A Next Generation Search of the Neutron EDM

13th PIKIMO Meeting

University of Cincinnati

November 12, 2022

Wolfgang Korsch

Oak Ridge National Laboratory

Funding Agencies

nEDM @SNS

Outline

- *Motivation for Permanent EDM Searches*
- *Short History and Present Status*
- *New Experiment at Spallation Neutron Source (nEDM@SNS)*
- *Conclusions*

One Motivation for EDM Searches

Baryon Asymmetry of the Universe (BAU) → today:

We live in a matter dominated Universe: $\dfrac{\phi_{\bar{p}}}{\phi_p} \sim 10^{-4}$

M. Aguilar et al., PRL 117, 091103 (2016)

Sakharov: Three Conditions:

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

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

Note: Standard EW baryogenesis assumes a 1st order phase transition, but Higgs boson too heavy → need add'l EW-scale scalar field + strong (Higgs) Yukawa couplings or other models ....

Leptogenesis?

Andrei Sahkarov

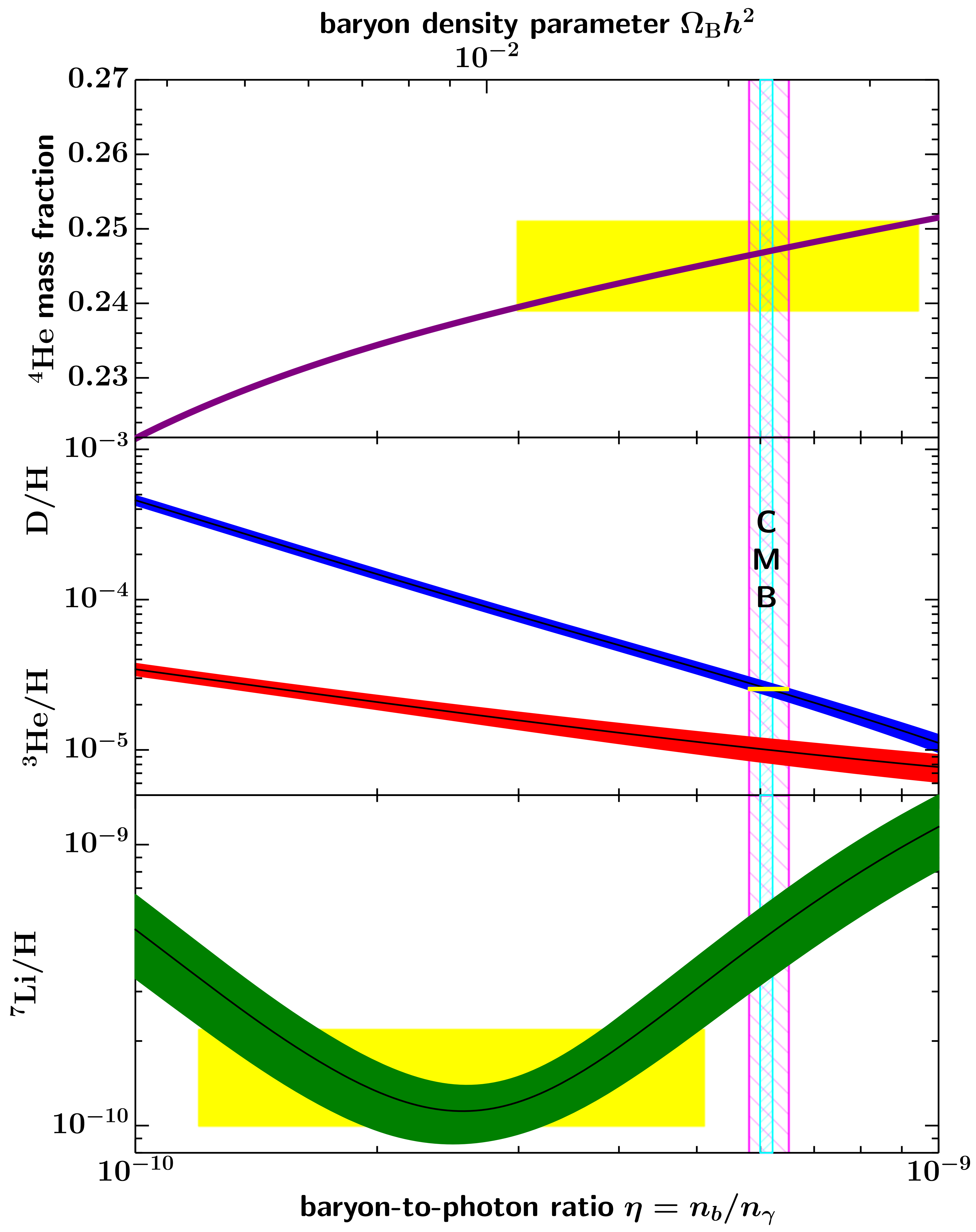
Present Baryon Asymmetry of the Universe

$$\eta = \left(\frac{n_b - n_{\bar{b}}}{n_\gamma}\right) \approx \left(\frac{n_b}{n_\gamma}\right) = \begin{cases} (5.8 - 6.5) \times 10^{-10} & \text{(BBN)} \\ 6.5^{+0.4}_{-0.3} \times 10^{-10} & \text{(WMAP CMB)} \\ (6.12 \pm 0.04) \times 10^{-10} & \text{(Planck CMB)} \end{cases}$$

Standard Model (CKM) estimate: $\eta_{SM} \lesssim 10^{-20}$

A. Shindler, Eur. Phys. J. A (2021) 57:128

☛ SM estimate too small ➡ new sources of $\cancel{CP}$ needed



R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022 , 083C01 (2022)

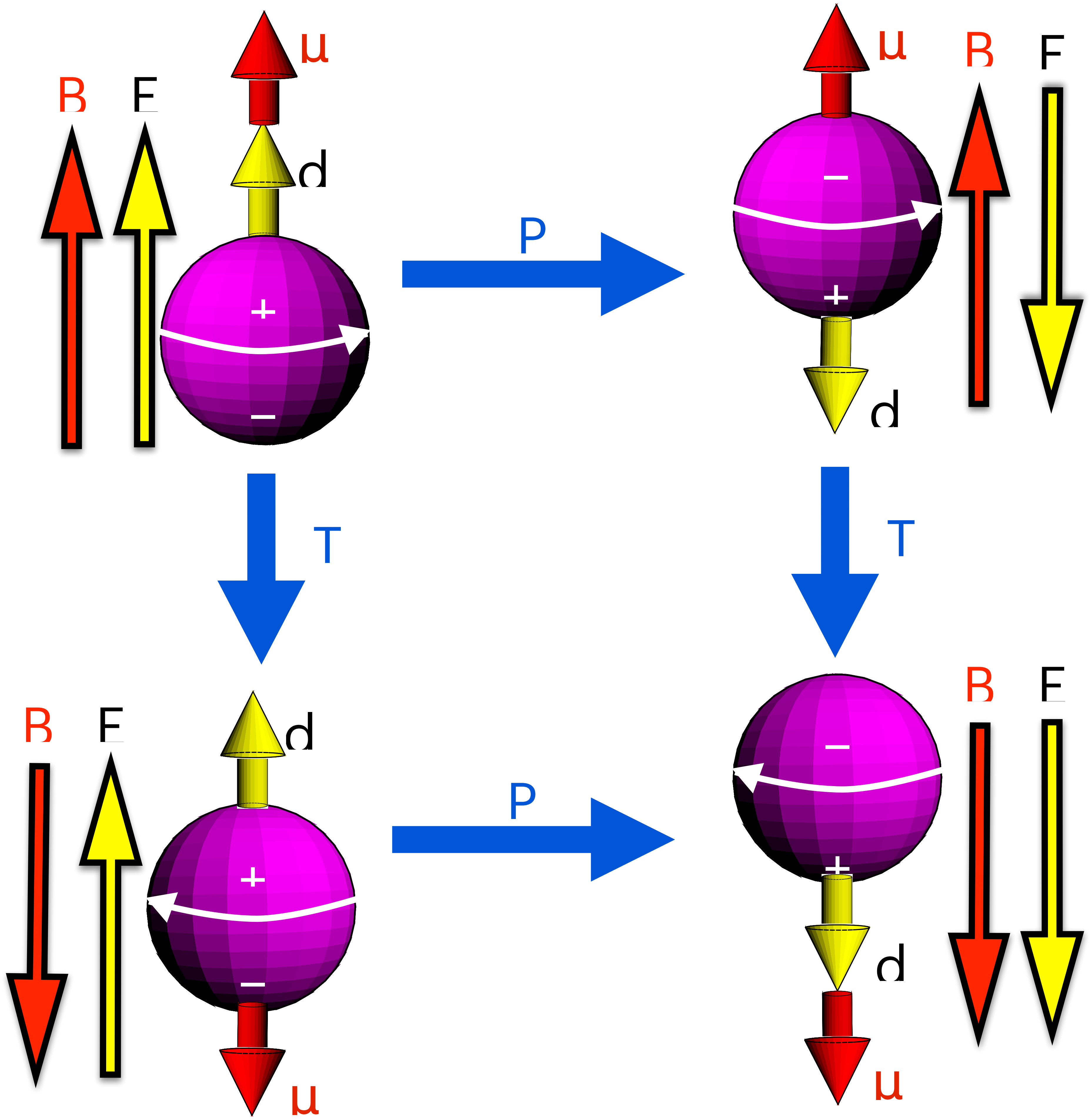
How Can Searches for Permanent EDMs Contribute ?

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

$$\vec{d} = d\vec{\sigma}$$

$$\left.\begin{array}{l}\vec{d} \rightarrow \text{vector} \\ \vec{\sigma} \rightarrow \text{axial-vector}\end{array}\right\} \Rightarrow \quad d = 0$$

Assuming CPT:
⇒ d ≠ 0 ⇔ CP violation, T violation



Sensitivity to New Particles

Simple estimate of sensitivity to new physics (SUSY):

dimensional analysis, under $SU(2)_L \times U(1)$ gauge invariance:

Quark EDM

$$d_d \sim e \cdot \frac{\alpha}{4\pi} \cdot \frac{m_d(MeV)}{\Lambda^2(TeV^2)} \cdot \sin(\phi_{CP})$$

loop factor

CP breaking scale

~~CP~~ phase

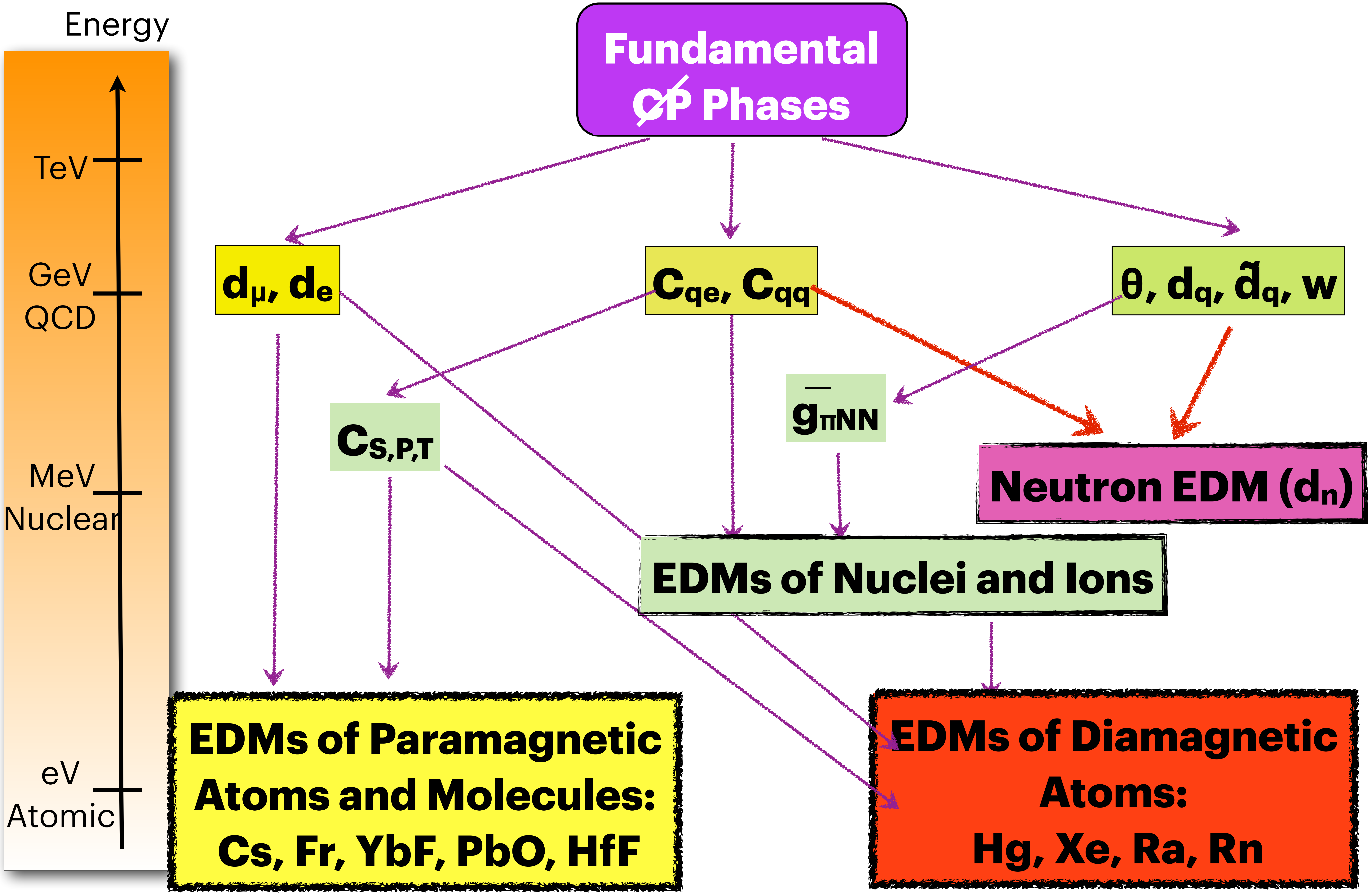
Assuming $\sin(\Phi_{CP}) \sim 1$:

☛ $d_n \sim d_d \sim 2 \cdot 10^{-26}$ e · cm ↔ $\Lambda \sim 3.4$ TeV

$d_d \sim 3 \cdot 10^{-28}$ e · cm ↔ $\Lambda \sim 28$ TeV

de Rujula et al., Nucl. Phys. B 357, 311 (1991)
T. Chupp, S. Gardner, and Z._L., Project X, arxiv.org/pdf/1306.5009

From Experiment to Theory



Fundamental $\cancel{CP}$ Phases

d_μ, d_e

C_{qe}, C_{qq}

θ, d_q, $\tilde{d}_q$, w

$C_{S,P,T}$

$\bar{g}_{\pi NN}$

Neutron EDM (d_n)

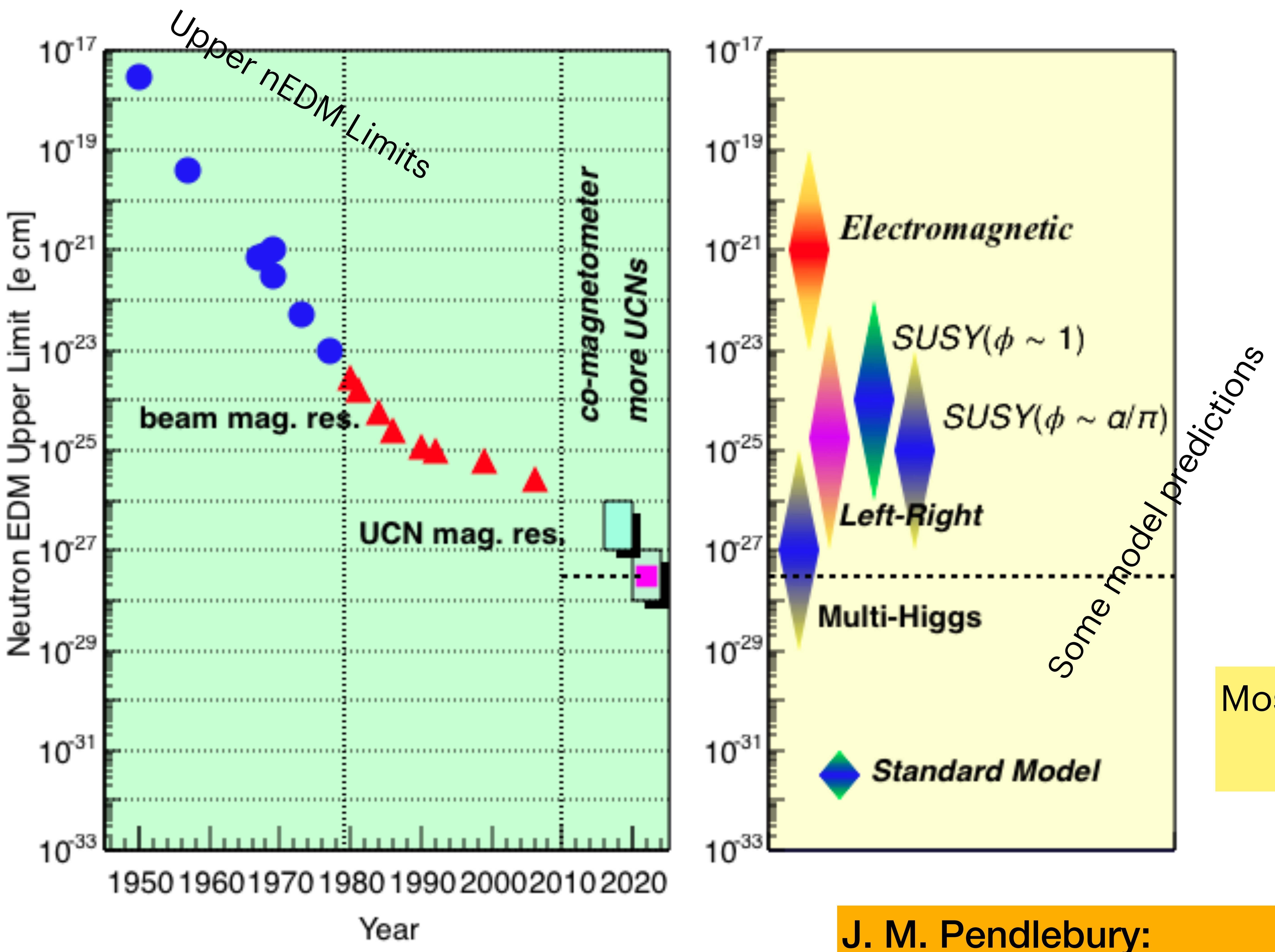
EDMs of Nuclei and Ions

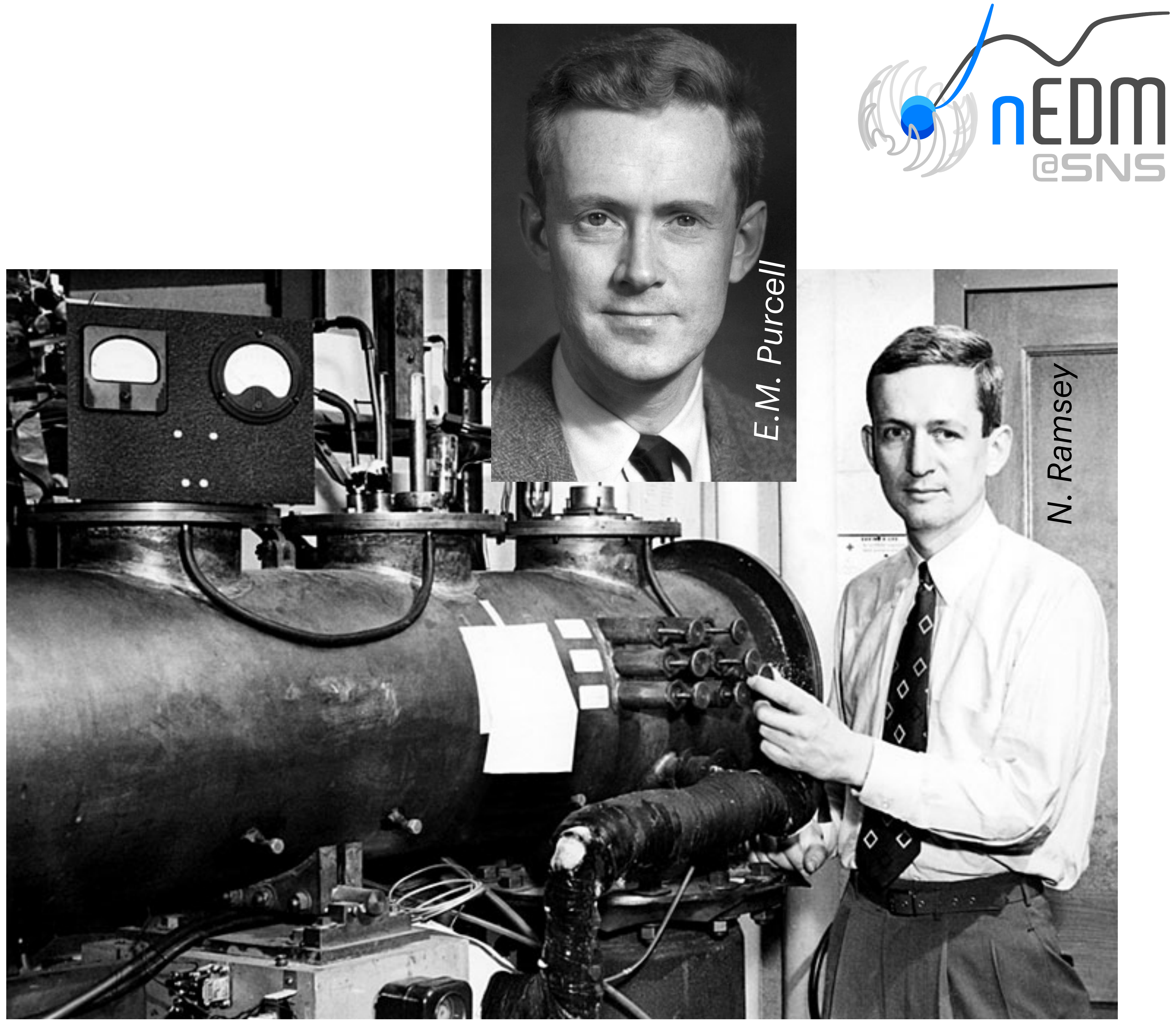
EDMs of Paramagnetic Atoms and Molecules: Cs, Fr, YbF, PbO, HfF

