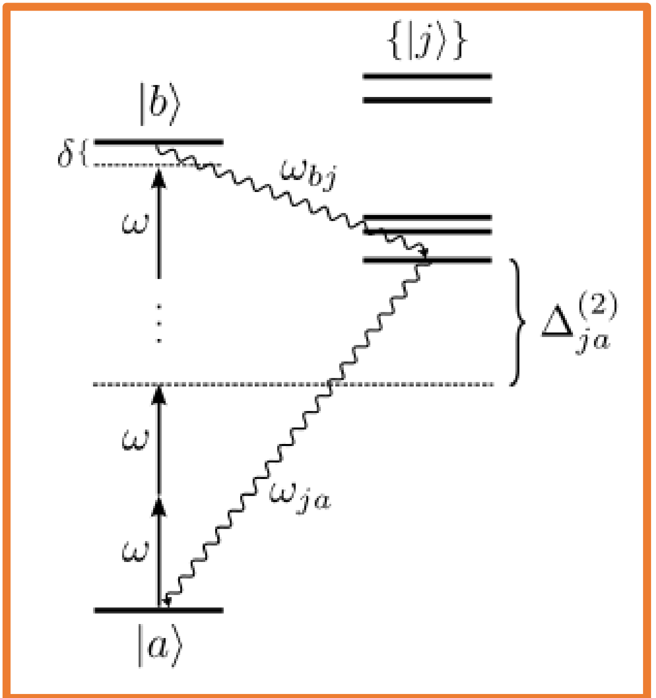
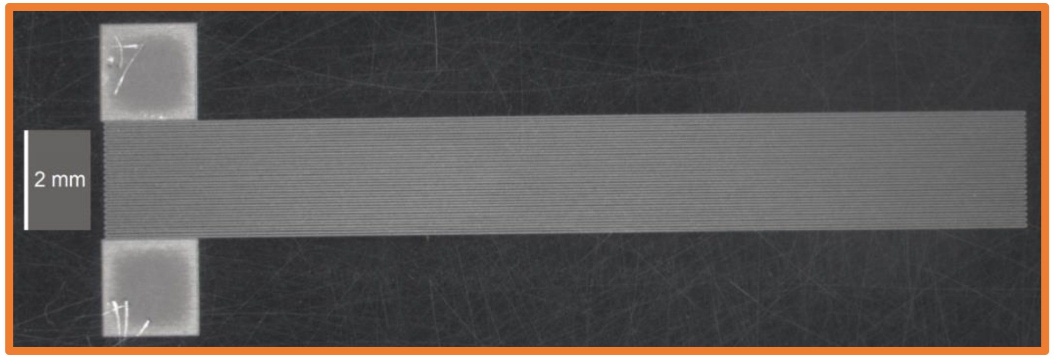
Polarized nuclei and neutrons: toward new tools for fundamental physics

Skyler Degenkolb, Institut Laue-Langevin

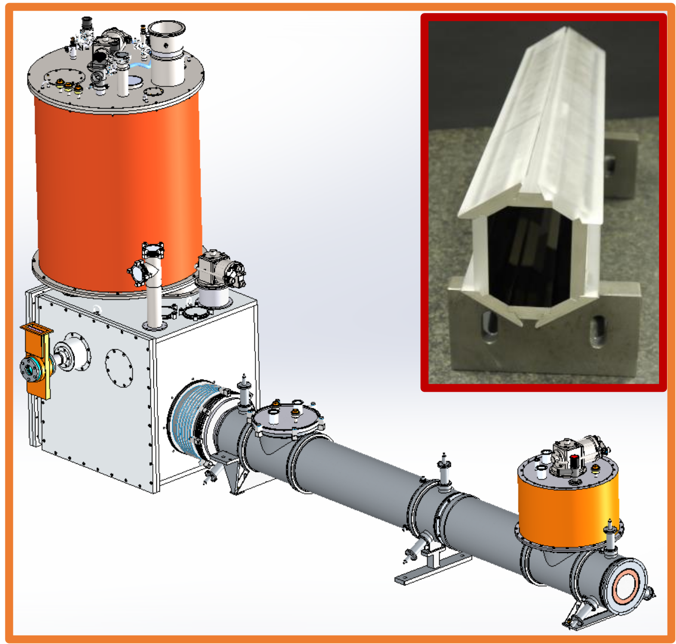
TRIUMF, 8 June 2020



R. Gernhaeuser, S. Winkler



JNR 20(4), 117-122 (2018)



Outline

0) Motivations: testing the Standard Model, and Beyond

1) Some remarks on contemporary EDM efforts (experiments and theory)

2) An "in-progress" experiment: SuperSUN-PanEDM [as of today]

3) A future experiment: *in-situ* multichamber nEDM [as of tomorrow]

Along the way: today's limitations, and the tools we will need to do better

- Precision physics with "new" atomic species: quantum spin dynamics at the cross-over of nuclear and atomic physics, optical spectroscopy
- *In-situ* UCN source/experiment: production, detection, spin dynamics
- Going beyond the old techniques: co-magnetometry, alkalis, pulsed NMR, SEOP

Symmetries and the Standard Model

- Standard Model gauge group SU(3)×SU(2)×U(1) and degrees of freedom
- Conservation laws and continuous symmetries
  - “A” vs. “p/d” and parity in even-dimensional spaces
  - *Be careful: Baryon or lepton number, etc.*
- Discrete symmetries C, P, T
  - Time-reversal in quantum mechanics: formal symmetry of the equations
  - “Arrow of Time” in statistical mechanics is unrelated
- Sources of CP-violation in the Standard Model (and connections within)
  - QCD θ term …[also BSM: axions]
  - CKM mixing phase …*B* and *K* physics
  - Neutrinos …Majorana or Dirac?
- Framework for precision tests: effective field theory / global analysis

Electromagnetic Moments

Classical source distributions:

$$Q = \int \rho(\boldsymbol{r}) d\boldsymbol{r}$$

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

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

…etc. for MQM and higher
(see standard E&M texts)

"Fundamental" fermion fields:

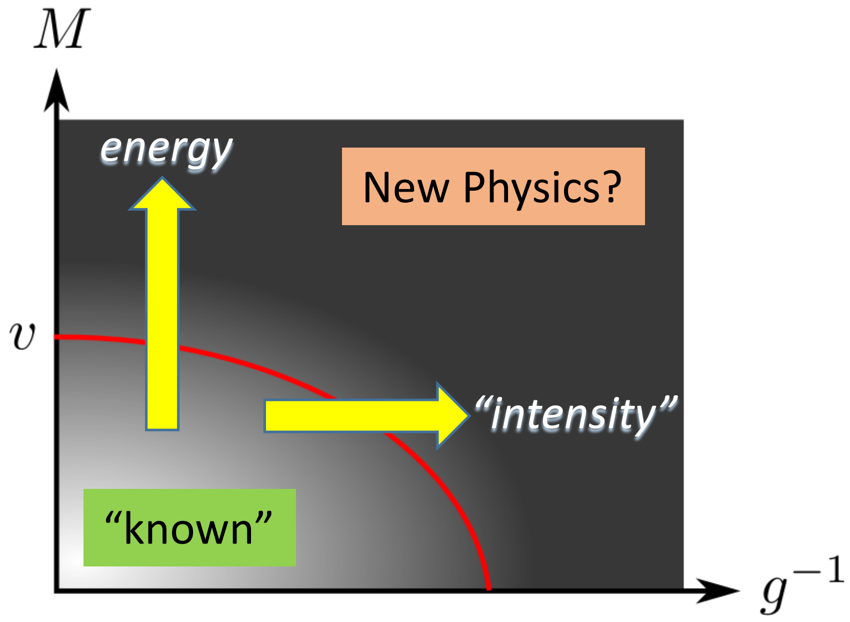
$$\boxed{\begin{array}{ll} Q = F_1(0) & \mu = \dfrac{F_1(0) + F_2(0)}{2m} \\ d = -\dfrac{F_3(0)}{2m} & a = F_4(0) \end{array}}$$

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

…see arXiv:physics/0402058v2

Generalities on EDM Searches

- Broad motivations:
  - Searches for new physics, potential for discovery of BSM phenomena
  - “Diagnose” the origins of CP violation and B violation (multiple systems)
  - Connection to mechanisms of symmetry-breaking required for baryogenesis
    - “Clean” signature of time-reversal violation



see also:

FRIB TA Topical Program – August 2019
V. Cirigliano, PPNS-2018
M. Ramsey-Musolf, APS April meeting 2018

Recent review:

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

Latest experimental results:

neutron: Phys. Rev. Lett. 124, 081803 (2020)
^{129}Xe: Phys. Rev. Lett. 123, 143003 (2019)

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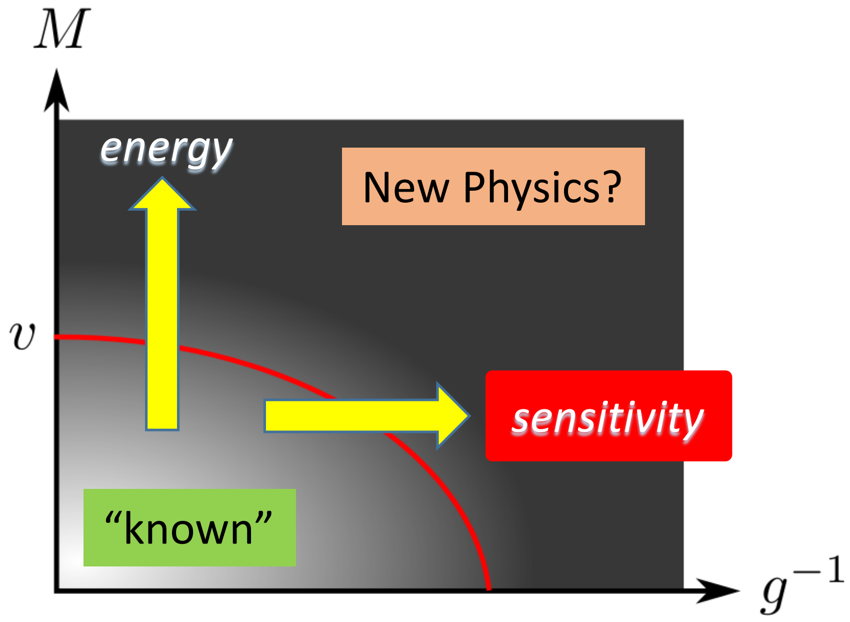

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EDM Searches and Effective Field Theory

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

Effective Lagrangian

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

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

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

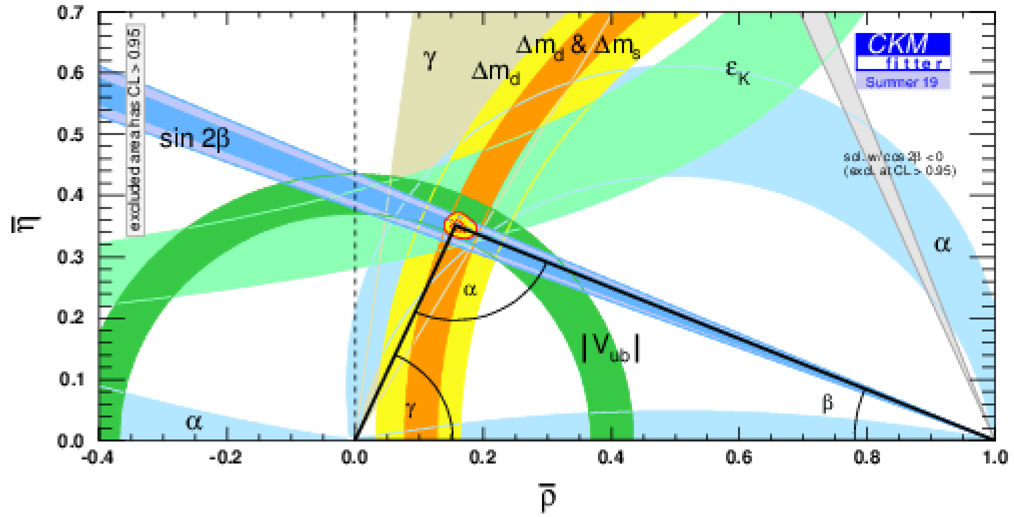
Wilson coefficient	Operator (dimension)	Number
$\bar{\theta}$	Theta term (4)	1
δ_e	Electron EDM (6)	1
$\text{Im}\, C_{\ell equ}^{(1,3)}$, $\text{Im}\, C_{\ell eqd}$	Semi-leptonic (6)	3
δ_q	Quark EDM (6)	2
$\tilde{\delta}_q$	Quark chromo EDM (6)	2
$C_{\tilde{G}}$	Three-gluon (6)	1
$\text{Im}\, C_{quqd}^{(1,8)}$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

“Global analysis”

- Quick outline:
  - Hierachy of energy scales
  - SMEFT = Standard Model Effective Field Theory
  - χPT = chiral Perturbation Theory

- Similar idea:

$$V_{\mathrm{CKM}} = \begin{bmatrix} V^{ud} & V^{us} & V^{ub} \\ V^{cd} & V^{cs} & V^{cb} \\ V^{td} & V^{ts} & V^{tb} \end{bmatrix}$$



“Global analysis”

- CP violation from three sources (ignoring neutrinos):

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

- CKM CP-violation:

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

- Strong CP-violation:

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

details:

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

“Global analysis”

- Scale of CKM CP-violation given by $\mathrm{Im}\,(V_{us}V^*_{cs}V_{cb}V^*_{ub}) \approx 3 \times 10^{-5}$

- Predictions for EDMs are far below current experimental sensitivities:

System	current	projected	SM (CKM)
e	$\sim 10^{-28}$	10^{-29}	$\sim 10^{-38}$
μ	$\sim 10^{-19}$		$\sim 10^{-35}$
τ	$\sim 10^{-16}$		$\sim 10^{-34}$
n	$\sim 10^{-26}$	10^{-28}	$\sim 10^{-31}$
p	$\sim 10^{-23}$	10^{-29} **	$\sim 10^{-31}$
^{199}Hg	$\sim 10^{-29}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
$\cdots$	$\cdots$		$\cdots$

V. Cirigliano, PPNS-2018

EDM Techniques and Systems

Sensitivity: / System:	Paramagnetic	Diamagnetic	"Particle"
Trap	Tl, Cs, PbO, HfF^+, Fr, BaF, ...	^{199}Hg, ^{129}Xe, ^{225}Ra, Rn, Pa, RaO, …	n (UCN)
Beam	YbF, ThO, WC	TlF	n
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), …

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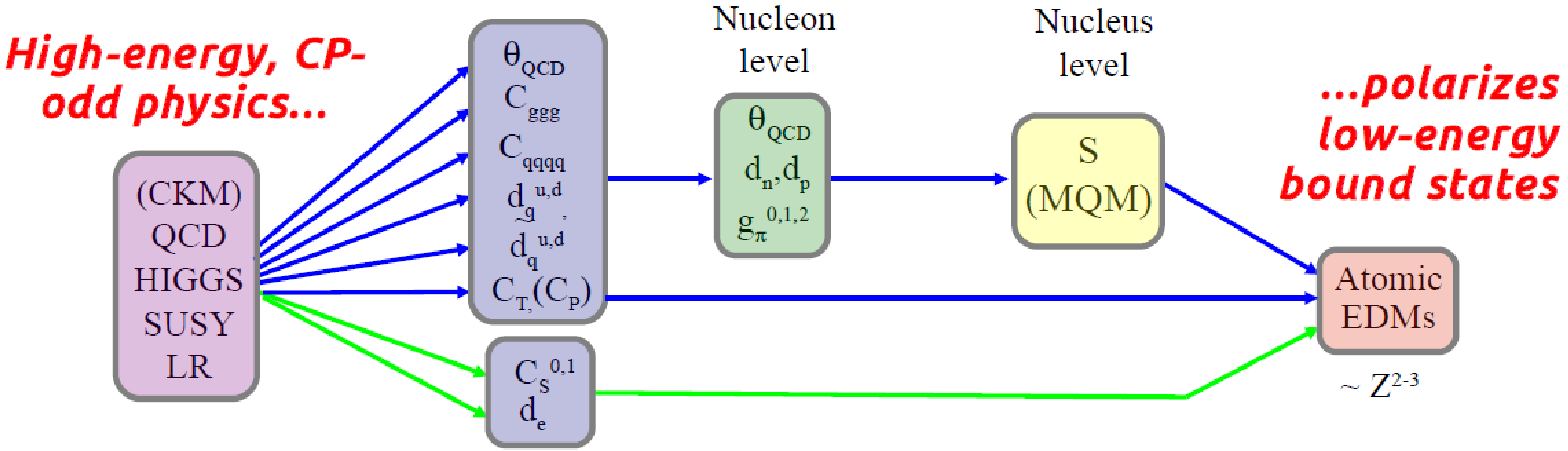
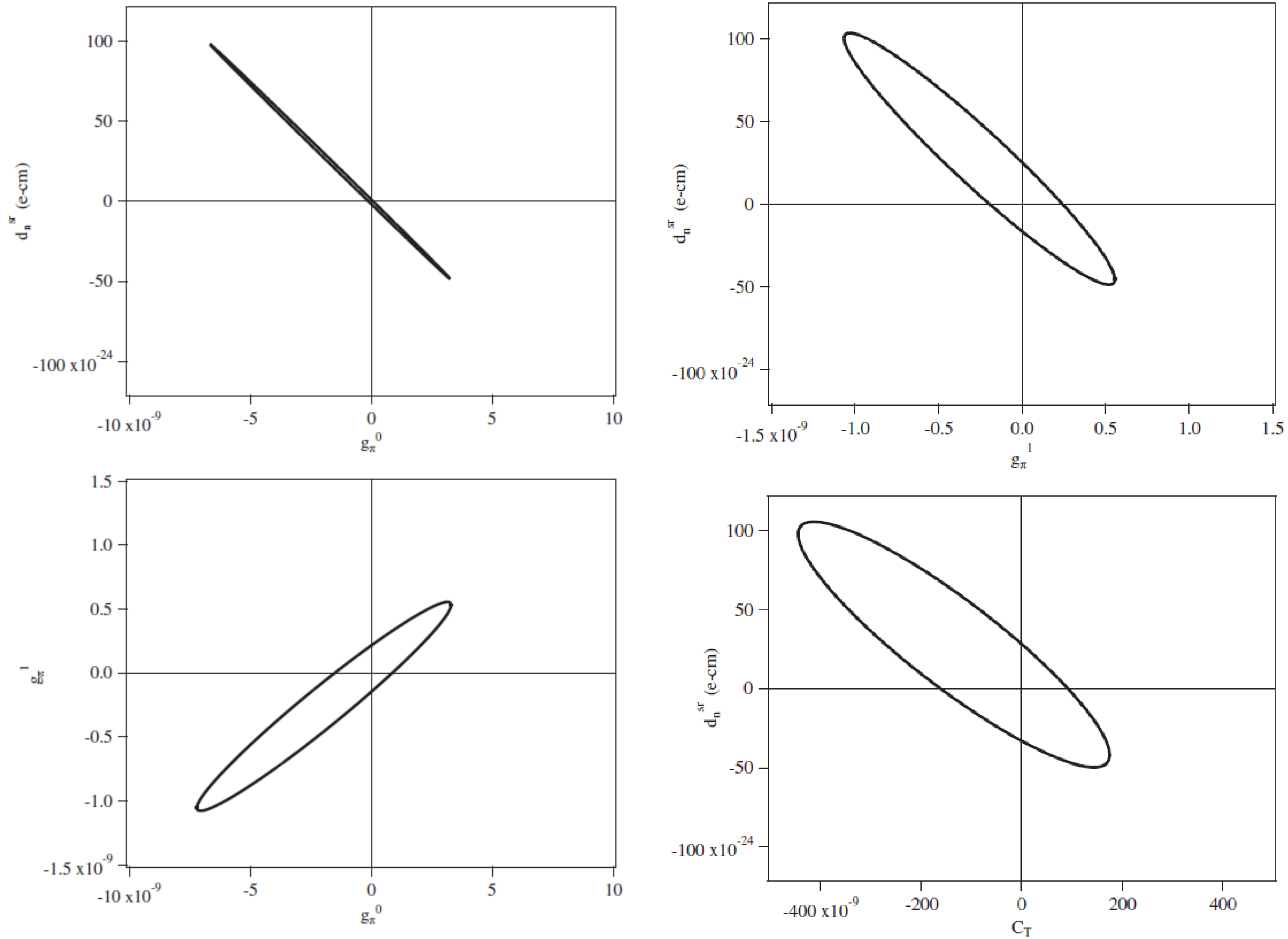
An Experimentalist’s View of the Situation



Set joint constraints via complementary experiments in different systems: $d_i = \sum_i a_{ij} C_j$

$$
\begin{array}{c}
\begin{array}{cccc} d_{\mathrm{Hg}} & d_{\mathrm{Xe}} & d_{\mathrm{TlF}} & d_{\mathrm{n}} \end{array} \\
a_{ij} = \begin{bmatrix}
-2.0\times 10^{-20} & -3.8\times 10^{-18} & 0 & 0 \\
4.0\times 10^{-21} & -2.9\times 10^{-19} & -2.2\times 10^{-19} & 0 \\
1.1\times 10^{-16} & 1.2\times 10^{-14} & -1.6\times 10^{-13} & 0 \\
0 & 1.5\times 10^{-14} & 1.4\times 10^{-16} & 1
\end{bmatrix}
\begin{array}{c} C_T \\ \tilde{g}_\pi^0 \\ \tilde{g}_\pi^1 \\ d_n^{sr} \end{array}
\end{array}
$$

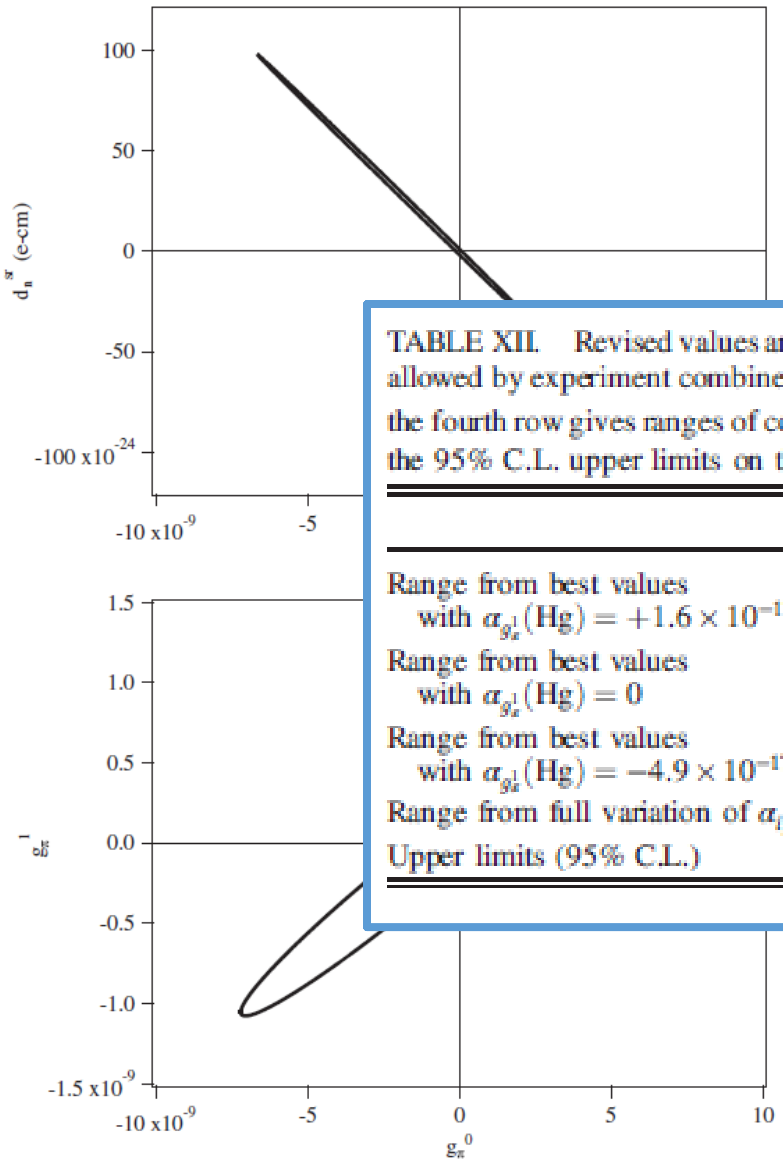
So what is today’s phenomenological situation?



Example “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

Combined Limits



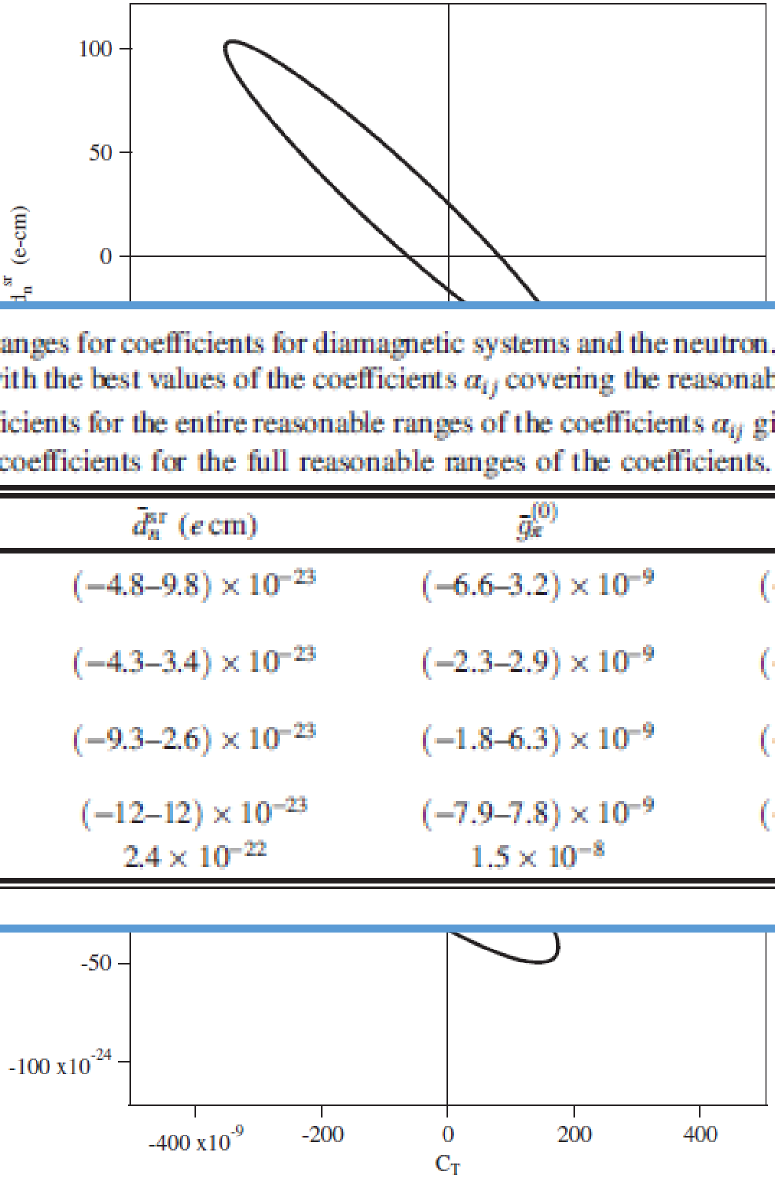


TABLE XII. Revised values and ranges for coefficients for diamagnetic systems and the neutron. The first three rows give the 68% C.L. range allowed by experiment combined with the best values of the coefficients α_{ij} covering the reasonable range of $\alpha_{\mathrm{Hg},\bar{g}_\pi^{(1)}}$ with $\alpha_{\mathrm{Ra},\bar{d}_n^{sr}} = -8 \times 10^{-4}$; the fourth row gives ranges of coefficients for the entire reasonable ranges of the coefficients α_{ij} given in Table IV, and the bottom row presents the 95% C.L. upper limits on the coefficients for the full reasonable ranges of the coefficients.

