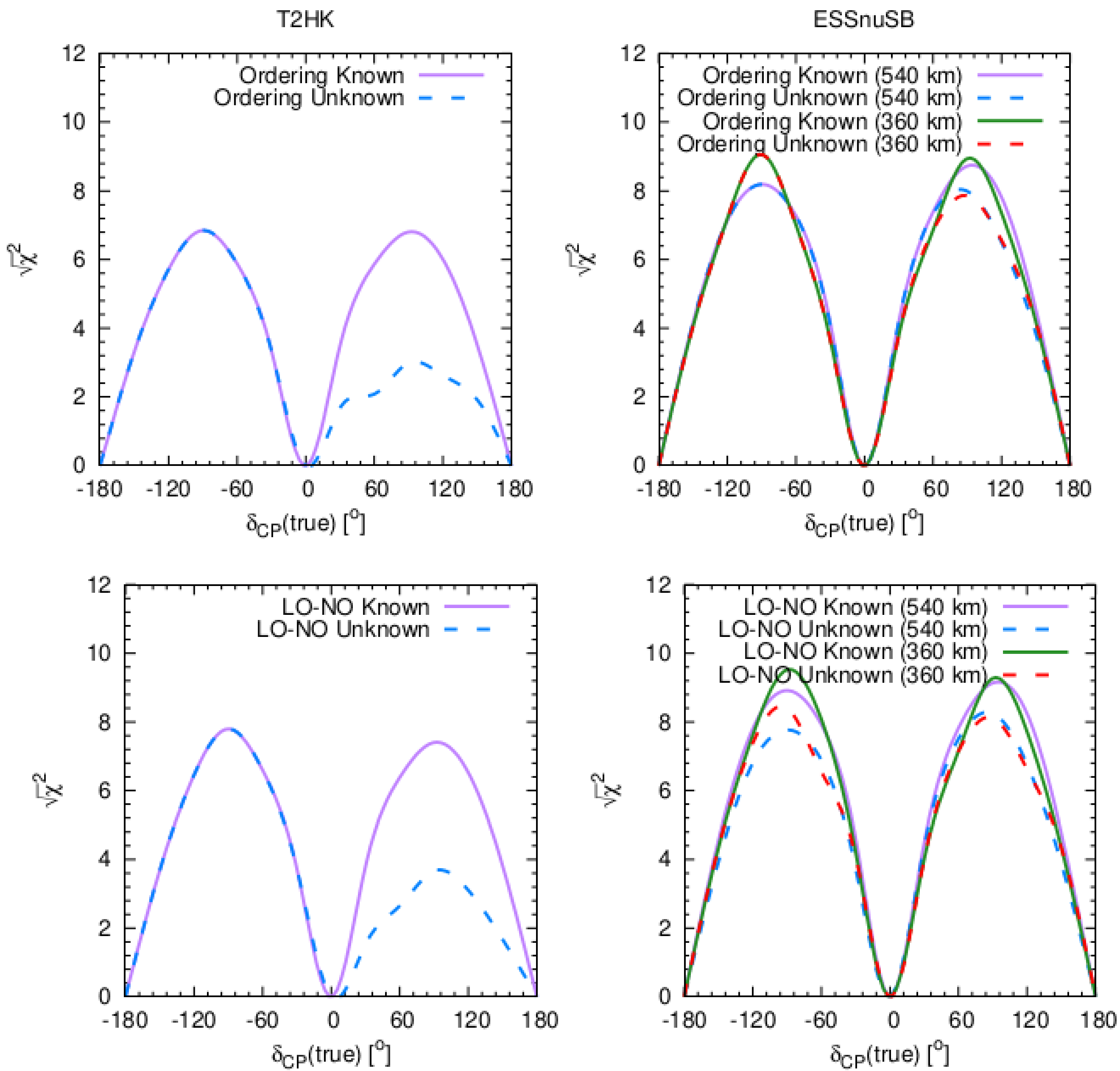
$$\mp \frac{1.27\Delta m_{21}^2 L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

