# Neutron EDM Searches

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TUCAN Collaboration

TUCAN

PSI2022

# Electric dipole moment, CP violation, and basic technique

- Hamiltonian of neutron in an EM field (non-relativistic limit)

$$H = -\mu_n \vec{\sigma} \cdot \vec{B} - \underline{d_n \vec{\sigma} \cdot \vec{E}}$$

$$\rightarrow \not{T} \rightarrow \not{CP}$$

- Experiment: precise measurement of neutron spin precession frequency to determine $d_n$

$$\hbar\omega = 2\mu_n B \pm 2 d_n E$$

- Statistical uncertainty:

$$\sigma_{d_n} = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

Precision frequency measurement requiring lots of neutrons

# Is the neutron EDM relevant any more?

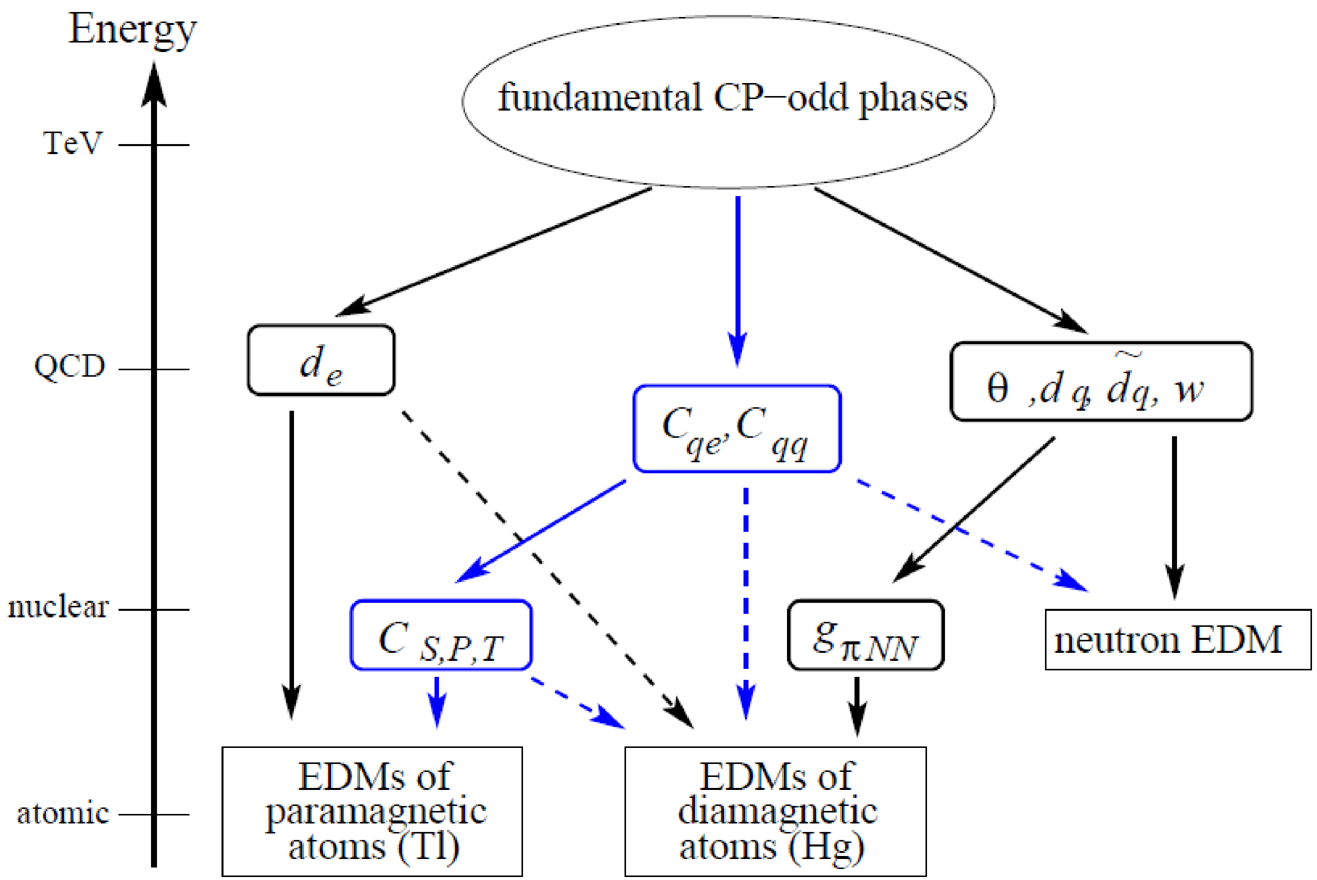
$d_e < 1.1 \times 10^{-29}$ e-cm (ACME ThO)

A. Vutha presentation

$d_n < 1.8 \times 10^{-26}$ e-cm (PSI nEDM)

$d_n < 1.6 \times 10^{-26}$ e-cm (U. Wash $^{199}$Hg)

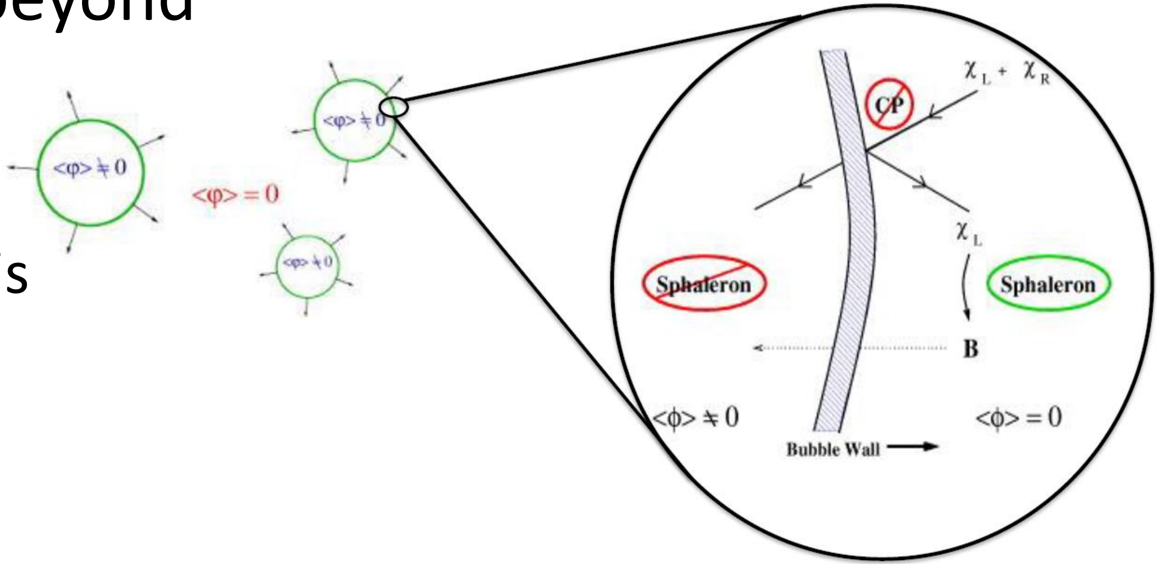
Yes! Theories…




- Figure: M. Pospelov & A. Ritz, Ann. Phys. **318**, 119 (2005).
- See also: J. Engel, M. Ramsey-Musolf, U. van Kolck, Prog. in Part. and Nucl. Phys. **71**, 21 (2013).
  T. Chupp, P. Fierlinger, M. Ramsey-Musolf, and J. Singh, Rev. Mod. Phys. 91, 015001 (2019).

# Physics of Neutron Electric Dipole Moment

- Search for new sources of CP violation beyond the standard model.
- Motivated by:
  - New physics for (electroweak) baryogenesis
  - SUSY CP problem / new TeV-scale physics
  - Strong CP problem / Peccei-Quinn, axions
  - Other new physics scenarios

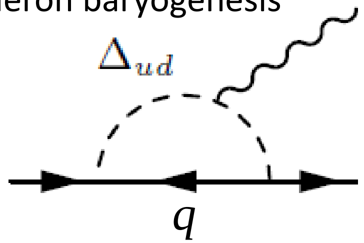



Adapted from Morrissey & Ramsey-Musolf New J. Phys. 2012

# Theoretical progress (examples)

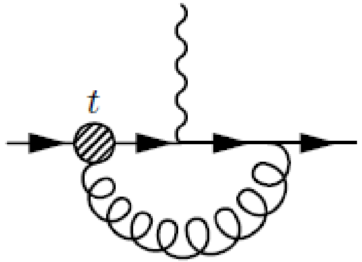
Themes:
- Baryogenesis (especially EWBG)
- New CP violation beyond SM
- Strong CP problem, axions

New scalar predicted by post-sphaleron baryogenesis




N.F. Bell, et al. PRD 99, 015034 (2019)

