Coherent Elastic ν–Nucleus Scattering @ ESS

- CEνNS provides a new avenue to explore fundamental neutrino and nuclear physics.

- ESS is the ***ultimate source*** for CEνNS, as far as the eye can see.

- As such, it deserves ***next-generation*** nuclear recoil (NR) detectors sensitive to CEνNS.

- ***Precision:*** removing statistical limitations is possible at the ESS with *non-intrusive* detectors

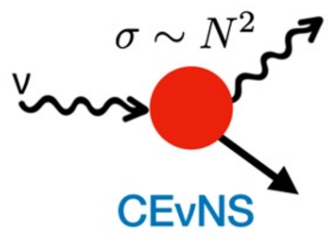
  (small footprint, no interference with neutron mandate)

- Developing ***three*** technologies to meet challenge via two ERC actions. Benefit from their synergies.

- Perfect timing vis-à-vis ESS start. Possible sites identified and studied via simulation (background measurements in preparation)

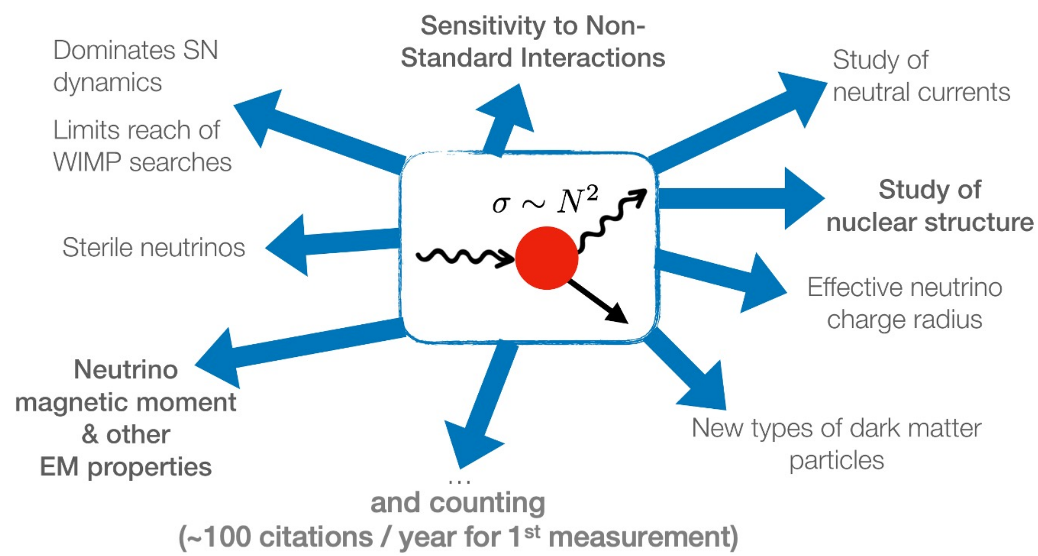
- Enthusiastic reception. Work (and flow of funding) has started!

Long wavelength, ν "sees" all nucleons simultaneously



Cross section increases as N². (largest of all -> small detectors) CATCH: sub-keV to few keV recoils are only observable.

First measurement only 7 years ago (40 years after description)



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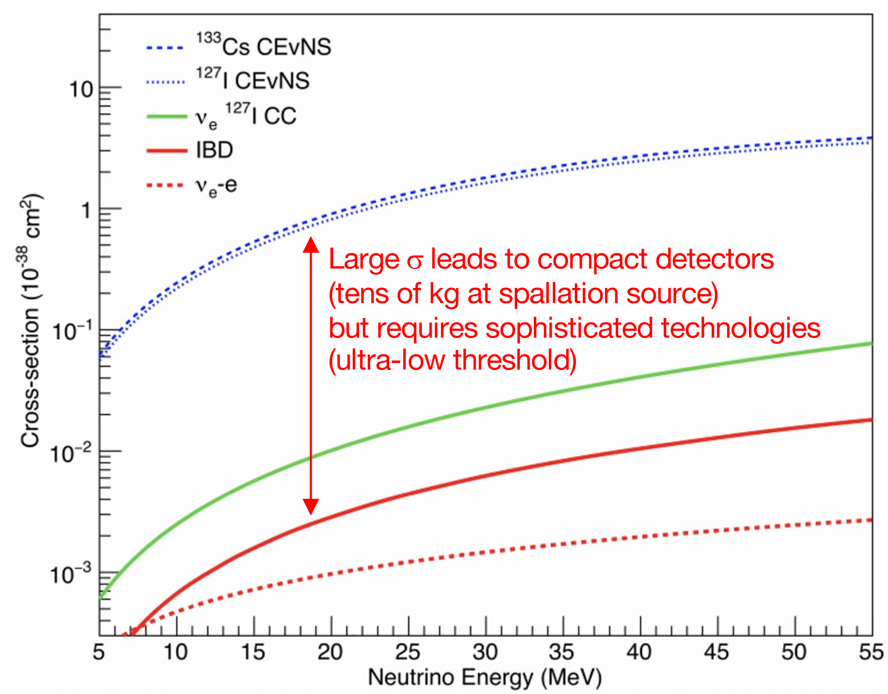

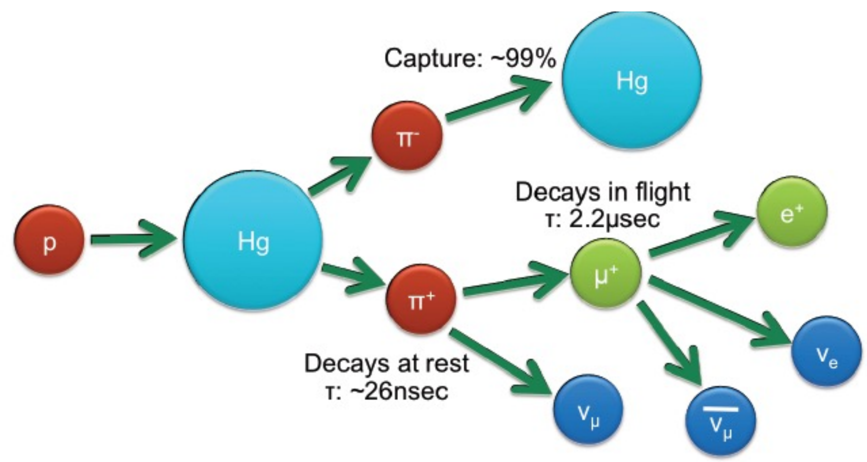

ESS: also a wondrous low-energy neutrino source, ideal for CEνNS studies

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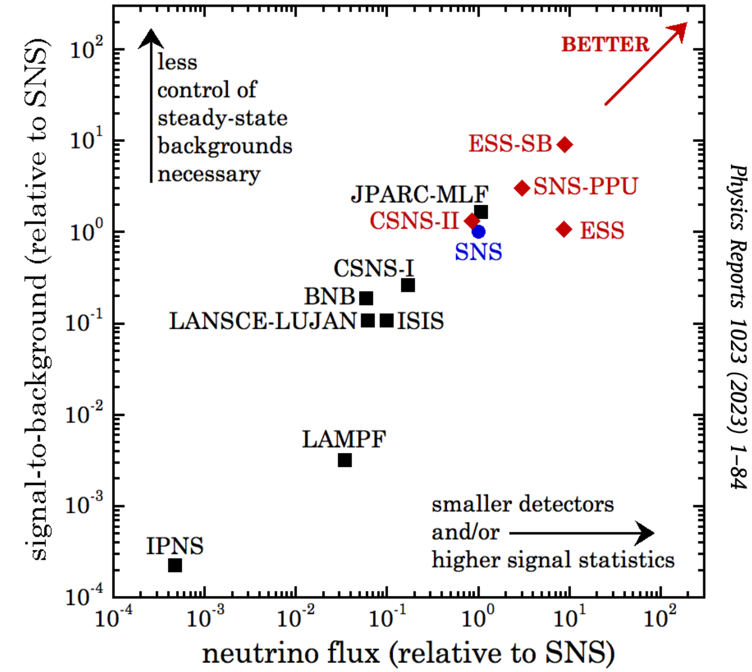
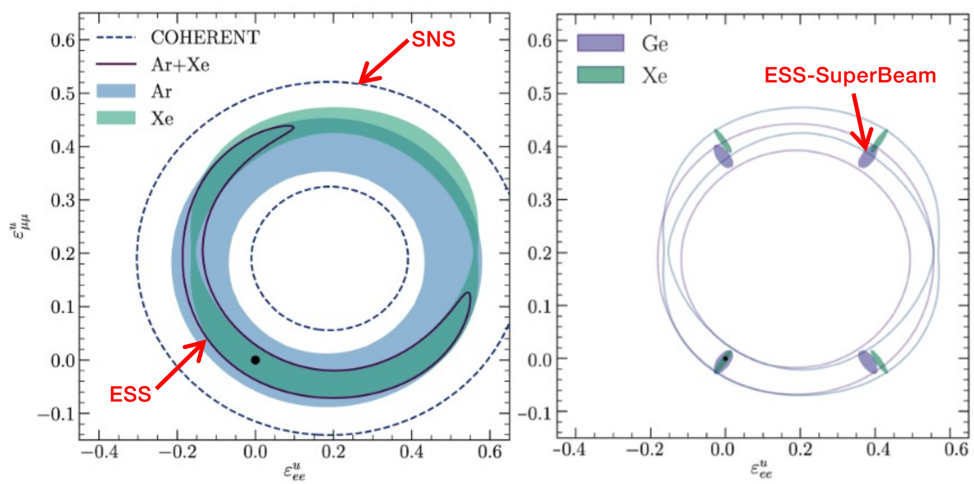
Comparison of past, present and future spallation sources for CEνNS:





Example: sensitivity to non-standard neutrino interactions (smaller is better)

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DIPC PIs:

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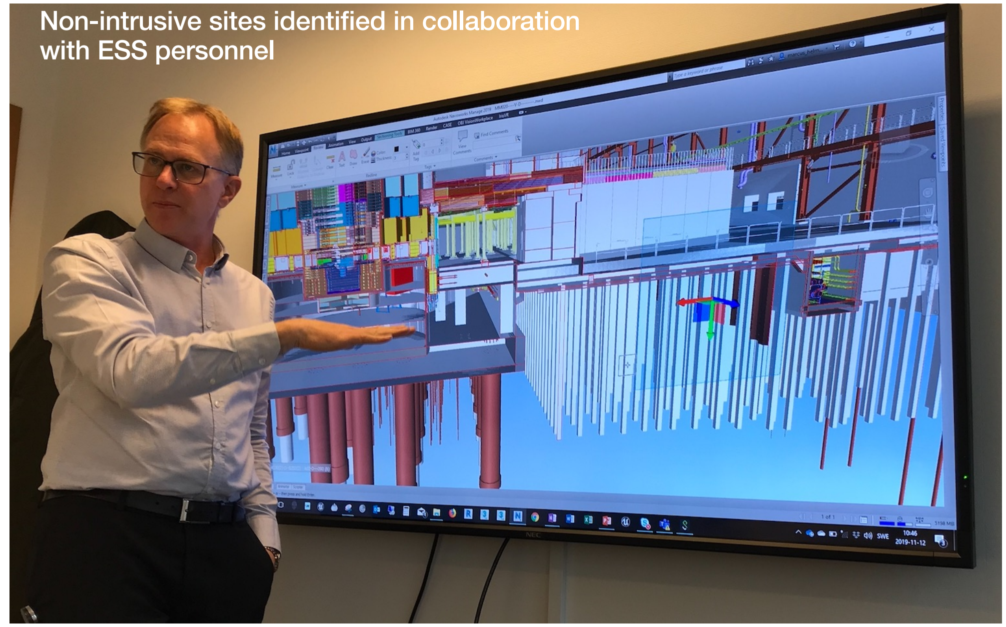

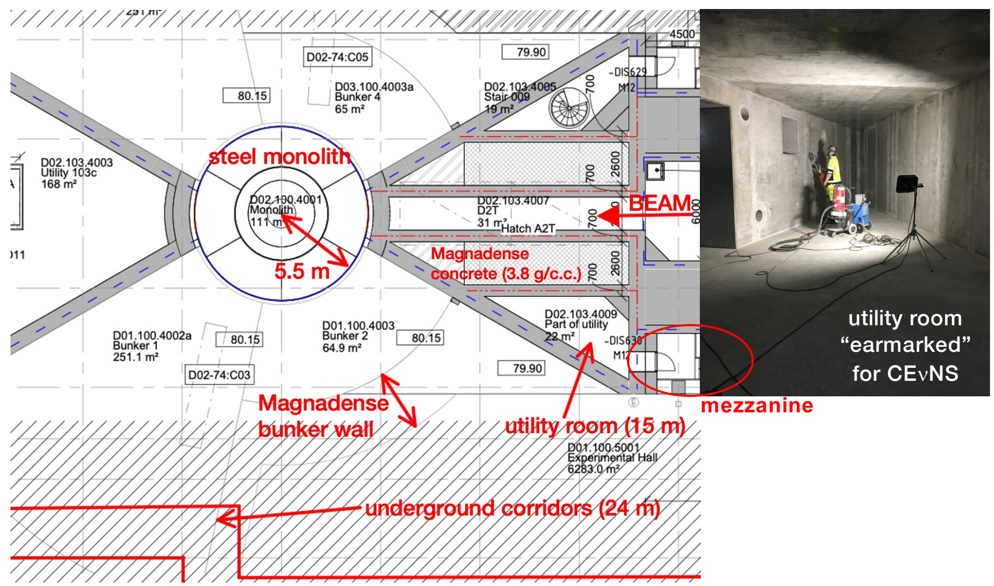

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Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source

D. Baxter,[1] J.I. Collar,[1,*] P. Coloma,[2,†] C.E. Dahl,[3,4] I. Esteban,[5,‡] P. Ferrario,[6,7,§] J.J. Gomez-Cadenas,[6,7,¶] M. C. Gonzalez–Garcia,[5,8,9,**] A.R.L. Kavner,[1] C.M. Lewis,[1] F. Monrabal,[6,7,††] J. Muñoz Vidal,[6] P. Privitera,[1] K. Ramanathan,[1] and J. Renner[10]

PHYSICAL REVIEW D **107**, 055019 (2023)

Constraining nonstandard interactions with coherent elastic neutrino-nucleus scattering at the European Spallation Source

Sabya Sachi Chatterjee,[1,*] Stéphane Lavignac,[1,†] O. G. Miranda,[2,‡] and G. Sanchez Garcia[2,3,§]

Coherent Elastic Neutrino-Nucleus Scattering at the ESS

Expression of Interest

J.I. Collar,[e] J.J. Gomez-Cadenas,[d,g] F. Monrabal,[d,g] P. Privitera,[e] A. Algora,[j] L. Arazi,[m] F. Ballester,[k] D. Baxter,[e] C. Blanco,[e] M. Blennow,[q] F. Calviño,[n] G. Carlsson,[t] J. Cederkall,[t] P. Coloma,[j] C.E. Dahl,[c,f] D. Di Julio,[t,u] C. Domingo-Pardo,[j] T.J.C. Ekelöf,[x] I. Esteban,[b] R. Esteve,[k] M. Fallot,[s] E. Fernandez-Martinez,[p] P. Ferrario,[d,g] H.O.U. Fynbo,[v] P. Golubev,[t] M.C. Gonzalez-Garcia,[a,b,h] A.M. Heinz,[w] J. A. Hernando,[i] P. Herrero,[d] V. Herrero,[k] P. Huber,[o] A.R.L. Kavner,[e] E.B. Klinkby,[u] C.M. Lewis,[e] M. Lindroos,[u] N. Lopez-March,[k] E. Lytken,[t] P.A.N. Machado,[f] M. Maltoni,[p] J. Martin-Albo,[j] T.M. Miller,[u] F.J. Mora,[K] G. Muhrer,[u] J. Muñoz-Vidal,[d] E. Nacher,[J] T. Nilsson,[w] P. Novella,[j] C. Peña-Garay,[l] K. Ramanathan,[e] J. Renner,[i] J. Rodriguez,[k] B. Rubio,[j] J. Salvado,[b] V. Santoro,[u] T. Schwetz,[r] J.L. Tain,[j] A. Takibayev,[u] A. Tarifeño-Saldivia,[n] J.F. Toledo,[k] U. Uggerhøj,[v] and L. Zanini[u]

