Experimental Perspectives on Next Generation EDM Searches

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UK UNIVERSITY OF KENTUCKY

Outline

- Motivation: Why search for permanent EDMs? (see talk by Emanuele Mereghetti)
- How to measure a permanent EDM?
- Technologies and Present Status
- Future Developments
- Summary

Why Search for Permanent EDMs?

S.Weinberg, "XXVI International Conference on High Energy Physics, Dallas, TX, 1992

arXiv:hepph/9211298

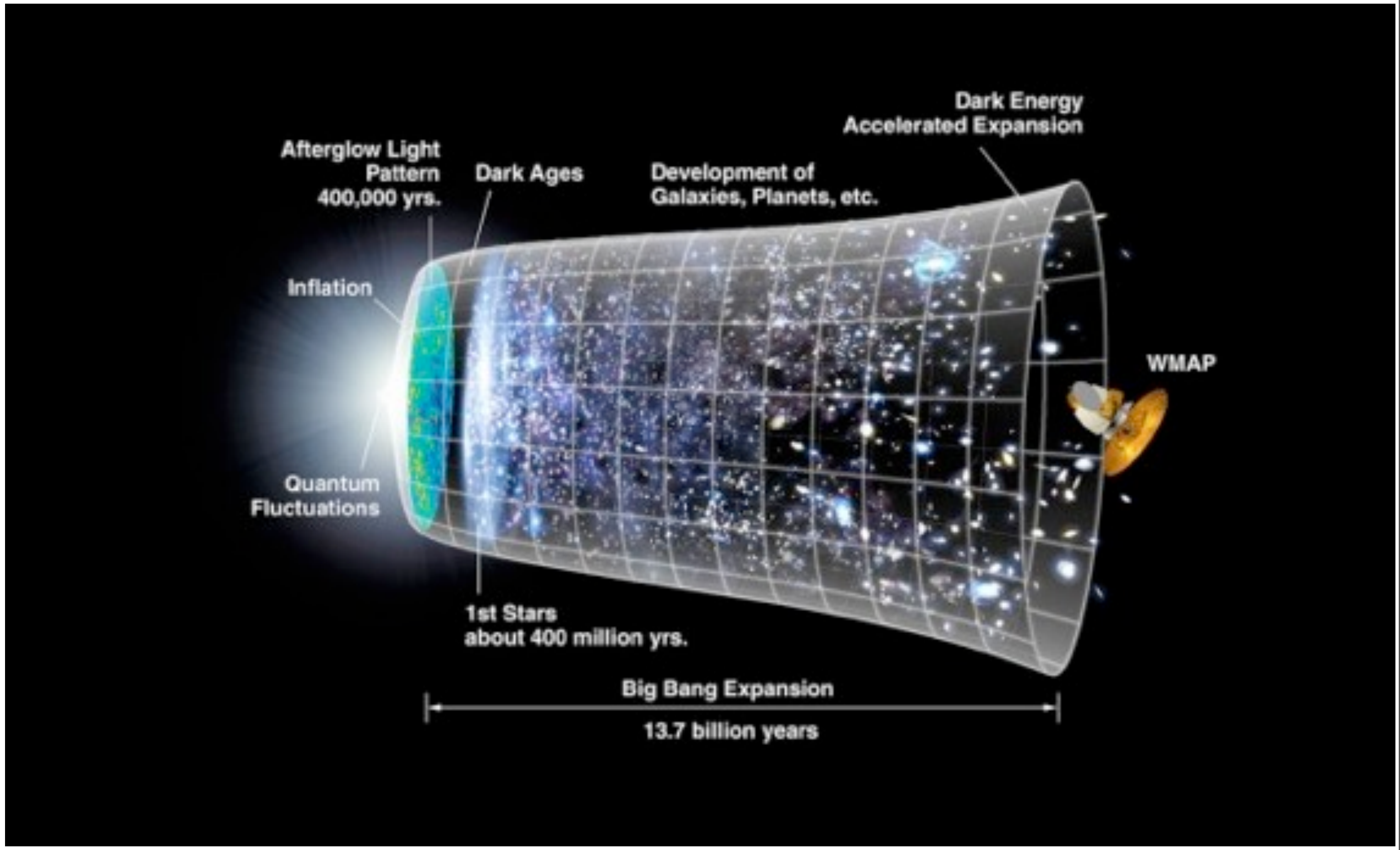
...... Also endemic in supersymmetry theories are CP violations that go beyond the CKM matrix, and for this reason it may be that the next exciting thing to come along will be the discovery of a neutron or atomic or electron electric dipole moment. These electric dipole moments were just briefly mentioned at this conference, but they seem to me to offer one of the most exciting possibilities for progress in particle physics. ....

Discrete Symmetries and the Universe

Baryon Asymmetry of the Universe (BAU)

$$\eta = \left(\frac{n_B - n_{\bar{B}}}{n_\gamma} \right) \approx 6.12^{+0.20}_{-0.25} \times 10^{-10}$$

(WMAP + COBE, 2003)



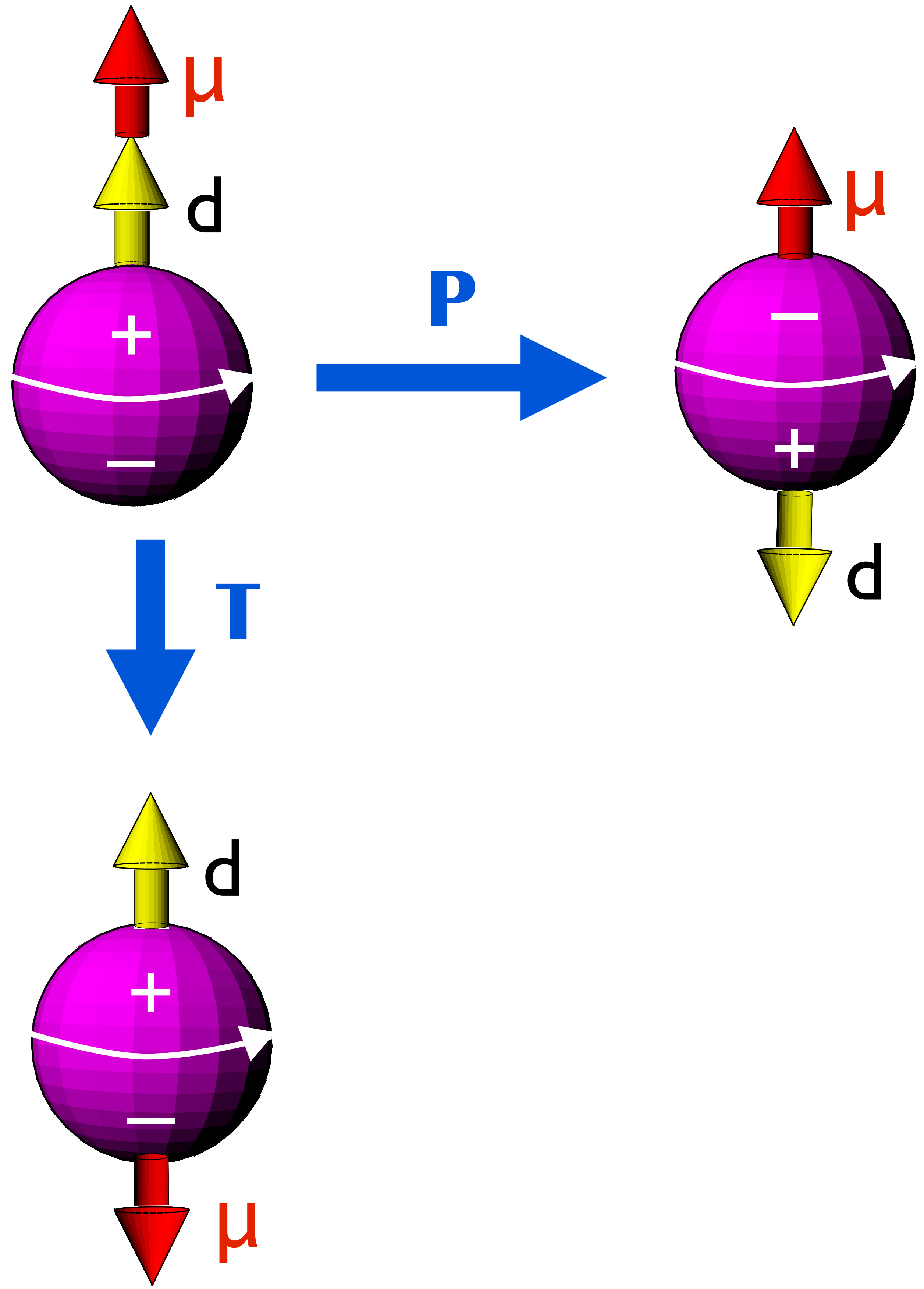
Sakharov: Three Requirements:

- Baryon number violation
- Violation of C and CP symmetries
- Departure from thermodynamic equilibrium

A. Sakharov; JETP Lett, 5, 24 (1967)

Permanent Electric Dipole Moments

$$H = -\left[d \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \vec{E} + \mu \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \vec{B} \right]$$



$\vec{\sigma} \rightarrow$ axial-vector, $\vec{E} \rightarrow$ vector:

⇒ d violates Parity

$\vec{\sigma} \xrightarrow{T} -\vec{\sigma}, \vec{E} \xrightarrow{T} \vec{E}$:

⇒ d violates T-reversal

⇒ CPT: d ≠ 0, CP violation

CP-odd Operators at ~1 GeV

Use Effective Field Theory (EFT) to provide model-independent parameterization of CP-violating operators at ~1 GeV:

Operator Product Expansion $L_{eff} = L_{\dim=4} + L_{\dim=5} + L_{\dim=6} + \ldots$

Dimension 4: $\bar{\theta}\alpha_s G\tilde{G}$ $\quad \bar{\theta} = \theta_0 + ArgDet(M_q)$

Extension of SM → Peccei-Quinn Symmetry : Axion (Goldstone Boson)

Dimension5: $\sum_{q=u,d,s} d_q \bar{q}F\sigma\gamma_5 q + \sum_{q=u,d,s} \tilde{d}_q \bar{q}G\sigma\gamma_5 q + d_e \bar{e}F\sigma\gamma_5 e + w g_s^3 GG\tilde{G}$

Dimension 6: $\sum_{q=u,d,s} C_{qq} \bar{q}q\bar{q}i\gamma_5 q + C_{qe} \bar{q}q\bar{e}i\gamma_5 e + \ldots$

M. Pospelov and A. Ritz, Ann. Phys. 318, 119 (2005)

$\not{C}\!\!\not{P}$ in QCD: θ -Term

QCD Lagrangian: $\mathcal{L} = \mathcal{L}_{QCD} + \boxed{\bar{\theta}\frac{g^2}{32\pi^2}G^{(A)}_{\mu\nu}\tilde{G}^{(A)\mu\nu}}$

$\not{C}\!\!\not{P}$ term

$$\boxed{G^{(A)}_{\mu\nu}\tilde{G}^{(A)\mu\nu} \propto \vec{\mathbf{E}}^c \cdot \vec{\mathbf{B}}^c}$$

→ $\not{P}$ and $\not{T}$

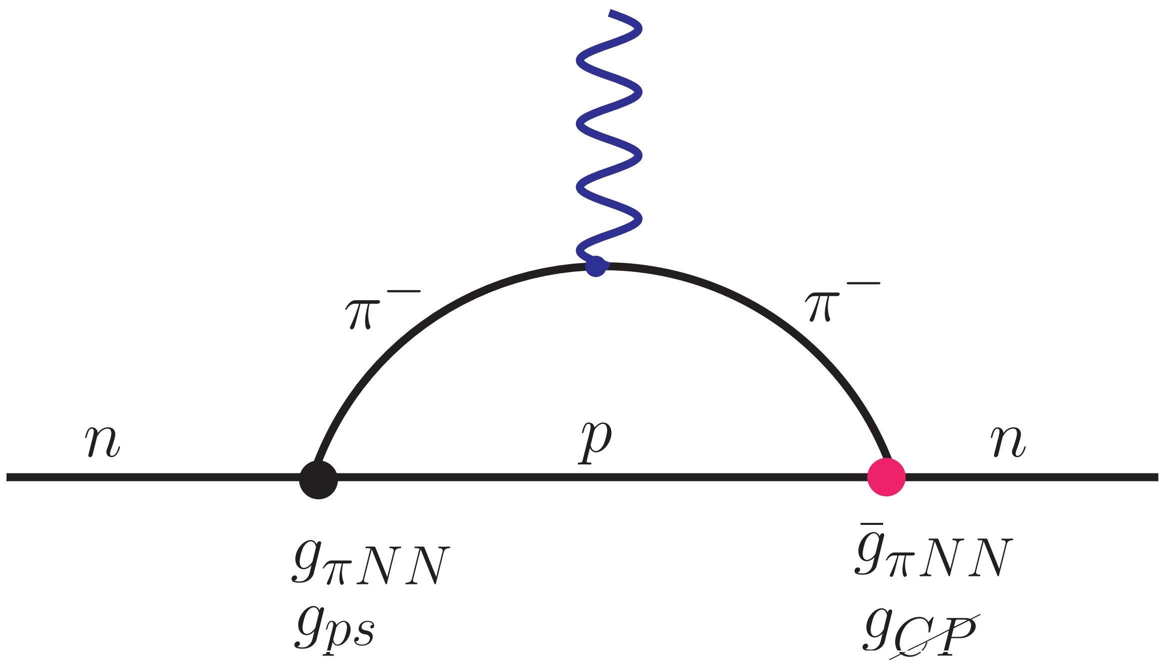
$d_E \neq 0$

Standard Model: θ not constrained, could be O(1).

Size of θ - Term

Neutron EDM in Chiral Perturbation Theory:

$$\boxed{\mathcal{L}_{\pi NN} = \vec{\pi} \cdot \bar{N}\vec{\tau}(i\gamma_5 g_{\pi NN} + \bar{g}_{\pi NN})N}$$



➔ estimate of neutron EDM: $g_{\pi NN} = 13.7, \ \bar{g}_{\pi NN} \approx -0.027\theta$

$$d_E(n) \sim e\frac{g_{\pi NN}\bar{g}_{\pi NN}}{4\pi^2 M_N} \ ln\left(\frac{M_N}{m_\pi}\right) \sim 2 \times 10^{-15} \ \theta \ e \cdot cm$$

Experiment: $d_E(n) < 10^{-25}$ e·cm → $\theta < 10^{-10}$

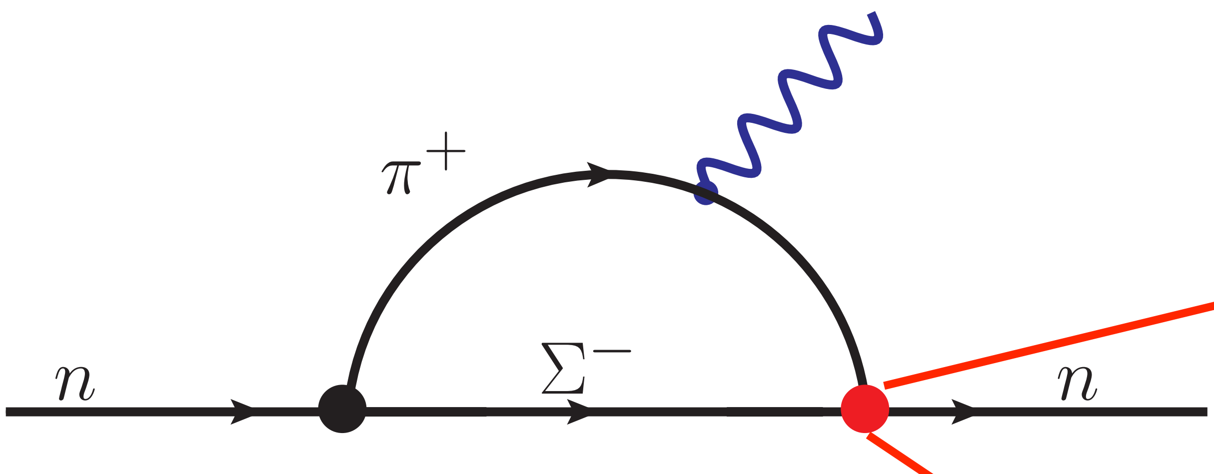
➔ "θ-term Puzzle"

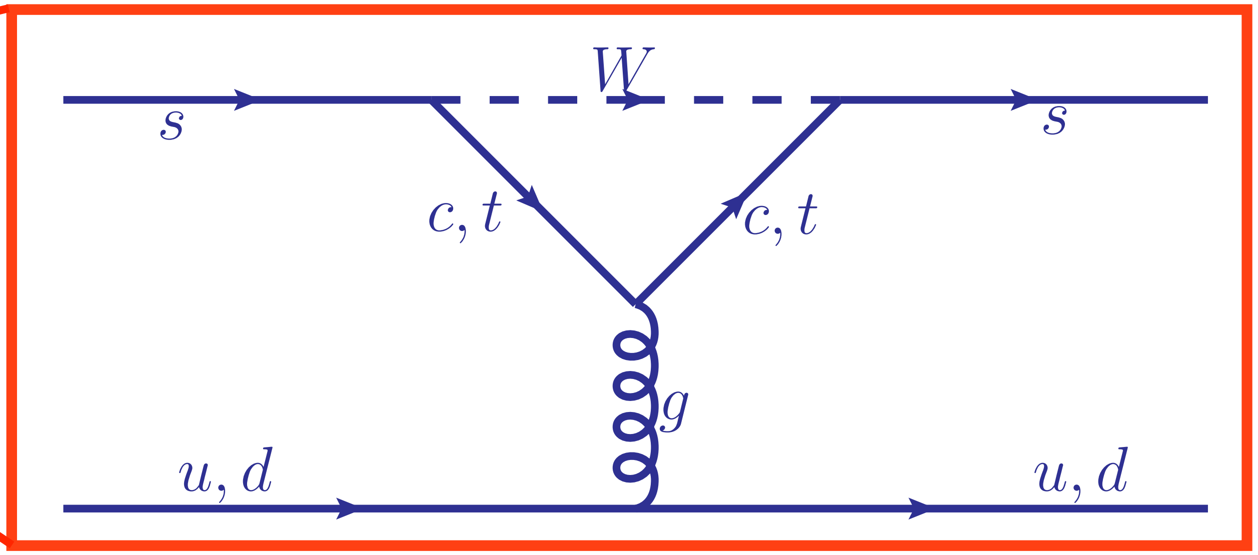
V. Baluni, Phys. Rev. D 19, 2227 (1979)
R.J. Crewther et al., Phys. Lett. 88, 123 (1979)

Standard Model and Beyond

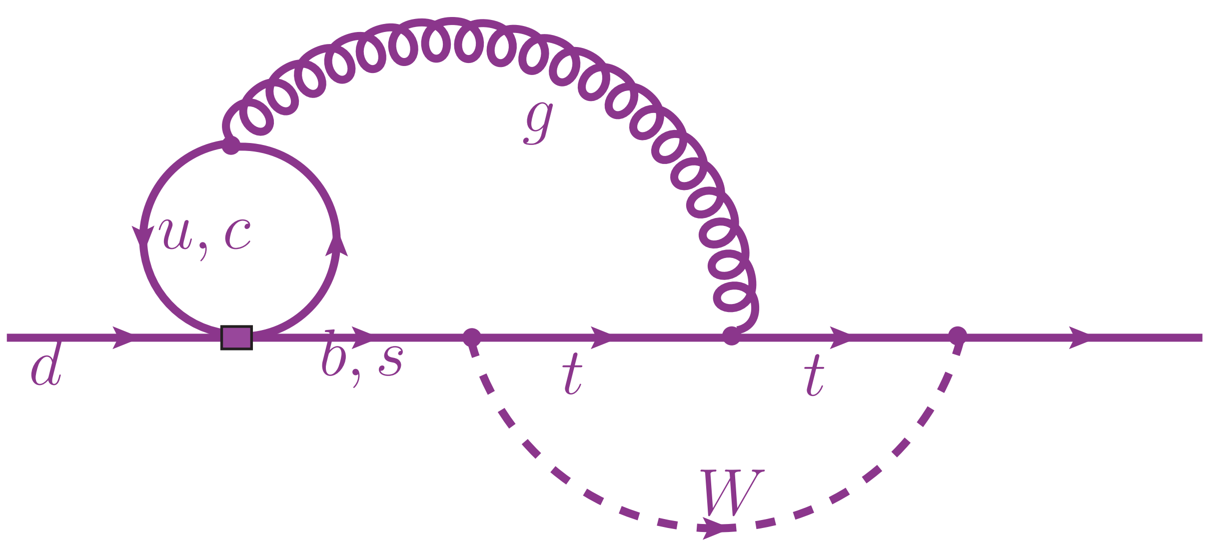
EDMs in the SM and MSSM are generated via radiative corrections.

SM: e.g. two-loop e.w. + strong penguin graphs :





and three- or more loop graphs, e.g:

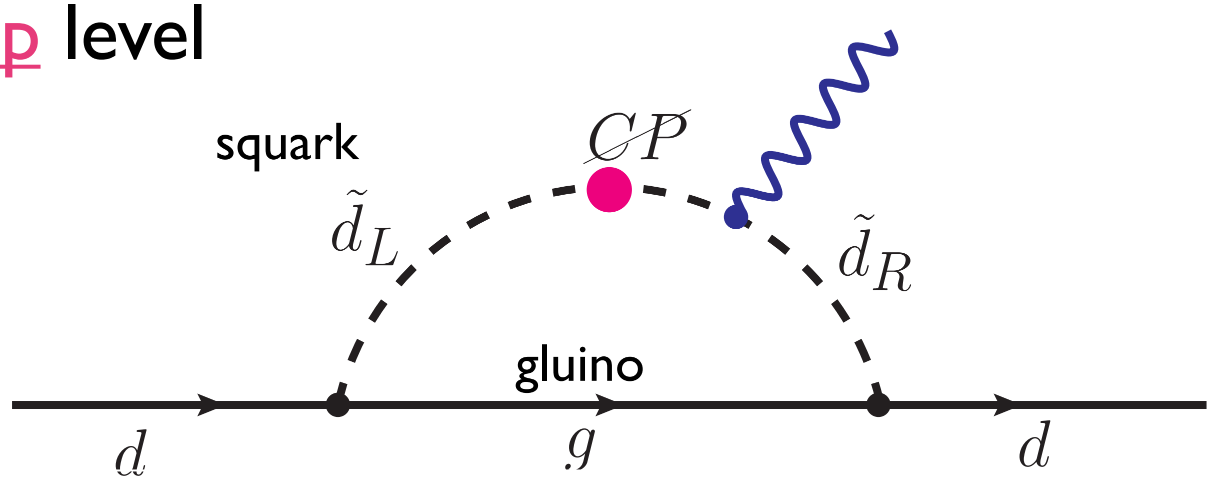


→ $d_E(n) \approx 10^{-32} - 10^{-31}$ e·cm

Sensitivity to New Physics

In SUSY models (MSSM): EDMs at one-loop level

→ $d_E(n) \approx 10^{-28} - 10^{-26}$ e·cm



- New physics (Supersymmetry (SUSY)) has (many) additional $\not{C}\not{P}$ phases in added couplings
- Flavor and gaugino mass universality: only two phases survive in (C)MSSM → θ_μ, θ_A
- Sensitivity to M_{SUSY} (4-generations):

