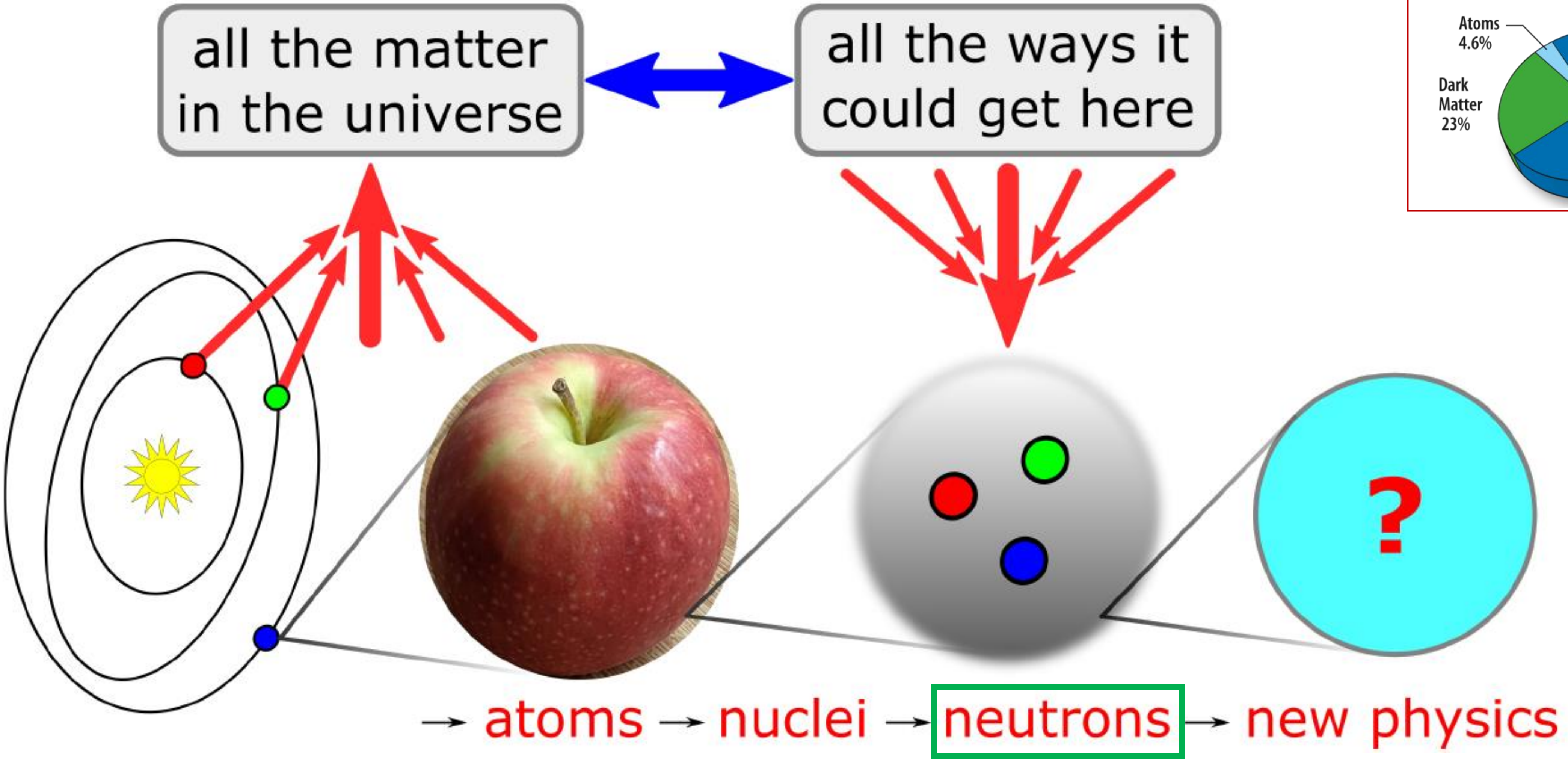
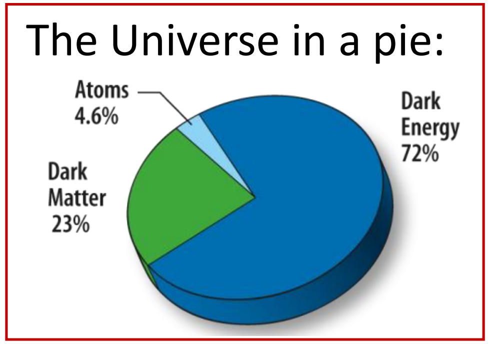
Updates on the PanEDM experiment and future outlook

Neutron Electric Dipole Moment: from theory to experiment
ECT* Trento, 05.08.2022

Skyler Degenkolb
Physikalisches Institut, Universität Heidelberg

Motivation, and a sense of scale





Un-natural Units (orders of magnitude)

$$10^{-26} e \text{ cm} \times \frac{1 \text{ MV}}{m} \times \frac{1}{2\pi\hbar} = 24 \text{ nHz}$$

$$\frac{1}{24 \text{ hours}} = 11.6 \ \mu\text{Hz}$$

$$\frac{1}{15 \text{ min}} = 1 \text{ mHz}$$

$$\mu_{\text{N}} \times \frac{1 \mu\text{T}}{2\pi\hbar} = 8 \text{ Hz}$$

$$\mu_{\text{B}} \times \frac{1 \mu\text{T}}{2\pi\hbar} = 14 \text{ kHz}$$

$$1 \ e \text{ cm} = 10^{13} e \text{ fm}$$

$$1 \text{ neV} = 1 \frac{\text{GeV}}{c^2} \times 1 \text{ cm} \times g$$

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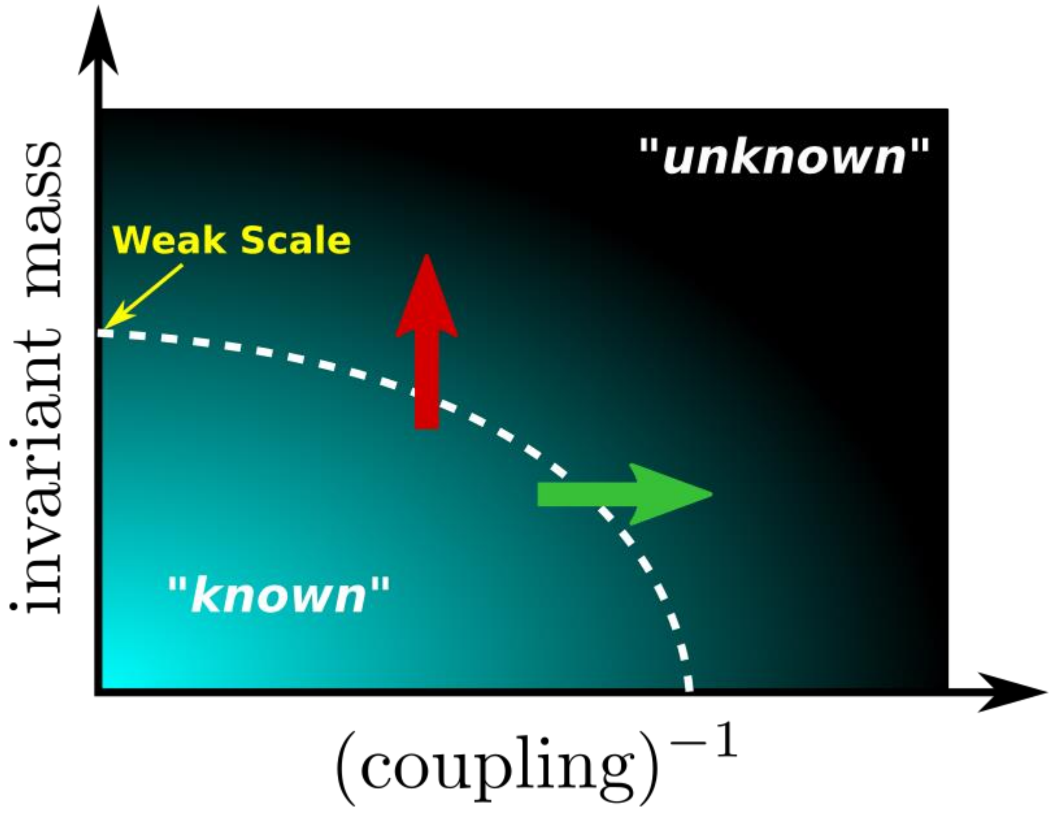
Terminology for Slow Neutron Spectra

Velocity	"Temperature"	Energy
$10^0 – 10^1$ m/s	Ultracold	5 neV – 500 neV
$10^1 – 10^2$ m/s	Very cold	0.5 μeV – 50 μeV
$10^2 – 10^3$ m/s	Cold	50 μeV – 5 meV
2.2×10^3 m/s	Thermal	25 meV
$2\times10^3 – 2\times10^4$ m/s	Hot	20 meV – 2 eV

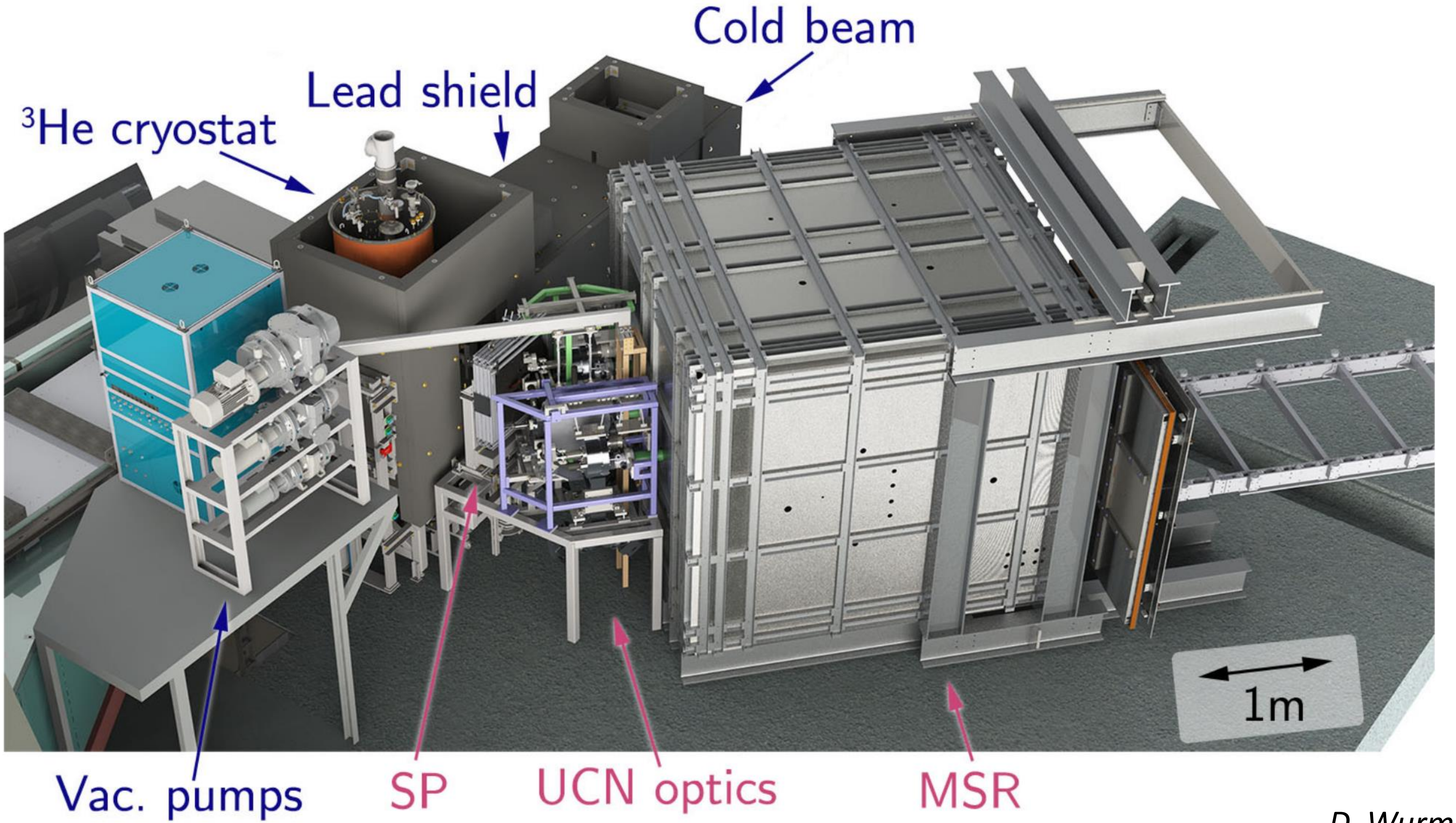
Agenda



1. The PanEDM experiment
2. Comagnetometry (or not)
3. How can we improve statistics?

1

The PanEDM Experiment



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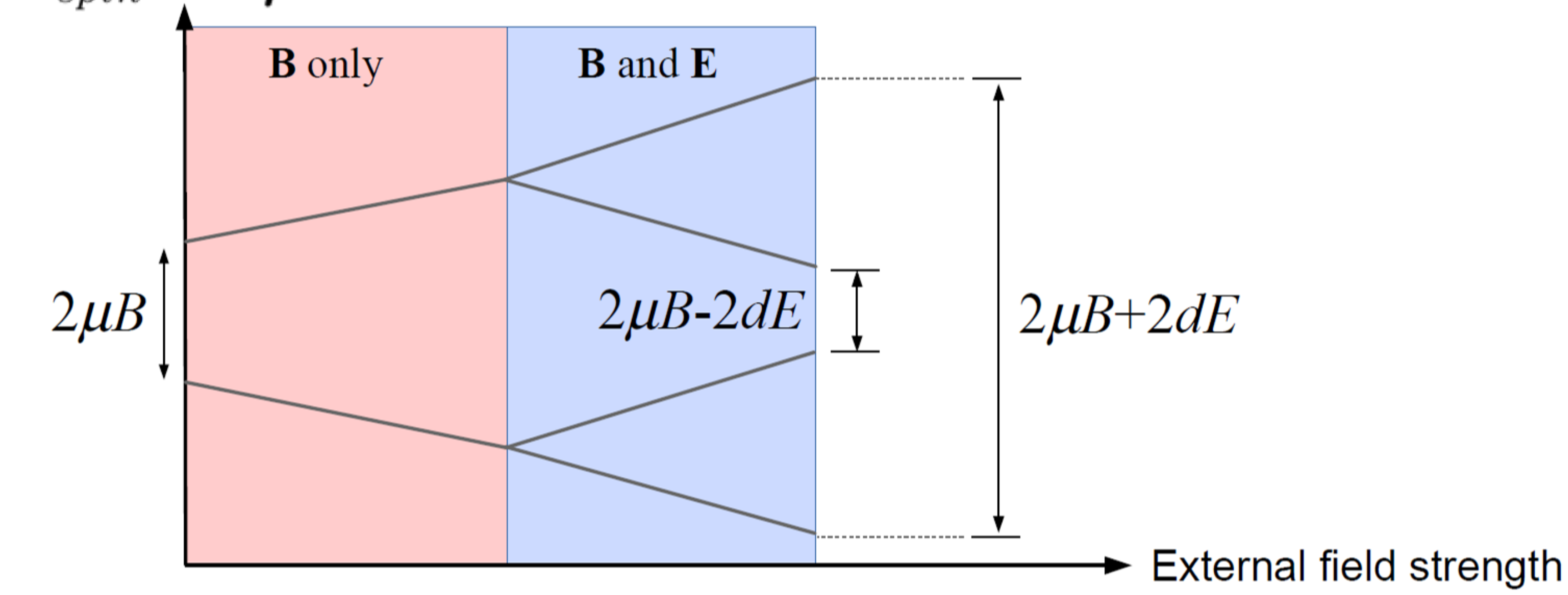
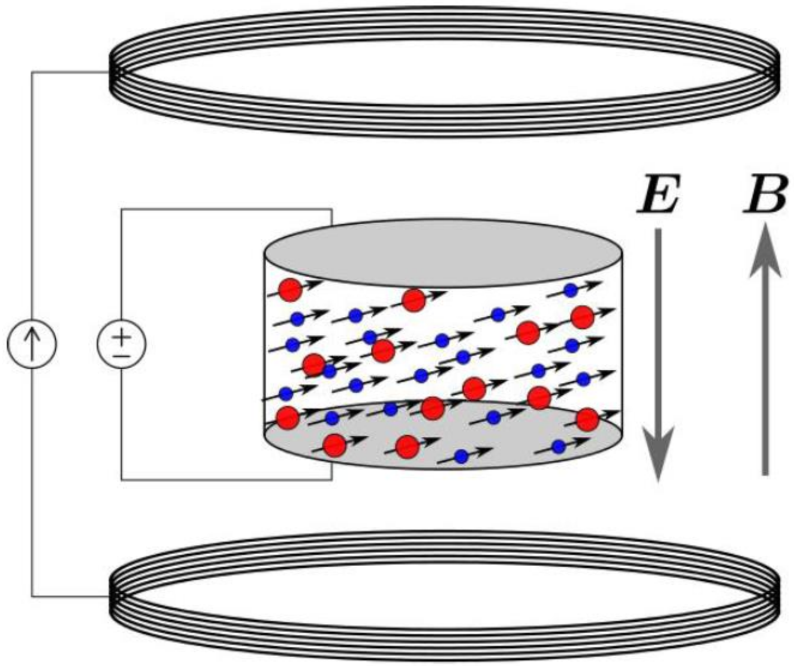
2

Comagnetometry

$$H_{spin} = -\boldsymbol{\mu} \cdot \mathbf{B} - \mathbf{d} \cdot \mathbf{E}$$





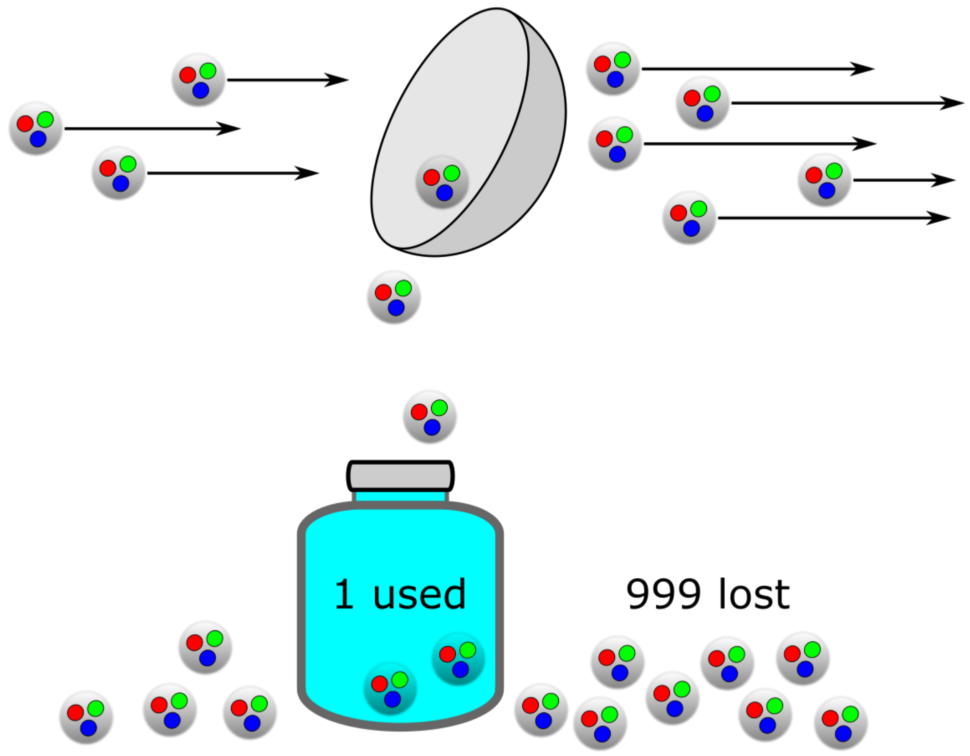
$$\hbar(\omega_+ - \omega_-) = 4dE$$

...up to drift, gradients, etc.

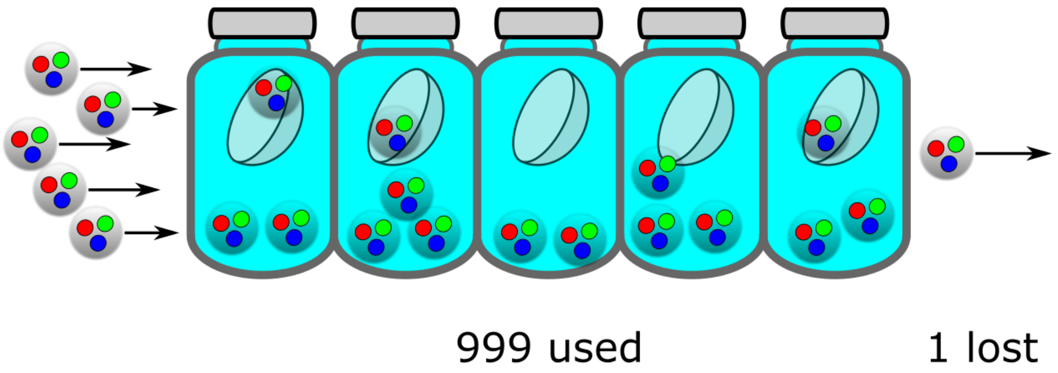
3

Statistics: our biggest challenge

State of the art: catch/pour
...with 0.1% success



New approach: catch them **all**, directly in many bottles



Note: scattering and absorption losses will still dominate over UCN production.

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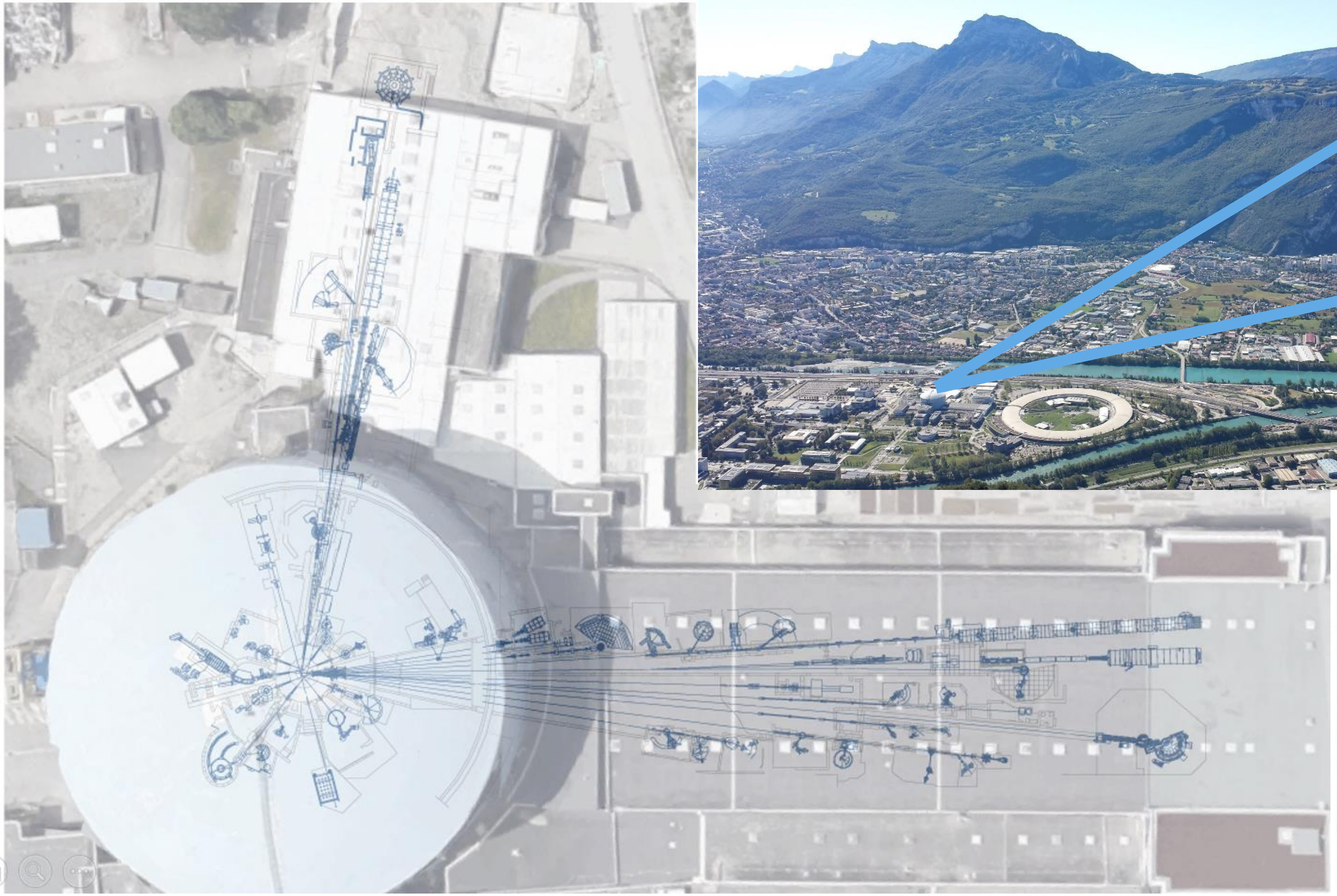