EDMs of Diamagnetic Atoms: Hg, Xe, Ra, Rn

A. Ritz and M. Pospelov, CIPANP 2009
for review see: hep-ph/0504231

History of Neutron EDM Searches





Photos: Physics Today 66 (2013), nobelprize.org

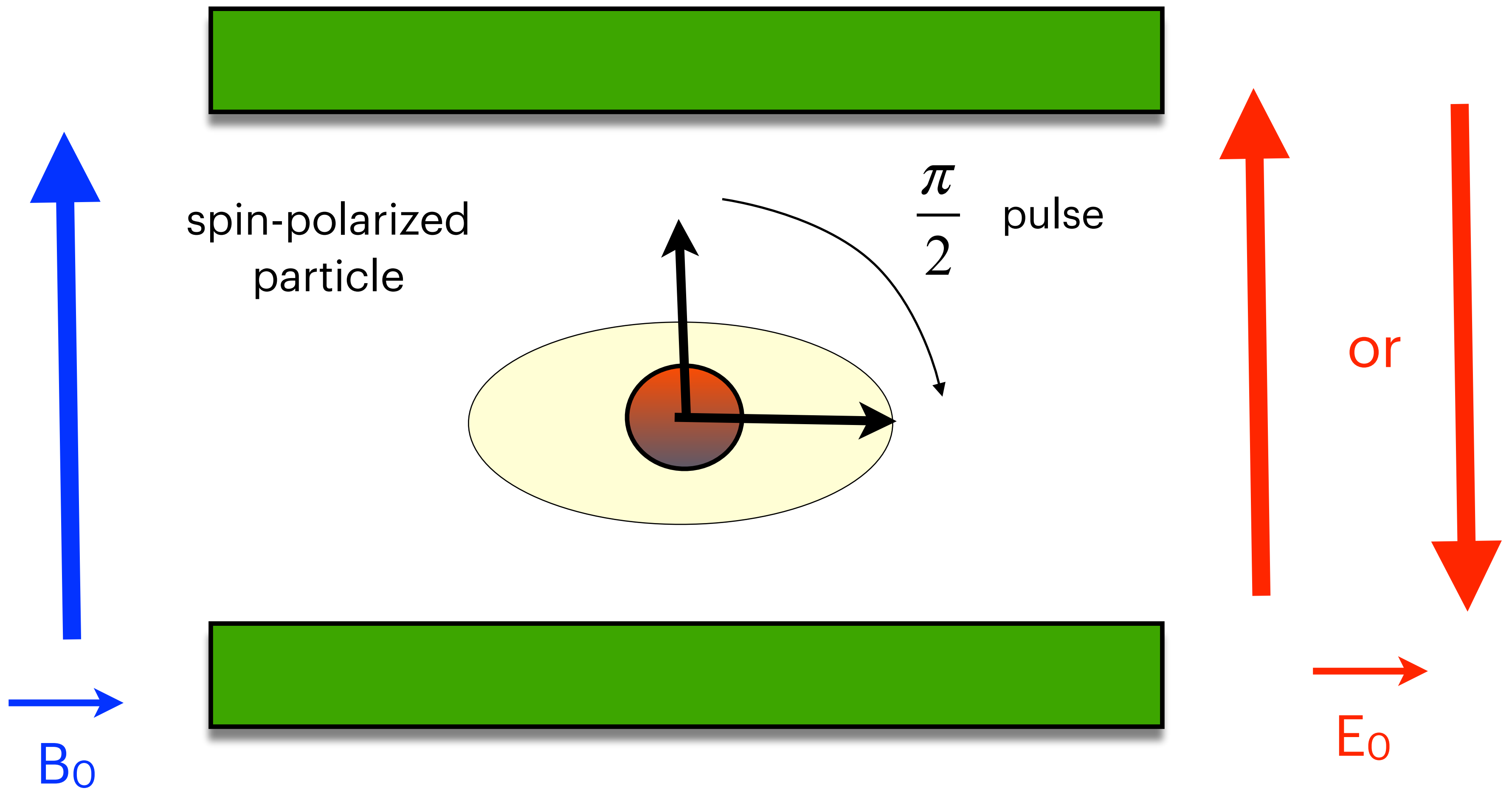
Most recent SM estimate for nEDM:

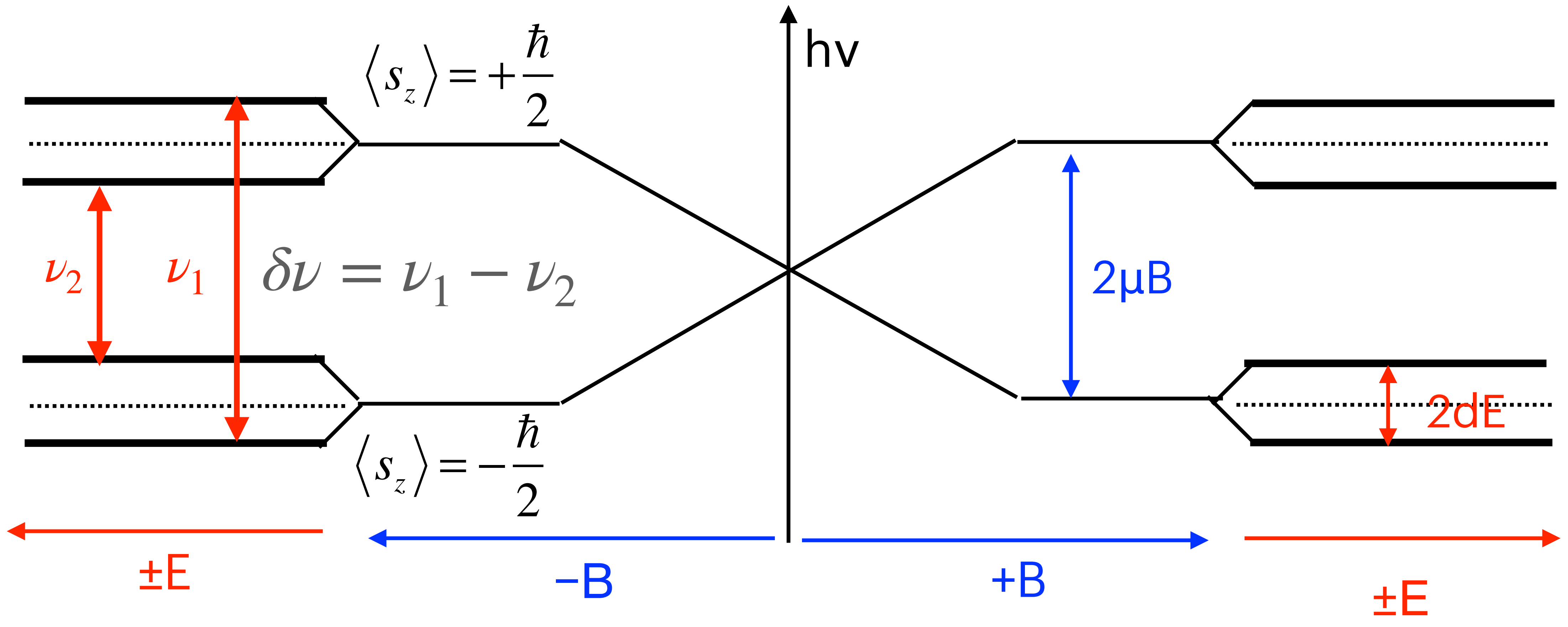
$$(1-6)\times 10^{-32} e \cdot cm$$

C.-Y. Seng, Phys. Rev. C 91, 025502

J. M. Pendlebury:
“nEDM has killed more theories than any other single experiment.”

General Idea of Modern EDM Searches





- ***$\mu_m \sim 1$ ☞ need small B_0***
- ***$d_e \sim 0$ ☞ E_0 very large***

$$h\nu = 2(\mu_m \cdot B_0 \pm d_e \cdot E_0)$$

$$\boxed{d_e = \frac{h\delta\nu}{4E_0}}$$

Sensitivity to EDMs

T_m = *time for one measurement*

Fundamental (q.m.) limit:

$$\left.\begin{array}{l}\Delta E\cdot\Delta T=\hbar\\ \Delta T=T_m\\ \Delta E=\hbar\cdot 2\pi\Delta\nu\end{array}\right\} ☛\ \Delta\nu=\frac{1}{2\pi T_m}$$

$$d_e=\frac{h\delta\nu}{4E_0}\quad\Rightarrow\quad\Delta d_e=\frac{h\Delta(\delta\nu)}{4E_0}=\frac{\hbar}{4E_0T_m}$$

N particles, m measurements

$$\Delta d_e=\frac{\hbar}{\alpha 4E_0T_m\sqrt{mN}}$$

It's all about measuring

$$\longrightarrow$$

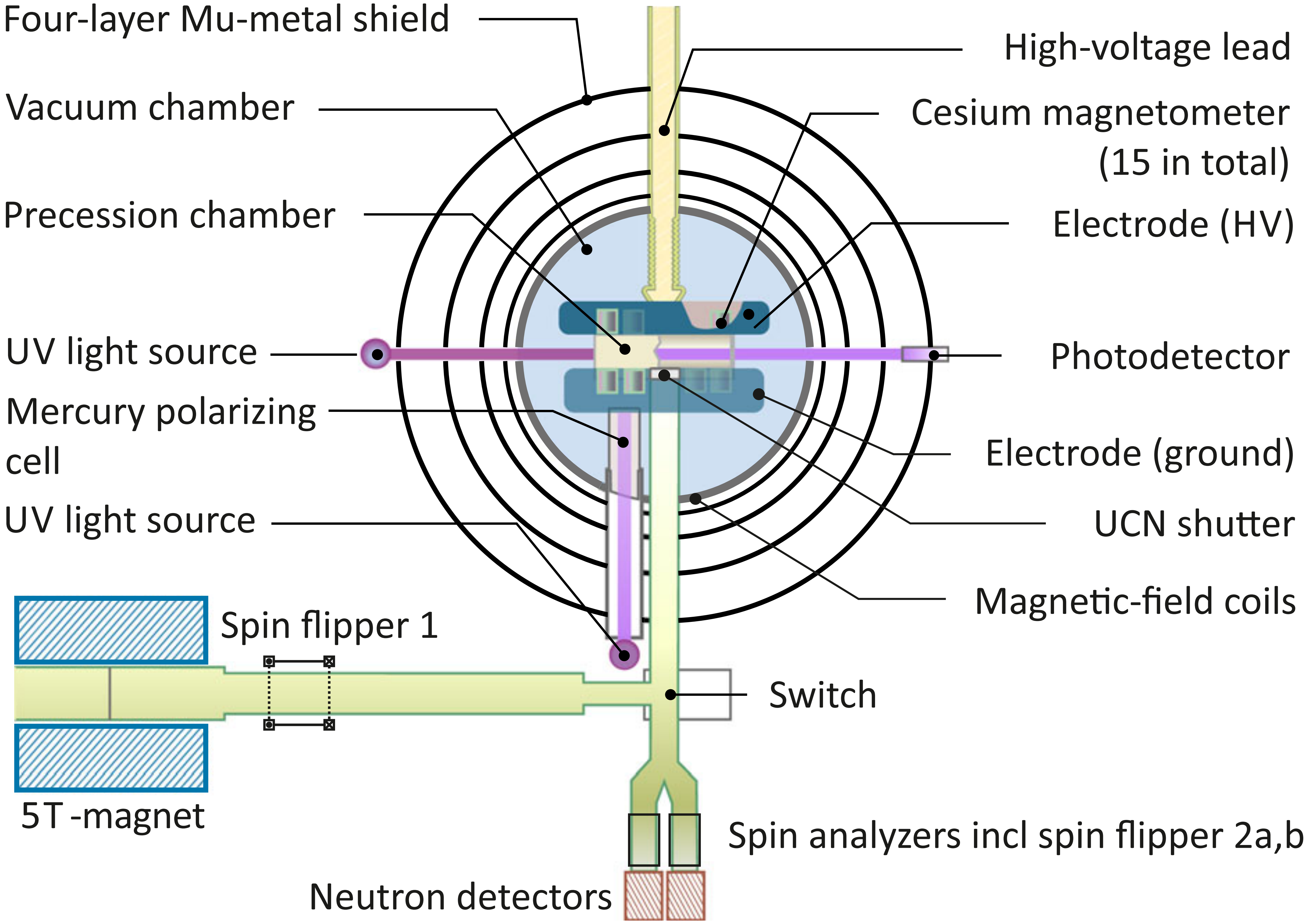
small phases

$$\delta\phi=\delta\nu\cdot T_m$$

(α imperfections, inefficiencies, backgrounds)

Where are we now? Best Limit on nEDM

Paul Scherrer Institute
(Villigen, Switzerland)



- Volume ~ 6.63 l
- T_m = 180 s (per cycle)
- $N \approx 11.4 \times 10^4$ (per cycle)
- E_0 = 11 kV/cm

ρ_{UCN} ~ 2/cm³

Ultra-cold Neutrons (UCN) in a storage cell (at T ~ 300 K):

dominating systematic uncertainties:

- *higher order B-field gradients - 1.0×10^{-27} e · cm*
- *uncompensated B-field gradient drifts - 0.75×10^{-27} e · cm*
- ….

$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys})\times10^{-26}$ e · cm

$|d_n| < 1.8\times10^{-26}$ e · cm (90% C.L.)

C. Abel et al., PRL 124, 081803 (2020)

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

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

It took 14 years to improve nEDM limit by ~40%!!

How Can We Improve Limit on nEDM ?

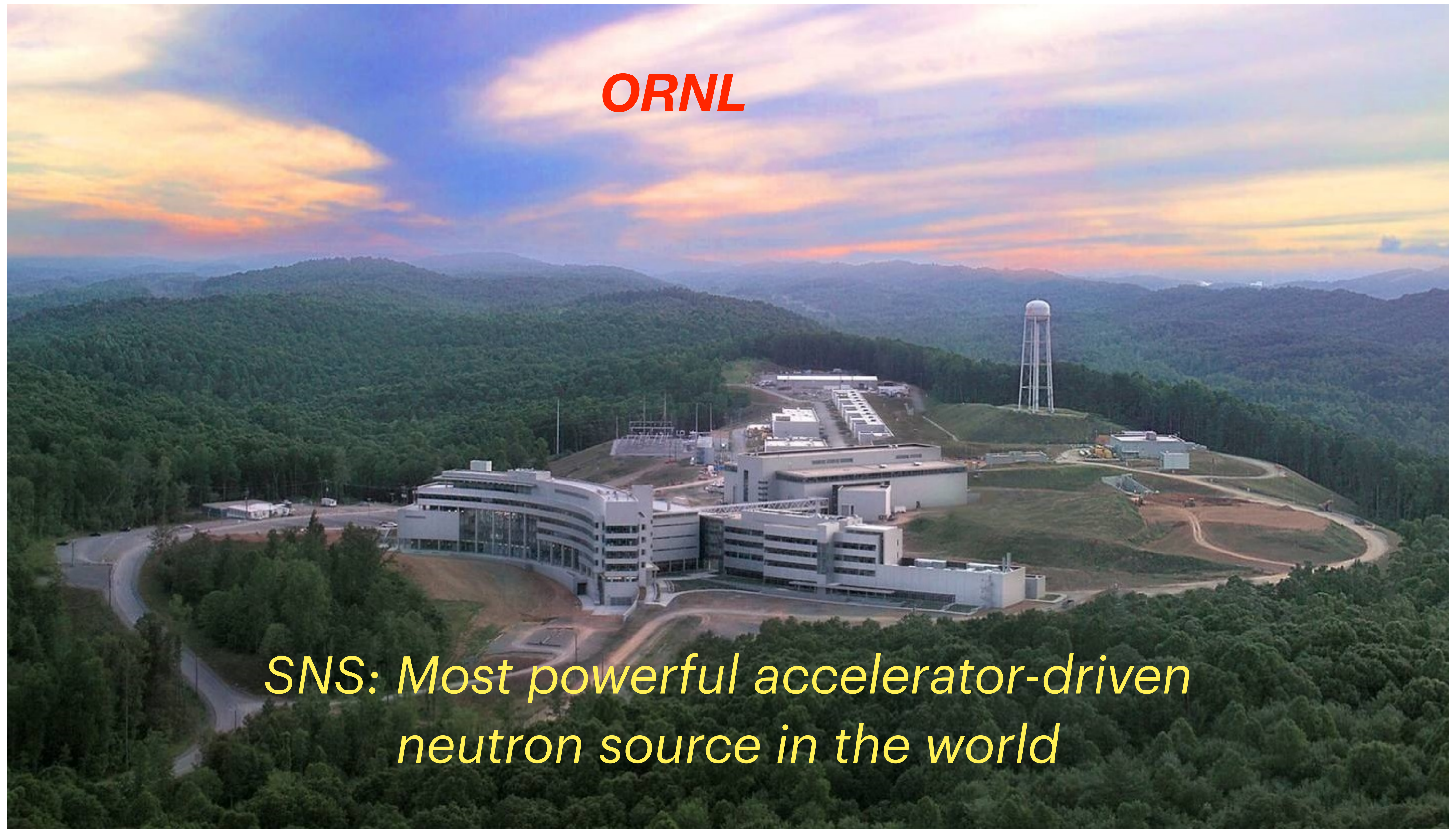
- ***more neutrons ⇒ produce "ultra-cold" neutrons in target***
- ***longer measuring times (limited by neutron lifetime: ~880 s)***
- ***higher electric fields***
- ***more uniform and stable magnetic fields***
- ***monitor magnetic field stability in target ⇒ co-magnetometer***

nEDM@SNS Collaboration

Co-spokespeople: V. Cianciolo, B. Filippone
Chief Senior Scientist: R. Golub
Chief Engineer: J. Ramsey

Experiment Director: P. Huffman
Experiment Managers: A. Saunders, B. Plaster

Collaboration: ~95 members



SNS: Most powerful accelerator-driven neutron source in the world

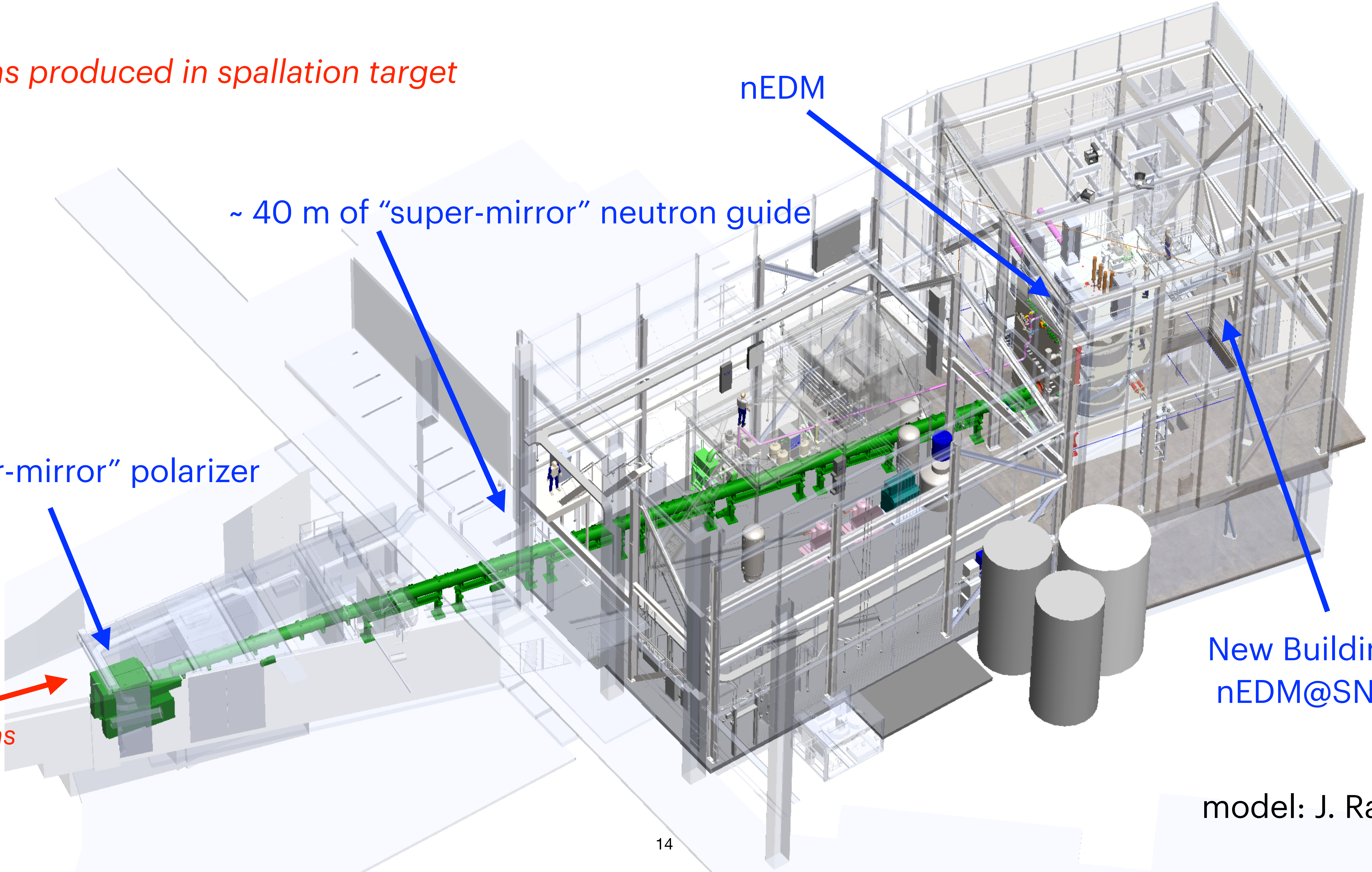
M.W. Ahmed,[a,b,c] **R. Alarcon,**[d] **A. Aleksandrova,**[e] **S. Baeßler,**[f,g] **L. Barron-Palos,**[h]
L.M. Bartoszek,[i] **D.H. Beck,**[j] **M. Behzadipour,**[e] **I. Berkutov,**[c] **J. Bessuille,**[k] **M. Blatnik,**[l]
M. Broering,[e] **L.J. Broussard,**[g] **M. Busch,**[b] **R. Carr,**[l] **V. Cianciolo,**[g] **S.M. Clayton,**[m]
M.D. Cooper,[m] **C. Crawford,**[e] **S.A. Currie,**[m] **C. Daurer,**[i] **R. Dipert,**[d] **K. Dow,**[k] **D. Dutta,**[n]
Y. Efremenko,[g,o] **C.B. Erickson,**[j] **B.W. Filippone,**[l,1] **N. Fomin,**[o] **H. Gao,**[b] **R. Golub,**[p,c]
C.R. Gould,[q] **G. Greene,**[o,g] **D.G. Haase,**[p,c] **D. Hasell,**[k] **A.I. Hawari,**[p] **M.E. Hayden,**[r] **A. Holley,**[s]
R.J. Holt,[l] **P.R. Huffman,**[p,g,c] **E. Ihloff,**[k] **S.K. Imam,**[o] **T.M. Ito,**[m] **M. Karcz,**[t] **J. Kelsey,**[k]
D.P. Kendellen,[b,c] **Y.J. Kim,**[k] **E. Korobkina,**[p,q,c] **W. Korsch,**[e] **S.K. Lamoreaux,**[u] **E. Leggett,**[n]
K.K.H. Leung,[p,c] **A. Lipman,**[p] **C.Y. Liu,**[t] **J. Long,**[t] **S.W.T. MacDonald,**[m] **M. Makela,**[m]
A. Matlashov,[m] **J.D. Maxwell,**[k,2] **M. Mendenhall,**[l,3] **H.O. Meyer,**[t] **R.G. Milner,**[k] **P.E. Mueller,**[g]
N. Nouri,[e] **C.M. O'Shaughnessy,**[m] **C. Osthelder,**[l] **J.C. Peng,**[j] **S.I. Penttila,**[g] **N.S. Phan,**[m]
B. Plaster,[e] **J.C. Ramsey,**[m,g] **T.M. Rao,**[j,4] **R.P. Redwine,**[k] **A. Reid,**[p,c,5] **A. Saftah,**[e] **G.M. Seidel,**[v]
I. Silvera,[w] **S. Slutsky,**[l] **E. Smith,**[m] **W.M. Snow,**[t] **W. Sondheim,**[m] **S. Sosothikul,**[p,c]
T.D.S. Stanislaus,[x] **X. Sun,**[l] **C.M. Swank,**[l] **Z. Tang,**[m] **R. Tavakoli Dinani,**[r,6] **E. Tsentalovich,**[k]
C. Vidal,[k] **W. Wei,**[h,i] **C.R. White,**[p,c] **S.E. Williamson,**[j] **L. Yang,**[j] **W. Yao**[g] **and A.R. Young**[p]

[a] *Department of Mathematics and Physics, North Carolina Central University, Durham, NC 27707, U.S.A.*
[b] *Department of Physics, Duke University, Durham, NC 27708, U.S.A.*
[c] *Triangle Universities Nuclear Laboratory, Durham, NC 27708, U.S.A.*
[d] *Department of Physics, Arizona State University, Tempe, AZ 85287-1504, U.S.A.*
[e] *Department of Physics and Astronomy, University of Kentucky, Lexington, KY, 40506, U.S.A.*
[f] *Physics Department, University of Virginia, 382 McCormick Road, Charlottesville, VA 22904, U.S.A.*
[g] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, U.S.A.*
[h] *Instituto de Física, Universidad Nacional Autónoma de México, Apartado Postal 20-364, 01000, Mexico*
[i] *Bartoszek Engineering, 818 W. Downer Place, Aurora, IL 60506-4904, U.S.A.*
[j] *Department of Physics, University of Illinois at Urbana-Champaign,*
1110 W. Green St., Urbana, IL 61801-3090, U.S.A.

