Opportunities with ultracold neutrons at the ESS

(—a somewhat incomplete and personal summary—)

UCN/VCN Workshop, European Spallation Source
09.05.2023

Skyler Degenkolb
Low-Energy Precision Physics, Physikalische Institut der Universität Heidelberg

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Key Questions/Considerations

- What can be done uniquely or exceptionally well at the ESS?
- What are the most important gaps and needs for the community?
- What can only be done with UCN?
- Where can UCN provide key complementary information?

  NB: *complementarity* does not mean obligatorily interdependent experiments!

Some Personal Observations/Opinions

- Much impressive work was already done with weak sources.
- The UCN community concentrates effort on rather few topics.
- Many basic issues are not well-understood (theory vs. experiment).
- Sources must be understood in detail, to do good experiments.

Some Personal Observations/Opinions

- Much impressive work was already done with weak sources.
  - 5% measurement of Fomblin loss factor with < 1 UCN / storage cycle (Bates)
  - 1982: storage in a material bottle, with all observed loss attributable to β decay (Mampe)
- The UCN community concentrates effort on rather few topics.
  - EDM (~7), lifetime (~4), gravitational states (2), decay correlations (*A* and *b*), charge
  - Not pursued: weak *e-n* current, gravity-induced polarization, interferometry, imaging, …
- Many basic issues are not well-understood (theory vs. experiment).
  - Transmission of metal foils, loss factors, transfer efficiencies, …
  - Production rates and other parameters phenomenologically scaled
- Sources must be understood in detail, to do good experiments.
  - Experiments are already challenging with good sources
  - "Pure" source development often seeds major experimental efforts… dilutes progress

Agenda

1. Sources
2. Science
3. Caveats

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2. Science
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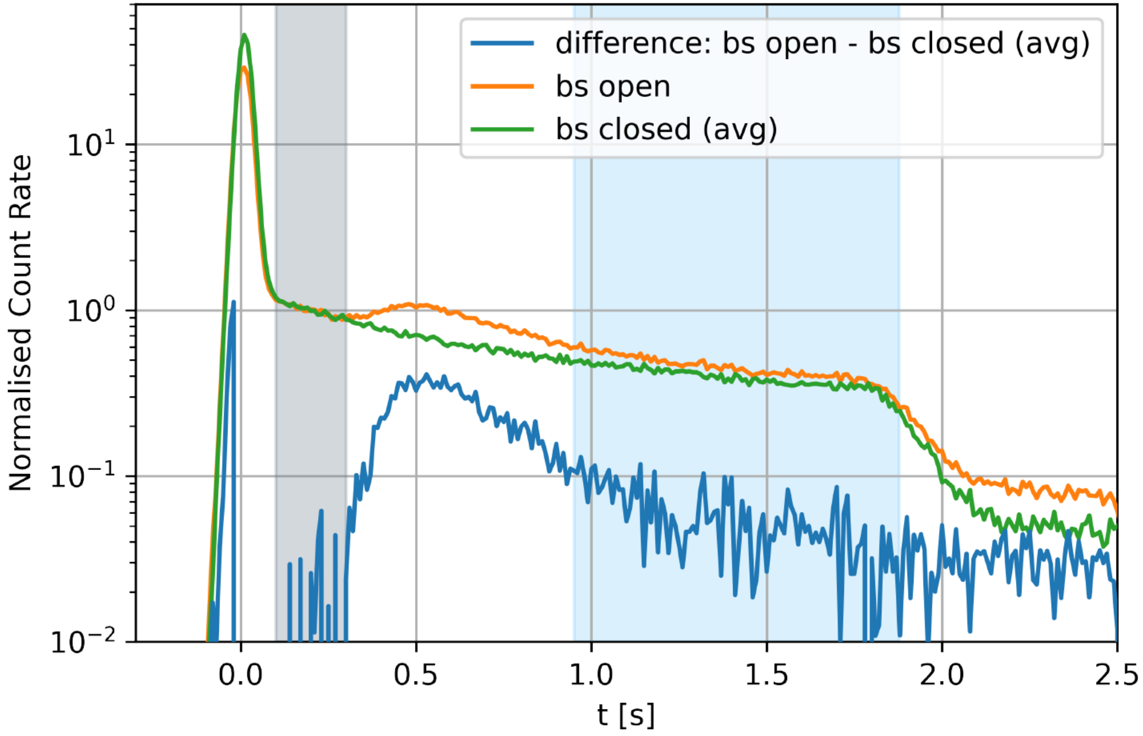
1

Figures of Merit, including “what is a UCN?”

- Recall the produced spectrum scales as $E^{3/2}$
  - High cut-off: trapping/guiding potential
  - Low cut-off: transmissive foils, or climbing in gravity

F. Hömke, 2022 Heidelberg/Mainz



General lesson: deliver the “useful” neutrons (that can be used by the experiment).

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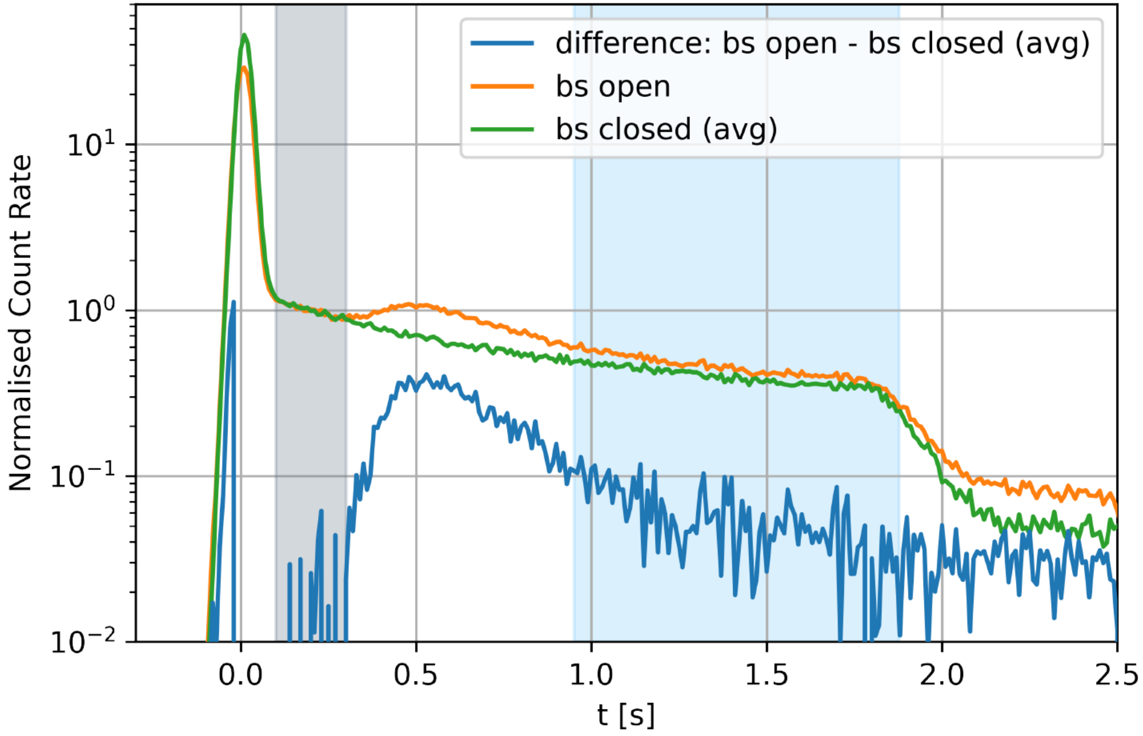
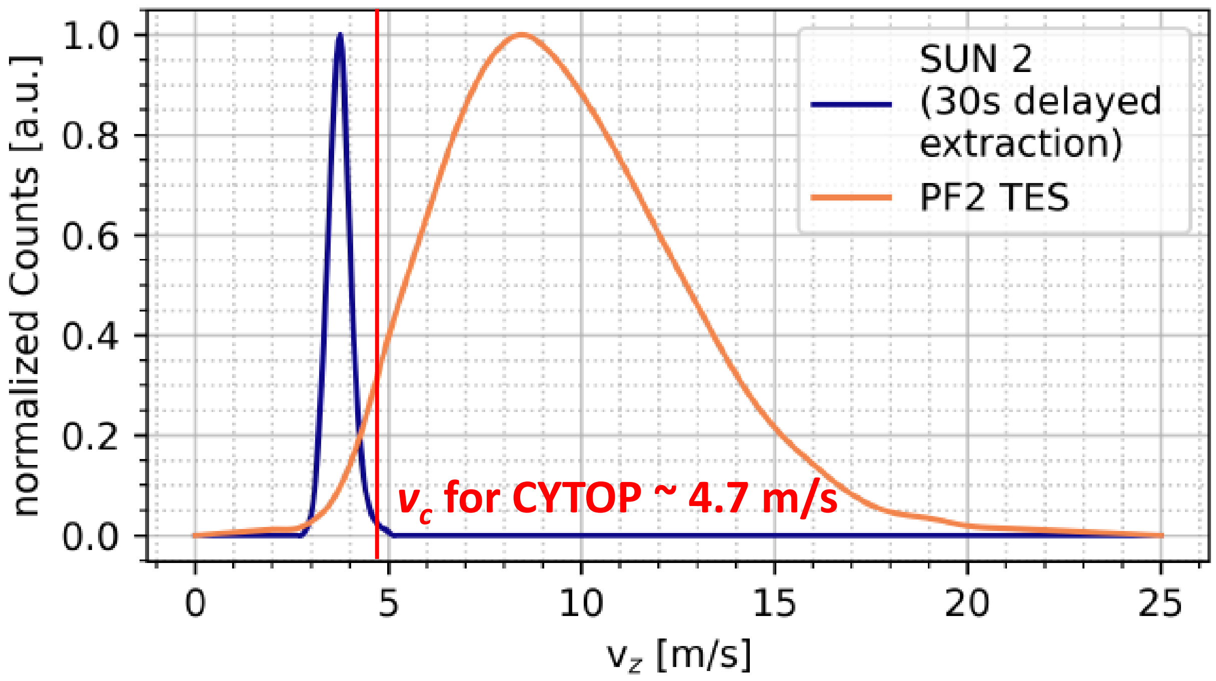


1D time-of-flight spectra from two ILL UCN sources

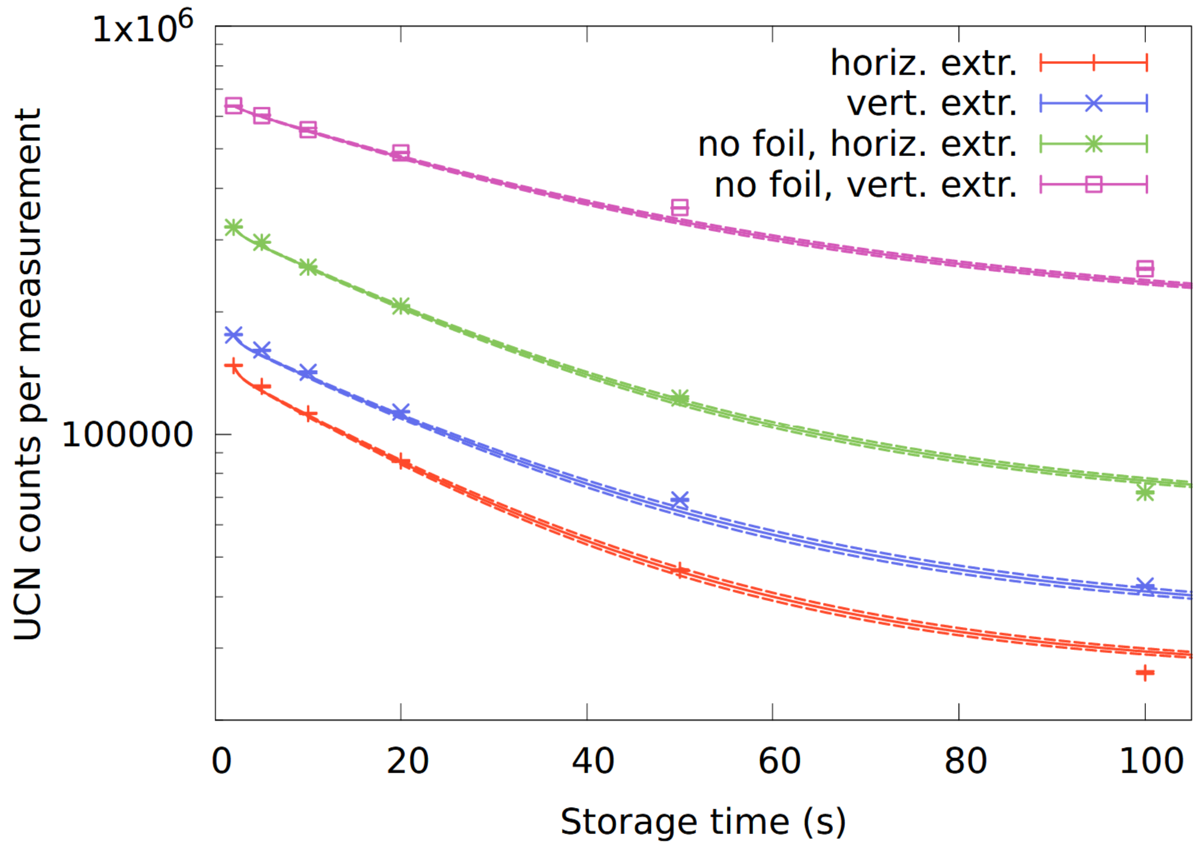


Cf. Neulinger et al., EPJA 58, 141 (2022)

