The quest for CEvNS* at nuclear reactors :

still some road ahead…

*Coherent Elastic Neutrino-Nucleus Scattering

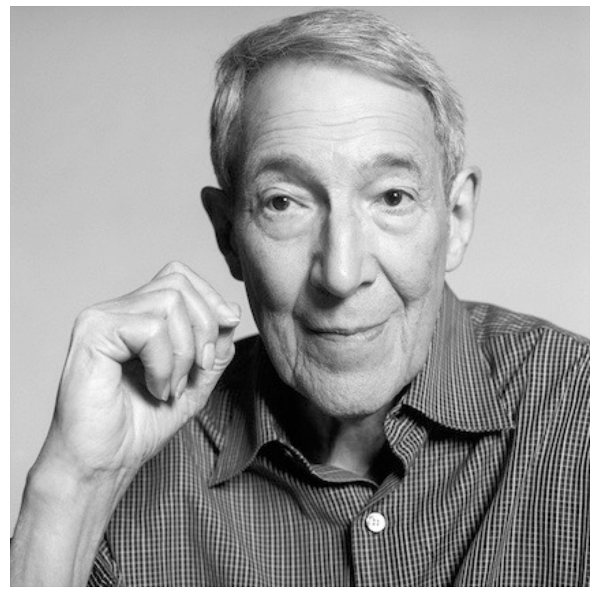
EDSU-Tools
Noirmoutier, 06/07/2024

Matthieu Vivier
CEA Paris-Saclay

The CEvNS process

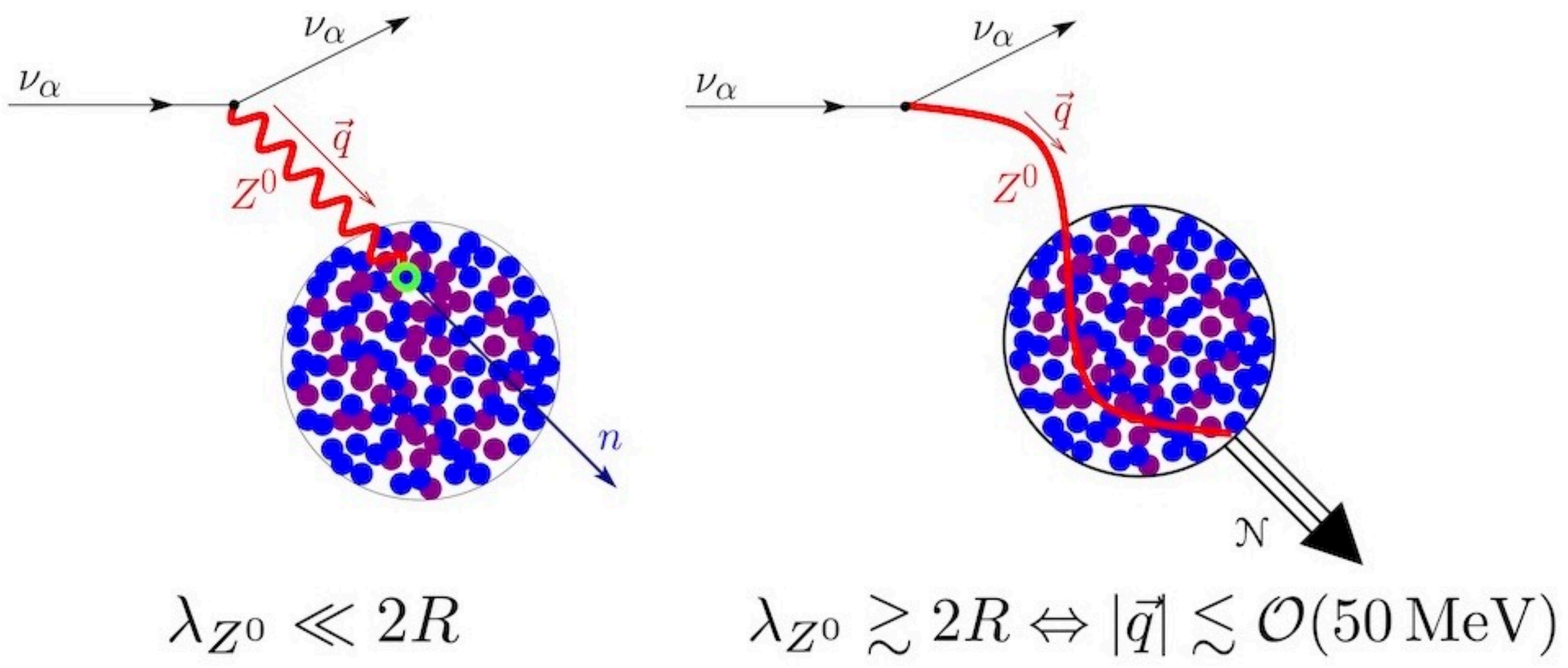
In a nutshell

D. Z. Freedman (1974)

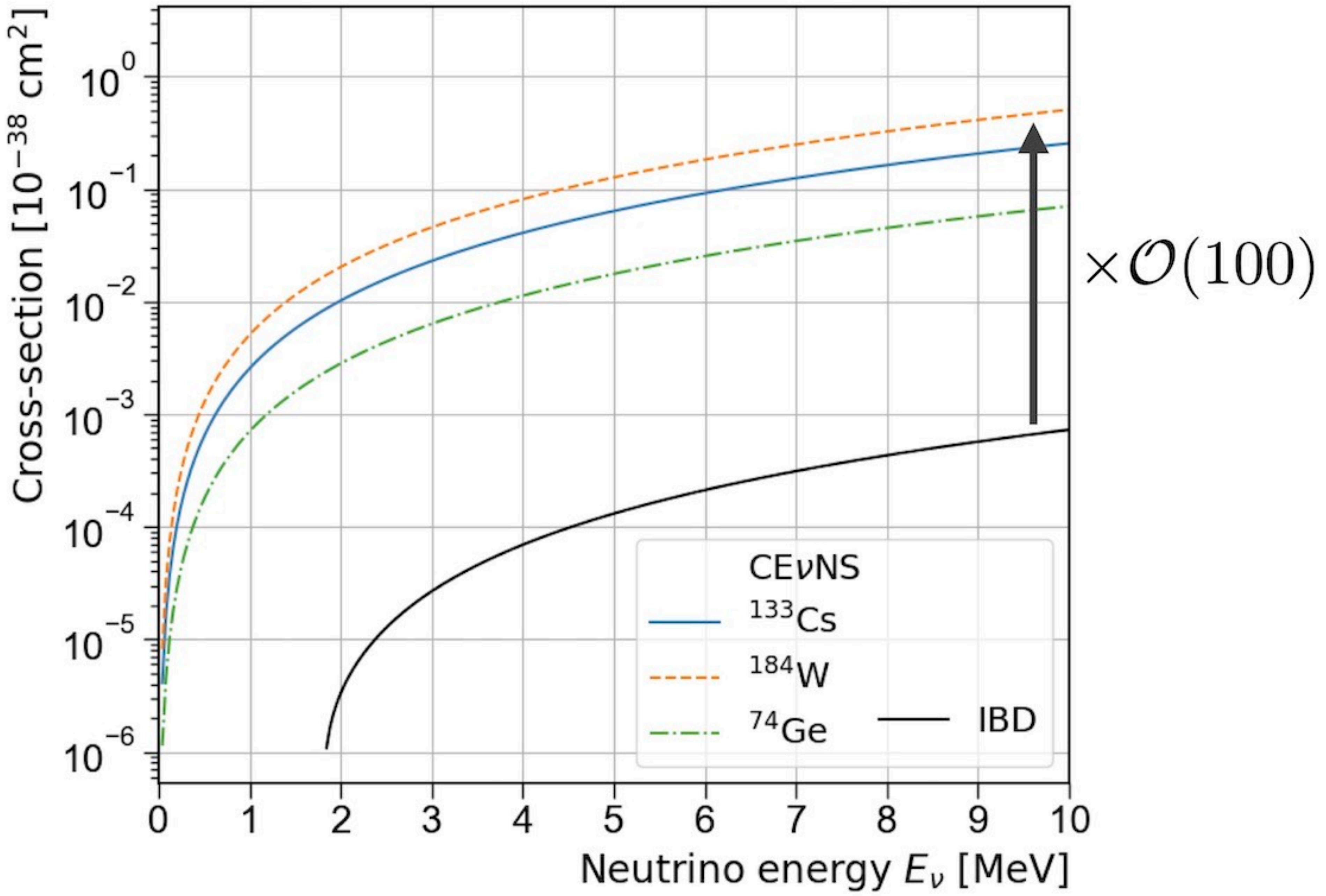


- Neutral current, flavor blind process
- Coherent interaction over a nucleus as a whole
  - ➡ N^2-enhancement of the cross-section
  - ➡ Tiny nuclear recoils
  - ➡ No threshold

Adapted from Cadeddu, et al. (2023)



C. Goupy



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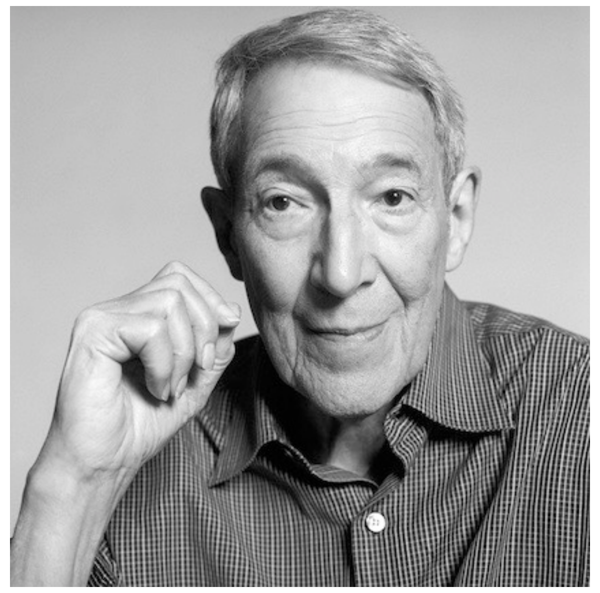

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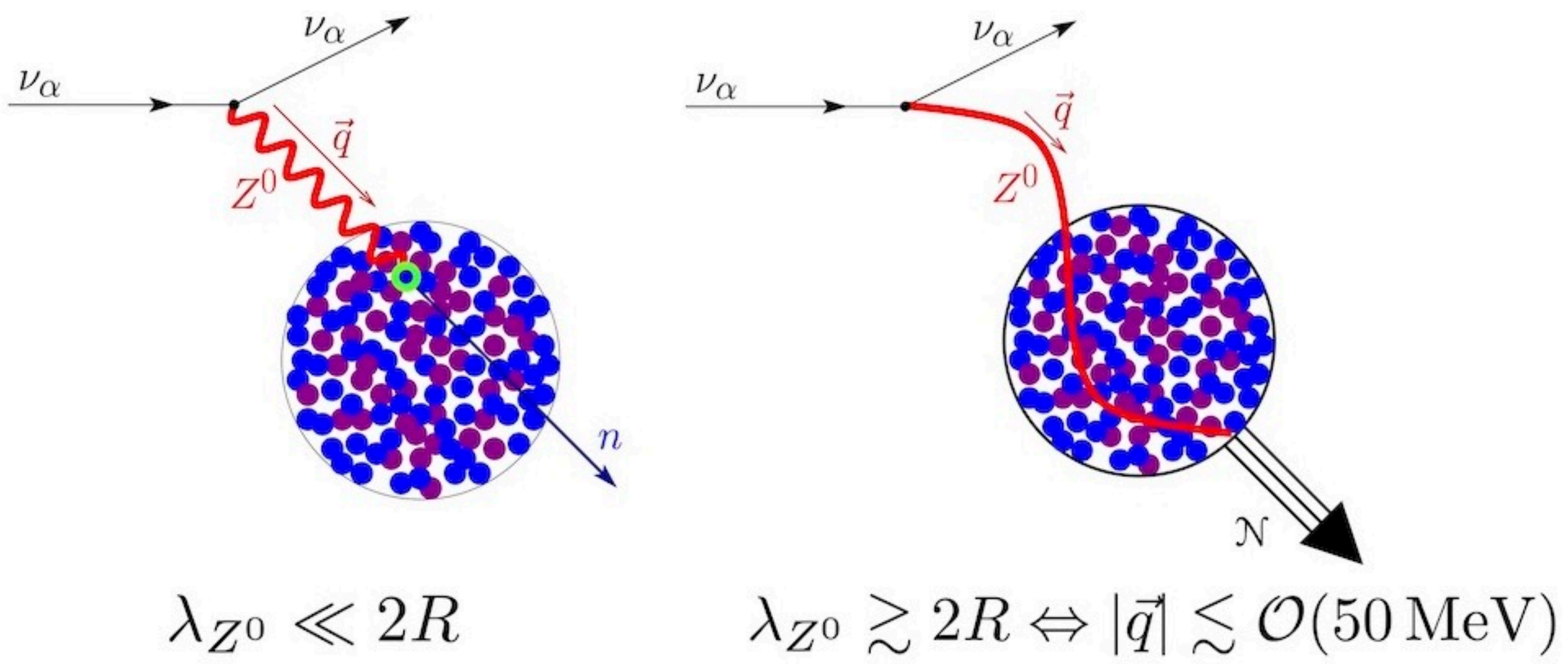

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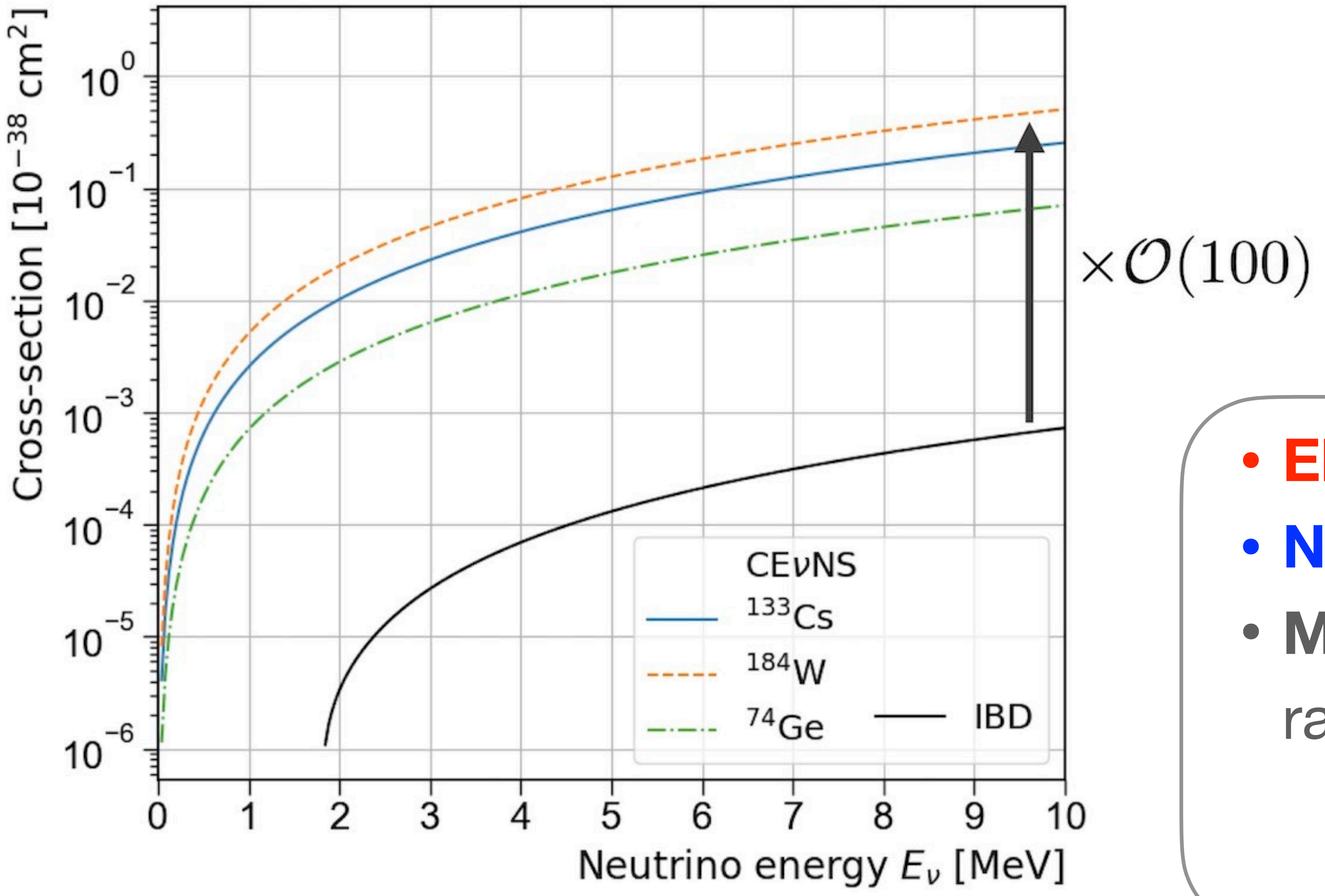
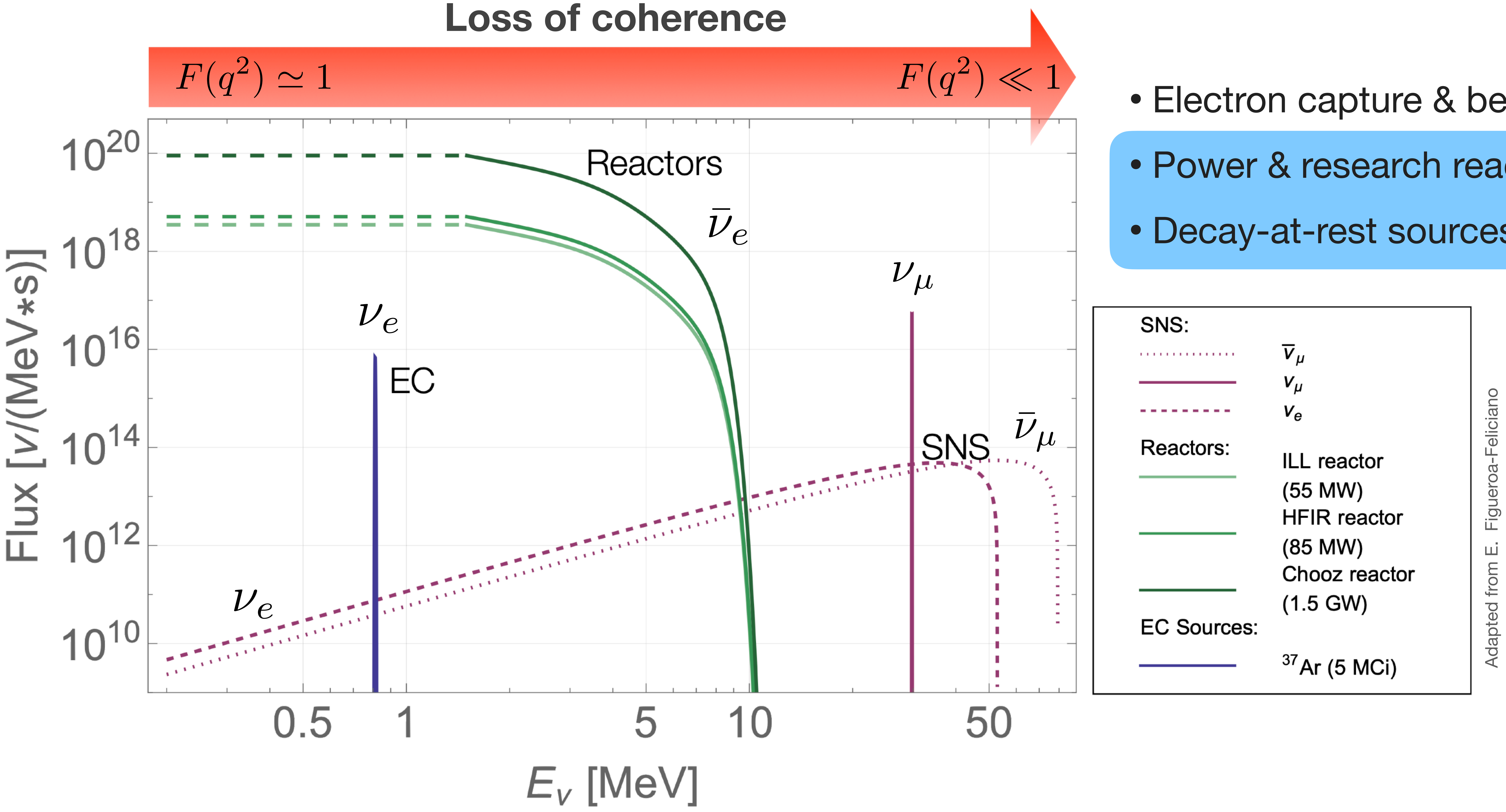


$$\frac{d\sigma}{dT} \propto \underbrace{\left[Z(1-4\sin^2\theta_W) - N\right]^2}_{\text{Electroweak physics}} \underbrace{F^2(q^2)}_{\text{Nuclear physics}}$$

- **Electroweak physics and BSM searches at the very low energy frontier**
- **New probe for nuclear matter**
- **Miniaturization of neutrino detectors:** many potential applications for the long range detection of neutrinos
  - ➡ Nuclear reactor safeguarding
  - ➡ Synergies with neutrino astronomy, DM detection, stellar astrophysics, etc.