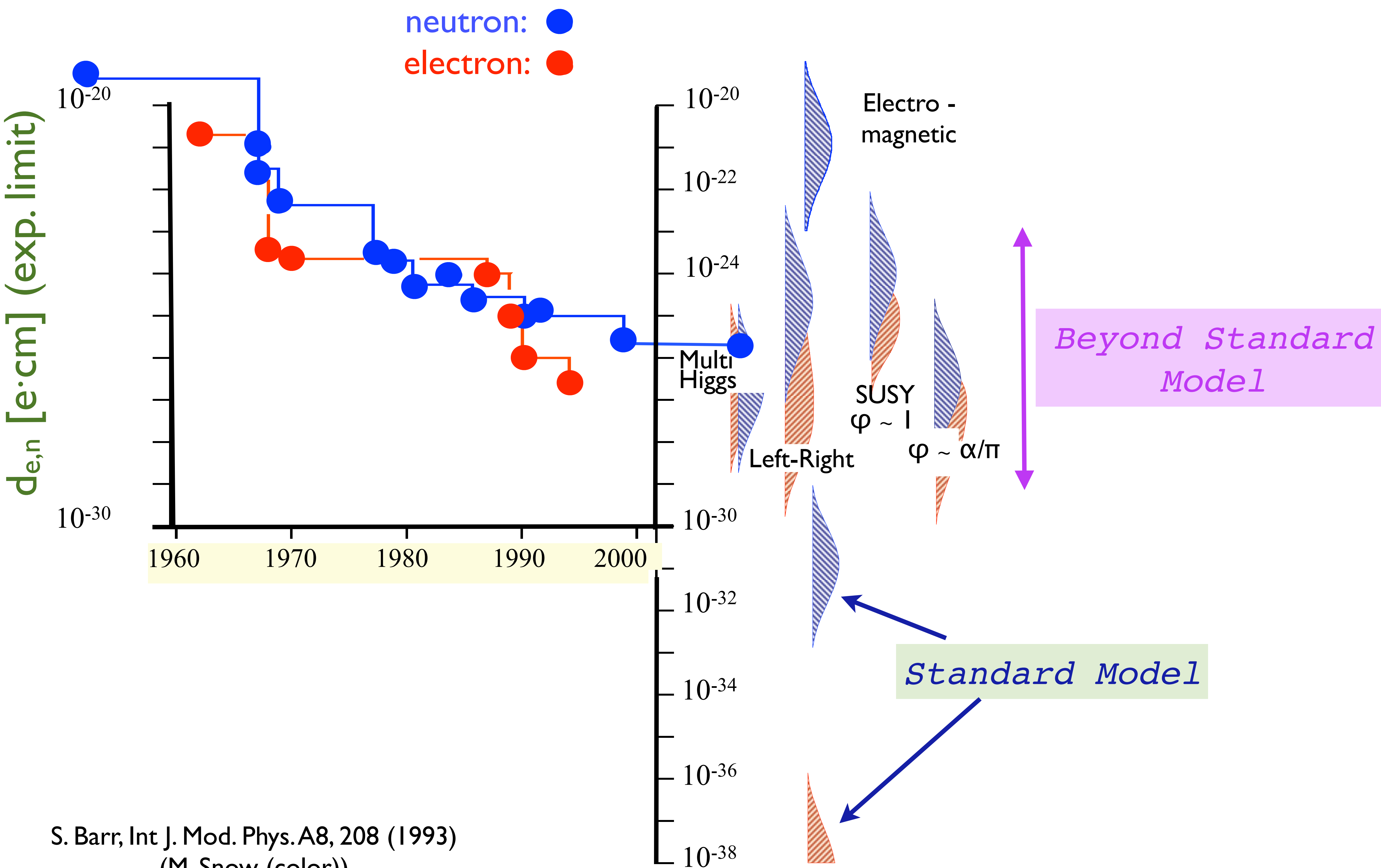
$$d_n \sim \mathrm{Im}(V_{ts}^* V_{tb'} V_{cb'}^* V_{cs}) \left(\frac{1200 GeV}{M_{SUSY}} \right)^2 \cdot 2.5 \times 10^{-23} e \cdot cm$$

C. Hamzaoui, M. Pospelov, and R. Roiban; PRD 56, 4295 (1997)

Assuming : $\mathrm{Im}\left(V_{ts}^* V_{tb'} V_{cb'}^* V_{cs}\right) \approx 10^{-3}$

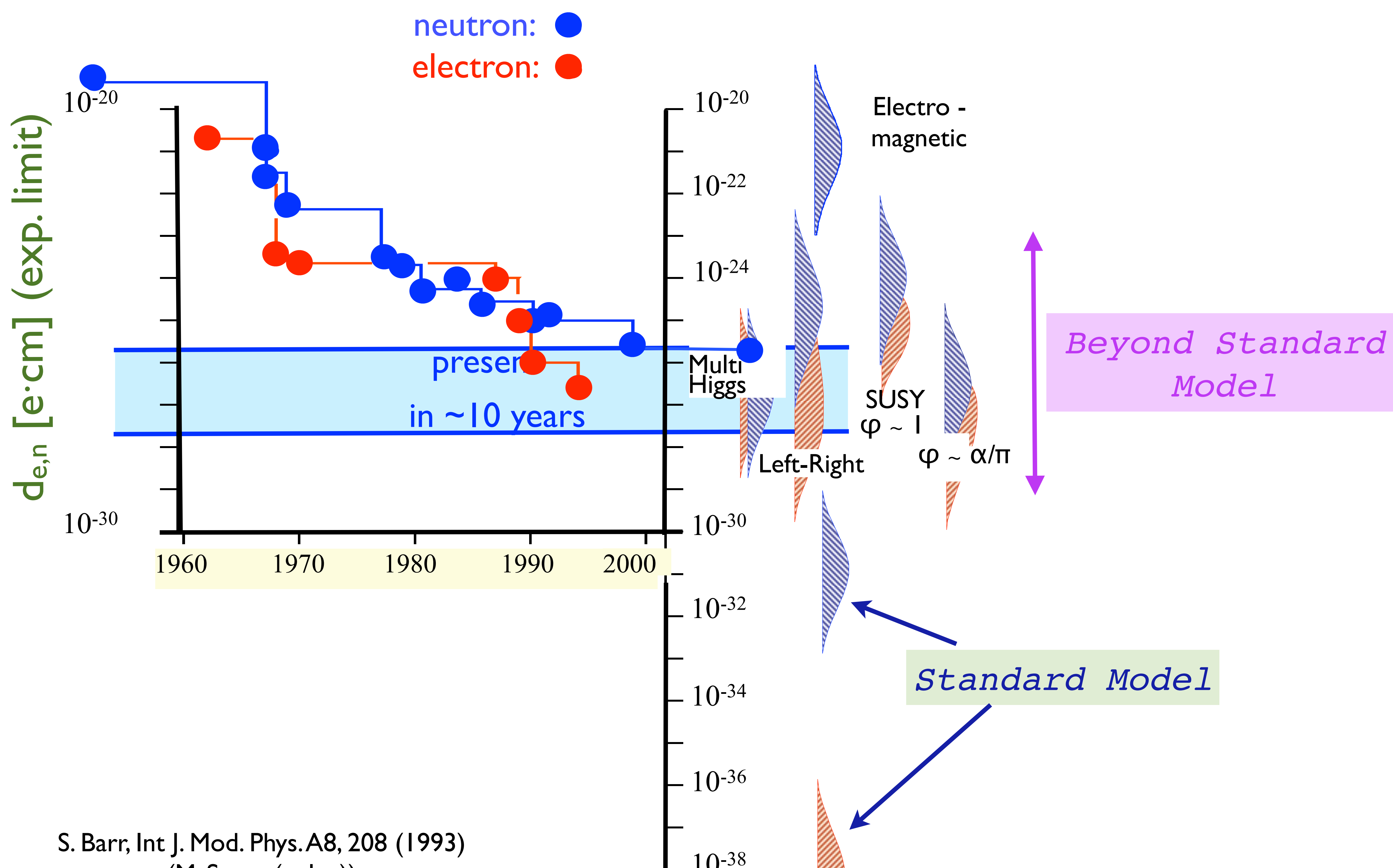
$$\rightarrow d_n \sim 3 \cdot 10^{-28}\ e \cdot cm \leftrightarrow M_{SUSY} \sim 11\ TeV$$

The History of Neutron and Electron EDMs



S. Barr, Int J. Mod. Phys. A8, 208 (1993)
(M. Snow (color))

The History of Neutron and Electron EDMs



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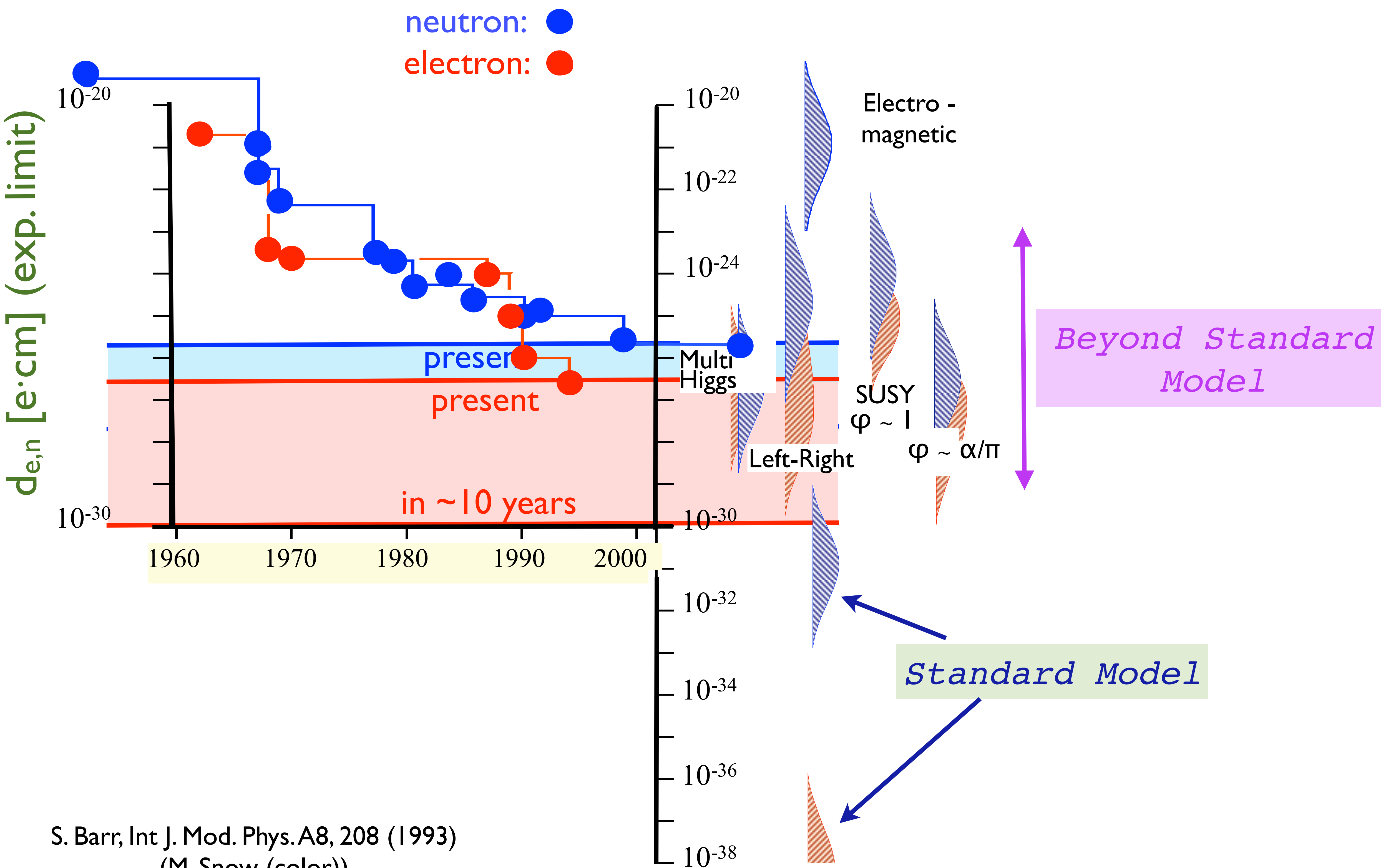

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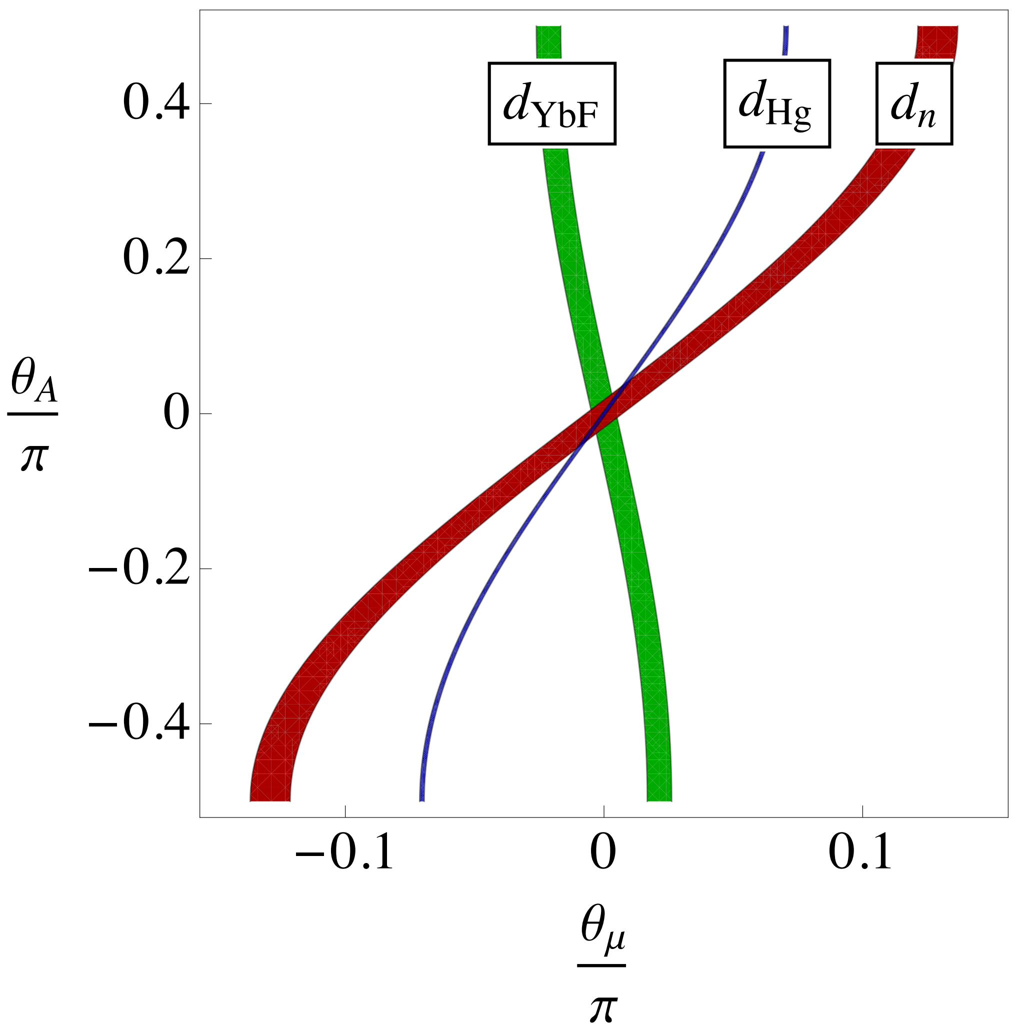
Constraining SUSY Parameters

➜ Need high precision low and high energy experiments to explore physics beyond the SM: EDM measurements on atoms , molecules, nucleons, electrons, ... + collider physics (LHC).

Example: Constraining ~~CP~~ phases in CMSSM:

Before LHC ....

M_{susy} = 500 GeV



$$tan\beta = \frac{\langle h_u^0 \rangle}{\langle h_d^0 \rangle} = 3$$

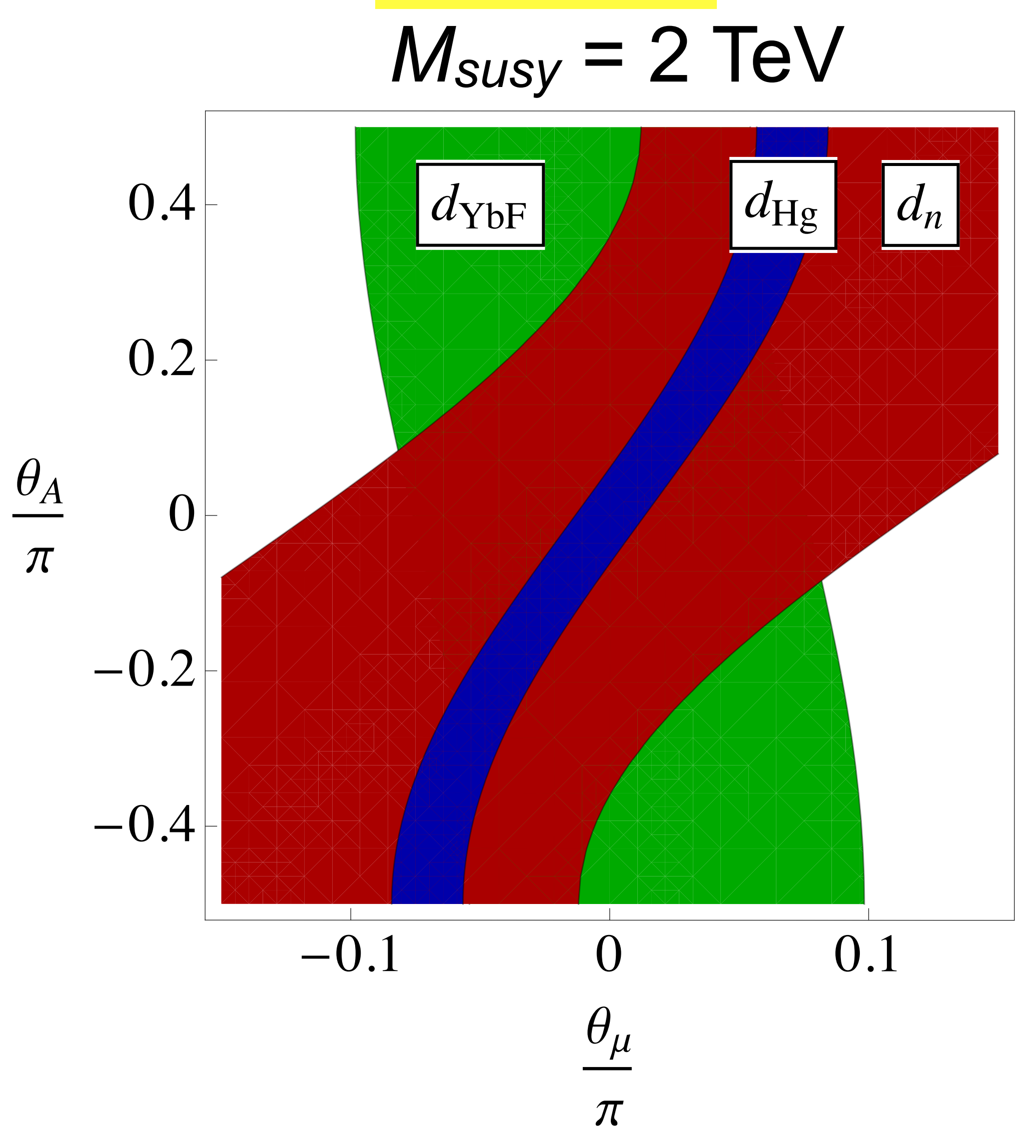
$\langle h_u^0 \rangle, \langle h_d^0 \rangle$ ➔ VEVs of neutral Higgs doublet,
tanβ measure of EW symmetry breaking.

Constraining SUSY Parameters

➜ Need high precision low and high energy experiments to explore physics beyond the SM: EDM measurements on atoms , molecules, nucleons, electrons, ... + collider physics (LHC).

Example: Constraining $\not{C}\!\!\not{P}$ phases in CMSSM:

Now ....



$$tan\beta = \frac{\langle h_u^0 \rangle}{\langle h_d^0 \rangle} = 3$$

$\langle h_u^0 \rangle, \langle h_d^0 \rangle$ ➔ VEVs of neutral Higgs doublet, tanβ measure of EW symmetry breaking.

How are Permanent (Atomic) EDMs generated?

Atomic EDMs:

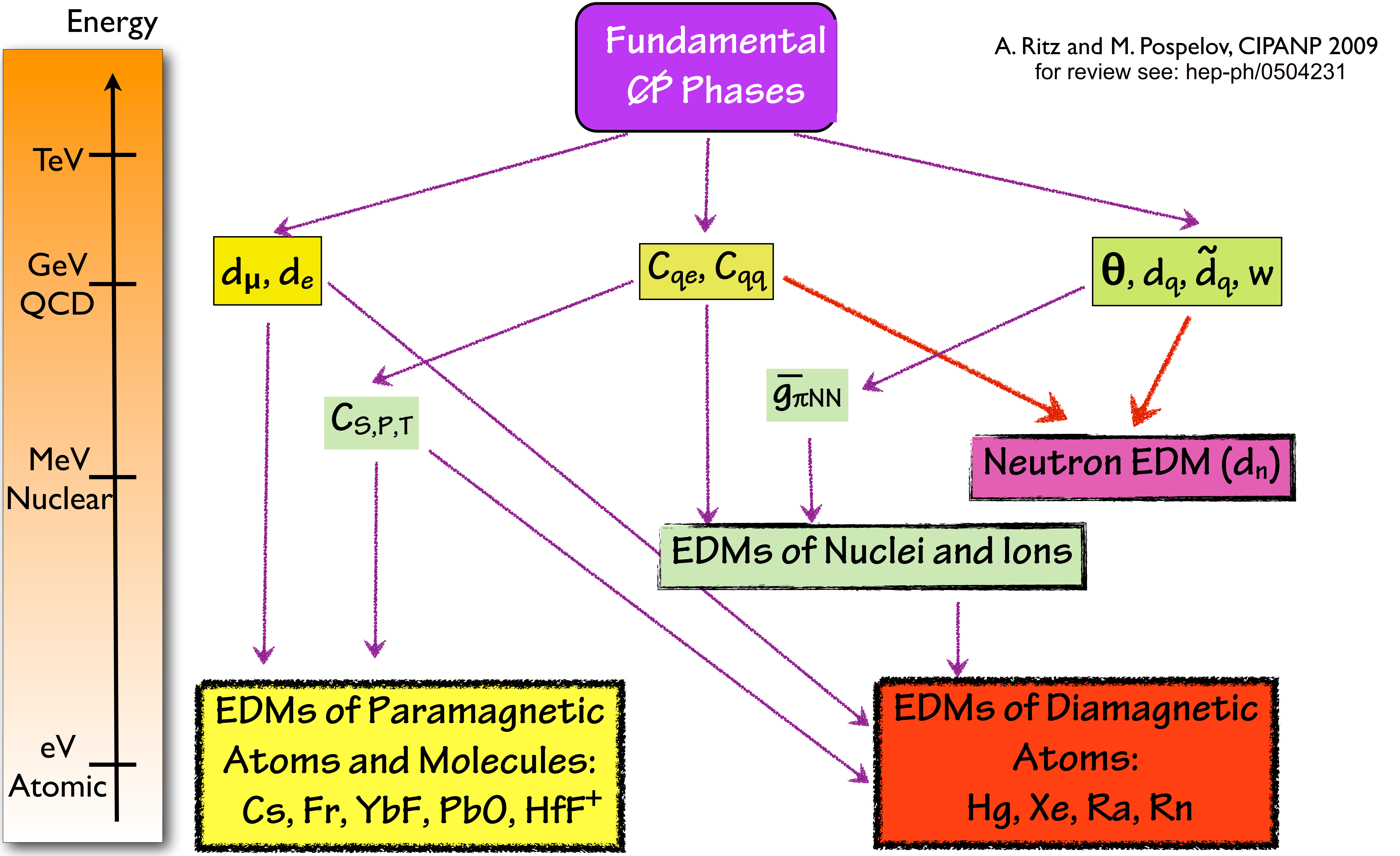
- intrinsic EDM of the electron
- P and T violating electron-electron interaction
- P and T violating electron-nucleon interaction
- intrinsic EDM of the nucleon
- P and T violation nucleon-nucleon interaction

Nucleon EDMs:

* intrinsic EDMs of quarks
* P and T violating quark-quark interaction
* θ-term (CPV in QCD Lagrangian):

  nEDM $\rightarrow \theta < 10^{-10}$!! "θ-term puzzle"

Energy scales involved



Present and Future Status of Limits on EDMs

List is not comprehensive ....

particle	Present limit (>90% c.l.) [e·cm]	Laboratory	Possible Sensitivity [e·cm]	SM Prediciton
e- (^{205}Tl) e- (YbF) e- (WC) e- (HfH+) e- (ThO) e- (GGG)	1.6×10^{-27} 1.05×10^{-27}	Berkely I.C. London U. Michigan Jila Harvard IU, Yale	$\sim 10^{-28}$ $\sim 10^{-30}$ $\sim 10^{-31}$ $\sim 10^{-31}$ $\sim 10^{-30}$	$< 10^{-39}$
μ μ	1.8×10^{-19} 1.1×10^{-18}	BNL CERN	$< 10^{-24}$	$< 10^{-36}$
n n n n	2.9×10^{-26}	ILL ILL PSI SNS	$\sim 3 \times 10^{-28}$ $\sim 5 \times 10^{-28}$ $\sim 3 \times 10^{-28}$	$\sim 10^{-32}$
p(^{199}Hg) p,d	8×10^{-25}	Seattle COSY, BNL	2×10^{-25} $\sim 10^{-29}$	$< 10^{-31}$
^{199}Hg ^{129}Xe ^{129}Xe ^{225}Ra ^{223}Rn	3.1×10^{-29} 3.3×10^{-27}	Seattle U. Michigan, Princeton,Mainz, Munich, Tokyo ANL, KVI TRIUMF	$\sim 10^{-29}$ $\sim 10^{-31}$ $\sim 10^{-29}$ $\sim 10^{-28}$	$\sim 10^{-33}$ $\sim 10^{-34}$

