Towards a search of the neutron electric dipole moment with a high-intensity ultracold neutron source

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on behalf of
the TUCAN collaboration

RCNP Workshop on Fundamental Physics Using Reactor
31.05.2022

Outline

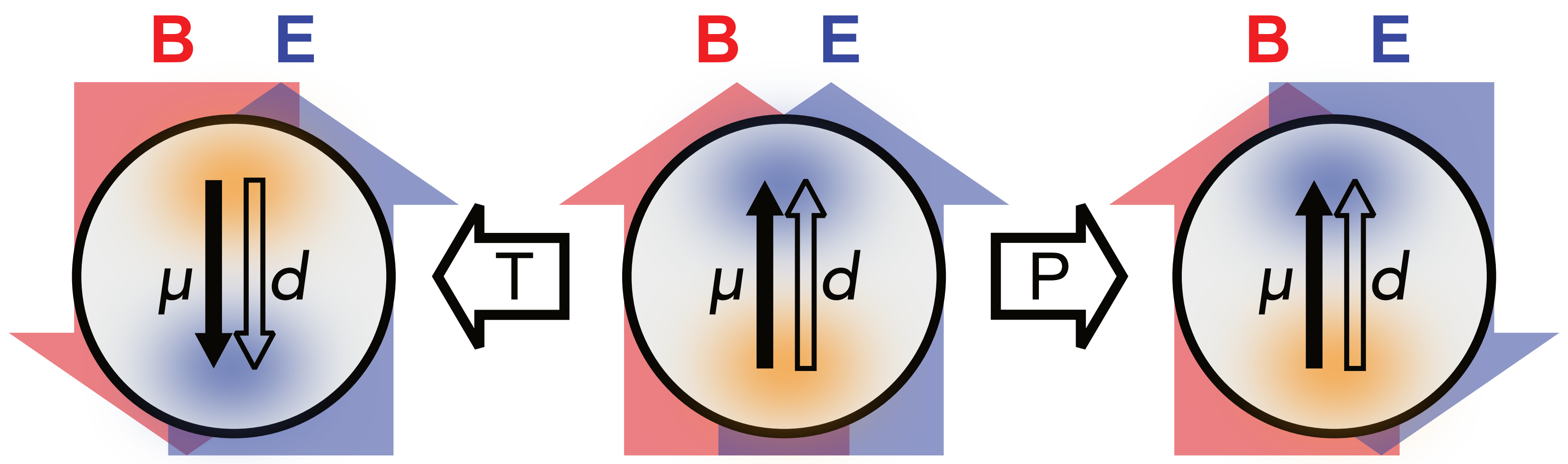
- **Introduction:** the neutron electric dipole moment (nEDM)
  - Background
  - Overview of nEDM experiments
  - TUCAN collaboration
- **UCN production**
  - Principle
  - Previous achievements
  - Next generation UCN source
- **TUCAN overview**
- **Recent activities**
  - Development of the helium cryostat for the new UCN source
  - Design of magnetic shield and compensation coils
  - Development of UCN spin analyzer
  - Characterization of UCN transmission/storage

Background

- **CP violation:** being searched in different domains
- **Electric Dipole Moment (EDM):**

- Sensitive probe for **time (T) reversal symmetry violation** → CP violation assuming CPT theorem
- Represented by a P- and T-violating coupling to the EM field

$$\mathcal{L}_{\mathrm{EDM}} = -\frac{i}{2} d_\psi \bar{\psi} \sigma_{\mu\nu} F^{\mu\nu} \gamma_5 \psi \xrightarrow{\text{Non-relativistic limit}} H = -d\vec{E} \cdot \frac{\vec{S}}{S}$$



- **Theoretical predictions:**

- Standard Model: $d_n^{\mathrm{CKM}} \sim 10^{-32}\, e\mathrm{cm}$
- Orders of magnitude larger values predicted by models beyond SM → Sensitive test of BSM models

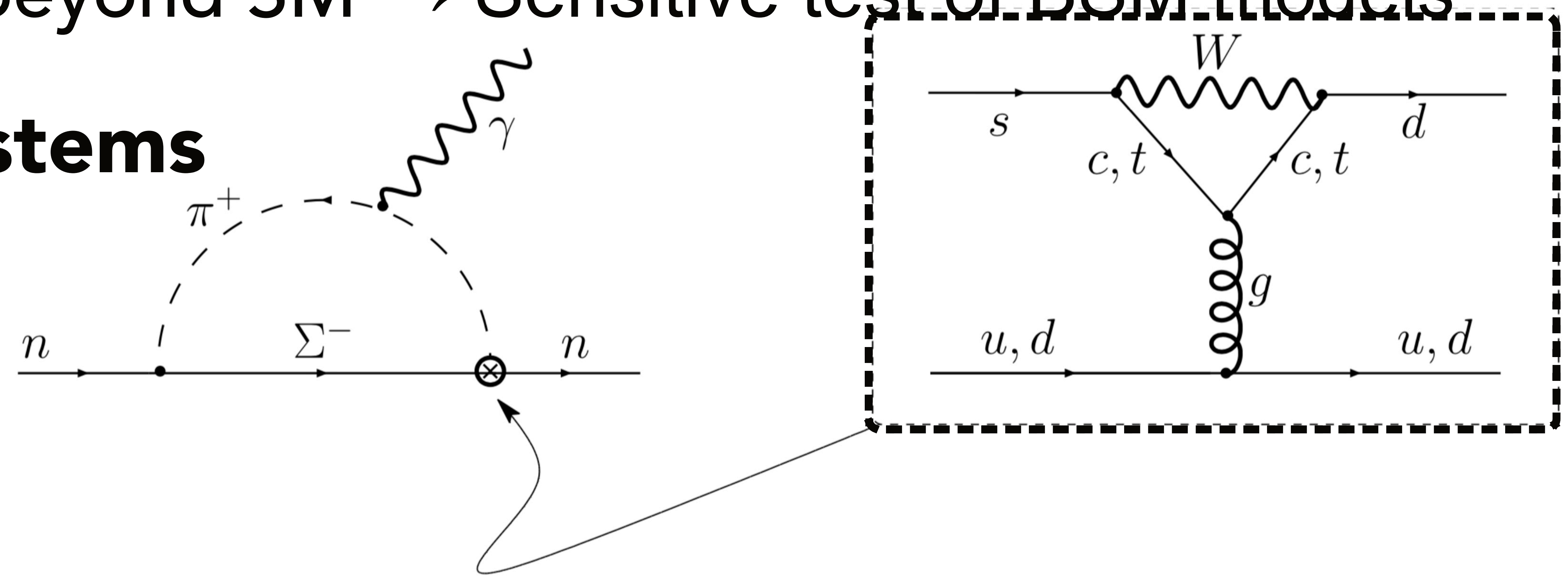
- **Complementarity with EDM searches in other systems**

$$d_n^{\bar{\theta}} \sim e \frac{\bar{\theta} m_*}{\Lambda^2_{\mathrm{had}}} \sim \bar{\theta} \cdot \left(6 \times 10^{-17}\right) e \text{ cm}$$

Strong CP problem

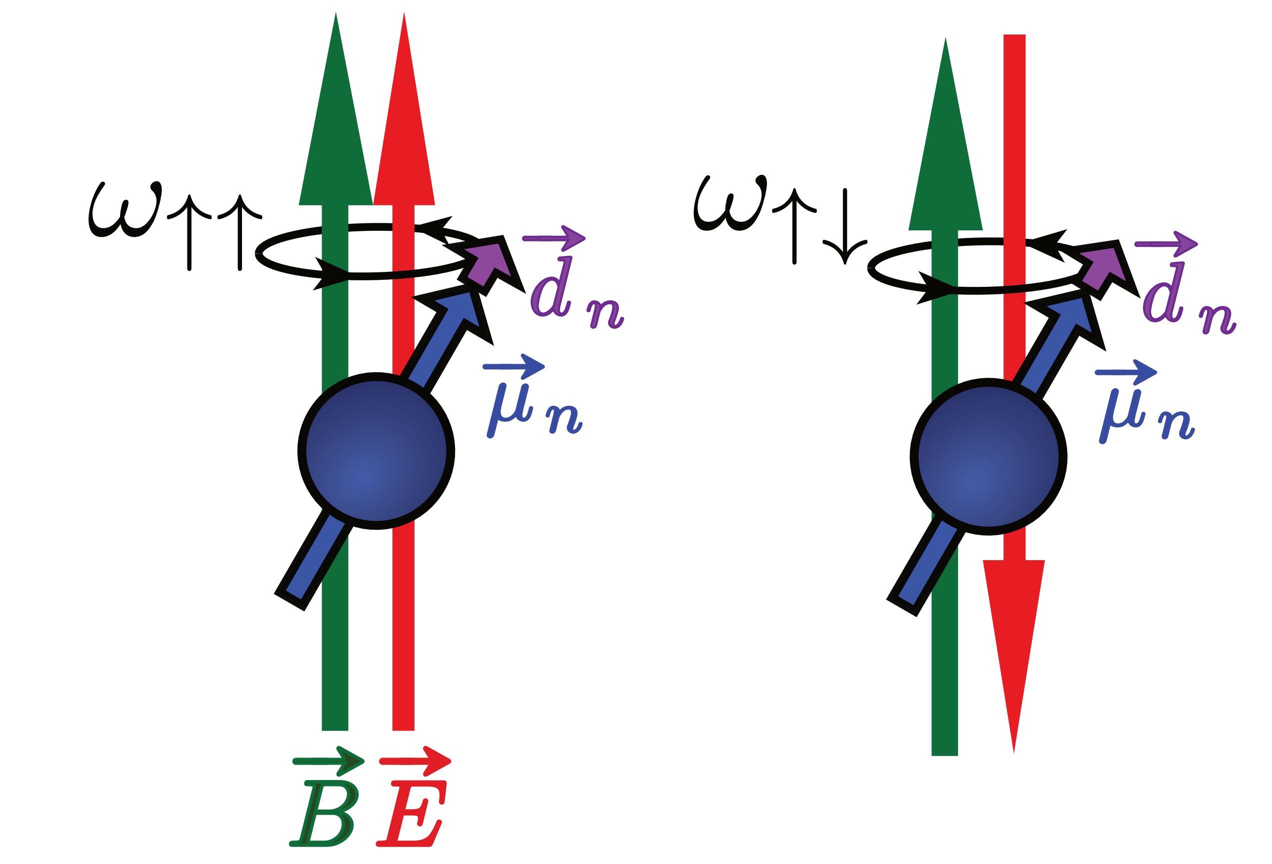
$|d_{n,exp}| < 1.8 \times 10^{-26}$ecm

$\Rightarrow |\bar{\theta}| < 10^{-10}$



M. Pospelov & A.Ritz, Ann. Phys. **318** (2005), 119; Y. Yamaguchi & N. Yamanaka, PRL **125** (2020), 241802

Experimental searches



$$d_n = \frac{\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}{4|E|}$$

■ Principle:

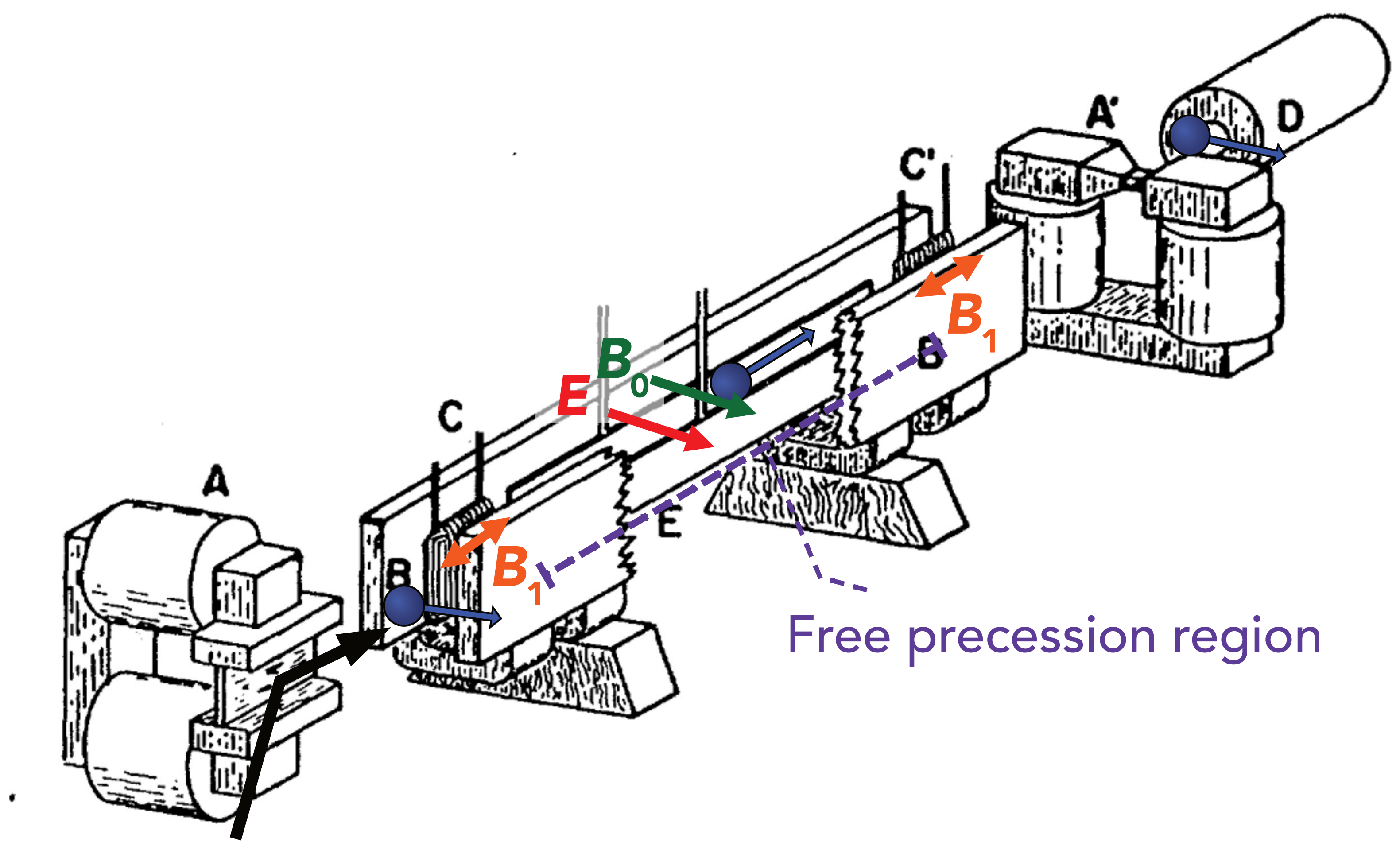
- Interaction Hamiltonian:

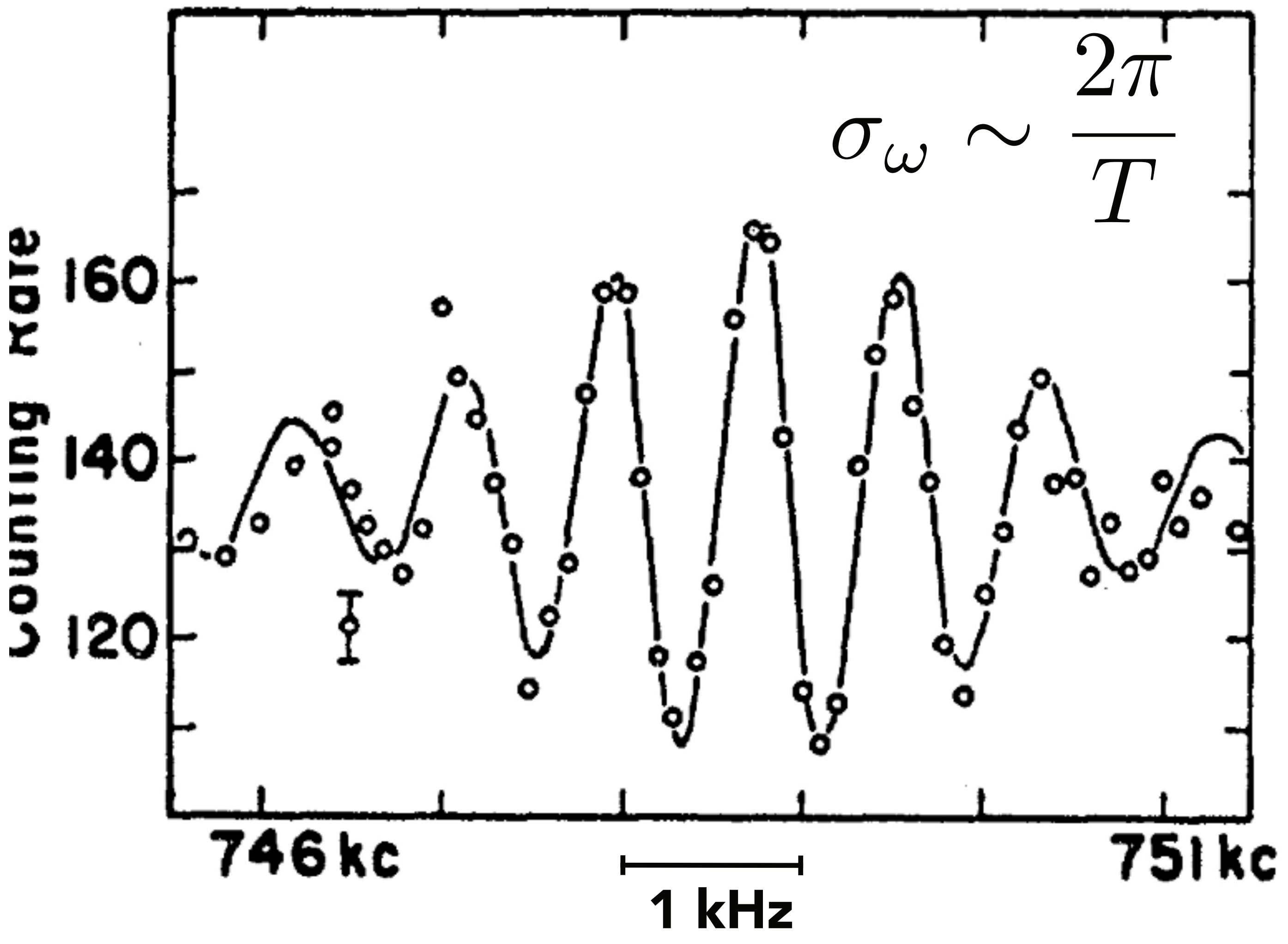
$$H = -\mu_n \vec{B} \cdot \frac{\vec{S}}{S} - d_n \vec{E} \cdot \frac{\vec{S}}{S}$$

