Electric Dipole Moments and Fundamental Symmetries

P. Fierlinger

Content

Focus: European efforts & items not covered later today

EDM searches

- Atoms / molecules
- Neutron EDM future
- Muon EDM

Low-energy precision experiments

- Gravity resonance
- Antihydrogen
- nnbar
- Neutron beta decay

Worldwide EDM activities map

Neutrons: (~ 200 ppl.)
- Beam EDM @ Bern
- LANL nEDM @ LANL
- nEDM @ PSI
- nEDM @ SNS
- PanEDM @ ILL
- PNPI/FTI/ILL @ ILL
- TUCAN @ TRIUMF

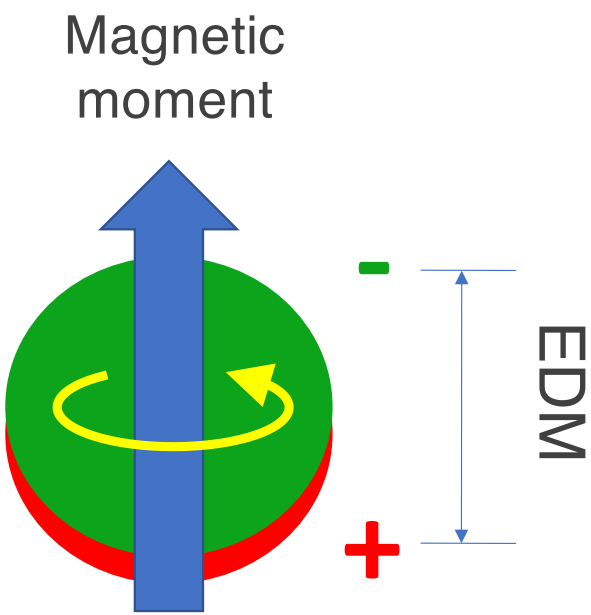
Storage rings: (~ 400 ppl.)
- CPEDM/JEDI
- muEDM @ PSI
- g-2 @ FNAL
- g-2 @ JPARC

Atoms: (~ 60 ppl.)
- Cs @ Penn State
- Fr @ Riken
- Hg @ Bonn
- Hg @ Seattle
- Ra @ Argonne
- Xe @ Heidelberg
- Xe @ PTB
- Xe @ Riken

Molecules: (~ 55 ppl.)
- BaF (EDM^3) @ Toronto
- BaF (NLeEDM) @ Groningen/Nikhef
- HfF+ @ JILA
- ThO (ACME) @ Yale
- YBF @ Imperial

https://www.psi.ch/en/nedm/edms-world-wide

Physics reach of EDM searches



$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

- An EDM violates P, T symmetry
  Purcell and Ramsey, PR78(1950)807
- CPT: CP violation ~ T violation
- Baryon asymmetry

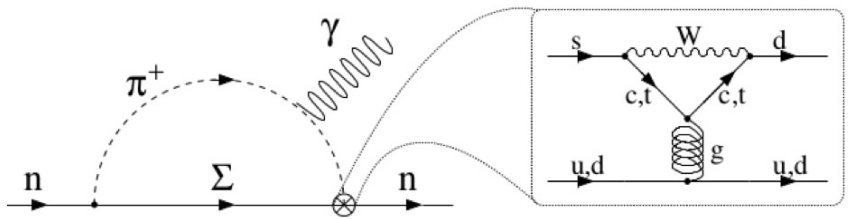
- Among the most precisely measured quantities:
  $d_{neutron} < 1.8 \cdot 10^{-26}$ ecm (10^{-22} eV)
- Non-zero meas. = new physics!
- More general than flavor physics experiments

EDM and the SM

Khriplovich Zhitnitsky (1986), McKellar et al., (1987)

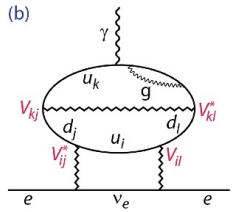
M. Pospelov, et al., Sov. J. Nucl. Phys. 53, 638 (1991)

CP violation from CKM



Neutron EDM $d_n \approx 10^{-32}$ ecm

$d_{electron} < 10^{-38}$ ecm…



Strong Interaction

CP-odd term:

$$L_\theta = \bar{\theta}\frac{\alpha_s}{8\pi}G\tilde{G}$$

$$d_n(\bar{\theta}) \sim \bar{\theta}\frac{e}{m_n}\frac{m_*}{\Lambda_{QCD}} \sim 6.10^{-17}\bar{\theta}e\cdot cm$$

$$\bar{\theta} < 10^{-10}$$

Strong CP problem, Axions

E.g. Pospelov, Ritz, Ann. Phys. 318(2005)119

Physics reach of EDM searches

Fundamental theory

Wilson coefficients (13)

$$\mathcal{L}_{\rm CPV}^{\rm eff} = \sum_{k,d} \alpha_k^{(d)} \left(\frac{1}{\Lambda}\right)^{d-4} \mathcal{O}_k^{(d)}$$

Low energy parameters

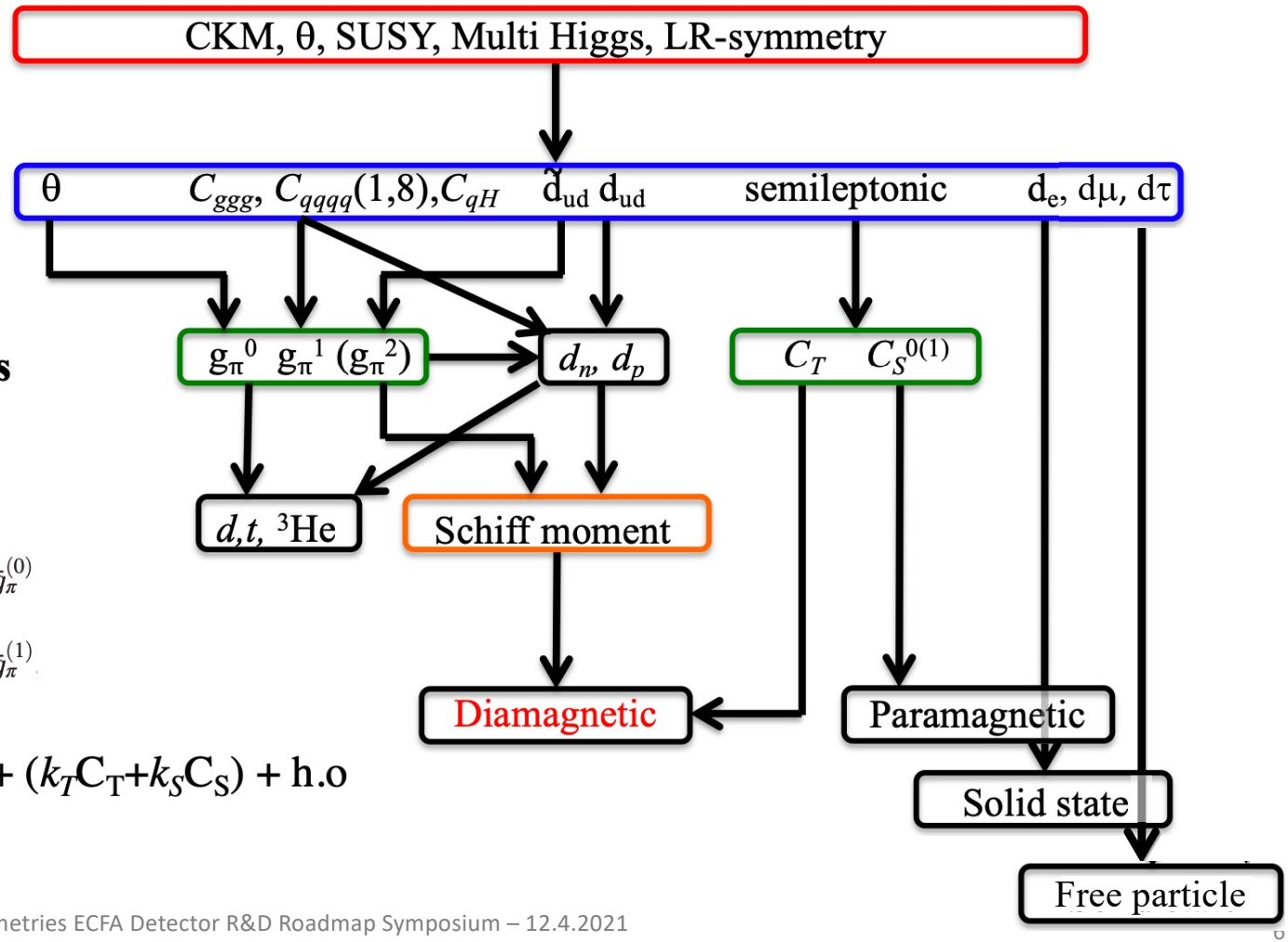
$$\bar{g}_{CP}^{0} \approx 0.027\ \theta_{QCD}$$

Nucleus level

$$S = s_N \bar{d}_N^{sr} + \left[\frac{m_N g_A}{F_\pi} a_0 + s_N \alpha_{n\bar{g}_\pi^{(0)}}\right] \bar{g}_\pi^{(0)} + \left[\frac{m_N g_A}{F_\pi} a_1 + s_N \alpha_{n\bar{g}_\pi^{(1)}}\right] \bar{g}_\pi^{(1)}$$

