Humboldt Kolleg on Particle Physics
"From the Vacuum to the Universe"
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The neutron Electric Dipole Moment experiment at PSI

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(on behalf of the nEDM Collaboration at PSI)
https://www.psi.ch/nedm/nedm-collaboration

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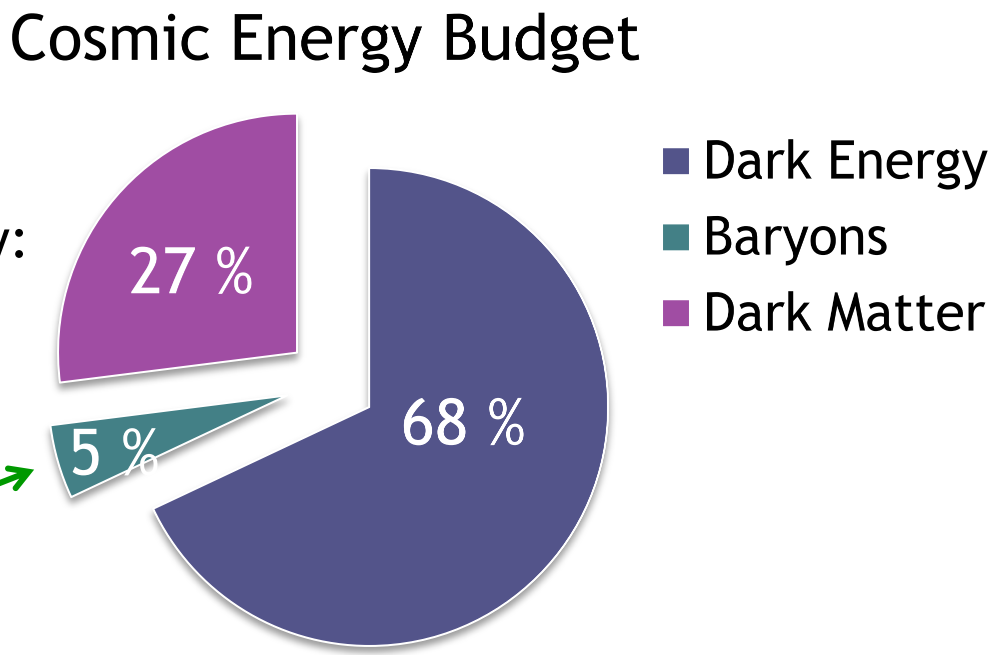
Outline

- Motivation
- EFT – “communication protocol”
- Electric Dipole Moments
- Neutron Electric Dipole Moment
- Ultra-Cold Neutrons
- Neutron EDM experiment at PSI - status
- Summary and outlook

The origin of Matter



- Matter-Antimatter asymmetry:
  - B violation (sphalerons)
  - C and CP violation
  - Out-of-equilibrium or CPT violation

- Scenarios of Bariogenesis:
  - Leptogenesis
  - EW Bariogenesis
  - Asymmetric DM
  - Post-spaleron bariogenesis
  - …

- New (larger) sources of CPV needed to explain EW Baryogenesis
- All CPV interactions contribute to EDMs
- EDMs provide stringent limits on BSM CPV models

Interpretation of EDM – EFT approach

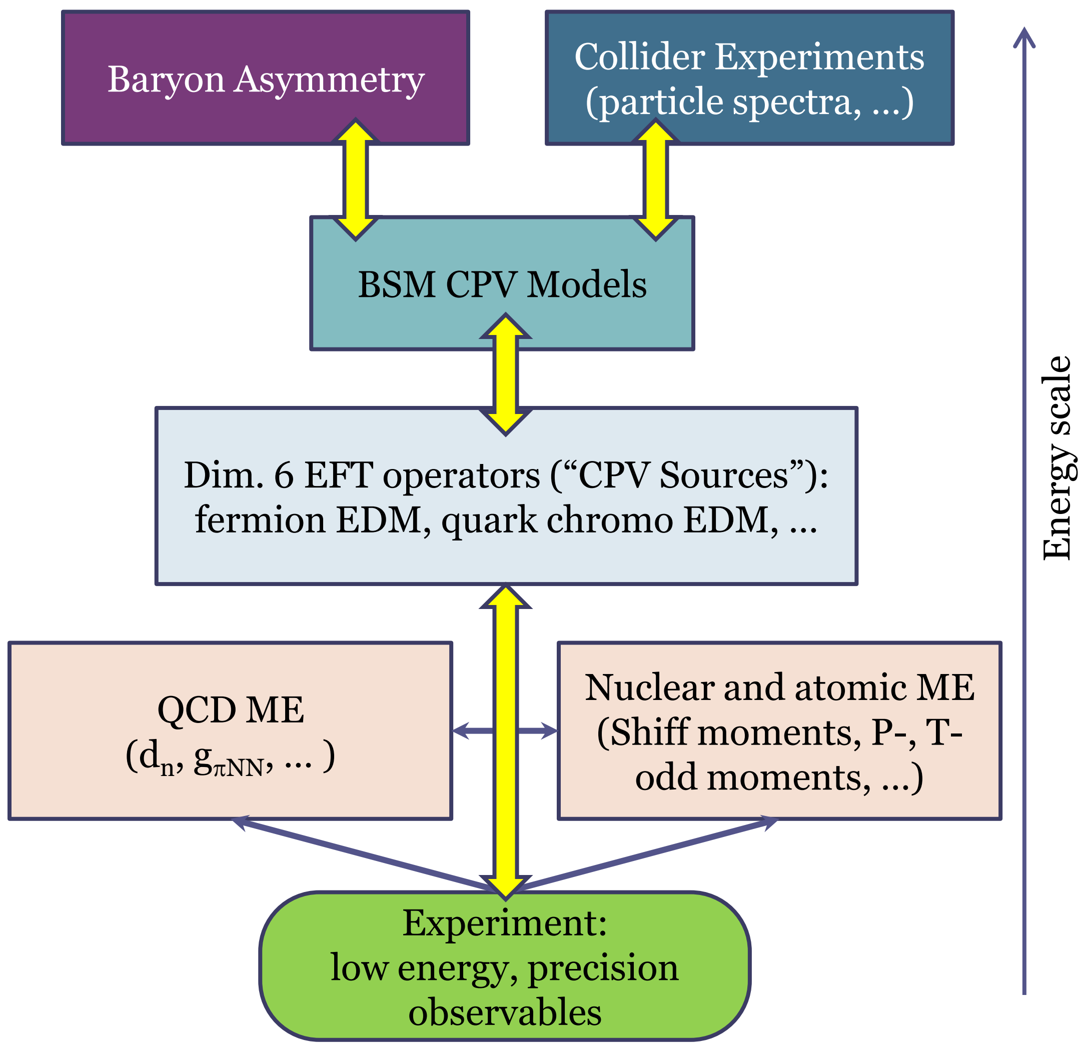
$$\mathcal{L}_{\text{CPV}} = \mathcal{L}_{\text{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\text{BSM}}^{\text{eff}}$$

$$\mathcal{L}_{\text{BSM}}^{\text{eff}} = \frac{1}{\Lambda^2} \sum \alpha_i^{(n)} \mathcal{O}_i^{(6)}$$

Wilson coefficients

δ_f	fermion EDM	(3)
$\tilde{\delta}_q$	quark cEDM	(2)
$C_{\tilde{G}}$	3 gluon	(1)
C_{quqd}	non-leptonic	(2)
$C_{lequ,ledq}$	semi-leptonic	(3)
$C_{\varphi ud}$	induced 4f	(1)

Bhattacharya et al, PRL 115 (2015) 212002
Bhattacharya et al, PRD92 (2015) 094511



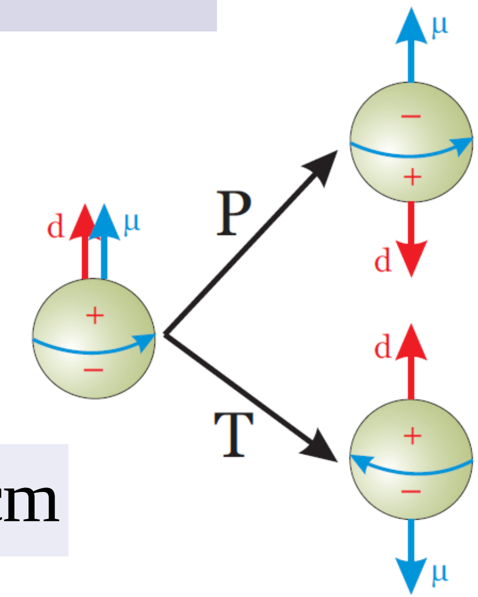
Permanent EDMs

EDM of elementary particles

- For non-degenerated spin ½ object:
  - Spin is the only reference direction for dipole magnetic moment μ and dipole electric moment d
  - Hamiltonians:

$$H_M = -\boldsymbol{\mu} \cdot \mathbf{B} = -\mu\, \boldsymbol{\sigma} \cdot \mathbf{B} \qquad H_E = -\mathbf{d} \cdot \mathbf{E} = -d\, \boldsymbol{\sigma} \cdot \mathbf{E}$$

  - ***d*** is T-odd and P-odd
  - $d \neq 0 \Rightarrow$ T is violated and CP is violated under assumption of CPT conservation



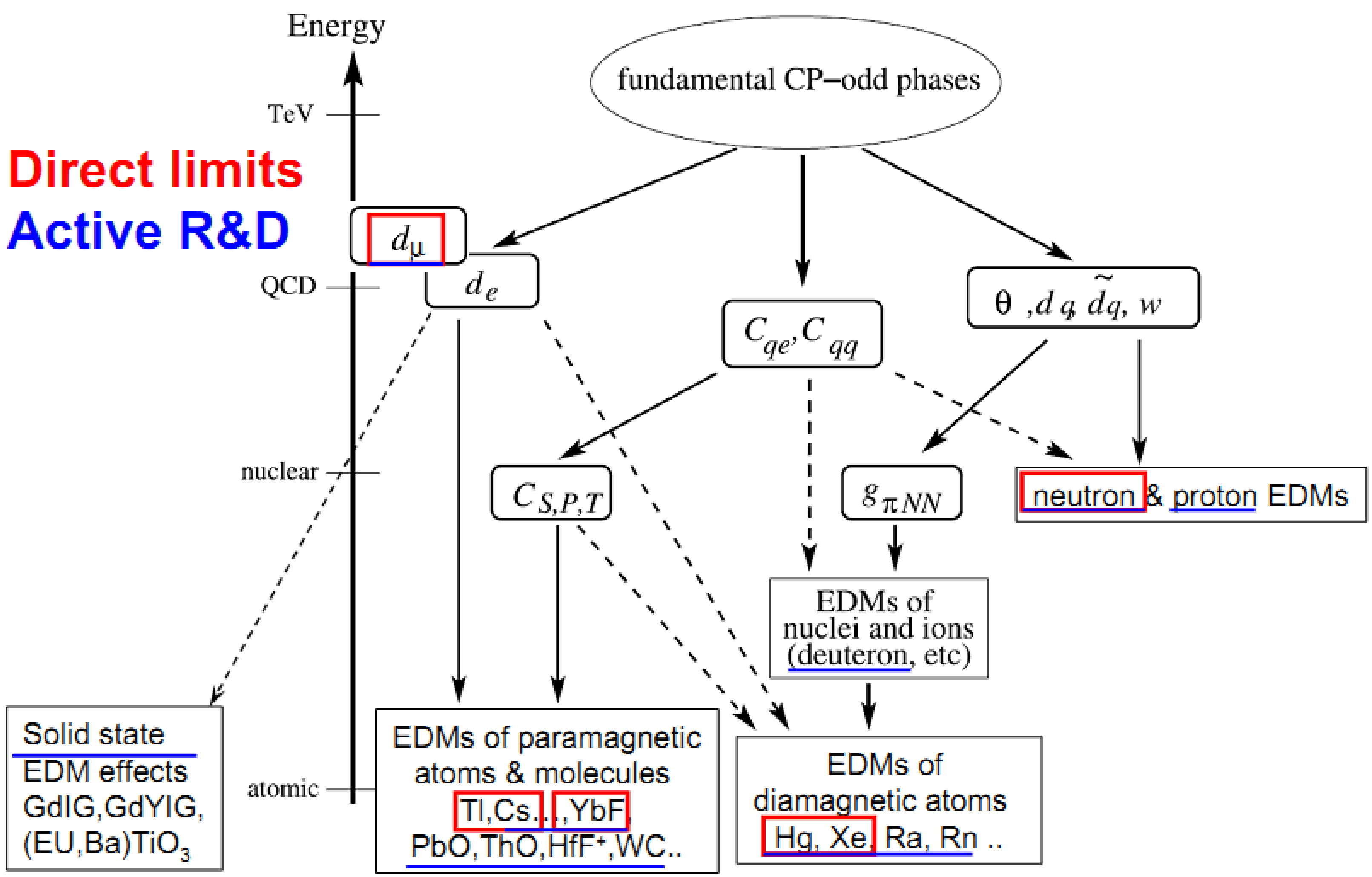
- SM contribution to ***d*** :

$$d_e \simeq 10^{-40}\, e \cdot \mathrm{cm} \qquad d_n \simeq 10^{-31}\, e \cdot \mathrm{cm}$$