Detection of CEvNS

Man-made neutrino sources



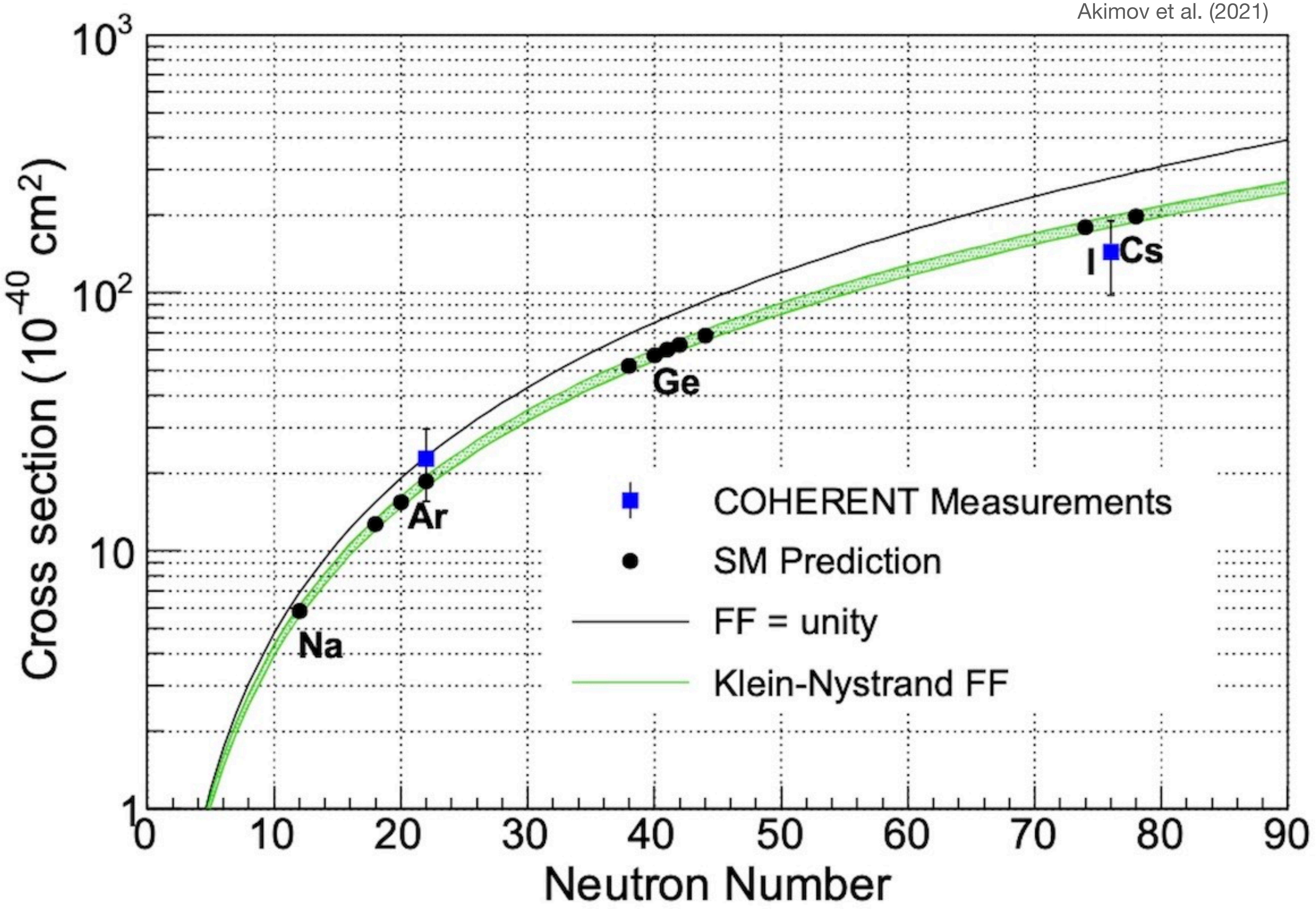
- Electron capture & beta-decay sources
- Power & research reactors
- Decay-at-rest sources

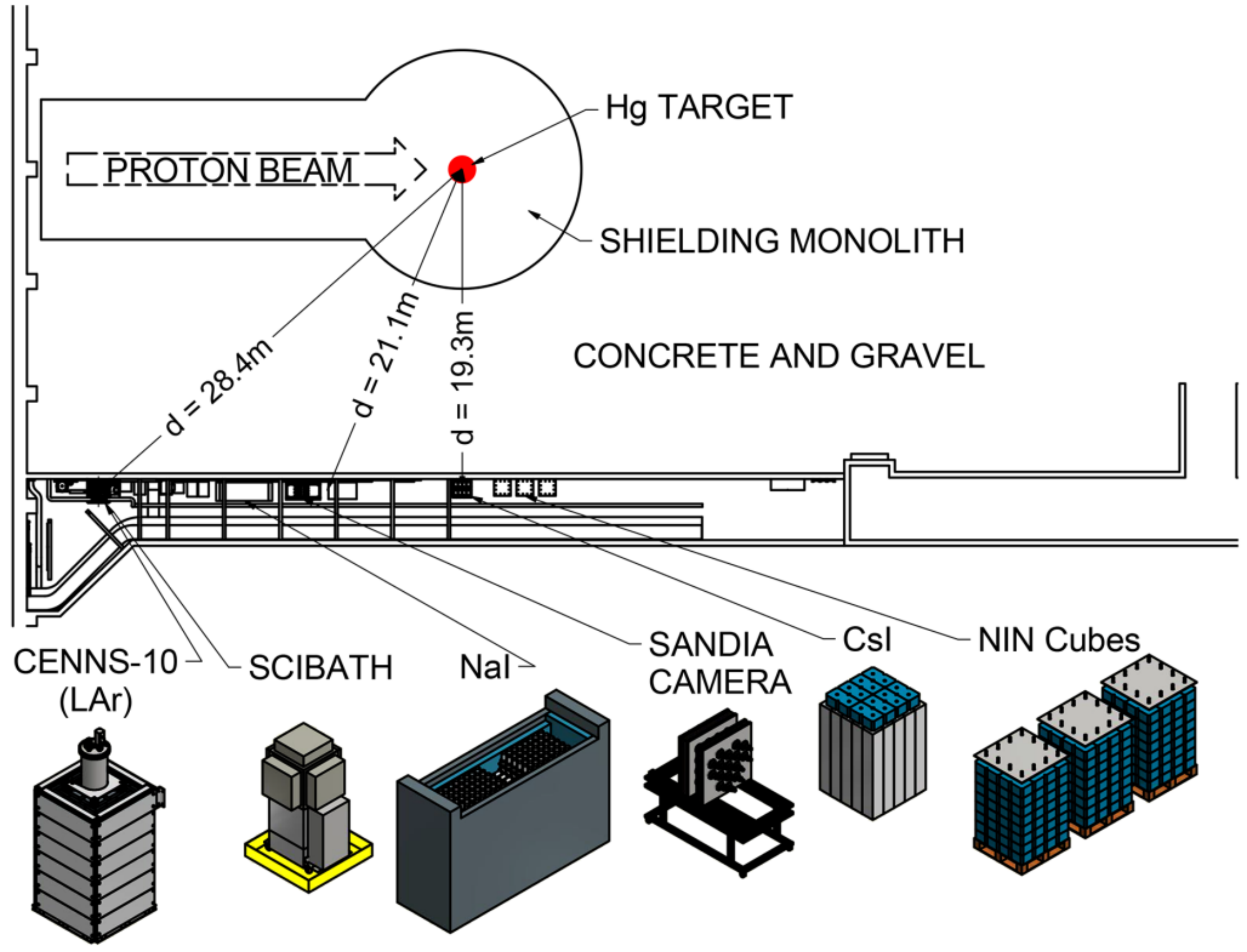
Status of the COHERENT program

Pion DAR source @ SNS (> 2016, Oakridge)

N²-dependence of (flux weighted) cross-section predicted by the SM

Akimov et al. (2021)





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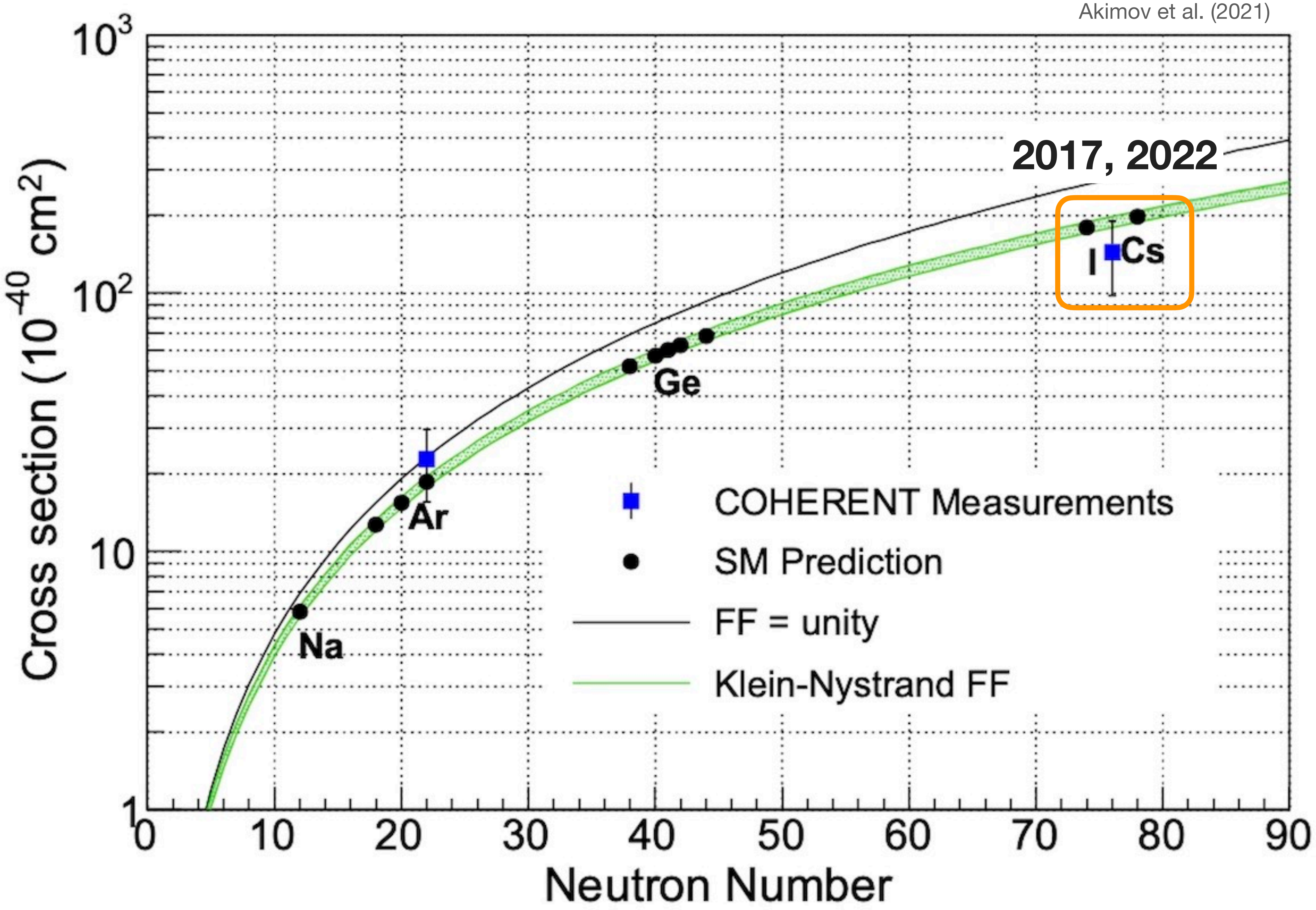
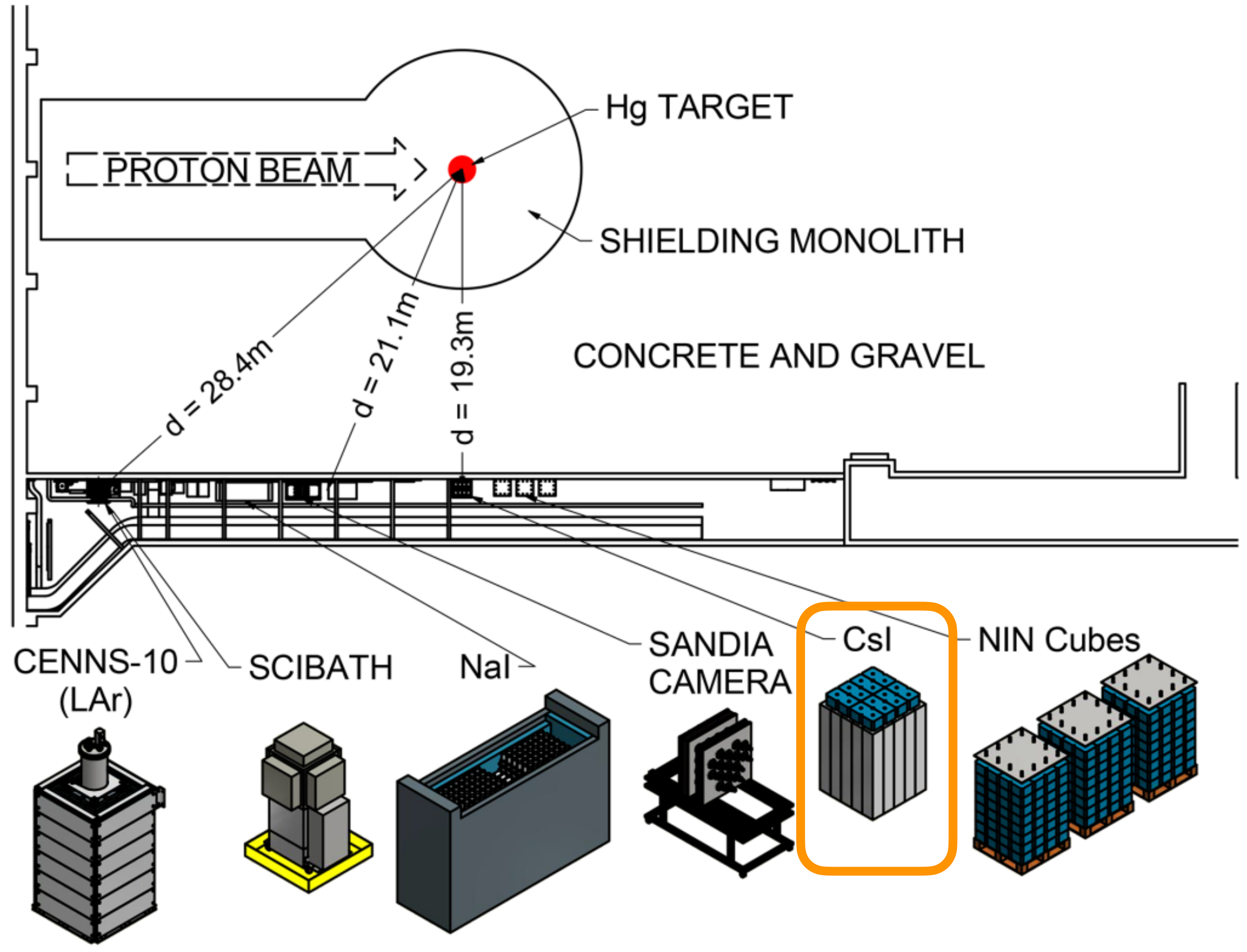


- First light in 2017 with **14.6-kg CsI[Na] detector**
  - ➡ Stat. limited
  - ➡ Dominant syst.: backgrounds + QF
- Improvements since (2022): 2 x stat. + better measurement of QF → Signal @ ~12σ
- Detector decommissioned



