

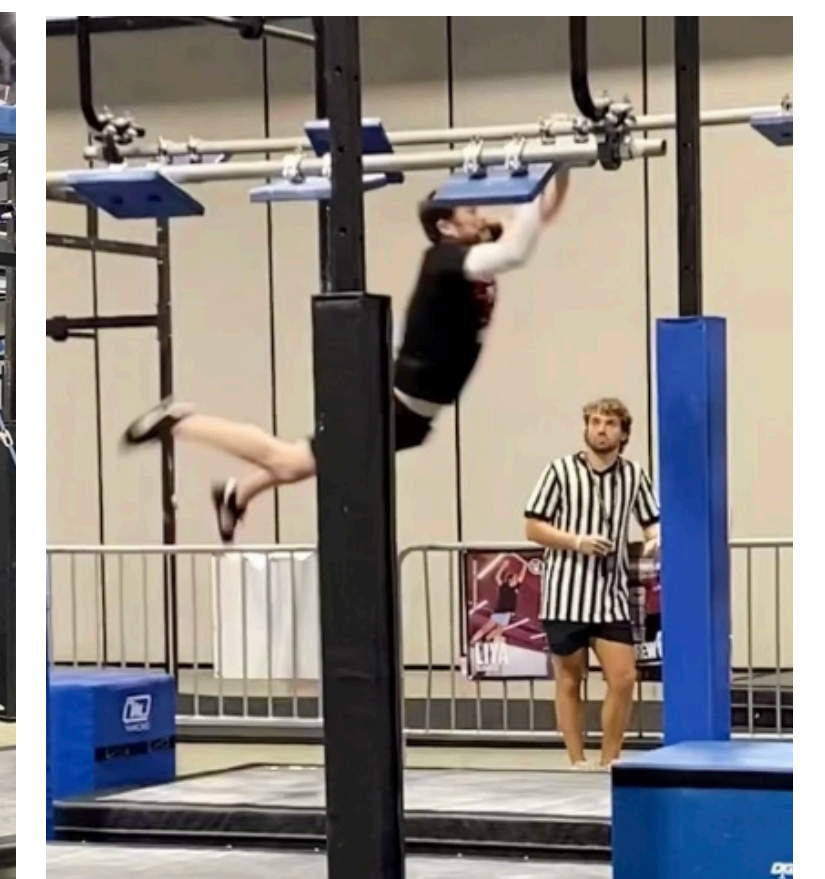
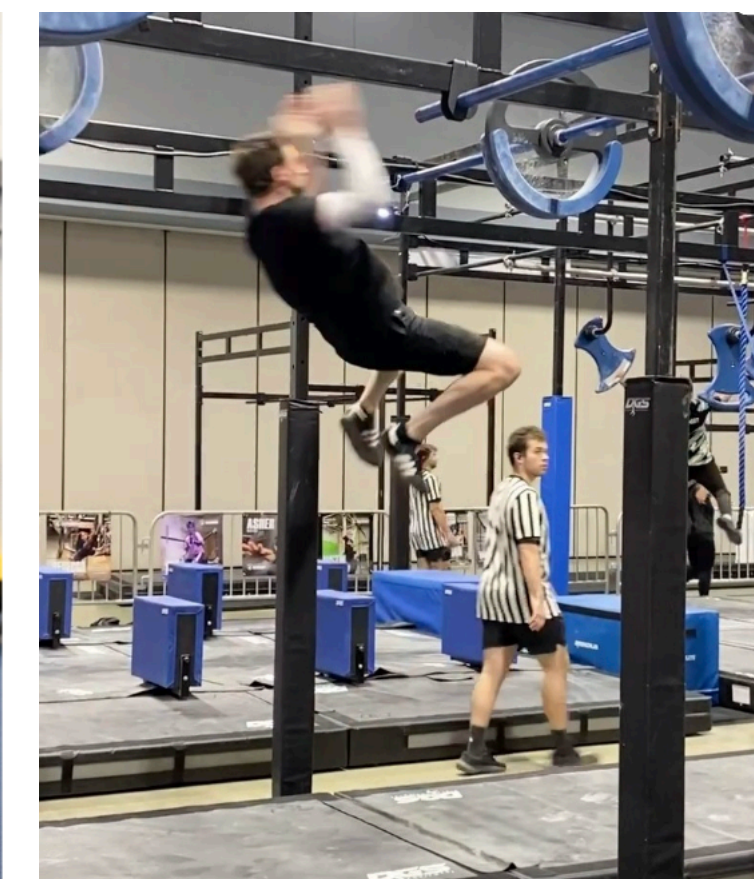
Threshold-less Neutrino Detection

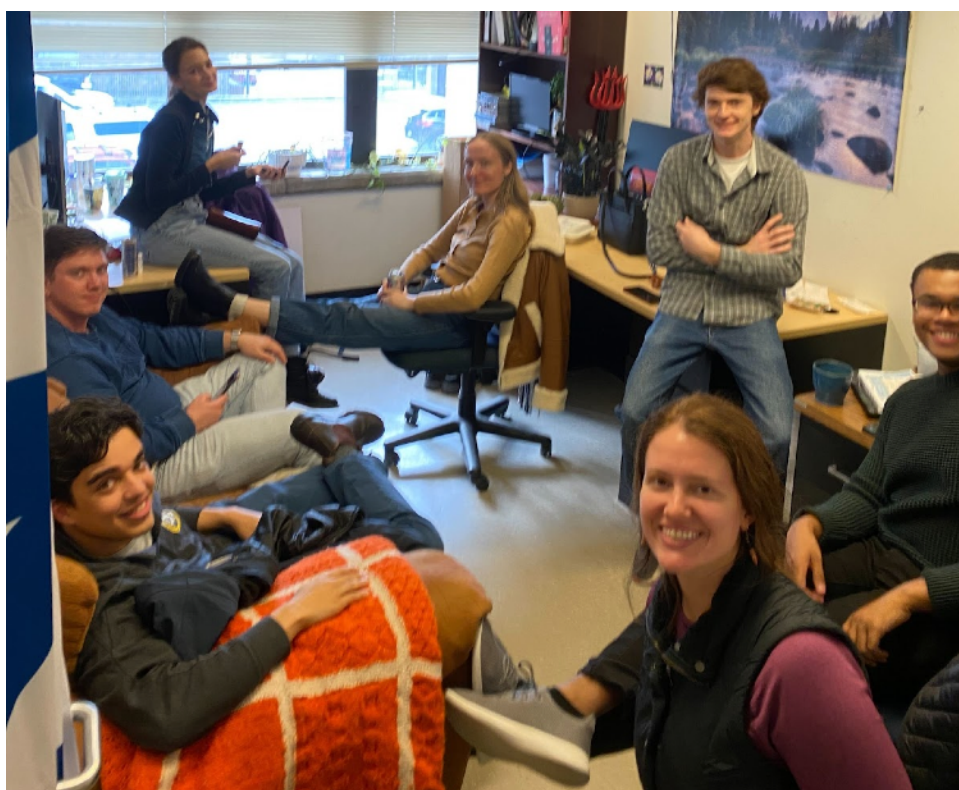
2026 Neutrino Summer School

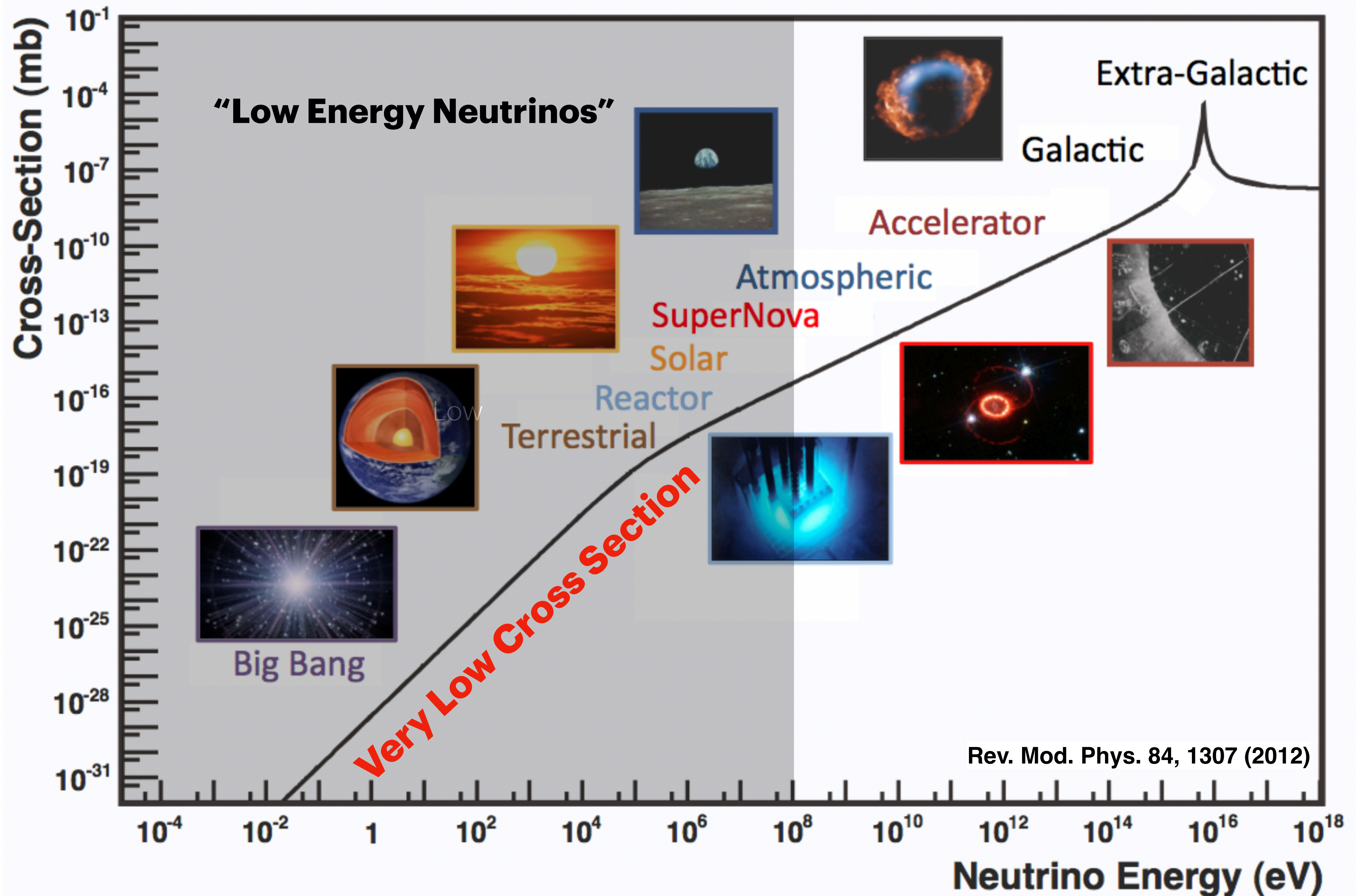
About Me

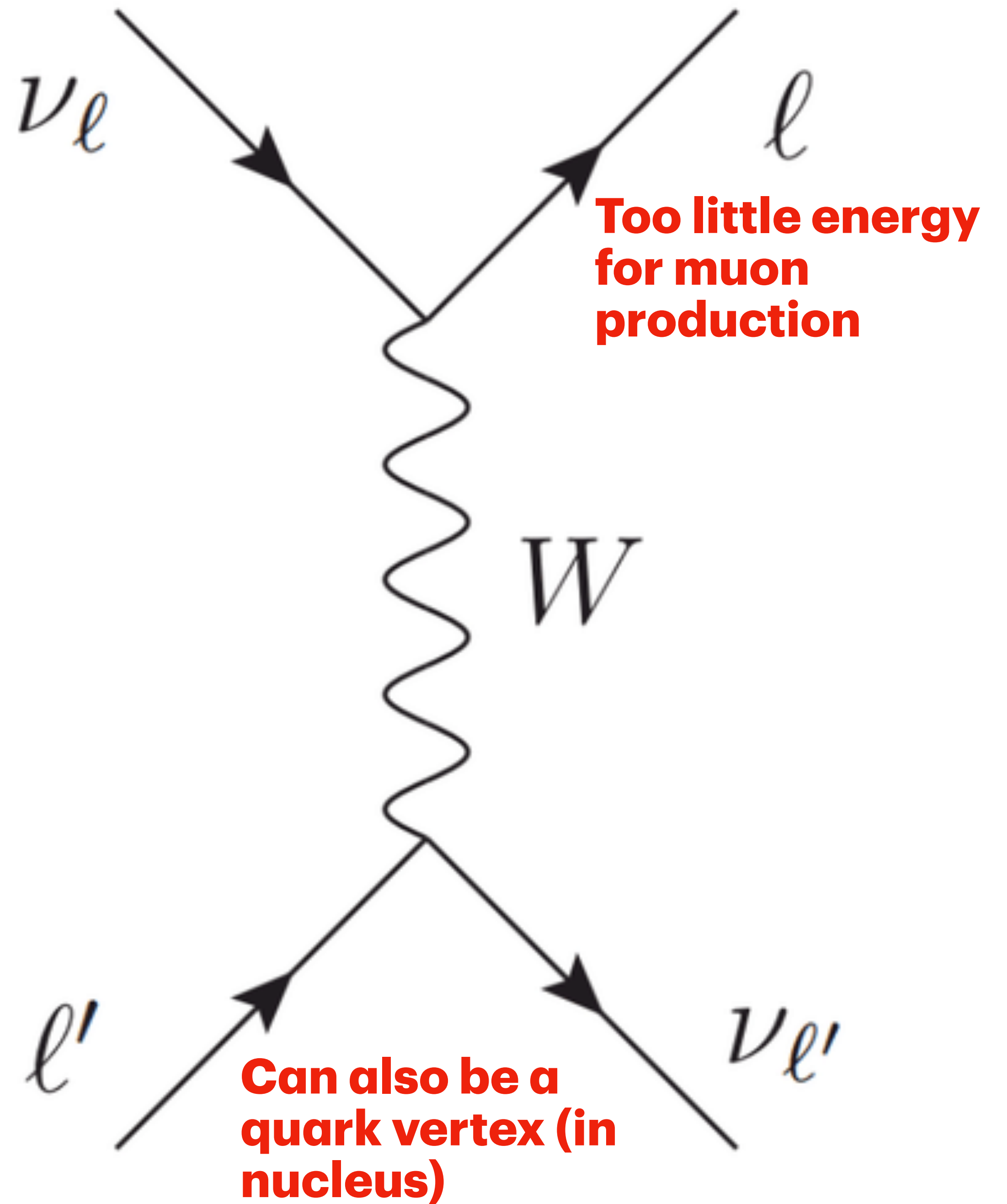
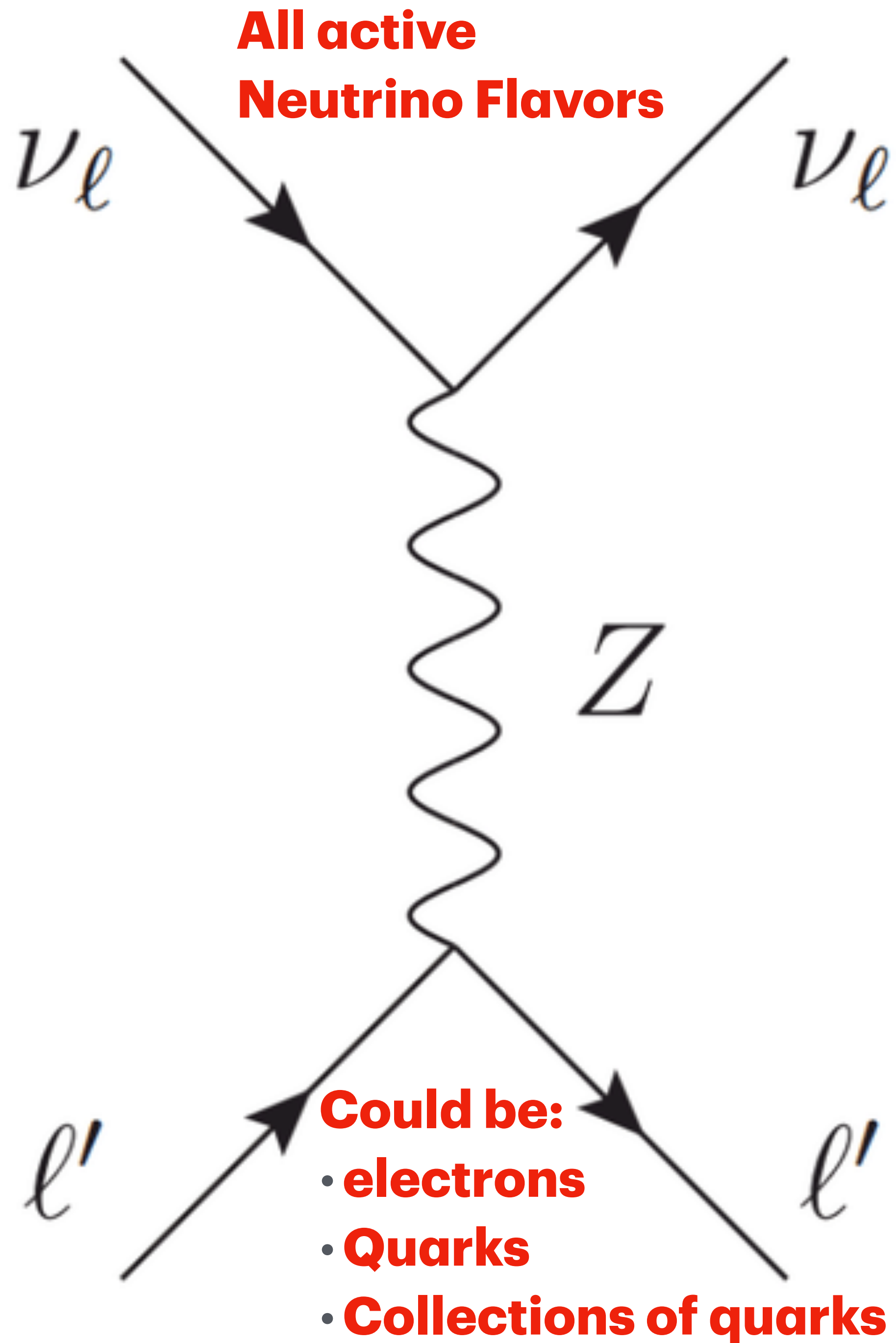


- Grew up in Chicago
- Undergrad and Grad at University of Chicago
 - Balloon Borne Cosmic Ray Detection with Dietrich Muller and Simon Swordy (TRACER) - UG
 - Neutrino and Dark Matter with Juan Collar (COGENT, COHONUDO, Majorana Demonstrator) - Grad
- Postdoc with Giorgio Gratta at Stanford on EXO-200 Neutrinoless Double Beta Decay
- Faculty at Duke
 - CEvNS (COHERENT)
 - Formerly Double Beta Decay (nEXO, LEGEND-200/1000)
 - Ultra-High Energy Neutrino Detection (P-One)
 - Dark Matter Detector Calibration (LUX/LZ, SuperCDMS, ANAIS, COSINE, NEW-G, etc.)
- Climber (and Faller)
- Obstacle Course Racing (Ninja Warrior)







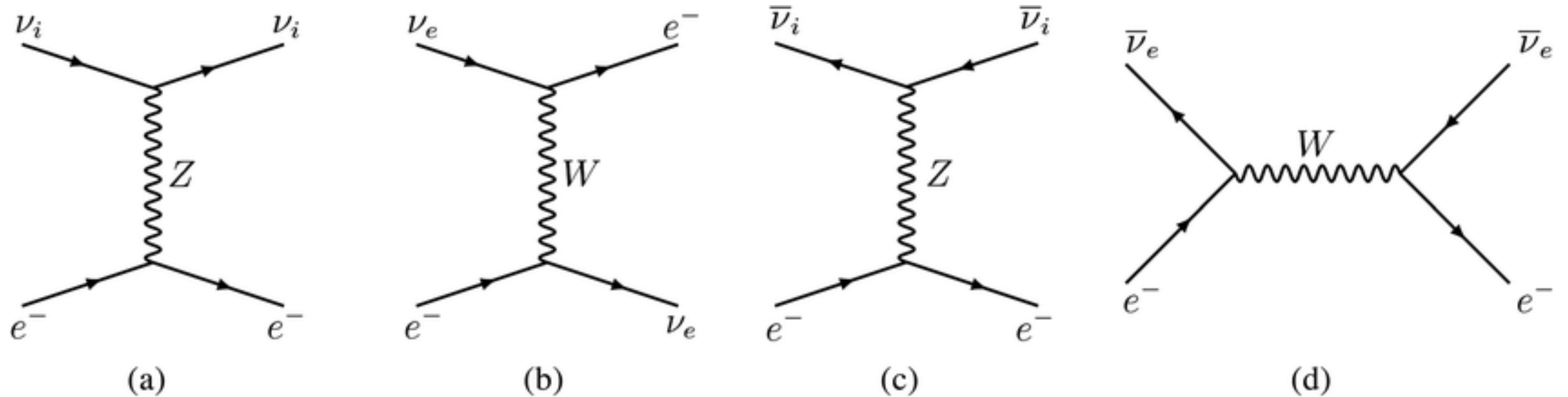


Signatures challenging to detect

- Start with *Thresholdless*
 - Neutrino-electron Elastic Scattering
 - Coherent ^{Low} **Elastic** Neutrino-Nucleus Scattering (CEvNS)
 - Neutrino Capture on **radioactive** Nuclei
- Next Lecture: Low-Threshold Neutrino Detection
 - Neutrino Capture on **stable** nuclei
 - Neutral Current **Inelastic** Scattering

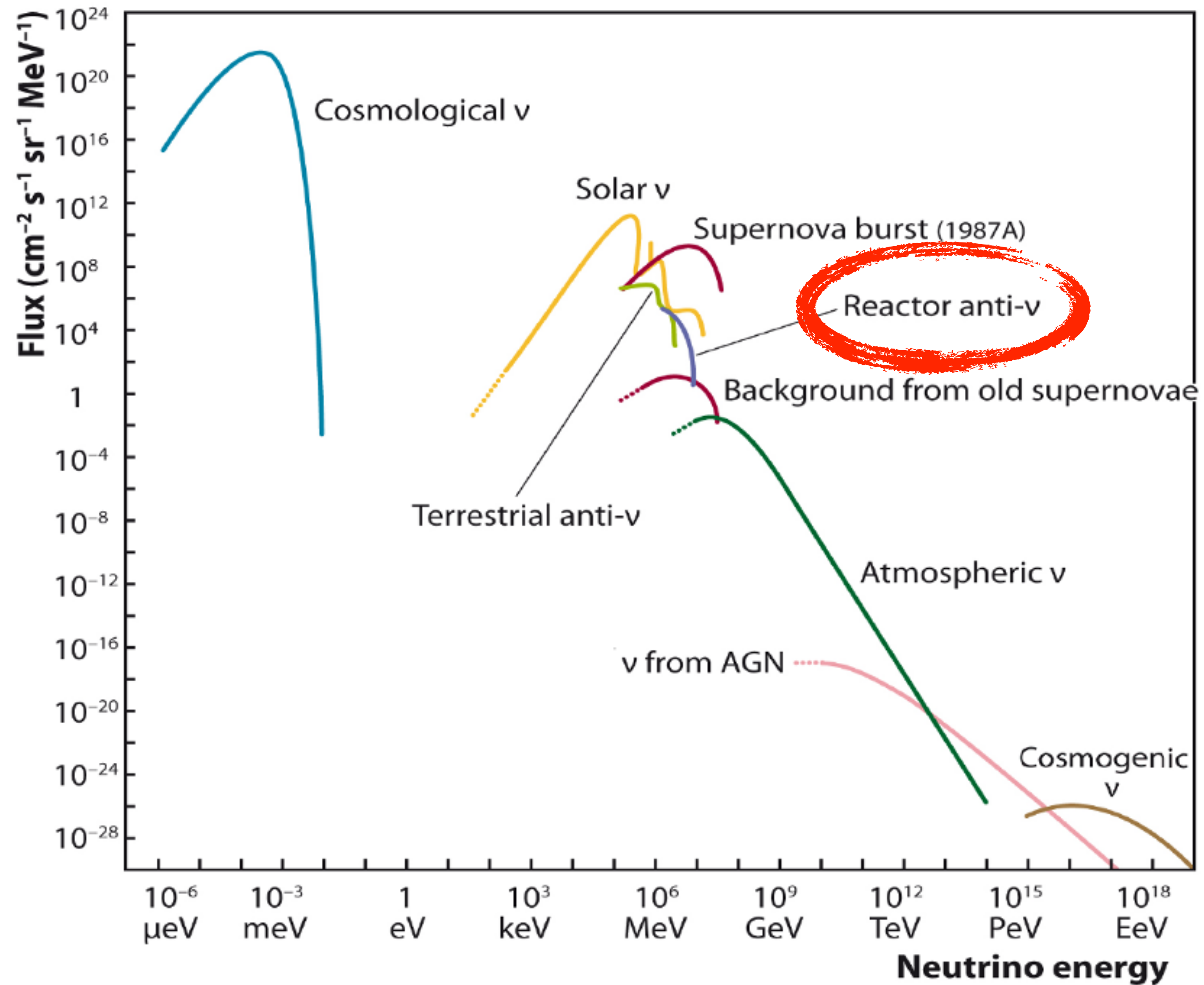
Neutrino Electron Elastic Scattering

Lowest order



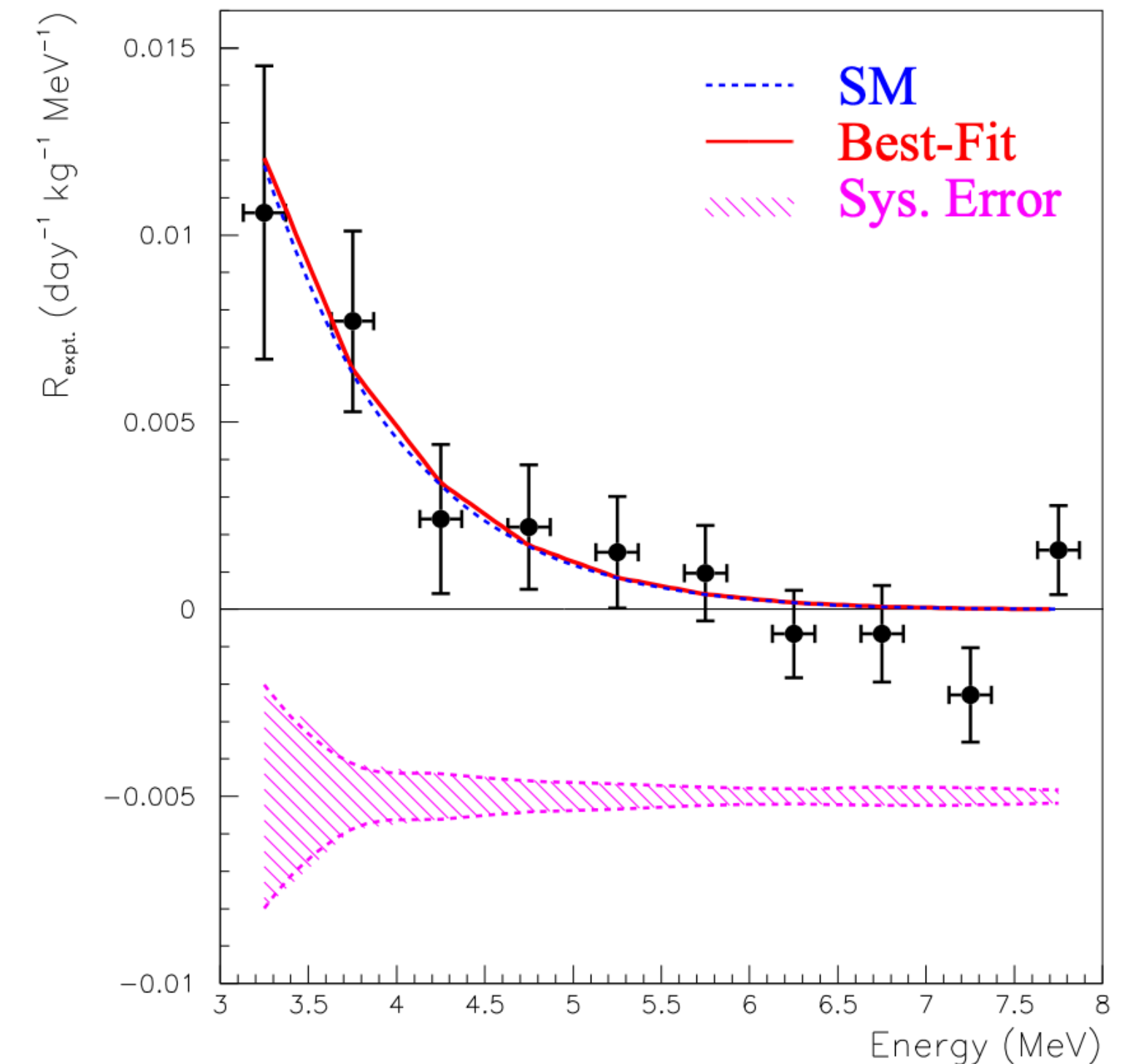
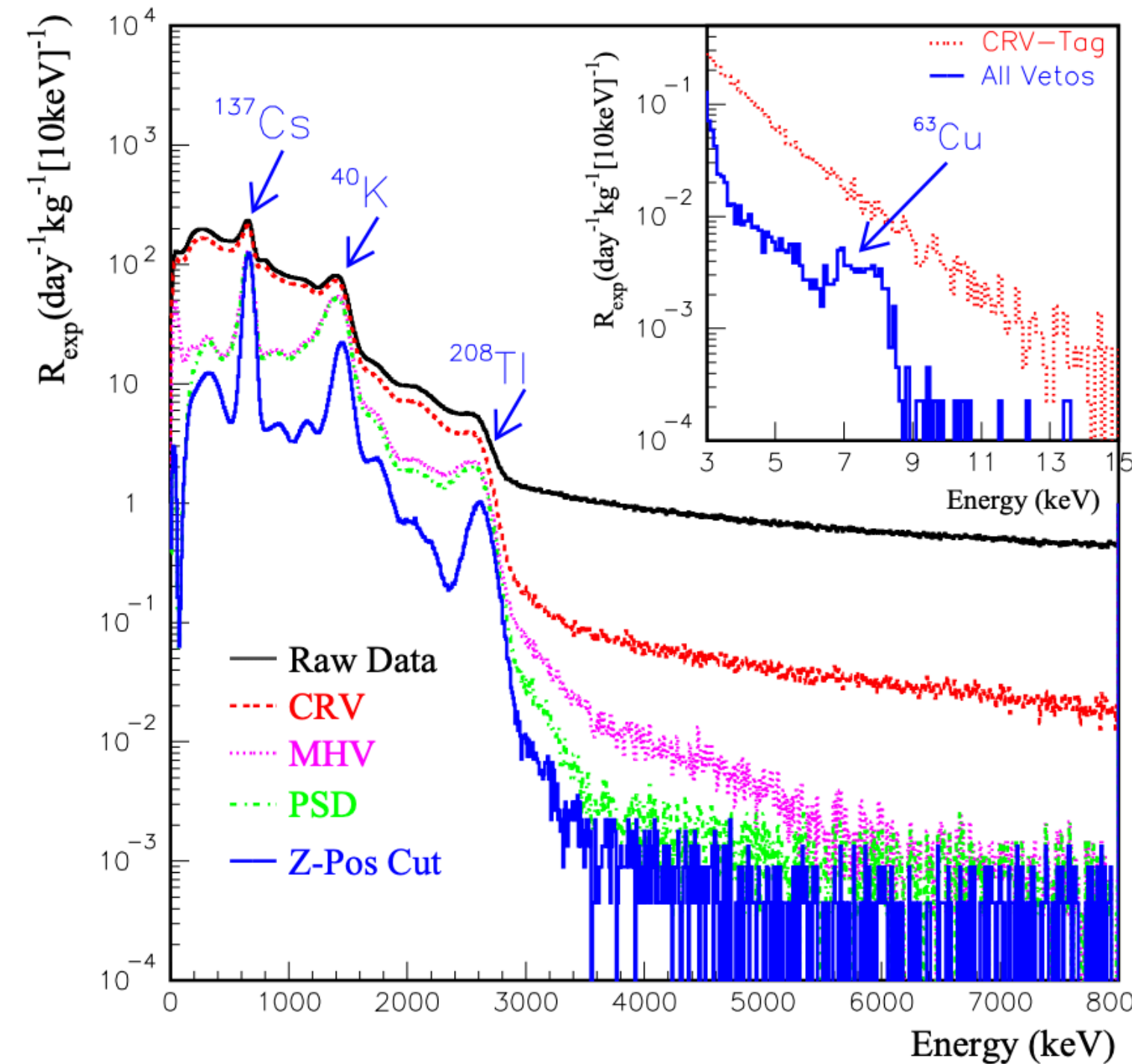
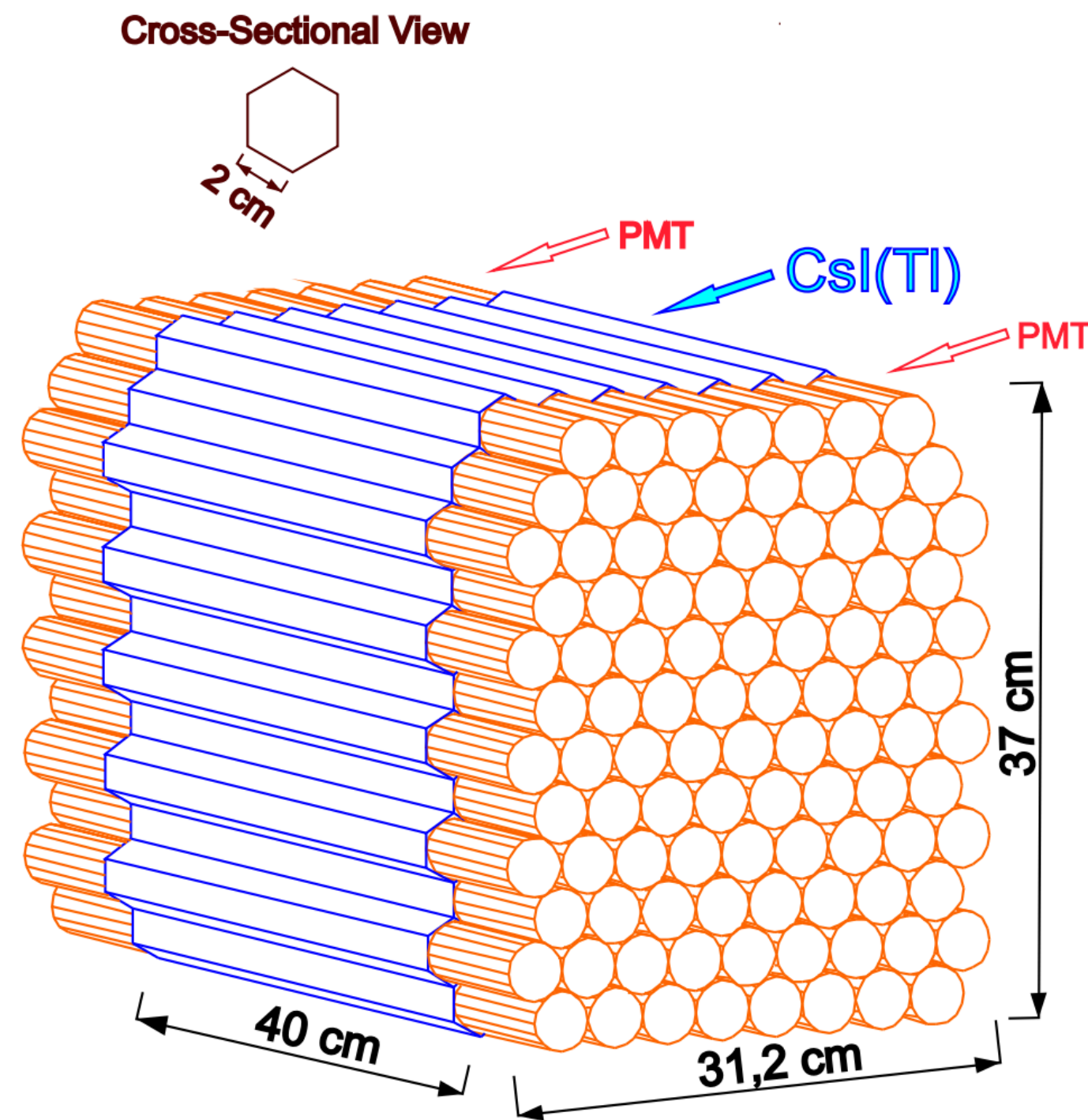
- For Low energies, nothing notable, except a recoiling electron
- Note: not actually zero threshold for most electrons: electron has binding energy in atom

Some Neutrino Sources



Neutrino Electron Elastic Scattering

TEXONO CsI[Na] at Kuo-Sheng Nuclear Reactor

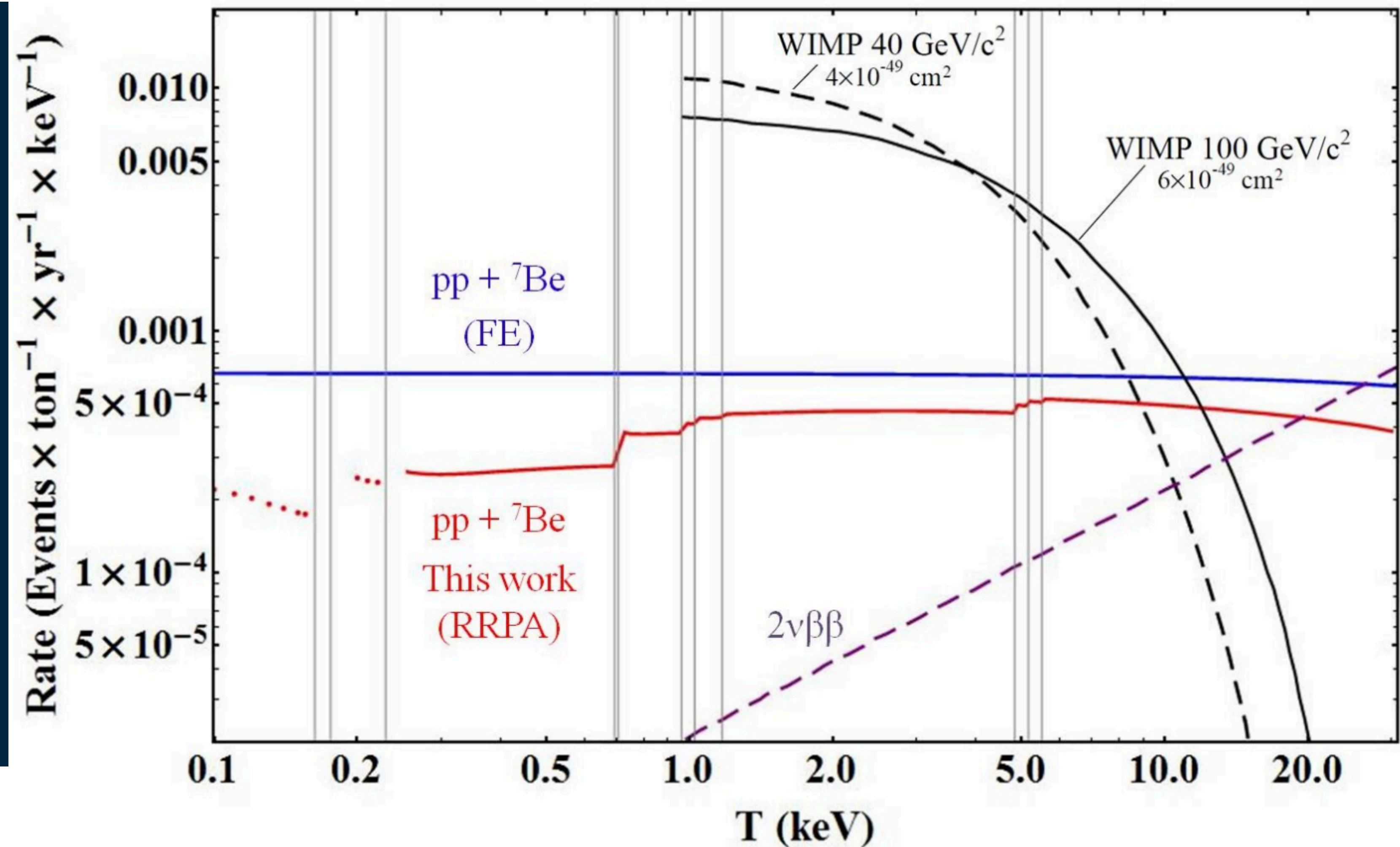
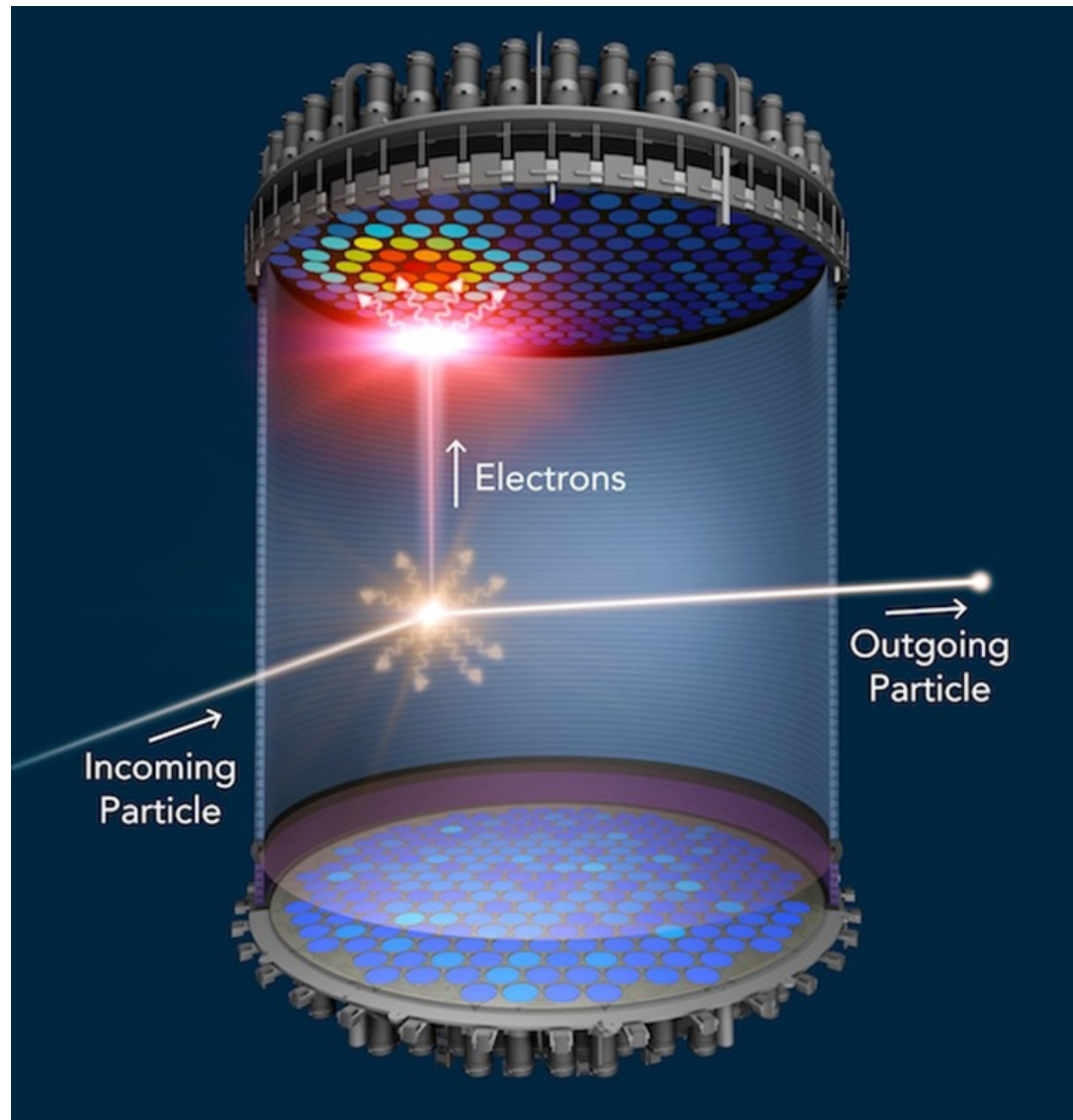