$$J_{CP,l} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{CP}$$

- $J_{CP,l} = 0.033 * \delta_{CP}$
- $J_{CP,q} = 3 \times 10^{-5}$



ESSnuSB Physics Potential



HIBEAM and NNBAR

Motivation in one minute

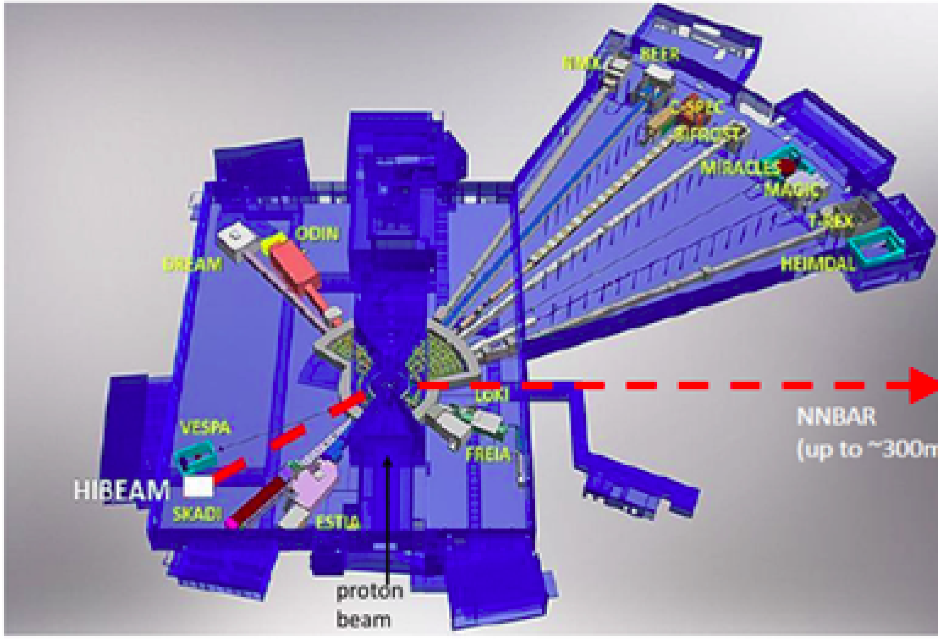
- Free n → nbar oscillation violates baryon number by 2 units
- Baryon number violation essential condition for baryogenesis
- Baryon number an accidental SM symmetry and is broken in extensions
- Neutron oscillations to antineutrons or sterile neutrons unique probe of BNV processes in which only BN is violated.
- Neutron oscillations in SUSY, dark matter (hidden sector), baryogenesis, extra dimensions
- An opportunity to test a global symmetry with three orders of magnitude better precision than previously done is rare. Even rarer to do it in Sweden.

HIBEAM and NNBAR

Staged experiment:

1. HIBEAM
(high intensity baryon extraction and measurement)

- mid to late 2020's
- world leading searches for $n \to n'$
- search for $n \to \bar{n}$ (with lower sensitivity)
- R&D for full experiment.



2. NNBAR

- Extremely high precision searches $n \to \bar{n}$, $n \to n'$
- Improve sensitivity to oscillation probability by a factor ~10^3
- Late 2020's

+ Test beam prototype/bg tests in 2023.

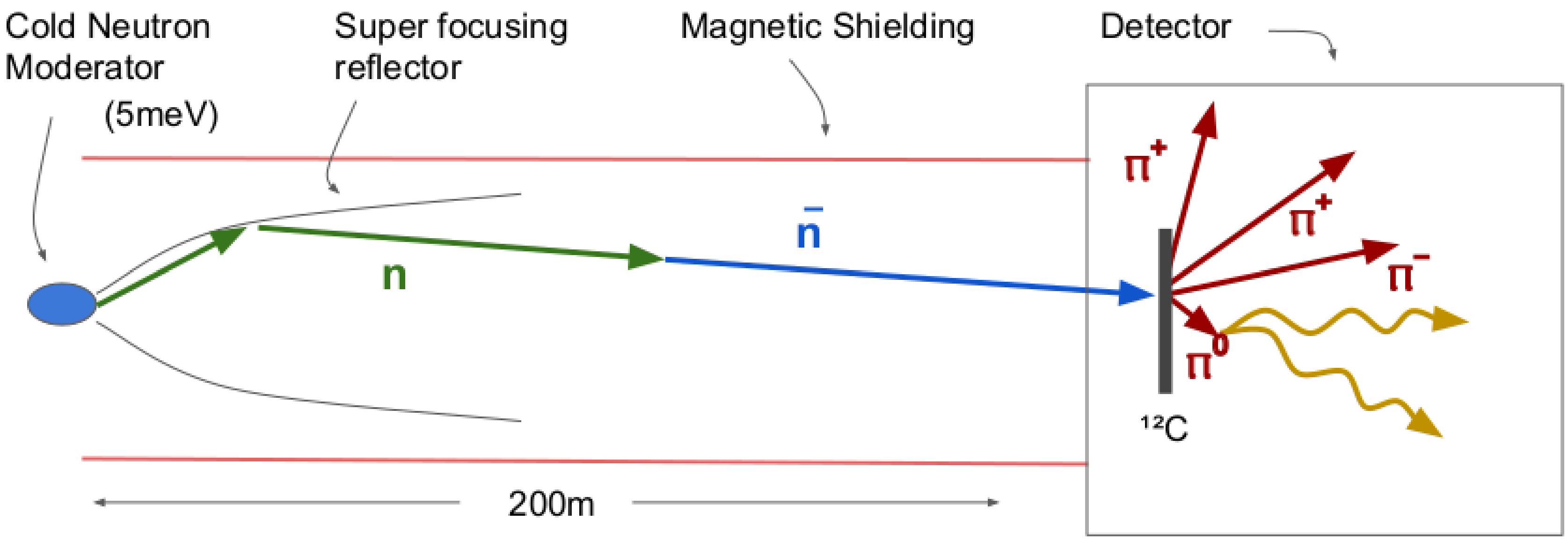
Free NNBAR search

- Goal: observe n → nbar
- Sensitivity 3 orders of magnitude greater than previous experiment
- Strategy: let as many cold neutrons "fly" for as long as possible
- Probability of free neutron transformation into an antineutron:

$$P(\bar{n}, t) = (t / \tau)^2 \qquad \text{FOM} = Nt^2$$

- t → neutron flight time; τ → "oscillation time" (BSM predicted, model dependent)

