Ricochet:
A Coherent Neutrino-Nucleus Scattering Sterile ν Search

Enectali Figueroa-Feliciano
Massachusetts Institute of Technology

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Ricochet "Proto-Collaboration"

- Columbia University
  - G. Karagiorgi, M. Shaevitz
- Duke University
  - K. Scholberg
- MIT
  - A. Anderson, E. Figueroa-Feliciano, J. Conrad, J. Formaggio, K. Palladino, J. Spitz
- Berkeley
  - M. Pyle

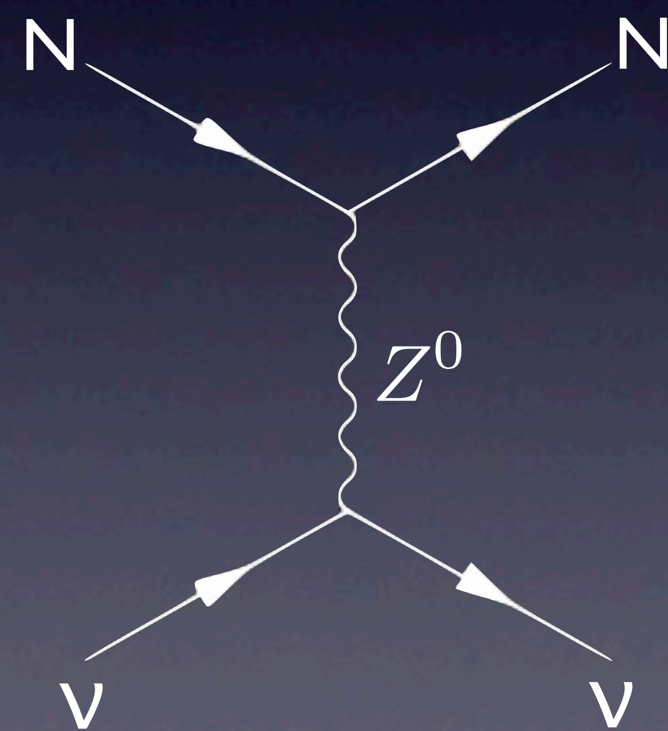
Ricochet

- A broad experimental program seeking to use cryogenic detectors for neutrino physics through coherent neutrino scattering

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
- F: Form Factor



No flavor-specific terms!!!

Same rate for ν_e, ν_μ, and ν_τ

Coherent ν Scattering

- Unmeasured SM Process!
- Elastic neutrino scattering that is coherent on the entire nucleus: cross section scales as A^2
- CNS cross section dominates other neutrino cross sections in the 1-50 MeV neutrino energy range
- Recoil energy is very low!

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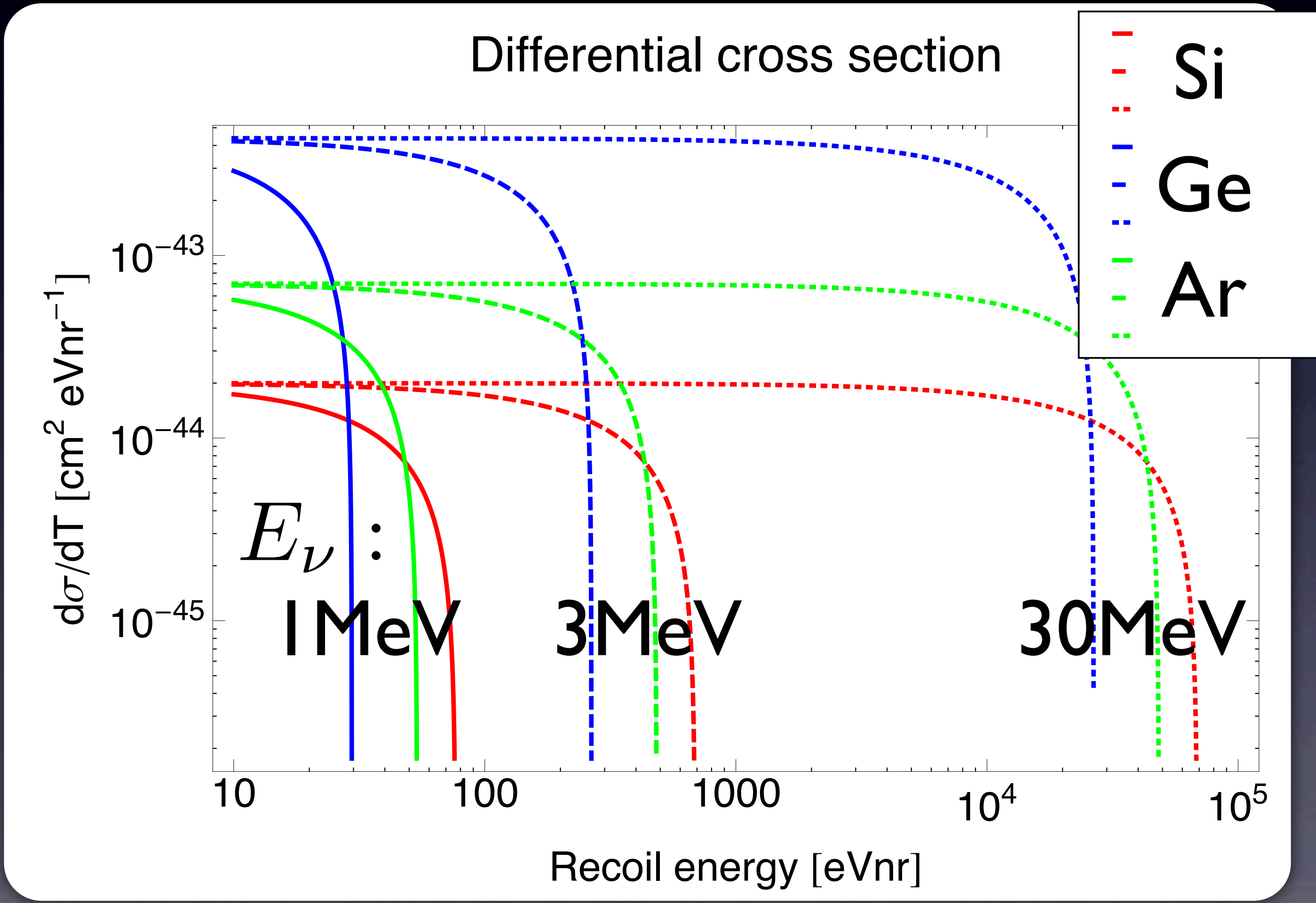


CNS Oscillation: A Definitive Sterile Signal

- At low energies, CNS dominates over other cross sections
- An positive oscillometry measurement with CNS is definitive proof of the sterile nature of the interaction, i.e., you don't get oscillations from NSI
- An experiment that can measure the energy spectrum *and* do oscillometry can do a sterile search *and* NSI at the same time (but beware of $F(q^2)^2$…

How to measure CNS?

- Sources:
  - MCi electron capture sources: ^{37}Ar, mono-energetic, ~800 keV PRD 85, 013009 (2012)
  - Reactors: 1-10 MeV e.g. JHEP 12 (2005) 021
  - Decay-at-rest stopped pion sources: 10-50 MeV PRD 84, 013008 (2011)
- Detectors:
  - Bolometric and Dark-Matter-derived detectors with low-energy thresholds

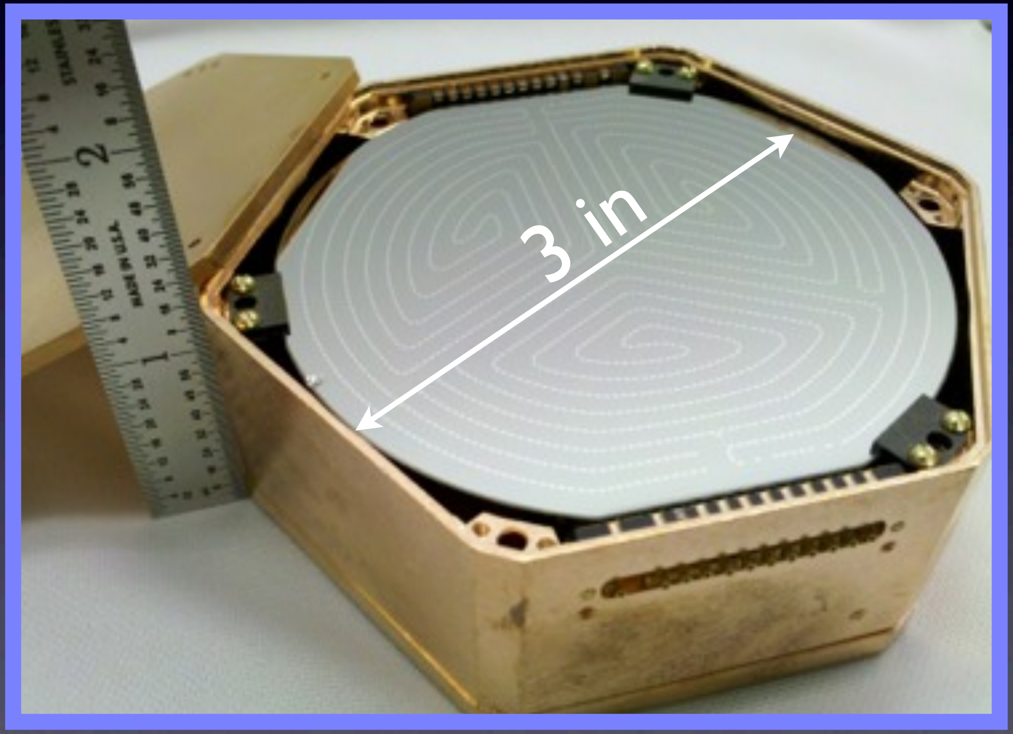
But Wait! No one has actually *seen* CNS!

Ricochet @ MIT: CNS Detection

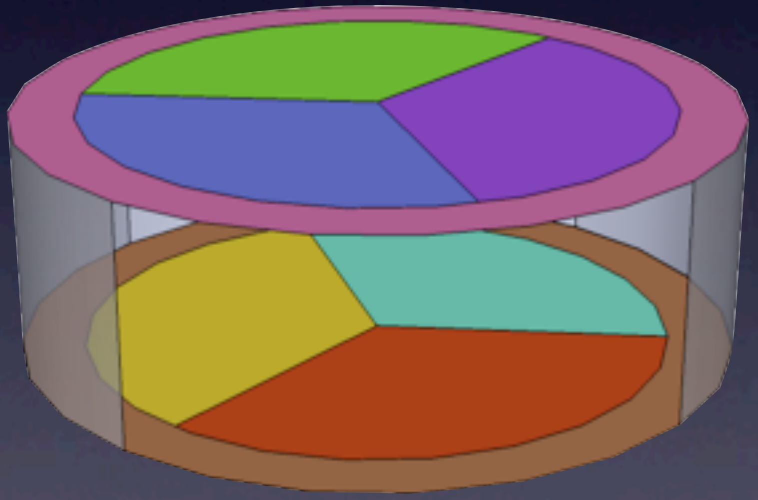
- Use existing strong ν source
- Exploit low-threshold detector development synergy with light-mass Dark Matter effort

New SuperCDMS Detectors: iZIP

Interleaved Z-measuring Ionization and Phonon



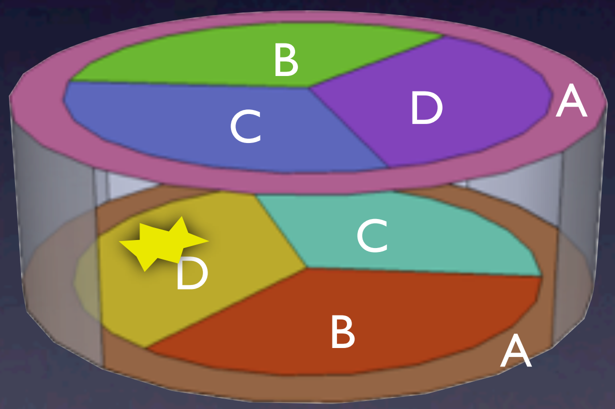
Top and bottom surfaces contain interleaved ionization and phonon sensors



Sensors are arranged into 8 phonon channels and 4 charge channels

New SuperCDMS Detectors: iZIP

8 phonon channels, 4 charge channels



Operating at
~40 mK

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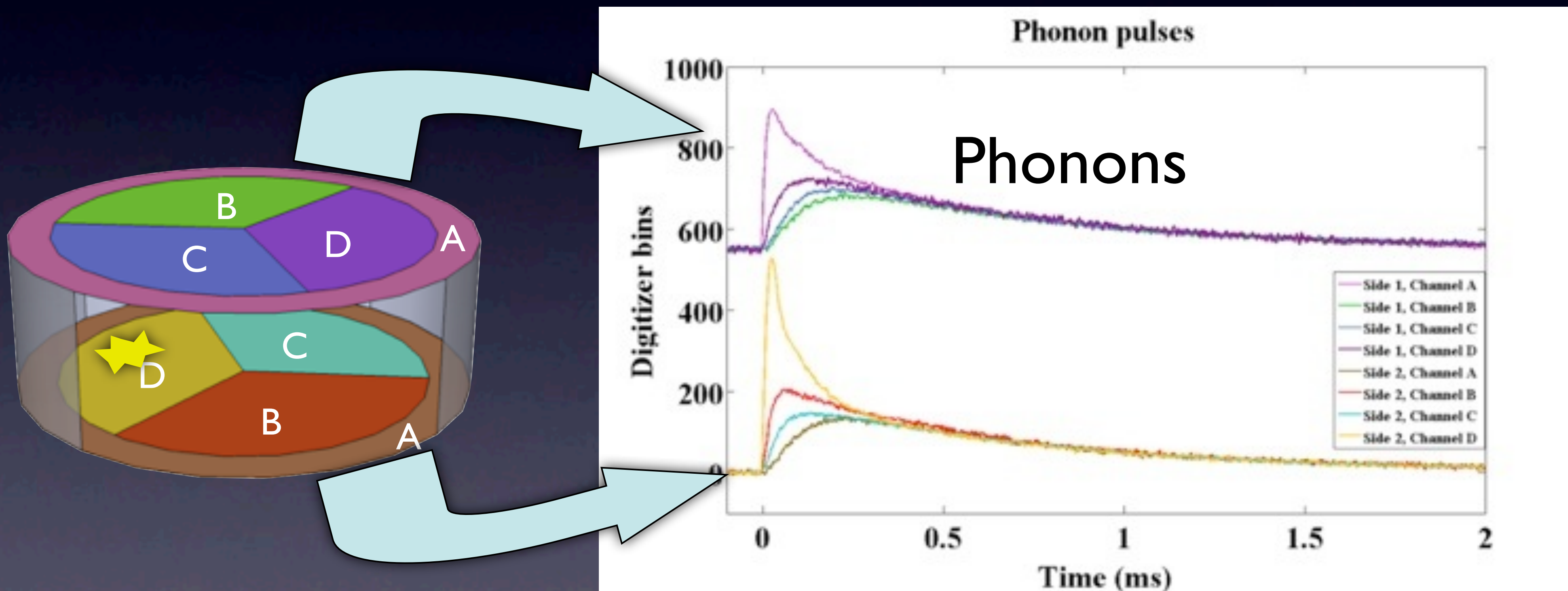

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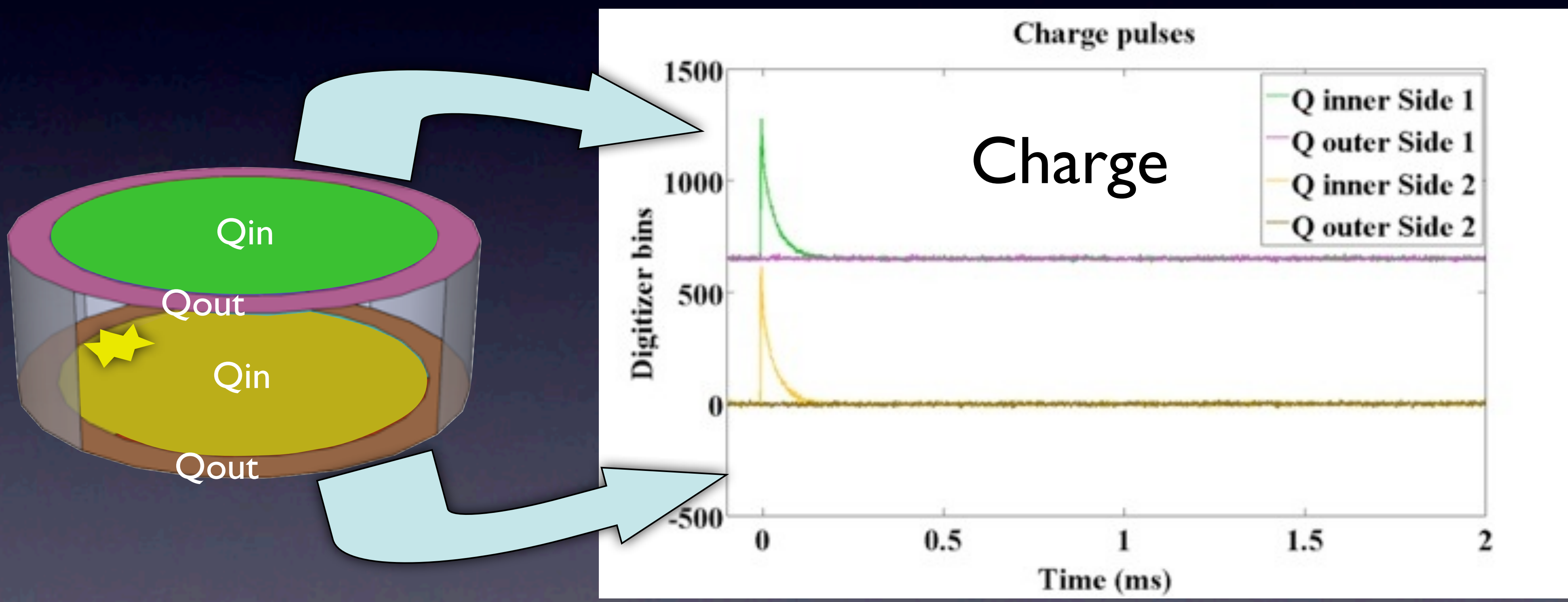


Operating at ~40 mK

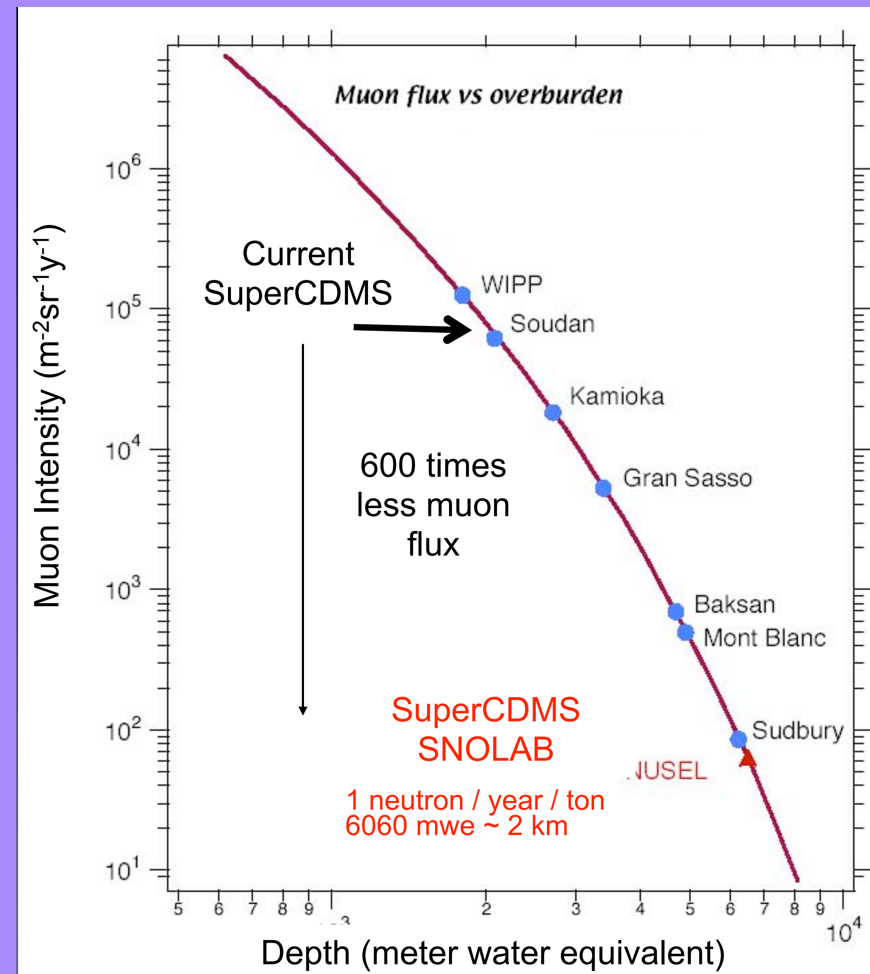
Experimental Setup

Some rock is nice...

