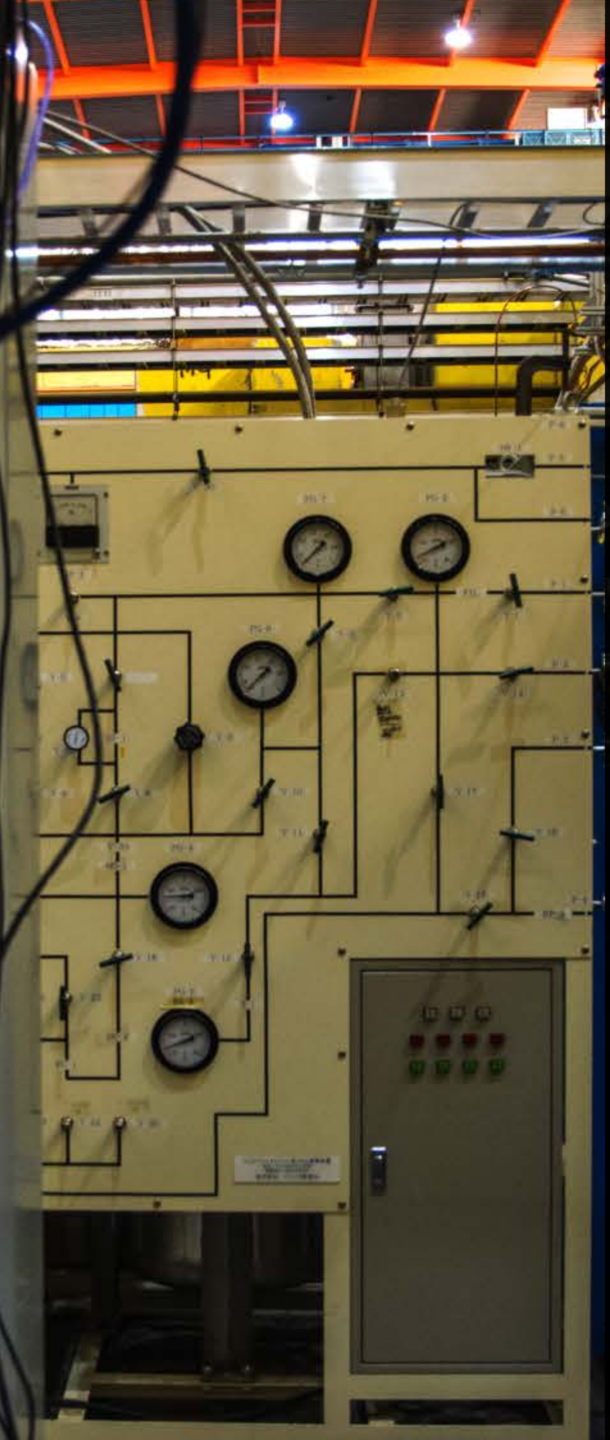
TRIUMF

TUCAN
TRIUMF Ultra Cold
Advanced Neutron source

TUCAN 2025-2030

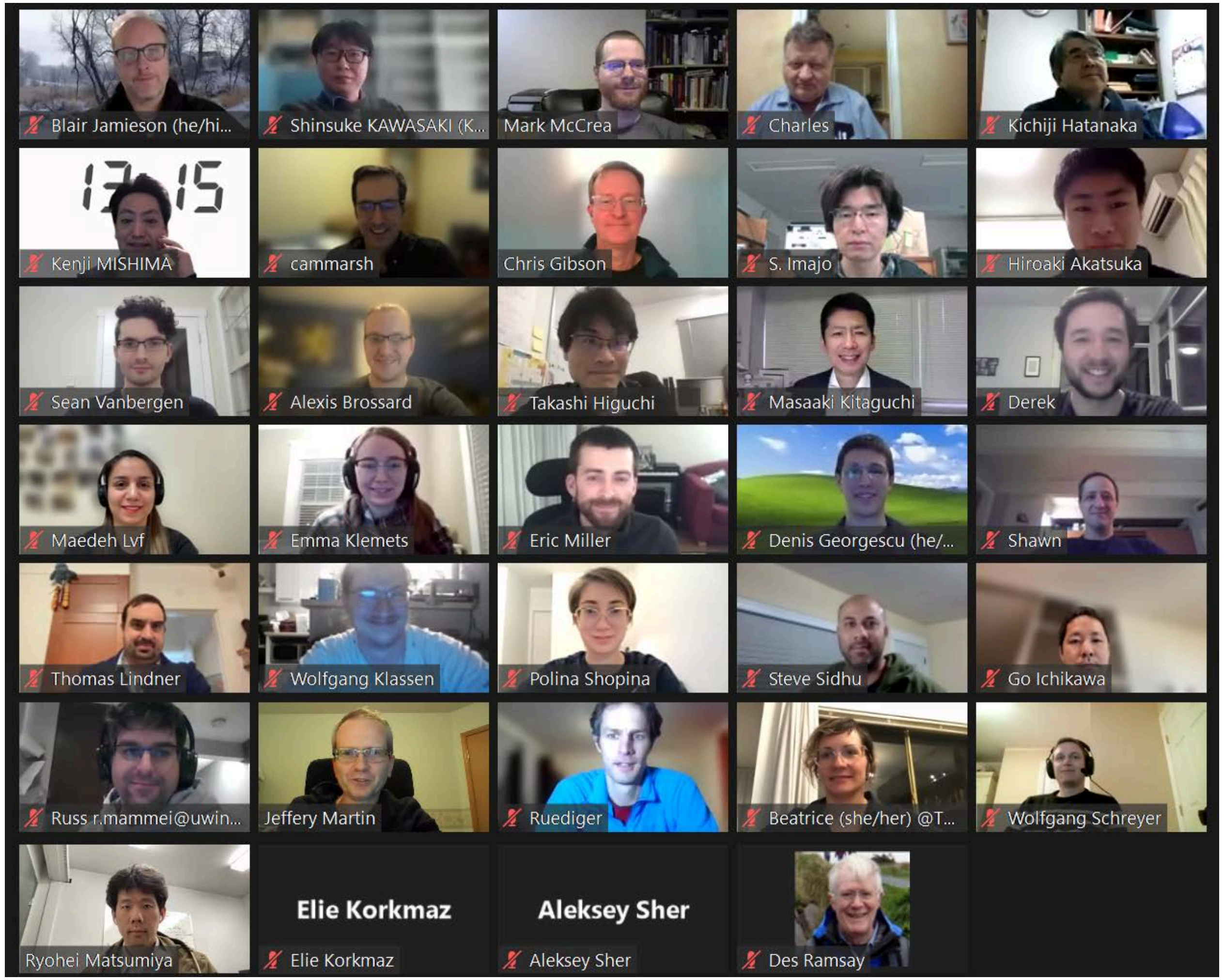


R. Picker for the TUCAN collaboration

Discovery, accelerated

TUCAN collaboration and goals

TRIUMF UltraCold Advanced Neutron Collaboration



Jan. 2022 virtual collaboration meeting

TUCAN collaboration goals:

1. Create the world's strongest ultracold neutron source.
2. Search for a neutron electric dipole moment with a sensitivity of 10^{-27} *e* cm (1-σ) in 400 beam days.
3. Create an international user facility for fundamental research using ultracold neutrons.

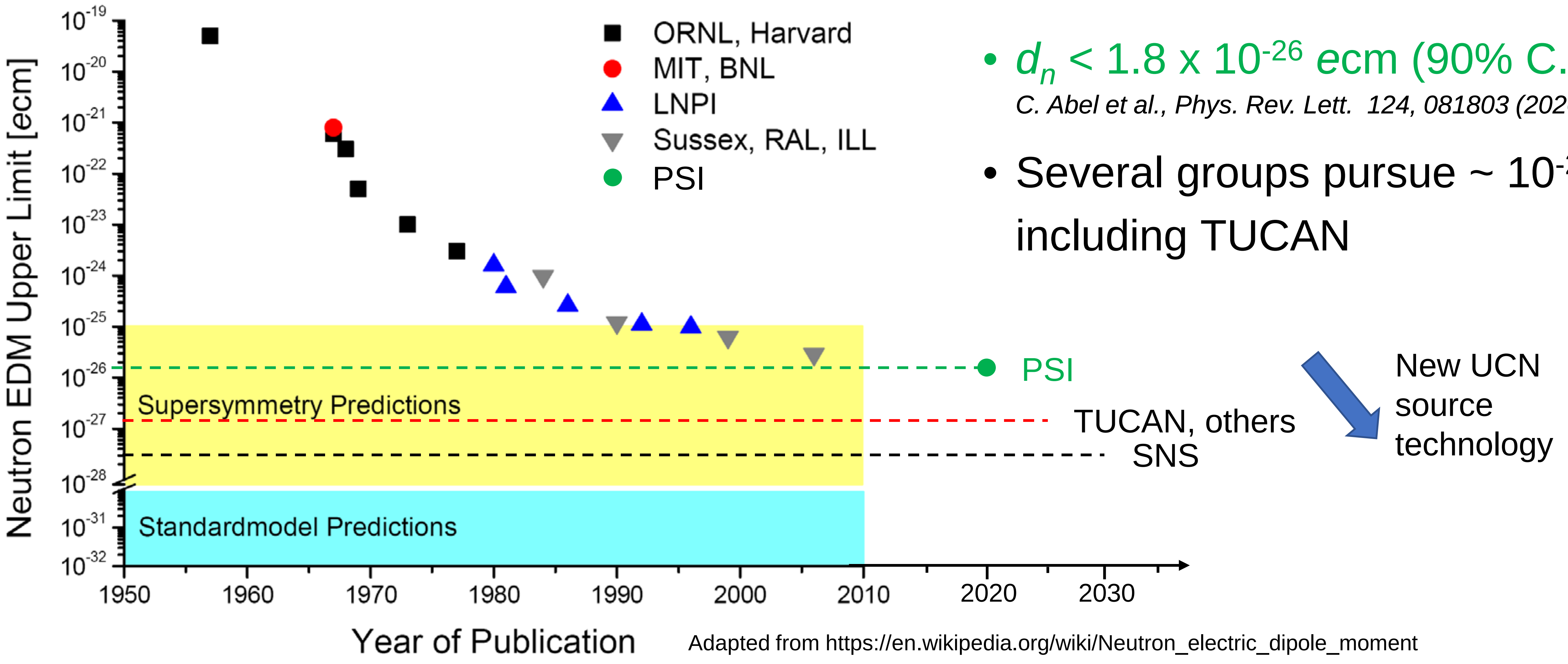
H. Akatsuka[1], C. Bidinosti[2], C. Davis[3], B. Franke[3,4], D. Fujimoto[3], M. Gericke[5], P. Giampa[6], R. Golub[7], S. Hansen-Romu[5,2], K. Hatanaka[8,*], T. Higuchi[8], G. Ichikawa[9], S. Imajo[8], B. Jamieson[2], S. Kawasaki[9], M. Kitaguchi[1], W. Klassen[4,5,2], E. Klemets[4], A. Konaka[3,10], E. Korkmaz[11], E. Korobkina[7], F. Kuchler[3], M. Lavvaf[5,2], T. Lindner[3,2], K. Madison[4], Y. Makida[9], J. Mammei[5], R. Mammei[2,3], J. Martin[2,*], R. Matsumiya[3], M. McCrea[2], E. Miller[4], K. Mishima[9], T. Momose[4], T. Okamura[9], H.J. Ong[8], R. Picker[3,12], W.D. Ramsay[3], W. Schreyer[3], A. Sher[3], H. Shimizu[1], S. Sidhu[12], S. Stargardter[5,2], I. Tanihata[7], S. Vanbergen[4], W.T.H. van Oers[5,3], Y. Watanabe[9]

