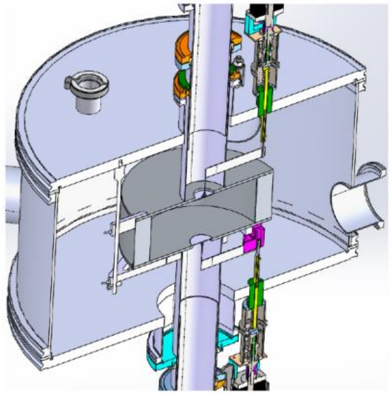
Searching for BSM physics with low-energy bound states: spin-polarized atoms and neutrons

KIT Particle Physics Colloquium, 28 April 2022

Skyler Degenkolb

Case 1: trapped neutron interferometry

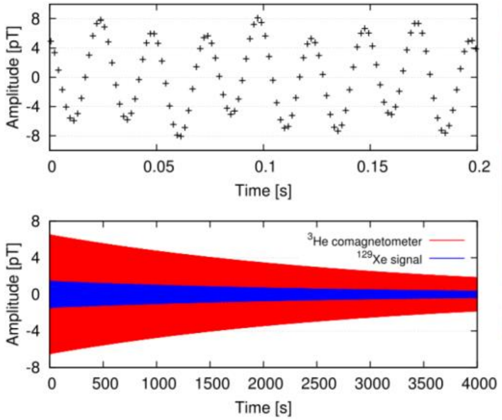


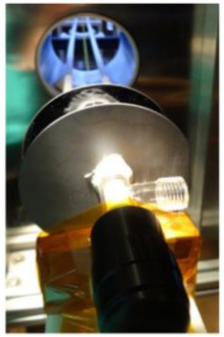
Low-Energy Precision Physics

Physikalisches Institut

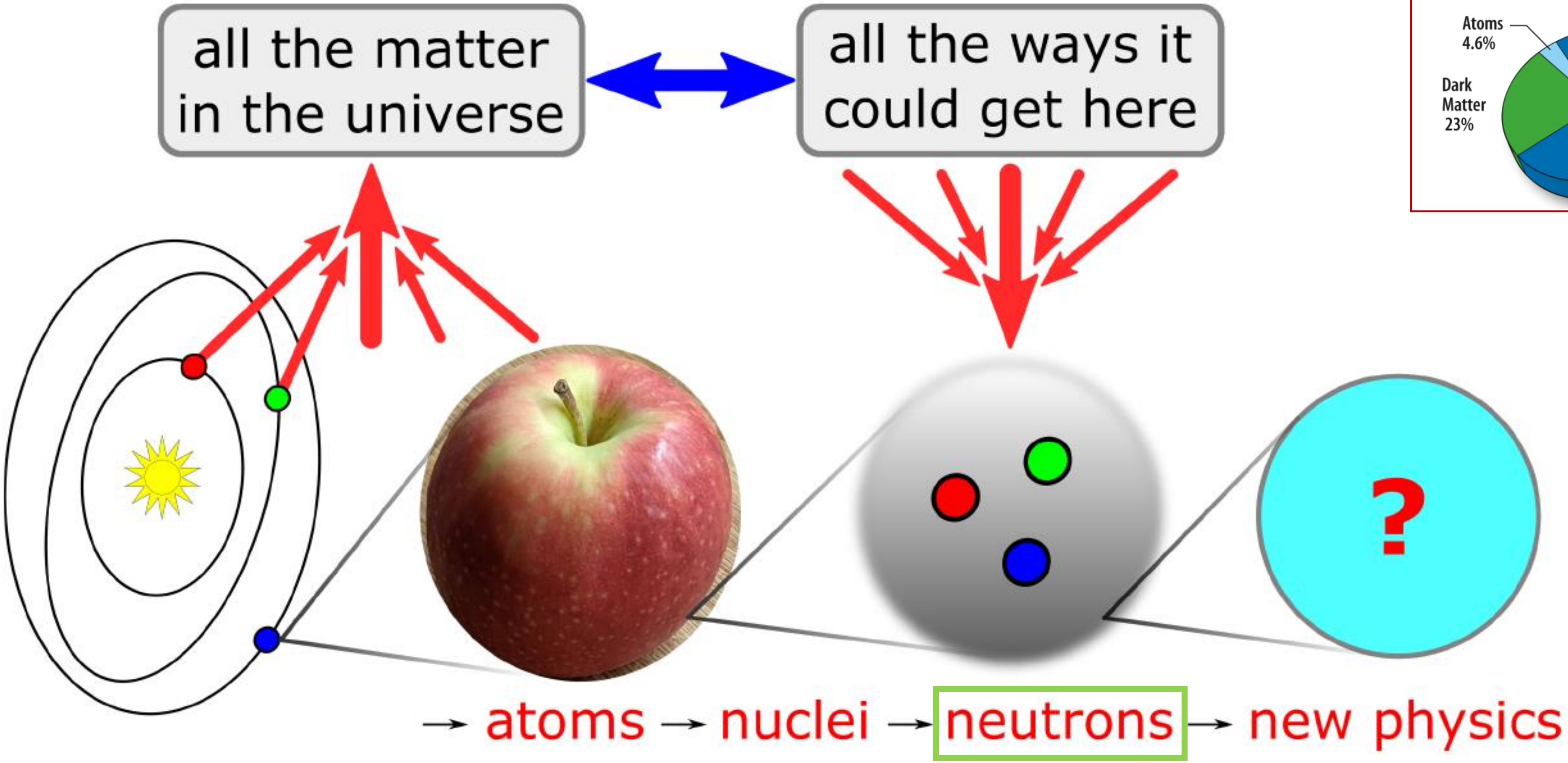
Universität Heidelberg

Case 2: nuclear spin gyroscopes





Our motivation, and a sense of scale

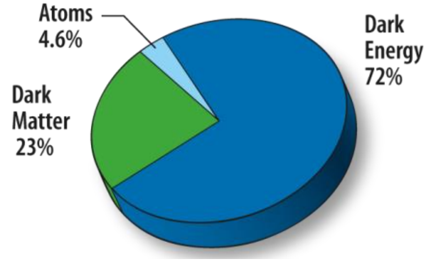


all the matter in the universe

all the ways it could get here

→ atoms → nuclei → neutrons → new physics

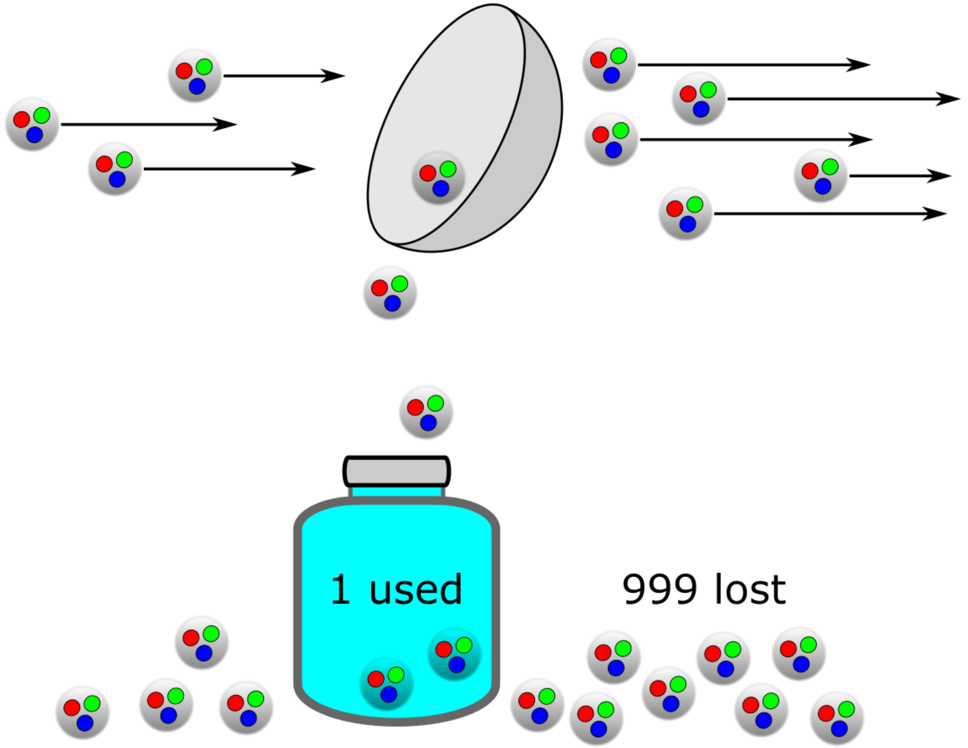
The Universe in a pie:



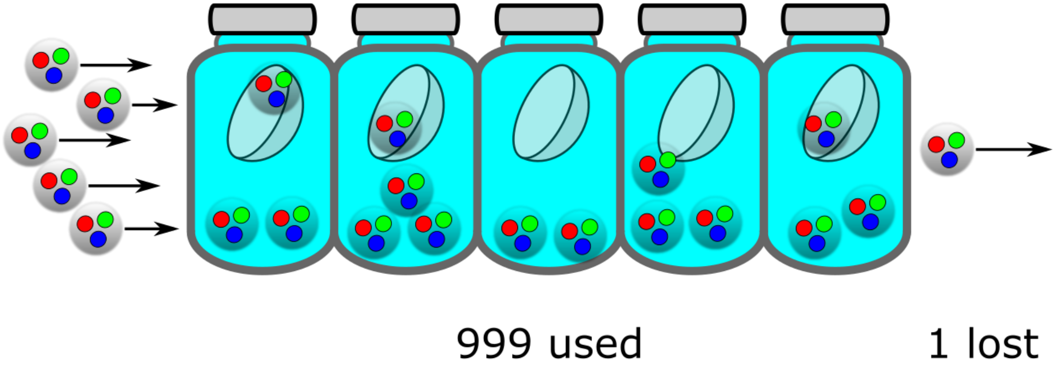
①

Challenge the first: statistics

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



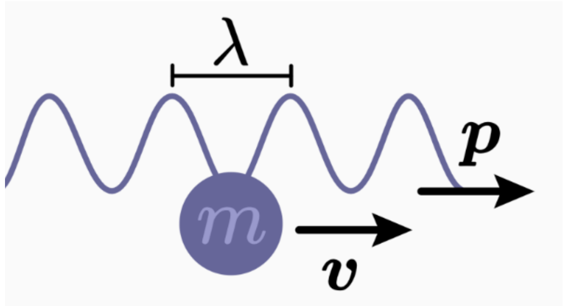
New approach: catch them **all**, directly in many bottles



② Challenge the second: observation time

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

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

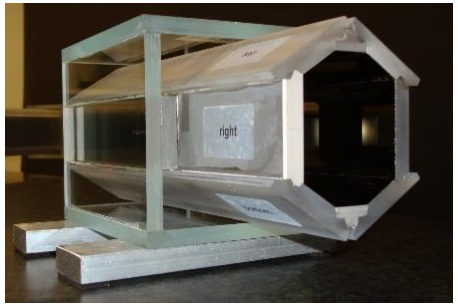


But… how to store or cool ensembles?

Wave optics, with massive particles!

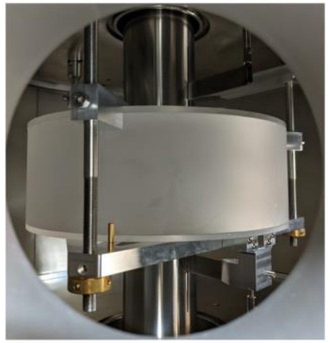
"Cold" beams: O(500 m/s)

particles fly through most experiments in milliseconds



S-DH

S-DH



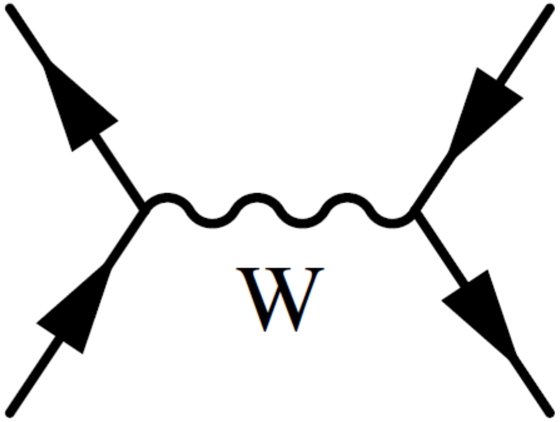
"Ultracold" traps: O(5 m/s)

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



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

"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!

“Permanent Electric Dipole Moment” = ?

Quantum eigenfrequencies:

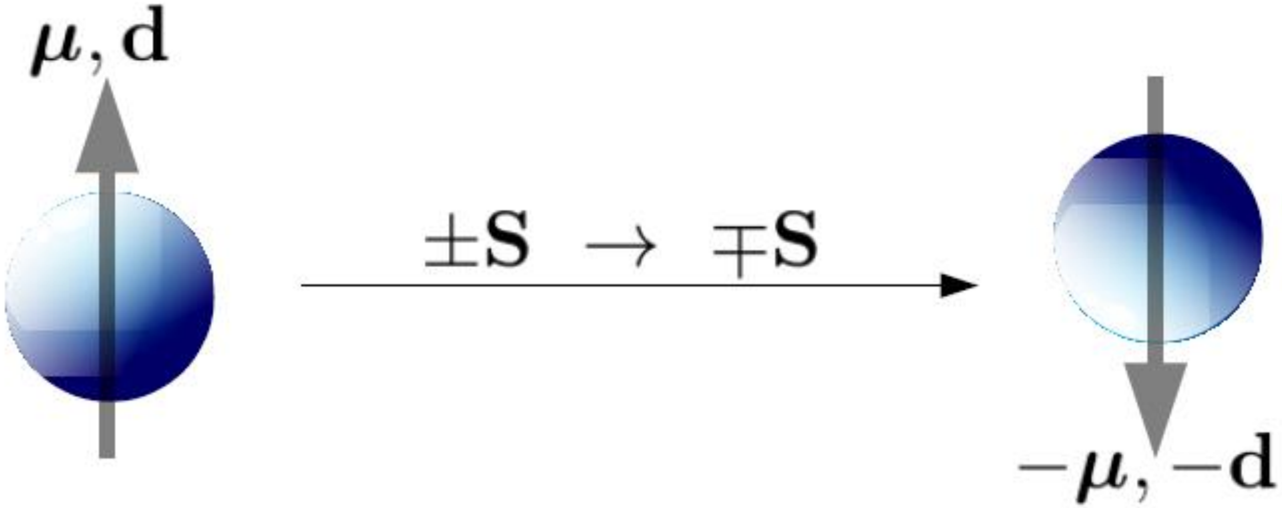
$$\hbar\omega_E \propto -d\boldsymbol{S}\cdot\boldsymbol{E}$$

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

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!

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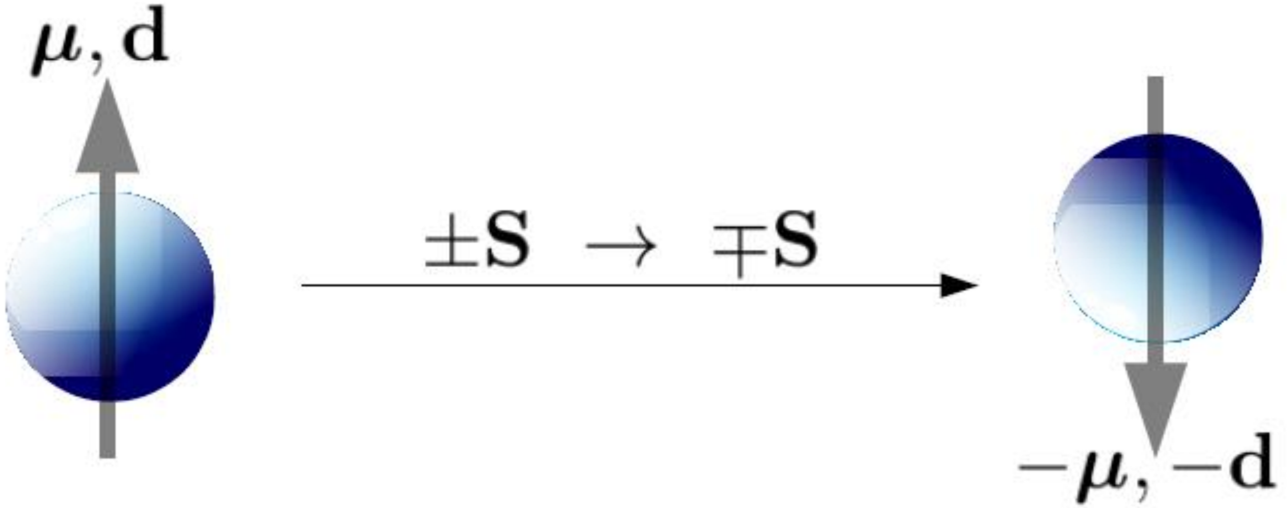
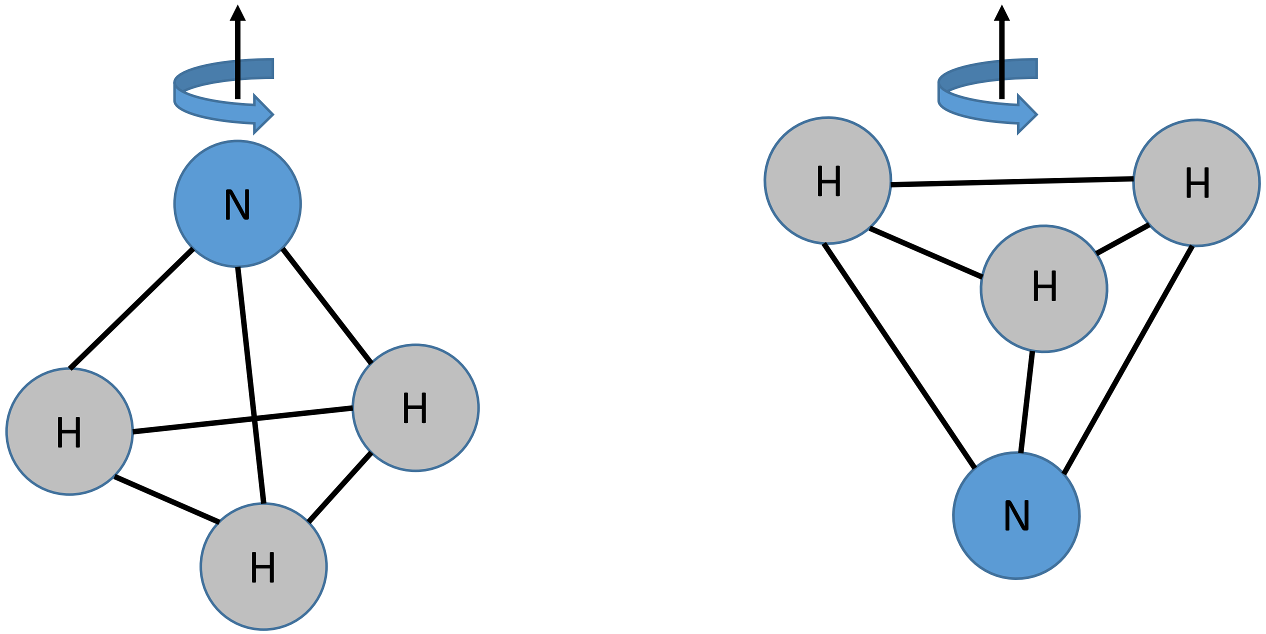


$$T\mathbf{r}T^{-1} = \mathbf{r}$$
$$T\mathbf{p}T^{-1} = -\mathbf{p}$$
$$T\boldsymbol{\sigma}T^{-1} = -\boldsymbol{\sigma}$$

Is it different from a molecular dipole?

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



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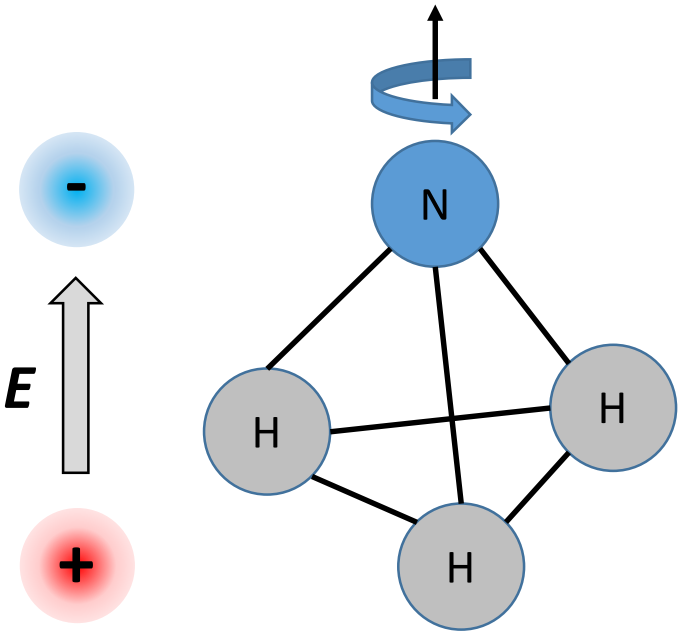

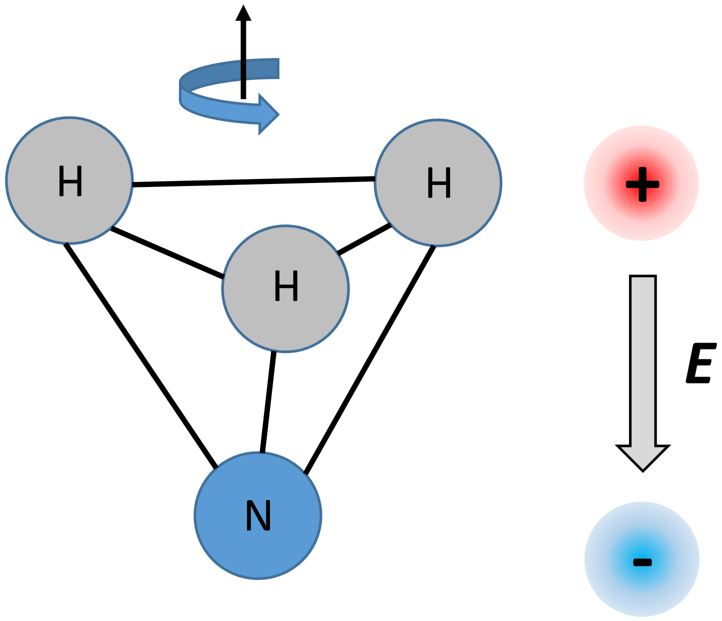

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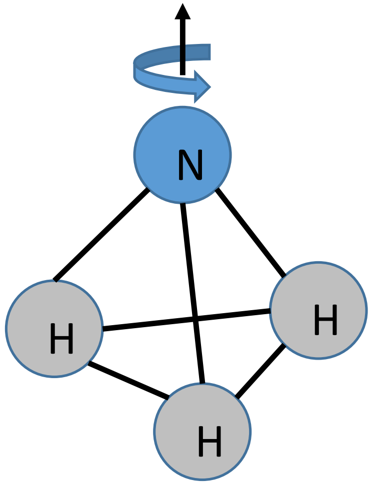
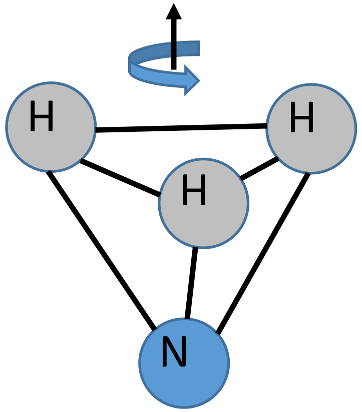


$|1\rangle$

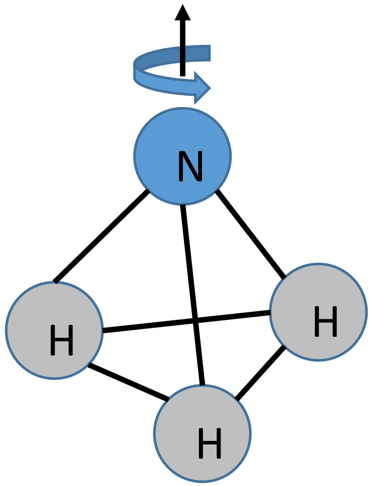


$|2\rangle$

The *energy* eigenstates are:

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

Is it different from a molecular dipole?



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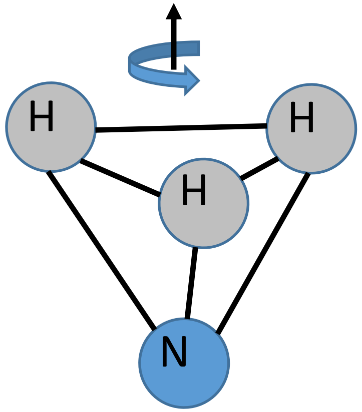

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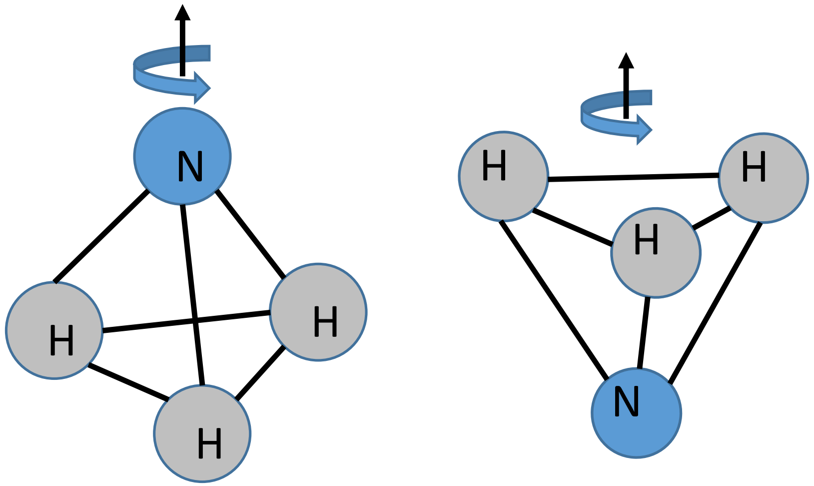
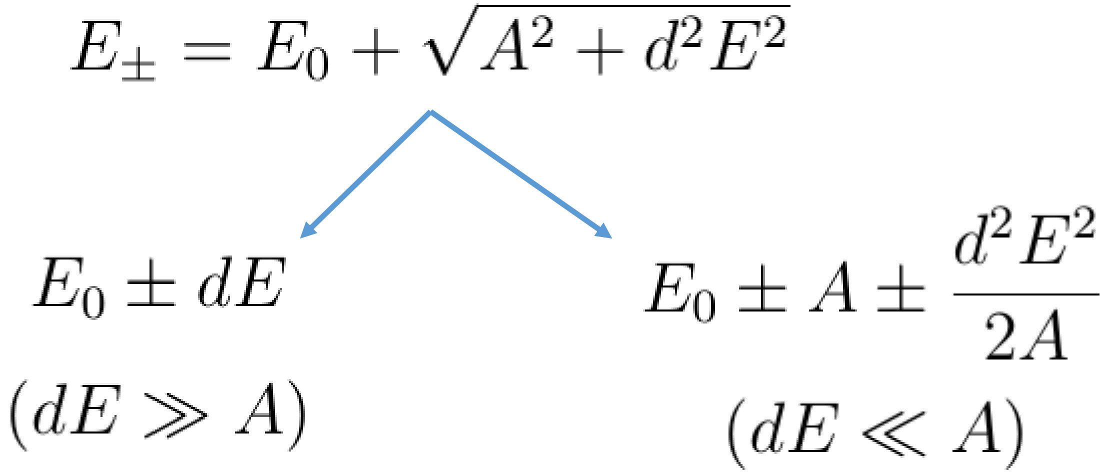


$|1\rangle$ $|2\rangle$



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

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

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

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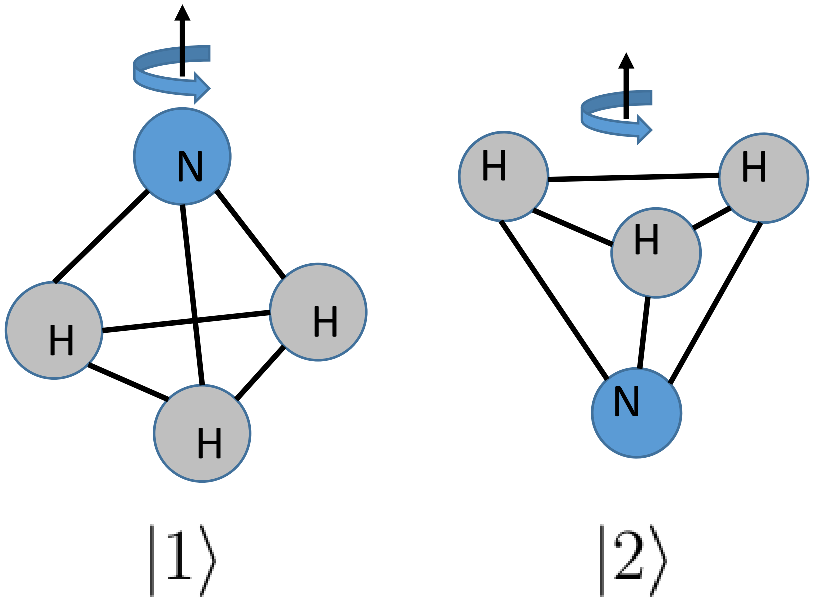

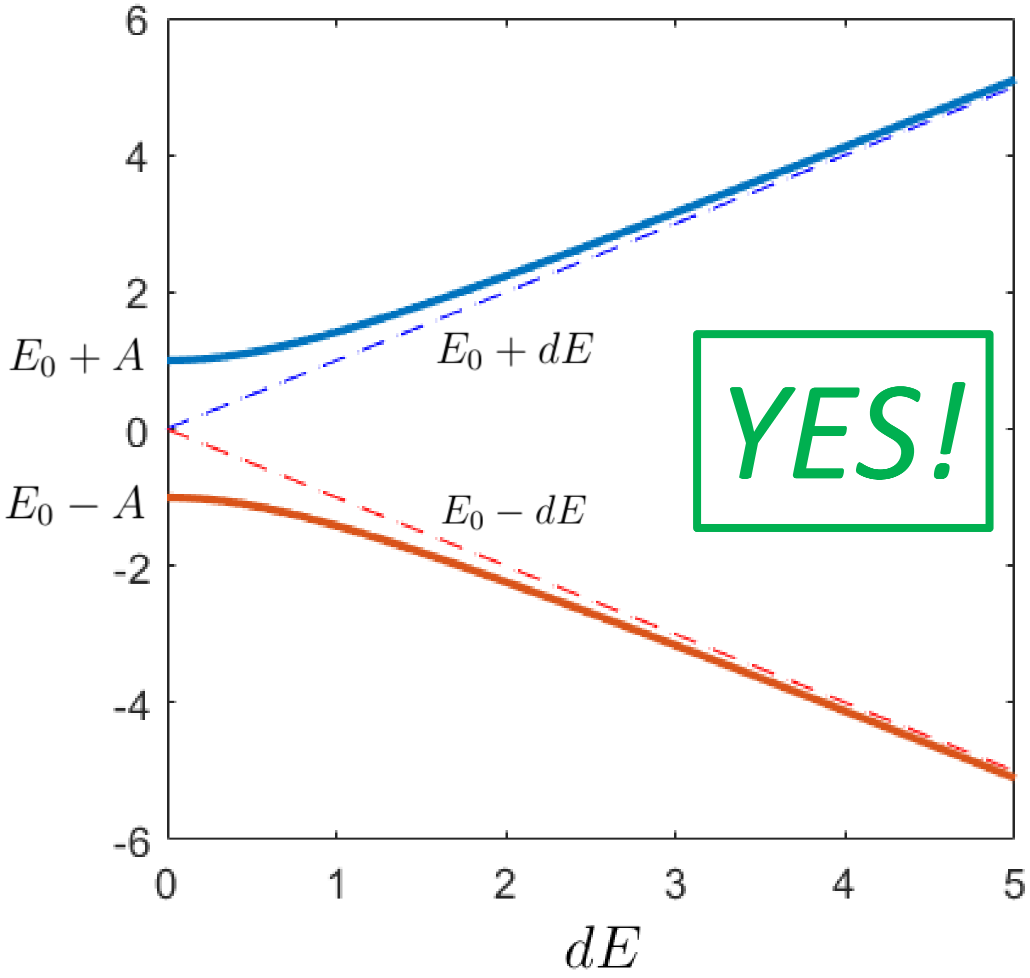

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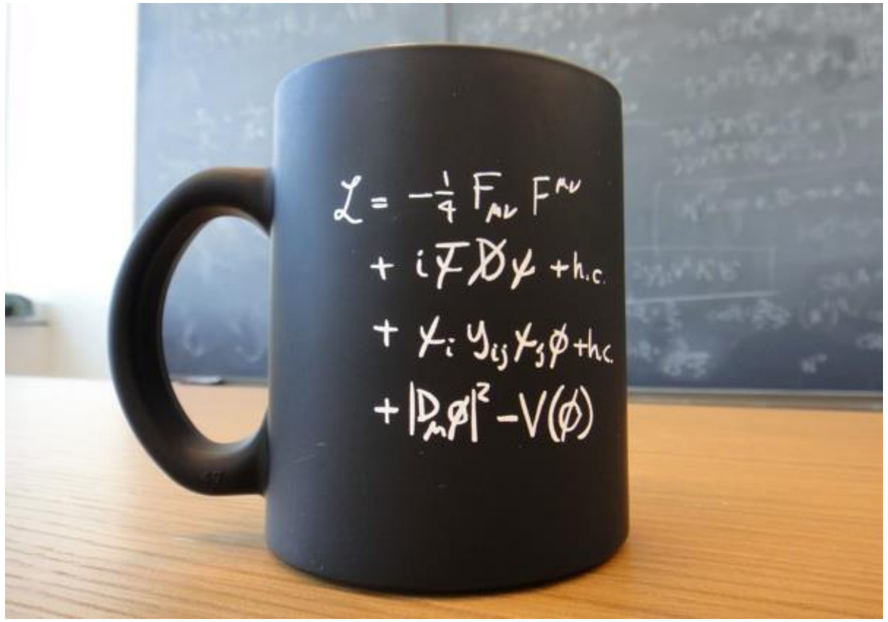
New Physics, in Familiar Terms

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

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!

