Japan, Canada, US,
and (soon) Mexico

TUCAN EDM Experiment

TRIUMF UltraCold Advanced Neutron Electric Dipole Moment Experiment

Jeff Martin, The University of Winnipeg

Other presentations this week:

M3-1	A. Zahra
POS-19	B. Algohi
T3-4	T. Hepworth

TRIUMF
UBC
UNBC
SFU
University of Manitoba
The University of Winnipeg
NC STATE UNIVERSITY
University of Saskatchewan
TUCAN

February 2024 Collaboration Meeting, Winnipeg

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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

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

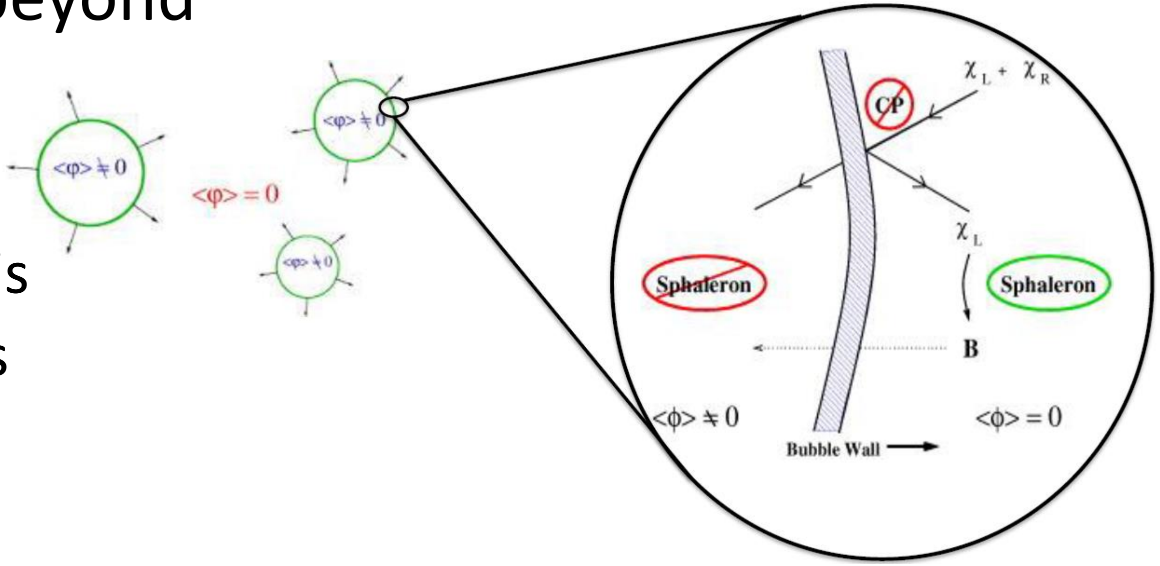
- Statistical uncertainty:

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

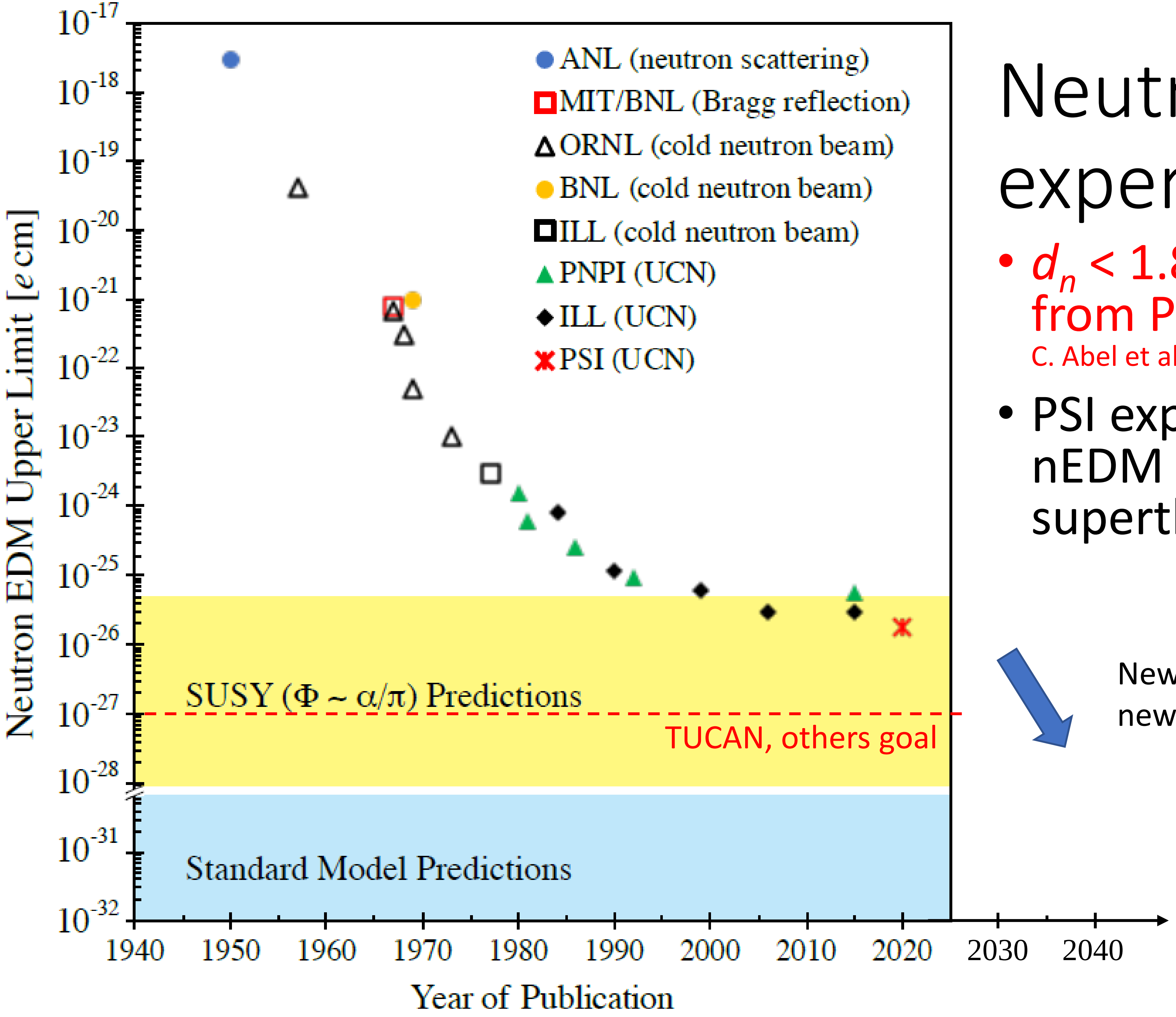
Precision frequency measurement requiring lots of neutrons