- Measure the difference of Larmor precession frequency with ($\vec{E}$, $\vec{B}$) parallel (↑, ↑) and anti-parallel (↑, ↓)

■ The first measurement by Smith, Purcell and Ramsey (1957)

- Used cold neutron beam polarized by a magnetized mirror
- Employed the technique of separately oscillating fields





nEDM sensitivity:

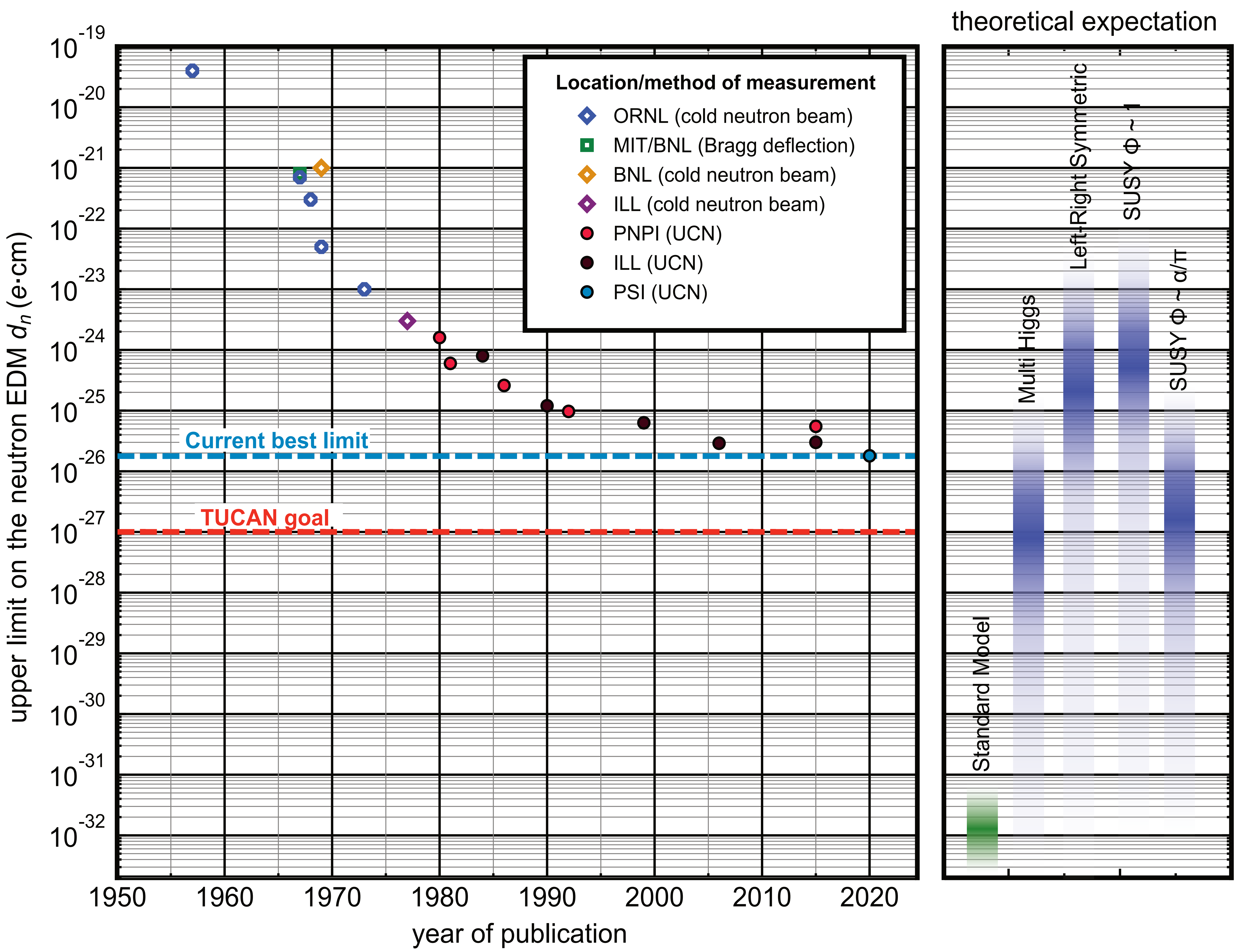
$$\sigma(d_n) \propto \frac{\hbar}{ET\sqrt{N}}$$

T: free precession time (~1 ms)
E: electric field (~70 kV/cm)
N: number of neutrons (~17000 per run) (15 runs in total)

$$d_n = (-0.1 \pm 2.4) \times 10^{-20}\ ecm$$

J.H. Smith, E.M. Purcell & N.F. Ramsey, Phys. Rev. **108** (1957) 120

Experimental searches (historical development)



J.M. Pendlebury & E. Hinds NIM A, **440** (2000), 471
T. Chupp et al., Rev. Mod. Phys., **91** (2019) 015001

Experimental searches (historical development)

- Limitation of the cold-neutron beam method: ***v*** x ***E*** systematics → **overcome by ultracold neutrons**

Neutron velocity

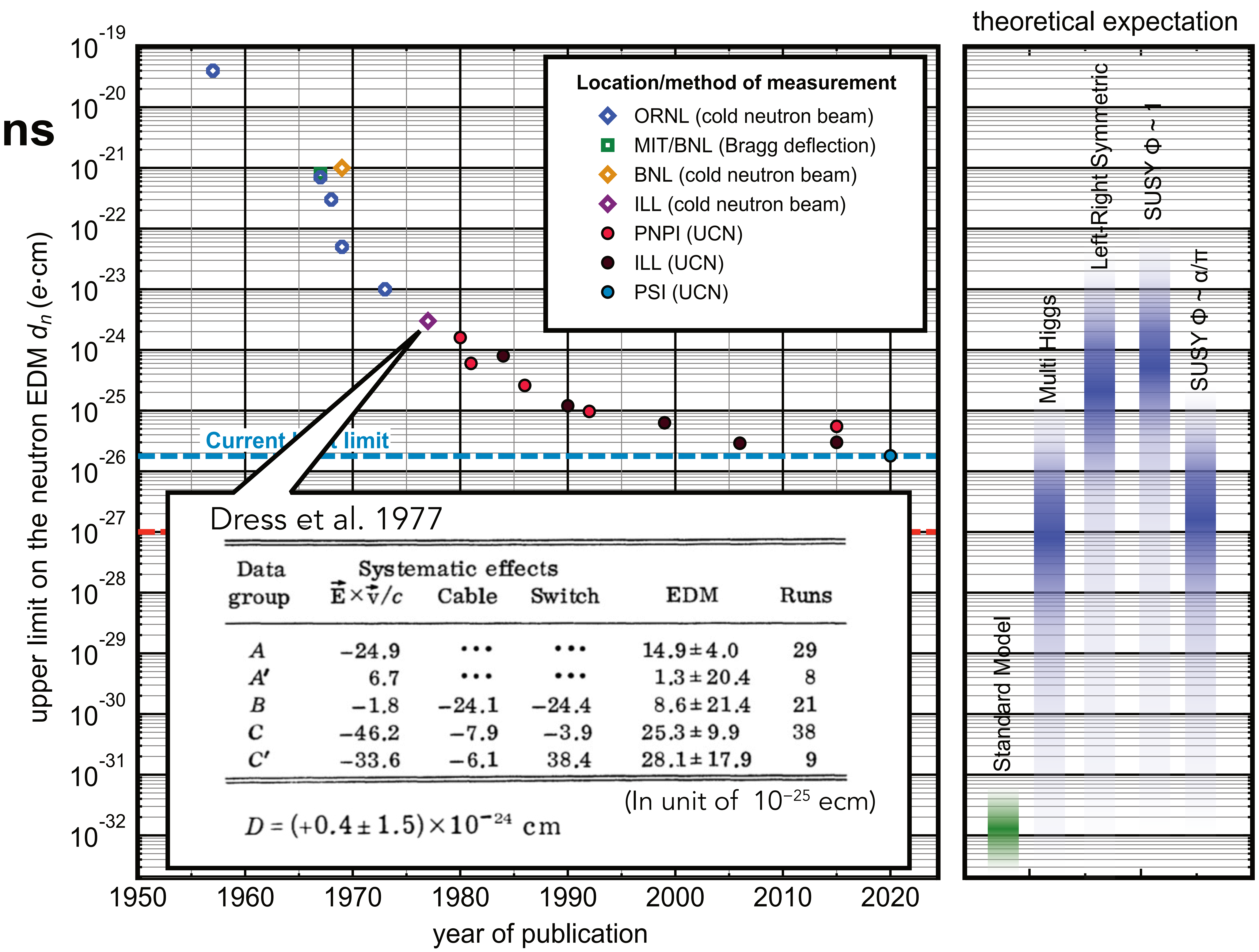
Cold neutrons: v=100–1000 m/s

⇒ UCN: v ≲ 10 m/s

Free precession time

Cold neutrons: 0.1–1.0 ms

⇒ UCN: 10–100 s



Data group	Systematic effects $\vec{E}\times\vec{v}/c$	Cable	Switch	EDM	Runs
A	−24.9	···	···	14.9±4.0	29
A′	6.7	···	···	1.3±20.4	8
B	−1.8	−24.1	−24.4	8.6±21.4	21
C	−46.2	−7.9	−3.9	25.3±9.9	38
C′	−33.6	−6.1	38.4	28.1±17.9	9

(In unit of 10^{-25} ecm)

$D = (+0.4 \pm 1.5)\times 10^{-24}$ cm

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Free precession time

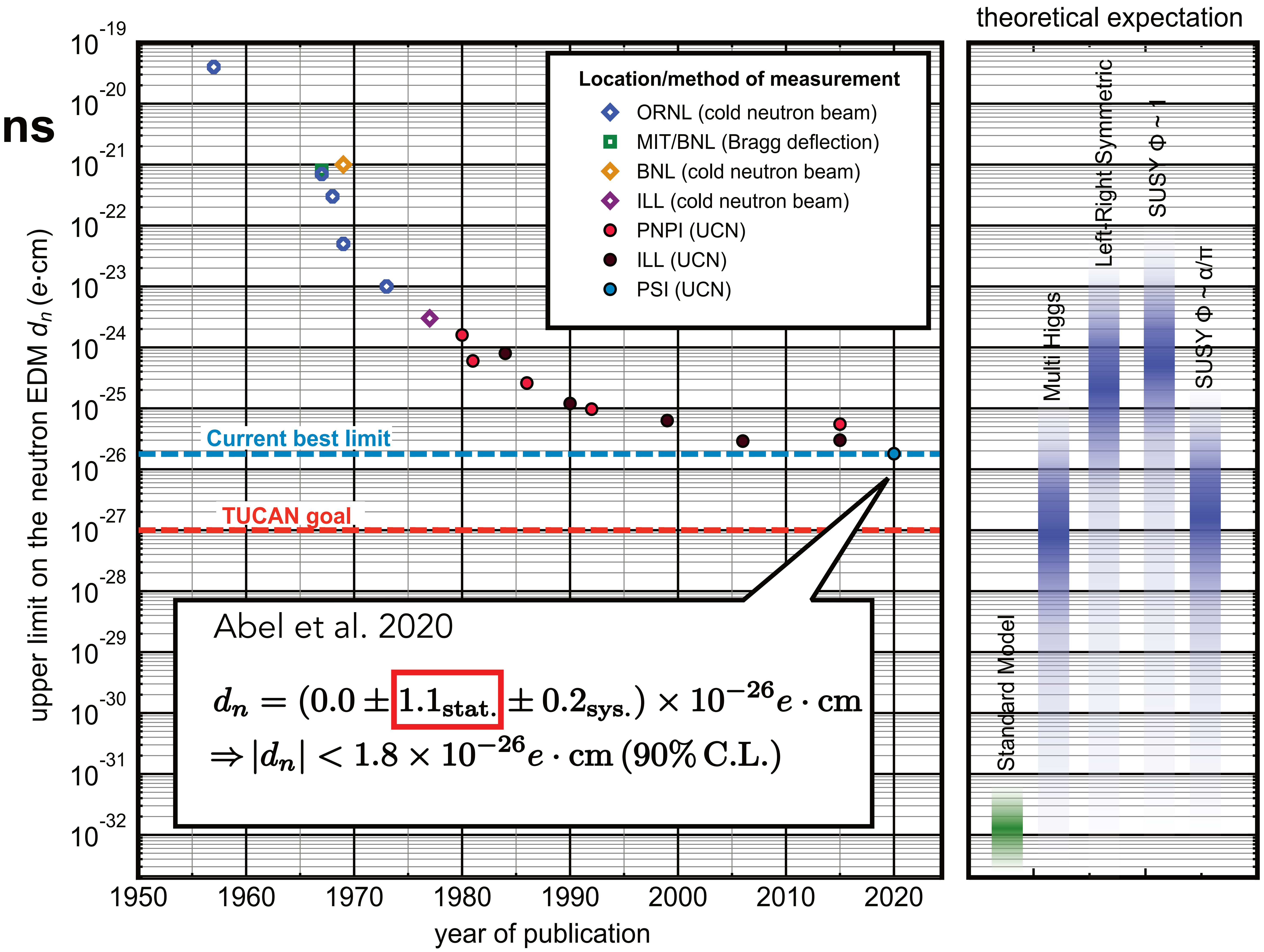
Cold neutrons: 0.1–1.0 ms

⇒ UCN: 10–100 s

- Limitation of the recent UCN measurements: **statistics**

The key for the next-generation:

Intense UCN source!



J.M. Pendlebury & E. Hinds NIM A, **440** (2000), 471

T. Chupp et al., Rev. Mod. Phys., **91** (2019) 015001

The TUCAN collaboration

TUCAN
TRIUMF Ultra Cold Advanced Neutron source

■ Goals:

1. Build a high-intensity UCN source at TRIUMF
2. Measure the nEDM with 10^{-27} ecm precision

■ Expected UCN intensity/density:

- **1.4–1.6×10⁷** UCN/s production
- ~**200** UCN/cm³ (polarized, filled in the EDM cell)

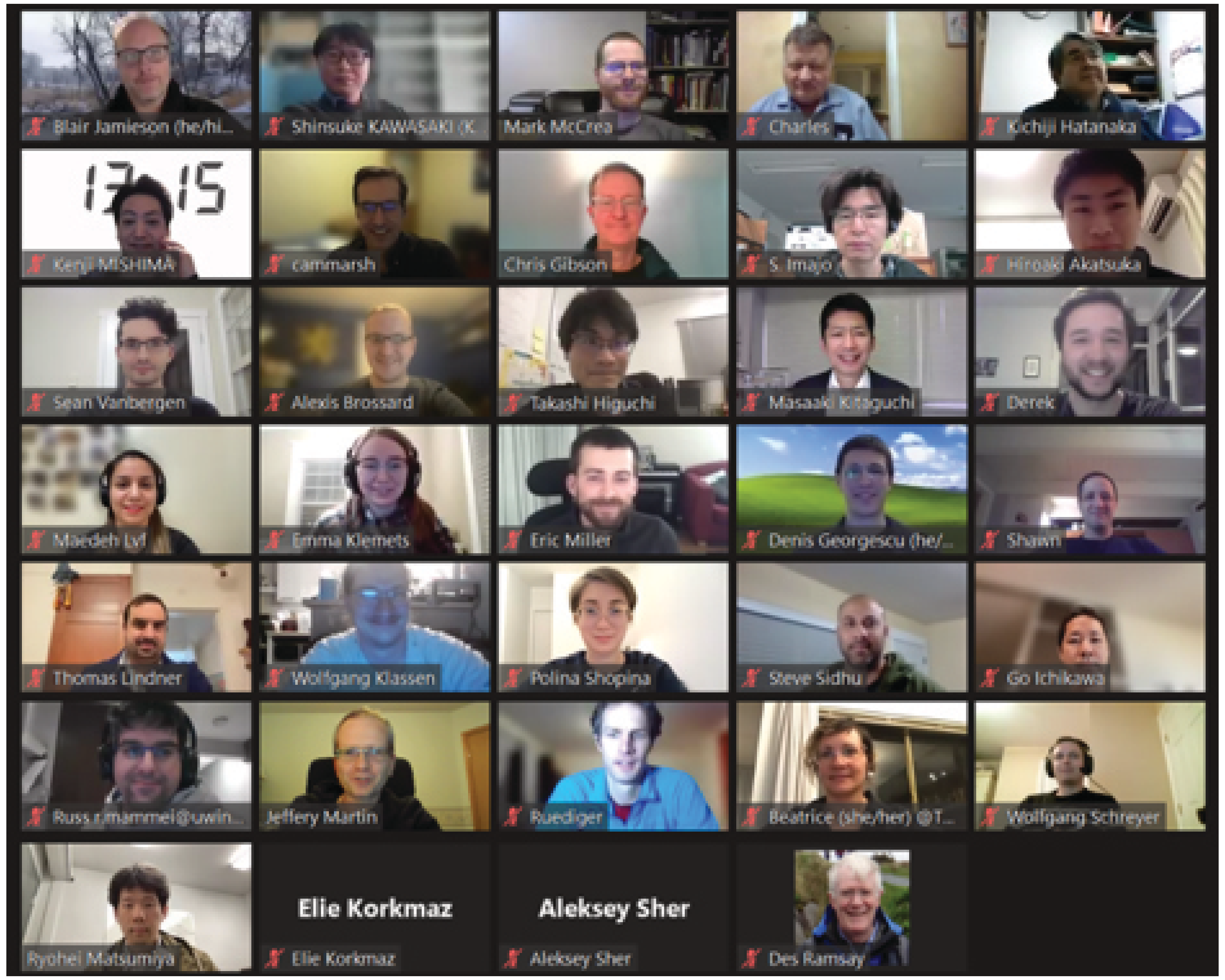
■ Recent achievements:

- UCN production scheme tested by a prototype source
- First UCN production at TRIUMF in 2017

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

■ Currently activities:

- Development of a new upgraded UCN source
- Development of subsystems of the nEDM spectrometer



TRIUMF, UBC, UNBC, University of Manitoba, The University of Winnipeg, SFU, KEK, RCNP, Nagoya University

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■ Goals:

1. Build a high-intensity UCN source at TRIUMF
2. Measure the nEDM with 10^{-27} ecm precision

■ Expected UCN intensity/density:

- **1.4–1.6×10⁷** UCN/s production
- **200–400** UCN/cm³ (polarized, filled in the EDM cell)

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T_0 \sqrt{N}}$$

α: visibility (~1)
T: free precession time
E: electric field
N: number of neutrons

T = 130 s
E = 10 kV/cm
N = 7×10^6 (per cycle) (× 300 of PSI2020: 1.14×10^4)

⇒ $\sigma(d_n)\sim10^{-25}$ecm per cycle

⇒ $\sigma(d_n)\sim10^{-27}$ecm in 400 days of measurement

(assuming 14h/day, one supercycle = 8 cycles (~ 0.3h) ↔ ~2×10^4 supercycles)