EDM of elementary particles (PDG)

Particle	Symbol	Experimental value (e·cm)
Electron	e	$< 1.05\times 10^{-27}$
Muon	μ	$(0.1\pm 0.9) \times 10^{-19}$
Tau	τ	$(>-0.22, <0.45) \times 10^{-16}$ (95% CL)
Electron neutrino	ν_e	?
Muon neutrino	ν_μ	?
Tau neutrino	ν_τ	$< 5.2 \times 10^{-17}$ (95% CL)
Neutron	n	$< 3.0 \times 10^{-26}$ (90% CL)
Proton	p	$< 5.4 \times 10^{-24}$
Hyperon Λ	Λ	$<1.5 \times 10^{-16}$ (95% CL)

Sources of CP violation and EDMs



Pospelov & Ritz, Ann. Phys. 318 (2005) 119

EDM of neutrons atoms and molecules

- Practical aspect – investigated object should be:
  - Electrically neutral (e.g. atom or neutron)
  - Artificially confined in the apparatus (e.g. storage ring) despite strong E
- Propagation of EDMs from constituents to compound objects
- Schiff's moment:

$$\boldsymbol{S} = \frac{1}{10}\int d^3r\,\rho_{\rm ch}(\boldsymbol{r})\left(r^2 - \frac{5}{3}\overline{r^2_{\rm ch}}\right)\boldsymbol{r}$$

- $\boldsymbol{S}$ transfers EDM of nucleons to atom
- For nuclei with static octupolar deformation $\boldsymbol{S}$ can be **10 - 1000** times larger than for spherical nuclei – **enhancement factor !**
- ***Perfect knowledge of structure (at all levels: nucleon, nuclear, atomic, molecular) is crucial for extraction of EDMs of elementary particles***

EDMs of neutron and atoms

R. Barbieri et al., Phys. Lett. 369B, 283 (1996)

$$d_{\mathrm{n}} = 1.6\left(\frac{4}{3}d_{\mathrm{d}} + \frac{1}{3}d_{\mathrm{u}}\right) + O\left(10^{-1}\right)d_{\mathrm{q}}^{\mathrm{QCD}} + O(1)\left(\frac{\theta}{10^{-9}}\right)d_{\mathrm{n}}^{1995}$$

$$d_{\mathrm{Tl}} = -600\,d_{\mathrm{e}} + O\left(10^{-4}\right)d_{\mathrm{q}} + O\left(10^{-3}\right)d_{\mathrm{q}}^{\mathrm{QCD}} + O\left(10^{-3}\right)\left(\frac{\theta}{10^{-9}}\right)d_{\mathrm{Tl}}^{1995}$$ paramagn.

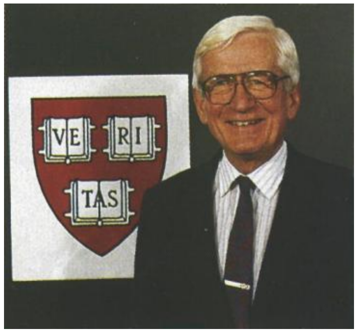
$$d_{\mathrm{Xe}} = 10^{-3}\,d_{\mathrm{e}} + O\left(10^{-4}\right)d_{\mathrm{q}} + O\left(10^{-3}\right)d_{\mathrm{q}}^{\mathrm{QCD}} + O\left(10^{-1}\right)\left(\frac{\theta}{10^{-9}}\right)d_{\mathrm{Xe}}^{1995}$$ diamagn.

$d_n^{1995} \leq 0.8\times10^{-25}$ e·cm, $d_{Tl}^{1995} \leq 6.6\times10^{-24}$ e·cm,
$d_{Xe}^{1995} \leq 1.4\times10^{-26}$ e·cm, d_q^{QCD} – quark-color EDM,
d_q – generated by Higgsa exchange

- ***Studies of complementary systems are essential for:***
  - *Finding non-zero EDMs*
  - *Disentangling CPV sources*

The neutron EDM

Neutron EDM



Norman Foster Ramsey Jr.
(1915-2011)

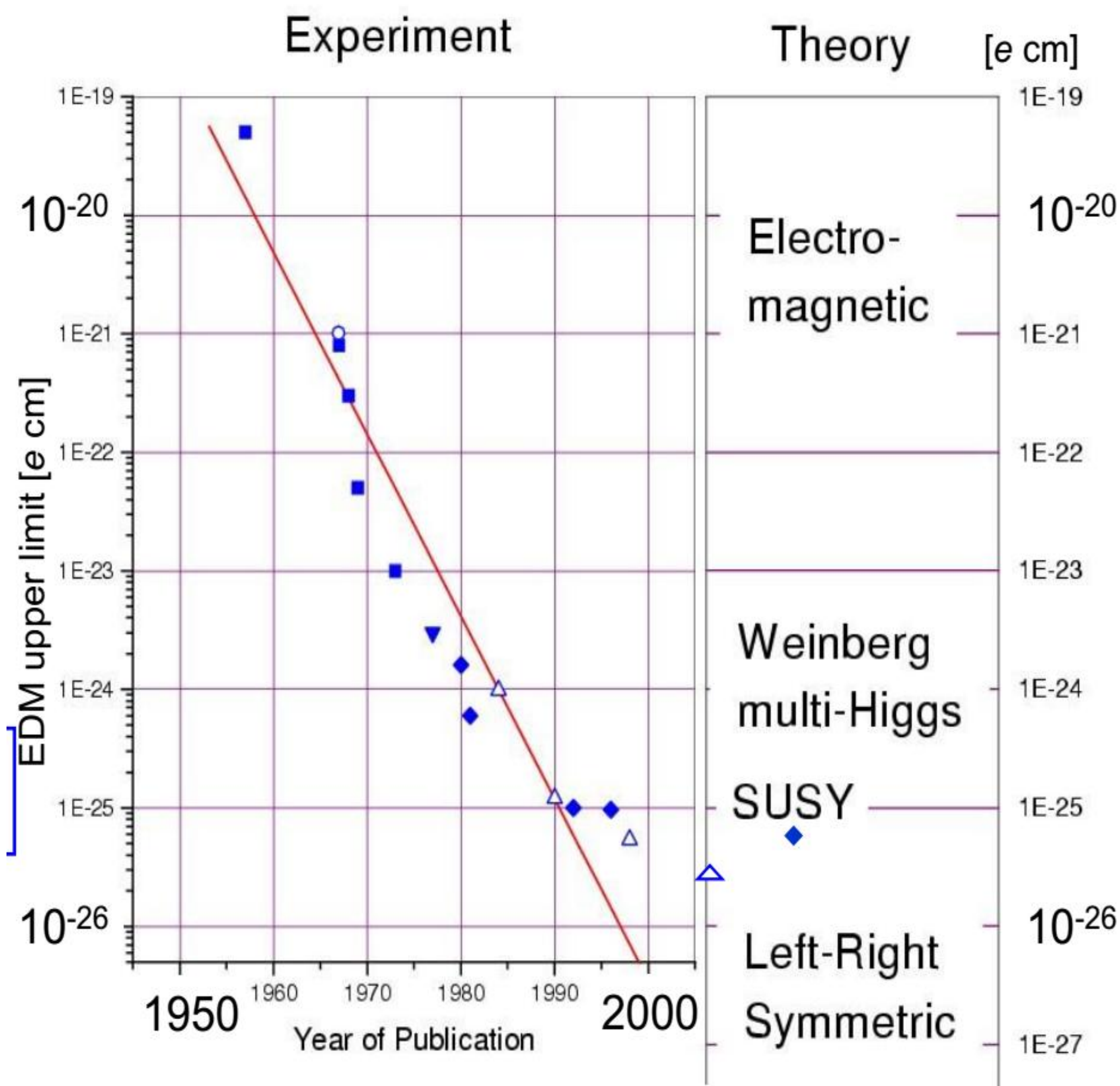
- Present exp. limit:

$$d_n < 3.0\times10^{-26}\,e\cdot\mathrm{cm}$$

C.A.Baker et al., PRL97 (2006) 0609055
J.M. Pendlebury et al., PRD 92(2015)092003

- Anticipated by new experiments:

$$d_n \sim 10^{-28}\,e\cdot\mathrm{cm}$$

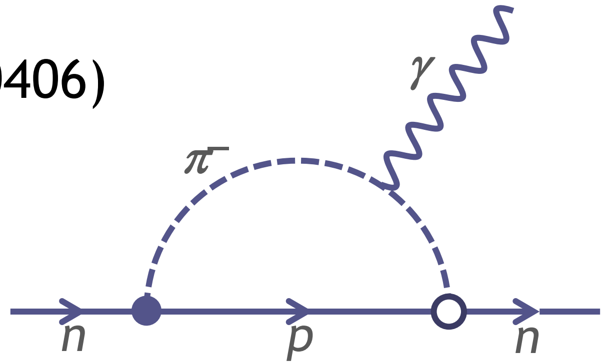


Neutron EDM

- **Neutron EDM** – ideal tool for search of CP-violation sources beyond SM: *no "SM-background" seen in e.g. K- and B-systems (ε, ε')*

- "**Strong CP problem**" (θ-term)
  - Fine tune is needed to accommodate very small EDM values (θ <2×10^{-10})
  - Axions? (Zavattini et al., PRL 96 (2006) 110406)

$$\mathcal{L}_{\mathrm{QCD}} \approx \mathcal{L}_{\mathrm{QCD}}^{\theta_{\mathrm{QCD}}=0} + \theta_{\mathrm{QCD}} \frac{g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

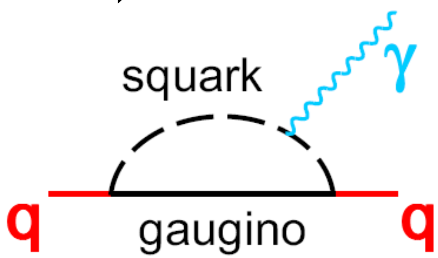


$$d_n \approx 10^{-16} e \cdot \mathrm{cm} \times \theta_{\mathrm{QCD}} \quad \Rightarrow \quad \theta_{\mathrm{QCD}} \le 10^{-10}$$

Why is θ_{QCD} so small?

Neutron EDM (cont.)

- "**SUSY CP problem**" ("overproduction" of EDM in SUSY models)



$$d_q = (\text{loop factor}) \times \frac{m_q}{\Lambda^2} \times \sin\varphi_{\mathrm{CP}}$$

loop factor $\sim \alpha/\pi$
scale of SUSY breaking $\Lambda \sim \mathrm{GeV}$
φ_{CP} – CP-phase

$$d_{u,d} = 3\times 10^{-24}\, e\cdot\mathrm{cm}$$

n EDM: $\Rightarrow$ $d_{u,d}$ are 10-100 times less !

