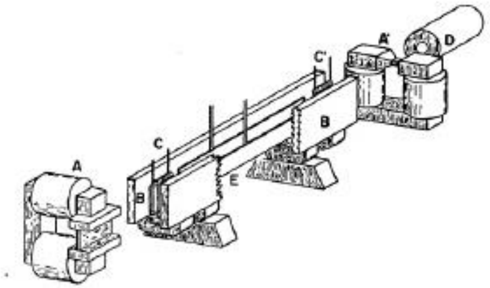
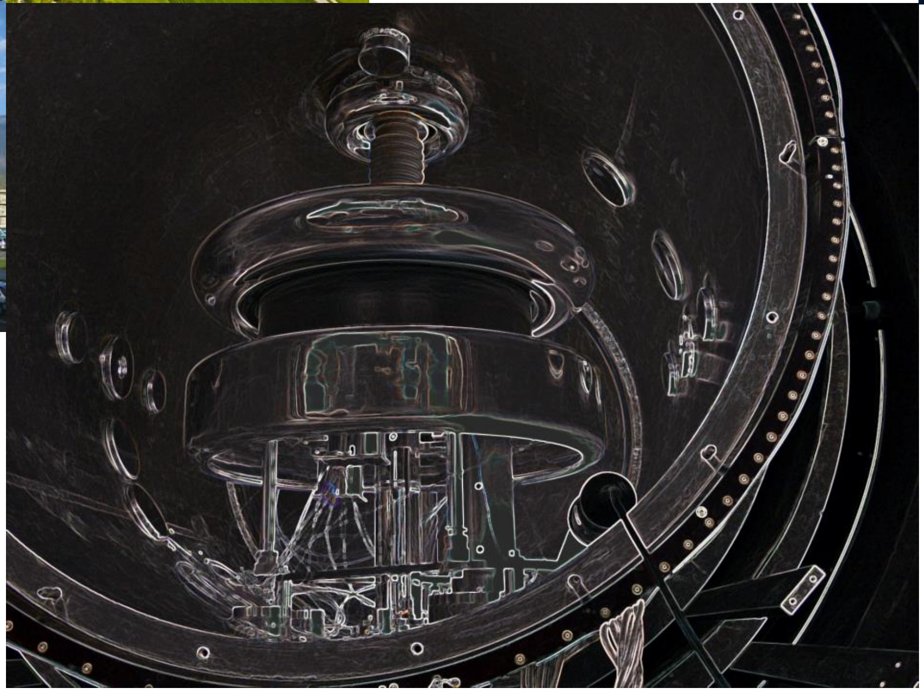
Les mesures de précision avec des neutrons ultra-froids



Stéphanie Roccia
LPSC

Ultra Cold neutrons ...

...are very slow neutrons

(v_{UCN} < 8 m/s , λ_{UCN} > 500 Å, E_{UCN}~100 neV)

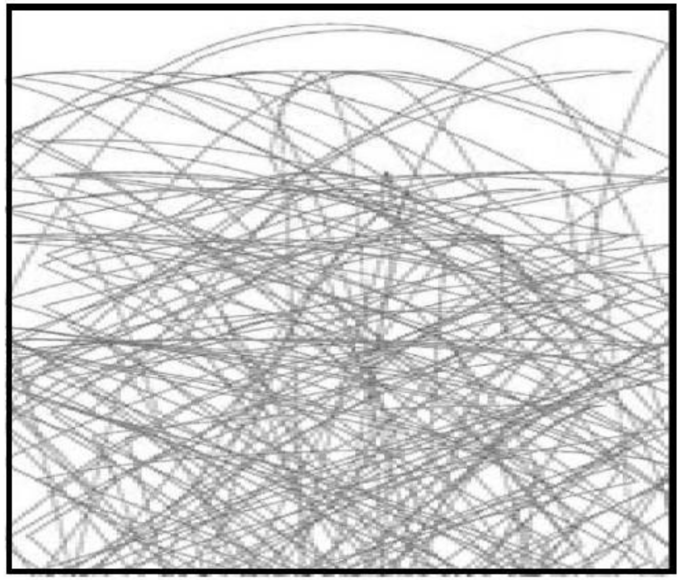
that cannot penetrate into materials

$\lambda_n \approx 800$ Å;

$v_n \approx 5$ m/s;

$T_n \approx 2$ mK ;

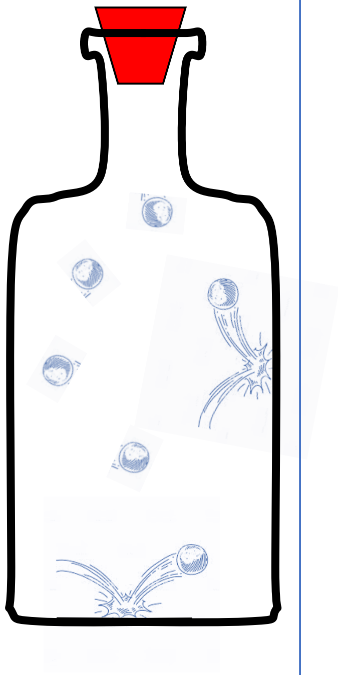
$E_n \approx 130$ neV



UCN are storable by material traps, gravity and/or magnetic fields!

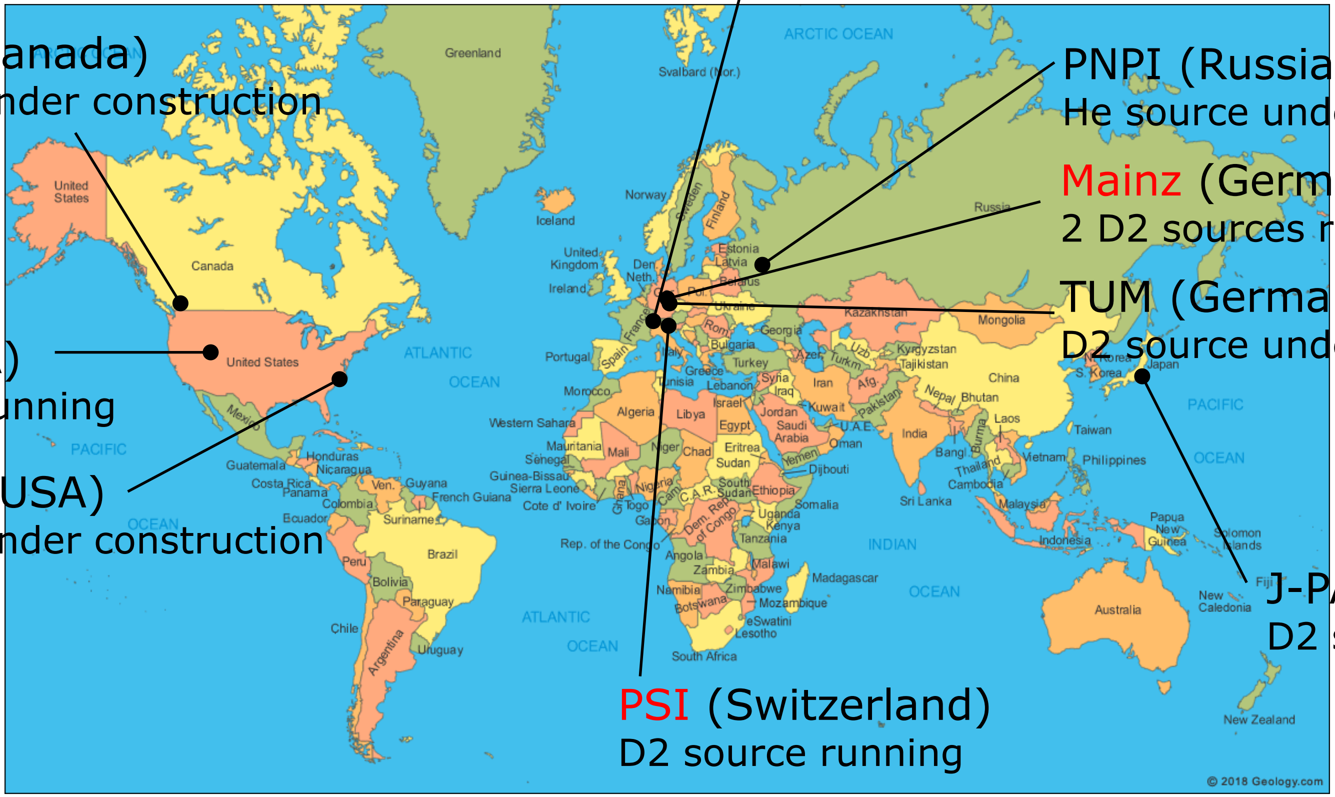
Storage and observation times of several minutes are feasible.

High precision measurements of the properties of the free neutron



Strong interaction Fermi potential	~100neV
Gravity $\Delta E = m_n g\ \Delta h$	~ 100 neV /m
Magnetic field $\Delta E = \mu_n B$	~ 60 neV / T
Weak interaction	β decay

