Physics with Slow Neutron Beams at Gamma Factory

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MITP Topical Workshop:
"Physics Opportunities with the Gamma Factory"

What are the neutron source properties one wants for this physics?
What are the physics topics addressed using slow neutrons now?
What areas might be promising to investigate for the gamma factory?

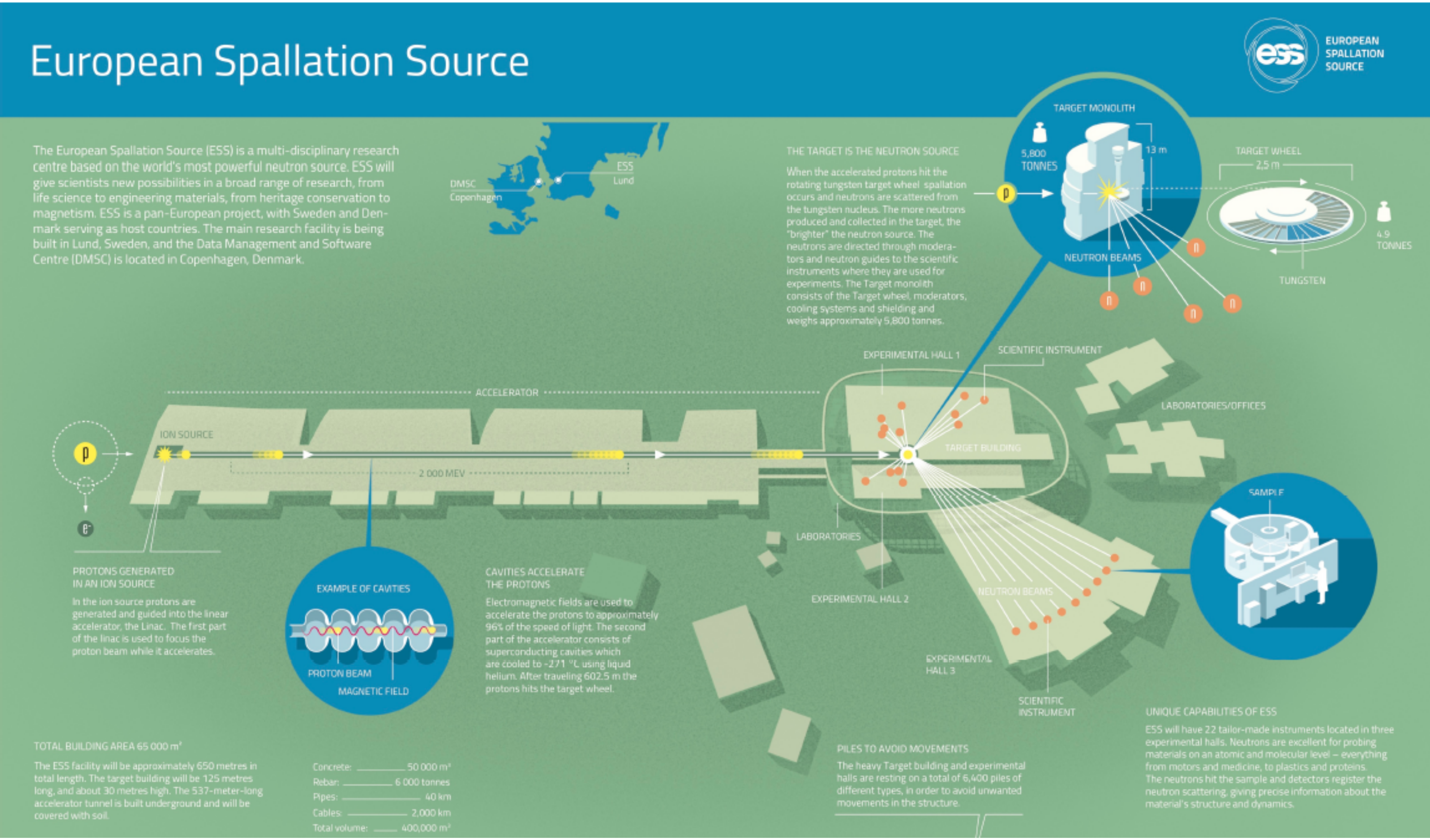
Reviews:

J. Nico and W. M. Snow, Annual Reviews of Nuclear and Particle Science **55**, 27-69 (2005).
H. Abele, Progress in Particle and Nuclear Physics **60**, 1-81 (2008).
D. Dubbers and M. Schmidt, Reviews of Modern Physics **83**, 1111 (2011).
W. M. Snow, Physics Today **66**, 50 (2013).

Neutrons at the Gamma Factory?

Neutrons with the expected intensity reaching **10^{15} neutrons/s** (first generation neutrons) and radioactive, neutron-rich ions with the intensity reaching 10^{14} ions/s. Preliminary estimates show that the intensity of the Gamma Factory beams of neutrons and radioactive ions **could approach** those of the European projects under construction, like **ESS** (and FAIR) and the planned EURISOL facility.

The Gamma Factory beams may turn out to be more effective in terms of their power consumption efficiency since almost 10% of the LHC RF power could be converted into the power of the neutron and radioactive ion beams if **the energy of the photon beam is tuned to the Giant Dipole Resonance (GDR) region of the target nuclei.**



5MW "long-pulsed" spallation neutron source
Rotating W spallation target

~3 msec pulses, 2 GeV proton linac, 14 Hz rep rate

Advantages of Slow Neutrons for Nuclear/Particle/Astrophysics

zero electric charge, ~zero electric dipole moment, small electric polarizability, small magnetic dipole moment

-> negligible decoherence from environment

-> precision tests of symmetry principles are possible

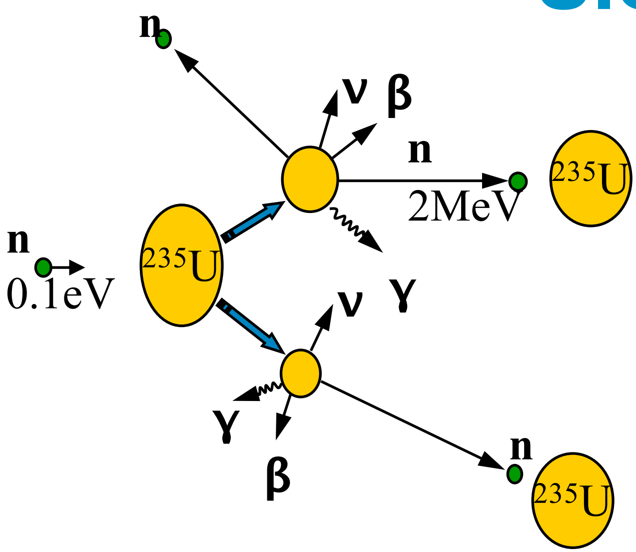
Slow decay rate, strong interaction with nucleus

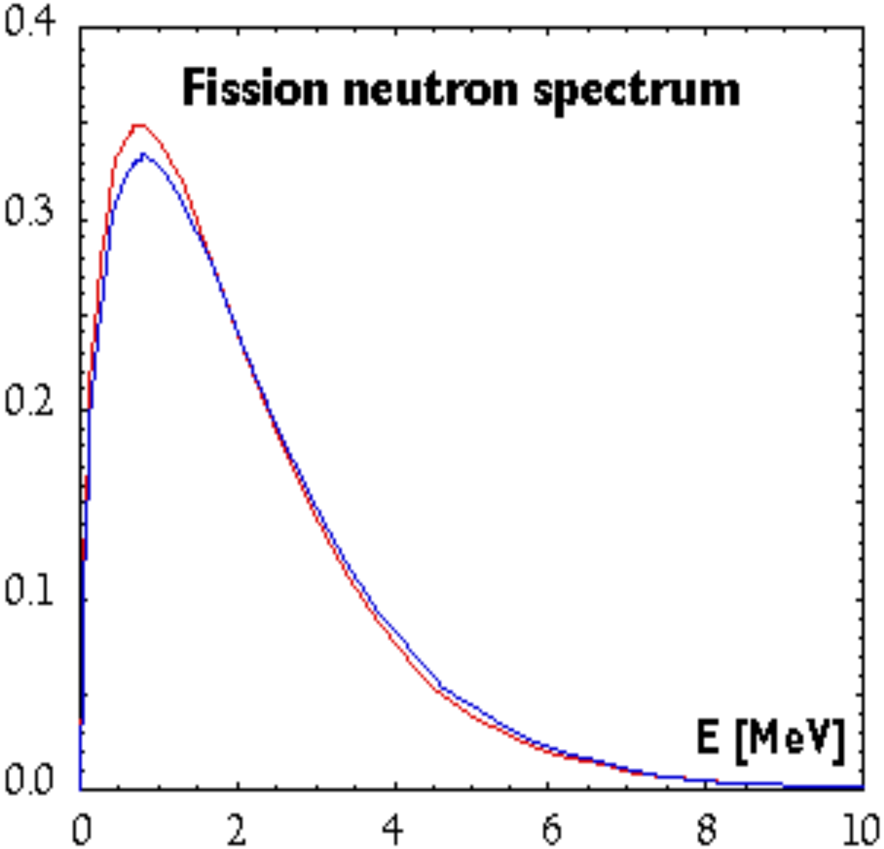
-> timescales relevant for Big Bang Cosmology

-> can use near-threshold n-A resonances as an “amplifier” of symmetry violation

To use free neutrons: need to liberate and cool them

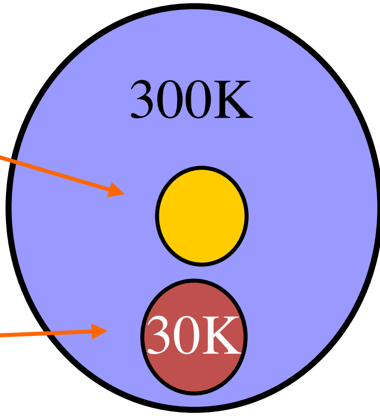
"Slow" Neutrons: MeV to neV

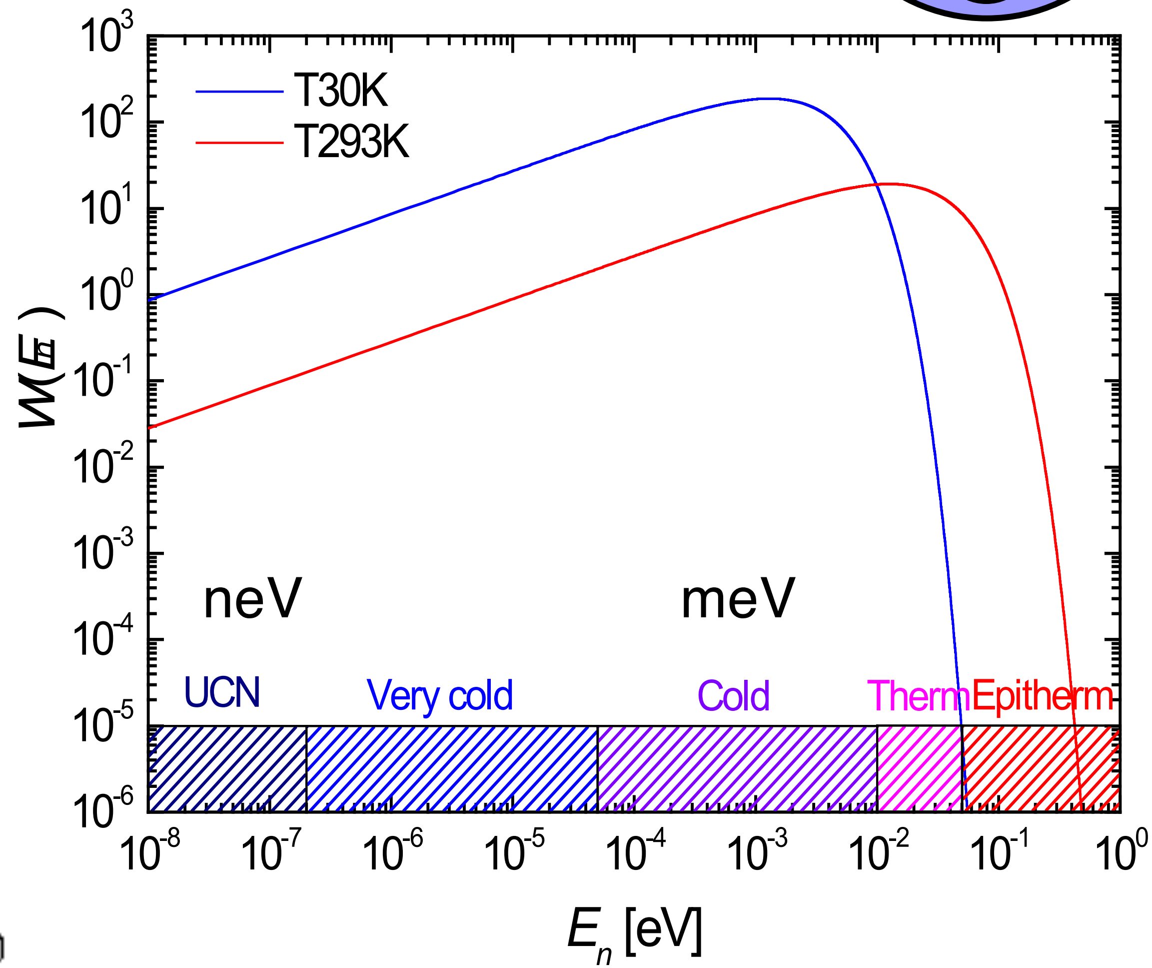




Nuclear reactor/
Spallation source

Neutron Moderator
(LH2, LD2)