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



Neutron EDM – experimental status

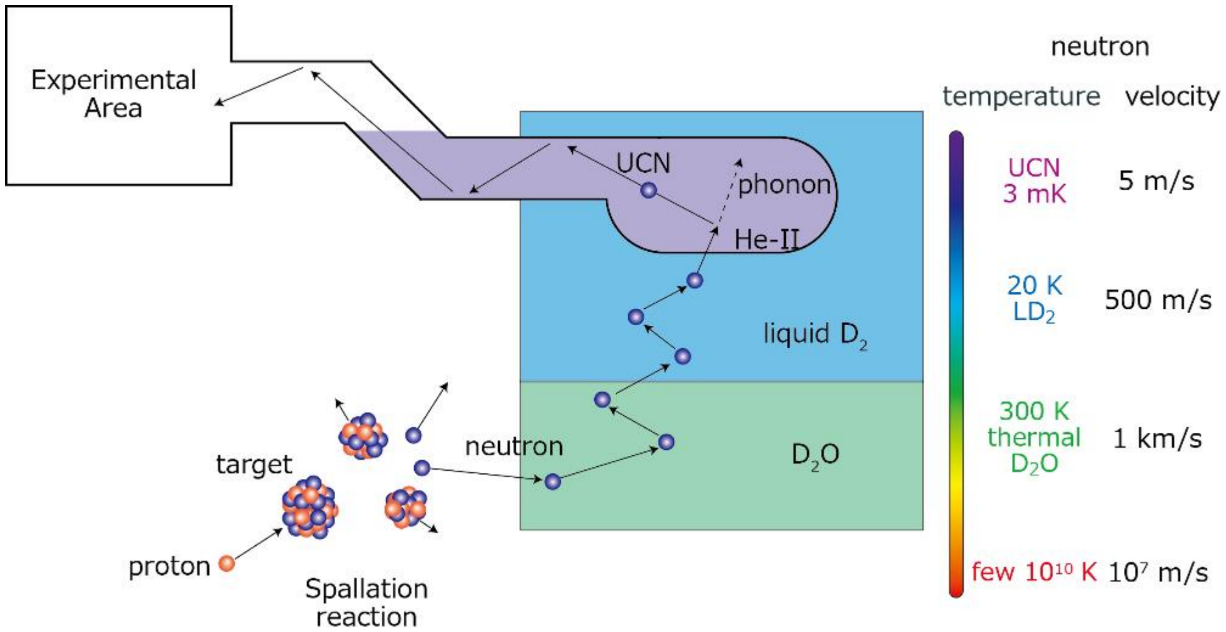
- $d_n < 1.8 \times 10^{-26}$ *e* cm (90% C.L.) from PSI experiment
  C. Abel et al., PRL 124, 081803 (2020)
- PSI experiment was the first nEDM measurement to use a superthermal UCN source

