Searching for Sterile Neutrinos with Low-Temperature Detectors

Enectali Figueroa-Feliciano
Massachusetts Institute of Technology

Searching for Sterile Neutrinos with Low-Temperature Detectors

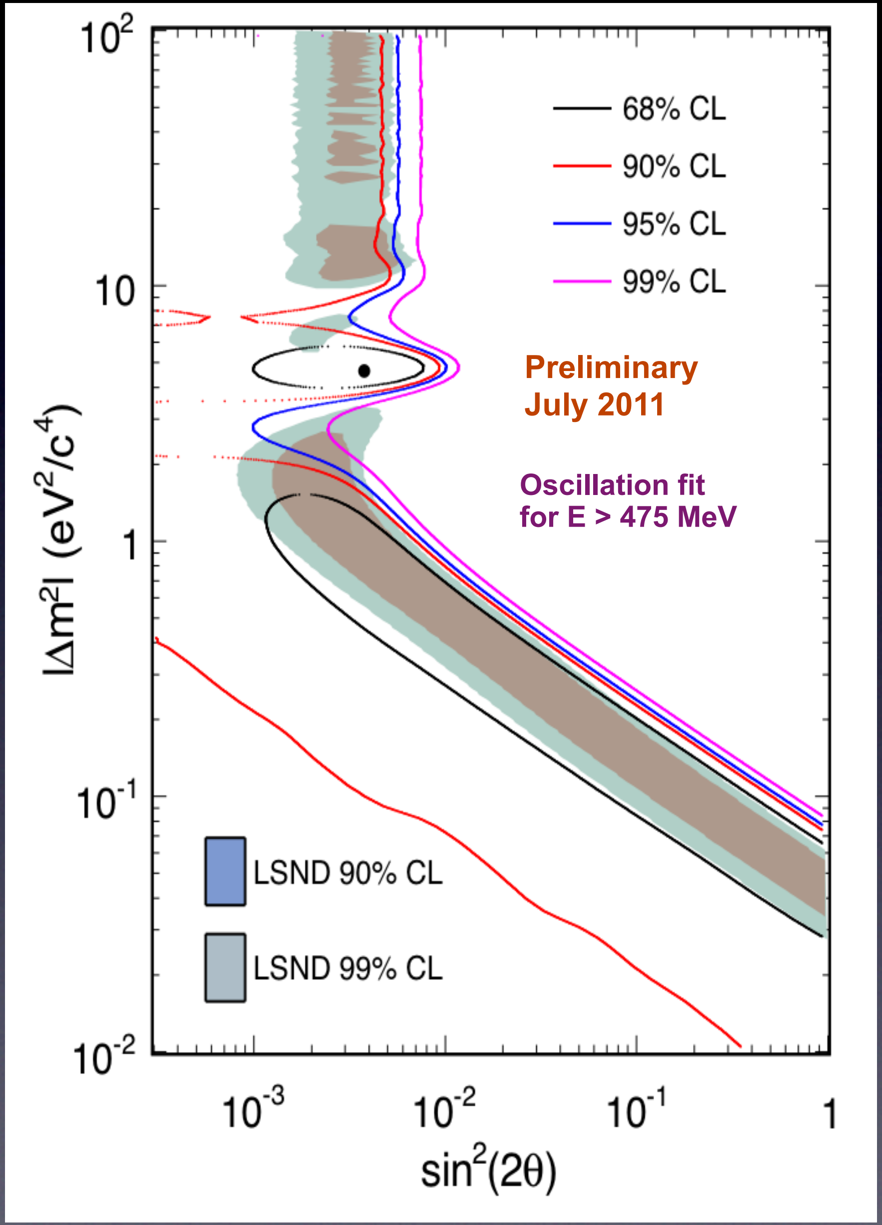
Enectali Figueroa-Feliciano
Massachusetts Institute of Technology

Overview

- Hints of Sterile Neutrinos
- Coherent Scattering of Neutrinos
- E_ν ~ 1 MeV Search for Sterile Neutrinos
- E_ν ~ 40 MeV Search for Sterile Neutrinos

LSND & MiniBooNE: Sterile ν?