UCNs around the world



TRIUMF (Canada)
He source under construction

LANL (USA)
D2 source running

NC-State (USA)
D2 source under construction

ILL (France)
Turbine source running
2(+1) He sources running

PNPI (Russia)
He source under construction

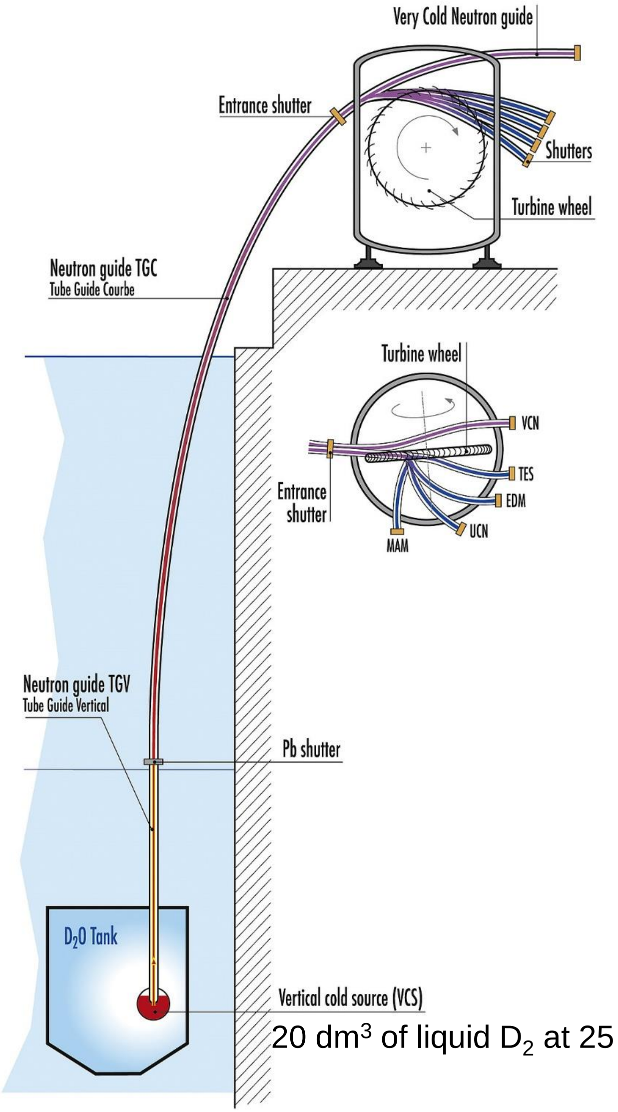
Mainz (Germany)
2 D2 sources running

TUM (Germany)
D2 source under construction

J-PARC (Japan)
D2 source planned

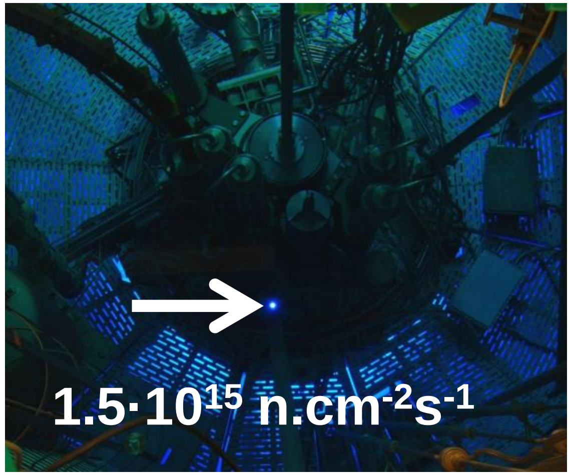
PSI (Switzerland)
D2 source running

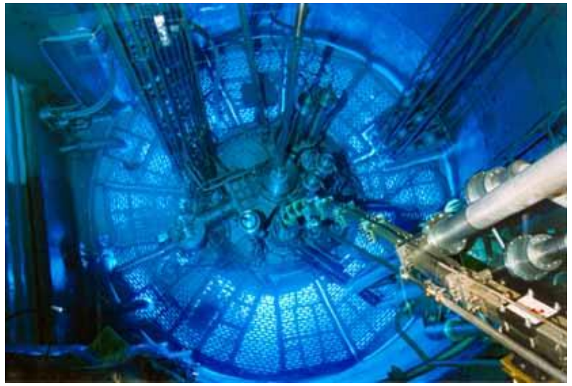
ILL



20 dm^3 of liquid D_2 at 25 K

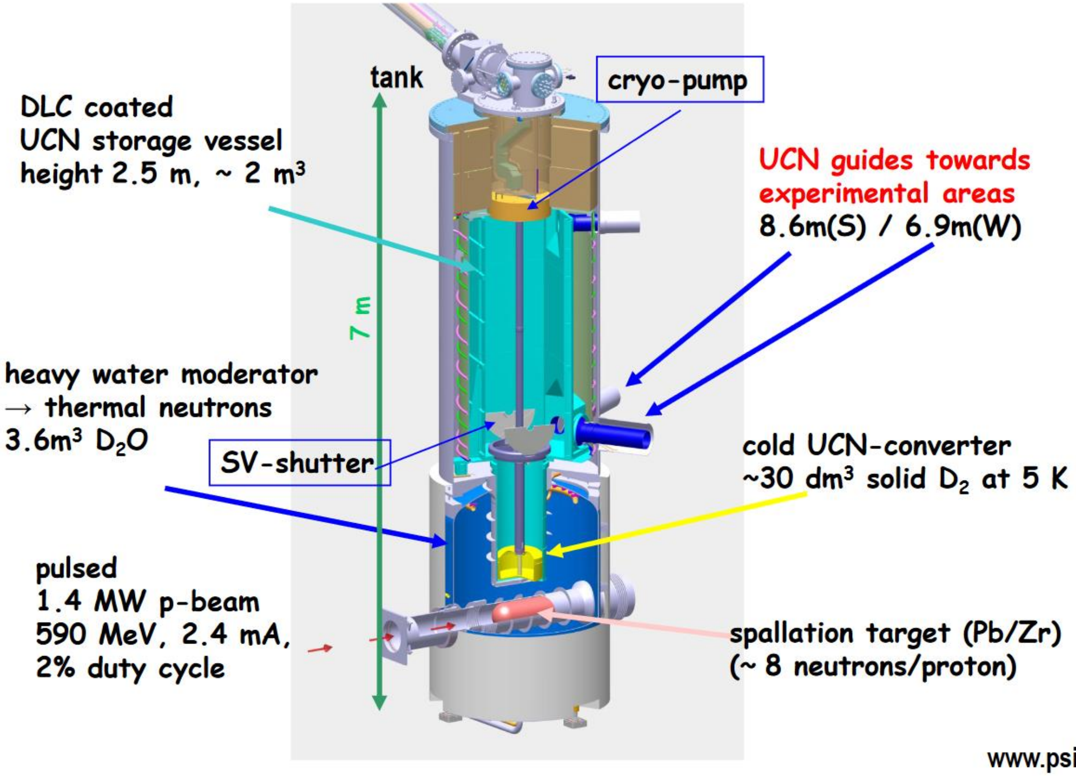
The highest neutron flux in Western Europe





PF2: Very-cold and Ultra-cold neutron facility
VCN: 20 - 400 Å, 0.4 x 10^5 cm^{-2}s^{-1}Å^{-1} (@ 100 Å)
UCN: 3.3 x 10^4 cm^{-2}s^{-1} (>500 Å)

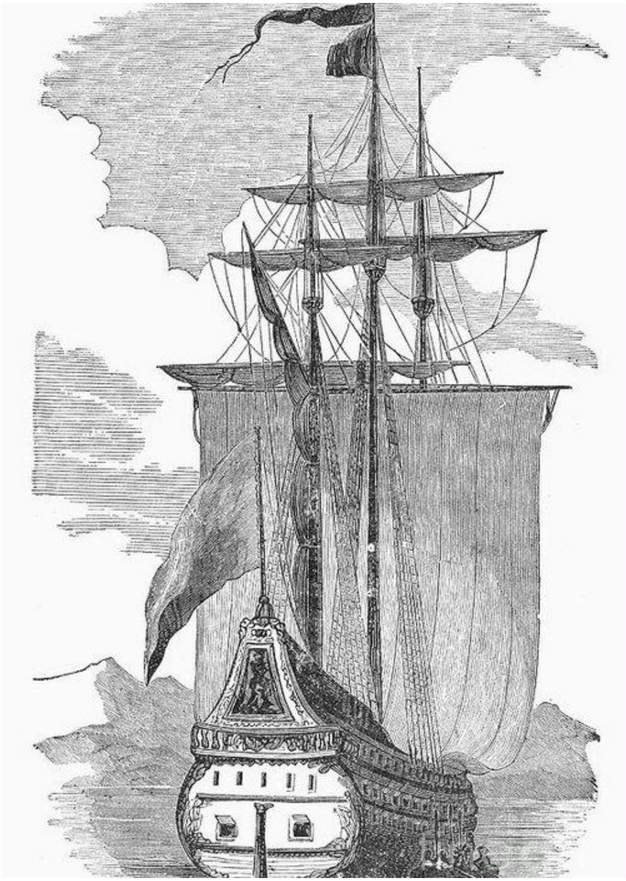
PSI



www.psi.ch/ucn/

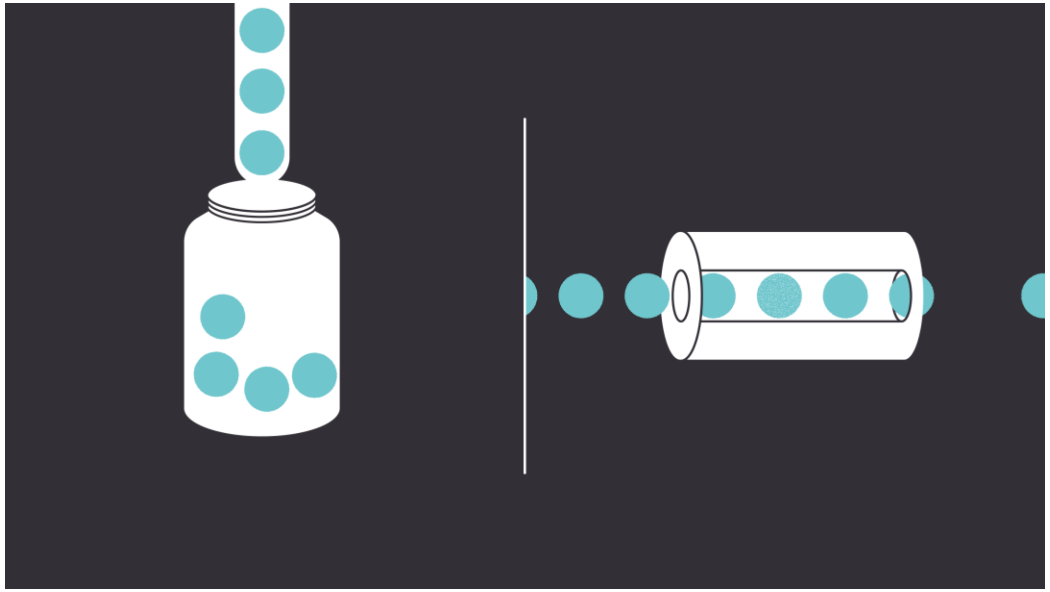
UCNs for particle physics

Measurement of the neutron lifetime
Search for the neutron electric dipole moment
Search for dark matter