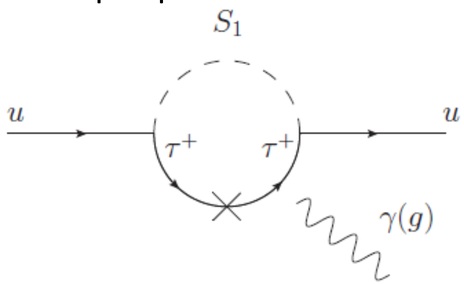
Quark (C)EDM, SMEFT, LEFT




P. Stoffer presentation

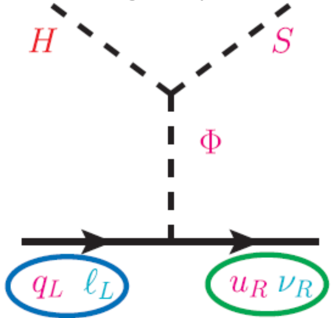
E. Mereghetti et al. JHEP04(2022)050

Scalar leptoquark



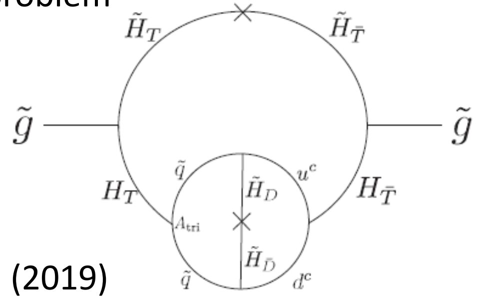

V. Cirigliano, et al. PRL 123, 051801 (2019)
A. Crivellin and F. Saturnino, PRD 100, 115014 (2019)

See-saw mechanism $\nu$ and strong CP problem




M. Carena, et al. PRD 100, 094018 (2019)

Grand unified parity solution to strong CP problem



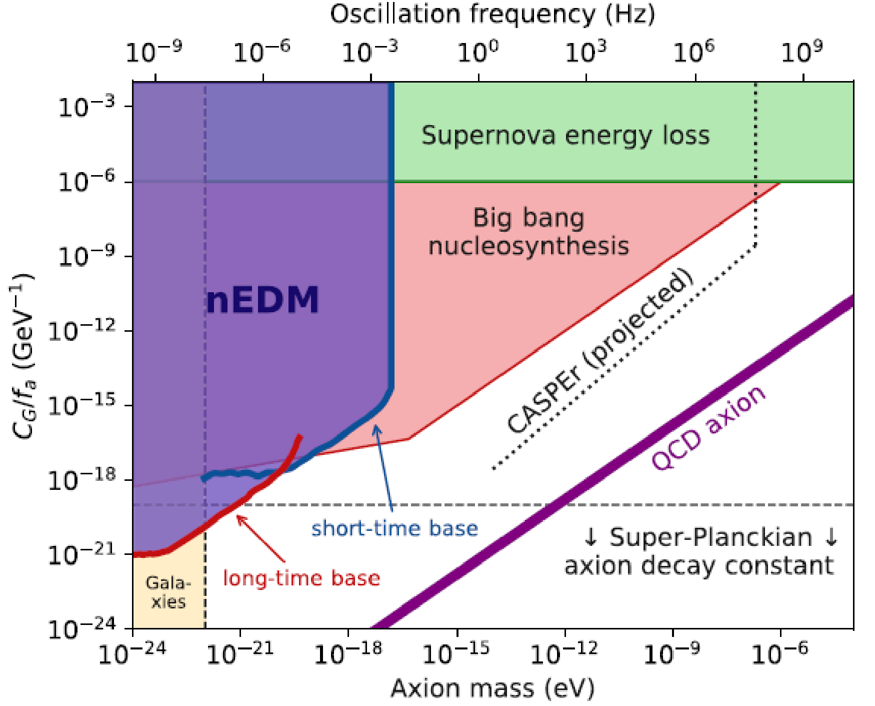

Y. Mimura, et al. PRD 99, 115025 (2019)

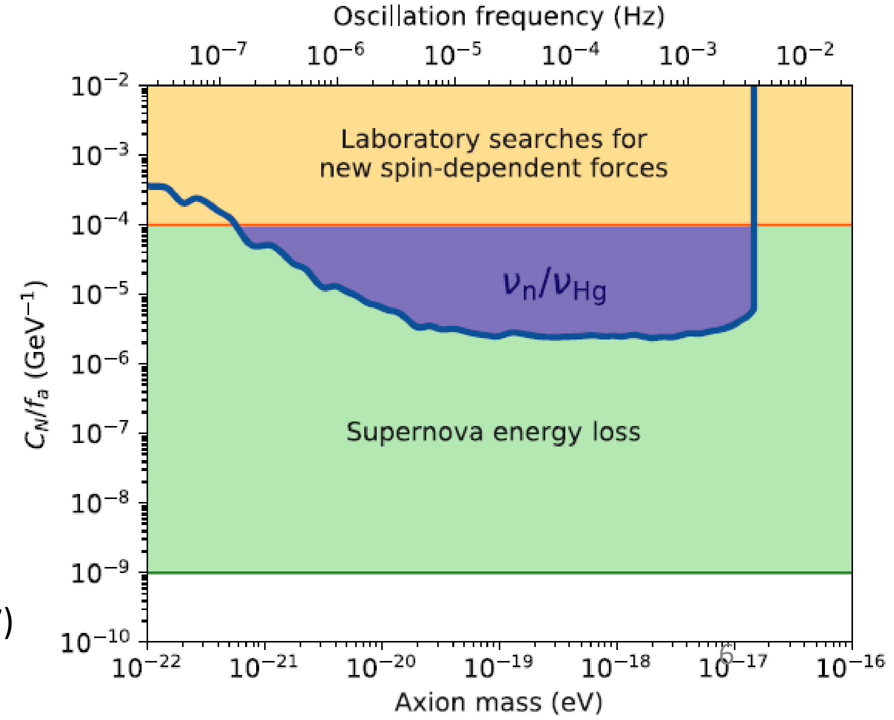
# Feebly Interacting Particles

- The neutron EDM was the original "evidence" for the axion, Peccei-Quinn symmetry.
- Recently: time-dependence of EDM's via oscillating axion field. $a = a_0 \cos m_a t$

$$d_n(t) \approx +2.4 \times 10^{-16} \frac{C_G a_0}{f_a} \cos(m_a t)\, e\,\mathrm{cm}$$

- Precision clock comparison (axion-like particles, Lorentz violation, background cosmic field, …)
- Also: mirror neutrons, …

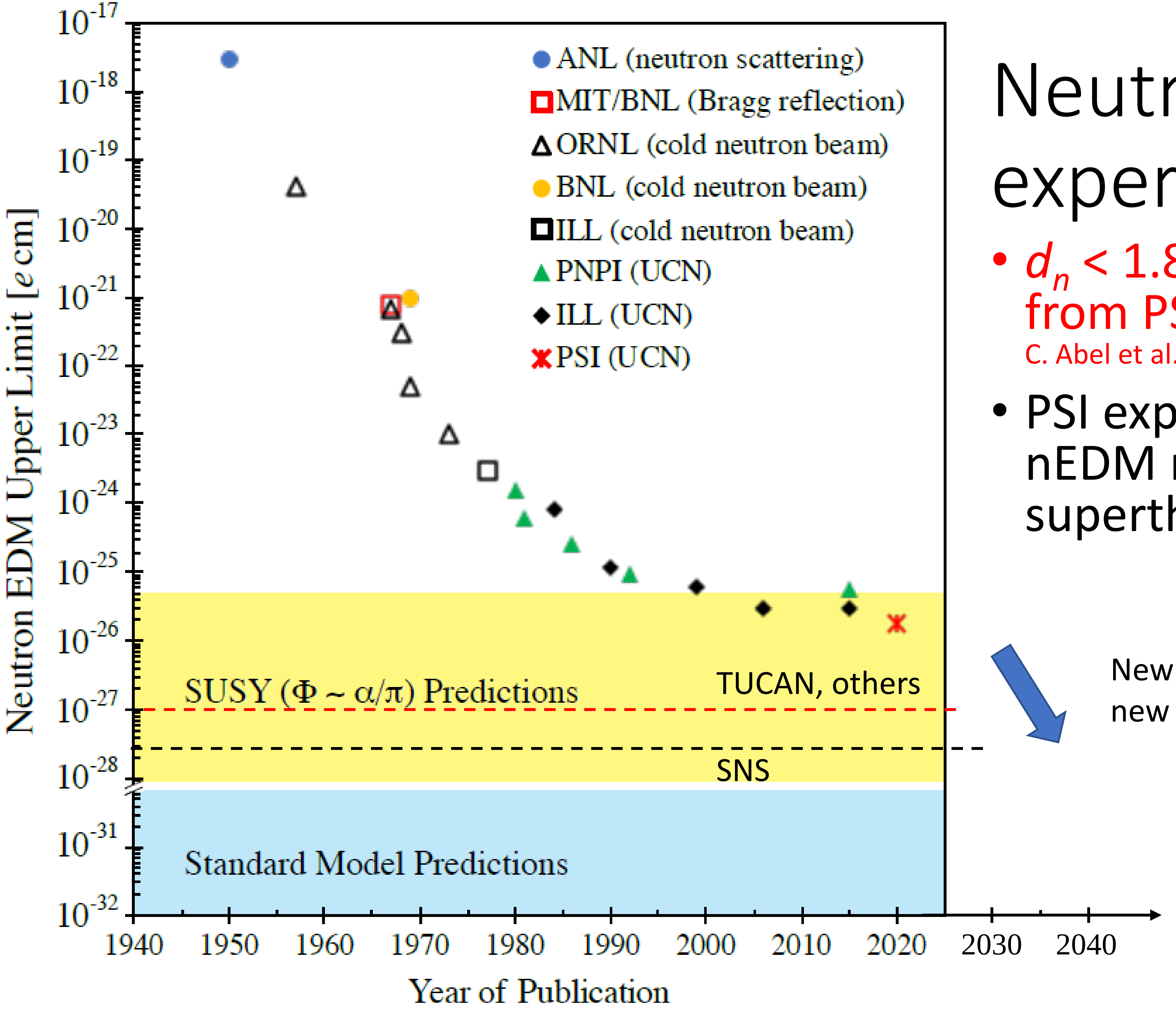



C. Abel et al. PRX 7, 041034 (2017)

# Neutron EDM – experimental status

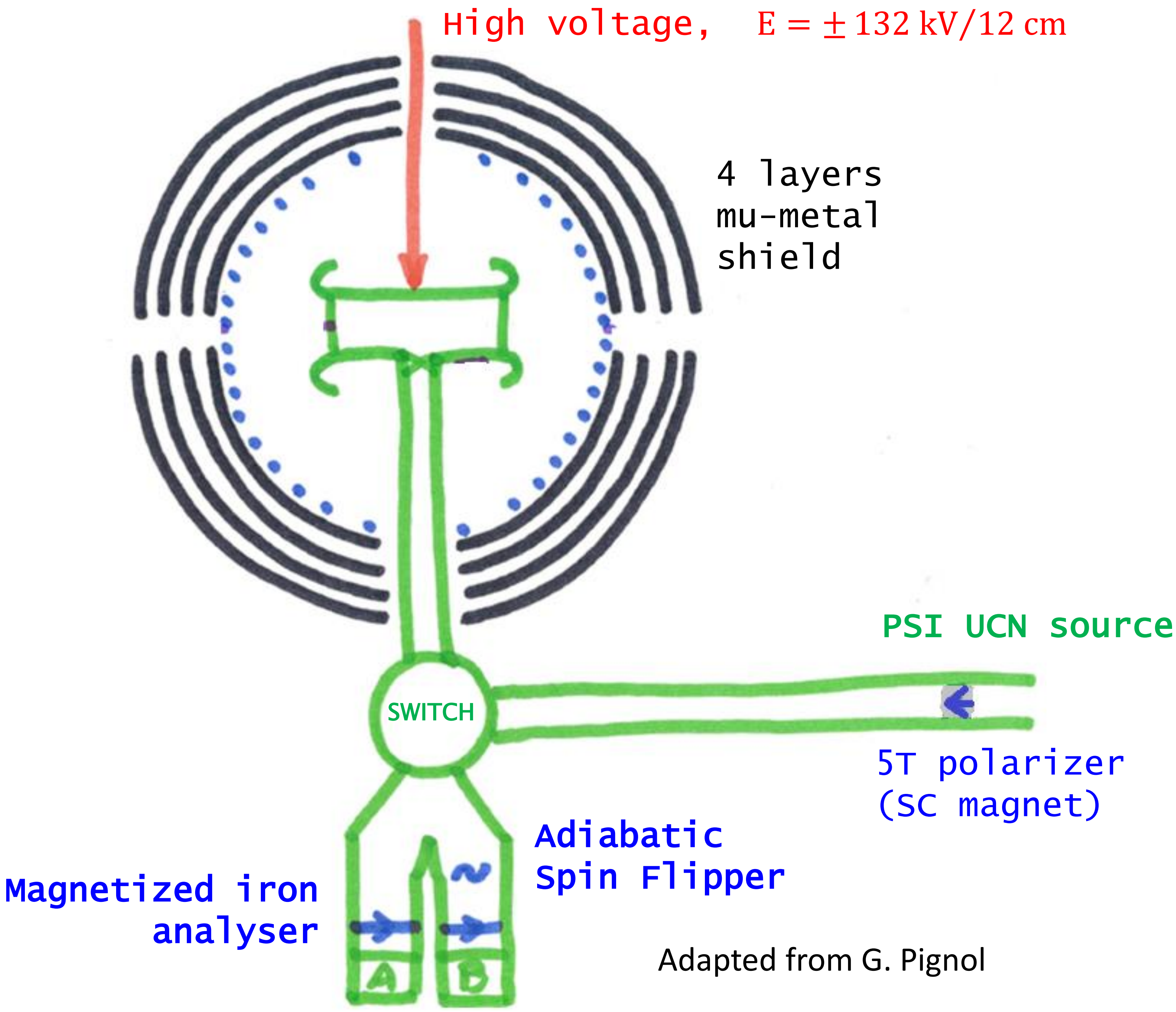
- $d_n < 1.8 \times 10^{-26}$ *e* cm (90% C.L.) from PSI experiment
  C. Abel et al., PRL 124, 081803 (2020)
- PSI experiment was the first nEDM measurement to use a superthermal UCN source