[a] *C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook NY 11794-3849, USA*
[b] *Departament de Fisica Quántica i Astrofísica, Institut de Ciéncies del Cosmos, Universitat de Barcelona, E-08028 Barcelona, Spain*
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[e] *Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA*
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[l] *Laboratorio Subterráneo de Canfranc, Canfranc Estación, Huesca, E-22880, Spain*
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[q] *Department of Physics, KTH Royal Institute of Technology, AlbaNova University Center, SE–106 91 Stockholm, Sweden*
[r] *Institut für Kernphysik, Karlsruhe Institute of Technology (KIT), 76344 Eggenstein-Leopoldshafen, Germany*
[s] *SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, F-44307 Nantes, France*
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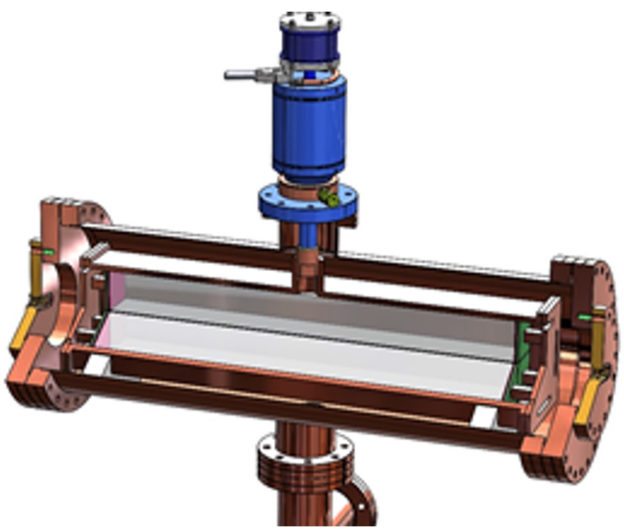
[v] *Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark*
[w] *Department of Physics, Chalmers University of Technology, S-41296 Gothenburg, Sweden*
[x] *Department of Physics and Astronomy, Uppsala University, SE-752 37 Uppsala, Sweden.*

Expression of Interest (61 researchers, 24 institutions). MOU DIPC/ESS submitted.

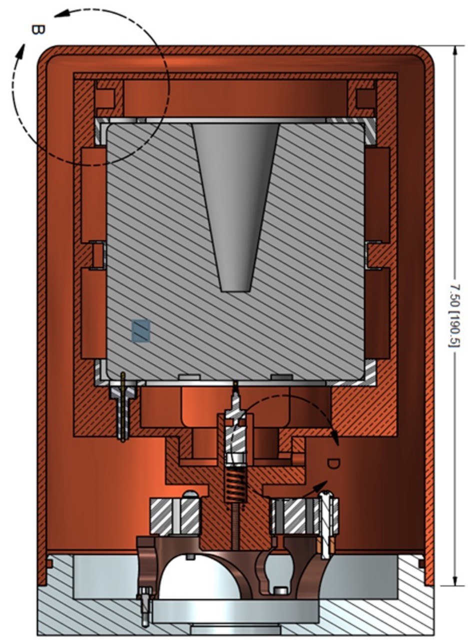
Funded detectors (thus far)

European Research Council

ikur estrategia

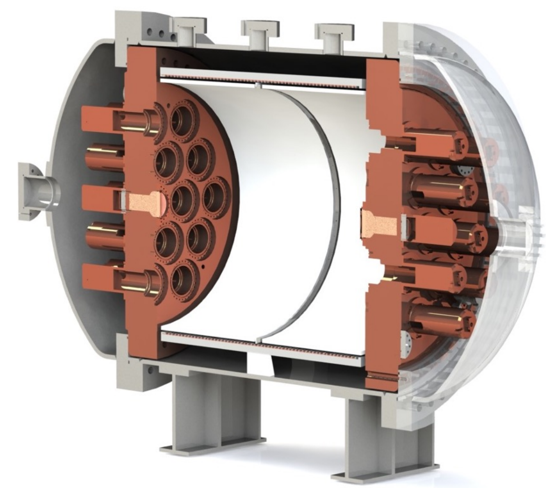


Cryogenic undoped CsI



p-type point contact Ge

ERC-Advanced grant

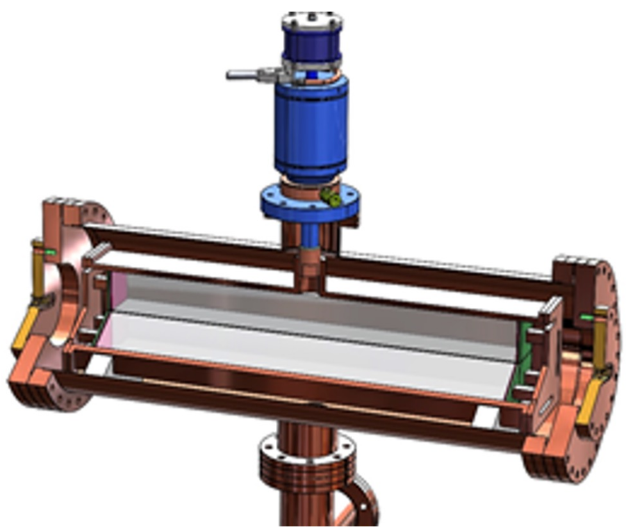


high pressure gas TPC

ERC-Starting grant

Funded detectors (thus far)

100 MEUR/ 10 yr IKERBASQUE program.
“Neutrionics” one of four poles.



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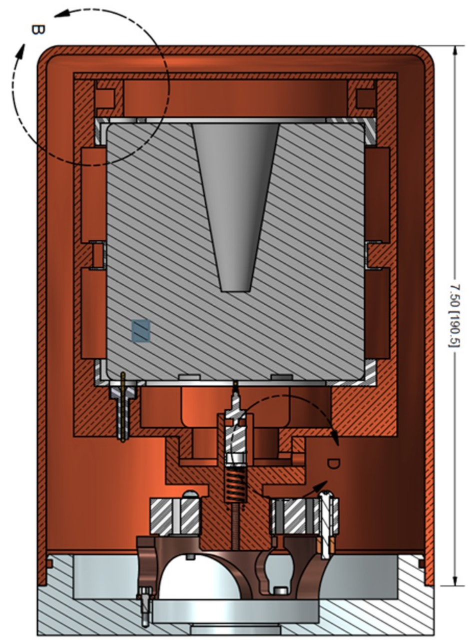

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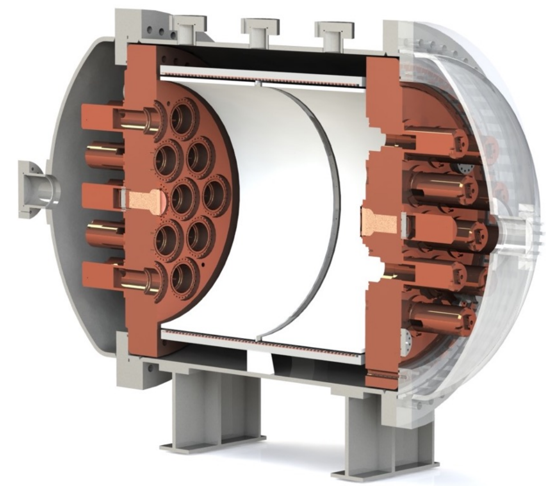

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ikur estrategia

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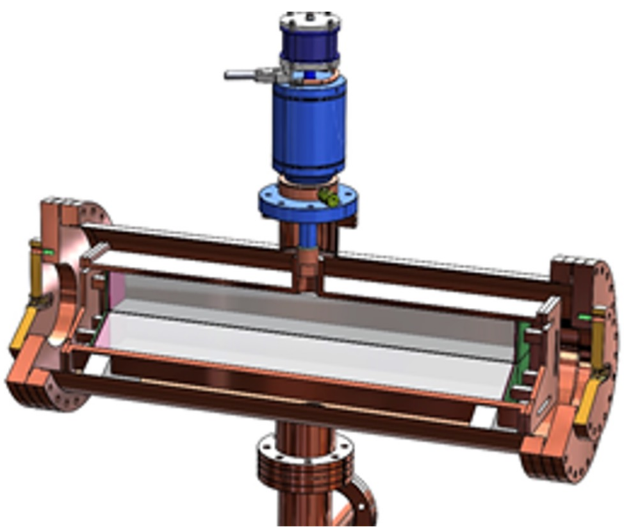

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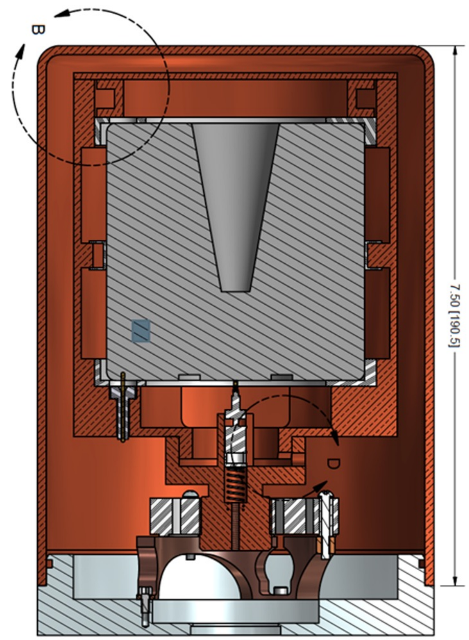

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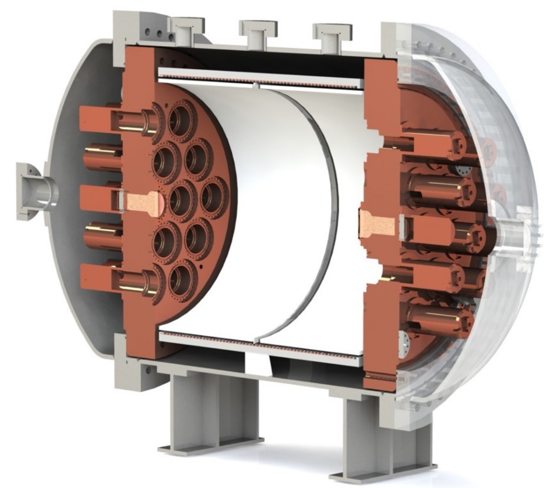

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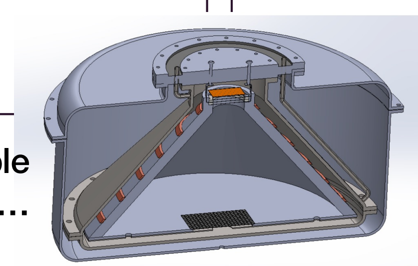
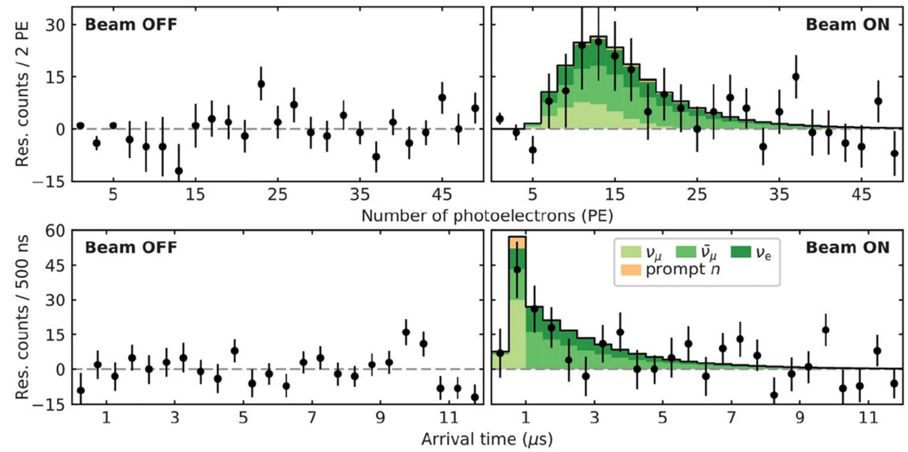
A COLINA visible
above the horizon…



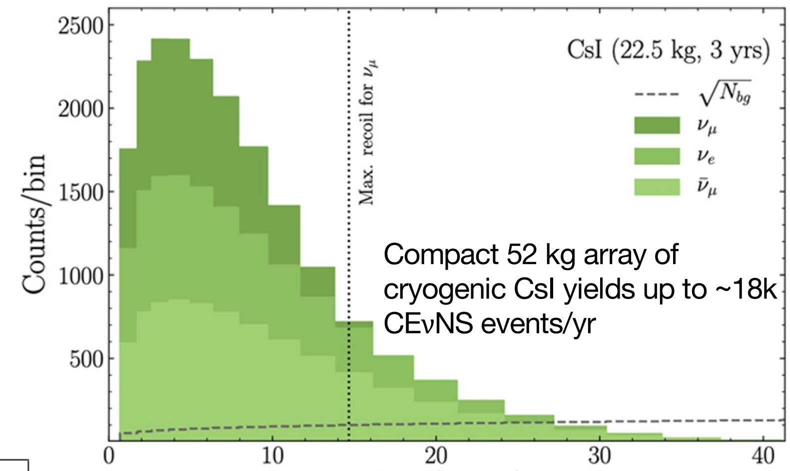
Cryogenic (87 K) undoped CsI array:

- Natural evolution from CsI[Na] at SNS (same advantages of large σ, similar Cs-I mass, low afterglow)
- Combine higher light yield (x2.5-3) and more efficient photosensors (x3 higher QE)
- Large mass increase to ~52 kg (seven 7x7x35 cm crystals)
- LAAPDs with >80% QE provide a measured < 55 eVee threshold in inorganic scintillator (!). Presently limited by charge-trapping noise in NTD silicon. R&D to bypass this in collaboration with industry (FAGOR semiconductors).
- Much improved internal radiopurity w.r.t. SNS, advanced inner active LAr veto.
- Well-studied Quenching Factor down to threshold.