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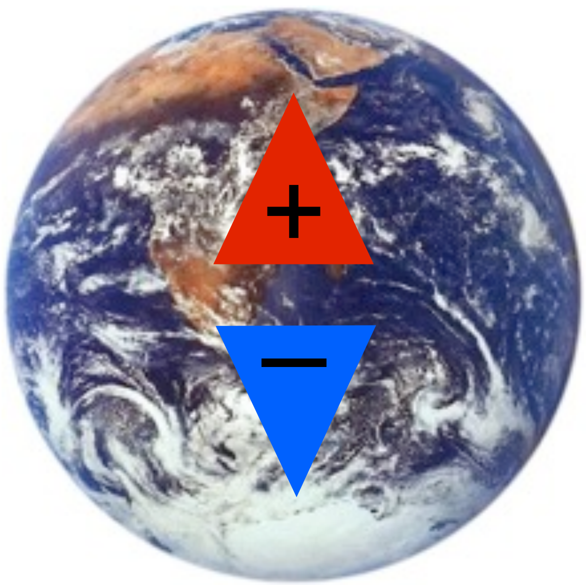
Non-zero EDM in next generation experiments: ☛ New Physics

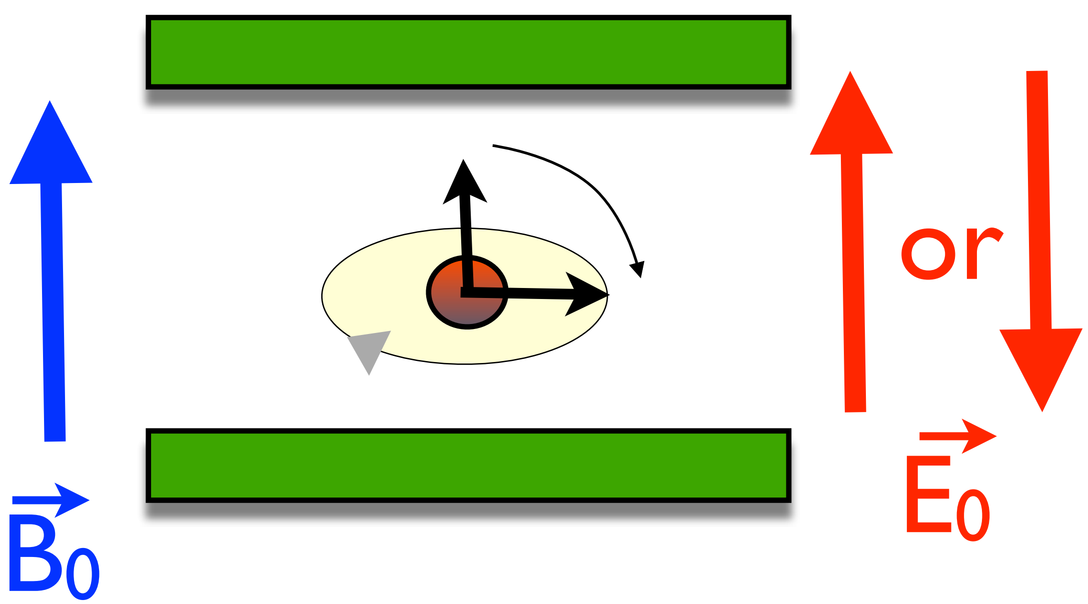
Sensitivity of Neutron EDM Measurements

If $d_n = 10^{-28}$ e·cm:



- Scale Neutron to size of Earth: charge separation: 40 nm (human hair: ~ 40 μm)
- Precession rate in E-field: 1 rev. in 26.4 years (50 kV/cm) or same precession in B-field: $B \sim 5{\cdot}10^{-16}$ T

Basic Concept of EDM Searches



- Transversely polarized particles in region of fixed uniform magnetic field, B_0, and a static uniform electric field, E_0:

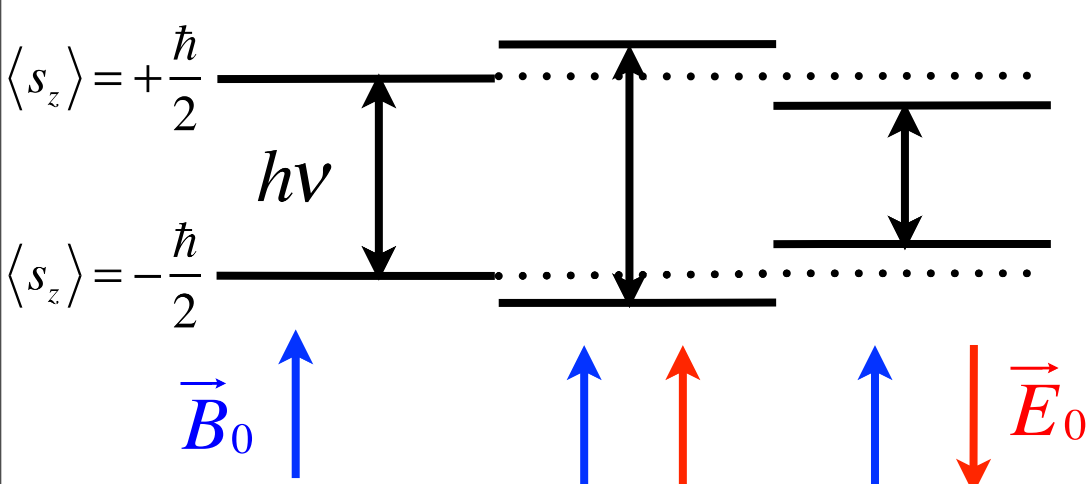
$$h\nu = 2\left(\mu \cdot B_0 \pm d \cdot E_0\right)$$

- Reverse E_0: $d = \dfrac{h\Delta\nu}{4E_0}$

- Statistical uncertainty:

$$\sigma \approx \frac{\hbar}{2\alpha E_0 T_m \sqrt{Nm}}$$

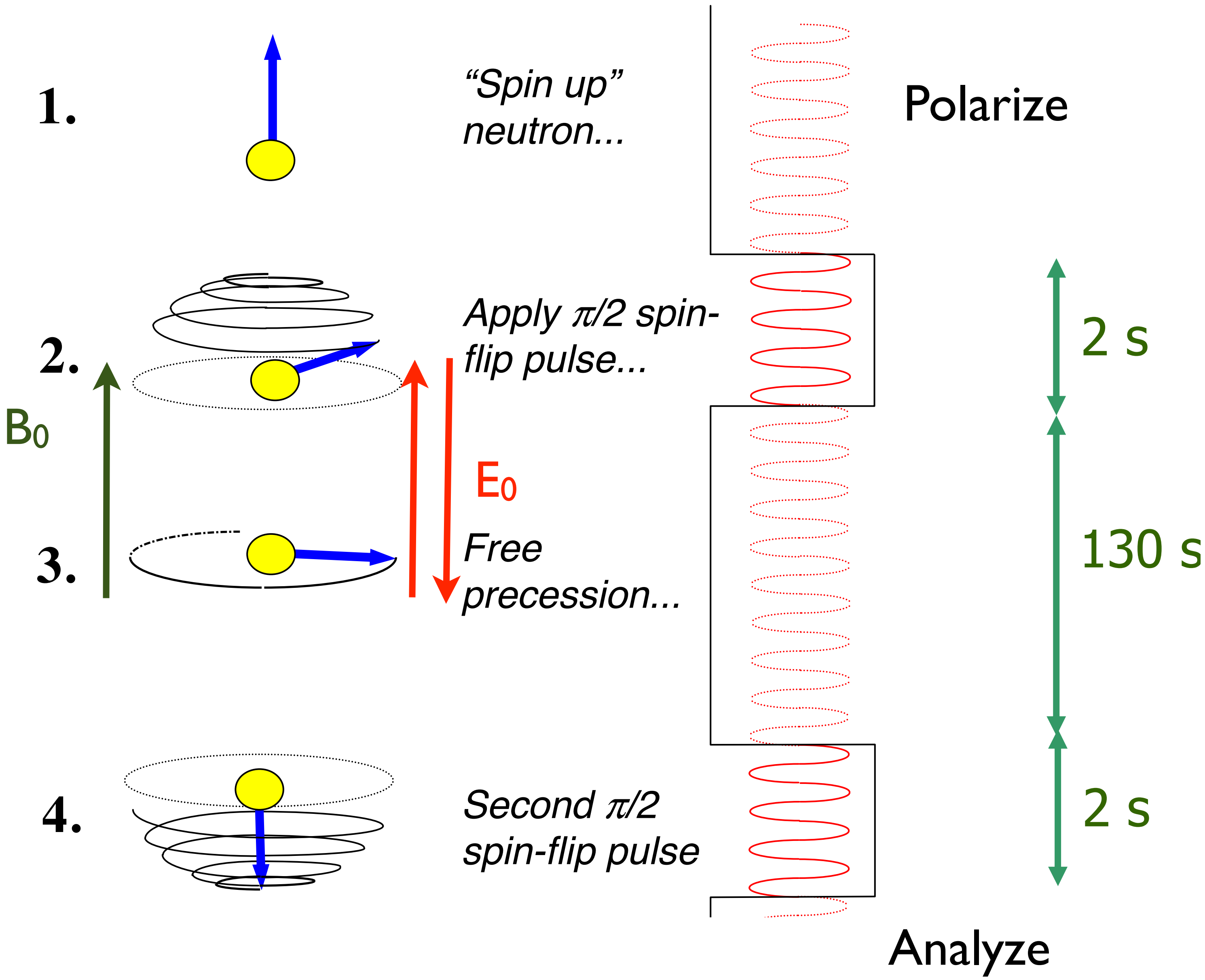
- *B_0 very small*
- *E_0 very large*

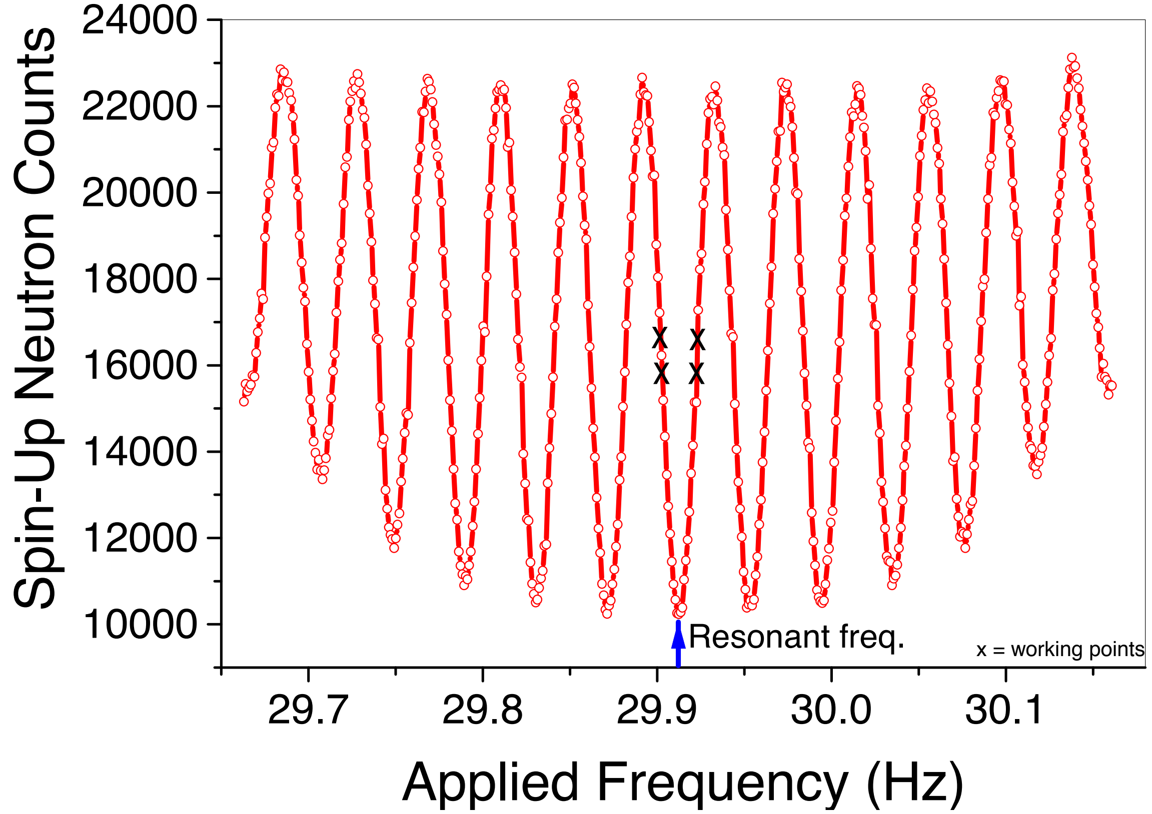


- ✦ Large number of particles (N)
- ✦ High electric field (E_0)
- ✦ Long measuring time (T_m)
- ✦ Many cycles (m)
- ✦ High Polarization (α)

Basic Concept for Most EDM Searches

Ramsey's method of separated oscillatory fields





Worldwide Efforts in EDM Searches

Atoms

Hg (Univ. Wash.)
Xe (Princeton)
Xe (Tokyo Tech.)
Xe (TUM)
Xe (Mainz)
Cs (Penn. State)
Cs (Univ. Texas)
Fr (RCNP/CYRIC)
Rn (TRIUMF)
Ra (ANL)
Ra (KVI)
Yb (Kyoto)

Molecules

YBf (London)
PbO (Yale)
ThO (Harvard)
HfF^{+} (JILA)
WC (Uni. Mich.)
PbF (Oklahoma)

Muons

μ (FNAL)
μ (J-PARC)

Ions

BNL
FZJ (COSY)

Neutrons

n (ILL)
n (ILL, PNPI)
n (PSI)
n (FRM-2)
n (RCNP, TRIUMF)
n (SNS)
n (J-PARC)

Solids

GGG (Indiana Univ.)
Ferro-electrics (Yale)

Technological Advances

Atoms
Laser cooling and atom trapping
Improved Lasers

Atoms
Evade Schiff's Theorem: finite size nuclei
Relativistic effects: $d_A \sim \alpha^2 Z^3 d_e$
Highly deformed nuclei
Closely spaced parity doublets

Neutrons
Intense UCN sources
Efficient UCN production

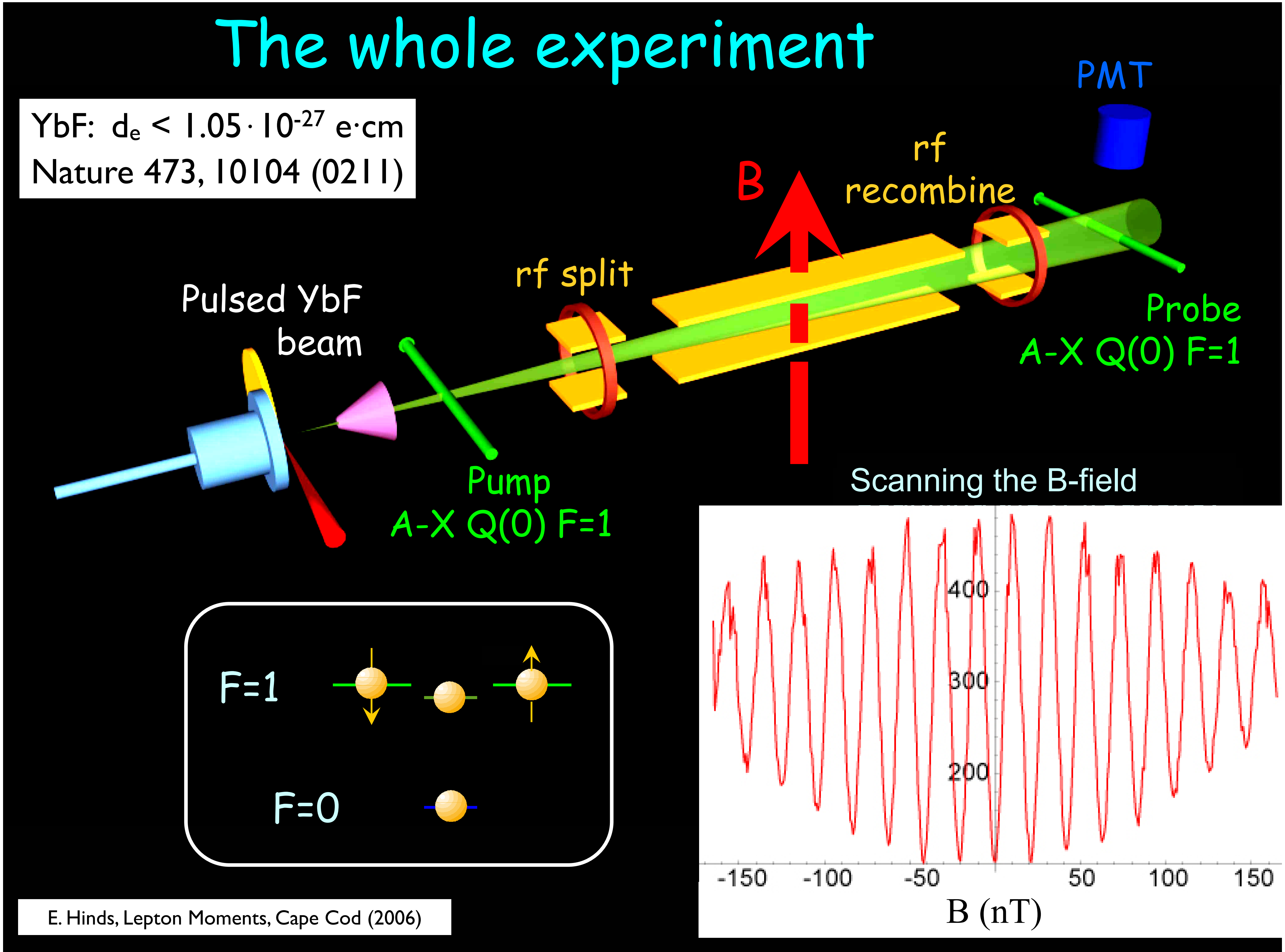
Factor $\gtrsim$ 100 Improvement

Molecules
Polar Molecules: Huge intrinsic E-fields: <100 GV/cm
Improved Lasers

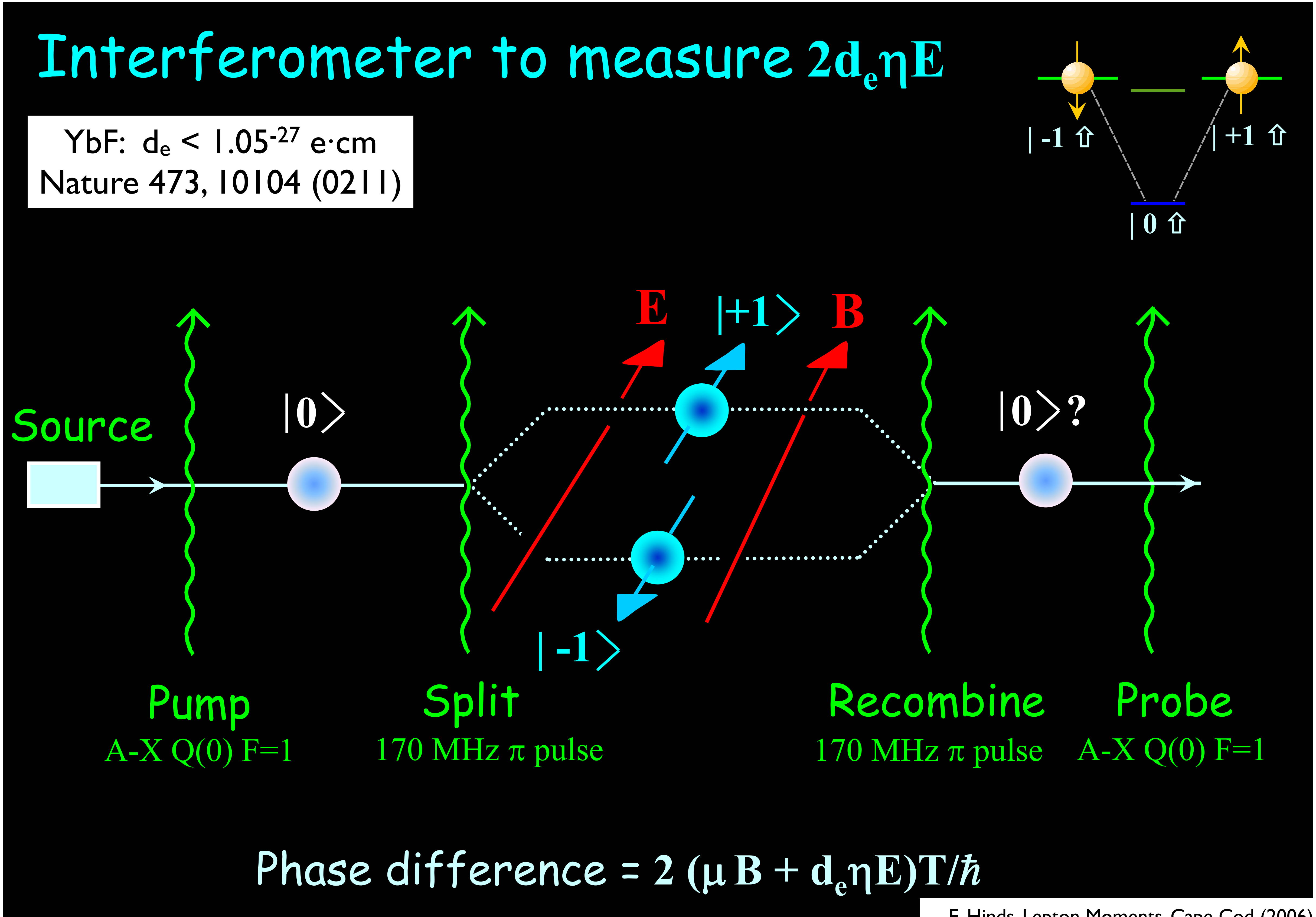
Neutrons, Atoms, Solids
Improved Magnetometry: SQUIDs, Co-Magnetometers

Ions
Storage Rings: Electric and Magnetic

Electron EDM (YbF)



Electron EDM (YbF)

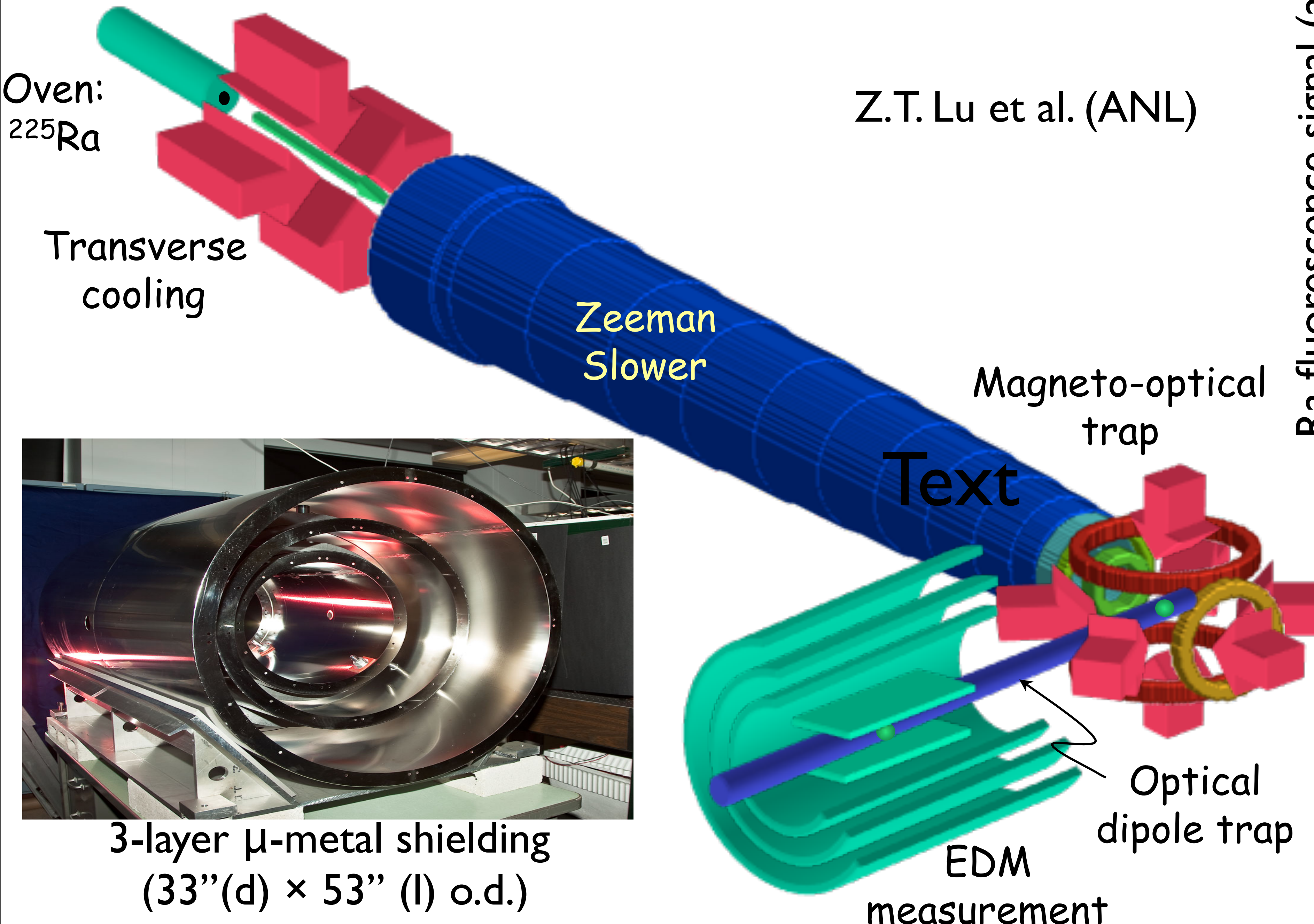


E. Hinds, Lepton Moments, Cape Cod (2006)

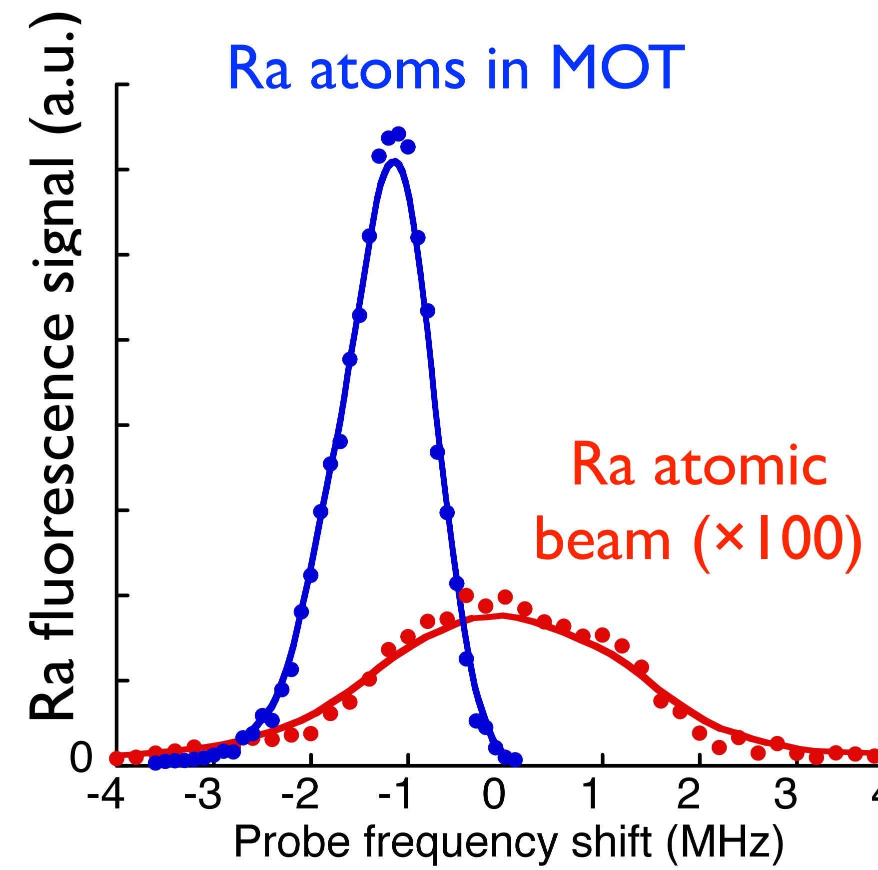
Atomic (Nuclear) EDM : ^{225}Ra

nuclear EDM: ^{225}Ra→ Schiff Moment enhancement: 200 - 1000

Z.T. Lu et al. (ANL)



3-layer μ-metal shielding
(33”(d) × 53” (l) o.d.)