	$\bar{d}_n^{sr}$ (e cm)	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$C_T^{(0)}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = +1.6 \times 10^{-17}$	$(-4.8\text{–}9.8) \times 10^{-23}$	$(-6.6\text{–}3.2) \times 10^{-9}$	$(-1.0\text{–}0.5) \times 10^{-9}$	$(-3.5\text{–}1.6) \times 10^{-7}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = 0$	$(-4.3\text{–}3.4) \times 10^{-23}$	$(-2.3\text{–}2.9) \times 10^{-9}$	$(-0.6\text{–}1.3) \times 10^{-9}$	$(-3.2\text{–}4.0) \times 10^{-7}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = -4.9 \times 10^{-17}$	$(-9.3\text{–}2.6) \times 10^{-23}$	$(-1.8\text{–}6.3) \times 10^{-9}$	$(-1.2\text{–}0.4) \times 10^{-9}$	$(-11\text{–}3.8) \times 10^{-7}$
Range from full variation of α_{ij}	$(-12\text{–}12) \times 10^{-23}$	$(-7.9\text{–}7.8) \times 10^{-9}$	$(-1.3\text{–}1.1) \times 10^{-9}$	$(-6.6\text{–}4.6) \times 10^{-7}$
Upper limits (95% C.L.)	2.4×10^{-22}	1.5×10^{-8}	2.4×10^{-9}	1.1×10^{-6}

The Global Interpretation of EDM Searches

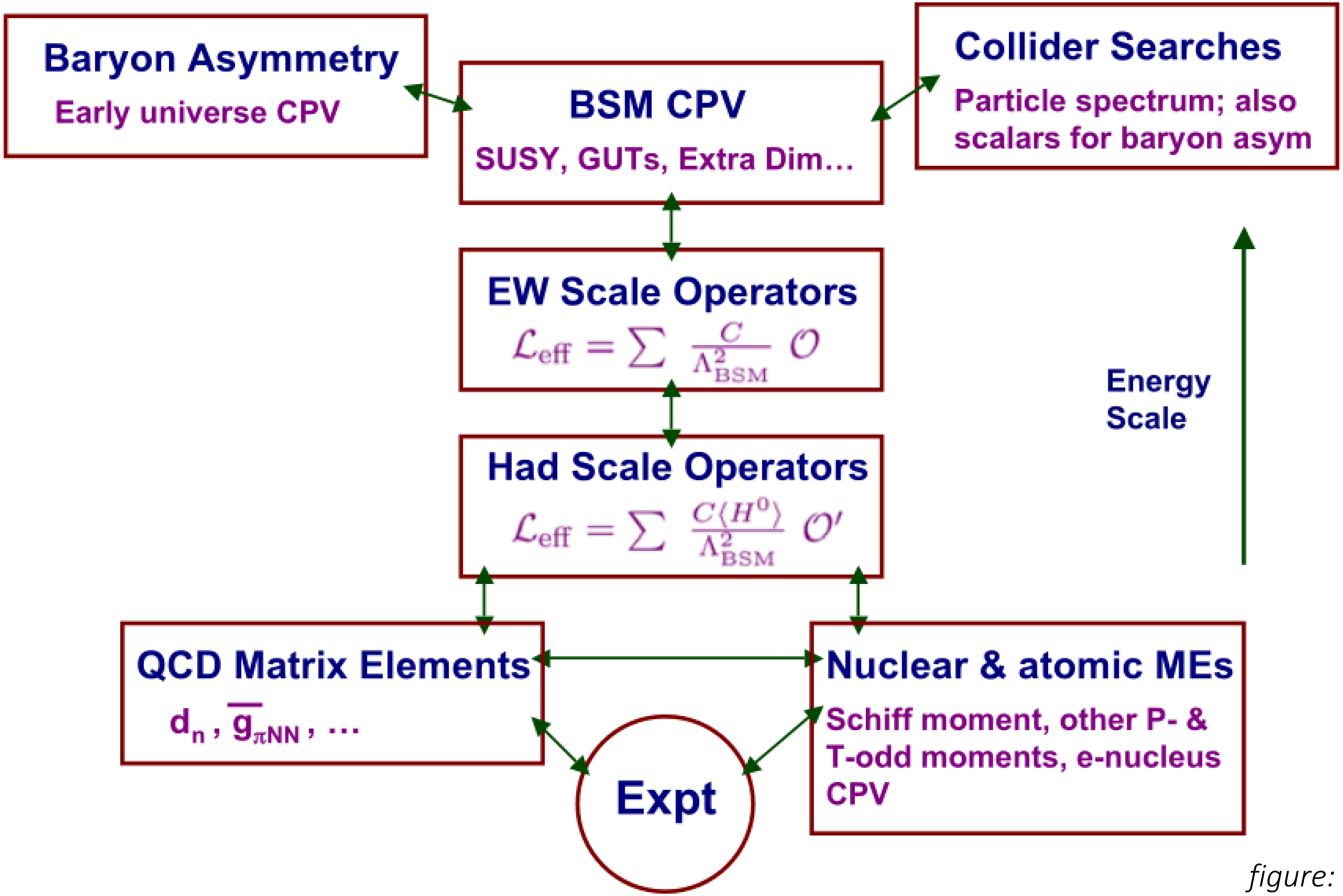
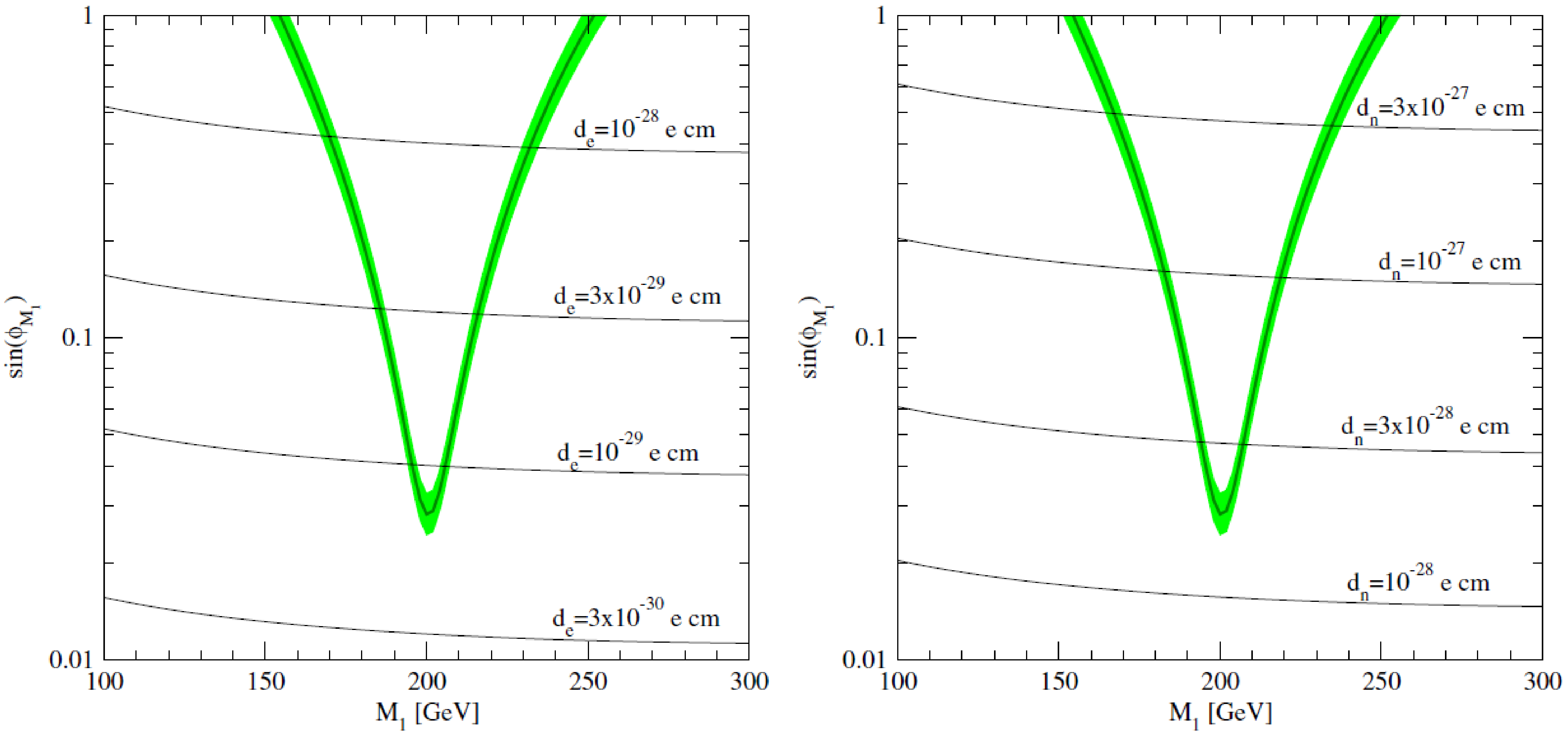


figure: Michael Ramsey-Musolf

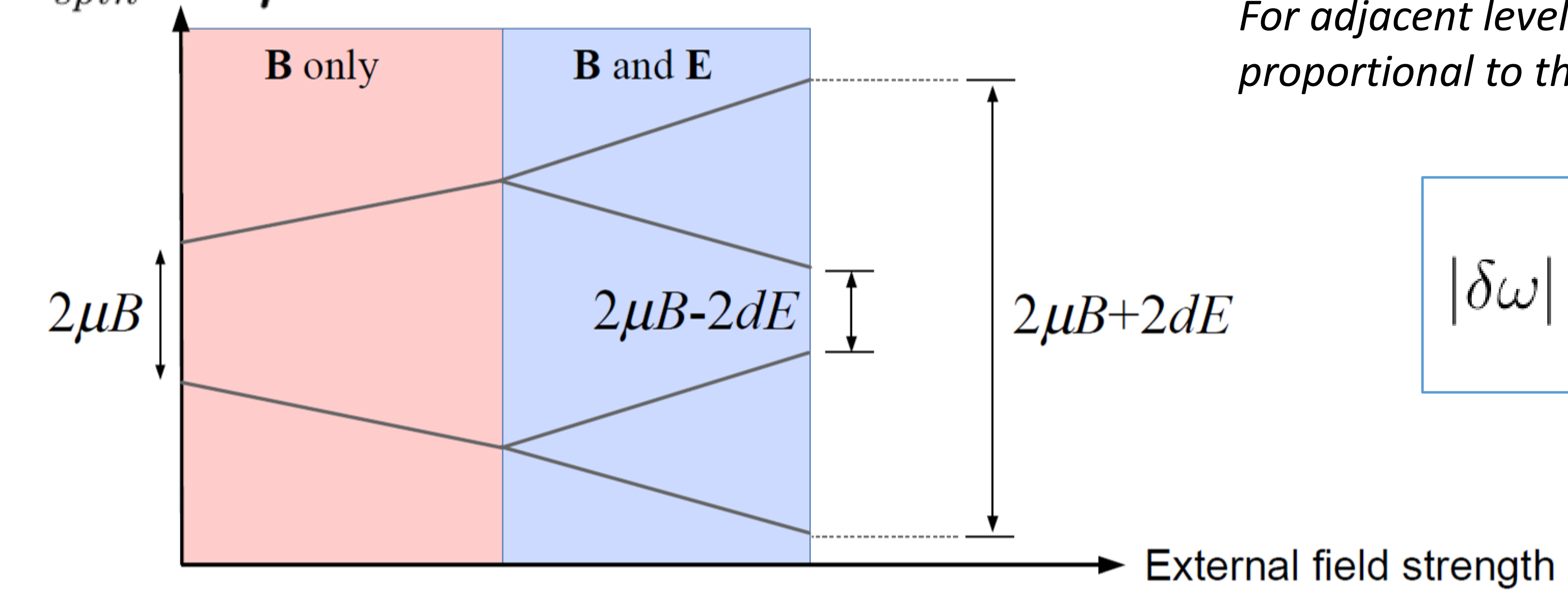
A case where EDMs set strong bounds



Li, Profumo, and Ramsey-Musolf
Phys. Lett. B ***673****, 95 (2009)*

How could you measure an EDM?

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



For adjacent levels we have a shift linear in E, and inversely proportional to the total angular momentum:

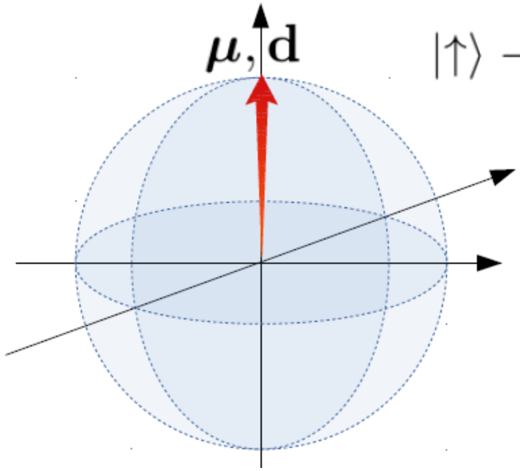
$$\boxed{|\delta\omega| = \frac{|dE|}{\hbar F} \qquad (\Delta m_F = 1)}$$

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

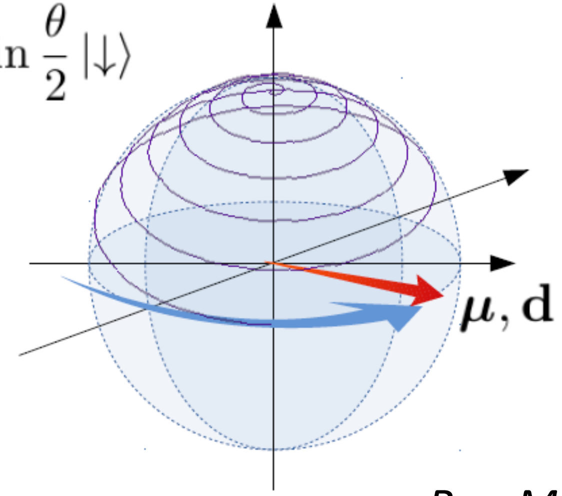
vious initial step toward understanding dynamical behavior. Second, in experimental physics a precision measurement is almost always a frequency measurement, and the easiest way to study an effect with precision is to find an observable frequency that is sensitive to that effect. In the case of dilute-gas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

How could you measure an EDM?

Listen to the Nobel Laureates, and actually measure frequencies:

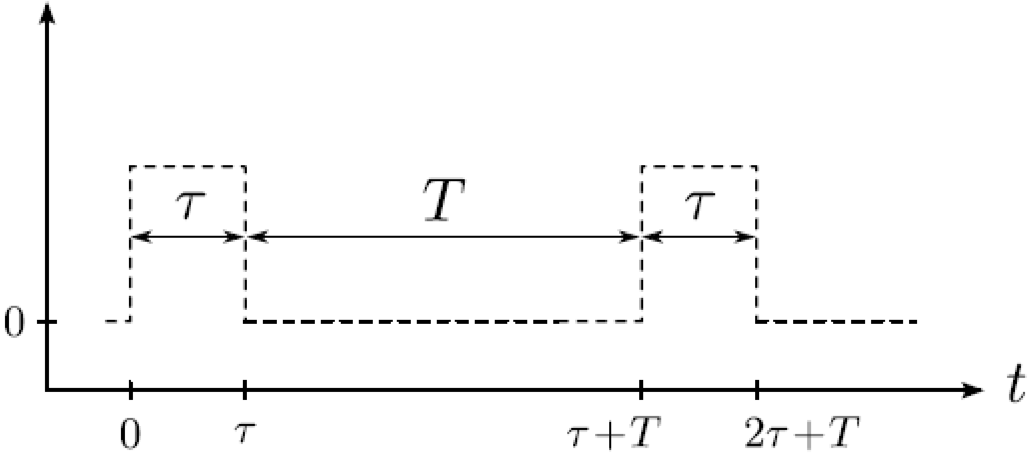


$$|\uparrow\rangle \longrightarrow \cos\frac{\theta}{2}\,|\uparrow\rangle + e^{i\omega t}\sin\frac{\theta}{2}\,|\downarrow\rangle$$



phase evolution:

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



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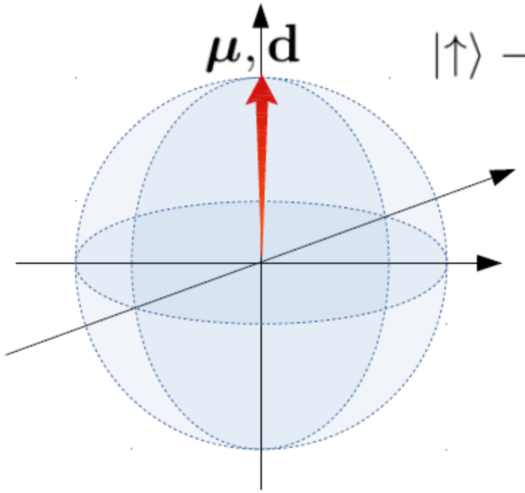

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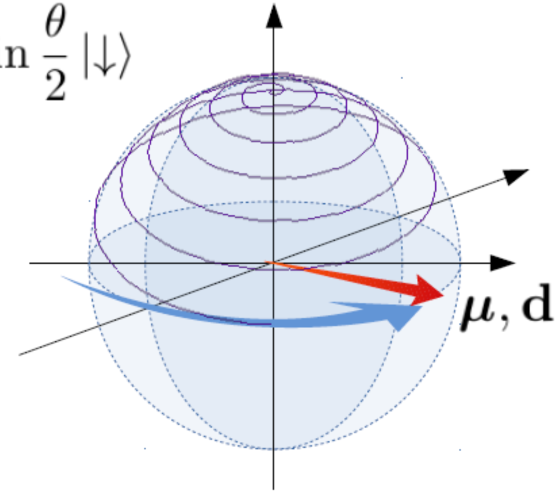

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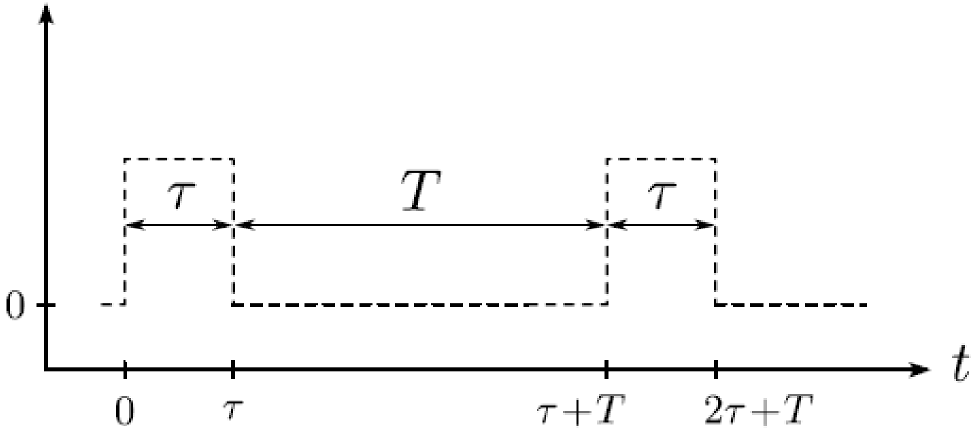
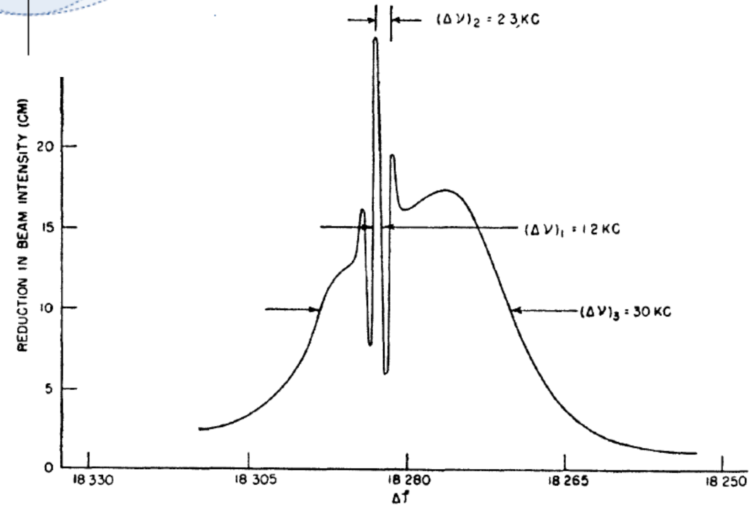


Ramsey Interferometry



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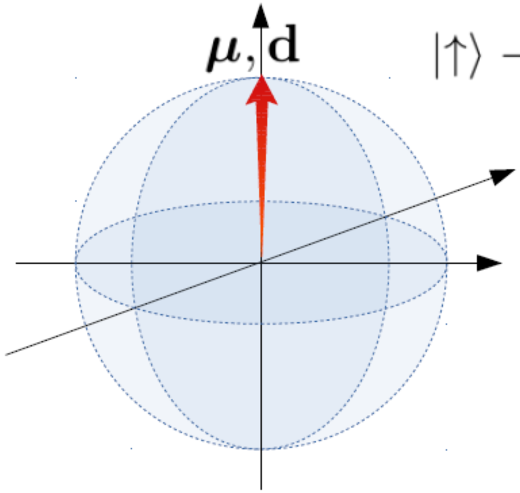

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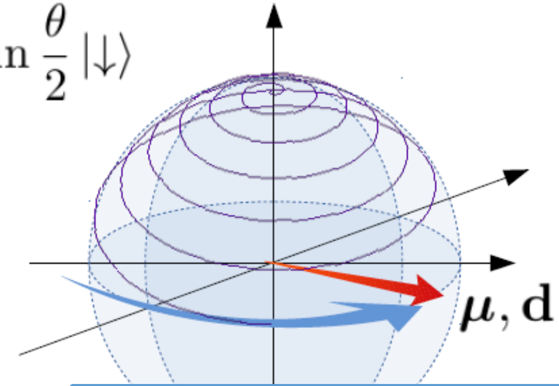

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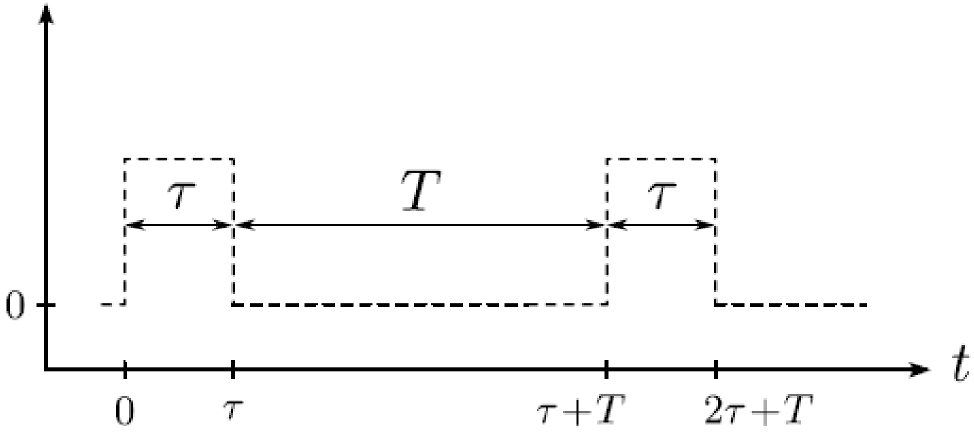
arXiv:2001.11966



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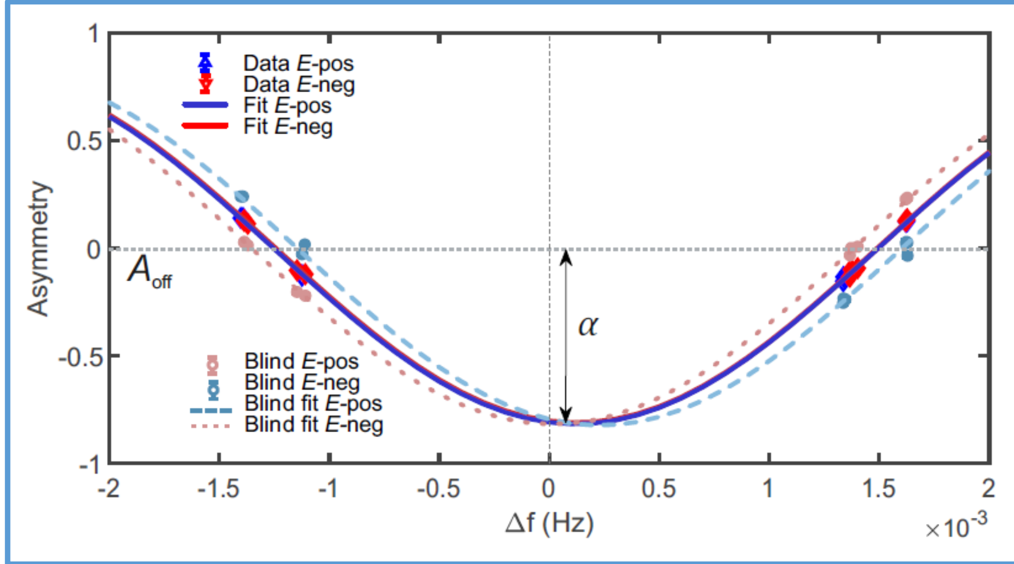

How could you measure an EDM?

If spin-precession is continuously observed:

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

$$\rightarrow \frac{h}{2ET_2}\frac{1}{\sqrt{\phi_n T_2}} \quad \text{Phase-noise limit}$$

$$\rightarrow \frac{h}{2ET_2}\frac{1}{\sqrt{N_\gamma}} \quad \text{Count-rate limit}$$

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

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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*

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

Hamiltonian of the charge-system (no EDM)

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

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

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

Add constituent EDMs
As a perturbation…

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

(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:

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

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*

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

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

…and we can even get lucky enhancements.

Octupole deformations:

PRL ***121**, 232501 (2018)*

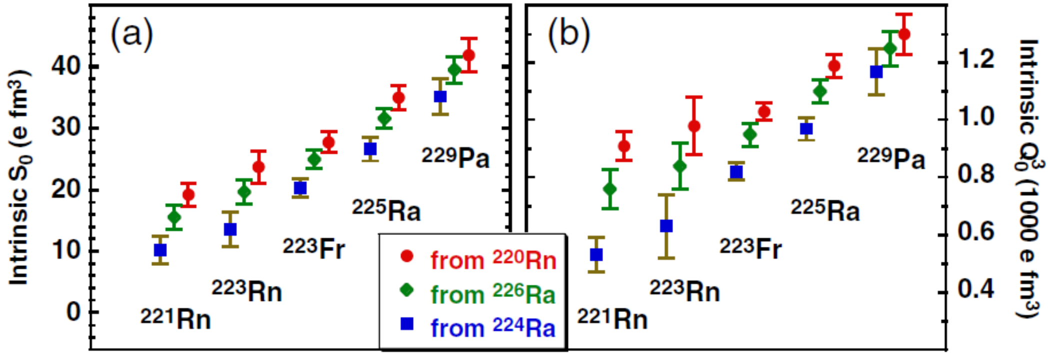
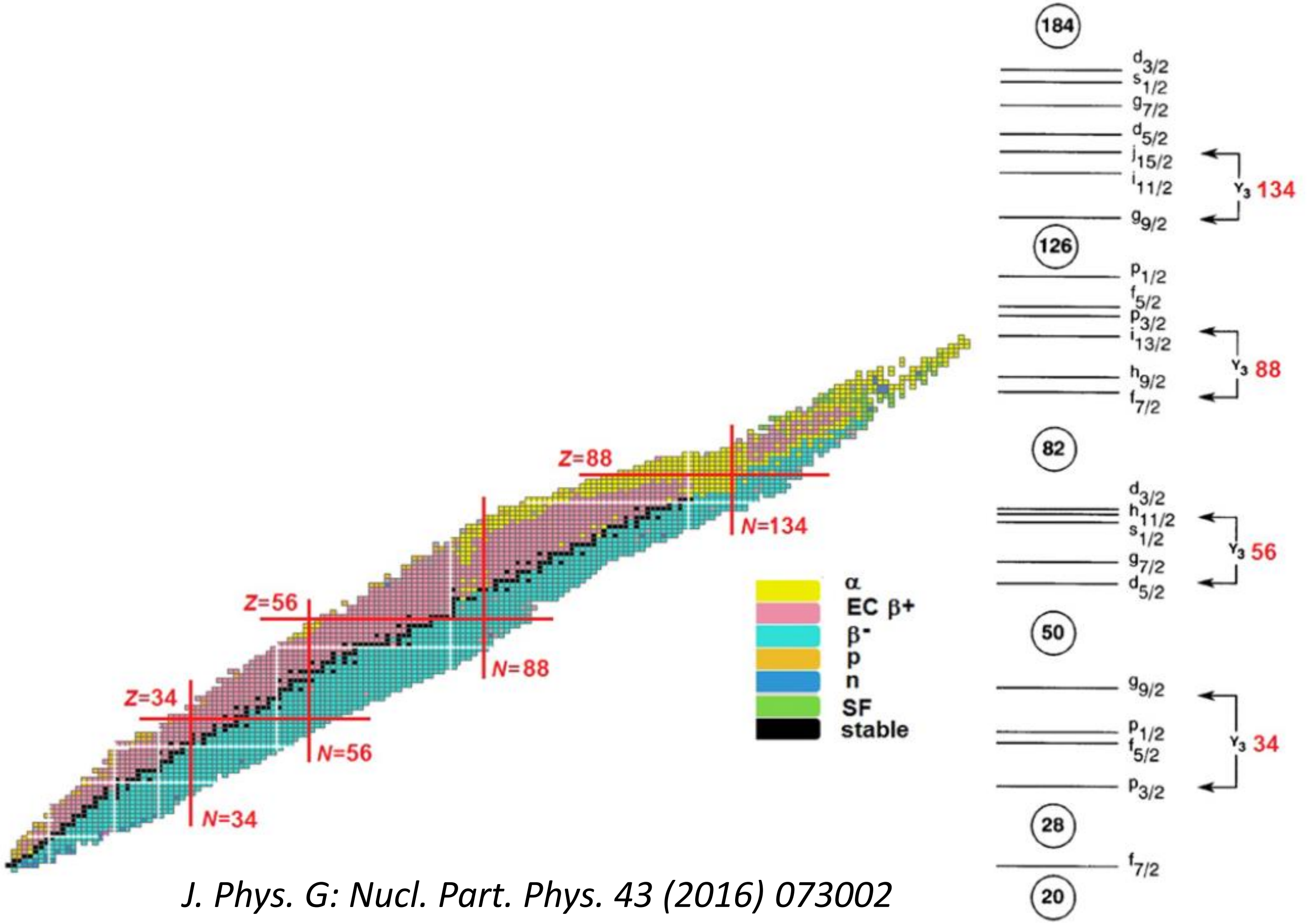


FIG. 3. Intrinsic Schiff moments S_0 in e fm^3 (a) and octupole moments Q_0^3 in units of 1000 e fm^3 (b) of ^{221}Rn, ^{223}Rn, ^{223}Fr, ^{225}Ra, and ^{229}Pa, determined from the experimental octupole moments of ^{224}Ra, ^{226}Ra, and ^{220}Rn.



J. Phys. G: Nucl. Part. Phys. 43 (2016) 073002

So which system should you measure?

So which system should you measure?

The one where you can discover an EDM, of course!

A "complete" experiment: HeXe as of Last October

- History of the experiment perhaps unusual… outer magnetic shield commissioned, but no UCN @FRM2 in 2013
- Complementarity of experimental techniques (as well as impact)

May 16, 2013

Attending:

Chupp, Nießen, Trahms, Degenkolb, Singh, Babcock, Fierlinger, F

Elements previously discussed:

- SQUIDS (only practical option due to sensitivity and small
- He-Xe combined cell
- Electric field (limited to $\sim$ 10 kV/cm, plastic box and gas to prevent discharge) …

October 4, 2019: $|d_A(^{129}\mathrm{Xe})| < 1.4 \times 10^{-27}\ e$ cm (95% C.L.)