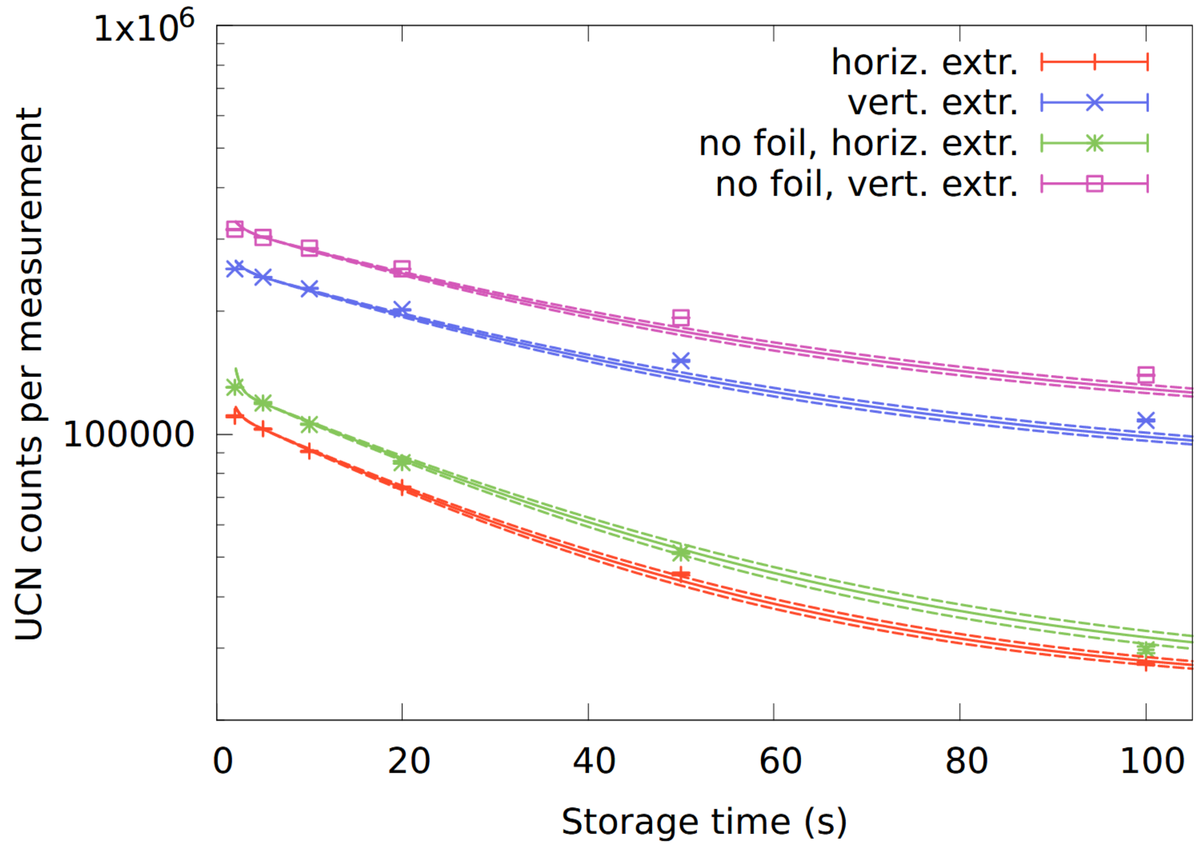
Extraction and Delivery

3

At PF2/EDM turbine exit height

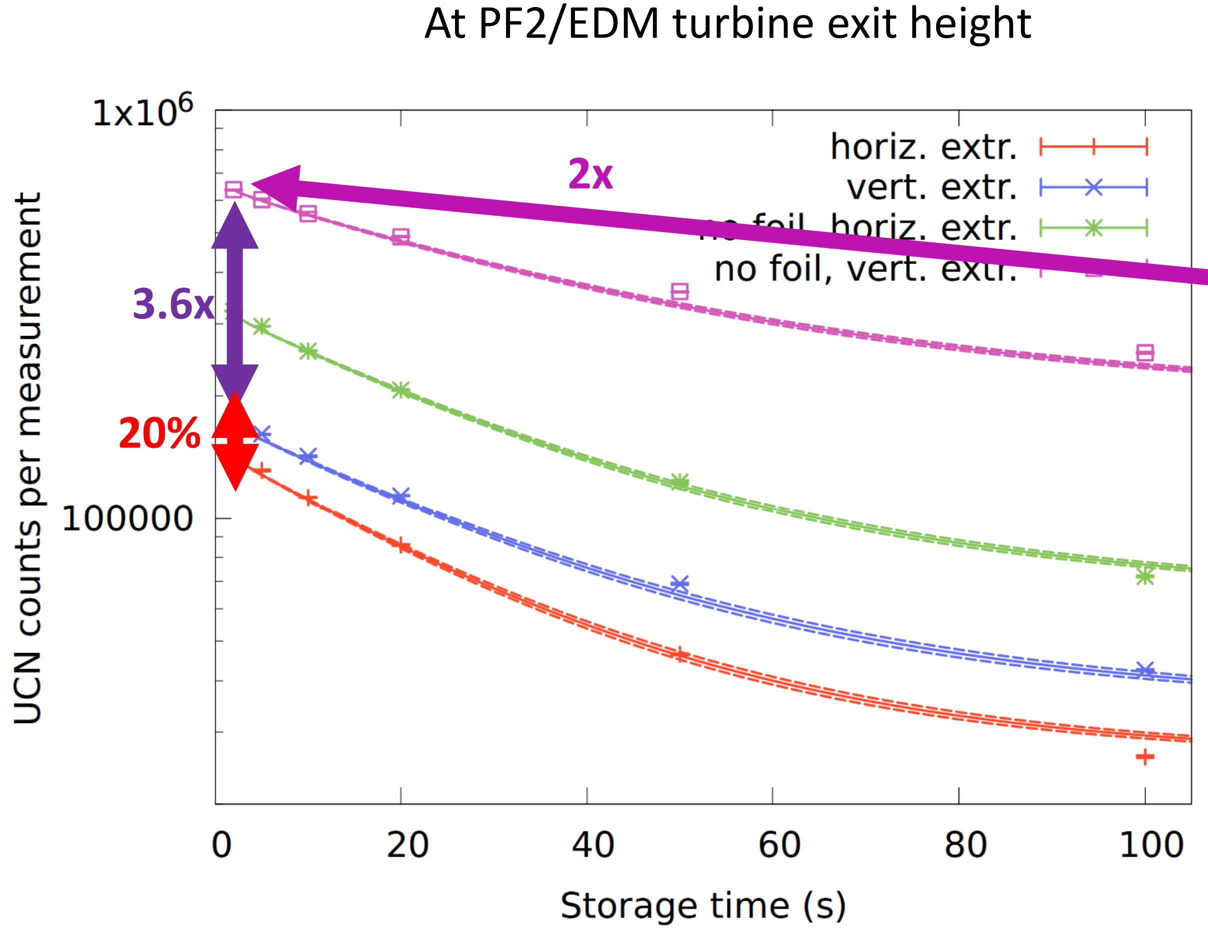


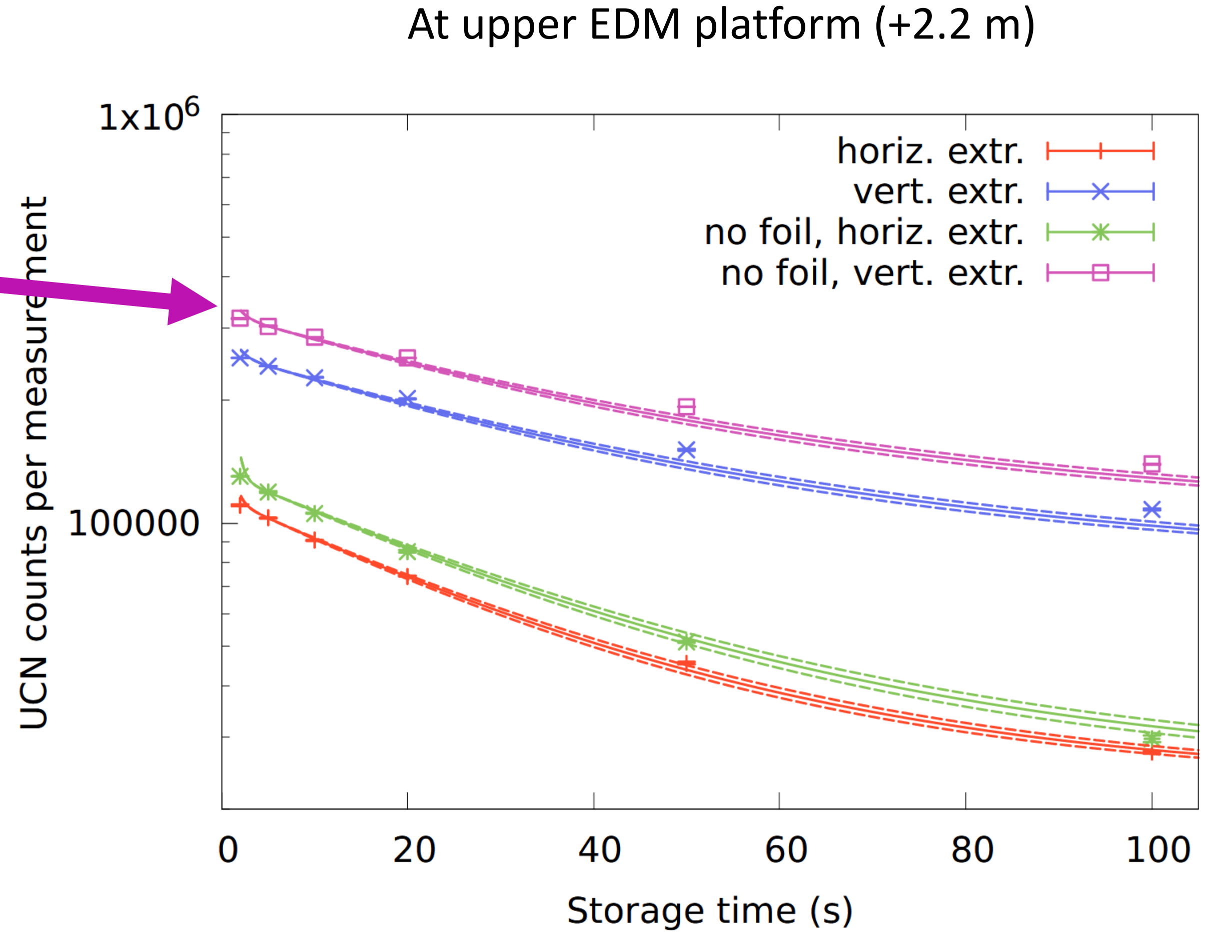
At upper EDM platform (+2.2 m)



Dieter Ries, PhD 2016: storage comparison measurements using a 32 liter stainless-steel reference bottle.
Reduction factor between 2 (horizontal) and 4 (vertical) from foil, but this is not well-understood.

Extraction and Delivery





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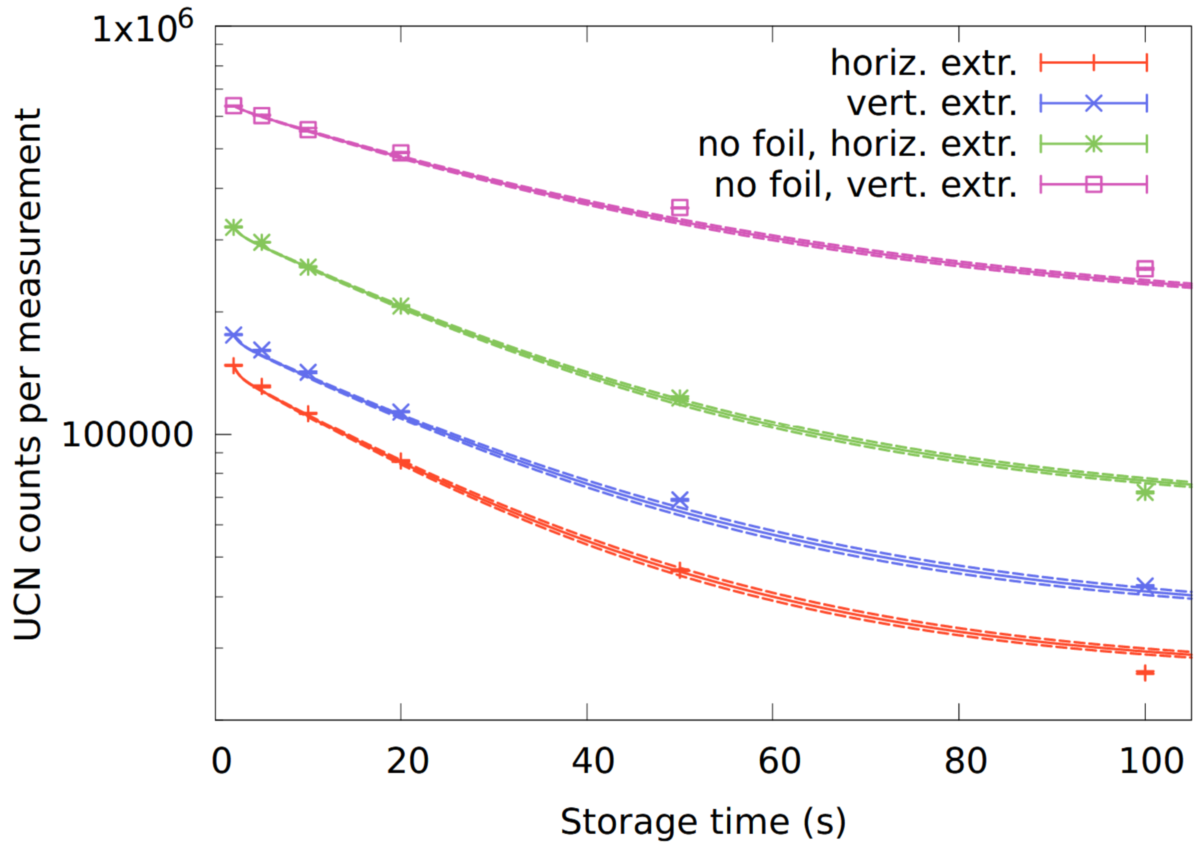
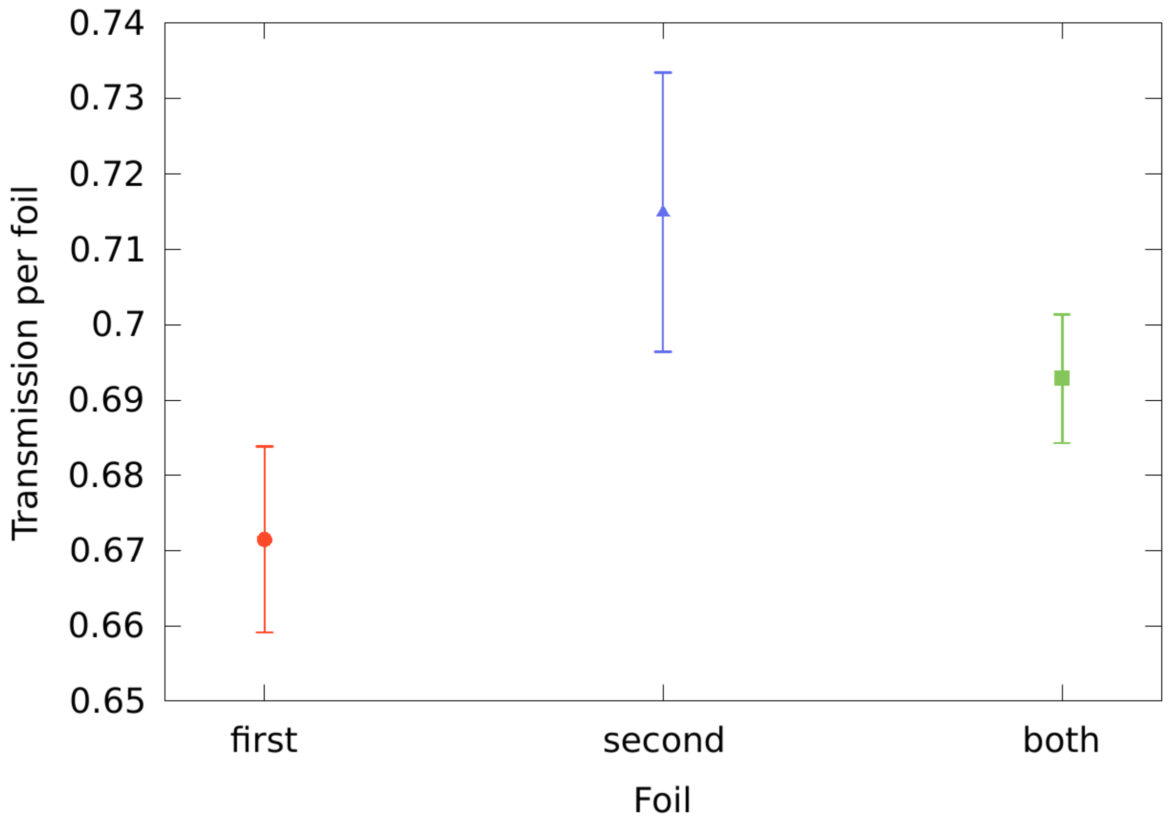


But: factor of 3.6 vs. 1.5 (same batch of foils!)



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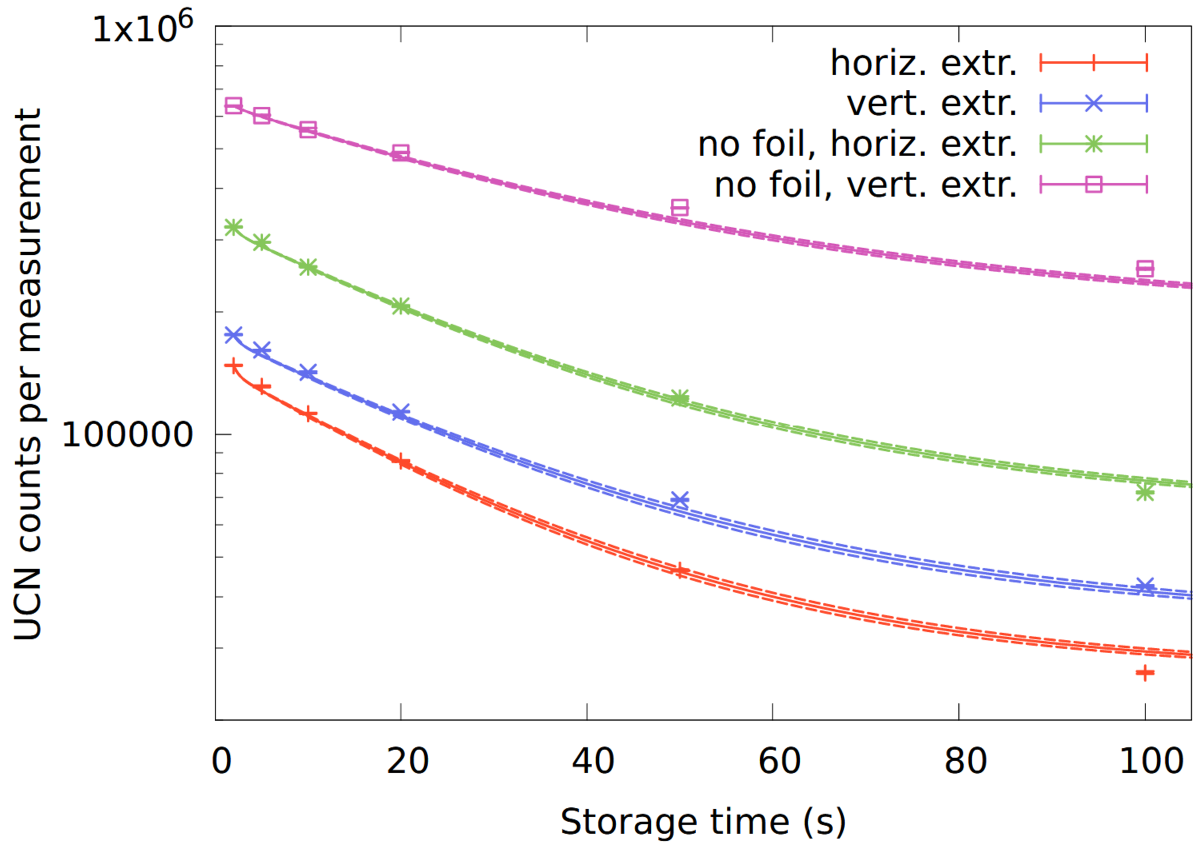