New UCN source technology, new techniques

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

TRIUMF Ultracold Advanced Neutron (TUCAN) Source

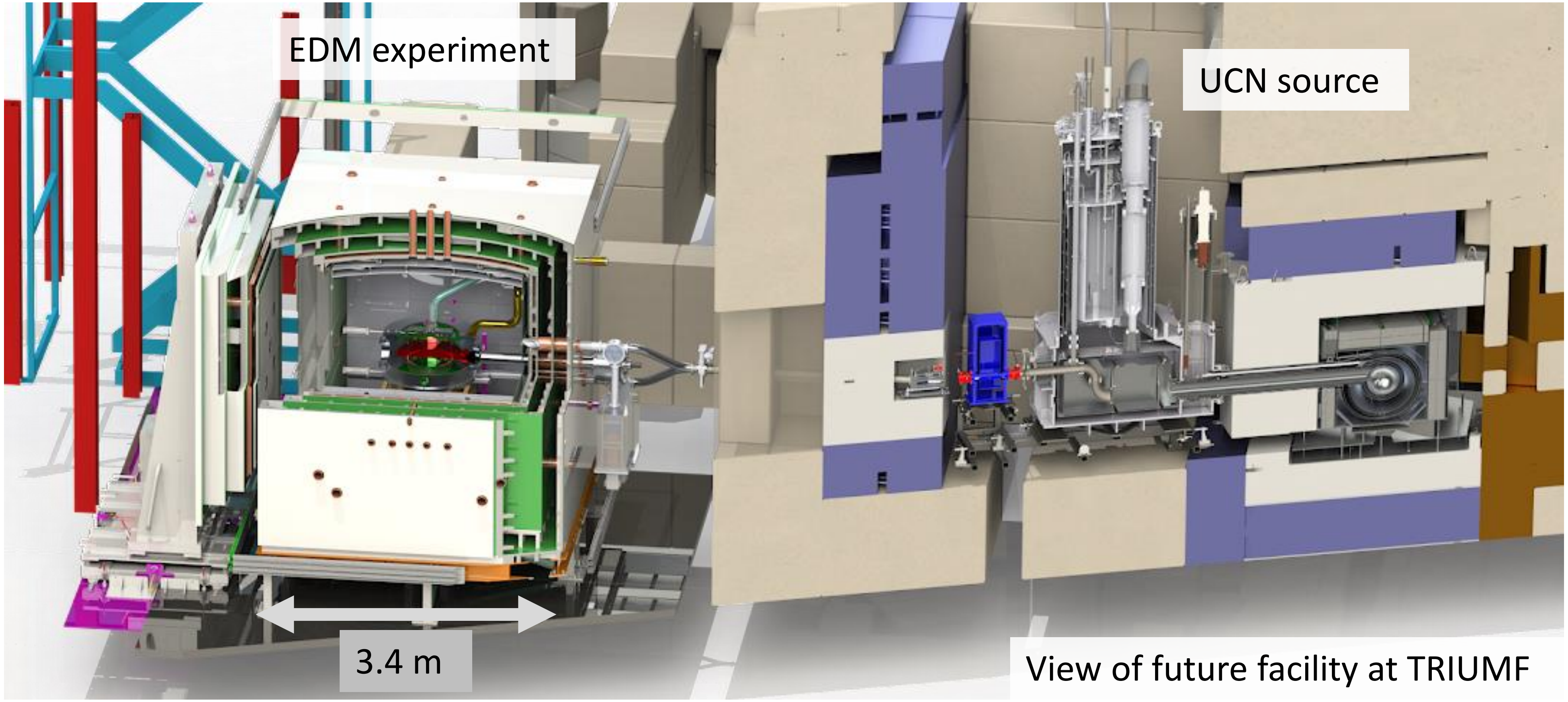
- Concept:
  - Use superfluid helium (He-II) to convert cold neutrons into **ultracold neutrons (UCNs)**
  - Couple the He-II directly to a spallation source of neutrons and cold moderators that can be optimized fully
  - Transport UCN to a room-temperature **neutron EDM experiment** located farther away from the neutron source and cryogenic systems
- We have been operating this system first at RCNP Osaka, then at TRIUMF. We are now completing a **new upgrade**, scaling up the previous system with several key improvements to reach world-record UCN performance.



