Experimental Challenges and Sensitivity Reach of CNS Measurements with Phonon Detectors

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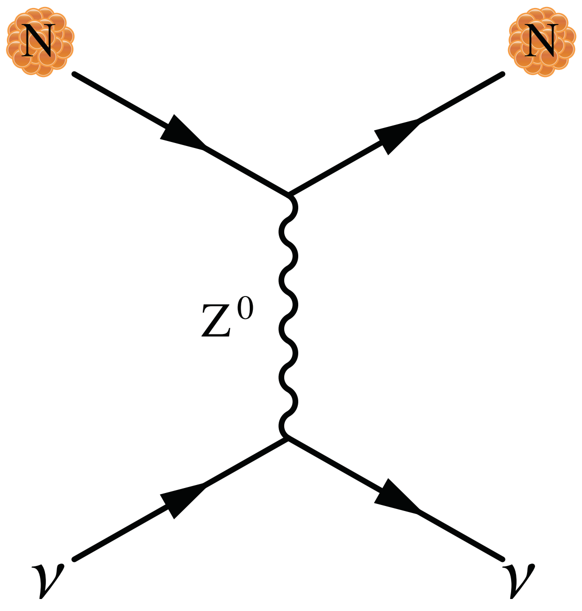
Coherent ν Scattering

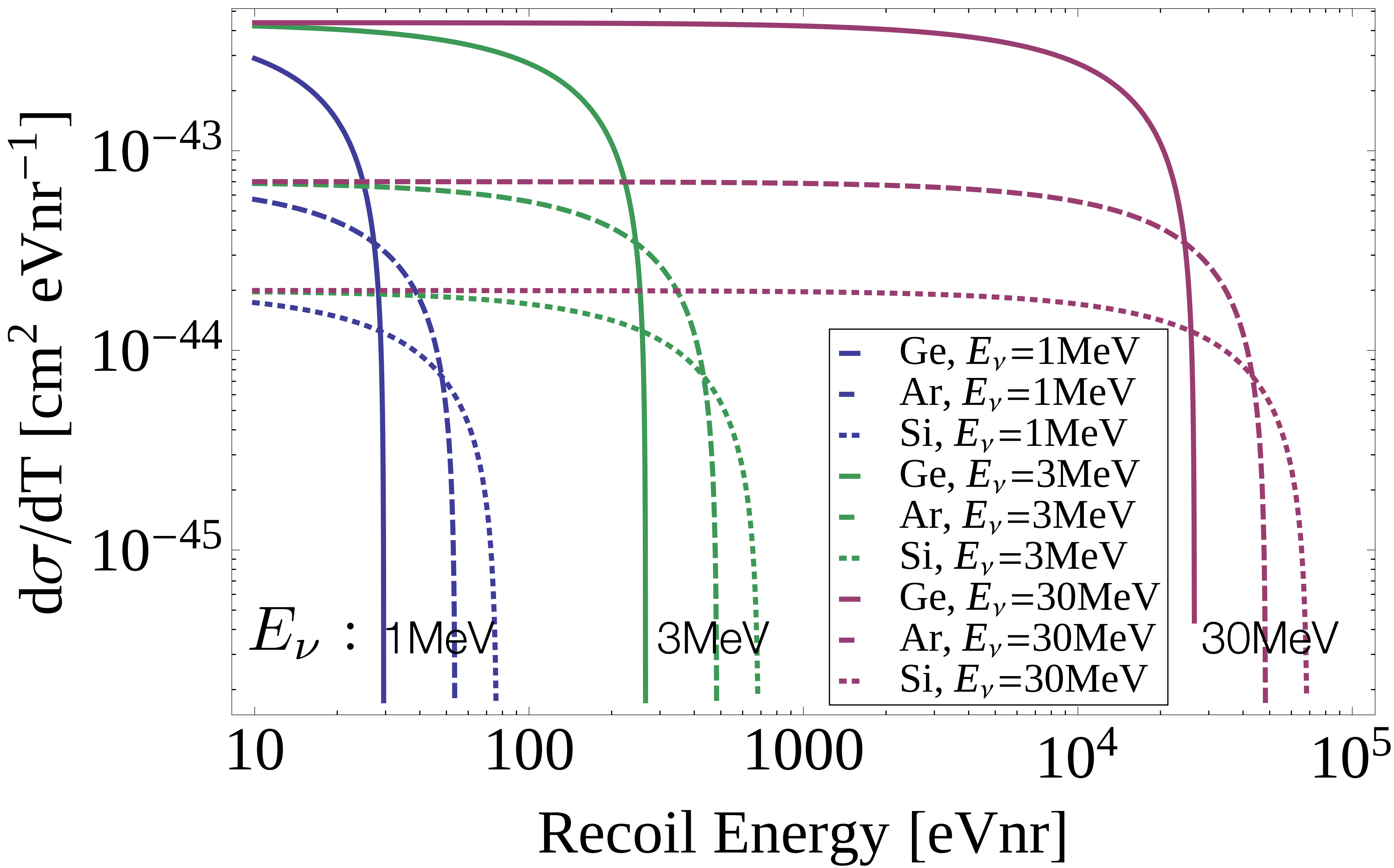
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(q^2)^2$$

- σ: Cross Section
- T: Recoil Energy
- E_ν: Neutrino Energy
- G_F: Fermi Constant
- Q_W: Weak Charge
- M_A: Atomic Mass



No flavor-specific terms!!!
Same rate for ν_e, ν_μ, and ν_τ

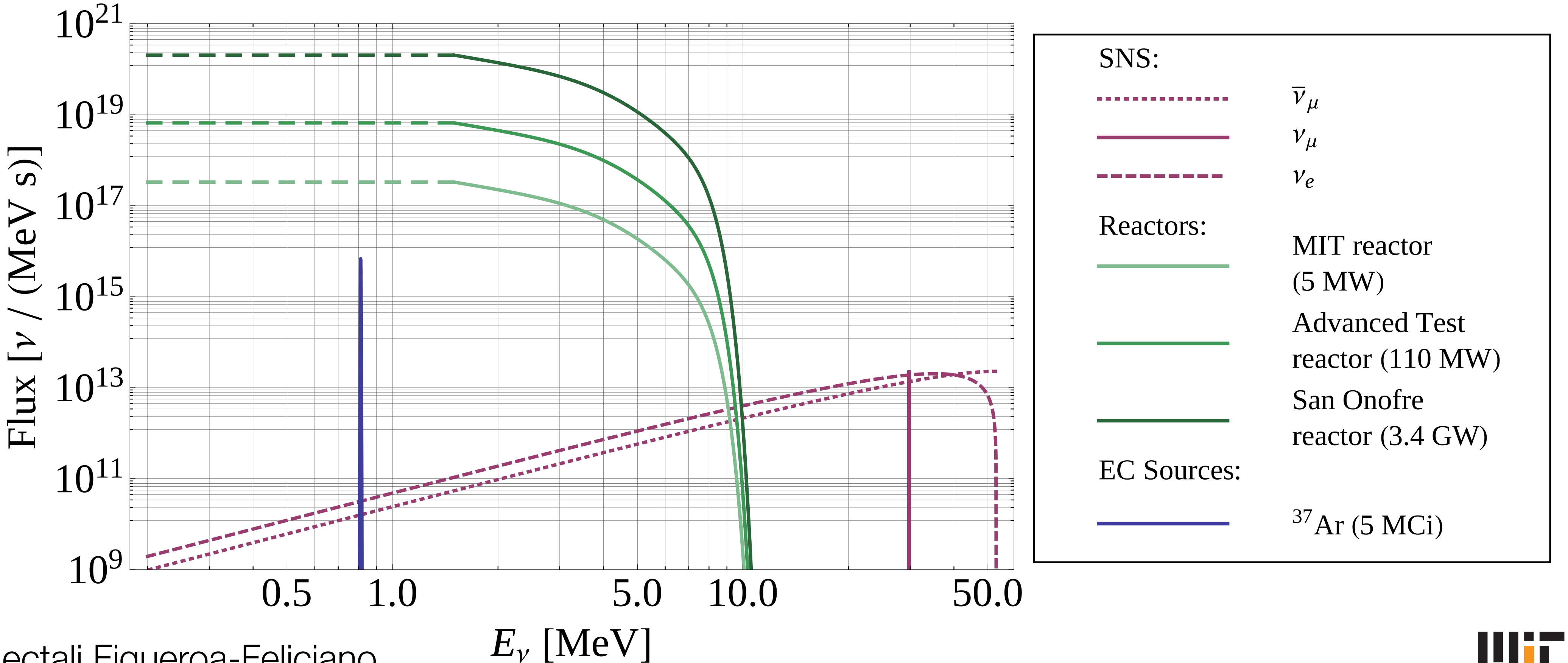
CNS Cross Sections



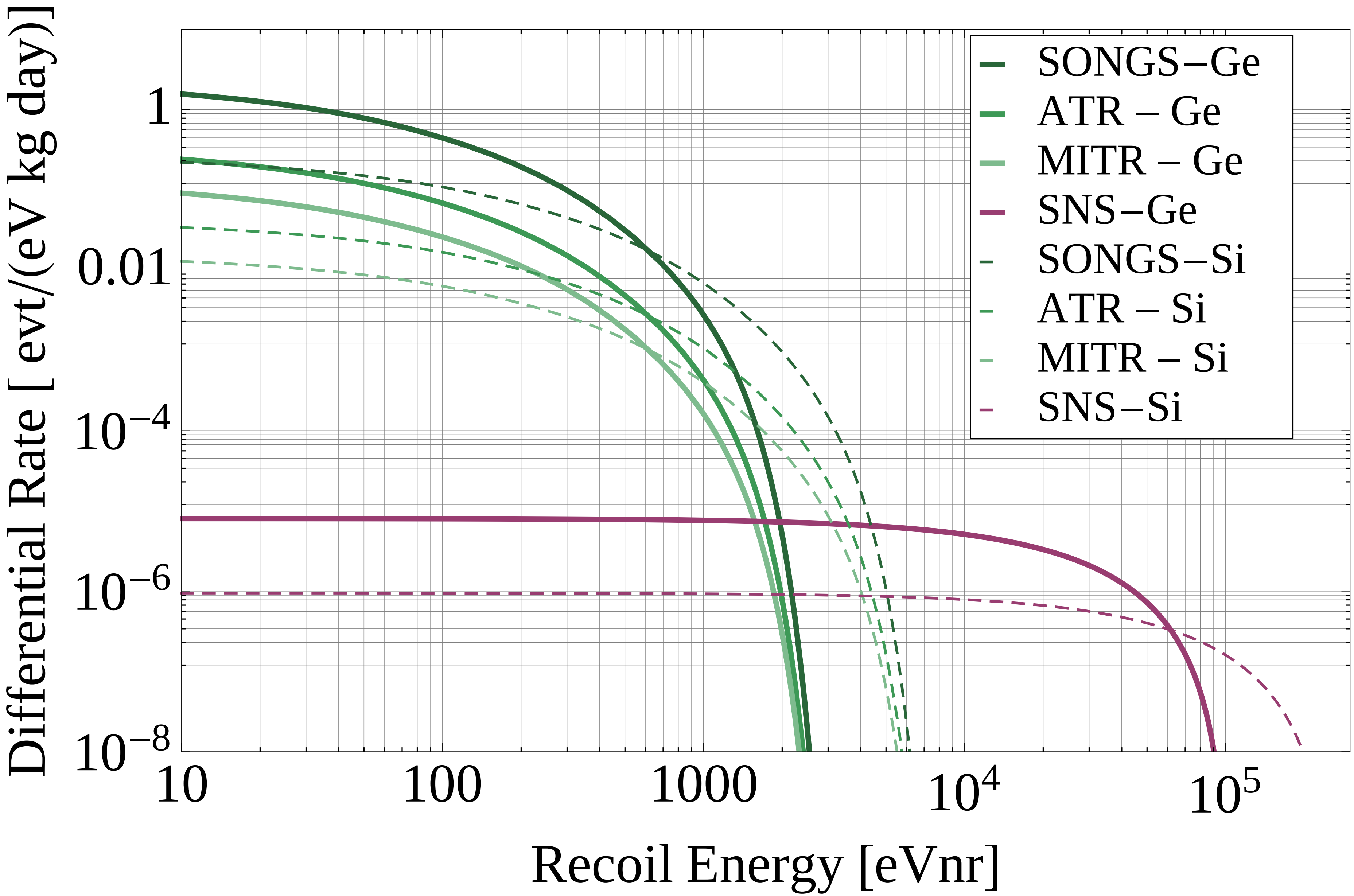
Neutrino Sources

3 sources to consider:

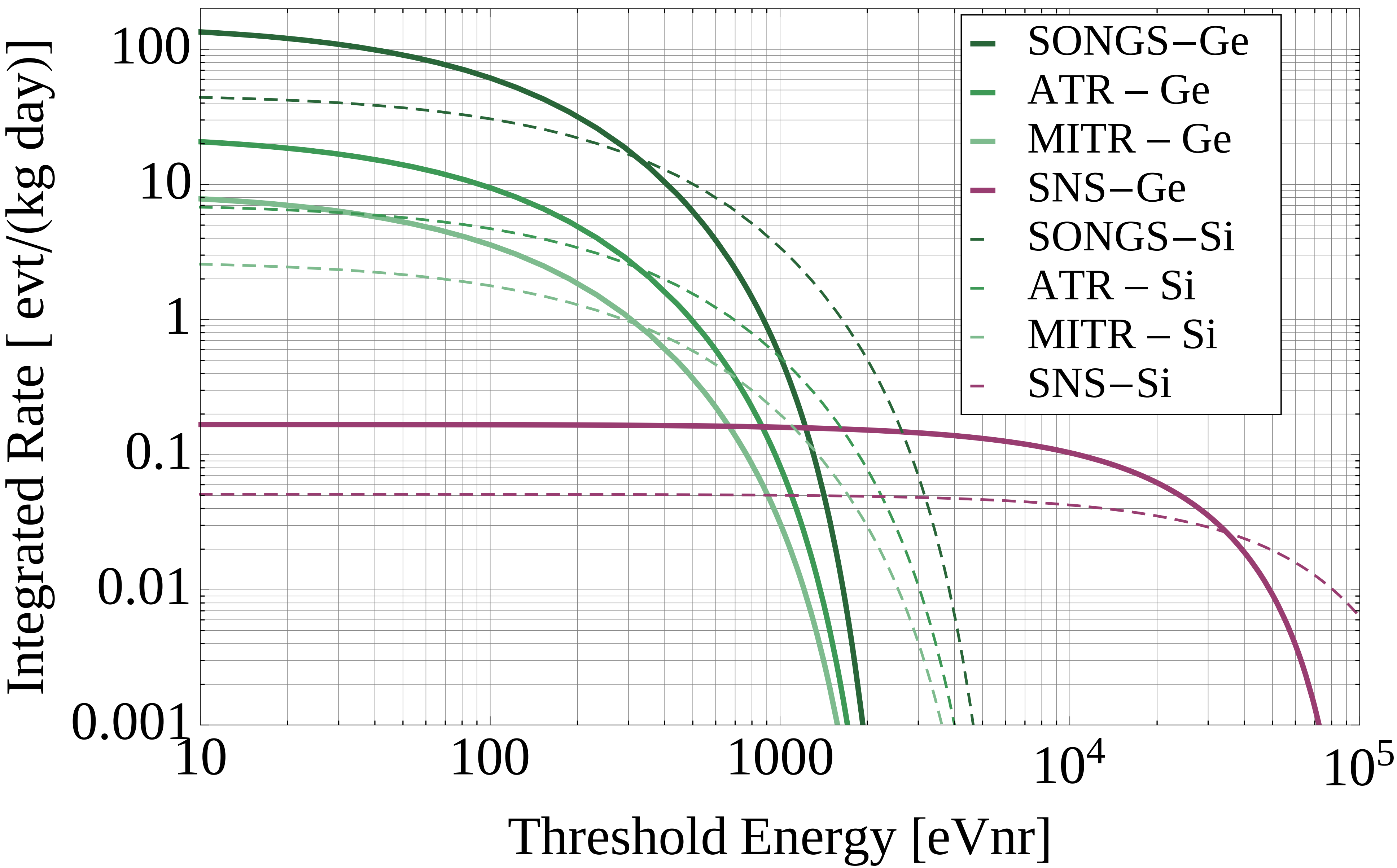
- Electron-capture sources (J. Formaggio)
- Reactors (A. Bernstein)
- Decay-at-rest sources (K. Scholberg, M. Shaevitz)



Differential rate at existing facilities



Integrated Rate at existing facilities



Neutrino Sources

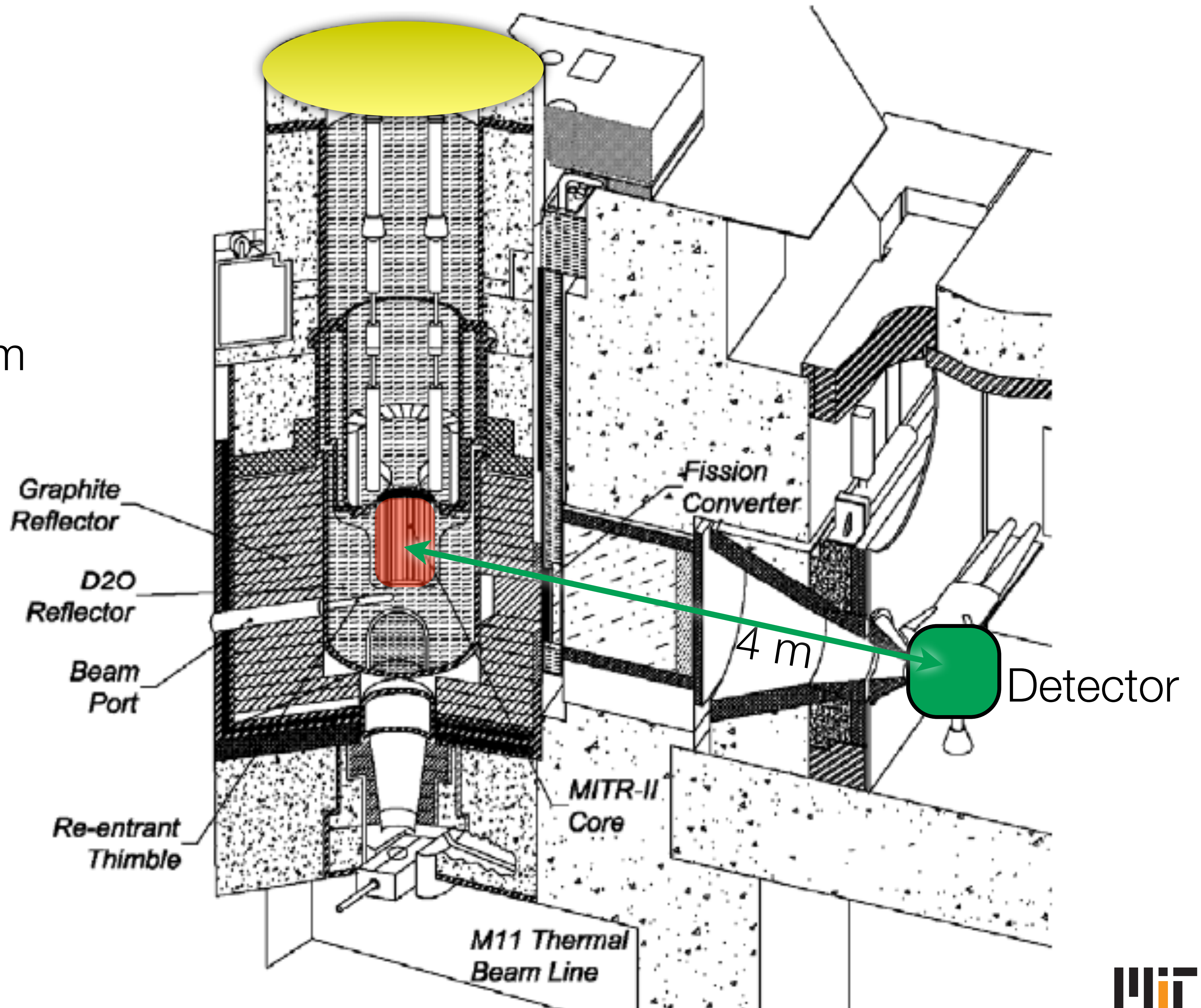
Sources	Pros	Cons
Electron Capture	Mono-energetic, can place detector < 1m from source, ideal for sterile neutrino search	< 1 MeV energies require very low (~10 eVnr) thresholds, 30 day half-life, costly
Nuclear Reactor	Free, highest flux	Spectrum not well known below 1.8 MeV, site access can by difficult, 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 similar flux but lower energy vs (mean Ev=6MeV) requires lower thresholds

MIT Nuclear Reactor (MITR)

- 5.5 MW Thermal Reactor
- 1x10^{18} ν/s
- 4.5x10^{11} ν/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