- Find copious neutrino source (reactor)
- Deploy low background crystals (Purified CsI[Na])
- Shield it like crazy
- Measure weak mixing angle
- Consistent with destructive interference

Neutrino Electron Elastic Scattering

Xenon Dark Matter Detectors

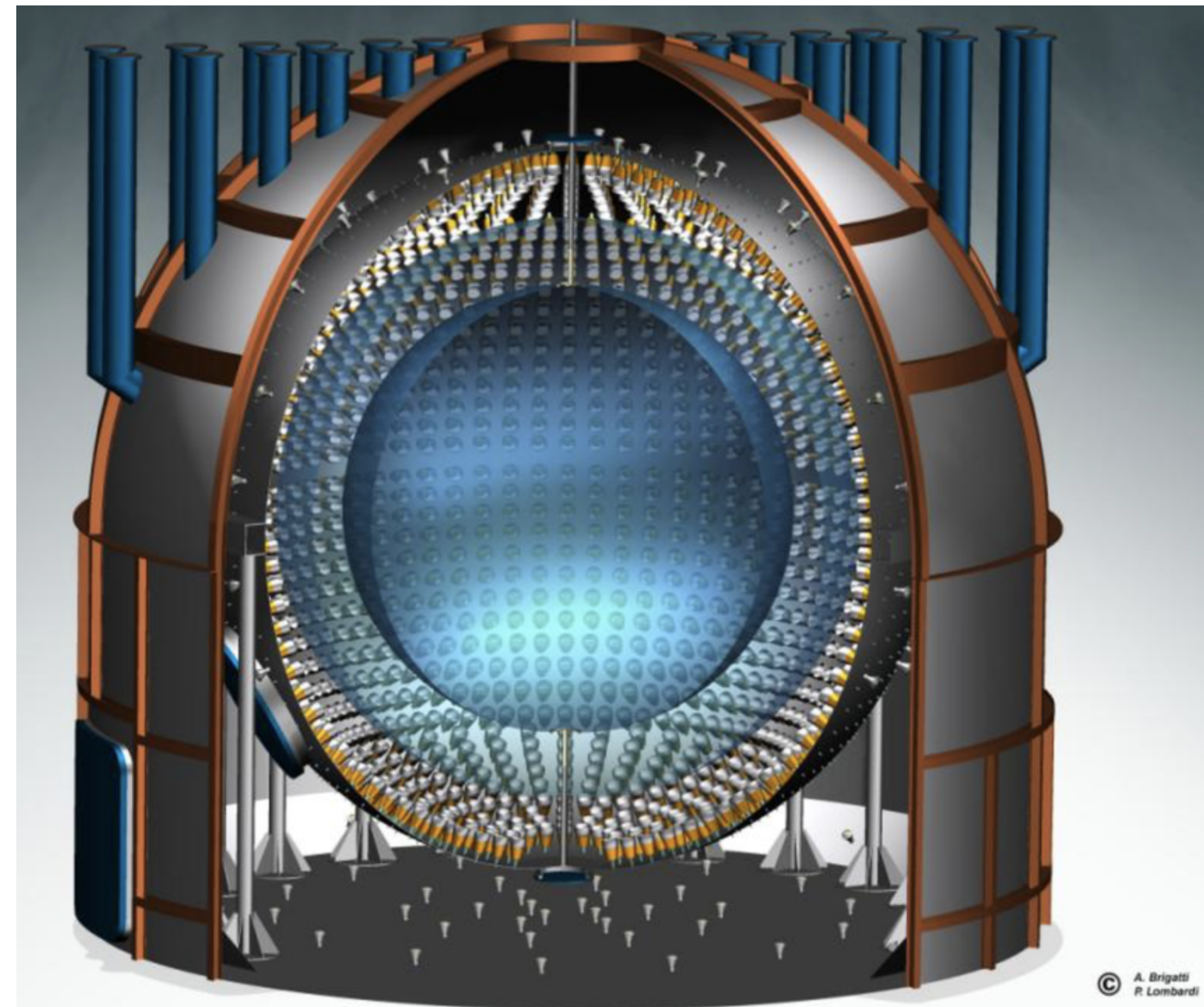
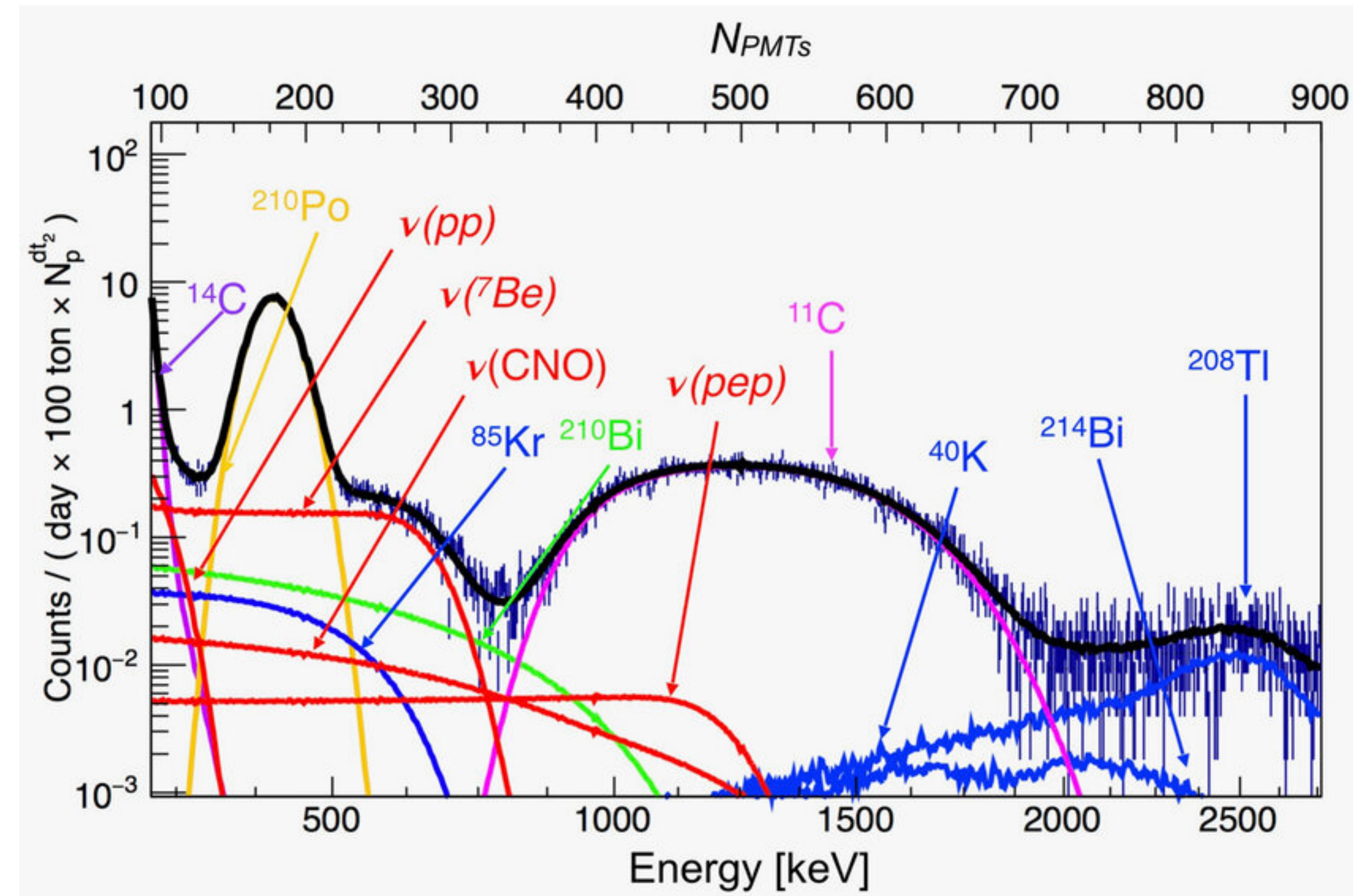
Not Quite Zero-Threshold!



Neutrino Electron Elastic Scattering

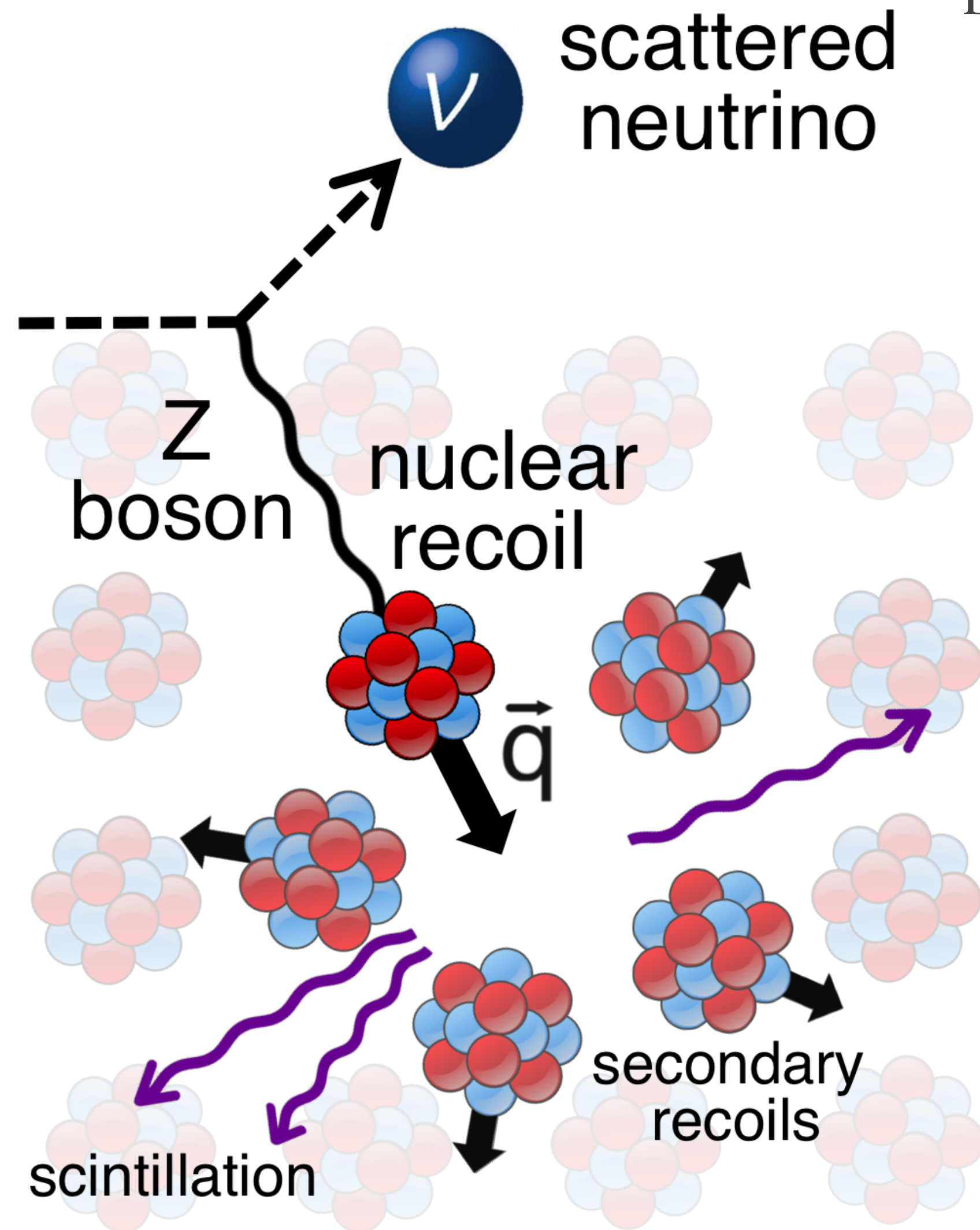
Borexino Observatory

**Excruciating control of backgrounds
in 278 tons of pseudocumene**



Coherent Elastic Neutrino-Nucleus Scattering

D. Z. Freedman, PRD 9 (5) 1974



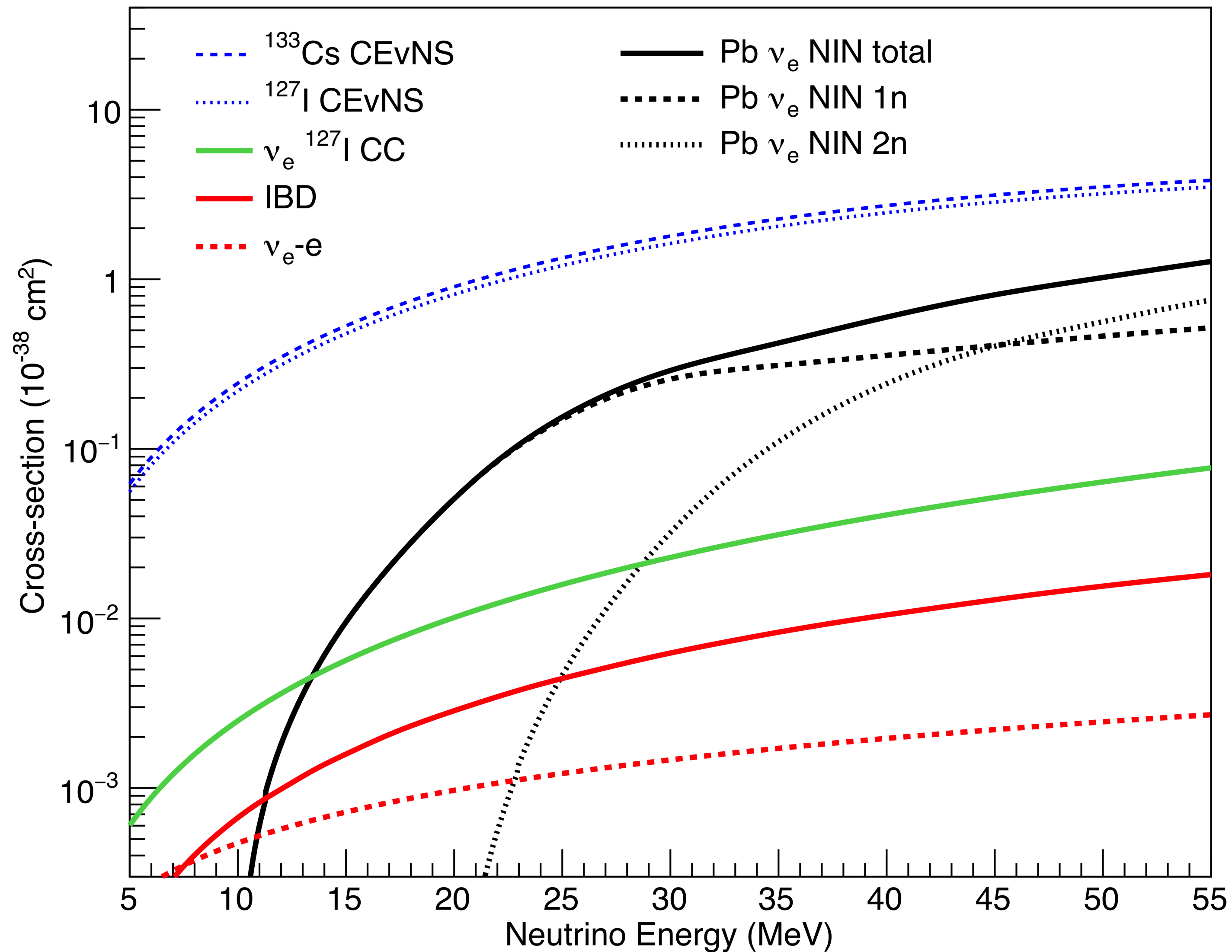
Nucleons Recoil in phase:

$$\sigma \propto (\mathbf{N} \cdot \boldsymbol{\Psi})^2$$

$$\Psi_i = \Psi_f$$

signature: ~ keV recoil

Coherent Elastic Neutrino-Nucleus Scattering



$$\sigma \propto E^2$$

As $E \rightarrow 100$'s MeV

$$\sigma \rightarrow (N \cdot \Psi)^{4/3}$$

loss of coherence

The Cross Section

$$\frac{dN_{\text{obs}}}{dE_{ee}} = \left[N_{\text{targets}} \int dE_{\nu} \frac{d\Phi}{dE_{\nu}} \frac{d\sigma}{dE_{\text{NR}}} \right] \otimes \mathcal{R}(E_{\text{NR}}, E_{ee}) + \frac{dN_{\text{bkg}}}{dE_{ee}}$$

$$\frac{d\sigma}{dE_{\text{NR}}} \approx \frac{G_F^2 M}{8\pi} [Z(1 - 4\sin^2\theta_W) - N]^2 \left[1 + \left(1 - \frac{E_{\text{NR}}}{E_{\nu}} \right)^2 - \frac{ME_{\text{NR}}}{E_{\nu}^2} \right] F(E_{\text{NR}})^2 + \text{axial} + \text{NSI}$$

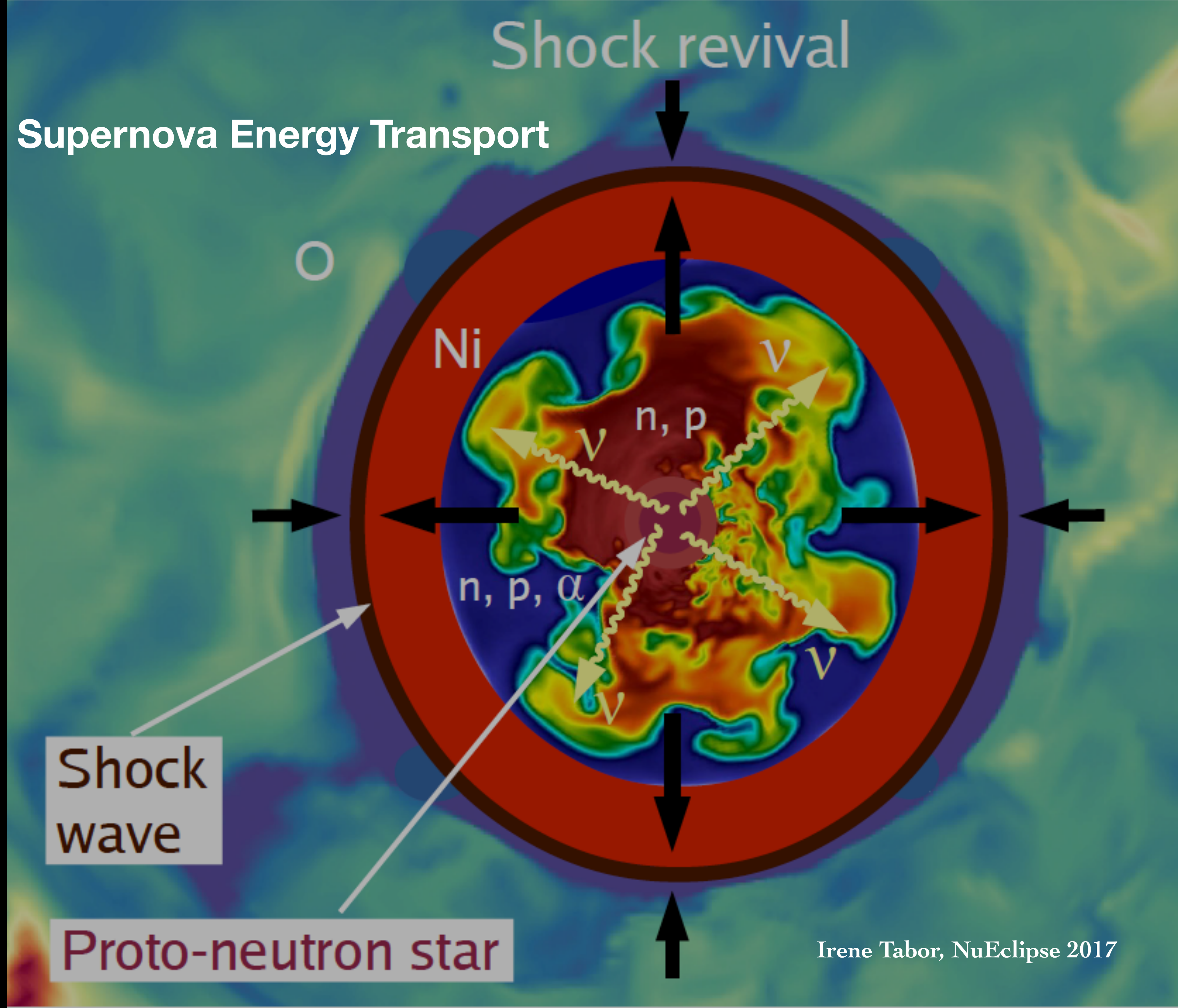
- Electroweak physics
- Nuclear physics
- NSI contributions
- Neutrino source + oscillations
- Detector effects
- Backgrounds

One of the most precisely predicted neutrino cross sections (<1%)

The cross section IS the Physics

Shock revival

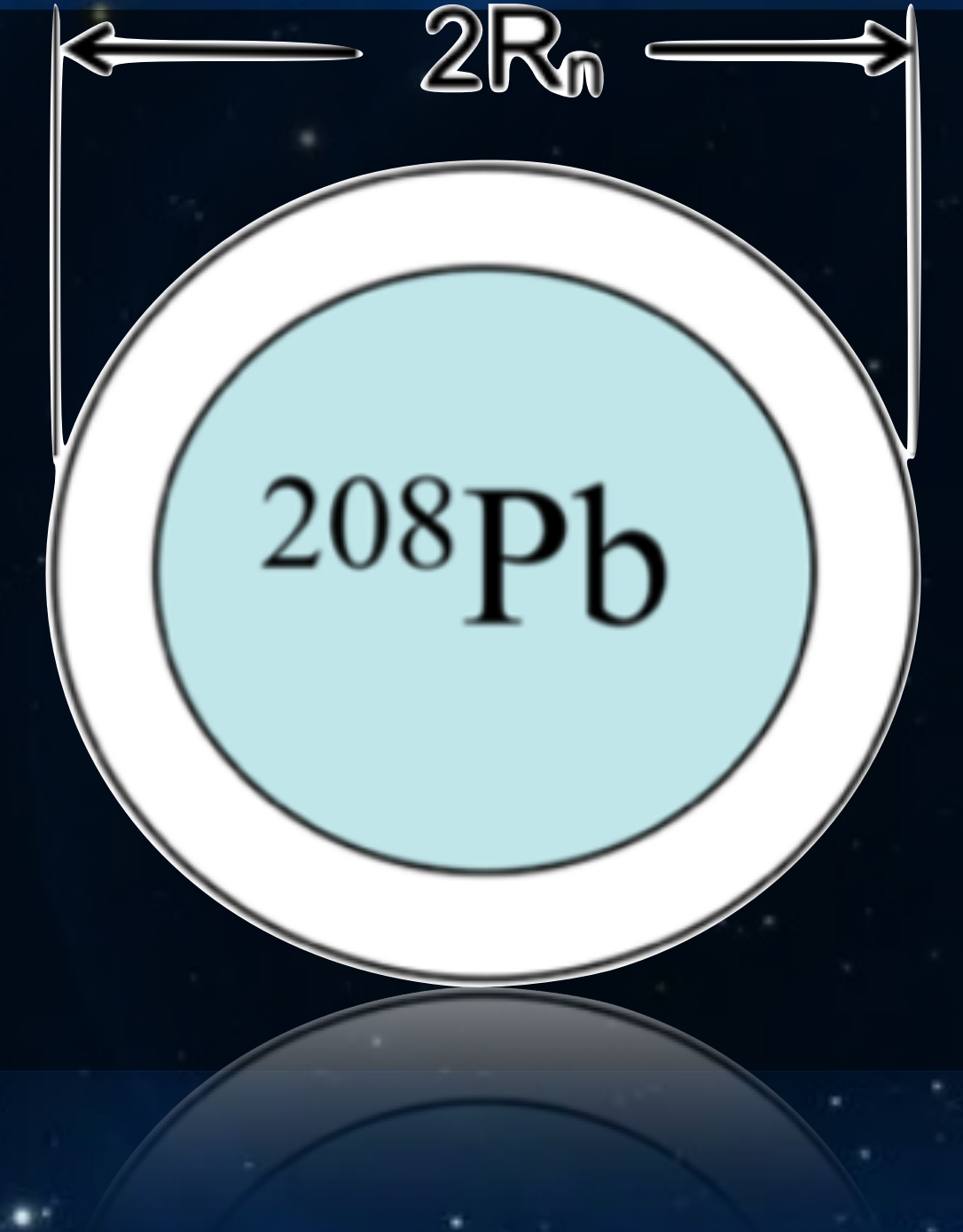
Supernova Energy Transport

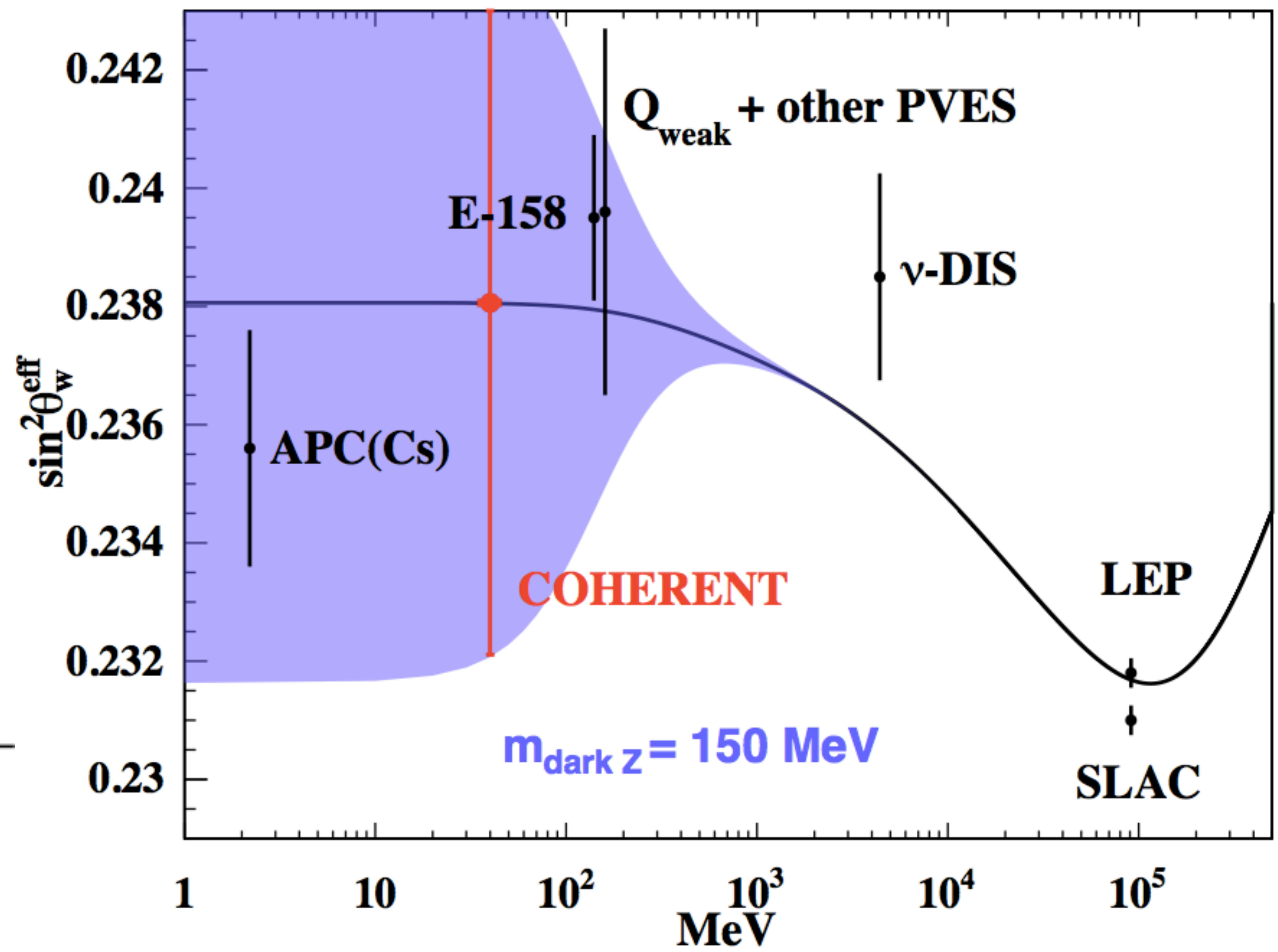
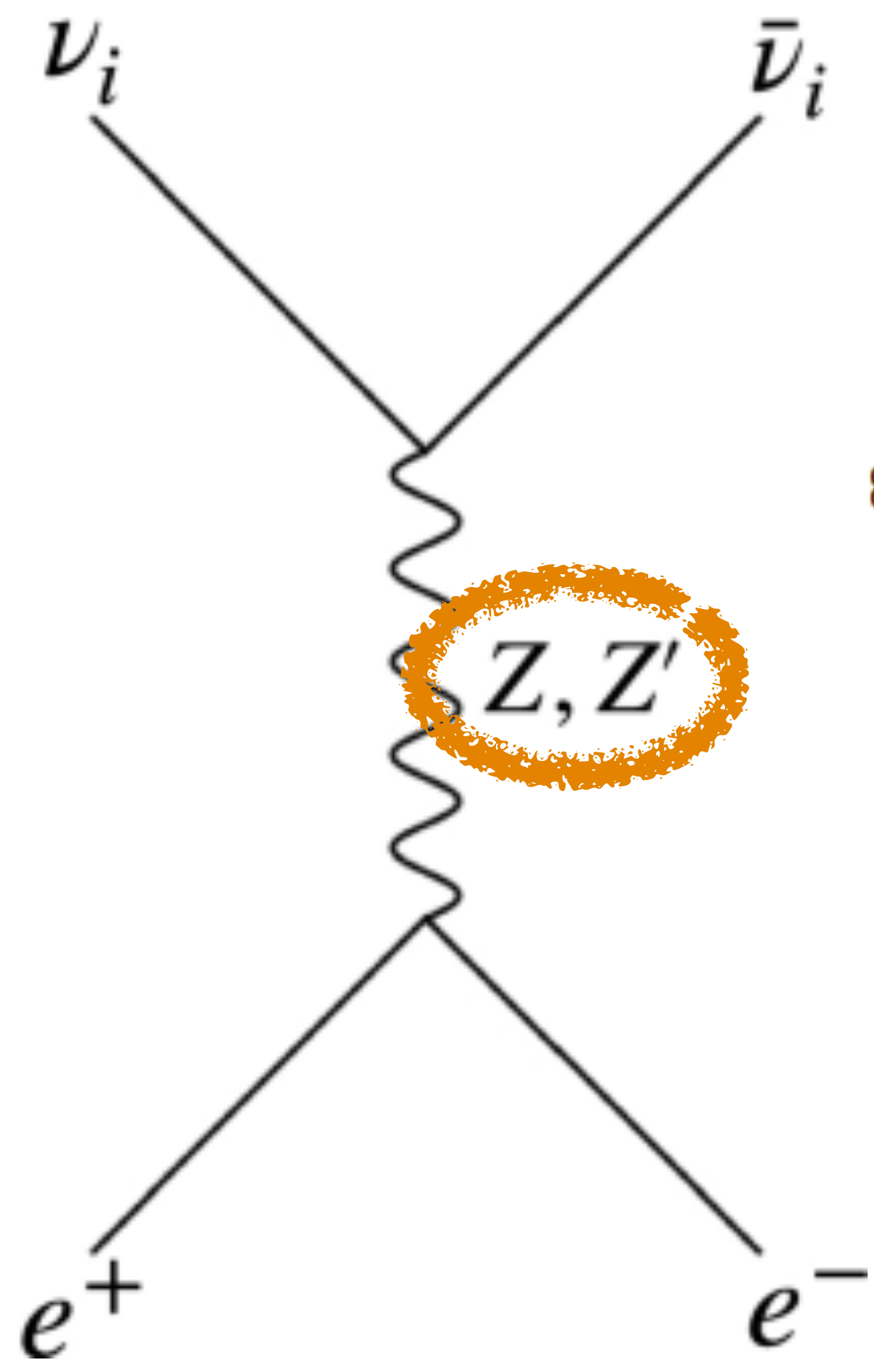


Shock wave

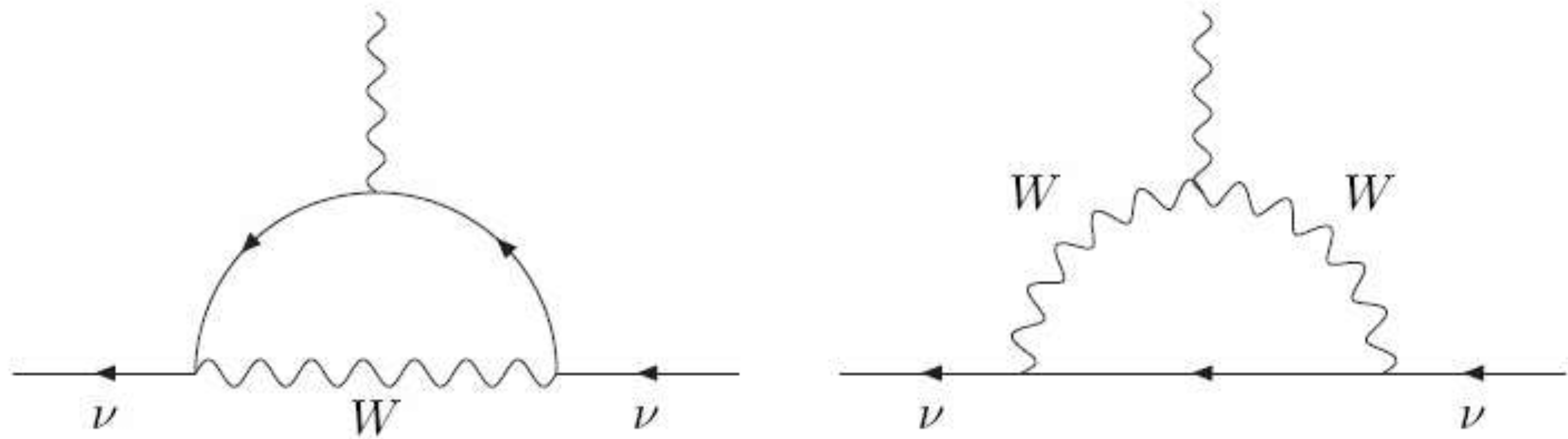
Proto-neutron star

Neutron Skin Depth



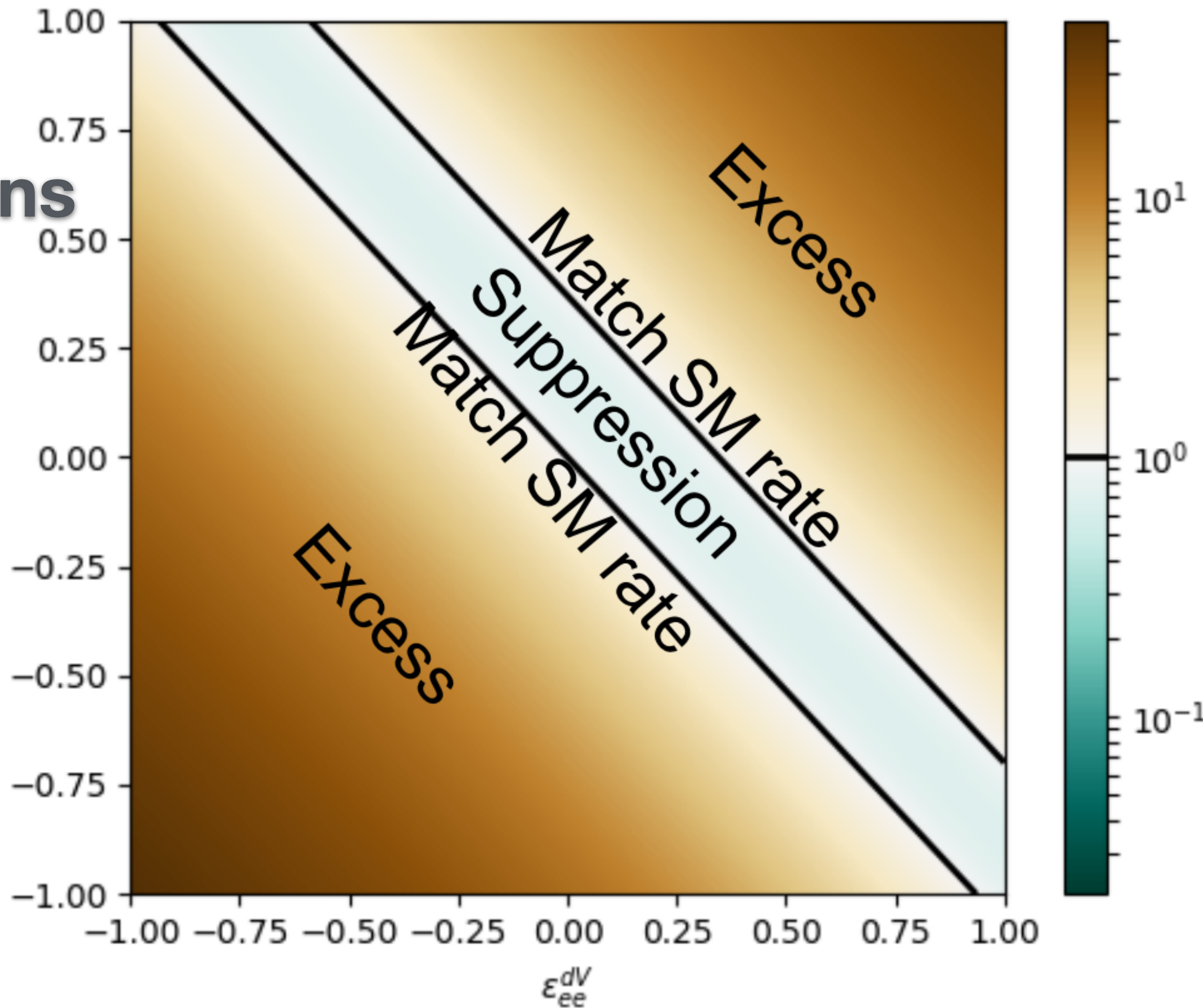
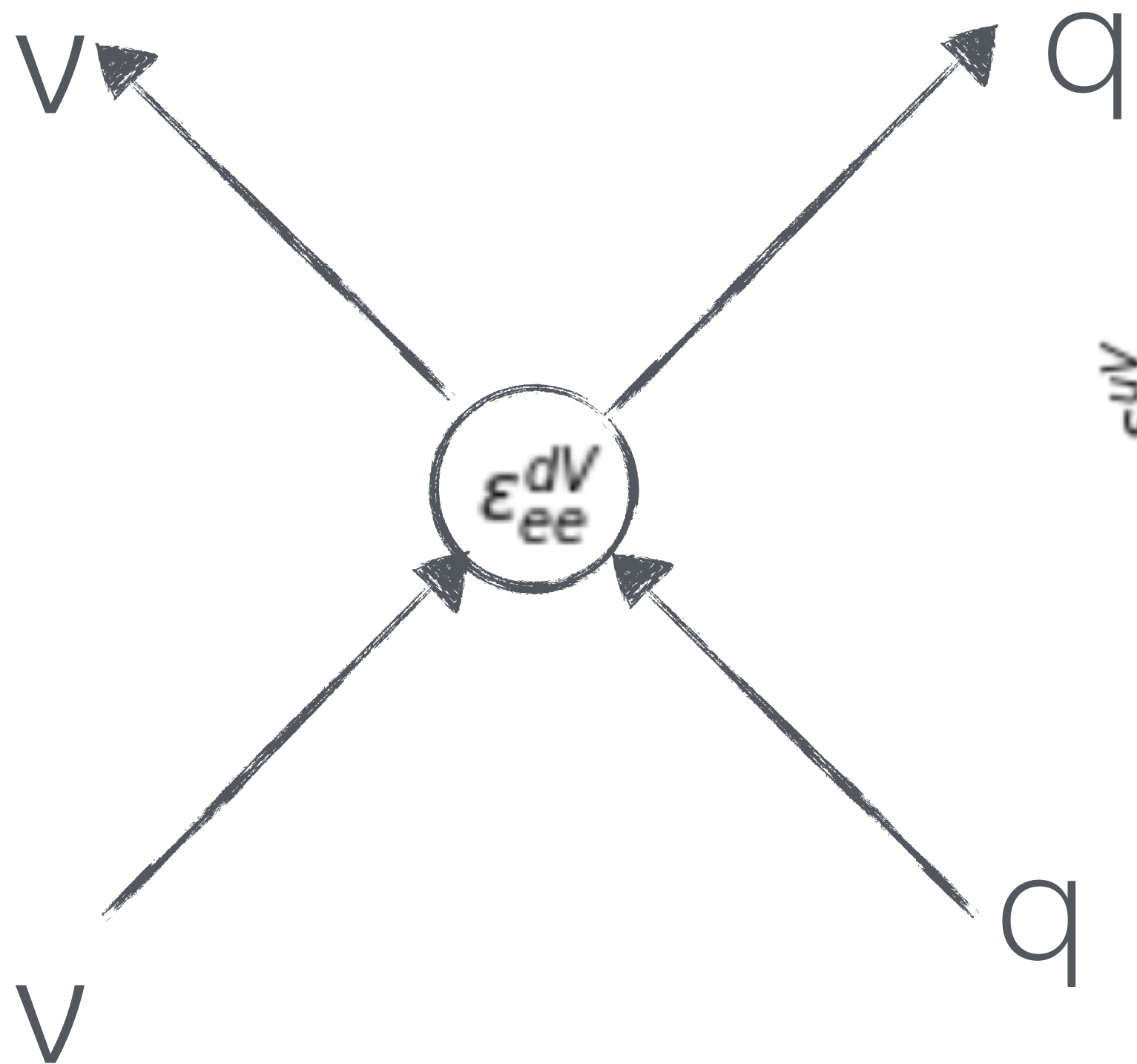