Other requirements:

- **Magnetic field stability:**
  - 10 fT/cycle effective (with co-magnetometer)
  - 10 pT/cycle inside magnetic shield
- **Magnetic field homogeneity:**
  - 1 nT/m in the central region
- High visibility
  low depolarization, high analyzing efficiency
- Efficient UCN transport

…

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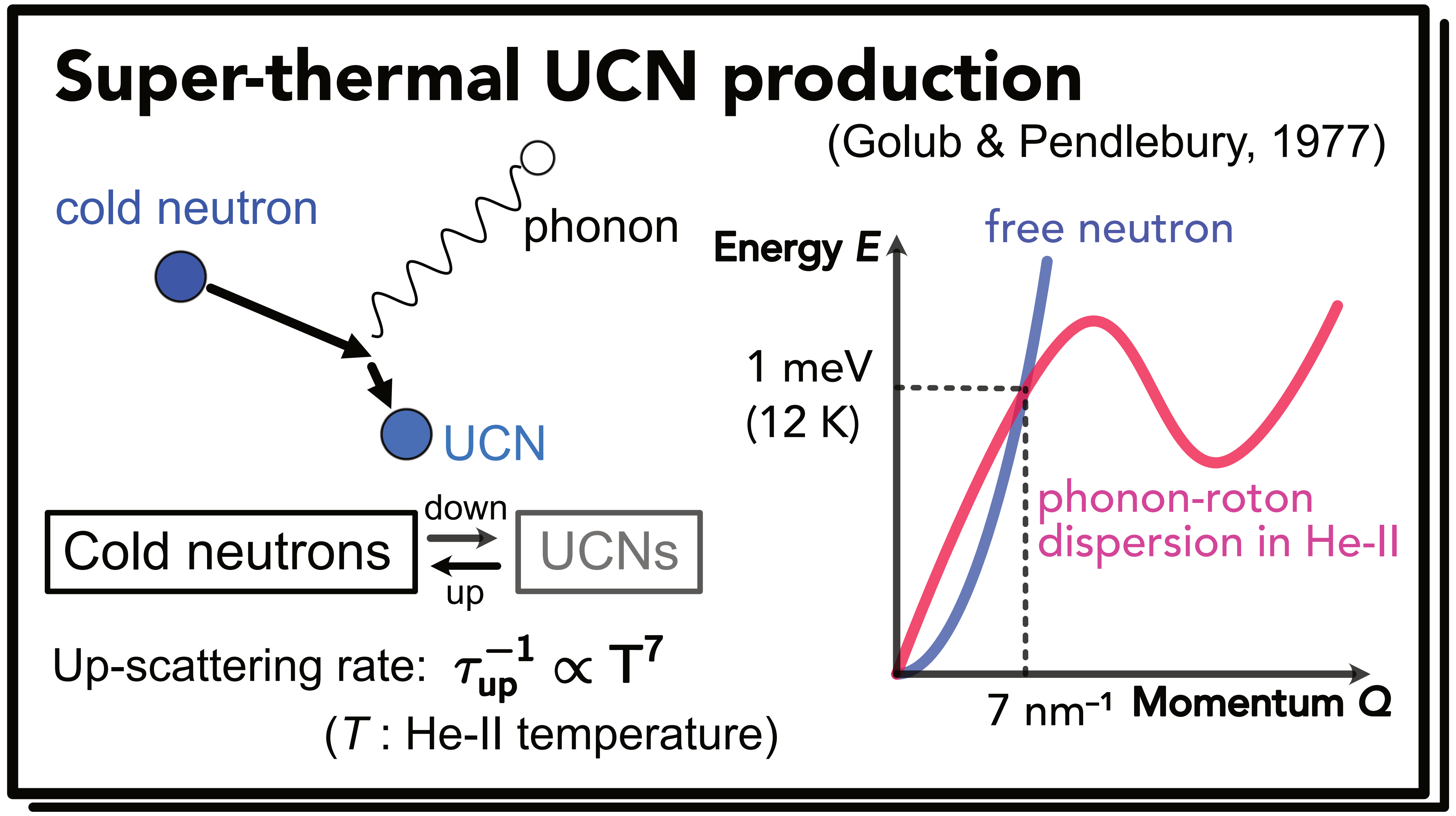
TUCAN UCN production scheme

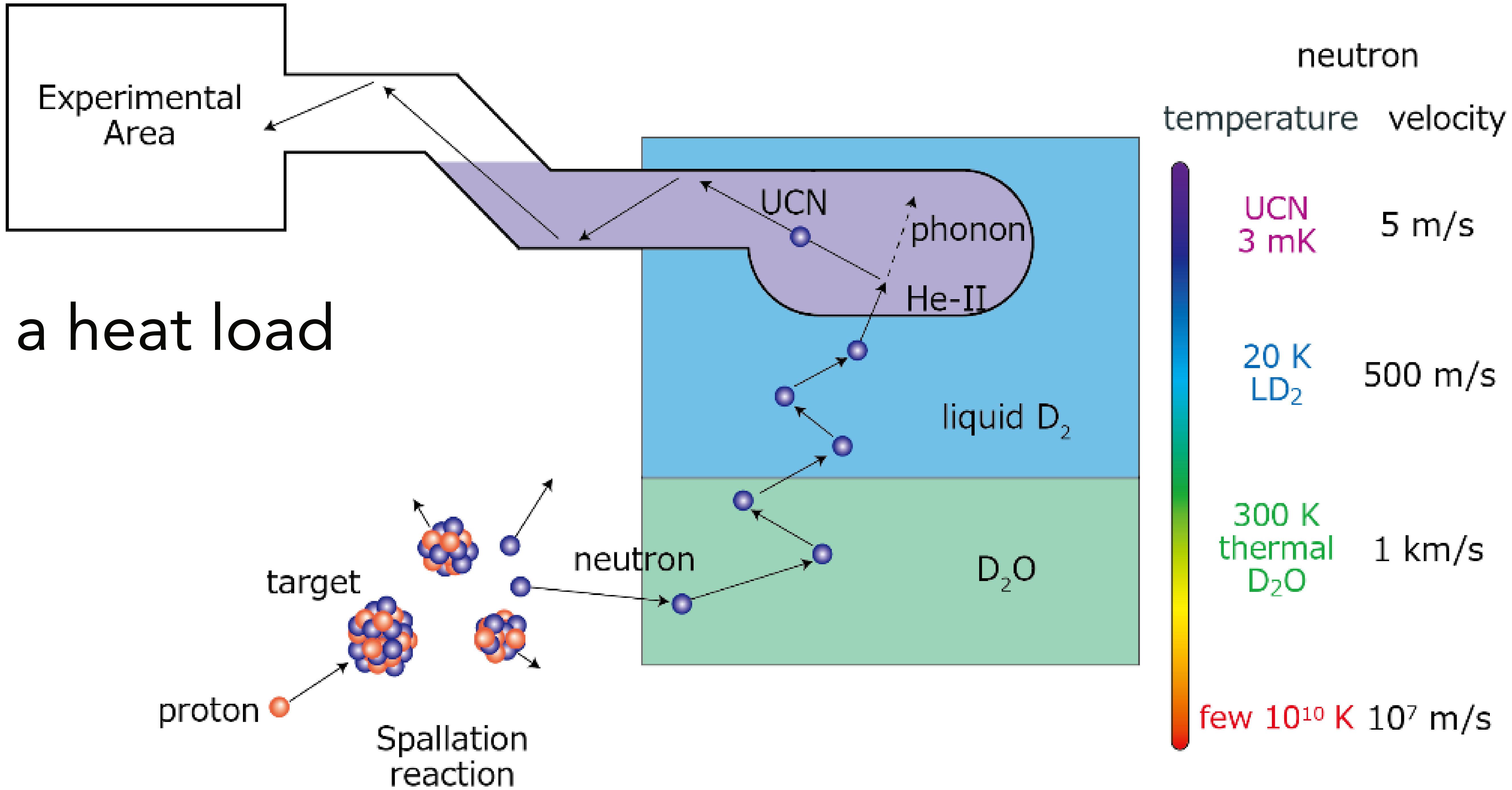
- **Combination of**
  - spallation neutron production
  - super-thermal UCN production with He-II

*Y. Masuda et al., PRL **108** (2012) 134801*

- Spallation neutrons (~MeV) produced by an accelerator beam are cooled in steps and eventually be converted to UCNs

- **Keys for high UCN yields :**
  - Keep the He-II temperature at **~1K** under a heat load due to beam irradiation
  - High cold neutron flux at **~1meV** energy



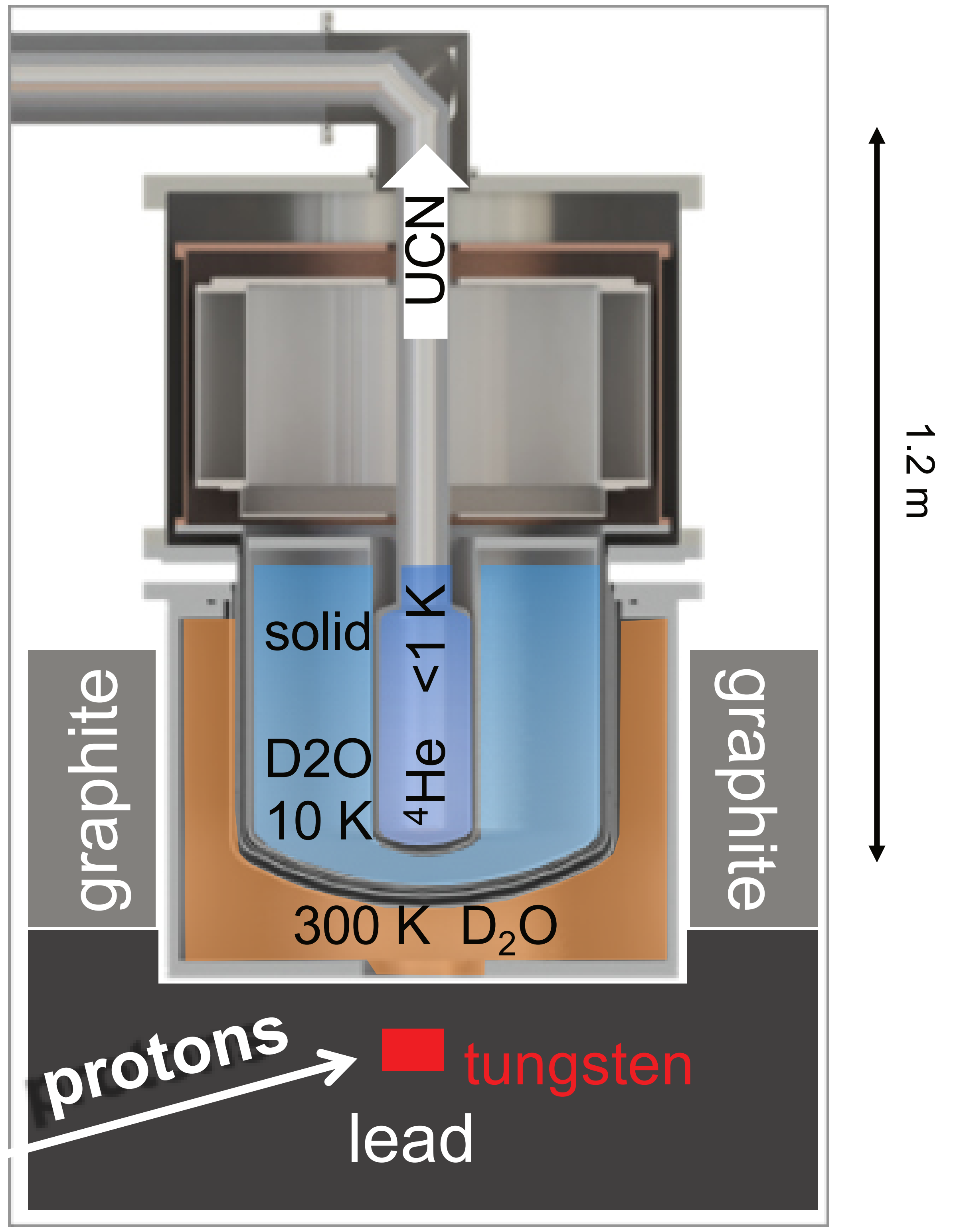


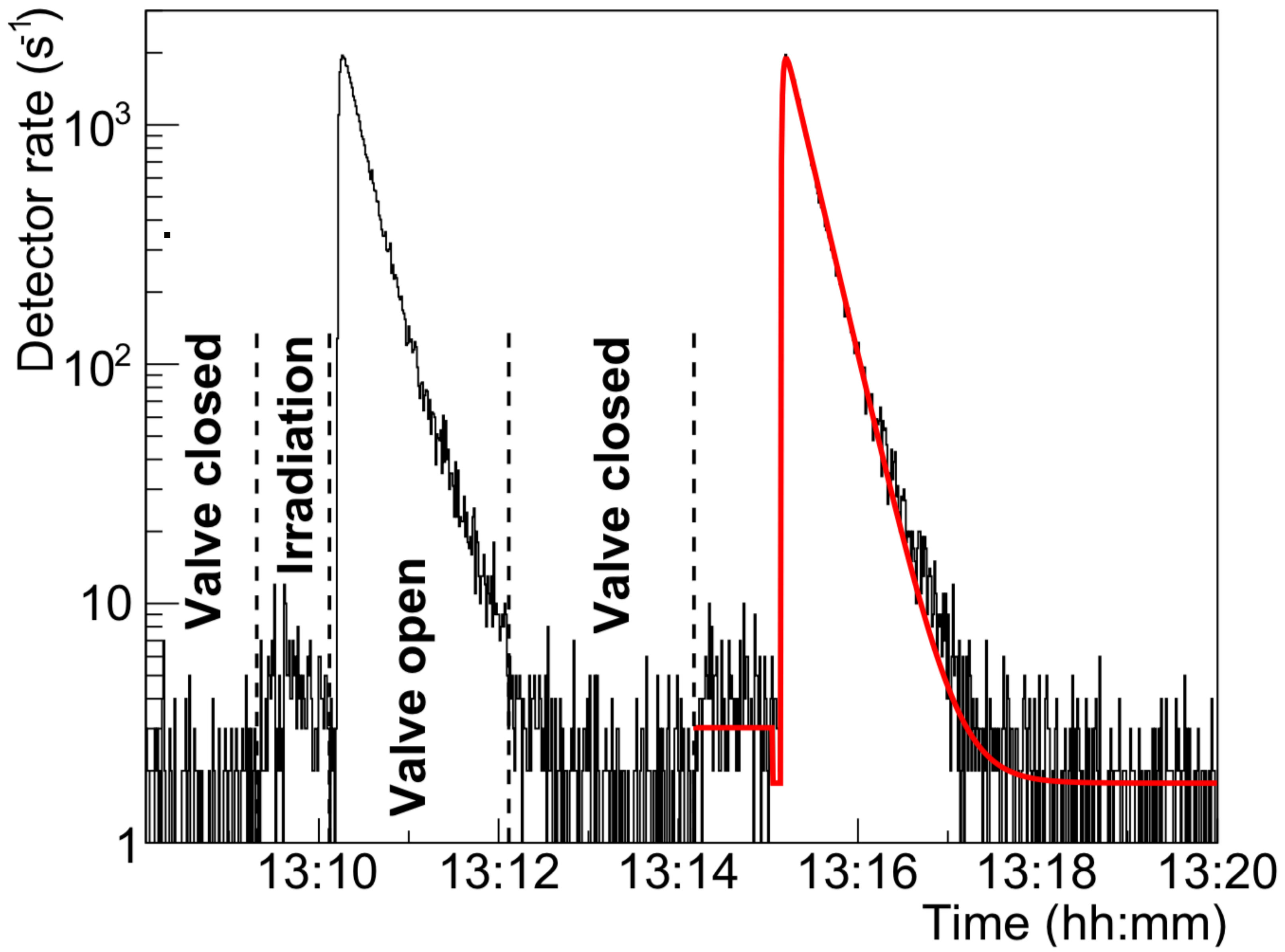
UCN production at TRIUMF in 2017

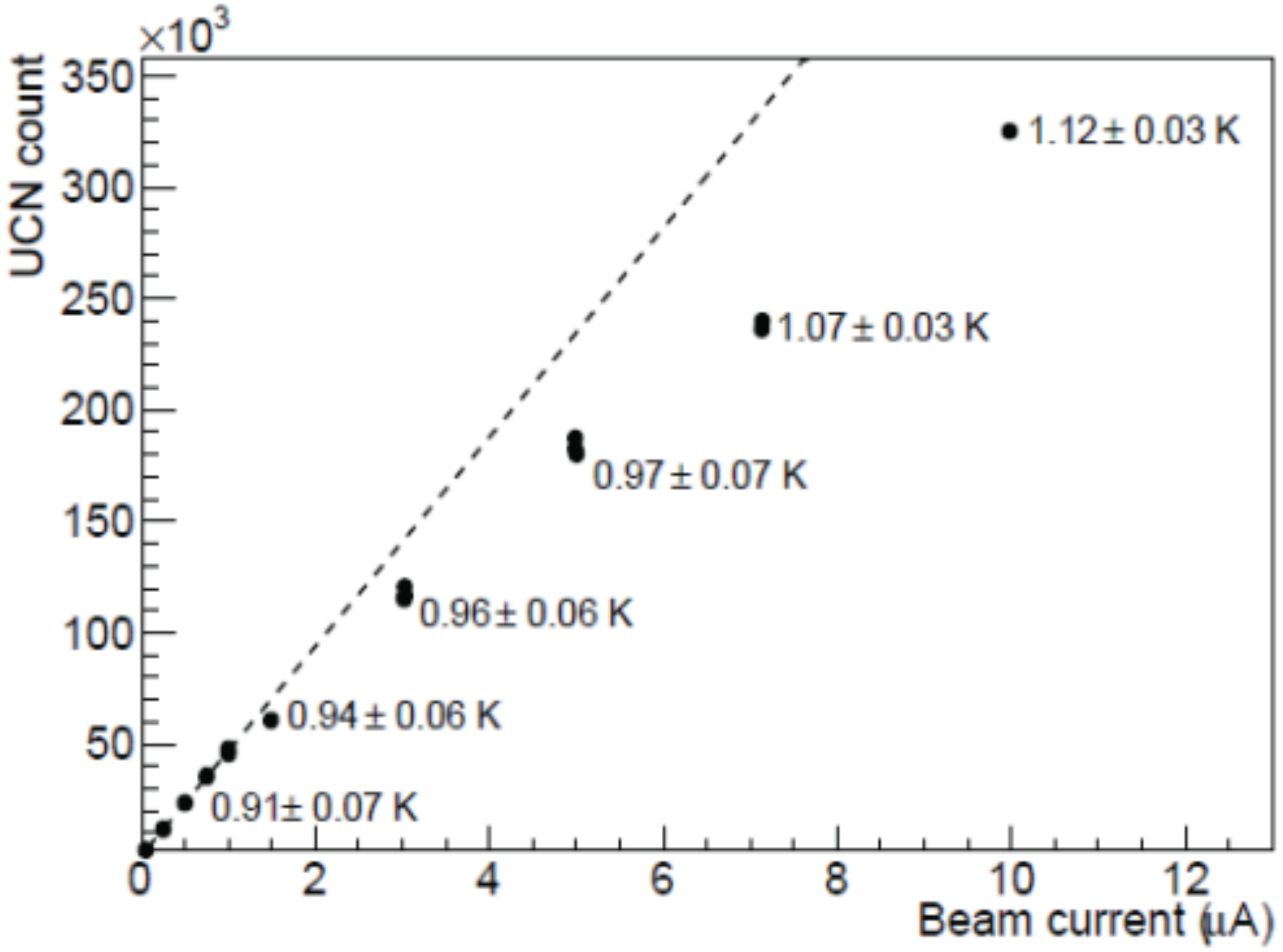
- First UCN production at TRIUMF with a prototype UCN source
- Major results