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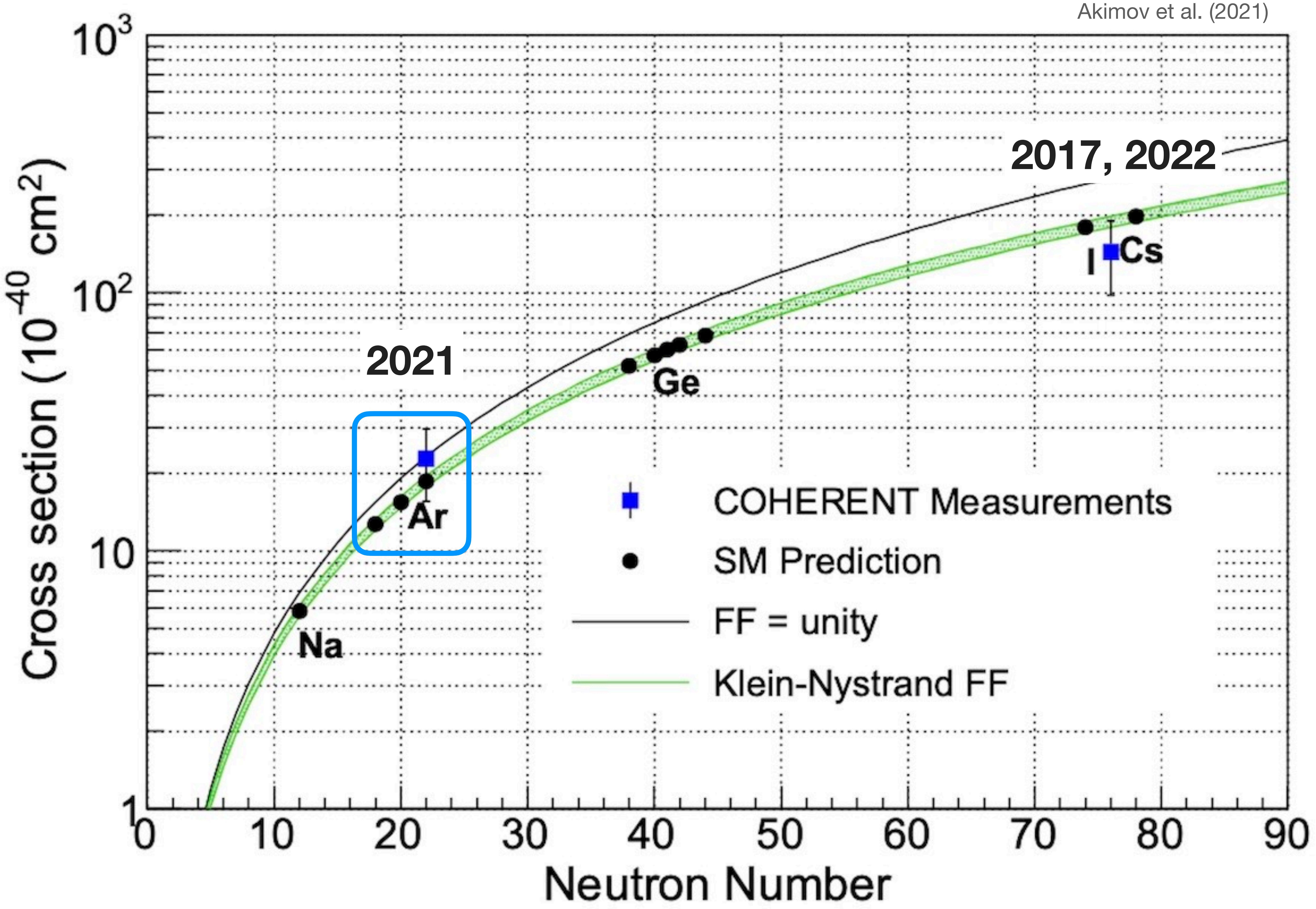
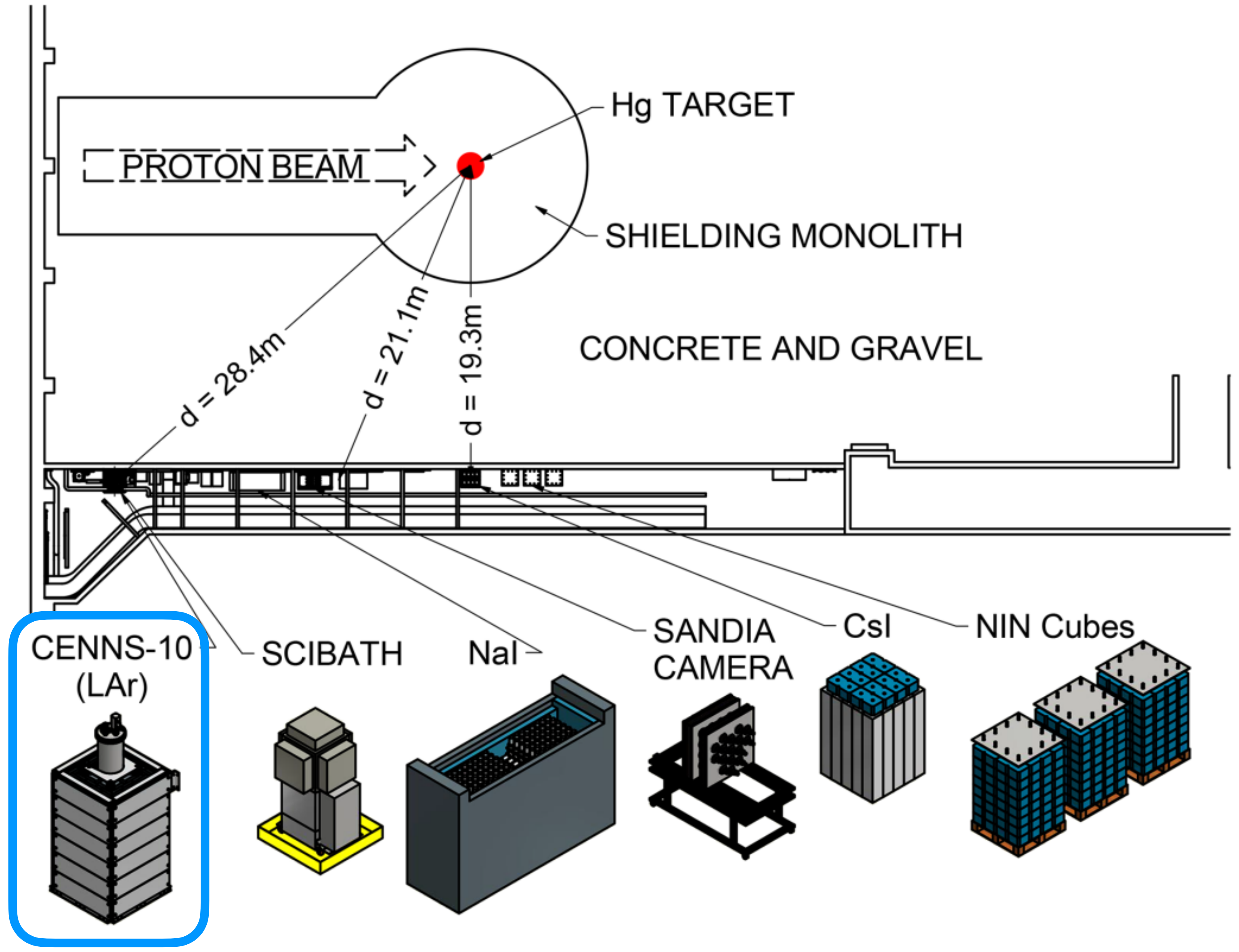
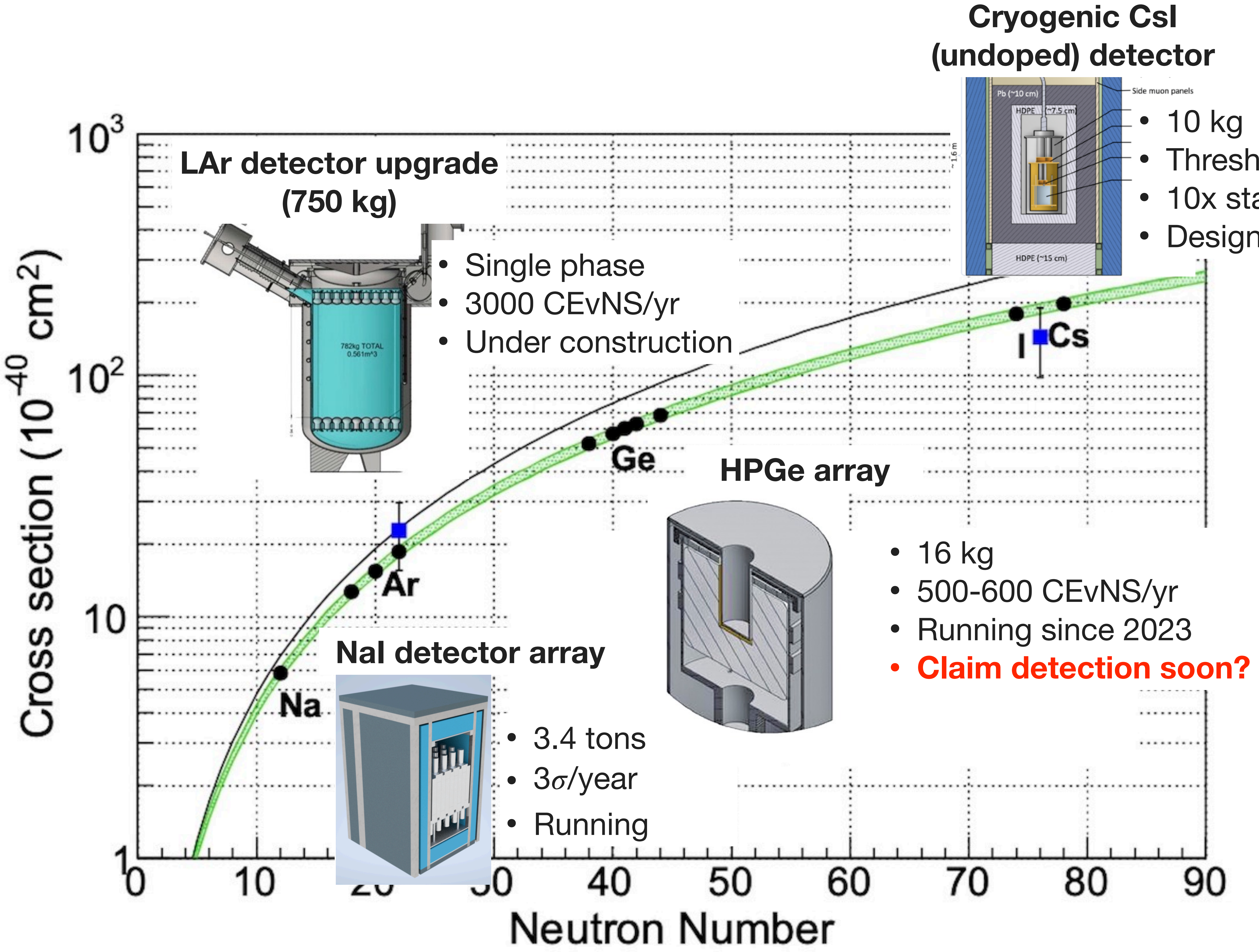


- Second light in 2021 with **24-kg LAr detector**
- > 3σ significance (~1.5 yr of data)
- More data to come, with 5σ in hand
- Upgrade to 750-kg payload



Future of COHERENT

Toward high precision measurements



Other activities: ↓ syst.

- Inelastic interactions + background measurements
- Flux measurements with D_2O Cherenkov detectors

Long-term plans:

- Upgrade of SNS beam
- Second target station construction with dedicated neutrino hall → ton-scale detectors

Detection of CEvNS

Why the detection at reactors is more challenging?

	DAR	REACTOR
Neutrino flavors	Multiple	Single (electronic)
Flux at O(10 m) [$cm^{-2}\ s^{-1}$]	~ 10^7-10^8	~ 10^{12}-10^{13}
Cross-section [$10^{-40}\ cm^2$]	10-100	0.1-1
Mean energy [MeV] Coherence	~ 30 $F(q^2) < 1$	~ 3 $F(q^2) \simeq 1$
Recoil energies [keV]	$\lesssim$ 100 keV	$\lesssim$1 keV
Signal timing	Pulsed	~ steady

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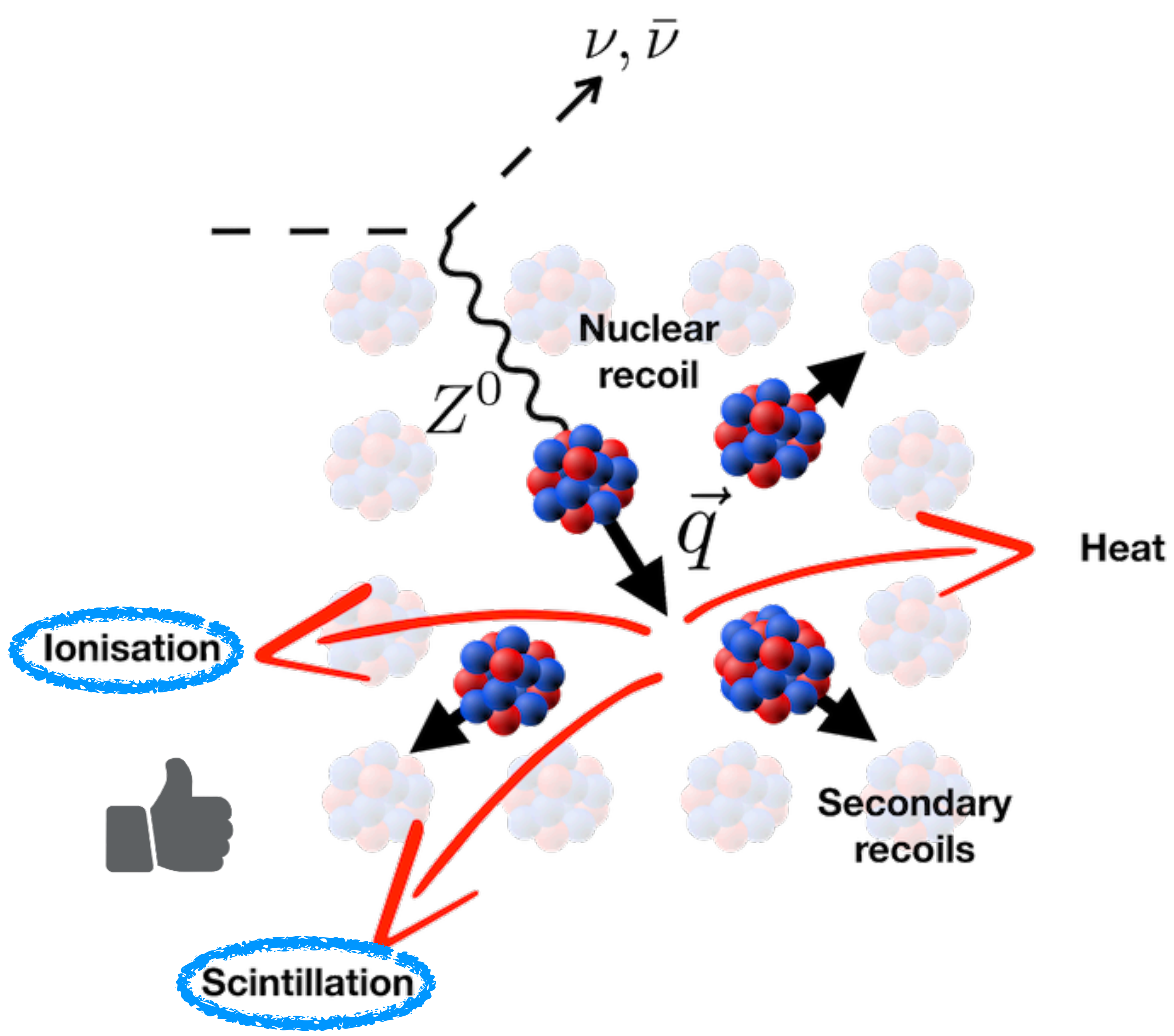
Thresholds easier to achieve with « standard » detection techniques



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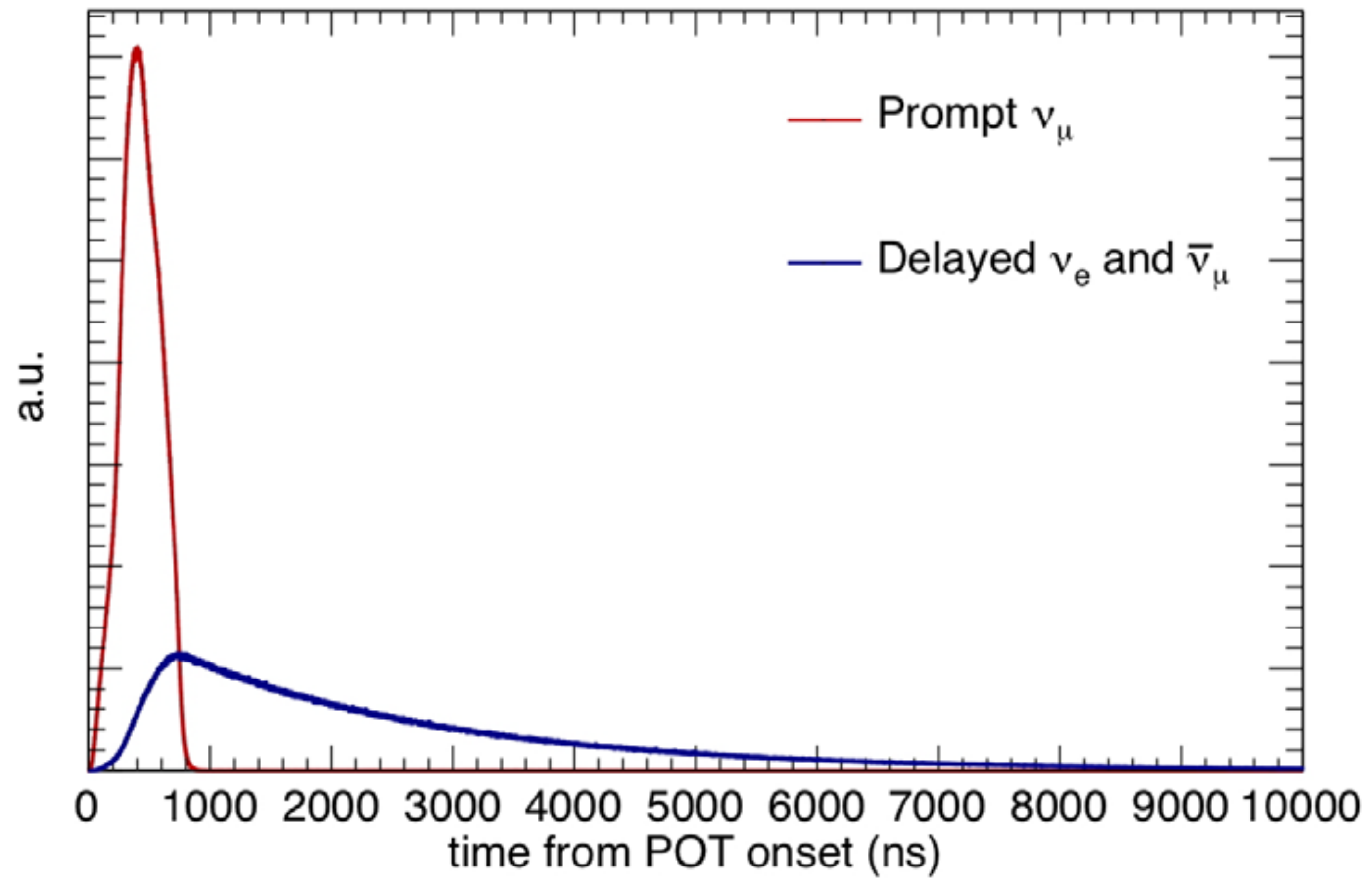
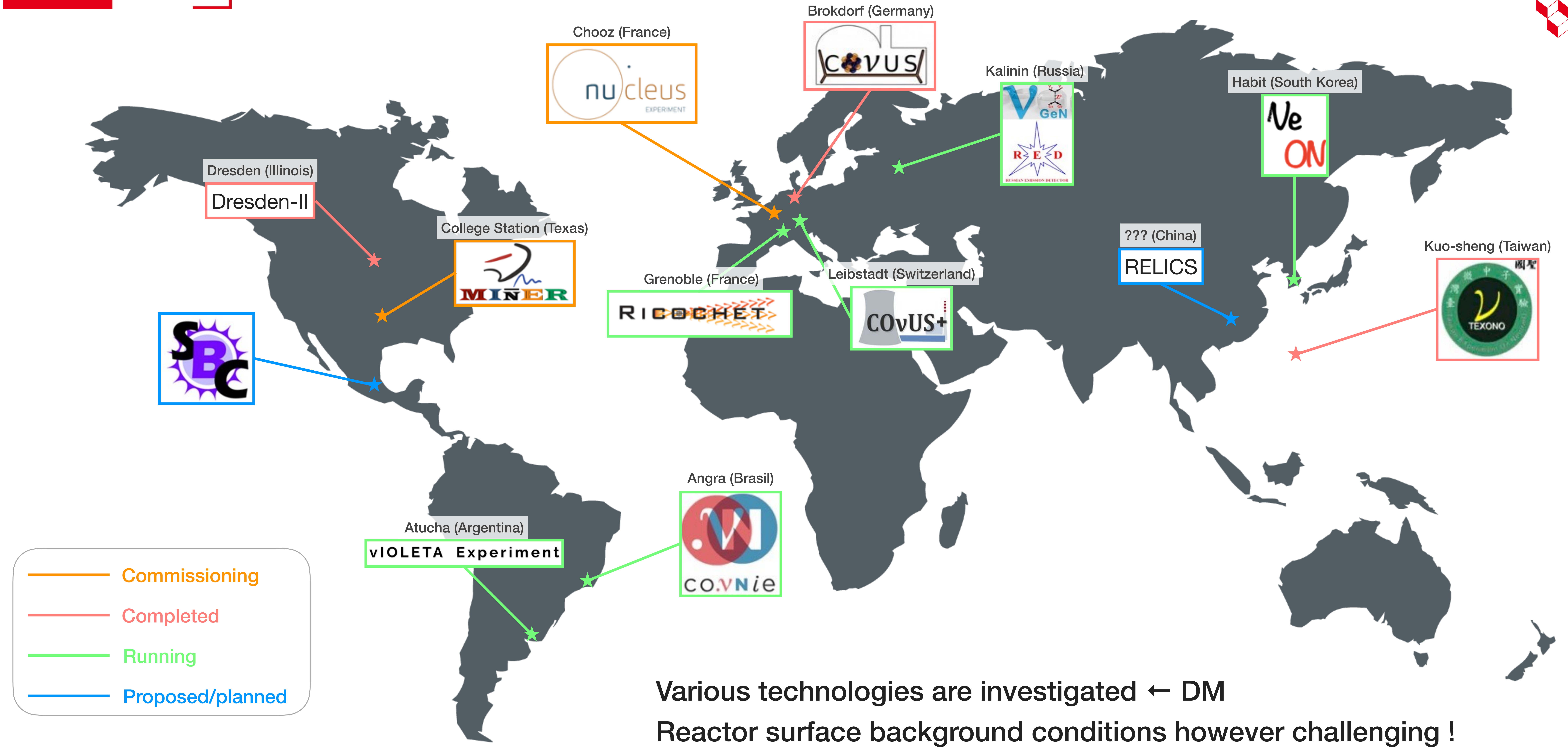
Background killer : we know when the signal comes !



Reactor experiments worldwide



Various technologies are investigated ← DM

Reactor surface background conditions however challenging !