Moving from ~100 events/yr…



…to ~18k events/yr



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Bigger is not always better:

	52 kg cryogenic CsI @ ESS	750 kg LAr @ SNS
events per year	~18,000	~3,000
energy threshold	~ 1 keVnr	~20 keVnr
energy resolution	~47 e-h(Si)/keVee	~4.2 PE/keVee

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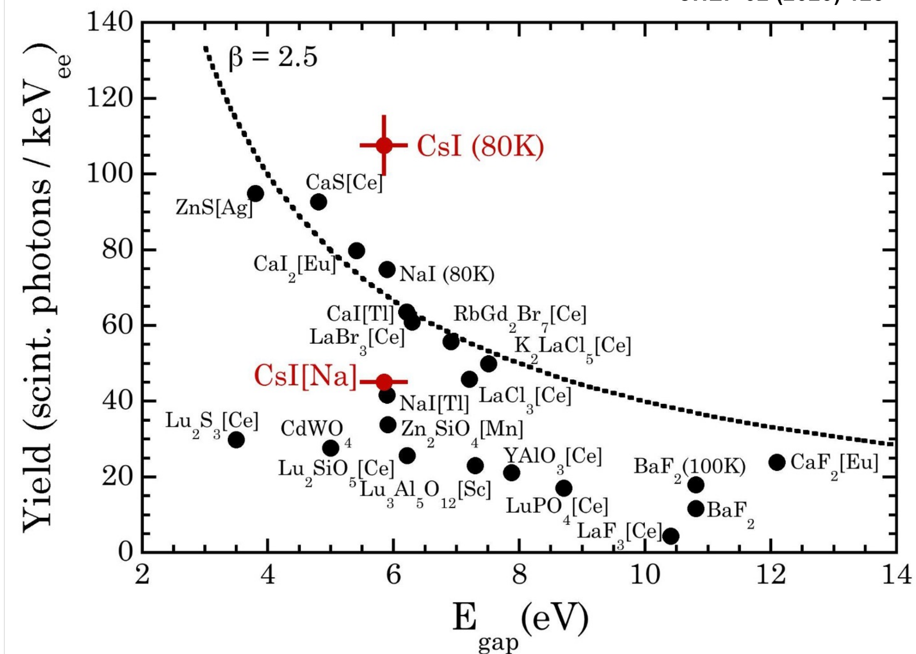

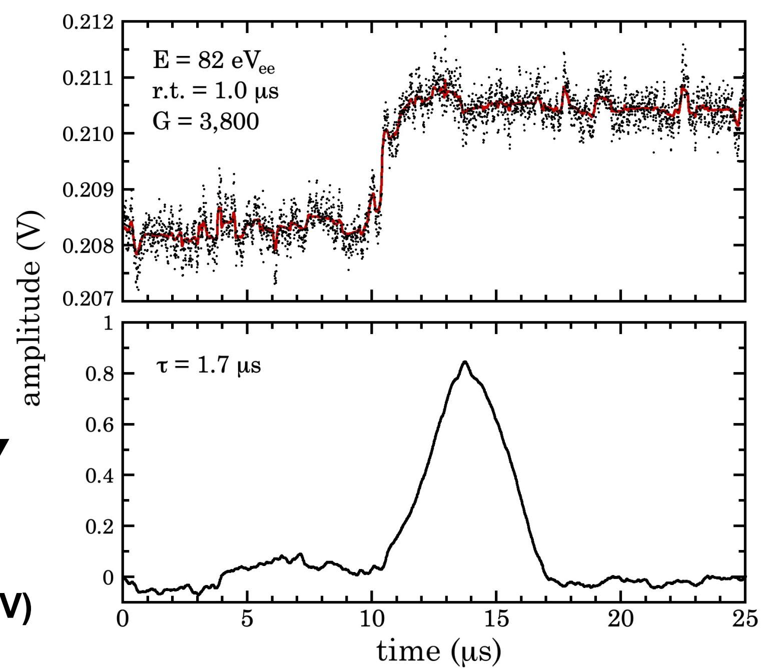

80K CsI
read out by 1.7 cm² LAAPD
(notice signal-to-noise at 82 eV)

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	Amcrys CsI[Na] @ SNS	SICCAS CsI @ ESS
Th-232	<0.5 mBq/kg	0.03 mBq/kg
U-238	2.4 mBq/kg	0.09 mBq/kg
K-40	16.7 mBq/kg	<4.1 mBq/kg
Cs-137	27.9 mBq/kg	1.3 mBq/kg
Cs-134	25.9 mBq/kg	33 mBq/kg
Rb-85	101 ppb	15.5 ppb
Rb-87	38 ppb	1.8 ppb

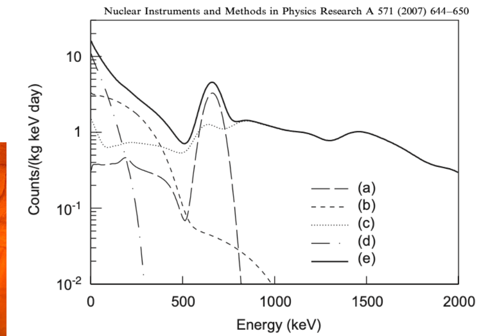
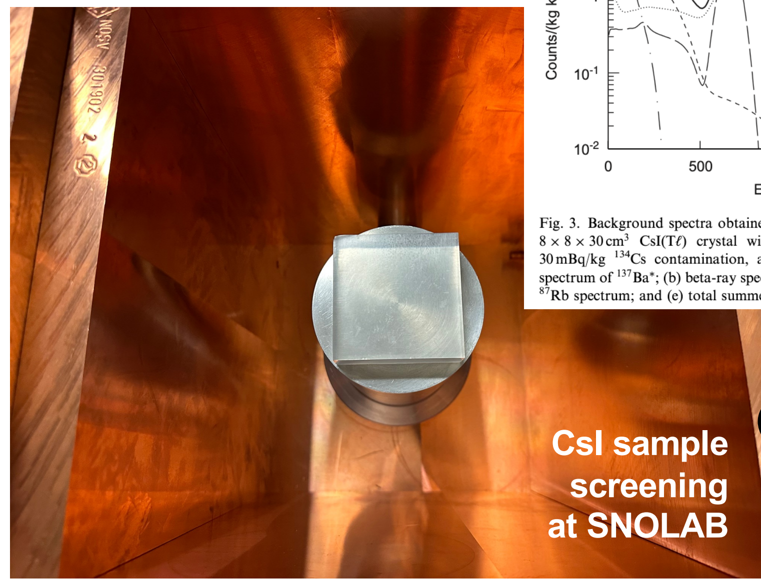


Fig. 3. Background spectra obtained using GEANT4 simulation for the 8 × 8 × 30 cm³ CsI(Tℓ) crystal with 10 mBq/kg ^{137}Cs contamination, 30 mBq/kg ^{134}Cs contamination, and 10 ppb ^{87}Rb contamination: (a) spectrum of ^{137}Ba*; (b) beta-ray spectrum of ^{137}Cs; (c) ^{134}Cs spectrum; (d) ^{87}Rb spectrum; and (e) total summed spectrum.



Attention paid to Rb, Cs (low-E emitters)

SICCAS low-background CsI selected:

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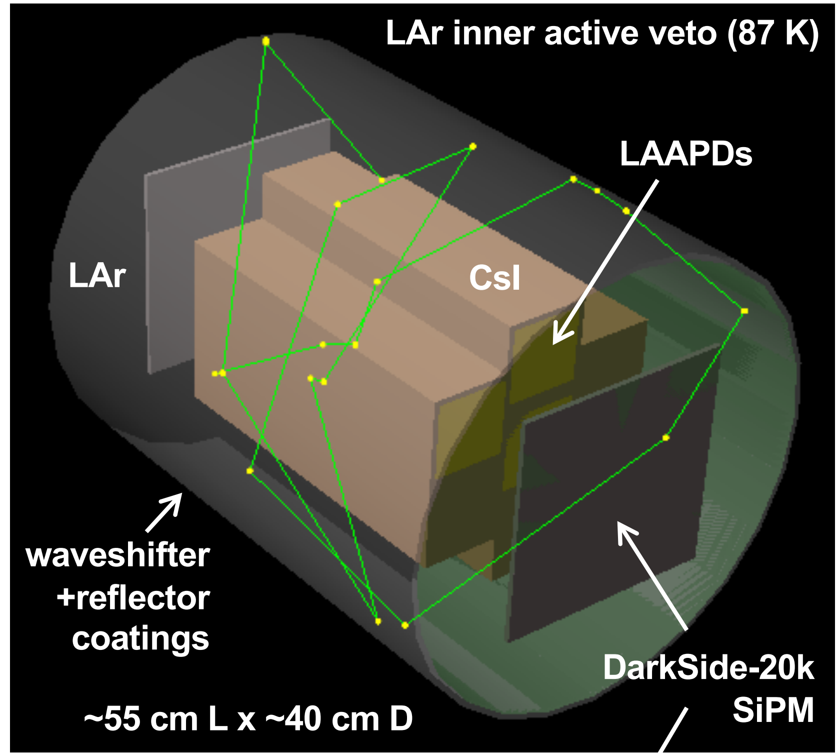

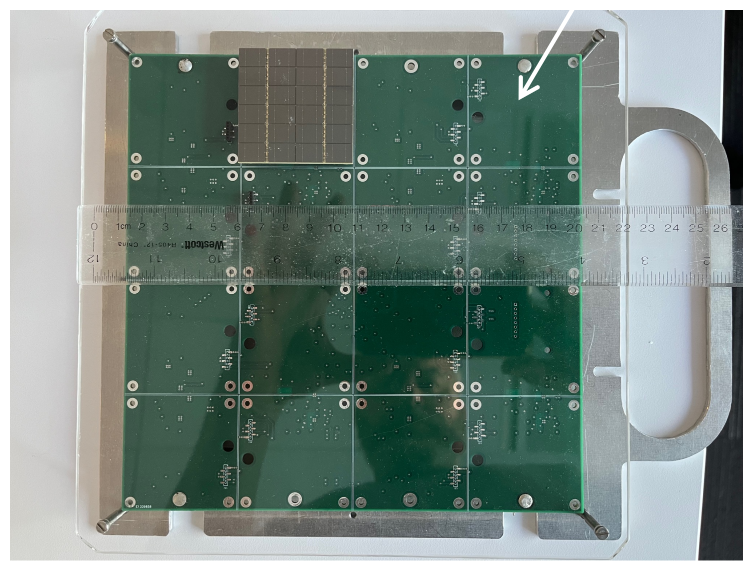

20x20 cm low-field modules
~80 Hz dark rate @ 87 K
(single photon operation)
16 channel output

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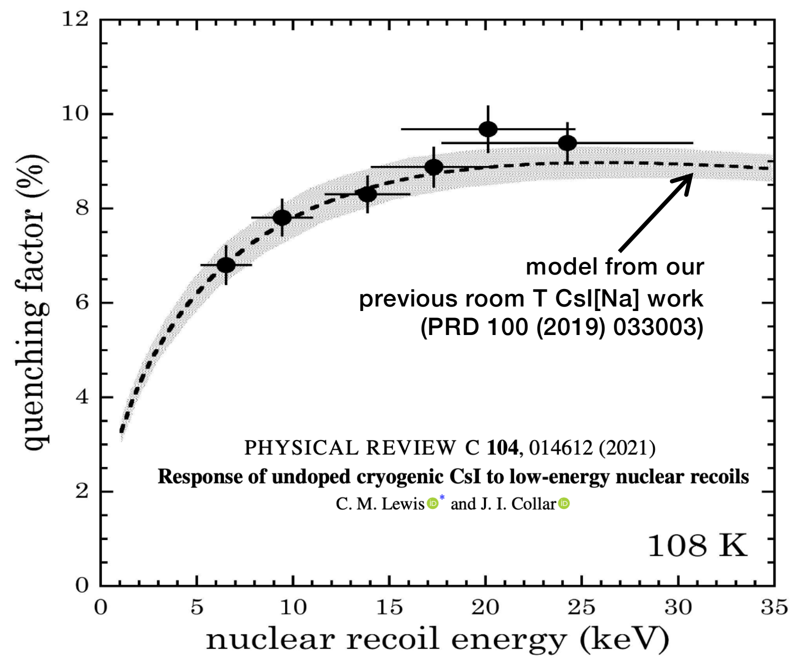
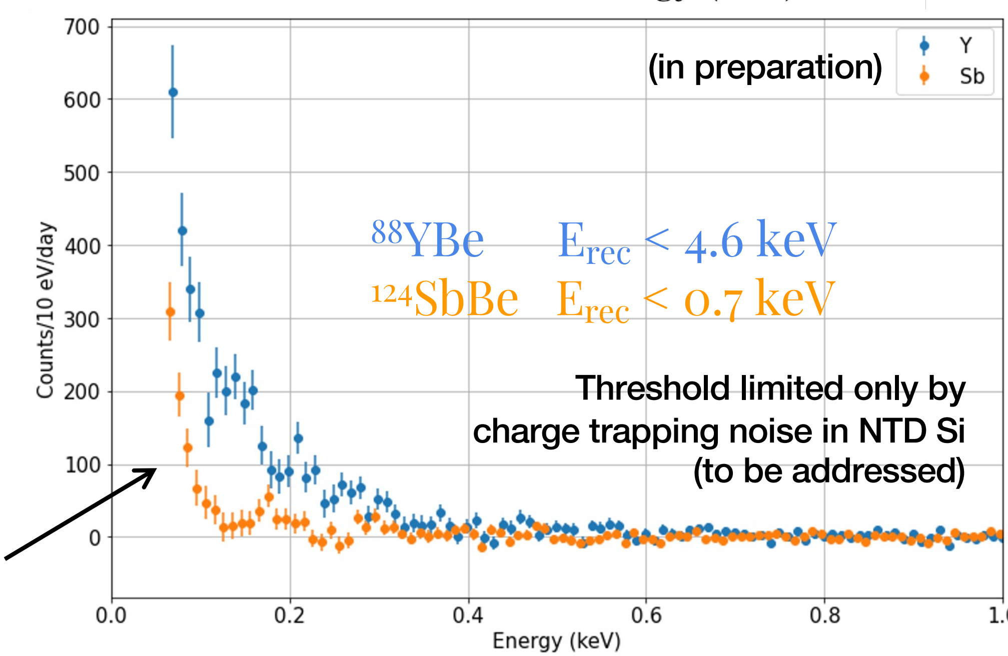
cryo CsI @ OSURR

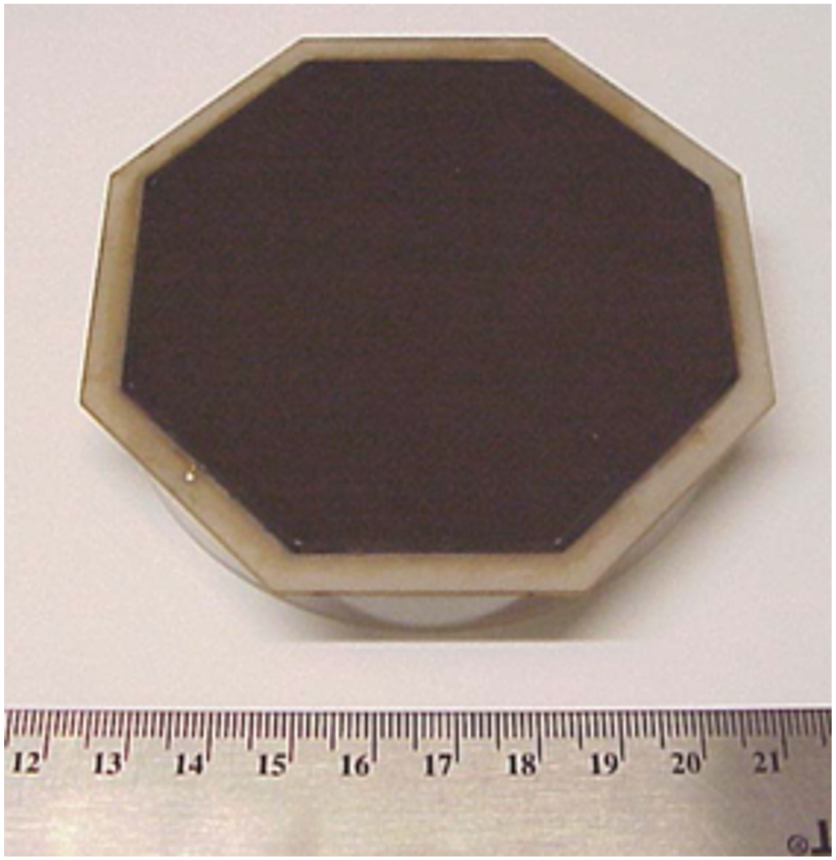


Sub-keV nuclear recoils detected in CsI



Collaboration with industry (and 1st spin-offs):

RMD 46 cm² LAAPD, ~4 photon threshold at 80K



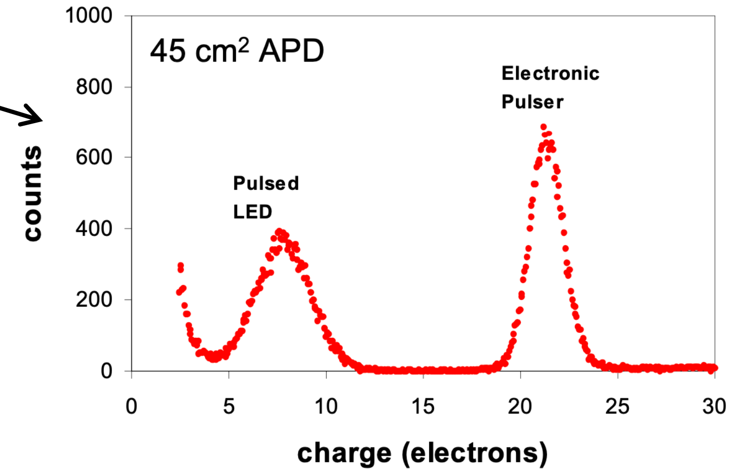


Figure 10. Detection of an optical pulse (<8 photoelectrons per pulse) and an electronic test pulse with the 45 cm² APD at 77 °K. The electronic noise of the large APD is ~0.8 electrons (rms).