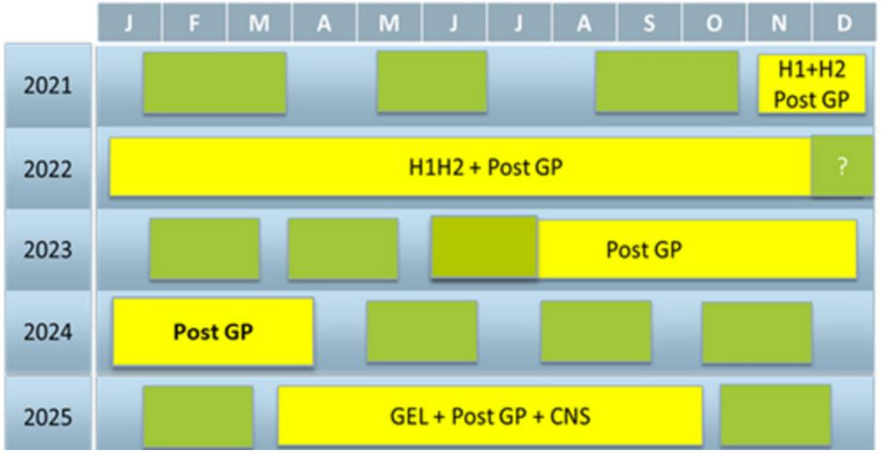

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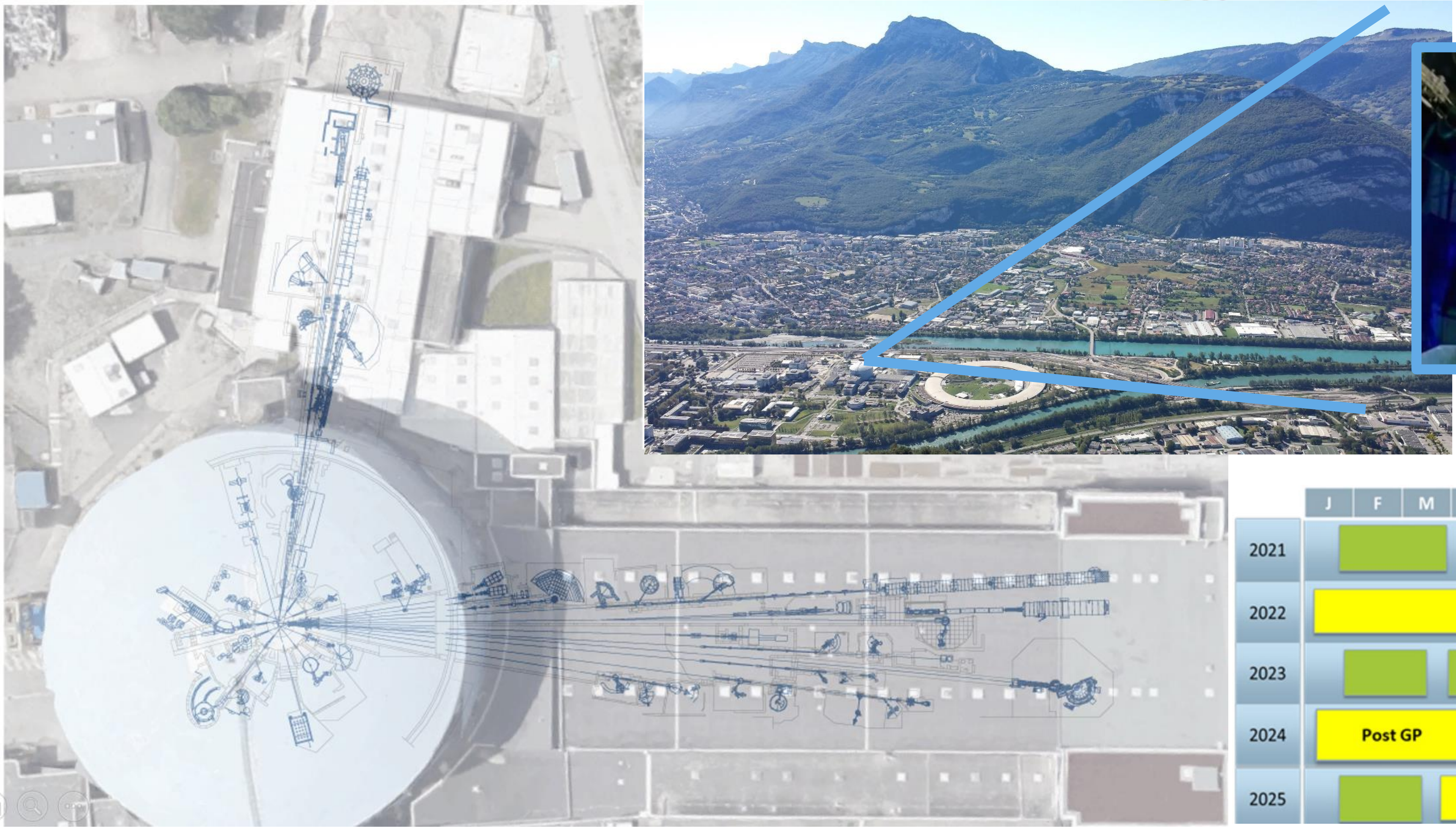
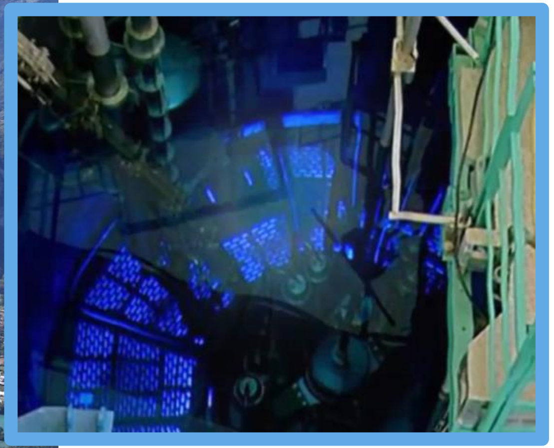
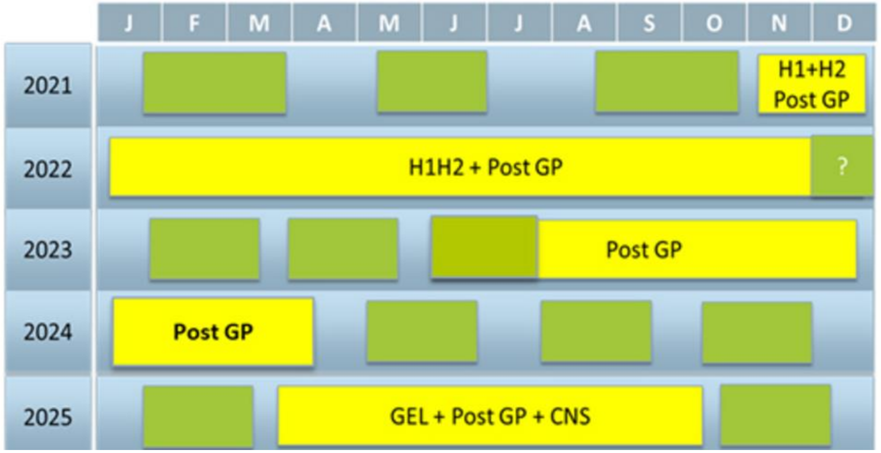
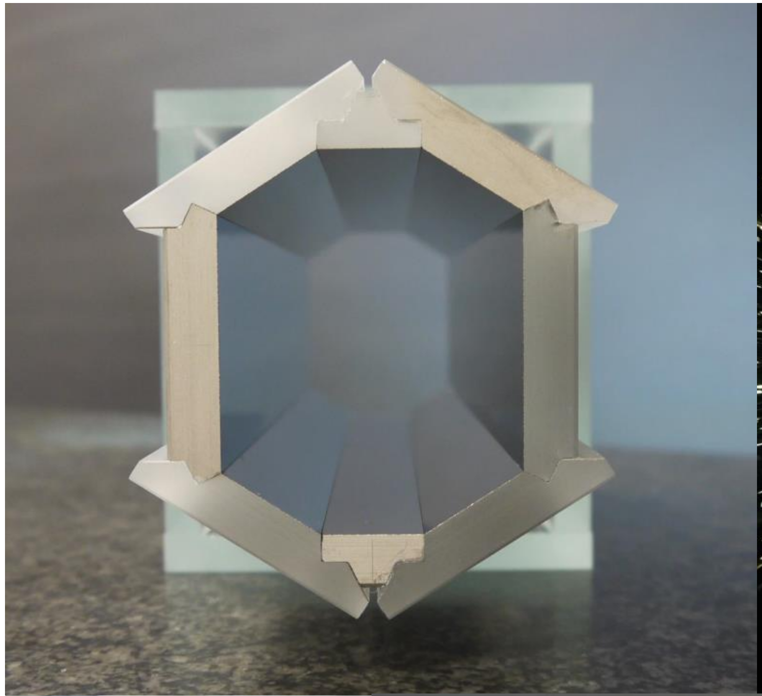
NEUTRONS FOR SOCIETY

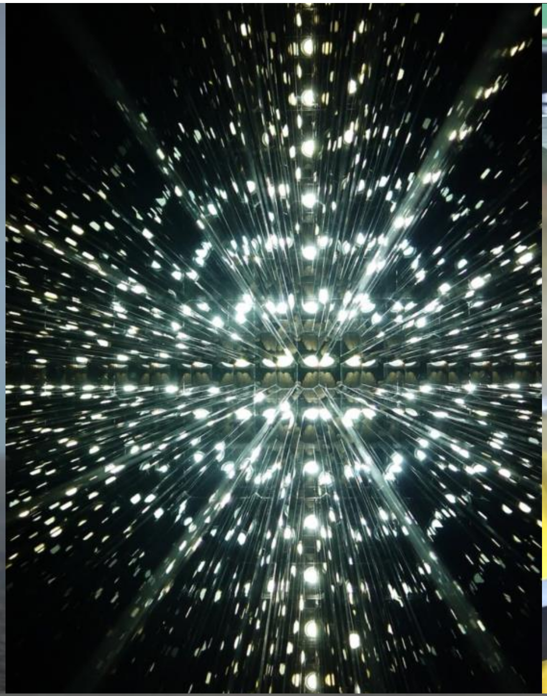


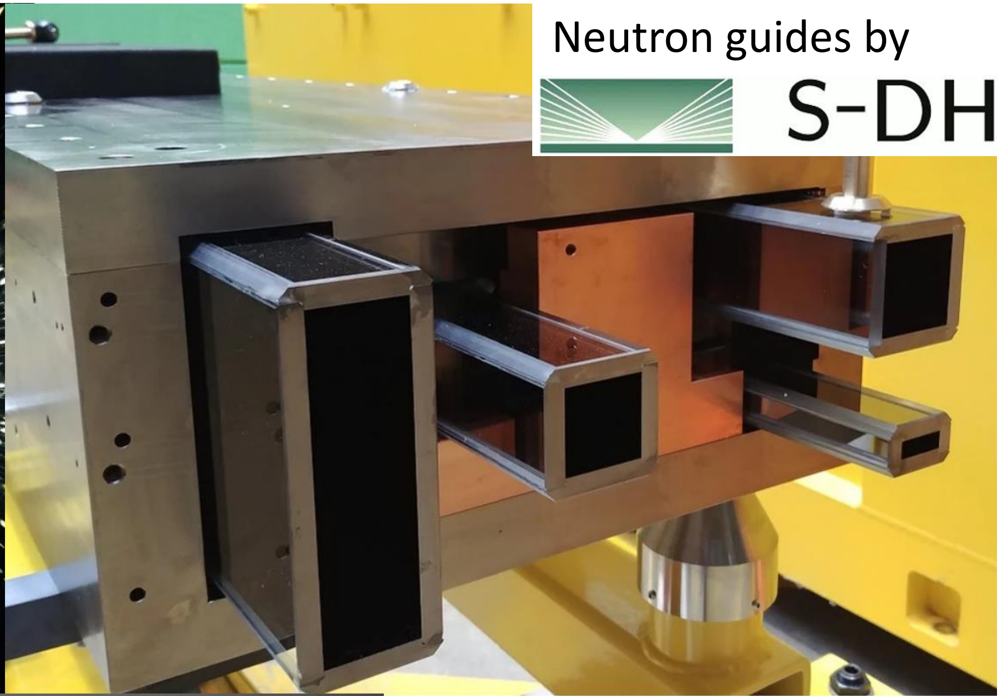




Some Neutron Guides

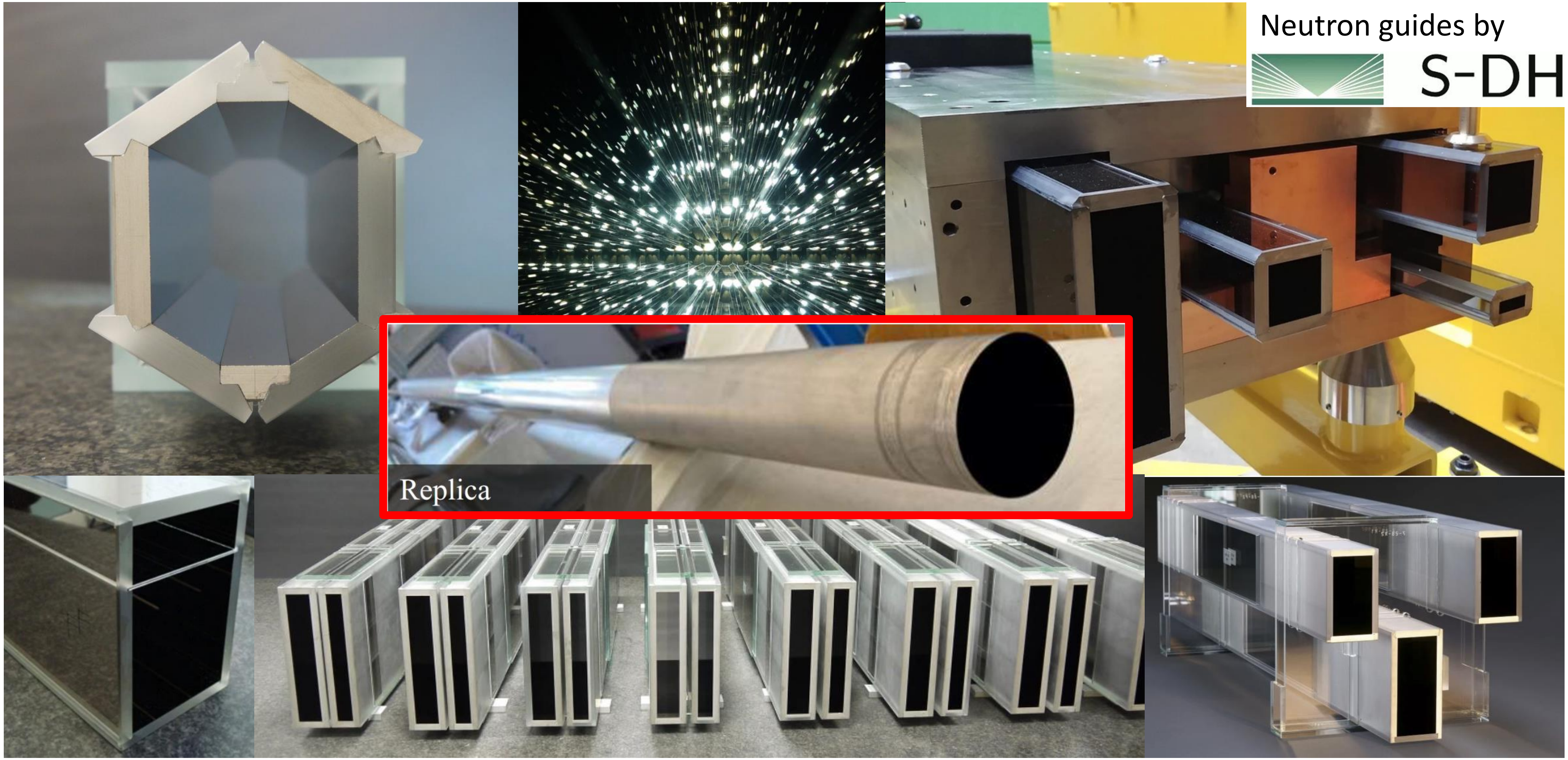






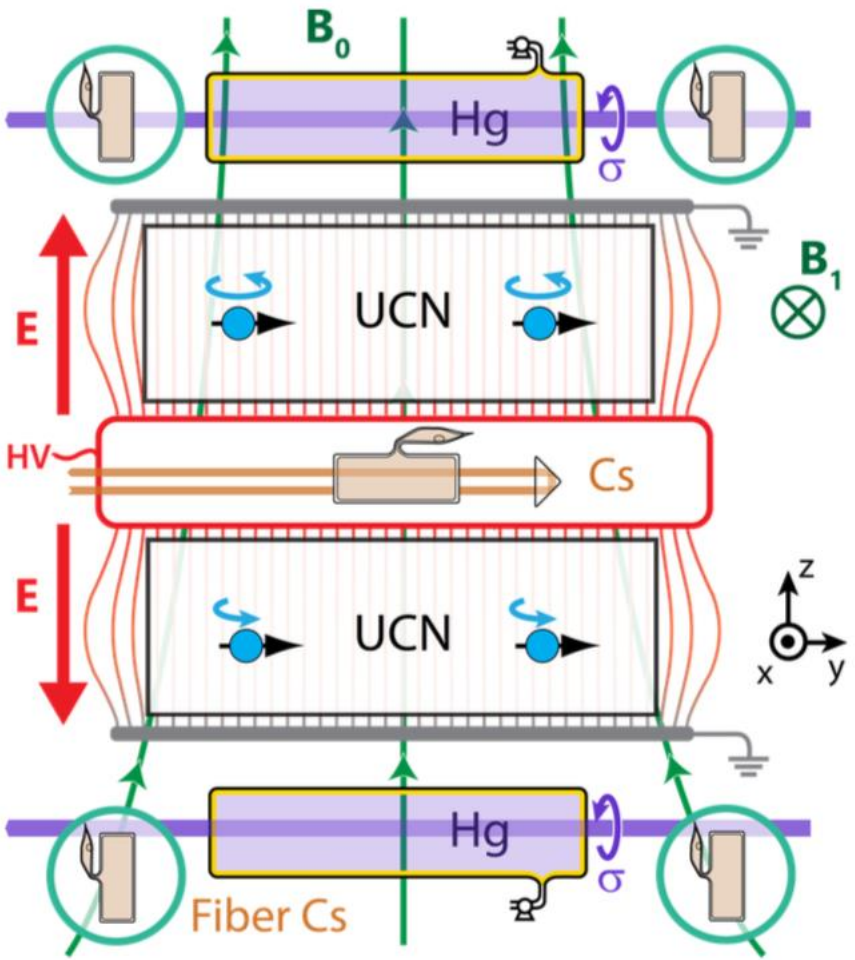
Neutron guides by S-DH

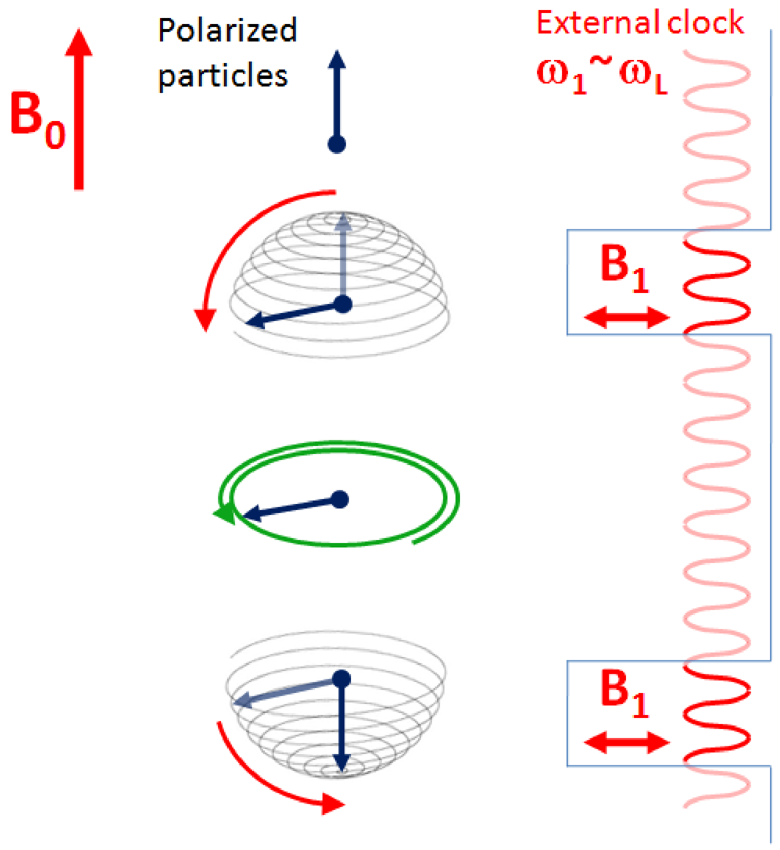
Neutron Guides



1

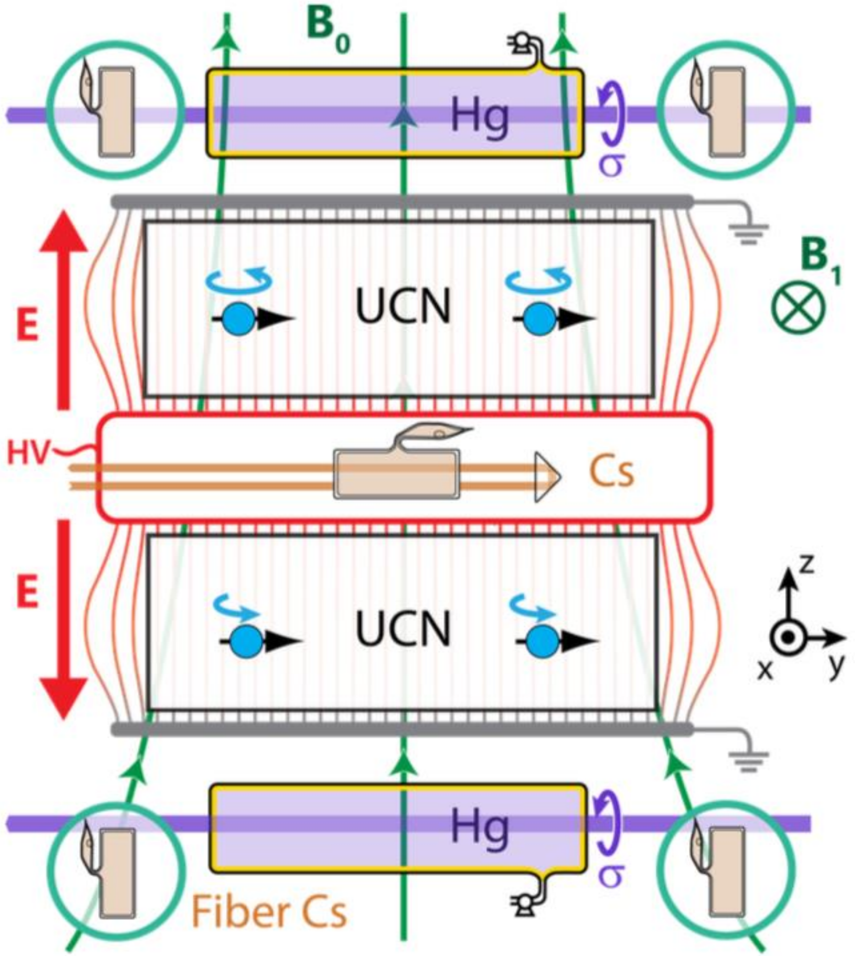
The PanEDM Experiment





EPJ Web of Conferences 219, 02006 (2019)

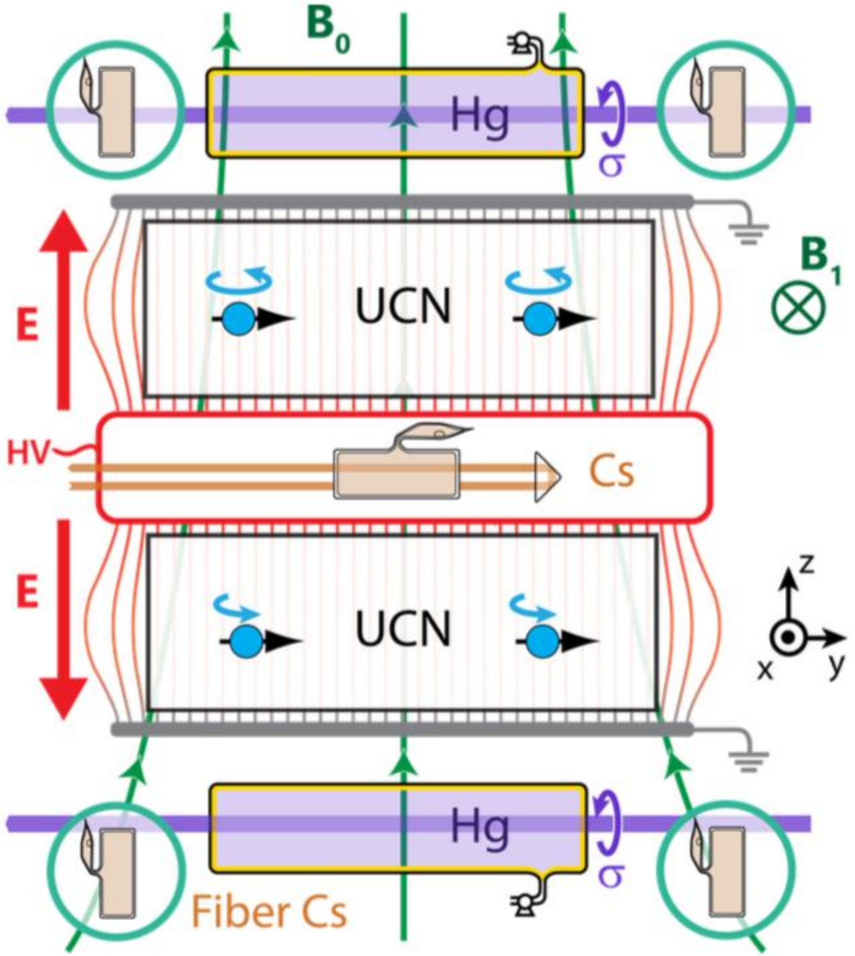
The PanEDM Experiment



- Double chamber Ramsey interferometer at room temperature (but T_{UCN} ~ 5mK)
- ^{199}Hg magnetometers with few-fT resolution
- Cs magnetometers (also at high voltage)
- Magnetic shielding factor: 6×10^6 at mHz
- Simultaneous spin detection for up/down
- SuperSUN UCN source at ILL in 2 phases:
  Phase I: unpolarized UCN with 80 neV peak
  Phase II: polarized UCN, magnetic storage
- Ongoing installation of parts, commissioning with UCN production in 2023-2024

EPJ Web of Conferences 219, 02006 (2019)

Much lower statistics!