Pospelov & Ritz, hep-ph/0504231

The neutron EDM at PSI

Neutrons: cold (CN) and ultra-cold (UCN)

- **Cold neutrons:** $E_{\mathrm{kin}}^{\mathrm{CN}} \sim 5\ \mathrm{meV}, \qquad v^{\mathrm{CN}} \sim 1\ \mathrm{km/s}$

- **Ultra-cold neutrons** - can be stored in material or magnetic traps - complete reflection

$$E_{\mathrm{kin}} < V_{\mathrm{F}} - \boldsymbol{\mu}_{\mathrm{n}} \cdot \mathbf{B} + mgh$$

$$V_{\mathrm{F}} = \frac{2\pi\hbar}{m} bN$$

V_F - Fermi pseudo-potential,
b - coherent bound scattering length,
N - number density

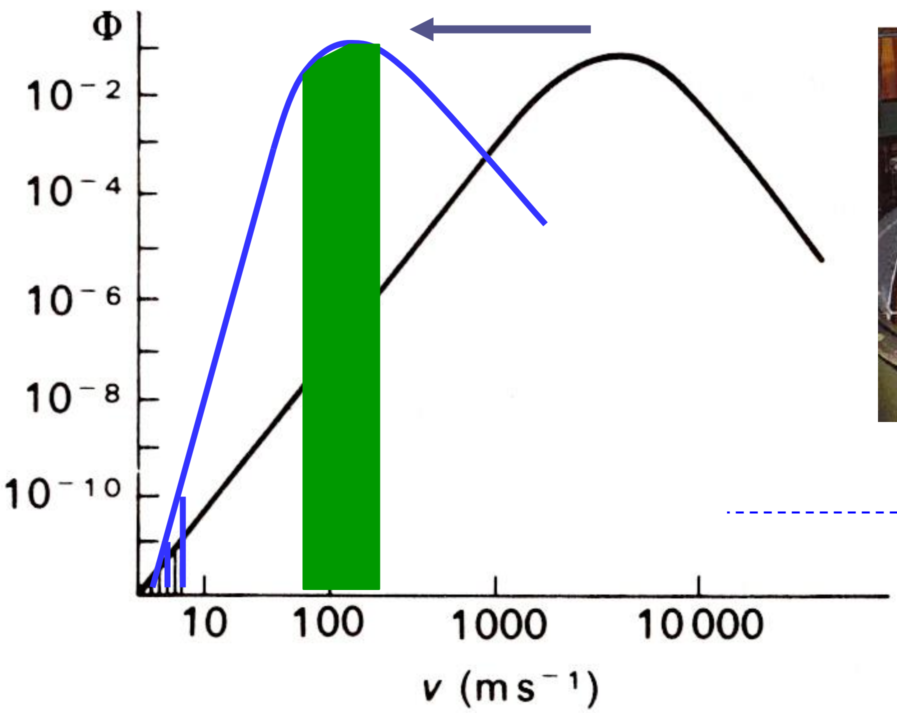
- $V_{\mathrm{F}}(\mathrm{Be}) \leftrightarrow E_{\mathrm{kin}} = 252\ \mathrm{neV}$,
- $\mu_{\mathrm{n}} B(1\ \mathrm{T}) \leftrightarrow E_{\mathrm{kin}} = 60\ \mathrm{neV}$,
- $mgh(1\ \mathrm{m}) \leftrightarrow E_{\mathrm{kin}} = 100\ \mathrm{neV}$

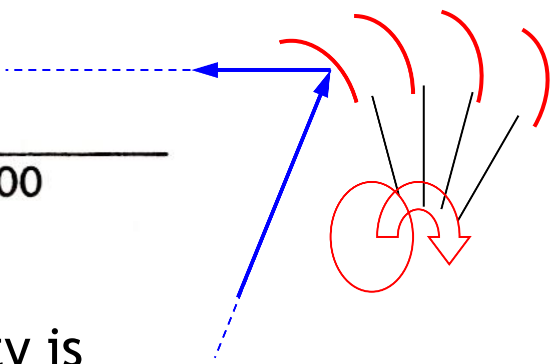
- $v^{UCN} < 8\ \mathrm{m/s}$,
- $T^{UCN} < 4\ \mathrm{mK}$,
- $\lambda^{UCN} > 50\ \mathrm{nm}$

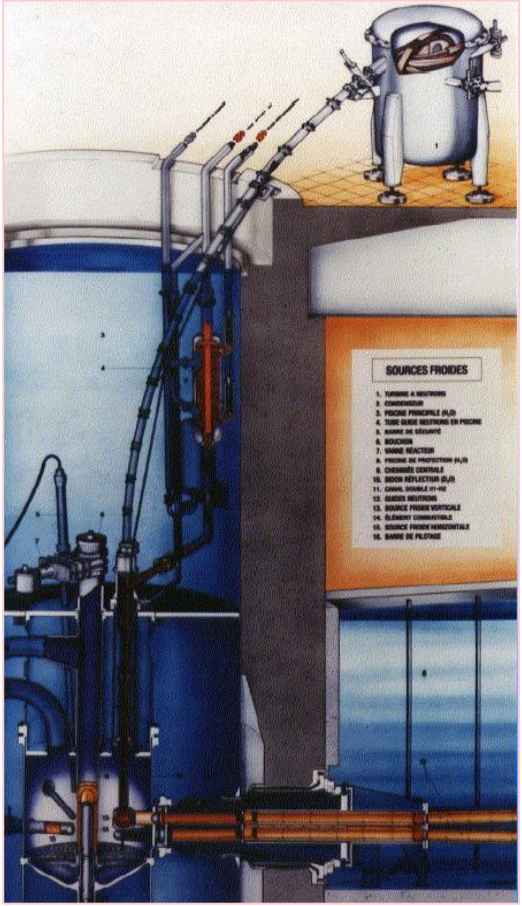
- UCN velocity spectrum evolves in time - faster neutrons die out quicker due to more frequent wall collisions $\Rightarrow$ density vertical gradient

UCN at ILL Grenoble

- Vertical extraction of CN
- Kinetic deceleration (Steyerl's turbine)

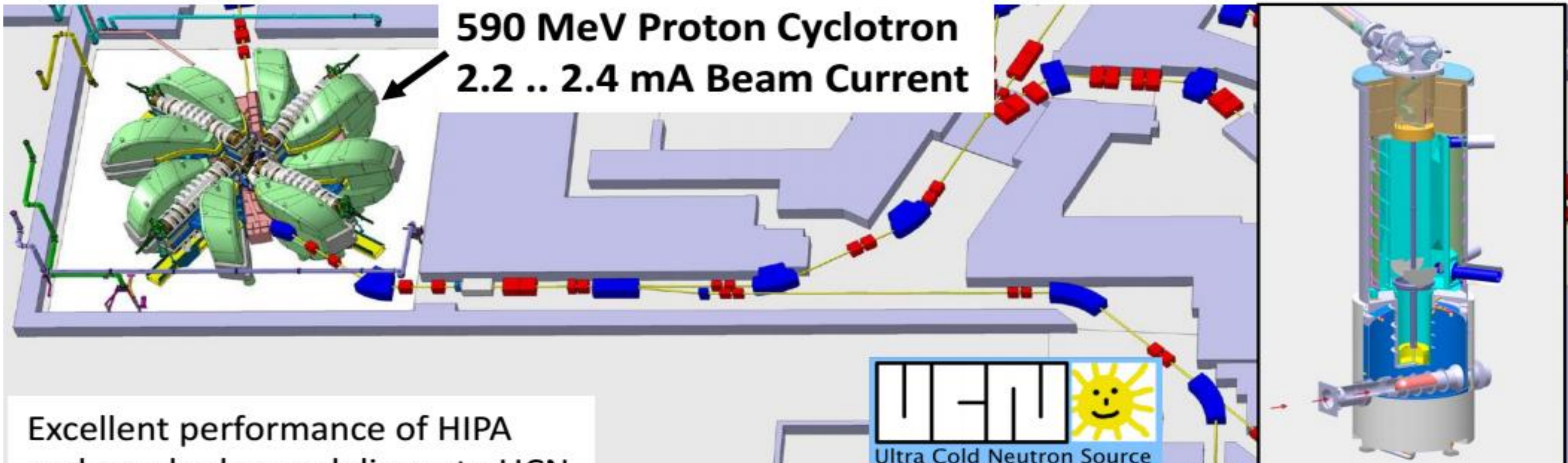


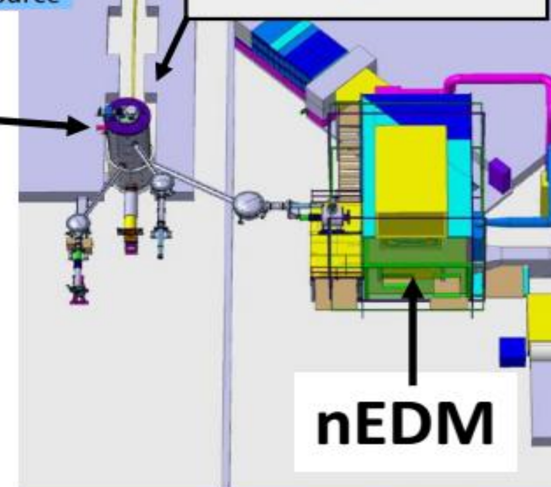




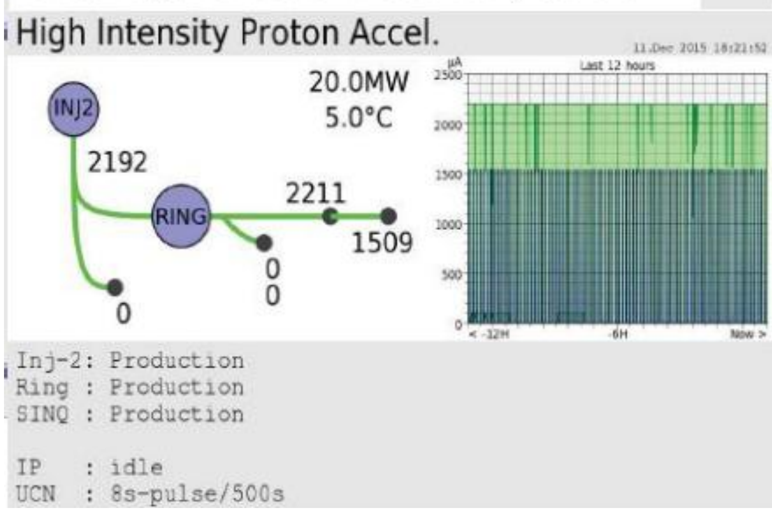
- Limitation of UCN density is due to Liouville's theorem

Ultra-cold Neutron Source and Facility at PSI





Excellent performance of HIPA and regular beam delivery to UCN



UCN-Source

- 1st test: 12/2010
- Safety approval: 06/2011
- UCN start 08/2011
- Reliable performance 2012
-     UCN to nEDM since 2012
  -> intensity 90x over 2010
- Increased duty factor 2015: 20 → 40 µA average
- 2016: towards 60µA