DOI: 10.1109/NSSMIC.2004.1462432

very simple structure…

Nuclear Instruments and Methods in Physics Research A 610 (2009) 207–209

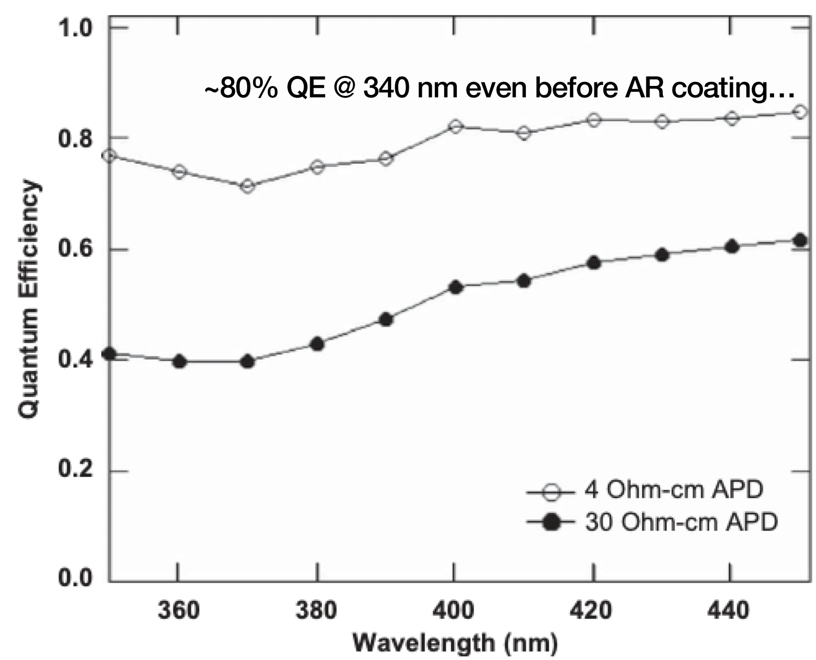
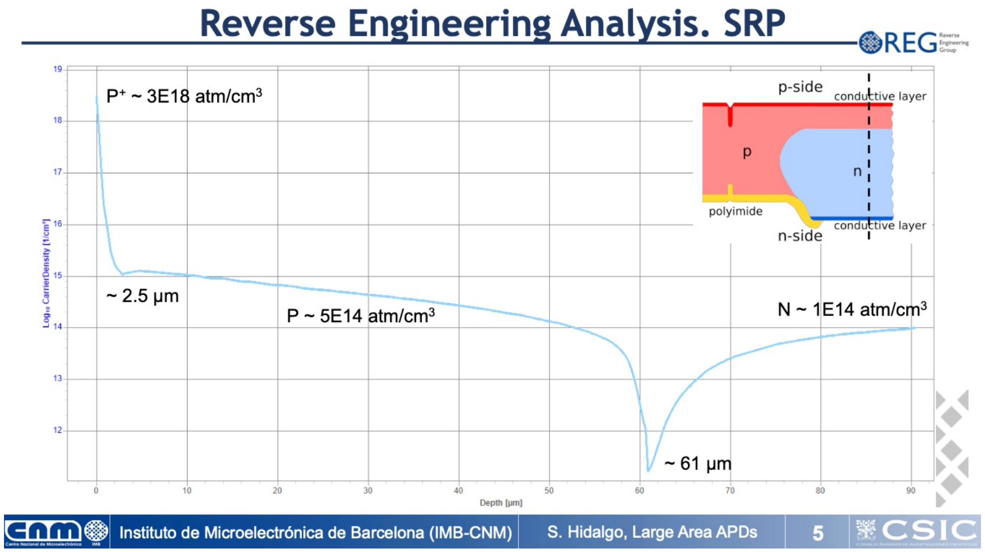
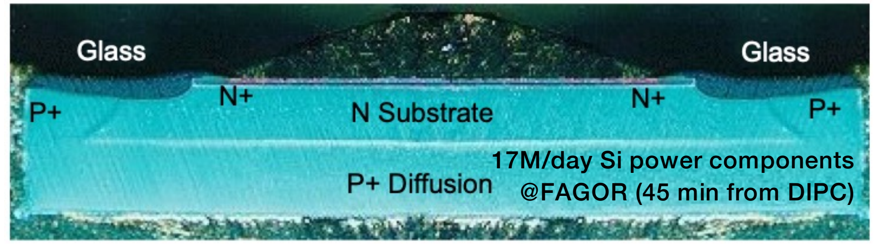


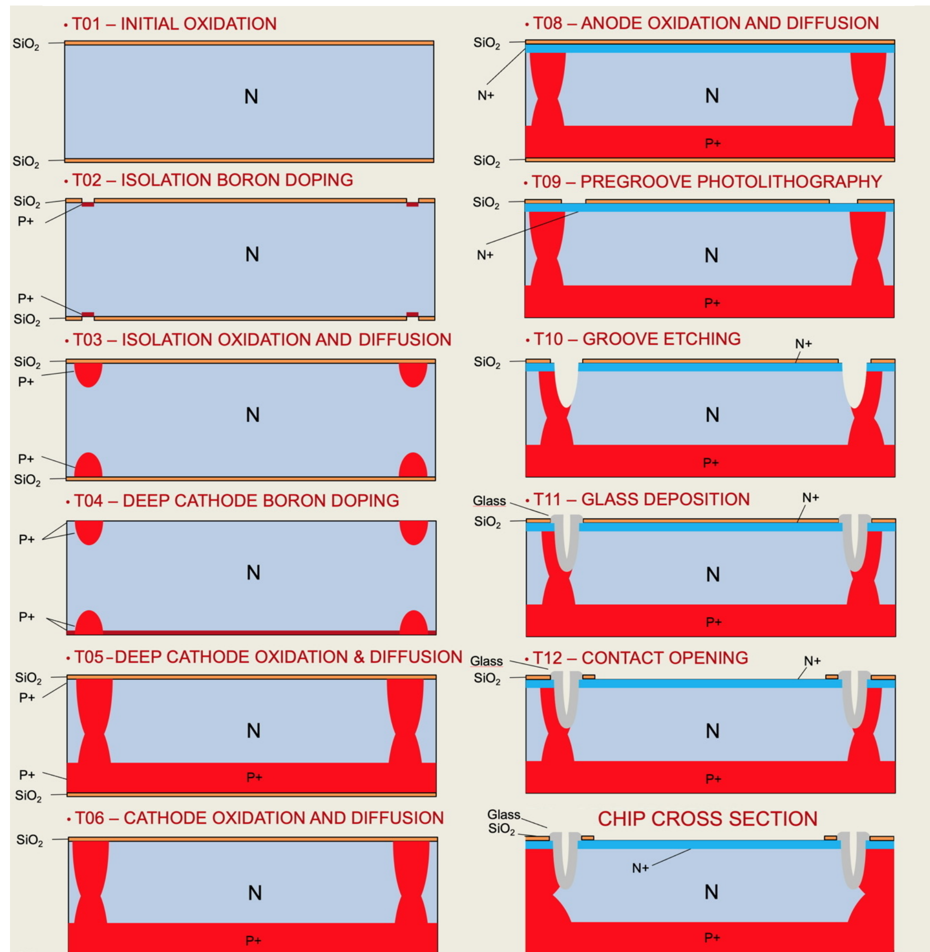
Fig. 3. Quantum efficiency vs. wavelength for a 4 and 30 Ω cm APD.

Collaboration with industry (and 1st spin-offs):



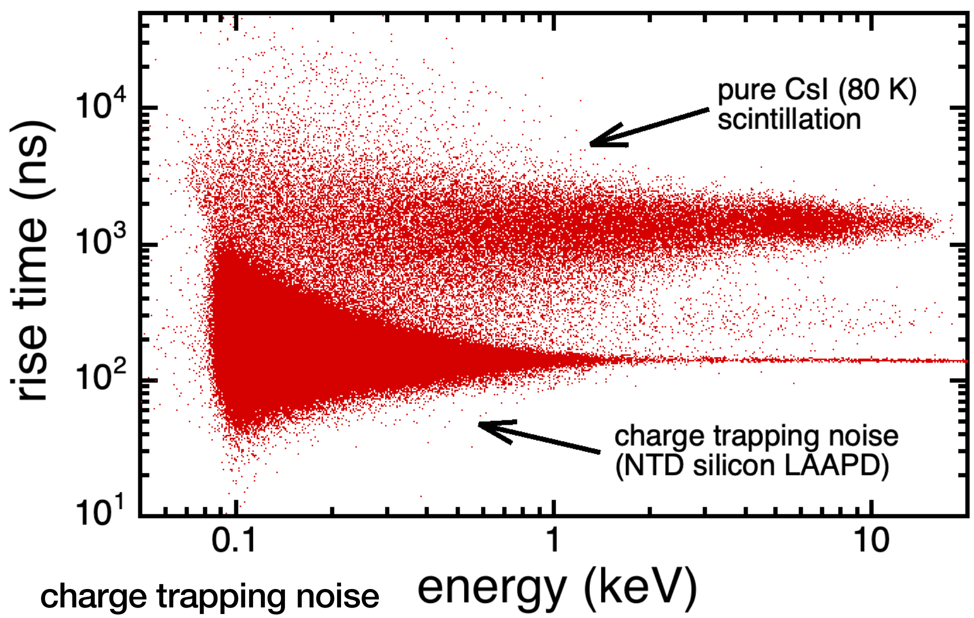
LAAPD “reverse engineering” at CNM





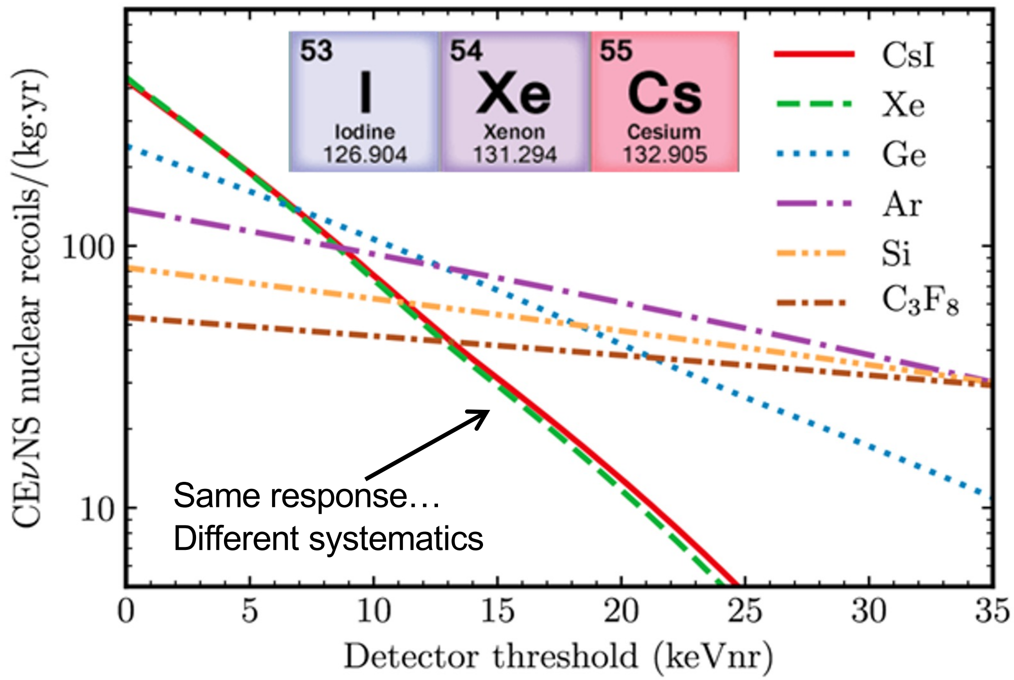
1st LAAPD production in progress

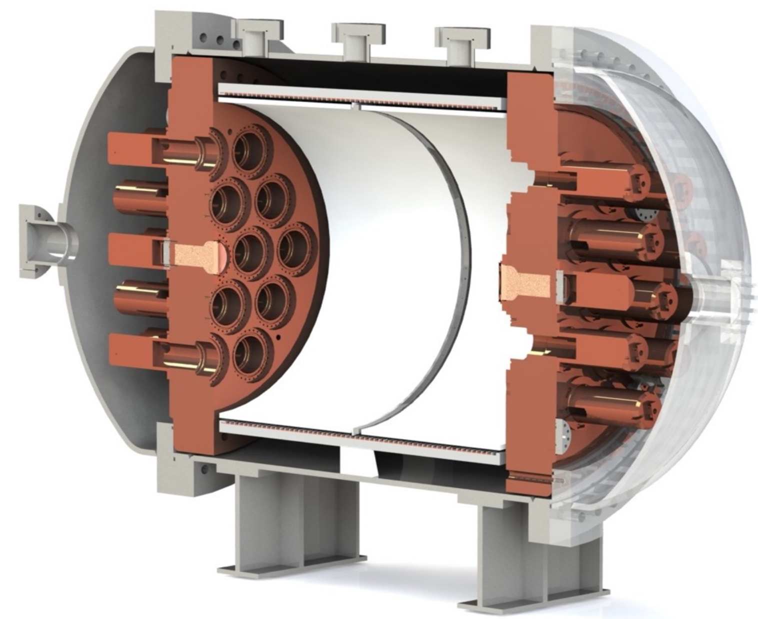
Fagor Electrónica



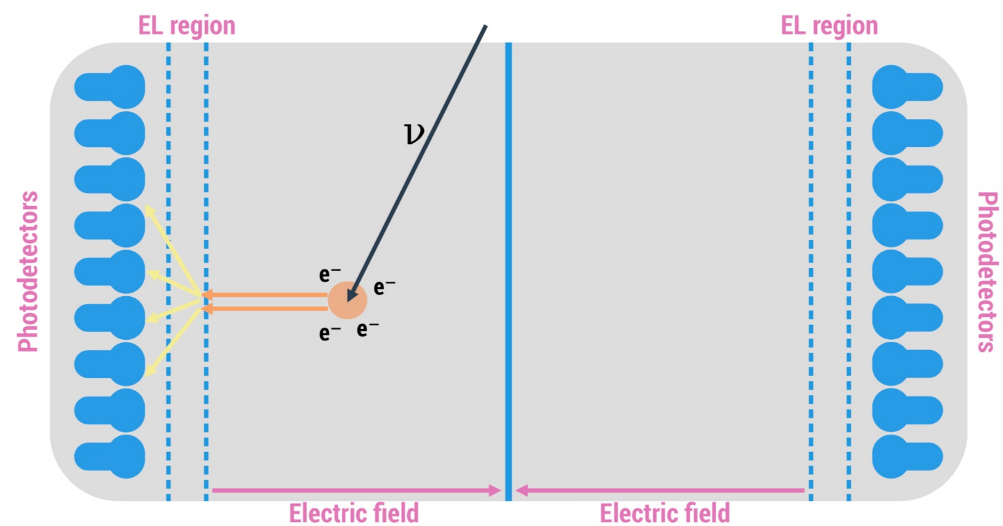
charge trapping noise
(nuisance, to be addressed w/ NTD -> PFZ Si)

High-pressure noble gases (GaνESS)