Potential step -> neutron index of refraction

with

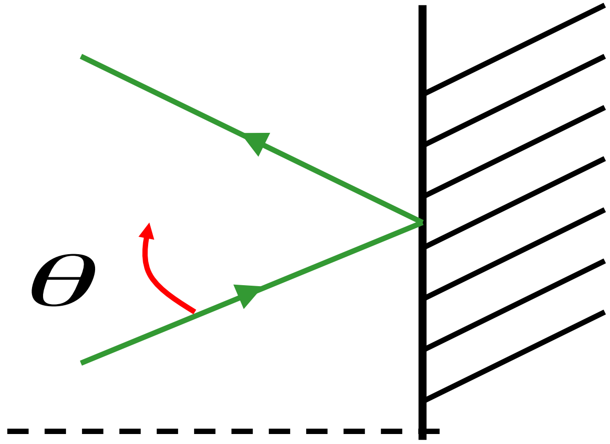
$$V_0 = \frac{2\pi a\hbar^2 n_0}{m_n}$$

$$n = \sqrt{1 - \frac{V_0}{E_n}}$$

E_n ← **Neutron kinetic energy**

If a > 0, total external reflection

$$\mathbf{n_{out} = 1}$$



$$\mathbf{n_{in} = \sqrt{1 - \frac{V_0}{E}}}$$

All forces contribute to the neutron optical potential:

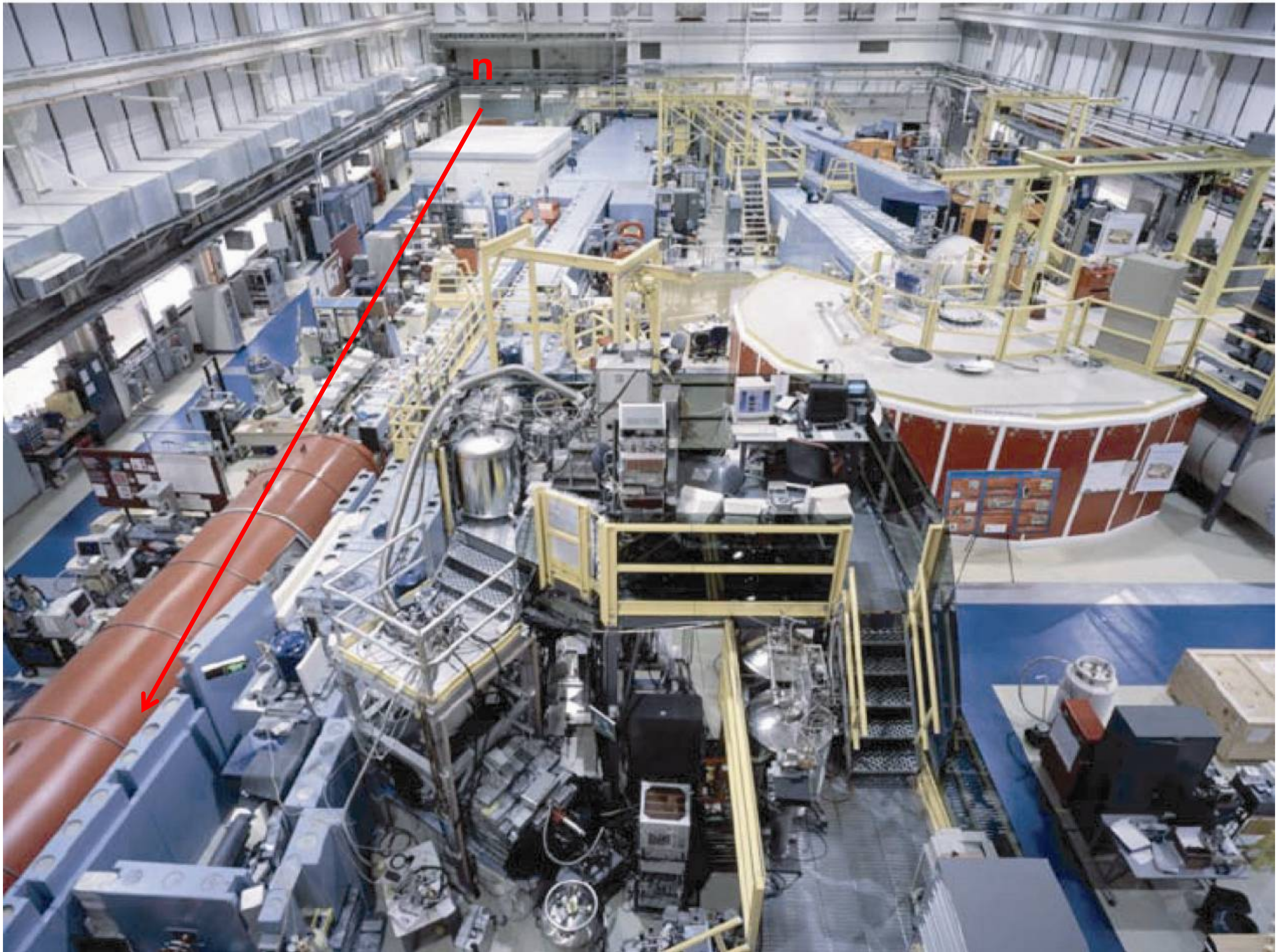
$\langle V_{strong}\rangle = 2\pi h^2 \rho b_s/m$, ~+/- 100 neV

$\langle V_{mag}\rangle = \mu B$, ~+/- 60 neV/Tesla

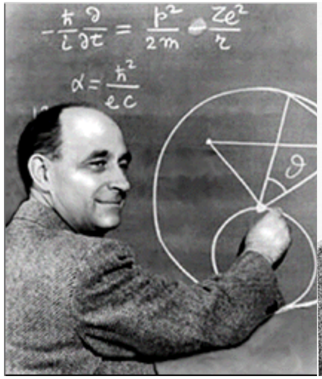
$\langle V_{grav}\rangle = mgz$ ~100 neV/m

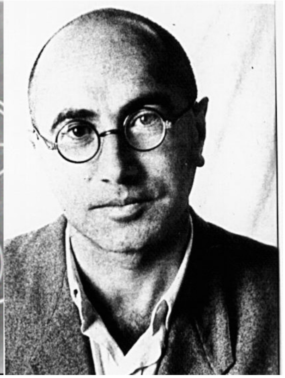
$\langle V_{weak}\rangle = [2\pi h^2 \rho b_w/m] s\cdot k/|k| \sim 10^{-7} \langle V_{strong}\rangle$

Cold Neutron Guide Hall at NIST



Ultra-Cold Neutrons (UCN) (Fermi/Zeldovich)

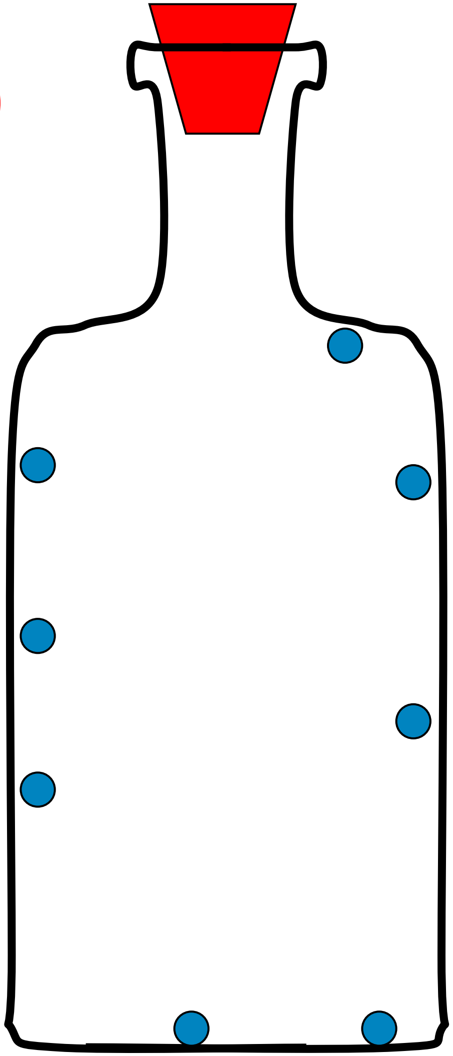




- What are UCN ?
  - Very slow neutrons

($v < 8$ m/s, $\lambda > 500$ Å, $E<V_{optical}$)

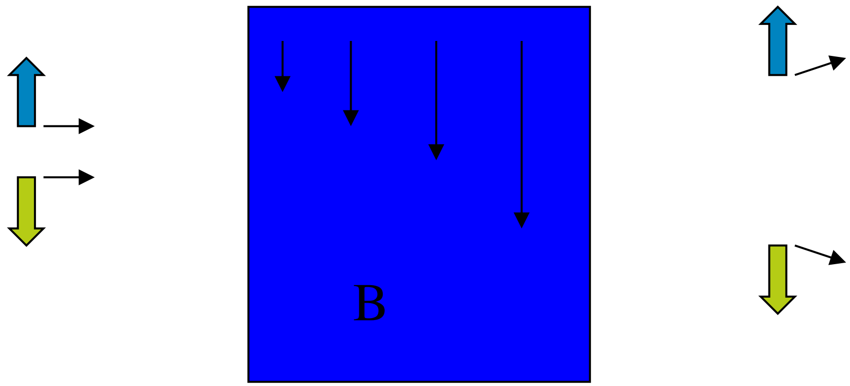
that cannot penetrate into certain materials



Neutrons can be trapped in material bottles or by magnetic fields

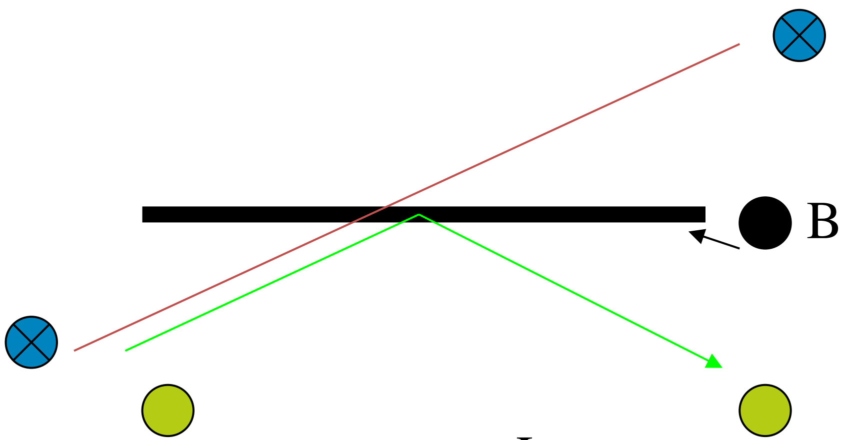
Many interesting nuclear/particle/astrophysics neutron expts. use UCN

What methods are used to polarize neutrons?