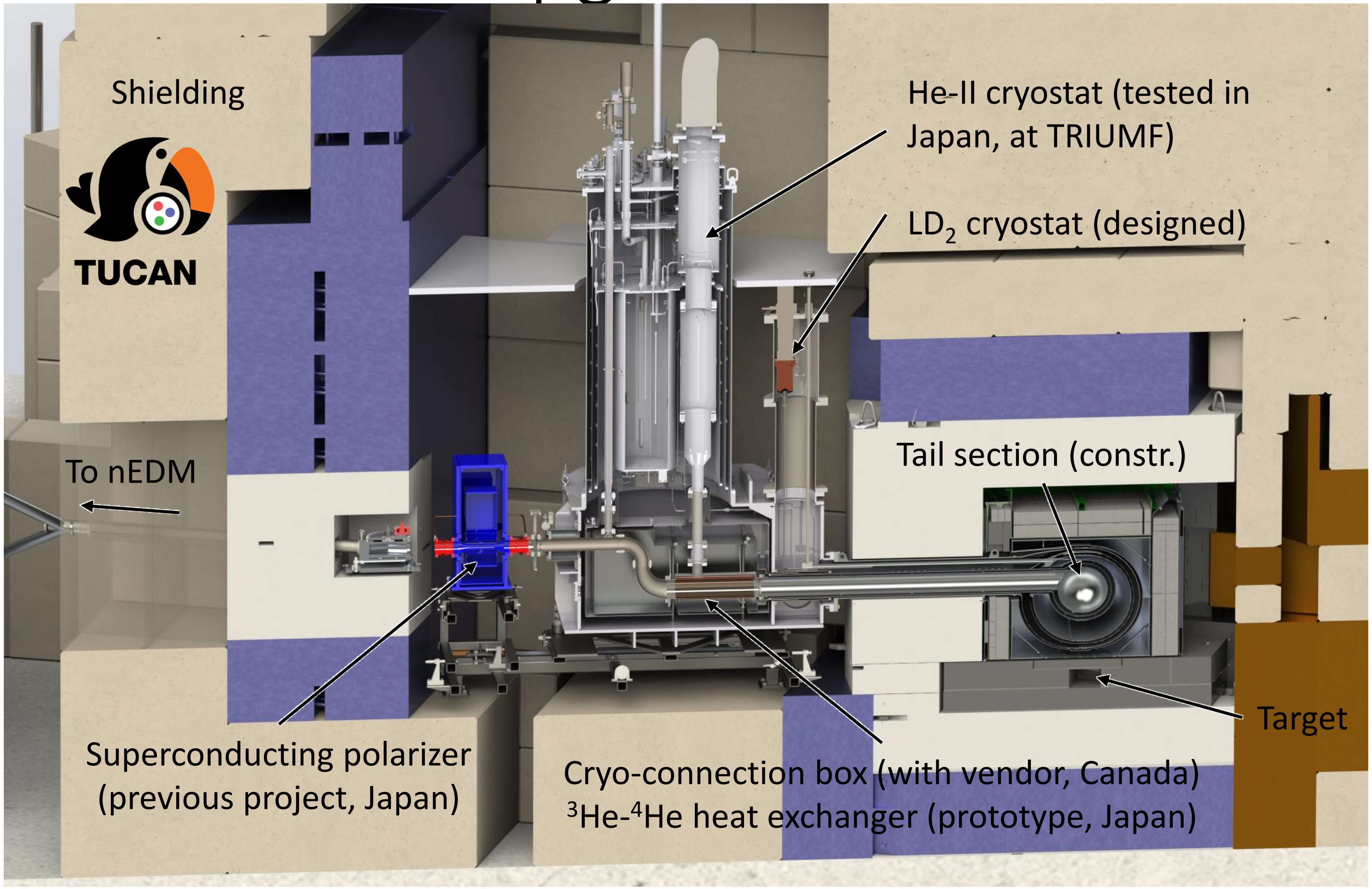
TUCAN source and EDM Experiment

TUCAN

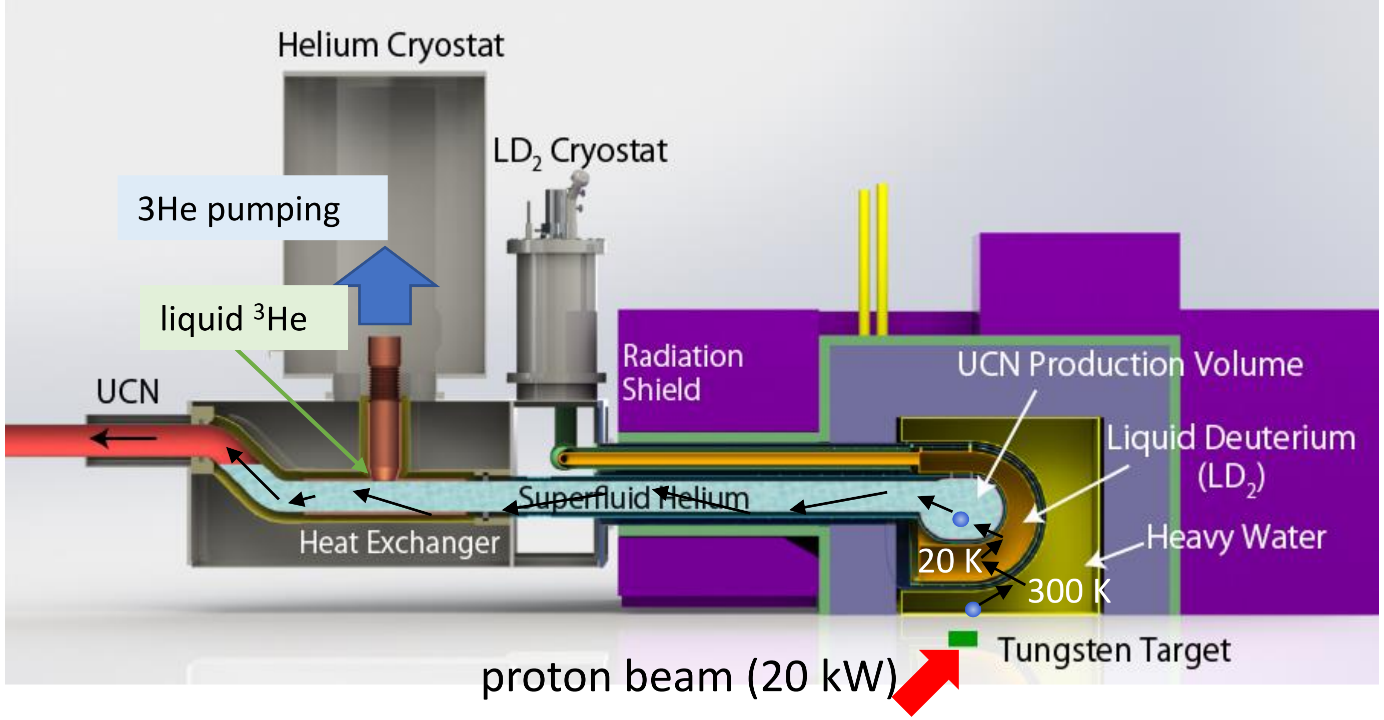
- Enable search for neutron EDM with 1×10^{-27} *e*cm precision.



Horizontal source upgrade



TUCAN Source Upgrade Concept and Goals



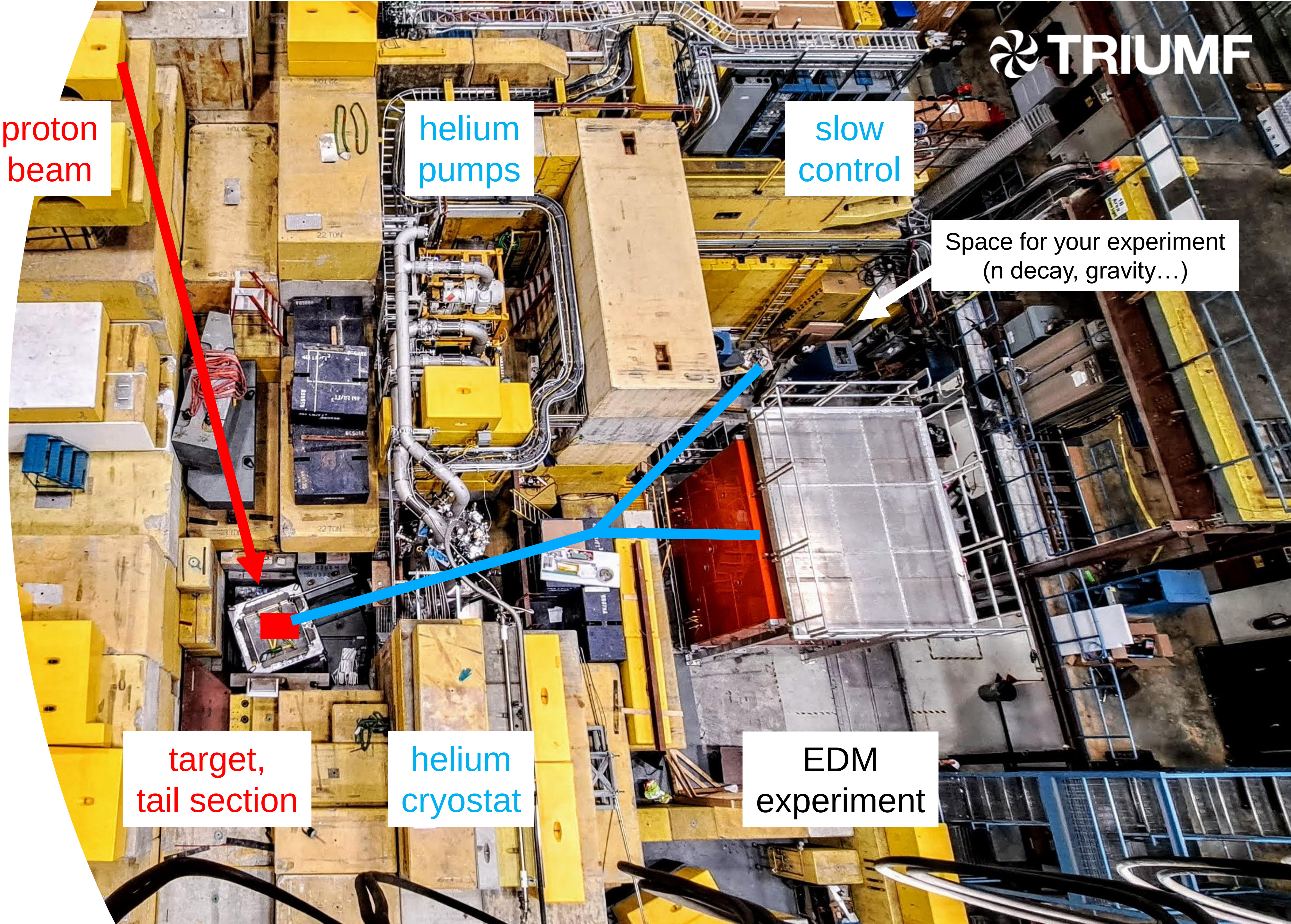
- LD_2 moderator
  - increase cold neutron flux at 1 meV (×2.5)
- Helium Cryostat with high cooling power
  - production volume (×3)
  - proton beam power (×50)
    - 0.5 kW -> 20 kW
    - heat load on superfluid : 8.1 W
      - include heat deposit on vessel
  - superfluid helium temperature (×1/3)
    - $T_{He\text{-}II}$ = 1.2 K (0.8 K@RCNP)
    - Storage lifetime : ~ 30 sec
- Estimated source performance
  - production rate: 1.4×10^7 UCN/s
  - UCN density
    - 6×10^3 UCN/cm^3 @ production
    - ~220 UCN/cm^3 @ measurement