Active veto	muon scintillator
Polyethylene	neutron moderation
Lead	shields gammas
Ancient Lead	shields ^{210}Pb betas
Polyethylene	shields ancient lead

Radiopure Copper inner can

Radiopure Ge "target"



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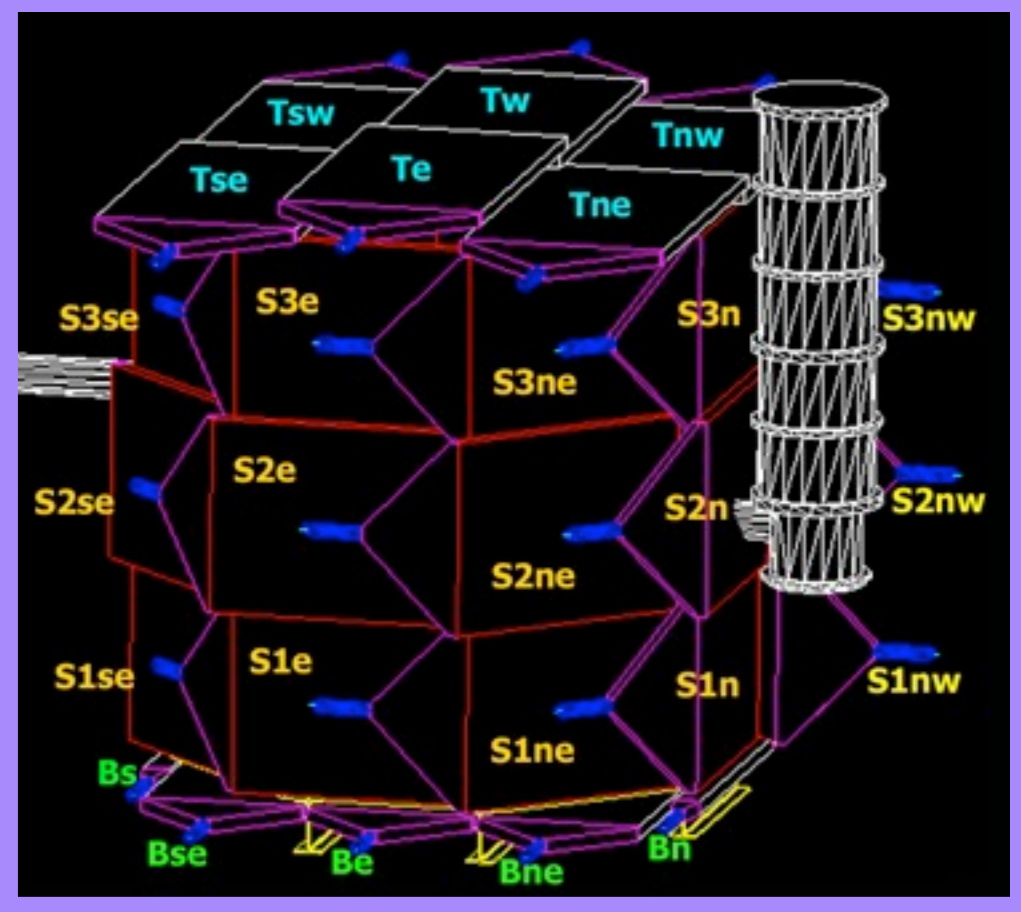

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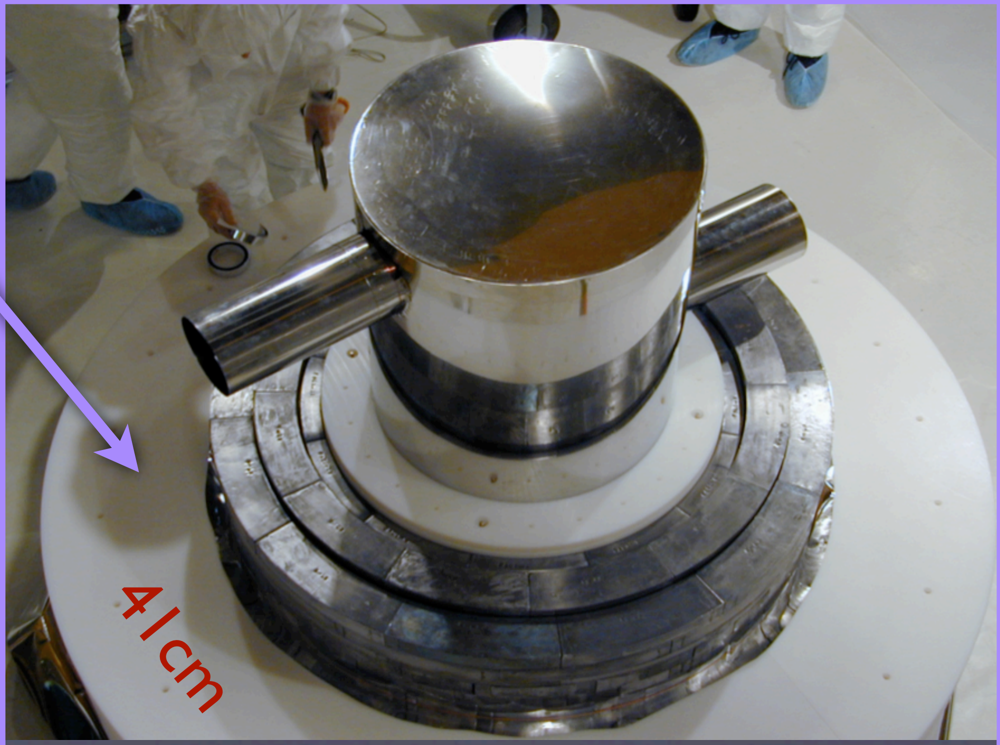

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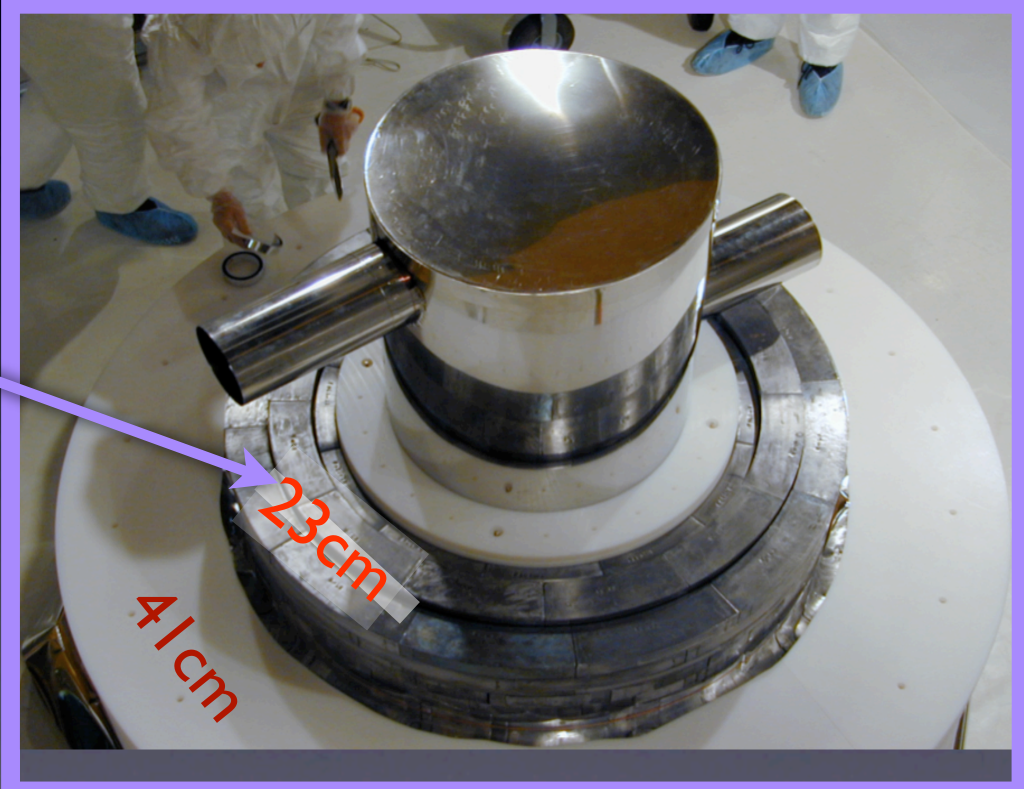

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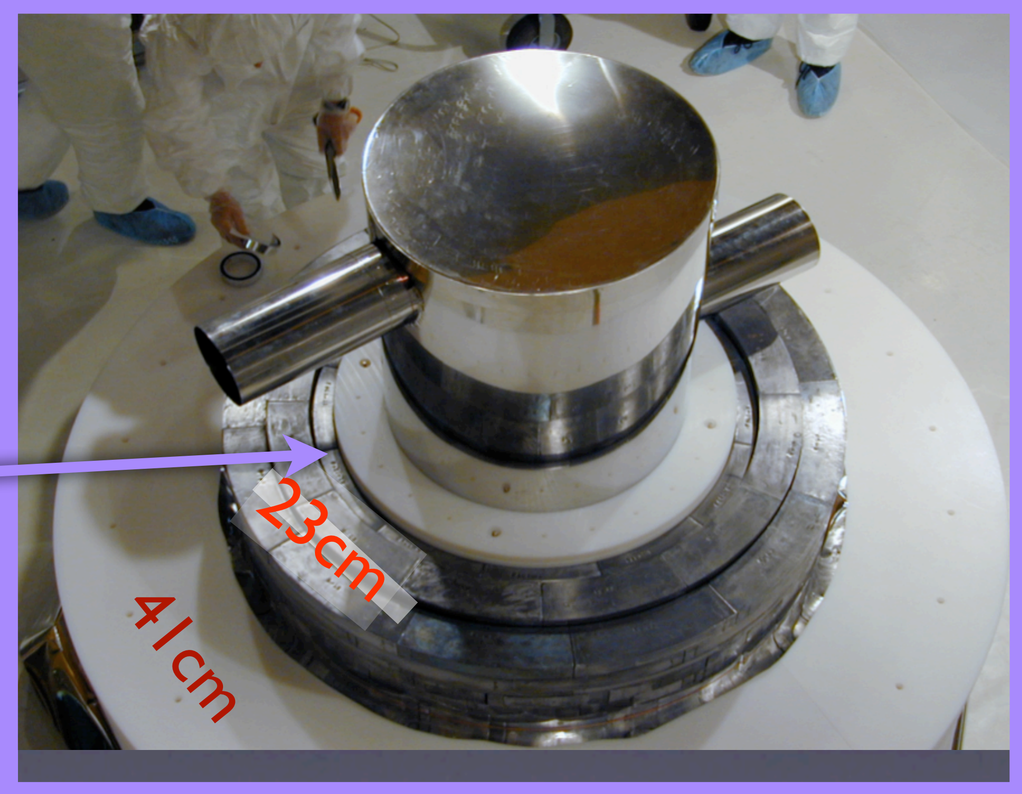

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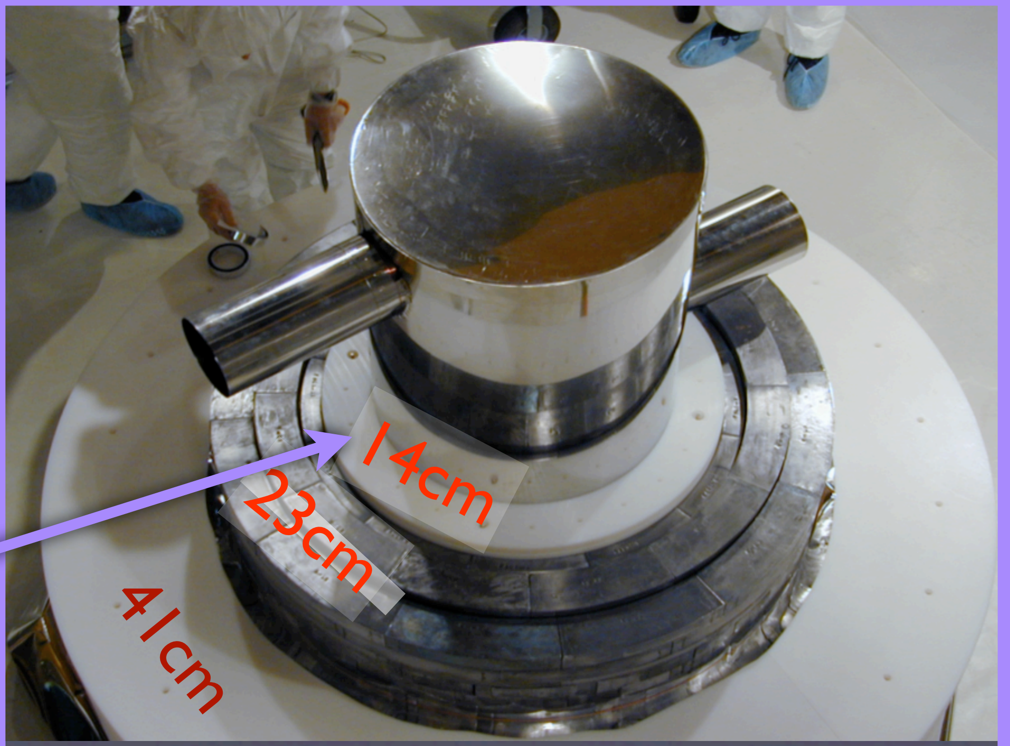

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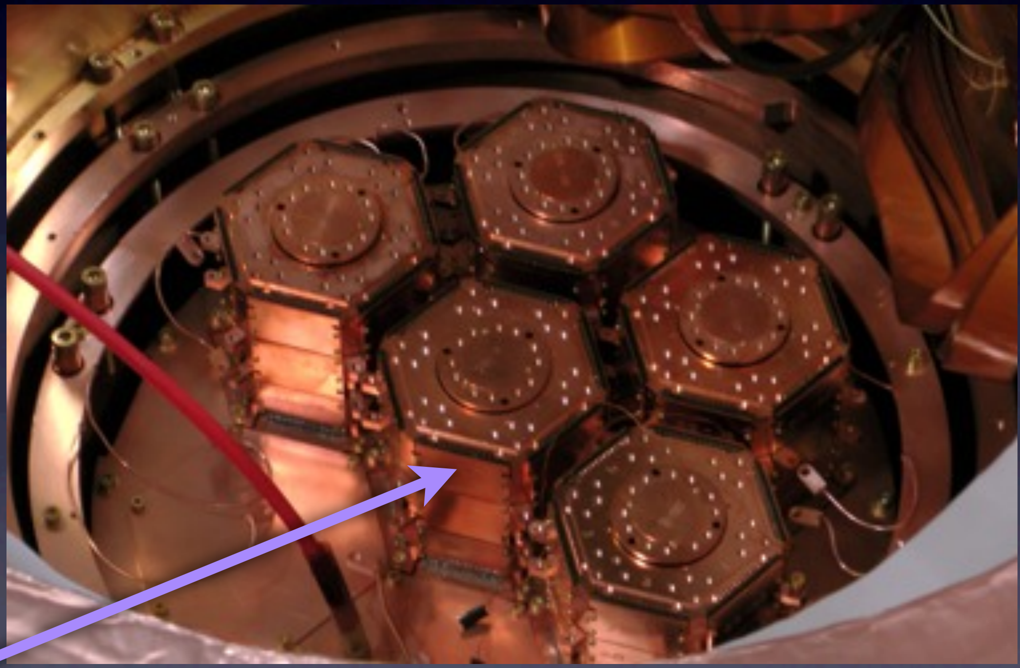