Statistical sensitivity:

$$\sigma(d_n) \gtrsim \frac{\hbar}{2\alpha|\mathbf{E}|T\sqrt{N}}$$

Frequency measurement:

$$|\delta\omega| = \frac{|dE|}{\hbar F}$$

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

$$\Delta E \Delta t \geq \hbar/2$$

EPJ Web of Conferences 219, 02006 (2019)

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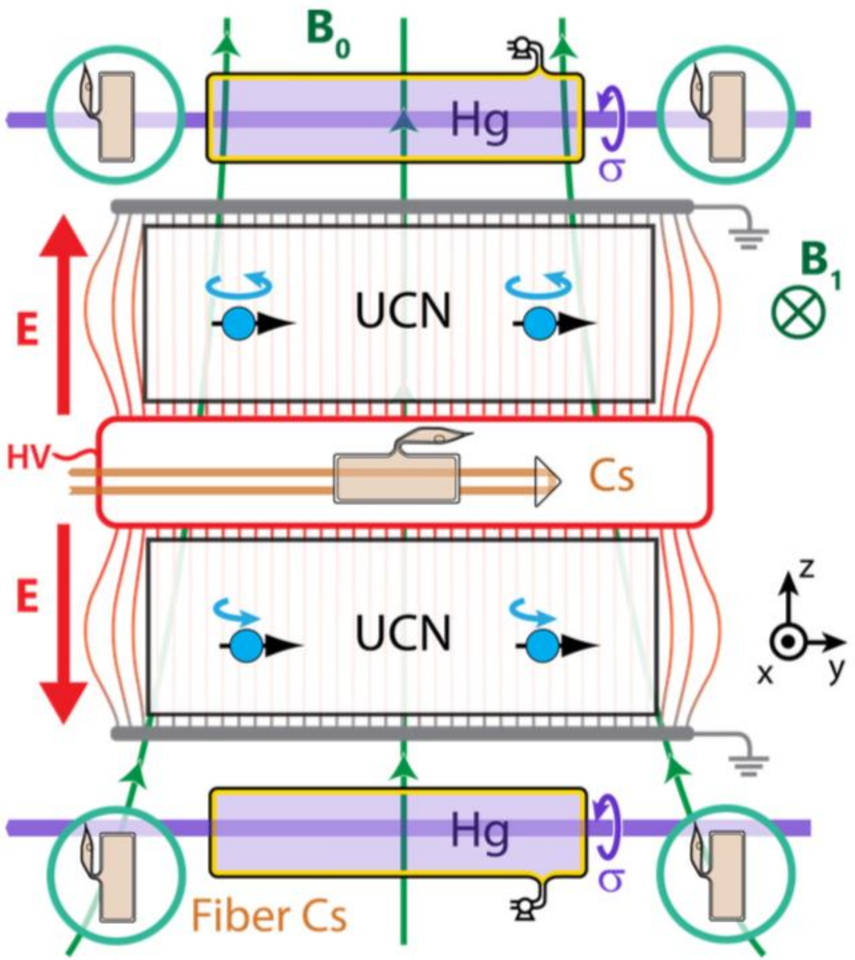

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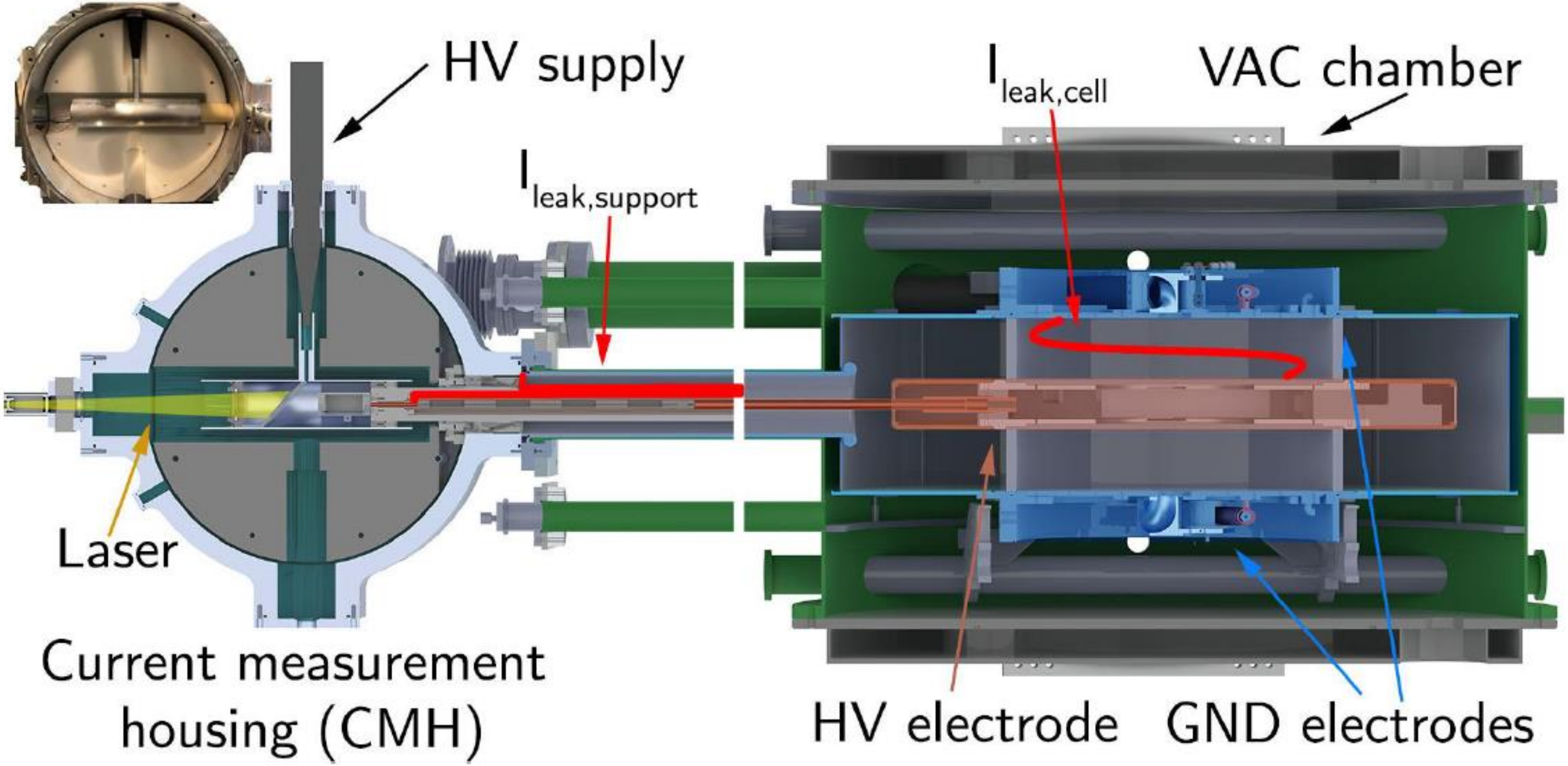
Per 100 days	3.8×10^{-27}

$|\mathbf{E}| \approx 2$ MV/m
$T \approx 250$ s
$\alpha \approx 0.85$

Transfer losses including dilution: 97-99% (for filling)

EPJ Web of Conferences 219, 02006 (2019)

The PanEDM Experiment



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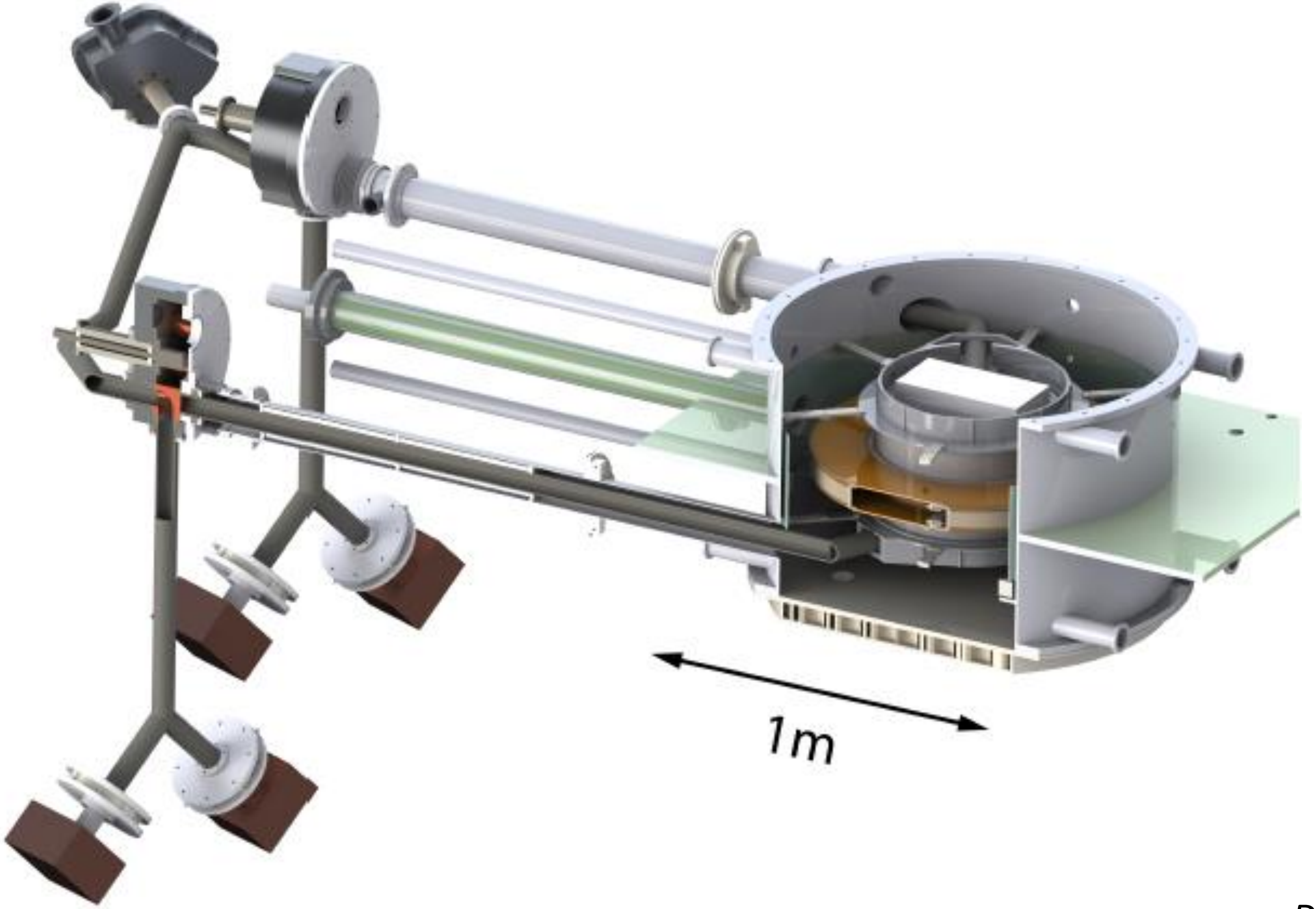
The PanEDM Experiment



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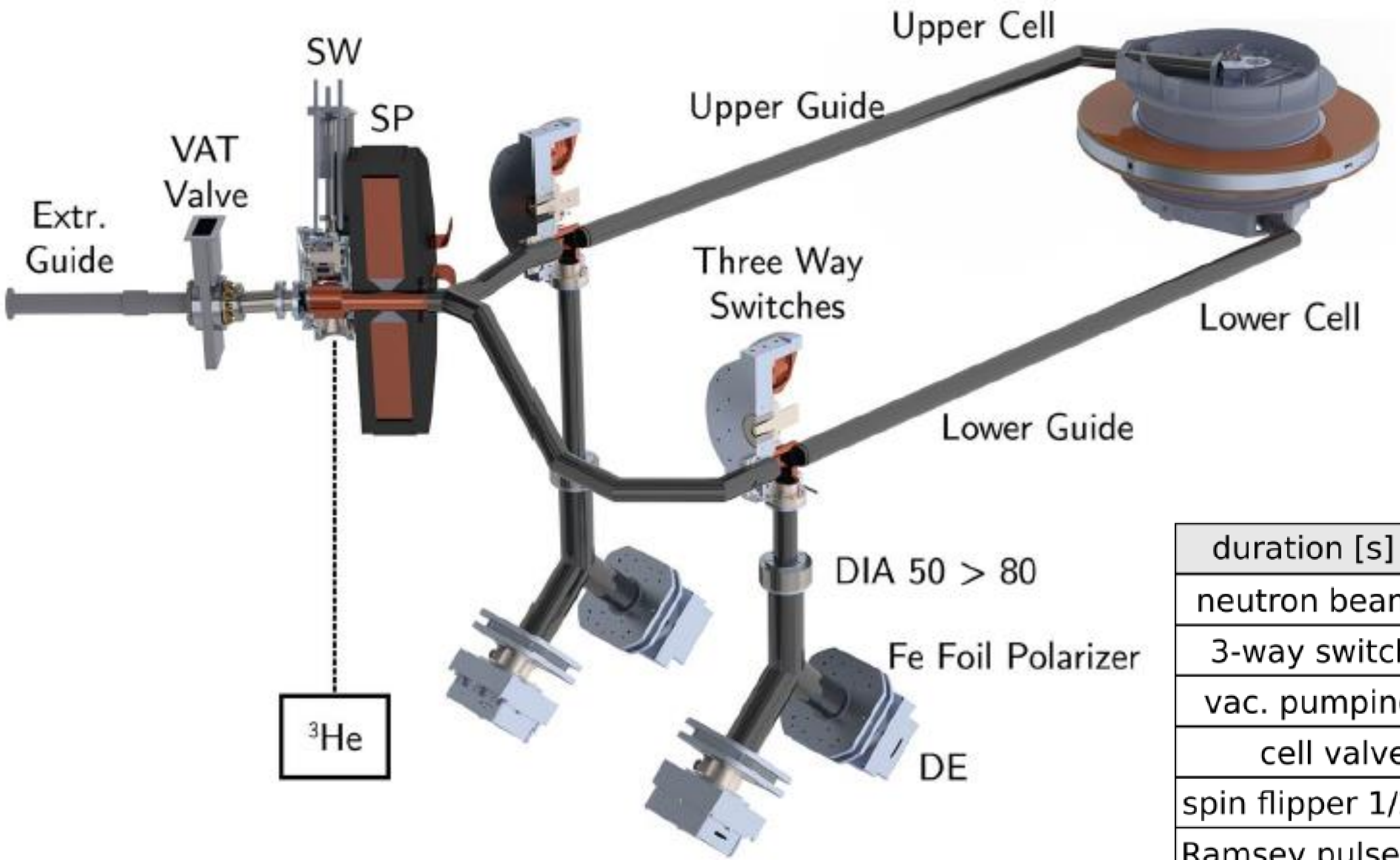

The recipe for an EDM measurement:

	preparation		Ramsey cycle			counting	
duration [s]	30	80	80	110	60	30	50
neutron beam	on	off			on		
3-way switch	vac	fill →	source ↴ detectors		detectors ↲ cells		
vac. pumping	cells		guides				
cell valves	open		closed			open	
spin flipper 1/2			various stability tests			1↑ 2↓	1↓ 2↑
Ramsey pulses			90°	180°	90°		
Hg magnet.		pumping	measure			syst. tests	
UCN detection	background, detector & souce - stability					UCN cnt	
B_0 field	set	measure					
E field	ramp	HV at setpoint					

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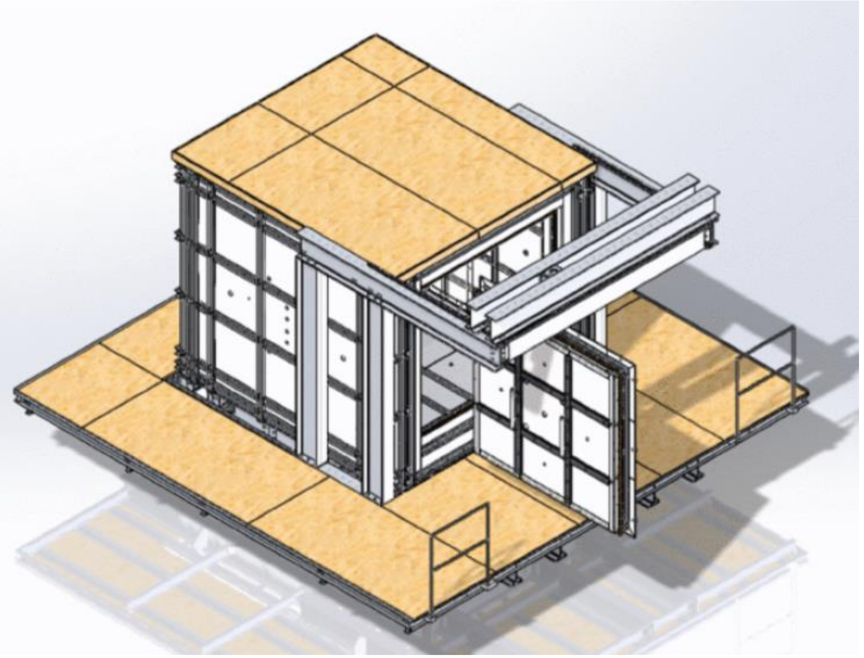
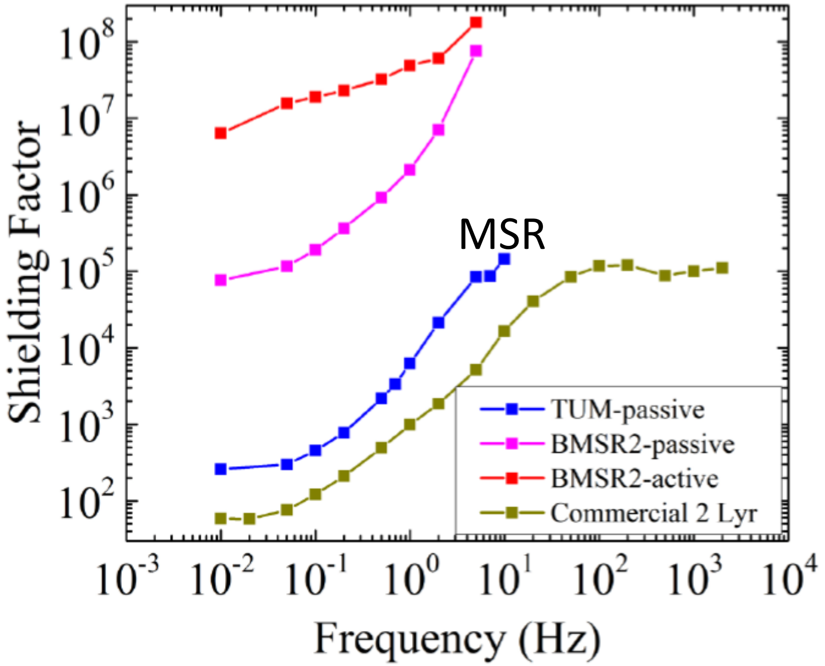
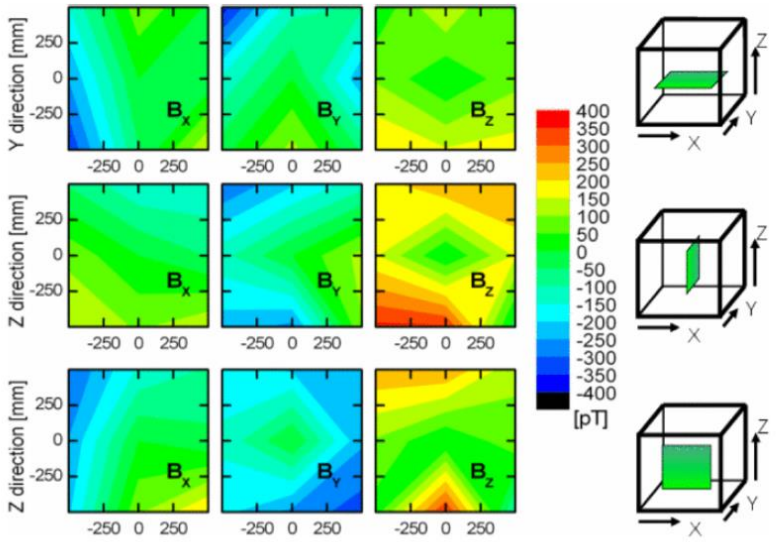
The PanEDM Experiment

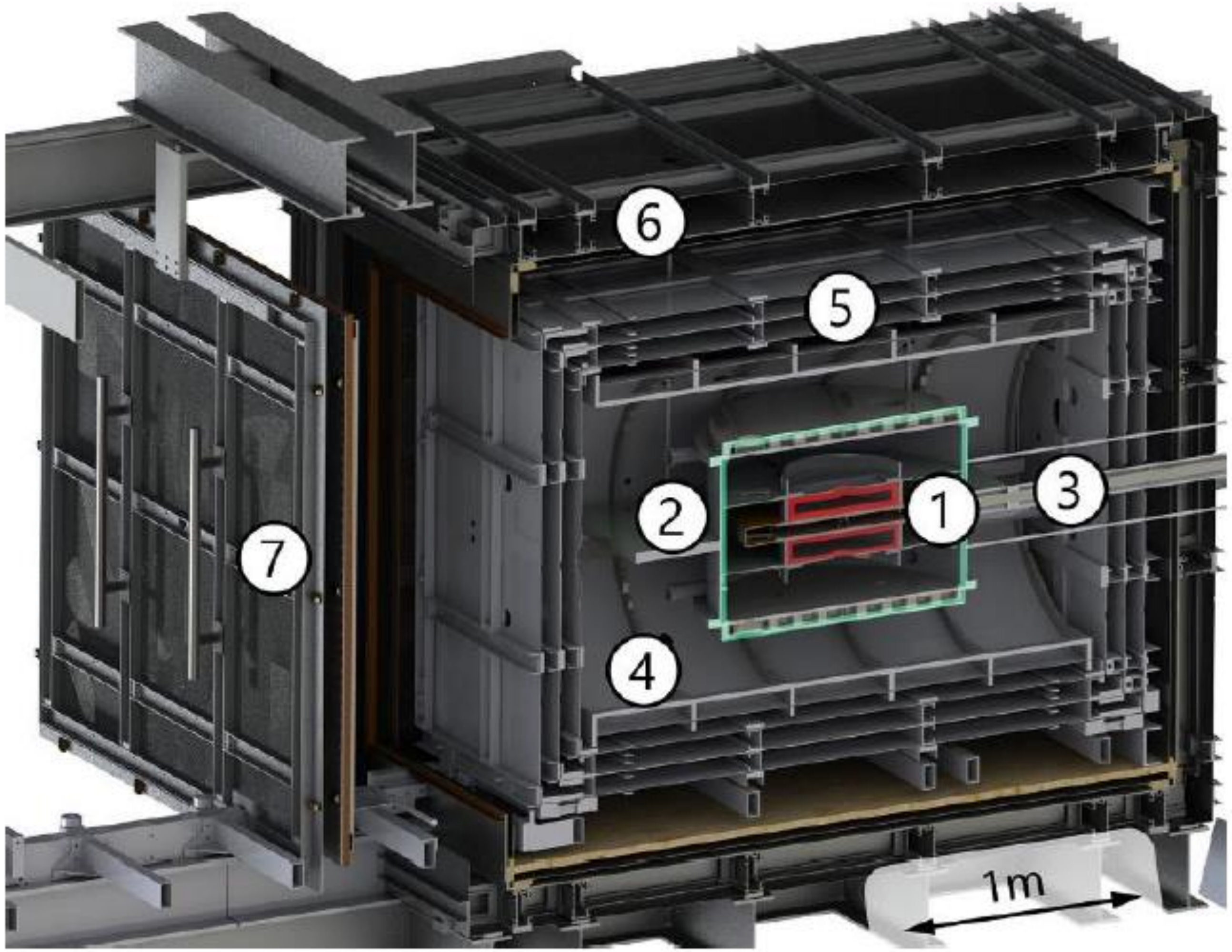






Rev. Sci. Instrum. **85**, 075106 (2014)
J. Appl. Phys. **117**, 183903 (2015)