Many groups pursuing $10^{-27}$ *e* cm measurement as next step, including TUCAN

# How these experiments work

- Guide polarized ultracold neutrons (UCN) into a bottle.
- Initiate precession in combined $E$ and $B$ fields.
- After ~ 100 s, drain UCN from bottle and measure accrued phase.
- Repeat, occasionally reversing direction of $E$




Adapted from G. Pignol

# Budget of systematic errors

TABLE I. Summary of systematic effects in $10^{-28}$ $e$.cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below that are considered separately.

| Effect | Shift | Error |
|---|---|---|
| Error on $\langle z \rangle$ | ... | 7 |
| Higher-order gradients $\hat{G}$ | 69 | 10 |
| Transverse field correction $\langle B_T^2 \rangle$ | 0 | 5 |
| Hg EDM [8] | –0.1 | 0.1 |
| Local dipole fields | ... | 4 |
| $v \times E$ UCN net motion | ... | 2 |
| Quadratic $v \times E$ | ... | 0.1 |
| Uncompensated $G$ drift | ... | 7.5 |
| Mercury light shift | ... | 0.4 |
| Inc. scattering $^{199}$Hg | ... | 7 |
| TOTAL | 69 | 18 |

**Leading systematics associated with B-field uniformity**

**Control of spurious E-B correlations with an array of Cesium magnetometers**

from G. Pignol

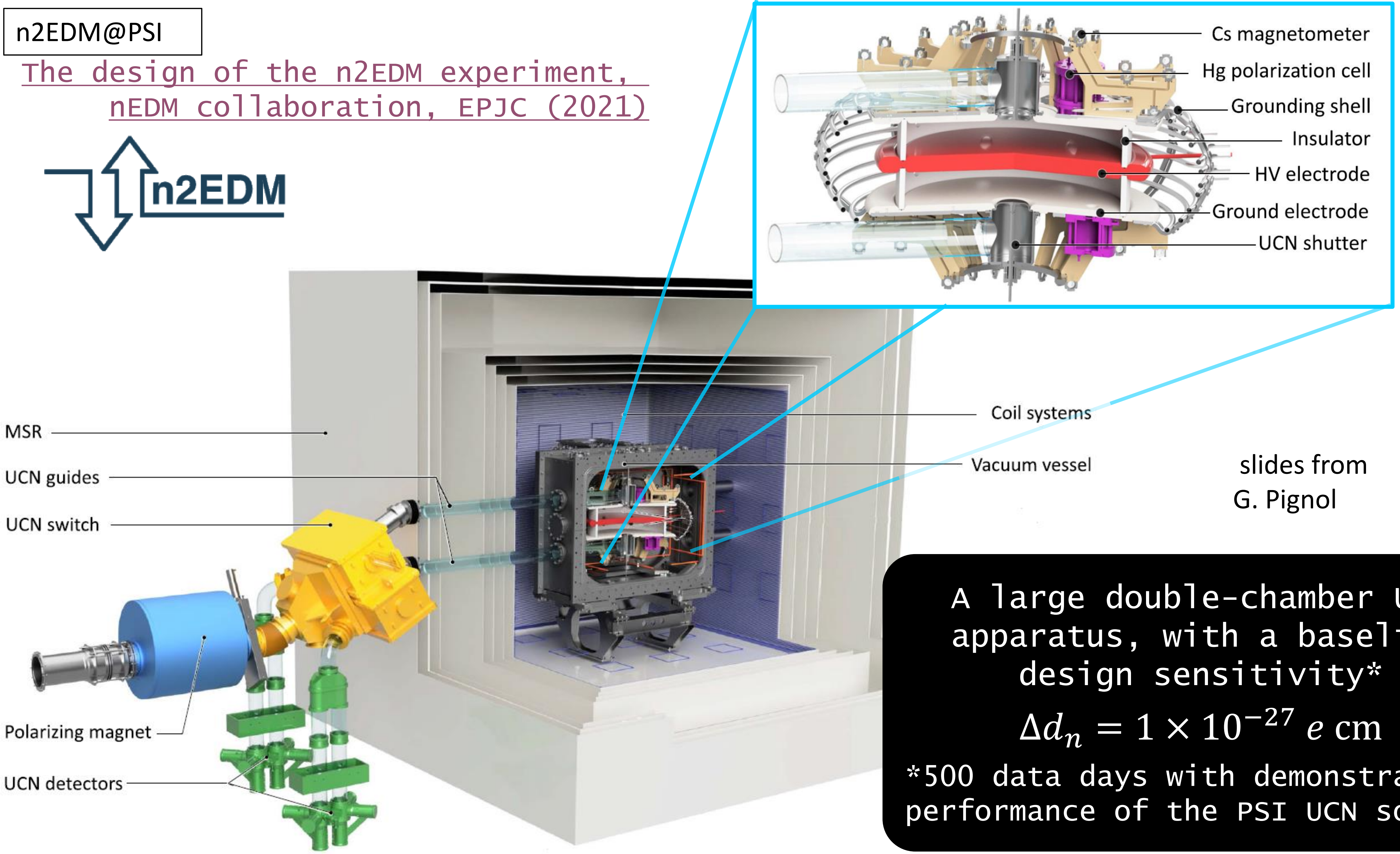
# Ongoing/Planned Neutron EDM Experiments

# Ongoing/Planned Neutron EDM Experiments

| Experiment | Source | Type |
|---|---|---|
| n2EDM@PSI | spallation so-$D_2$ | UCN |
| PanEDM (ILL/Munich) | reactor He-II | UCN |
| LANL nEDM | spallation so-$D_2$ | UCN |
| TUCAN (Japan/Canada) | spallation He-II | UCN |
| ILL/PNPI/Gatchina | reactor He-II | UCN |
| nEDM@SNS | He-II source/experiment | UCN |
| BeamEDM at ILL/ESS | intense neutron beam | CN |
| J-PARC crystal | high E in crystal | CN |

n2EDM@PSI

The design of the n2EDM experiment, nEDM collaboration, EPJC (2021)




slides from G. Pignol

A large double-chamber UCN apparatus, with a baseline design sensitivity*

$$\Delta d_n = 1 \times 10^{-27}\, e\,\text{cm}$$

*500 data days with demonstrated performance of the PSI UCN source

# n2EDM progress and schedule

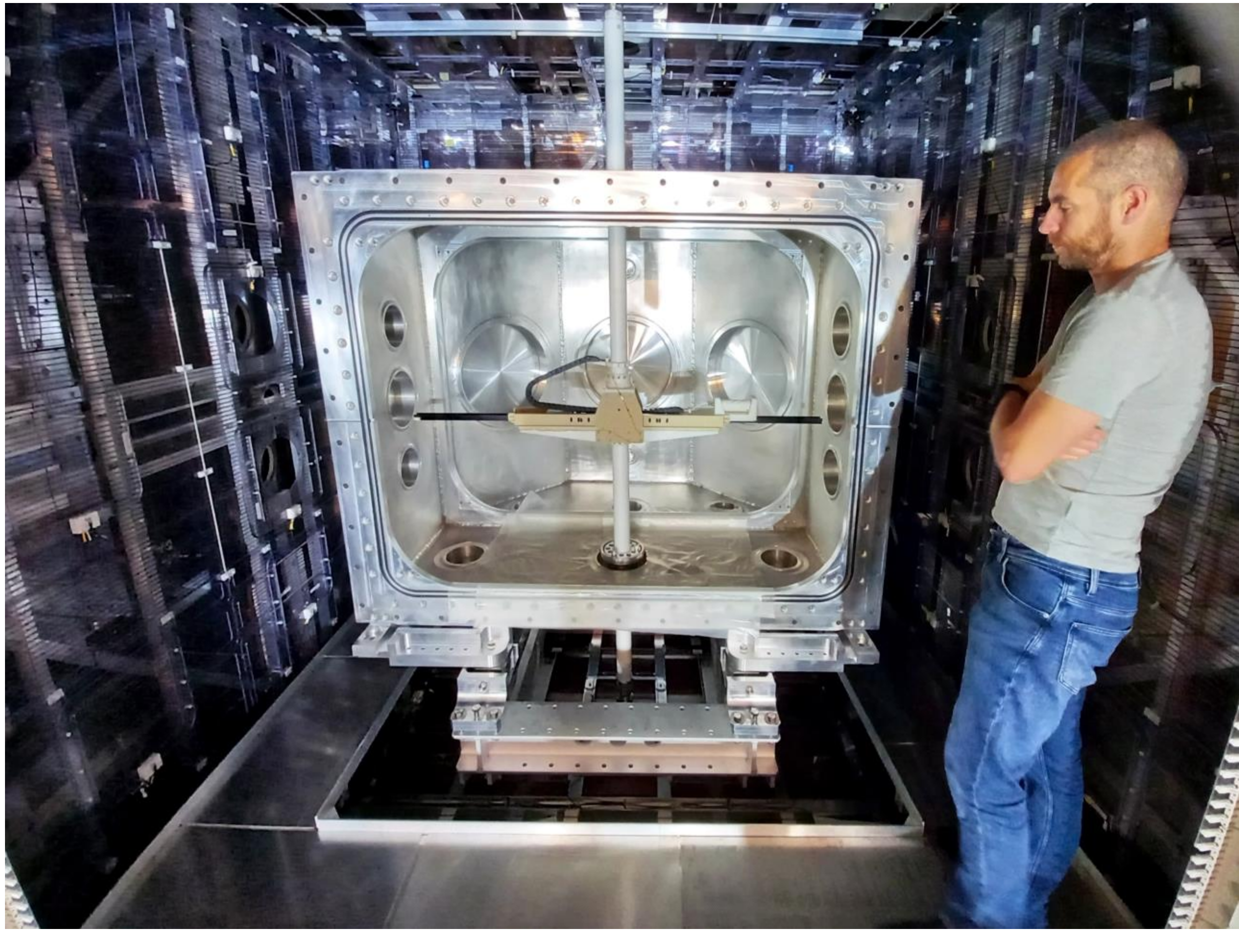
n2EDM@PSI

2020: Commissioning of the MSR
[The very large n2EDM magnetically shielded room, nEDM collaboration, Rev. Sci. Instrum. (2022)]