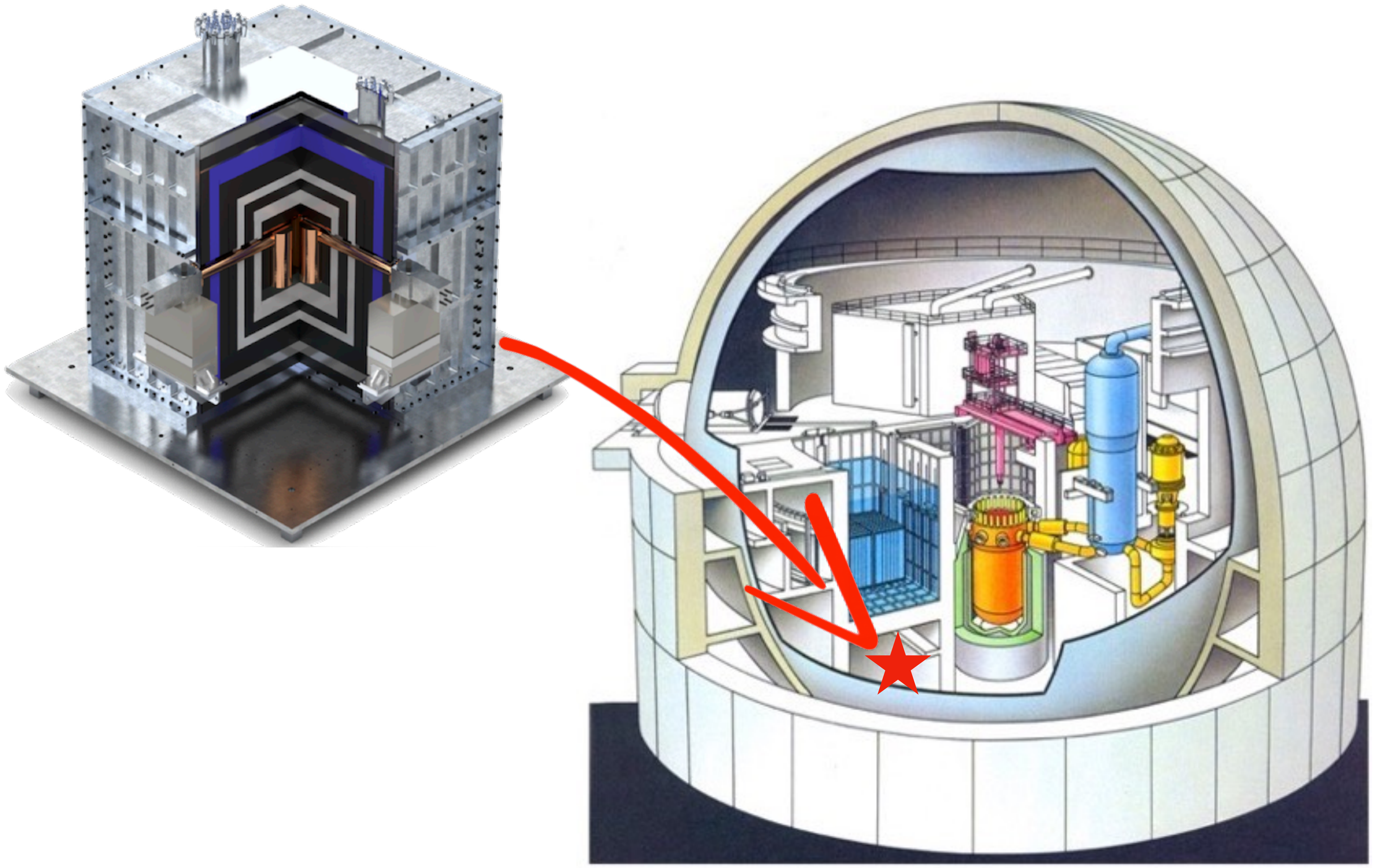
HPGe ionization detectors

CONUS at Brokdorf (2018-2022, Germany)

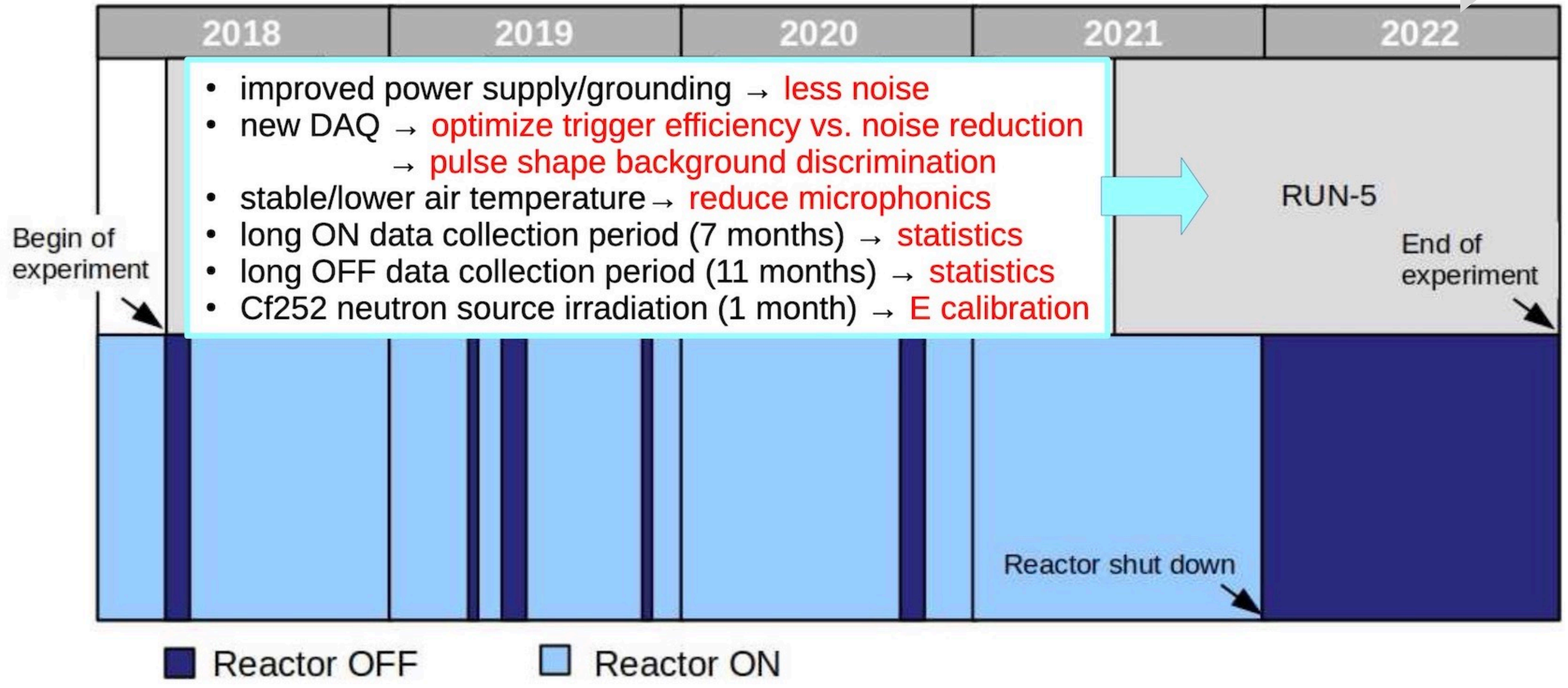
Key features

- Intense neutrino flux: ϕ = 2.3 x 10^{13} cm^{-2} s^{-1}
- Overburden: 15-45 mwe
- Ultra low threshold: ~ 200 eV_{ee}
- Ultra low background in RoI: O(10) dru

5 years of successful operation of 4 x 1-kg Ge detectors @ 17 m distance from a 3.9 GW_{th} reactor core



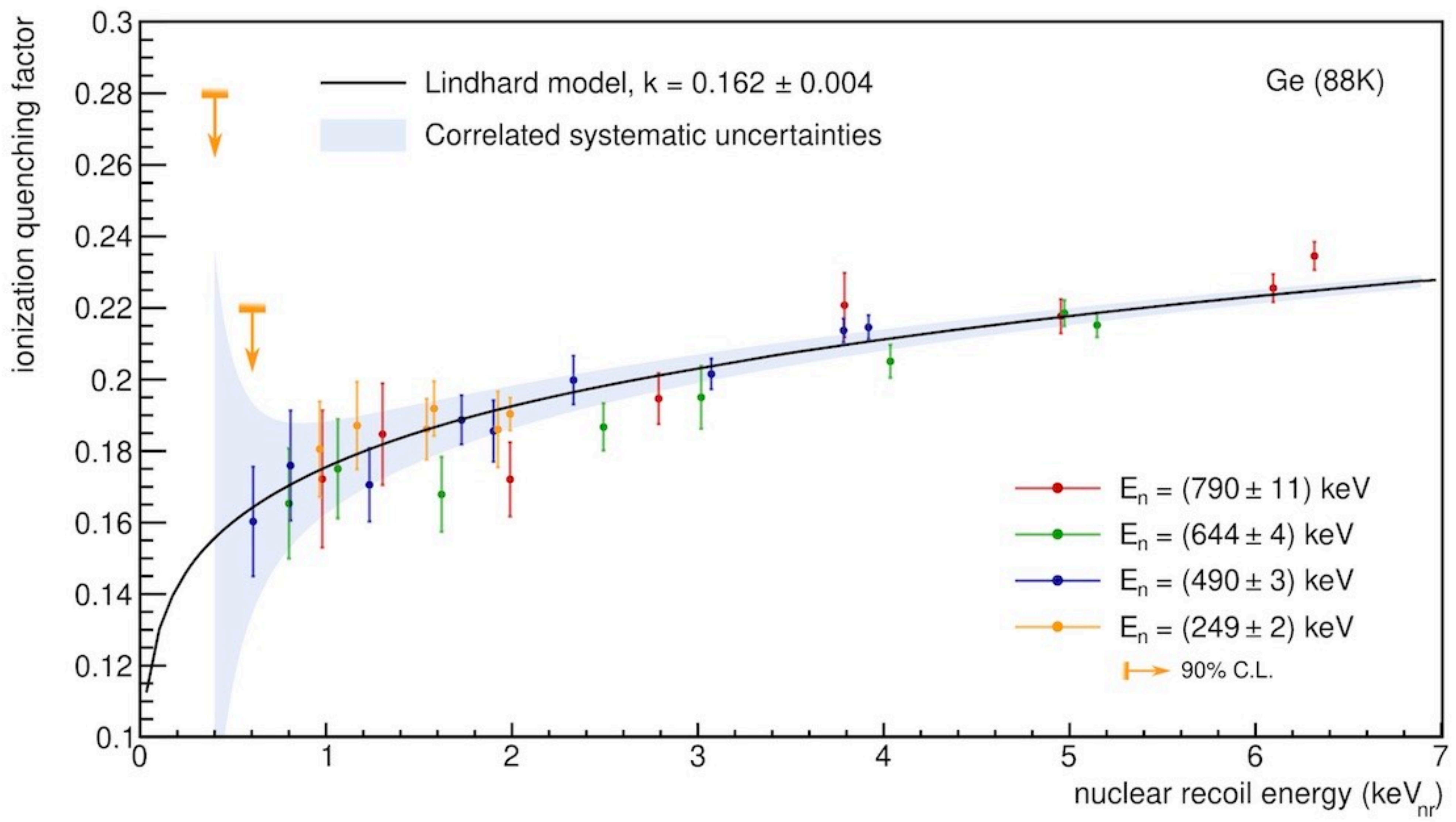
Detector performances and stability continuously enhanced



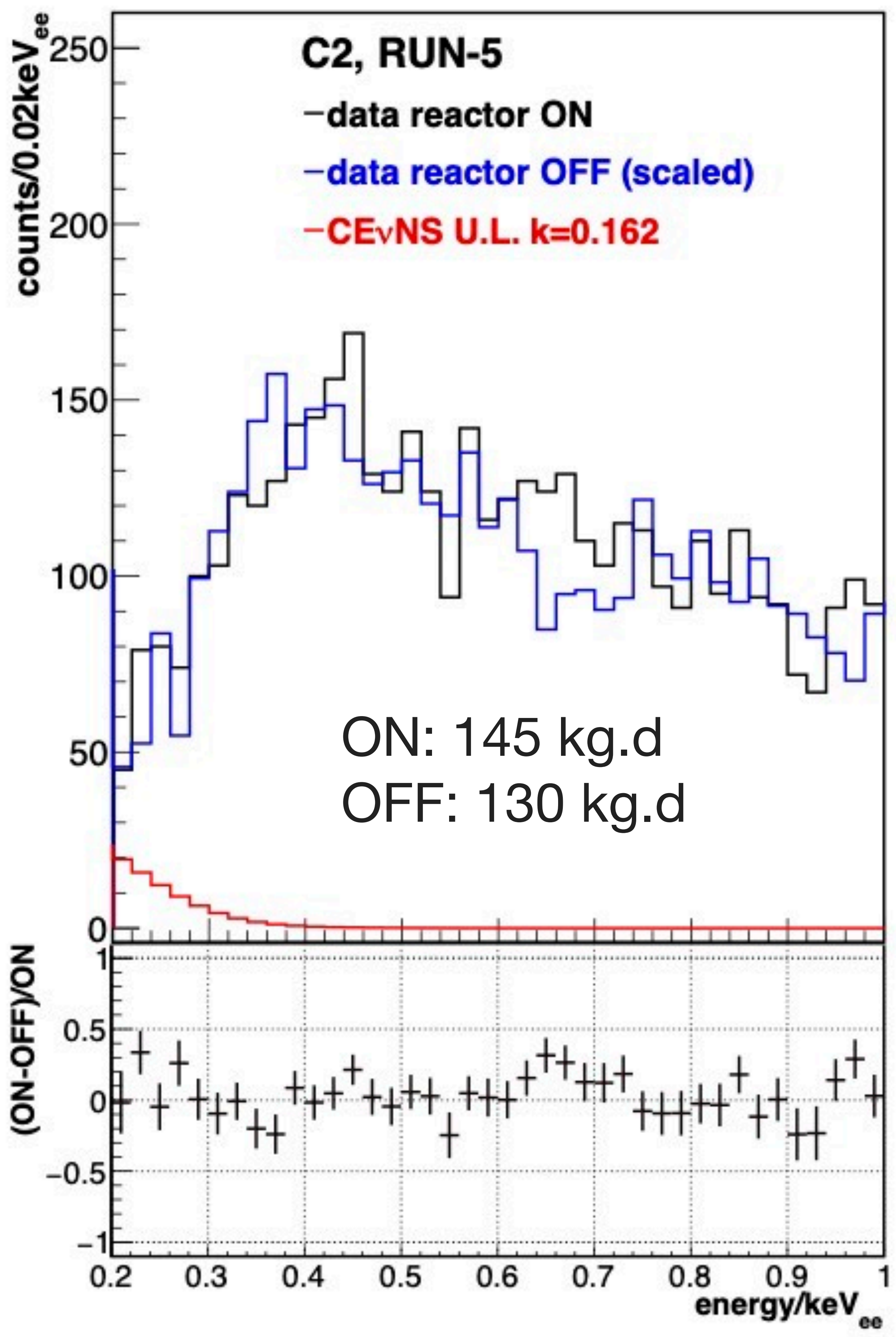
HPGe ionization detectors
CONUS at Brokdorf (2018-2022, Germany)

Achievements

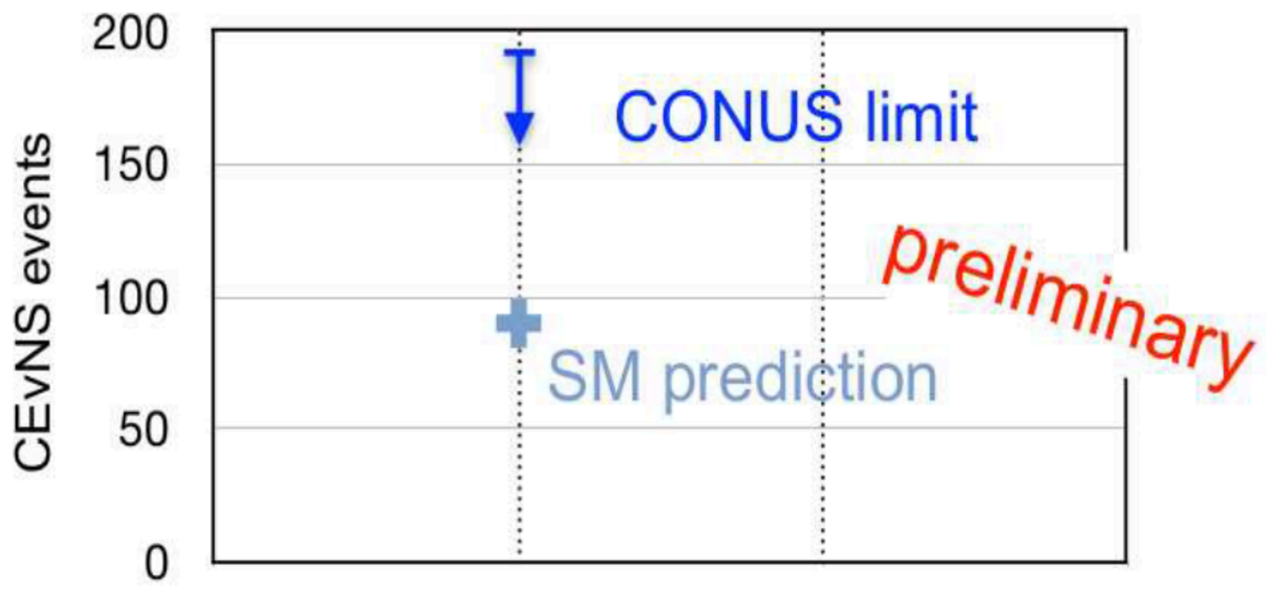
- **Full background decomposition and understanding** → reactor-correlated neutrons negligible
- **Precise ionization quenching measurements** down to 0.4 keV_{nr}
  - Validity of Lindhard theory confirmed !
  - Quenching factor k = 0.162 ± 0.04 (stat. + syst.)



Final results (2023)



- **Limits on CEvNS signal from reactor antineutrinos: factor ~2 above SM prediction**
- Competitive limits on BSM physics

