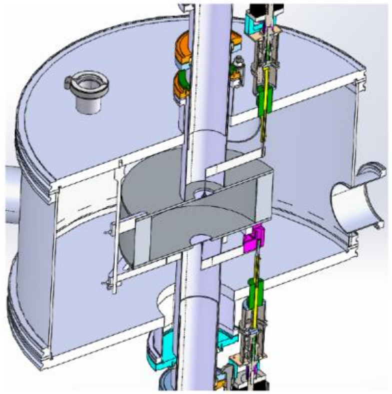
From the lowest energies to the highest: constraints on CP violation from permanent electric dipole moments

MPIK Gentner Colloquium, 30 November 2022

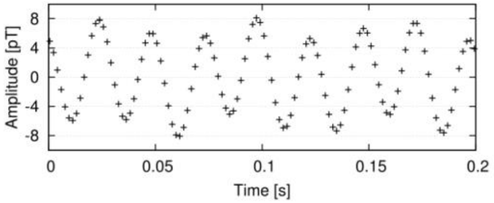
Skyler Degenkolb

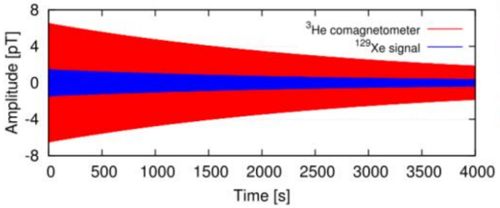
Case 1: trapped neutron interferometry

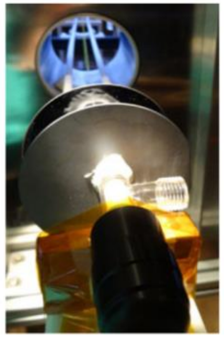


Low-Energy Precision Physics
Physikalisches Institut
Universität Heidelberg

Case 2: nuclear spin gyroscopes





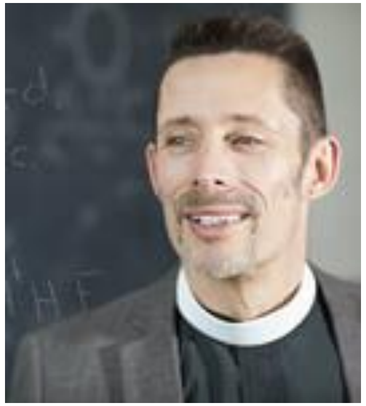


Typical(?) experiment/theory interaction

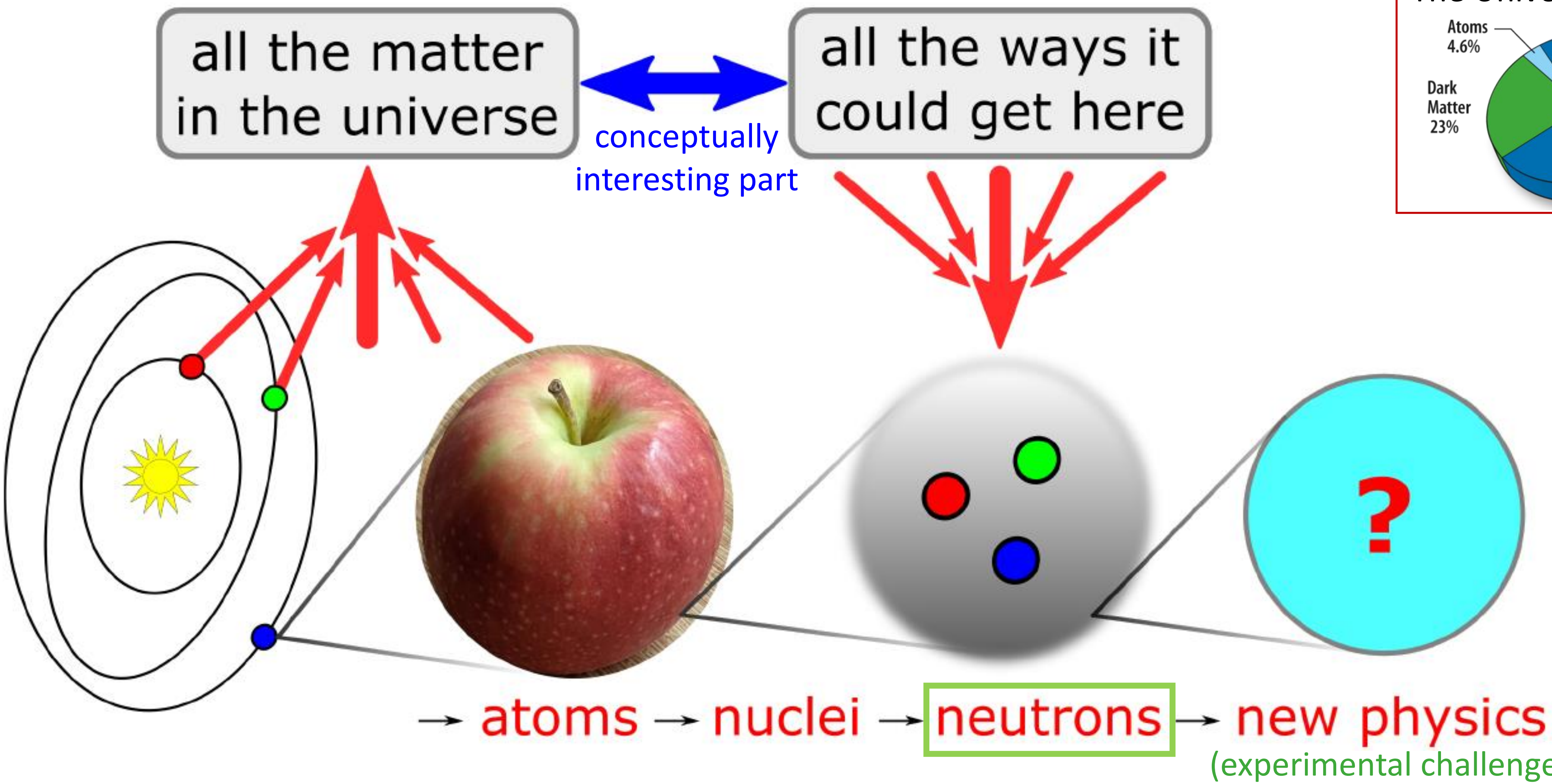
TC: "How many EDM experiments do we need?"

MJRM: "Only the one that discovers an EDM"

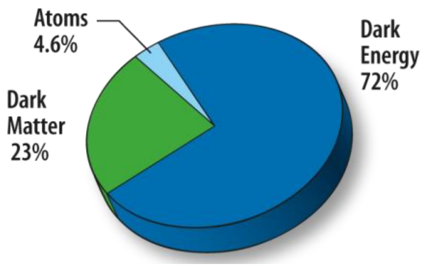
TC: "Oh – so now I know which one to work on…?"



Our motivation, and a sense of scale



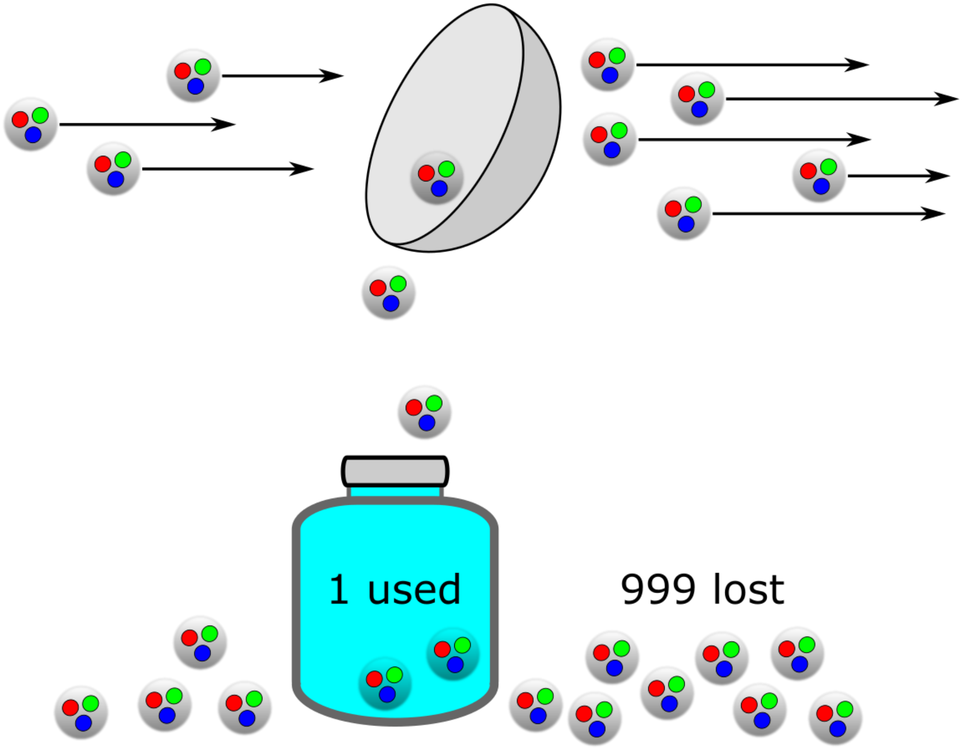
The Universe in a pie:



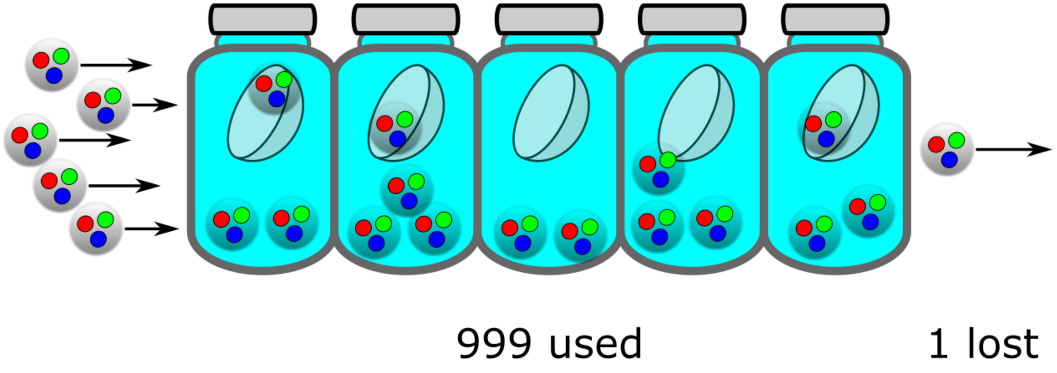
1

Challenge the first: statistics

State of the art: catch/pour
...with 0.1% success



New approach: catch them **all**, directly in many bottles

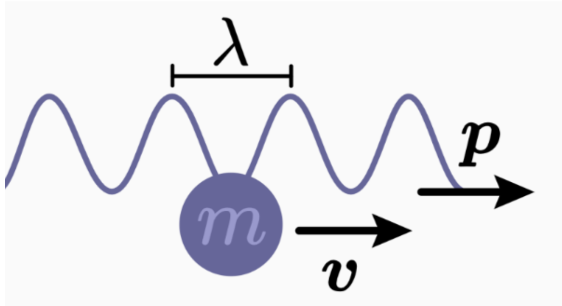


Challenge the second: observation time

2

> *"Never measure anything but frequency"*
>
> –Arthur Schawlow (1981 Physics Nobel Prize)

$$\delta\omega \sim \frac{1}{\delta t}$$

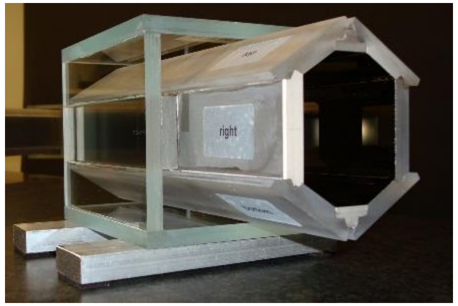


But… how to store or cool ensembles?

Wave optics, with massive particles!

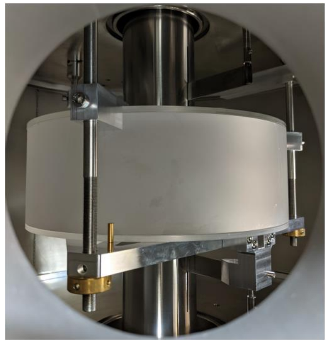
"Cold" beams: O(500 m/s)

particles fly through most experiments in milliseconds



S-DH

S-DH



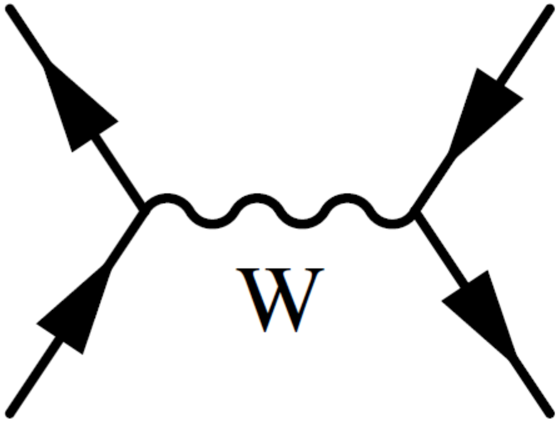
"Ultracold" traps: O(5 m/s)

particles stored for minutes (>10^5 ms)

③ Challenge: does this approach even make sense?

Well, suppose the scale of new physics is far above the SM…

…or imagine we couldn't access the heavy gauge bosons we already know



$$\frac{-i}{k^2 - m_W^2}\left(g_{\mu\nu} - \frac{k_\mu k_\nu}{m_W^2}\right) \sim \frac{1}{m_W^2}$$

"resonance" "high energy" k≈0

If the scale of new physics is >> TeV, it looks the same whether we probe it at TeV or neV!

Orders of Magnitude

Some recent experimental EDM limits:

$$\begin{aligned} n\!: \; |d| &< 1.8 \times 10^{-26}\ e\ \text{cm (90\% C.L.)} \\ {}^{129}\text{Xe}\!: \; |d| &< 1.4 \times 10^{-27}\ e\ \text{cm (95\% C.L.)} \\ \text{ThO}\!: \; |d| &< 1.1 \times 10^{-29}\ e\ \text{cm (90\% C.L.)} \end{aligned}$$

$$\underbrace{10^{-26} e\ \text{cm} \times \frac{1\ \text{MV}}{m}}_{10^{-22}\ \text{eV sensitivity}} \times \frac{1}{2\pi\hbar} = 24\ \text{nHz}$$

$$\text{(cf. } 10^{13}\ \text{eV for new physics scale)}$$

Another example of jumping across several orders:

$$\text{neutron capture} \rightarrow\ 10^{6-7}\ \text{eV products}$$

$$\text{nEDM systematics} \rightarrow\ 10^{-7}\ \text{eV shifts}$$

Some handy conversion factors:

$$1\ \text{neV} = 1\frac{\text{GeV}}{c^2} \times 1\ \text{cm} \times g$$

$$1\ e\ \text{cm} = 10^{13} e\ \text{fm}$$

… so how to get 10^{-14} in energy (or equivalent in momentum)?

“Permanent Electric Dipole Moment” = ?

__Quantum eigenfrequencies:__

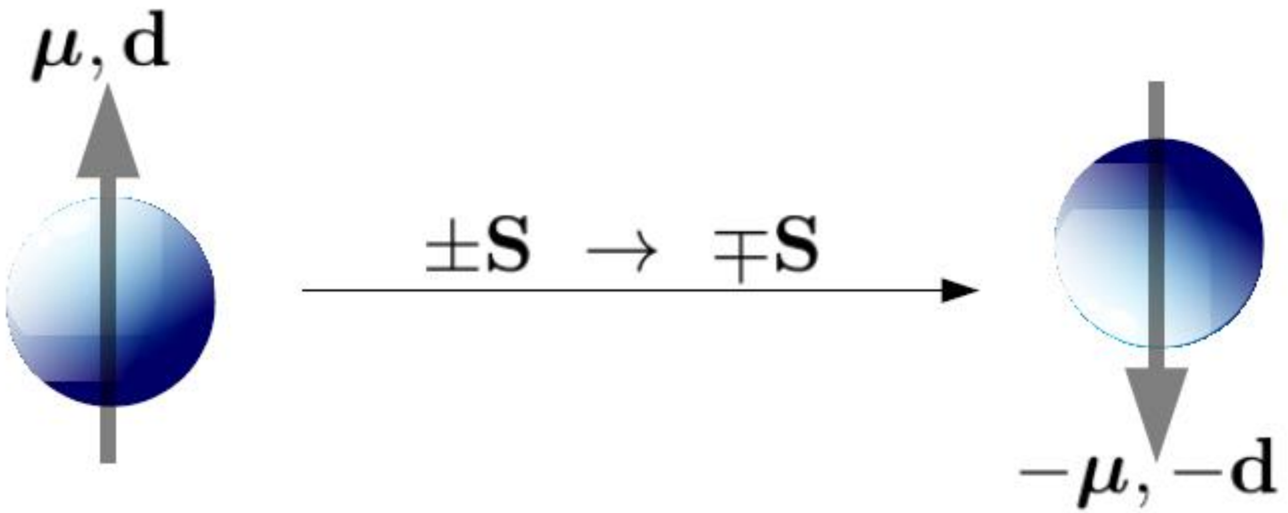
$$\hbar\omega_E \propto -d\boldsymbol{S}\cdot\boldsymbol{E}$$

$$\hbar\omega_B \propto -\mu\boldsymbol{S}\cdot\boldsymbol{B}$$

__Classical moments:__

$$\mathbf{d} = \int \mathbf{r}\rho(\mathbf{r})d\mathbf{r}$$

$$\boldsymbol{\mu} = \frac{1}{2}\int \mathbf{r}\times\mathbf{J}(\mathbf{r})d\mathbf{r}$$



Beware of pictures like this!

“Permanent Electric Dipole Moment” = ?

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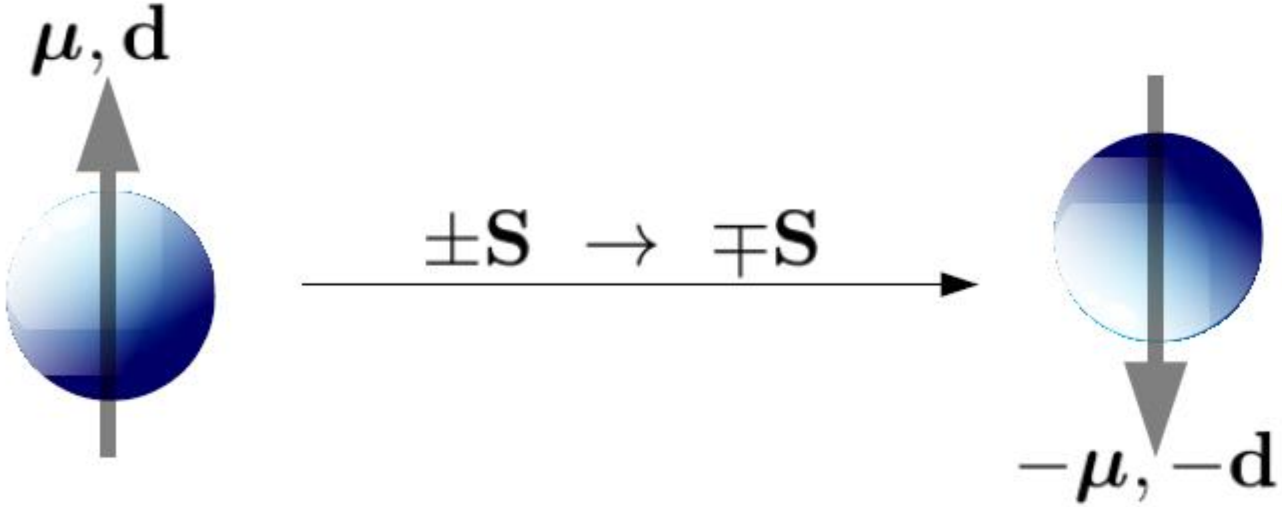
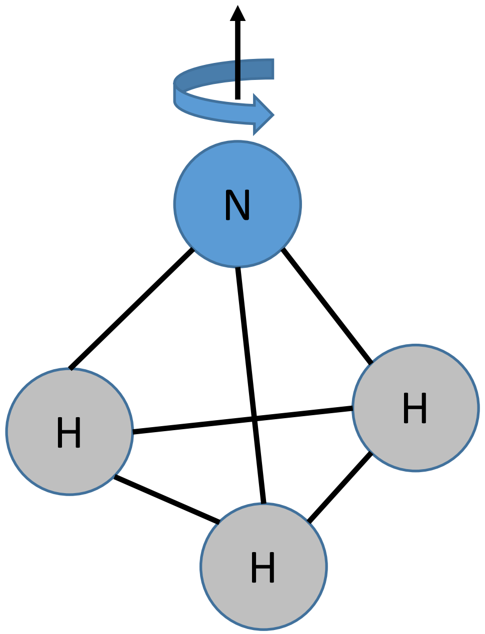
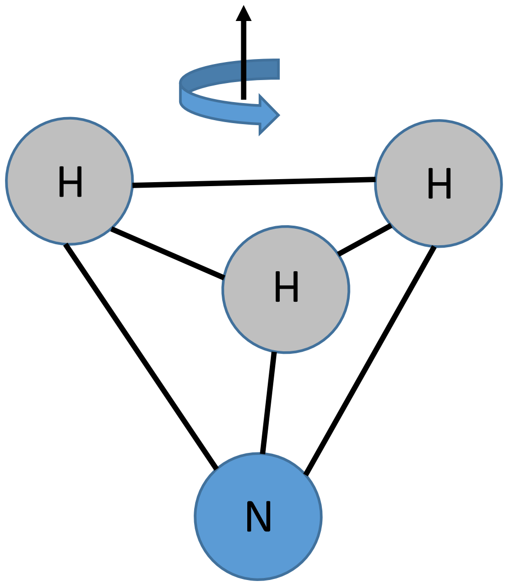


$$\begin{aligned} T\mathbf{r}T^{-1} &= \mathbf{r} \\ T\mathbf{p}T^{-1} &= -\mathbf{p} \\ T\boldsymbol{\sigma}T^{-1} &= -\boldsymbol{\sigma} \end{aligned}$$

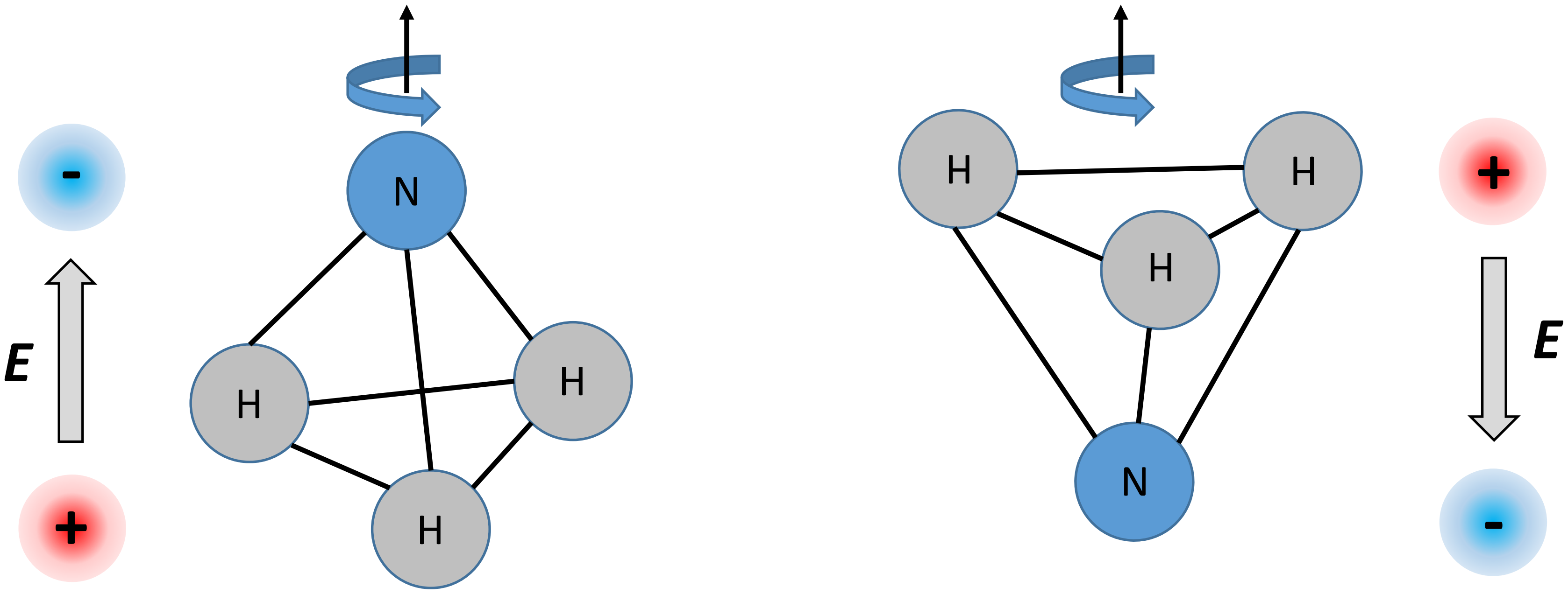
Is it different from a molecular dipole?