2021-2022: Magnetic commissioning
B0 coil installation, field mapping

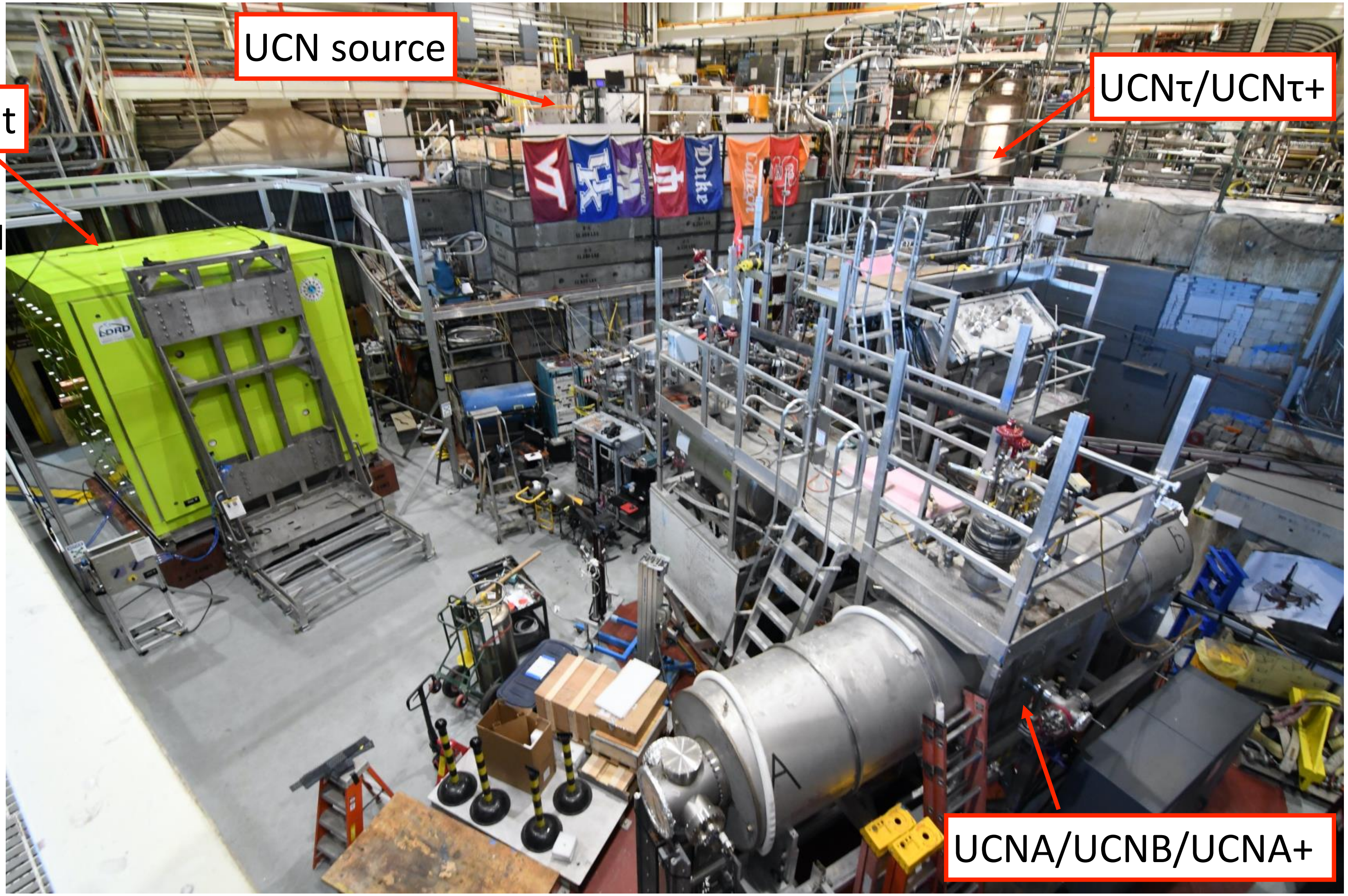
2022-2023: UCN commissioning
Detectors, UCN transport, Ramsey chambers, high voltage
=> apparatus ready for data taking

J. Thorne presentation



View inside the n2EDM magnetically shielded room during the installation of the field mapper in the vacuum vessel

# LANL UCN Experimental Hall



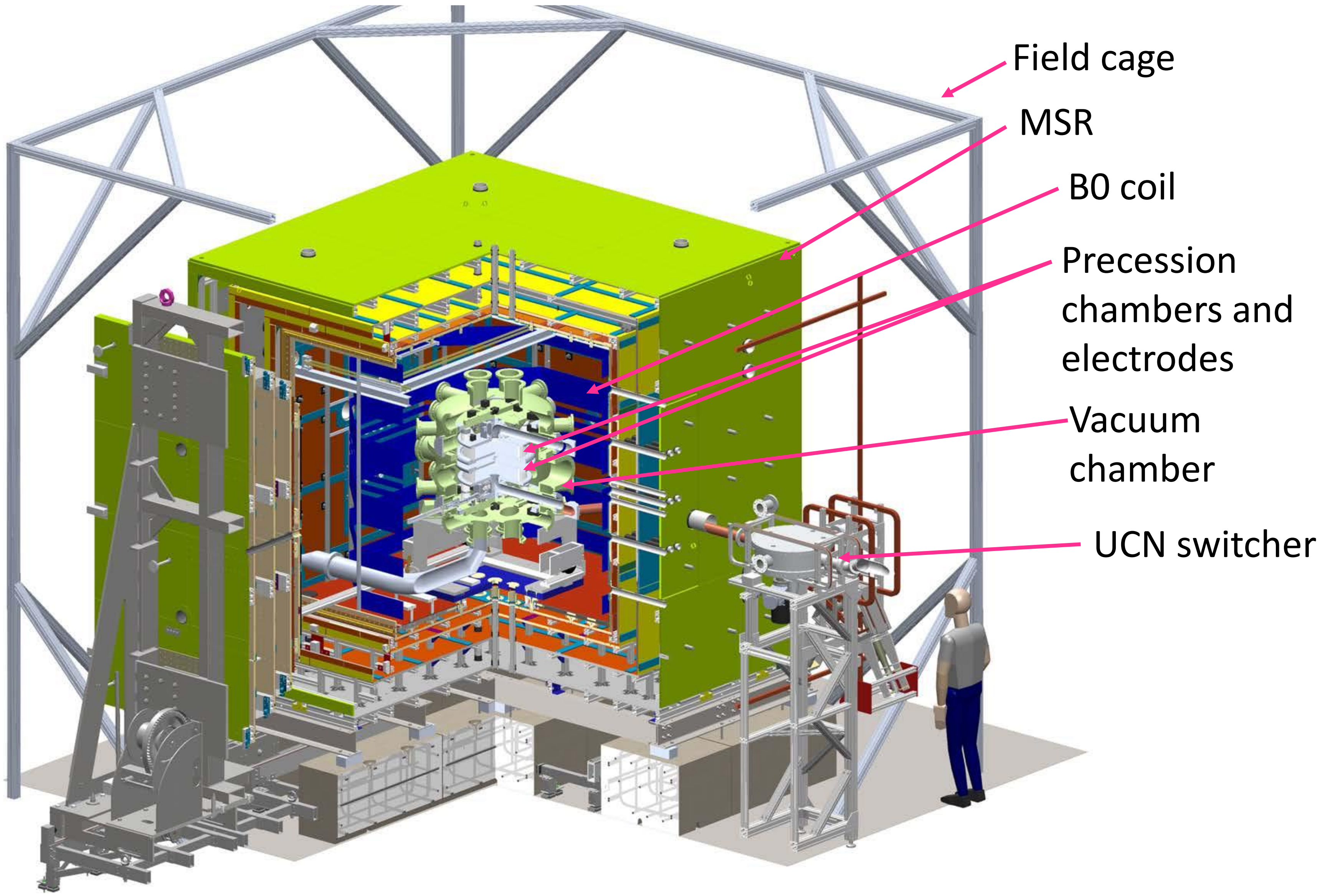

- Successfully upgraded LANL UCN source has demonstrated the UCN density required for an nEDM experiment with $\delta d_n \sim O(10^{-27})$ *e*cm
- Venue for the US nEDM community to obtain physics results, albeit less sensitive, in a shorter time scale with much less cost while development for the SNS nEDM experiment continues.
- Based on the measured stored polarized UCN density, we expect to achieve a statistical sensitivity of $2\times10^{-27}$ *e*cm in one live-year of running.

slides from
T. Ito

LANL nEDM

# LANL nEDM experiment

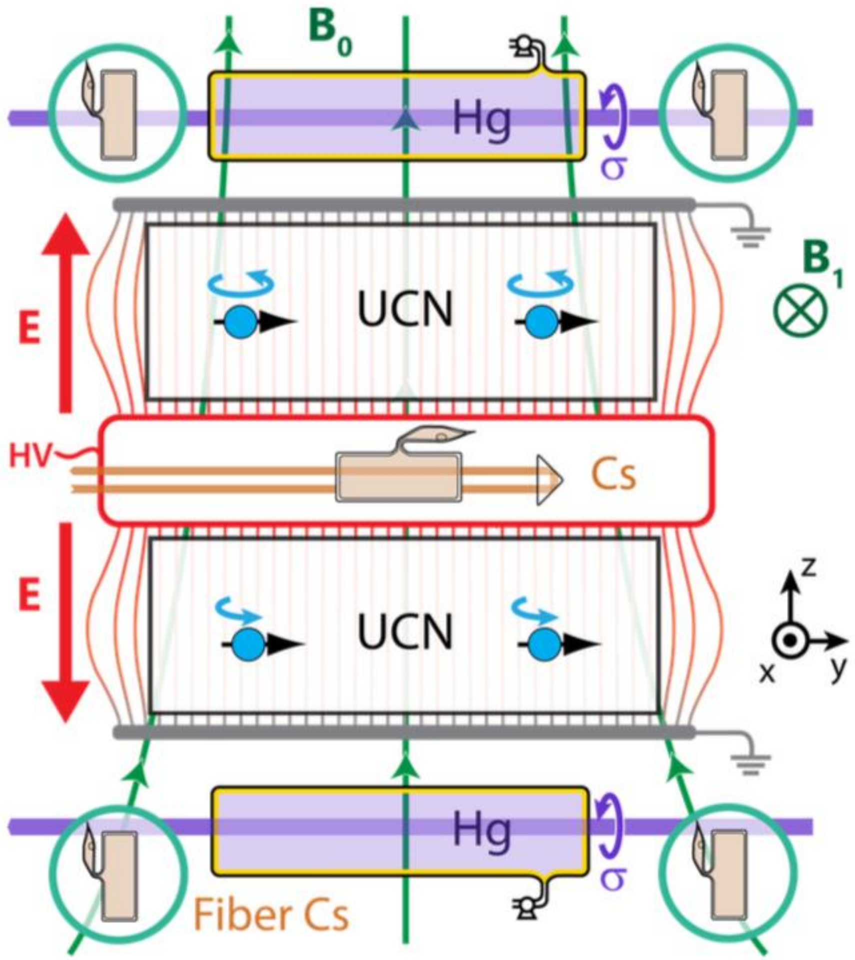
- MSR has been installed. It has been shown to meet the specs on both the shielding factor ($10^5$ @ 0.01 Hz) and the residual field ($\lesssim$ 0.5 nT).
- Currently assembling the precession chambers and UCN valves.
- Plan to start engineering run in CY2022.




