Searches for the Electric Dipole Moment of the Neutron: An Experimental Overview

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Why Search for Permanent EDMs?

Baryon Asymmetry of the Universe (BAU) → today:

$$\eta = \left(\frac{n_B - n_{\bar{B}}}{n_\gamma}\right) \approx \left(\frac{n_B}{n_\gamma}\right) \approx 6 \times 10^{-10}$$

(WMAP + COBE, 2003; Steigman 2012)

SM: Estimates of baryon excess much too small, $n_B / n_\gamma \approx 5 \times 10^{-19}$

☛ $(n_B - n_{\bar{B}})$ larger than expected → new sources of $\not{C}\!P$ needed

Sakharov: Three Requirements:

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

A. Sakharov; JETP Lett, 5, 24

Permanent Electric Dipole Moments

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

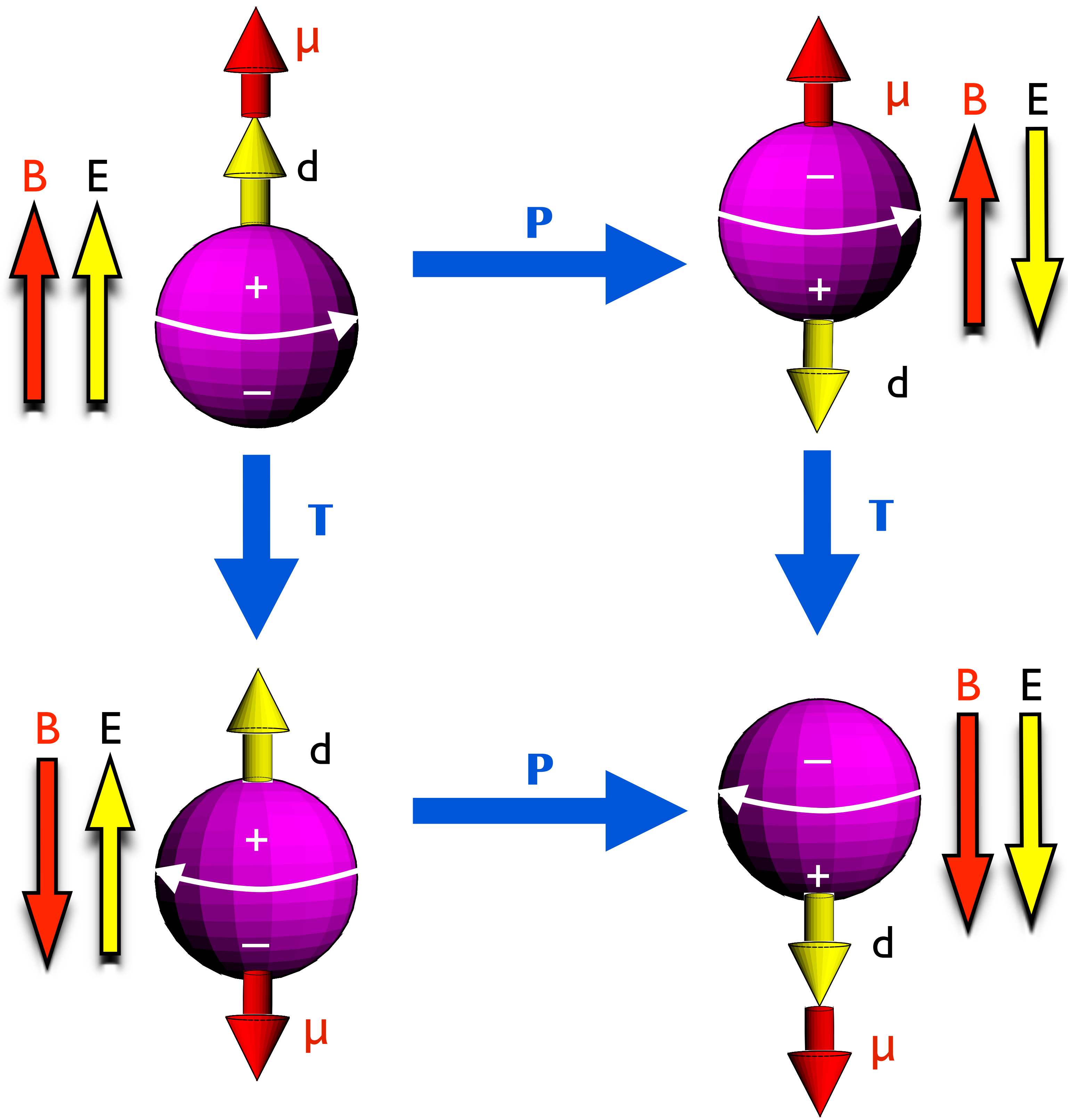
$\vec{\sigma} \rightarrow$ axial-vector, $\vec{E} \rightarrow$ vector:

⇒ d violates Parity

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

⇒ d violates T-reversal

⇒ CPT: d ≠ 0, CP violation



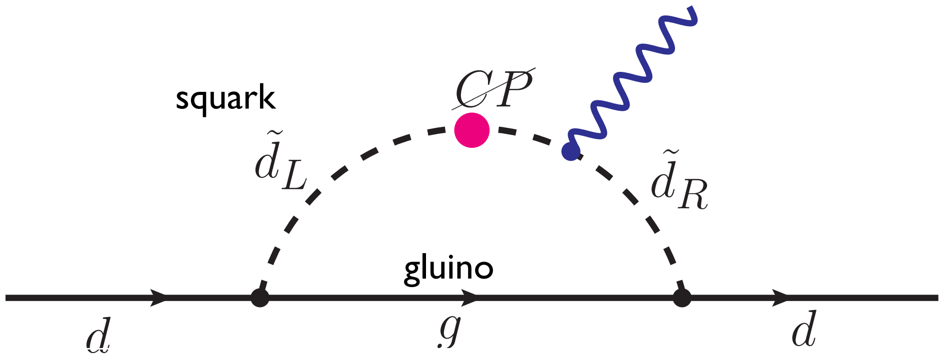
What to Expect?

In SM EDMs are generated at three-loop level:

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

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

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



de Rujula et al., Nucl. Phys. B 357, 311 (1991)
S. Gardner, priv. comm.

Simple estimate of sensitivity to new physics

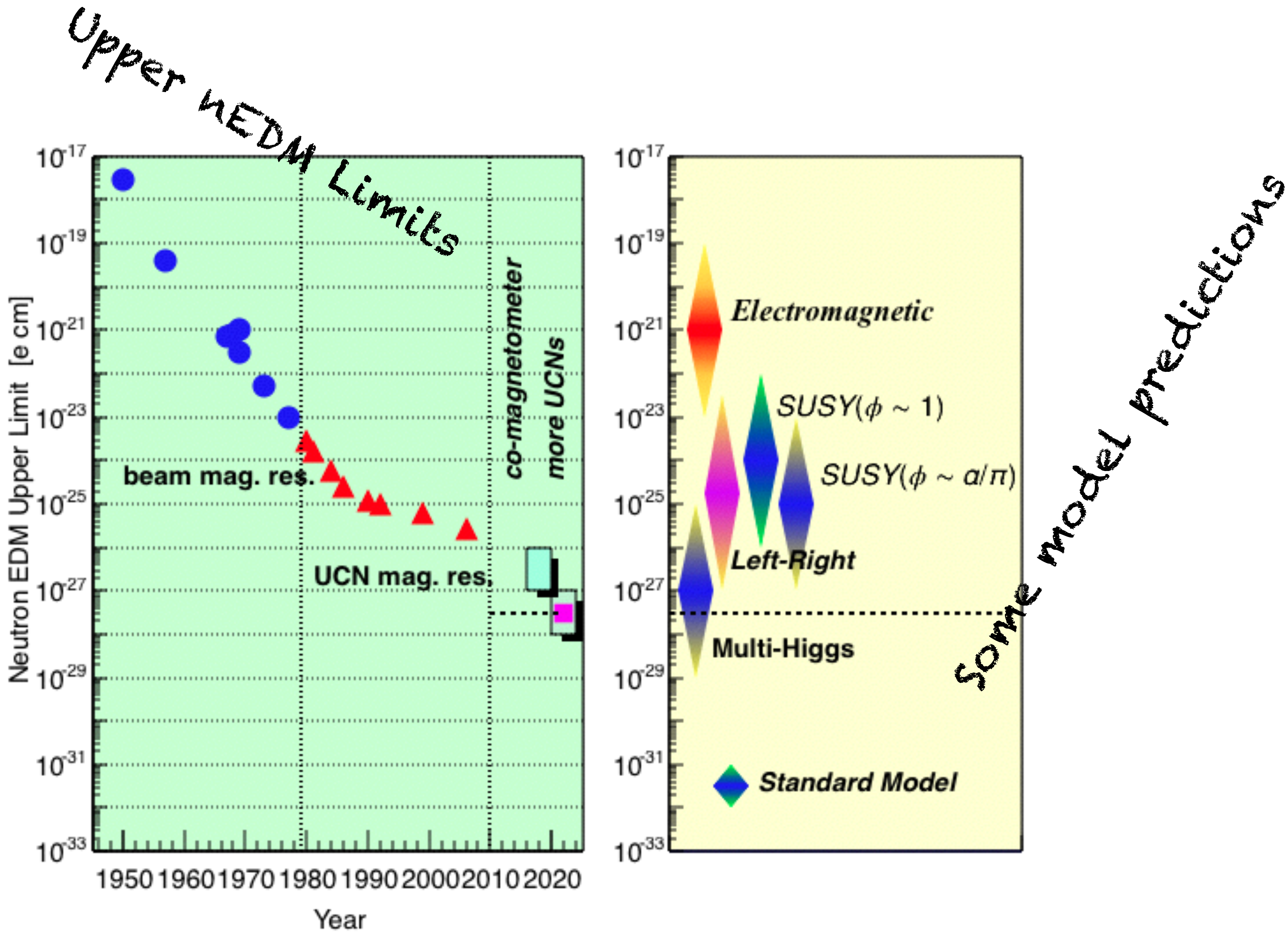
Estimate based on dim. analysis, under $SU(2)_L \times U(1)$ gauge invariance:

$$sin(\phi_{CP}) \sim 10^{-2}, \quad d_d \sim 10^{-2} e \cdot \frac{m_d\,(MeV)}{\Lambda^2(TeV^2)} \sim \frac{10^{-24}}{\Lambda^2(TeV^2)}\; e \cdot cm$$

(Λ is CP breaking scale, coupling O(1) assumed)

→ $d_d \sim d_n \sim 3{\cdot}10^{-26}$ e·cm ↔ Λ ~ 6 TeV,
$d_d \sim 5{\cdot}10^{-28}$ e·cm ↔ Λ ~ 45 TeV