The PanEDM Experiment

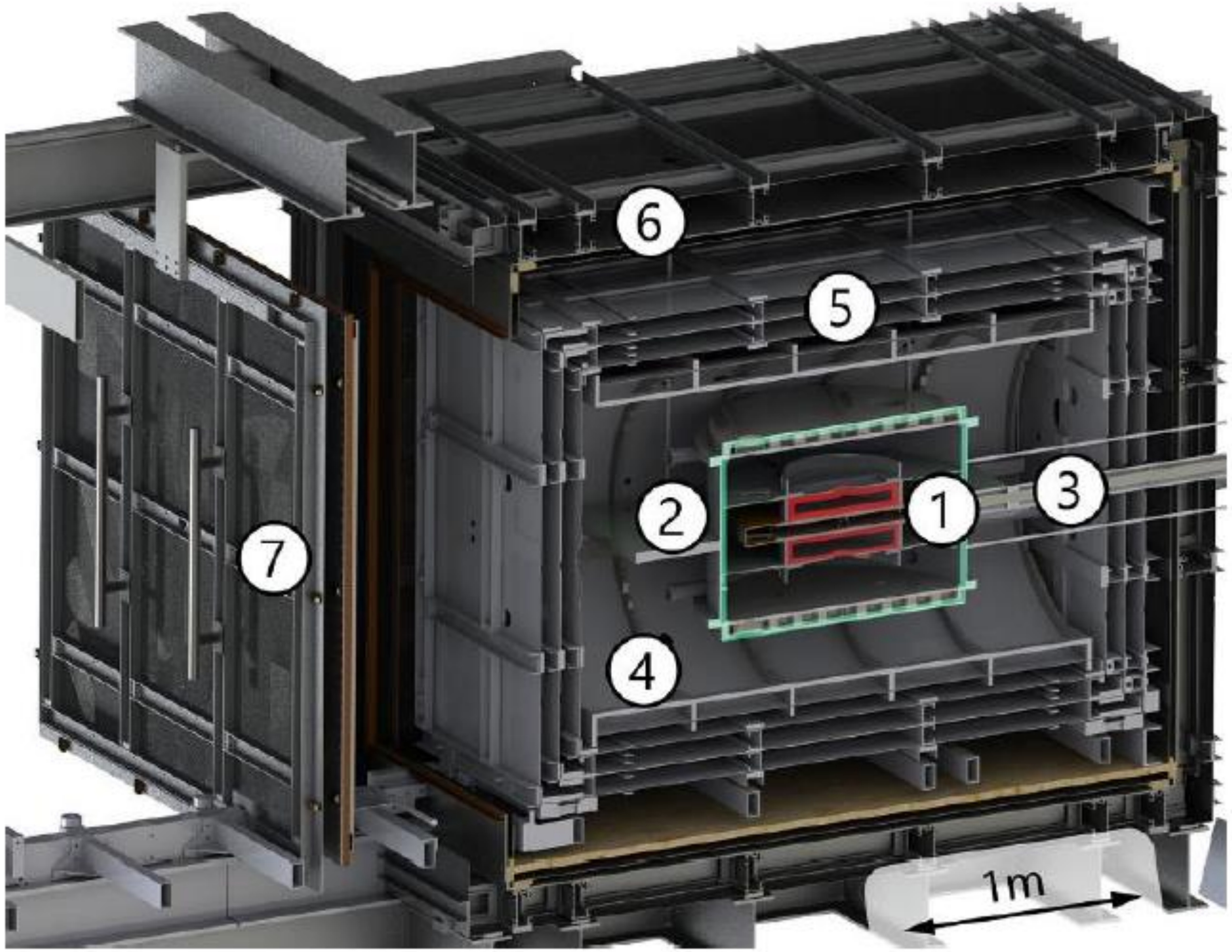


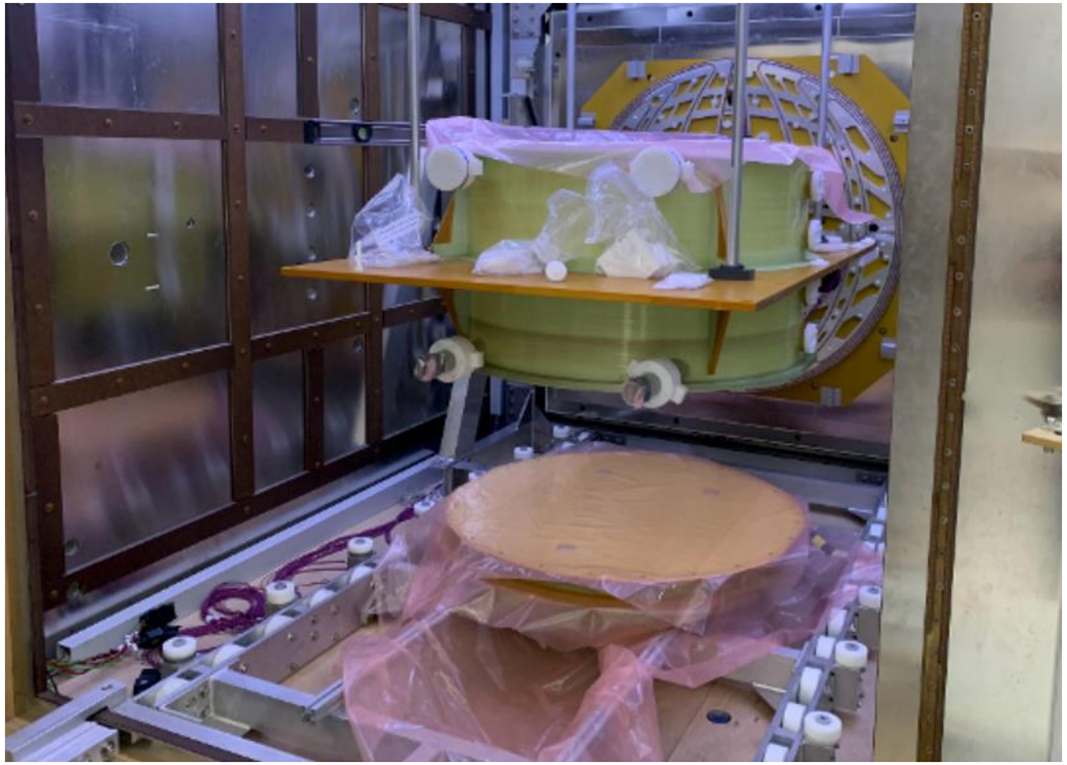
1: EDM cells
2: Vac. Chamber
3: HV feed
4: B_0 & B_1 coil
5: Inner shield
6: Outer shield
7: Outer shield door

PanEDM @ ILL, 2021

EPJ Web of Conferences 219, 02006 (2019)

The PanEDM Experiment

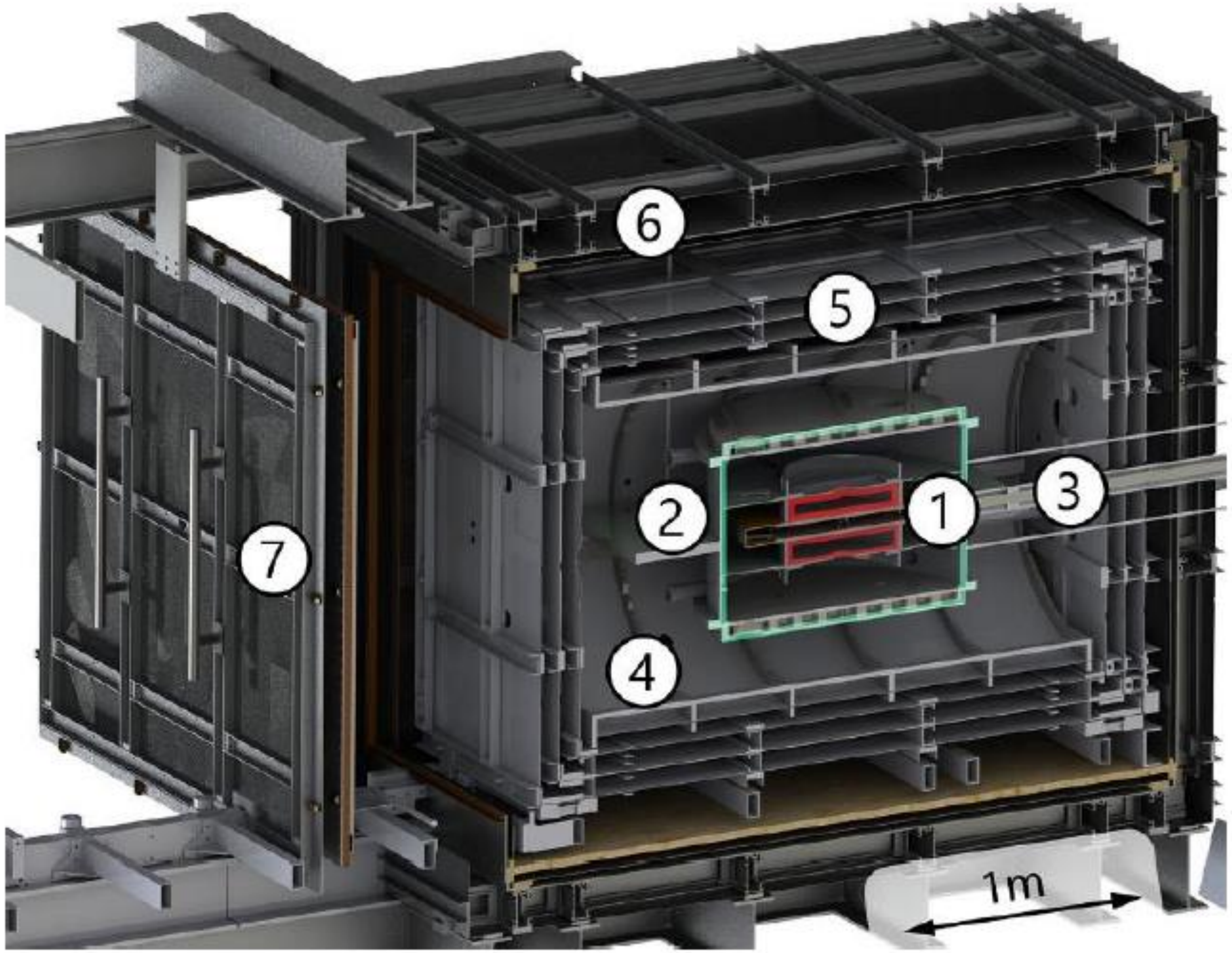




PanEDM @ ILL, 2021

EPJ Web of Conferences 219, 02006 (2019)

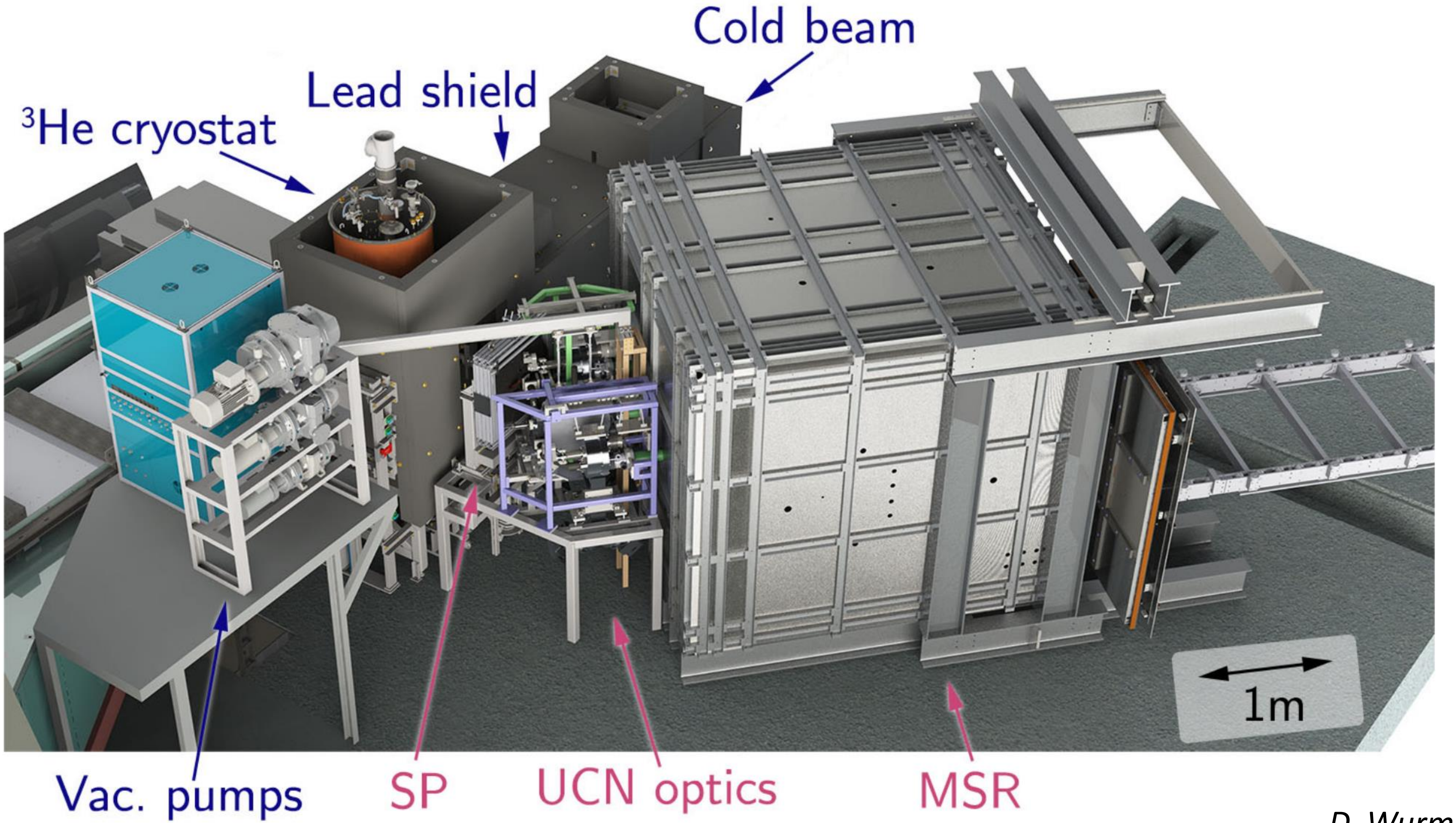
The PanEDM Experiment



Rev. Sci. Inst. 85(7), 075106 (2014)
J. Appl. Phys. 117(18), 183903 (2015)

EPJ Web of Conferences 219, 02006 (2019)

The SuperSUN-PanEDM Installation



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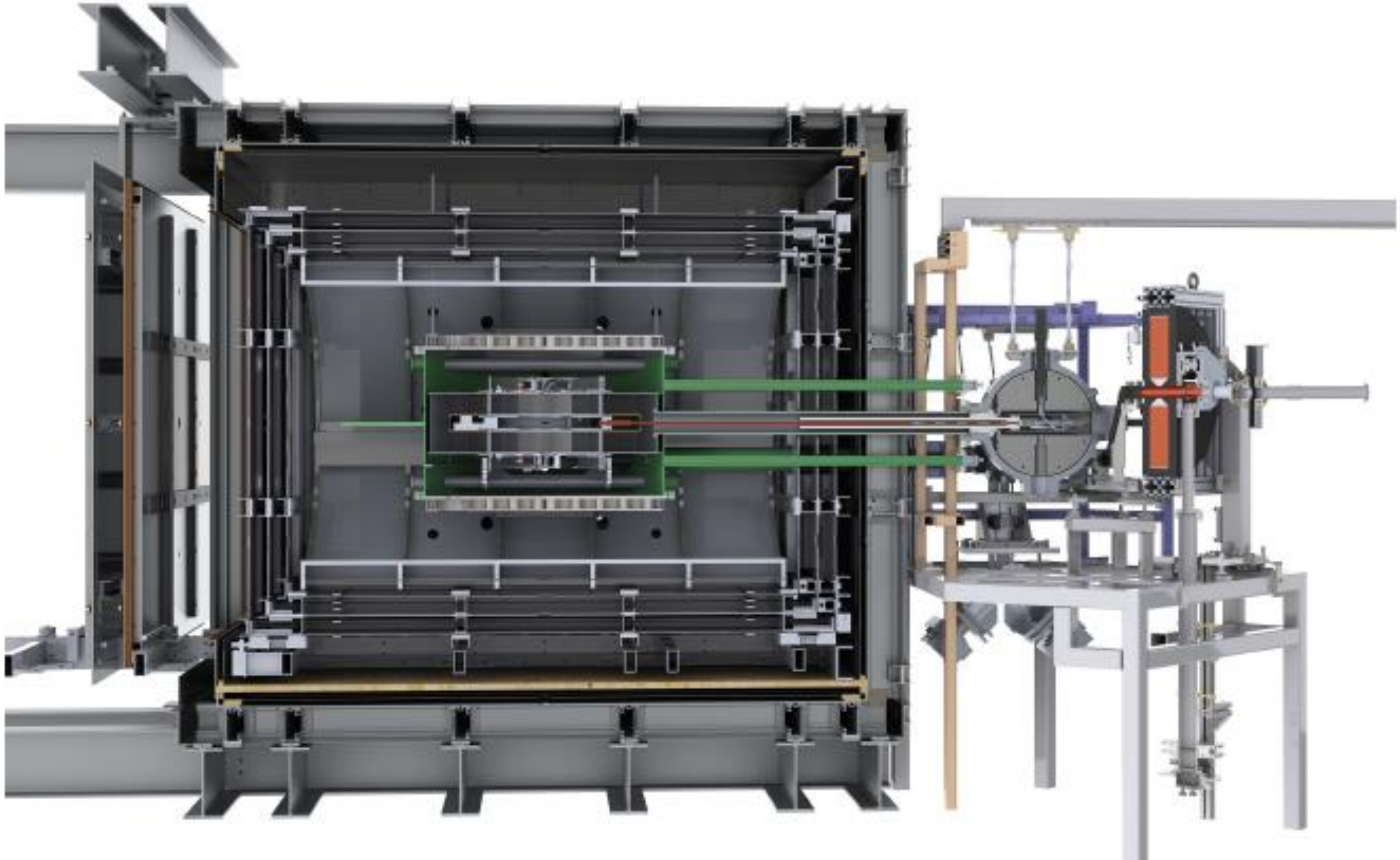

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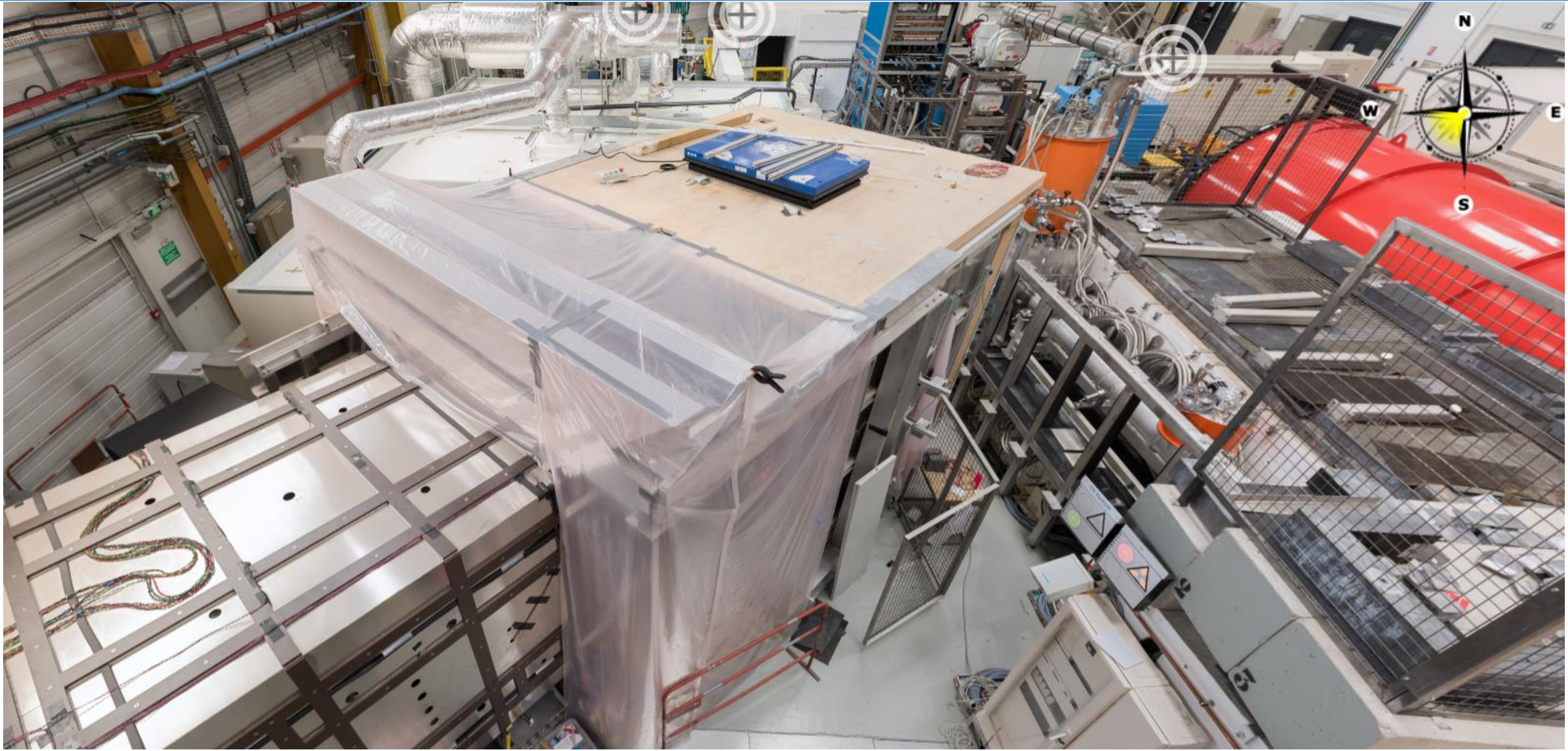
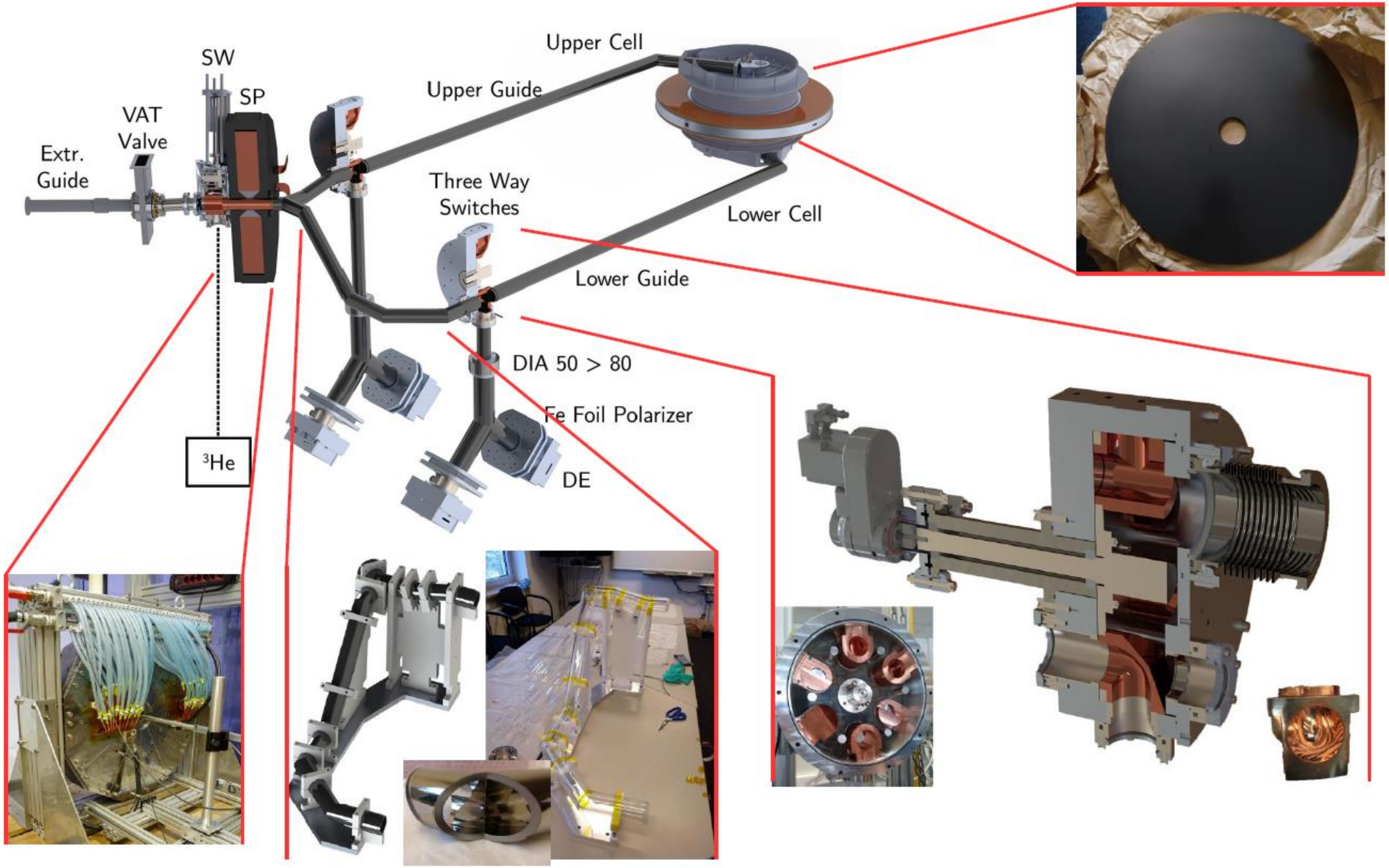
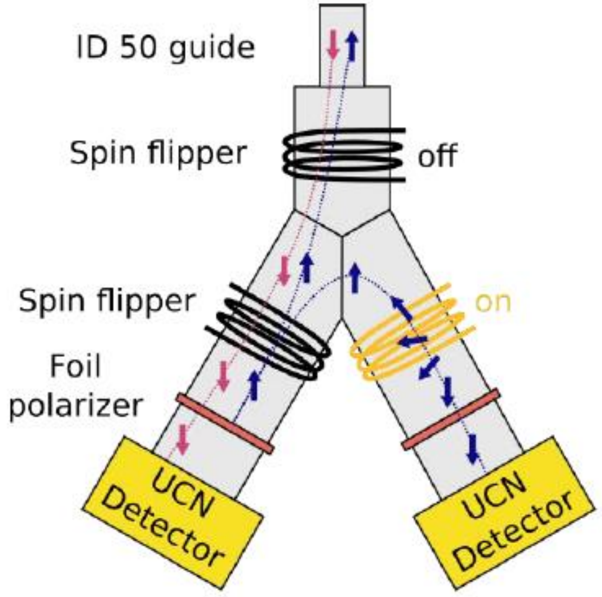
Reality always looks messier!