Neutrino Magnetic Moments



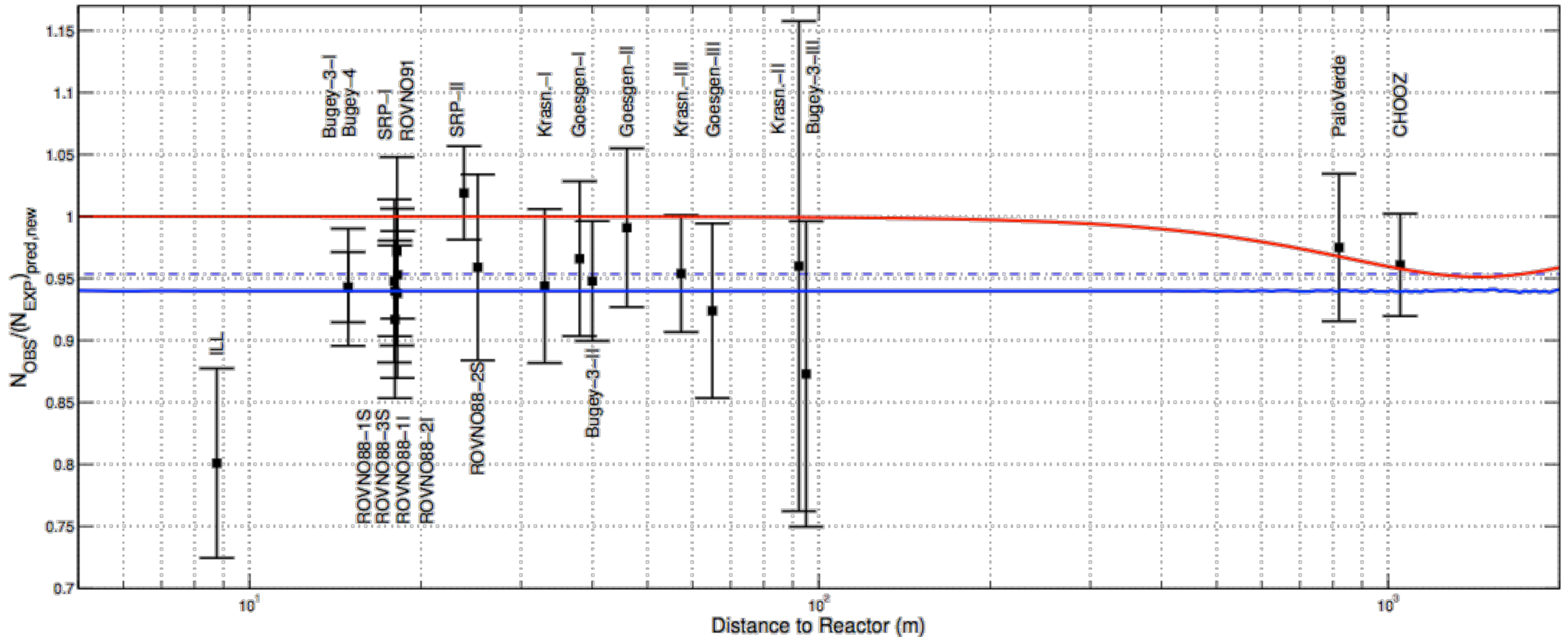
**This photon is another coherent-scattering vertex
Additive to CEvNS**

Non-Standard Neutrino Interactions

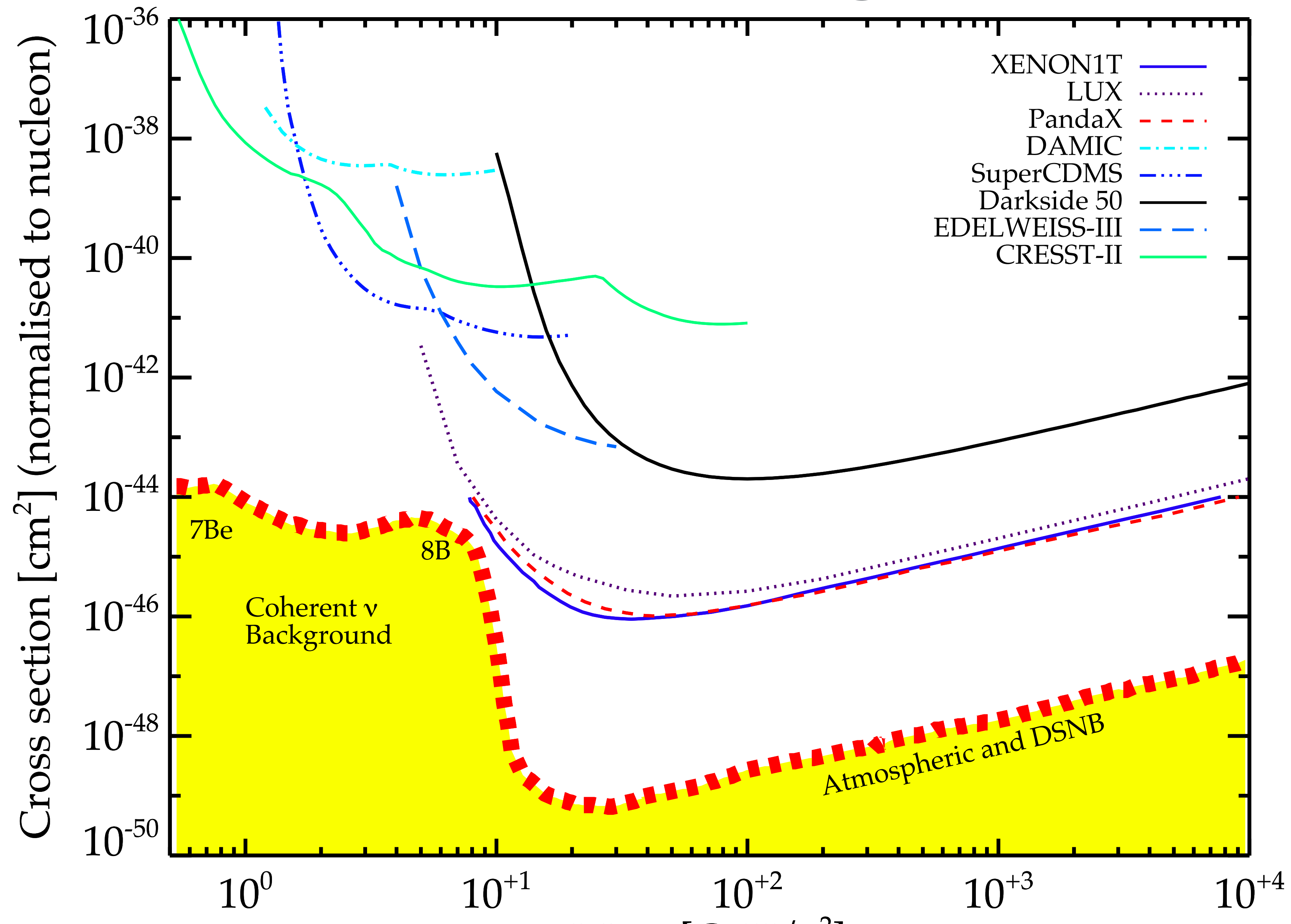


Total Neutral Current Disappearance

Searches for Sterile Neutrinos



WIMP Dark Matter Background





CEVNS

dark matter

supernovae

solar neutrinos

sterile neutrinos

new detectors

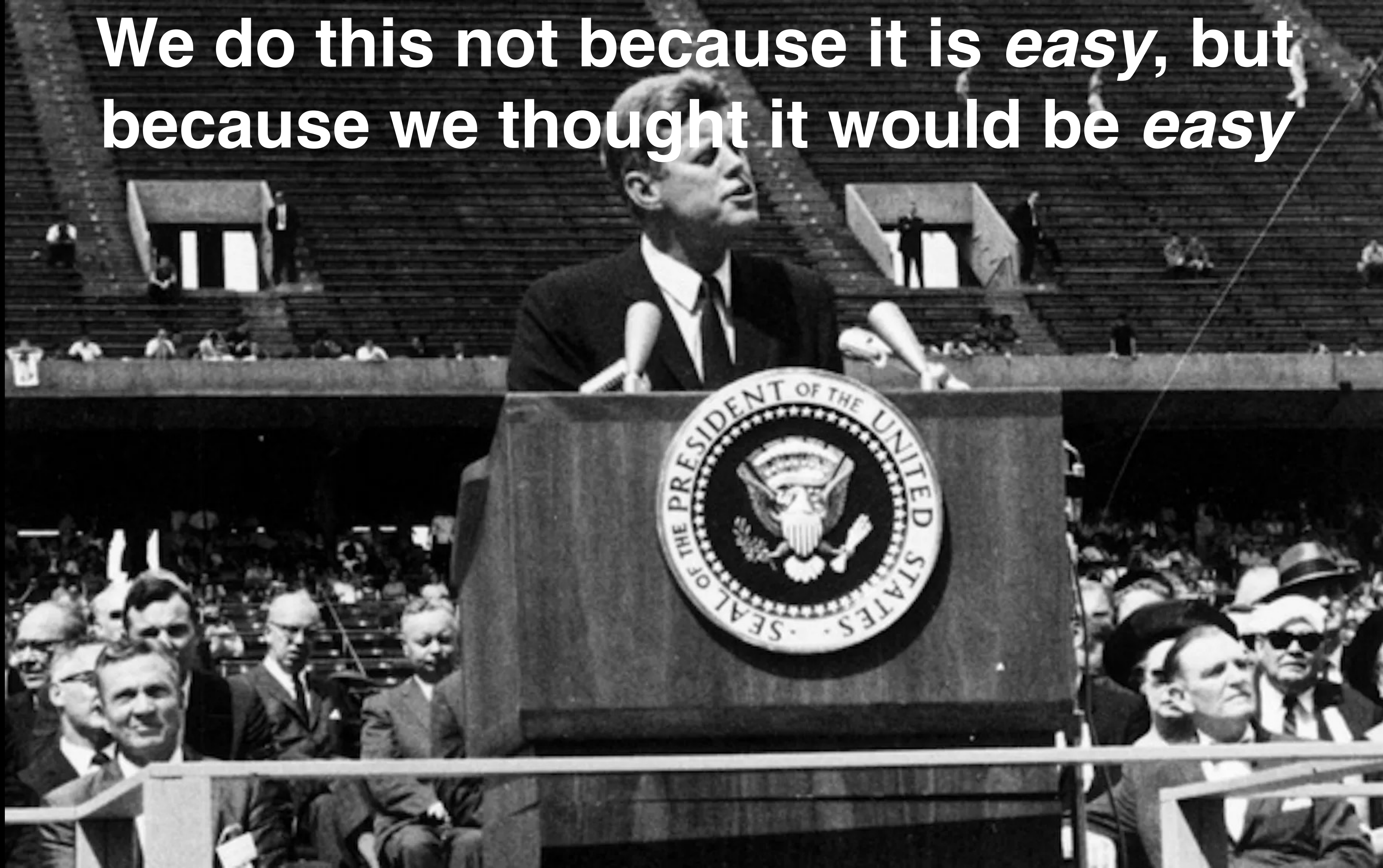
new ν properties

new interactions

nuclear form factors

EW precision tests

We do this not because it is *easy*, but because we thought it would be *easy*



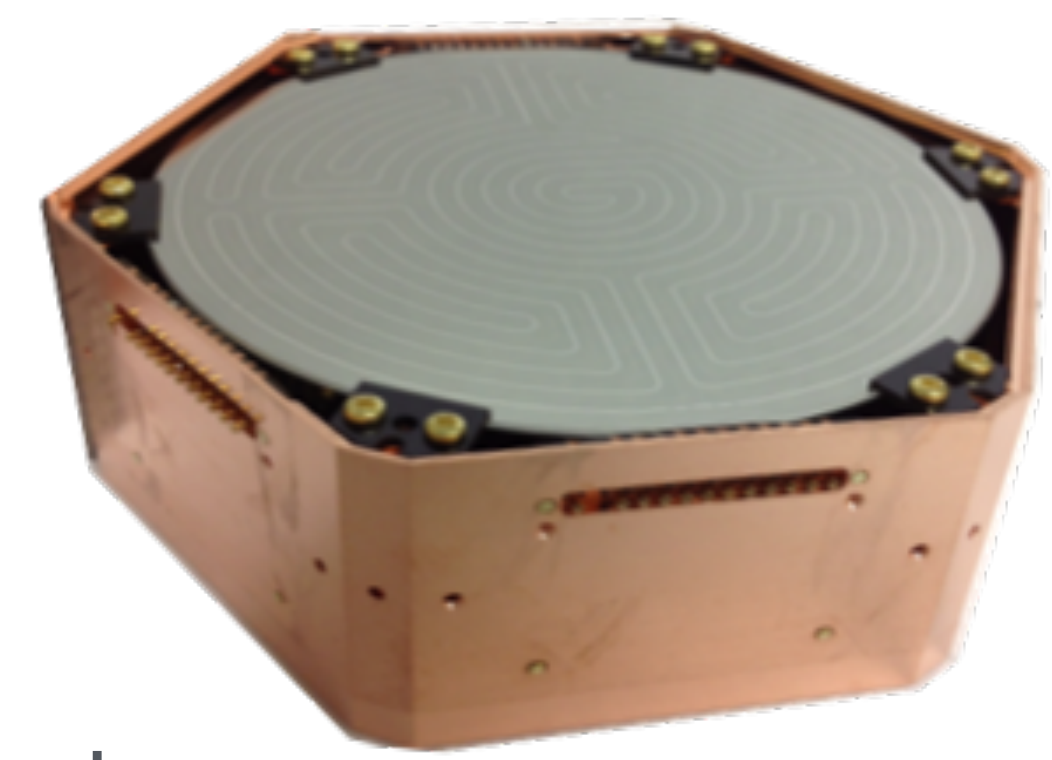
So...Why is this so hard?

1st detection 43 years after prediction

- Interaction rates are still low → Need large source of neutrinos
- Low Thresholds: signals VERY hard to see
- Nothing Special: lots of backgrounds cause low energy signals
- Detector Response: Calibrating low energy recoils is not easy either

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

A little History



“Bolometric Detection of Neutrinos” **PRL 55, 25 (1985)**, Blas Cabrera, Lawrence Krauss and Frank Wilczek

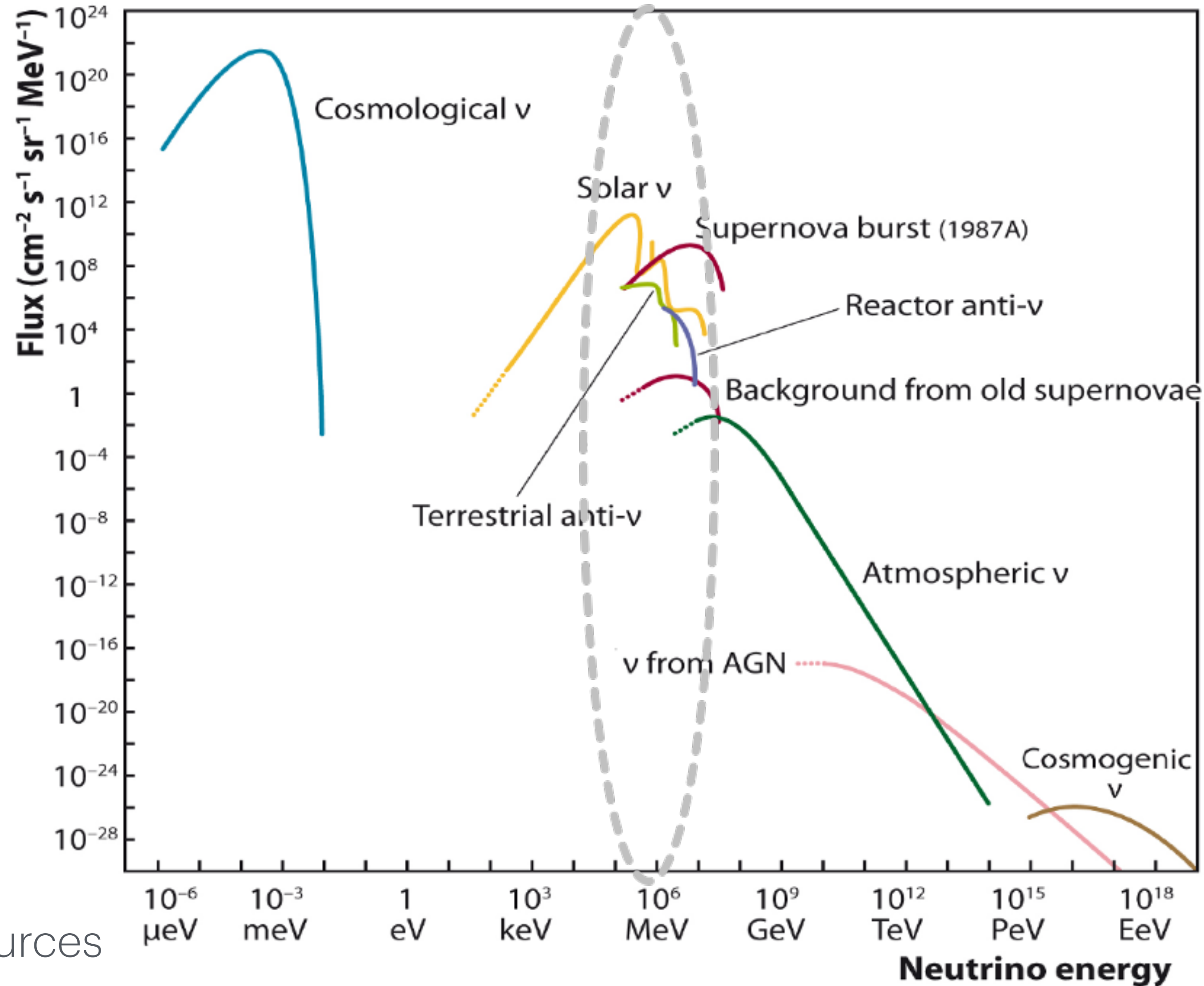
*“We propose new detectors for bolometric measurement of low-energy ν interactions, **including coherent nuclear elastic scattering**. A new and more sensitive search for oscillations of reactor antineutrinos is practical (~ 100 Kg of Si), and would lay the groundwork for a more ambitious measurement of the spectrum pp, Be7 and B8 solar ν 's, and supernovae anywhere in our galaxy (~ 10 tons of Si).”*

This was the precursor to the **CDMS Dark Matter search**

Ok, but how?

Pick a Source

**Below Detector
threshold**



Lose Coherence

Plus Electron-Capture sources

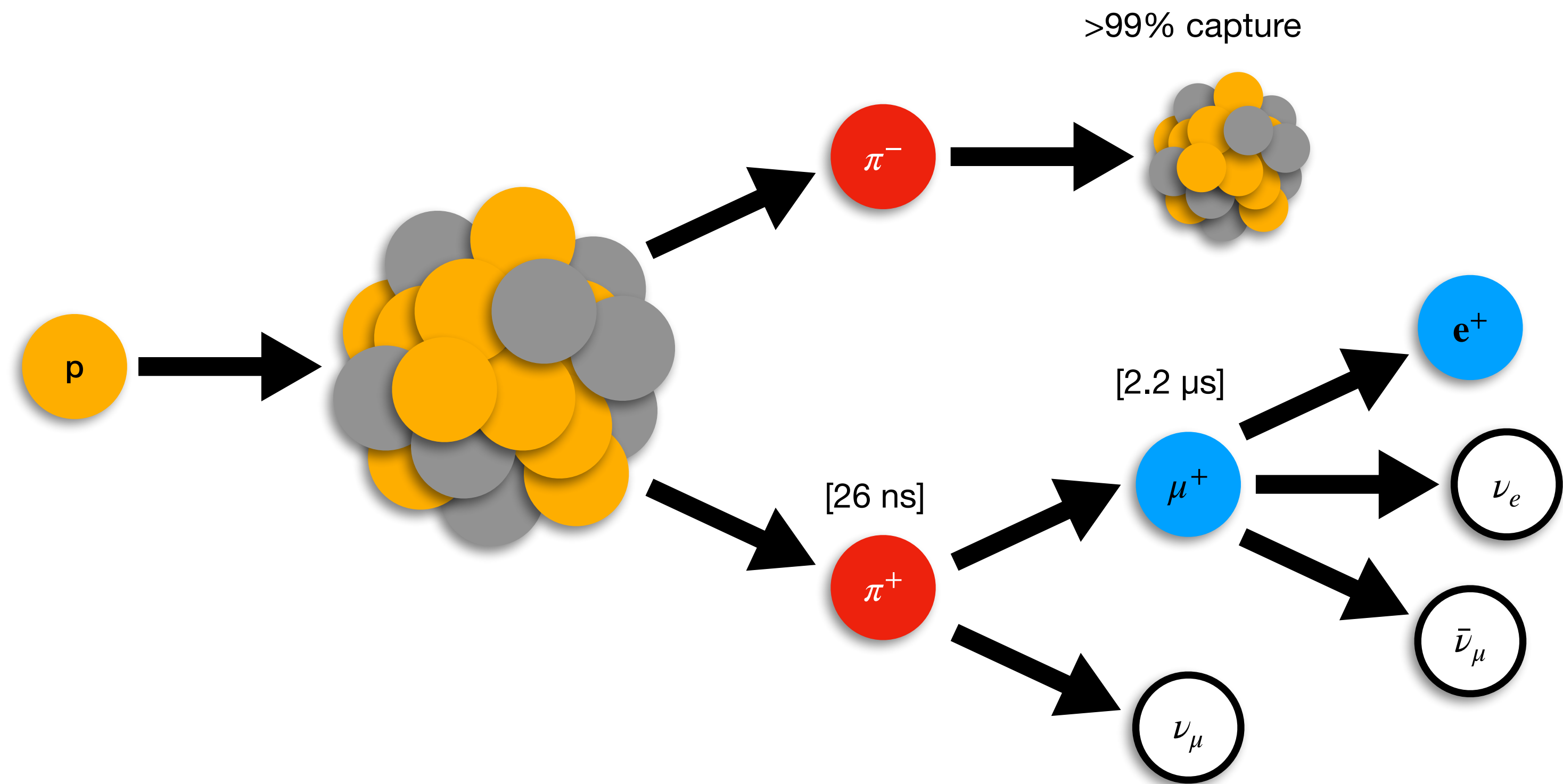
Spallation Neutron Source

- 1.3 GeV protons strike a mercury (60 Hz), 2 MW beam Power

- ~350ns FWHM

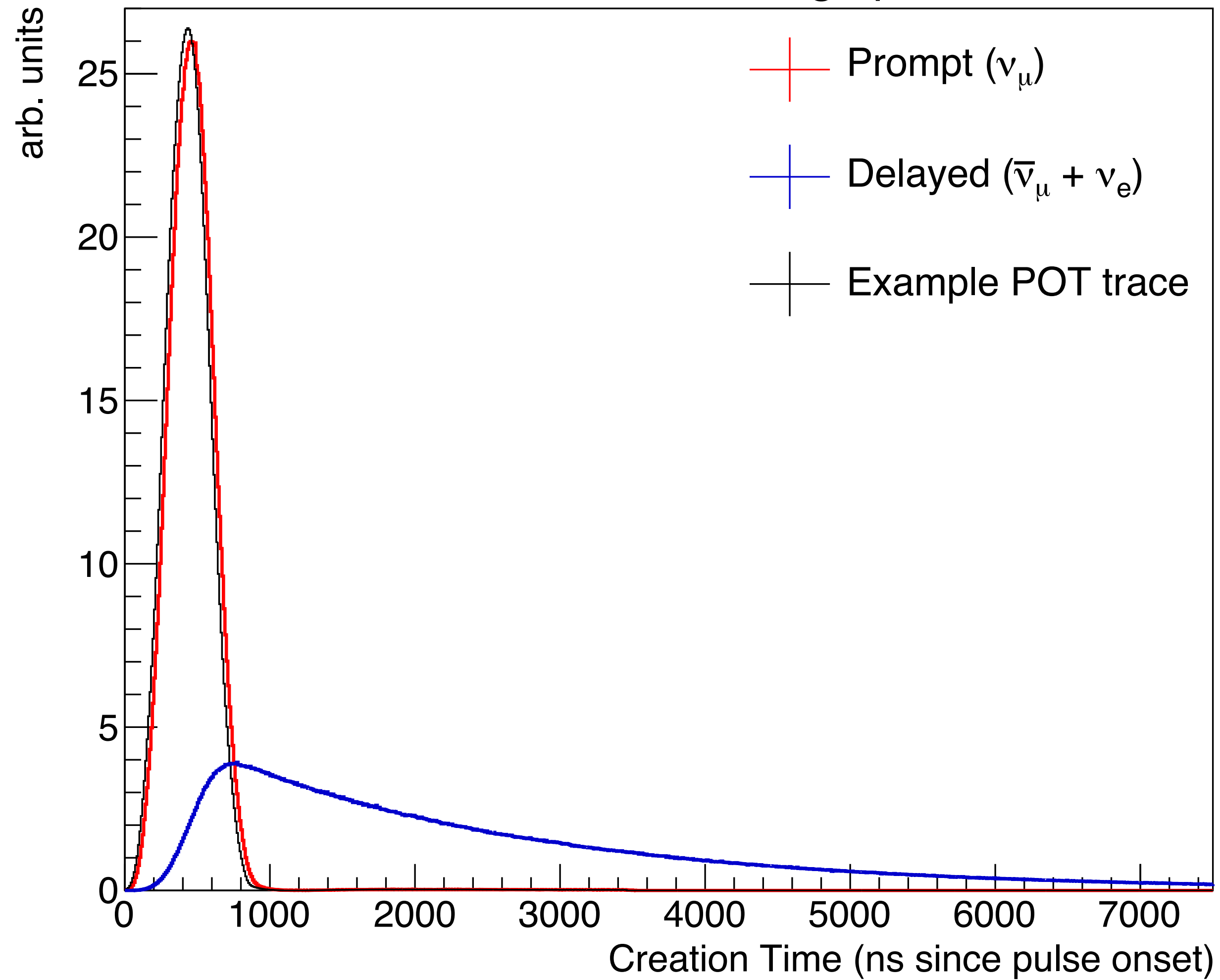
- Prompt and delayed ν 's

- $\sim 3.5 \times 10^{15}$ ν /second

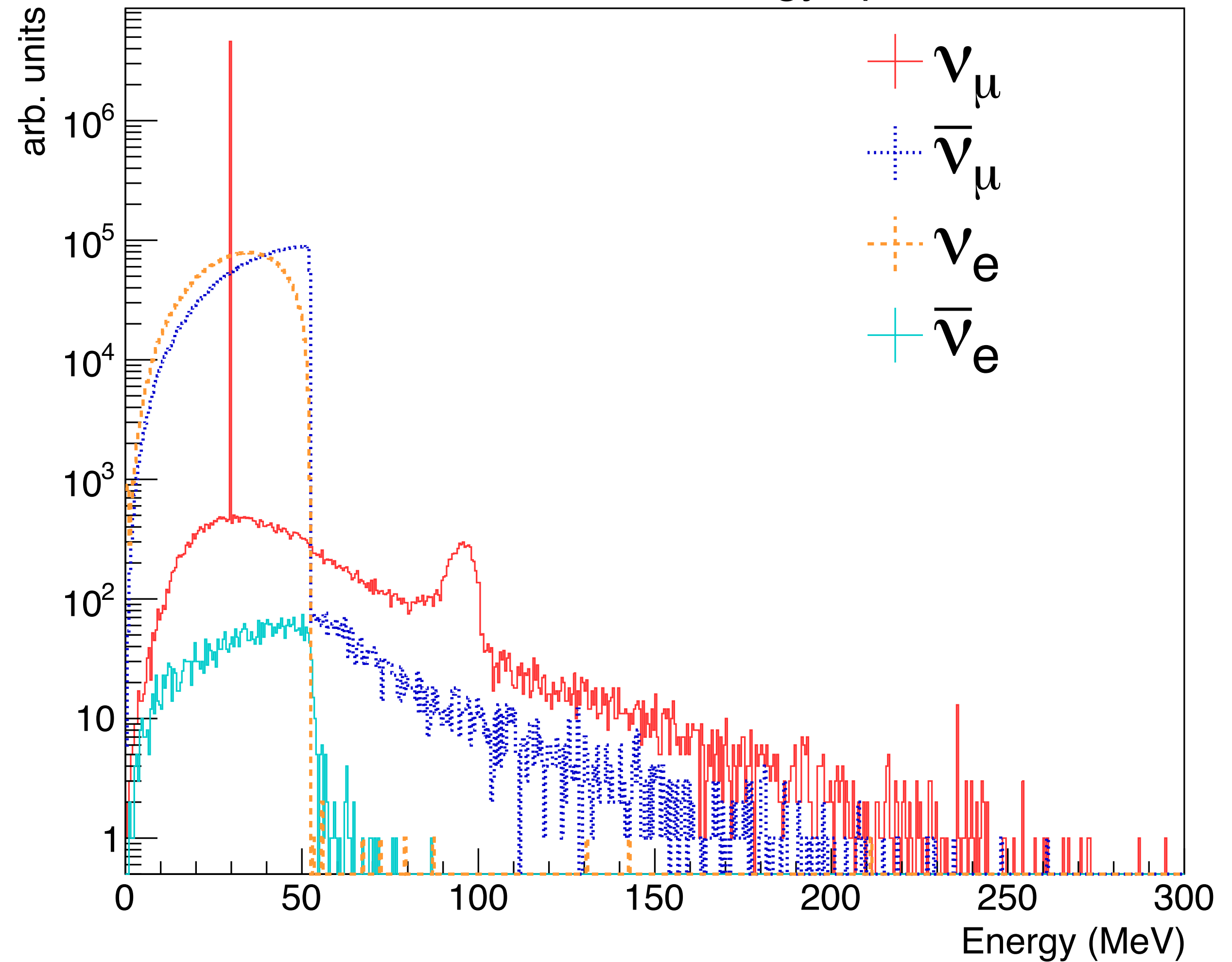


SNS Neutrinos

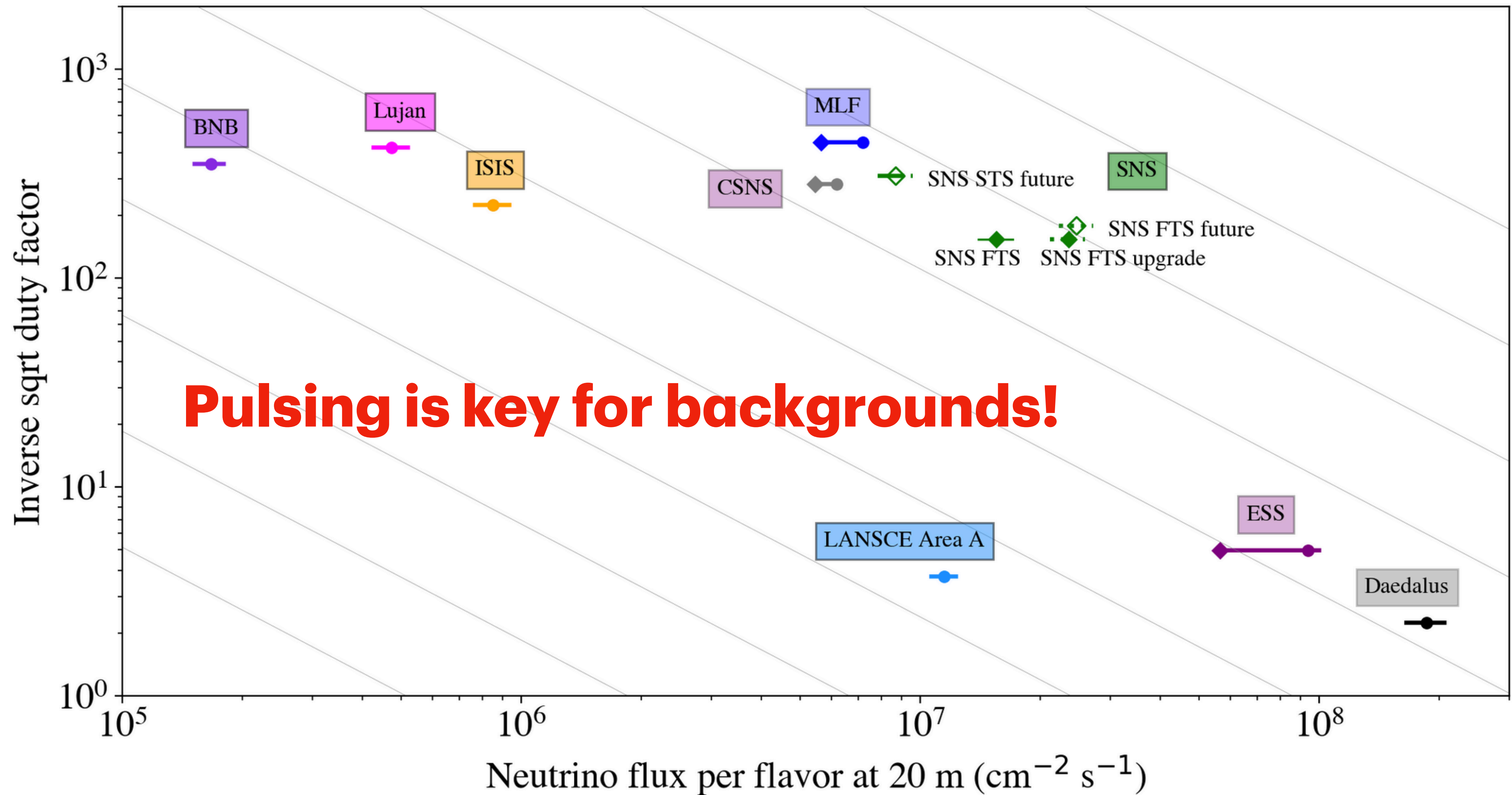
Simulated neutrino timing spectrum



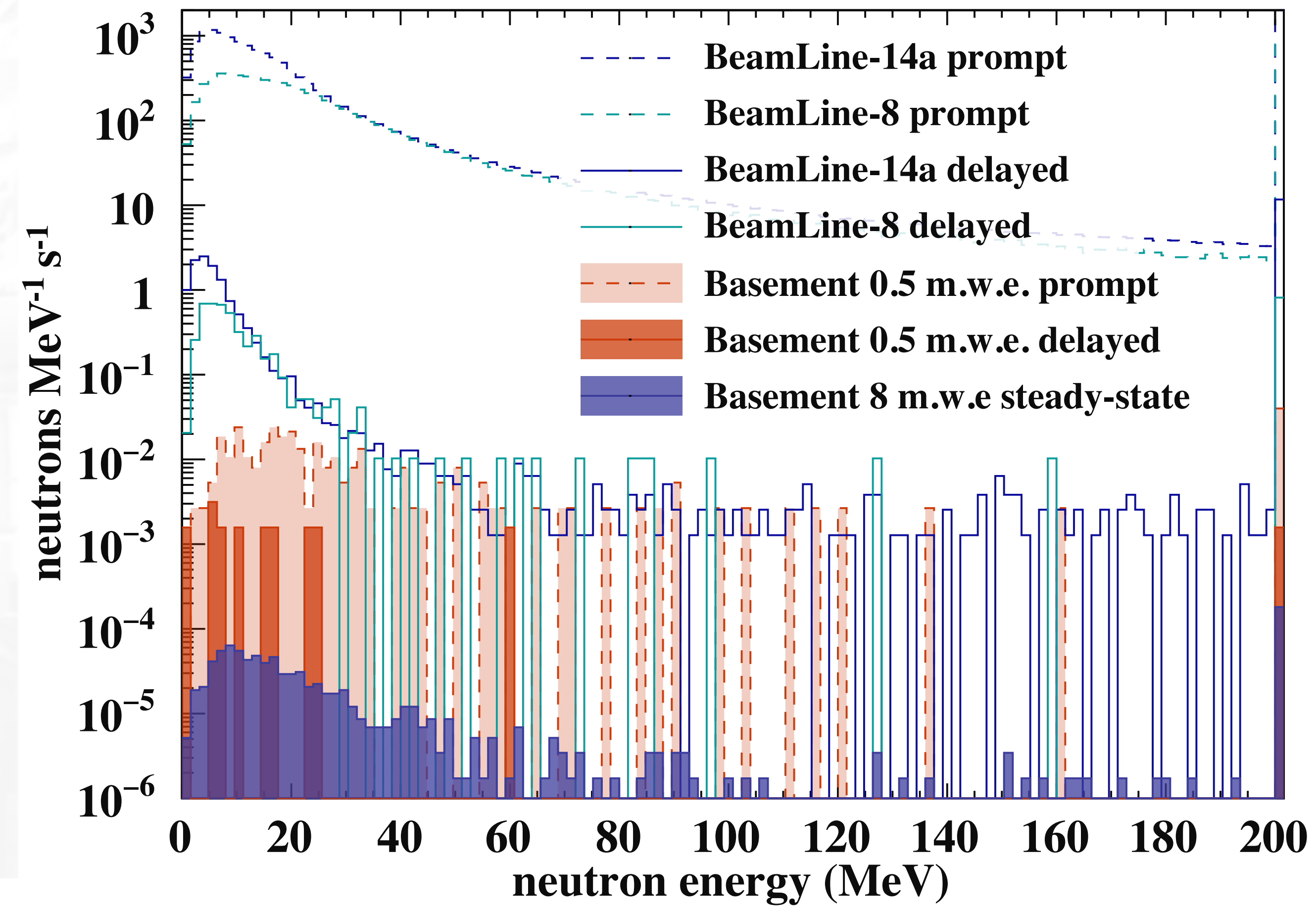
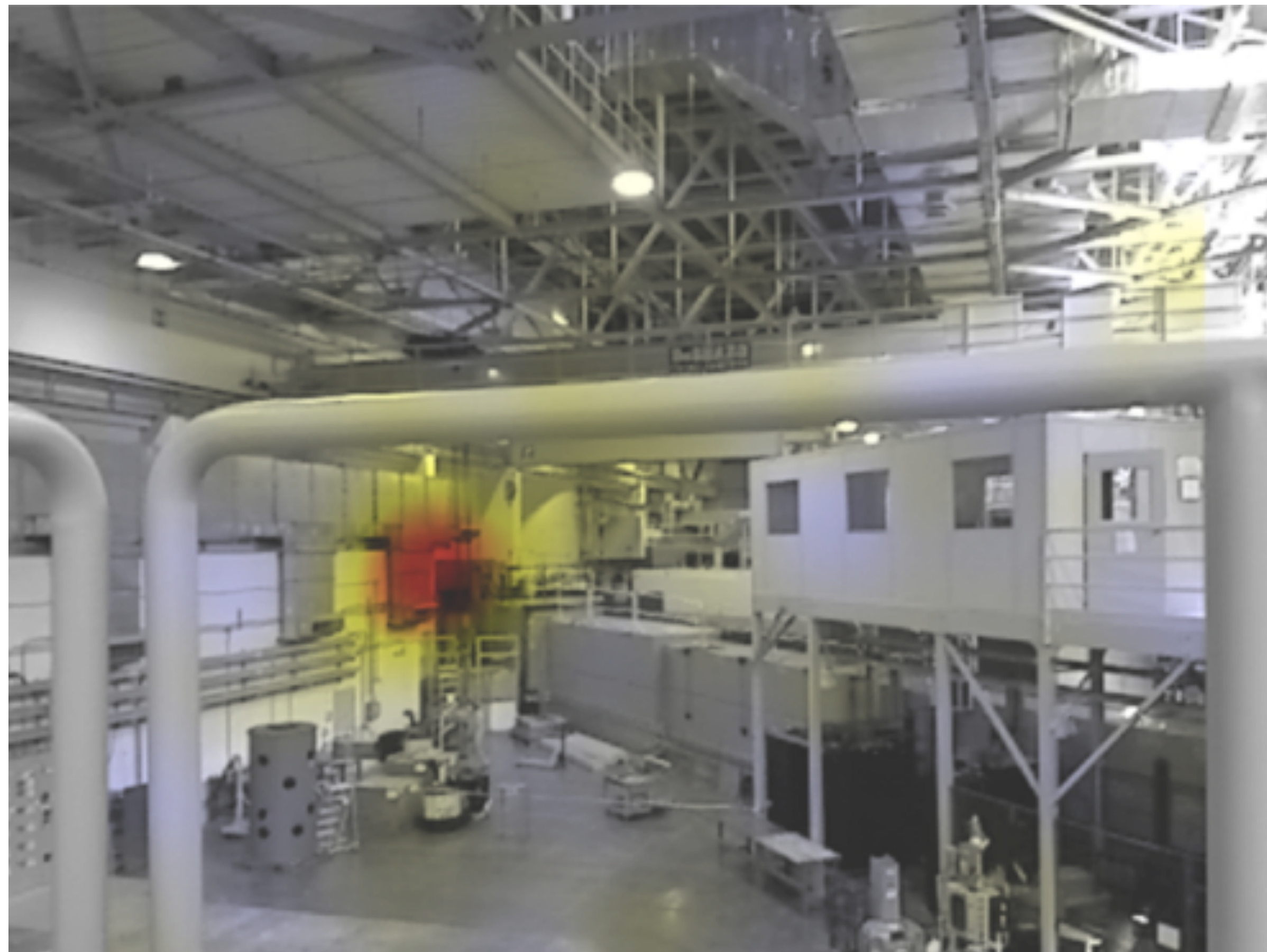
Simulated neutrino energy spectrum