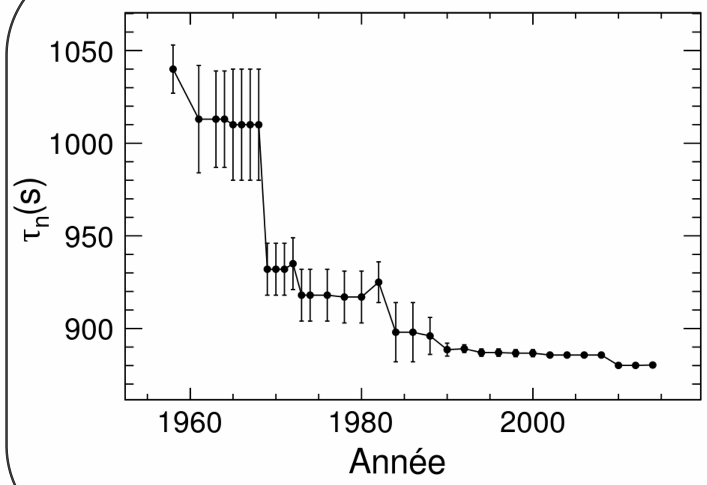


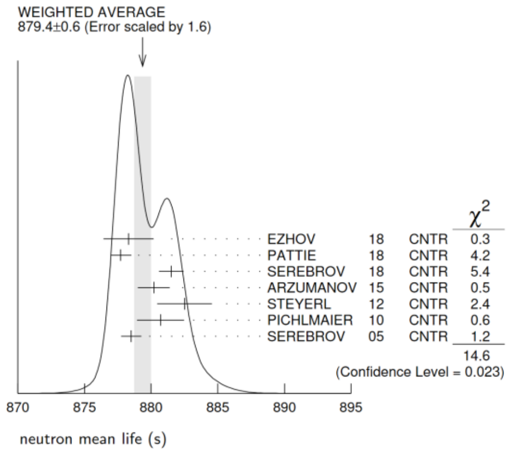
Neutron lifetime

Storage:
Counting the
living ones



Beam:
Counting the
dead ones





PDG

Neutron lifetime

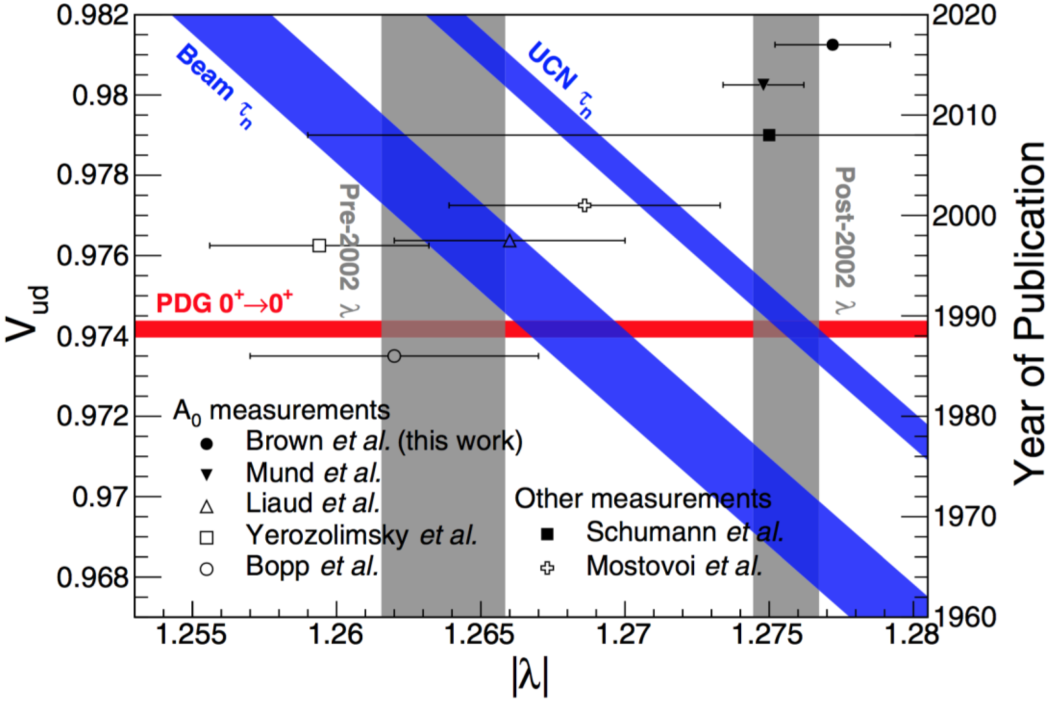
- Input to models of BBN
  - ^{4}He abundance prediction
  - Need $\delta t_n \approx 1$ s or better.

- Tests for BSM physics
  - CKM unitarity $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1$
  - $\delta t_n = 0.4$ s would match the present uncertainty of radiative corrections.
  - The dark sector

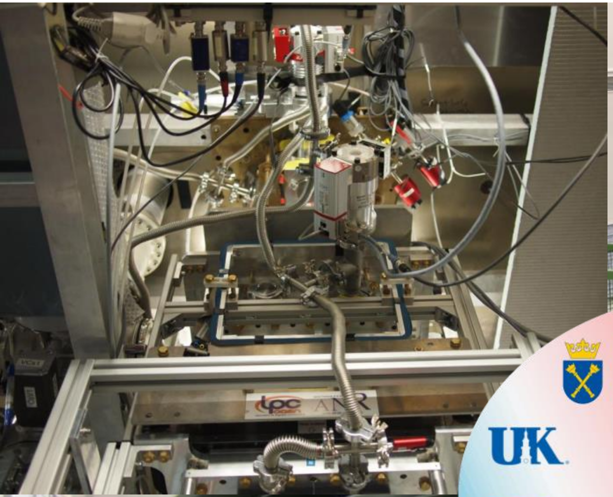
Marciano and Sirlin, PRL 96 (2006), 032002.

Neutron Decay Master Relation

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)s}{\tau_n\,(1+3\lambda^2)}$$

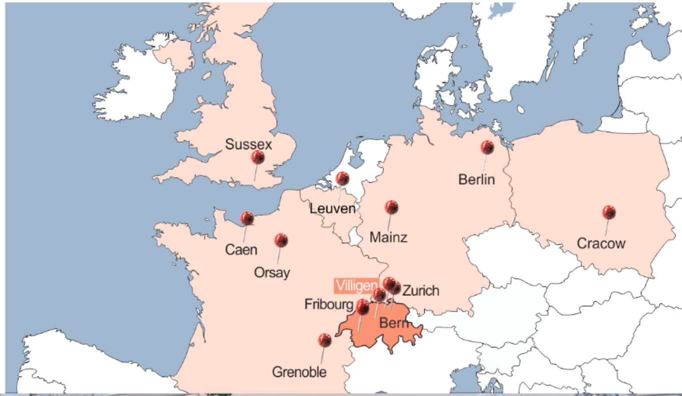


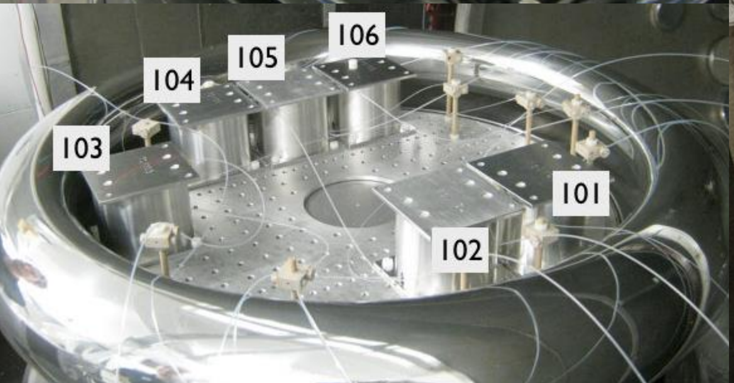
ratio of axial vector and vector coupling constants




Collaboration Meeting, Mainz TRIGA
Reactor, November 2019


Lexington


Sussex
Berlin
Leuven
Mainz
Caen
Cracow
Orsay
Villigen
Zurich
Fribourg
Bern
Grenoble


106
105
104
103
101
102

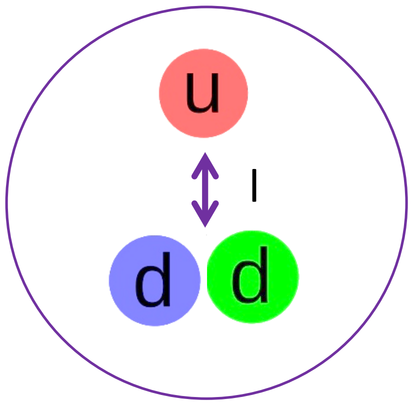

Four-layer magnetic shield
High-voltage lead
Vacuum chamber
Cesium magnetometer
Precession cell
Electrode (HV)
Photodetector
Electrode (ground)
Magnetic-field coils
Switch
Spin analyzers
Neutron detectors

The search for the neutron EDM

$$H = -\vec{\mu}_n.\vec{B} - \vec{d}_n.\vec{E} = \frac{hf_n}{2}$$

30 Hz in 1μT

58 nHz in 12 KV/cm



d_n =2/3 e*l

l=0.1r_n → d_n=4.10^{-14} e.cm

But d_n<1.8 10^{-26} e.cm (90% C.L.)

d_n is CP-odd

In the standard model: $d_n \approx 10^{-32}\ e.cm$

* PRL(2015)062001

The strong CP problem and the axion

$$L_{eff} = L_{QCD} + \theta \frac{\alpha_S}{8\,\pi}\, \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

From lattice calculations: $d_n = -0.0039(2)(9)\theta\ e.fm$*

Experimental upper limit: $|d_n| \leq\ 2.10^{-13}\ \ e.fm$

→ $\theta \leq 10^{-10}$

The strong CP problem

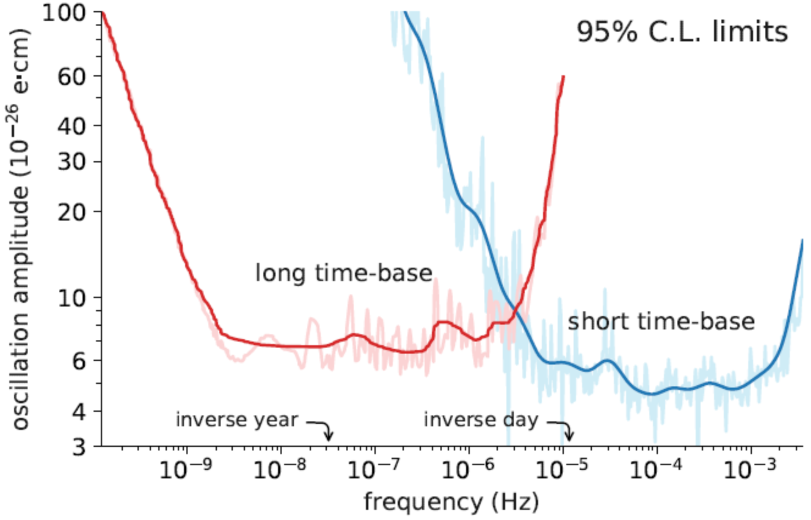
* One mass quark is exactly zero but PDG: $m_u\ = 2.2^{+0.6}_{-0.4}\ MeV$
* Introducing a global chiral U(1) symmetry