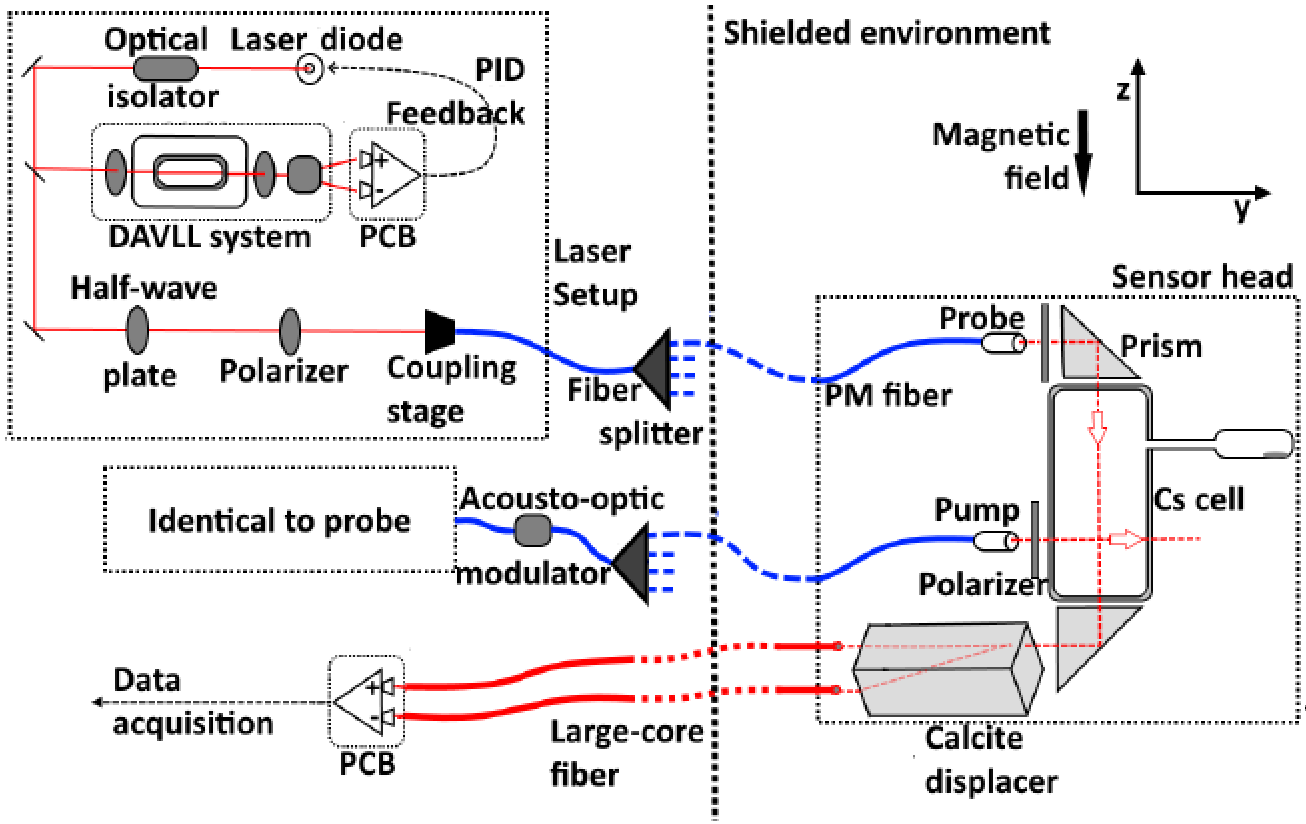
SuperSUN-PanEDM Interface

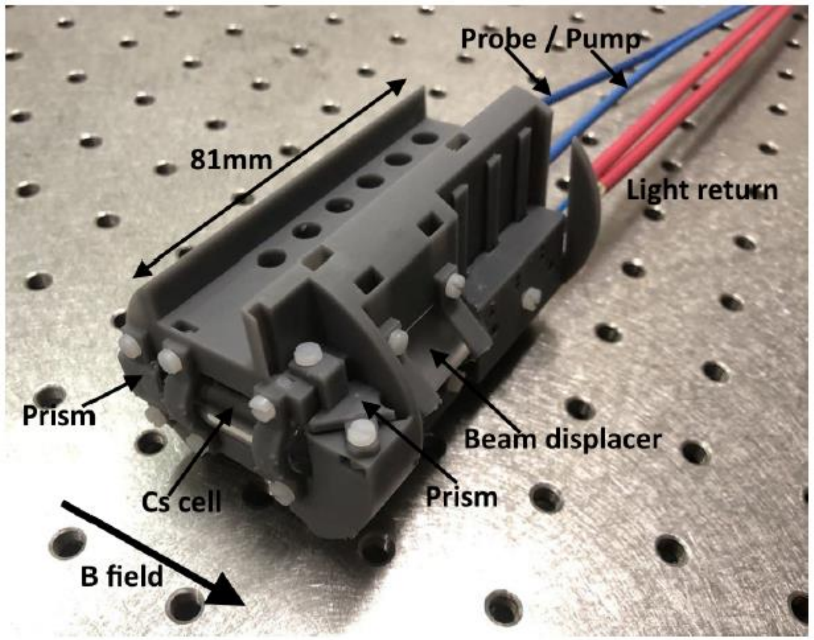


Simultaneous spin detection



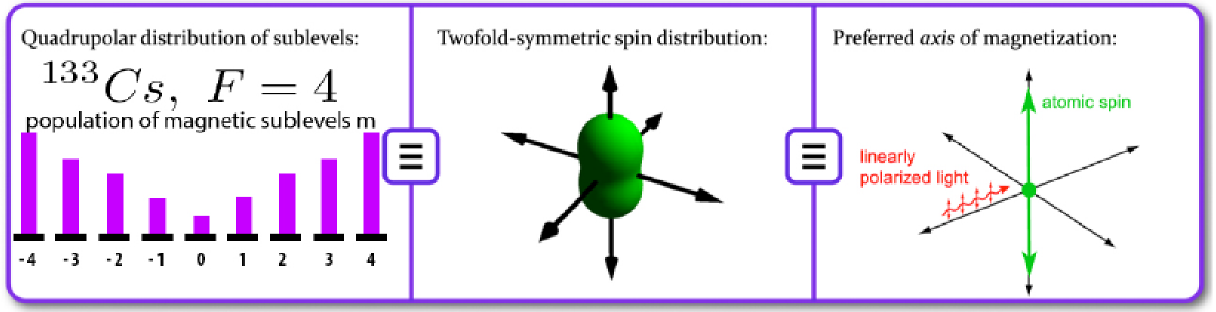
Cesium Magnetometry

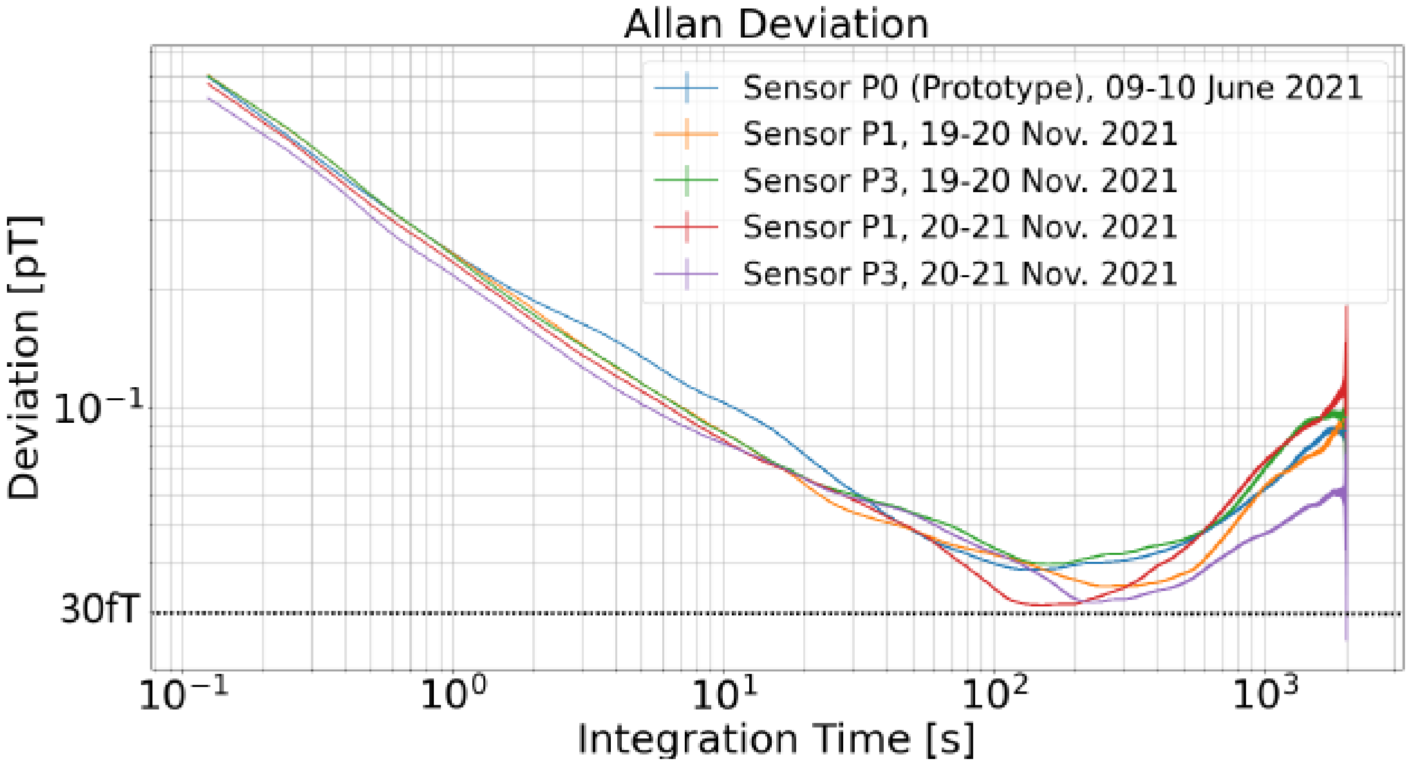


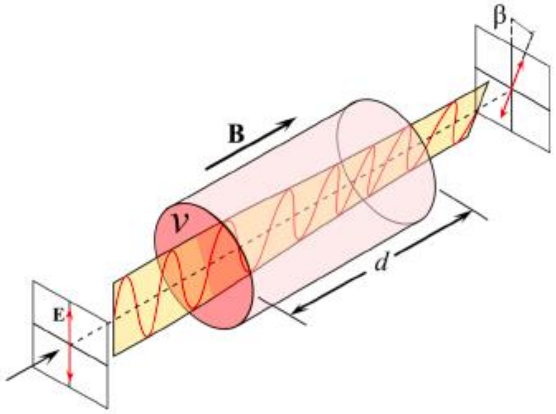


Appl. Phys. Lett. 120, 161102 (2022)

Cesium Magnetometry



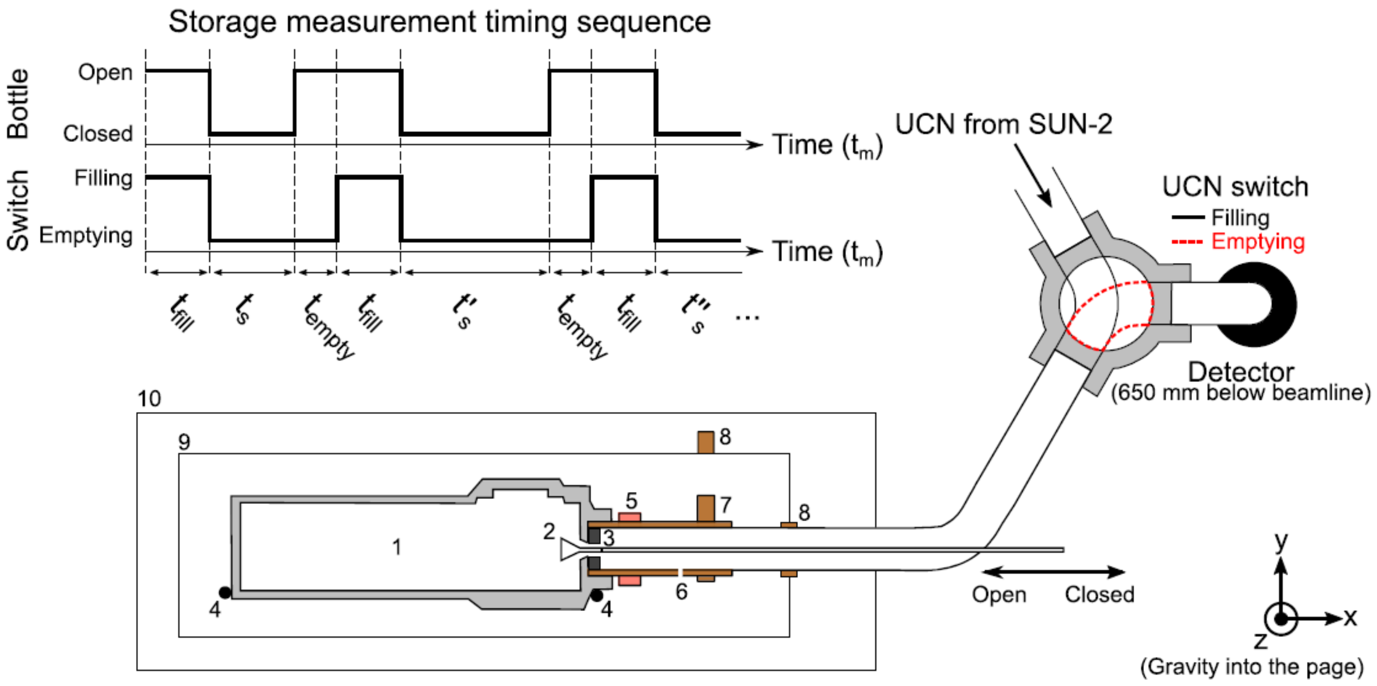


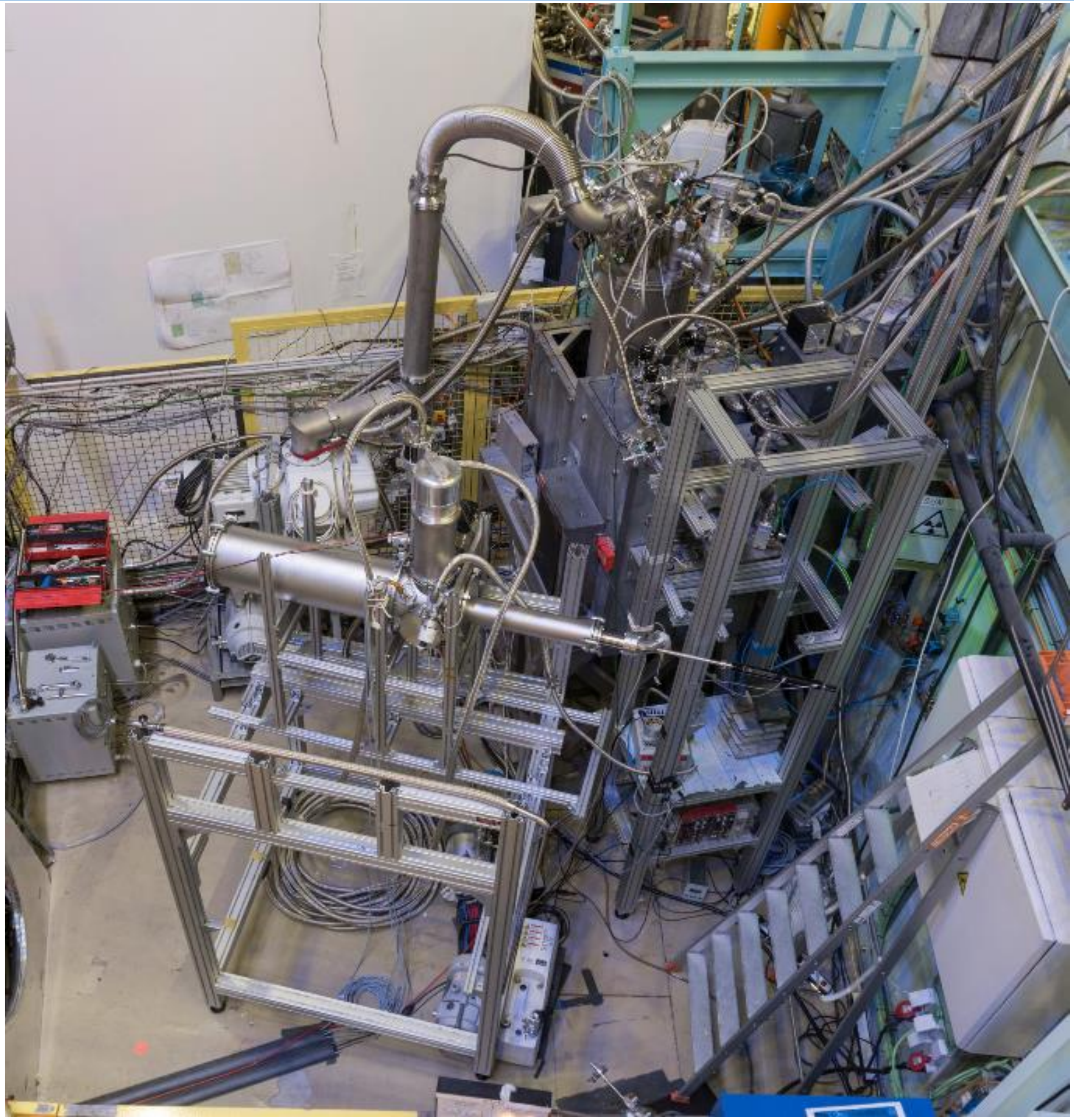


- Stable below 50 fT, between 70 - 600 seconds integration
- Residual offset < 15 pT
- Using a SQUID-stabilized bias field at BMSR-2, PTB Berlin
- For >100 s integration, limited by field drifts
- Compatible with longer holding times in EDM cycles!

Appl. Phys. Lett. 120, 161102 (2022)

Using the SUN-2 prototype source for R&D

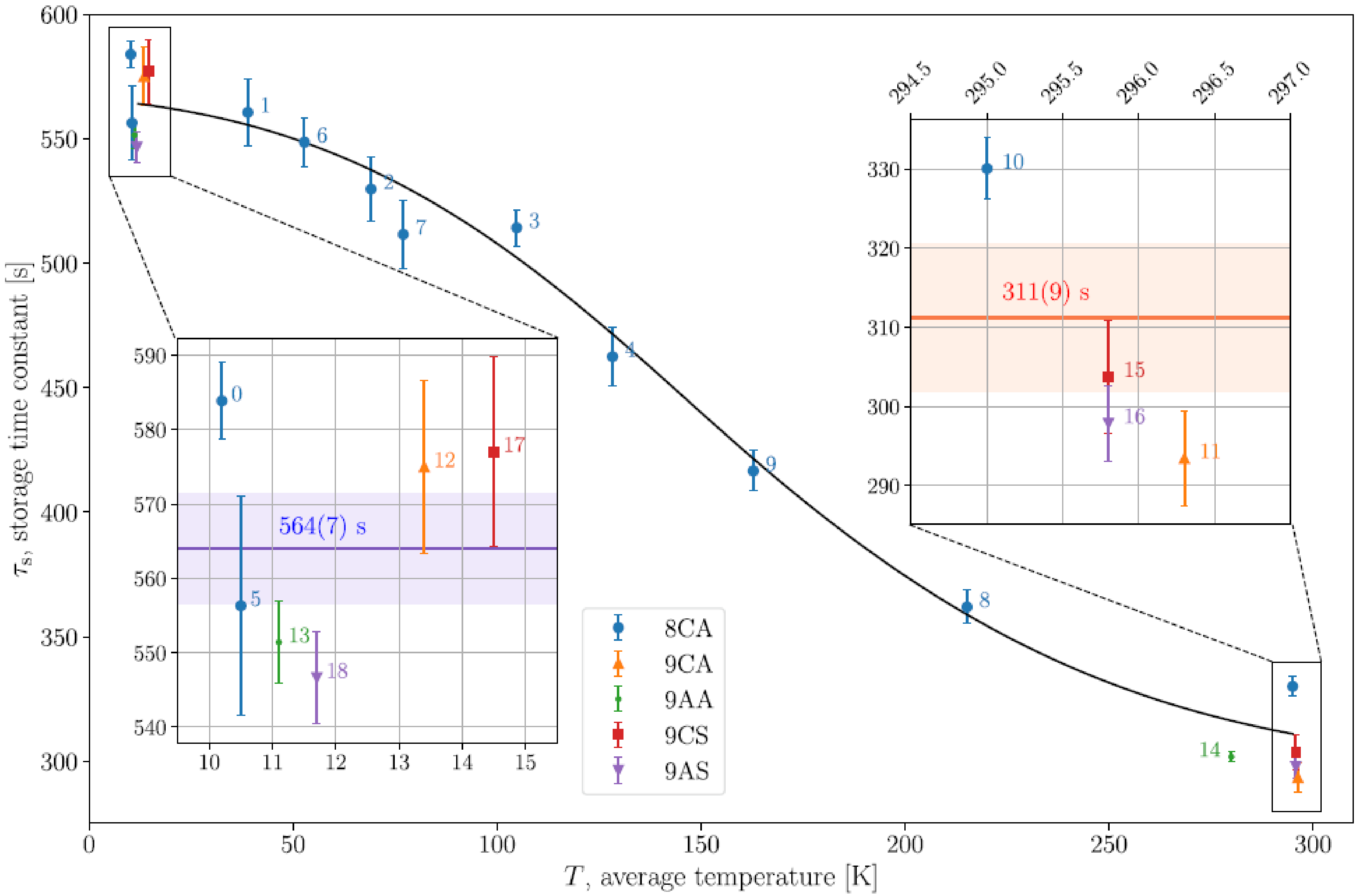




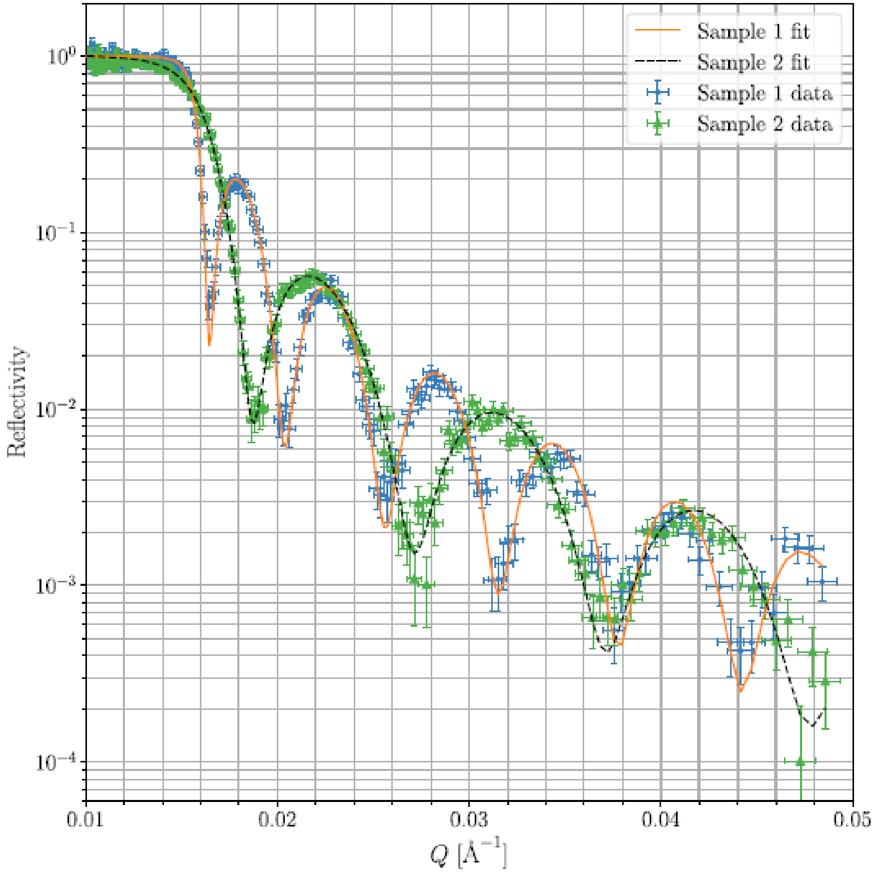
“Suniño” test vessel: J. Hingerl, MSc. 2019

Storage measurements: T. Neulinger, PhD 2021

CYTOP™ as a UCN wall coating



Reflectometry at D17, ILL



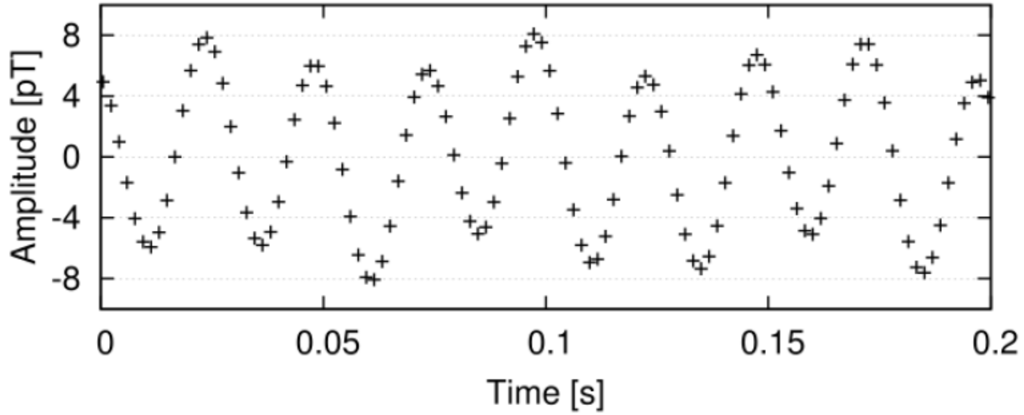
T. Neulinger, PhD 2021

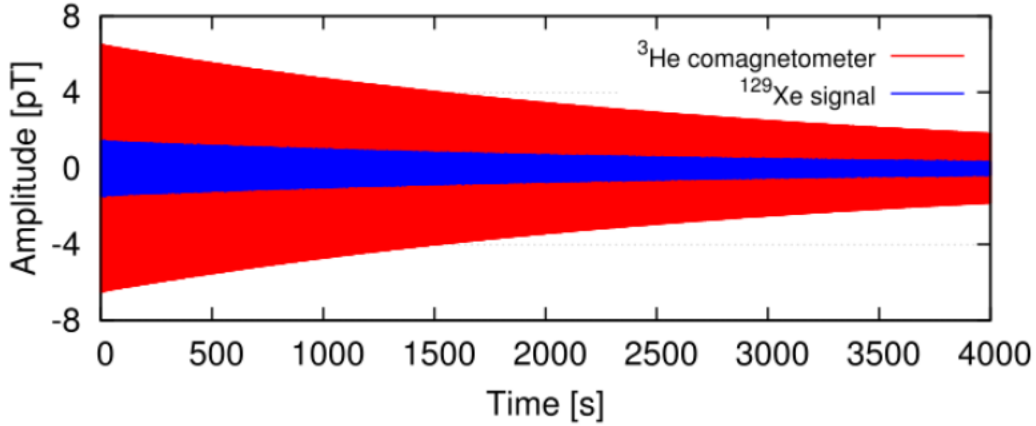
Eur. Phys. J. A **58**: 141 (2022)

2

Comagnetometry: cf. Noble Gases

A digression on why comagnetometry gets harder with improved precision, in another very specific case: hyperpolarized noble gases.