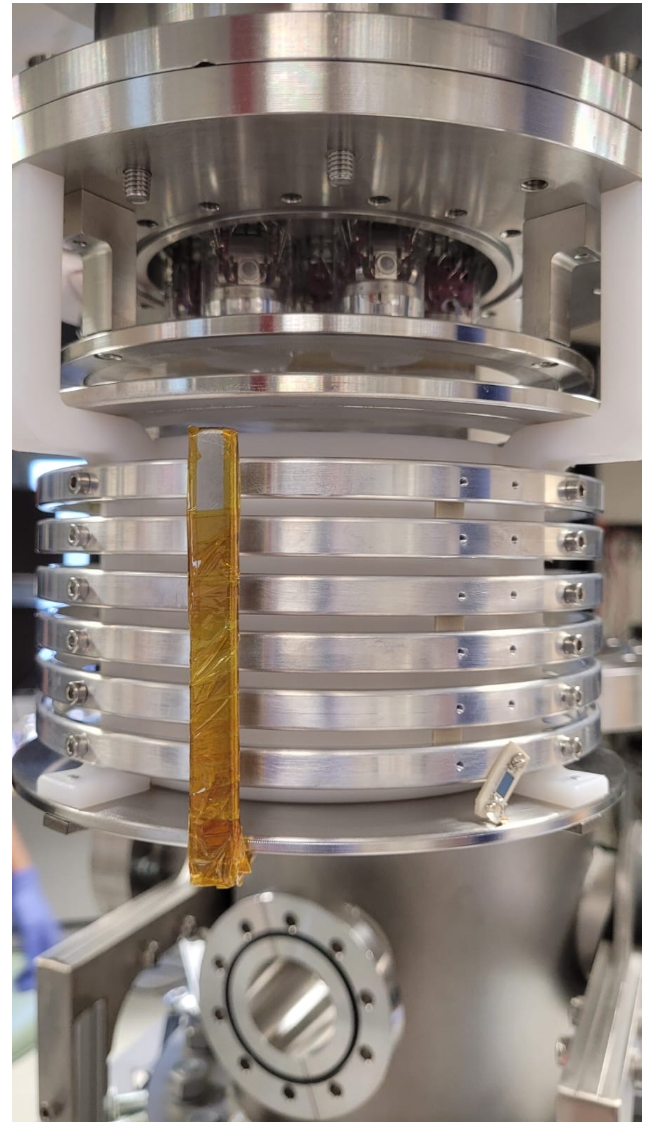
- Profit from NEXT 0νββ technology (low background, high pressure)
- Room temperature operation
- 1-2 e^- thresholds (~50 eV_{ee}) via EL
- ER/NR discrimination demonstrated
- Excellent energy resolution
- variety of nuclei -> Ar, Kr, Xe
- Complementarity CsI-Xe



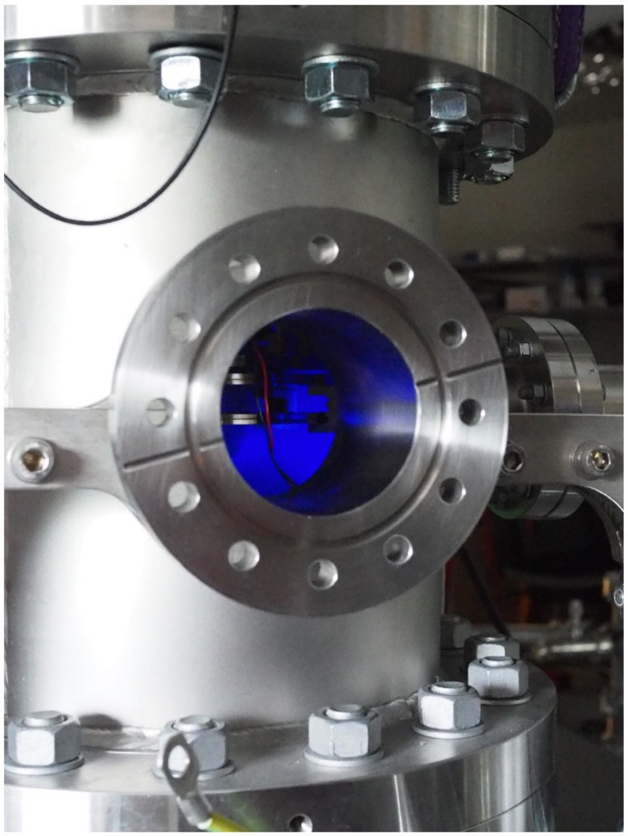
GaνESS's gaseous prototype (GaP)

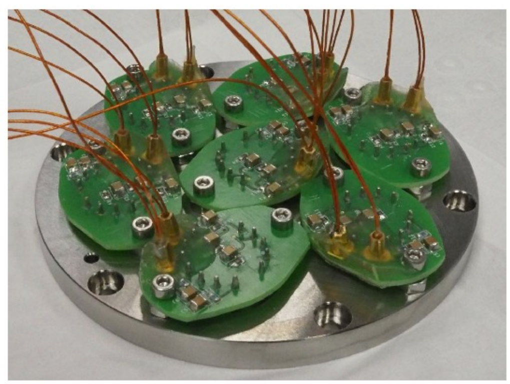
- opportunity to evaluate the technique in different conditions
  - multiple targets (Ar, Kr, Xe)
  - pressure up to 50 bar
- characterization of the low-energy response to nuclear recoils
  - **quenching factor measurements**
  - detection threshold

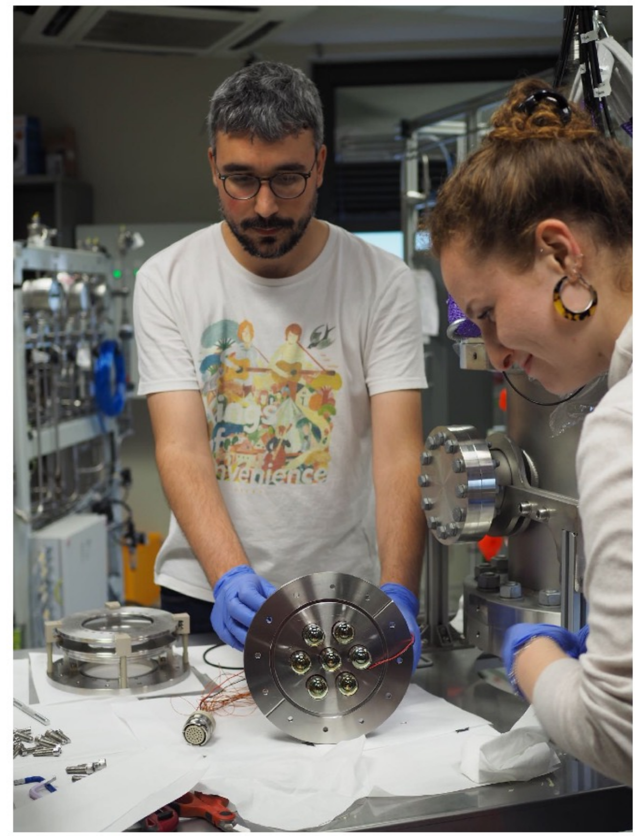
Currently characterizing ER signals with gaseous Ar at ~9.5 bar



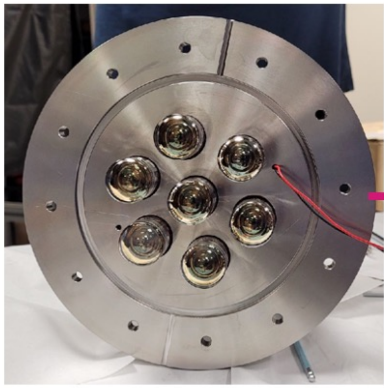
The Gaseous Prototype (GaP) Assembly



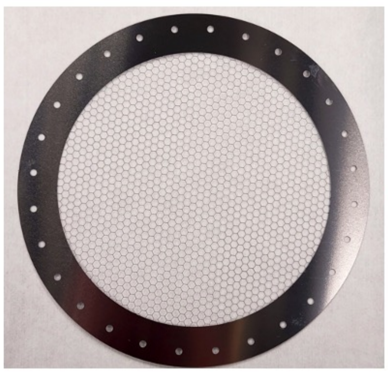




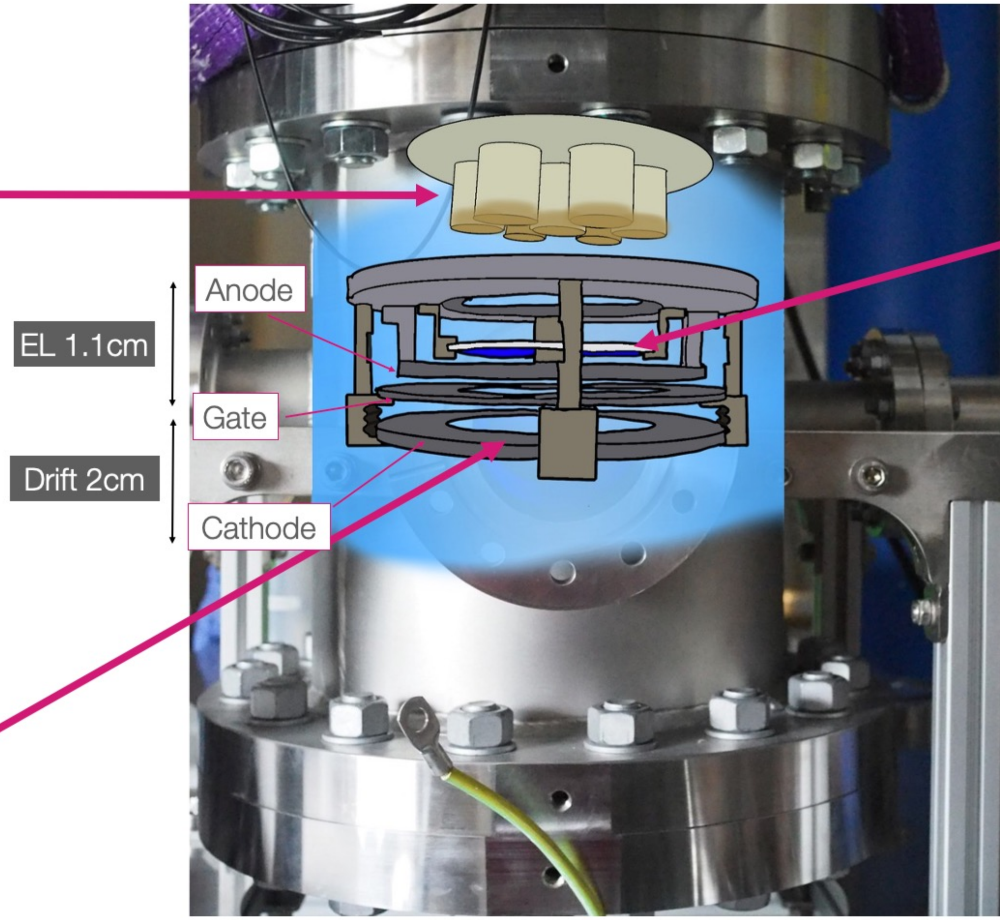
GaP inside

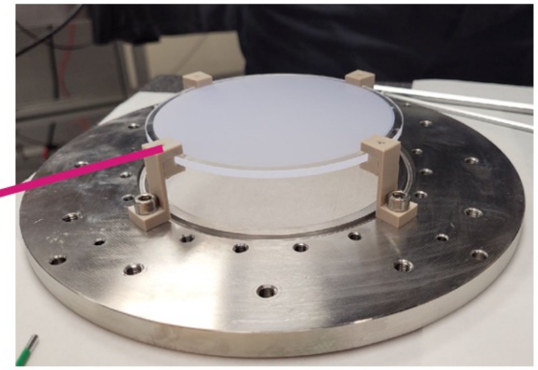


7 Hamamatsu R7378 PMTs

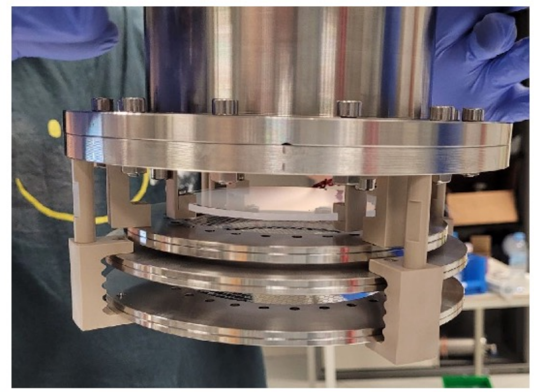


Photochemical etched mesh



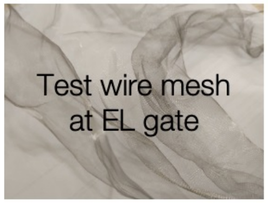


TPB coated window

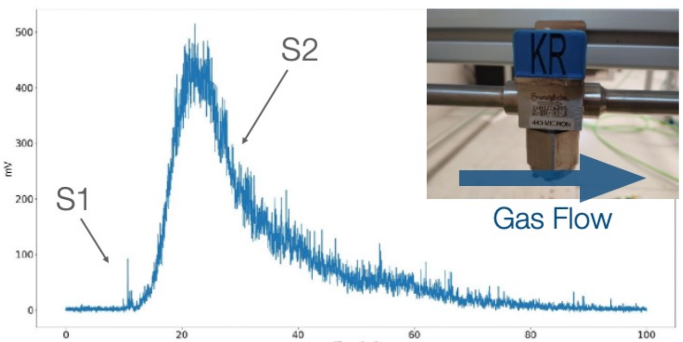


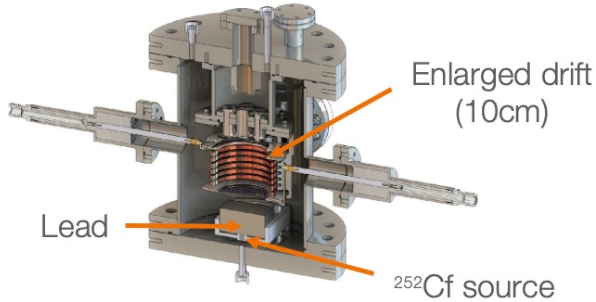
TPC

GaP timeframe

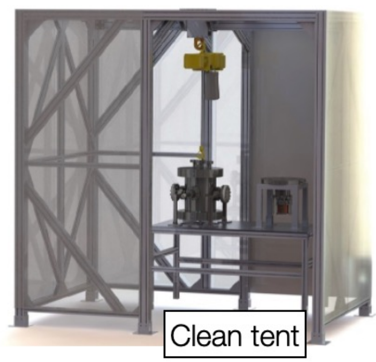


Characterizing ER signals:
- Gaseous Ar at ~9.5 bar.
- ^{83m}Kr source coupled to gas system.
- Threshold EL operation **(~0.6 kV/cm/bar).**
- Soon testing: ^{241}Am, ^{133}Ba, ^{57}Co, ^{22}Na, ^{137}Cs.





Start looking at NR signals:
- ^{252}Cf source (exempt <1000 n/s).