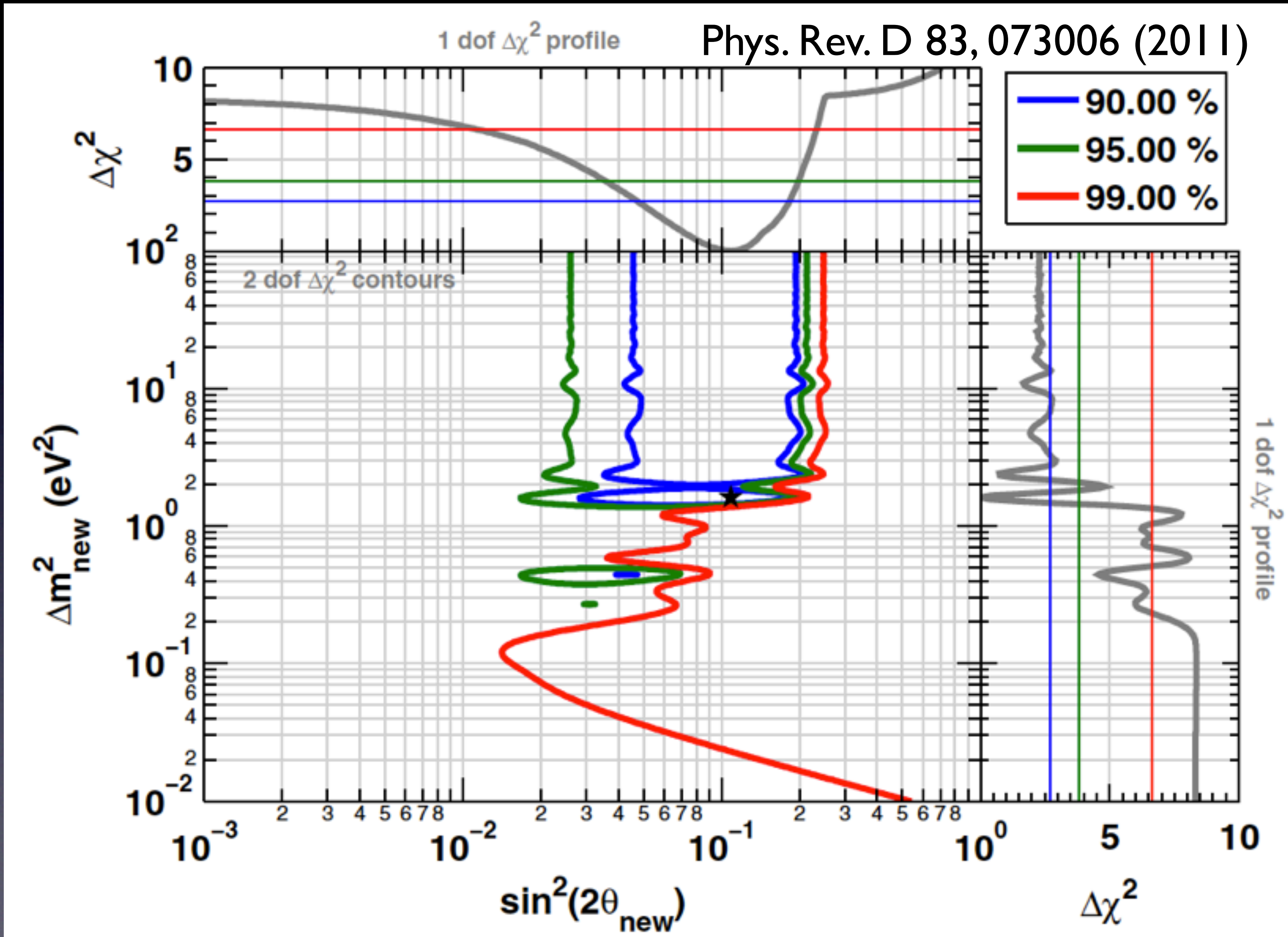
- Evidence for oscillation from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ in both experiments
- MiniBooNE now favors oscillations at the 91.1 % confidence level
- LSND: E_ν ~ 50 MeV, L ~ 30 m
- MB: E_ν ~ 500 MeV, L ~ 450 m