Phase 1: d~10^{-26} e·cm, Phase II: d~10^{-29} e·cm

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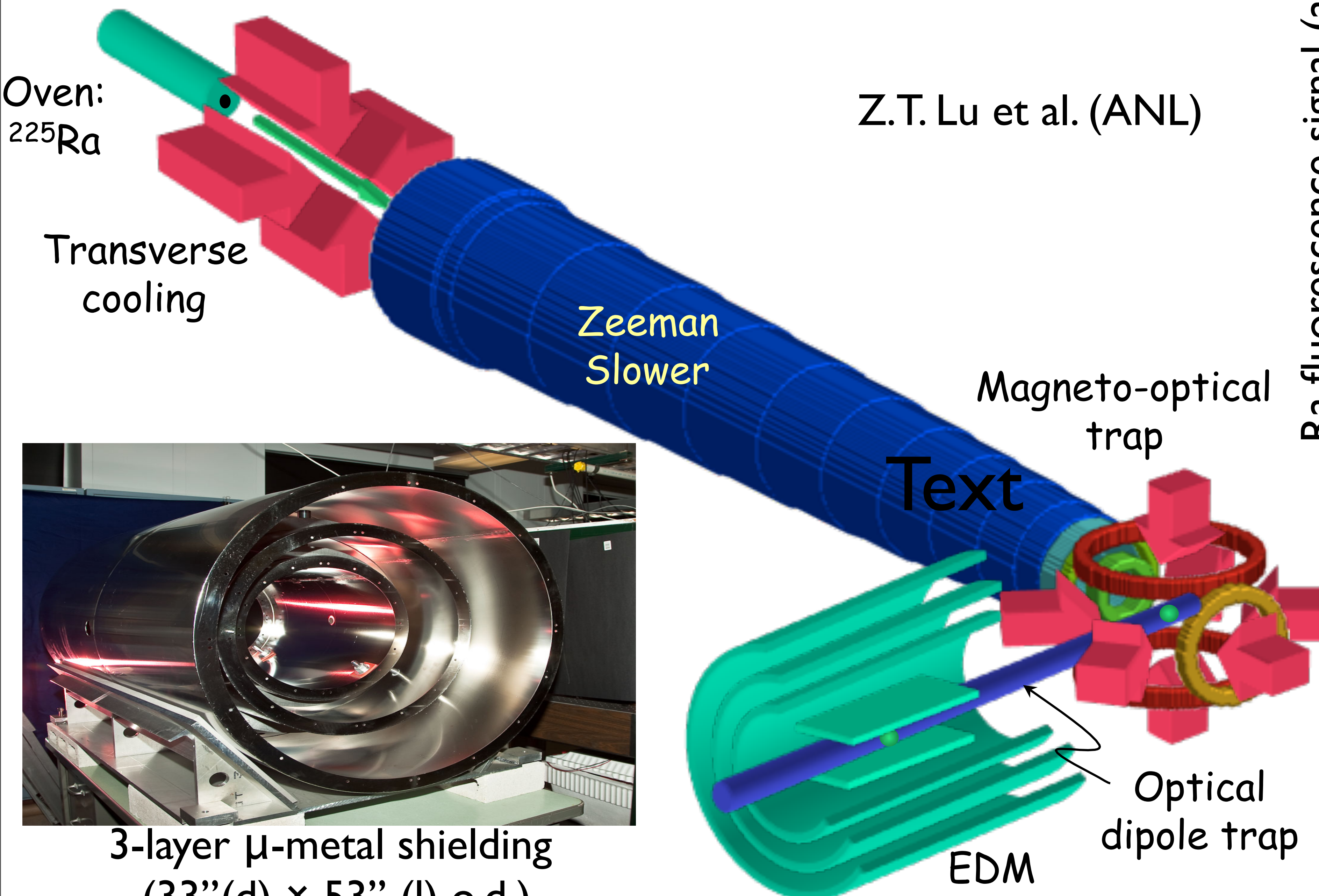

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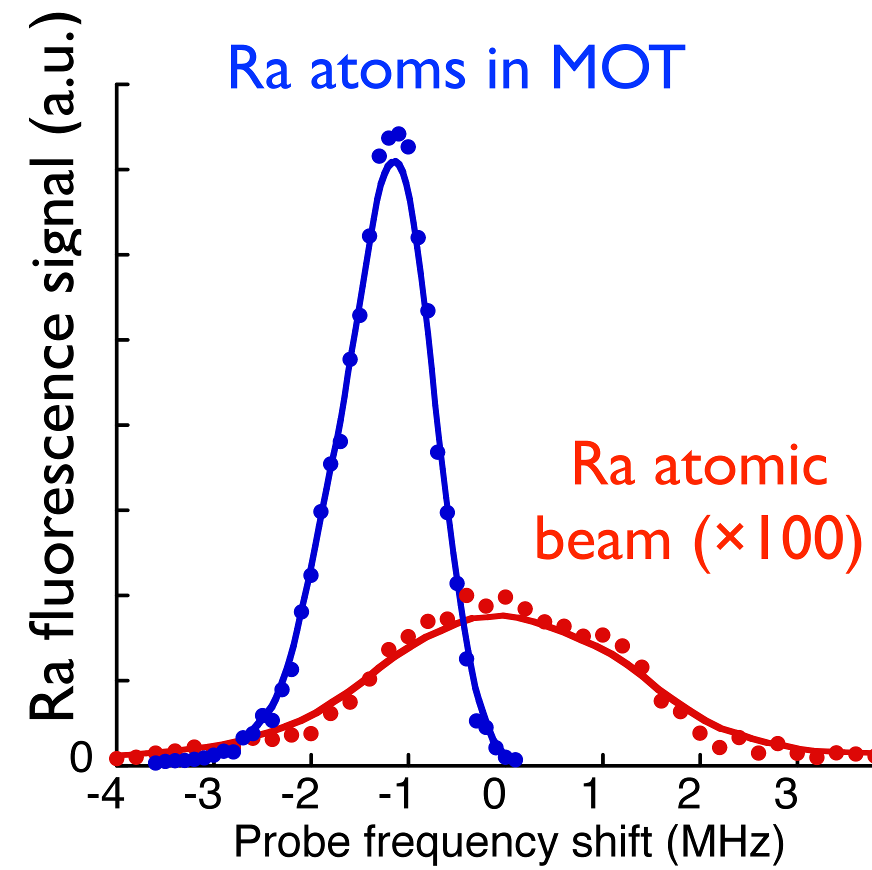
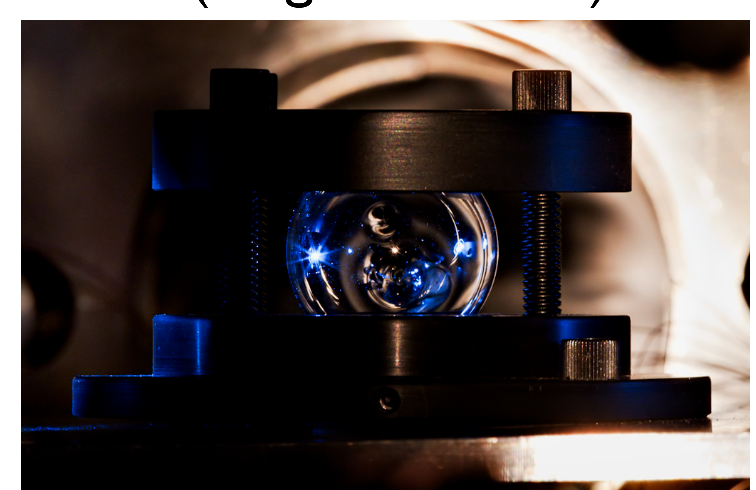


paraffin coated Rb cell
(magnetometer)

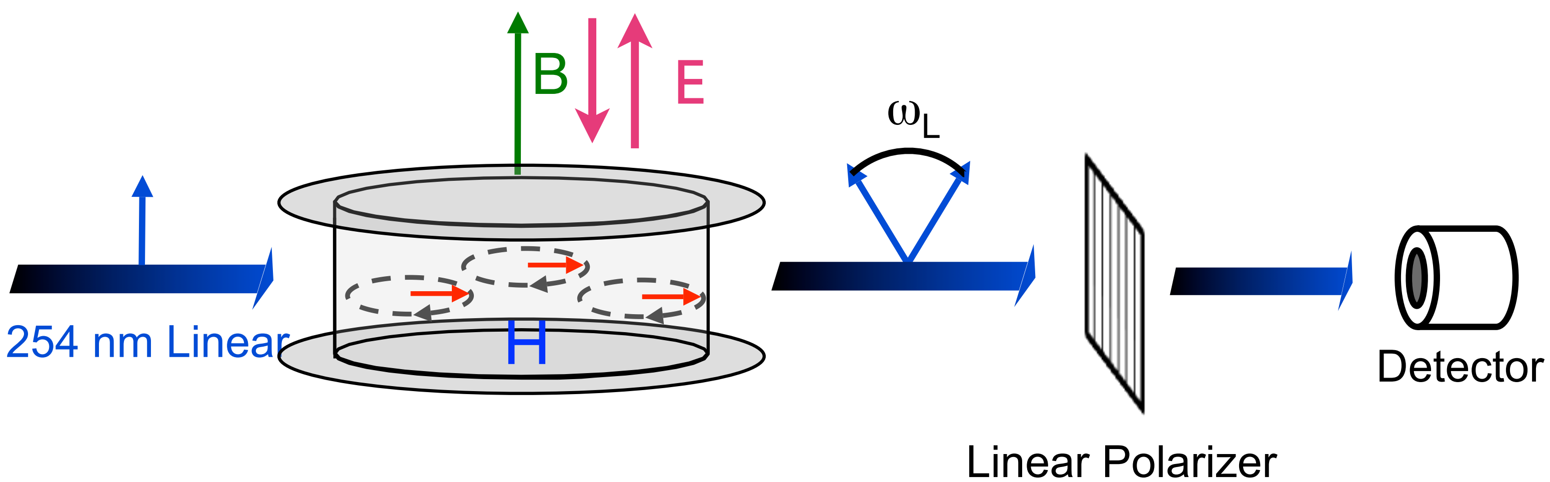


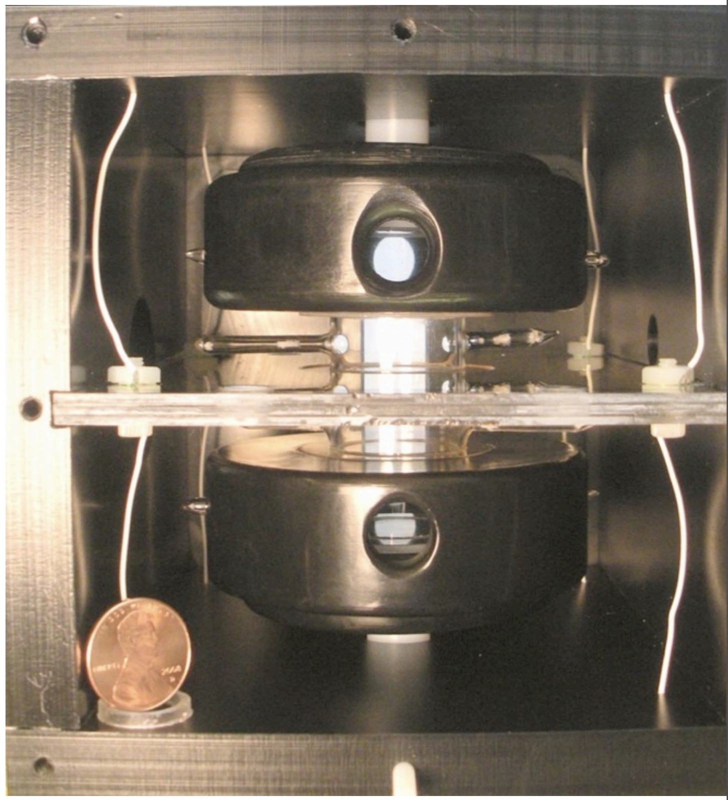
Phase 1: d~10^{-26} e·cm, Phase II: d~10^{-29} e·cm

Atomic (Nuclear) EDM: ^{199}Hg

University of Washington (Seattle): ^{199}Hg

Measure ω_L via Optical Rotation





➜ $|d_{199Hg}| < 3.1 \times 10^{-29}$ e cm (95% c.l)

W.C. Griffith et al., PRL 102, 101601 (2009)

$\delta(\Delta\nu_{EDM})$ = 0.85 nHz (stat.), ν_L = 16 Hz

Best absolute EDM measurement so far!!!

Atomic (Nuclear) EDM: ^{199}Hg

Limits on CP-odd parameters from ^{199}Hg

If EDM is dominated by:

Parameter	^{199}Hg bound	Hg theory	Best alternate limit
$\tilde{d}_q$ (cm) [a]	6×10^{-27}	[15]	n: 3×10^{-26} [3]
d_p (e cm)	7.9×10^{-25}	[16]	TlF: 6×10^{-23} [17]
C_S	5.2×10^{-8}	[18]	Tl: 2.4×10^{-7} [19]
C_P	5.1×10^{-7}	[18]	TlF: 3×10^{-4} [1]
C_T	1.5×10^{-9}	[18]	TlF: 4.5×10^{-7} [1]
$\bar{\theta}_{\mathrm{QCD}}$	3×10^{-10}	[20]	n: 1×10^{-10} [3]
d_n (e cm)	5.8×10^{-26}	[16]	n: 2.9×10^{-26} [3]
d_e (e cm)	3×10^{-27}	[21,22]	Tl: 1.6×10^{-27} [18]

[a] For ^{199}Hg, $\tilde{d}_q = (\tilde{d}_u - \tilde{d}_d)$, while for n, $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$.

One measurement!

W.C. Griffith et al., PRL 102, 101601 (2009)

Light Ion EDMs

Protons, deuterons, ... : charged particles in E-fields?

Polarized particles in storage rings:

In rest frame of particle: for $\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0$ spin motion relative to momentum is given by $\frac{d\vec{S}_{rf}}{dt_{rf}} = \vec{\Omega}\times\vec{S}_{rf}$

<u>*Thomas - BMT Equation:*</u>

$$\vec{\Omega} = -\frac{q}{m_0}\left\{G\vec{B} + \left(\frac{1}{\gamma^2-1} - G\right)\left(\frac{\vec{\beta}\times\vec{E}}{c}\right) + d\frac{m_0 c}{q\hbar CS}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right\}$$

$$G = \frac{g-2}{2}$$

→ use magnetic and/or electric storage rings

J. Pretz, SSP12, Groningen 2012

Light Ion EDMs

Storage ring options: Pure Electric Ring and $\left(\frac{1}{\gamma^2-1}-G\right)=0,$

works for G>0 only

$$\vec{\Omega}=-\frac{q}{m_0}\left\{G\vec{B}+\left(\frac{1}{\gamma^2-1}-G\right)\left(\frac{\vec{\beta}\times\vec{E}}{c}\right)+d\,\frac{m_0 c}{q\hbar CS}\left(\frac{\vec{E}}{c}+\vec{\beta}\times\vec{B}\right)\right\}$$

$$G=\frac{g-2}{2}$$

Brookhaven National Lab: → sensitivity: σ~ 10^{-29} e·cm/year

J. Pretz, SSP12, Groningen 2012

Light Ion EDMs

Storage ring options: Combined Electric and Magnetic Ring and

$$\left\{ G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G \right) \left(\frac{\vec{\beta} \times \vec{E}}{c} \right) \right\} = 0,$$

$$\vec{\Omega} = -\frac{q}{m_0} \left\{ G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G \right) \left(\frac{\vec{\beta} \times \vec{E}}{c} \right) + d \frac{m_0 c}{q\hbar C S} \left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right\}$$

$$G = \frac{g-2}{2}$$

COSY, Jülich: → sensitivity: σ~ 10^{-29} e·cm/year

J. Pretz, SSP12, Groningen 2012

Light Ion EDMs

Storage ring options: Pure Magnetic Ring

$$\vec{\Omega} = -\frac{q}{m_0}\left\{G\vec{B} + \left(\frac{1}{\gamma^2-1} - G\right)\left(\frac{\vec{\beta}\times\vec{E}}{c}\right) + d\,\frac{m_0 c}{q\hbar CS}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right\}$$

$$G = \frac{g-2}{2}$$

COSY, Jülich → sensitivity:

$\sigma \sim 10^{-24}$ e·cm/year

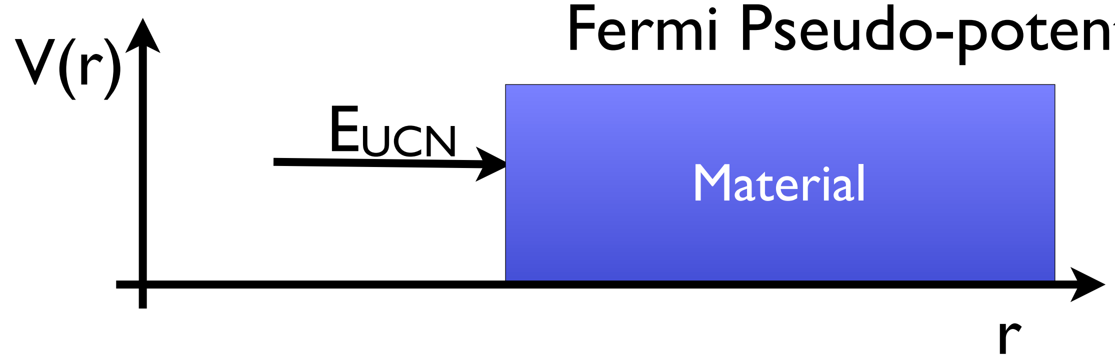
JEDI: systematic studies

J. Pretz, SSP12, Groningen 2012

Neutron EDM: Ultra Cold Neutrons

- $v_n \lesssim 10$ m/s
- $T_n \lesssim 4$ mK
- $\lambda_n \gtrsim 500$ Å
- $E_n \lesssim 300$ neV

Fermi Pseudo-potential:



Gravitational Interaction: $V_G = m_n \cdot g \cdot h \approx 103$ neV/m $\cdot h$

Magnetic Interaction: $V_M = -\mu_n \cdot B \approx \pm 60$ neV/T $\cdot$ B

Strong Interaction:

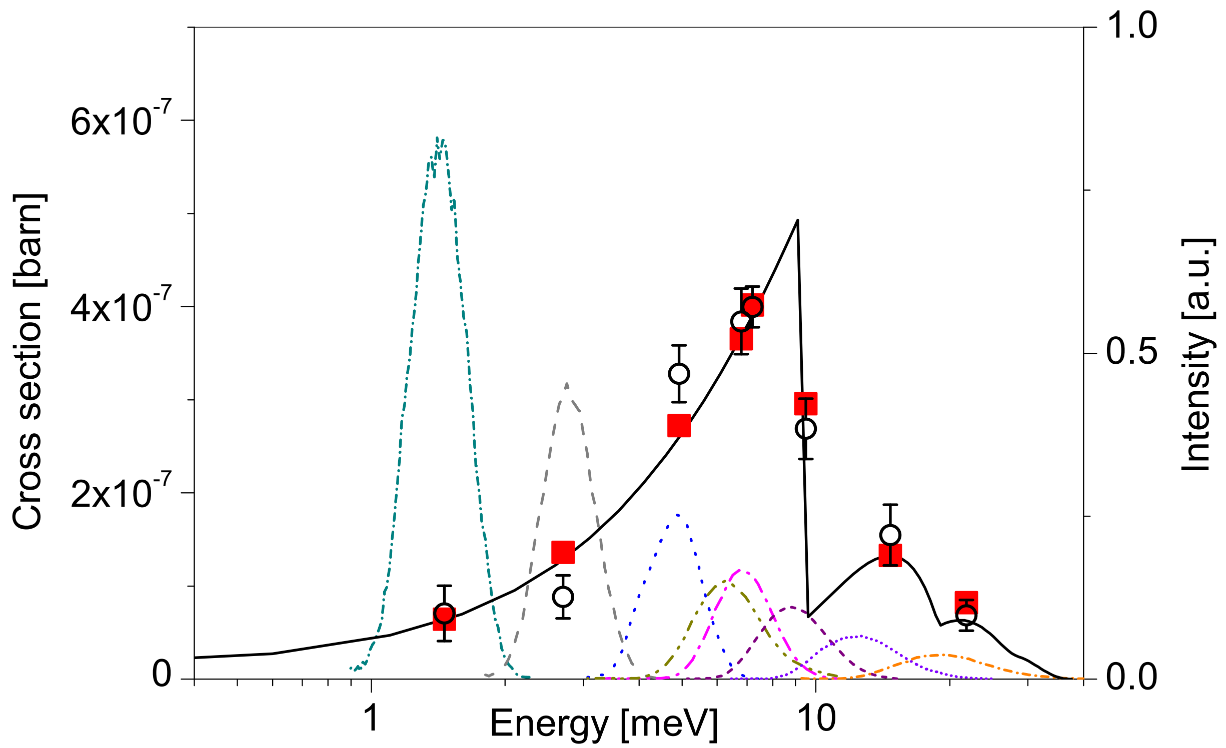
Material	V_F [neV]
Ni^{58}	335
BeO	261
Teflon	123
Al	54
H_2O	-14.7
Ti	-48

UCNs can be trapped gravitationally, in magnetic fields, or in boxes.