B gradients (Stern-Gerlach, sextupole magnets) electromagnetic

$F=(\mu\bullet\nabla)B$

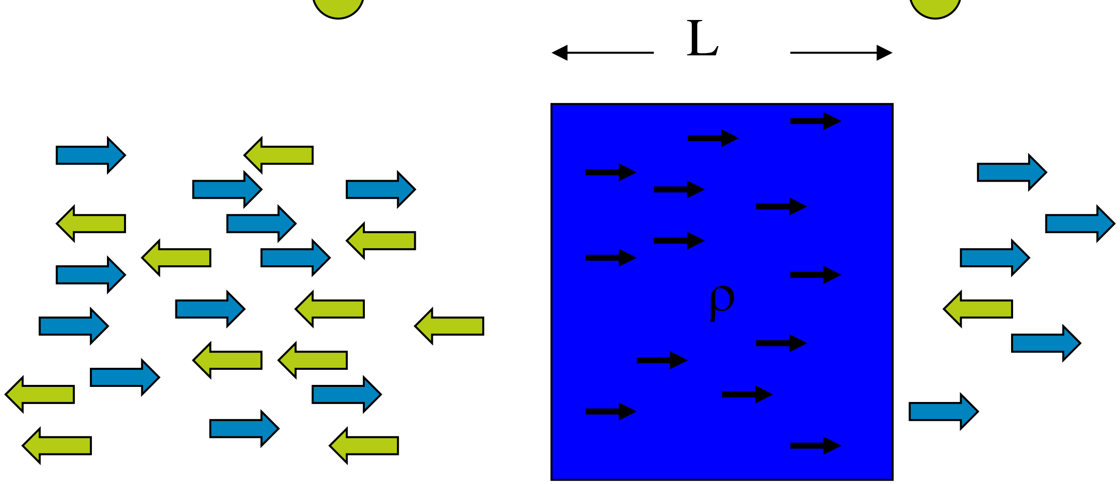


Reflection from magnetic mirror: electromagnetic+ strong

$f\pm=a(\text{strong})\ +/-\ a(\text{EM})$

with $|a(\text{strong})|=|a(\text{EM})|$

$\Rightarrow f+=2a,\ f-=0$

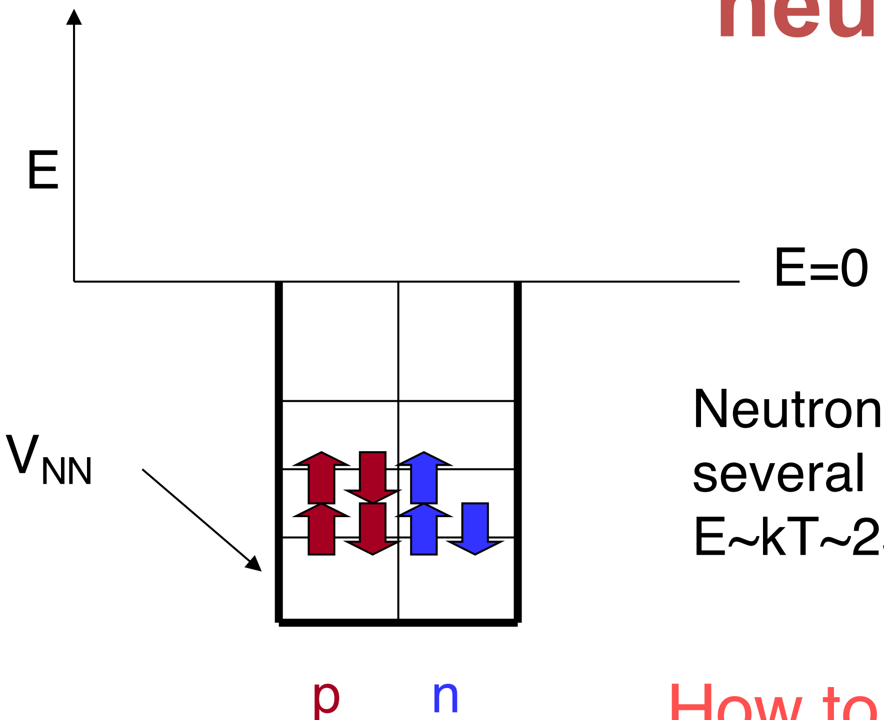


Transmission through polarized nuclei: strong

$\sigma+\neq\sigma- \Rightarrow T+\neq T-$

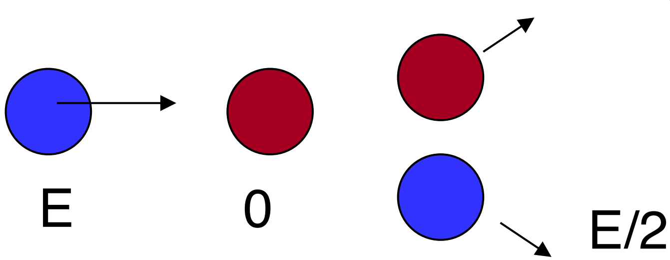
Spin Filter: $T_{\pm}=\exp[-\rho\sigma_{\pm}L]$

Why is it such hard work to get slow neutrons?



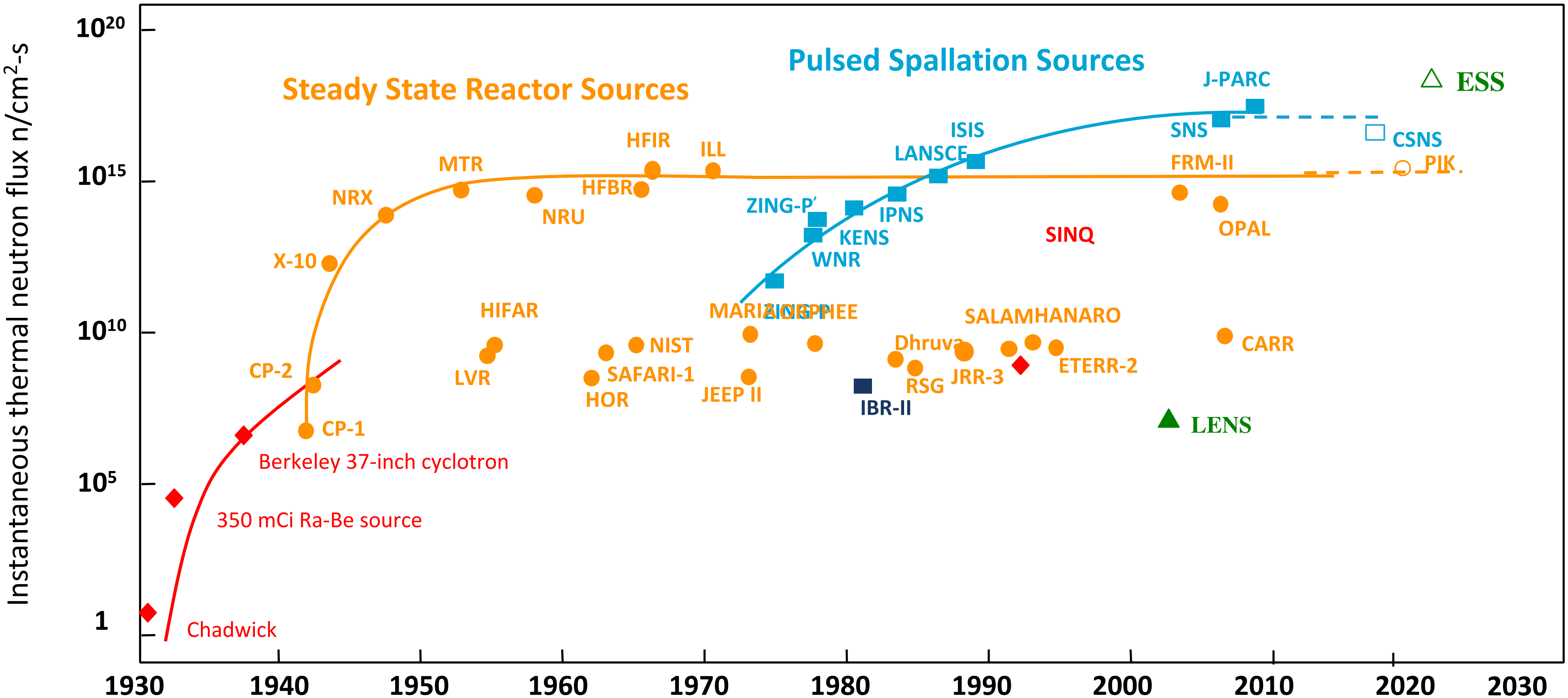
Neutrons are bound in nuclei, need several MeV for liberation. We typically want E~kT~25 meV (room temperature) or less

How to slow down a heavy neutral particle with $M_n = M_p$? Lots of collisions…



$[1/2]^N$=(1-100 MeV)/(25 meV) for N collisions. N~20

Slow Neutron Source Brightness: (very) slow rise



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

Why so flat?

Reactor core/spallation target heat transfer limit: target melts

Conservation of baryon #

No courage to try fission multiplier (Dubna?)

Existing (gamma, n) photoneutron sources: lower/not on the plot

- Fission reactors
- Particle driven (pulsed)
- Particle driven (long pulse)
- Particle driven (steady state)
- Pulsed reactor

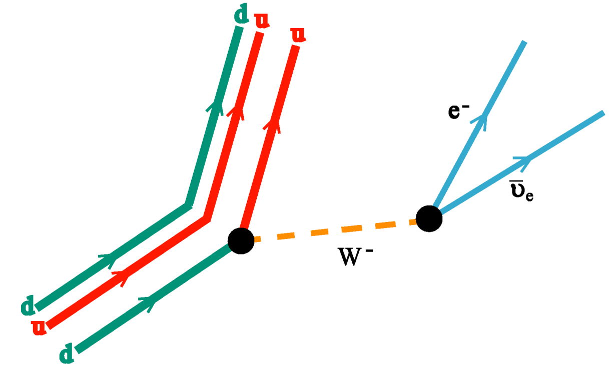
Neutrons at the Gamma Factory?

almost 10% of the LHC RF power could be converted into the power of the neutron and radioactive ion beams if **the energy of the photon beam is tuned to the Giant Dipole Resonance (GDR) region of the target nuclei.**

Questions/considerations:

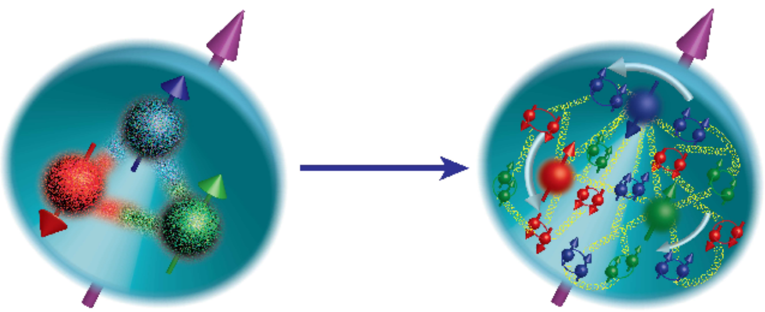
(1) CW, or possibility of pulsed operation ~10-100 Hz? (latter is regime needed for slow neutron TOF energy measurement)
(2) Efficiency of (gamma, n) conversion for GDR excitation?
(3) Other ideas to consider:
(a) deuteron photodisintegration JUST above threshold: neutron can emerge "already slow" [~keV]
(b) Choose one of the many sharp (gamma, n) resonances in heavy nuclei [natural widths ~100 meV, Doppler-broadened widths ~eV, some of these resonances close to the unitarity limit]

Recent Particle Physics with Slow Neutrons: Four Main Scientific Areas



Neutron beta decay:
Weak interaction physics/cosmology

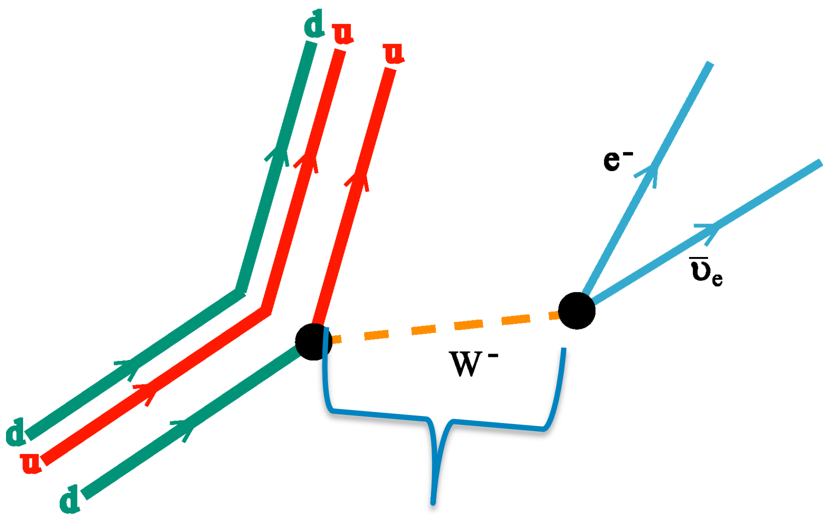
Neutron-neutron/neutron-proton weak interactions:
Strong interaction physics \computational frontier