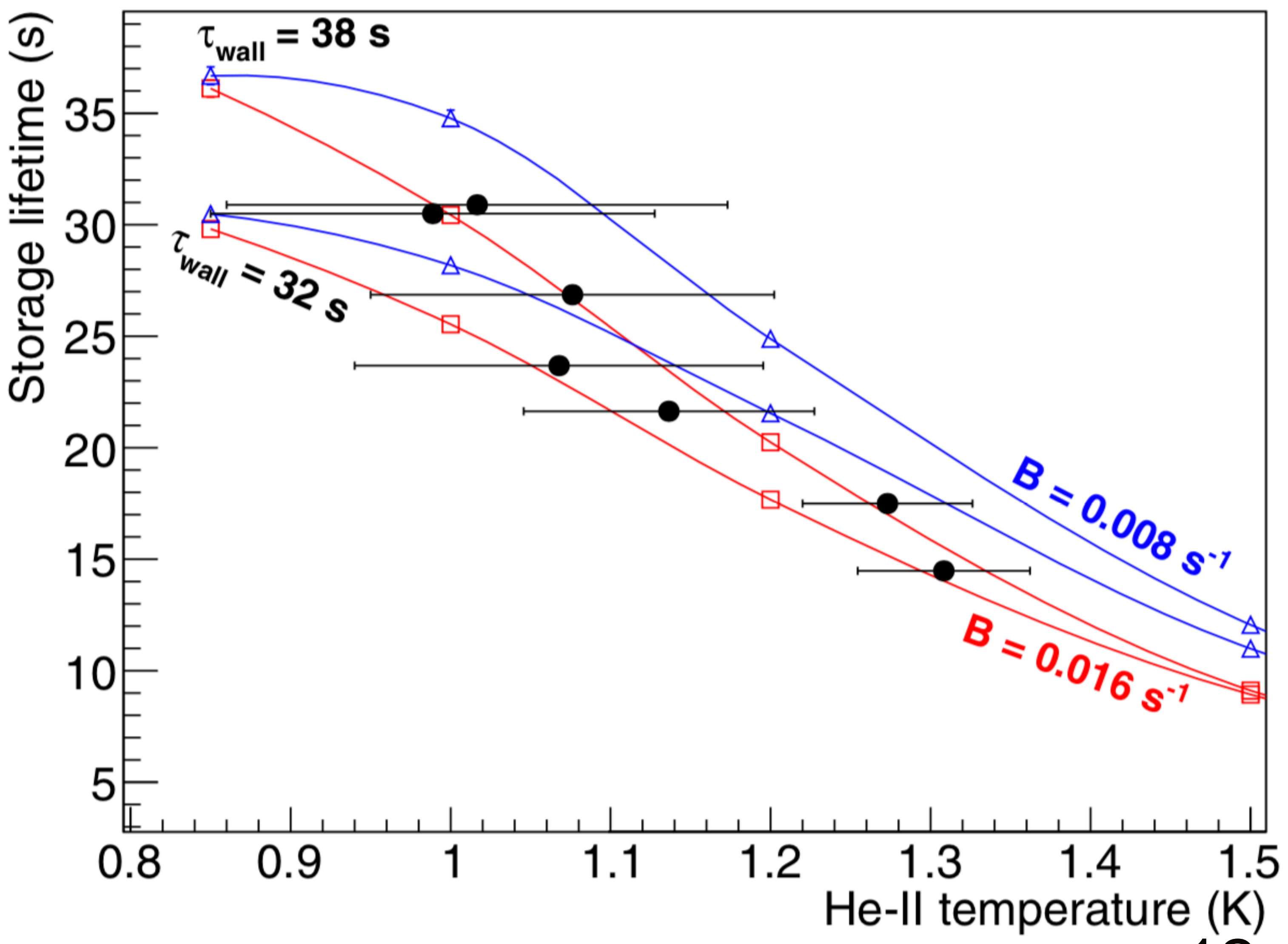
*S. Ahmed et al., PRAB, **22** (2019)102401*
*S. Ahmed et al., PRC, **99** (2019) 025503*

  - Successful UCN production:
    - **2×10^4 UCN/s** (3.25×10^5 UCN/cycle) **@ 1 μA** proton beam current
  - **Limited by cooling power of the helium cryostat**
  - Characterized the scaling of the UCN lifetime: $\tau \propto T^{-7}$

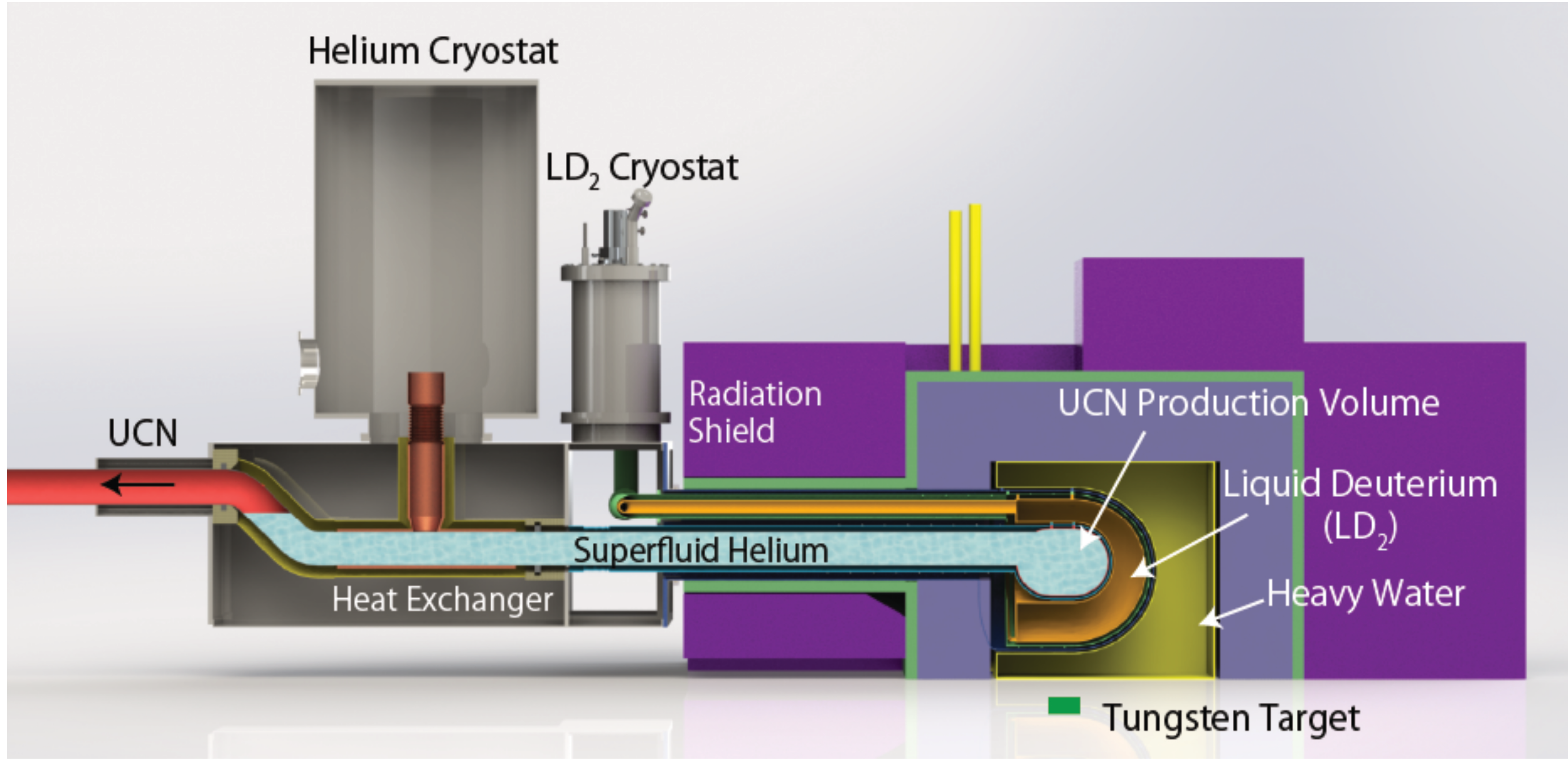








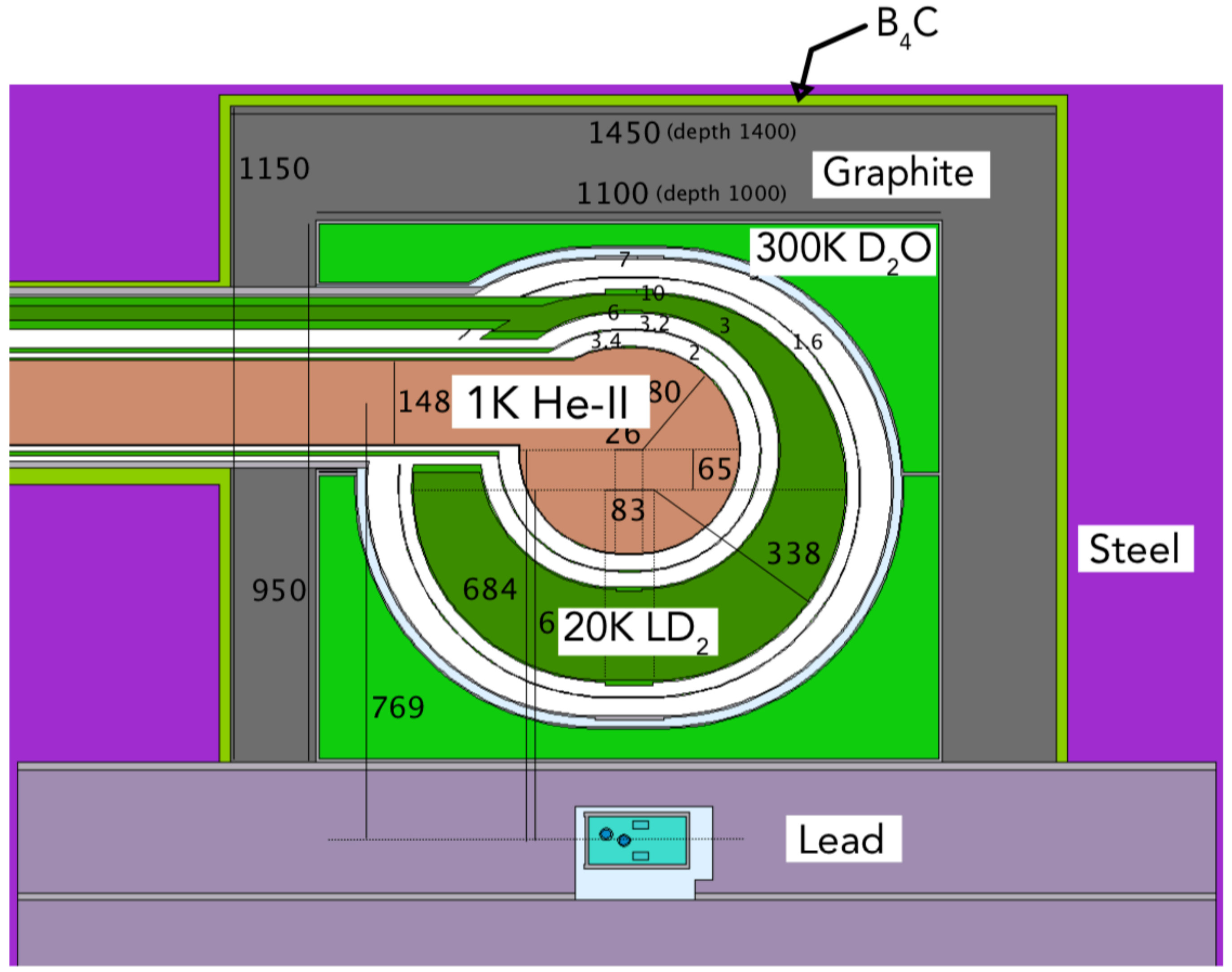
Design of the new UCN source



■ New UCN source under development:

- Higher cooling power of the helium cryostat:
  - Higher cooling power of the He cryostat (0.4 W→ 10W)
  - Enables operation of higher beam current (1 μA→ 40 μA)
- Cold neutron moderator:
  - sD_2O → LD_2: increases cold neutron flux at ~ 1meV that are crucial for UCN production
- Moderator/converter geometry optimized by MC simulation

*W. Schreyer et al., NIM A **959** (2020) 163525*



	Prototype source	New source	UCN gain factor
Beam current	1 μA	40 μA	x40
He cryostat cooling power	0.4 W	10 W	
Cold neutron moderator	sD2O	LD2	x3
UCN production volume	8 L	27 L	x3
Operation temperature	0.9 K	1.0K	

➡ Expected UCN yield: **1.4–1.6×10^7 UCN/s** (× 500 of the prototype)

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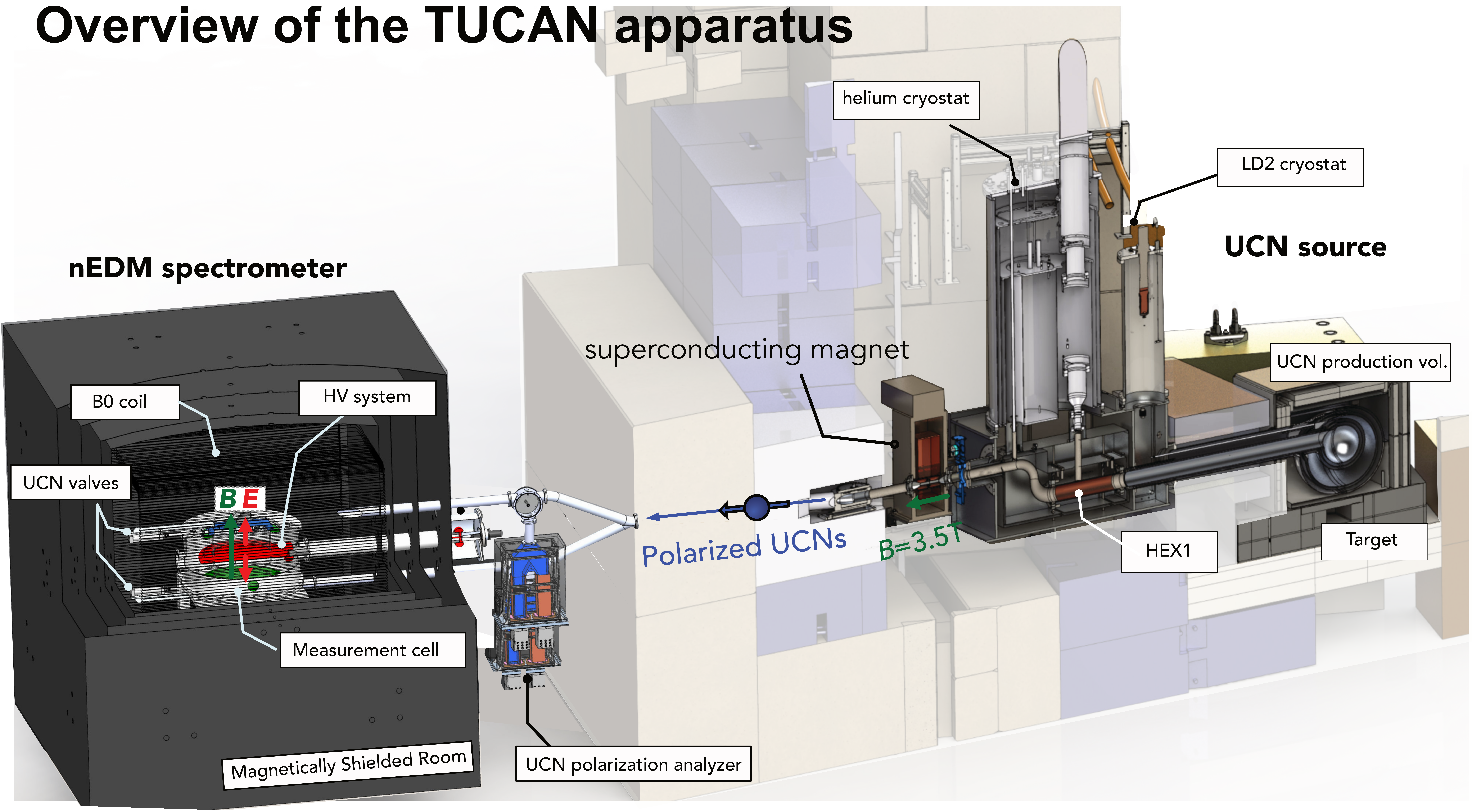
Overview of the TUCAN apparatus