Physics concept: R. Golub and S. K. Lamoreaux, Phys. Rep. 237, 1 (1994)

Neutron Transport

Neutrons produced in spallation target



nEDM

~ 40 m of “super-mirror” neutron guide

“super-mirror” polarizer

8.9 Å neutrons from FNPB

New Building for nEDM@SNS (EB2)

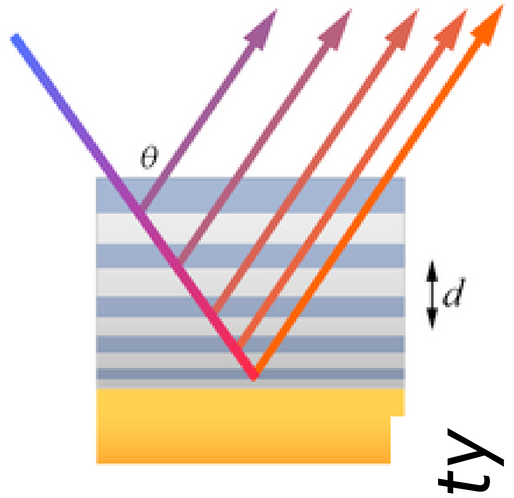
model: J. Ramsey

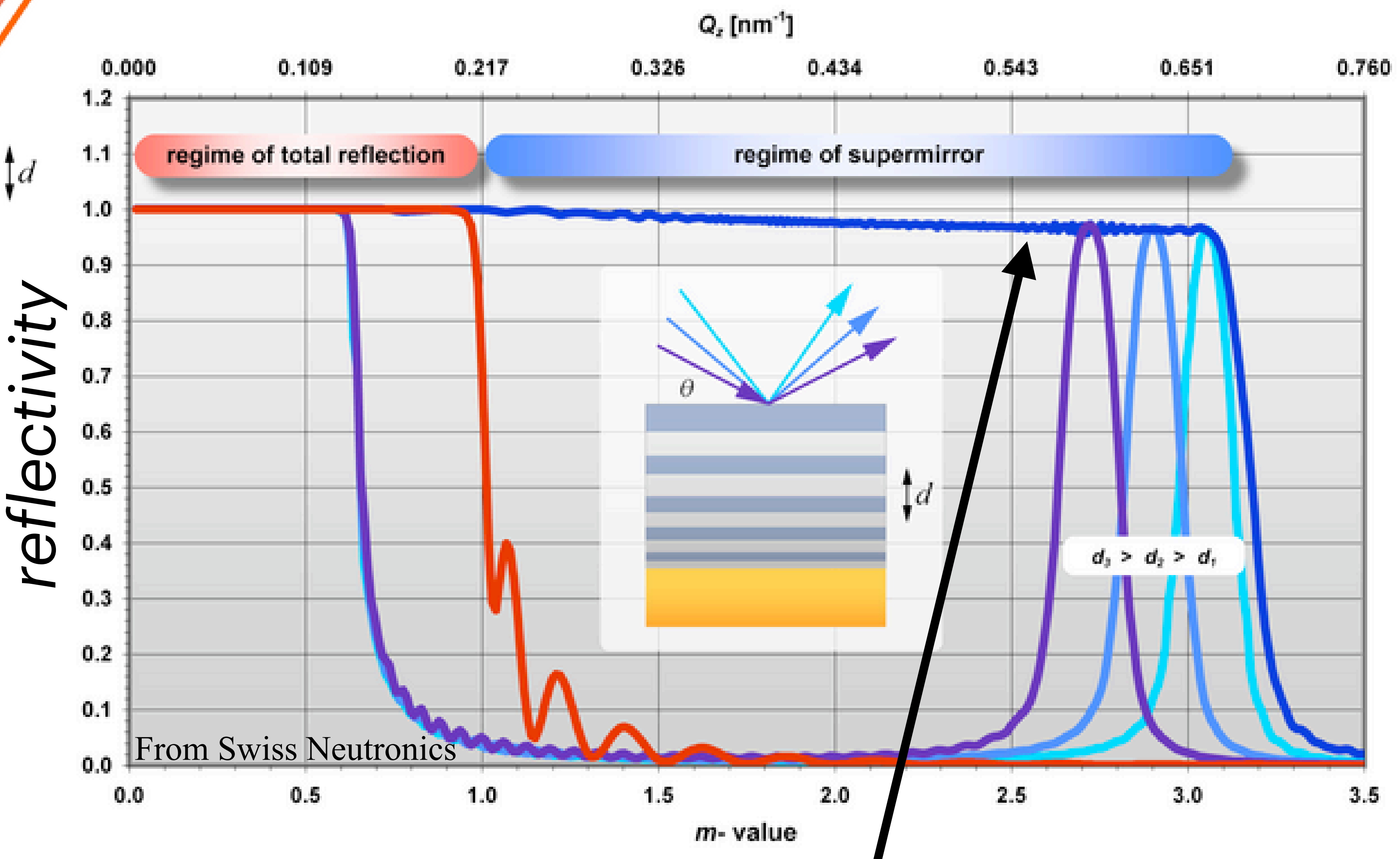
Beamline for Neutrons

Deposit (sputter) coatings e.g. float glass: “grow crystal” = “super-mirror”

100’s of Ni/Ti layers with varying thickness ➜ additional Bragg reflection

Material	V_F [neV]
Ni^{58}	335
Ti	-48





From Swiss Neutronics

100’s of Bragg diffraction peaks
⇒ extents (nearly) continuous reflectivity

Magnetic super-mirrors:

Magnetic potential:

$$V_M = \frac{2\pi\hbar^2 n_0}{m} b = \mu B$$

Spin-dependent index of refraction:

$$n_\pm = 1 - \frac{n_0 \lambda^2}{2\pi}(a \pm b)$$

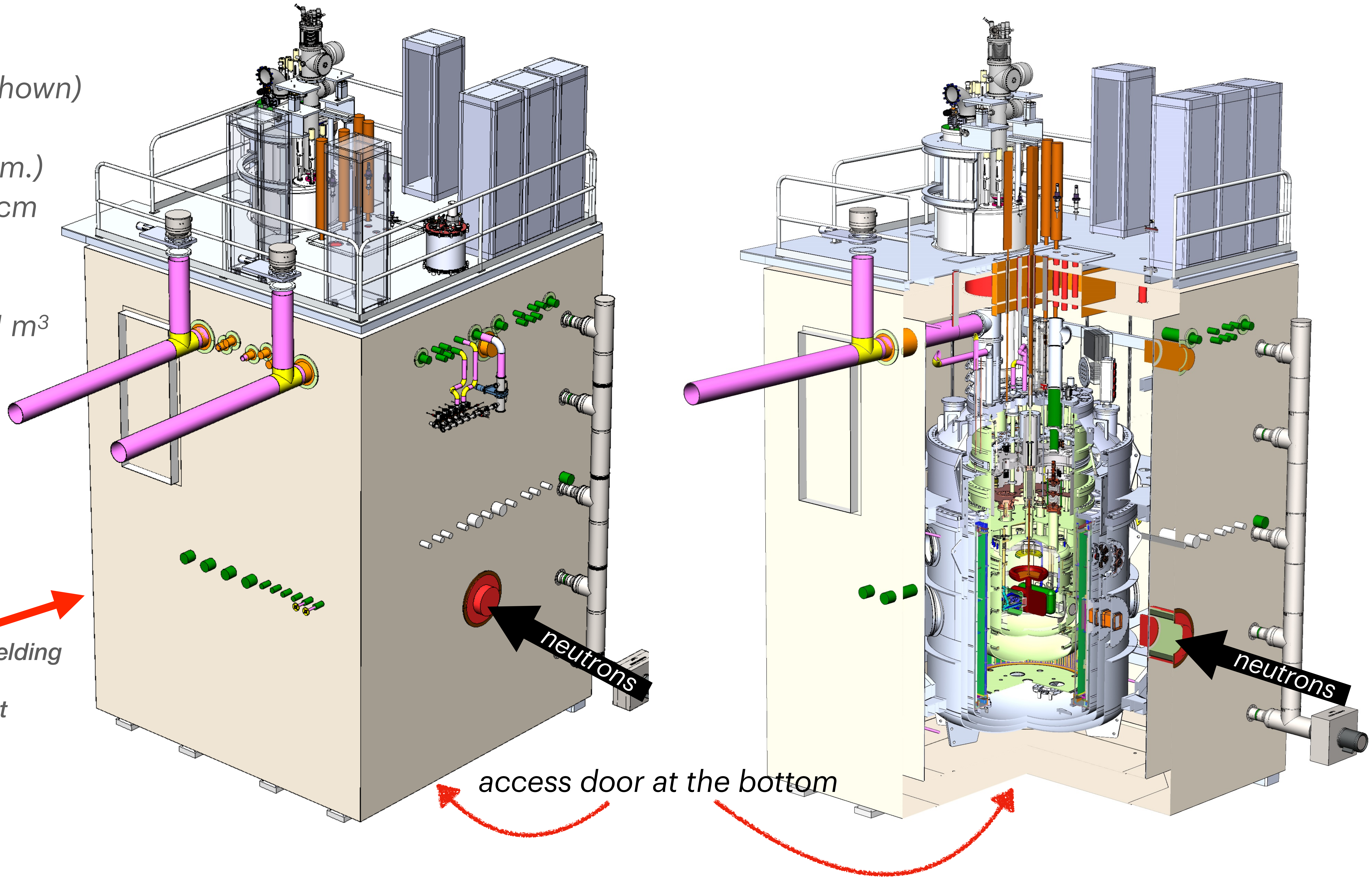
➯ Polarize neutrons
(e.g. Fe/Ti coating)

nEDM Magnetic Shielding Requirements

Outer shielding:
- *Field compensation coils (not shown)*
- *Magnetic shielding enclosure*
  - *4.1 m × 4.1 m × 6.1 m (inner dim.)*
  - *2 × 3 mm μ-metal layers, 40 cm separation*
  - *residual field < 10 nT*
  - *gradient < 2 nT/m in central 1 m^3*
  - *SF 100 @ 0.01 Hz*

Inner shielding:
- *Superconducting Pb*
- *SF ~1000*

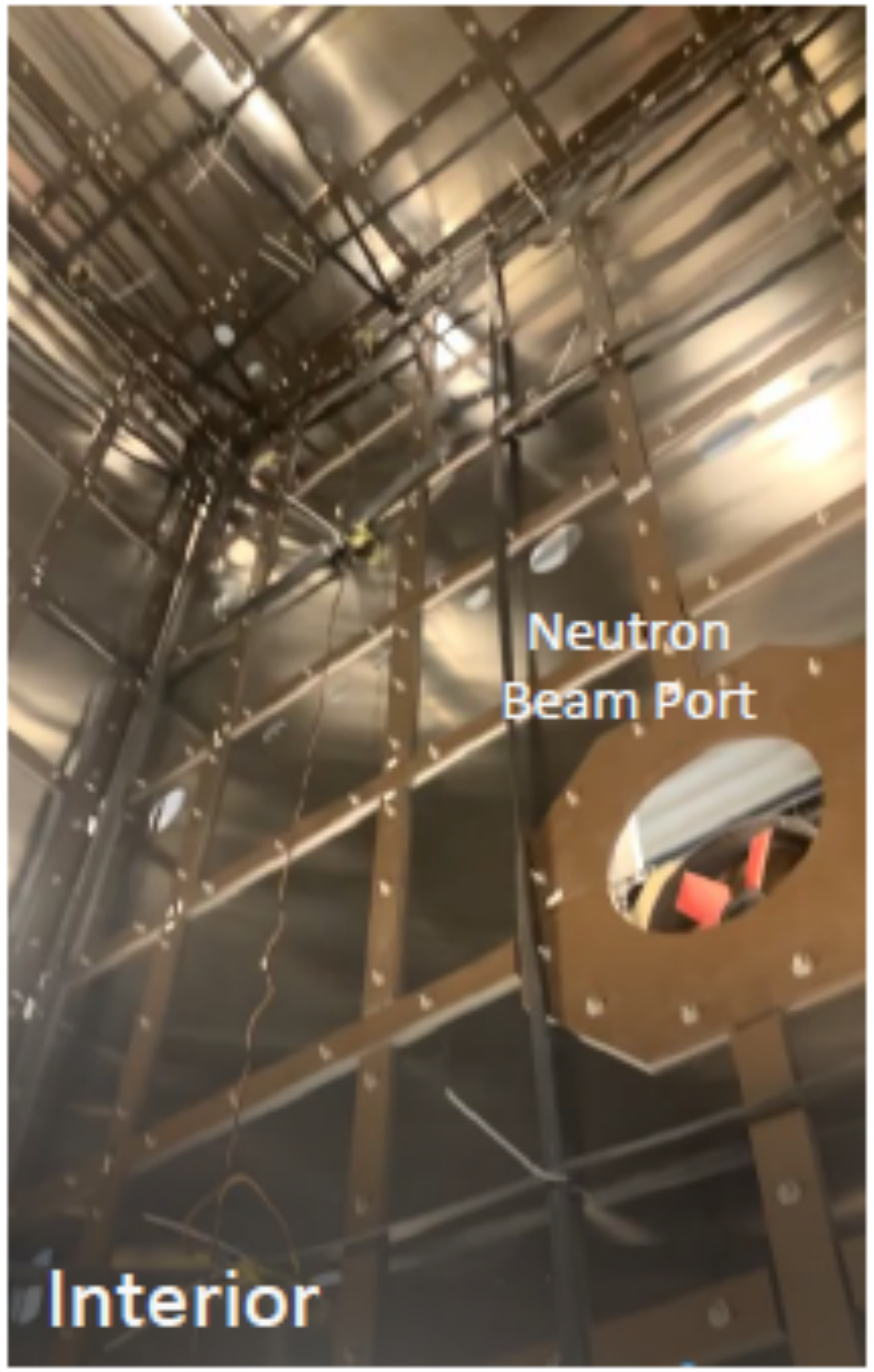
- ***2 layer μ-metal magnetic shielding enclosure***
- ***presently being assembled at IMEDCO***



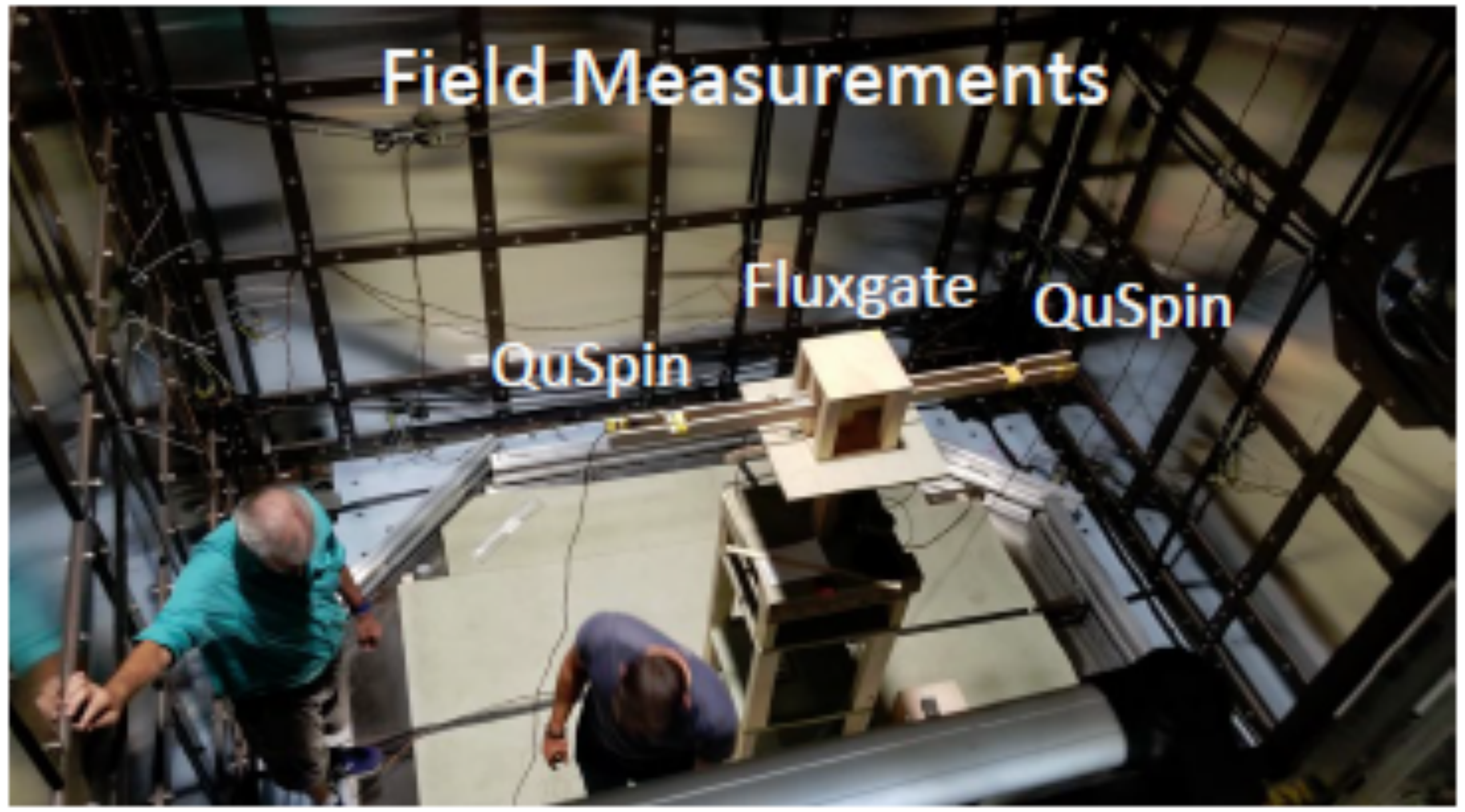
model: J. Ramsey (ORNL)

nEDM Outer Magnetic Shielding


External Coils for Shielding Factor Measurement



Interior dimensions: 4.1 m × 4.1 m × 6.1 m

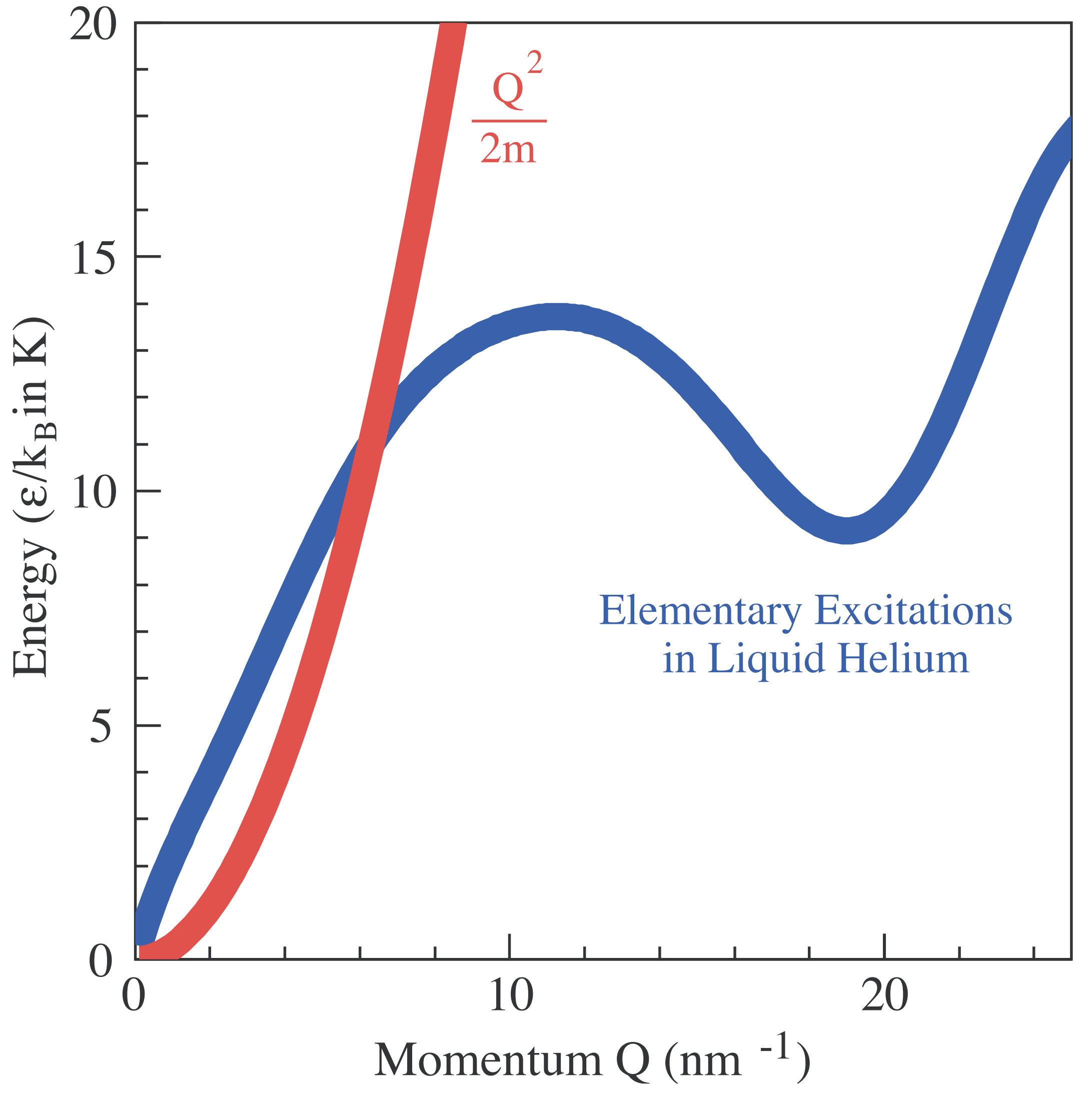


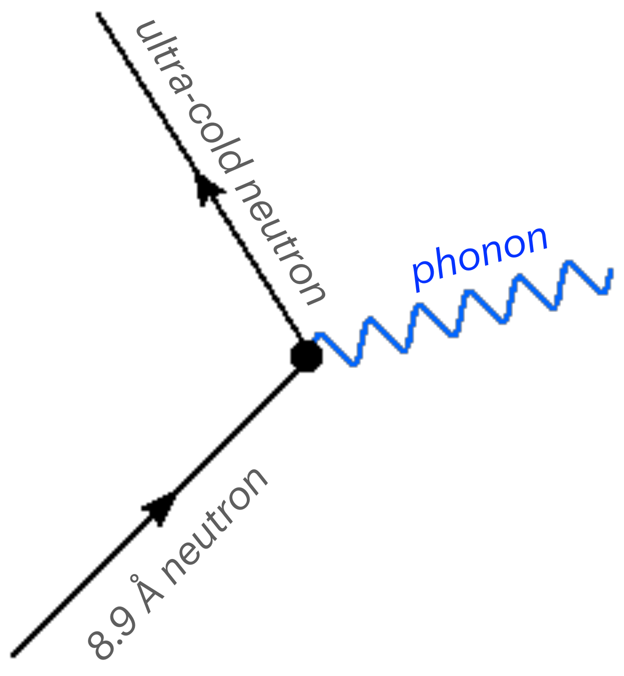
Why 8.9 Å Neutrons ?