…or, “a warm-up for non-relativistic quantum methods”

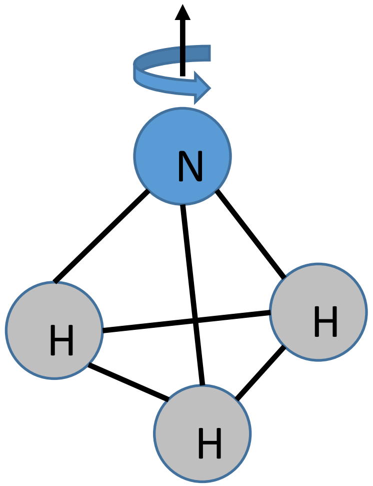




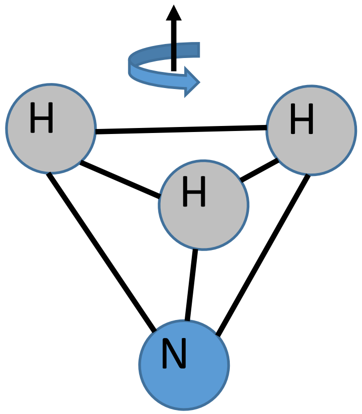
What happens in an electric field?



Find the eigenstates



$|1\rangle$

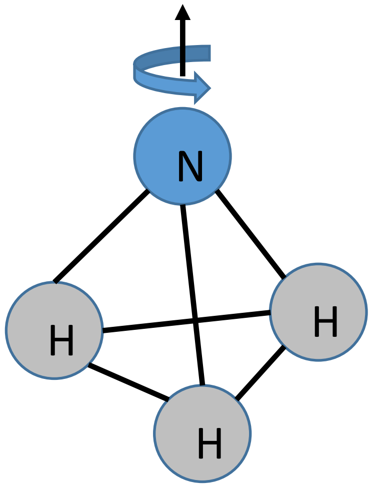


$|2\rangle$

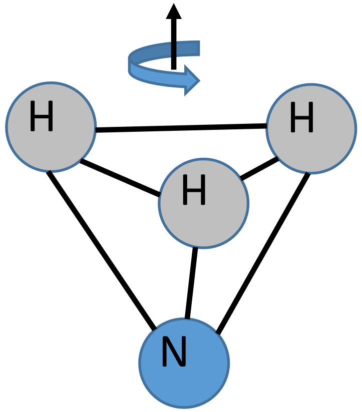
The *energy* eigenstates are:

$$\frac{1}{\sqrt{2}}\left(|1\rangle \pm |2\rangle\right)$$

Check the limiting cases



$|1\rangle$



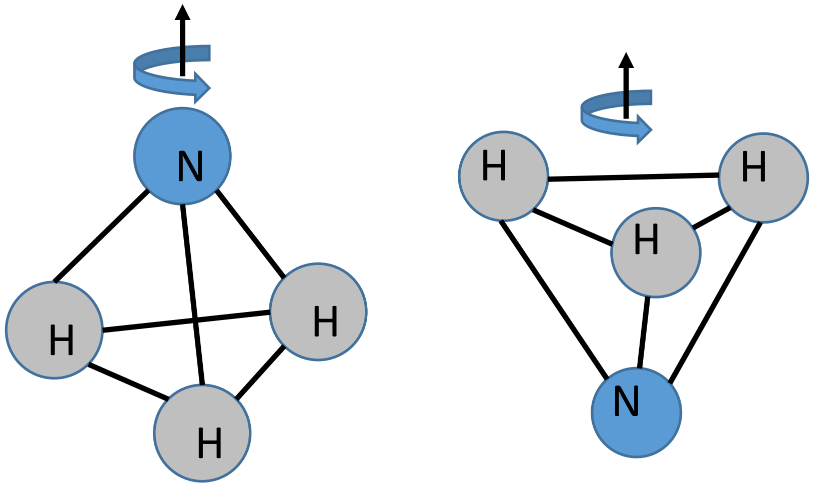
$|2\rangle$

$$E_{\pm} = E_0 + \sqrt{A^2 + d^2 E^2}$$

The *energy* eigenstates are:

$$\frac{1}{\sqrt{2}}\left(|1\rangle \pm |2\rangle\right)$$

No surprises, actually



$|1\rangle$ $|2\rangle$

$$E_\pm = E_0 + \sqrt{A^2 + d^2E^2}$$

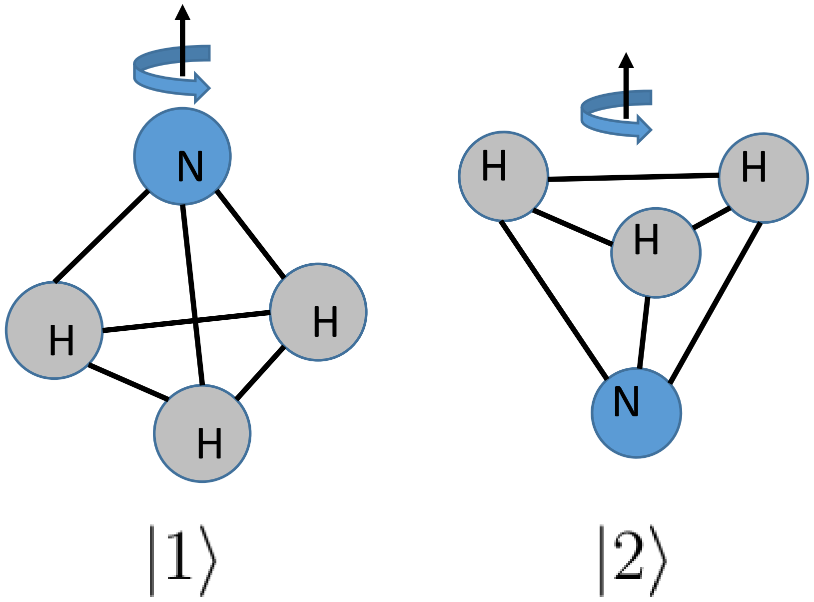
$$E_0 \pm dE \quad (dE \gg A)$$

$$E_0 \pm A \pm \frac{d^2E^2}{2A} \quad (dE \ll A)$$

The *energy* eigenstates are:

$$\frac{1}{\sqrt{2}}\left(|1\rangle \pm |2\rangle\right)$$

So... is it different from a molecular dipole?



The *energy* eigenstates are:

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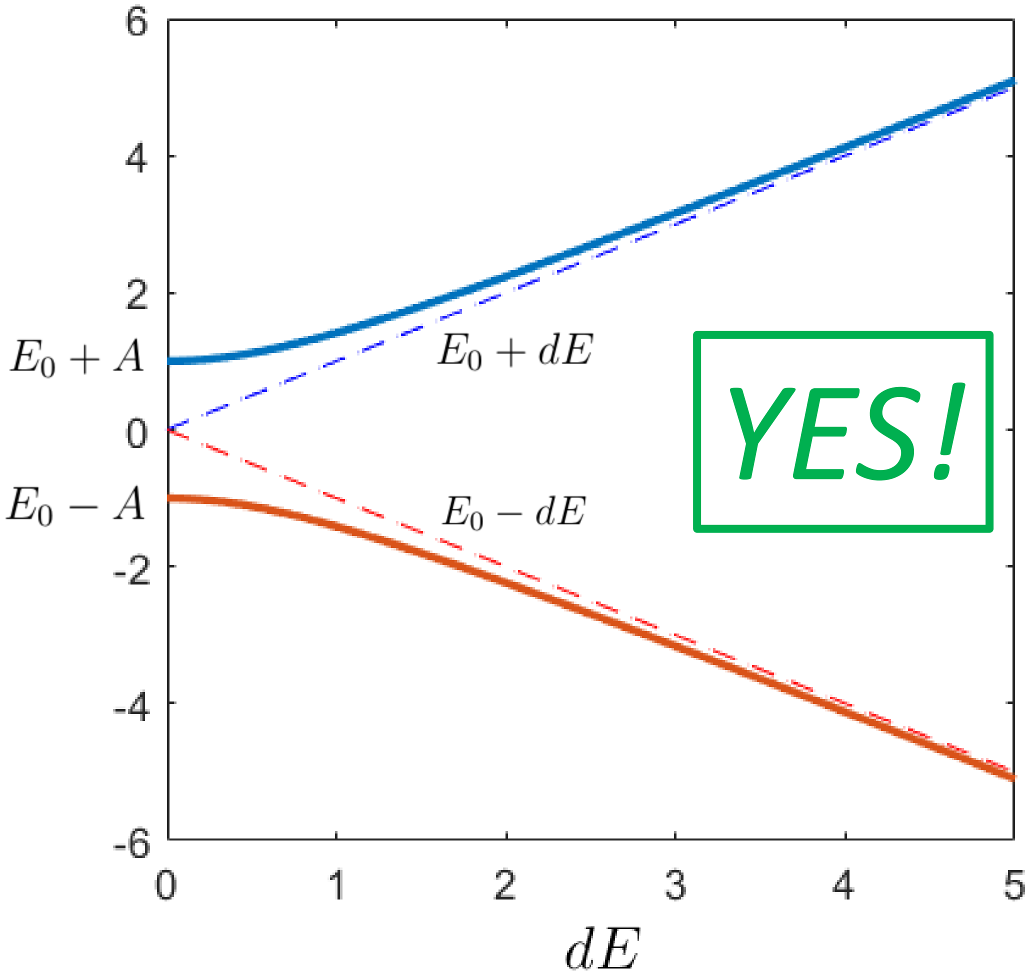


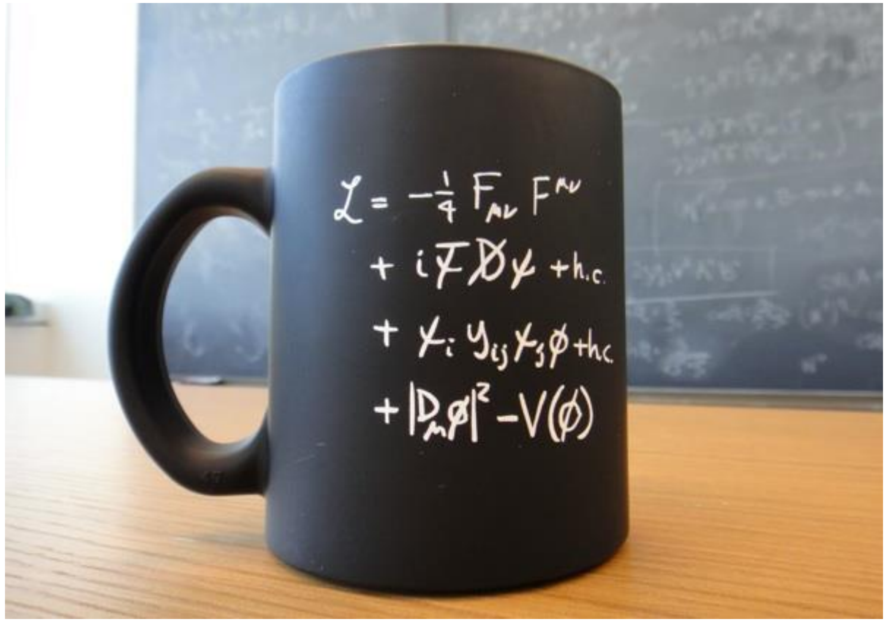
New Physics, in Familiar Terms

$$\mathscr{L}_{\text{fermion}} = -\frac{\mu}{2}\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi - i\frac{d}{2}\bar{\psi}\sigma^{\mu\nu}\gamma^5 F_{\mu\nu}\psi$$

MDM

EDM

- Non-conservation of *P* and *T* already apparent in EDM term
- Consistency with zero vs. consistency with SM



A Taxonomy of Form Factors*

*which are not just for composite particles!

$$\mathscr{L}_{\text{fermion}} = -\frac{\mu}{2}\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi - i\frac{d}{2}\bar{\psi}\sigma^{\mu\nu}\gamma^5 F_{\mu\nu}\psi$$

MDM **EDM**

$$\begin{aligned}\langle p_f|\, j^\mu \,|p_i\rangle = \bar{u}(p_f)\Big[& F_1(q^2)\gamma^\mu \\ & + \frac{i\sigma^{\mu\nu}}{2m}q_\nu F_2(q^2) \\ & + i\epsilon^{\mu\nu\rho\sigma}\sigma_{\rho\sigma}q_\nu F_3(q^2) \\ & + \frac{1}{2m}\left(q^\mu - \frac{q^2}{2m}\gamma^\mu\right)\gamma_5 F_4(q^2)\Big]u(p_i)\end{aligned}$$

$$d = -\frac{F_3(0)}{2m} \qquad Q = F_1(0)$$

$$\mu = \frac{F_1(0)+F_2(0)}{2m} \qquad a = F_4(0)$$

A Taxonomy of Form Factors

$$\mathscr{L}_{\text{fermion}} = \underbrace{-\frac{\mu}{2}\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi}_{\text{MDM}} \underbrace{- i\frac{d}{2}\bar{\psi}\sigma^{\mu\nu}\gamma^5 F_{\mu\nu}\psi}_{\text{EDM}}$$

$$\begin{aligned}\langle p_f | j^\mu | p_i \rangle = \bar{u}(p_f) \Big[& F_1(q^2)\gamma^\mu \\ & + \frac{i\sigma^{\mu\nu}}{2m} q_\nu F_2(q^2) \\ & + i\epsilon^{\mu\nu\rho\sigma}\sigma_{\rho\sigma}q_\nu F_3(q^2) \\ & + \frac{1}{2m}\left(q^\mu - \frac{q^2}{2m}\gamma^\mu\right)\gamma_5 F_4(q^2) \Big] u(p_i)\end{aligned}$$

$$d = -\frac{F_3(0)}{2m} \qquad Q = F_1(0)$$

$$\mu = \frac{F_1(0) + F_2(0)}{2m} \qquad a = F_4(0)$$

Summary of Motivation

Problem: 1 extra baryon in every 10^9

- Asymmetry: $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$
- n_γ comes from CMB decoupling
- Actually normalize to entropy density s, since universe expands

Requirements: Sakharov's criteria

- Baryon-number (B) violation
- C and CP-violation
- Departure from thermal equilibrium

Solution: ???

- No complex antimatter nuclei
- No annihilation fronts
- No adequate symmetry-breaking

Prediction:

- New CP-violating physics
- Coupling to Standard Model baryons
- Polarization of bound states

Dimensional Analysis

Naïve estimate for generic new physics:

$$d_n \propto \frac{m_q}{\Lambda^2} \cdot e \cdot \phi_{\rm CPV}$$

Current experiments: 10^{-26} *e* cm $\longrightarrow$ $\Lambda \sim 10 - 100\ \rm TeV$

Analysis: neutron in Global context

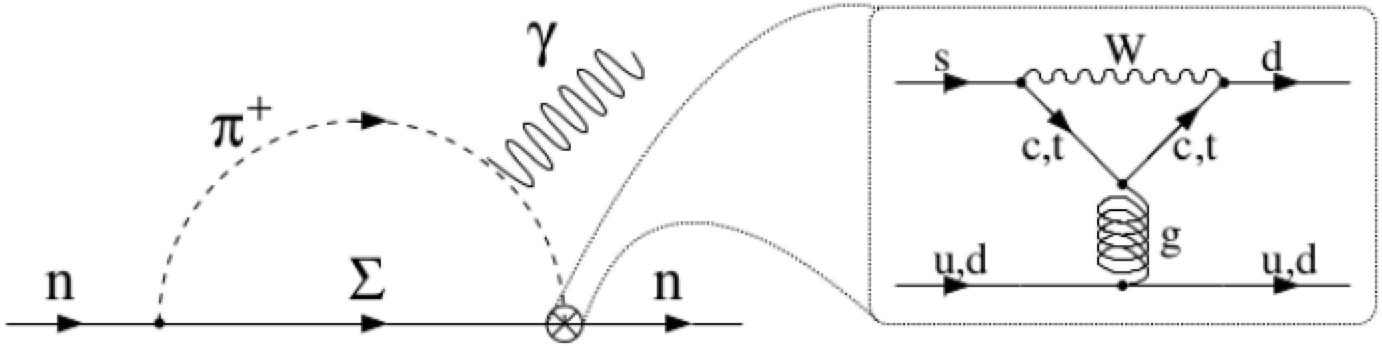
Naïve estimate for generic new physics:

$$d_n \propto \frac{m_q}{\Lambda^2} \cdot e \cdot \phi_{\mathrm{CPV}}$$

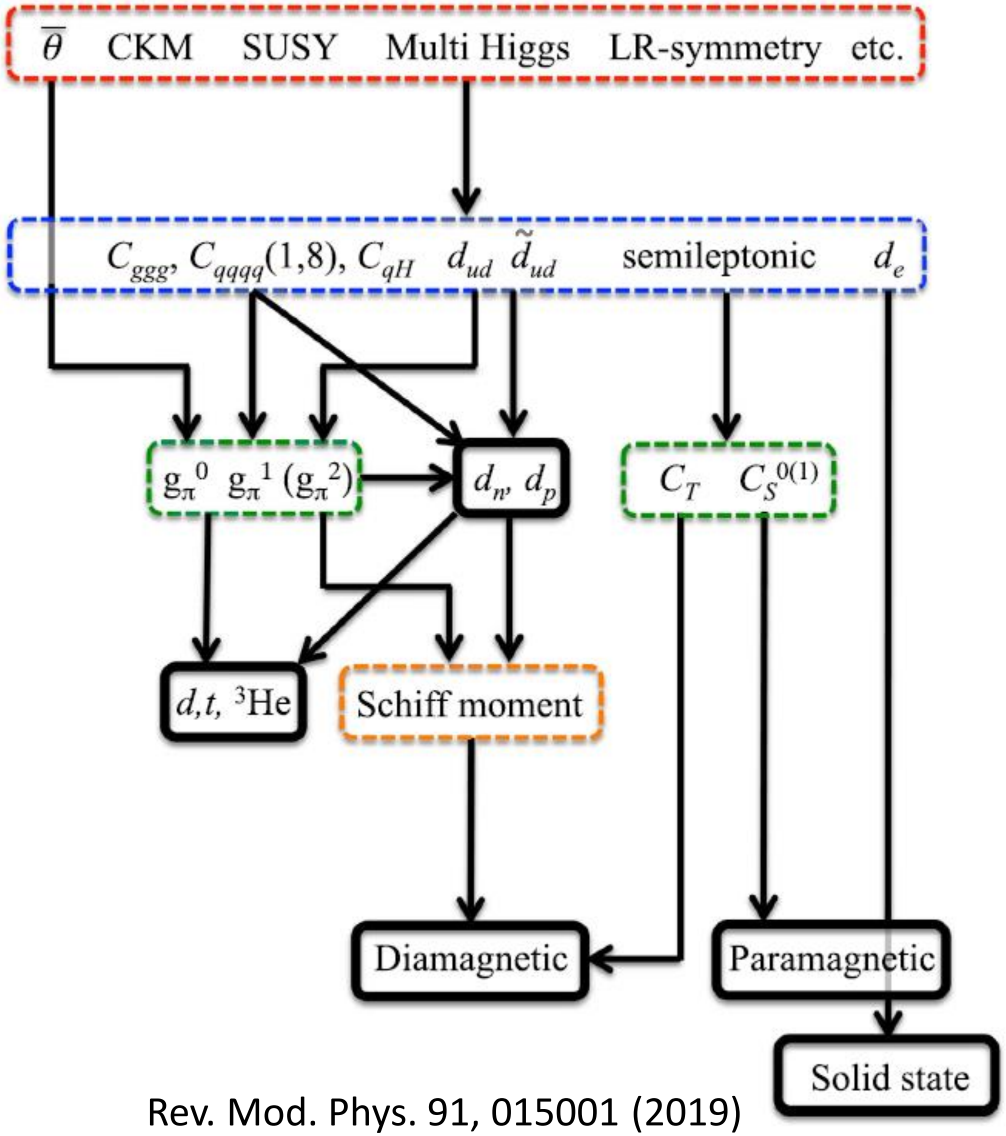
Current experiments: 10^{-26} *e* cm → $\Lambda \sim 10 - 100\ \mathrm{TeV}$

Standard Model CKM: 10^{-32} *e* cm
Standard Model QCD: ??? → $d_n \approx (10^{-16} e\ \mathrm{cm})\bar{\theta}$

Neutron EDM from CP-violating pion couplings:



Pospelov & Ritz, *Annals of Physics* 318 (2005): 119-169



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

Analysis: neutron in Global context

Define a matrix a_{ij} according to $d_i = \sum_i \alpha_{ij} C_j$, e.g.,

$$d_n \approx \bar{d}_n^{\rm sr} + 1.6 \times 10^{-14} \bar{g}_\pi^{(0)} - 8.6 \times 10^{-16} \bar{g}_\pi^{(1)} + 1.5 \times 10^{-18} C_T^{(0)}$$

for global analysis at the atomic/nuclear level.

Lattice calculations would* also give us some control at the hadronic level:

$$d_n^{\rm sr} = g_T^{(n,u)} d_u + g_T^{(n,d)} d_d + g_T^{(n,s)} d_s$$

FLAG 2021, 5-10% for *u*, *d*

$$-(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d$$

*QCD sum rules

$$+ \text{ Weinberg } + \text{ 4-fermion}$$

*Naïve dim. analysis

"Global analysis" (hadronic/nuclear)

values: *Rev. Mod. Phys.* ***91****, 015001 (2019)*

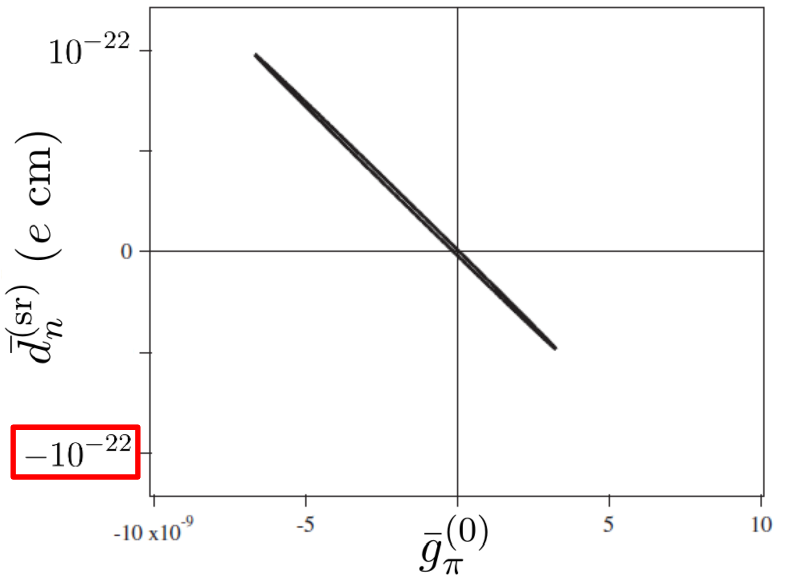
Define a matrix a_{ij} according to $d_i = \sum_i \alpha_{ij} C_j$,

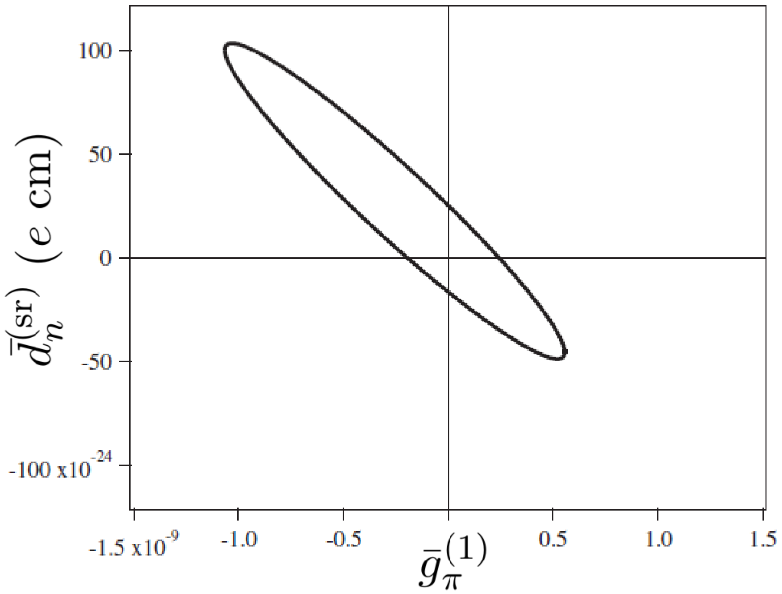
$$
\begin{array}{cc}
 & \begin{array}{cccc} d_{\mathrm{n}} & d_{\mathrm{Xe}} & d_{\mathrm{Hg}} & d_{\mathrm{Ra}} \end{array} \\
\alpha_{ij} = & \begin{pmatrix}
1.0 & 1.6\times10^{-14} & -8.6\times10^{-16} & 1.5\times10^{-18} \\
1.9\times10^{-5} & -8.6\times10^{-21} & -2.1\times10^{-19} & -6.1\times10^{-21} \\
-5.7\times10^{-4} & -1.3\times10^{-17} & 1.9\times10^{-17} & 3.1\times10^{-20} \\
1.2\times10^{-2} & 2.2\times10^{-15} & -8.1\times10^{-15} & -8.4\times10^{-19}
\end{pmatrix}
\begin{array}{c} \bar{d}_n^{(\mathrm{sr})} \\ \bar{g}_\pi^{(0)} \\ \bar{g}_\pi^{(1)} \\ C_T^{(0)} \end{array}
\end{array}
$$

