Tests of discrete symmetries at low energies

DISCRETE 2022, Baden-Baden, 10 November 2022

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Low-Energy Precision Physics

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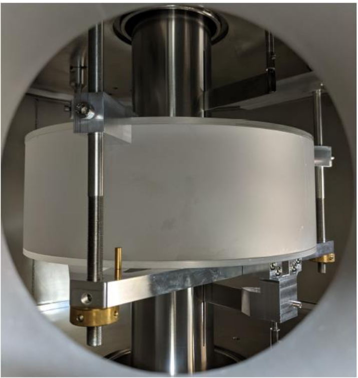

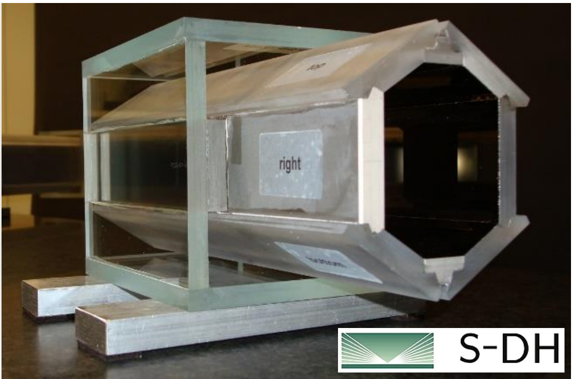

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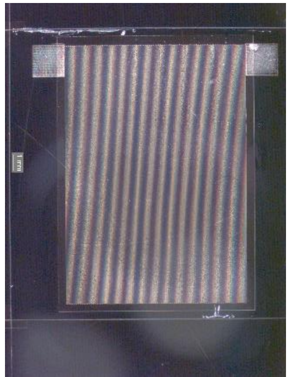
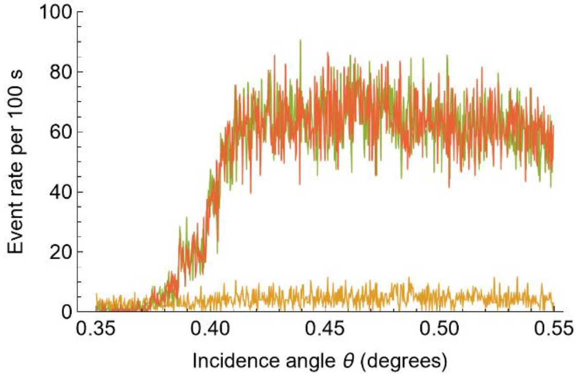
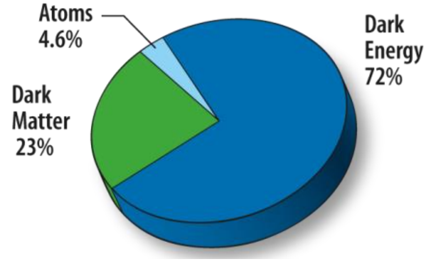




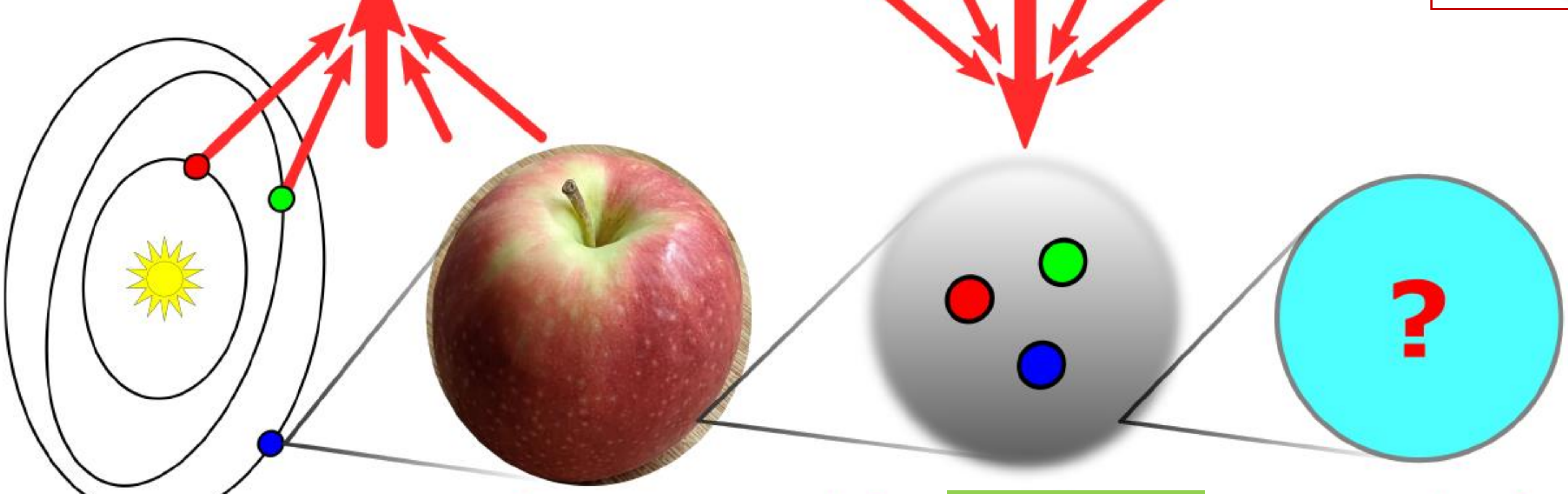
Our motivation, and a sense of scale

The Universe in a pie:



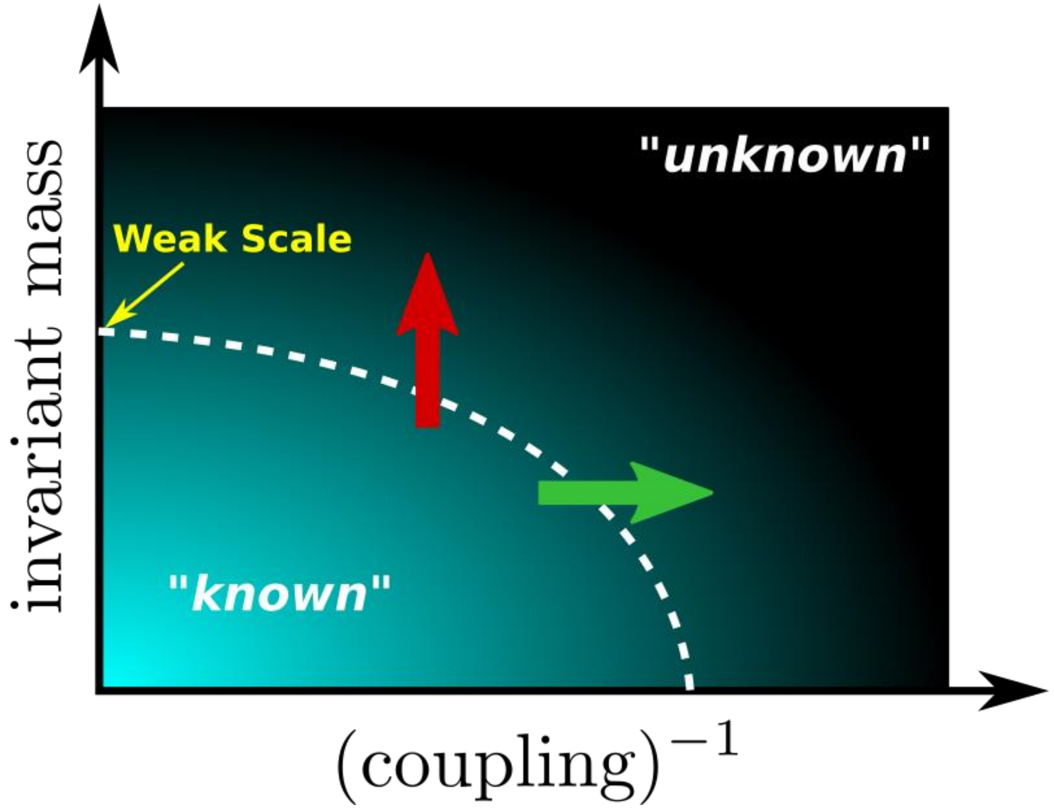
all the matter in the universe

all the ways it could get here



→ atoms → nuclei → neutrons → new physics

Focus: hadronic/nuclear EDMs



① Complementarity

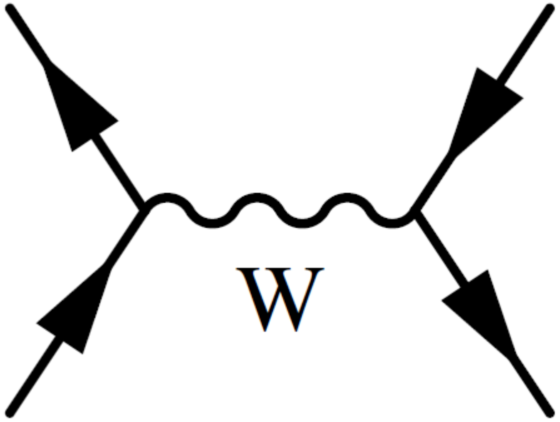
② Xenon

③ Neutron

Motivating low-energy searches

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



$$\frac{-i}{k^2 \underset{\substack{\uparrow \\ \text{“resonance”}}}{-} m_W^2}\left(g_{\mu\nu} - \frac{k_\mu k_\nu}{\underset{\substack{\uparrow \\ \text{“high energy”}}}{m_W^2}}\right) \sim \frac{1}{\underset{\substack{\uparrow \\ k\approx 0}}{m_W^2}}$$

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

New Physics, in Familiar Terms

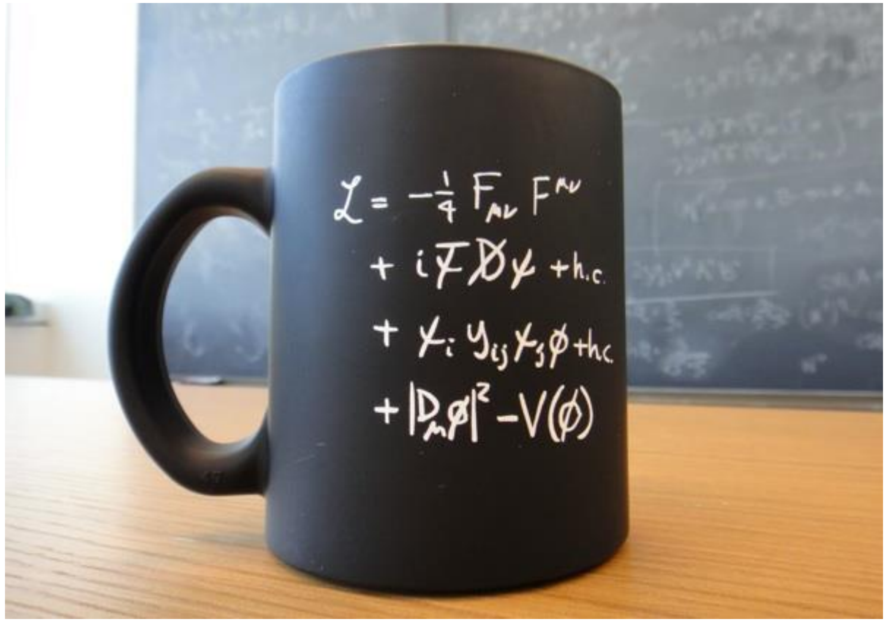
①

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

$\downarrow$ **MDM**

$\downarrow$ **EDM**

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



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MDM

EDM

Naïve estimate for generic new physics:

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

Current limit (neutron): 10^{-26} *e* cm

$\longrightarrow$ $\Lambda \sim 10 - 100\ \text{TeV}$

Standard Model CKM: 10^{-32} *e* cm

$\longrightarrow$ Insufficient for baryogenesis

Standard Model QCD: [???]