[1]Nagoya University, [2]The University of Winnipeg, [3]TRIUMF, [4]The University of British Columbia, [5]University of Manitoba, [6]SNOLAB, [7]North Carolina State University, [8]RCNP Osaka, [9]KEK, [10]Osaka University, [11]University of Northern BC, [12]Simon Fraser University

*cospokespersons (K. Hatanaka and J. Martin)

EDM motivation and history

- EDM experiments essentially search for sources of CP violation beyond the standard model.
- Lowering EDM limits seriously restricts BSM theories.



- $d_n < 1.8 \times 10^{-26}$ ecm (90% C.L.)

  C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020)

- Several groups pursue ~ 10^{-27} ecm, including TUCAN

Adapted from https://en.wikipedia.org/wiki/Neutron_electric_dipole_moment

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Why should we have an edge? Density!

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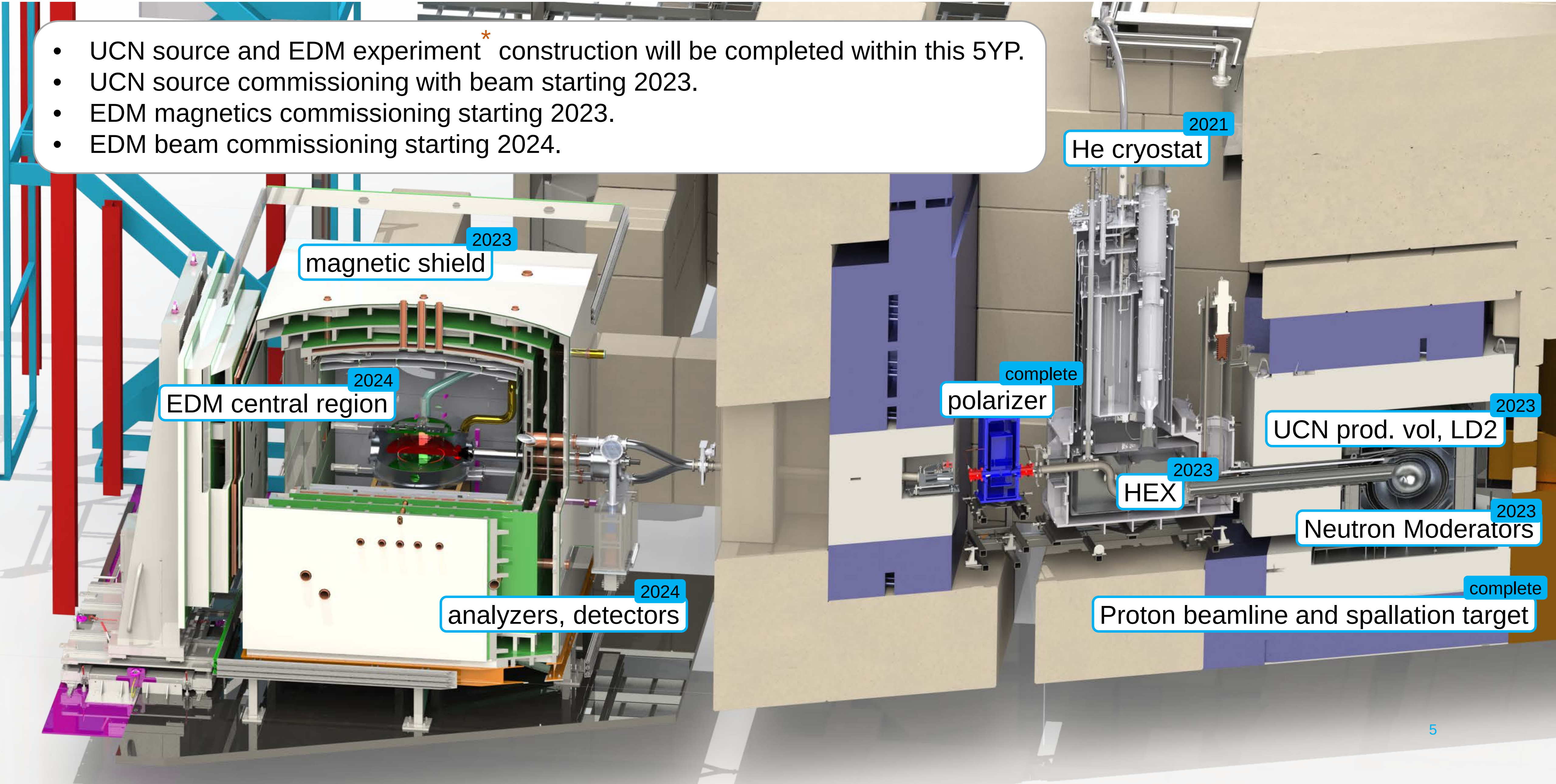
Experiment	ILL	PSI nEDM	PSI n2EDM*	TUCAN**
UCN detected per cycle	14 000	15 000	121 000	1 600 000
Size	20 l	20 l	116 l	63 l
Density detected	0.7	0.75	1	26

½ to ¼ compared to expectations

* expected, based on PSI nEDM.
** expected, extensive MC.