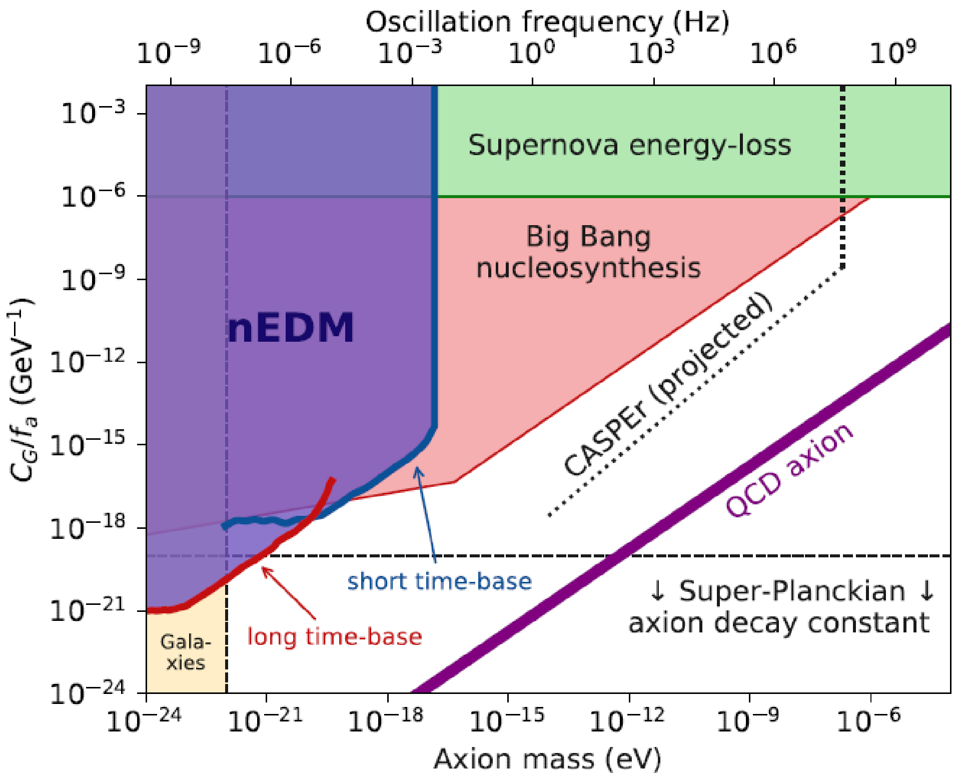
This symmetry is necessarily spontaneously broken, and its introduction into the theory effectively replaces the static CP-violating angle θ with a dynamical CP- conserving field- the axion. The axion is the Nambu-Goldstone boson of the broken U(1) symmetry.

The axion is a well motivated dark matter candidate

Search for Axion-like dark matter

$$d_n(t) \approx +2.4 \times 10^{-16} \frac{C_G a_0}{f_a} \cos(m_a t)\ e \cdot \mathrm{cm}\,.$$



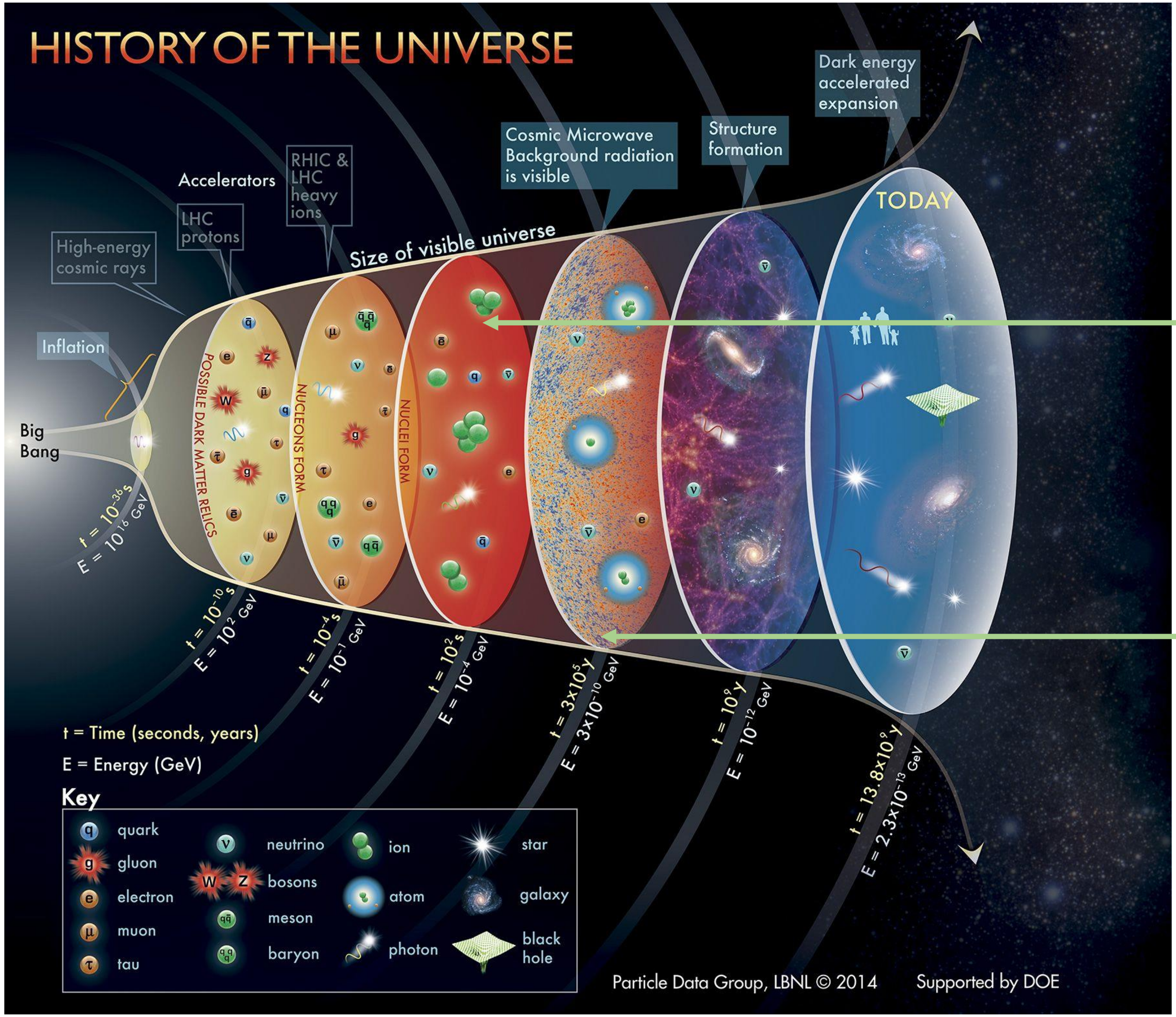


ILL data: long data taking

PSI data: high sensitivity
Still blinded

C. Abel et al., Phys. Rev. X 7, 041034 (2017)

Matter/Antimatter Asymmetry of the Universe



$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

The abundances of the light elements depend almost solely on the baryon-to-photon ratio

D/H measurements* + nucleosynthesis models

$$5.8\ 10^{-10} < \eta < 6.6\ 10^{-10}$$

The Planck result**: fraction of cosmological density contained in baryons:

$$\eta = 6.09\ (6)\ 10^{-10}$$

*Universe 3, 44 (2017)
**Astron. & Astrophys. 594, A13 (2016)

Matter/Antimatter Asymmetry of the Universe

How this asymmetry can be explained with particle physics?
→ **Sakharov criteria for baryogenesis**

1) There must exist an interaction that violates B-number.

2) The B-violating interaction must go out of thermal equilibrium.

3) There must be an interaction that violates C & CP.

Electroweak baryogenesis

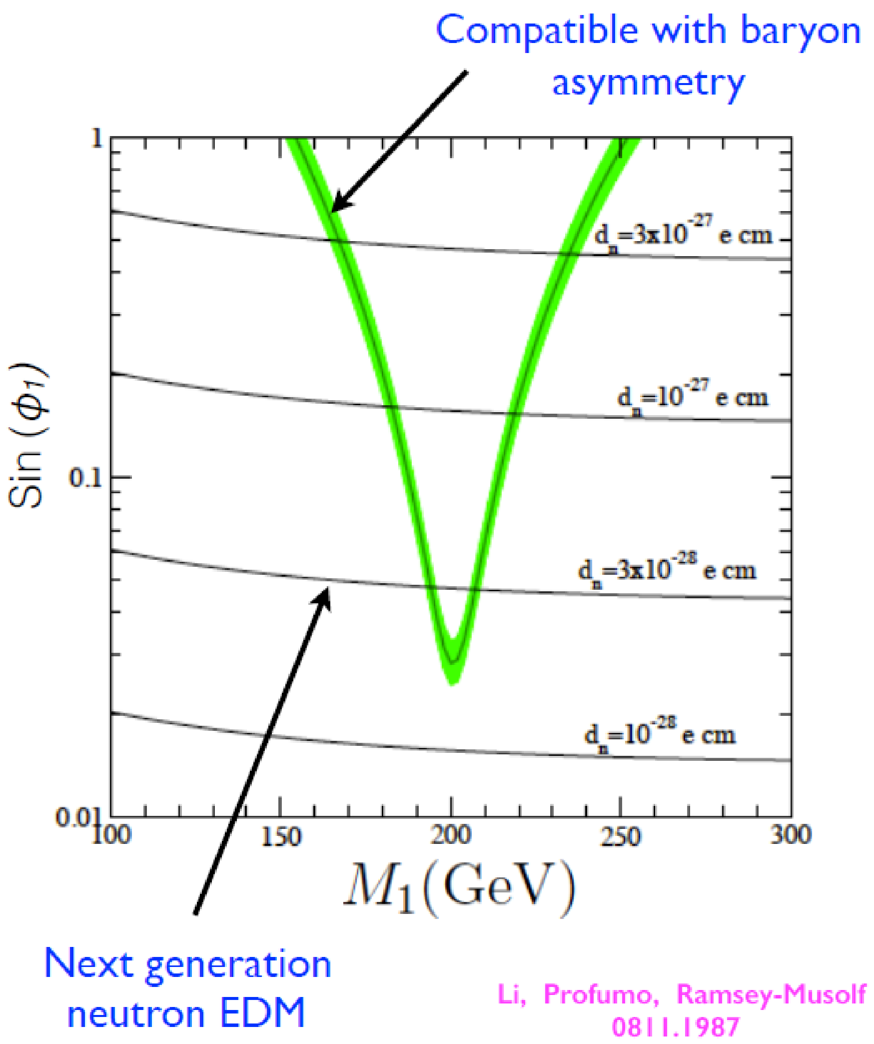
New CP violating phases contributes to

* baryonic asymmetry of the universe
* neutron EDM

$$d_n = d_n^{CKM} + 10^{-16}\, e.cm\, (\theta) + 10^{-24}\, e.cm \left(\frac{200\ GeV}{M}\right)^2 \sin(\varphi_{CP})$$