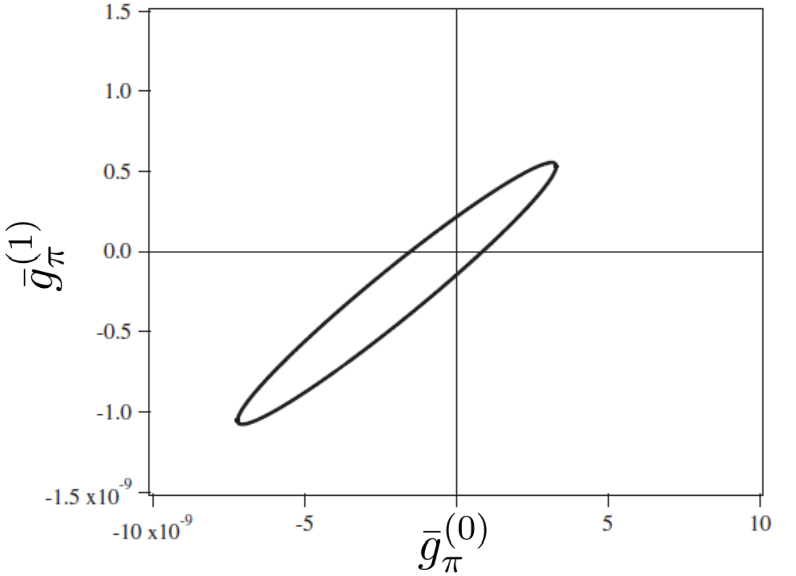
…and invert it:

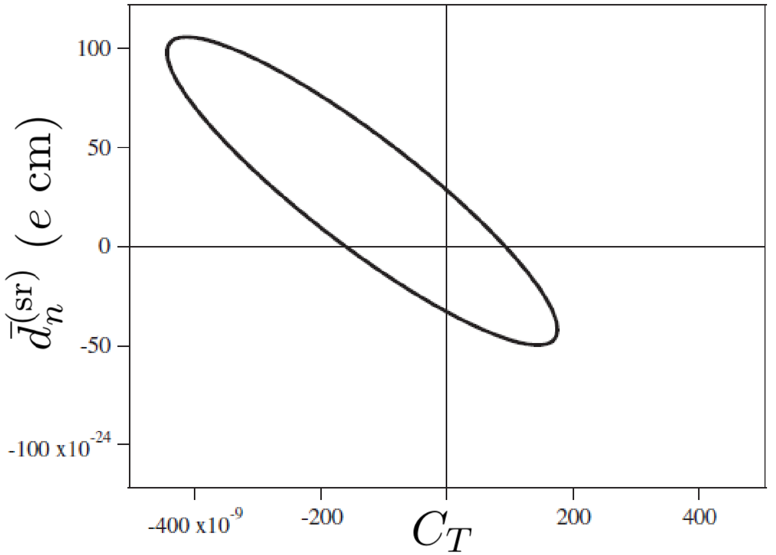
$$
\begin{pmatrix} \bar{d}_n^{(\mathrm{sr})} \\ \bar{g}_\pi^{(0)} \\ \bar{g}_\pi^{(1)} \\ C_T^{(0)} \end{pmatrix}
=
\begin{pmatrix}
1.0 & 1.6\times10^{-14} & -8.6\times10^{-16} & 1.5\times10^{-18} \\
1.9\times10^{-5} & -8.6\times10^{-21} & -2.1\times10^{-19} & -6.1\times10^{-21} \\
-5.7\times10^{-4} & -1.3\times10^{-17} & 1.9\times10^{-17} & 3.1\times10^{-20} \\
1.2\times10^{-2} & 2.2\times10^{-15} & -8.1\times10^{-15} & -8.4\times10^{-19}
\end{pmatrix}
\begin{pmatrix} d_n \\ d_{\mathrm{Xe}} \\ d_{\mathrm{Hg}} \\ d_{\mathrm{Ra}} \end{pmatrix}
$$

Status from 2019: (hadronic/nuclear)







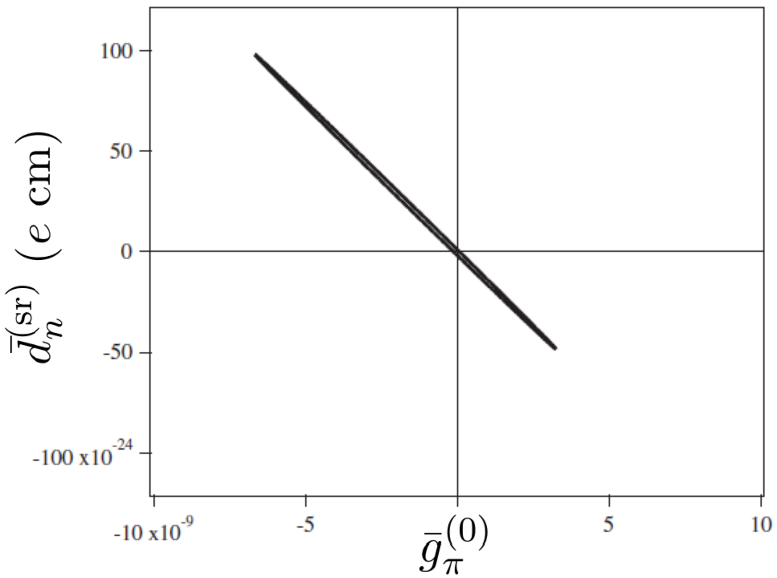


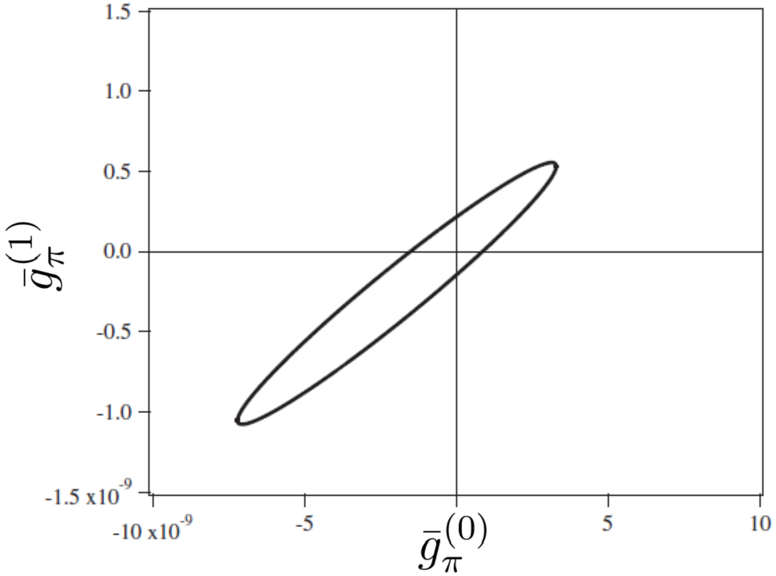
Global Analysis: T. Chupp, M. Ramsey-Musolf
Rev. Mod. Phys. ***91****, 015001 (2019)*
Phys. Rev. C ***91****, 035502 (2015)*

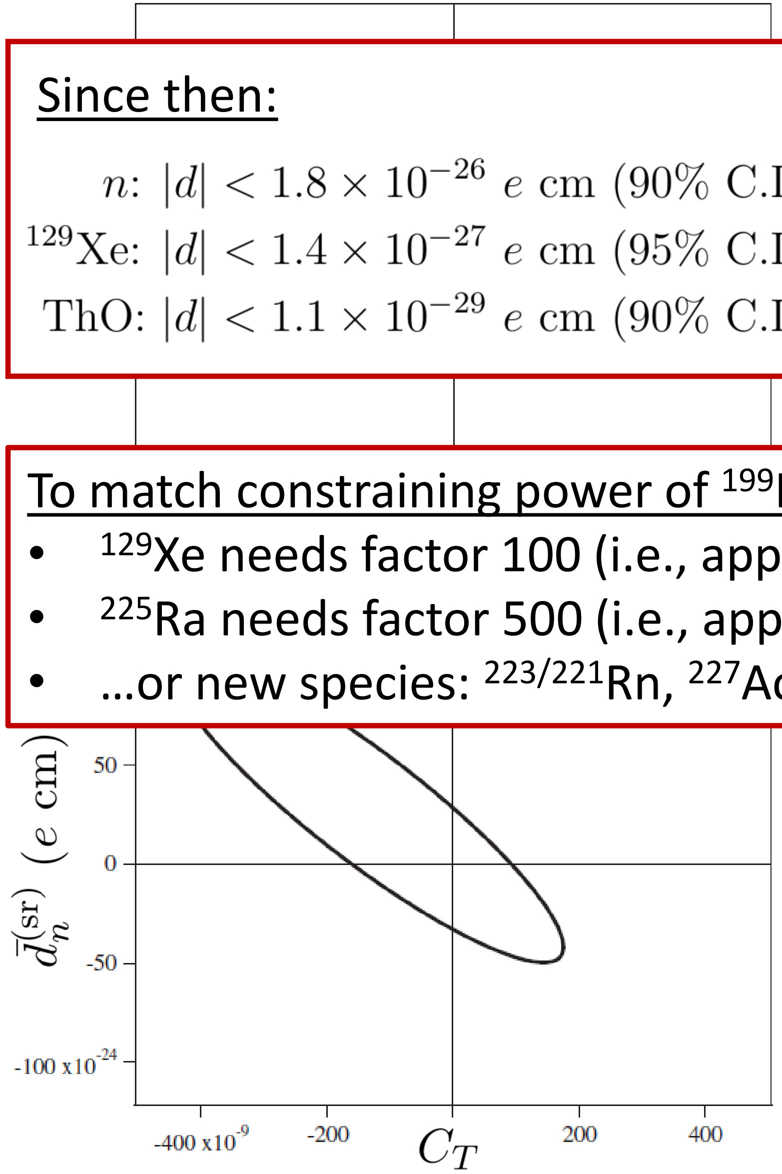
"Sole source" limits:

LE parameter	System	95% u.l.
d_e	ThO	$9.2 \times 10^{-29}\, e$ cm
C_S	ThO	8.6×10^{-9}
C_T	^{199}Hg	3.6×10^{-10}
$\bar{g}_\pi^{(0)}$	^{199}Hg	3.8×10^{-12}
$\bar{g}_\pi^{(1)}$	^{199}Hg	3.8×10^{-13}
$\bar{g}_\pi^{(2)}$	^{199}Hg	2.6×10^{-11}
$\bar{d}_n^{sr}$	Neutron	$3.3 \times 10^{-26}\, e$ cm
$\bar{d}_p^{sr}$	TlF	$8.7 \times 10^{-23}\, e$ cm
$\bar{d}_p^{sr}$	^{199}Hg	$2.0 \times 10^{-25}\, e$ cm
	Other parameters	
d_d	$\approx 3/4 d_n$	$2.5 \times 10^{-26}\, e$ cm
$\bar{\theta}$	$\approx \bar{g}_\pi^{(0)}/(0.015)$	2.5×10^{-10}
$\tilde{d}_d - \tilde{d}_u$	$5 \times 10^{-15} \bar{g}_\pi^{(1)}\, e$ cm	$2 \times 10^{-27}\, e$ cm

Updates now in progress…







<u>Since then:</u>

n: $|d| < 1.8 \times 10^{-26}$ e cm (90% C.L.) PSI: Phys. Rev. Lett. 124, 081803 (2020)

^{129}Xe: $|d| < 1.4 \times 10^{-27}$ e cm (95% C.L.) HeXe: Phys. Rev. Lett. **123**, 143003 (2019)

ThO: $|d| < 1.1 \times 10^{-29}$ e cm (90% C.L.) ACME: Nature **562**, 355–360 (2018)

"Sole source" limits:

<u>To match constraining power of ^{199}Hg</u> ($|d| < 7.4 \times 10^{-30}$ e cm, 95% C.L.)

- ^{129}Xe needs factor 100 (i.e., approaching 10^{-30} e cm)
- ^{225}Ra needs factor 500 (i.e., approaching 10^{-26} e cm)
- …or new species: $^{223/221}$Rn, ^{227}Ac even with worse sensitivity!

$\bar{g}_\pi^{(1)}$	^{199}Hg	3.8×10^{-13}
$\bar{g}_\pi^{(2)}$	^{199}Hg	2.6×10^{-11}
$\bar{d}_n^{sr}$	Neutron	3.3×10^{-26} e cm
$\bar{d}_p^{sr}$	TlF	8.7×10^{-23} e cm
$\bar{d}_p^{sr}$	^{199}Hg	2.0×10^{-25} e cm
	Other parameters	
d_d	$\approx 3/4 d_n$	2.5×10^{-26} e cm
$\bar{\theta}$	$\approx \bar{g}_\pi^{(0)}/(0.015)$	2.5×10^{-10}
$\tilde{d}_d - \tilde{d}_u$	$5 \times 10^{-15} \bar{g}_\pi^{(1)}$ e cm	2×10^{-27} e cm

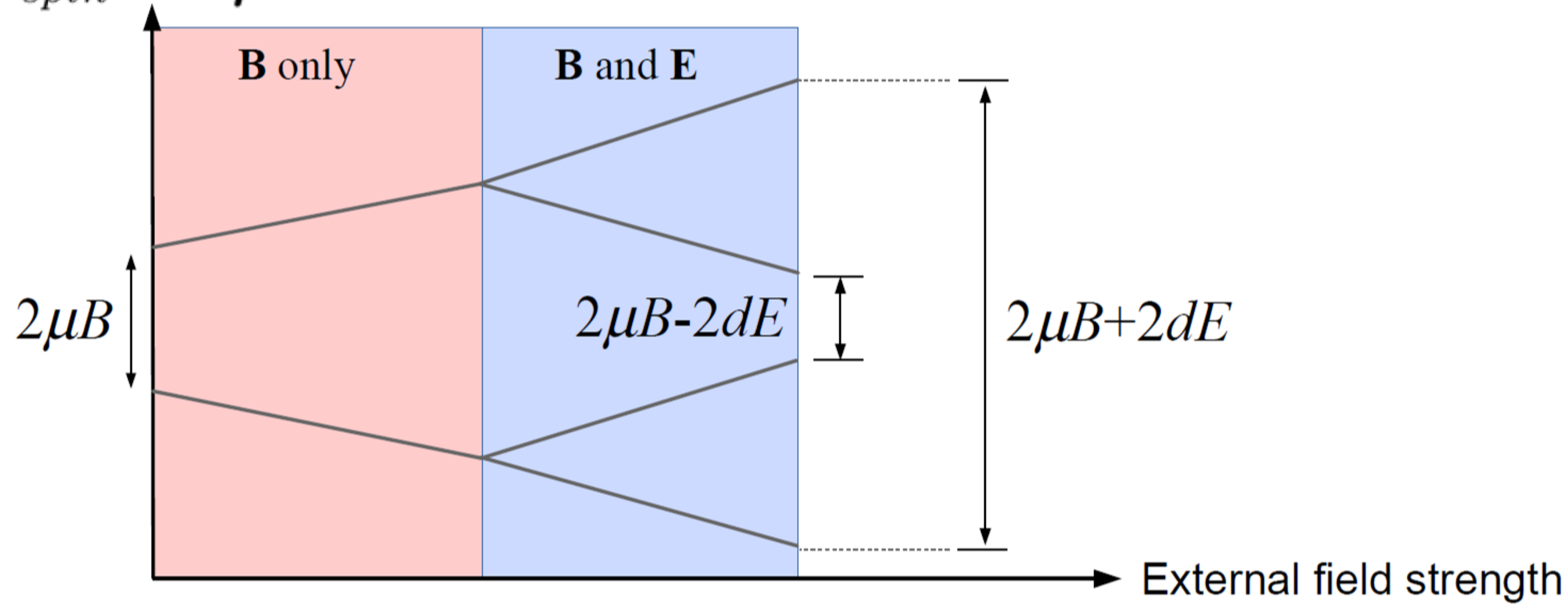
Many Parameters / Many Experiments

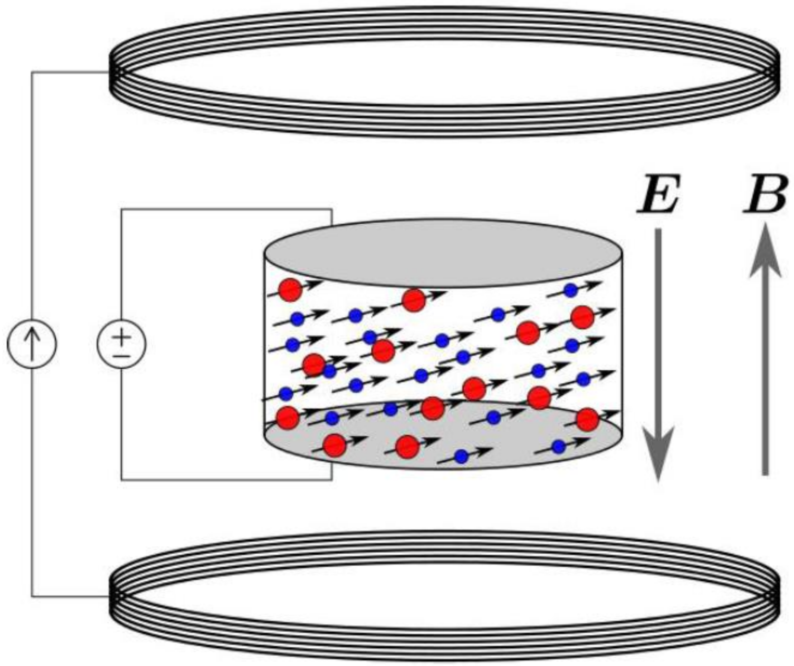
System: \ Sensitivity:	Paramagnetic	Diamagnetic	"Particle"
Trap	Tl, Cs, PbO, HfF^+, Fr, BaF, ...	^{199}Hg, ^{129}Xe, ^{225}Ra, Rn, Pa, RaO, …	n (ultra-cold)
Beam	YbF, ThO, WC	TlF	n (cold)
Storage ring	TaO^+	**?**	p, d, $^3He^{++}$, μ, …

Other: solid state ($Gd_3Ga_5O_{12}$, $Eu_{0.5}Ba_{0.5}TiO_3$), colliders (τ, Λ, ν, …), crystal (n scattering on quartz), …

How could you measure an EDM?

$$H_{spin} = -\boldsymbol{\mu} \cdot \mathbf{B} - \mathbf{d} \cdot \mathbf{E}$$



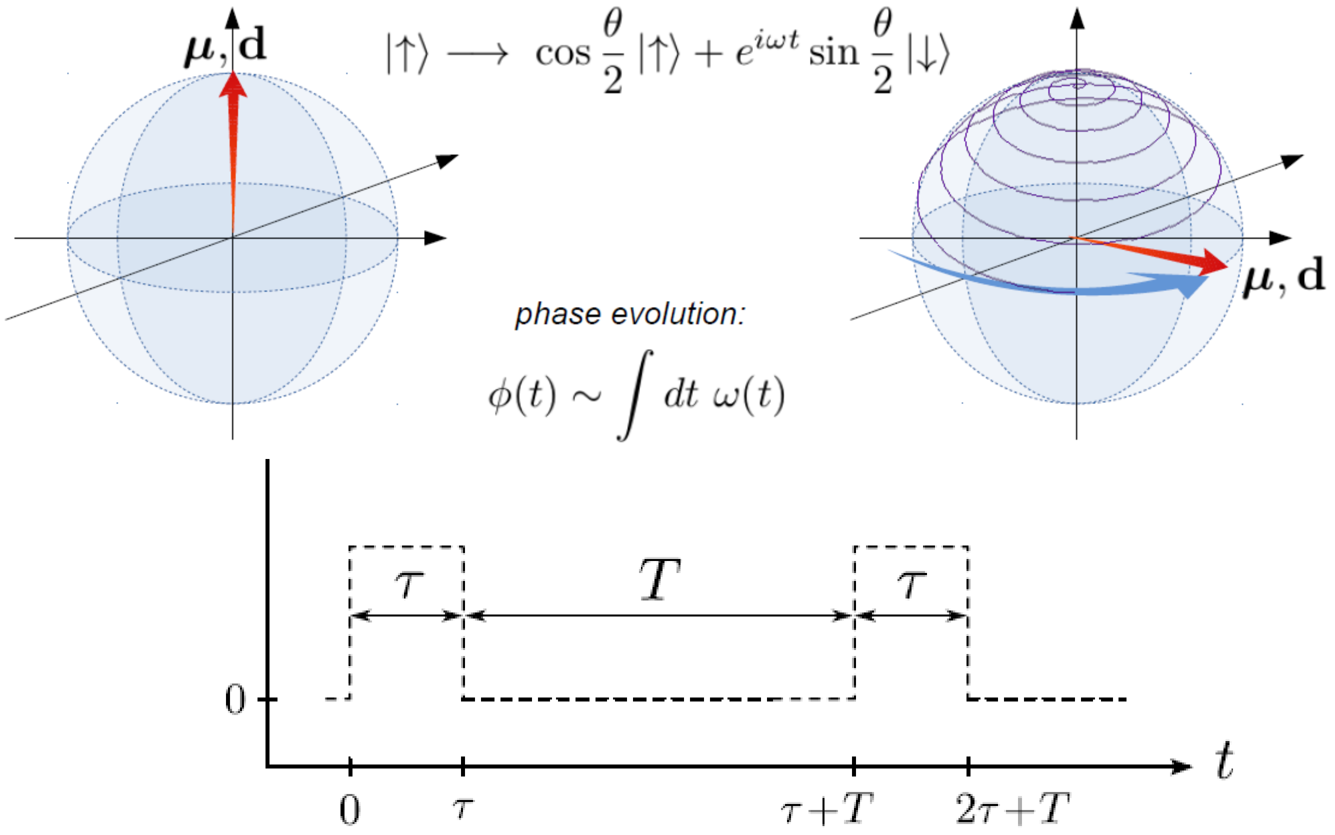


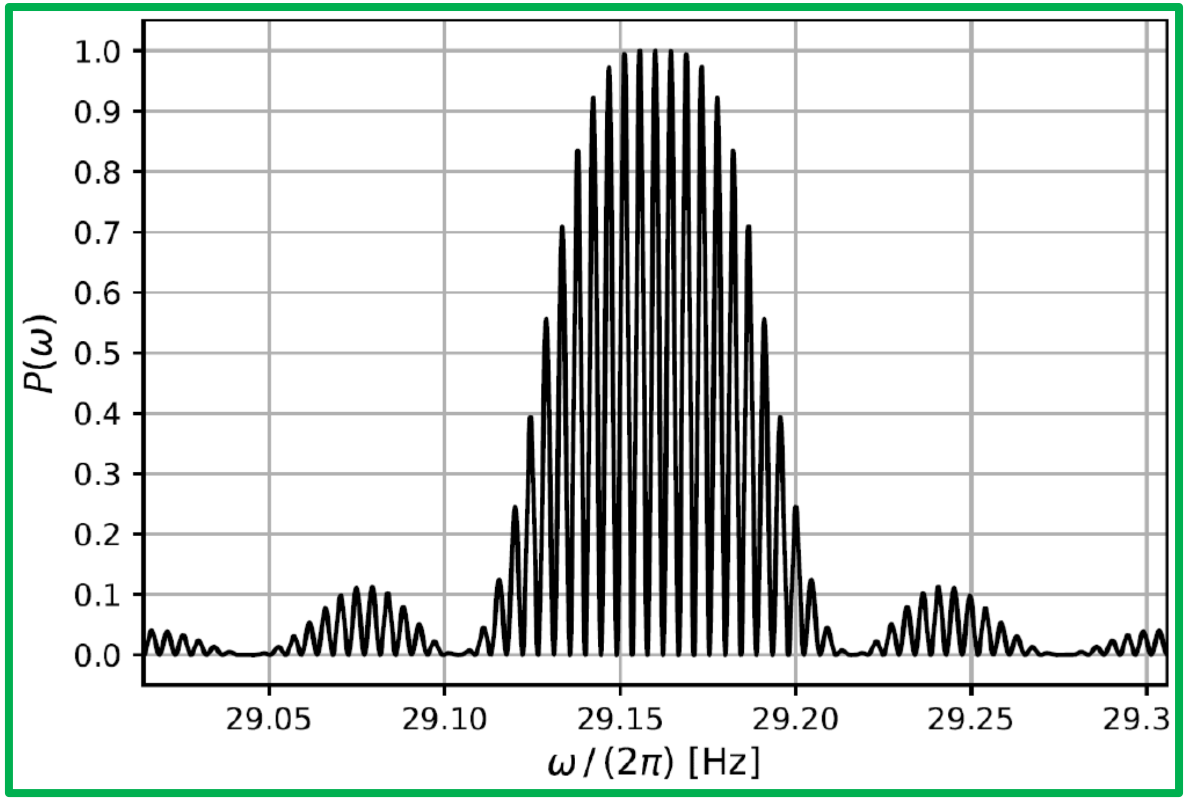
$$\boxed{\hbar(\omega_+ - \omega_-) = 4dE}$$

…up to drift, gradients, etc.