The History of Neutron and Electron EDMs

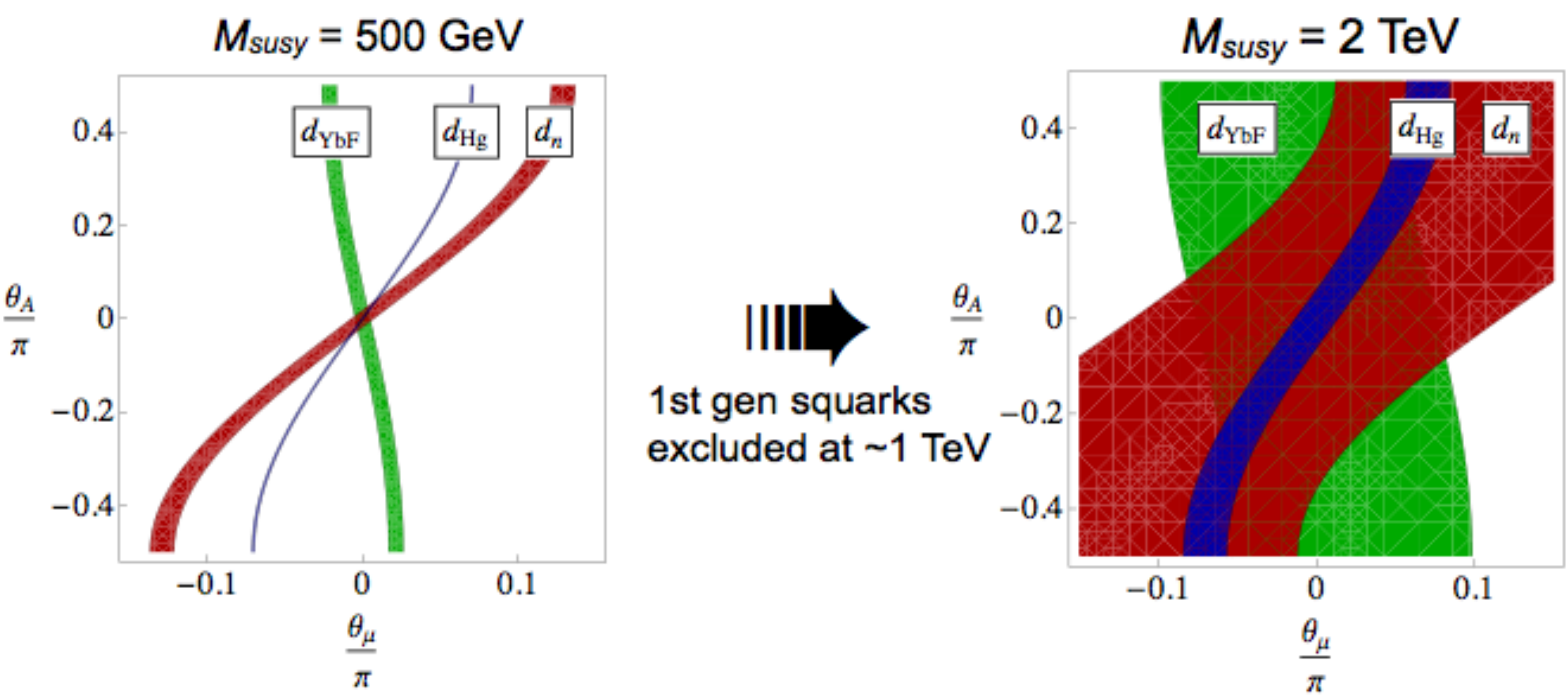


Constraining SUSY Parameters

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

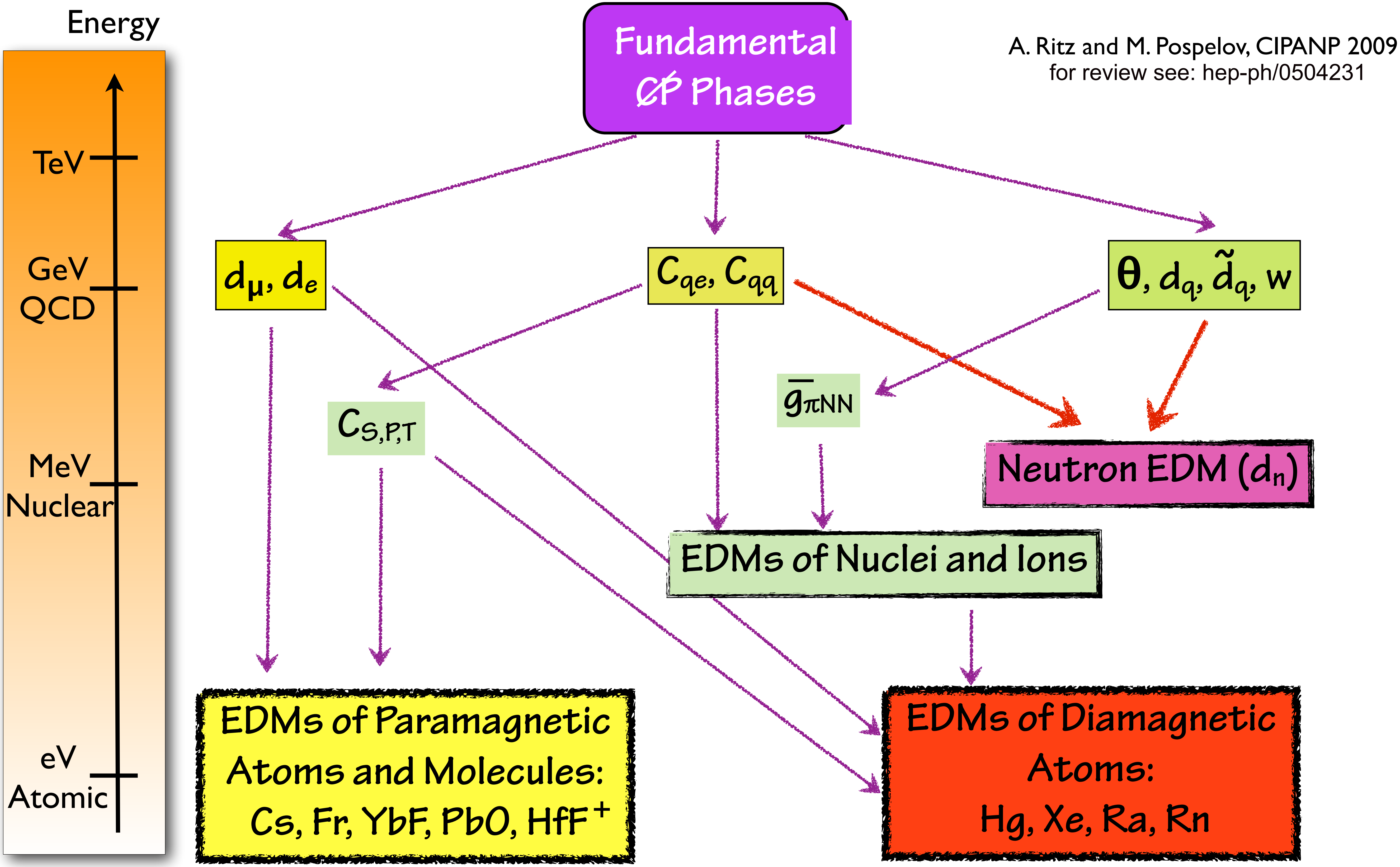
Example: Constraining CP̸ phases in CMSSM:

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

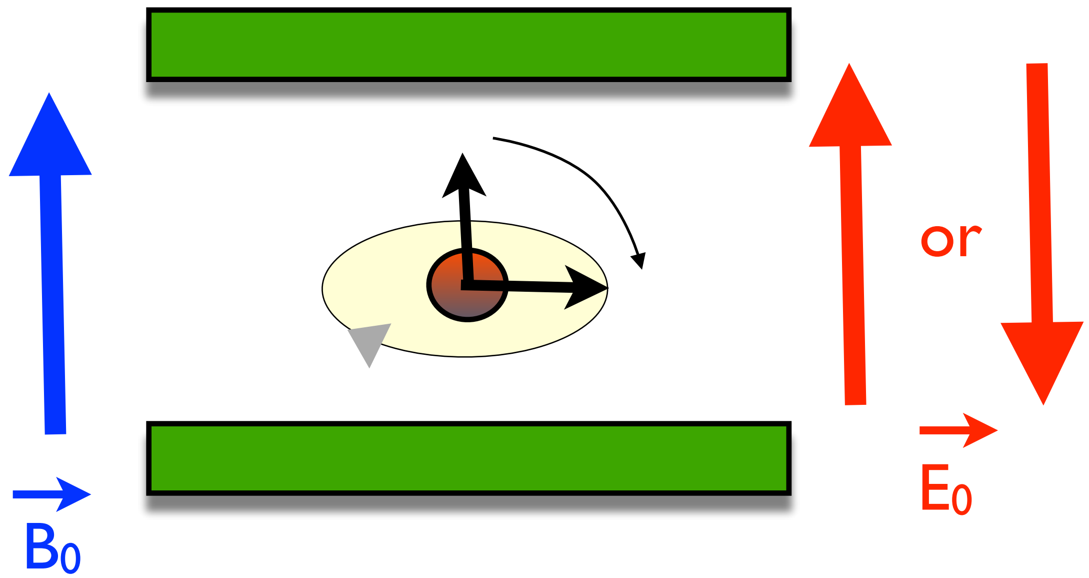


M. Pospelov and A. Ritz, Ann. Phys. 318, 119 (2005),
A. Ritz, Symmetries, Groningen 2012

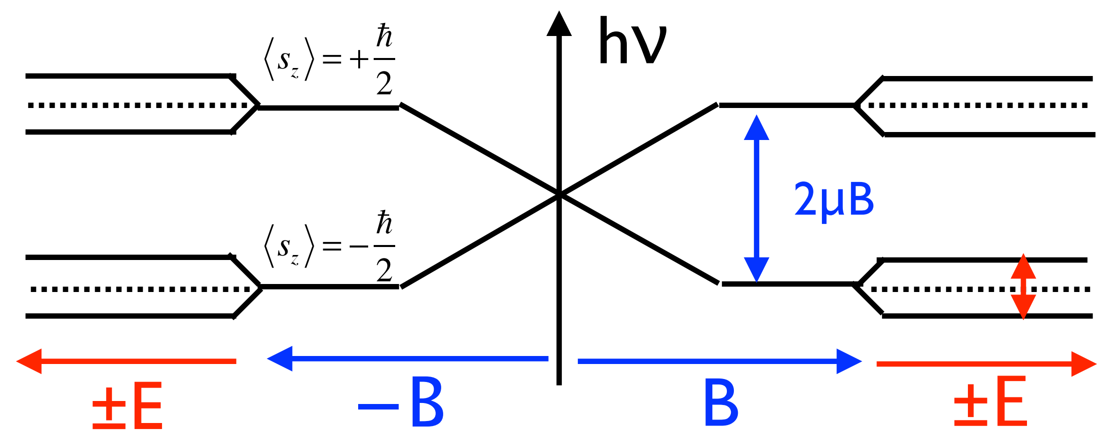
Energy scales involved



Basic Concept of EDM Searches



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



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

- Statistical uncertainty:

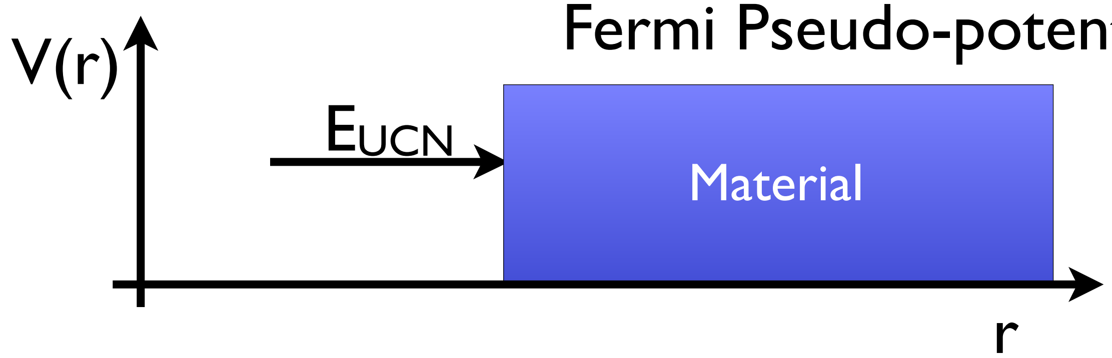
$$\sigma \approx \frac{\hbar}{2\alpha E_0 T_m \sqrt{Nm}}$$

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

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

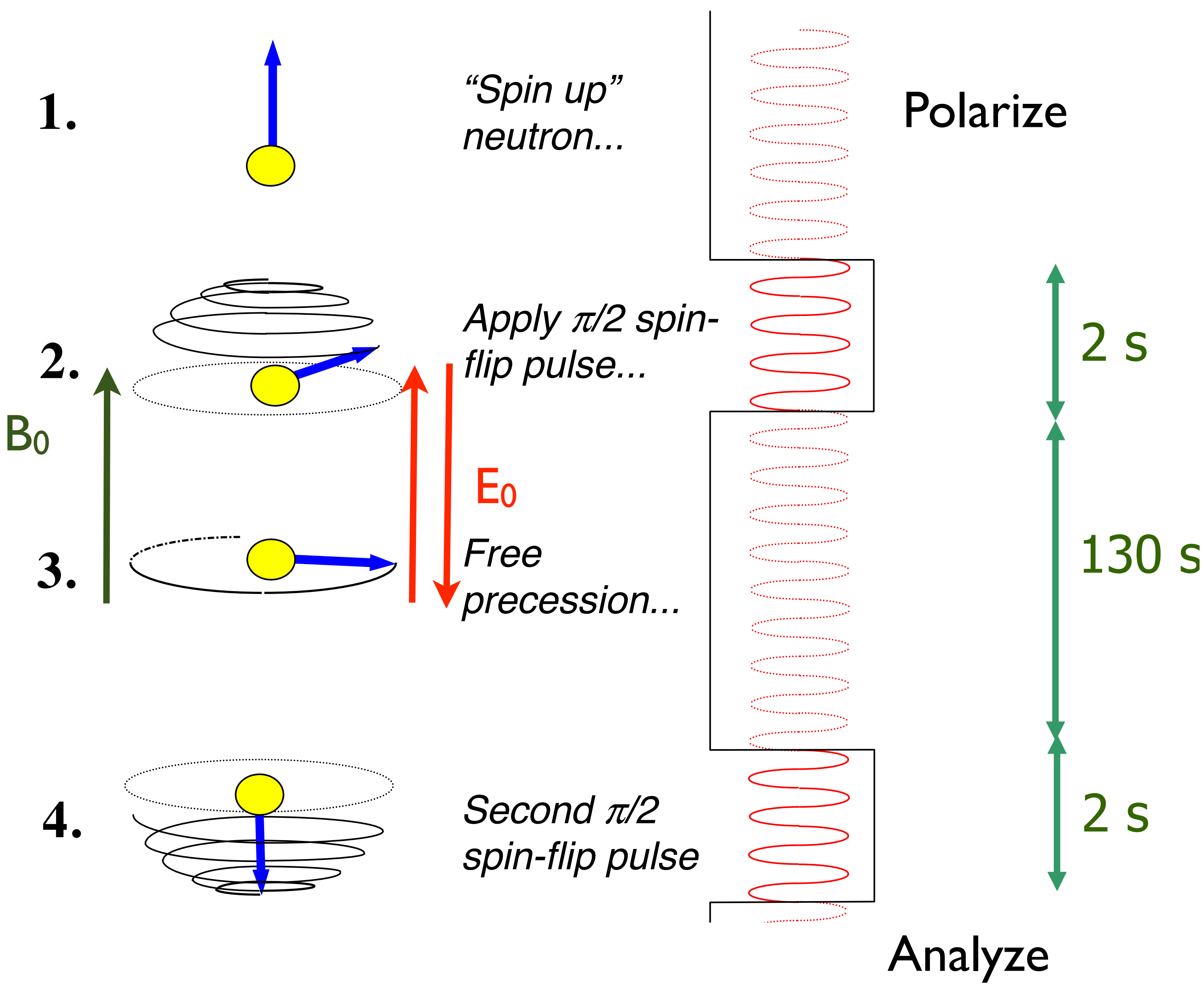
Strong Interaction:

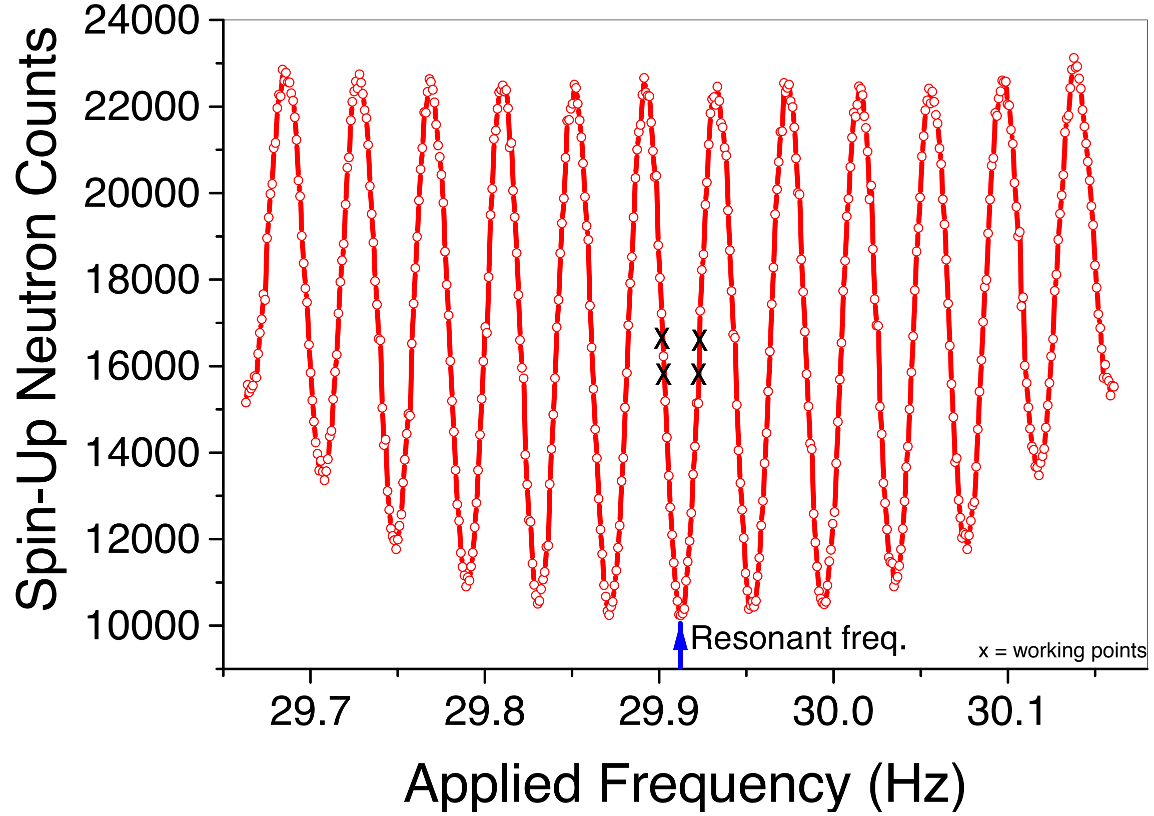
Material	V
Ni	335
BeO	261
Teflon	123
Al	54
H	-14.7
Ti	-48