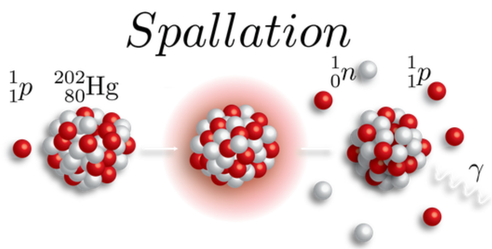
$\tau > 8.7\ 10^7$s (ILL)



Free NNBAR search (cont.)

- Neutrons are bound in nuclei → several MeV for liberation

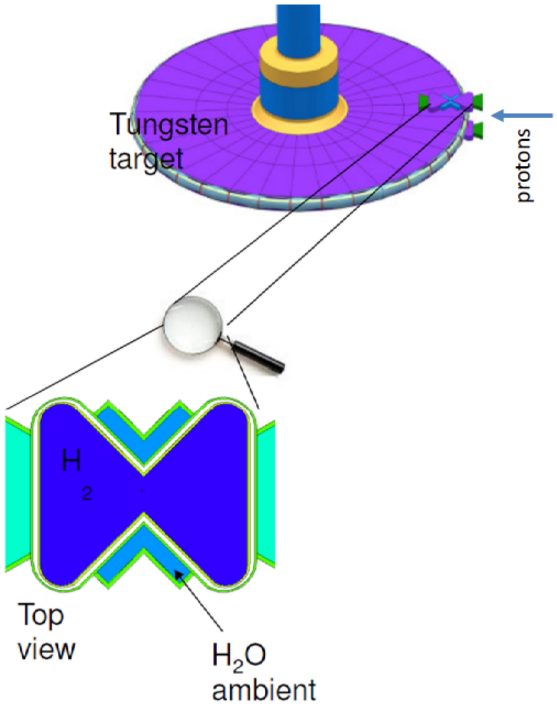
  → fission
  → spallation (can be kept under full control)



Extract of figure from Mads Ry Vogel Jørgensen, Aarhus University

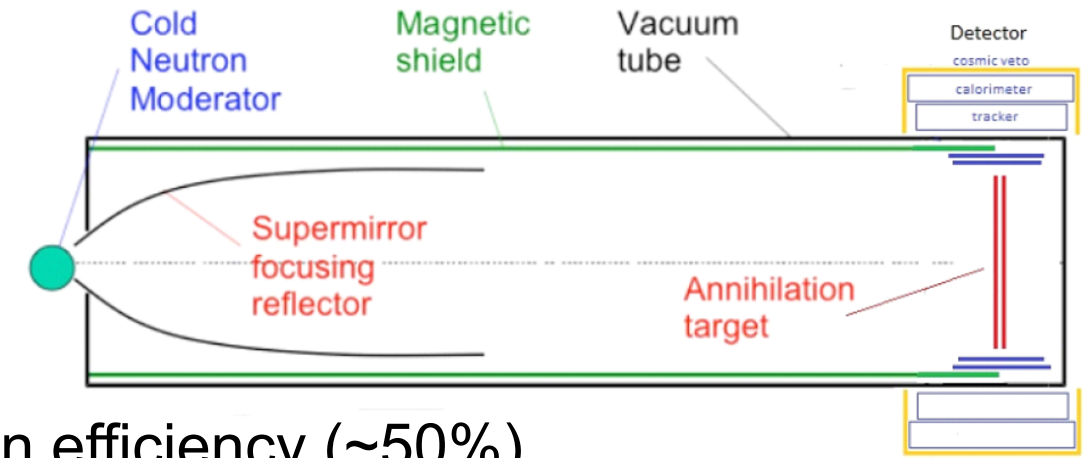
- **To increase *P*:**
- *t* large → slow (a.ka. “cold” → few meV)
  need lots of collisions → moderators
- We also want as many neutrons as possible

  →



NNBAR experiment Conceptual Design

- **Increase number of neutrons**
  - Flux (Moderator brightness and area)
  - Angular acceptance
  - Longer run



