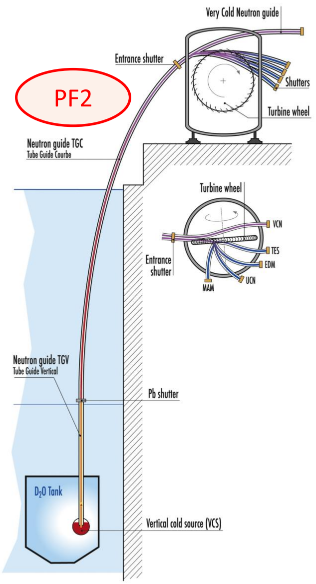
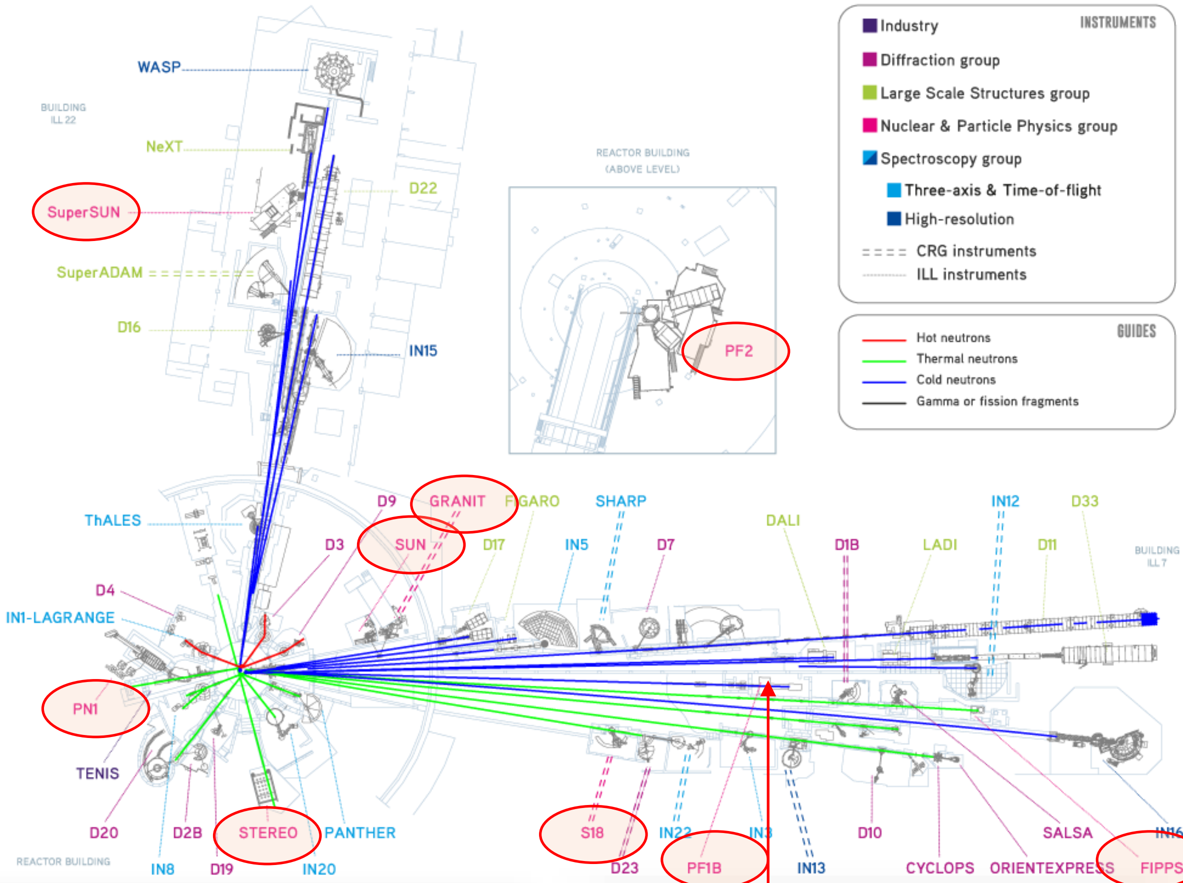
Activities of the Nuclear and Particle Physics Group of the ILL

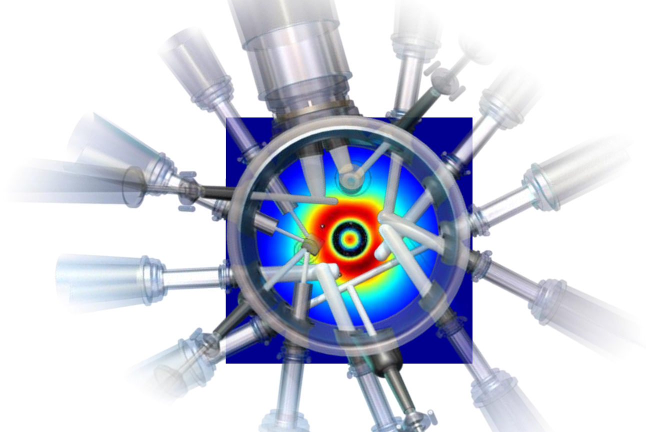
Michael Jentschel

NPP at ILL

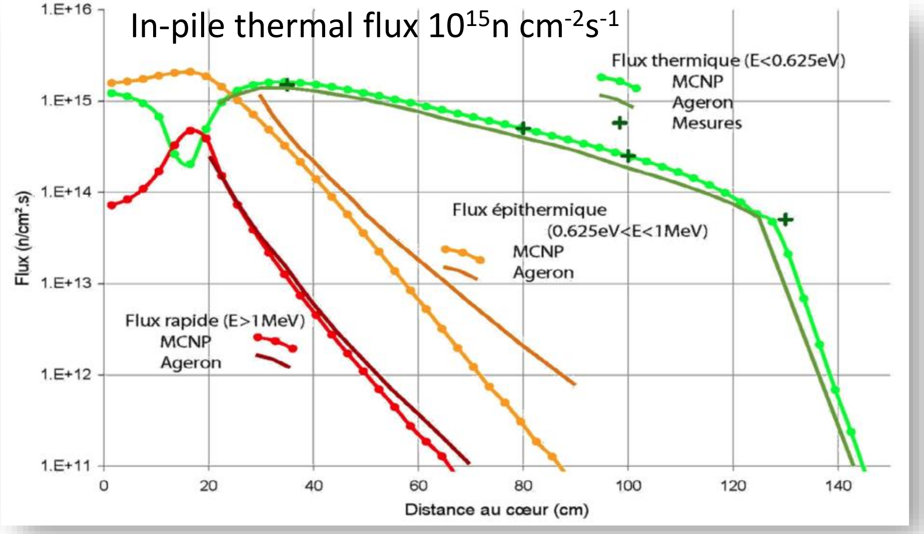
NEUTRONS FOR SOCIETY

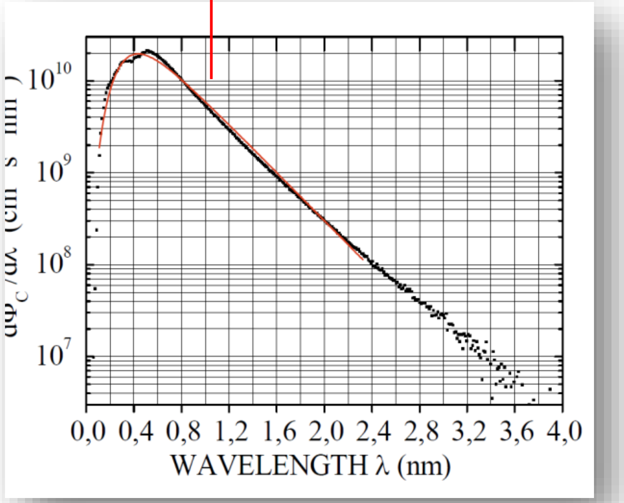






Two cold liquid D_2 sources
1 UCN source (turbine)
2 superliquid 4He sources
1 hot source





Outline

Neutrino activities

- STEREO (short base line neutrino oscillation experiment)
- RICOCHET (Experiment on coherent neutrino nucleus scattering)

UCN activities

- PF2 (Mirror neutron, qbounce, D2 cross section, VCN optics)
- Status of SuperSun and PanEDM

Cold Neutron activities

- PF1B (BRAND, PERKEOIII, Beam EDM, diffraction enhancement, new polarizer, optimizing VCN production/transport)

Thermal neutron activities

- S18 (which way experiments, split crystal interferometer)

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Neutrino activities at ILL

cea PARIS-SACLAY

Irfu

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LAPP
Laboratoire d'Annecy de Physique des Particules

LPSC
GRENOBLE | MODANE

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

STEREO

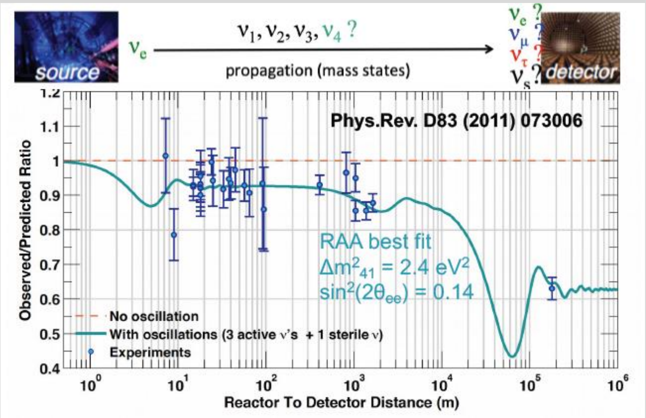
ELSEVIER

Physics Letters B
Volume 99, Issue 3, 19 February 1981, Pages 251-256

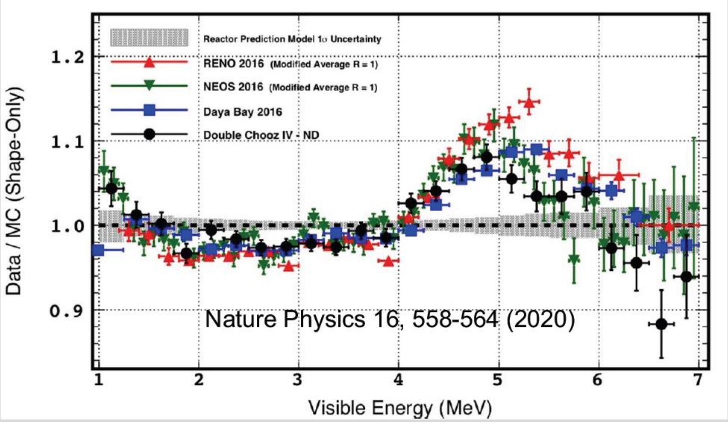
Absolute measurement of the beta spectrum from ^{235}U fission as a basis for reactor antineutrino experiments

K. Schreckenbach [a], H.R. Faust [a], F. von Feilitzsch [c], A.A. Hahn [b], K. Hawerkamp [a], J.L. Vuilleumier [b]

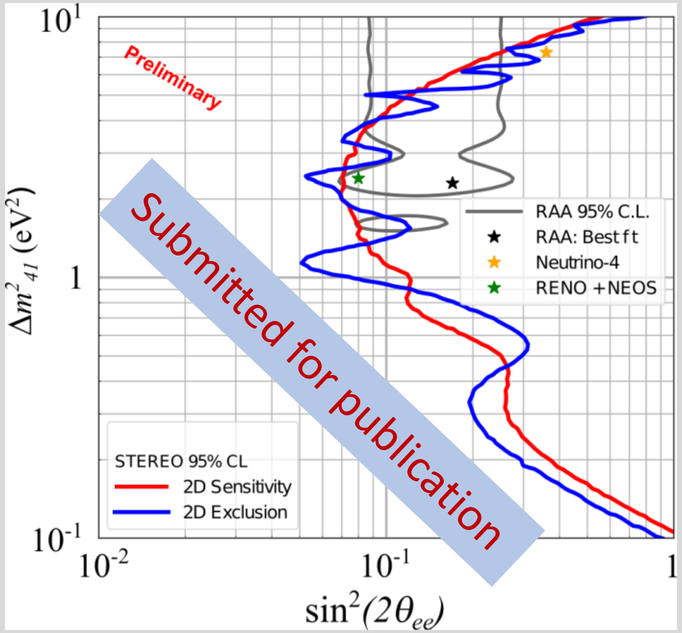
Sterile neutrino constraints from STEREO



Reactor antineutrino anomaly (2011): ~6%
Sterile neutrino: $\sin^2(2\theta_{ee}) \sim 0.17, \Delta m^2_{41} \sim 2.3\ eV^2$



Daya Bay, RENO, Double Chooz (2014):
Excess - "5 MeV bump"



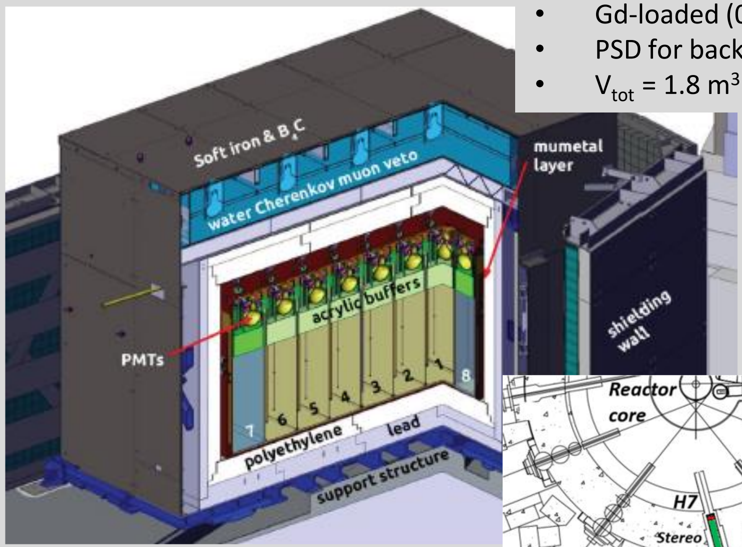
<u>Phase II+III:</u>

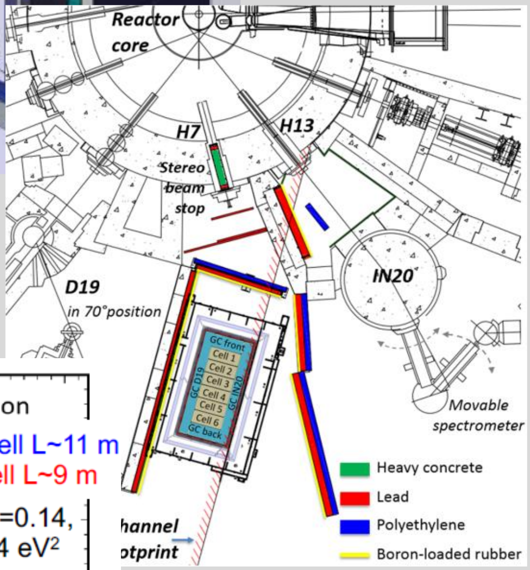
~350 reactor days
~700 off days

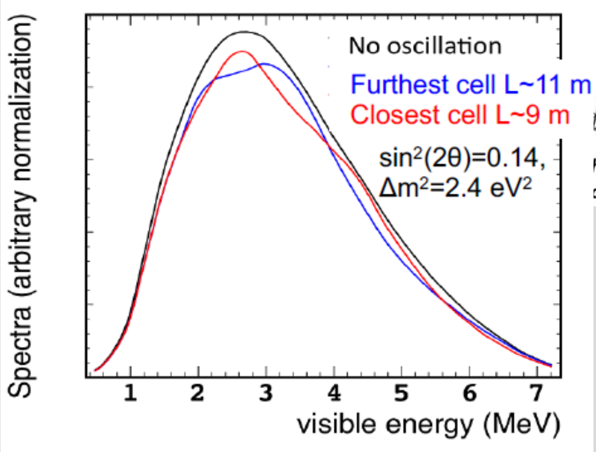
Exclude most RAA allowed parameter space at 95% CL for $\Delta m^2_{41} < 4\ eV^2$:

- No oscillation not excluded (p = 0.54)
- RAA best fit excluded at $\geq 4\sigma$
- Neutrino-4 excluded at 3.1 σ
- Neos-RENO best fit excluded at 2.8 σ

- 6 identical cells
- Gd-loaded (0.2% in mass)
- PSD for background discrimination
- V_{tot} = 1.8 m^3







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Antineutrino yield and spectrum of ^{235}U(n,f) from STEREO

NEUTRONS FOR SOCIETY

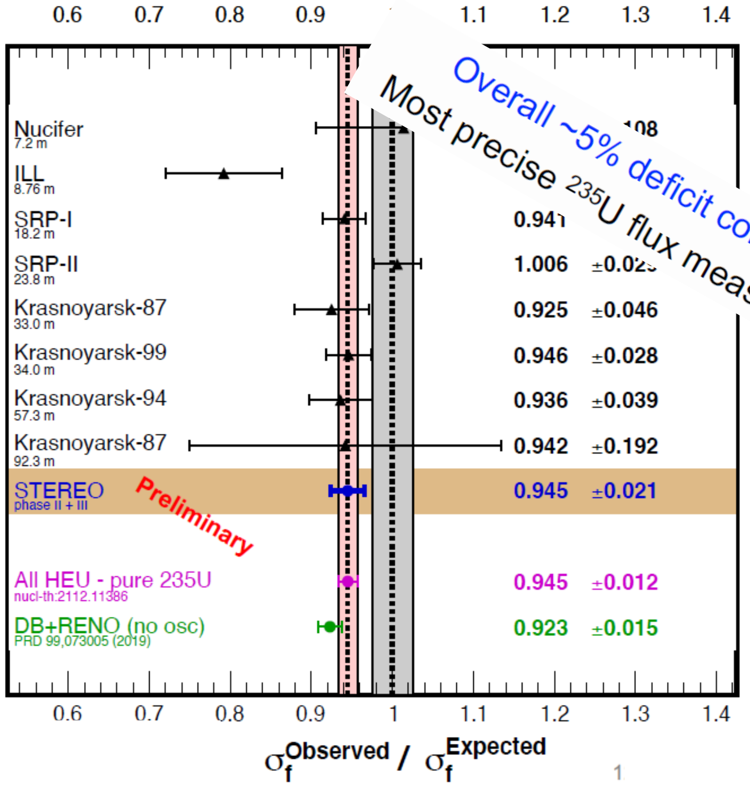
PHYSICAL REVIEW LETTERS **125,** 201801 (2020)