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

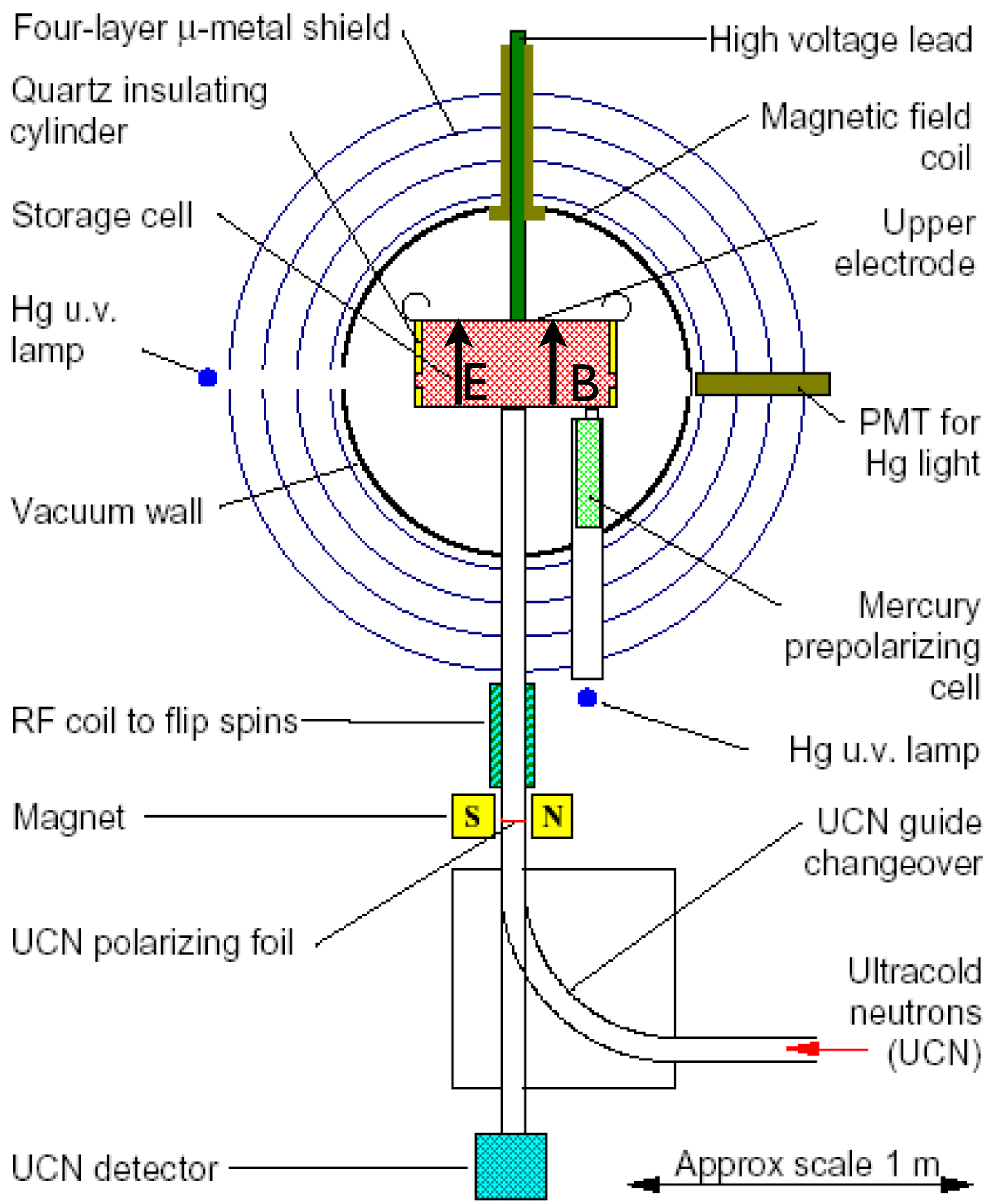
Basic Concept for Most EDM Searches

Ramsey's method of separated oscillatory fields





Neutron EDM: Best Limit

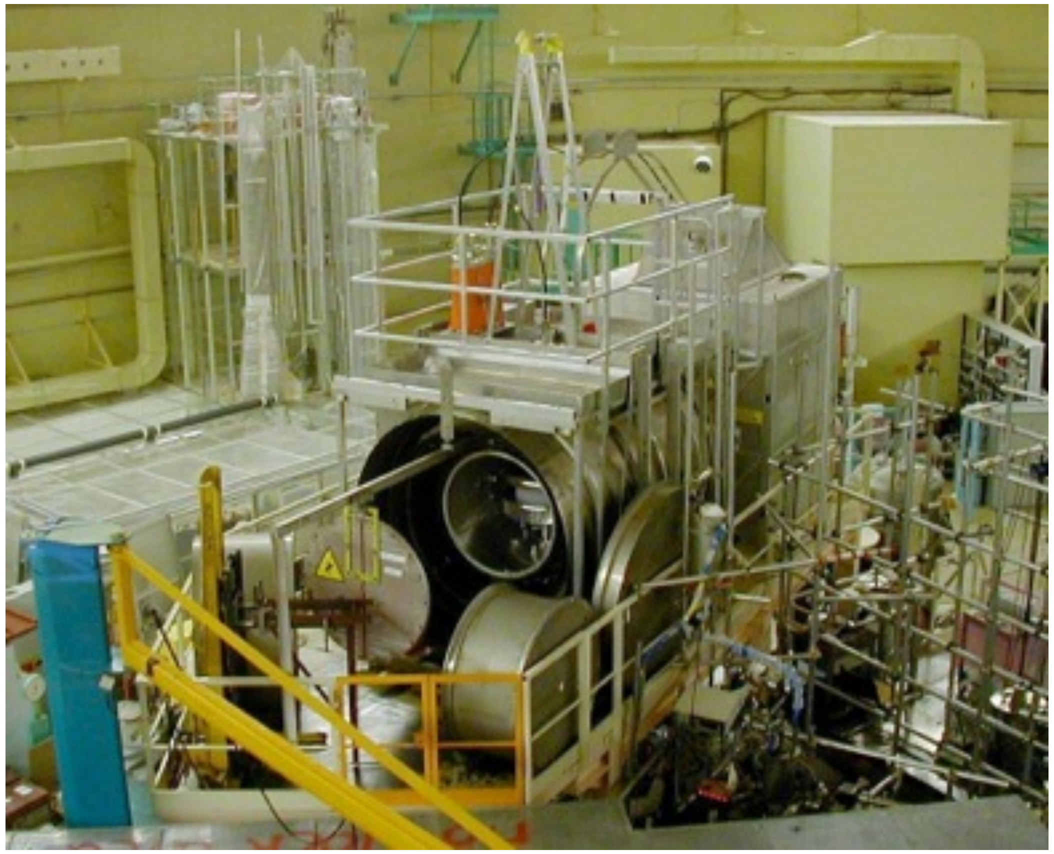


Ultra-cold Neutrons (UCN) in a storage cell (at T ~ 300 K): ρ_{UCN} ~ 1/cm^3

- 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)

Present and Future Searches for nEDMs

Experiment	UCN Source	Target Cell	Technique	σ (10^{-28} e·cm)
ILL-CryoEDM	Superfluid ^4He	Superfluid ^4He	Cryo HV, SuperCond., Ramsey technique, external SQUID mag.	<5
ILL-PNPI	ILL Turbine PNPI Solid D_2	Vacuum	Ramsey technique for ω, E=0 cell for magnetometer	Phase I < 100 Phase II < 10
ILL-Crystal	Cold n beam	Solid (Crystal)	Crystal Diffraction Non-Centrosymmetric crystal	< 100
PSI-nEDM	Solid D_2	Vacuum	Ramsey for ω, external Cs & ^3He, Hg co- mag., Xe or Hg co-mag.	Phase I ~50 Phase II <5
Munich FRM-II	Solid D_2	Vacuum	Room Temp. , Hg co-mag., also external Cs mag.	<5
RCNP/TRIUMF	Superfluid ^4He	Vacuum	Small vol., Xe co-mag. @ RCNP Then move to TRIUMF	<50 <5
SNS-nEDM	Superfluid ^4He	Superfluid ^4He	Cryo-HV, ^3He capture for ω, ^3He co-mag. with SQUIDS & dressed spins, supercond	<5
J-PARC	Solid D_2	Vacuum	Under Development	<5
J-PARC	Solid D_2	Solid (Crystal)	Crystal Diffraction Non-Centrosymmetric crystal	<10(?)
LANL	Solid D_2	Vacuum	R&D	~30

(shaded) = sensitivity < 5×10^{-28} e·cm

Compilation → B. Filippone

Present and Future Searches for nEDMs

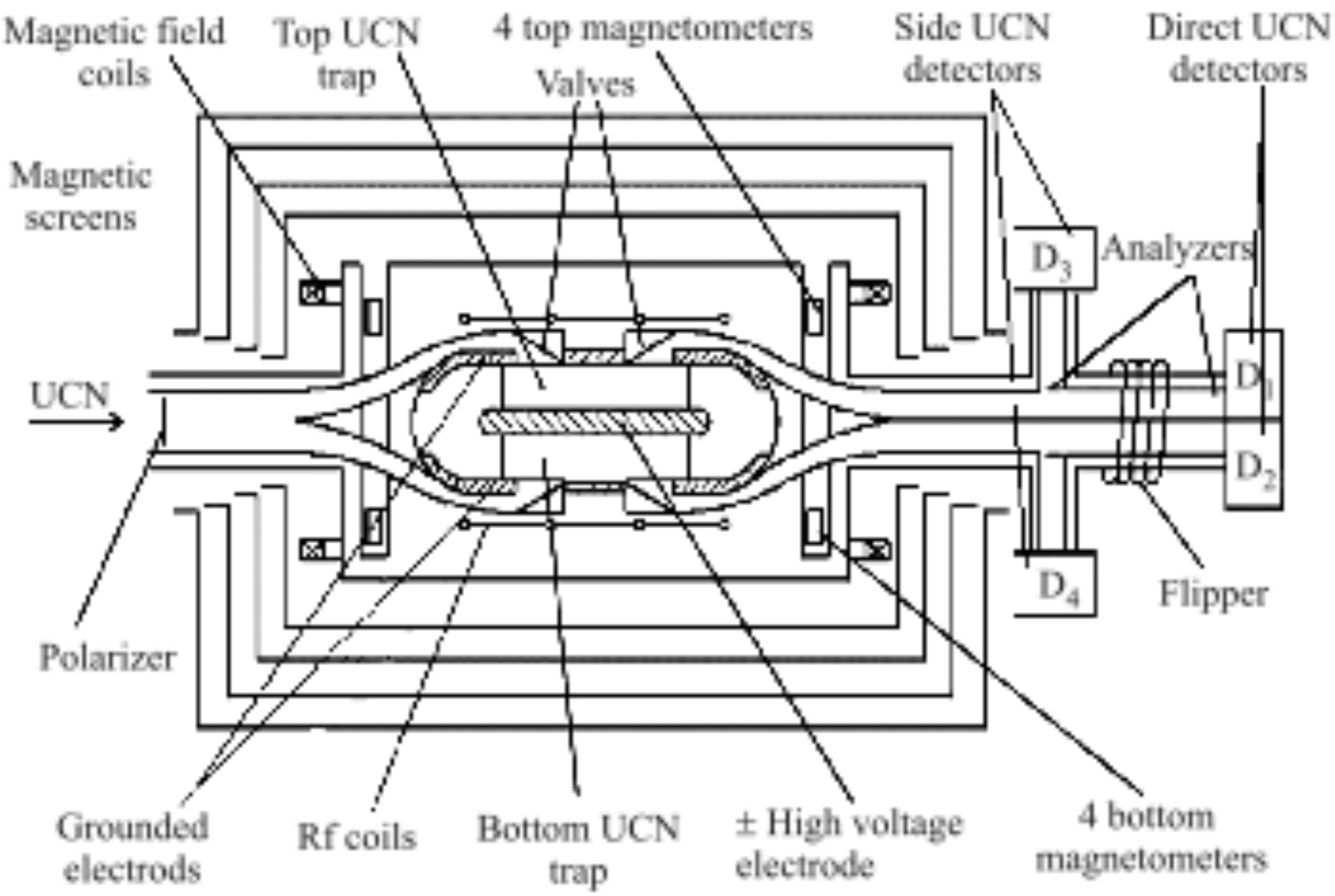
Experiment	UCN Source	Target Cell	Technique	σ (10^{-28} e·cm)
ILL-CryoEDM	experiment being phased out due to lack of resources			
ILL-PNPI	ILL Turbine PNPI Solid D_2	Vacuum	Ramsey technique for ω, E=0 cell for magnetometer	Phase I < 100 Phase II < 10
ILL-Crystal	Cold n beam	Solid (Crystal)	Crystal Diffraction Non-Centrosymmetric crystal	< 100
PSI-nEDM	see talk by Malgorzata Kasprzak		ω, external Cs & ^{3}He, Xe or Hg co-mag.	Phase I ~50 Phase II <5
Munich FRM-II	Solid D_2	Vacuum	Room Temp., Hg co-mag., also external Cs mag.	<5
RCNP/TRIUMF	Superfluid ^{4}He	Vacuum	Small vol., Xe co-mag. @ RCNP Then move to TRIUMF	<50 <5
SNS-nEDM	Superfluid ^{4}He	Superfluid ^{4}He	Cryo-HV, ^{3}He capture for ω, ^{3}He co-mag. with SQUIDS & dressed spins, supercond	<5
J-PARC	under consideration		Under Development	<5
J-PARC	under consideration		Crystal Diffraction Non-Centrosymmetric crystal	<10(?)
LANL	see talk by Leah Broussard			~30