New Limit on the Permanent Electric Dipole Moment of ^{129}Xe Using ^{3}He Comagnetometry and SQUID Detection

N. Sachdeva, I. Fan, E. Babcock, M. Burghoff, T. E. Chupp, S. Degenkolb, P. Fierlinger, S. Haude, E. Kraegeloh, W. Kilian, S. Knappe-Grüneberg, F. Kuchler, T. Liu, M. Marino, J. Meinel, K. Rolfs, Z. Salhi, A. Schnabel, J. T. Singh, S. Stuiber, W. A. Terrano, L. Trahms, and J. Voigt
Phys. Rev. Lett. **123**, 143003 – Published 4 October 2019

HeXe EDM Sensitivity + Shielding

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

$\longrightarrow$ require nHz per run

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

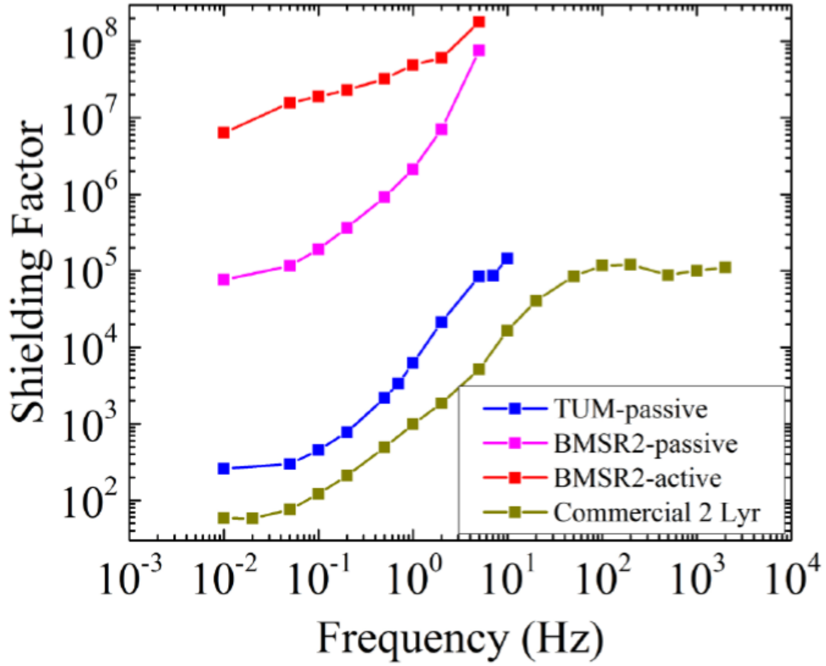
$\longrightarrow$ few $\times 10^{-27}$ e cm$/\sqrt{N}$

$E \sim 4$ kV/cm

$\tau \sim 4000$ s

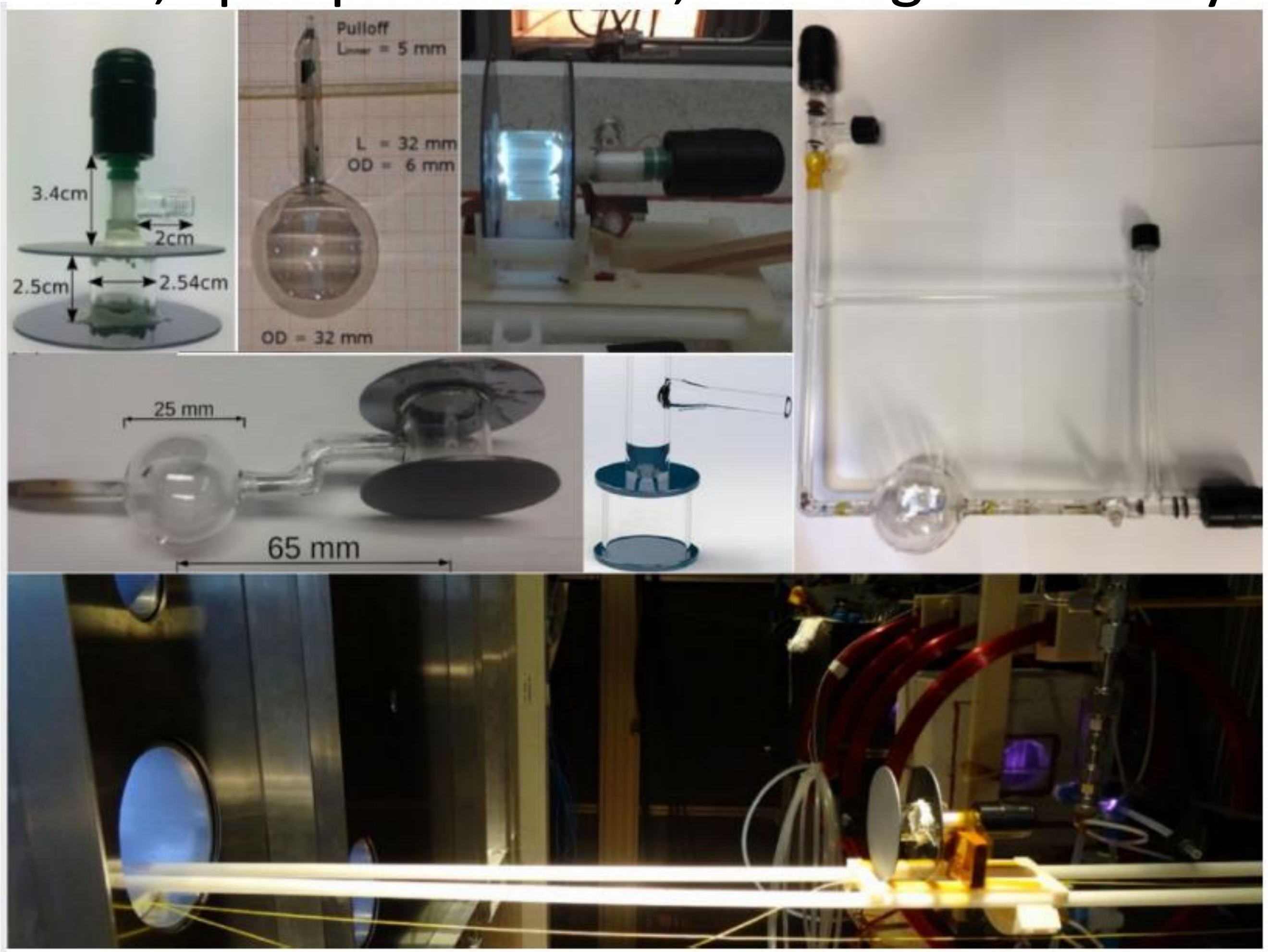
$S \sim 20$ pT

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

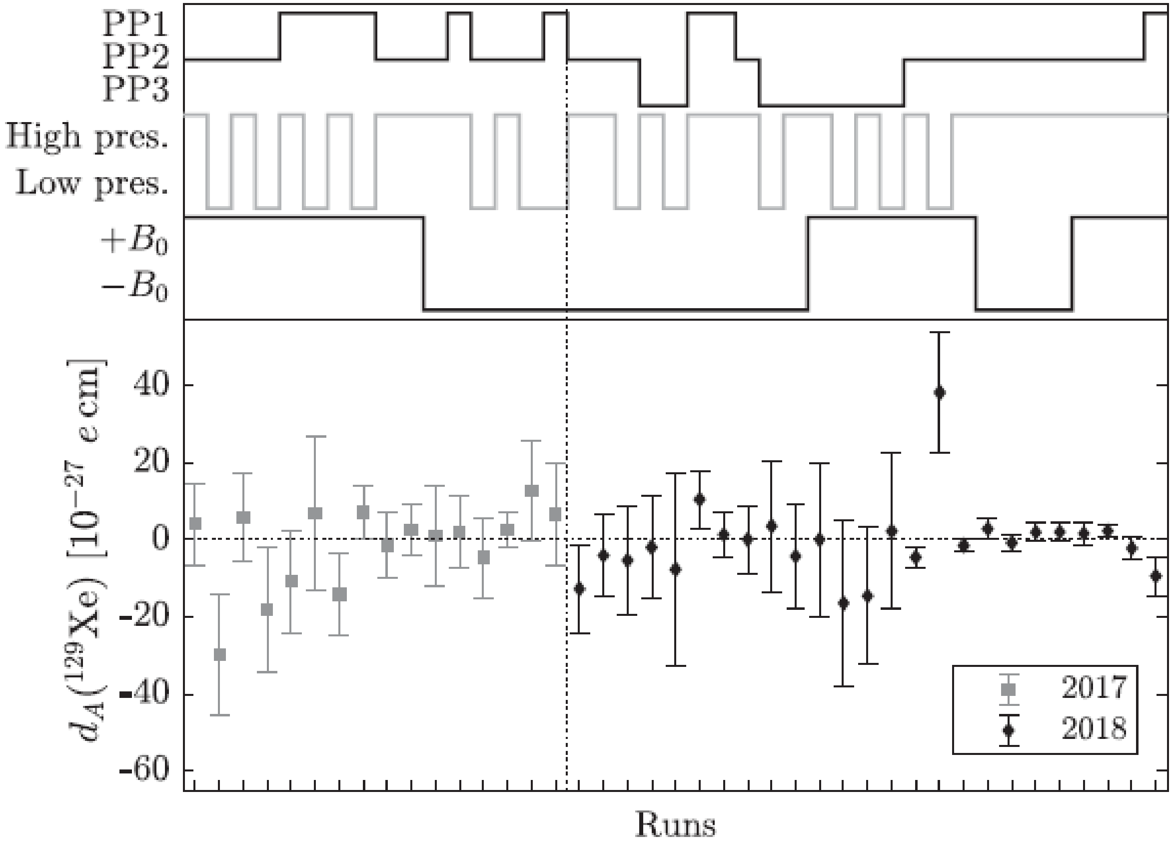


EDM Searches: more on HeXe and “complementarity”

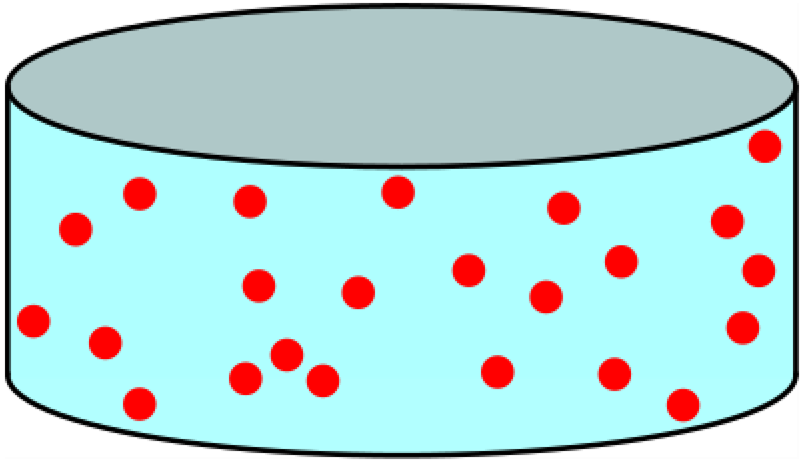
Cells, spin-polarization, co-magnetometry



Analysis methods



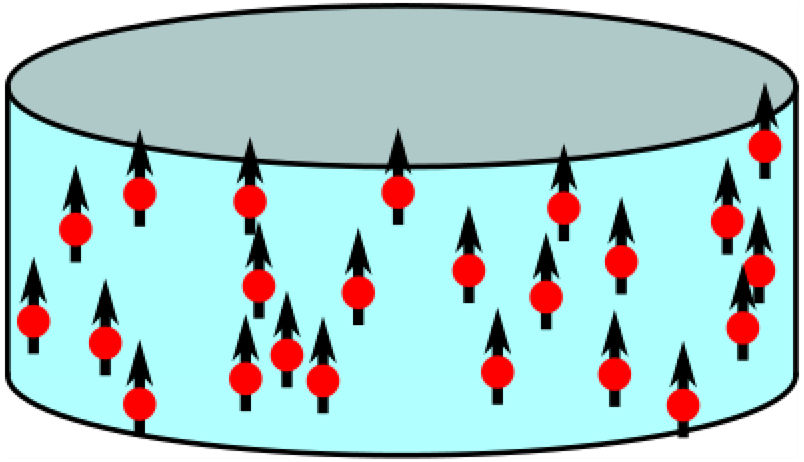
A Note on Systematic Effects



The Generic Storage Cell EDM Recipe:

1) Fill polarized particles into cell
2) Initiate spin precession (pulse/field)
3) Wait…
4) Measure (continuously/Ramsey pulse)
5) Repeat

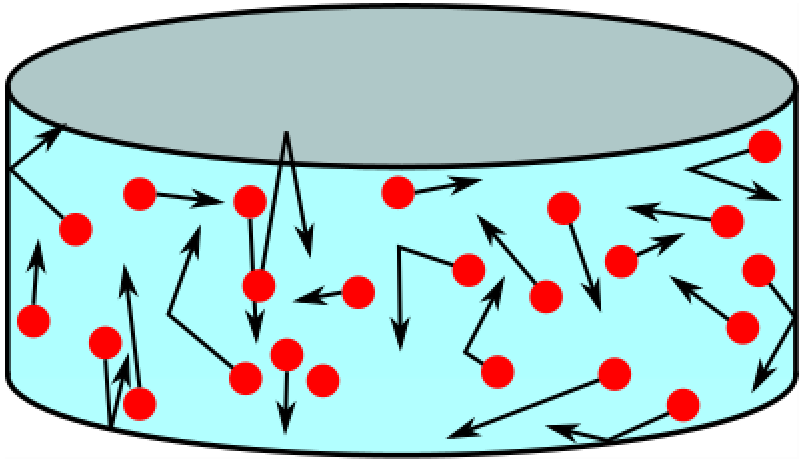
nEDM searches: Co-Magnetometry



<u>Problems for polarized spins in fields:</u>

Field uniformity
Field stability
Field gradients
Depolarization
…

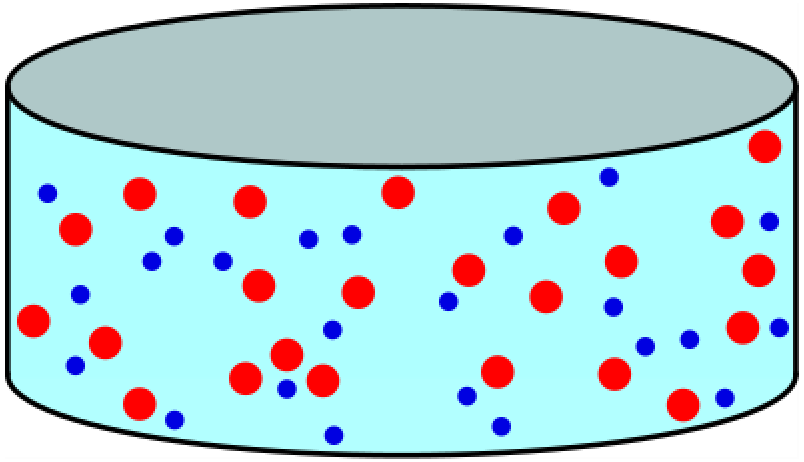
nEDM searches: Co-Magnetometry



Problems for polarized spins in fields:

- Field uniformity
- Field stability
- Field gradients
- Depolarization
- …
- Particle motion (volume averaging)
- Geometric phases
- Motional fields

nEDM searches: Co-Magnetometry



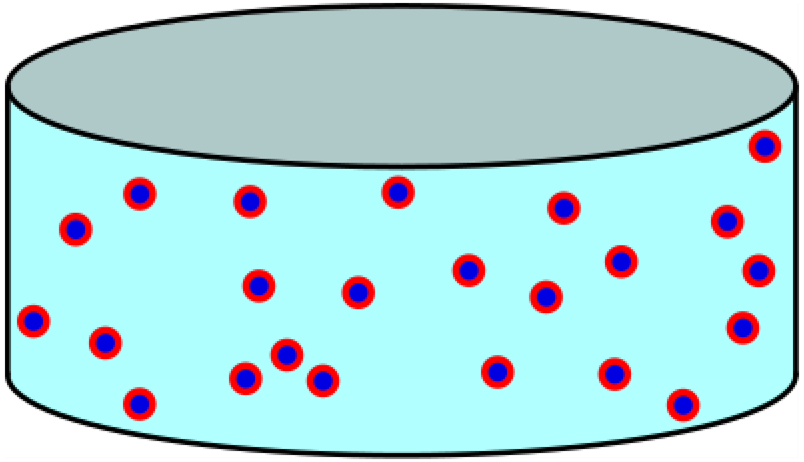
<u>Co-magnetometry:</u>

Measure a *difference* of two EDMs,

$$\omega_{\mathrm{co}} = \omega_1 - R\omega_2$$

correct automatically for “magnetic” physics

nEDM searches: Co-Magnetometry



Co-magnetometry:

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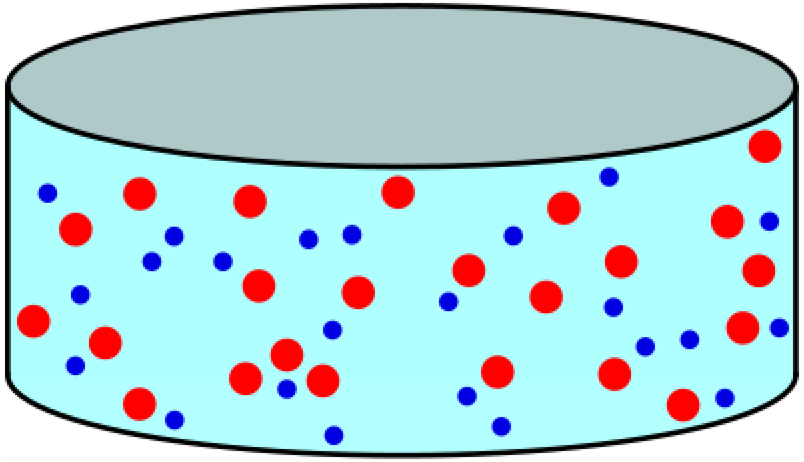
nEDM searches: Co-Magnetometry



<u>Co-magnetometry:</u>

Not so simple…

$$\begin{aligned}\omega_{\text{co}} \approx \omega_d &- \gamma_2' \Delta R |\boldsymbol{B}| \\ &+ (1-R)\boldsymbol{\Omega}\cdot\hat{\boldsymbol{B}} \\ &+ \gamma_1' \langle \Delta B_1 \rangle - \gamma_1' \langle \Delta B_2 \rangle \\ &+ \left(\omega_1^{\text{sd}} - R\omega_2^{\text{sd}}\right)\end{aligned}$$

nEDM searches: Good Co-Magnetometry is Hard

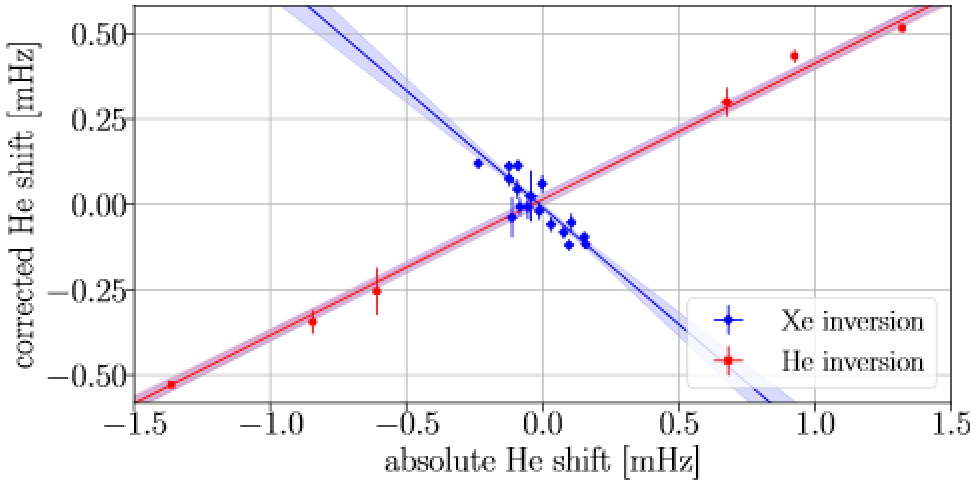


FIG. 5. Change in the absolute (ω_{He}) and corrected ($\widetilde{\omega}_{\mathrm{He}}$) ^{3}He frequencies when the longitudinal magnetizations of ^{129}Xe and ^{3}He are inverted (blue diamonds and red squares). Measurements taken in the valved cell, some errors are hidden by the symbols. The slope of the lines measures the shifts in the ratios of interest, with 1-σ error (shaded) from the covariance of the fit to a line. If the comagnetometer correction canceled frequency shifts from longitudinal magnetization (Eq. 2b) the lines would be horizontal.

Phys. Rev. A **100**, 012502 (2019)

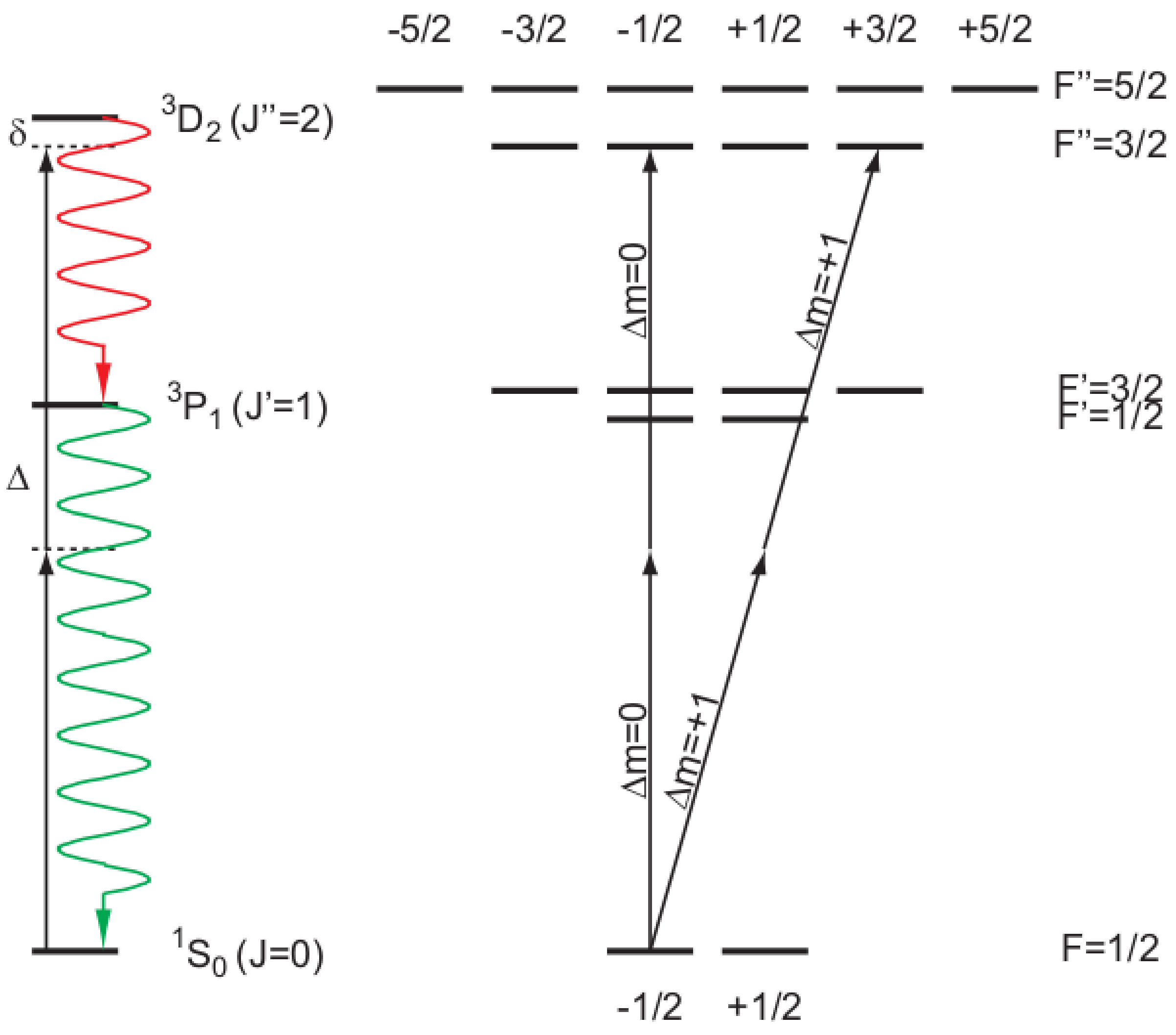
<u>Co-magnetometry:</u>

Not so simple…

$$
\begin{aligned}
\omega_{\mathrm{co}} \approx \omega_d &- \gamma_2' \Delta R |\boldsymbol{B}| \\
&+ (1 - R)\boldsymbol{\Omega} \cdot \hat{\boldsymbol{B}} \\
&+ \gamma_1' \langle \Delta B_1 \rangle - \gamma_1' \langle \Delta B_2 \rangle \\
&+ \left(\omega_1^{\mathrm{sd}} - R\omega_2^{\mathrm{sd}}\right)
\end{aligned}
$$

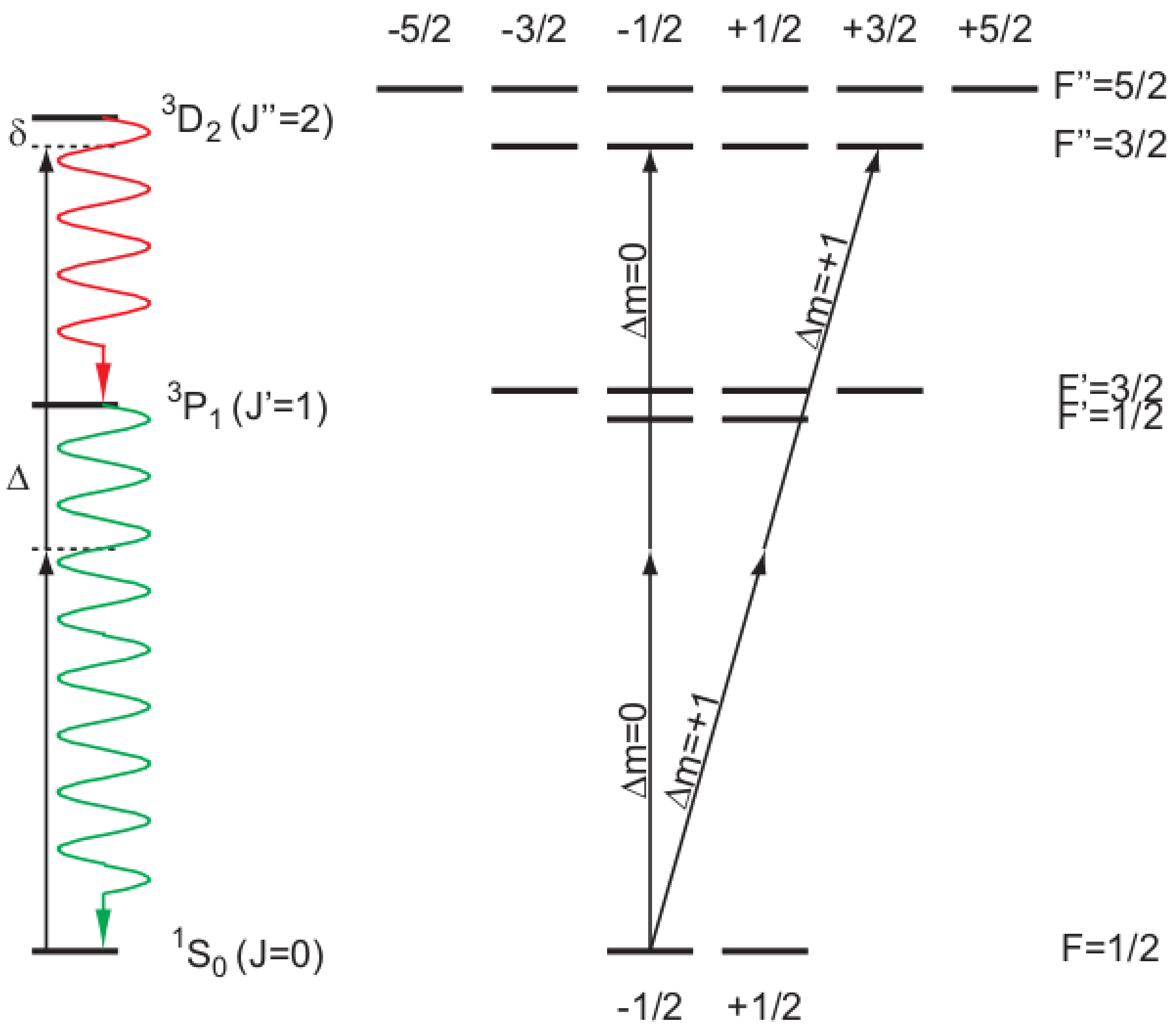
“New” Detection Methods: Laser Spectroscopy

- No strong cycling transition
  - No unwanted chemistry
- Can't use coils at low field
  - Optical detection preferred
- Nuclear magnetic moment
  - Well-shielded
- Faraday rotation very weak
  - Fluorescence is background-free
- Nonlinear scattering rate
  - Can be used to get spatial resolution