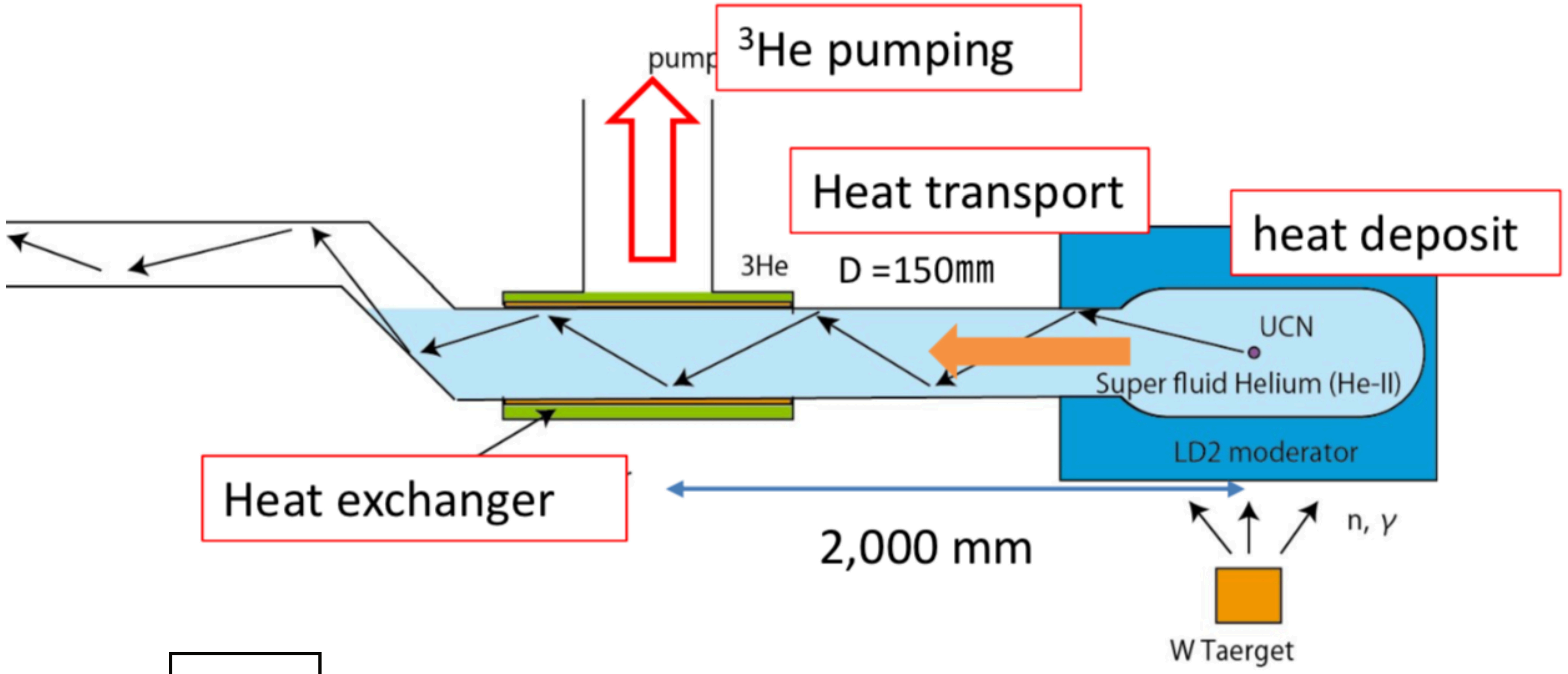
Recent developmental status

Recent developmental status

Development of the helium cryostat

- **Requirement:**
  - Keep the production volume at **~1K** under **10 W** of heat load
- **Cryostat concept:** *S. Kawasaki et al., IOP Conf. Ser.: Mater. Sci. Eng.* ***755*** *(2020), 012140*
  - Heat exchanger placed downstream by 2 m to avoid radiation
  - ^{3}He pool-boiling HEX @~0.8 K, makes use of higher SVP of ^{3}He

^{3}He vs. ^{4}He (at 0.8 K)
- vapour pressure
  - ^{3}He: 3 Torr
  - ^{4}He: 0.01 Torr
- Cooling power with S=10,000m^3/h
  - ^{3}He: 15W
  - ^{4}He: 0.13 W



$$T_{3\mathrm{He}} + \Delta T_{3\mathrm{He\text{-}Ni}} + \Delta T_{\mathrm{Ni\text{-}HeII}} + \Delta T_{\mathrm{HeII}} = T_{\mathrm{prod.}}$$

$T_{3\mathrm{He}}$ ~0.8K; $T_{\mathrm{prod.}}$ ~1K

Kapitza conductance

Cooling power:

$$Q = \frac{n}{t} L(T_{\mathrm{liq}}) = \frac{p(T_{\mathrm{liq}})\, S L(T_{\mathrm{liq}})}{R T_{\mathrm{pump}}}$$

$$\left(\because n = \frac{p(T_{\mathrm{liq}})\, S t}{R T_{\mathrm{pump}}}\right)$$

n : quantity (mol)
t : time
$p(T_{liq})$: vapour pressure,
S: pumping speed

$L(T_{liq})$: latent heat per mol
R : ideal gas constant
T_{pump} : pump temperature (room temperature)

Development of the helium cryostat

■ Requirement:

- Keep the production volume at ~1K under 10 W of heat load

■ Cryostat design: *S. Kawasaki et al., IOP Conf. Ser.: Mater. Sci. Eng.* ***755*** *(2020), 012140*

- Heat removed by the latent heat of He-3 evaporation

$$\dot{m} = \frac{Q}{L} = \frac{10\,\mathrm{W}}{11.2\mathrm{J/g}} = 0.89\,\mathrm{g/s} \Leftrightarrow 7000\,\mathrm{m^3/h}$$

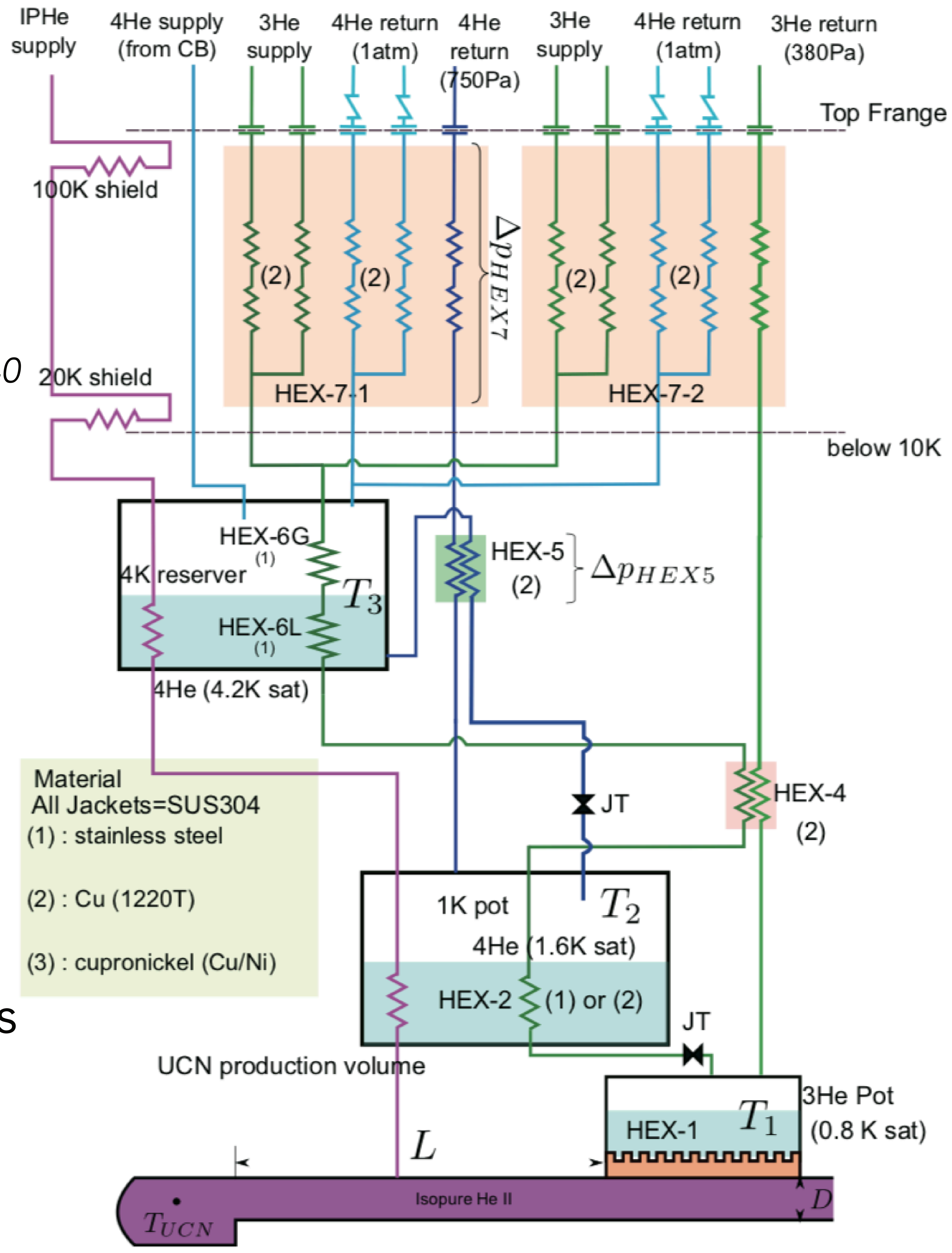
($\dot{m}$~8000 m^3/h with Joule-Thomson efficiency included)

- Fluid cooled through Joule-Thomson expansion
- HEX1: Cu HEX between He-3 and He-II
- Other HEXs to efficiently recover enthalpy of evaporating gas

■ Cryogenic challenges:

- Heat transfer of superfluid helium at ~1K: no measurement exists
- Heat transfer between interface of Cu-He: Kapitza conductance

⇒ Designed based on conservative estimates,
Will obtain some numbers by measurement with ^{3}He



Construction/testing of the helium cryostat at KEK

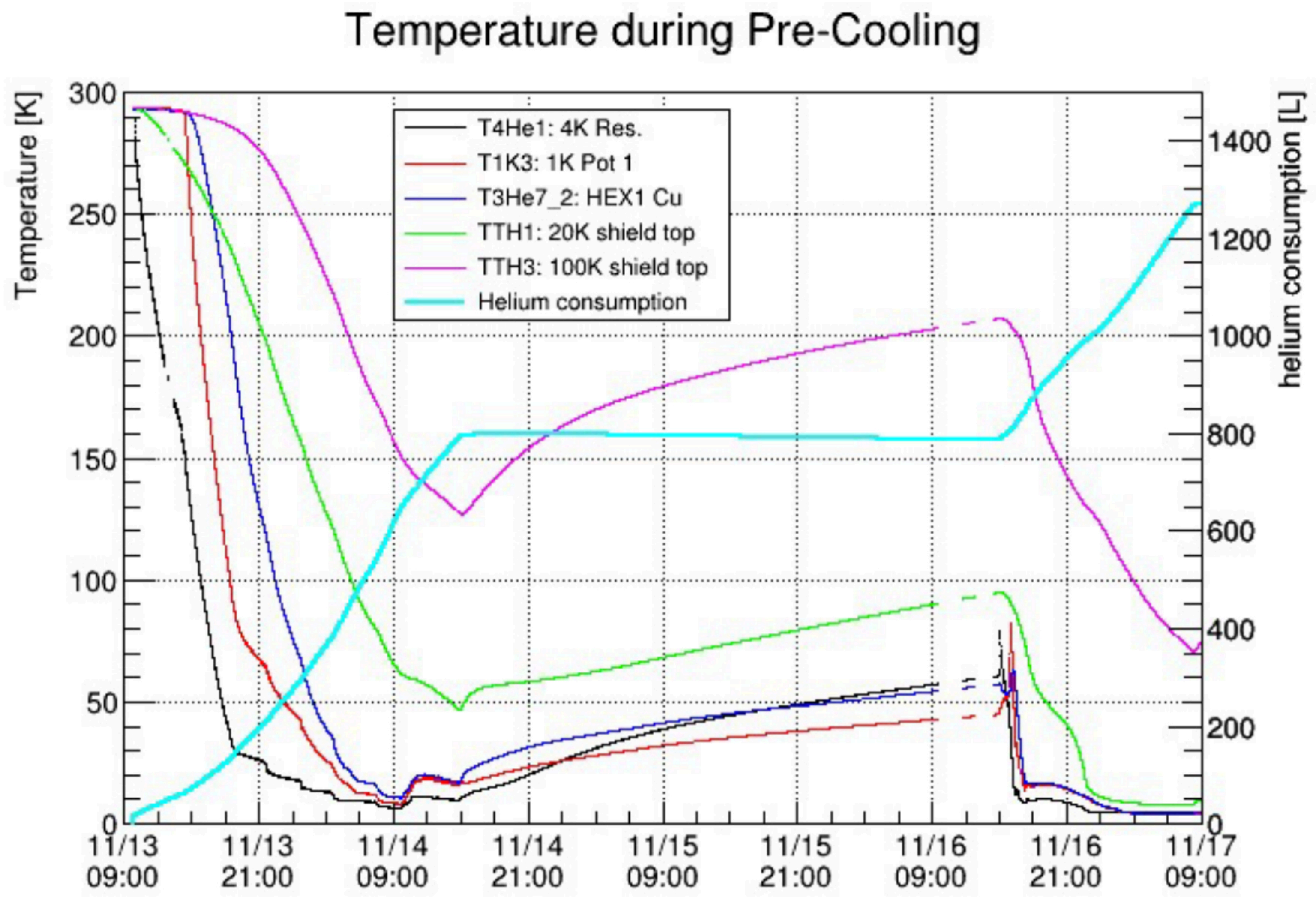
- Component tests (heat exchangers, superfluid leak tests) (2019)

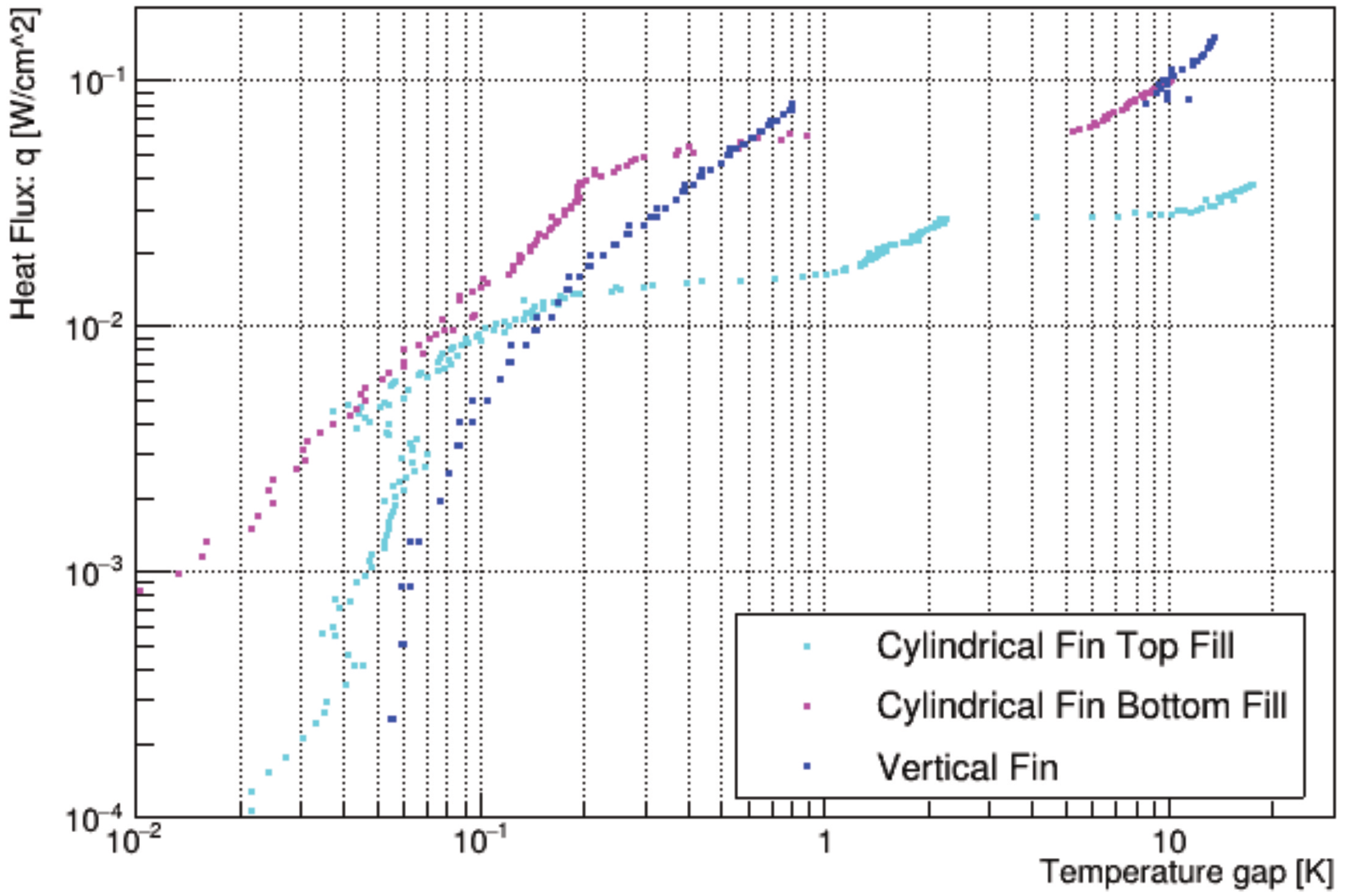
T. Okamura et al., IOP Conf. Ser.: Mater. Sci. Eng., ***755*** *(2020) 012141*