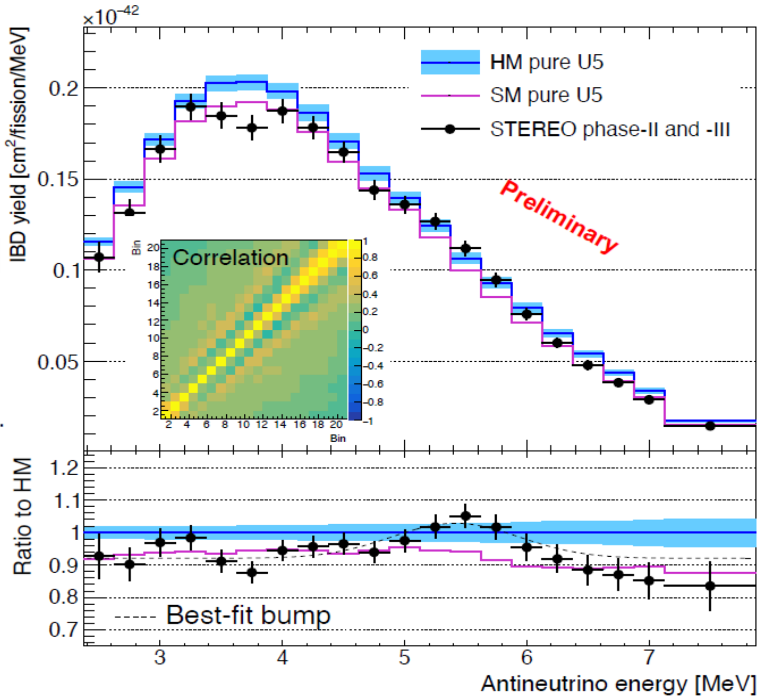
Accurate Measurement of the Electron Antineutrino Yield of ^{235}U Fissions from the STEREO Experiment with 119 Days of Reactor-On Data

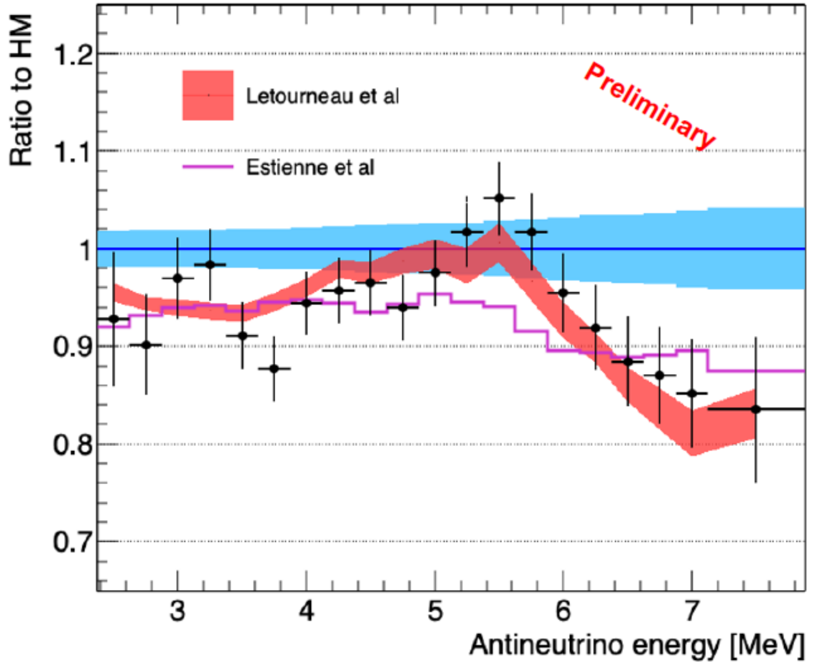
H. Almazán,[1,*] L. Bernard,[2,†] A. Blanchet,[3,‡] A. Bonhomme,[1,3] C. Buck,[1] P. del Amo Sanchez,[4] I. El Atmani,[3,§] J. Haser,[1] L. Labit,[4] J. Lamblin,[2] A. Letourneau,[3,∥] D. Lhuillier,[3] M. Licciardi,[2] M. Lindner,[1] T. Materna,[3] A. Minotti,[3,¶] A. Onillon,[3] H. Pessard,[4] J.-S. Réal,[2] C. Roca,[1] R. Rogly,[3] T. Salagnac,[2,**] V. Savu,[3] S. Schoppmann,[1,††] V. Sergeyeva,[4,‡‡] T. Soldner,[5] A. Stutz,[2] and M. Vialat[5]

- Joint phase II + III unfolding ($E_{rec} \rightarrow E_{\nu}$)
- Bump observed (4.6 σ) at ~5.5 MeV
- Reference measurement of ν-spectrum from ^{235}U
  - From antineutrino problem -> nuclear data problem
  - A. Letourneau et al. (arXiv:2205.14594, sub. to PRL)

Since this publication further evaluation of data:





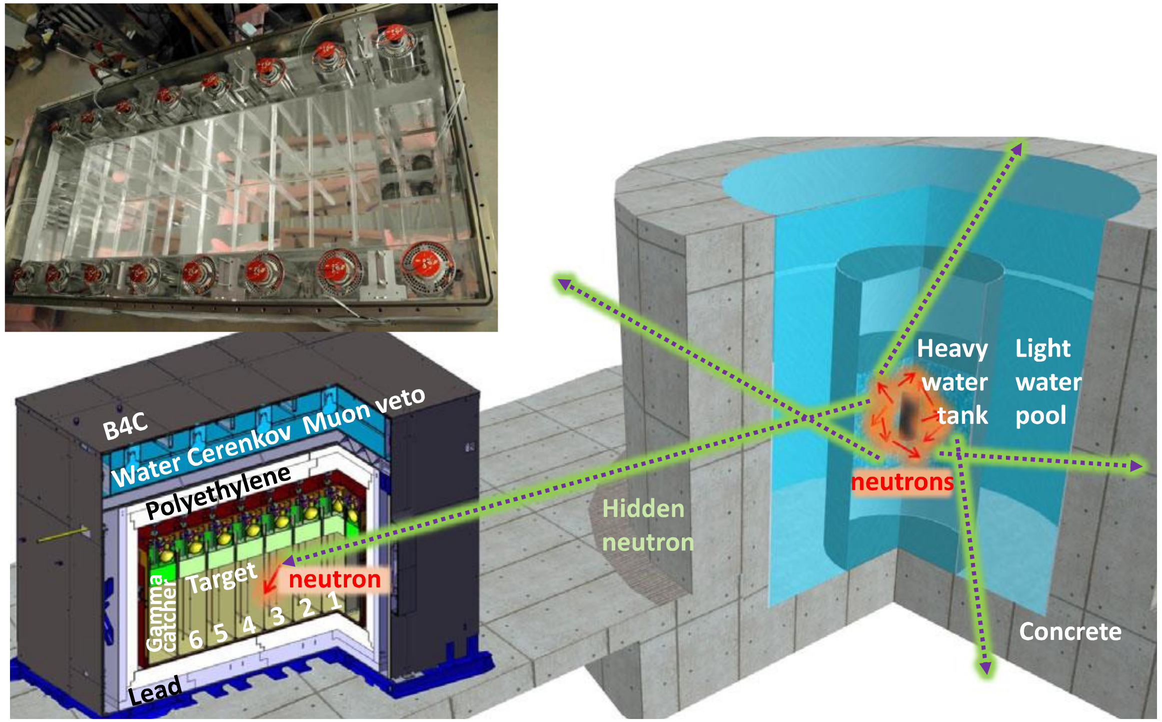


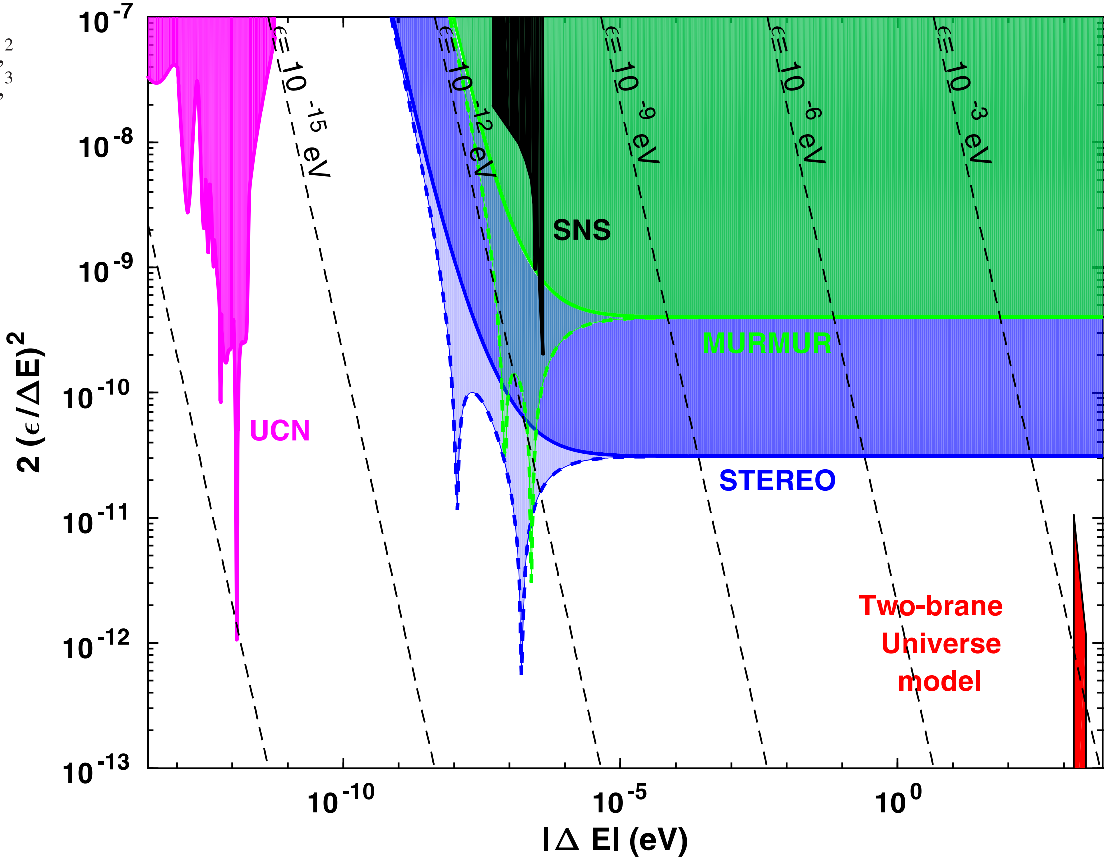
Hidden neutron limit from STEREO

PHYSICAL REVIEW LETTERS **128,** 061801 (2022)

Searching for Hidden Neutrons with a Reactor Neutrino Experiment: Constraints from the STEREO Experiment

H. Almazán,[1,*] L. Bernard,[2,†] A. Blanchet,[3,‡] A. Bonhomme,[1] C. Buck,[1] P. del Amo Sanchez,[4] I. El Atmani,[3,§] L. Labit,[4] J. Lamblin,[2,∥] A. Letourneau,[3] D. Lhuillier,[3] M. Licciardi,[2] M. Lindner,[1] T. Materna,[3] O. Méplan,[2] H. Pessard,[4] G. Pignol,[2] J.-S. Réal,[2] J.-S. Ricol,[2] C. Roca,[1] R. Rogly,[3] T. Salagnac,[2,¶] M. Sarrazin,[5,6,**] V. Savu,[3] S. Schoppmann,[1,††] T. Soldner,[7] A. Stutz,[2] and M. Vialat[7]





New Neutrino activity: coherent scattering

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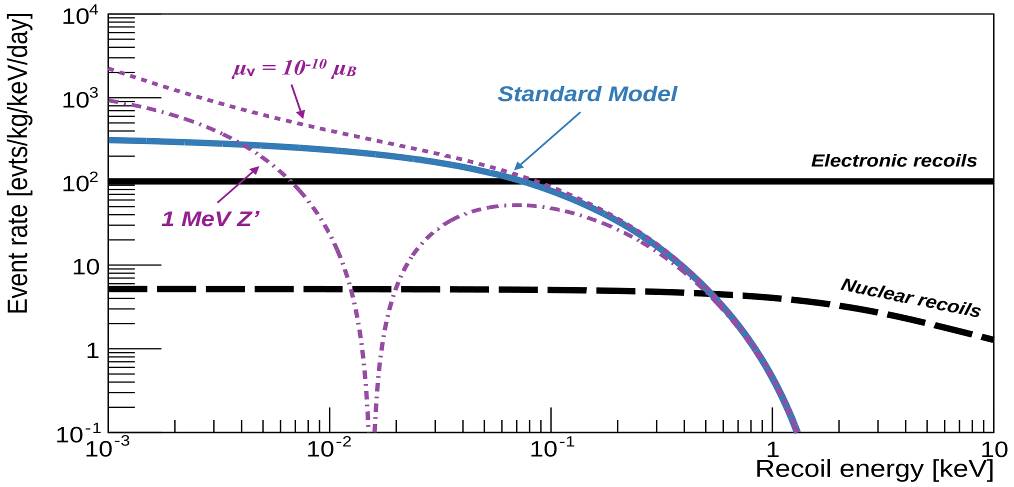
- Detect **C**oherent **E**lastic **N**eutrino **N**ucleus **S**cattering with reactor antineutrinos
- Measure nuclear recoil spectrum
  - with different detector materials:
  - Weinberg angle
  - Search for **neutrino magnetic moment** with sensitivity of $10^{-11}\ \mu_B$
  - Improve limits on **new massive mediators Z'**
  - Discover or exclude **non-standard neutrino-quarks neutral-current interactions** in the low-energy sector
  - Reduce uncertainties in the **CENNS cross-section**
  - **Precise recoil spectrum for ^{235}U** down to E_ν~1 MeV (nuclear physics processes in core, non-proliferation)



RICOCHET
A Coherent Neutrino Scattering Program

Lyon 1
iP2i LES 2 INFINIS LYON
MIT
NÉEL
THE UNIVERSITY of WISCONSIN MADISON
LPSC Grenoble
Northwestern University
CSNSM
UMASS AMHERST

Detectors and Setup

RICOCHET
A Coherent Neutrino Scattering Program

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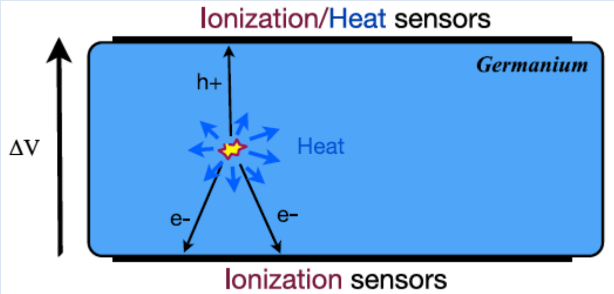
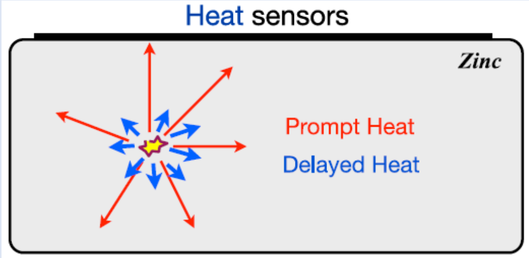
CryoCube (French partners)



Q-array (US partners)

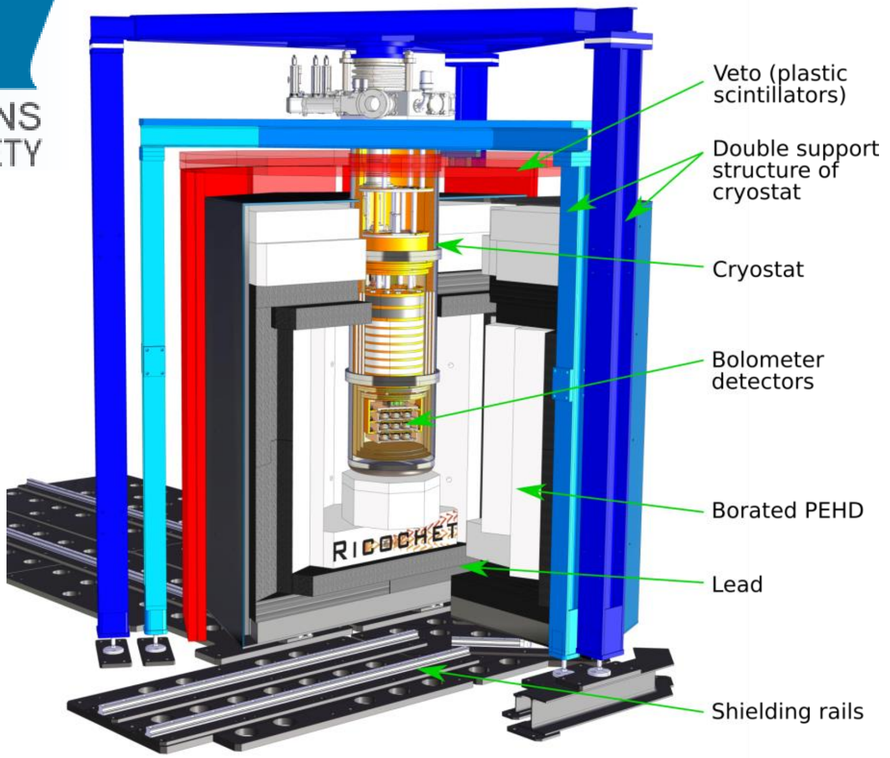


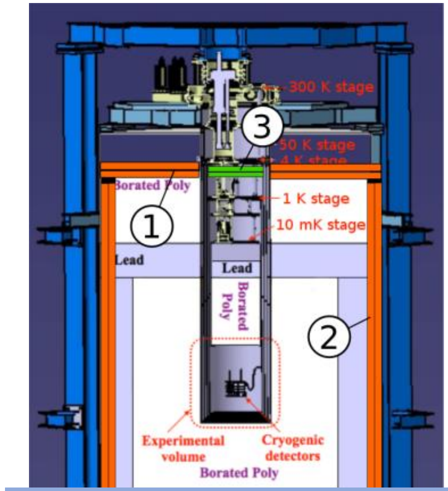
~ 15 mK

- Ionisation/heat for semiconductor bolometer (Ge, 27x30 g)
- 50 eV heat threshold demonstrated
- 10x improvement of ionization by HEMT preamps & optimisation

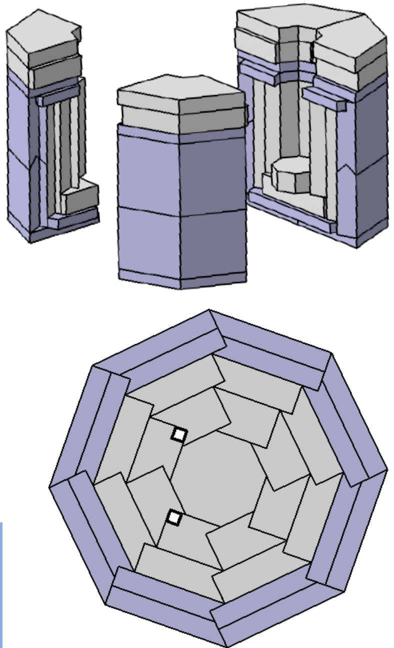
- Pulse shape of heat signal for superconducting metal (Zn, 9 x 40 g)
- New concept:
  - Excellent theoretical performance ($\Delta E/E$, particle ID) not yet demonstrated
  - Single channel readout -> scalable