$$\omega_d \equiv \omega_{d_{\rm Xe}} - R\omega_{d_{\rm He}}$$

$$\omega_{\rm co} \approx \omega_d - \gamma'_{\rm He}\Delta RB + (1-R)\vec{\Omega}\cdot\hat{B} + \gamma'_{\rm Xe}(\Delta B^{\rm dif}_{\rm Xe} - \Delta B^{\rm dif}_{\rm He}) + (\omega^{sd}_{\rm Xe} - R\omega^{sd}_{\rm He})$$

Pressure dependence

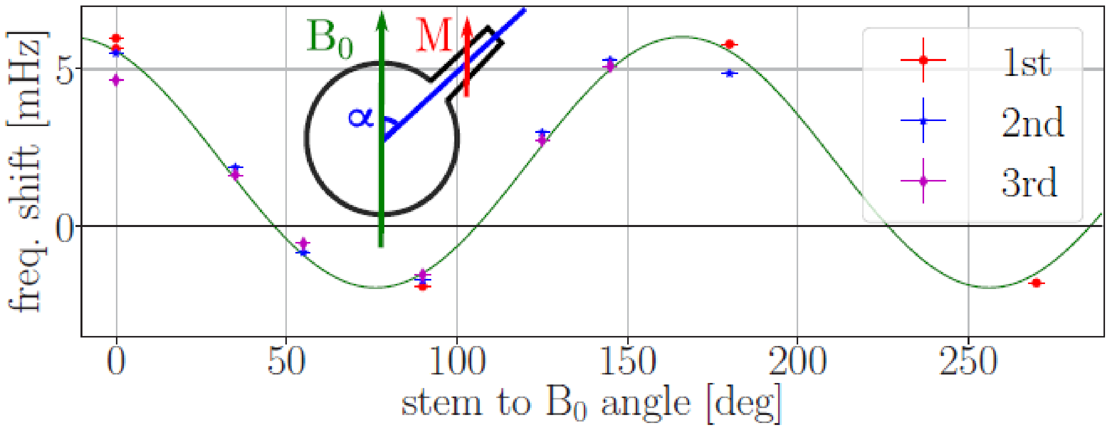
Earth's rotation

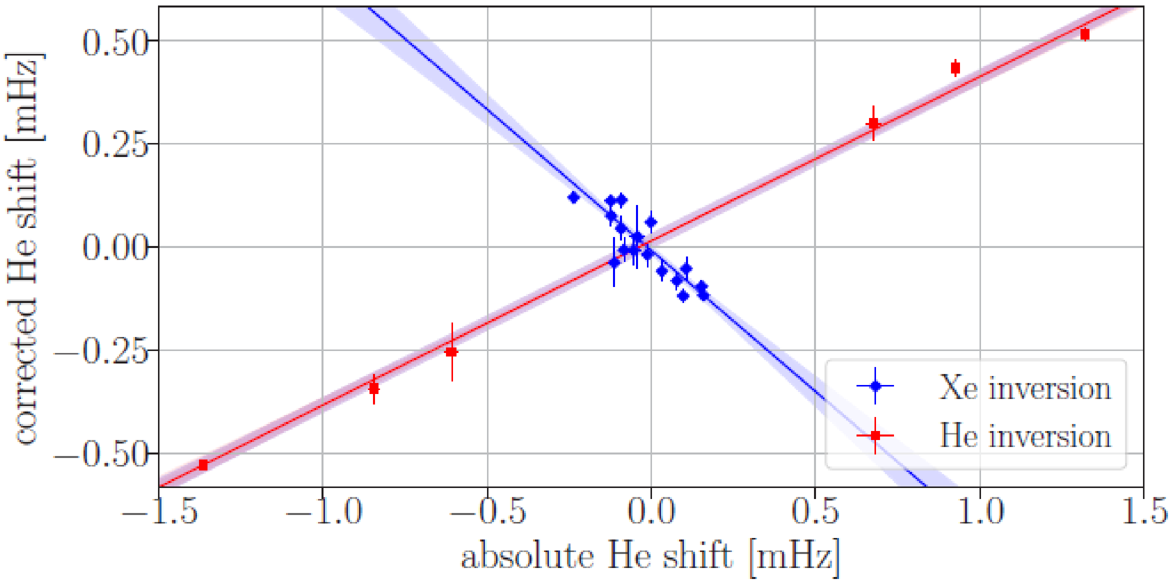
Volume averaging

Species-dependent shifts

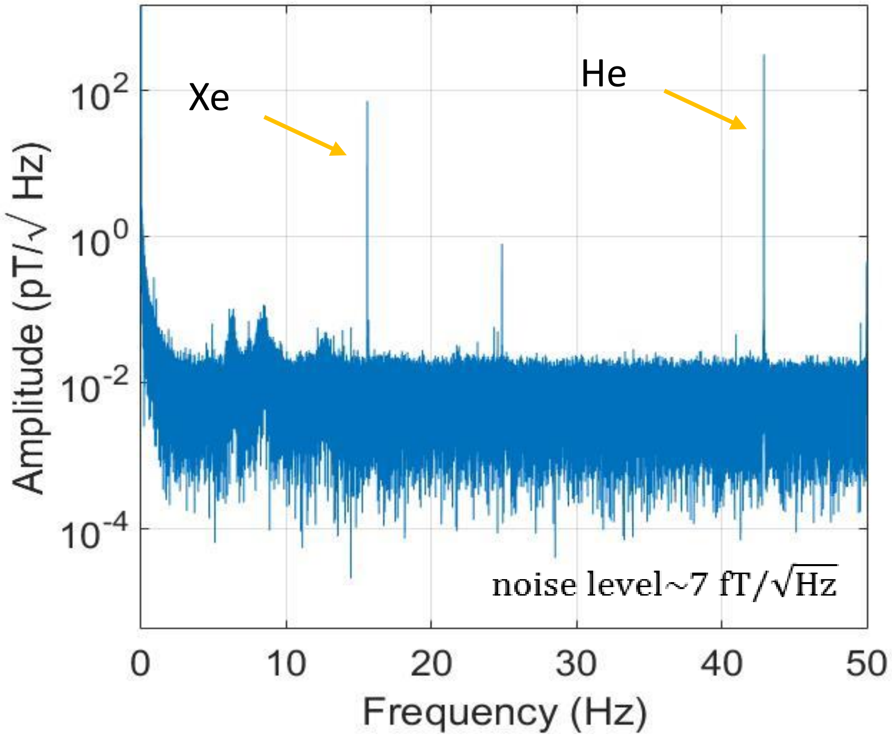
Phys. Rev. Lett. **123**, 143003 (2019)
Phys. Rev. A **100**, 012502 (2019)

Comagnetometry: cf. Noble Gases





Cell asphericity and cross-species couplings.
(Note that different effects dominate for nEDM!)



Phys. Rev. Lett. **123**, 143003 (2019)
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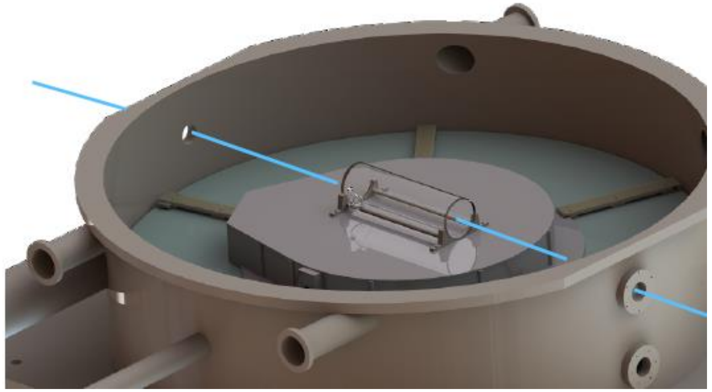
Comagnetometry: PanEDM phase I

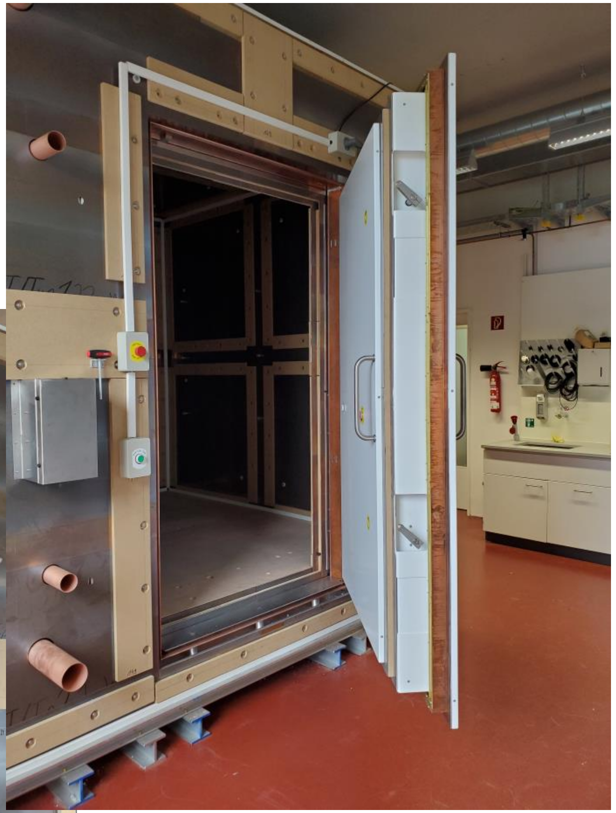


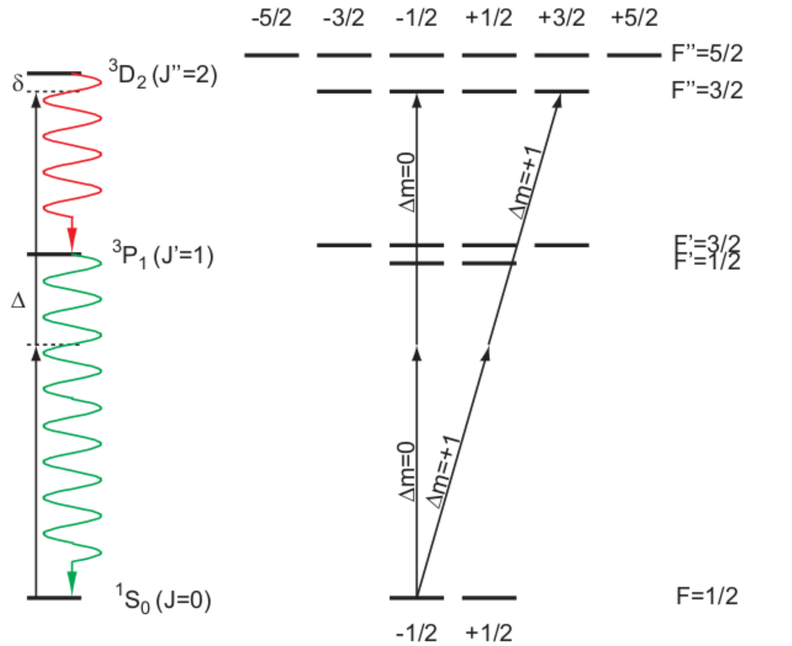
- Cell dimensions match the ~250s holding time for UCN
- 12 fT sensitivity in 100s
- Need 4 fT differential across the stack, for phase I
- Ultimately need global gradients below ~300 pT/m
- Local dipoles below 2 pT at 3cm
- Challenging to constrain HV-correlated local dipoles without long measurements

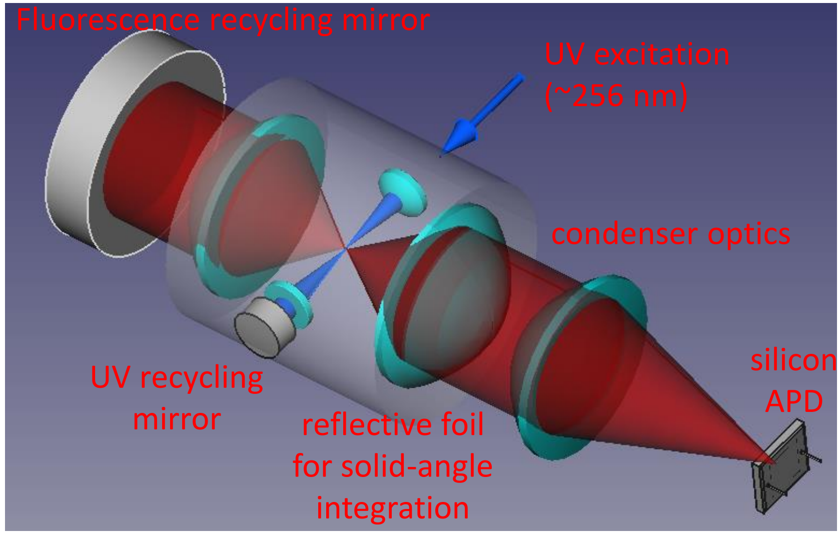
EPJ Web of Conferences 219, 02006 (2019)

Resources: Screening and Systematics

New magnetically shield room @HD! Dedicated facility…







Next order-of-magnitude pursued by refining now-known methods

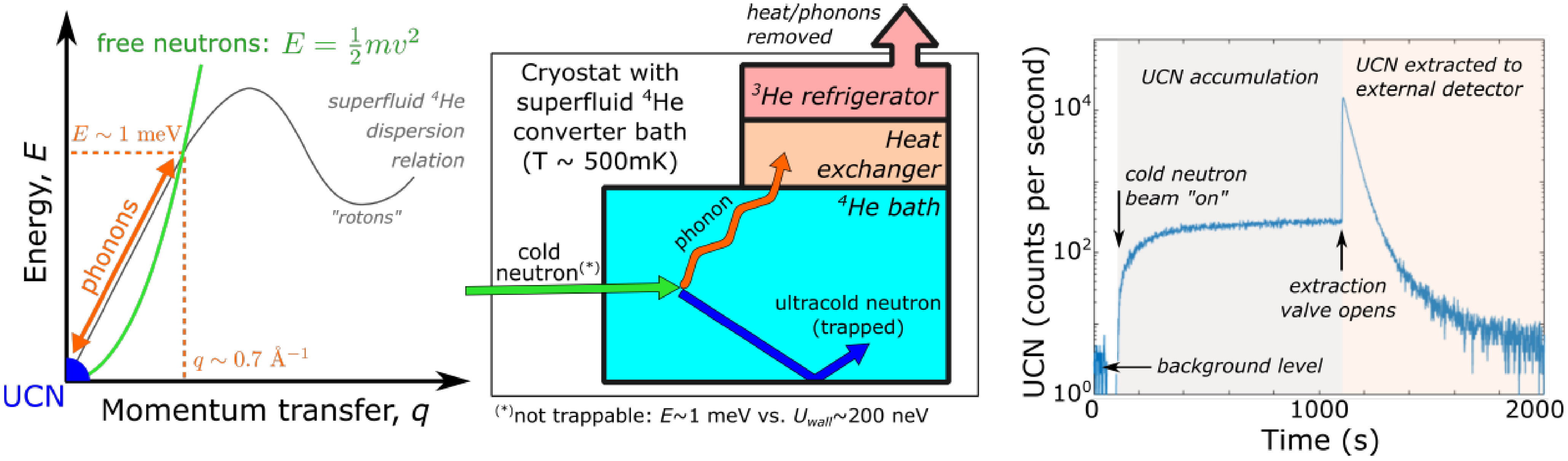
U. Schmidt, SMD

Laser spectroscopy may complement or eventually replace SQUIDS… new tools, also for nEDM!

3

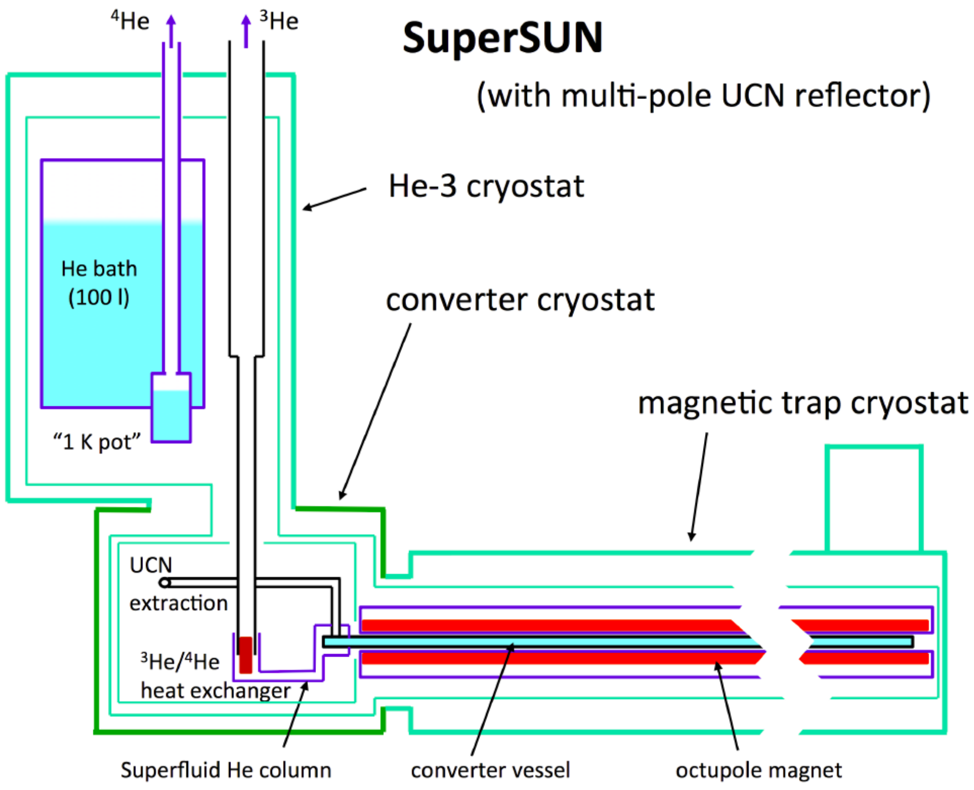
The SuperSUN UCN Source

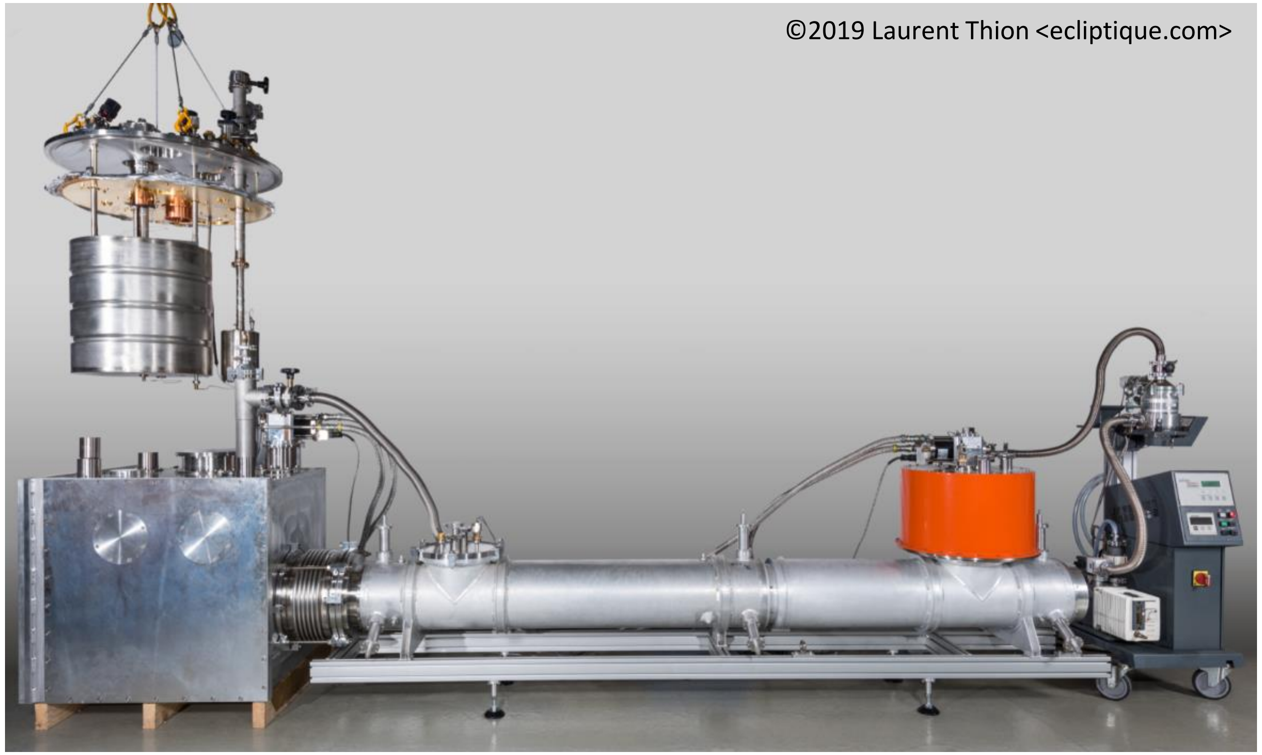
NEUTRONS FOR SOCIETY



- Figure of merit for production: $\tau \cdot \int d^3\boldsymbol{k}\,(1 - e^{-n\sigma l(\boldsymbol{k})})\,\frac{d\Phi}{d\lambda}\Big|_{8.9\text{Å}}$
- Note: partial mean free path $\lambda_{\text{"UCN"}} \sim 10$ km, while $\lambda_{\text{tot}} \sim 10$ m
- Loss for a 3m converter: factor 10 (unused CN beam)
- Loss for *ex-situ* storage: factor 100 (UCN extraction/transport/detection)