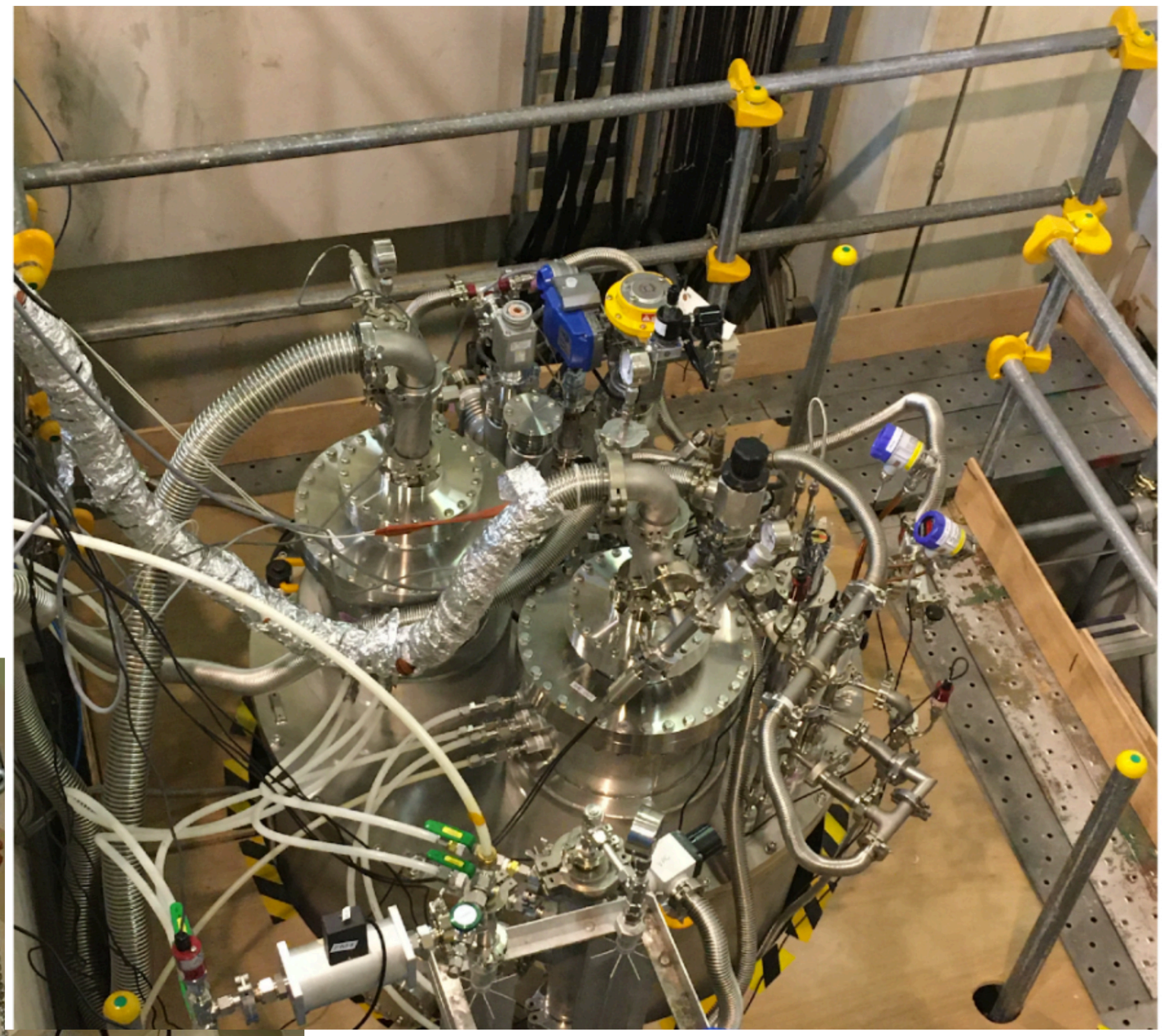
  - Validated the thermo-fluid calculations/simulations used for the design

v

- Tests of the assembled cryostat (2020.08–2021.03)
  - Successful cooled down of the full system (pre-cooled to 4 K in 48 h)
  - Low static heat load: 600 mW (4K res.), 50 mW (1 K pot), 5 mW (^{3}He pot)
  - Reached 1.23 K with pumped ^{4}He (corresponds to 0.65 K ^{3}He)
  - Characterization of boiling curves of HEX 1 prototypes

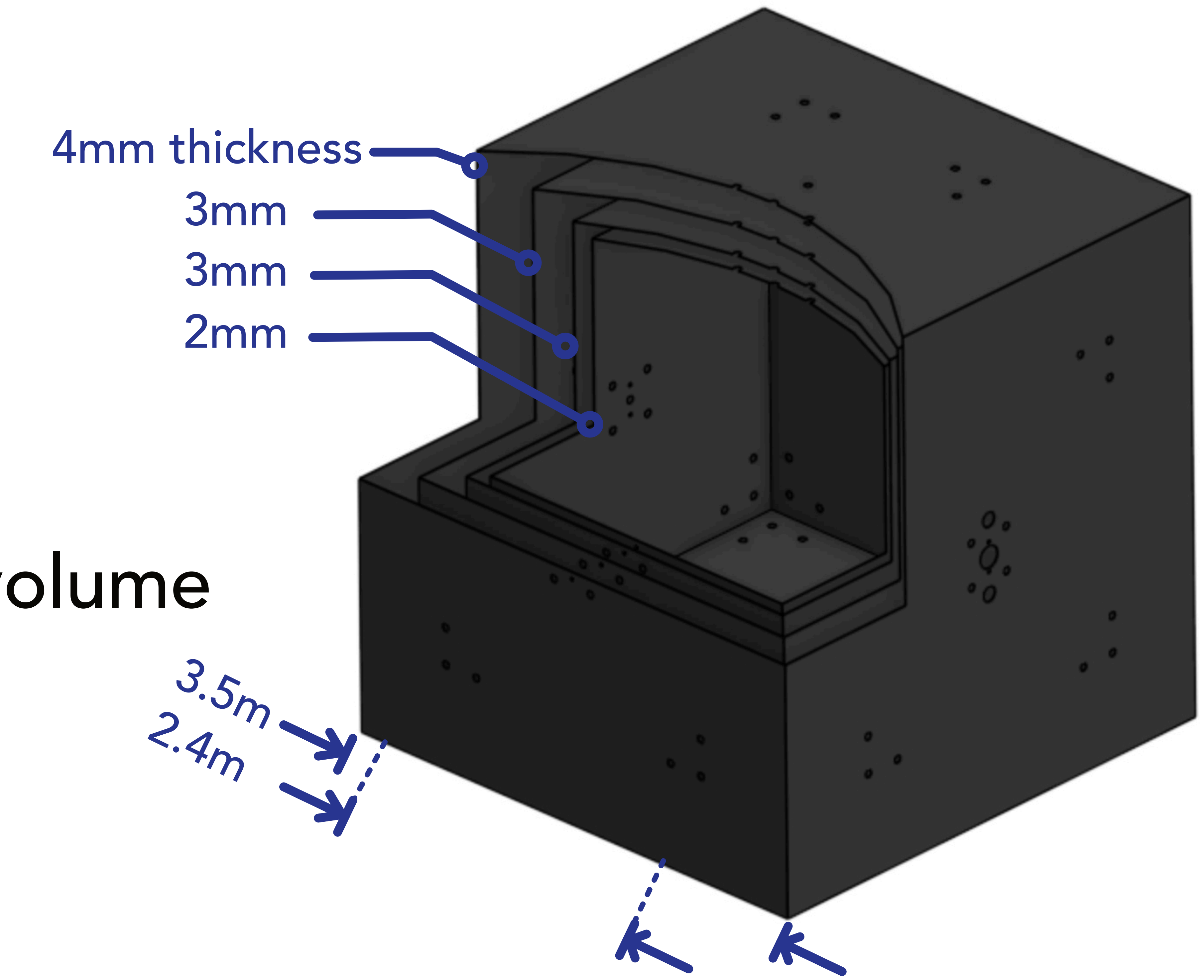






Magnetically Shielded Room (MSR)

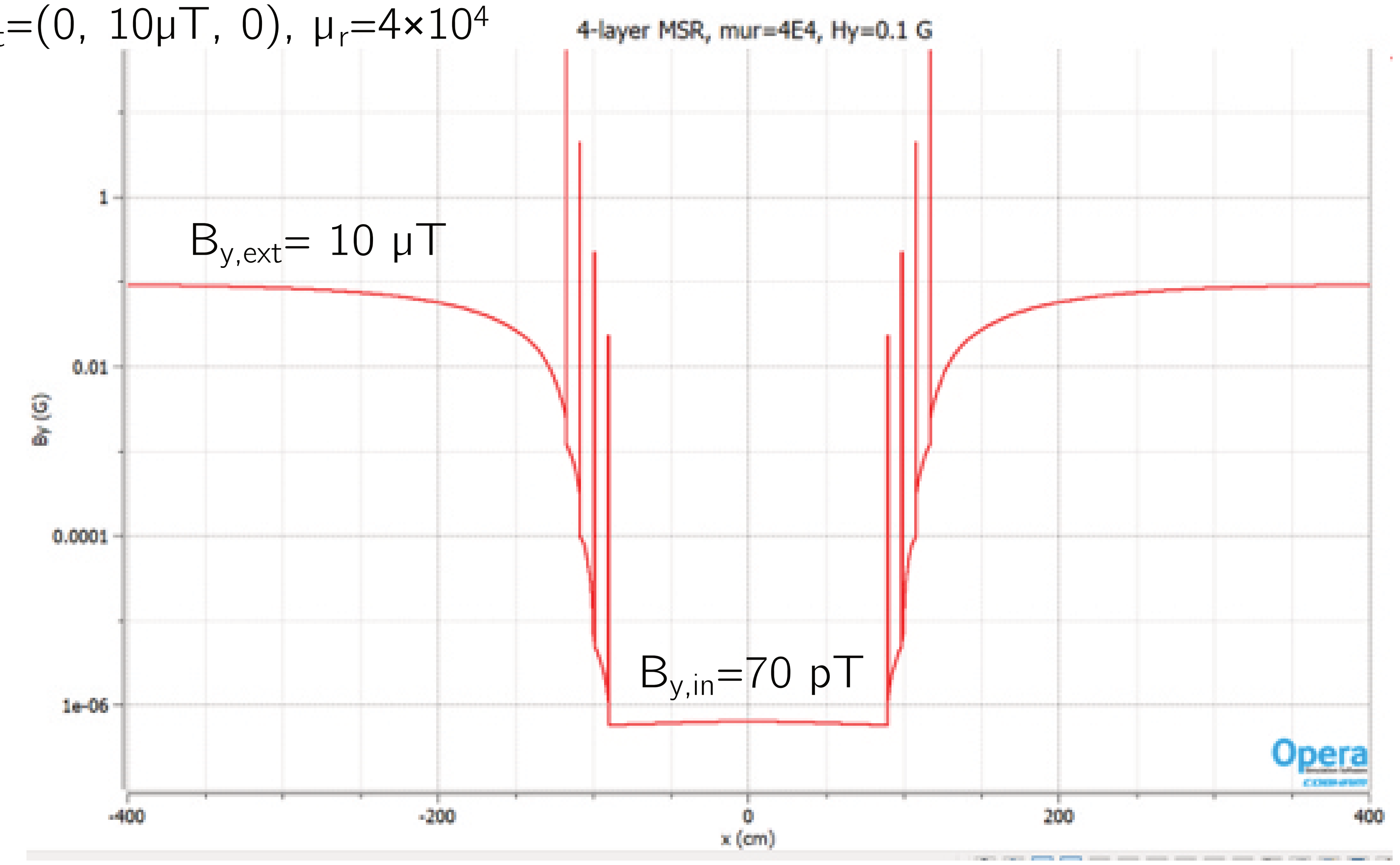
■ Requirements for the nEDM measurement:
- Shielding factor ~ 10^5 (@10 mHz or higher)
  - To provide ~1pT/cycle stability (1 cycle~100s)
- Fields < 1nT, gradient < 100 pT/m in the central $(1\ m)^3$ volume



■ TUCAN MSR specifications
- 4-layer mumetal shield
- Size:
  - Outermost layer: $(3.5\ m)^3$
  - Innermost layer : $(2.4\ m)^3$
- Design shielding factor (@10mHz): ~10^5
  - Confirmed by FEA simulations
- Currently working on detailed design with the manufacturer (Magnetic Shields Limited)

■ Installation planned from July 2022

For B_{ext}=(0, 10μT, 0), $\mu_r = 4\times10^4$

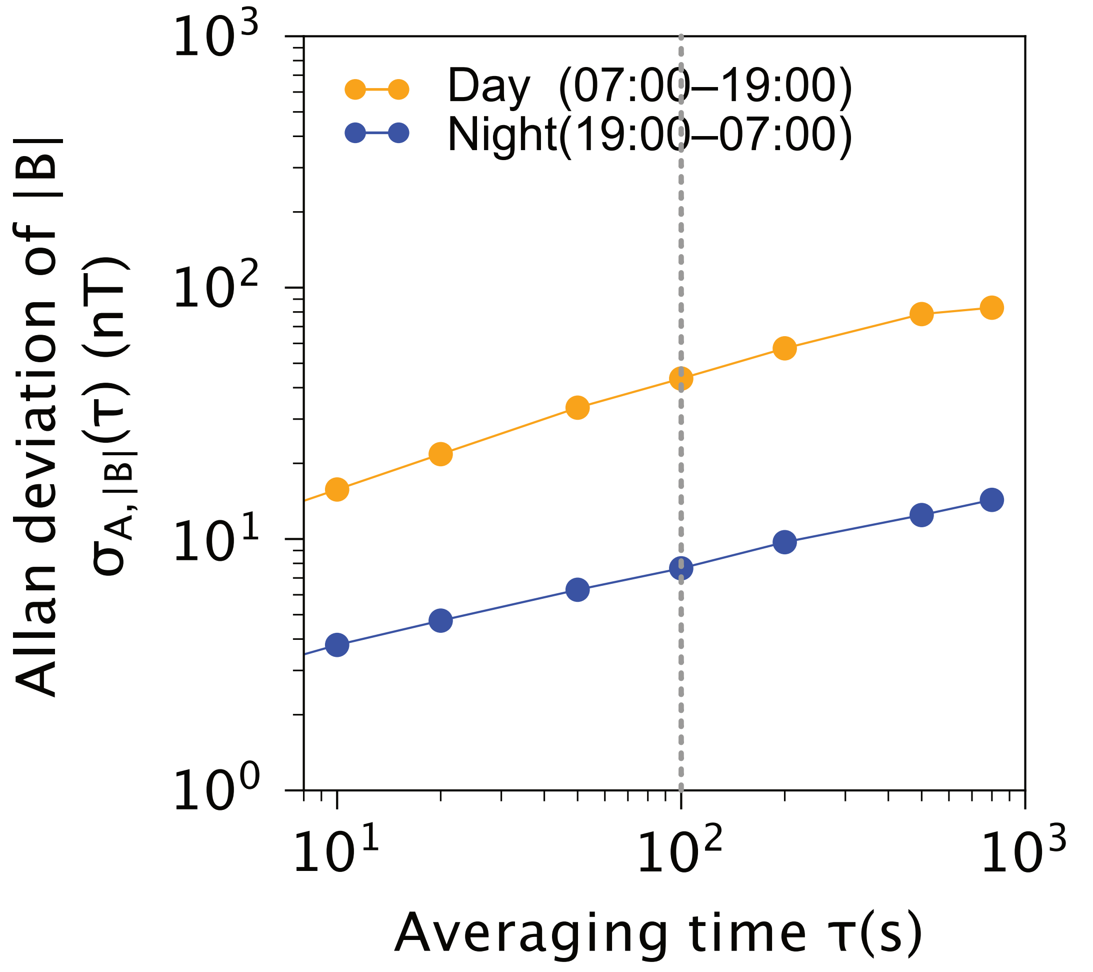


Magnetic field characterization at TRIUMF Meson Hall

- **Recent magnetic field measurements on the TUCAN area in TRIUMF Meson Hall**
  - Monitoring of ambient magnetic field on the area to estimate typical field fluctuations
  - Three-dimensional mapping of the ambient field on the area