Main ingredients and status

- UCN source and EDM experiment* construction will be completed within this 5YP.
- UCN source commissioning with beam starting 2023.
- EDM magnetics commissioning starting 2023.
- EDM beam commissioning starting 2024.



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*: Budget constraints require some descoping

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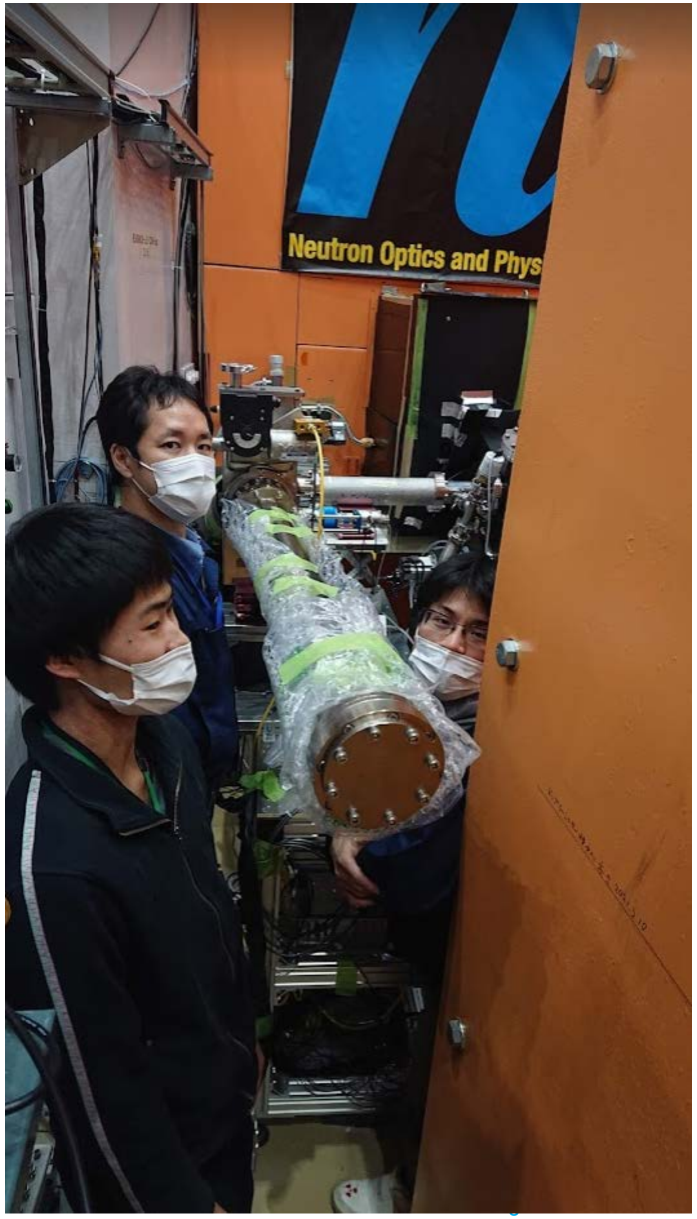
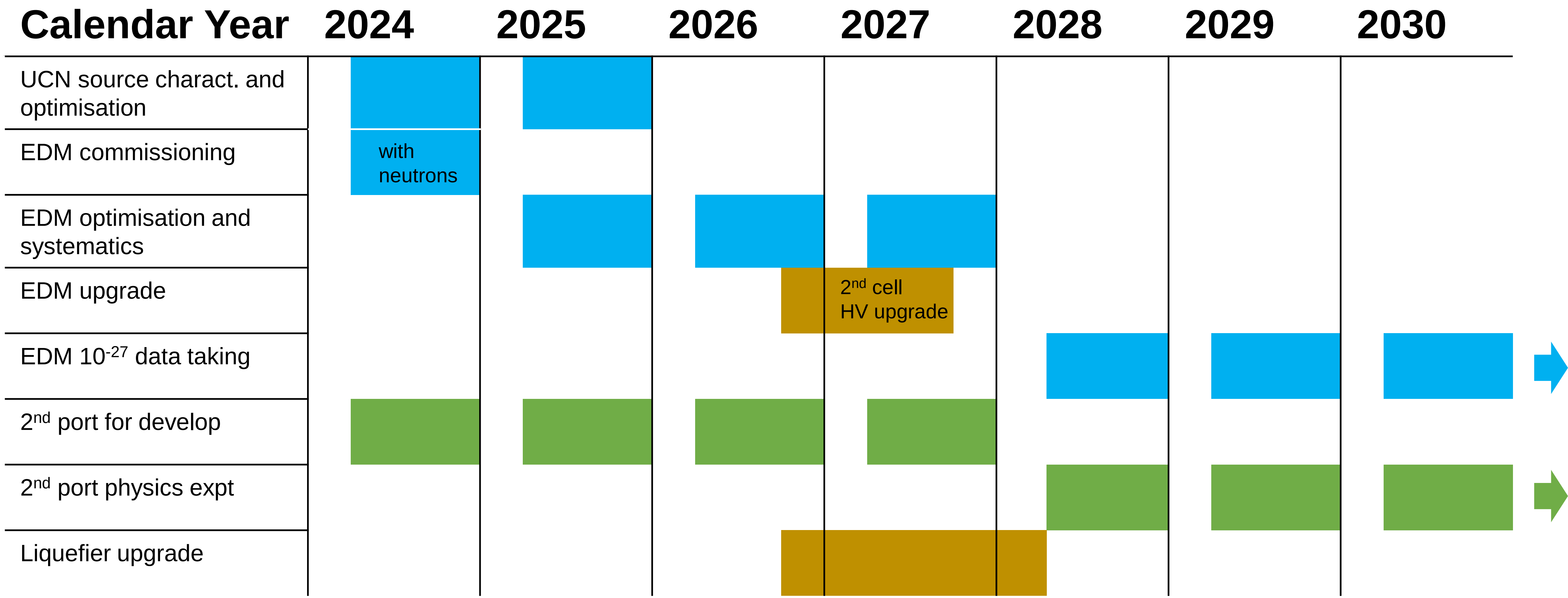
- Cost increases due to **labour overages** and **pandemic price increases** will require to descope some EDM features to a future funding request.
- Detailed planning just ongoing, will be completed by standing External Advisory Committee (EAC) review in May.
- Scope reduction could reach from just performing Ramsey cycles with UCN to only finding cost savings.
- Most promising option at the moment: **HV at 50 %** and using **1 cell** instead of 2 saves significant budget, reduced sensitivity reach by a factor of 3 but allows to commission and thoroughly test all systems.
- New funding from JSPS and/or CFI during next rounds.