Interaction of neutrons with **superfluid ^{4}He**:

$T_{He} < 2.17K$

8.9 Å (at 12 K)





- neutrons lose "all" energy (completely inelastic collision)
  ➛ one phonon excitation ⇨T_{final} < 1 mK ("super-thermal process")
- up-scattering strongly Boltzmann suppressed: $e^{-12K/T_{LHe}}$ (for T_{LHe} < 1 K)

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

The neutrons are now "ultra-cold":

- **E_n ~ 300 neV**
- **v ~ 4 m/s**
- **λ ~ 500 Å**

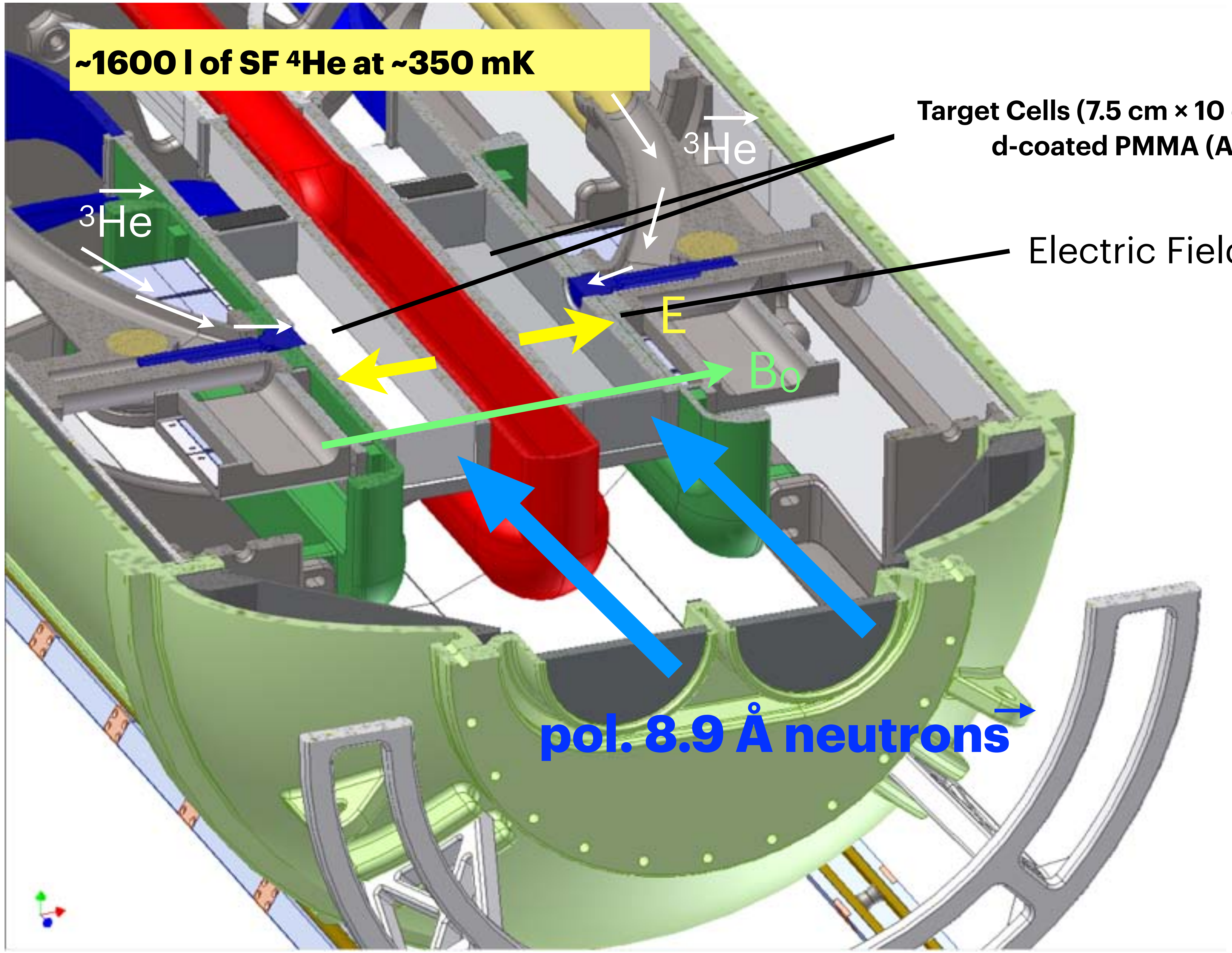
Gravitational Interaction: $V_G = m_n \cdot g \cdot h \approx 103$ neV/m · h

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

Strong Interaction: scattering length > 0 for certain materials

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

The Central Experimental Region



Target Cells (7.5 cm × 10 cm × 40 cm)
d-coated PMMA (Acrylic)

Electric Field

Expected UCN production rate:

- 0.31 UCN/cm^3/s
- V_{cell} = 3,000 cm^3 (each)

- $\delta B(t) \le 8$ nG per cycle
- $\langle \partial B_z/\partial z \rangle < 50$ nGauss/cm at 30 mGauss
- E = 75 kV/cm
- apply π/2 pulse →

Basic Concept of Experiment: Free Precession

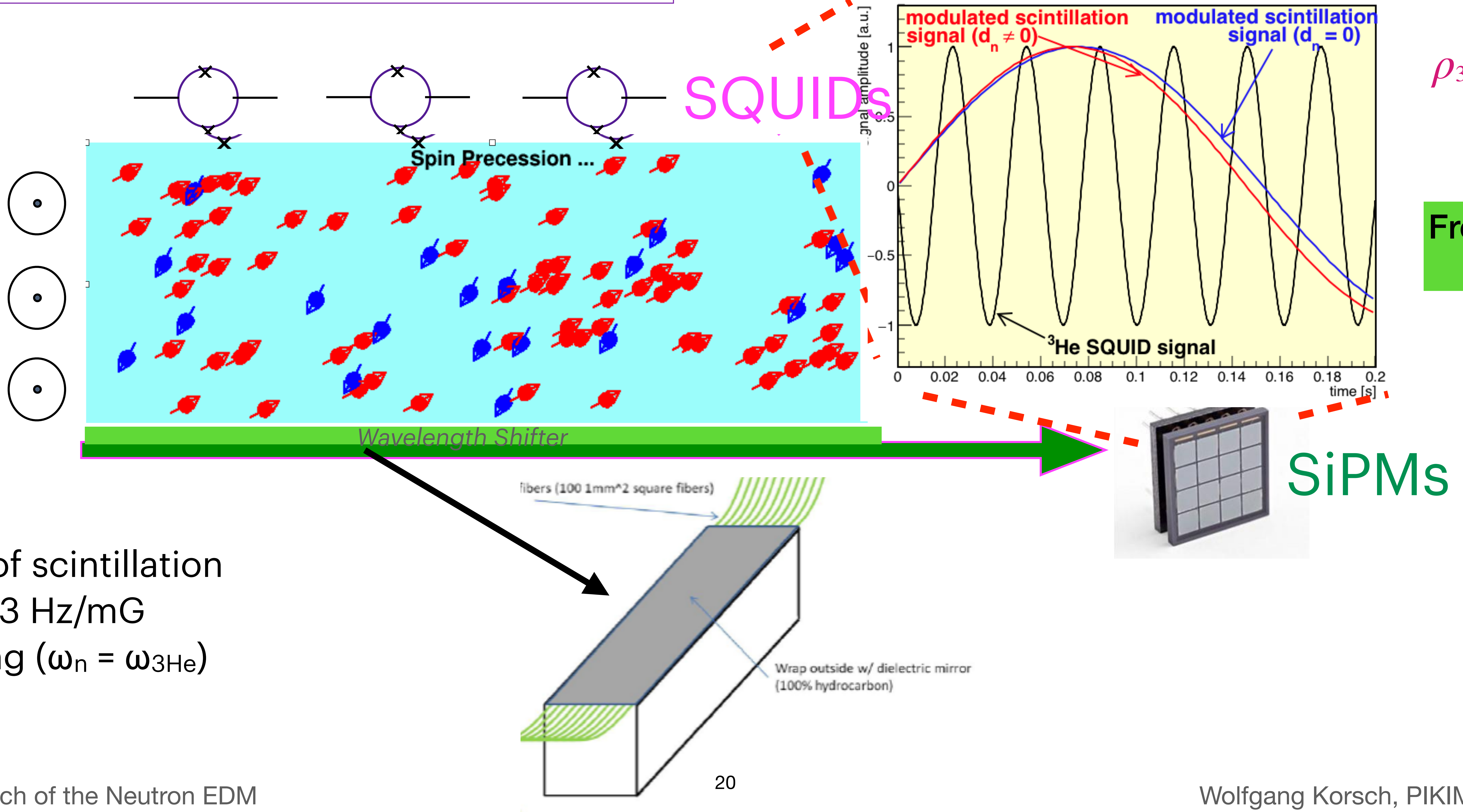
Take advantage of the strong spin-dependent cross section:

- store polarized UCNs in a box and add polarized ^{3}He
- $n + {}^3He^{++} \rightarrow p + t$ +764 keV
- detect scintillation light in SFLHe ($^4He_2^*$)

G. Greene: "The reason for the existence of helium is to measure the neutron EDM"

E-Field

B-Field



$$\rho_{^3He} \approx 10^{10} \rho_n$$

Free precession mode

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

… or Use Critical Spin Dressing

New concept:

- Apply *non-resonant magnetic RF field in x(or y) direction:* $B_x(t) = B_{rf} \cdot cos(\omega_{rf}t)$
- Look at *time-averaged component of spin along B₀-direction:*

$$< cos(\theta(t)) >_T = \frac{1}{T}\int dt \cdot cos(\gamma\left(B_{rf}/\omega_r\right) sin(\omega_{rf}t)) = J_0(x),\ x = \gamma\left(B_{rf}/\omega_{rf}\right)$$

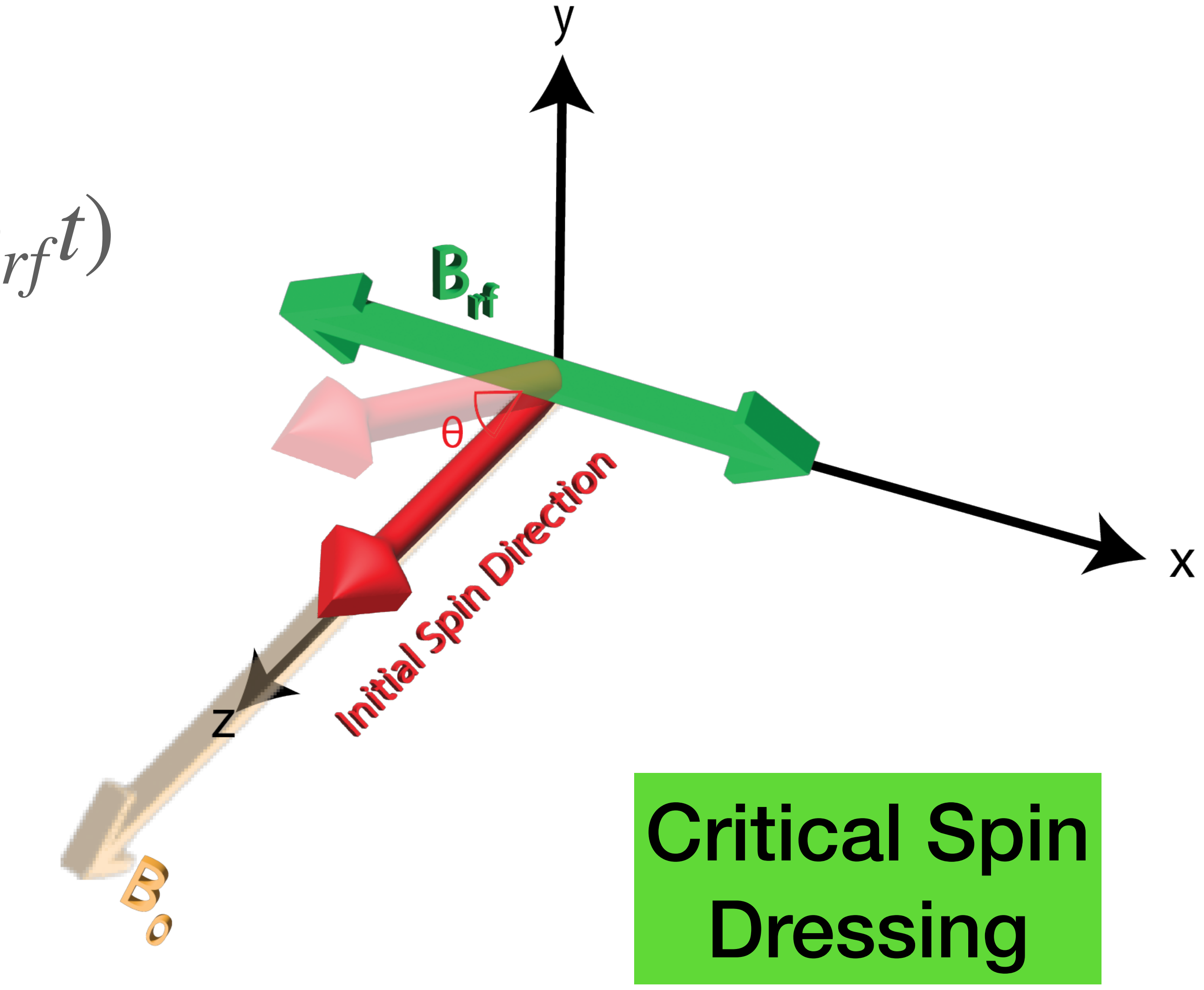
- *Effective magnetic moment along B₀-direction:* $\gamma^{eff} = \gamma J_0(x)$
- *Applying this to polarized neutrons and ³He:* → *relative precession frequency*

$$\omega_{rel} = (\gamma_n^{eff} - \gamma_{^3He}^{eff}) \cdot B_0$$

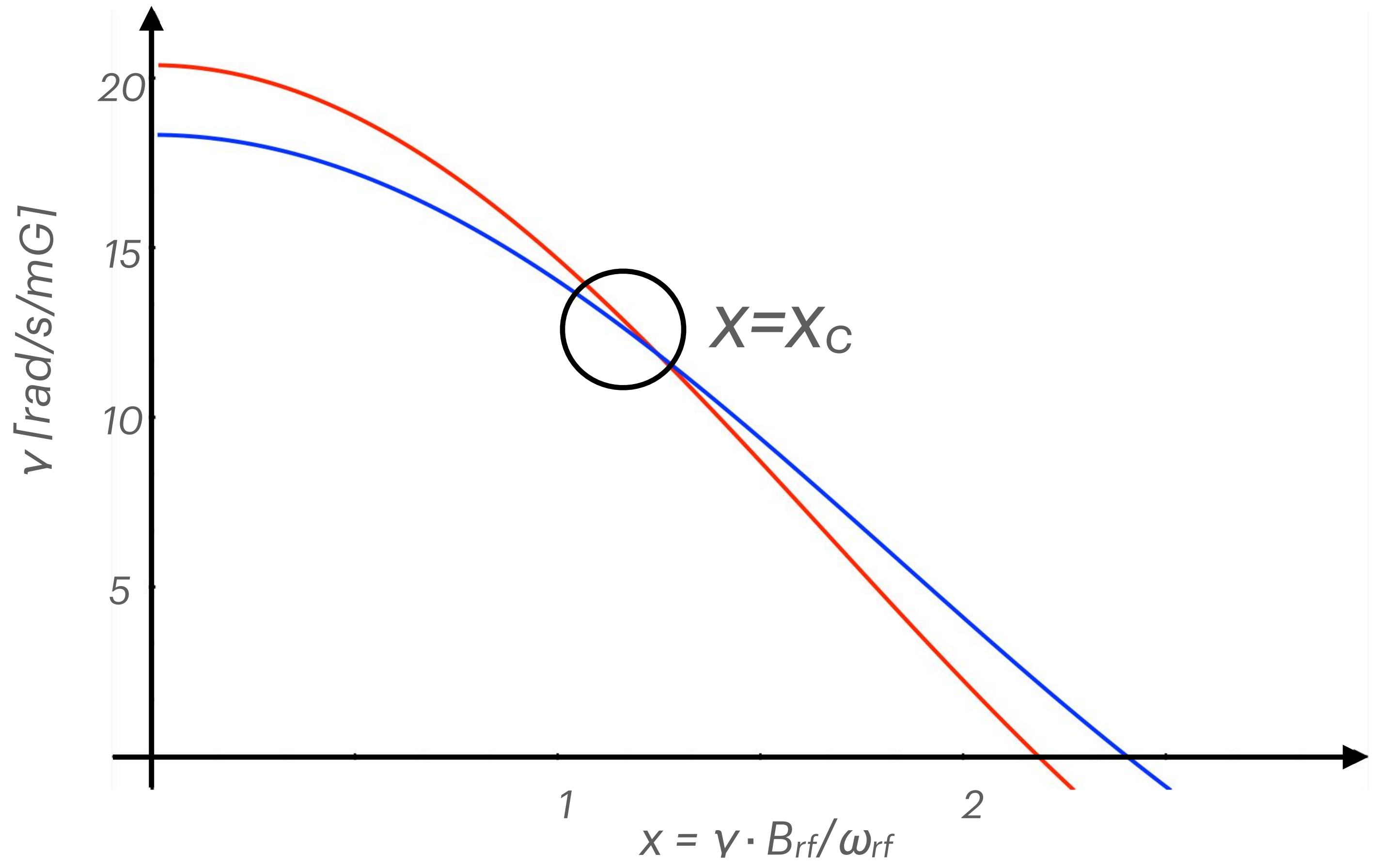
- ***Eliminate effect of magnetic field B₀*** *if*

$$(\gamma_{^3He}^{eff} - \gamma_n^{eff}) = \gamma_n J_0(x_n) - \gamma_{^3He} J_0(x_{3He}) = 0$$

"Critical Spin Dressing"



Critical Spin Dressing

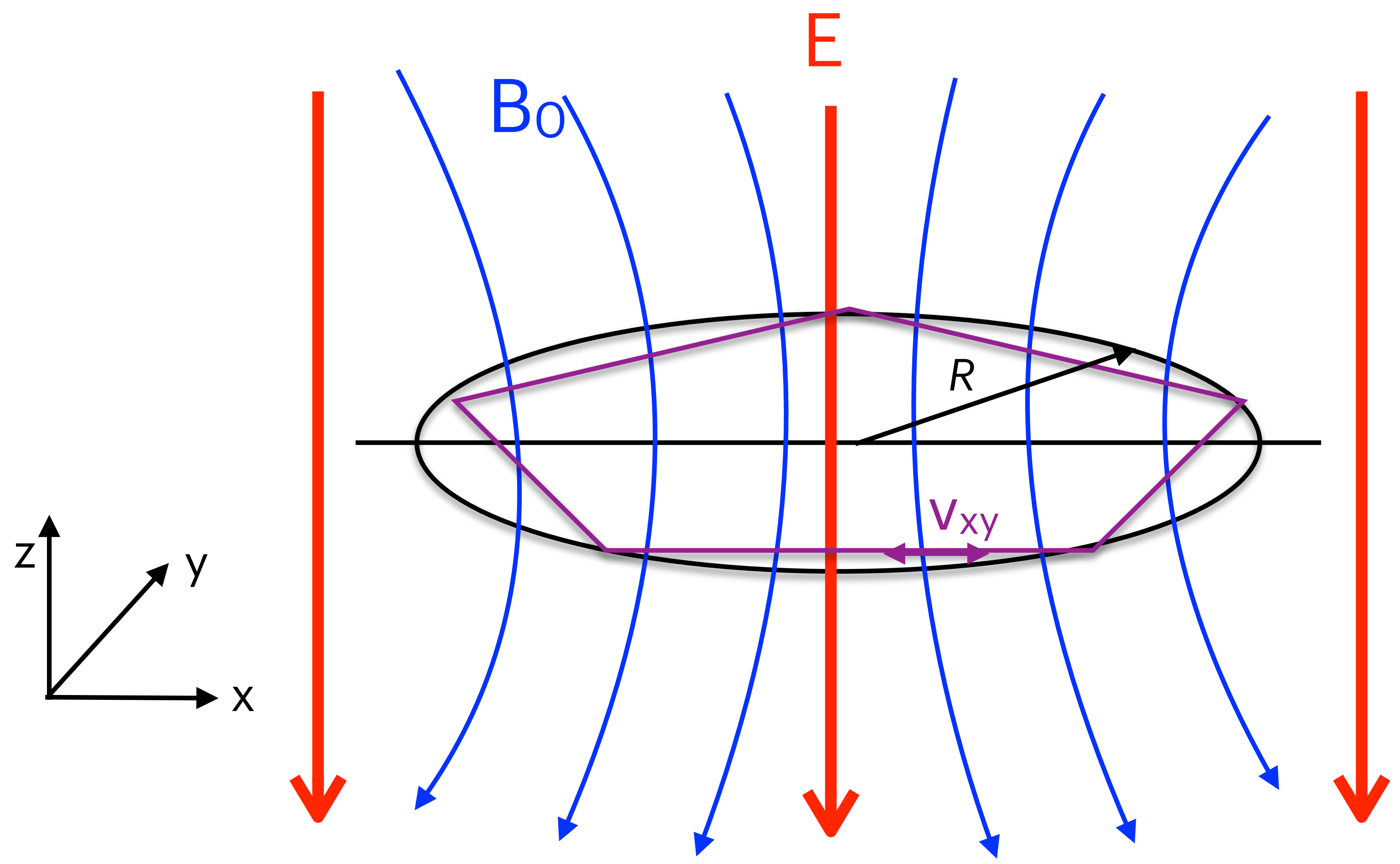


☞ Improved sensitivity to EDM

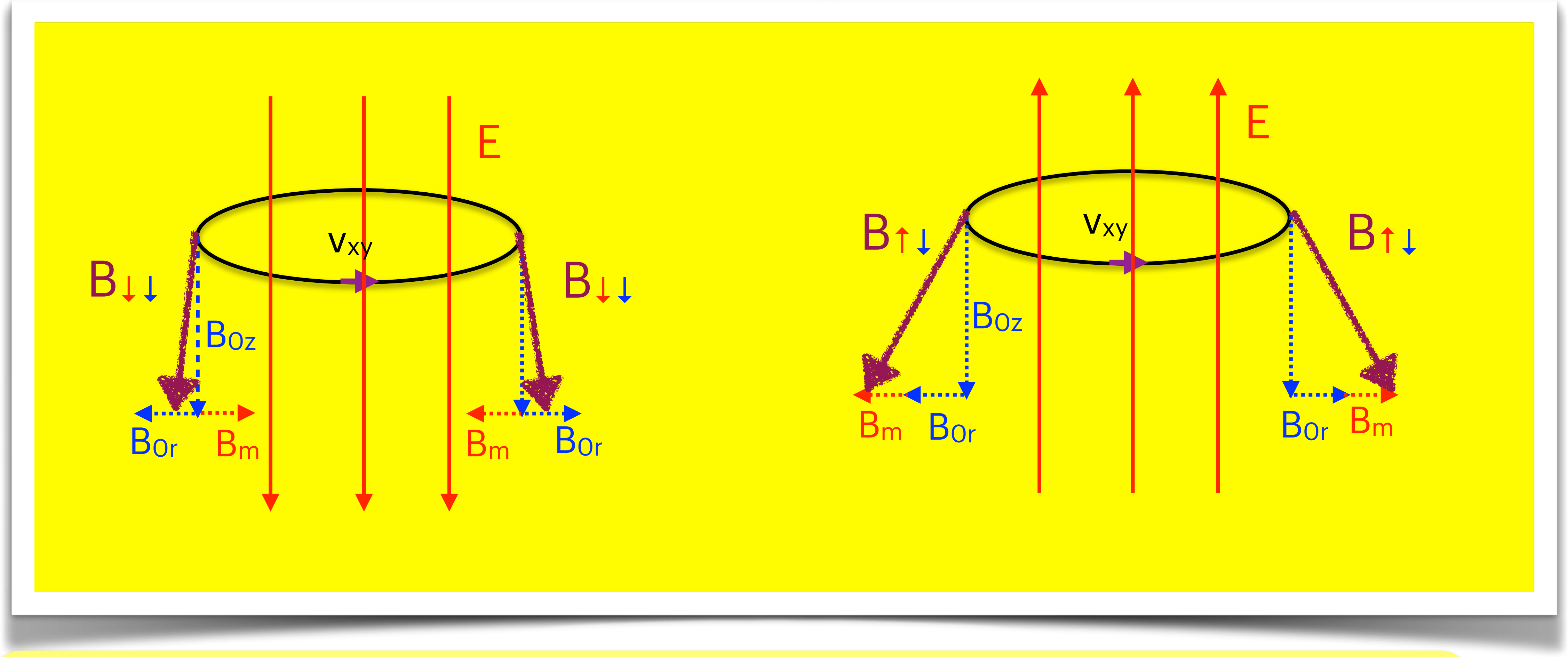
Many known (and yet unknown) Systematic Effects