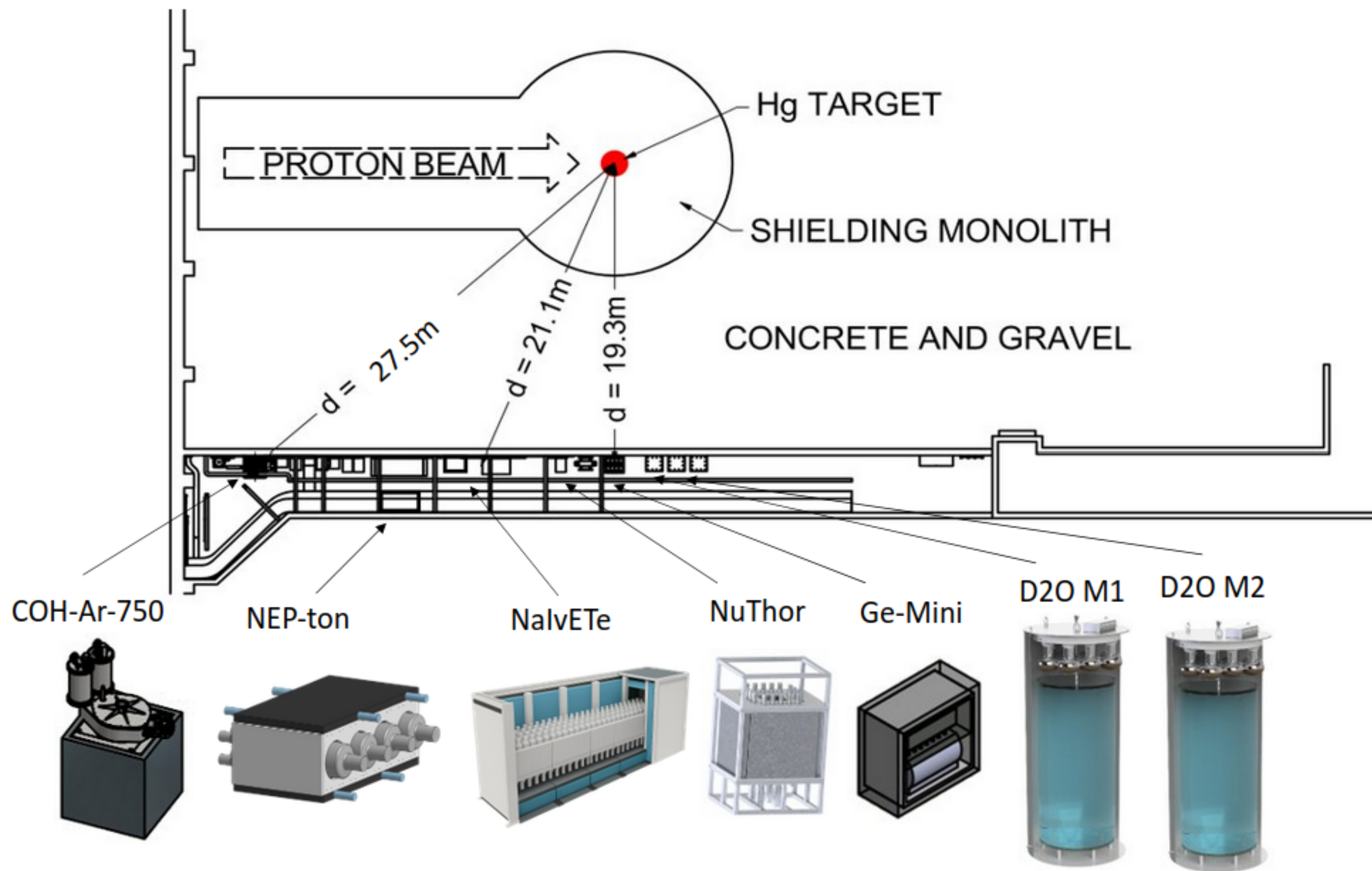
Spallation Sources in general



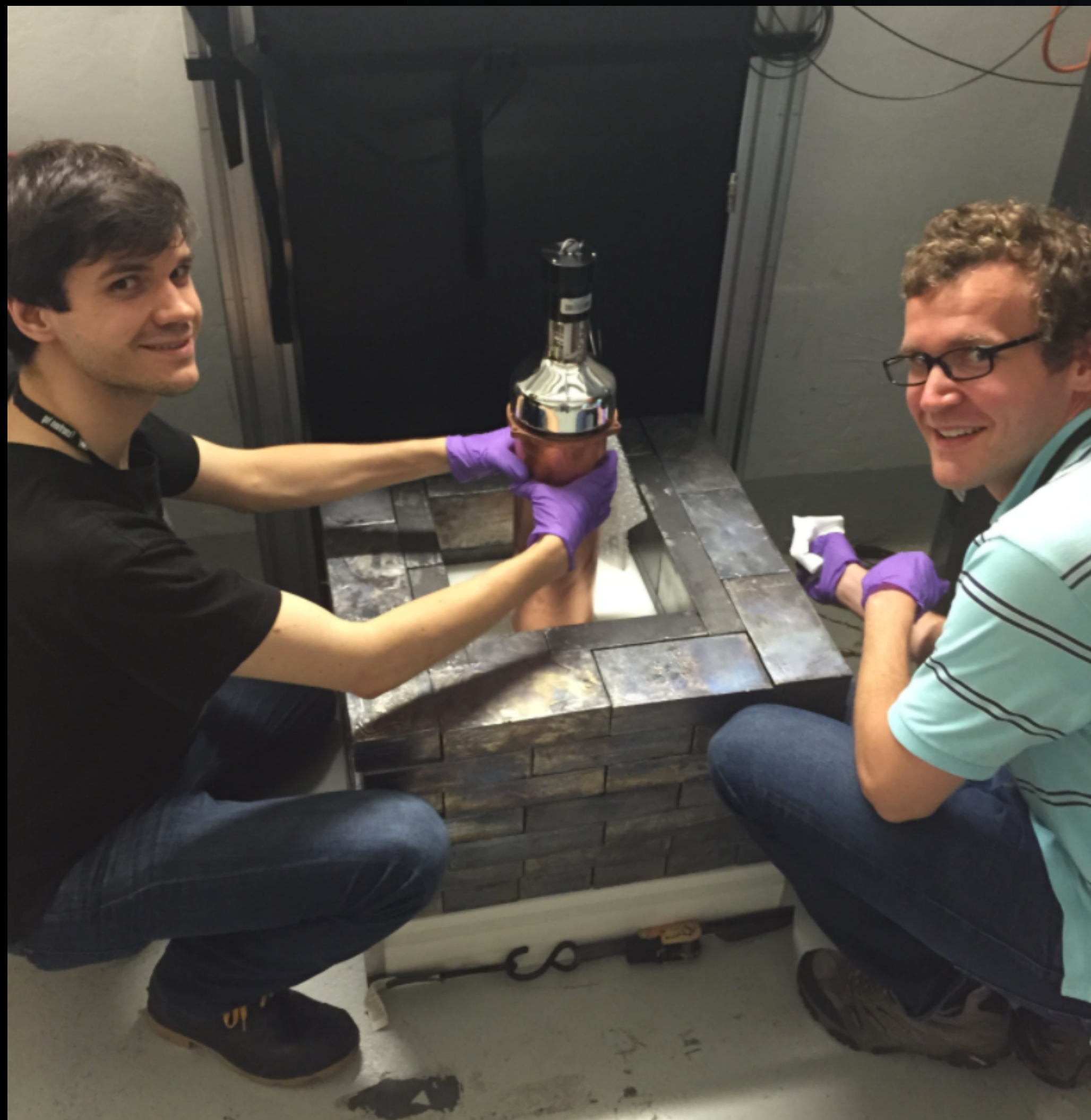
Neutron backgrounds



Hide in "Neutrino Alley"



First Light!



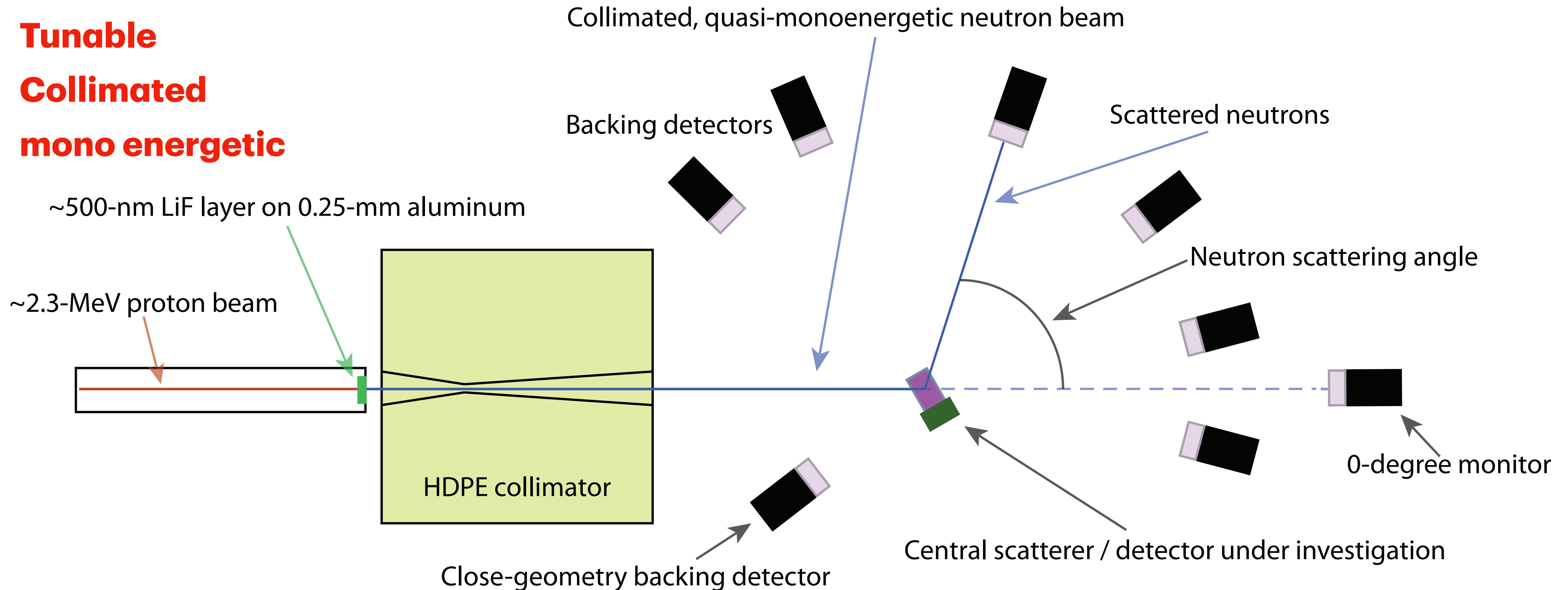
14.7 kg CsI[Na]
Inorganic
Crystal
Scintillator

High Light Yield → thresholds
 λ matched to photocathode
Na-doping → low afterglow
 ^{133}Cs β a problem → purify

Need to Calibrate your detectors

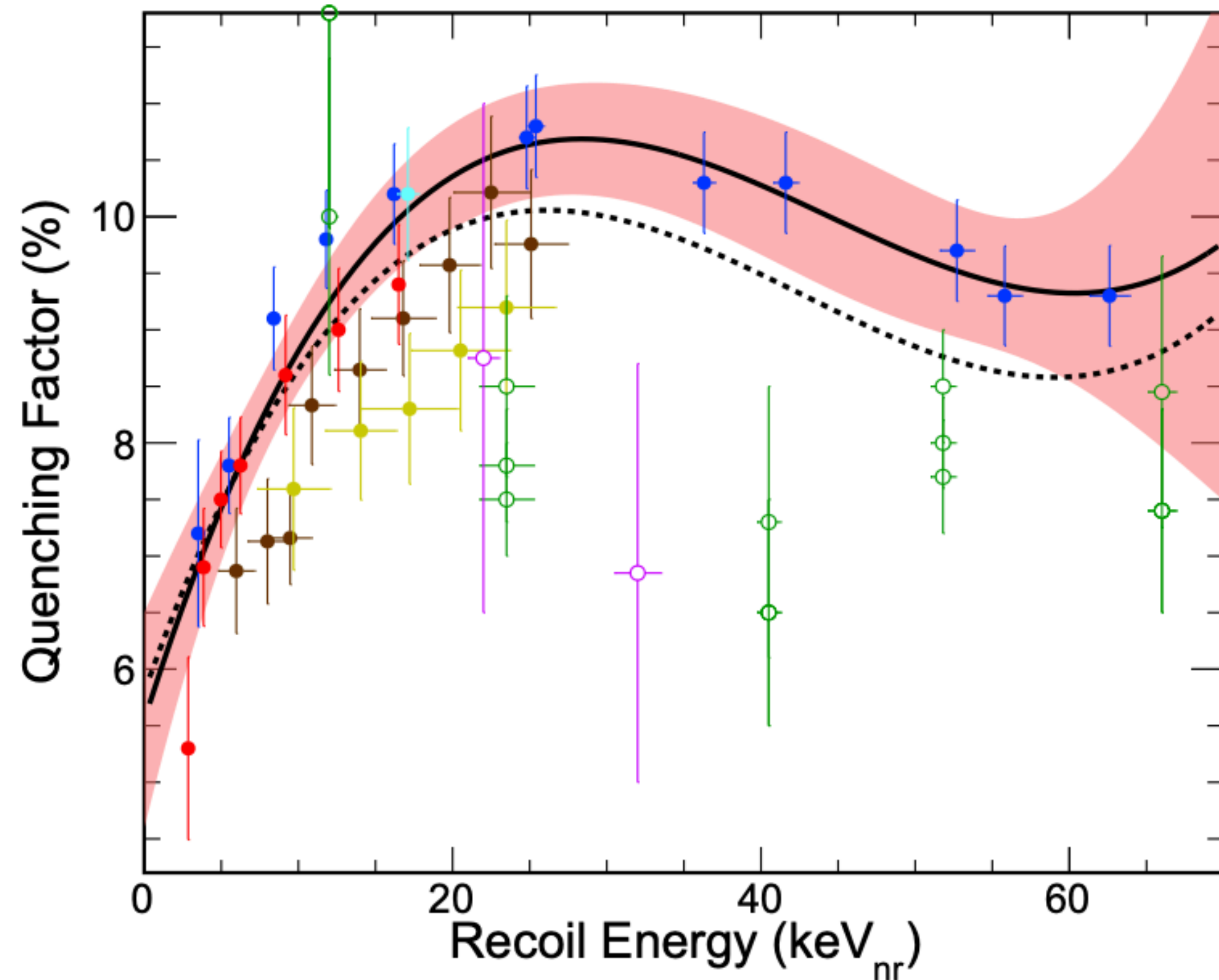
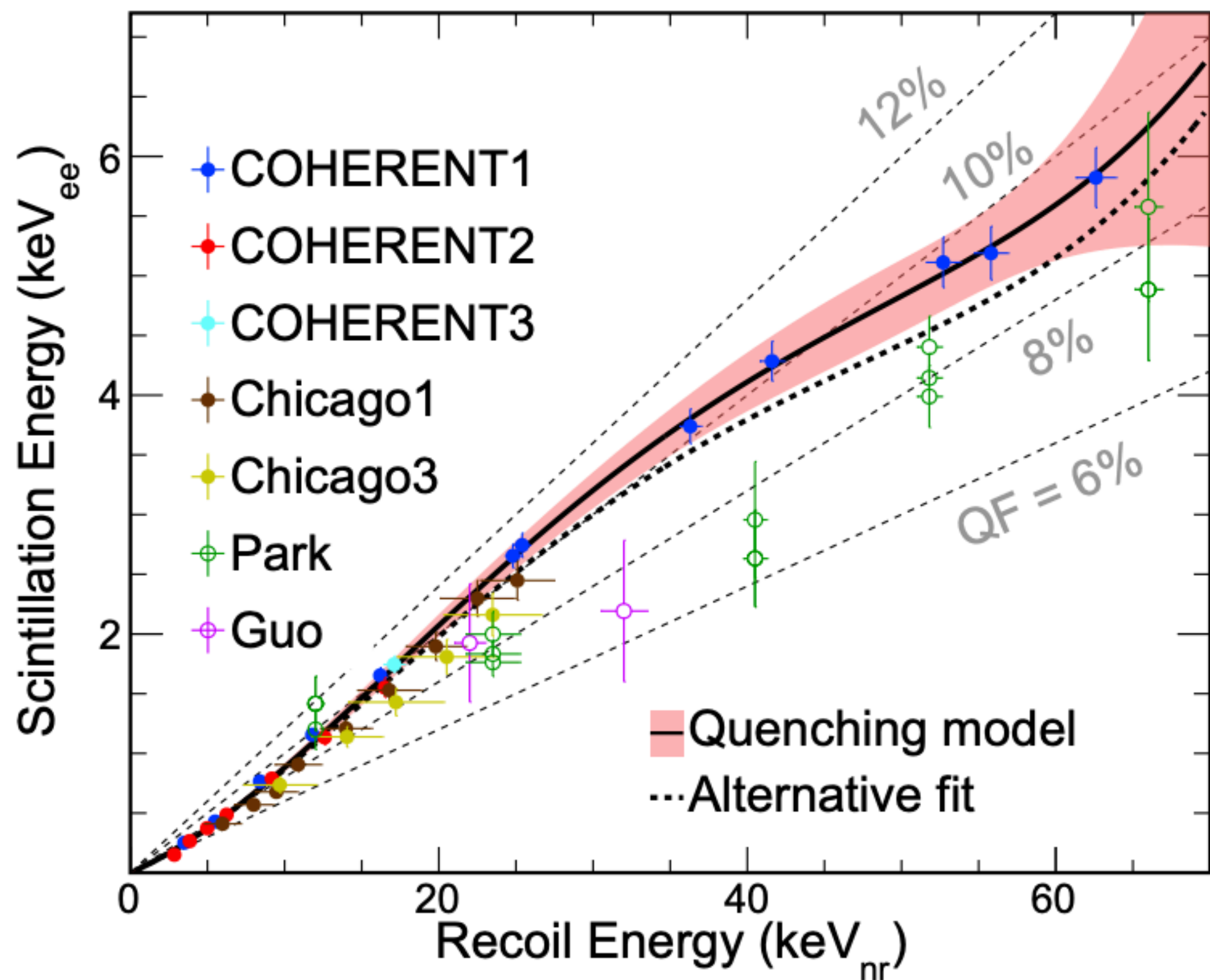
“Best way” - Neutron Elastic Scattering

Pulsed
Tunable
Collimated
mono energetic



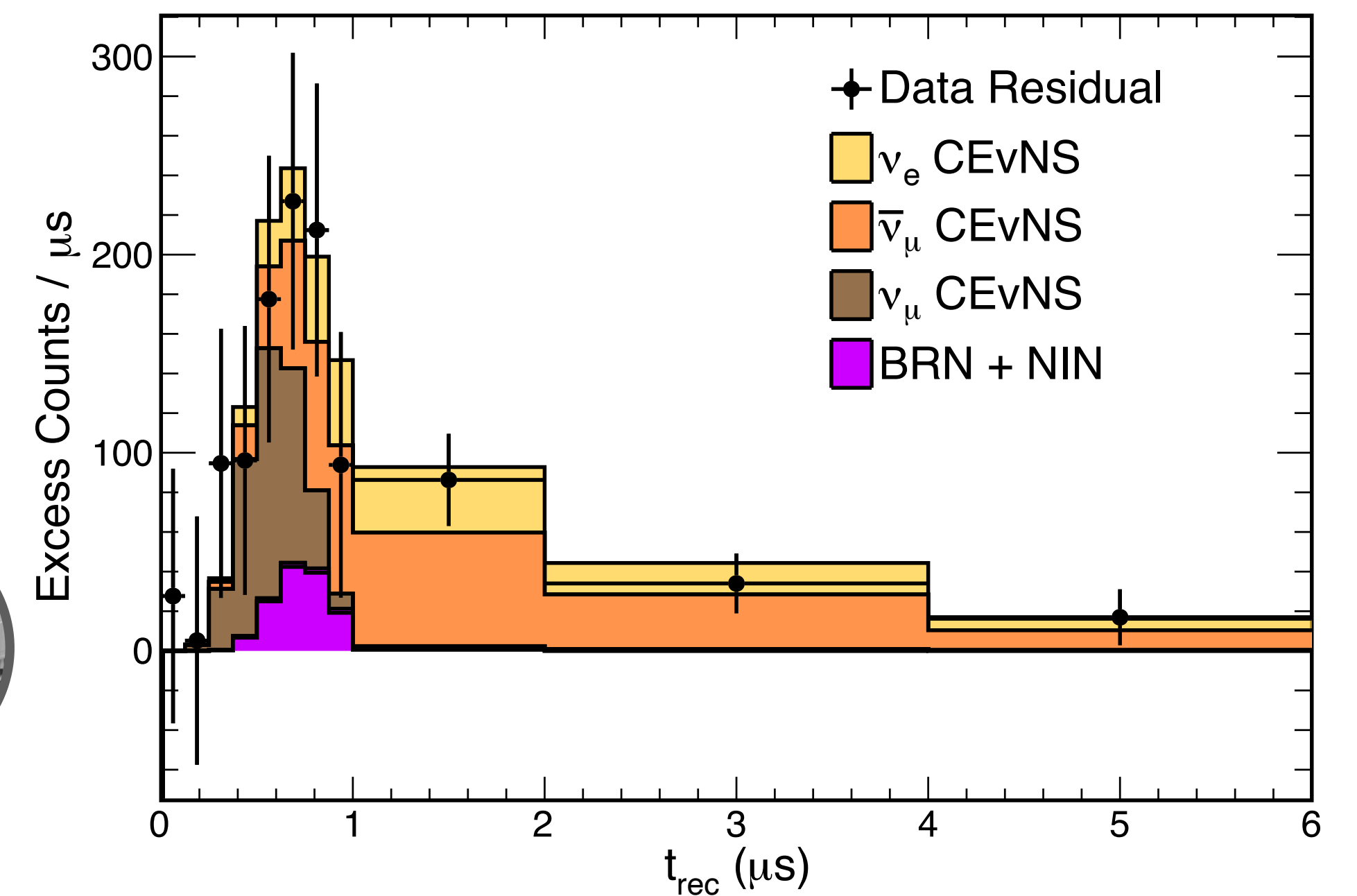
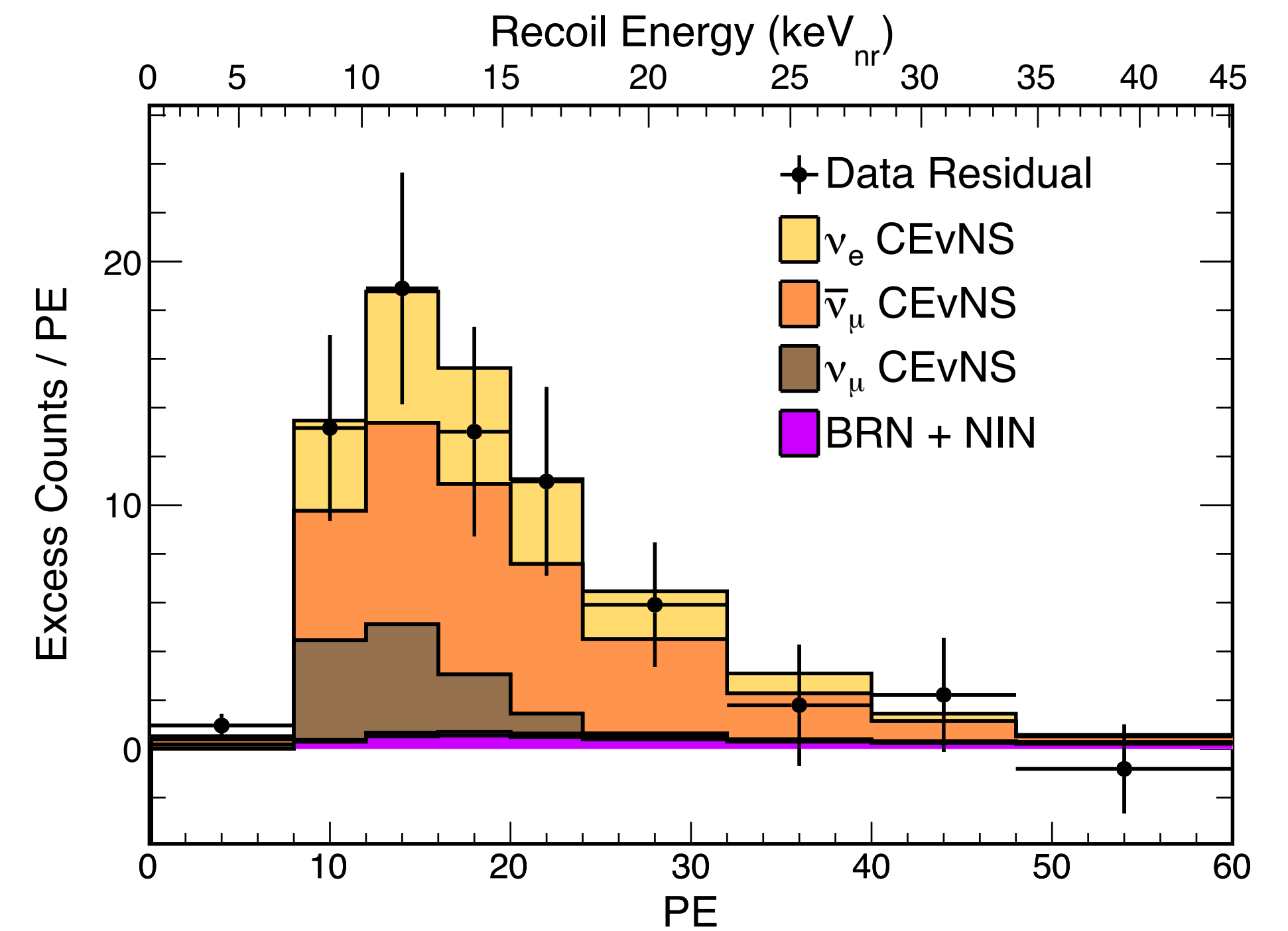
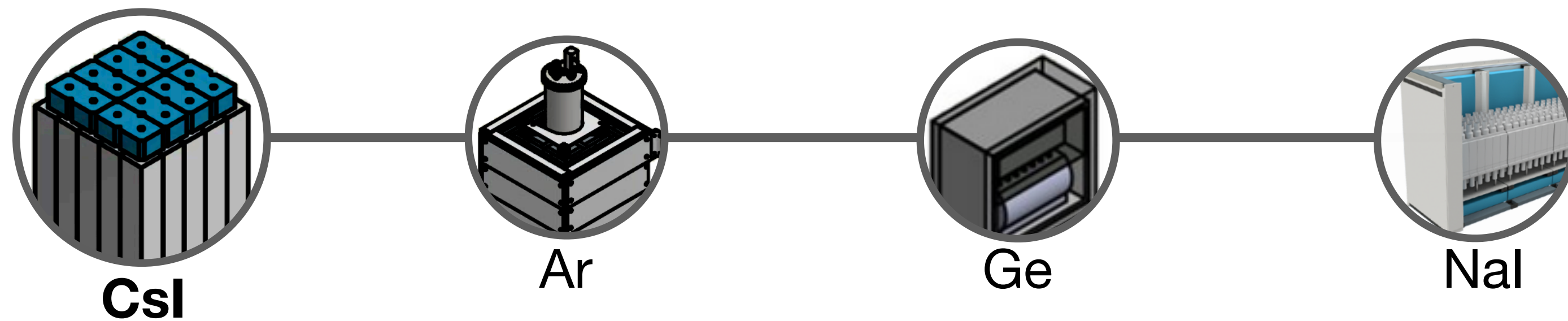
Need to Calibrate your detectors

“Best way” - Neutron Elastic Scattering



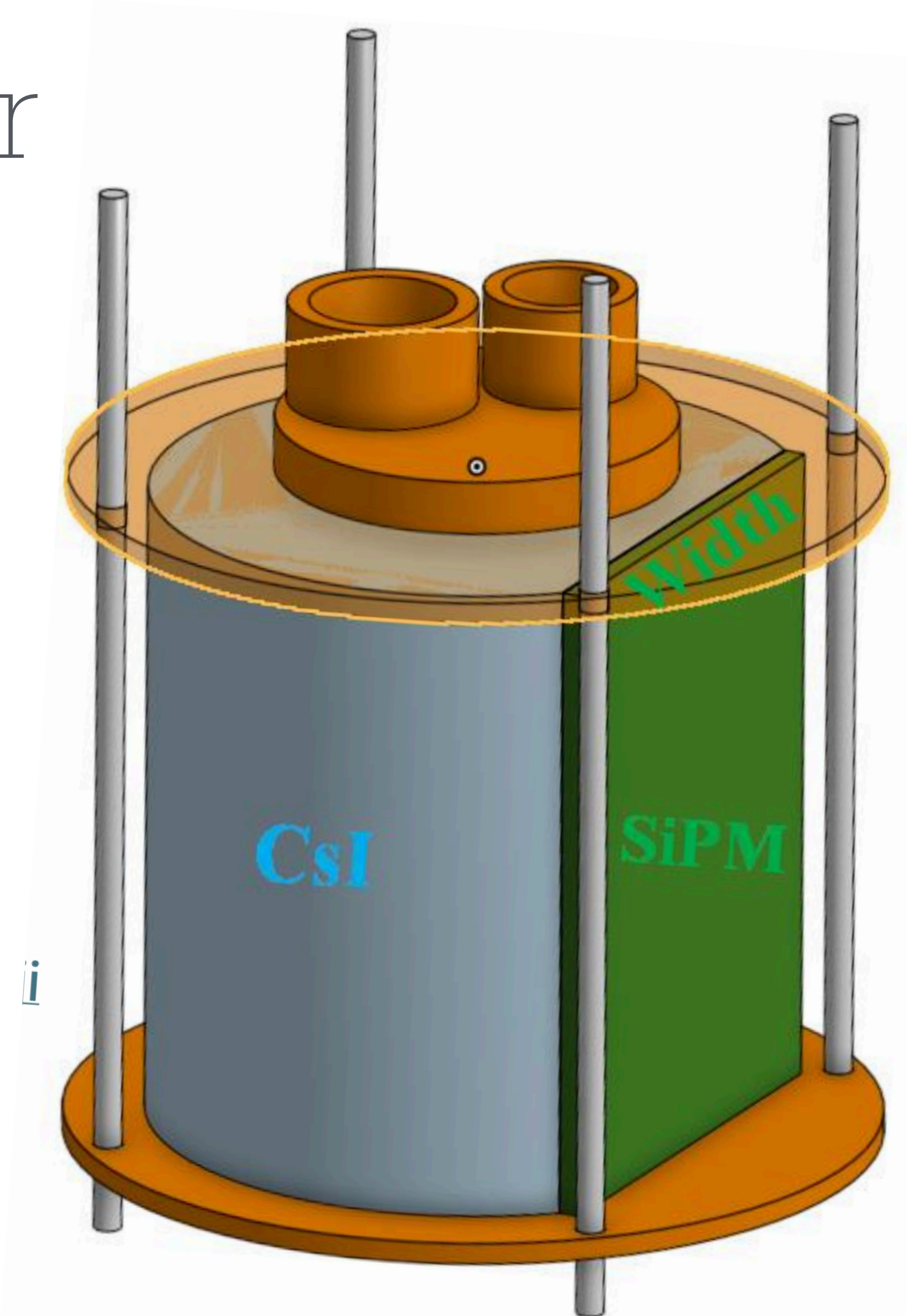
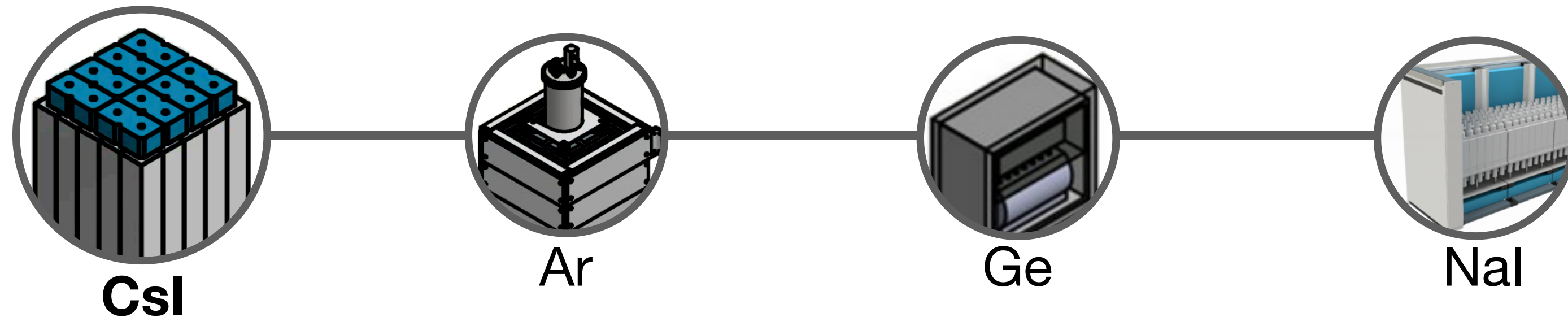
Full CsI[Na] Dataset

- Beam Related Neutrons
- Neutrino Induced Neutrons
- **Characteristic 2.2 μs decay**



Cryogenic CsI Scintillator

- 6.4 kg of undoped CsI operated at 77 K
 - LY: 13.35 PE/keV \rightarrow \sim 37 PE/keV
 - Threshold: 5 keV_{NR} \rightarrow 0.5 keV_{NR}
 - **Longer-lived excitons, less trapping in pure crystal (but slower!)**