Atom/molecule level

$$d_A = \eta_e d_e + \kappa_S S(\theta_{QCD}, g_\pi) + (k_T C_T + k_S C_S) + \text{h.o}$$



Rev. Mod. Phys. v. 91 015001 (2019)

Experiments are complementary

- Paramagnetic atoms

$$d_{para} = \eta_{d_e} d_e + k_{C_S} \bar{C}_S$$

- Polar molecules

$$\Delta\omega^{\not{P}\not{T}}_{para} = \frac{-d_e E_{eff}}{\hbar} + k^{\omega}_{C_S} \bar{C}_S$$

- Diamagnetic atoms

$$d_{dia} = \kappa_S S(\bar{g}^{0,1}_{\pi}) + k_{C_T} C_T + \ldots$$

- Nucleons

$$d_{n,p} = d^{lr}_{n,p}(\bar{g}^{0,1}_{\pi}) + d^{sr}_{n,p}(\tilde{d}_{u,d}, d_{u,d})$$

- Fundamental fermions

$$d_e, d_\mu, (d_\tau)$$

...Higher orders (199-Hg!) :

$$d_A = (k_T C_T + k_S C_S) + \eta_e d_e + \kappa_S S + \text{h.o. (MQM)}$$

$$d_i = \sum_i \alpha_{ij} C_j$$

e and μ EDM

Nuclear-spin-dependent e-N coupling C_T,

Nuclear-spin independent couplings C_S^0

Intrinsic quark EDMs and chromo EDMs

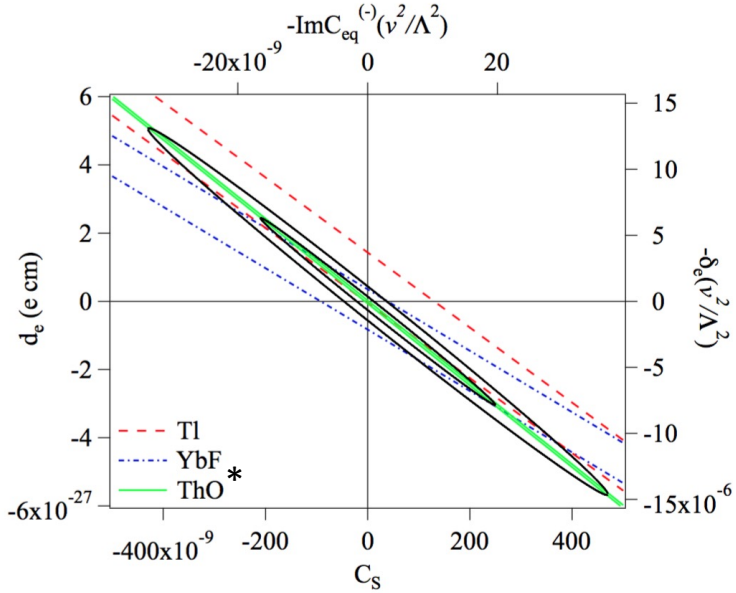
Meson-nucleon couplings $g_\pi^{0,1,(2)}$

Joint analysis

Measured limits
(note: ‘sole-source‘ analysis)

	Result	95% u.l.		ref.
Paramagnetic systems				
Xe^m	$d_A = (\ \ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22}	e cm	a
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23}	e cm	b
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25}	e cm	
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}		
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7}	$\mu_N R_{Cs}$	
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24}	e cm	c
	$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27}	e cm	
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27}	e cm	d
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29}	e cm	e
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}		
HfF^+	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28}	e cm	f
Diamagnetic systems				
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30}	e cm	g
^{129}Xe	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27}	e cm	h
^{225}Ra	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23}	e cm	i
TlF	$d\ \ = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23}	e cm	j
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26}	e cm	k
Particle systems				
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19}	e cm	l
τ	$Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17}	e cm	m
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16}	e cm	n

Illustration: parameters are not independent:
e.g. d_e as function of C_S



$$d_{\text{para}}^{\text{exp}} = d_e + \frac{\alpha_{C_S}}{\alpha_{d_e}} C_S$$

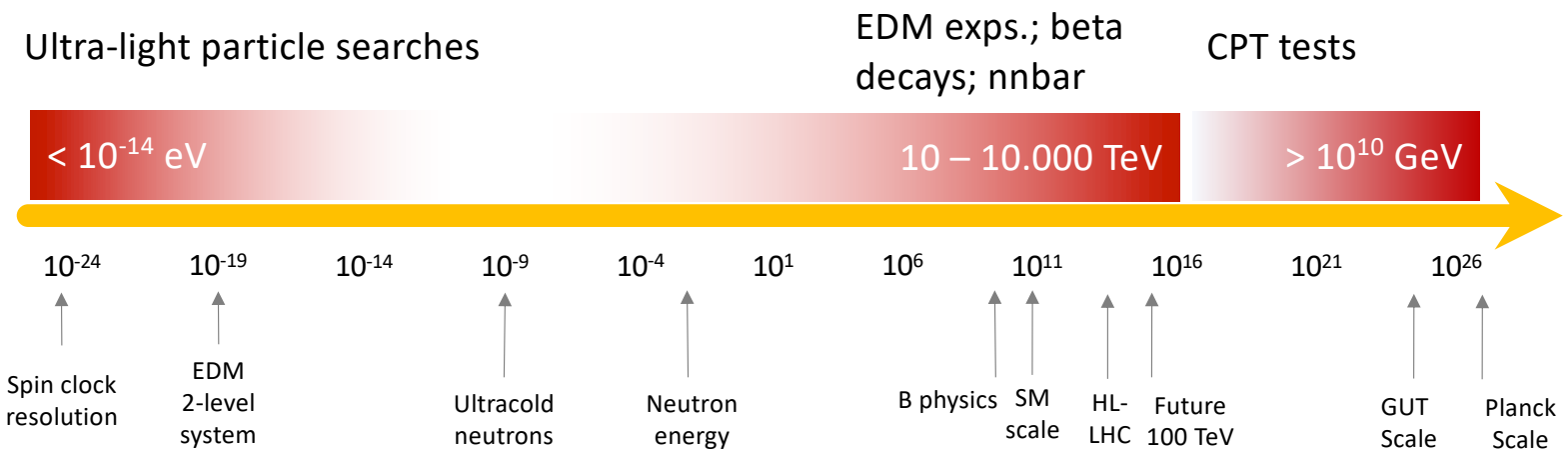
T. Chupp & M.J. Ramsey-Musolf (2015)

*) new data available

Energy reach of EDMs and symmetry tests

EDMs & (non-accelerator / low-energy) precision experiments:

- probe extremely high energies, beyond future accelerators
- probe otherwise inaccessible parameter space
- open (only) a small window to new physics, but with only few details



Energy reach of EDMs and symmetry tests

- EDMs complement HEP experiments
- Effective field theory approach enables combining HEP / B physics and low-energy experiments together.
- Spin offs: e.g. dark matter searches

C. Abel *et al.*, PRX7(20017)041034

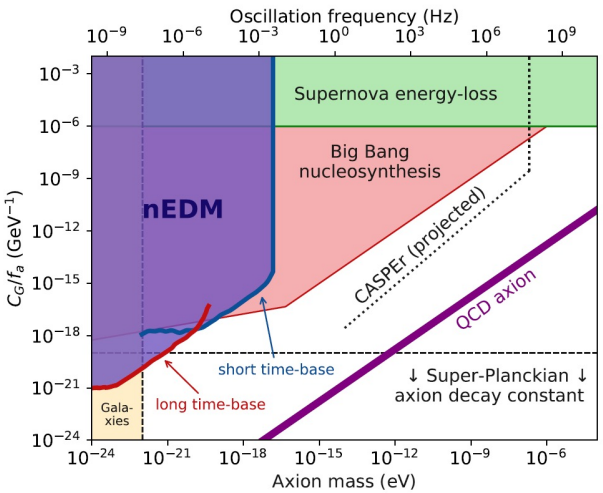
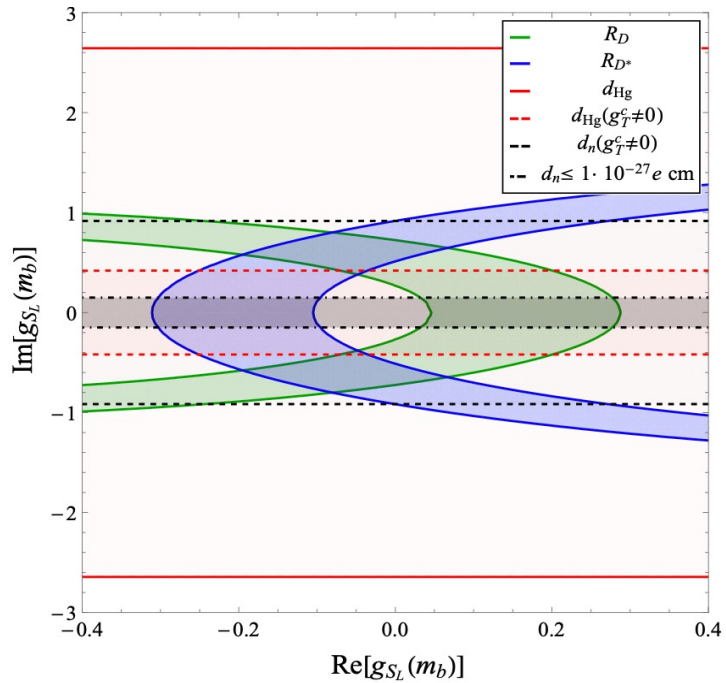