Other Data *Consistent* with Sterile ν

- MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ yes; $\nu_\mu \to \nu_e$ no...
  - 97.6% CL Phys. Rev. Lett. 102, 101802 (2009)
- Reactor antineutrino anomaly
  - Phys. Rev. D 83, 073006 (2011)
- Combined Reactor and Oscillation Data Fits
  - arXiv:1103.4570
- Fits From Cosmological Data
  - PRL 105, 181301 (2010)

Reactor + MiniBooNE Fits



Coherent ν Scattering

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_W^2 M \left(1 - \frac{M E_r}{2E_\nu^2}\right) F(E_r^2)^2$$

- σ: Cross Section
- E_r: Recoil Energy
- E_ν: Neutrino Energy
- G_F: Fermi Constant
- Q_W: Weak Charge
- M: Nuclear Atomic Mass
- F: Form Factor

No flavor-specific terms!!!

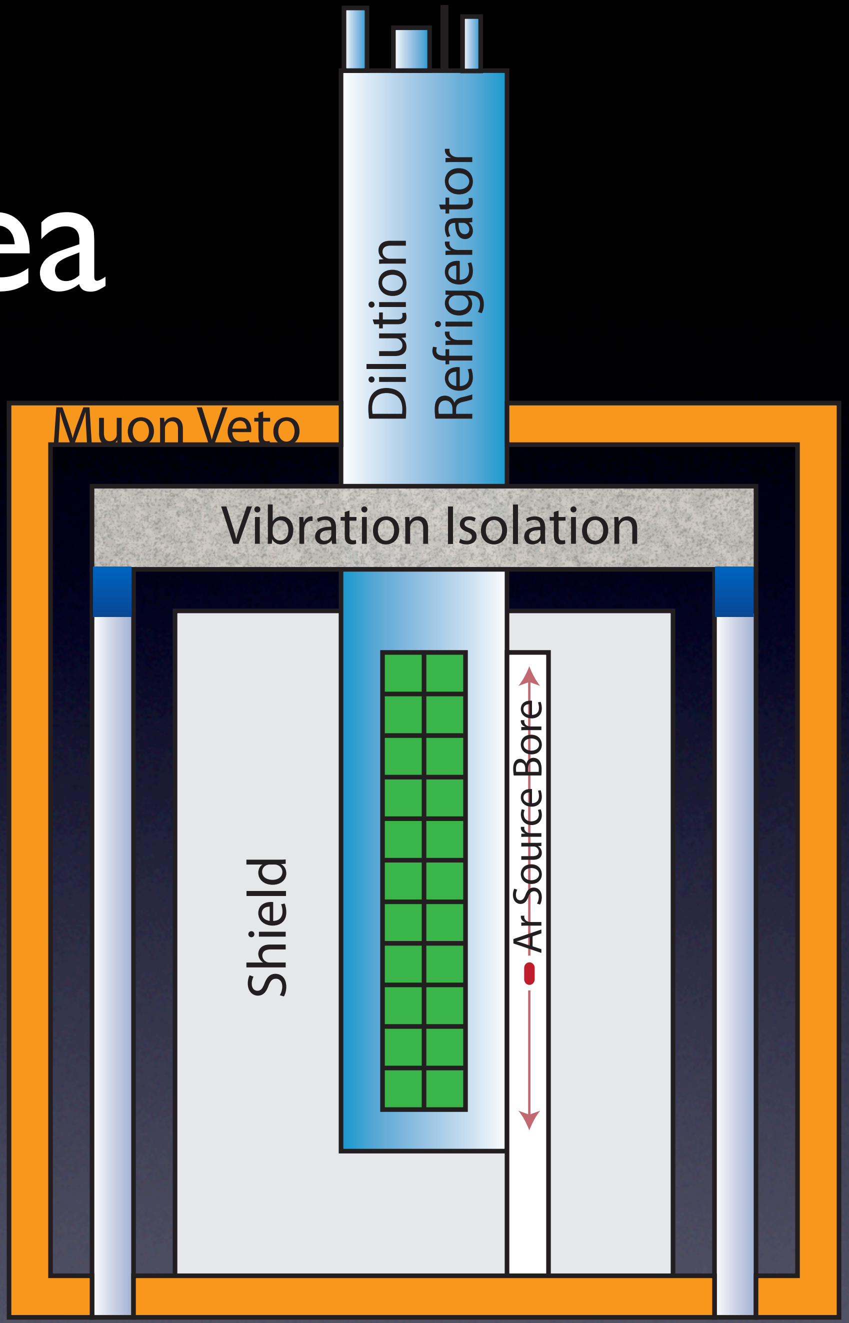
Same rate for ν_e, ν_μ, and ν_τ

Overview

- Hints of Sterile Neutrinos
- Coherent Scattering of Neutrinos
- E_ν ~ 1 MeV Search for Sterile Neutrinos
- E_ν ~ 40 MeV Search for Sterile Neutrinos

The Idea

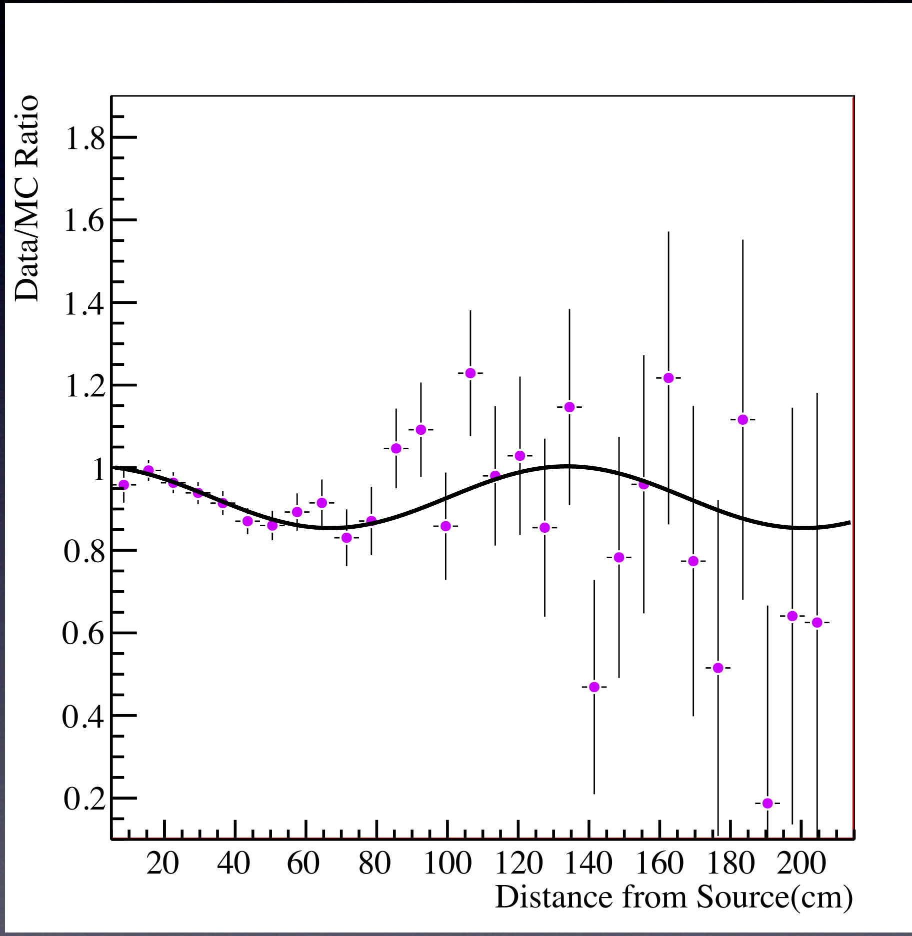
- Detect oscillation as a function of distance in an array of detectors through coherent scattering
- For the LSND signal of $\Delta m^2 = 1\ eV^2$, L/E = 0.6, a neutrino $E_\nu = 1$ MeV would have an oscillation scale of L~1 meter.