Time-Domain Interferometry

Ramsey's method to measure frequencies*:

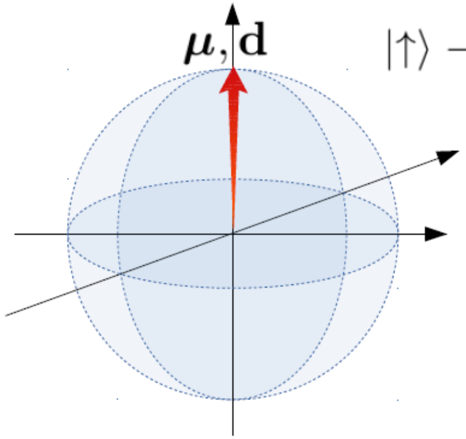




*we'll come back to *frequency* vs. *phase*

How could you measure an EDM?

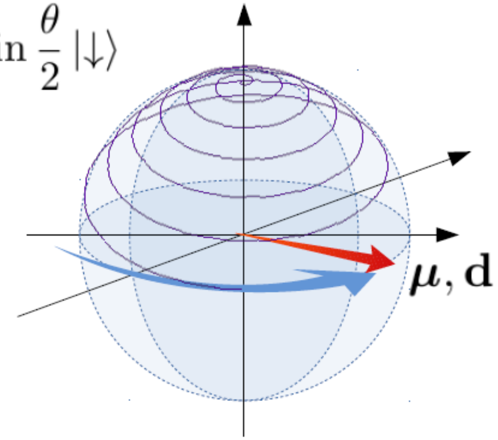
Ramsey's method to measure frequencies*:

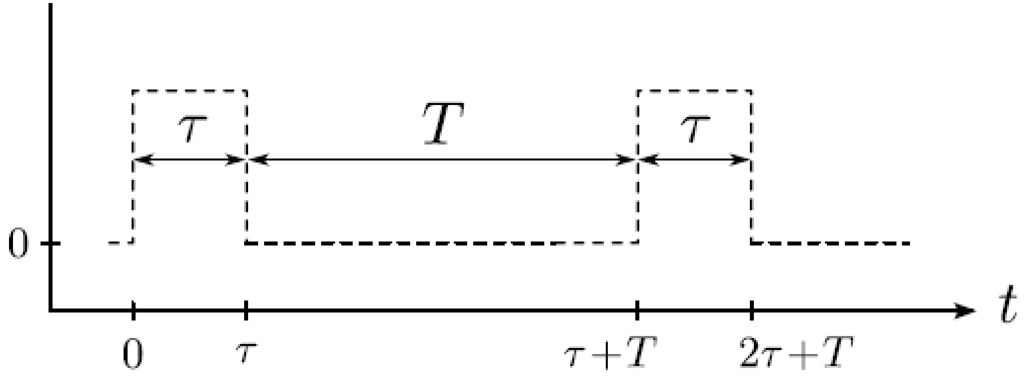


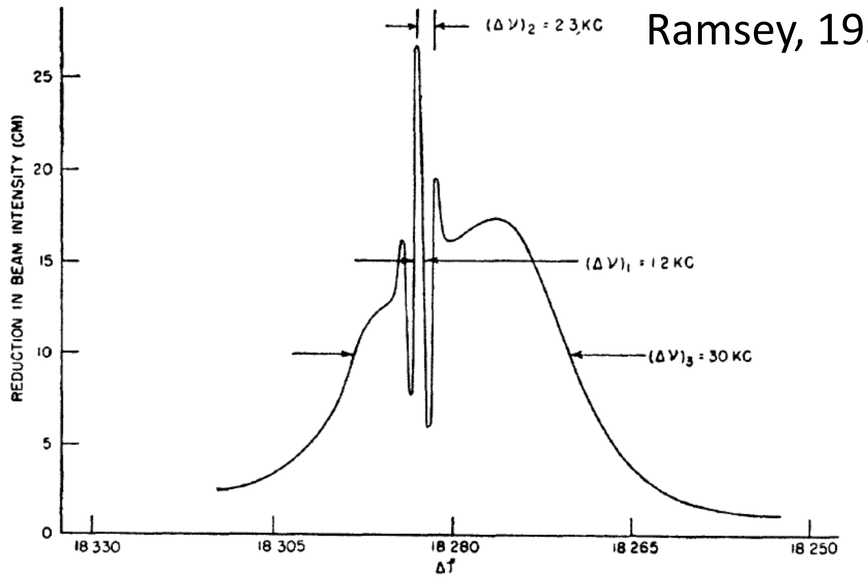
$$|\uparrow\rangle \longrightarrow \cos\frac{\theta}{2}\,|\uparrow\rangle + e^{i\omega t}\sin\frac{\theta}{2}\,|\downarrow\rangle$$

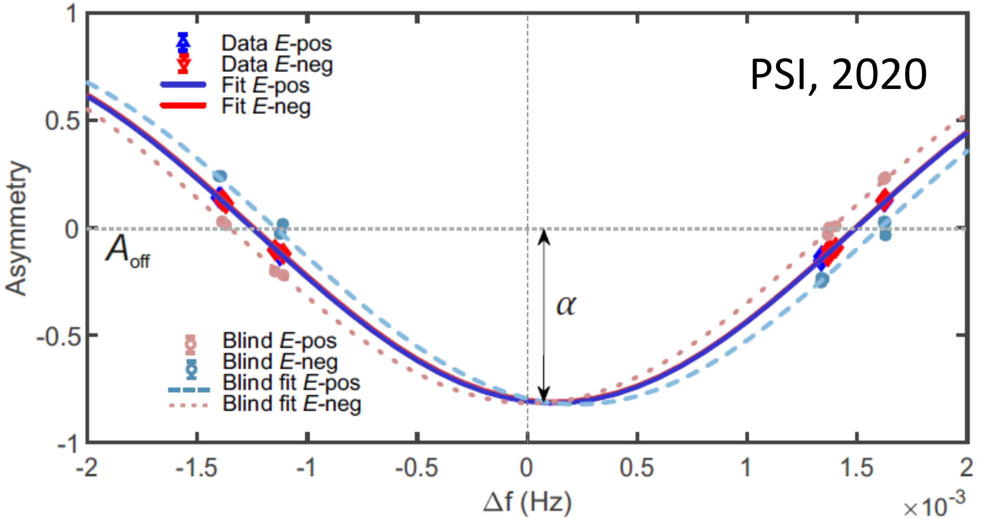
phase evolution:

$$\phi(t) \sim \int dt\ \omega(t)$$



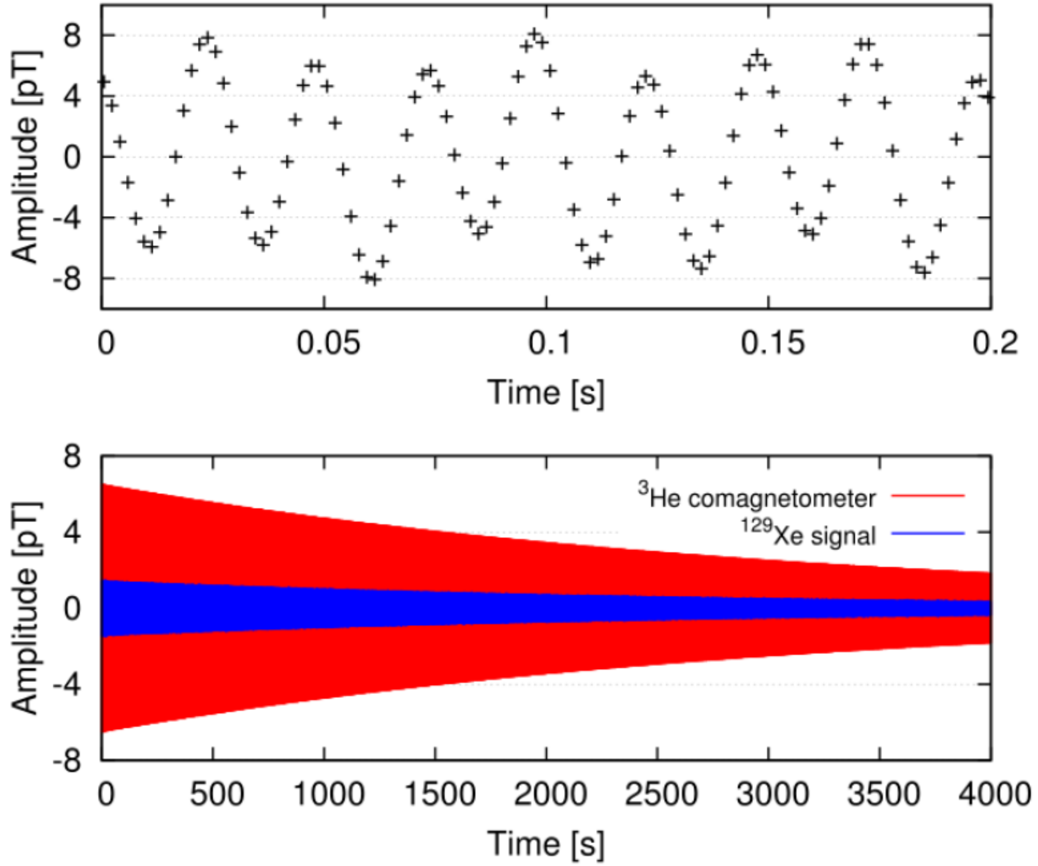






How could you measure an EDM?

What if we could measure continuously?



"phase noise" limit

$$\delta d \sim \frac{h}{2ET_2}\frac{1}{S/N}$$

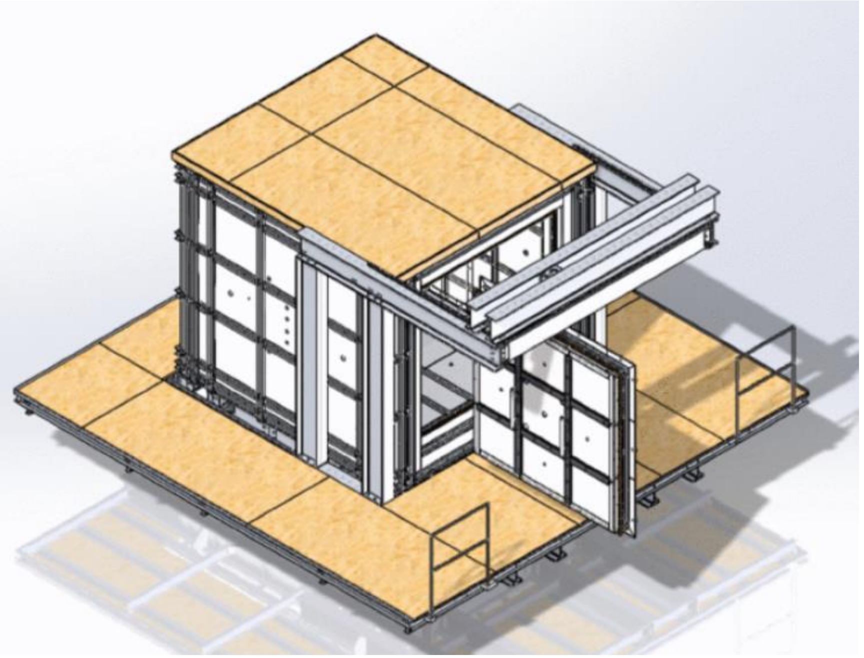
$$\frac{h}{2ET_2}\frac{1}{\sqrt{\phi_n T_2}}$$

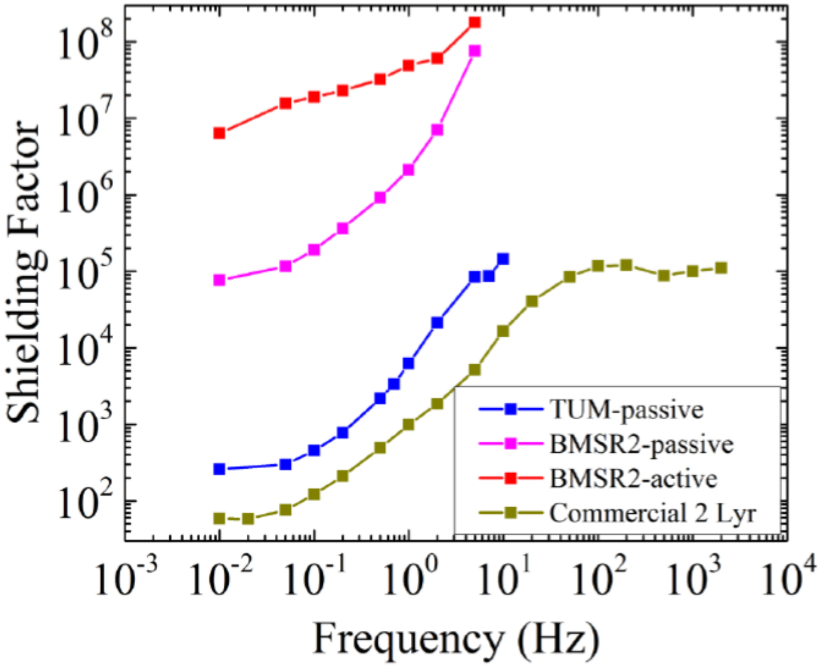
$$\frac{h}{2ET_2}\frac{1}{\sqrt{N_\mathrm{n}}}$$

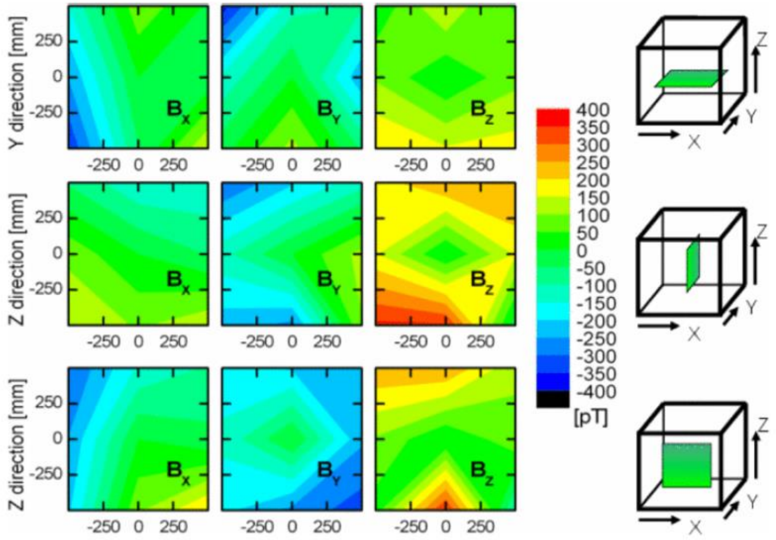
"count rate" limit

The HeXe Experiment: ^{129}Xe

Use the best magnetic shields available (at least to start with…)







Rev. Sci. Instrum. **85**, 075106 (2014)
J. Appl. Phys. **117**, 183903 (2015)

The HeXe Experiment

We do *not* expect a large Schiff enhancement in ^{129}Xe

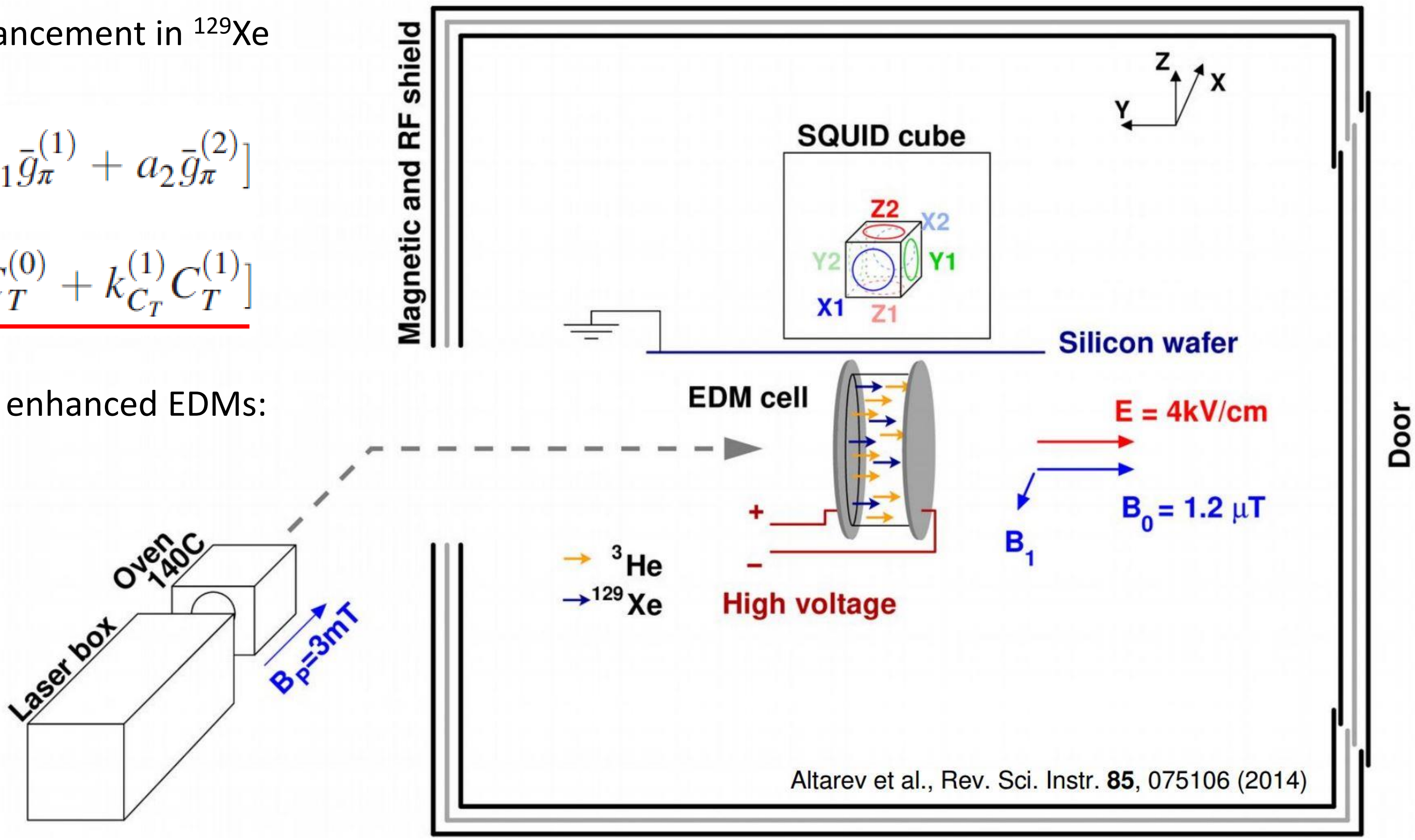
$$S = s_N d_N + \frac{m_N g_A}{F_\pi}\left[a_0 \bar{g}_\pi^{(0)} + a_1 \bar{g}_\pi^{(1)} + a_2 \bar{g}_\pi^{(2)}\right]$$

$$\longrightarrow \quad d_A(\text{dia}) = \kappa_S S - \underline{\left[k_{C_T}^{(0)} C_T^{(0)} + k_{C_T}^{(1)} C_T^{(1)}\right]}$$

Octupole-deformed nuclei can have enhanced EDMs:

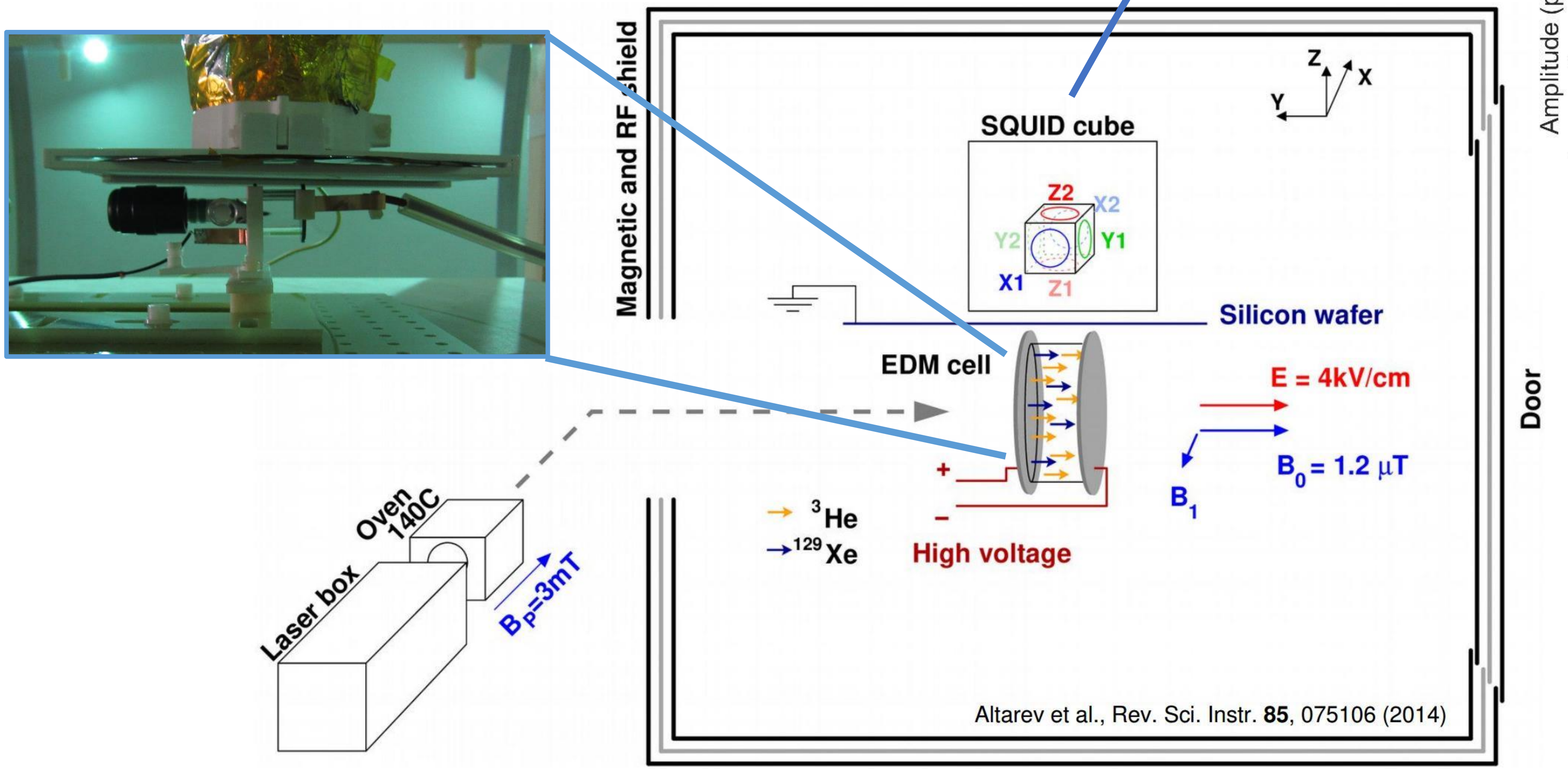
$$S \propto \frac{\eta \beta_1 \beta_3^2 A^{\frac{2}{3}} r_0^3}{E_+ - E_-}$$

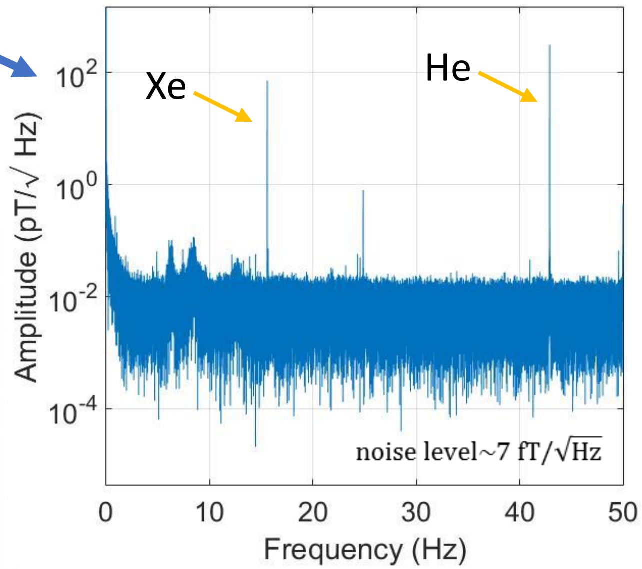
…but new challenges for those.