$\longrightarrow$ $d_n \approx (10^{-16}\ e\ \text{cm})\bar{\theta}$

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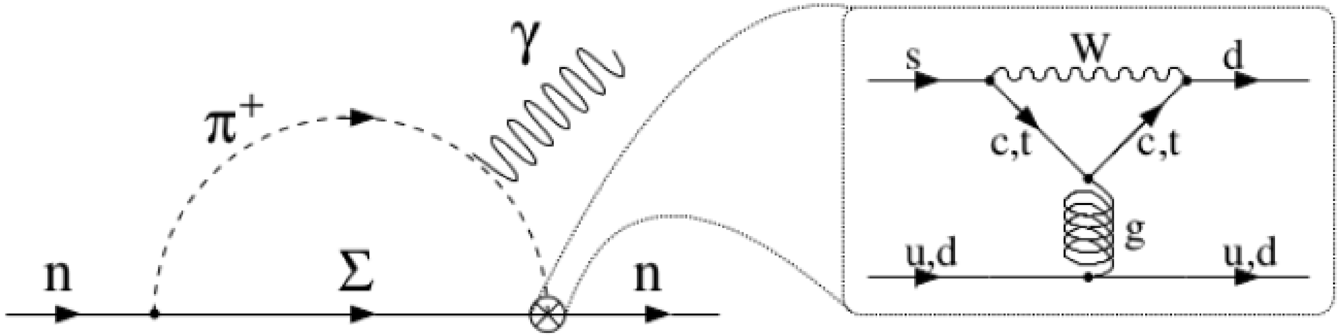
MDM

EDM

Neutron EDM from CP-violating pion couplings:



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

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A Taxonomy of Form Factors*

①

*which are not just for composite particles!

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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

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EDMs in the SM do not vanish

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- CP violation from three sources (ignoring neutrinos):

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

- CKM CP-violation (Standard Model):

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

- 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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*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:

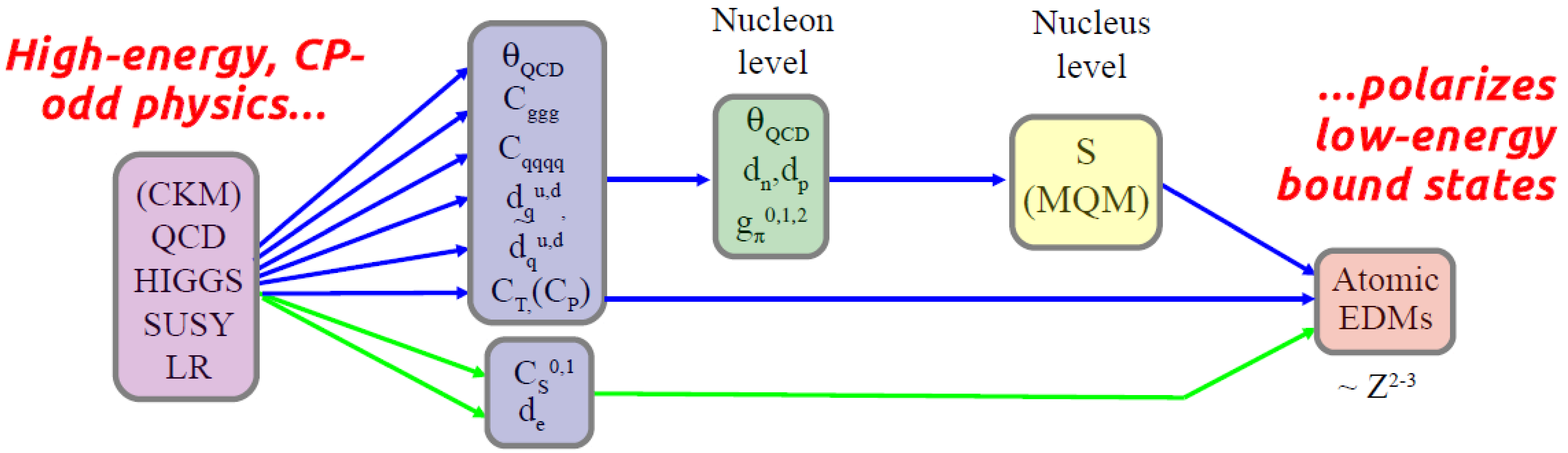
$$\mathscr{L}_{\text{eff}}^{(6)} = -\frac{i}{2}\sum_{l,q} d_q \bar{q}\sigma_{\mu\nu}\gamma^5 F^{\mu\nu} q - \frac{i}{2}\sum_q \tilde{d}_q g_s \bar{q}\sigma_{\mu\nu}\gamma^5 G^{\mu\nu} q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

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

Wilson coefficient	Operator (dimension)	Number
$\bar{\theta}$	Theta term (4)	1
δ_e	Electron EDM (6)	1
$\text{Im}\, C_{\ell equ}^{(1,3)}$, $\text{Im}\, C_{\ell eqd}$	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
$\text{Im}\, C_{quqd}^{(1,8)}$	Four-quark (6)	2
$\text{Im}\, C_{\varphi ud}$	Induced four-quark (6)	1
Total		13

Interpreting EDM bounds

①



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

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

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

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

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

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

Many Parameters / Many Experiments

①

Sensitivity: System:	**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), …

“Global analysis” (hadronic/nuclear)

①

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

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

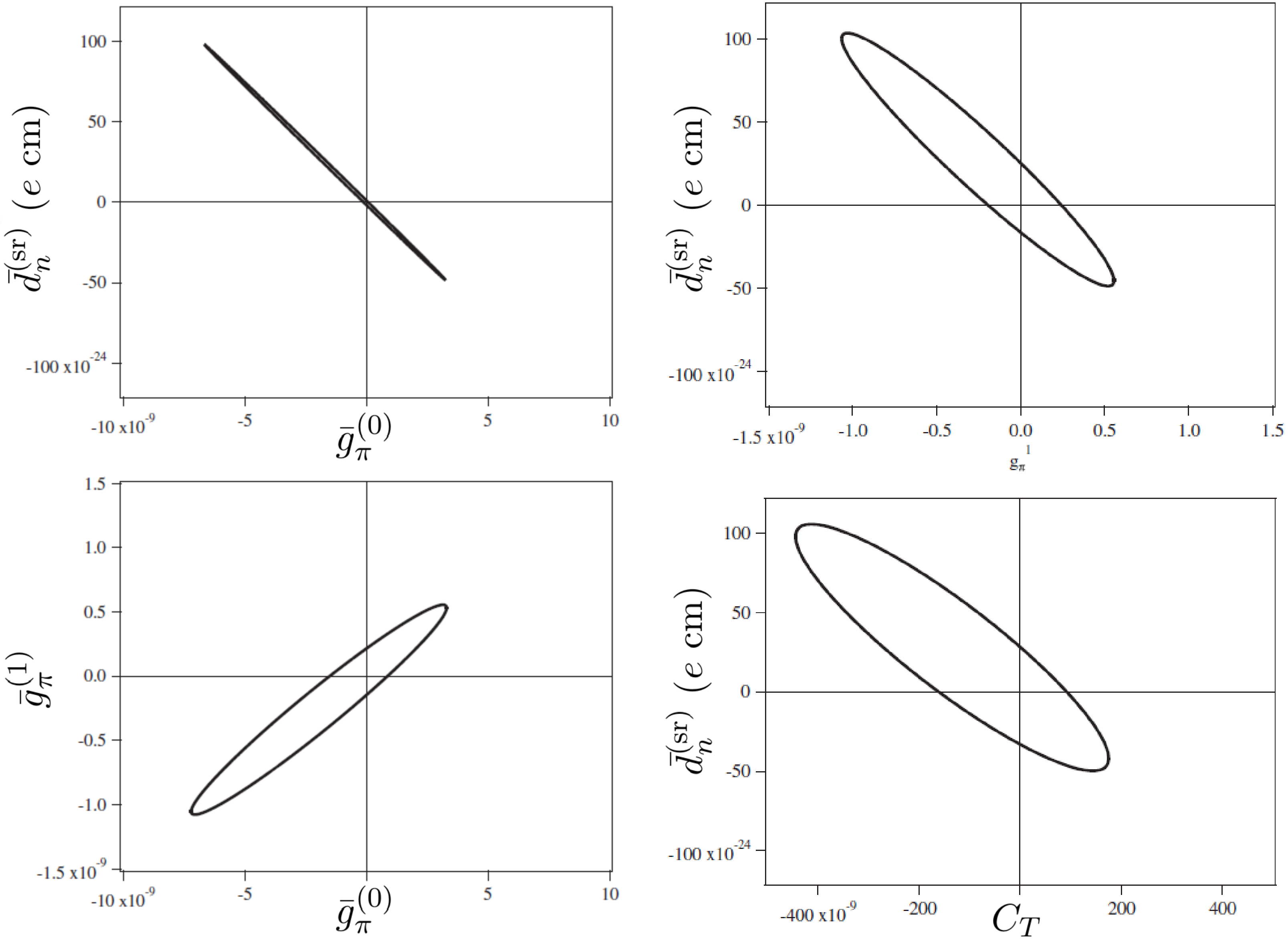
$$\alpha_{ij} = \begin{array}{ccccc} d_{\mathrm{n}} & d_{\mathrm{Xe}} & d_{\mathrm{Hg}} & d_{\mathrm{Ra}} & \\ 1.0 & 1.6\times10^{-14} & -8.6\times10^{-16} & 1.5\times10^{-18} & \bar{d}_n^{(\mathrm{sr})} \\ 1.9\times10^{-5} & -8.6\times10^{-21} & -2.1\times10^{-19} & -6.1\times10^{-21} & \bar{g}_\pi^{(0)}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

...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 in 2019: (hadronic/nuclear)