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

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!



The ~ MeV ν Source

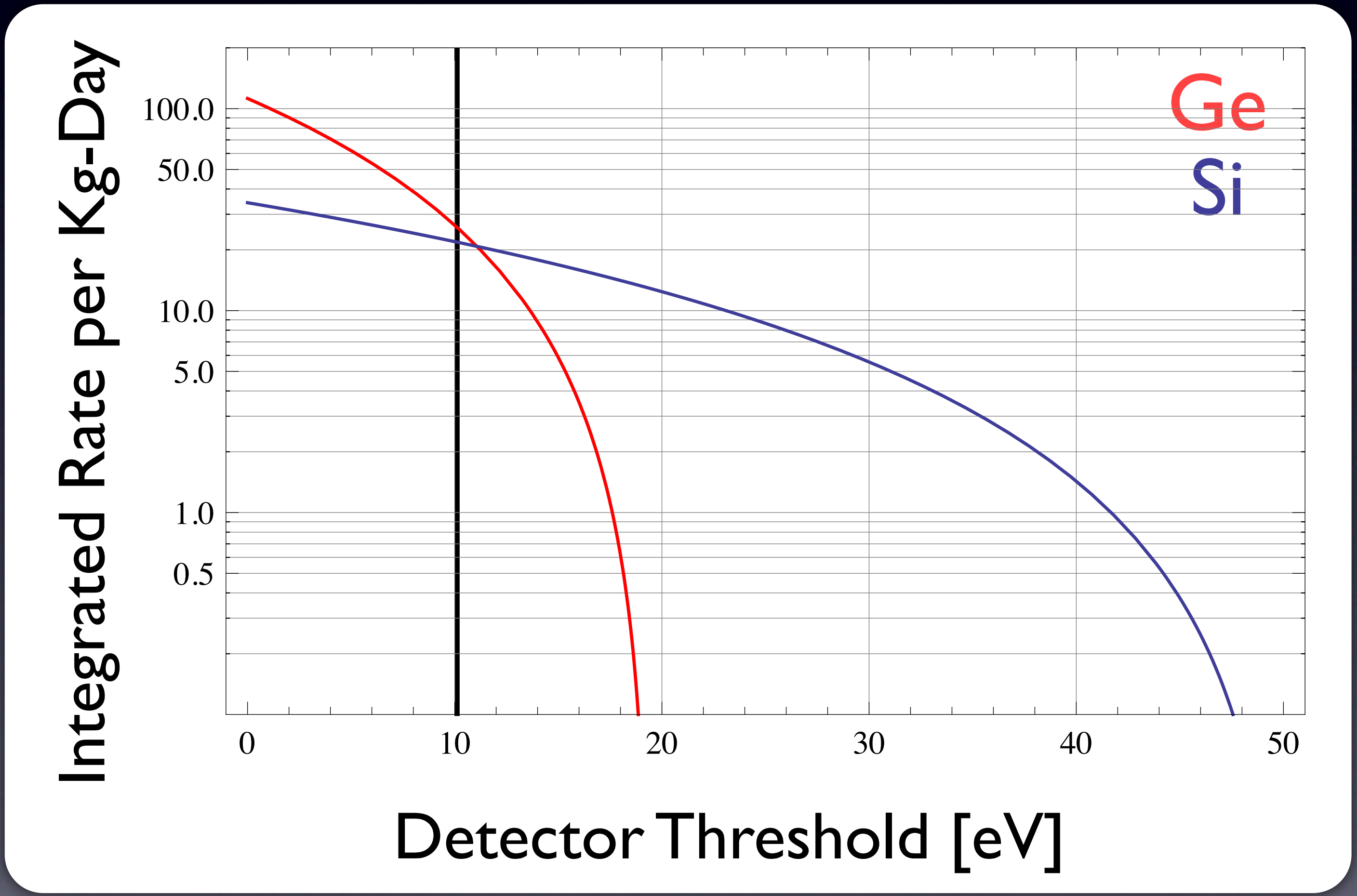
- ^{37}Ar 5 MCi Source, 811 and 813 keV ν_e
- Not available at Walmart… made from ^{40}Ca at a fast neutron reactor E_n > 2 MeV
- 30.5 day half life
- Produces only ν_e and internal bremsstrahlung photons
- Size ~ 10 cm

Phy. Rev. C 73, 045805 (2006)

We need a very LOW threshold!