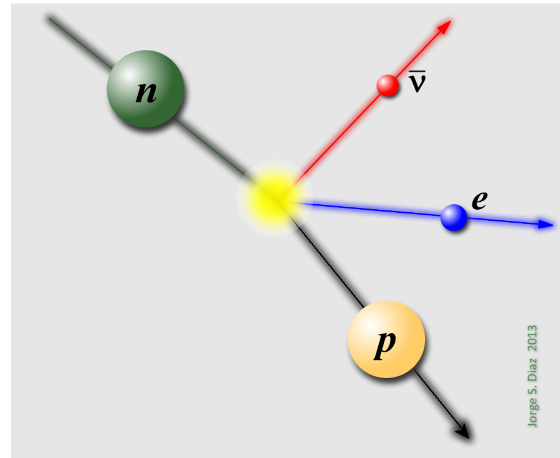
Searches for T and B violation:
BSM/Cosmology

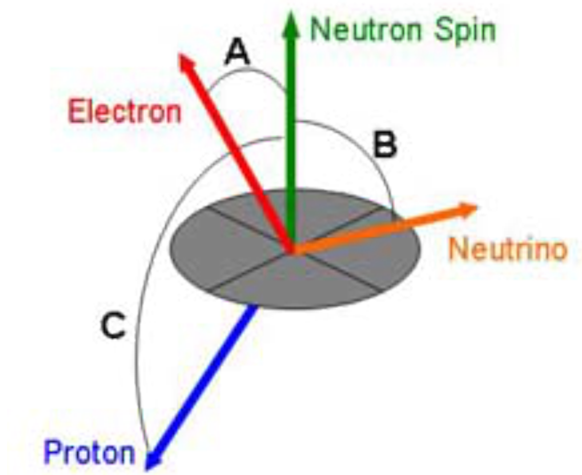
Searches for light, weakly-coupled particles:
BSM/Cosmology

Neutron β-decay: an "80 GeV event"



distance exaggerated here
by factor ~100





amplitude for
beta decay
process

$$= \frac{1}{M_W^2} \bar{\psi}_\nu \bar{\psi}_e \psi_u \psi_d$$

M_W~80 GeV

Measurement of neutron decay correlation to 10^{-4} precision is sensitive to new physics at a scale ~10 TeV

uses the simplest three-quark bound state (->theory is clean)

Classical Theory of Weak Decay

Standard Model for neutron decay:

$$H = \frac{G_F}{\sqrt{2}} V_{ud} \quad \bar{p} \left\{ \gamma_\mu (1 + \lambda\gamma_5) + \frac{\mu_p - \mu_n}{2m_p} \sigma_{\mu\nu} q^\nu \right\} n \quad \bar{e}\gamma^\mu (1 - \gamma_5) \nu_e$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = U_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$U_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta$$

Unitarity of CKM matrix

Expression for neutron lifetime in Standard Model

Very active research area!

$$\tau^{-1} = V_{ud}^2 G_F^2 (1 + 3\lambda^2) \frac{f^R m_e^5 c^4}{2\pi^3 \hbar^7}$$

Deviations from CKM unitarity at ~few sigma level: stay tuned

Big Bang nucleosynthesis

1 µs

Thermal equilibrium
(T > 1 MeV)

$$\frac{n}{p} \propto e^{-Q/T}$$

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$$n + \nu_e \leftrightarrow p + e^-$$

1 s

After freezeout
n/p decreases due to
neutron decay

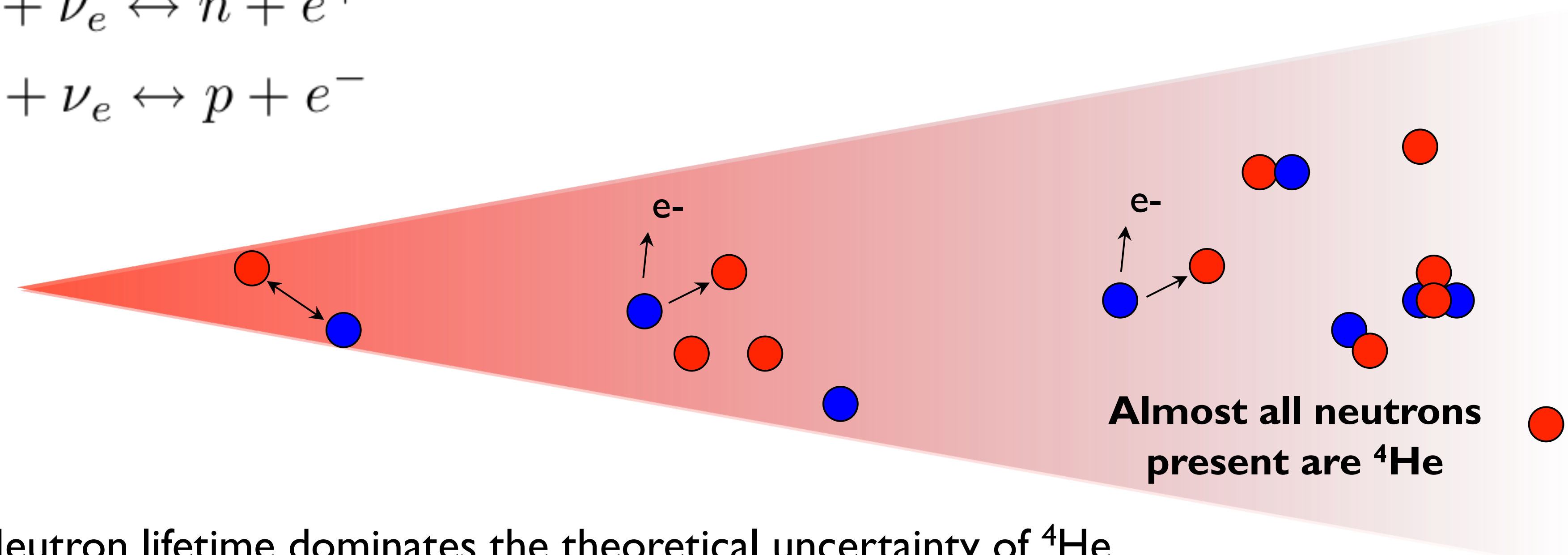
$$n \rightarrow p + e^- + \bar{\nu}_e$$

100s

Nucleosynthesis (T~0.1 MeV)
Light elements are formed

$$p + n \rightarrow d + \gamma$$

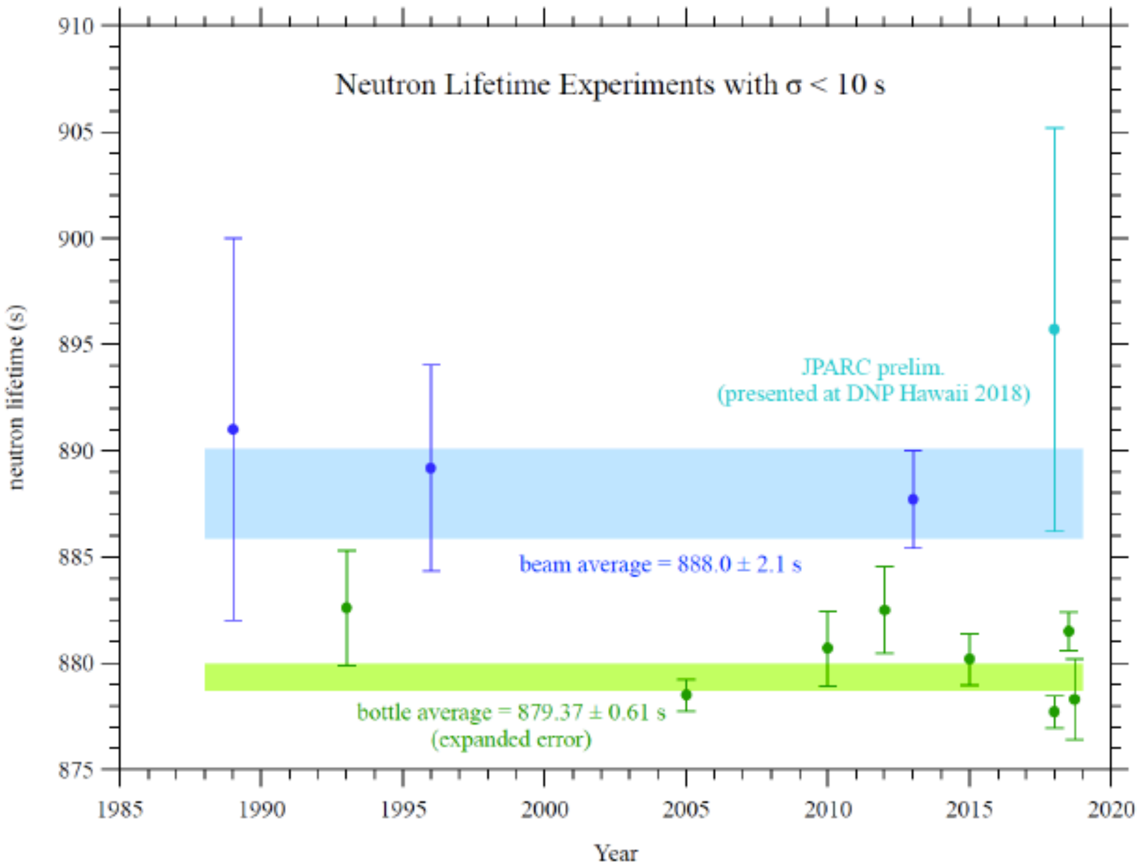
$$d + d \rightarrow {}^4\mathrm{He} + \gamma$$

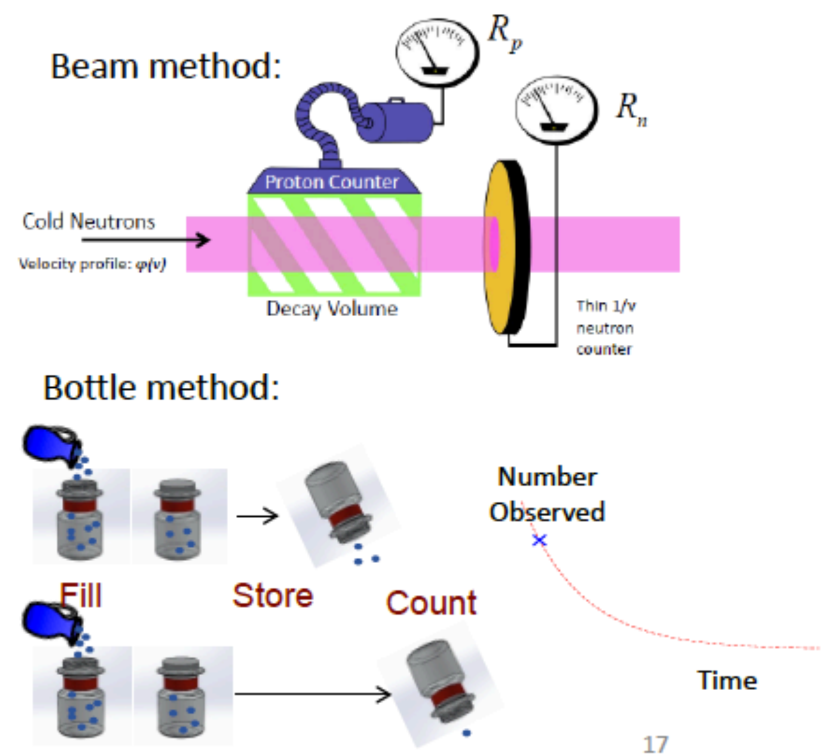


Neutron lifetime dominates the theoretical uncertainty of ^{4}He abundance.
As microwave background measurements improve: chance to learn something new