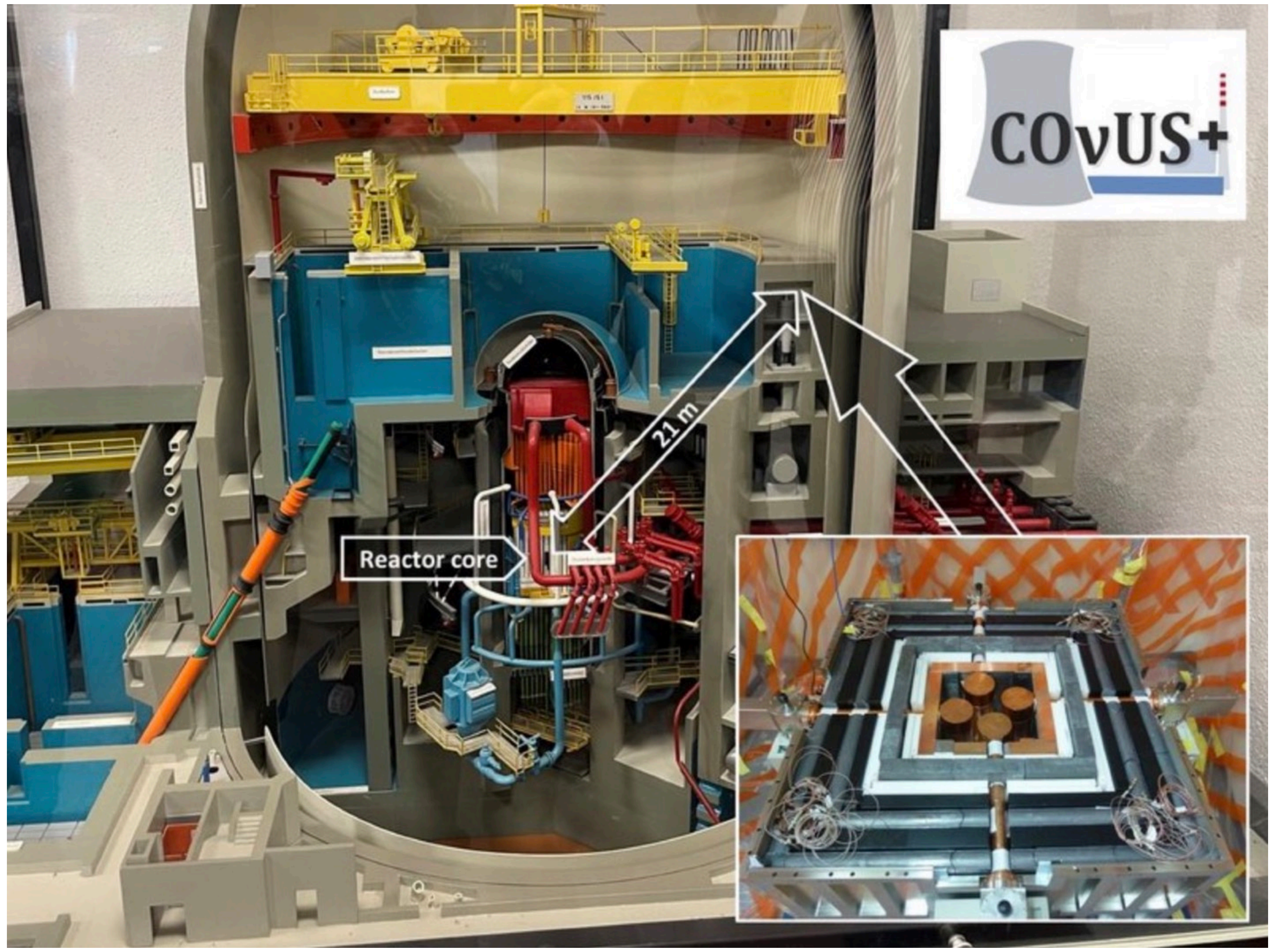


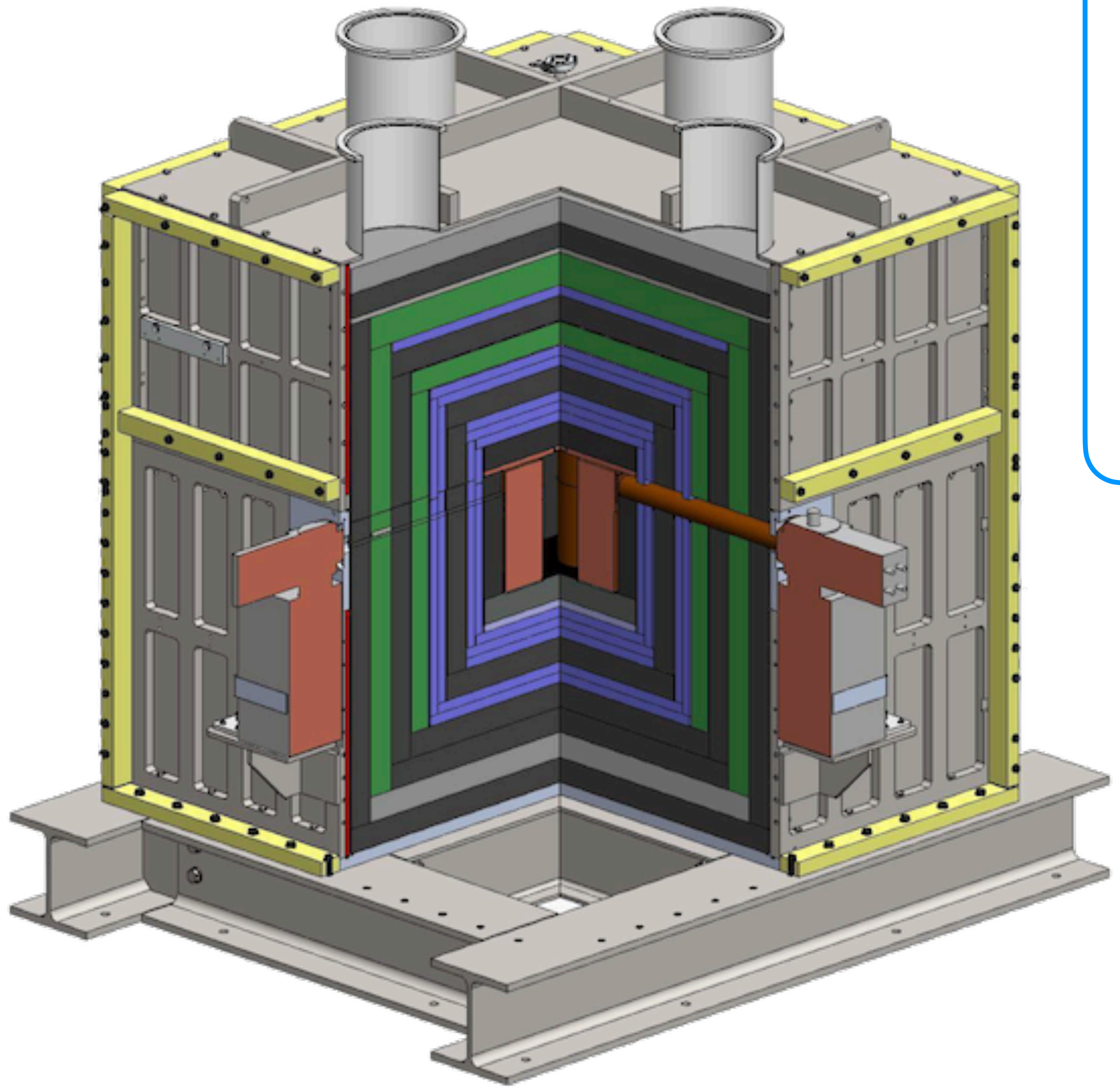
HPGe ionization detectors

CONUS+ → Leibstadt (> 2023, Switzerland)

Upgrade of 4 x 1-kg Ge detectors @ 21 m distance from a 3.6 GW_{th} reactor core

Key features
- Intense neutrino flux: $\phi = 1.5 \times 10^{13}$ cm^{-2} s^{-1}
- Overburden: 7-8 mwe
- Ultra low threshold: < 200 eV_{ee}





- Full bck characterization of detector location → higher reactor-correlated neutron flux !
- Shielding adapted to new back conditions (2nd μ veto, etc.)
- HPGe setup upgraded: energy resolution and threshold improved.

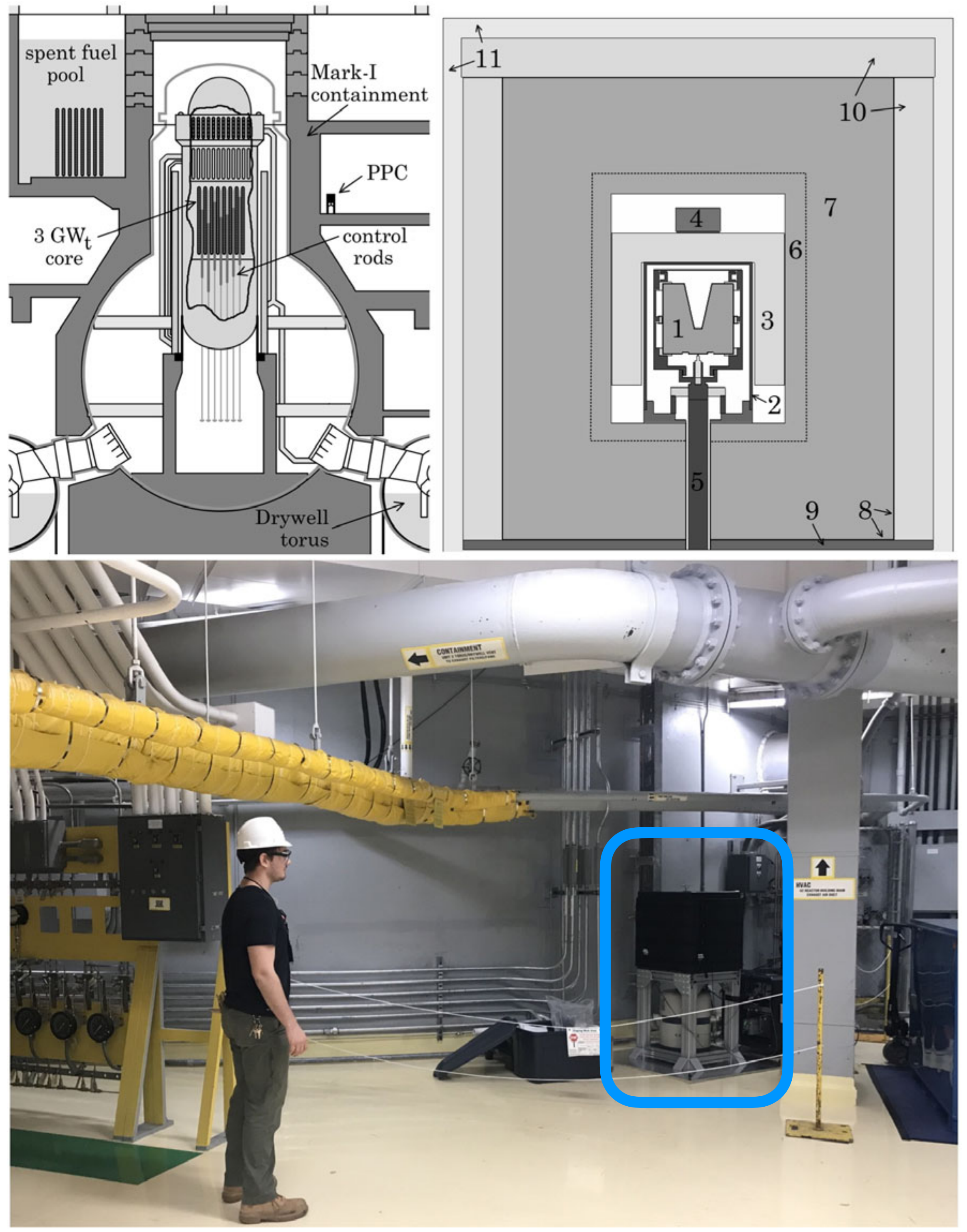
Status
- Installation over summer 2023
- Data taking started in November 2023
- Reactor OFF data this spring
- First results coming soon !

HPGe ionization detectors

The DRESDEN-II detection claim (2022)

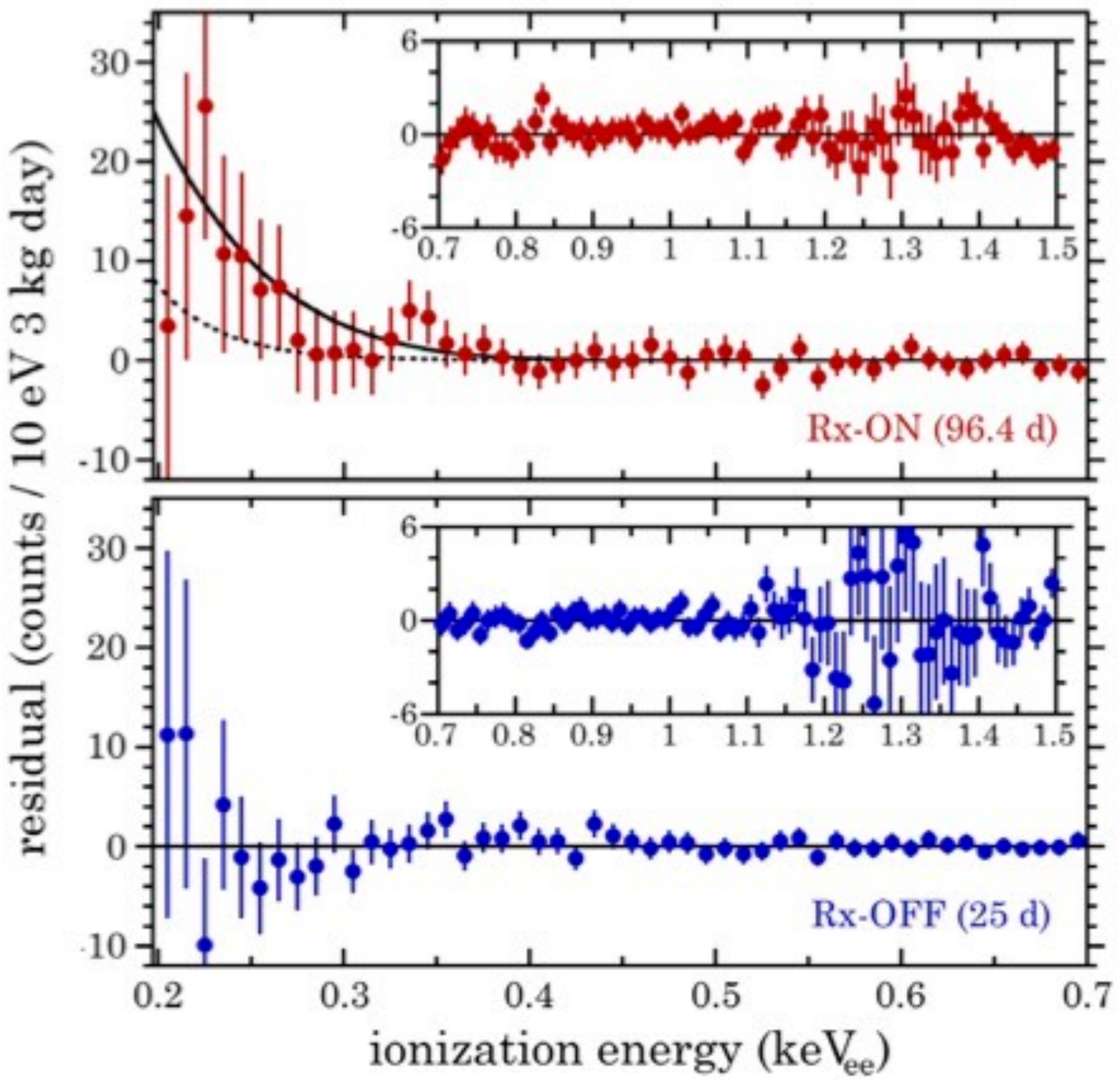
Key features

- Neutrino flux: $\phi = 4.8 \times 10^{13}$ cm^{-2} s^{-1}
- 3-kg PPC detector @ 10.4 m from core
- Ultra low threshold: ~200 eV_{ee}
- Ultra compact shielding !



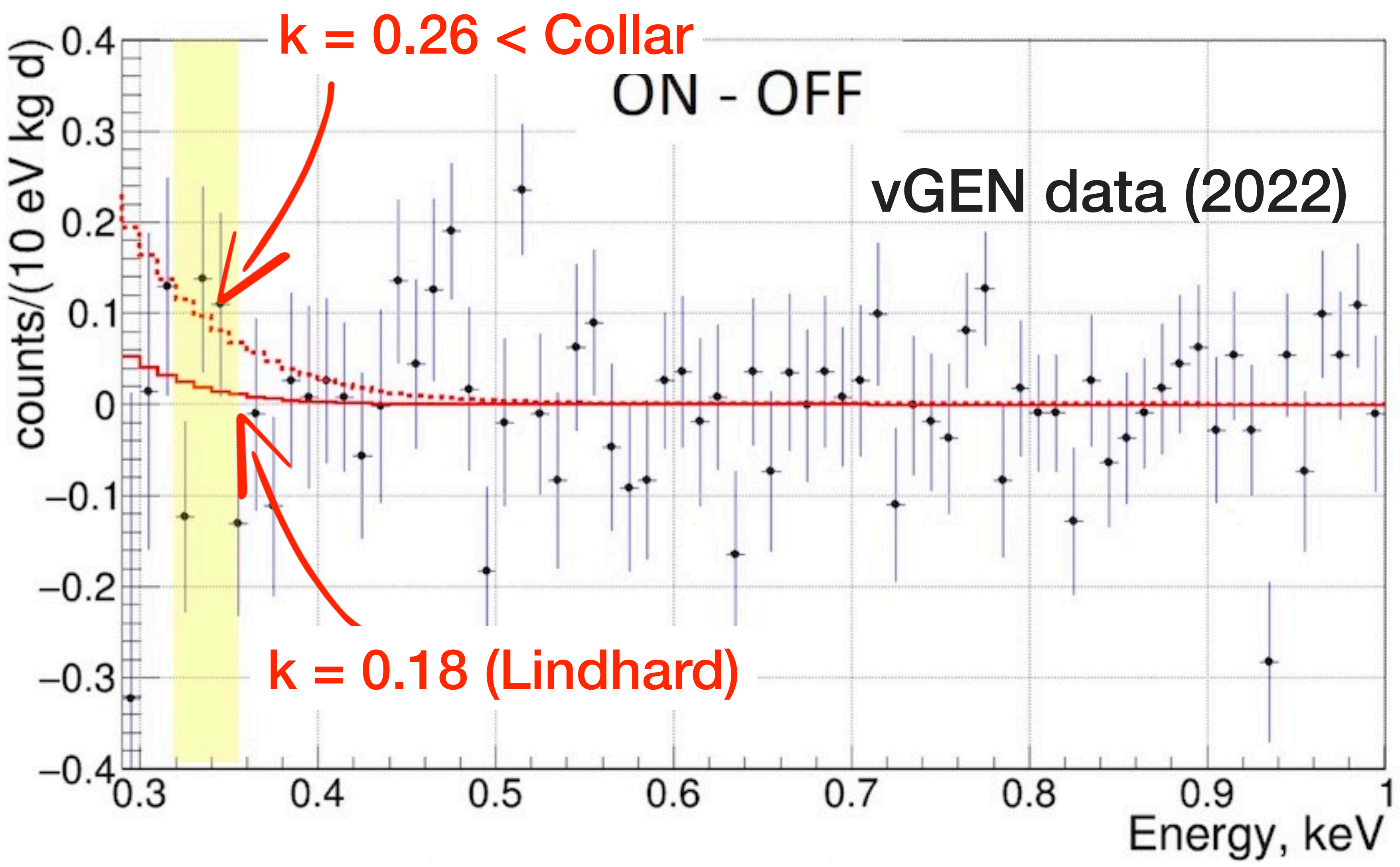
Claimed strong preference for the presence of CEvNS ($p < 1.2\ 10^{-3}$)

Background subtracted residual



Clarifications necessary !

- Mitigation of reactor-correlated neutrons
- Model-dependent background subtraction
- Quenching factors (~ 2 x Lindhard) incompatible with CONUS and vGEN



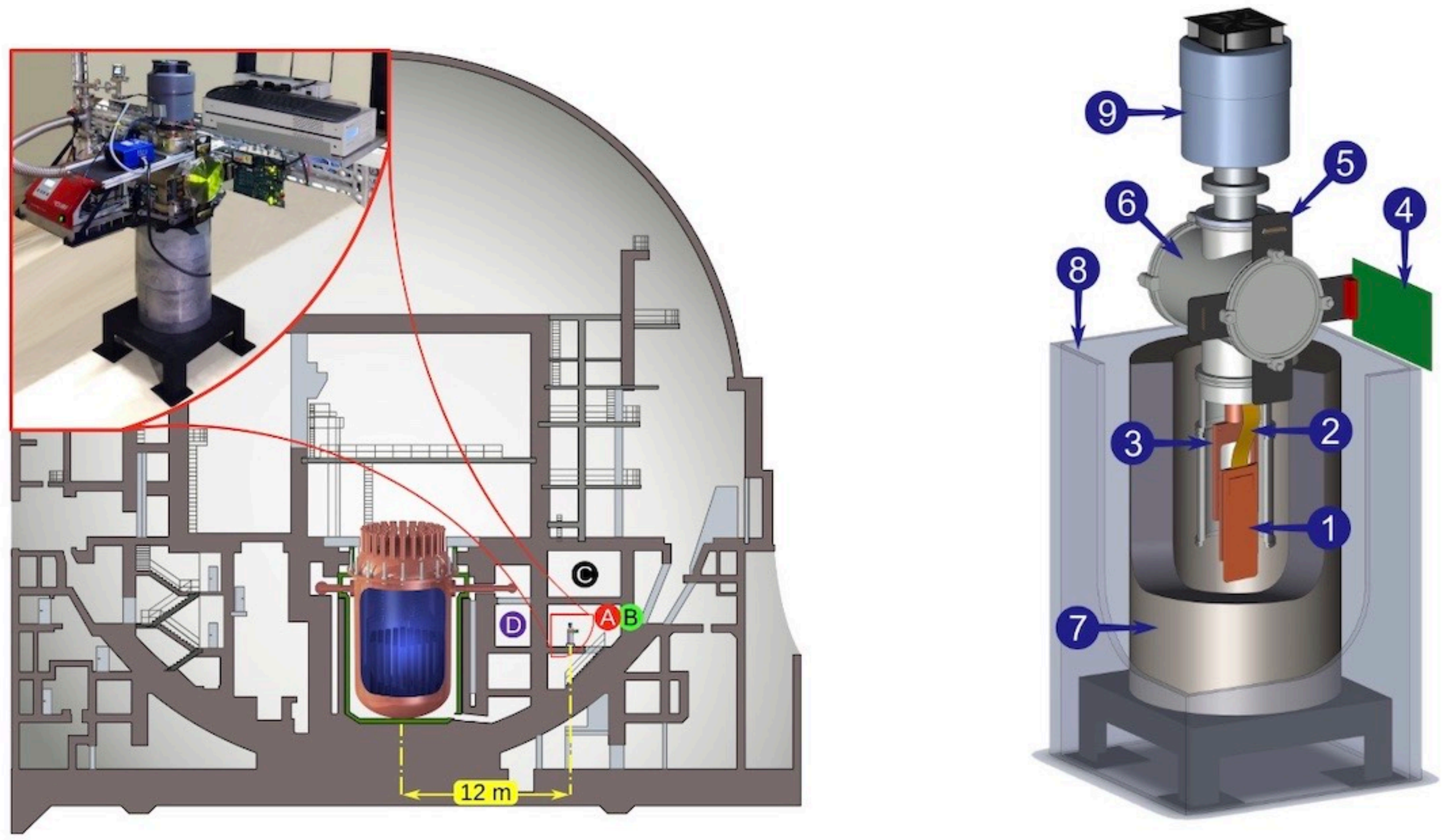
CCD efforts in south America

CONNIE at Angra-2 (> 2016, Brasil) & vIOLETA at Atucha-2 (> 2020, Argentina)