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

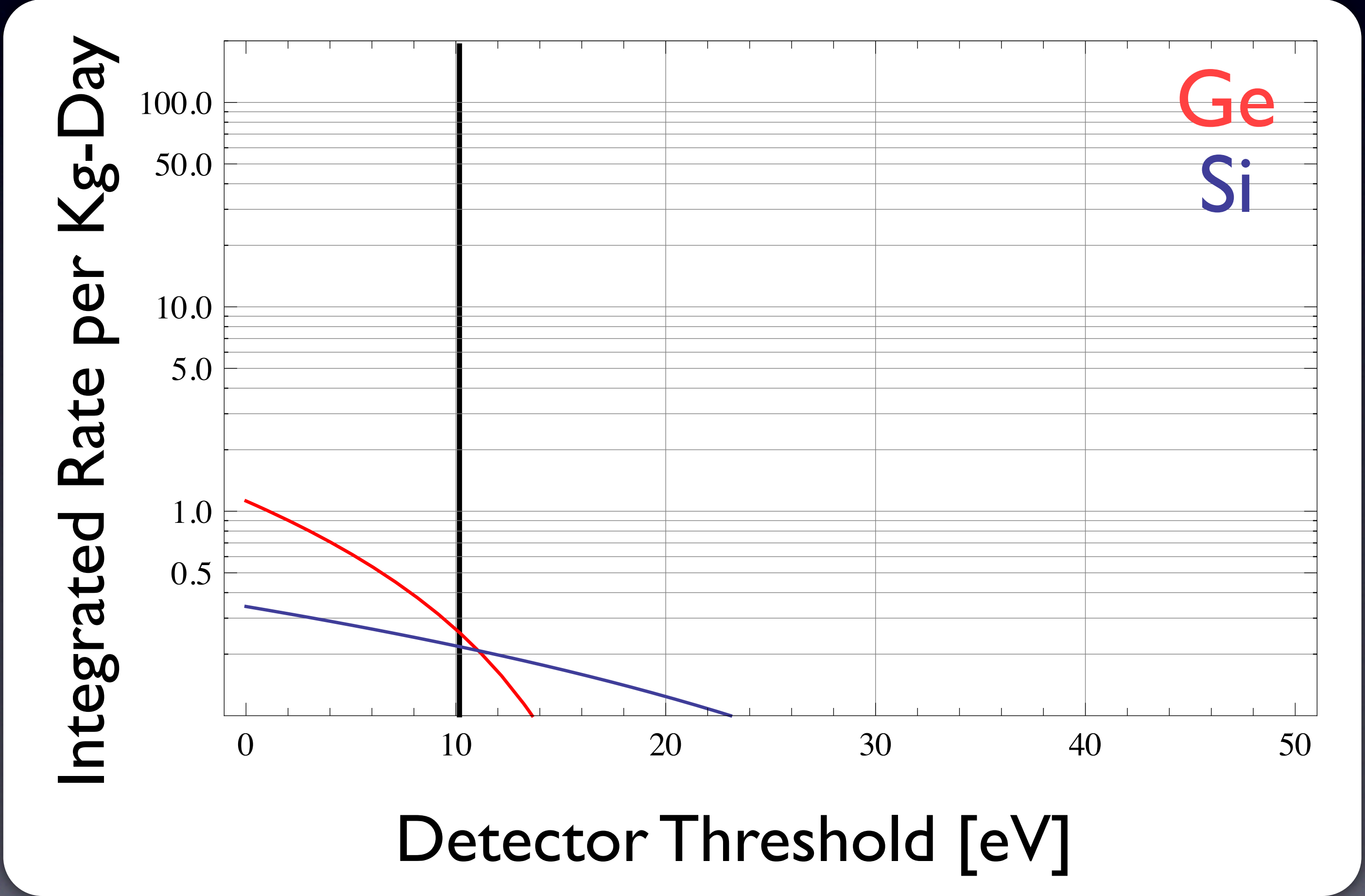
600 events/kg total given the 30 day half life (at 20 cm)



To measure oscillations we need a fairly large mass!