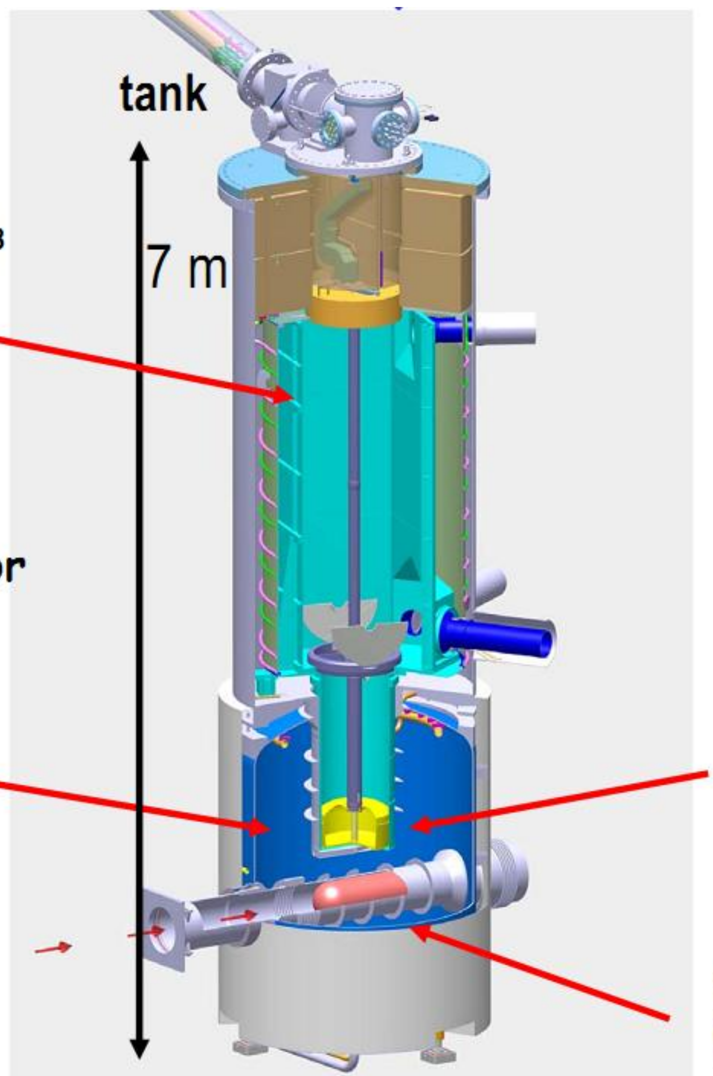
K. Kirch

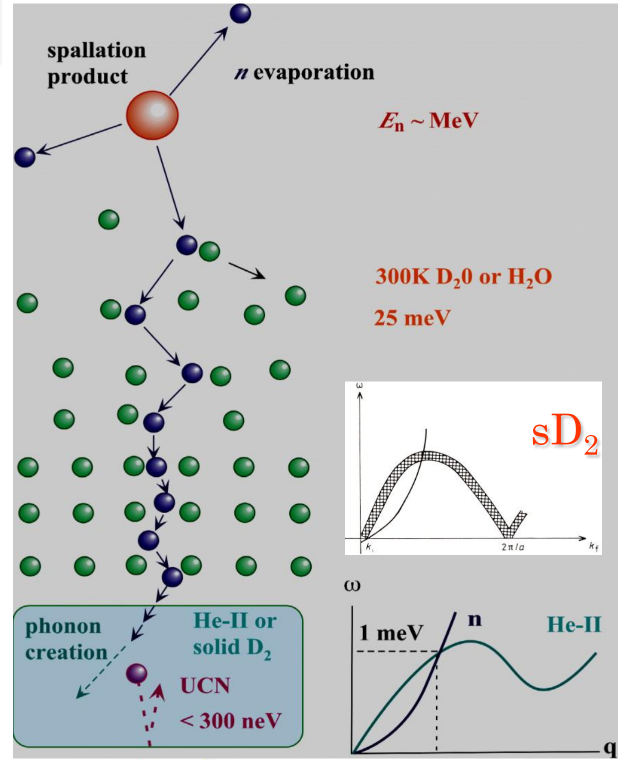
UCN spallation source at PSI

DLC coated
UCN storage volume
height 2.5 m, ~ 2 m³

heavy water moderator
→ thermal neutrons
3.6m³ D_2O

pulsed
1.3 MW p-beam
600 MeV, 2.4 mA,
2% duty cycle

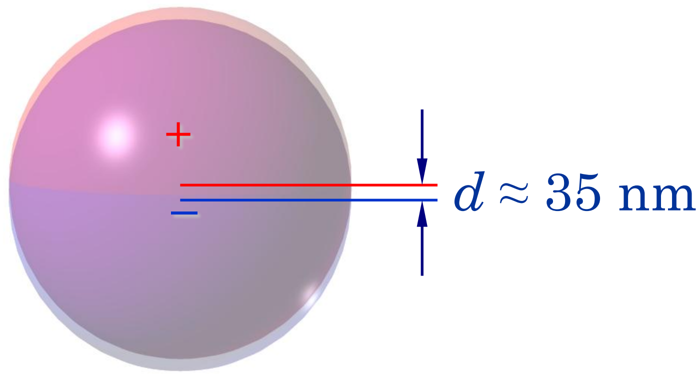


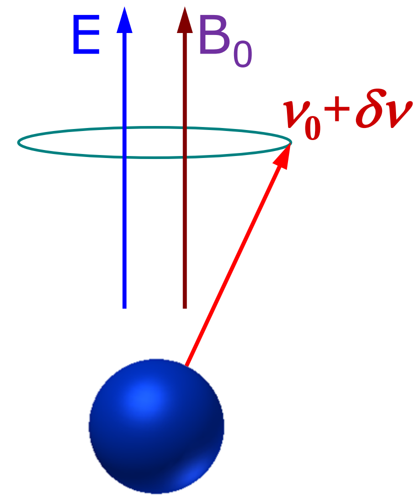


cold UCN-converter
30 dm³ solid D_2 at 5 K

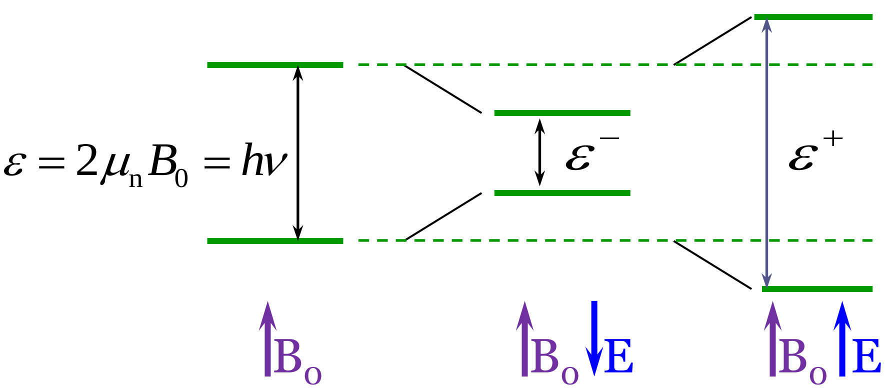
spallation target (Pb/Zr)
(~ 8 neutrons/proton)

Neutron EDM measurement



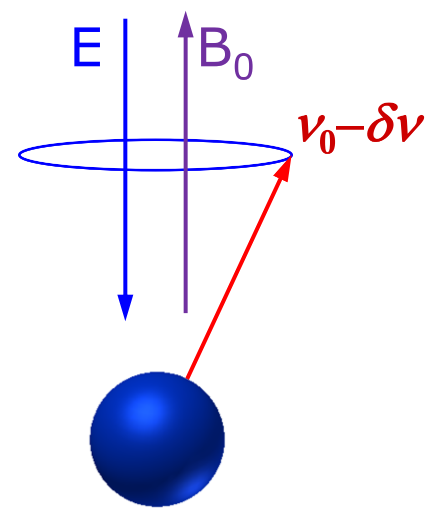


- Measure change of energy splitting (eqiv. to Larmor frequency shift) in B and E fields oriented parallel and anti-parallel

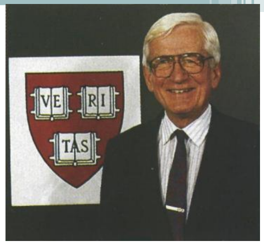


$$\Delta\varepsilon = \varepsilon^{+} - \varepsilon^{-} = 4 d_{\mathrm{n}} E_0$$
$$= h(\nu^{+} - \nu^{-}) = 2h\,\delta\nu$$

$$\Delta\varepsilon = 1.2\times10^{-23}\,\mathrm{eV}$$
$$\begin{pmatrix} d_{\mathrm{n}} = 2\times10^{-28}\,\mathrm{e\cdot cm} \\ E = 15\,\mathrm{kV/cm} \end{pmatrix}$$

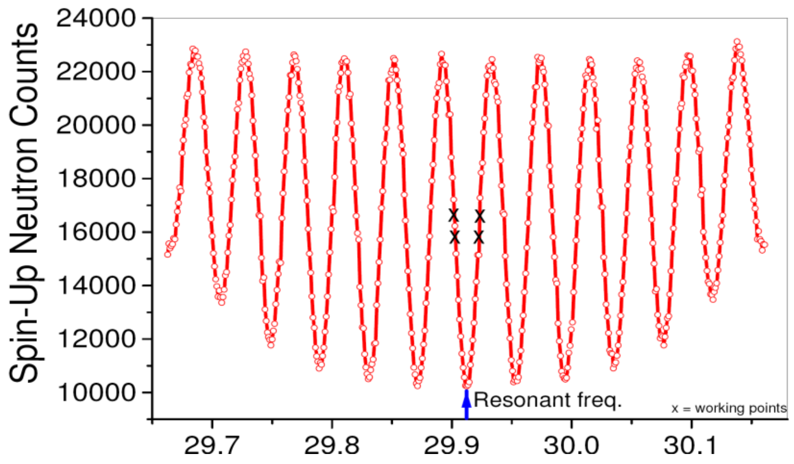


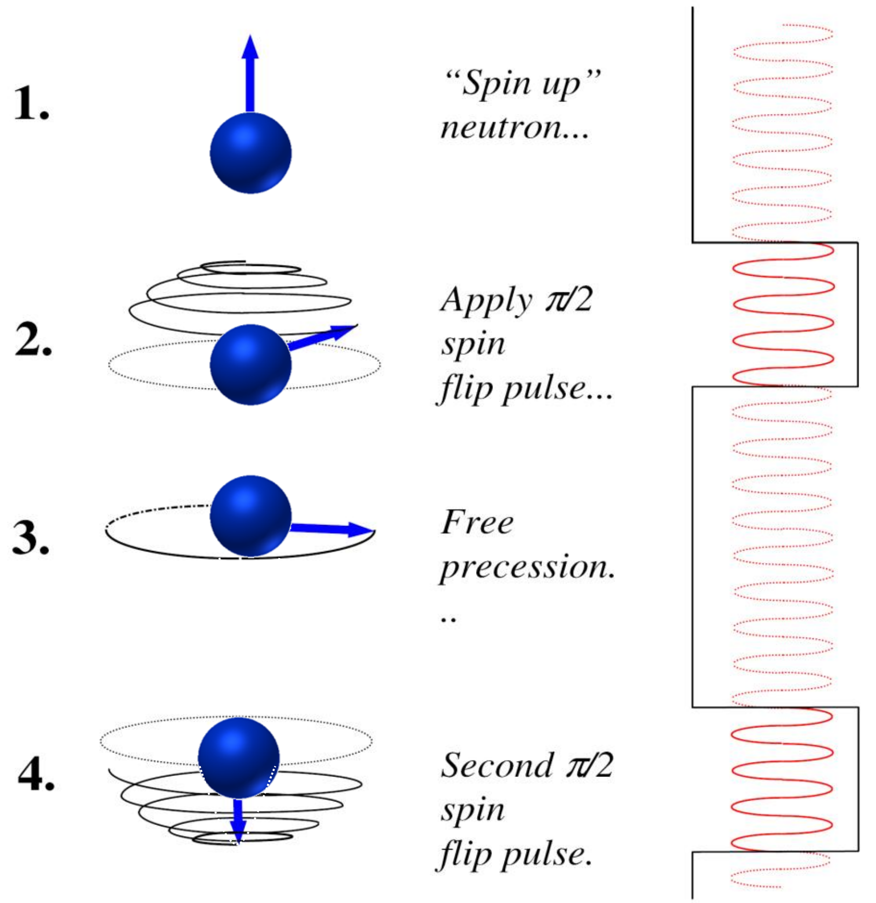
Neutron EDM measurement



- Ramsey method of separated oscillating fields
- Probability of transition between Zeeman levels:

$$W(\omega_0 - \omega, T, \delta) \approx \cos^2 \frac{(\omega_0 - \omega)T - \delta}{2}$$