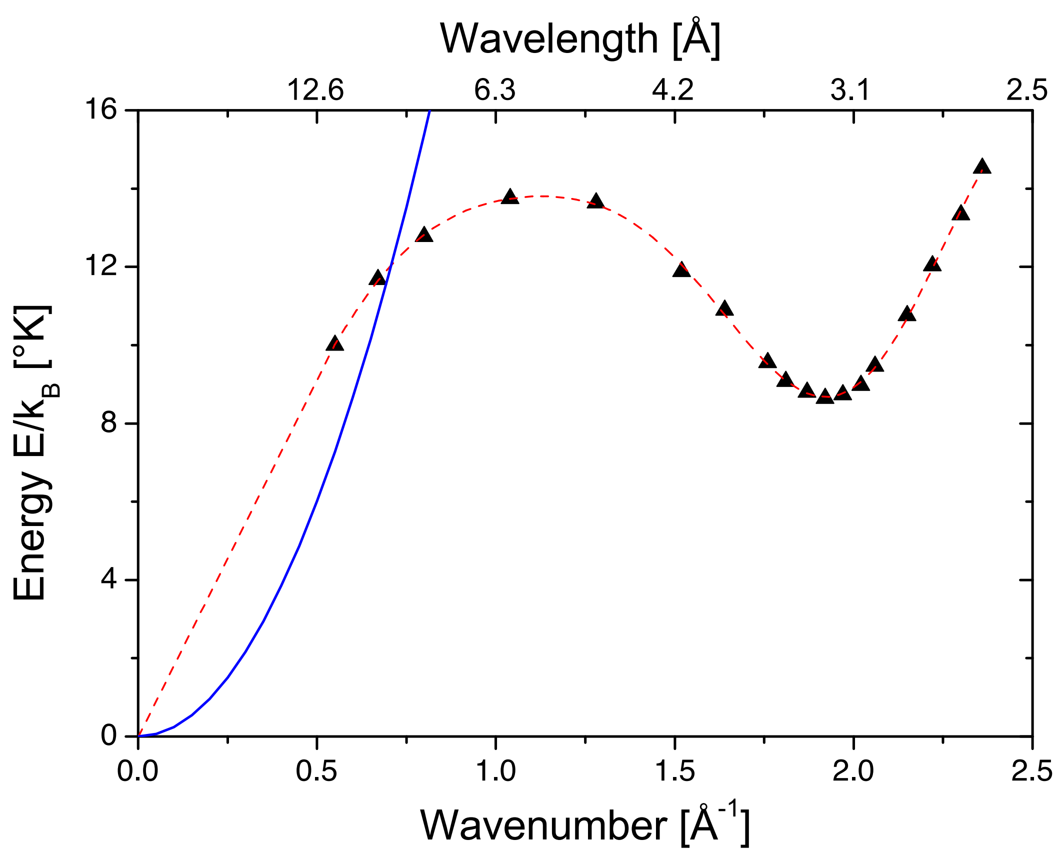
Neutron EDM: Ultra Cold Neutrons

Production of UCNs: Down-scatter cold neutrons via completely inelastic collisions in solid-D_2 or superfluid ^{4}He (one or multi-phonon excitation) ☛ "superthermal process"

R. Golub and J.M. Pendlebury; Phys. Lett. **53A,** (1975), Phys. Lett. **62A** (1977)



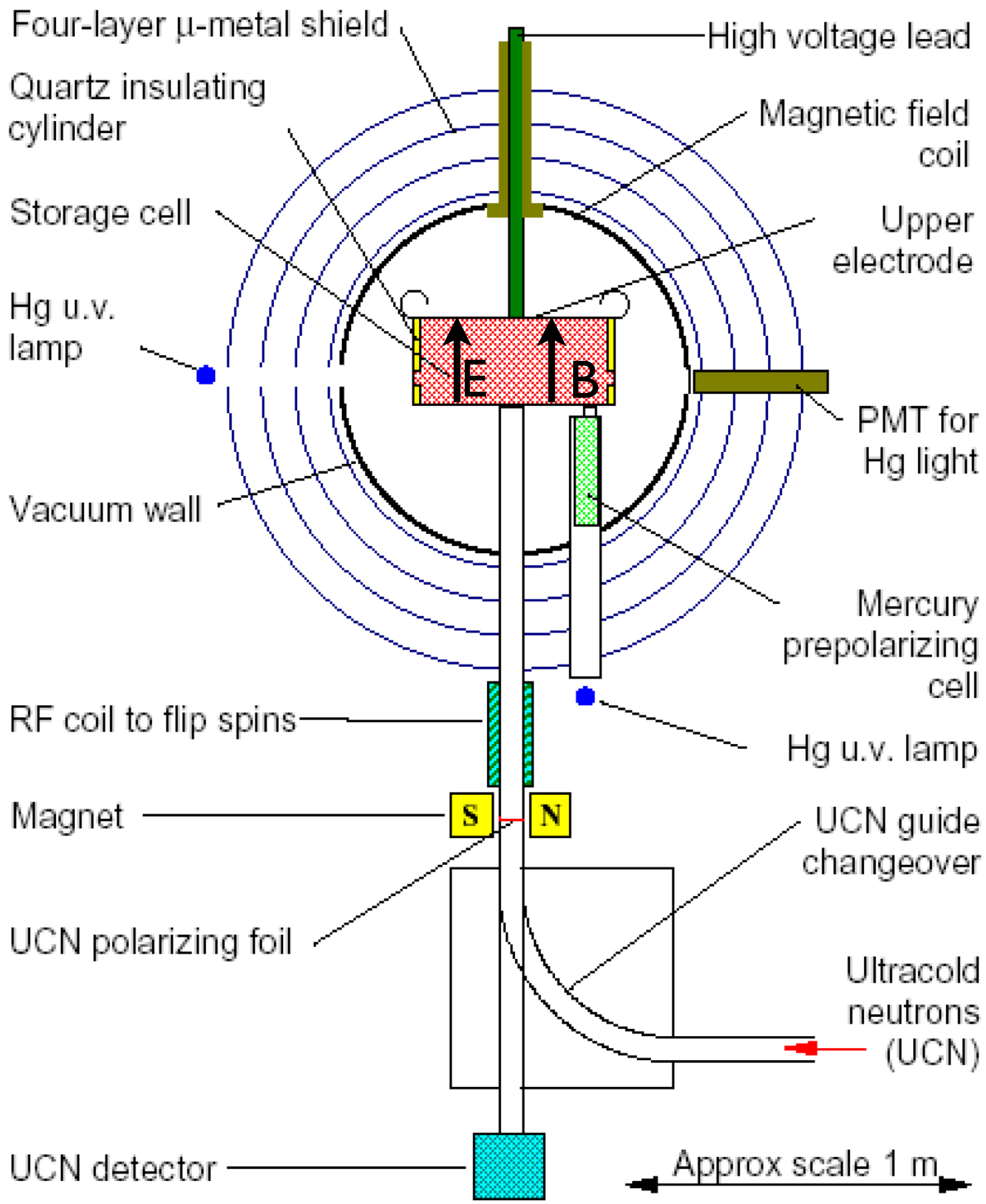
UCN production from solid-D_2



Figures: A. Knecht (2009)

UCN production from superfluid ^{4}He

Neutron EDM: Best Limit

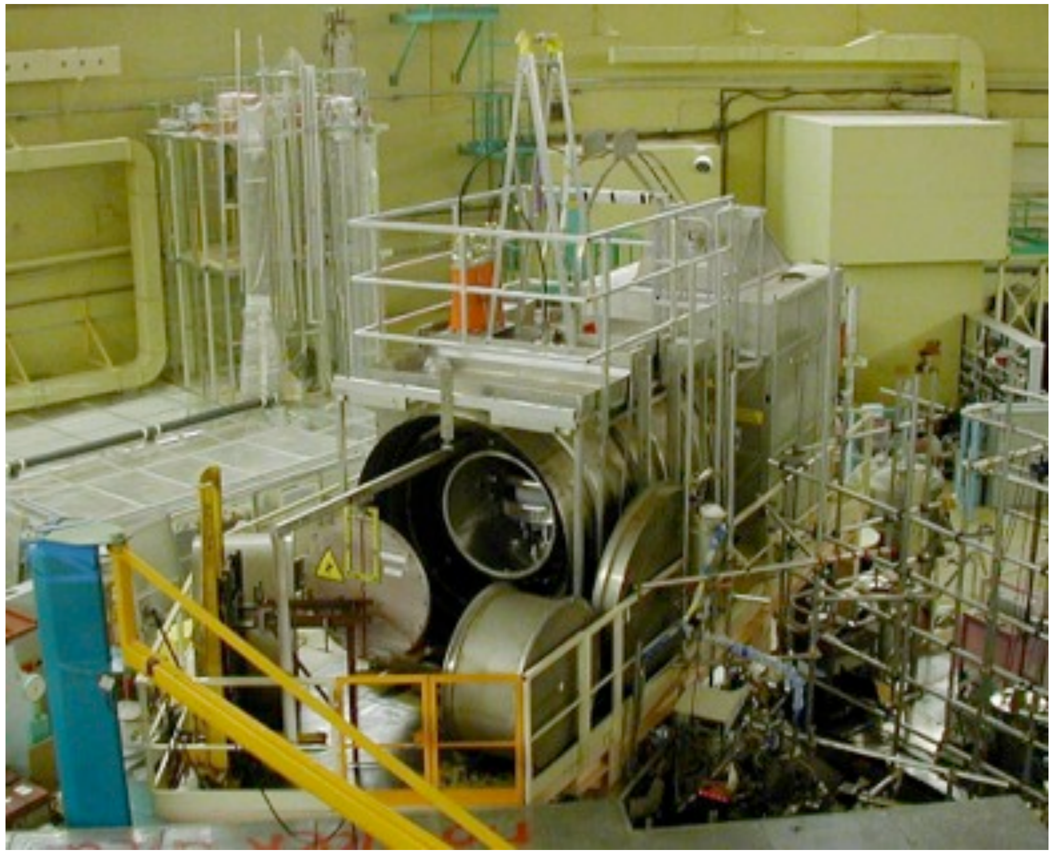


Ultra-cold Neutrons (UCN) in a storage cell (at T ~ 300 K): ρ_{UCN} ~ 1/cm^3

- V_{cell} = 21 liters
- T_m = 130 s (per cycle)
- N ≈ 1.4 × 10^4 (per cycle)
- E_0 = 10^4 V/cm

$|d_n| < 2.9\times10^{-26}$ e·cm (90% C.L.)

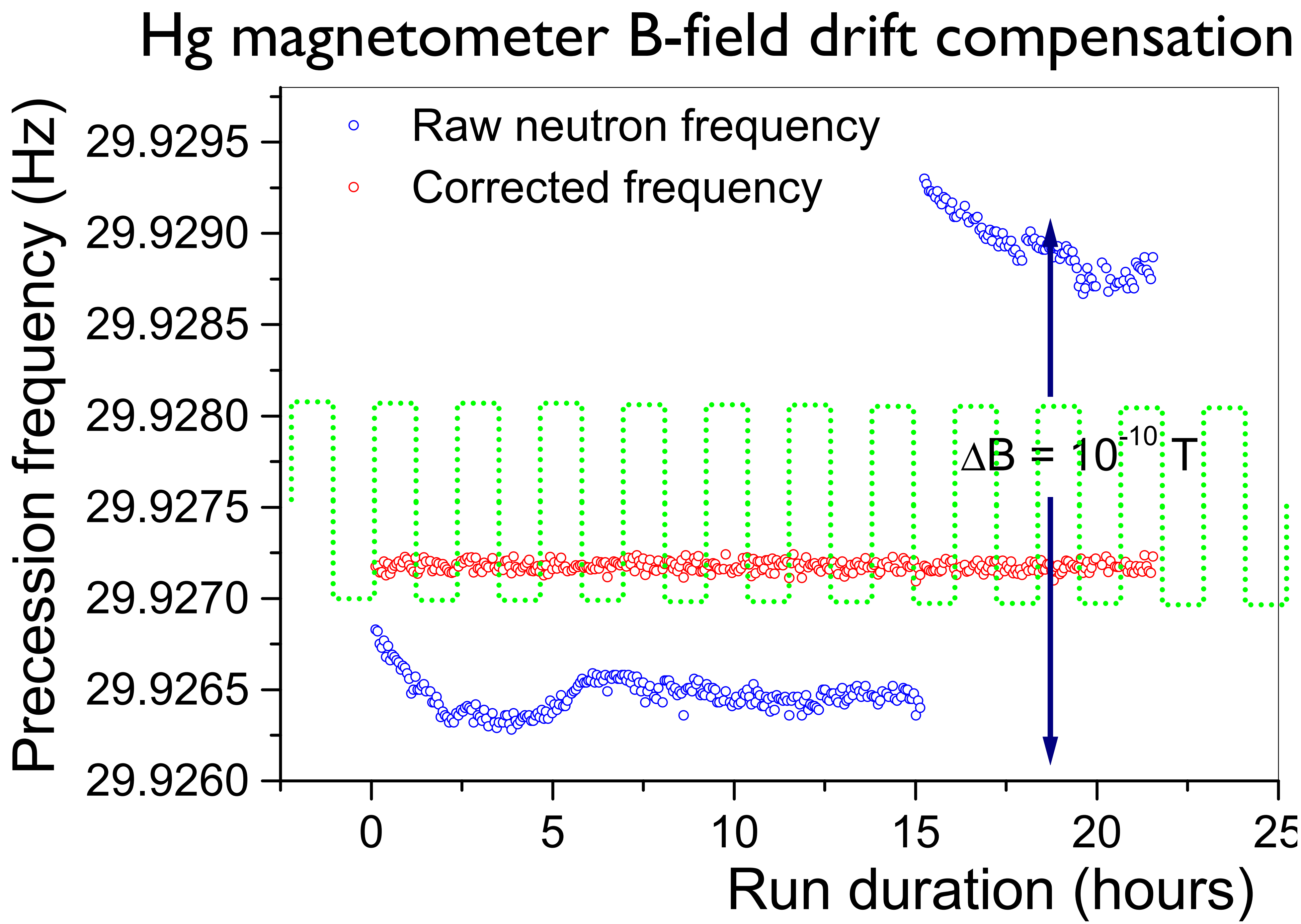
C.A. Baker et al., PRL 97, 131801 (2006)



Institut Laue-Langevin (Grenoble)

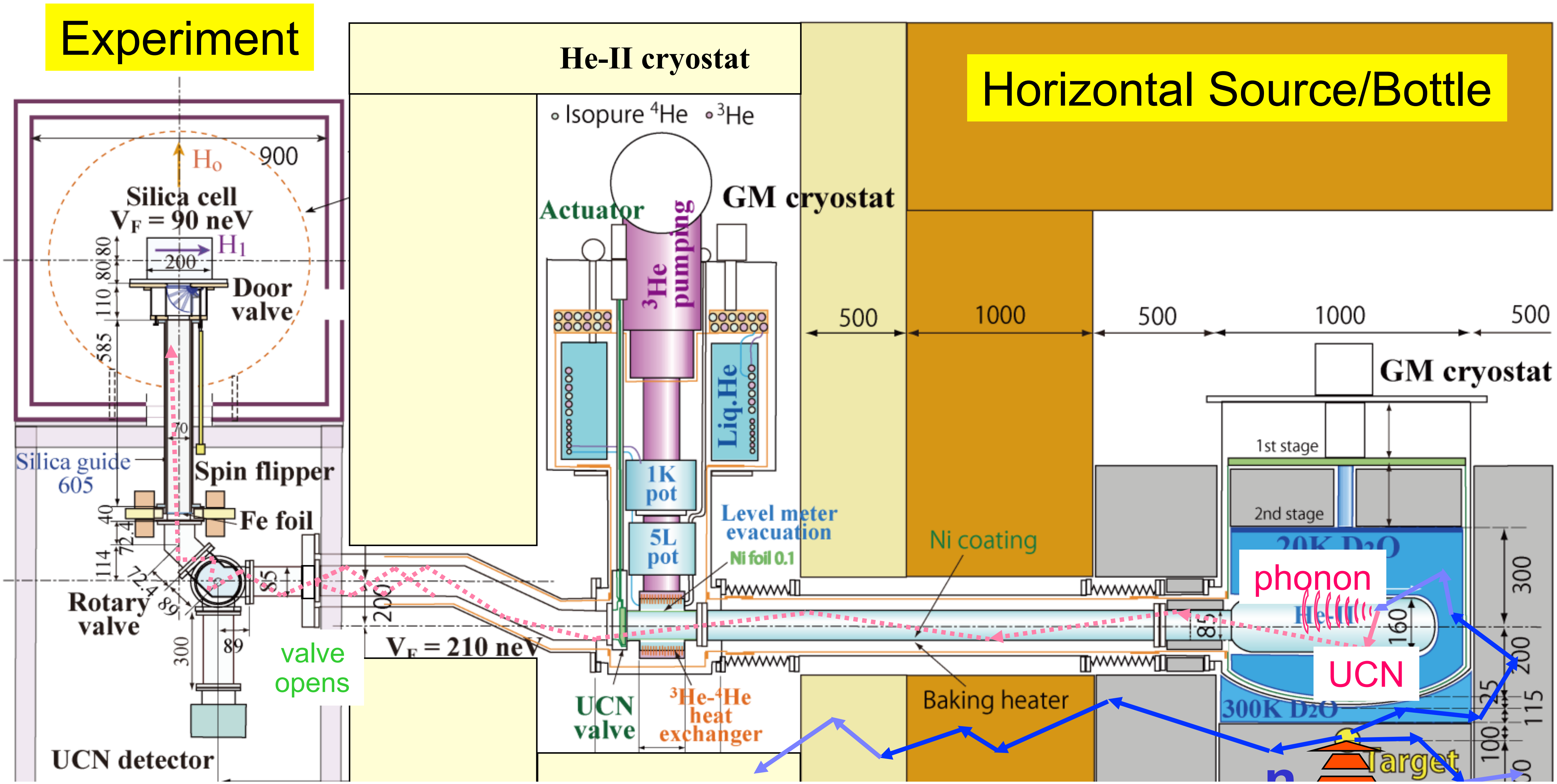
Neutron EDM: Co-Magnetometer

ILL experiment:



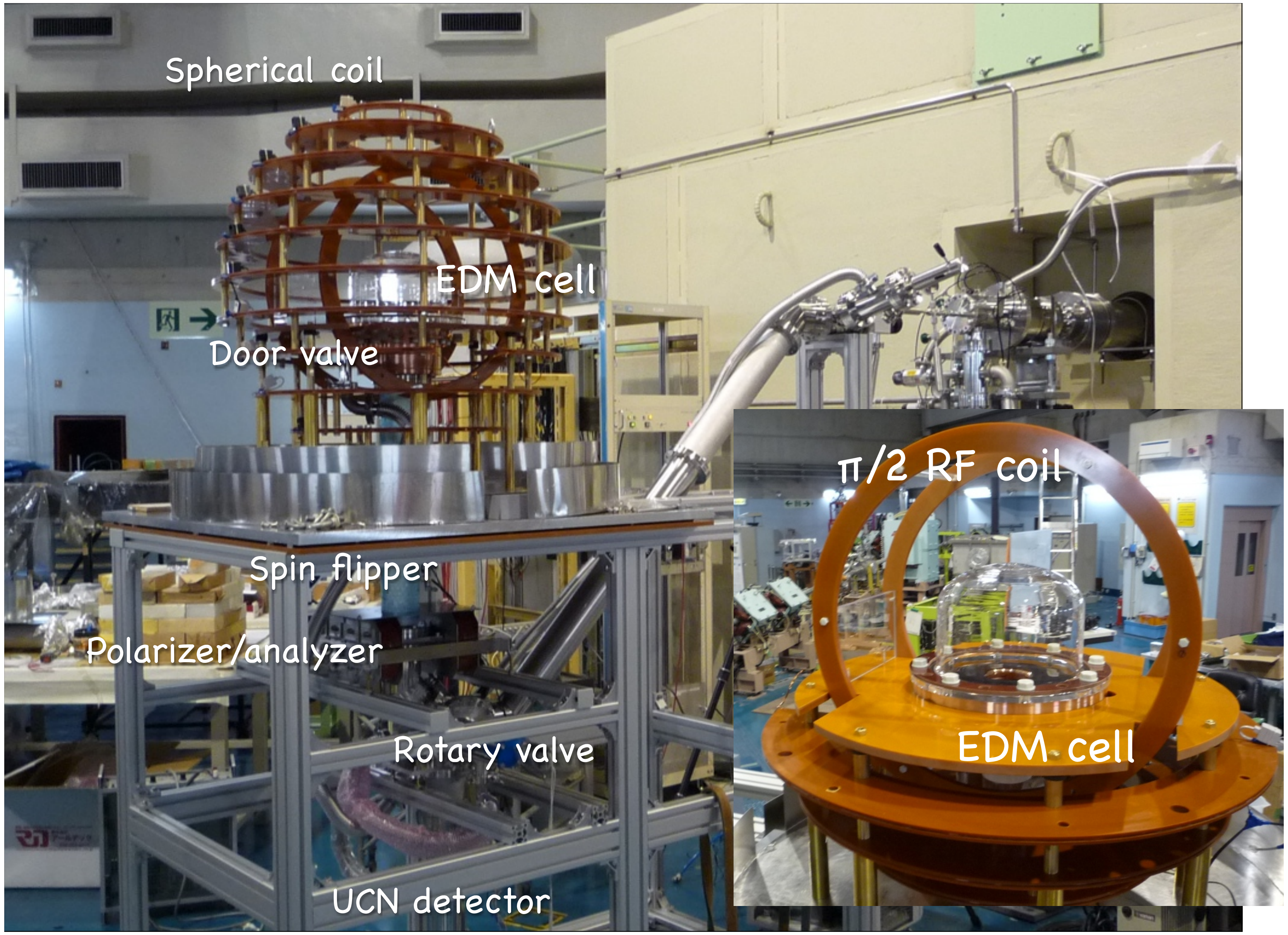
C.A. Baker et al., PRL 97, 131801 (2006)

Neutron EDM (TRIUMF)



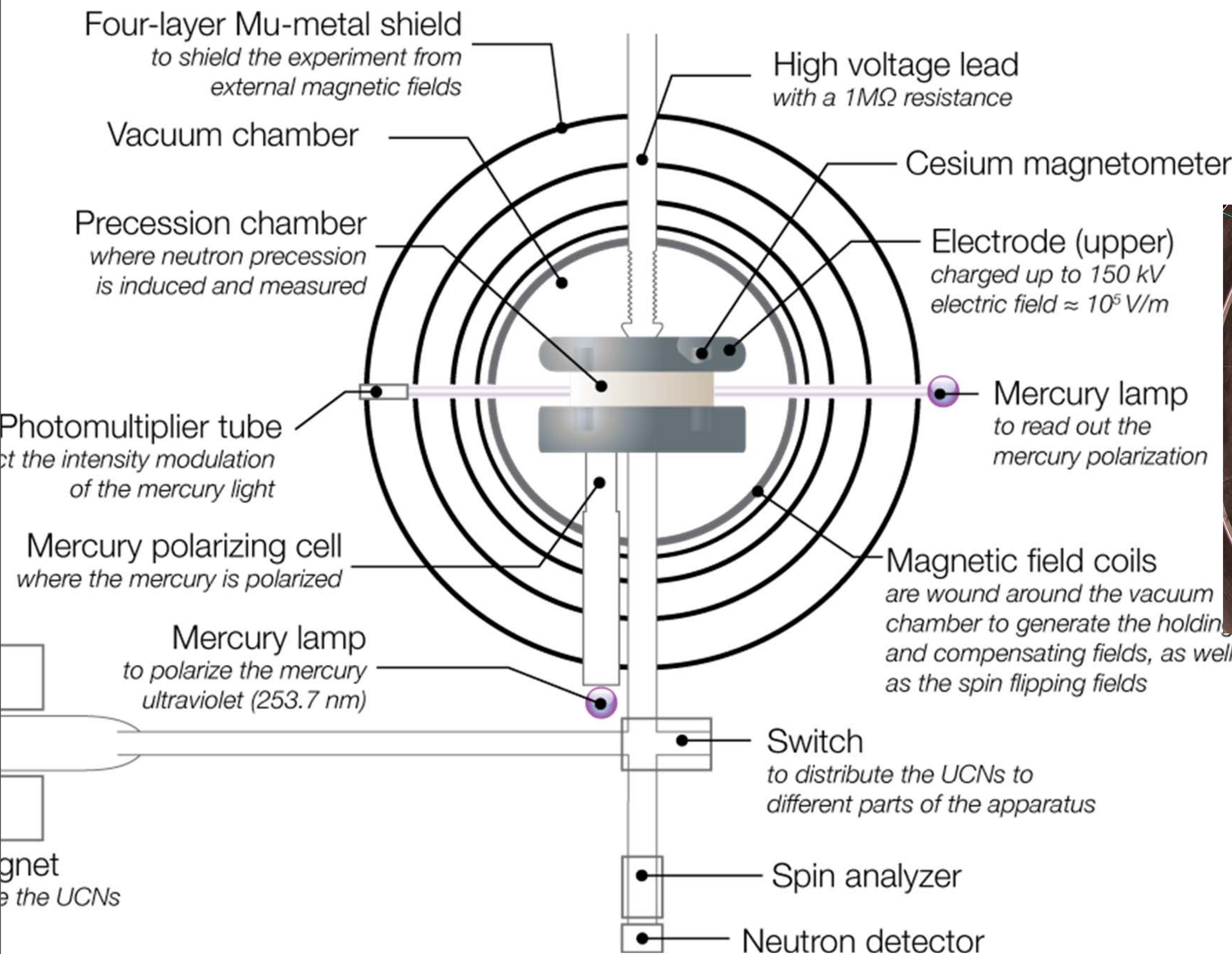
Neutron EDM (TRIUMF)