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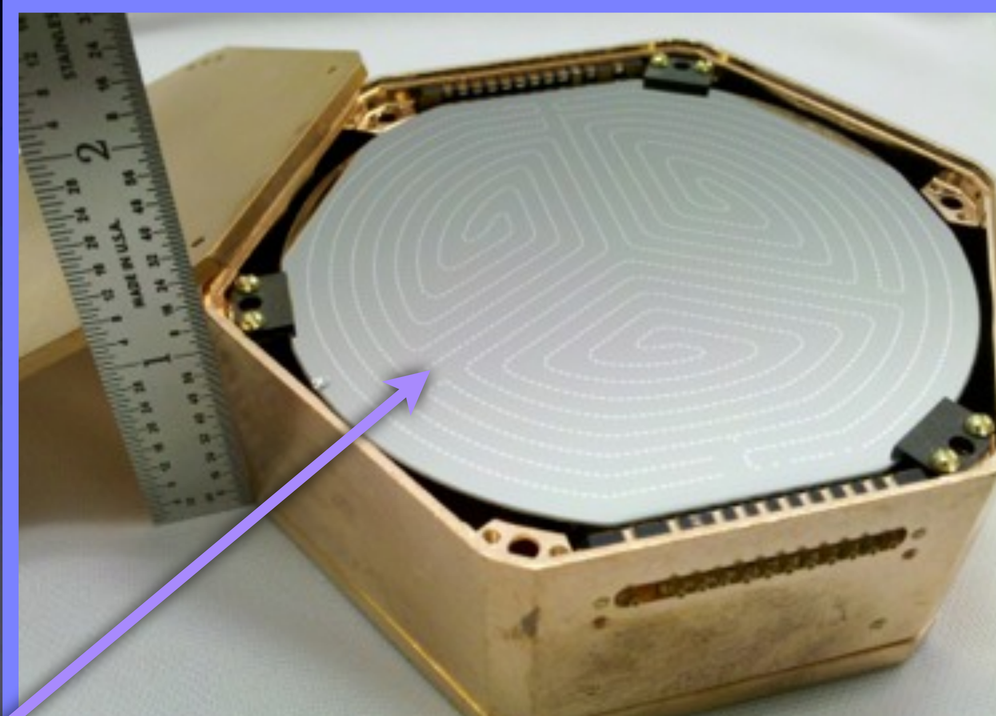
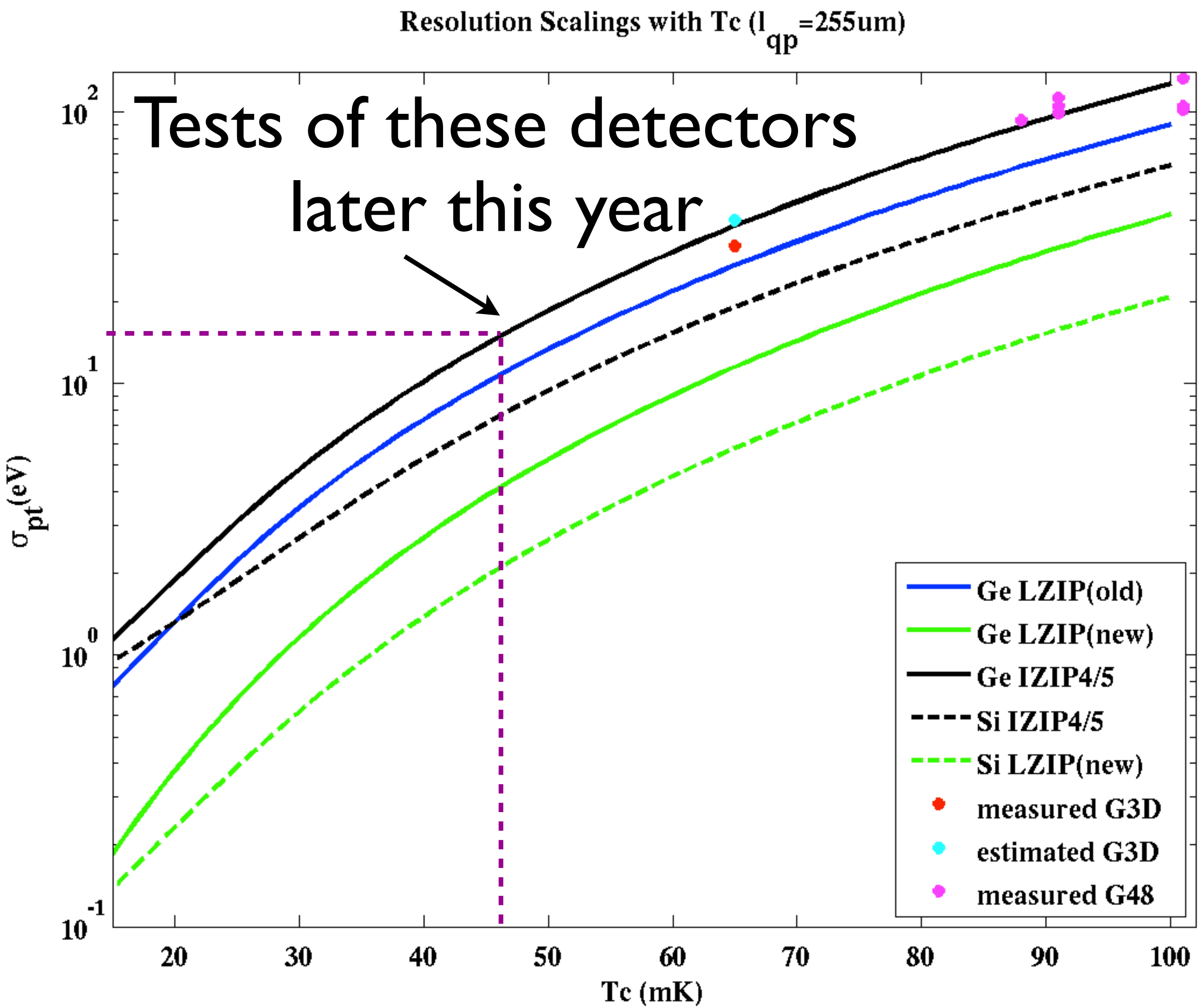


To Lower the Energy Threshold: Lower T_c!

(and some optimization + higher voltage operation)

Energy resolution eV_{RMS}

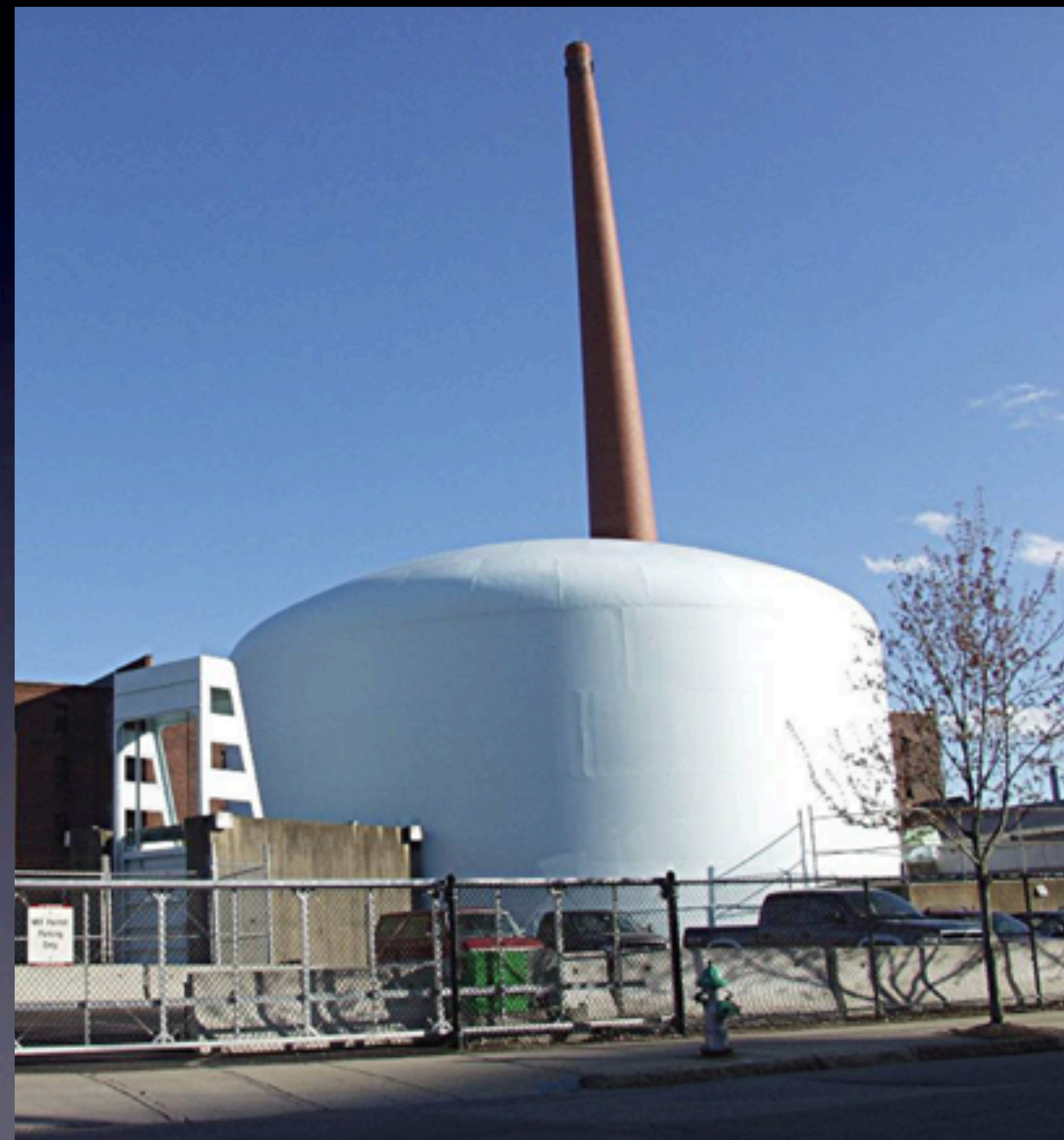


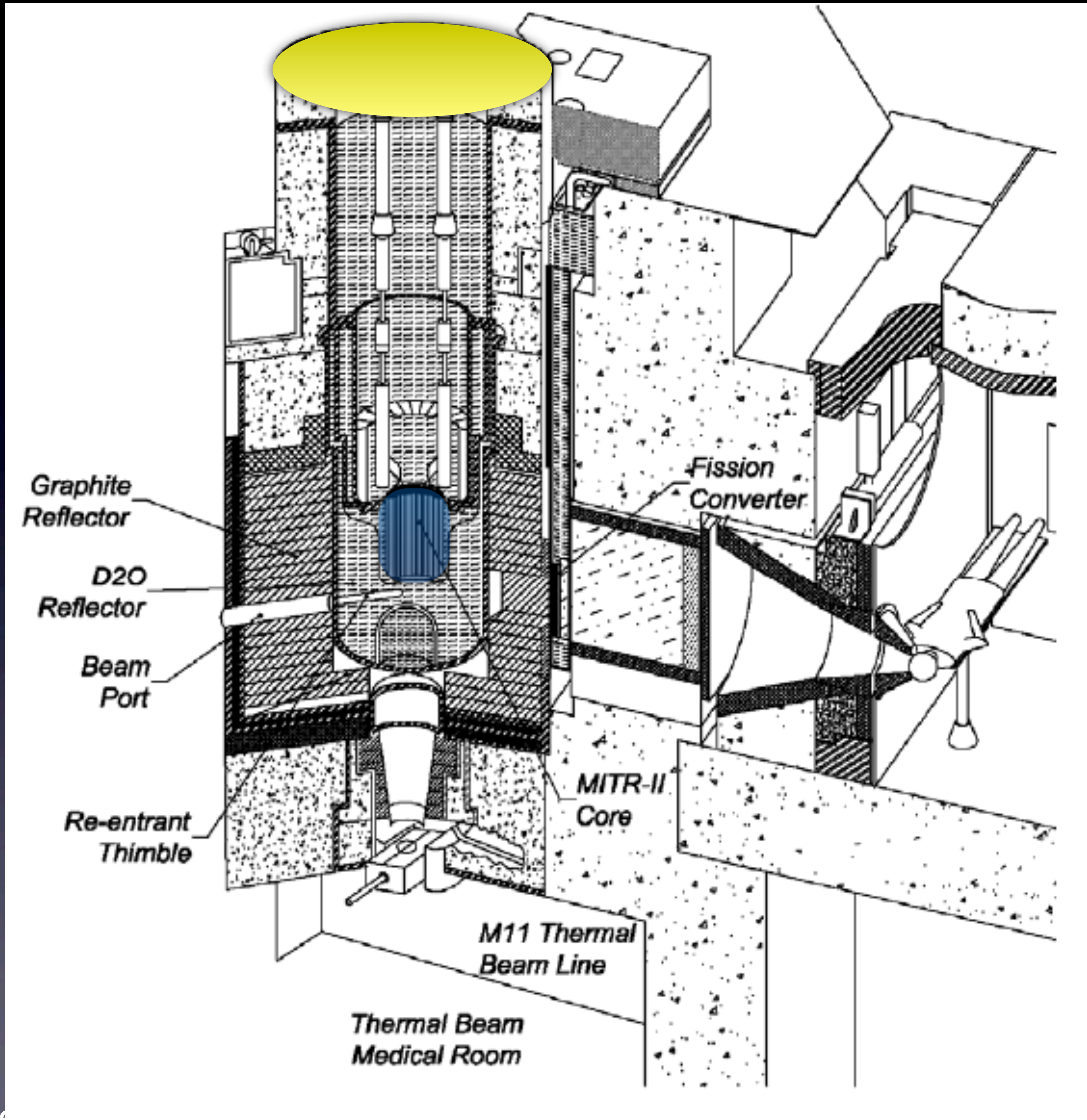
To lower the threshold, you give up some some discrimination, but if you have a source, you don't need the discrimination of CDMS

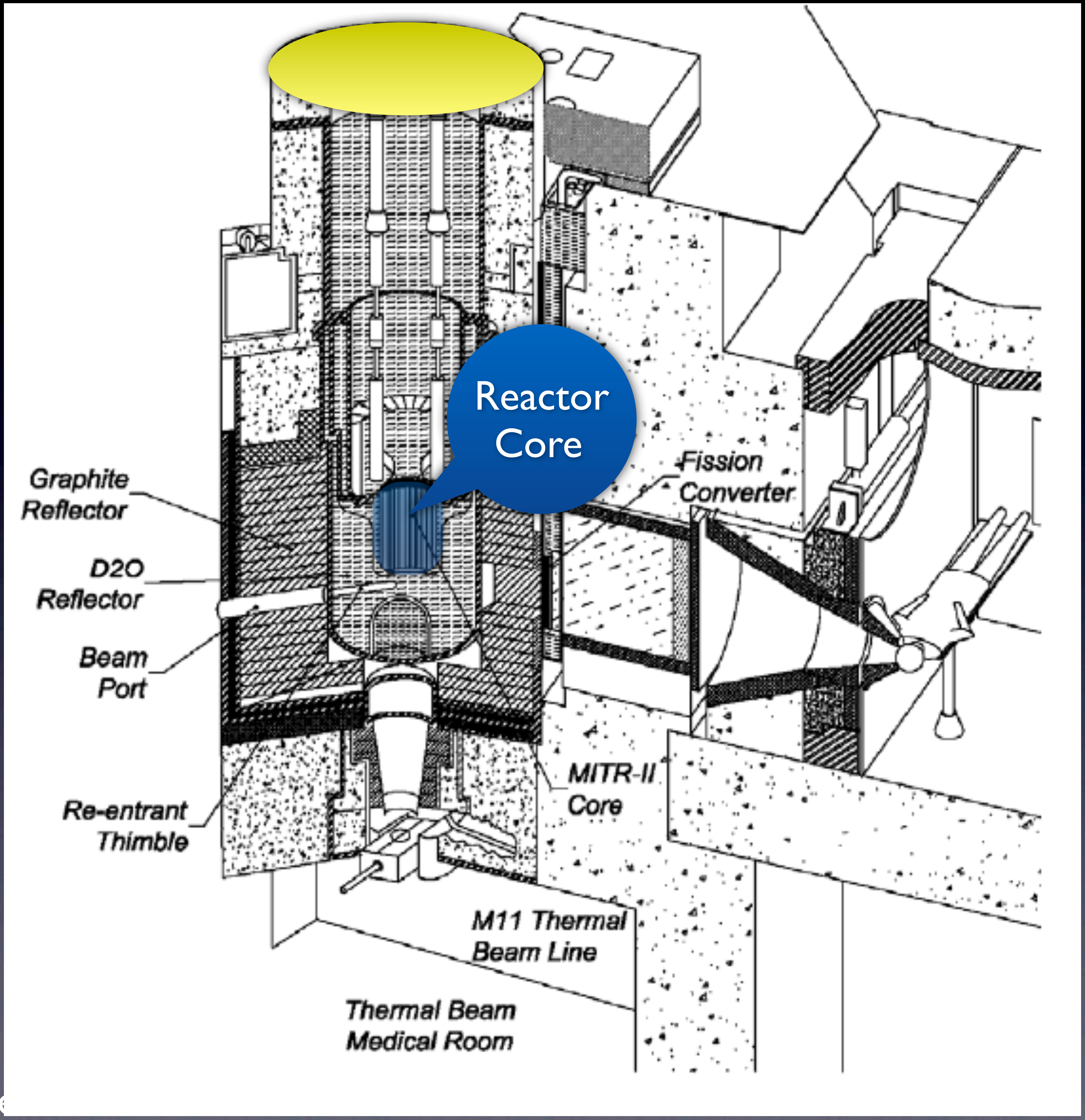
14 eV_{RMS} Resolution For 100 eV Threshold

MIT Nuclear Reactor

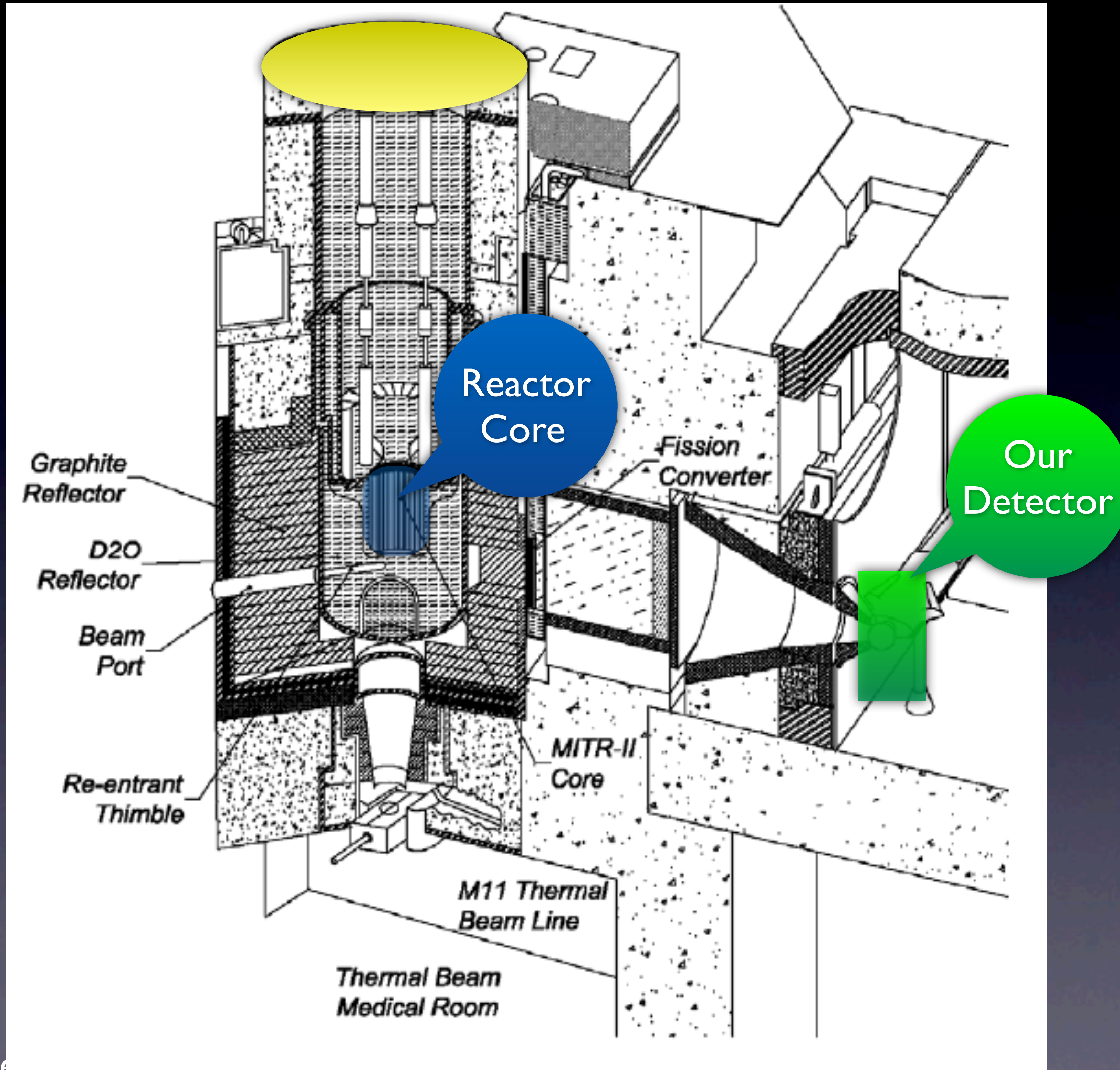
- 5.5 MW Thermal Reactor
- 1×10^{18} ν/s
- 5.2×10^{11} ν/cm^2/s @ 4 meters from core
- 4 week cycle with 1 week refueling and maintenance