Recent progress

- Oct 2023: He cryostat connected to liquefier and cooled to 4.2 K
- Dec 2023: He cryostat cooled to 1.09 K using large subatmospheric pumps and short prototype of main heat exchanger
- 2024: completion of “tail section” and installation

TUCAN

Top view of TUCAN area in Meson Hall at TRIUMF (April 4, 2024)



courtesy of R. Picker

Magnetically Shielded Room

Platform and MSR (April 2024)

- Construction at TRIUMF was completed in fall 2023
- Our magnetic verification and testing revealed problems!
- Company will install another shielding layer, August 2024
- Redesign of some parts of EDM experiment was necessary
- EDM experiment installation performed in stages. Precision magnetometry set to begin in September.

T3-4 T. Hepworth

TUCAN Sensitivity Estimate

TUCAN

UCN production rate	1.4×10^7 UCN/sec	
UCN loaded into EDM cell	220 pol. UCN/cm^3	14M UCN
UCN detected at end of cycle	23 pol. UCN/cm^3	**1.4M UCN**

S. Sidhu, et al. EPJ Web of Conferences 282, 01015 (2023)

Compare to typ **15,000 UCN** detected at previous best expt. (ILL/PSI), **121,000 UCN** *projected* for n2EDM

N. J. Ayres, et al., EPJ C 81, 512 (2021)

$$\sigma_d = \frac{\hbar}{2\alpha E t_c \sqrt{N}}$$

E = 12.5 kV/cm
t_c = 188 s
α = 0.6 (visibility)

$\sigma_d = 2 \times 10^{-25}$ ecm/cycle

To reach statistical sensitivity of $\sigma_d = 1 \times 10^{-27}$ ecm
400 days of running required

Additional infrastructure needed, CFI IF 2025

What is needed:

- For the UCN source:
  - High-capacity helium liquefier in Meson Hall (**long run times**) ($$$)
  - Additional ^{3}He cryogen, pumping power, and moderator (**squeeze out the most UCNs possible**)
  - Laser upgrade for UWinnipeg UCN guide coating facility (**efficient UCN transport**)
  - Infrastructure dedicated to the 2nd UCN port (**fully exploit the UCNs**)
- For the EDM experiment:
  - Upgrades to EDM experiment for full HV, two cells, four detectors
  - Comagnetometer laser upgrade, Cs magnetometers similar in scale to PSI
  - Upgraded external magnetic compensation system, …
  - Upgrades aimed at **maximizing statistics, and detailed control of systematics on par with competitors**