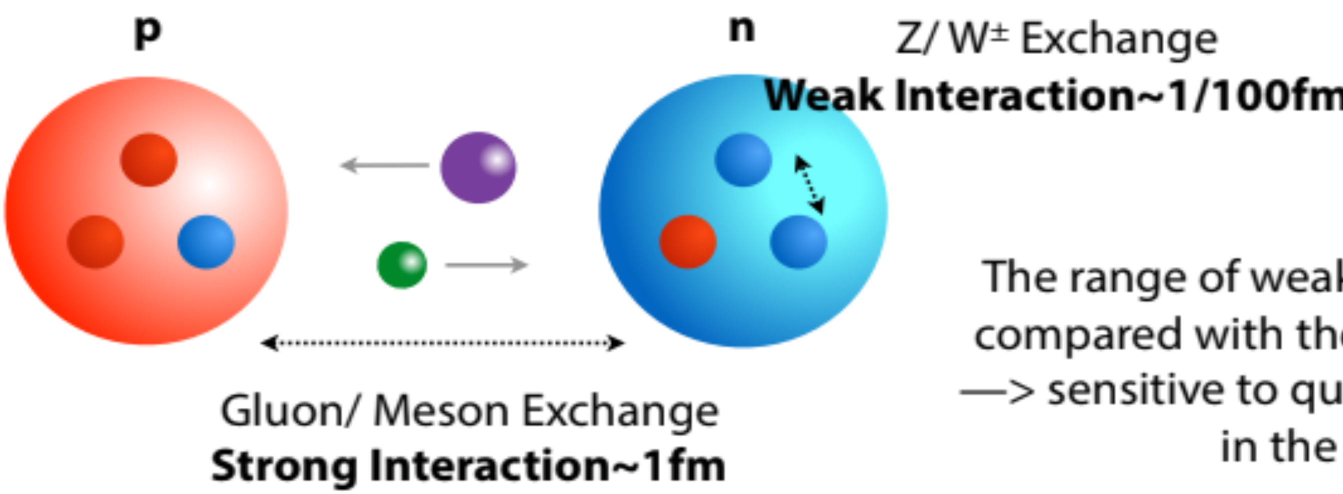
However, there is a unresolved discrepancy between two leading methods to measure the neutron lifetime.

The Situation Today - 2019





Weak Interaction in Hadronic Systems: “computational frontier” of QCD



The range of weak interaction is short compared with the size of the nucleon —> sensitive to quark-quark correlation in the nucleon

The weakness of the weak interaction leaves the ground state nucleons unchanged. Weak interaction violates parity, strong interaction conserves parity

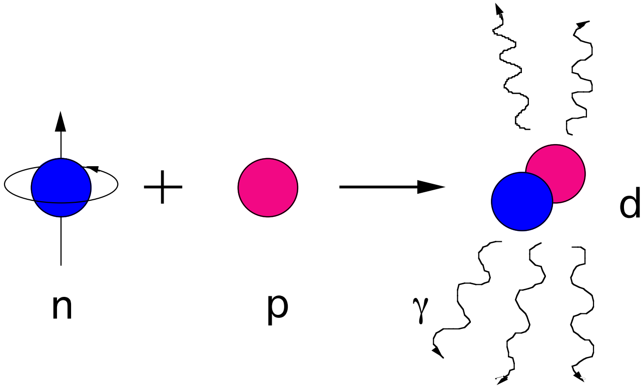
Weak NN interactions are first-order sensitive to quark-quark correlations

Nucleon-nucleon (NN) weak interactions can provide a unique test of QCD in the low energy limit. Lattice gauge theory can calculate this with exascale computers

SciDAC Scientific Discovery through Advanced Computing

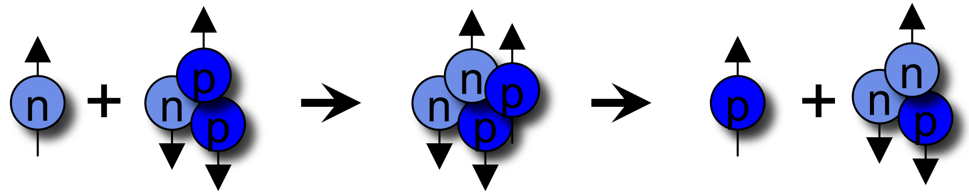
FASTMATH

Example P-odd Observables in n-p, n-^{3}He, and n-^{4}He



$$\vec{\sigma}_n \cdot \vec{k}_\gamma$$

Blyth et al (NPDGamma), PRL **121**, 242002 (2018)

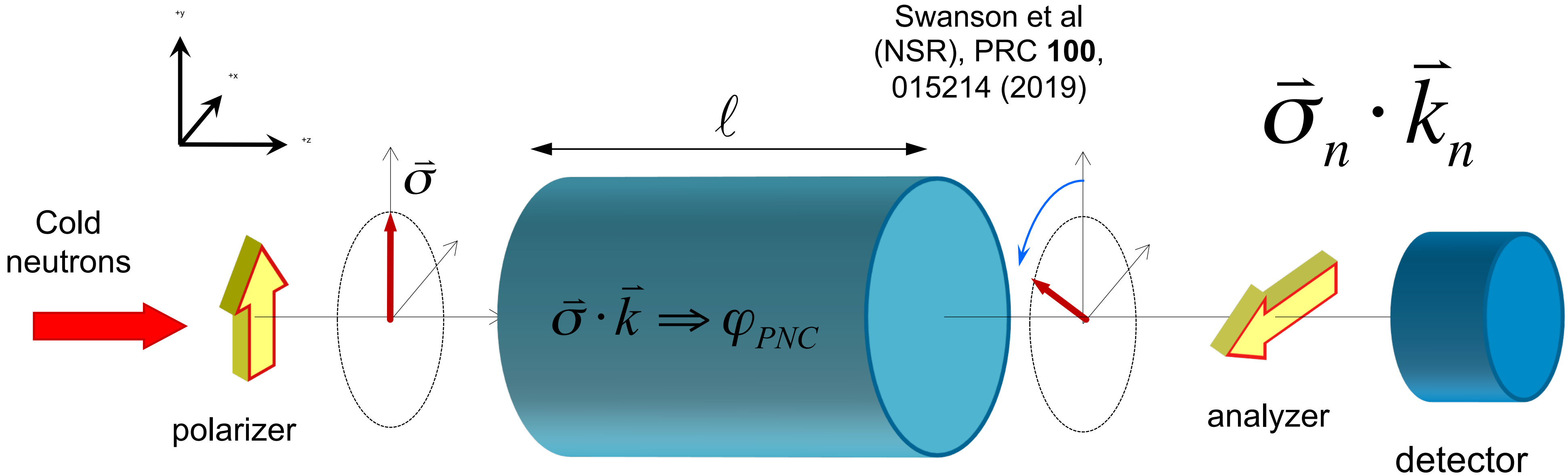


$$\vec{\sigma}_n \cdot \vec{k}_p$$

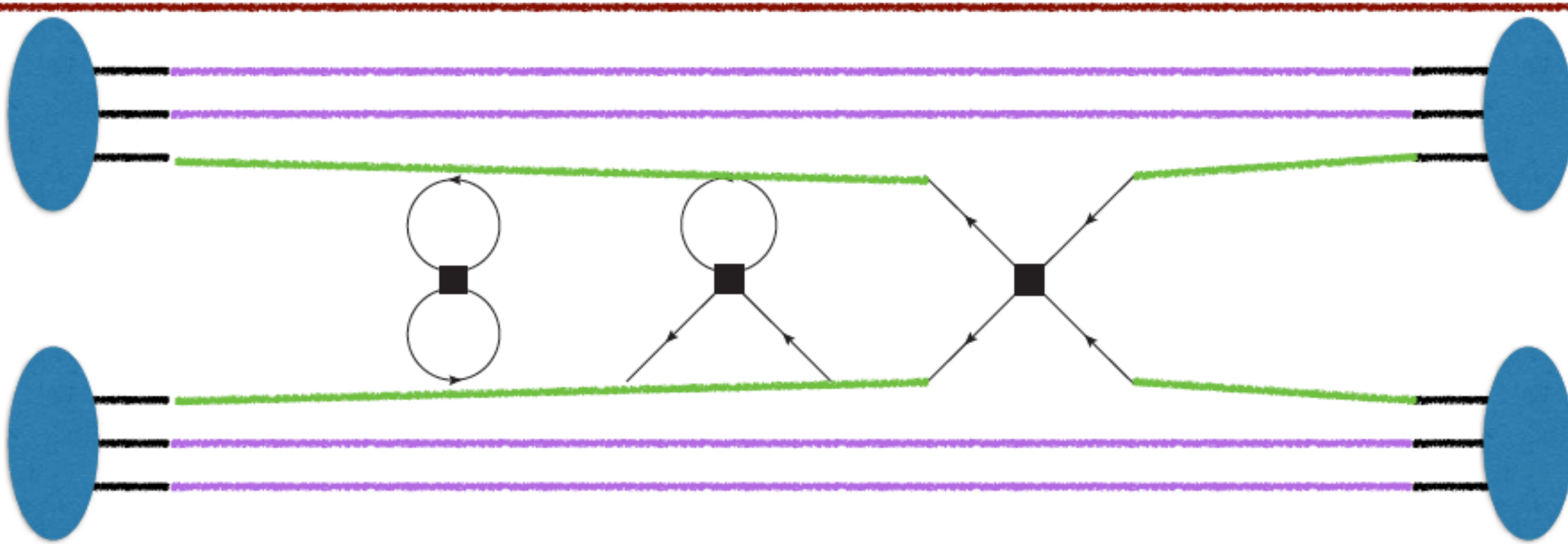
Gericke et al (N3He), PRL **125**, 131803 (2020)

Swanson et al (NSR), PRC **100**, 015214 (2019)

$$\vec{\sigma}_n \cdot \vec{k}_n$$



LQCD Challenges for Parity Nonconservation



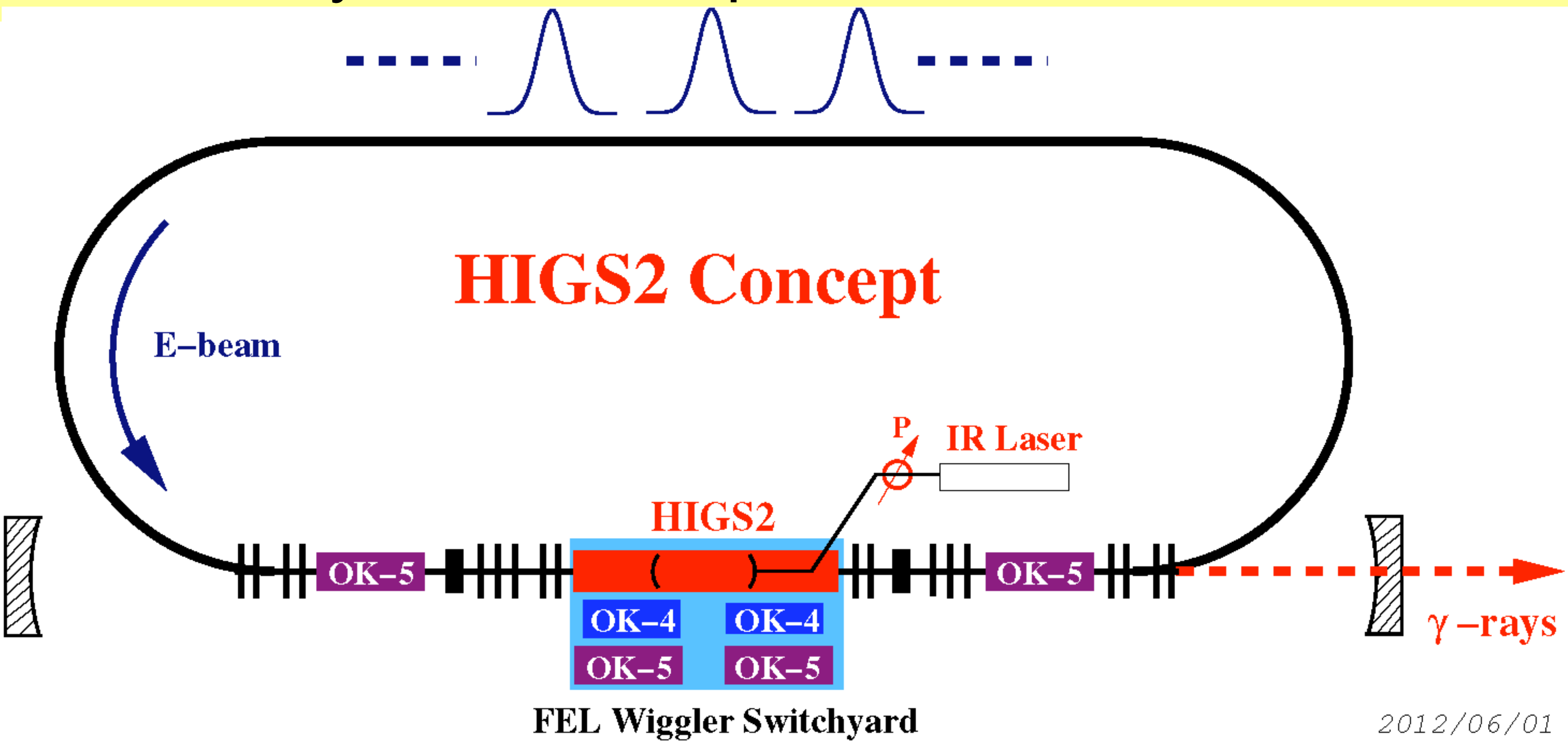
$\Delta I=0,1,2$

- The “disconnected” quark loops are numerically more expensive, and stochastically noisier
- LQCD calculations can project onto definite ΔI

The **ΔI=2 P-odd 4-quark operator** is the easiest one to calculate on the lattice. Cal-Lat +collaborators plan to perform the calculation.