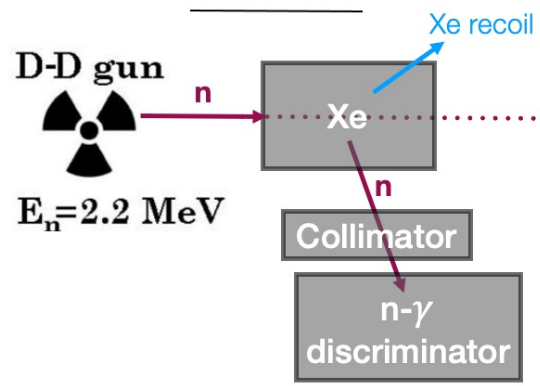


Improved quenching factor measurements

Using quasi-monoenergetic neutron sources

Photoneutron sources

^{88}YBe (~153 keV n)
^{124}SbBe (~24 keV n)

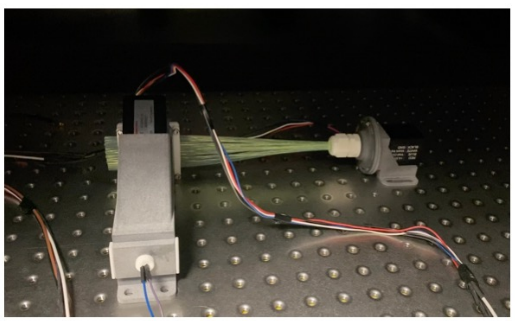


Move to Xenon and repeat

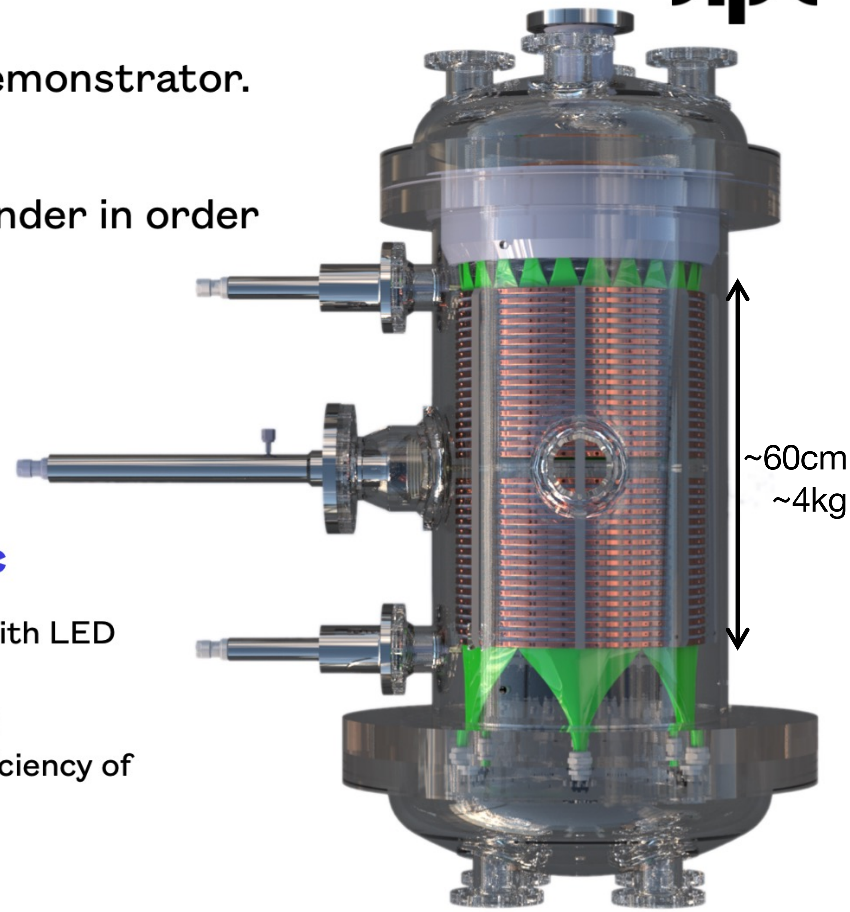
HD-DEMO

- Dual purpose detector: Scaling NEXT and ESS large demonstrator.
- Currently in construction, to operate in DIPC in 2025
- **Barrel of WLS fibers** will cover the surface of the cylinder in order to detect Xe scintillation light (175 nm).
- Different options being explored:
  - Green-to-blue fibers coated with TPB.
  - UV-to-blue fibers coated with p-terphenyl.
  - Readout with cooled SiPMs (Hamamatsu, FBK)

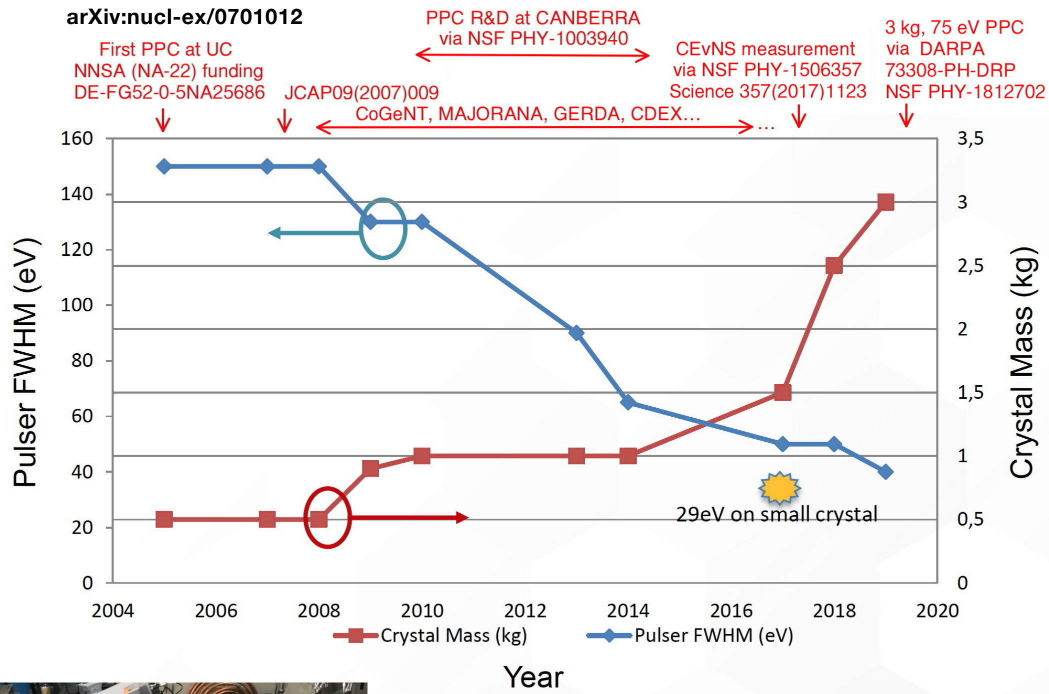
Fiber R&D at DIPC

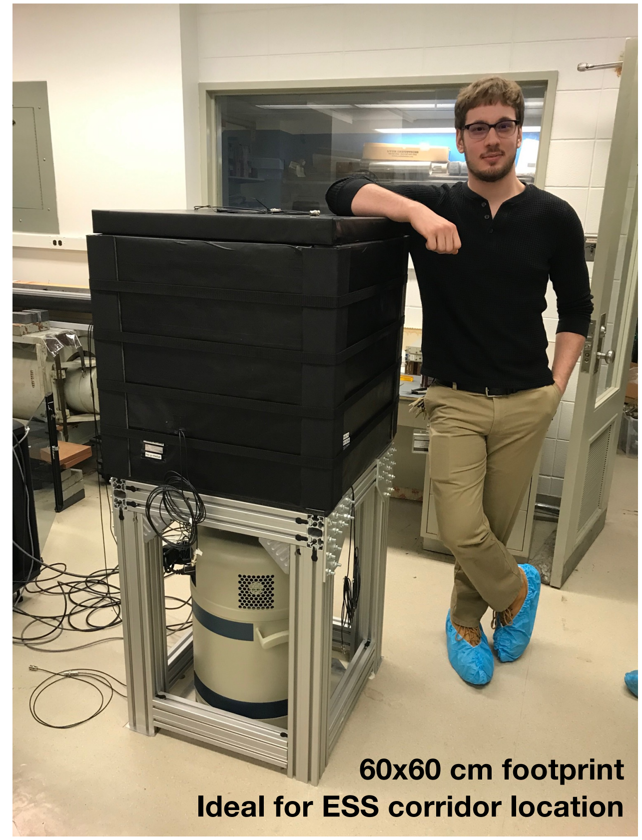


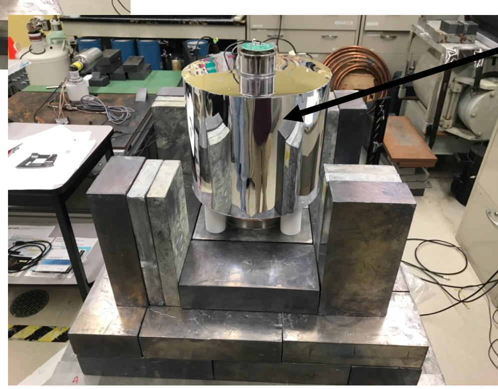
- Illuminate different fibers with LED and read out with different photosensors (PMT, SiPMs)
- Measure light collection efficiency of the system



P-type Point Contact (PPC) germanium detectors



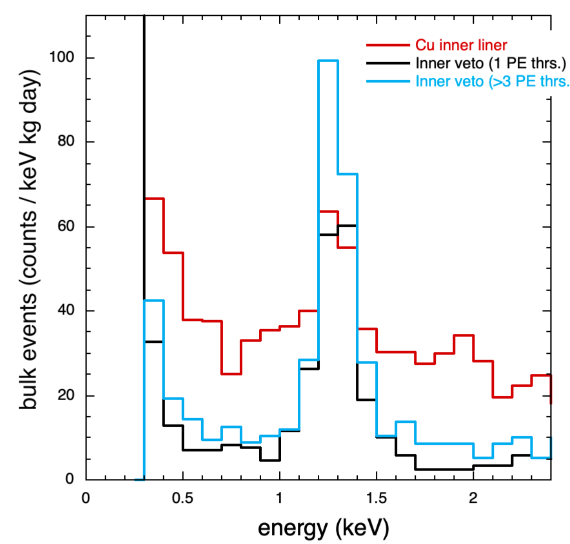




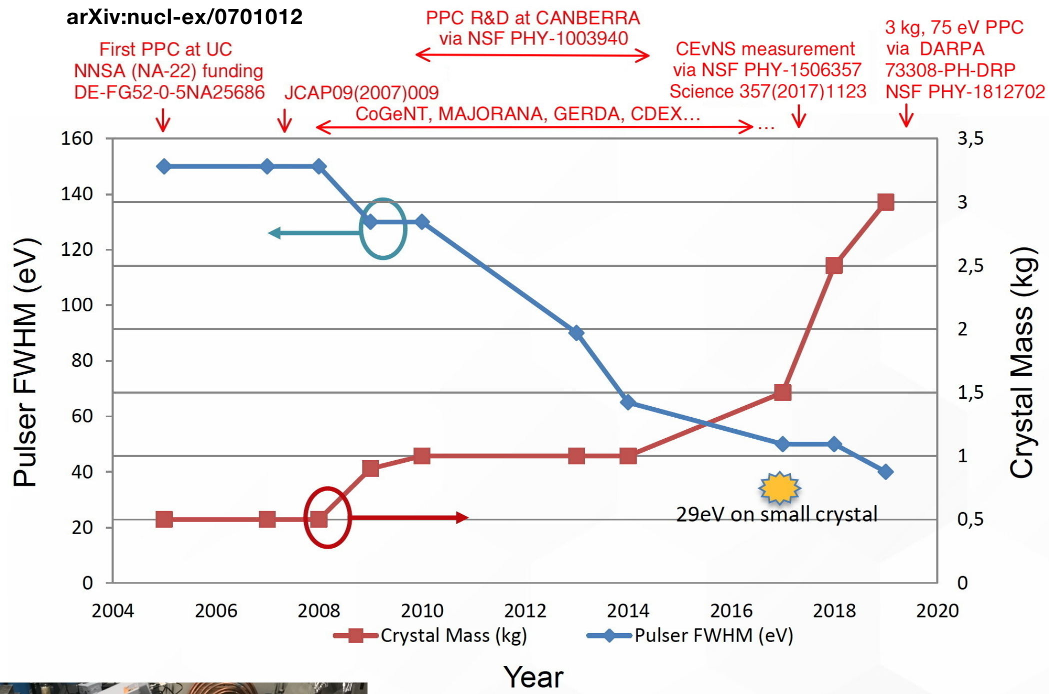
Entirely mature:

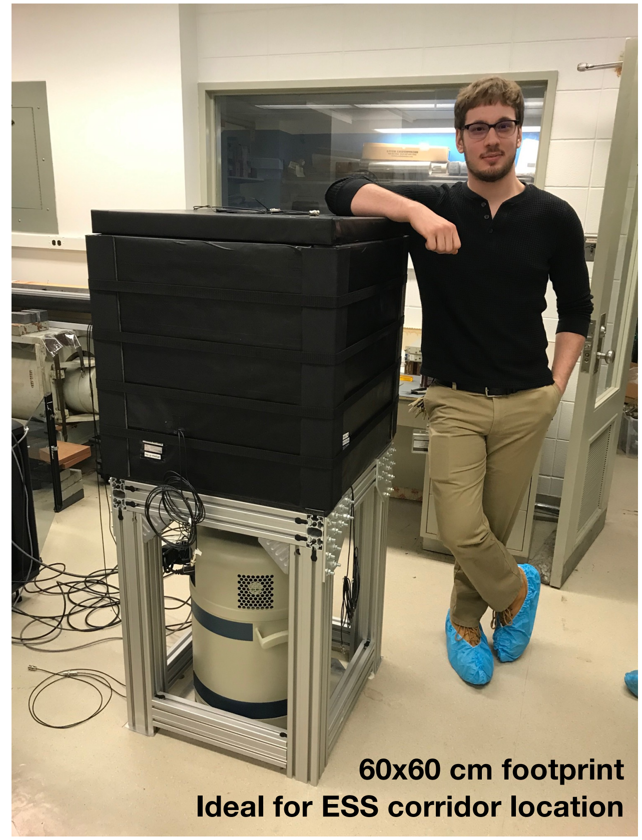
if ESS was producing ν's today
we would be measuring them already

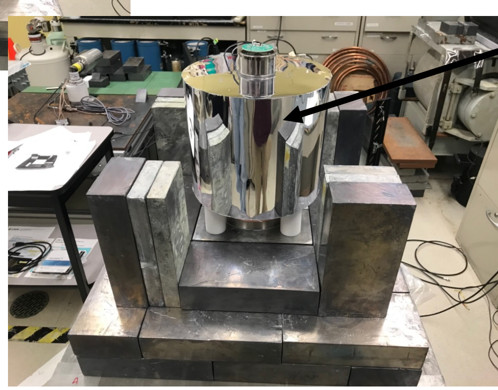
Inner plastic scintillator veto is highly effective against beam-related neutron backgrounds