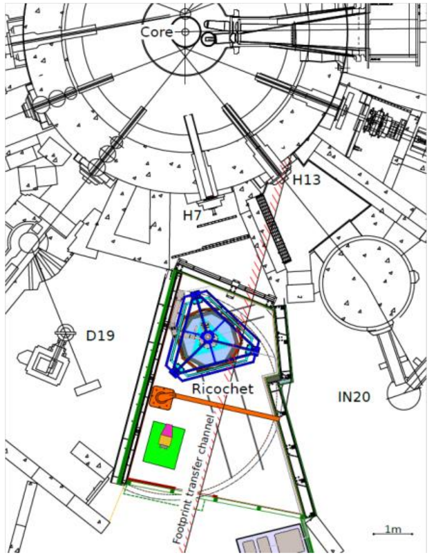
- Currently preparation of experimental zone
- until spring 2023 installation of shielding
- Validation of shielding during 2023 reactor operation
- Installation and commissioning until autumn 2023





(1) Horizontal scintillator panels
(2) Vertical scintillator panels
(3) Cryogenic veto element





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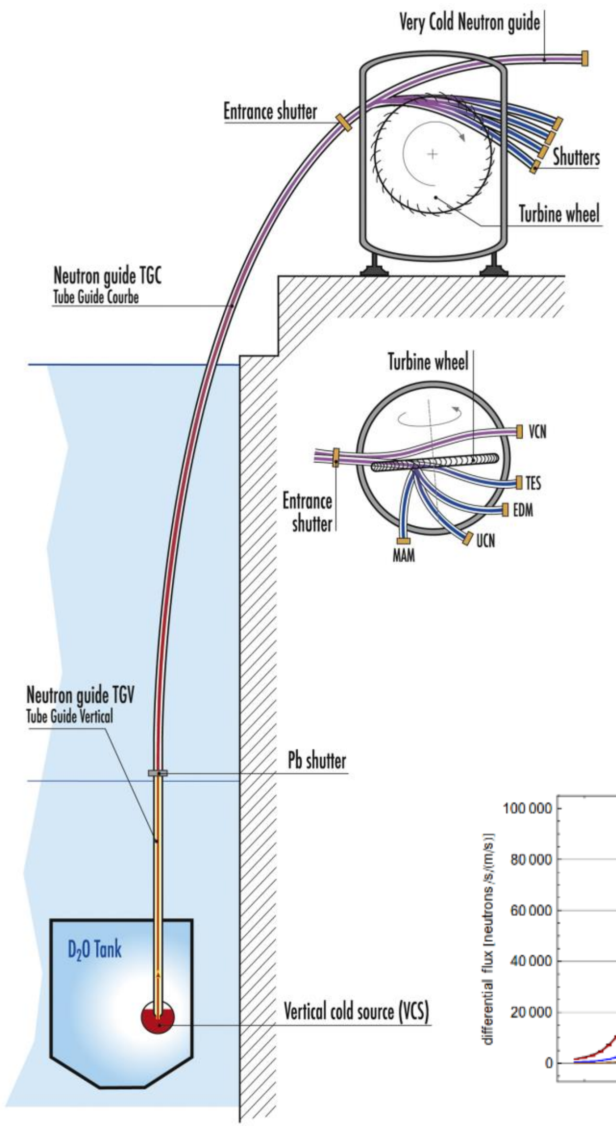
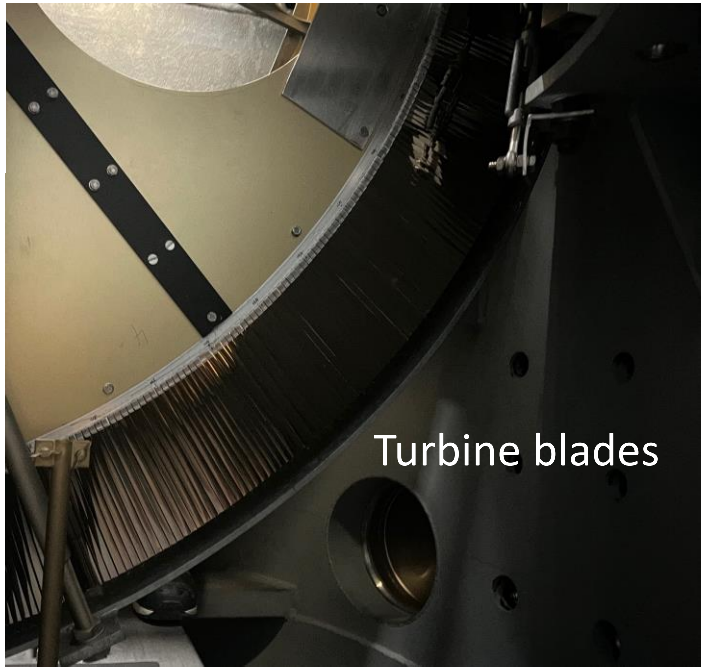


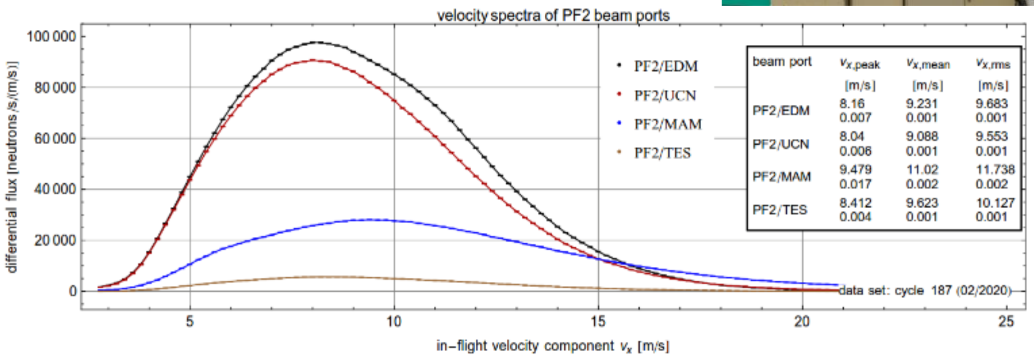
<u>Provides:</u>

- High reliability during 150 days of reactor
- DC operation
- Complete UCN/VCN infrastructure
- Very versatile setups
- 4 beams of UCN
- 1 beam of VCN

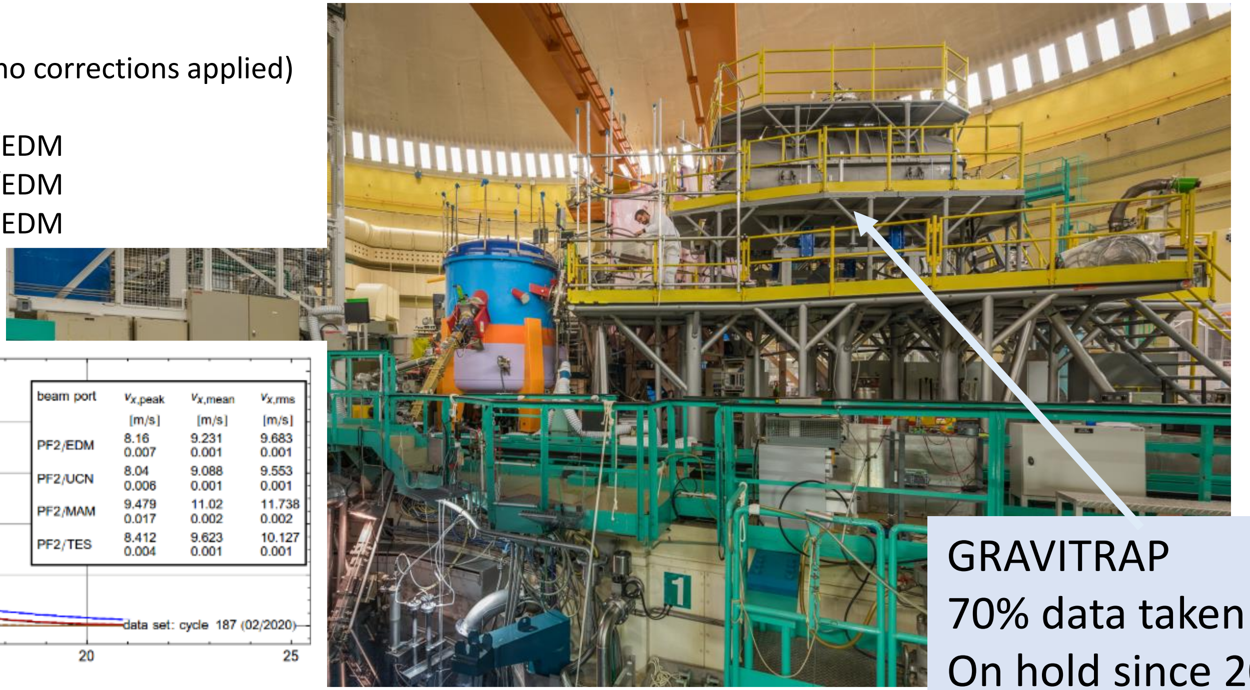


Total output:

- PF2/EDM: 733.000 cps (no corrections applied) (detector efficiency: 80%)
- PF2/UCN: 89.7% of PF2/EDM
- PF2/MAM: 36.9% of PF2/EDM
- PF2/TES: 05.9% of PF2/EDM



beam port	$v_{x,peak}$ [m/s]	$v_{x,mean}$ [m/s]	$v_{x,rms}$ [m/s]
PF2/EDM	8.16 0.007	9.231 0.001	9.683 0.001
PF2/UCN	8.04 0.006	9.088 0.001	9.553 0.001
PF2/MAM	9.479 0.017	11.02 0.002	11.738 0.002
PF2/TES	8.412 0.004	9.623 0.001	10.127 0.001



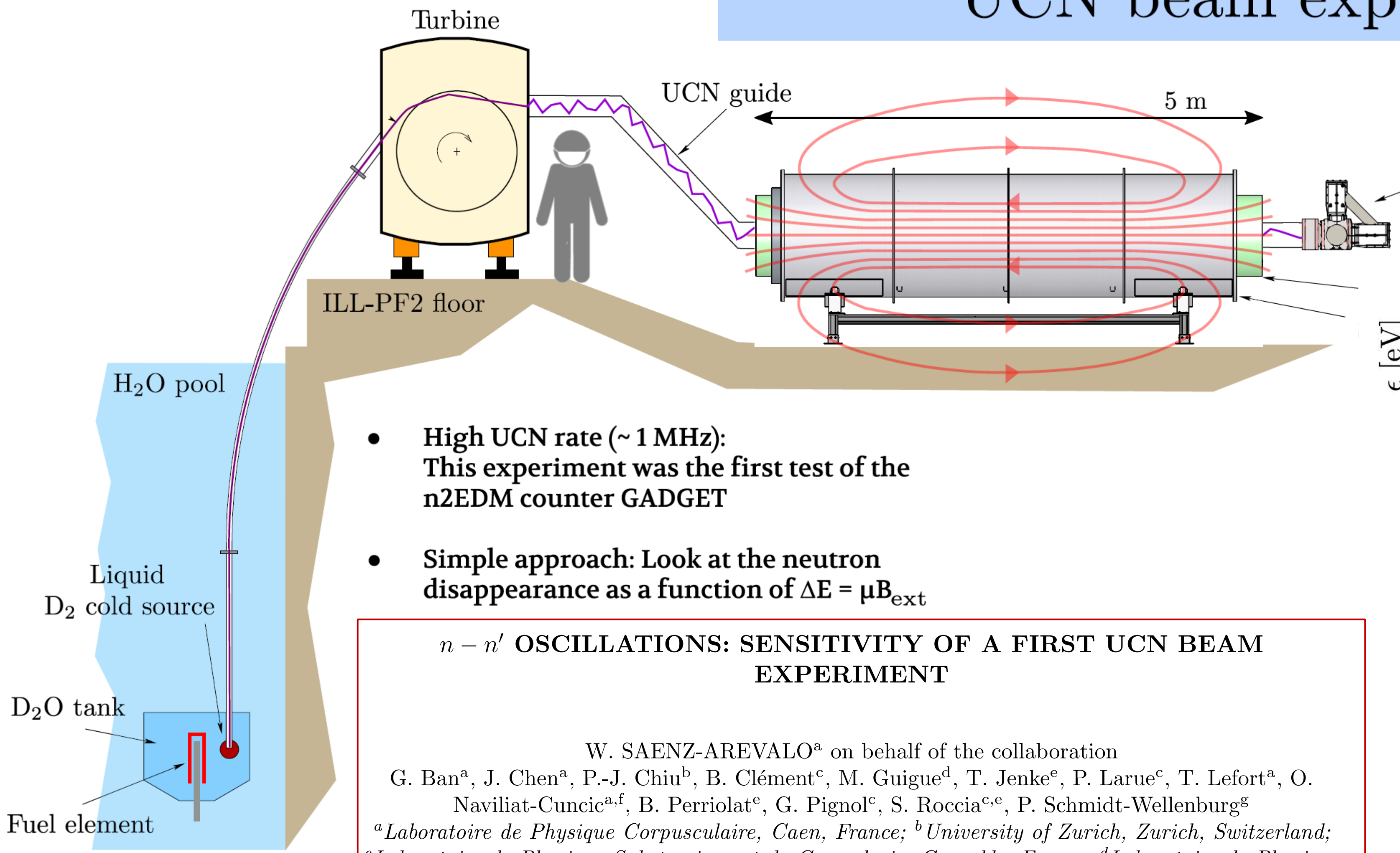
GRAVITRAP
70% data taken
On hold since 2019

Setting limit for mirror neutrons at PF2

ULTRACOLD NEUTRONS FOR SCIENCE

NEUTRONS FOR SOCIETY

UCN beam experiment

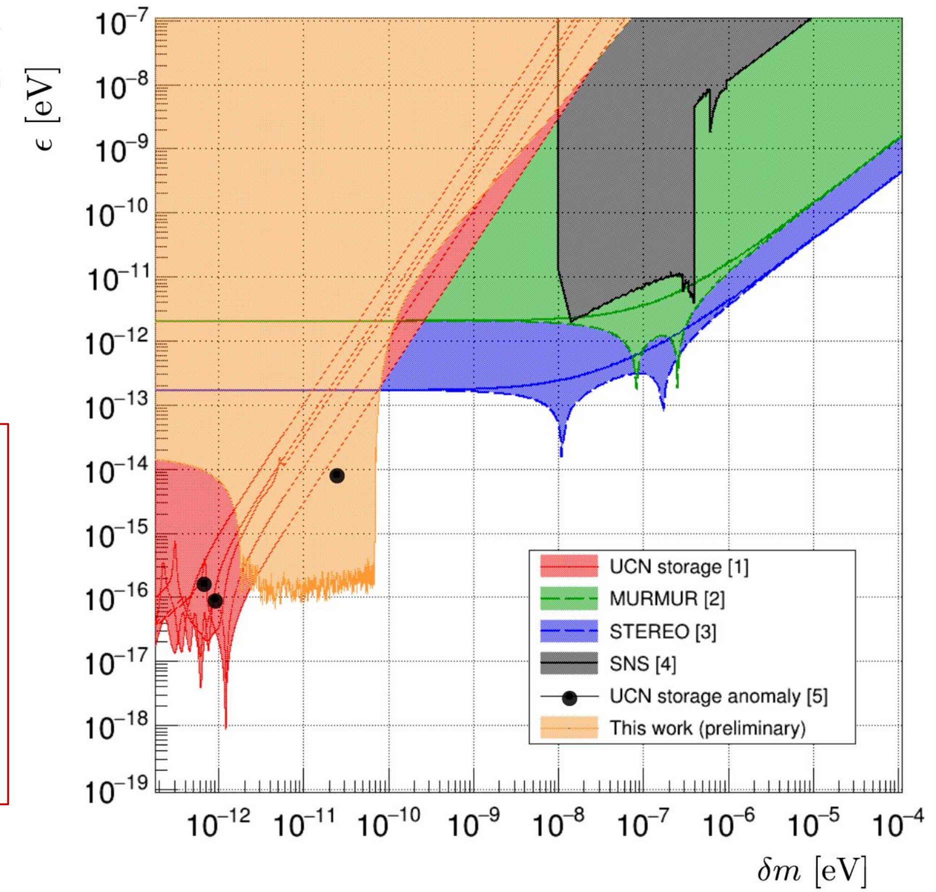


- **High UCN rate (~ 1 MHz): This experiment was the first test of the n2EDM counter GADGET**
- **Simple approach: Look at the neutron disappearance as a function of $\Delta E = \mu B_{ext}$**

$n - n'$ **OSCILLATIONS: SENSITIVITY OF A FIRST UCN BEAM EXPERIMENT**

W. SAENZ-AREVALO[a] on behalf of the collaboration
G. Ban[a], J. Chen[a], P.-J. Chiu[b], B. Clément[c], M. Guigue[d], T. Jenke[e], P. Larue[c], T. Lefort[a], O. Naviliat-Cuncic[a,f], B. Perriolat[e], G. Pignol[c], S. Roccia[c,e], P. Schmidt-Wellenburg[g]
[a]*Laboratoire de Physique Corpusculaire, Caen, France;* [b]*University of Zurich, Zurich, Switzerland;* [c]*Laboratoire de Physique Subatomique et de Cosmologie, Grenoble, France;* [d]*Laboratoire de Physique Nucléaire et des Hautes Énergies, Paris, France;* [e]*Institut Laue-Langevin, Grenoble, France;* [f]*Michigan State University, Michigan, United States;* [g]*Paul Scherrer Institute, Villigen, Switzerland*

$$P_{nn'}(t) = \frac{4\ldots}{4\epsilon_{nn'}^2+(\delta m-\mu B_{\mathrm{ext}})^2}\ldots$$



qBounce: Gravity Resonance Spectroscopy at PF2

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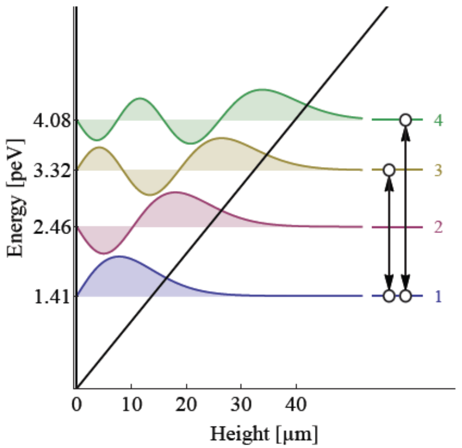
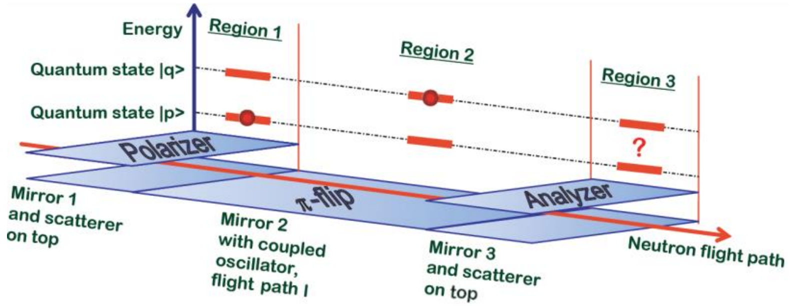
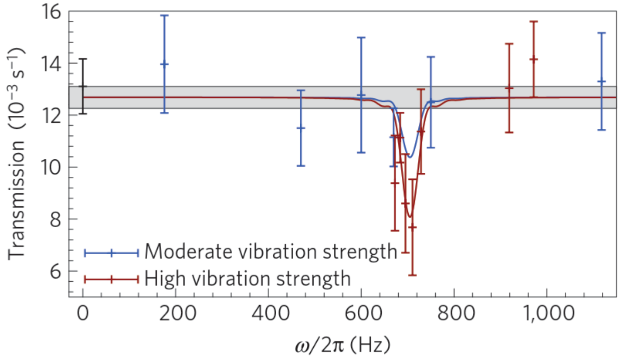
ATOMINSTITUT