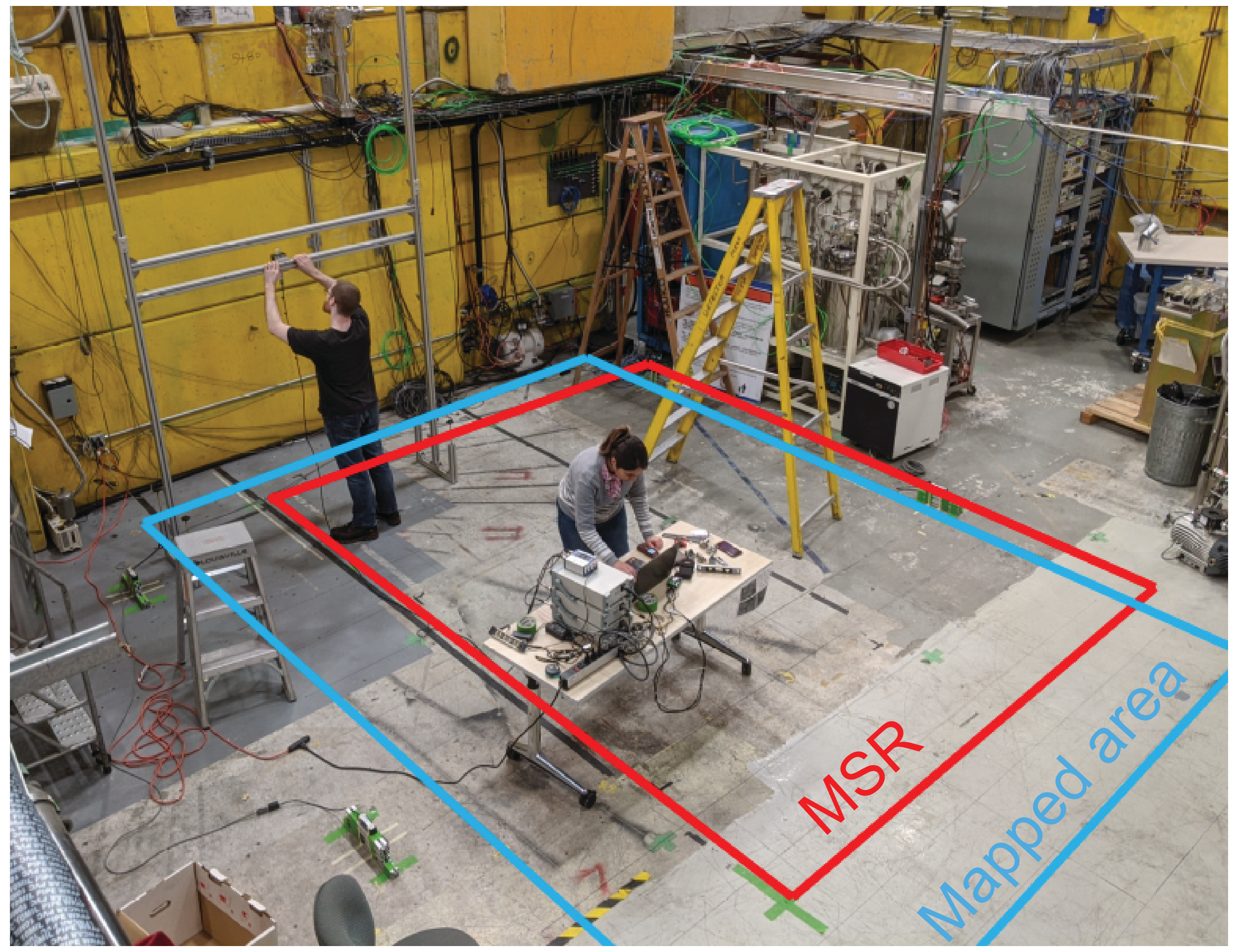
- **Results**

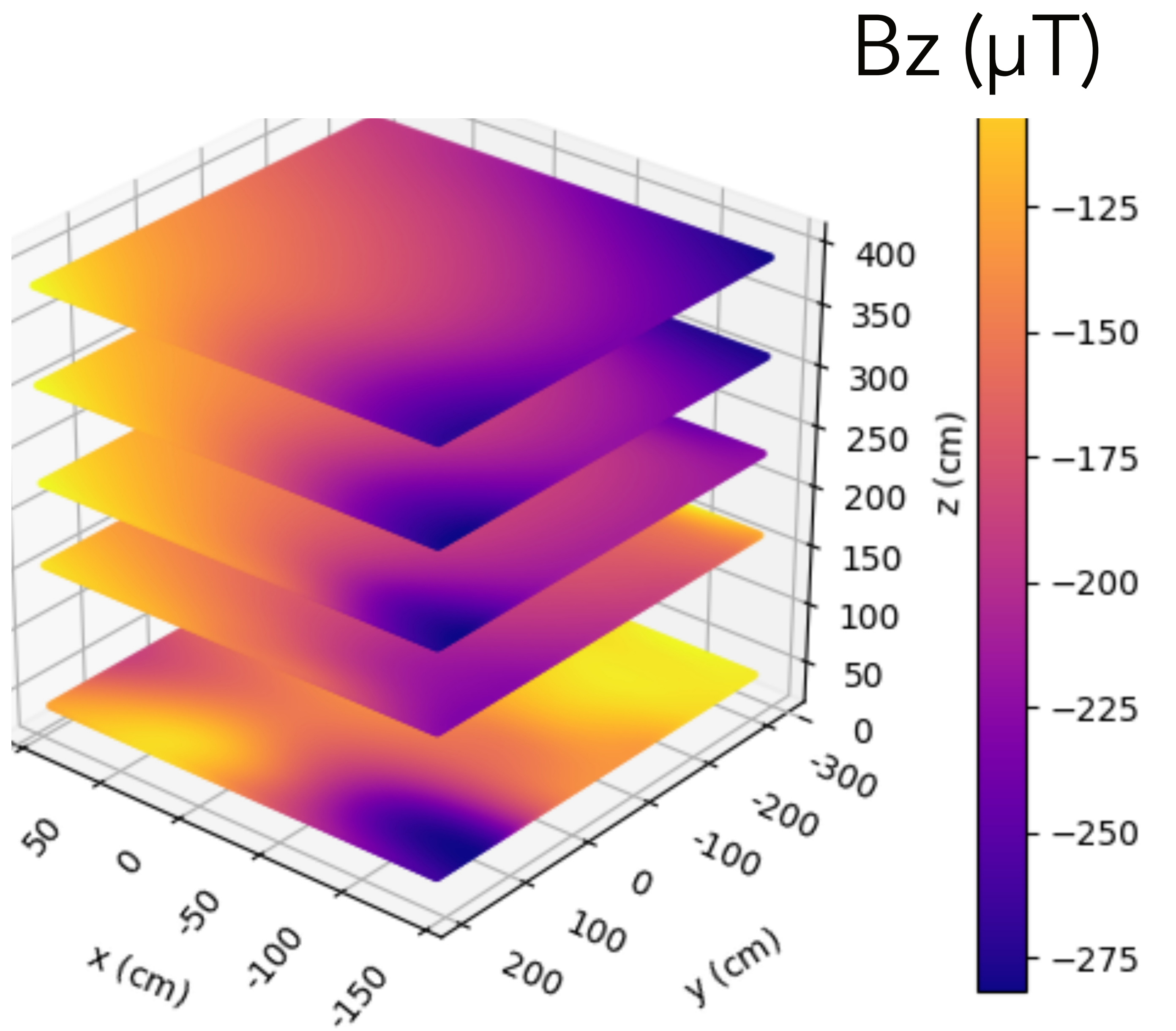
Field fluctuations



Typically **|B| < 150 nT** (@ 100s averaging)
→ **MSR will provide sufficient field stability**

Magnetic field mapping

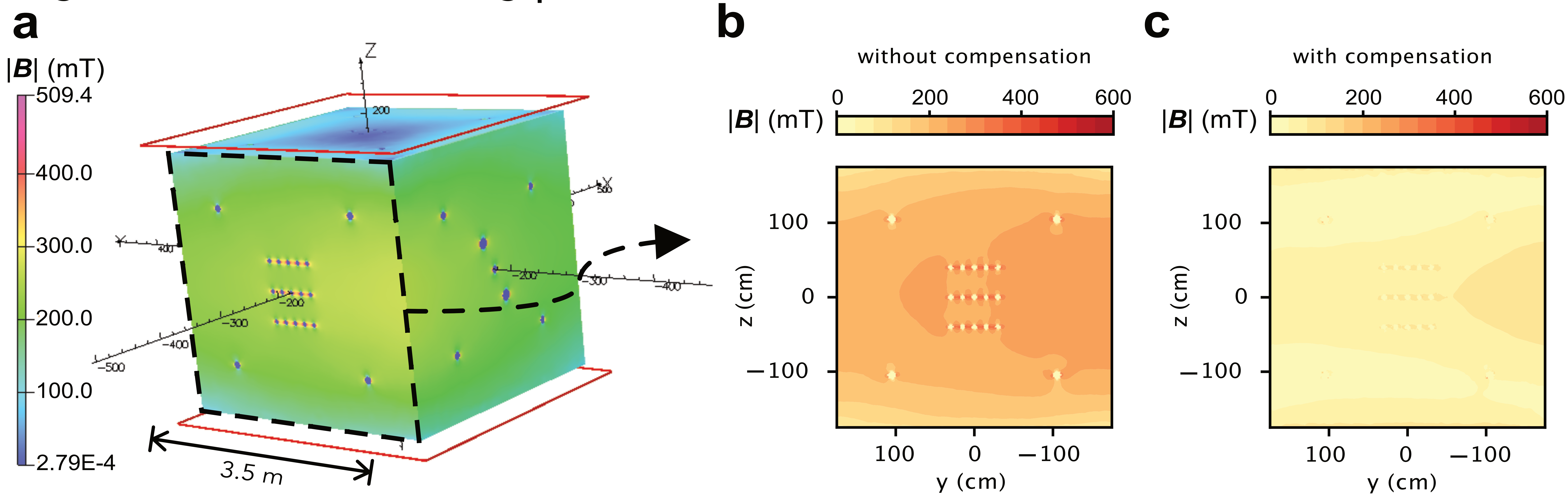




- **|B| ≈ 370 μT** at maximum
- Some hot spots near the floor; For higher z: dipole-like field from the cyclotron
- Designing compensation coils which cancel the magnetic flux induced in the MSR

Saturation risk of the MSR and design of the compensation system

- The background field in the area is up to ≈ 370 μT
  - Produces in-plane B ~ 500 mT in mumetal, x2 around holes
  - Could saturate mumetal near the MSR holes (B_s of mumetal: 700 mT)
- Designing a set of coils which compensate the effects of the background field and guarantee the shielding performance of the MSR



a. MSR placed in a dipole B-field, modelling the cyclotron stray field

b. In-plane |B| of +x plane: up to 500 mT

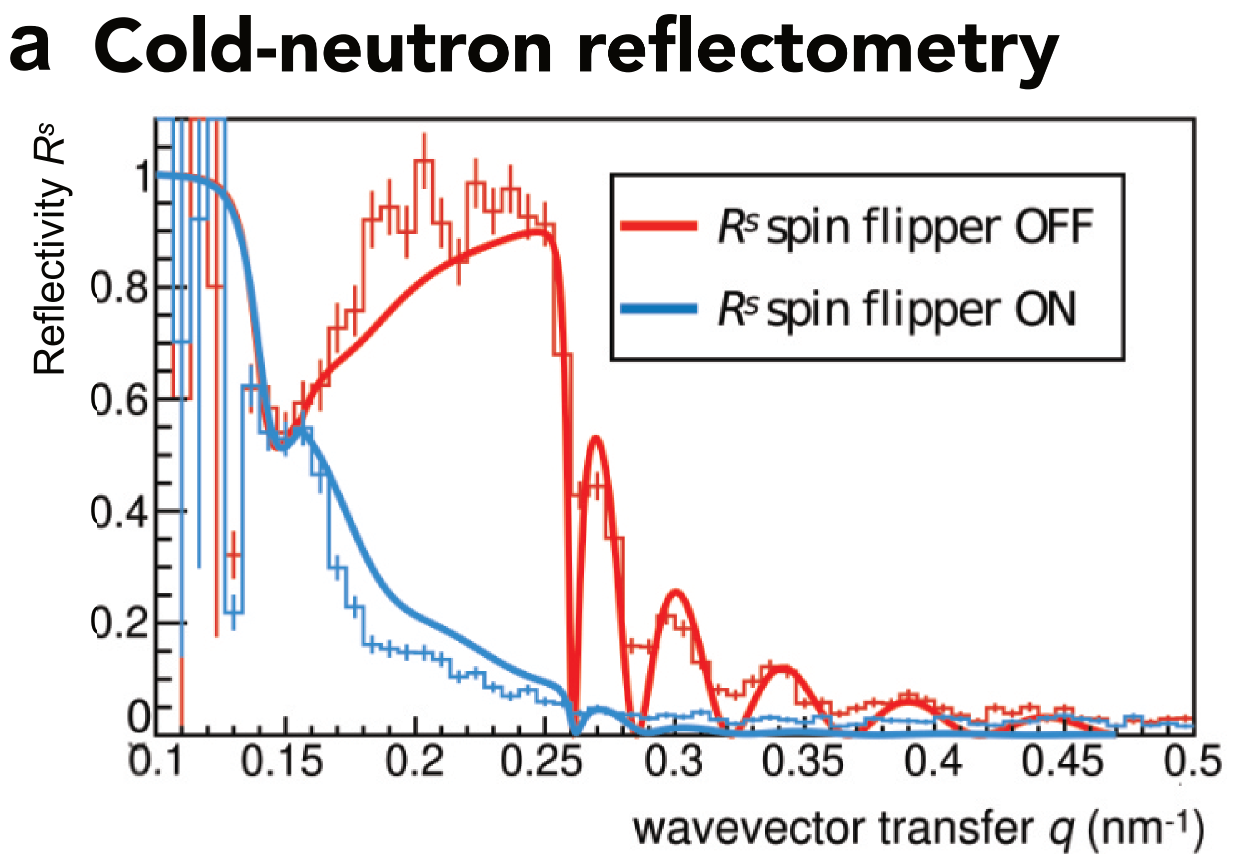
c. Coils activated (1000 AT): |B| reduced to <150 mT

Development of the UCN spin analyzer

- Principle of UCN spin analysis: a magnetized iron foil with ~2 T provides a sufficient potential barrier to select UCN spin state
- Developing iron thin foils by an ion beam sputtering facility at KURNS
  - Thin (≲ 100 nm) Fe foils on Al or Si substrate

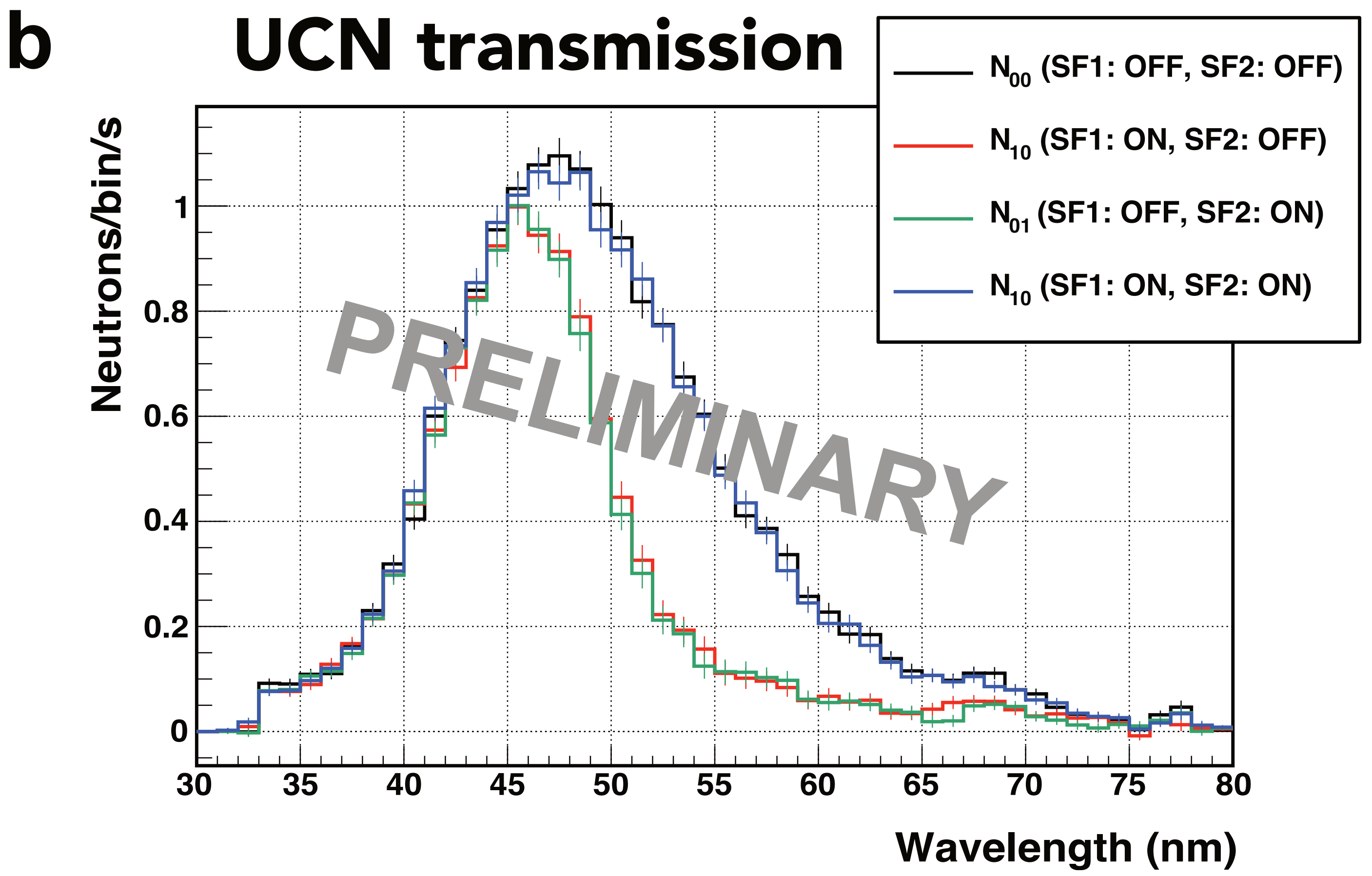
M. Hino et al, Nucl. Inst. Meth. A, **797** (2015), 265

- Characterization by
  - Vibrating sample magnetometry (VSM)
  - Cold-neutron reflectometry measurement at J-PARC/MLF (July 2021)
  - UCN transmission measurement at J-PARC/MLF (March 2022)



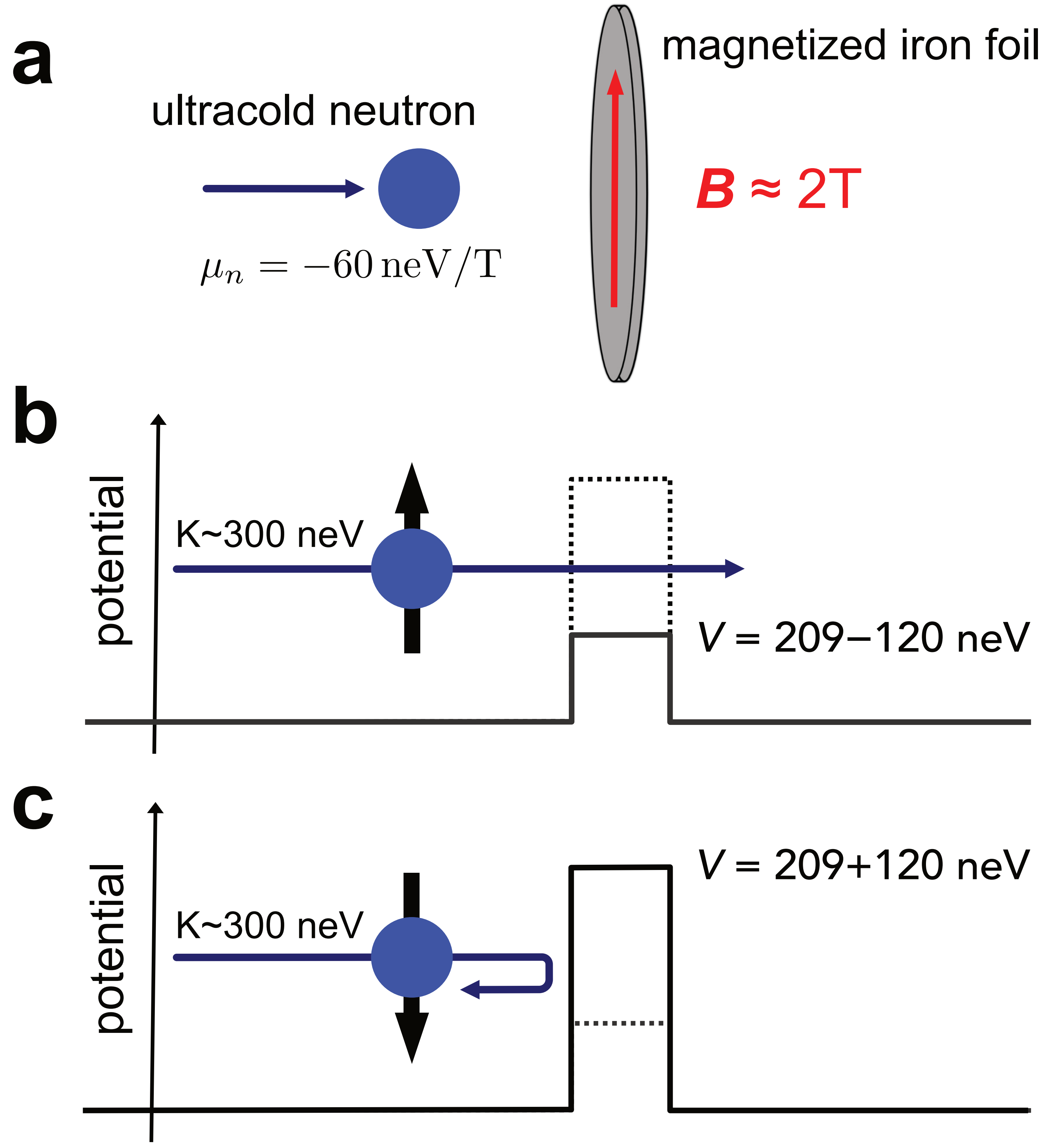
Si-substrate Fe film (90 nm) @ 80 Oe
(Sample size: 20 x 30 mm^2)

Reflectivity fitted to a single-layer model convoluted with beam polarization
q_c = 0.25 nm^{-1} ↔ 328 neV ↔ 20 kG