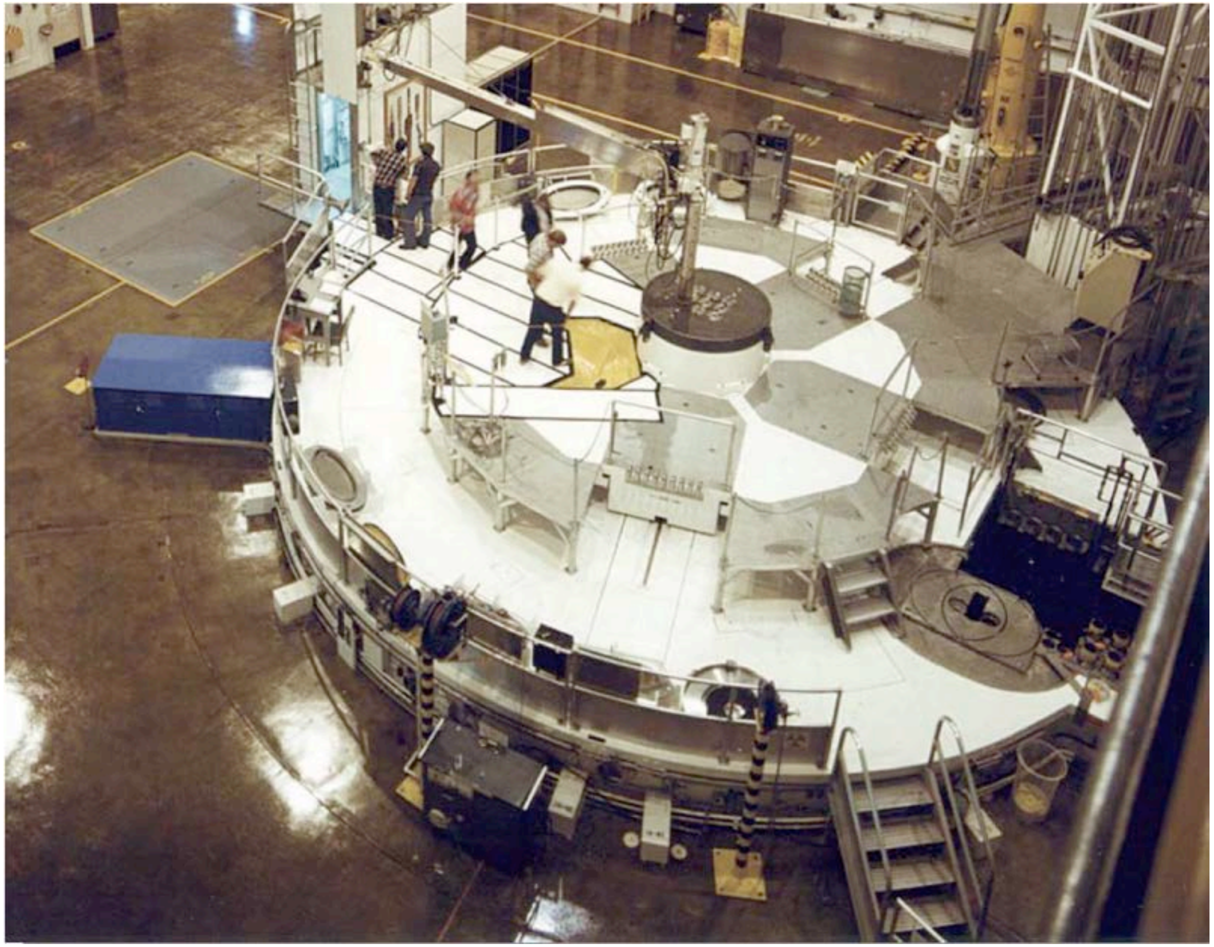
MITR experimental site

- Room available 4m from core



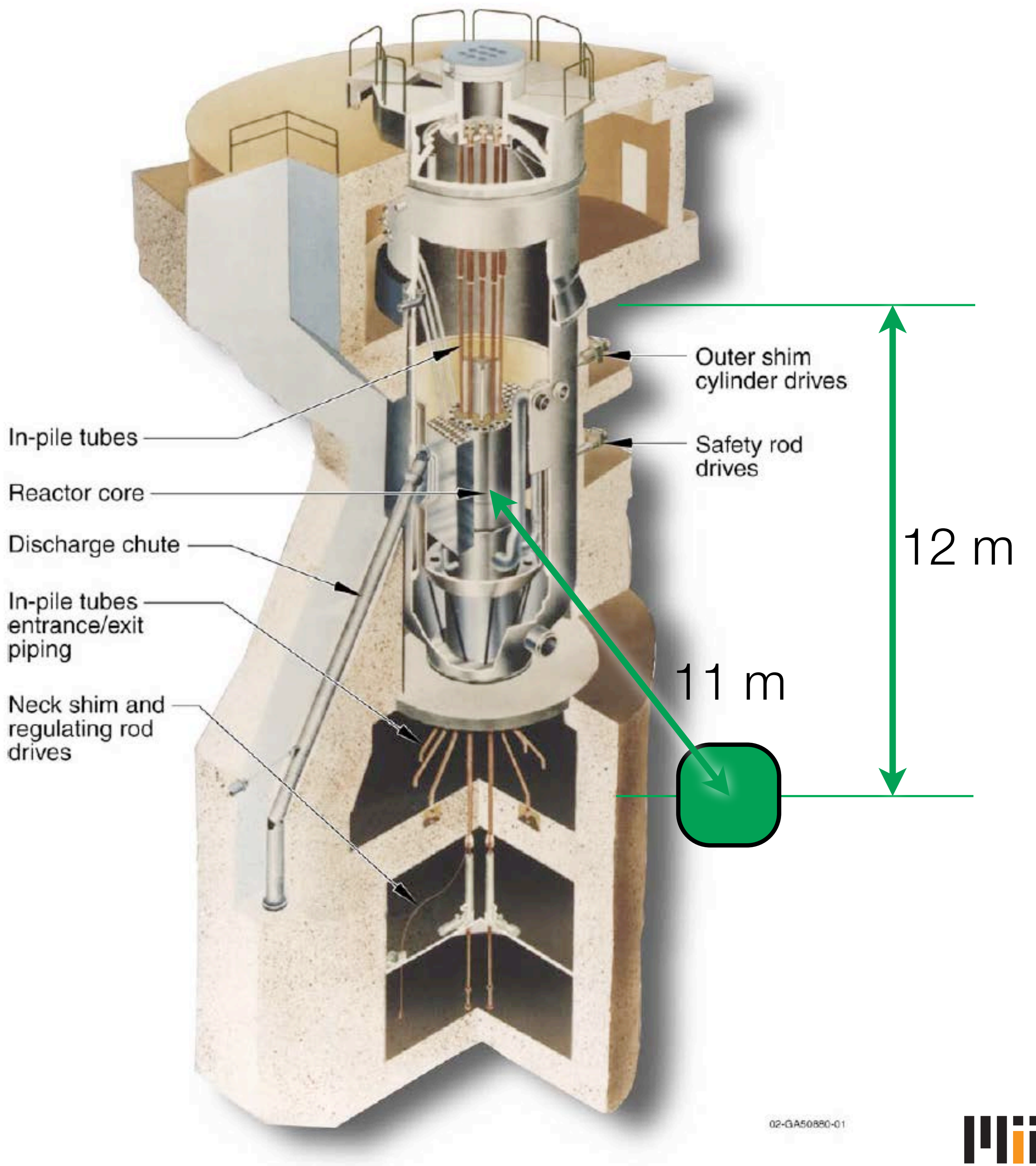
Advanced Test Reactor (ATR), Idaho Nat. Lab.

- 110 MW Thermal Reactor
- $2x10^{19}$ ν/s
- $1.2x10^{12}$ ν/cm^2/s @ 11 meters from core
- 6-8 weeks on, 1-2 weeks off operating cycle



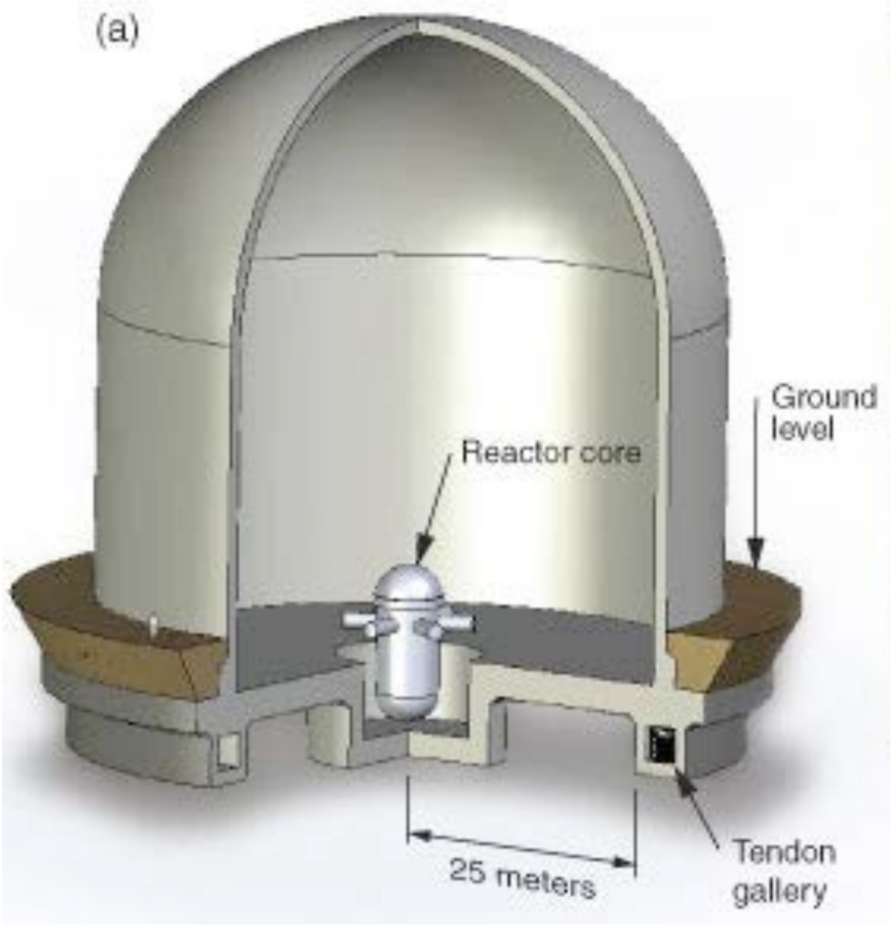
ATR experimental site

- Room available:
  - In first basement (outer shim corridor), 7 m from the core
  - In second basement, 11 m from the core
- Easier deployment site compared to SONGS...



SONGS power plant

- 3.4 GW Thermal Reactor
- $5.6x10^{20}$ ν/s
- $7.8x10^{12}$ ν/cm2/s @ 24 meters from core
- Off every 1.5 years?
- Tendon gallery 24 m from core, 10 m underground



Phonon vs. Ionization Readout

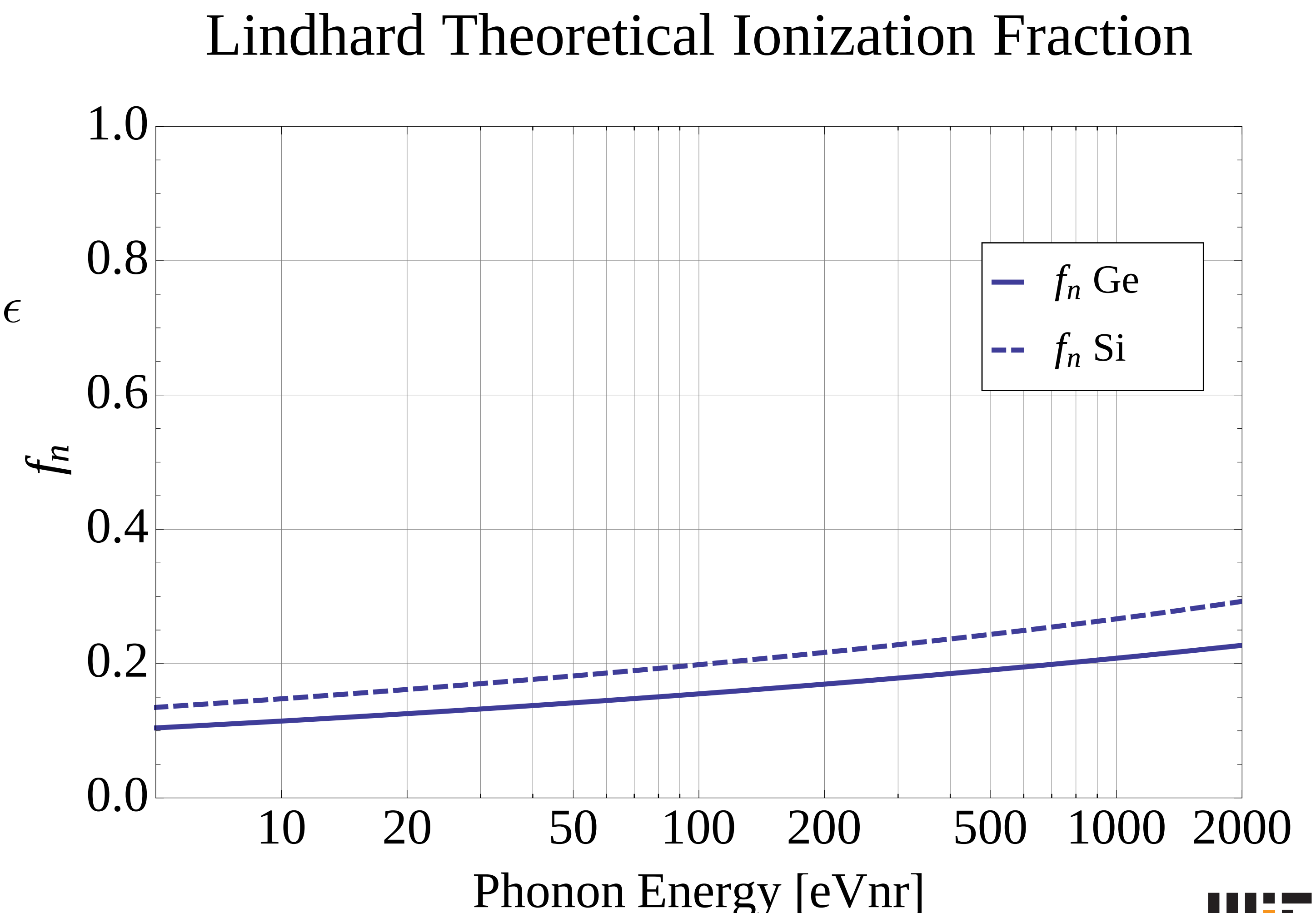
$$f_n = \frac{k g(\epsilon)}{1 + k g(\epsilon)}$$

Fraction of recoil energy deposited in target converted to ionization signal

$$k = 0.2$$

$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$

$$\epsilon = 11.5\,T\,Z^{-7/3}$$



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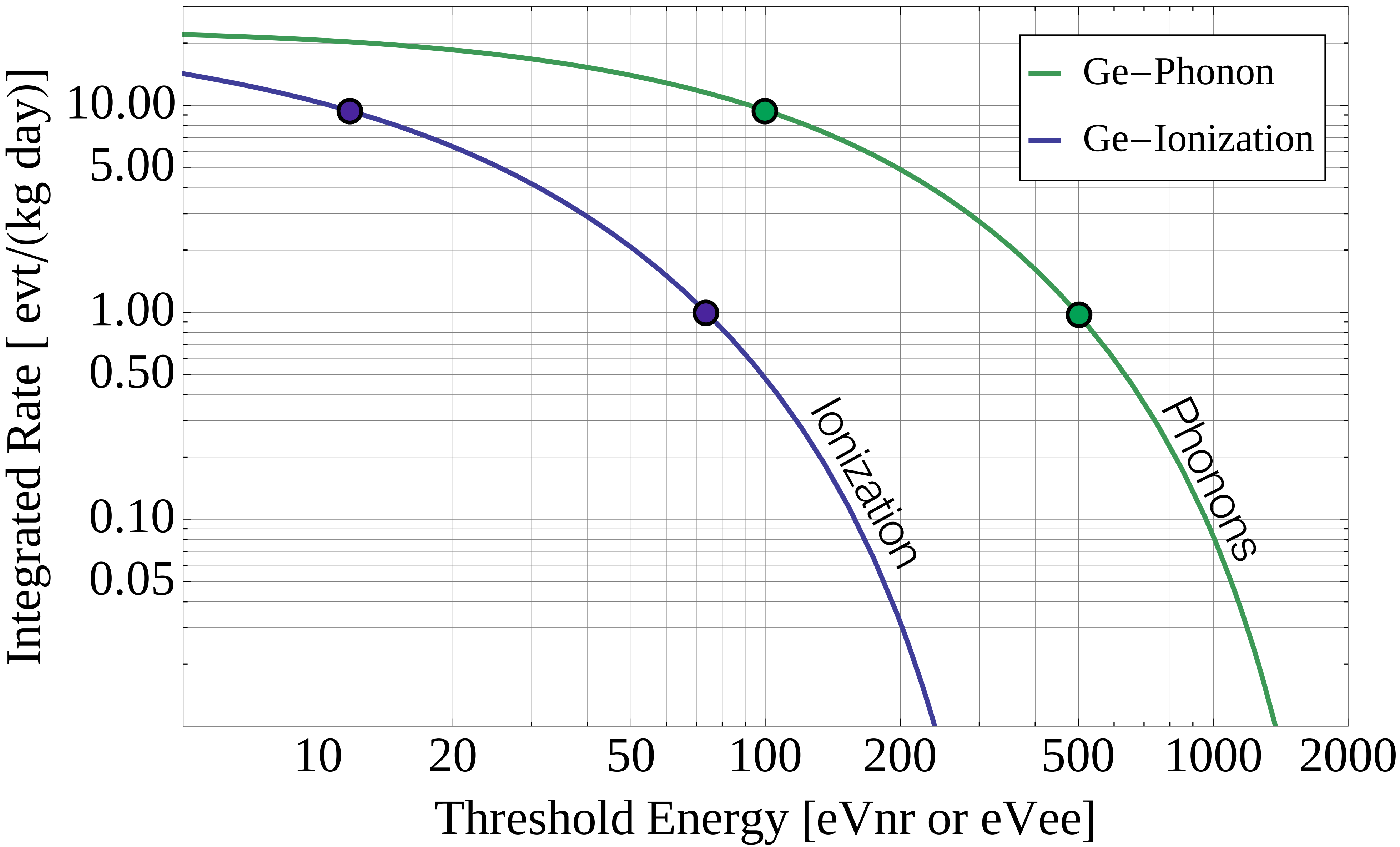
Event rates at ATR for phonon and ionization

Ionization readout requires much lower thresholds for the same rates



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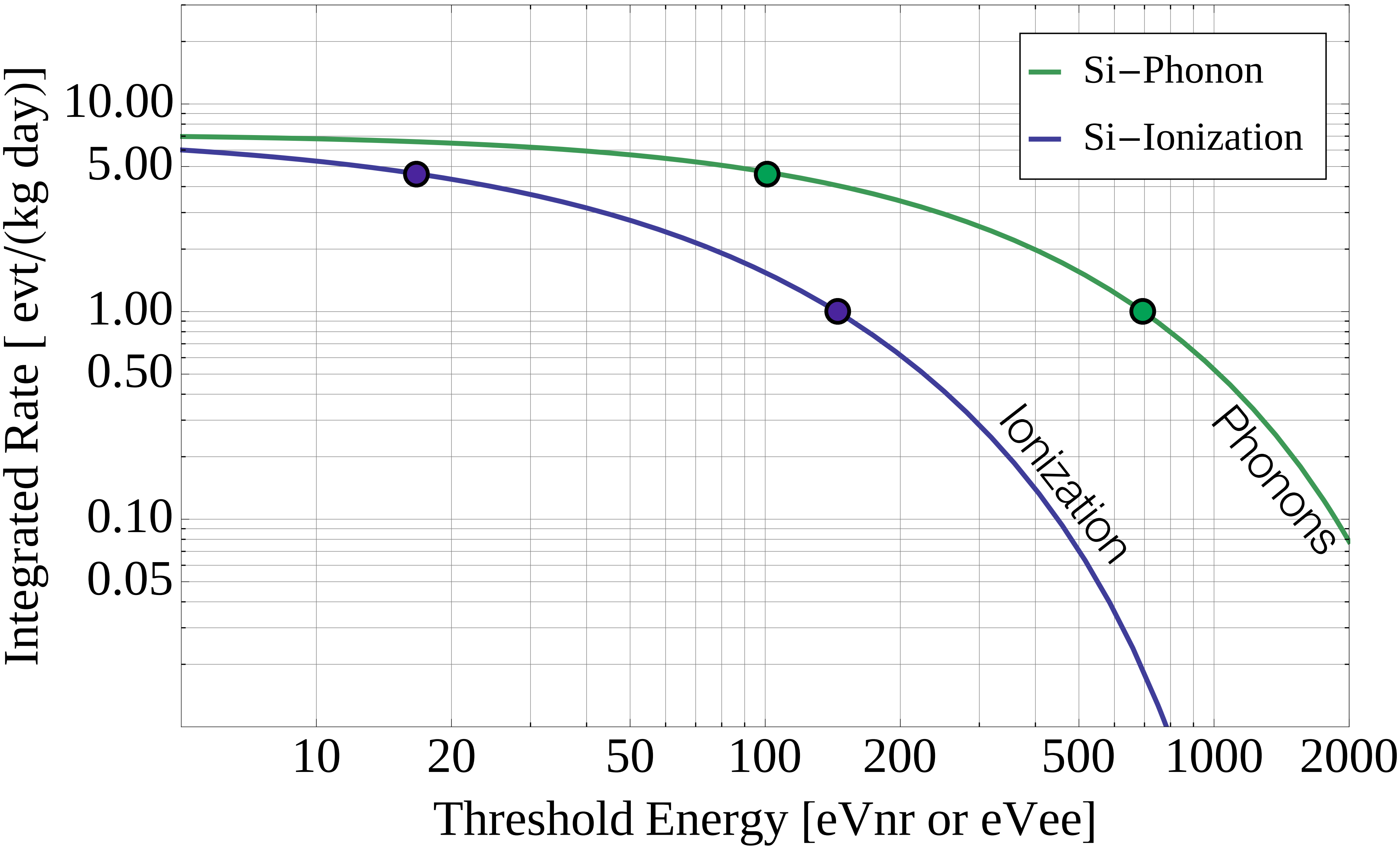
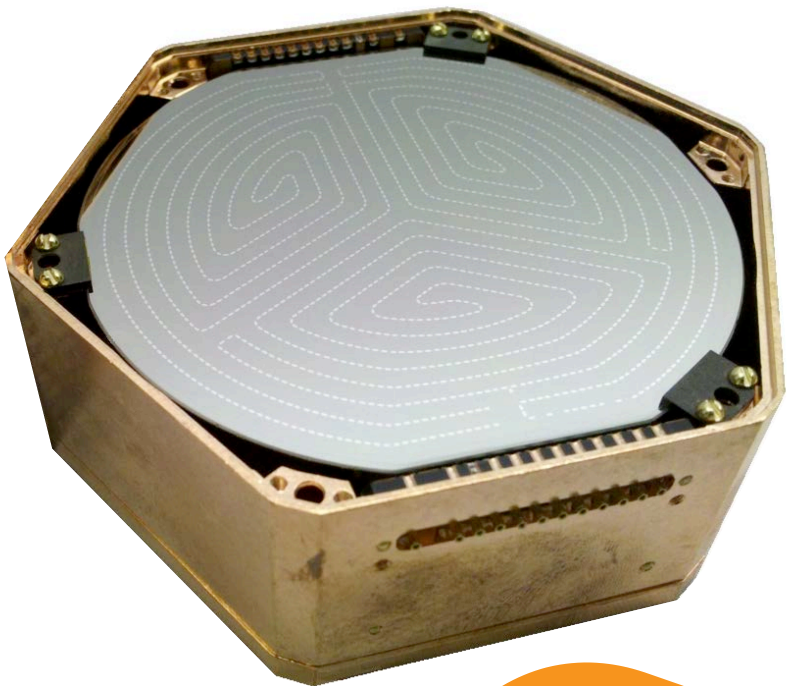