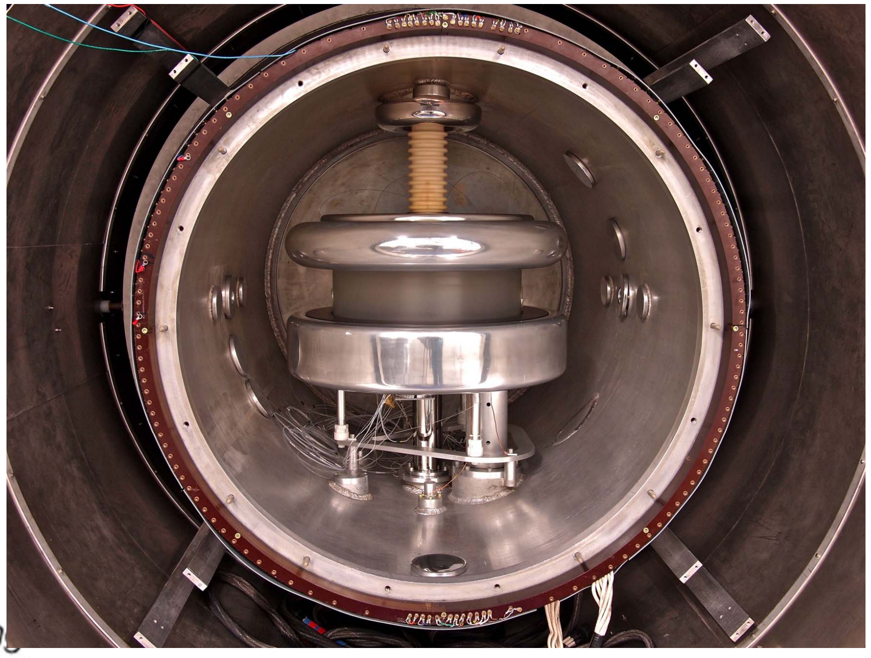
- Spherical Coil for DC field
- ^{129}Xe nuclear spin buffer gas co-magnetometer
- Room-temperature experiment
- Small cell size
- Modern magnetic shielding
- Superfluid-^{4}He UCN source
- Basic source in operation



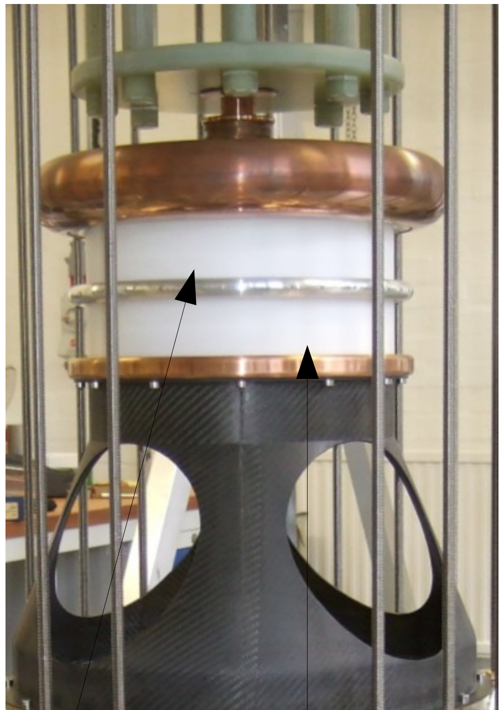
Larry Lee, TRIUMF, University of Manitoba (2011)

Neutron EDM (PSI)

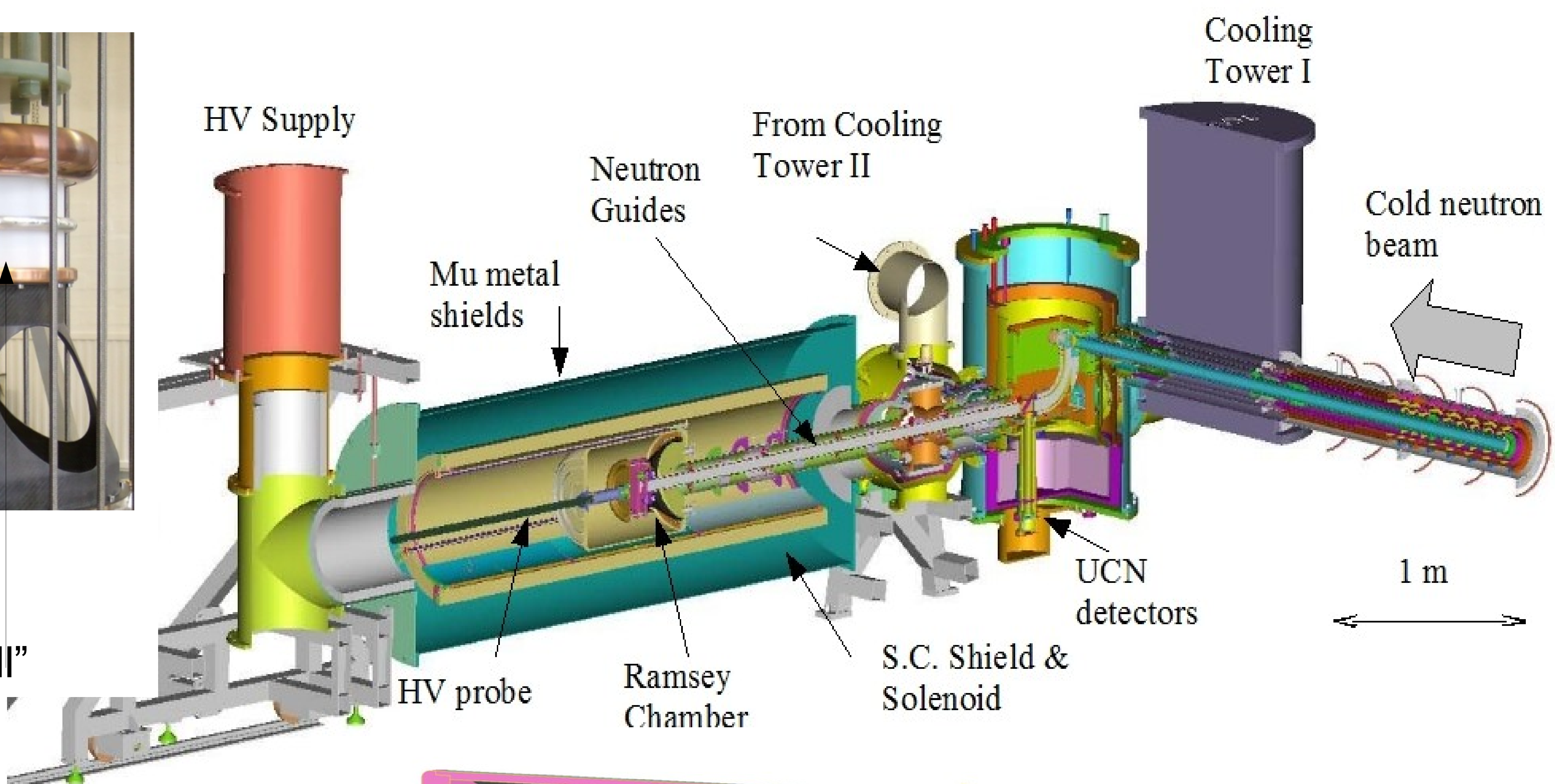


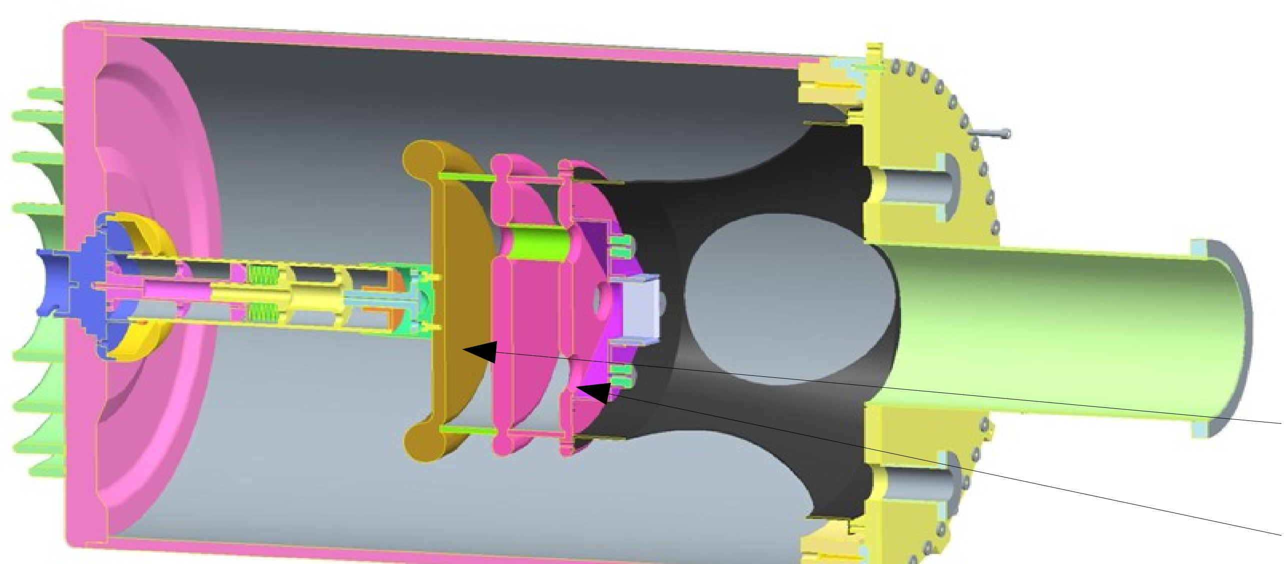


Neutron EDM (CryoEDM-ILL)



“HV Cell”
“neutral cell”

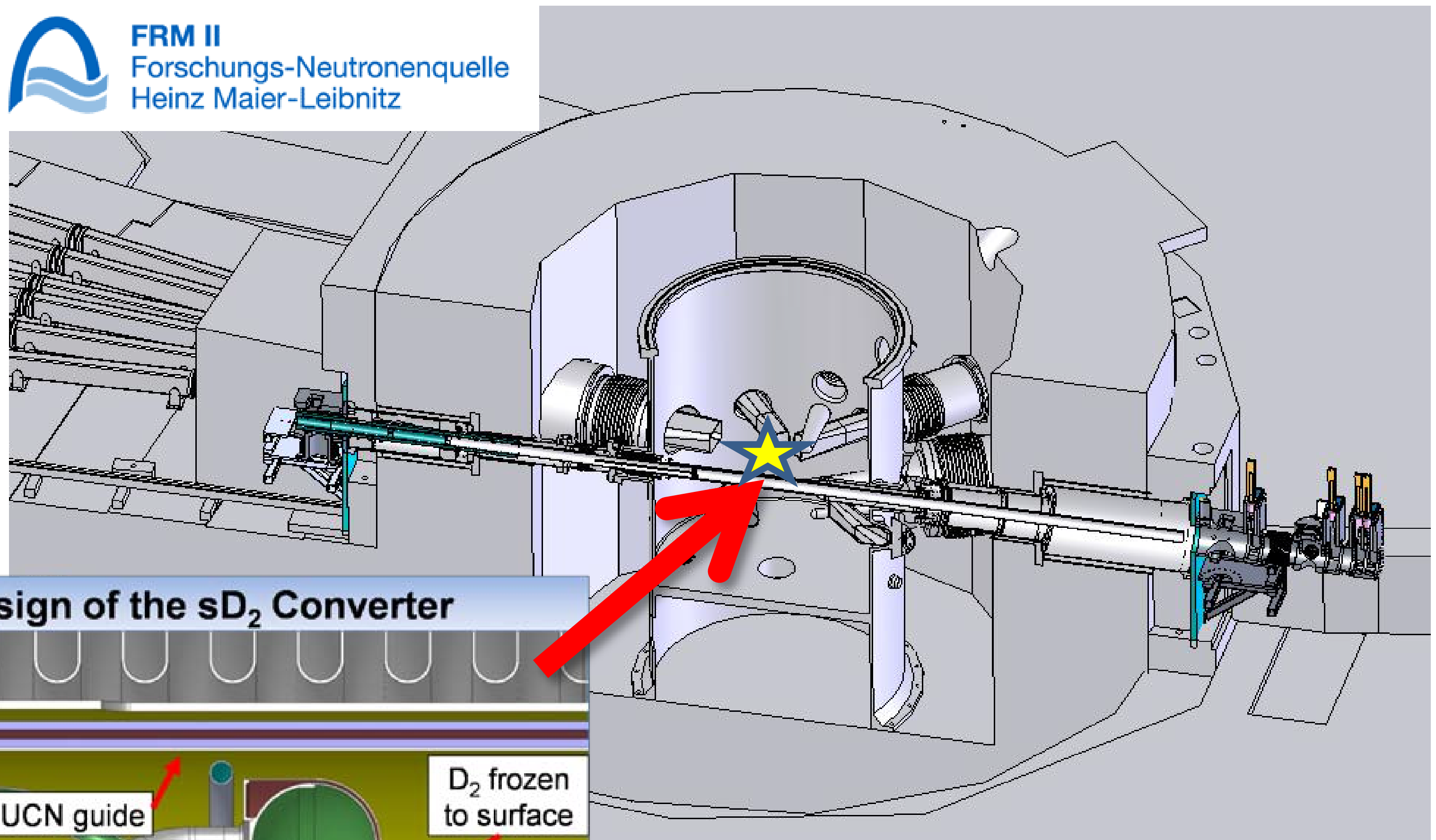


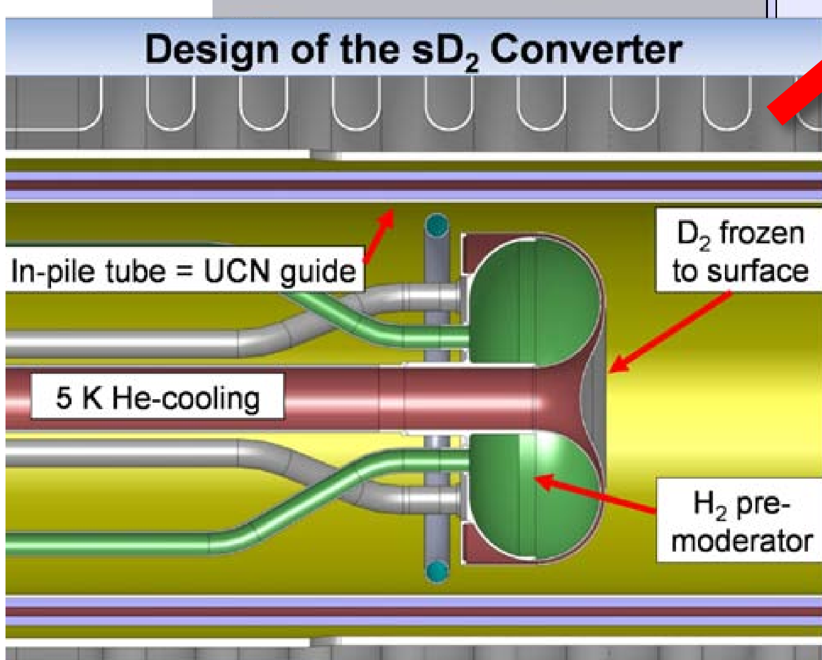


Neutron EDM (Munich,FRM-2)

E.g. superthermal solid D_2, at the FRM-2 reactor, TU München

Molceular excitations used to cool neutrons to zero energy -
similar: LANL, Mainz, NCSU, PNPI, PSI,





~10^{15} n/s on source

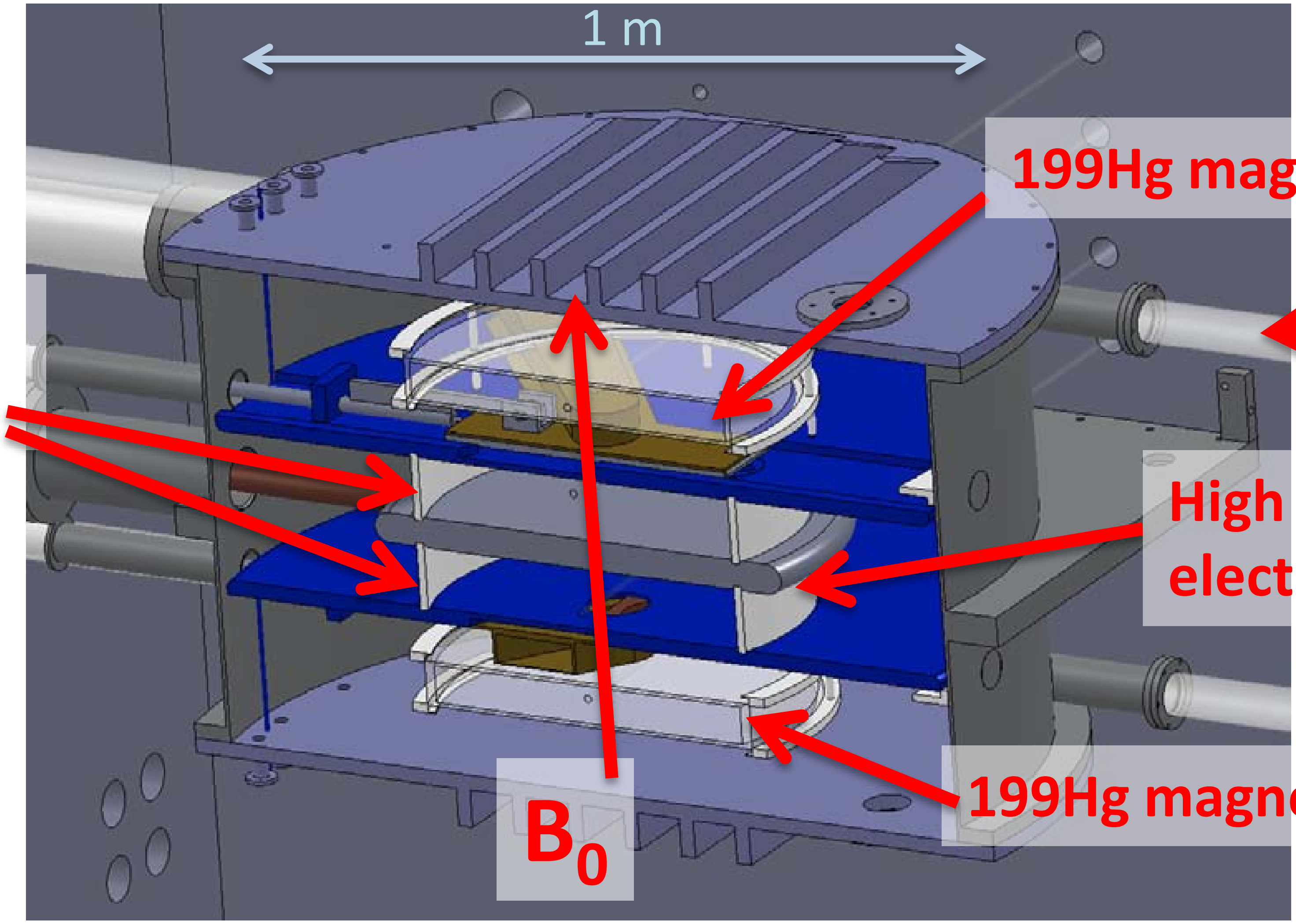
Goal: 10^3 UCN/cm^3 in the experiment (2013)

Other sources use superfluid He-II (via phonons): ILL, KEK, SNS, TRIUMF(?),

P. Fierlinger, SSP2012

Neutron EDM (Munich, FRM-2)

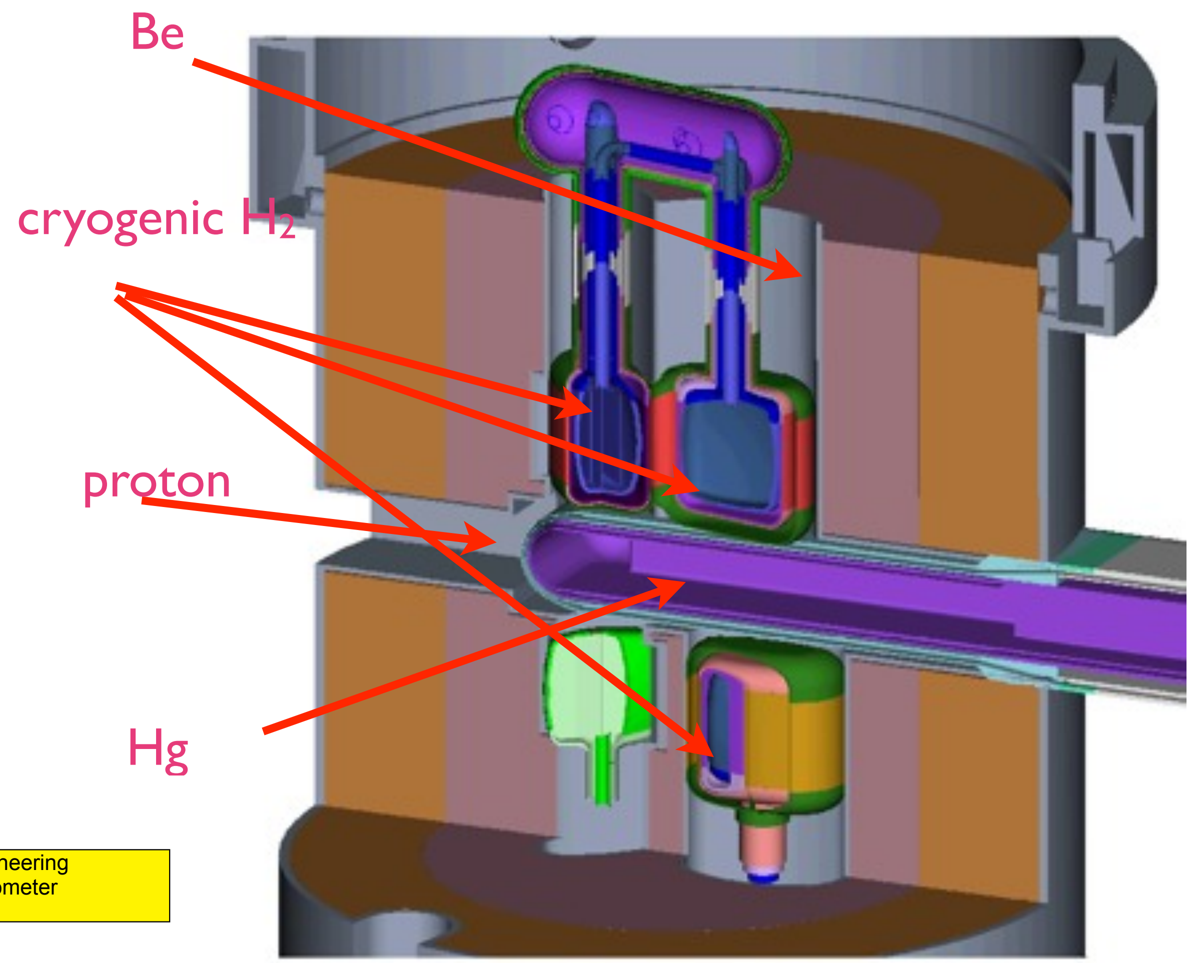
Double chamber Ramsey experiment with UCN stored at room temperature

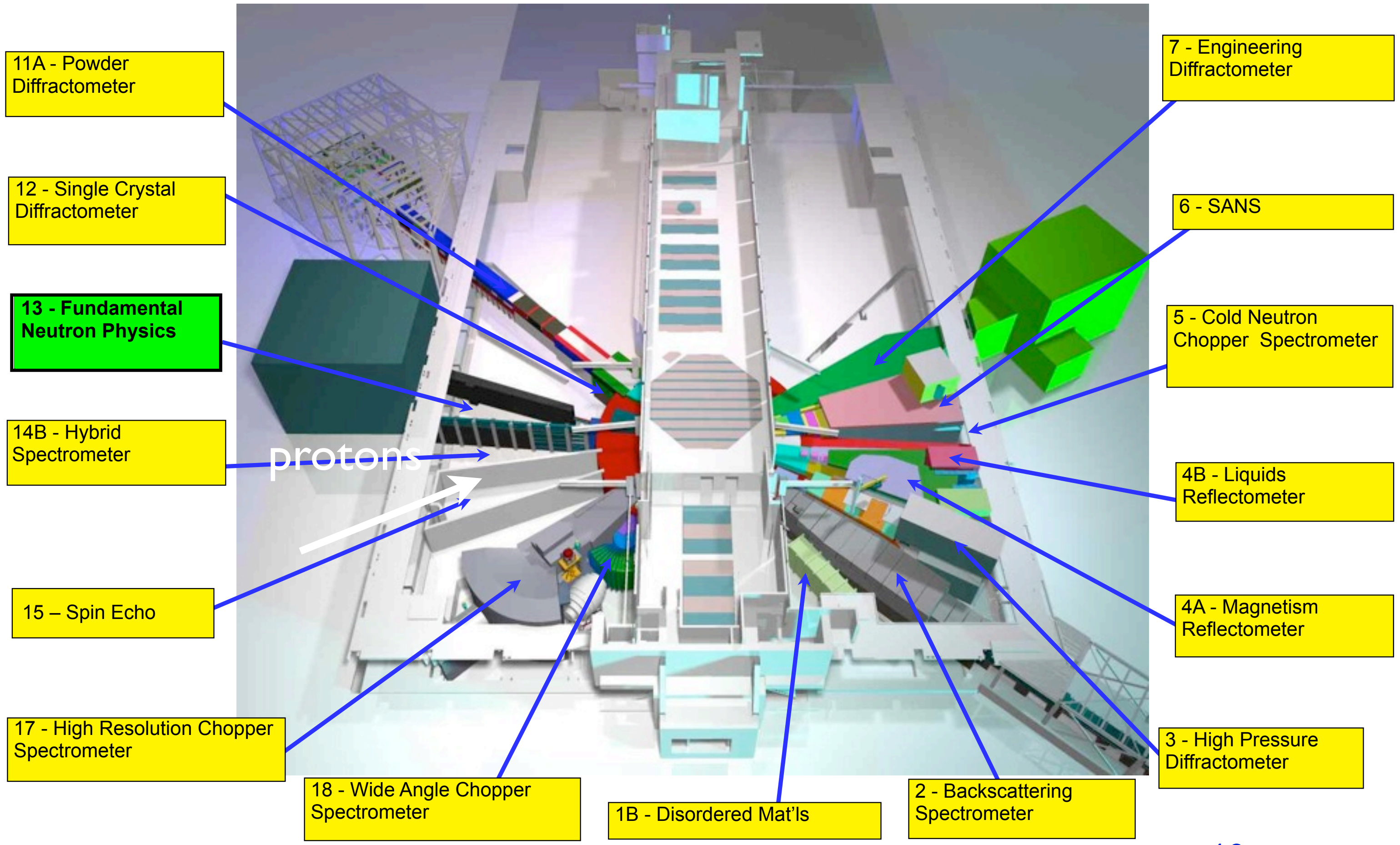


Limit of the concept: $d_n < 5 \cdot 10^{-28}$ ecm (3σ), stat. + syst.