UCN tests at J-PARC BL05, 2021

TUCAN plans 5YP 2025-2030



Requirements for executing this plan

Equipment and costs

- UCN source
  - commissioning will show validity of most of our choices
  - possible upgrade $1M
- EDM experiment
  - descoped components $1M
- Liquefier
  - current liquefier does not allow full duty cycle
  - commissioning and proving source ok
  - upgrade required for EDM statistics runs $3M-$5M

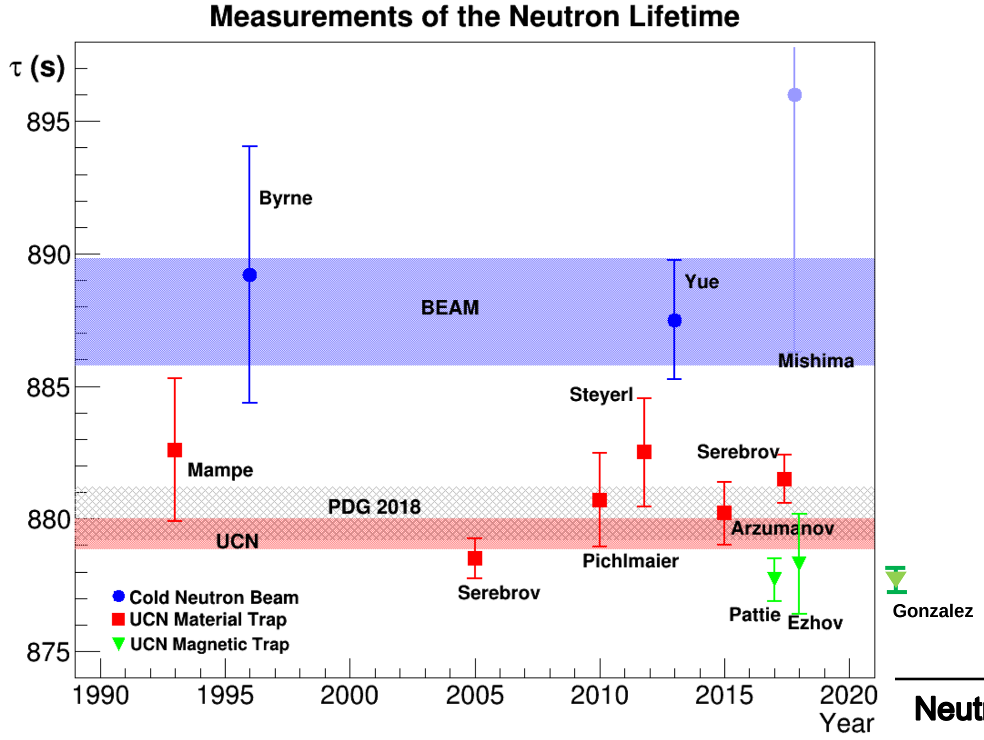
Human resources

- need additional BAE or P&S
  - source, EDM and 2nd port cannot be handled by 2 BAEs
- technician
  - required for all three above
  - paid from CFI as possible
- project engineer
  - needed for source, liquefier and EDM upgrades

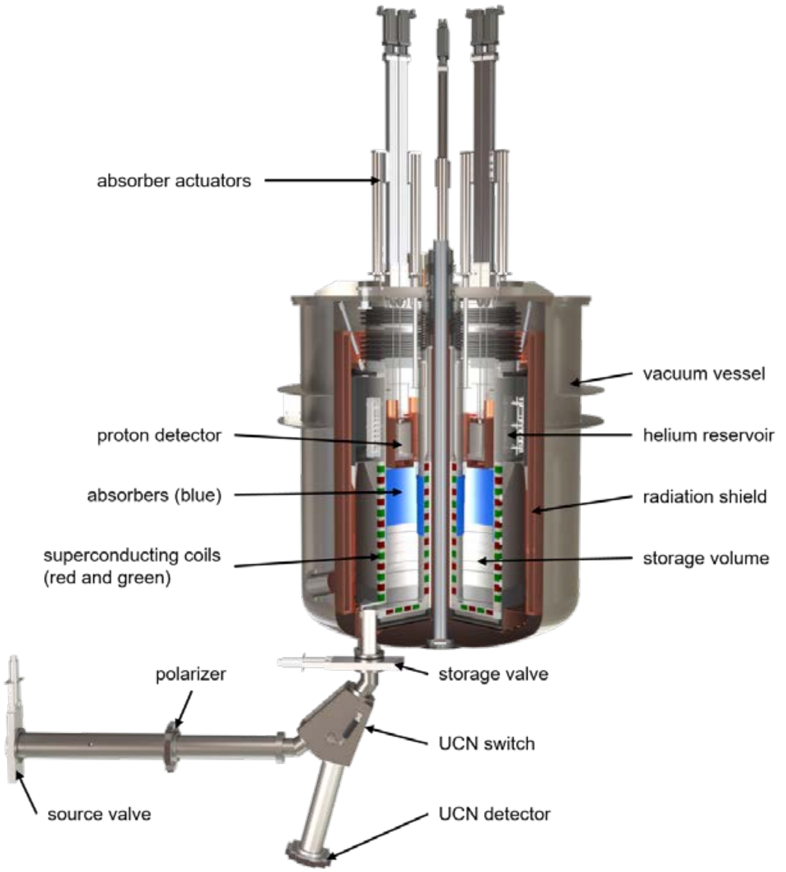
Synergies possible with HAICU and Center for Quantum/AMO/precision: cryogenics, magnetic fields, spin gymnastics