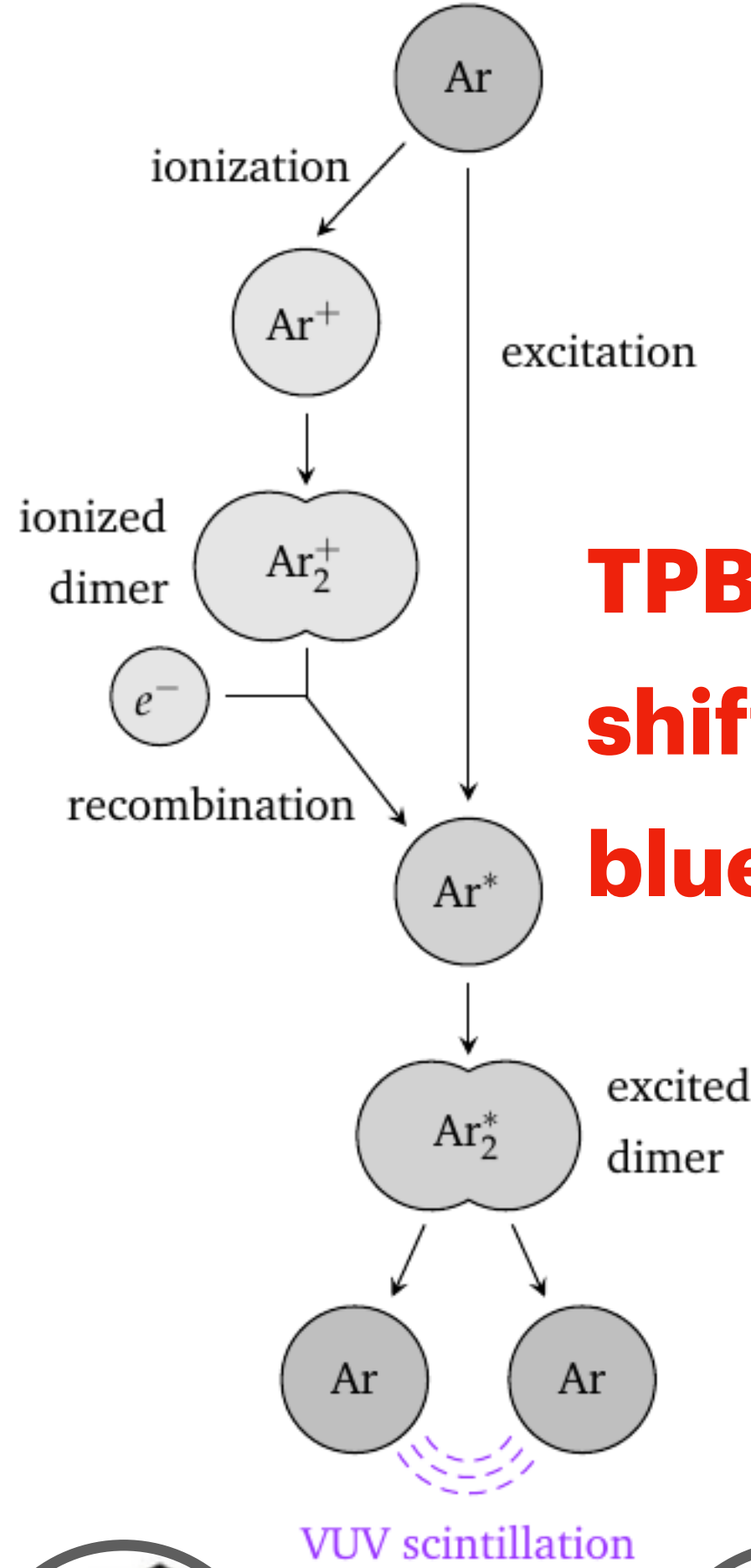


CENNS-10: Scintillation

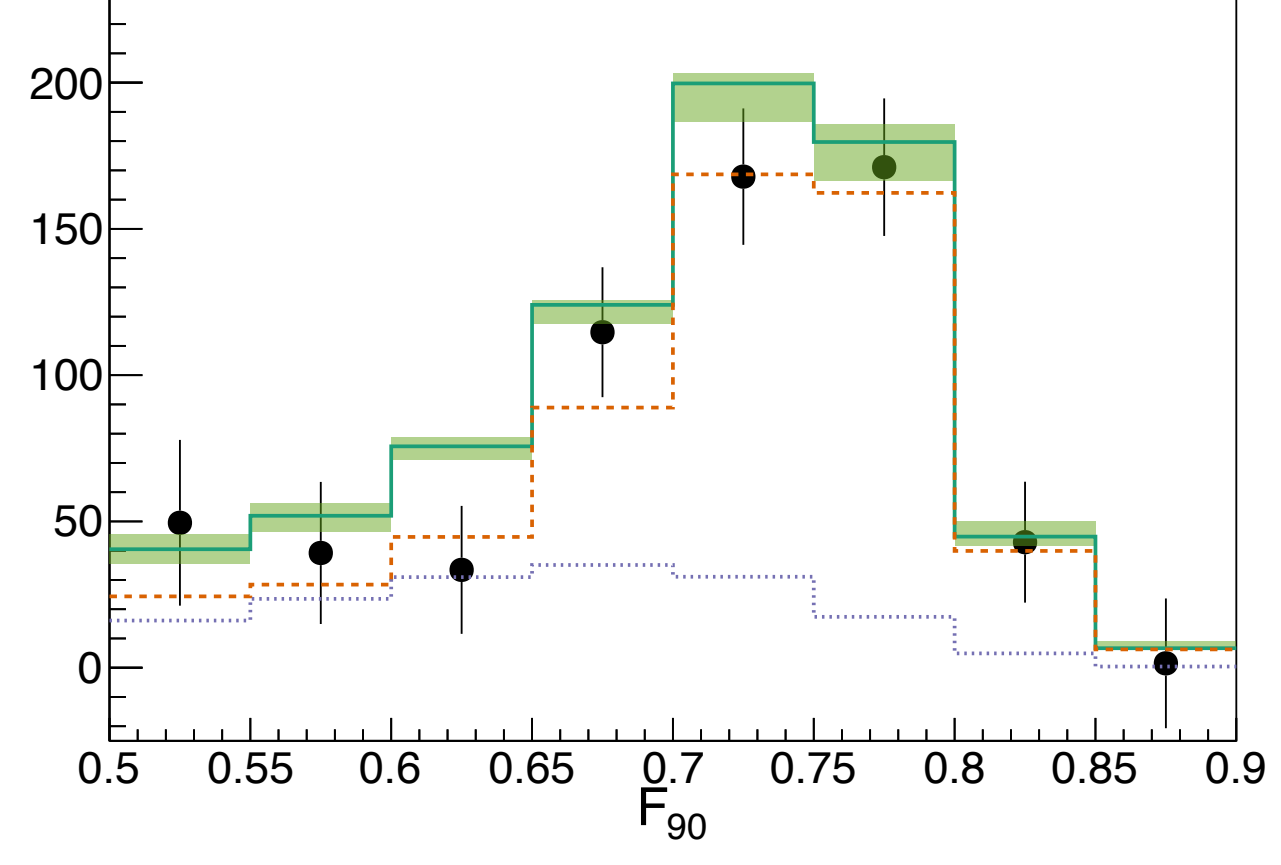
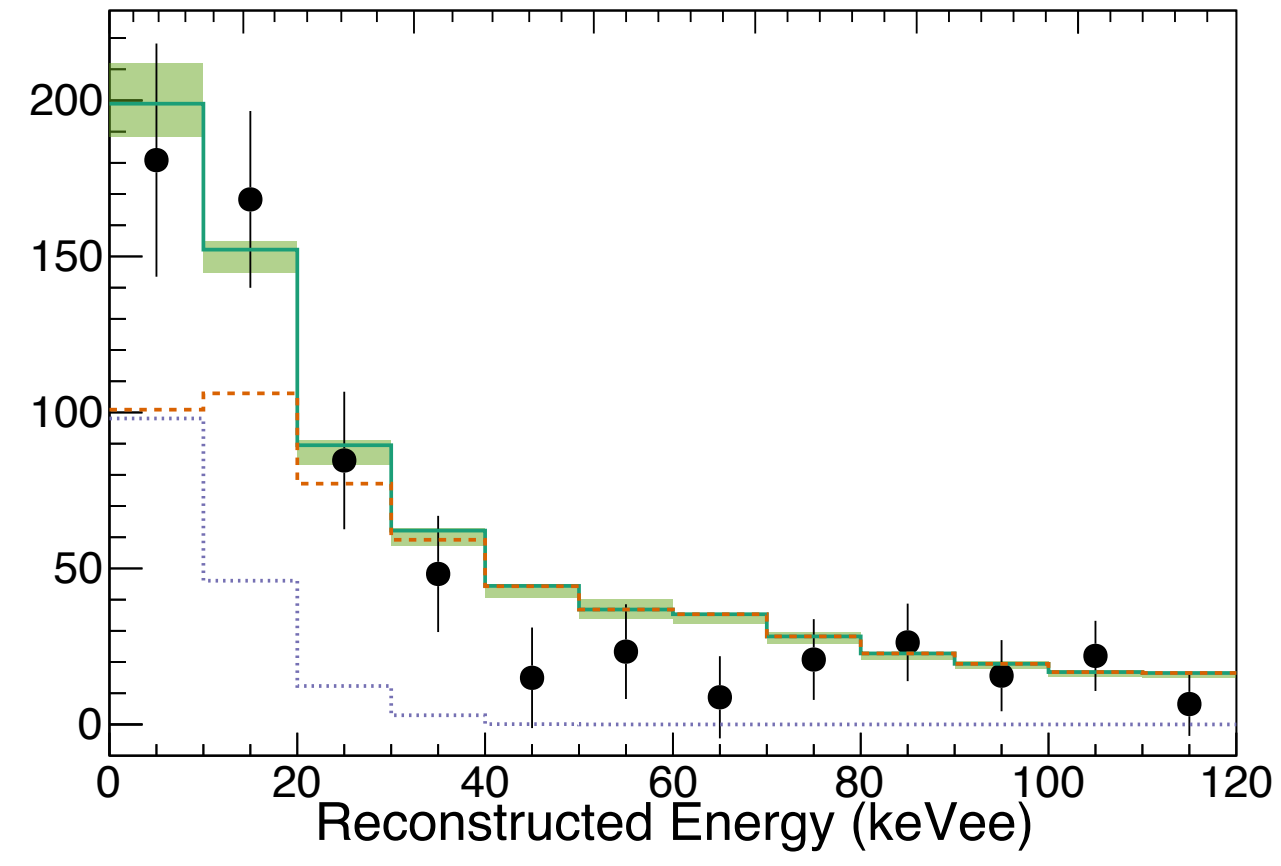
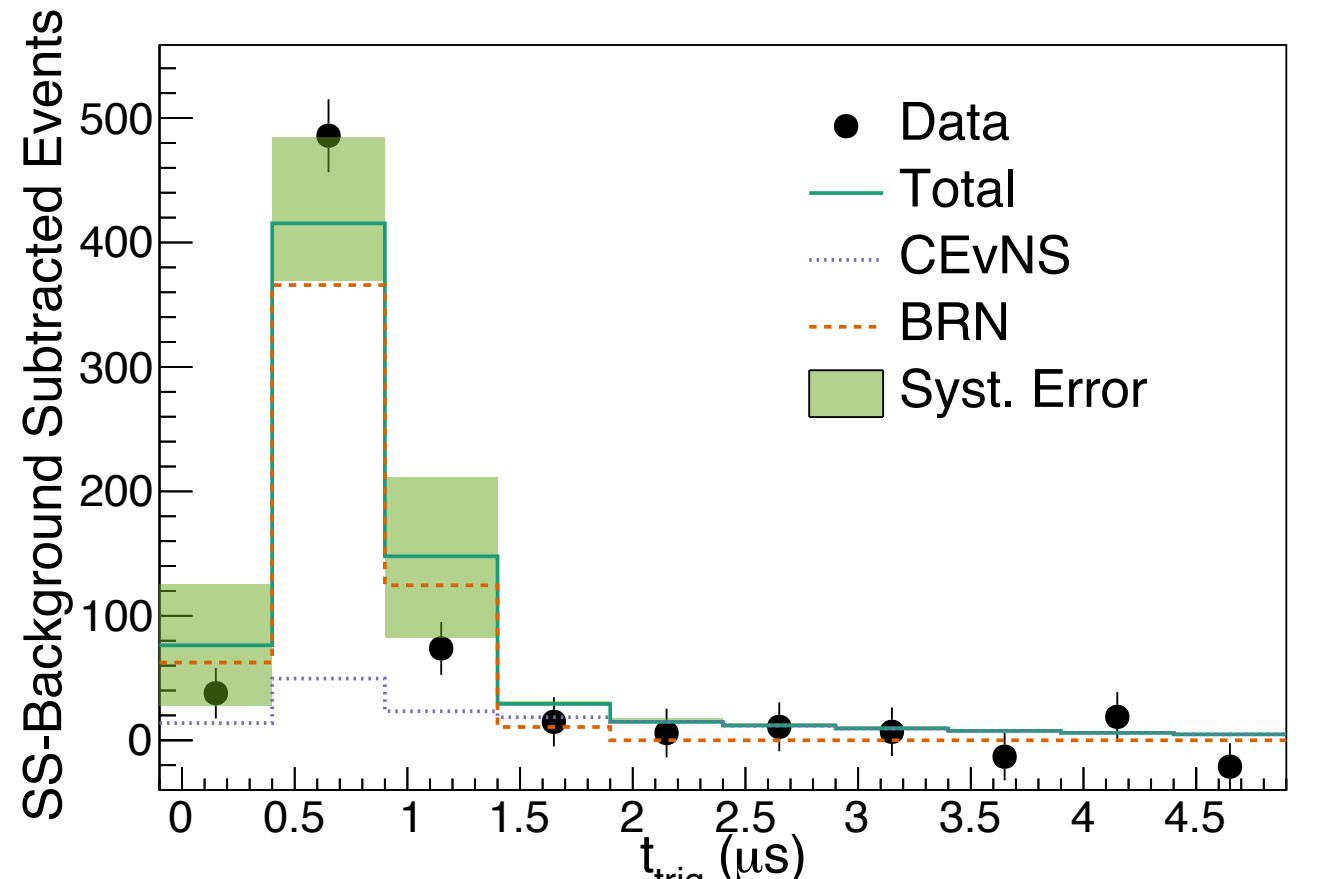
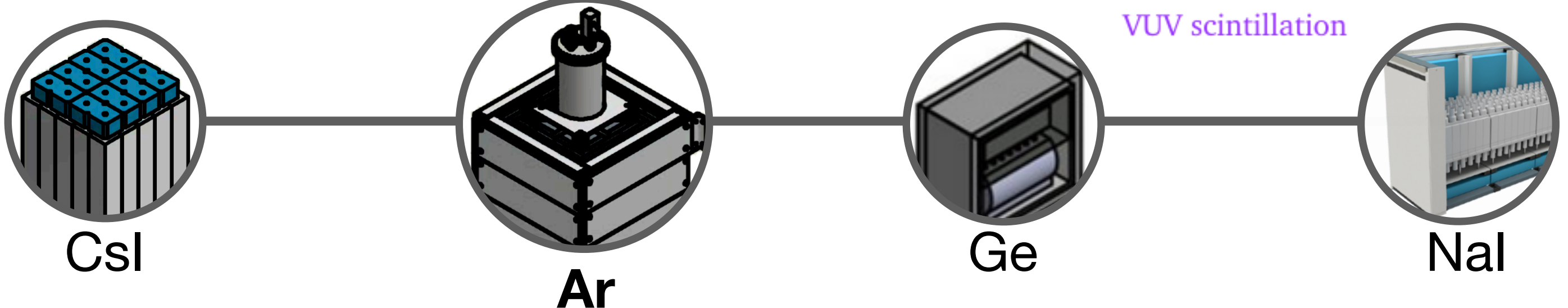
Energy deposited in Ar dimers decay → high-yield scintillation

^{39}Ar β α problem

Single-Triplet ratio of dimers a function of Recombination and Linear Energy Transfer → PSD

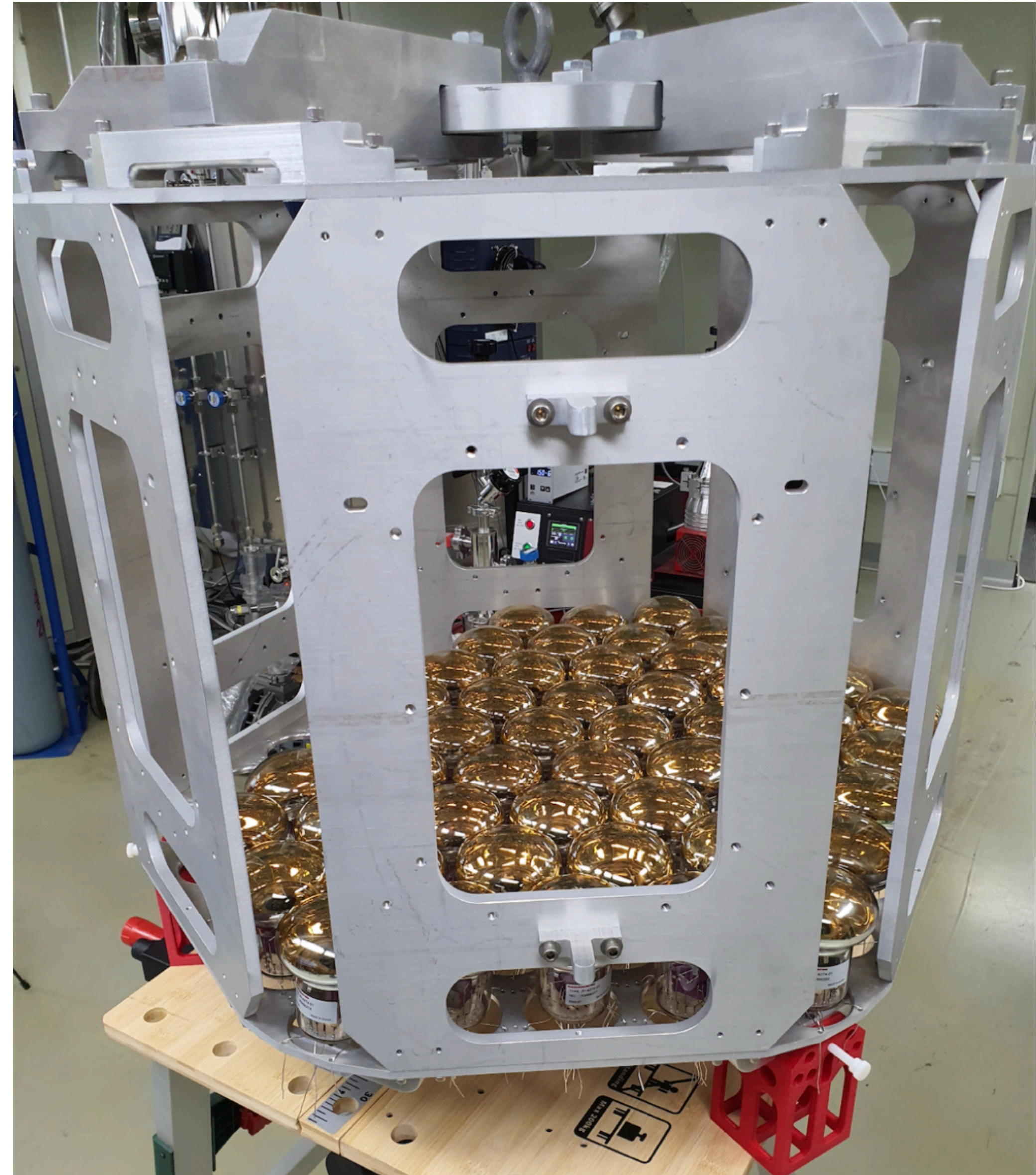
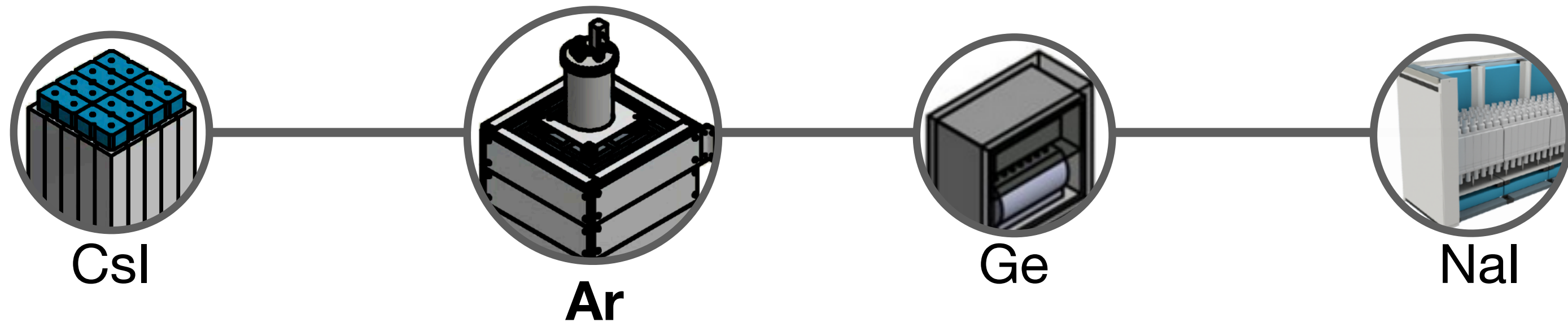


TPB wave-shifting to blue



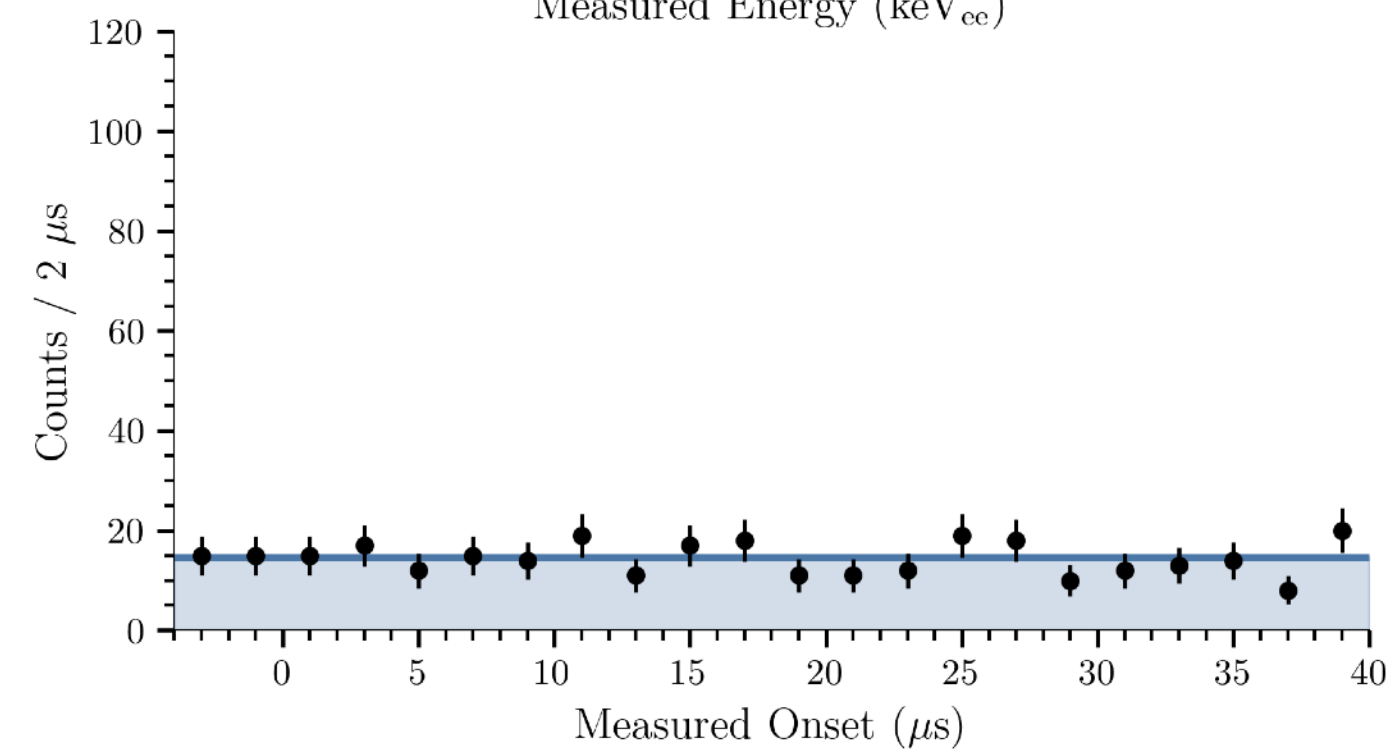
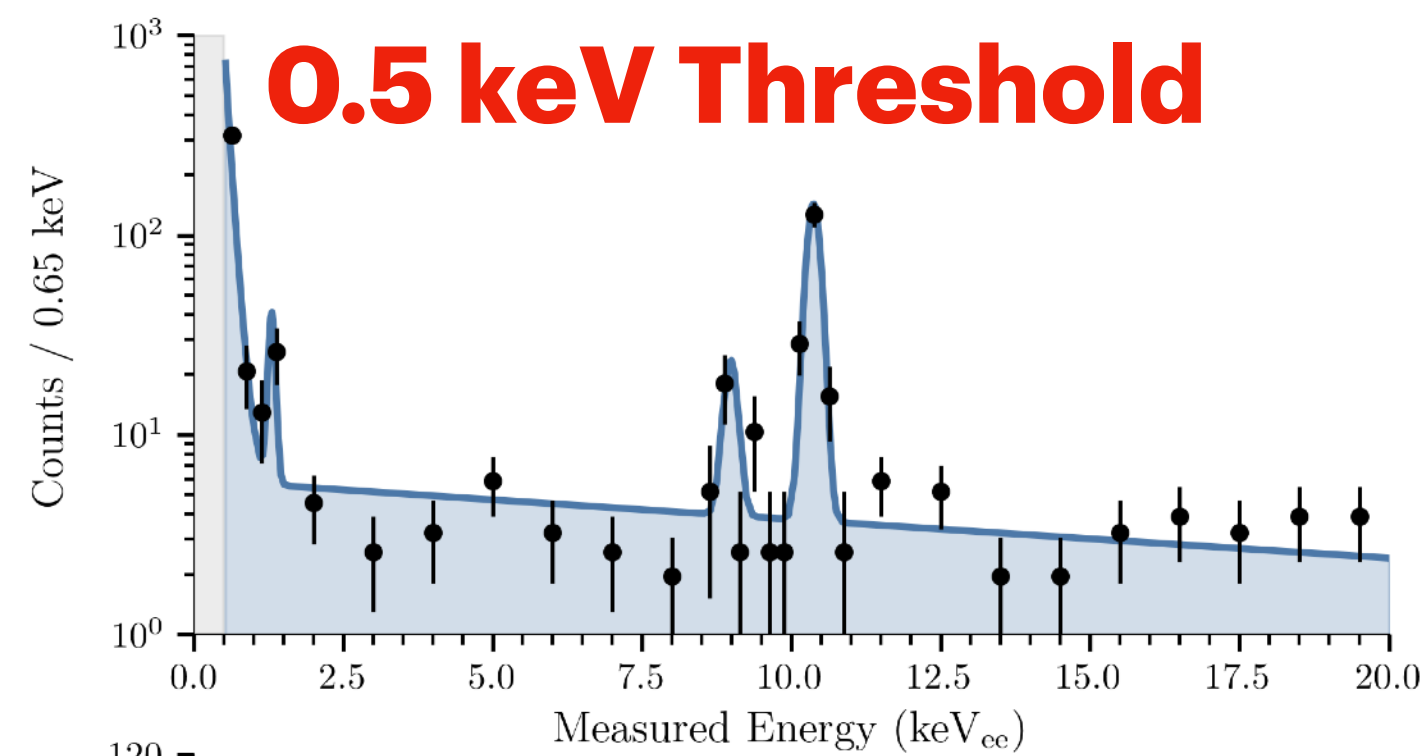
COH-Ar-750: Scintillation

- **Lighter targets see fewer events**
- Single phase 750-kg liquid argon detector
- Expect ~5,000 CEvNS counts/year
- **Can put liquid neon in CENNS-10!**

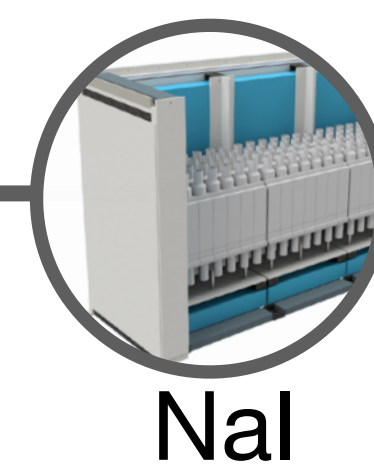
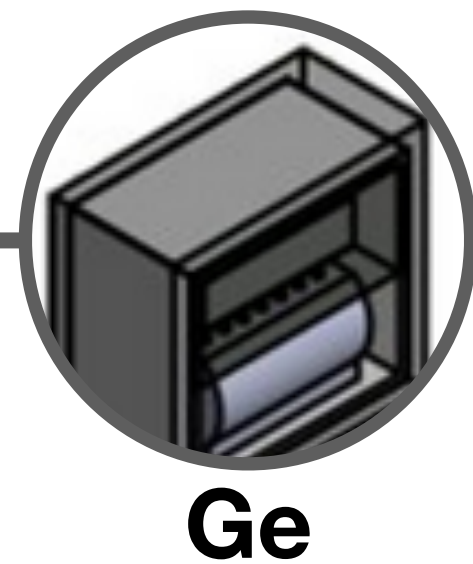
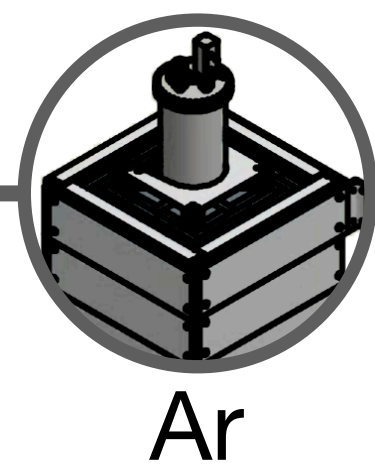
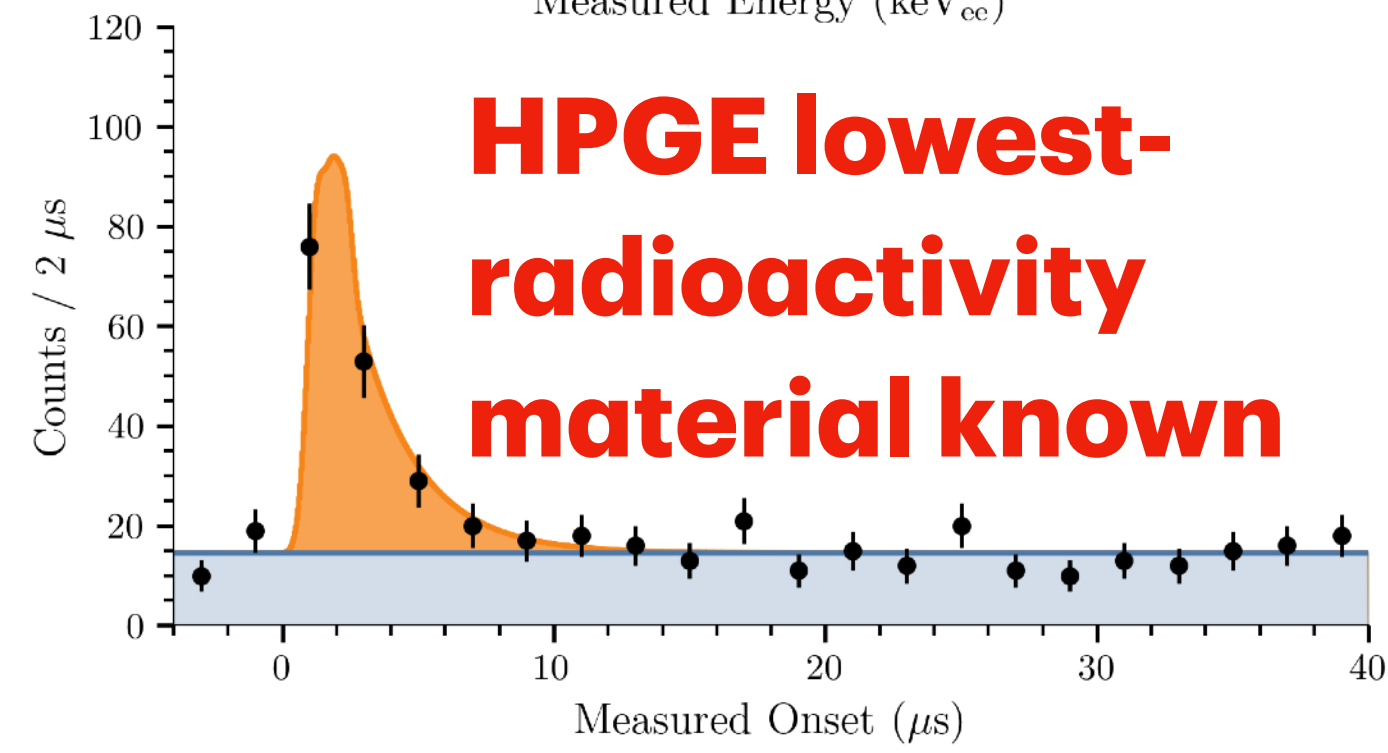
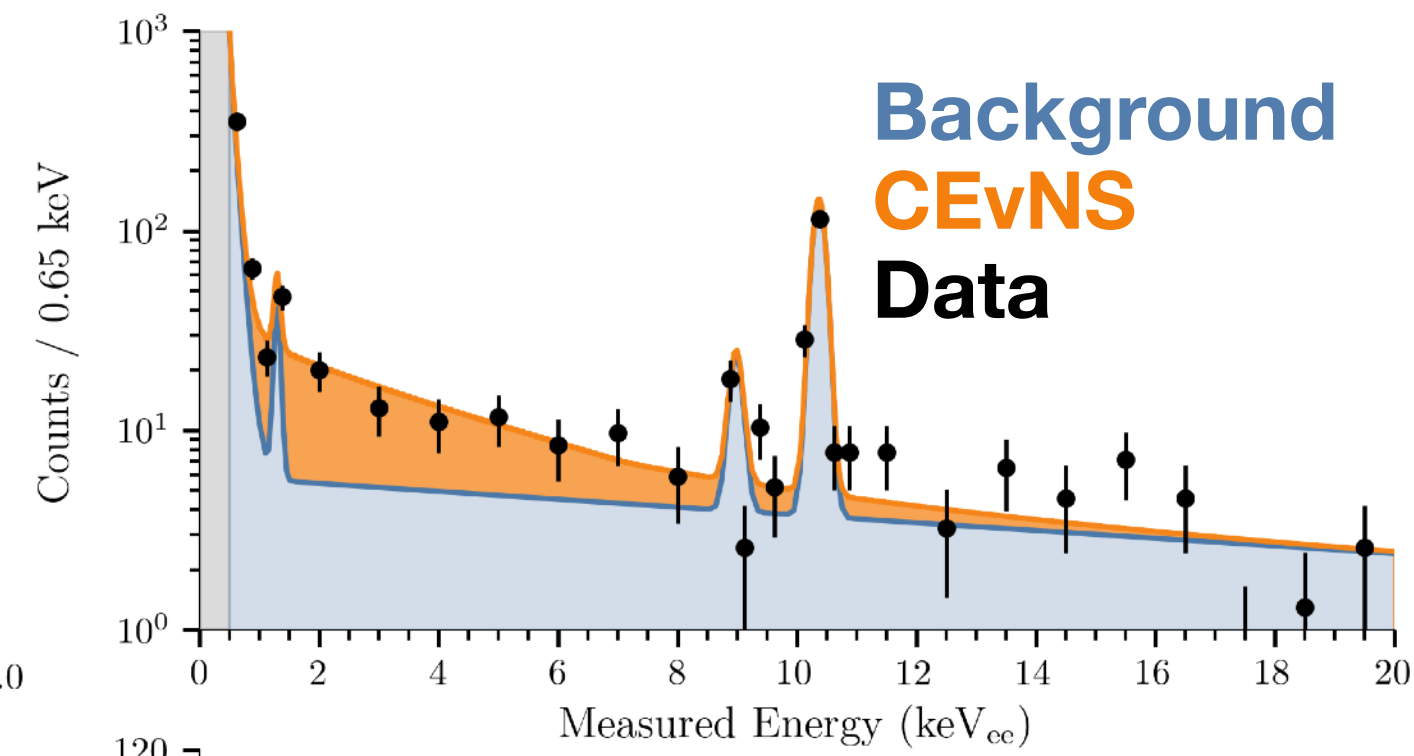


Ge-Mini: ionization

Beam-off



Beam-on



NaIvETE: Scintillation

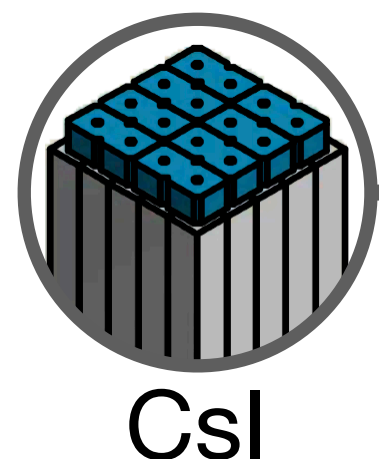
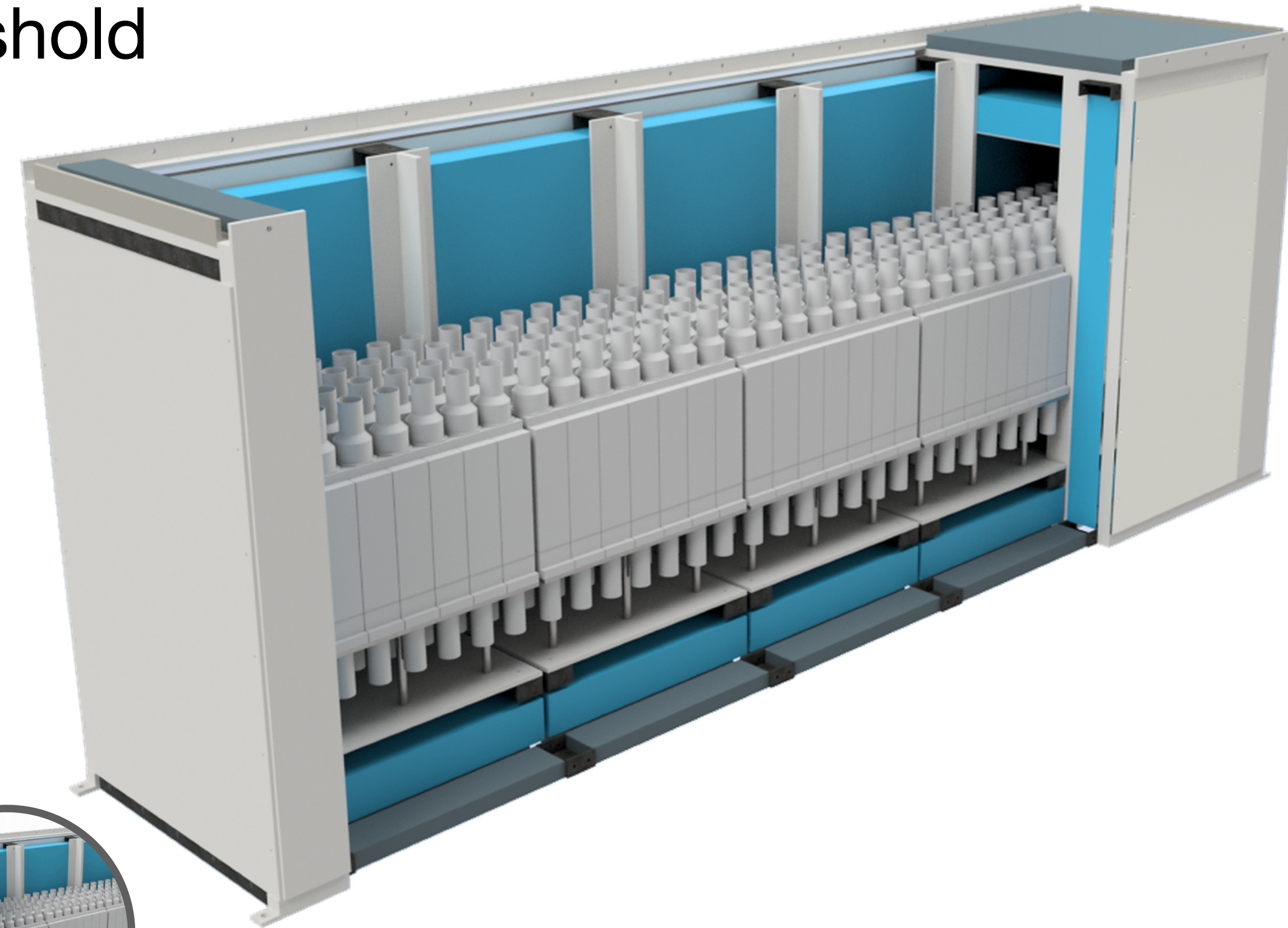
NaI ν -Experiment TonnE-scale

- Lightest target: ^{23}Na recoils w/3 keV_{ee} threshold

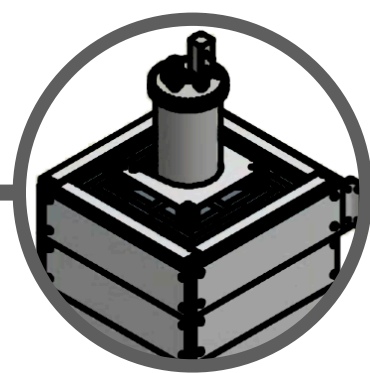
Backgrounds NOT super critical with pulsing

Na small part of target mass

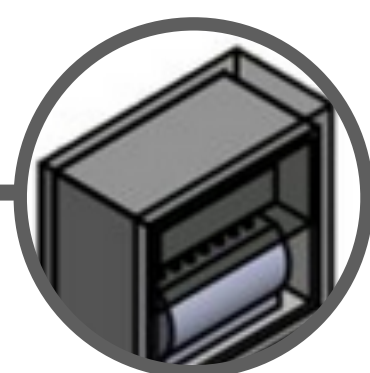
Tl-doping \rightarrow Faster response



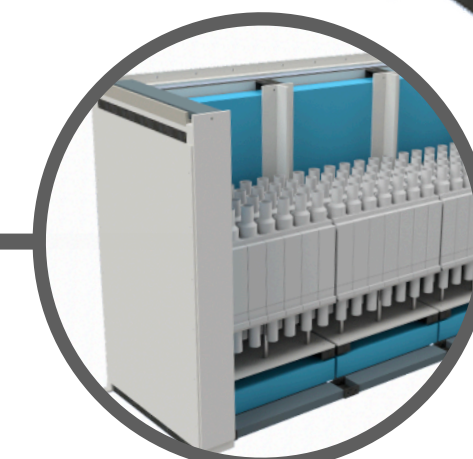
CsI



Ar

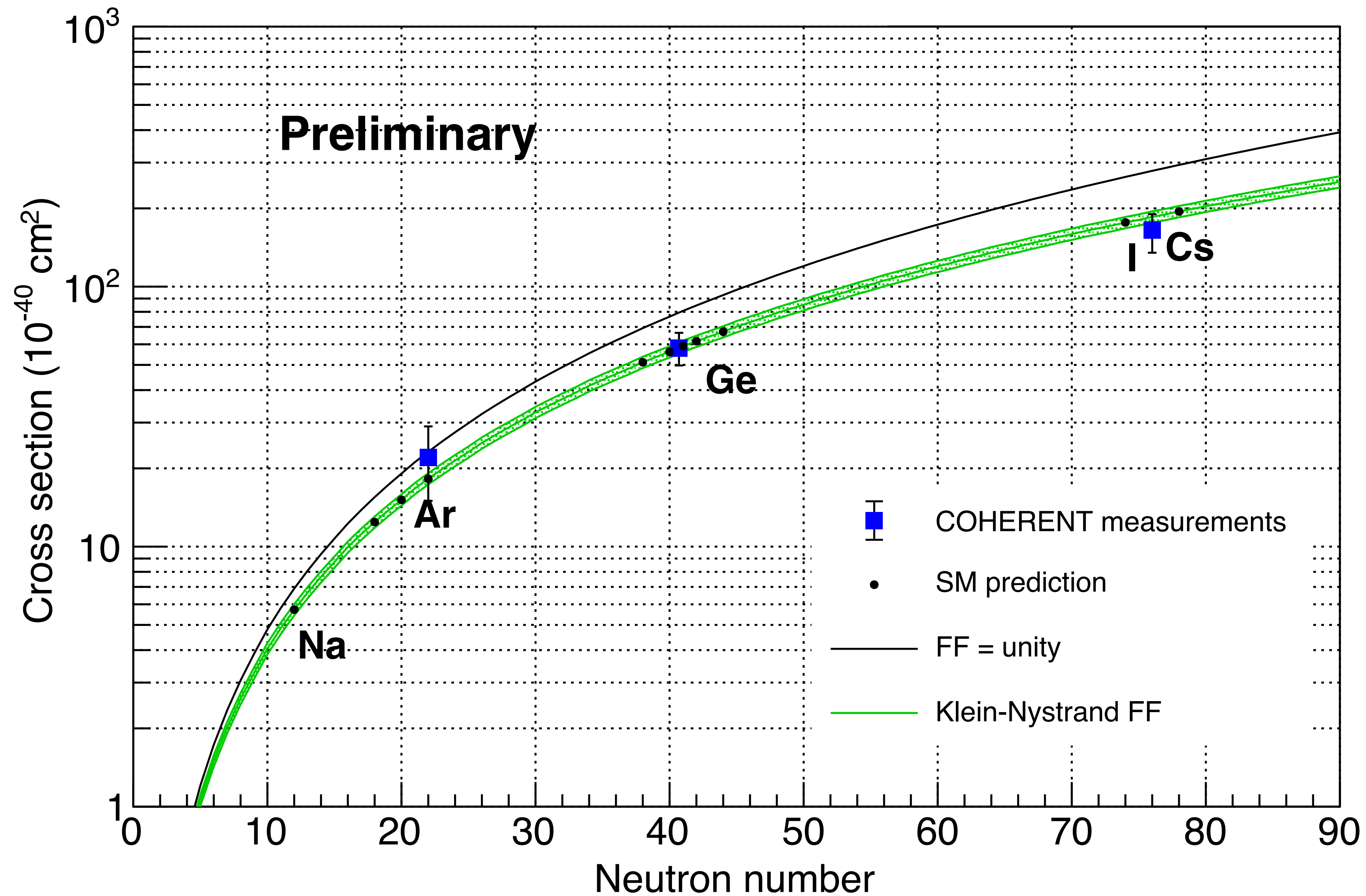


Ge



NaI

N^2 Dependence



Pulsed Sources Guidelines

- **Intrinsic backgrounds** not critical
- Fast pulsing a huge advantage (**$< 1 \mu\text{s}$**)
- **Fast Response** Detectors a requirement
- Rules out most **Bolometric style detectors** (e.g. Bubble Chambers, Super-CDMS style, etc)
- Faster detectors often compromise with only measuring a part of the energy deposited
 - **Careful Quenching Factor Calibrations a must!**

Creative work-arounds possible!