P. Fierlinger, SSP2012

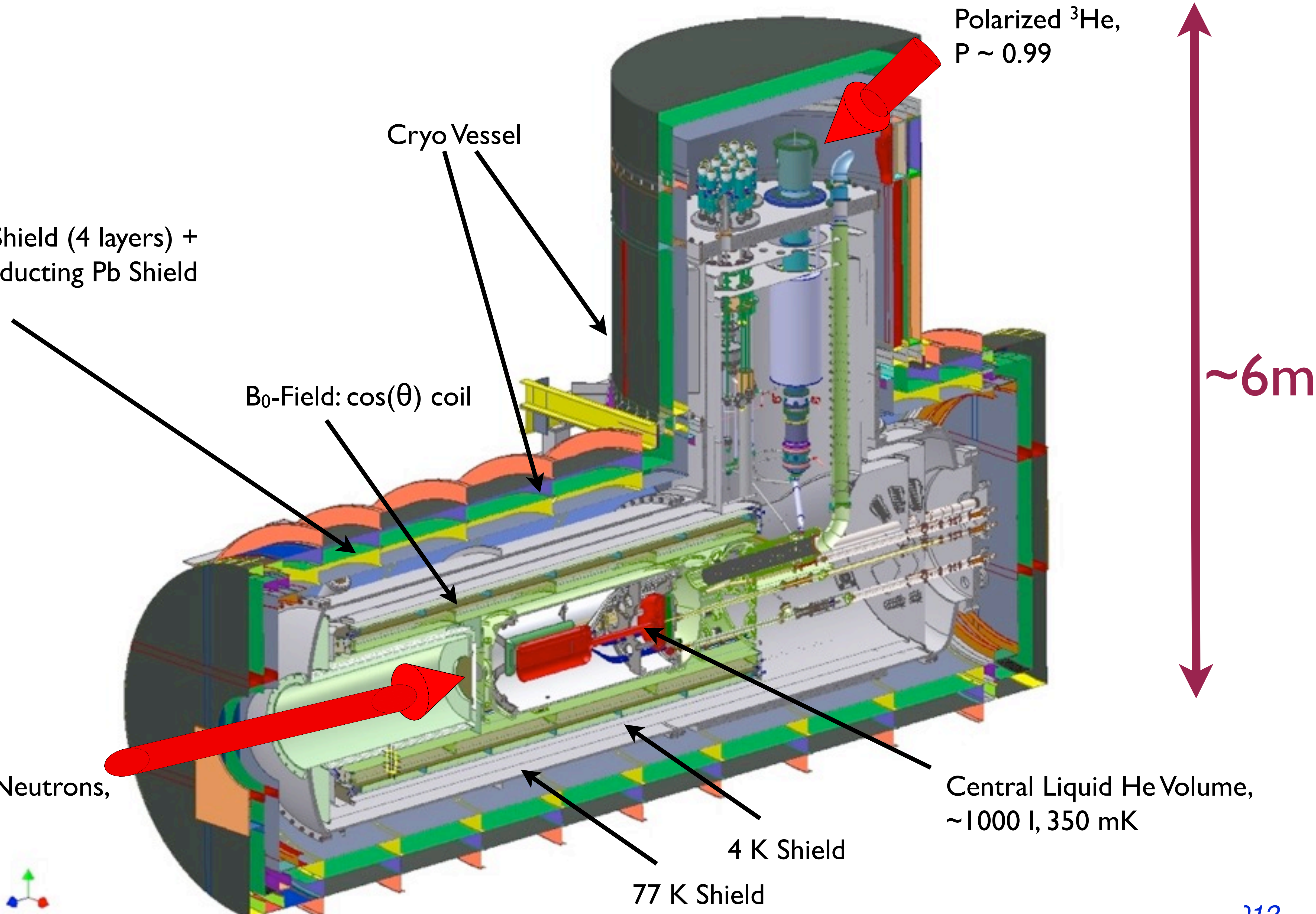
Neutron EDM: SNS





- ORNL Spallation-Neutron-Source: 1 GeV protons, I_p = 1.4 mA on Hg target, 18 beam lines
- First SNS beam on target - April 2006
- P = 1.4 MW
- Final peak neutron flux: 20-100 × ILL

Neutron EDM: SNS



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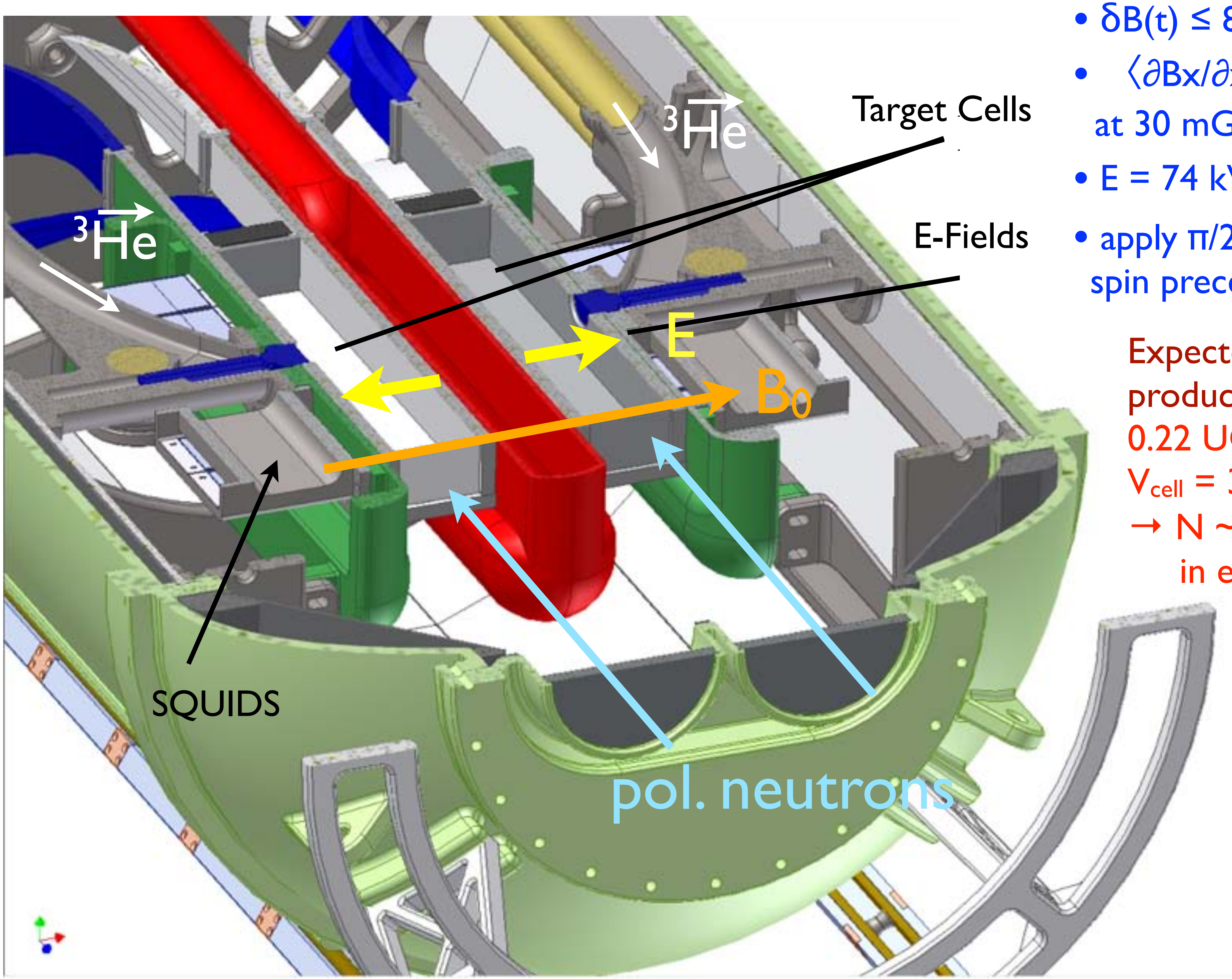
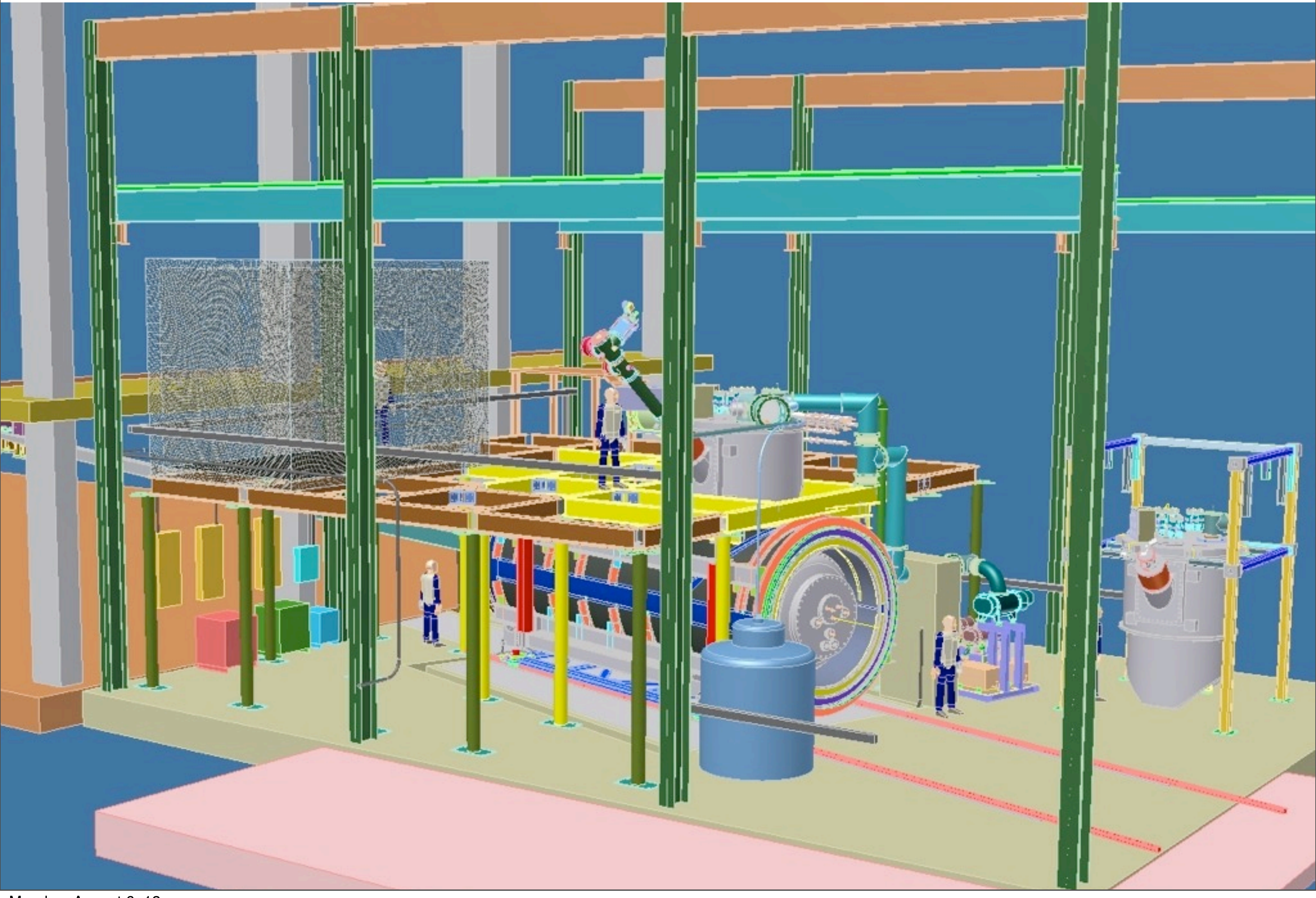


- $\delta B(t) \leq 8$ nG per cycle
- $\langle \partial B_x/\partial x \rangle < 50$ nGauss/cm at 30 mGauss
- E = 74 kV/cm
- apply $\pi/2$ pulse → monitor spin precession

Expected UCN production rate:
0.22 UCN/cm^3/s
V_{cell} = 3,000 cm^3 (each)
→ N ~ 3.8×10^5 at t=0 in each cell

Neutron EDM: SNS



Neutron EDM: SNS

Dominating nuclear reaction: n + $^3He^{++} \rightarrow$ p + t +764 keV

➜ detect scintillation light in LHe ($^4He_2^*$)

n-3He spin-dependent cross section [b]

	v=2200 m/	v= 5 m/s
J=0	~1.1 x 10^4	~4.8 x 10^6
J=1	~0	~0

- modulation of scintillation light: ~0.3 Hz/mG
- spin dressing ($\omega_n = \omega_{3He}$)

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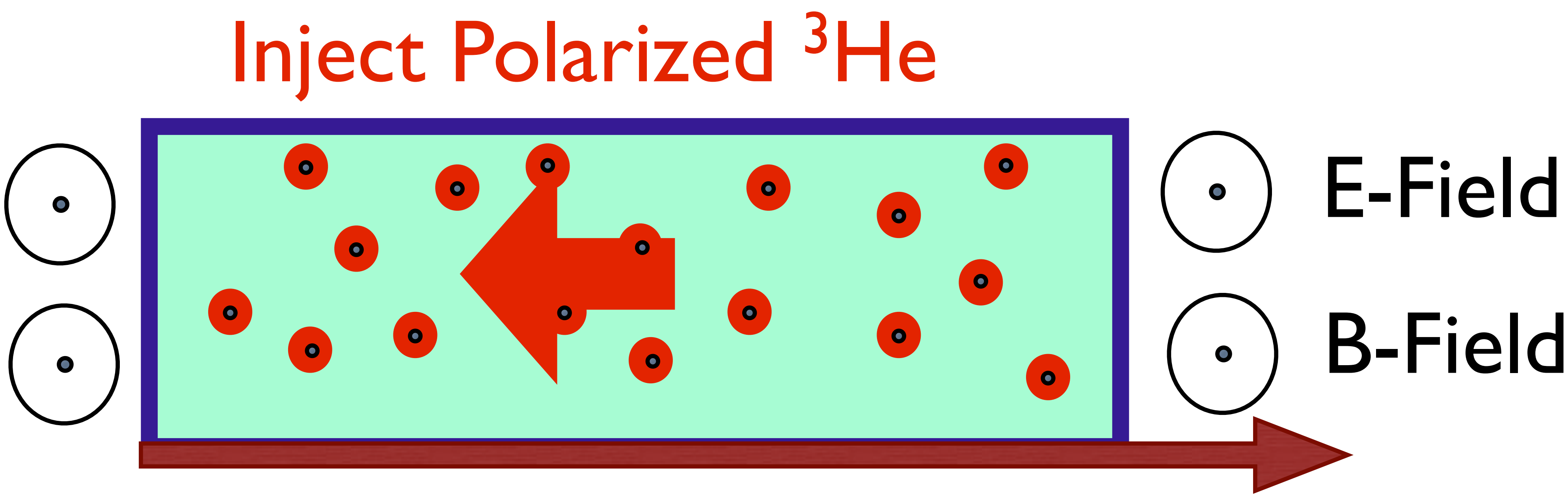

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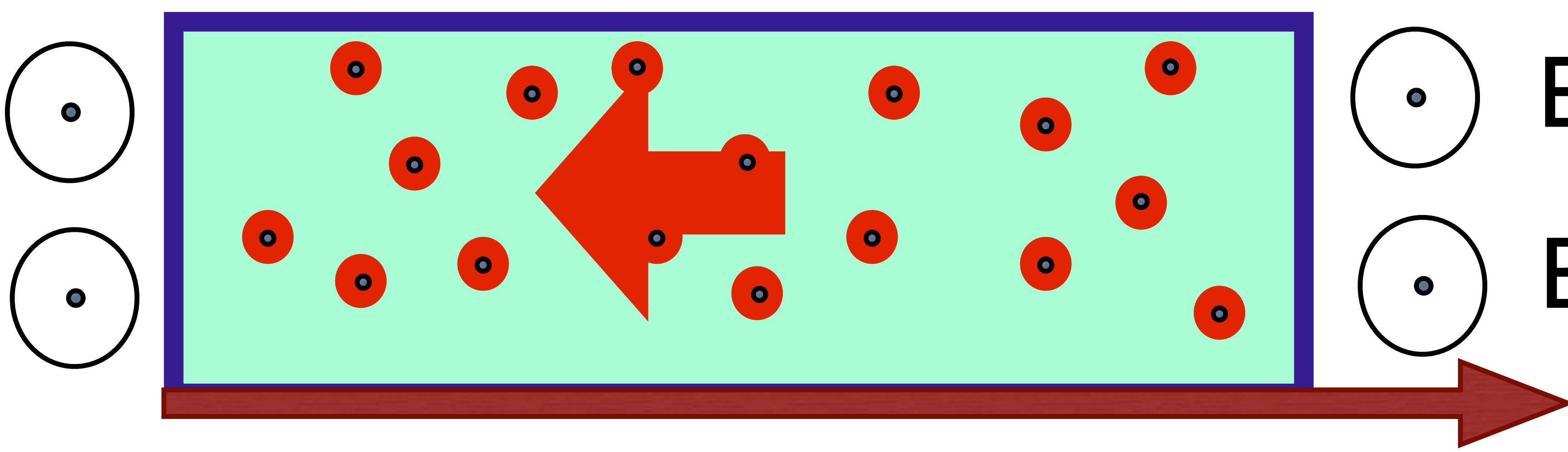

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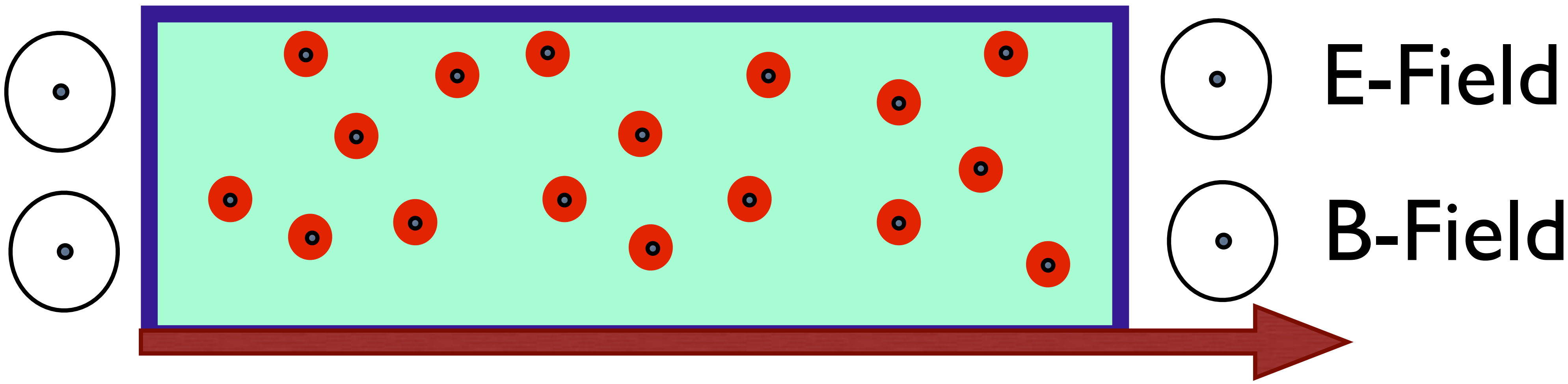

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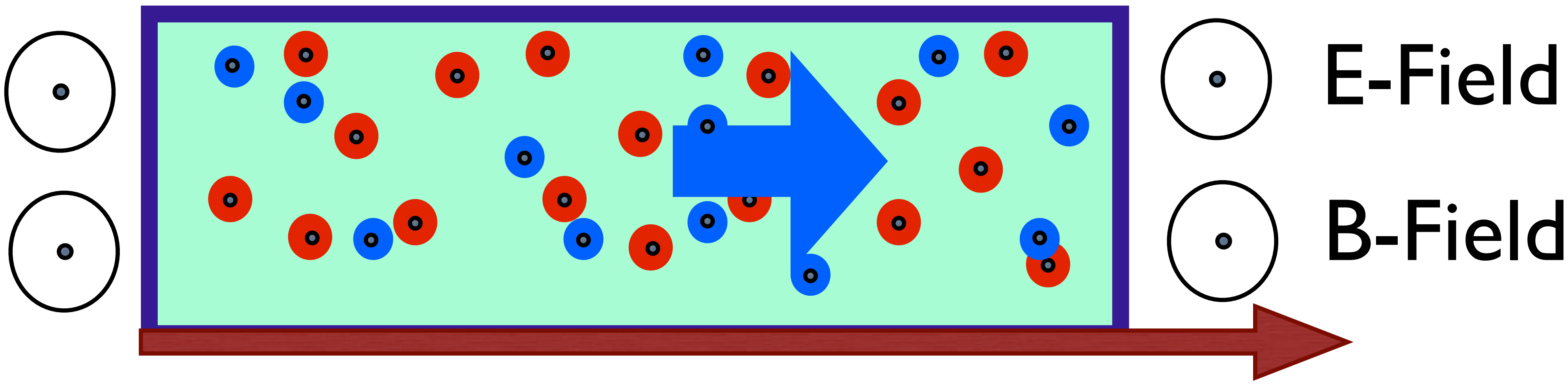
Inject Pol. Neutrons → UCNs



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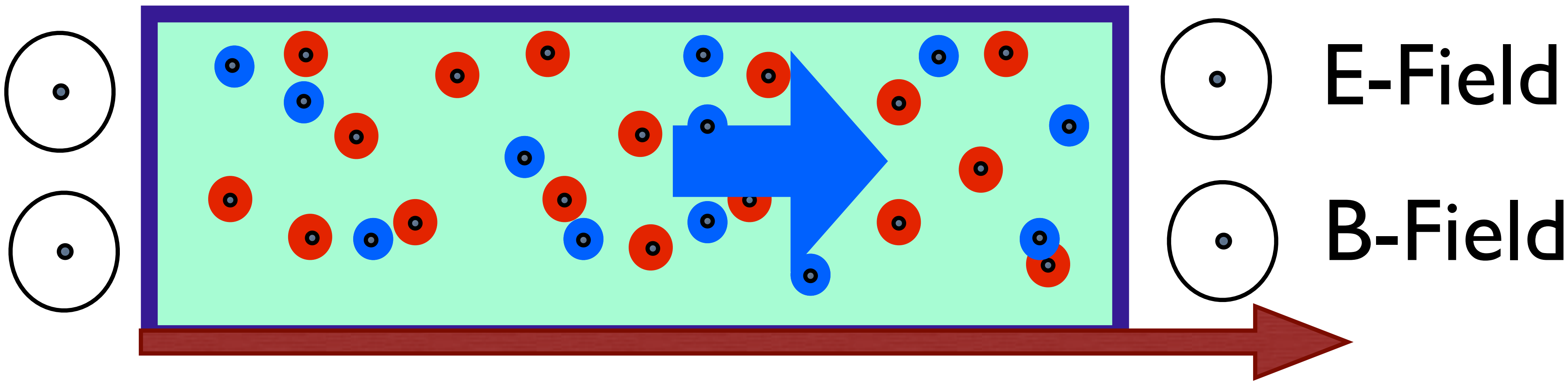