The nEDM is the most stringent test of electroweak baryogenesis via $\frac{\sin(\varphi_{CP})}{M^2}$

But requirements for electroweak baryogenesis do provide complementary constraints on the mass scale and CP-violating phases



Another possibility is the leptogenesis

Picture by V. Cirigliano

The search for the neutron EDM

$$H = -\vec{\mu}_n.\vec{B} - \vec{d}_n.\vec{E} = \frac{hf_n}{2}$$

First limitation ….. Magnetic field fluctuations

$$\begin{array}{lcccc}
\text{h } f_n\ (\uparrow\uparrow) & = & 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) & + & 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow) \\
\text{h } f_n\ (\uparrow\downarrow) & = & 2\ \vec{\mu}_n.\vec{B}(\uparrow\downarrow) & - & 2\ \vec{d}_n.\vec{E}(\uparrow\downarrow) \\
\hline
\text{h}(f_n\ (\uparrow\uparrow)\text{- } f_n\ (\uparrow\downarrow)) & = & 2\vec{\mu}_n.(\vec{B}(\uparrow\uparrow) - \vec{B}(\uparrow\downarrow)) & - & 2\vec{d}_n.(\vec{E}(\uparrow\uparrow) + \vec{E}(\uparrow\downarrow))
\end{array}$$

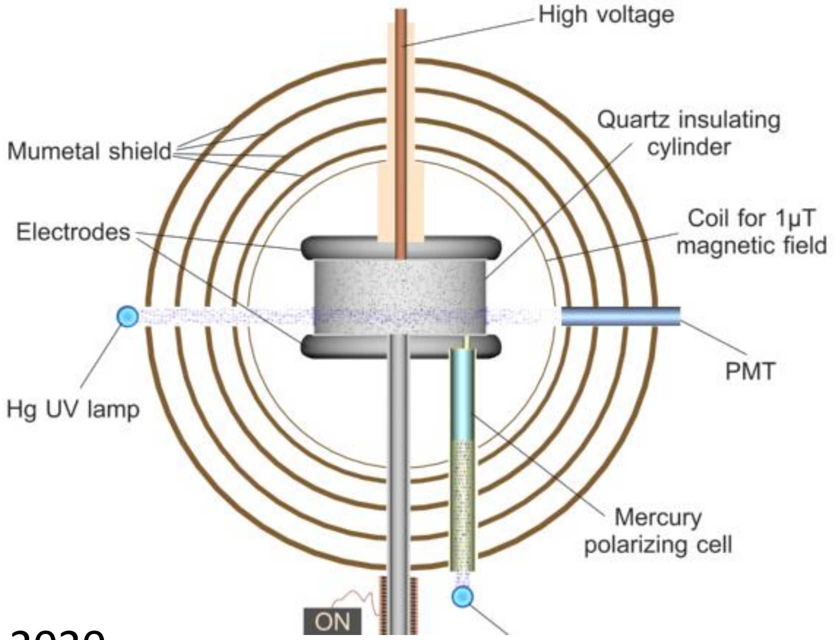
The search for the neutron EDM

First limitation ….. Magnetic field fluctuations

$$\mathrm{h}\ f_n\ (\uparrow\uparrow) = 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) + 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow)$$

$$\mathrm{h}\ f_n\ (\uparrow\downarrow) = 2\ \vec{\mu}_n.\vec{B}(\uparrow\downarrow) - 2\ \vec{d}_n.\vec{E}(\uparrow\downarrow)$$

$$\mathrm{h}(f_n\ (\uparrow\uparrow) - f_n\ (\uparrow\downarrow)) = 2\vec{\mu}_n.(\vec{B}(\uparrow\uparrow) - \vec{B}(\uparrow\downarrow)) - 2\vec{d}_n.(\vec{E}(\uparrow\uparrow) + \vec{E}(\uparrow\downarrow))$$



nEDM 2005-2020

Mercury co-magnetometer (1998)

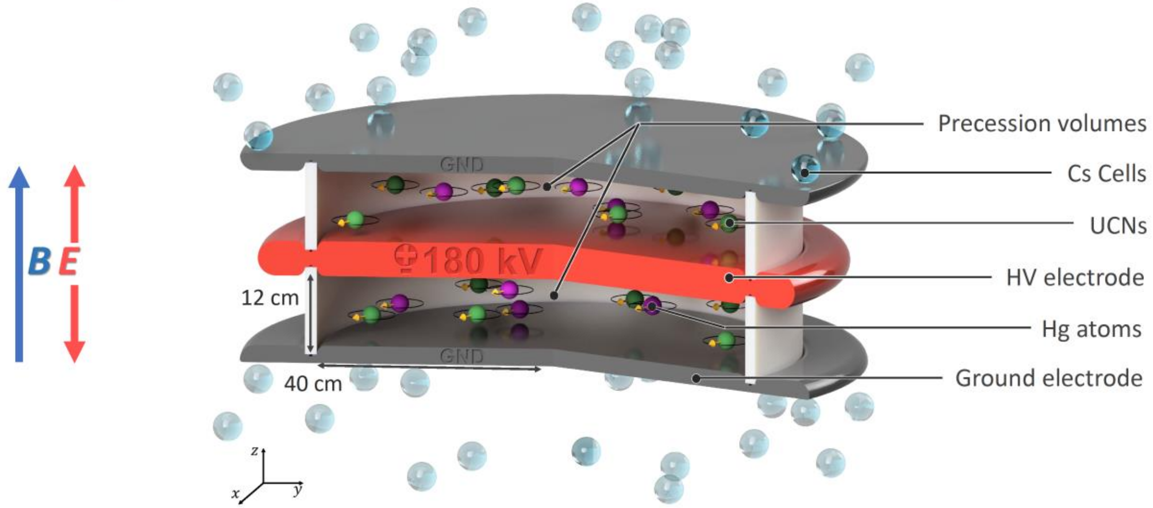
$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n B_n}{\gamma_{Hg} B_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}$$

Cesium magnetometer array (2009)

The search for the neutron EDM

First limitation ….. Magnetic field fluctuations

$$
\begin{array}{lclcl}
h\ f_n\ (\uparrow\uparrow) & = & 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) & + & 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow) \\
h\ f_n\ (\uparrow\downarrow) & = & 2\ \vec{\mu}_n.\vec{B}(\uparrow\downarrow) & - & 2\ \vec{d}_n.\vec{E}(\uparrow\downarrow) \\
\hline
h(f_n\ (\uparrow\uparrow)\text{-}\ f_n\ (\uparrow\downarrow)) & = & 2\vec{\mu}_n.(\vec{B}(\uparrow\uparrow) - \vec{B}(\uparrow\downarrow)) & - & 2\vec{d}_n.(\vec{E}(\uparrow\uparrow) + \vec{E}(\uparrow\downarrow))
\end{array}
$$



$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n B_n}{\gamma_{Hg} B_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}$$

$$d_n = \frac{\pi h f_{Hg}}{4|E|}\left(\mathcal{R}^T_{\uparrow\downarrow} - \mathcal{R}^T_{\uparrow\uparrow} + \mathcal{R}^B_{\uparrow\downarrow} - \mathcal{R}^B_{\uparrow\uparrow}\right)$$

The search for the neutron EDM

nEDM 2005-2020

-> most stringent upper limit to date

-> reduce by factor 5 systematic error budget

$$d_n = (0.0 \pm 1.1_{\rm stat} \pm 0.2_{\rm sys}) \times 10^{-26}\ e.\rm{cm}.$$

n2EDM 2012-

-> phase one : gain an order of magnitude in sensitivity

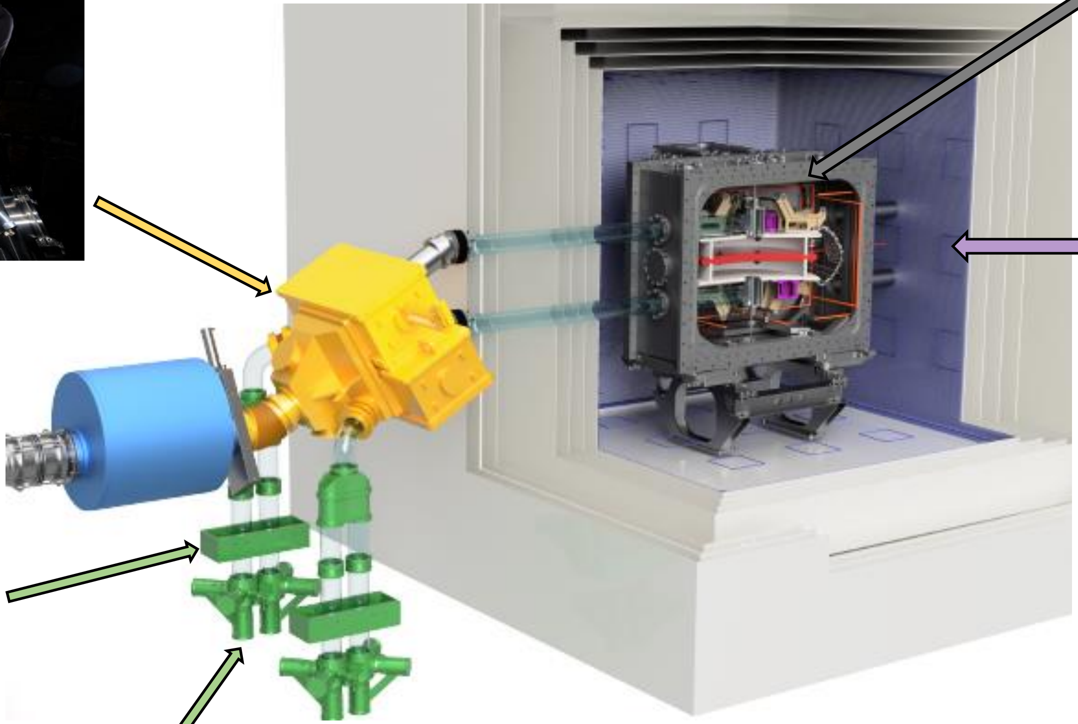
-> phase two : gain again an order of magnitude in sensitivity