= sensitivity < 5 × 10^{-28} e·cm

Compilation → B. Filippone

Neutron EDM (PNPI-ILL)

UCN source PF2 at ILL



- 2008 Detectors, electronics, and magnetometers installed
- ρ_{UCN} = 7.5 cm^{-3} (unpol.) at entrance of EDM apparatus
- HV: 18 kV/cm
- 8 Cs co-magnetometers
- T_{trap} = 70-100 s

Neutron EDM (PNPI-ILL)

Pis'ma v ZhETF, vol. 99, iss. 1, pp. 7 – 11

New measurements of neutron electric dipole moment

A. P. Serebrov[1)], E. A. Kolomenskiy, A. N. Pirozhkov, I. A. Krasnoschekova, A. V. Vassiljev, A. O. Polushkin, M. S. Lasakov, A. K. Fomin, I. V. Shoka, V. A. Solovey, O. M. Zherebtsov, P. Geltenbort[+], S. N. Ivanov[+], O. Zimmer[+], E. B. Alexandrov[*], S. P. Dmitriev[*], N. A. Dovator[*]

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Submitted 10 December 2013

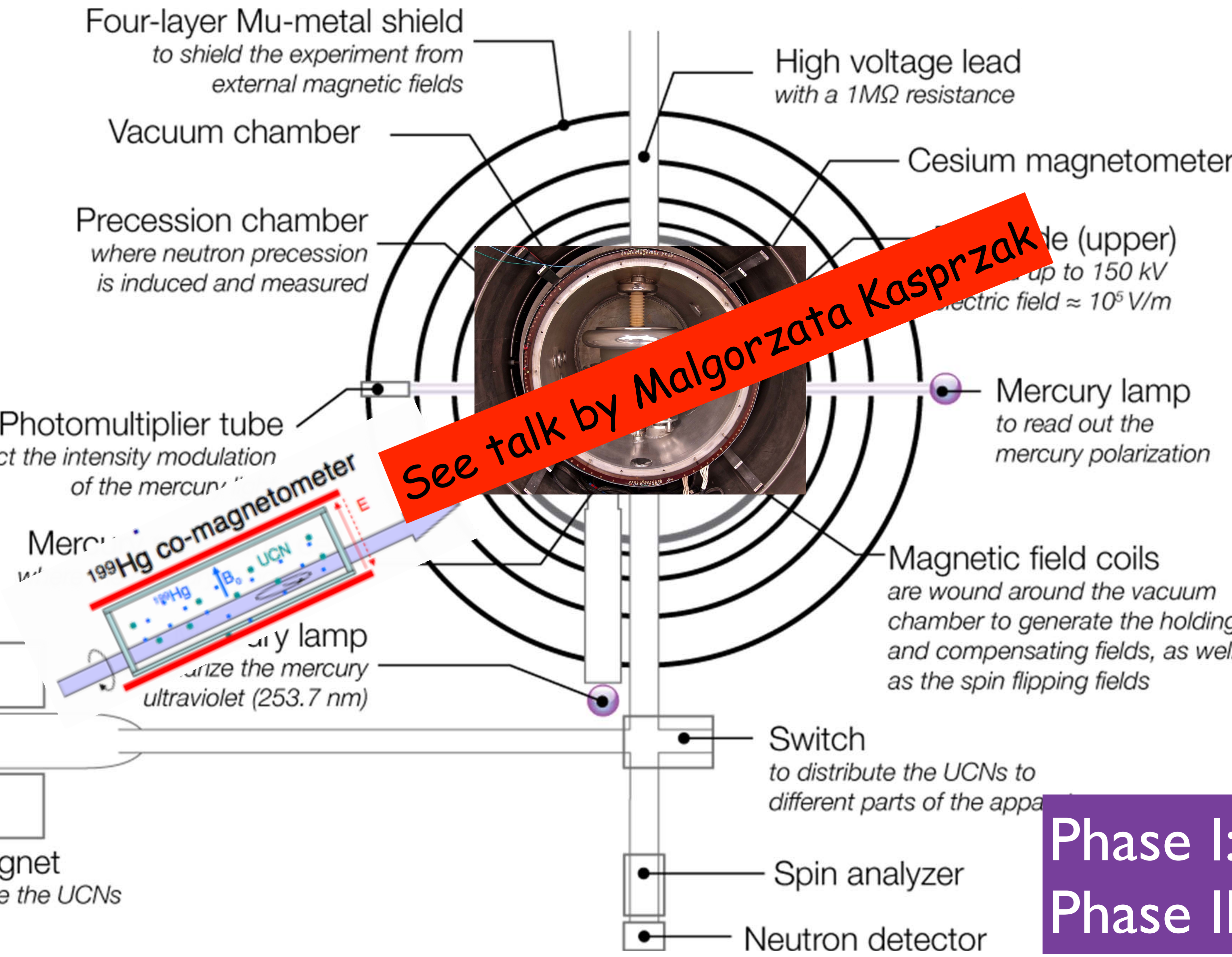
We report a new measurement of the neutron electric dipole moment with the PNPI EDM spectrometer using the ultracold neutron source PF2 at the research reactor of the ILL. Its first results can be interpreted as a limit on the neutron electric dipole moment of $|d_n| < 5.5 \cdot 10^{-26}$ e · cm (90% confidence level).

DOI: 10.7868/S0370274X14010020

$|d_n| < 5.5 \cdot 10^{-26}$ e·cm (90% confidence level)

Projection:
Phase I: $|d_n| < 1 \times 10^{-26}$ (100 days)
Phase II: $|d_n| < 3 \times 10^{-27}$ (100 days)

Neutron EDM (PSI)



Parameter	Value
Efficiency and Polarization	α = 0.75
Electric Field	E = 12 kV/cm
Coherence Time (per cycle)	T = 150 s
# of UCNs (per cycle)	N = 350,000

Phase I: $|d_n| < 5 \times 10^{-27}$ (2 yrs)
Phase II: $|d_n| < 5 \times 10^{-28}$

DFG Priority Program SPP 1491

SLOW NEUTRONS DFG SPP 1491

Precision experiments in particle- and astrophysics with cold and ultracold neutrons

A - CP-symmetry violation and particle physics in the early universe
- Neutron EDM

B - The structure and nature of weak interaction and possible extensions of the Standard Model
- Neutron β-decay V – A Theory

C - Relation between gravitation and quantum theory
- Neutron bound gravitational quantum states

D- Charge quantization and the electric neutrality of the neutron
- Neutron charge

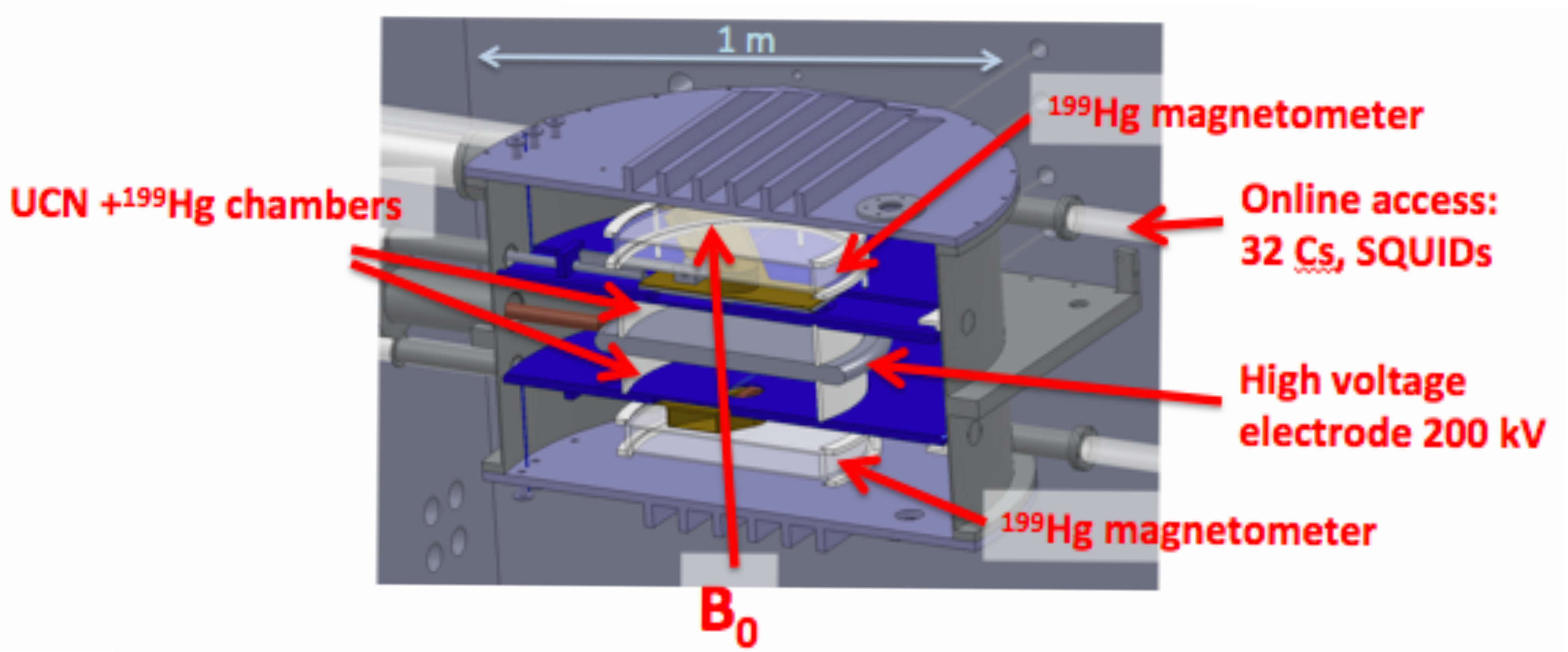
E- New measuring techniques

ST Braunschweig / Univ. Heidelberg / ILL / Univ. Jena / Univ. Mainz / Exzellenzcluster ‚Universe' München / Techn. Univ. München / PTB Berlin / Vienna University of Technology (1st period)

P. Fierlinger

Neutron EDM (Munich,FRM-II)

(nedm.ph.tum.de
Berkeley, ILL, LANL, MSU, PTB, RAL, TUM, UIUC, UMich, YALE)



- Goal: 10^{-28} ecm
- ‚Conventional' UCN trap at room temperature, double chamber
- New UCN / Hg / HV compatible storage materials
- First UCN measurements in 2015
- Unique tool to investigate systematics: UCN velocity tuning
- Cs, ^{3}He, ^{199}Hg, ^{129}Xe (co)magnetometers
- Unique magnetic field quality

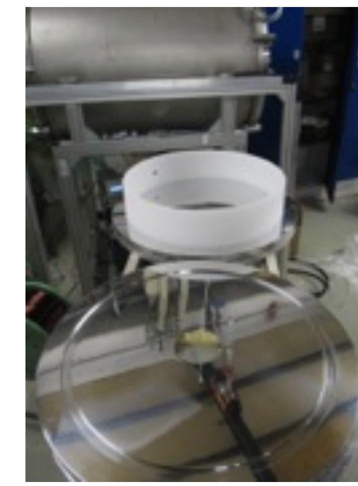
P. Fierlinger

Neutron EDM (Munich,FRM-II)