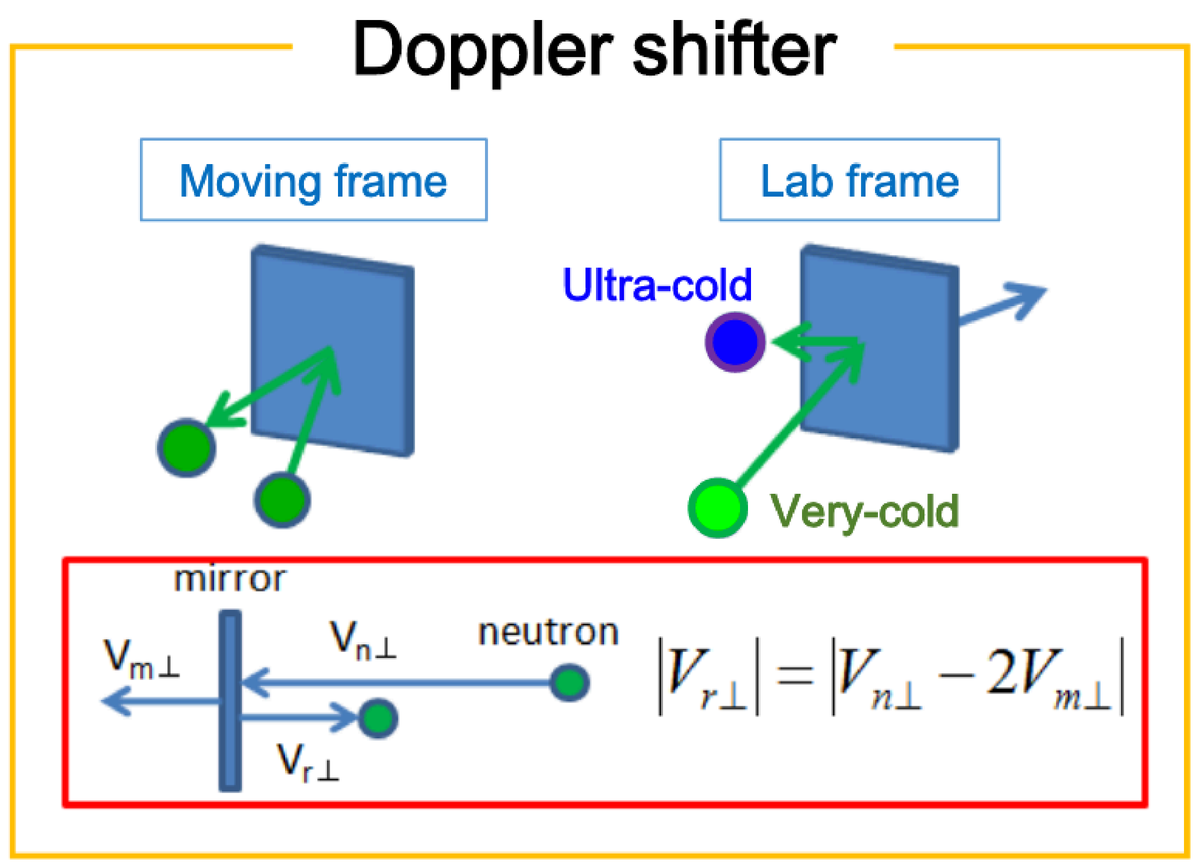


Al-substrate Fe films (90 nm) @ 60 Oe
(Sample size: Φ 84mm)

Decrease of transmission observed by activating spin flippers between two films

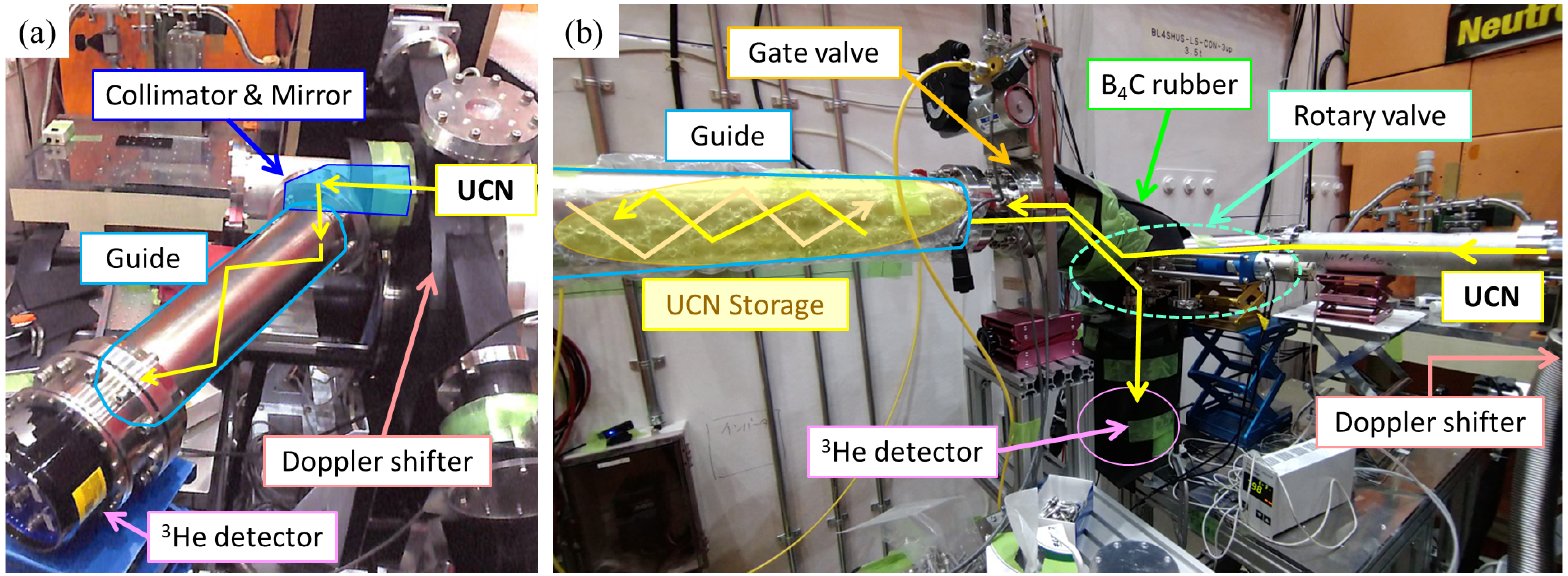


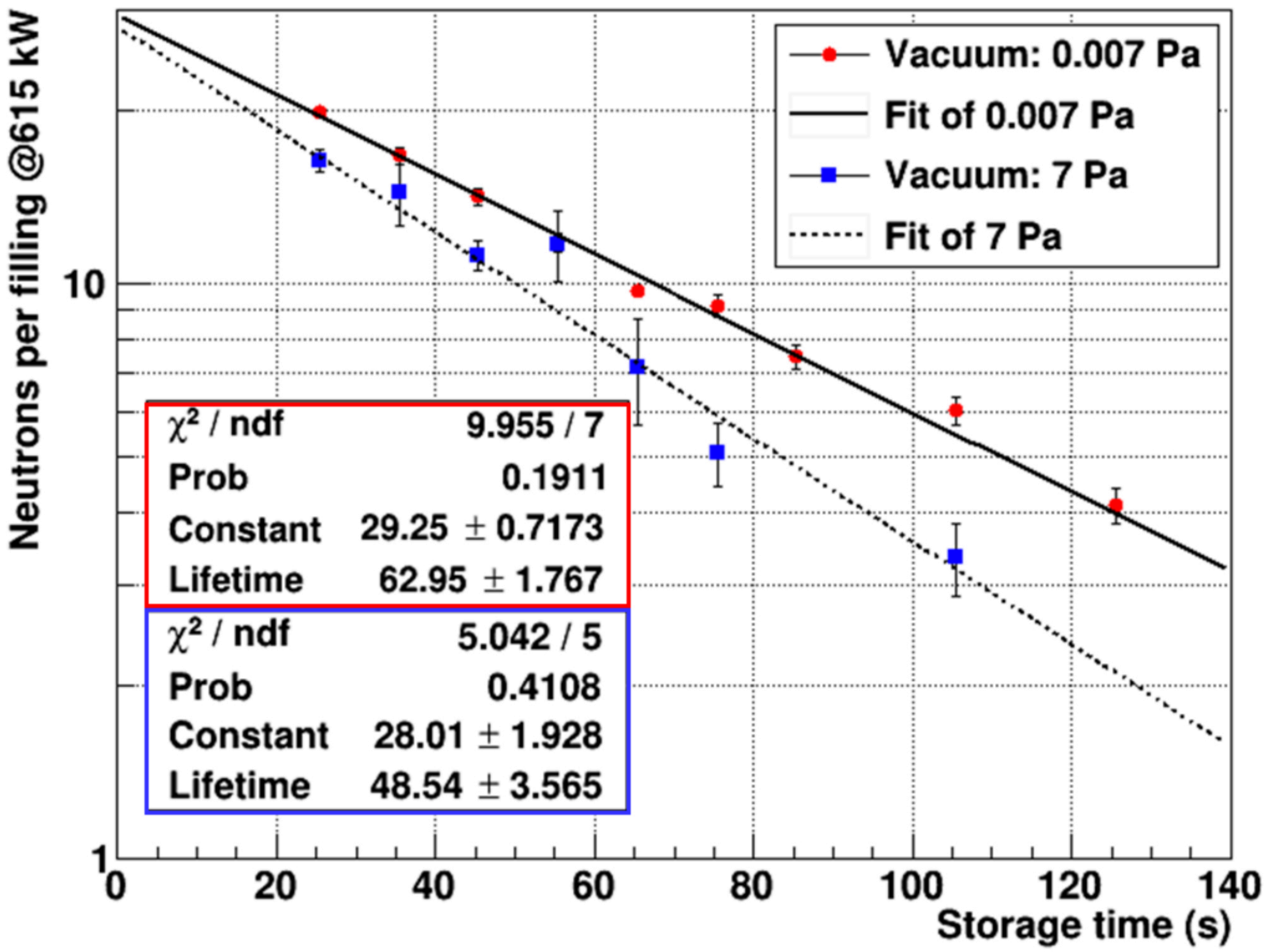
Characterization of UCN transmission/storage



- Doppler-shifter pulsed UCN source at J-PARC/MLF BL05

  S. Imajo et al., Prog. Theor. Exp. Phys. ***2016****(2016), 013C02*
  - Decelerate very cold neutron (VCN, ~ 50 μeV) beam with a neutron super-mirror moving backward
  - Provides ~40 UCN/s pulse → velocity-resolving evaluation by ToF
- Used for component tests for the new UCN source
  - (a) transmittance measurements of UCN guides: measurement completed
  - (b) storage test of EDM cell and valve: beamtime in June 2022

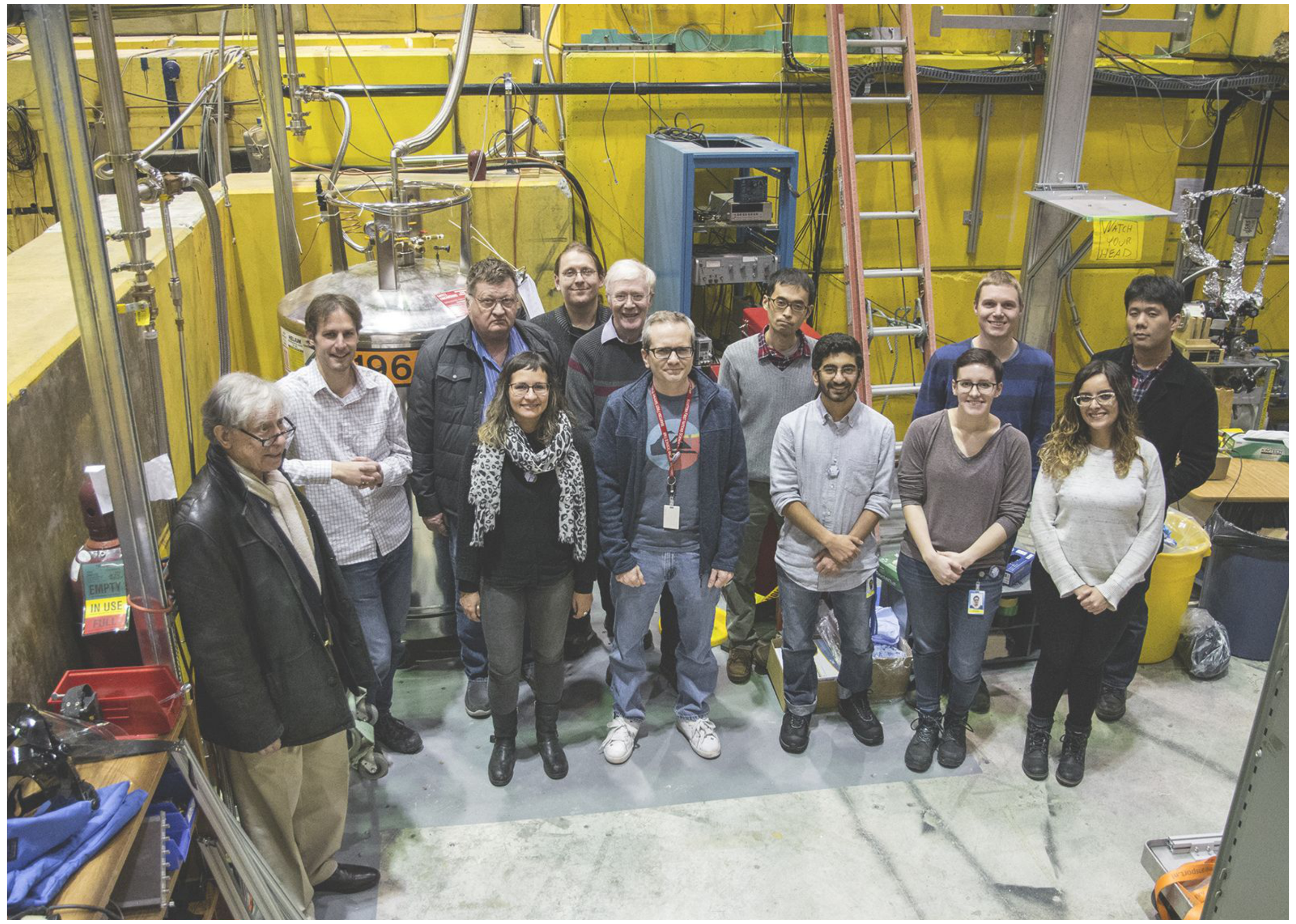


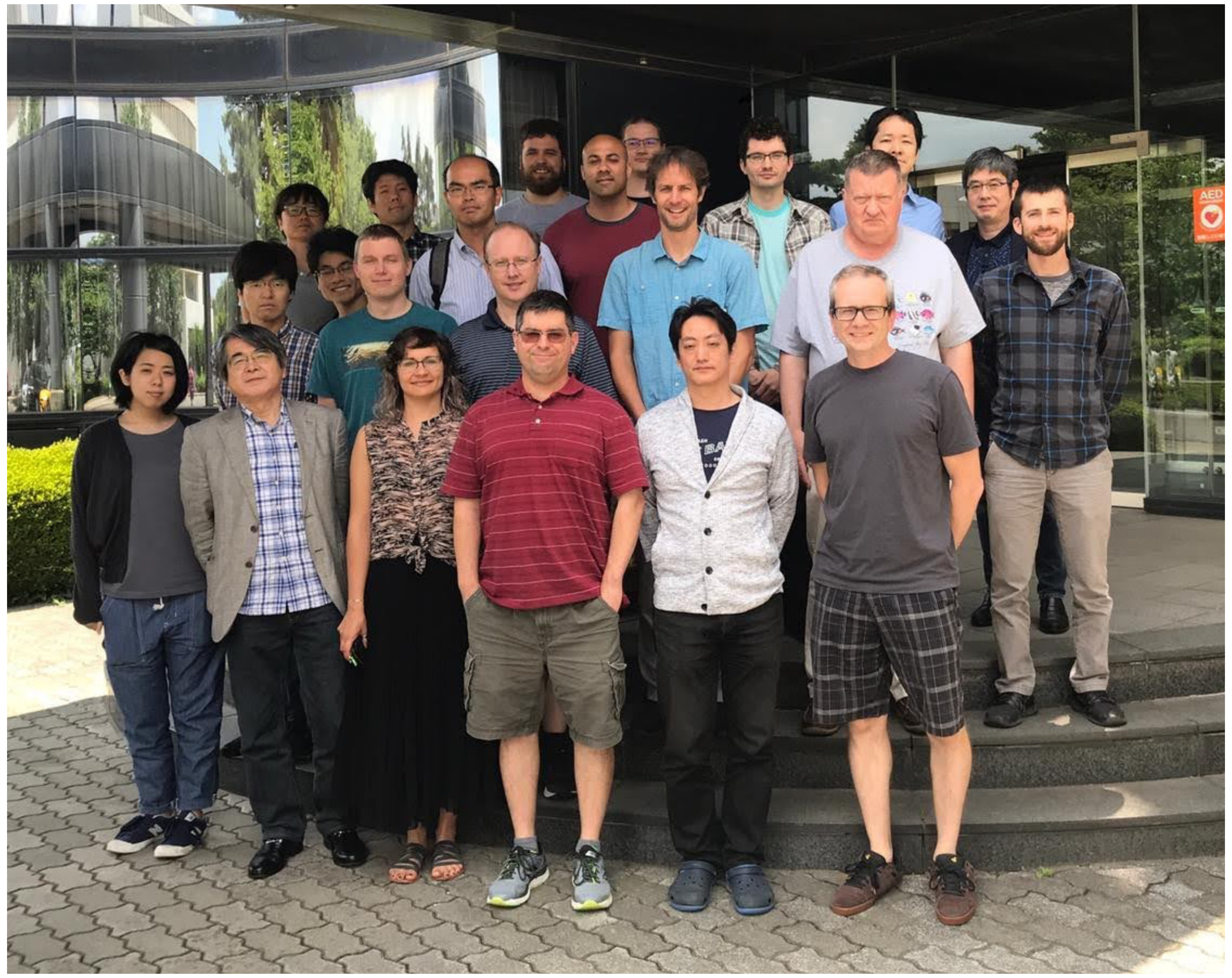


Summary

- The neutron EDM: sensitive probe of CP violation
- The TUCAN collaboration:
  - High intensity new UCN source ⇒ a breakthrough nEDM measurement with 10^{-27}ecm precision
  - The UCN production scheme demonstrated by a prototype UCN source
- Current status :
  - The new UCN source under construction:
    - Installation of the major components planned in 2022−2023
    - First UCN production with the new source in 2023
  - The nEDM spectrometer developed in parallel:
    - MSR will be installed in 2022−2023, followed by the other subsystems
    - Aiming to start nEDM spectrometer commissioning in 2024
- Highlights of recent activities
  - Completion of the helium cryostat
  - On-site magnetic field characterization and design of compensation coils for the MSR
  - Development of UCN spin analyzer
  - Component tests with the Doppler-shifter pulsed UCN source at J-PARC

Acknowledgements





Thank you for your attention!

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