①



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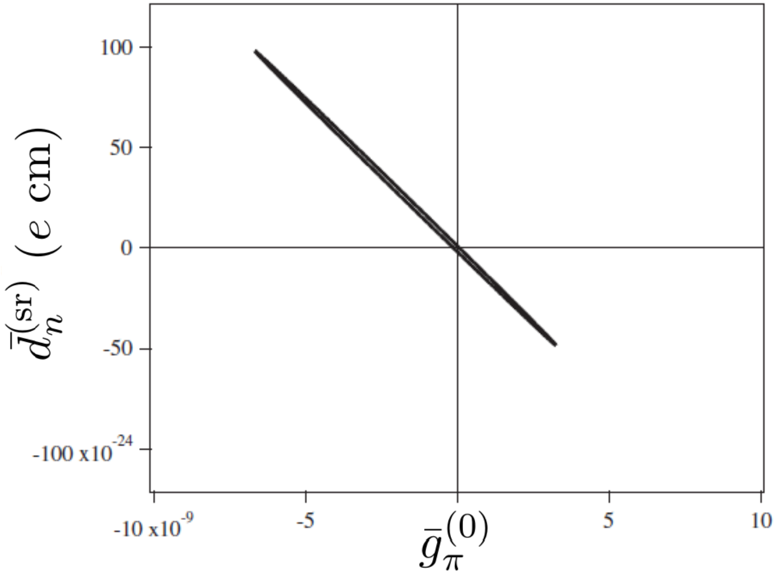
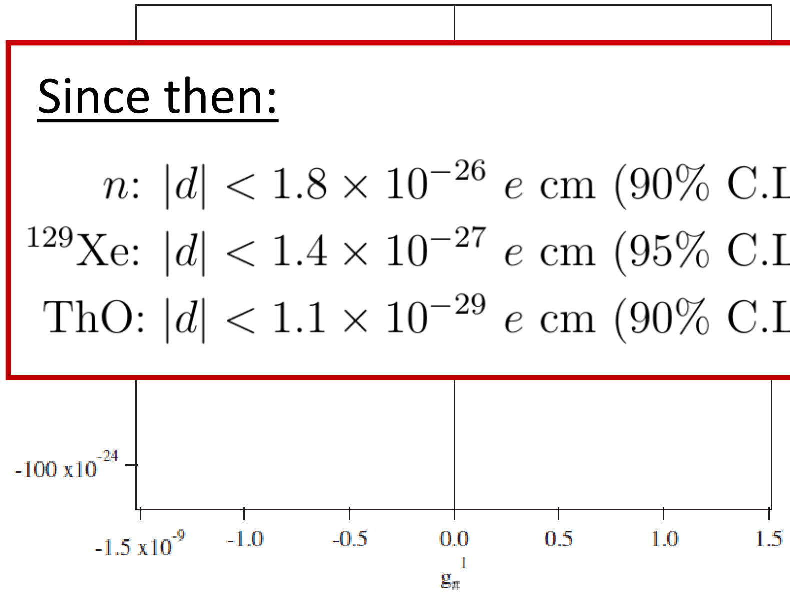
"Sole source" limits:

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 in progress...

①



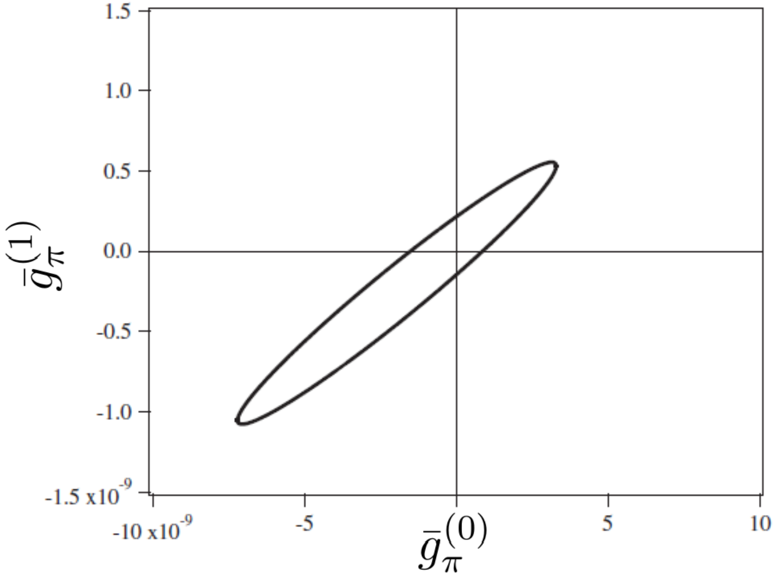


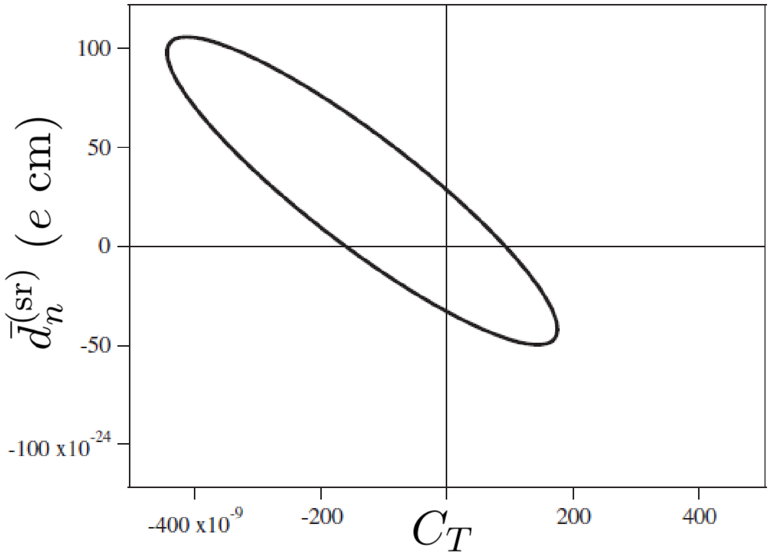
Since then:

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)





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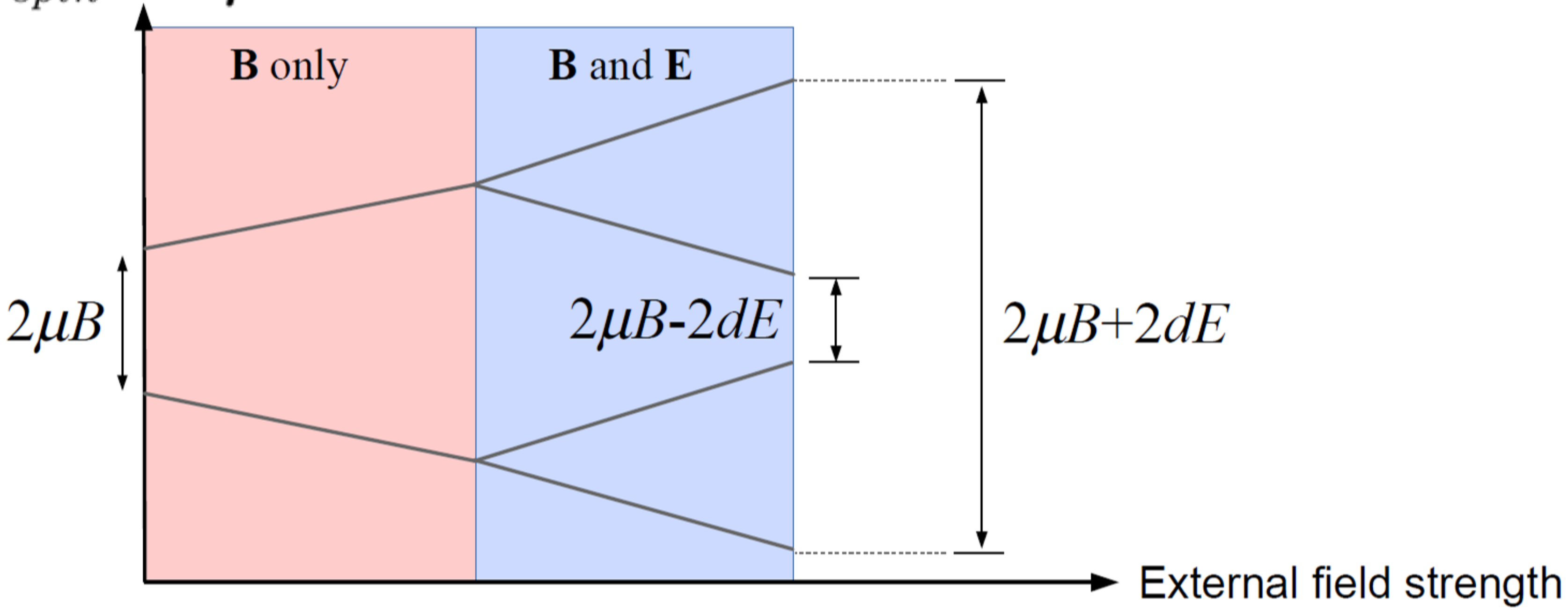
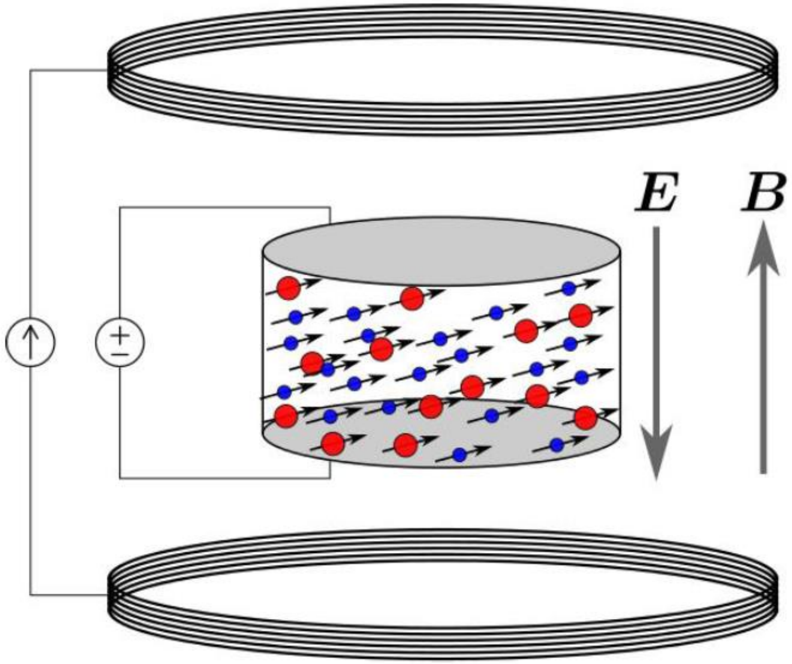
$\tilde{d}_d - \tilde{d}_u$	$5 \times 10^{-15}\,\bar{g}_\pi^{(1)}\,e$ cm	$2 \times 10^{-27}\,e$ cm

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.