RICOCHET

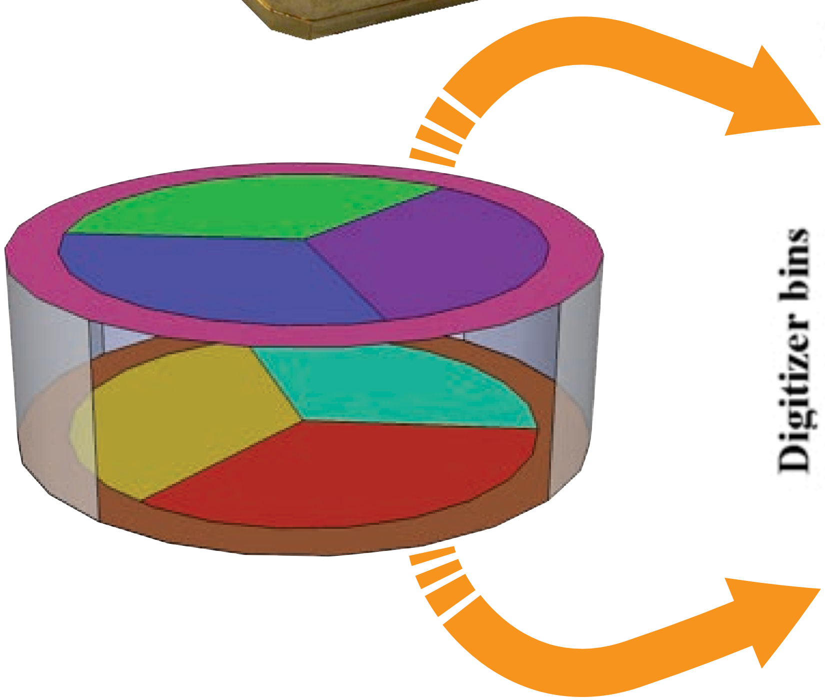
A Coherent Neutrino Scattering Program

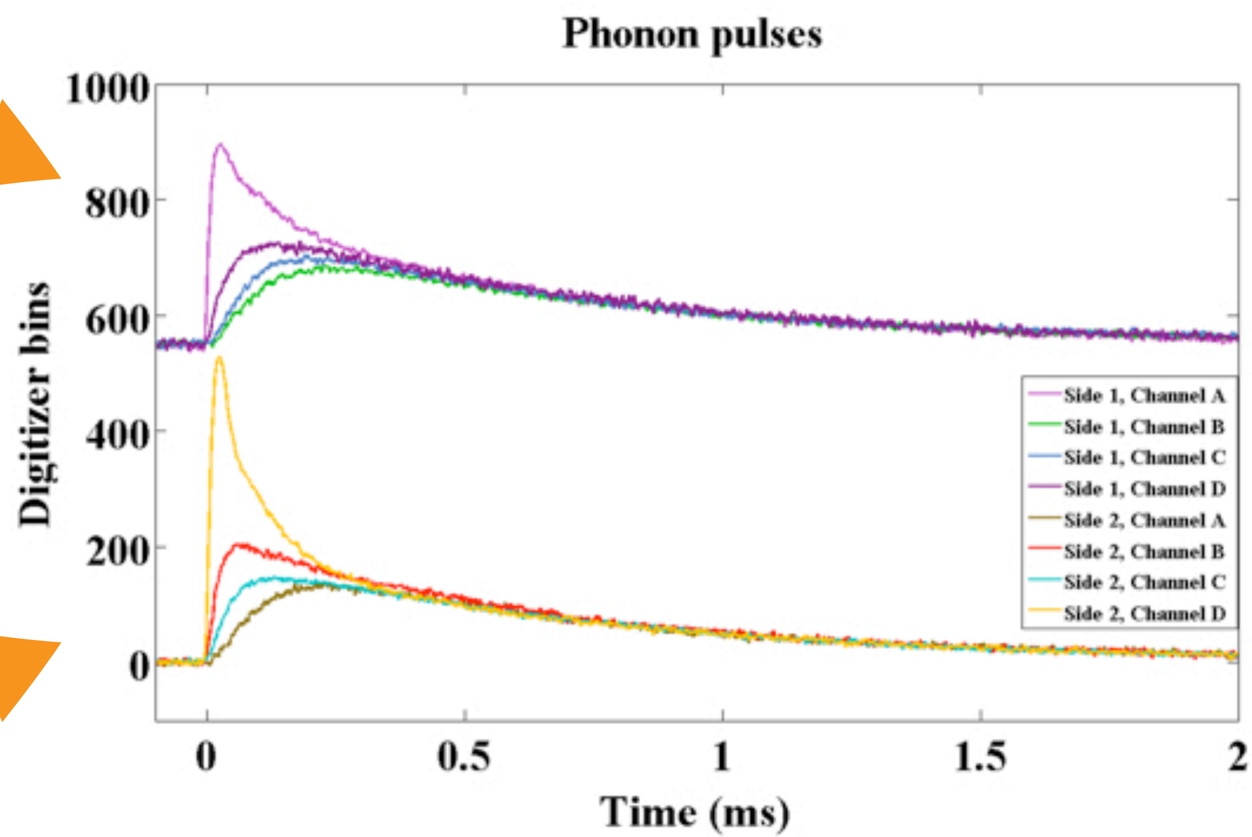
Enectali Figueroa-Feliciano

Detectors

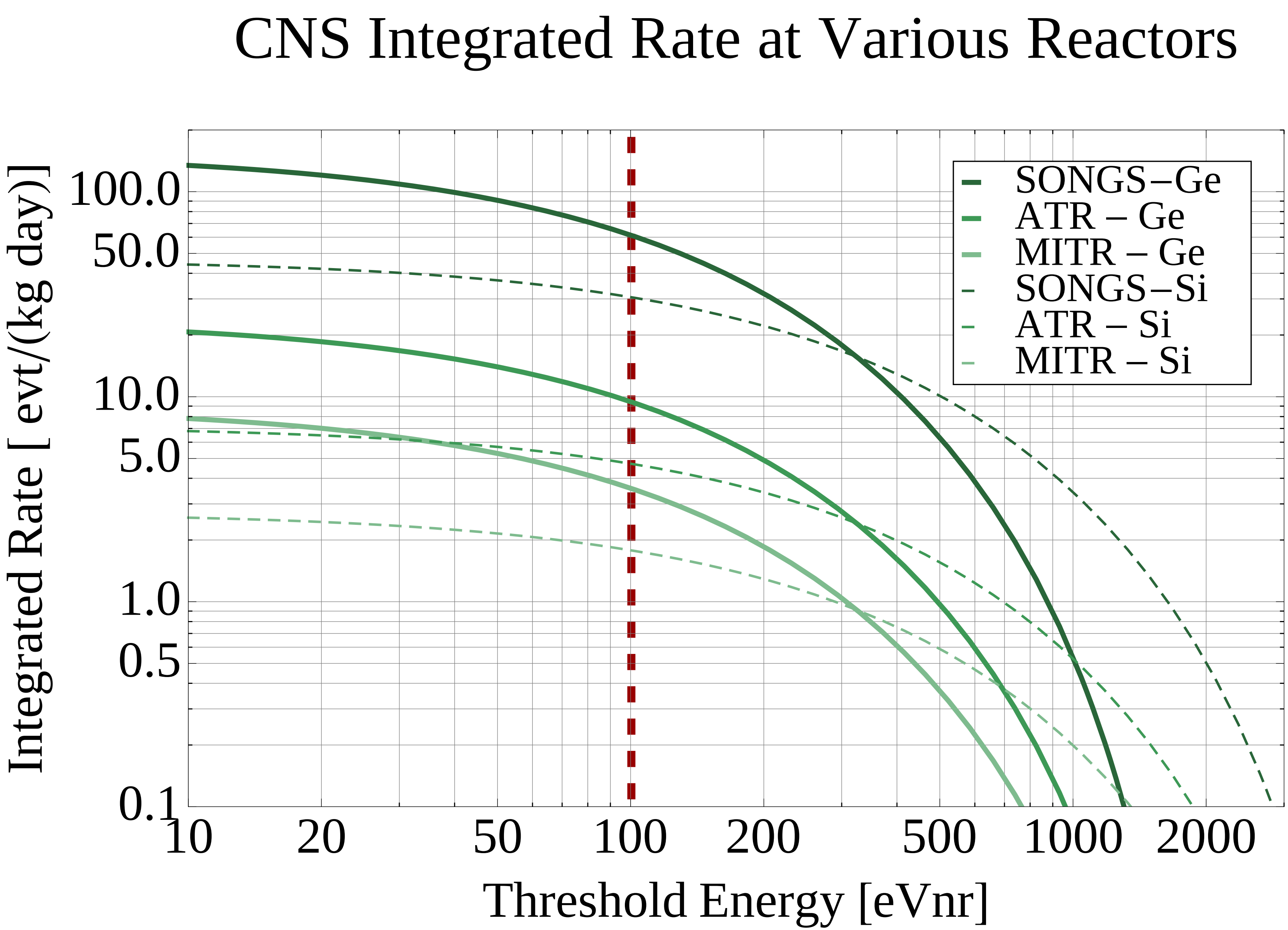


- Optimization of SuperCDMS detectors for low threshold
- Assume 100 eV threshold for reactor experiment. 5 kg Si, 5 kg Ge
- See talks by B. Cabrera and B. Sadoulet





CNS Signal


CNS Integrated Rate at Various Reactors
Integrated Rate [evt/(kg day)]
100.0
50.0
10.0
5.0
1.0
0.5
0.1
10
20
50
100
200
500
1000
2000
Threshold Energy [eVnr]
SONGS−Ge
ATR − Ge
MITR − Ge
SONGS−Si
ATR − Si
MITR − Si

Event Rates for 100 eVnr Threshold

	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

Why use Silicon?

- Germanium provides a rate around 3.3 times larger per unit mass, and 7.5 times larger per unit volume. So why use Silicon?
  - Si provides a cross check against backgrounds, especially since a neutron background would scale differently between Ge and Si than the ν signal
  - A Ge and Si CNS measurement provides additional physics reach through strong constraints on Non-Standard Interactions

Backgrounds

We have a good handle on the signal, but what about the backgrounds?

We have been working on this at MIT, but today we are only showing a work in progress..

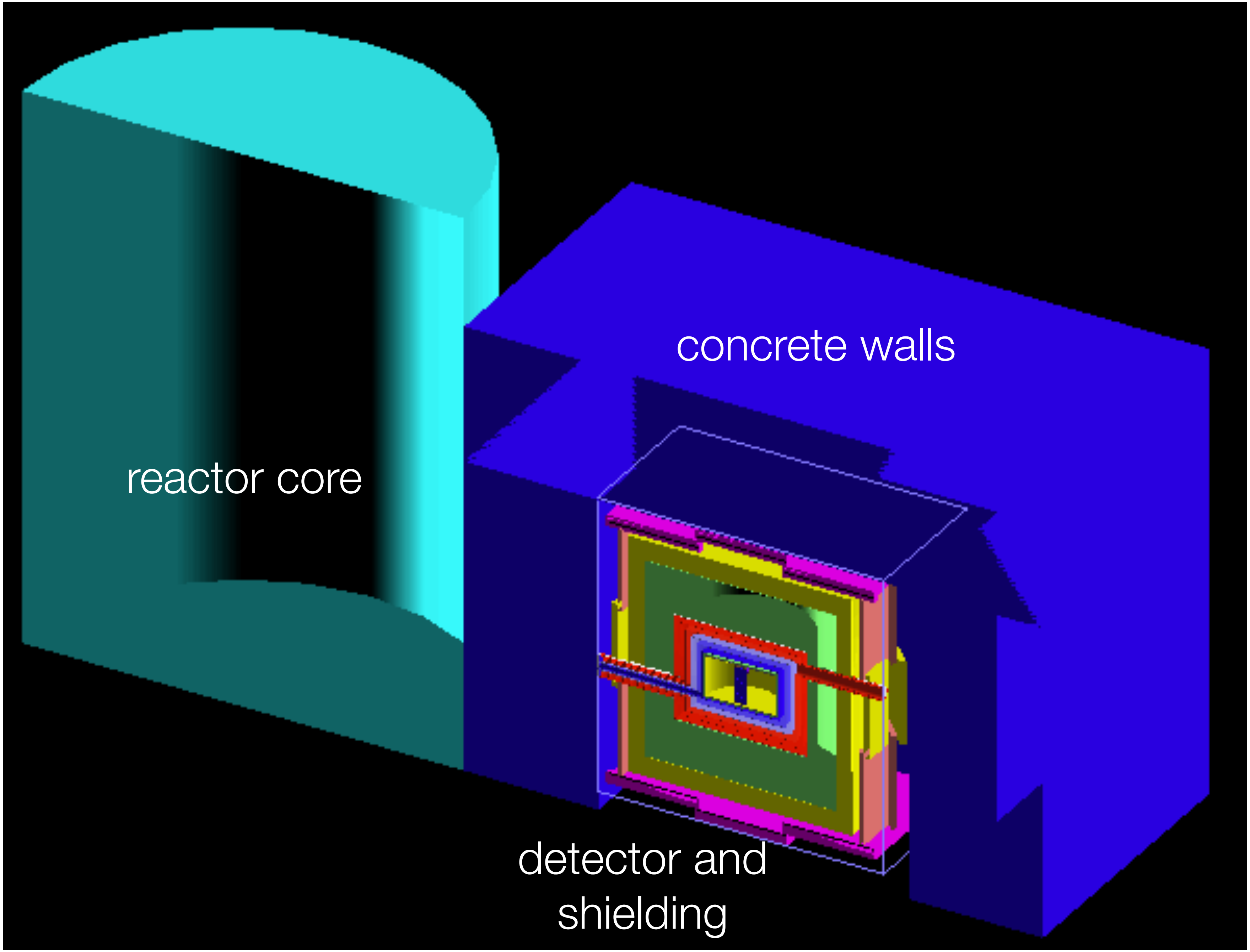
We assume no electron/nuclear recoil discrimination, thus our backgrounds are composed of γ, β, n, and α coming from:

- Cosmogenic backgrounds
- Radiogenic backgrounds
- "Reactogenic" backgrounds

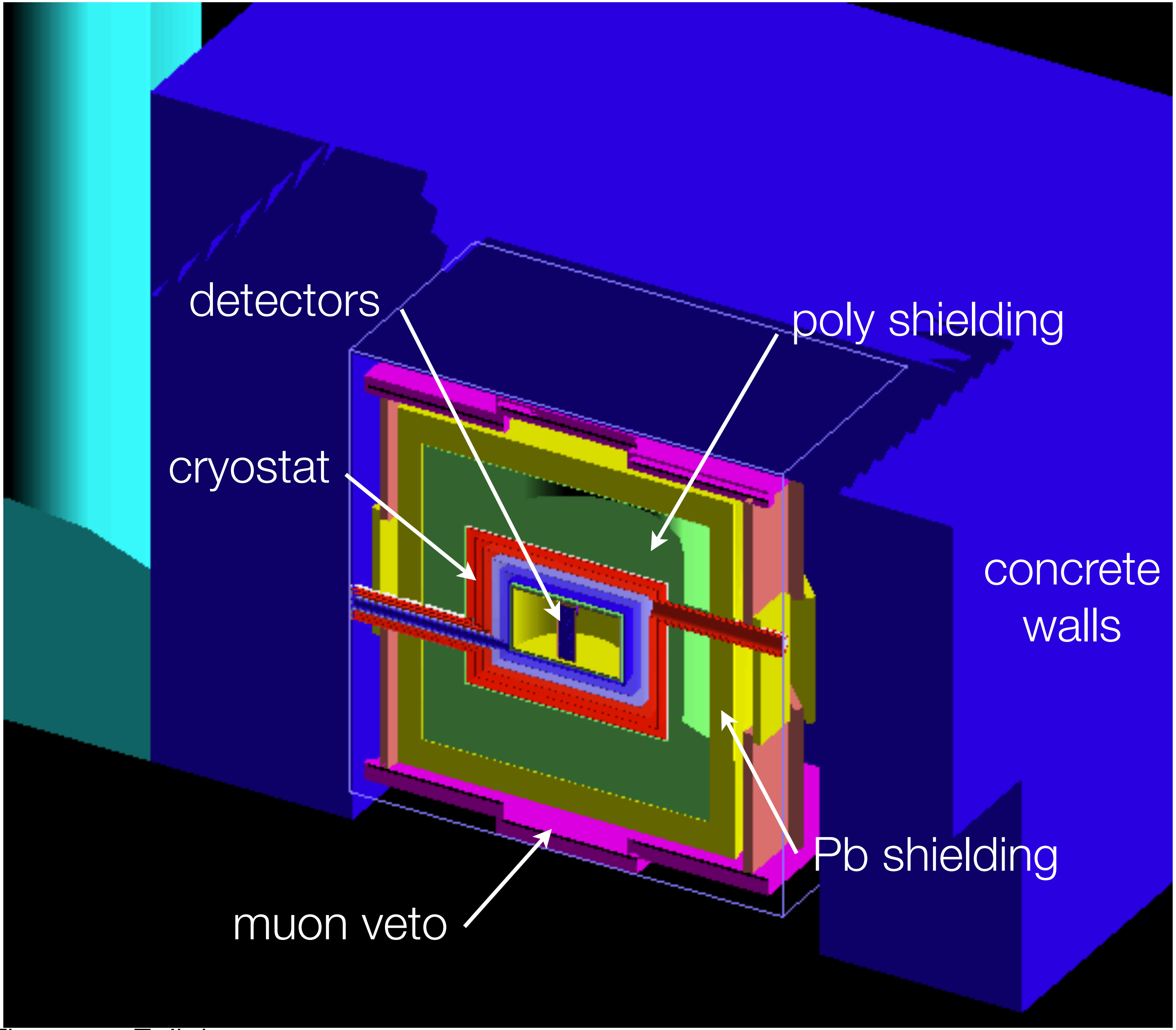
Backgrounds

- In our signal's low-energy band, we expect background events from surface interactions (β and low-energy γ and α), and bulk neutron recoils and Compton scatters.
- We are working on simulating the background environment through GEANT4 simulations of our experiment (including shielding and muon veto), using several packages to introduce the cosmogenic, radiogenic, and reactor backgrounds.

Ricochet Monte Carlo in GEANT4

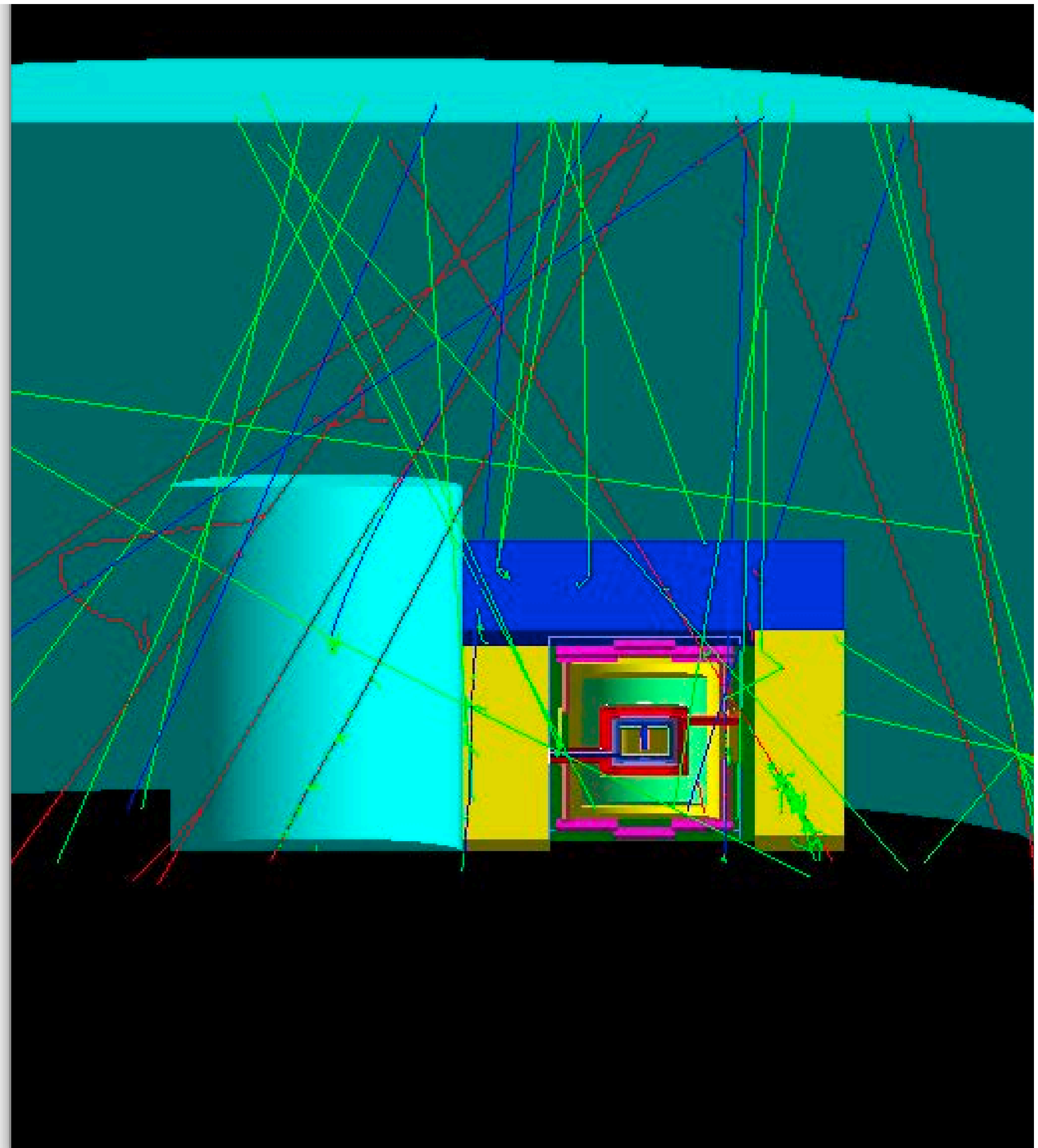


Ricochet Monte Carlo in GEANT4



Cosmogenic Backgrounds

- MITR experimental space has minimal overburden. Can we run a cryogenic detector at the surface?
- ATR and SONGS will offer much better protection from cosmics, but we will still want an estimate of what the rate is.