Altarev et al., Rev. Sci. Instr. **85**, 075106 (2014)

The HeXe Experiment





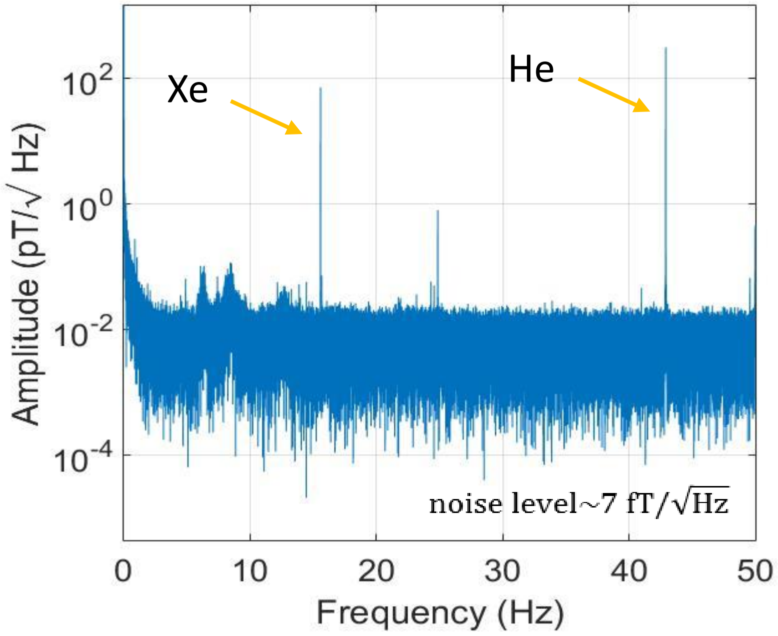
The HeXe Experiment

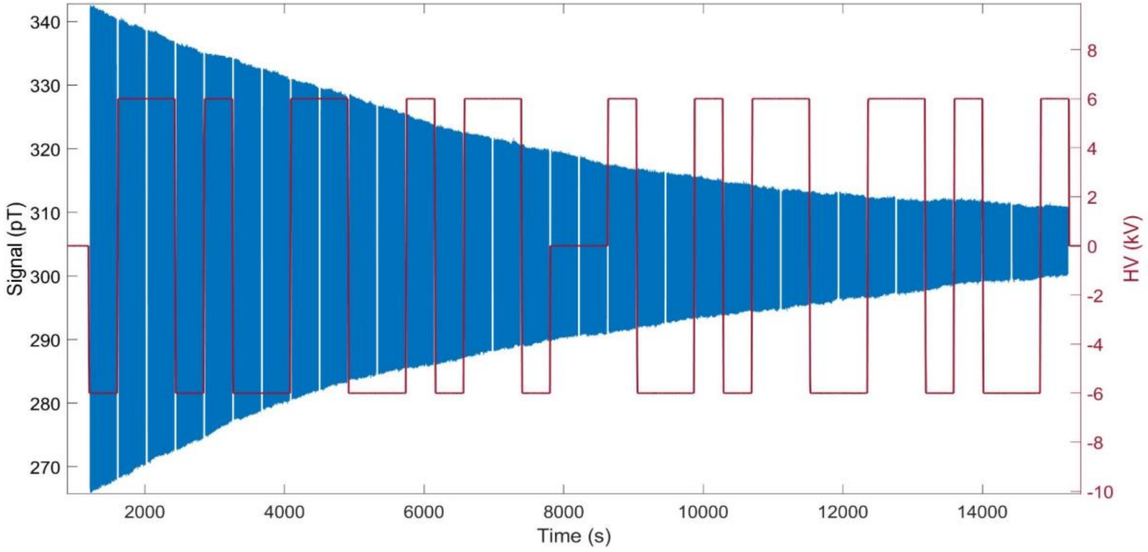
$E \sim 4\ \mathrm{kV/cm}$

$\tau \sim 4000\ \mathrm{s}$

$S \sim 20\ \mathrm{pT}$

$\epsilon \sim 8\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$





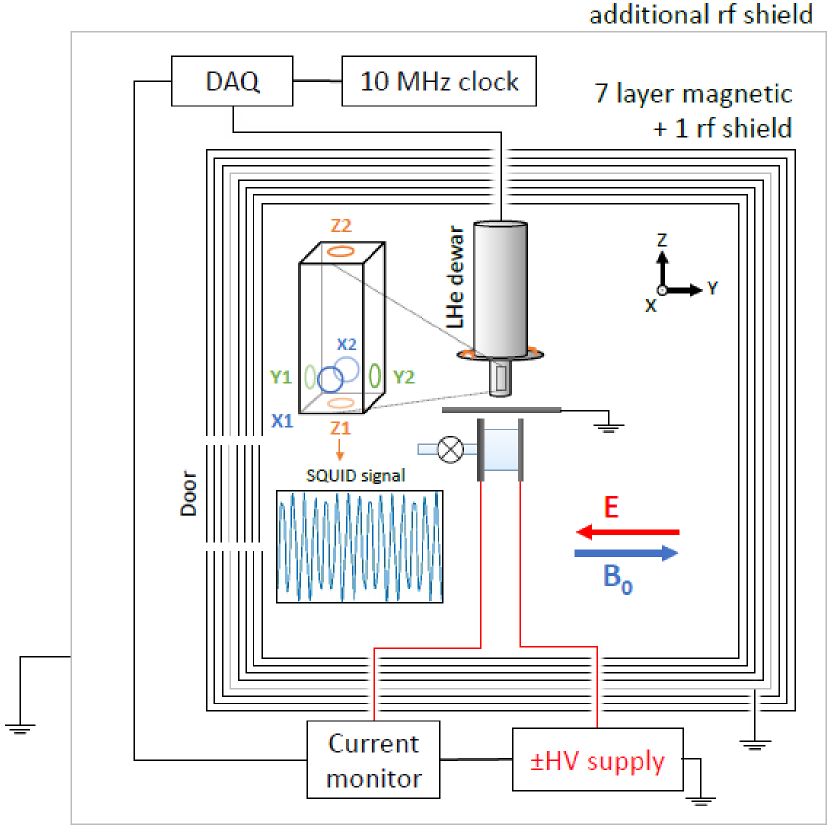
$$\delta\omega = \frac{1}{\tau (S/n)\sqrt{N}} = \frac{\epsilon\sqrt{f_{\mathrm{BW}}}}{\tau S\sqrt{N}}$$

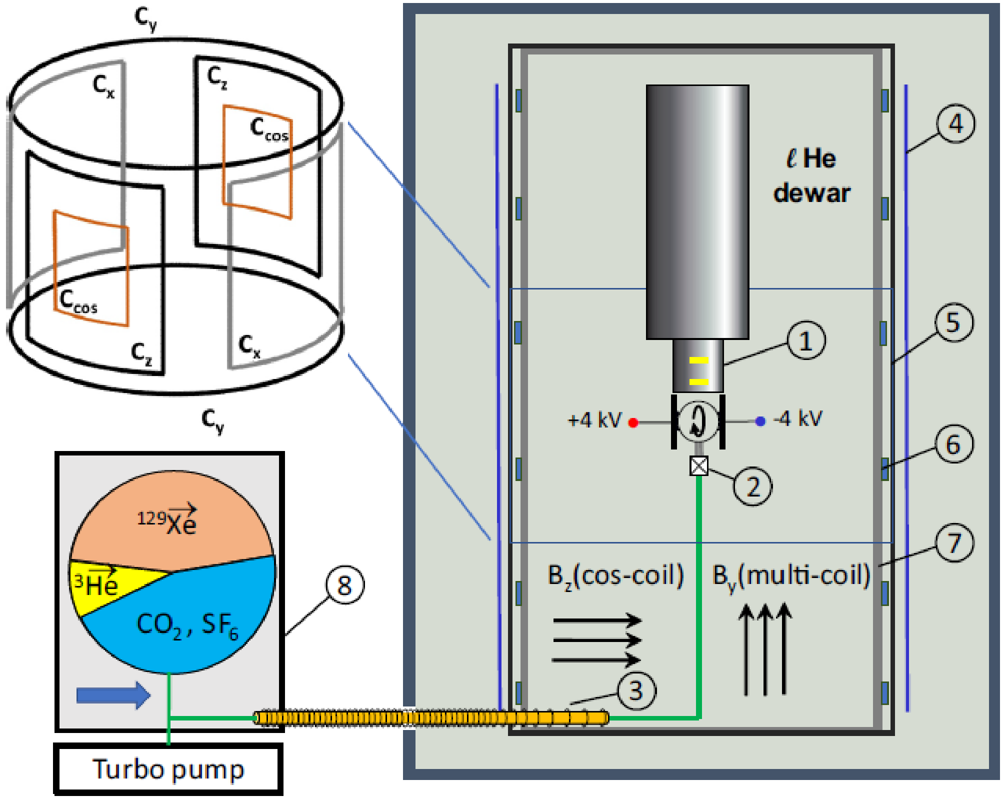
$\longrightarrow$ require nHz per run

$$\sigma_{\mathrm{d}} = \frac{\hbar}{2E}\frac{\epsilon}{\tau^{3/2} S\sqrt{N}} = \frac{\hbar}{2E}\frac{\epsilon}{\tau S\sqrt{T}}$$

$\longrightarrow$ few $\times 10^{-27}\ e\ \mathrm{cm}/\sqrt{N}$

A rapidly-moving field!





Our result from HeXe:

$$d_A(^{129}\mathrm{Xe}) = (1.4 \pm 6.6_{\mathrm{stat}} \pm 2.0_{\mathrm{syst}}) \times 10^{-28}\ e\,\mathrm{cm}$$

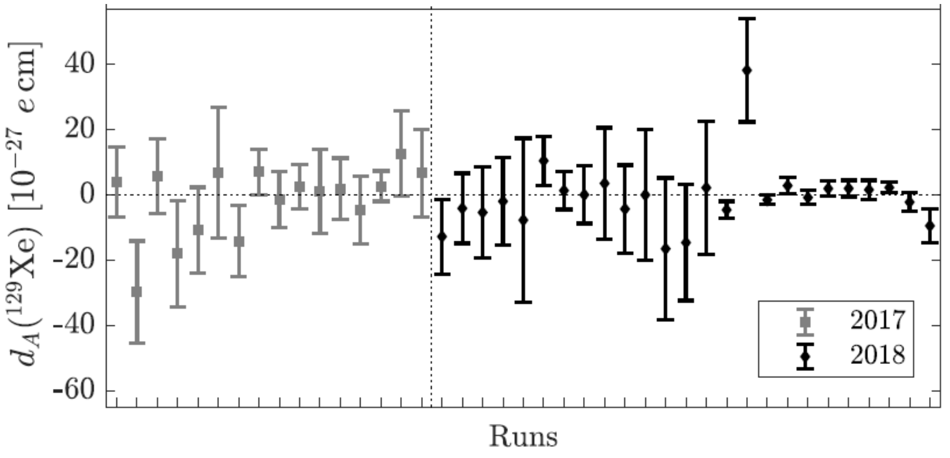
Phys. Rev. Lett. **123**, 143003 (2019)

Near-simultaneous from MiXed:

$$d_{\mathrm{Xe}} = (-4.7 \pm 6.4) \cdot 10^{-28}\ e\mathrm{cm}$$

Phys. Rev. A **100**, 022505 (2019)

A rapidly-moving field!



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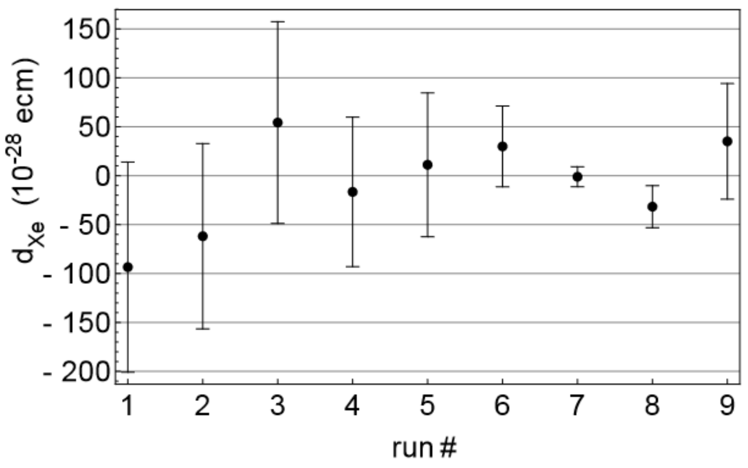
Phys. Rev. Lett. **123**, 143003 (2019)



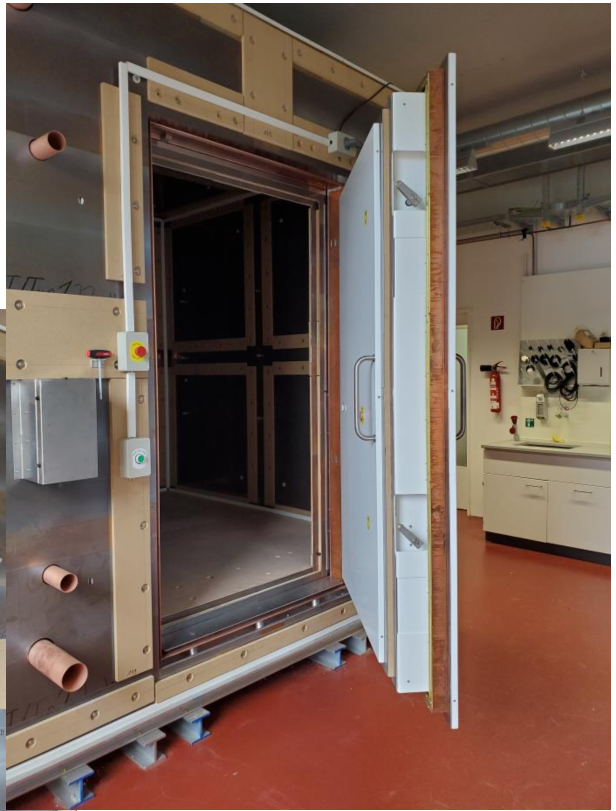
Near-simultaneous from MiXed:

$$d_{\mathrm{Xe}} = (-4.7 \pm 6.4) \cdot 10^{-28}\ e\mathrm{cm}$$

Phys. Rev. A **100**, 022505 (2019)

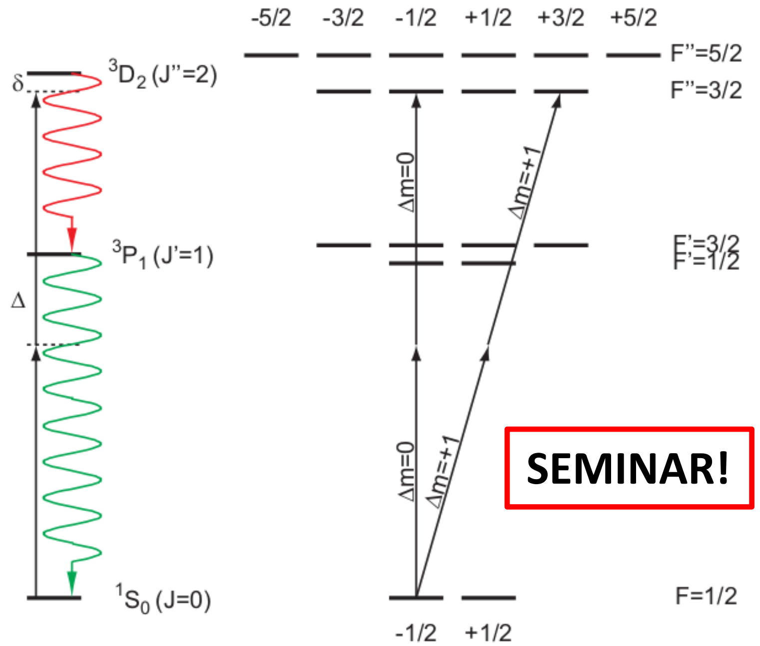
A United Future at the PI

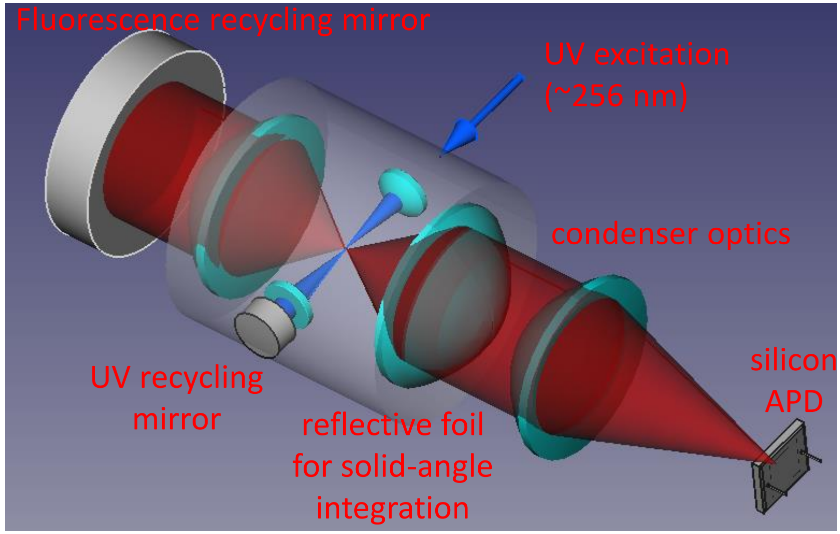
New magnetically shield room @HD! Dedicated facility…



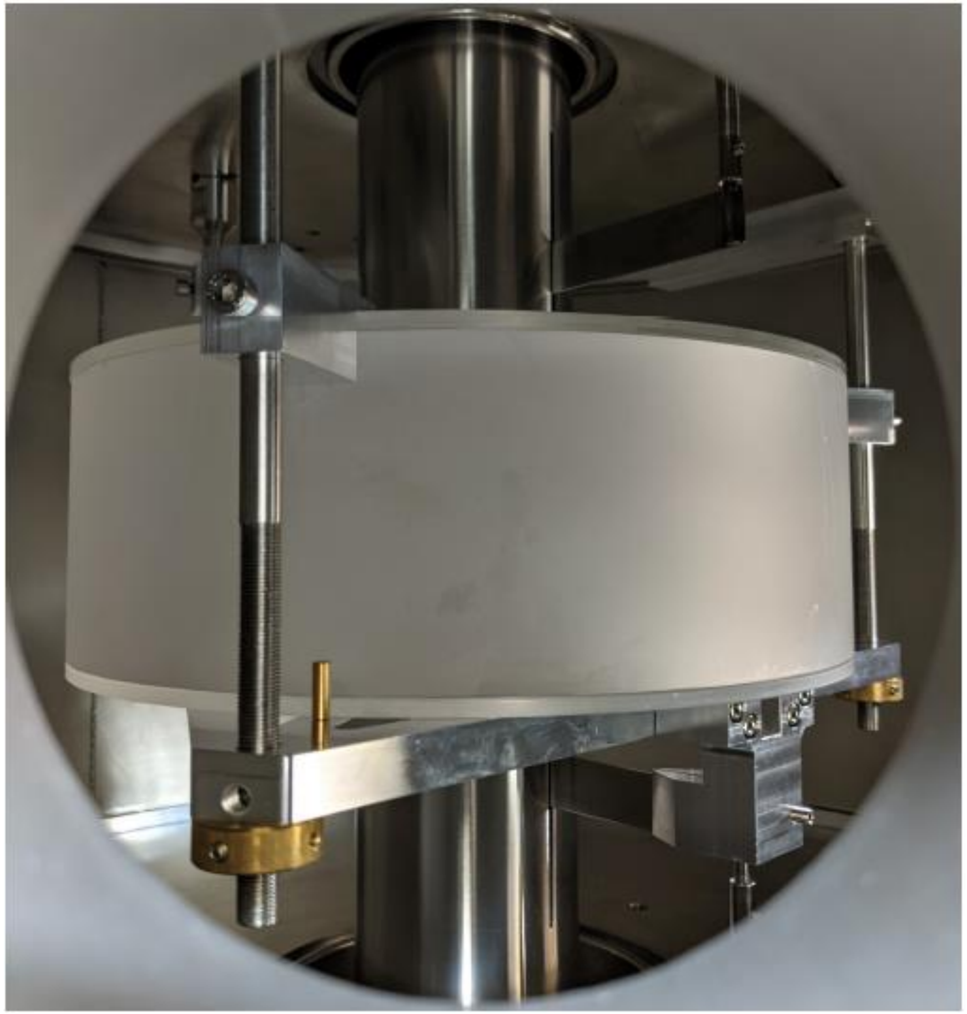
Next order-of-magnitude pursued by refining these now-known methods

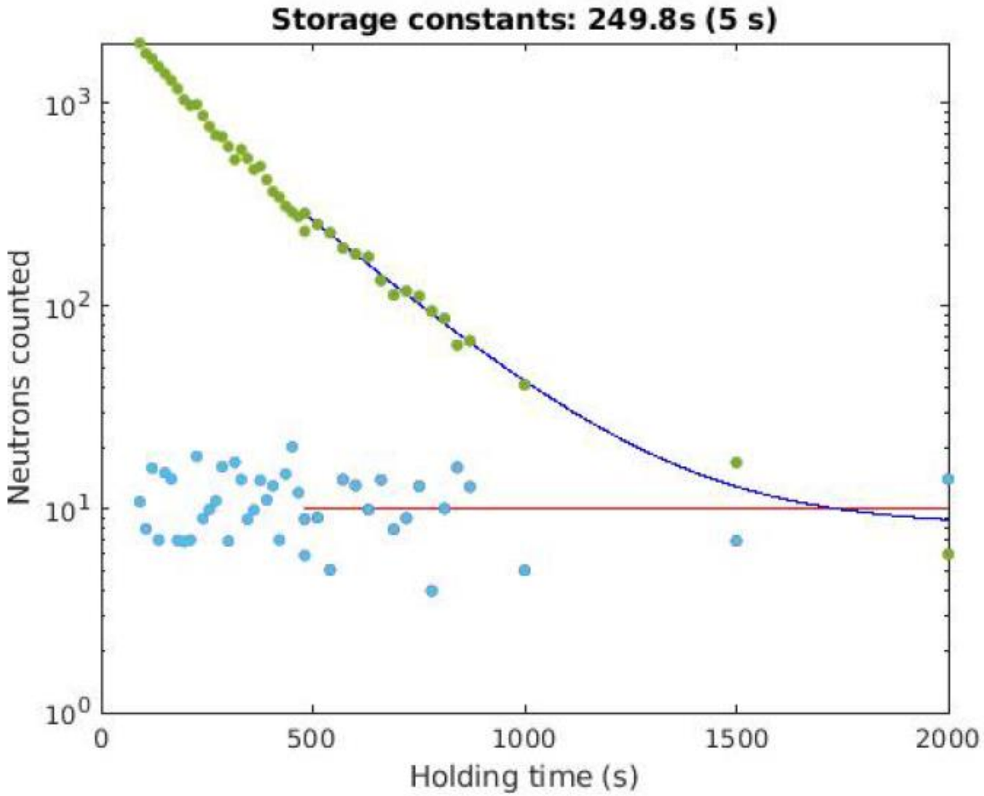
Laser spectroscopy may complement or eventually replace SQUIDS… new tools!





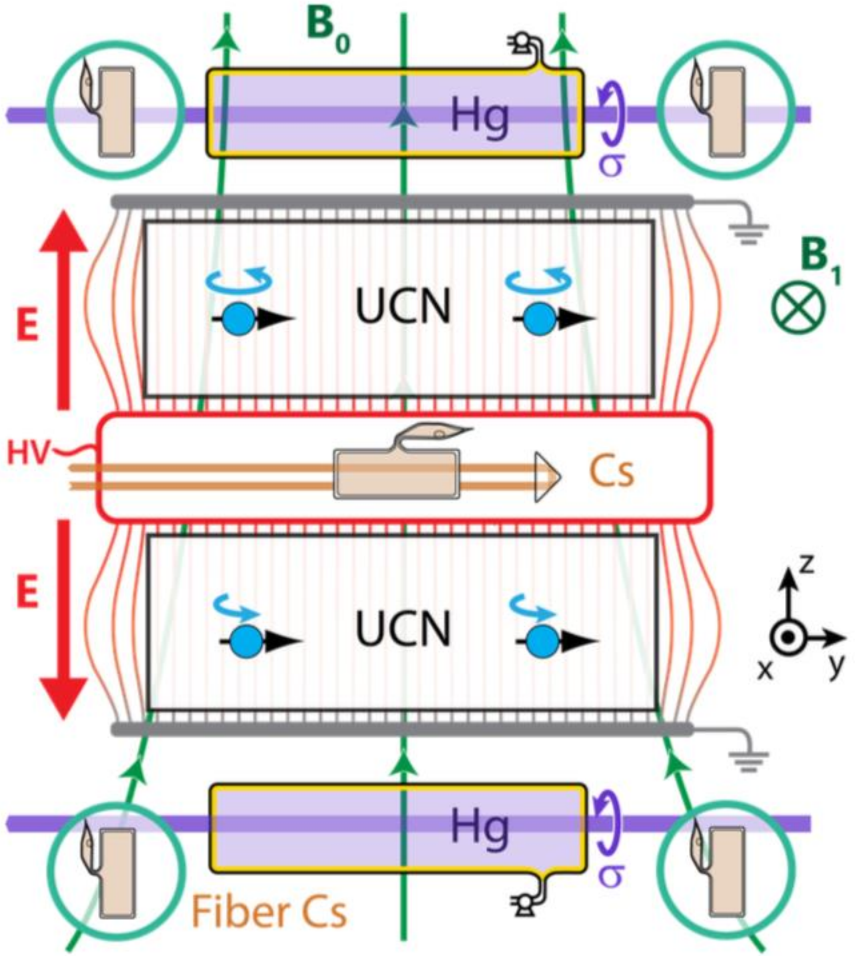
By contrast: neutrons disappear faster!