The EDM is “locked” to the spin

Spin-precession based magnetometry:

- $E = -\boldsymbol{\mu} \cdot \boldsymbol{B}$
- $\boldsymbol{\tau} = \boldsymbol{\mu} \times \boldsymbol{B}$
- $\boldsymbol{\mu} = \gamma \boldsymbol{L} \rightarrow \boldsymbol{\omega}_L = -\gamma \boldsymbol{B}$

Time evolution from Bloch equations:

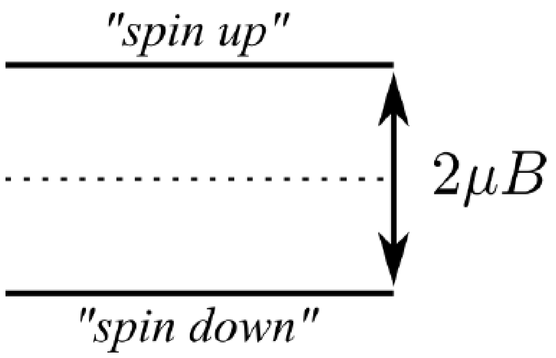
$$\frac{d\boldsymbol{\mu}}{dt} = \gamma \boldsymbol{\mu} \times \boldsymbol{B} - (\textit{relaxation terms})$$

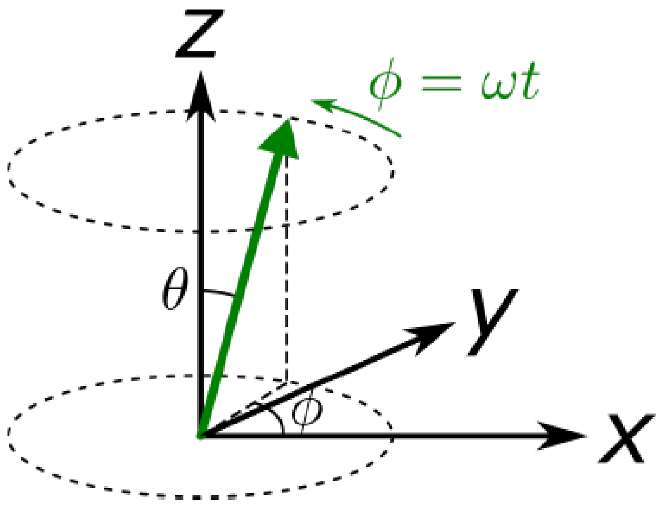
Sensitivity from: $\Delta E \Delta t \geq \hbar/2$

- relaxation limits measurement time
- many particles → many measurements

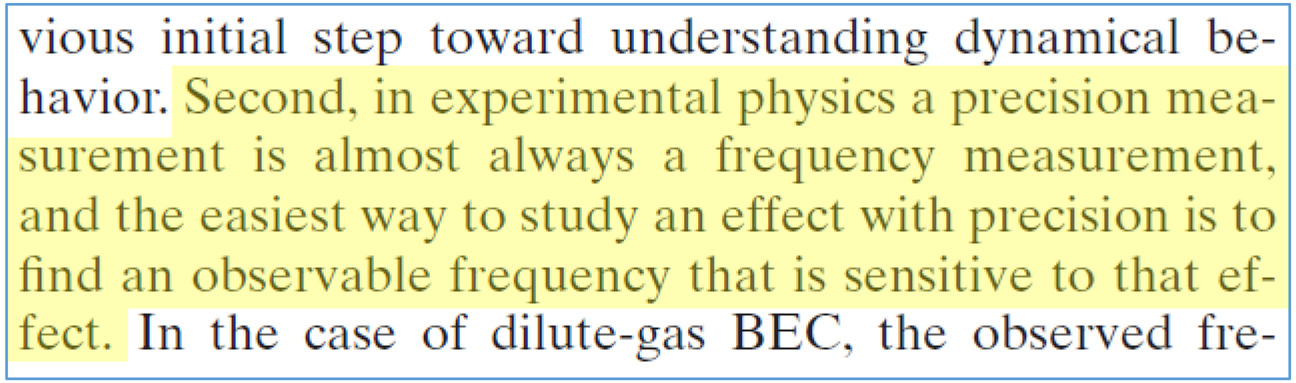
EDM fundamental sensitivity:

$$|\delta\omega| = \frac{|dE|}{\hbar F} \qquad (\Delta m_F = 1)$$





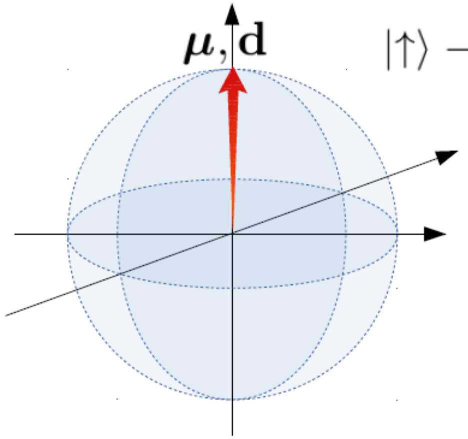
Cornell and Wieman… Nobel 2001, Rev. Mod. Phys. 74, 875 (2002)



vious initial step toward understanding dynamical behavior. Second, in experimental physics a precision measurement is almost always a frequency measurement, and the easiest way to study an effect with precision is to find an observable frequency that is sensitive to that effect. In the case of dilute-gas BEC, the observed fre-

How could you measure an EDM?

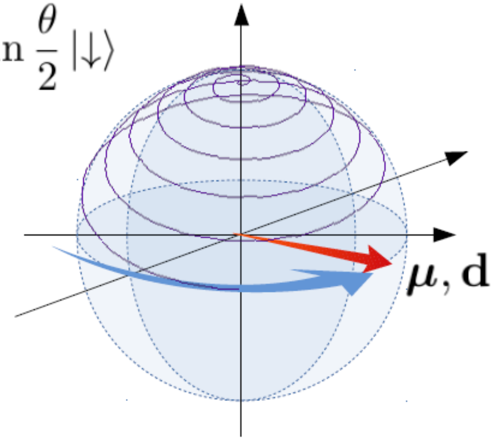
Ramsey's method to measure frequencies*:

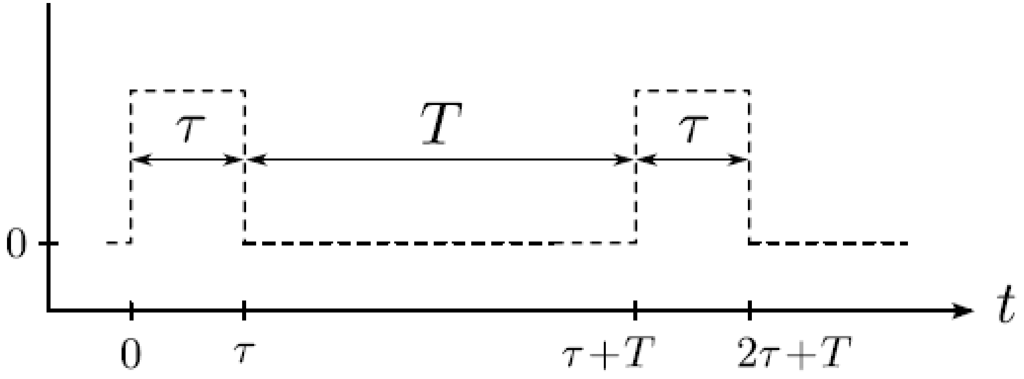


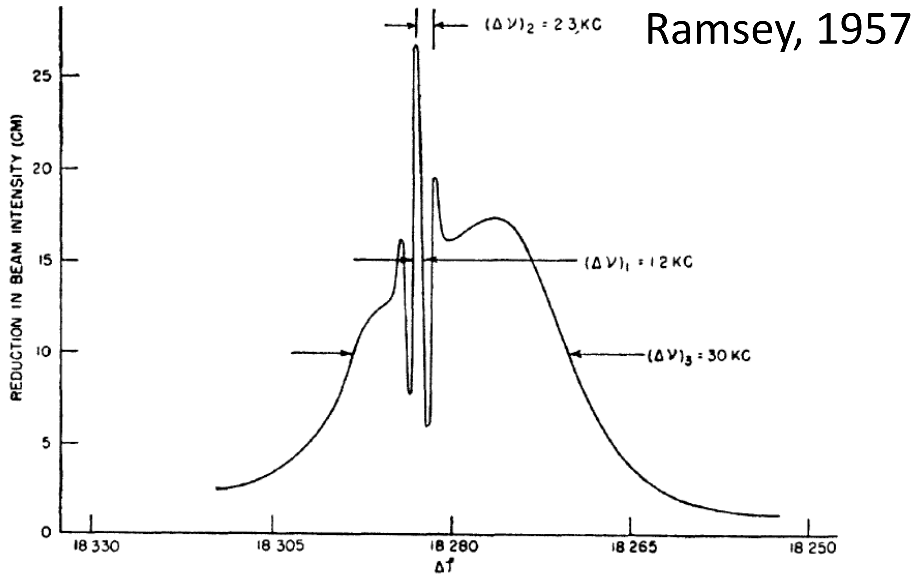
$$|\uparrow\rangle \longrightarrow \cos\frac{\theta}{2}\,|\uparrow\rangle + e^{i\omega t}\sin\frac{\theta}{2}\,|\downarrow\rangle$$

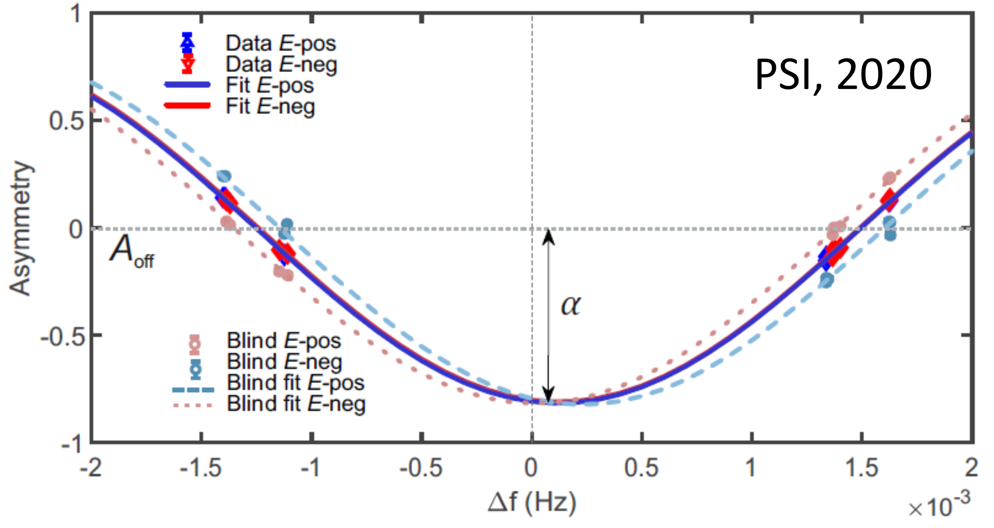
phase evolution:

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







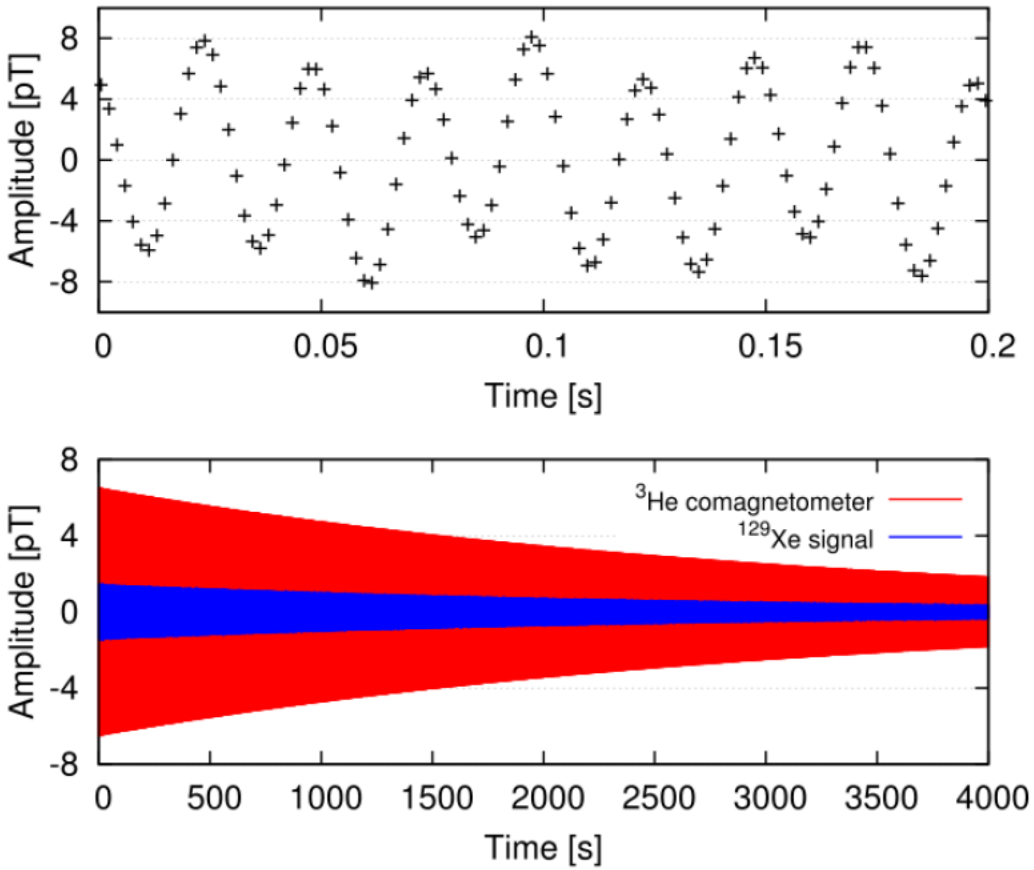


*subtle difference in some cases: *frequency* vs. *phase*

How could you measure an EDM?

②

What if we could measure continuously?



“phase noise” limit

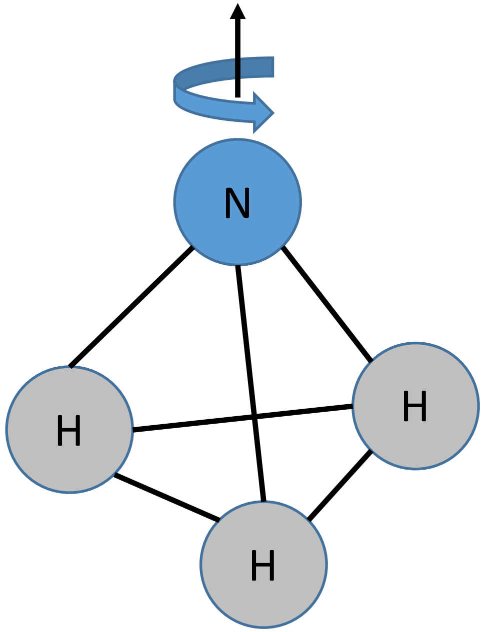
$$\delta d \sim \frac{h}{2ET_2}\frac{1}{S/N} \begin{cases} \longrightarrow \dfrac{h}{2ET_2}\dfrac{1}{\sqrt{\phi_n T_2}} \\ \longrightarrow \dfrac{h}{2ET_2}\dfrac{1}{\sqrt{N_\mathrm{n}}} \end{cases}$$

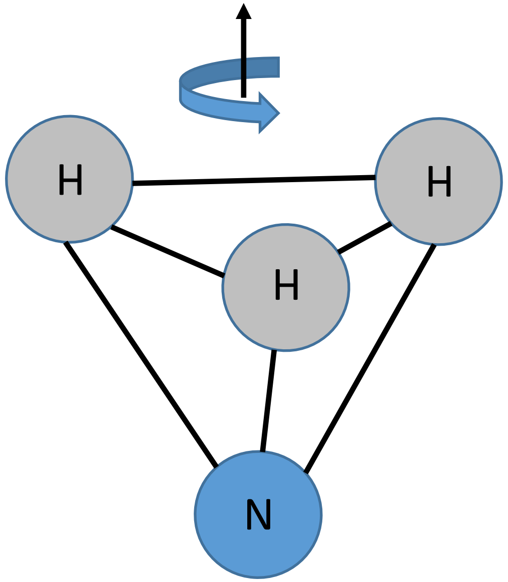
“count rate” limit

HeXe data for Xenon / Phys. Rev. Lett. **123**, 143003 (2019)

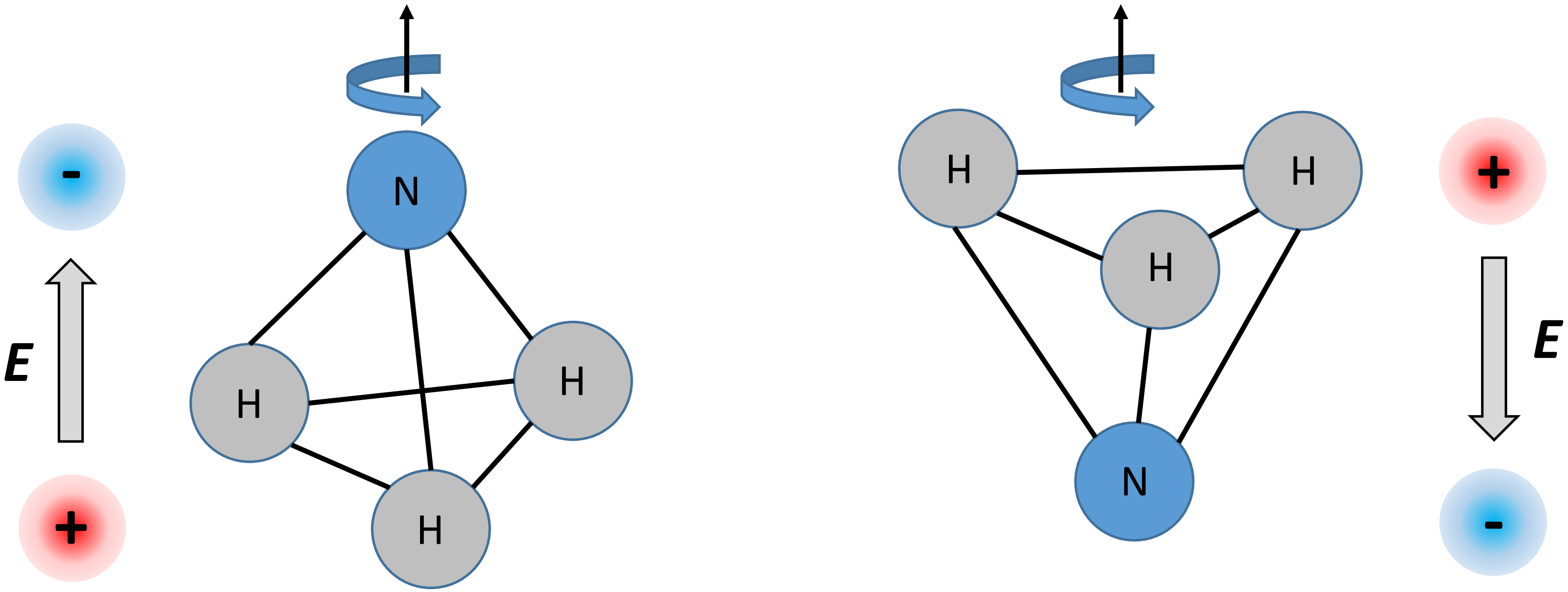
Is it different from a molecular dipole?

…or, “reviewing non-relativistic quantum mechanics”





Is it different from a molecular dipole?



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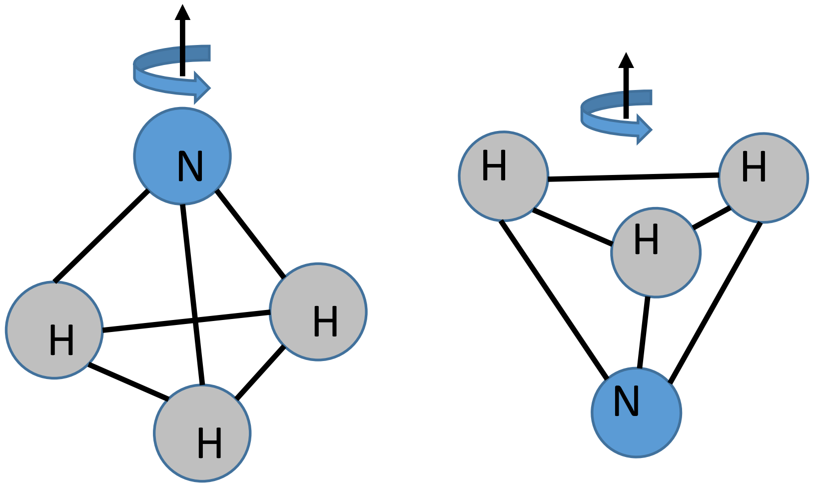

$|1\rangle$ $|2\rangle$

The *energy* eigenstates are:

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

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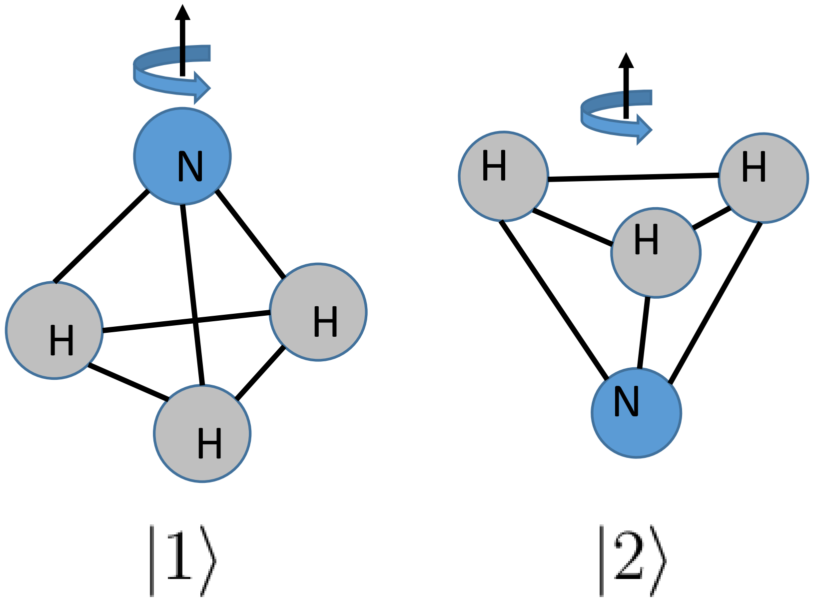

$$E_{\pm} = E_0 + \sqrt{A^2 + d^2 E^2}$$

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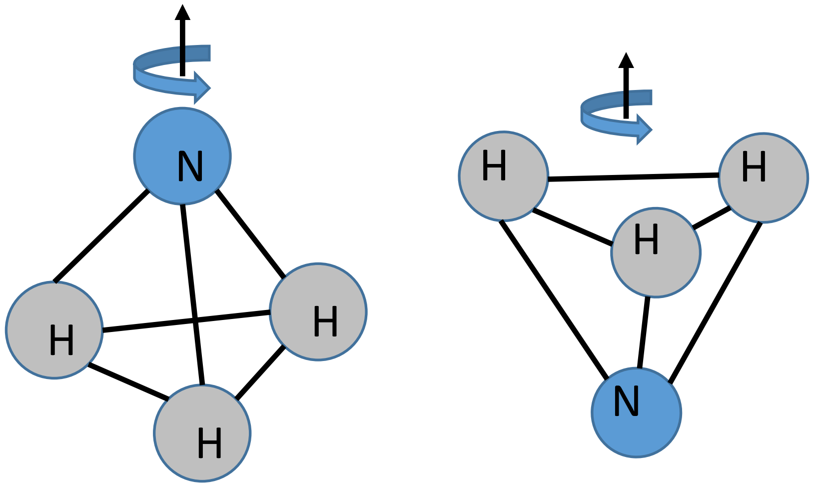

$|1\rangle$ $|2\rangle$

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

$$E_0 \pm dE$$

$$(dE \gg A)$$

$$E_0 \pm A \pm \frac{d^2E^2}{2A}$$

$$(dE \ll A)$$

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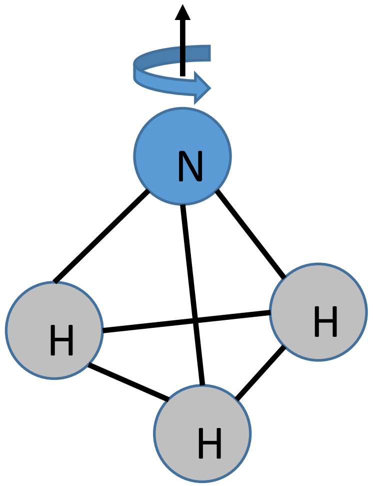
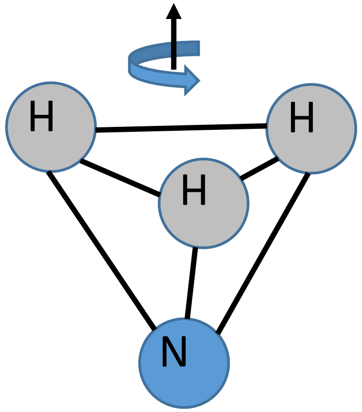


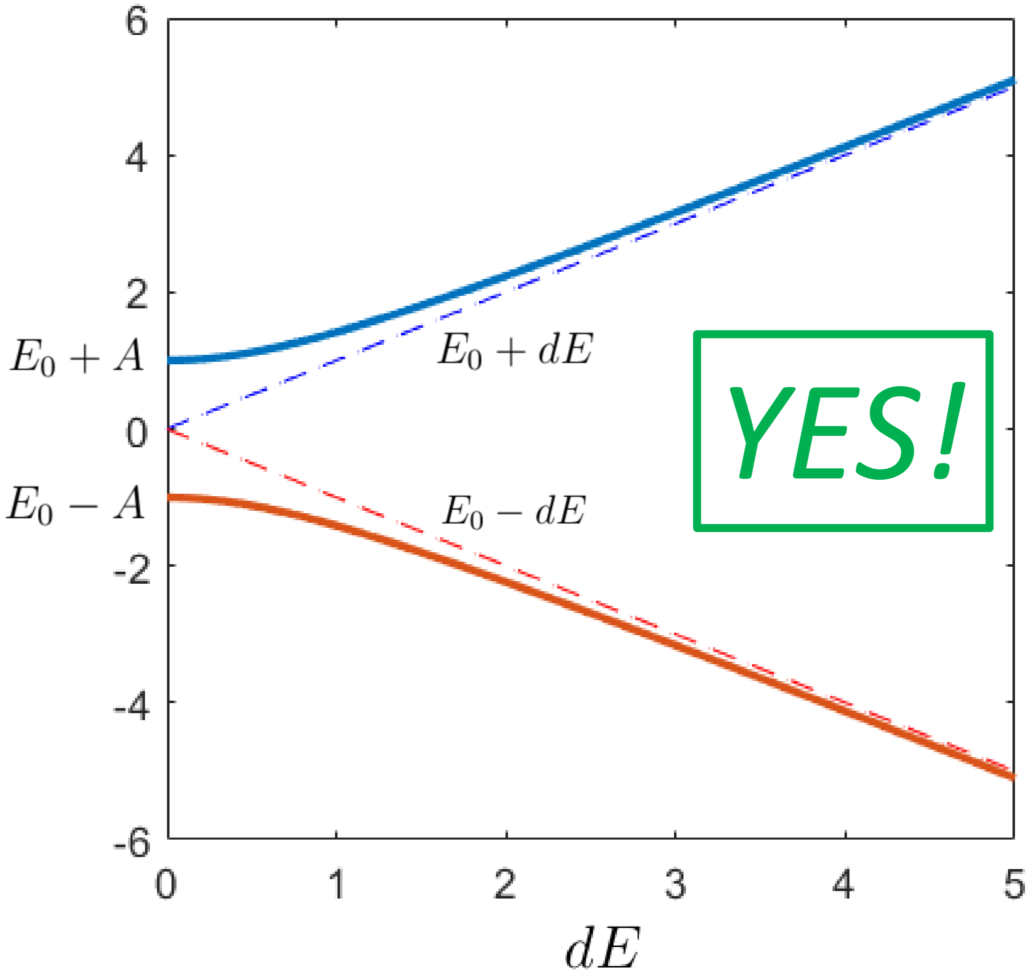
$|1\rangle$



$|2\rangle$

The *energy* eigenstates are:

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



YES!

Caveats for atomic/molecular bound states

- Schiff's theorem assumes:
  - pointlike particles ⟶ *incorrect for nuclei*

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

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

  - non-relativistic treatment ⟶ *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)

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Nuclear structure enhancements!

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

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

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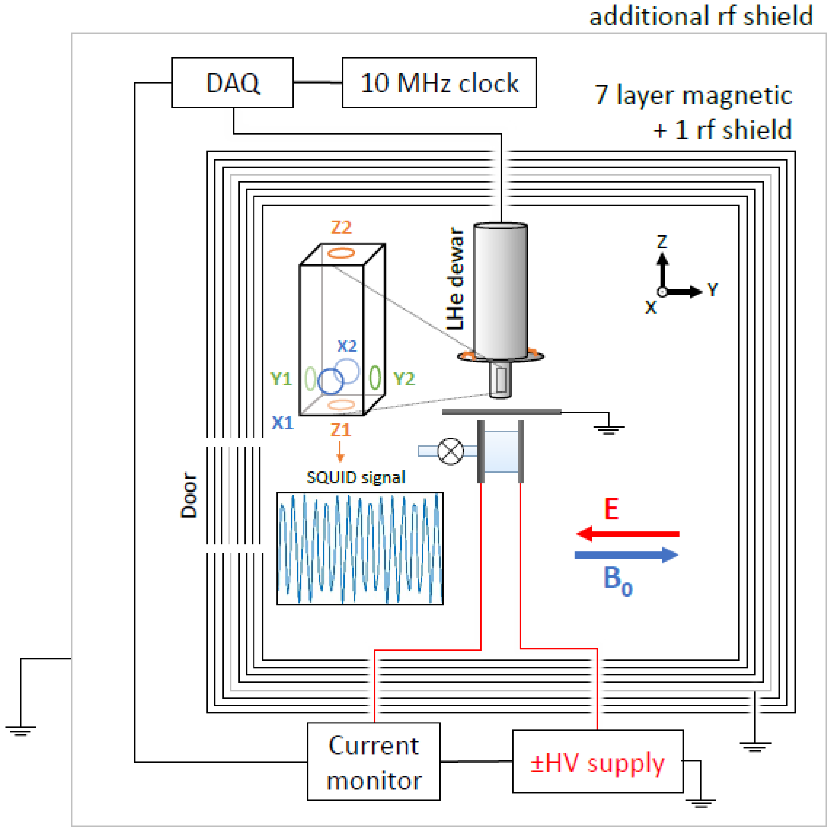
A rapidly-moving field!

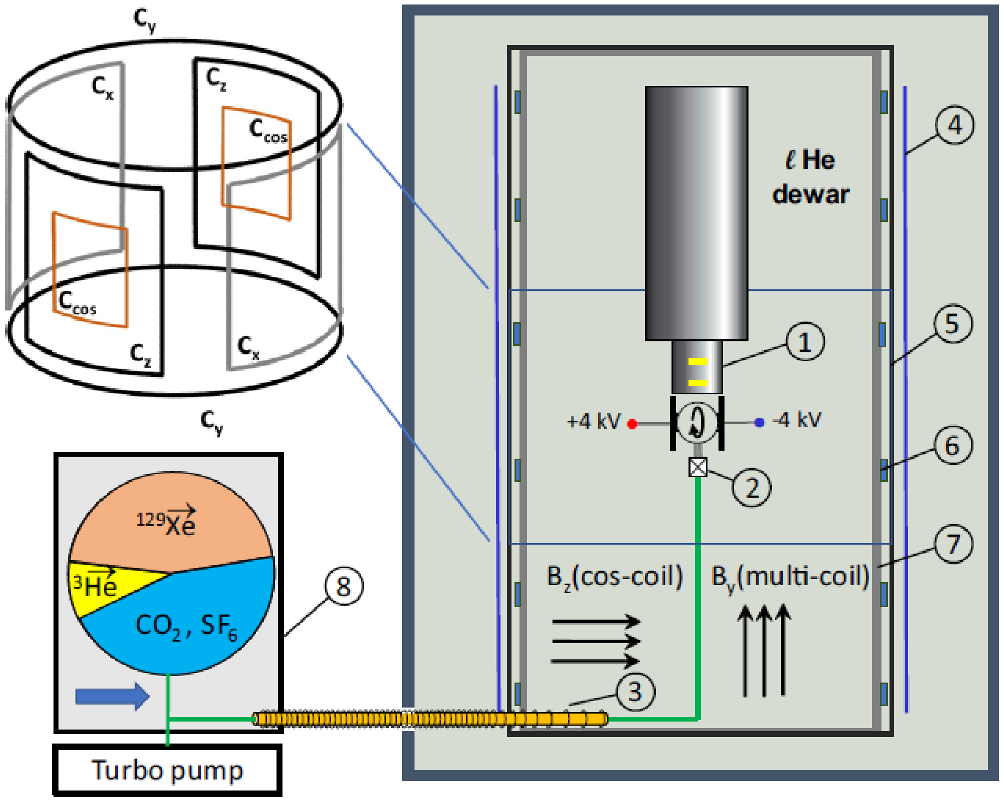
②



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)