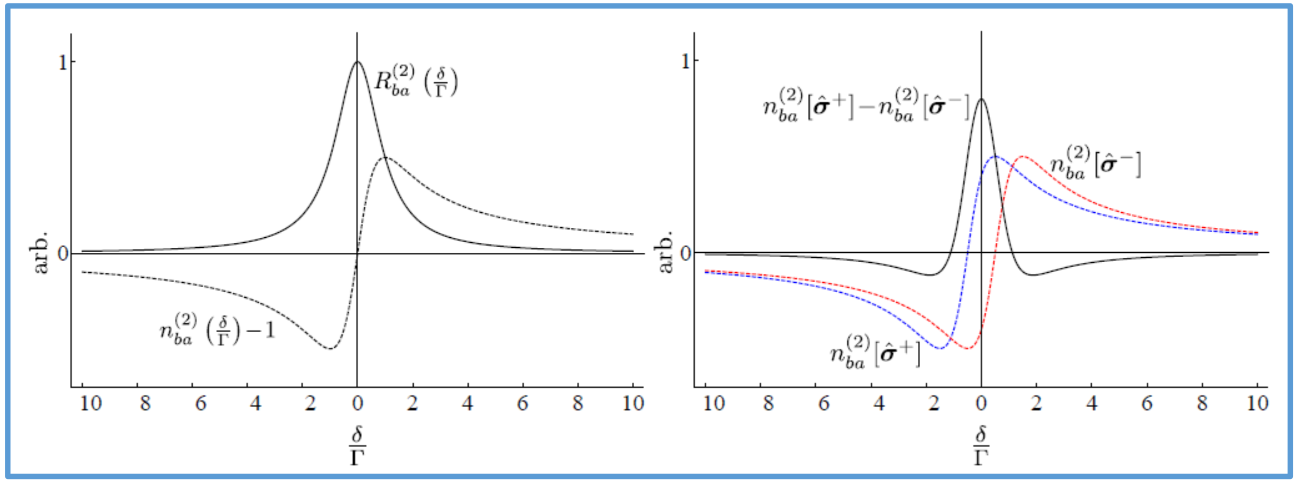


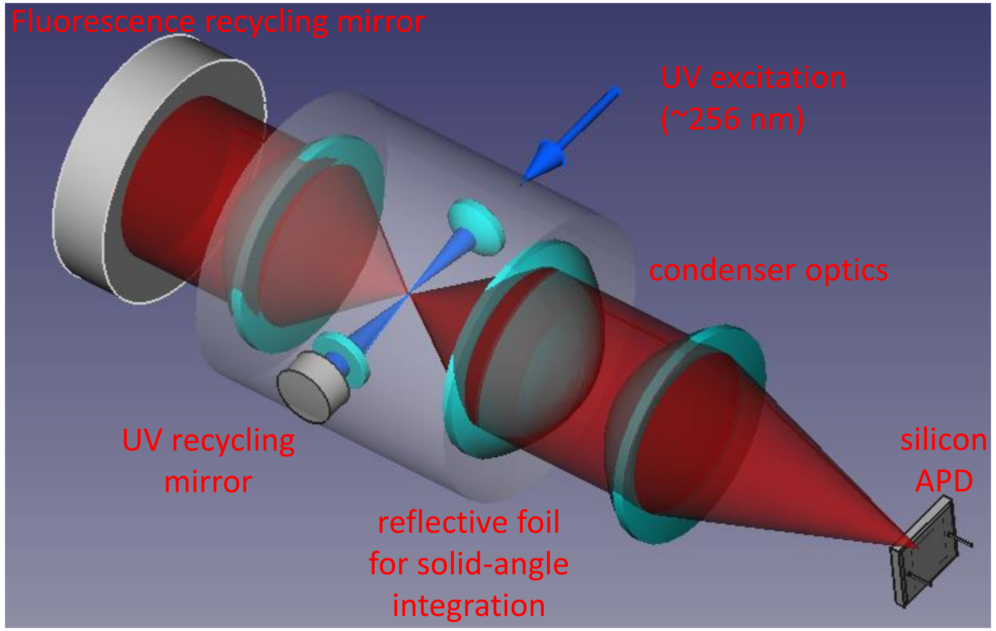
“New” Detection Methods: Laser Spectroscopy

- So what can we do with it?
  - Use “new” atoms for magnetometry, EDMs
  - Direct excitation to metastable levels
  - Study isotope shifts and hyperfine structure
  - Trapping and cooling (atoms *and* molecules)
    - Especially with frequency combs, for repump
  - Optical pumping of “difficult” atoms (given enough photons)
  - Access to “wrong-parity” states (even *N*)



Multiphoton Spectroscopy for Nuclear Spins





- Perturbation theory:

$$R_{ba}^{(n)} = \left| \frac{E^n}{\hbar^n} \sum_{i,j,\ldots,k} \frac{d_{ai} d_{ij} \cdots d_{kb}}{\Delta_{ia}^{(n-1)} \Delta_{ja}^{(n-2)} \cdots \Delta_{ka}^{(1)}} \right|^2 2\pi\rho(\delta)$$

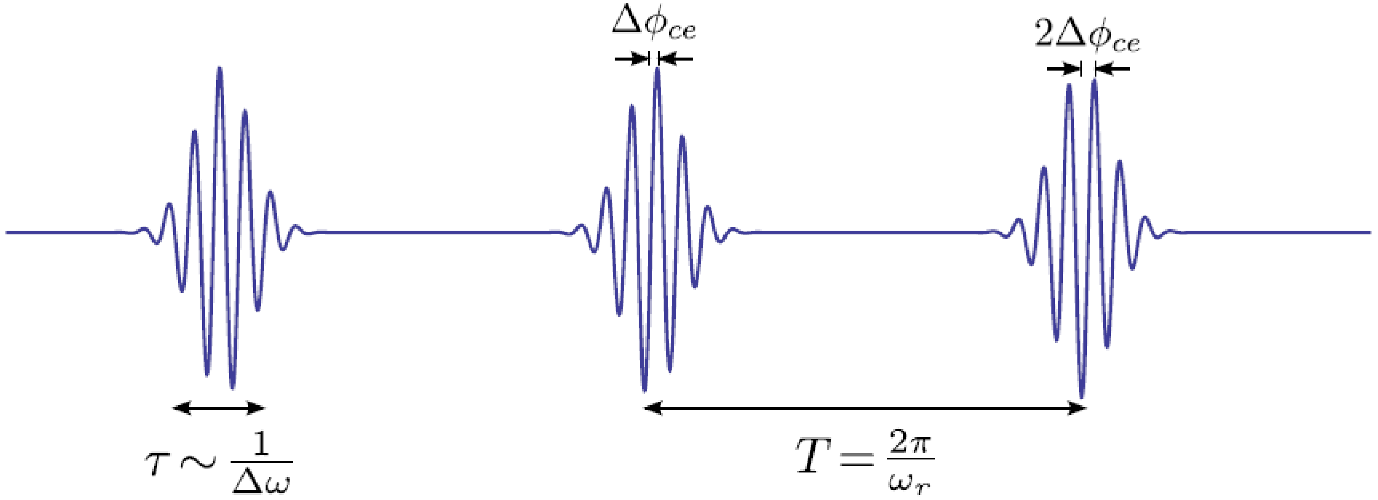
- Two-photon effective operators [*Bonin, **JOSA B** 1(1),52-55 (1984)*]:

$$R_{ba}^{(2)} \propto \left| \sum_k \sum_{J=0}^{2} \left\langle \gamma F_b \left\| D^{(J)}(k) \right\| \delta F_a \right\rangle (-1)^{F_b+J+2F_a} \sqrt{2J+1} \sum_{\mu,\nu=0,\pm 1} \sum_M (-1)^{M_b} \begin{pmatrix} F_b & J & F_a \\ -M_b & M & M_a \end{pmatrix} \begin{pmatrix} J & 1 & 1 \\ -M & \mu & \nu \end{pmatrix} \right|^2$$

- Two-photon "cross-sections":

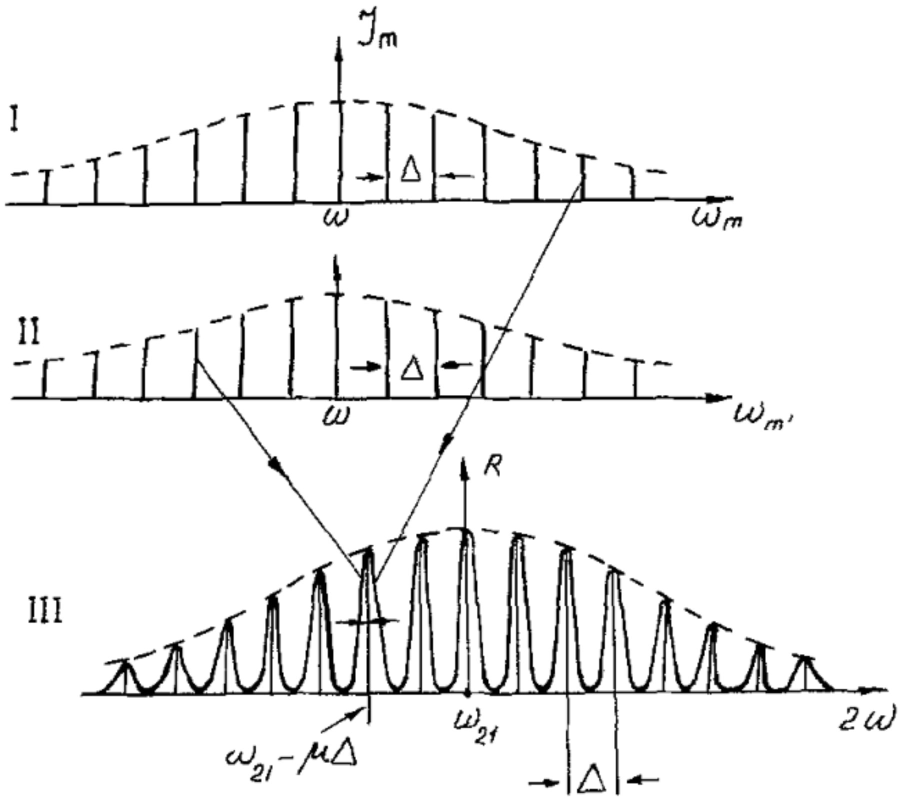
$$R_{ba}^{(2)} = (2\pi)^3 a_0^4 t_0 \alpha^2 \omega_1 \omega_2 \sigma^{(2)} F_1 F_2$$

A Brief Introduction to Modelocked Lasers



- Optical spectrum determined by two independent RF parameters
- Higher *peak* (power conversion efficiency and scattering rate)
- Technical: better in terms of cavities and optics damage

Appl. Phys. 12, 97-99 (1977)



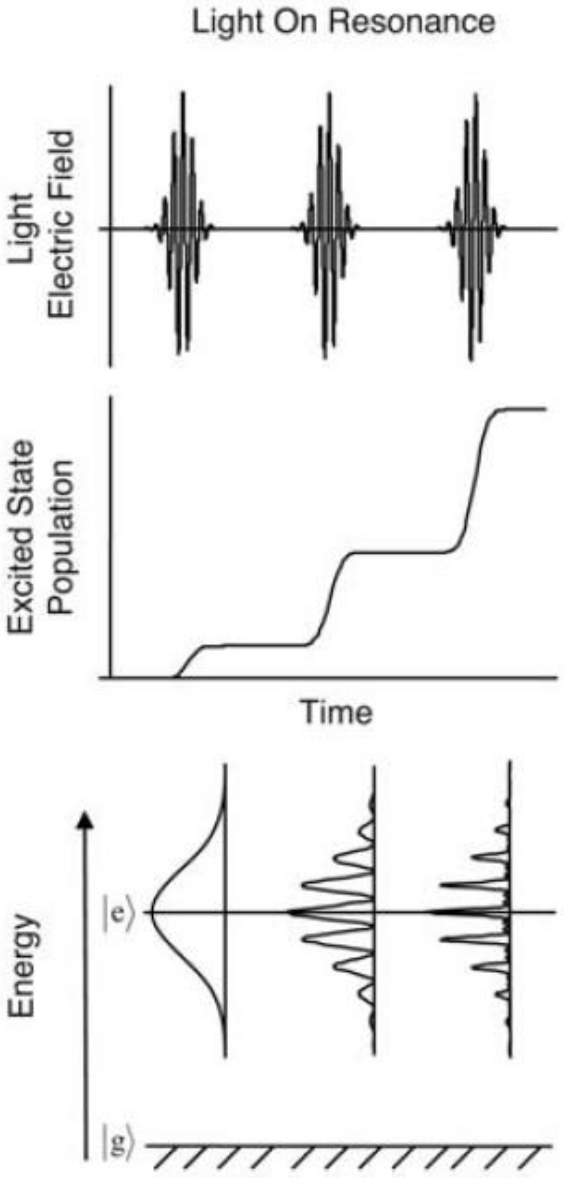
…already proposed in 1977 to get more 243nm laser power for hydrogen 1S-2S!

A Brief Introduction to Modelocked Lasers

$$\mathcal{E}^{(N)}(t) \equiv \sum_{n=0}^{N-1} \mathcal{E}(t - nT)$$

$$\tilde{E}^{(N)}(\omega) = \frac{1 - e^{iN\omega T}}{1 - e^{i\omega T}} \tilde{E}(\omega)$$

$$I^{(N)}(\omega) = \frac{1 - \cos(N\omega T)}{1 - \cos(\omega T)} I(\omega)$$



Atomic Excitation by *Two-Photon Direct Frequency Comb Spectroscopy*

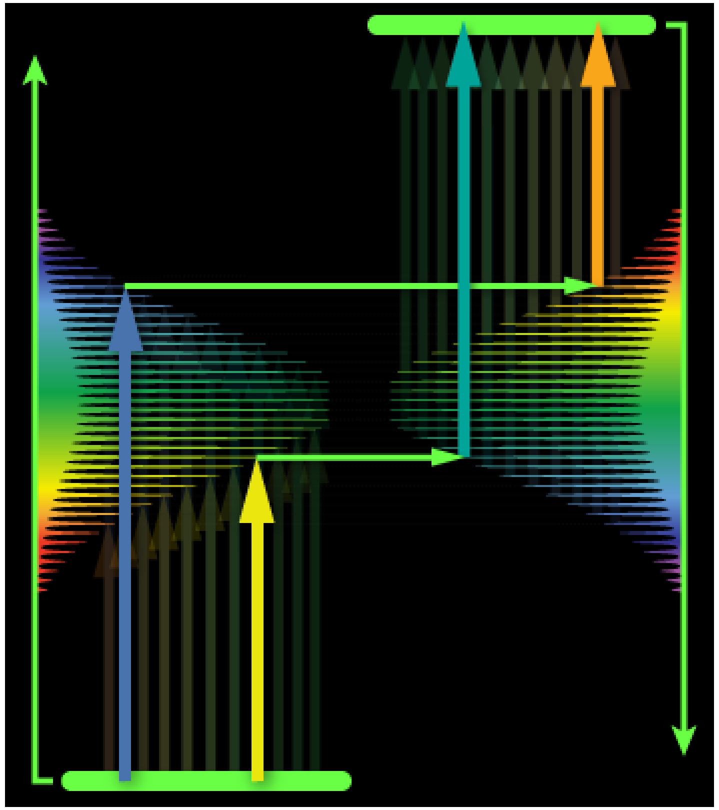
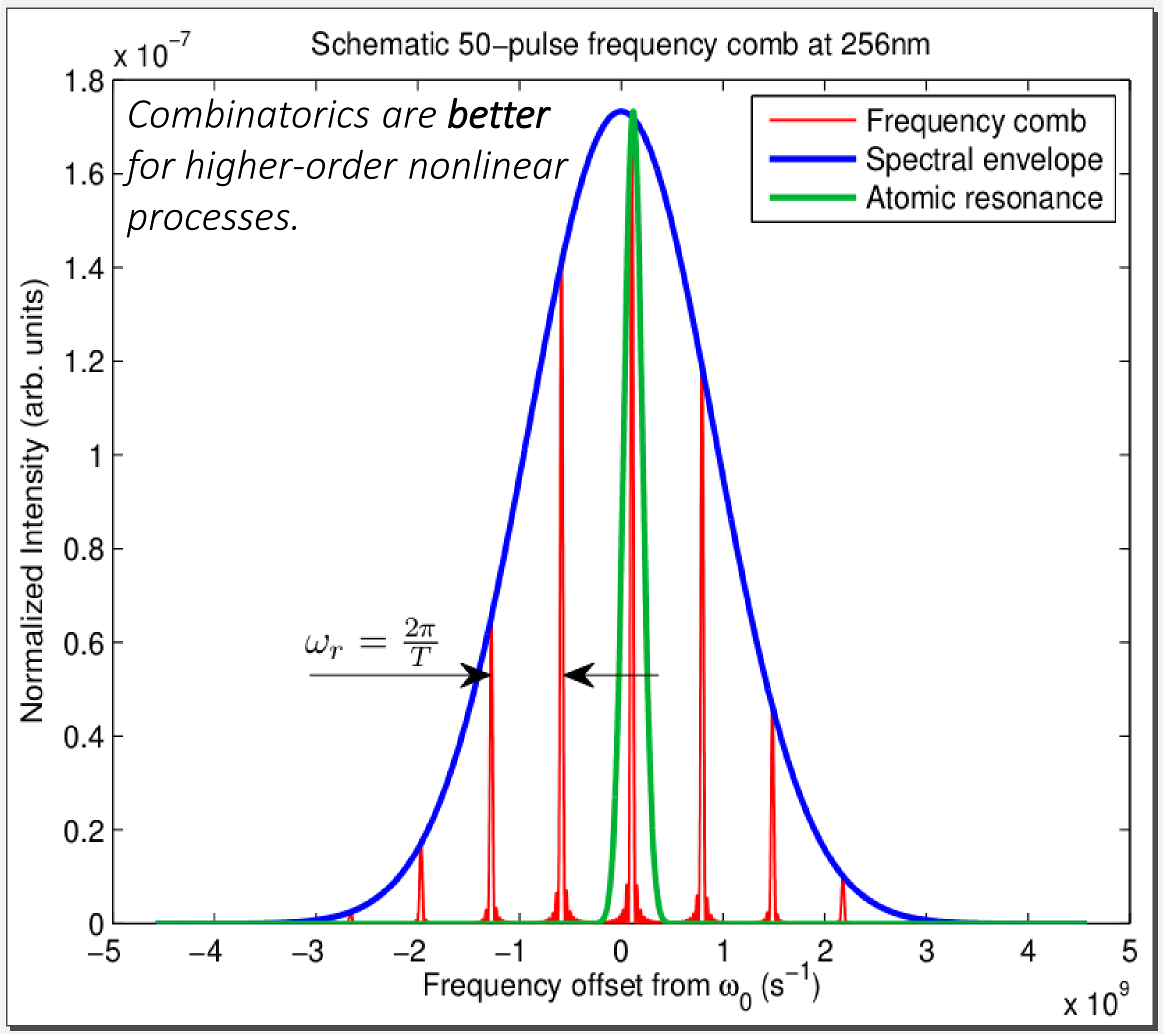


Figure: W. Campbell, see also
PRX 6, 041004 (2016)

Siegman, *Lasers*
Stowe, DOI:10.1016/S1049-250X(07)55001-9

Caveats...



Note: pulse chirp causes problems, and the spectral phase must be well-controlled to use the full comb power!

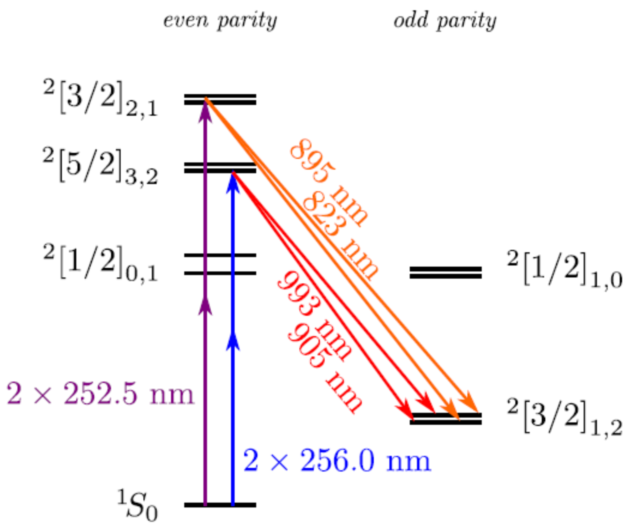
$$\langle e|M|g\rangle \sim e^{-2i(\omega_0-\omega_c)t}\sum_k A_k A_{-k} e^{i(\phi_k-\phi_{-k})}$$

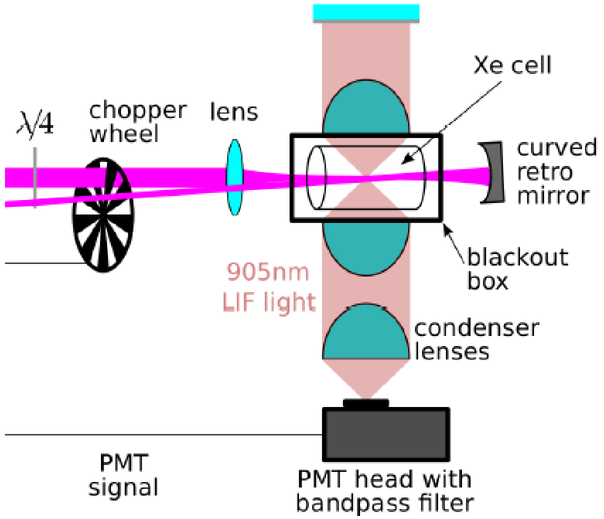
...chirp precompensation can avoid this to some extent.

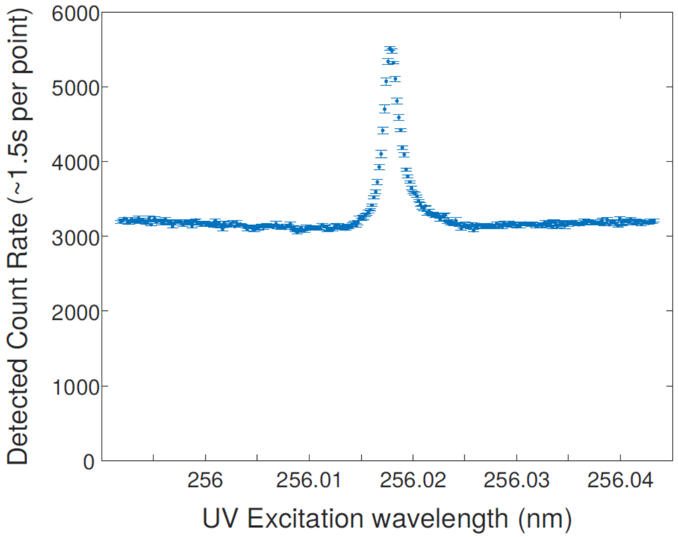
Also watch out for different intermediate-state detunings, and photoionization cross-sections from the excited state!

Proof-of-Principle: Yb Beam (pulsed), Xe Cell (cw)

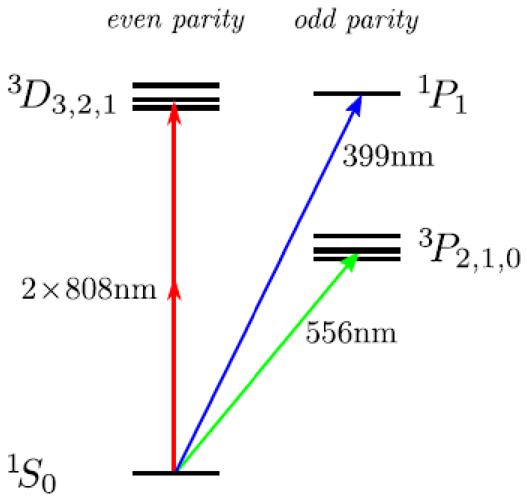
Xe

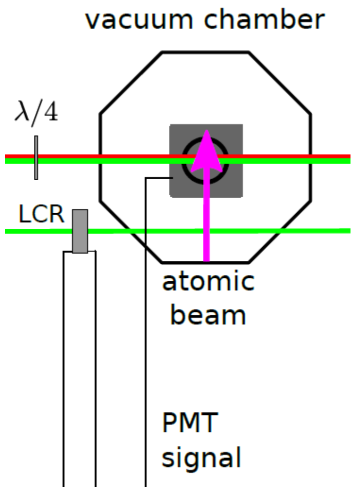


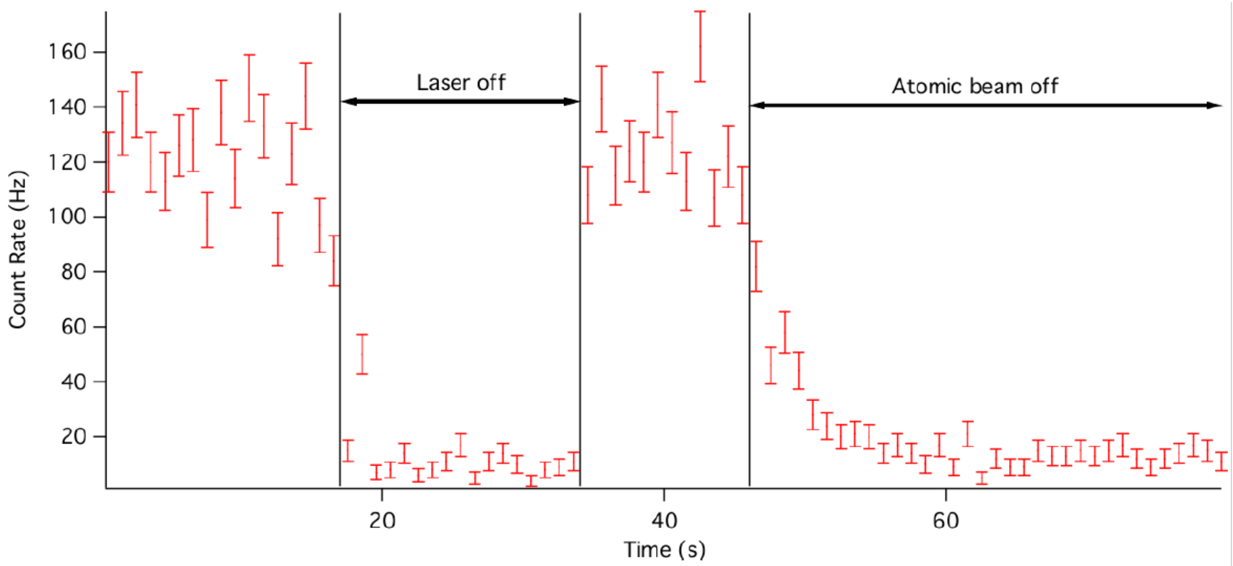




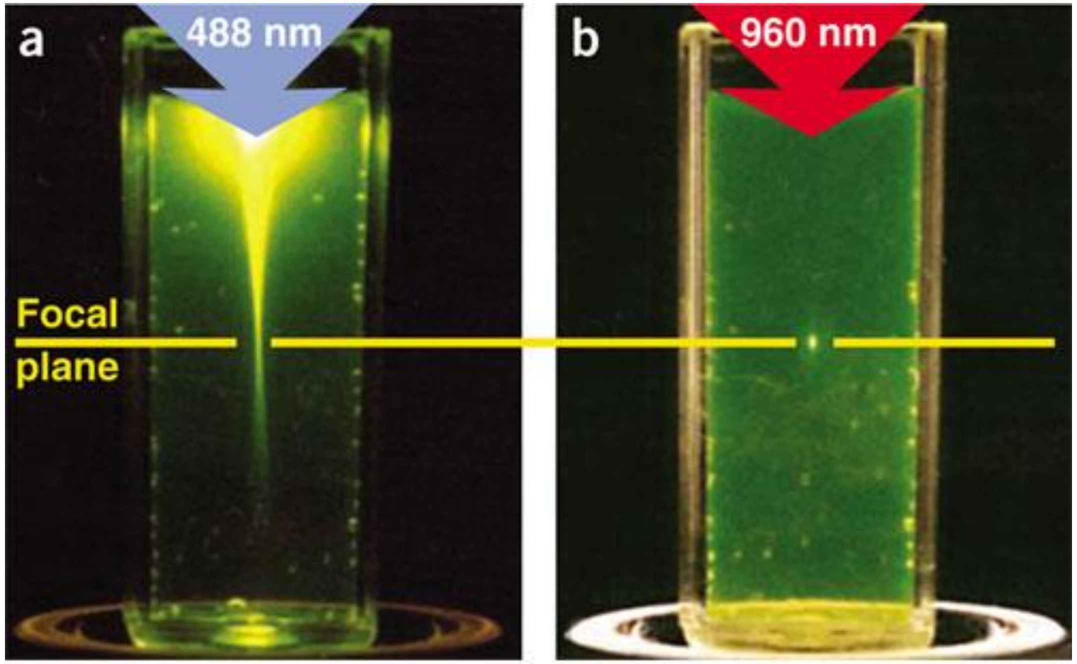
Yb







New Features: Spatial Resolution



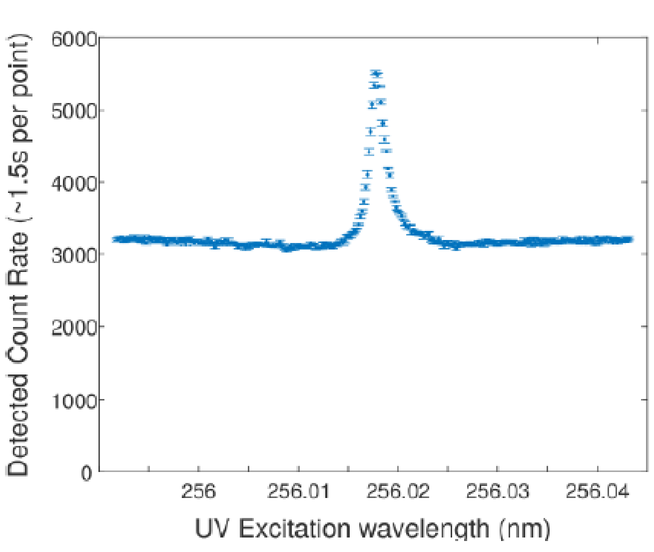
R. Boyd, *Nonlinear Optics*

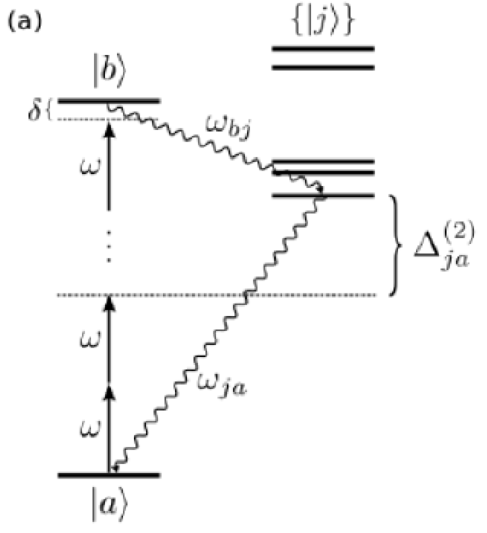
$$R \sim \rho V I^2 \sim \rho(\pi w_0^2)(\frac{\pi w_0^2}{\lambda})\frac{P^2}{(\pi w_0^2)^2}$$
$$\sim \rho\frac{P^2}{\lambda}$$

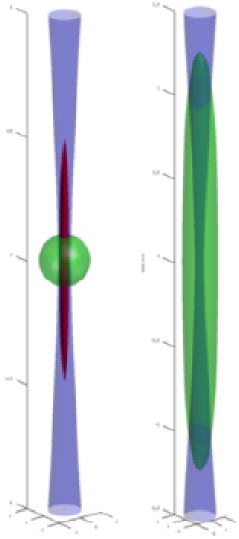
- Diffusion time T ~ $4L^2/v\lambda$
- λ ~ 1mm for co-magnetometer densities
- T ~ several seconds, for L ~ few cm
- Higher pressure: still OK for external cells
- GP suppressed by short mean free path
- Collisions reset motional fields, but not vertical gradients
- High resolution spatial maps
  - extract spatial frequencies within storage volume...