A. Walker-Loud

Parity Violation Experiments at HiGS2?



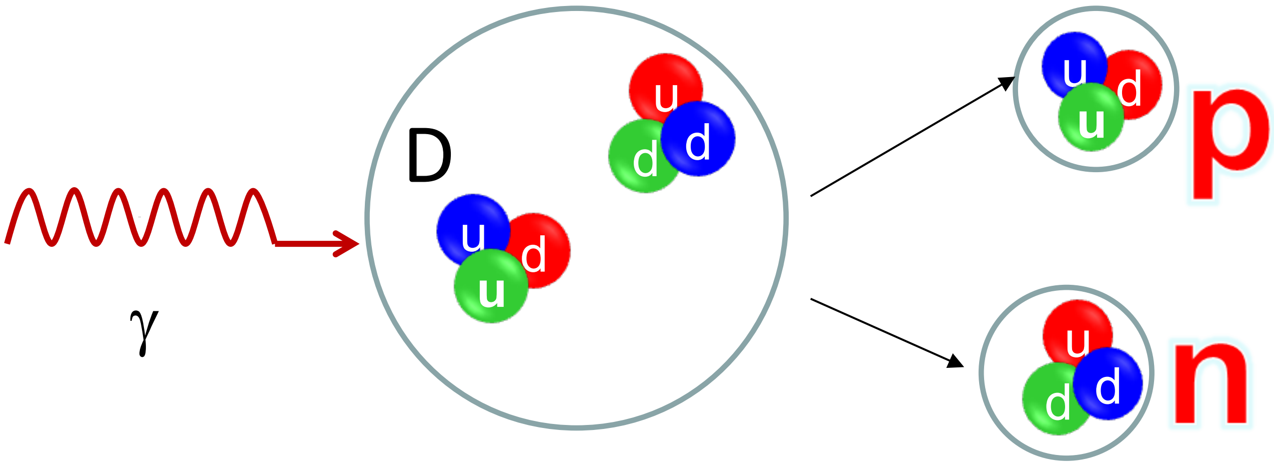
~10^{11} to 10^{12} polarized γ/sec (X100 increase in polarized gamma flux relative to HiGS1.)

Circularly polarized gammas (>~90%), fast (~100 Hz) and high-quality gamma helicity reversal possible

Controlled beam phase space: ~1% energy resolution on gamma energy (2-12 MeV)

These are attractive features in principle for parity violation experiments

Parity Violation in deuteron photodisintegration



Parity violation leads to helicity dependence of photodisintegration cross section

The neutron can escape the target and its intensity can be detected in current mode

Signal is helicity dependence of neutron current from target

Detect also scattered and transmitted gammas for normalization/systematics effect suppression

Dominated by the $\Delta I=2$ NN weak amplitude, calculable on the lattice

Need to supply >~10^{16} gammas just above photodisintegration threshold.

Matter/Antimatter Asymmetry in the Universe in Big Bang, starting from zero

Sakharov Criteria to generate matter/antimatter asymmetry from the laws of physics

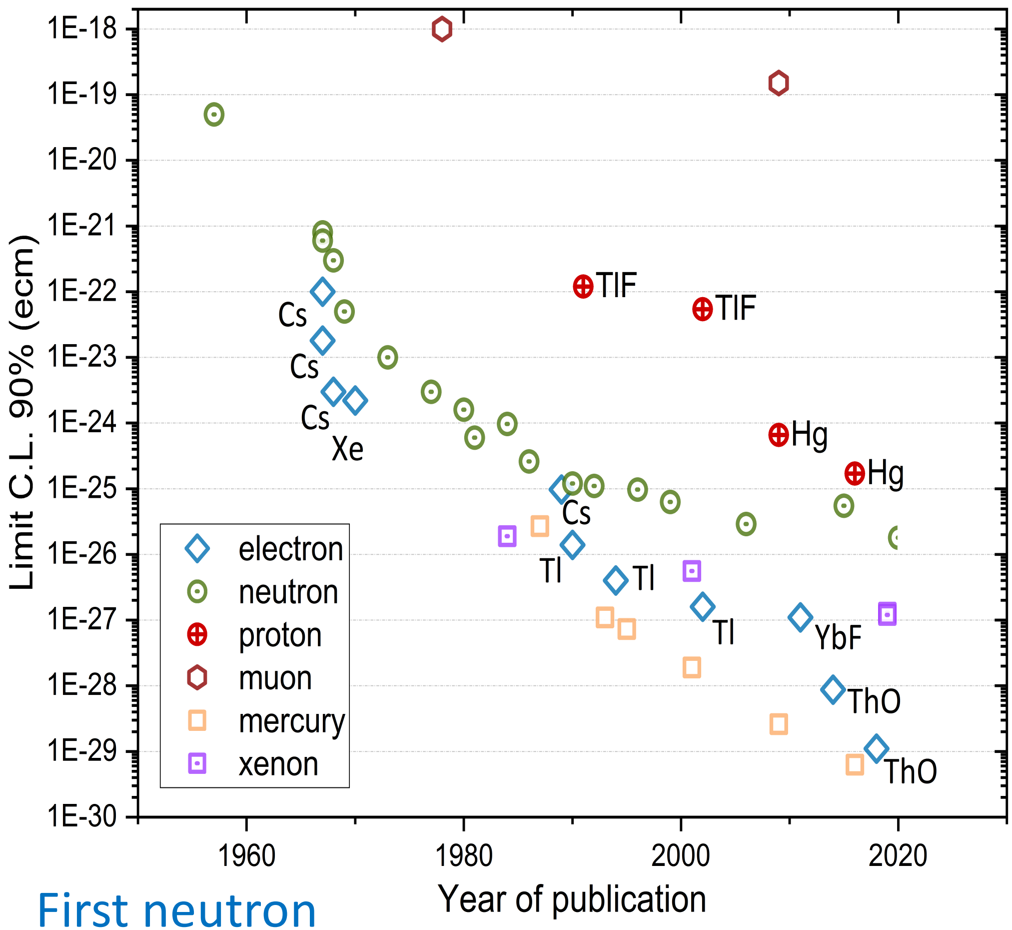
- Baryon Number Violation (not yet seen)
- C and CP Violation (seen but too small by ~10^{10})
- Departure from Thermal Equilibrium

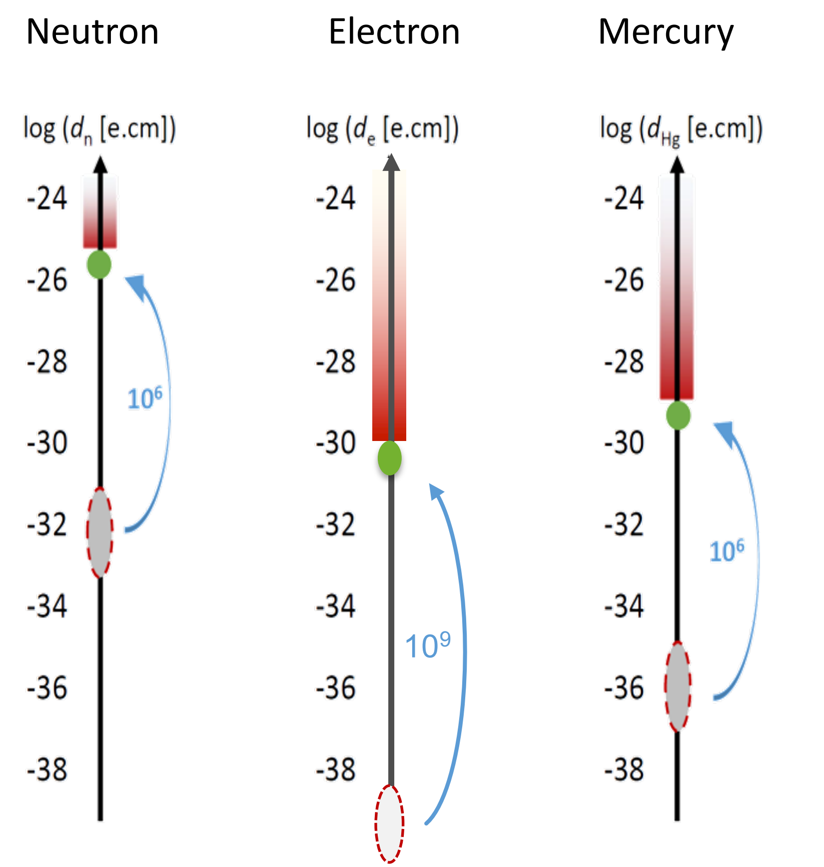
A.D. Sakharov, JETP Lett. 5, 24-27, 1967

Relevant neutron experimental efforts:

Neutron-antineutron oscillations ($\not{B}$)
Electric Dipole Moment searches ($\not{T}$=$\not{C}$P)
T Violation in Polarized Neutron Optics ($\not{T}$=$\not{C}$P)