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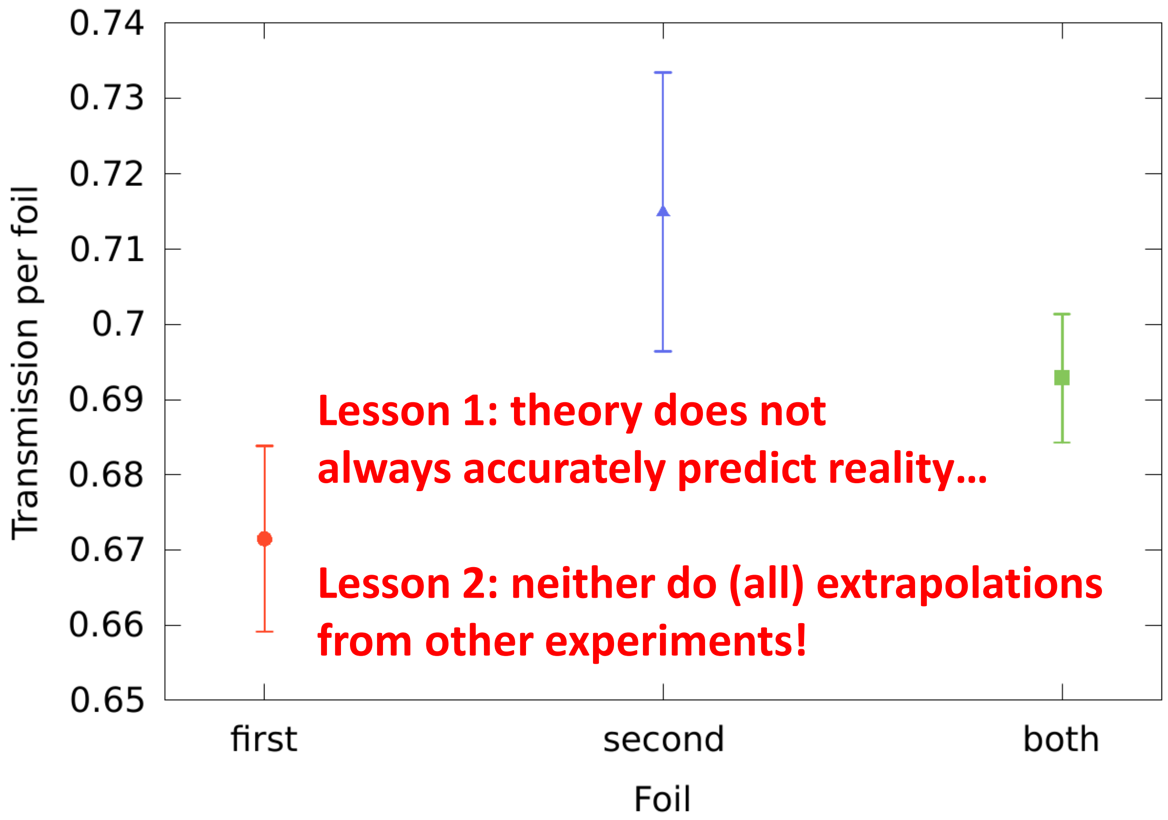

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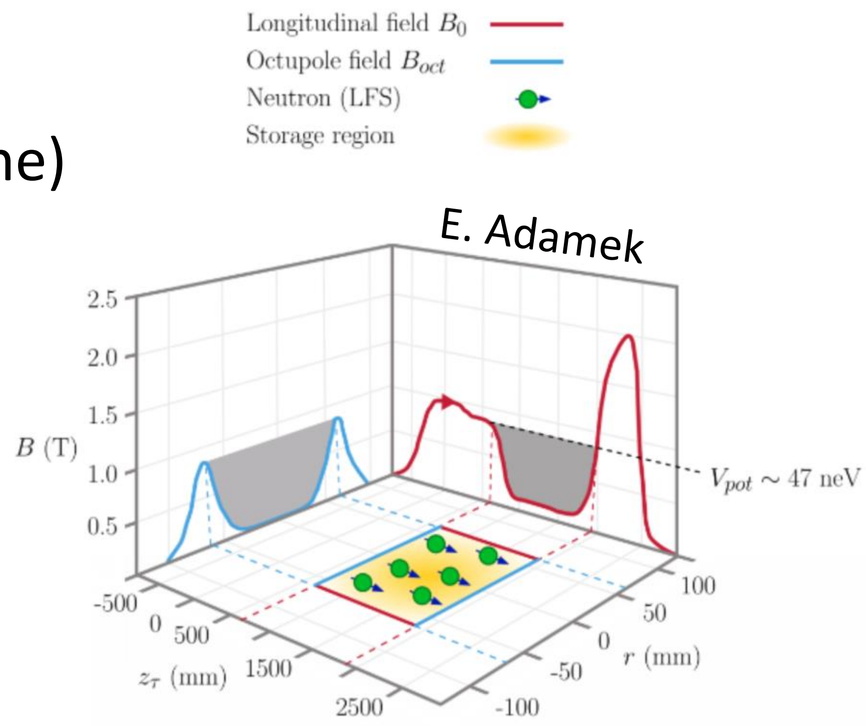
Magnetic trapping in τSPECT (Mainz/PSI)



- Further issues
  - Supercritical contamination can be a problem (e.g., lifetime)
  - Unknown angular spectrum difficult to diagnose
    - TOF and integral spectrometry – also many different approaches
  - Energy-dependent systematic effects

- With the right compromises, one can still win

2 Figures of Merit, including "what is a UCN?"

- Important parameters for an experiment include the measurement time T and the ***counted*** number N of UCN per repetition
- Count-rate limited measurements, sensitivity ~ $N^{-1/2}$
- Frequency measurements, sensitivity ~ T^{-1} or $T^{-3/2}$

- Some examples:
  - Electric dipole moment (EDM): $\sigma \sim T^{-1} N^{-1/2}$, new physics above E ~ $\sigma^{-1/2}$
  - Neutron lifetime τ: $\sigma \sim \tau^{3/2} T^{-1/2} N^{-1/2}$, new physics hidden by SM discrepancy (!)
  - Neutron oscillations, period τ: $\sigma \sim \tau^{1} T^{-1} N^{-1/2}$, new physics above E ~ $\sigma^{-1/5}$

- General trend: high numbers, long time… but time limitations can differ

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- Two more important caveats:
  - Different spectra for different purposes
  - Also integrated angular spectrum (storage) vs. collimated flux (GQS, present-day)

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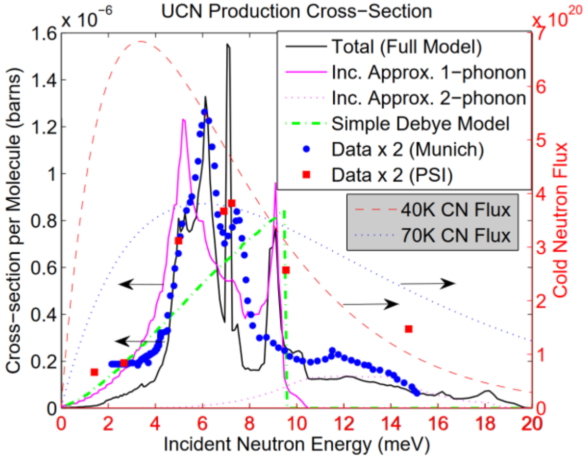
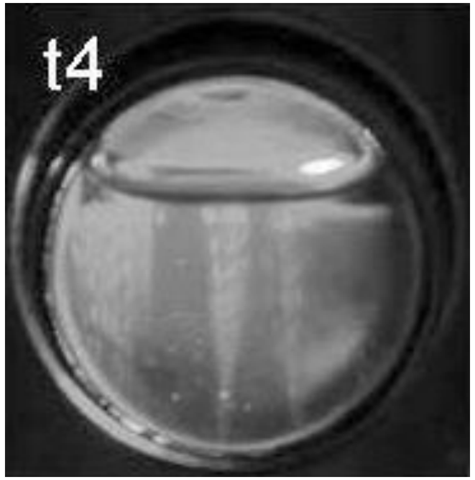
arXiv:1005.1016v1



I. Altarev



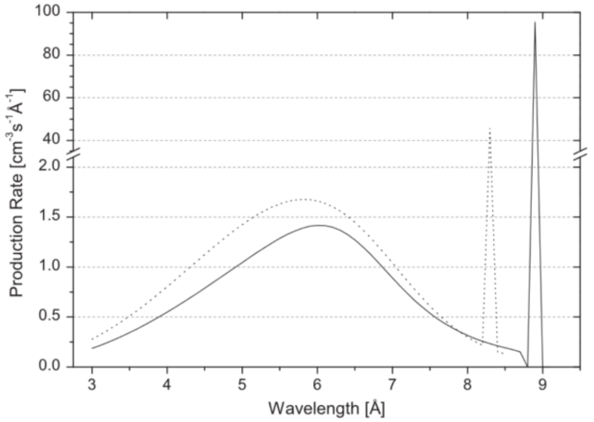
105 neV

~40 ms

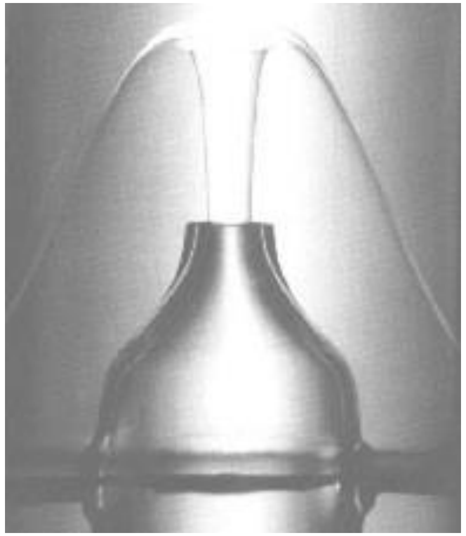
~4 K

0.3 nm

NIM A 611 (2009) 259–262



E. Tretkoff / APS



18.5 neV

~700 s

~1 K

0.9 nm

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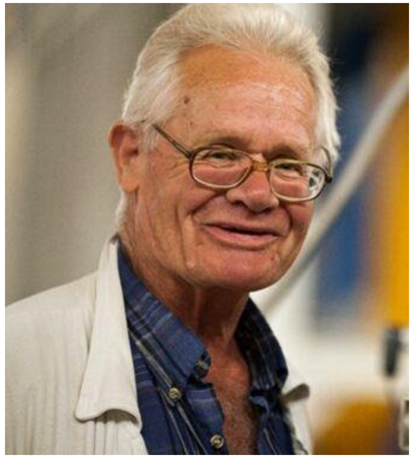

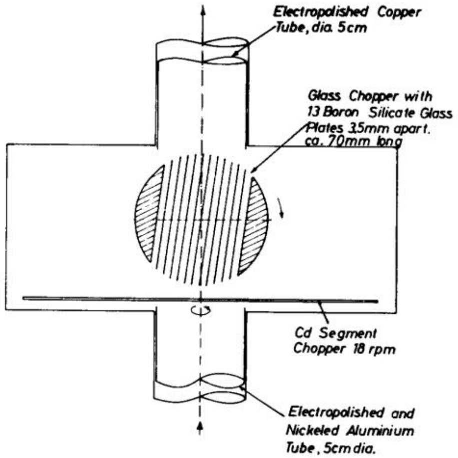

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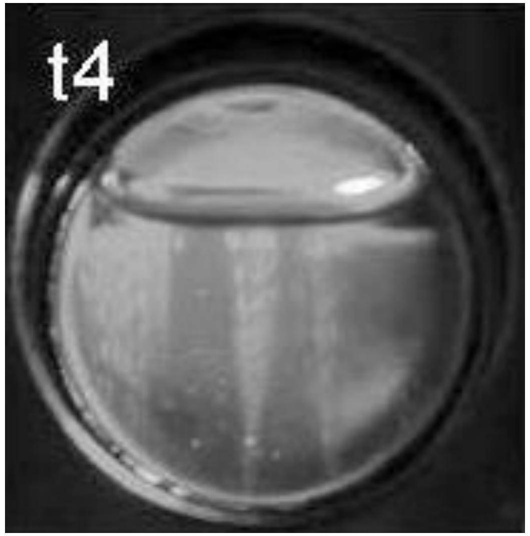


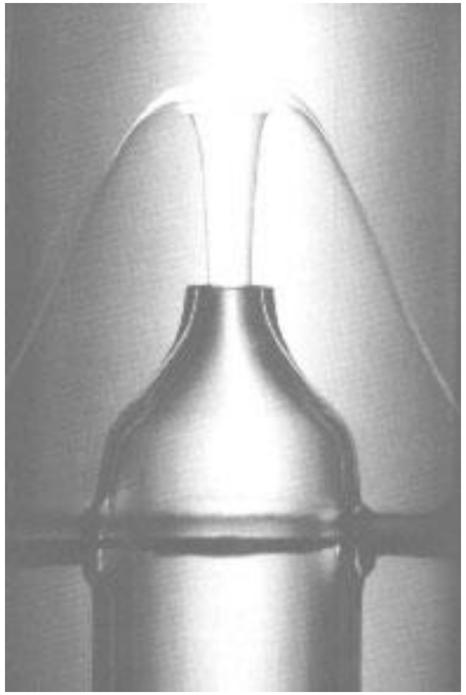
MEASUREMENTS OF TOTAL CROSS SECTIONS FOR VERY SLOW NEUTRONS WITH VELOCITIES FROM 100 m/sec TO 5 m/sec

A. STEYERL
Physik-Department, Technische Hochschule München, Munich, Germany

Received 24 February 1969

Very cold neutrons from 60 μeV to 0.1 μeV were obtained through a vertical total-reflecting neutron guide tube. Total cross sections measured by time-of-flight technique for gold and aluminium were found to obey the $1/v$ law.

E. Tretkoff / APS



105 neV

~40 ms

~4 K

0.3 nm

Remember that mechanical phase-space transformation is a longstanding workhorse solution!

18.5 neV

~700 s

~1 K

0.9 nm

Some UCN sources worldwide

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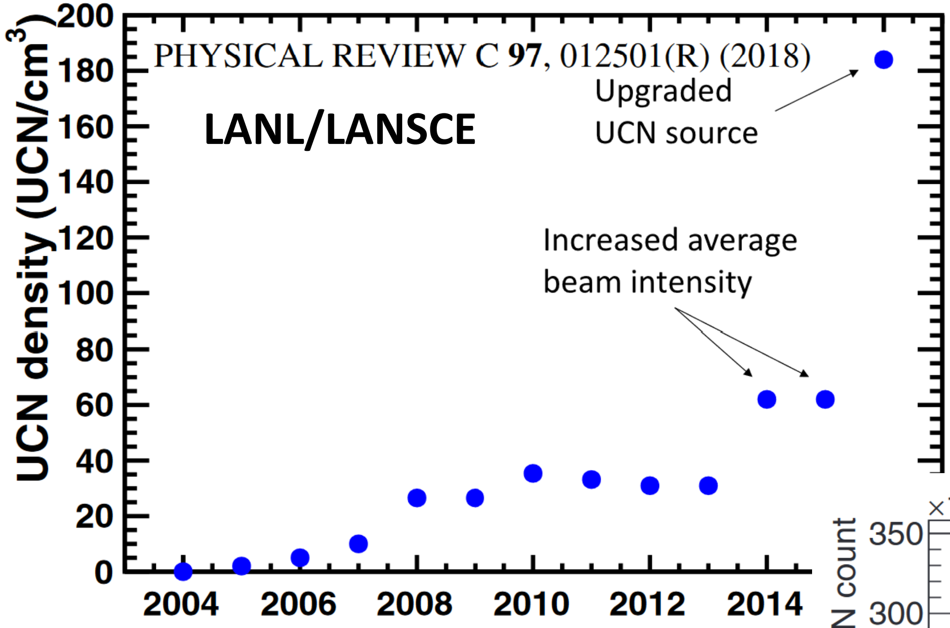

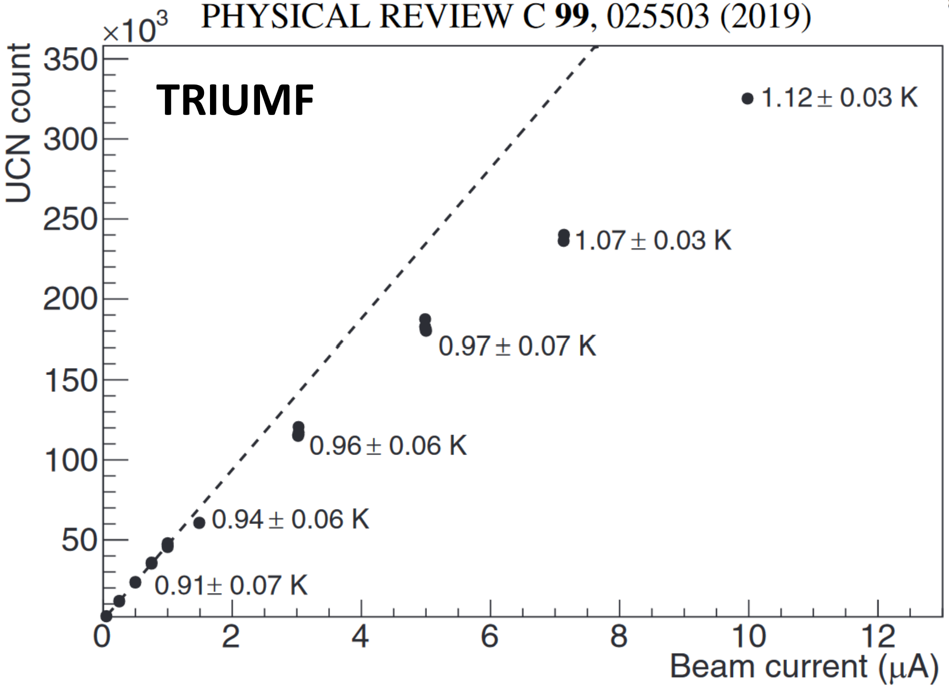

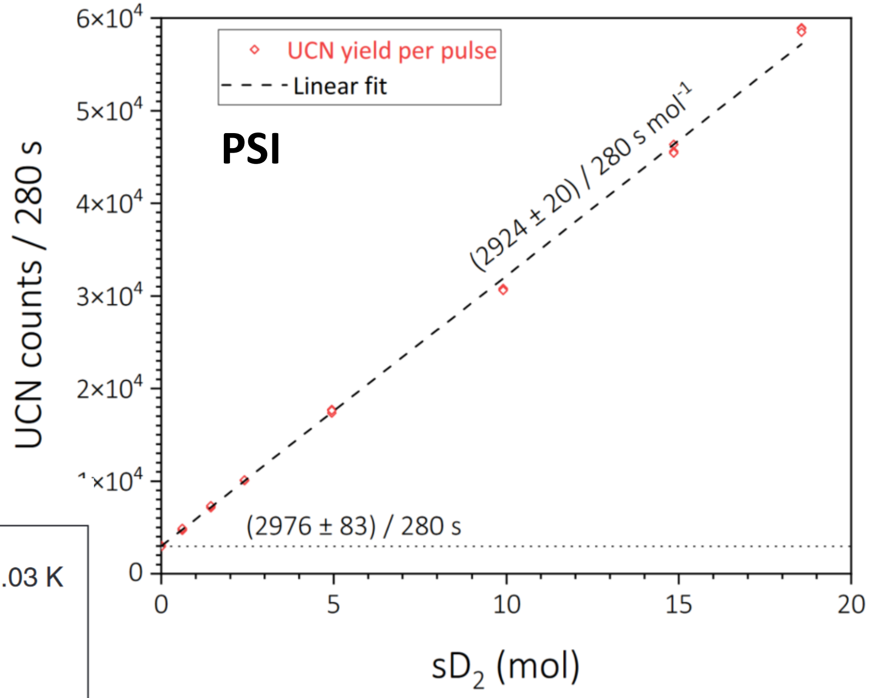

PHYSICAL REVIEW C **107**, 035501 (2023)

$$(33.3 \pm 0.2) \times 10^{-3}\ \mathrm{cm}^{-3}\ \mu\mathrm{C}^{-1}$$

In today's experiments:

"Good" UCN densities ~ 1-10 cm^{-3}
"Excellent" UCN densities: ~ 100 cm^{-3}

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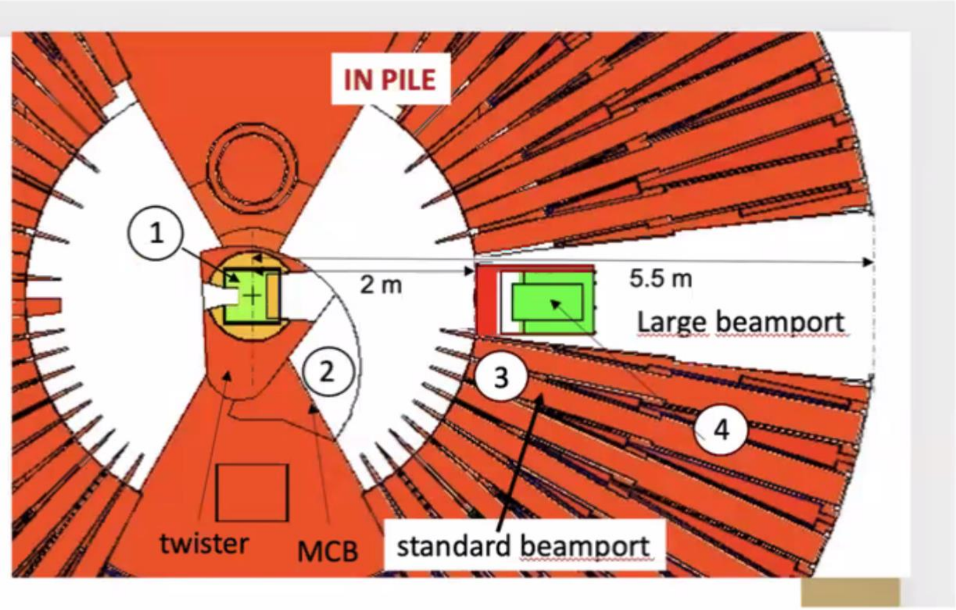
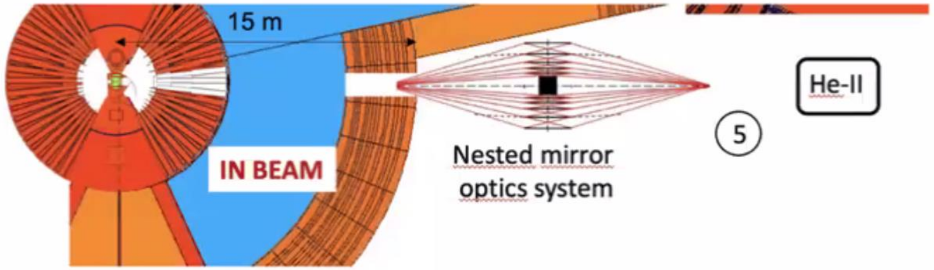
Survey of HighNESS studies





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		SD_2 thin slab in twister - location 1		
Fig. 5	1.81	3.1×10^5	5.6×10^8	760
Fig. 6	1.75	7.7×10^5	1.4×10^9	2910
Fig. 7	0.38	1.3×10^6	5.0×10^8	560
Fig. 9	0.13	1.7×10^6	2.2×10^8	520
		full SD_2 in twister - location 1		
Fig. 10	48.2	6.56×10^5	1.32×10^9	39886
		SD_2 thin slab in MCB - location 2		
Fig. 18a	0.91	3.8×10^4	3.4×10^7	159
		He-II in MCB - location 2		
Fig. 21	24.3	2160	5.23×10^7	328
		He-II in LBP - location 4		
Fig. 24	58	369	2.1×10^7	8
		He-II in beam - location 5		
in-beam (D4.3)	114	234	1.53×10^7	

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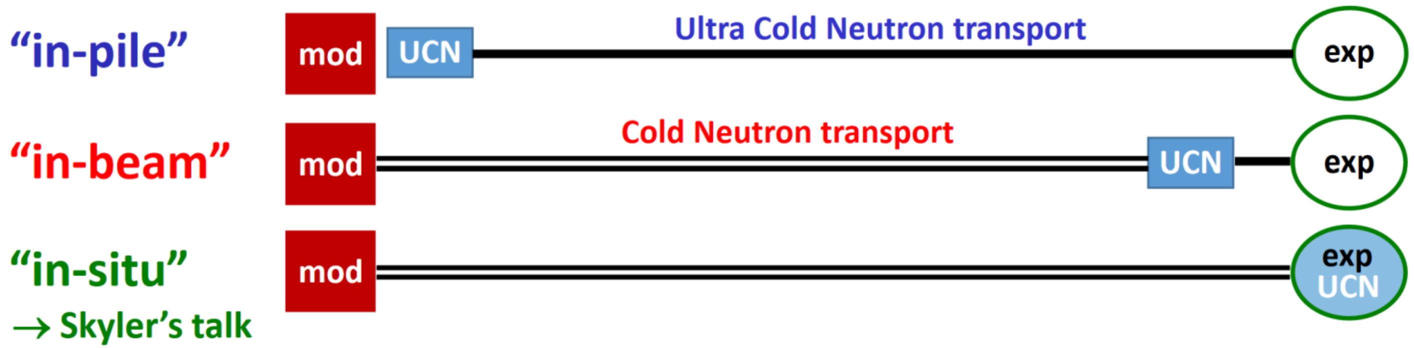
Further conceptual options:

- In-pile He-II (to be studied)
- In-beam He-II (standard guide)
- In-beam, *in-situ* He-II

O. Zimmer, previous workshop



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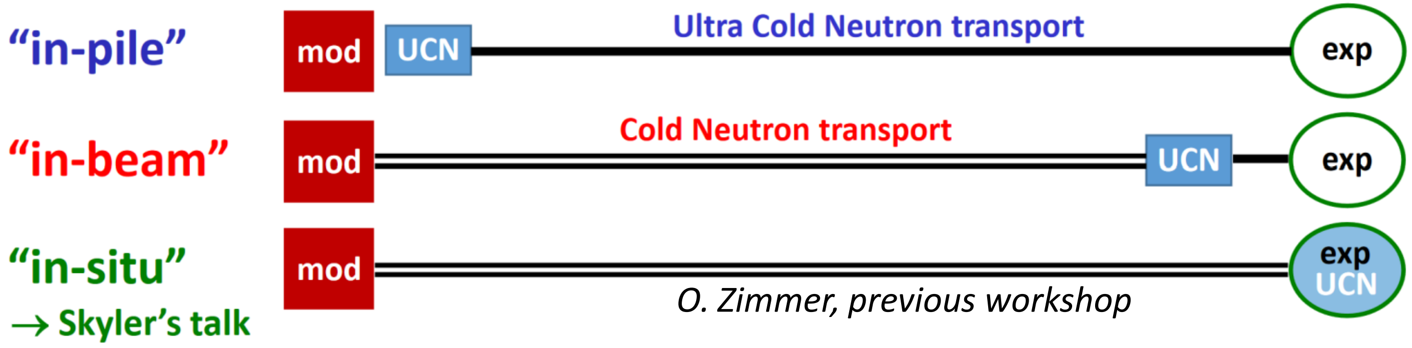

Challenges and advantages, broadly speaking:

- In-pile cooling requirements for T< 1K would be extreme, but academically interesting
- In-beam with standard guides: more reliable/flexible/faster, but less throughput
- *In-situ*: must adapt to experiment (modular approach) – but reduce losses 100x or more

Journal of Neutron Research 24 (2022) 123–143 123, DOI 10.3233/JNR-220044

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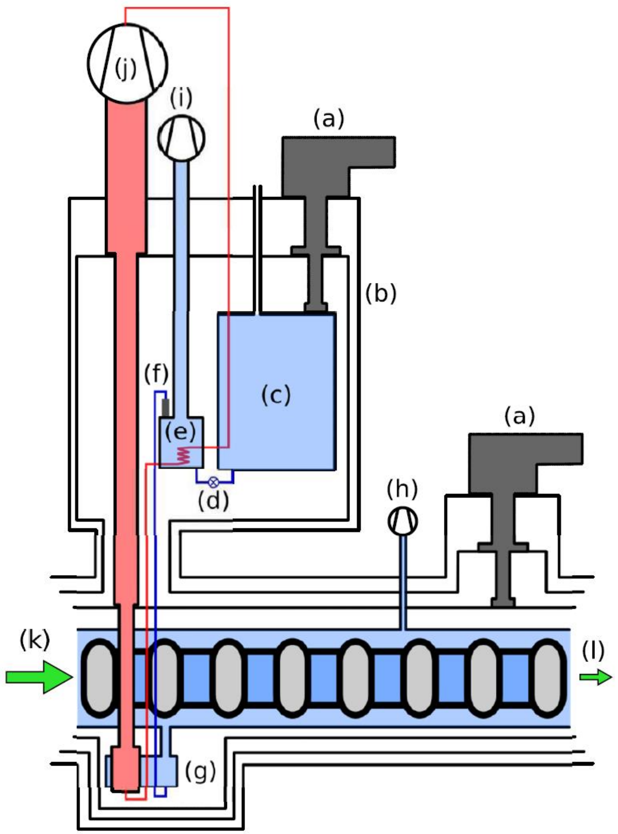
“in-situ”
→ Skyler’s talk

O. Zimmer, previous workshop



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Beamline	$\frac{d\Phi}{d\lambda}\|_{8.9\,\text{Å}}$ [cm^{-2} s^{-1} Å^{-1}]		P_I [cm^{-3} s^{-1}]	ρ [cm^{-3}]		ρ_{700} [cm^{-3}]	
ILL/H172b (SUN-2)	1×10^8	[23,41]	5.0	220	[58]	3200	
ILL/H113 (PF1b)	1.5×10^8	[4]	7.5	370		5300	
ILL/H523 (SuperSUN)	2.7×10^8		13.5	330*		1700†	[58]
ESS/ANNI (2 MW)	8.4×10^7	[46]‡	4.2	210		2900	
ESS/ANNI (5 MW)	2.1×10^8	[46]	11	540		7700	
ESS/LBP (2 MW)	1.7×10^9	[60,63]‡	84	4100		6.6×10^4	
ESS/LBP (5 MW)	4.2×10^9	[60,63]	209	1.0×10^4		1.5×10^5	

* The values given for P_I and ρ correspond to the phase I configuration, which uses to a CYTOP-on-nickel convertor vessel rather than $V_c = 233$ neV [12].

† The storage time constant in SuperSUN phase II will be extended by a 2.1 T magnetic trapping potential together with a CYTOP-on-nickel material wall, as discussed in Section 3.2 [12,65]. The value of 1700 cm^{-3} was estimated for polarized UCN with respect to this situation rather than the reference value $V_c = 233$ neV that was used for other values in this column.

‡ 5 MW values scaled to 2 MW.

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UCN produced in SD2, with *in-situ* energy up to 150 neV (104 – 254 neV extracted)

Similar upper cutoff, but only the helium spectrum includes UCN below 100 neV (~20%)

UCN produced in He-II, with *in-situ* energy up to 233 neV (18.5 – 252 neV extracted)

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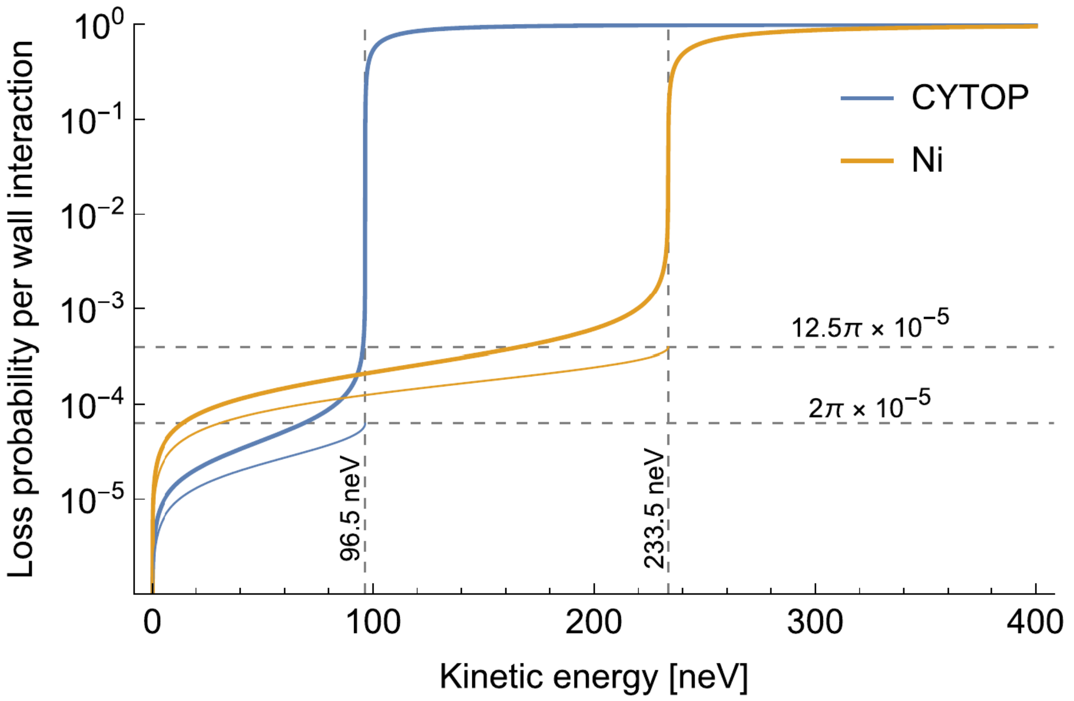
No UCN below 100 neV (SD_2 options)

~20% below 100 neV (He-II options)

Optical Potential:

$$U = \frac{2\pi\hbar^2}{m}\rho\left(a_r - i a_i\right) \pm \mu B$$



Storage Losses:

$$\tau^{-1} = \frac{A}{4V} v \bar{\mu}(E) + \tau_\beta^{-1}$$

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Thin SD_2 slab in Twister

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Considerations:

- Maximum extraction distance
- Separate backgrounds?
- Transmissive foils likely required
- Height of experiment

- Science cases
  - High flux flow-through experiments
  - Low density or high-duty storage
  - User-mode research and development