Much better at low temperature: Neulinger *et al.*, EPJA 58, 141 (2022)

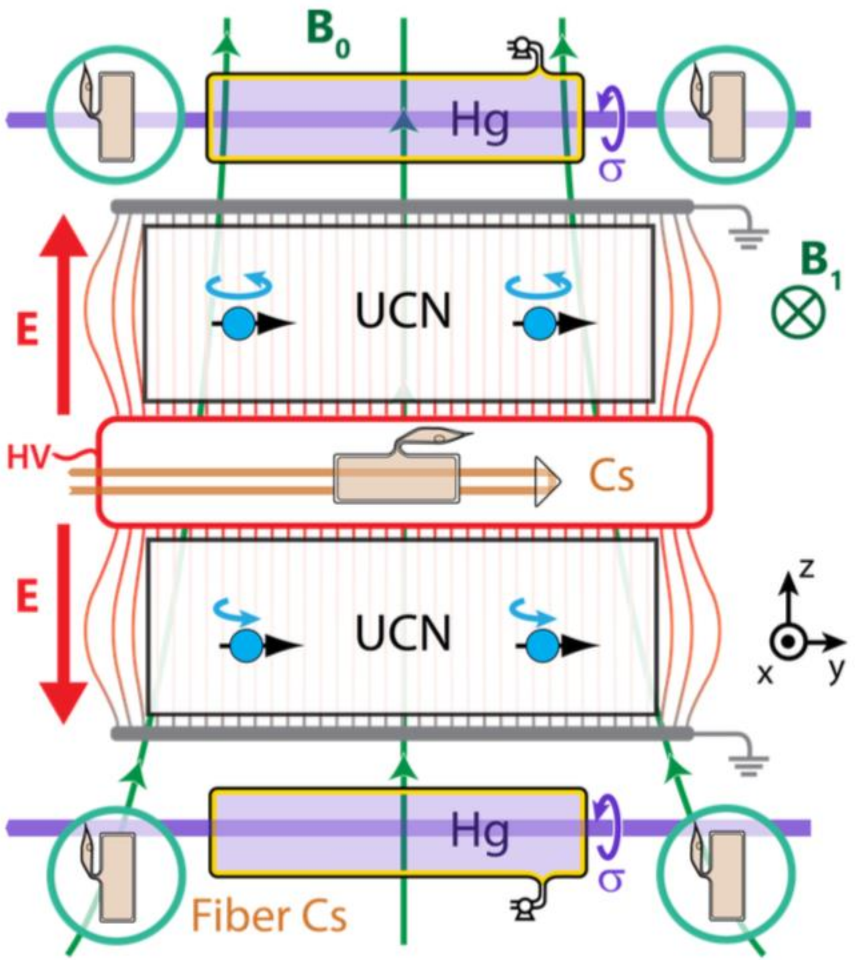
The PanEDM Experiment



- Double chamber Ramsey interferometer at room temperature (but T_{UCN} ~ 5mK)
- ^{199}Hg magnetometers with few-fT resolution
- Cs magnetometers (also at high voltage)
- Magnetic shielding factor: 6×10^{6} at 1 mHz
- Simultaneous spin detection for up/down
- SuperSUN UCN source at ILL in 2 phases:
  Phase I: unpolarized UCN with 80 neV peak
  Phase II: polarized UCN, magnetic storage
- Ongoing installation of parts, commissioning with UCN production in 2023-2024

EPJ Web of Conferences 219, 02006 (2019)

Much lower statistics!



Statistical sensitivity:

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

Frequency measurements:

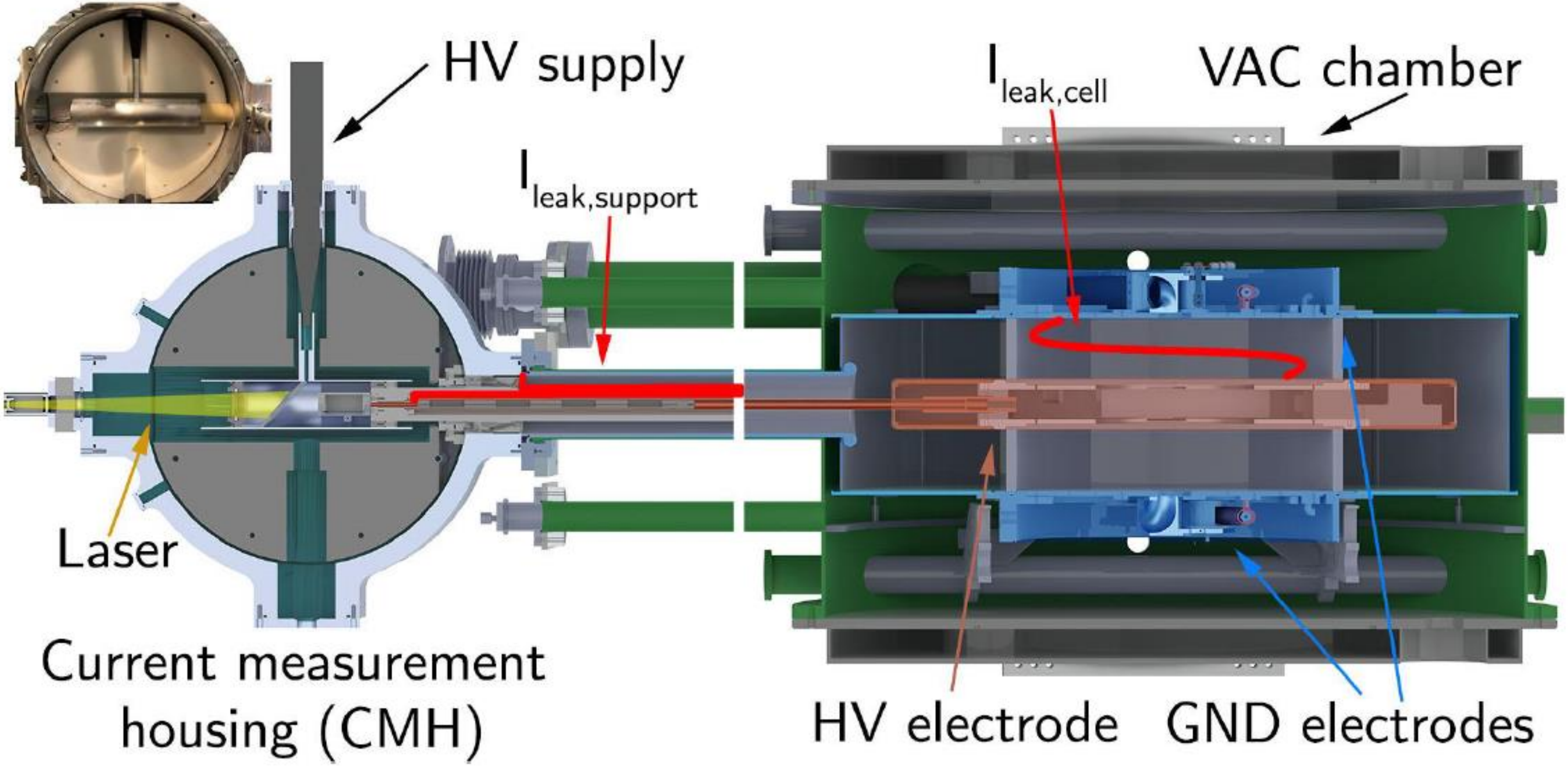
$$|\delta\omega| = \frac{|dE|}{\hbar F}$$

SuperSUN	Phase I
Saturated source density [cm^{-3}]	330
Diluted density [cm^{-3}]	63
Density in cells [cm^{-3}]	3.9
PanEDM Sensitivity [1σ, e cm]	
Per run	5.5×10^{-25}
Per day	3.8×10^{-26}
Per 100 days	3.8×10^{-27}

$$\Delta E \Delta t \geq \hbar/2$$

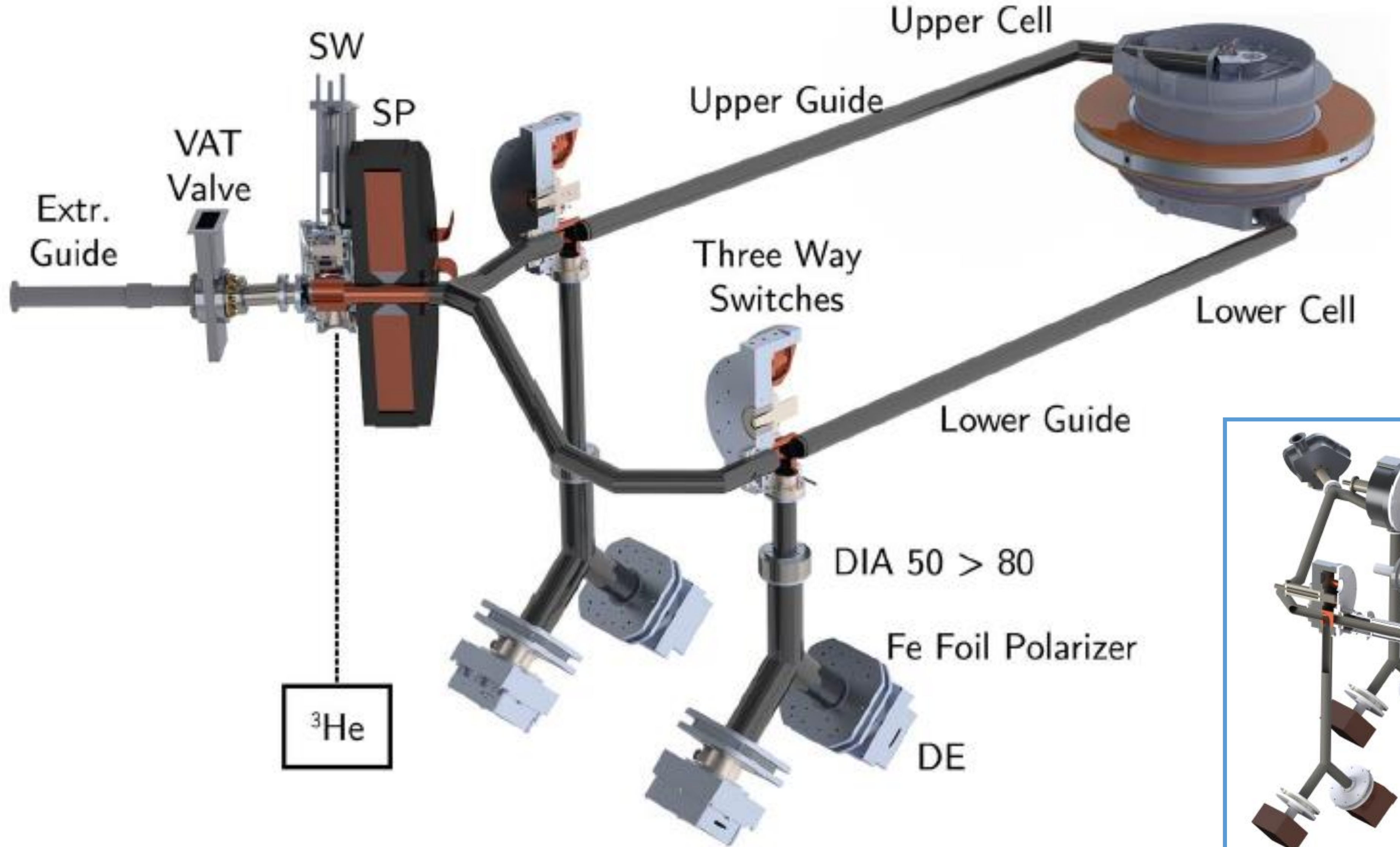
EPJ Web of Conferences 219, 02006 (2019)

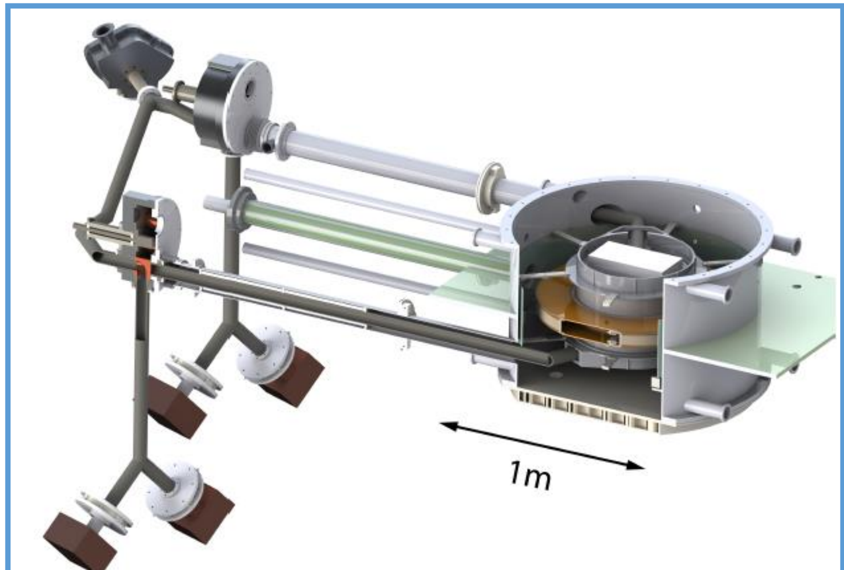
The PanEDM Experiment



D. Wurm, PhD 2021

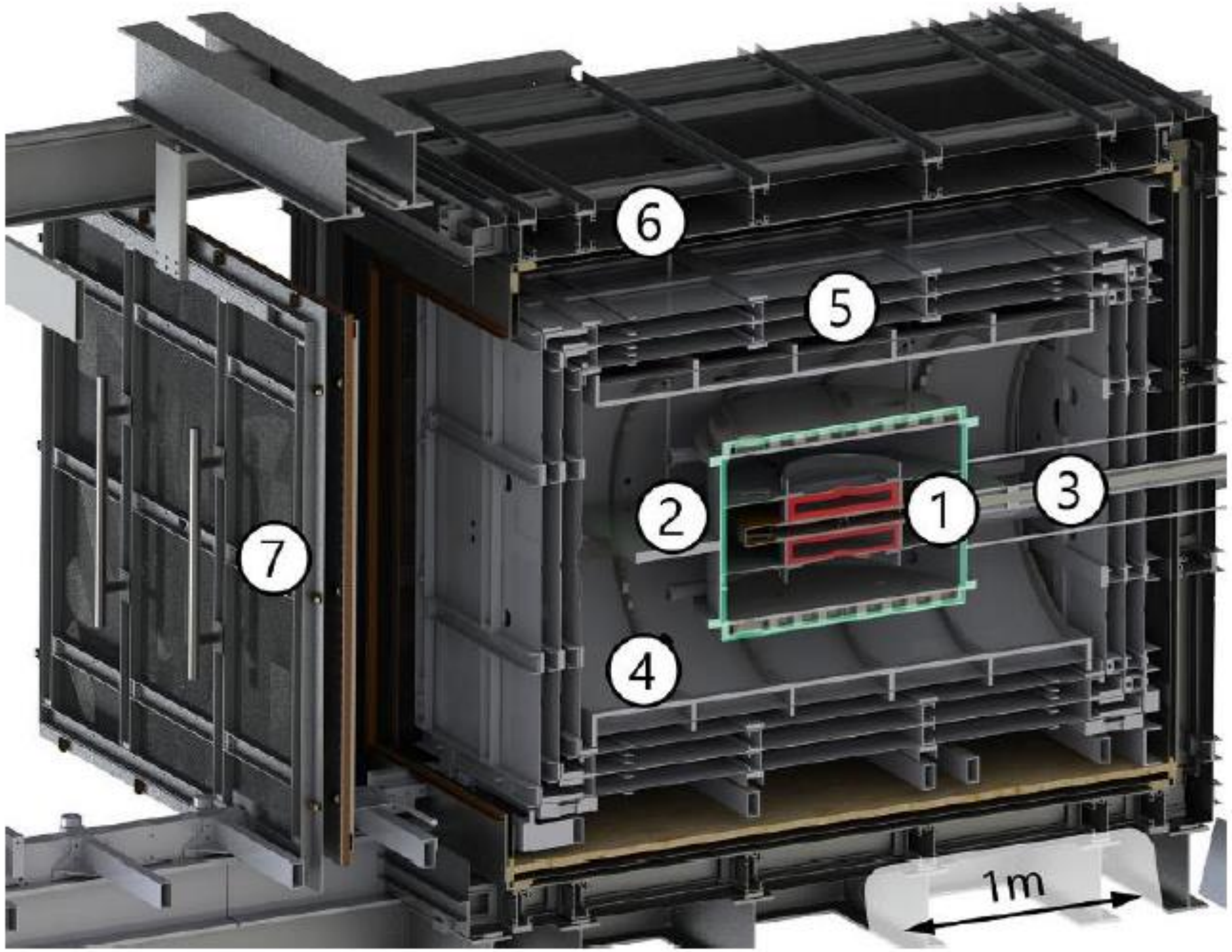
The PanEDM Experiment





D. Wurm, PhD 2021

The PanEDM Experiment

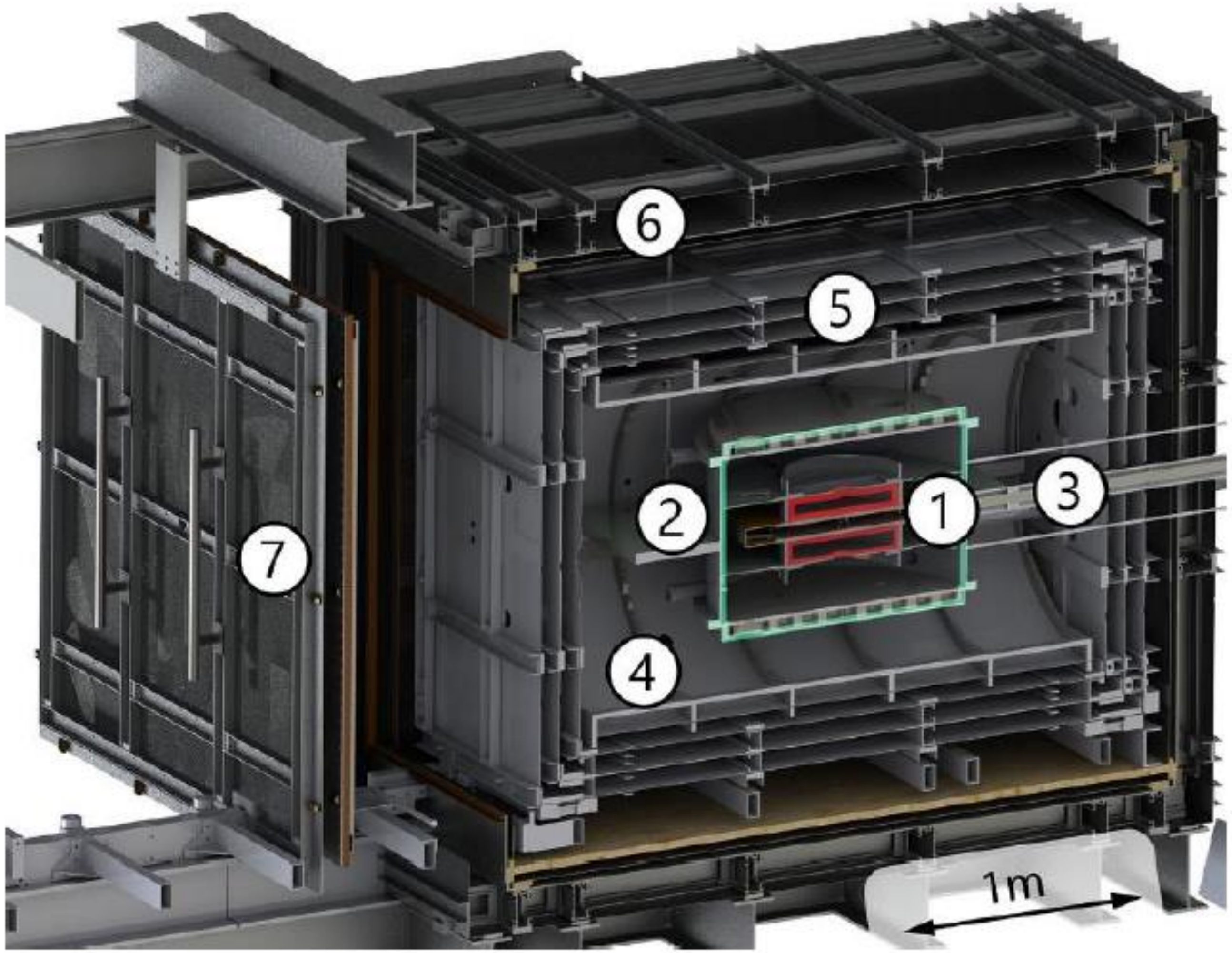


1: EDM cells
2: Vac. Chamber
3: HV feed
4: B_0 & B_1 coil
5: Inner shield
6: Outer shield
7: Outer shield door

PanEDM @ ILL, 2021

EPJ Web of Conferences 219, 02006 (2019)

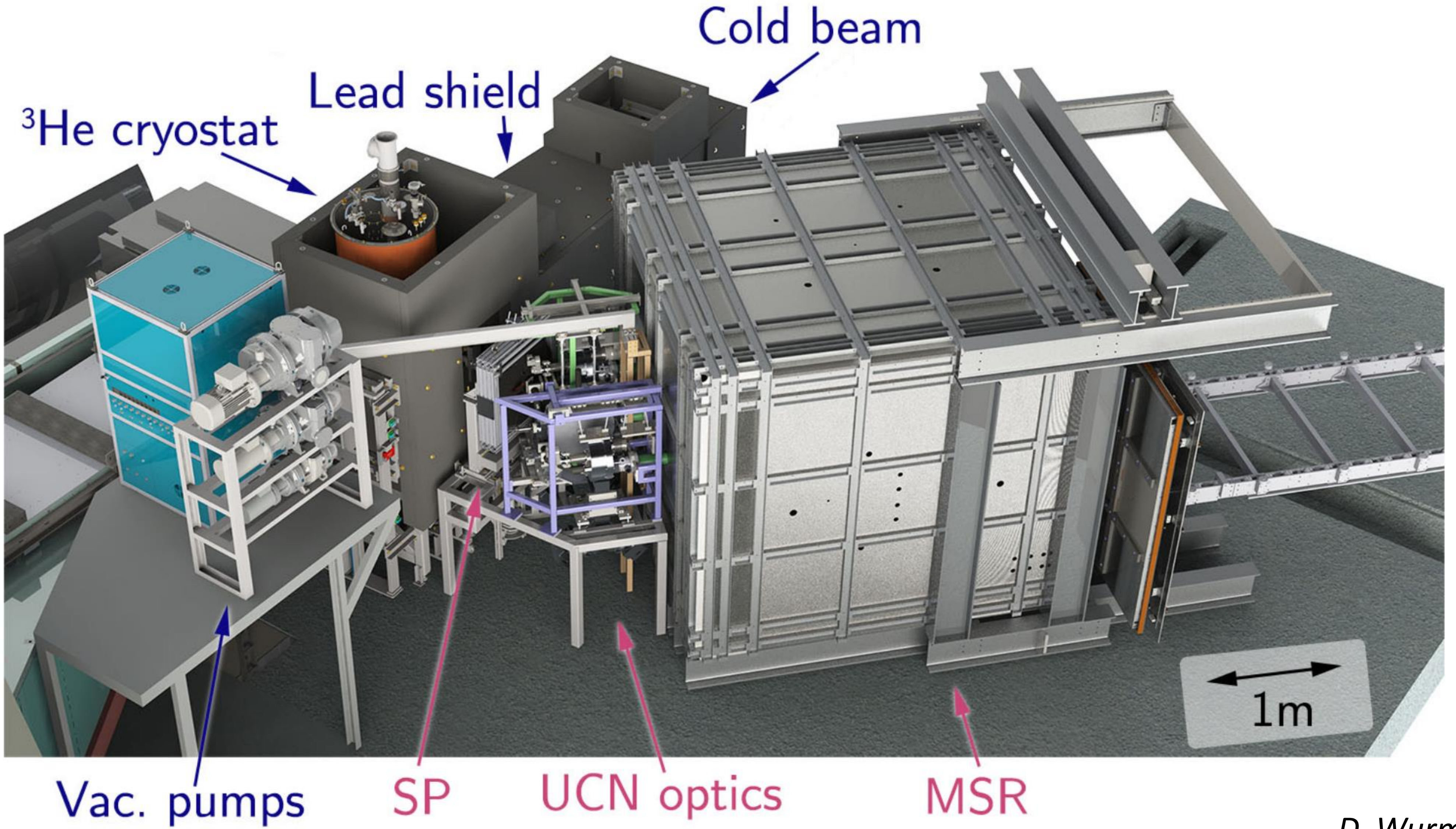
The PanEDM Experiment



Rev. Sci. Inst. 85(7), 075106 (2014)
J. Appl. Phys. 117(18), 183903 (2015)