A brief history of EDM searches





First neutron

Smith, Purcell, Ramsey

$d_n < 5 \times 10^{-20}$ e cm

PR 108 (1957) 120

~ 60 years

Previous

RAL-Sussex-ILL

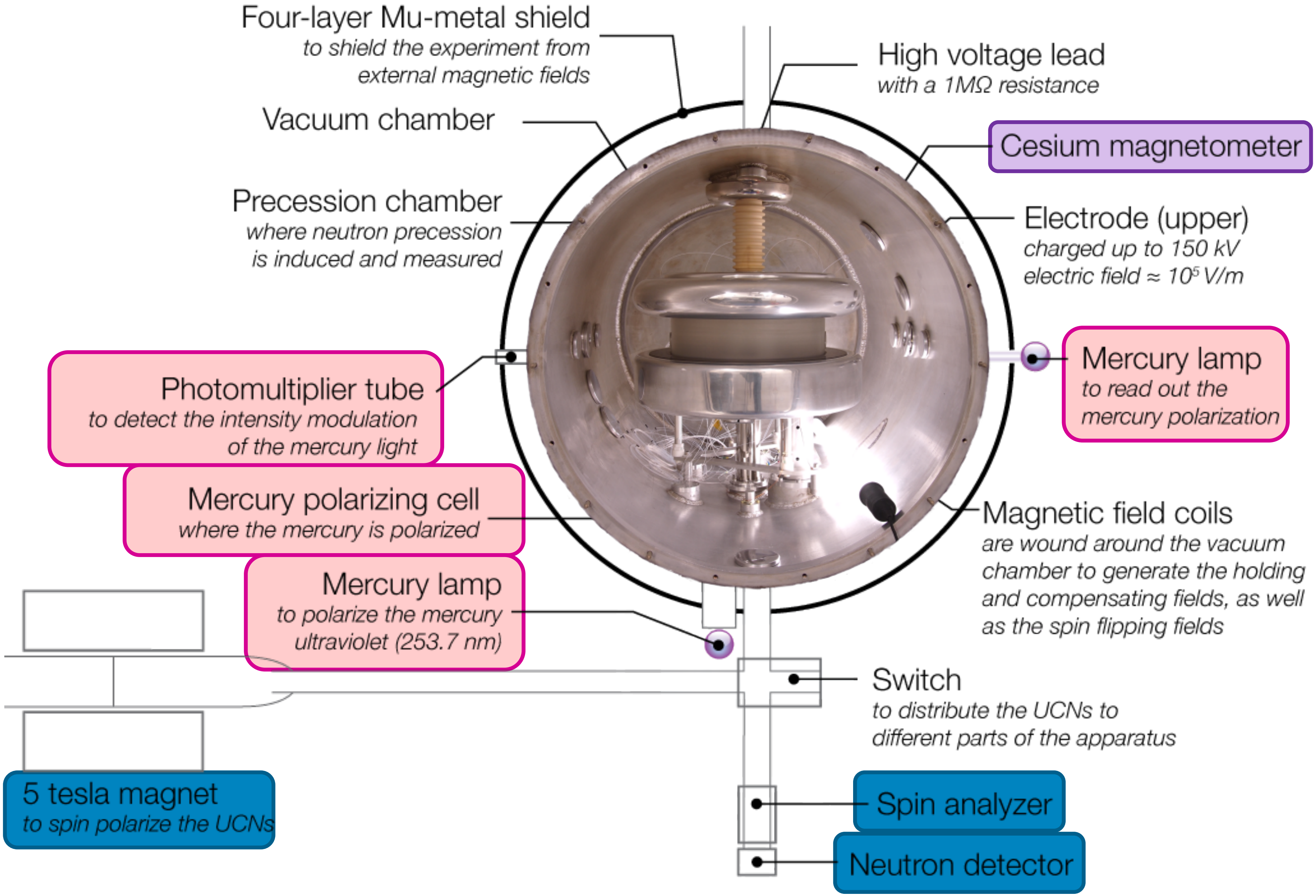
$d_n < 3 \times 10^{-26}$ e cm (90% C.L.)

C.Baker et al. PRL(2006) 131801

J.M. Pendlebury et al., PRD 92 (2015) 092003

P. Schmidt-Wellenburg

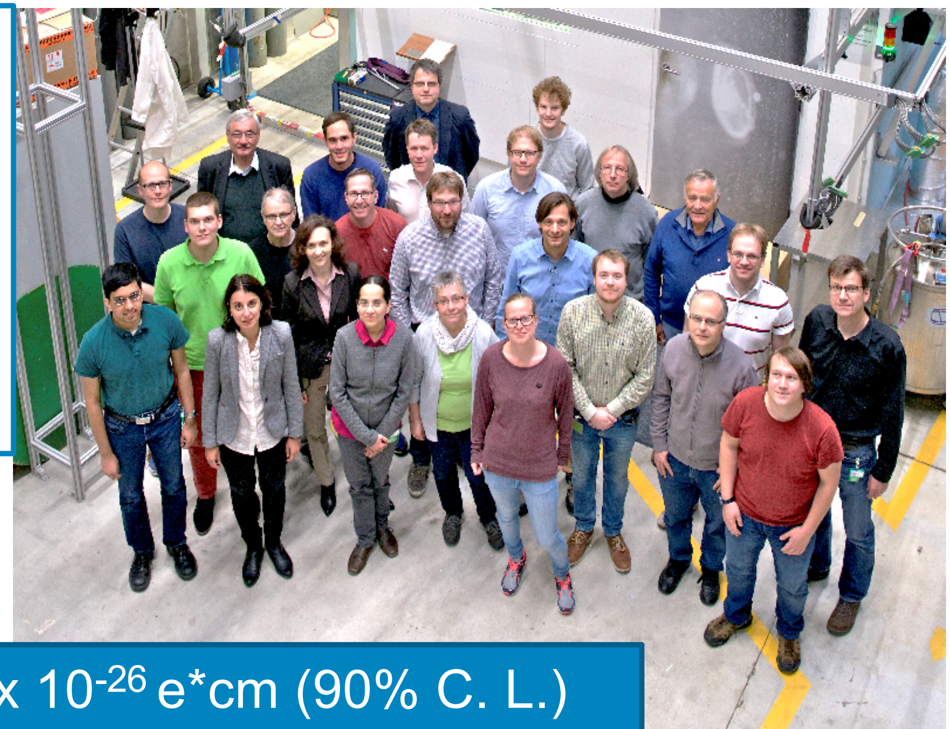
The nEDM spectrometer at PSI

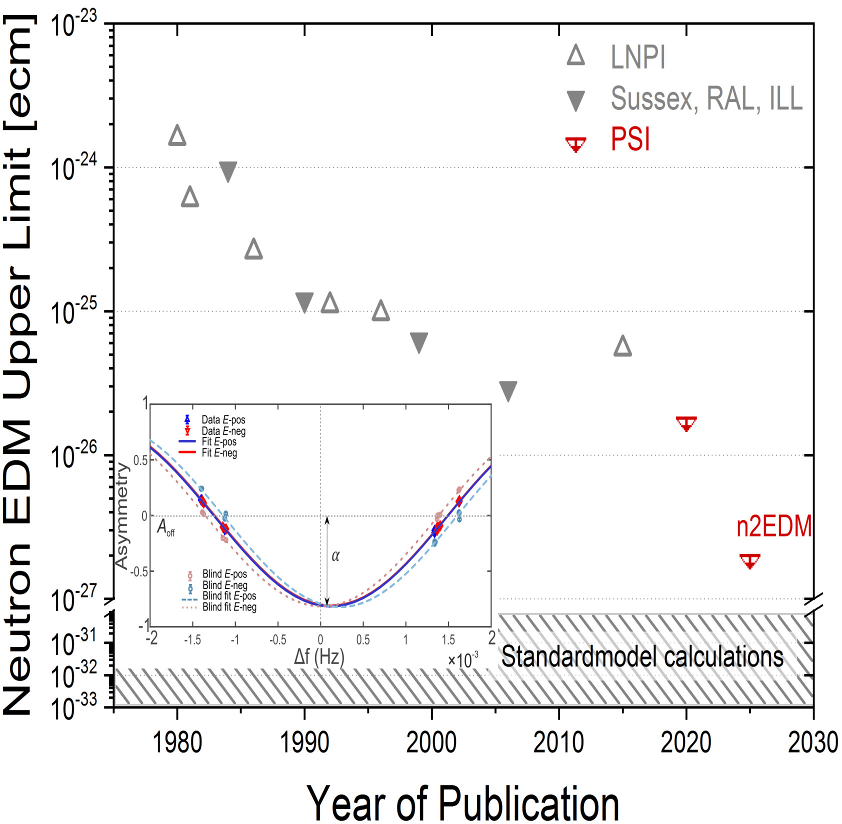


Most sensitive result on neutron electric dipole moment (EDM) measured at the PSI UCN source

EDMs unambiguously indicate charge parity violation (CPV)

- CPV natural in beyond standard model theories
- CPV required for matter / antimatter asymmetry
- Neutron EDM uniquely sensitive to strong CPV





$d_n < 1.8 \times 10^{-26}$ e*cm (90% C. L.)
Phys. Rev. Lett. 124, 081803 (2020)

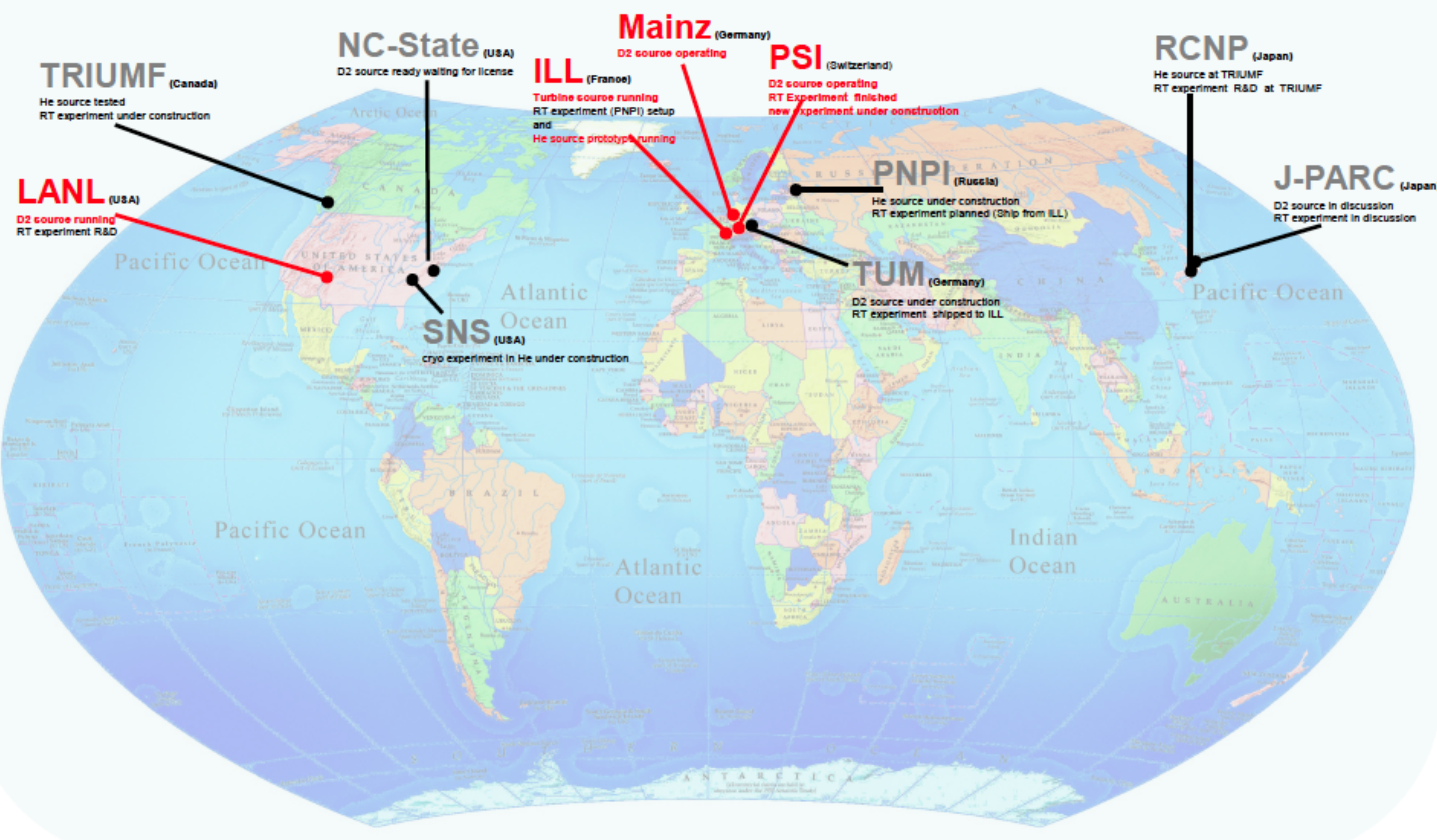
Unique features of result published in **PRL**

- Limit improved by factor 1.7
- **Systematic errors reduced by factor five**
- Full comprehension of systematic effects from higher order magnetic field non-uniformity
- First fully blinded analysis in two distinct teams