D. Wong presentation

ILL/Munich
PanEDM

# The PanEDM Experiment

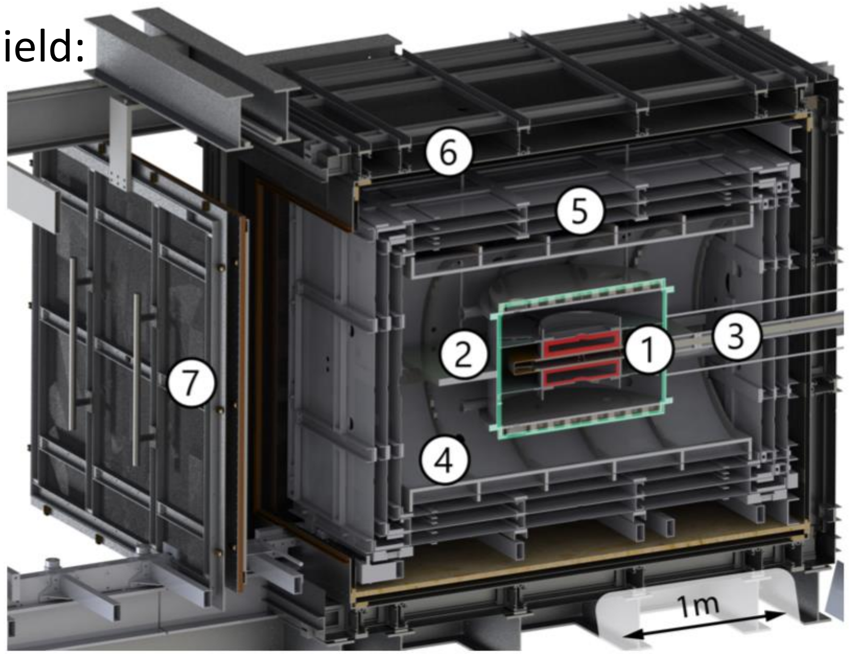



- Double chamber Ramsey experiment at room temperature
- 199Hg magnetometers with few fT resolution
- Cs magnetometers also at HV
- Magnetic shield with SF $6.10^6$ at 1 mHz
- Simultaneous spin detection
- SuperSUN UCN source at ILL
  Two stages –
  - 1: unpolarized UCN with 80 neV peak
  - 2: polarized UCN, magnetic storage

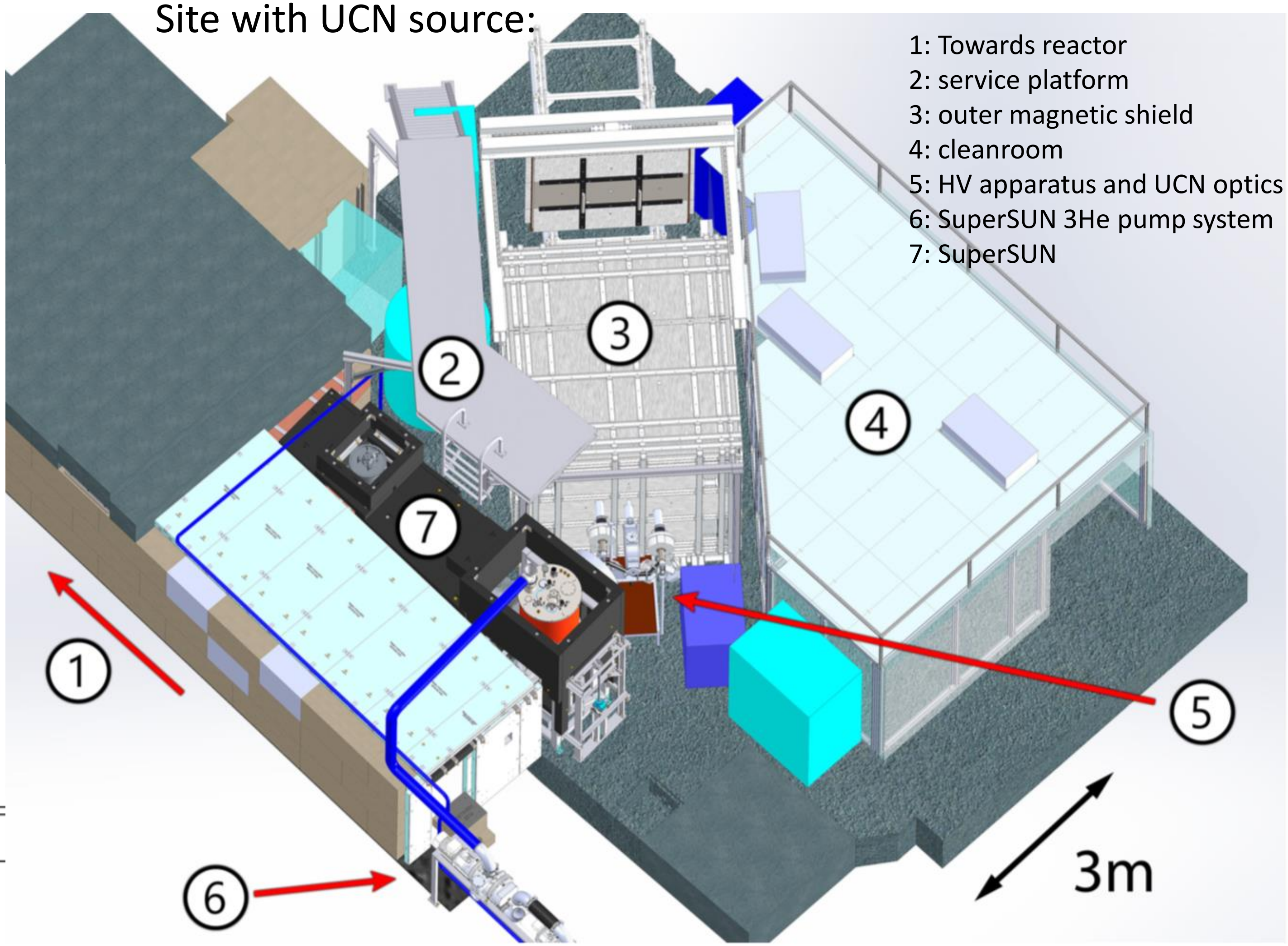
Adapted from P. Fierlinger

ILL/Munich
PanEDM

Magnetic shield:




Site with UCN source:



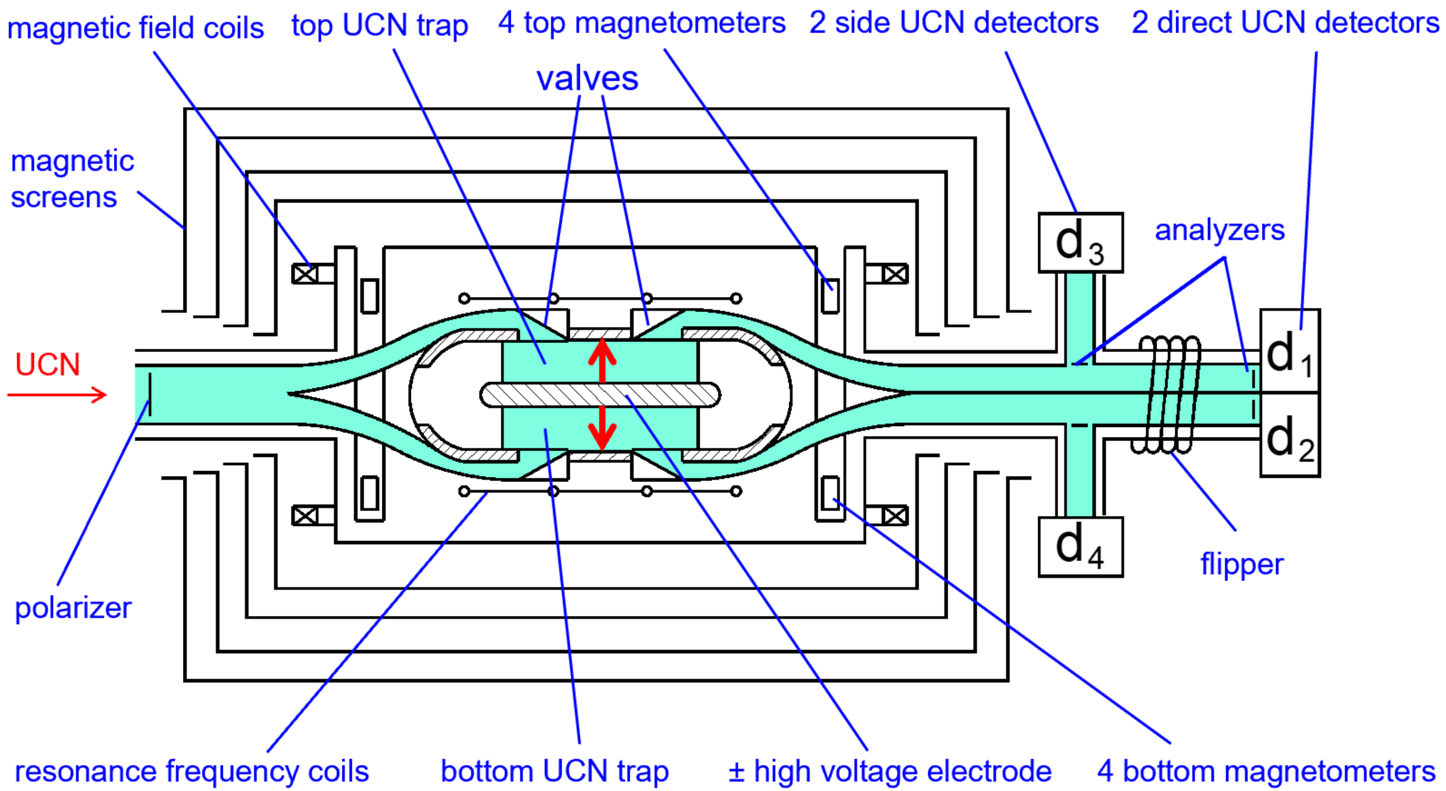

Statistical sensitivity:

| **SuperSUN** | **Phase I** |
|---|---|
| Saturated source density [$cm^{-3}$] | 330 |
| Diluted density [$cm^{-3}$] | 63 |
| Density in cells [$cm^{-3}$] | 3.9 |
| **PanEDM Sensitivity** [$1\sigma$, $e$ cm] | |
| Per run | $5.5 \times 10^{-25}$ |
| Per day | $3.8 \times 10^{-26}$ |
| Per 100 days | $3.8 \times 10^{-27}$ |