Long-Term Impact: Beyond Nuclear EDMs

Optical Xe Excitation	Multiphoton Magnetometry	New Properties







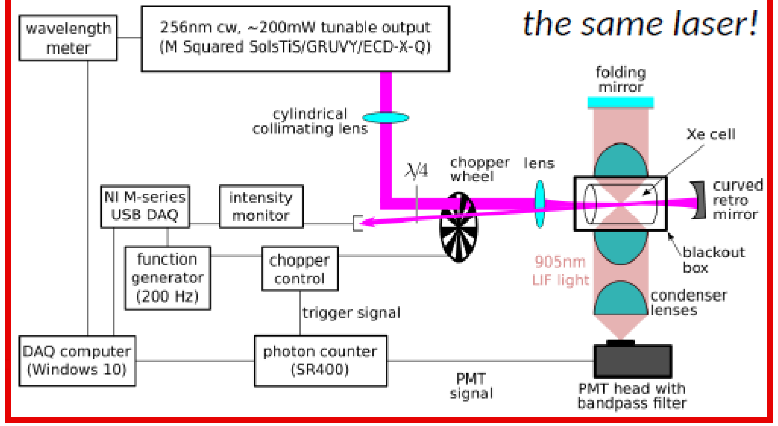
- New atomic species
- Direct nuclear polarization without SEOP/MEOP
- Spatial resolution and systematics
- Schiff/nuclear EDMs

octupole-deformed nuclei

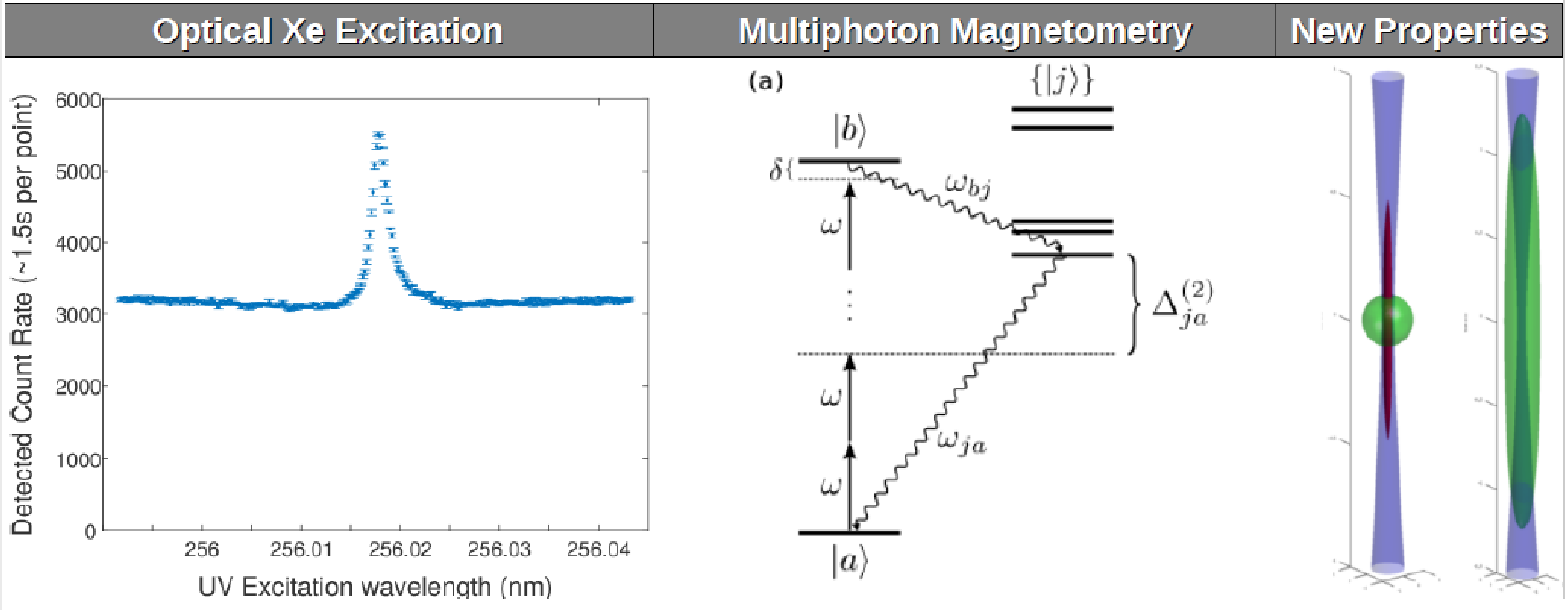
projected error budget for EDM of ^{223}Rn

	TRIUMF - γ Anisotropy	Laser	FRIB
Production (s^{-1})	2×10^7	2×10^7	2×10^9
N_γ (1 minute)	7×10^6	10^9	10^{11}
σ_d (1 day)	3×10^{-25}	3×10^{-26}	3×10^{-27}
σ_d (30 days)	5×10^{-26}	5×10^{-27}	3×10^{-28} (100 days)

EDM sensitivity for 223Rn, assuming E = 10kV/cm and τ = 15s, with a 50% duty cycle.



Long-Term Impact: Beyond Nuclear EDMs



- Interesting wavelengths (non-exhaustive)
  - 257nm: Rn
  - 256nm: Xe
  - 215nm: Kr
  - 215nm: He (4 photons)
  - 207nm: N
  - 205nm: H (1S-3D)

octupole-deformed nuclei

projected error budget for EDM of ^{223}Rn

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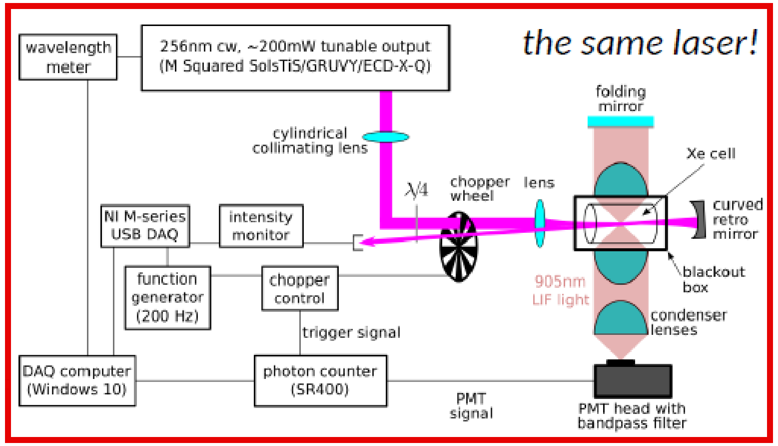


A Generic Introduction to Neutrons

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
$2{\times}10^3 – 2{\times}10^4$ m/s	Hot	20 meV – 2 eV

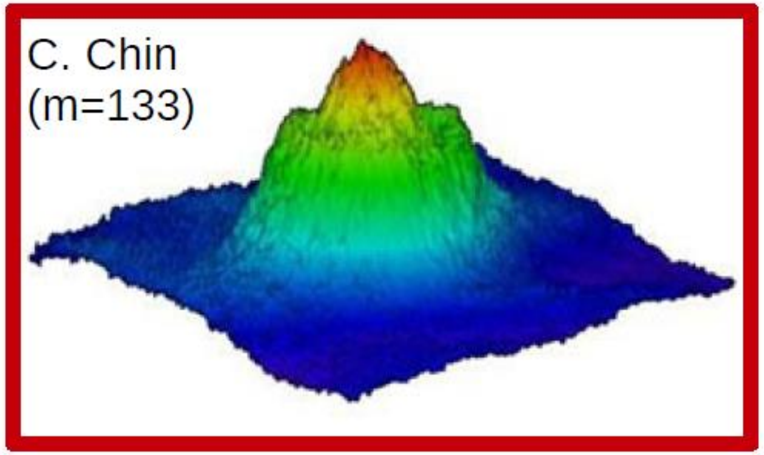
mass = 1.0087 amu
spin = ½ (μ = -1.9 μ_N)
τ_β = 880 s

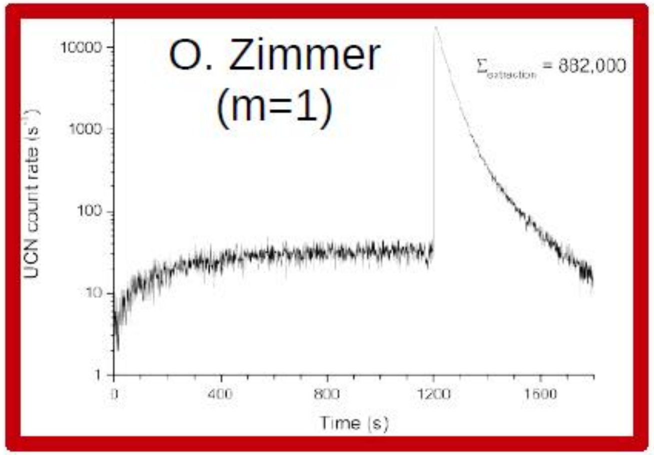
mgh = 103 neV (h = 1 m)
μB = 60 neV (B = 1T)
U_S = 168 neV (copper in vacuum)

can also bind two H nuclei and possibly also one H nucleus. In the one case, this entails the possible existence of an atom of mass nearly 2 carrying one charge, which is to be regarded as an isotope of hydrogen. In the other case, it involves the idea of the possible existence of an atom of mass 1 which has zero nucleus charge. Such an atomic structure seems by no means impossible. On present views, the neutral hydrogen atom is regarded as a nucleus of unit charge with an electron attached at a distance, and the spectrum of hydrogen is ascribed to the movements of this distant electron.

–Rutherford, 1920 (Bakerian lecture)

“Ultracold” Translation Table…





Number of Particles	10^4	90×10^4
“Temperature”	10^{-5} mK	1 mK
Wavelength	1.5 μm	0.1 μm
Velocity	10^{-3} m/s	4 m/s
Phase Space Density	2.5	2×10^{-13}

Ultracold Neutrons… How and Why?

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
$2{\times}10^3 - 2{\times}10^4$ m/s	Hot	20 meV – 2 eV

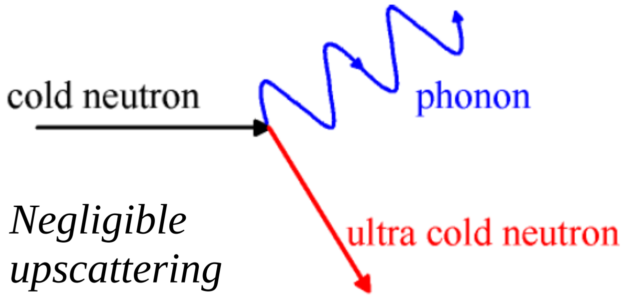
mass = 1.0087 amu
spin = ½ (μ = -1.9 μ_N)
τ_β = 880 s

mgz = 103 neV (z = 1 m)
μB = 60 neV (B = 1T)
U_S = 168 neV (copper in vacuum)

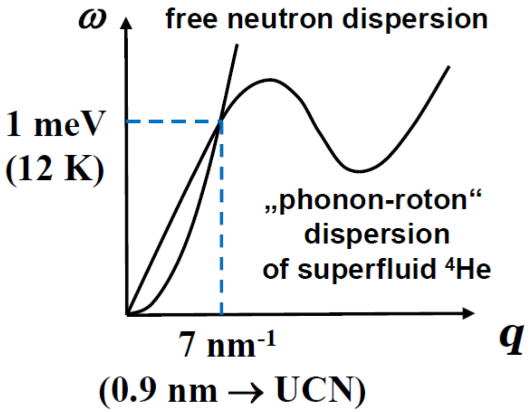
Moderation vs. "conversion"

phase space compression
need for dissipative physics
flux vs. density

Superthermal conversion in LHe

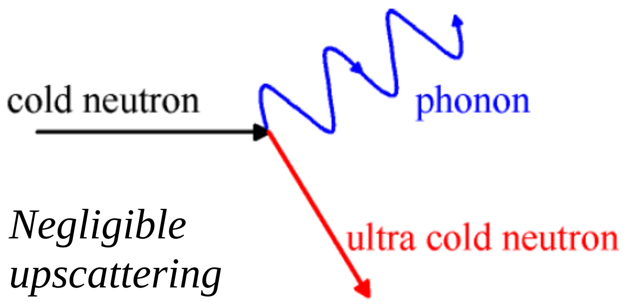


Negligible upscattering below 0.6K



Ultracold Neutrons… Superthermal Sources

Superthermal conversion in LHe



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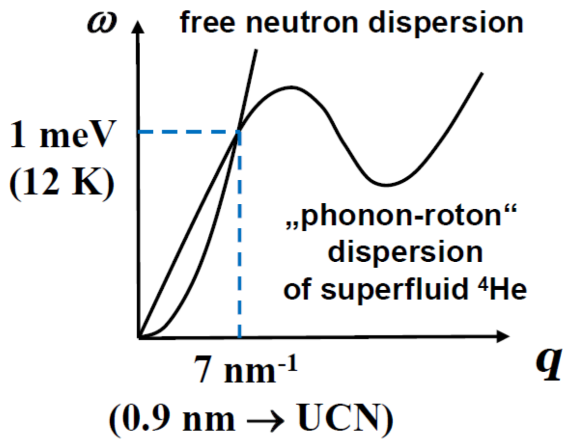
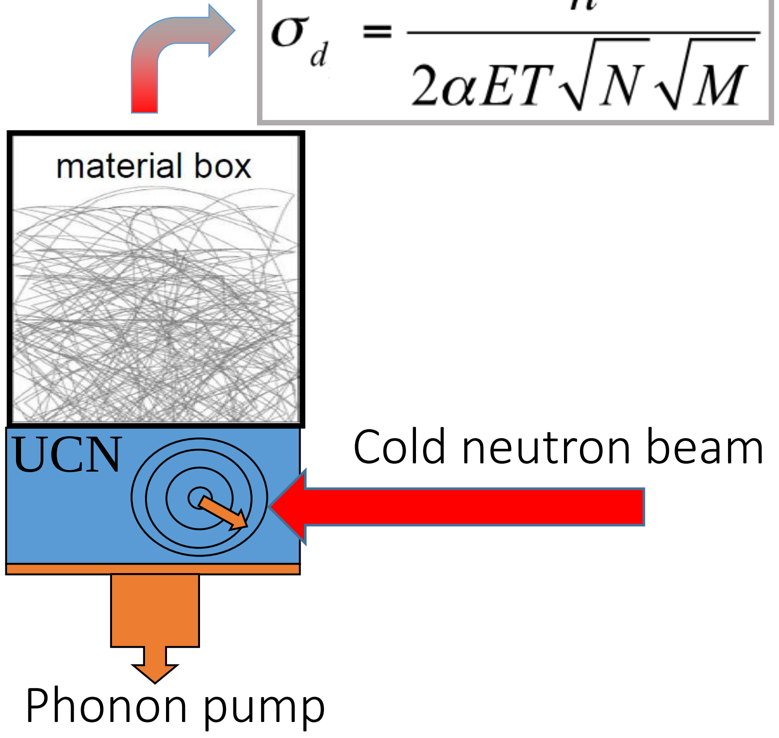


$$\dot{\rho} \approx 5 \times 10^{-8}\,\text{Å}\,\text{cm}^{-1} \left.\frac{d\Phi}{d\lambda}\right|_{9\text{Å}}$$

T [K]	τ_{max} [s]
1	100
0.8	310
0.7	510
0.5	820
0	880

For EDM experiments:

$$\sigma_d = \frac{\hbar}{2\alpha E T \sqrt{N}\sqrt{M}}$$



Optical Potential and Losses

- Complex potential including loss

$$U = \frac{2\pi\hbar^2}{m}\rho(a_r - ia_i) \pm \mu B$$

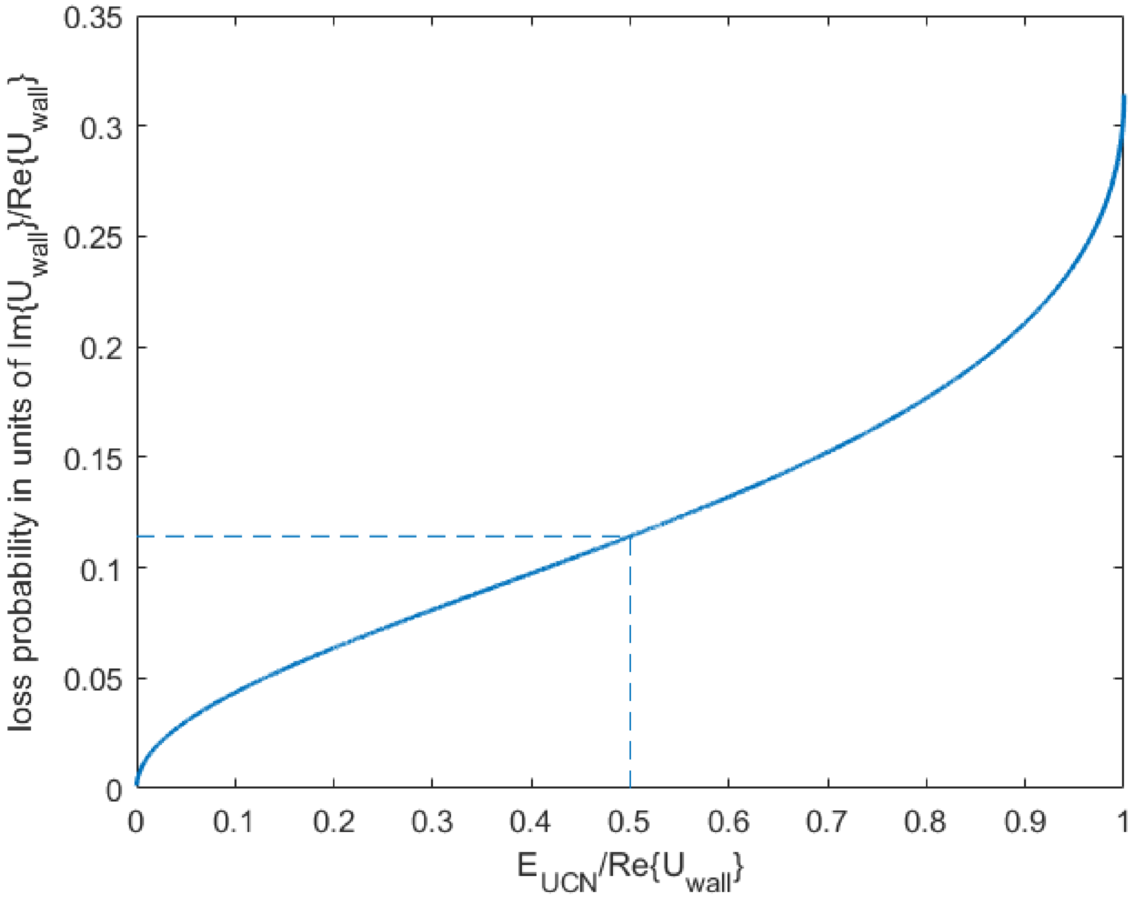
- Can also define a refractive index

$$(\nabla^2 + k^2)\psi(\mathbf{r}) = 4\pi[\rho a(\mathbf{r})]\psi(\mathbf{r})$$

$$n(\mathbf{r}) = \sqrt{1 - \frac{4\pi[\rho a(\mathbf{r}')]}{k^2}}$$

- Total *external* reflection
  → Neutron guides and storage!

Loss per wall interaction



Losses

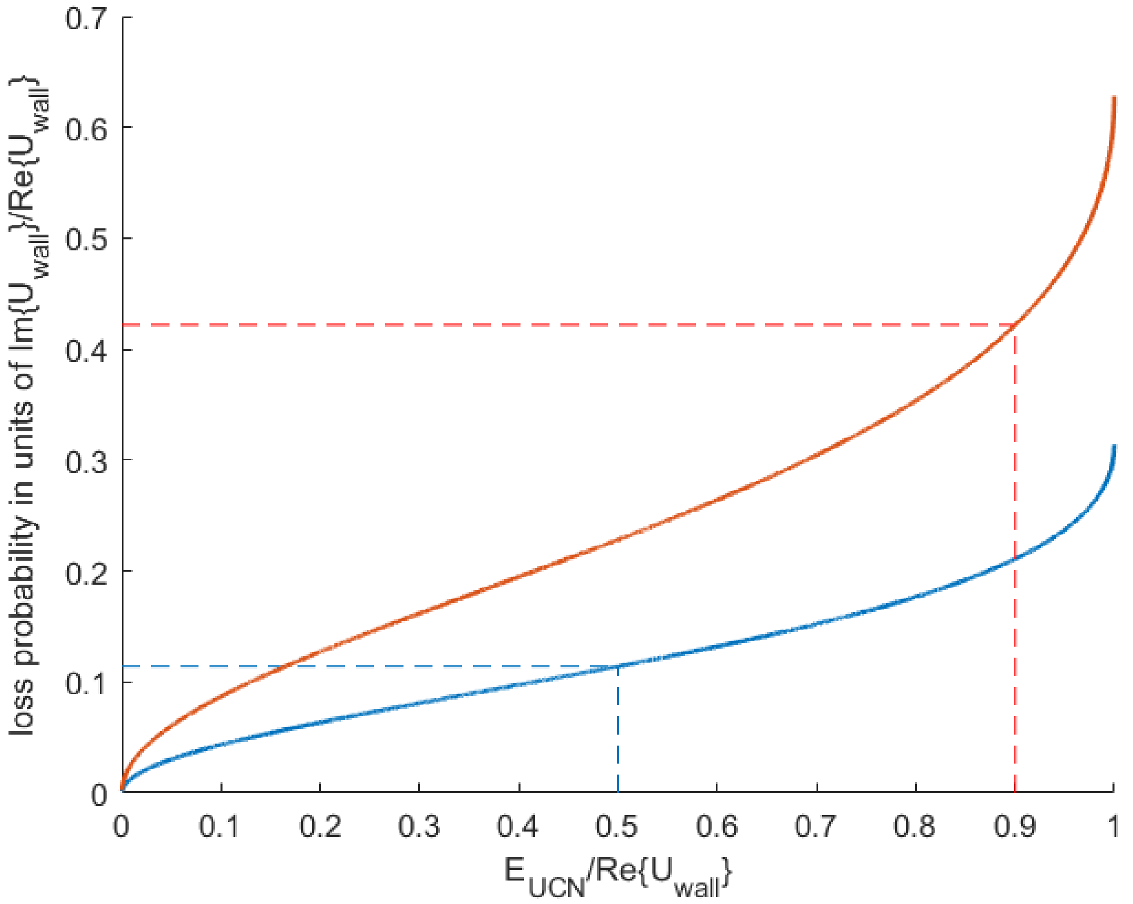
- Complex potential including loss

$$U = \frac{2\pi\hbar^2}{m}\rho(a_r - ia_i) \pm \mu B$$

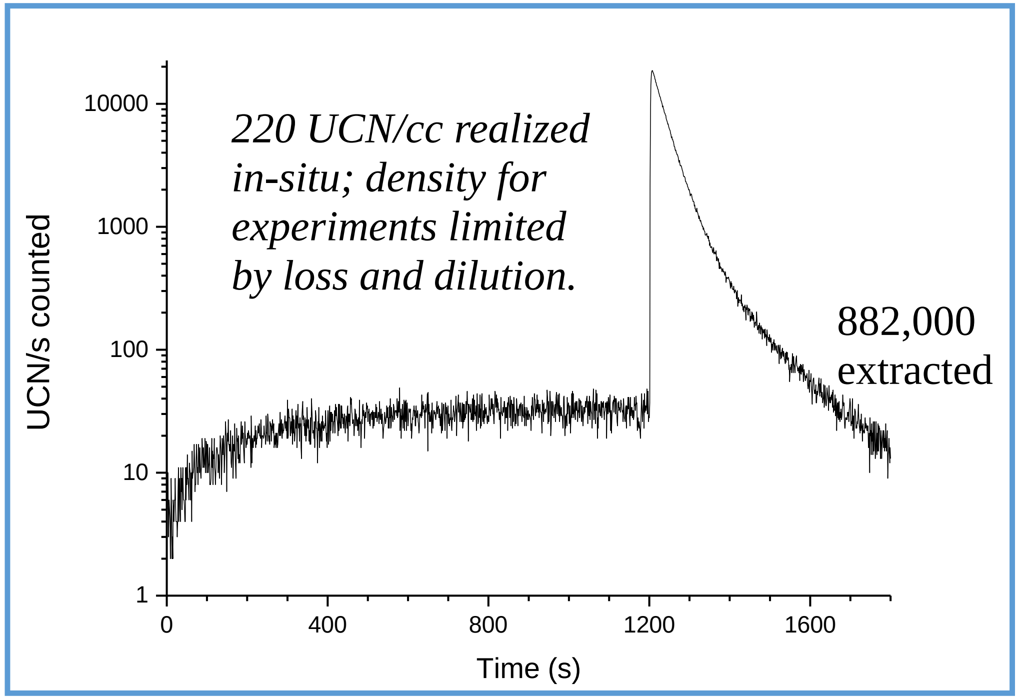
- Storage loss rates: many contributions

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

- Loss probability in a specific coating layer has strong energy dependence



What Can LHe UCN Sources Deliver Now?