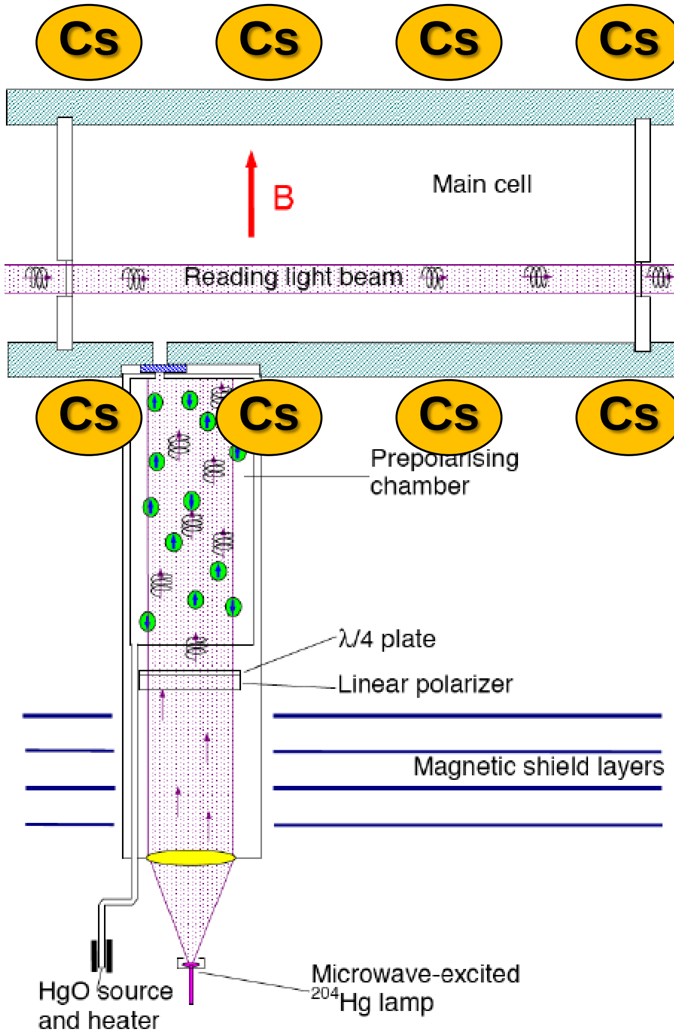


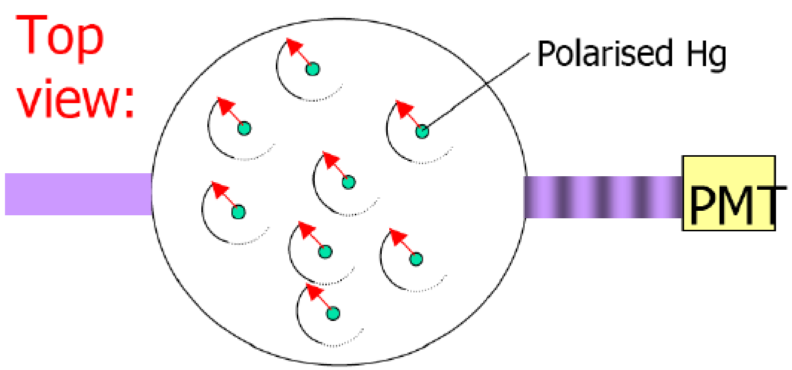


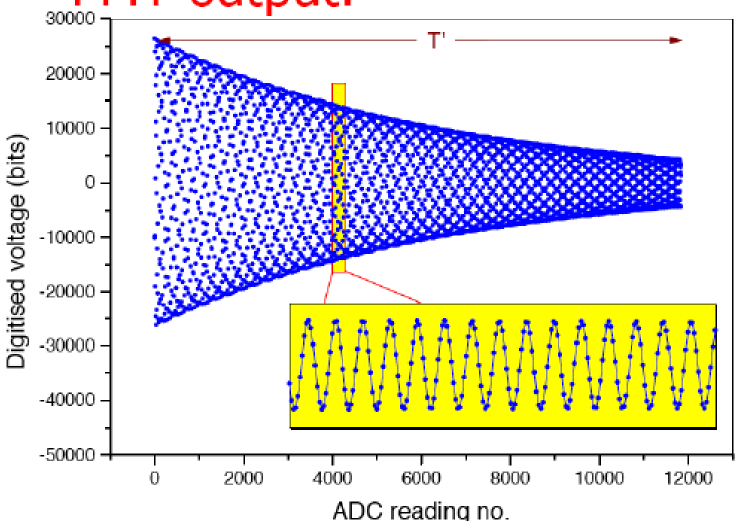
- Analogy to diffraction on two slits

Neutron EDM at PSI

Cs-OM for monitoring of B field gradients







Experimental uncertainties

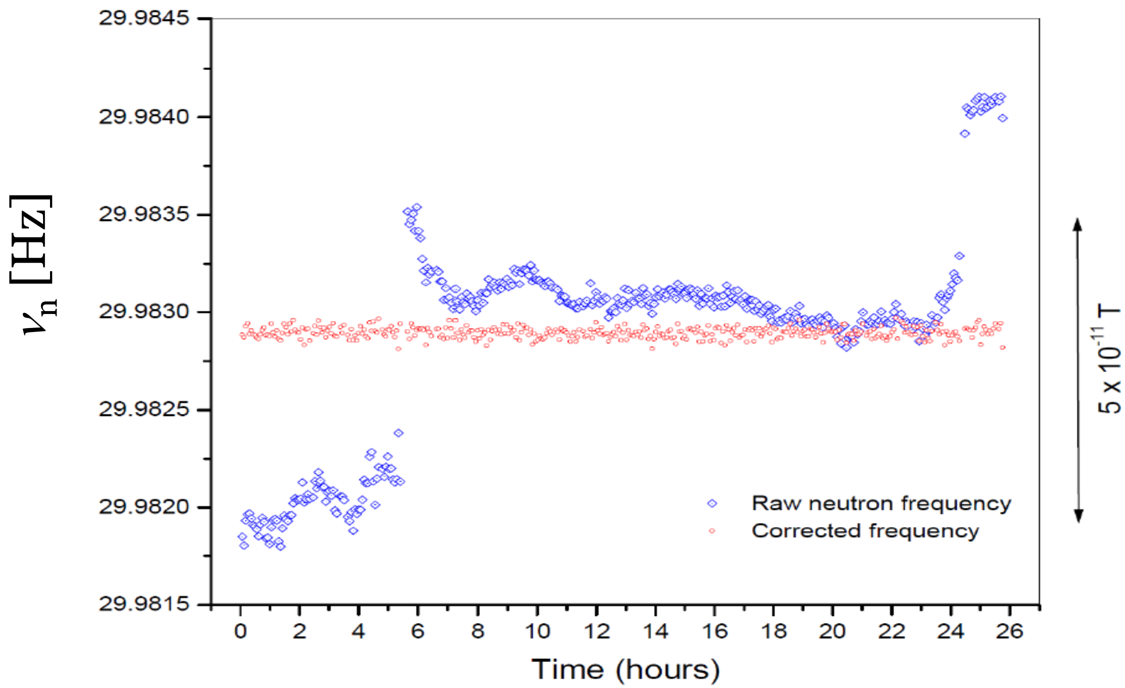
- Sensitivity

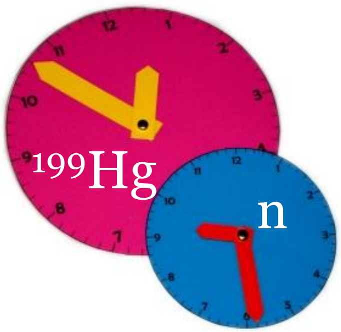
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

- Main systematic uncertainties

No.	Effect	Shift (Ref. [26]) $[10^{-27}\ e\mathrm{cm}]$	σ (Ref. [26]) $[10^{-27}\ e\mathrm{cm}]$	σ (Phase II) $[10^{-27}\ e\mathrm{cm}]$
1.	Door cavity dipole	-5.60	2.00	**0.10**
2.	Other dipole fields	0.00	6.00	**0.40**
3.	Quadrupole difference	-1.30	2.00	**0.60**
4.	$\mathbf{v} \times \mathbf{E}$ translational	0.00	0.03	0.04
5.	$\mathbf{v} \times \mathbf{E}$ rotational	0.00	1.00	**0.10**
6.	Second-order $\mathbf{v} \times \mathbf{E}$	0.00	0.02	0.01
7.	ν_{Hg} light shift (geo phase)	3.50	0.80	**0.40**
8.	ν_{Hg} light shift (direct)	0.00	0.20	0.20
9.	Uncompensated B drift	0.00	2.40	**0.90**
10.	Hg atom EDM	-0.40	0.30	*0.06*
11.	Electric forces	0.00	0.40	0.40
12.	Leakage currents	0.00	0.10	0.10
13.	ac fields	0.00	0.01	0.01
	Total	-3.80	7.19	**1.31**

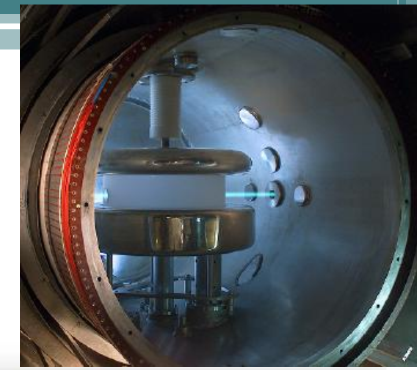
Neutron EDM at PSI – clock comparison experiment





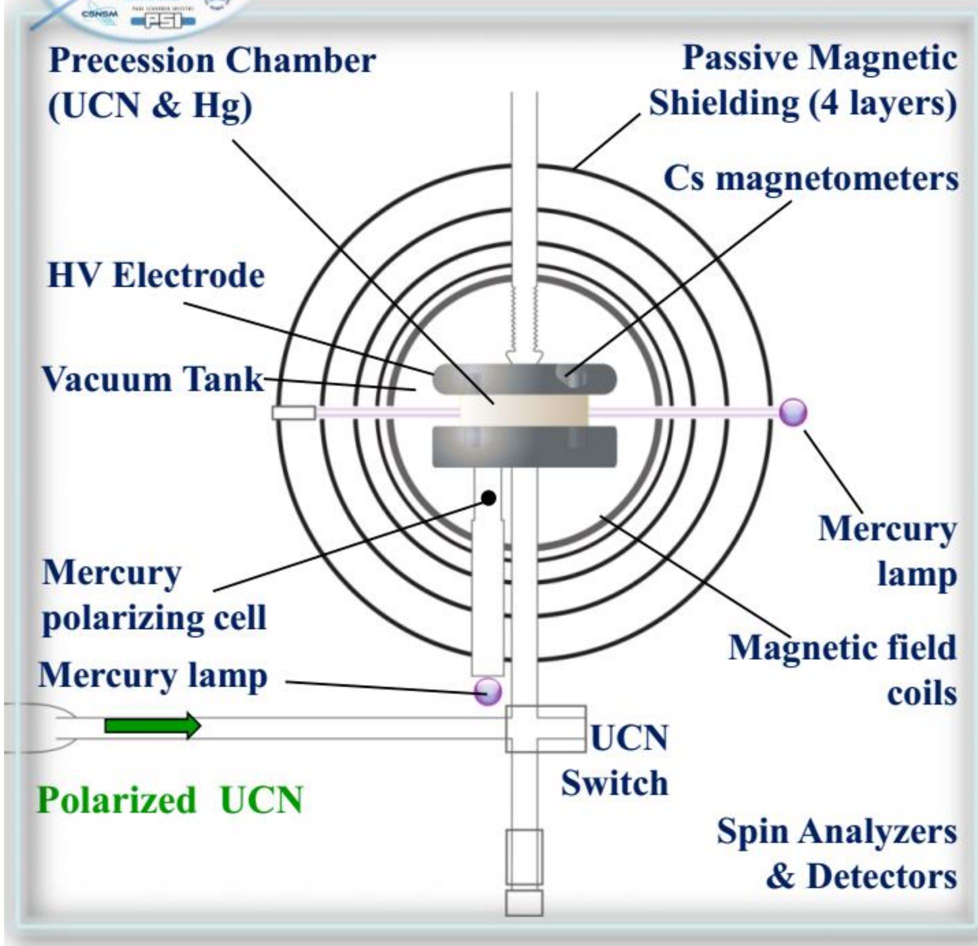
- Effectively neutron EDM is measured relatively to (much better constrained) ^{199}Hg EDM

- Apparatus can be also used for several exotic physics searches
  - Lorentz Invariance (CPT) violation
  - Neutron – mirror neutron oscillations
  - Short range spin dependent forces



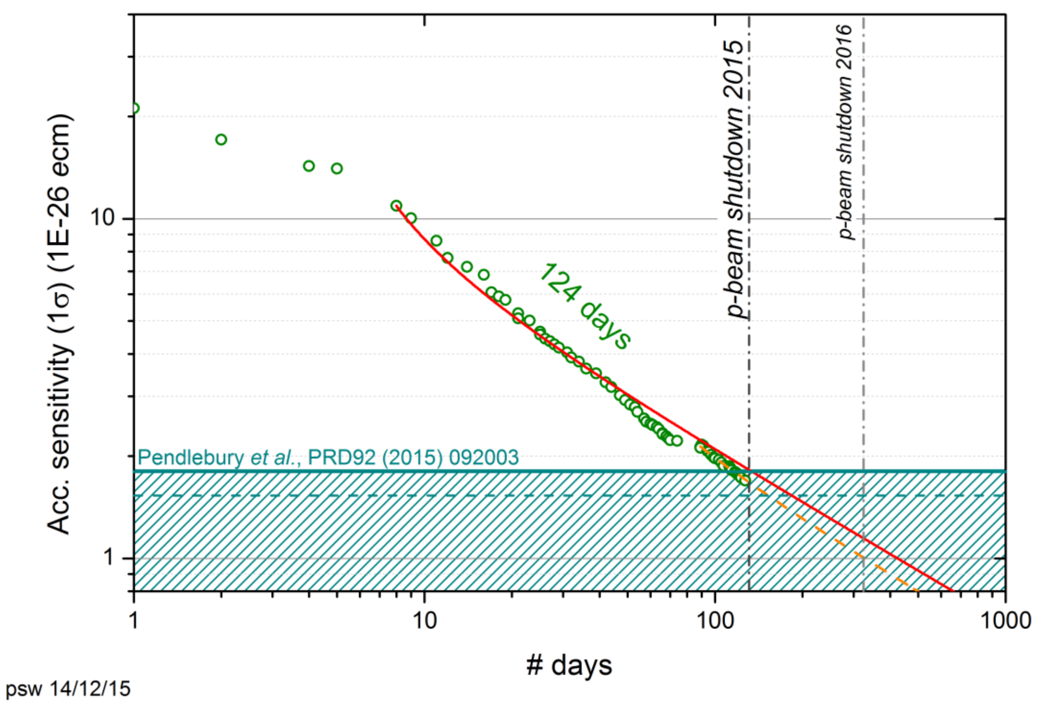
Neutron EDM at PSI

- Improved RAL-Sussex-ILL setup



Neutron EDM at PSI

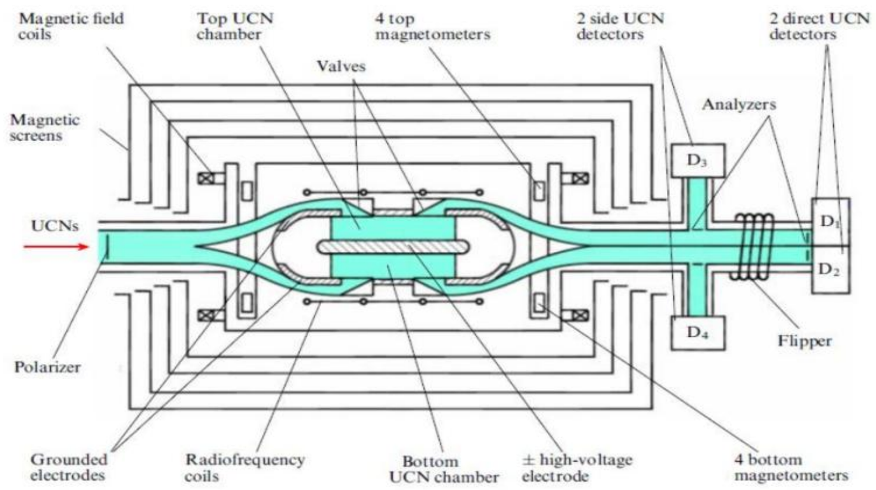
- **Best sensitivity per day** (ever) reached in 2015: 1.1×10^{-25} e·cm/day
- **UCN performance** – continuously increasing
- **UCN density in spectrometer** (after filling): 0.3 - 0.7 /cm^3



