Sterile Neutrinos & Neutral Current Scattering

Coherent Scattering Workshop
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MIT

Motivation for Measurement

Technique

Sources and Detectors

Projected Sensitivity

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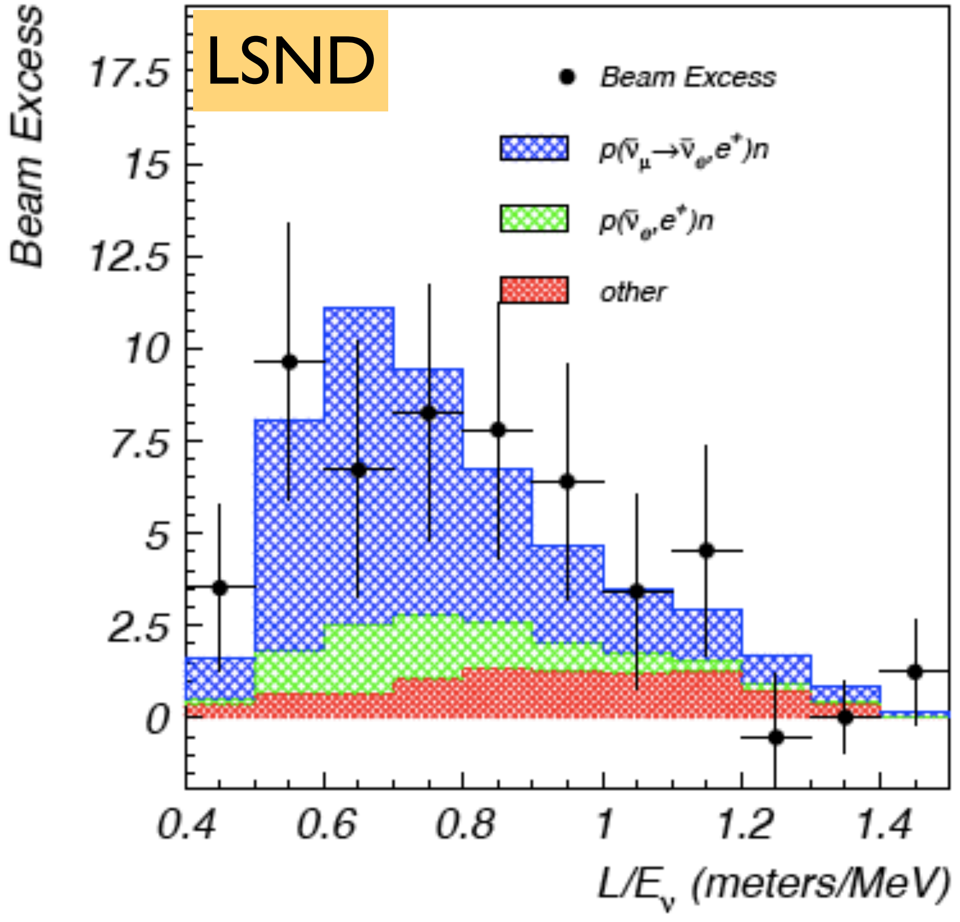
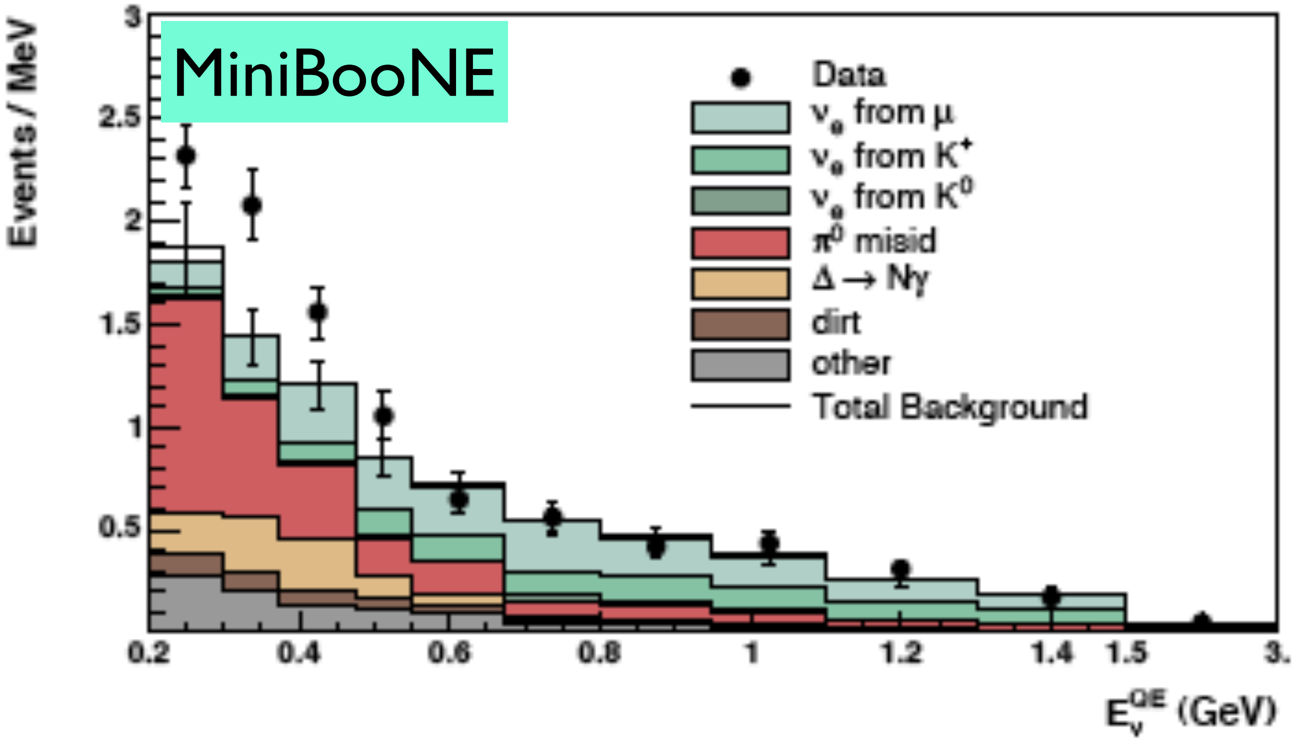
Sources and Detectors

Projected Sensitivity

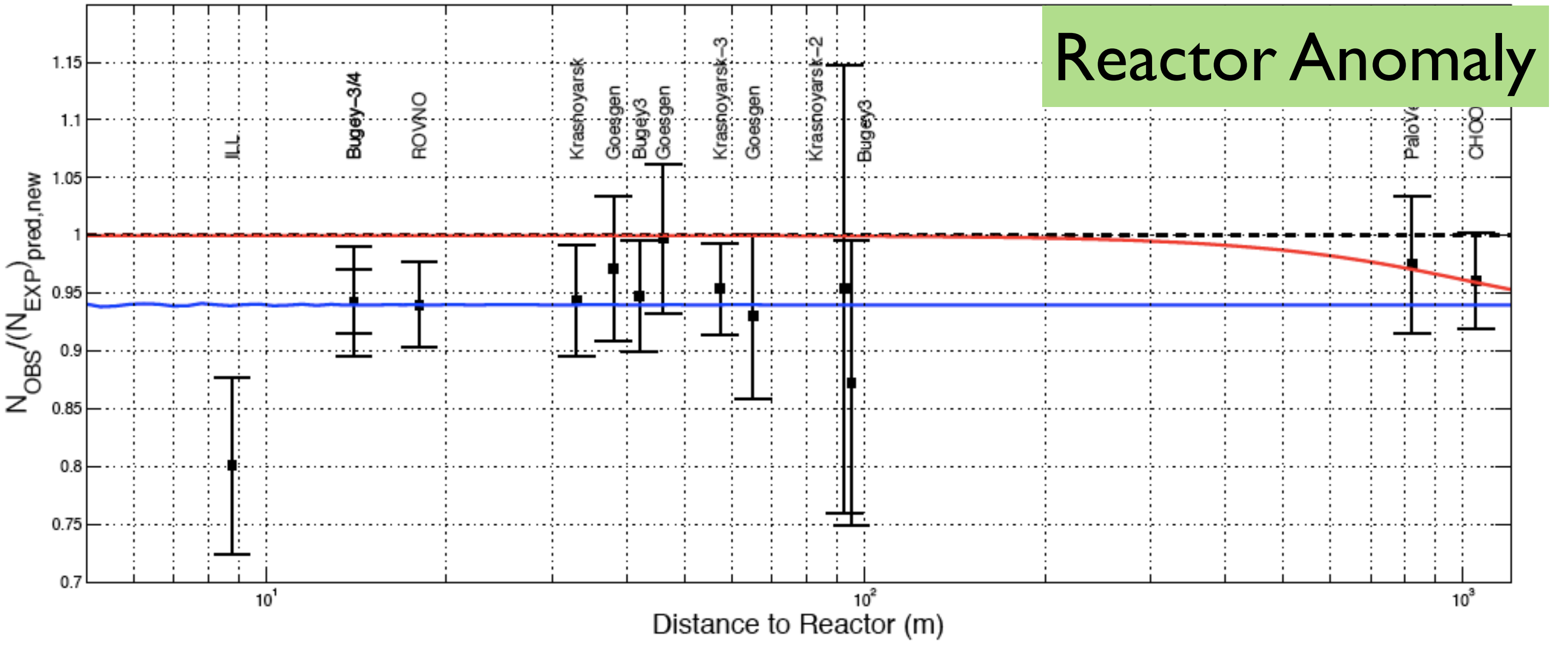
The Case for Sterile Neutrinos

- A number of recent (and not so recent) results seem to indicate the possibility of sterile neutrinos.
- Evidence stems from a variety of sectors:
    - Cosmology (somewhat diminished from most recent PLANCK data)
    - Short-baseline (LSND/MiniBooNE)
    - Reactor anomaly
    - Gallex / SAGE Calibration source
- All suggestive, but no “smoking gun” accepted by the community at the moment.





The Case for Sterile Neutrinos


Reactor Anomaly

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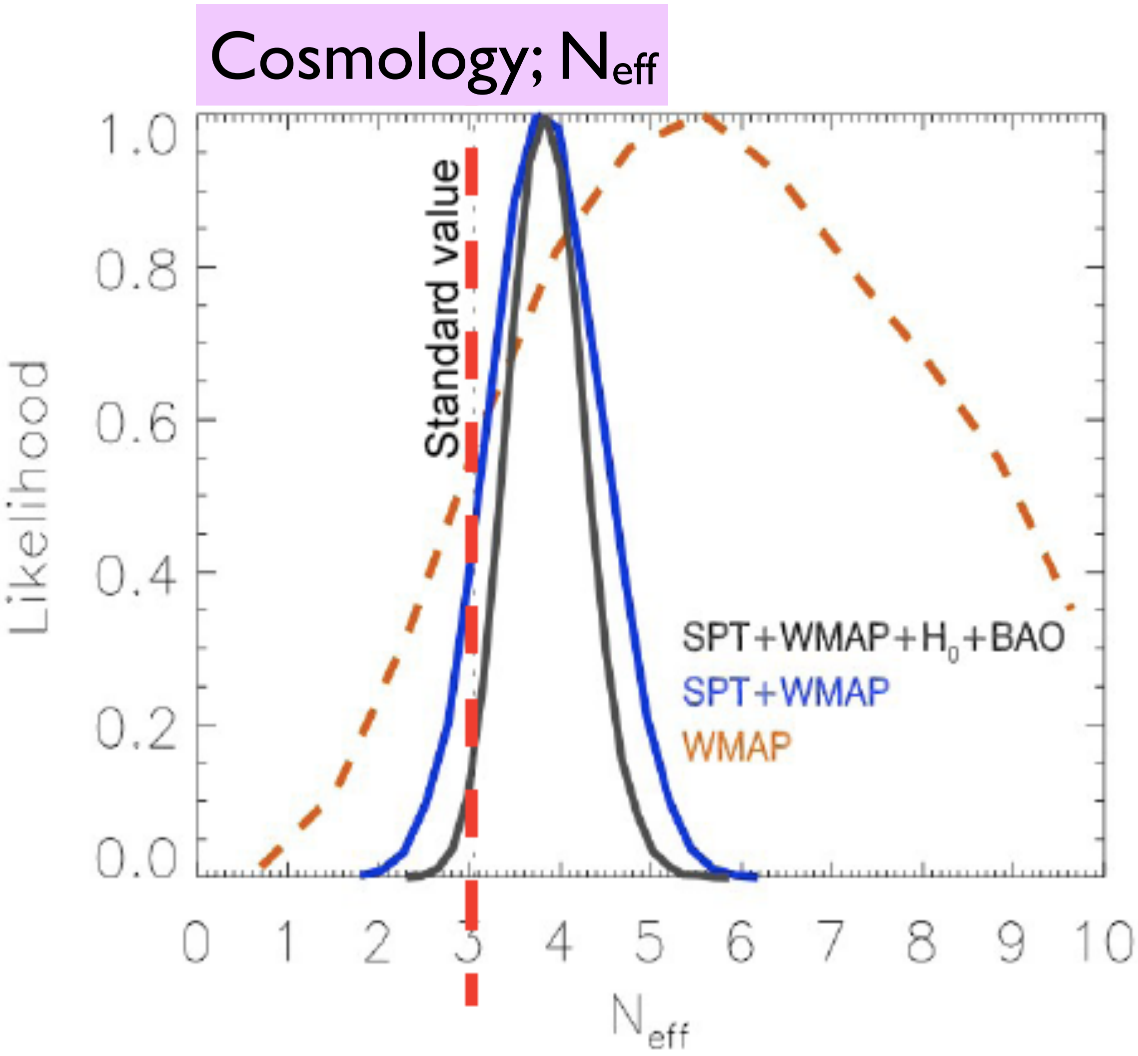

Cosmology; N_{eff}

Keisler et al. [South Pole Telescope] 2011

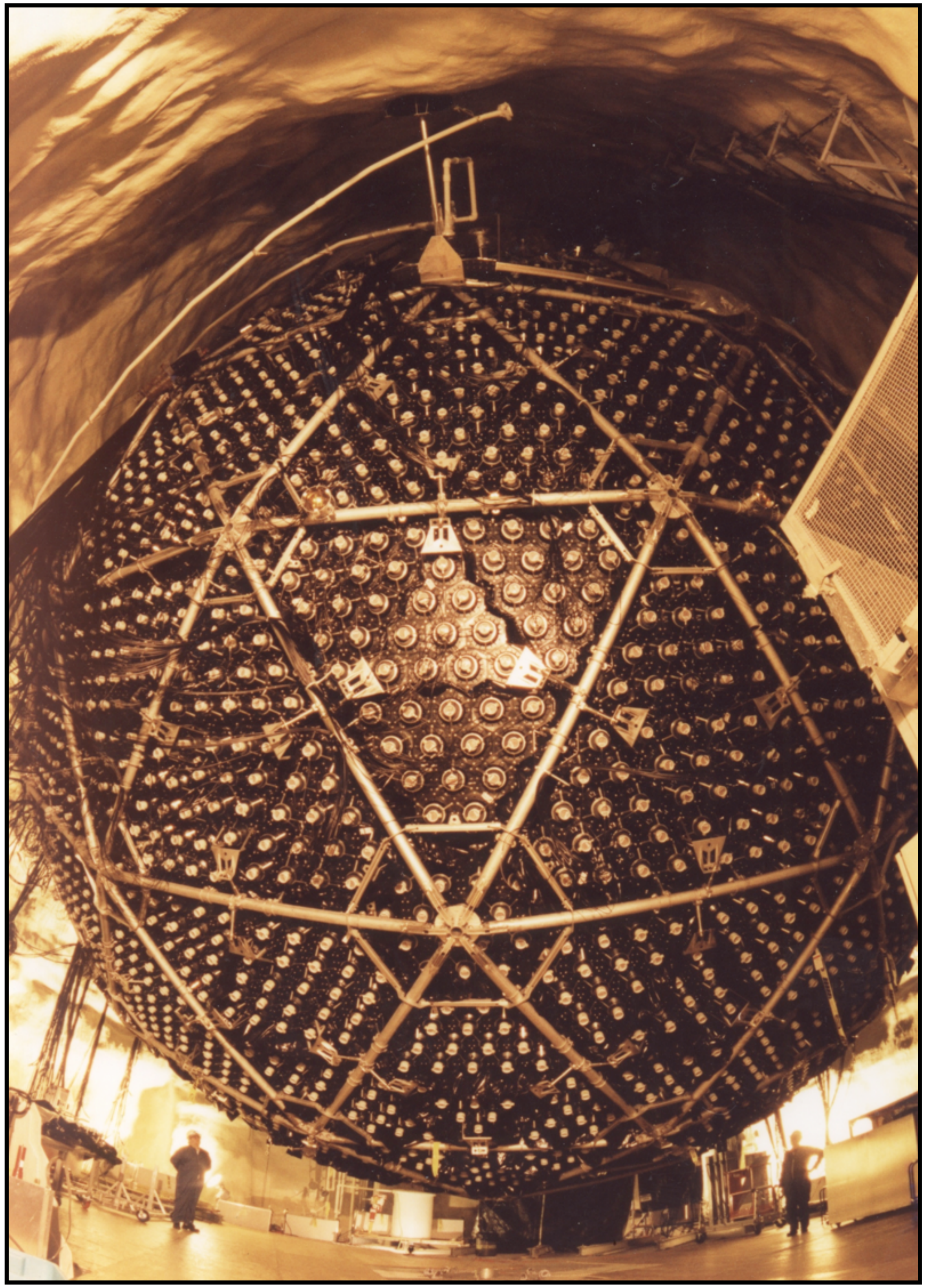
A Smoking Gun, yes, but how?