Graphite Reflector
D2O Reflector
Beam Port
Re-entrant Thimble
Fission Converter
MITR-II Core
M11 Thermal Beam Line
Thermal Beam Medical Room



Enectali Figue



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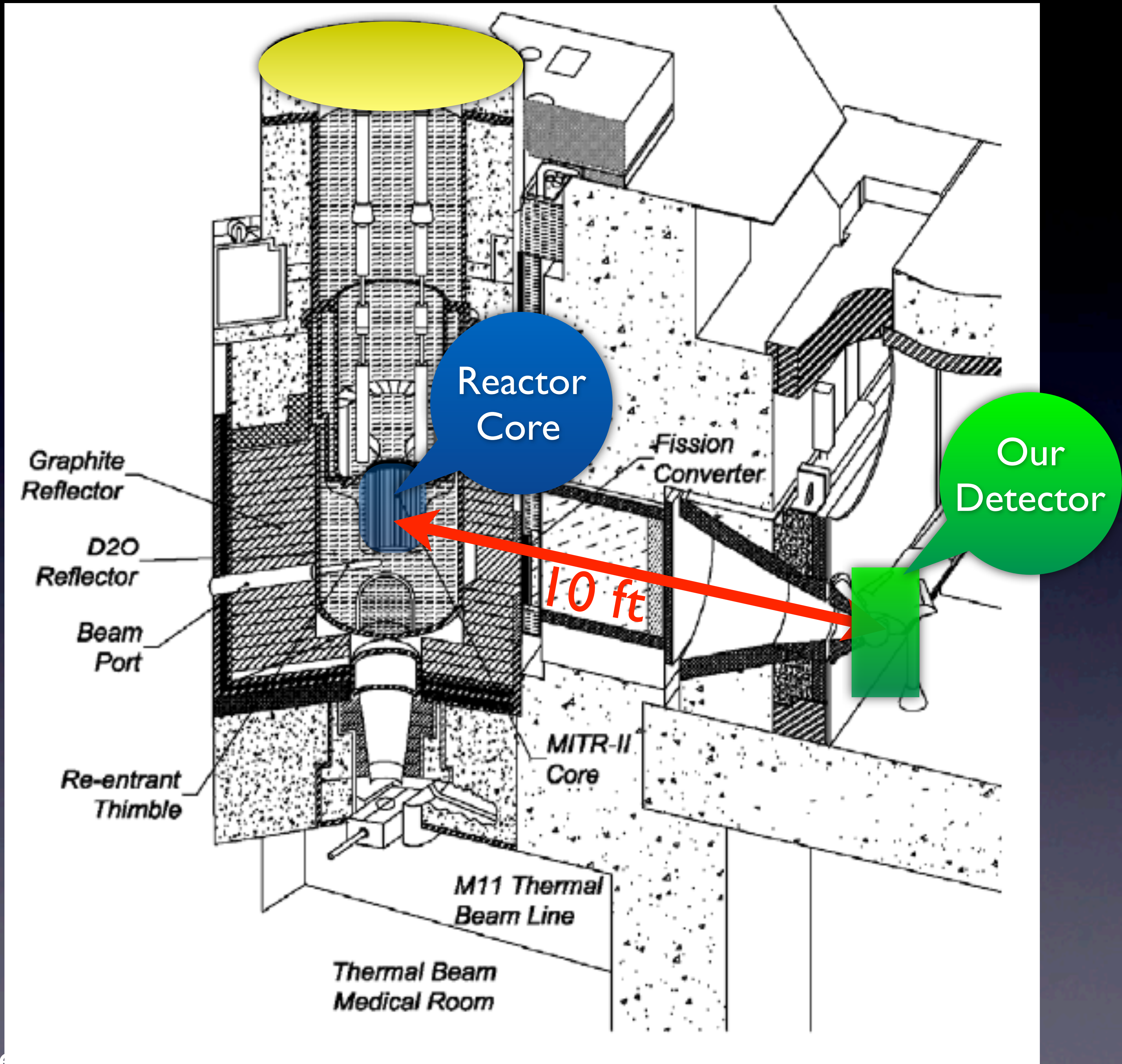
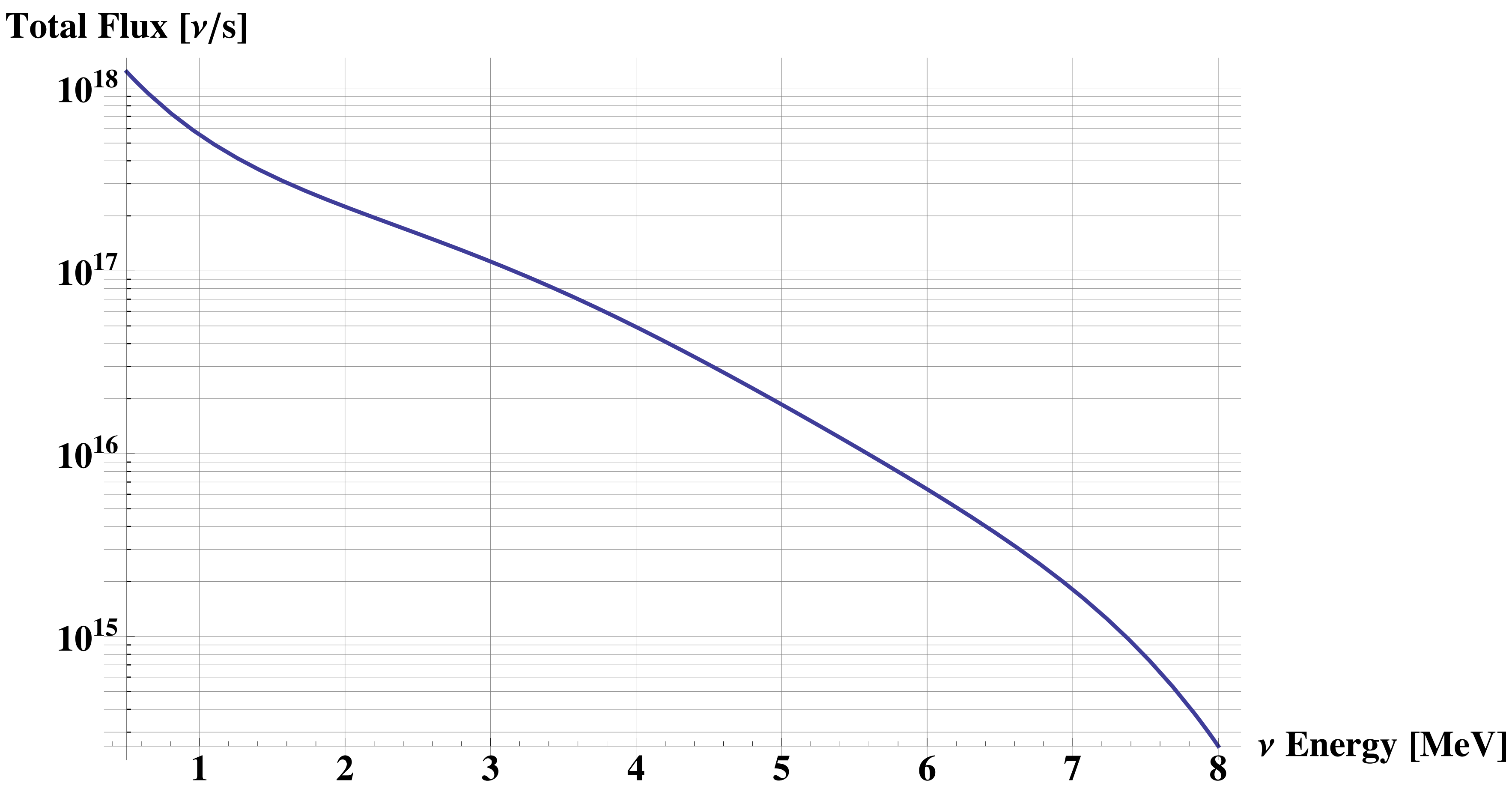
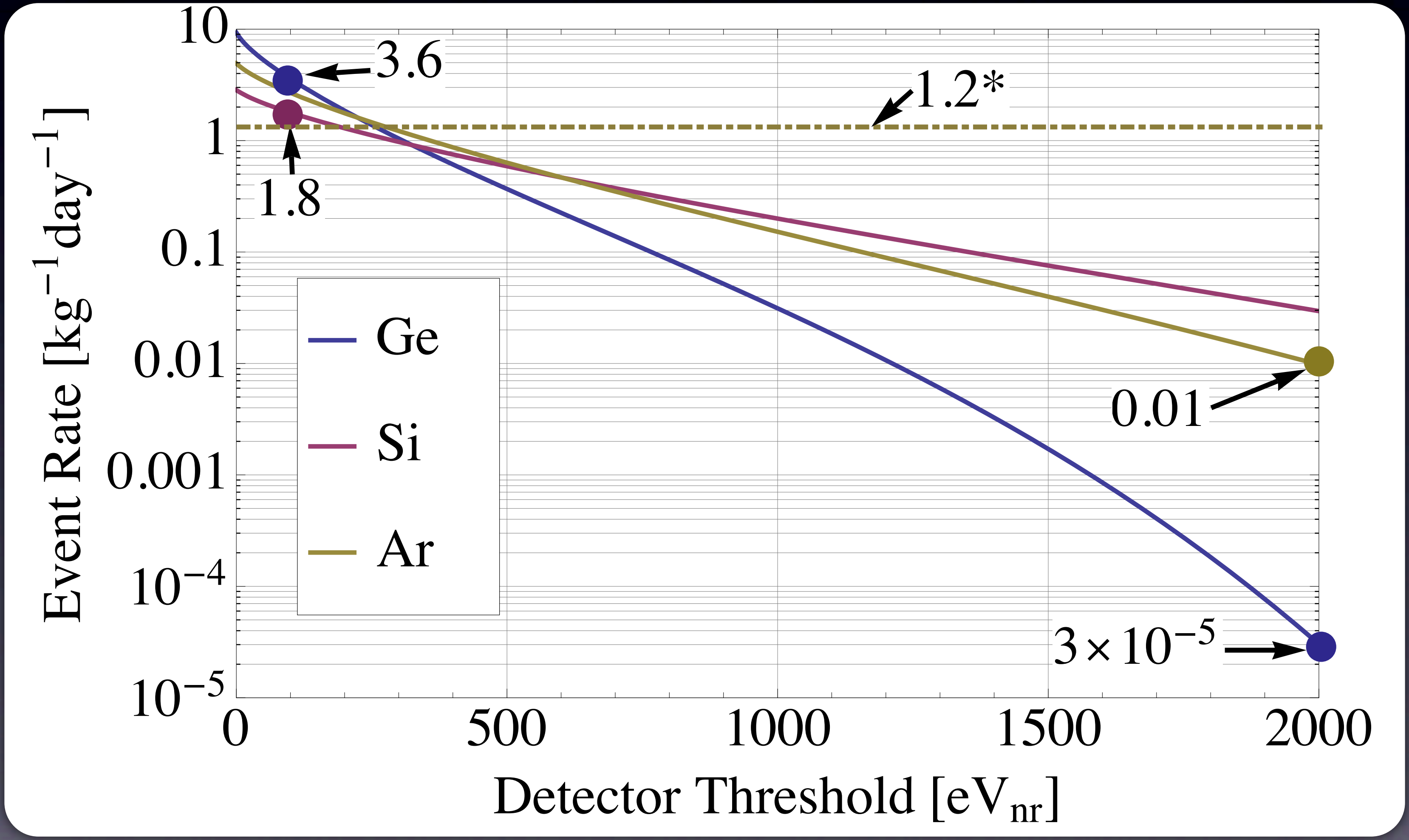


Enectali Figue

Neutrino Flux From Reactor is High!



The rates are 10's of events per day for 6 kg detector



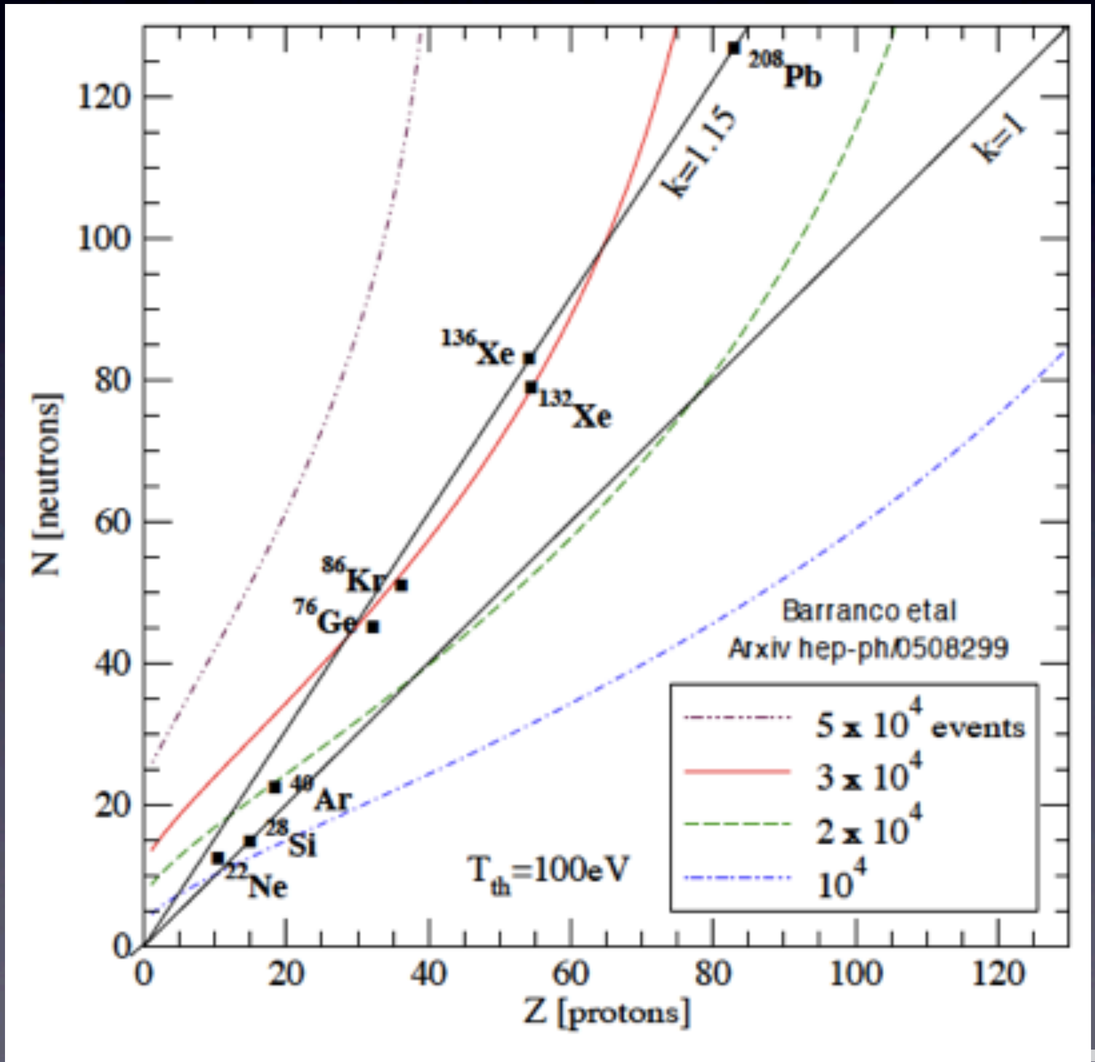
NSI Sensitivity!

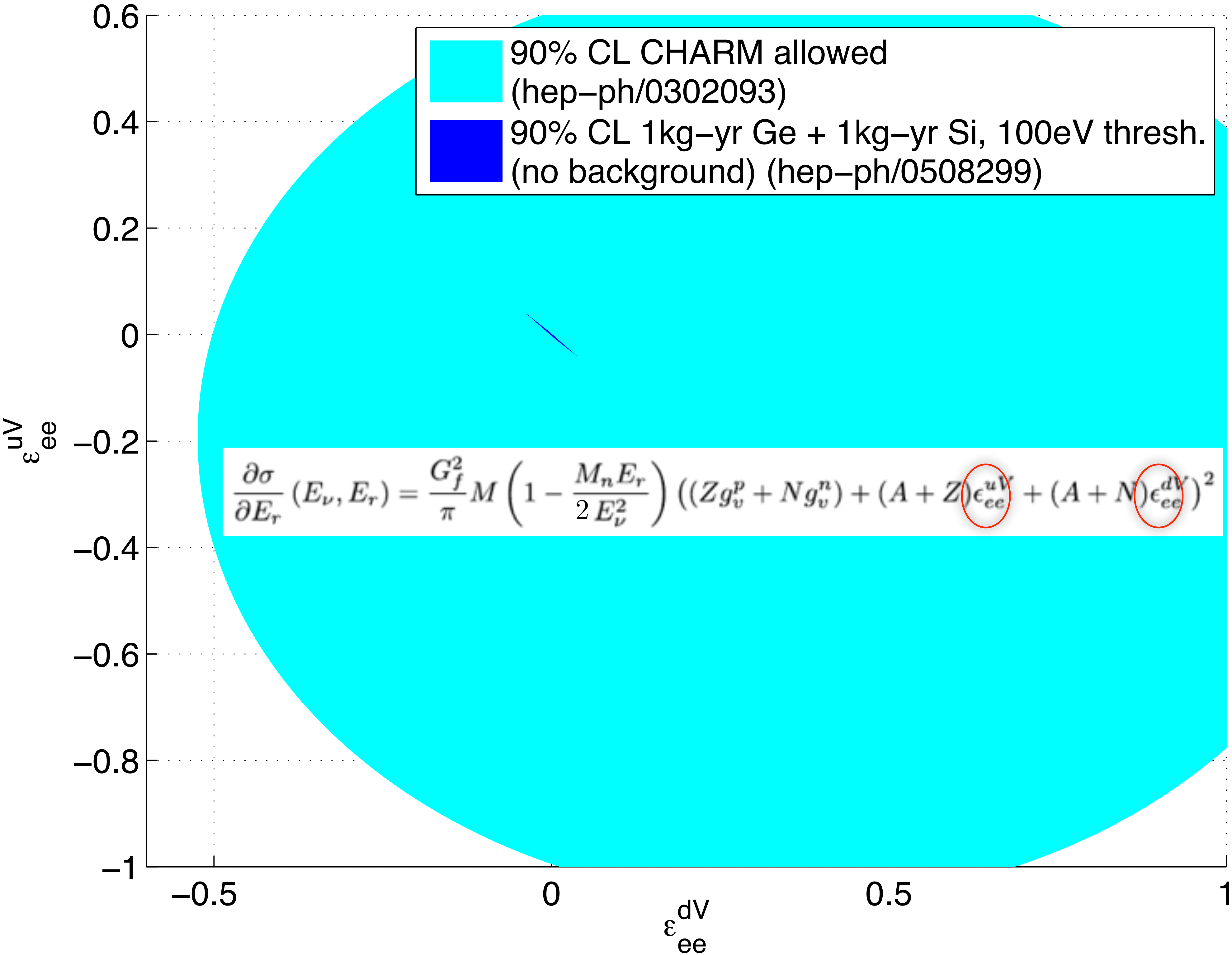
- Non-Standard Interactions is a way to search for physics beyond the standard model by parametrizing deviations in the interaction rates between particles
- Our proposed experiment can place world-leading limits on some of these parameters

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

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!