Other Spallation Sources



at Lund (Sweden) under construction,
first neutron production planned in 2027
full capacity of 5 MW at 14 Hz: 2030s
beam width: 2.86 ms
target material: tungsten

Planned CEvNS projects:

- Cryogenic undoped CsI
- Point contact HPGe detectors
- High-pressure TPC (GanESS)
with Ar, Kr, Xe

(exploration of j-PARC as alternative)



located at Dongguan, upgrade to 0.5 MW
at 25 Hz set to be completed this year
beam width: 0.5 ms
target material: tungsten

Planned CEvNS project: CICENNS
with 300 kg of CsI crystals,
Commissioning this year

CEvNS around the world

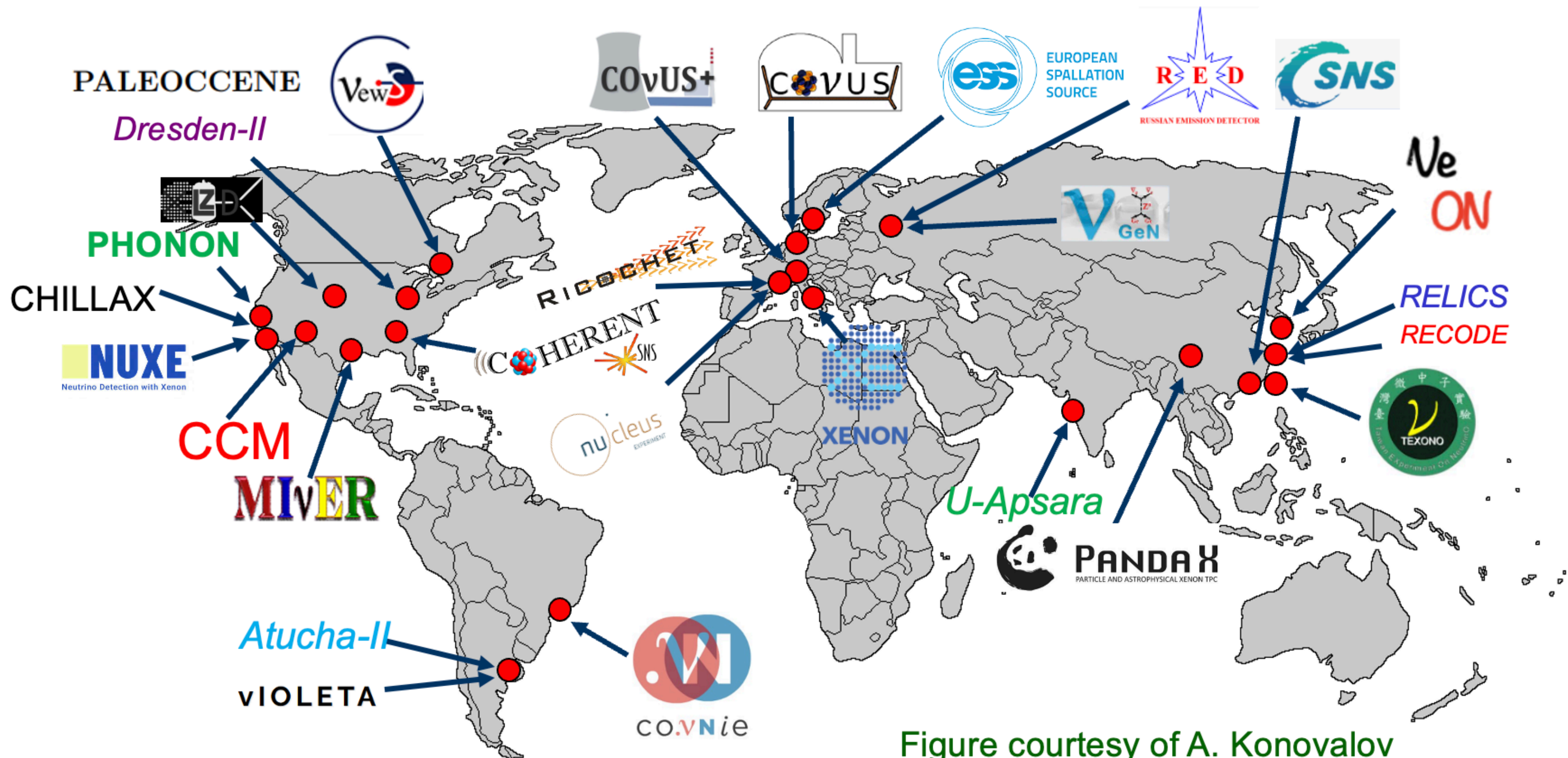
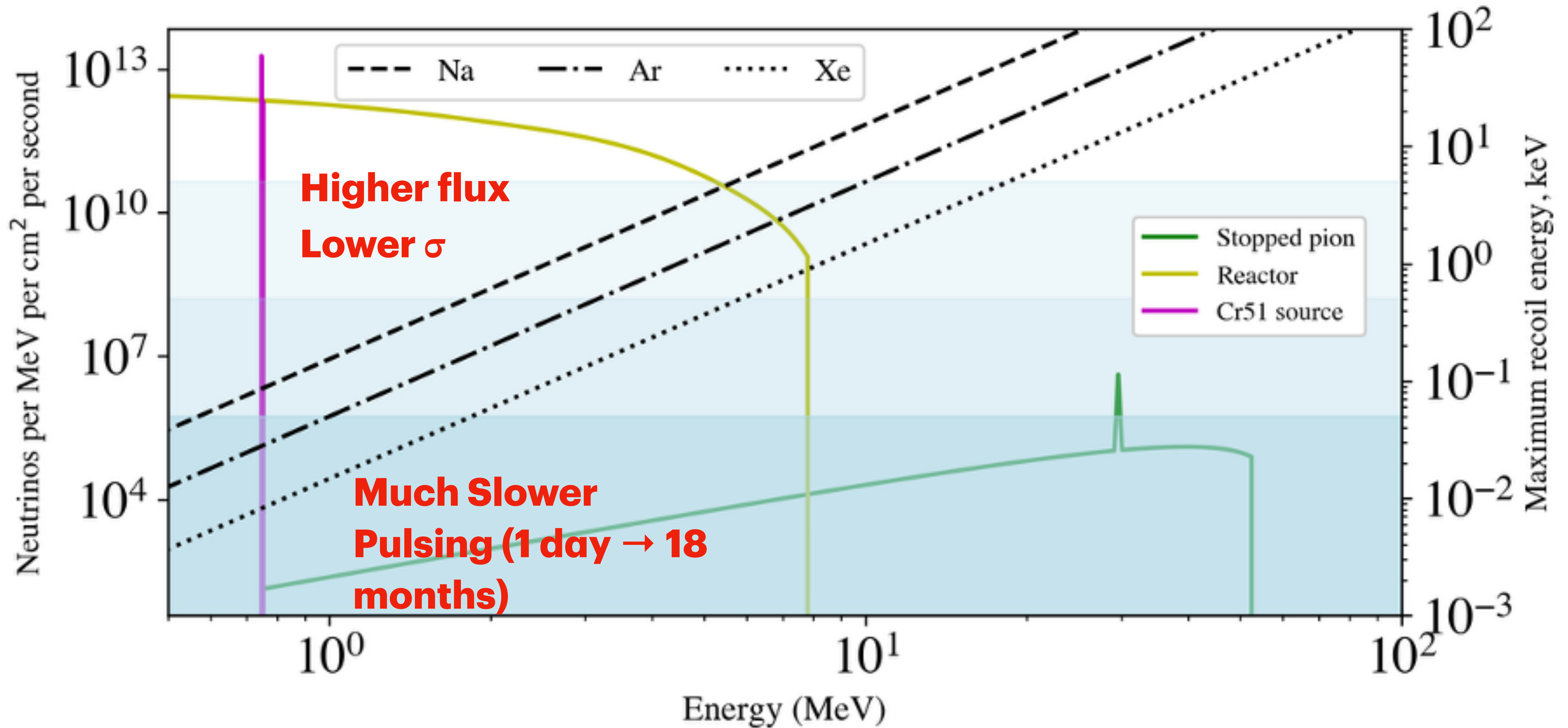
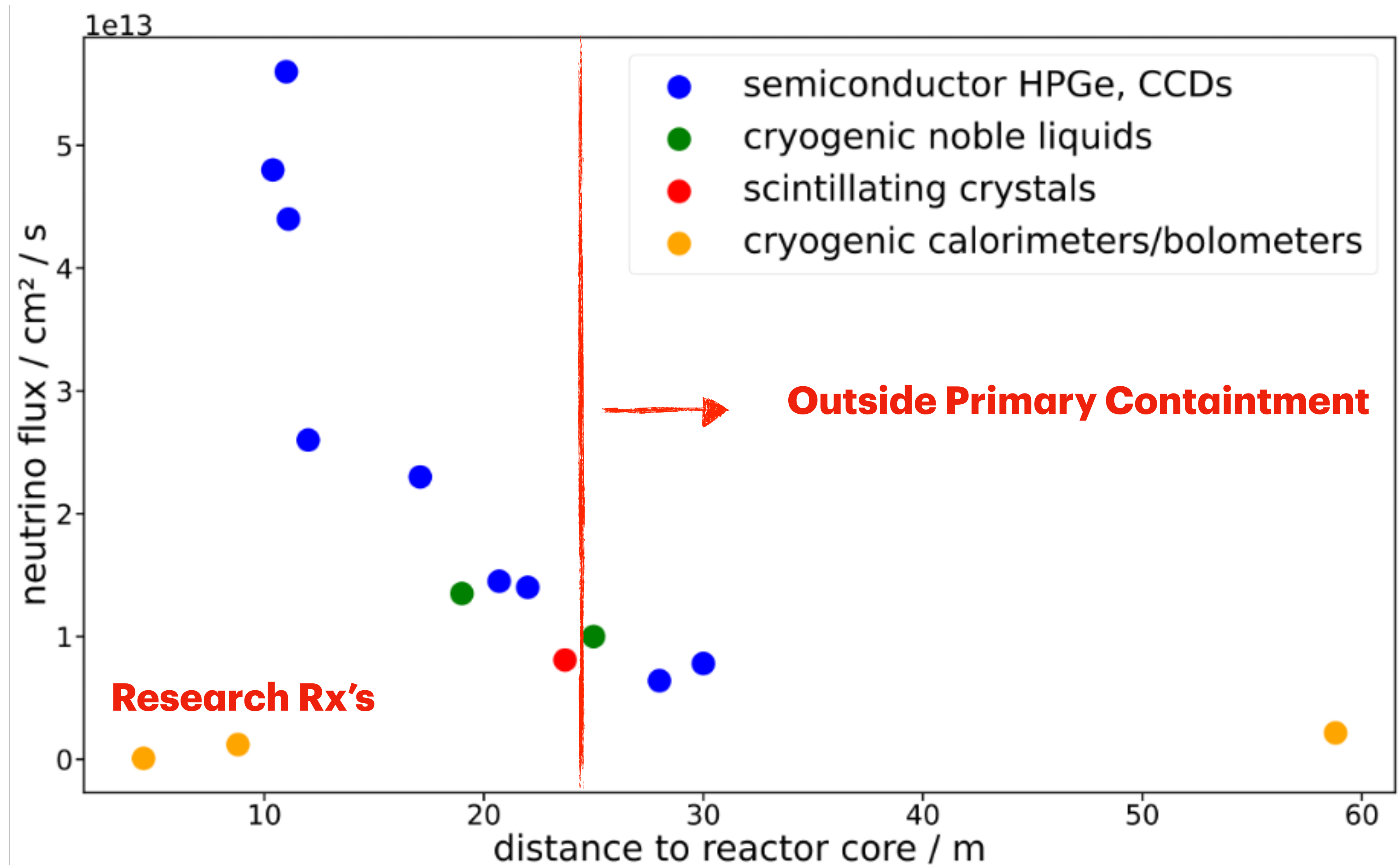


Figure courtesy of A. Kononov

Anthropogenic Sources



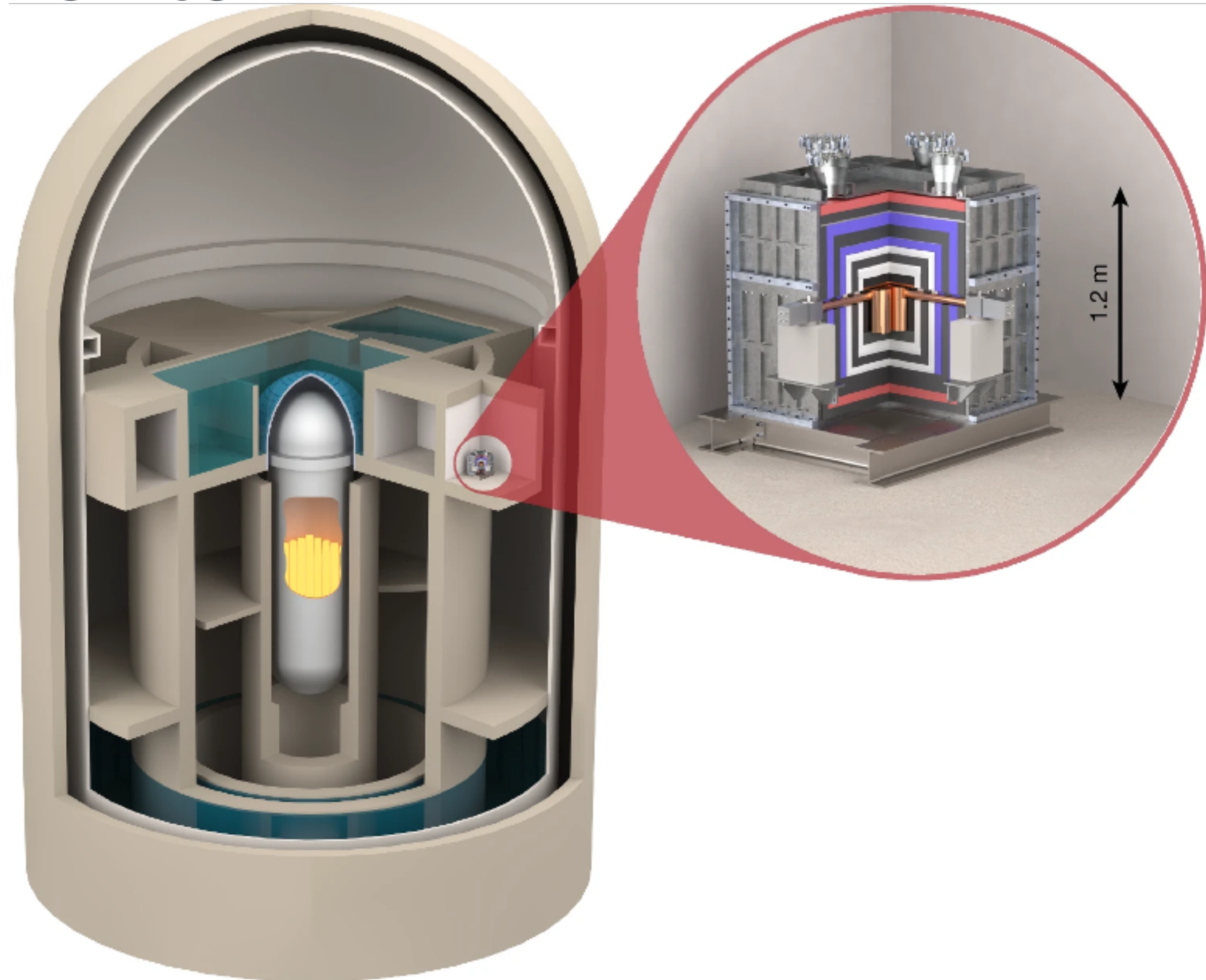
CEvNS at Reactors



Reactor Experiments

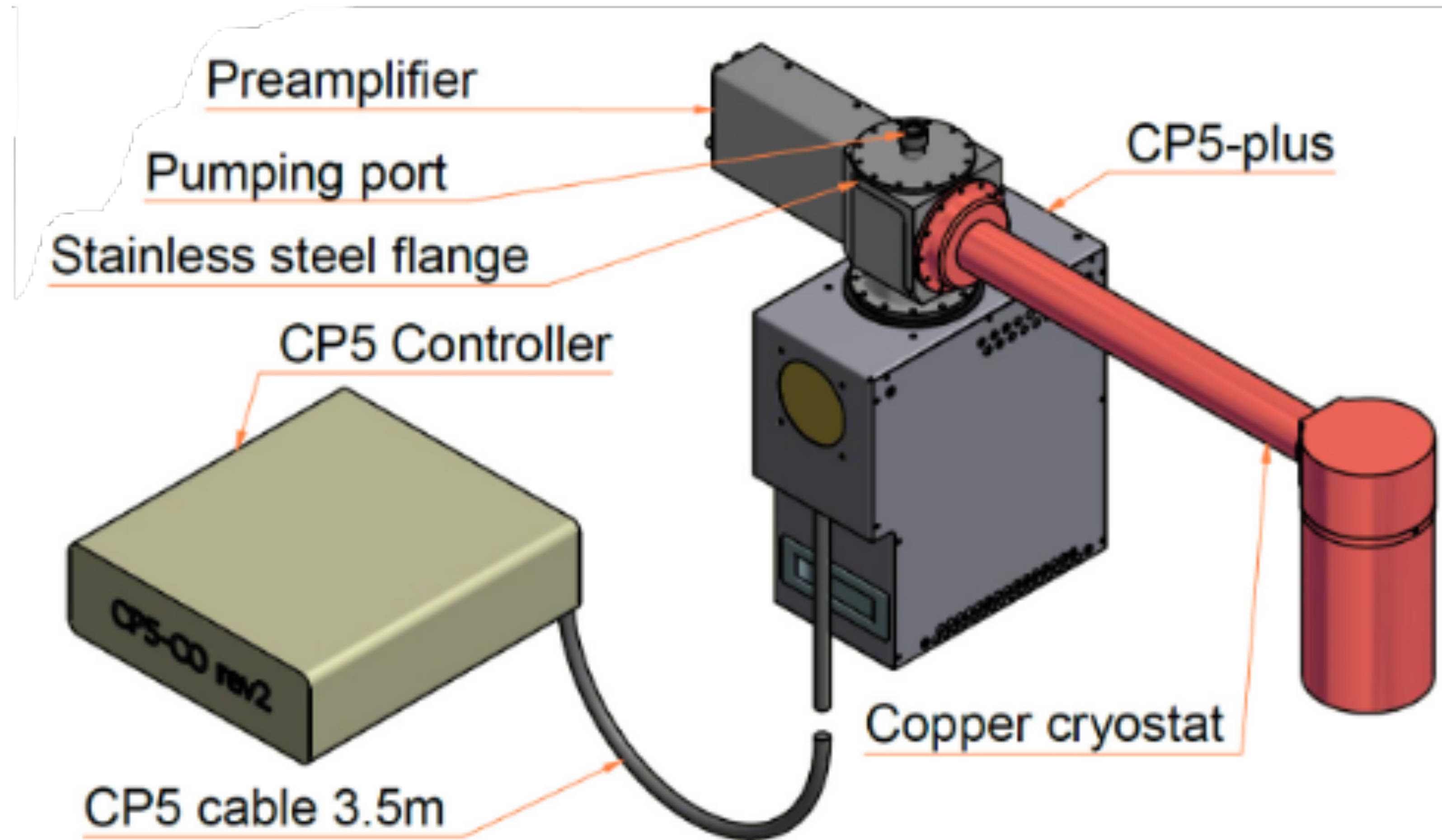
CONUS+

- 20 m to core $\sim 10^{13}$ ν / cm^2 /s
- 7.4 m.w.e. overburden
- >20 cm Pb (γ 's)
- >30 cm Poly (neutrons)
- Borated Poly (thermal neutrons)
- Plastic Scintillator (μ veto >99.9%)



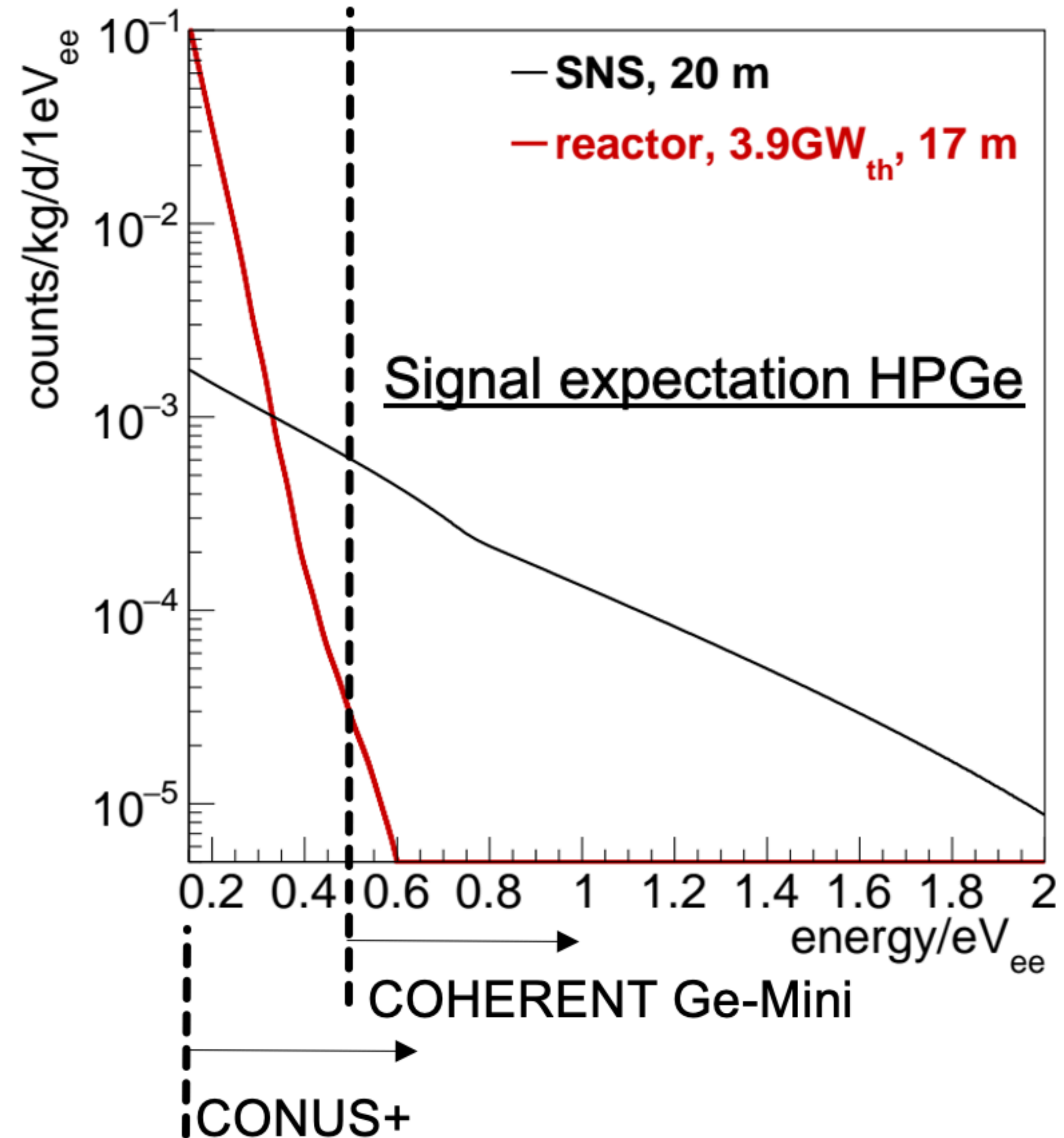
CONUS+ Ge detectors

- Ionization detector (careful QF measurements required)
- 2.83 kg detectors
- 160-180 eV thresholds



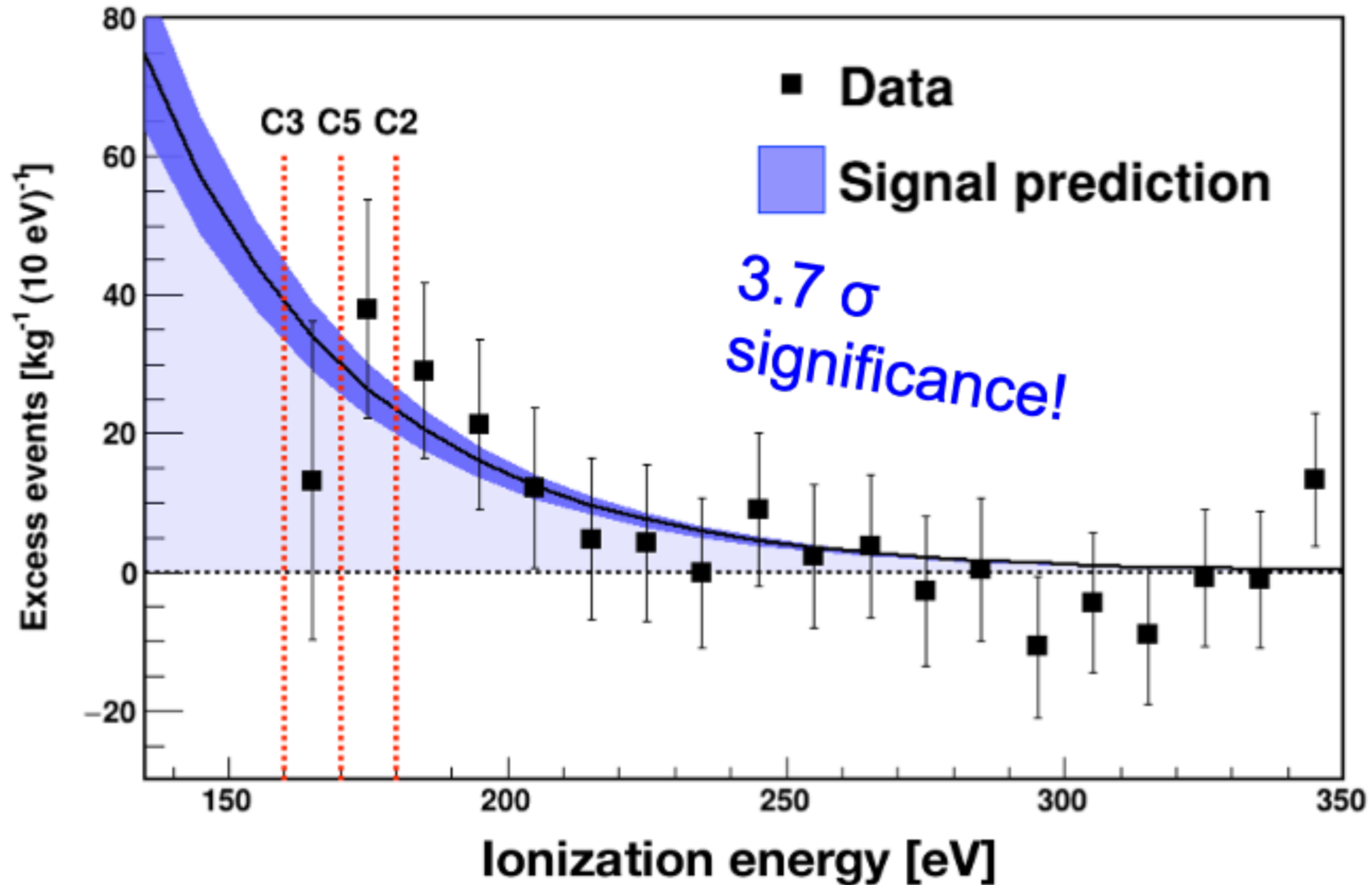
Reactor Experiments

CONUS+

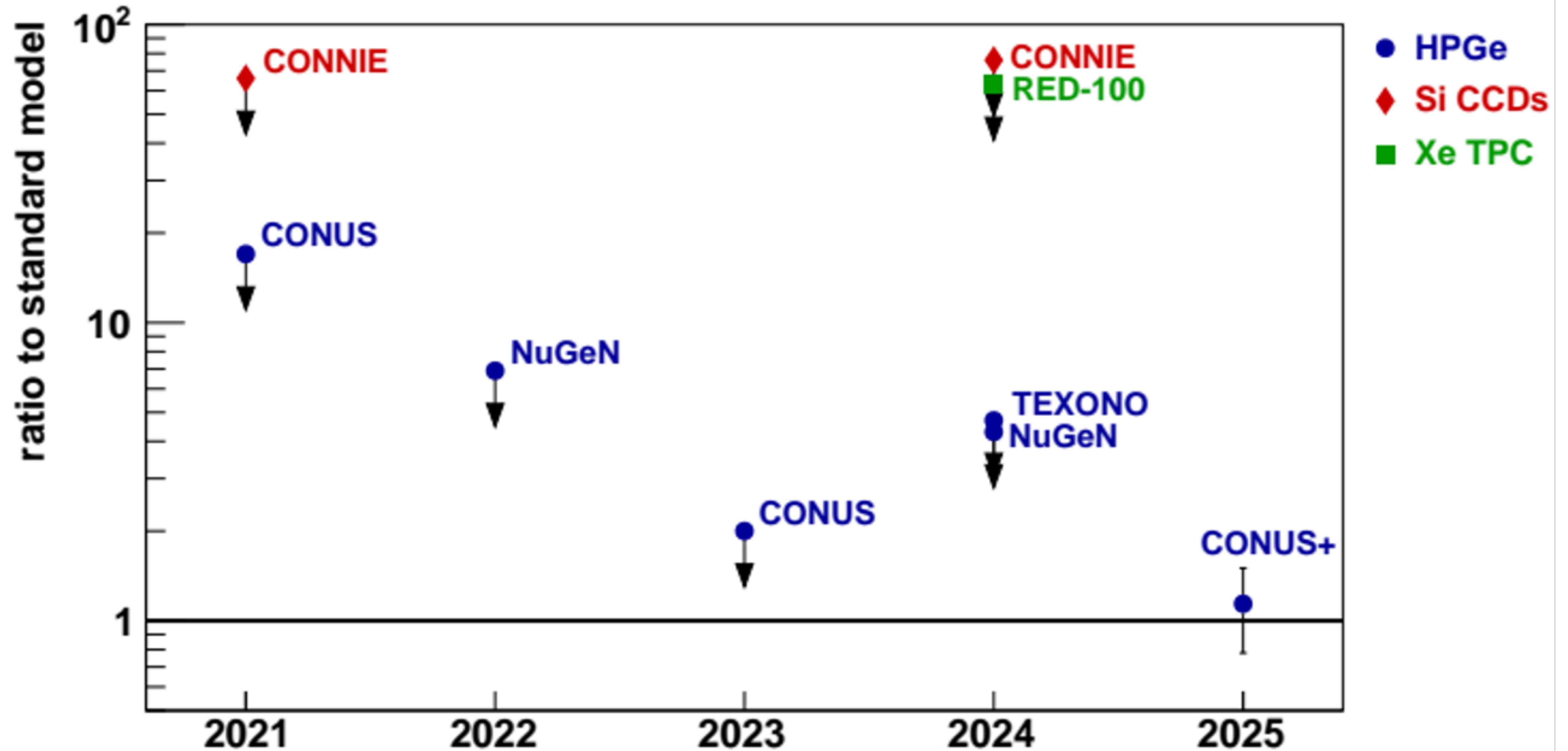


CONUS+ Results

Ratio to SM:
 1.14 ± 0.36



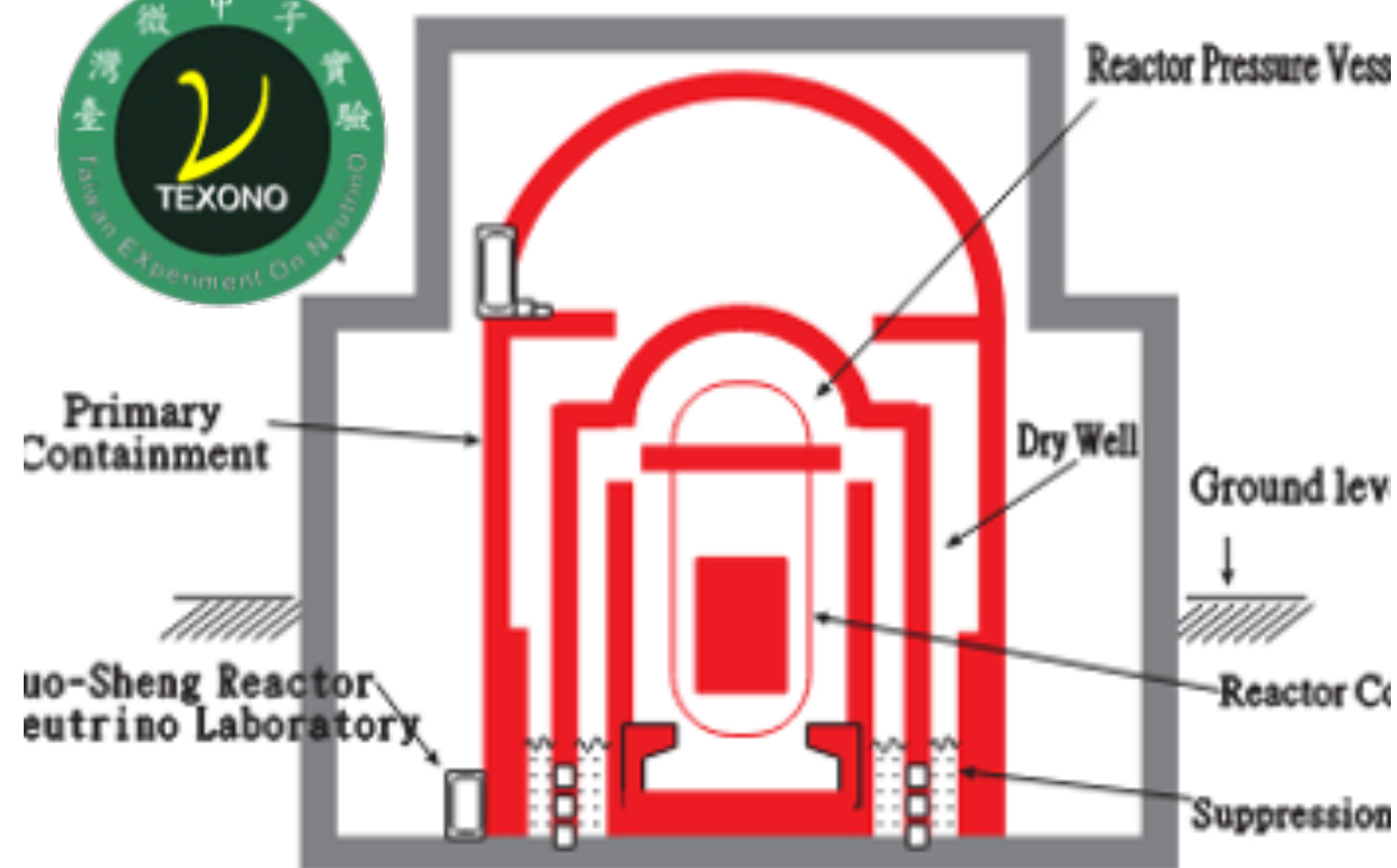
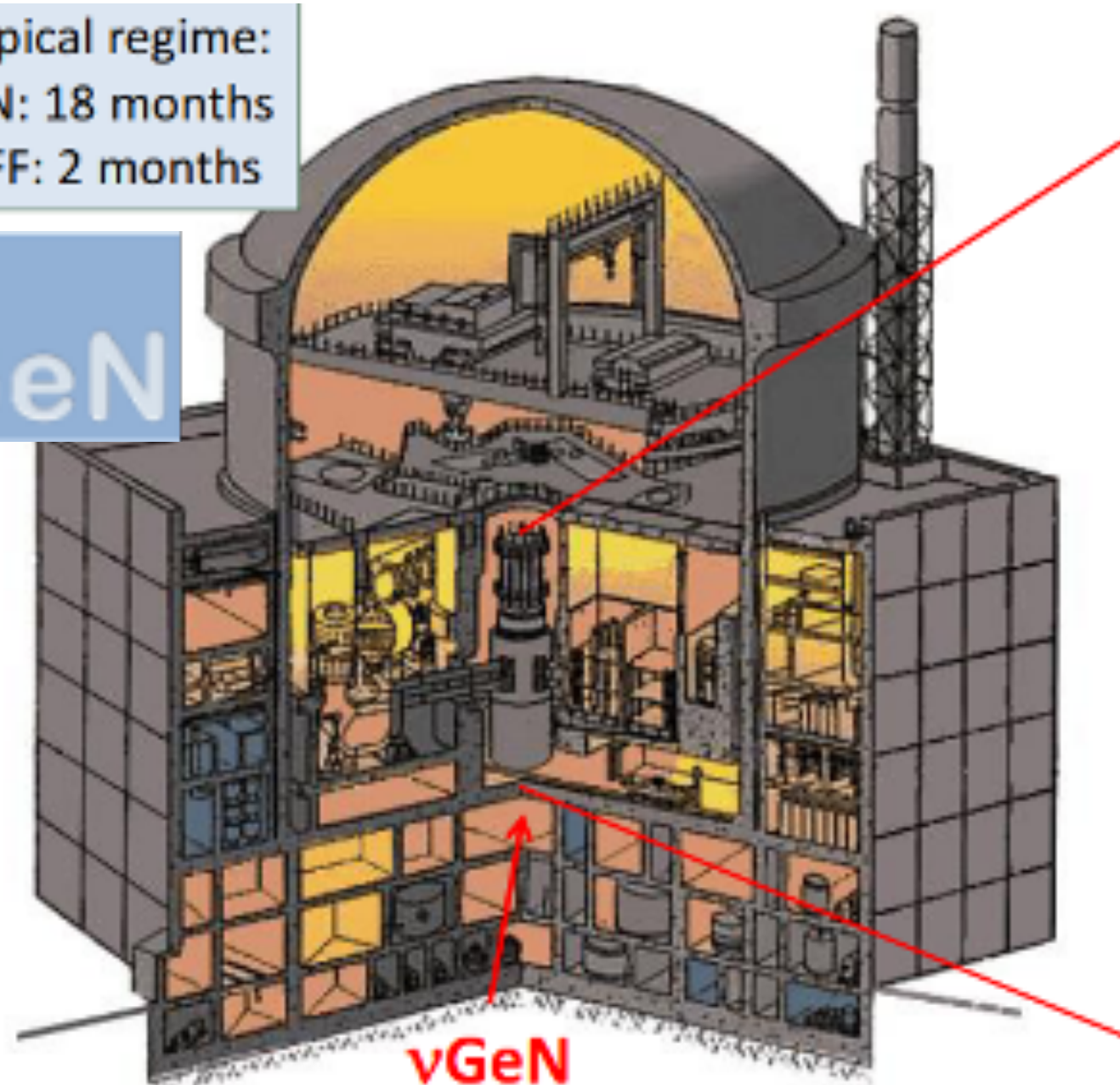
Reactor CEvNS Status



HPGE CEvNS at Reactors

Typical regime:
ON: 18 months
OFF: 2 months

vGeN



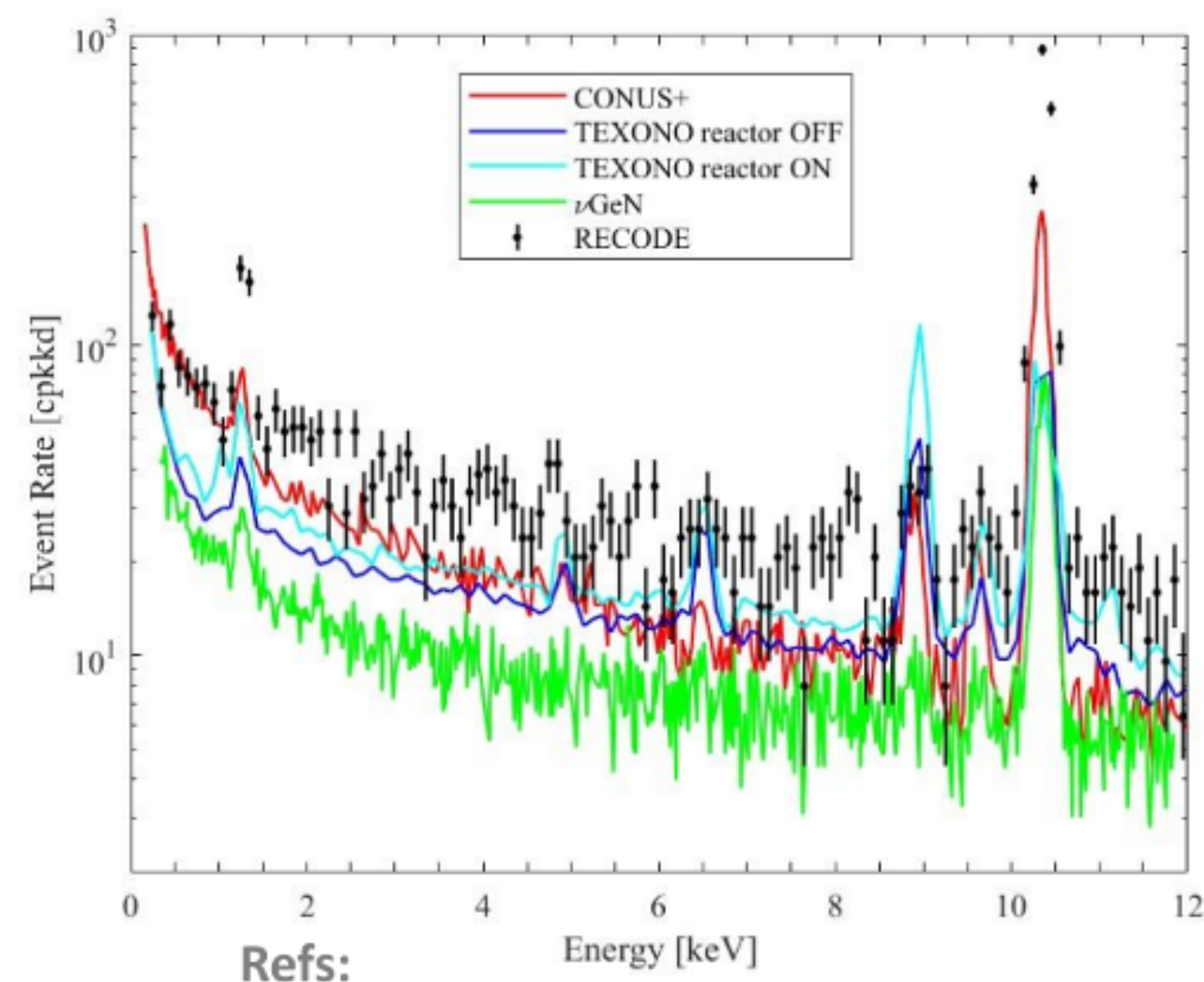
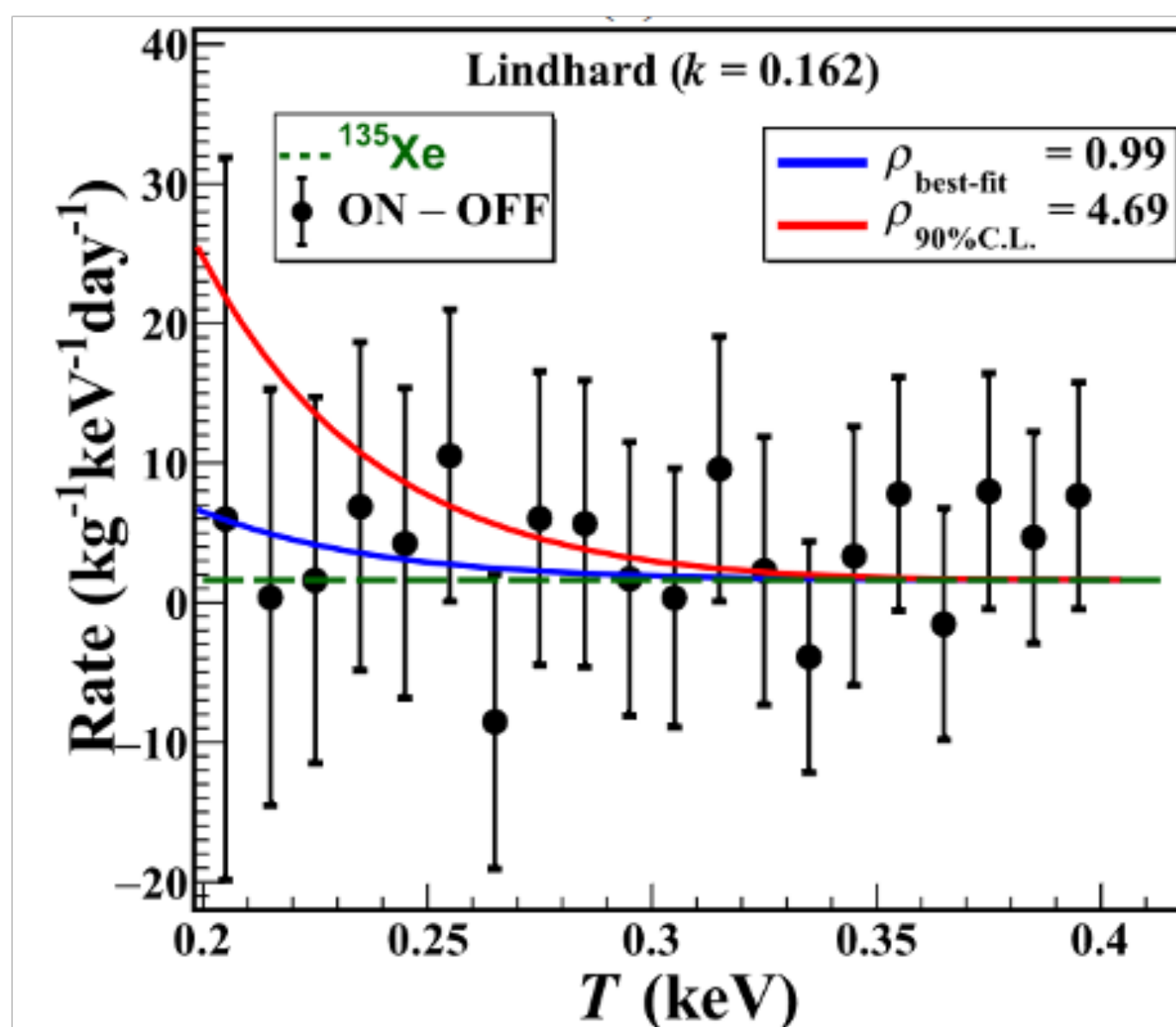
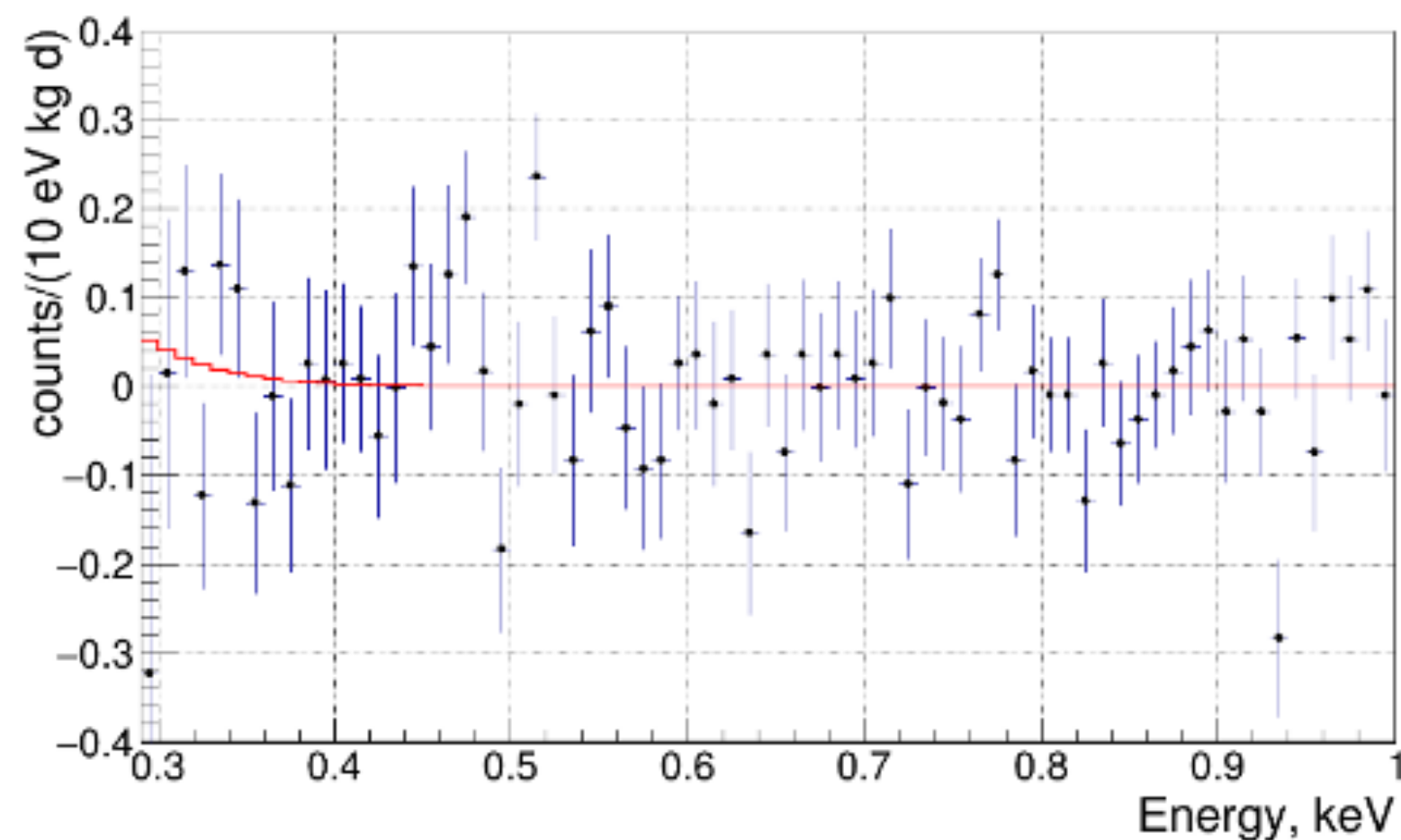
RECODE