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

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



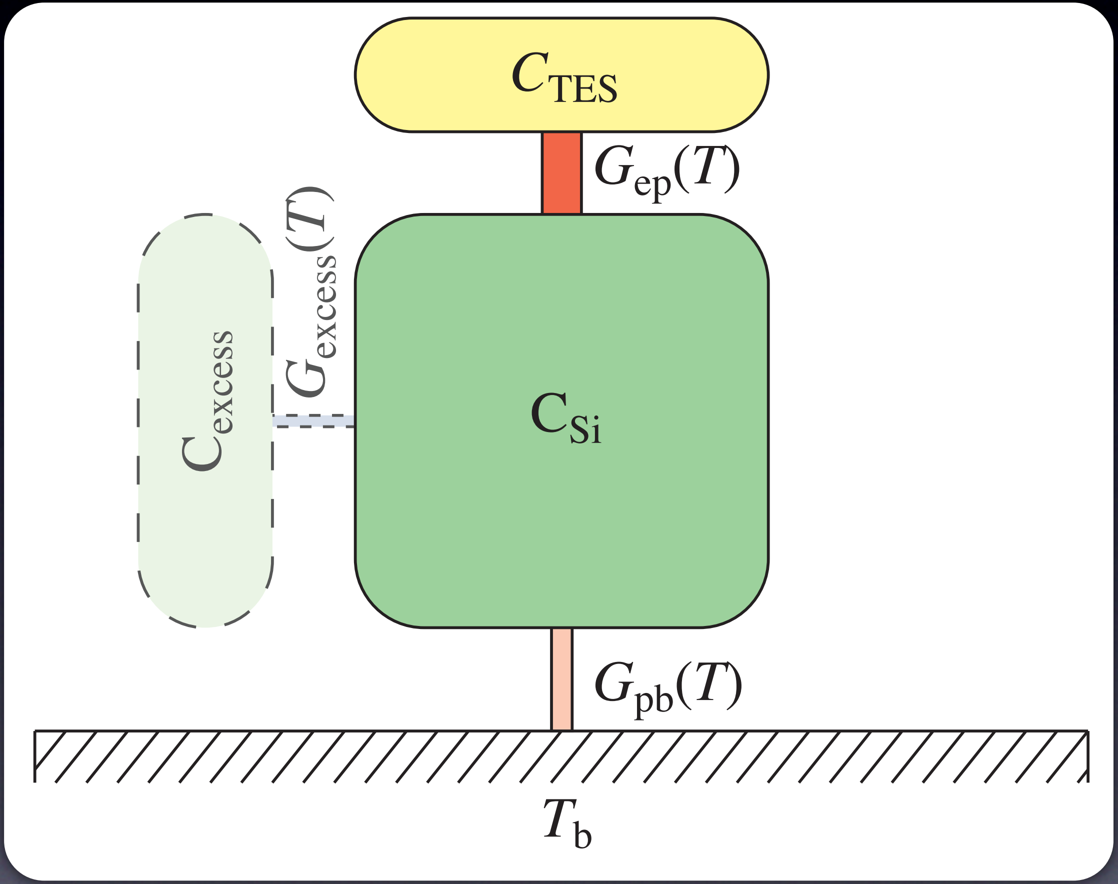
Bolometers to the rescue?