Systematic effects:
- Geometric phase effect: well controlled magnetic field
- No comagnetometer: we estimate overall better performance without in phase I, given extremely stable magnetic background

H. Filter, E. Chanel posters, M. Jentschel presentation

# ILL/PNPI



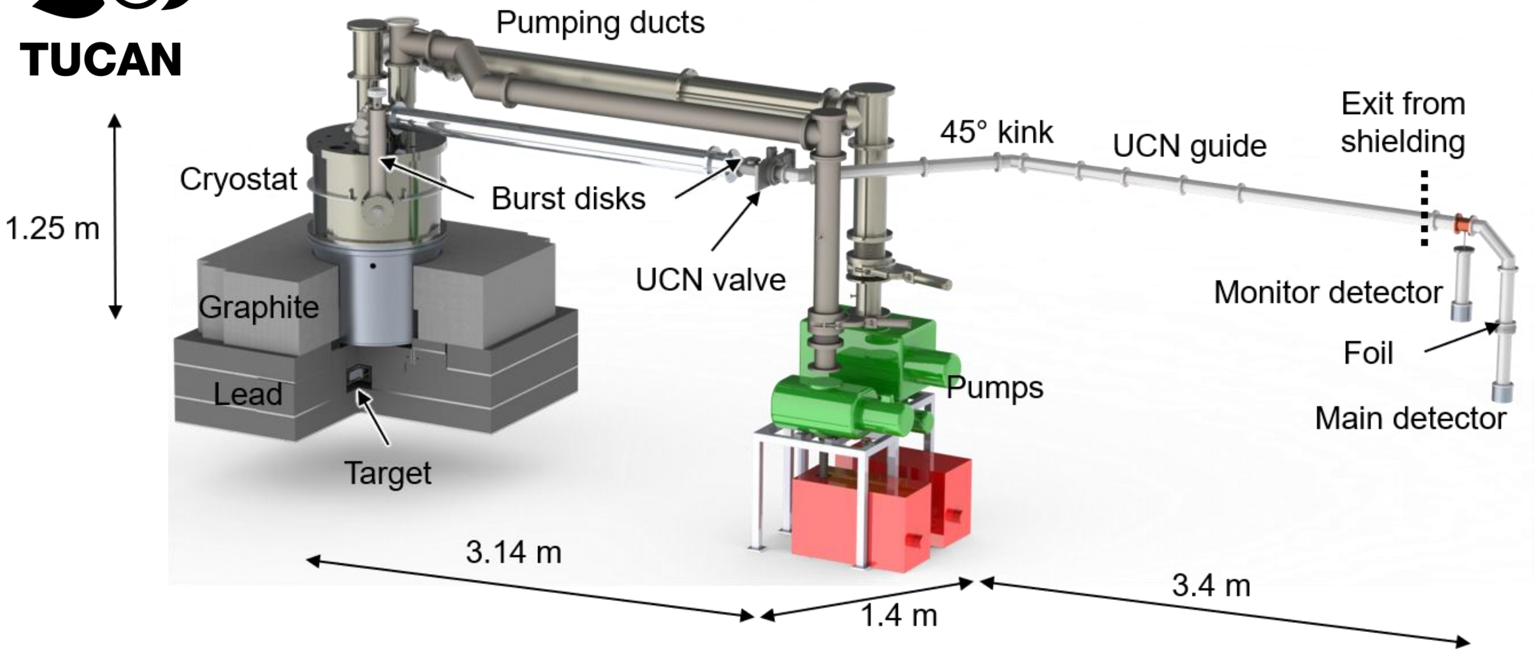

Spectrometer used

- 1985 – 1996 at PNPI
- 2008 – 2013 at ILL
- Plan to move to PNPI (Gatchina) to a new He-II UCN source