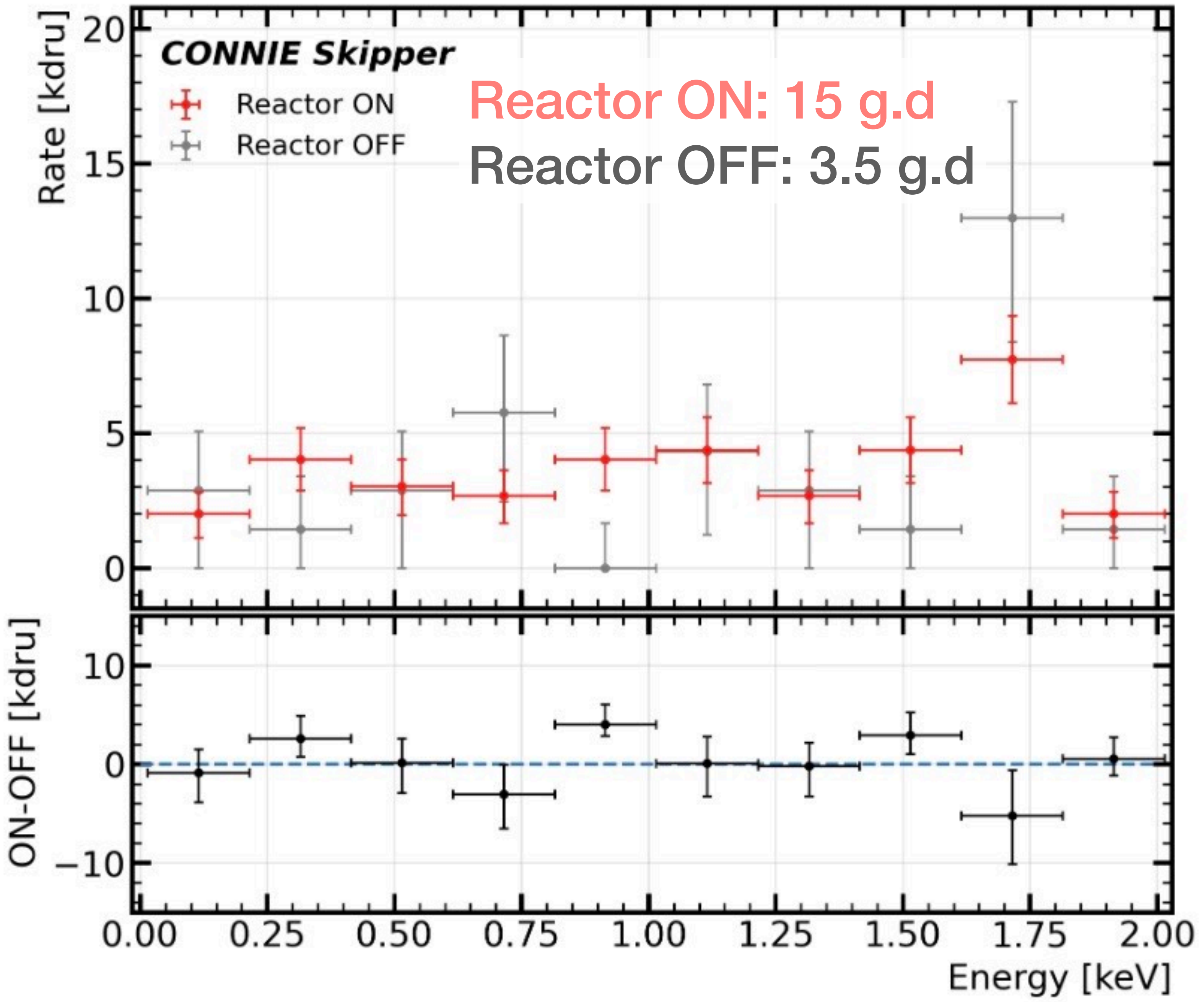
Key features

- Neutrino flux: $\phi \simeq 10^{13}$ cm^{-2} s^{-1}
- Gram-scale Skipper CCDs with sub-e^- readout noise
- Ultra low threshold: ~40 eV_{ee}
- No muon veto possible…

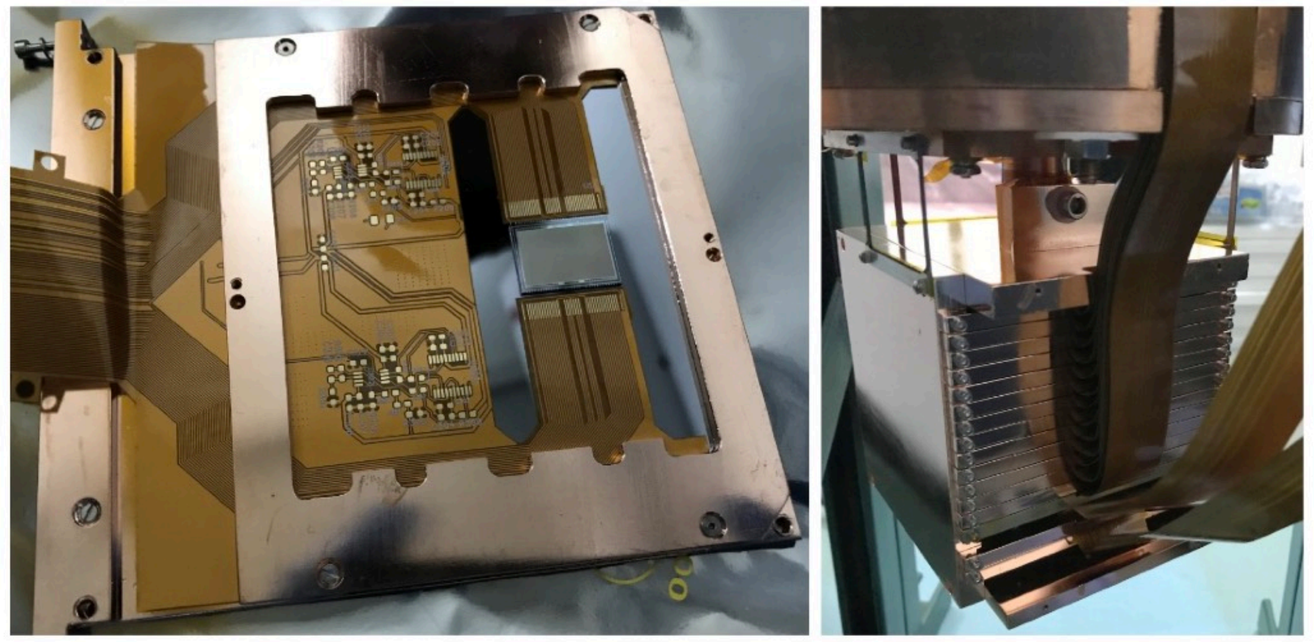
vIOLETA Skipper CCD at Atucha-2 (2023)



CONNIE Skipper CCD run at Angra-2 (2023)

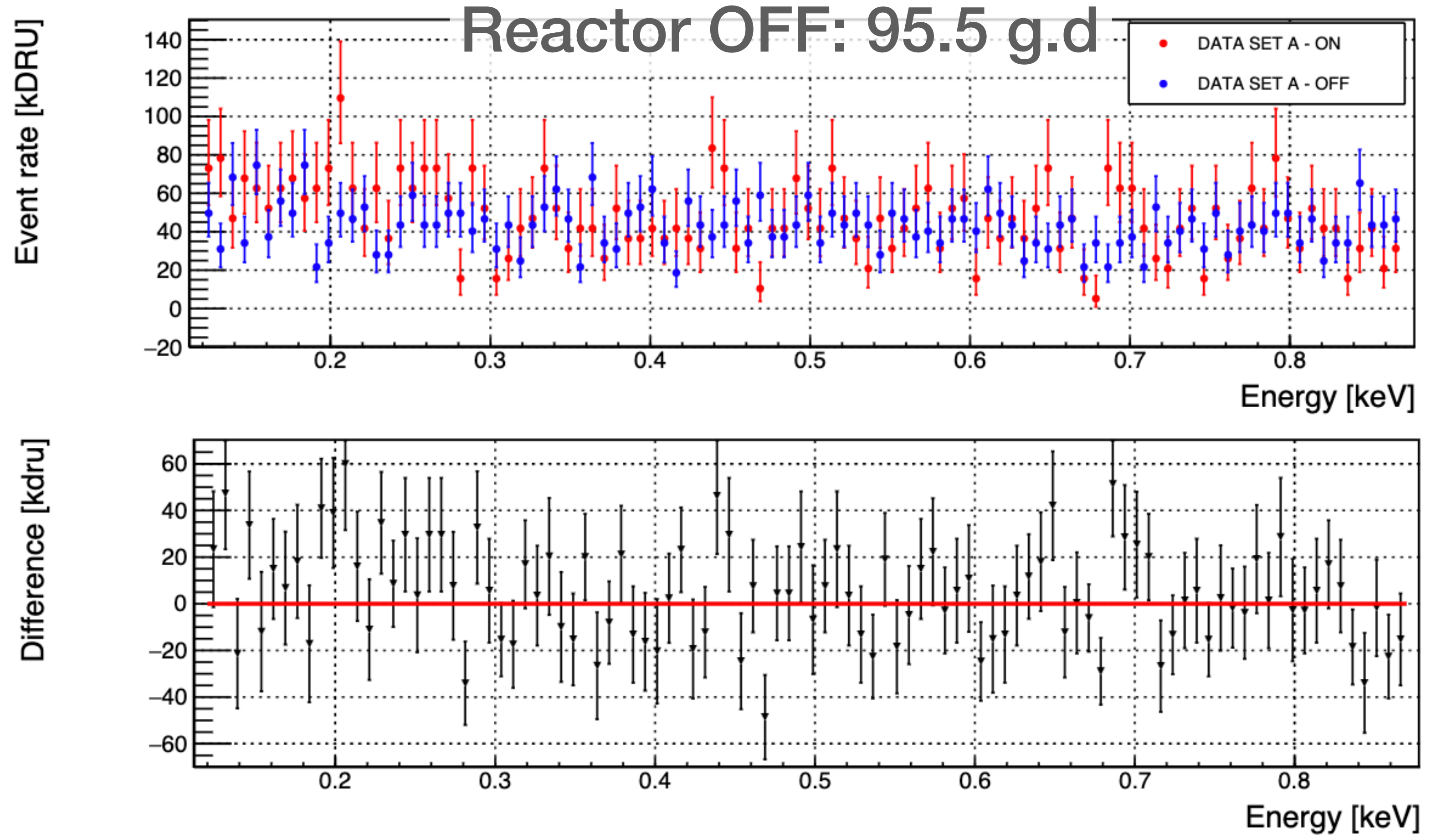


CONNIE Skipper-CCD



Reactor ON: 57 g.d

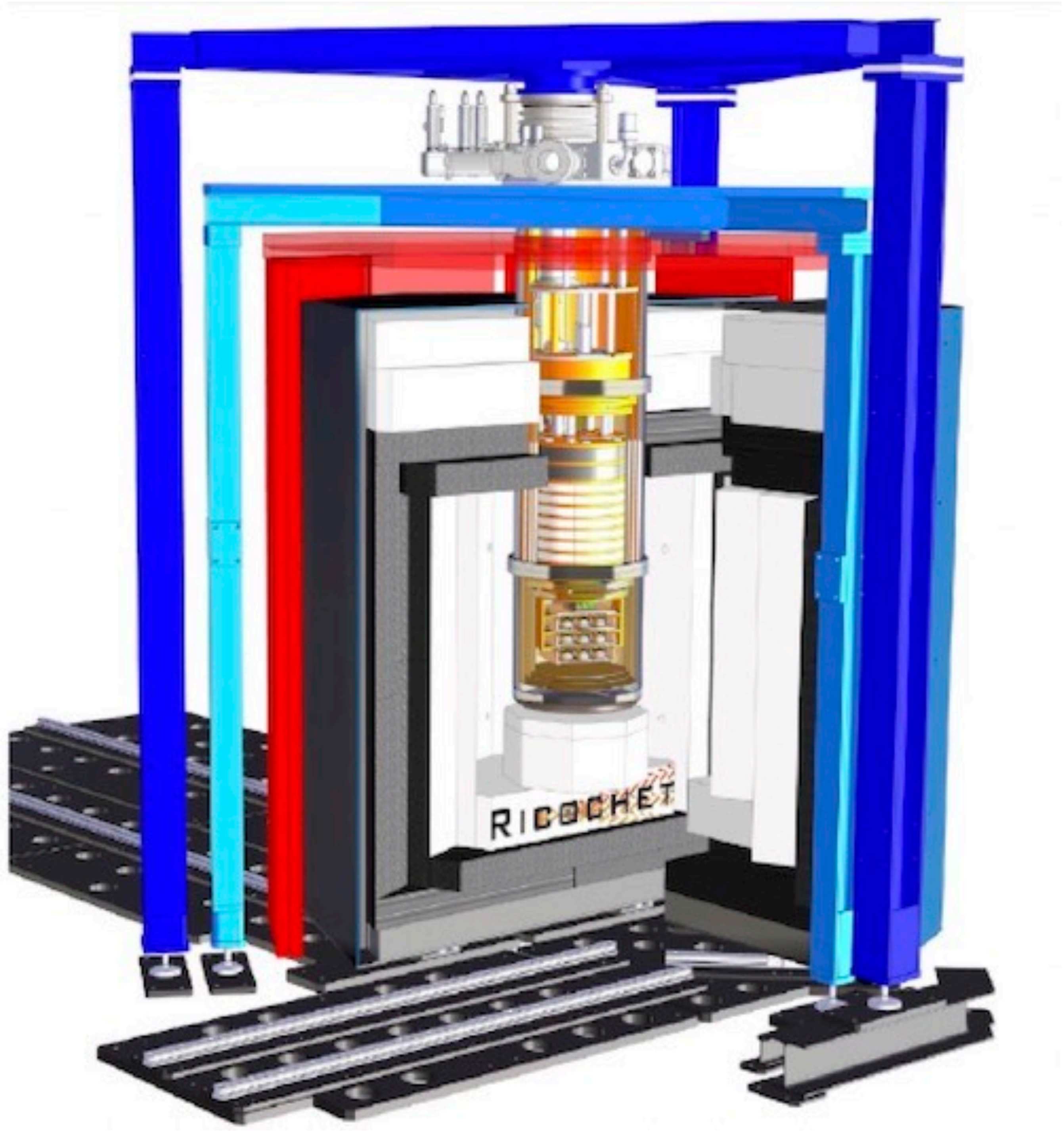
Reactor OFF: 95.5 g.d



Bolometric detection

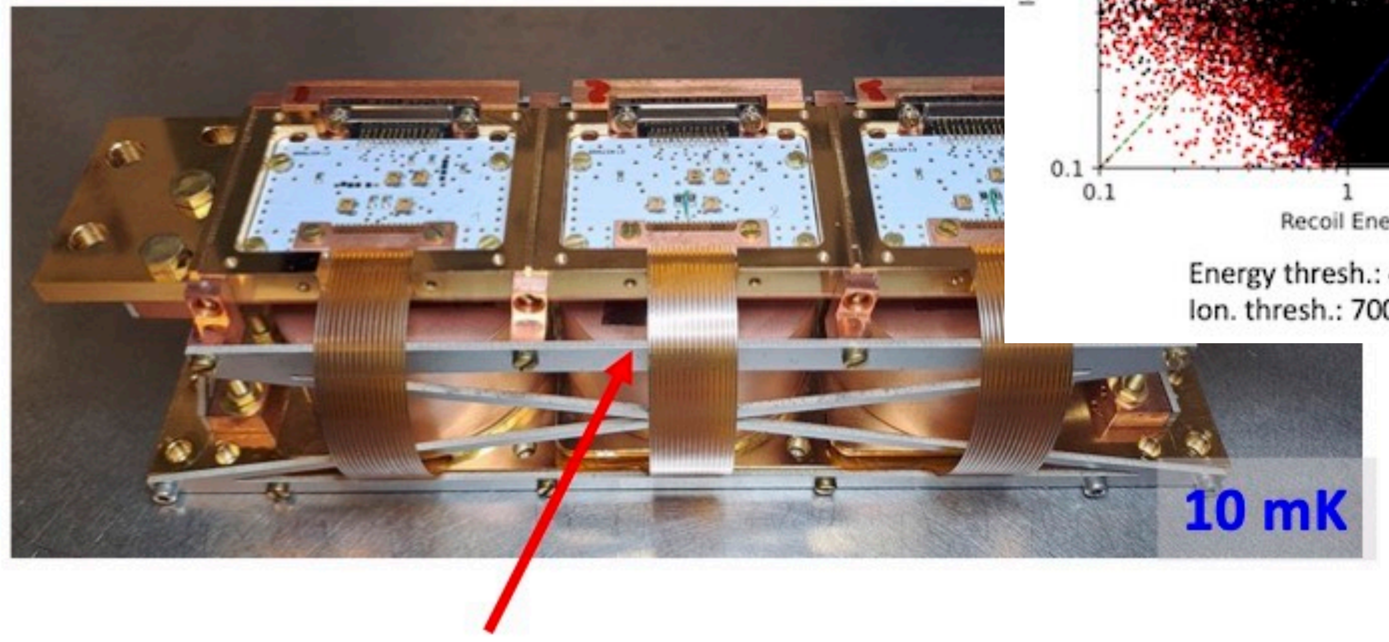
RICOCHET at ILL (> 2024, France)

Key features
- Neutrino flux: $\phi = 10^{12}$ cm^{-2} s^{-1}
- 0.75-1 kg Ge dual readout (heat/ion.) + superconducting Zn
- Ultra low threshold: ~100 eV$_{ee}$ (ion.) + ~100 eV (heat)



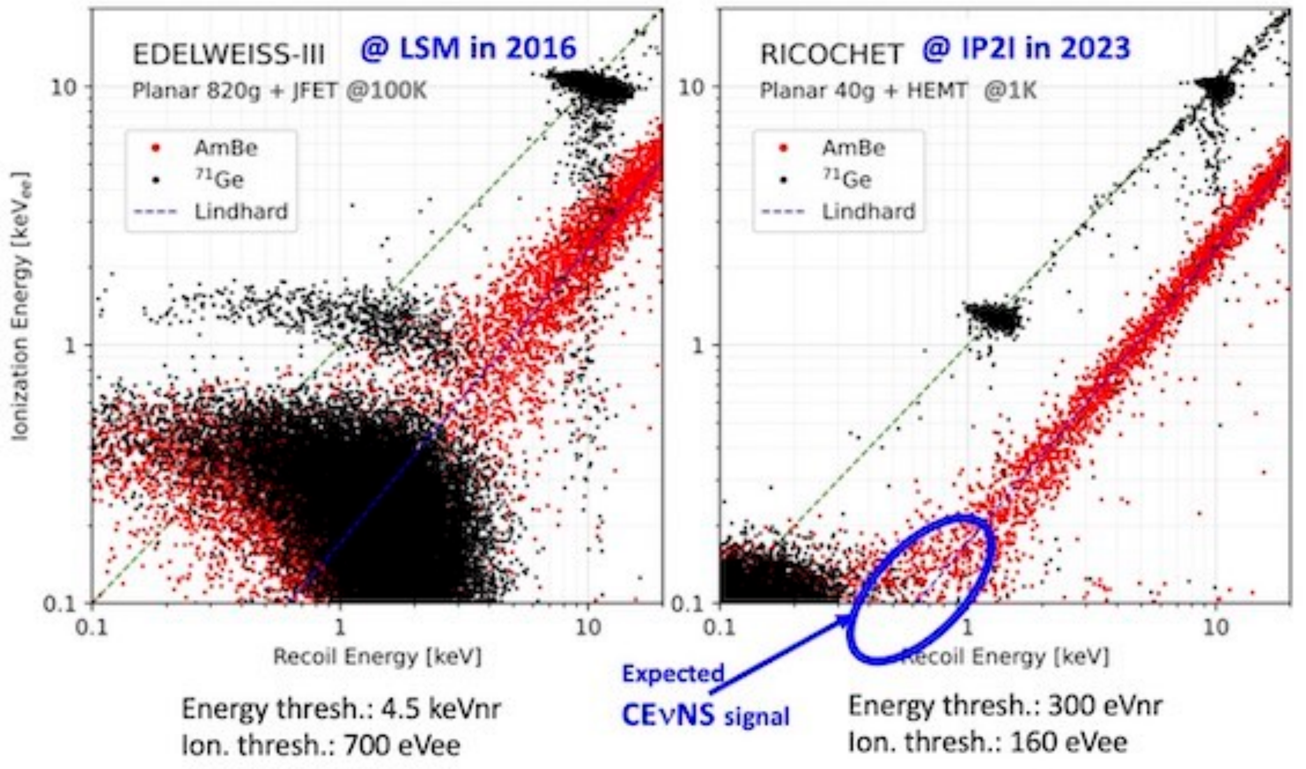
Ricochet at ILL

Ge Mini CryoCube



Thermal decoupling: TiMetal

Improvement on ER/NR discrimination



Status
- Ge CryoCube development well-advanced → almost on specs !
- Shieldings and cryostat installed @ ILL
- Commissioning run with a light detector version (120 g) on-going → first results on reactor data probably soon !