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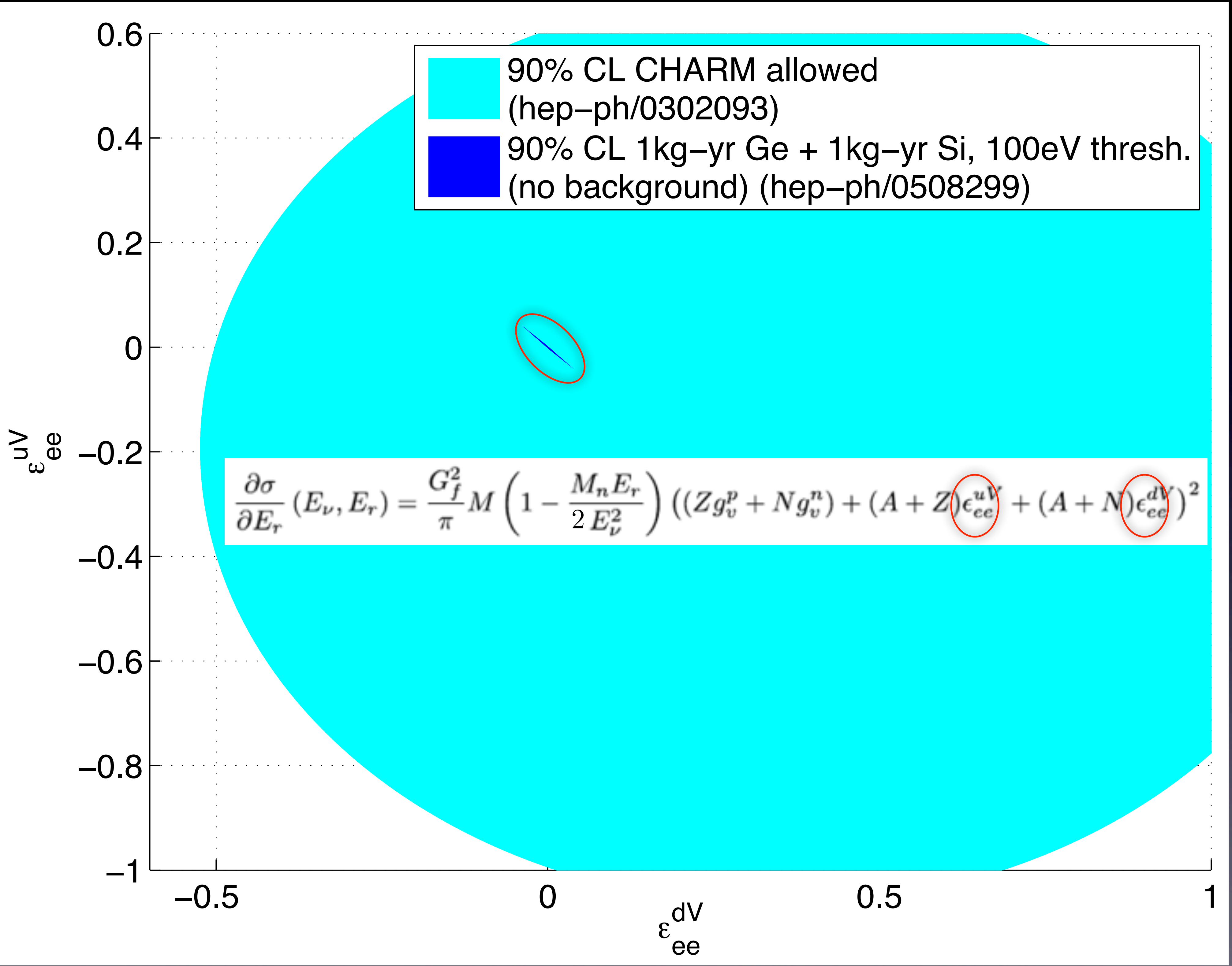

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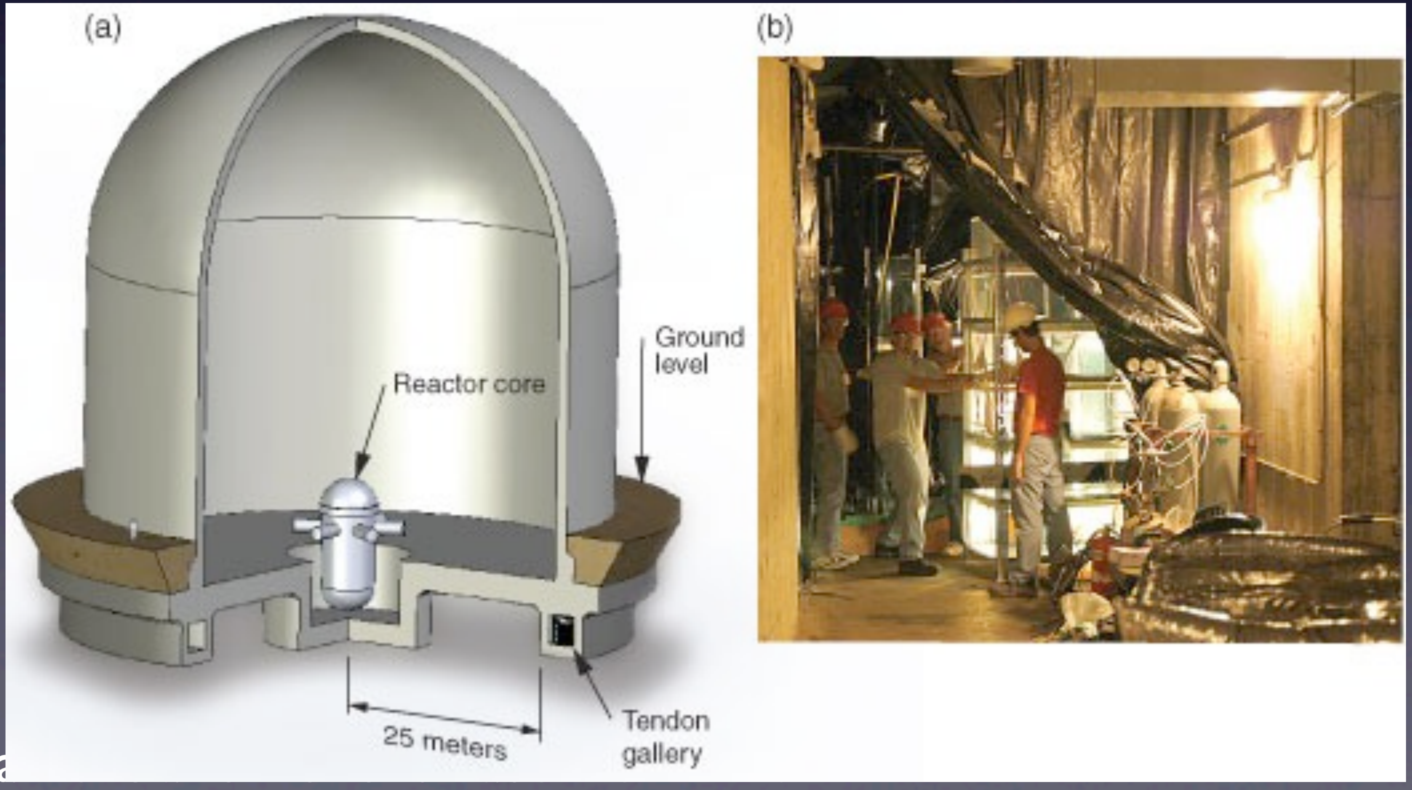
The Next Step: SONGS San Onofre Nuclear Generation Station: Precision CNS Measurements



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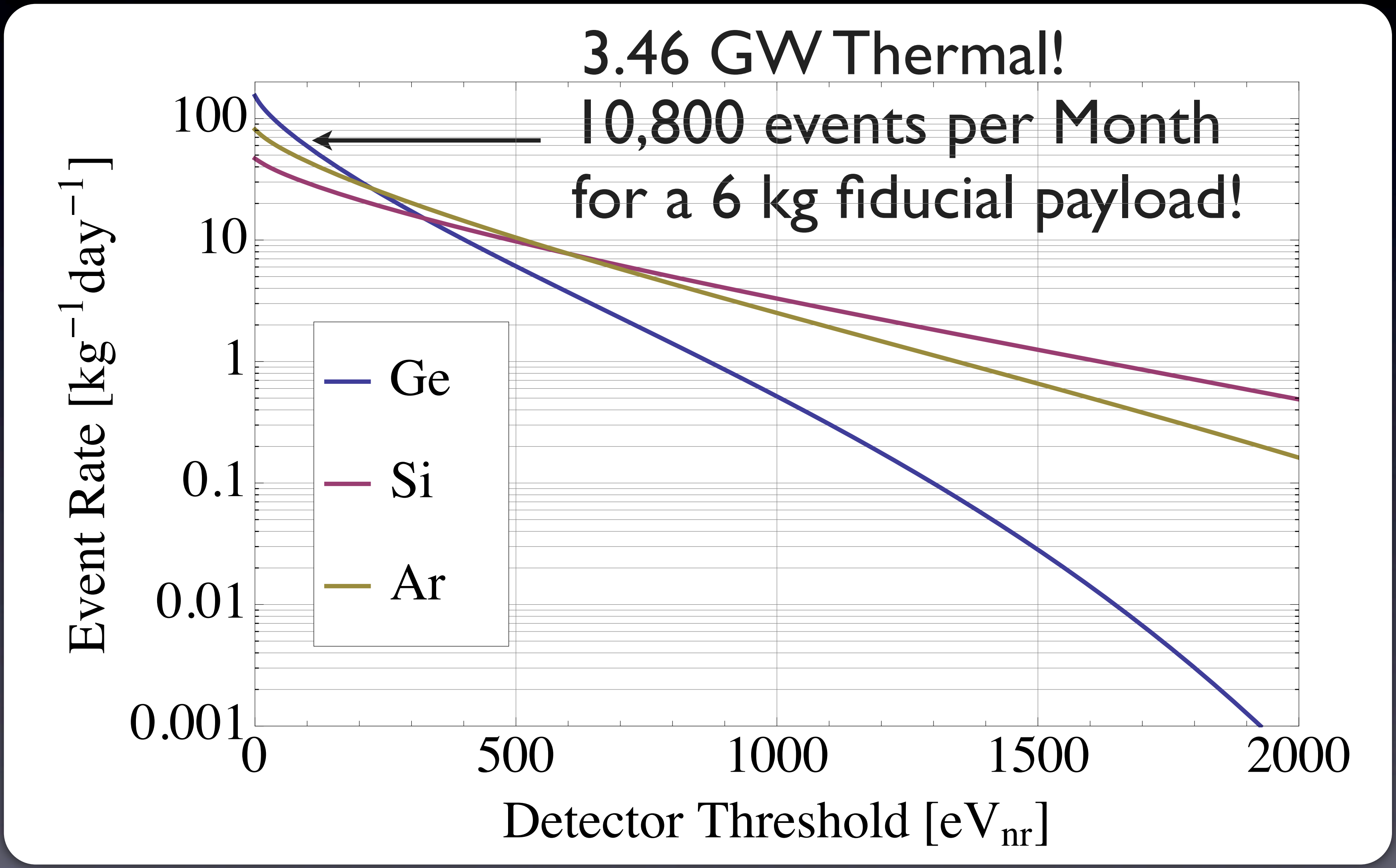
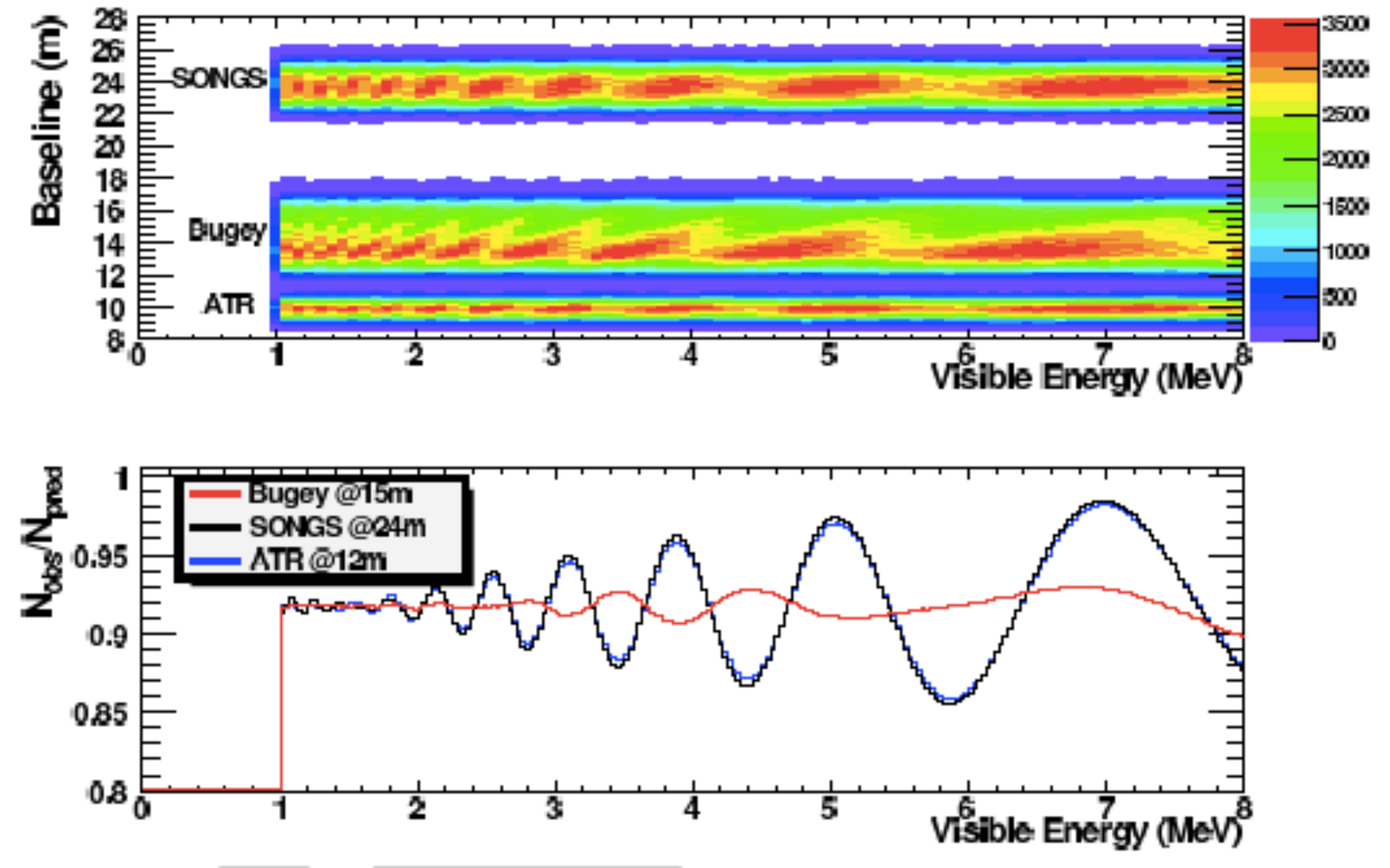


CNS Sterile Search at Reactors?

- At SONGS, the size of the core is on the order of the oscillation length --- need to model this!
- At MIT, the reactor is small, but the rate at the detector is 16 times less than at SONGS ($1/r^2$ helps) --- larger detector? near/far detectors?