‚Ultimate‘ magnetic environment at TUM:

- Noble gas magnetometer measurements
- Atomic, nuclear, SQUID magnetometer tests ongoing
- Geometric phases controlled at 1.10^{-27} ecm level
- FRM-II UCN source under construction (Goal: 10^3 UCN/cc)

Inner shield with UCN part during assembly (June 2014):

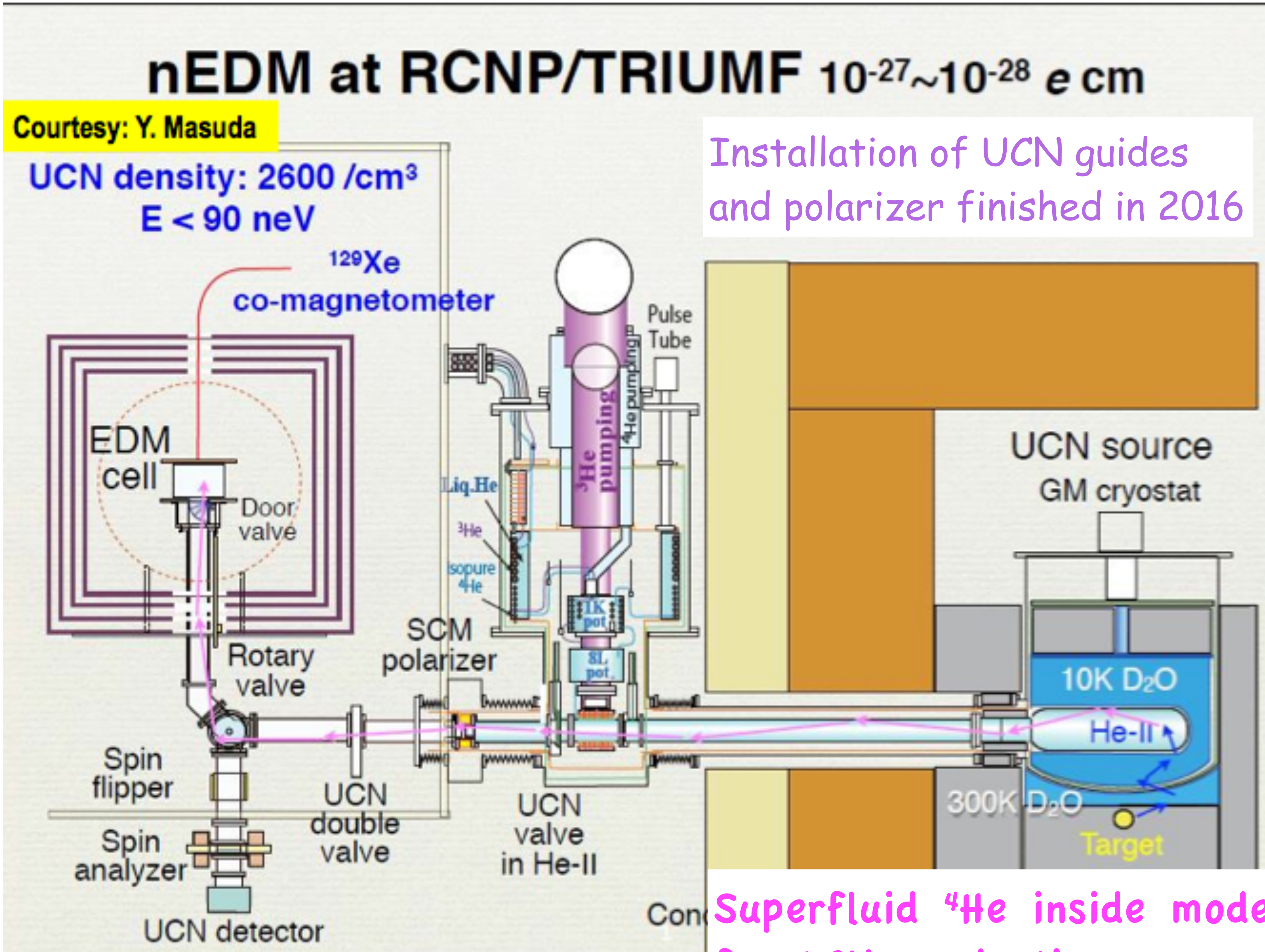


Example fig:
Chamber parts

- Commissioning and optimization of inner apparatus with UCN at test-source
- First EDM measurements next year
- HV and coating tests with UCN ongoing

P. Fierlinger

Neutron EDM (KEK-RCNP/TRIUMF)

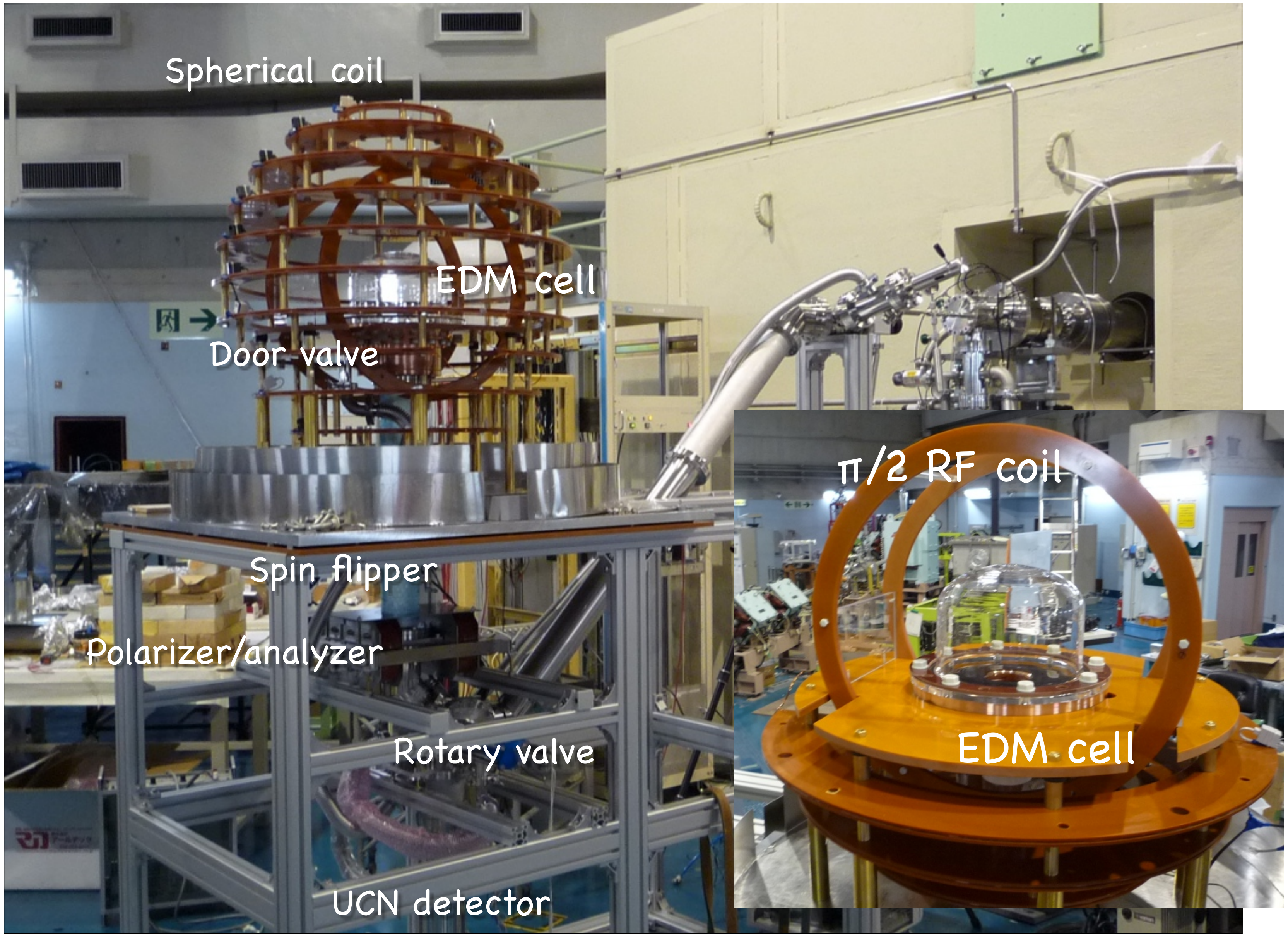


Installation of UCN guides and polarizer finished in 2016

Superfluid ⁴He inside moderator for UCN production

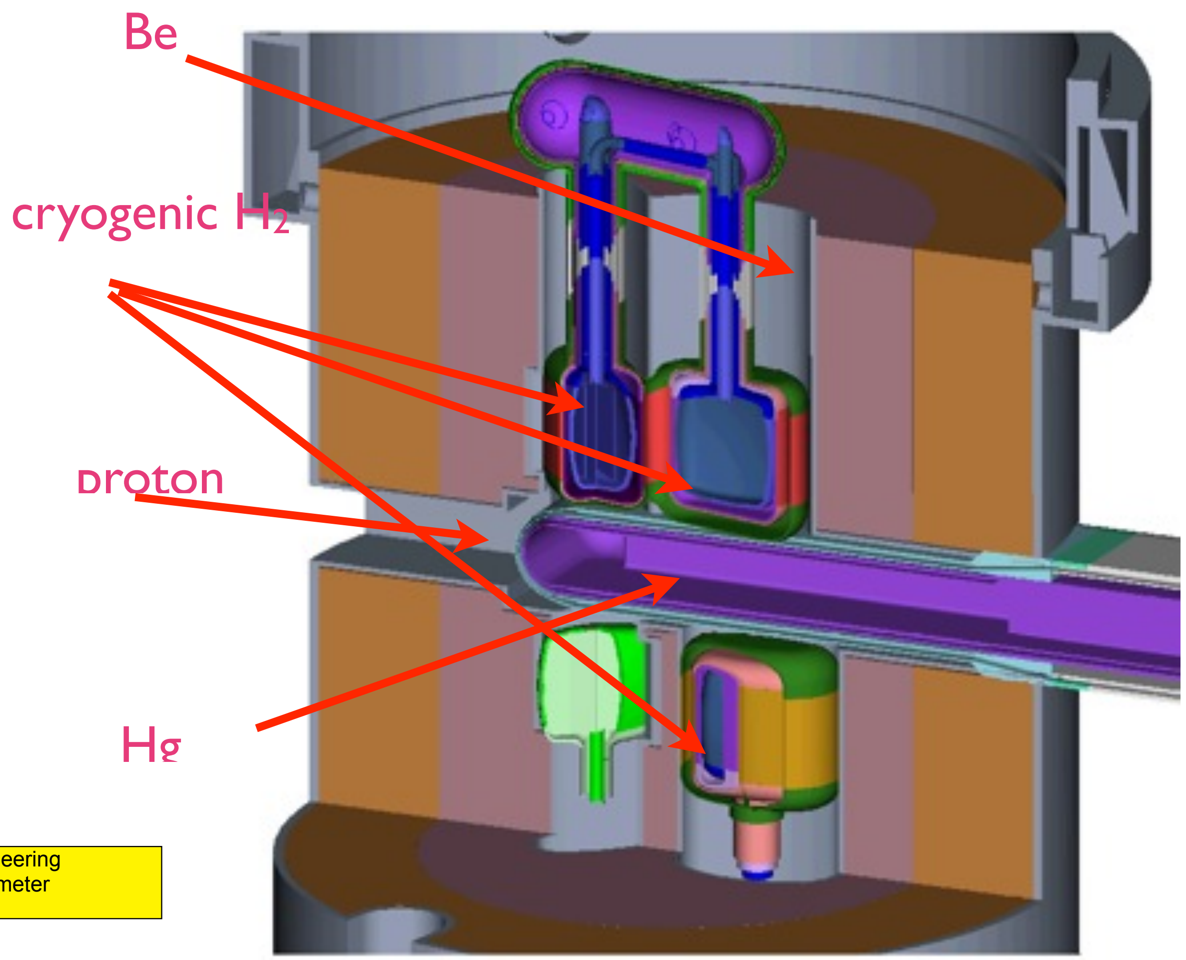
Neutron EDM (KEK-RCNP/TRIUMF)