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

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

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

A Taxonomy of Form Factors

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

$$Q = F_1(0)$$

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

$$a = F_4(0)$$

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

Analysis: Dimensional vs. Global

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 → $\Lambda \sim 10 - 100\ \mathrm{TeV}$

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

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

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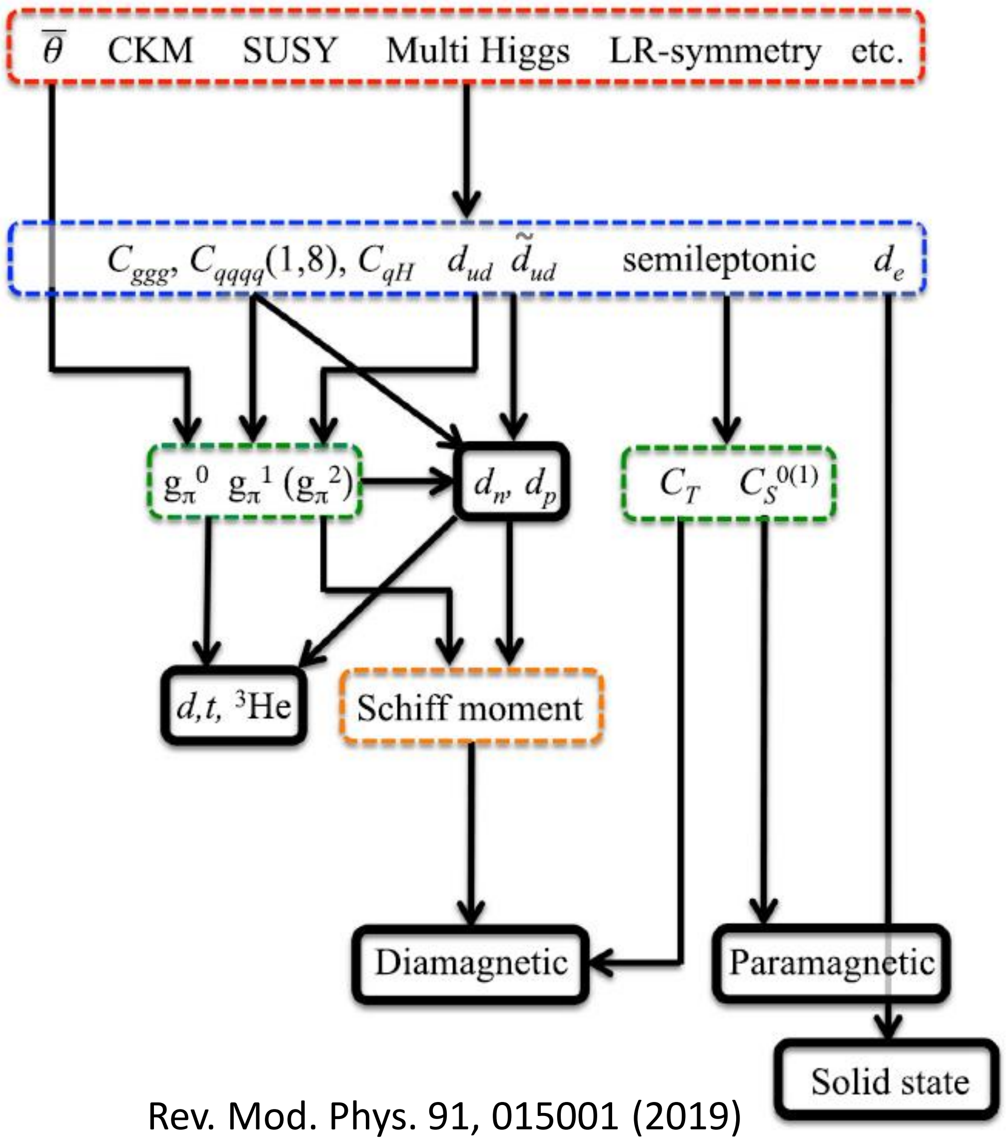

Rev. Mod. Phys. 91, 015001 (2019)

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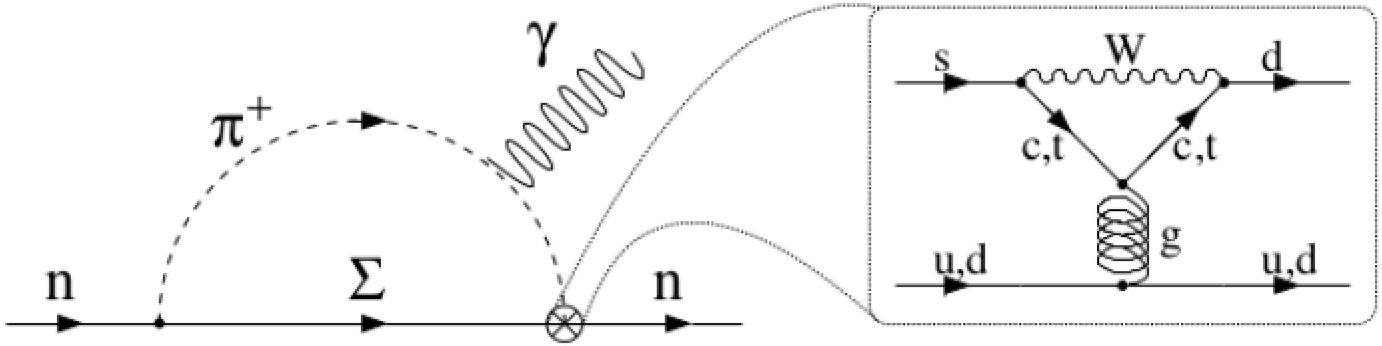
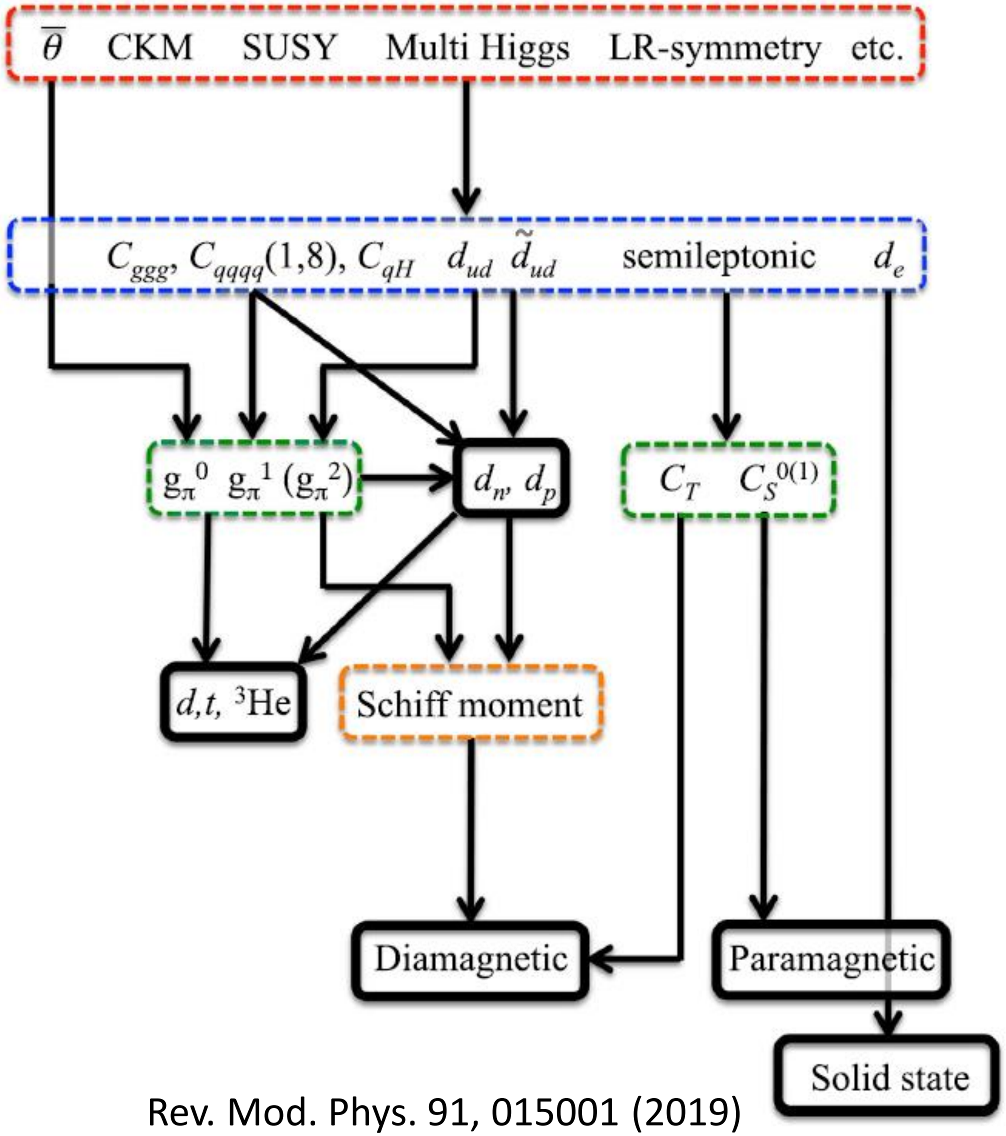
Neutron EDM from CP-violating pion couplings:



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



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Many Parameters / Many Experiments

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), …

Un-natural Units; Orders of Magnitude

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

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

$$\frac{1}{24 \text{ hours}} = 11.6 \; \mu\text{Hz}$$

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

$$\frac{1}{15 \text{ min}} = 1 \text{ mHz}$$

$$\mu_{\text{N}} \times \frac{1 \mu\text{T}}{2\pi\hbar} = 8 \text{ Hz}$$

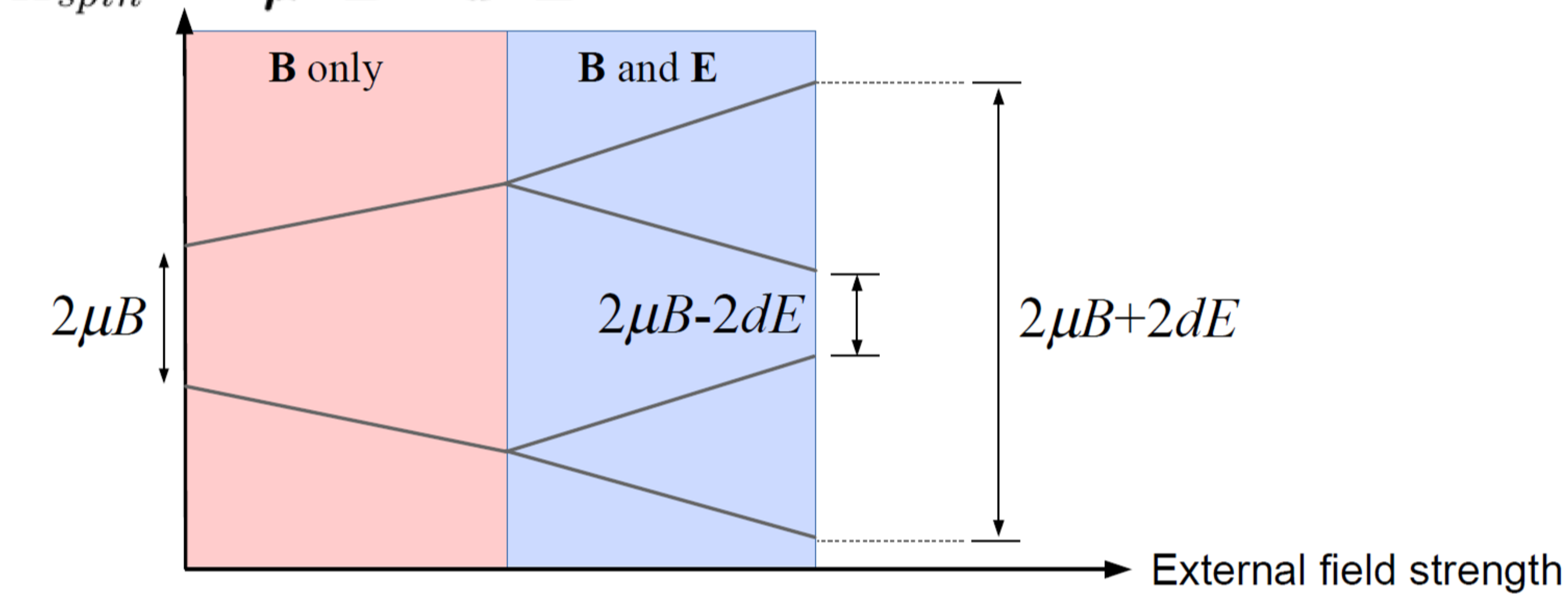
$$\mu_{\text{B}} \times \frac{1 \mu\text{T}}{2\pi\hbar} = 14 \text{ kHz}$$

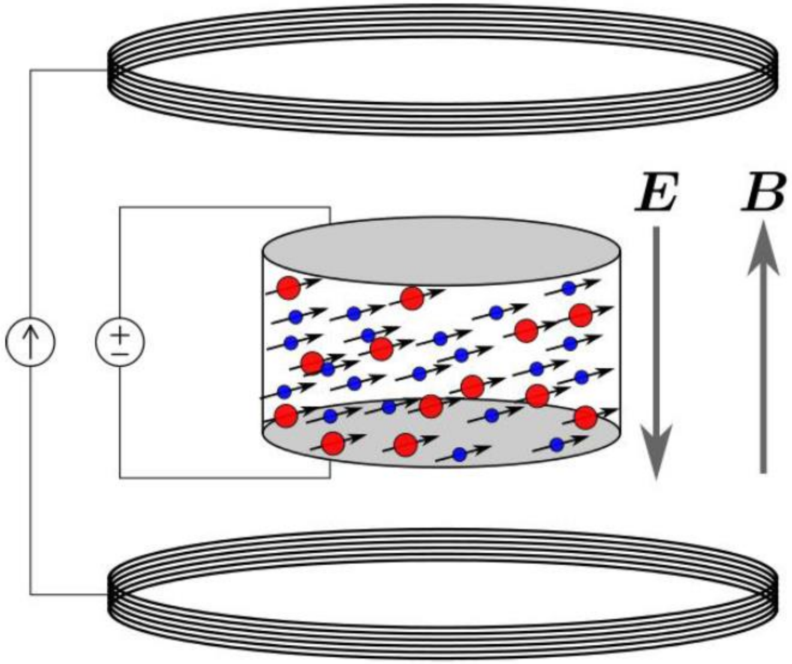
Some recent experimental EDM limits:

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

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.

Remember it 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:

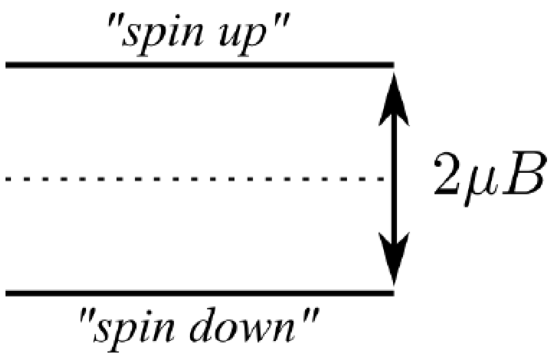
$$\frac{d\boldsymbol{\mu}}{dt} = \gamma \boldsymbol{\mu} \times \boldsymbol{B} - (\textit{relaxation terms})$$

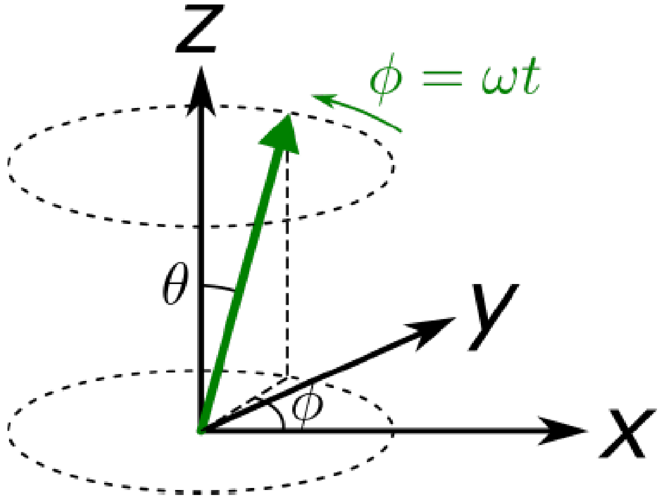
Sensitivity from: $\Delta E \Delta t \geq \hbar/2$

- relaxation limits measurement time
- many particles → many measurements

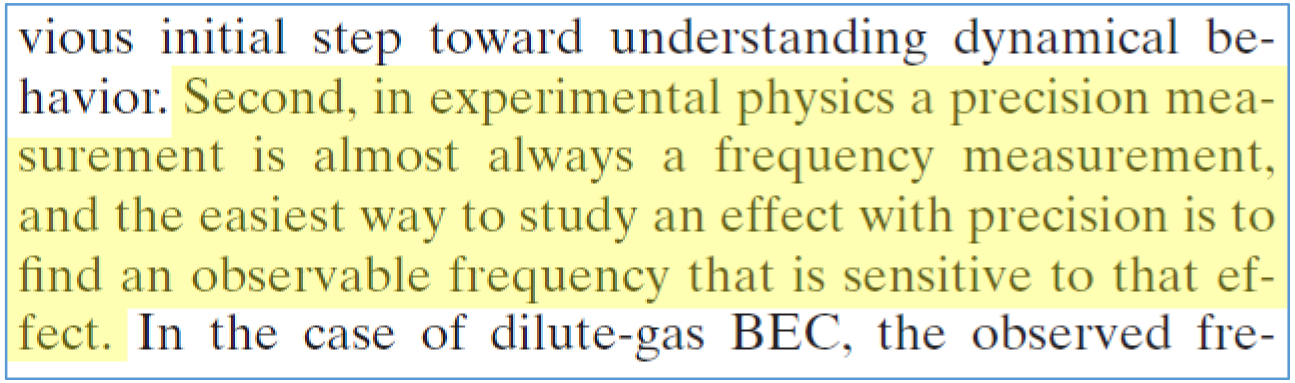
EDM fundamental sensitivity:

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





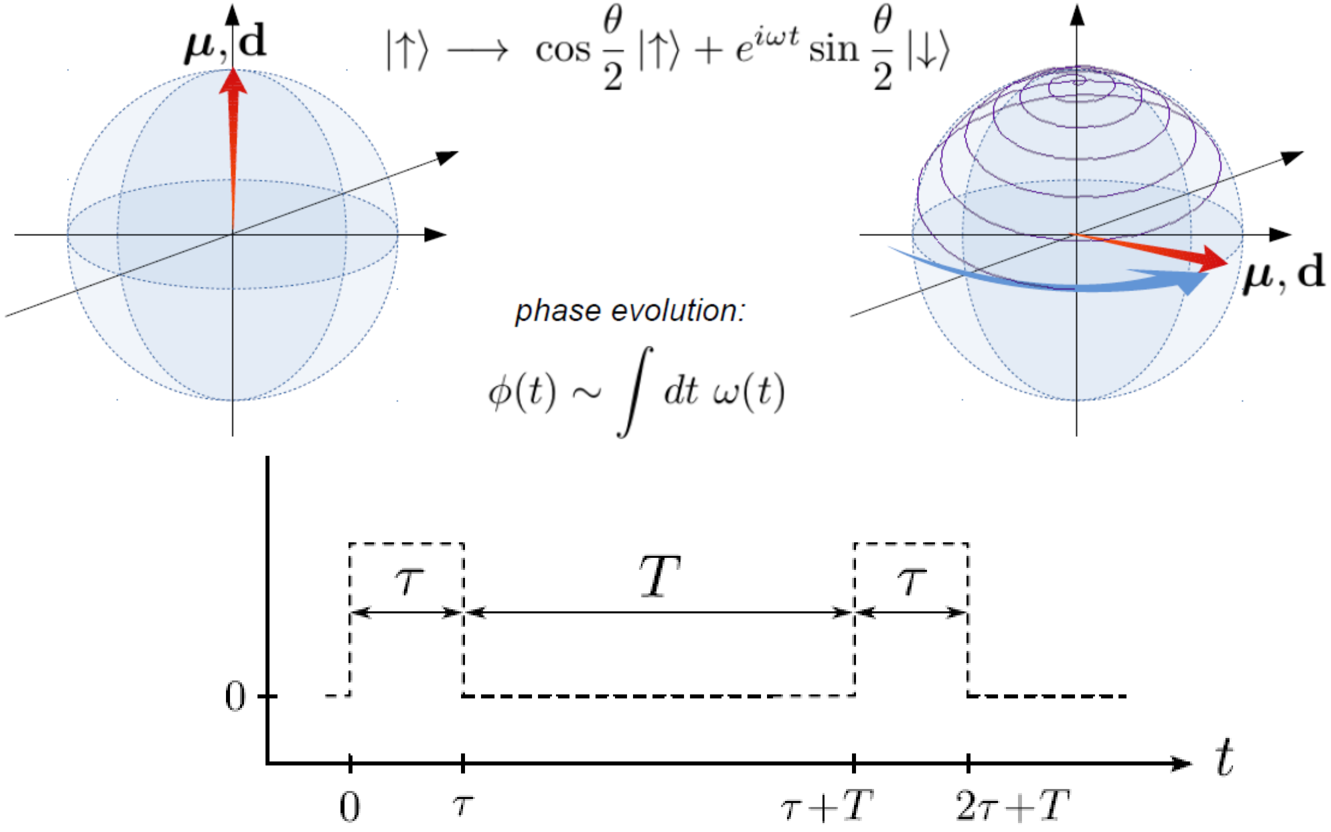
Cornell and Wieman… Nobel 2001, Rev. Mod. Phys. 74, 875 (2002)



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-

Time-Domain Interferometry

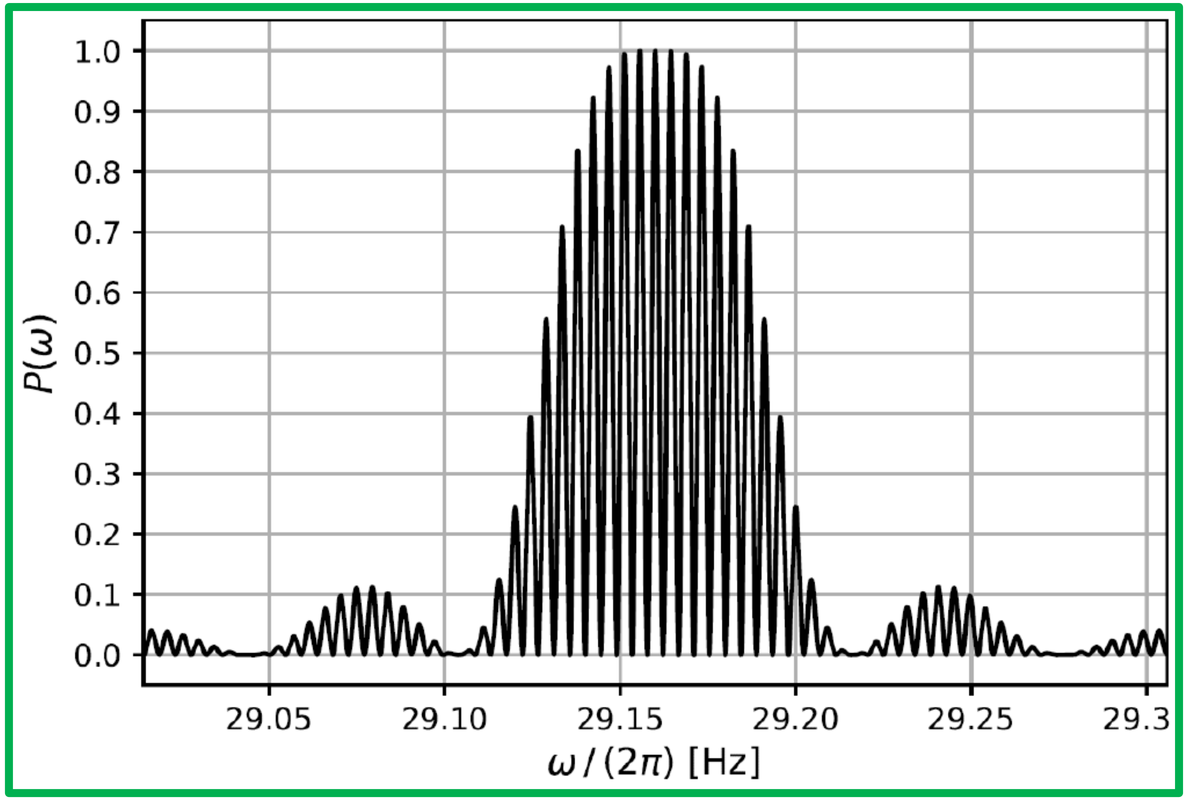
Ramsey's method to measure frequencies*:



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

phase evolution:

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



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

How could you measure an EDM?

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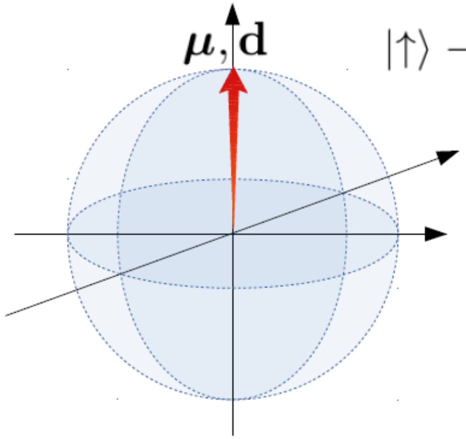

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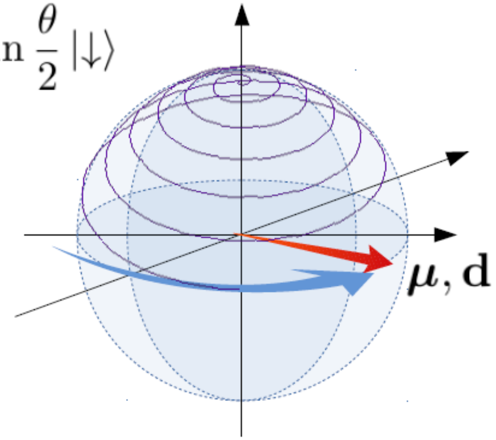

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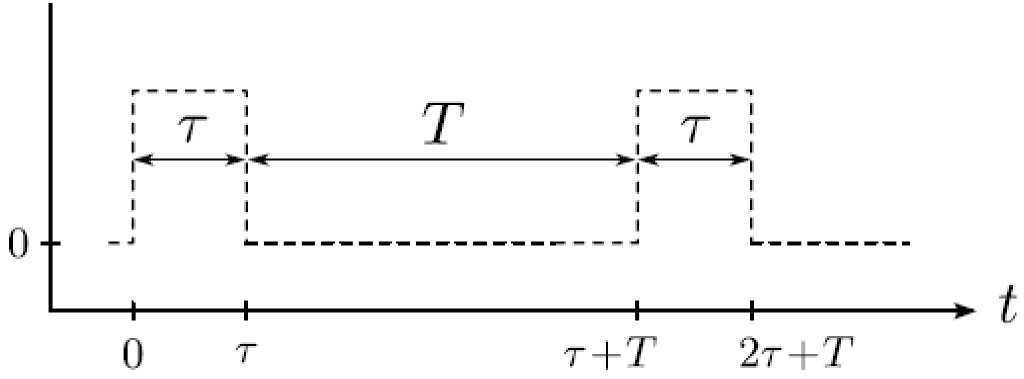
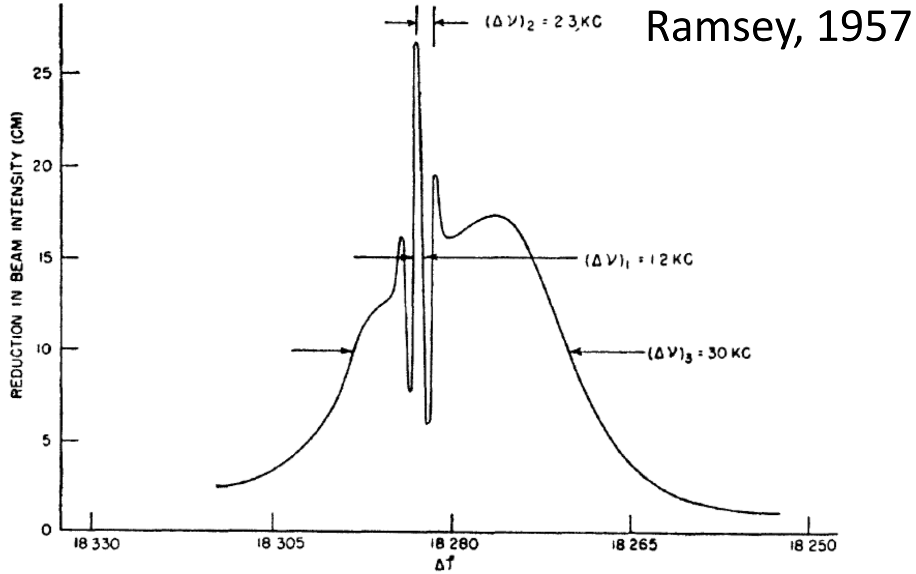
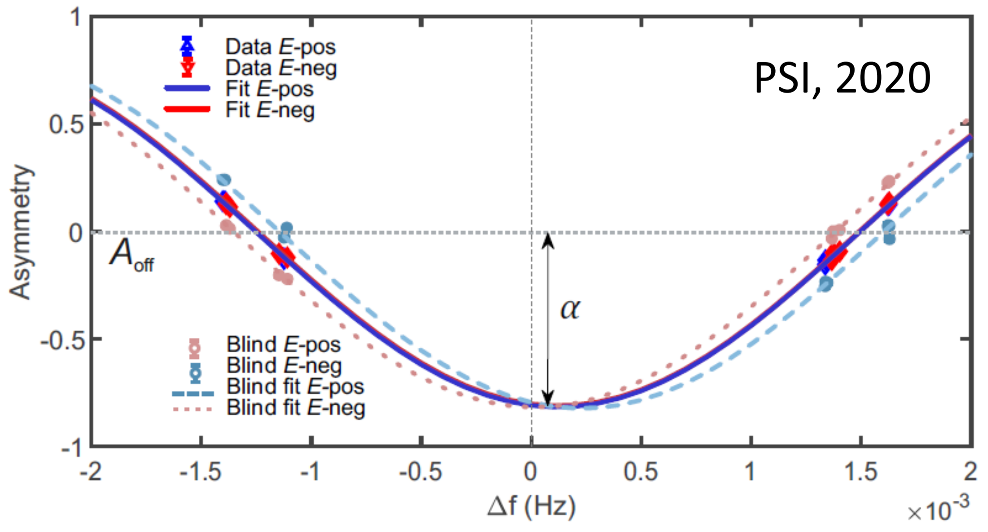




Ramsey, 1957

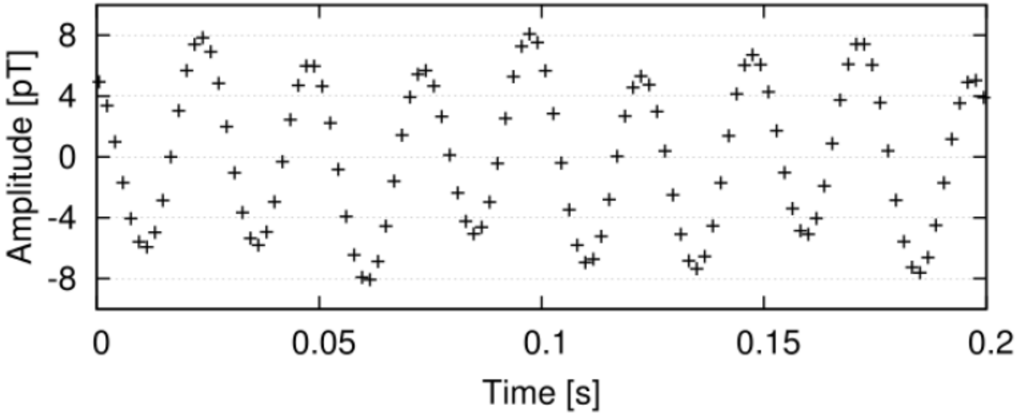


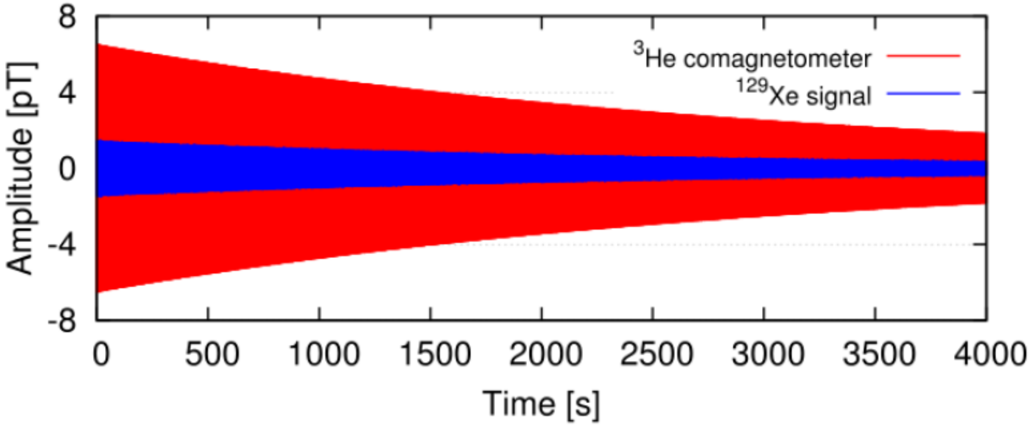
PSI, 2020

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

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

So which system should you measure?