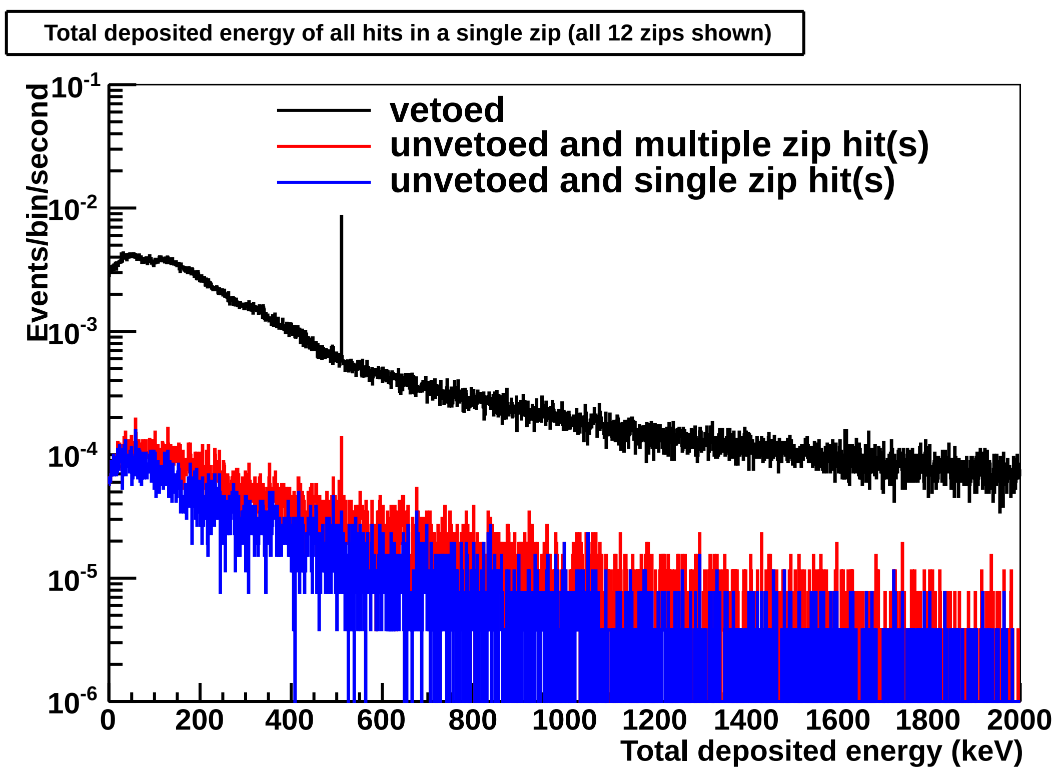
Introduction to CRY (Cosmic-Ray Shower Library)

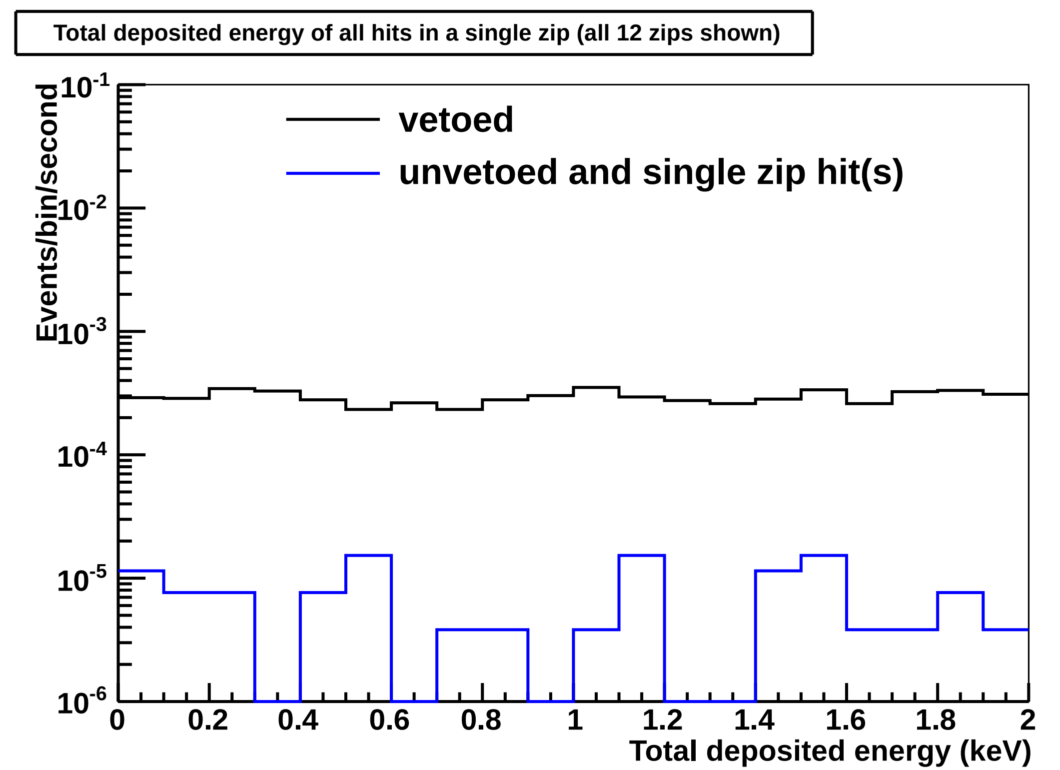
- Generates correlated cosmic-ray particle showers at sea level for use as input to (e.g.) Geant4.
- Primary (1 GeV-100 TeV) and secondary (1 MeV-100 TeV) particles are generated.
- Provides all particle production (muons, neutrons, protons, electrons, photons, and pions) within a specified 2D box as well as time of arrival and zenith angle of secondary particles.
- Accounts for latitude and solar cycle variations.
- "Fast simulation" based on precomputed input tables coming from full MCNPX simulations of primary cosmic rays with a complete atmospheric model.
- CRY is used by MicroBooNE (@ surface), LBNE, and possibly many more experiments.
- Info can be found at: http://nuclear.llnl.gov/simulation/main.html

Cosmogenic Event Rates at MITR

- CRY cosmic ray generator in RicochetMC.
    - Cosmic rays generated at the surface from a 10x10 m^2 area above Ricochet.
- Exposure time: 2.5 days, corresponding to $6x10^9$ cosmic rays (mostly muons) simulated.

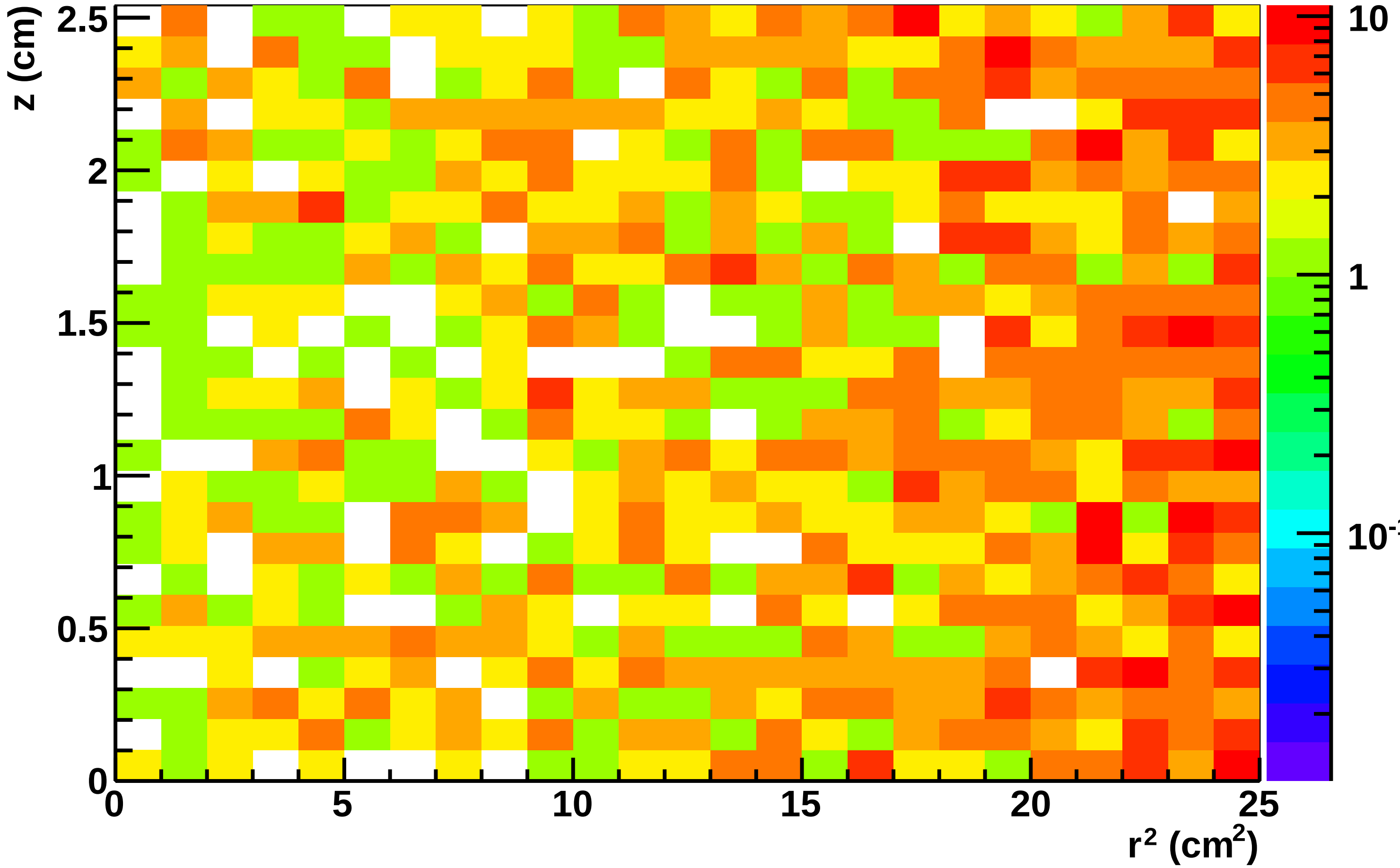
~2 events/kg/day from 0-2 keVr





Single scatter distribution in crystal

- Use all single scatter events (vetoed and unvetoed by muon veto) in all detectors in the 0-2 keVnr window.
- Close-packing in tower makes the outer radial surface the most exposed to surface events.

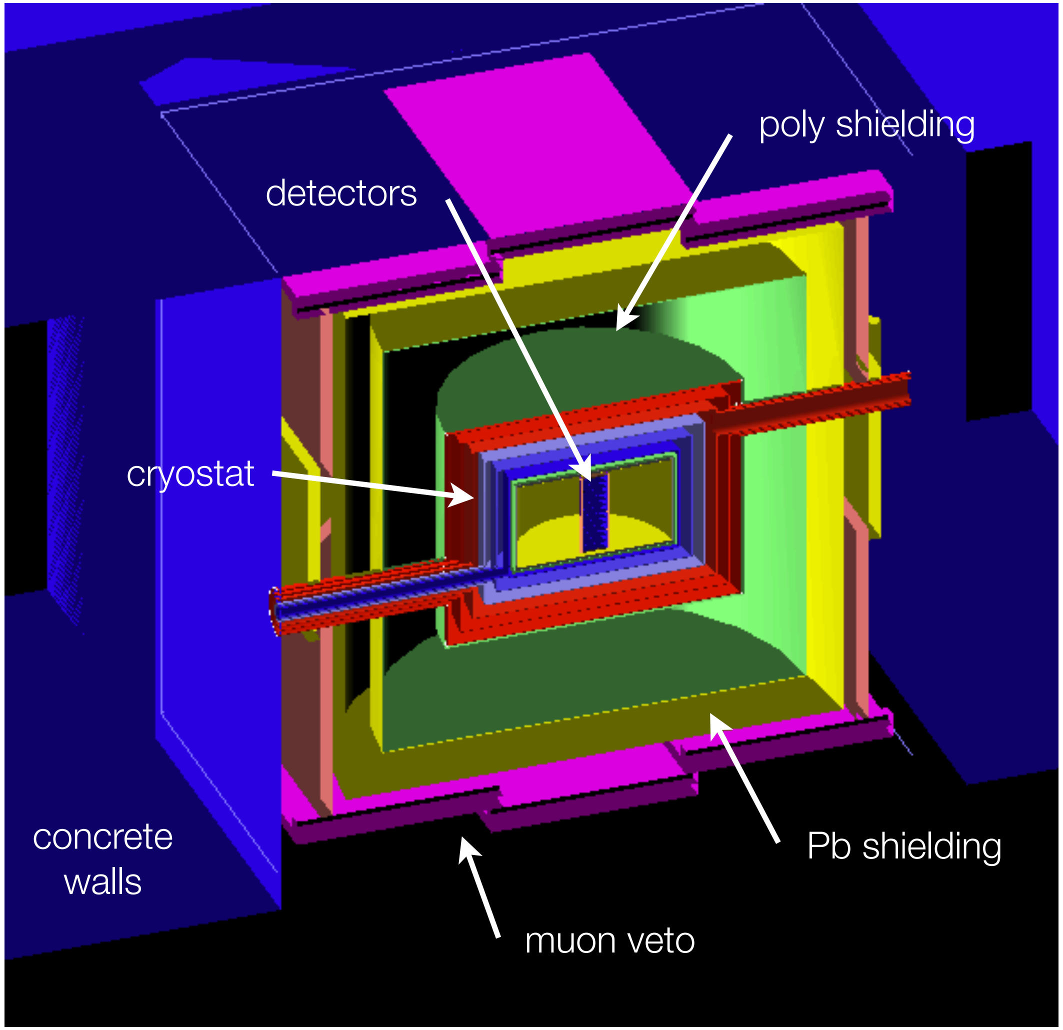


Center of Crystal

Outer Surface

Radiogenic Backgrounds

- Implemented radiogenic contamination in materials in RicochetMC
- Used contamination levels based on measured levels in CDMS-II and XENON-100



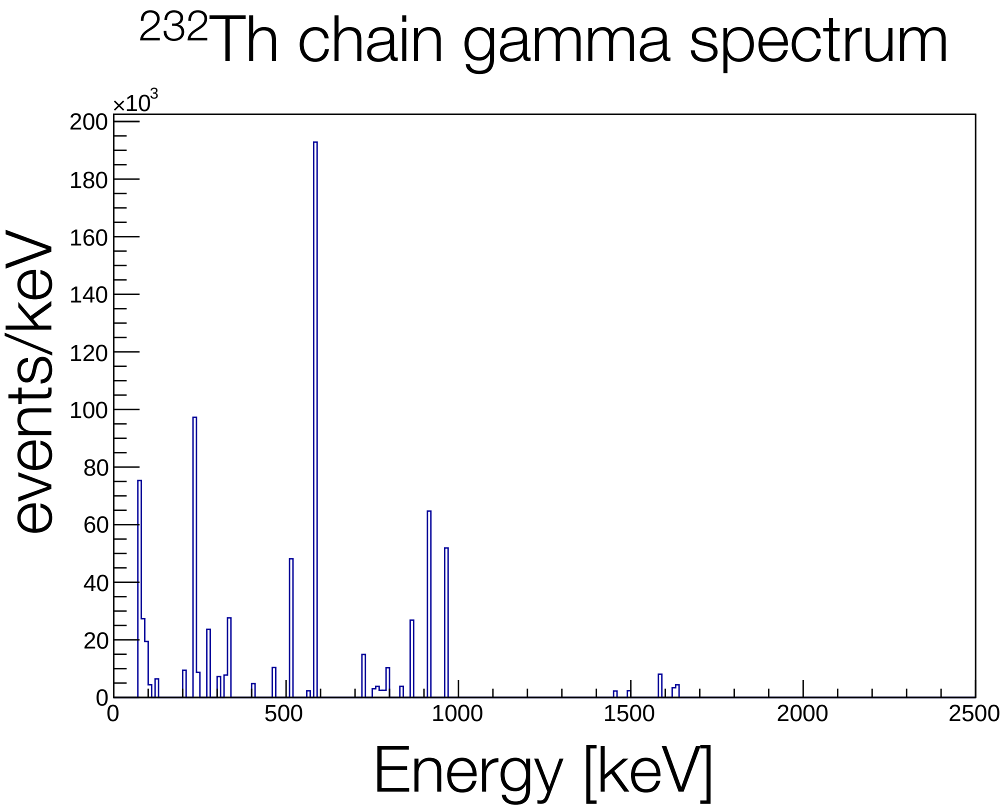
Radiogenic Backgrounds

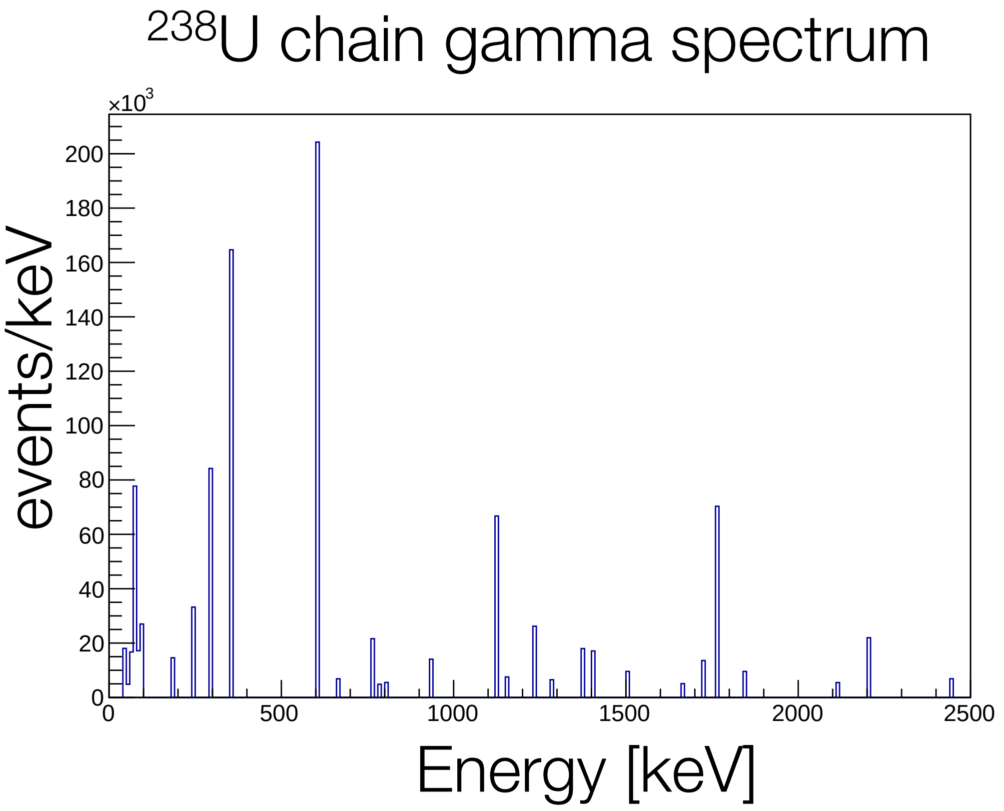
Poly shield	Pb shield	Cu housing	Detectors
• U, Th, K	• U, Th, K	• U, Th, K • Cosmic activation • Radon Daughters	• U, Th, K • Cosmic activation: L-, M-shell EC lines in Ge •Radon Daughters