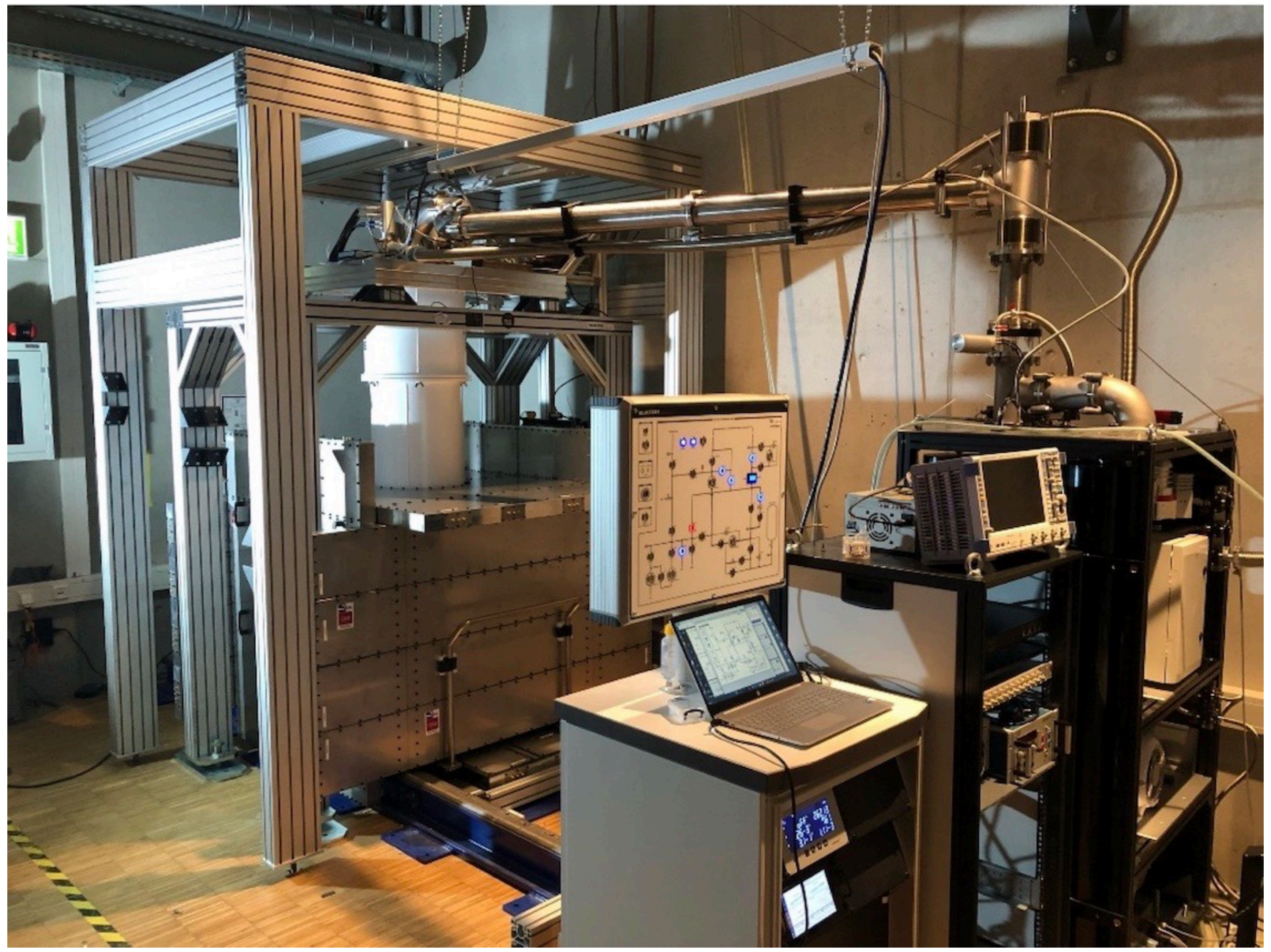
Bolometric detection

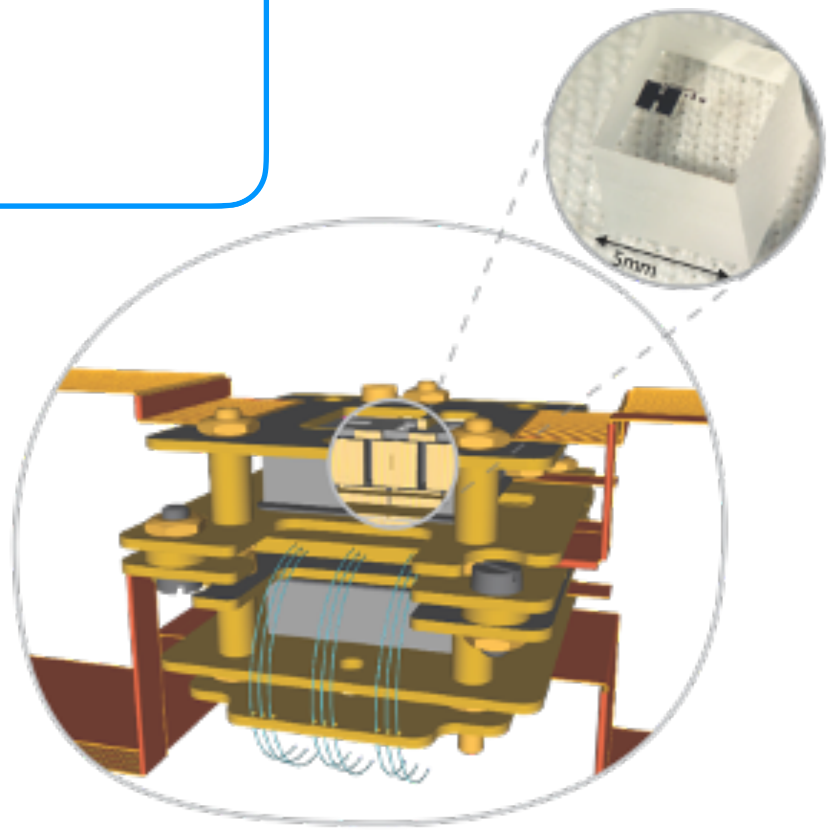
NUCLEUS at Chooz (> 2025, France)

Key features

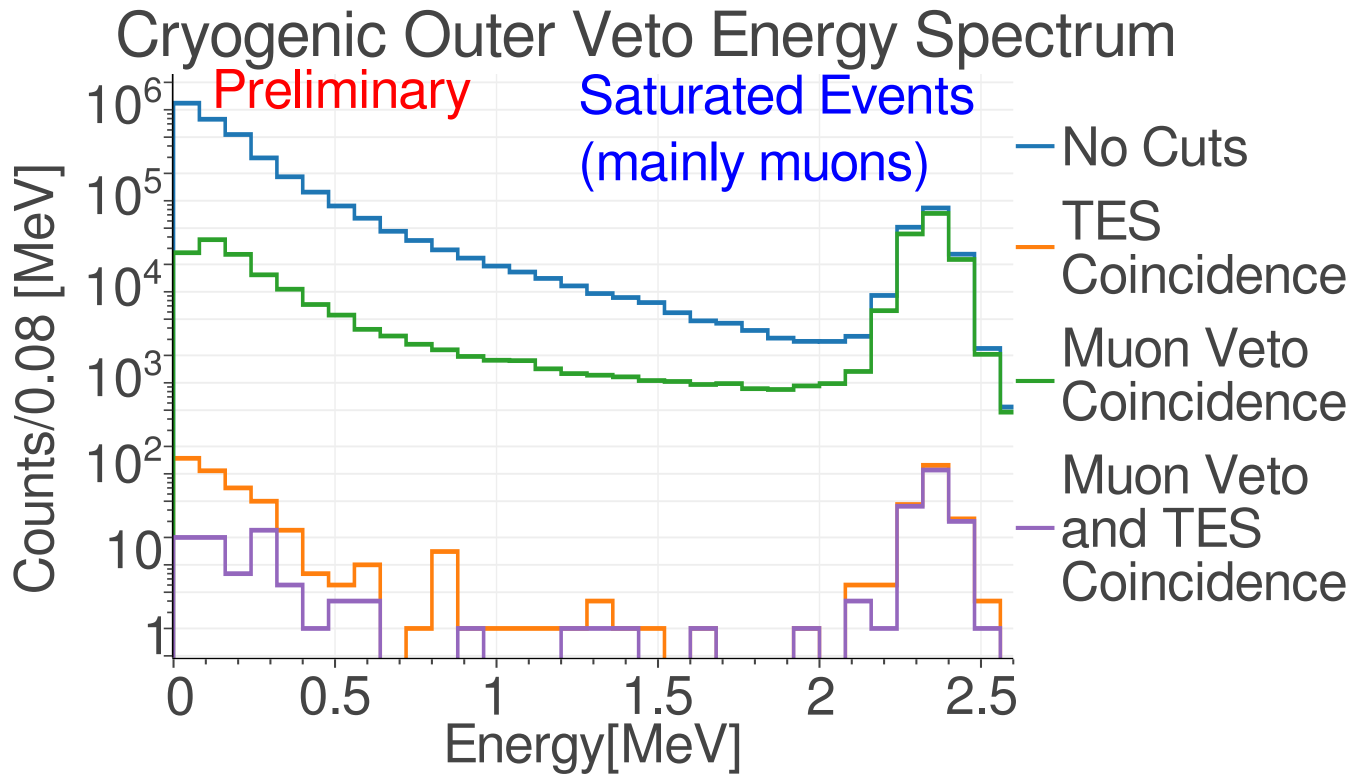
- Neutrino flux: $\phi = 1.7 \times 10^{12}$ cm^{-2} s^{-1}
- 10-g $CaWO_4$ + Al_2O_3 with TES readout (heat only)
- Ultra low threshold: O(10 eV)
- Insensitive to quenching

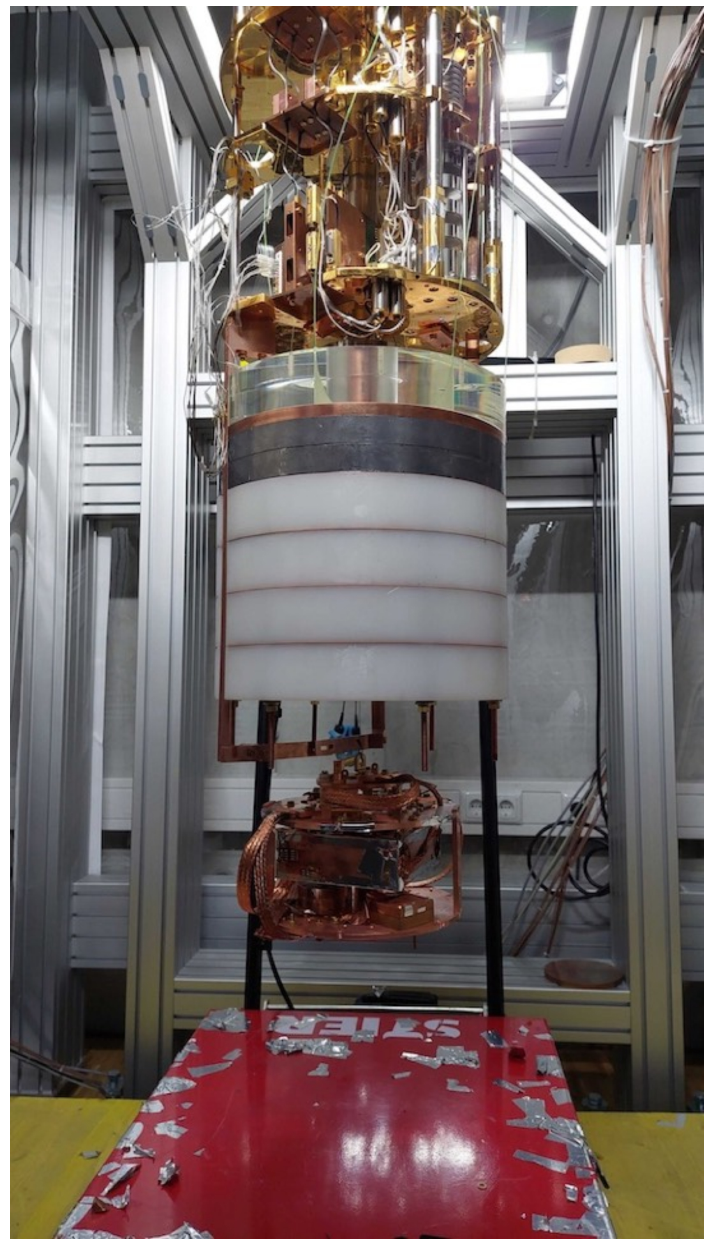
Commissioning at Munich





First operation of target det. with vetoes





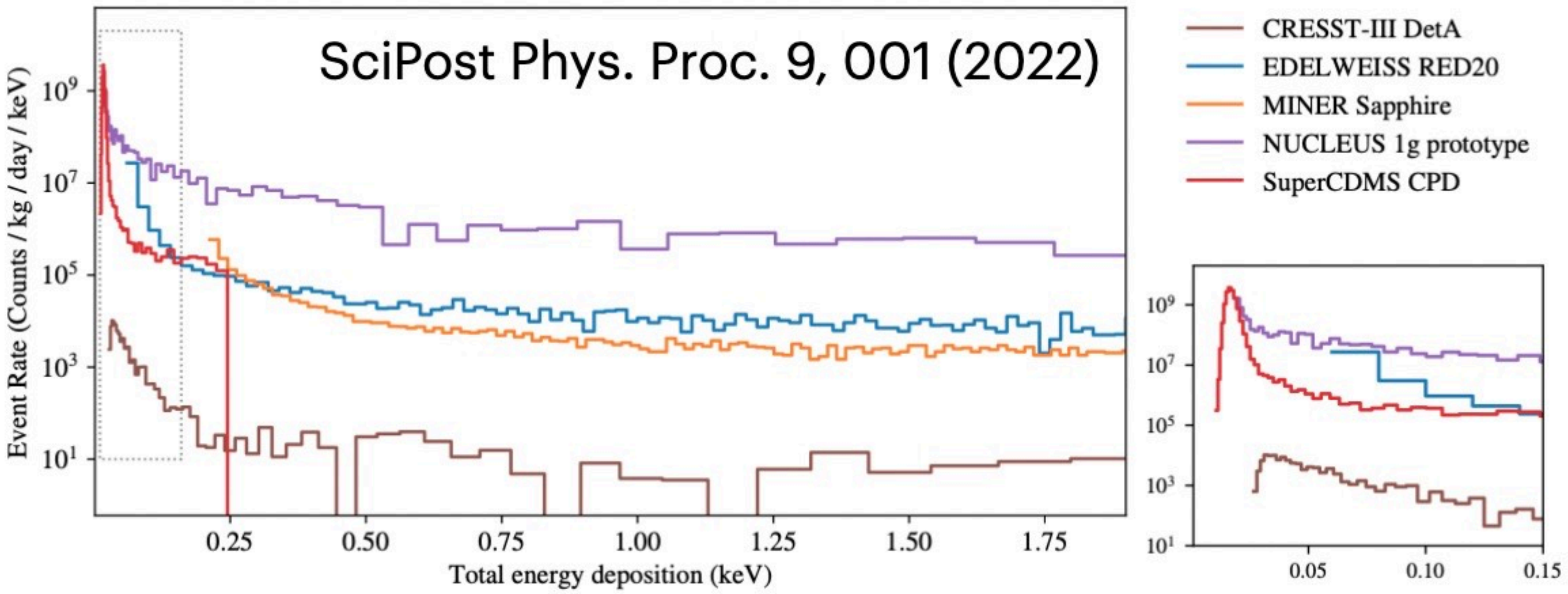
Status

- External shieldings fully operational
- Commissioning of a light detector version on-going at TUM → first data by end of this year
  - Background validation
  - Low energy excess investigation and mitigation
- Relocation to Chooz planned early 2025

Bolometric detection

Beating the « Low Energy Excess »…

- Many low-threshold (cryogenic) detector experiments observe rising event rates of yet unknown origin below a few hundreds eV and above particle-background expectations…
- Significant impact on CEvNS sensitivity