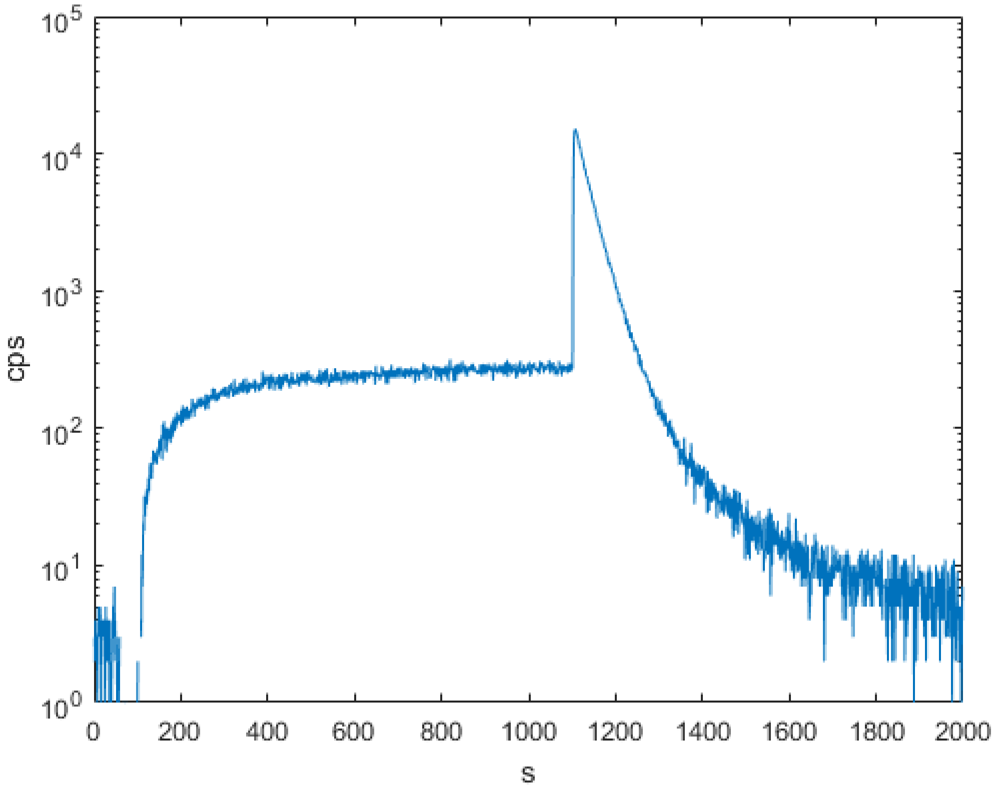


Characteristic output:

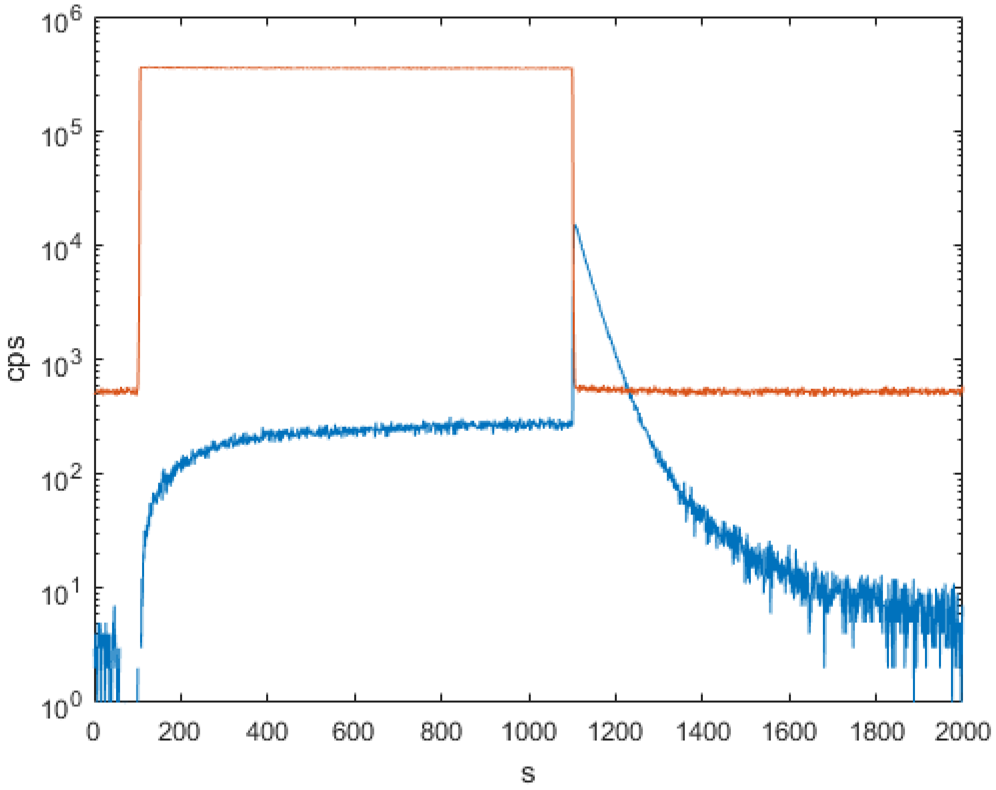
- λ ~ 900 Å (v ~ 4 m/s)
- Φ ~ 500 n/s/cm^2 (~ 3×10^{-13} Φ_{pool})

- ρ ~ 2 cm^{-3} (~ 1×10^{-10} $\rho_{rest\text{-}gas}$)
- $\rho_{phase\text{-}space} < 10^{-13}$ ~ (900 Å)^3(220 cm^{-3})

More real-life examples



More real-life examples



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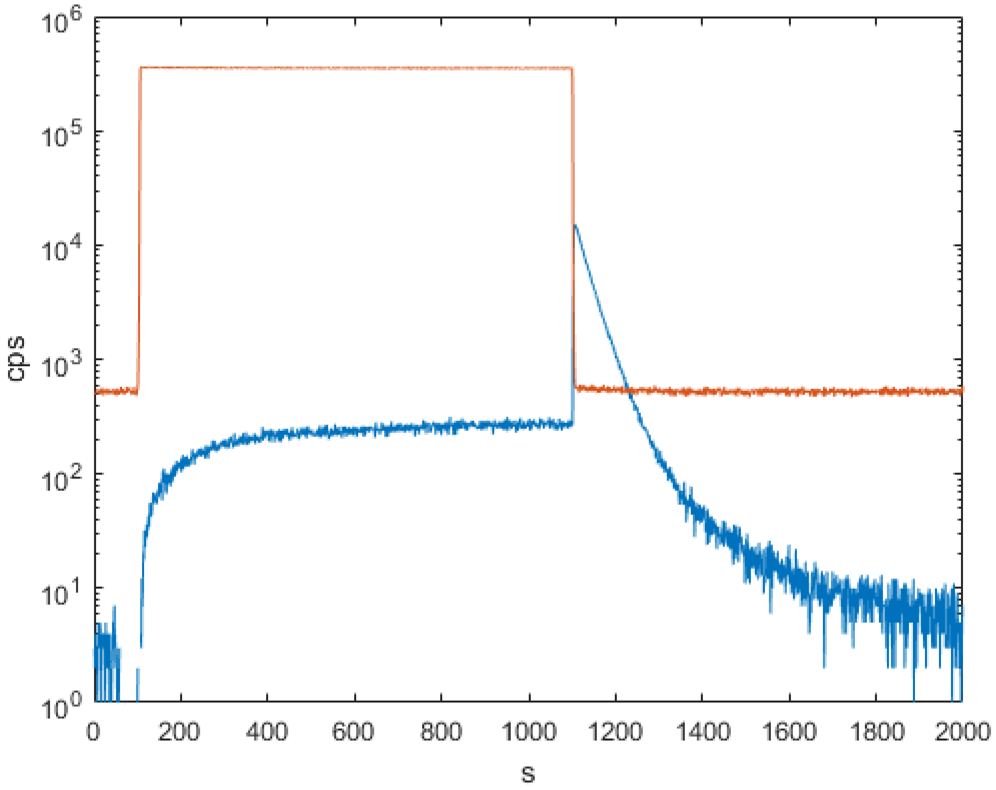
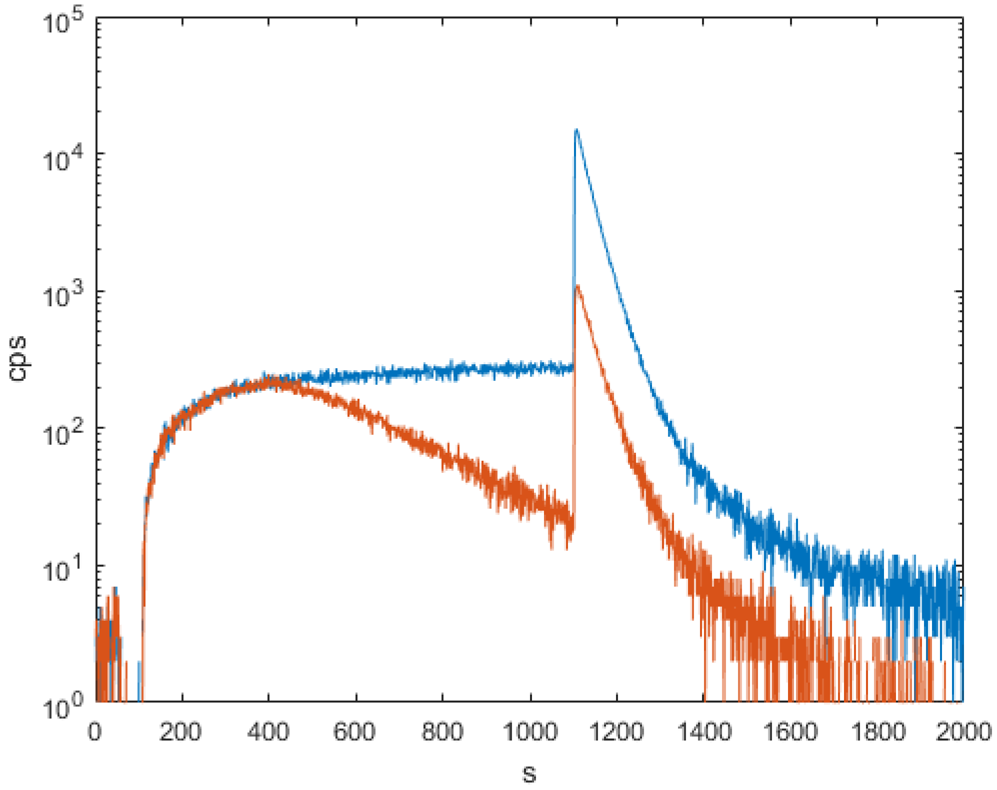
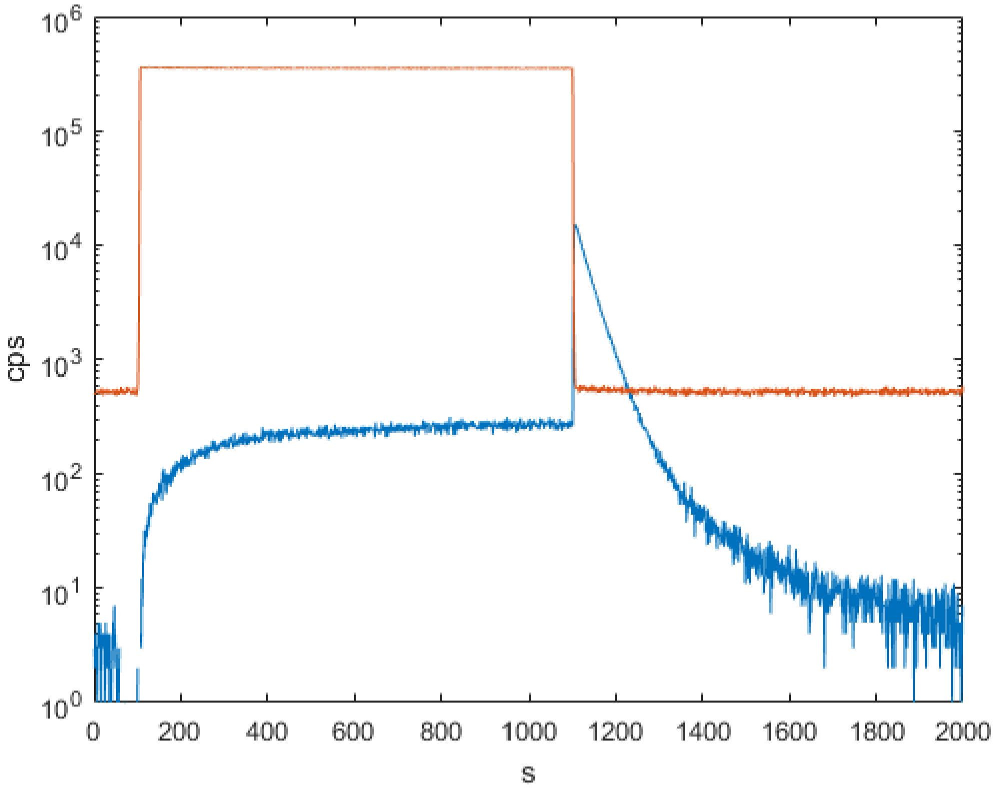
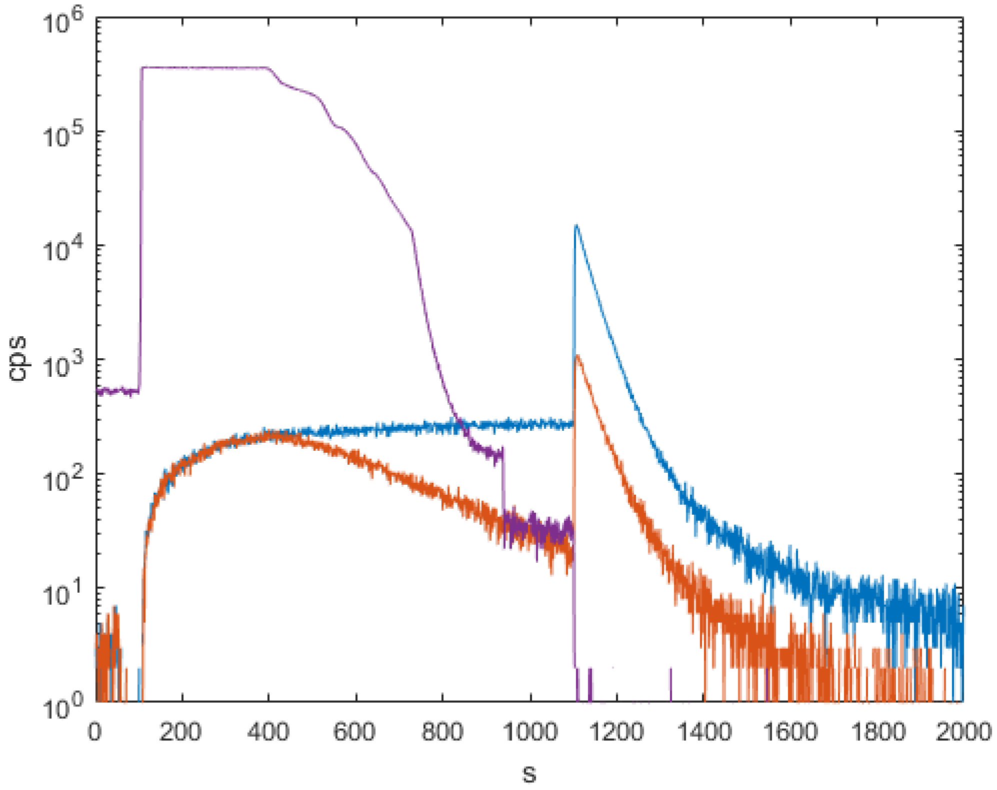


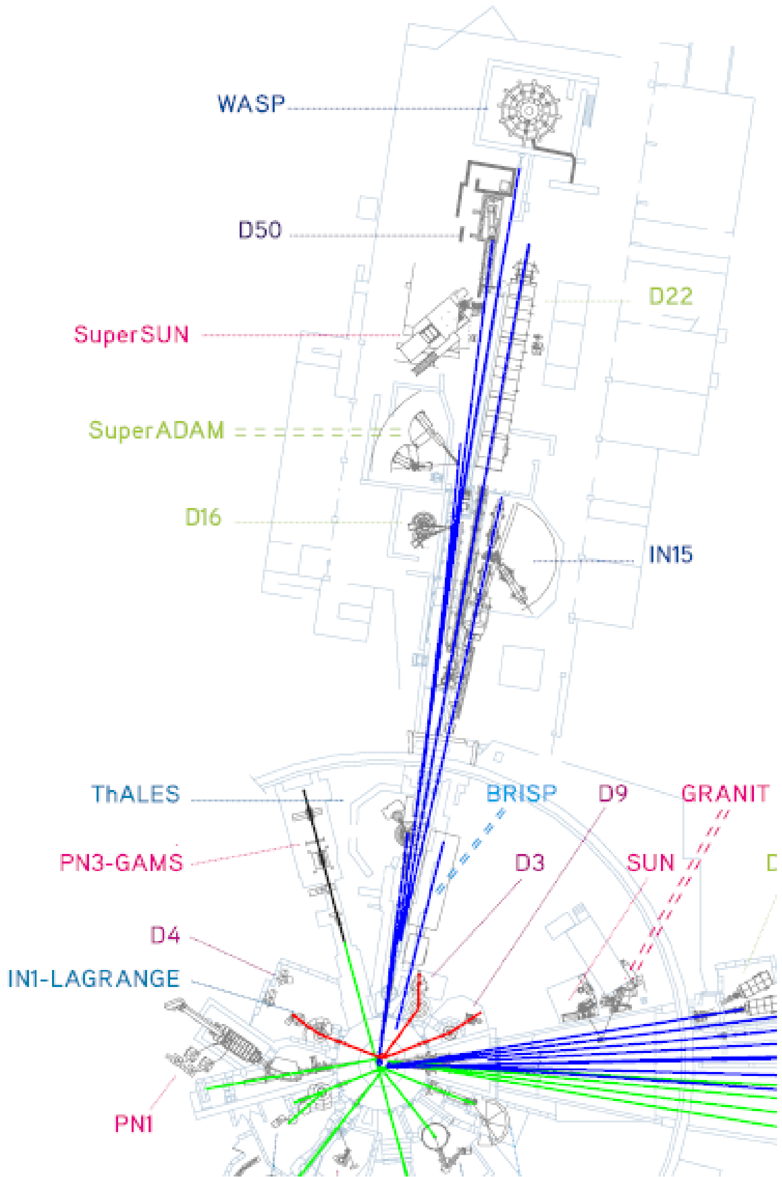


More real-life examples





A neutron’s journey to become “ultracold”



In pile:

- $\Phi \sim 1.5\times10^{15}$ n/s/cm^2

Cold source:

- $\Phi \sim 10^{13}$ n/s/cm^2

End of guide:

- $\Phi \sim 3\times10^{10}$ n/s/cm^2

In converter vessel:

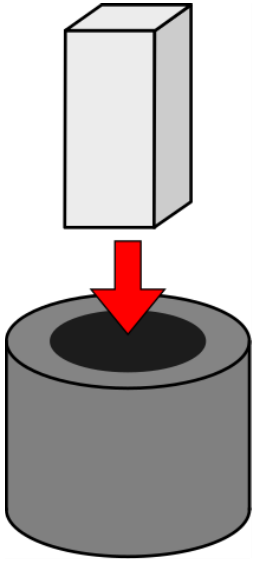
- $R \sim 15$ UCN/s/cm^3

A Theme to Consider…

Physics Problem

A Theme to Consider…

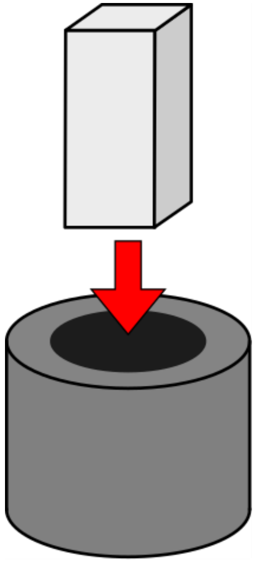
Physics Problem



Technical Limitation

A Theme to Consider…

Physics Problem

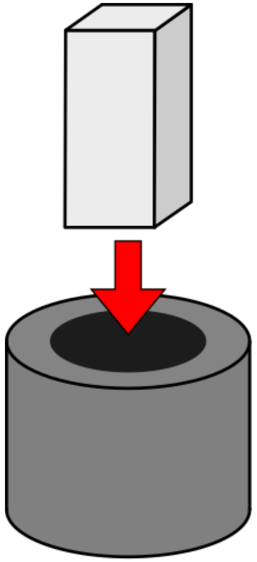


Technical Limitation

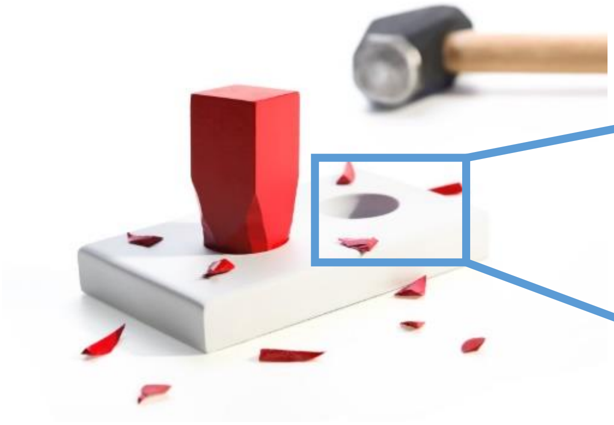
Technical Development

A Theme to Consider…

Physics Problem



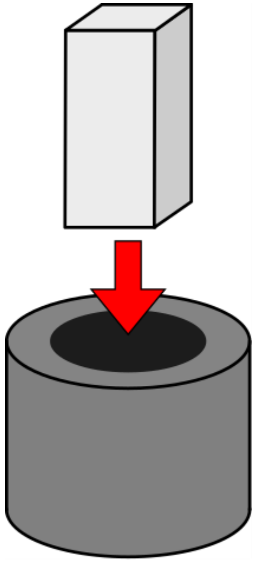
Technical Limitation

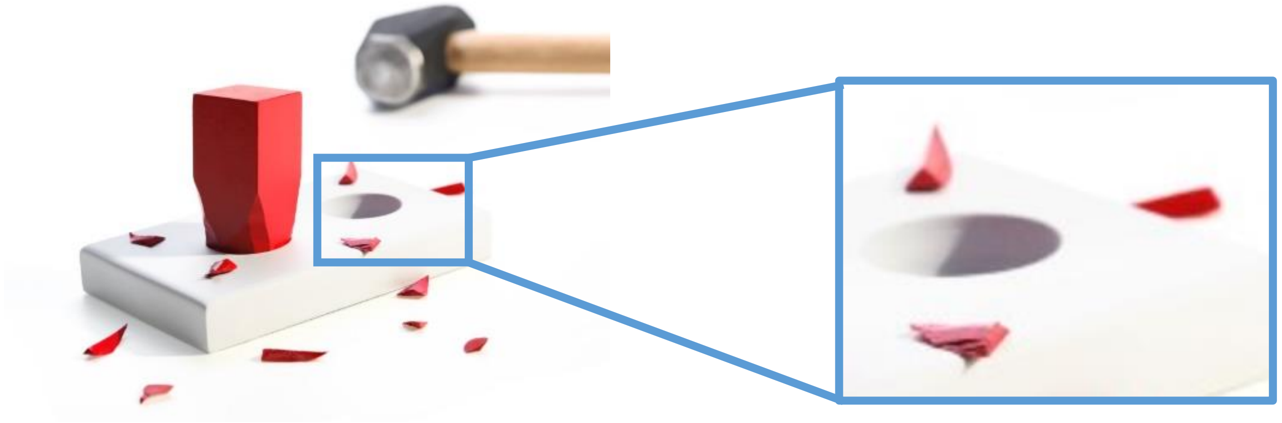


Technical Development

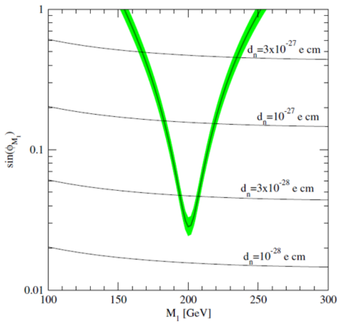
New Physics Problem

A Theme to Consider…

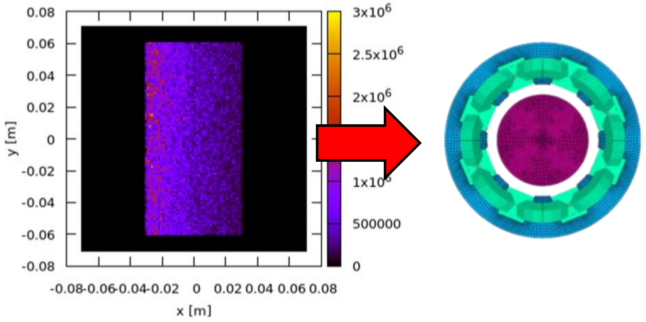




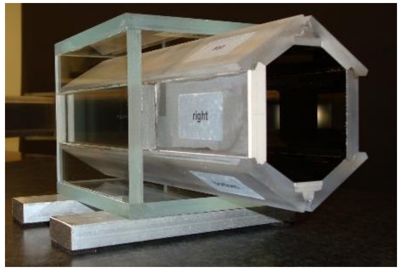
Physics Problem



Technical Limitation

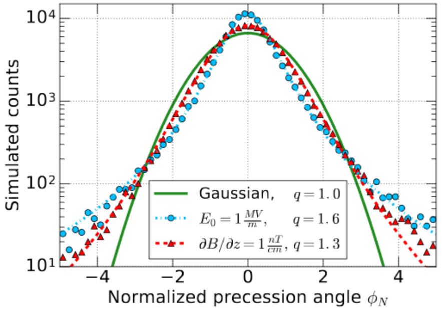


Technical Development

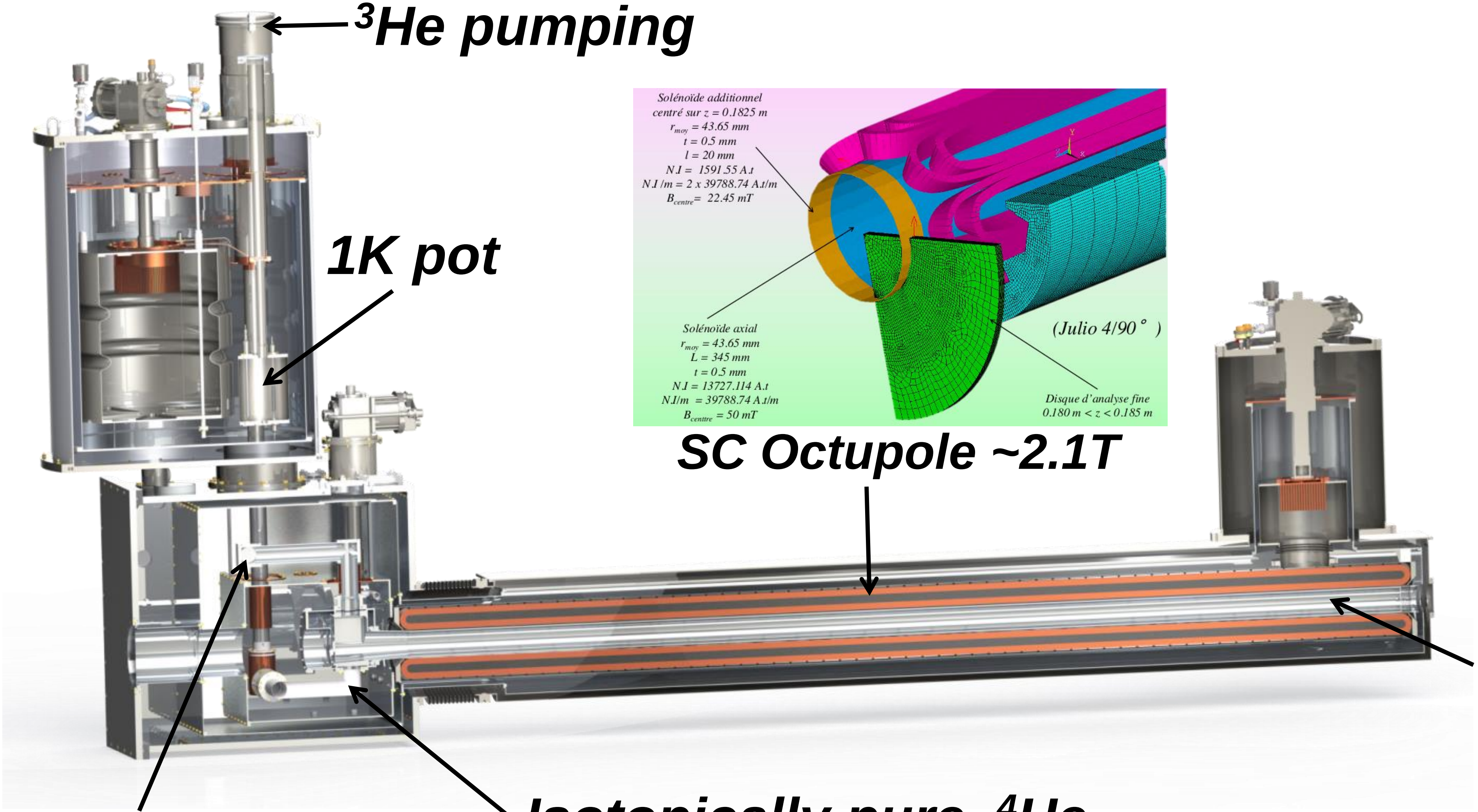


S-DH

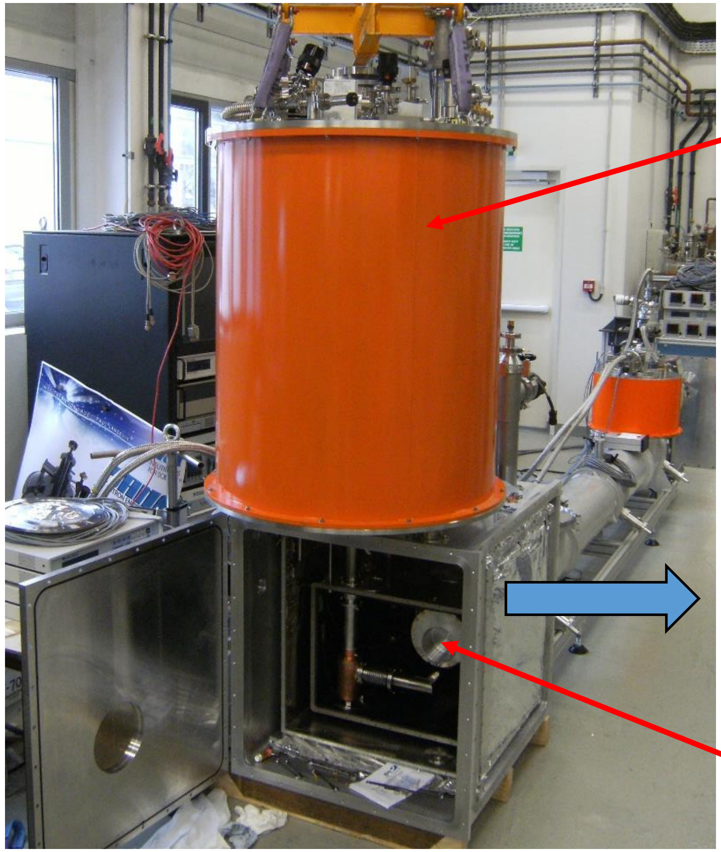
New Physics Problem

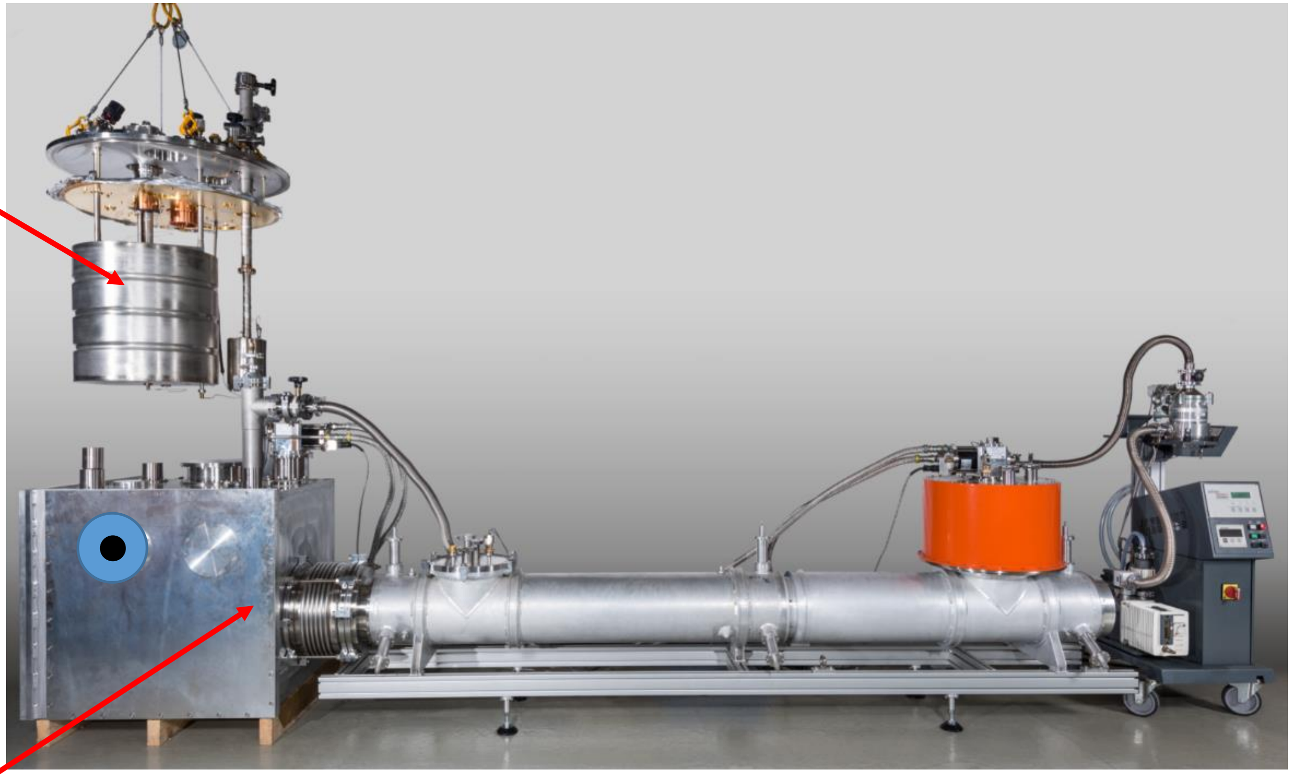


SuperSUN UCN source: Cutaway



SuperSUN: Reality so far…





^{3}He Cryostat

Direction of
UCN Extraction
(PanEDM interface)