SuperSUN Neutron Source: Cutaway

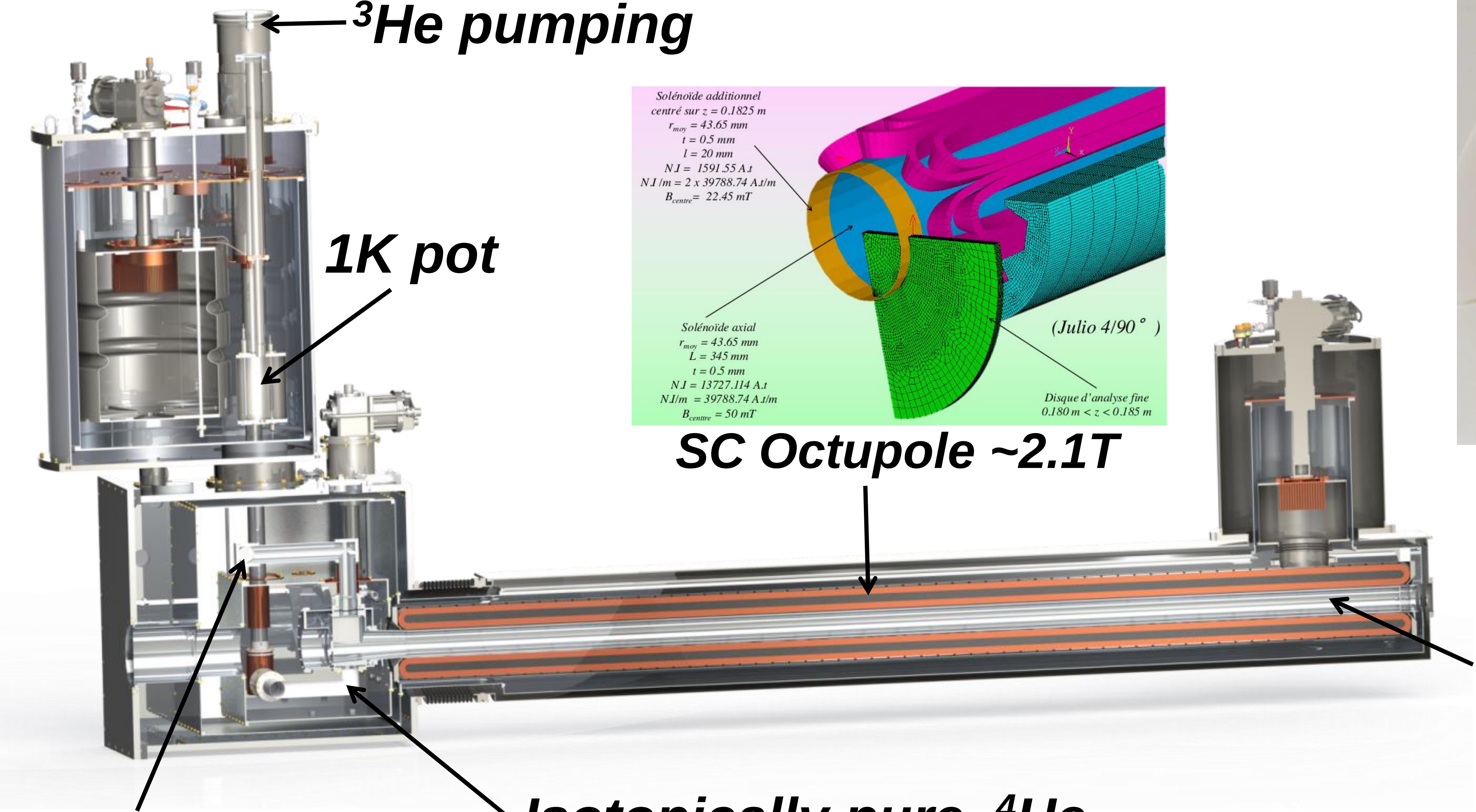




Demonstrated 100mW cooling power at 0.6 K

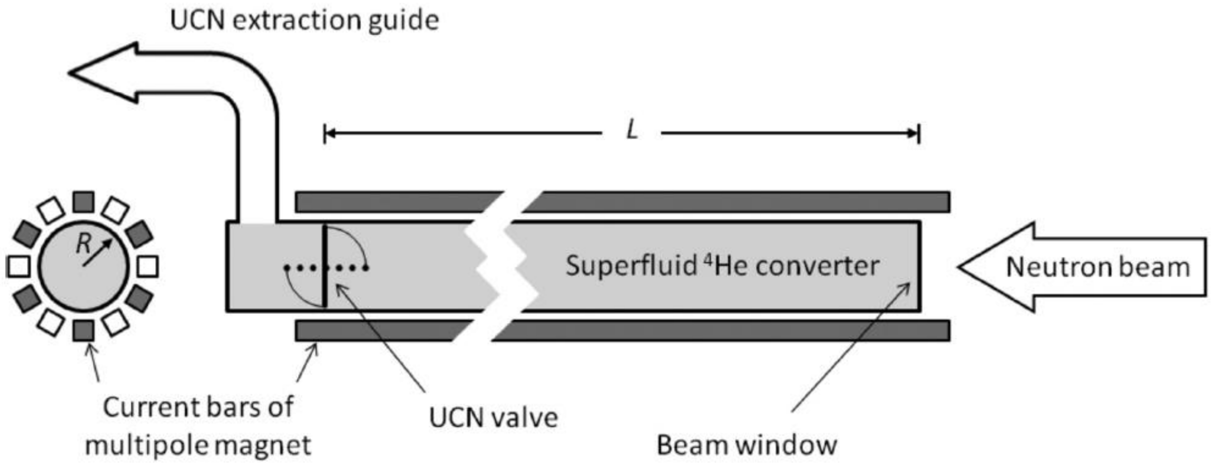
E. Chanel, SMD, O. Zimmer, SANE, NPP…

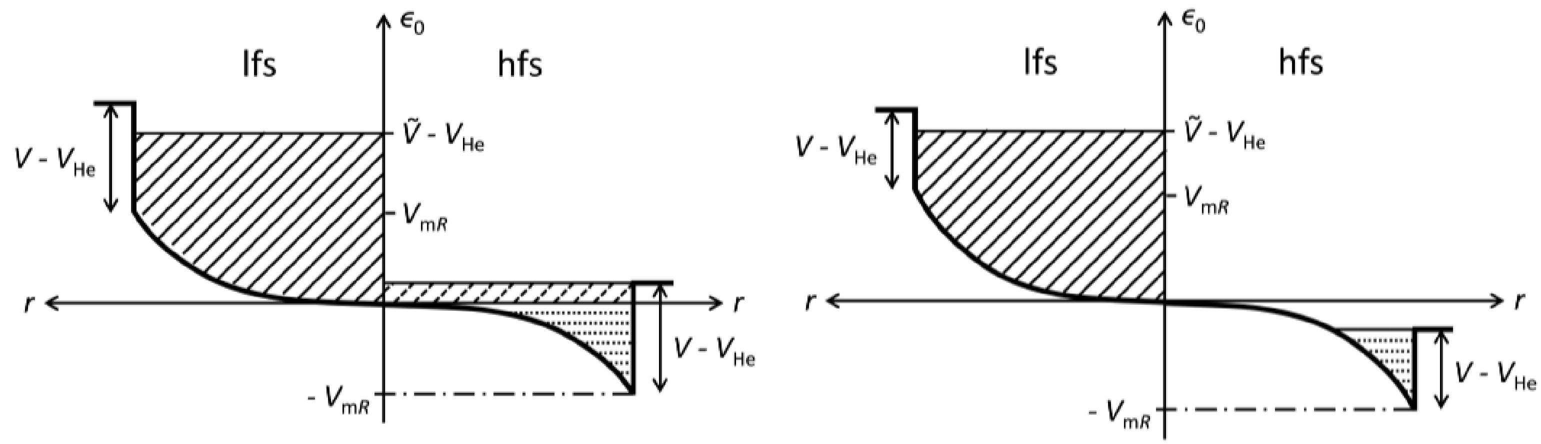
SuperSUN Neutron Source: Cutaway



Minimizing UCN Storage losses

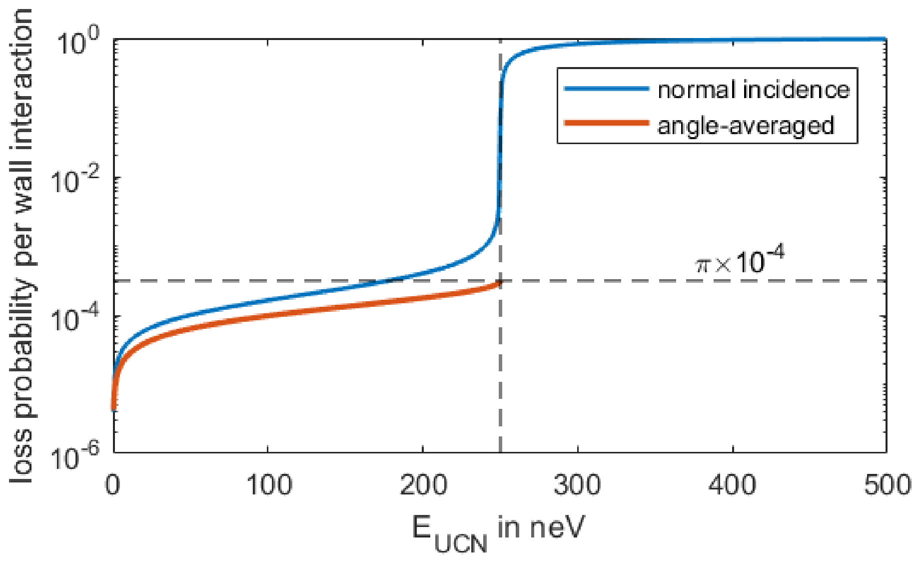
SuperSUN phase II: magnetic octupole reflector

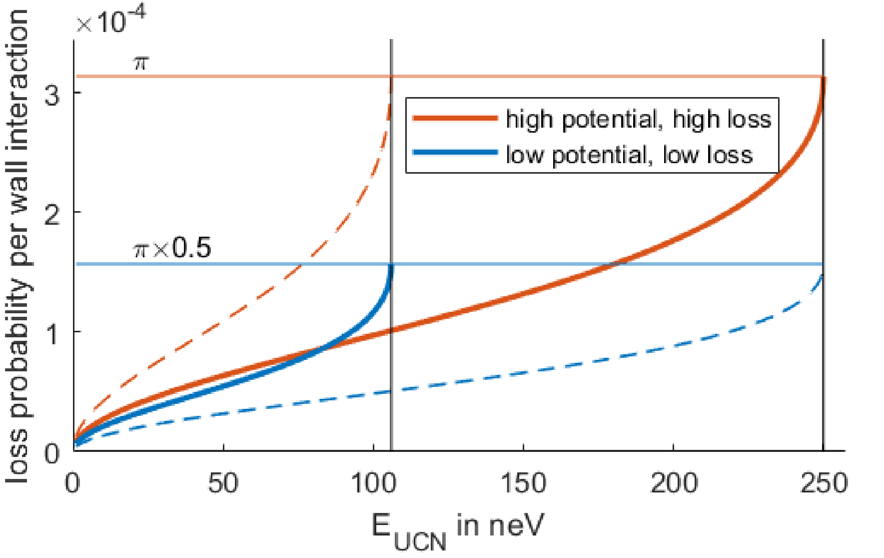




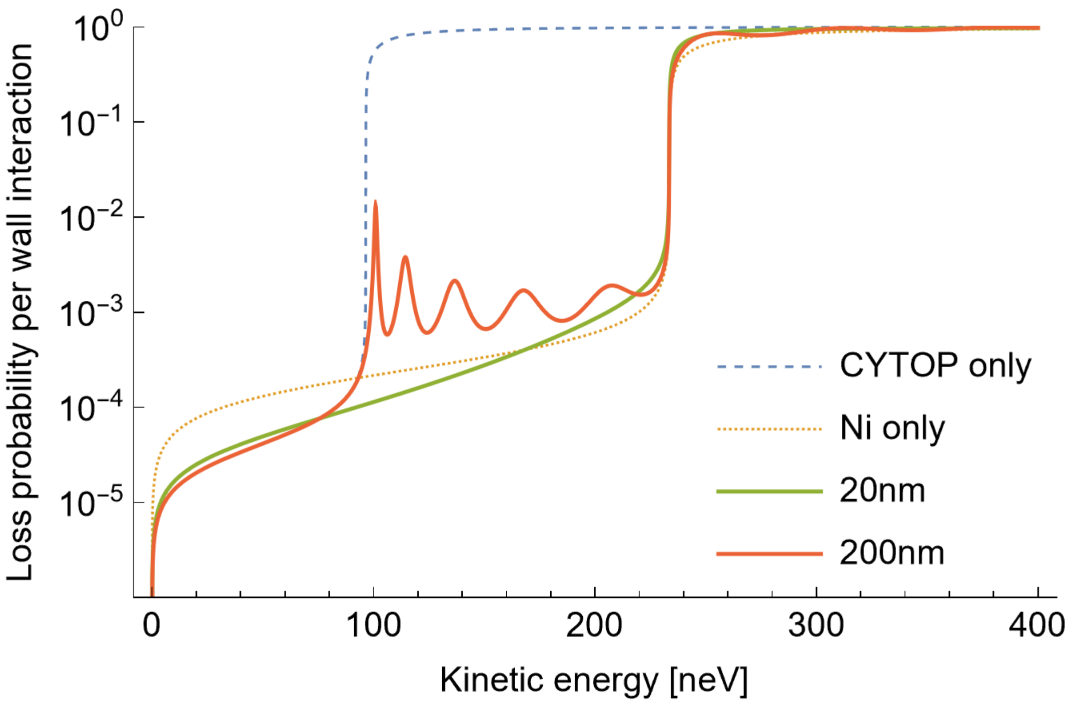
Phys. Rev. C **92**: 015501 (2015)

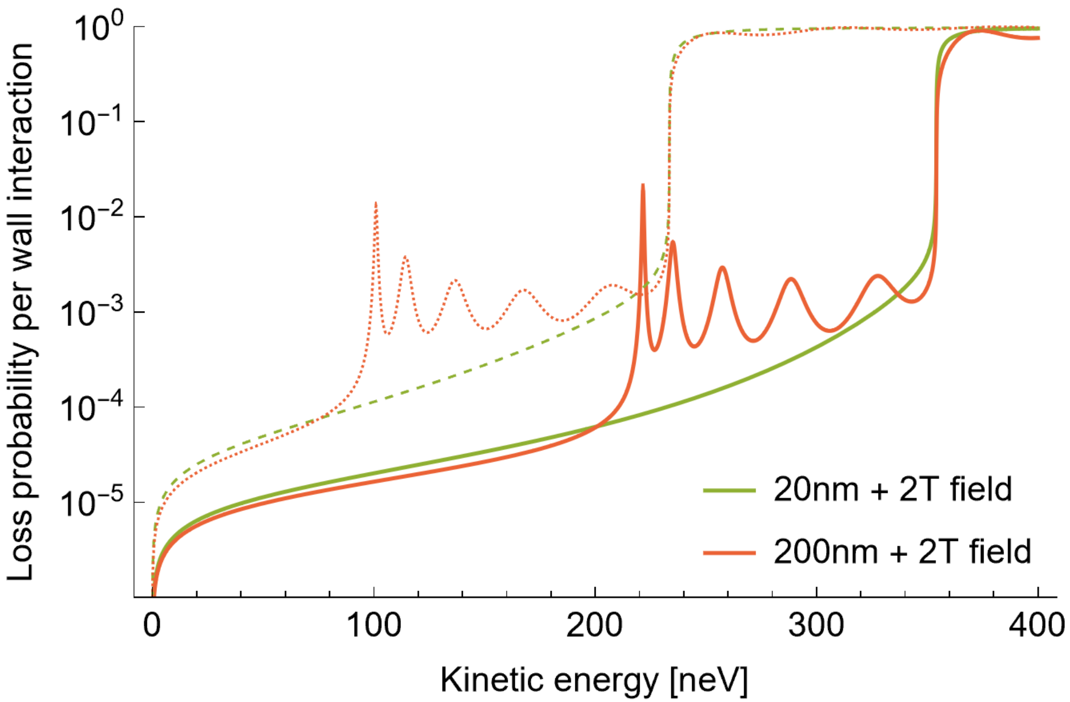
Material wall potentials





Minimizing UCN Storage losses





ILL Instruments and Beamlines

In SuperSUN's converter vessel:

- $R \sim 15$ UCN/(cm^3 s) expected

End of guide H523:

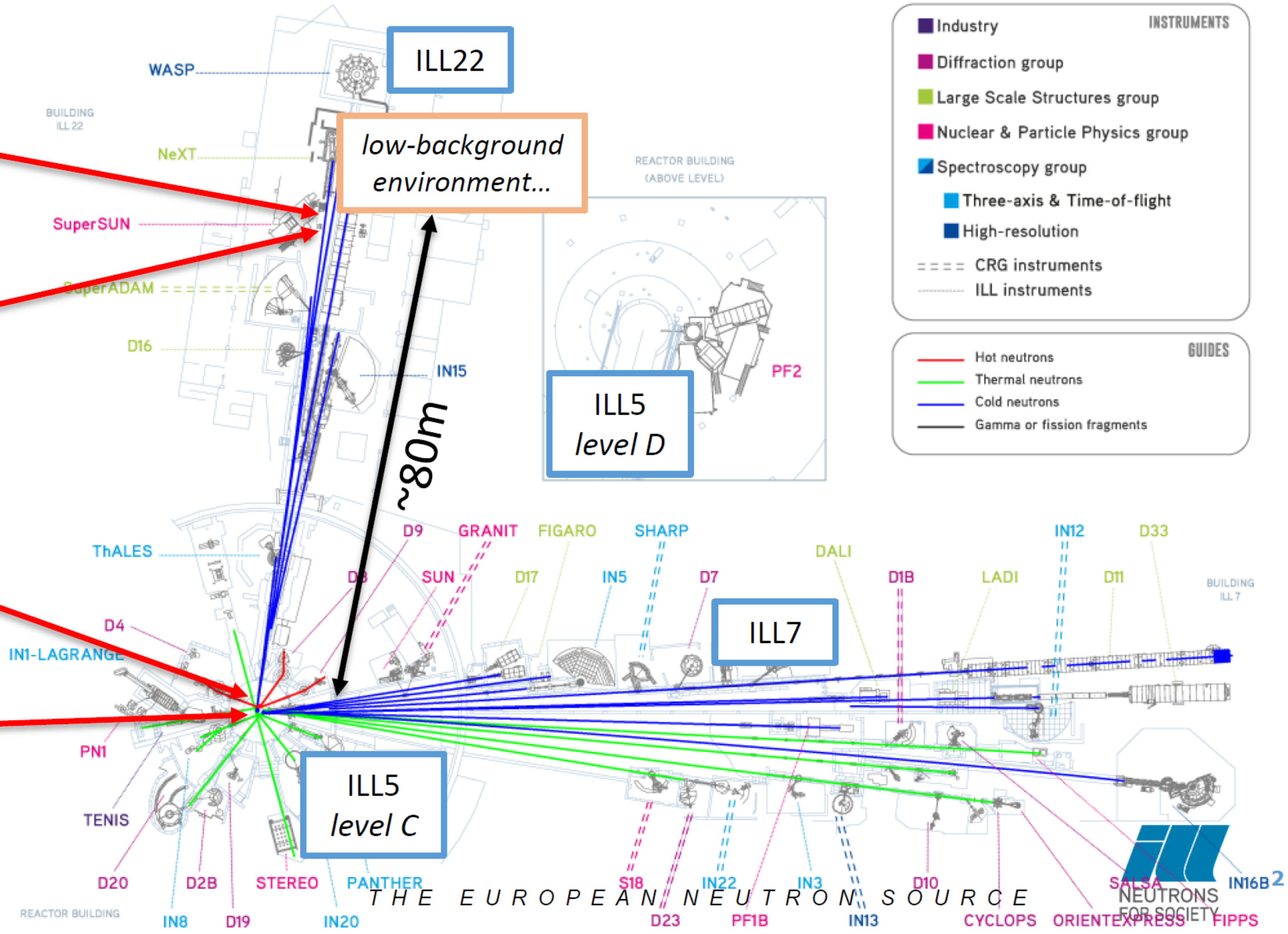
- $\Phi \sim 2\times10^{10}$ n/(cm^2 s)

Horizontal Cold Source:

- $\Phi \sim 10^{14}$ n/(cm^2 s)

In pile:

- $\Phi \sim 1.5\times10^{15}$ n/(cm^2 s)



Statistics considerations

Statistics

- Flux vs. *density*
  - want to count many UCN, after storage
  - transport losses and dilution
- Storage time (including T_1/T_2)
- Total measurement time/repetitions
  - duty factor vs. accumulation time
  - long-term stability becomes important
- Polarization (incl. analyzing power)
- Electric field
- Cold neutron losses

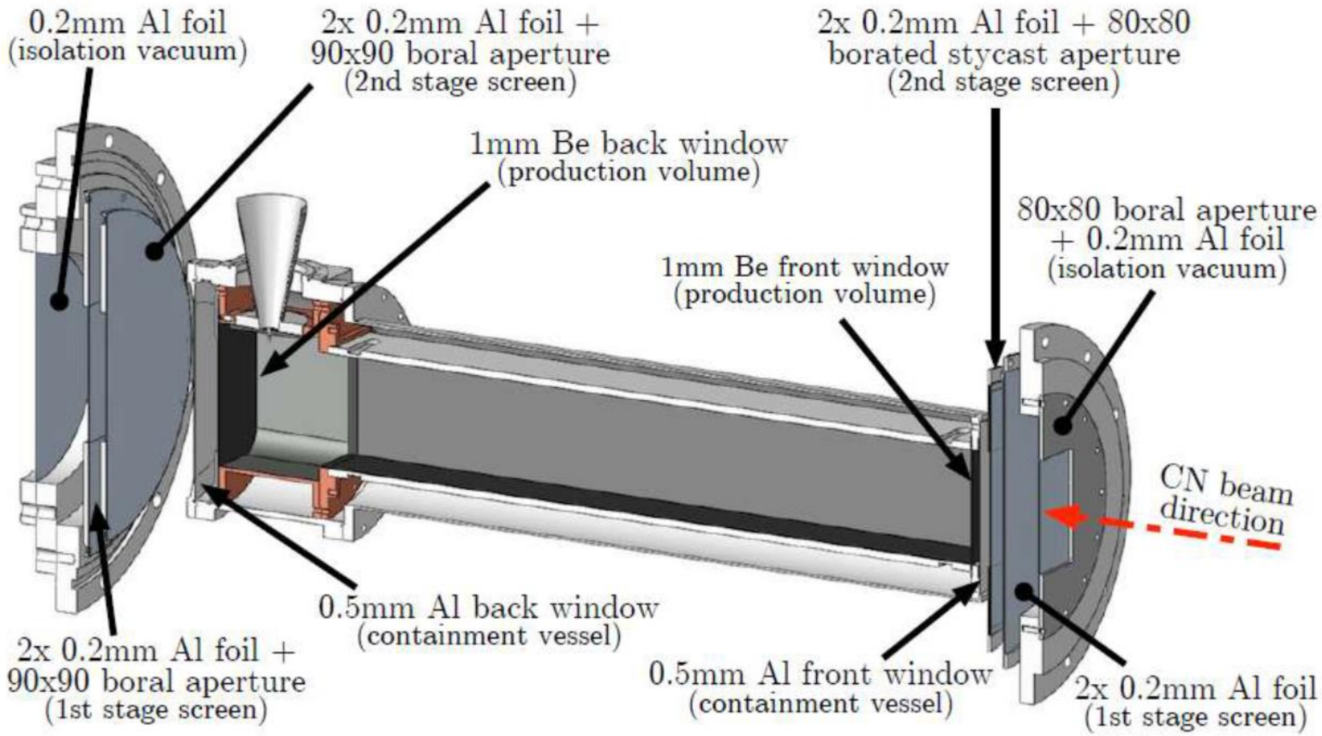
$$N_{\mathrm{cell}} \sim \rho_{\mathrm{cell}} V_{\mathrm{cell}} \sim \frac{\rho_{\mathrm{source}} V_{\mathrm{cell}}}{1 + \frac{V_{\mathrm{cell}} + V_{\mathrm{guide}}}{V_{\mathrm{source}}}}$$

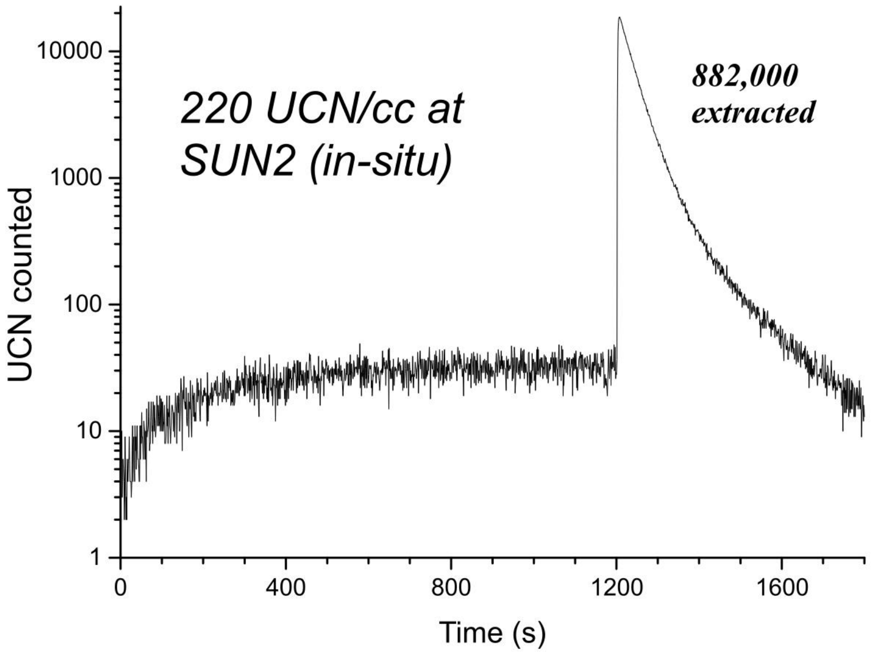
$$\frac{1}{\tau} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\mathrm{up}}} + \frac{1}{\tau_{\mathrm{capture}}} + \frac{1}{\tau_{\mathrm{wall}}} + \cdots$$

Systematics (not exhaustive)

- Cell size and quality
- Field stability, monitor quality
- Magnetic screening
- Environment/backgrounds