- **Blinded analysis** – two independent groups
- **Data taking** – two campaigns (2016, 2017) with present setup in view
- **Change to double chamber spectrometer** (phase n2EDM) planned in 2018

n2EDM at PSI

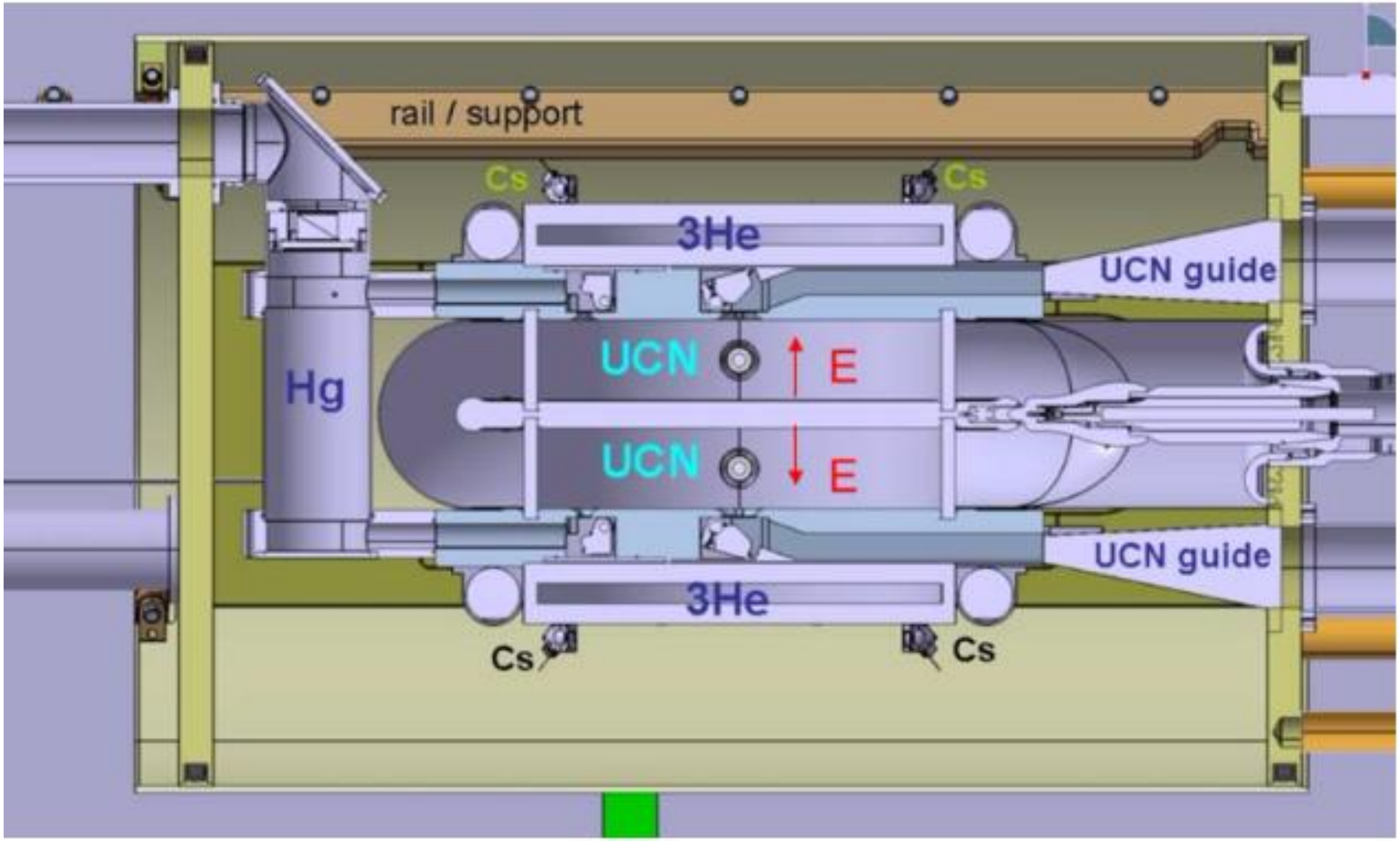
- Ultimate goal: **$\sigma(d_n) < 5\times10^{-28}$ e·cm**
- Two larger, symmetric precession chambers operated with opposite sign E fields – leads to significant reduction of certain systematic errors
- Magnetometry based on ^{199}Hg, Cs, ^{3}He
- Advanced passive and active magnetic shielding with much better performance
- Significantly improved B-field uniformity and better stability (self-compensating B_0 coil; reduced interaction with shield)
- Optimized UCN feeding system
- Measurement architecture similar to prototype configuration of PNPI 96' measurement



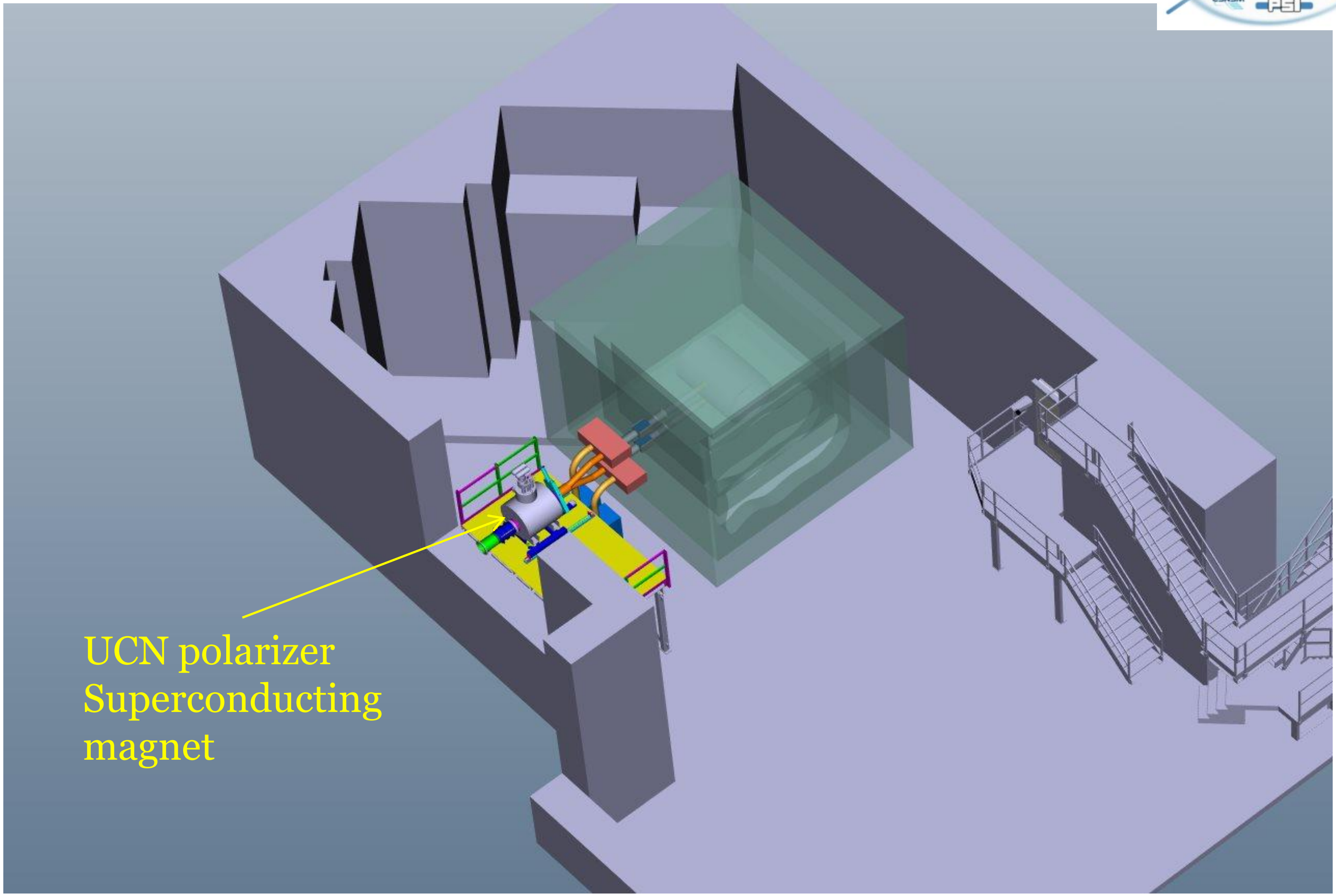
PNPI, 1996

n2EDM at PSI

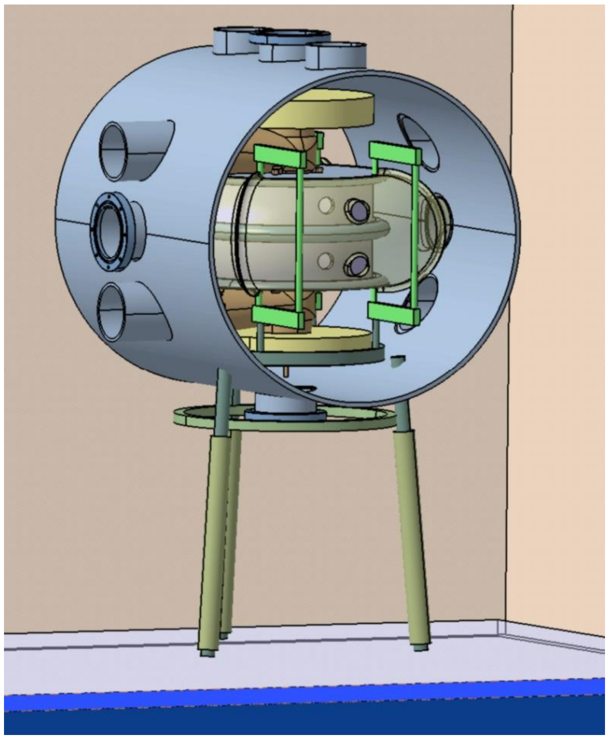
- Double precession chamber



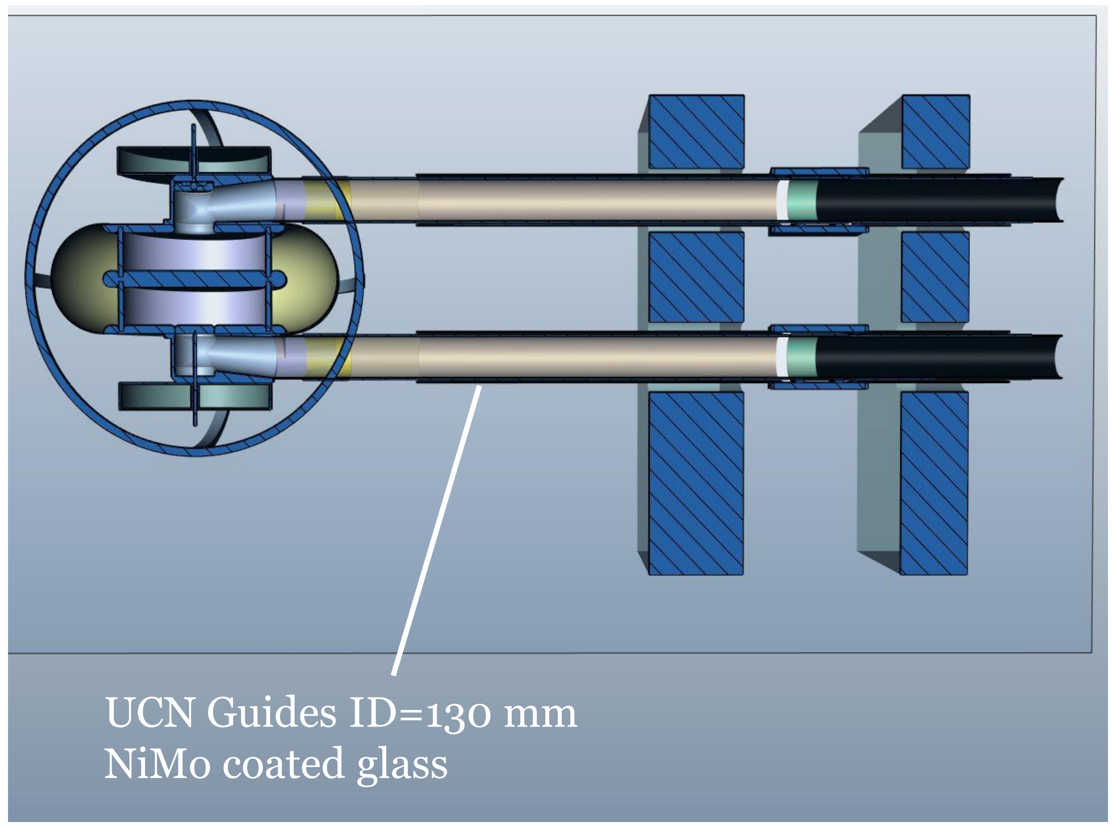
n2EDM at PSI



n2EDM at PSI



Inside setup and vacuum vessel mechanically decoupled from shield



nEDM Collaboration at PSI

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Institute of Nuclear Physics, Polish Academy of Sciences, Cracow
University of Sussex, Brighton
Département de physique, Université de Fribourg, Fribourg
University of Kentucky, Lexington
Centre de Spectrométrie Nucléaire et de Spectr. de Masse, Paris
Laboratoire de Physique Subatomique et de Cosmologie, Grenoble
Institut für Kernchemie, Gutenberg Universität, Mainz
Katholieke Universiteit, Leuven
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Eidgenössische Technische Hochschule Zürich
Paul Scherrer Institut, Villigen