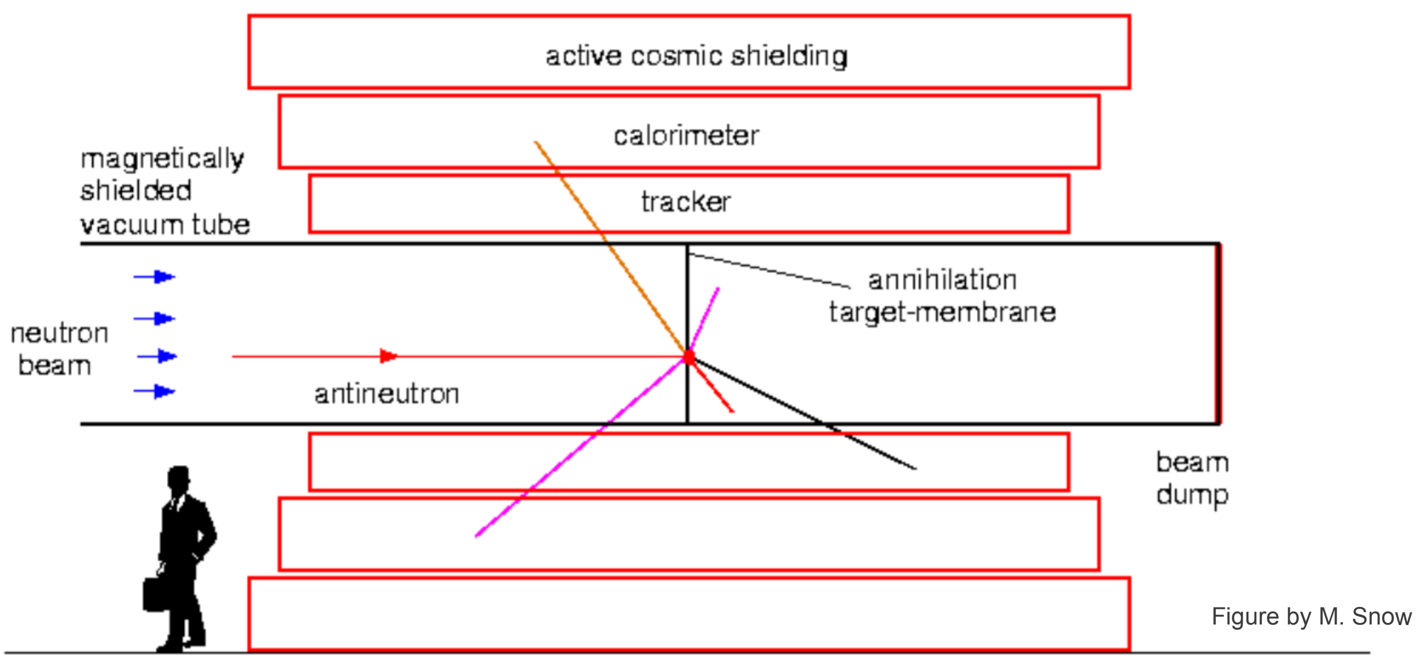
- **Increase time-of-flight**
  - Colder neutrons
  - Longer beamline
- Keep (or even increase) detection efficiency (~50%), keep background at ~0
  - Established hardware and software technologies (NNBAR@ILL in 1994...)
- Better B Earth suppression (B field < 5 nT)
  - Improved passive (+ active?) shield

Potential Gains wrt ILL

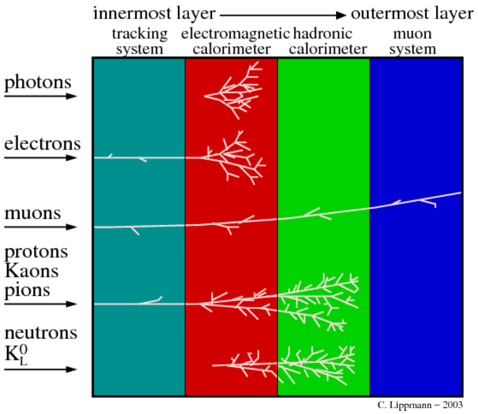
Factor	Gain wrt ILL
Source Intensity	≥ 2
Neutron Reflector	40
Length	5
Run time	3
Total gain	≥ 1000

Detector

- Subsystems annihilation detector (ordered radially outward):
- (i) annihilation target and detector vacuum region;
- (ii) tracker;
- (iii) time of flight systems (before and after the tracker);
- (iv) calorimeter;
- (v) cosmic veto system



Detector design (preliminary ideas!)



- Hadronic cal: plastic scintillators
- Eletromagnetic cal: lead-glass (absorber)
- Tracking: TPC