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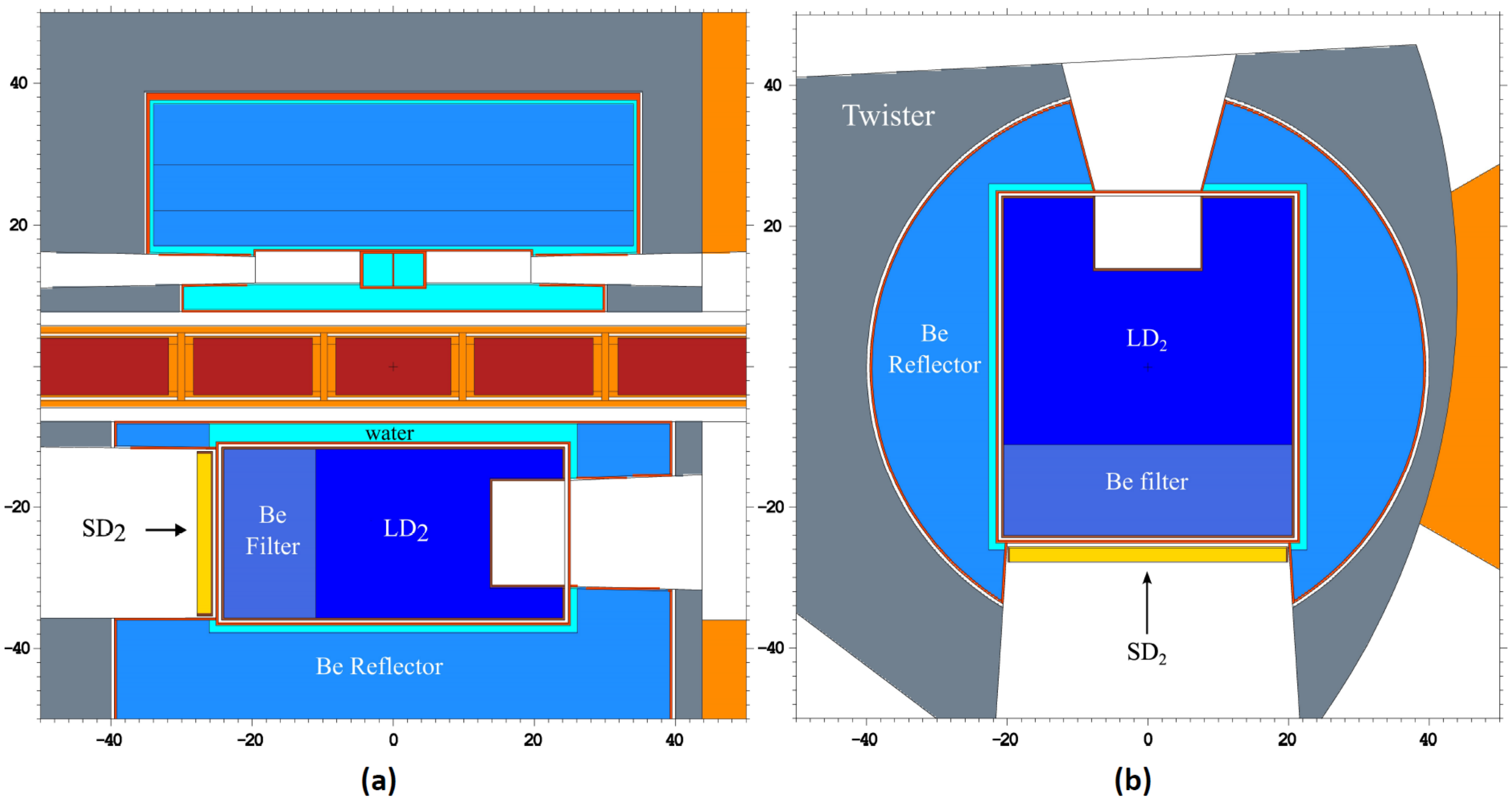

Figure 5: MCNP model of a 2-cm-thick SD_2 UCN source complementing the LD_2 baseline for UCN production. (a) vertical cut, perpendicular to the proton beam direction. (b) cut parallel to the target plane with the proton beam impinging from the left.

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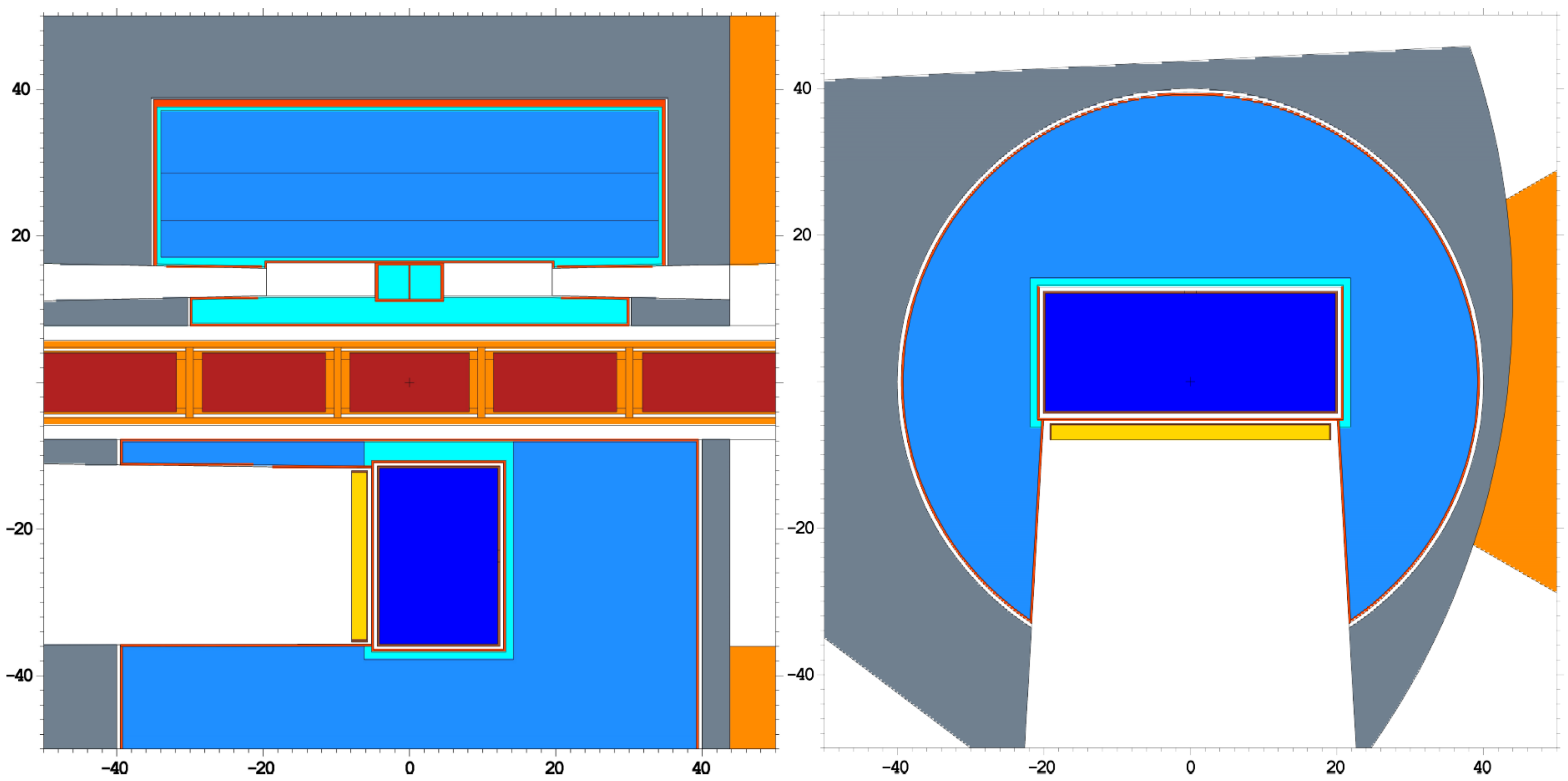

(a) (b)

Figure 6: Fixed 2-cm SD_2 UCN source with optimized cold LD_2 moderator. (a) vertical cut, perpendicular to the proton beam direction. (b) cut parallel to the target plane with the neutron beam impinging from the left. The figure of merit for the optimization was the mean UCN production rate density inside the SD_2 converter.

1

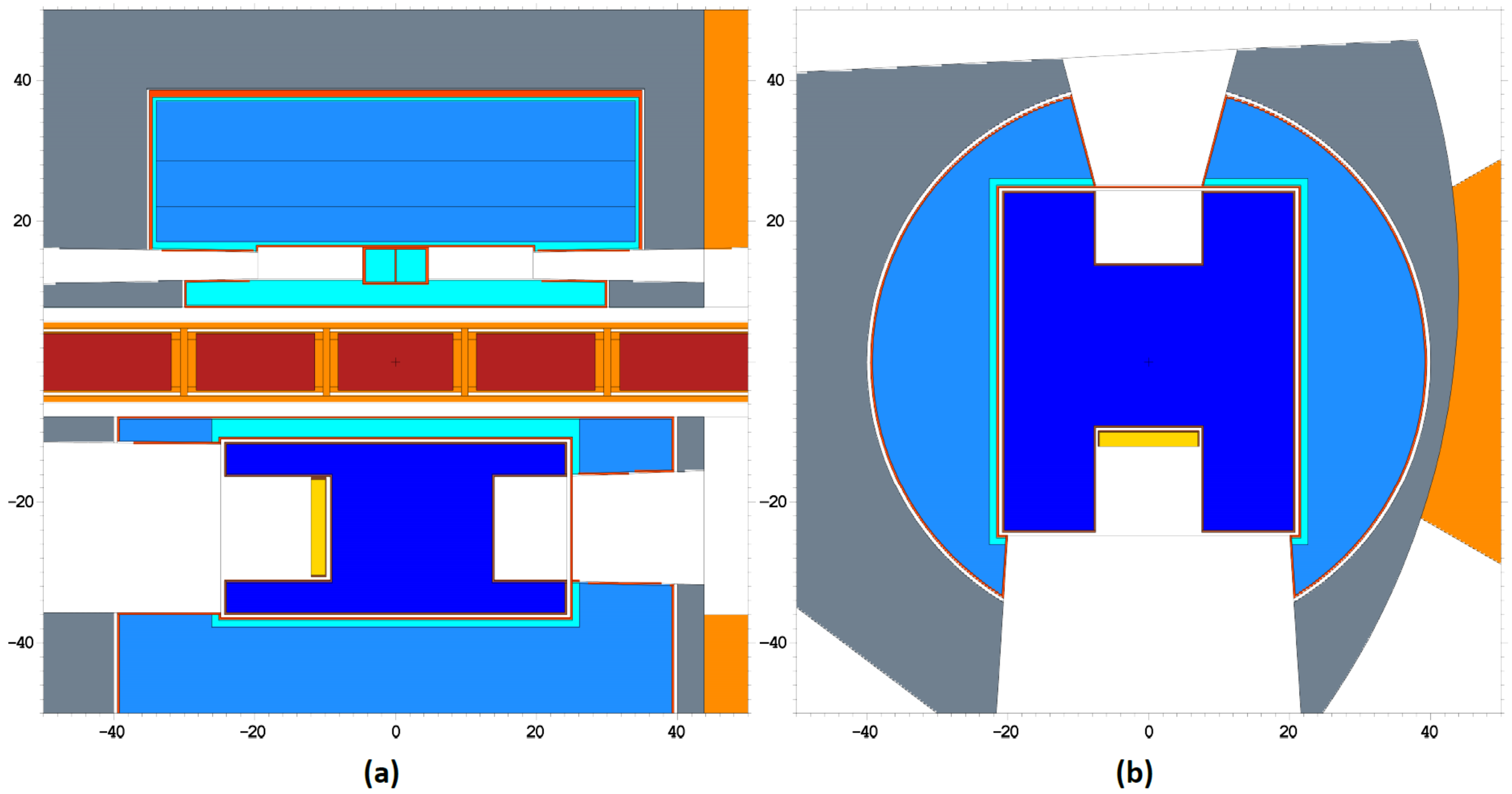

Figure 7: Fixed 2-cm SD_2 UCN source in a reentrant hole inside the LD_2 moderator, hence closer to the hot-spot of cold neutrons production. (a) vertical cut, perpendicular to the proton beam direction. (b) cut parallel to the target plane with the neutron beam impinging from the left. The figure of merit for the optimization was the UCN production rate density inside the SD_2 converter.

1

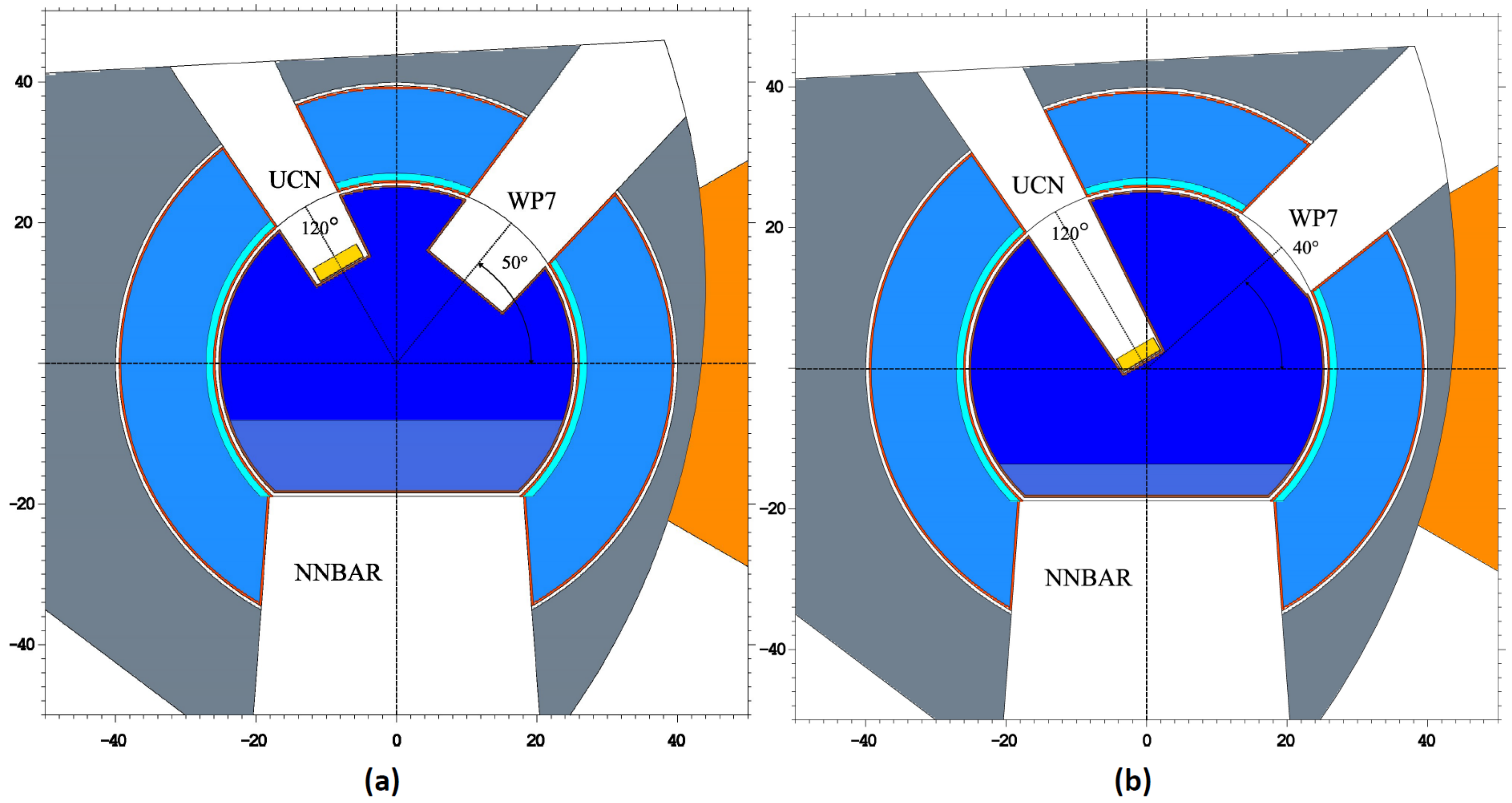

Figure 9: Cylindrical cold moderator (45 cm diameter) with three openings for NNBAR, UCN and neutron scattering experiments. The SD_2 converter has a fixed thickness of 2 cm (a) design with tentative dimensions and (b) design with reentrant-hole depths and Be filter that maximise P_{UCN}. The cut is parallel to the target plane with the neutron beam impinging from the left.