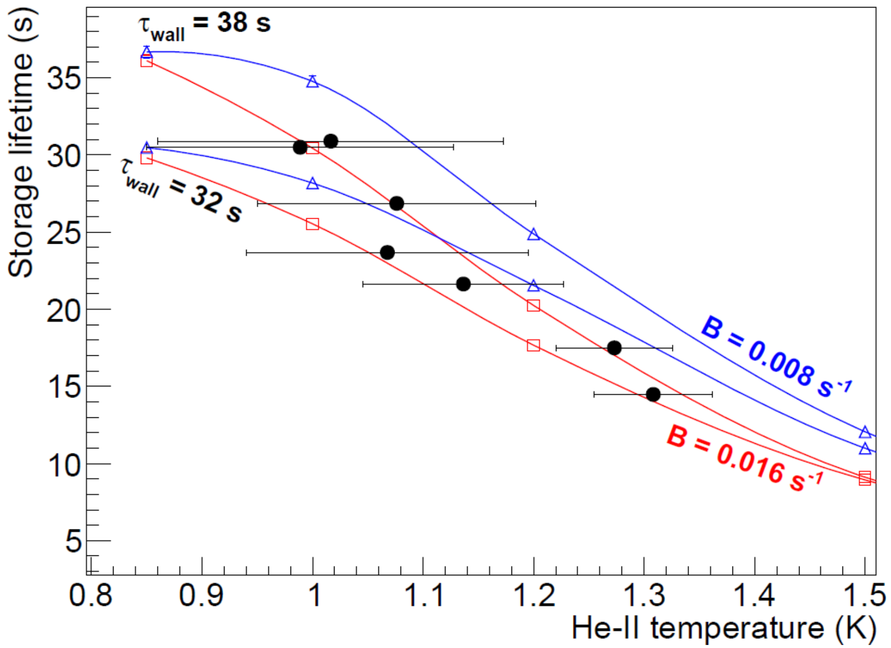
Adapted from A. Serebrov

# Previous "Vertical" UCN Source at TRIUMF

TUCAN

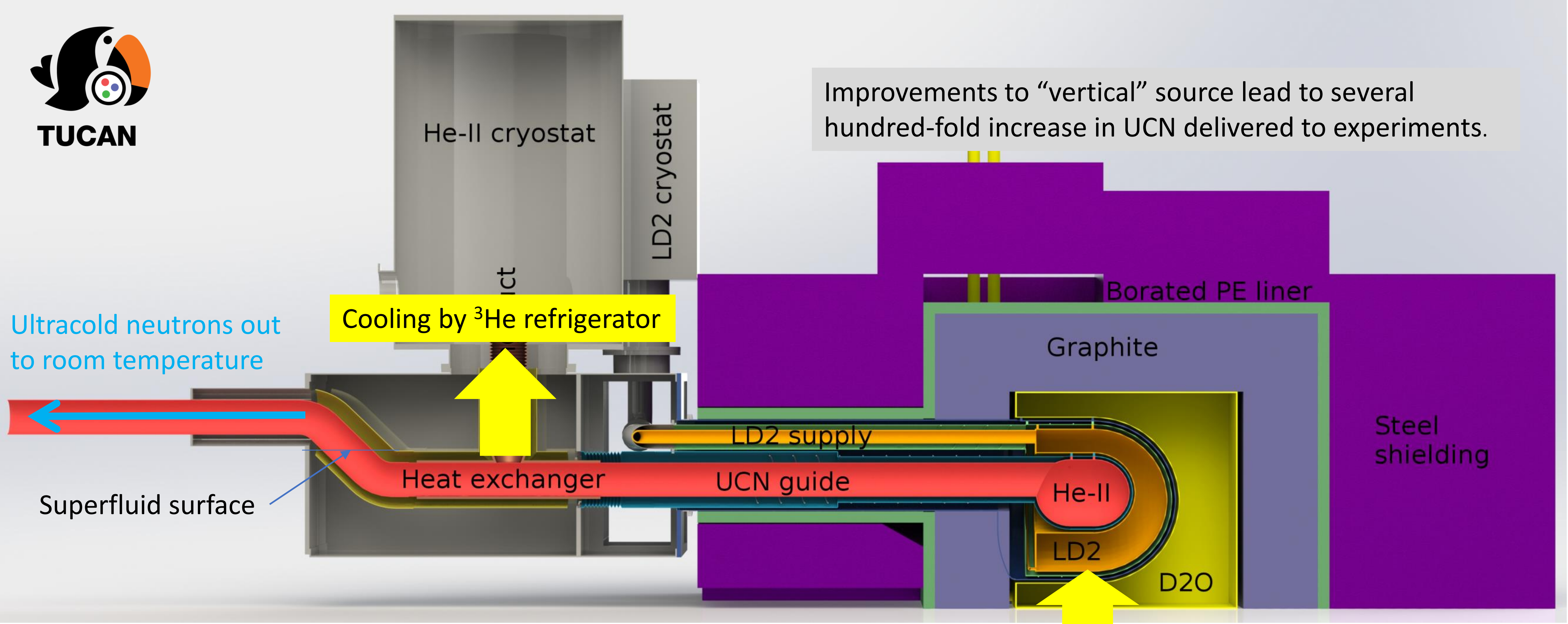



S. Ahmed *et al.* (TUCAN Collaboration )
PRC **99**, 025503 (2019)



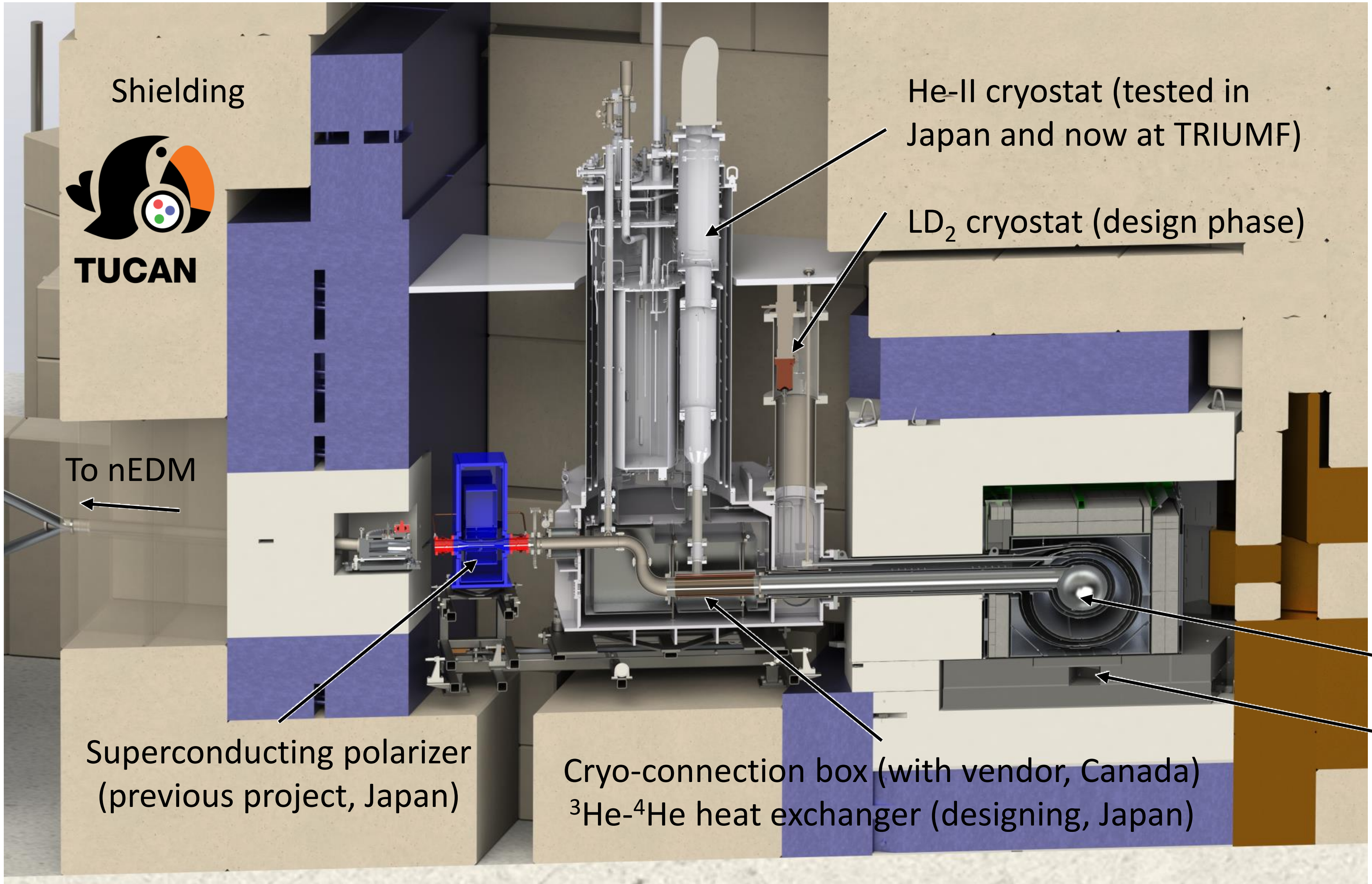

- Operated from 2017-2019 at TRIUMF, then decommissioned to make way for upgrade.
- In preparation (Phys. Rev. C): new data that collapses the horizontal error bars on this plot (~ 10 mK).
- Allows extraction of the parameters describing the interaction of UCN with phonons in the He-II.

# Ongoing upgrade: Next generation He-II cryostat (the “horizontal source”)

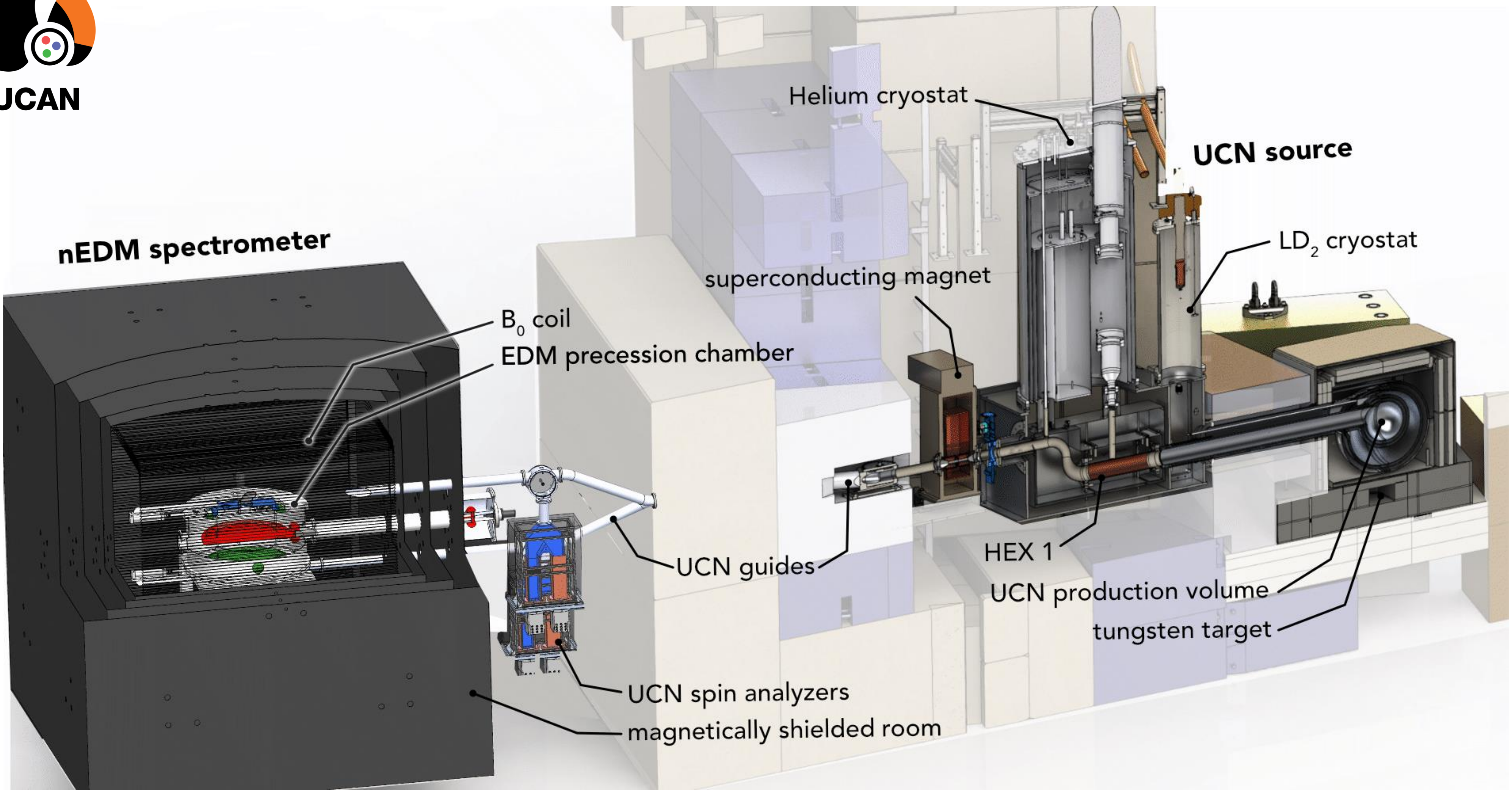



Hot neutrons from spallation target

# Horizontal source status




TUCAN


Helium cryostat
UCN source
nEDM spectrometer
LD$_2$ cryostat
superconducting magnet
B$_0$ coil
EDM precession chamber
UCN guides
HEX 1
UCN production volume
tungsten target
UCN spin analyzers
magnetically shielded room

# TUCAN recent progress and plans

- Recent progress:
  - Completion & commissioning of dedicated spallation beamline BL1U
  - Install & Operation of prototype UCN source with successful beam times 2017/2018/2019
  - Design, construction & first testing of new UCN source cryostat; installation at TRIUMF in progress (2022-2023)
  - Installation of Magnetically Shielded Room for nEDM experiment in progress
- Timeline:
  - 2024 UCN production with new TUCAN source
  - 2025 Readiness for nEDM data taking
- Initial goal to demonstrate $10^{-27}$ *e*cm capability

T. Higuchi presentation

# Overview of nEDM@SNS

Experiment under construction at the Spallation Neutron Source at Oak Ridge National Laboratory

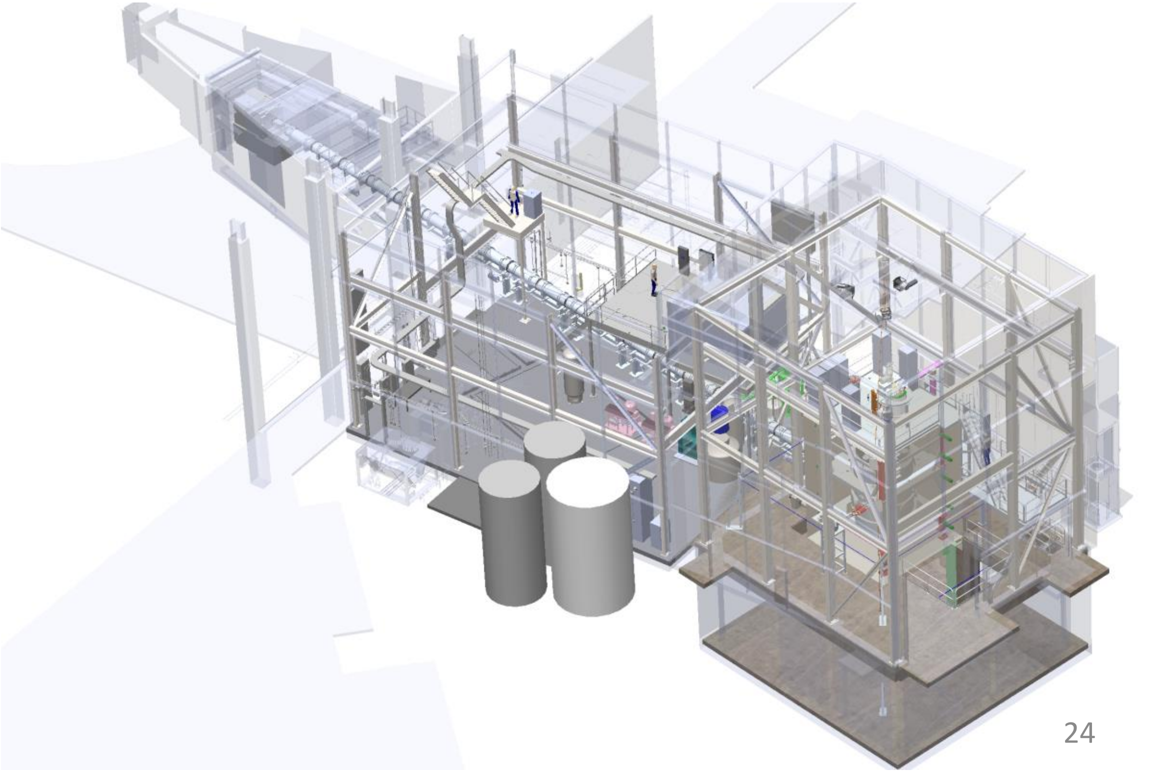
Based on the pioneering concept of R. Golub and S. K. Lamoreaux, Phys. Rept. 237, 1 (1994)