- Such anomalous observations warrant further experimental verification, and to a certain degree that occurs and continues to occur
- Example. LSND → MiniBooNE.
- Similar follow-up experiments also planned for the reactor anomaly.

- What do we want from a “smoking gun”?
  - Evidence that it is sterile.
  - Evidence that is it oscillations (length/energy dependence).

$$\mathcal{P}(\nu_a \to \nu_s) = 1 - \sin^2{(2\theta_s)}\sin^2{(1.27\Delta m_S^2 \frac{L}{E_\nu})}$$

The Argument for Coherent Scattering



- Coherent scattering allows to probe neutrinos using a neutral current channel; oscillation signature would be clear sign of active → sterile mixing.

- Previous evidence mainly in energy. Uses distance (oscillometry) instead, same detector:

  - For $\Delta m^2 \sim 1$ eV

  - $L \sim O(1\text{ meter})$; $E_\nu \sim O(1\text{ MeV})$

  - Simpler if just source is monochromatic.

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  - Simpler if just source is monochromatic.

- In conjunction with other experiments, could be very powerful (e.g. KamLAND & SNO)

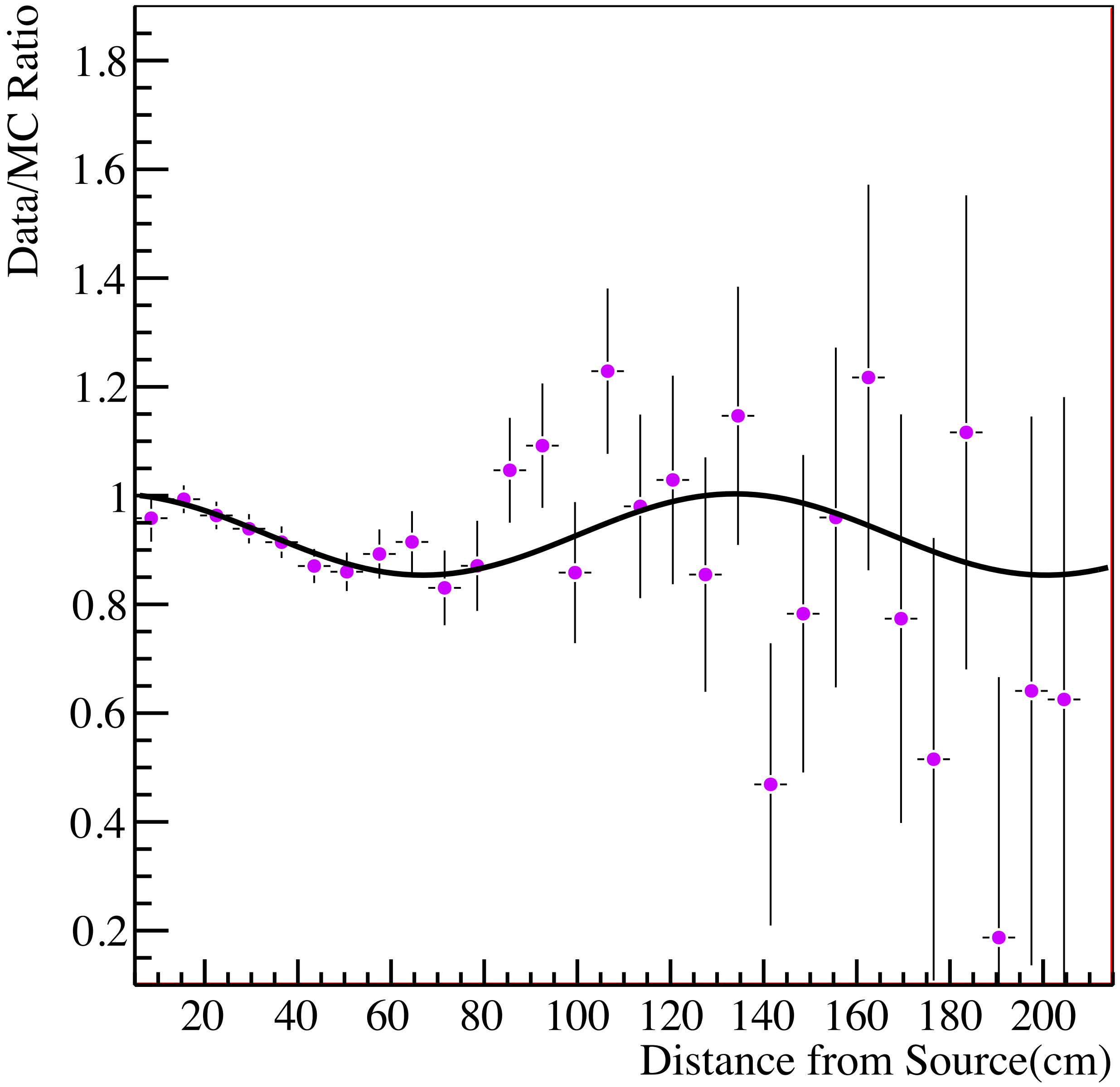
Look for Radioactive Source & Coherent Scattering detector

Oscillometry

Manifestation of oscillations over distance (L) within same experiment very powerful smoking gun. Effect difficult to mimic.

Proposed in conjunction with sterile neutrino searches numerous times in literature.

For 1 MeV neutrinos at 1 eV, implies 1 meter scale.



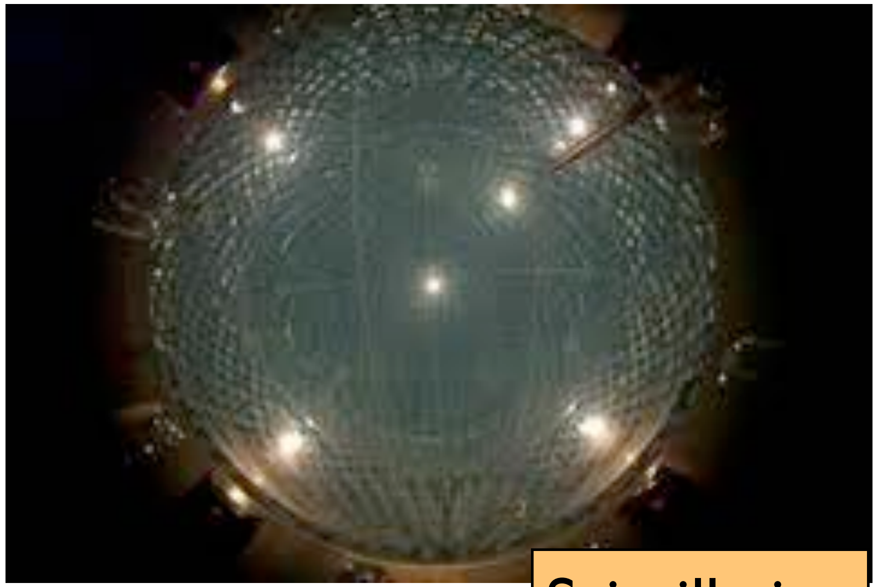
Search for $1/r^2$ deviation

One big obstacle...

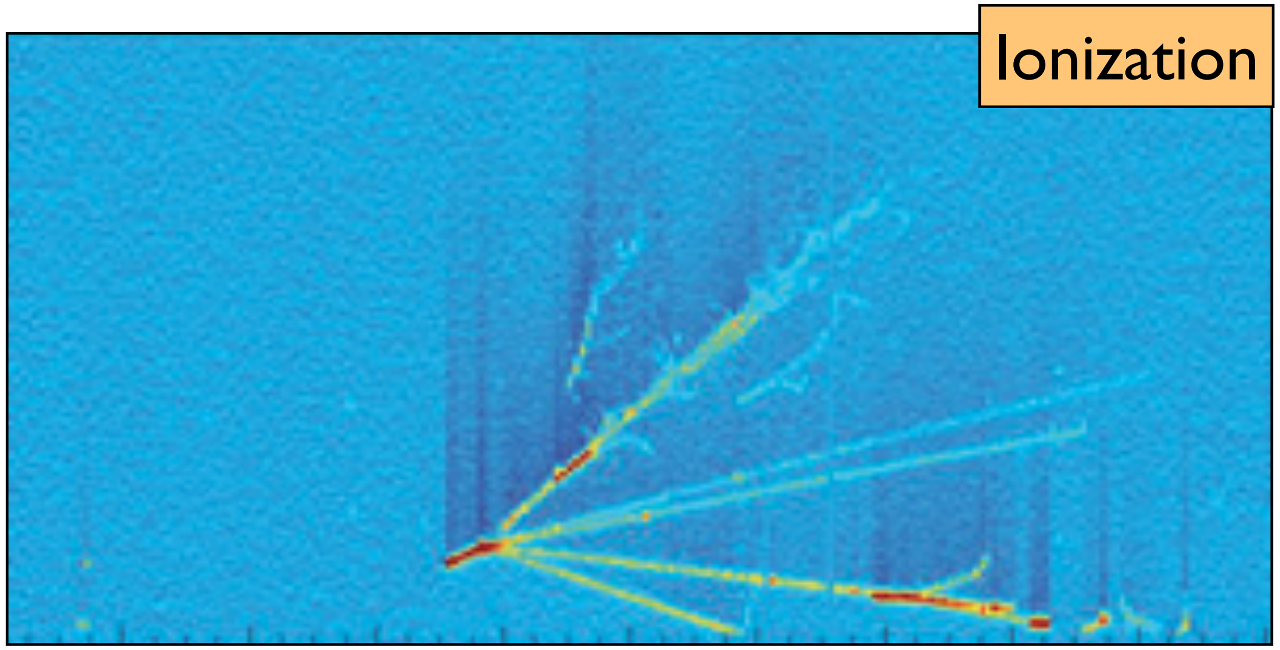
$$T_{\max} \leq \frac{E_\nu}{1 + \frac{M_A}{2E_\nu}}$$

$$T_{\max} \leq 50 \text{ eV for Si at } 0.8 \text{ MeV}$$

- For neutral current coherent scattering on a silicon target, the maximum kinetic energy is 50 eV. So a threshold of ~10 eV is necessary.
- Methods involving e-h pair detection have very low (or zero) quenching factors at these energies.
- Likewise, energies of at least few eV required to produce scintillation photons. Would yield poor statistics.
- Only remaining option is pure phonon detection.



Scintillation



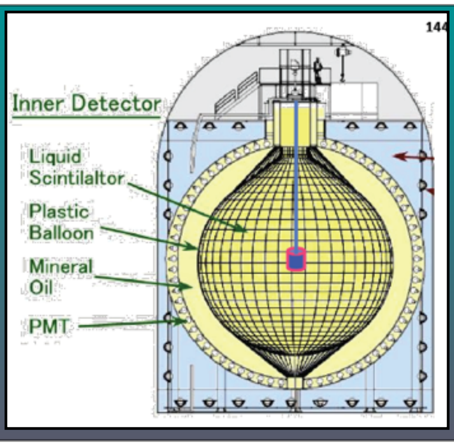
Ionization

Oscillometry Techniques

Neutrino-Electron Scattering, MegaCurie Sources

Allows for much higher thresholds. Sensitive to neutrino magnetic moment.

Henning, arXiv:1011.3811v1; BOREXINO, etc.