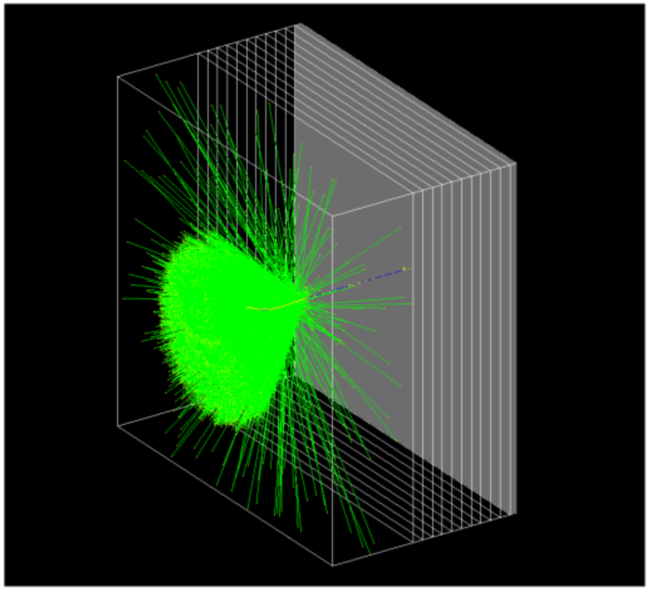
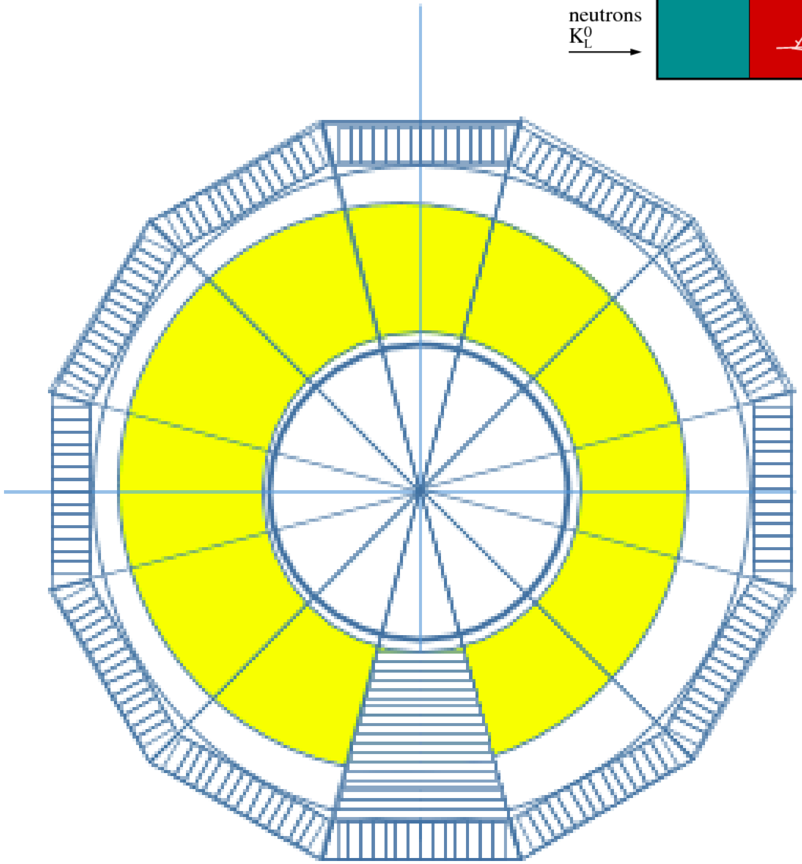


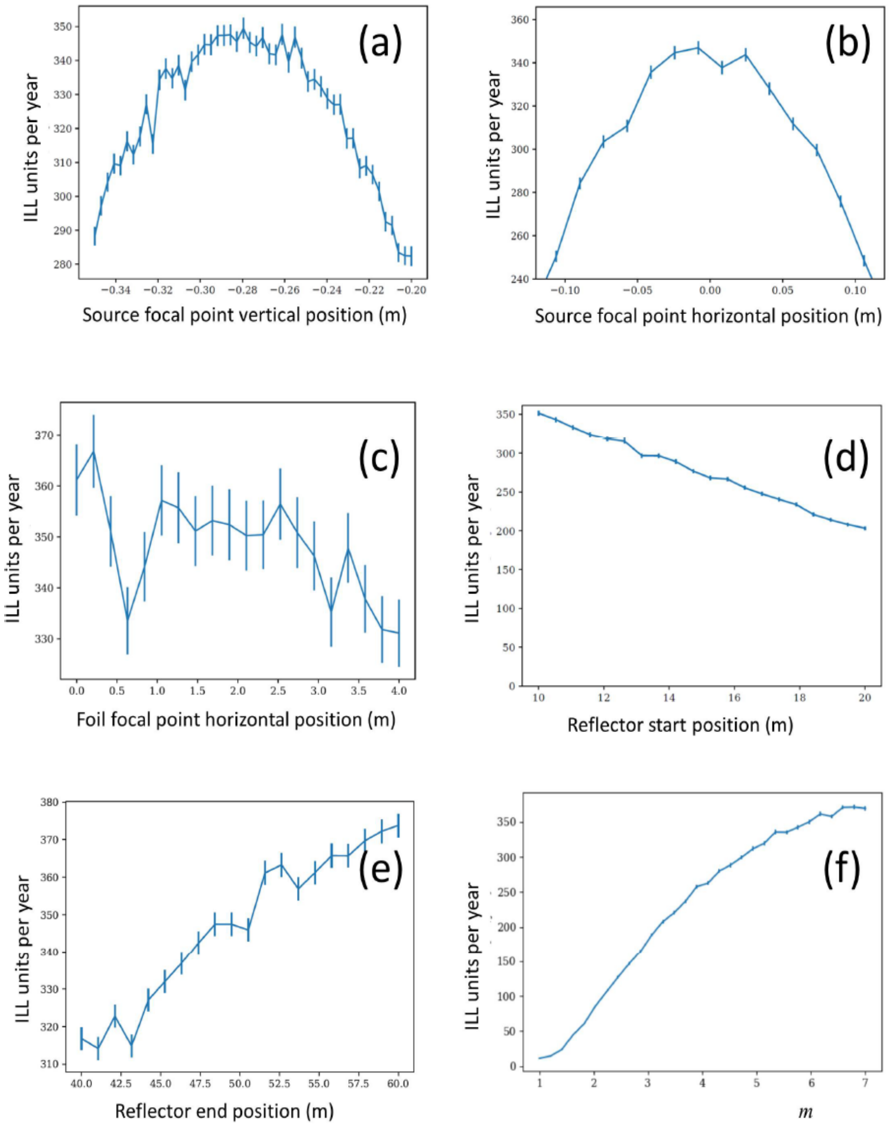
Figure A.35: A GEANT-4 visualisation of a calorimeter module with ten layers of plastic scintillator and a lead-glass block. The Cerenkov photons (green) are shown as is the pion track.