End of production vessel

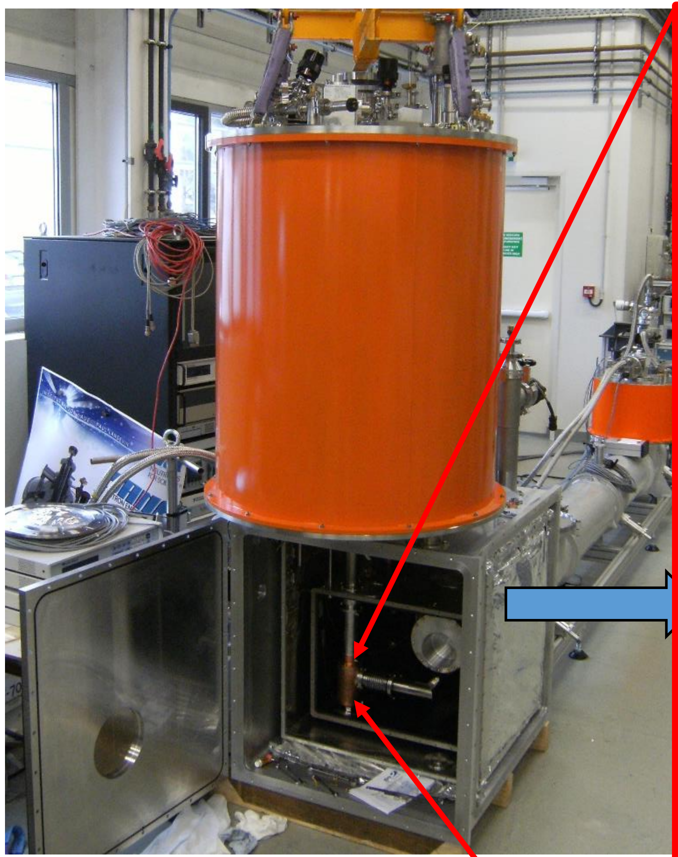
Some open issues

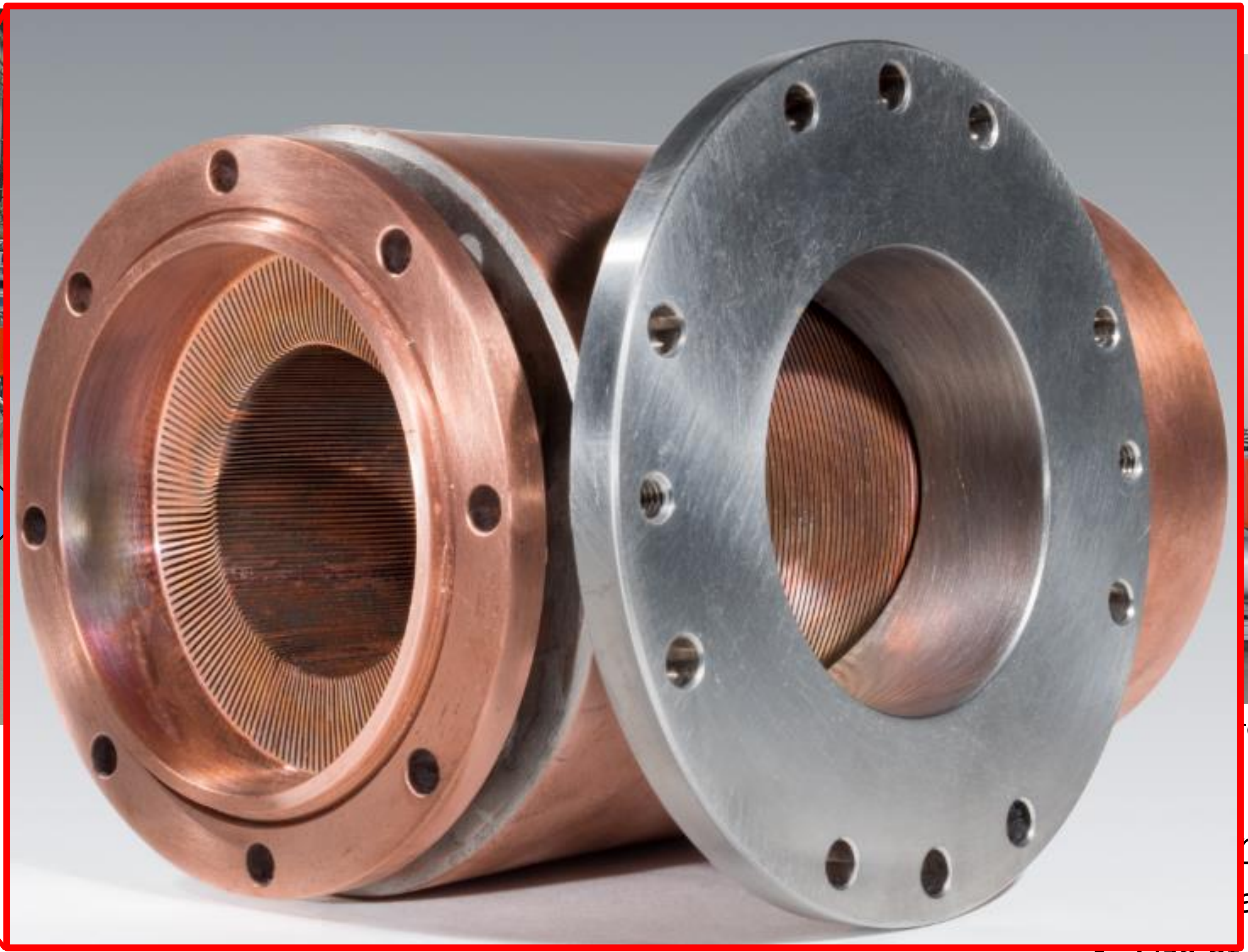
- *Supermirror replica guide*
- *Converter UCN coating*
- *Phase II extraction system*
- *"Deuterated" DLC on Ge*

Final limitations

- *Cold beam brightness*
- *Size of converter vessel*

SuperSUN: Reality so far…





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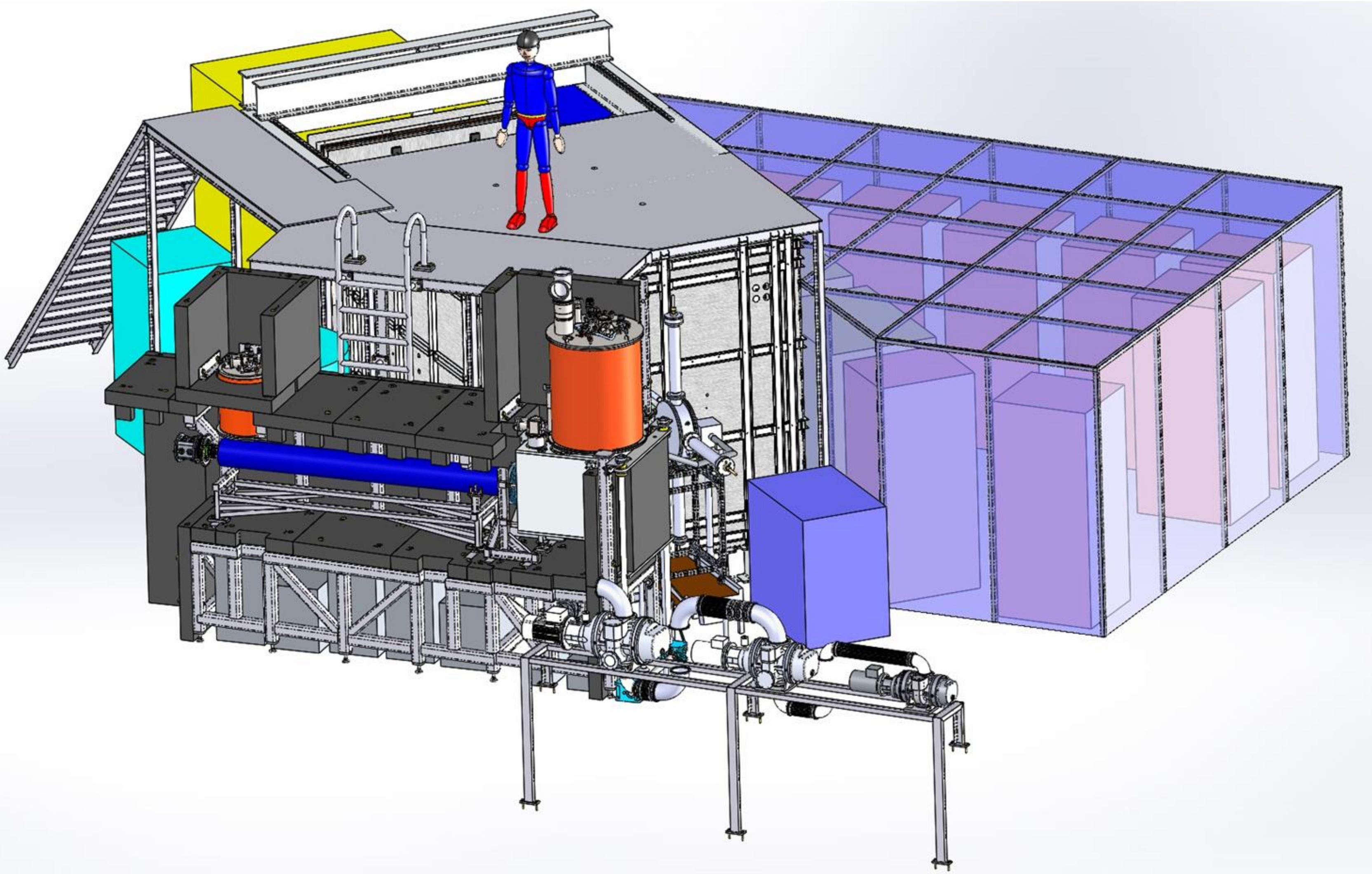
<u>*Some open issues*</u>

- *Supermirror replica guide*
- *Converter UCN coating*
- *Phase II extraction system*
- *"Deuterated" DLC on Ge*

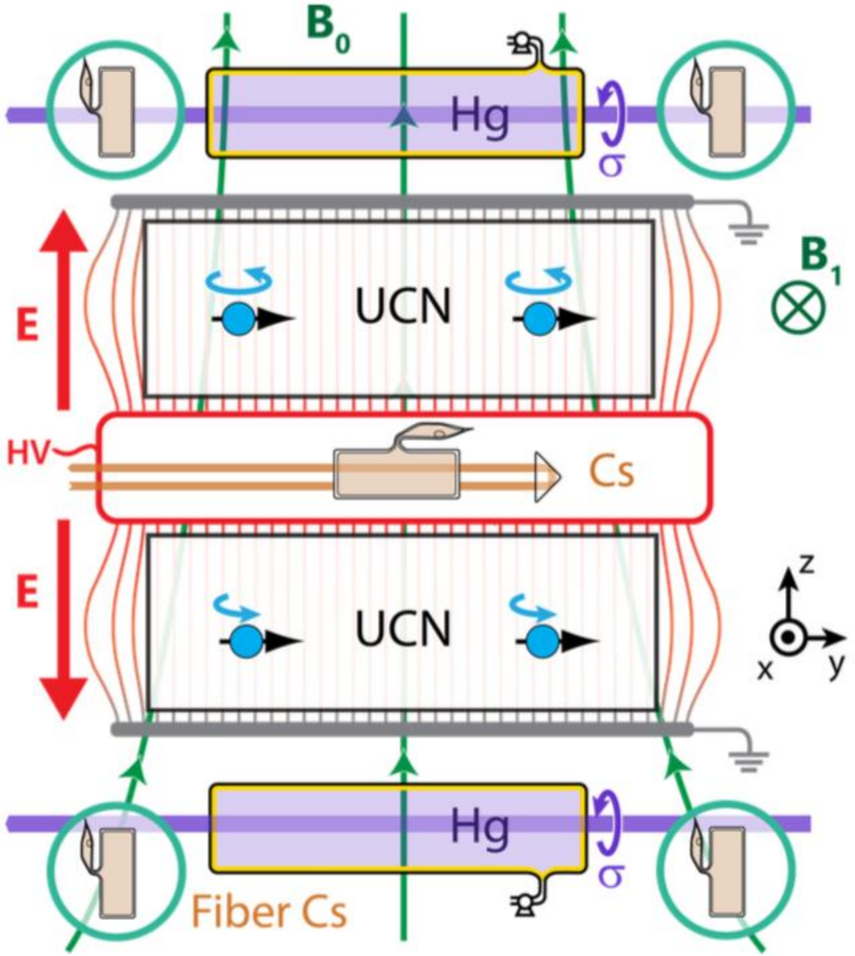
<u>*ns*</u>

- *eam brightness*
- *Size of converter vessel*

Commissioning progress



The PanEDM Experiment



- Double chamber Ramsey experiment at room temperature
- ^{199}Hg magnetometers with few-fT resolution
- Cs magnetometers (also at HV)
- Magnetic shield with SF 6×10^6 at 1 mHz
- Simultaneous spin detection
- 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, start of data taking in 2021

The PanEDM Experiment

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

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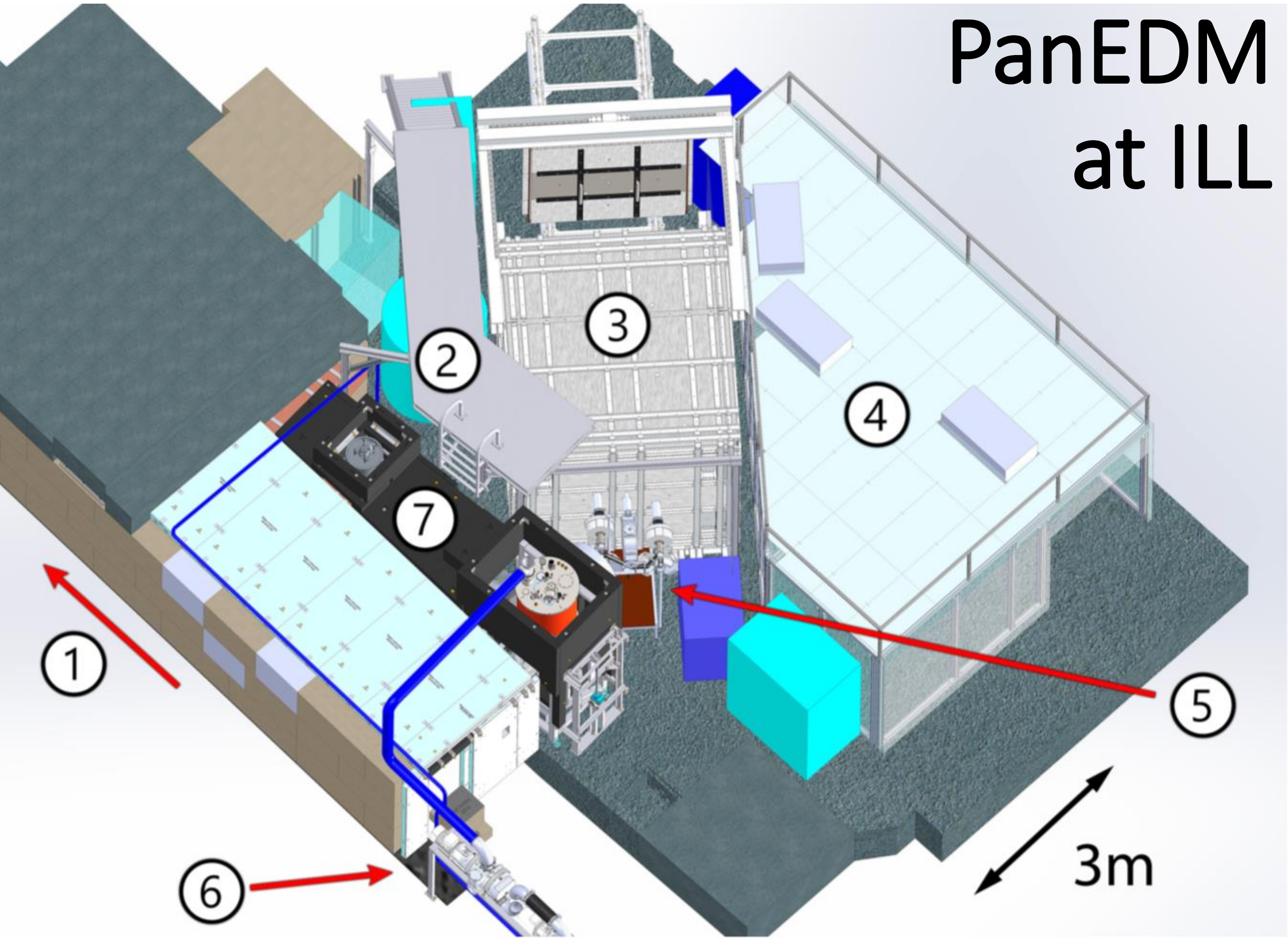
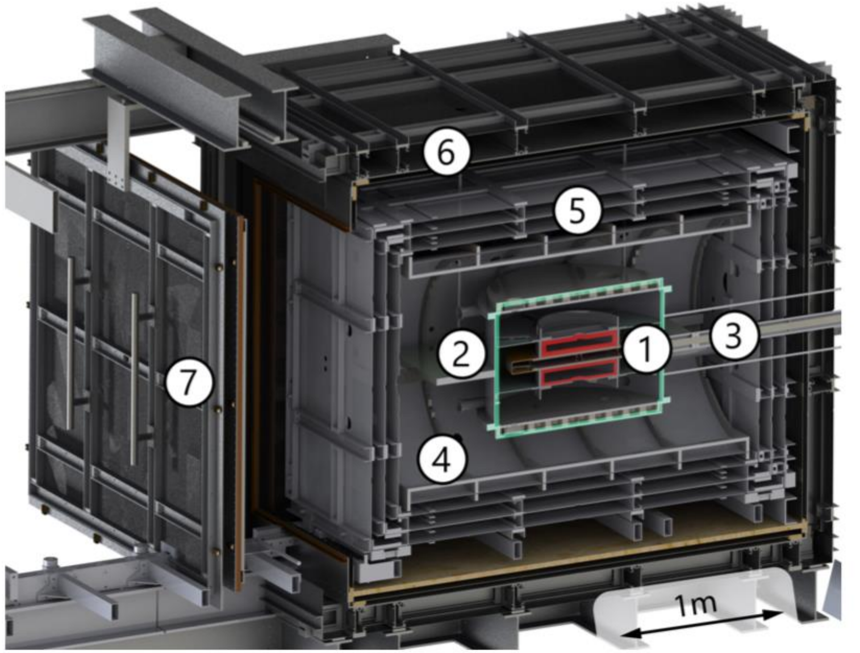


1: Towards reactor
2: service platform
3: outer magnetic shield
4: cleanroom
5: HV apparatus and UCN optics
6: SuperSUN ^{3}He pump system
7: SuperSUN

Statistical sensitivity:

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}

Magnetic shield:

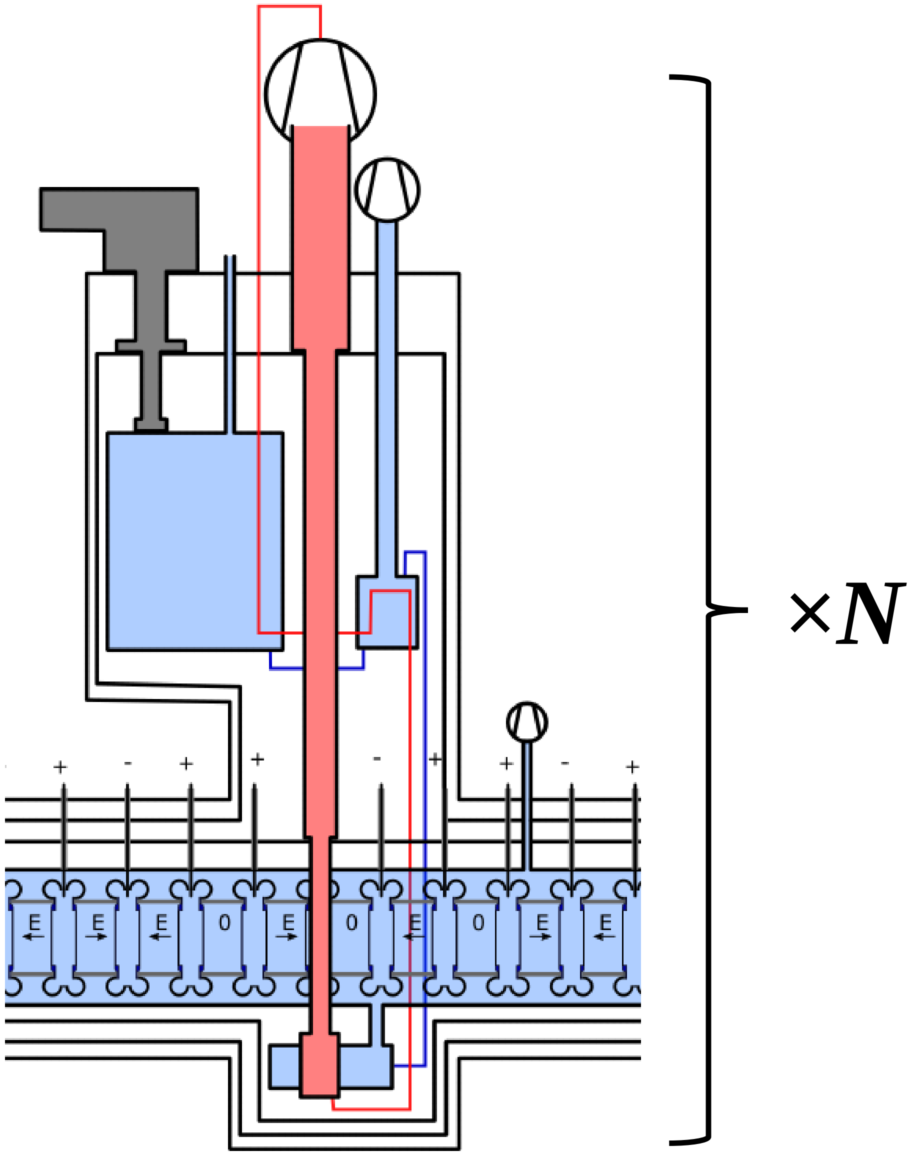


Systematic effects:

“Geometric phase” : well controlled magnetic field

No comagnetometer: estimate better performance without in phase I, given magnetic stability

nEDM searches: Next Generation and Beyond

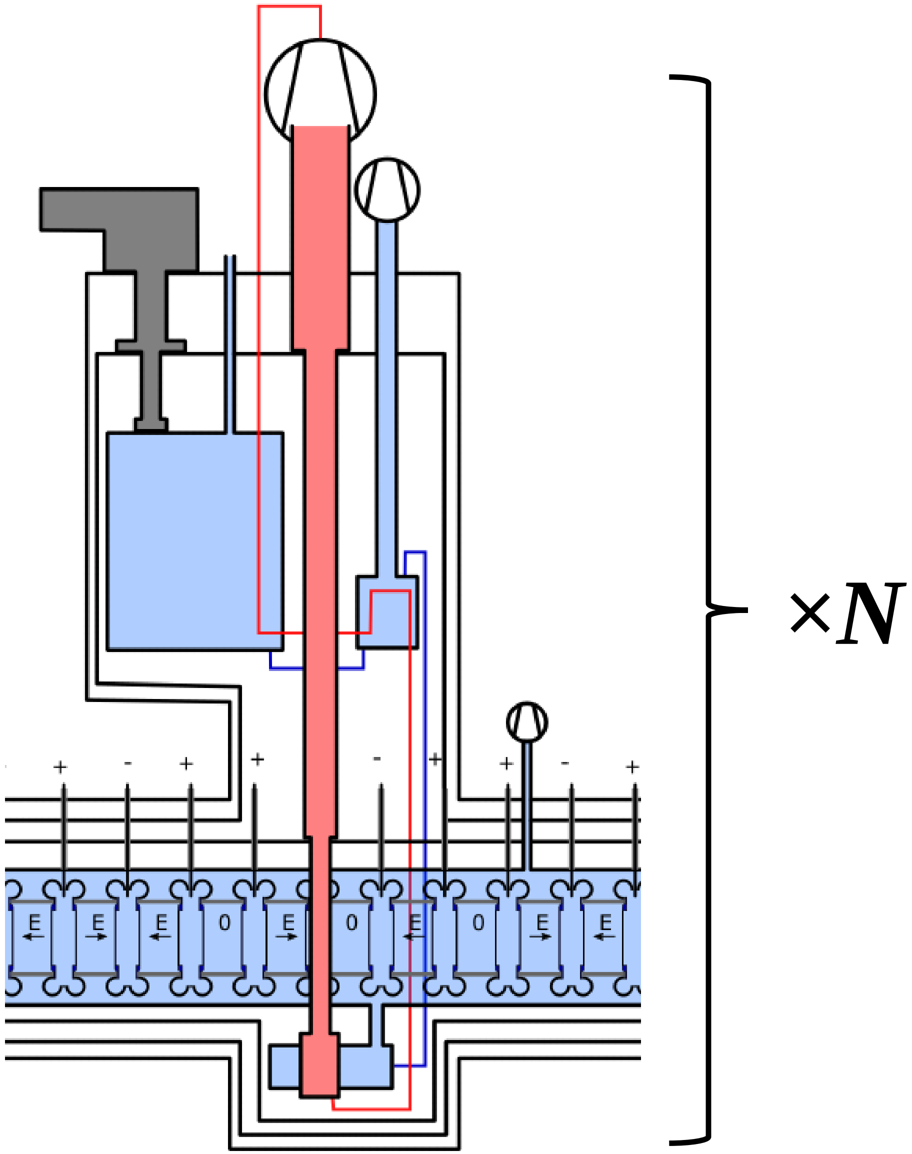


- What is the ultimate limit (using what we know today)

…and how can we get there?