Charged Current Scattering, MegaCurie Sources

Uses ^{115}In with low threshold (114 keV) to search for sterile component

C. Grieb, J. M. Link, and R. S. Raghavan, Phys. Rev. D 75 093006 (2007).

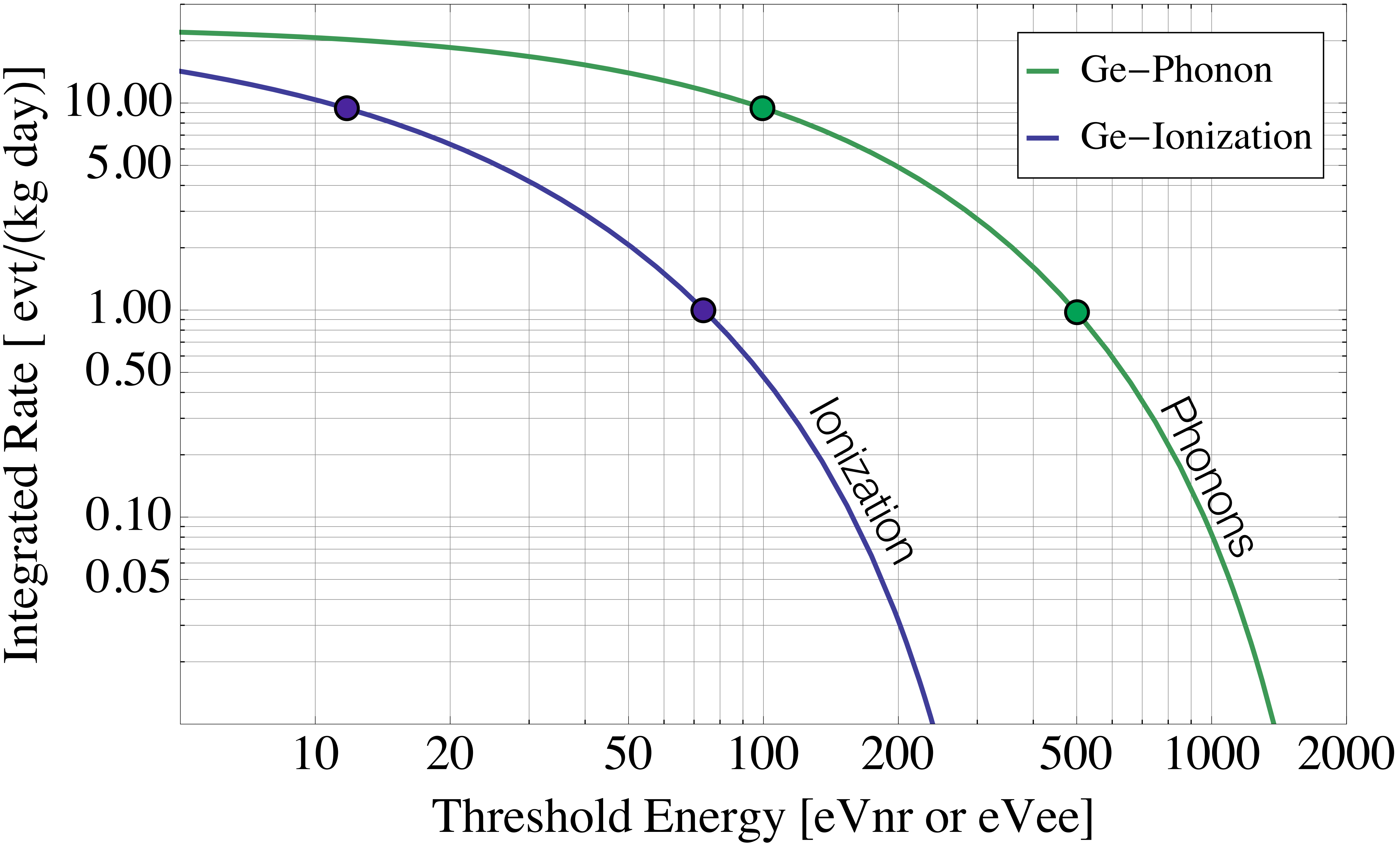
Neutral Current Coherent Scattering, MegaCurie Sources

Uses bolometry to probe down to the eV recoil spectrum.

J. Formaggio, ,E. Figueroa-Feliciano, A. Anderson, hep-ex/1107.3512 (2012). This talk.

Event rates for phonon versus ionization

Ionization readout requires much lower thresholds for the same rates



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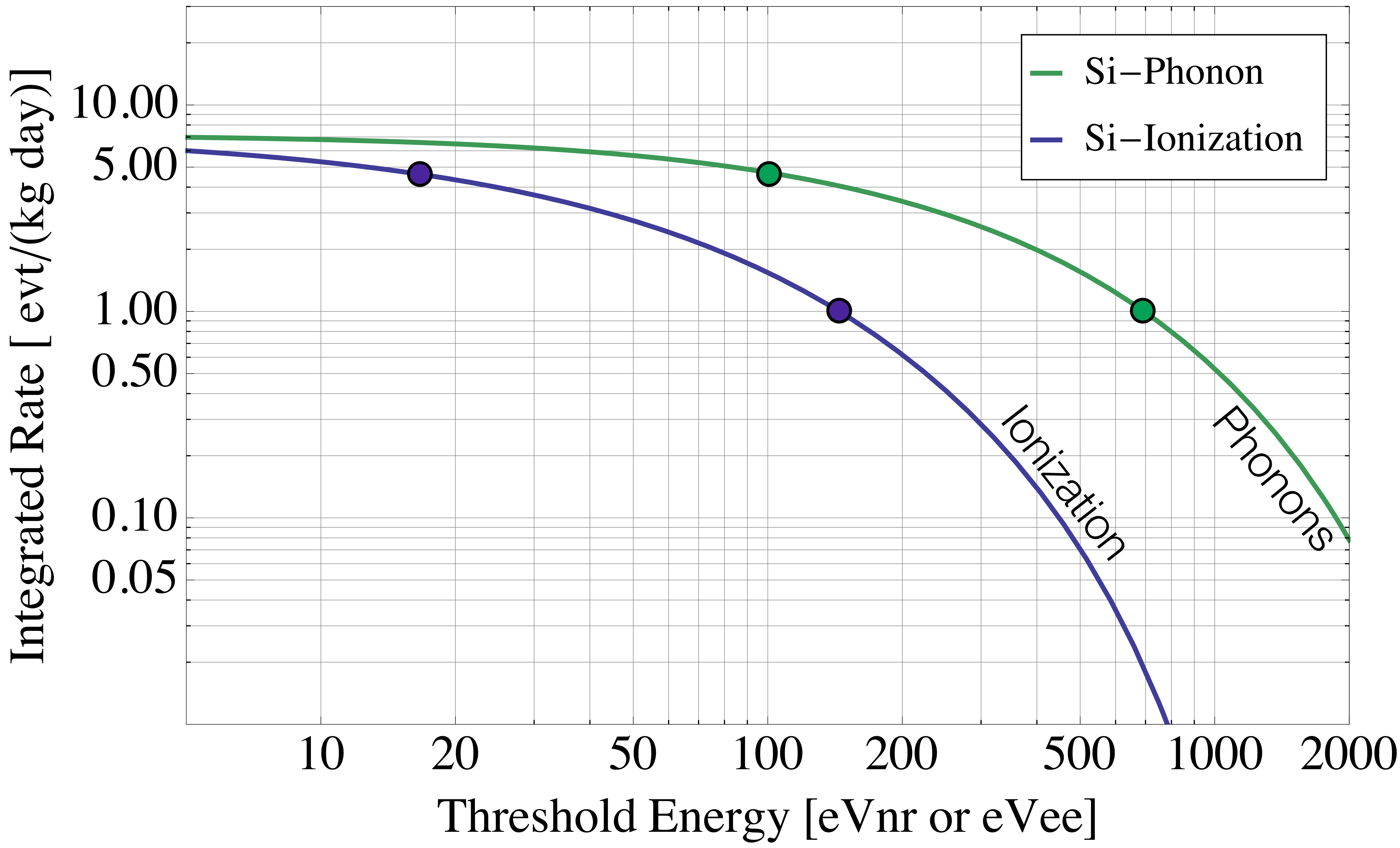
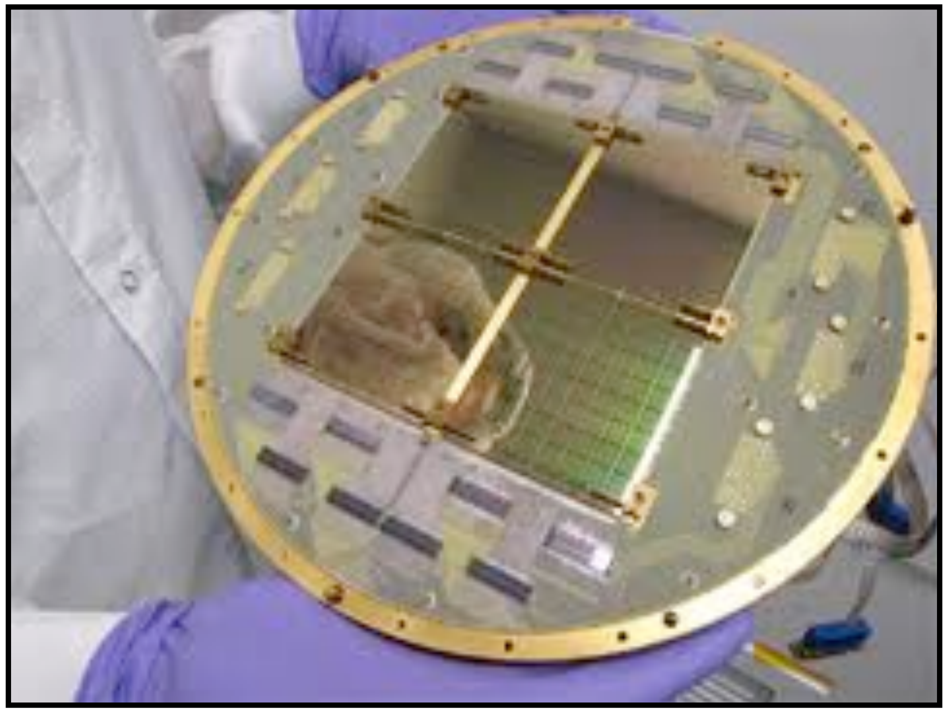


RICOCHET

A Coherent Neutrino Scattering Program

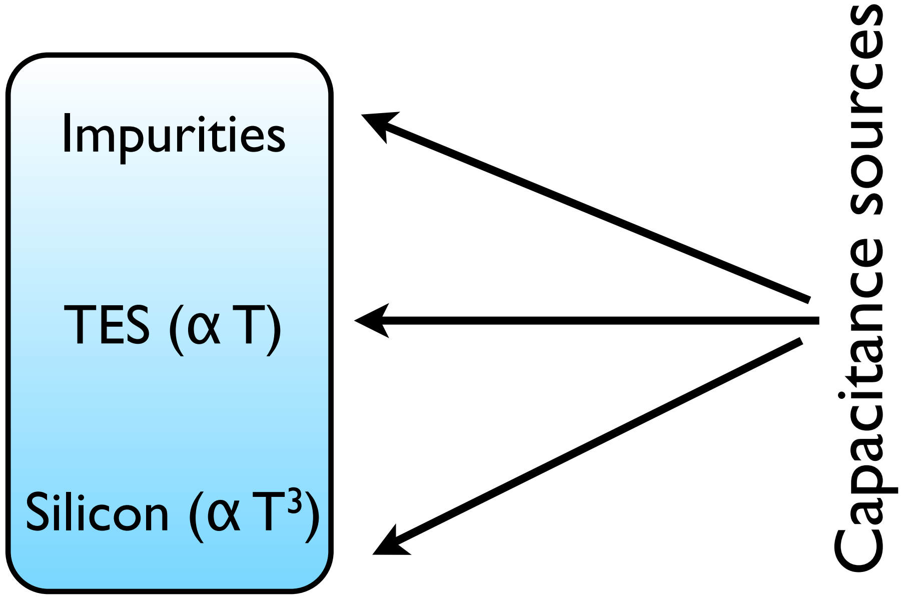
The Detector

- Given historical precedent, we focus on Transition Edge Sensors (TES) as the technology to push down to the 10 eV scale.
- Energy resolution dominated by the total heat capacitance of system (C_{tot}).
- At 15 mK, a 10 eV threshold could be achieved with a system capacitance of $C_{\mathrm{tot}} < 300$ pJ/K.
- Model must include noise sources from other internal decouplings.



SCUBA II Detector (10,000 pixels, each extremely small)

$$\sigma_E \approx \sqrt{\frac{4k_BT^2C_{\mathrm{tot}}}{\alpha}\sqrt{\frac{\beta+1}{2}}}$$

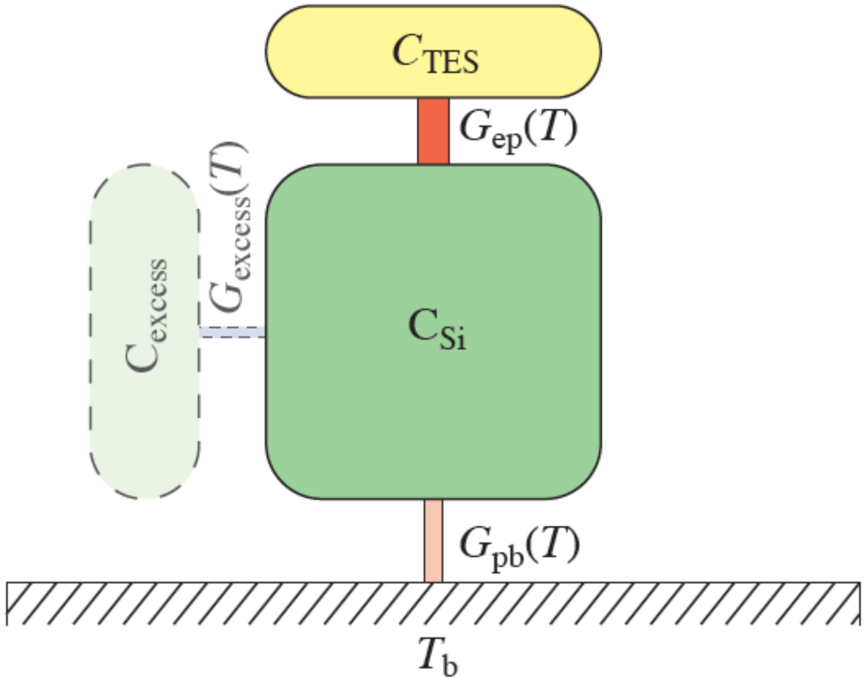


Impurities

TES (α T)

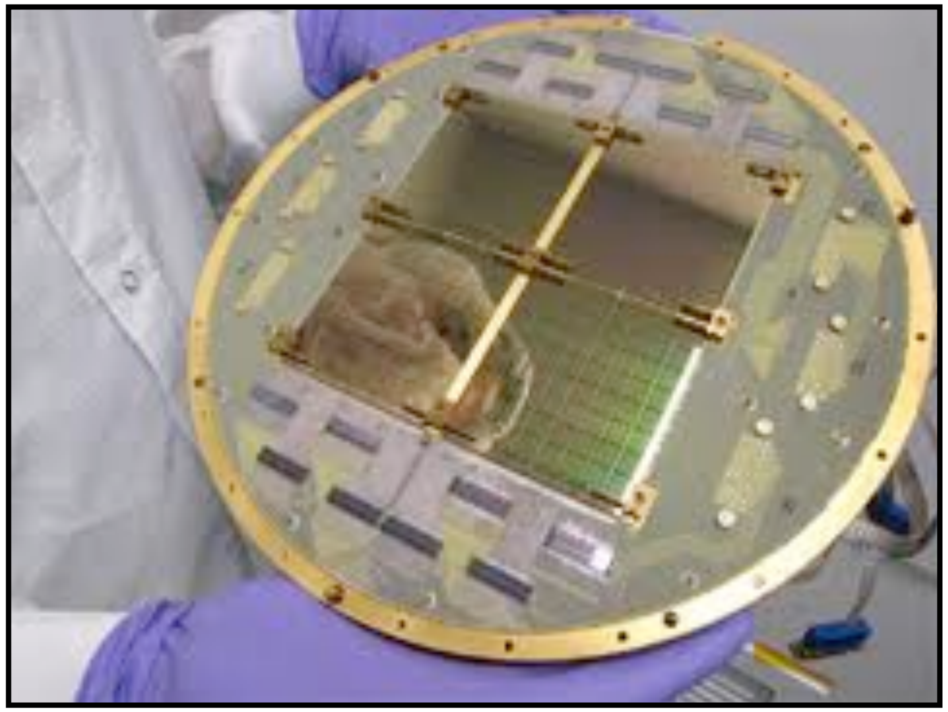
Silicon (α T^3)

Capacitance sources



Detector Properties

Parameter	Value	Units	Description
C_{Si}	43.2	pJ/K	Debye heat capacity
C_{TES}	39.8	pJ/K	TES electron heat capacity
G_{ep}	37.5	nW/K	TES-Si thermal conductance
G_{pb}	0.30	nW/K	Si-bath thermal conductance
T_b	7.5	mK	Cold bath temperature
T_c	15	mK	TES temperature
R_o	3	mΩ	Quiescent TES resistance
I_o	18.3	μA	Quiescent TES current
P_o	1.0	pW	Quiescent TES power
$\alpha = \frac{T_c}{R_o}\frac{dR}{dT}$	80	-	TES sensitivity
τ_{o}	276.7	ms	Natural decay time $C_{\mathrm{tot}}/G_{\mathrm{pb}}$
τ_{eff}	20.0	ms	Response time with TES speedup
τ_{decay}	11.8	ms	Decay time with readout circuit
L	13	μH	Readout inductance