UCN experiments for 2nd port

- At first: 2nd port will be used for source characterization and component testing for EDM
- neutron lifetime experiment
  - large discrepancy between beam and bottle measurements
  - discussion about possible addition dark decay channel largely resolved => systematic effect?
  - collaboration with PENeLOPE exists, could move to TRIUMF



Neutron lifetime puzzle



PENeLOPE neutron lifetime experiment

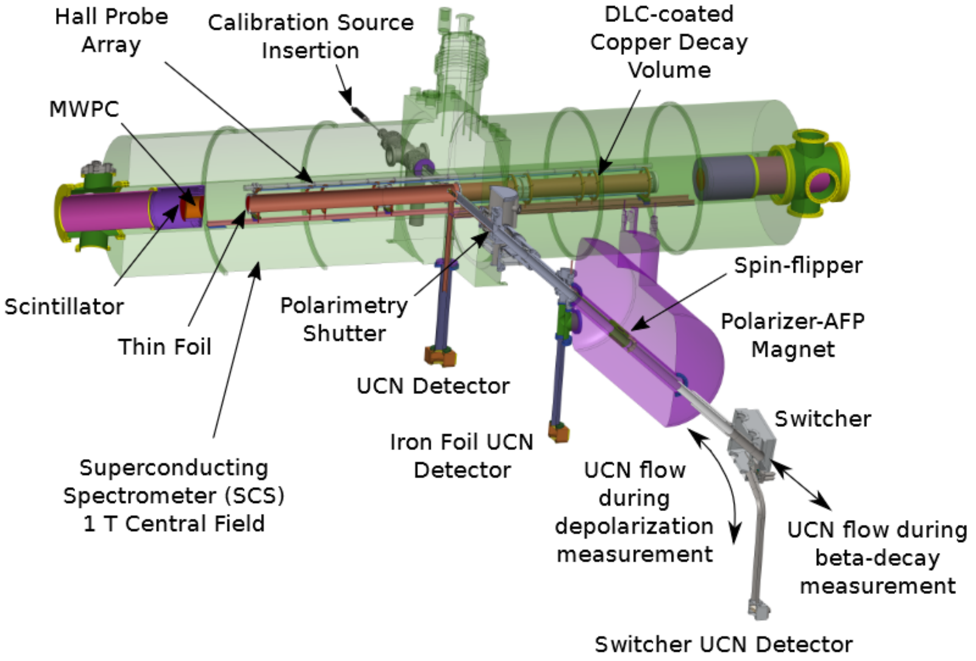
UCN experiments for 2nd port

- At first: 2nd port will be used for source characterization and component testing for EDM
- neutron lifetime experiment
  - large discrepancy between beam and bottle measurements
  - discussion about possible addition decay channel (dark matter?)
  - collaboration with PENeLOPE exists, could move to TRIUMF
- neutron decay expts.
  - e.g. A, the correlation between the electron momentum and the initial spin of the neutron in neutron β-decay

$$A_0 = \frac{-2(\lambda^2 - |\lambda|)}{1 + 3\lambda^2}. \quad \lambda \equiv \frac{g_A}{g_V}$$

  - together with neutron lifetime can obtain V_{ud}, the first CKM matrix element

$$|V_{\mathrm{ud}}|^2 \tau_n (1 + 3g_A^2) = 4908.6(1.9)\ \mathrm{s},$$



UCNA experiment to measure A with UCN

UCN experiments for 2nd port

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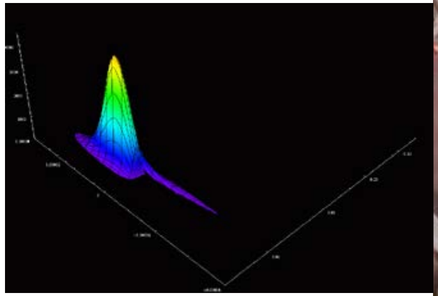

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$$|V_{ud}|^2 \tau_n (1 + 3g_A^2) = 4908.6(1.9)\ \mathrm{s},$$

- gravitational experiments with UCN
  - can determine the wavefunction of the neutron in the gravitational potential very precisely
  - allow putting constraints on non-Newtonian gravity distances of µm, and thus Axions or Chameleons

- These are mostly **statistics limited**, so higher UCN densities will boost the sensitivity reaches but also allow to explore new experimental ideas.