P. Schmidt-Wellenburg

PAUL SCHERRER INSTITUT PSI

ULTRACOLD NEUTRON SOURCES AND NEDM EXPERIMENTS: THE WORLDVIEW



B. Lauss, AFCI workshop

Neutron-Antineutron Oscillations: 2 x 2 Formalism

$\Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$ n-nbar state vector

α≠0 allows oscillations

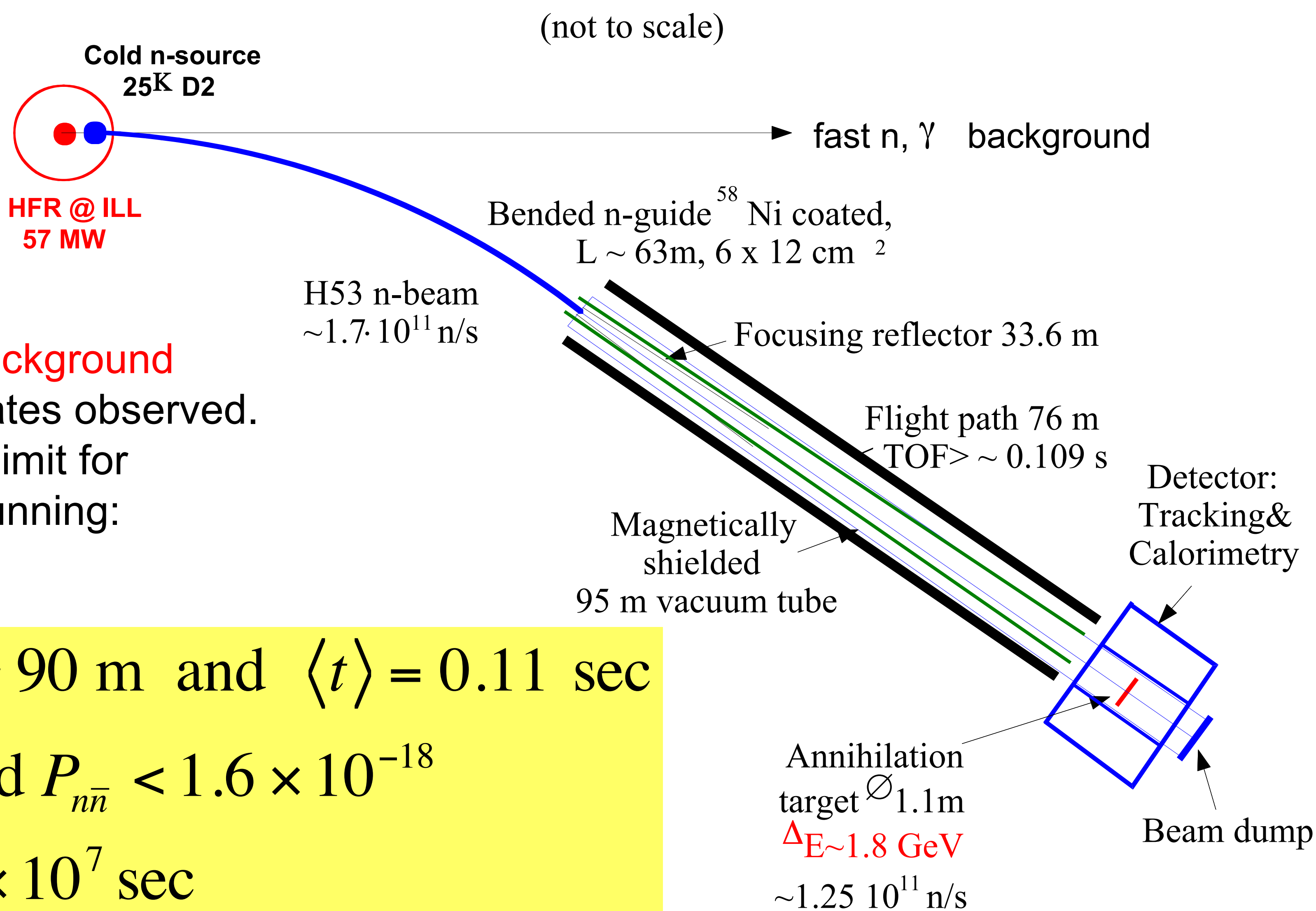
$H = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}$ Hamiltonian of n-nbar system

$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}}$$

Note :

- α real (assuming T)
- $m_n = m_{\bar{n}}$ (assuming CPT)
- $U_n \neq U_{\bar{n}}$ in matter and in external B [$\mu(\bar{n}) = -\mu(n)$ from CPT]

N-Nbar search at ILL (Heidelberg-ILL-Padova-Pavia)



No GeV background

No candidates observed.

Measured limit for
a year of running:

$$\text{with L} \sim 90 \text{ m and } \langle t \rangle = 0.11 \text{ sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6 \times 10^{-18}$$

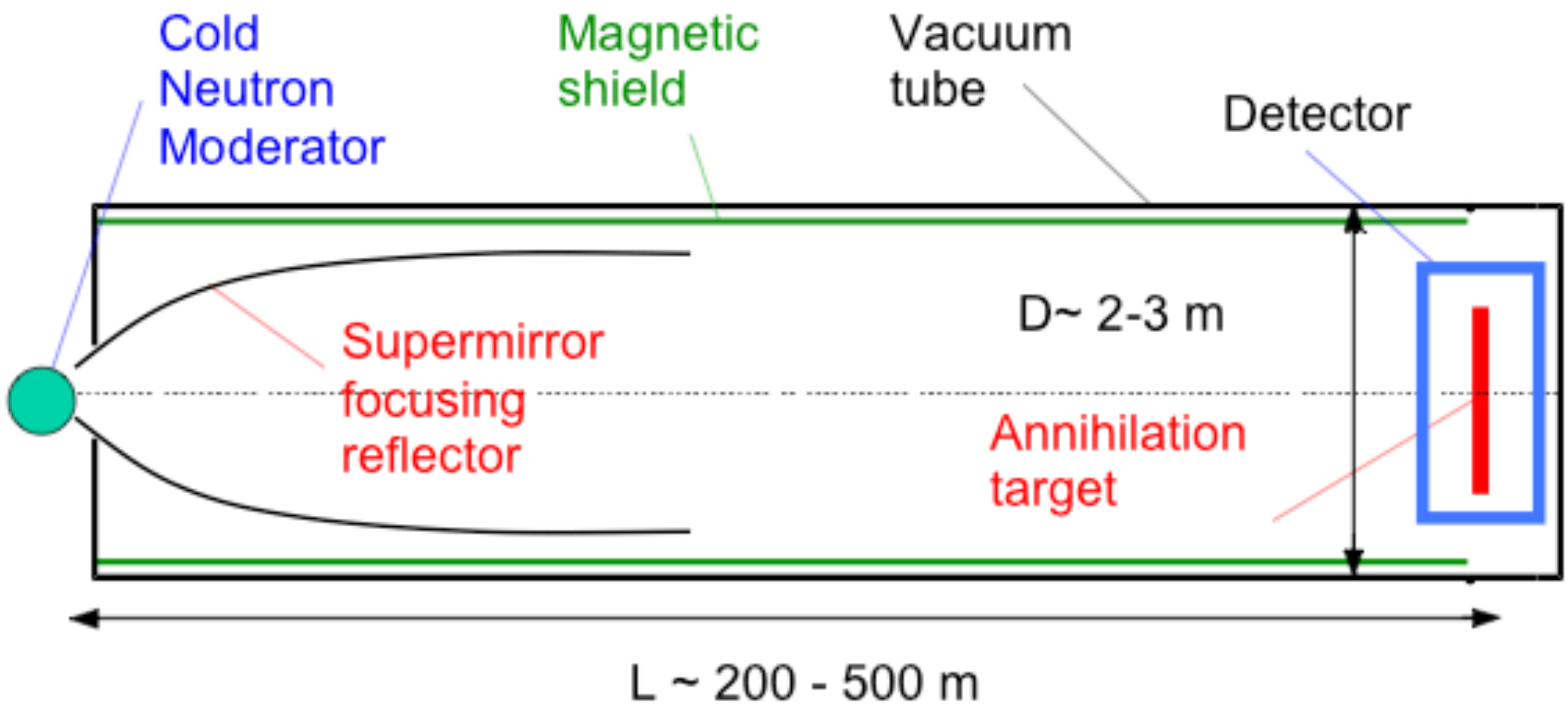
$$\tau > 8.6 \times 10^{7} \text{ sec}$$

Baldo-Ceolin M. et al., Z. Phys. C63,409 (1994).

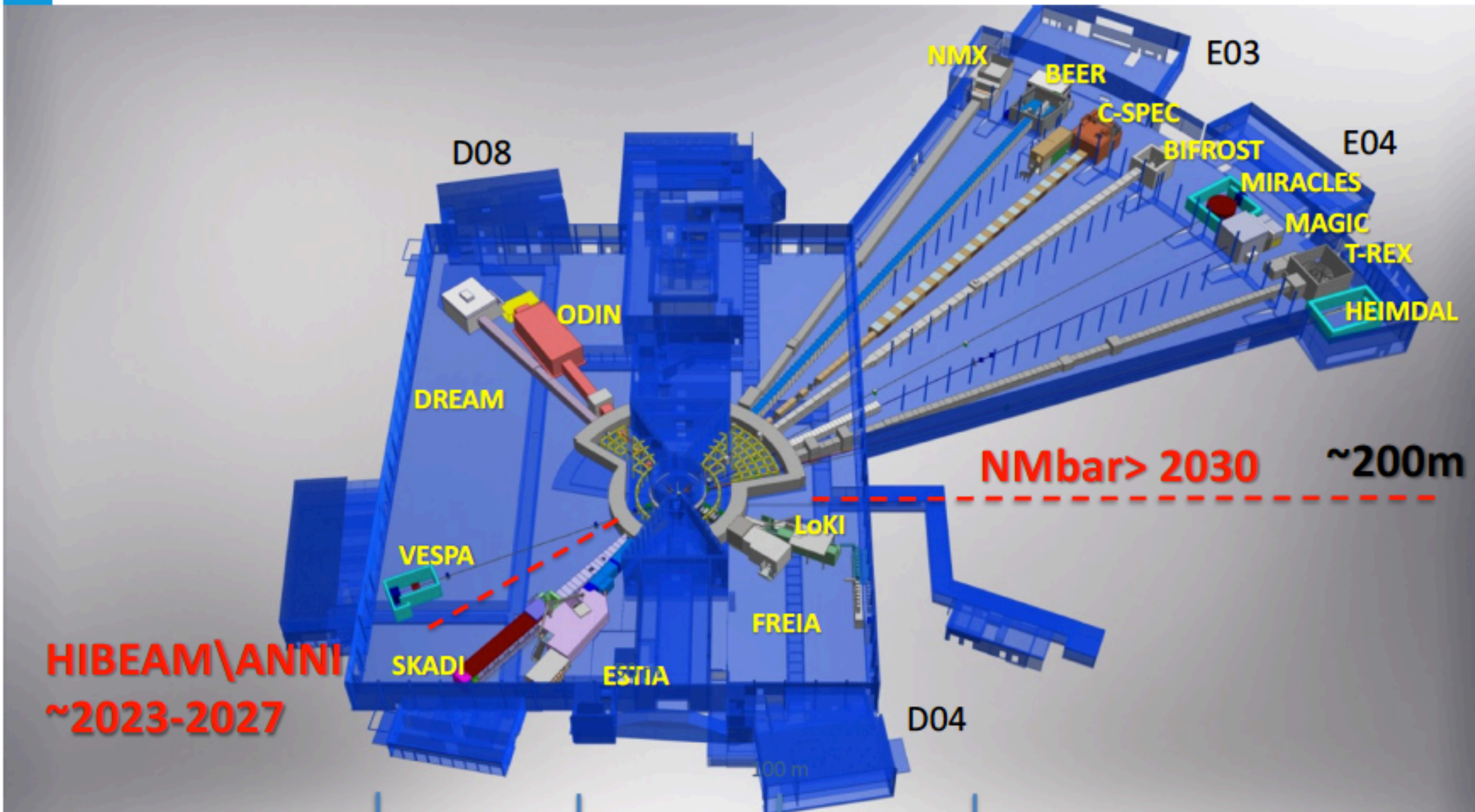
Better Cold Neutron Experiment (Horizontal beam)

- need cold neutron source at high flux n source, close access of neutron focusing reflector to cold source, free flight path of ~200m

Improvement on ILL experiment by factor of ~1000 in transition probability is possible! An uncommon opportunity…



ESS Neutron Instruments 1-15 and HIBEAM and NNBAR locations



…G. Brooijmans,…. et al, arXiv: 2006.04907

Conclusions

Slow neutrons can address many interesting scientific questions in nuclear/particle/astrophysics and cosmology

Slow neutron beams for this physics at CW and pulsed neutron sources already exist, but they are busy.

Two natural (to me) possibilities for neutron physics at this proposed gamma facility:

(1) Parity violation in deuteron photodisintegration. Enables Standard Model test in an uncommon regime. Can be done using the gammas.
(2) Neutron-antineutron oscillation search. CERN a "natural" place to do this physics if no luck at ESS

Other opportunities might also exist depending on source details (GDR? Photodisintegration? Compound resonances?)