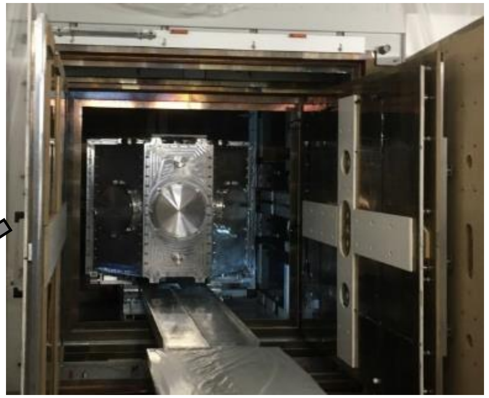
Design strategy in a nutshell:

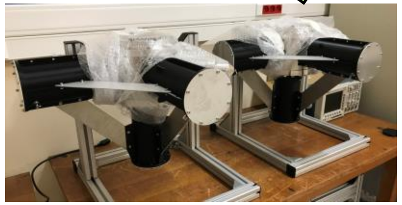
- To push up the statistic
  -> make your spectrometer bigger
- To push down the systematic error
  -> make your spectrometer smaller and/or improve your magnetic field

The search for the neutron EDM

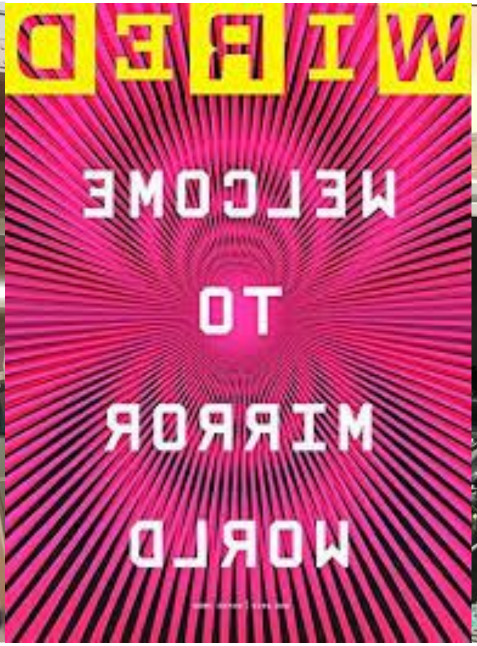
© Vincent MONCORGE

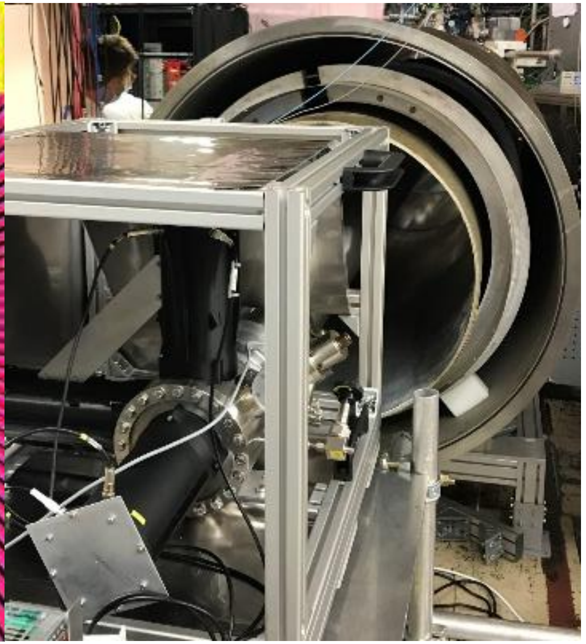






n2EDM in reality


WIRED
WELCOME TO MIRROR WORLD



Seriously a mirror world?

- Proposed by Lee and Yang in 1956 to restored parity in the weak interaction: introduction of a parity-conjugated copy of weakly interacting particles.
- In 1966, Kobzarev, Okun and Pomeranchuk: the mirror particles do not interact with « normal » particles via weak, strong and electromagnetic interactions. Within the mirror world the mirror particles interact among themselves via mirrored interaction: **mirror magnetic fields exist (assuming the mirror world does exists)**.
- Mirror matter is a dark matter candidate
- Changes the effective neutron lifetime (nucleosynthesis) and maybe even the baryogenesis
- Impact on some experimental issue such as neutron lifetime crisis and reactor anomaly

- The mixing between the two worlds can be probe via oscillation of neutral particles into/from its mirror partner.

Seriously a mirror world?

Very simple phenomenological model. Generic approach:

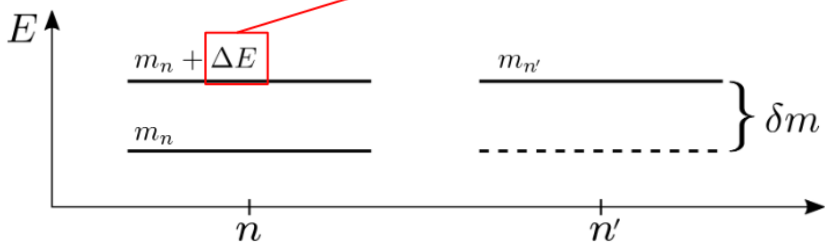
neutron - matter interaction

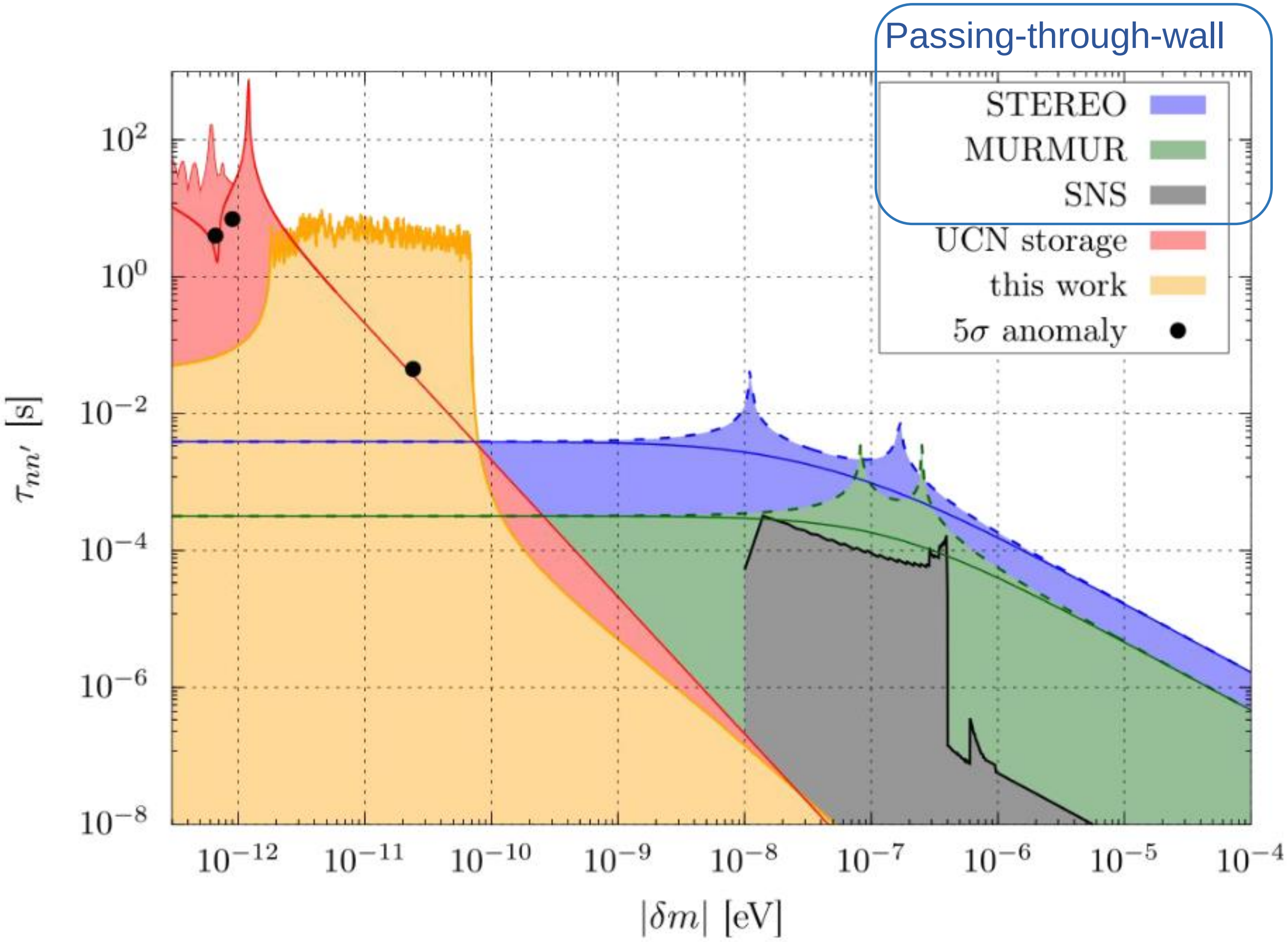
mixing term ($= 1/\tau_{nn'}$)

$$\hat{H} = \begin{pmatrix} m_n + \Delta E & \epsilon_{nn'} \\ \epsilon_{nn'} & m_n + \delta m \end{pmatrix}$$

mass splitting

Experimentally accessible: Tuned to scan δm





Courtesy W. Saenz

Thank you very much

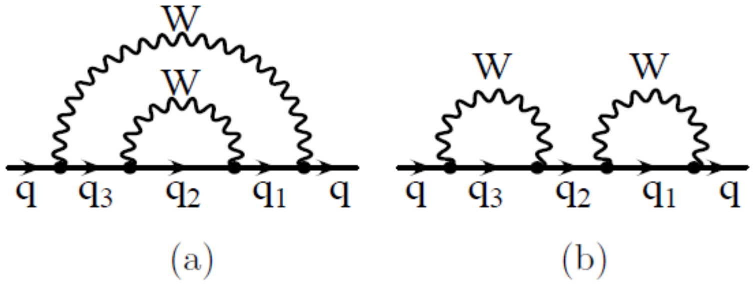
MERCI

CP violation in the standard model: the weak sector

The quarks' EDM (Phys.Rev.Lett.78:4339-4342,1997)