Example of Important Systematic Effect: Geometric Phase

Induced false EDM due to magnetic field gradients and special relativity



B-field with radial gradient



$$(\Delta\phi_{\uparrow\uparrow} - \Delta\phi_{\uparrow\downarrow}) = \gamma_n R \frac{\partial B_{0z}}{\partial z} |B_m| \frac{|\omega_r|}{(\omega_0^2 - \omega_r^2)} \cdot T$$

Geometric Phase →false EDM signal

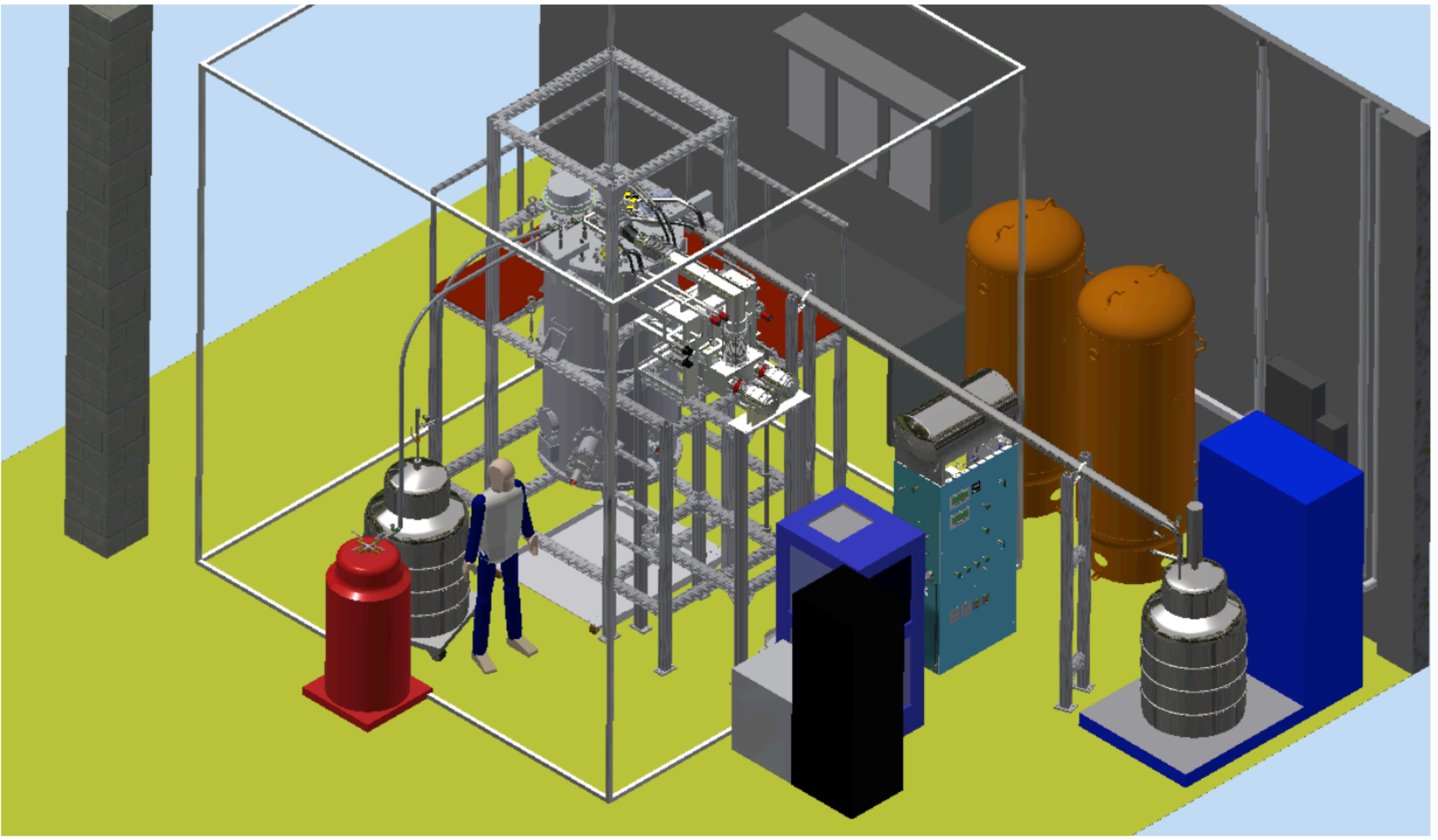
v × E → linear in E !!

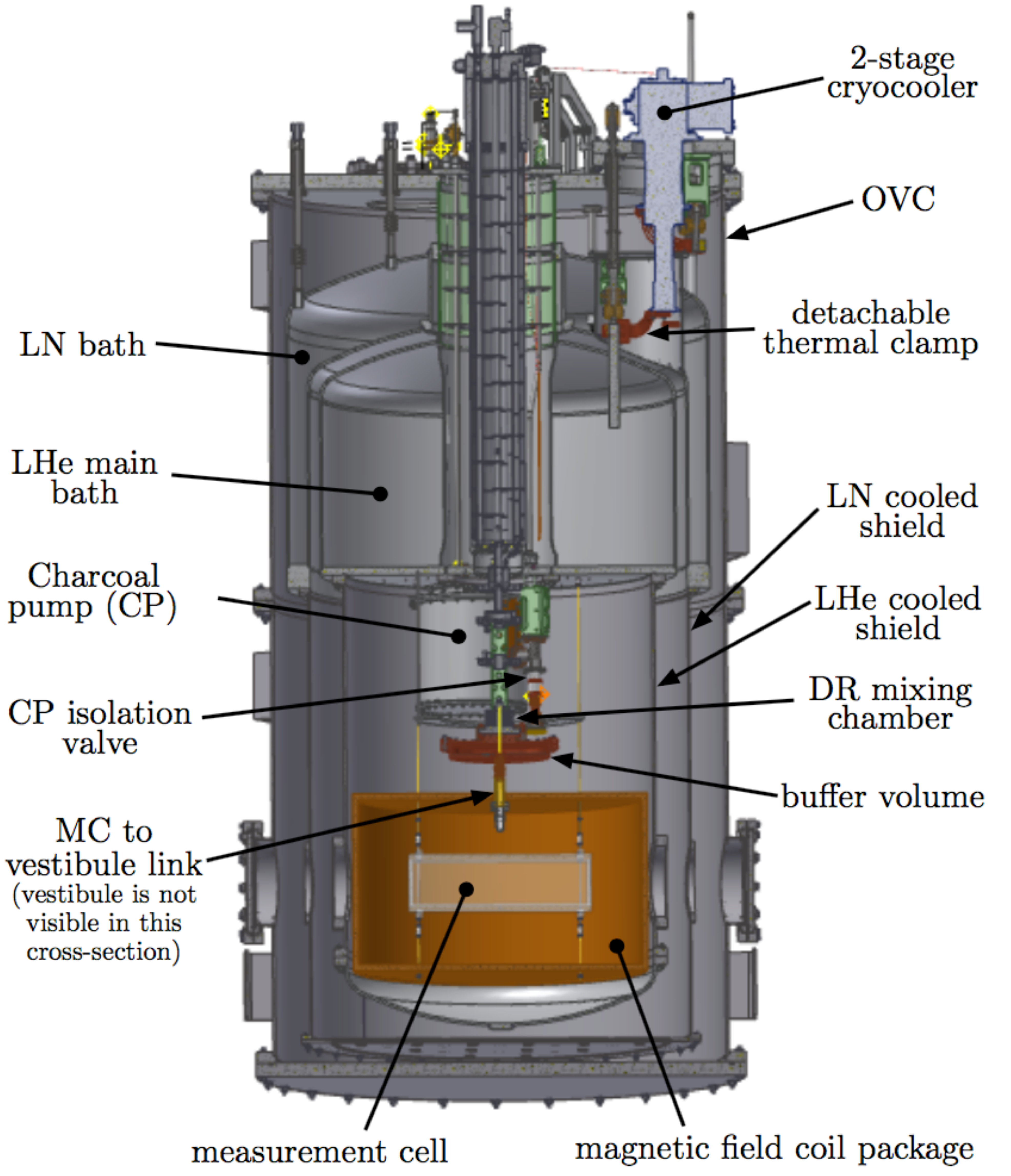
- Relativistic effect for particles with v ~ 4 m/s
- Effect doesn't cancel for $v_{xy} \leftrightarrow -v_{xy}$
- Effect is linear in E → causes false EDM signal
- Need uniform B-field (here |∇B| < 3 ppm/cm (<100 nG/cm @ 30 mG)

Systematics and Operational Studies (SOS) @ Pulstar

Perform systematic studies relevant for nEDM@SNS at the NCSU Pulstar reactor

- *UCNs from Pulstar*
- *polarized ^{3}He from MEOP source*
- *one measurement cell only*
- *no electric field*
- ***smaller size than nEDM@SNS → faster thermal cycling***
- ***study spin dressing***
- *study control of initial phase between n-^{3}He spins*
- ***study geometric phase***
- *characterize production measurement cells*
- ....





Systematics and Operational Studies (SOS) @ Pulstar

Dewar commissioning with cryocooler and DR finished

NCSU Lab

Requirements:

- T_2 at least 700 s
- ^{3}He polarization ≳70%
- UCN density 1-10 n/cm^3
- SQUID noise level 0.2-0.25 fT/√Hz (3He concentration $x=10^{-10}$, SNR=20, 1 run)
- $T_{cell} \gtrsim 300$ mK (during operation)
- 10 ppm stability and noise on power supply for spin dressing