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Qbounce @ ILL

Summary

- UCN source and (descoped) EDM experiment construction will be completed during this 5YP.
- **Beginning of next 5YP** dedicated to **optimizing** source and EDM experiment.
- **Later half of 5YP** shall allow full duty cycle and therefore **statistics runs** and PP experiment at 2nd port.
- **External funding** and **TRIUMF matching** required to execute plan.
- Physics, technical and engineering human resources required.

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Questions?

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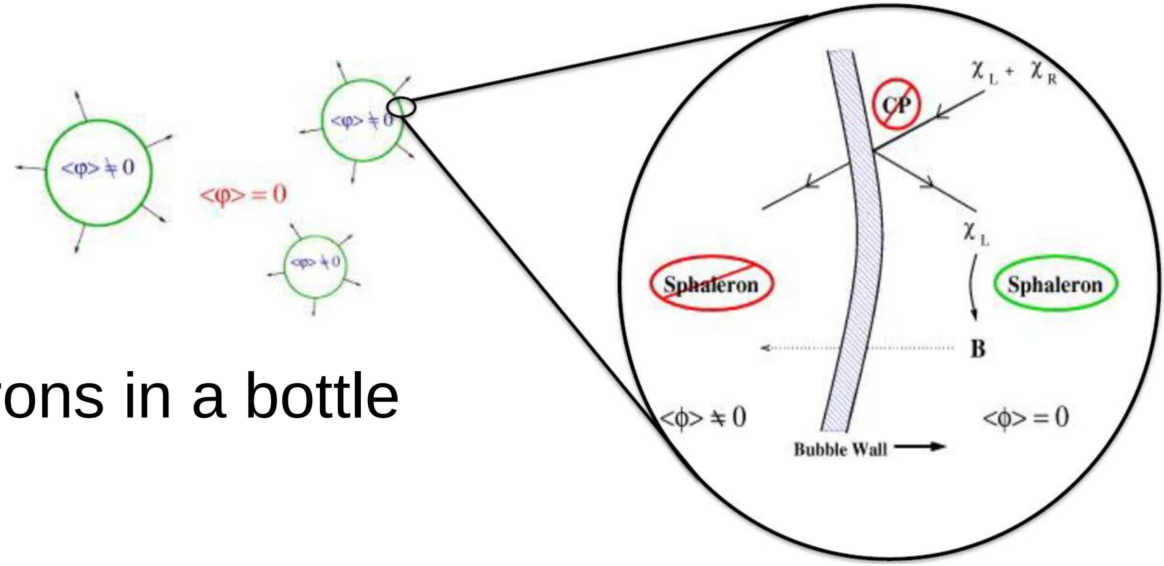
Physics of the neutron EDM

- 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
- Spin precession frequency of ultracold neutrons in a bottle



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

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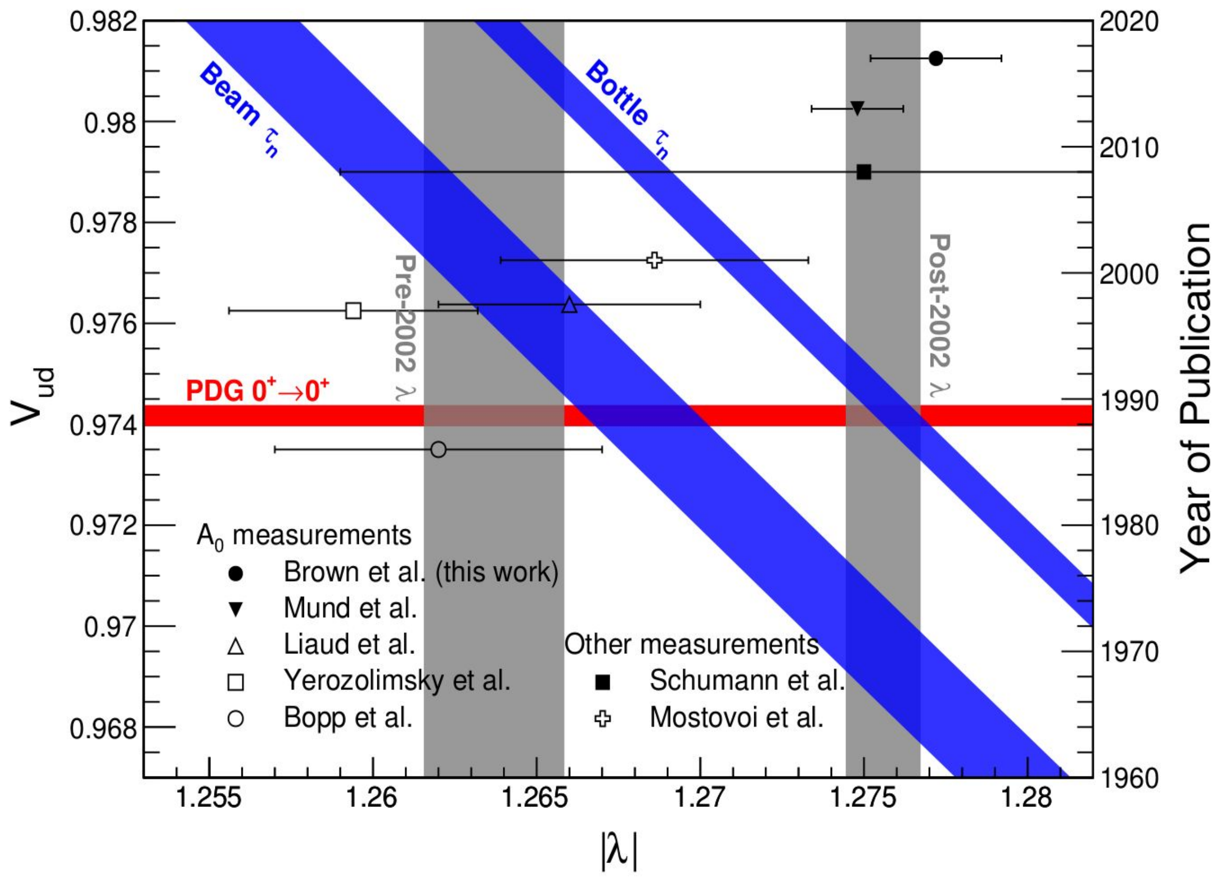
UCN EDM experiments (please don't quote numbers from here…)