TU WIEN

From Rabi to Ramsey: pushing sensitivity by 3 orders of magnitude







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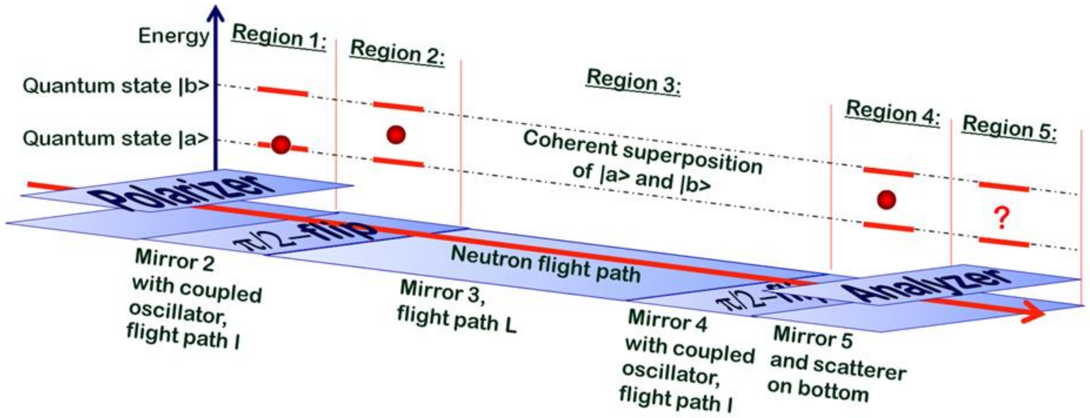
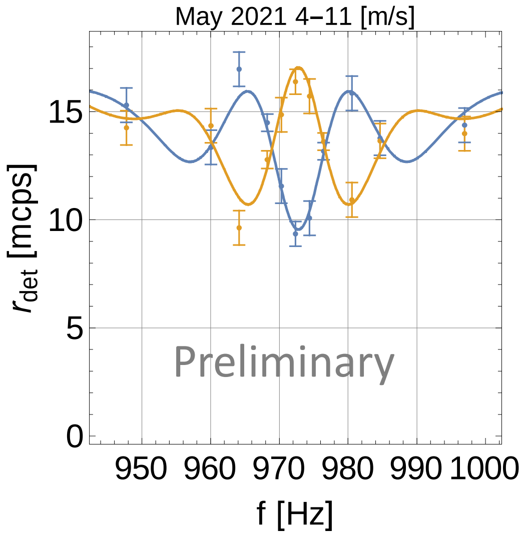




972.77 ±0.14

Talk of Jakob Micko -> Wednesday
Poster of Joachim Bosina

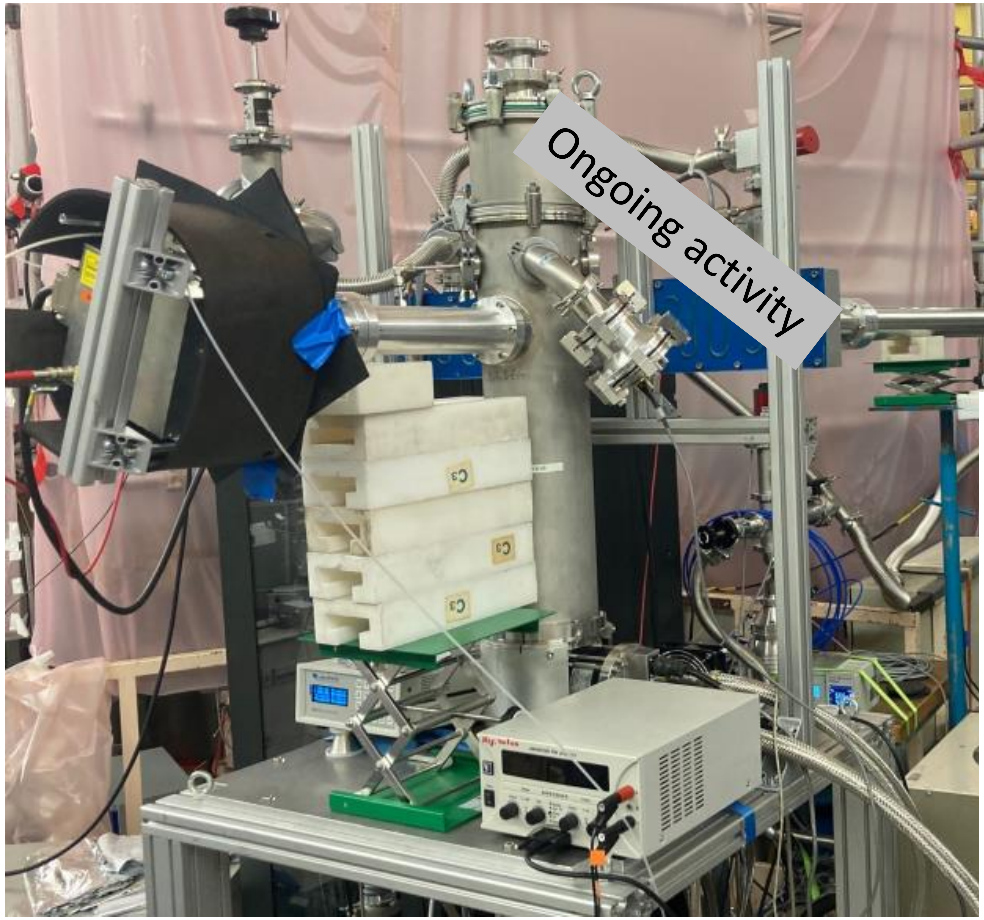
Measurement of the total transmission cross section of UCN in sold ortho D_2

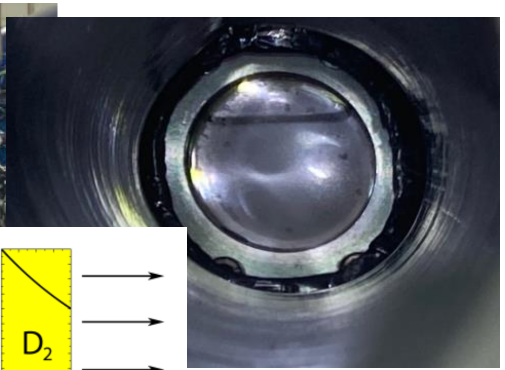
S. Döge, Fig. 2.1 & 4.2, Dissertation (TU München), 2019.

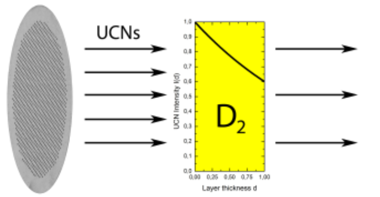
PHYSICAL REVIEW B **106**, 054102 (2022)

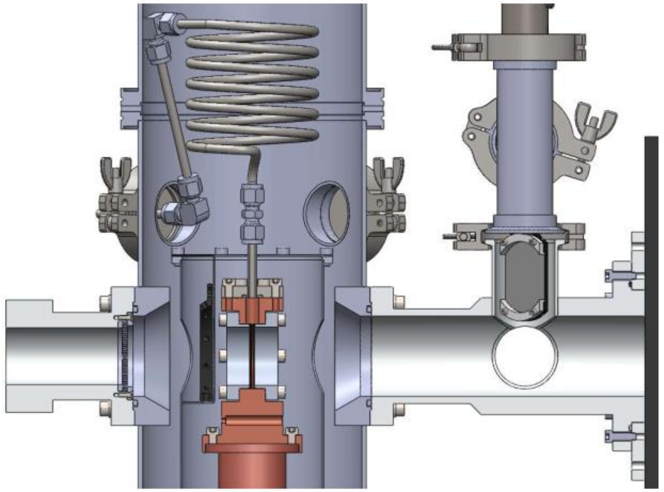
Direct measurement of the scattering cross sections of liquid ortho-deuterium for ultracold neutrons and comparison with model calculations

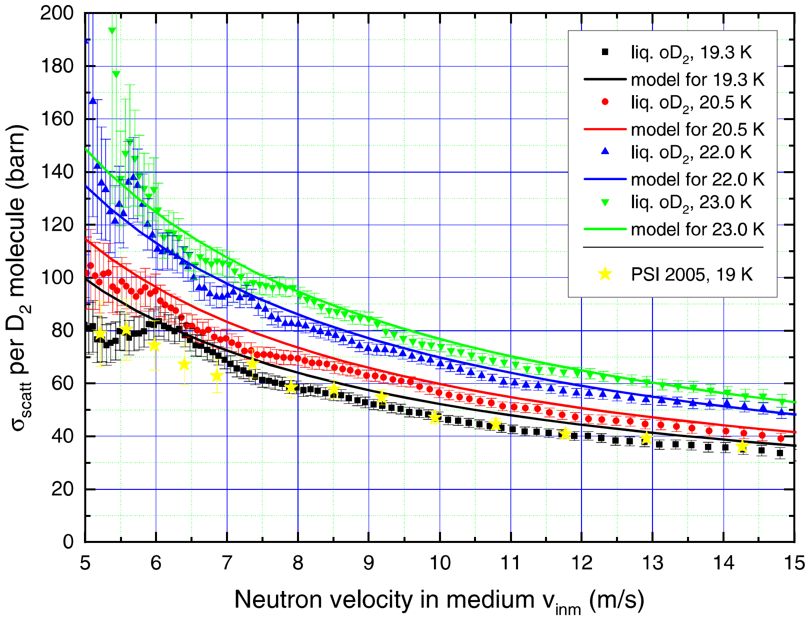
Stefan Döge,[1,2,*] Jürgen Hingerl,[1,2] Winfried Petry,[2,3] and Christoph Morkel[2]







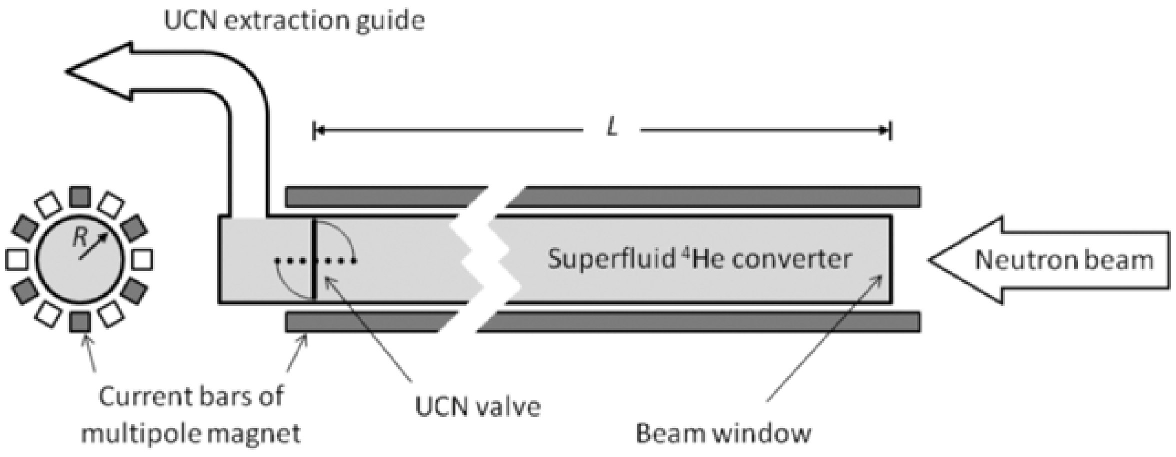


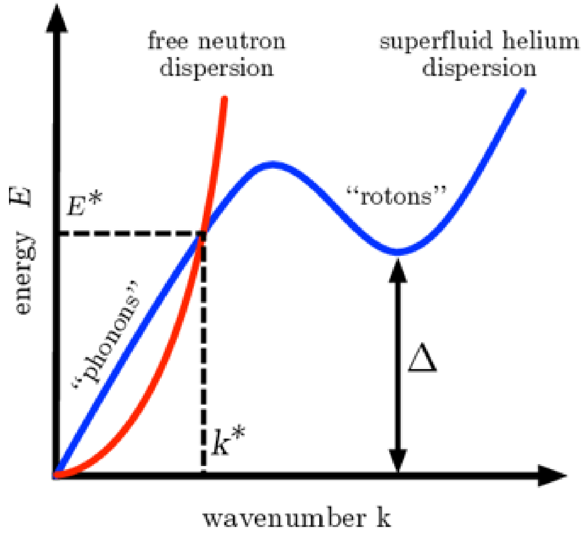


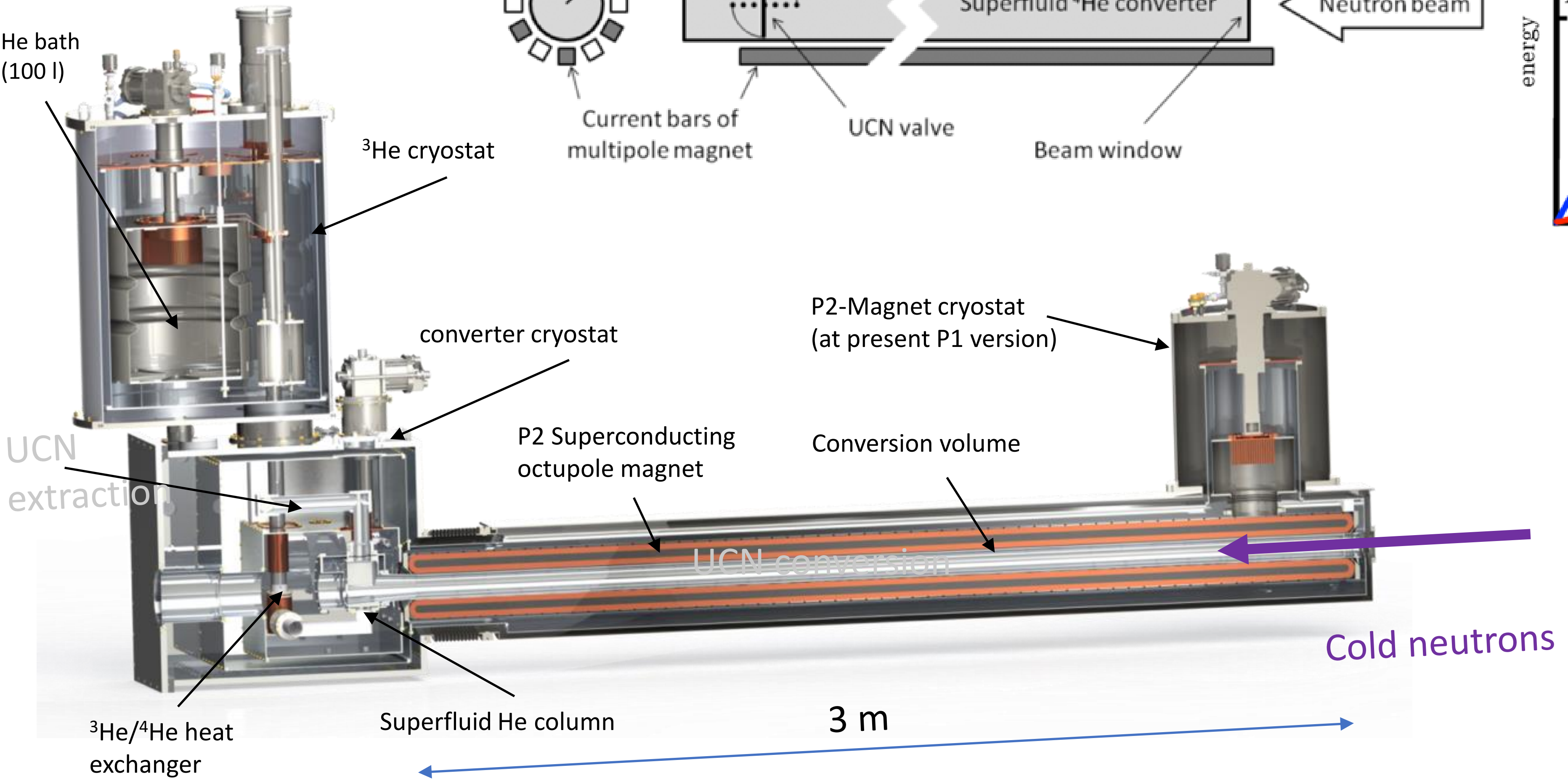
Physik Department E21 & E18, TU München, Germany

SuperSUN – a new high density source of UCN at ILL

Phase I: no B-field
Phase II: 2.1T B-field





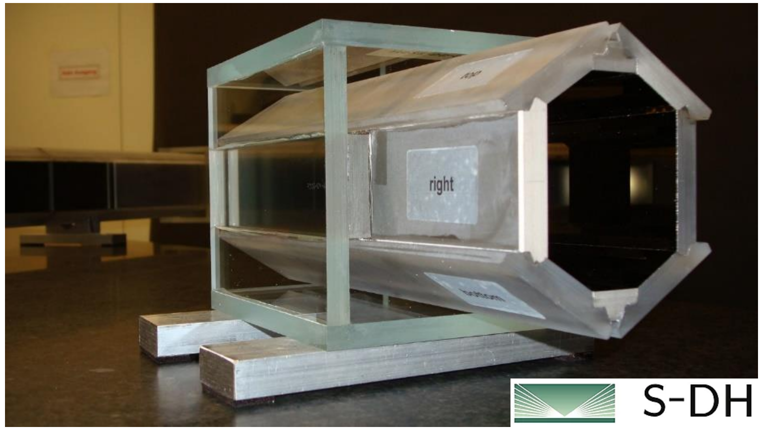


A few challenges:

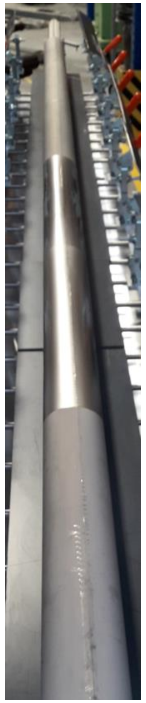
- Cryostat for < 0.6K in beam operation
- Rectangular n-guide to round converter
- 3 m cryogenic conversion volume
- 3 m long octupole 2T field
- …