Contamination Assumptions

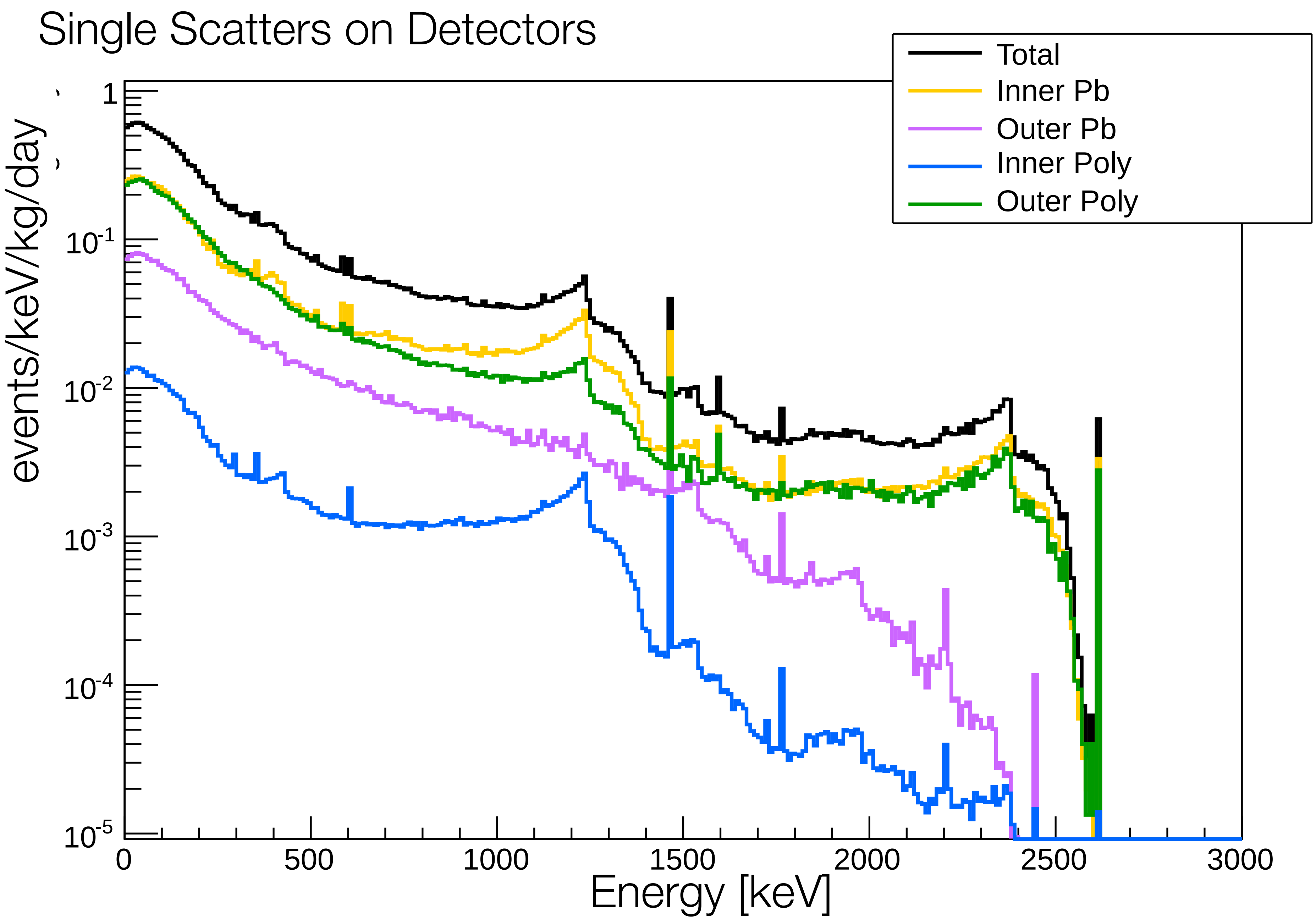
	^{238}U [mBq / kg]	^{232}Th [mBq / kg]
Outer Pb	3.8	9.4
Inner Pb	1.0	1.0
Outer poly	0.8	1.2
Inner poly	0.8	1.2

U, Th Gamma Lines



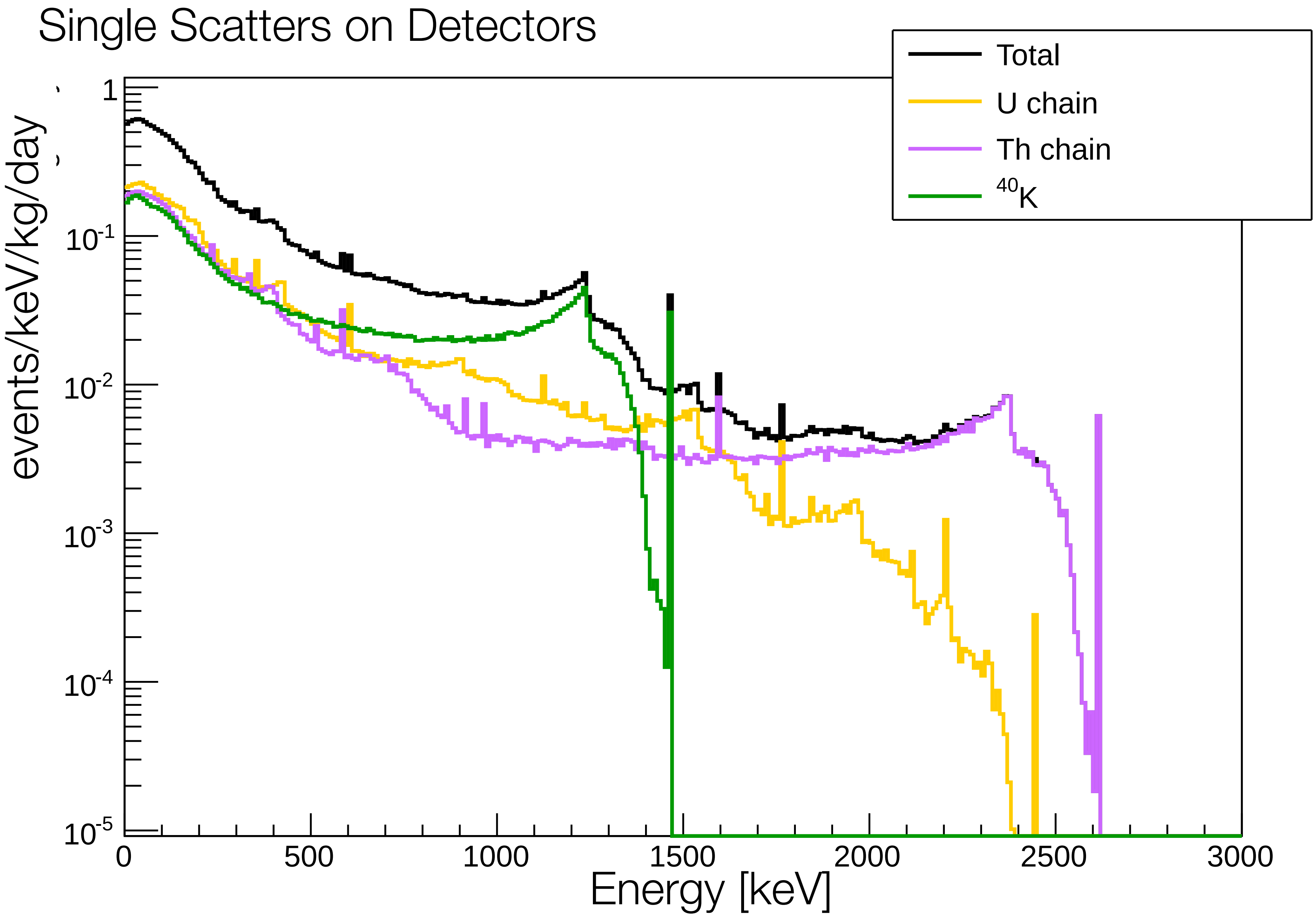


U, Th Spectra



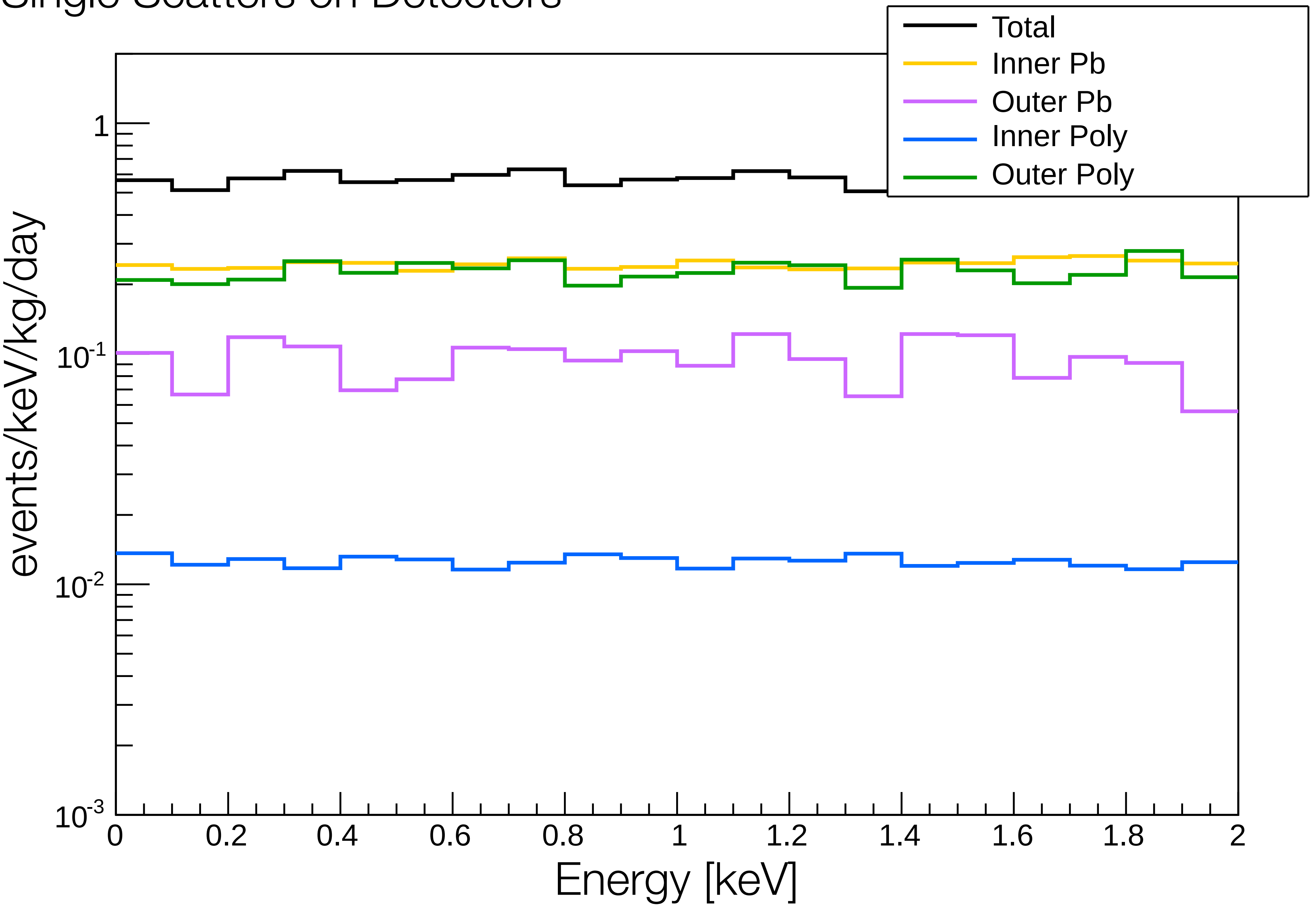
Single Scatters on Detectors
Total
Inner Pb
Outer Pb
Inner Poly
Outer Poly
events/keV/kg/day
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
500
1000
1500
2000
2500
3000
Energy [keV]

U, Th Spectra


Single Scatters on Detectors
Total
U chain
Th chain
40K
events/keV/kg/day
1
10-1
10-2
10-3
10-4
10-5
0
500
1000
1500
2000
2500
3000
Energy [keV]

U, Th Spectra

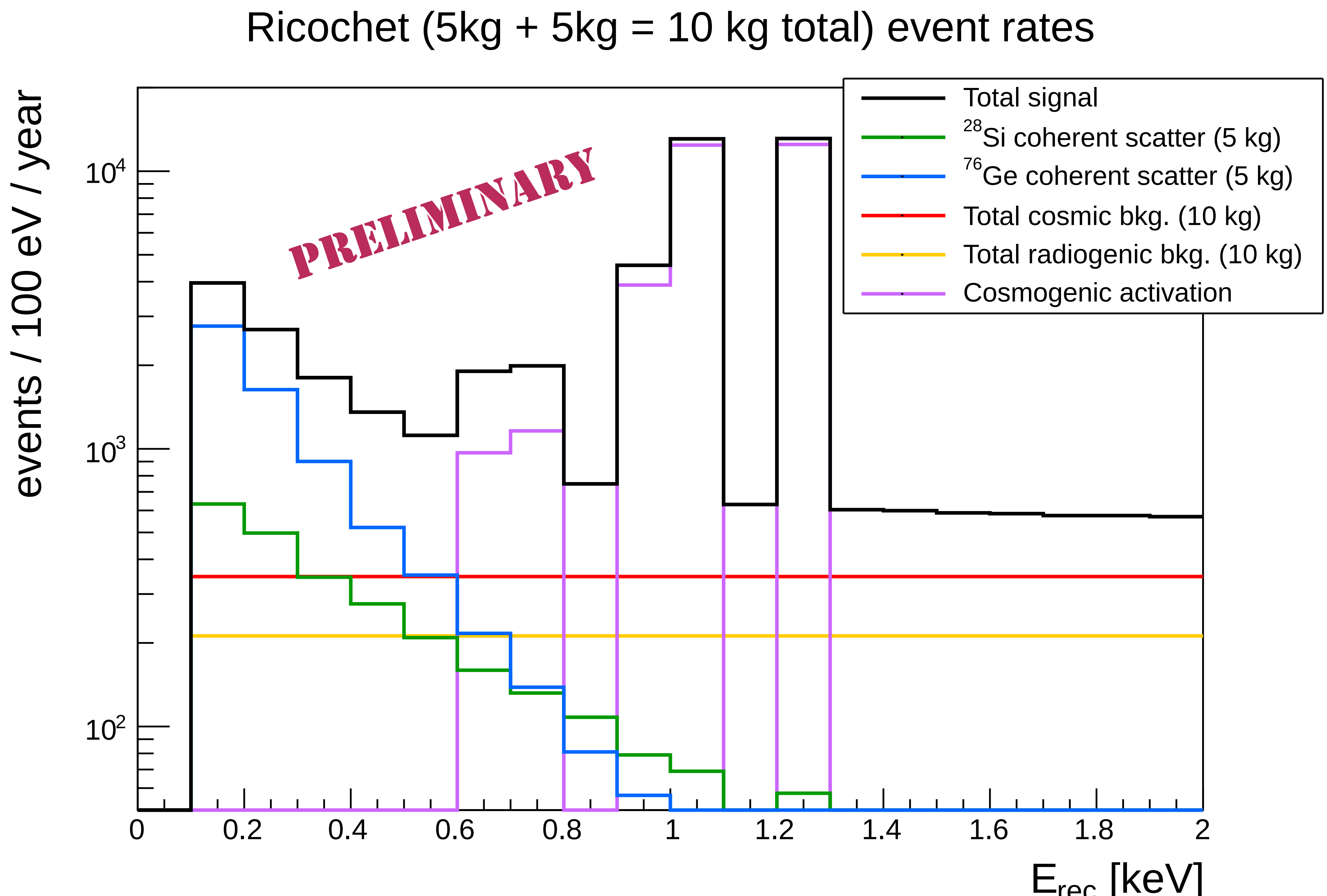
Single Scatters on Detectors



Putting together what we have so far...

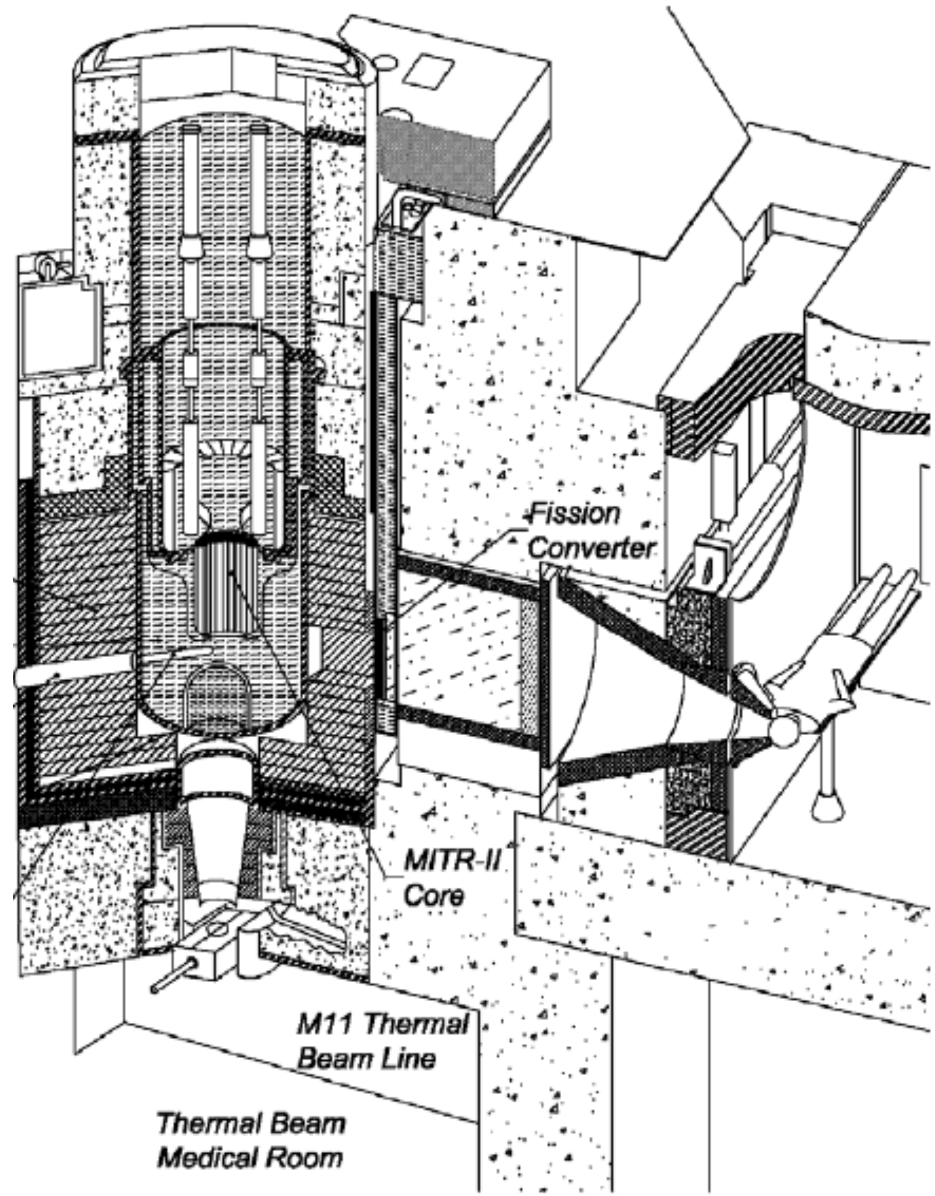
- Created simulated signal and background spectra for MITR and ATR sites.
- What is in:
  - CNS signal
  - Cosmogenics: full CRY simulation with latitude, altitude, and seasonal corrections
  - U, Th, and K in Poly and Pb
  - L-shell electron capture lines from cosmogenic activation of Ge due to the isotopes: 68Ge, 60Co, 65Zn, 58Co, 57Co, 56Co, 54Mn, 55Fe
- What is not in:
  - Cosmogenic activation in copper housing
  - Residual U, Th contamination of copper housing
  - Radon daughters (surf. evnts)
  - Neutron Background from reactor
  - Unknowns (atomic transitions, etc..)
- Payload will need to be modified once we know what we want to put in (number and size of Ge and Si detectors).
- This is a work in progress!!!

MITR Simulated Spectrum



Neutrons at MITR

- The room at MITR was designed for Boron Neutron Capture Therapy, a type of cancer therapy using epithermal neutrons.
- The room has a neutron beamline to deliver the neutrons from the reactor to the patient and moderate them into epithermal neutrons.
- When not in use, the beamline has a neutron “shutter” made of aluminum, PTFE, lead, water, and boronated concrete.
- A thesis with a detailed MCNP simulation of the reactor, the shutter, and the actual room exists.