1

Massive SD_2 in Twister

Option	Volume [liters]	P_{UCN} [cm^{-3} s^{-1}]	$\dot{N}_{UCN}$ [s^{-1}]	Heat [Watt]
		SD_2 thin slab in twister - location 1		
Fig. 5	1.81	3.1×10^5	5.6×10^8	760
Fig. 6	1.75	7.7×10^5	1.4×10^9	2910
Fig. 7	0.38	1.3×10^6	5.0×10^8	560
Fig. 9	0.13	1.7×10^6	2.2×10^8	520
		full SD_2 in twister - location 1		
Fig. 10	48.2	6.56×10^5	1.32×10^9	39886
		SD_2 thin slab in MCB - location 2		
Fig. 18a	0.91	3.8×10^4	3.4×10^7	159
		He-II in MCB - location 2		
Fig. 21	24.3	2160	5.23×10^7	328
		He-II in LBP - location 4		
Fig. 24	58	369	2.1×10^7	8
		He-II in beam - location 5		
in-beam (D4.3)	114	234	1.53×10^7	

Considerations:

- Likely *very* challenging...
- Otherwise, as other in-pile SD2

1

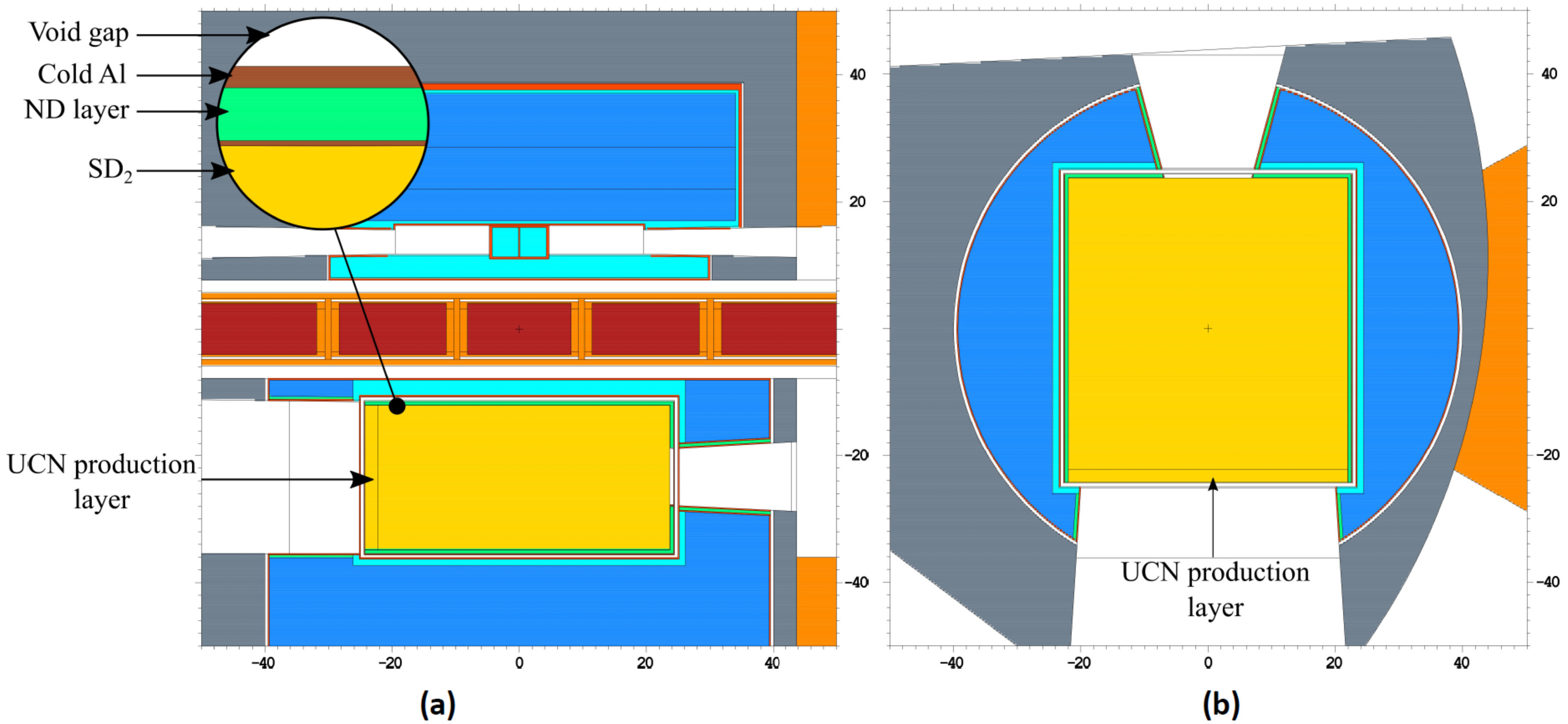

Figure 10: MCNP model of a 41 x 48 x 24 SD_2 moderator for VCN and UCN production. (a) vertical cut, perpendicular to the proton beam direction. The inset zooms on the 5-mm ND reflector layer and its aluminum case (b) cut parallel to the target plane with the neutron beam impinging from the left.

1 Thin SD_2 in Moderator Cooling Block

Option	Volume [liters]	P_{UCN} [cm^{-3} s^{-1}]	$\dot{N}_{UCN}$ [s^{-1}]	Heat [Watt]
		SD_2 thin slab in twister - location 1		
Fig. 5	1.81	3.1×10^5	5.6×10^8	760
Fig. 6	1.75	7.7×10^5	1.4×10^9	2910
Fig. 7	0.38	1.3×10^6	5.0×10^8	560
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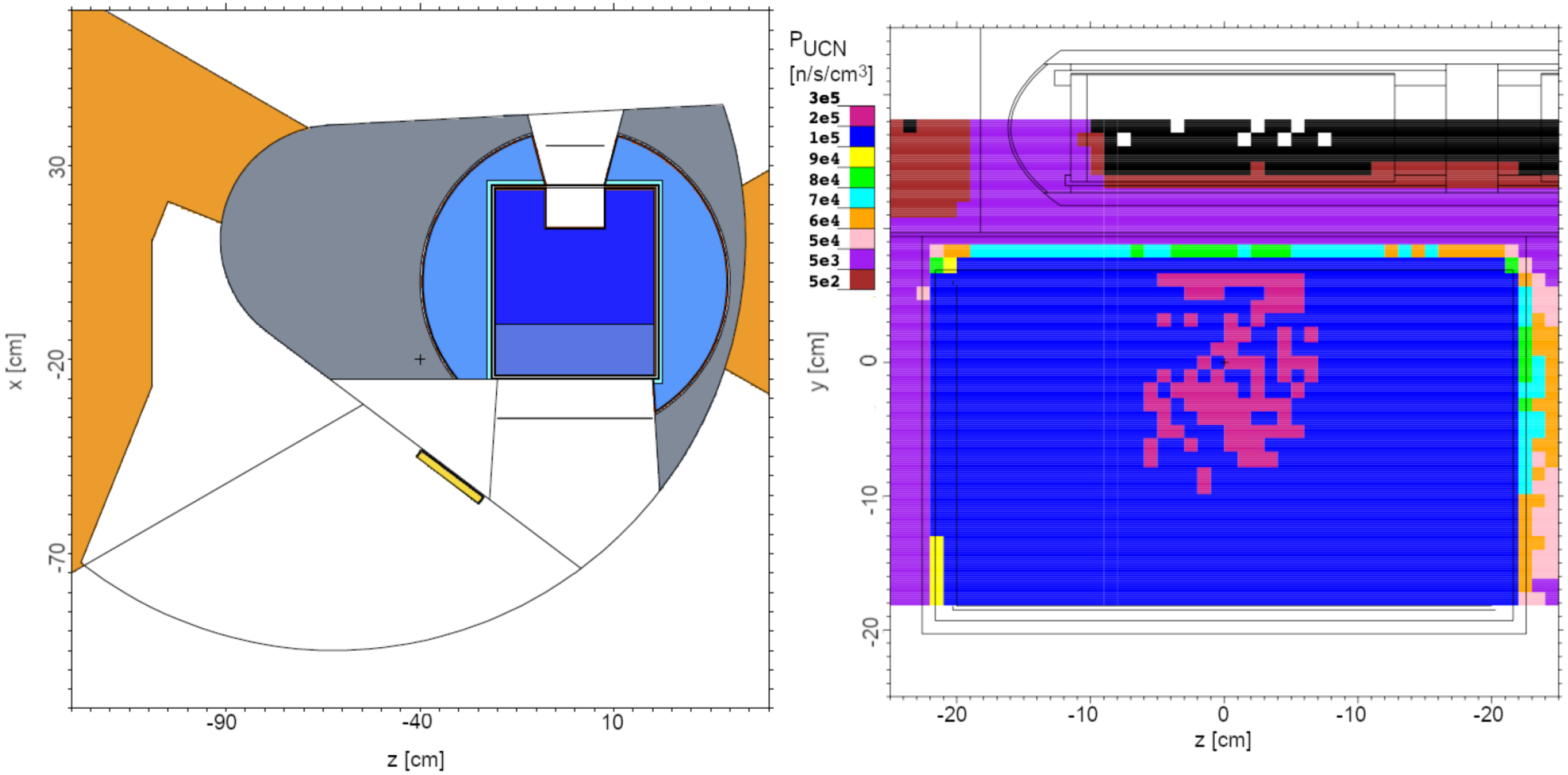
Fig. 21	24.3	2160	5.23×10^7	328
		He-II in LBP - location 4		
Fig. 24	58	369	2.1×10^7	8
		He-II in beam - location 5		
in-beam (D4.3)	114	234	1.53×10^7	

Considerations:

- Lower overall statistics
- Shorter extraction path (?)
- Same vertical position
- Otherwise same spectrum

1



(a) **(b)**

Figure 18: (a) Thin box-shaped SD_2 UCN converter placed in MCB. (b) P_{UCN} map in the yz plane measured at the NNBAR emission surface.

1

He-II in Moderator Cooling Block

Option	Volume [liters]	P_{UCN} [cm^{-3} s^{-1}]	$\dot{N}_{UCN}$ [s^{-1}]	Heat [Watt]
		SD_2 thin slab in twister - location 1		
Fig. 5	1.81	3.1×10^5	5.6×10^8	760
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Fig. 24	58	369	2.1×10^7	8
		He-II in beam - location 5		
in-beam (D4.3)	114	234	1.53×10^7	

Considerations:

- UCN extraction and heat load
- Dilution/transport time and loss
- Continuous production or fill/empty?
- Soft spectrum cannot go uphill

- Science cases:
  - Host both storage/flow-through users
  - Low density / long storage (lifetime?)
  - Staged experiments

1

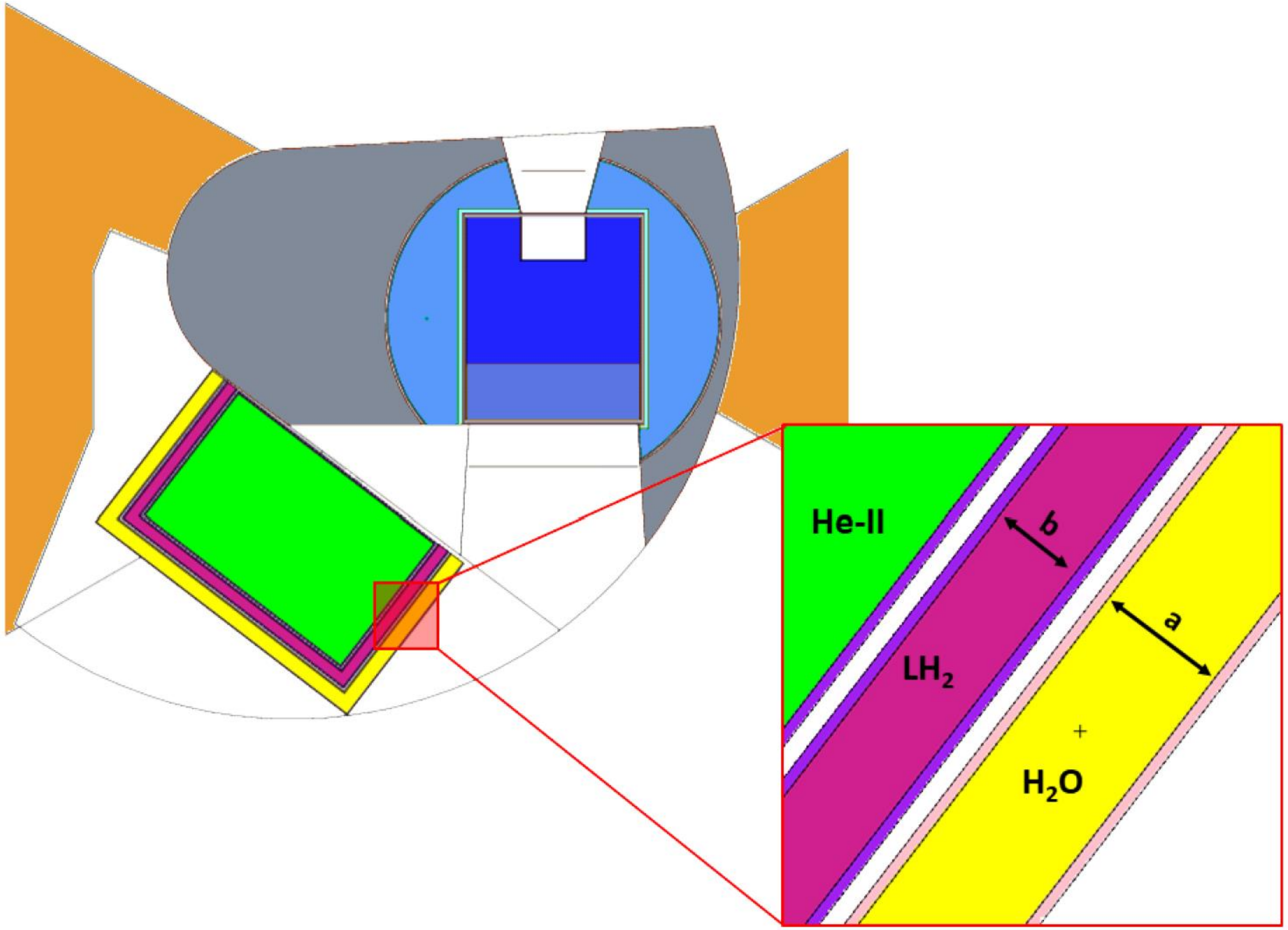

Figure 21: MCNP model (Concept 1 ”coaxial shell design”) of He-II source in the MCB. See explanation in the text.

1

He-II in Large Beam Port

Option	Volume [liters]	P_{UCN} [cm^{-3} s^{-1}]	$\dot{N}_{UCN}$ [s^{-1}]	Heat [Watt]
		SD_2 thin slab in twister - location 1		
Fig. 5	1.81	3.1×10^5	5.6×10^8	760
Fig. 6	1.75	7.7×10^5	1.4×10^9	2910
Fig. 7	0.38	1.3×10^6	5.0×10^8	560
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Fig. 24	58	369	2.1×10^7	8
		He-II in beam - location 5		
in-beam (D4.3)	114	234	1.53×10^7	

Considerations:

- UCN extraction and heat load
- Dilution/transport time and loss
- Soft spectrum cannot go uphill
- Closer to experimental areas

- Science cases:
  - Larger volume more easily fills small experiments (or permits shared use)
  - How will extracted densities compare to He-II in MCB? (Volume, guiding)
  - *In-situ* experiments may be possible?

1

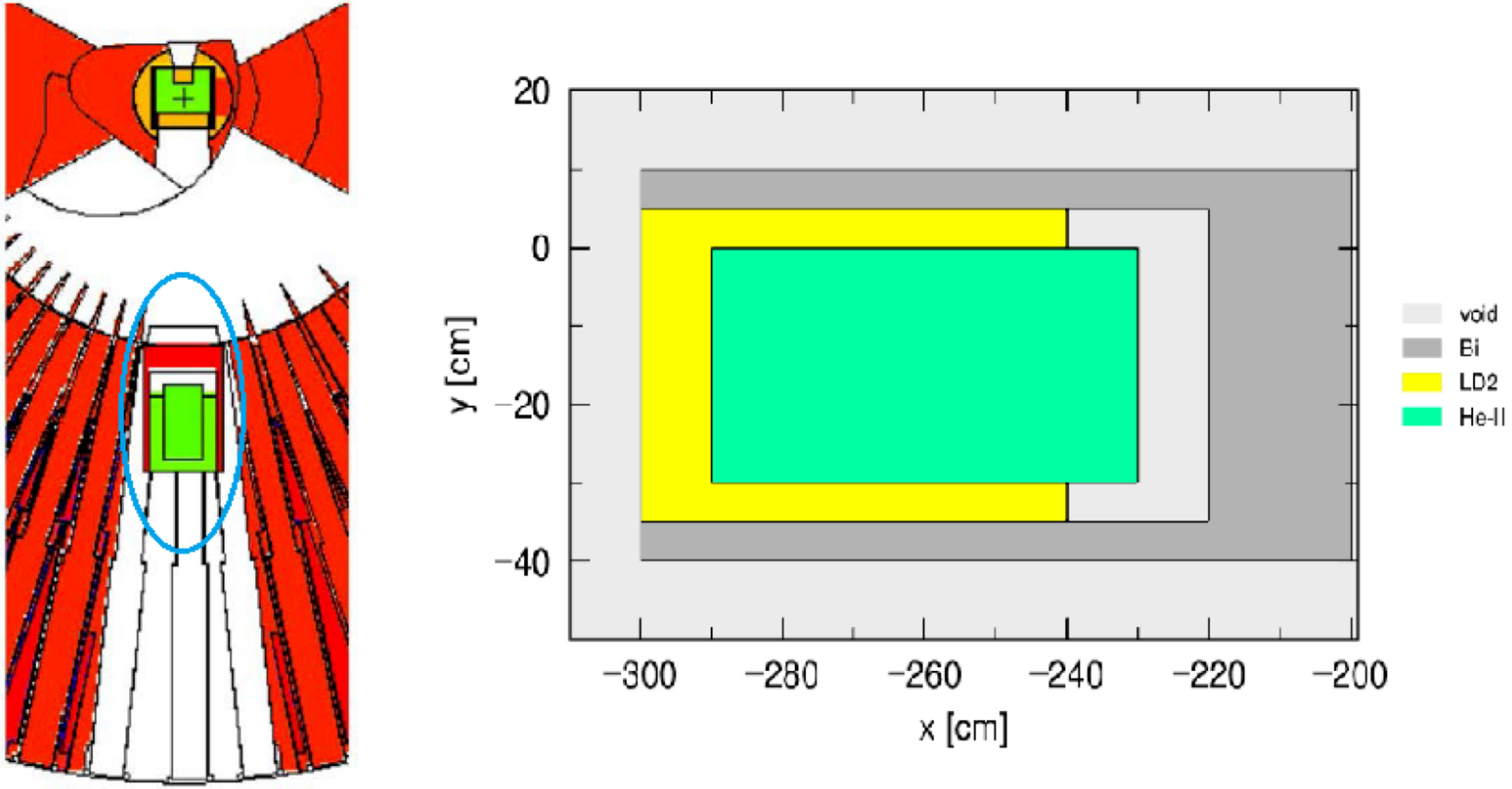

Figure 24: *Left*: MCNP geometry showing the He-II source backed by a LD_2 reflector in the large beamport, concept of Serebrov and Lyamkin [4]. *Right*: The geometry and the materials used in the UCN source located at LBP plotted by PHITS 3.27 [35].