From cold towards ultra-cold neutrons

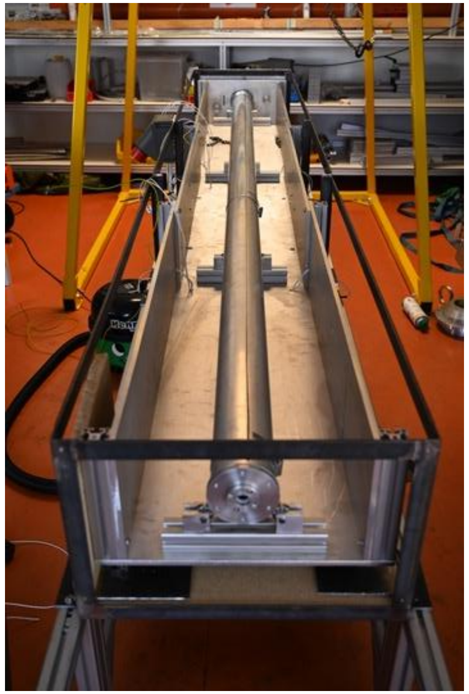
Octagonal Supermirror neutron guide allowing to transfer rectangular guide neutrons into round converter



R&D laser welding of Ni+M3 Supermirror

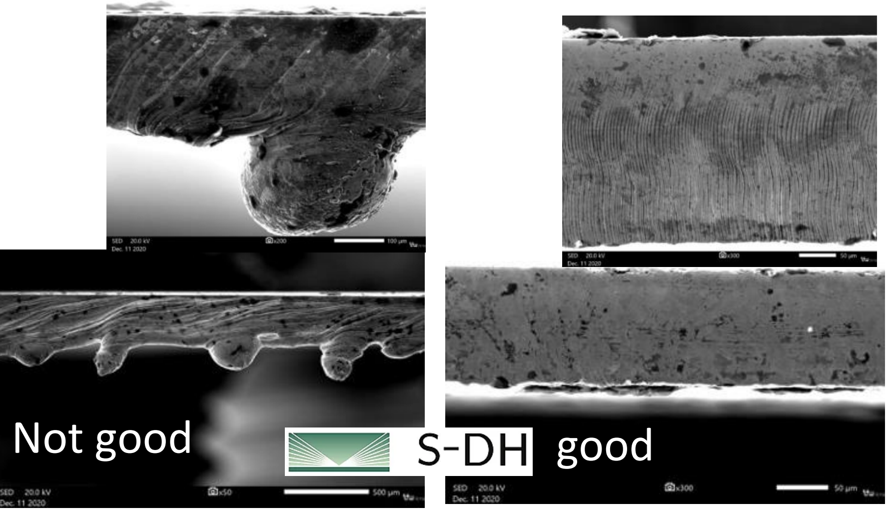


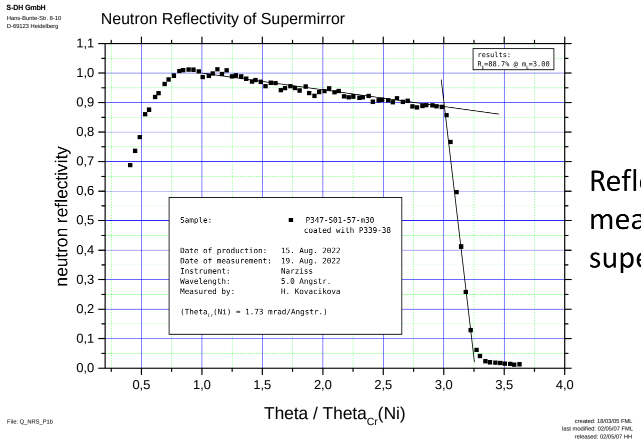
Final converter volume



Coating with CYTOP for better UCN storage time

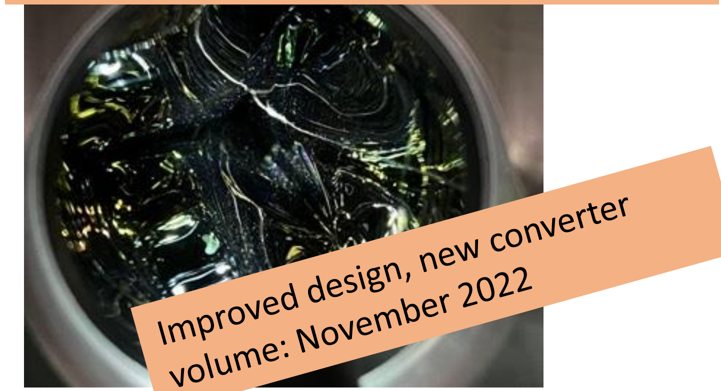
Integration into stainless steel vessel for cryostat





Reflectivity measurement of supermirror

Conversion volume destroyed by technical incident

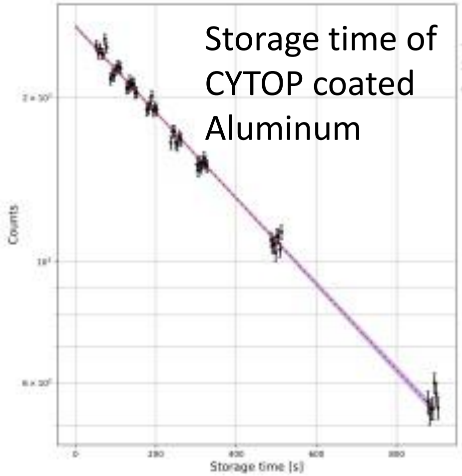


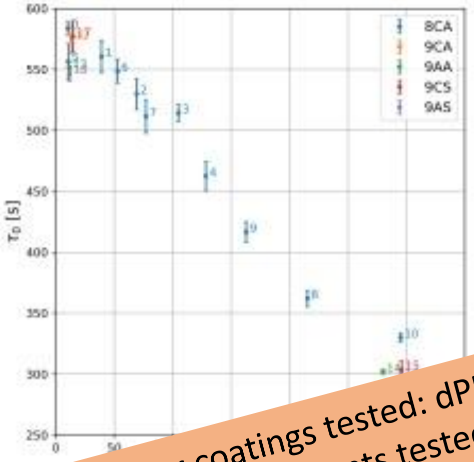
Component tests at SUN2 and PF2

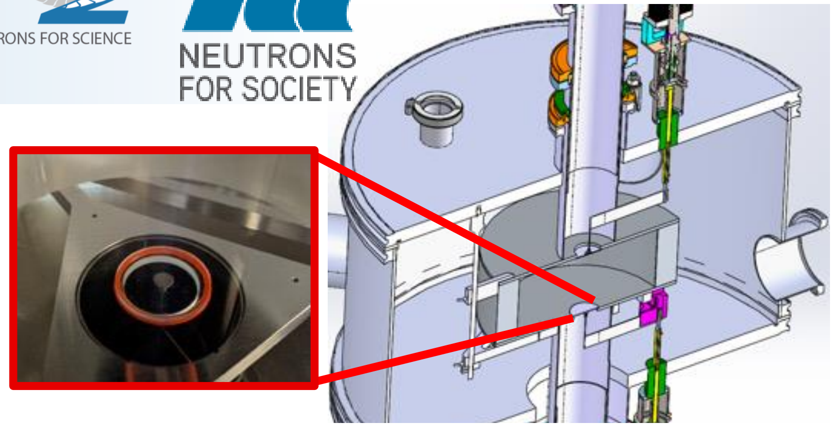
ULTRACOLD NEUTRONS FOR SCIENCE

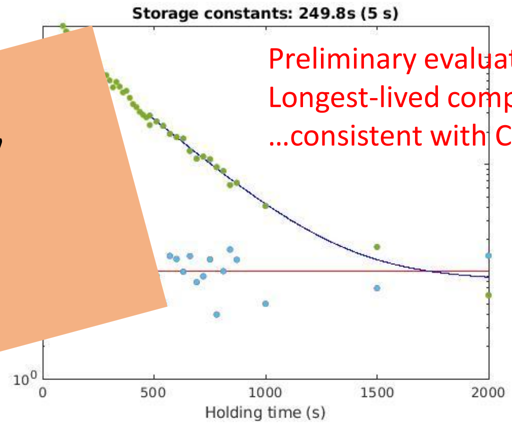
NEUTRONS FOR SOCIETY

T. Neulinger PhD-Thesis









Preliminary evaluation: Longest-lived component ...consistent with CYTOP

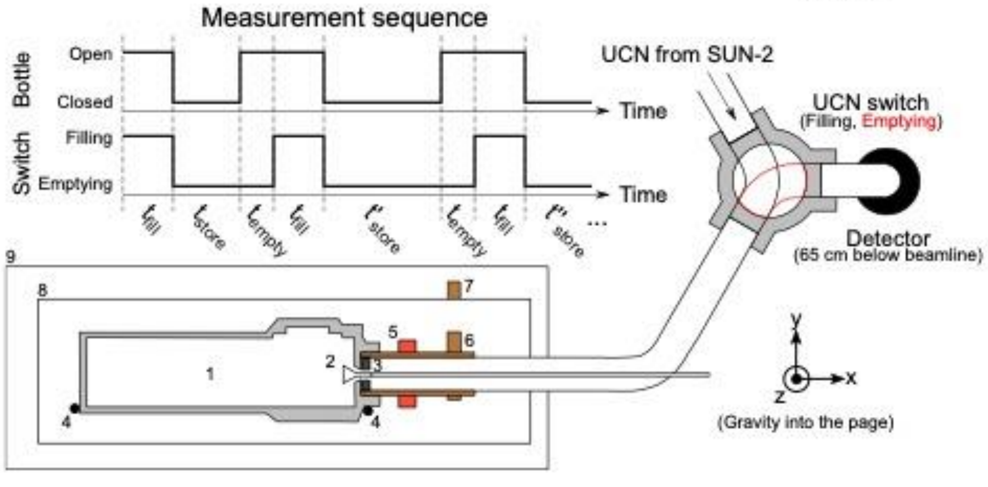


Figure 3.3: Overhead diagram of storage experiment, not to scale. Measurement timing sequence indicated at top with varying t_{store}. Gravity into the page. All elements are shown in the horizontal plane, except for the UCN detector, whose aluminum entrance window sits 650 mm below the axis of the bottle. (1) storage bottle; (2) coated steel bottle plug; (3) removable steel entrance cover; (4) temperature sensors—only two are shown, there are four in total; (5) heater; (6) thermal anchoring to first stage of pulse-tube refrigerator (not shown); (7) thermal anchoring to second stage; (8) thermal screen; (9) vacuum vessel.

Other coatings tested: dPE, various DLC
Other components tested: transmission of guides, multi-way switcher, polarizers, detectors

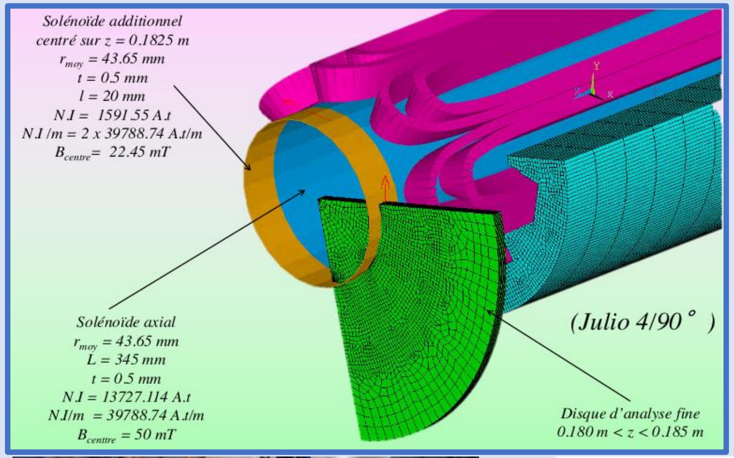
Posters
E. Chanel, Hanno Filter, T. Neulinger

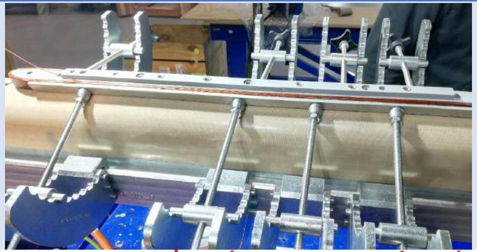
R&D towards a 3m long superconducting magnet

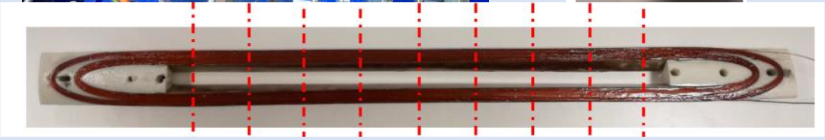
ELYTT ENERGY

NEUTRONS FOR SOCIETY

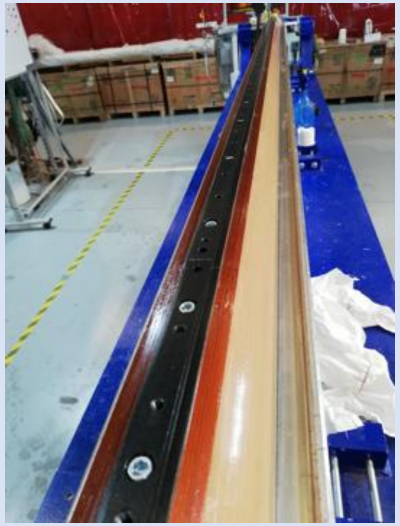
Simulations by M.Thomas (ILL)