P-type Point Contact (PPC) germanium detectors







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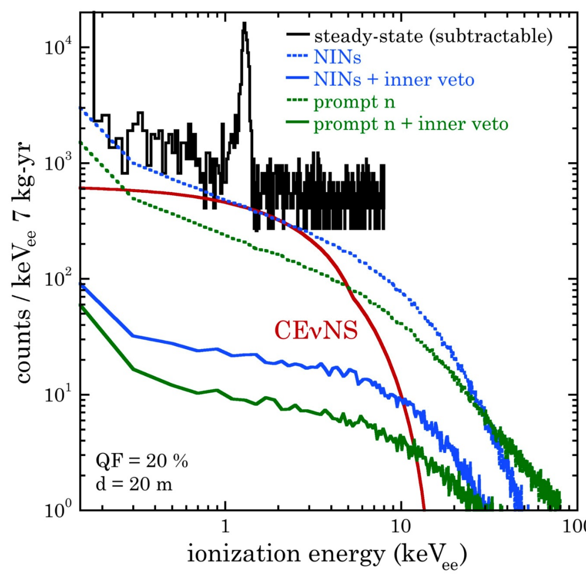
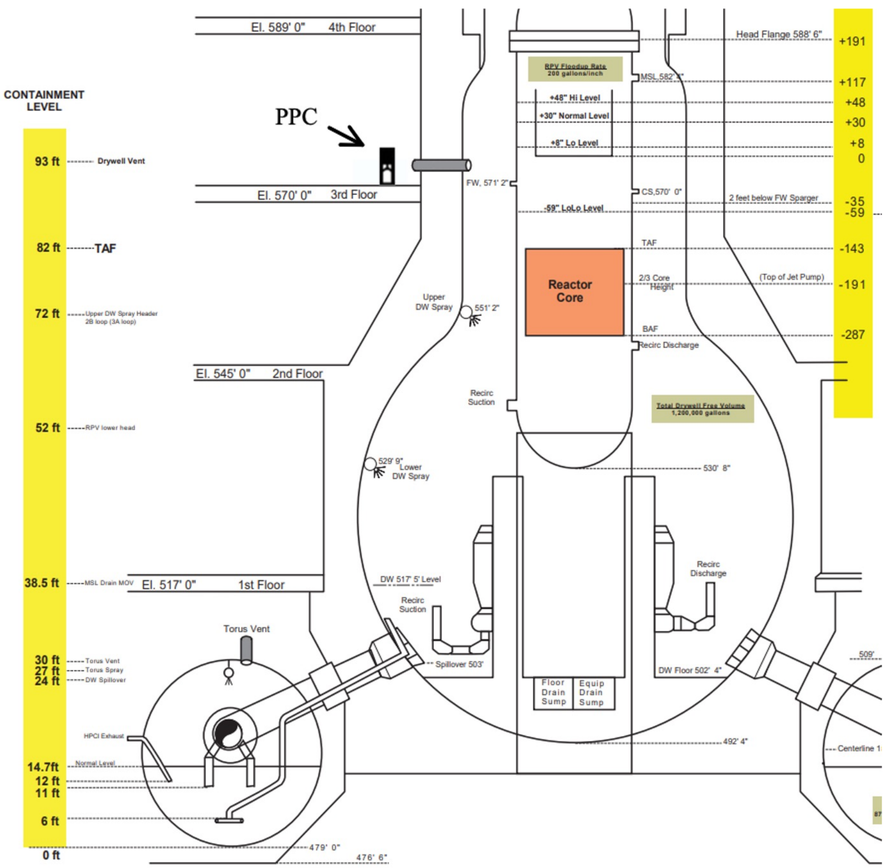
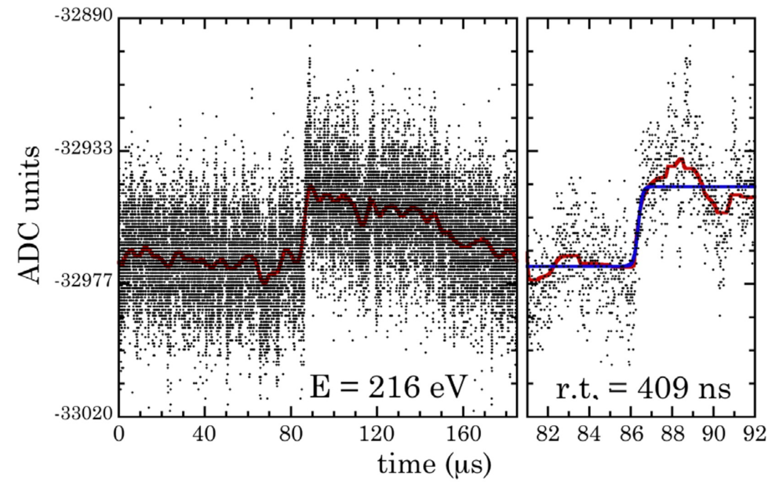
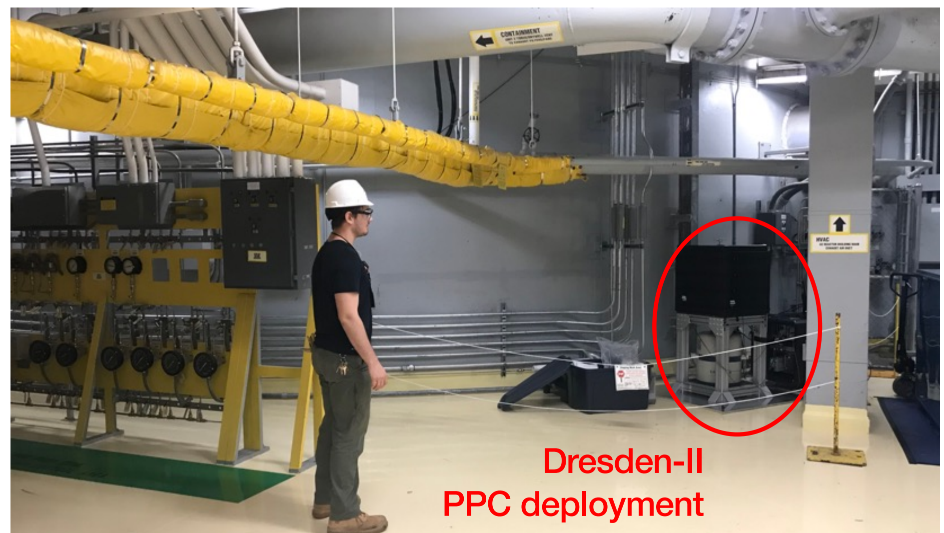


P-type Point Contact (PPC) germanium detectors



In the process of reducing this noise by ~×2, accessing lower NR energies





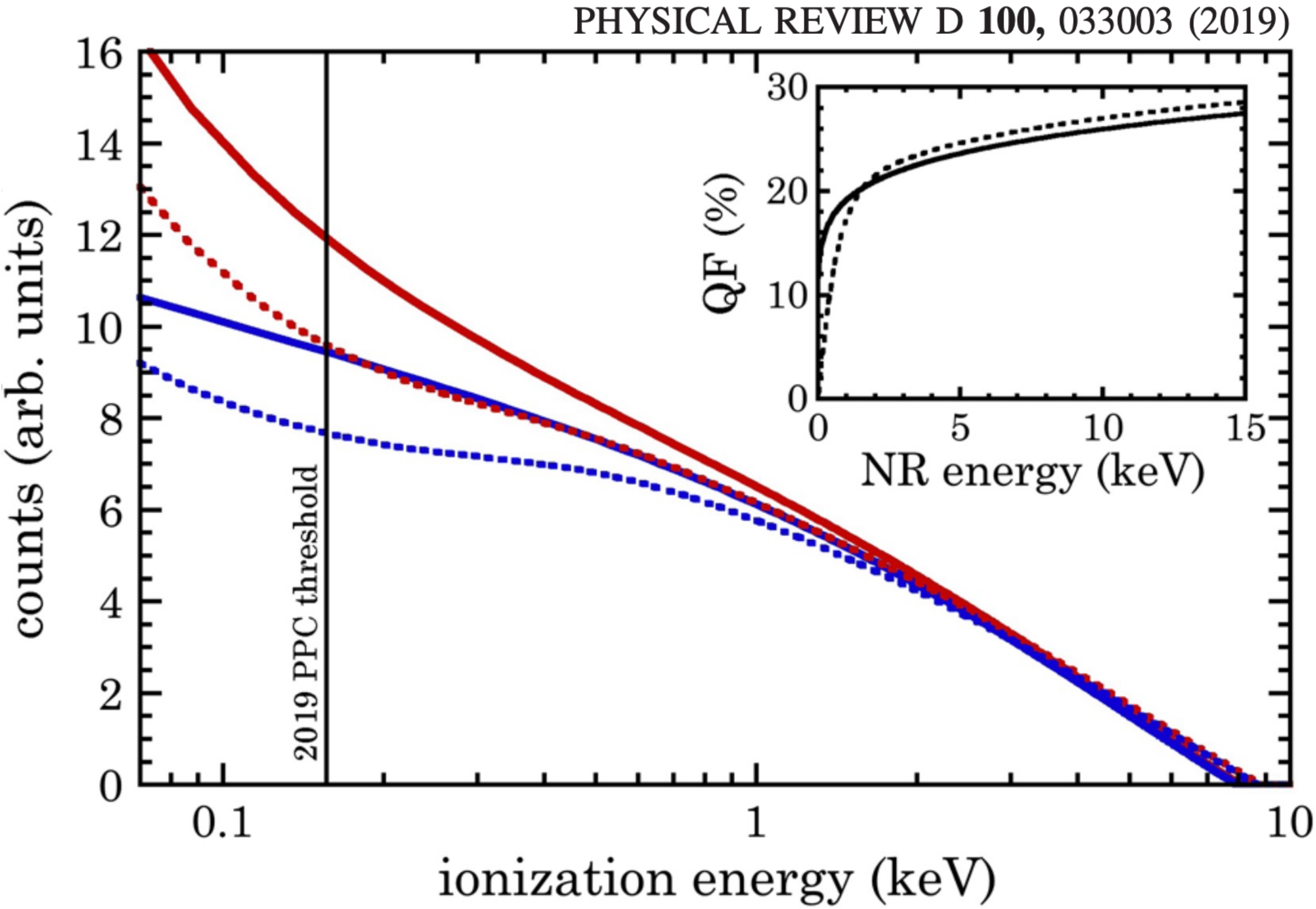
PHYSICAL REVIEW LETTERS 129, 211802 (2022)

Measurement of Coherent Elastic Neutrino-Nucleus Scattering from Reactor Antineutrinos

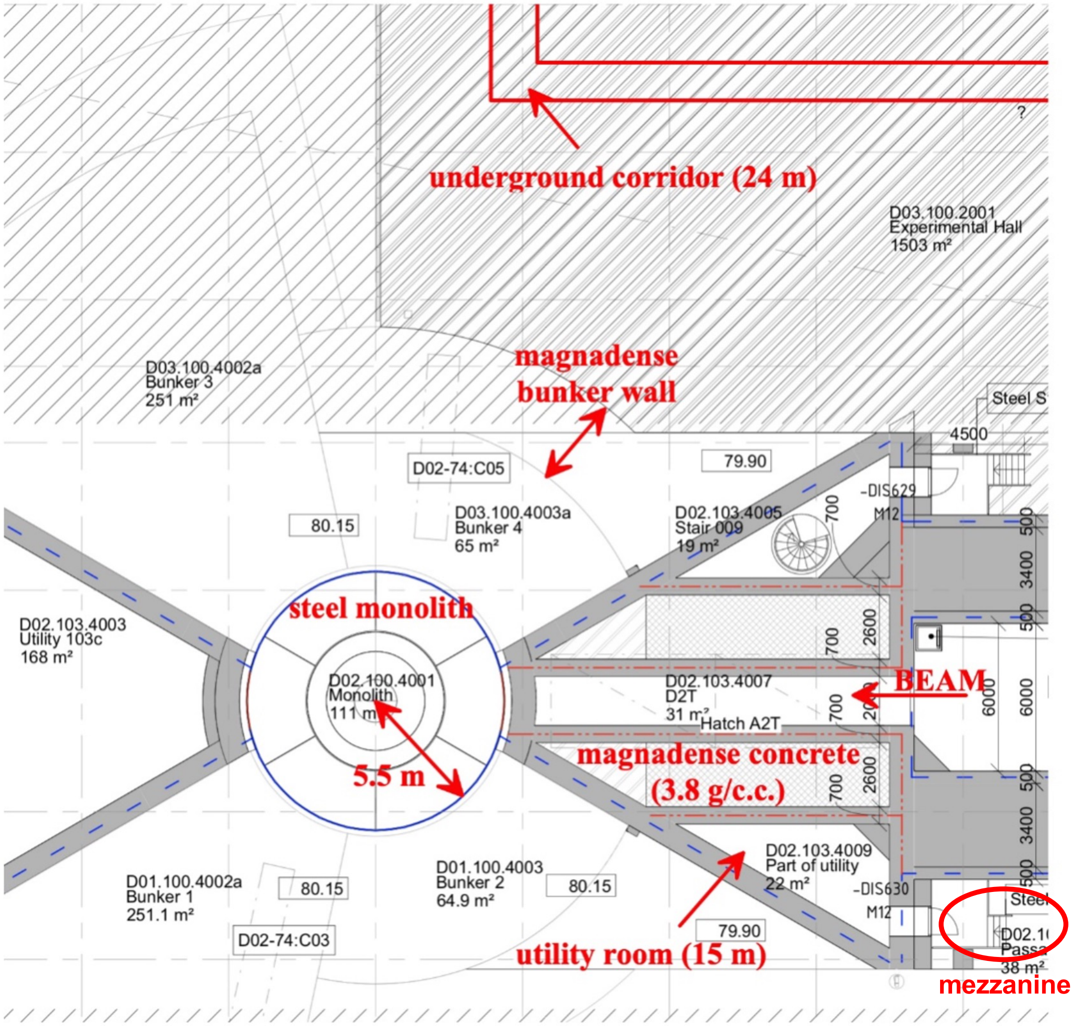
J. Colaresi,[1] J. I. Collar,[2,*] T. W. Hossbach,[3] C. M. Lewis,[2] and K. M. Yocum[1]

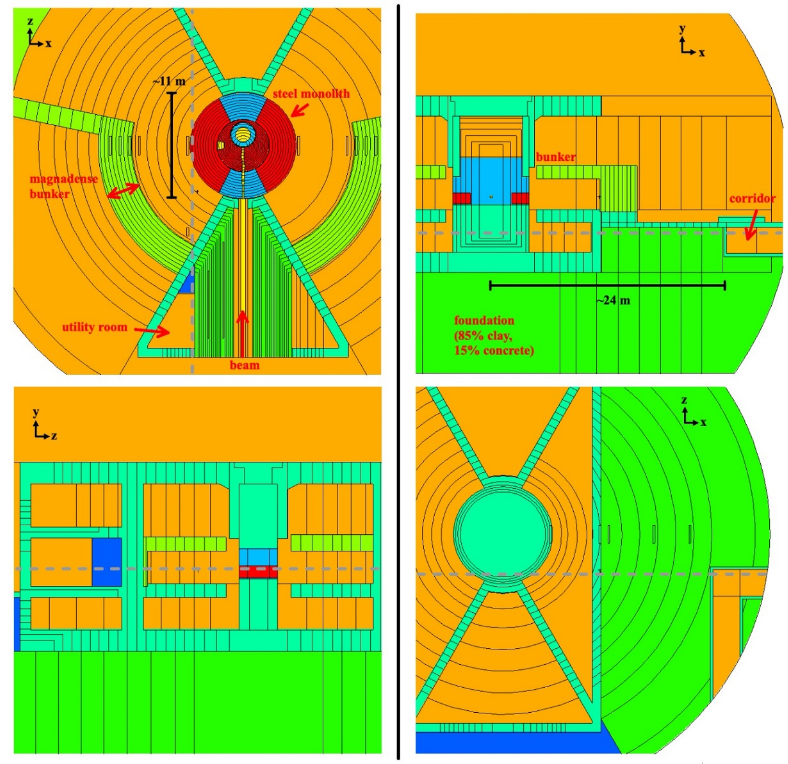
Never-ending story
(more QF measurements)
1E5 NR below 700 eVnr, testing FIFRADINA libraries

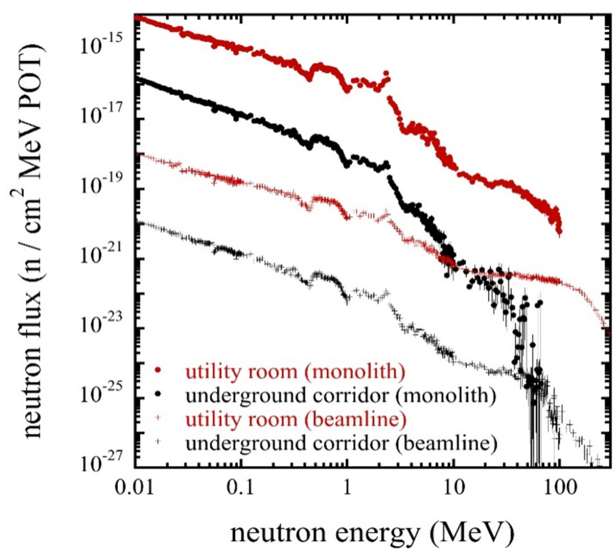
Why is the Quenching Factor so important for CEνNS?