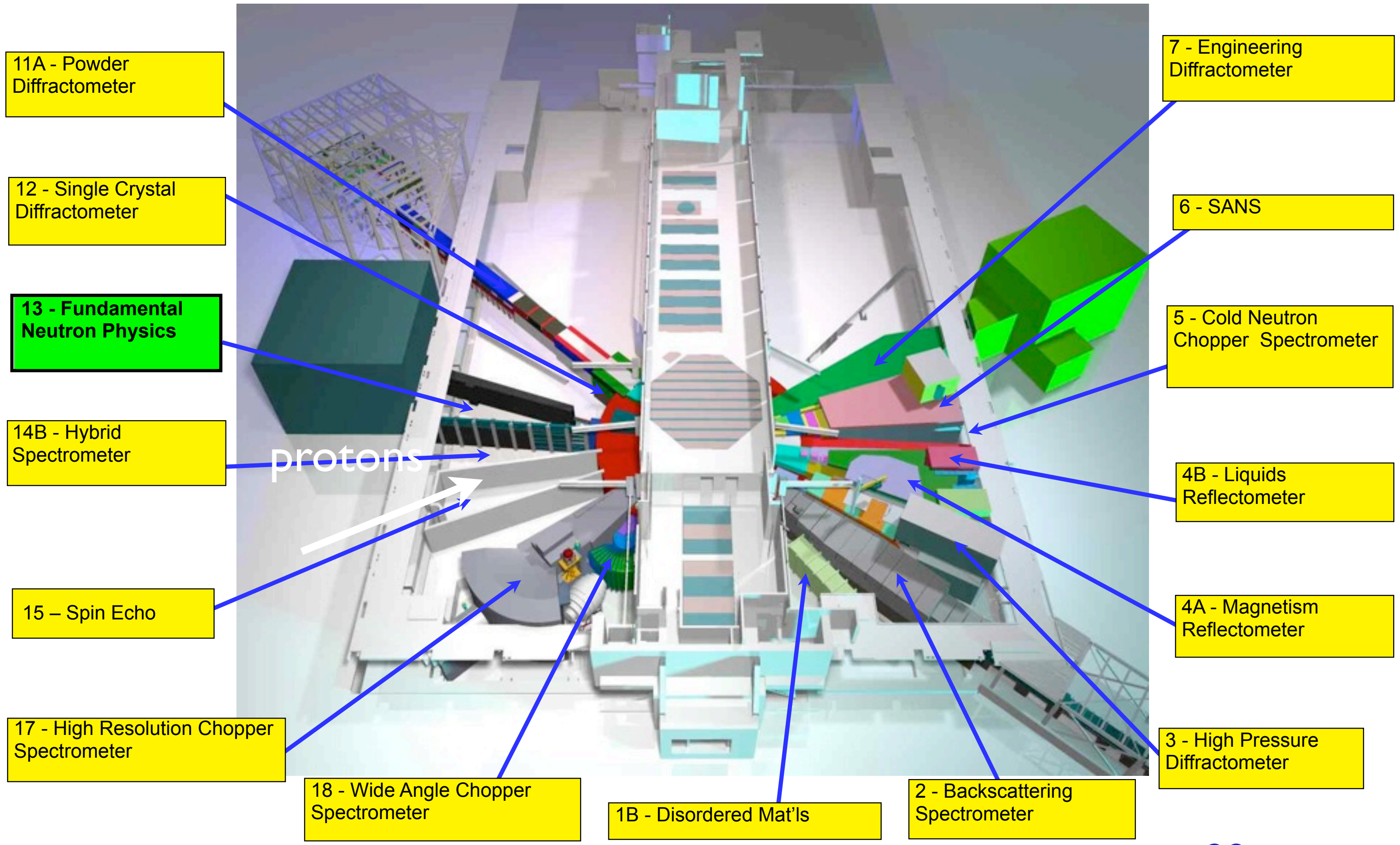
- Spherical Coil for DC field
- ^{129}Xe nuclear spin buffer gas co-magnetometer
- Room-temperature experiment
- Small cell size
- Modern magnetic shielding
- Ramsey separated oscillatory field method



Goal: start measurement in 2016

Neutron EDM (SNS)





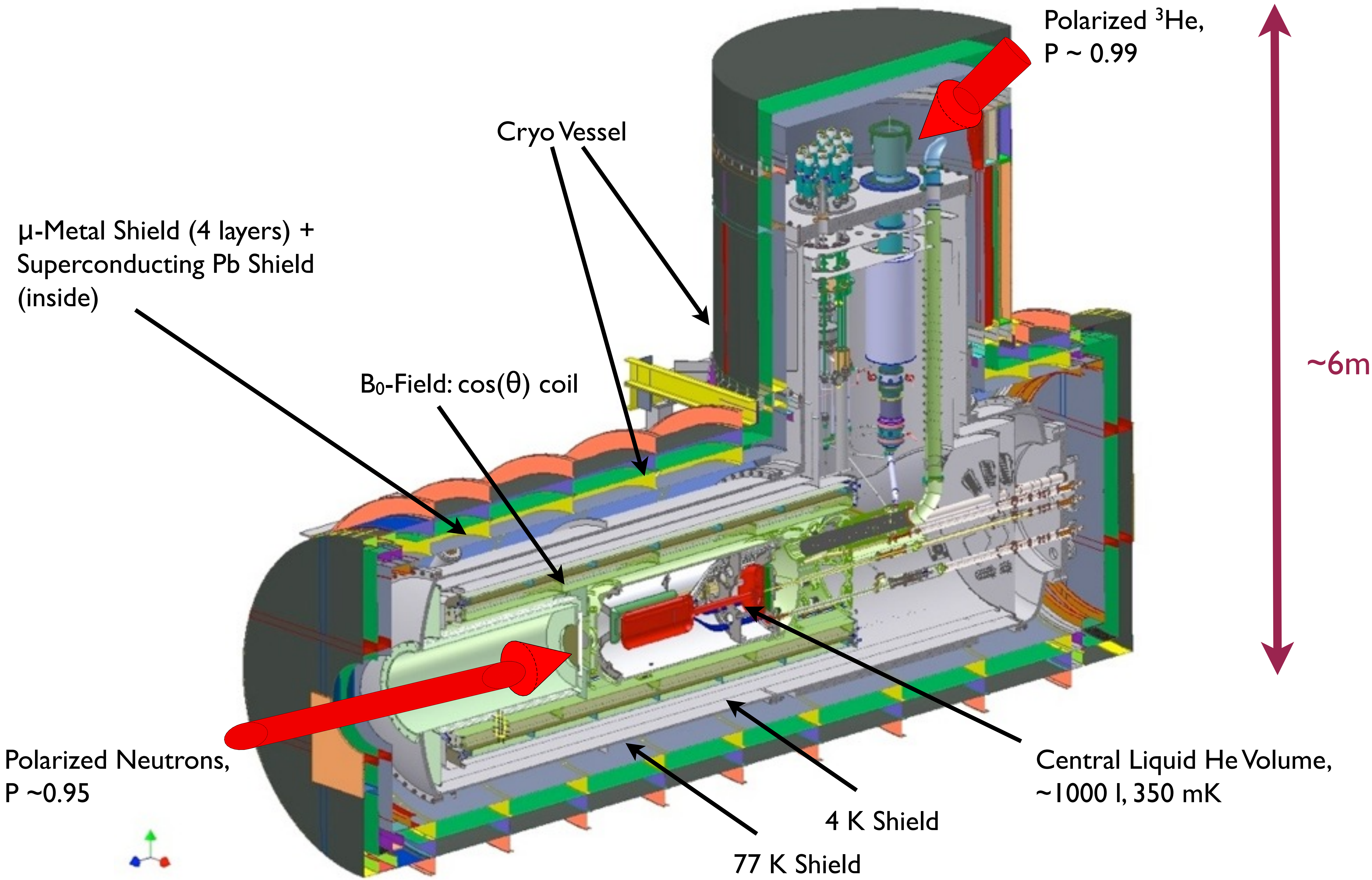
- ORNL Spallation-Neutron-Source: 1 GeV protons, I_p = 1.4 mA on Hg target, 18 beam lines
- First SNS beam on target - April 2006
- P = 1.4 MW
- Final peak neutron flux: 20-100 × ILL

Neutron EDM (SNS)