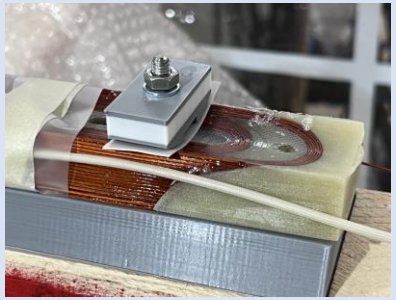




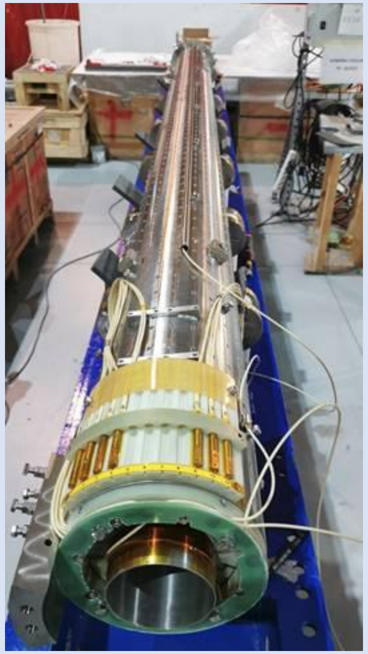


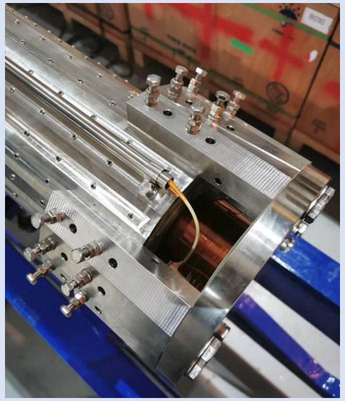
ELYTT ENERGY

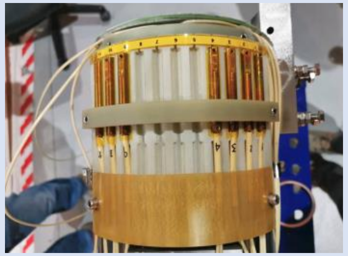


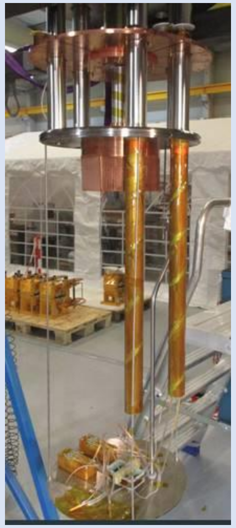


ELYTT ENERGY









ELYTT ENERGY

Phase I implementation in ILL22 guide hall

Installation ready for commissioning once new converter volume is installed

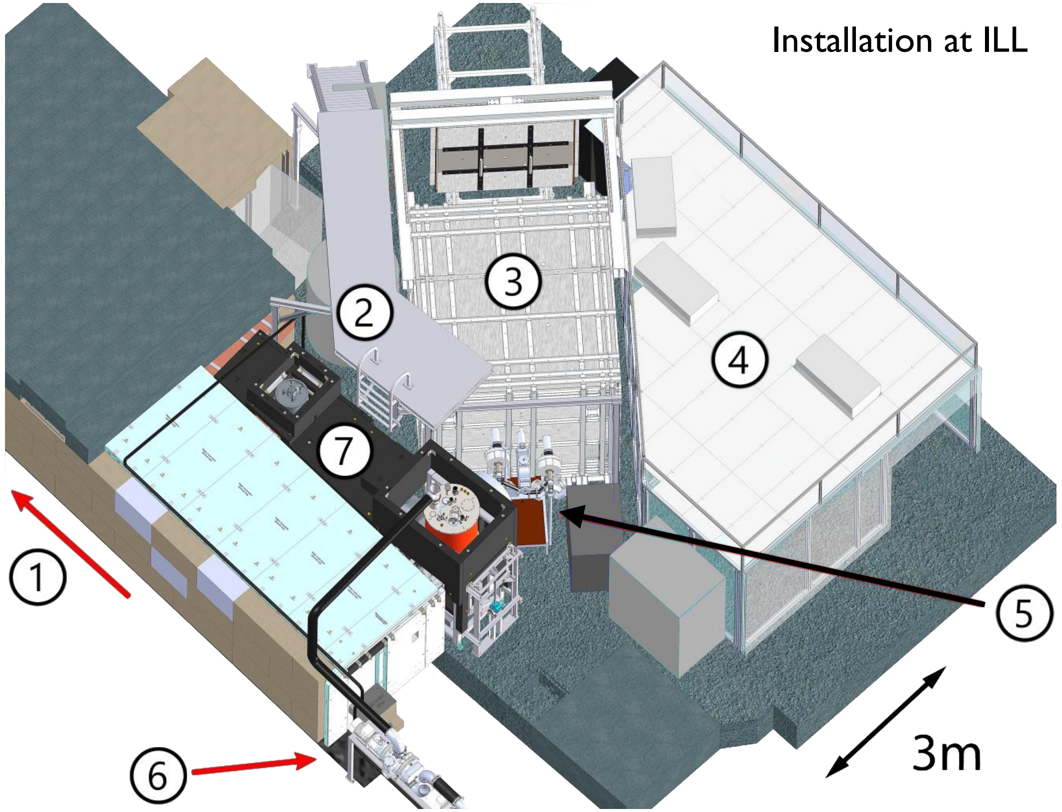
Posters
E. Chanel, Hanno Filter

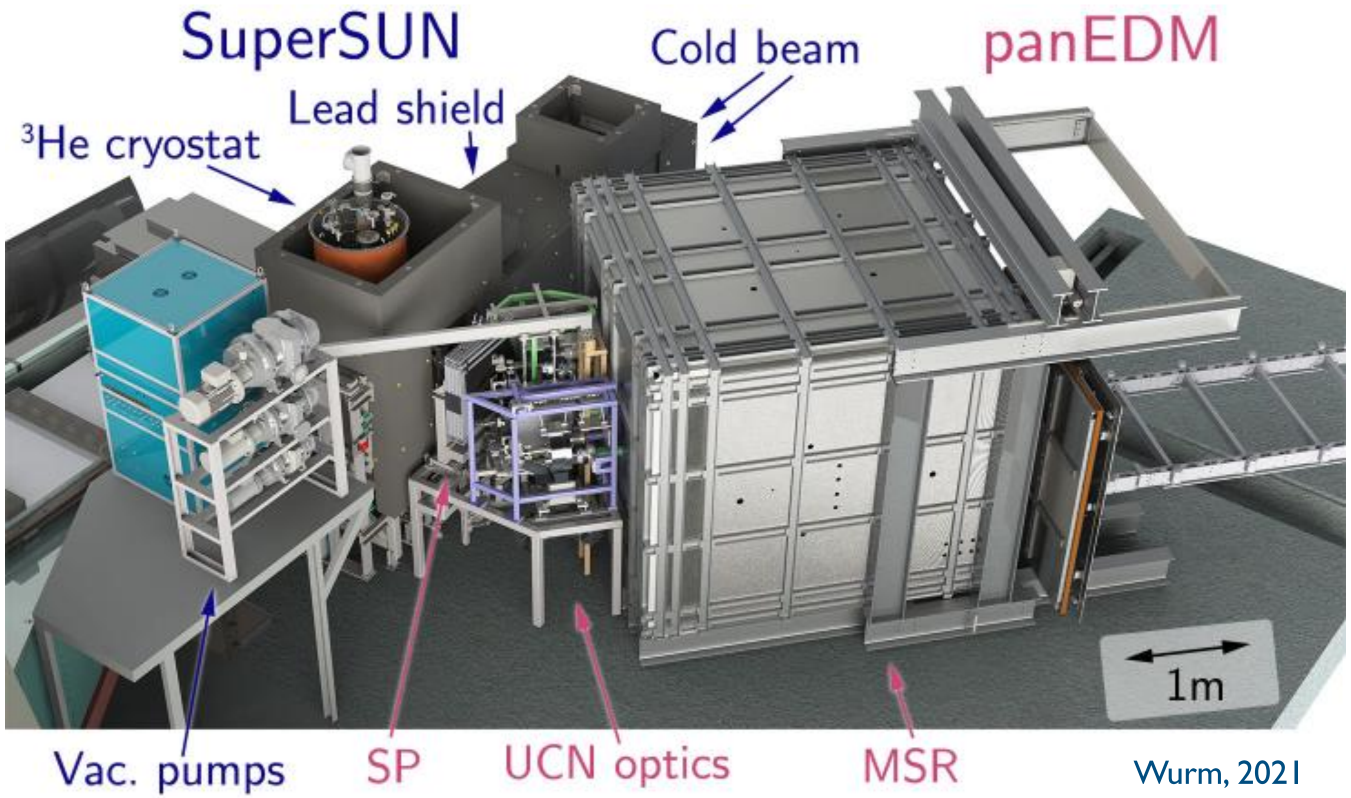
Preparing interface of Phase I to PanEDM

1. Neutron guide H523
2. Experiment platform
3. Magnetically shielded room
4. Clean room
5. Neutron guide and detection section
6. 3He Pumps
7. Ultra-cold neutron source - SuperSUN

Posters
E. Chanel, Hanno Filter

Installation at ILL

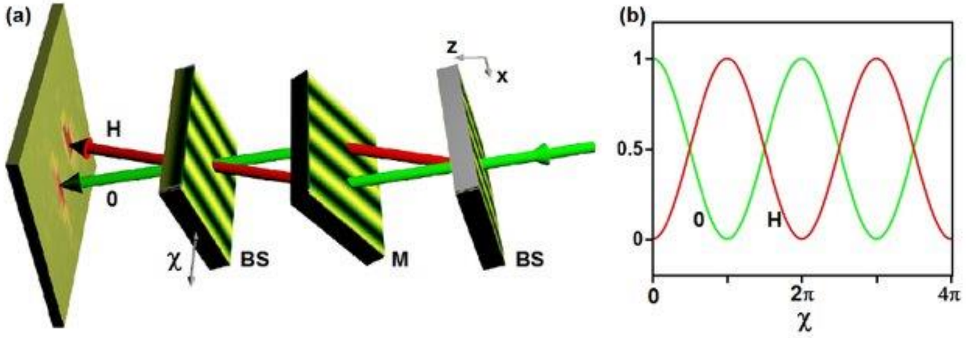




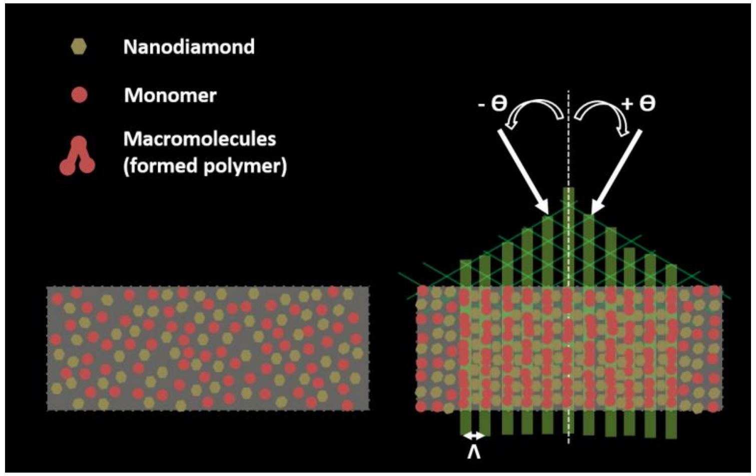
Wurm, 2021

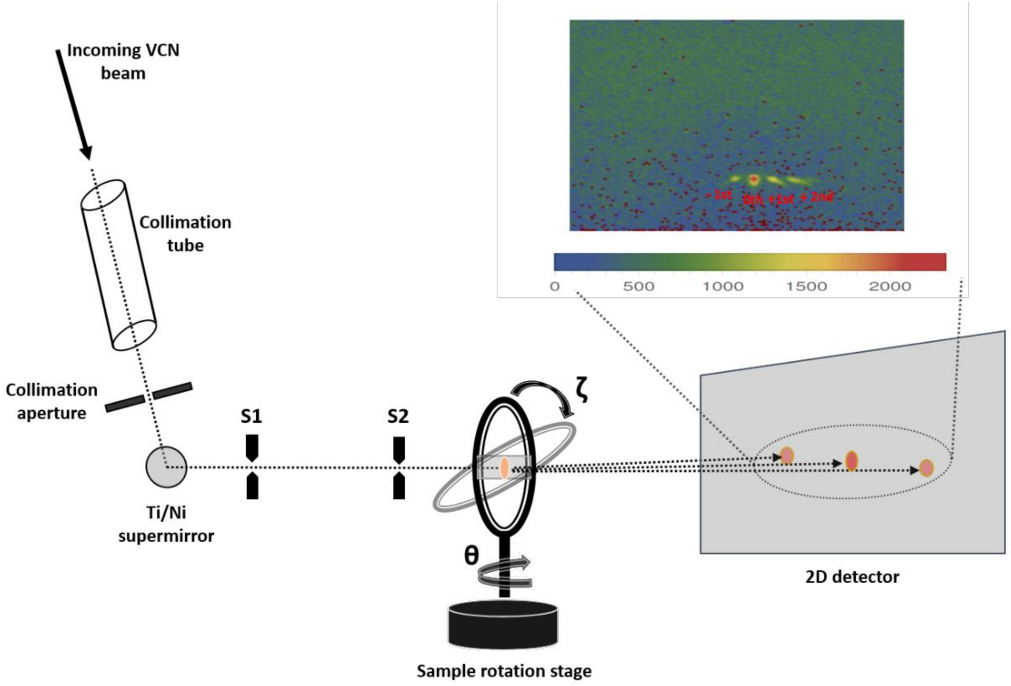
Towards state of the art interferometry with VCN at PF2

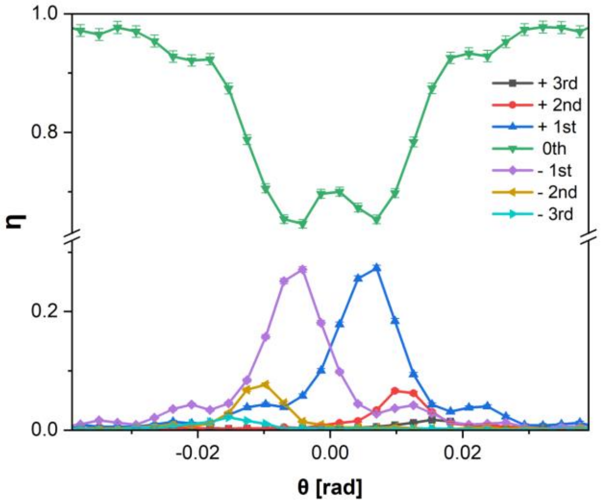
Interferometry with VCN: longer interaction times, larger area, no crystals



Development of efficient gratings needed







Hadden et al. Proc. SPIE 12151, Photosensitive Materials and their Applications II, 1215109 (2022)

Outline

Neutrino activities

- STEREO (short base line neutrino oscillation experiment)
- RICOCHET (Experiment on coherent neutrino nucleus scattering)

UCN activities

- PF2 (Mirror neutron, qbounce, D2 cross section, VCN optics)
- Status of SuperSun and PanEDM

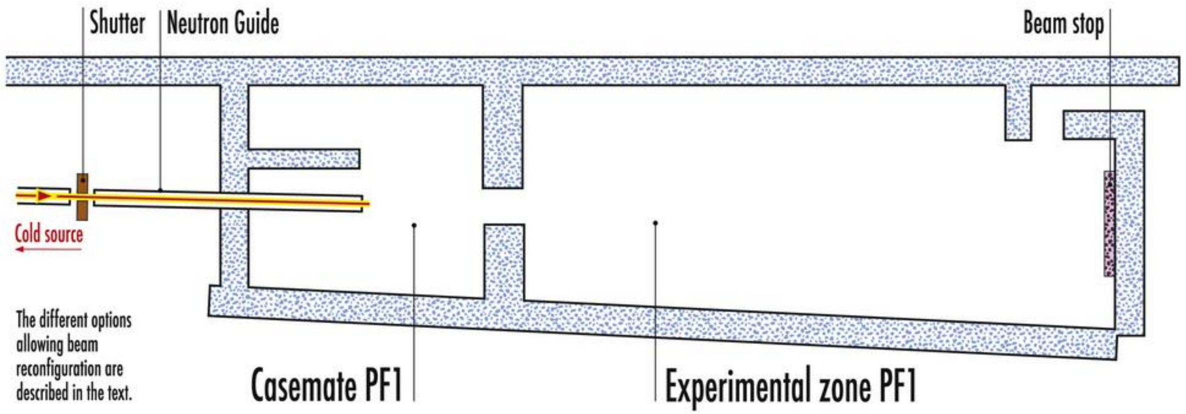
Cold Neutron activities

- PF1B (BRAND, PERKEOIII, Beam EDM, diffraction enhancement, new polarizer, optimizing VCN production/transport)

Thermal neutron activities

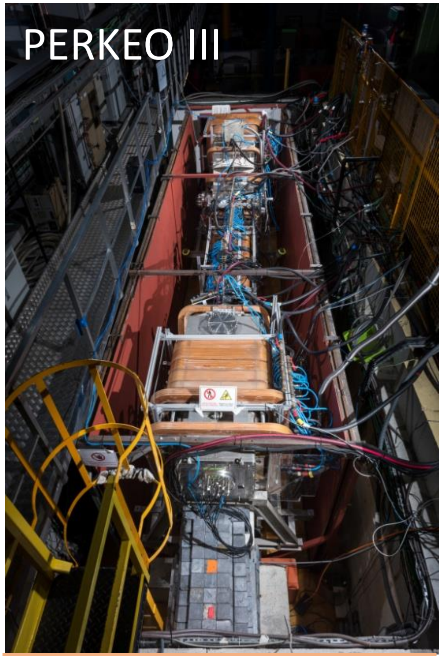
- S18 (which way experiments, split crystal interferometer)

Pf1b – cold neutron facility



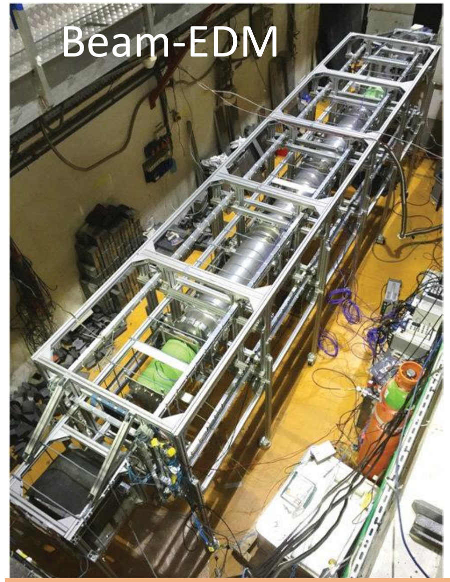
Unpolarized beam cross section:	6x20 cm^2
Polarized beam cross section:	3x4.5cm^2 or 6x8cm^2
Un-polarized capture flux:	$2x10^{10}$ n $cm^{-2}s^{-1}$
Polarized capture flux:	$3x10^9$ n $cm^{-2}s^{-1}$
Beam height above ground:	140 cm
Mean neutron wavelength:	4-4.5 A

Large Particle Physics Experiments

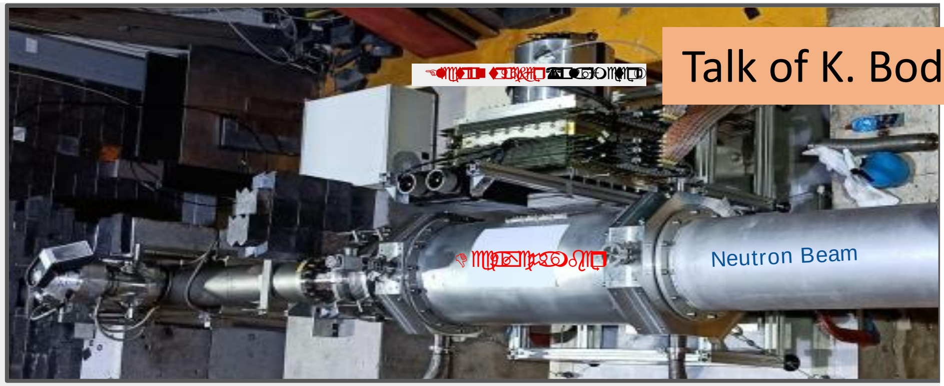


Talk of B. Märkisch

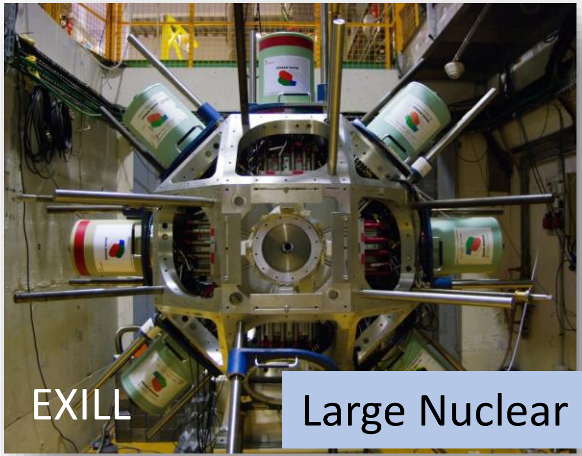
Talk of U. Schmidt

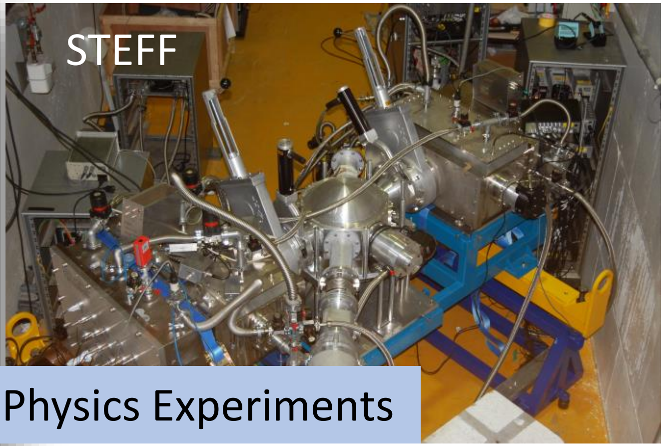


Talk of I. Schuldthess



Talk of K. Bodek





Large Nuclear Physics Experiments

10^7x sensitivity enhancement by diffraction

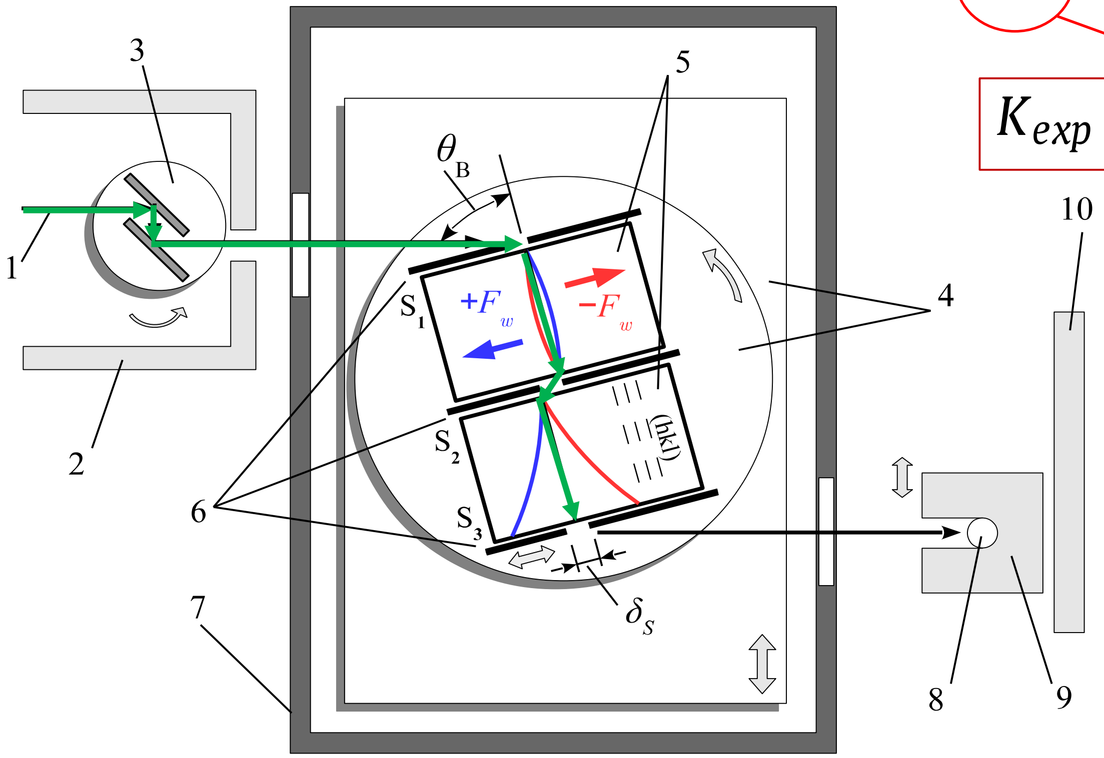
$$\psi^{(1)}(\mathbf{r}) = \cos\gamma e^{i\mathbf{k}^{(1)}\mathbf{r}} + \sin\gamma e^{i[\mathbf{k}^{(1)}+\mathbf{g}]\mathbf{r}},$$
$$\psi^{(2)}(\mathbf{r}) = -\sin\gamma e^{i\mathbf{k}^{(2)}\mathbf{r}} + \cos\gamma e^{i[\mathbf{k}^{(2)}+\mathbf{g}]\mathbf{r}}.$$