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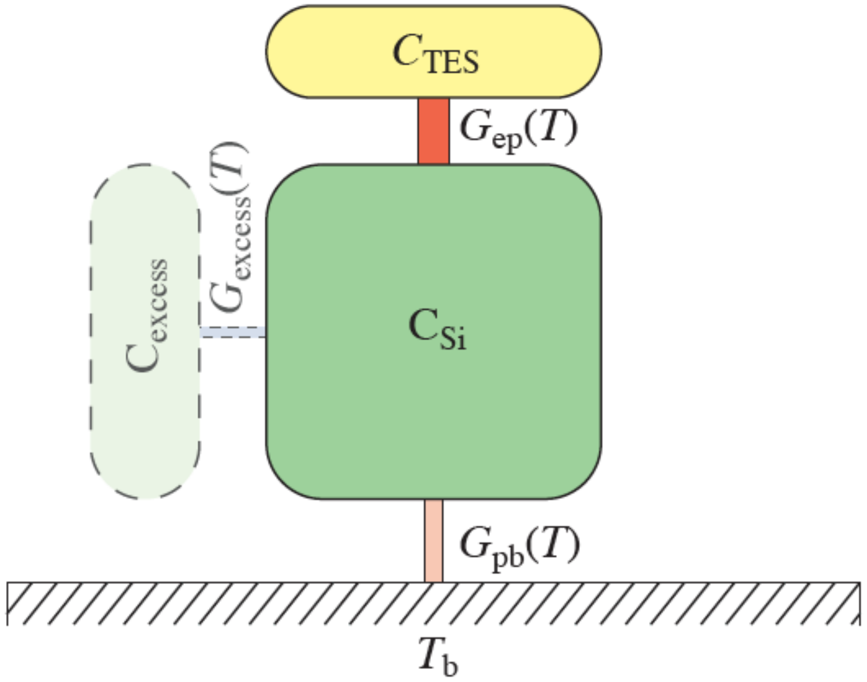
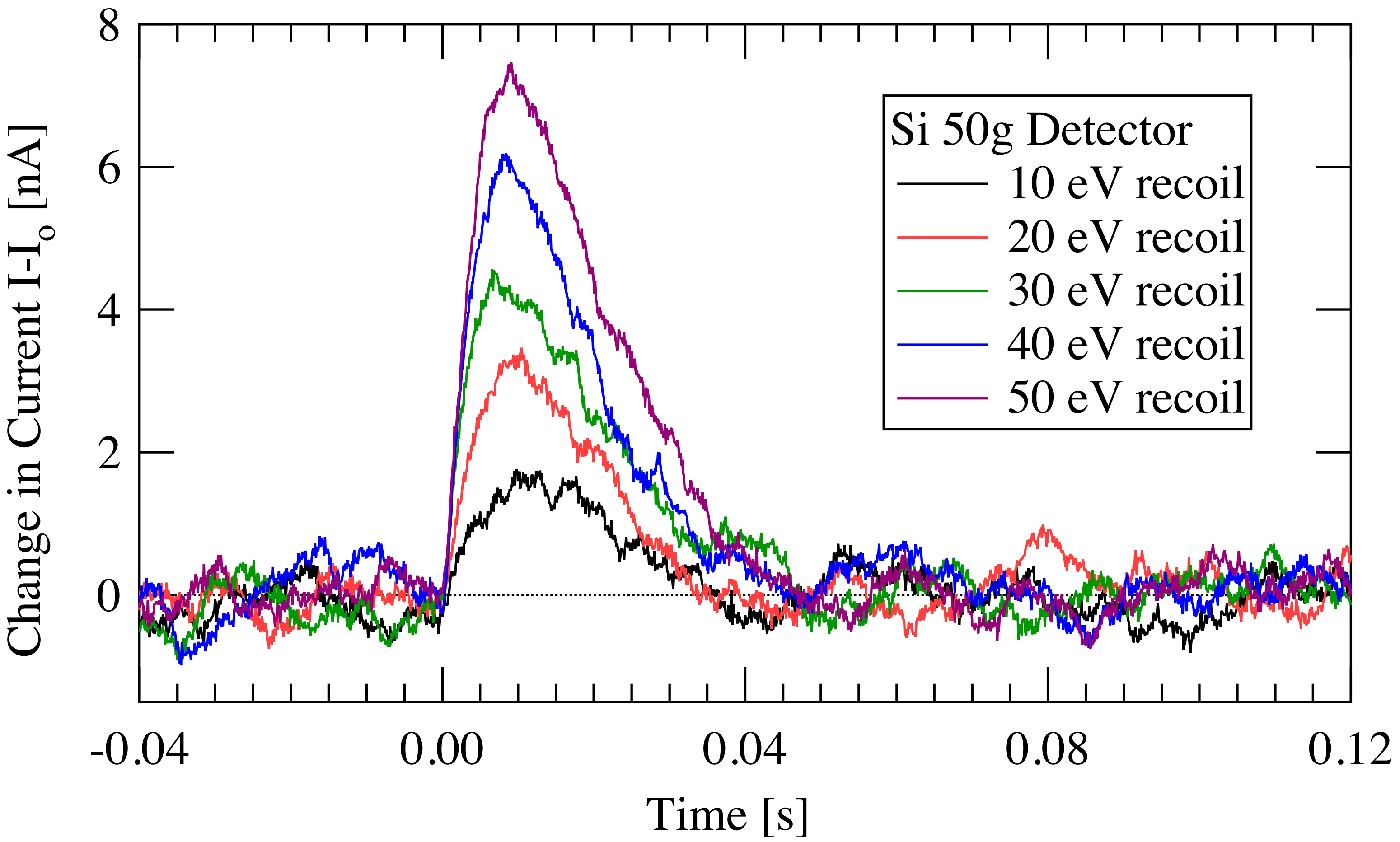
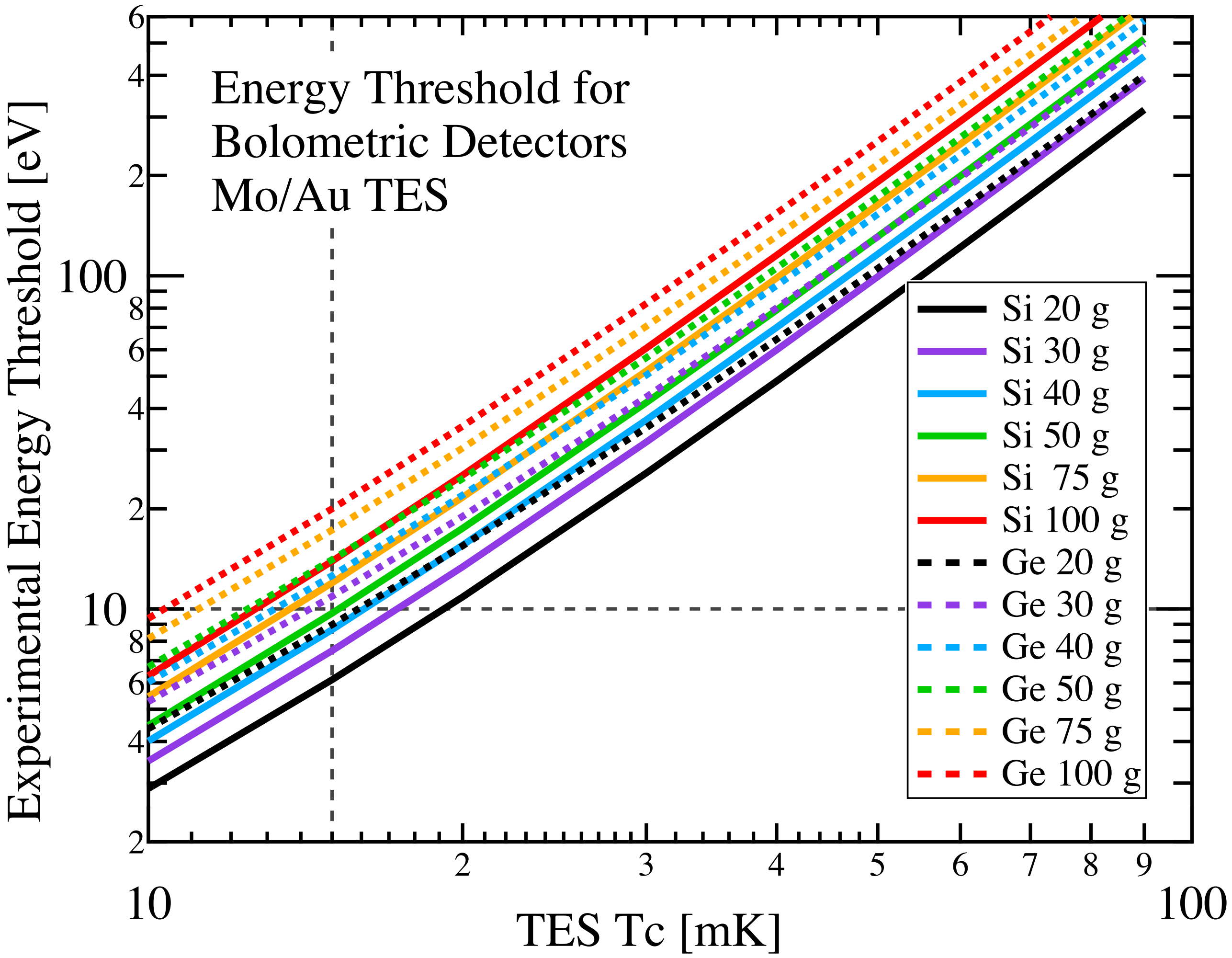


Detector Optimization

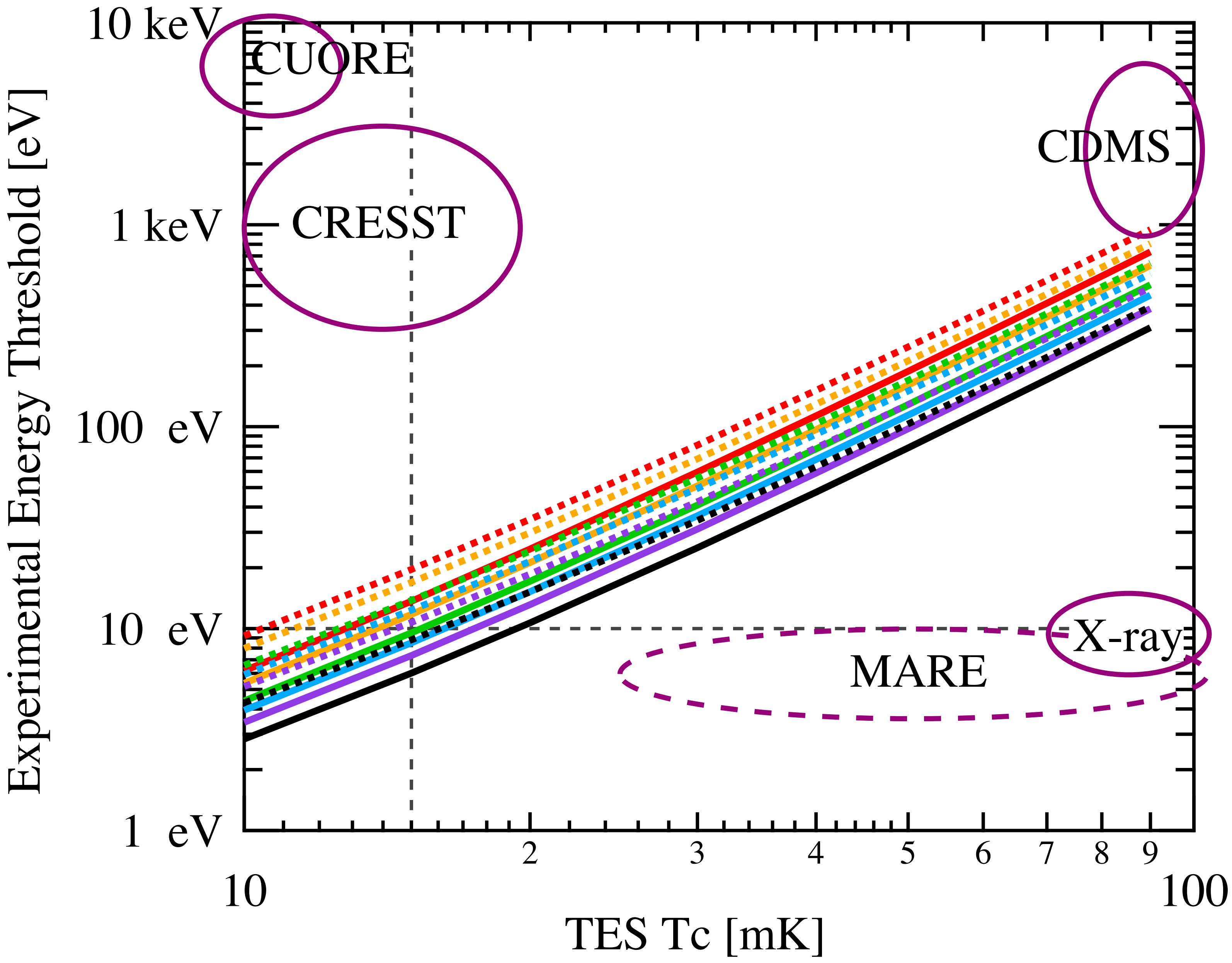


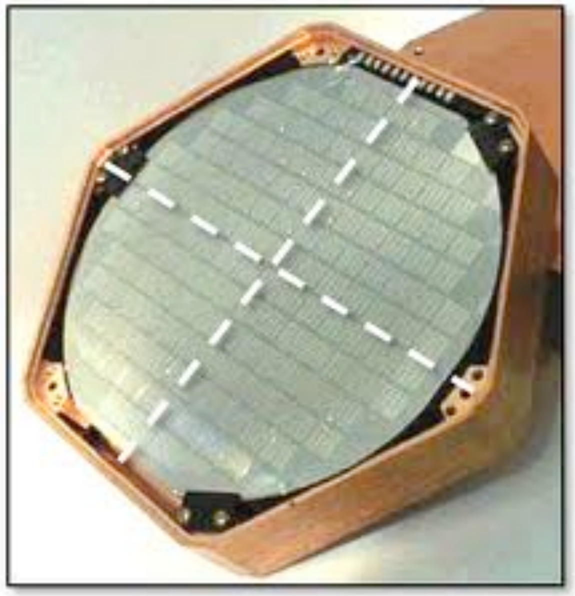


- System’s mass optimized to reach 10 eV threshold assuming 15 mK temperature.
- Yields 50 g Si (20 g Ge) cube.
- Signal pulses show remarkable linearity.

Precedent

- Knaack and Meibner have achieved low enough impurities (O(10^{12})) where Debye heat capacity dominates.
- Using Mo-Au TES, 2 eV resolutions (FWHM) have been achieved, hence used here as well.