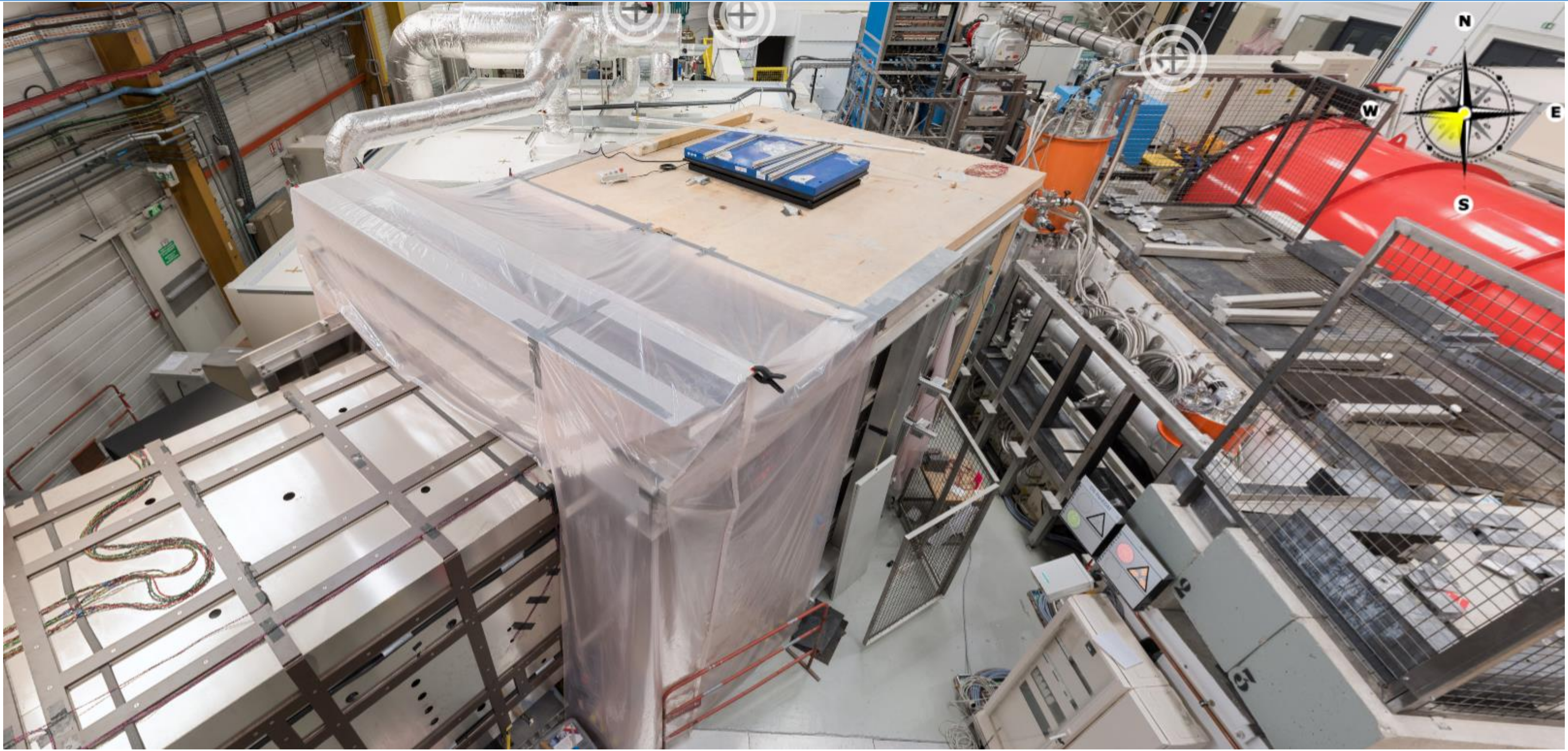
EPJ Web of Conferences 219, 02006 (2019)

The SuperSUN-PanEDM Installation

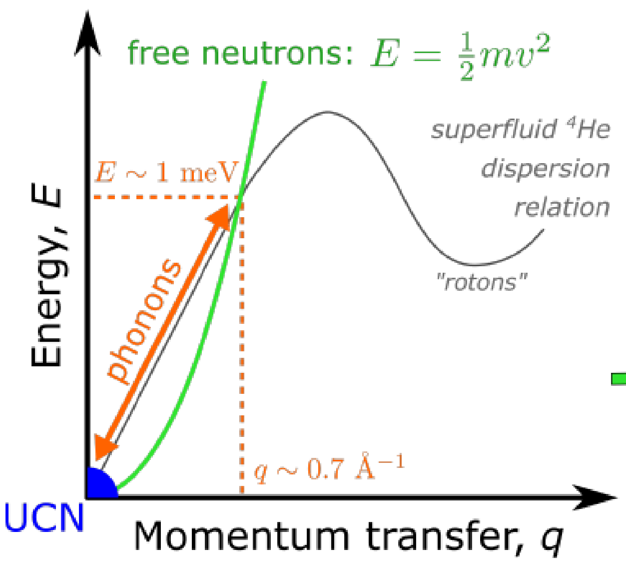


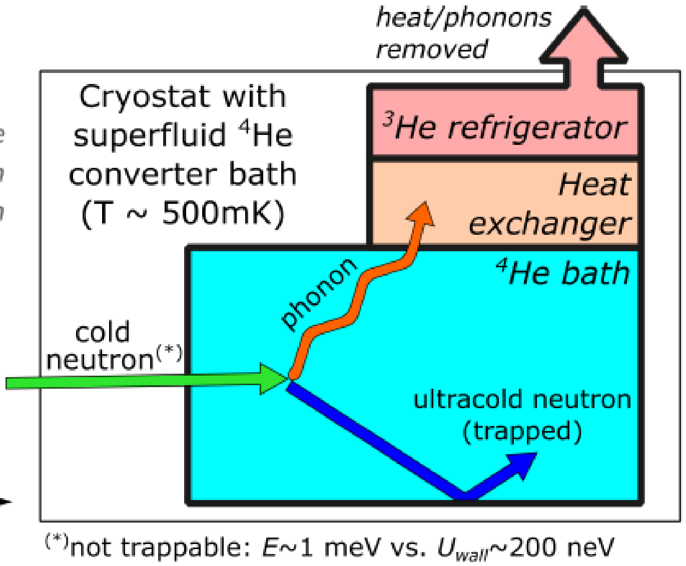
D. Wurm, PhD 2021

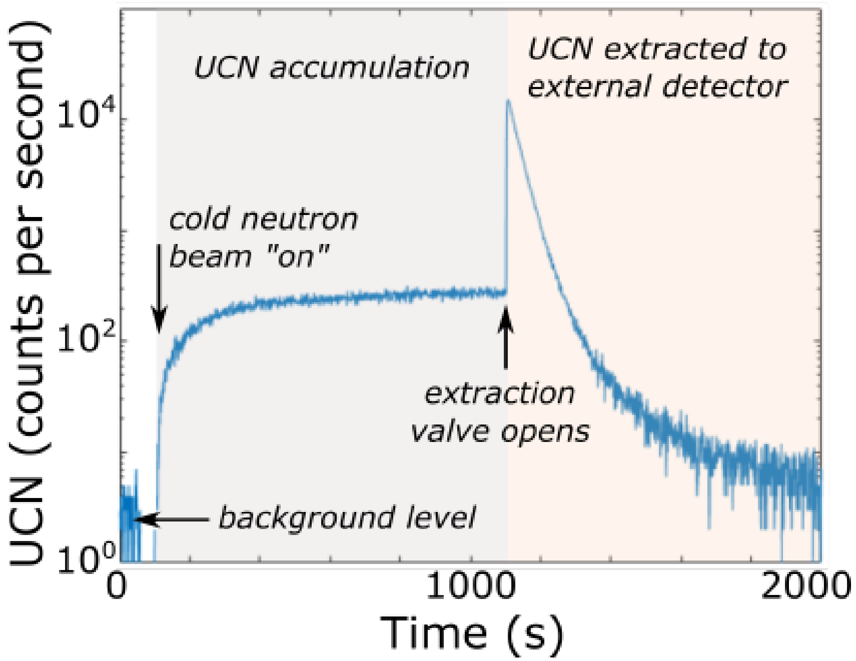
Reality always looks messier!



UCN and Production in He-II





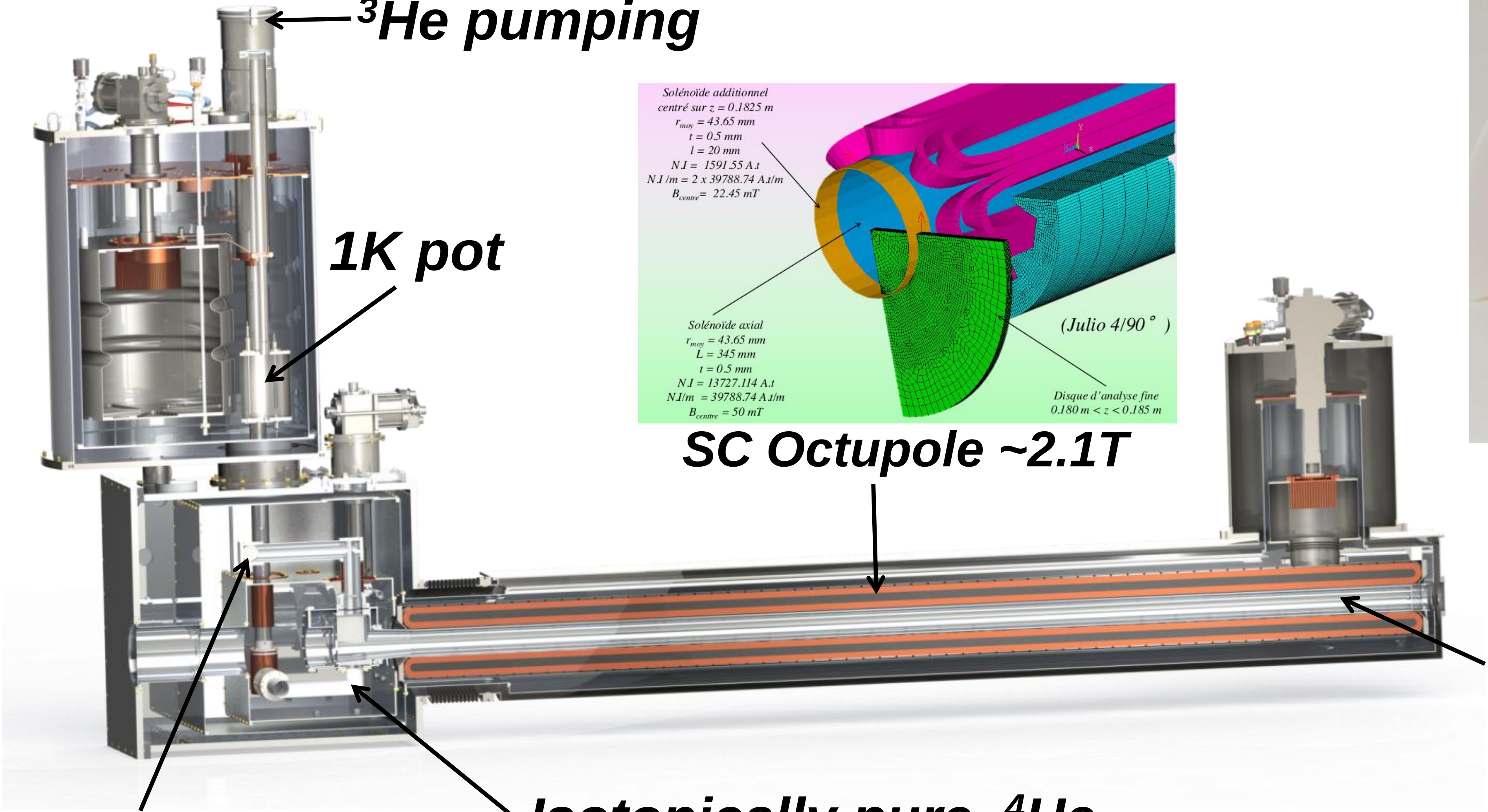


Velocity	“Temperature”	Energy
$10^0 - 10^1$ m/s	Ultracold	5 neV – 500 neV
$10^1 - 10^2$ m/s	Very cold	0.5 µeV – 50 µeV
$10^2 - 10^3$ m/s	Cold	50 µeV – 5 meV
2.2×10^3 m/s	Thermal	25 meV
$2\times10^3 - 2\times10^4$ m/s	Hot	20 meV – 2 eV

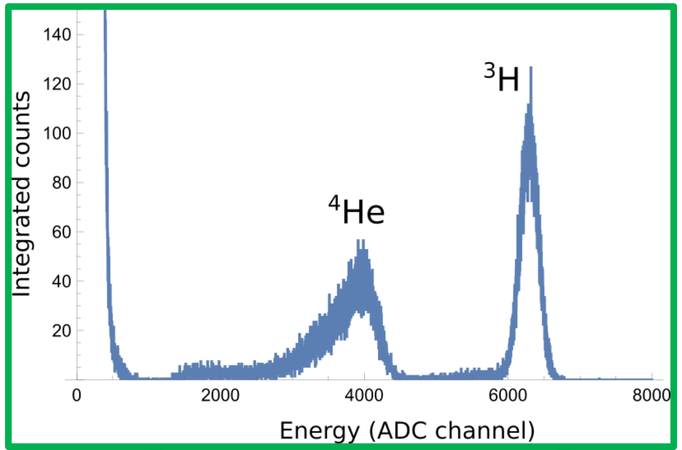
$$R \sim \left(\frac{5\times10^{-8}}{\mathrm{cm^3\ s}}\right) \times \left.\frac{d\Phi}{d\lambda}\right|_{8.9\text{Å}} \times \left(\frac{V_{\mathrm{trap}}}{233\ \mathrm{neV}}\right)^{\frac{3}{2}}$$ **production**

$$\frac{1}{\tau} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\mathrm{up}}} + \frac{1}{\tau_{\mathrm{capture}}} + \frac{1}{\tau_{\mathrm{wall}}} + \cdots$$ **loss**

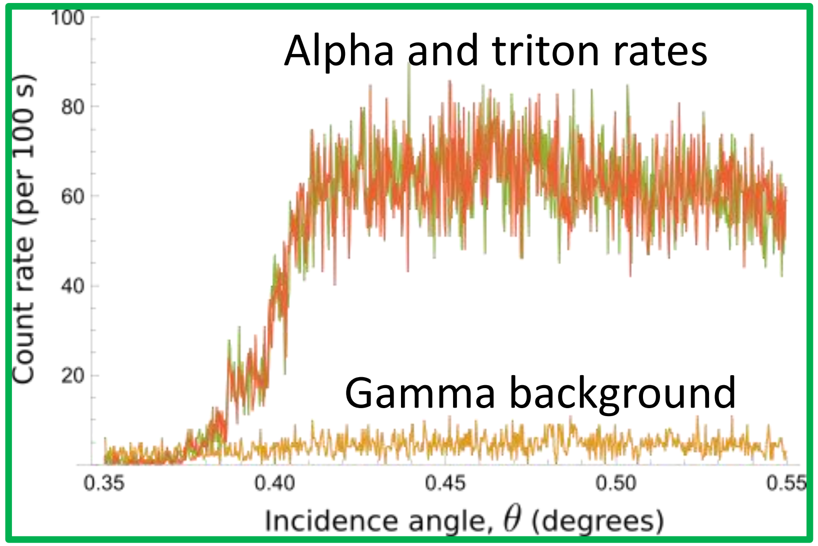
SuperSUN Neutron Source: Cutaway

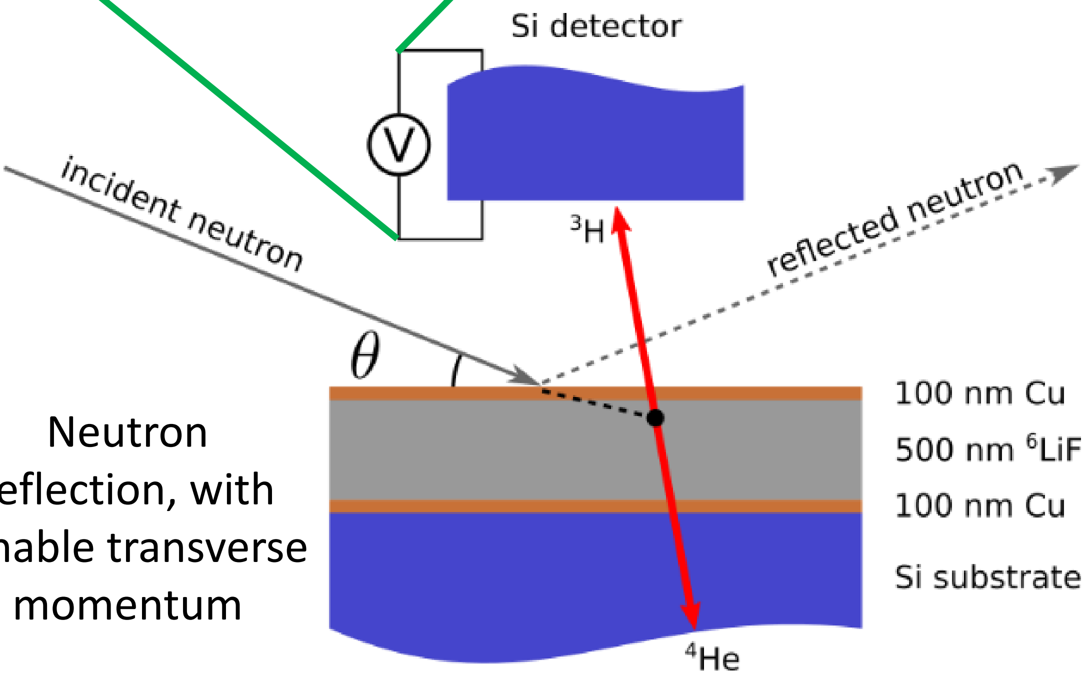


Proof-of-principle: quantum sensing

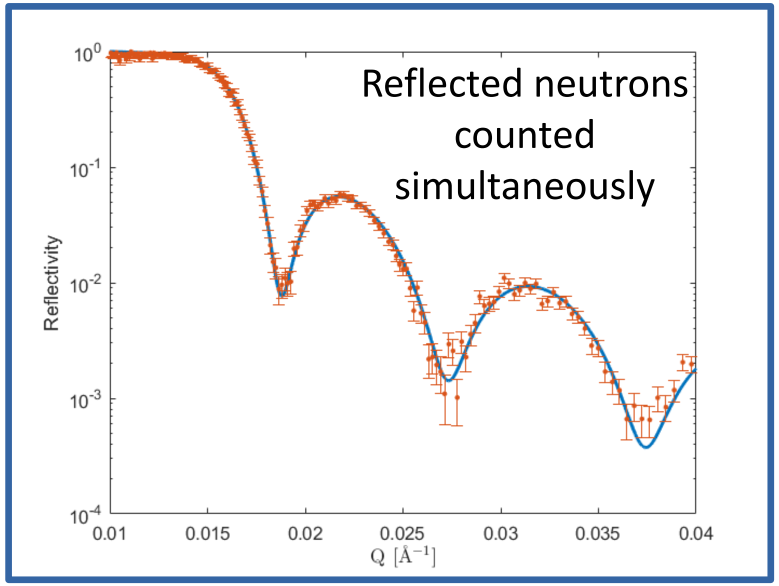


Capture products counted with Si-detector



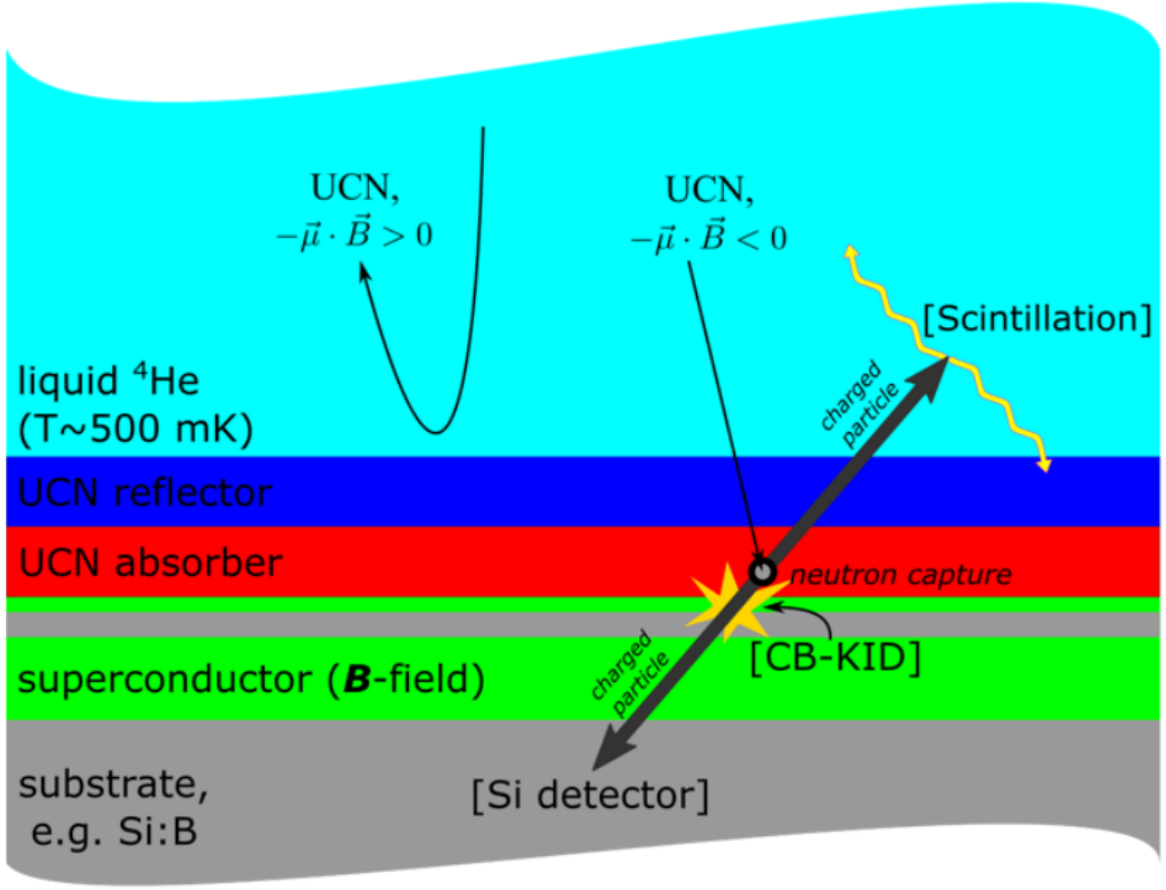


Neutron reflection, with tunable transverse momentum

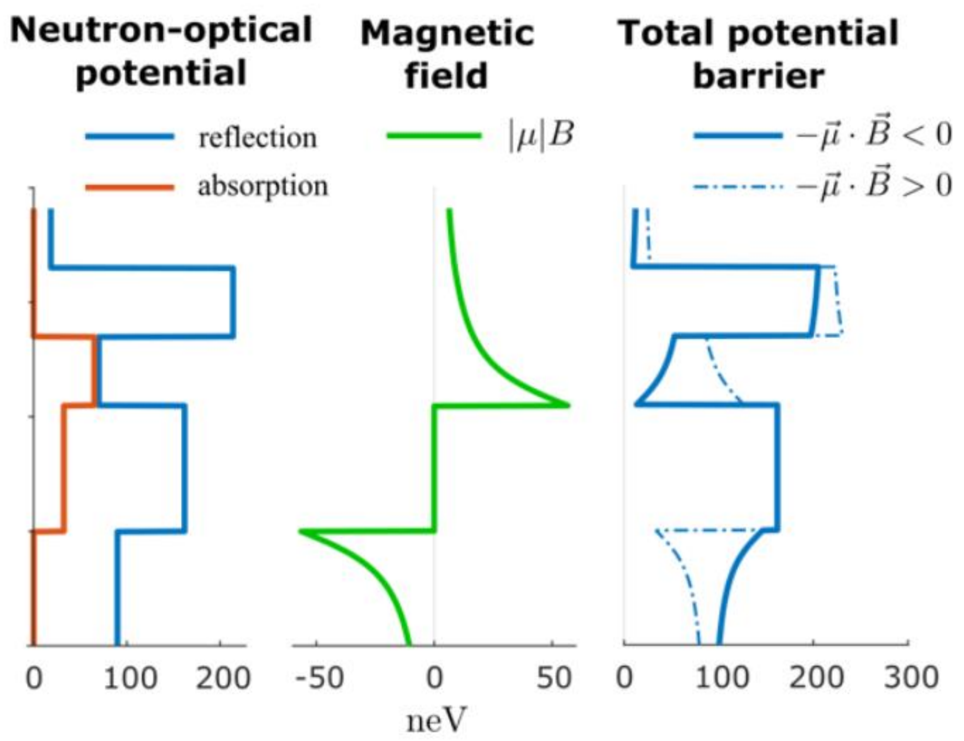


SEMINAR!