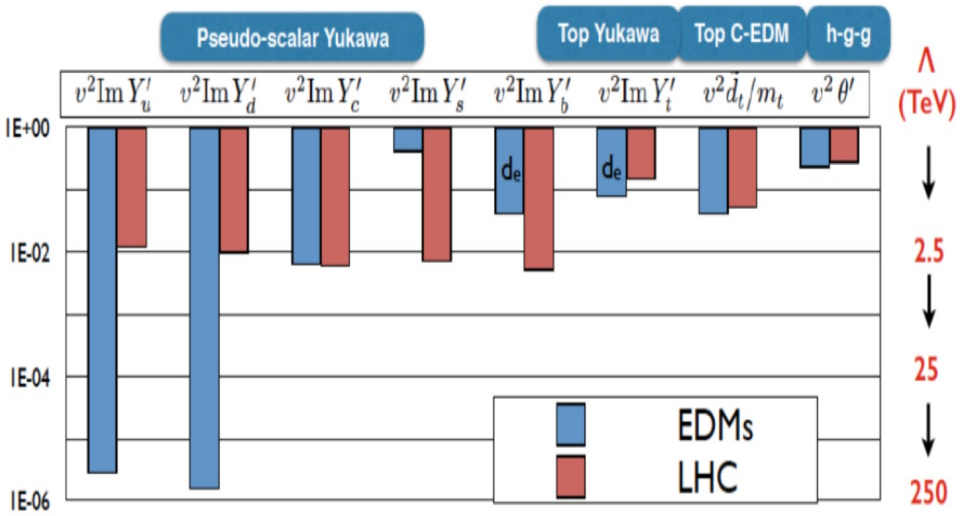
Illustration:
combined NP limits from EDM and B physics



M. Jung et al., JHEP 69, 2019 (2019)

EDMs are complementary to HEP experiments

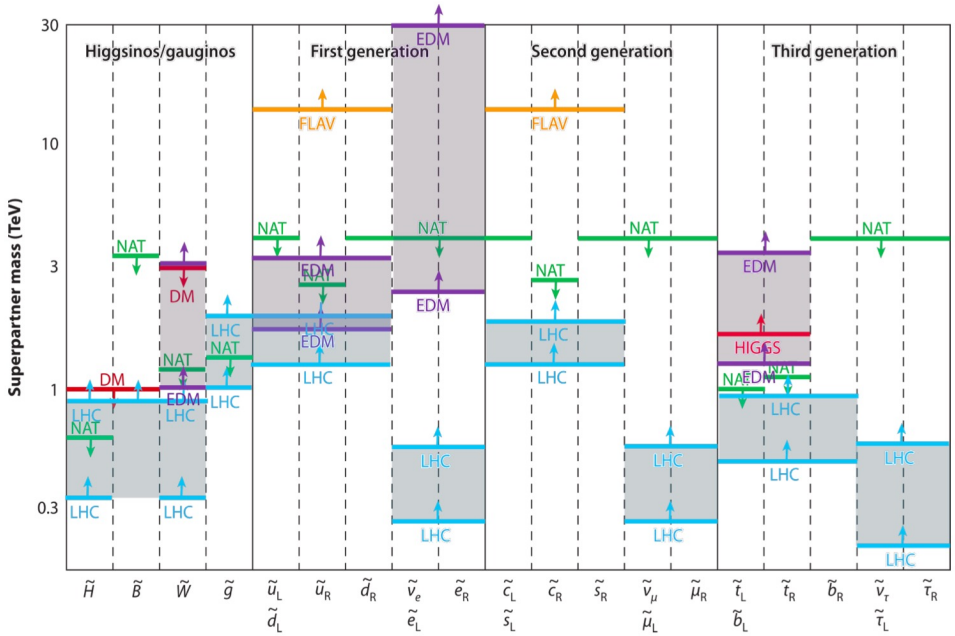
Constraints on different non-standard CPV Higgs couplings - Higgs production at LHC vs. EDMs



Y.-T. Chien, V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

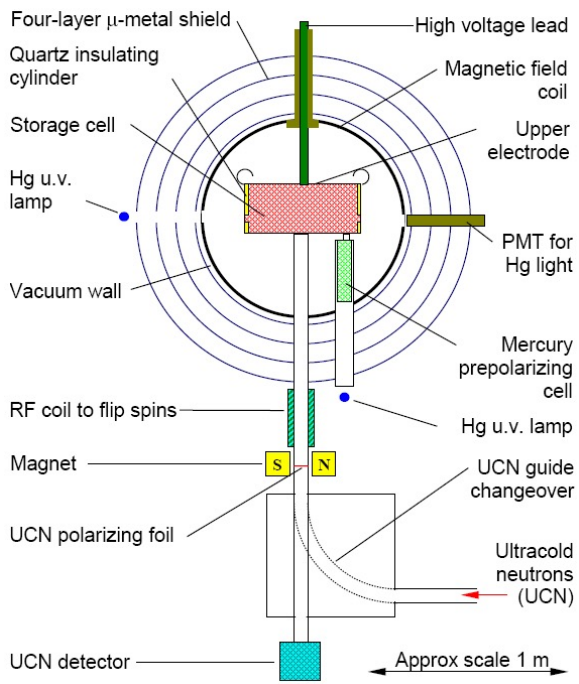
Picture by V. Cirigliano (PPNS2018)

Constraints on different SUSY type parameters

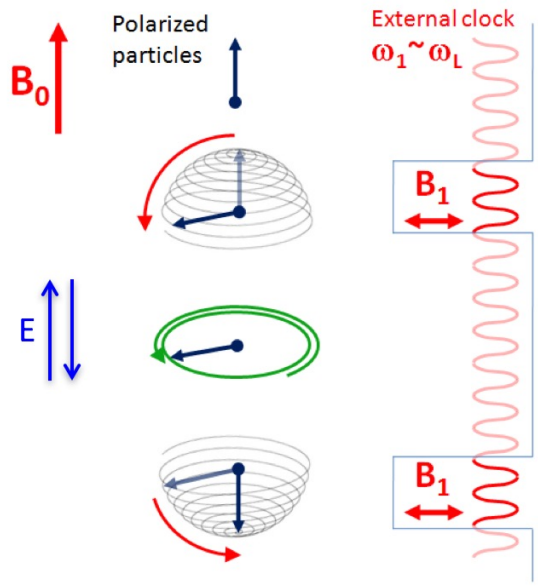


Shading shows progress since 2013 (LHC, ACME, ^{199}Hg) – from Ann. Rev. Nuc. Part. Scie 63, 351 (2019) adapted, taken from N. Hutzler

Basic measurement method

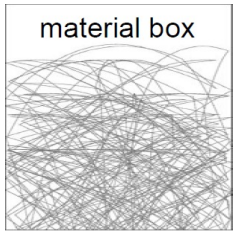


(Still) state of the art: ~ few trapped neutrons / cm^3



$$\hbar\omega_L \sim \mu B + dE$$

Trapped ultra-cold neutrons with nano-eV kinetic energy



Statistical sensitivity:

$$\sigma_{d_n} = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

Systematics: magnetic fields! -> often used: a 'co-habitating magnetometer'

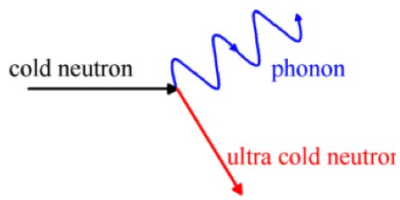
Neutron EDM

- **Approaches with trapped UCN:**

	RAL Sussex ILL	PSI nEDM	PSI n2EDM	PanEDM	PanEDM II	(EDM)^n	LANL	SNS	PNPI	PNPI	TRIUMF
Temperature	RT	RT	RT	RT	RT	0.7K	RT	0.7K	RT	0.7K	RT
Comagnetometer	199-Hg	199-Hg	199-Hg	none	?	none	199-Hg	3-He	none	none	9-Xe, 199-Hg
Source	Turbine	spall + D2	spall + D2	4He	4He	4He (in situ)	spall + D2	4He (in situ)	Turbine	4He	4He
# of cells	1	1	2	2	2	>100	1	2	2	>2	2
UCN density	2	3	5	6	>100	>1000	50	125	4	10000	700
goal [ecm]	3.00E-26	1.80E-26	1.00E-27	5.00E-27	<1e-27	1.00E-29	E-27	2.00E-28	5.00E-26	<1E-27	1.00E-27
Date	2006	2020	2022?	2022	2024	2024+	2022	2022	2015	2022+	2022+
Status	completed	completed	commiss.	commiss.	planned	concept	source ready	install. ongoing	completed		install. ongoing
Comment		upgrade of RAL/Sussex/ ILL	magnetic shield completed	source startup summer 2021	component design	first test experiments 2021	magnetic shield being installed				first UCN from prototype source 2017

- **Beam:**
  - Crystal EDM (Nagoya)
  - Beam EDM -> cold beam at ESS
  - (EDM)^n is also a beam experiment