$$F_w = \frac{m_0 d}{\pi \tan^2\theta_B} \cdot \frac{2E_n}{L^2} \cdot \delta_s \equiv \frac{1}{K_e} \cdot \frac{2E_n}{L^2} \cdot \delta_s$$

$$K_e^{(220)} = \frac{\pi \tan^2\theta_B}{m_0 d} = 2.1 \cdot 10^5 \cdot \tan^2\theta_B$$

$$\boxed{K_{exp} \sim 2 \cdot 10^5 \tan^2\theta_B}$$

~10^7



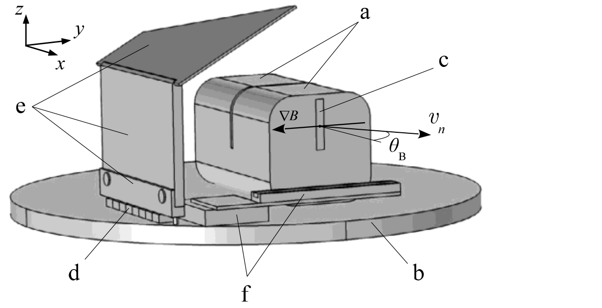
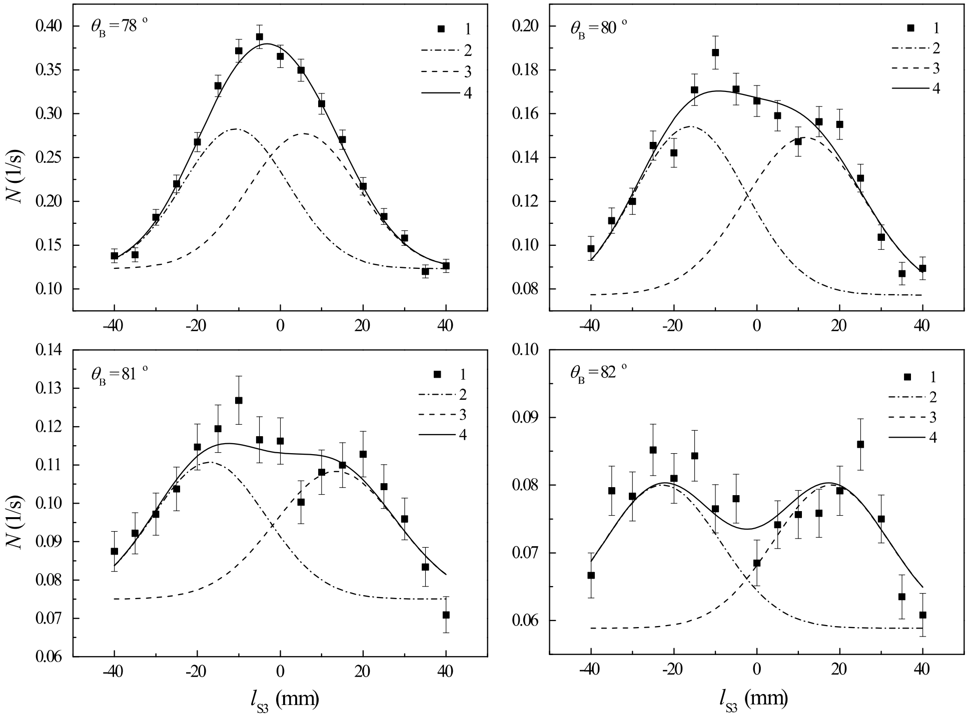


Fig. 3. Schematic view on probing silicon crystal and magnetic field guide: a – probing silicon crystal, b – rotation stage (also part of field guide), c – neutron beam exit area, d – permanent magnets, e – magnetic field guide, f – piezomotor positioner of exit slit S_3 (slit is not shown).

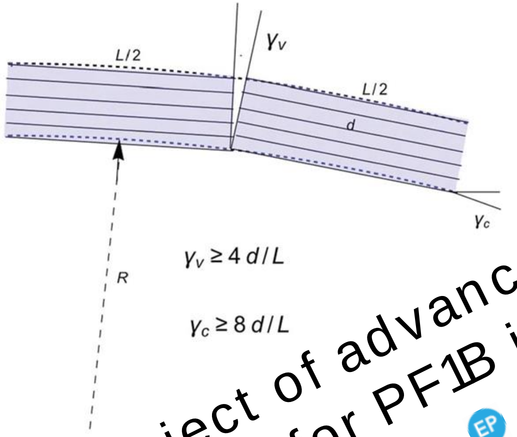


V.V. Voronin et al., Physics Letters B 809 (2020) 135739

A new advanced solid-state polarizer for cold neutrons

Old Polarizer: Co/Ti/Gd coating on borofloat glas: P=0.985, T=0.49 or in X-geometry P=0.997, T=0.25

Activated due to Co, damaged due to $^{10}B(n,\alpha)$ in glass substrate



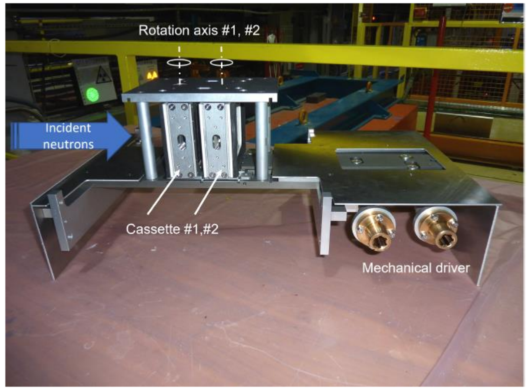
New Polarizer:

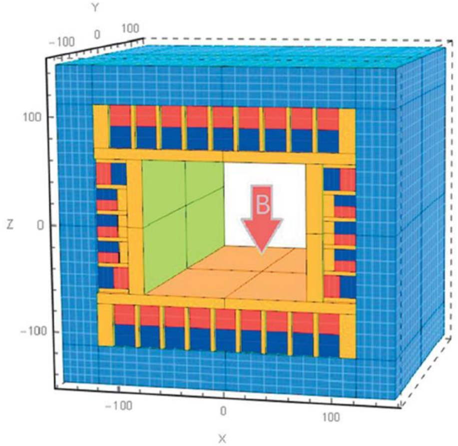
- (603)Fe/Si …
  Sapph…

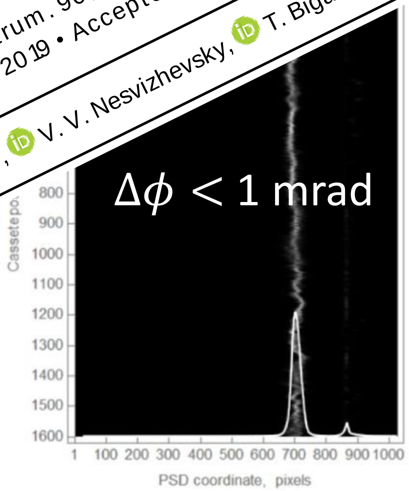
A project of advanced solid-state neutron polarizer for PF1B instrument at Institut Laue-Langevin

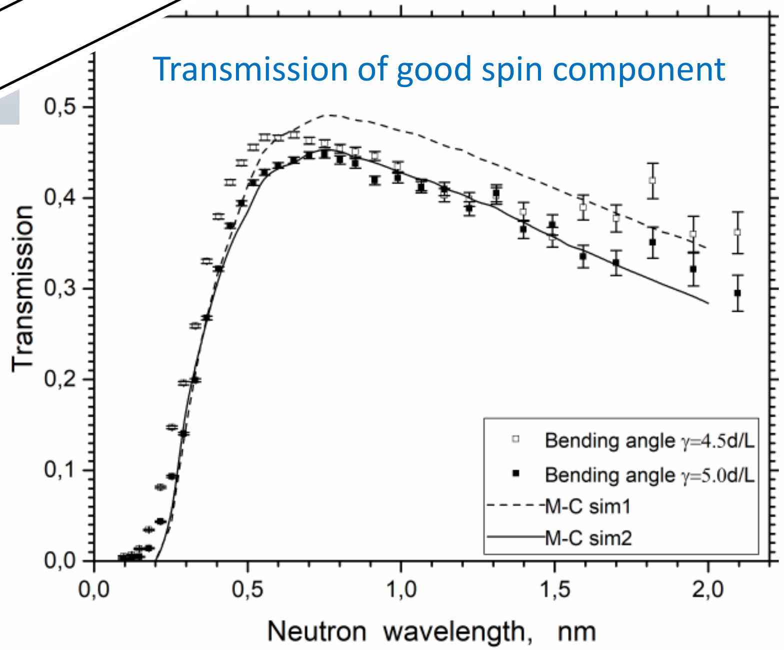
Cite as: Rev. Sci. Instrum. 90, 085112 (2019); https://doi.org/10.1063/1.5114796
Submitted: 11 June 2019 • Accepted: 06 August 2019 • Published Online: 28 August 2019

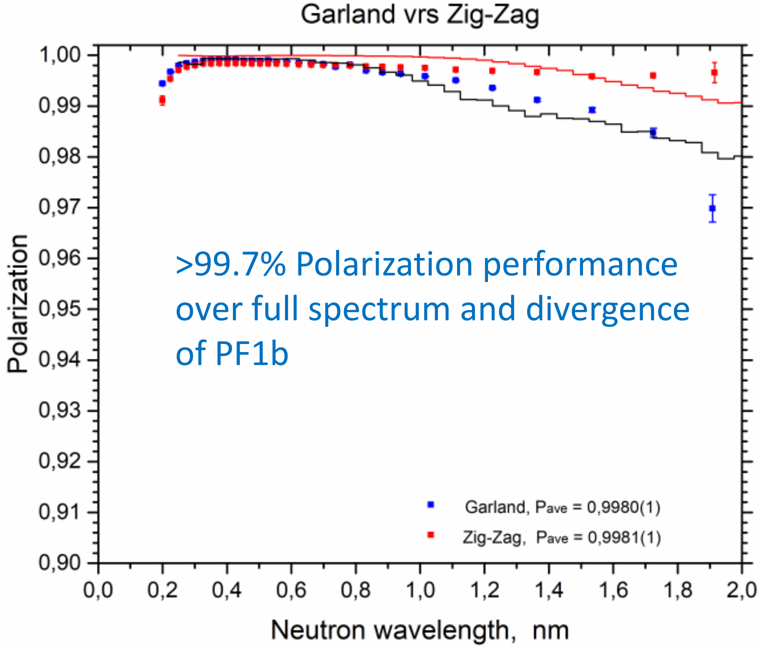
A. K. Petukhov, V. V. Nesvizhevsky, T. Bigault, et al.







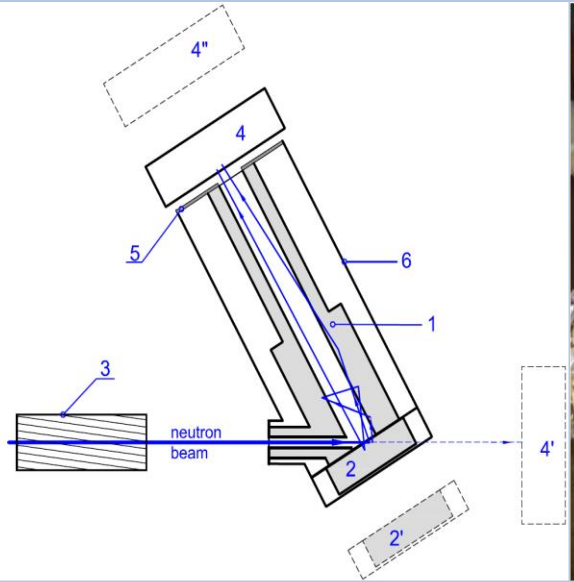


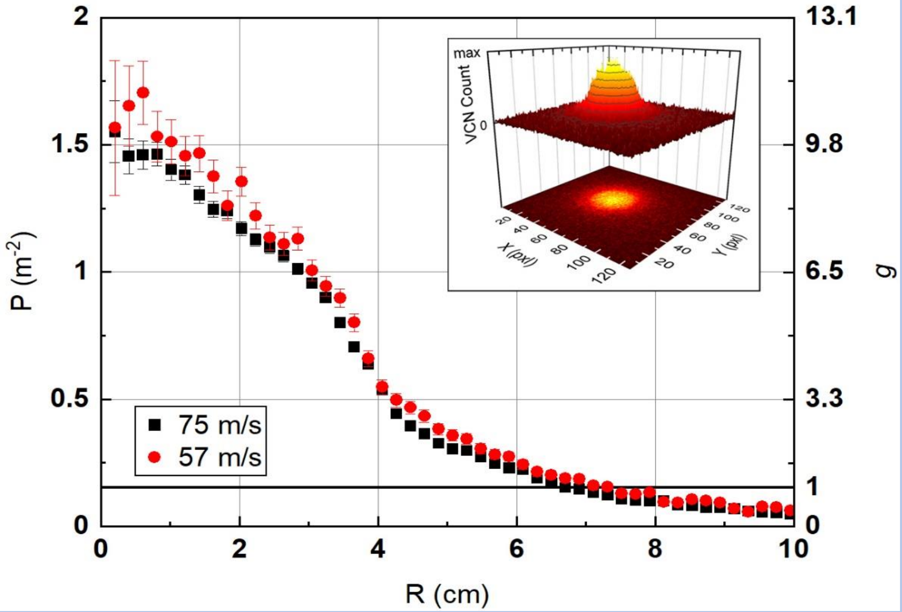


Towards new reflectors and moderators for VCN sources

NEUTRONS FOR SOCIETY

A. Aleksenskii et al., Nanomaterials 11 (2021) 3067;



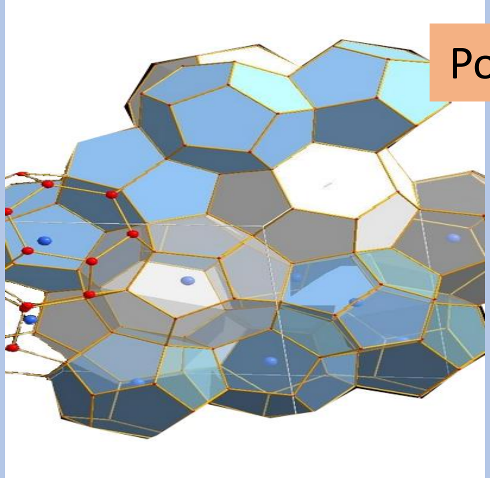


JINR

UNIVERSITÉ Clermont Auvergne

Innovative moderator materials for VCN:

- Clathrates – crystalline water-based solids
- With guest molecules trapped inside cages
- Weakly absorbing
- Large albedo for cold neutrons



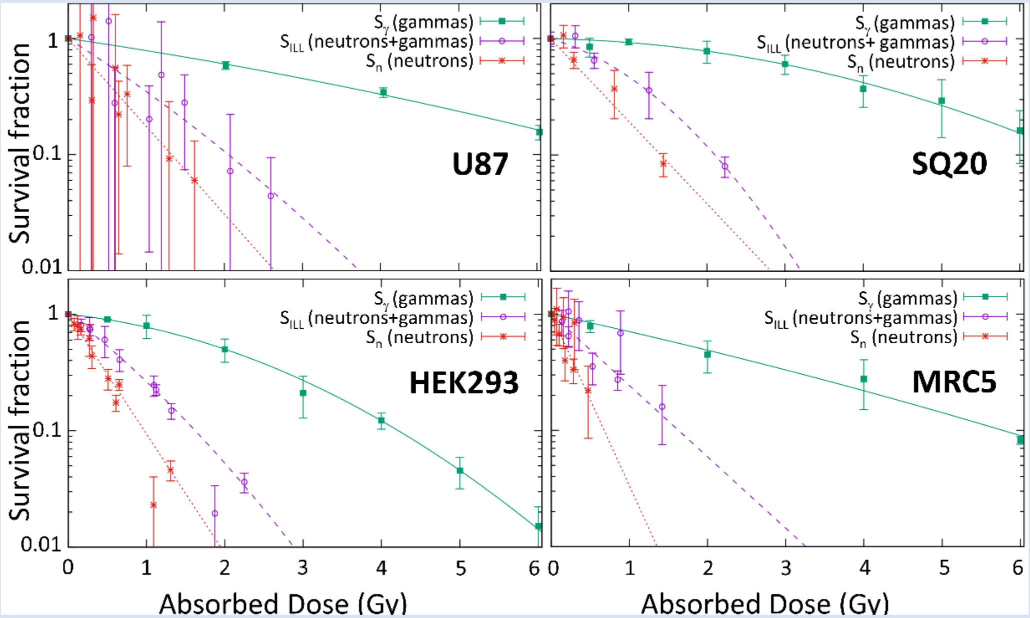
Poster by Valentin Czamler

ess EUROPEAN SPALLATION SOURCE

HighNess

Activities with cold neutrons at PF1b

- **BRAND, BeamEDM, PERKEO, ASPECT** (Talks K. Bodek, I. Schulthess, B. Maerkisch, U. Schmidt)
- Diffraction Enhancement with cold neutrons
- New solid state polarizer
- New reflector materials based on Nanodiamonds
- New VCN moderator materials (Poster of V. Czamler)
- Medical Applications: BNCT