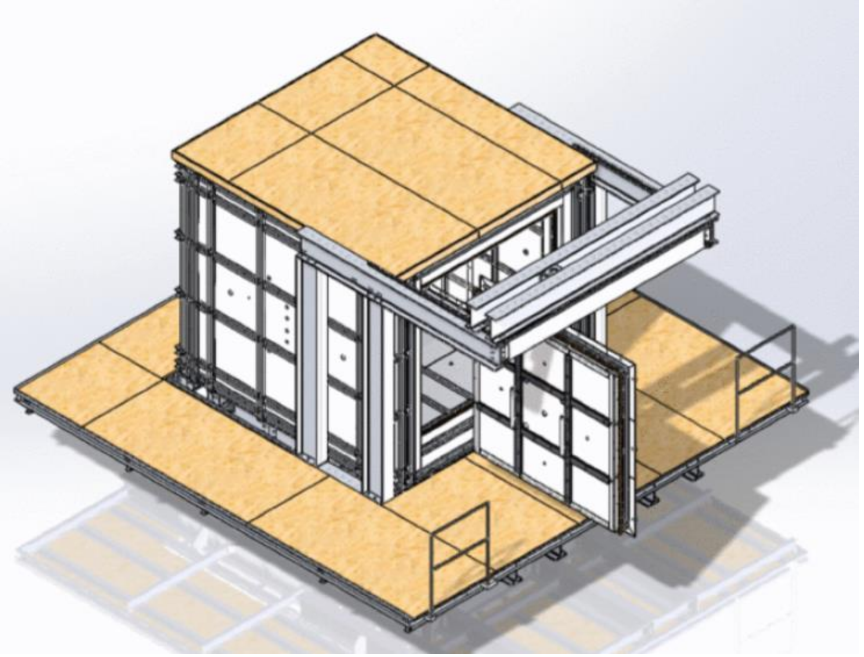
So which system should you measure?

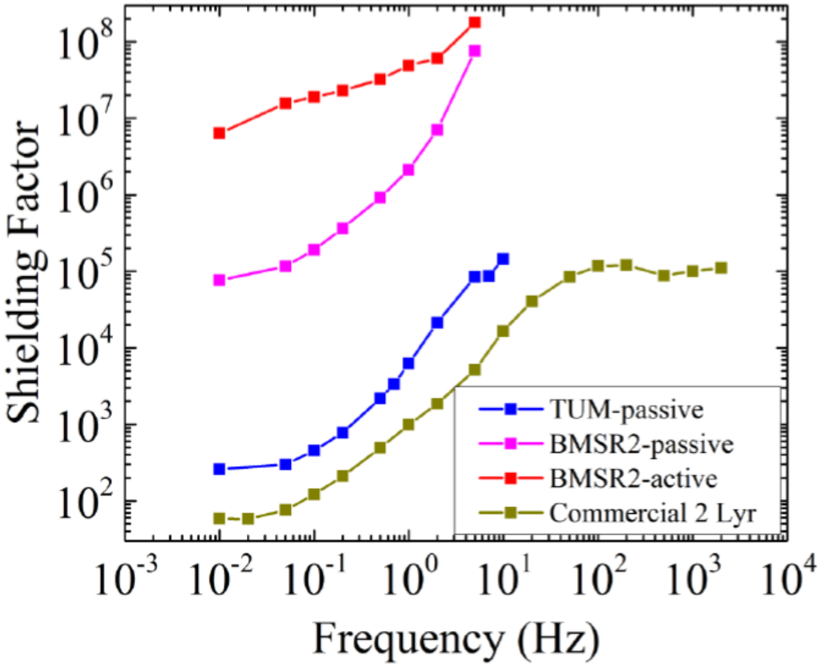
The one where you can discover an EDM, of course!

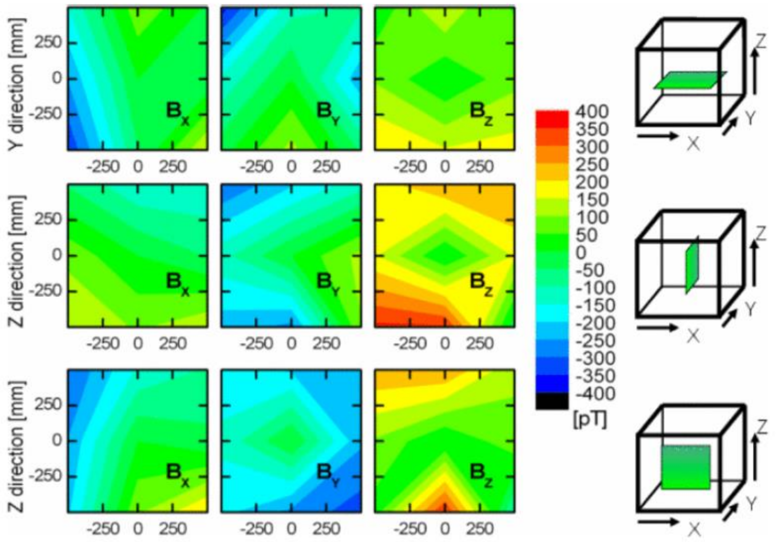
- M. Ramsey-Musolf

The HeXe Experiment

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

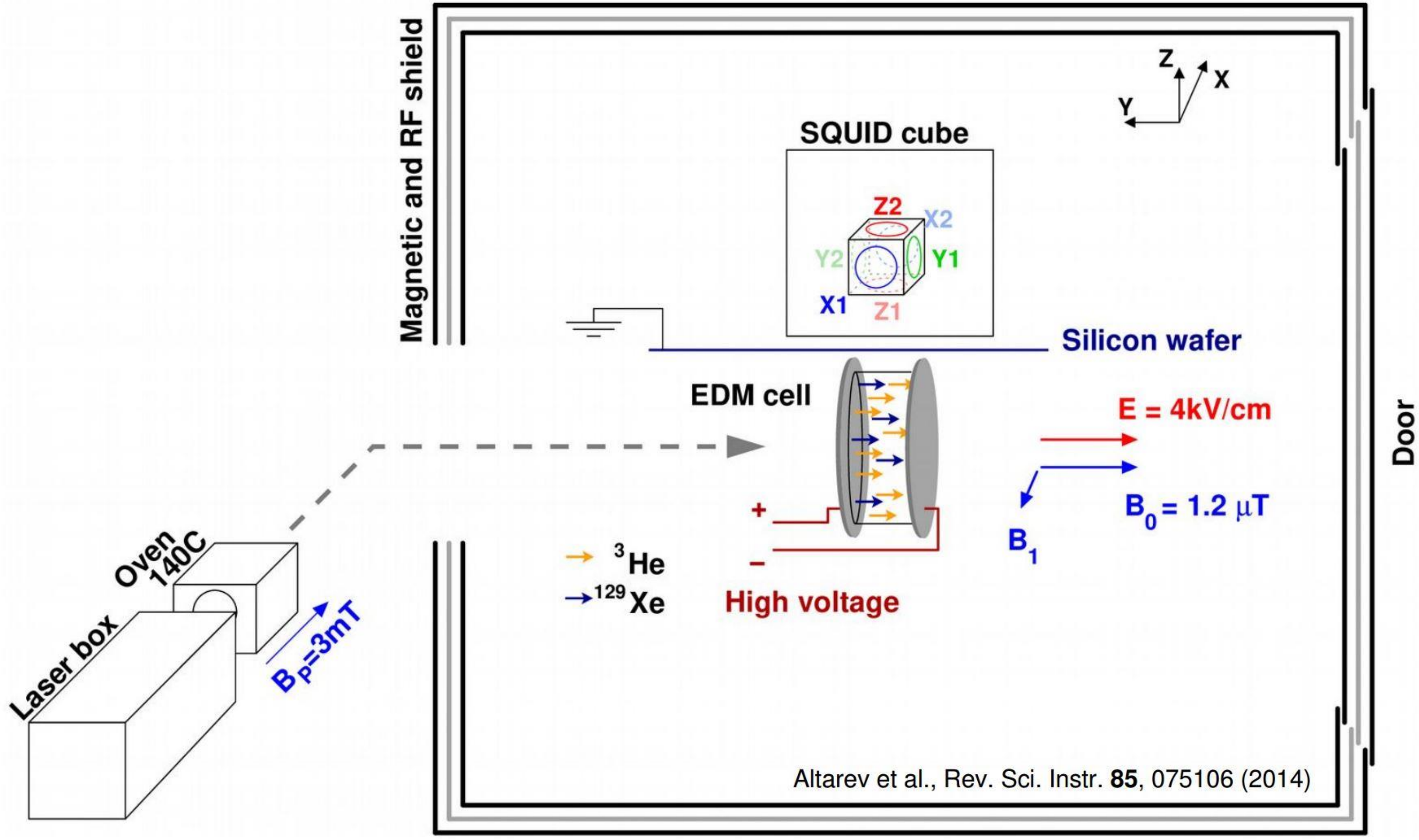






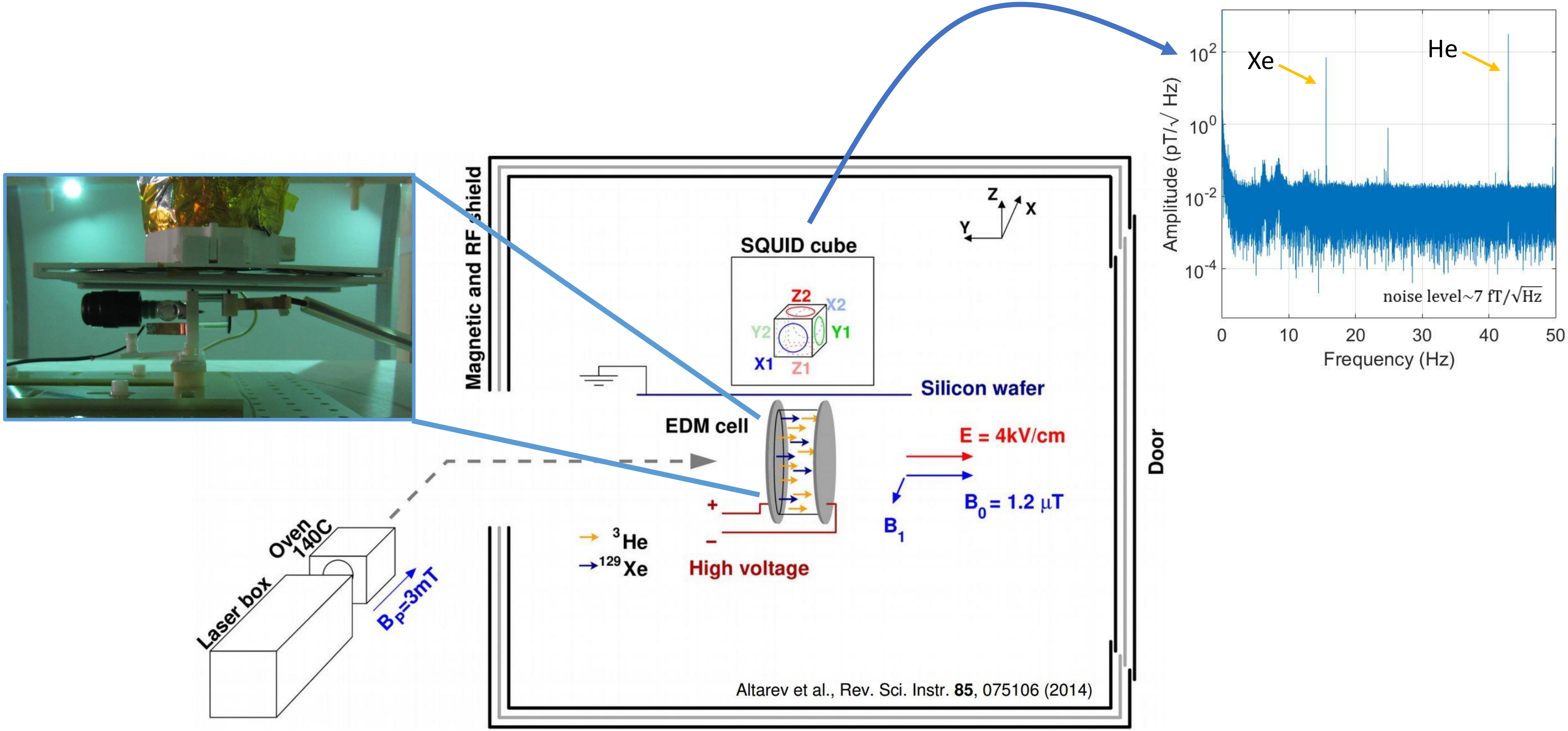
Rev. Sci. Instrum. **85**, 075106 (2014)
J. Appl. Phys. **117**, 183903 (2015)

The HeXe Experiment



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

The HeXe Experiment



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

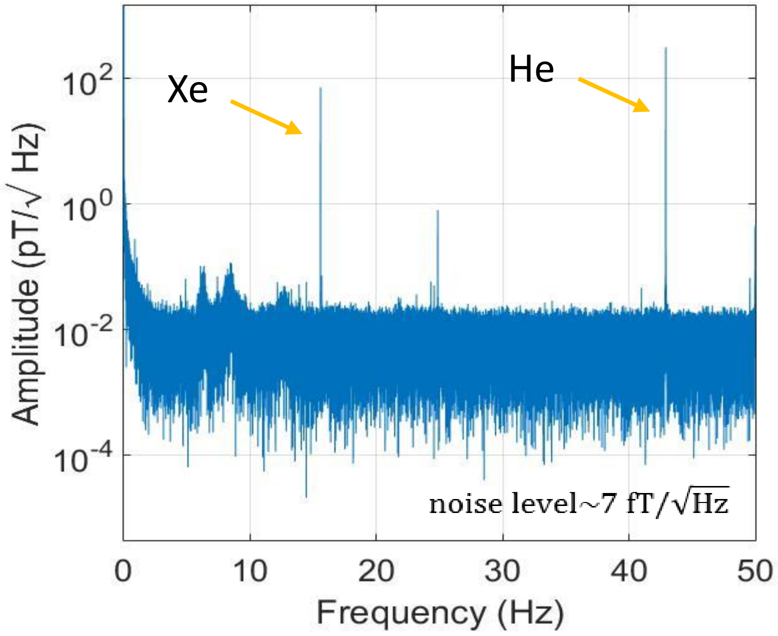
The HeXe Experiment

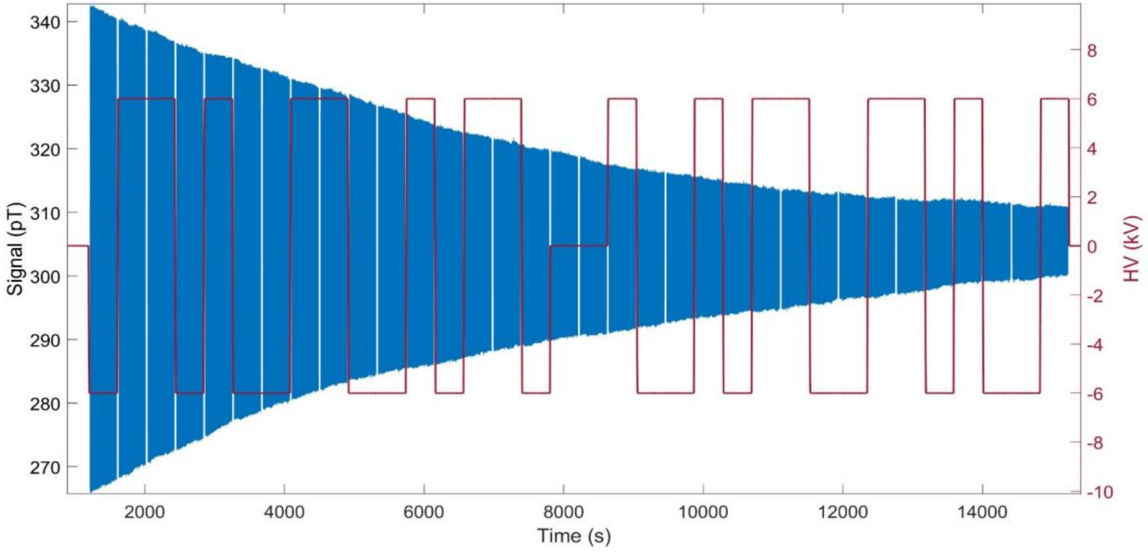
$E \sim 4\ \mathrm{kV/cm}$

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

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

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





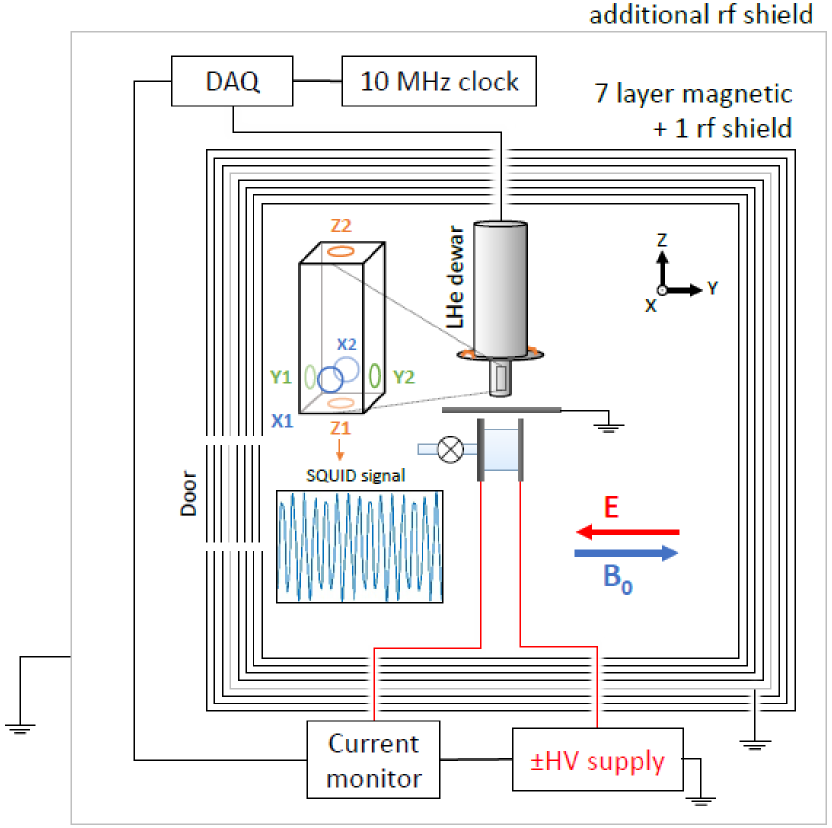
$$\delta\omega = \frac{1}{\tau (S/n)\sqrt{N}} = \frac{\epsilon\sqrt{f_{\mathrm{BW}}}}{\tau S\sqrt{N}}$$

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

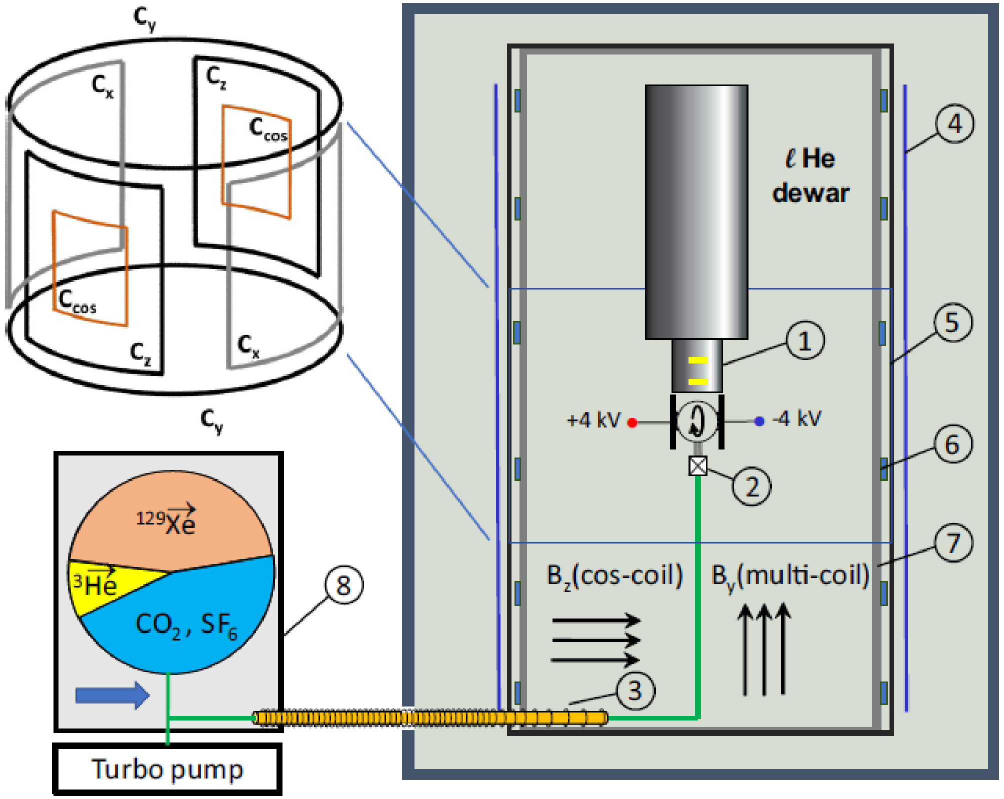
A rapidly-moving field!



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)

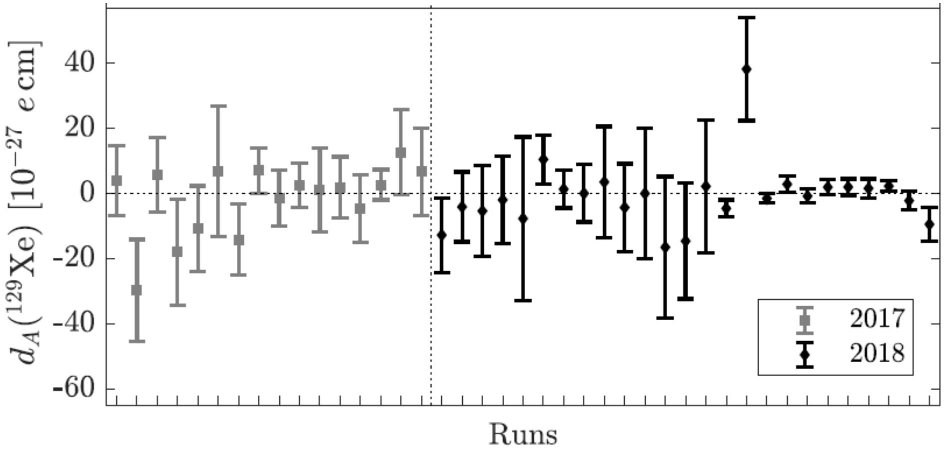


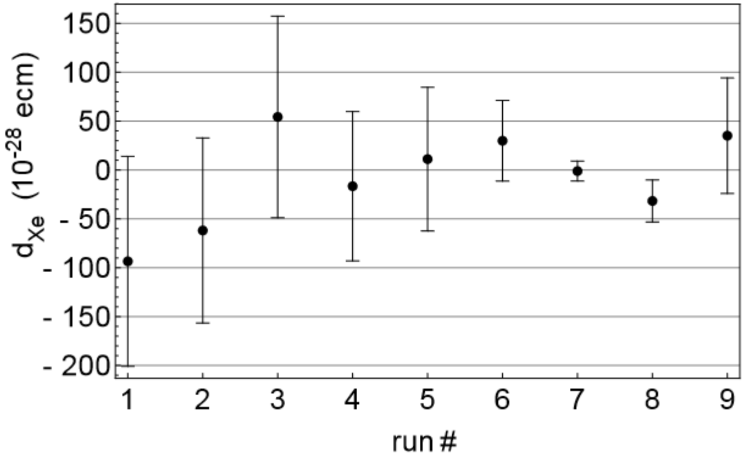
Near-simultaneous from MiXed:

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

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

A rapidly-moving field!





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

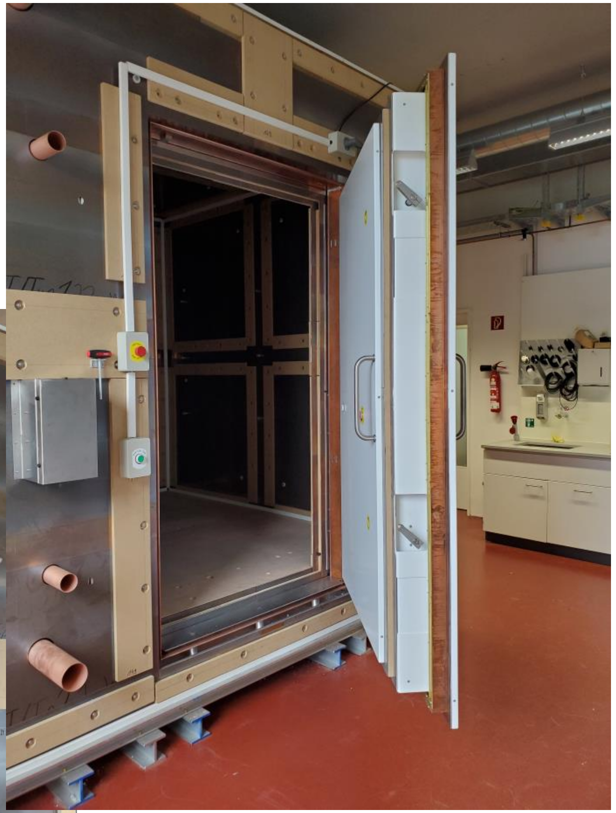
Near-simultaneous from MiXed:

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

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

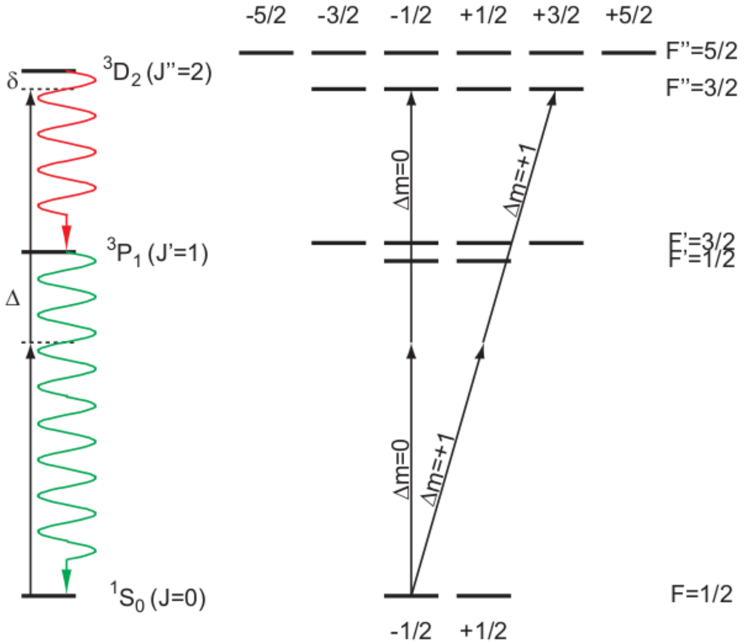
A United Future: collective experience

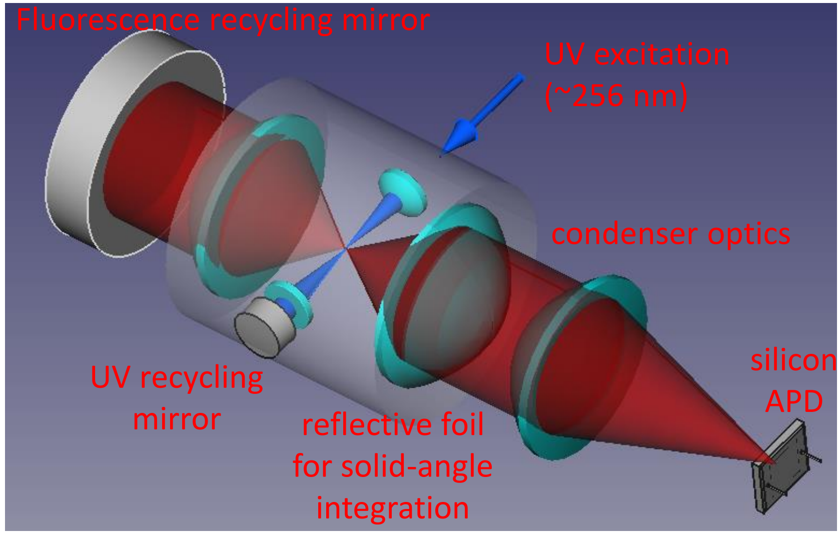
New magnetically shield room @HD! Dedicated facility…



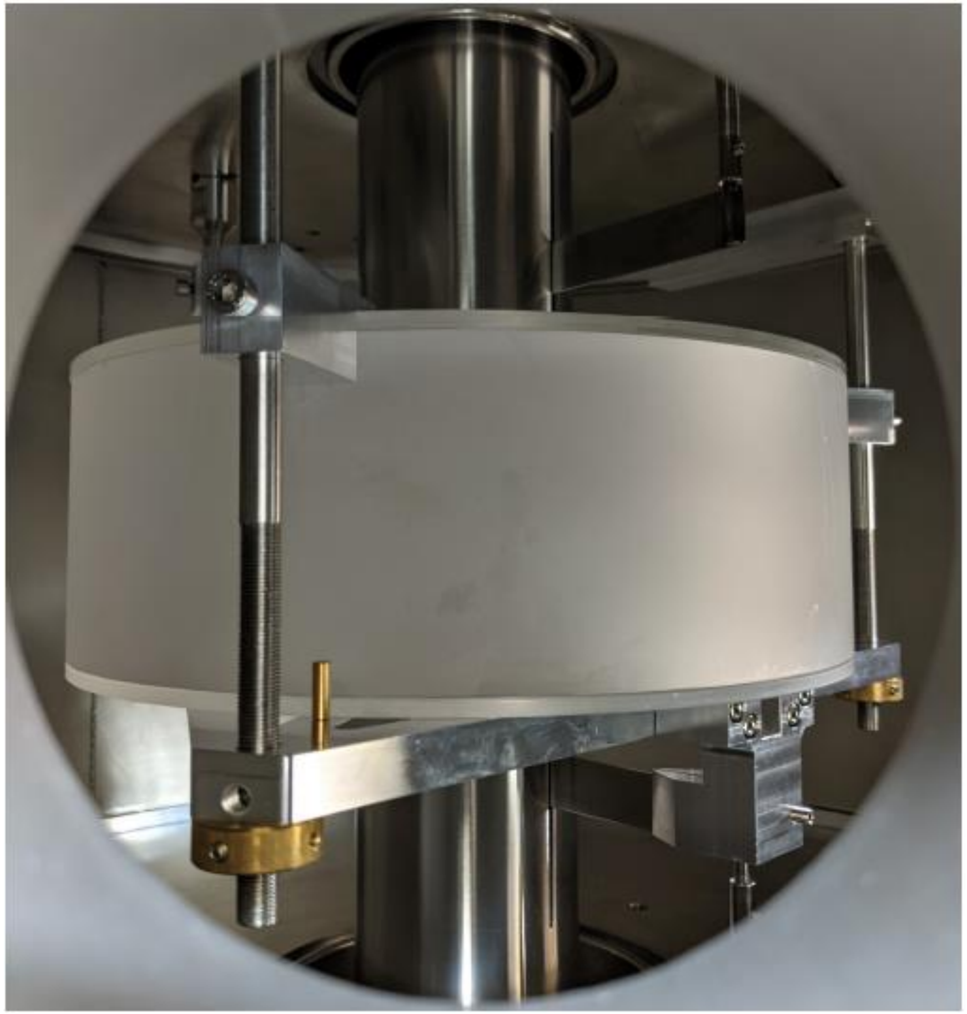
Next order-of-magnitude pursued by refining these now-known methods

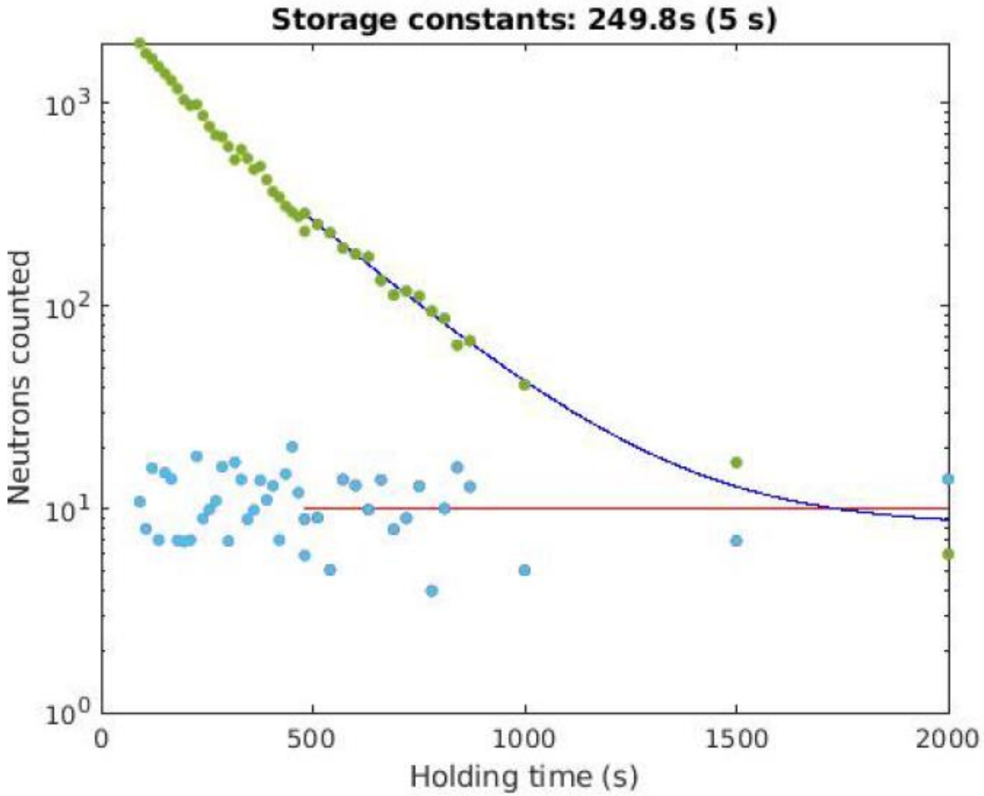
Laser spectroscopy may complement or eventually replace SQUIDS… new tools!