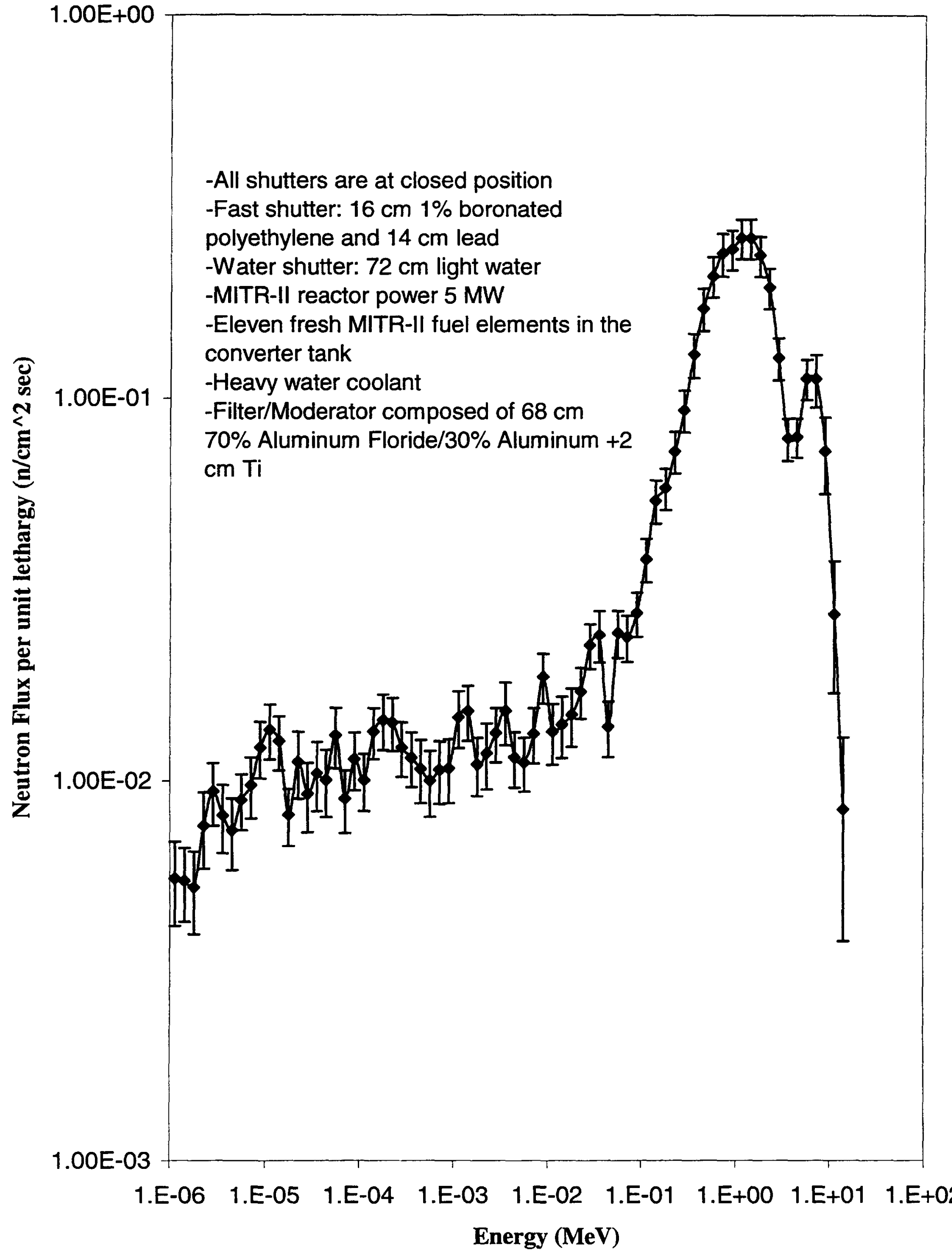


Neutrons at MITR

- 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.



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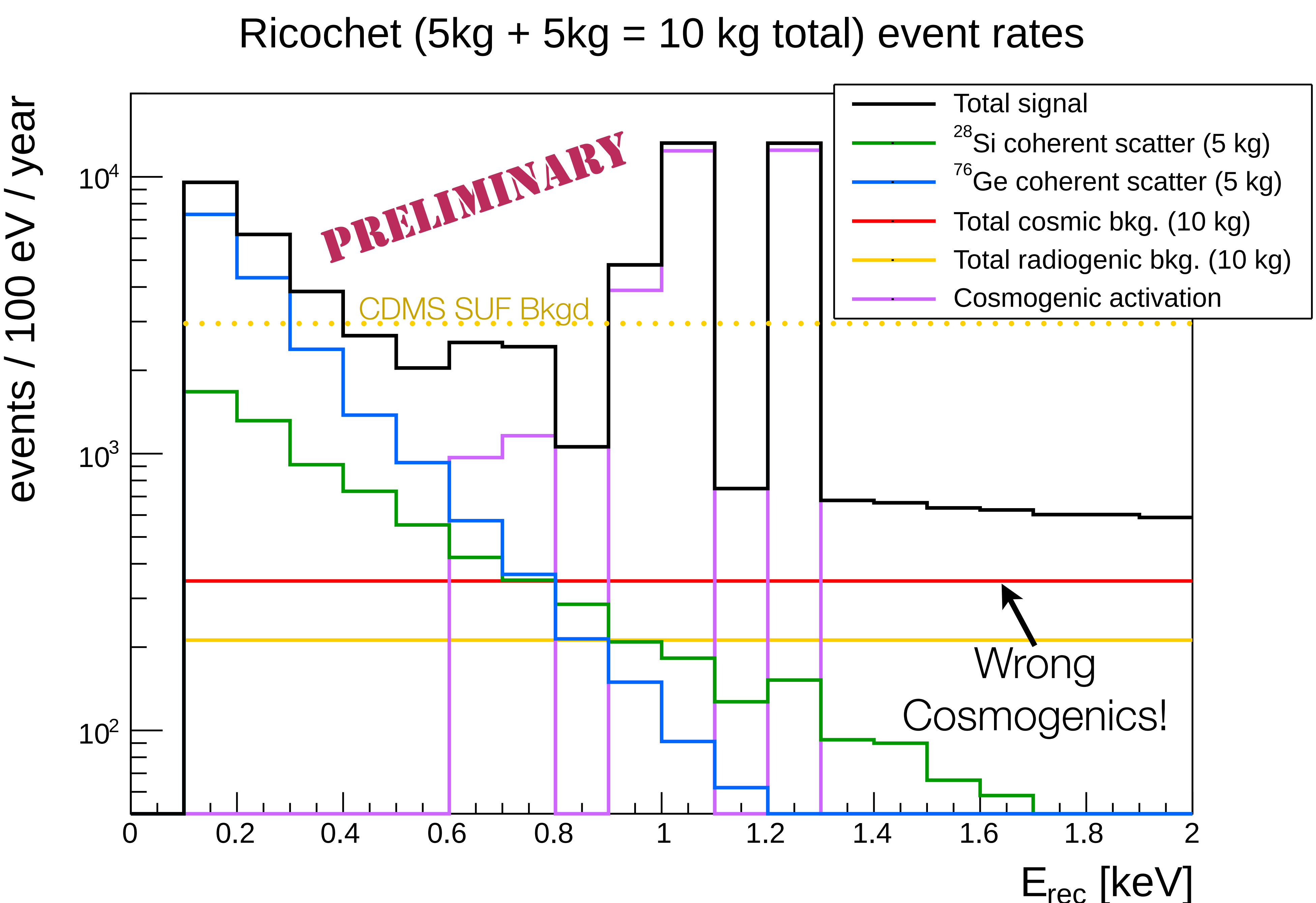
ATR Simulated Spectrum - just scaled rate



Ricochet Science

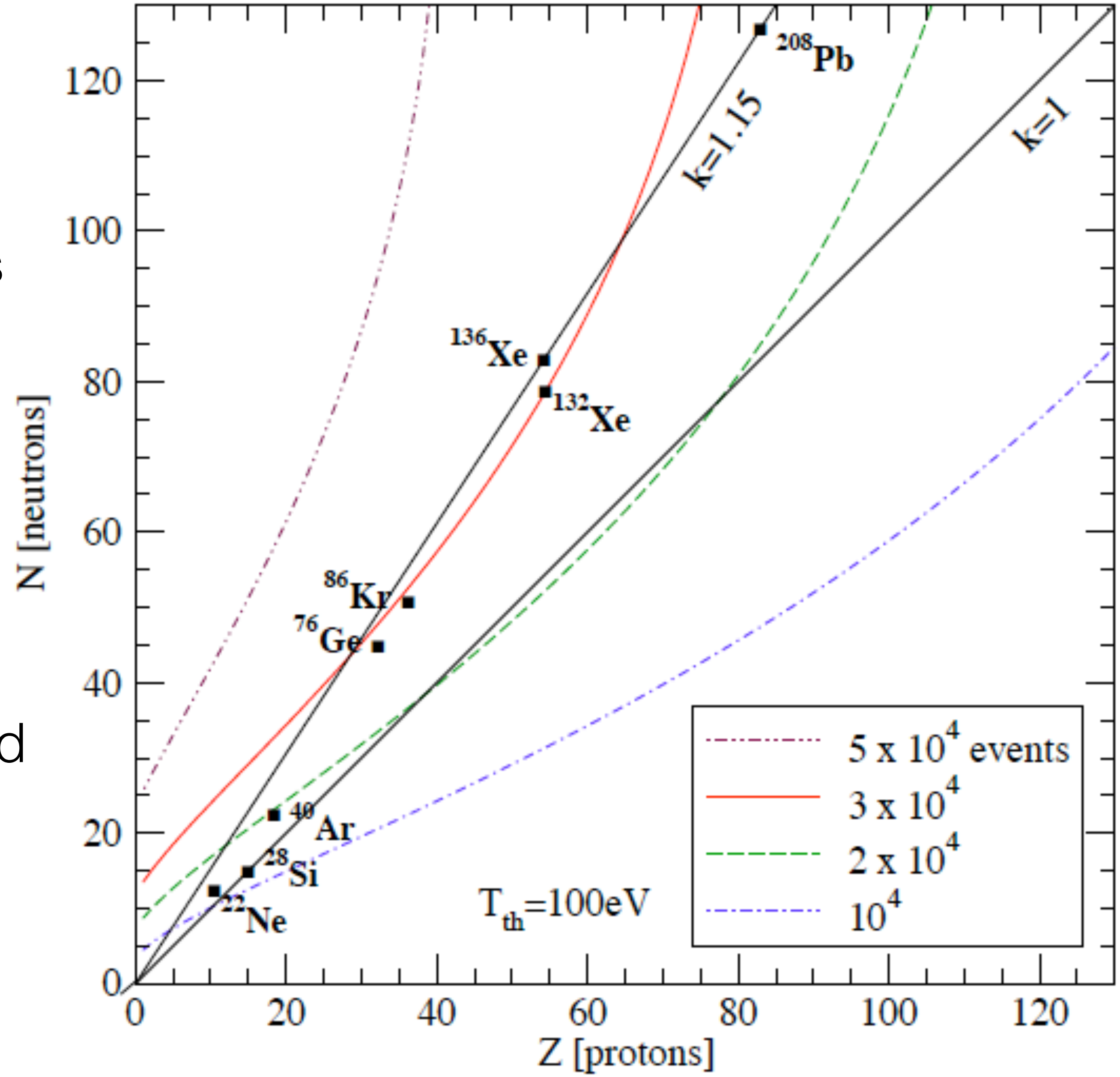
NSI Sensitivity

$$\frac{\partial\sigma}{\partial T}(E_\nu, T) = \frac{G_f^2}{\pi} M \left(1 - \frac{MT}{2E_\nu^2}\right) \left((Zg_v^p + Ng_v^n) + (A+Z)\epsilon_{ee}^{uV} + (A+N)\epsilon_{ee}^{dV}\right)^2$$

- Non-Standard Interactions are a way to search for physics beyond the standard model by parametrizing deviations in the interaction rates between particles
- Our proposed experiment can place world-leading limits on some of these parameters

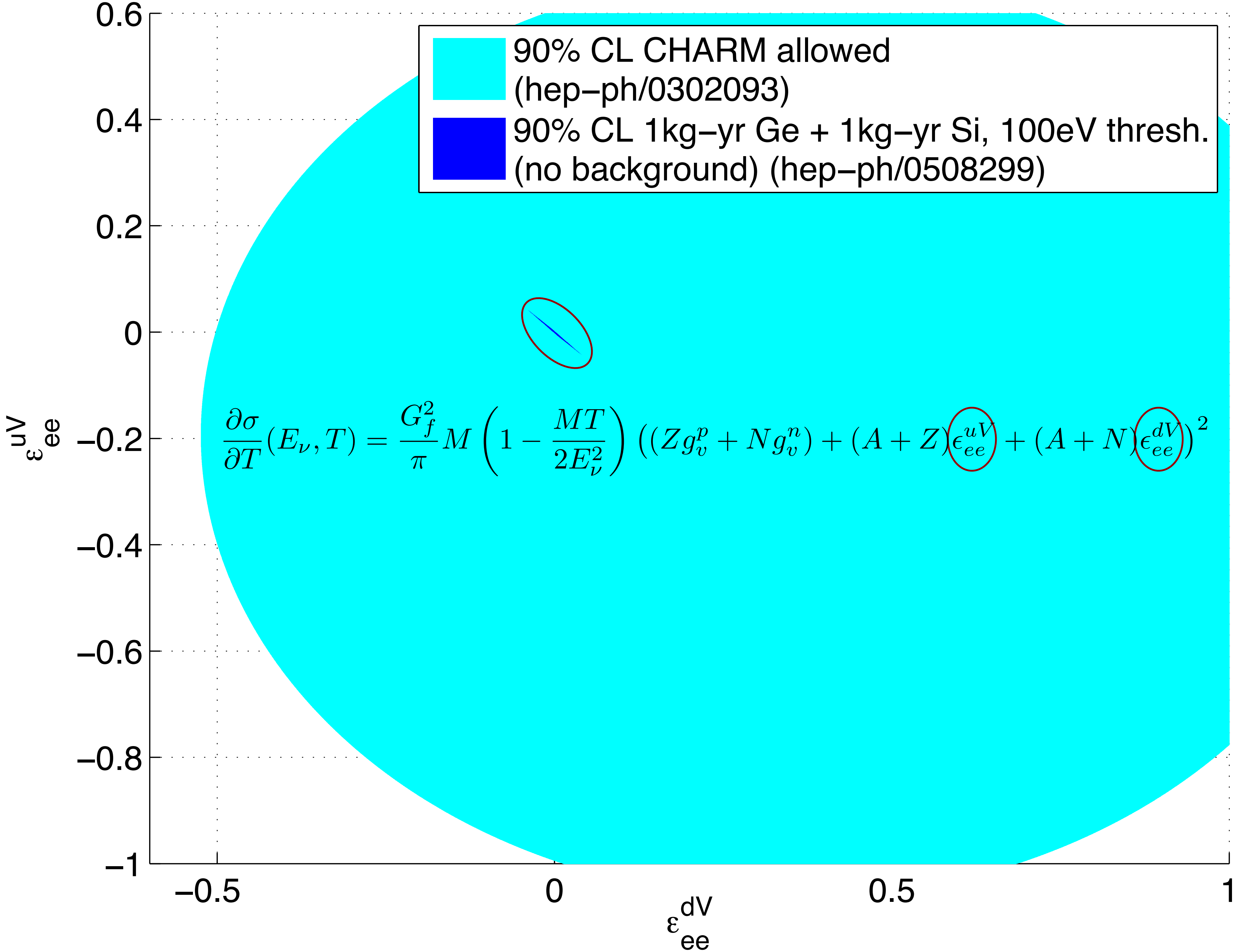
Need Two Targets for Optimal NSI Sensitivity

- The important term is the difference in the N/Z ratio
- Ge and Si are the ideal choice!
- Plot: difference in event rates for Ge and Si with a 100 eV threshold



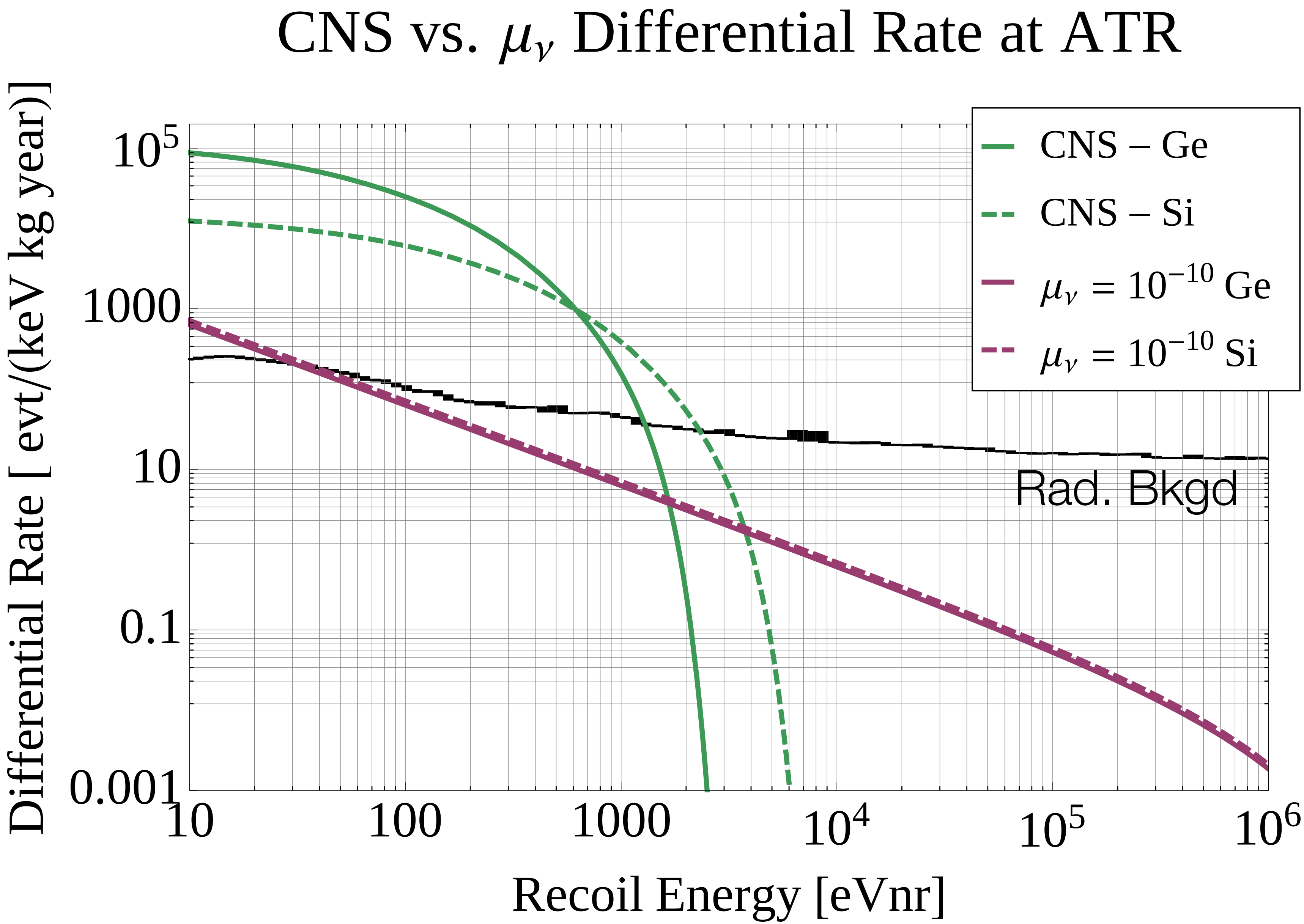
Barranco 2005, hep-ph/0508299

Potential Sensitivity



$$\frac{\partial\sigma}{\partial T}(E_\nu,T)=\frac{G_f^2}{\pi}M\left(1-\frac{MT}{2E_\nu^2}\right)\left((Zg_v^p+Ng_v^n)+(A+Z)\epsilon_{ee}^{uV}+(A+N)\epsilon_{ee}^{dV}\right)^2$$

Magnetic Moment Limits at ATR?

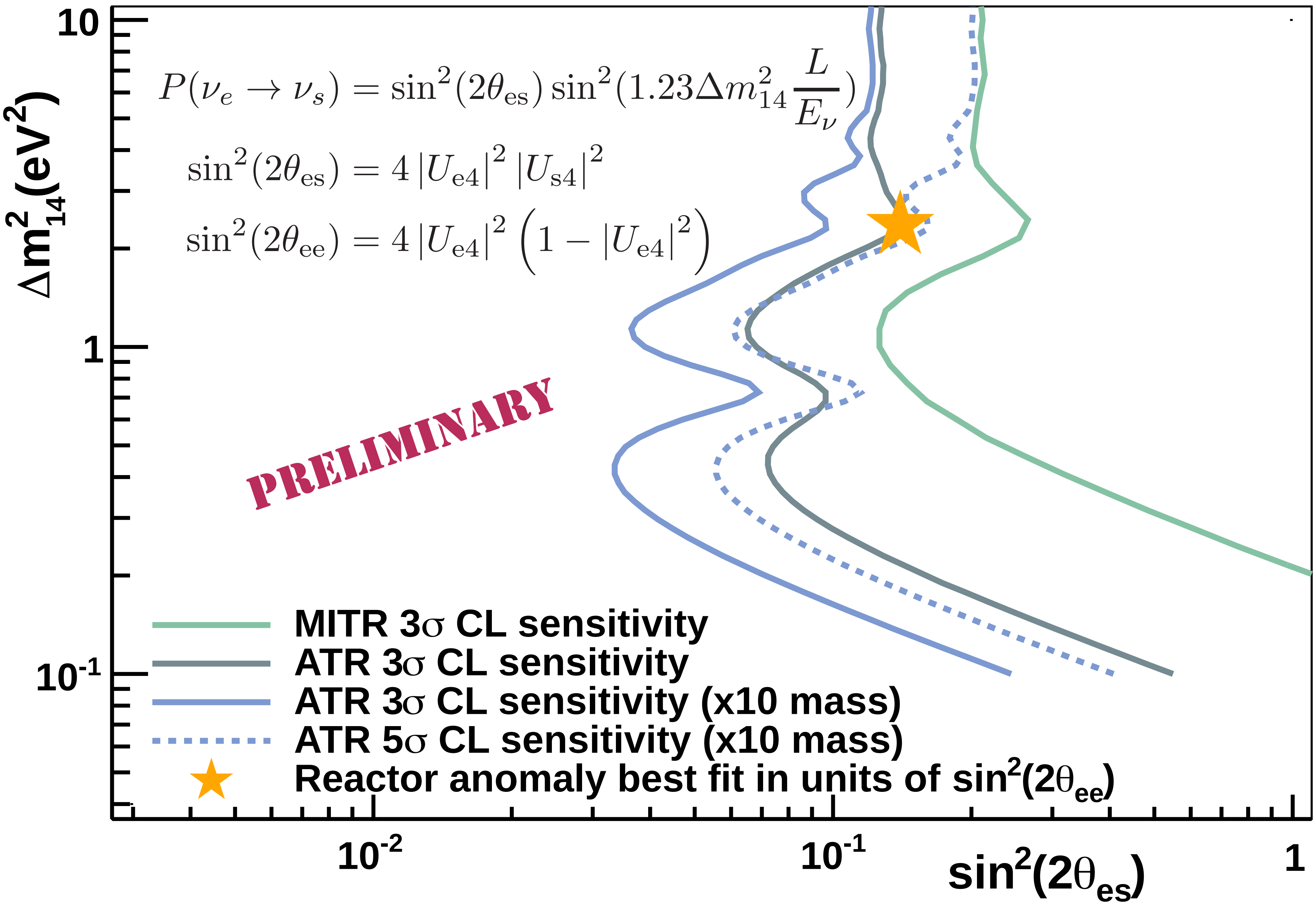


Sterile Neutrino Search at the ATR?