Hunting for non-intrusive detector locations





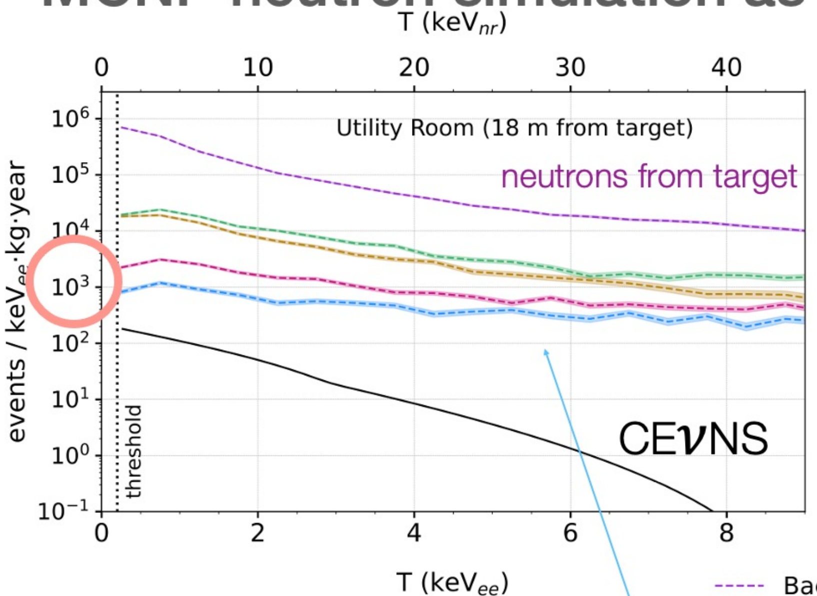


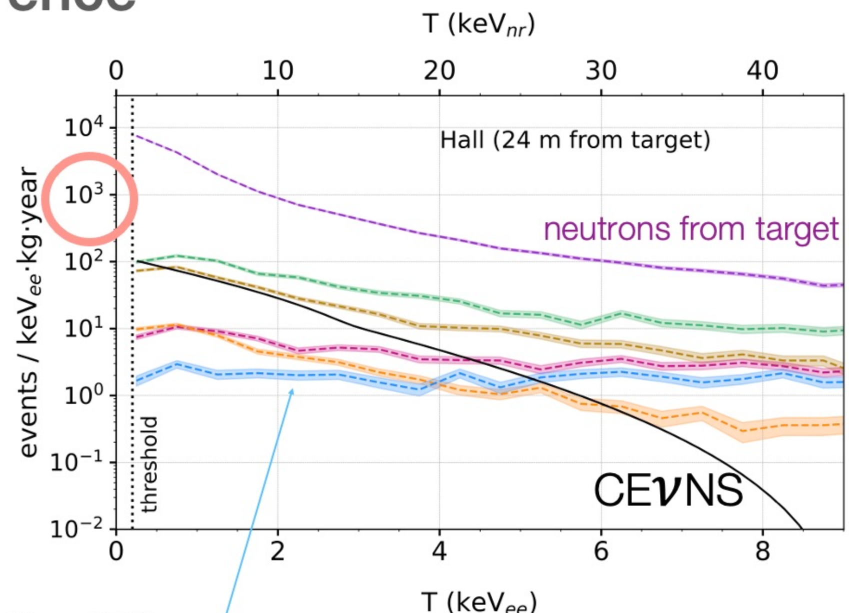
- steady-state backgrounds are subtractable (C-AC)
- prompt neutron leakage from target is main background
- MCNP simulations completed (GEANT in progress)
- neutron camera for on-site measurements (remedial shielding in utility room)

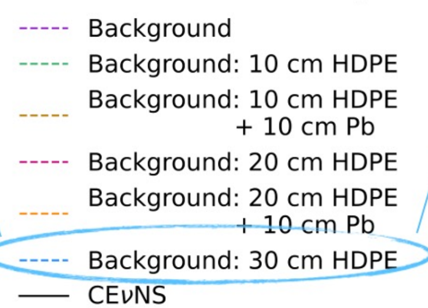
ESS neutron induced background

Operating for 1 year

MCNP neutron simulation as reference







Assuming 20 bar of Xe detector

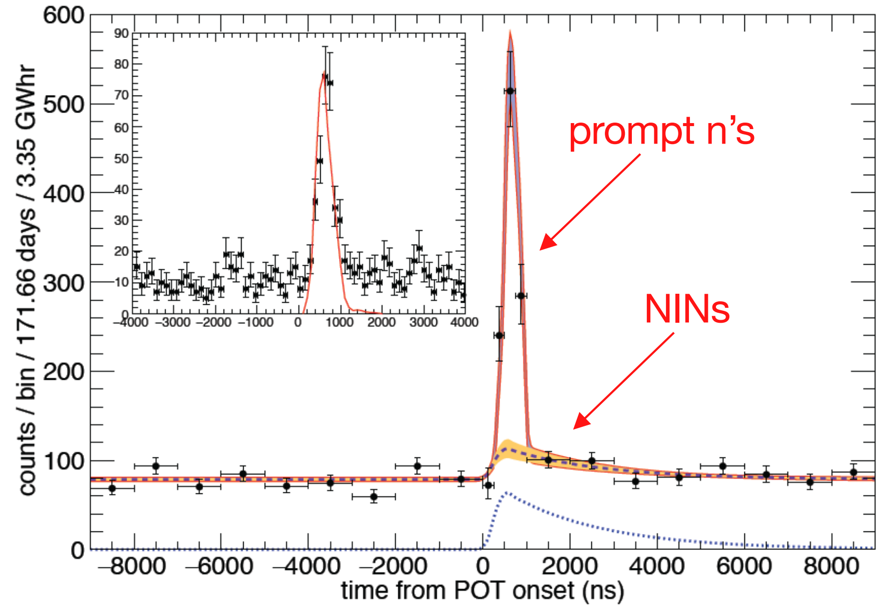
Only neutrons produced at target

We need to evaluate more shielding options

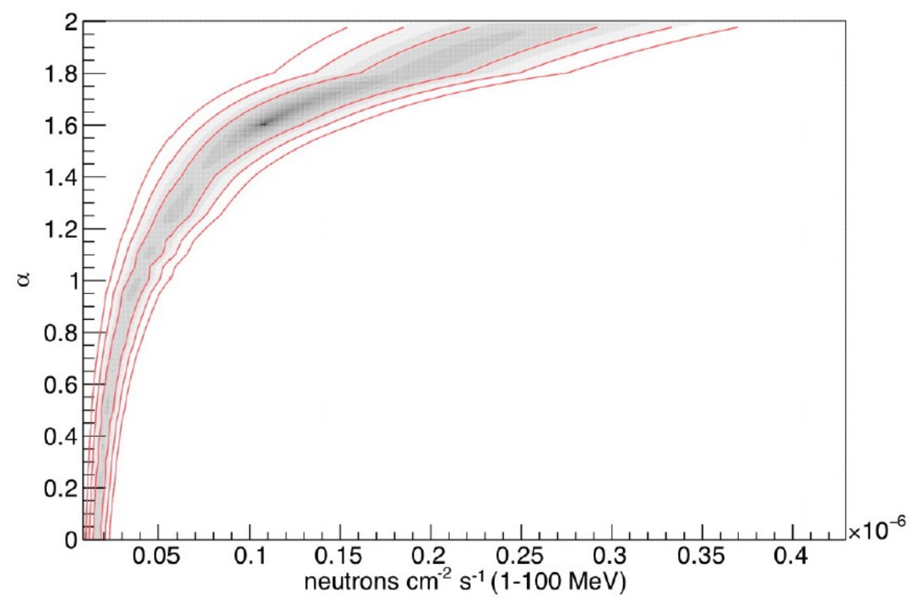
M.Jiménez Master thesis

Déjà vu all over again: *in situ* neutron bckg measurements

The “neutrino alley” @ SNS

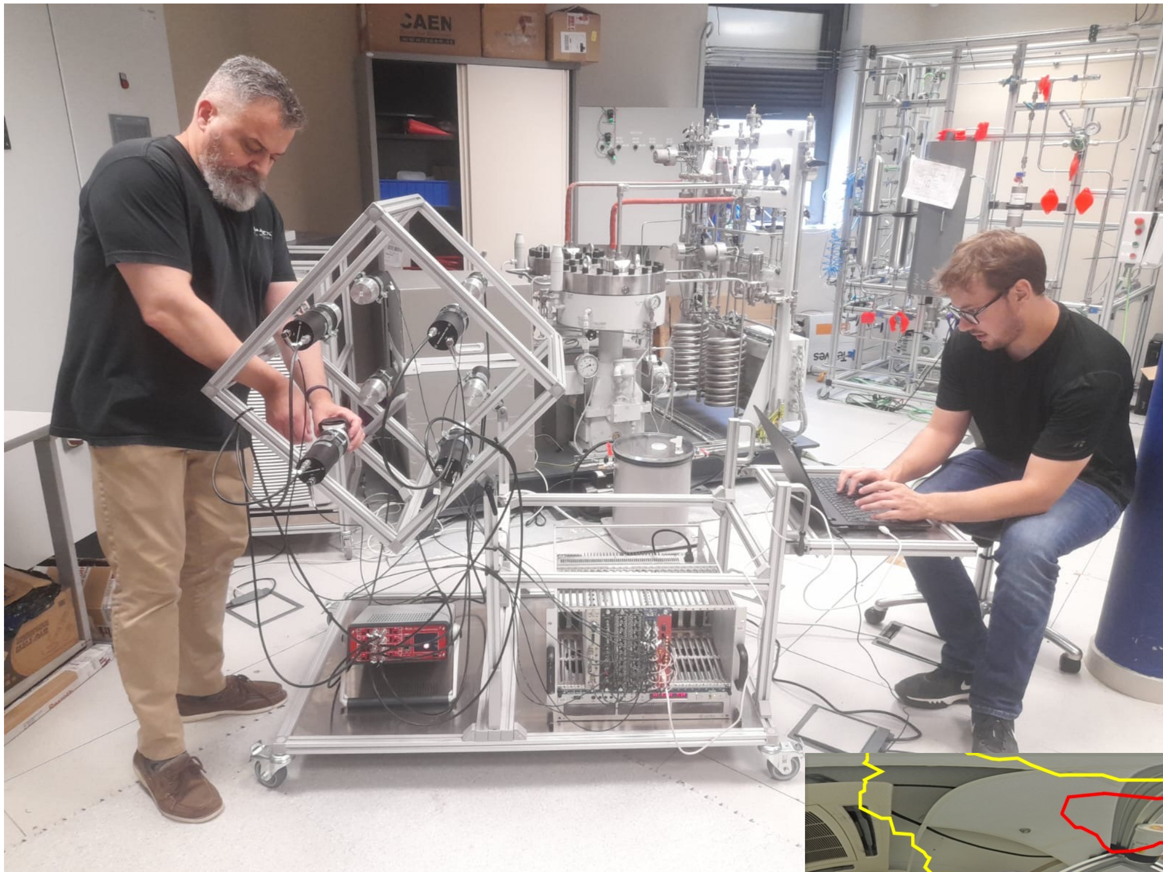


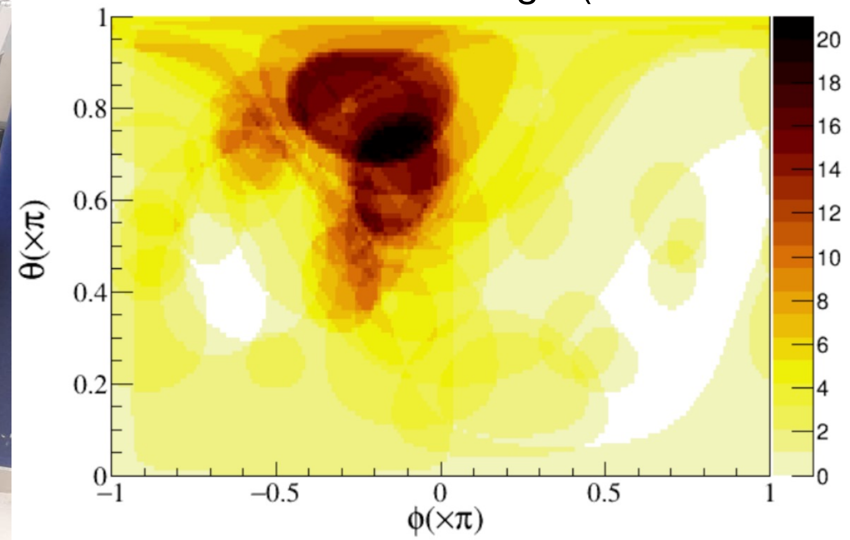
Measured NIN and prompt n bckg rates
are x50 and x20
smaller than CEνNS signal rate.

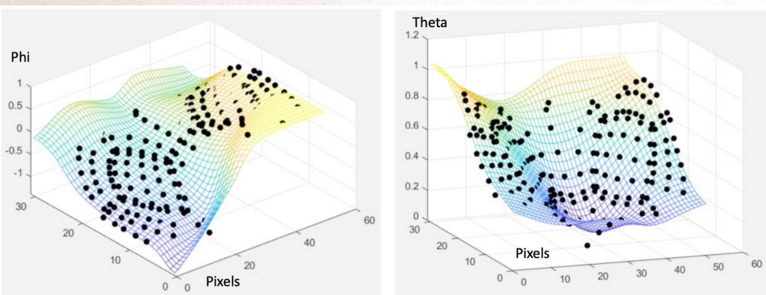


Neutron scatter camera ready for first POT

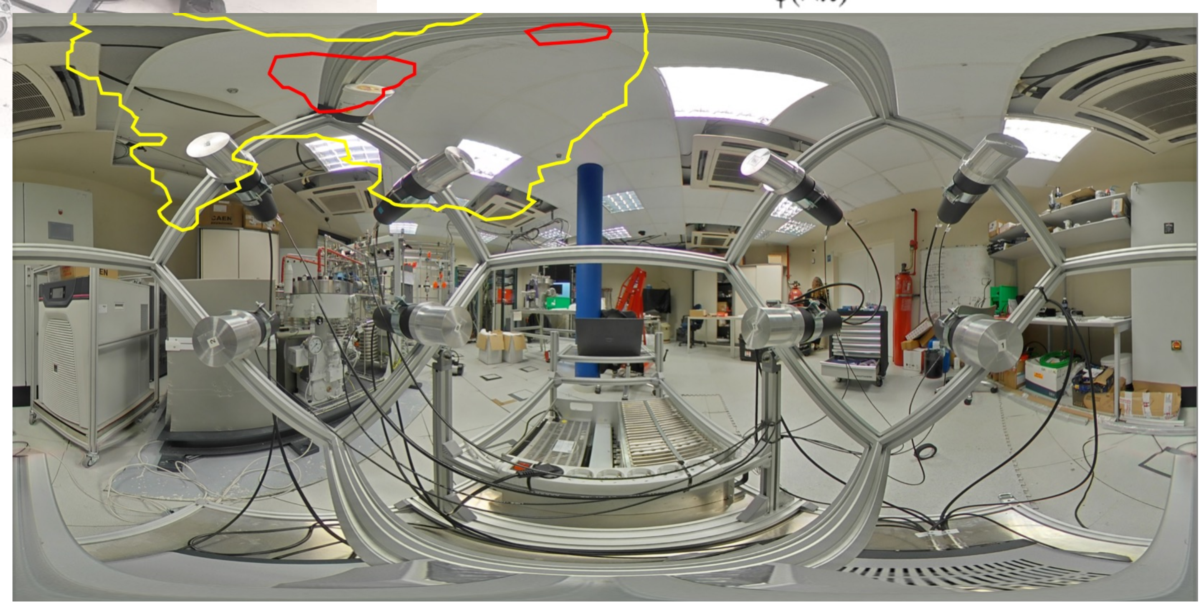
- Optimized for expected ESS neutron bckgs
- True 4π sensitivity (a novelty)
- Plastic scintillator with n/γ discrimination
- Portable (of interest to other ESS users)
- Determine n flux **and** origin (remedial action)







ANN-based spatial projection



Res ipsa loquitur:

- We are ready to land and start running.
- Our requirements from the ESS are minimal (by design).
- The beginning of a long program, with many others to benefit.