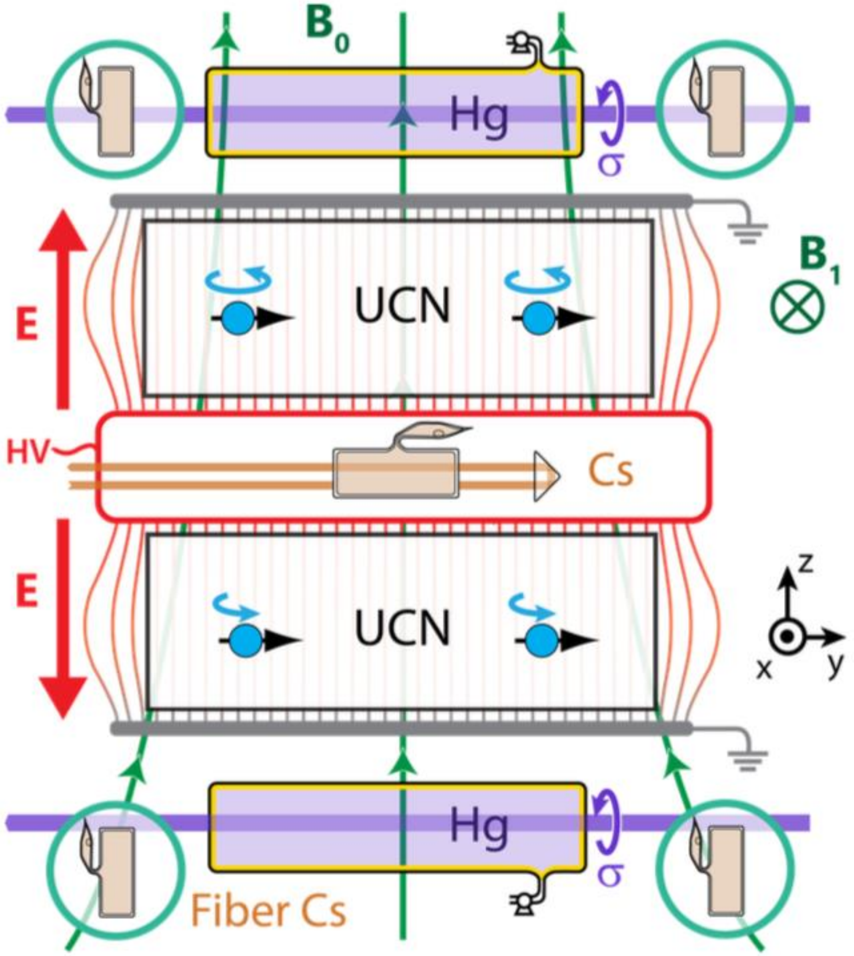
A contrast: neutrons disappear faster!

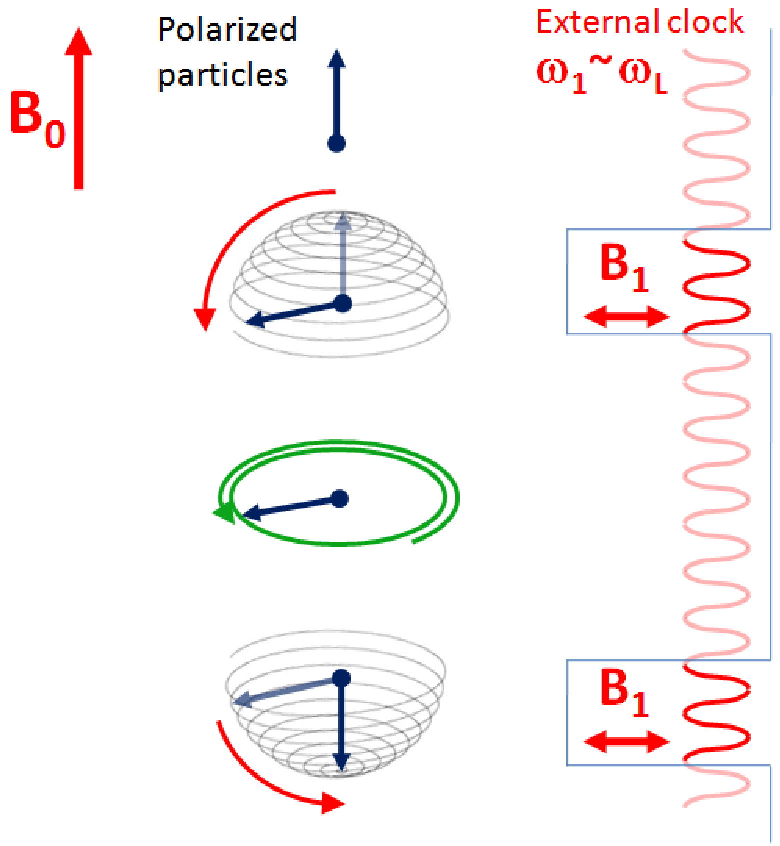




Magnetic fields would be good for loss… bad for systematics

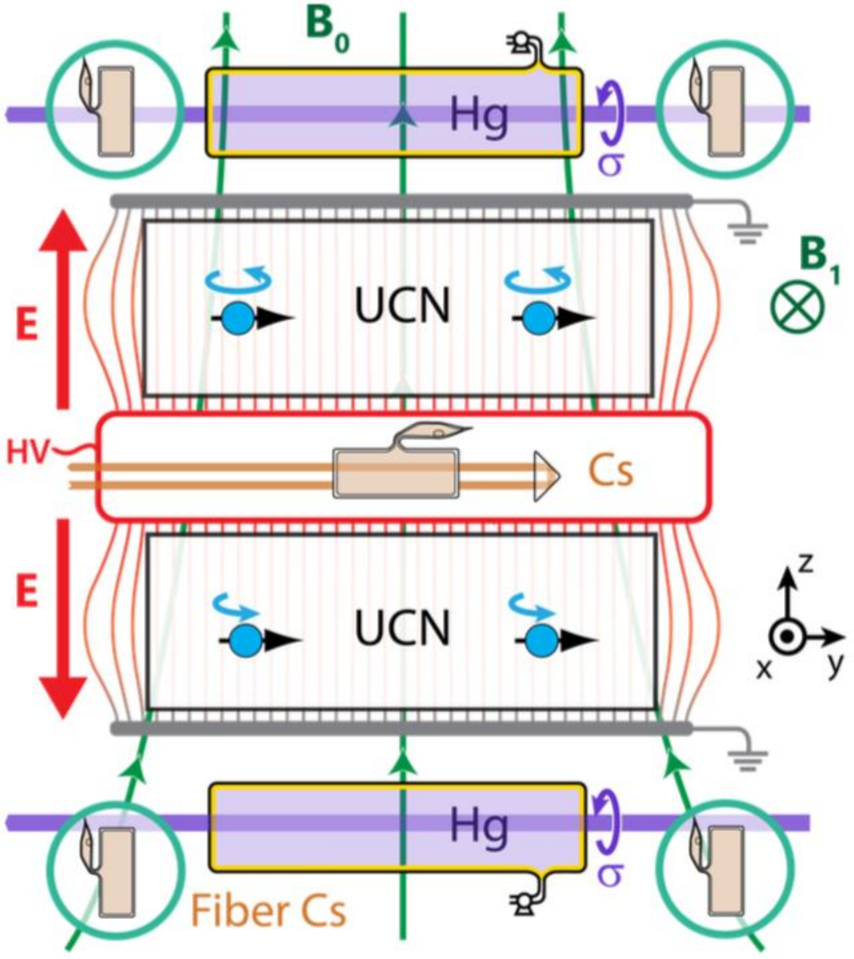
The PanEDM Experiment





EPJ Web of Conferences 219, 02006 (2019)

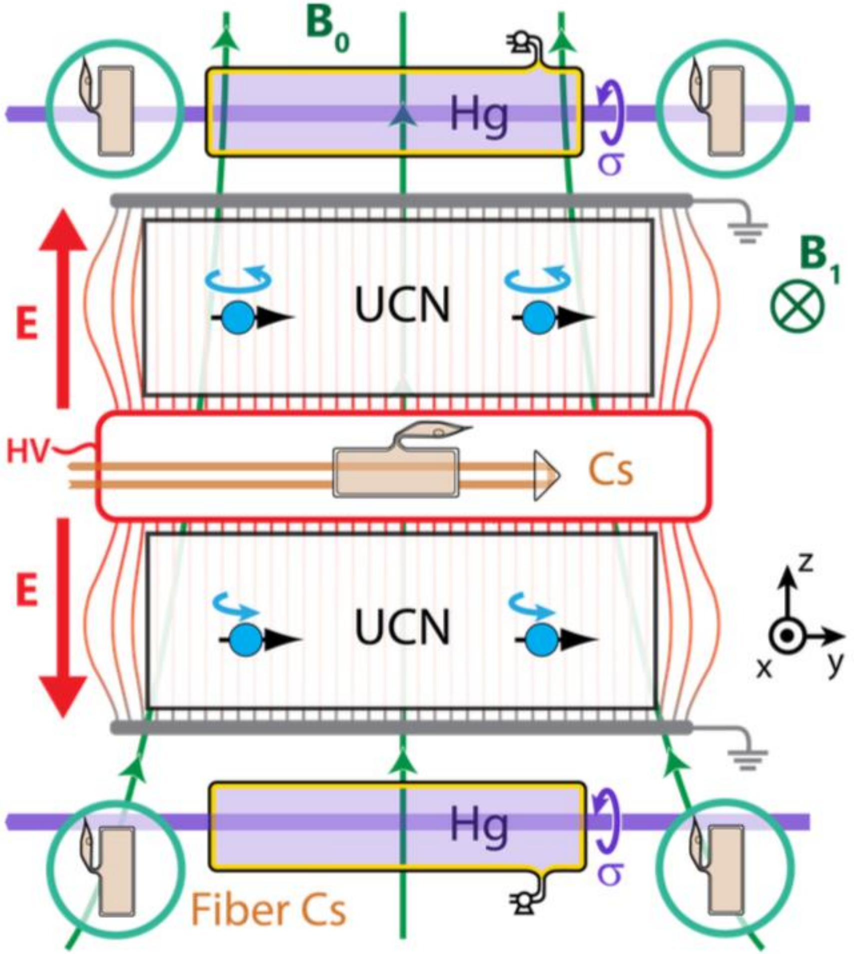
The PanEDM Experiment



- 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 measurement:

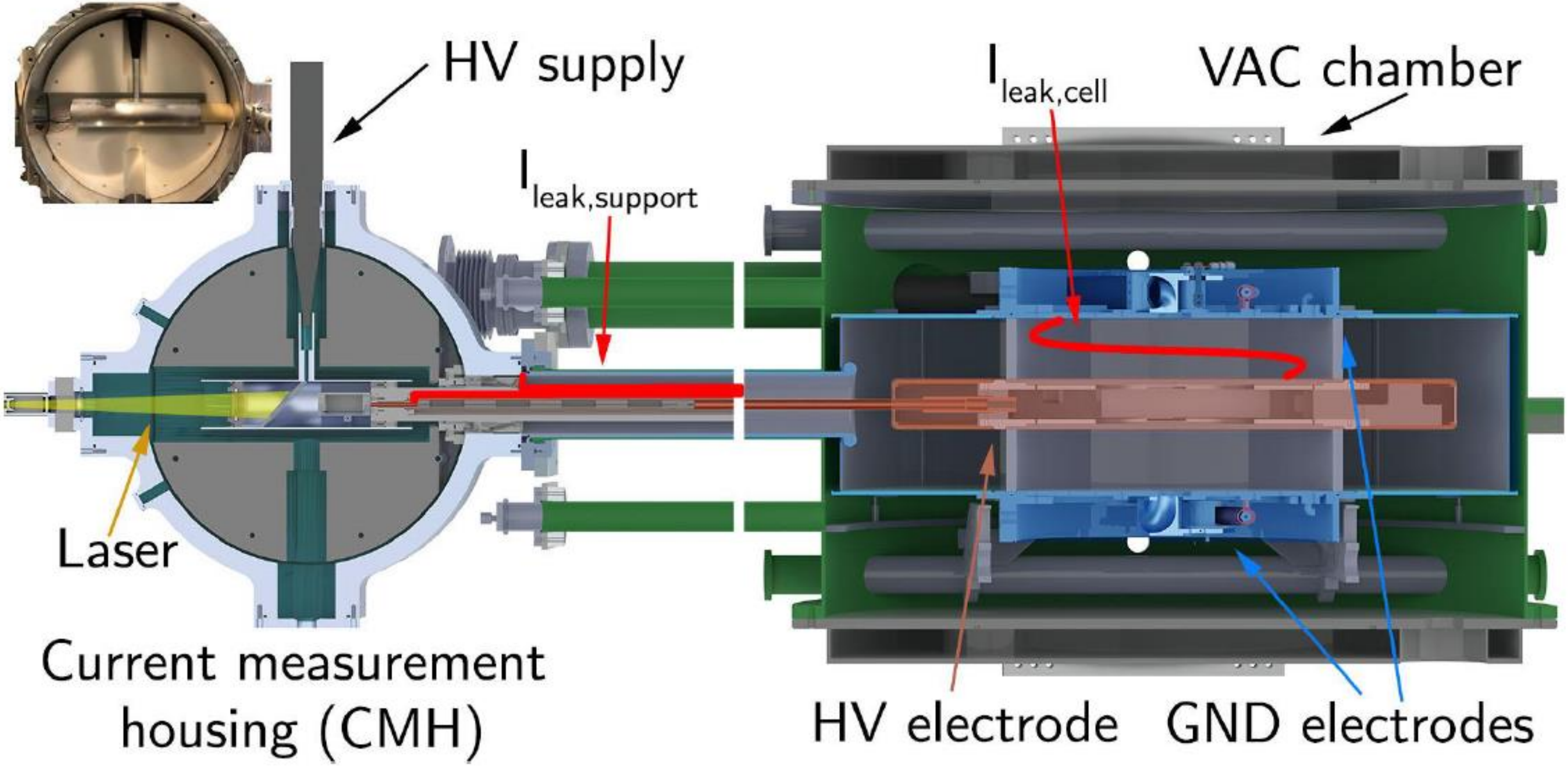
$$|\delta\omega| = \frac{|dE|}{\hbar F}$$

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}

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

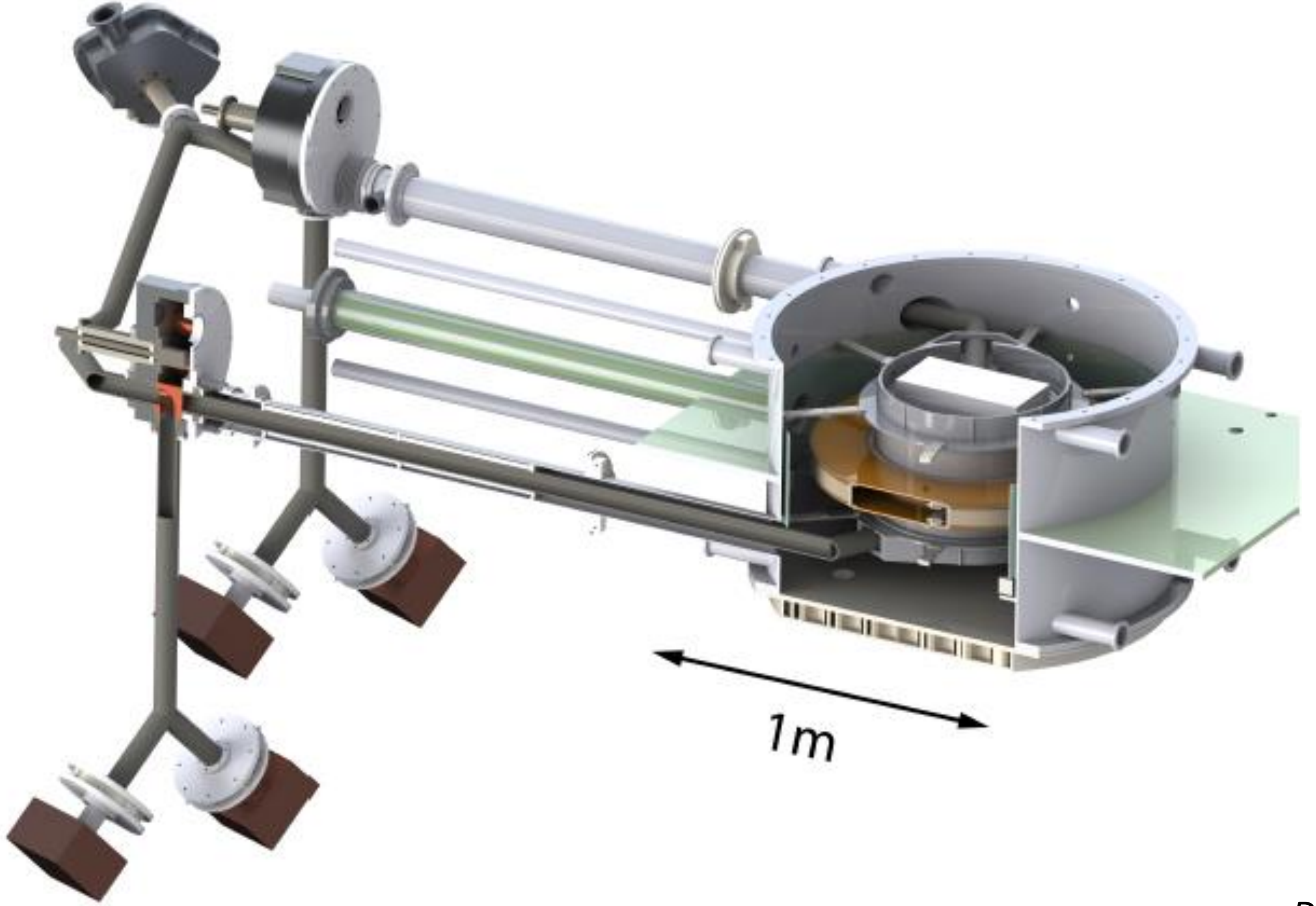
EPJ Web of Conferences 219, 02006 (2019)

The PanEDM Experiment



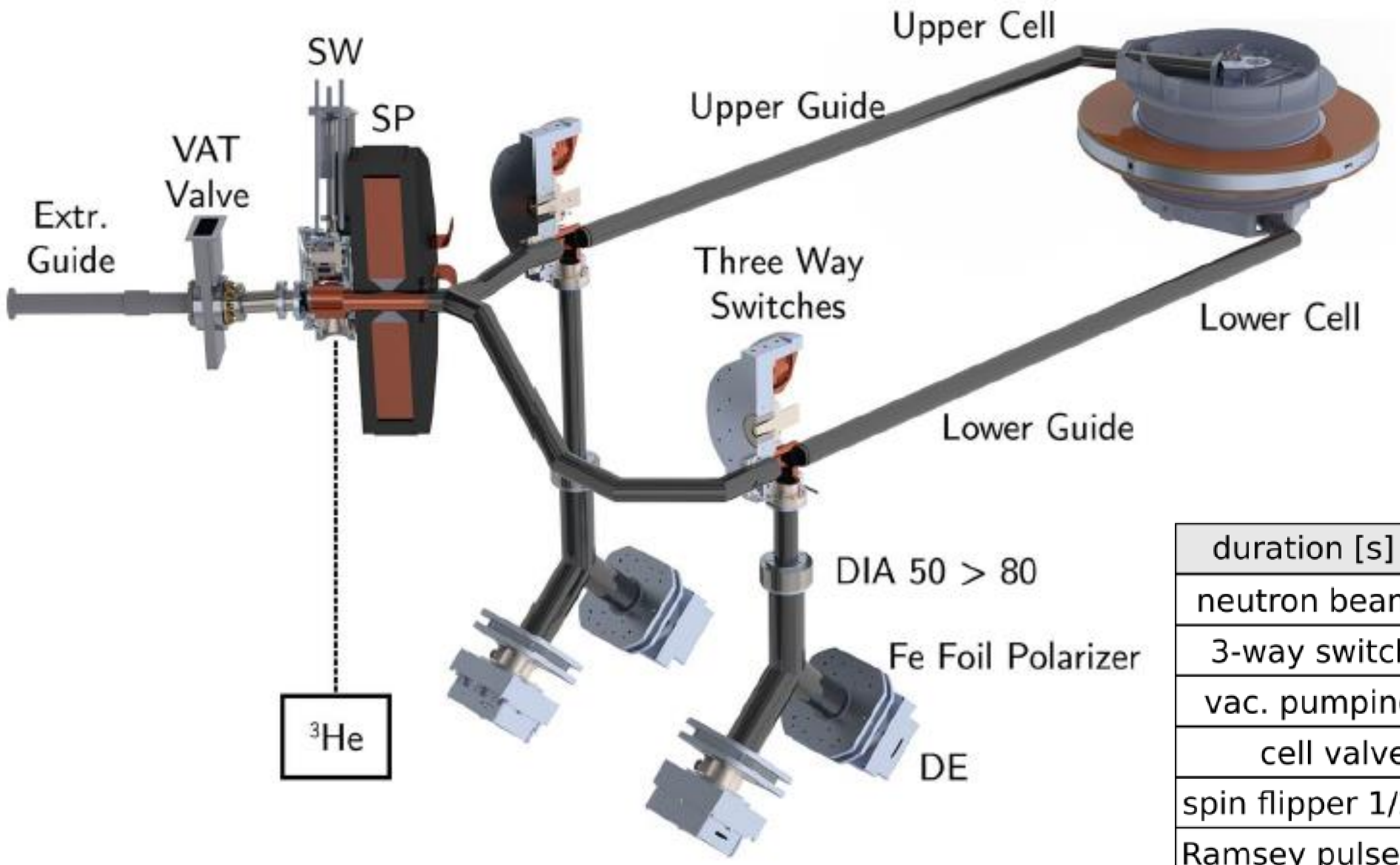
D. Wurm, PhD 2021

The PanEDM Experiment



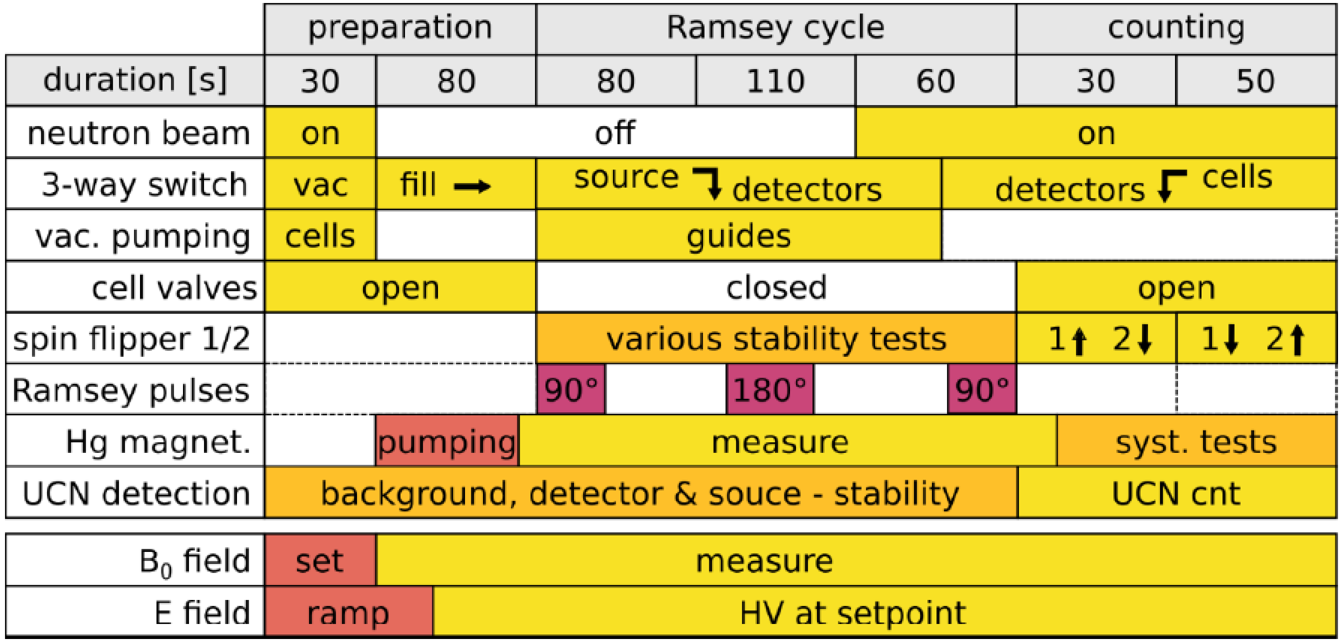
D. Wurm, PhD 2021

The PanEDM Experiment



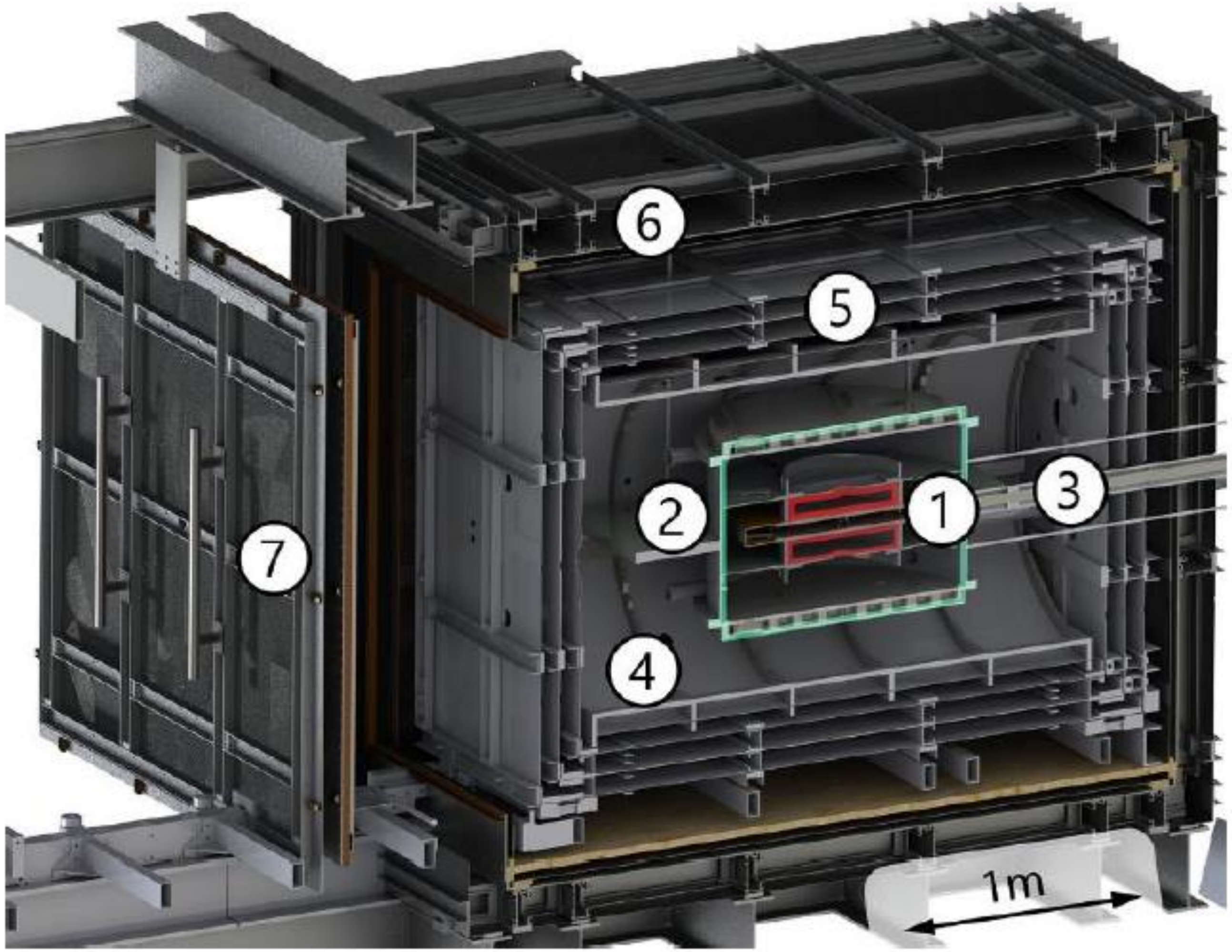
D. Wurm, PhD 2021

The recipe for an EDM measurement:



	preparation		Ramsey cycle			counting	
duration [s]	30	80	80	110	60	30	50
neutron beam	on	off			on		
3-way switch	vac	fill →	source ↴ detectors			detectors ↲ cells	
vac. pumping	cells		guides				
cell valves	open		closed			open	
spin flipper 1/2			various stability tests			1↑ 2↓	1↓ 2↑
Ramsey pulses			90°	180°	90°		
Hg magnet.		pumping	measure			syst. tests	
UCN detection	background, detector & souce - stability					UCN cnt	
B_0 field	set	measure					
E field	ramp	HV at setpoint					