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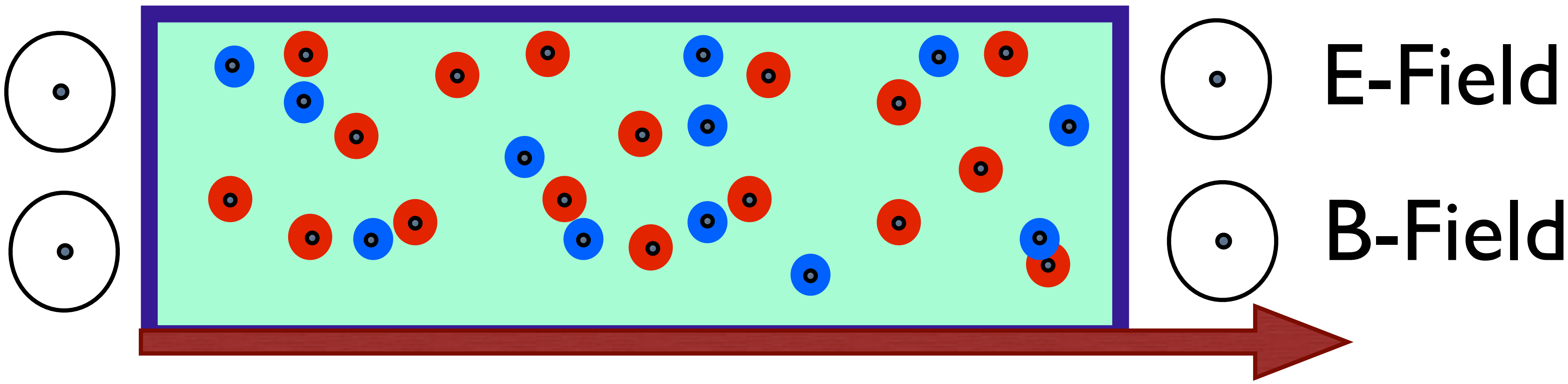

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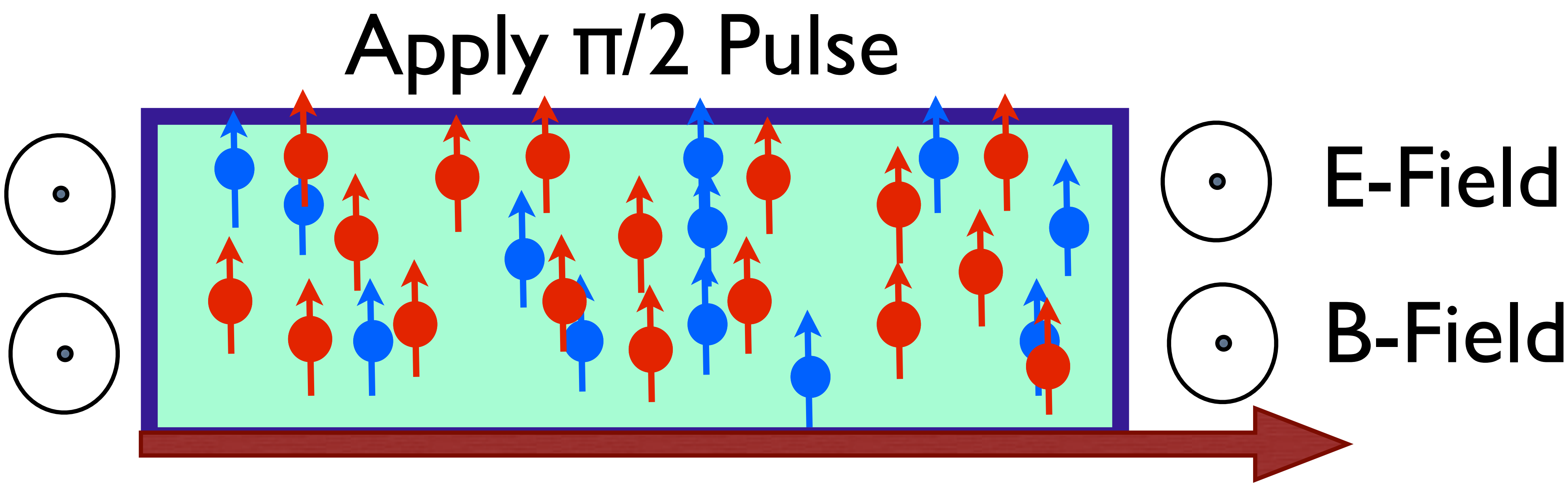

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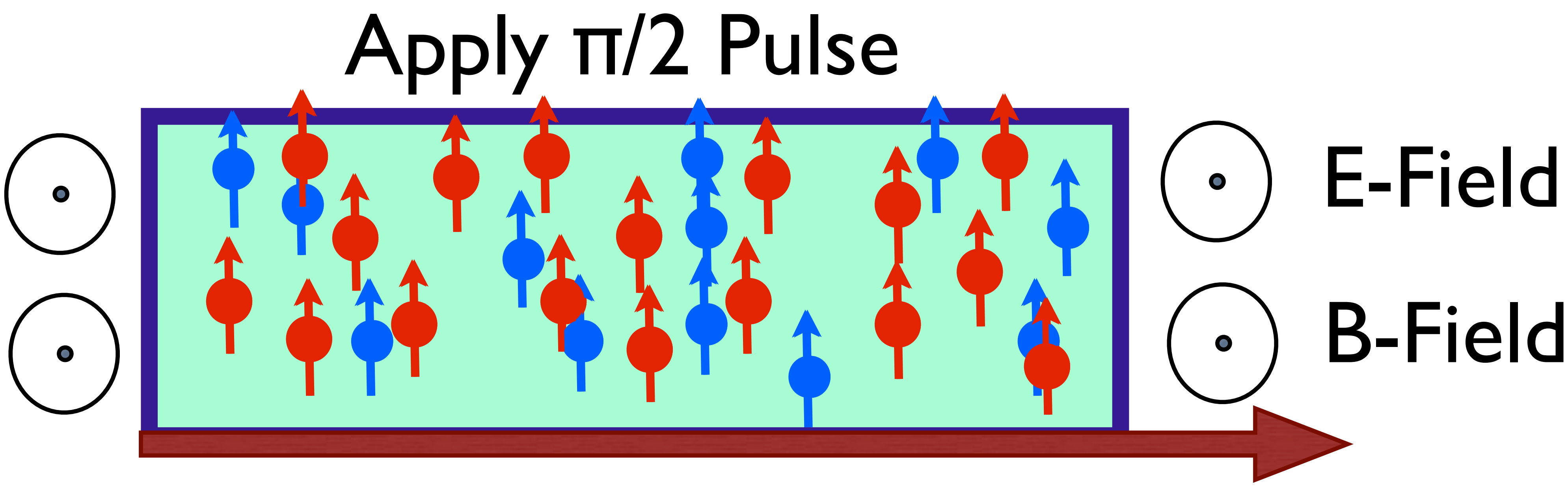

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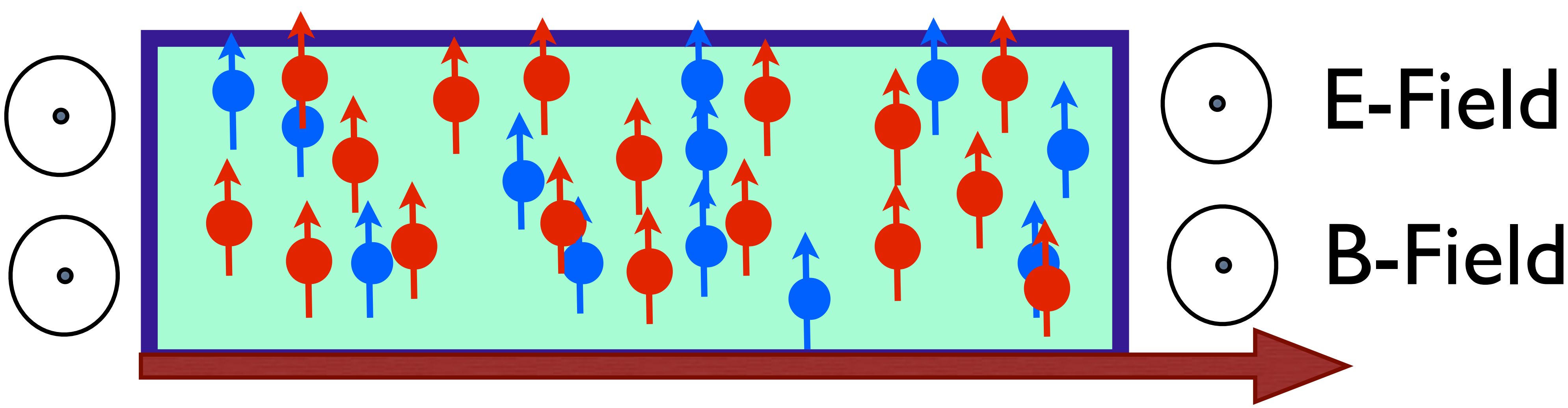

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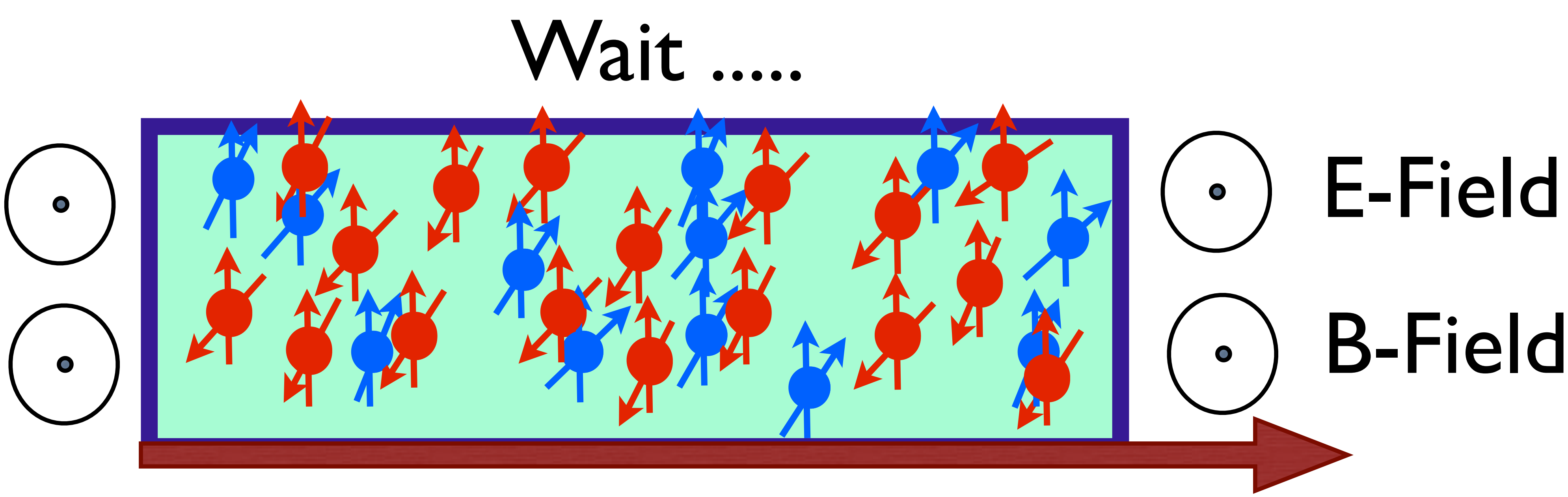

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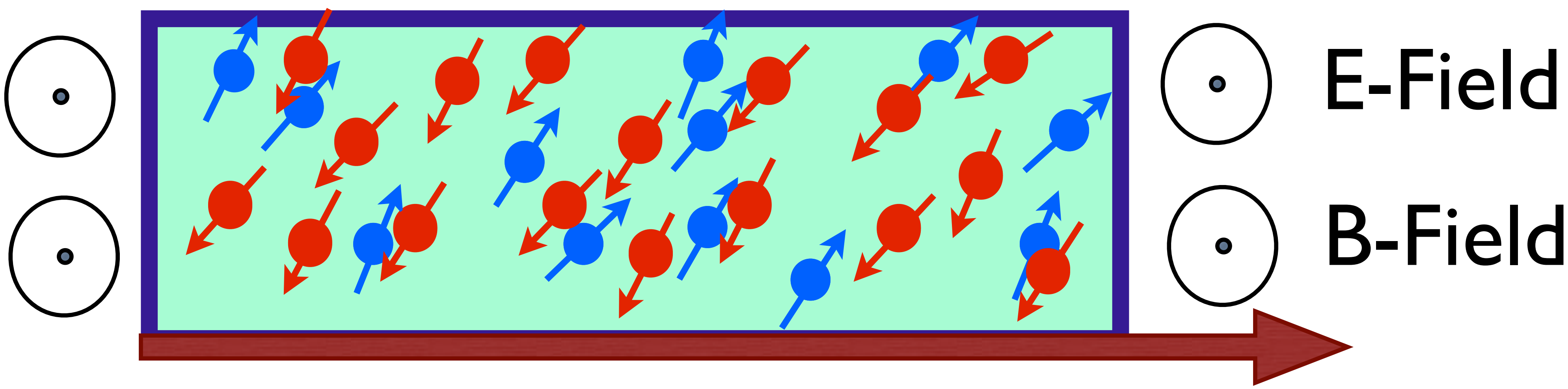
Wait .....



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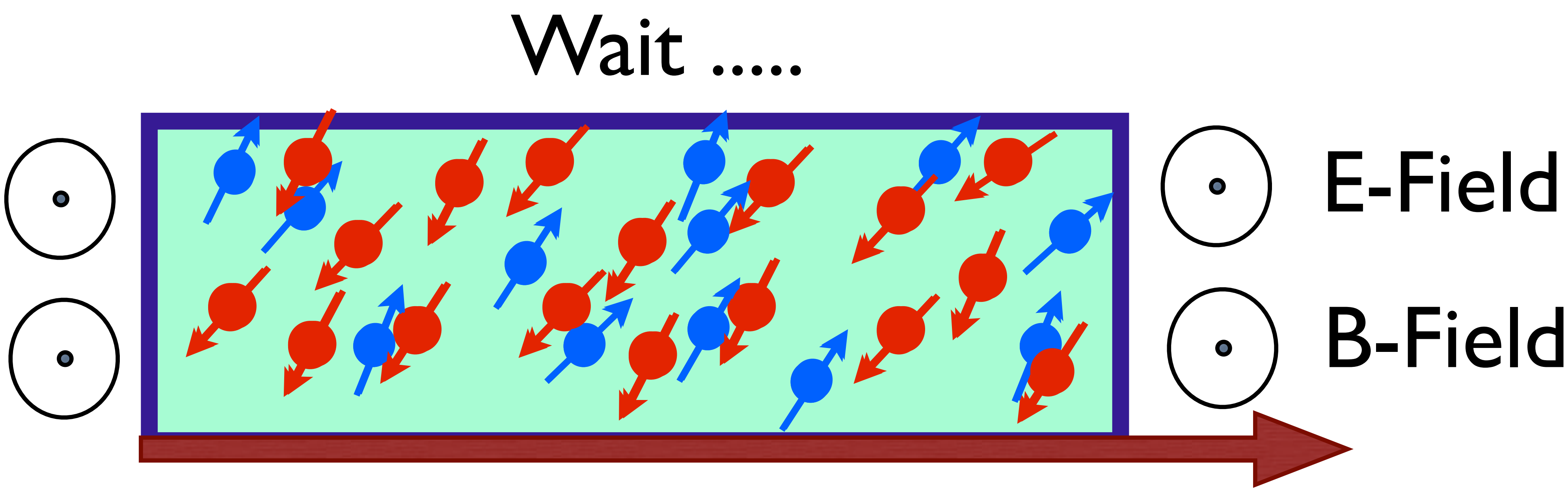

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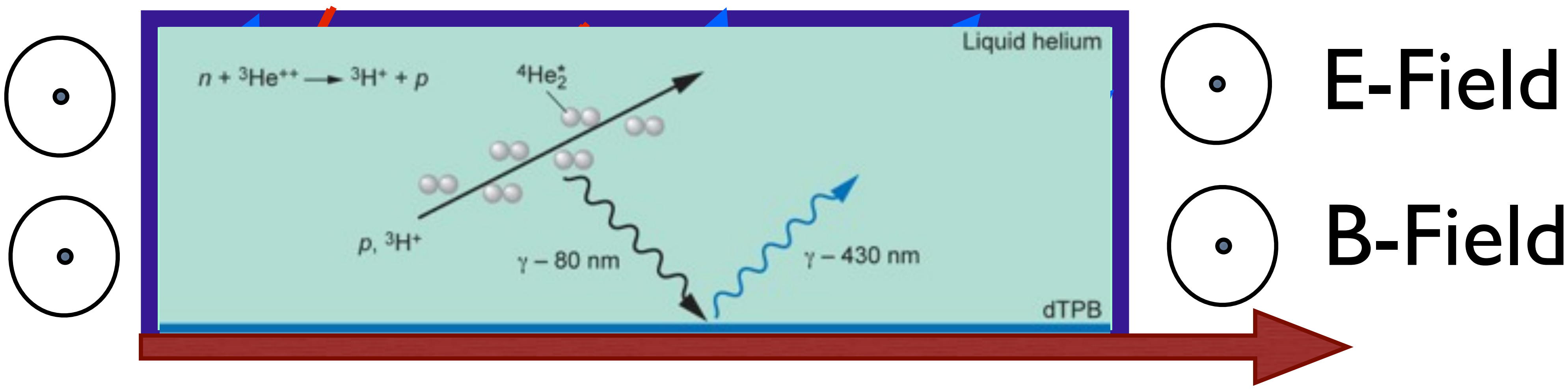

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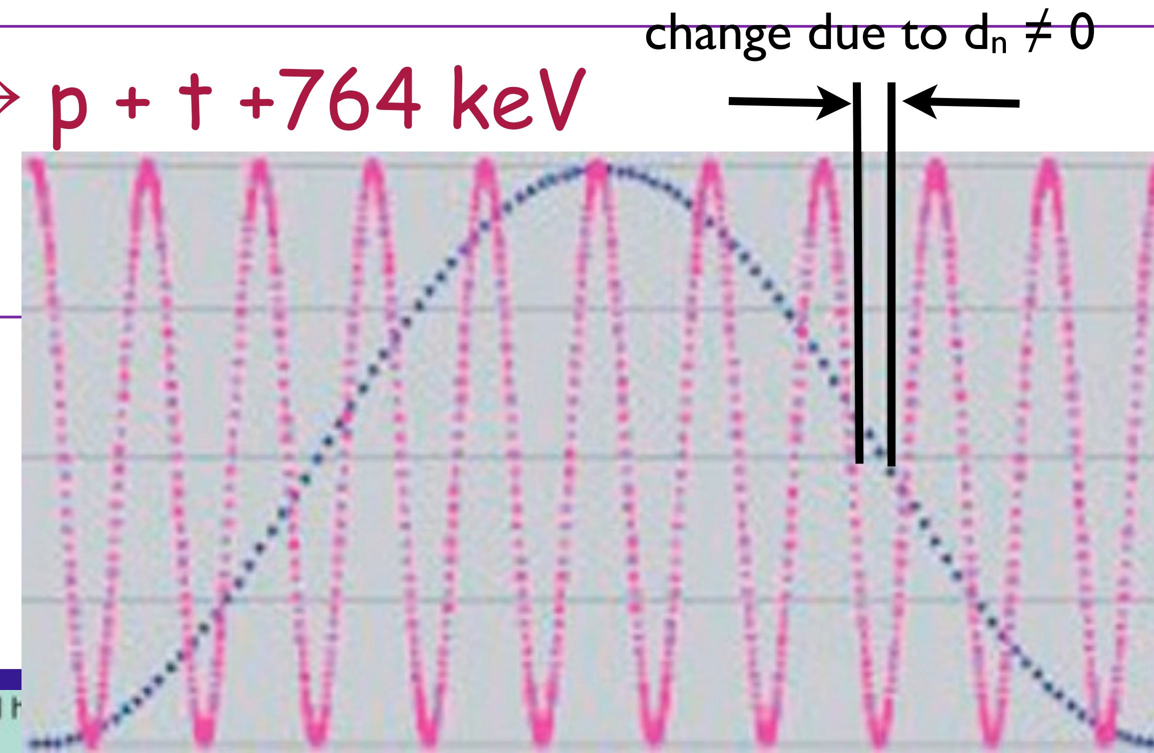
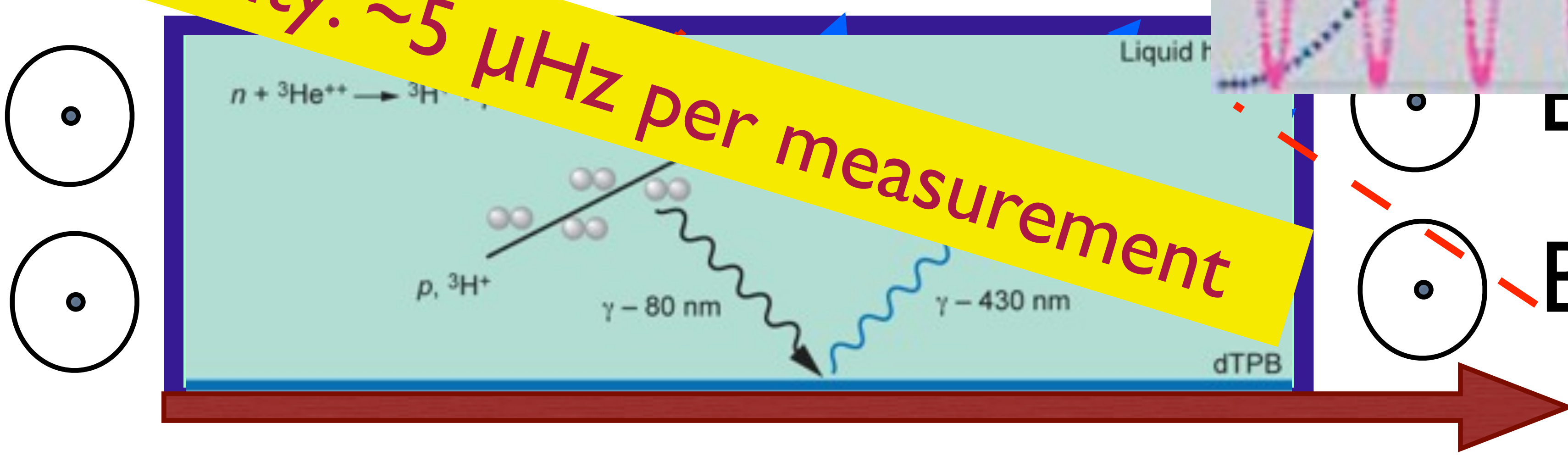
➜ detect scintillation light in LHe



Wait .....



Sensitivity: ~5 μHz per measurement

PMTs, SQUIDs

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- spin dressing ($\omega_n = \omega_{3He}$)

Systematic Effects and Controls

Source of Error	Sys. Uncert. (e·cm)	Comment
Linear v×E (Geometric Phase)	$< 1 \times 10^{-28}$	Uniformity of B_0-Field
Quadratic v×E	$< 0.5 \times 10^{-28}$	E-field reversal < 1%
Pseudo-magnetic Field Effects	$< 1 \times 10^{-28}$	π/2 pulse, comparing two cells
Gravitational Offset	$< 0.2 \times 10^{-28}$	1 nA leakage currents
Heat due to Leakage Currents	$< 1.5 \times 10^{-28}$	< 1 pA
v×E Rotational Neutron Flow	$< 1\times 10^{-28}$	E-field uniformity < 0.5%
E-Field Stability	$< 1 \times 10^{-28}$	ΔE/E < 0.1%
Miscellaneous	$< 1 \times 10^{-28}$	other v×E, wall losses

Neutron EDM : Comparison

	(co-) magnetometer	size of EDM-cell	ρ_{UCN} [1/cm^3]	E-field [kV/cm]	τ [s]
KEK-RCNP/ TRIUMF	^{129}Xe buffer gas	small	>5000	10	150
CryoEDM (ILL)	UCNs at E=0	large	1000	10	150
SNS	polarized ^{3}He	large	500	74	500
PSI	Cs	large	1000	12	150
Munich(FRM-2)	^{199}Hg,^{129}Xe	large	1000	18	250

Summary

- Exciting time to search for new limits on permanent EDMs
- Worldwide efforts with several 100 researchers
- Improvements on all systems expected in upcoming years:
  - Factor of 10 in next five years
  - Factor of 100 in next 10 years
- New limits on EDMs: stringent tests for SUSY models

Exciting years ahead of us!