If we mount the experiment on rails, can we search for sterile neutrinos at the ATR?

Run period	1 year at each baseline
Baselines	4,6 m for MITR, 7,10 m for ATR
Target	Ge
Core size	0.38x0.61 m for MITR, 1.2x1.2 m for ATR
Flux	^{238}U only, from Mueller
Neutrino rate	3.2E25 $\overline{\nu}$/year for MITR, 6.4E26 $\overline{\nu}$/year for ATR
Active volume	10 kg
Detection efficiency	60%
Background (flat spectrum)	4.4 cts/kg/day in 6 kg fiducial
Energy threshold	100 eVr
Flat syst. unc. (mostly flux norm.)	2%
Correlation coefficient between baselines	0.99
Energy smear near threshold	20%

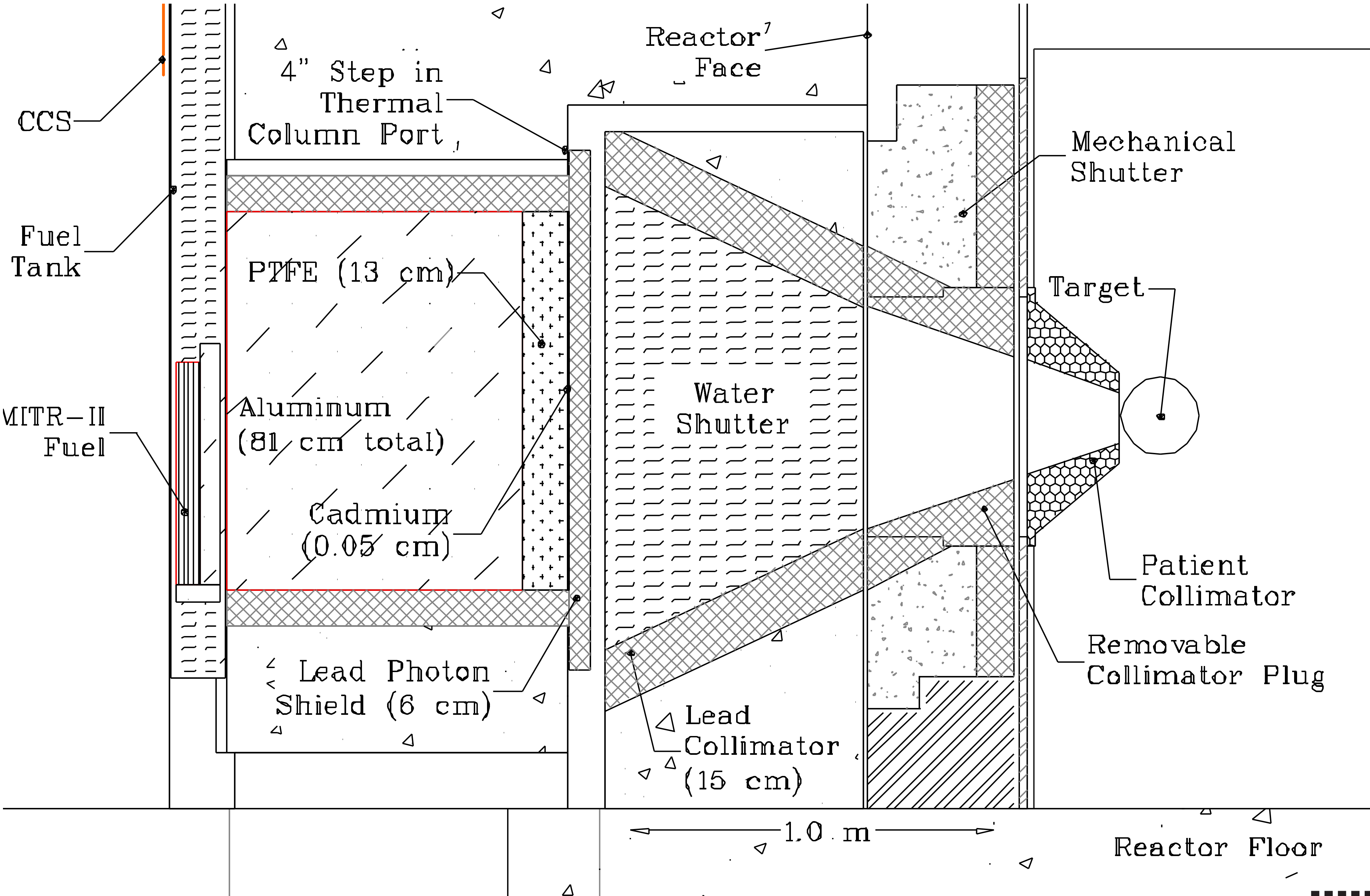
Sterile Neutrino Search?



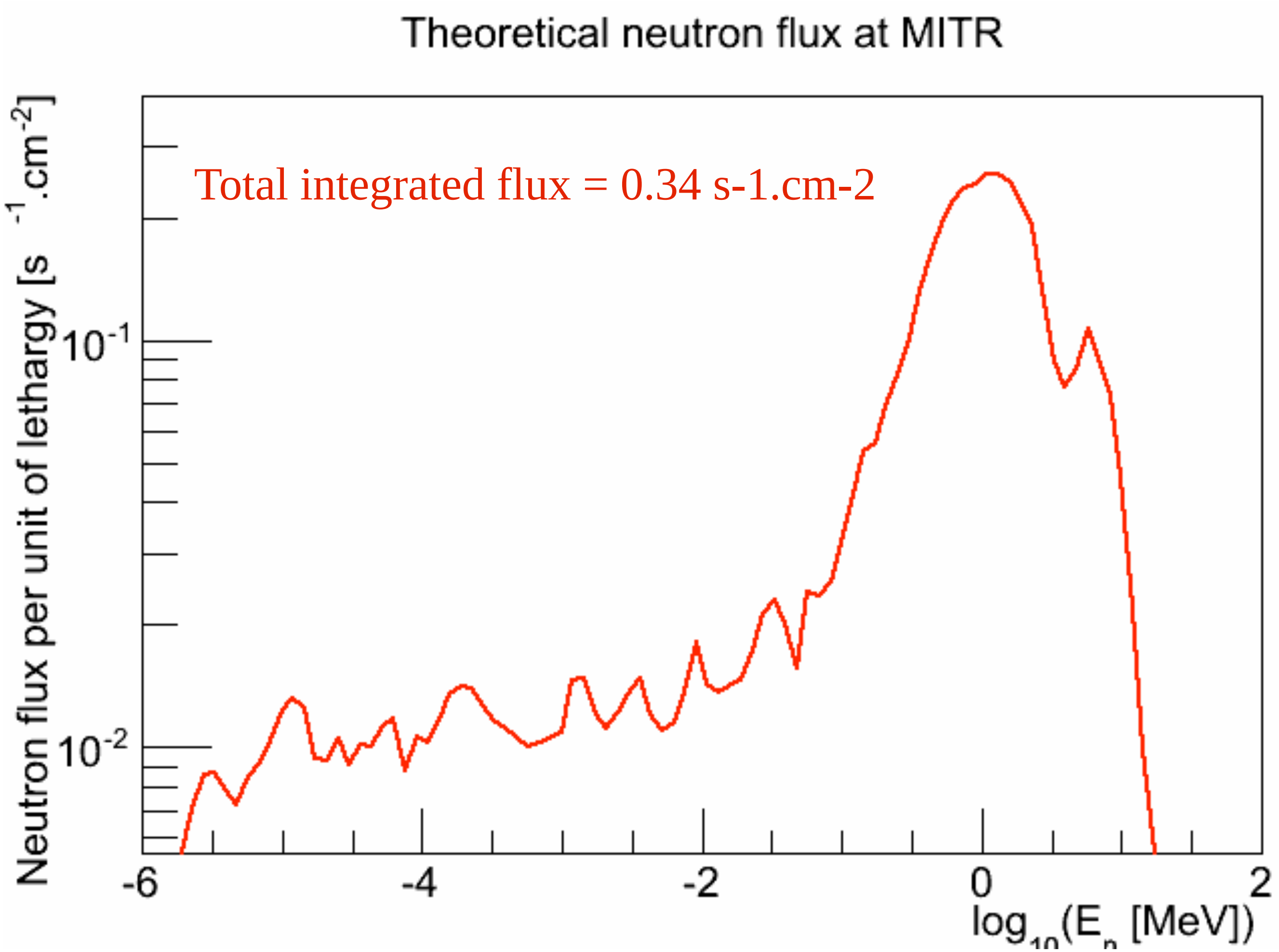
Conclusions

- Low-threshold phonon detectors derived from the SuperCDMS program are a very promising technology for CNS and associated science.
- We have calculated the CNS rates for several reactor sites and developed a GEANT4 Monte Carlo (RicochetMC) that allows us to calculate the backgrounds expected from this experiment.
- Background calculations are still ongoing. Neutron backgrounds need to be modeled and measured.
  - We are working on a ^{3}He Moderated Neutron Capture Detector to measure the neutron flux and spectrum concurrently with the CNS measurement

MITR Neutron Shutter



Neutron monitoring



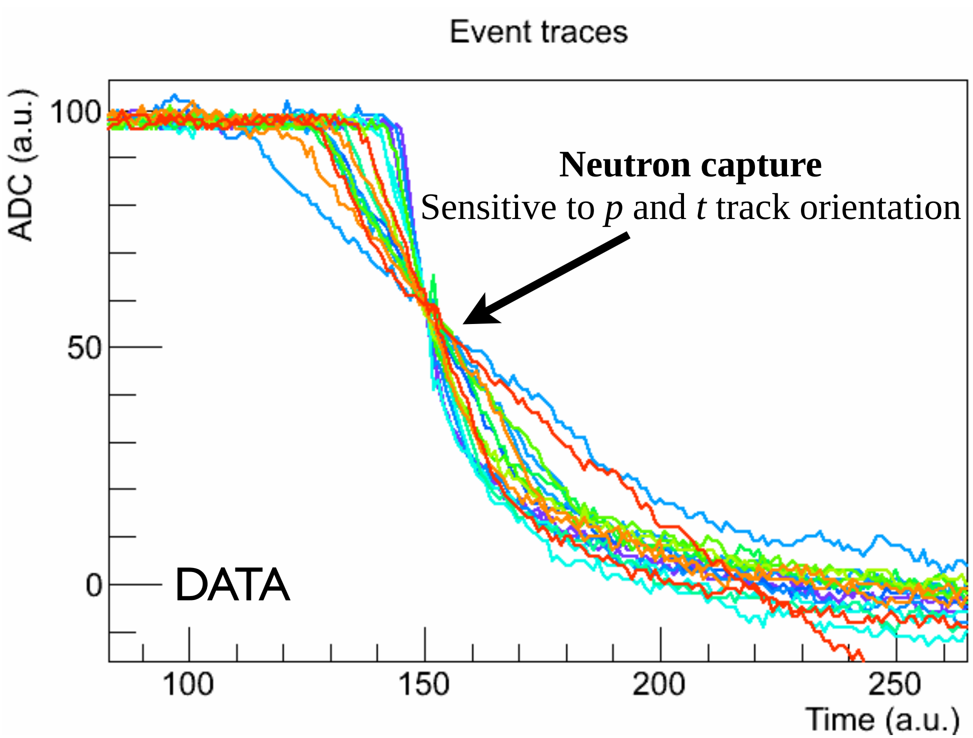
Need to measure neutron flux over 7 orders of magnitude with high precision

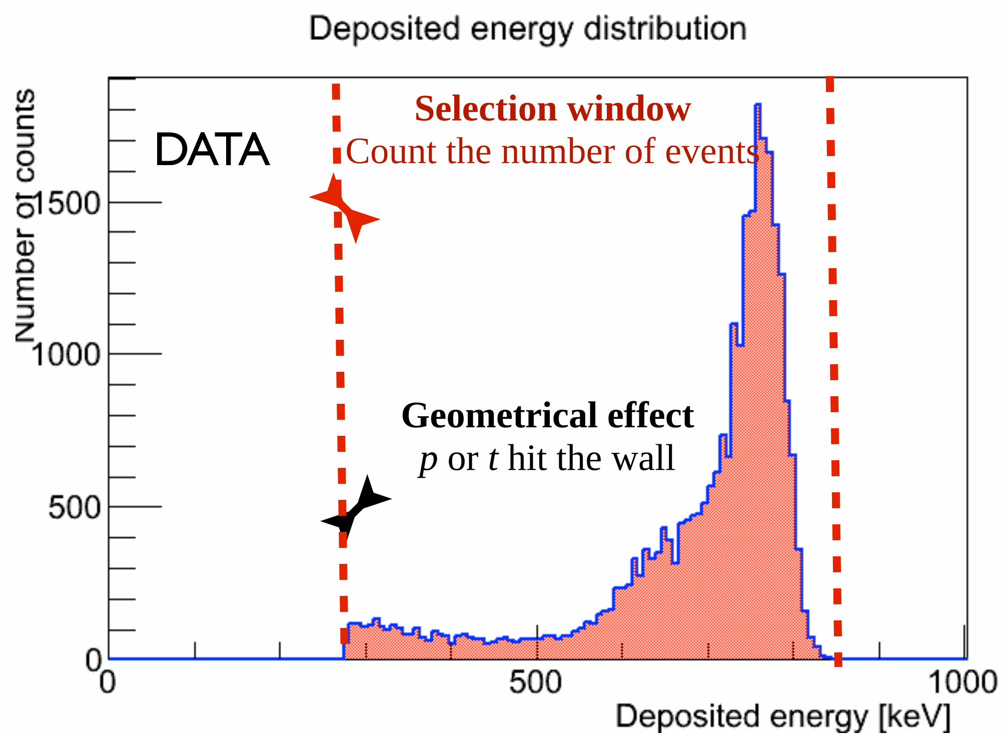
Neutron monitoring

Use of He3 Neutron Capture Detector (NCD) based on the following process:

$$n + ^3\mathrm{He} \rightarrow p + t \quad (Q = 764\ \mathrm{keV})$$

- **Cylinder shape:** 200 cm long, 5.08 cm diameter => active volume ~ 4000 cm3
- **Gaseous TPC:** 85% 3He + 15% CF4 @ 2.53 bar
- **Charge readout:** charge preamplifier Canberra 2001A
- **Optimal HV:** 1.95 kV
- **Energy resolution @ 764 keV**: 3.3%





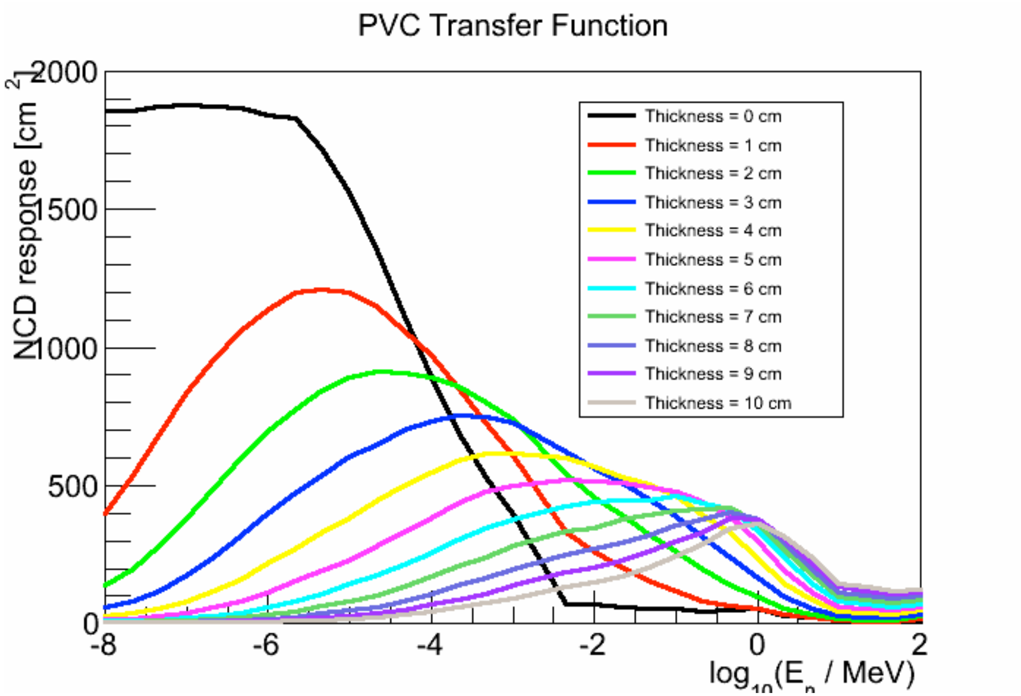
Neutron monitoring

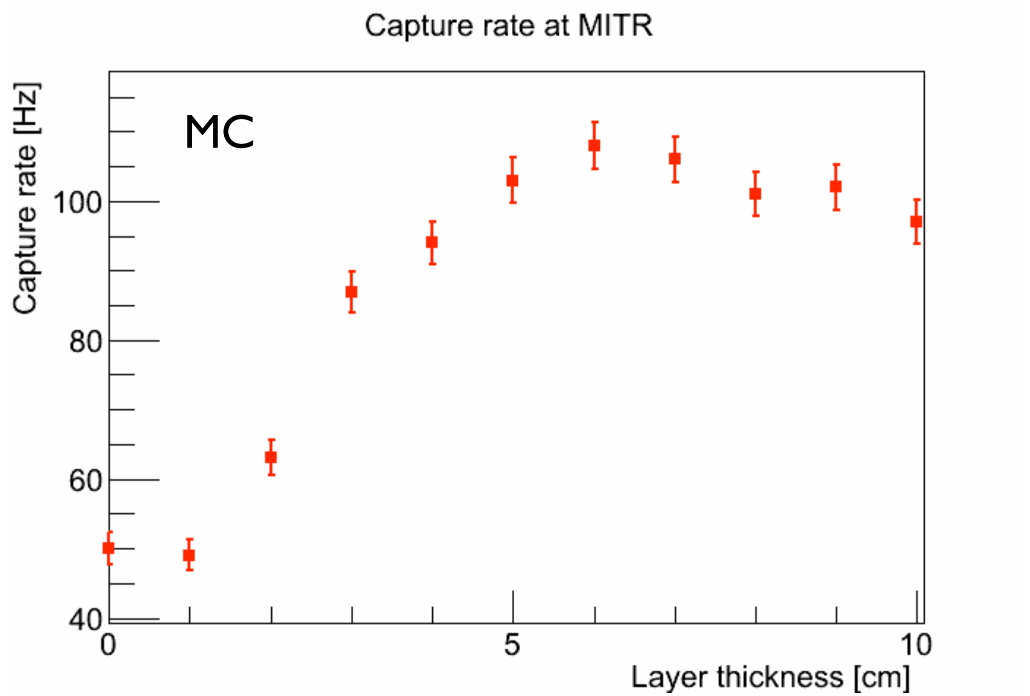
A bonner sphere approach

NCD are mostly sensitive to thermal neutrons (cross section ~ 10^4 barns)

Use layers of PVC to slow down neutrons due to multiple collisions with hydrogen (mostly)

With PVC thicknesses up to 10 cm, we are sensitive to MeV neutrons!