Most approaches use cooling process to increases phase space density:



$$\tau_{\mathrm{up}}^{-1} \sim \frac{(T[K])^7}{100\ \mathrm{s}}$$

New systematic issues are expected…

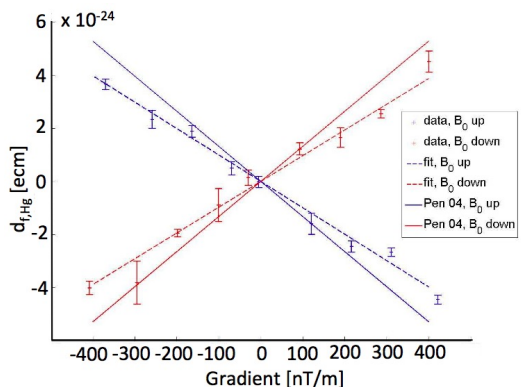
Geometric phase effect:

$$\Delta\omega = \frac{\omega_{xy}^2}{2(\omega_0 - \omega_r)}$$

$$\omega_{xy}^2 = \left(\frac{\partial B_{0z}}{\partial z}\alpha\right)^2 + \left(\frac{E\times v}{c^2}\right)^2 + \boxed{2\frac{\partial B_{0z}}{\partial z}\alpha \cdot \frac{E\times v}{c^2}}$$

B field requirements for 10^{-28} ecm – level accuracy:

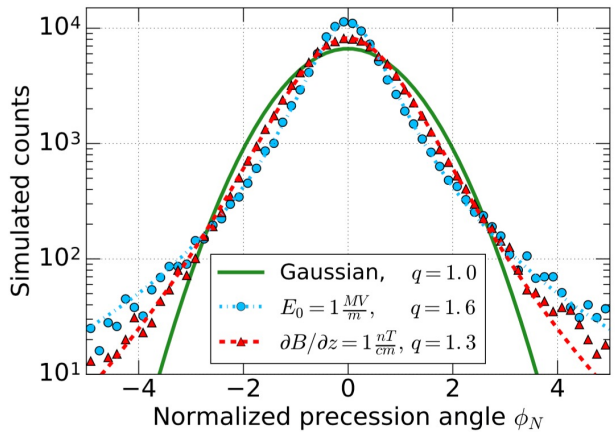
- < 0.3 nT/m gradient
- Max. 1 dipole with 5 pT in 2 cm distance
- < 10 fT drift stability



Pendlebury et al., Phys. Rev. A **70**, 032102 (2004) and many more…

Potentially new class of systematics identified:

- Non-gaussian spin distributions in traps with gradients or E-fields
- Time-dependent shape of distributions

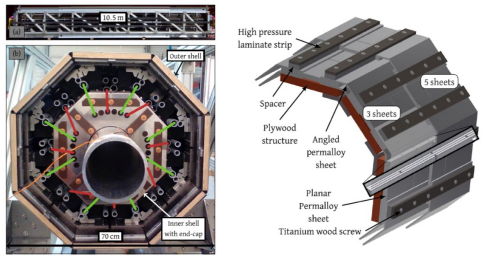


M. Bales et al., EPL 2017

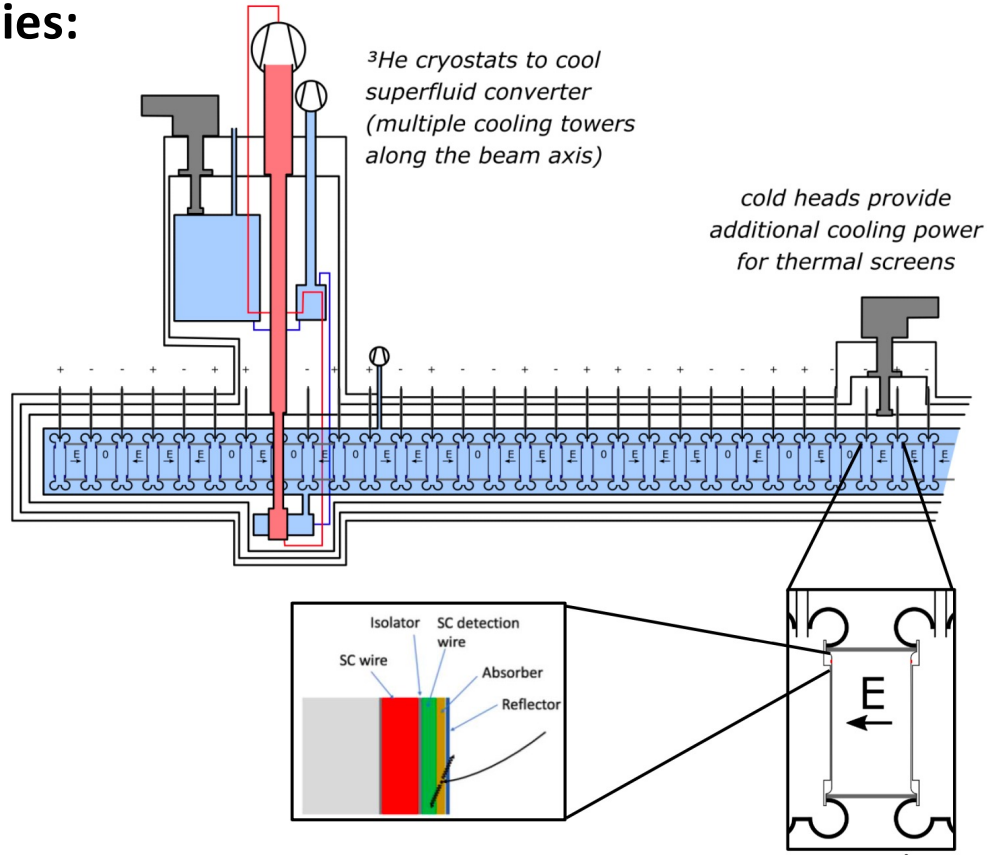
Future neutron EDM

Combining (independently) existing technologies:

- UCN production + trapping in superfluid He
- Magnetic shielding
- Avoiding most loss channels: in-situ UCN production + <u>in-situ detection</u>
- Suitable for the best existing beams (ILL)
- Modular design, fits future sites (ESS)
- 1.10^{-29} ecm sensitivity in principle possible (factor 1000 compared to now!)



Magnetic Shielding
(Rev. Sci. Instrum. 91, 035117 (2020)

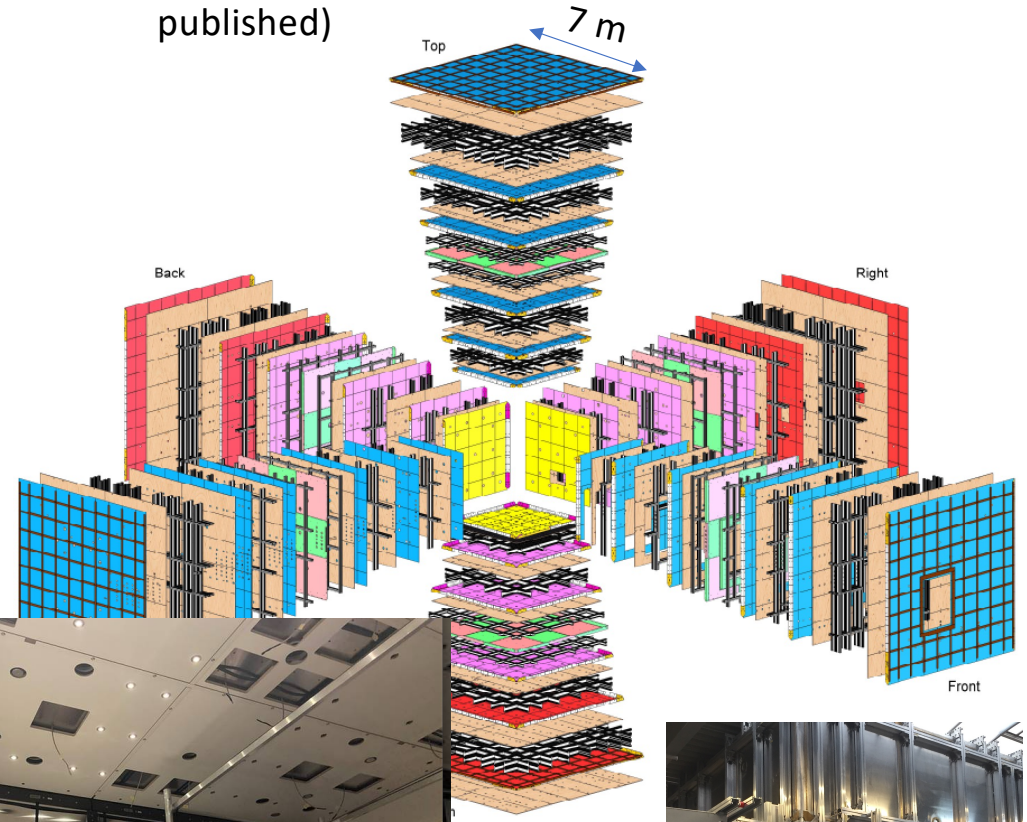


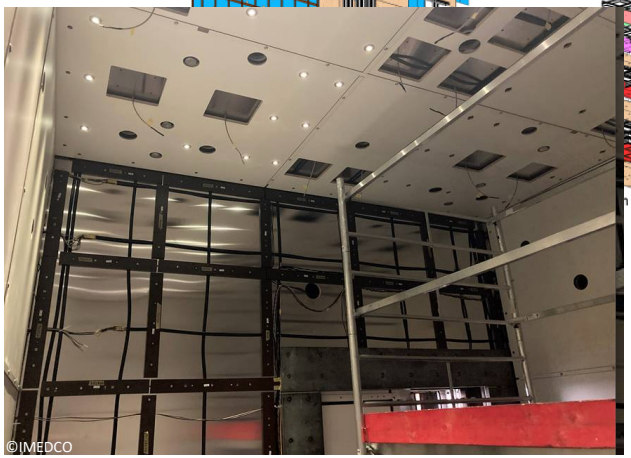
See <u>S. Degenkolb</u> presentation

Technology drivers, e.g.:

- Many precise measurements need small magnetic fields & gradients: sample sizes, systematic issues (geometric phase), polarization life-times
- Quantitative numerical modeling
- Factor 1000 improvement in residual gradient in last 20 years

Figure: world's largest shield (2020): ~ 100 pT in 30 m^3 (to be published)





Bx bottom (pT)

38.4	27.0	15.6
7.8	3.8	-0.1
-22.9	-19.4	-15.9

By bottom (pT)

27.0	20.4	13.9
-0.1	31.4	-2.3
-27.2	-22.9	-18.5

Bz bottom (pT)

15.6	13.9	12.1
-8.0	-6.2	-4.5
-31.6	-26.4	-21.1

Bx center (pT)

-1.9	-7.1	-12.4
-6.3	-7.1	-8.0
-10.6	-7.1	-3.6

By center (pT)

7.7	0.3	-7.1
2.5	-1.9	-2.3
-2.8	-0.1	2.5

Bz center (pT)

17.4	7.7	-1.9
11.2	7.3	3.4
5.1	6.9	8.6

Bx top (pT)

14.9	9.7	4.4
7.9	-1.7	-11.3
0.9	-13.1	-27.1

By top (pT)

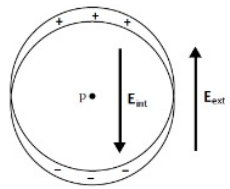
19.3	12.3	5.3
8.8	-0.8	-8.7
-1.7	-12.2	-22.7

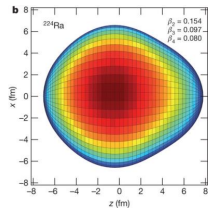
Bz top (pT)

23.7	14.9	6.2
9.7	1.8	-6.1
-4.3	-11.3	-18.3

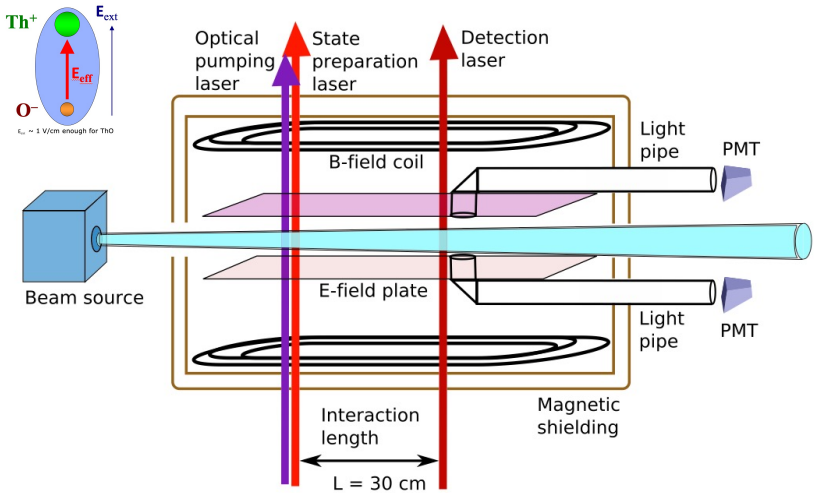
Improving the sensitivity

- **Schiff moment**: suppression for ^{129}Xe, ^{199}Hg: ~ 10^{-2}, enhancement for e ~ Z^3
- Enhancement due to **nuclear deformations** for ^{220}Rn, ^{224}Ra - enhancement ~ $10^{2\text{-}4}$
- Enhancement due to **large E-fields in molecules**: YbF, ThO, HfF^+ - enhancement ~ > 10^4





ACME I - Basic experiment principle:



(ACME proposal)

J. Phys. B: At. Mol. Opt. Phys. **43** (2010) 074007

ThO substructure of the 'science state' Δ with J = 1:

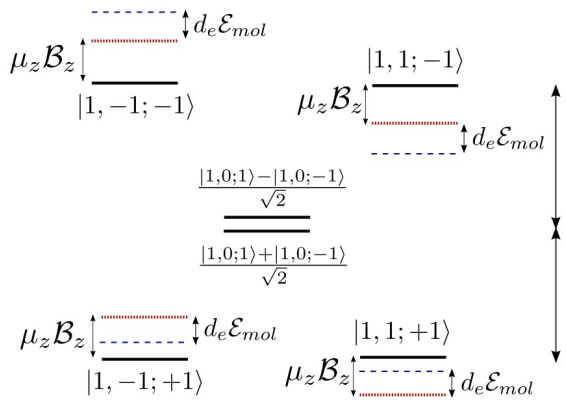


Figure 3. Schematic level structure and energy shifts of the ThO $H^3\Delta_1(J=1)$ manifold of sublevels, in the presence of the applied external fields $\boldsymbol{\mathcal{E}} = \mathcal{E}\hat{z}$ and $\boldsymbol{\mathcal{B}} = \mathcal{B}\hat{z}$ (not to scale). States are labelled by their quantum numbers $|J, M_J; \mathcal{N}\rangle$, where $\mathcal{N} = \mathrm{sgn}(\hat{n}\cdot\boldsymbol{\mathcal{E}})$ describes the orientation of the fully polarized molecules. Note the different signs of the eEDM shift in the $\mathcal{N} = \pm 1$ Ω-doublet levels.

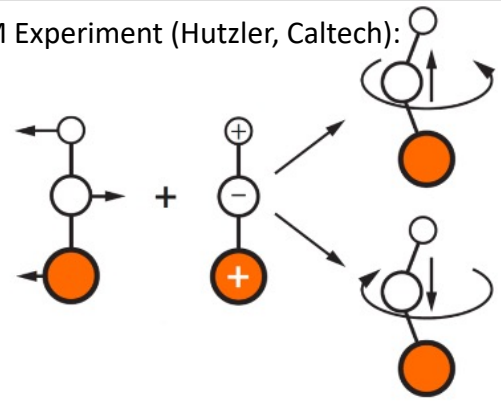
- Alignment of E-field, molecular axis and angular momentum optically
- Co-magnetometer
- Small lab E-fields
- Modest B-field problems
- Science state is metastable (in this system)

Improving the sensitivity

Improving statistics and systematics:

- **Polyatomic molecules** like YbOH (many choices!)
- <u>internal co-magnetometer AND suitable structure for laser cooling</u>
- Internal field saturation already at low lab fields
- Spin-off: first MQM measurements

PolyEDM Experiment (Hutzler, Caltech):



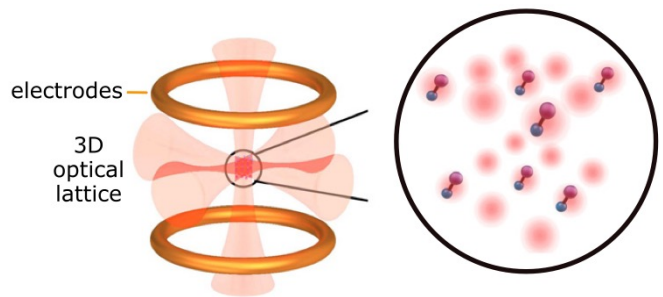
I. Kozyryev and NRH, PRL 119, 133002 (2017)

Recent advances in preparing high intensity cold molecule beams:

- Possible laser cooling / trapping / fountain e.g. with YbF:
- Line width ~ dispersion of sample in space ~ coherence time.
- Numbers from proposal: 10^6 trapped YbF molecules; $\tau = 10$ s; 18 kV/cm … shot noise limit of 10^{-32} ecm / day.

Note: more physics with molecules etc. see M. Safronova's talk

Illustration of MOT / optical lattice with EDM E-field electrodes (Hinds, Imperial):



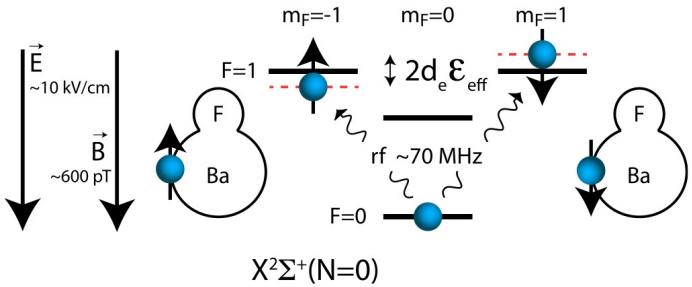
Phys. Rev. Lett. 120, 123201 (2018)
Quantum Sci. Technol. **6** (2021) 014006

Molecules: BaF

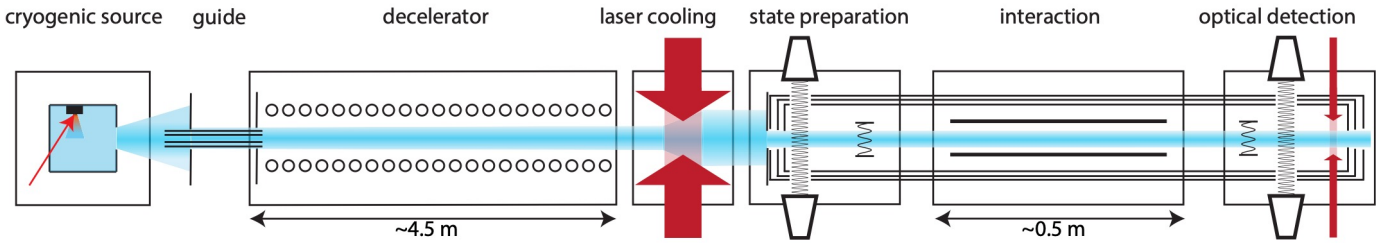
$5 \cdot 10^{-30}$ ecm level in first generation of experiment:

- High intensity slow beam (using all recent advancements)
- Relatively low E_{int} ~ 6-8 GV/cm at saturation
- Efficient laser cooling due to light weight & suitable el. structure / ground state

Ground state as science state:

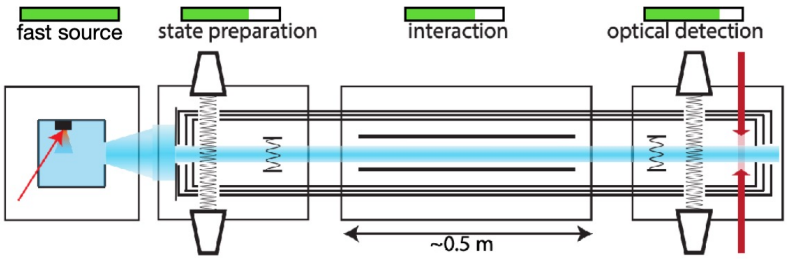


Planned full experiment:

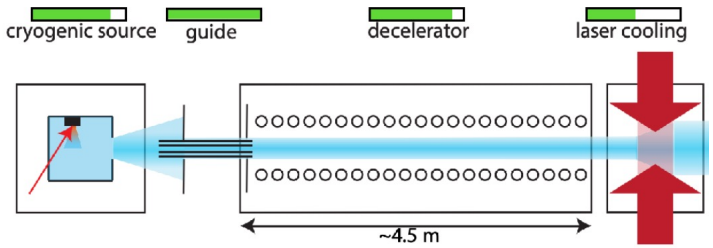


Approach:

Status: a) Fast beam to demonstrate control of systematics



b) Slow beam for full statistics

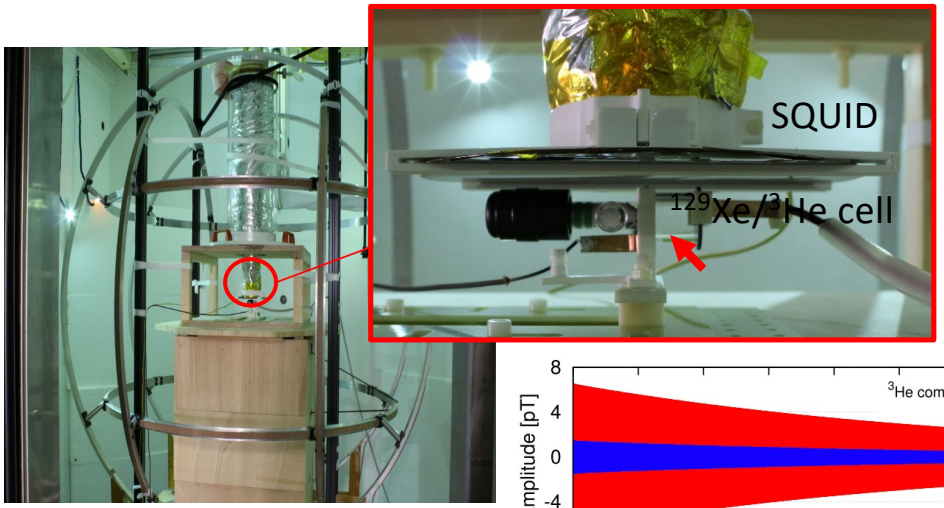


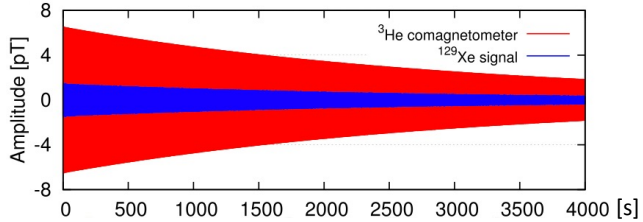
Figures: S. Hoekstra, Groningen

Eur. Phys. J. D **72**:197 (2018)

129-Xe EDM – Example: HeXe

Experiment scheme:



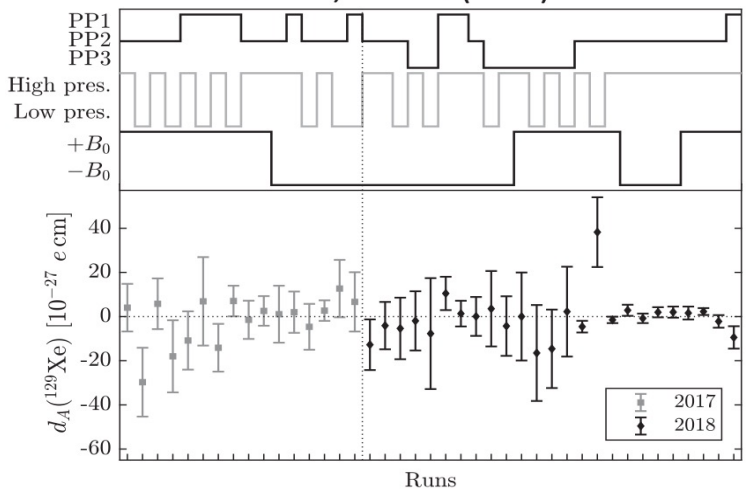


- Hyperpolarized ^{3}He and ^{129}Xe, B~ μT, E ~ few kV/cm
- Spin precession in low field detected with SQUIDs
- Potential: 10^{-30} ecm
- Important contribution to joint EFT parameter analysis
- Other efforts: MIXed, Liquid Xe, Active Maser, Xe-comag

EDM data extraction:

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N} \propto \frac{1}{\tau^{3/2}}$$

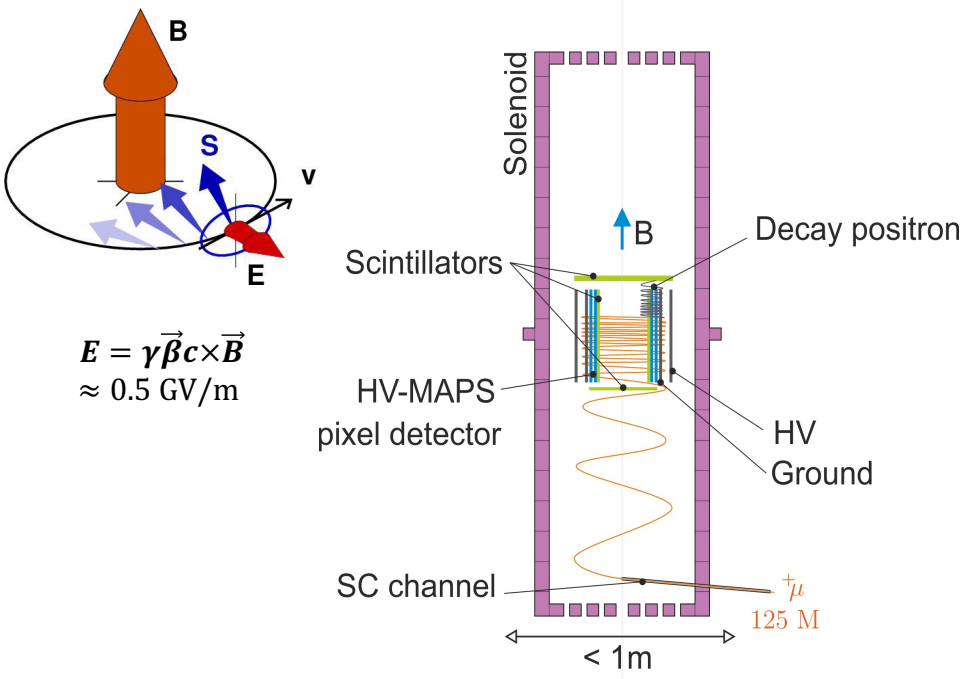
PRL 123, 143003 (2019)



$$d_A(^{129}\mathrm{Xe}) = (1.4 \pm 6.6_{\mathrm{stat}} \pm 2.0_{\mathrm{syst}}) \times 10^{-28}\ e\,\mathrm{cm}$$
$$|d_A(^{129}\mathrm{Xe})| < 1.4 \times 10^{-27}\ e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.}).$$

Muon EDM

Basic idea: frozen spin method, out-of-plane polarization due to EDM



$$\boldsymbol{E} = \gamma\vec{\boldsymbol{\beta}}\boldsymbol{c}\times\vec{\boldsymbol{B}}$$
$$\approx 0.5\ \mathrm{GV/m}$$

Letter of intent: arXiv:2102.08838 [hep-ex]

- Testing CPV in a second generation lepton, clean of nuclear and atomic background
- Expected sensitivity using existing PSI beamlines:

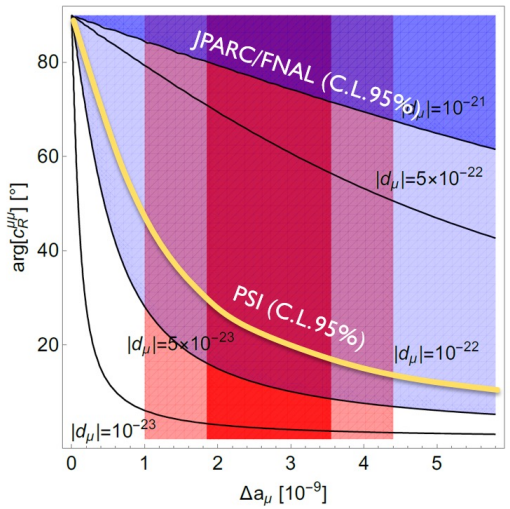
$$d_\mu < 6\times10^{-23} e\mathrm{cm}$$

Further advances in future: HIMB and muCool.