UCN guide coating	
M3-1	A. Zahra
POS-19	B. Algohi

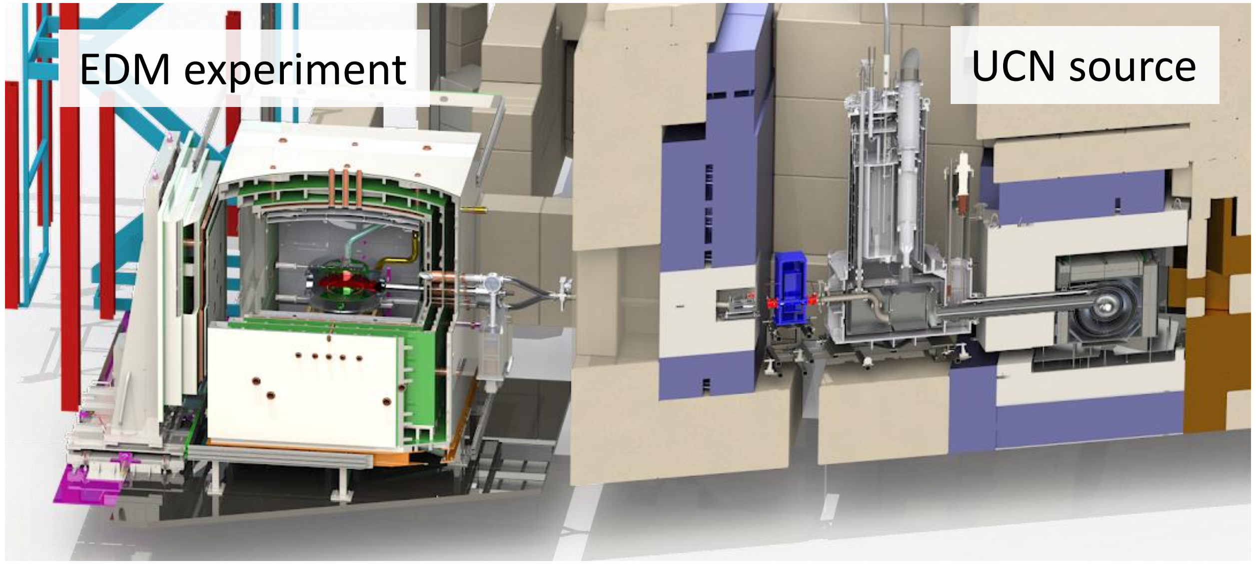
Securing infrastructure needed for long-term running of an EDM experiment and full exploitation of the capabilities of the UCN source

Summary and Schedule

TUCAN

- TUCAN source upgrade will enable a search for neutron EDM with 1×10^{-27} *e*cm precision.
- Neutron source upgrade completion 2024.
  - He-II cryostat built and tested in Japan 2020-2021. Now at TRIUMF and ready to install.
- Magnetically shielded room complete August 2024, ready for EDM experiment installation
- First UCN operations in 2024
- Need additional infrastructure to support long-term running (CFI IF 2025)