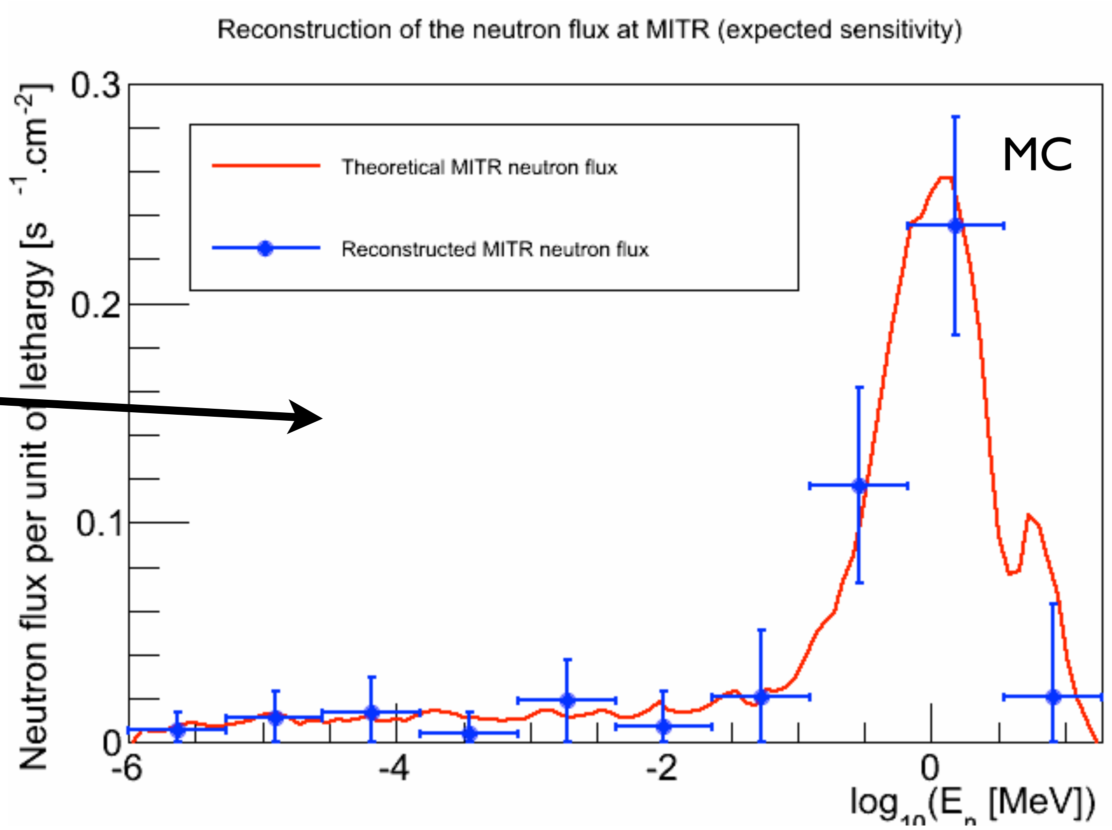
Neutron monitoring

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



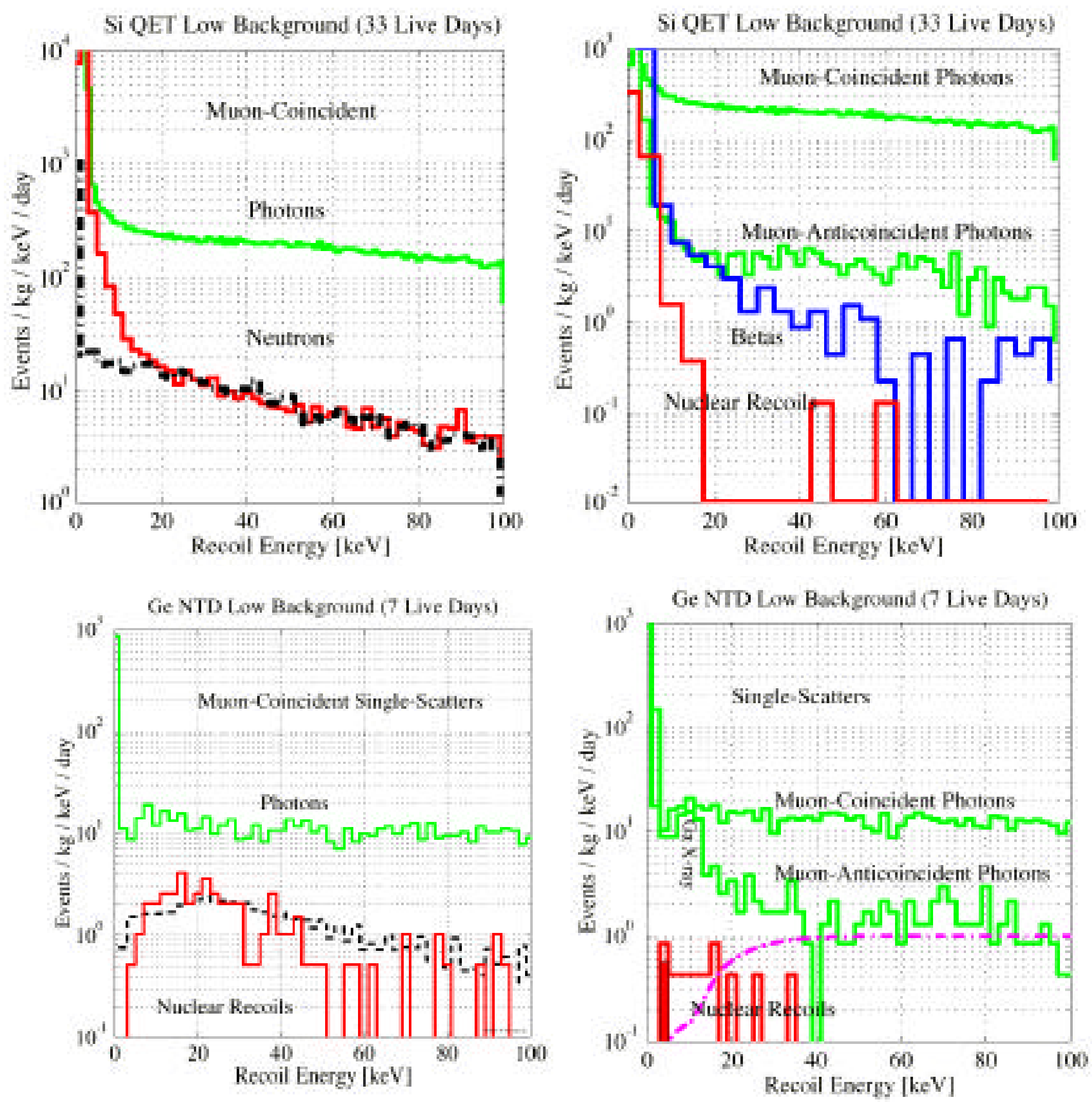
This example considers:
- MITR theoretical neutron flux
- 10 neutron energy bins
- 11 PVC layers
- An acquisition time of **20 minutes** per layer

Reconstructed total flux = 0.348 ± 0.021 neutron /s/cm2 (~5% uncertainty)

Validation of the method using a monoenergetic deuteron neutron source is ongoing…

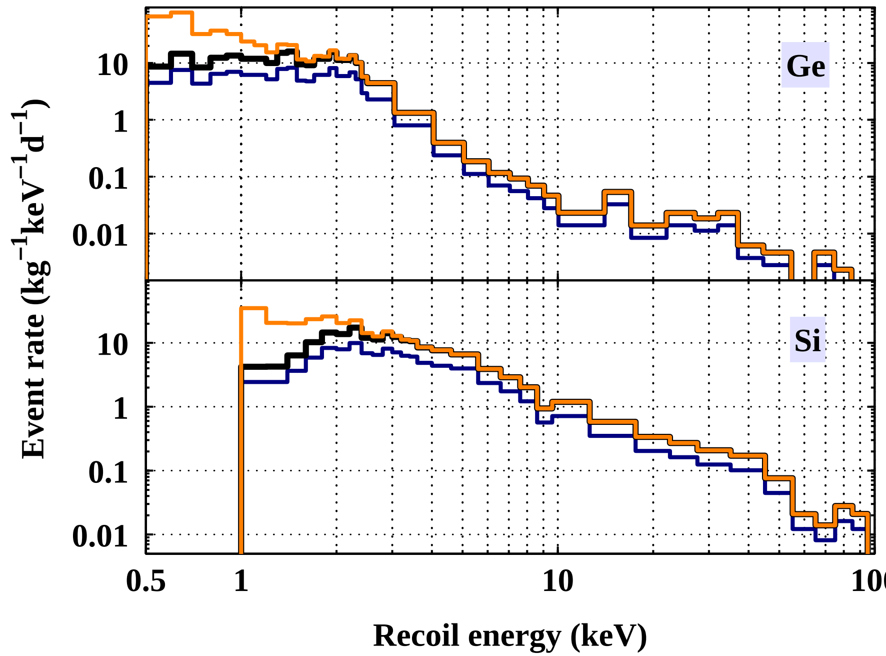
CDMS backgrounds at SUF

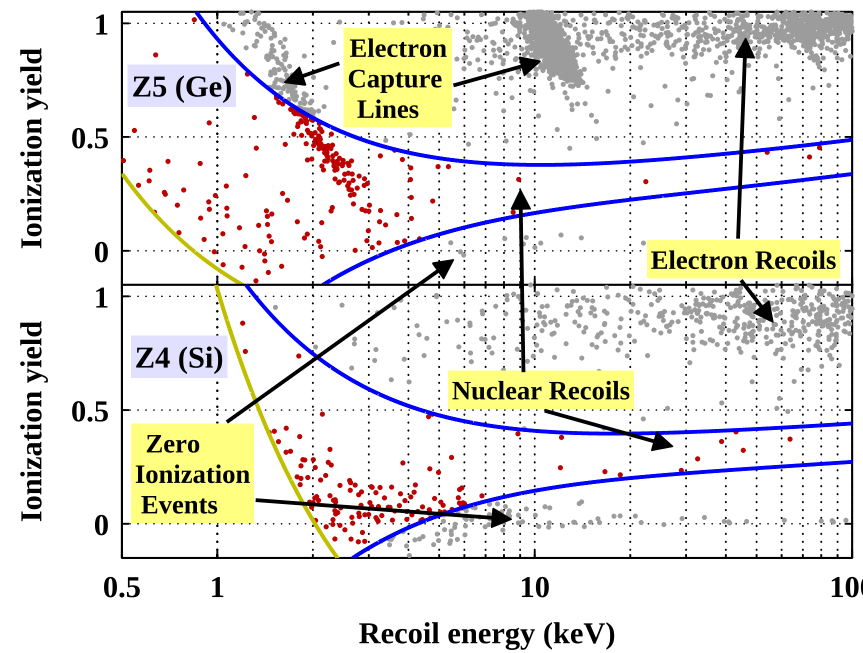
- Upper two plots for Si detectors
- Left muon coincident
- Right muon anti-coincident
- Lower two plots for Ge detectors
- Left muon coincident
- Right muon anti-coincident



Detailed analysis of SUF data

- Top plot is combined Ge (upper panel) and Si (bottom panel) WIMP candidate event rates as a function of recoil energy.
- Bottom plot is ionization yield vs recoil energy for unvetoed single scatters for Ge (top panel, Z5 6 V) and Si (bottom panel, Z4 3 V) WIMP searches
- From PHYSICAL REVIEW D 82, 122004 (2010)





A few example generator/data comparisons

(from http://nuclear.llnl.gov/simulation/main.html)

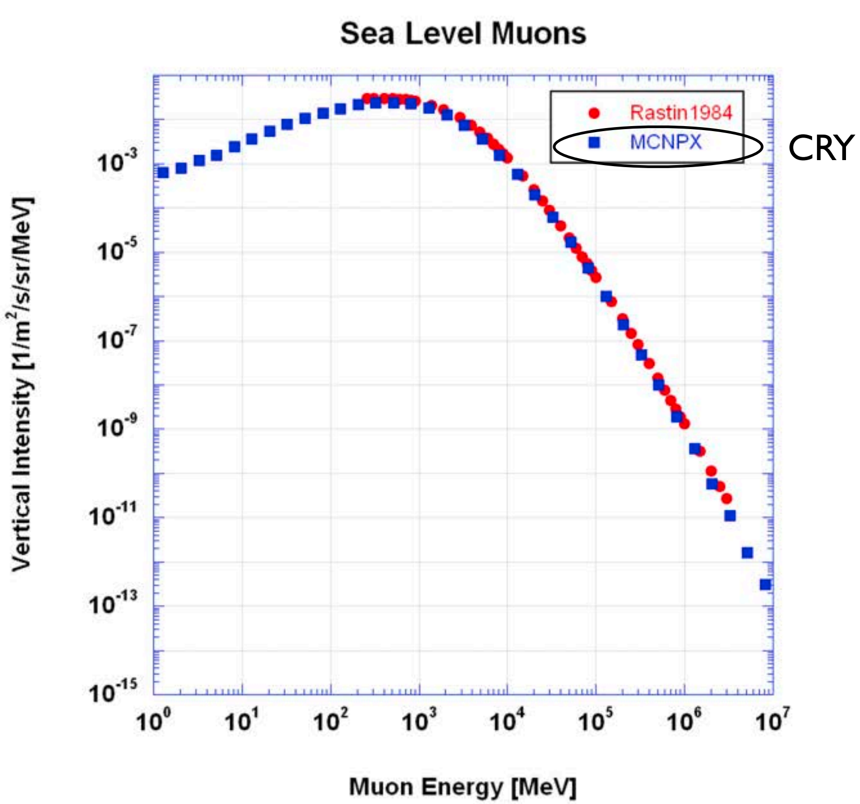


Figure 4: MC-generated muon spectrum and data measured at sea level.

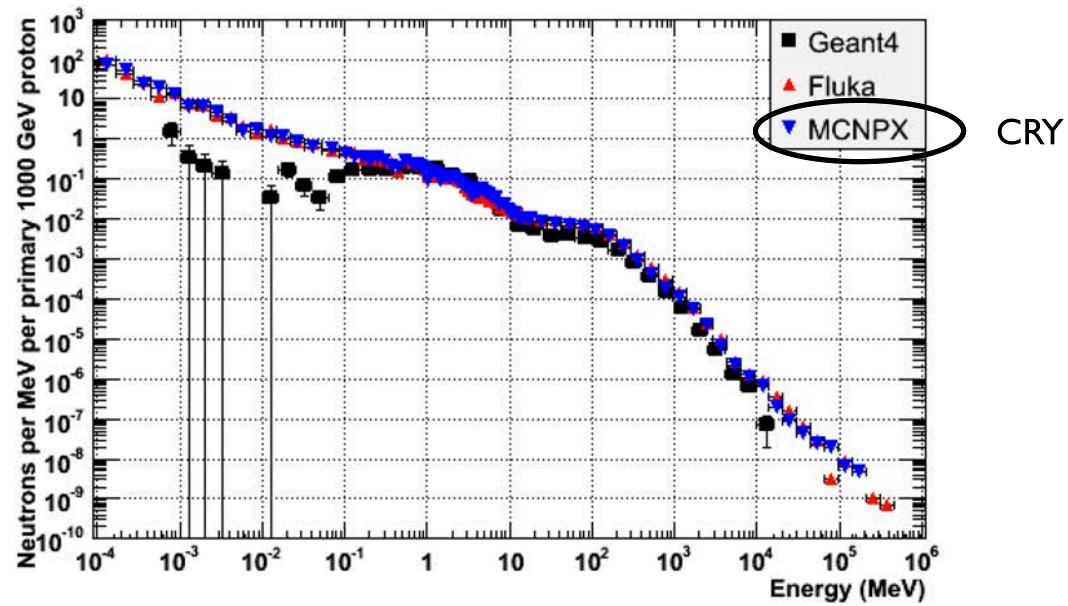
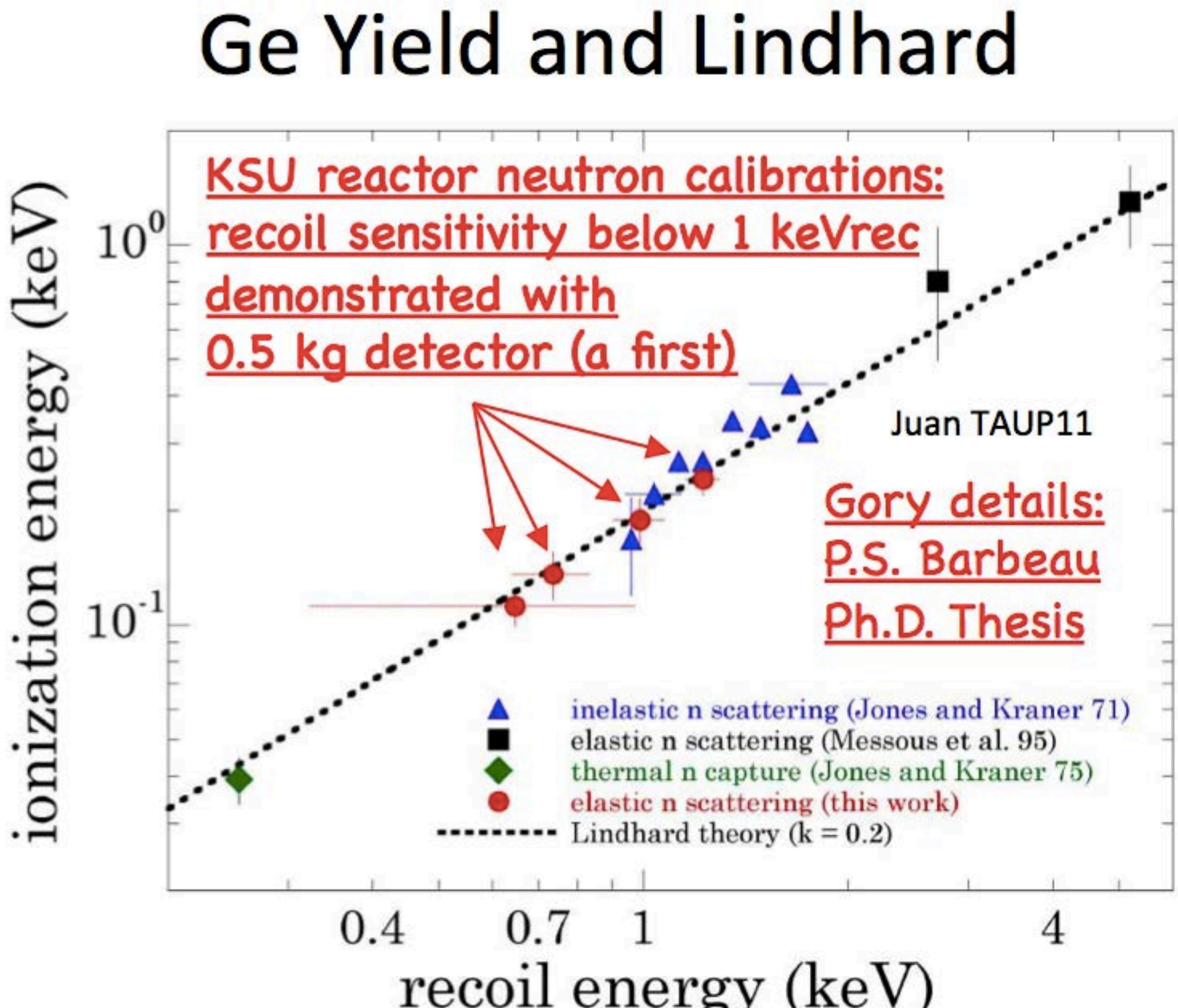


Figure 2: MC-generated neutron spectra at sea level. The incident proton energy is 1TeV.

Calibration of Ionization vs Recoil Energy



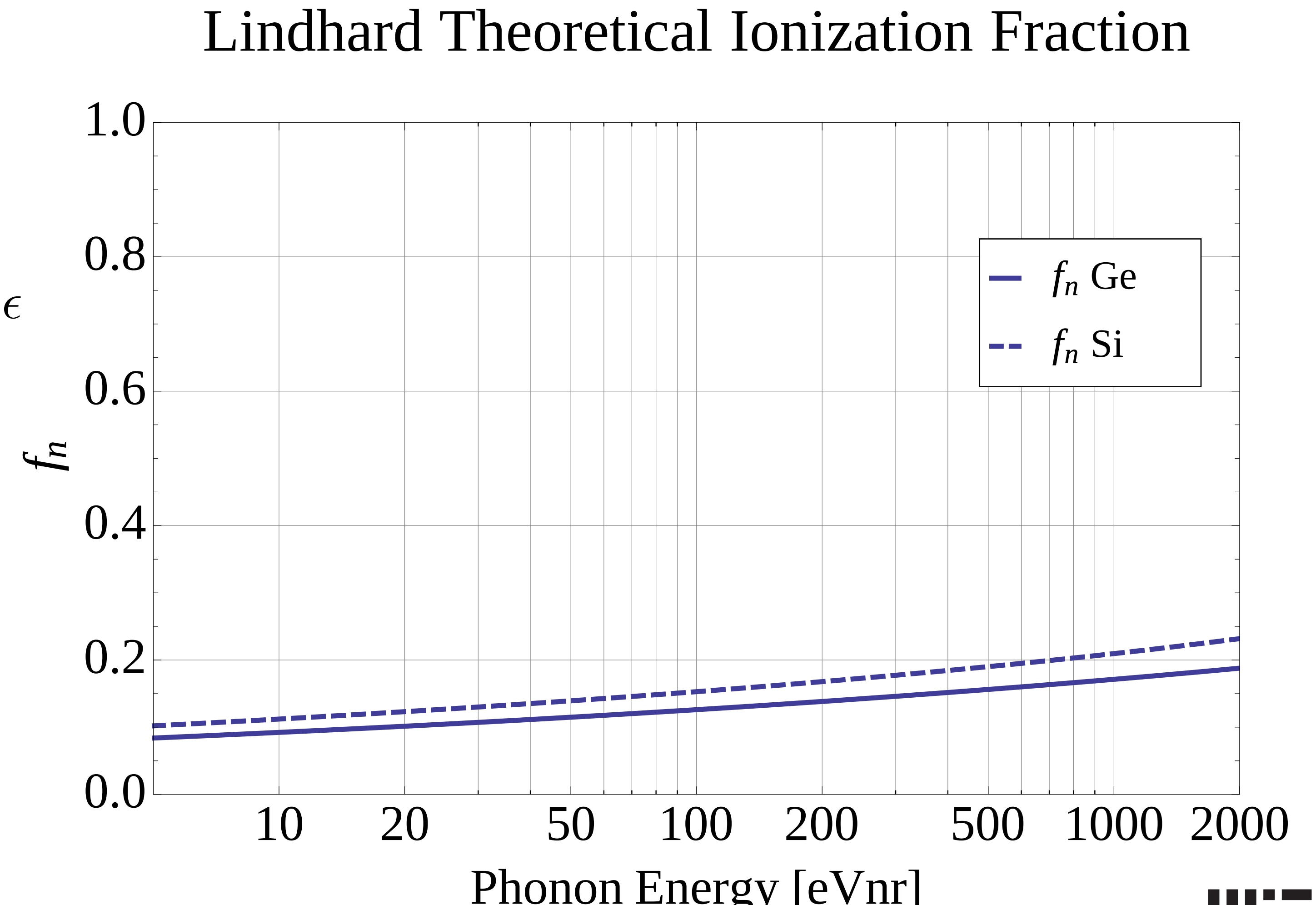
Phonon vs. Ionization Readout

$$f_n = \frac{kg(\epsilon)}{1+kg(\epsilon)}$$

Fraction of recoil energy deposited in target converted to ionization signal

$$k = 0.133\, Z^{2/3}\, A^{-1/2}$$
$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$
$$\epsilon = 11.5\, T\, Z^{-7/3}$$

$$k_{\mathrm{Ge}} = 0.157$$
$$k_{\mathrm{Si}} = 0.146$$



RICOCHET

A Coherent Neutrino Scattering Program

Enectali Figueroa-Feliciano

Massachusetts Institute of Technology