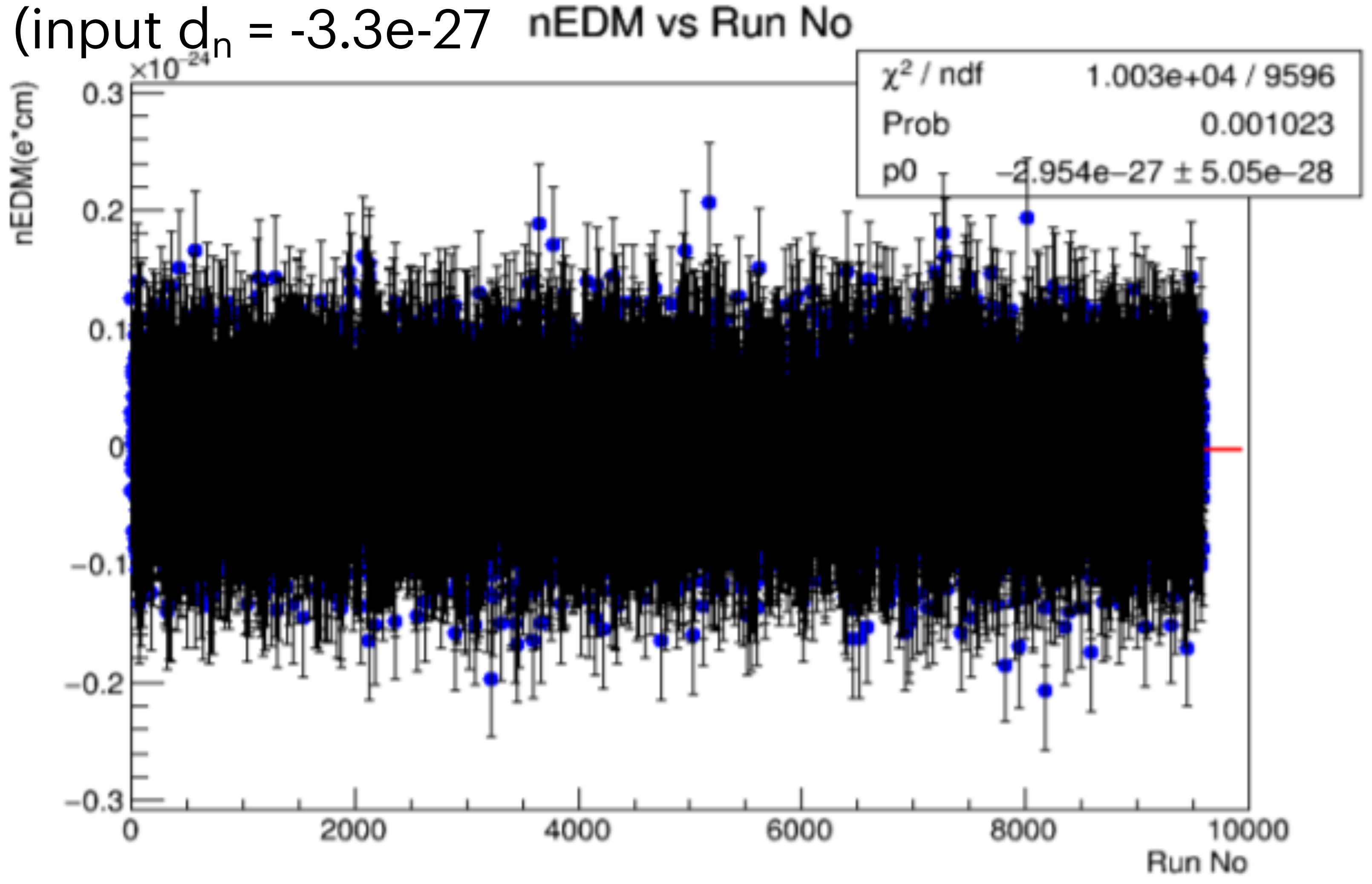
slide credit: E. Korobkina

Data Analysis and Simulations

nEDM = =(-2.954±0.505)e-27 e*cm

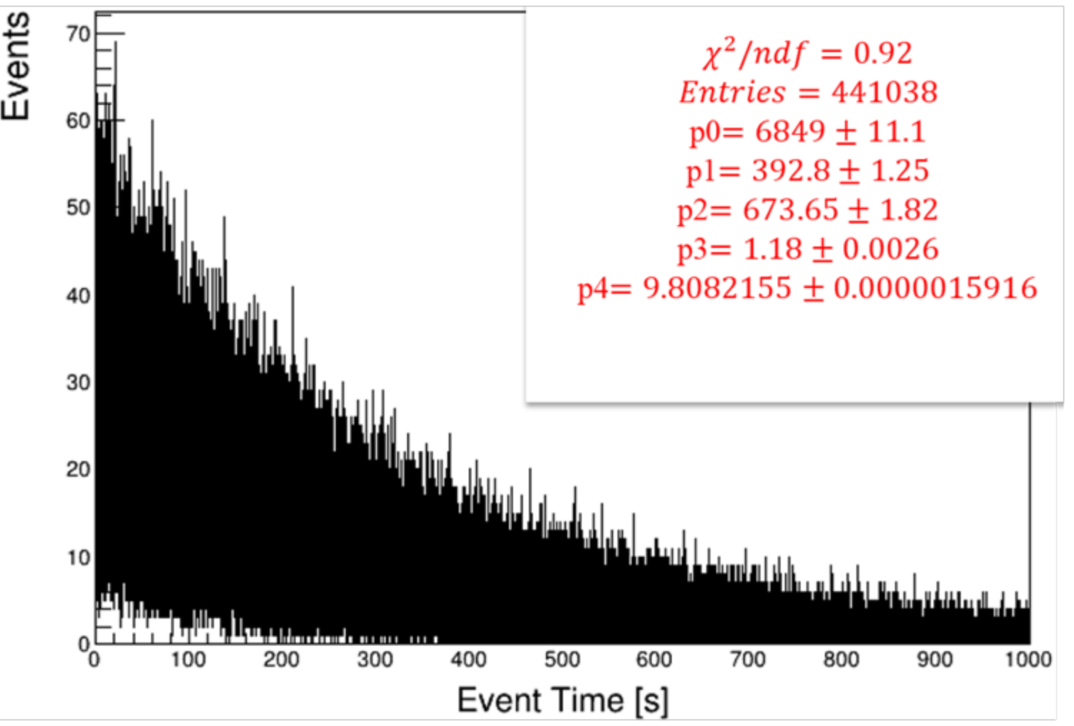
Mock Data Challenge at full sensitivity

(input d_n = -3.3e-27

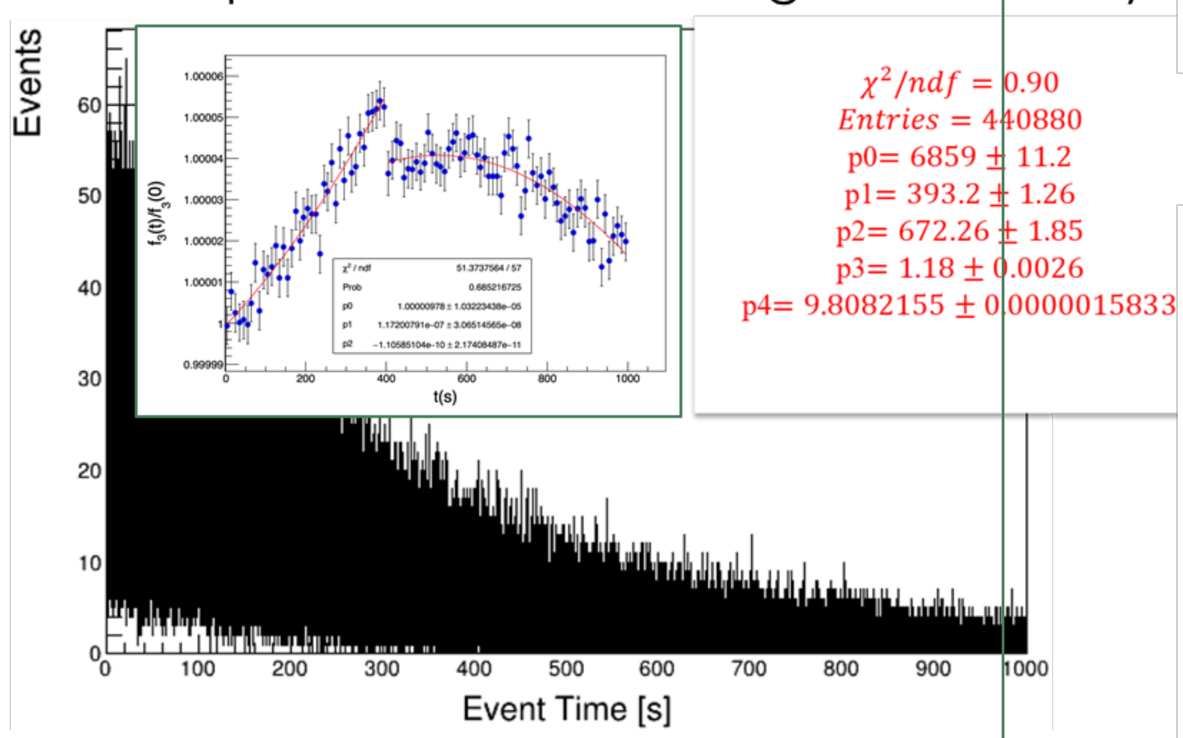


Preparing to handle non-uniform B-fields
M. Behzadipour, B. Plaster

Constant field

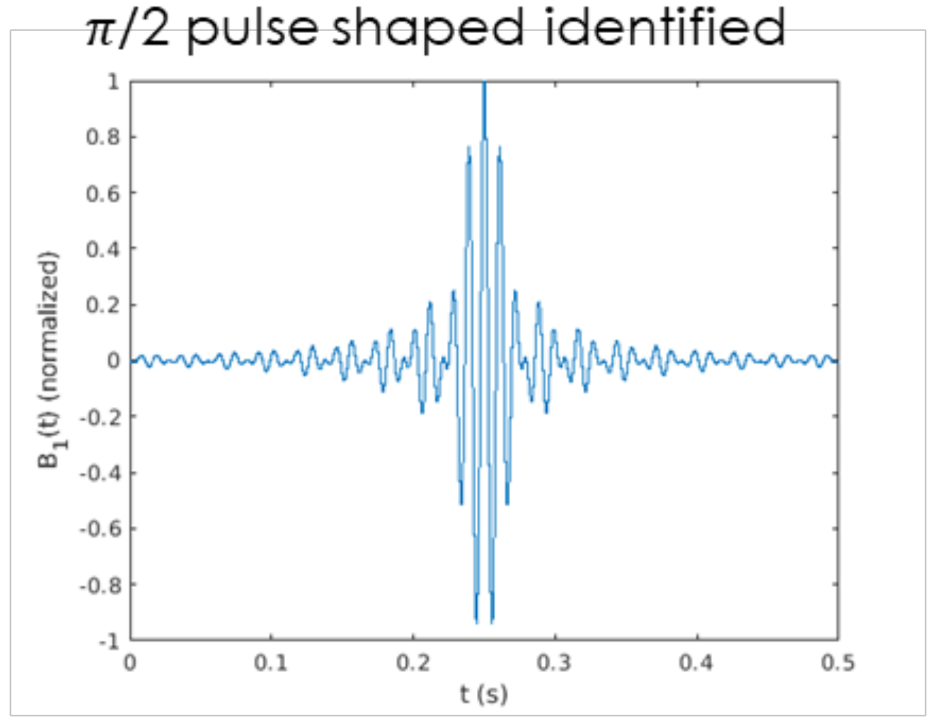


Jumps + drifts → no change in sensitivity

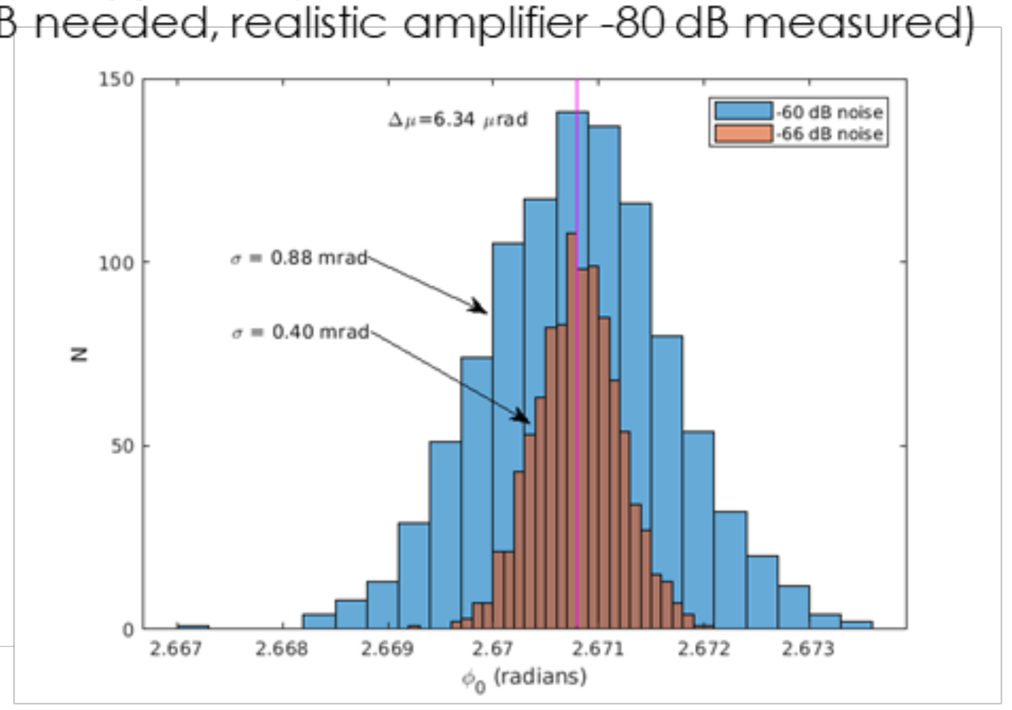


Developing spin-manipulation techniques
(first test at PULSTAR). C. Swank

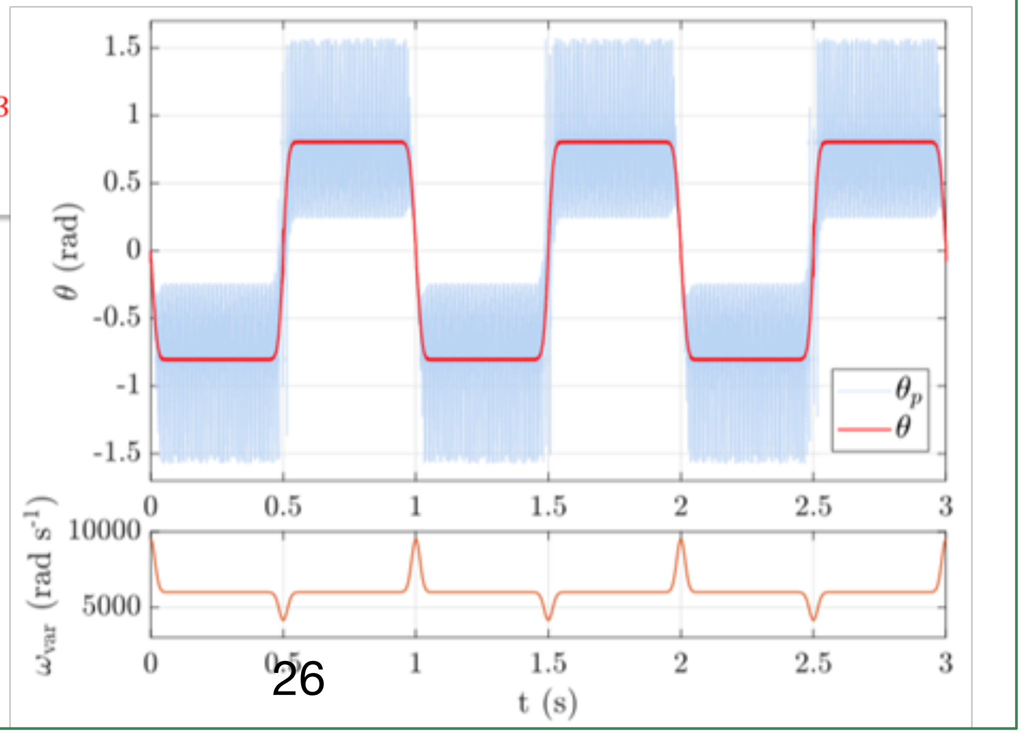
$\pi/2$ pulse shaped identified



Stability of ϕ_0 in the presence of AC field noise
(-60 dB needed, realistic amplifier -80 dB measured)



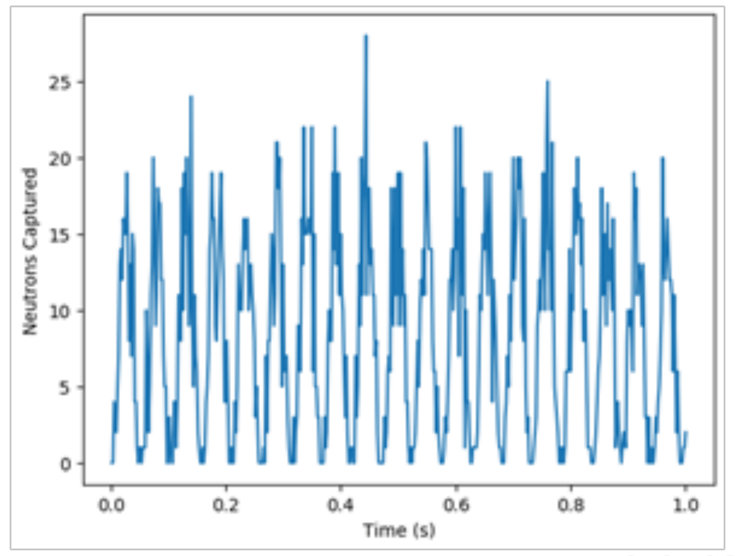
Critical spin-dressing calculation with
pulse modulation. From PRA paper

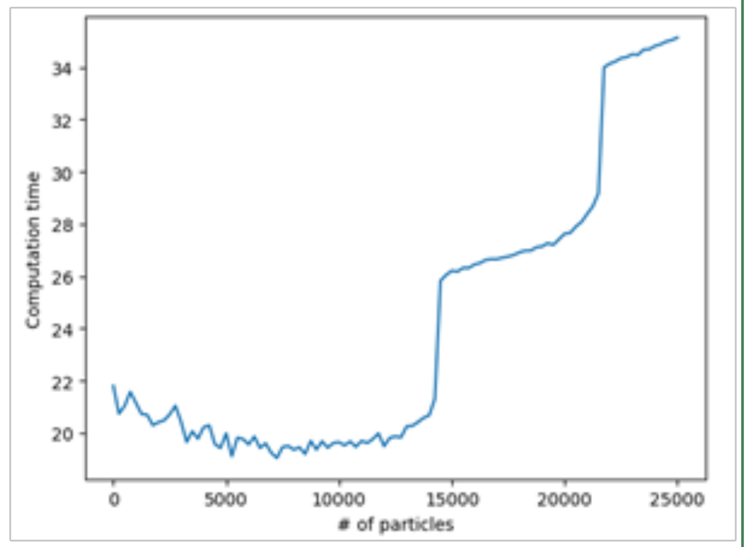


Learning to use GPUs for spin tracking

Simulated UCN
precession on GPU

Processing time per
GPU vs. # particles





M. Kline (SULI), L. Broussard

slide credit: V. Cianciolo

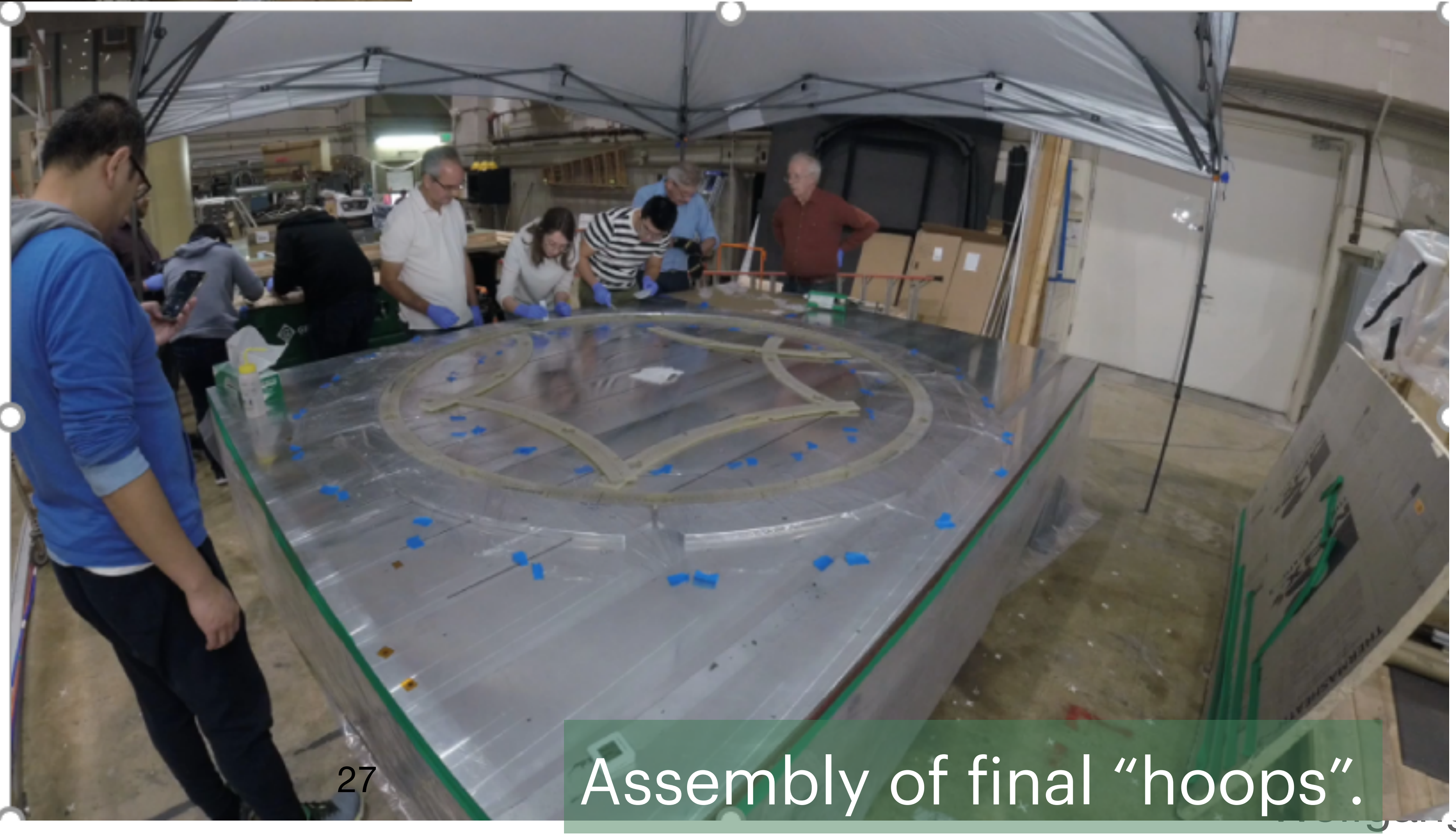
Final Components

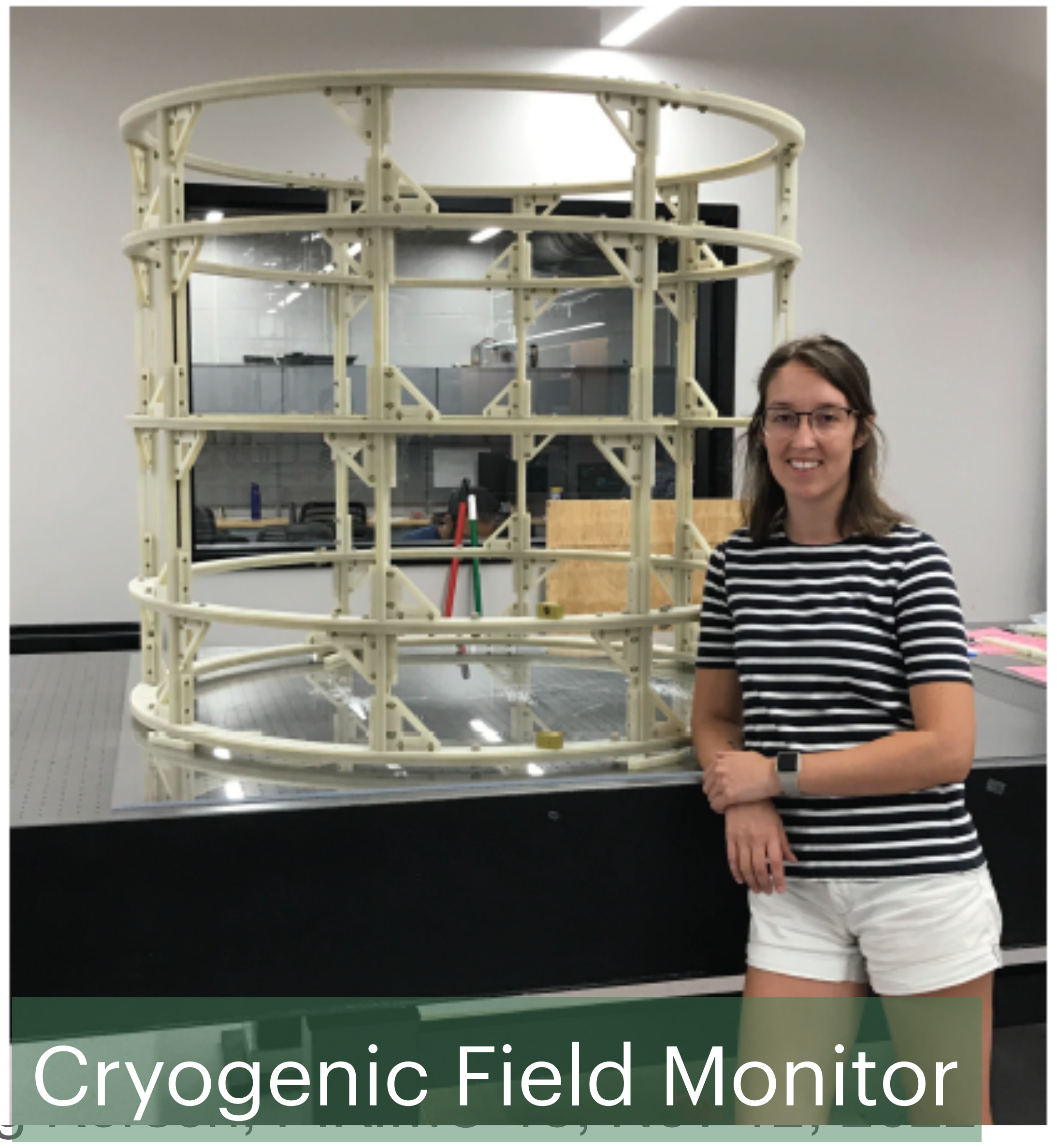

Lower Outer Vacuum Vessel


Lower 77K Shield


Inner Magnet Volume (IMV)


Magnet cryocooler


Assembly of final “hoops”.


Cryogenic Field Monitor

Some Features of the nEDM@SNS Experiment

Basic sensitivity equation:

$$\sigma_d = \frac{\hbar}{2|\mathbf{E}|T_m\sqrt{mN}}$$

- *E → electric field*
- *T_m → time per cycle*
- *$\sqrt{mN}$ → # of cycles × # of neutrons per cycle*
- *no background*
- *stable B- and E-fields*

Goal:

- **$|d_n| \lesssim 2.9\times 10^{-28}$ e-cm @ 90% C.L. (spin dressing)**
- **$|d_n| \lesssim 5.7 \times 10^{-28}$ e-cm @ 90% C.L. (free precession)**

(300 live-days each)

- ***Large number of trapped UCNs***
  - *down-scattering of 0.89 Å neutrons via photons in SF^{4}He*
  - *store neutrons in LHe target cells*
- ***Use two cells with E-fields in opposing directions***
  - *two measurements at the same time → better systematics*
- ***LHe as a HV insulator***
  - *higher electric fields*
- ***mu-metal magnetic shield enclosure + superconducting shield***
  - *reduction of magnetic field variation*
- ***Stable B_0 field using superconducting magnet***
- ***Use of ^{3}He co-magnetometer***
  - *correct for systematic effects due to changing B-fields*
- ***Variation of LHe temperature to study v x E systematics***
  - *study and minimize geometric phase*
- ***Precession frequency measurements via two techniques***
  - *Critical spin dressing*
  - *free spin precession*
  - *compare methods → different systematic effects*

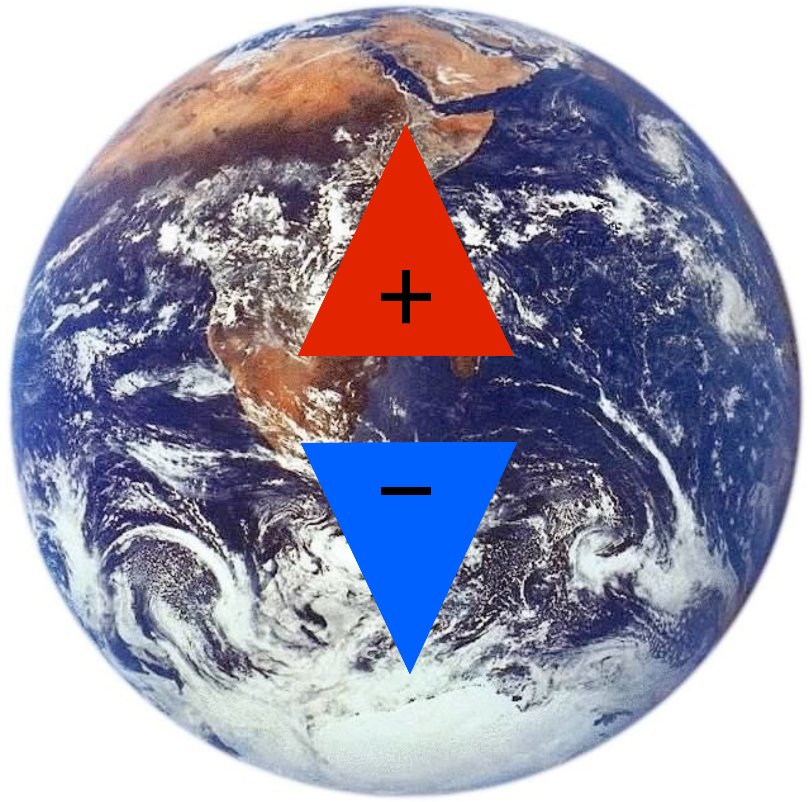
Working Parameters

Quantity	Definition	Value
P_{UCN}	UCN production rate	0.31 UCN/cc/s
N_0	Number of UCNs in each cell at t=0	4.5×10^5
V_{cell}	Measurement cell volume	3000 cc
τ_3	UCN-^{3}He absorption time	500 s
τ_{cell}	UCN-wall absorption time	2000 s
$\lvert E \rvert$	Electric field	75 kV/cm
T_M	Measurement time	1000 s
T_f	Cold neutron fill time	1000 s
T_d	Dead time between cycles	400 s
P_3	^{3}He initial polarization	0.98
P_n	UCN initial polarization	0.98
τ_P	^{3}He & UCN depolarization time	20,000
ε_3	Detection efficiency for UCN-^{3}He capture	0.93
ε_β	Detection efficiency for β-decay	0.5
R_B	Non β-decay background rate	5 Hz

Spin Dressing: $|d_n| \lesssim 2.9 \times 10^{-28}$ e-cm @ 90% C.L. (300 live-days)
Spin Dressing: $|d_n| \lesssim 5.7 \times 10^{-28}$ e-cm @ 90% C.L. (300 live-days)

Human Readable Sensitivity of Next Generation EDM Searches

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 17.6 years (75 kV/cm)*
  or same precession in B-field: B ~ 7.5 · 10^{-16} T ($B_{Earth} = 5 \cdot 10^{-5}$ T)
- *Energy splitting in E-field (75 kV/cm): 2.25 · 10^{-23} eV*

Summary and Timeline

- ***Construction of subsystems is well under way***
  - *New experimental hall (EB2) and neutron guide are "shovel ready" subsystems*
  - *all other subsystems are well into construction phase*
  - *no known showstoppers yet*

More details: J. Inst. , 14, P11017 (2019), "A new cryogenic apparatus to search for the neutron electric dipole moment"

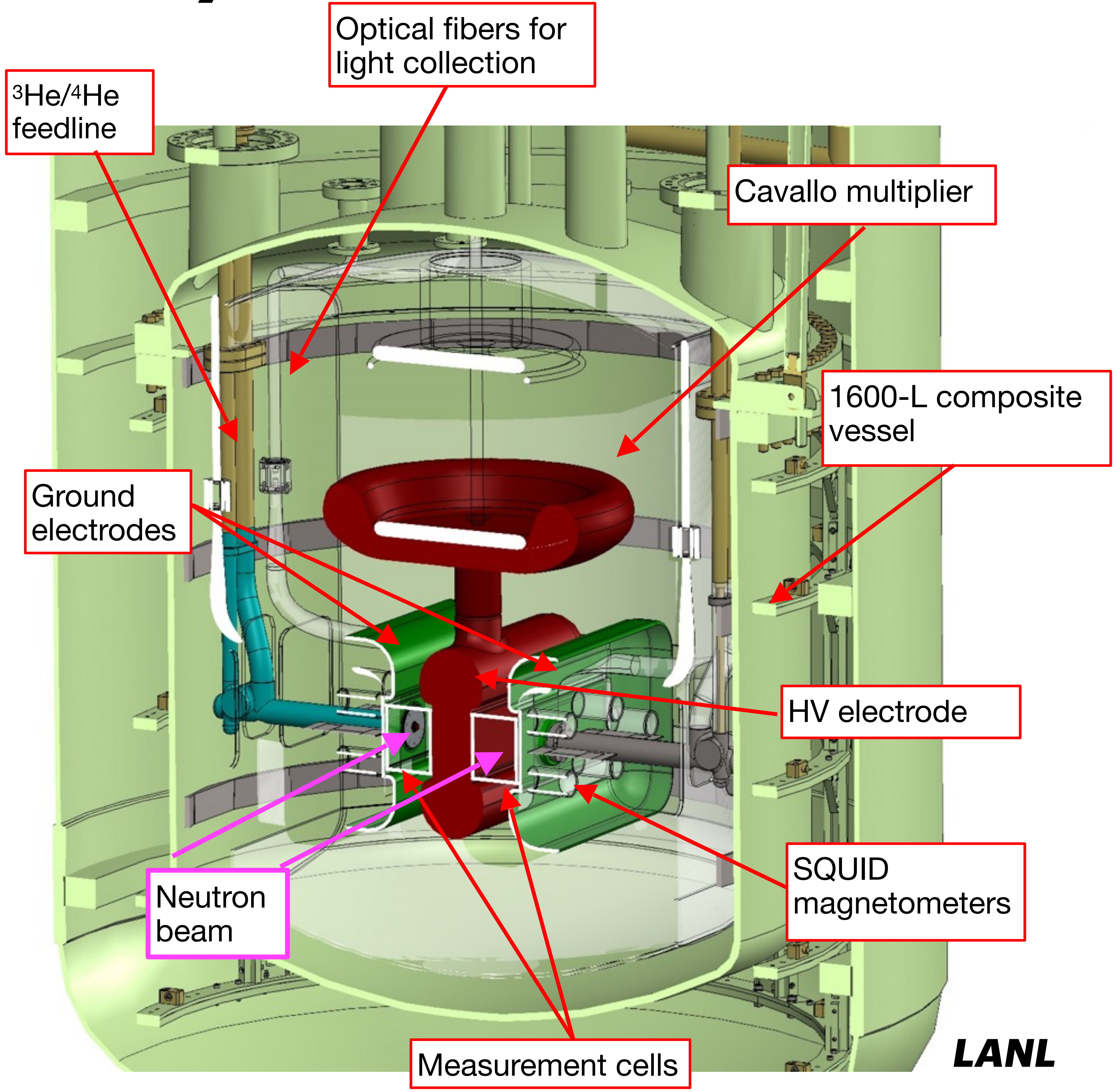
- ***Timeline:***
  - *Timeline is budget driven*
    - *start date late 2027*

- ***Other experiments:***
  - *PSI, ILL, TRIUMF, LANL, ….:* $\gtrsim \Delta d_n \sim 10^{-27}$ *e · cm*
    - *start dates > 2025 (my guess)*

Exciting times are ahead of us! Thanks.