Future facility at TRIUMF

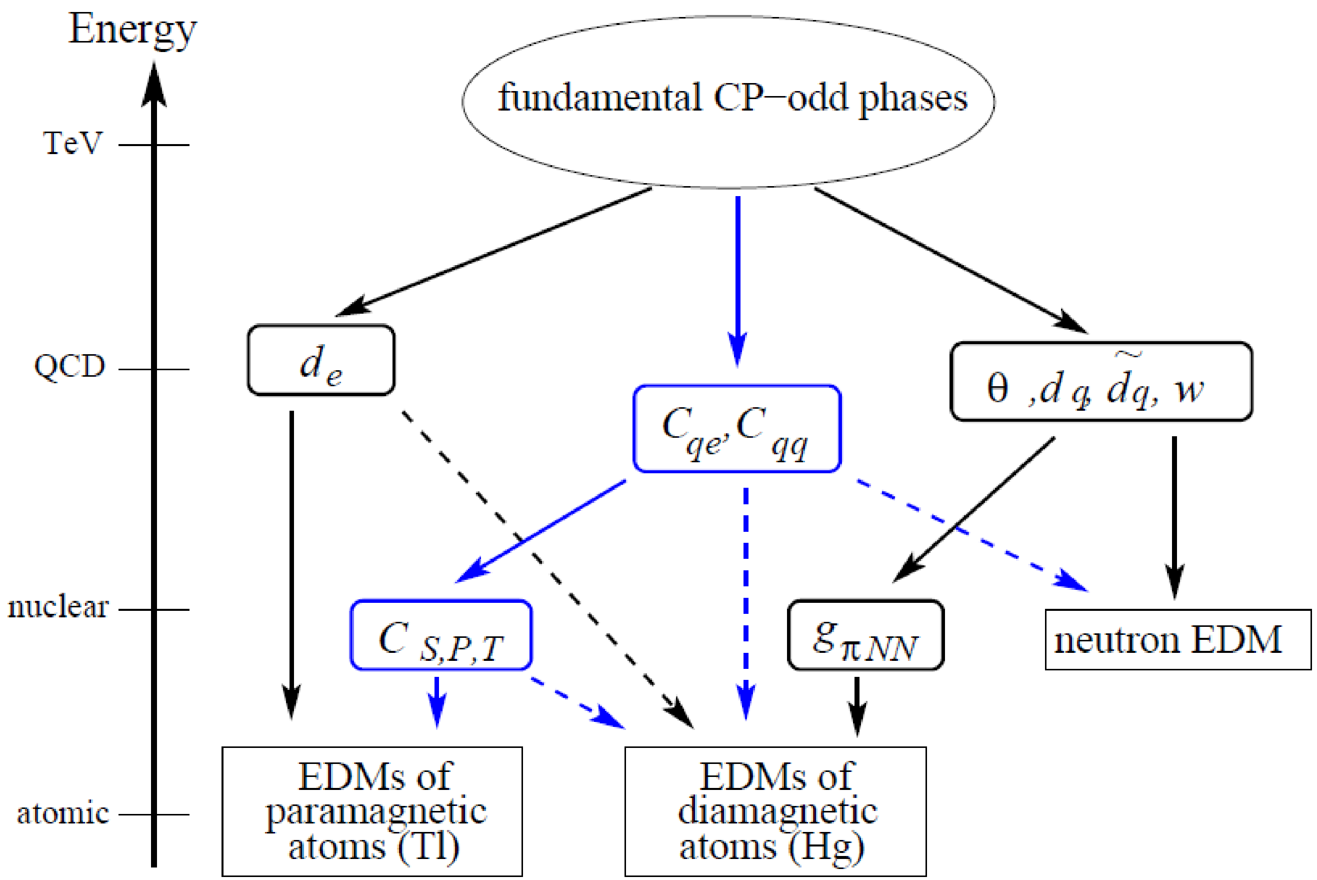


Is the neutron EDM relevant any more?

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

$d_n < 1.8 \times 10^{-26}$ e-cm
(PSI nEDM)
$d_n < 1.6 \times 10^{-26}$ e-cm
(U. Wash ^{199}Hg)

Yes! Theories…

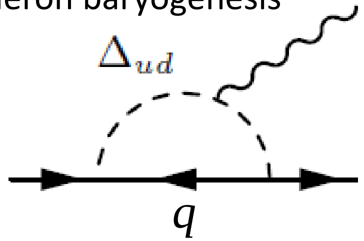


- Figure: M. Pospelov & A. Ritz, Ann. Phys. **318**, 119 (2005).
- See also: J. Engel, M. Ramsey-Musolf, U. van Kolck, Prog. in Part. and Nucl. Phys. **71**, 21 (2013).
  T. Chupp, P. Fierlinger, M. Ramsey-Musolf, and J. Singh, Rev. Mod. Phys. 91, 015001 (2019).

Theoretical progress (examples)

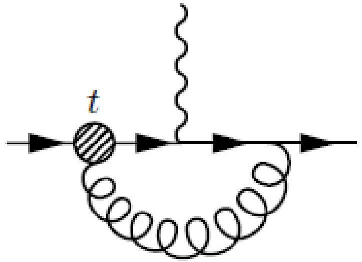
Themes:
- Baryogenesis (especially EWBG)
- New CP violation beyond SM
- Strong CP problem, axions

New scalar predicted by post-sphaleron baryogenesis



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

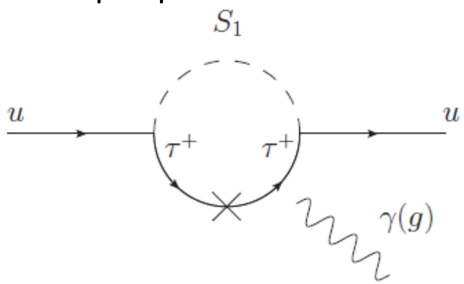
Quark (C)EDM, SMEFT, LEFT



P. Stoffer presentation

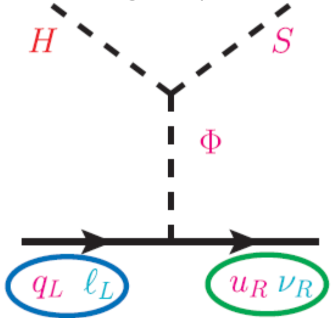
E. Mereghetti et al. JHEP04(2022)050

Scalar leptoquark



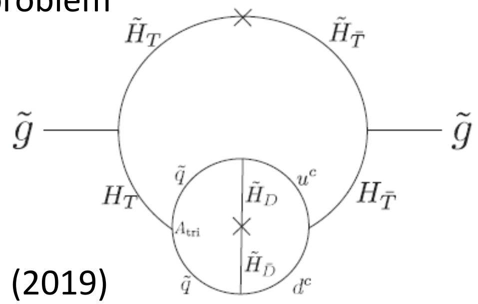
V. Cirigliano, et al. PRL 123, 051801 (2019)
A. Crivellin and F. Saturnino, PRD 100, 115014 (2019)

See-saw mechanism ν 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. $a = a_0 \cos m_a t$

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

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

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