Neutron EDM projects worldwide

- **Operational:**
  - PNPI+ILL+PTI@ILL - upgrading
  - nEDM@PSI – takes data upgrade to n2EDM in 2018
- **R&D and construction:**
  - @RCNP/TRIUMF (Canada)
  - @FRM-2 (Germany)
  - @SNS (USA)
  - @PNPI (Russia)
  - @LANL (USA)
- **Possible future projects:**
  - @PIK (Russia)
  - @J-PARK (Japan)
  - @ESS (Sweden)
- ***All projects aim at 1 - 2 orders of magnitude improvement***

Summary and outlook

- **Permanent EDMs of elementary particles:**
  - *Directly test SM and search for TeV scale physics beyond SM (BSM)*
- **Complementarity:**
  - *LHC may find BSM particle(s) on-shell and low energy observables (e.g. EDMs) provide indications or establish strong limits to BSM CPV models*
  - *EDMs of different systems are essential for disentangling BSM CPV sources*
- **Neutron EDM:**
  - *Primarily sensitive to quark EDMs*
  - *Addressed in several labs worldwide*
  - ***nEDM at PSI** is on the forefront – takes data with world best sensitivity and prepares 2nd generation setup to reach*

$$\sigma(d_n) \approx 5\times10^{-28}\ e\cdot cm$$

Backup slides

Fundamental neutron physics

- **Main goal of Particle Physics:**
  Establish consistent picture of Nature's fundamental interactions

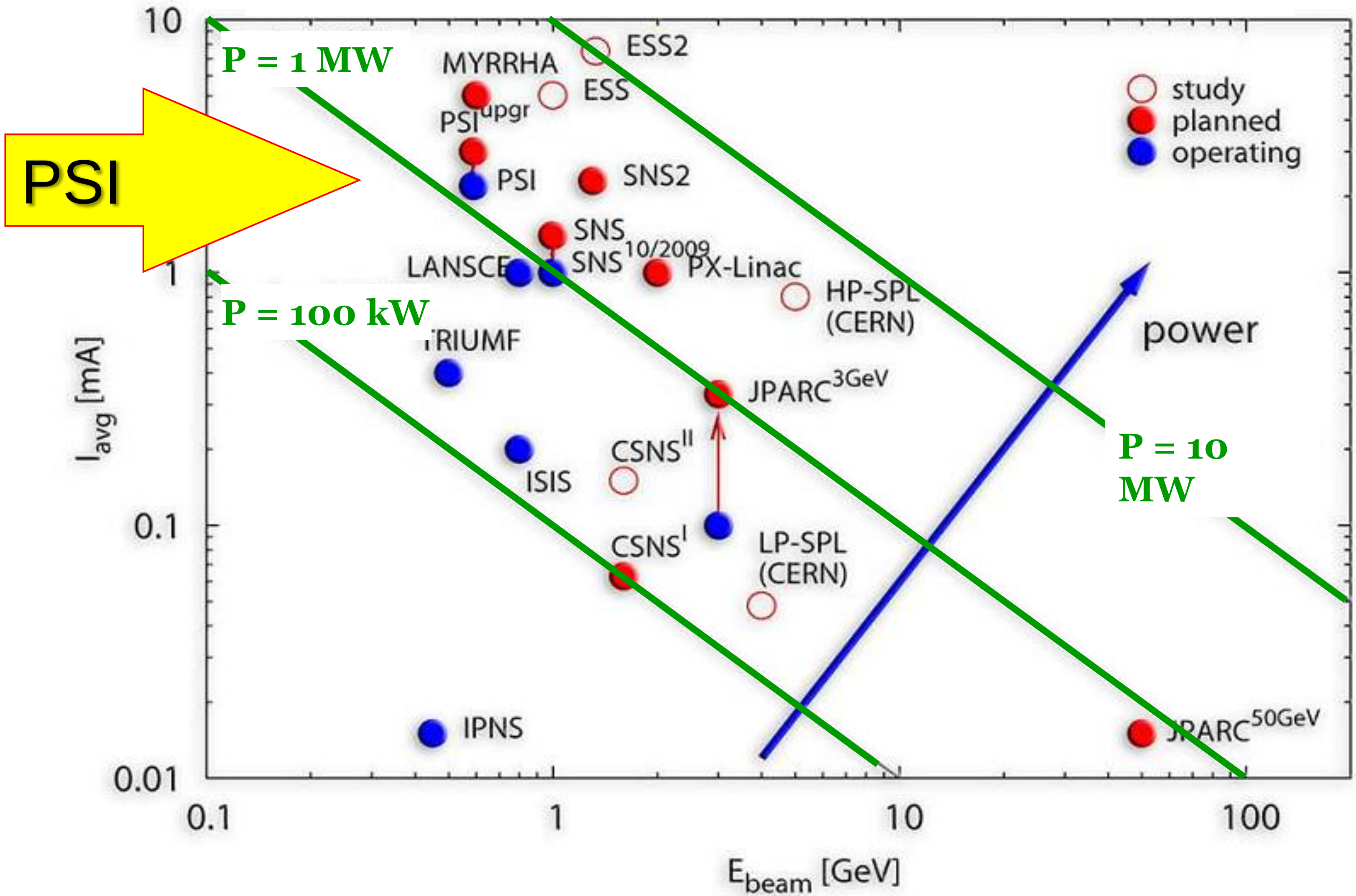
"ENERGY frontier"

- **High Energy PP**:
  - Operates at TeV scale (10^{12} eV)
    $\Rightarrow$ study of 2nd (s, c, μ, ν_μ) and 3rd (b, t, τ, ν_τ) particle families
- **Low Energy PP (e.g. with neutrons)**:
  - Operates at neV scale (10^{-9} eV)
    $\Rightarrow$ study of 1st (u, d, e, ν_e) particle family
  - Reveals respectable sensitivity:
    - Energy: $\Delta E/E \sim 10^{-11} \div 10^{-13}$ ($\Delta E \sim 10^{-23}$ eV)
    - Momentum: $\Delta p/p \sim 10^{-10} \div 10^{-11}$
    - Spin polarization: $\Delta s/s \sim 10^{-7}$

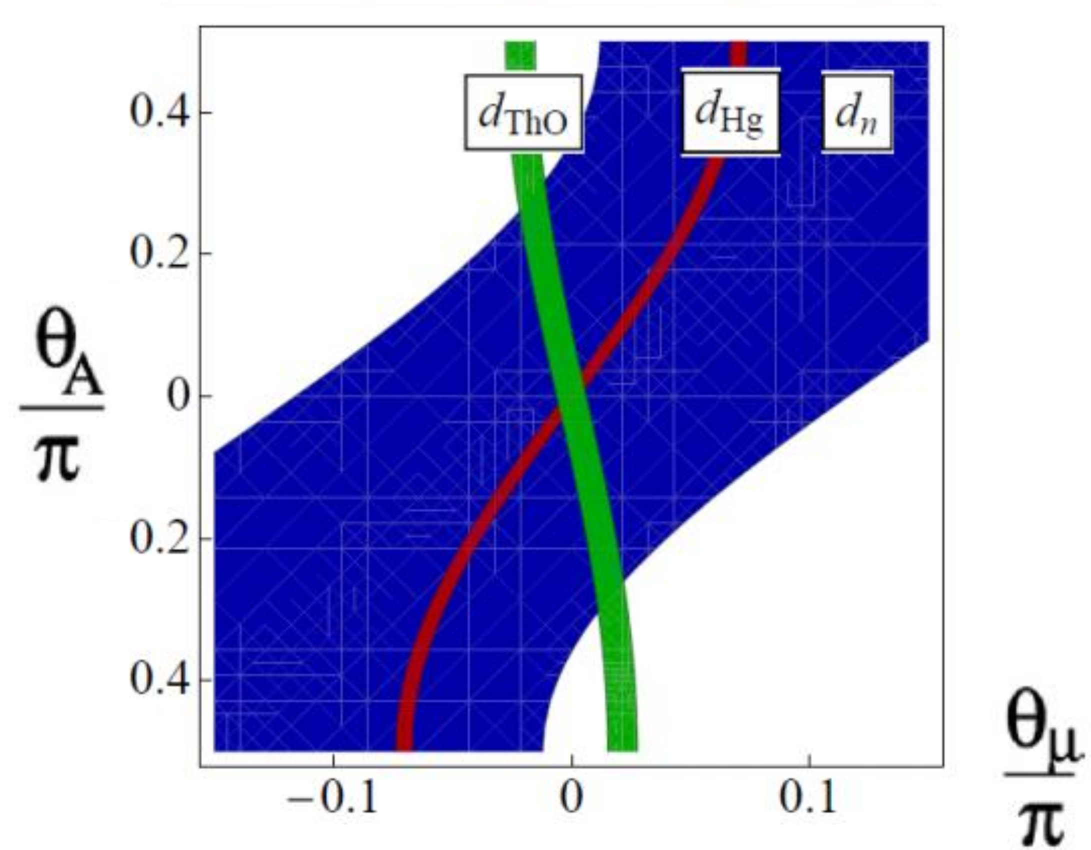
"PRECISION (intensity) frontier"

- *Fundamental neutron physics provides more than **20** observables reach in information which is difficult to achieve (or not achievable at all) in other fields of Particle Physics*