Scintillator layer
Endcap

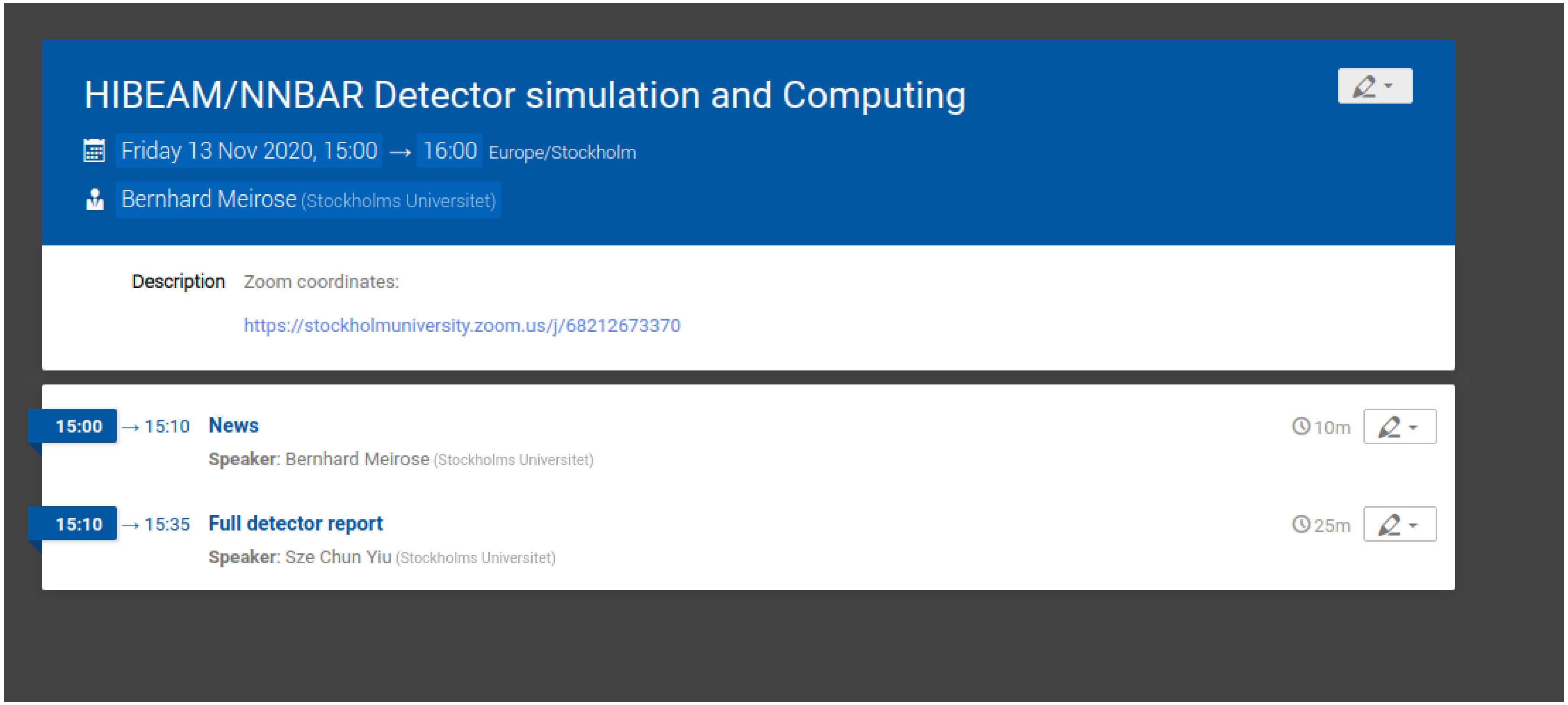
NNBAR sensitivity

- With cold LD moderator
- ~350 ILL units per year
- Conservative assumptions (e.g. low efficiency)
- Room for surprises, e.g., low ESS power.