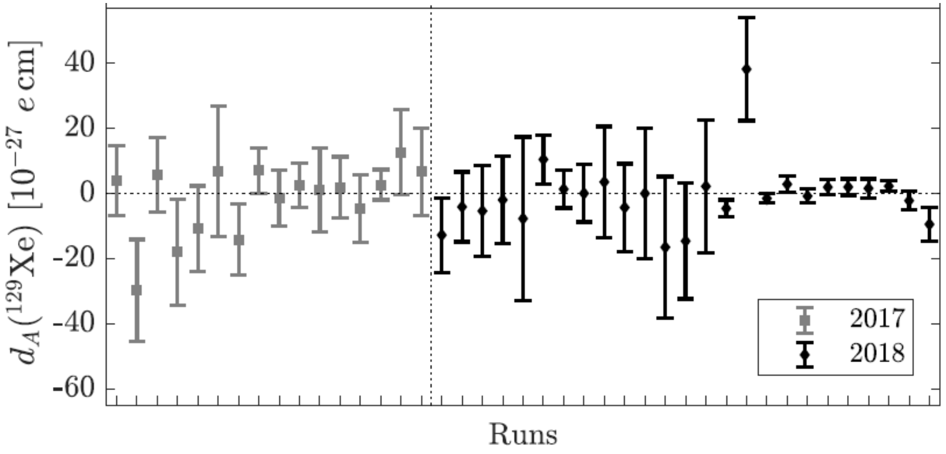


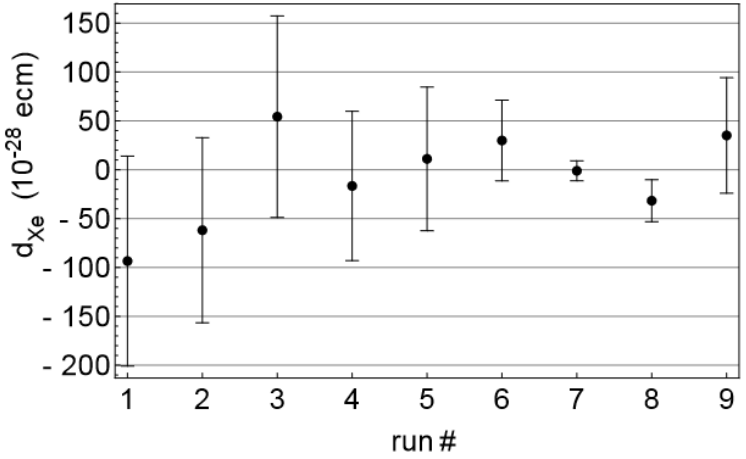
Near-simultaneous from MiXed:

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

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

A rapidly-moving field!





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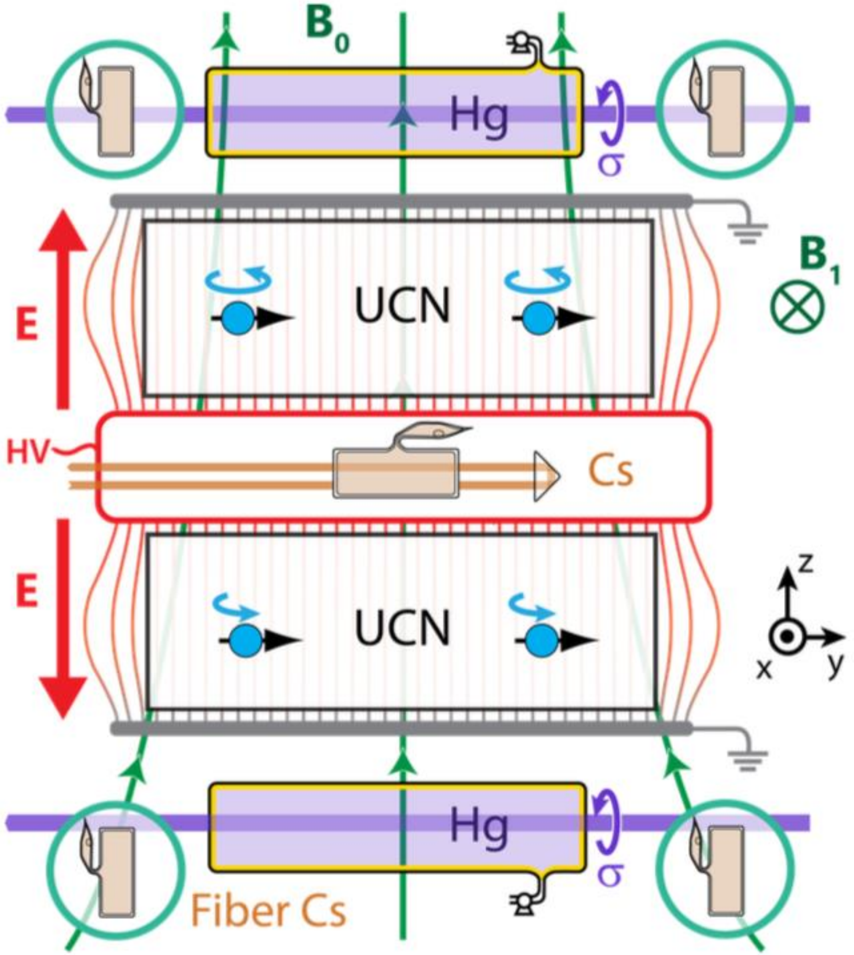
Phys. Rev. A **100**, 022505 (2019)

nEDM suffers much lower statistics



Statistical sensitivity:

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

Frequency measurement:

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

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}

$|\mathbf{E}| \approx 2$ MV/m
$T \approx 250$ s
$\alpha \approx 0.85$

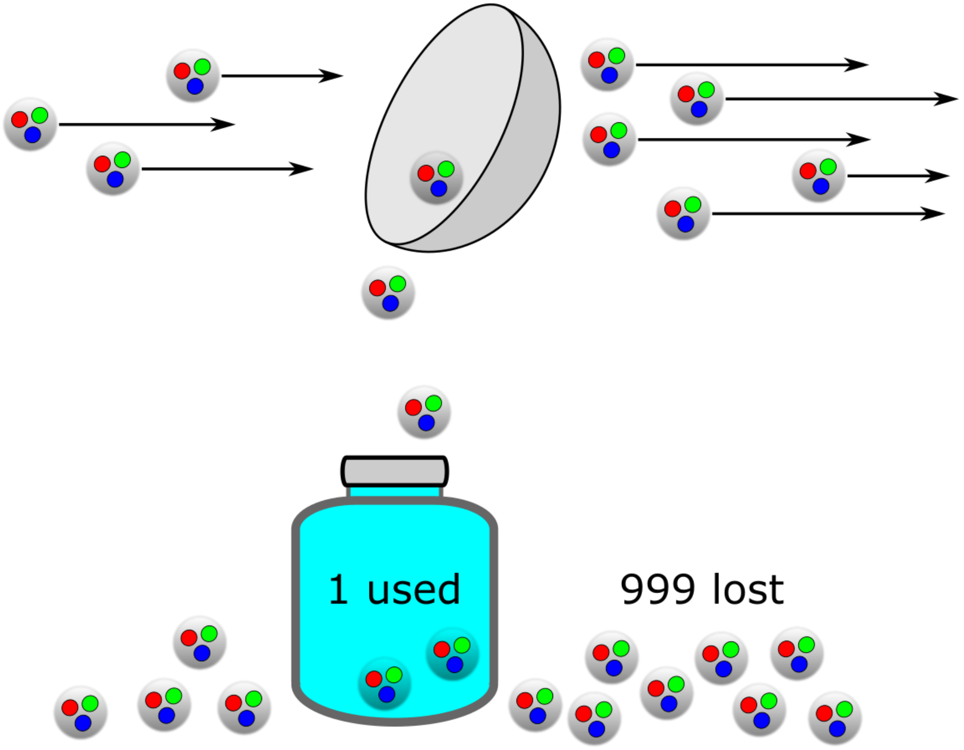
Transfer loss including dilution: 97-99% for filling

$$\boxed{\Delta E \Delta t \geq \hbar/2}$$

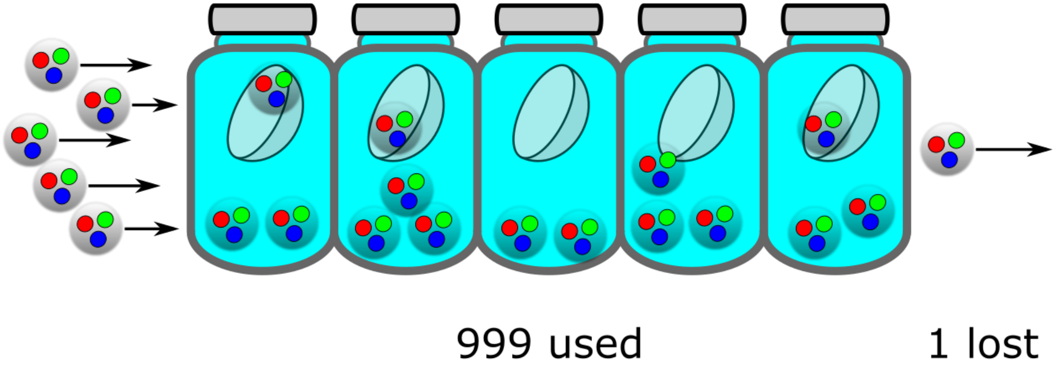
EPJ Web of Conferences 219, 02006 (2019)

Challenge the first: statistics

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



New approach: catch them
all, directly in many bottles

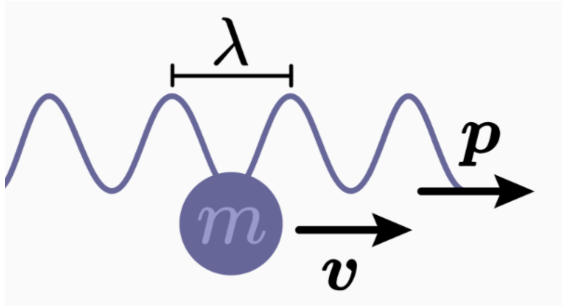


Challenge the second: observation time

③

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

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

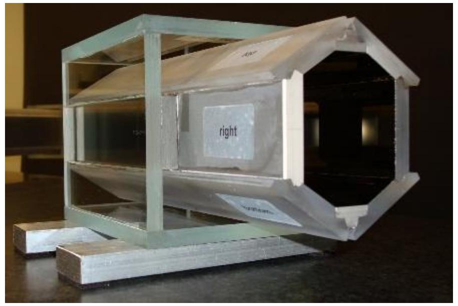


But… how to store or cool ensembles?