Extrapolation from SUN-2 Prototype





O. Zimmer

Extrapolation from SUN-2 Prototype

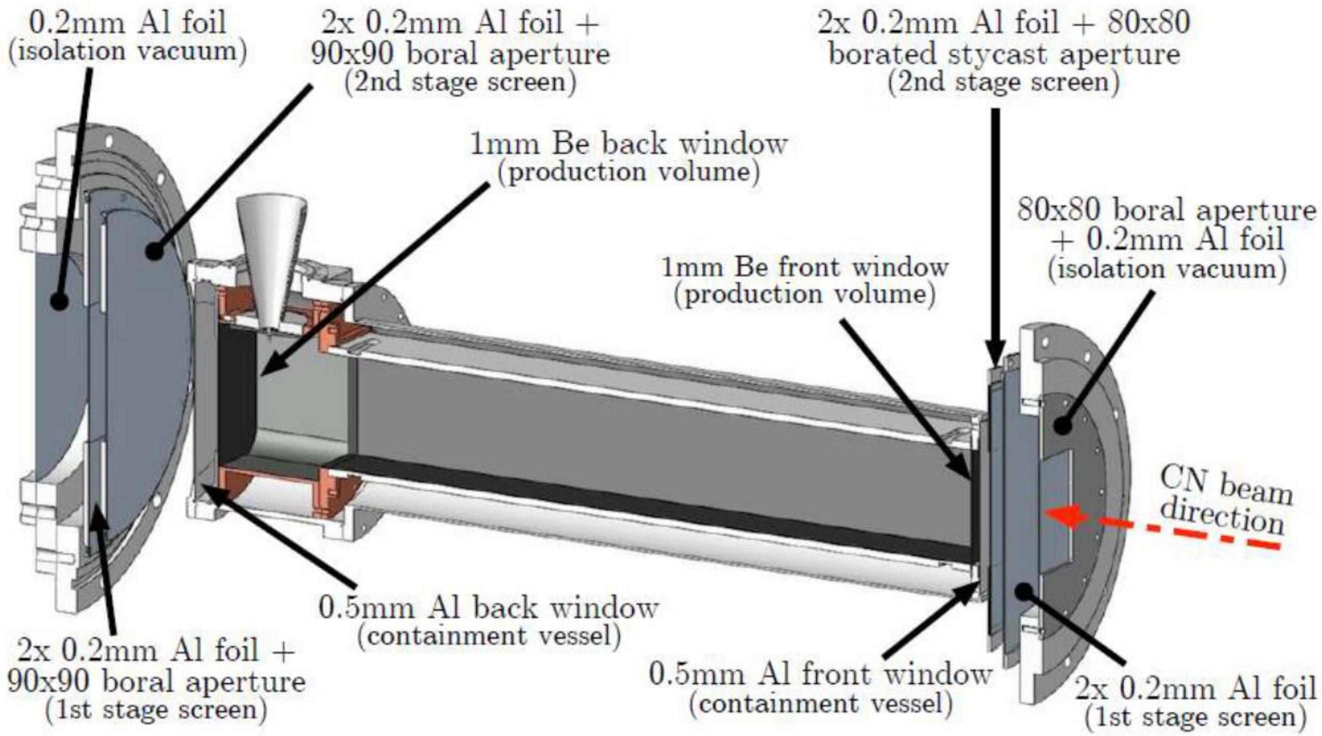
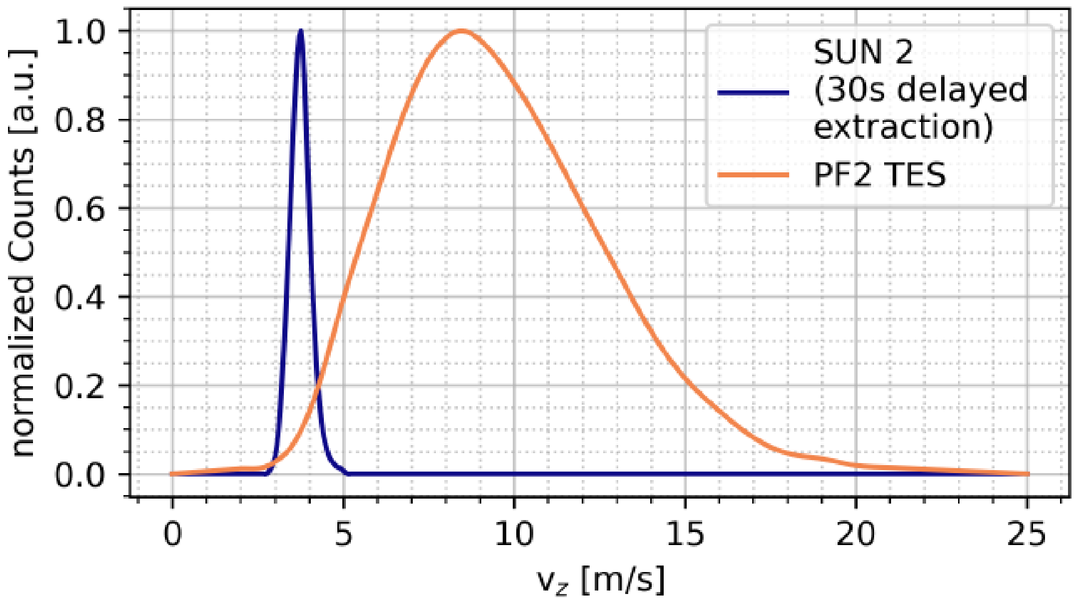
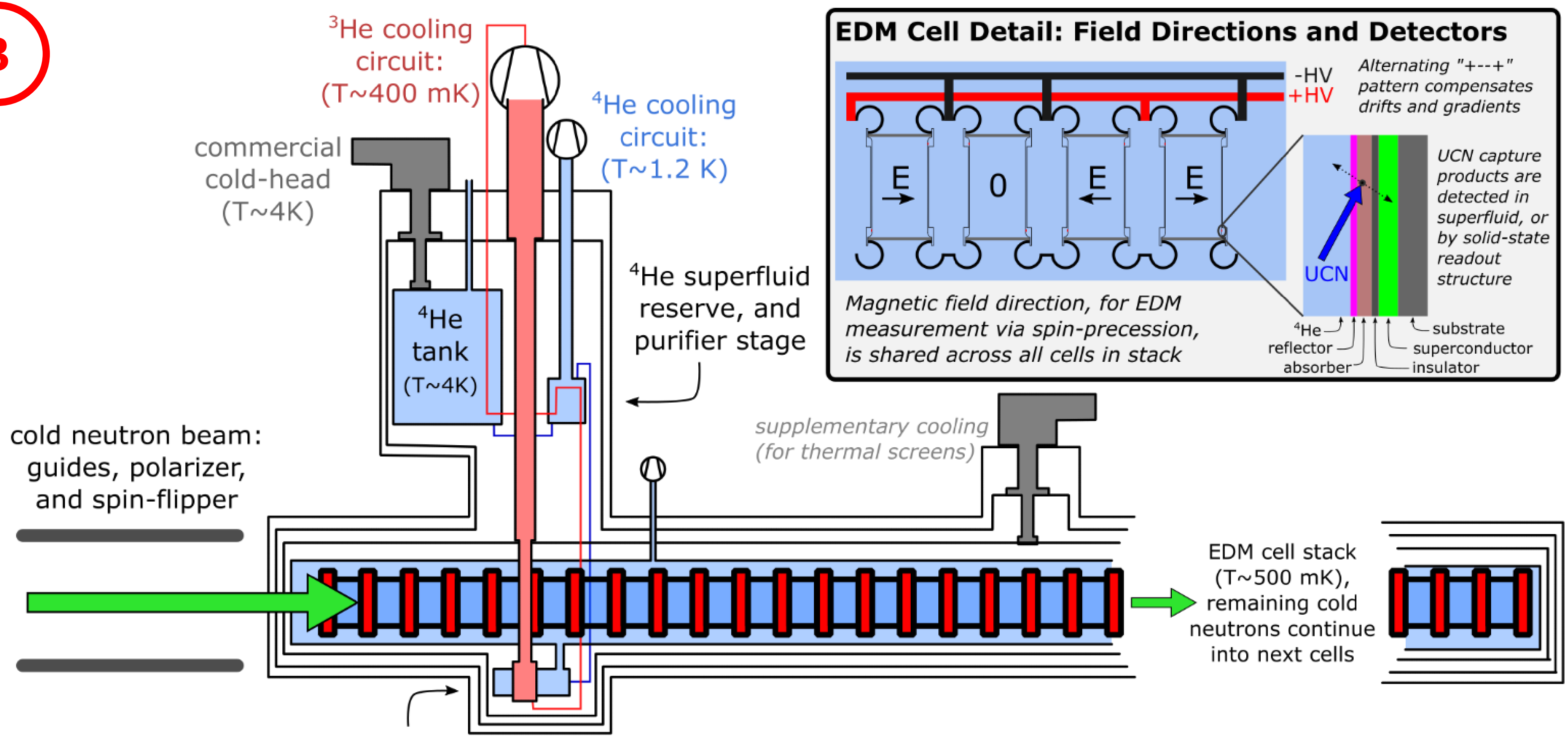


figure: D. Wurm



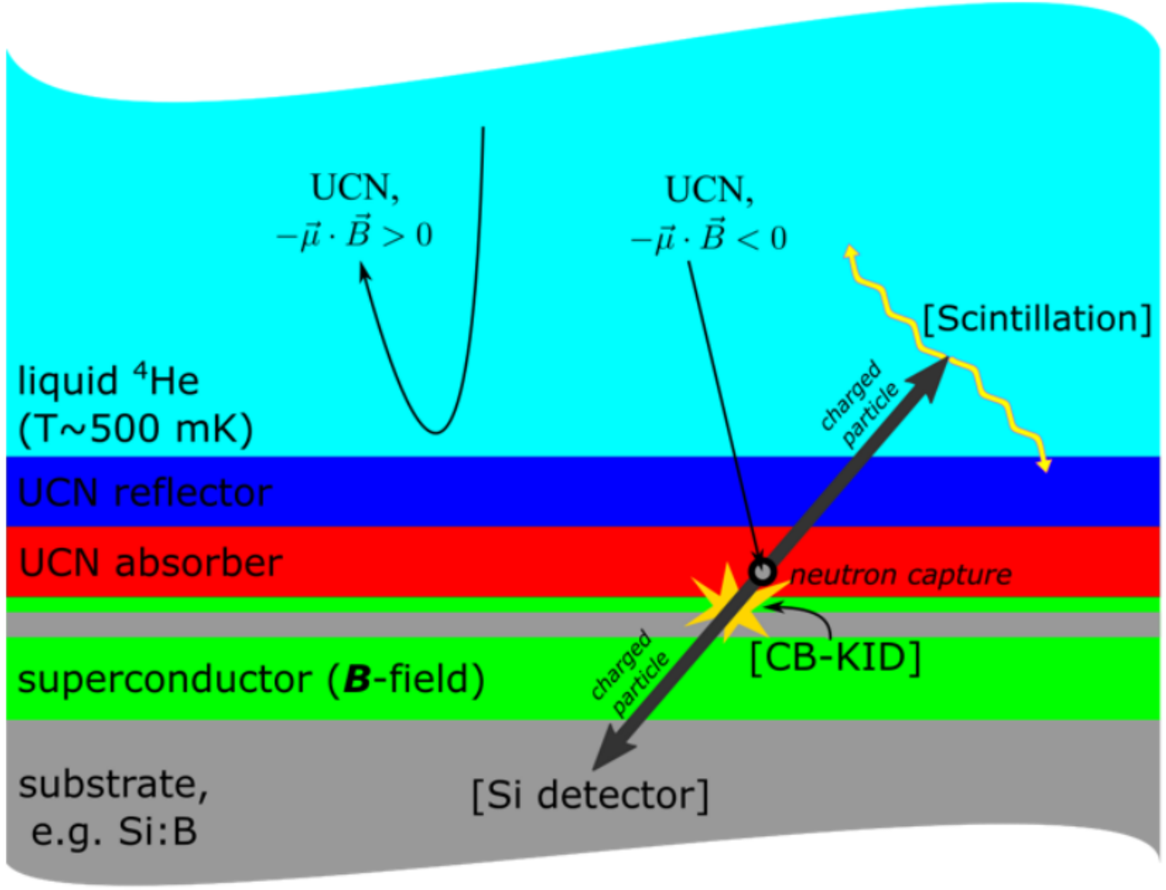
The next generation*... scaling up!

3



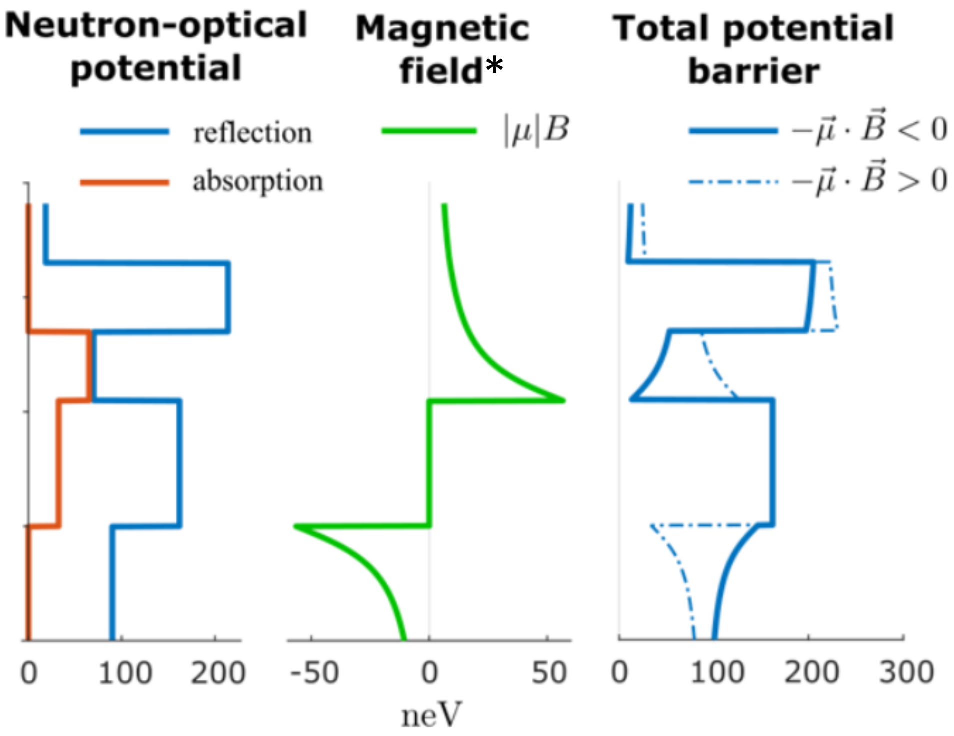
*conceptual idea – no promises yet, only a direction to explore!
proceed via small/modular R&D steps ...systematics not yet clear

"Quantum Sensing" for Neutrons



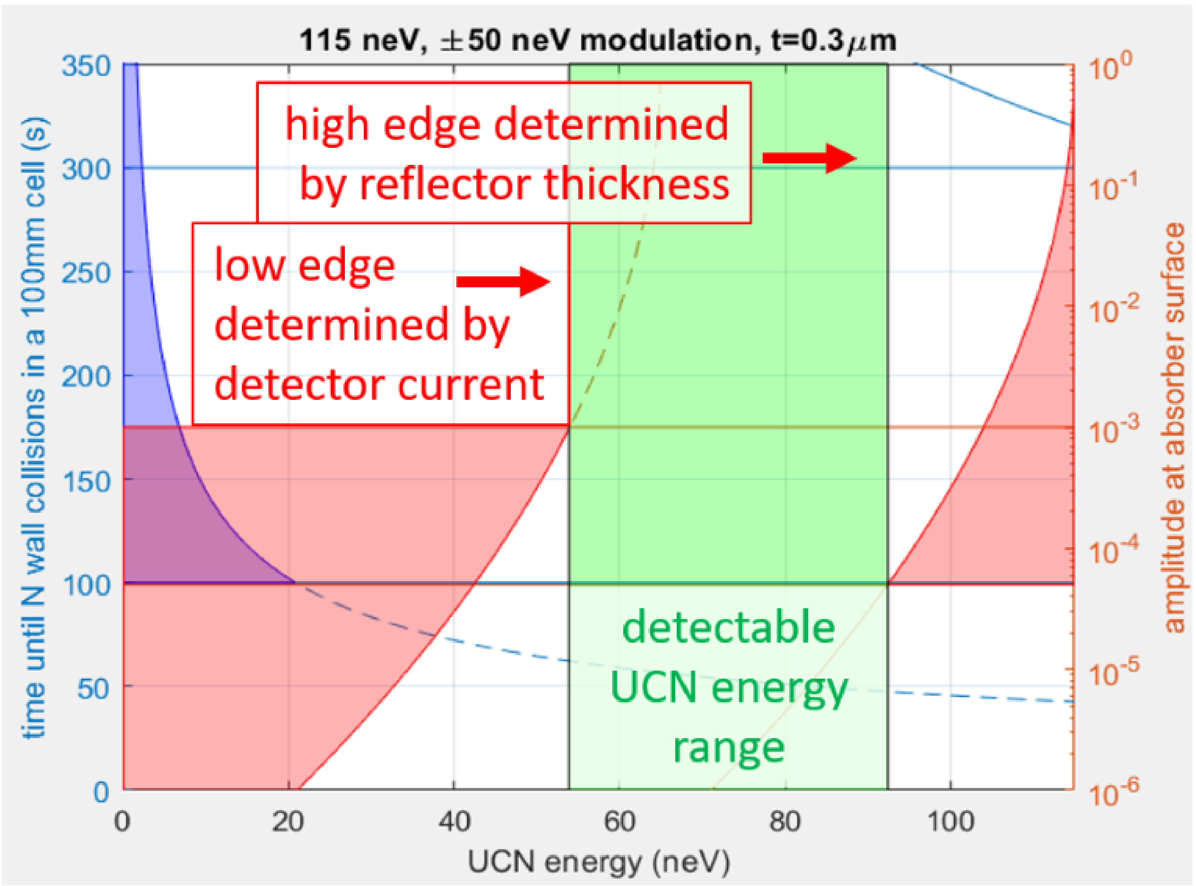
Several possibilities for readout

Ultracold neutron (UCN) detection with polarization-sensitivity, via applied magnetic fields partially cancelling the neutron-optical potential for one spin state. Various readout mechanisms to be explored.



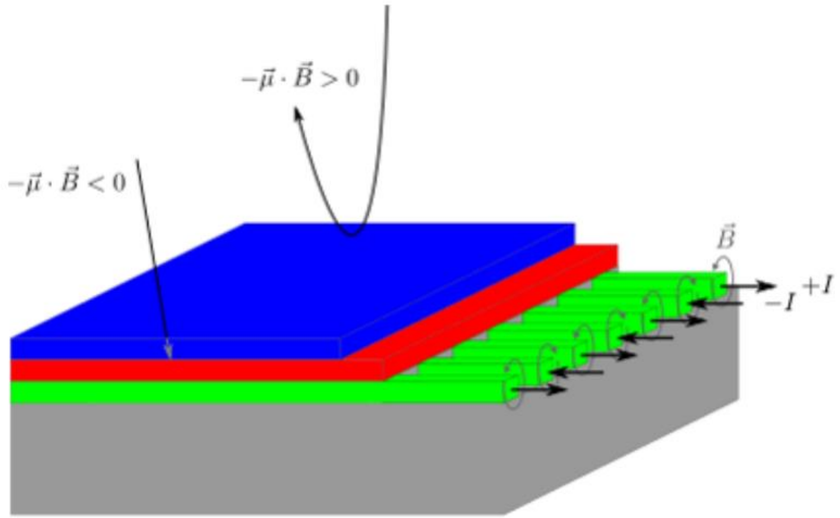
*magnetic shift exaggerated for clarity

“Quantum Sensing”: Spin and Energy

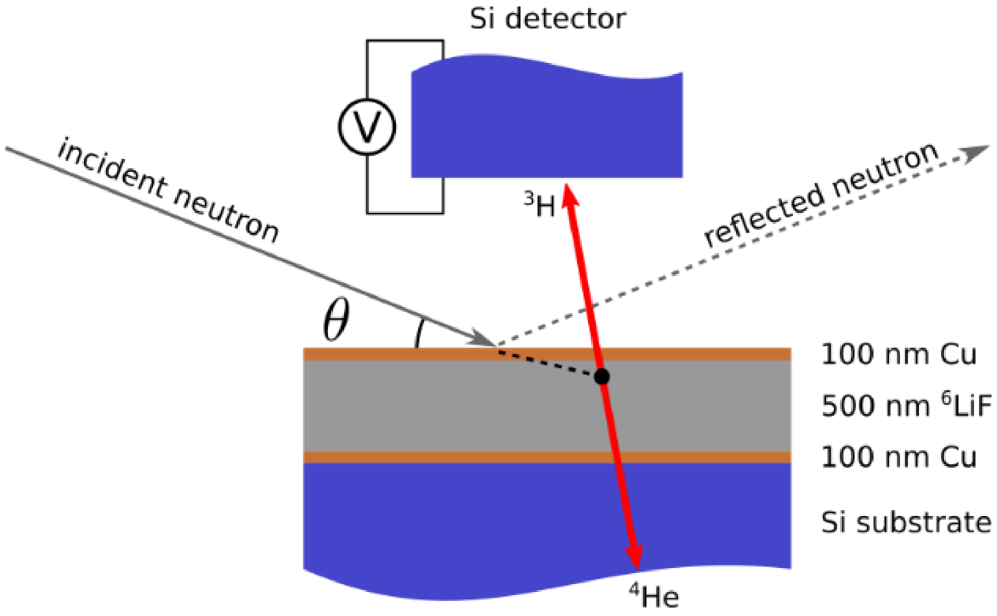


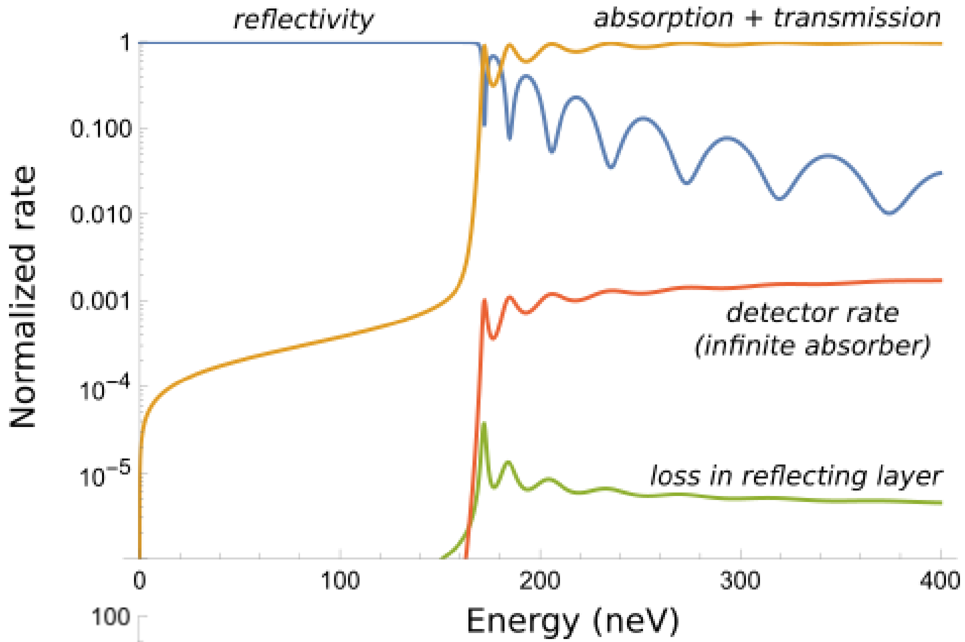
*magnetic shift exaggerated for clarity
(different zones can have different sensitivity ranges)

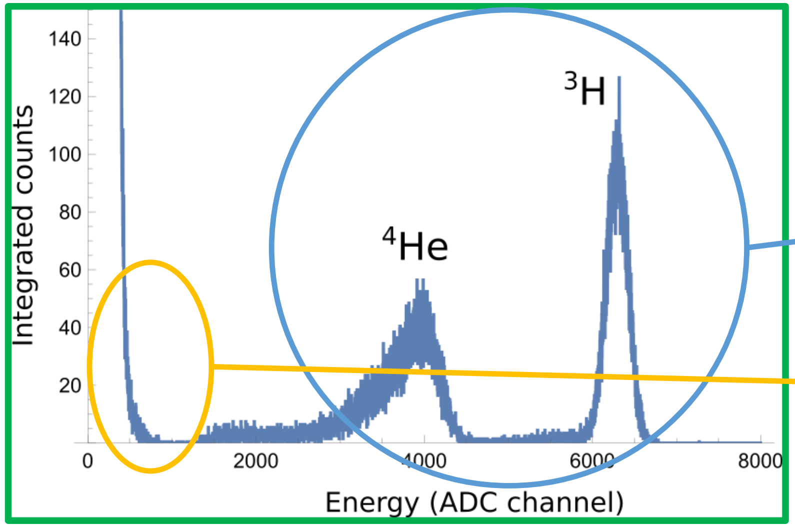
low-field seekers repelled;
high-field seekers drawn in

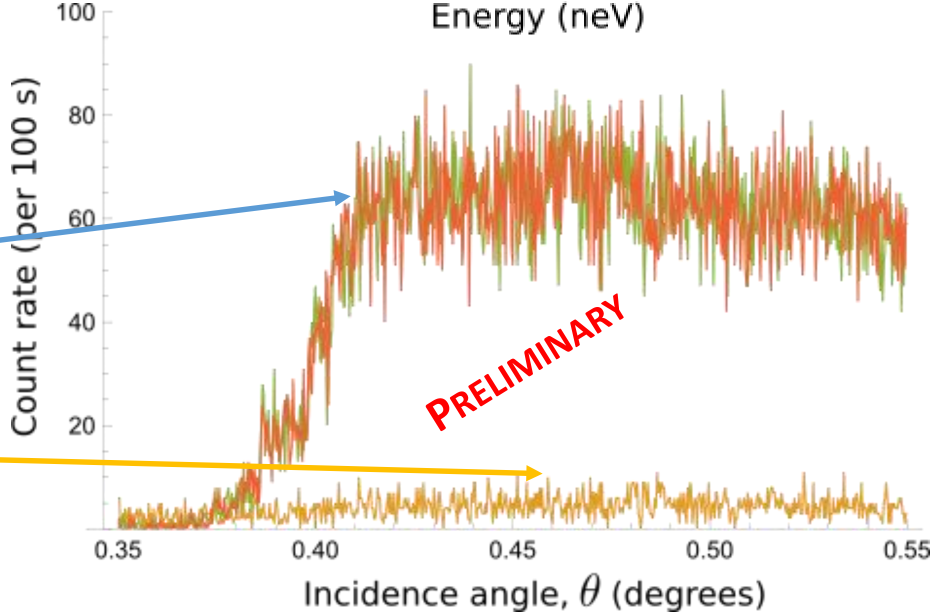


“Quantum Sensing”: Spin and Energy

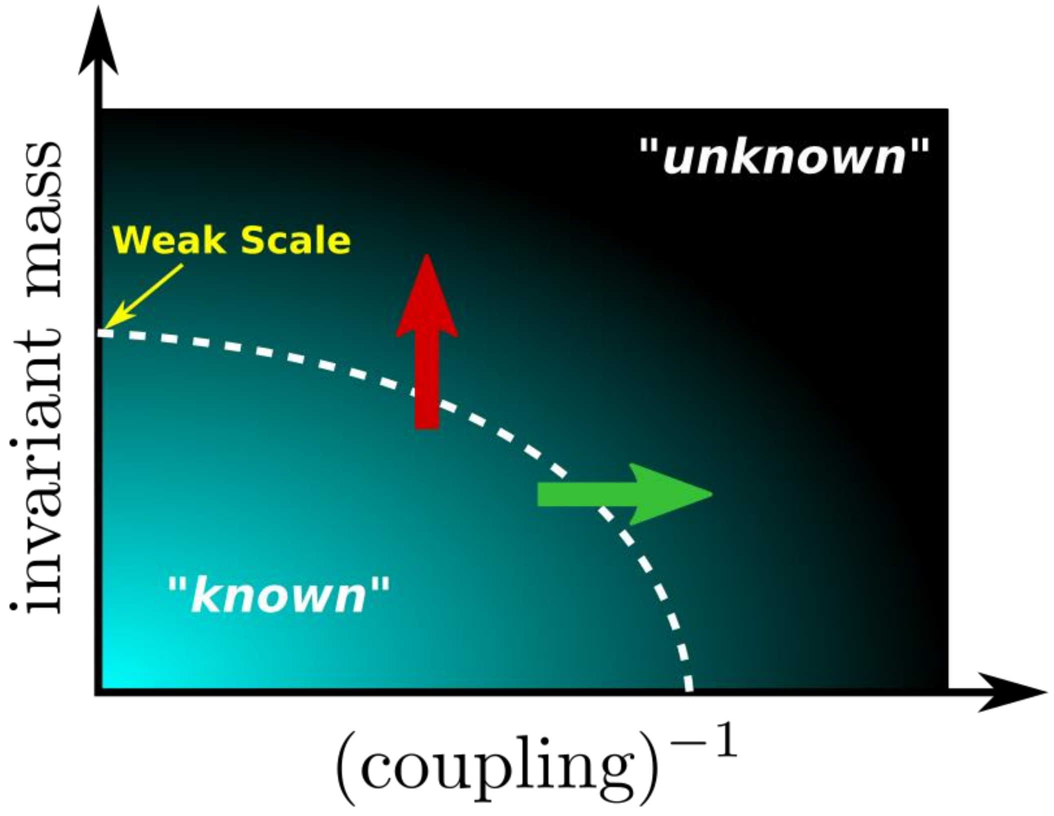








Recapitulation



1. PanEDM is moving forward
2. Comagnetometry is very hard
3. Statistics can be improved!
   (systematics not yet clear)

Seeking students and Post-Docs!

xkcd.com

Faddeev-Popov?

Questions?

what-if.xkcd.com

Special thanks to:

PanEDM collaboration
HeXe collaboration

Institut Laue-Langevin, NPP division
Institut Laue-Langevin, SANE division

S-DH, GmbH
Budapest Neutron Centre, GINA team