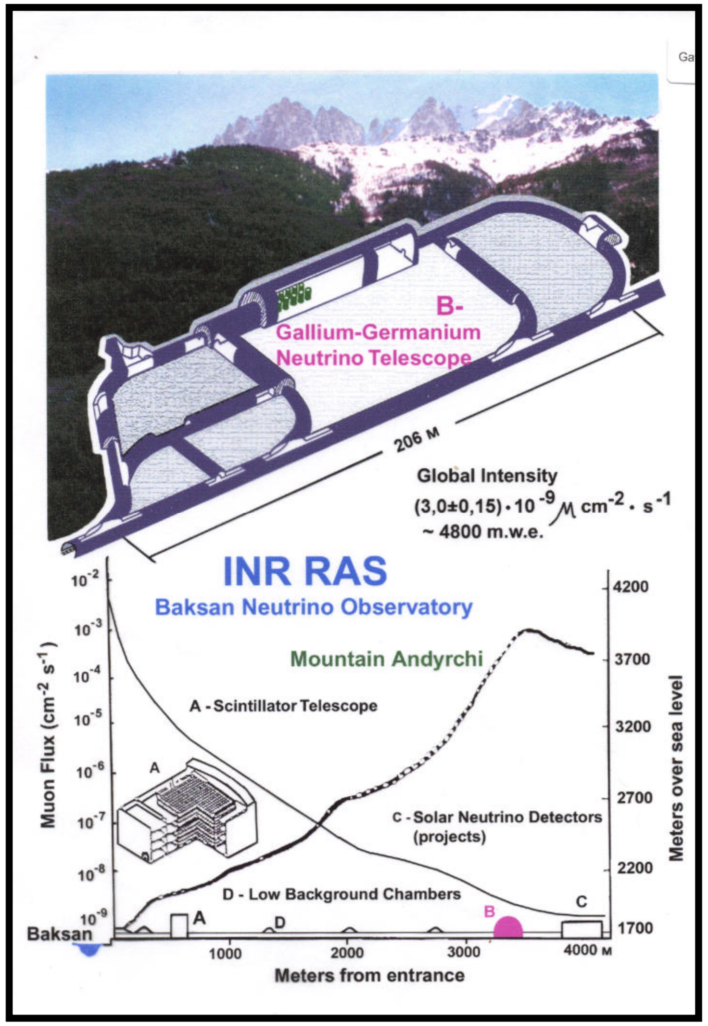
- Some existing experiments use similar technology, but are optimized for different parameters, such as mass, resolution, and timing. But no new technology is postulated.

Neutrino Sources

Sources	Pros	Cons
Electron Capture *(original motivation for Ricochet)*	Mono-energetic, can place detector < 1m from source, ideal for sterile neutrino search	< 1 MeV energies require very low (~10 eVnr) thresholds, 30 day half-life, costly
Nuclear Reactor *(first experimental stepping stone)*	Free, highest flux	Spectrum not well known below 1.8 MeV, site access can by difficult, potential neutron background at research reactors, reactor rarely off for GW power plants
Spallation/Decay at Rest	Higher energies can use higher detector thresholds, timing can cut down backgrounds significantly	SNS funding travails, ESS and Daedalus don't exist, ISODAR will have a low flux requiring large detectors

The Source

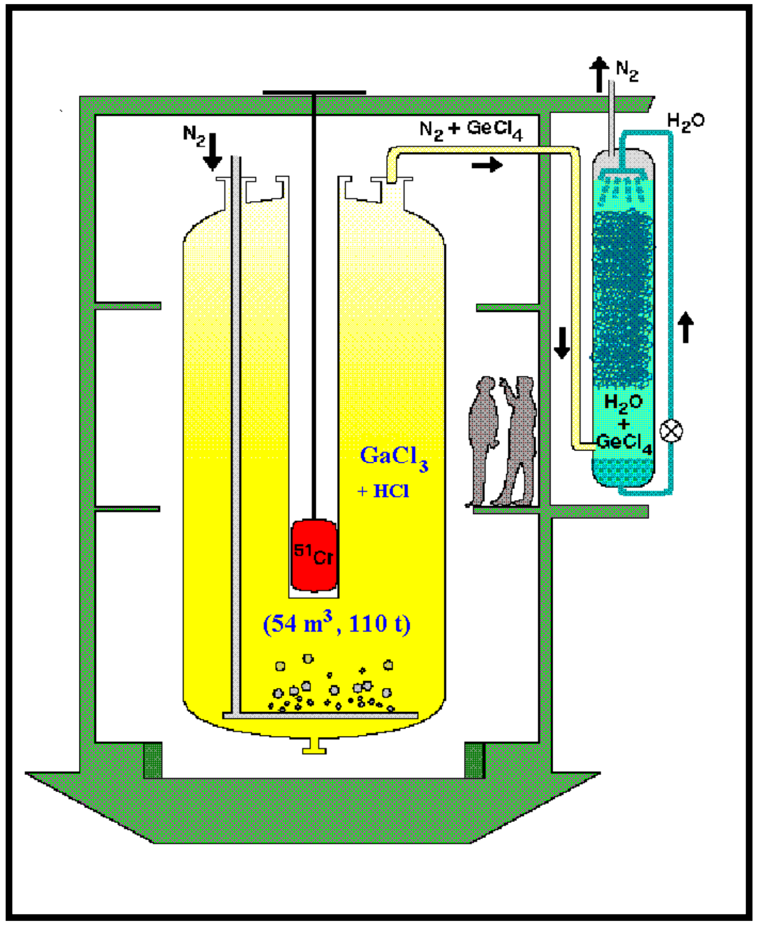
- Ideal mono-energetic sources have been constructed for experiments previously (SAGE, GALLEX), of order 1 MCi activity.
- A compact ^{37}Ar is particularly attractive, since only inner brem photons produced. However, difficult to produce.
- ^{51}Cr less ideal (but easier to produce) source. Allows for “recharging” for greater yield.
- Recently also been looking at ^{144}Ce (SOX) as possible *available* strong source.



SAGE

^{71}Ga + ν_e --> ^{71}Ge + e^-

Use of ^{37}Ar and ^{51}Cr



Gallex/GNO

^{71}Ga + ν_e --> ^{71}Ge + e^-

Use of ^{51}Cr

Source	Half-Life	Progeny	Production	E_ν
^{37}Ar	35.04 days	^{37}Cl	^{40}Ca(n,α)^{37}Ar	811 keV (90.2%), 813 keV (9.8%)
^{51}Cr	27.70 days	^{51}V	n capture on ^{50}Cr	747 keV (81.6%), 427 keV (9%), 752 keV (8.5%)
^{65}Zn	244 days	^{65}Cu	n capture on ^{64}Zn	1343 keV (49.3%), 227 keV (50.7%)

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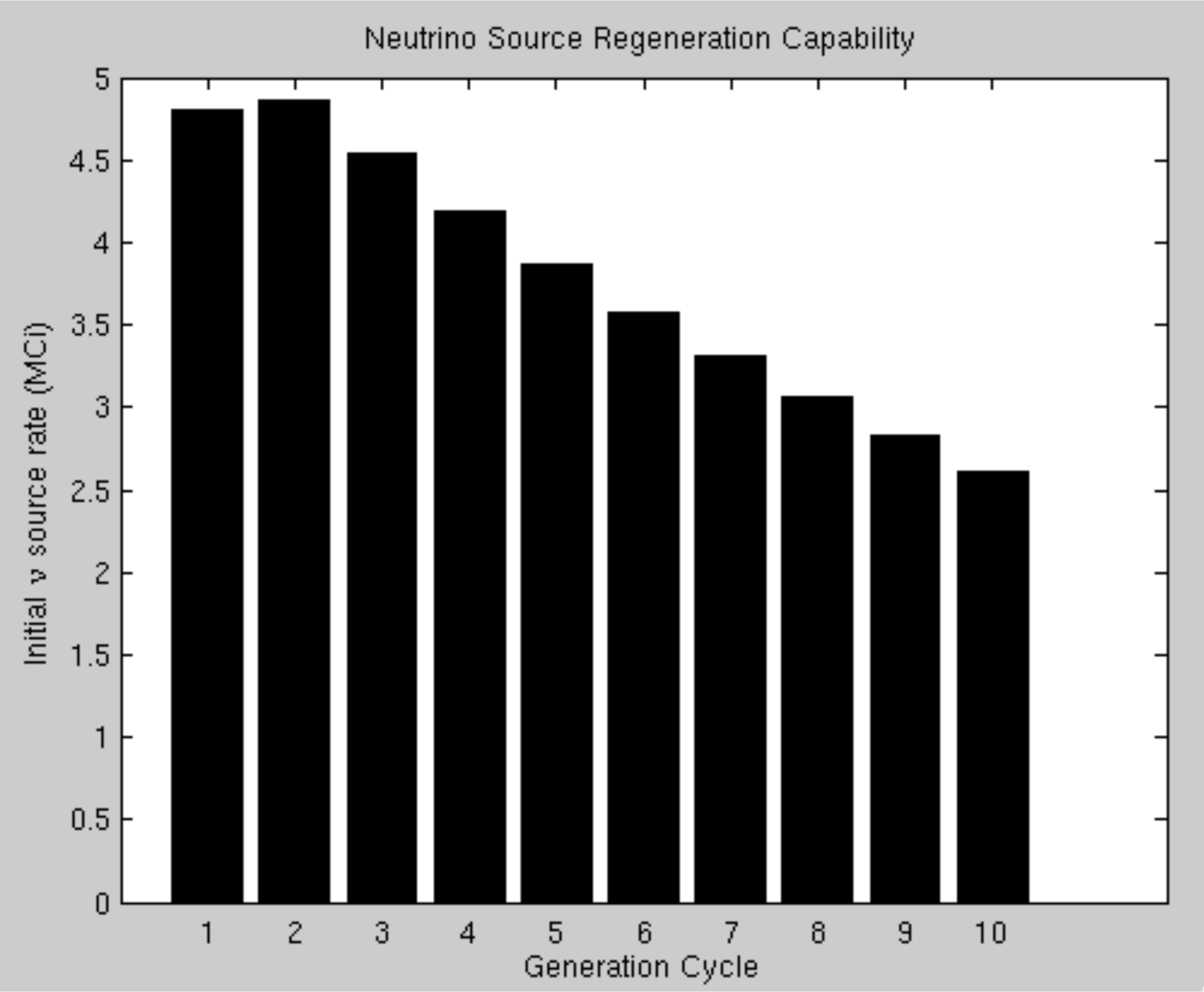

Recharging ^{51}Cr source (37.6MCi equivalent), M. Pyle

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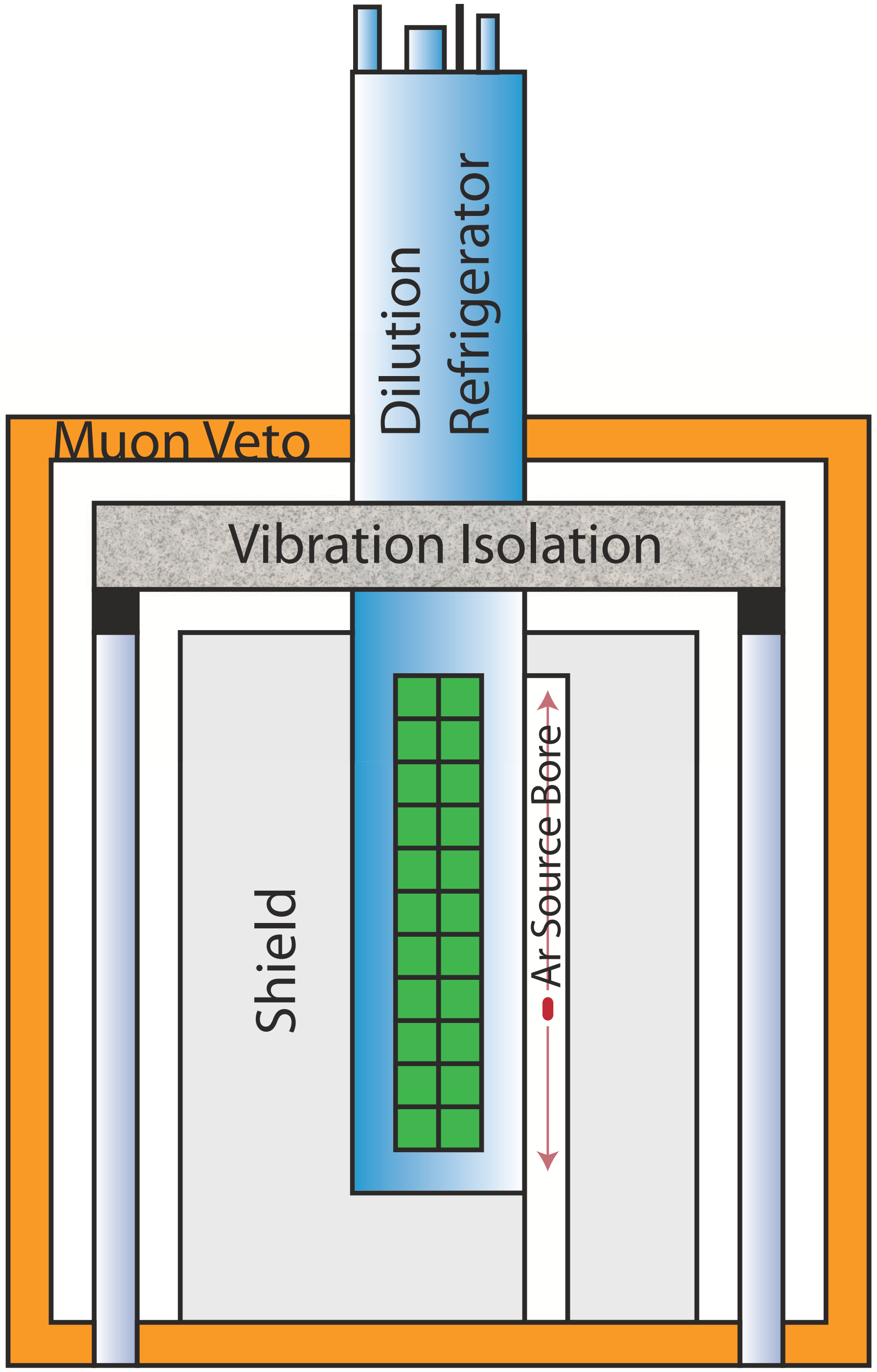
The Array

- Array of 10,000 elements with Ar/Cr source just outside shield (10 cm closest distance). System would be a merger of CUORE-like cryogenic design and SCUBA-II like readout.

- Yields 500 kg Si / 200 kg Ge array.

- Source insertion outside system. Moved for in-situ calibration.