Wave optics, with massive particles!

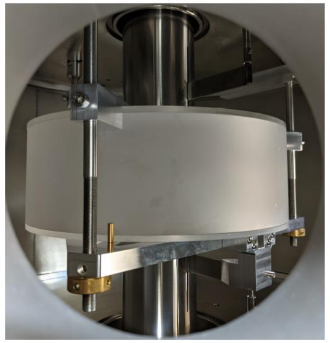
“Cold” beams: O(500 m/s)

particles fly through most experiments in milliseconds



S-DH

S-DH

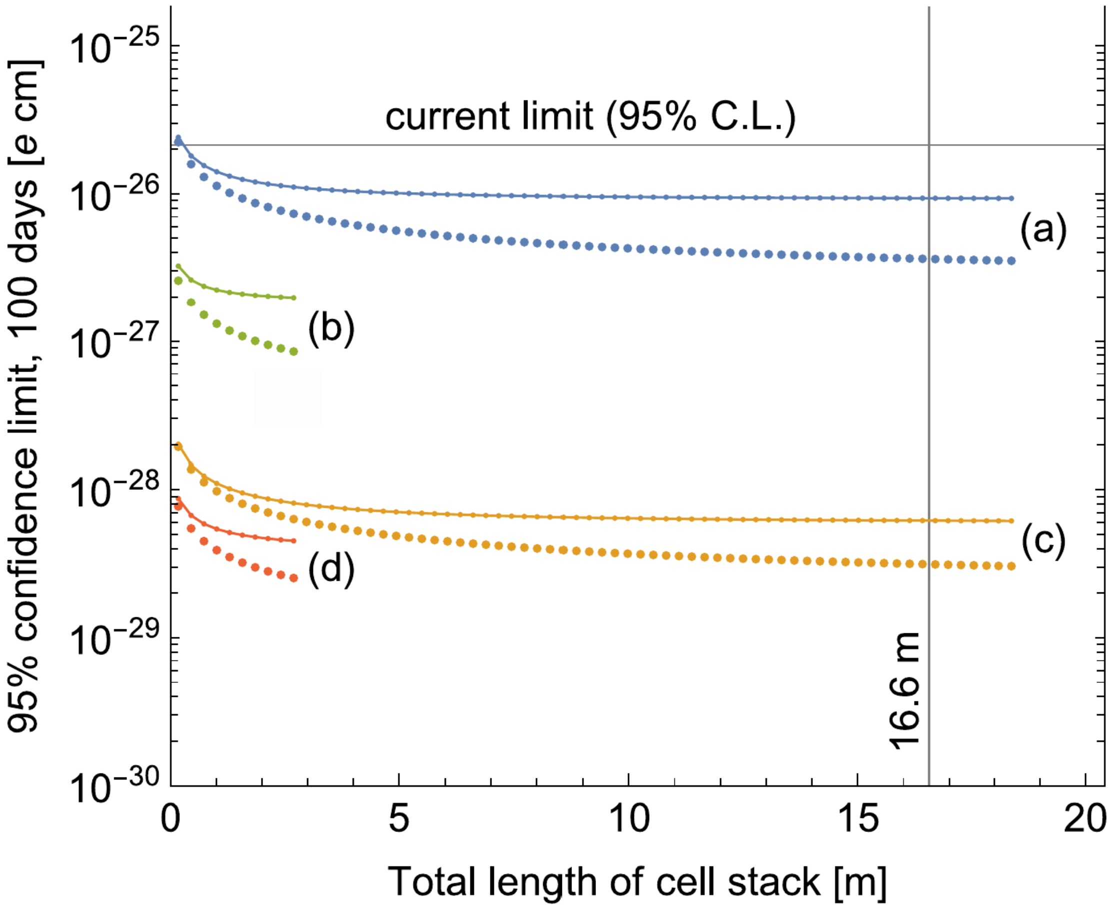


“Ultracold” traps: O(5 m/s)

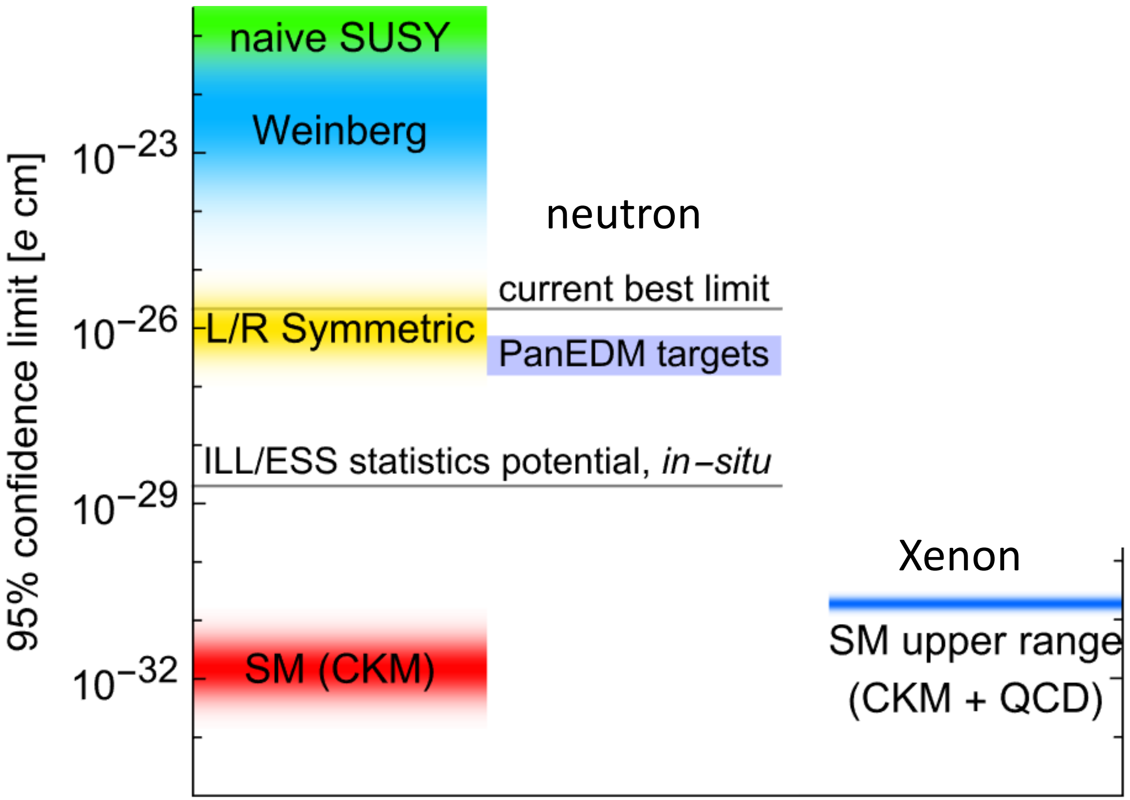
particles stored for minutes (>10^5 ms)

Where are we going with this?

In-situ UCN: statistics ONLY



Current limits, new targets, old theories



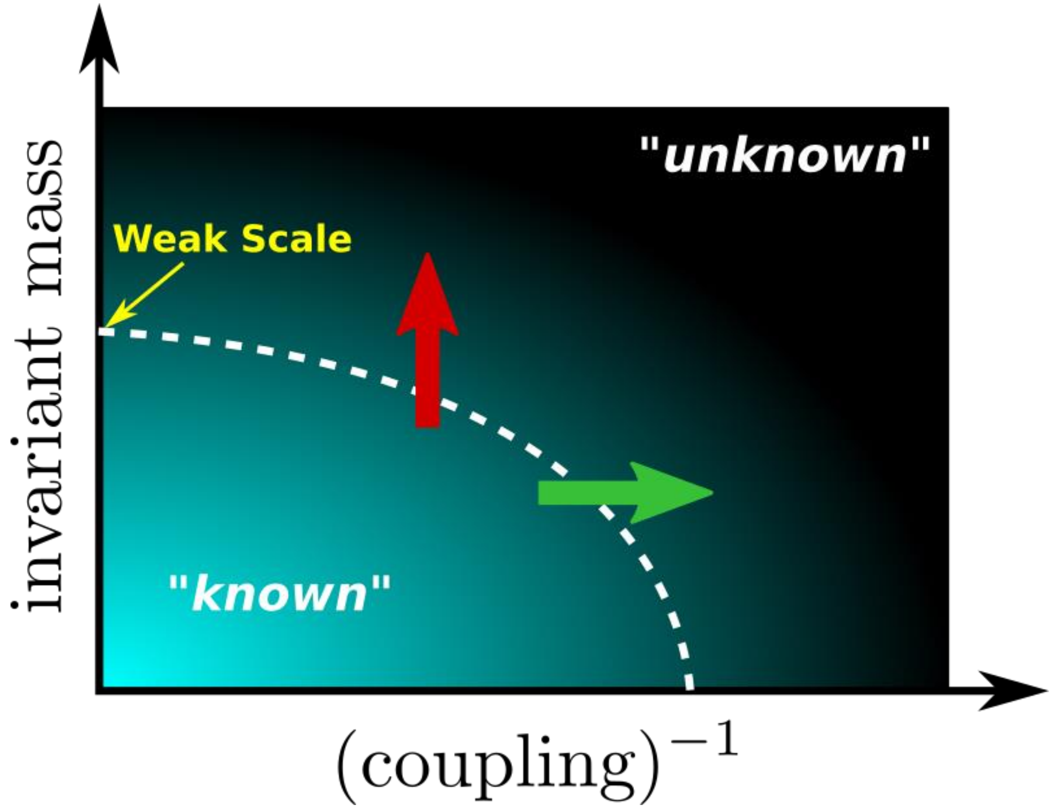
Upcoming publications:

Review on particle physics cases for the ESS

Approaches to *in-situ* nEDM with UCN

Systematics *tour de force* (PSI result): Phys. Rev. Lett. **124**, 081803 (2020)

Thematic Recap



① Complementarity

Global analysis…

…more systems!

② Xenon

Systematics limiting

③ Neutron

Statistics limiting

Questions?

(now hiring students and post-docs...)

what-if.xkcd.com

Special thanks to:

T. Chupp, P. Fierlinger, V. Cirigliano

HeXe Collaboration
SuperSUN-PanEDM collaboration

Institut Laue-Langevin, NPP & SANE

U. Heidelberg & KIT theory

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

Add constituent EDMs
As a perturbation…

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

(sum over constituents)

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Add constituent EDMs
As a perturbation…

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

(sum over constituents)

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

Now see what effect this has…

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

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

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

Eigenstates receive an energy shift due to the perturbation:

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

It’s not so simple after all…

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

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