The PanEDM Experiment

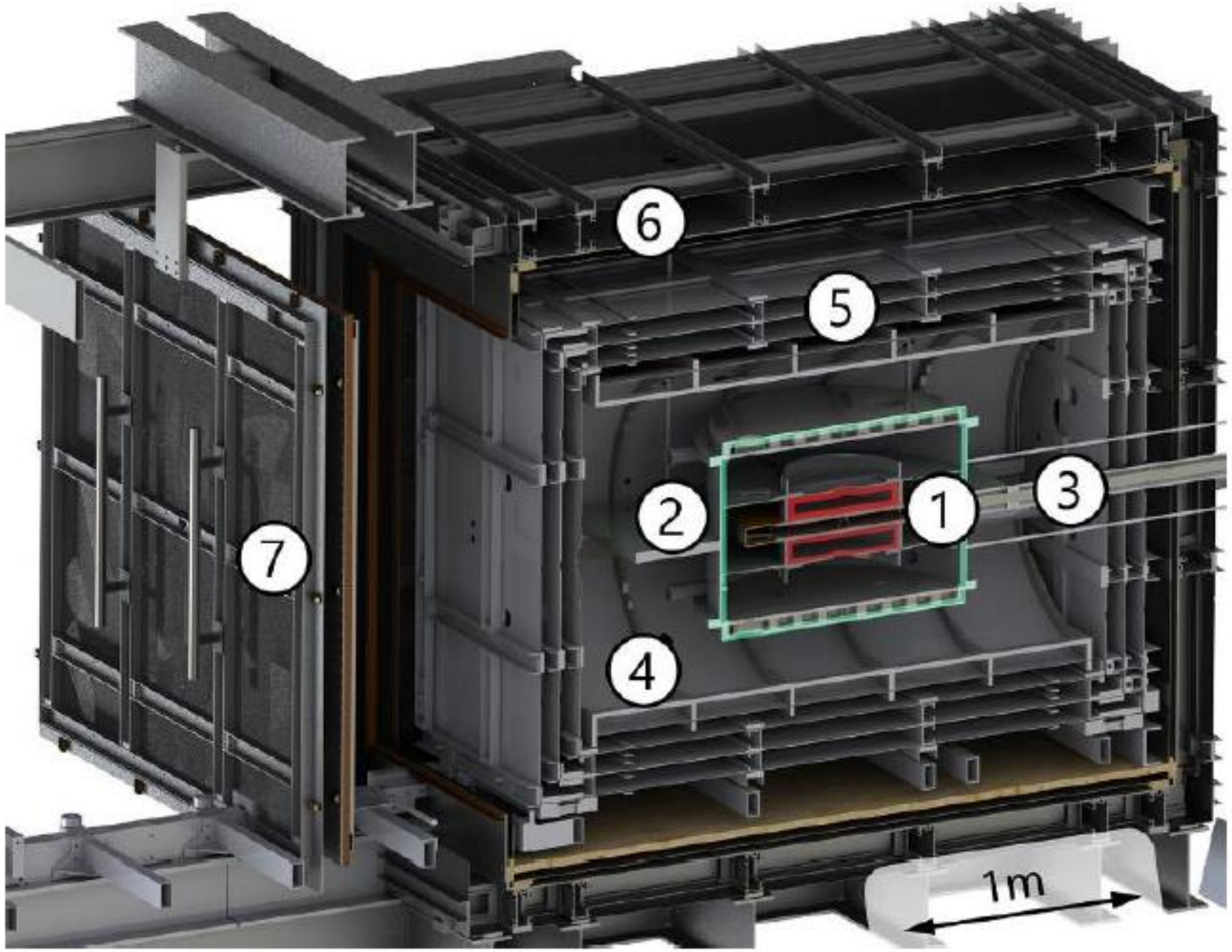


1: EDM cells
2: Vac. Chamber
3: HV feed
4: B_0 & B_1 coil
5: Inner shield
6: Outer shield
7: Outer shield door

PanEDM @ ILL, 2021

EPJ Web of Conferences 219, 02006 (2019)

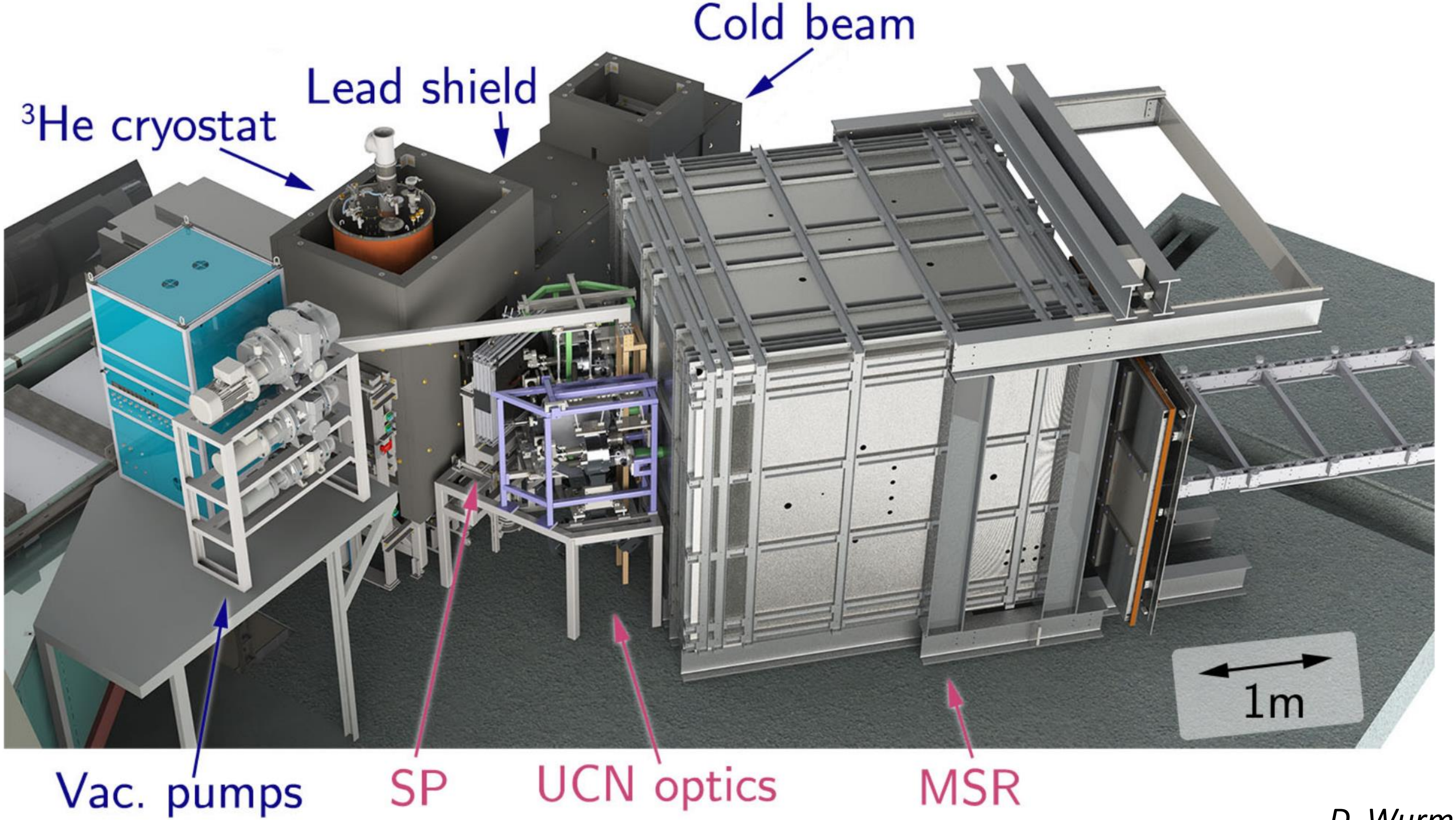
The PanEDM Experiment



EPJ Web of Conferences 219, 02006 (2019)

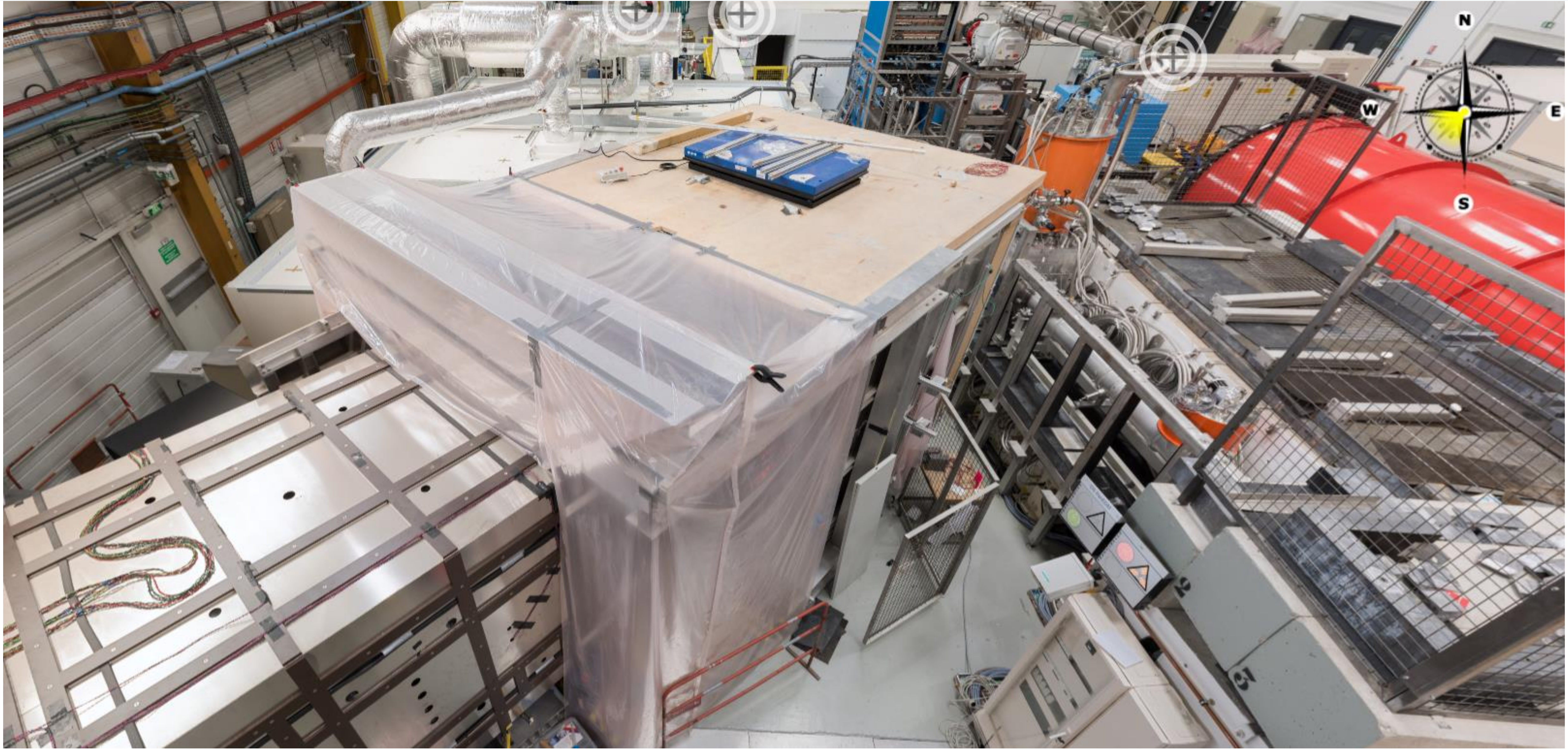
Rev. Sci. Inst. 85(7), 075106 (2014)
J. Appl. Phys. 117(18), 183903 (2015)

The SuperSUN-PanEDM Installation

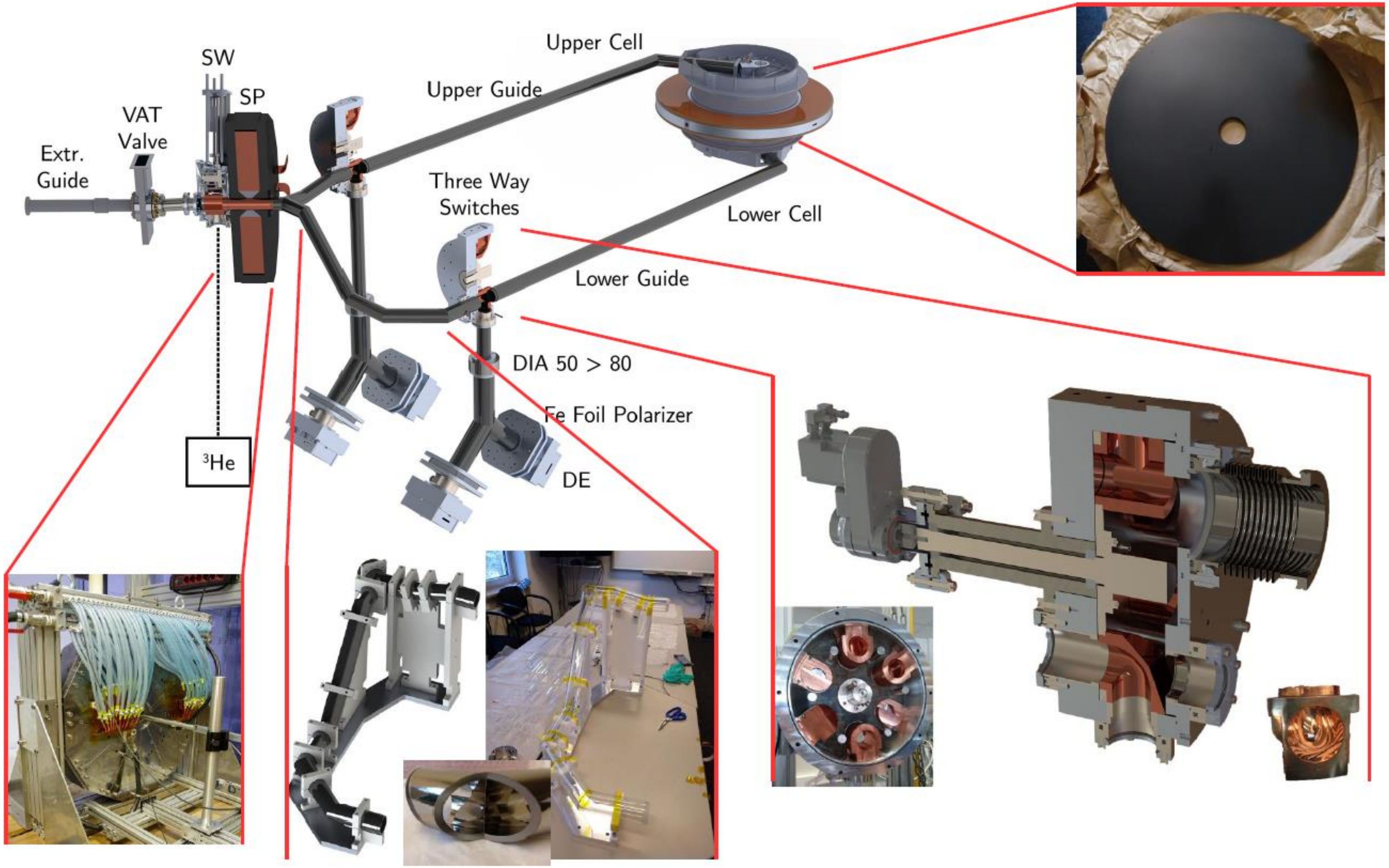


D. Wurm, PhD 2021

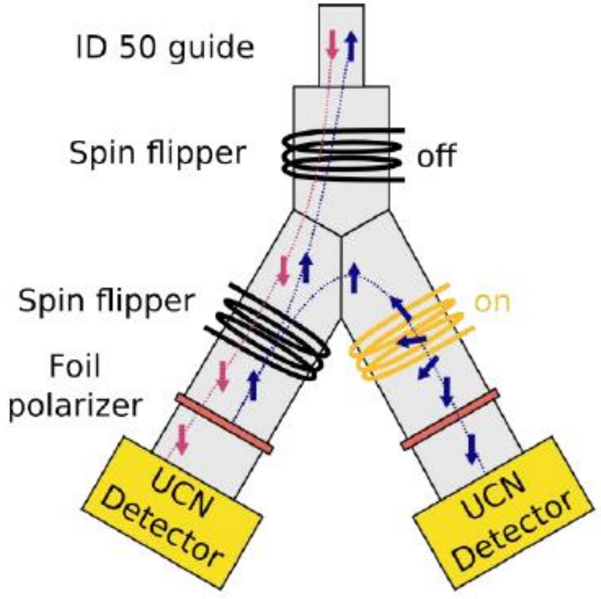
Reality always looks messier!



SuperSUN-PanEDM Interface

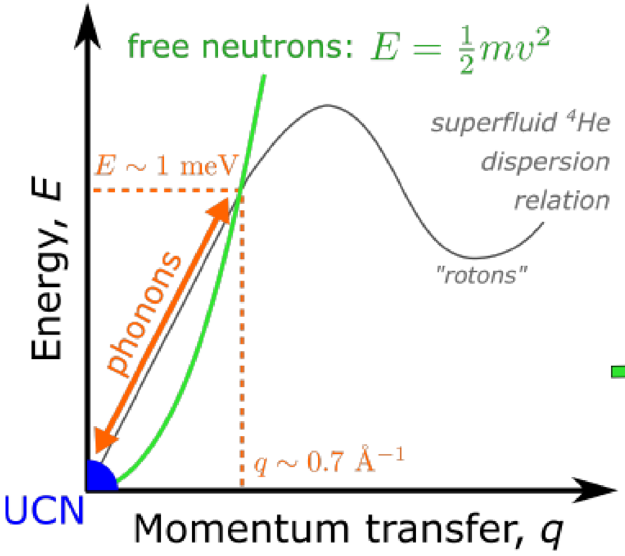


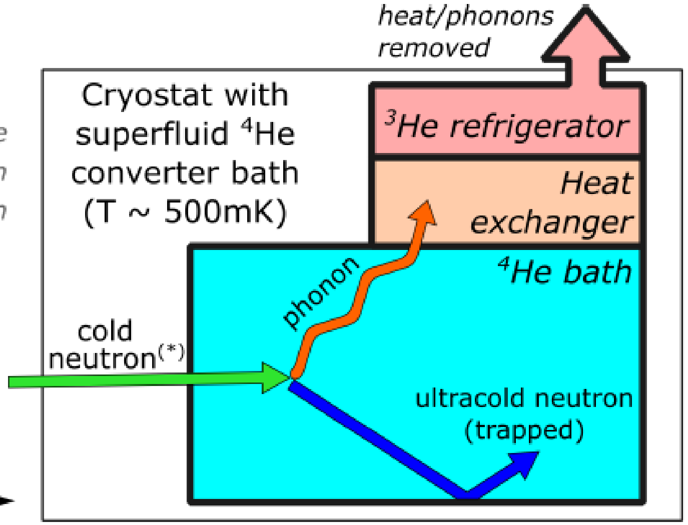
Simultaneous spin detection



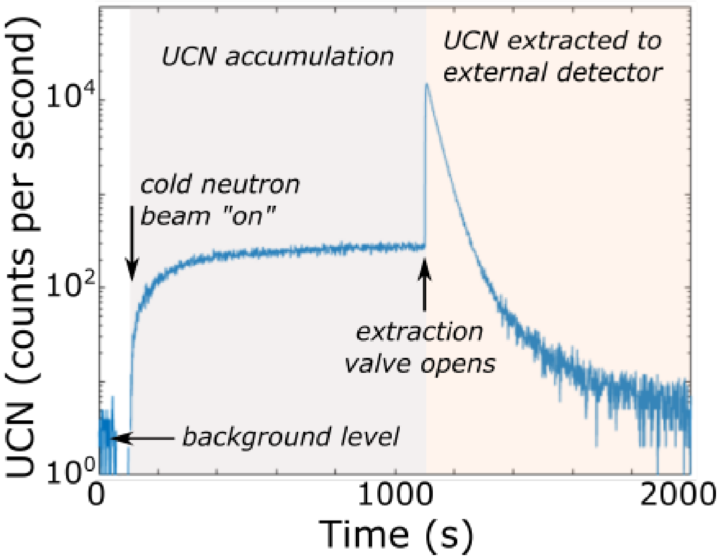
D. Wurm, PhD 2021

The SuperSUN Neutron Source



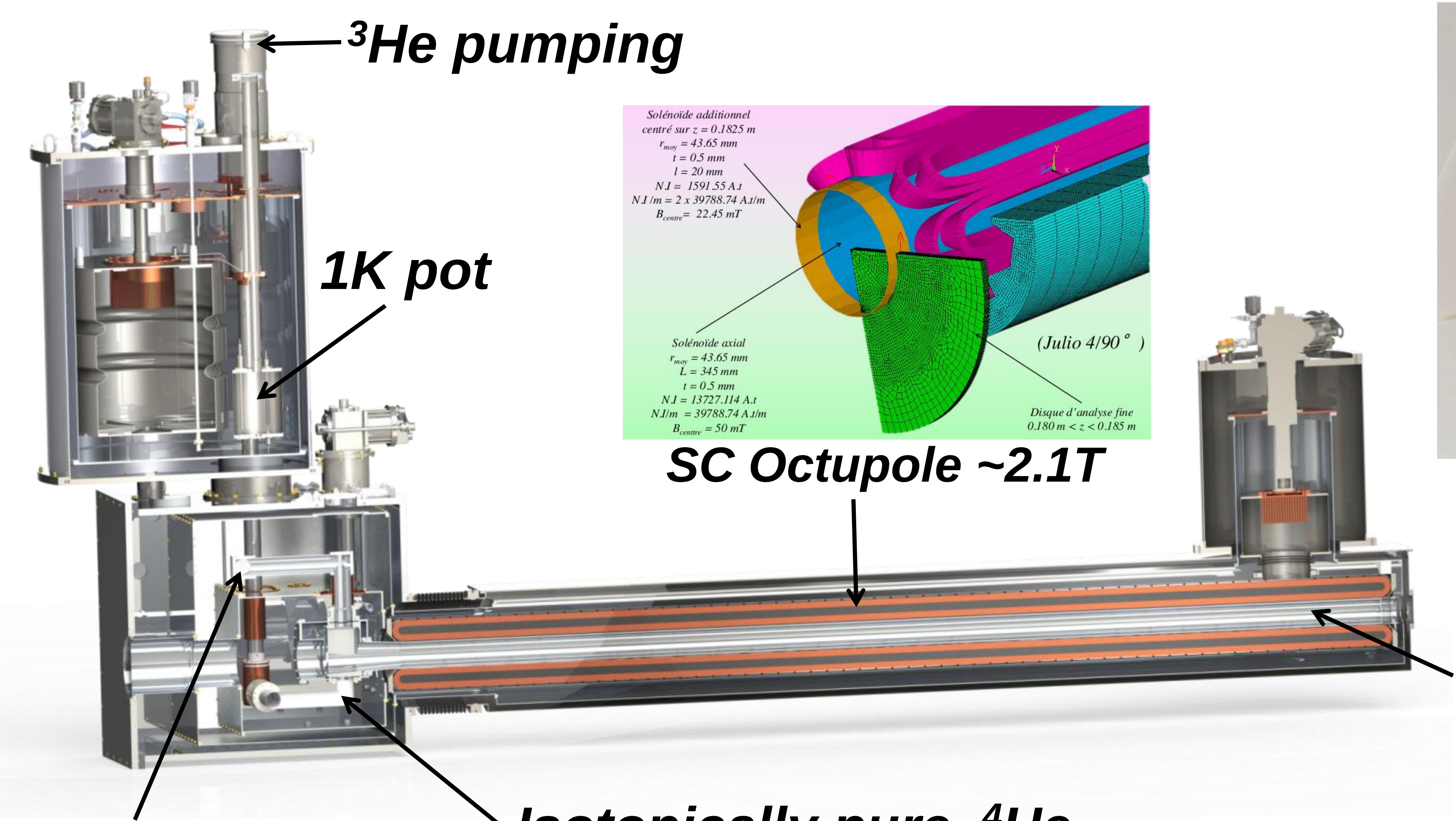


$^{(*)}$not trappable: $E\sim1$ meV vs. $U_{wall}\sim200$ neV



- Figure of merit for production: $\tau \cdot \int d^3\boldsymbol{k}\,\left(1 - e^{-n\sigma l(\boldsymbol{k})}\right)\,\frac{d\Phi}{d\lambda}\Big|_{8.9\text{Å}}$
- Note: partial mean free path $\lambda_{\text{“UCN”}} \sim 10$ km, while $\lambda_{\text{tot}} \sim 10$ m
- Loss for a 3m converter: factor 10 (unused CN beam)
- Loss for *ex-situ* storage: factor 100 (UCN extraction/transport/detection)

SuperSUN Neutron Source: Cutaway



^{3}**He pumping**

1K pot

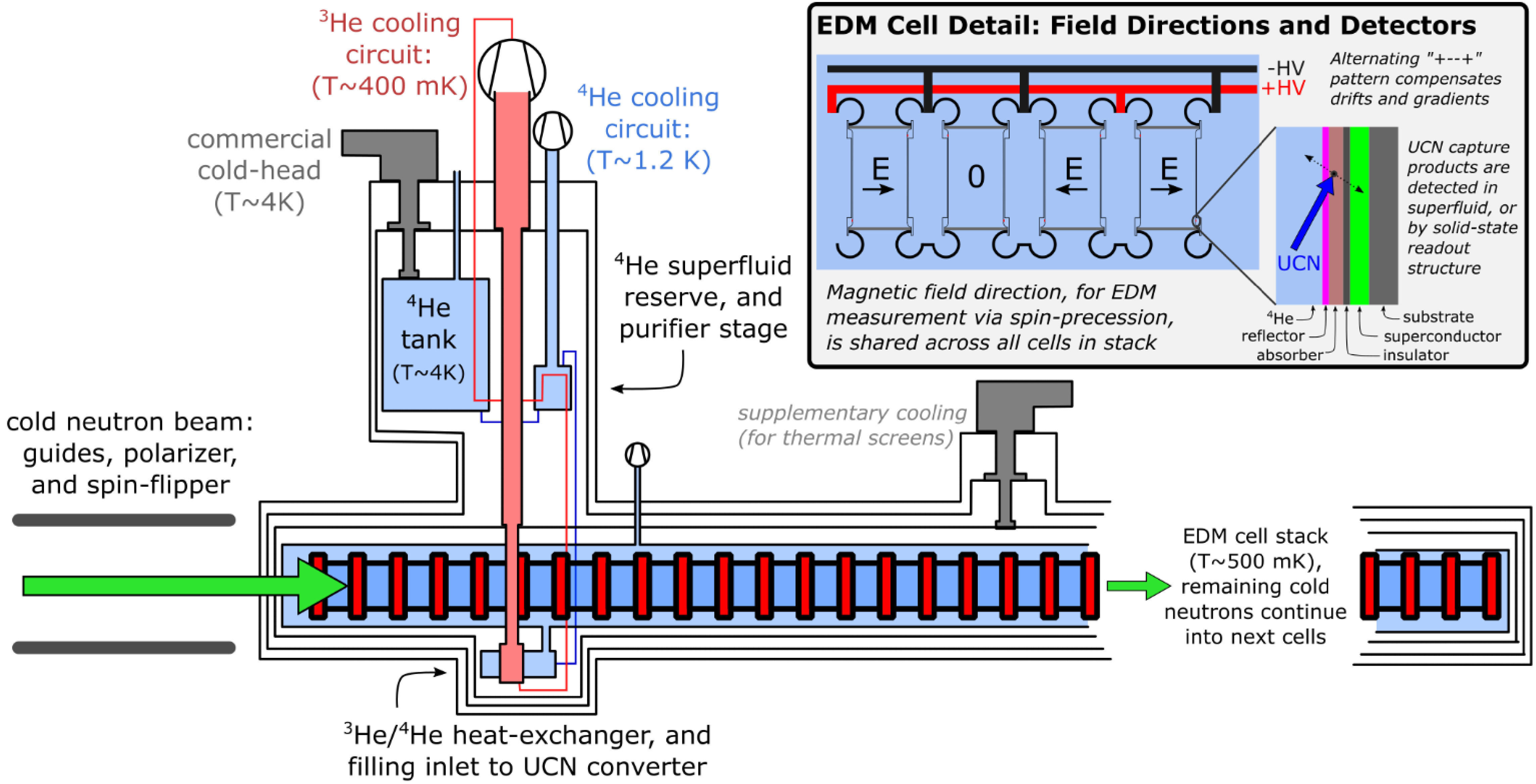
SC Octupole ~2.1T

cryogenic CN guide

Isotopically pure ^{4}He

UCN out

The next generation… scaling up!