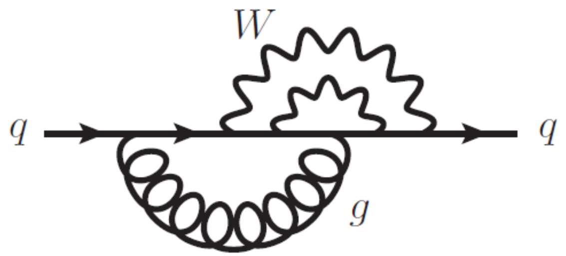
* One loop level (single boson exchange), no change in quark flavor, each CKM matrix element is accompanied by its complex conjugate; no T-violating complex phase can arise

* Two loop level, individual diagrams have complex phases and contribute to the EDM. However, the sum over all quark flavors in the intermediate states leads to the accidental vanishing of the EDM



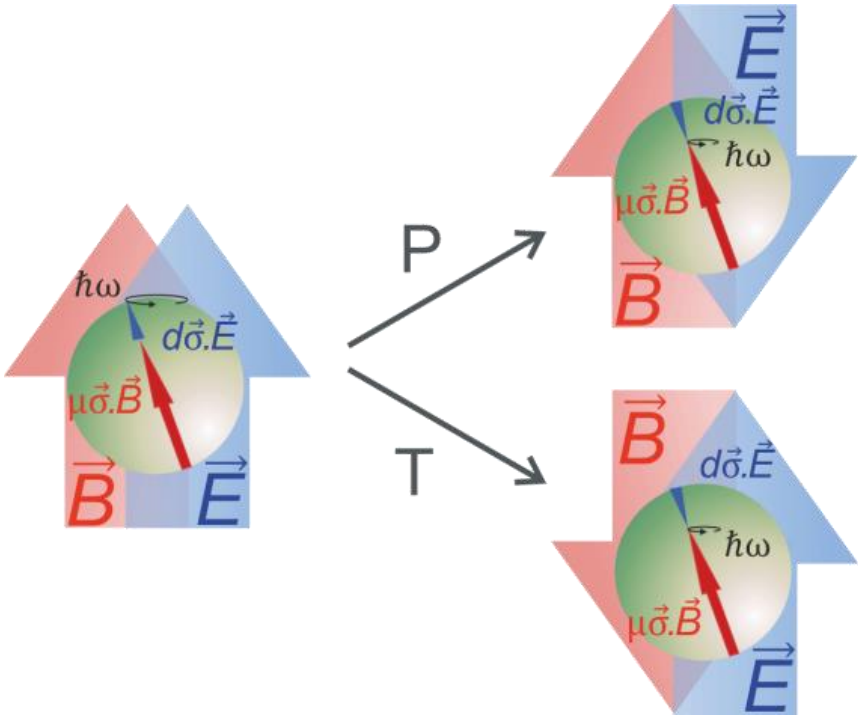
* The fact that the quark EDM appears only at the three loop level in the standard model greatly complicates theoretical estimates. The largest effect is due to the exchange of two W bosons and one gluon

$$d_d = -0.7 \times 10^{-34} \; e \text{ cm}$$
$$d_u = -0.15 \times 10^{-34} \; e \text{ cm}$$



The search for the neutron EDM

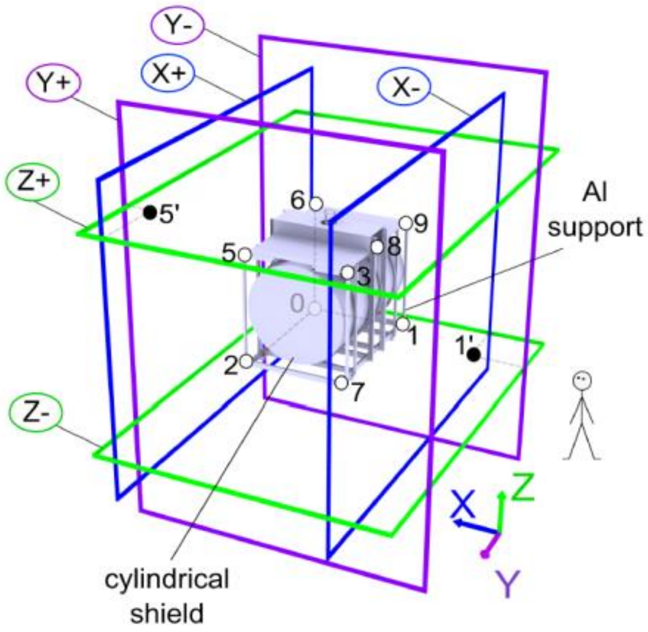
$$H = -\vec{\mu}_n.\vec{B} - \vec{d}_n.\vec{E} = \frac{hf_n}{2}$$

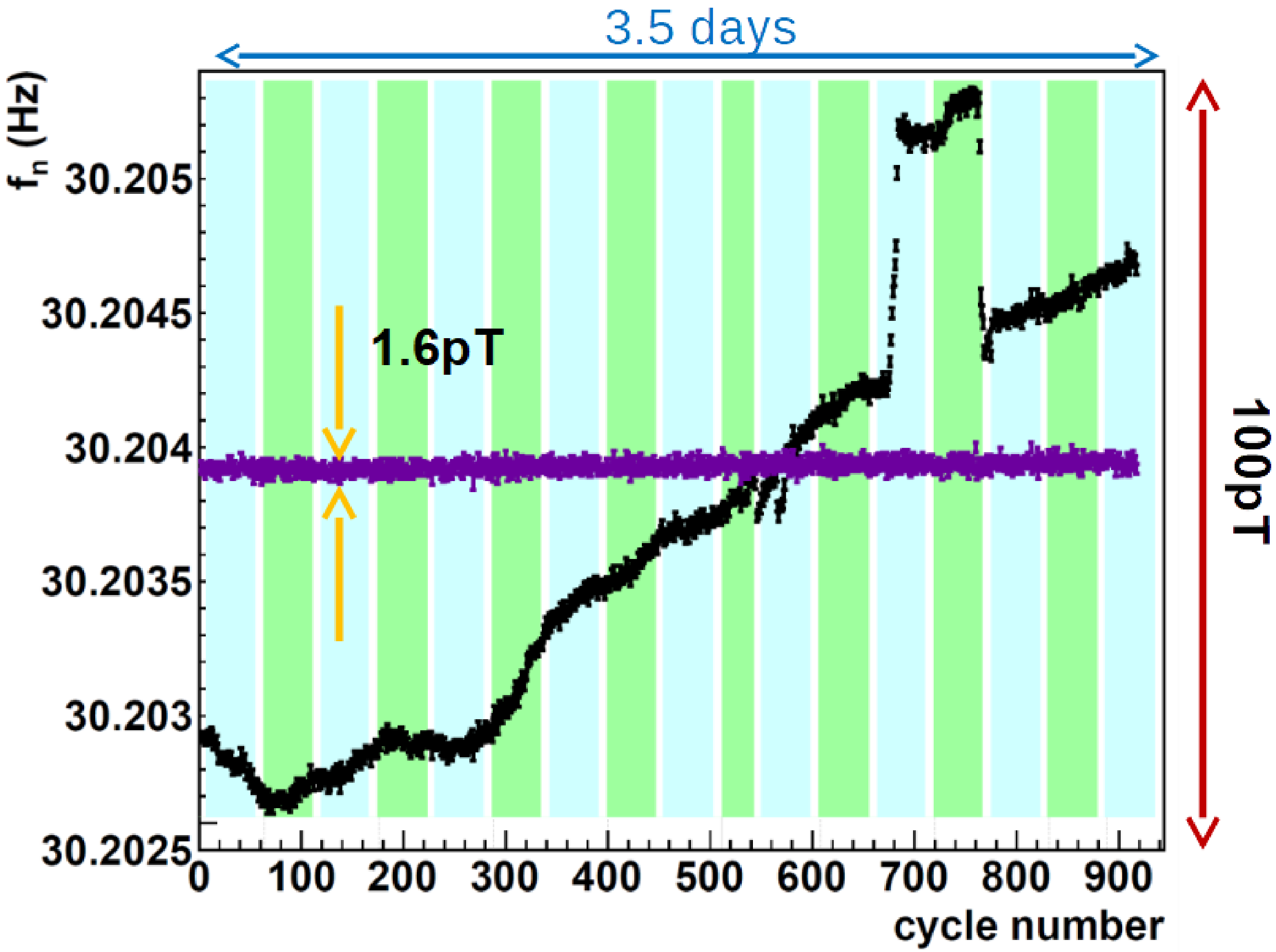


We have this quantity, that is breaking P, T and CP symmetries.

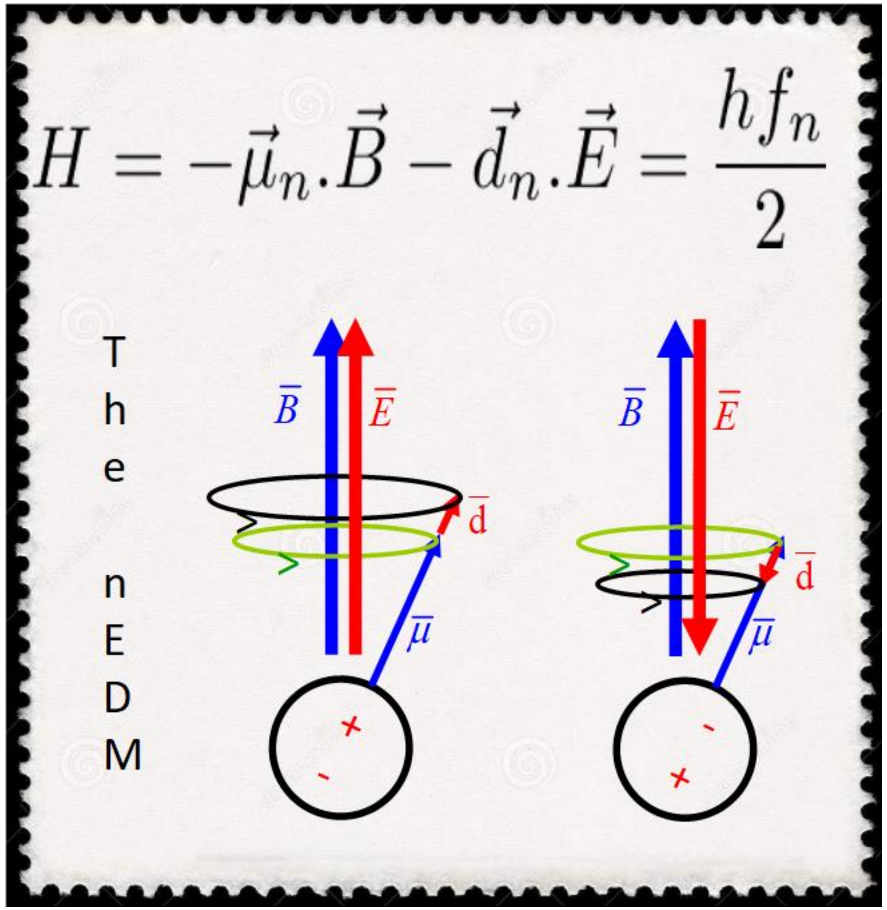
What is it interesting for?