Bolometric detection

Beating the « Low Energy Excess »…

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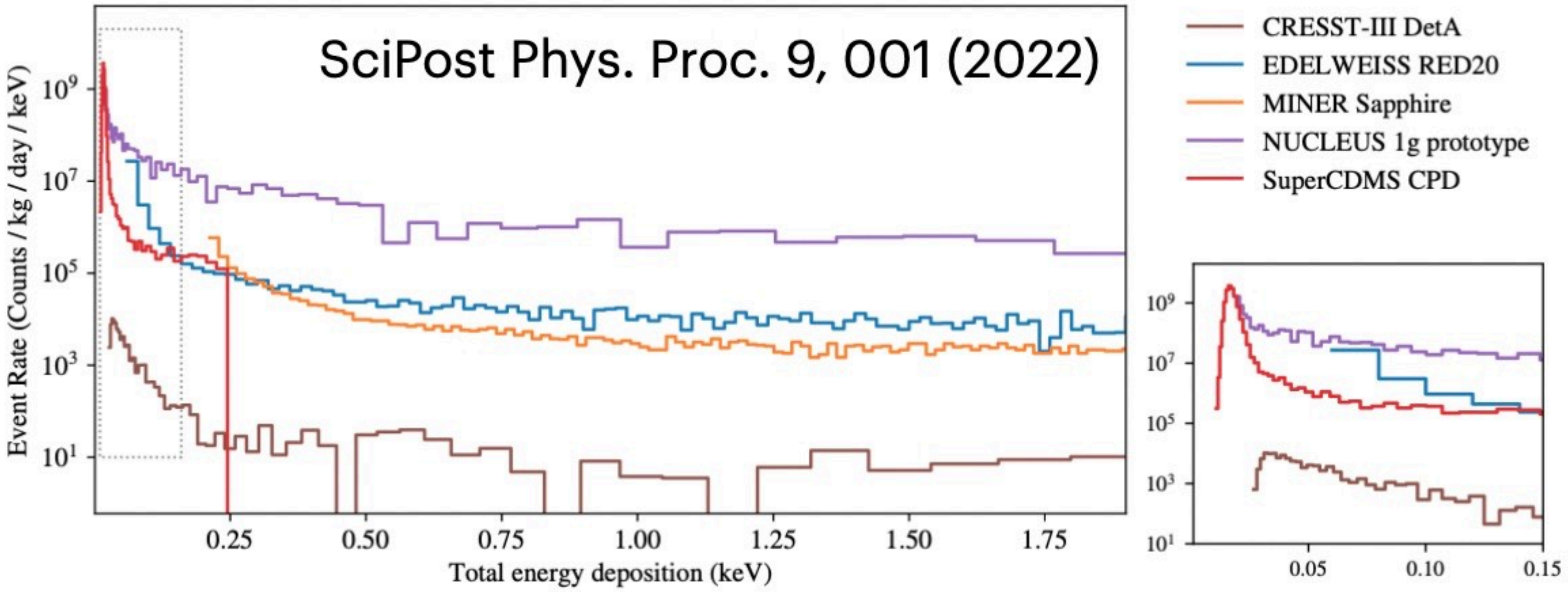
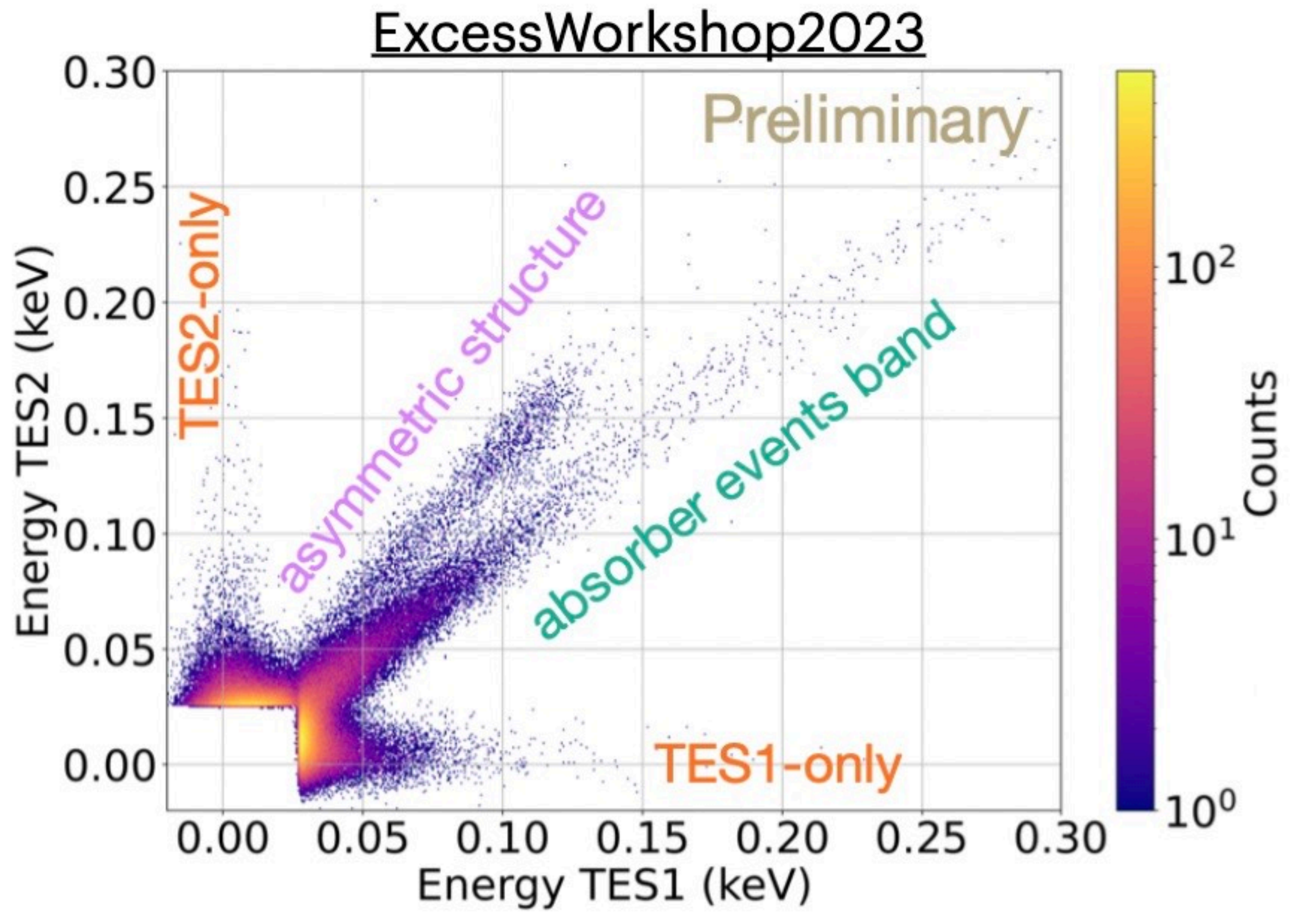
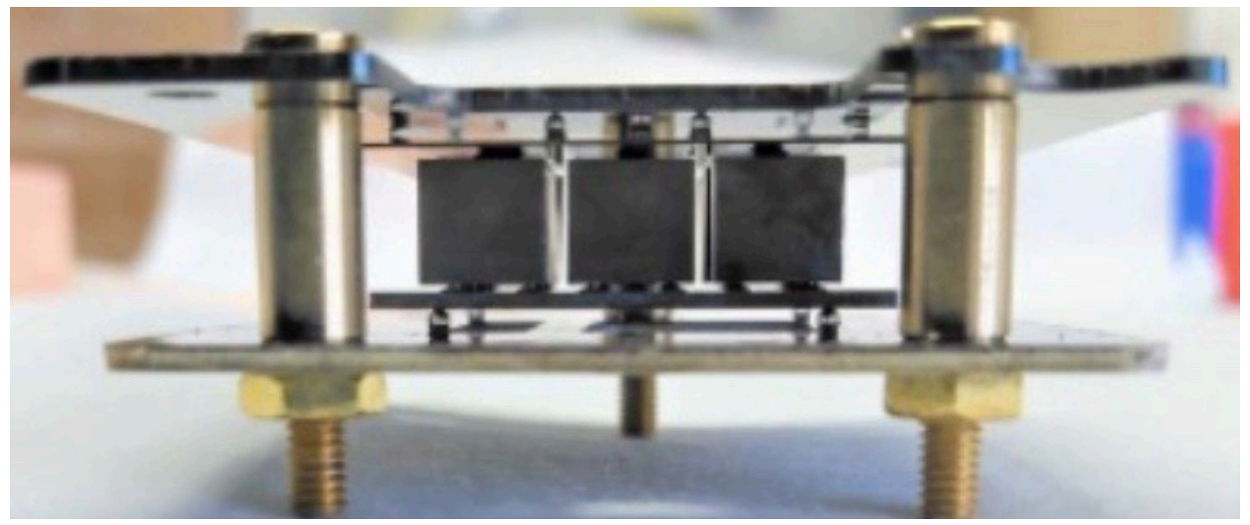
- Significant impact on CEvNS sensitivity
- Many ideas to investigate and mitigate it



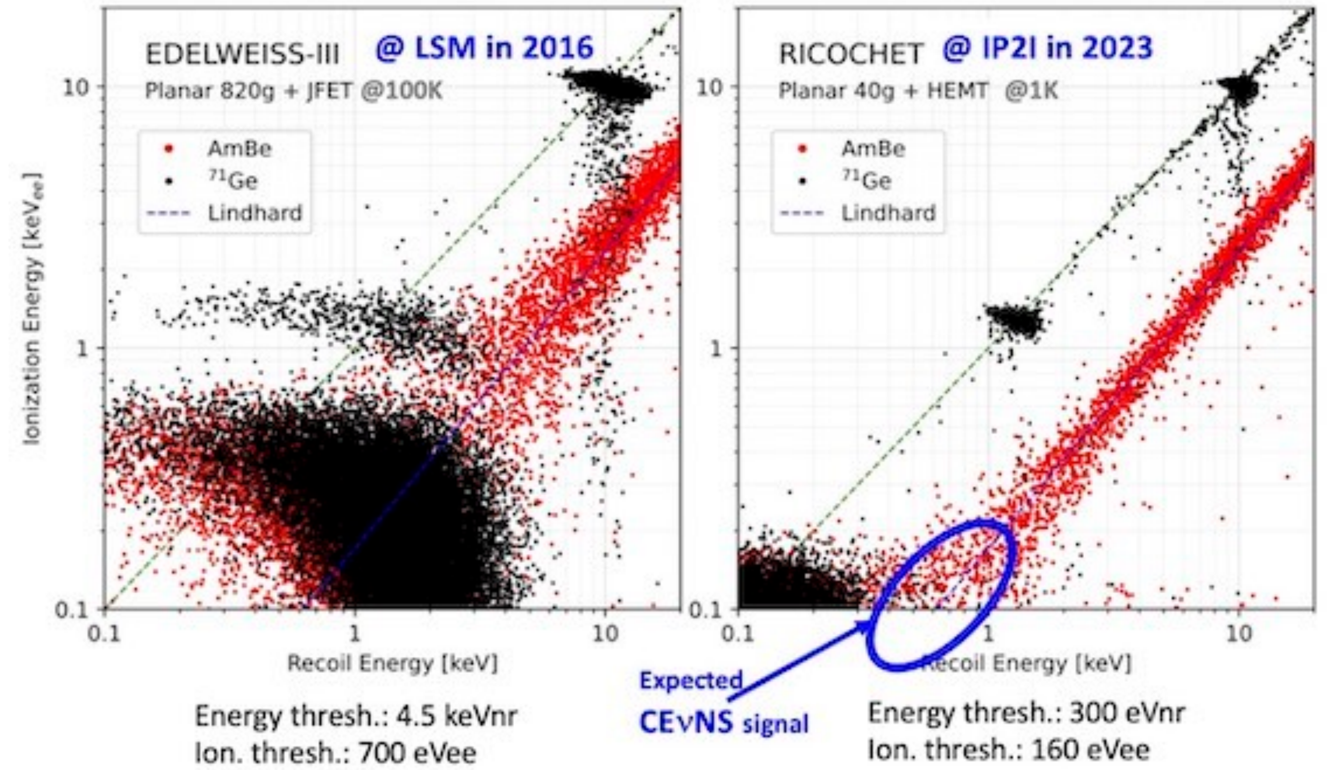
Double-TES readout (e.g NUCLEUS)



Instrumented holders (e.g CRESST)

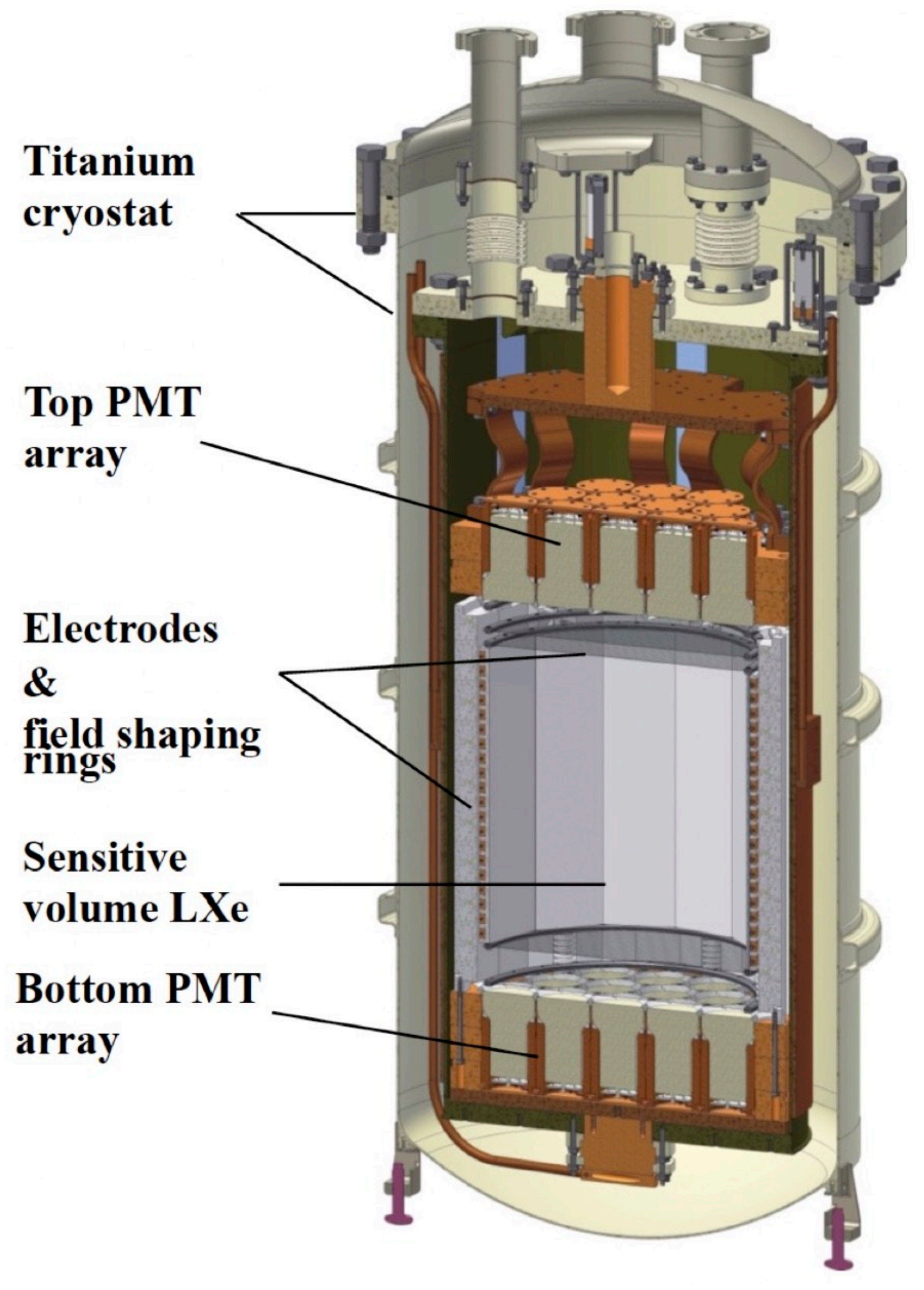


Pushing down ionization det. th. (e.g. Ricochet)

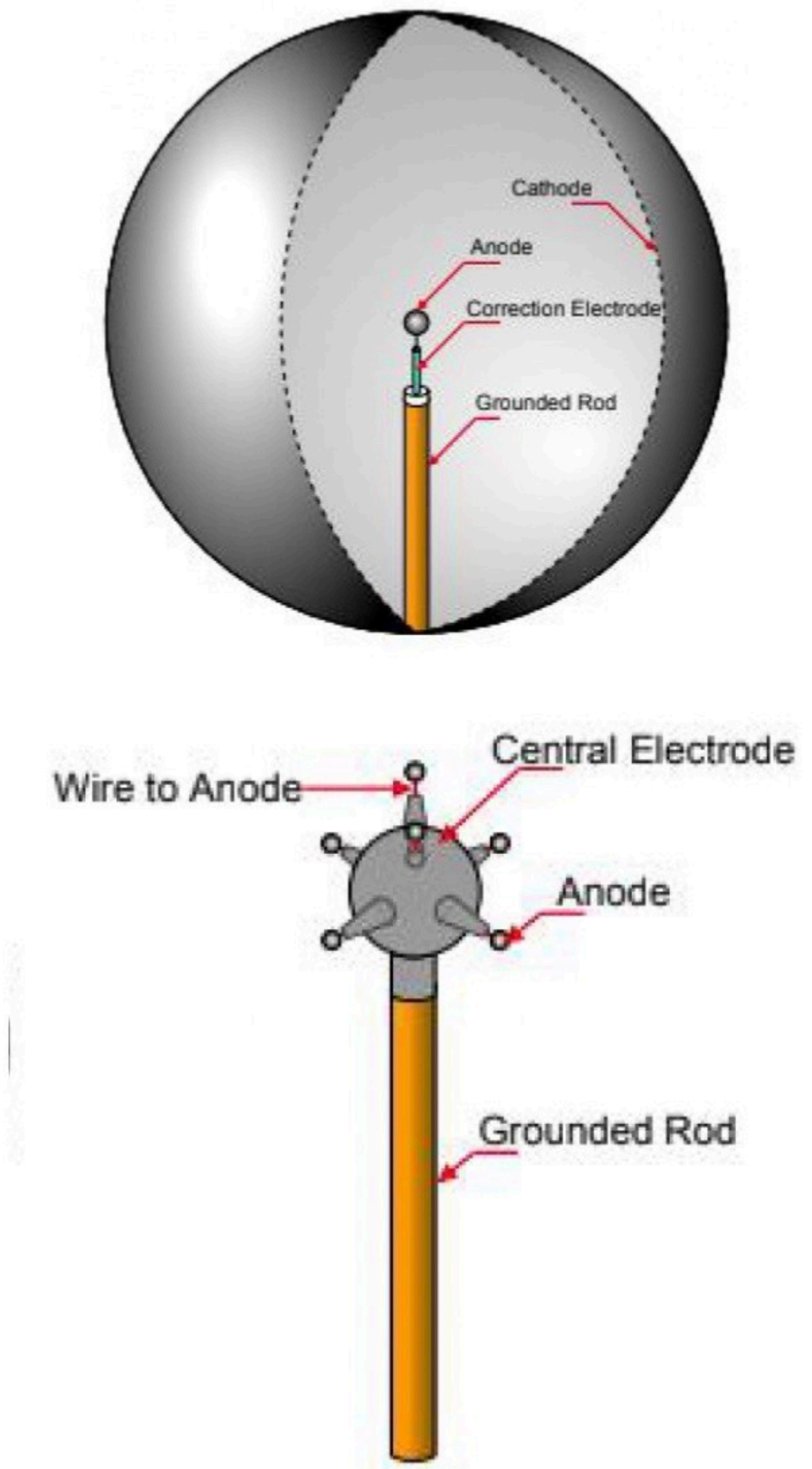


Other experimental efforts…

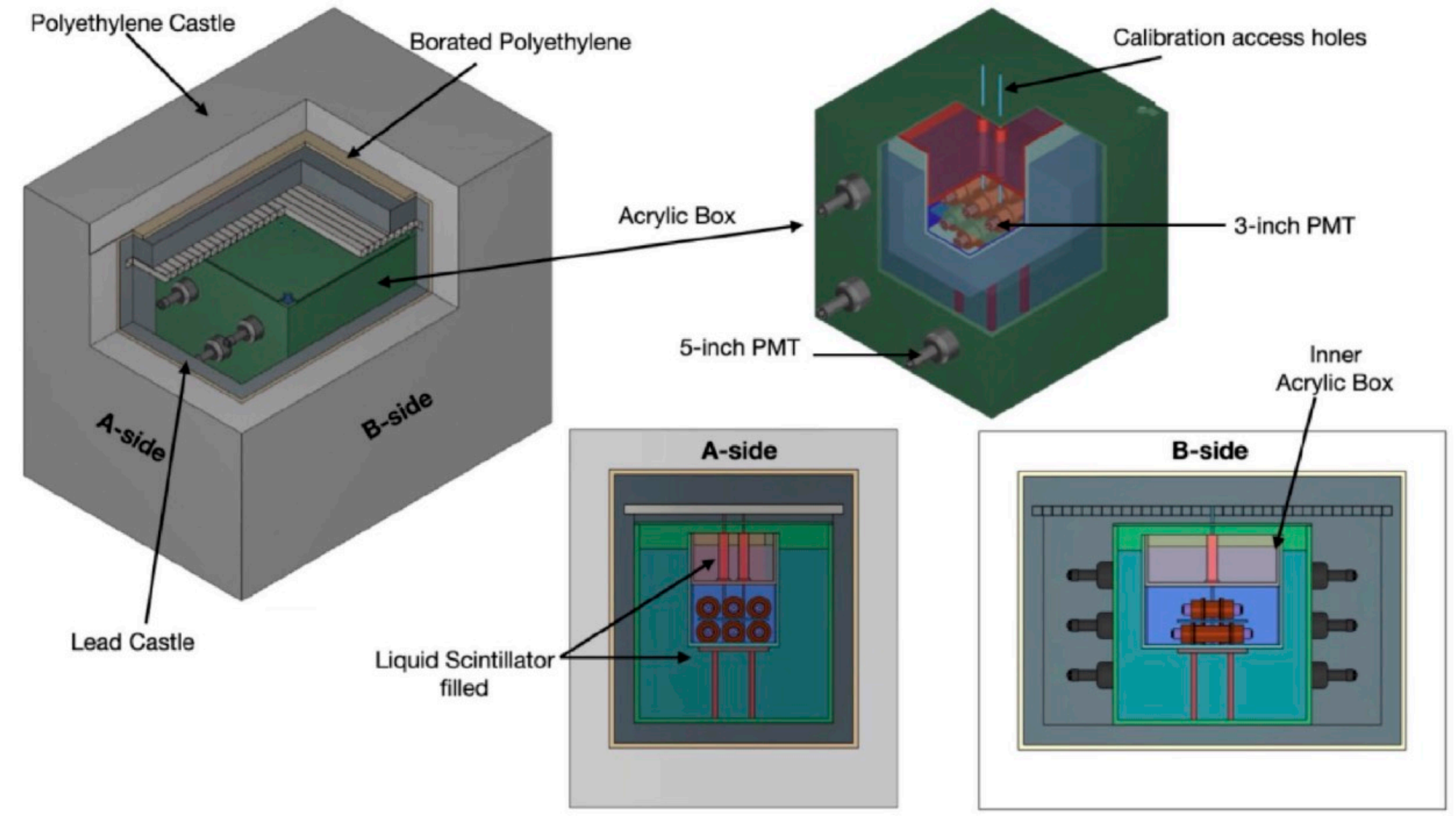
RED-100 @ Kalinin (Russia)
Dual phase noble liquid TPC
Successful data run with Xe, moving to Ar



NEWS-G³
Spherical proportional counter



NEON
Low-treshold NaI (17 kg) @ Hanbit (Korea)
Data taking on-going, probably some results soon



+ many more:
- SBC (Scintillating Bubble Chamber)
- RELICS (LXE TPC)
- BULLKID (Kinectic inductance detectors)
- …

Summary

- CEvNS is a **blooming field in neutrino physics**: new probe for BSM physics at the very low energy frontier, applications in nuclear physics, astrophysics and the long range detection of neutrinos (long-term future)
- A **huge variety of detection techniques**, mostly steaming from the DM community, are investigated
- At present, first detection at reactors remains to be done
  - Nuclear reactor environments very challenging !
  - Needs **background, threshold & mass**: currently no experiments fully demonstrated these three requirements together
  - CONUS (4-kg Ge) currently the closest to detection: factor 2 missing

Magnificent CEvNS workshop (2023, Munich)

Mag7s 2024 workshop next week in Valencia, probably new exciting results to come !