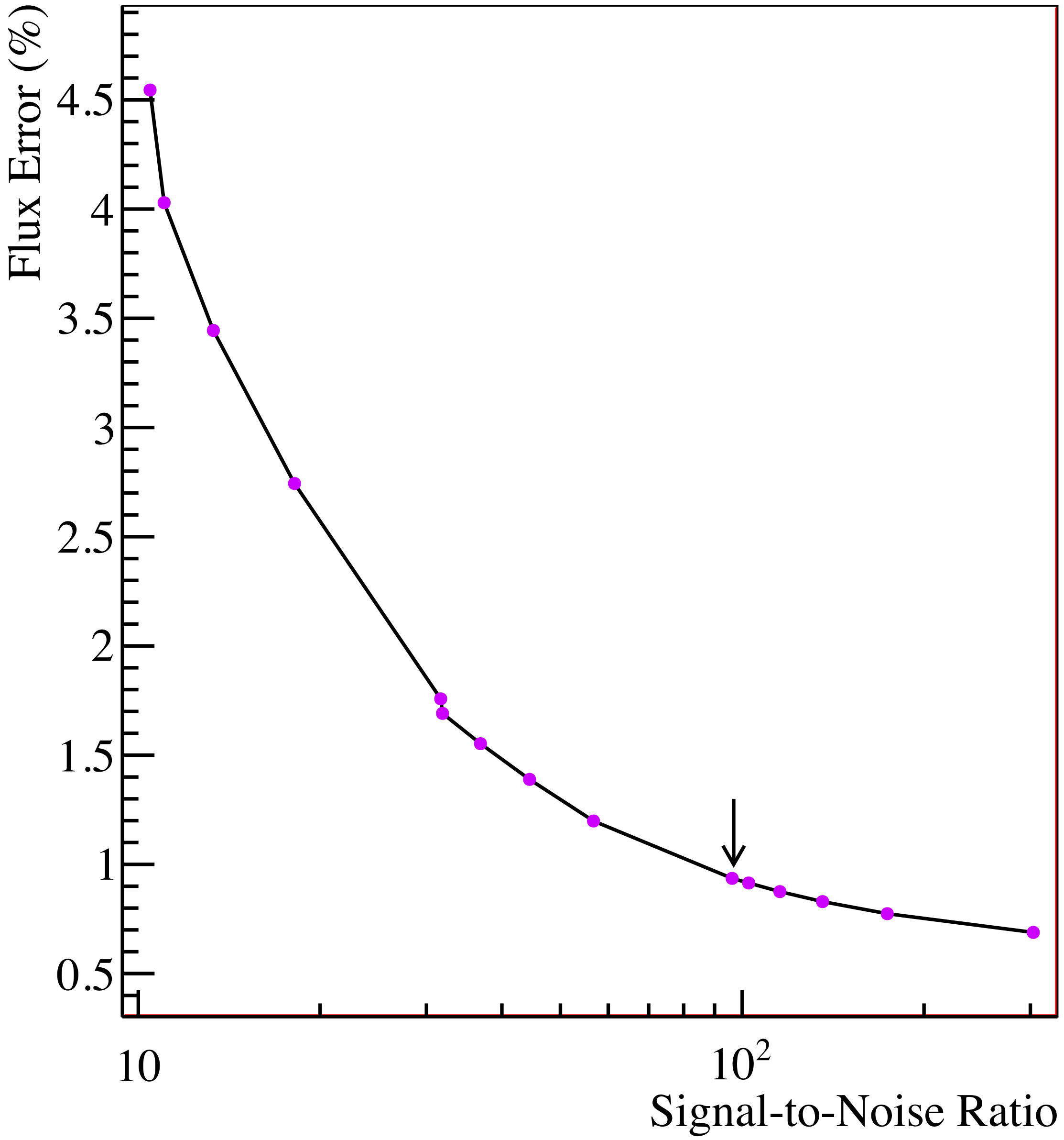
Parameter	Detector Type	
Detector Material	Si	Ge
Atomic Number	28	72.6
$\sigma_0(E_\nu)$ (10^{-42} cm^2)	0.44	3.82
$T_{\max}$	50.3 eV	19.4 eV
Threshold	10 eV	
Efficiency ($f(E_\nu, T_0)$)	64.2%	23.6%
Detector cube size	28 mm	15.5 mm
Detector Mass	50 g	20 g
Number of Detectors	10,000	
Total Mass	500 kg	200 kg
Yield at 10 cm (kg^{-1}day^{-1}MCi^{-1})	15.28	19.0
Signal Rate at 10 cm	3.82 day^{-1}	1.90 day^{-1}



RICOCHET
A Coherent Neutrino Scattering Program

Backgrounds and Systematics

- Backgrounds stem from various sources:
    - Radiogenic impurities (U, Th, ^{60}Co, and ^{3}H). Most have signatures well above region of interest. Some, like ^{3}H, have betas that have phase space in ROI.
    - Compton and photo-absorption.
    - Surface photons from atomic transitions.
    - Neutrons (< 0.1 eV/kg/yr in 10-100 keV, from CDMS measurements)
    - Neutrino-elastic scattering (not in energy range)



Estimates from CDMS place background at 40 events/kg/day/keV in the 1-10 keV region.

Leads to 1-2 events/kg/day in ROI

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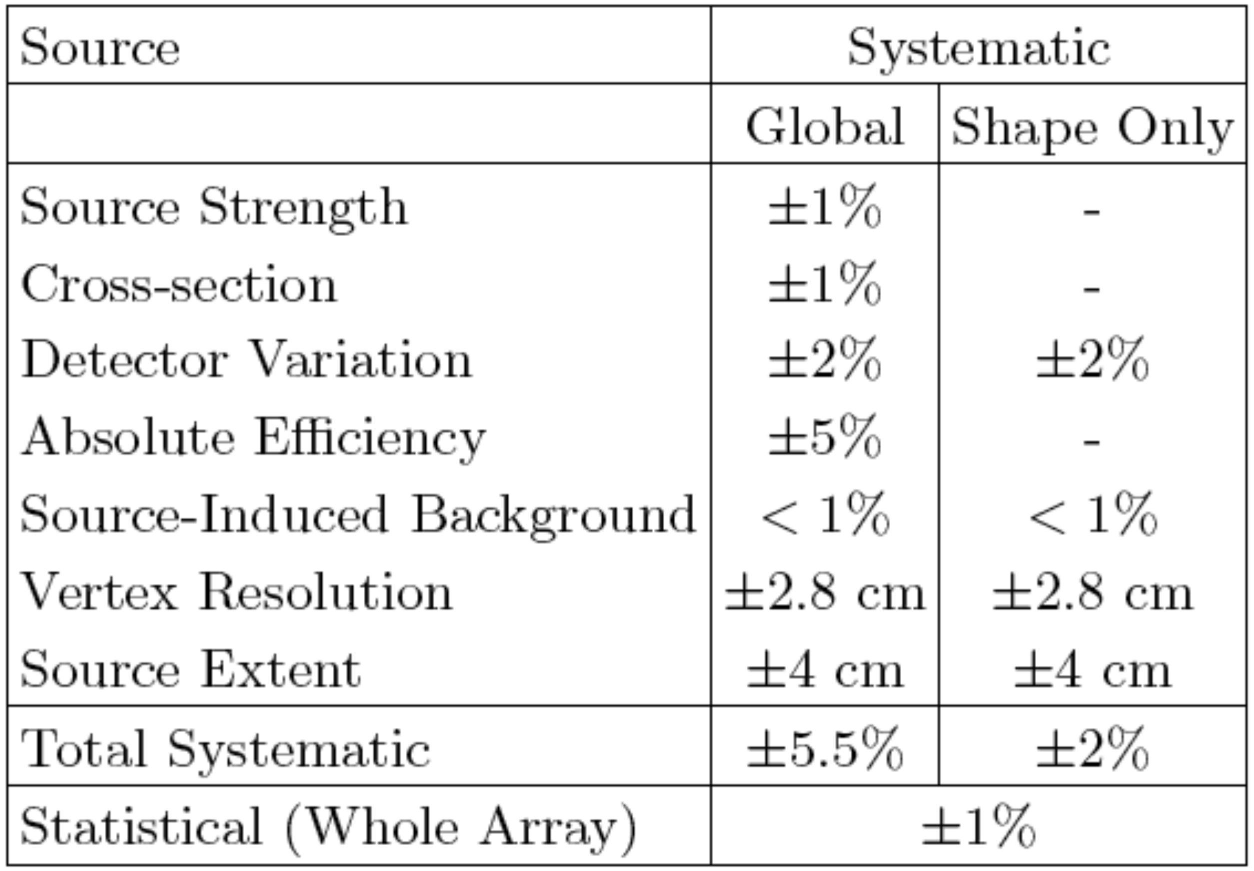

Source	Systematic	
	Global	Shape Only
Source Strength	±1%	-
Cross-section	±1%	-
Detector Variation	±2%	±2%
Absolute Efficiency	±5%	-
Source-Induced Background	$< 1\%$	$< 1\%$
Vertex Resolution	±2.8 cm	±2.8 cm
Source Extent	±4 cm	±4 cm
Total Systematic	±5.5%	±2%
Statistical (Whole Array)	±1%	

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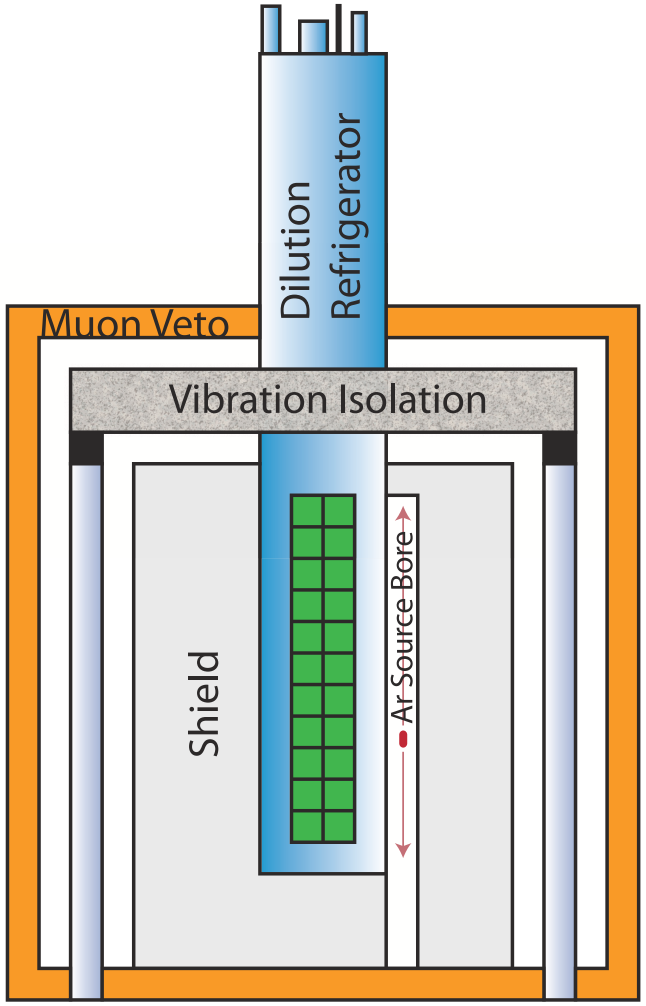
Sensitivity Studies

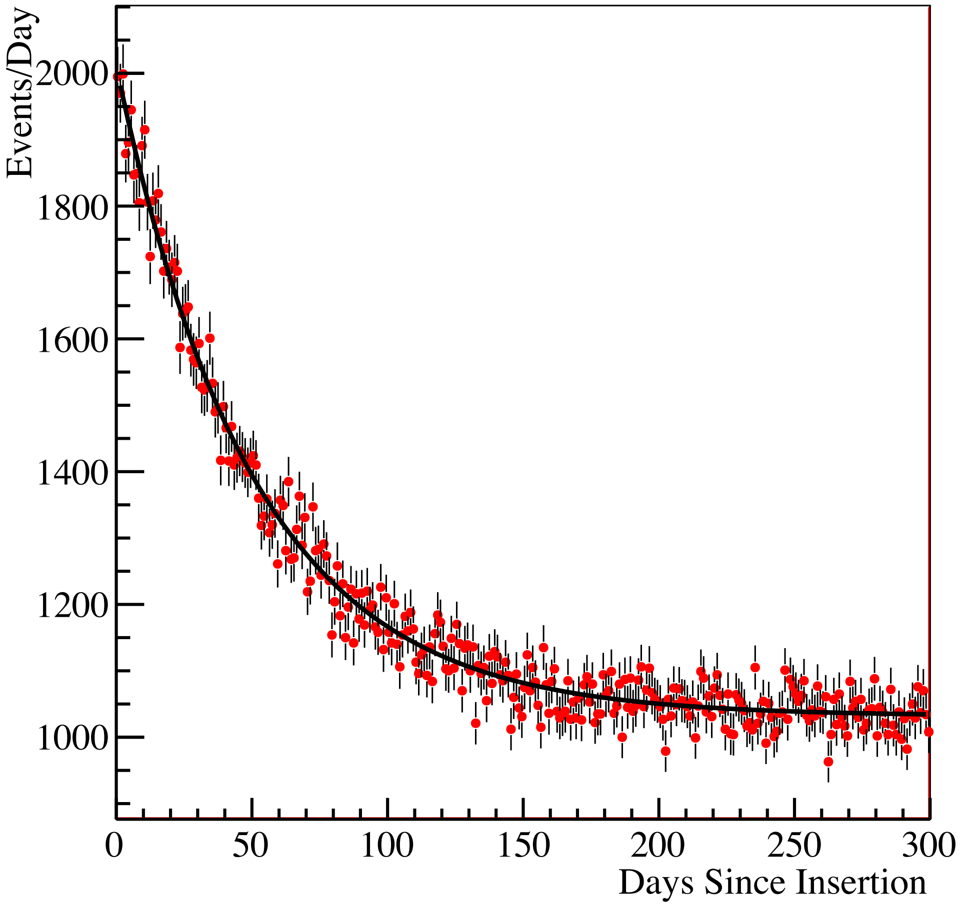


- Wanted to determine what the potential sensitivity of such an experiment for a sterile neutrino at the 1 eV mass splitting scale.

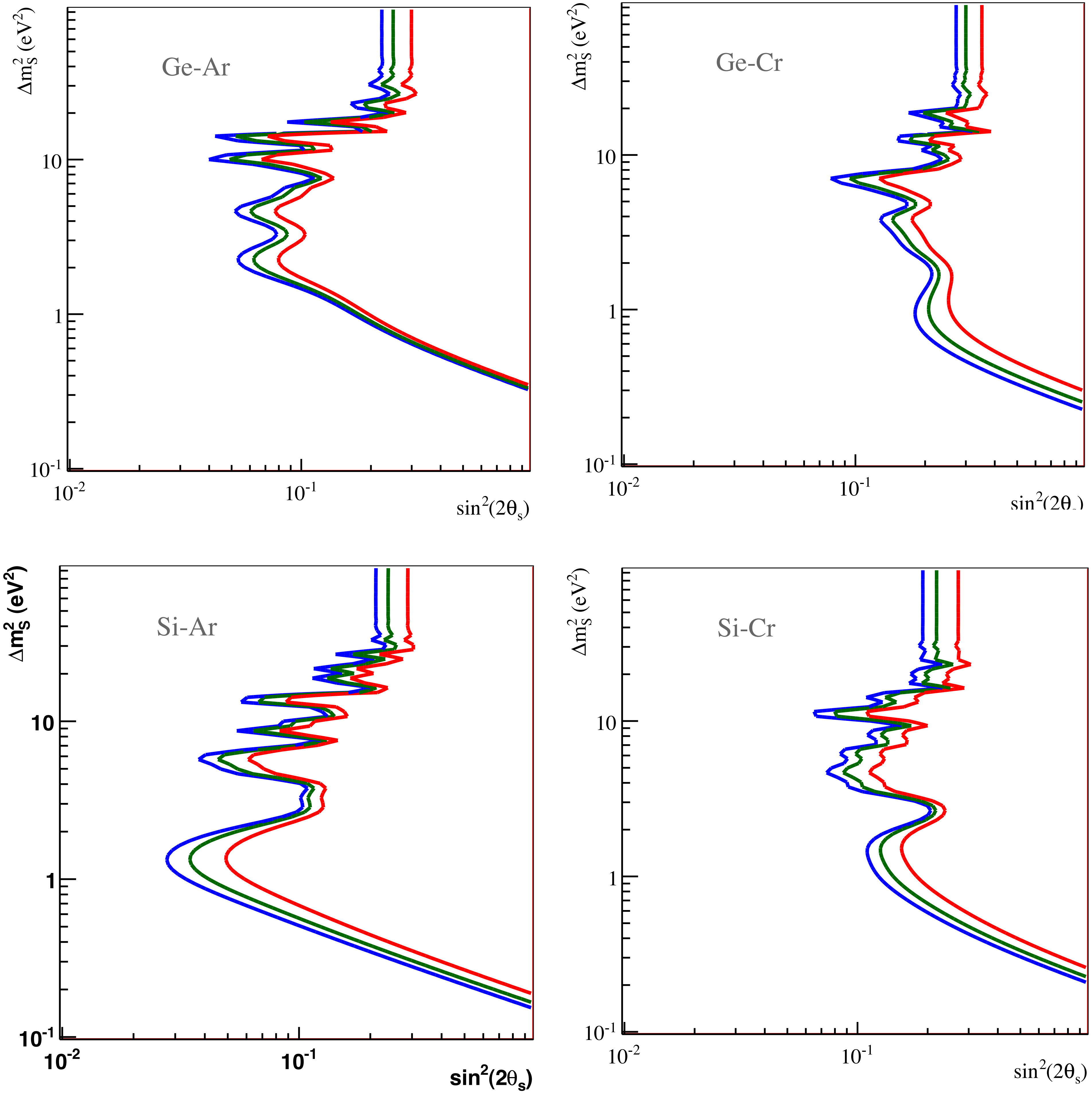
- Array of 10,000 elements with Ar/Cr source just outside shield (10 cm closest distance).