Backup Slides

The HV System



LANL

Goal: E-field: 75 kV/cm → ~635 kV !!

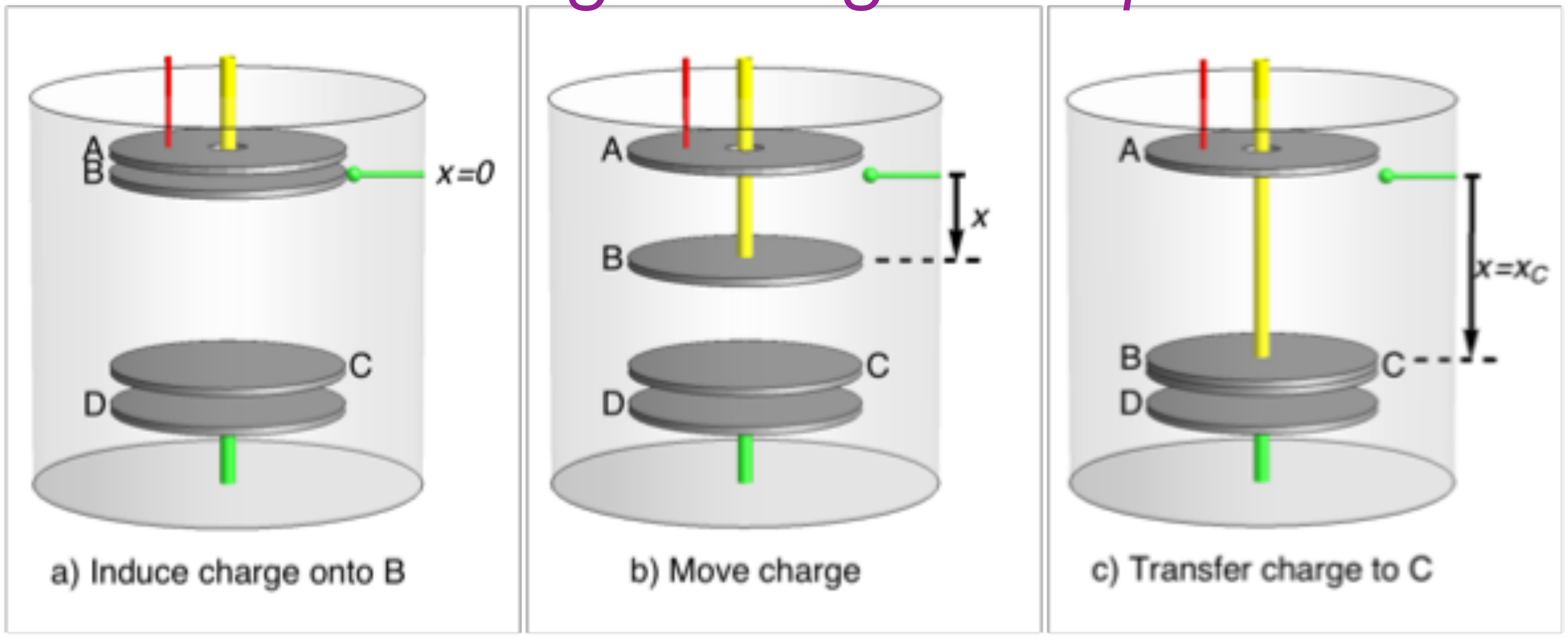
Three development stages:

- ***Small-Scale HV System (IU, LANL)**: study dielectric strength of SF4He as a function of pressure and temperature (finished)*
- ***Medium-Scale HV System (LANL)**: electrode tests → shape, surface, material (SS, PMMA), stability (finished)*
- ***Half-Scale HV System (LANL)**: electrode tests → size (scalability), surface, stability, material (in construction)*
- ***Full-Scale HV System***

Cavallo HV Multiplier

Challenge: E > 75 kV/cm for a gap size of ~10 cm → ~635 kV!!

Cavallo high voltage multiplier



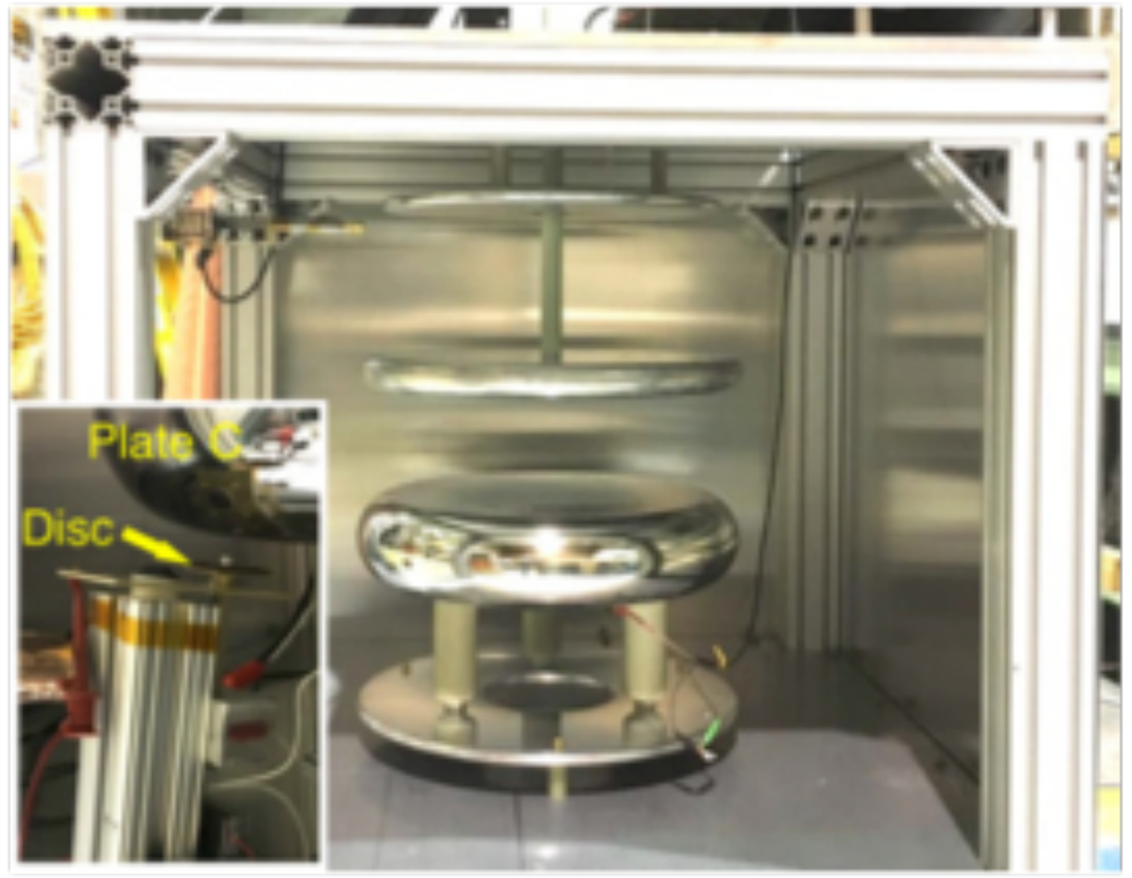
a) Induce charge onto B   b) Move charge   c) Transfer charge to C

- Achievable potential is limited by
  1. Capacitance between C and B in initial position. Total charge loaded onto B is
     - $Q_B^0 = -C_{AB}^0 V_A - C_{BC}^0 V_C$
  2. Stray capacitance to B when contacting C. Charge remaining on B is
     - $Q_B^1 = C_{AB}^1 (V_C - V_A) + C_{BG}^1 V_C$

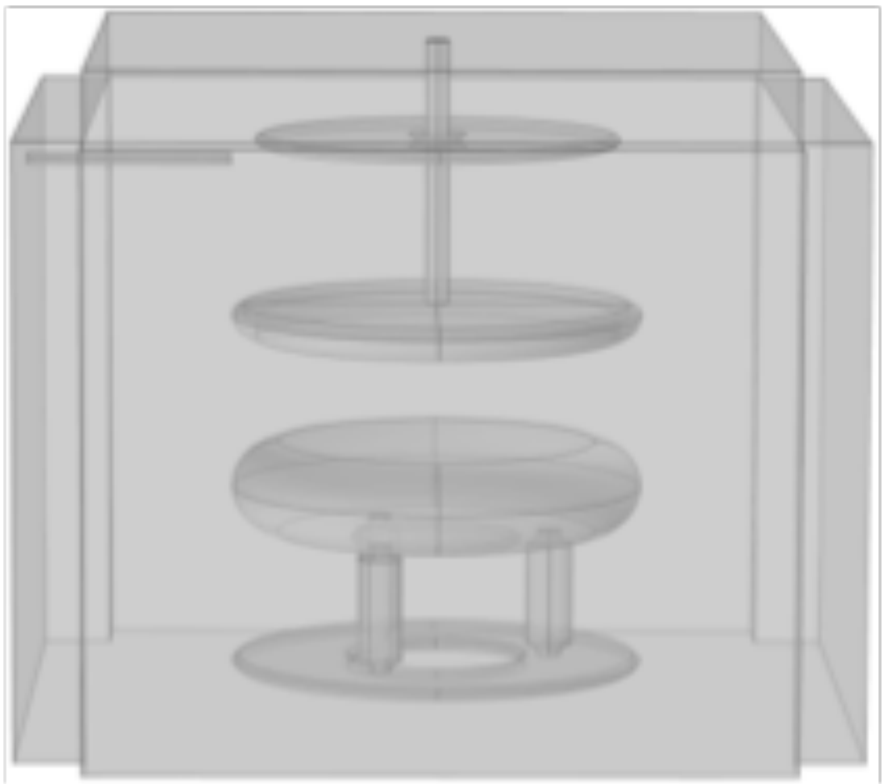
  Maximum possible V_C potential is when $Q_B^0 = Q_B^1$

$$V_C^{\max} = \frac{C_{AB}^0 - C_{AB}^1}{C_{BC}^0 + C_{AB}^1 + C_{BG}^1} V_A$$

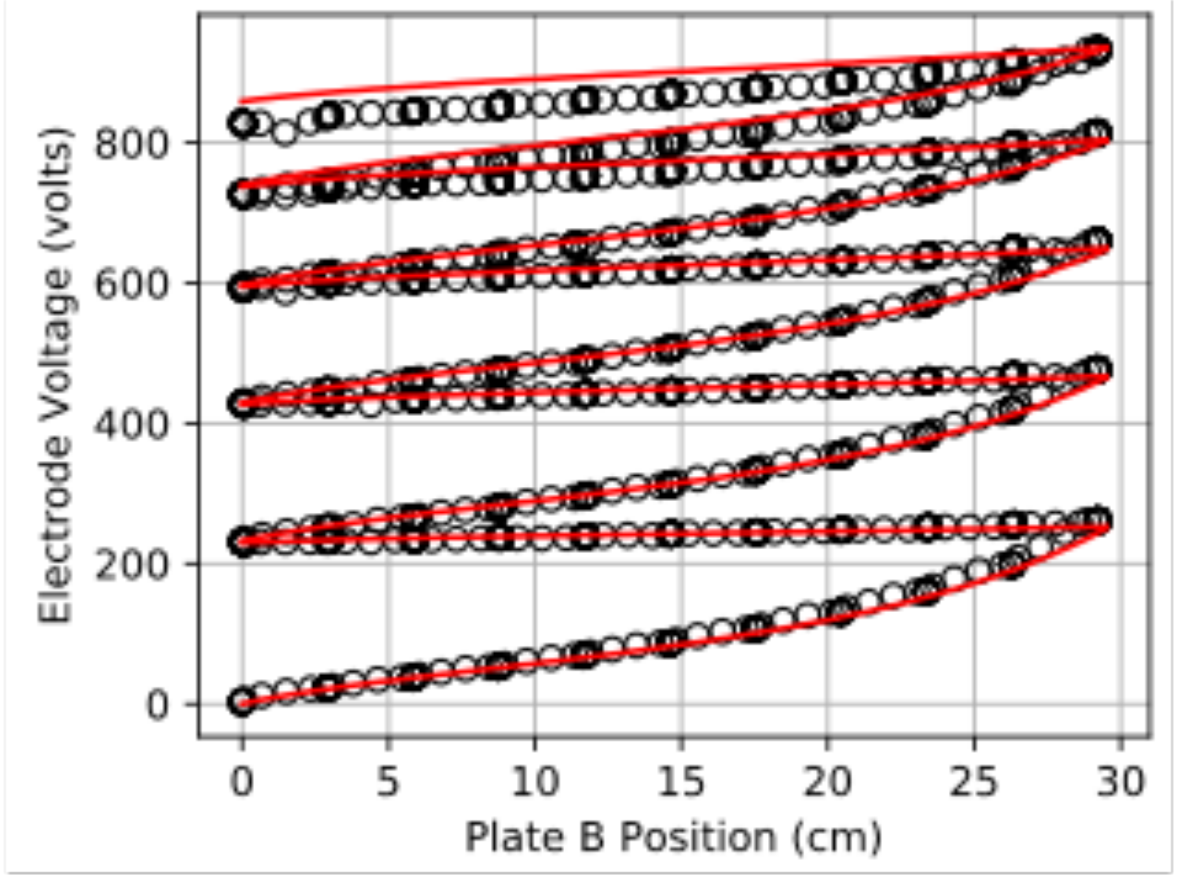
Room temperature demonstrator



LANL



COMSOL geometry



○ Measurement
— Calculation

Cryogenic test in preparation

details: talk by Marie Blatnik

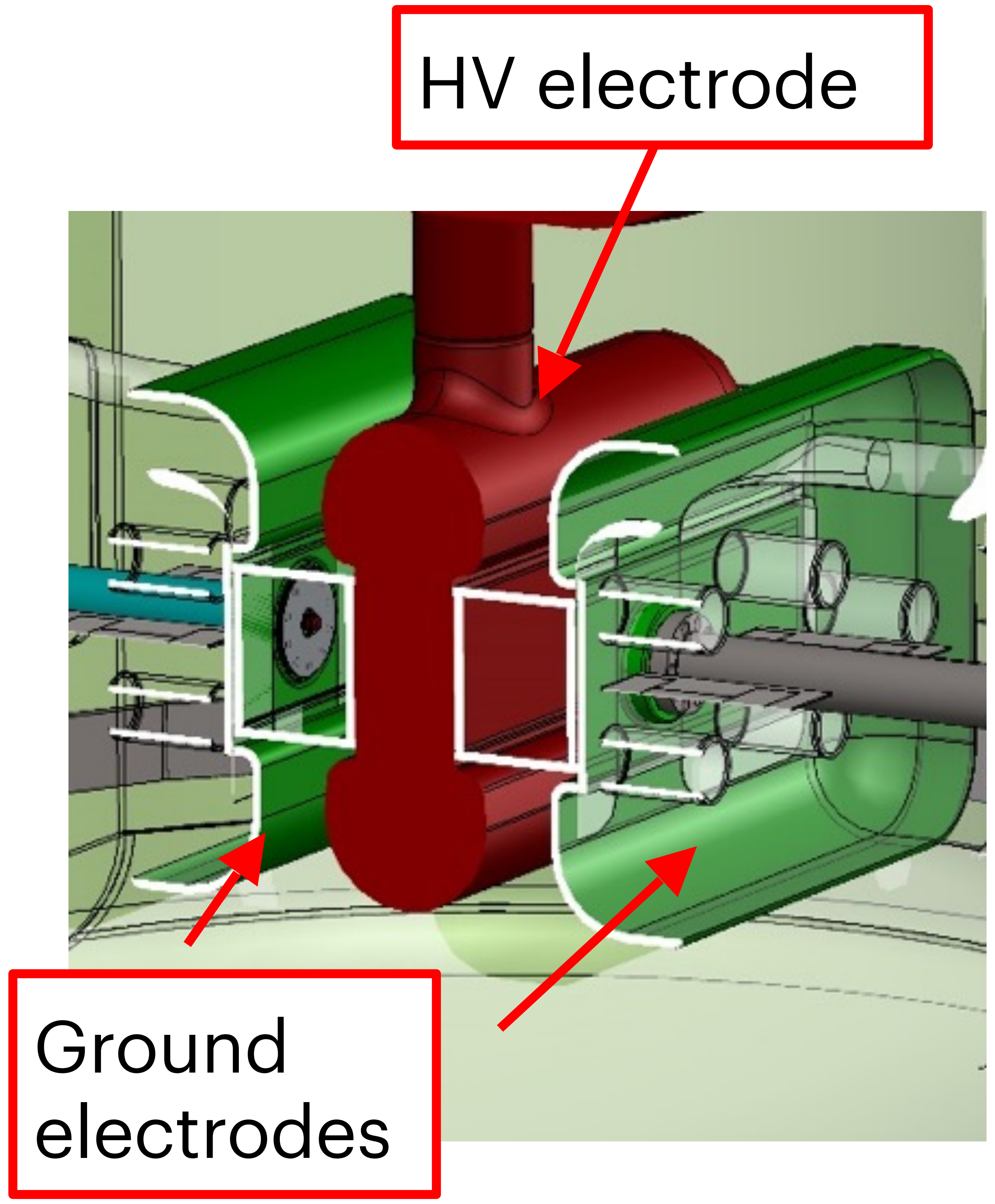
slide credit: T. Ito

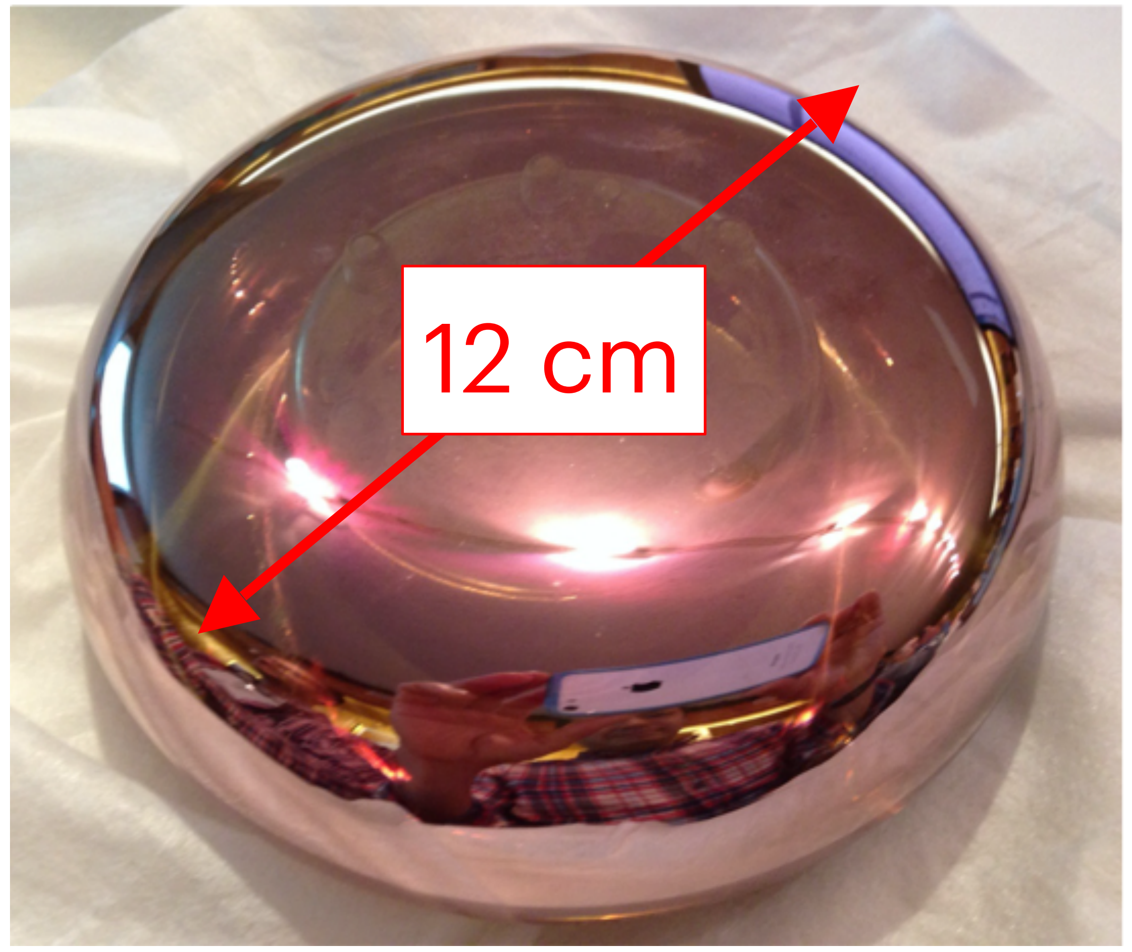
S.M.Clayton et al. JINST **13** P05017 (2018)