^{3}He cooling circuit: (T~400 mK)

^{4}He cooling circuit: (T~1.2 K)

commercial cold-head (T~4K)

^{4}He tank (T~4K)

^{4}He superfluid reserve, and purifier stage

cold neutron beam: guides, polarizer, and spin-flipper

supplementary cooling (for thermal screens)

EDM cell stack (T~500 mK), remaining cold neutrons continue into next cells

^{3}He/^{4}He heat-exchanger, and filling inlet to UCN converter

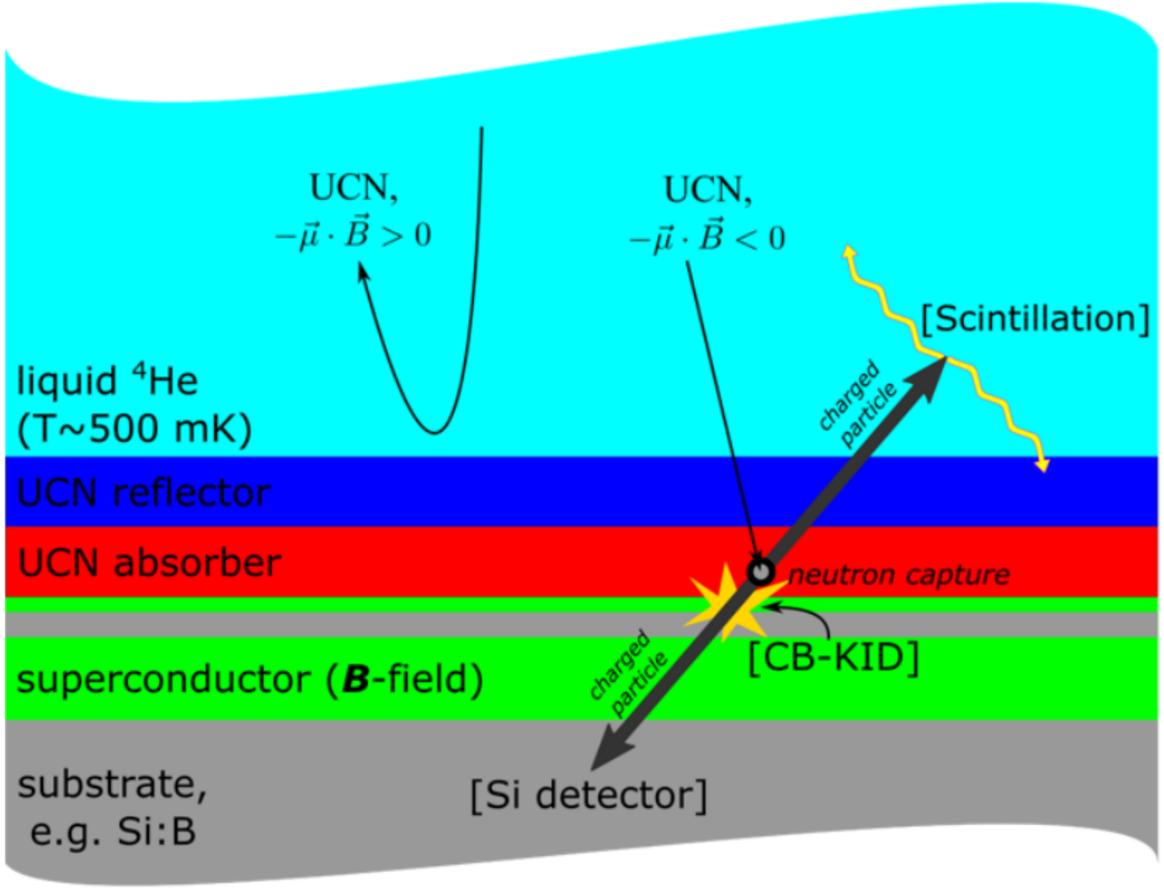
EDM Cell Detail: Field Directions and Detectors

Alternating "+--+" pattern compensates drifts and gradients

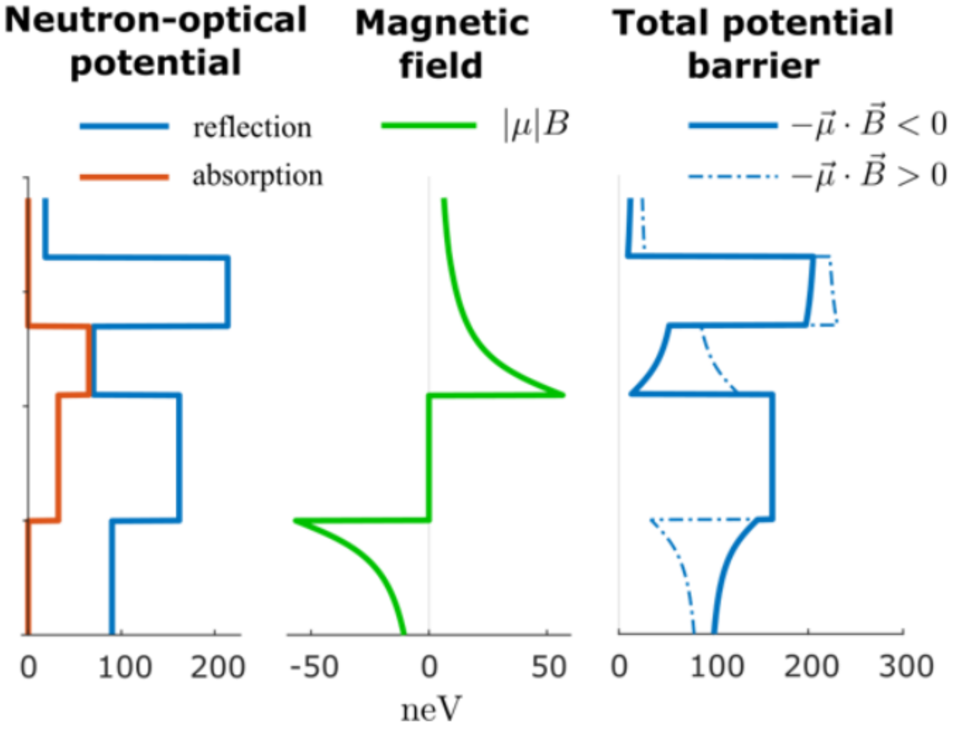
Magnetic field direction, for EDM measurement via spin-precession, is shared across all cells in stack

UCN capture products are detected in superfluid, or by solid-state readout structure

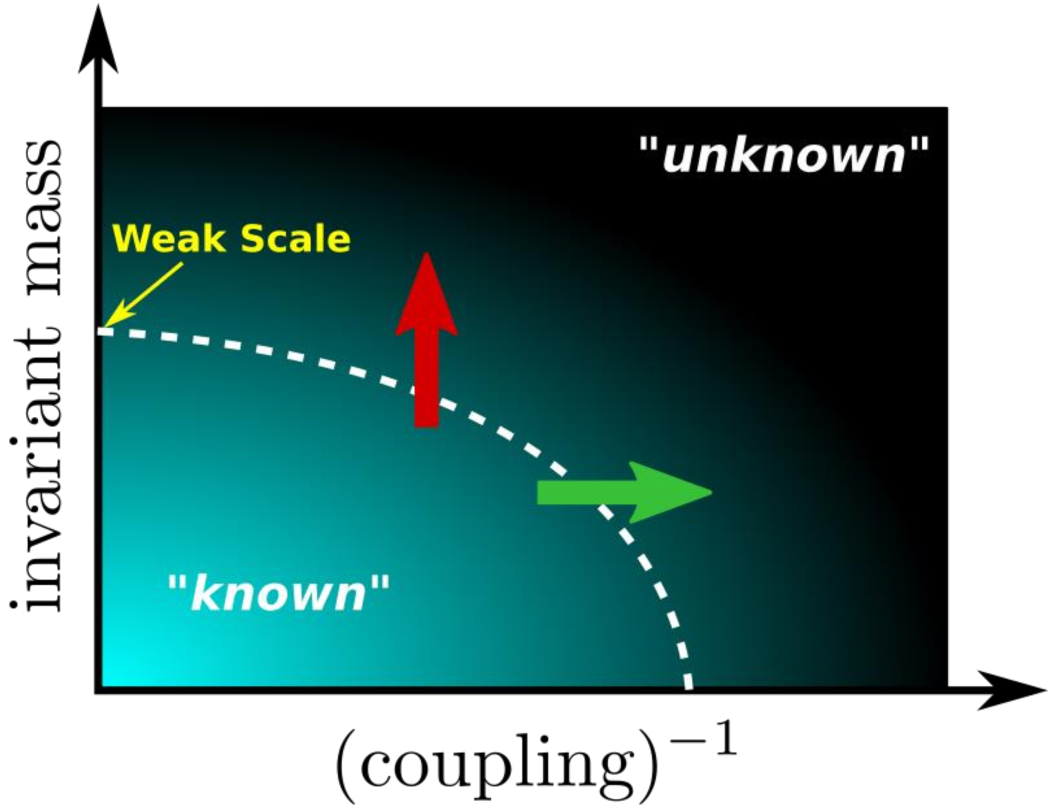
“Quantum Sensing” for Neutrons



Ultracold neutron (UCN) detection with polarization-sensitivity, via applied magnetic fields partially cancelling the neutron-optical potential for one spin state. Various readout mechanisms to be explored.



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:

U. Schmidt, Heidelberg
Heidelberg mechanical workshop
Heidelberg technical design office

Institut Laue-Langevin, NPP division
Institut Laue-Langevin, SANE division

PanEDM collaboration
HeXe collaboration

Seeking students and Post-Docs!

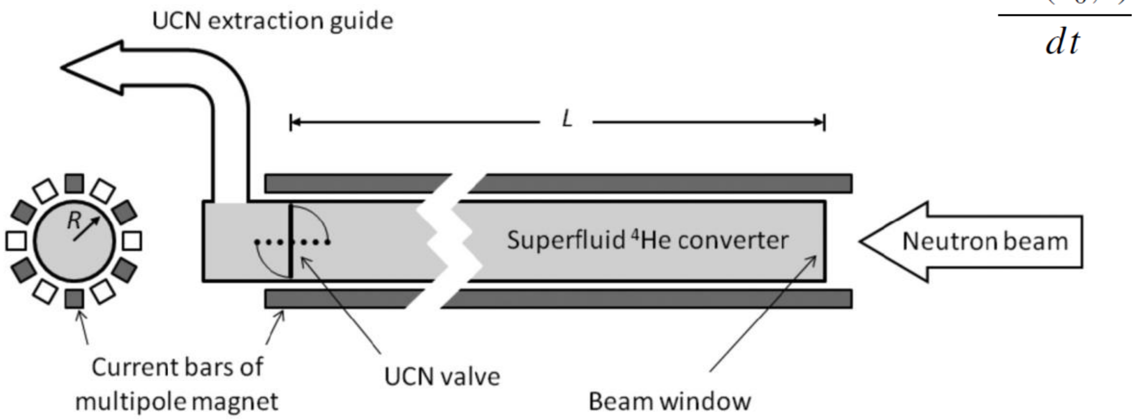
xkcd.com

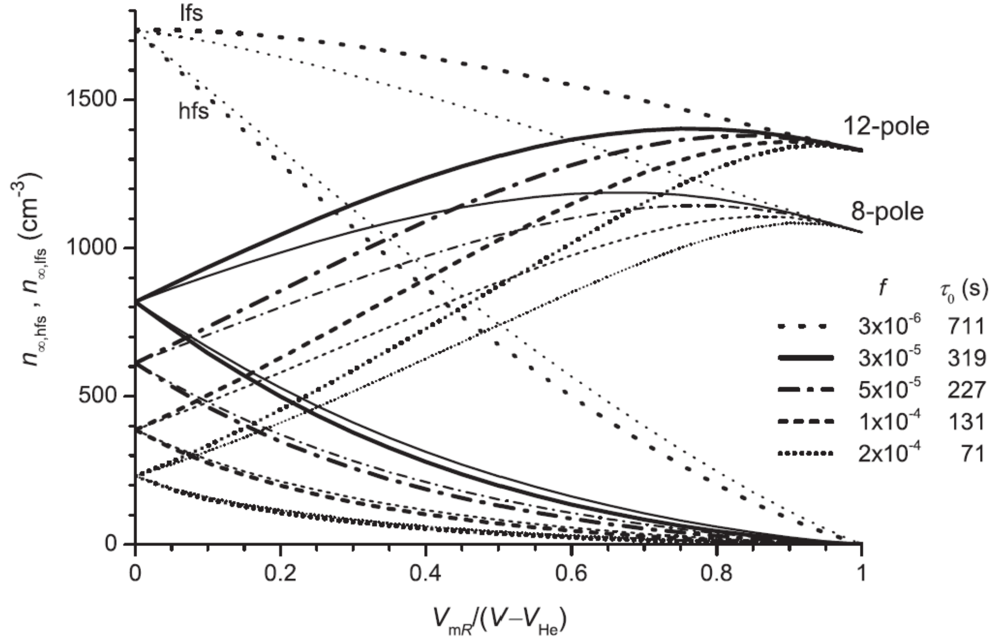
Faddeev-Popov?

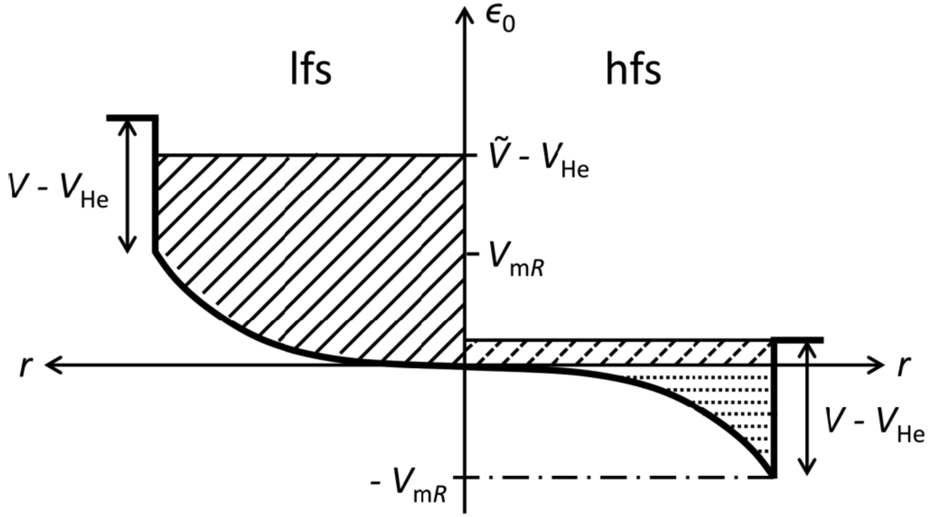
Minimizing UCN Storage losses

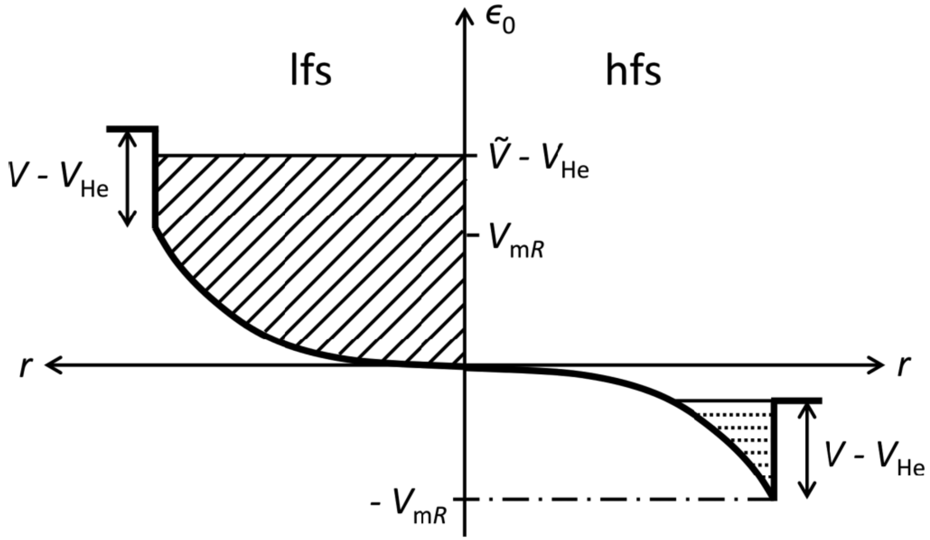
PHYSICAL REVIEW C **92**, 015501 (2015)

$$\frac{dn(\epsilon_0,t)}{dt} = p(\epsilon_0) - \frac{n(\epsilon_0,t)}{\tau(\epsilon_0)}$$









Neutron Delivery to SuperSUN

In SuperSUN's converter vessel:

- *R* ~ 15 UCN/(cm^3 s) expected

End of guide H523:

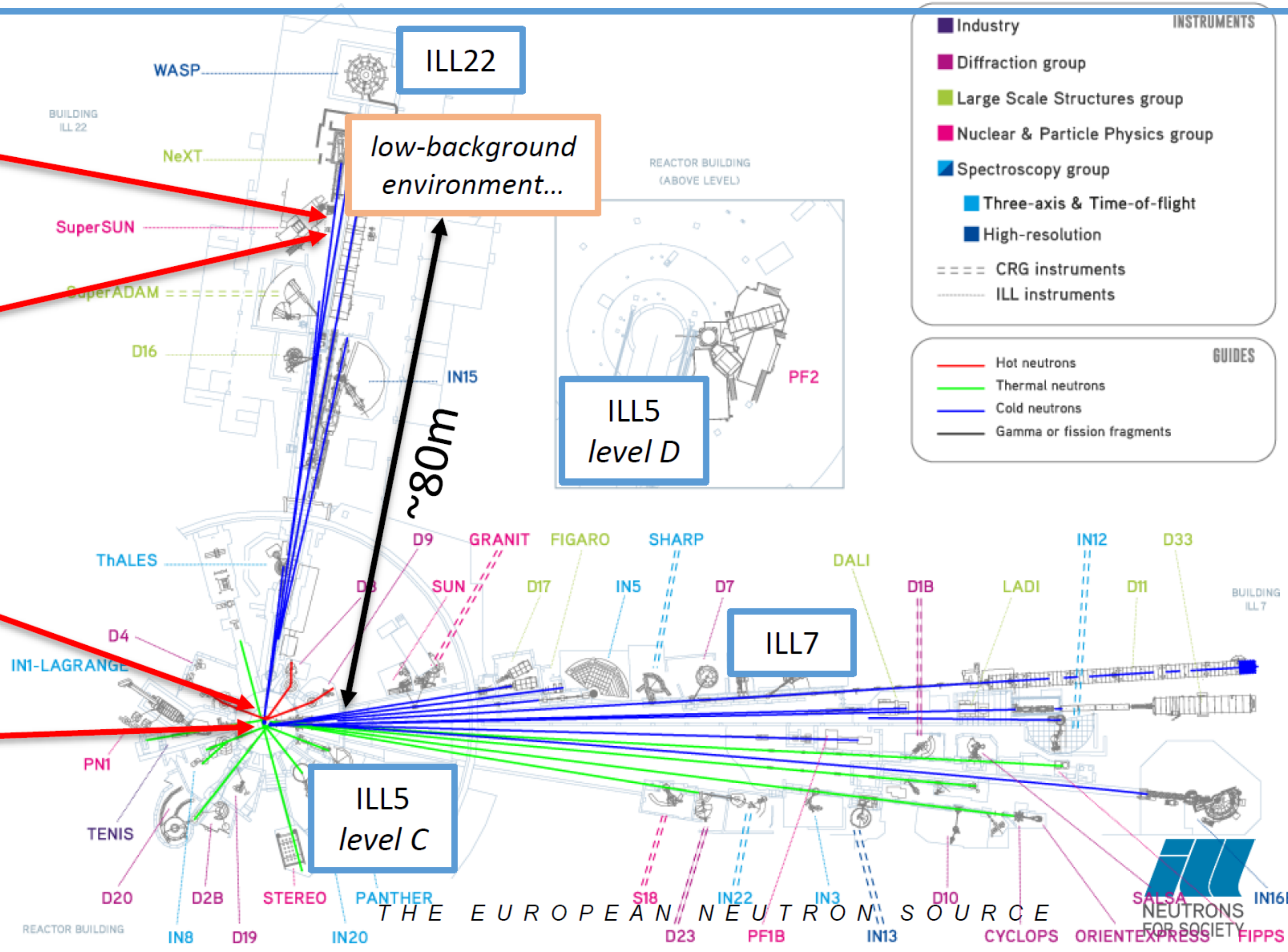
- $\Phi \sim 2\times10^{10}$ n/(cm^2 s)

Horizontal Cold Source:

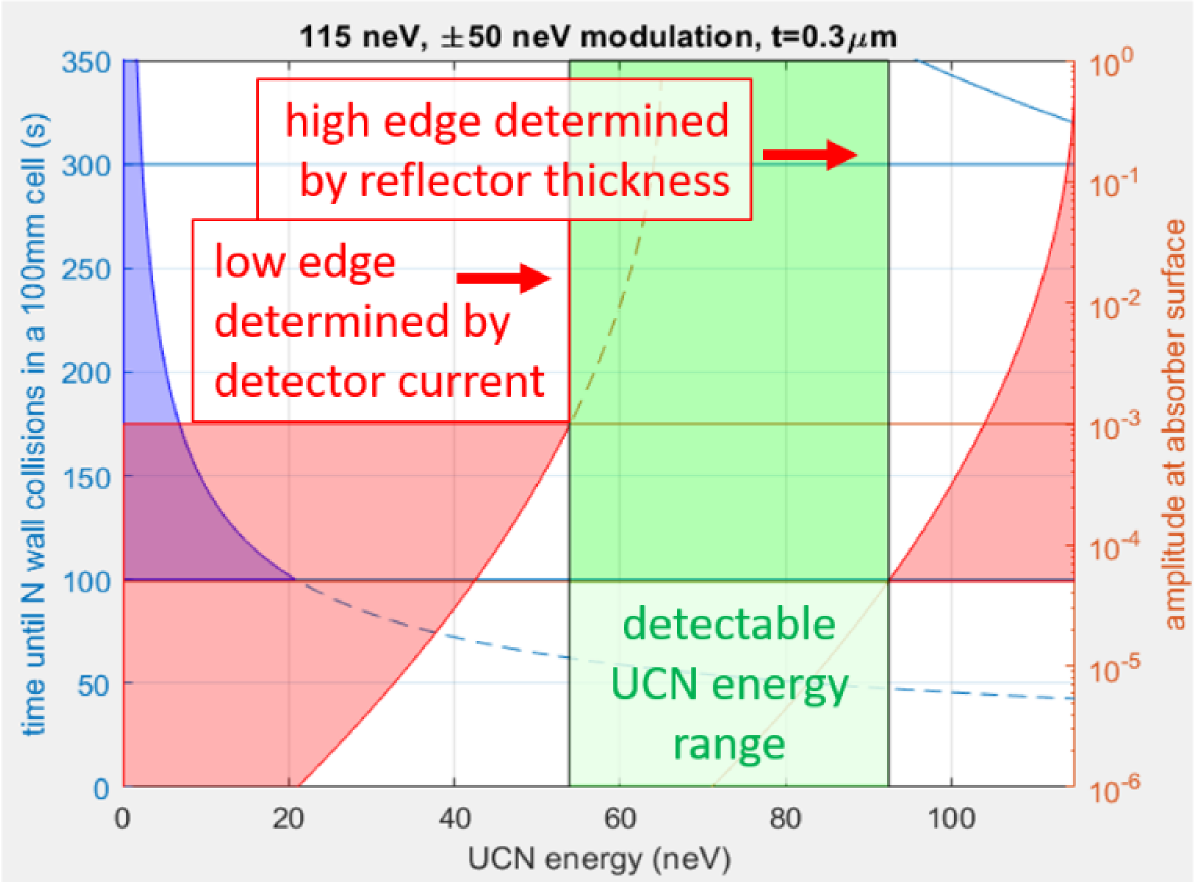
- $\Phi \sim 10^{14}$ n/(cm^2 s)

In pile:

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



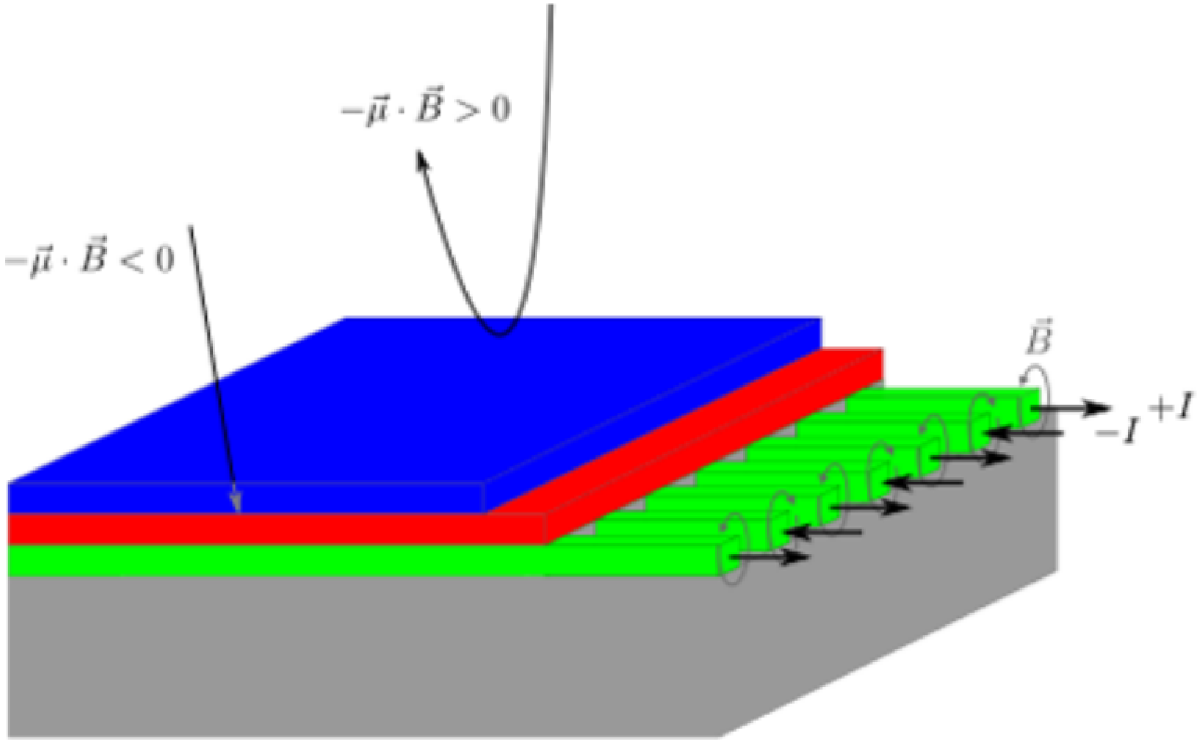
“Quantum Sensing”: Spin and Energy



high edge determined by reflector thickness

low edge determined by detector current

detectable UCN energy range



A digression on childrens' toys…

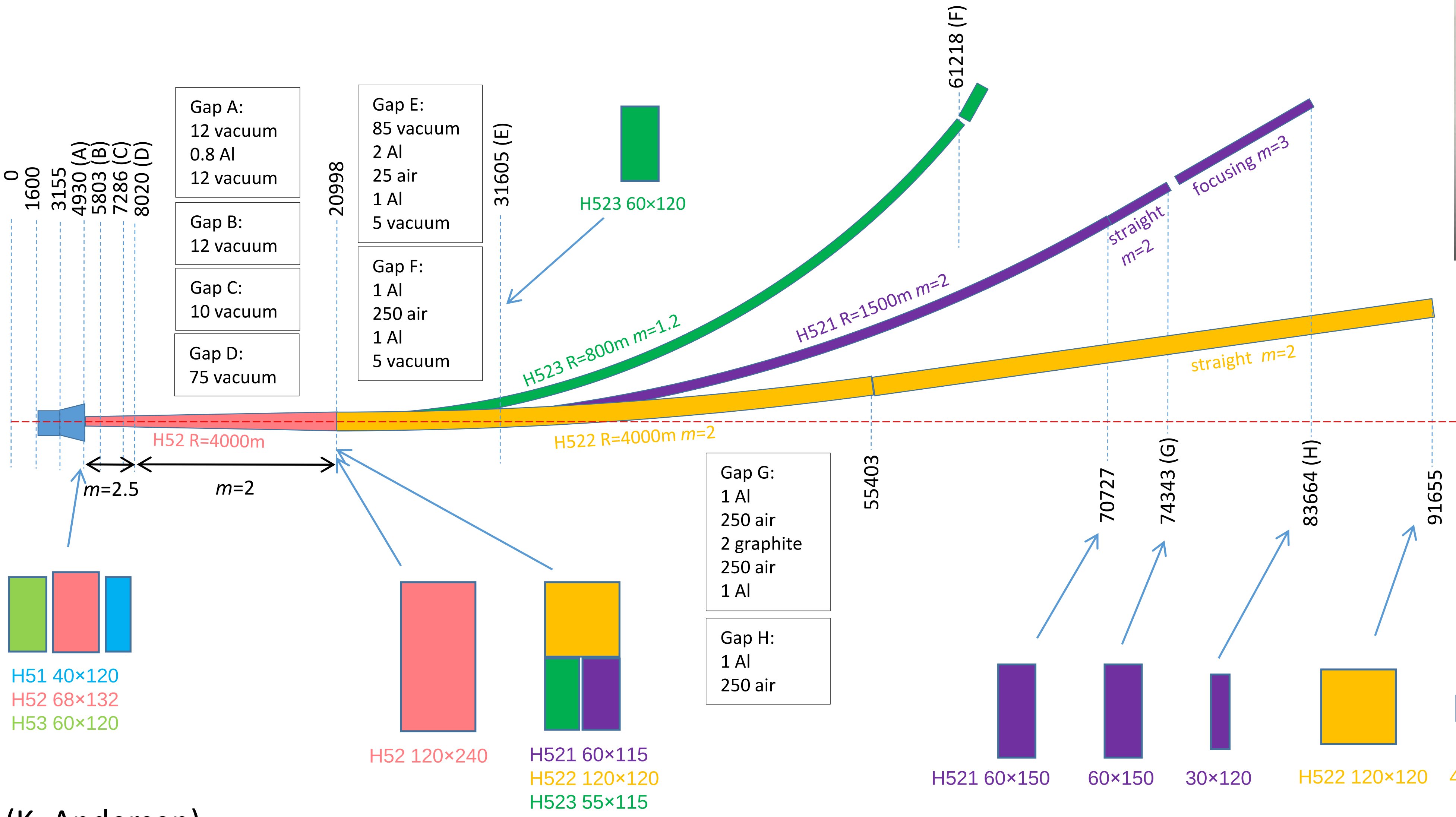
The SuperSUN Tapered Transition Guide with Irregular Octagonal Cross-Section,

or,

How to Fit
Square Pegs
into Round Holes

“Peg”

…or the ILL22 cold neutron guides



Gap A:
12 vacuum
0.8 Al
12 vacuum

Gap B:
12 vacuum

Gap C:
10 vacuum

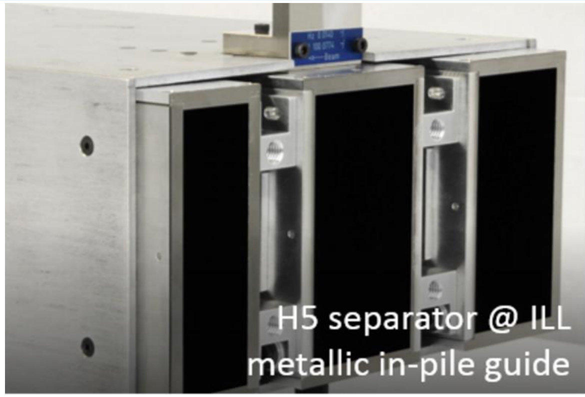
Gap D:
75 vacuum

Gap E:
85 vacuum
2 Al
25 air
1 Al
5 vacuum

Gap F:
1 Al
250 air
1 Al
5 vacuum

Gap G:
1 Al
250 air
2 graphite
250 air
1 Al

Gap H:
1 Al
250 air

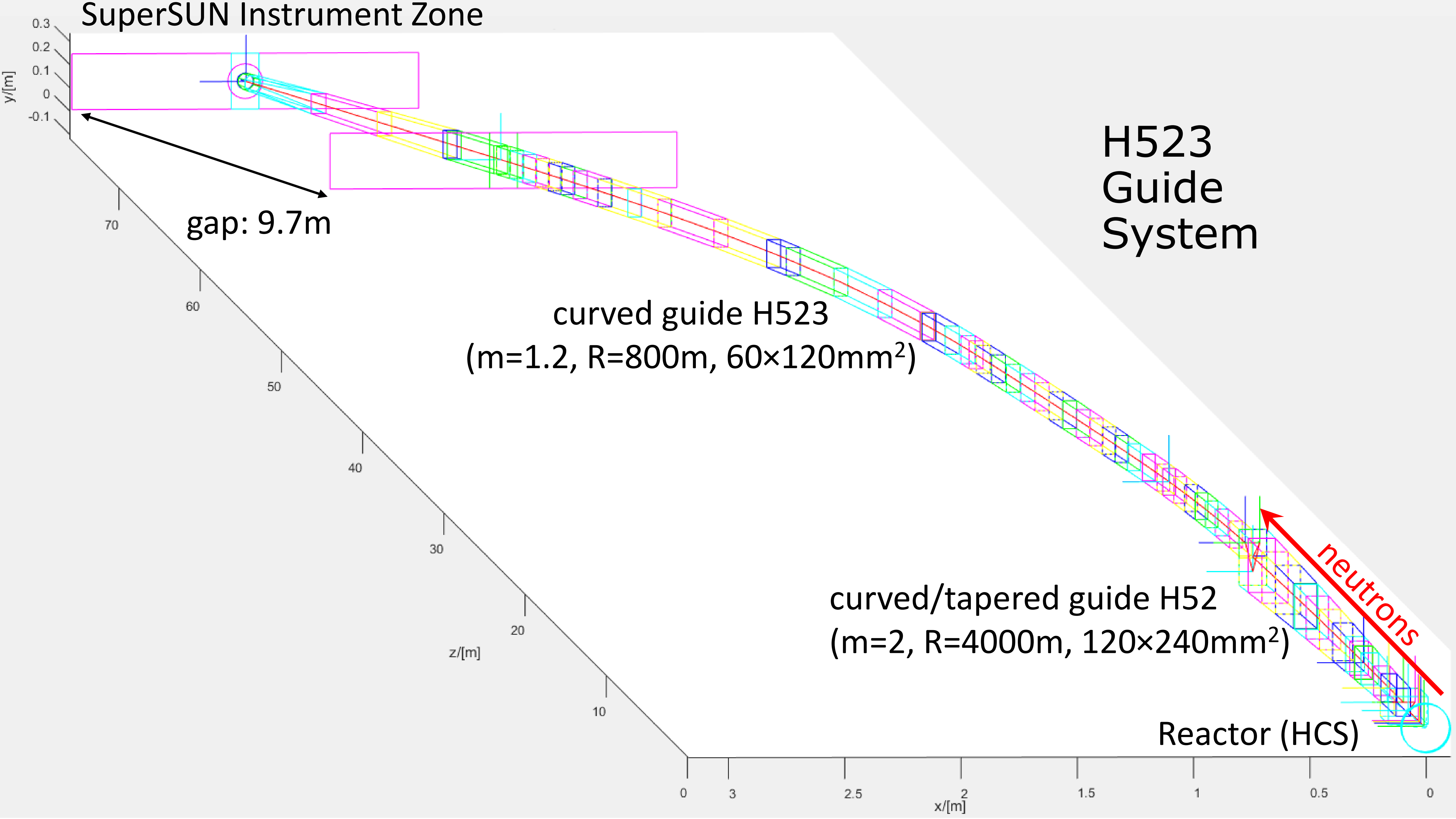


H5 separator @ ILL
metallic in-pile guide

swissneutronics.ch

(K. Andersen)

H523 Guide System



SuperSUN Instrument Zone

gap: 9.7m

curved guide H523
(m=1.2, R=800m, 60×120mm^2)