Sanmen, China

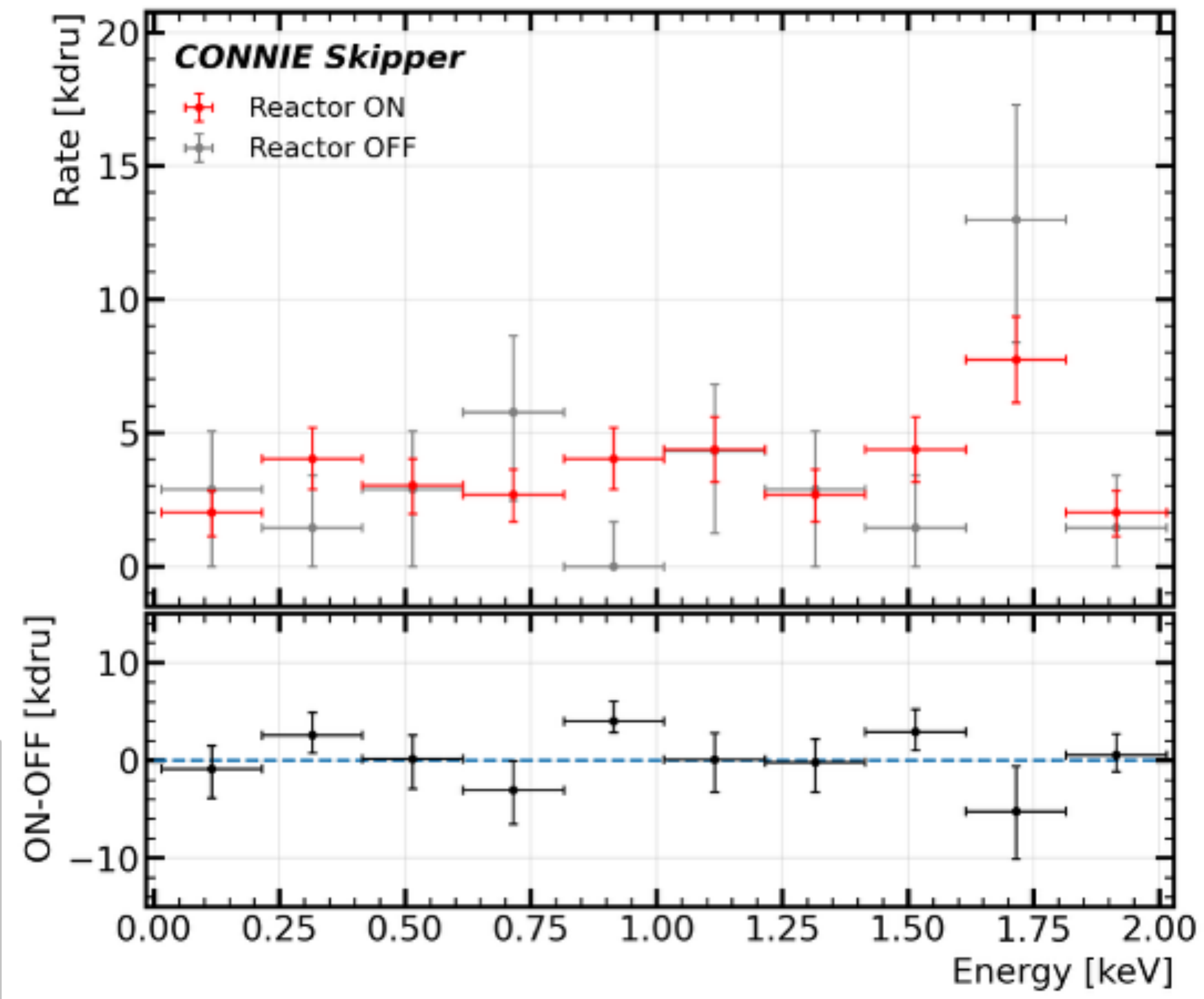
different distances to the reactor core (11 m, 22 m, (7 m))

Start of data taking: Oct 2025

Current achieved threshold:
210/220 eV_{ee}

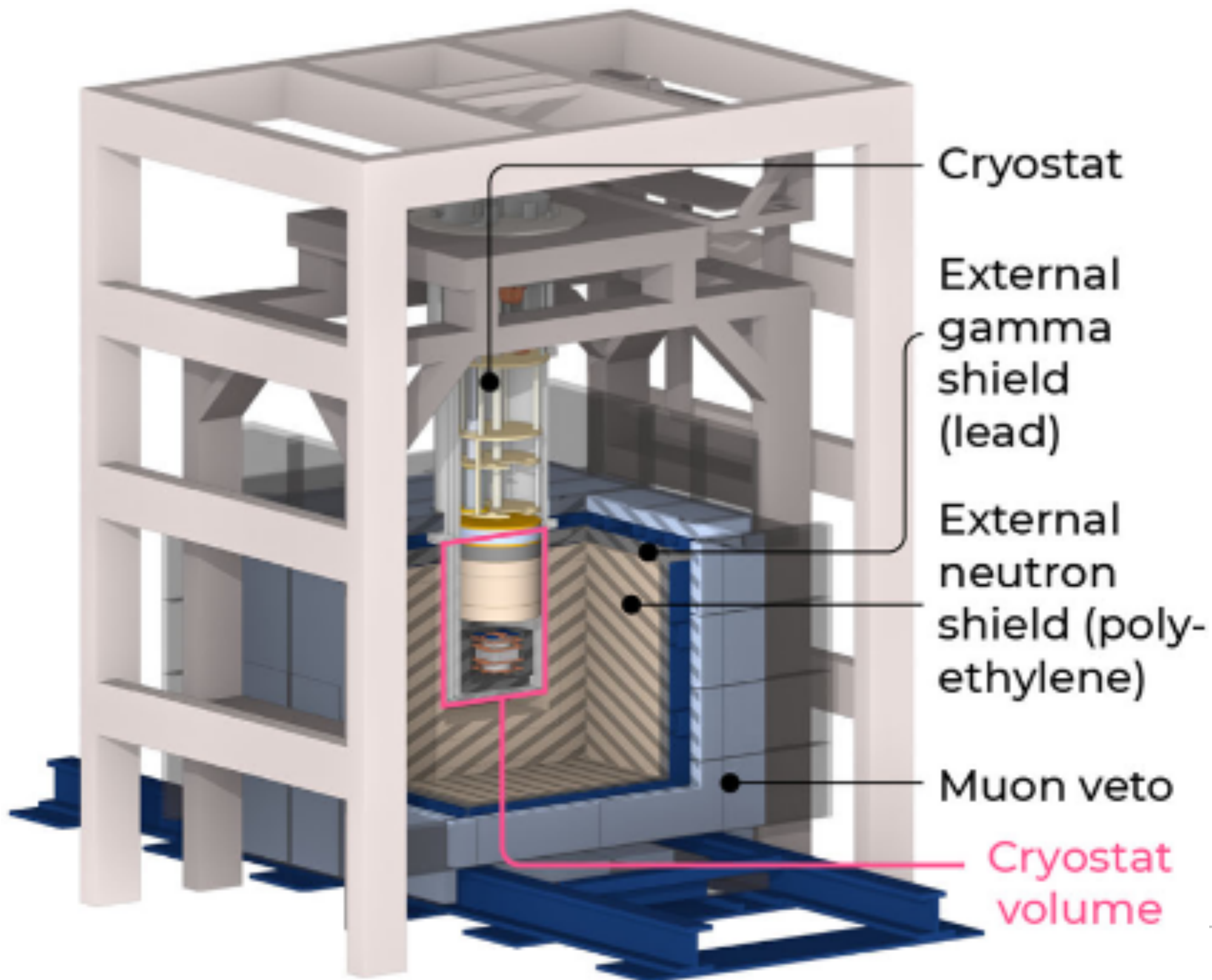


CCDs at Reactors

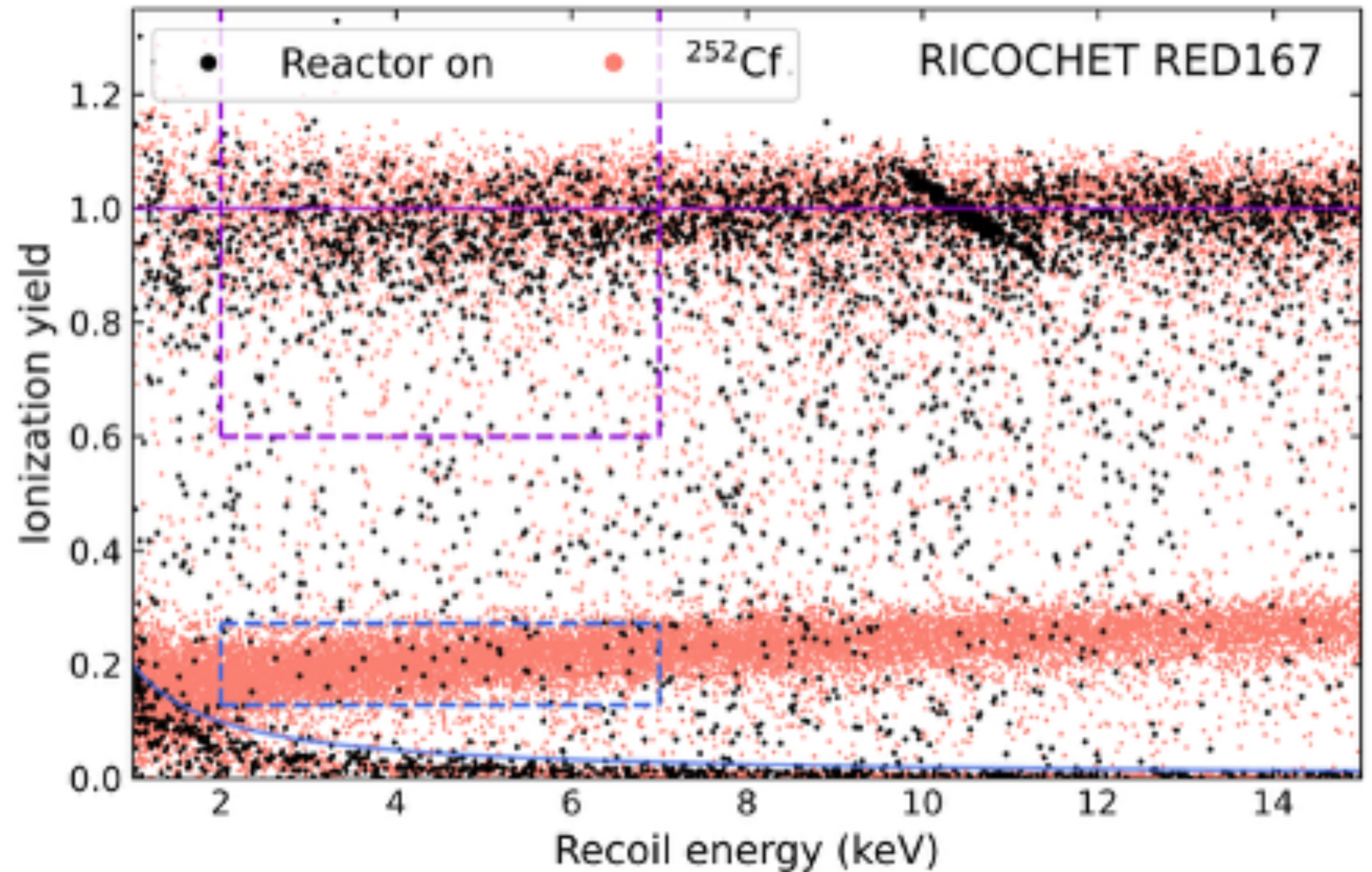


Bolometers at Reactors

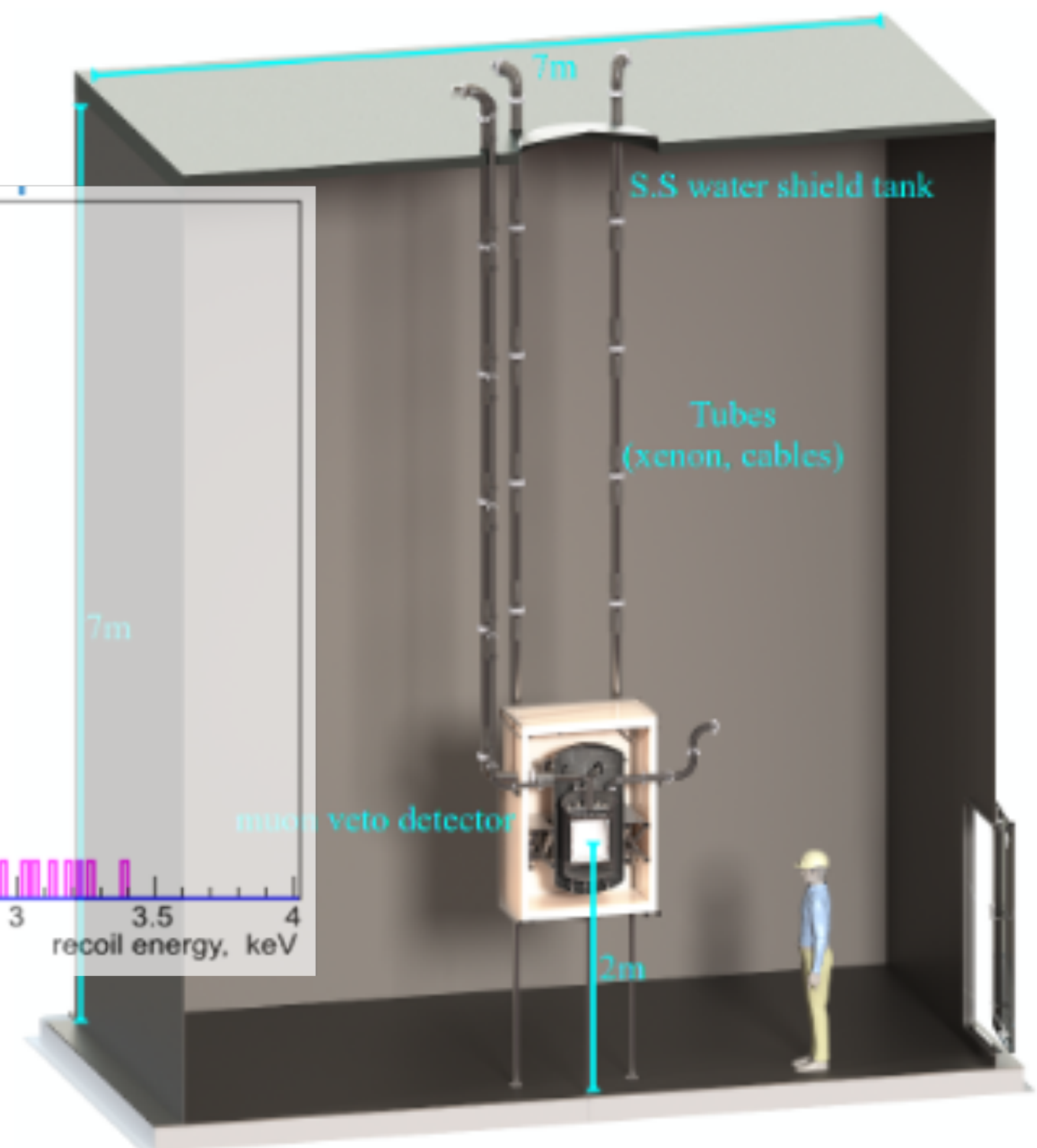
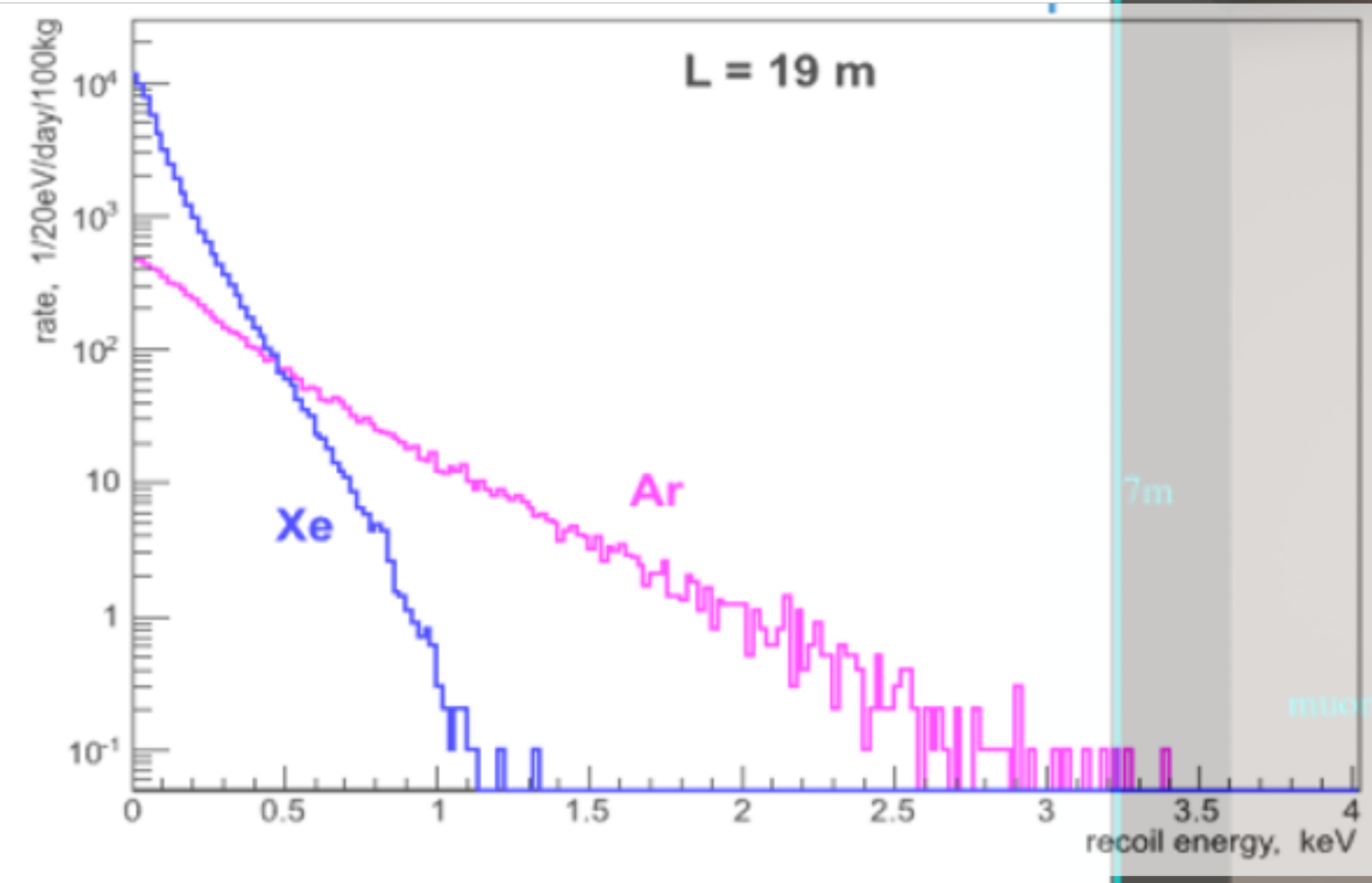
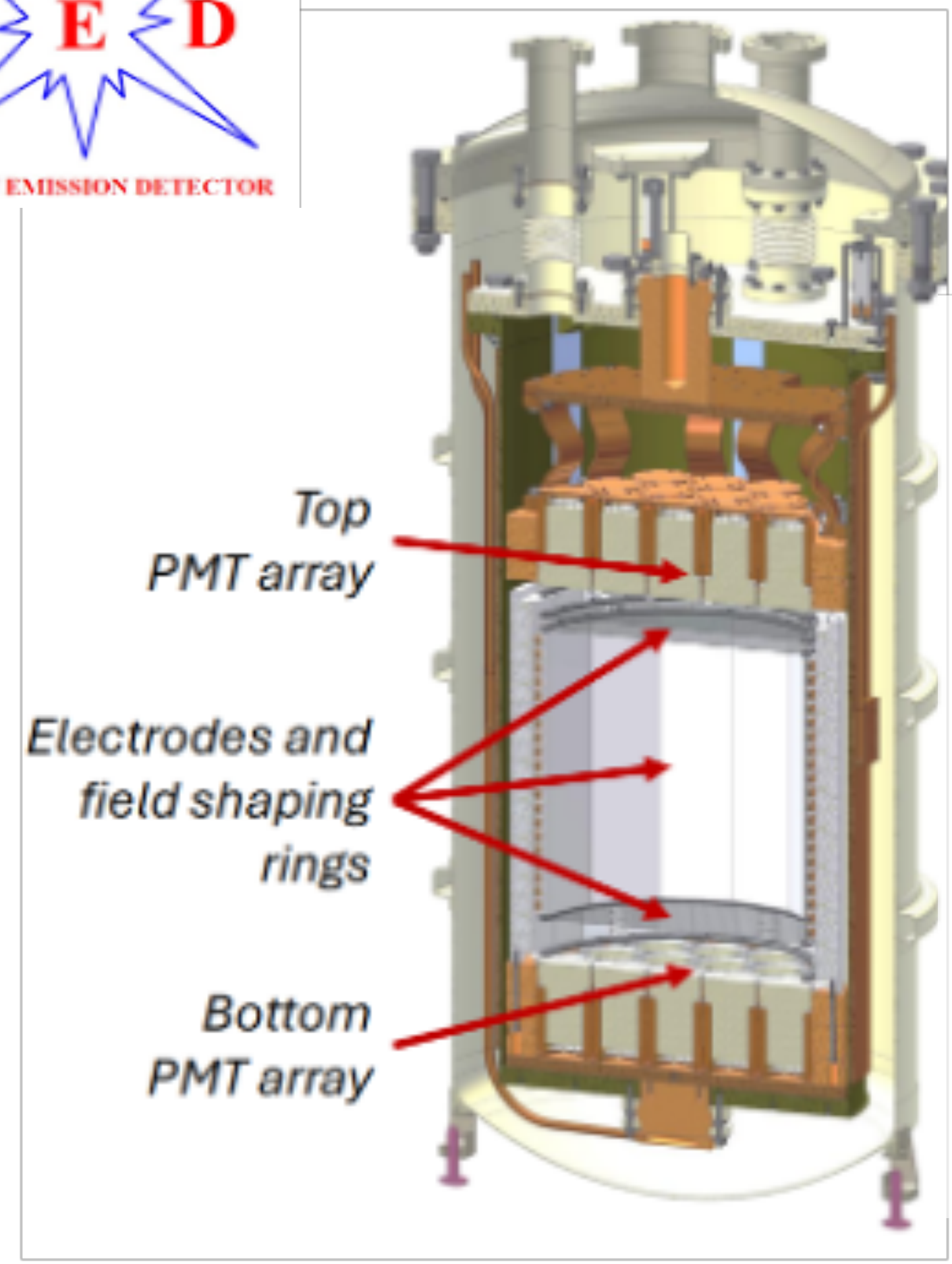
RICOCHET



ionization **and** phonon channel → bkg rejection



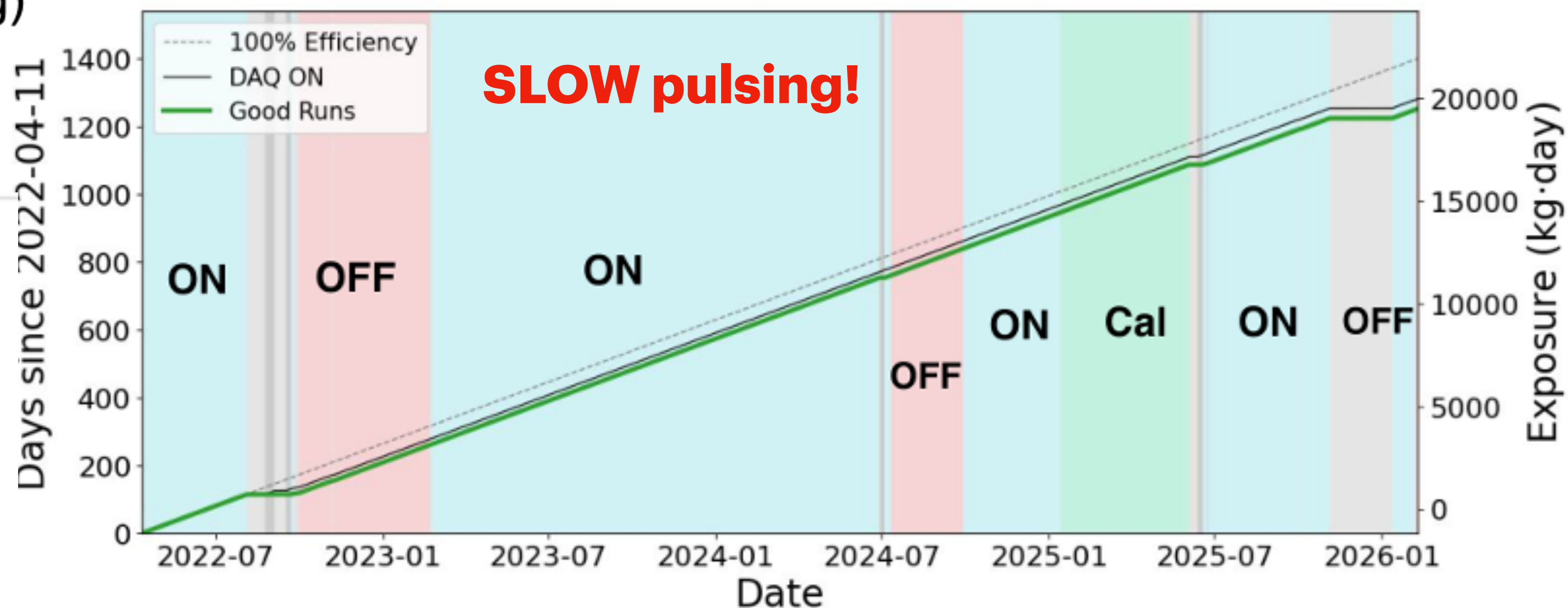
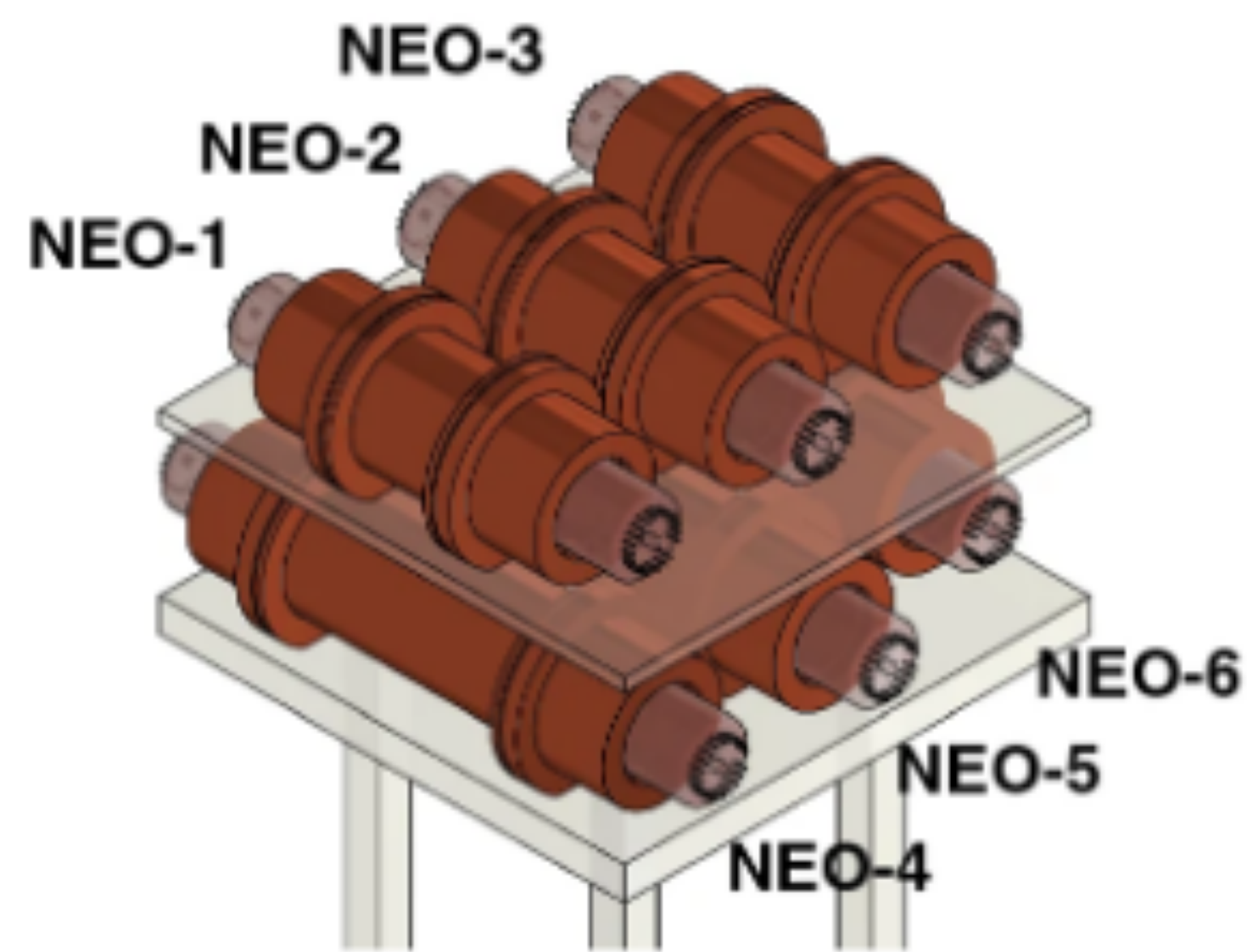
Noble Liquids at Reactors



Scintillators at Reactors



6 NaI crystals
with PMT readout
(total 12.5 kg)



aimed threshold for CEvNS detection:

5 PE \rightarrow ~ 0.2 keV_{ee}

Hanbit, Korea, 24 m

CEvNS around the world

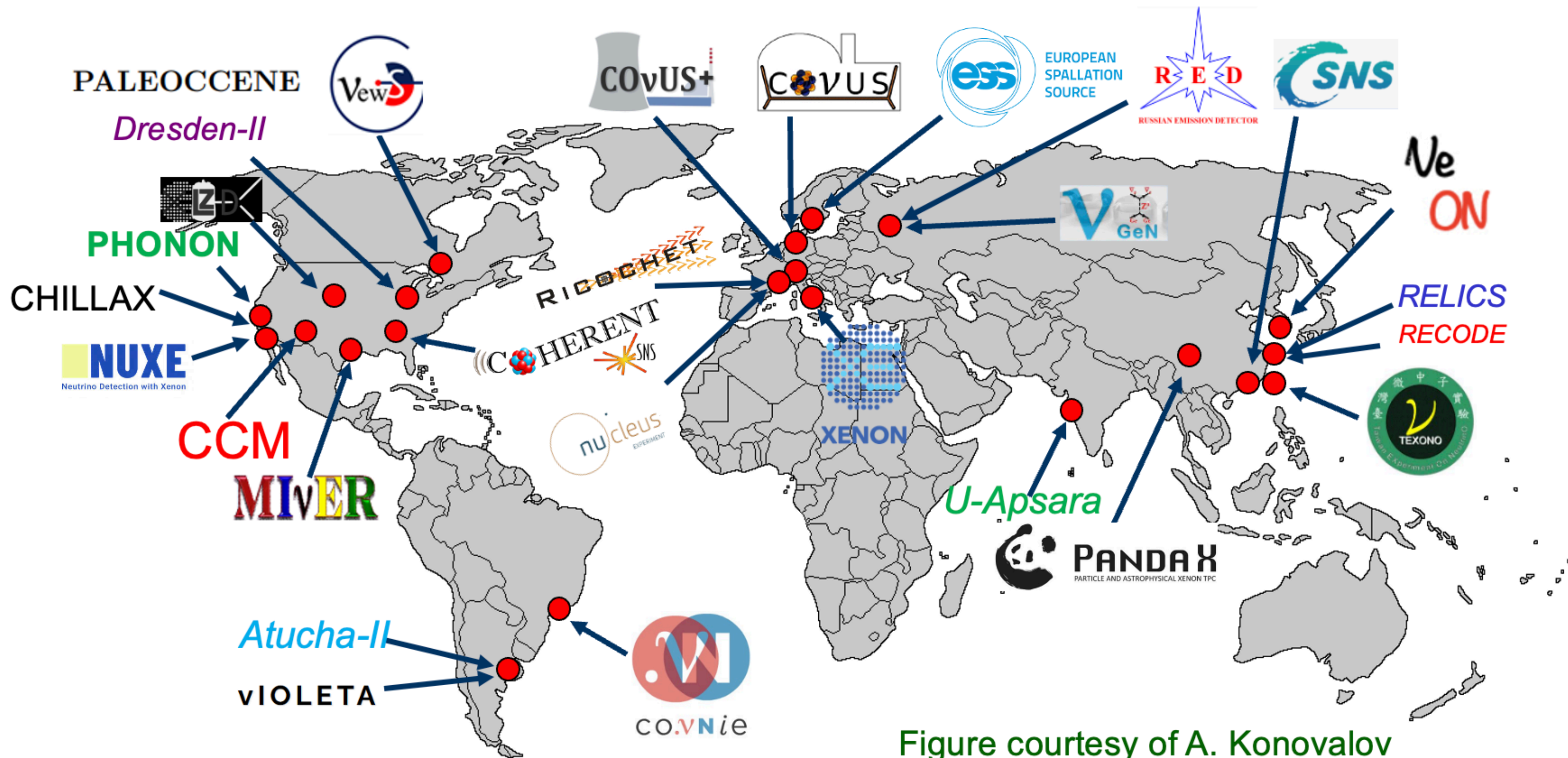
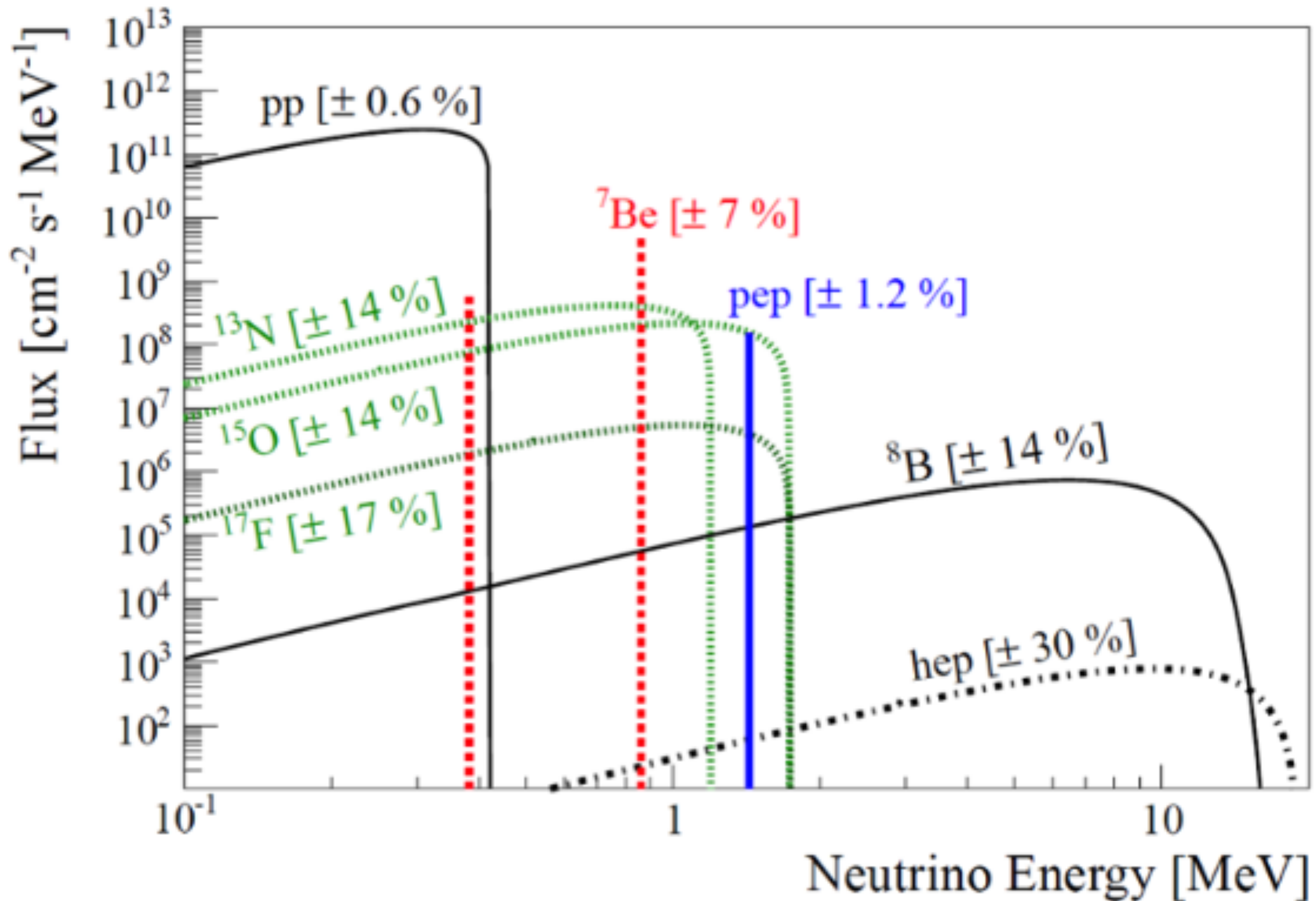