Measurement Cell Electrodes

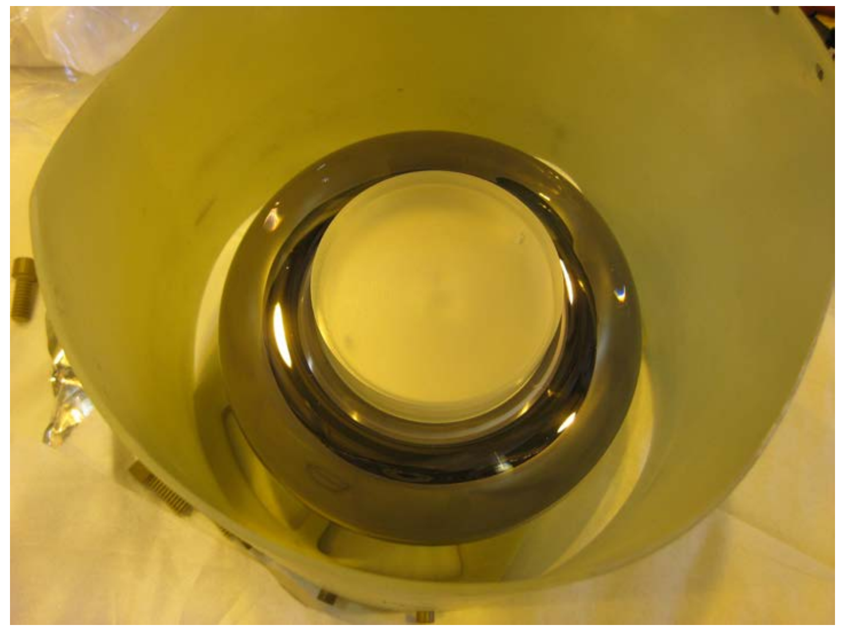
- **Ultimate goal:**
  - $E_{Cell} > 75$ kV/cm
- **Material requirements:**
  - Conductive coating on PMMA to match the CTE to the measurement cells and to keep magnetic Johnson noise and eddy current heating low
  - $100\ \Omega/\square < \sigma < 10^8\ \Omega/\square$
- **Current design:**
  - PMMA with ion implanted Cu or GeCu coating
- **Challenge:**
  - Understanding how breakdown depends on various parameters, including: electrode surface condition, electrode area & gap size, LHe pressure & temperature
  - Finding suitable materials that meet all the requirements
- **Development status:**
  - *Demonstrated stable E>85 kV/cm in the MSHV system with coated PMMA electrodes (~1/5 scale)*
  - Data-based area scaling method developed, allowing us to predict the performance of the full scale system
  - Currently commissioning the HSHV system, to confirm the scaling and test the electrode design and candidate materials with a ½ scale prototype
- **Risks:**
  - Coated PMMA electrode surfaces not performing as well as electropolished SS
  - Coated PMMA electrode surface changing its properties for each thermal cycling

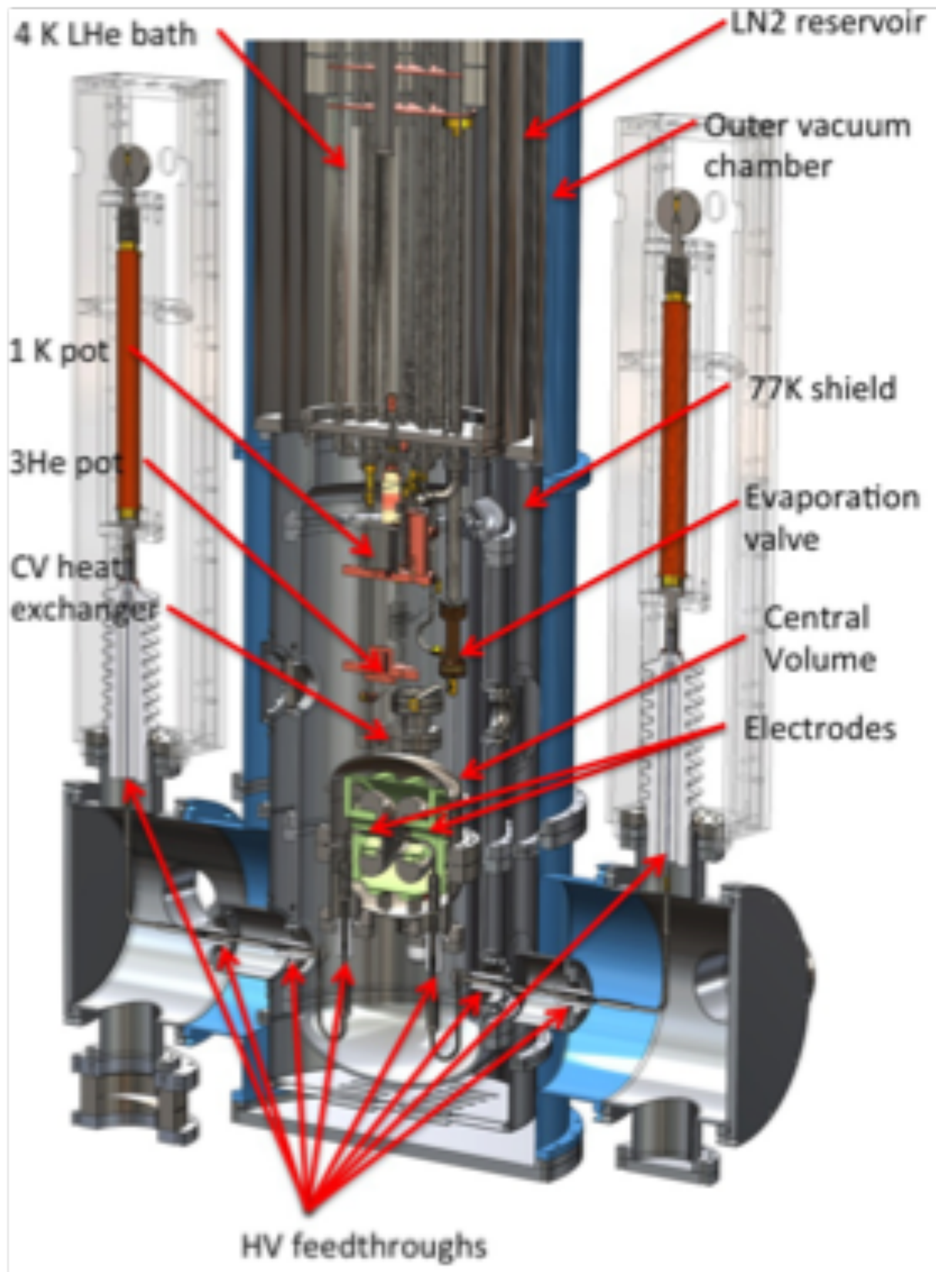
slide credit: T. Ito





PMMA electrode with Cu implantation for MSHV.
E> 85 kV/cm achieved.





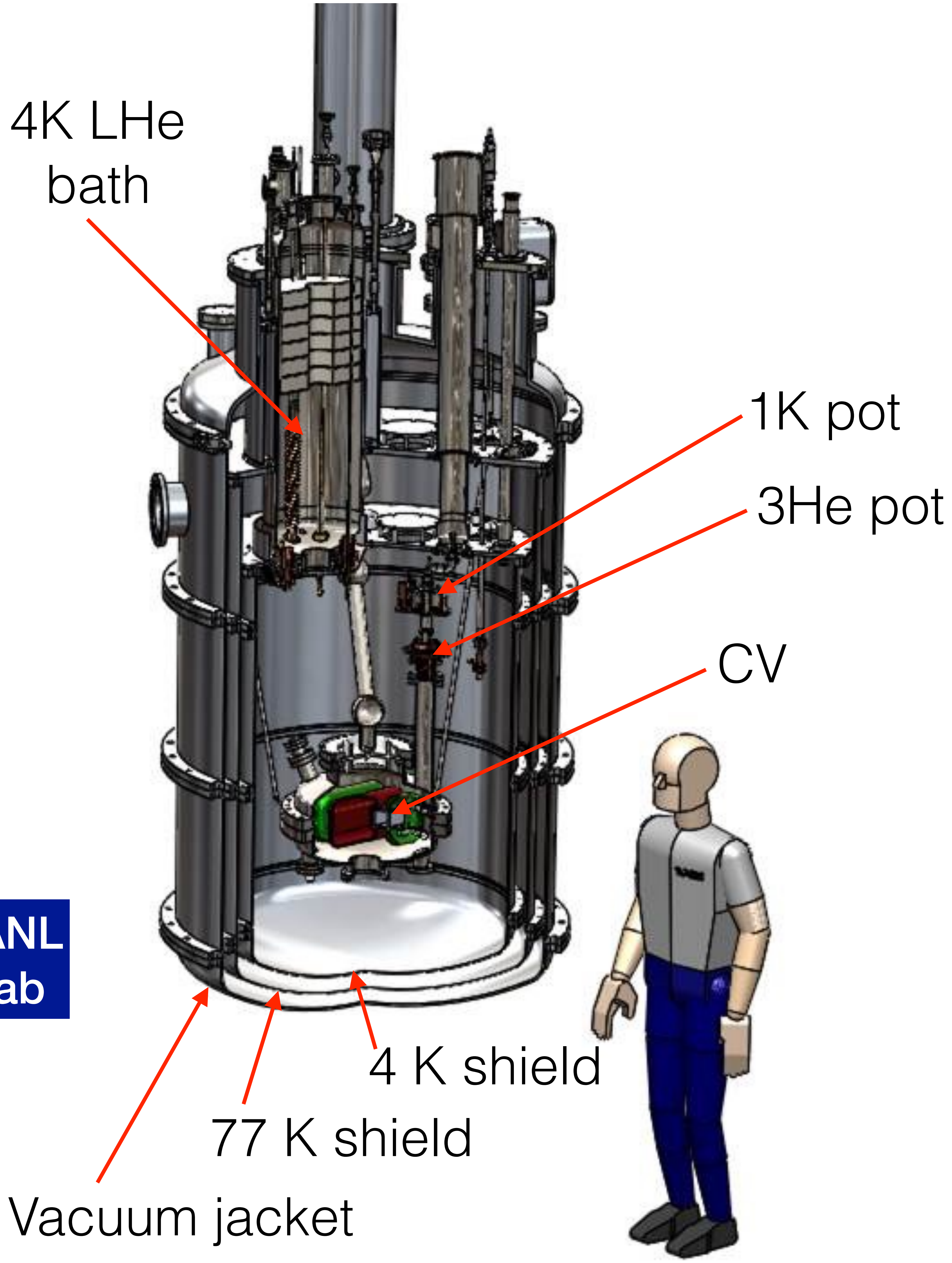
MSHV system

details: talk by Nguyen Phan

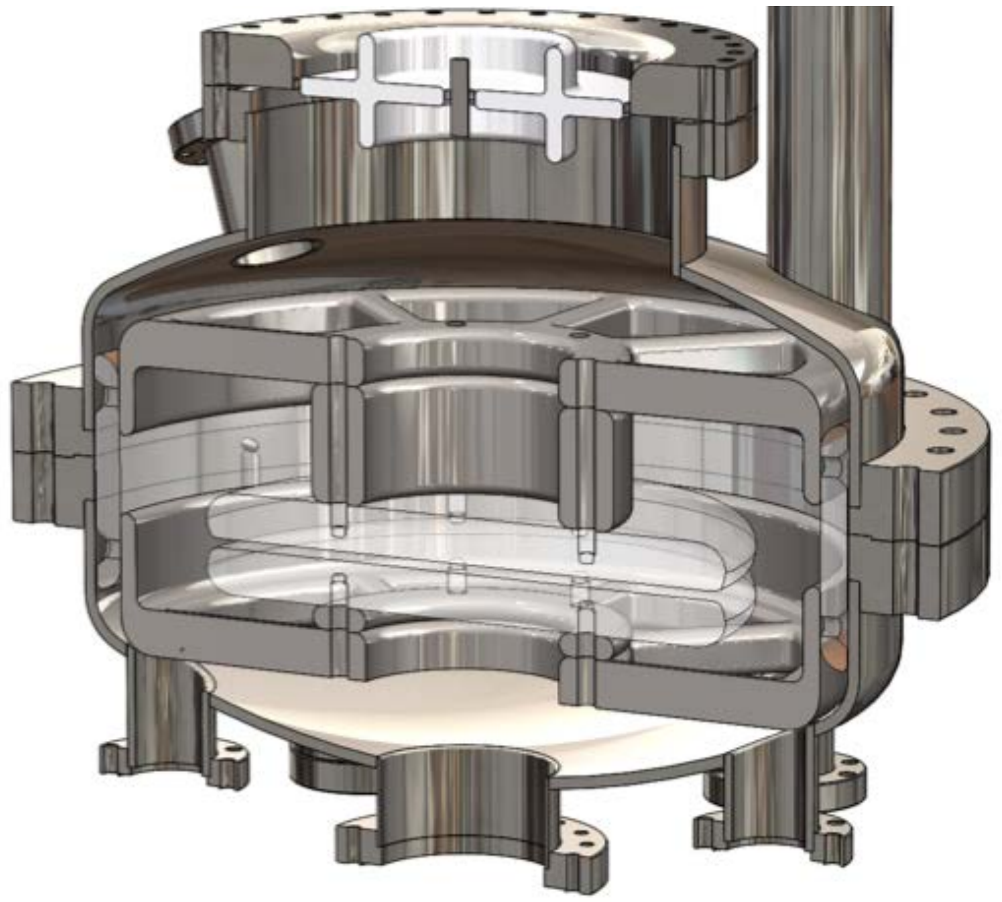
HV Electrode Testing

A half-scale electrode system is immersed in 40 liter LHe volume cooled to 0.4 K. HV performance test will be performed with 200 kV direct HV feed. The cryostat is currently being commissioned.

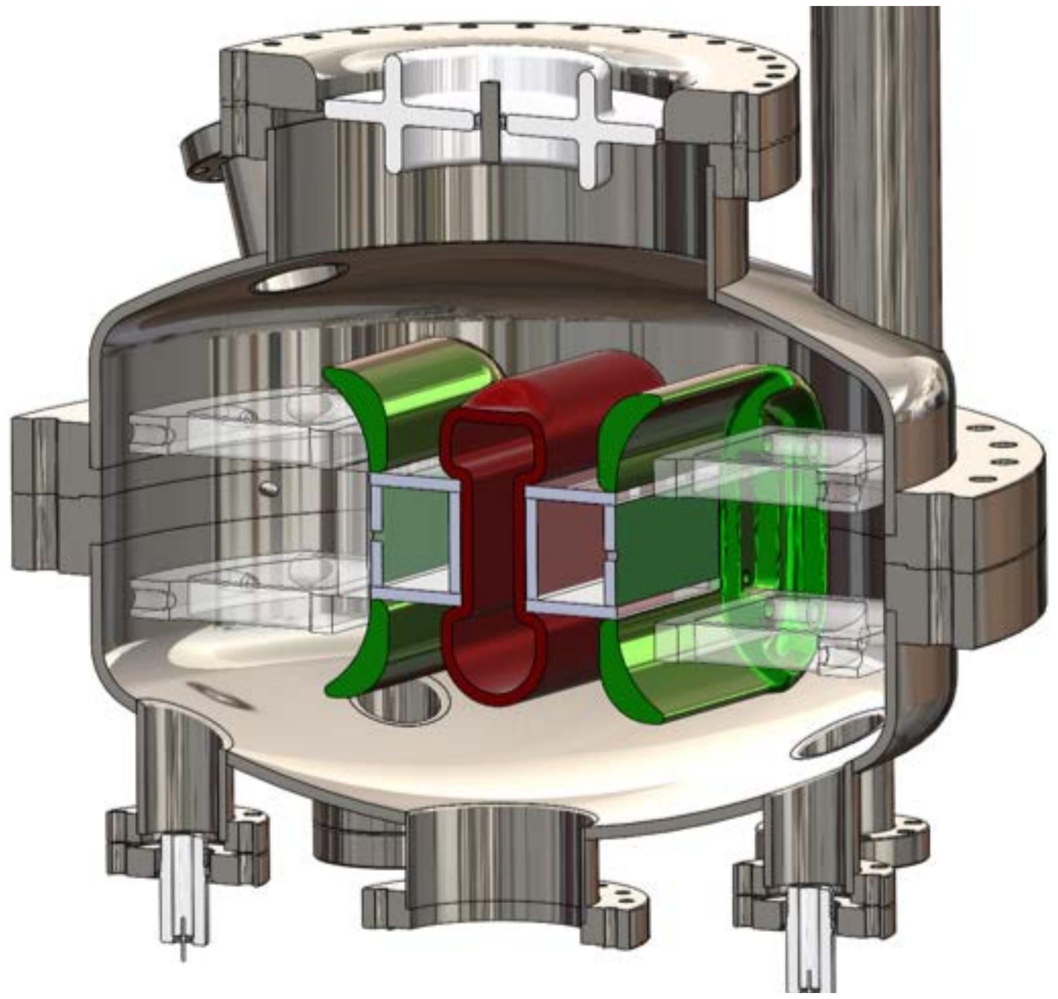
LANL Lab



T. Ito



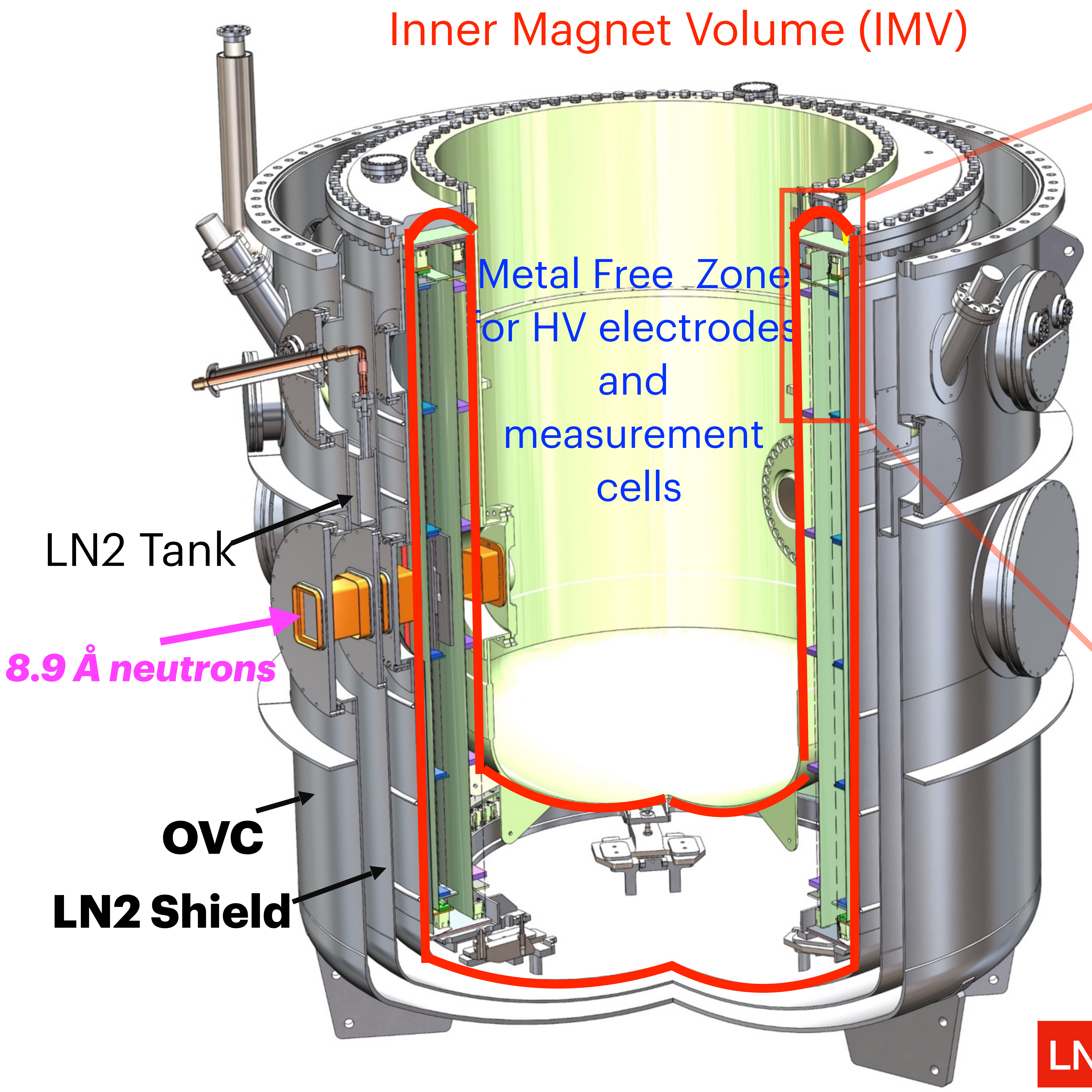
Uniform field electrodes

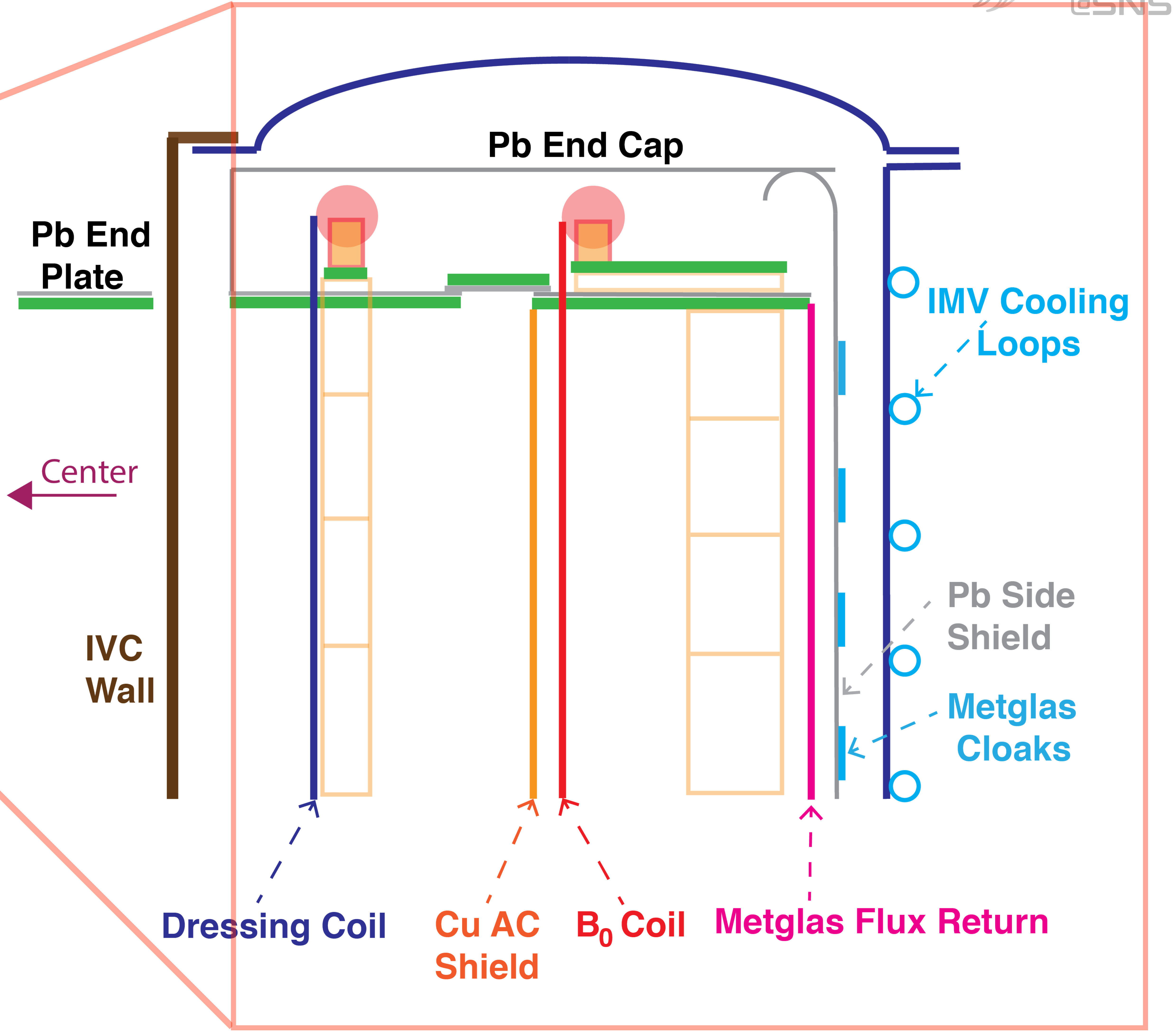


1/2 scale measurement cell electrodes

details: talk by Grant Riley

Magnet Package





LN2 shield successfully cooled to 88K @ CIT

slide credit: B. Filippone