Activities with cold neutrons at PF1b

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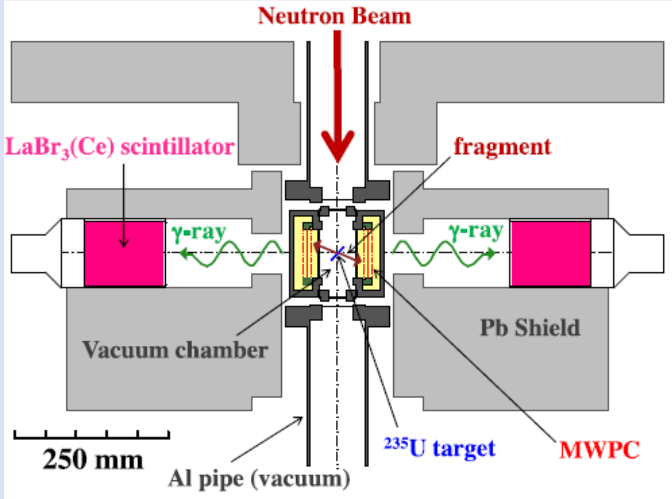
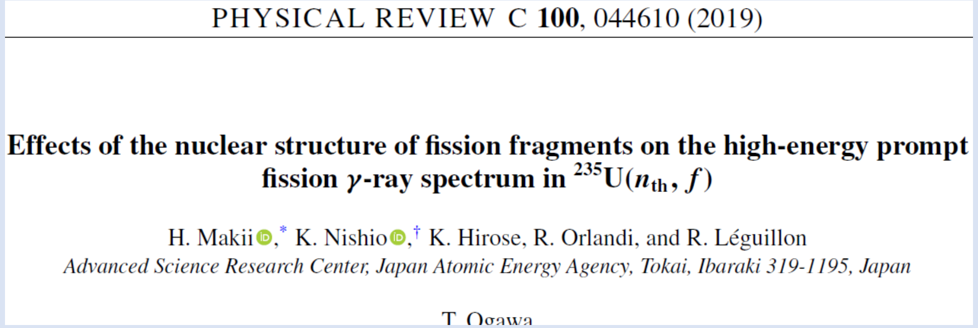
- New reflector materials based on Nanodiamonds
- New VCN moderator materials (Poster of V. Czamler)
- Medical Applications: BNCT
- Nuclear Data:



- High-energy end of fission neutron spectrum: Irradiation ^{235}U with (n,x) monitor foils
- High-energy end of gamma neutron spectrum


PHYSICAL REVIEW C **100**, 044610 (2019)

Effects of the nuclear structure of fission fragments on the high-energy prompt fission γ-ray spectrum in $^{235}\mathrm{U}(n_{\mathrm{th}}, f)$

H. Makii,* K. Nishio,† K. Hirose, R. Orlandi, and R. Léguillon
Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan

T. Ogawa

Outline

NEUTRONS FOR SOCIETY

Neutrino activities

- STEREO (short base line neutrino oscillation experiment)
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UCN activities

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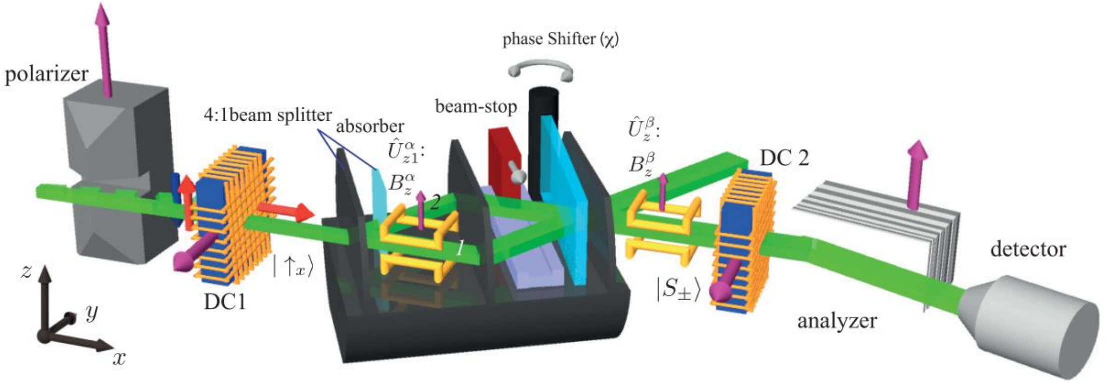
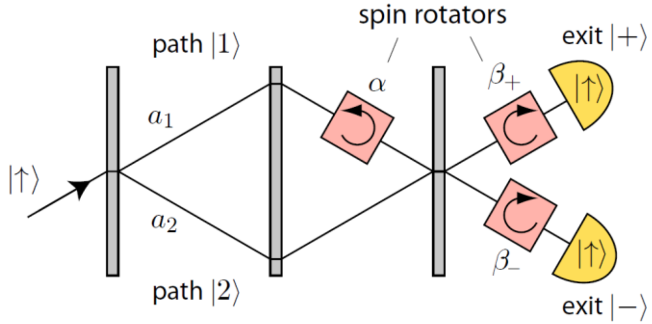
- S18 (which way experiments, split crystal interferometer)

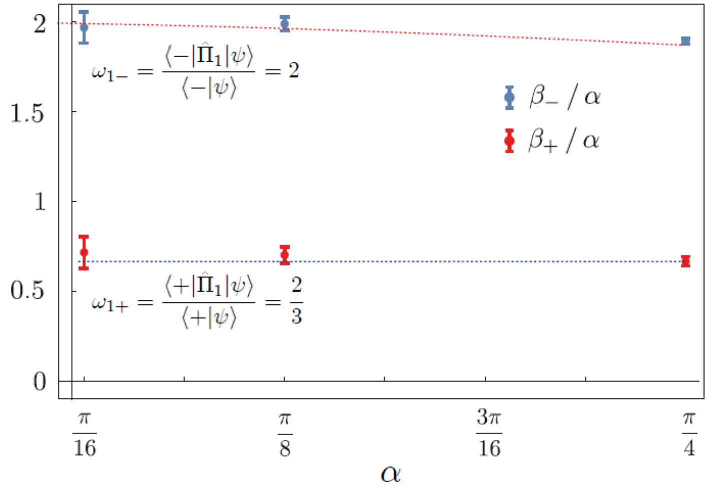
Which way experiment at S18





$$|\psi\rangle = a_1|1\rangle + a_2|2\rangle$$

$$\omega_{1\pm} = \frac{\beta}{\alpha}$$



1. Which way experiment via double slit:

- Measuring $p_1 = |\langle 1|\psi\rangle|^2$ directly in path $|1\rangle$ destroys interference
- Better measure only in the exit beams $|\pm\rangle = \frac{1}{\sqrt{2}}\big(|1\rangle \pm |2\rangle\big)$

2. Which way via weak measurement:

- Mark particle in one path by spin rotation α
- Make α small to maintain interference, measure many times
- Analyze spin $\Rightarrow$ Weak Value of path 1 projection operator = Path-1 “presence“:

$$\omega_{1\pm} = \frac{\langle \pm|\hat{\Pi}_1\psi\rangle}{\langle \pm|\psi\rangle} = \frac{a_1}{a_1 \pm a_2}$$

- Weak Measurement gives only ensemble average

3. Which way via weak measurement and feedback compensation:

- β compensates α and restores the initial spin state (“feedback“: optimal β depends on exit path $\pm$)
- pure final spin state measured $\Rightarrow$ vanishing variance

$$\omega_{1\pm} = \frac{\beta_\pm}{\alpha}$$

$\Rightarrow$ Path presence applies to every single neutron.

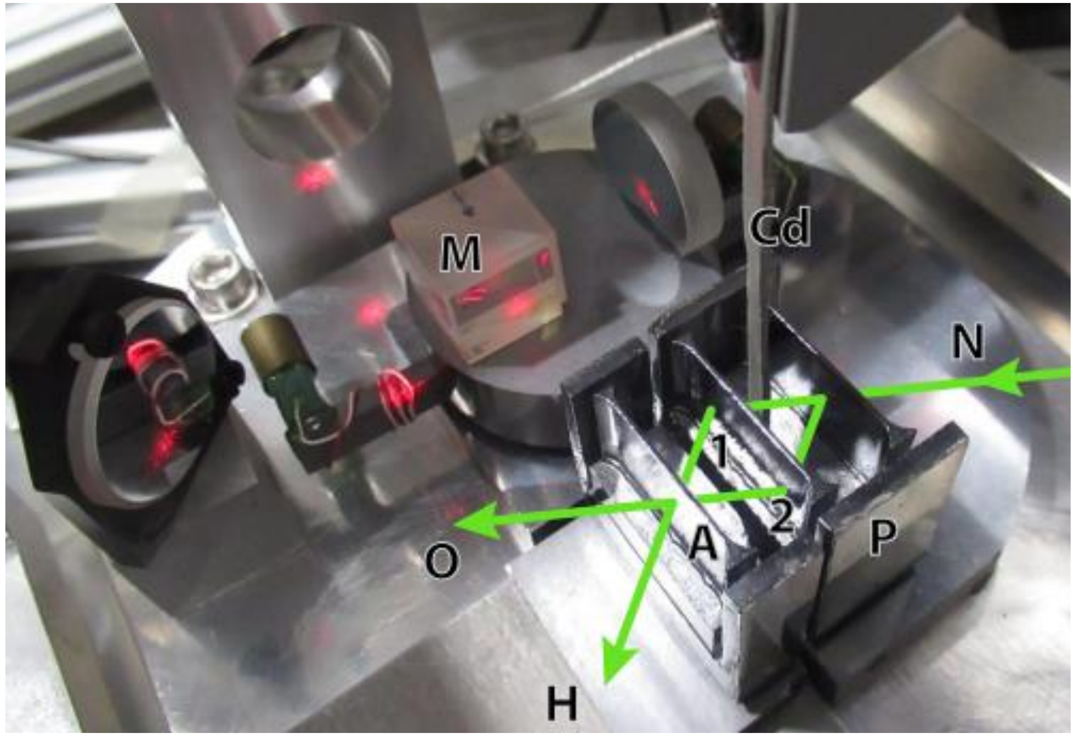
e.g. asymmetric beam splitter: $a_1 = 2/\sqrt{5}$ $\quad \omega_{1+} = 2/3$ $\quad \omega_{1-} = 2$
$a_2 = 1/\sqrt{5}$ $\quad \omega_{2+} = 1/3$ $\quad \omega_{2-} = -1$

probability to reach final states: $p_+ = 9/10$ $\quad p_- = 1/10$

$$p_+\omega_{1+} + p_-\omega_{1-} = p_1$$

averaging weak values over final states $\Rightarrow$ original probability

Demonstration of split crystal

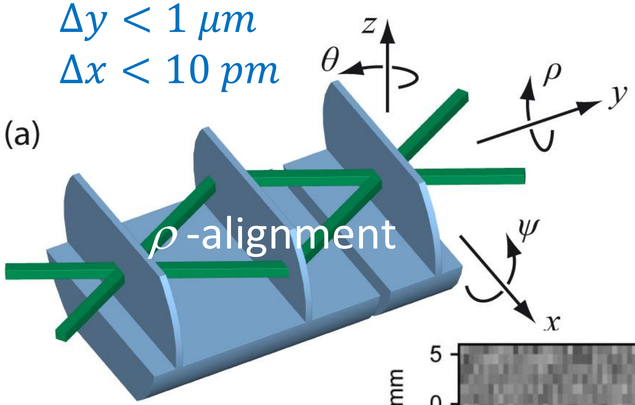


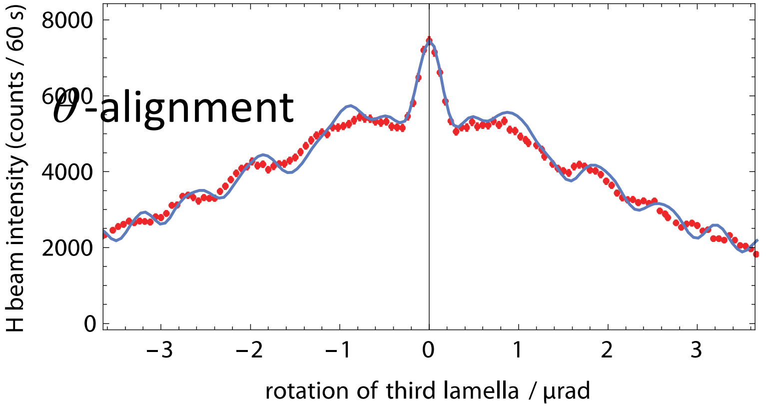
H. Lemmel et al., Journ. Appl. Cryst. 55 (2022) 870 -875

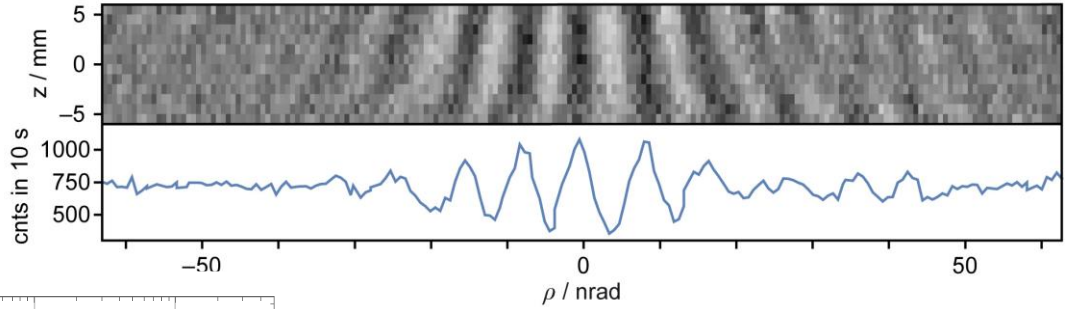
Next step: Building combined X-ray, Optical- and Neutron interferometer

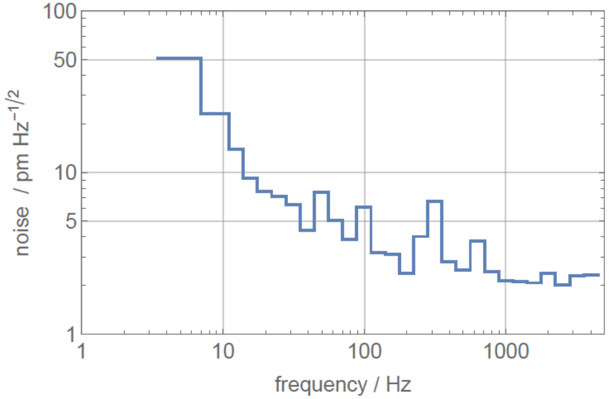
$\Delta\theta < 0.1\ \mu rad$
$\Delta\rho < 1\ nrad$
$\Delta y < 1\ \mu m$
$\Delta x < 10\ pm$

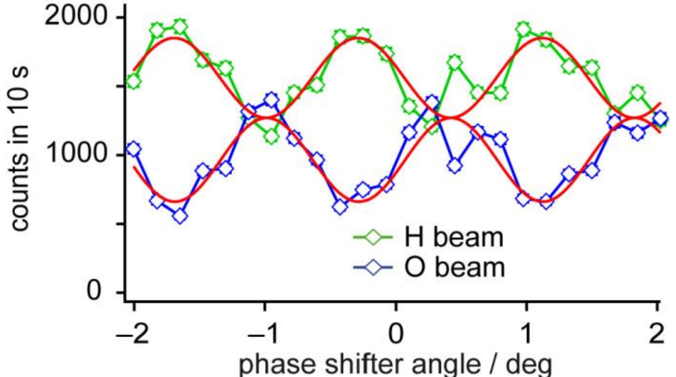
(a)





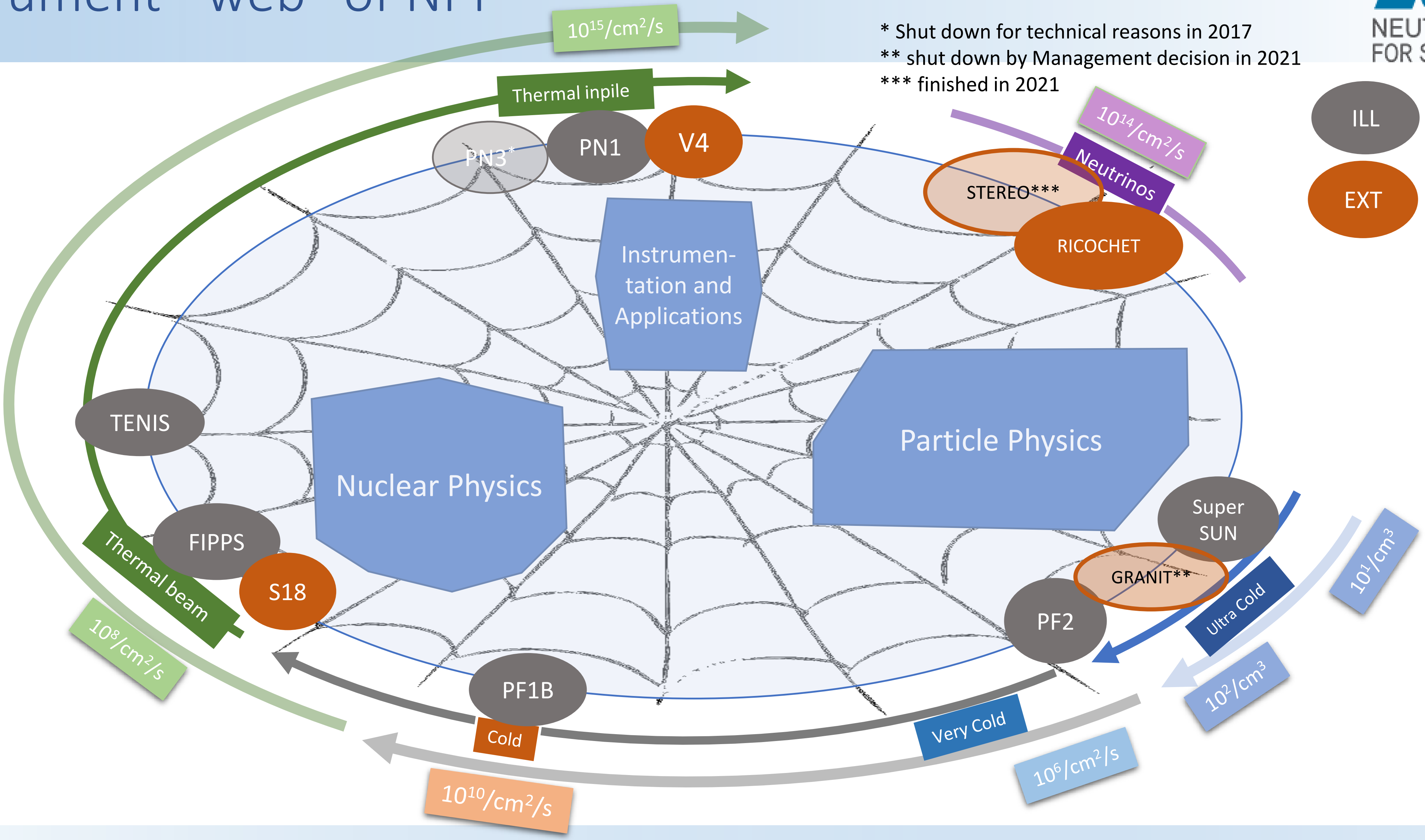






The “Instrument - web” of NPP

* Shut down for technical reasons in 2017
** shut down by Management decision in 2021
*** finished in 2021



All instruments contribute to a larger picture.
Main activity of NPP: Particle Physics, Nuclear Physics, Instrumentation & Applications.