0.5 K Superfluid $^4$He Environment

In-situ UCN production (8.9 Å cold beam)

Dilute mixture of polarized $^3$He as co-magnetometer and spin analyzer

Large electric field breakdown strength



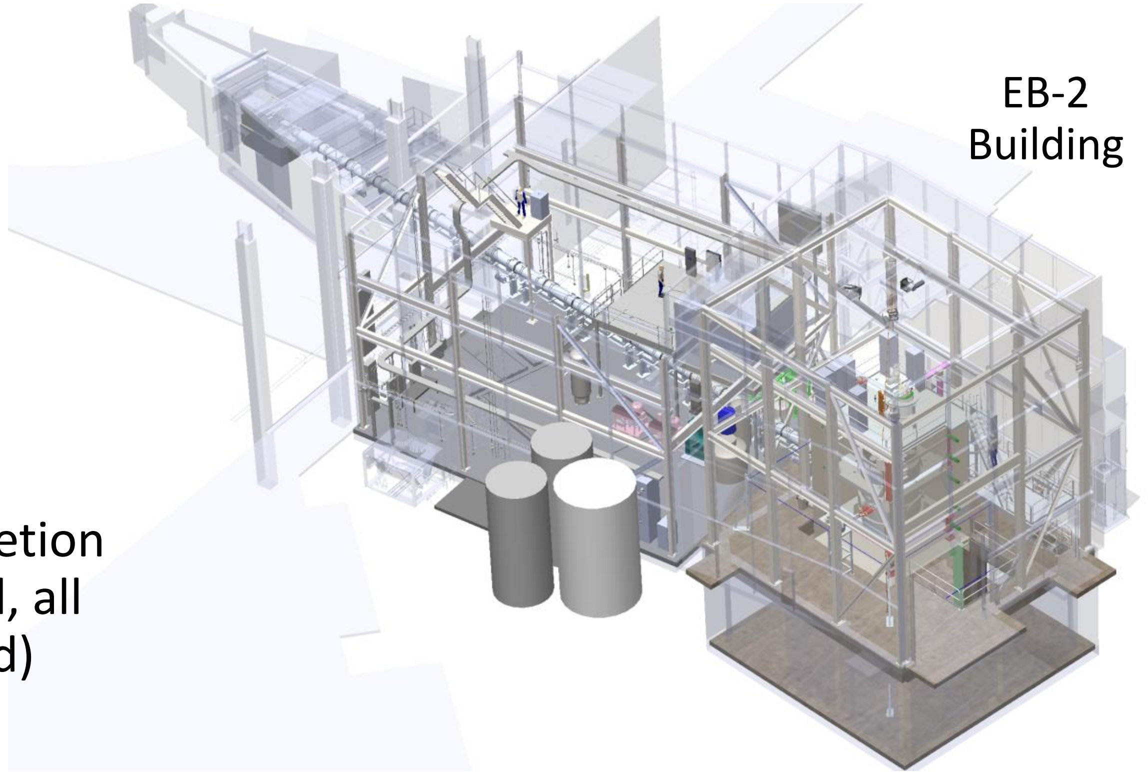
Projected 90% CL Sensitivity

"Free Precession": $5.7 \times 10^{-28}$ e-cm

"Dressed Spin": $2.9 \times 10^{-28}$ e-cm

nEDM@SNS

# Experiment Timeline



EB-2 Building

Rigorous project management process in place with hands-on oversight by the funding agencies (DOE and NSF) and review panels

Most recent bottom-up schedule update projects completion of the project in late-2027 (i.e., apparatus commissioned, all performance parameters on previous slide demonstrated)

However, this schedule assumed construction of the EB-2 Building starting in 2023

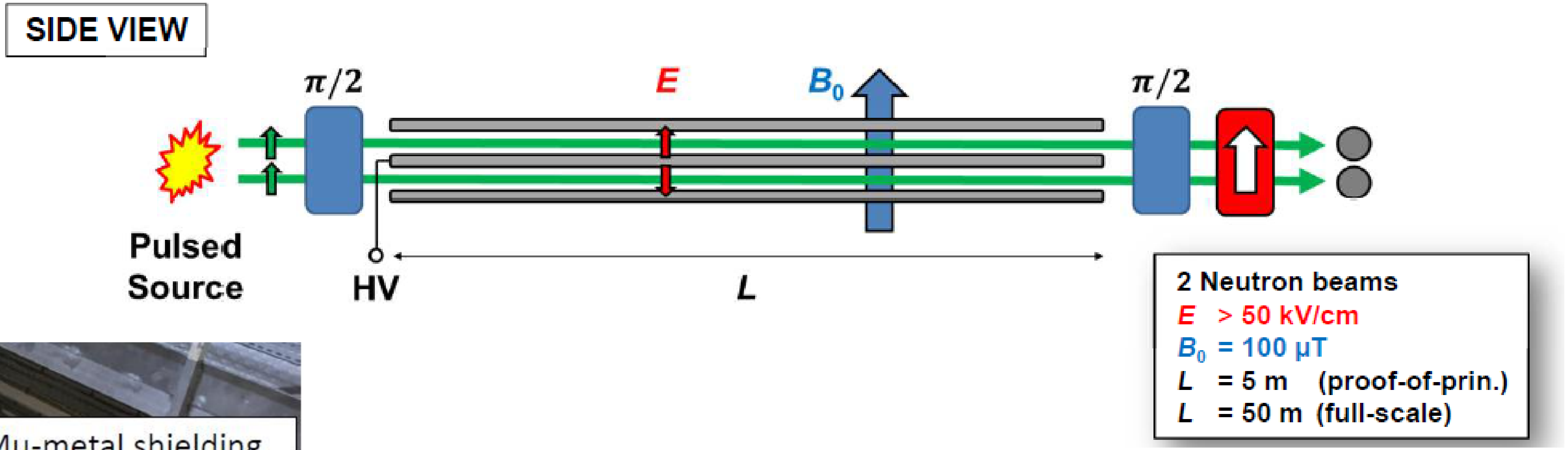
B. Plaster presentation

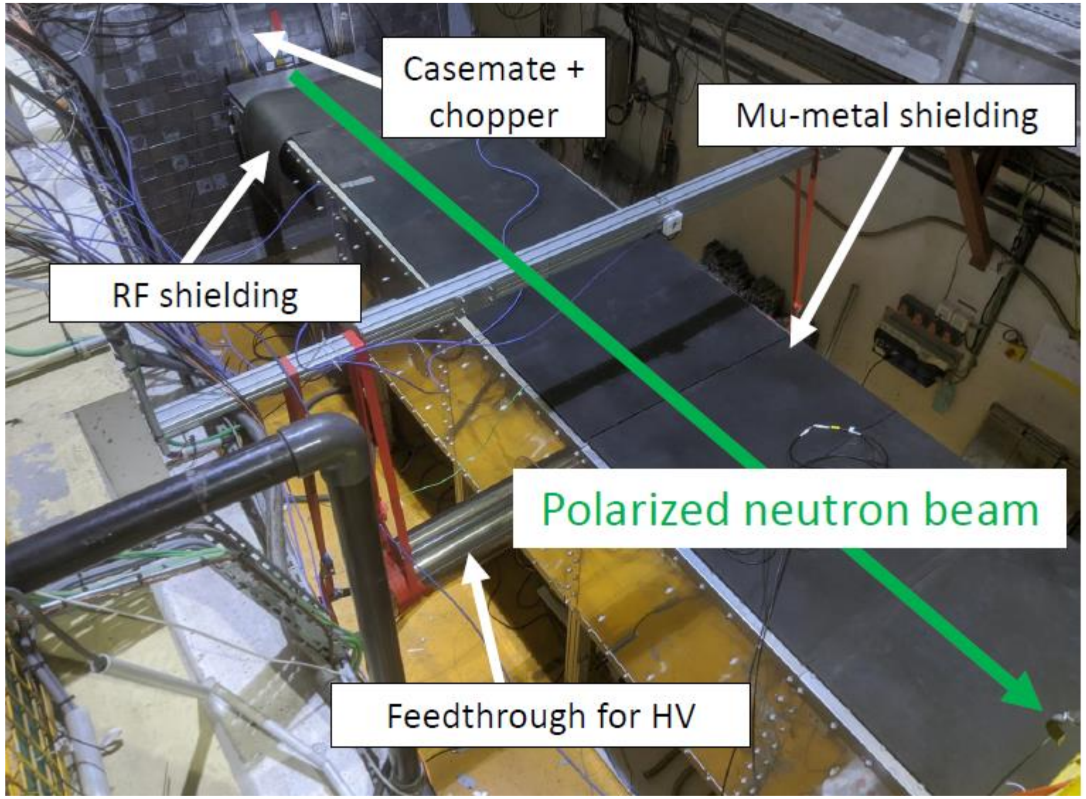
We are now planning, in close communication with the funding agencies, for construction of the EB-2 Building to start in 2024.  We are currently evaluating the impact of this delay to the EB-2 construction on the overall schedule for project completion.

BeamEDM @ ILL/ESS

Many more neutrons, higher E

$\vec{B}_{v\times E} = -\frac{\vec{v}\times\vec{E}}{c^2}$ -> False EDM




- First EDM measurements at ILL
- Most recent run in 2020
- Full-scale apparatus envisioned for ESS

A. Fratangelo poster

Adapted from F. Piegsa, J. Thorne

# Conclusions

- Strong physics interest with tight constraint placed on CP violation.
  - nEDM offers a particularly strong constraint when new physics couples to quarks/gluons.
  - Highly competitive field with many new ideas, technologies.
  - Community holds nEDM workshops every 2-4 years
    - October 2017: Harrison Hot Springs, BC http://nedm2017.triumf.ca
    - February 2021: Ecole des Houches (virtual) https://lpsc-indico.in2p3.fr/event/2584
    - November 2023: Santa Fe, NM
- Next generation of experiments aims at $10^{-27}$ e-cm uncertainty, order of magnitude improvement mostly arising from UCN source increase.
- Experiments developing innovative techniques to achieve $10^{-28}$ e-cm.

# Thanks

- G. Pignol (U. Grenoble Alpes), B. Lauss (PSI), J. Thorne (Bern), T. Ito (LANL), C.-Y. Liu (UIUC), B. Filippone (Caltech), B. Plaster (U. Kentucky), P. Fierlinger (TUM), S. Degenkolb (ILL), A. Serebrov (PNPI)
- My collaborators in TUCAN (esp. R. Picker, B. Franke, S. Kawasaki, and T. Higuchi)
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