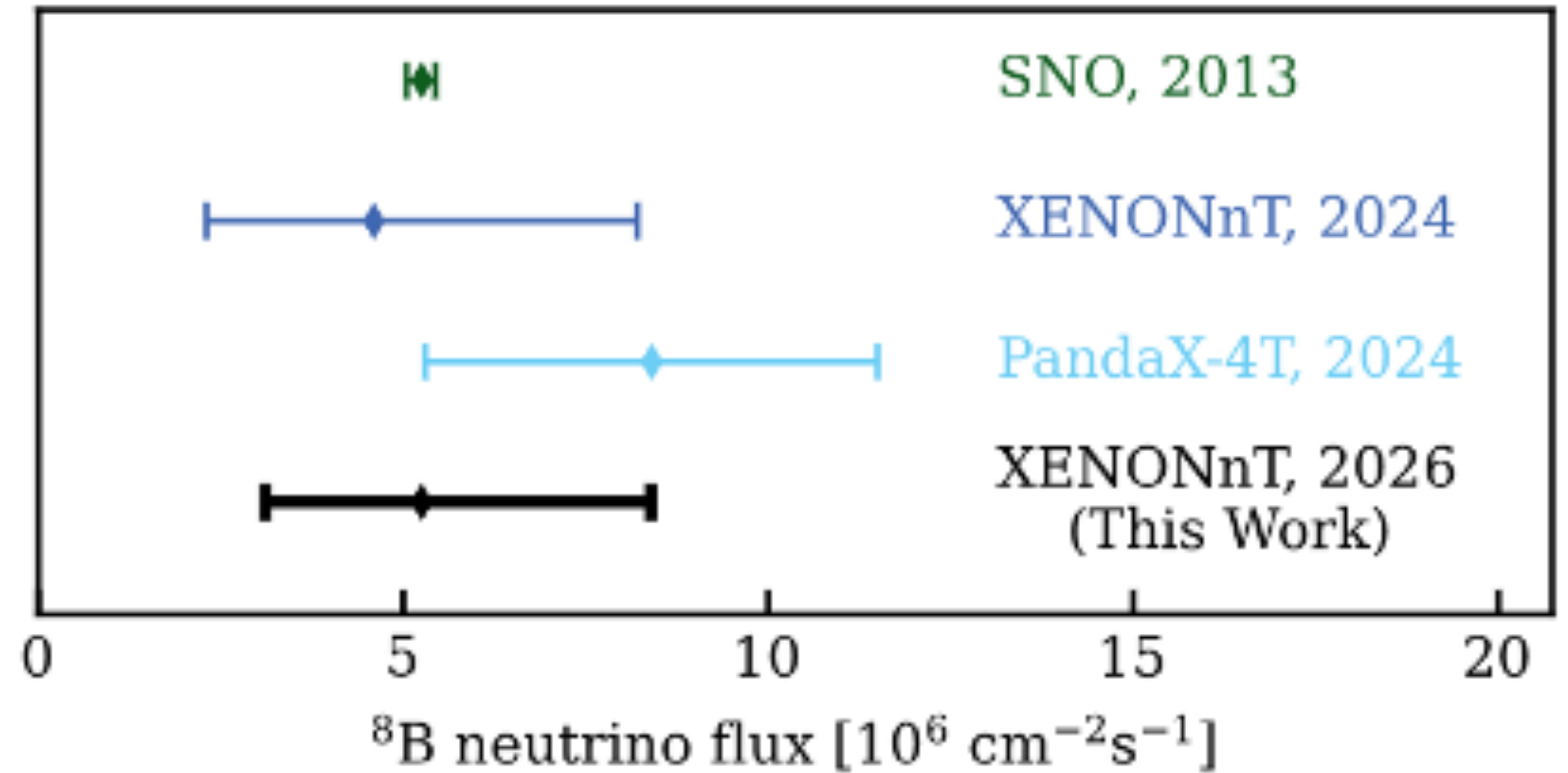
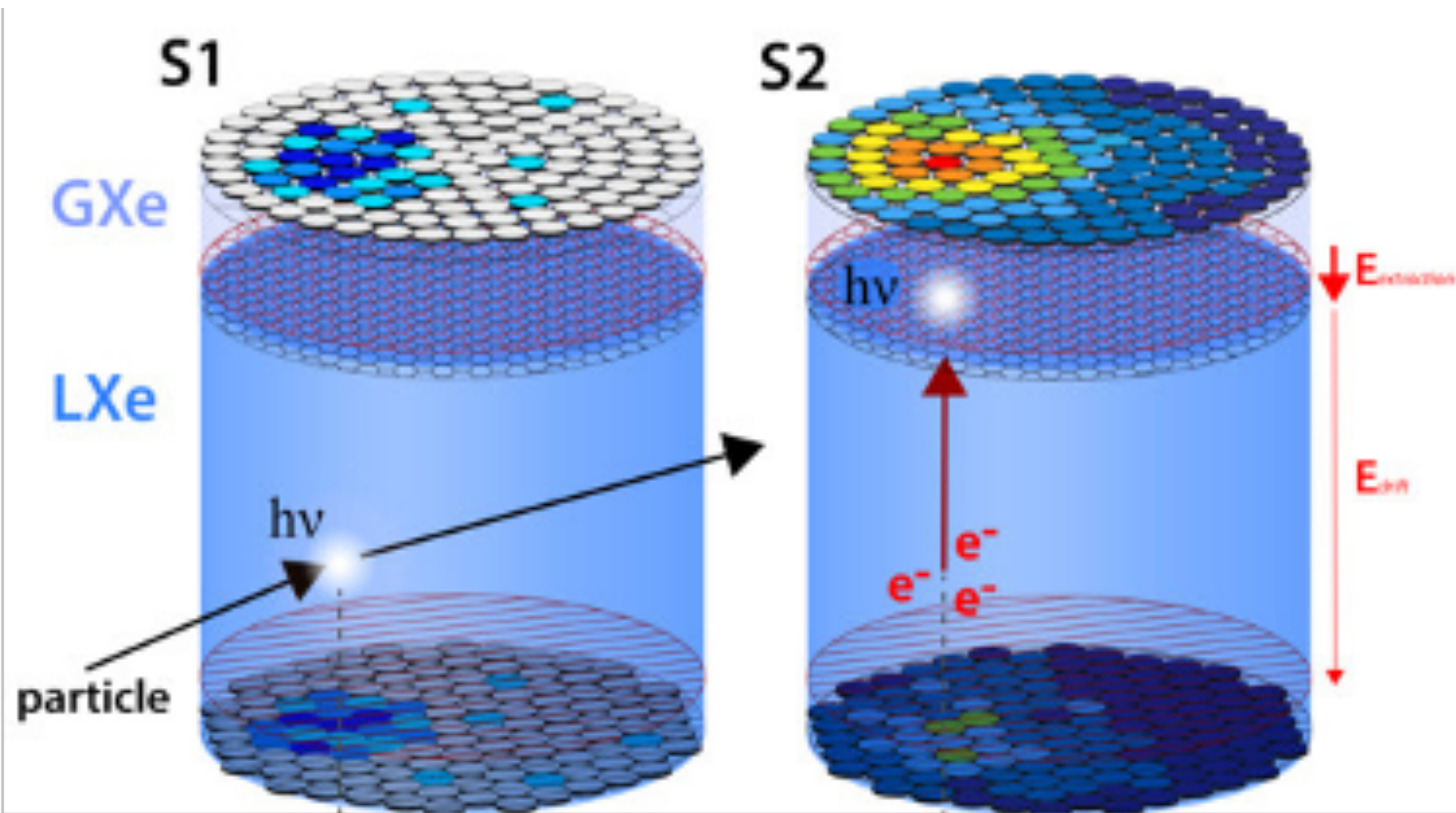
Figure courtesy of A. Kononov

Solar Neutrinos

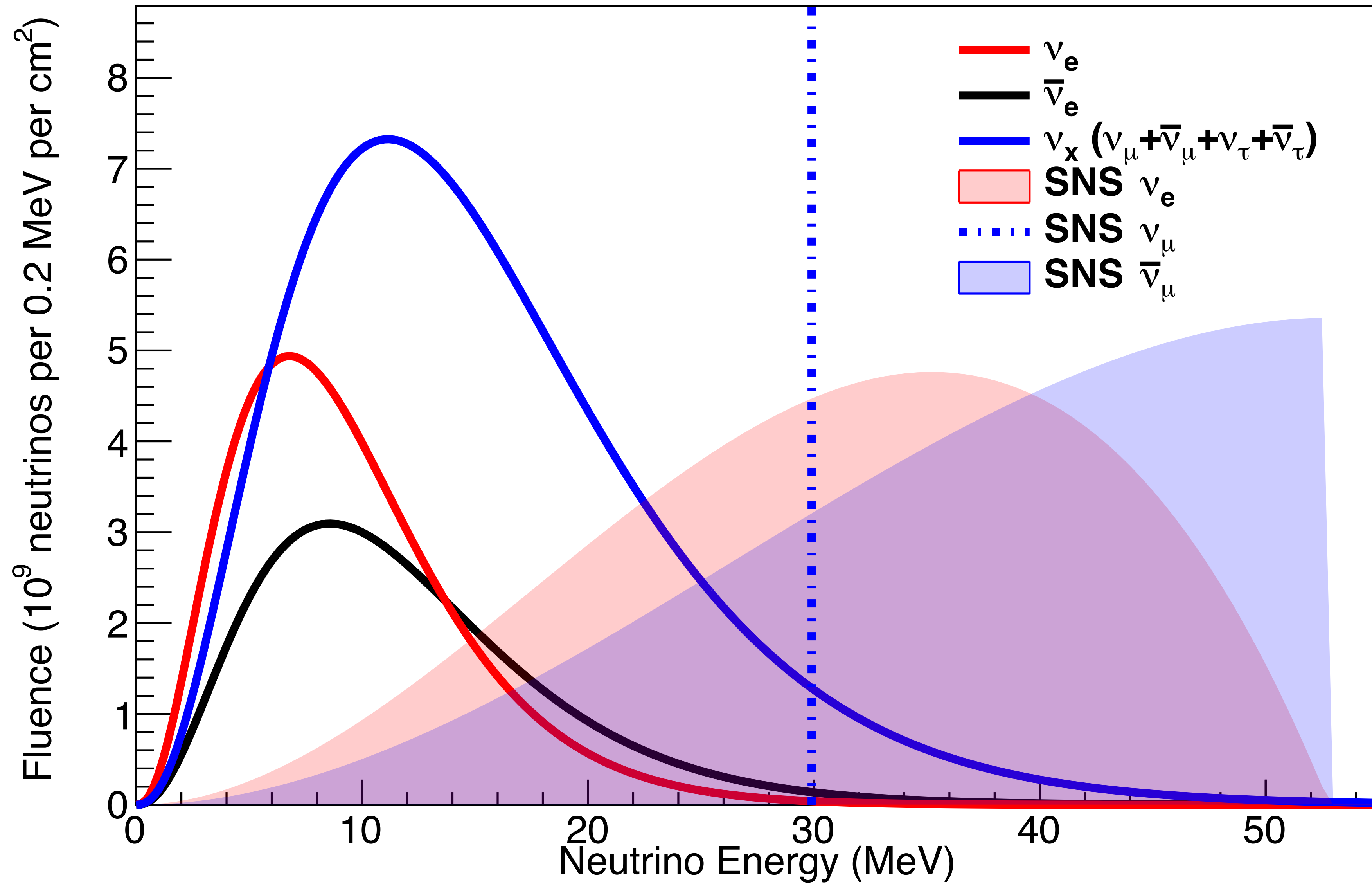


2-Phase Xe Time Projection Chambers

Primary Purpose = Dark Matter Direct Detection



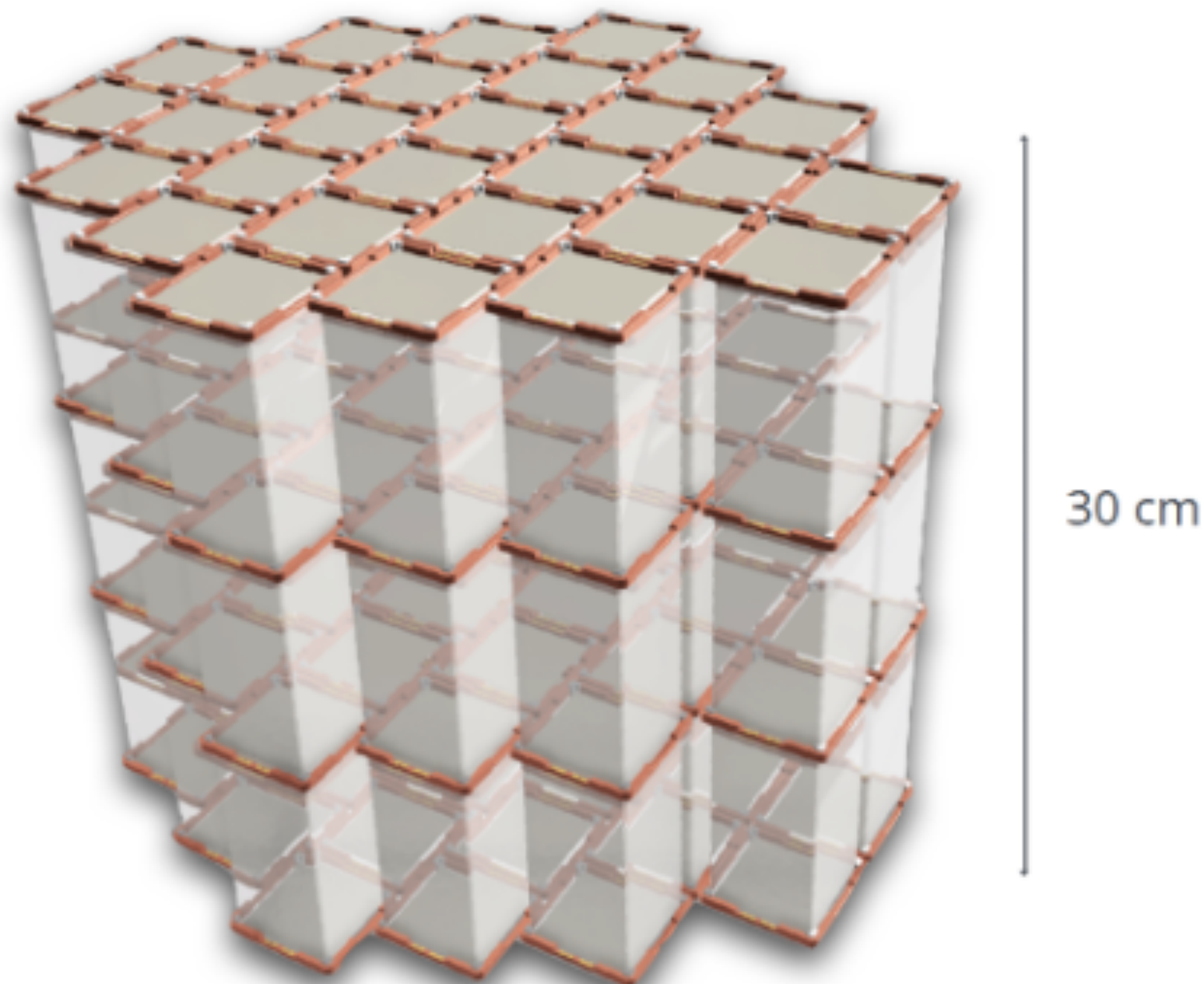
Supernova Neutrinos



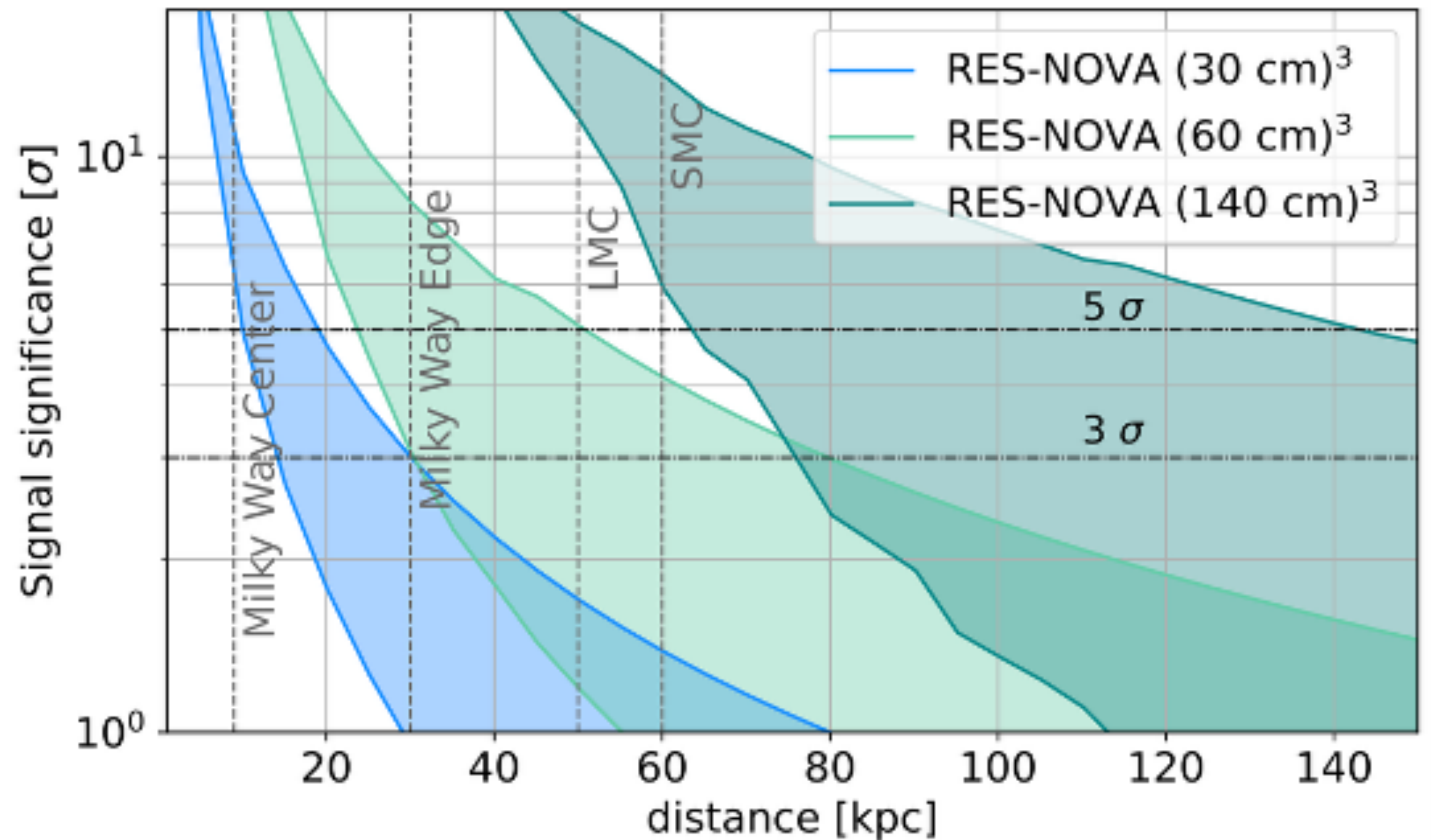
Supernova Detectors: Bolometers

RES-Nova:

- Pb-based cryogenic calorimeters from ancient lead
- threshold: $\sim 1\text{keV}_{\text{nr}}$
- detector production started
- first prototype operating at end of 2026 at LNGS

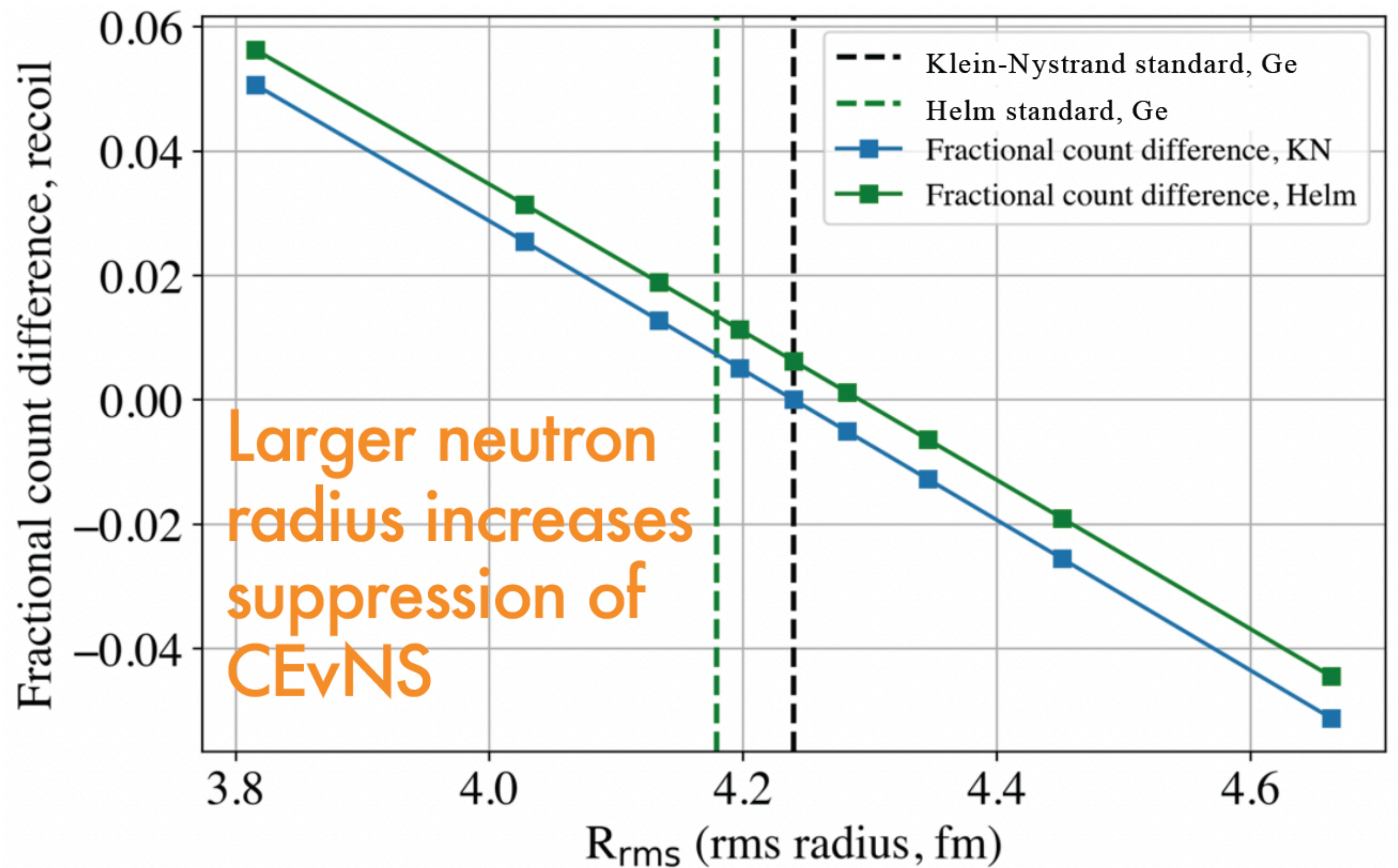
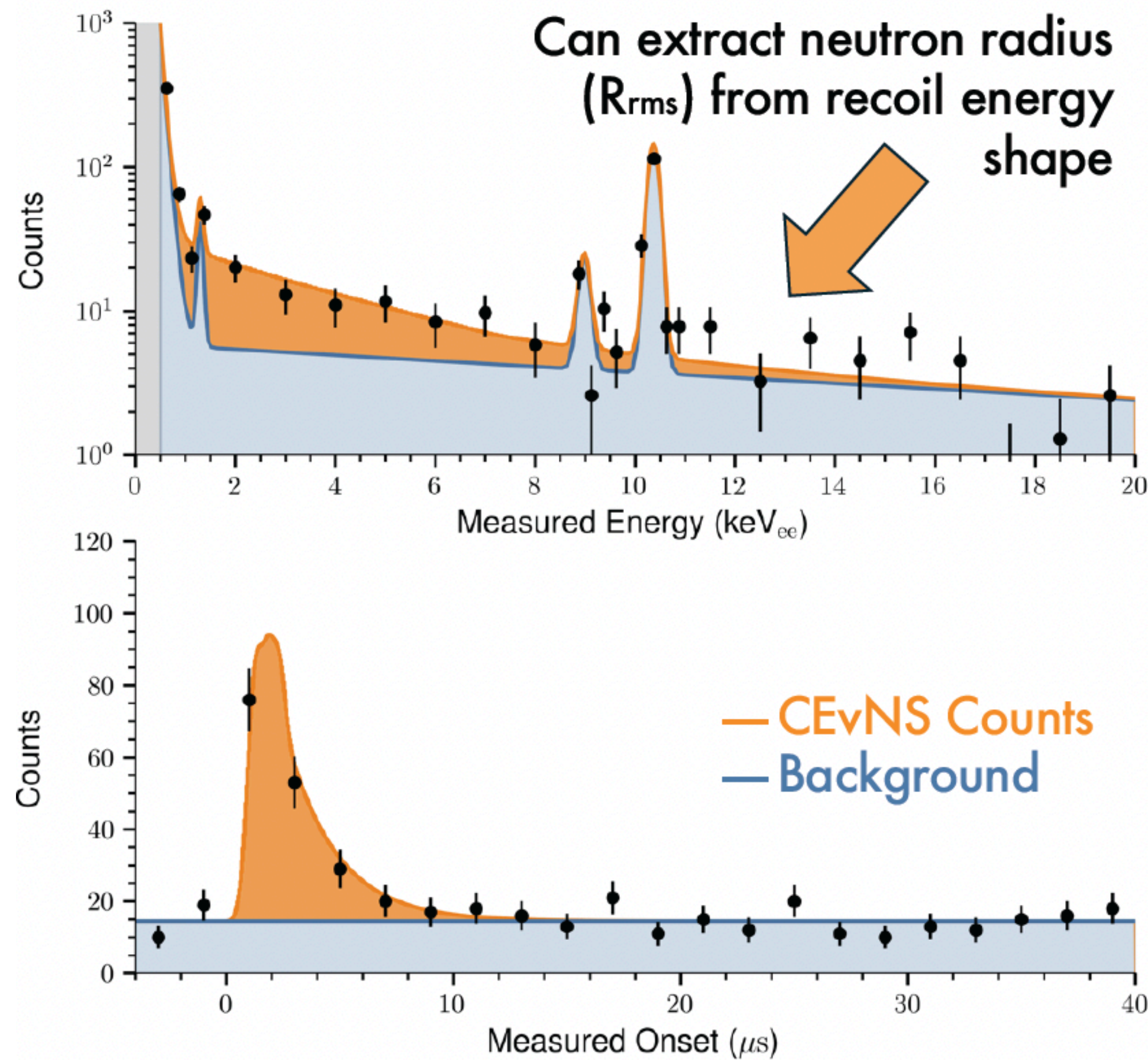


Sensitivity to core collapse supernovae



Coherence at Large Scales

- As the size of the target increases, the deBroglie wavelength no longer probes entire nucleus

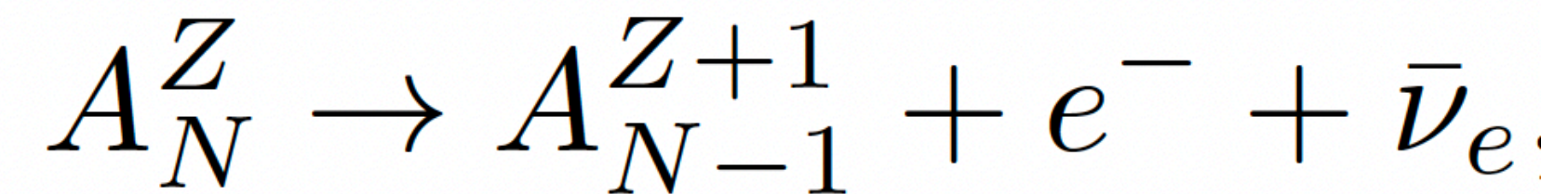


Coherence at Large Scales

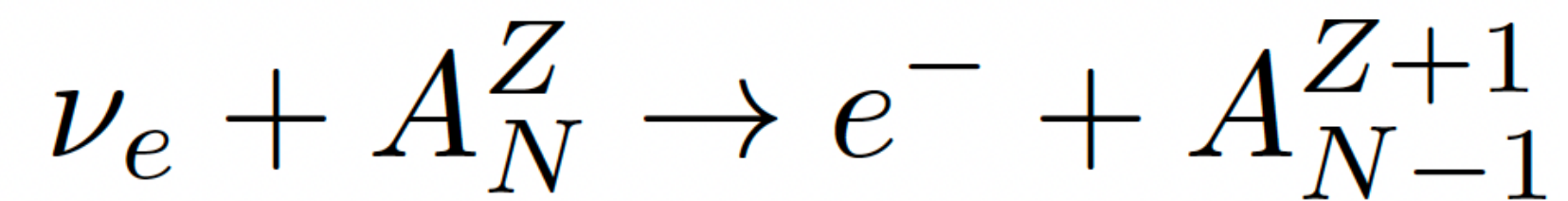
- As the size of the target increases, the deBroglie wavelength no longer probes entire nucleus
- BUT! It can probe objects at larger scales: Atoms, molecules, crystals, macroscopic objects...
- Question: For what energy would the table in front of you become reflecting to neutrinos?
- Hint: Cross section drops like E^2 , but number of nucleons explodes

Neutrino Capture on Radioactive Nuclei

Ordinary Beta Decay



Neutrino Capture



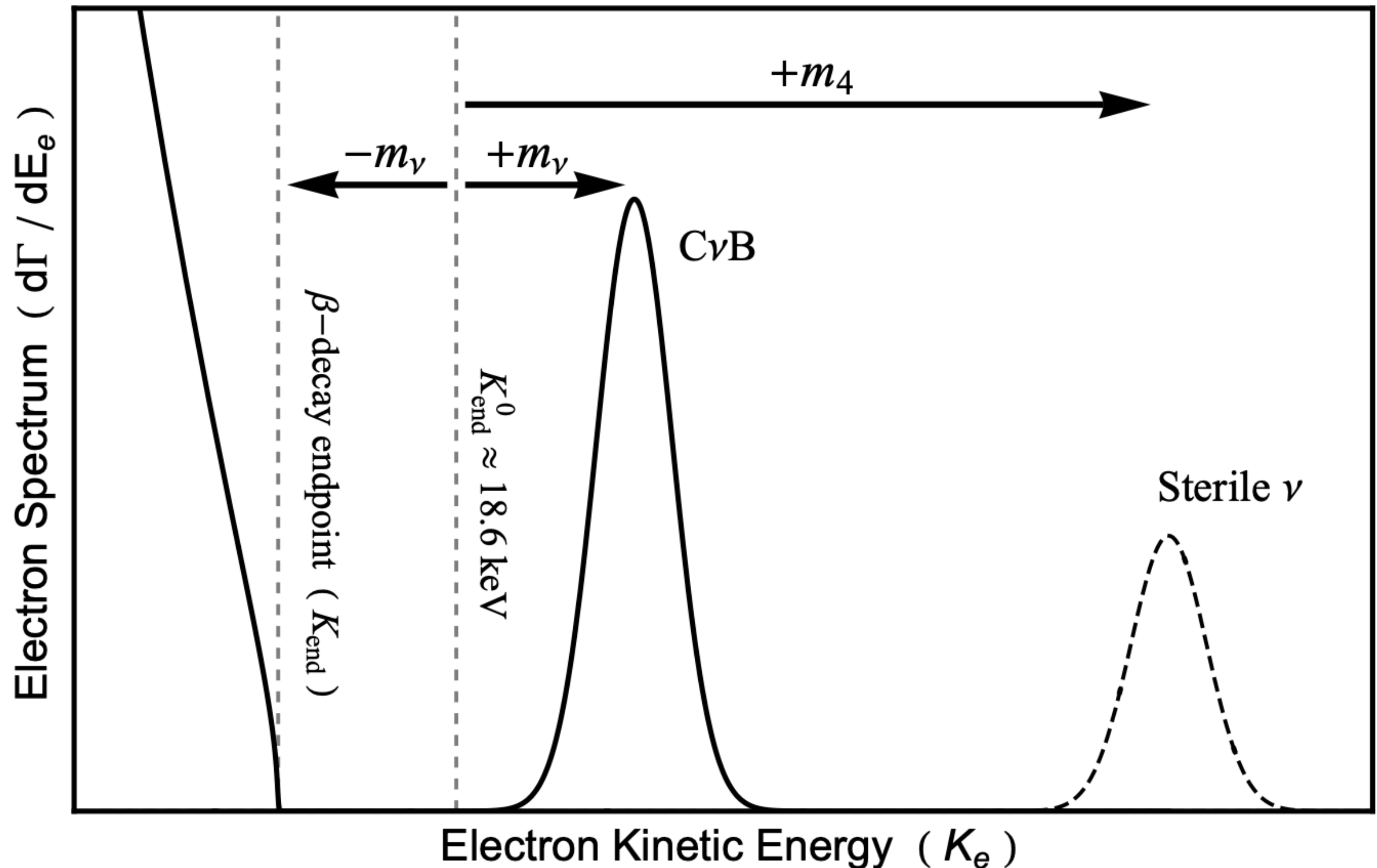
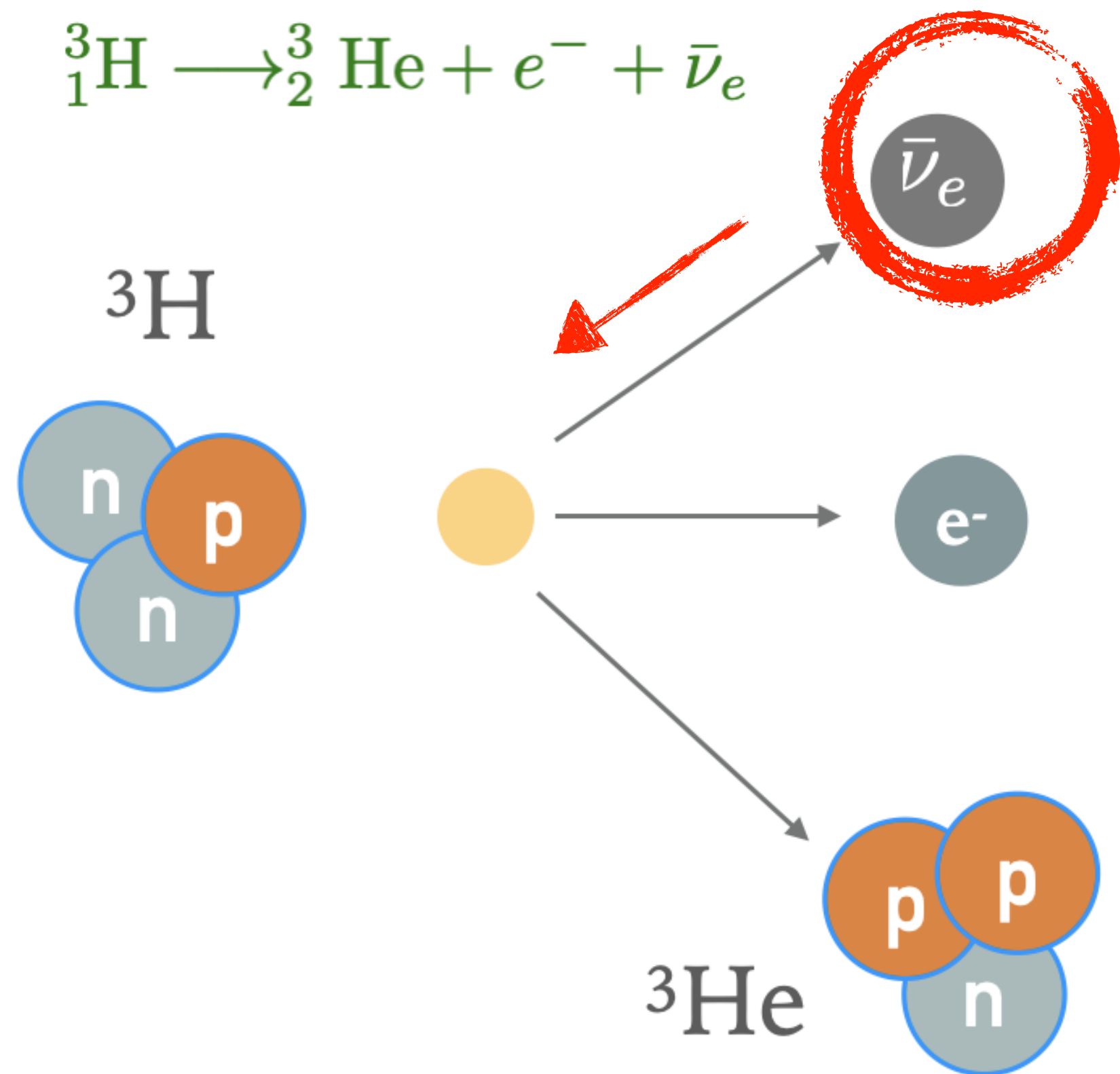
Cross section related to beta decay amplitude

Reaction exothermic: no threshold

(dependent on and quantum numbers of daughter)

Neutrino Capture on Radioactive Nuclei

Tritium - More from Diana Parno on Katrin



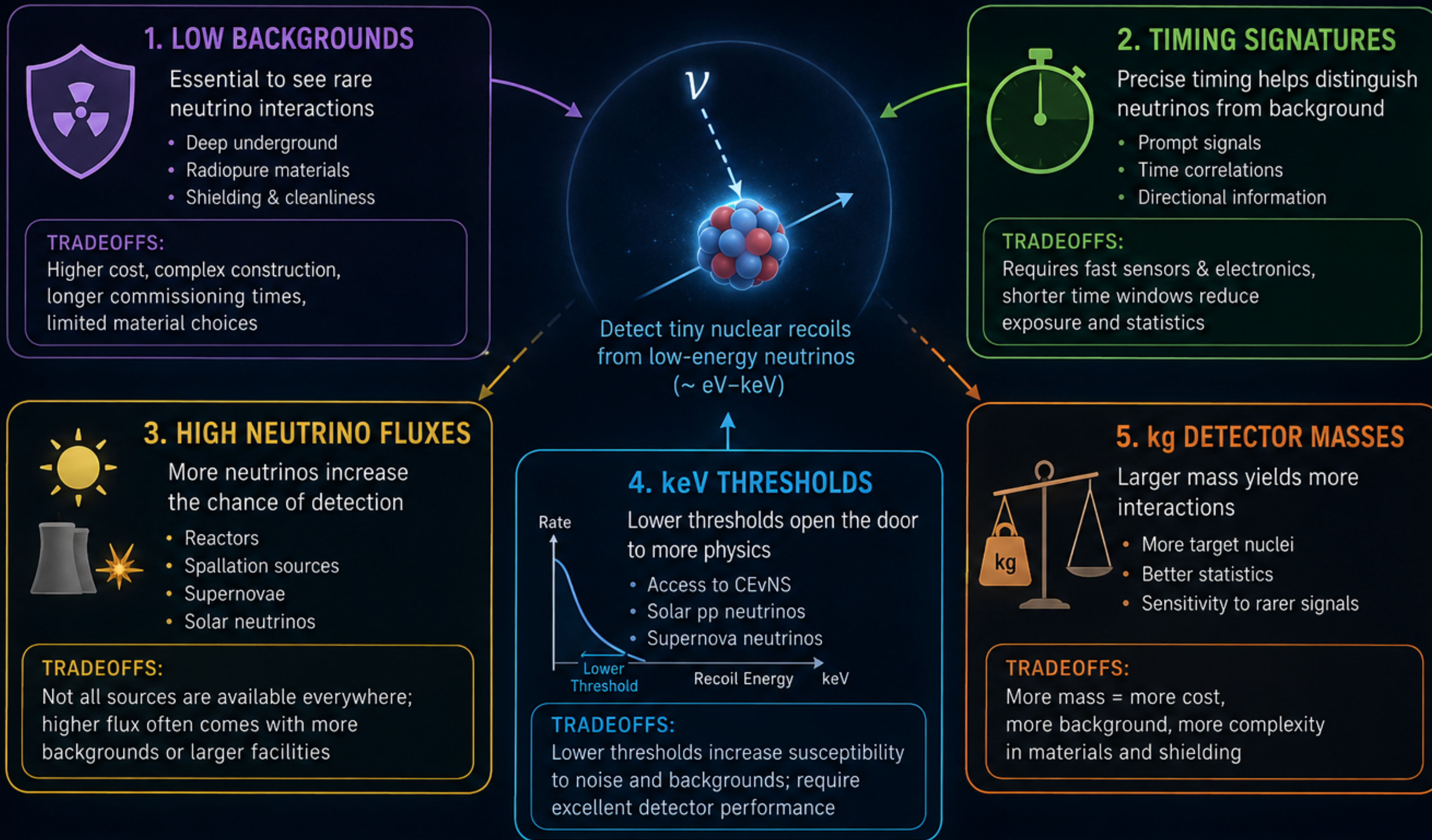
Tradeoffs

- Low Backgrounds (0.1 - 100 counts /keV / kg / day)
- Timing signatures (pulsing or on/off)
- High Fluxes (10^7 - 10^{13} /cm² / s)
- keV-scale energy thresholds
- kg-scale Masses
- Rarely characteristic signatures

THE TRADEOFFS OF LOW-ENERGY NEUTRINO DETECTION

To see the weakest neutrino signals, every advantage matters—and improvements in one area often come at the cost of another.

AI's version of the story



 **OPTIMIZING A DETECTOR IS BALANCING THESE TRADEOFFS TO ACHIEVE THE BEST OVERALL SENSITIVITY.**
There is no single solution—only the right balance for the physics goal.

Signatures challenging to detect

- Start with *Thresholdless*
 - Neutrino-electron Elastic Scattering
 - Coherent **Elastic** Neutrino-Nucleus Scattering (CEvNS)
 - Neutrino Capture on **radioactive** Nuclei
- Next Lecture: Low-Threshold Neutrino Detection
 - Neutrino Capture on **stable** nuclei
 - Neutral Current **Inelastic** Scattering