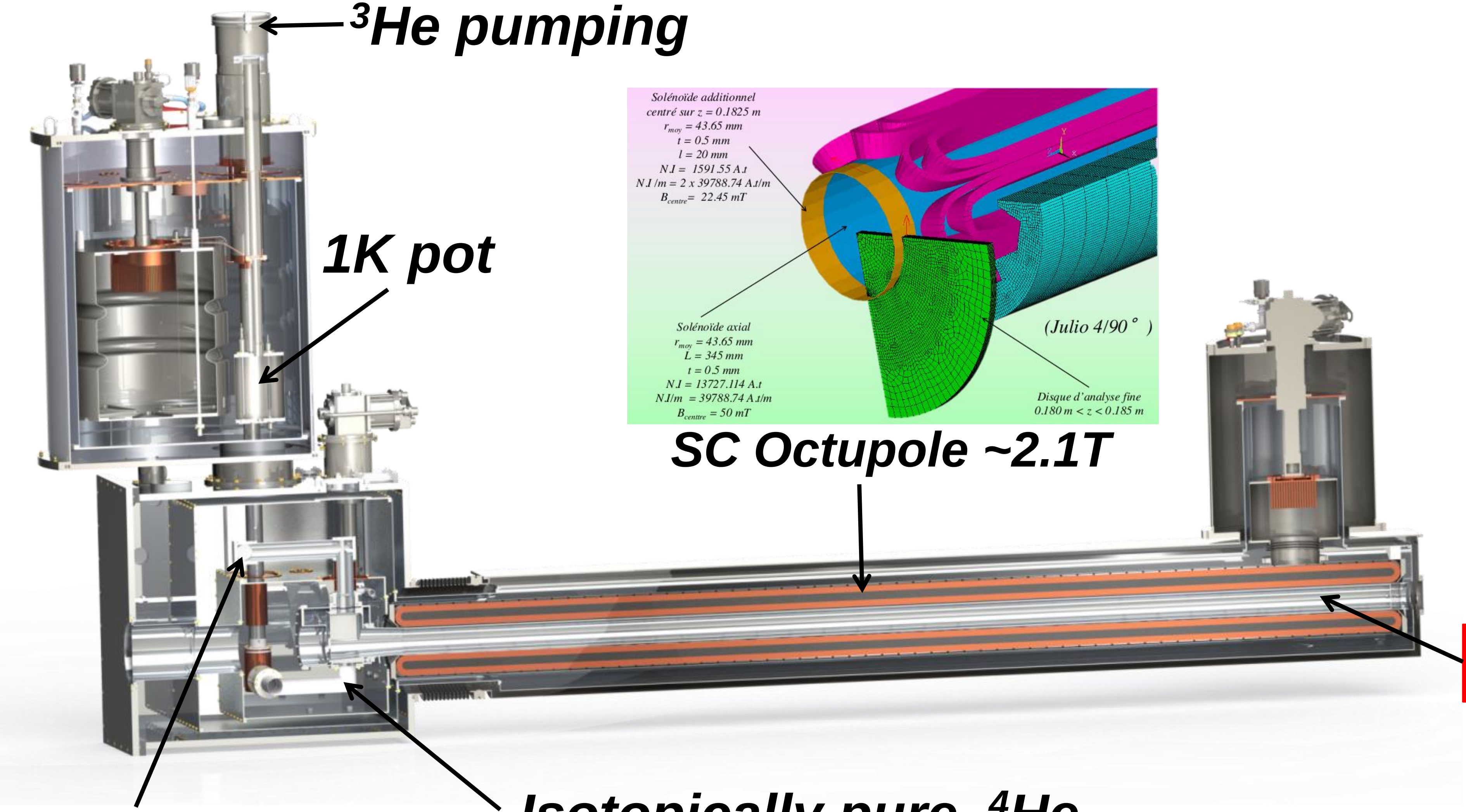
curved/tapered guide H52
(m=2, R=4000m, 120×240mm^2)

neutrons

Reactor (HCS)

“Hole”

…or admittance matching



^{3}He pumping

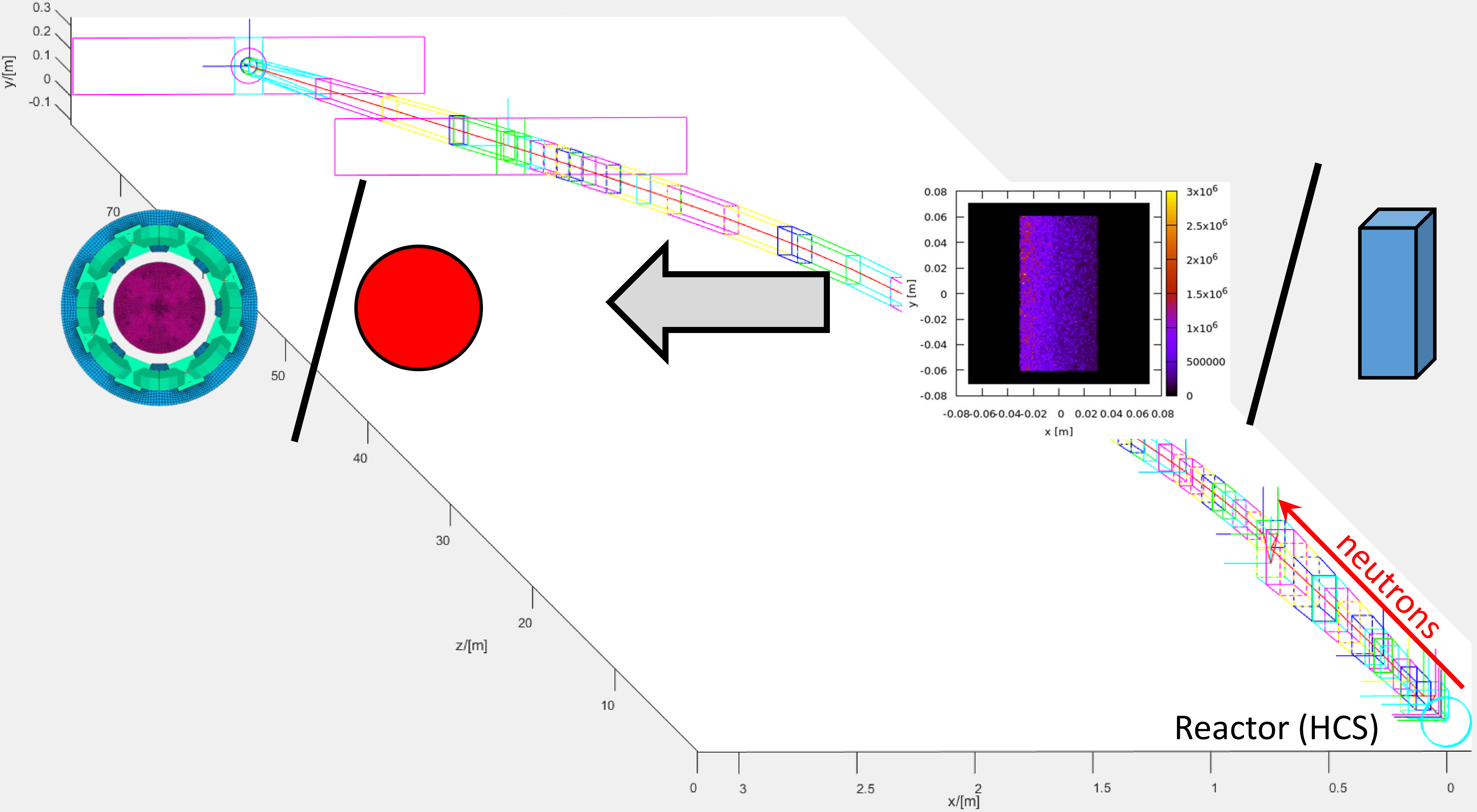
1K pot

SC Octupole ~2.1T

cryogenic CN guide

UCN out

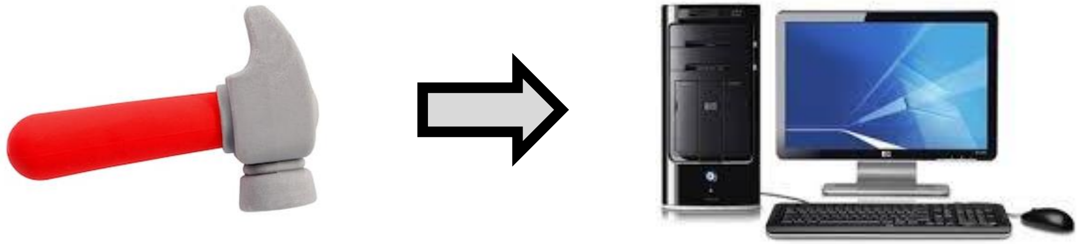
Isotopically pure ^{4}He


0.3
0.2
0.1
0
-0.1
y/[m]
70
50
40
30
20
10
z/[m]
0
3
2.5
2
1.5
1
0.5
0
x/[m]
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
y [m]
-0.08-0.06-0.04-0.02 0 0.02 0.04 0.06 0.08
x [m]
$3x10^6$
$2.5x10^6$
$2x10^6$
$1.5x10^6$
$1x10^6$
500000
0
neutrons
Reactor (HCS)

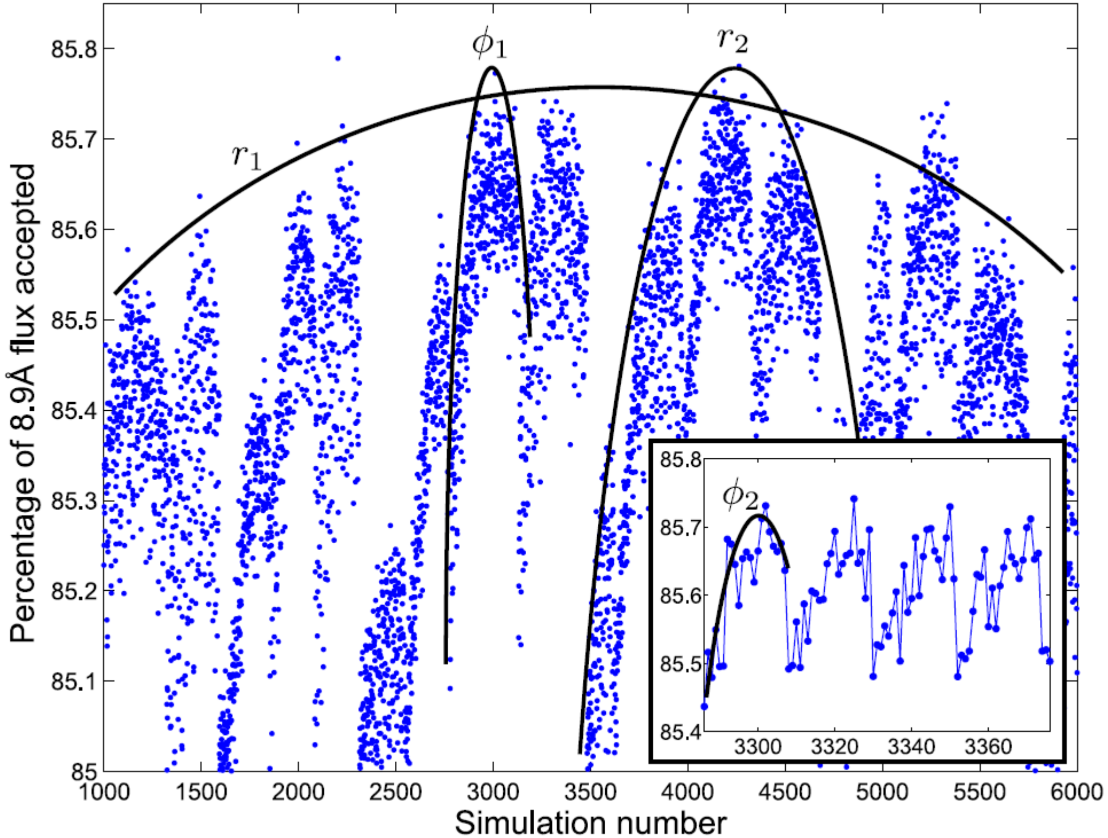
We are still missing a tool…

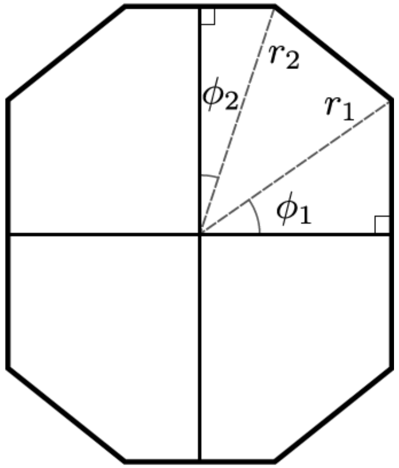
“Hammer”

…or brute force solution



Each point:
~10^7 particles
~5min

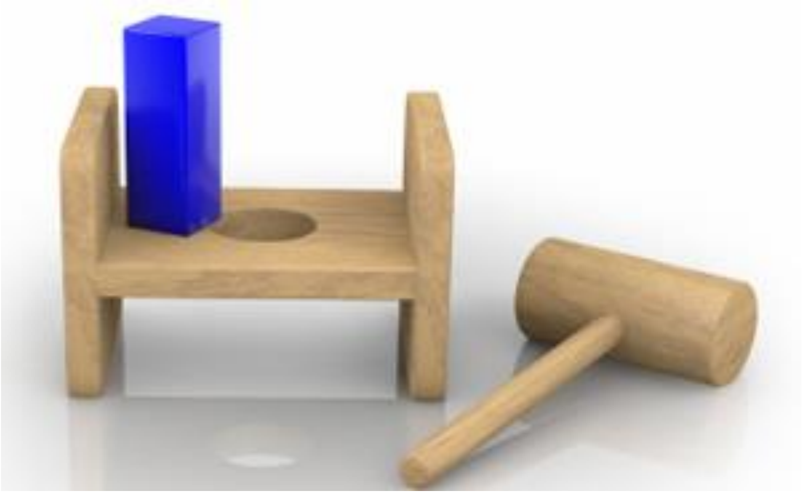




“general” octagon parameterization

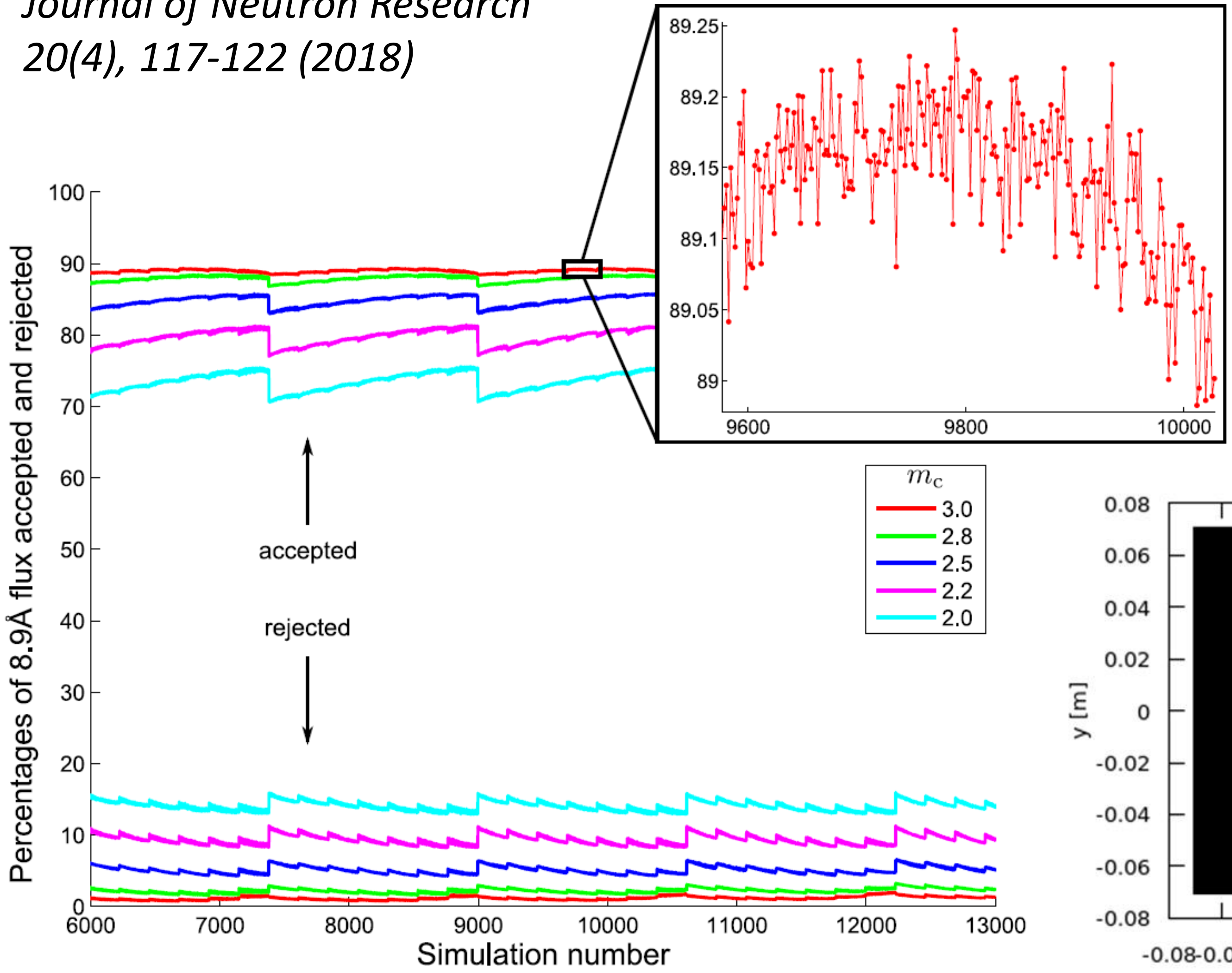
Journal of Neutron Research 20(4), 117-122 (2018)

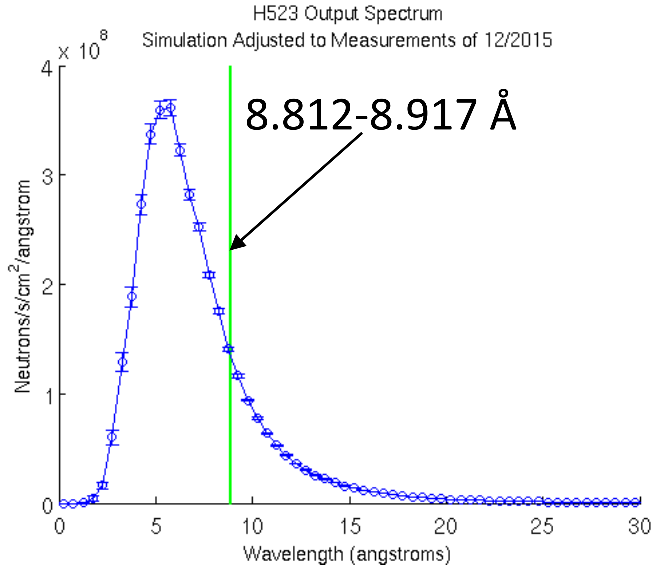
The complete toolset



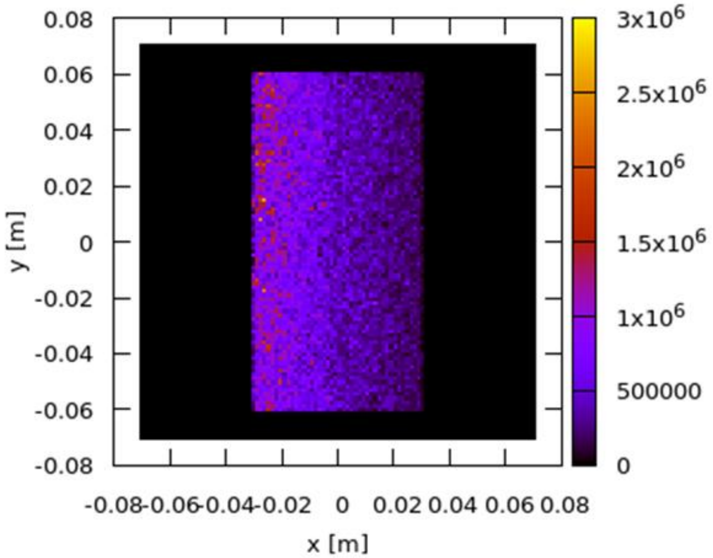
Optimize the remaining parameters…

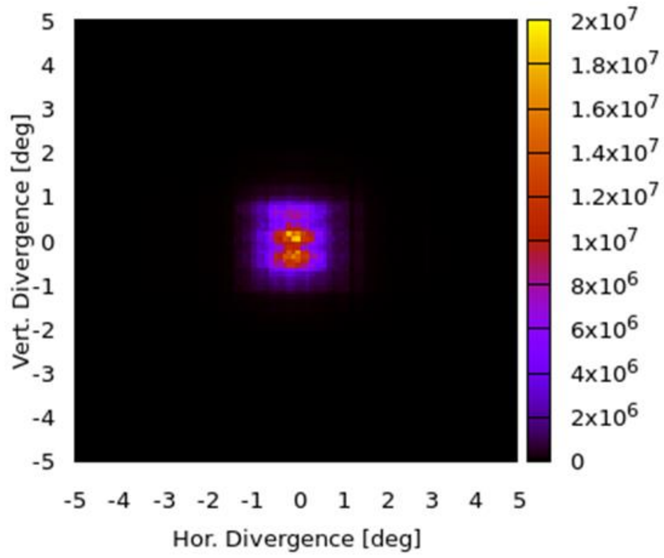
Journal of Neutron Research
20(4), 117-122 (2018)





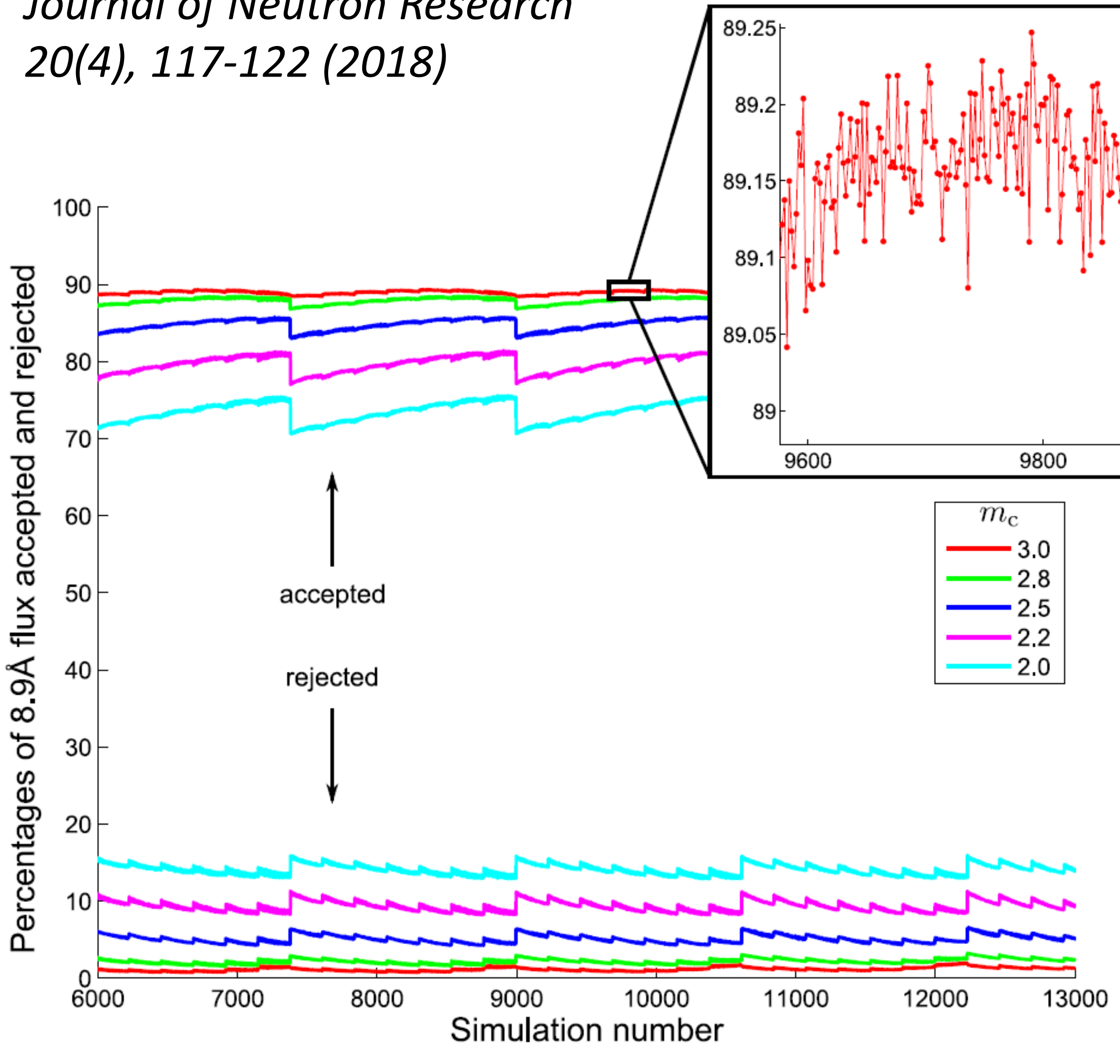
8.812-8.917 Å

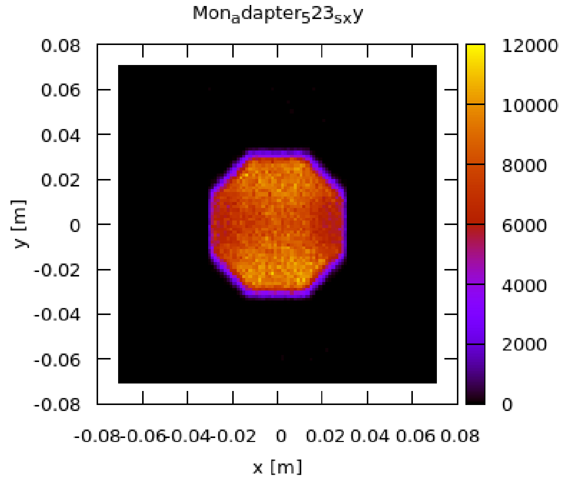


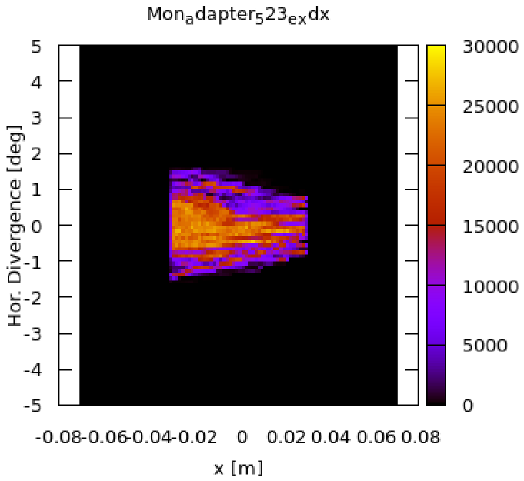


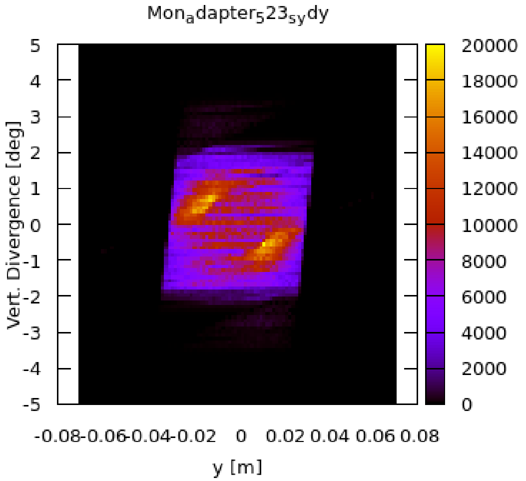
Optimize the remaining parameters…

Journal of Neutron Research
20(4), 117-122 (2018)

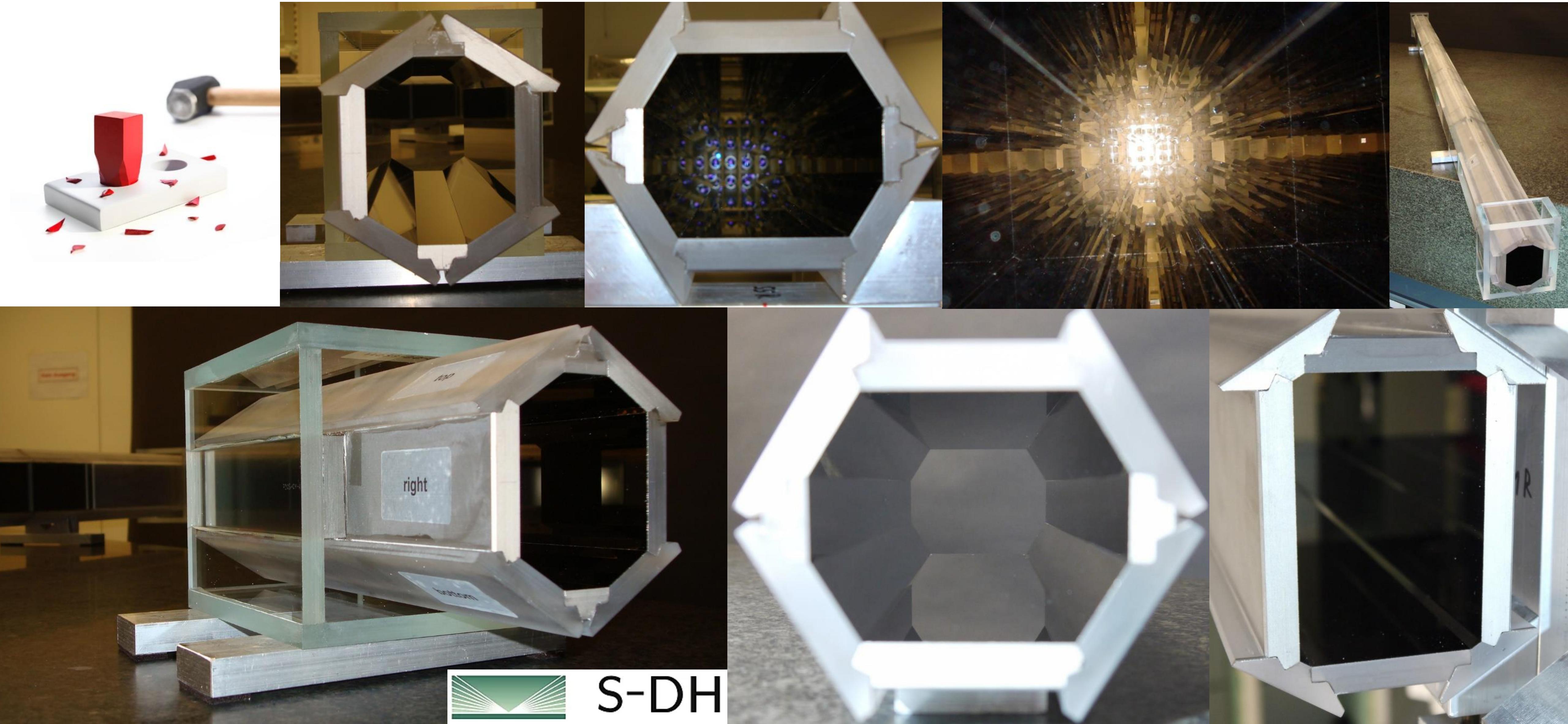








…and implement the solution



What would a finite neutron EDM mean?