Flavor violating models:
EFT phase of Wilson parameter $c_R^{\mu\mu}$ hardly constrained

A. Crivellin *et al.*, PRD 98 (2018) 113002

Other physics motivations: New scalars and fermions, MSSM, Leptoquarks



P. Schmidt-Wellenburg

Antihydrogen spectroscopy

Standard Model Extension SME:

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \tfrac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + i c^e_{\mu\nu}\gamma^\mu D^\nu + i d^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0\,.$$

CPT & LORENTZ VIOLATION

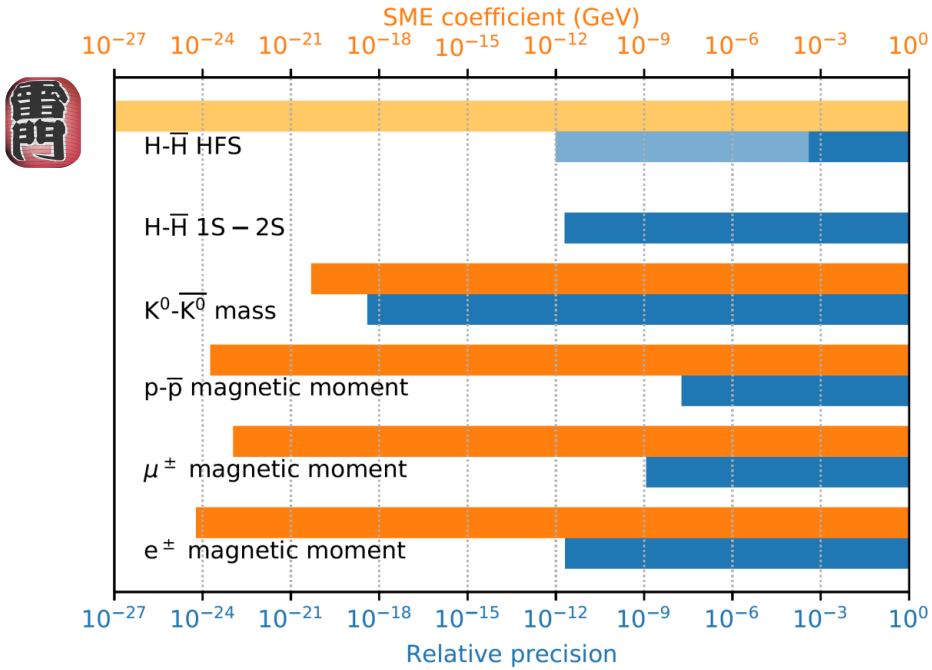
LORENTZ VIOLATION

D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

- Minimal SME: CPTV only in hyperfine splitting
- Non-minimal SME: … also in 1S-2S
- HFS meas. precision: 1S-2S at 10^{-4} level in trapped anti-H (no effect doe to mag. field)

Widmann, E. et al. *Hyperfine Interact. 240:5 (2019)*

Bluhm, R., Kostelecky, V., & Russell, N., PRL 82, 2254–2257 (1999).
Kostelecký, V.A. & Vargas, A.J., PRD, 92, 056002 (2015)

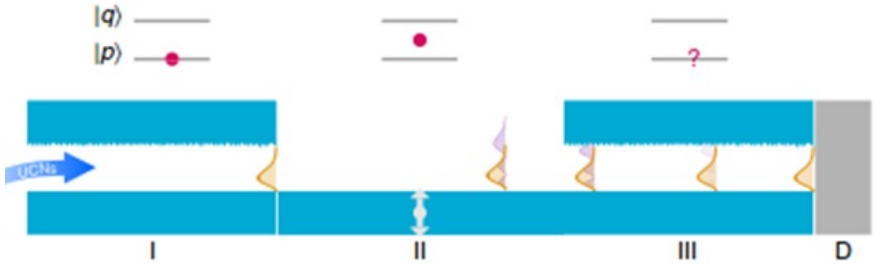


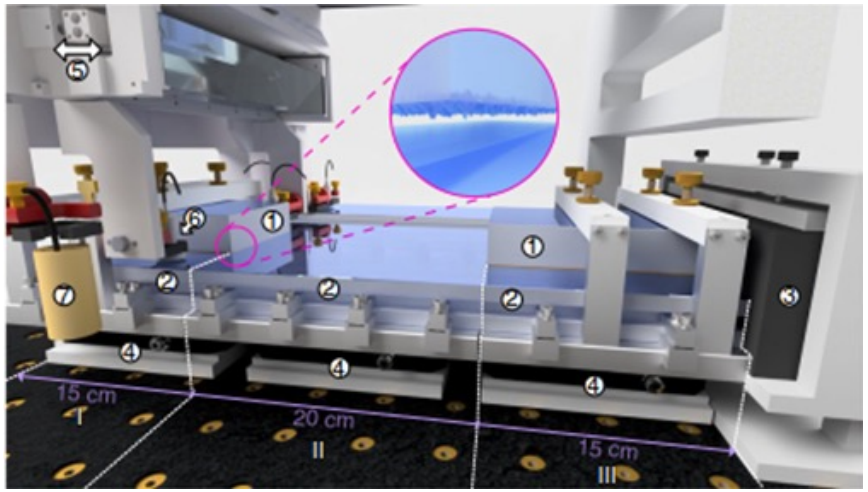
PDG, Kostelecky & Bluhm arXiv:0801.0287

Dark blue: measured for particle and antiparticle
Light blue: measured for particle only
Orange: measured SME coefficient
Yellow: potentially reachable accuracy

E. Widmann

Gravity resonance spectroscopy

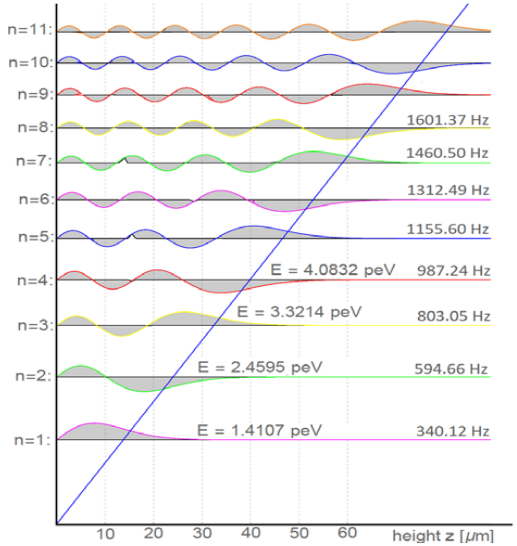




- Ultra-cold neutrons are put into a superposition of gravitational quantum states; typical scale: micrometers
- Mirror oscillations provide transitions between states: Rabi & Ramsey spectroscopy
- Future: e.g. storage on top of mirror = long ‚exposure times‘
- CPT, Lorentz invariance

  Phys. Lett. B 798 134819 (2019)
- Dark matter
  - Axions
  - Chameleons
  - Symmetrons

  Nature Physics 14, 1022 (2018)

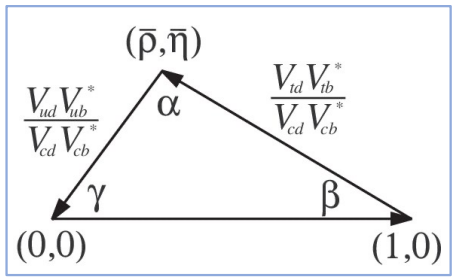


H. Abele

Neutron decay: PERC

- Physics case:

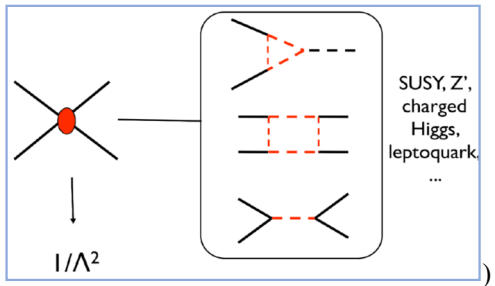
Precision unitarity test of CKM's first row



$$V_{ud} = \left(\frac{5099.34\,\mathrm{s}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}\right)^{1/2}$$
$$= 0.97301(10)_{\mathrm{RC}}(44)_{\tau_n}(35)_{\lambda}$$
$$= 0.97301(58),$$

Seng, Gorchtein, Ramsey-Musolf Phys. Rev. Lett.121 (2018)