NNBAR Advertisiment 1

- Detector simulations on Fridays at 15:00



- NNBAR general and technical meetings Mondays at 15:00
- Lists:
- nnbar-general@listserv.nevis.columbia.edu
- nnbar-computing@listserv.nevis.columbia.edu

NNBAR Advertisiment 2

- Partikeldagarna talks:

15. HighNESS and Future Free Neutron Oscillation Searches @ ESS
Valentina Santoro (ESS)
Tuesday afternoon

19. A Neutron-Antineutron Annihilation Detector for the NNBAR Experiment
Katherine Dunne (Stockholm Universit...)
Wednesday morning

23. Cosmic ray backgrounds at the NNBAR experiment
Sze Chun Yiu (Stockholm University)
Wednesday morning

NNBAR Advertisiment 3

arXiv.org > physics > arXiv:2006.04907

Search...

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Physics > Instrumentation and Detectors

[Submitted on 8 Jun 2020]

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

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The violation of Baryon Number, $\mathcal{B}$, is an essential ingredient for the preferential creation of matter over antimatter needed to account for the observed baryon asymmetry in the universe. However, such a process has yet to be experimentally observed. The HIBEAM/NNBAR %experiment program is a proposed two-stage experiment at the European Spallation Source (ESS) to search for baryon number violation. The program will include high-sensitivity searches for processes that violate baryon number by one or two units: free neutron-antineutron oscillation ($n \to \bar{n}$) via mixing, neutron-antineutron oscillation via regeneration from a sterile neutron state ($n \to [n', \bar{n}'] \to \bar{n}$), and neutron disappearance ($n \to n'$); the effective $\Delta\mathcal{B} = 0$ process of neutron regeneration ($n \to [n', \bar{n}'] \to n$) is also possible. The program can be used to discover and characterise mixing in the neutron, antineutron, and sterile neutron sectors. The experiment addresses topical open questions such as the origins of baryogenesis, the nature of dark matter, and is sensitive to scales of new physics substantially in excess of those available at colliders. A goal of the program is to open a discovery window to neutron conversion probabilities (sensitivities) by up to three orders of magnitude compared with previous searches. The opportunity to make such a leap in sensitivity tests should not be squandered. The experiment pulls together a diverse international team of physicists from the particle (collider and low energy) and nuclear physics communities, while also including specialists in neutronics and magnetics.

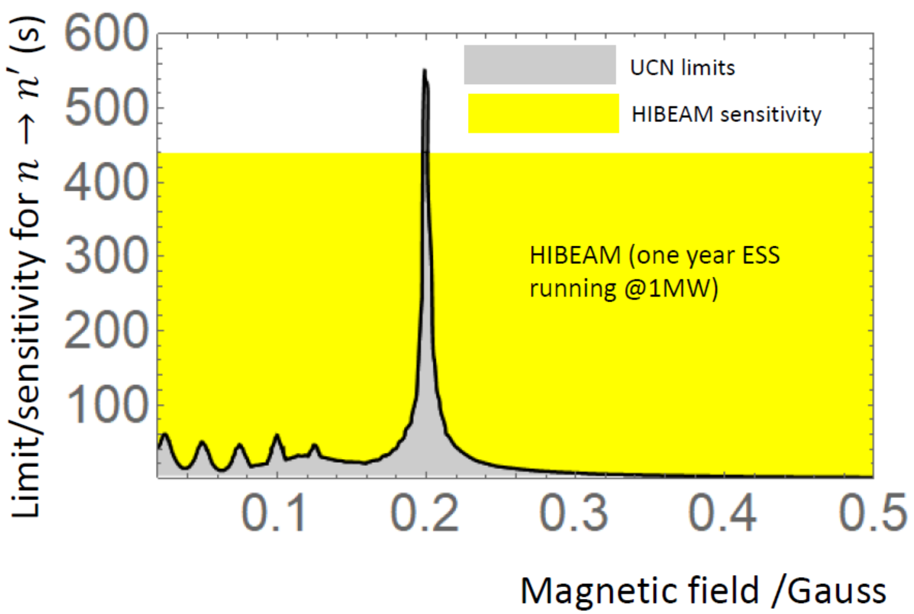
Summary

- Several great opportunities and exciting particle physics experiments can (and I hope will!) be realized at ESS
- Experiments are complementary to the LHC program and offers the opportunity to discover BSM physics with very signficant impact
- I focused on just a few experiments (neglected most of UCN)
- Fundamental physics beamline at ESS

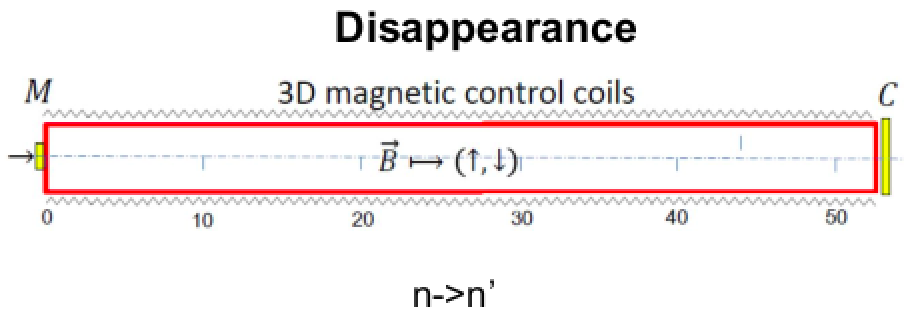
  → Sweden((and Lund!) in particle physics world map
- You can ask me or find online conatcts for all experiements
- For NNBAR and HIBEAM feel free to contact me :-)