- 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):

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

- 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)*

Effective Field Theory

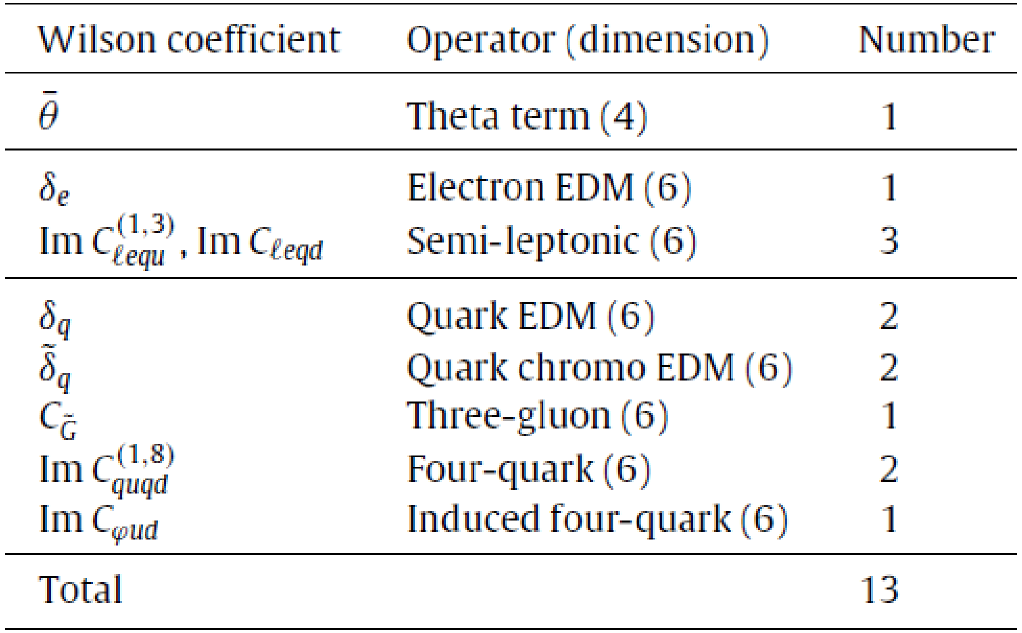
General Effective Lagrangian:

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

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
$\text{Im}\, C^{(1,3)}_{\ell equ}$, $\text{Im}\, C_{\ell eqd}$	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
$\text{Im}\, C^{(1,8)}_{quqd}$	Four-quark (6)	2
$\text{Im}\, C_{\varphi ud}$	Induced four-quark (6)	1
Total		13

“Global analysis”

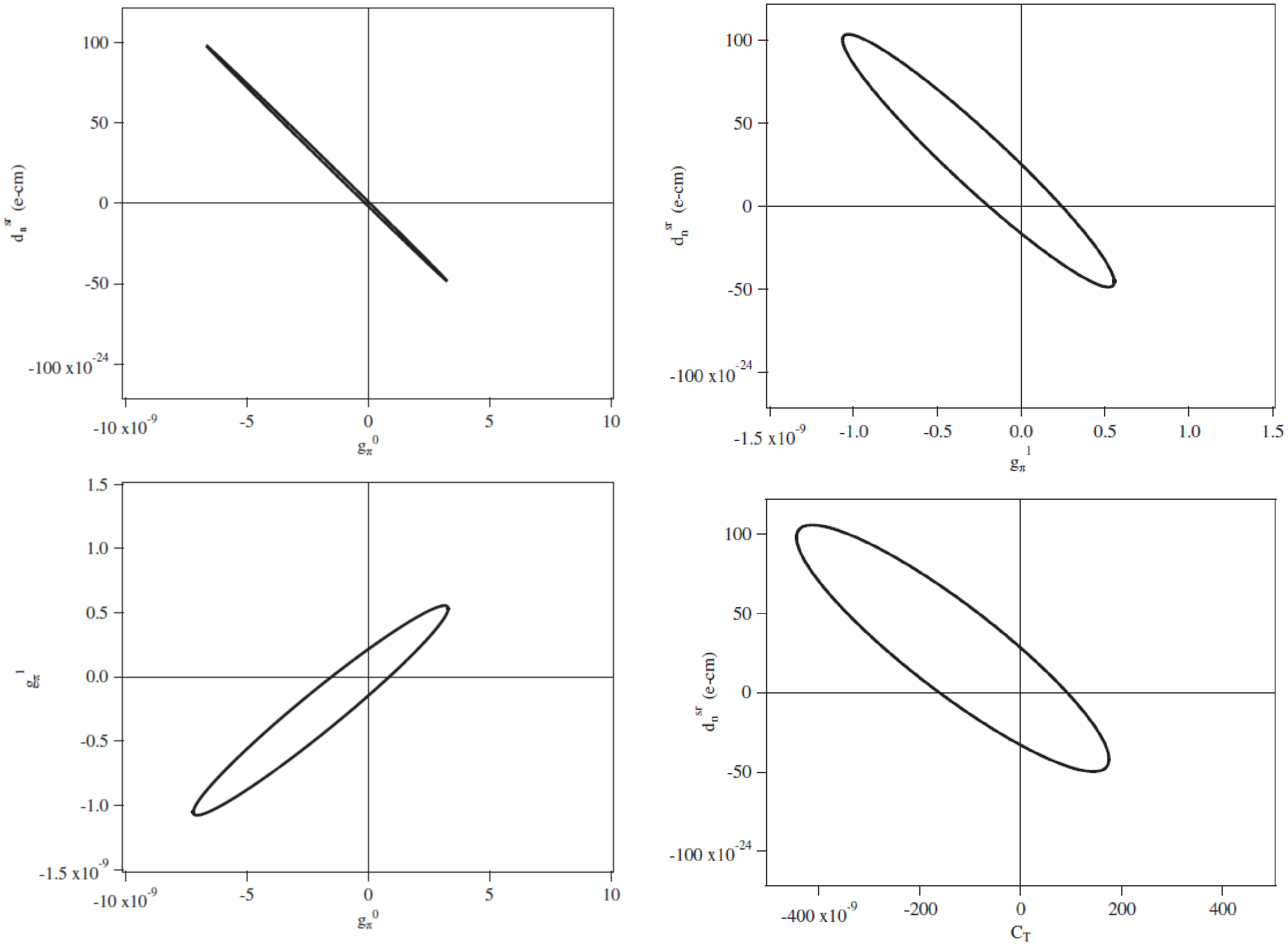
Define a matrix *α* according to $d_i = \sum_i \alpha_{ij} C_j$,

$$\alpha_{ij} = \begin{array}{ccccc} d_{\mathrm{Hg}} & d_{\mathrm{Xe}} & d_{\mathrm{TlF}} & d_{\mathrm{n}} & \\ -2.0\times10^{-20} & -3.8\times10^{-18} & 0 & 0 & C_T \\ 4.0\times10^{-21} & -2.9\times10^{-19} & -2.2\times10^{-19} & 0 & \tilde{g}_\pi^0 \\ 1.1\times10^{-16} & 1.2\times10^{-14} & -1.6\times10^{-13} & 0 & \tilde{g}_\pi^1 \\ 0 & 1.5\times10^{-14} & 1.4\times10^{-16} & 1 & d_n^{sr} \end{array}$$

…and invert it:

$$\begin{bmatrix} C_T \\ \tilde{g}_\pi^0 \\ \tilde{g}_\pi^1 \\ d_n^{sr} \end{bmatrix} = \begin{bmatrix} -1.48\times10^{19} & 1.83\times10^{20} & -2.52\times10^{14} & 0 \\ -1.85\times10^{17} & -9.64\times10^{17} & 1.32\times10^{12} & 0 \\ -2.41\times10^{16} & 5.36\times10^{16} & -6.32\times10^{12} & 0 \\ 2.78\times10^{3} & 1.44\times10^{4} & -1.90\times10^{-2} & 1 \end{bmatrix} \times \begin{bmatrix} d_{Hg} \\ d_{Xe} \\ d_{TlF} \\ d_n \end{bmatrix}$$

So what is the situation today?



“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

So what is the situation today?

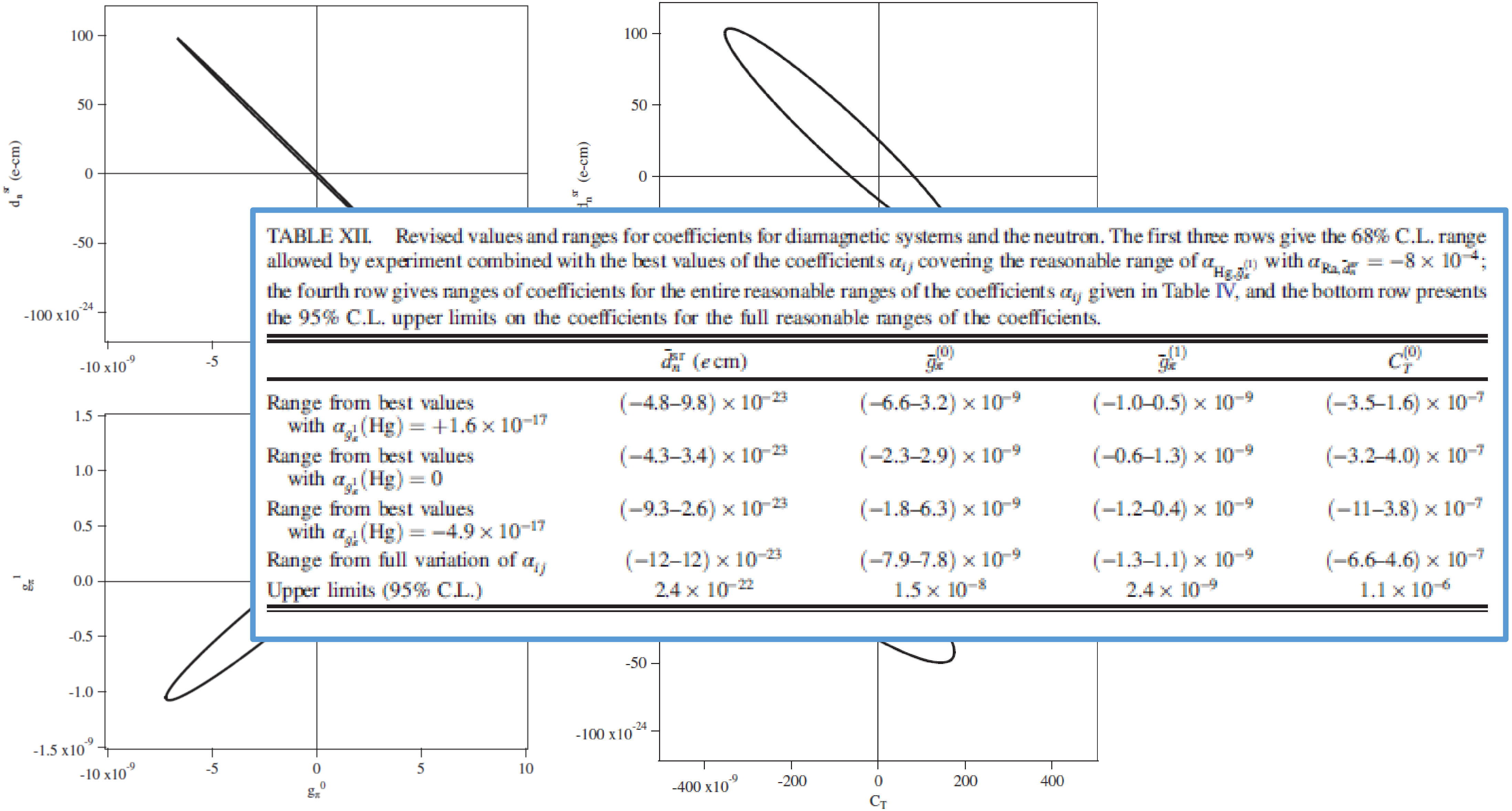
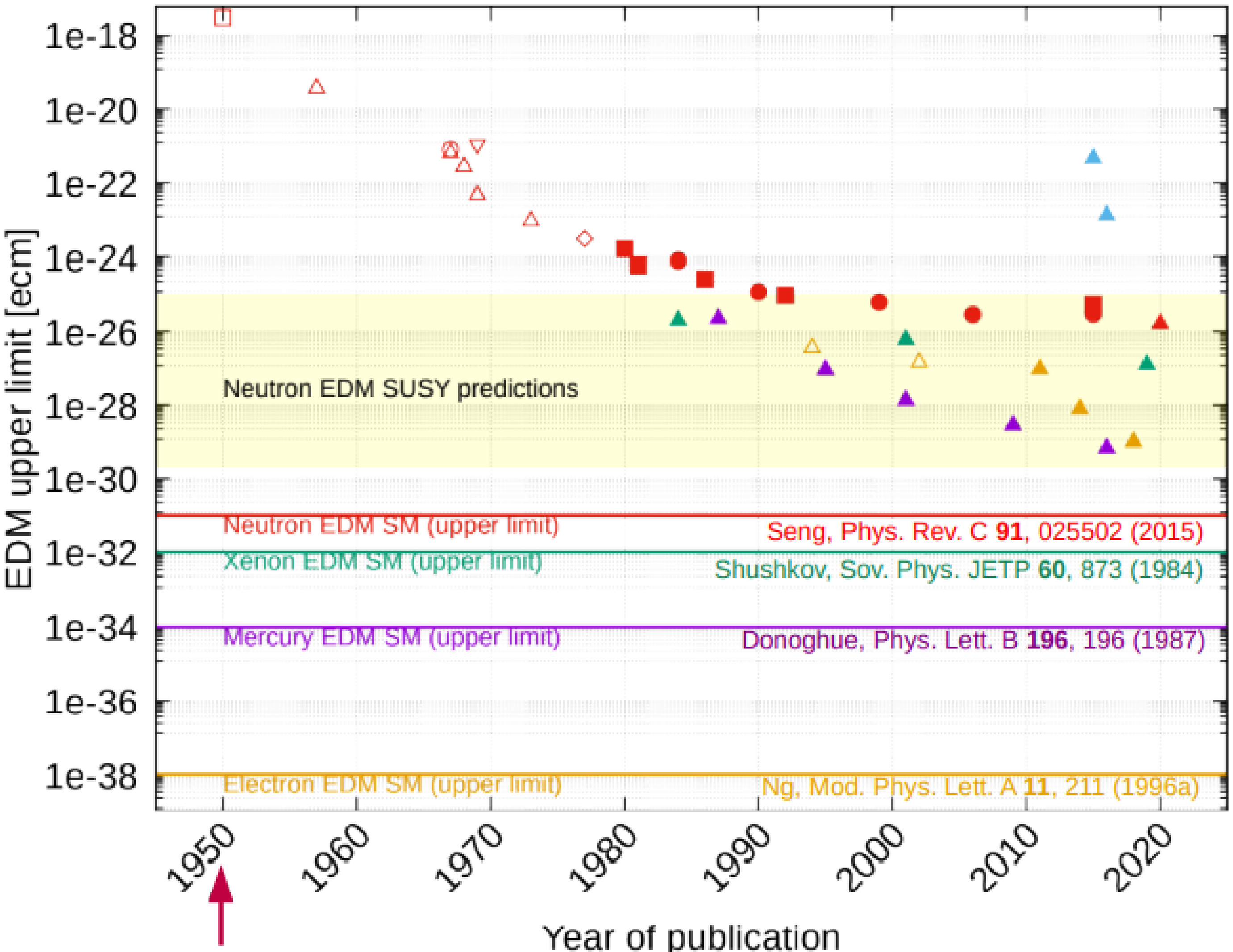


TABLE XII. Revised values and ranges for coefficients for diamagnetic systems and the neutron. The first three rows give the 68% C.L. range allowed by experiment combined with the best values of the coefficients α_{ij} covering the reasonable range of $\alpha_{\mathrm{Hg},\bar{g}_\pi^{(1)}}$ with $\alpha_{\mathrm{Ra},\bar{d}_n^{sr}} = -8 \times 10^{-4}$; 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 $\alpha_{g_\pi^1}(\mathrm{Hg}) = +1.6 \times 10^{-17}$	$(-4.8–9.8) \times 10^{-23}$	$(-6.6–3.2) \times 10^{-9}$	$(-1.0–0.5) \times 10^{-9}$	$(-3.5–1.6) \times 10^{-7}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = 0$	$(-4.3–3.4) \times 10^{-23}$	$(-2.3–2.9) \times 10^{-9}$	$(-0.6–1.3) \times 10^{-9}$	$(-3.2–4.0) \times 10^{-7}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = -4.9 \times 10^{-17}$	$(-9.3–2.6) \times 10^{-23}$	$(-1.8–6.3) \times 10^{-9}$	$(-1.2–0.4) \times 10^{-9}$	$(-11–3.8) \times 10^{-7}$
Range from full variation of α_{ij}	$(-12–12) \times 10^{-23}$	$(-7.9–7.8) \times 10^{-9}$	$(-1.3–1.1) \times 10^{-9}$	$(-6.6–4.6) \times 10^{-7}$
Upper limits (95% C.L.)	2.4×10^{-22}	1.5×10^{-8}	2.4×10^{-9}	1.1×10^{-6}

What does it mean, if we see it?



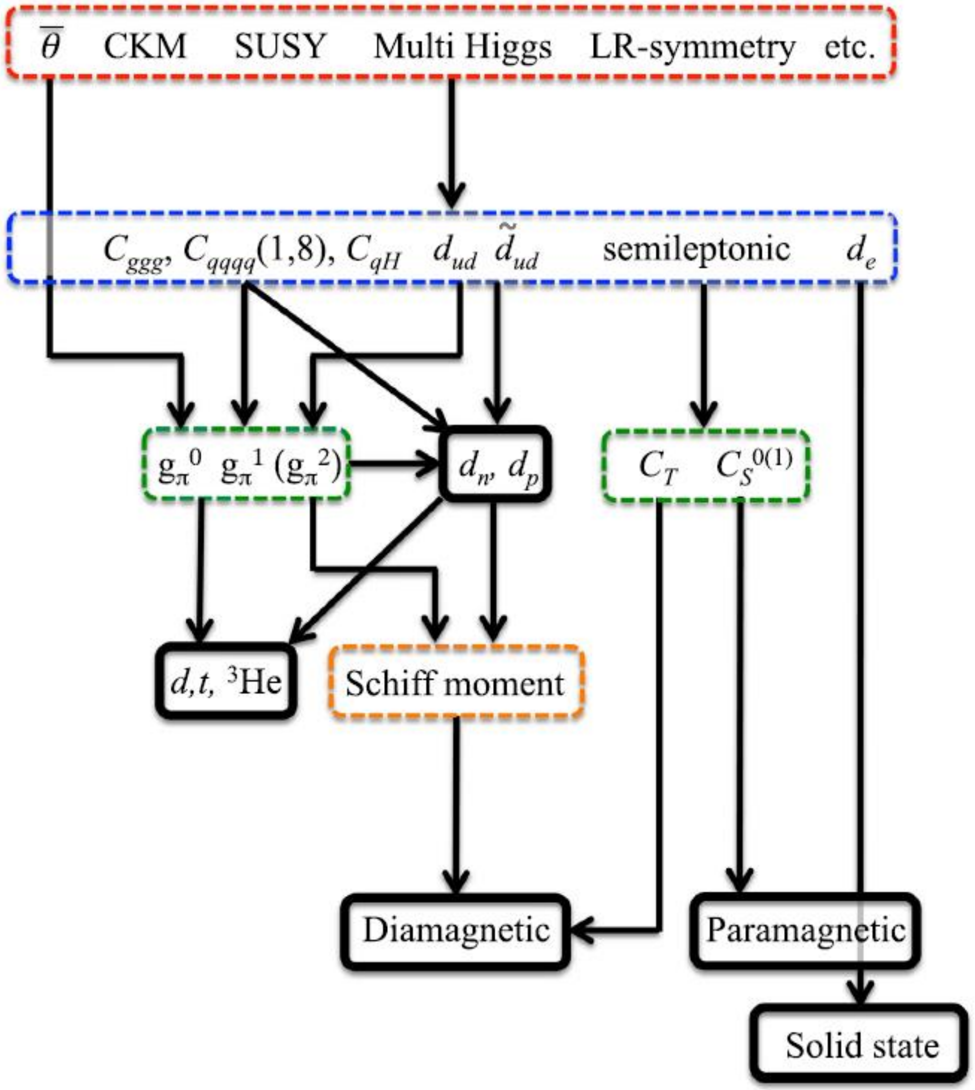
Seng, Phys. Rev. C **91**, 025502 (2015)

Shushkov, Sov. Phys. JETP **60**, 873 (1984)

Donoghue, Phys. Lett. B **196**, 196 (1987)

Ng, Mod. Phys. Lett. A **11**, 211 (1996a)

Purcell et al, Phys. Rev. **78**, 807 (1950)



$\bar{\theta}$ CKM SUSY Multi Higgs LR-symmetry etc.

C_{ggg}, $C_{qqqq}(1,8)$, C_{qH} d_{ud} $\tilde{d}_{ud}$ semileptonic d_e

g_π^0 g_π^1 (g_π^2)

d_n, d_p

C_T $C_S^{0(1)}$

d, t, ^{3}He

Schiff moment

Diamagnetic

Paramagnetic

Solid state

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

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

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

Add constituent EDMs
As a perturbation…

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

(sum over constituents)

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…

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

(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

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

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

Eigenstates receive an energy shift due to the perturbation:

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

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 → *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)

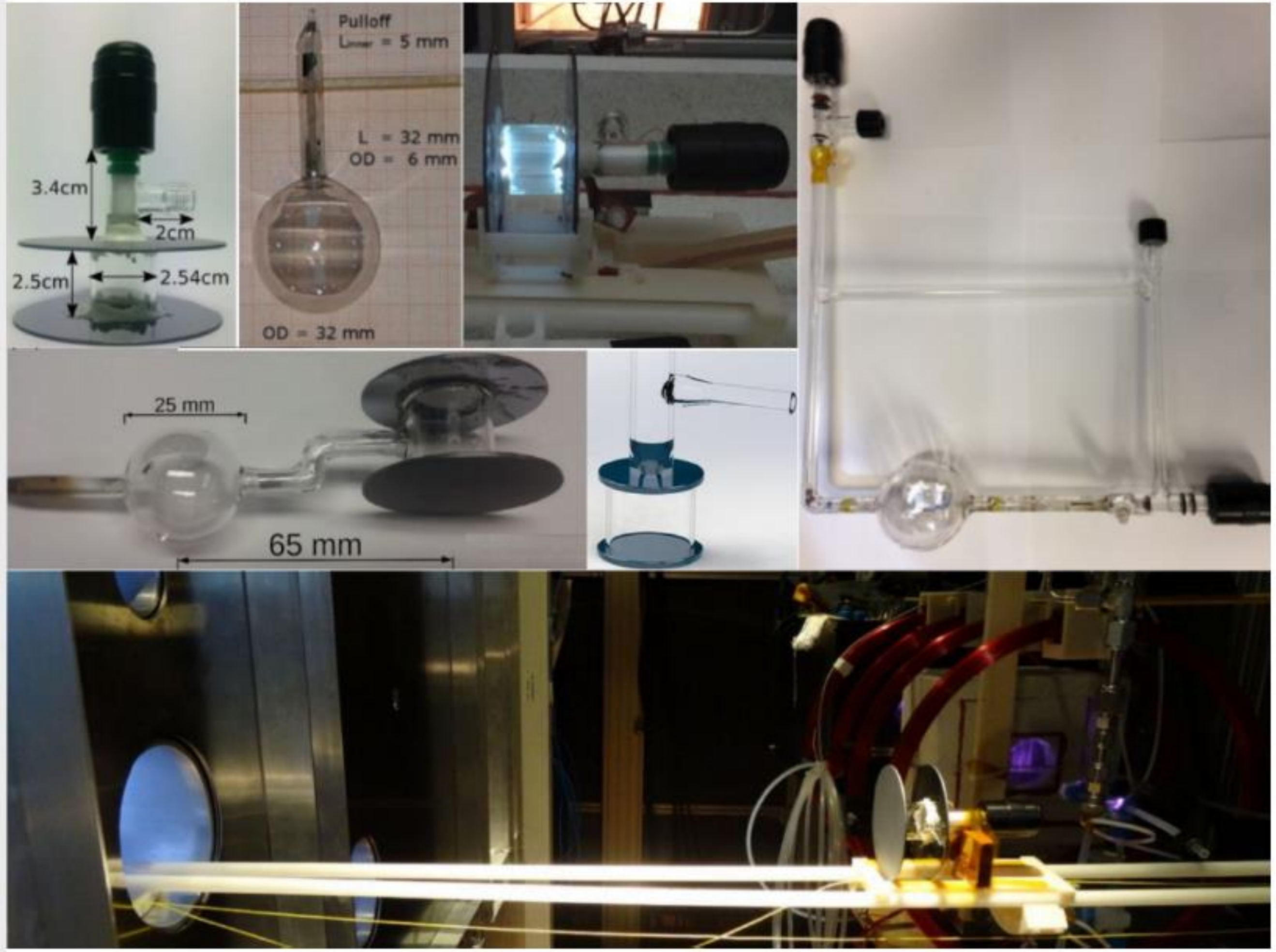
  - non-relativistic treatment → *incorrect for atomic electrons*

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

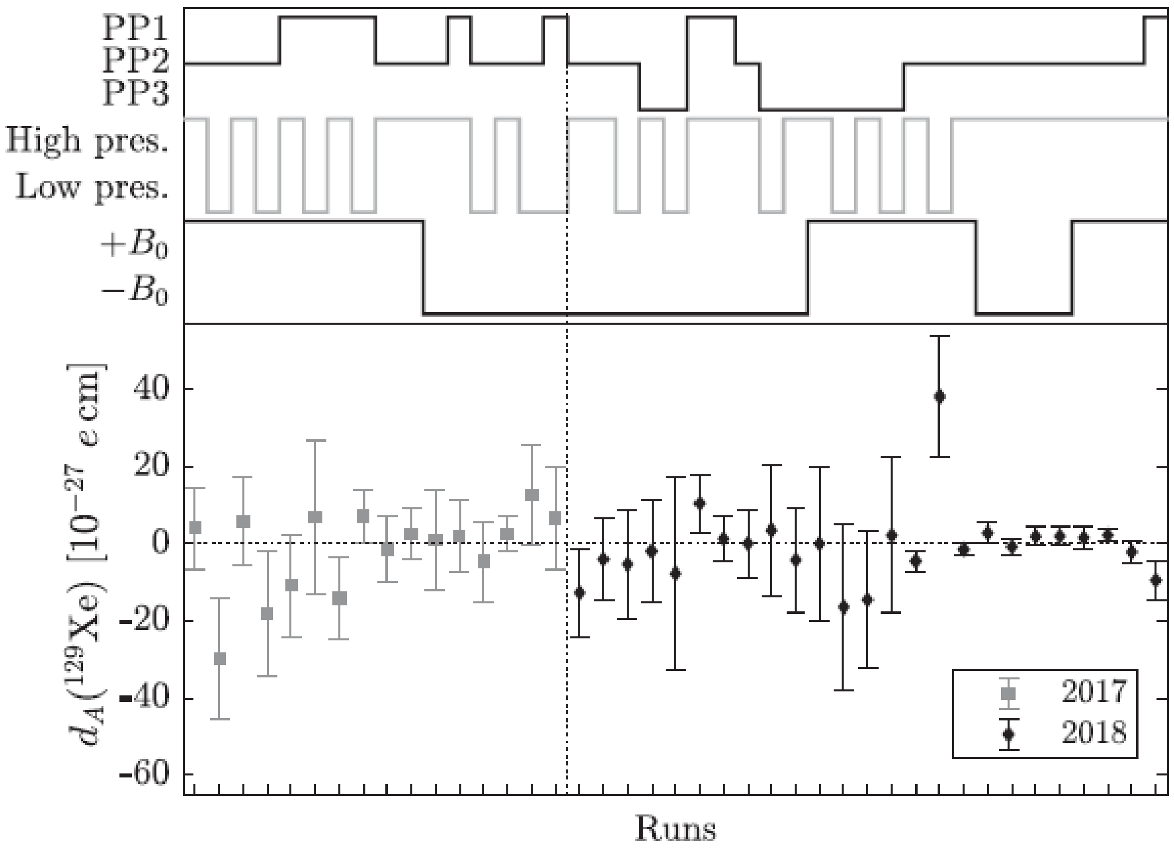
…see American Journal of Physics **75**, 532 (2007)

More on HeXe and “complementarity”

Cells, spin-polarization, co-magnetometry

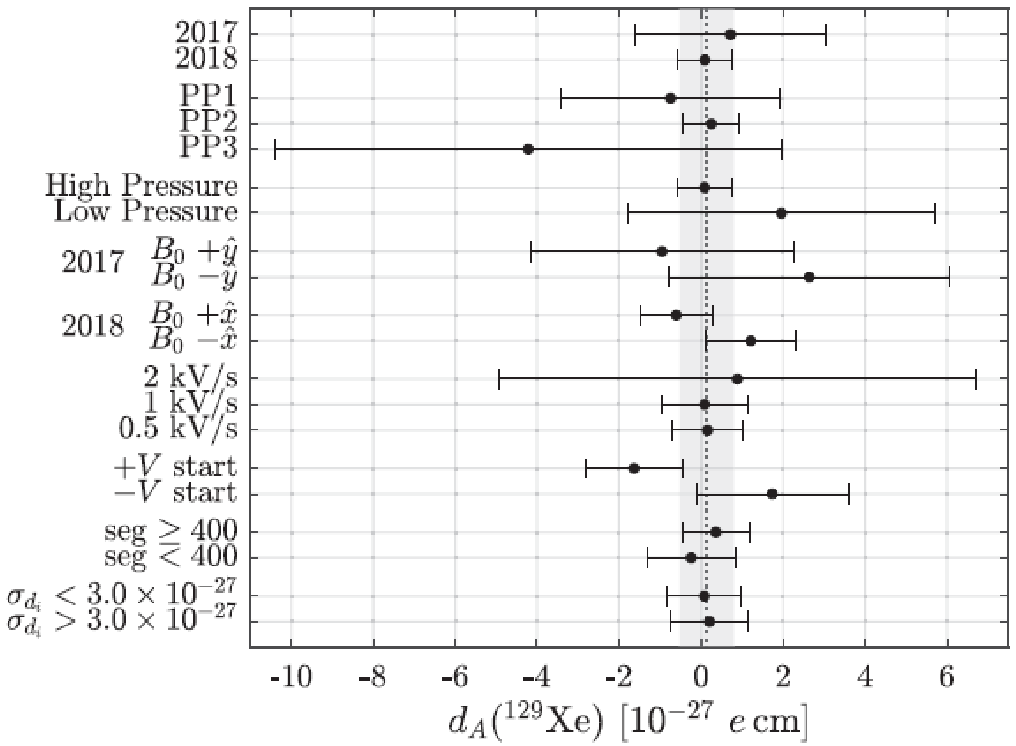


Analysis methods



HeXe EDM @TUM/PTB…
…laid groundwork for SuperSUN/PanEDM @ILL

- Gave a reference point for what it takes to go from concept to result in a new type of EDM experiment… obviously less complex than nEDM, but still with significant equipment and technique overlap



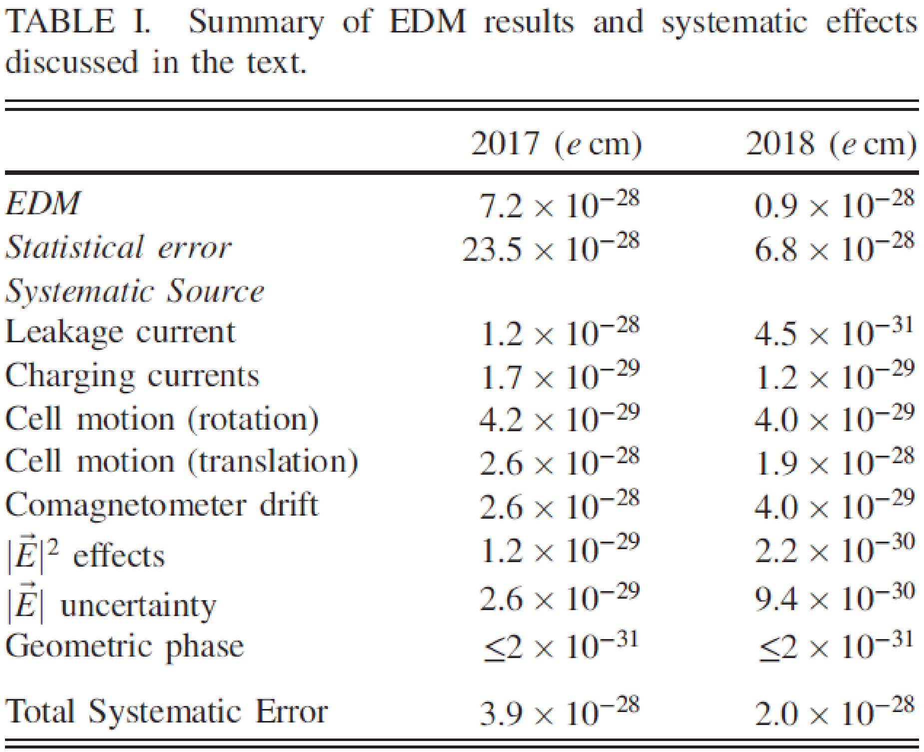


TABLE I. Summary of EDM results and systematic effects discussed in the text.

	2017 (e cm)	2018 (e cm)
EDM	7.2×10^{-28}	0.9×10^{-28}
Statistical error	23.5×10^{-28}	6.8×10^{-28}
Systematic Source		
Leakage current	1.2×10^{-28}	4.5×10^{-31}
Charging currents	1.7×10^{-29}	1.2×10^{-29}
Cell motion (rotation)	4.2×10^{-29}	4.0×10^{-29}
Cell motion (translation)	2.6×10^{-28}	1.9×10^{-28}
Comagnetometer drift	2.6×10^{-28}	4.0×10^{-29}
$\lvert\vec{E}\rvert^2$ effects	1.2×10^{-29}	2.2×10^{-30}
$\lvert\vec{E}\rvert$ uncertainty	2.6×10^{-29}	9.4×10^{-30}
Geometric phase	$\leq 2 \times 10^{-31}$	$\leq 2 \times 10^{-31}$
Total Systematic Error	3.9×10^{-28}	2.0×10^{-28}

Measuring the ^{129}Xe EDM at Heidelberg PI