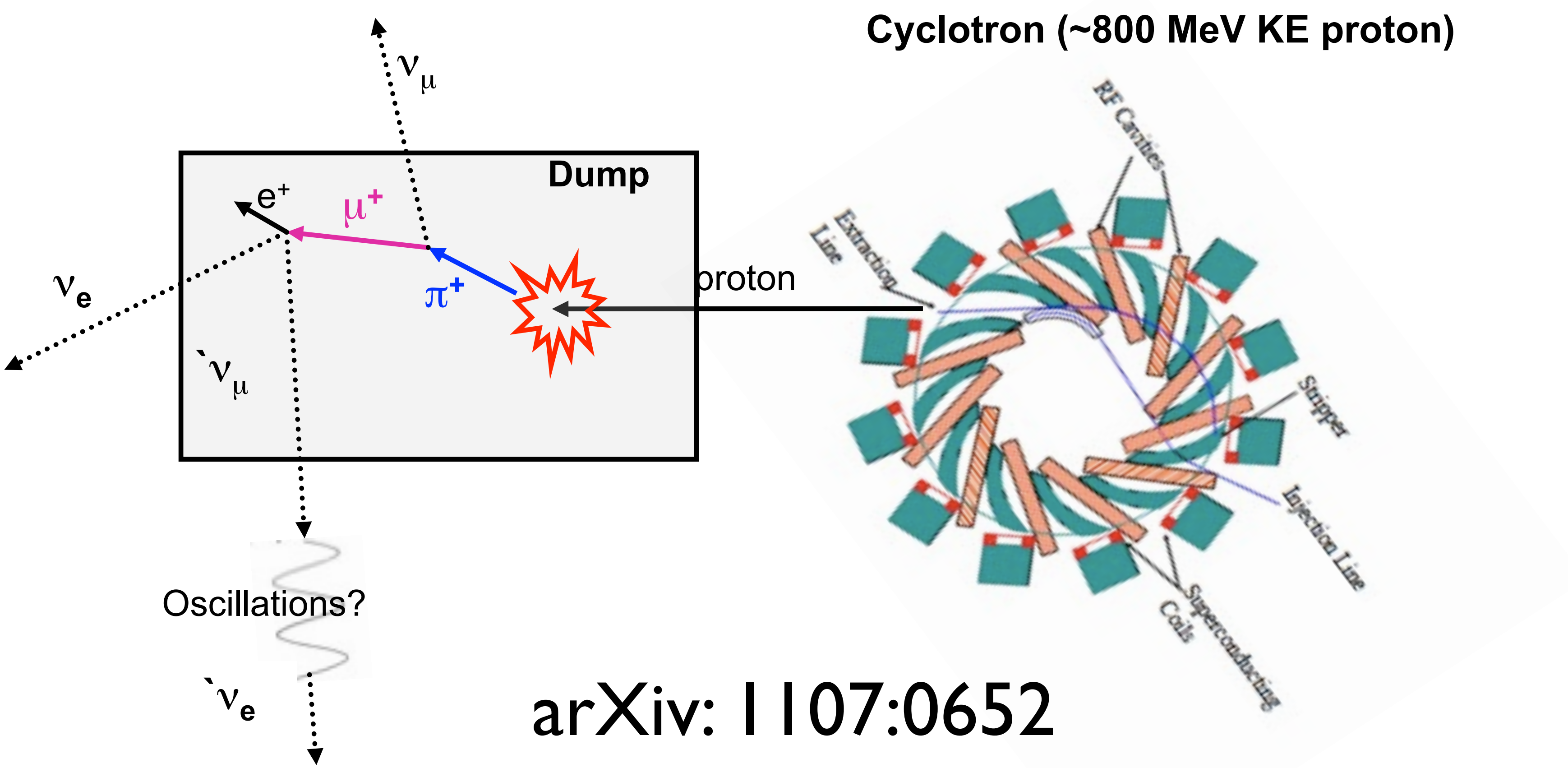
On the other hand...

- Stolen from the SCRAAM section of the sterile ν white paper (LLNL)



Ricochet @ DAR

A Different ν Source: DAR (DAEδALUS or other)



arXiv: 1107:0652

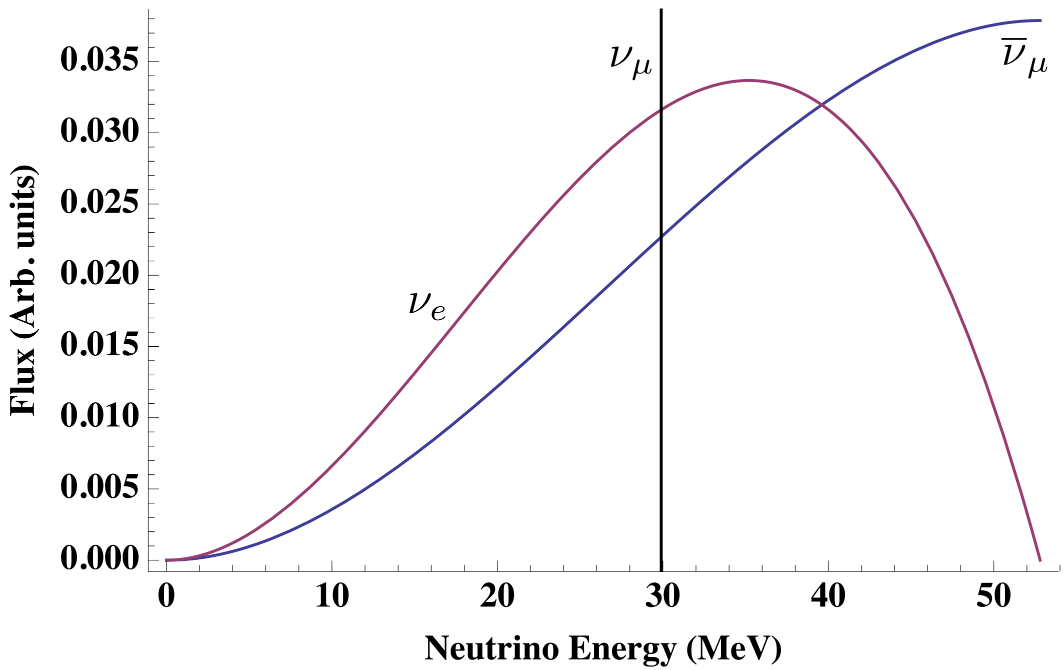
Jose Alonso: 148-High Power, High Energy Cyclotrons for Decay-At-Rest Neutrino Sources: The DAEdALUS Project

Decay-At-Rest Source

- 800 MeV proton beams
  - Produces pions at low velocity
- π^+ stopped, decay
  - (π^- absorbed)

- $\pi^+ \rightarrow \mu^+ \nu_\mu$

  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$



- NO electron anti-neutrinos
  - $\bar{\nu}_e$ contribution (π^- decay) is insignificant: $<10^{-2}\%$

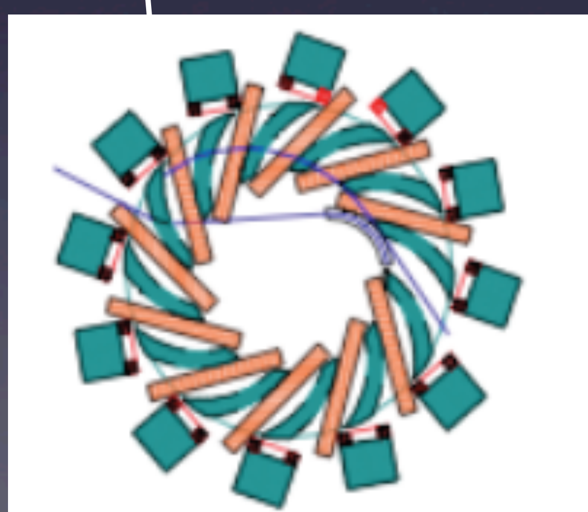
Total Flux: $3\ 10^{15}\ \nu/s$

DAEδALUS

Look For Oscillations at 10's of Meters

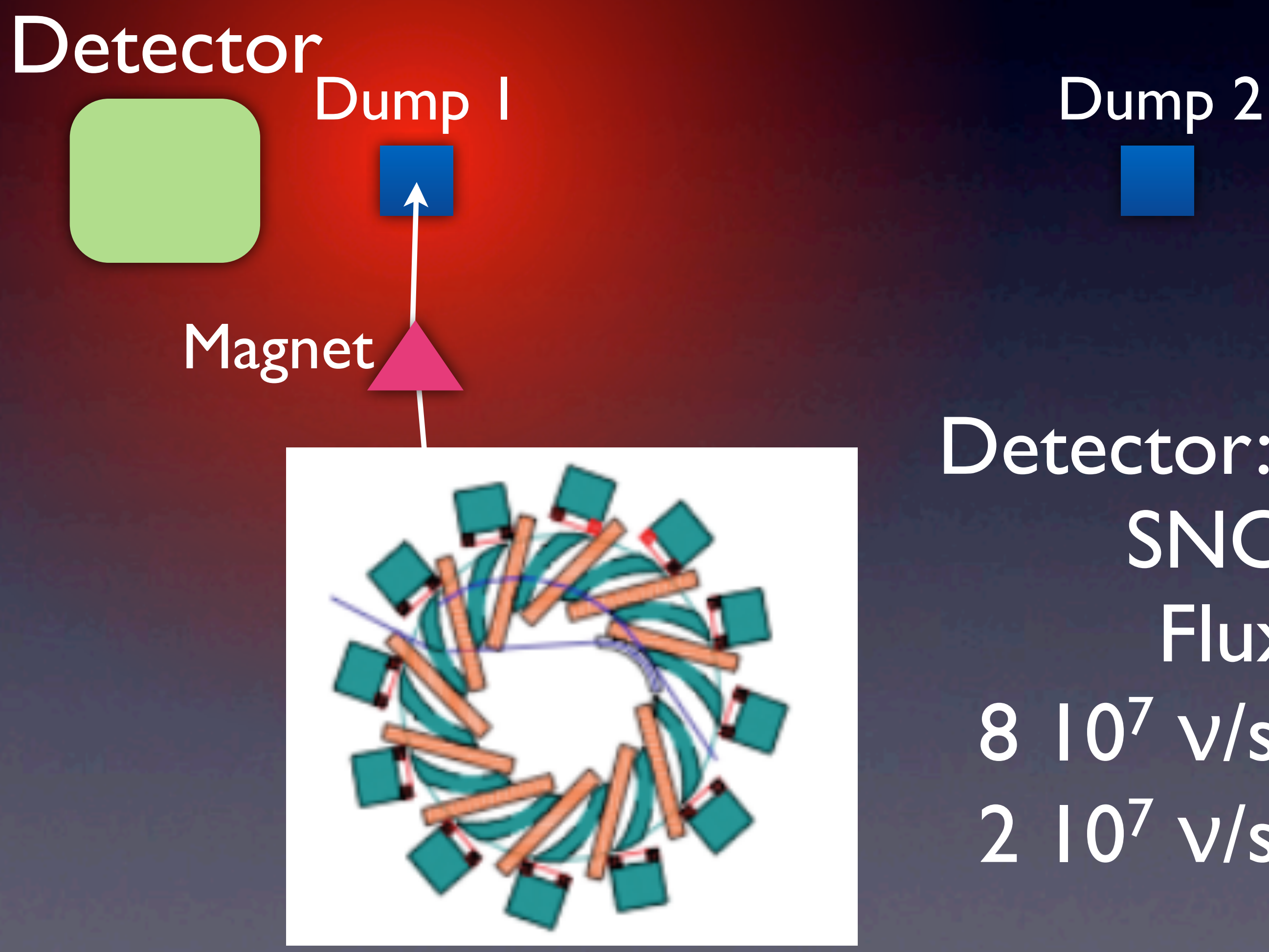
- At E_ν = 40 MeV, with Δm^2 = 1 eV^2, L ~ 40 meters
- Realize multiple baselines by having multiple dumps
- Detection through coherent scattering
  arXiv: 1103.4894

Multiple Dumps, Multiple Baselines



Detector: 100 kg SuperCDMS
SNOLAB duplicate
Flux at Detector:
8 10^7 ν/s/cm^2 from Dump 1
2 10^7 ν/s/cm^2 from Dump 2

Multiple Dumps, Multiple Baselines



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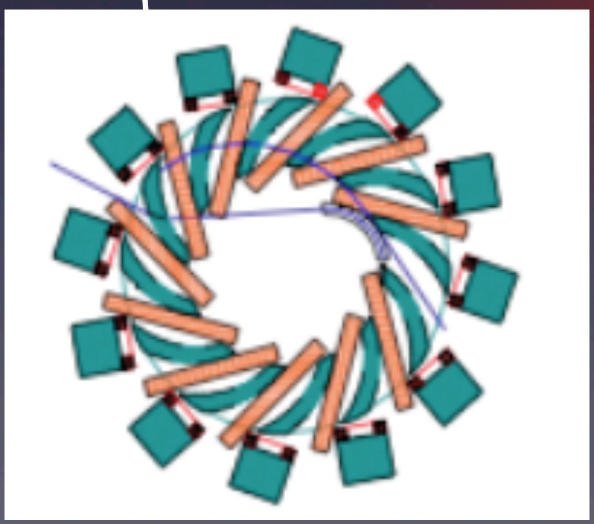

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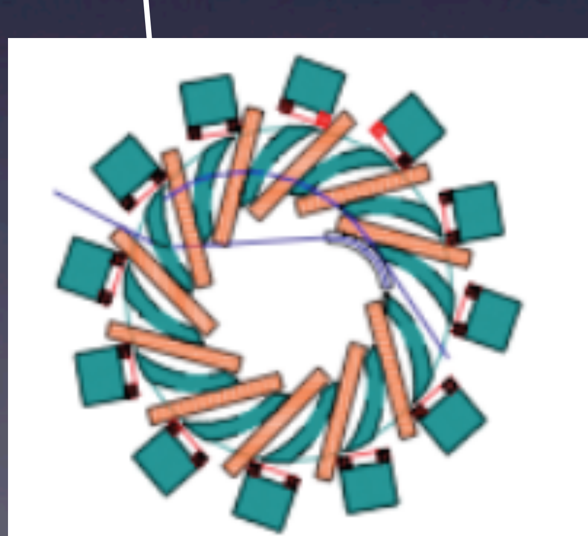

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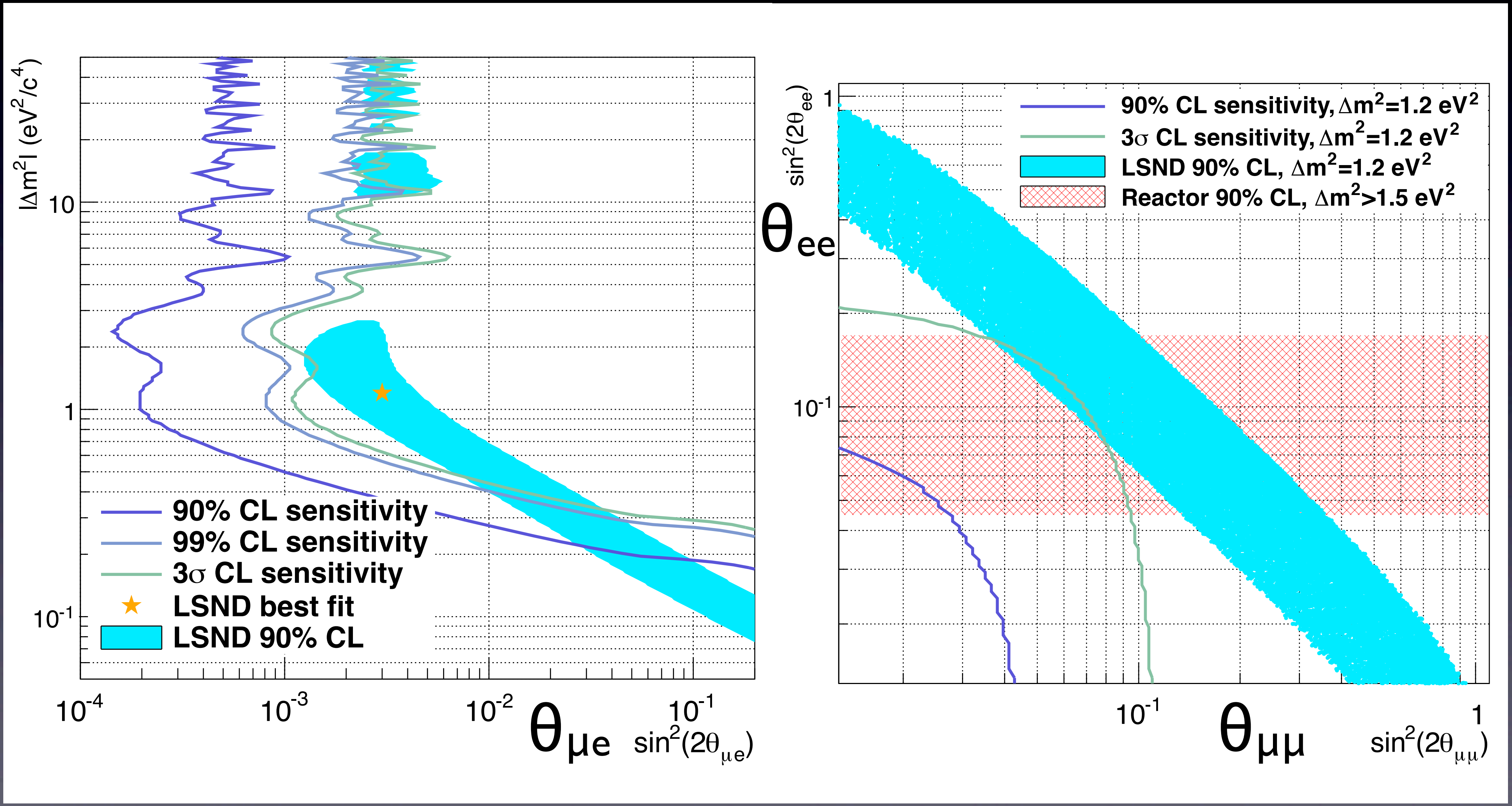
Sensitivity

5 years, 100 kg Ge detector



Ricochet Underground

The ~ MeV ν Source

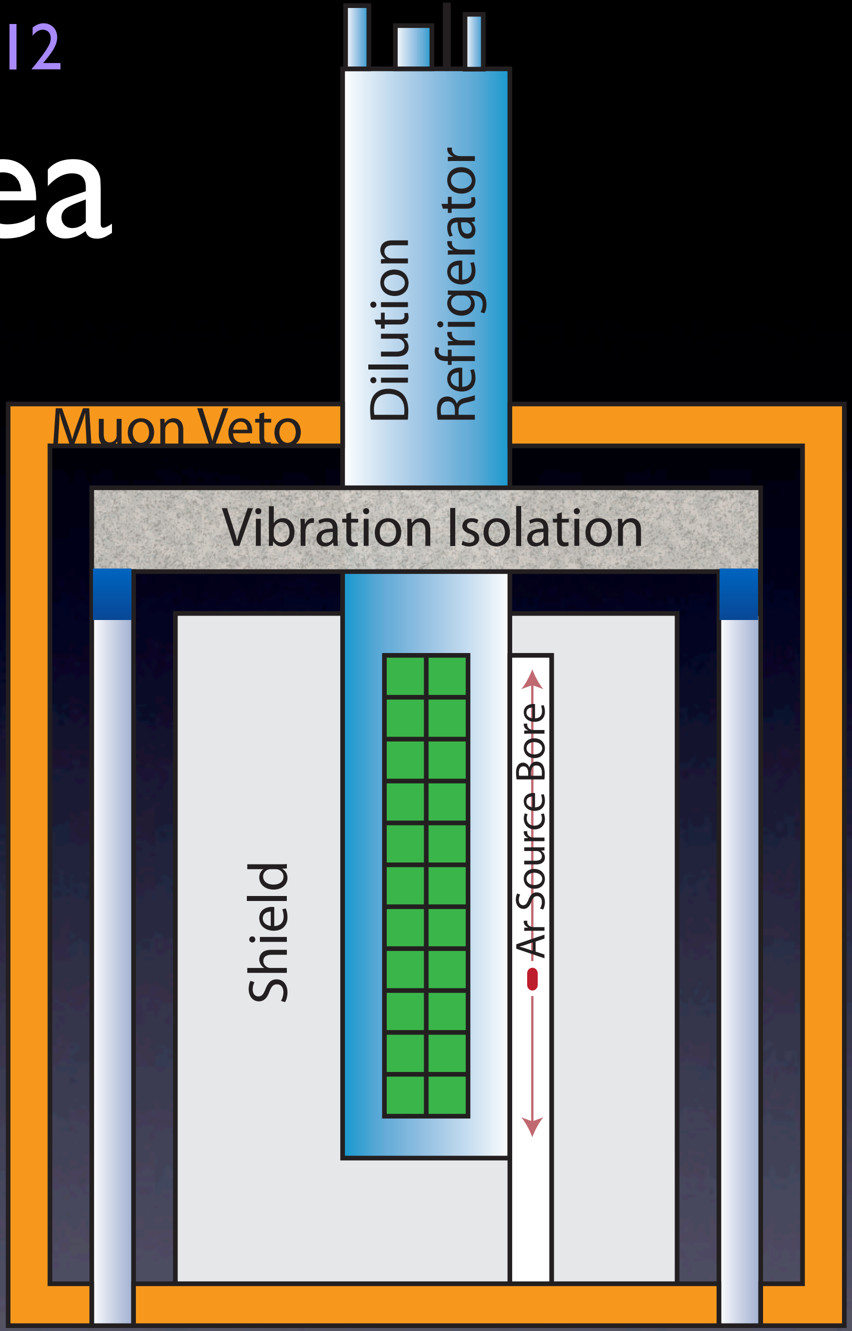
- ^{37}Ar 5 MCi Source, 811 and 813 keV ν_e
- Not available at Walmart… made from ^{40}Ca at a fast neutron reactor E_n > 2 MeV
- 30.5 day half life
- Produces only ν_e and internal bremsstrahlung photons
- Size ~ 10 cm