He-II in extracted beam

1

Option	Volume [liters]	P_{UCN} [cm^{-3} s^{-1}]	$\dot{N}_{UCN}$ [s^{-1}]	Heat [Watt]
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Fig. 24	58	369	2.1×10^7	8
		He-II in beam - location 5		
in-beam (D4.3)	114	234	1.53×10^7	

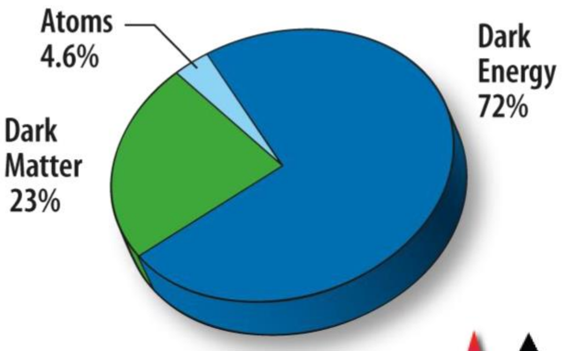
Considerations:

- Best environment for backgrounds
- Best environment for space/access
- Most flexible/adaptable scenario
- What determines the source volume?
- Larger volumes more easily fill small experiments, or permit shared use (?)

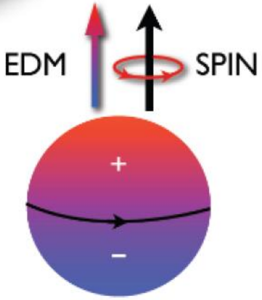
- Science cases:
  - High-density, long-duration storage
  - Closest experiment/source distance
  - *In-situ* experiments

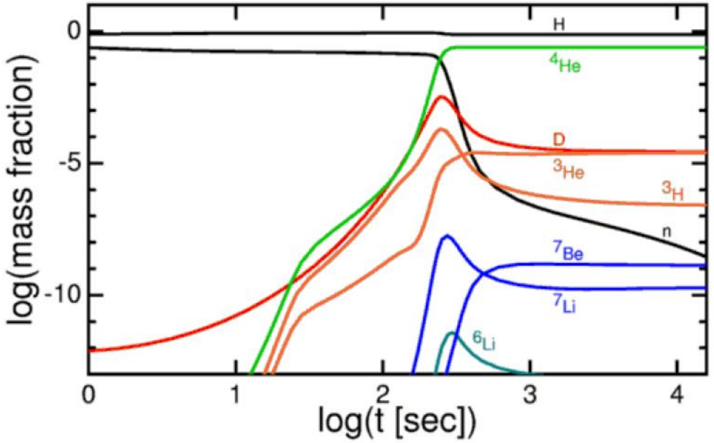
Science topics

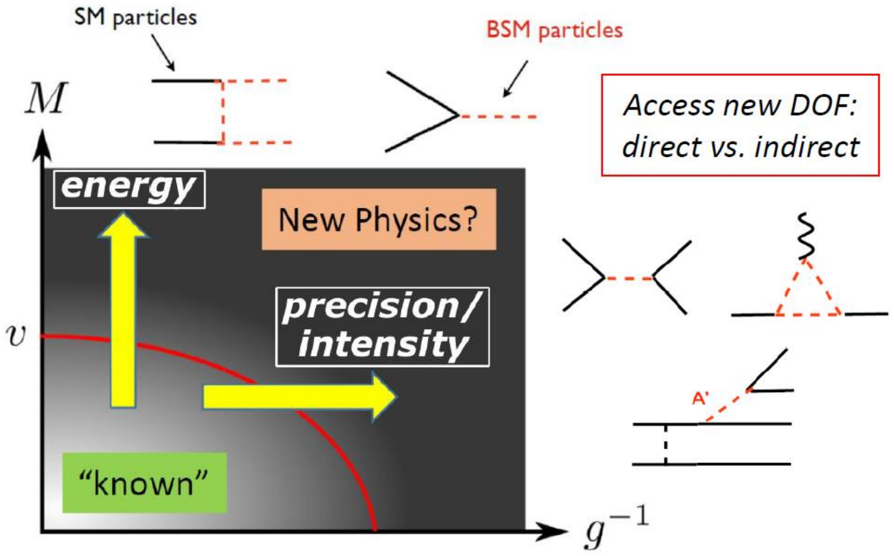
2



Leptons	e	μ	τ
	ν_e	ν_μ	ν_τ
Quarks	u	c	t
	d	s	b



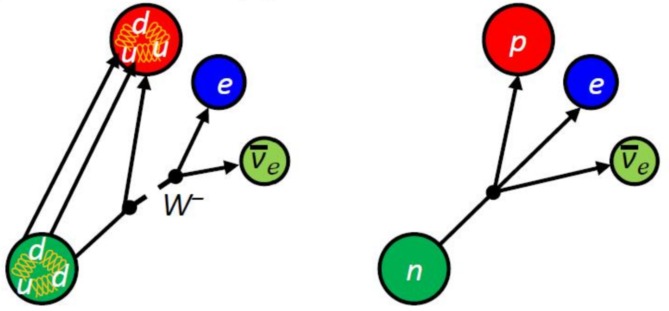


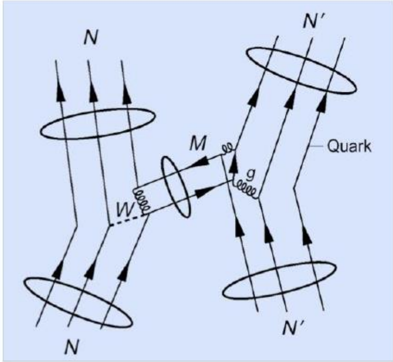


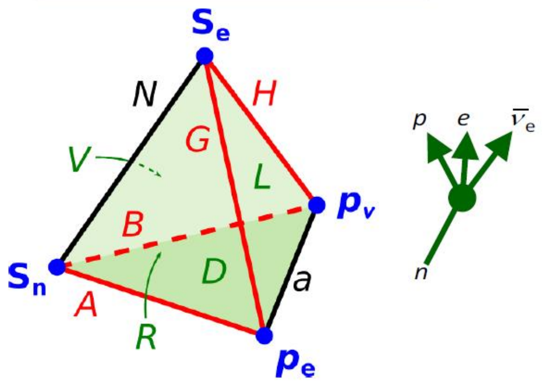
$$\mathcal{L}_{\rm BSM} \rightarrow \mathcal{L}^{\rm eff}_{\rm CPV} = \sum_{k,d} \alpha_k^{(d)} \left(\frac{1}{\Lambda}\right)^{d-4} \mathcal{O}_k^{(d)}$$

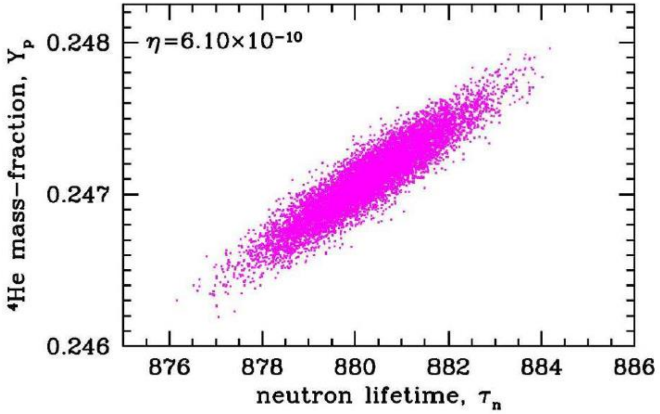
EFT for BSM (e.g. CP-violation)

...cf. Fermi theory for weak interaction

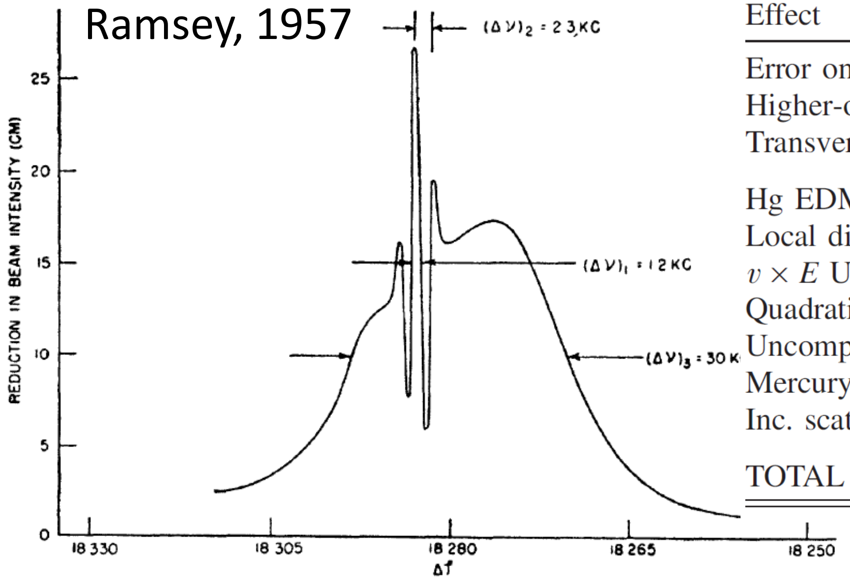








② Electromagnetic Moments (Charge, EDM, MDM, etc.)



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

10^{-28} e.cm

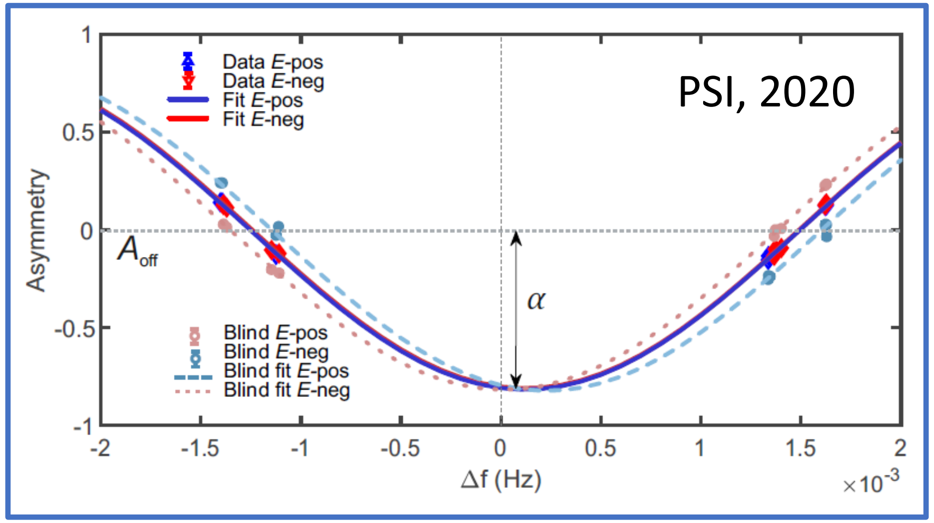
Previous result (ILL), J.M. Pendlebury *et al*, Phys. Rev. D **92** 092003 (2015)

$$d_n = (-0.2 \pm 1.5_{stat} \pm 1.0_{syst}) \times 10^{-26}\ ecm$$

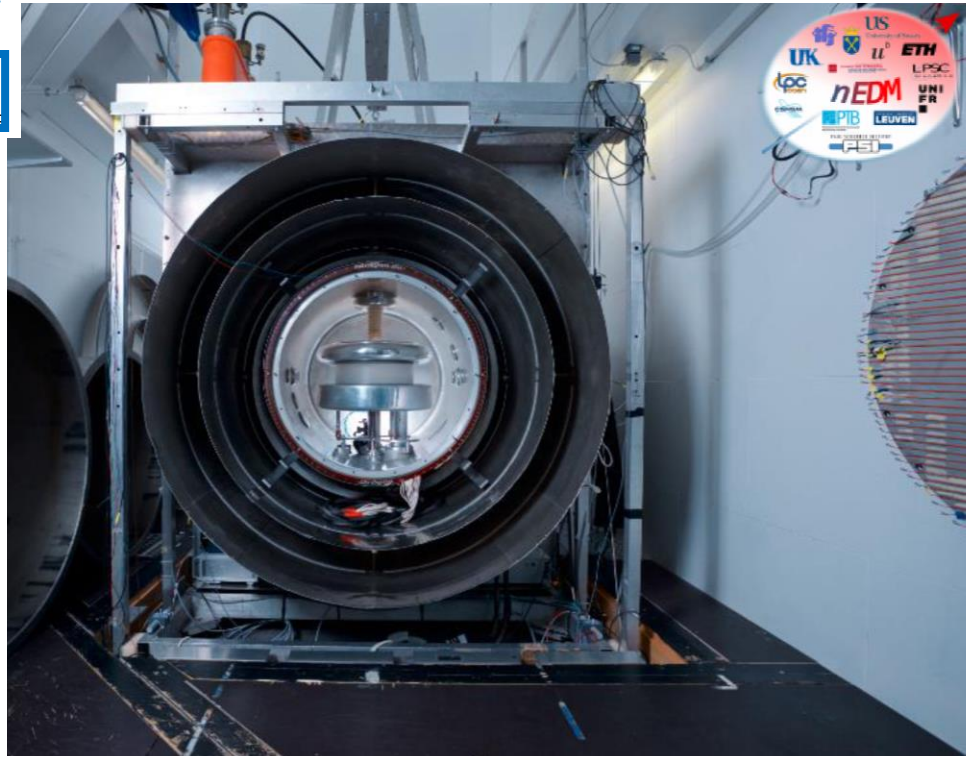
NEW RESULT (PSI)

$$d_n = (\ 0.0\ \pm\ 1.1_{stat}\ \pm\ 0.2_{syst}) \times 10^{-26}\ ecm$$

PRL124(2020)081803



Latest nEDM experimental result: *Tour-de-force* systematics (characterization and control), in a field limited by statistics for > 20 years



2

EDMs and the need for complementarity

"Sole source" limits in 2019:

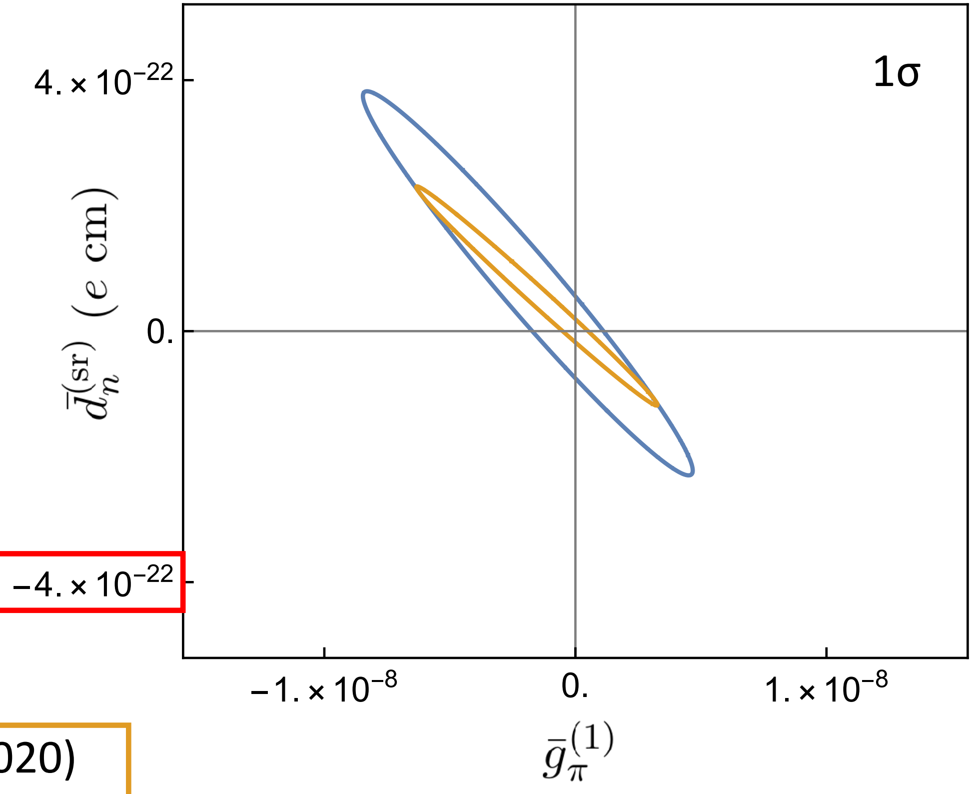
LE parameter	System	95% u.l.
d_e	ThO	$9.2 \times 10^{-29}\, e$ cm
C_S	ThO	8.6×10^{-9}
C_T	^{199}Hg	3.6×10^{-10}
$\bar{g}_\pi^{(0)}$	^{199}Hg	3.8×10^{-12}
$\bar{g}_\pi^{(1)}$	^{199}Hg	3.8×10^{-13}
$\bar{g}_\pi^{(2)}$	^{199}Hg	2.6×10^{-11}
$\bar{d}_n^{sr}$	Neutron	$3.3 \times 10^{-26}\, e$ cm

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

Now using also: (SMD, 2023 update)

^{199}Hg: $(|d| < 7.4 \times 10^{-30},\ 95\%\ \text{C.L.})$ PhysRevLett.119.119901

^{225}Ra: $(|d| < 1.4 \times 10^{-23},\ 95\%\ \text{C.L.})$ PhysRevC.94.025501



Since then:

n: $|d| < 1.8 \times 10^{-26}$ e cm (90% C.L.) PSI: PhysRevLett.124.081803 (2020)

^{129}Xe: $|d| < 1.4 \times 10^{-27}$ e cm (95% C.L.) HeXe: PhysRevLett.123.143003 (2019)

ThO: $|d| < 1.1 \times 10^{-29}$ e cm (90% C.L.) ACME: Nature **562**, 355–360 (2018)

Neutron Decay Parameters

2

- Lifetime: UCN lead the world → Discrepancy limited by beam
  still of interest: detect decay products in parallel
- Radiative decay → Very low branching ratio
- Decay correlations (esp. *A* and *b* for UCN) → Systematics are challenging; cold neutrons are very powerful here*

Pure *V-A* (left-hand)

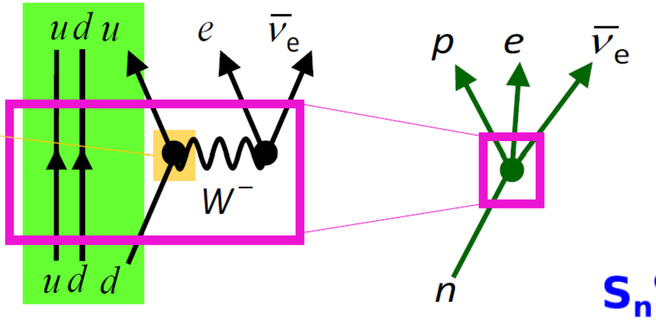
$$\begin{pmatrix} e_L \\ \nu_{eL} \end{pmatrix} \quad \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

Really? Why?