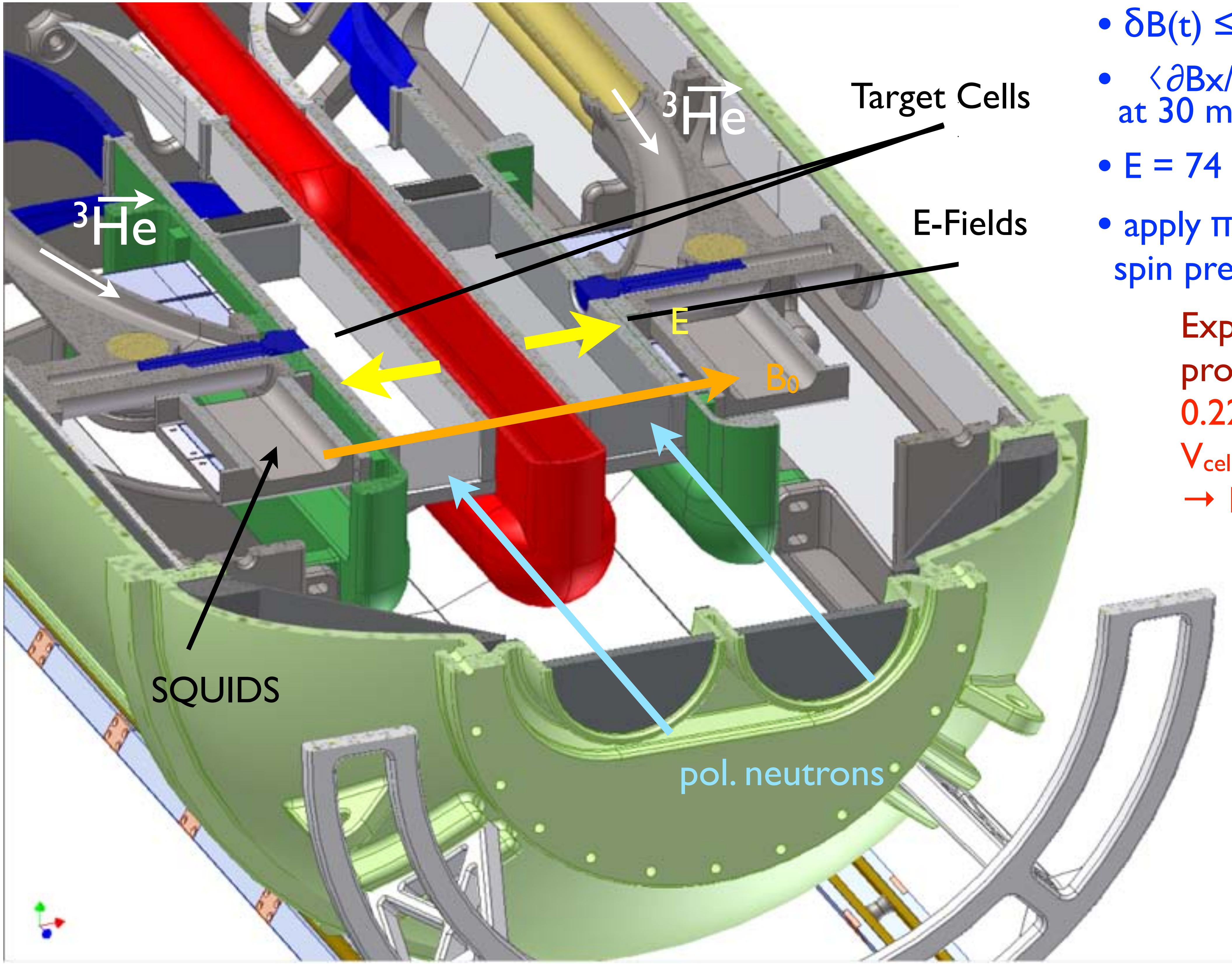
Key features:

- Production of UCNs in superfluid ^{4}He
- Polarized ^{3}He co-magnetometer
  - used as neutron precession monitor via spin-dependent n-^{3}He capture
    → detected via wavelength shifted light in SF ^{4}He
  - Vary influence of external B-fields via "dressed spins"
    → Extra RF field allows control of n and ^{3}He relative precession frequency
  - Study dependence on B-field, B-gradients and ^{3}He density
- Highly uniform E and B fields
- Superconducting magnetic shield
- Two cells with opposite fields
- Control of central temperature
  - vary ^{3}He diffusion which changes geometric phase effect on ^{3}He

Neutron EDM: SNS



Neutron EDM (SNS)



- $\delta B(t) \leq 8$ nG per cycle
- $\langle \partial B_x/\partial x \rangle < 50$ nGauss/cm at 30 mGauss
- E = 74 kV/cm
- apply π/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

EDM(SNS): Systematic Effects and Controls

Source of Error	Sys. Uncert. (e·cm)	Comment
Linear v×E (Geometric Phase)	$< 1 \times 10^{-28}$	Uniformity of B
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 (SNS)

Passed DOE/NSF review in Dec. 2013

- Key technical milestones largely met
  - High E-fields (in medium scale apparatus)
  - Uniform magnetic fields
  - Polarized 3He transport demonstrated
  - Progress on UCN storage, SQUIDs, and light collection

Comparison with ILL

	ILL (published)	SNS (projected)
N	13,000	400,000
E-Field	10 kV/cm	74 kV/cm
T	130 s	1000 s
m (cycles/day)	270	25
σ (e · cm/day)	3×10^{-25}	3.5×10^{-27}

Path to experiment

- 4 year "Critical Component Demonstration"
- Complete construction in 2 years
- Commissioning in 2019-2020

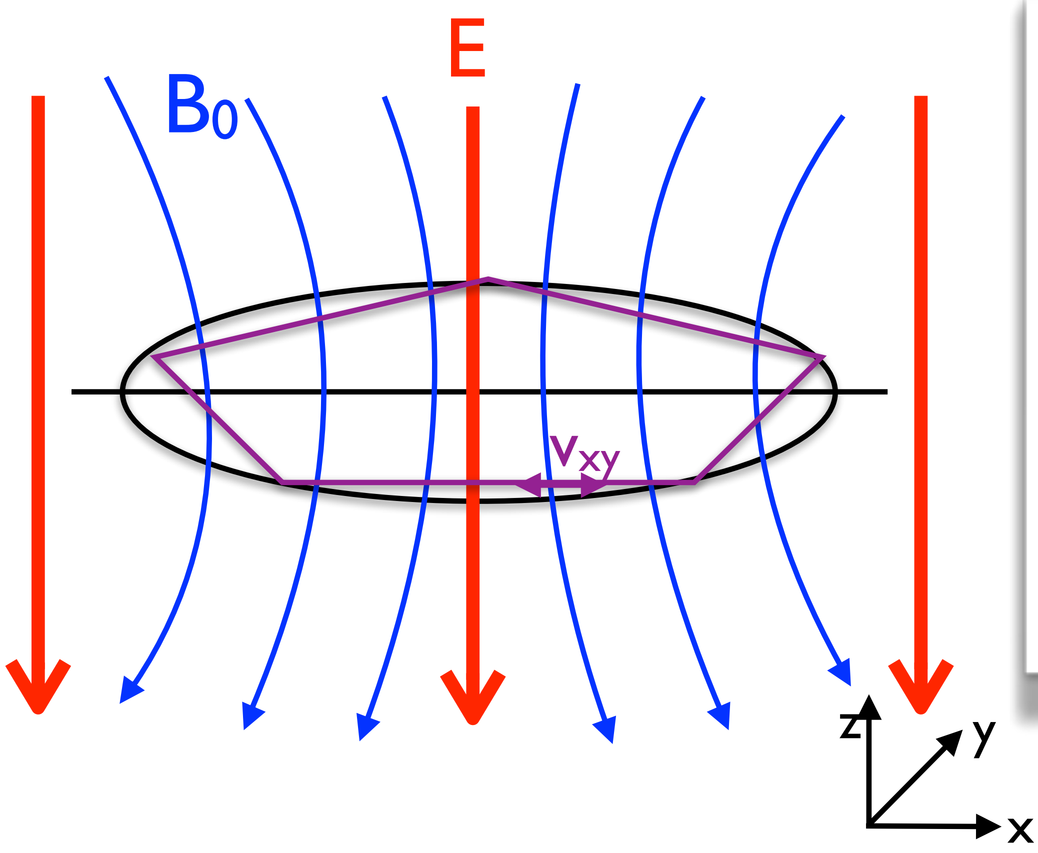
Summary

- Exciting time to search for new limits on permanent neutron 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 and other BSM models

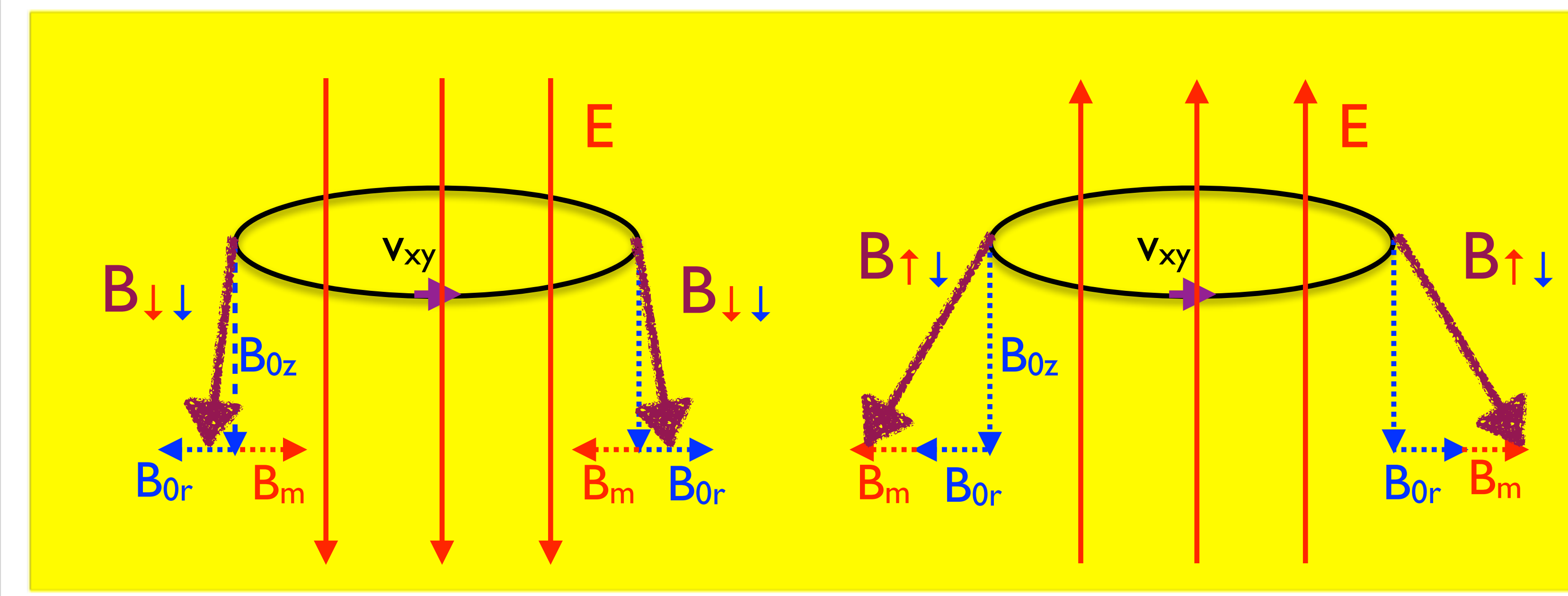
Exciting years ahead of us!

Backup Slides

Systematics Example: Geometric Phase



B-field with radial gradient



$$(\Delta\phi_{\uparrow\uparrow} - \Delta\phi_{\uparrow\downarrow}) = -2\gamma^2 B_{0r}|B_m|\frac{|\omega_r|}{(\omega_0^2 - \omega_r^2)} \cdot T$$

Due to field gradient

v × E

- Relativistic effect for particles with v ~ 4 m/s
- Effect doesn't cancel for $v_{xy} \leftrightarrow -v_{xy}$
- Effect is linear in E → causes false EDM signal
- Need uniform B-field (here $|\nabla B|$ < 3 ppm/cm (100 nG/cm @ 30 mG)