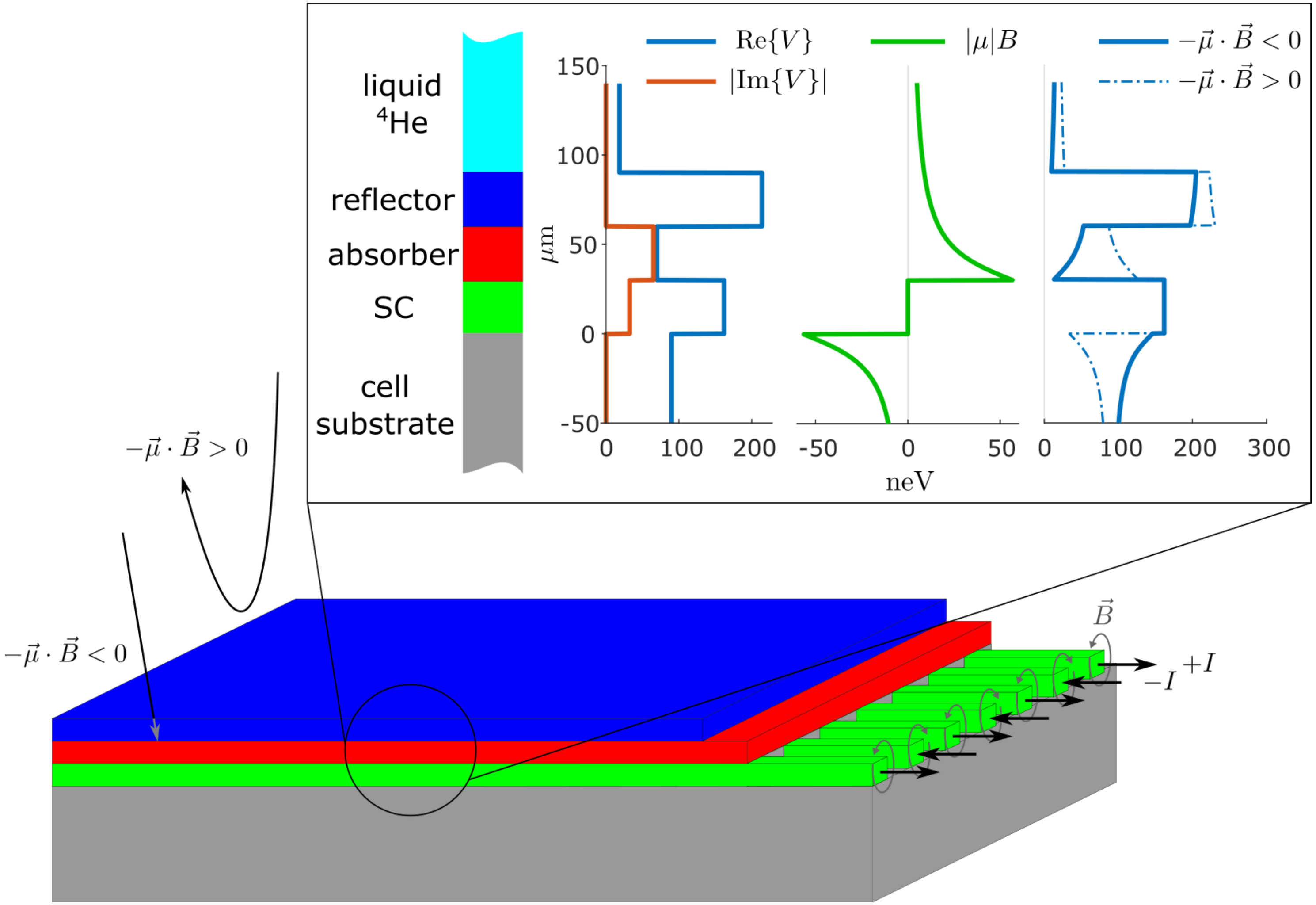
	Full Version	Small Scale
E	10 MV/m	7 MV/m
T	300s	250s
UCN/cc	1000	55
UCN/cell pair	4.4×10^{6}	6×10^{4}
N(T)/cell pair	1.6×10^{6}	2×10^{4}
M	$170 \times 144 = 24480$	1440
α	0.85	0.85
σ_d	1.8×10^{-29} *e* cm	7×10^{-27} *e* cm

nEDM searches: Next Generation and Beyond



- In-situ production and measurement
  - Eliminate transport/dilution loss
- Modular and scalable components
  - Disentangle source/spectrometer
- Use the “entire” cold beam
- Lots of R&D… cryogenics and detector developments on scale of university laboratory

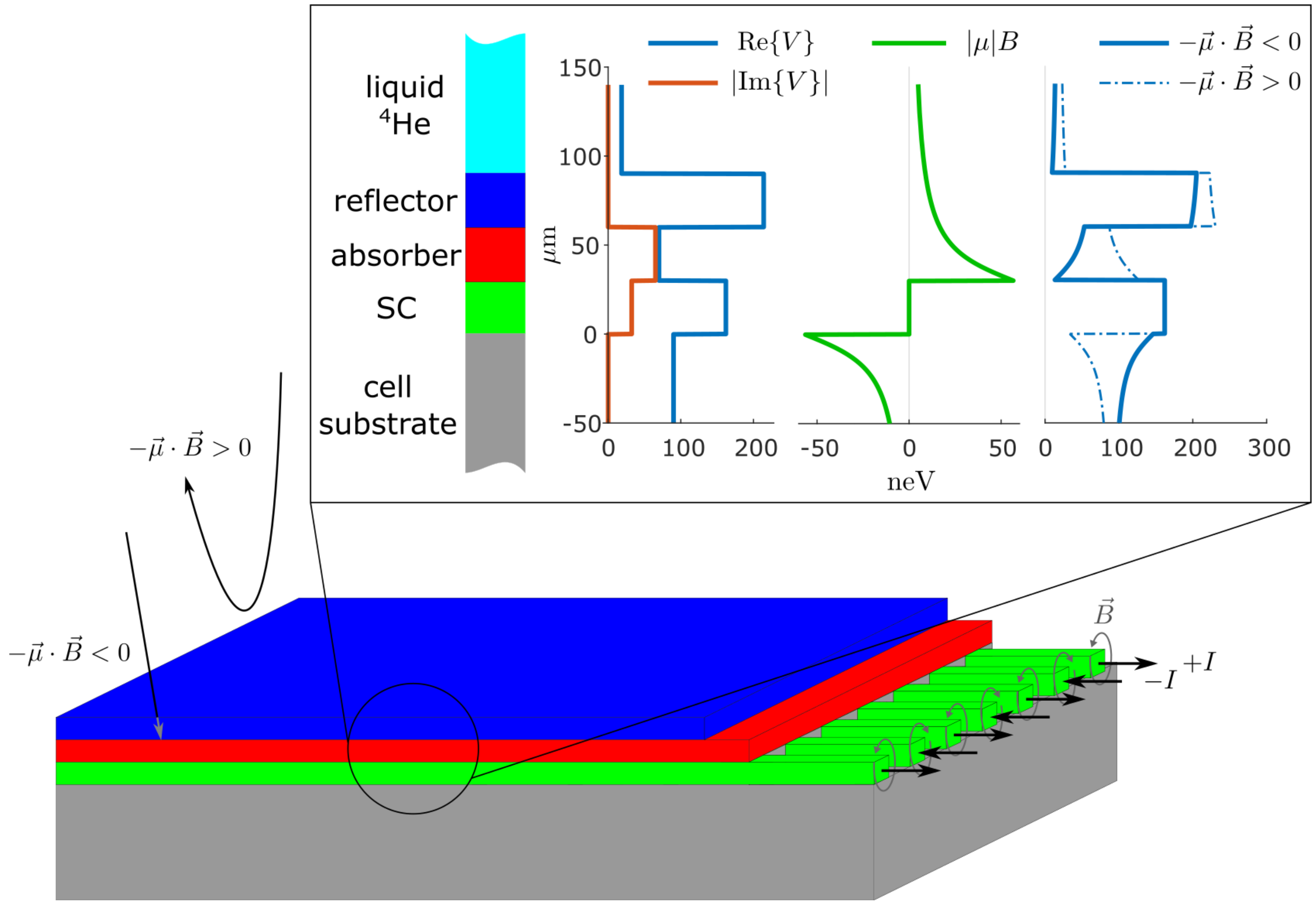
Critical Techniques: Detectors



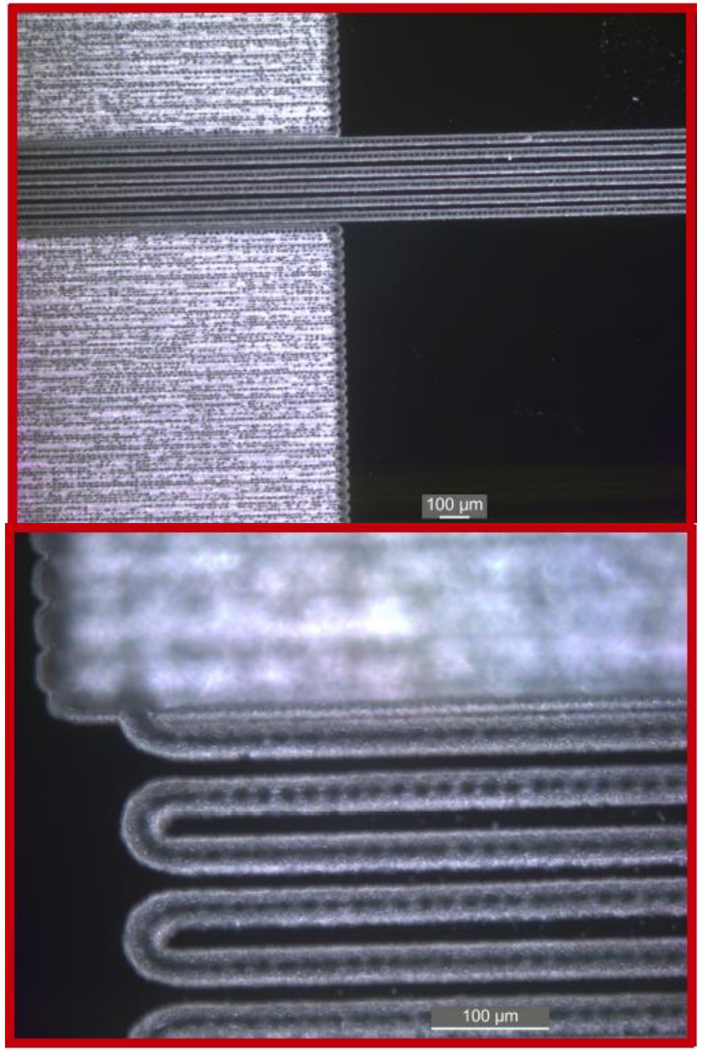
- UCN can have many chances to be detected
- Meander field creates strong *local* gradient at surface
- Limitations from:
    - Slowest UCN never penetrate
    - Fastest UCN always penetrate
    - Cell dimensions
    - Holding time
    - Readout efficiency

- Remember the theme…
- Central contribution: in-situ **polarization sensitive** UCN detectors

High-Order Multipoles by Lithography



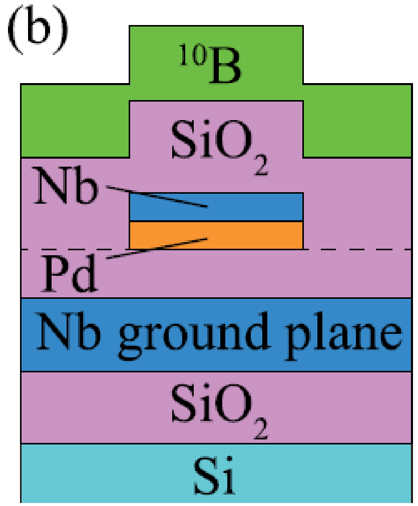
Nb on Si: R. Gernhäuser, S. Winkler

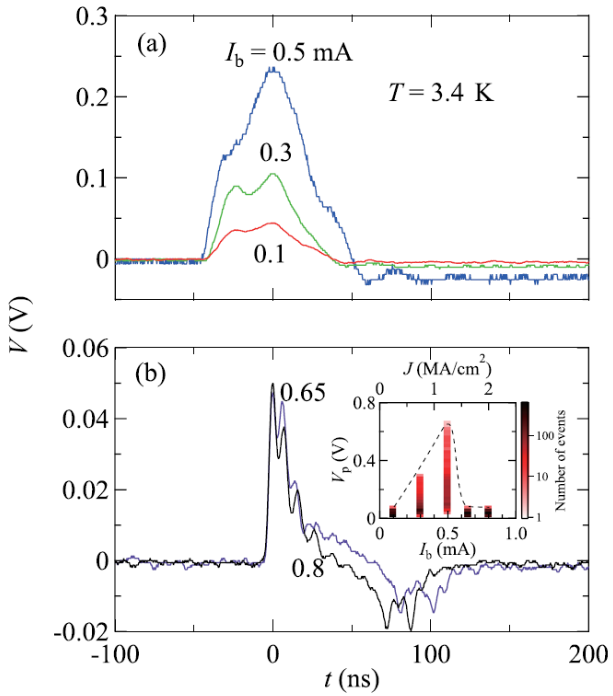


Quantum sensing / in-situ UCN detection

- CB-KID preferred to TES
    - Already used for neutron detection (Nb)
    - Operate well-below T_c (get higher J_c)
- Testable via small user experiments
    - First: using simple cryo environment (dry)
    - Next: ~1K by pumping on LHe
    - Later: T<1K w/ ^{3}He cryostat?
- Need to define materials and obtain samples
    - Nb microstructures on Si already possible @TUM (no cryo or neutron tests yet)
    - HTc requires more research, but MgB_2 promising

$$V = I_b\left(\frac{dL_k}{dt} + \frac{dL_m}{dt}\right) + (L_k + L_m)\frac{dI_b}{dt} \simeq I_b\frac{dL_k}{dt}$$





Appl. Phys. Lett. **107**, 232601 (2015)

Next Generation: First Developments

<u>Test Cryostat and Cell Fabrication</u>

- Reflectometry for CB-KID detectors
- Test cells and coatings
  - Surface tests at cold neutron and UCN facilities
  - Film electrodes (need SANS input)
- UCN production in a single test cell
  - Detection by vanadium activation (or similar)

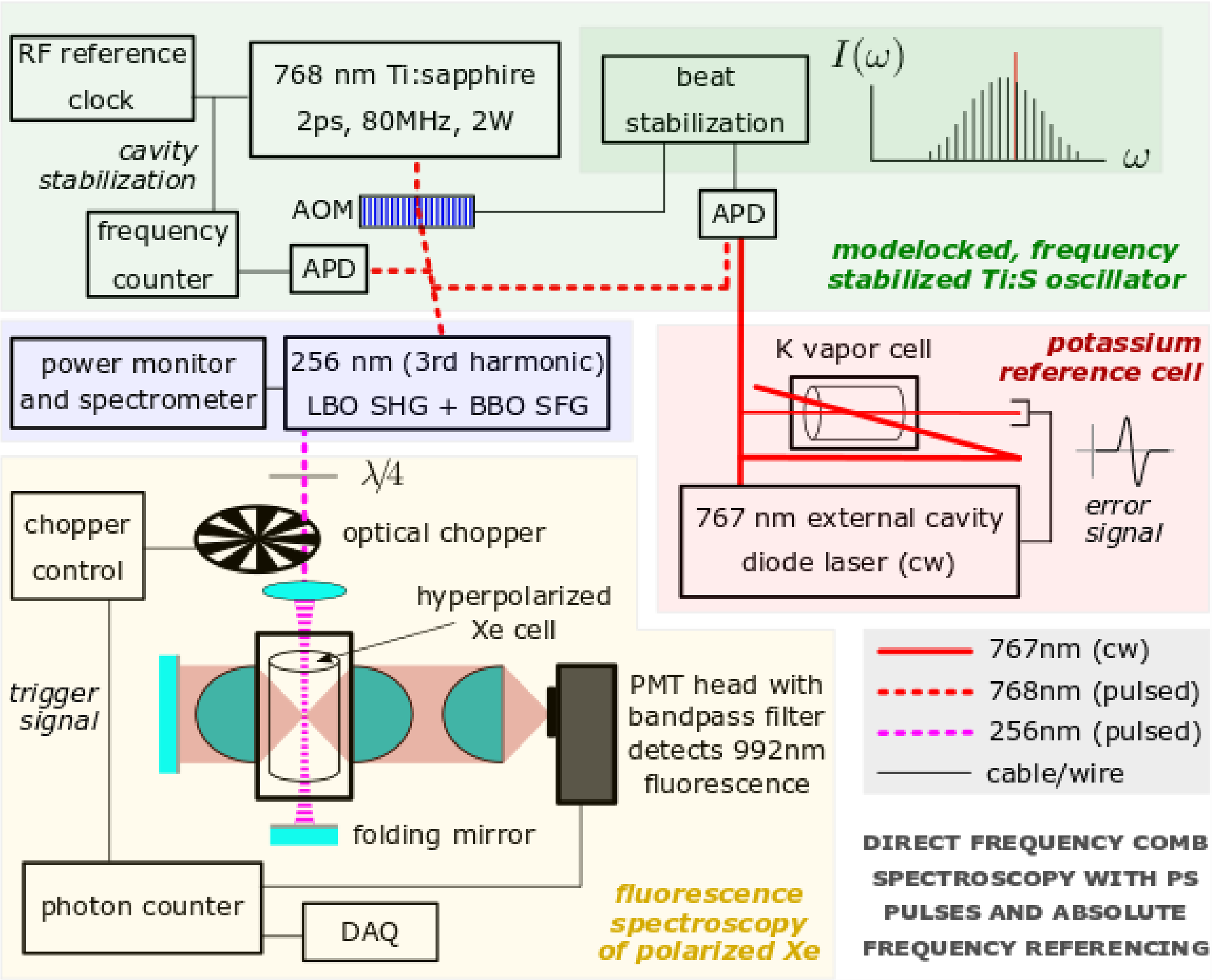
- Combine cell prototypes with detector prototypes
  - Can avoid coupling these problems until components are relatively advanced

Thank you!

Modified targets for 2020 & 2021

Reference reactor schedule (dates are tentative)

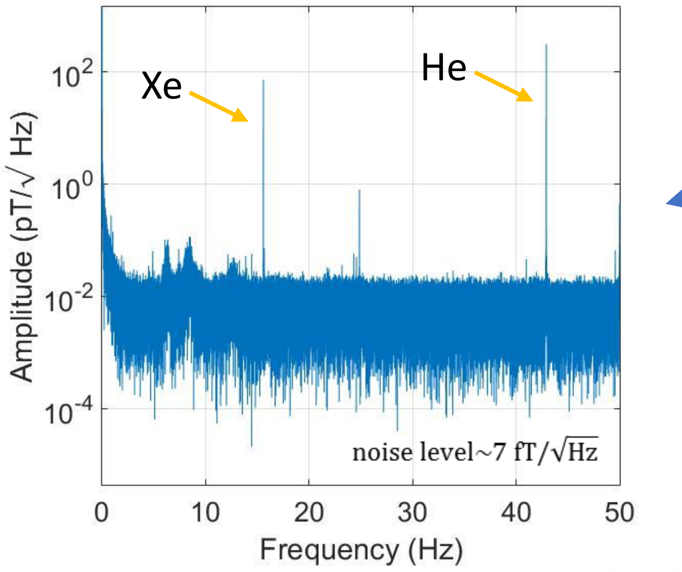
First Experiments with Mutiphoton Probes

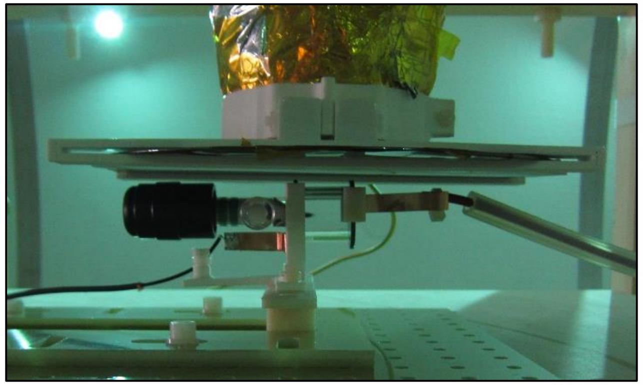


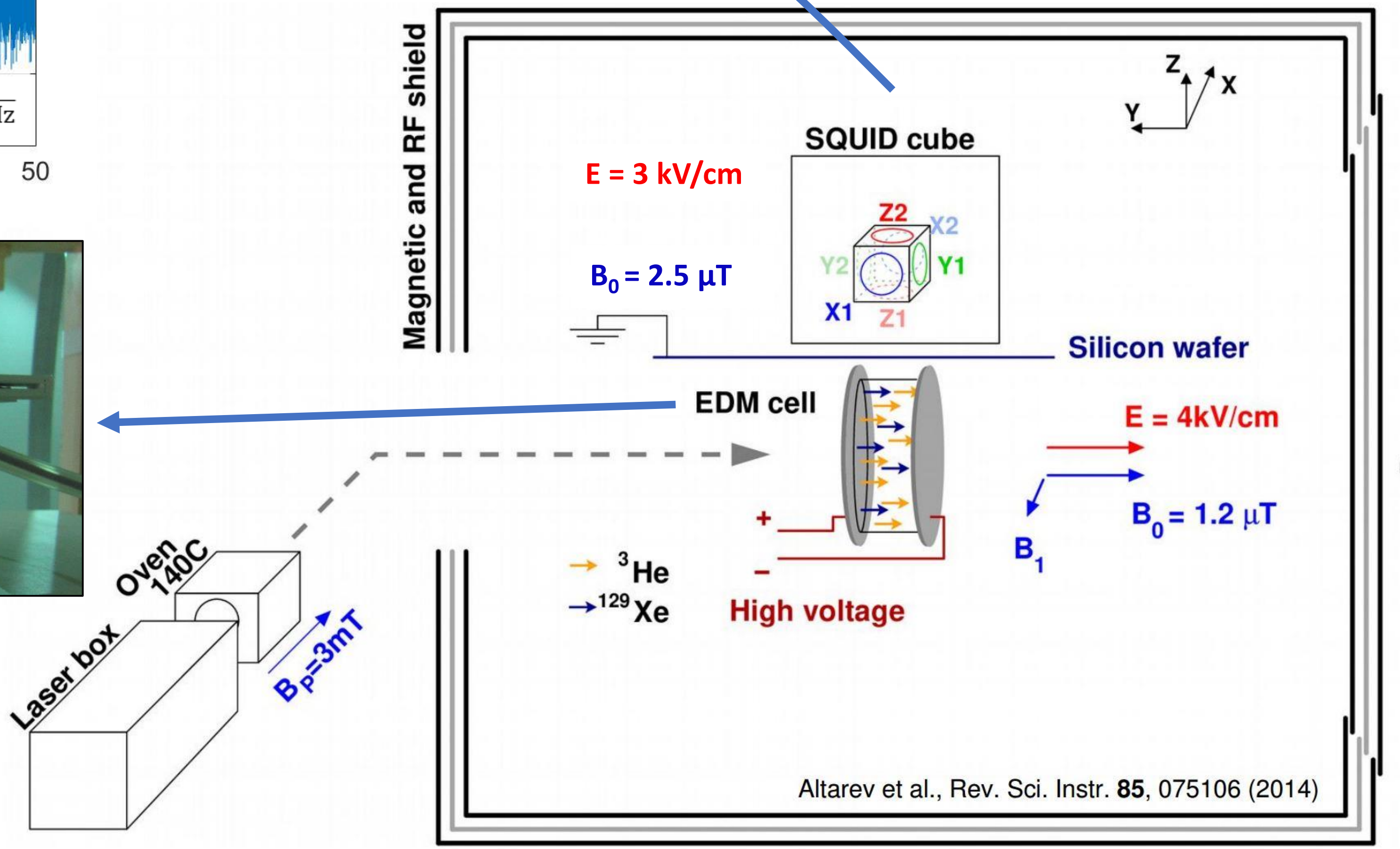
- Significant hardware investment opens the door to longer-term developments with potential high impact
- Same system can do:
  - Basic cw tests with alkali atoms (K, Rb, Cs)
  - Basic pulsed tests with alkali atoms (K, Rb, Cs)
  - Low-efficiency SEOP for ^{3}He and ^{129}Xe
  - Two-photon probe of ^{129}Xe for magnetometry

  - Nonlinear spectroscopy of alkaline-earths*
  - Two-photon probe of ^{129}Xe for EDM*
  - Two-photon probe of ^{223}Rn for EDM*
  - Some R&D on ^{199}Hg magnetometry for nEDM*
  - Two-photon laser trapping of alkalis*
  - Early tests for TPOP/MPOP*

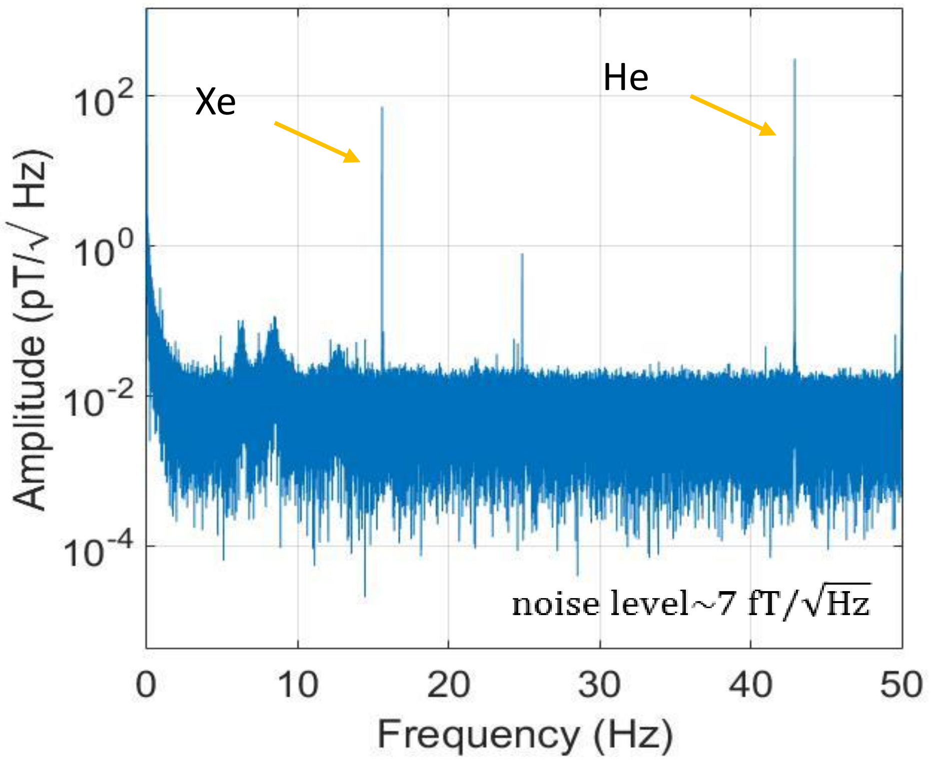
Measurement of ^{129}Xe and ^{3}He (co-magnetometer) spin-precession signals

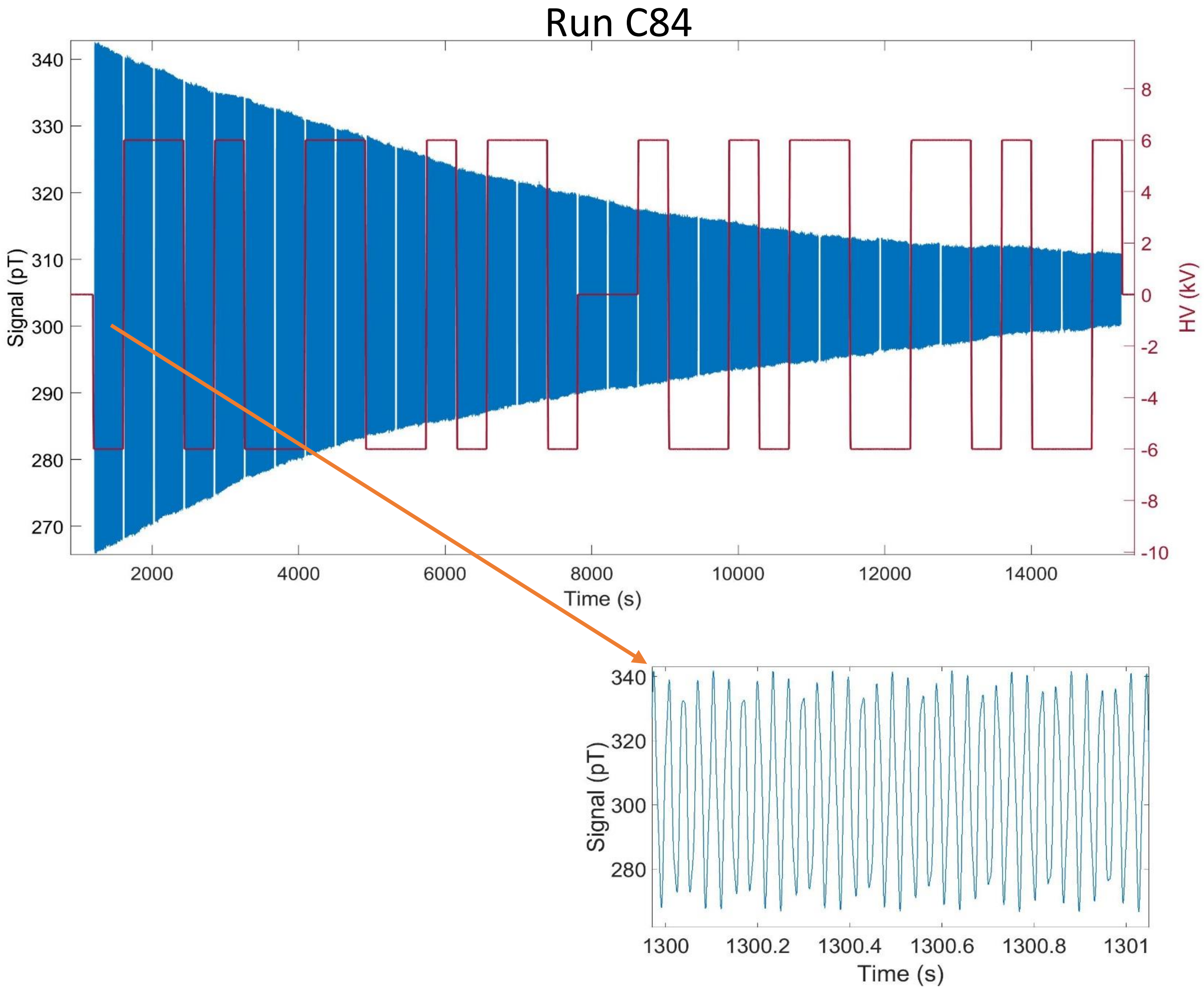






Continuous Spin Readout (SQUID)



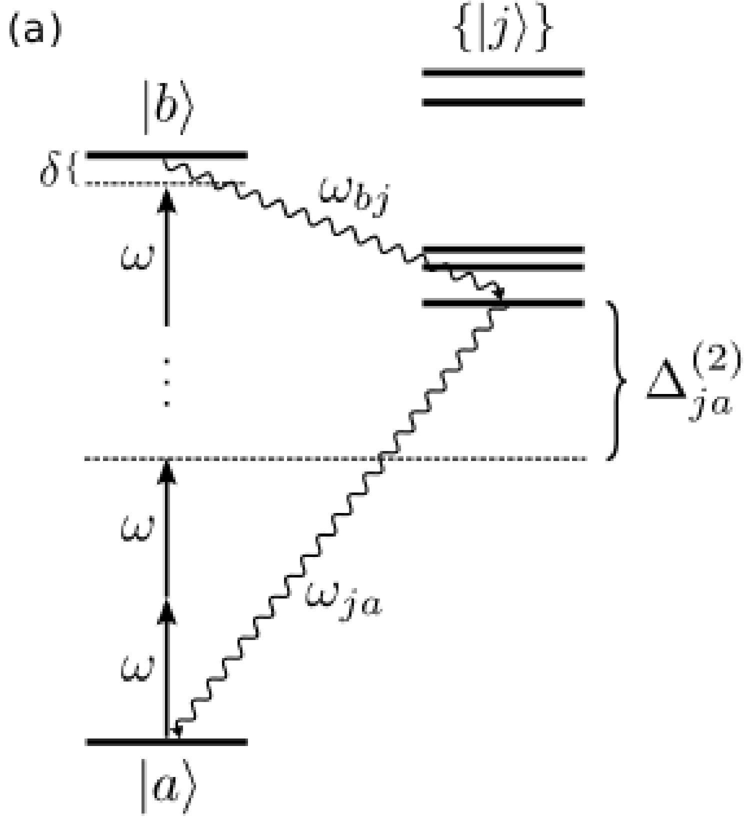


Result:

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

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

Spatially Resolved Magnetometry



$$R^{(n)}_{ba} = \left| \frac{E^n}{\hbar^n} \sum_{i,j,\ldots,k} \frac{\mu_{ai}\mu_{ij}\cdots\mu_{kb}}{\Delta^{(n-1)}_{ia}\Delta^{(n-2)}_{ja}\cdots\Delta^{(1)}_{ka}} \right|^2 2\pi\rho(\delta)$$

- Diffusion time T ~ $4L^2/v\lambda$
- λ ~ 1mm for co-magnetometer densities
- T ~ several seconds, for L ~ few cm
- Higher pressure: still OK for external cells
- GP suppressed by short mean free path
- Collisions reset motional fields, but not vertical gradients
- High resolution spatial maps

  extract spatial frequencies within storage volume...