Phy. Rev. C 73, 045805 (2006)

J. Formaggio, EFF, A. Anderson arXiv:1107.3512

The Idea

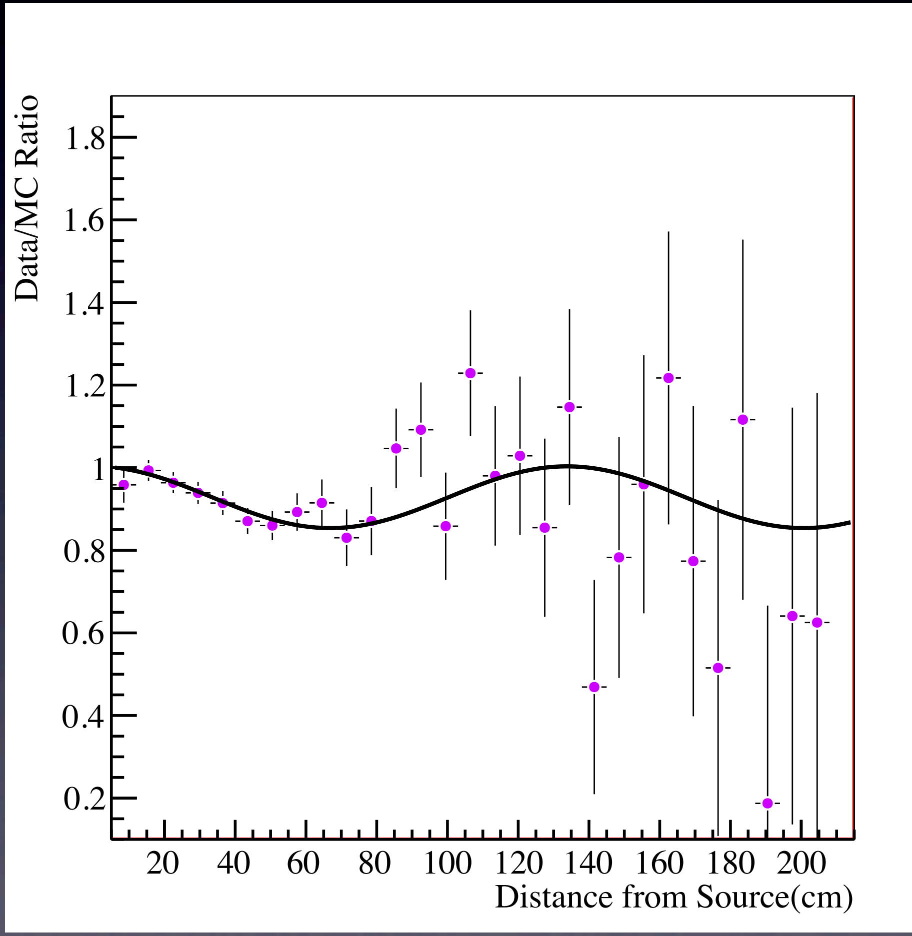
- Direct oscillometry measurement
- 500 kg of detector
- 10,000 50g pixels (use mm-astronomy-derived readout)
- For $\Delta m^2 = 1\ eV^2$, $E_\nu = 1$ MeV would have an oscillation scale of L~1 meter.
- Same mass an size scale as CUORE



$$P_{osc}(\nu_a \rightarrow \nu_b) = \sin^2(2\theta)\ \sin^2\left(\frac{1}{4\hbar c}\Delta m^2 \frac{L}{E}\right)$$

The Signal

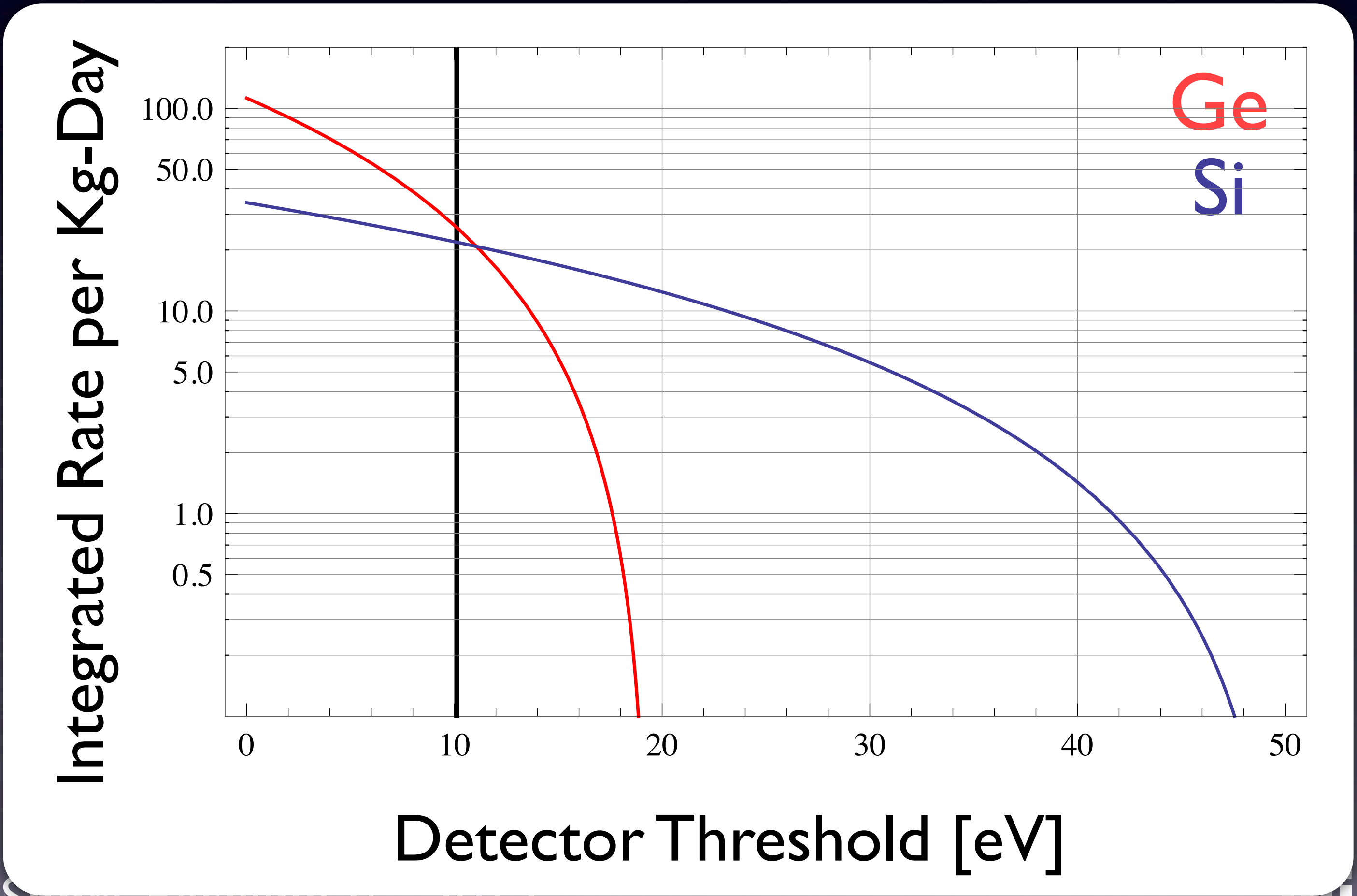
- The rate in each pixel will go as $1/r^2$
- Look for Oscillations in Rate on top of the $1/r^2$ term
- If you see these oscillations through coherent scattering, they are oscillations into a sterile neutrino!



We need a very LOW threshold!

Rate for a 5 MCi ^{37}Ar source 20 cm away from target

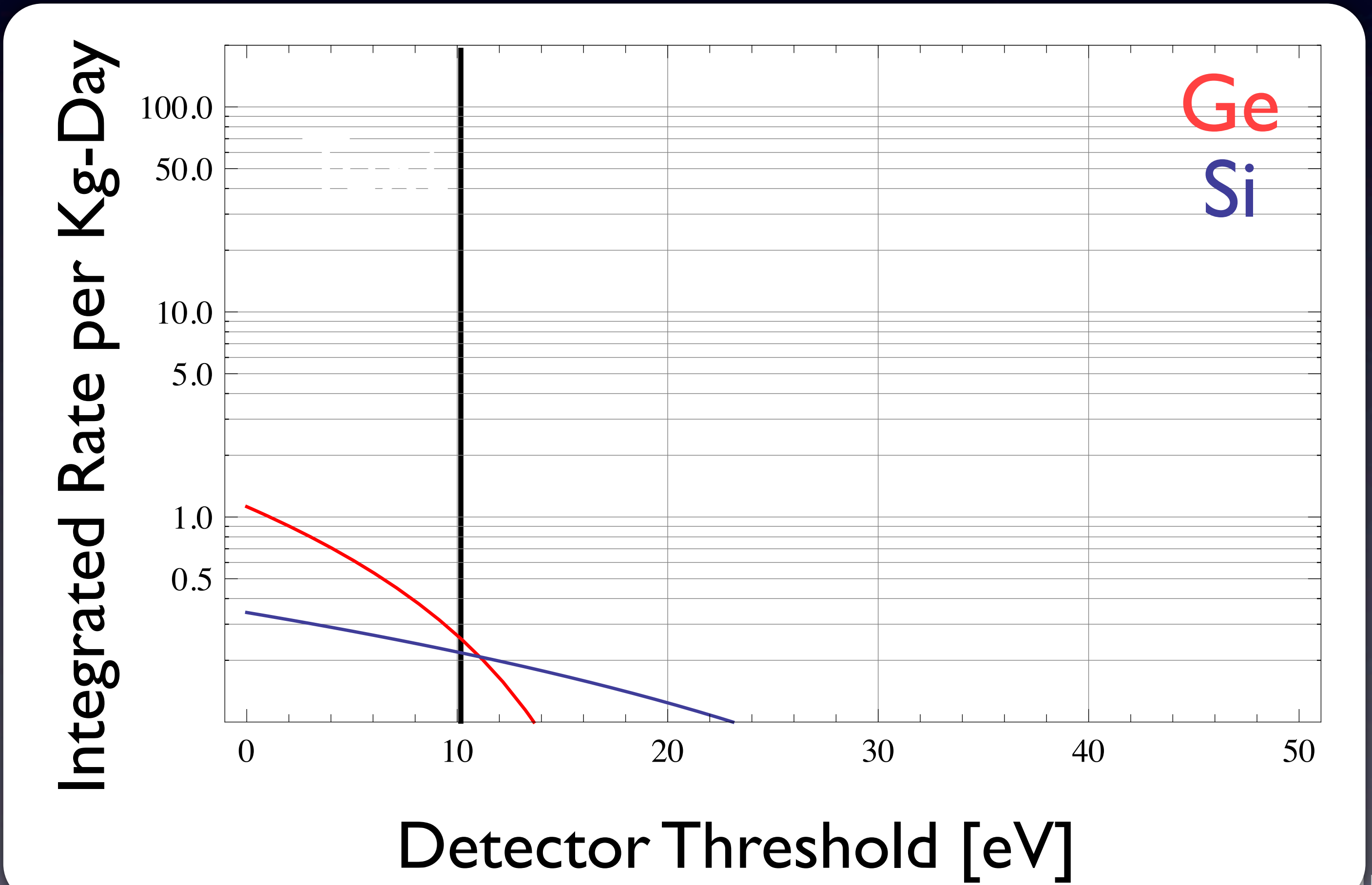
600 events/kg total given the 30 day half life (at 20 cm)



To measure oscillations we need a fairly large mass!

Rate for a 5 MCi ^{37}Ar source <u>2 m</u> away from target

6 events/kg total given the 30 day half life (at 2 m)



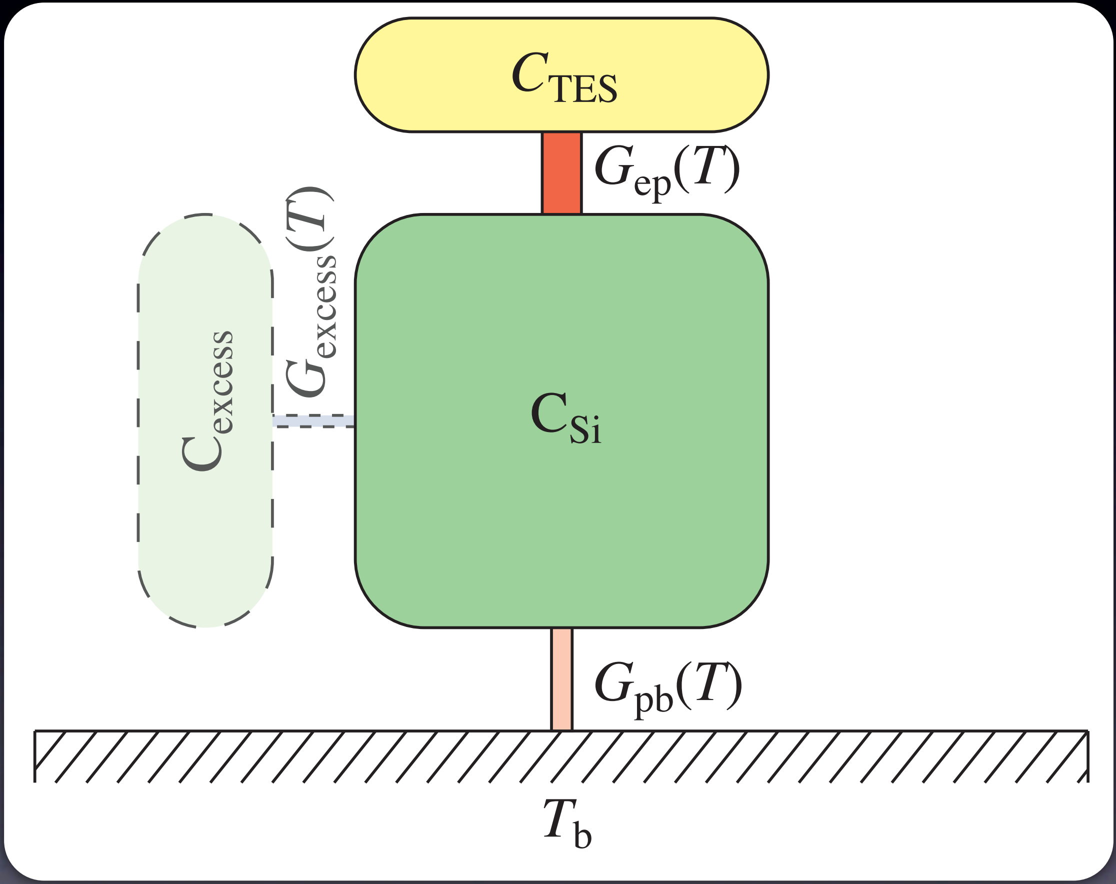
Calorimeters to the rescue!

- Need very good resolution to have a low threshold (~3 eV FWHM for 10 eV threshold)
- Want hundreds of kilograms of mass
- X-ray microcalorimeter pixel mass ~ μg!
- Need thousand-fold increase in mass with the same energy resolution… hopeless?

Doable - at low temps!