Bold means achieved!	RAL SUSSEX ILL (Grenoble, FR)	PSI (Villigen, CH)		PanEDM TUM ILL (Grenoble, FR ⇒ Munich, DE)		LANL EDM (Los Alamos, US)	SNS EDM (Oakridge, US)	PNPI ILL (Grenoble, FR ⇒ Gatchina, RU)		TUCAN TRIUMF (Vancouver, CA)
temperature	**RT**	**RT**		RT	RT (cryo)	RT	0.7 K	**RT**		RT
comag	**Hg**	**Hg**		none			^{3}He	**none**		Hg
source	**reactor, turbine**	**spall., sD$_2$**		reactor, cold neutrons, ^{4}He		D2	spall, internal ^{4}He	reactor, turbine, ^{4}He		spall., ^{4}He
nr of cells	**1**	**1**	2	2			2	2	>2	2
Cell size [l]	**20**	**20**	2 x 75	2 x 17		2 x 20	2 x 3.2	**2 x 20?**		2 x 31
[UCN/cc] at T=0	**2**	**3**	5	4	40	40	125	**4**	10^4	233
goal [e·cm]	**$3\cdot10^{-26}$**	**$1.8\cdot10^{-26}$**	$1\cdot10^{-27}$	$4\cdot10^{-27}$	$8\cdot10^{-28}$	$1\cdot10^{-27}$	$2\text{-}5\cdot10^{-28}$	**$5\cdot10^{-26}$**	$5\cdot10^{-28}$	$1.7\cdot10^{-27}$
date	**2006**	**2020**	2020	2019	?	2021	2023	**2015**	202?	2024
status	**done!**	**done!**	Big infrastructure installed.	modifications for Munich ⇒ ILL, D$_2$ ⇒ He		Magnetic shield isntalled, UCN storage tested.	Critical Component Demonstration passed	PNPI source components ready, reactor offline.		Component development phase
comment	**Best limit so far!**	More UCN density expected from source, compensating with cell size.		regulatory issues for UCN source in Munich ⇒ ILL for now			great new concept, high risk, high gain	Very promising UCN source design.		Best nEDM experiment in Canada!

Beta decay puzzle continued



GRS results and impact

Chameleons

dark energy candidates

$$V_{\rm eff} = V(\Phi, n) + e^{\beta\Phi/M'_{\rm Pl}}\rho.$$

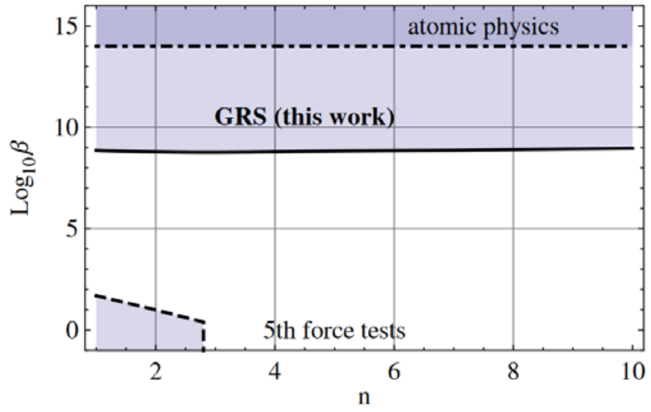


FIG. 3 (color online). Exclusion plot for chameleon fields (95% confidence level). Our newly derived limits (solid line) are 5 orders of magnitude lower than the upper bound from precision tests of atomic spectra (dot-dashed line) [27]. Pendulum experiments [28] provide a lower bound (dashed line).

Axions

dark matter candidates

$$V(\vec{r}) = \hbar^2 g_s g_p \frac{\vec{\sigma}\cdot\vec{r}}{8\pi m_M r}\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda}.$$

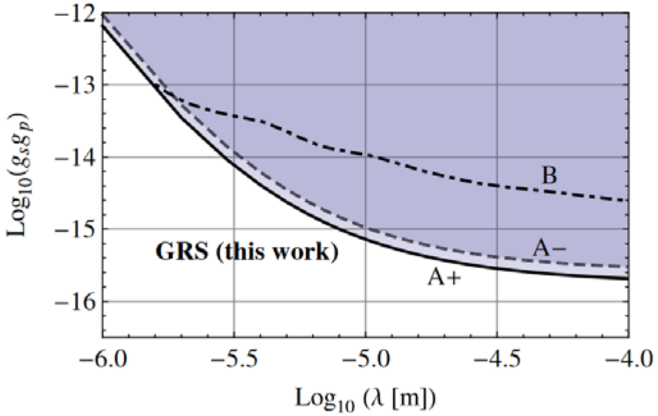


FIG. 4 (color online). Limits on the pseudoscalar coupling of axions (95% confidence level). Our limit for a repulsive (attractive) coupling is shown in a solid (dashed) line marked with A + (A−). The limits are a factor of 30 more precise than the previous ones derived from a direct measurement at the micron length scale [29] derived from our previous experiment with UCN marked B [13,14].