- Measuring time of 300 days (for Ar, equivalent of 50 days signal, 250 days background).

- Background rate of ~2 events/kg/day



Results


Ge-Ar
Δm^2_S (eV^2)
10
1
10^{-1}
10^{-2}
10^{-1}
$\sin^2(2\theta_s)$
Ge-Cr
Δm^2_S (eV^2)
10
1
10^{-1}
10^{-2}
10^{-1}
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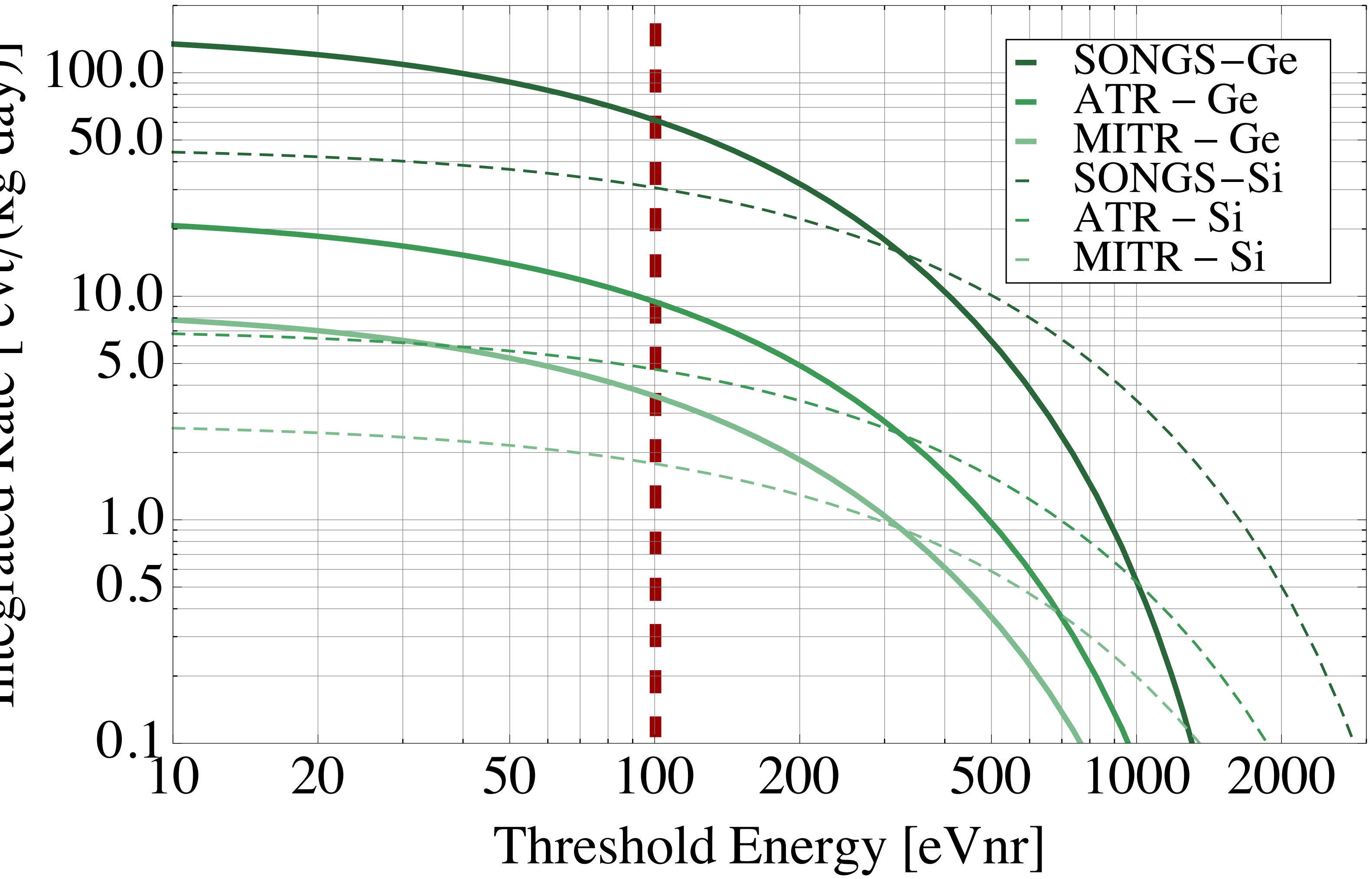
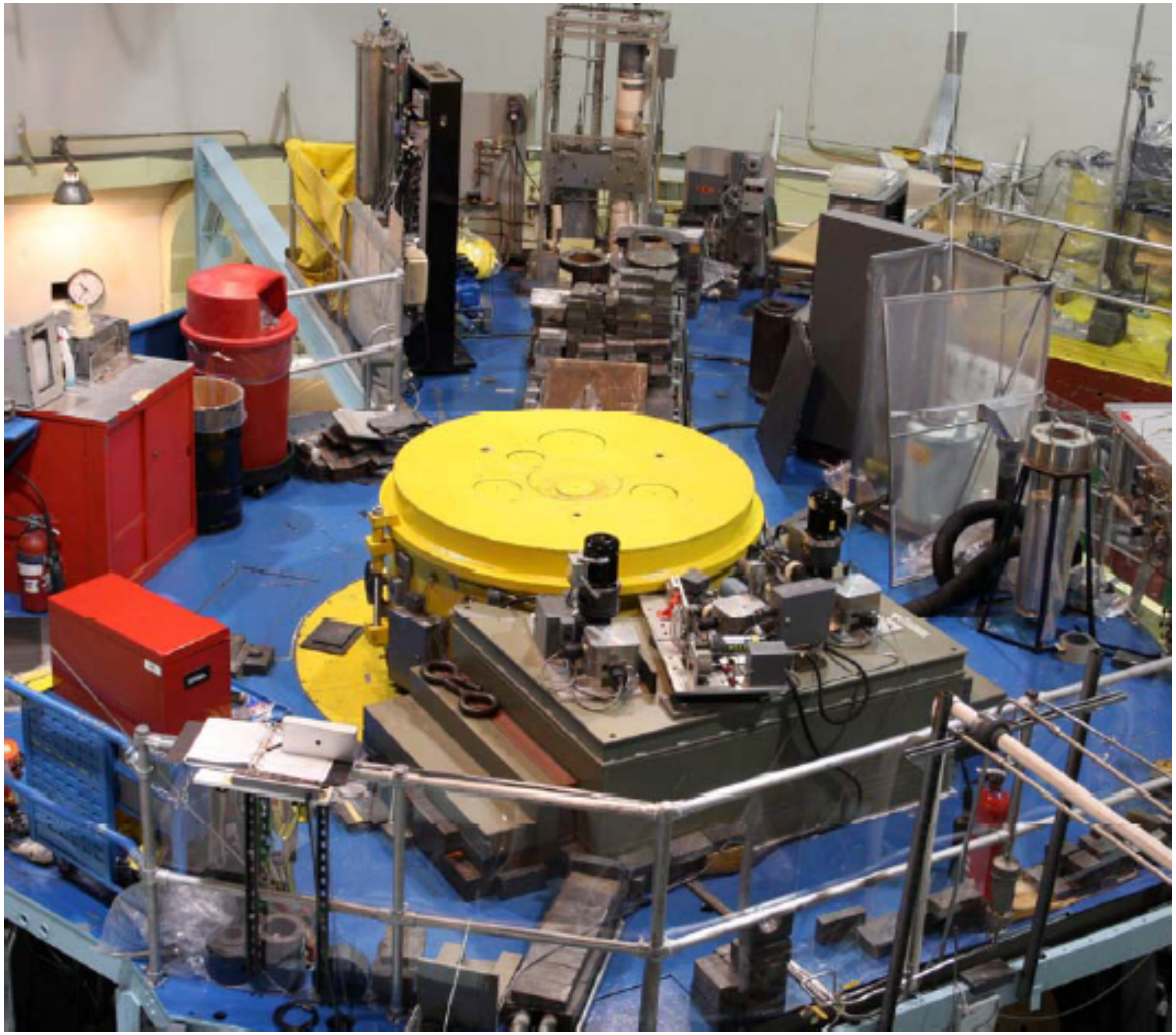
CNS Signal

	MITR	ATR	SONGS
Baseline	4 m	11 m	24 m
Ge evt/kg/day	3.6	9.6	61.4
Si evt/kg/day	1.8	4.7	30.6


CNS Integrated Rate at Various Reactors

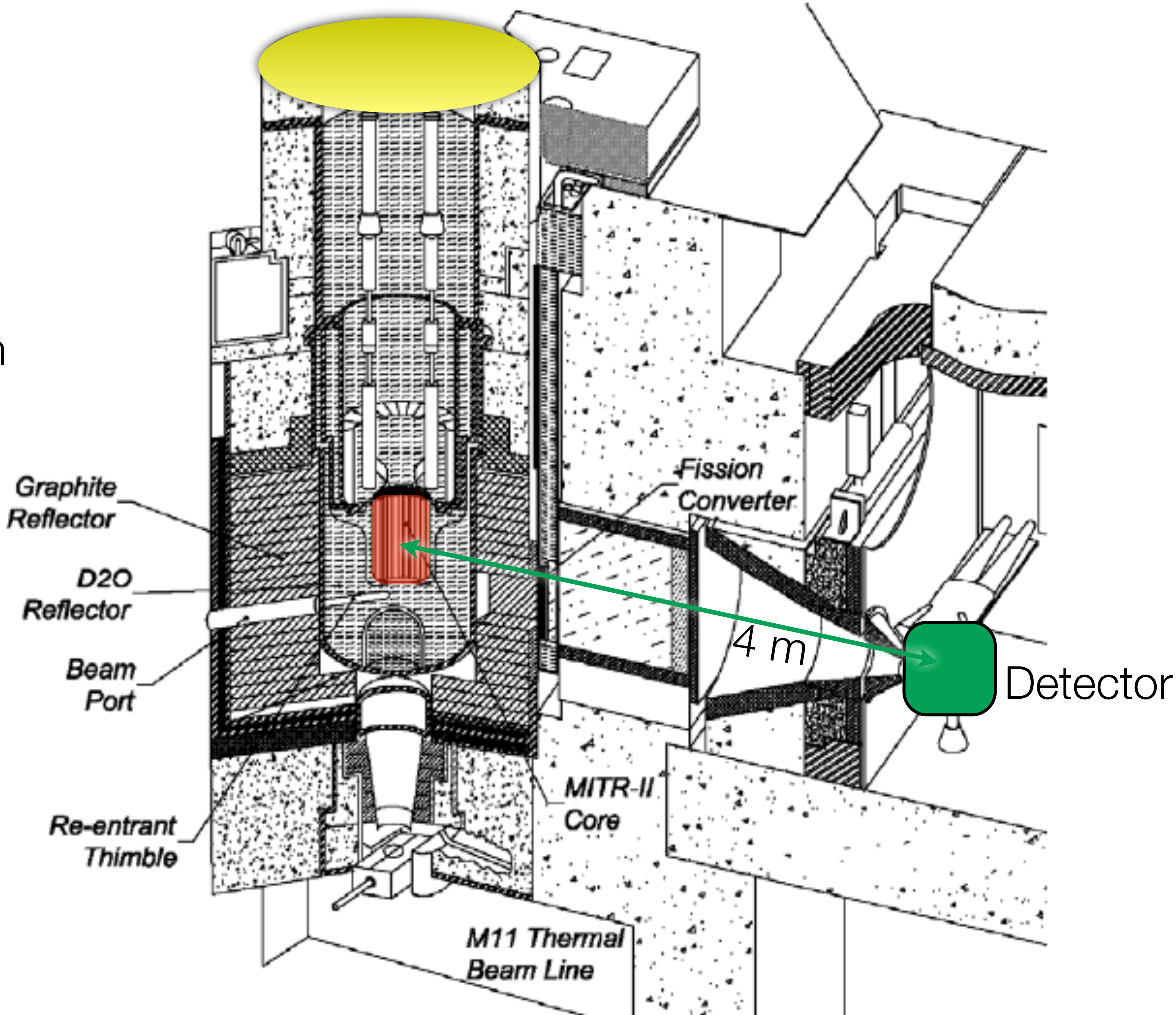
MIT Nuclear Reactor (MITR)

- 5.5 MW Thermal Reactor
- $1x10^{18}$ v/s
- $4.5x10^{11}$ v/cm^2/s @ 4 meters from core
- 4 weeks on, 1 week off operating cycle
- CONs: practically no overburden, neutron background is likely too large