Assumptions:

- Debye heat capacity for Si and Ge
- TES volume optimized at 15 mK ($C_{TES} \sim C_{abs}$)
- Engineer Conductance to Bath (Gpb) to fixed pulse decay time to 50 ms



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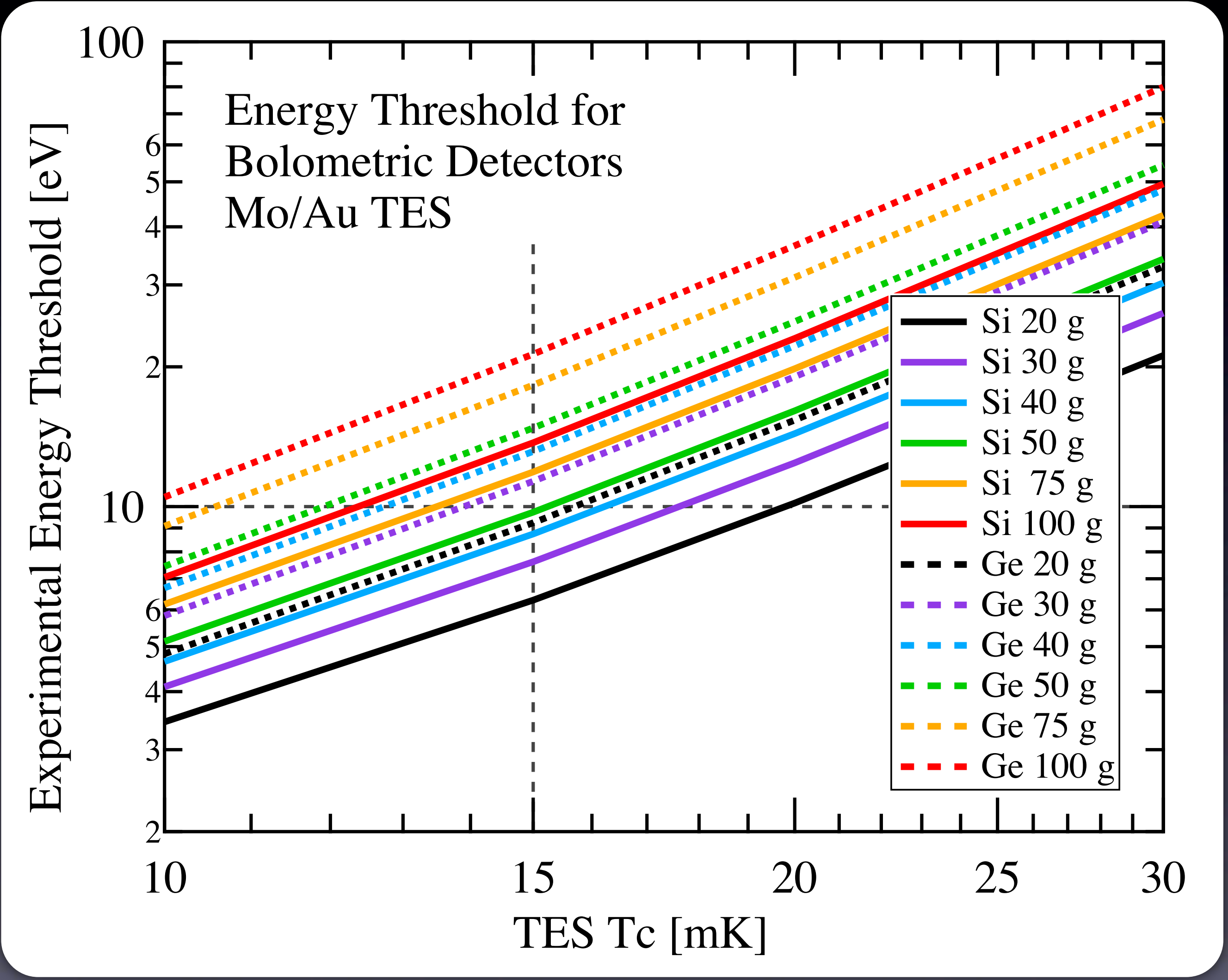

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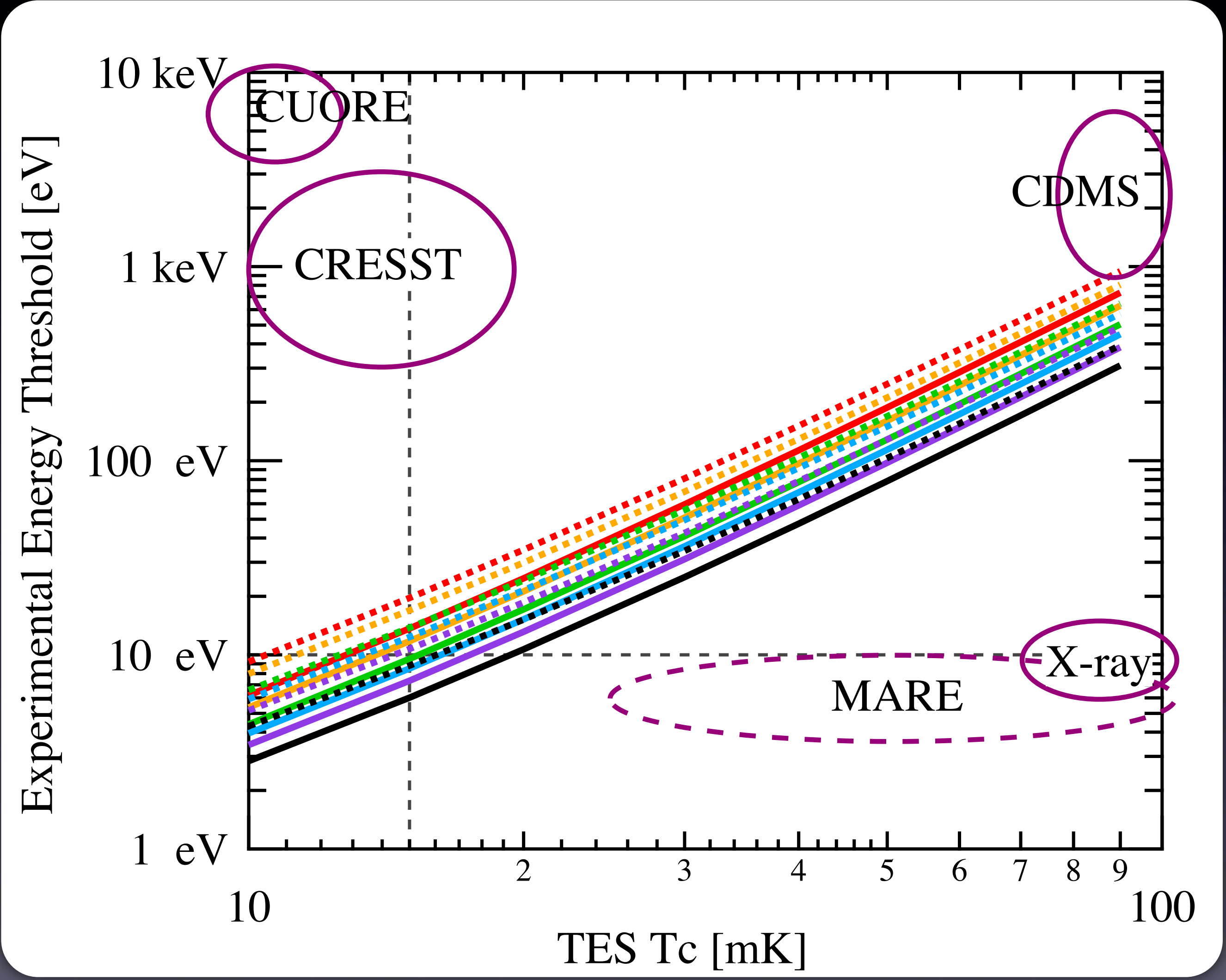
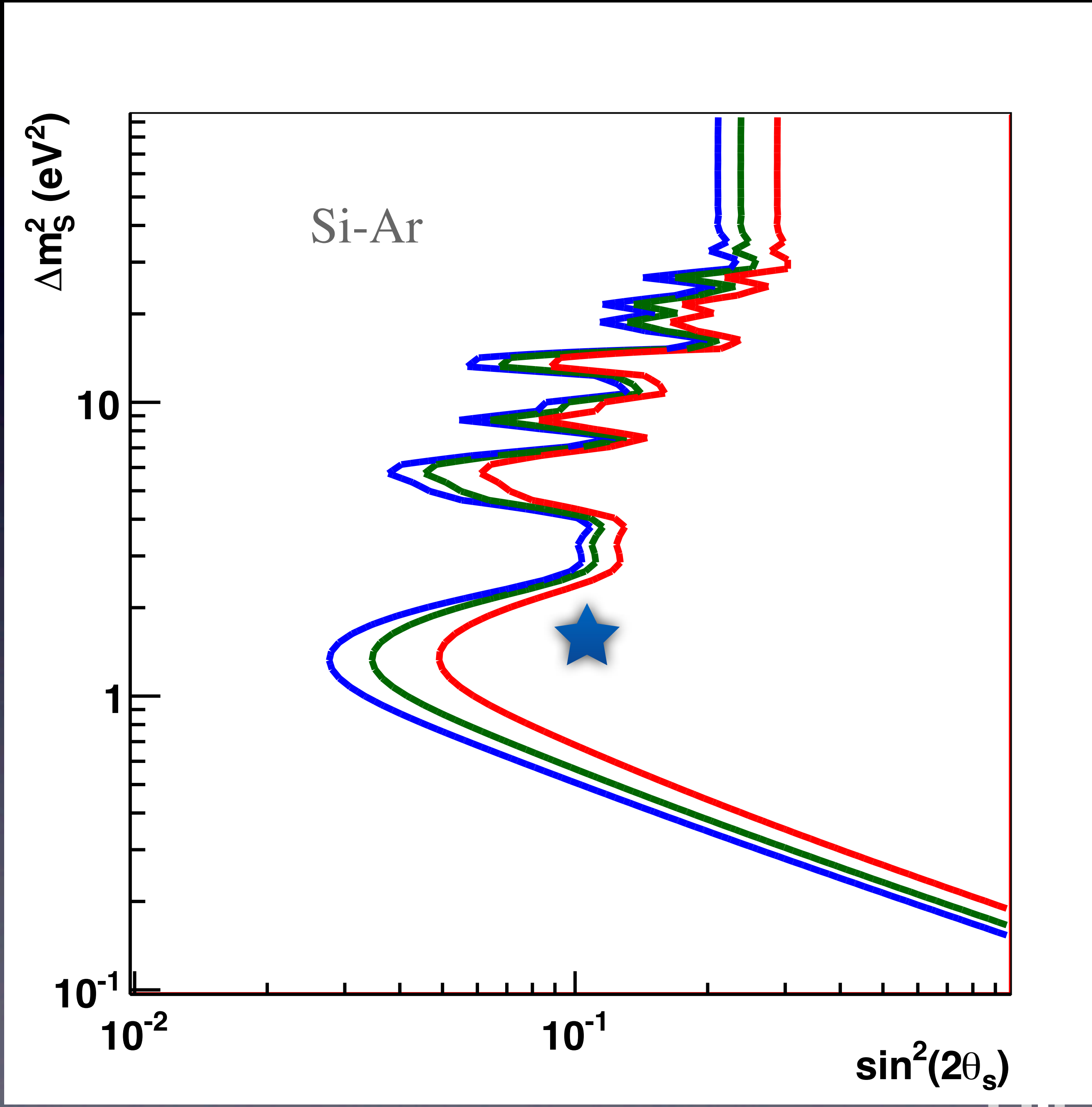
- TES volume optimized at 15 mK ($C_{TES} \sim C_{abs}$)
- Engineer Conductance to Bath (Gpb) to fixed pulse decay time to 50 ms



Sensitivity

- 10 eV threshold
- 500 kg target
- 5 MCi ^{37}Ar source
- Background:
  1 event/kg/day in
  10 - 50 eV region
  of interest

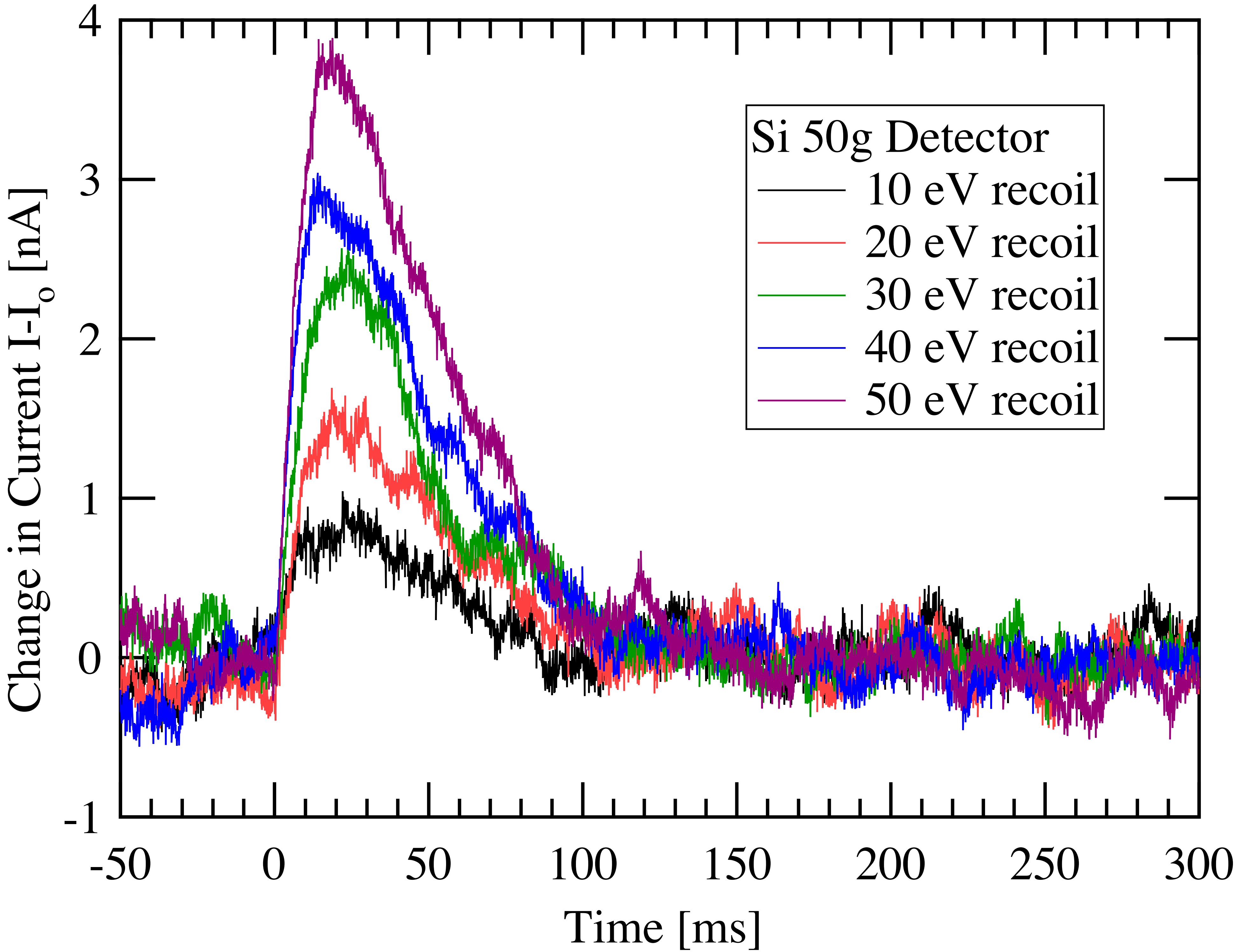


Conclusions

- CNS is a completely new channel to search for physics beyond the standard model
- It is a complimentary approach to other Sterile Search proposals.
- Several options with different neutrino sources are possible.
- Cryogenic detectors can achieve the low thresholds and high energy resolution required for precision measurements of CNS.
- Exciting possibilities for the future!

arxiv:1107.3512, 1202.3805

Backup Slides



Si 50g Detector
10 eV recoil
20 eV recoil
30 eV recoil
40 eV recoil
50 eV recoil
Change in Current $I-I_o$ [nA]
Time [ms]
4
3
2
1
0
-1
-50
0
50
100
150
200
250
300

Design Issues...

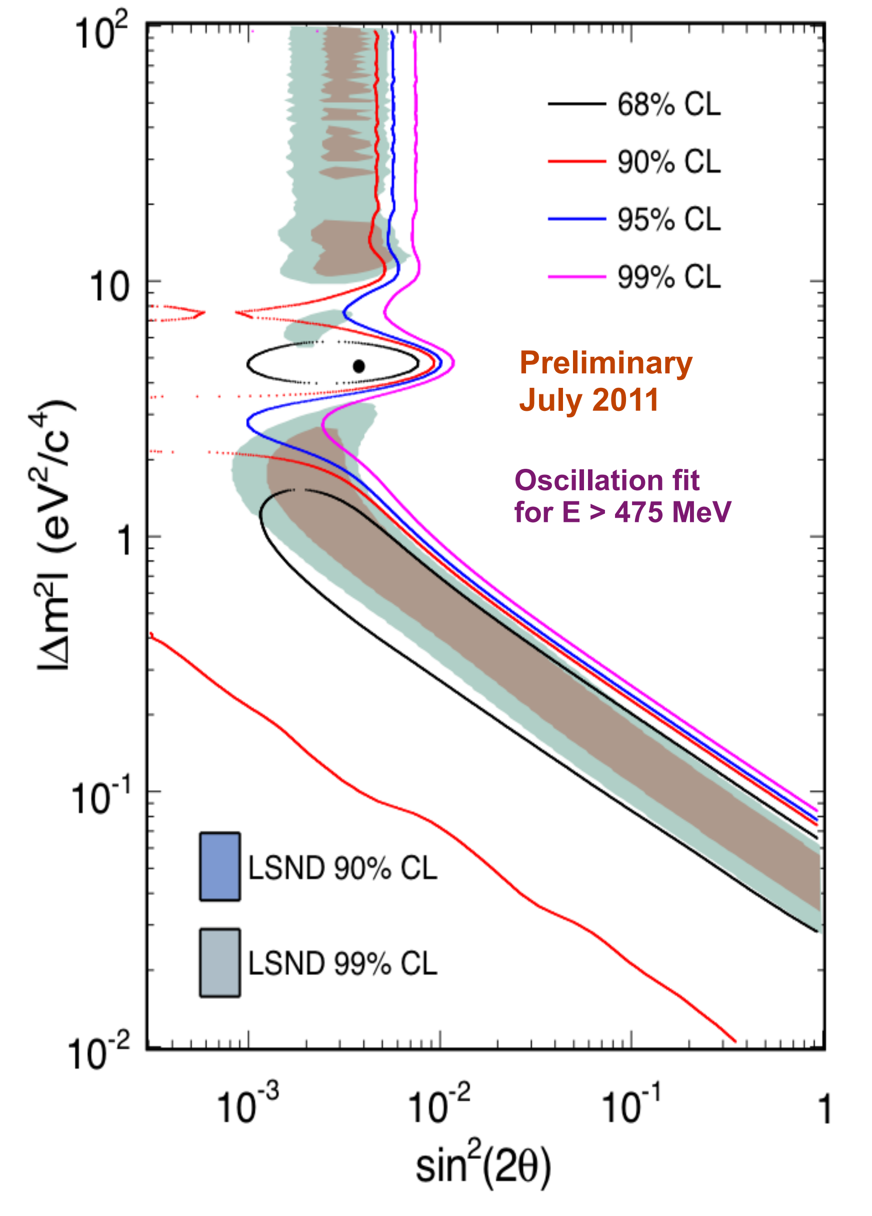
- With 50 g detectors a 10,000 SQUID MUX would yield 500 kg.
  - 50 ms fall times makes SQUID MUX "straightforward"
- Can one get Debye Heat Capacity at 15 mK?
  - No measurements below 50 mK!
  - TLS, surface states, impurity bands…
- Can one get α=50 at 15 mK?
- What is the background at 10 eV? (we assume a very conservative 1 event/kg/day in the 10-50 eV band)
- Can one do this with athermal detectors? (we think so…)

TABLE II: Model parameters for a 50 g Si target coupled to a Mo/Au TES operated at 15 mK. The Si target is a 28 mm cube, and the TES is an 25 mm × 2 mm film 600 nm thick deposited on the Si surface. The energy resolution for this model is 3 eV FWHM, with a 10 eV threshold. Pulses from this model are shown in Fig 4.

Parameter	Value	Units	Description
C_{Si}	43.3	pJ/K	Debye heat capacity
C_{TES}	31.1	pJ/K	TES electron heat capacity
G_{ep}	29.3	nW/K	TES-Si thermal conductance
G_{pb}	0.17	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	14.1	μA	Quiescent TES current
P_o	0.6	pW	Quiescent TES power
$\alpha = \frac{T_c}{R_o}\frac{dR}{dT}$	50	-	TES sensitivity
τ_{o}	436.2	ms	Natural decay time $C_{\mathrm{tot}}/G_{\mathrm{pb}}$
τ_{eff}	51.1	ms	Response time with TES speedup
τ_{decay}	29.2	ms	Decay time with readout circuit
L	30	μH	Readout inductance

LSND & MiniBooNE: Sterile ν?

- Evidence for oscillation from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ in both experiments
- MiniBooNE now favors oscillations at the 91.1 % confidence level
- LSND: E ~ 50 MeV, L ~ 30 m
- MB: E ~ 500 MeV, L ~ 450 m



Reactor + MiniBooNE Fits

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