Intensity proton machines



EDM and MSSM



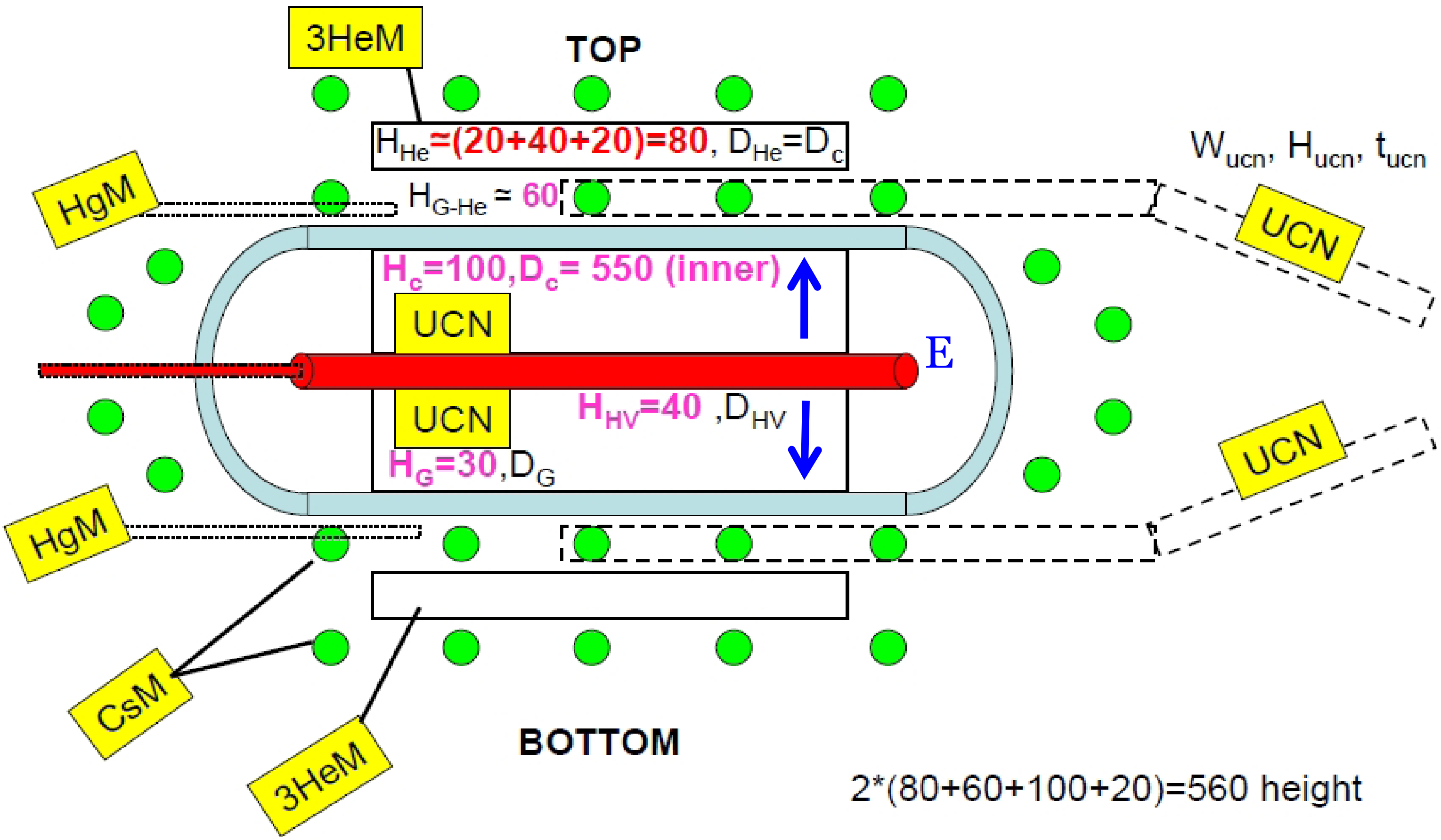
A. Ritz, update 2016

M. Pospielov, A. Ritz, Ann. Phys. 318, 119 (2005)

n2EDM at PSI

n2EDM at PSI

- Goal: **5×10^{-28} e·cm**



Ultra Cold Neutrons (UCN)

- **Discovery:**
  - Y. Zeldovich, 1959: **UCN can be stored in material vessels**
  - Shapiro group (Dubna), 1969: first experiment with UCN
- **Storage time:**
  - Wall collision losses can be as small as 10^{-6} (per collision) for certain materials and proper surface morphology
  - Storage time depends on wall collision frequency in the storage vessels and may be comparable with the neutron lifetime (880 s)
  - In nEDM experiment at PSI storage time is about 200 s
- **UCN production via moderation of CN:**
  - Earth gravitational field and/or scattering from turbine blades (ILL)
  - Super-thermal process e.g. in solid D_2 (PSI, LANL, GUM) or super-fluid He (ILL; in development)

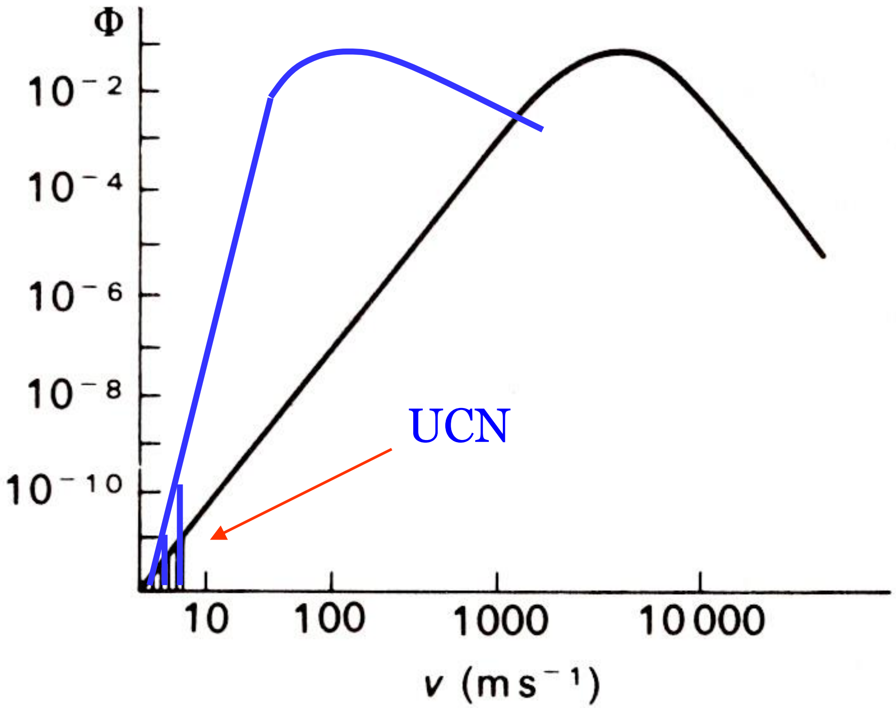
UCN production methods

- UCN are present in the moderator of fission reactor but they are rare there and impossible to extract (Fermi potential barrier)

$$\frac{\Phi_{\text{UCN}}}{\Phi_0} \approx 5\times10^{-12}$$

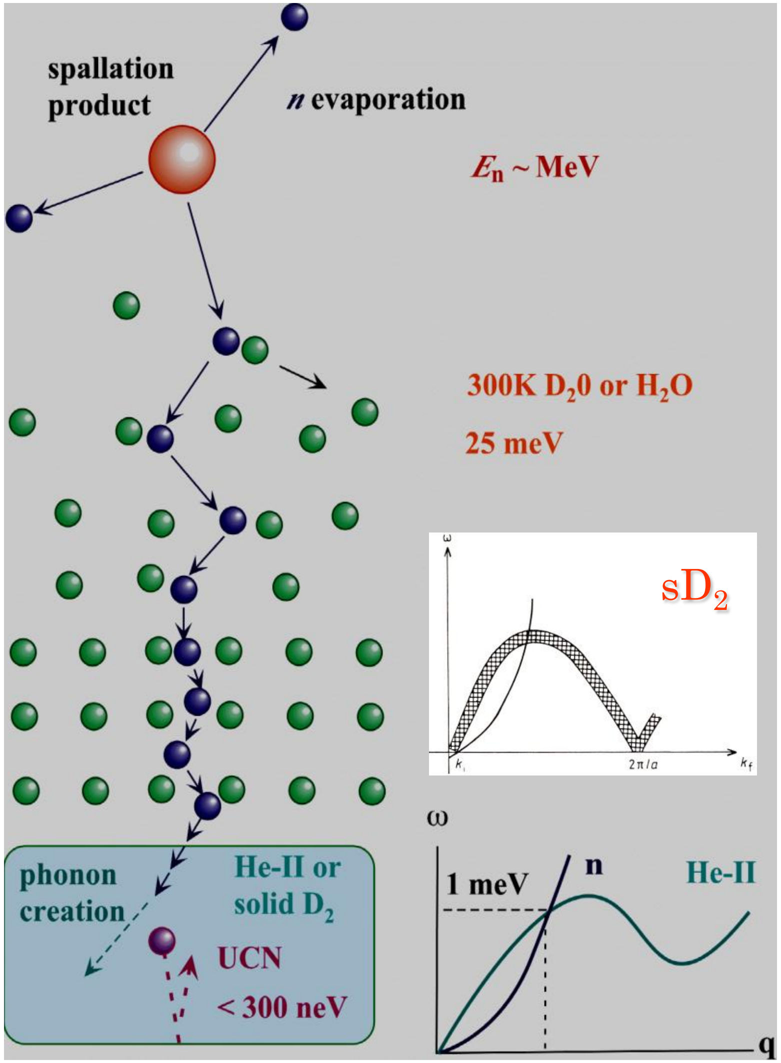
$$\rho_{\text{UCN}} \approx 10^{-13}\Phi_0\ \text{cm}^{-3}$$

- Cooling moderator (~20 K) improves situation insignificantly

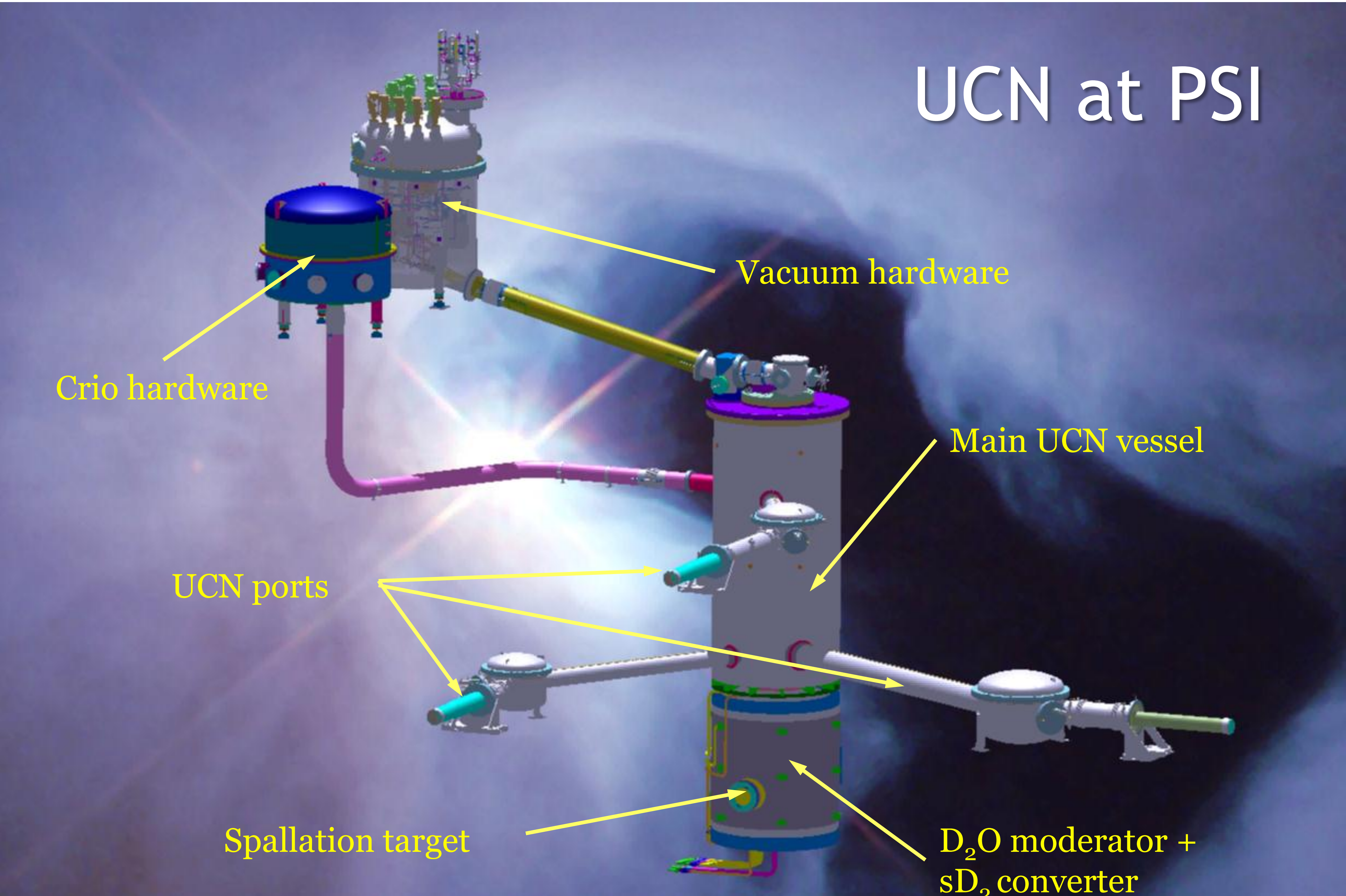


Super-thermal sources

- „Fool" Liouville's theorem:
  - Energy dissipation in super-thermal converter
  - Size of phase space occupied by neutron states decreases on cost of increasing phase space of converter space ⇒ increases UCN density
  - Liouville's theorem is fulfilled in the total system (UCN + converter)
- Super-thermal process:
  - Inelastic scattering of cold neutrons with creation of phonons (or magnons) in e.g. sD_2, sO_2, sCH_4
  - Creation of rotons in super-fluid He



UCN at PSI


Vacuum hardware
Crio hardware
Main UCN vessel
UCN ports
Spallation target
D_2O moderator +
sD_2 converter