BACKUP

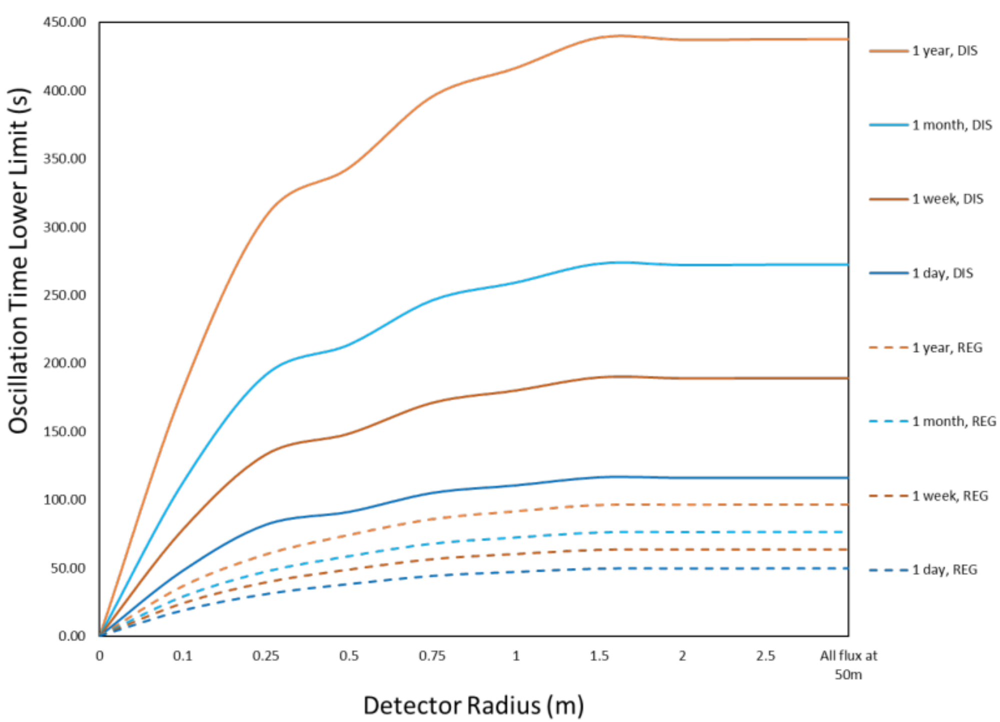
HIBEAM: n⟶n'



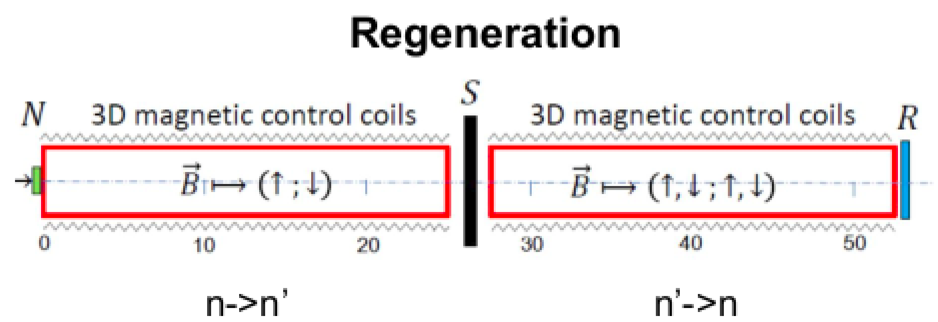
Limit/sensitivity for $n \to n'$ (s)
600
500
400
300
200
100
UCN limits
HIBEAM sensitivity
HIBEAM (one year ESS running @1MW)
0.1
0.2
0.3
0.4
0.5
Magnetic field /Gauss



Disappearance
M
3D magnetic control coils
C
$\vec{B} \mapsto (\uparrow, \downarrow)$
0
10
20
30
40
50
n->n'



Oscillation Time Lower Limit (s)
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0
0.1
0.25
0.5
0.75
1
1.5
2
2.5
All flux at 50m
Detector Radius (m)
1 year, DIS
1 month, DIS
1 week, DIS
1 day, DIS
1 year, REG
1 month, REG
1 week, REG
1 day, REG



Regeneration
N
3D magnetic control coils
S
3D magnetic control coils
R
$\vec{B} \mapsto (\uparrow ; \downarrow)$
$\vec{B} \mapsto (\uparrow, \downarrow ; \uparrow, \downarrow)$
0
10
20
30
40
50
n->n'
n'->n