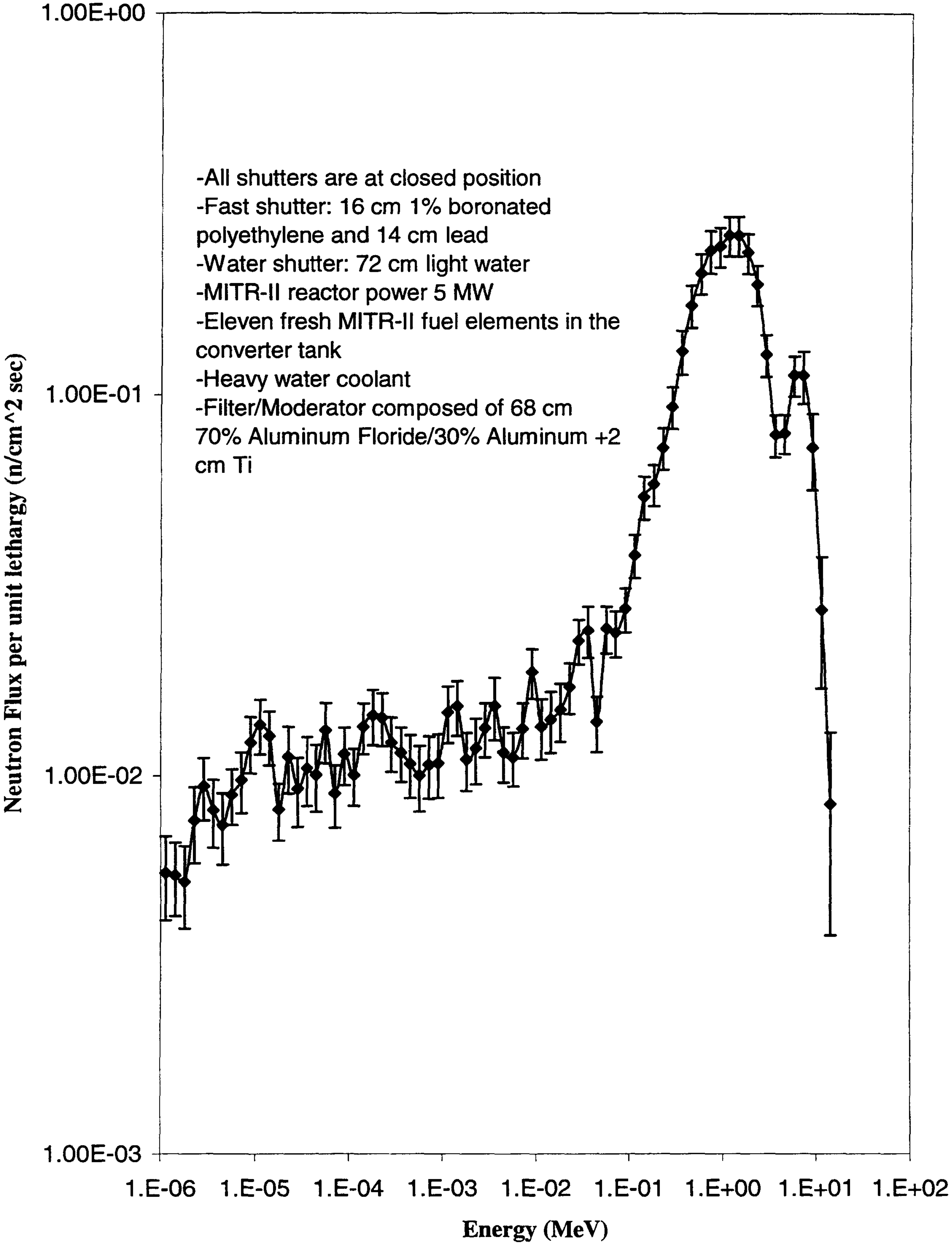
MITR experimental site

- Room available 4m from core



Neutrons at MITR

- Thesis: "Engineering design of a fission converter-based epithermal beam for neutron capture therapy," Sutharshan, Balendra, MIT Nuclear Eng. 1998 PhD Thesis
- Using this spectrum on the RicochetMC indicates that current CDMS I shield is insufficient for this neutron flux.
- MITR is likely not a good option for Ricochet, although a study with more shielding will be done soon.



Neutron monitoring

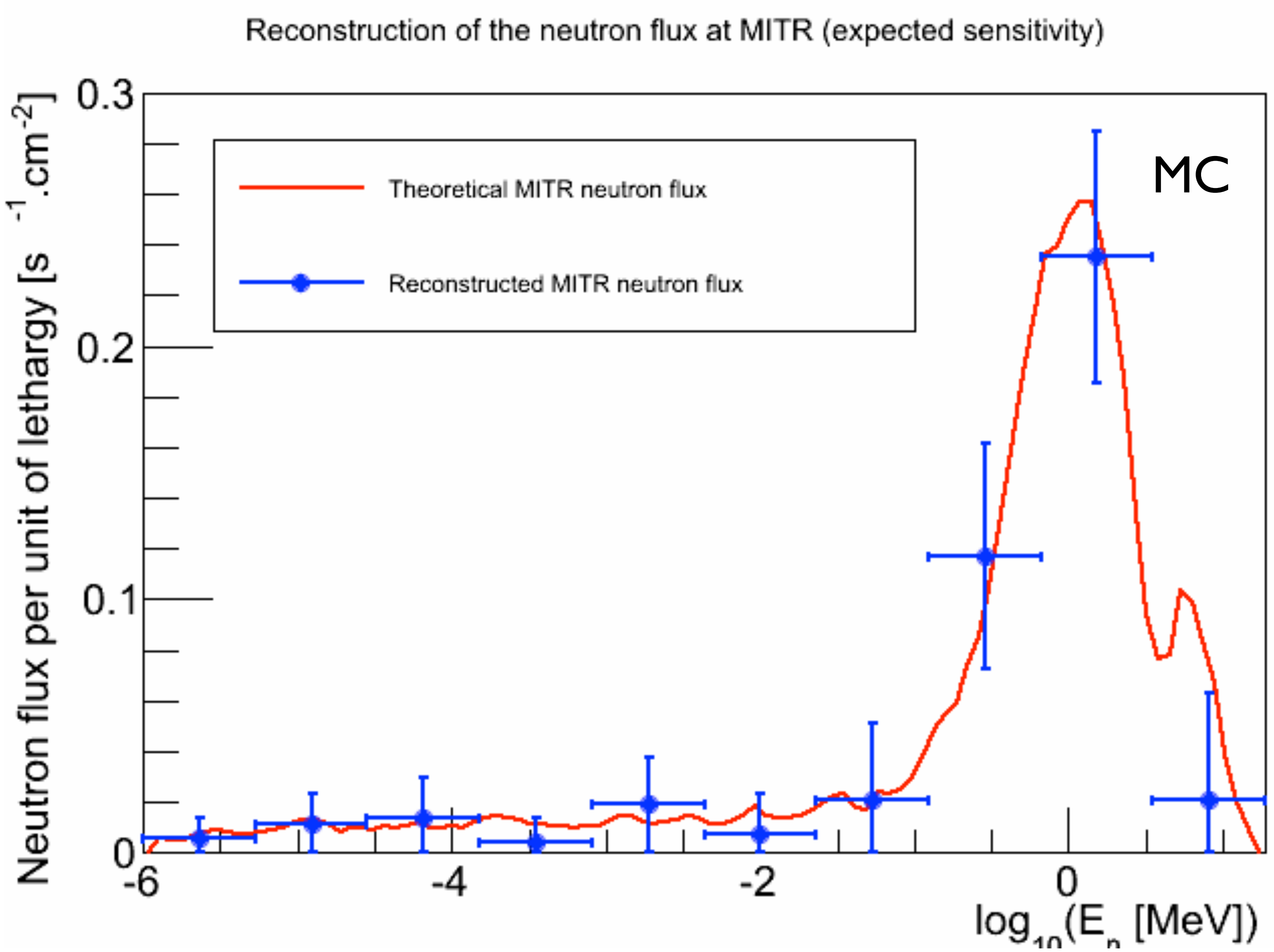
Recovering the neutron flux from NCD rate measurements
Likelihood approach

Definition of the likelihood function:

$$\mathscr{L}(\vec{F}) = \prod_{i=1}^{l} \exp\left[-\frac{(N_i^{th} - N_i^{obs})^2}{N_i^{obs}}\right]$$

Expected neutron flux reconstruction sensitivity using maximum likelihood distribution

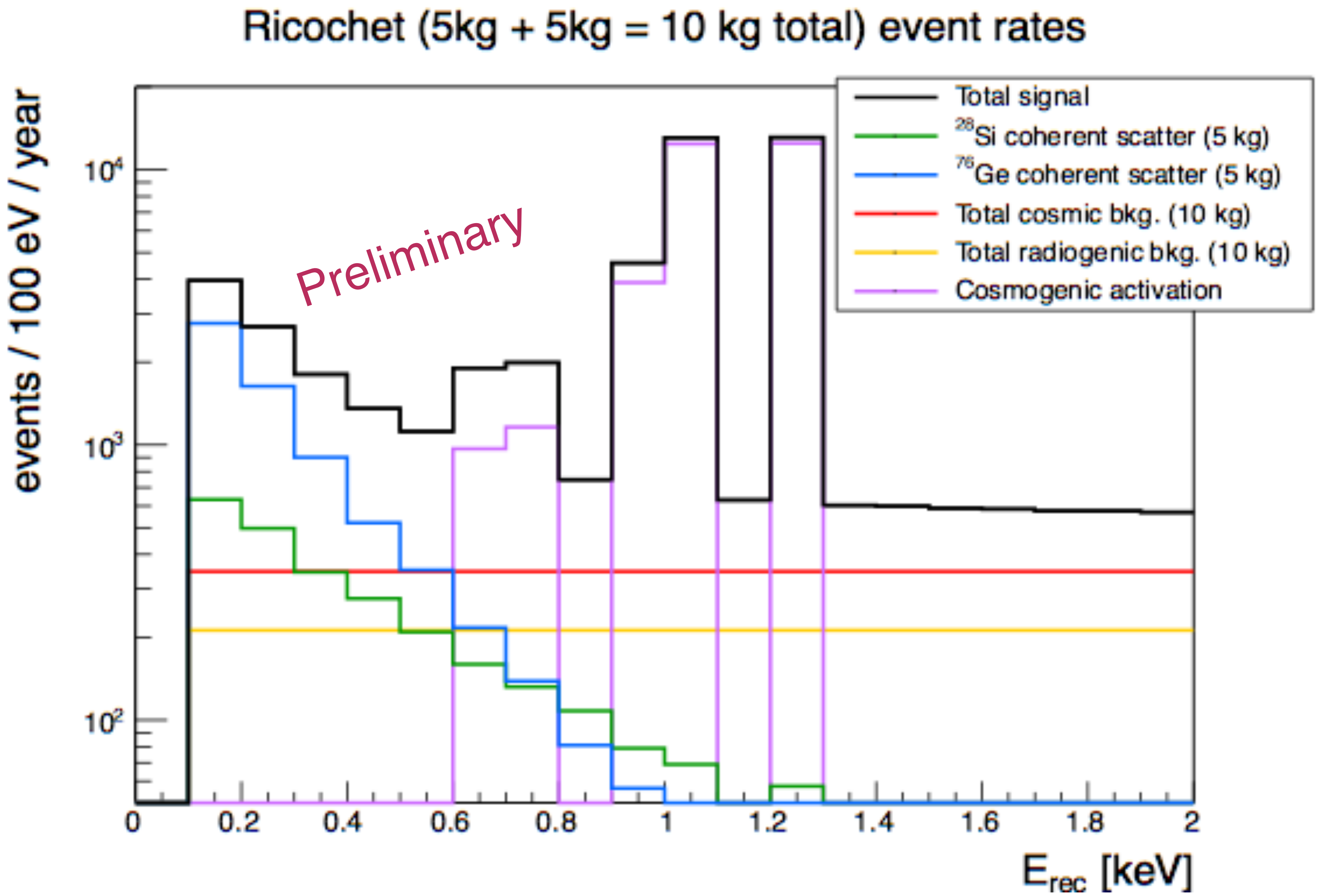
This example considers:
- MITR theoretical neutron flux
- 10 neutron energy bins
- 11 PVC layers
- An acquisition time of **20 minutes** per layer



Reconstructed total flux = 0.348 ± 0.021 neutron /s/cm^2 (~5% uncertainty)

Validation of the method using a mon-oenergetic deuteron neutron source.
Measurements at MITR starting now.

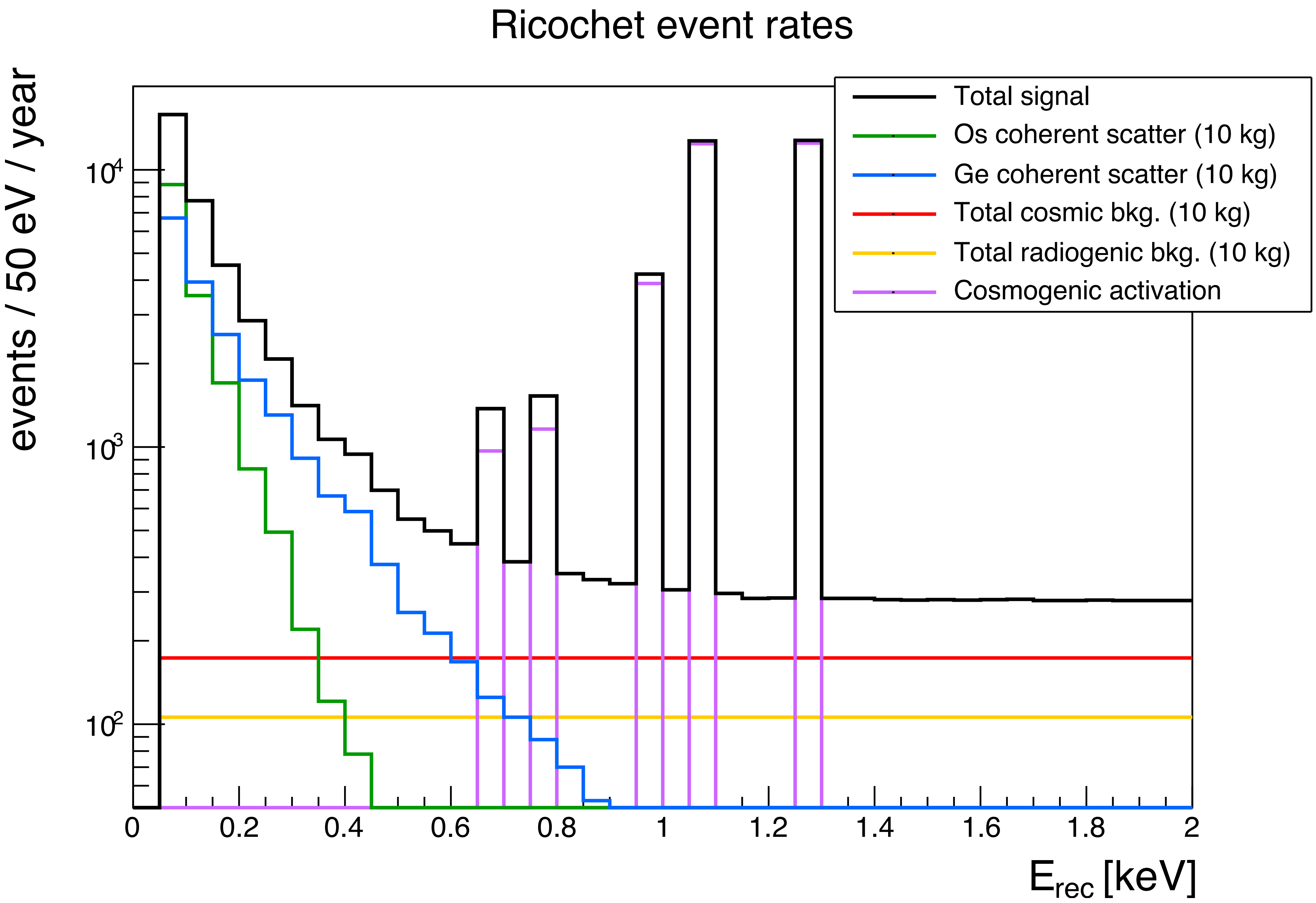
MITR Simulated Spectrum



Neutron measurements at MITR to be validated and added to the model.

Likely to dominate.

MITR Simulated Spectrum



- Also looking into the possibility of osmium detectors:
    - Potential reduced response to electromagnetic interactions.
    - One of the highest density materials in the world (with large A)

Starting steps focus on the reactor option to push on the low threshold technology.

Background measurements at the MITR commencing.

Detector technology for ~100 eV threshold (Ge, Si, or Os detectors) focus of next phase.

Thank you