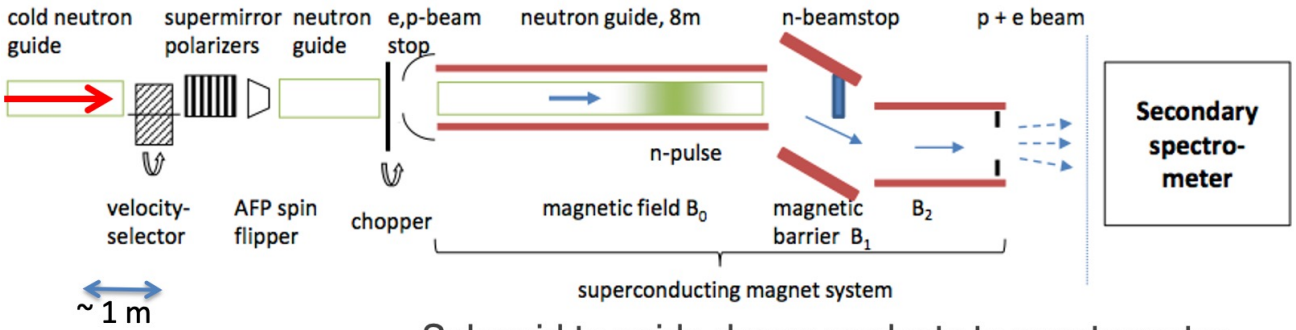
Search for New Physics through EFTs, reach ~ 10-100 TeV



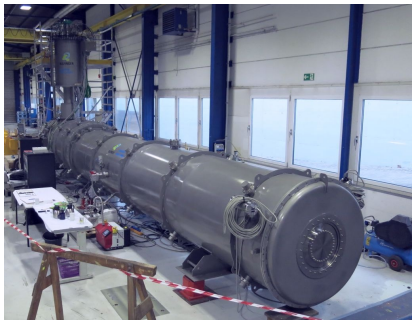
Märkisch *et al.*, Phys. Rev. Lett. 122 (2019)

See e.g.
M. González-Alonso
for low-energy EFTs

- PERC instrument at FRM-II (TUM) - future: ESS - improvement x 30



Solenoid to guide decay products to spectrometer

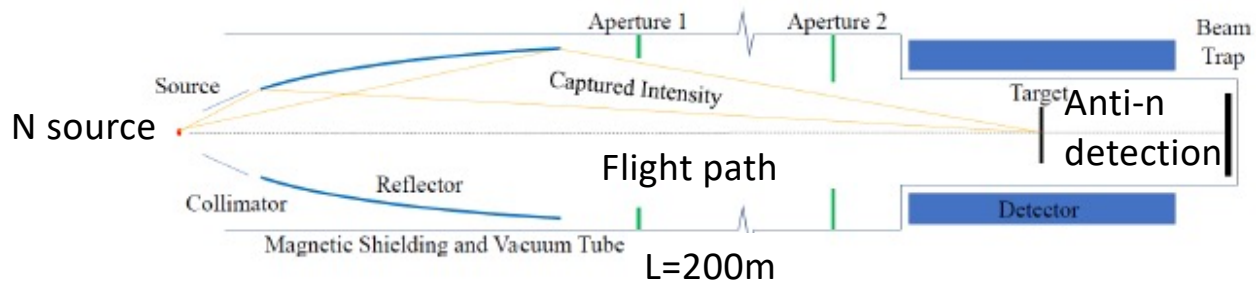


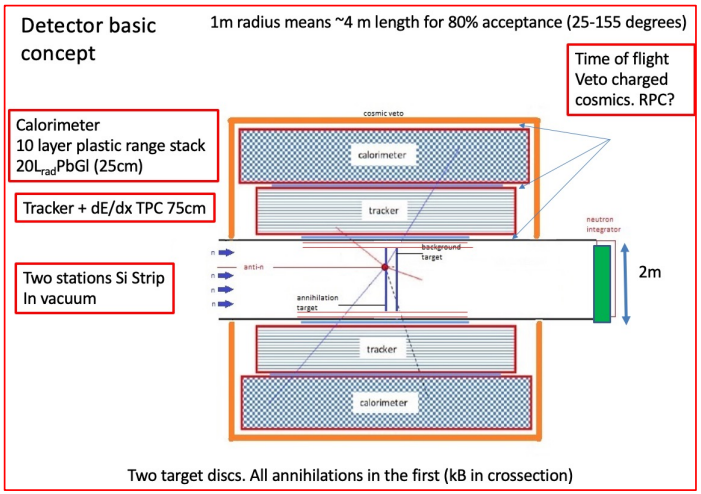
B. Märkisch

Neutron-antineutron oscillations

Idea: free neutron converts to antiparticle in flight: $n \rightarrow \bar{n}$ $\quad \mathcal{H} = \begin{pmatrix} E_n & \varepsilon_{n\bar{n}} \\ \varepsilon_{n\bar{n}} & E_{\bar{n}} \end{pmatrix}$

Physics case: Baryogenesis (eg post-sphaleron baryogensis), RPV-SUSY, LR symmetric models, Extra dimensions …



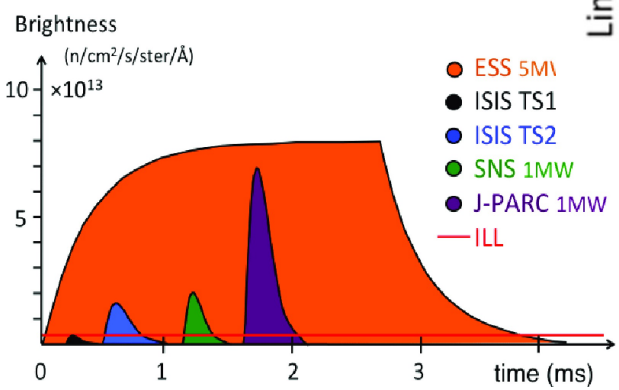


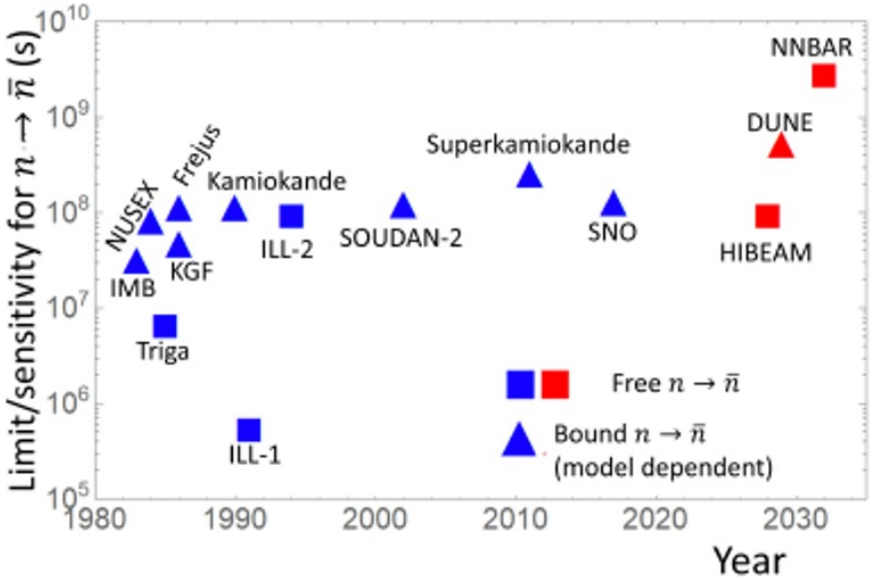
- Neutron optics with large angular acceptance
- Magnetic shield around free neutron flight path
- Annihilation target + detector
- Potential: factor 1000 improvement compared to previous generation experiment

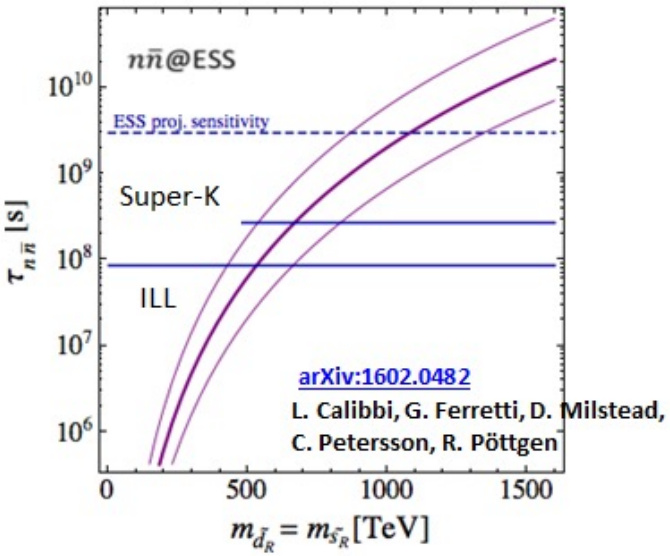
V. Santoro

Neutron-antineutron oscillations

... European Spallation Source ESS will (in long-term) replace reactor neutron source ILL – pulses instead of continuous flux







- 2 stages: HIBEAM (>2025), NNBAR (> 2030)

Where are we in 20 years?

- EDM experiments are
  - long-term efforts: historically 8 years per order of magnitude (eEDM: now faster!)
  - very difficult, subject to unexpected problems
- It is dangerous to promise and predict EDM results.
  - My naïve guess: surviving/novel efforts reach PeV-scale

- New concepts to improve EDM sensitivities in many areas:
  - nucleon, atom, electron, muon, tau
- Close connection between EDM/low-energy symmetry tests and HEP through EFTs: naively irrelevant cases might become more interesting through this
- Polyatomic molecules, electrostatic storage rings… AMO and nuclear/particle techniques will be closely connected
- New facilities online and available, e.g. for fundamental physics at ESS