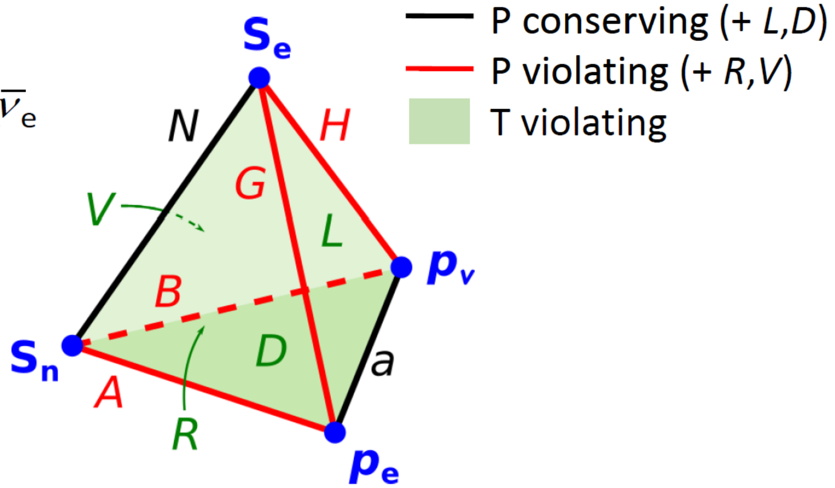
Quark mixing

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

How many? Unitarity?



$$\lambda = \frac{g_A}{g_V}$$



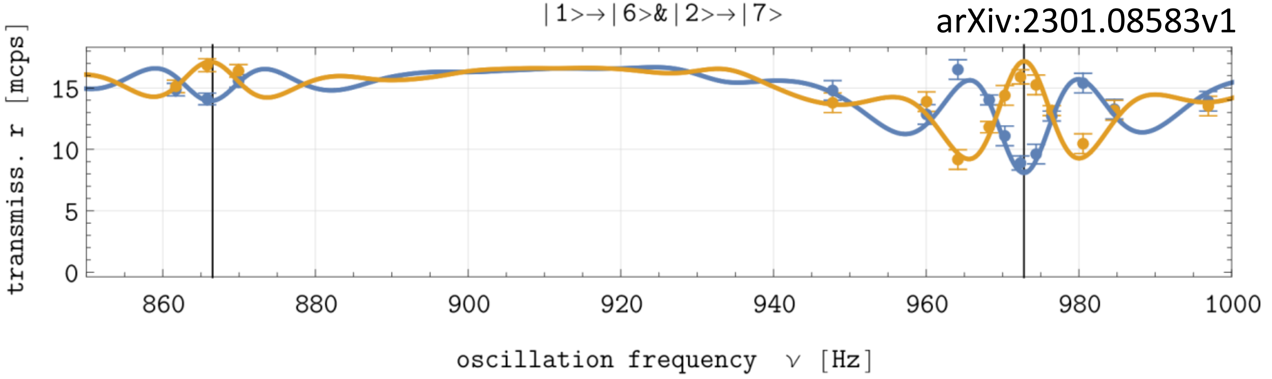
*Cf. complementary programs planned for ANNI at ESS and ongoing work at ILL/PF1b, NIST, LANL, …

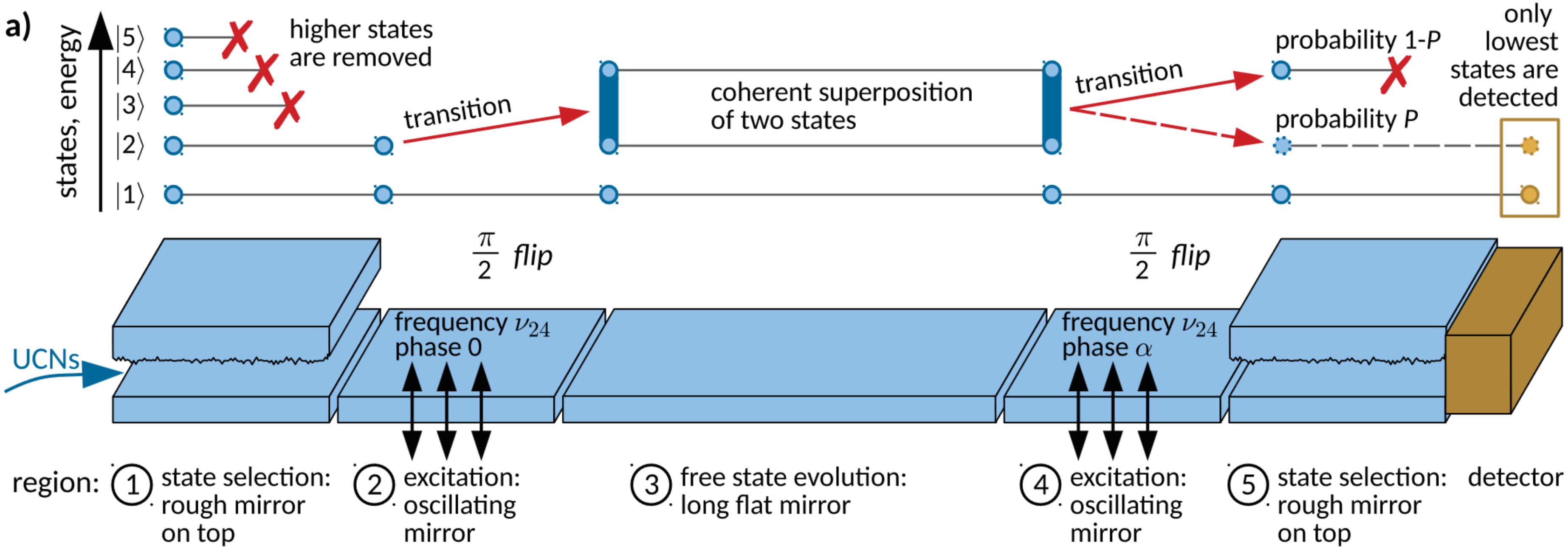
Gravitational Quantum States

2

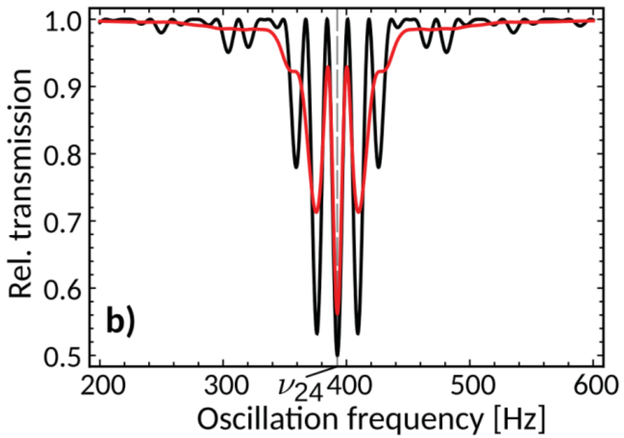
- Precision tests at short range
- Weak equivalence principle tests
- Specific models (e.g., symmetrons)

arXiv:2301.08583v1





Ramsey interferometry without electromagnetism…

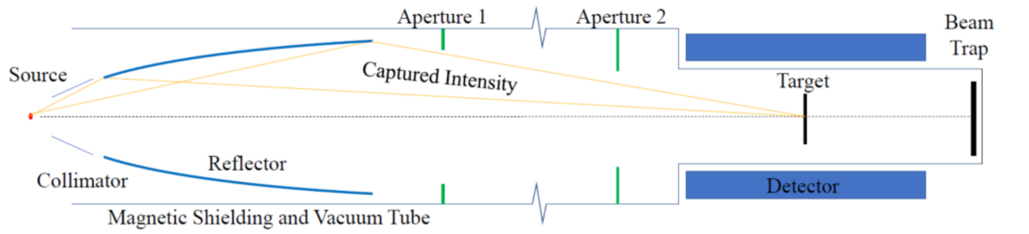


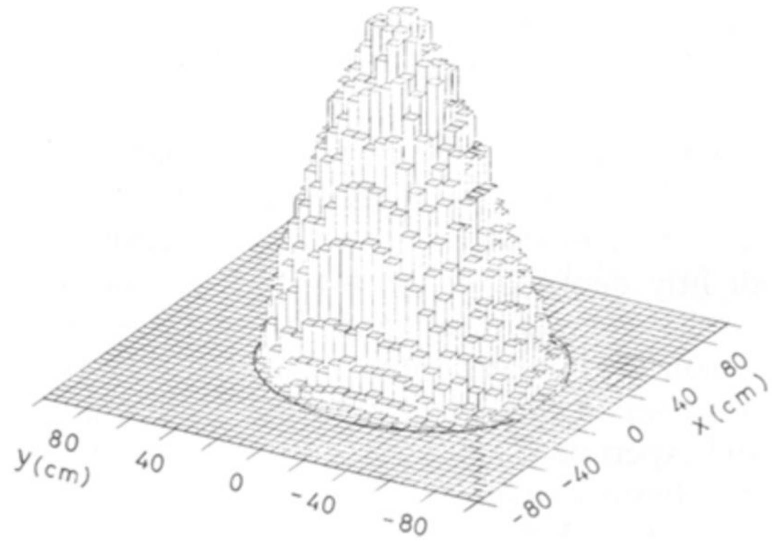
EPJ Web of Conferences 219, 05004 (2019)

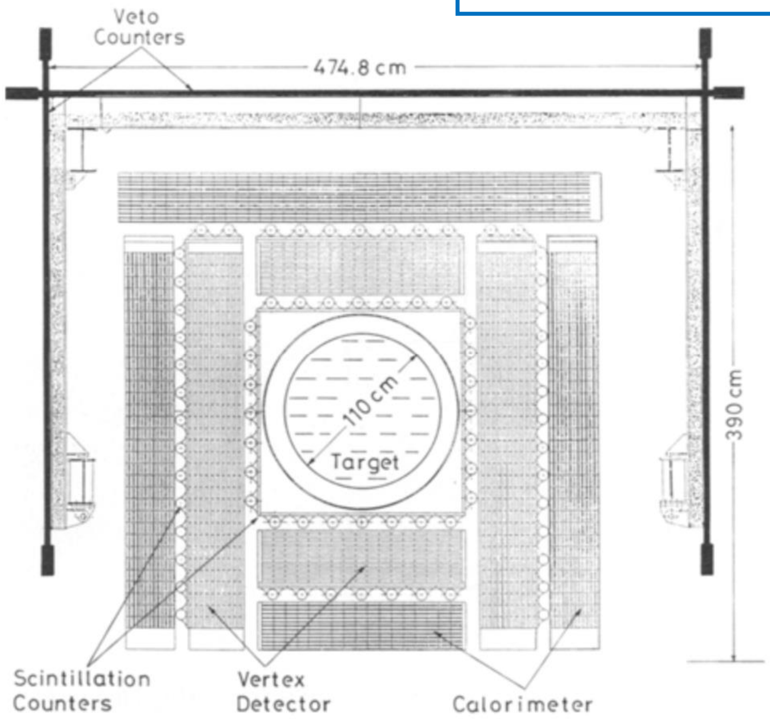
Neutron Oscillations

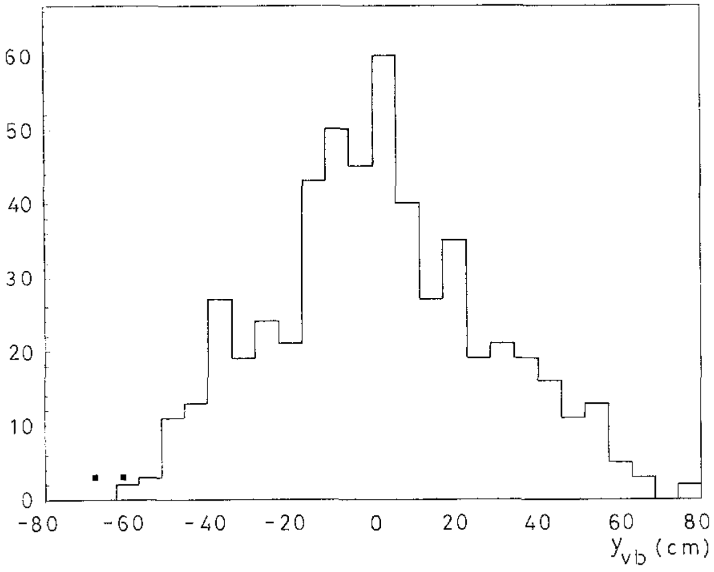
- Anti-neutrons: B violation
- Mirror neutrons: left/right
- Generic *n'*: [*insert here*]

→ already pursued with CN and VCN









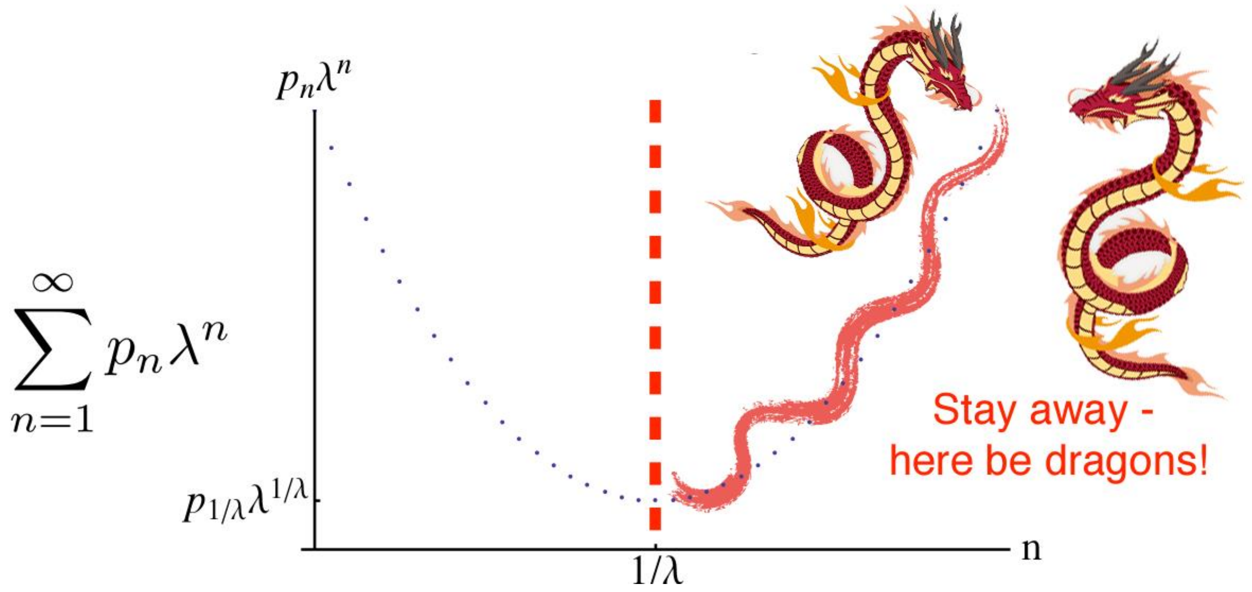
Baldo-Ceolin *et al.*, Zeitschrift für Physik C Particles and Fields v. 63, pp. 409–

2 Further Particle Physics Topics

- Weak electric current-neutron interaction: ~10^{-17} Hz signal
- Gravitationally induced polarization: ~10^{-7} / storage time
- Nondynamical phases

- And more besides:
    - Scattering
    - Imaging
    - Interferometry
    - …

Aleksey Cherman



Some Personal Observations/Opinions

- ✓ Start early to make progress on long-term important challenges

- ○ Make contact-with-reality via present-generation science and techniques – use them as a resource!

Some Personal Observations/Opinions

✓ Start early to make progress on long-term important challenges

- Make contact-with-reality via present-generation science and techniques – use them as a resource!
  - ILL (SUN-2/PF2/SuperSUN)
  - PSI
  - Mainz / TRIGA
  - LANL / SNS
  - TRIUMF
  - NCSU
  - KEK
  - …