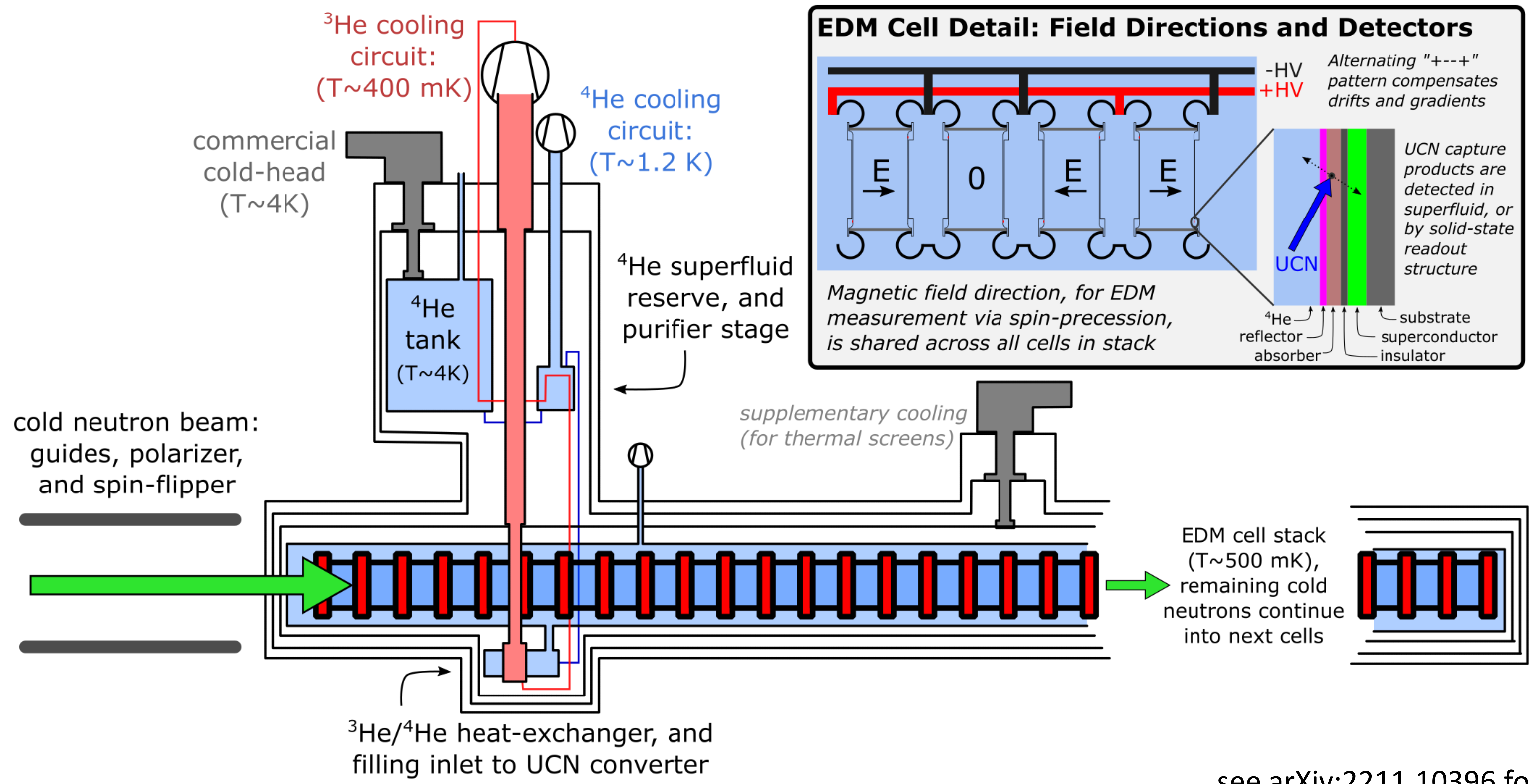
“Quantum Sensing” for Neutrons



Spin-dependent shifts of the wall potential
(magnetic field increased for visibility)

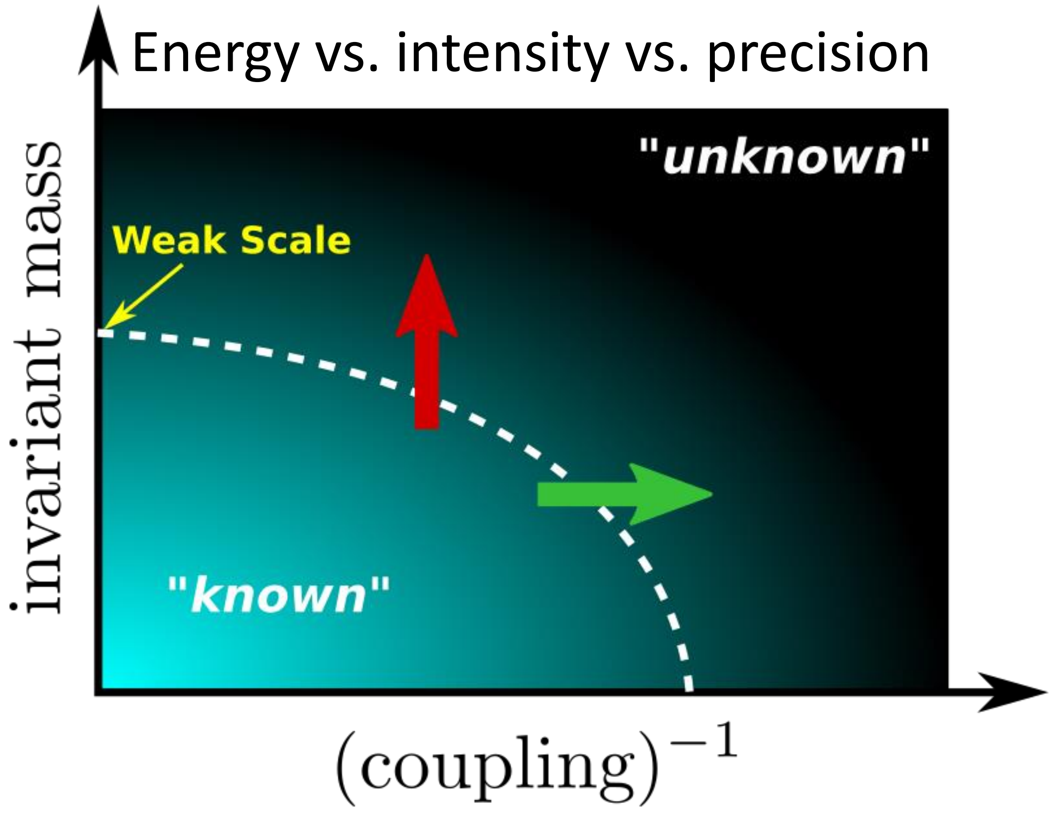


The next generation… scaling up!



…see arXiv:2211.10396 for details

Thematic Recap



1. Statistics are the first key!

2. Observation time is the second

3. … and yes, it finally makes sense to follow the green arrow!

Questions?

what-if.xkcd.com

Special thanks to:

V. Cirigliano, J. de Vries, U. Schmidt

PI mechanical workshop
PI technical design office

Institut Laue-Langevin, NPP & SANE
BNC GINA team and user support

PanEDM collaboration
HeXe collaboration

Seeking students and Post-Docs!

xkcd.com

Faddeev-Popov?

EDMs in the SM do not vanish

- CP violation from three sources (ignoring neutrinos):

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

- CKM CP-violation (Standard Model):

$$\mathcal{L}_{\text{CKM}} = -\frac{ig_2}{\sqrt{2}}\sum_{p,q} V^{pq}\bar{U}_L^p \not{W}^+ D_L^q + \text{H.c.}$$

- Strong CP-violation (Standard Model):

$$\mathcal{L}_{\bar{\theta}} = -\frac{\alpha_S}{16\pi^2}\bar{\theta}\text{Tr}(G^{\mu\nu}\tilde{G}_{\mu\nu})$$

details:

Rev. Mod. Phys. ***91****, 015001 (2019)*
Phys. Rev. C ***91****, 035502 (2015)*
Prog. Part. Nucl. Phys. ***71****, 21 (2013)*

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details:

Rev. Mod. Phys. ***91****, 015001 (2019)*

Phys. Rev. C ***91****, 035502 (2015)*

Prog. Part. Nucl. Phys. ***71****, 21 (2013)*

*recently called into question: arXiv:2205.15093, 2001.07152, 1912.03941, 2106.11369

Effective Field Theory for EDMs

General Effective Lagrangian:

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Global Analysis: T. Chupp, M. Ramsey-Musolf
Rev. Mod. Phys. ***91**, 015001 (2019)*
Phys. Rev. C ***91**, 035502 (2015)*

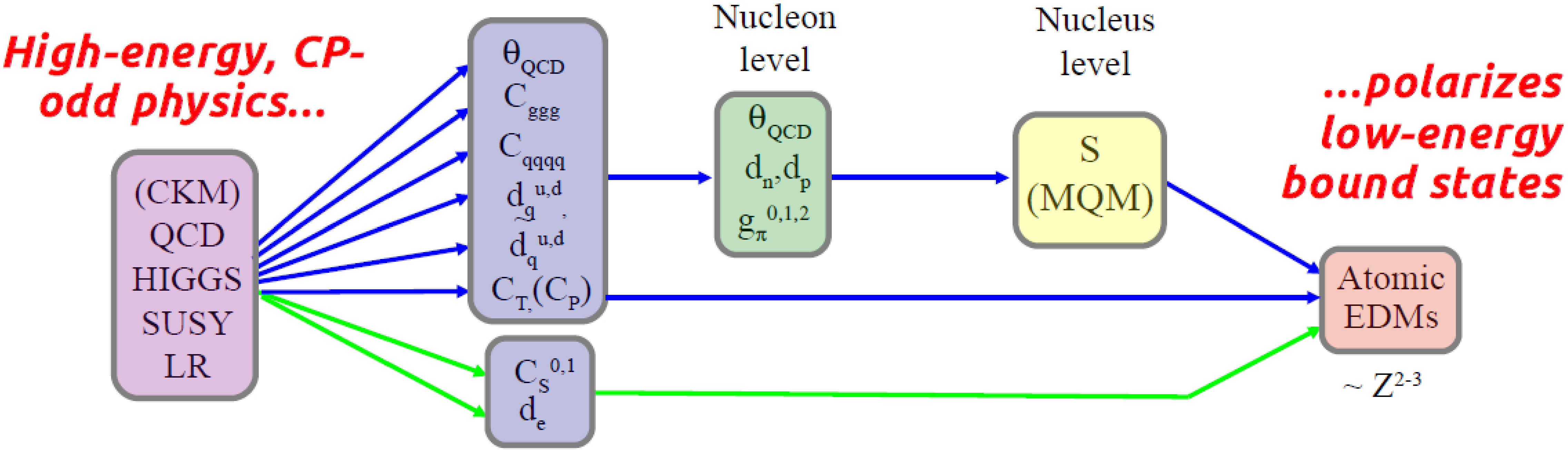
Dimension-Six terms for the neutron:

$$\mathscr{L}_{\text{eff}}^{(6)} = -\frac{i}{2} \sum_{l,q} d_q \bar{q} \sigma_{\mu\nu} \gamma^5 F^{\mu\nu} q - \frac{i}{2} \sum_q \tilde{d}_q g_s \bar{q} \sigma_{\mu\nu} \gamma^5 G^{\mu\nu} q + d_W \frac{g_s}{6} G \tilde{G} G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

Prog. Part. Nucl. Phys. ***71**, 21 (2013)*

Wilson coefficient	Operator (dimension)	Number
$\bar{\theta}$	Theta term (4)	1
δ_e	Electron EDM (6)	1
$\mathrm{Im}\, C_{\ell equ}^{(1,3)}$, $\mathrm{Im}\, C_{\ell eqd}$	Semi-leptonic (6)	3
δ_q	Quark EDM (6)	2
$\tilde{\delta}_q$	Quark chromo EDM (6)	2
$C_{\tilde{G}}$	Three-gluon (6)	1
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	Four-quark (6)	2
$\mathrm{Im}\, C_{\varphi ud}$	Induced four-quark (6)	1
Total		13

Interpreting EDM bounds



neutron: $\bar{d}_n^{sr},\ \bar{g}_\pi^{(0)},\ (\ \bar{g}_\pi^{(1)})$

diamagnetic: $\bar{g}_\pi^{(0,1)},\ C_T^{0,1}$

paramagnetic: $d_e,\ C_S^{(0)}$

$$\mathcal{L}_{\pi NN} = \bar{N}\left[\bar{g}^{(0)}_{\pi NN}\vec{\tau}\cdot\vec{\pi} + \bar{g}^{(1)}_{\pi NN}\pi^0 + \bar{g}^{(2)}_{\pi NN}(3\tau_3\pi^0 - \vec{\tau}\cdot\vec{\pi})\right] N$$

$$\mathcal{L}_T = \frac{8G_F}{\sqrt{2}}\bar{e}\sigma^{\mu\nu}e v_\nu \bar{N}\left[C_T^{(0)} + C_T^{(1)}\tau_3\right] S_\mu N$$

$$\mathcal{L}_S = -\frac{G_F}{\sqrt{2}}\bar{e}i\gamma_5 e\ \bar{N}\left[C_S^{(0)} + C_S^{(1)}\tau_3\right] N$$

It's not so simple after all…

- ***Schiff's theorem:*** the field due to an EDM induces a displacement of the bound charges, which exactly cancels it*

$$H_0 = \sum \frac{p^2}{2m} + U(\mathbf{r})$$

Hamiltonian of the charge-system (no EDM)

Schiff: Phys. Rev. **132, 2194 (1963)*
J. Engel: elegant formulation used here

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$$\boxed{H_0 = \sum \frac{p^2}{2m} + U(\mathbf{r})}$$

Add constituent EDMs
As a perturbation…

$$\boxed{\mathbf{d}_{\mathrm{tot}} = \sum_i \mathbf{d}_i}$$

(sum over constituents)

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$$\begin{aligned} H &= H_0 - \sum \mathbf{d} \cdot \mathbf{E} \\ &= H_0 + \sum \mathbf{d} \cdot \frac{\nabla U(\mathbf{r})}{q} \\ &= H_0 + \sum \frac{i}{q} [\mathbf{d} \cdot \mathbf{p}, H_0] \end{aligned}$$

Now see what effect this has…

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Eigenstates receive an energy shift due to the perturbation:

$$\begin{aligned} |0\rangle \rightarrow |\tilde{0}\rangle &= |0\rangle + \sum_n \frac{|n\rangle \langle n| \sum \frac{i}{q} \left[\mathbf{d} \cdot \mathbf{p}, H_0\right] |0\rangle}{E_0 - E_n} \\ &= \left(1 + \sum \frac{i}{q} \mathbf{d} \cdot \mathbf{p}\right) |0\rangle \end{aligned}$$

It’s not so simple after all…

- What is the total, observable, dipole moment after this shift?

$$
\begin{aligned}
\tilde{\mathbf{d}} &= \sum \mathbf{d} + \langle \tilde{0} | \sum q\mathbf{r} \, | \tilde{0} \rangle \\
&= \sum \mathbf{d} + \langle \tilde{0} | \left(1 - \sum \frac{i}{q} \mathbf{d} \cdot \mathbf{p} \right) \sum q\mathbf{r} \left(1 + \sum \frac{i}{q} \mathbf{d} \cdot \mathbf{p} \right) | \tilde{0} \rangle \\
&= \sum \mathbf{d} + i \, \langle 0 | \left[\sum q\mathbf{r}, \sum \frac{1}{q} \mathbf{d} \cdot \mathbf{p} \right] | 0 \rangle \\
&= \sum \mathbf{d} - \sum \mathbf{d} \\
&= 0
\end{aligned}
$$

But some details can save us!

- Schiff's theorem assumes:

  - pointlike particles $\longrightarrow$ *incorrect for nuclei*

$$\boldsymbol{S} = \frac{1}{10}\left\langle r^2 \boldsymbol{d}\right\rangle - \frac{1}{6Z}\left\langle r^2\right\rangle \left\langle \boldsymbol{d}\right\rangle$$

…see Prog. Part. Nucl. Phys. **71**, 21 (2013)

  - non-relativistic treatment $\longrightarrow$ *incorrect for atomic electrons*

$$U_{\text{lab}} = -\boldsymbol{d}_{\text{lab}} \cdot \boldsymbol{E} = -\boldsymbol{d}_{\text{rest}} \cdot \boldsymbol{E} + \frac{\gamma}{1+\gamma}(\boldsymbol{\beta} \cdot \boldsymbol{d})(\boldsymbol{\beta} \cdot \boldsymbol{E})$$

…see American Journal of Physics **75**, 532 (2007)

A Key Systematic Effect

2

Motional magnetic field: $$\boldsymbol{B} = \frac{1}{c^2}\boldsymbol{E} \times \boldsymbol{v}$$

Magnetic field gradients: $$\boldsymbol{B}_\perp = -\frac{\boldsymbol{R}}{2}\frac{\partial B_z}{\partial z}$$

Leading false EDM effect at 2$^{\text{nd}}$ order:

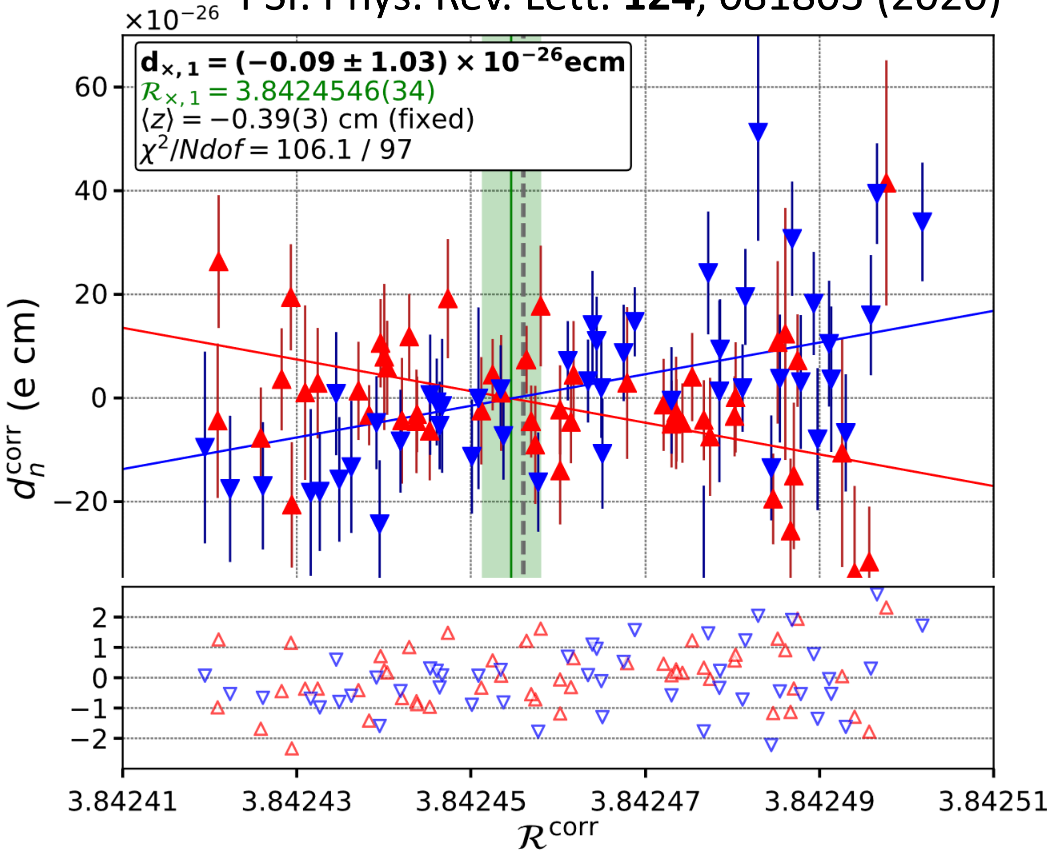
$$d_{\text{false}}^{(\text{slow})} = -\frac{\hbar}{4c^2}\left(\frac{v_\perp}{B_z}\right)^2 \frac{\partial B_z}{\partial z}$$

Adiabatic (UCN)

$$d_{\text{false}}^{(\text{fast})} = -\frac{\hbar}{8c^2}\gamma^2 R^2 \frac{\partial B_z}{\partial z}$$

Diabatic (atomic magnetometer)

PSI: Phys. Rev. Lett. **124**, 081803 (2020)



$$\mathcal{R}^{\text{corr}} = \left|\frac{\gamma_{\text{UCN}}}{\gamma_{\text{Hg}}}\right| \frac{1 + \delta_T + \delta_{\text{Earth}} + \delta^{\text{EDM}} + \delta_{\text{false}}^{\text{EDM}} + \cdots}{1 + \delta_T + \delta_{\text{Earth}}}$$

Baryon asymmetry

Consider

$$p + \bar{p} \leftrightarrow \gamma + \gamma$$

$$\eta_p = \frac{n_p - n_{\bar{p}}}{n_\gamma}$$

Threshold energy/temperature:

$$T \gg \frac{2\ \mathrm{GeV}}{k_\mathrm{B}} \sim 2 \times 10^{13}\ \mathrm{K}$$

After freeze-out:

$$n_\gamma = \int_0^\infty \frac{d\omega}{c^3\pi^2} \frac{\omega^2}{e^{\frac{\hbar\omega}{k_\mathrm{B}T}} - 1} = 16\pi \left(\frac{k_\mathrm{B}T}{hc}\right)^3 \zeta(3)$$

Statistics of the photon gas

$$N_\gamma = \int d\omega \frac{g(\omega)}{e^{\frac{\hbar\omega}{k_\mathrm{B}T}} - 1}$$

$$g(\omega) = \frac{V\omega^2}{c^3\pi^2}$$

$$\langle E \rangle = \int_0^\infty \hbar\omega \frac{g(\omega)}{e^{\frac{\hbar\omega}{k_\mathrm{B}T}} - 1}$$

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$$\boxed{\frac{1}{T} = \left(\frac{\partial S}{\partial E}\right)_V}$$

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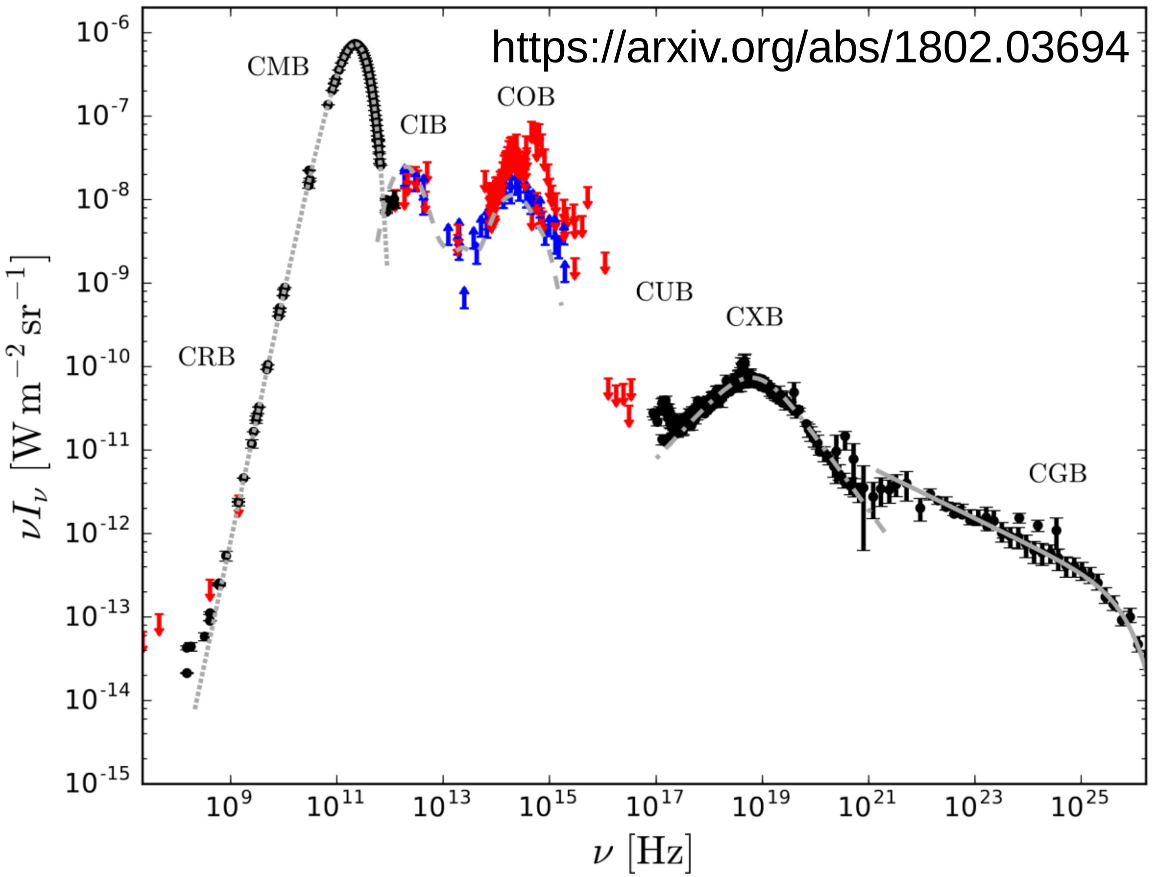

Photons:	**411 / cm^3**	**(observed)**
Protons:	**10 / m^3**	**(predicted**
	0.2 / m^3	**(observed)**