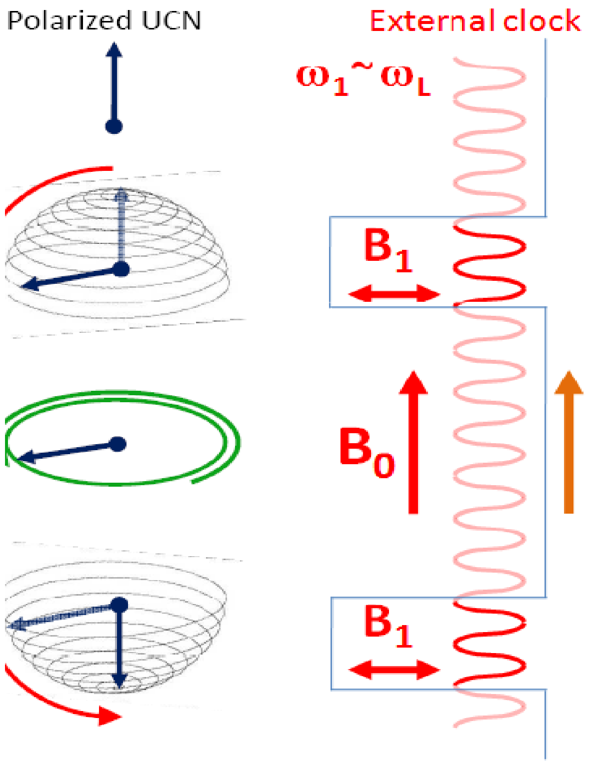
The search for the neutron EDM

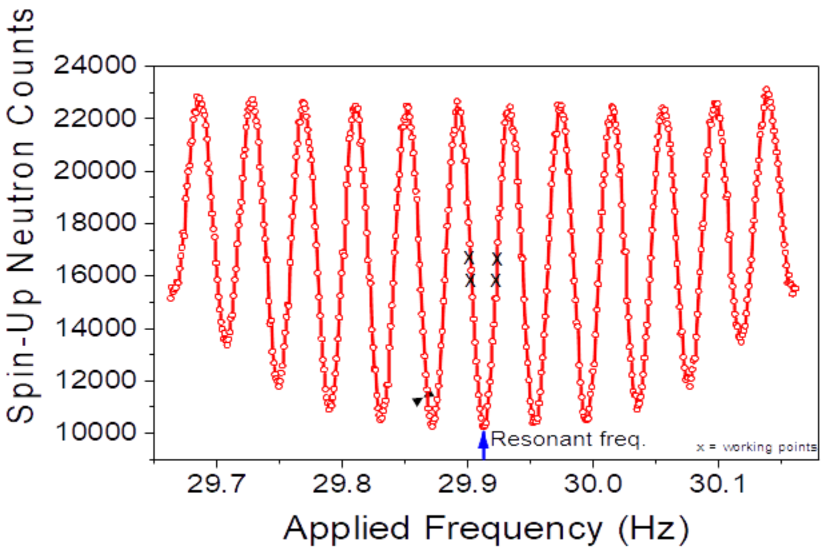




The search for the neutron EDM







$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

The Ramsey's method of separated oscillating fields

Axion detour

The axion is a well motivated dark matter candidate

Axion density relative to the critical density of the universe

$$\Omega_a \approx \left(\frac{6\,\mu\mathrm{eV}}{m_a}\right)^{\frac{7}{6}} \approx \Omega_m = 0.23\ (m_a \approx 20\ \mu eV)$$

Entire dark matter density

The theory is quite predictive

Essentially all of the physics of the axion depends on a large unknown energy scale f_a, at which Peccei-Quinn symmetry is broken.

$$m_a \approx 6\,\mathrm{eV}\left(\frac{10^6\,\mathrm{GeV}}{f_a}\right)$$

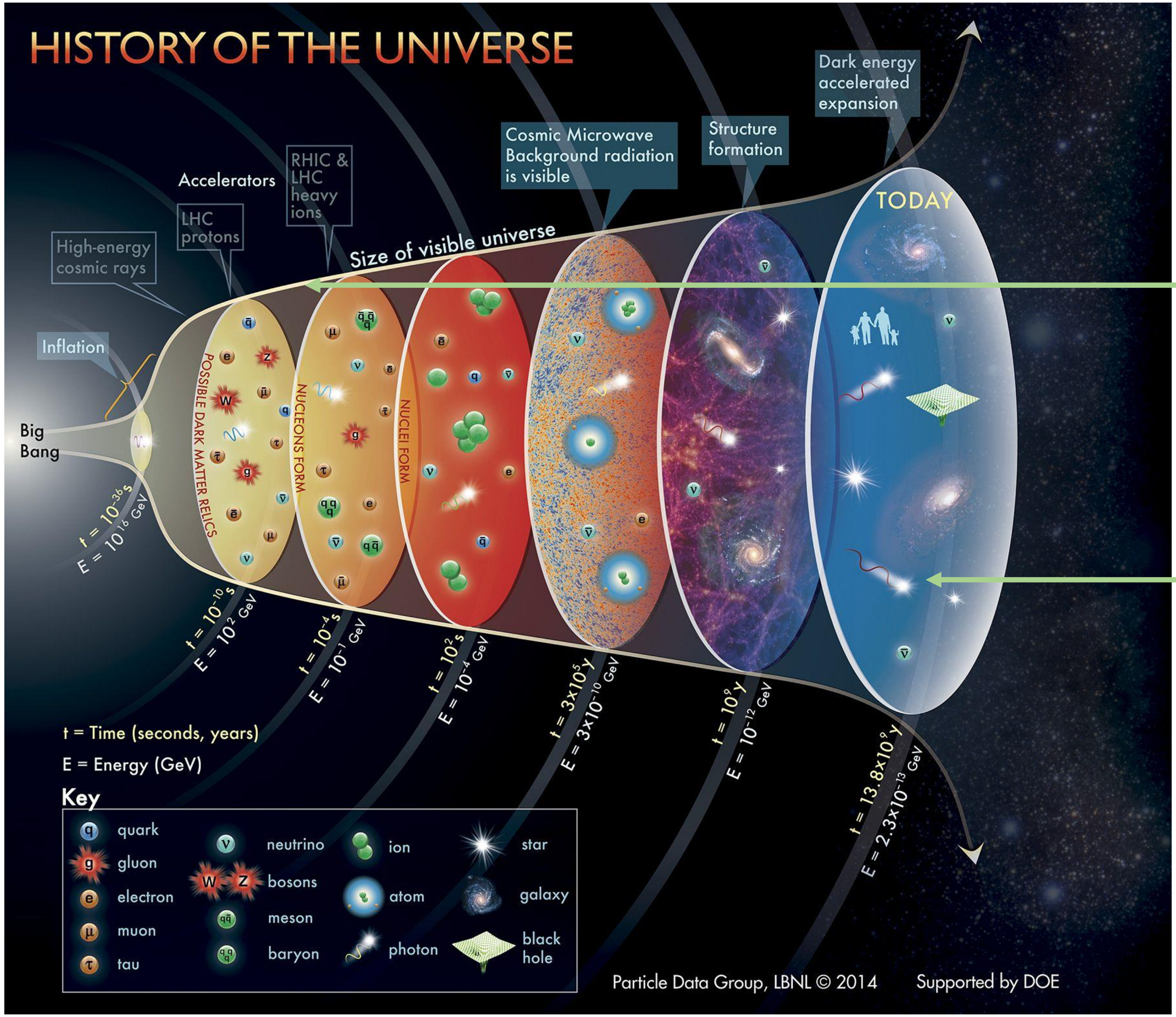
The axion has a two photons coupling,

and g_γ is model dependant.

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$$

Annual Review of Nuclear and Particle Science Vol. 65:485-514 (2015)

Matter/Antimatter Asymmetry of the Universe



$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

(1) You prepare the system in thermal equilibrium with

$$A_{B\bar{B}} = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \approx 0$$

(2) Baryogenesis happens.

(3) You find the system in thermal with

$$A_{B\bar{B}} = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \approx 1, \eta \approx 0$$

Can we say anything general about what happens in Step 2?

CP violation in the standard model: the weak sector

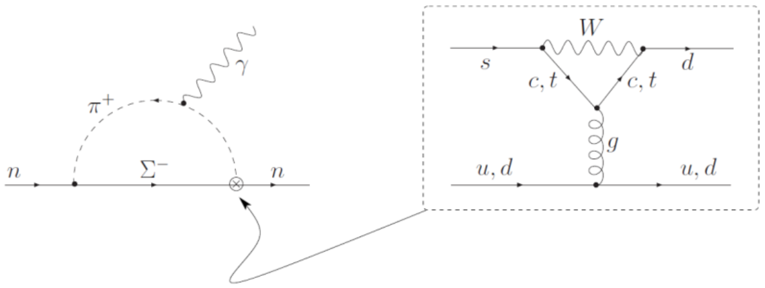
The neutron EDM (from quarks' EDM)

Naive (valence) approach: $$d_n = \frac{4}{3}d_d - \frac{1}{3}d_u \leq 10^{-34}\ e.cm$$

The neutron EDM (from "long" distance effect)

The largest Standard Model contribution to d_n comes not from quark EDMs, but from a four-quark operator generated by a so-called "strong penguin" diagram. This is enhanced by long distance effects, namely the pion loop, and it has been estimated that this mechanism

$$d_n \approx 10^{-32}\ e.cm$$



The neutron EDM is essentially free of SM background!

Annals of Physics 318 (2005) 119–169