- 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:

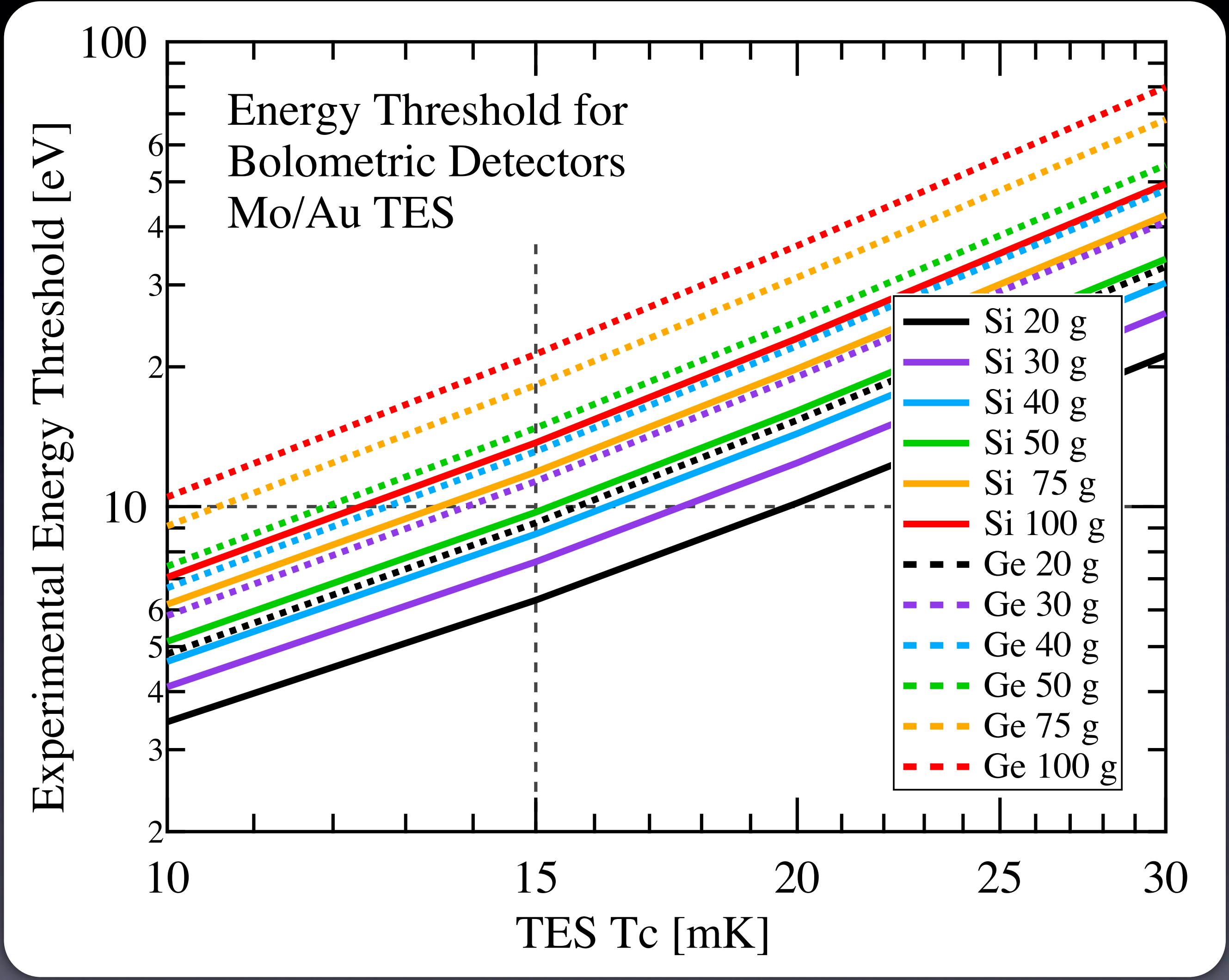
- Debye heat capacity for Si and Ge
- TES volume optimized at 15 mK (C_{TES} ~ C_{abs})
    - $\tau_o \sim 10\ \tau_{ETF}$
    - Si temp = TES temp
- Fixed pulse decay time to 50 ms



Doable - at low temps!

Assumptions:

- Debye heat capacity for Si and Ge
- TES volume optimized at 15 mK ($C_{TES} \sim C_{abs}$)
  - $\tau_o \sim 10\ \tau_{ETF}$
  - Si temp = TES temp
- Fixed pulse decay time to 50 ms

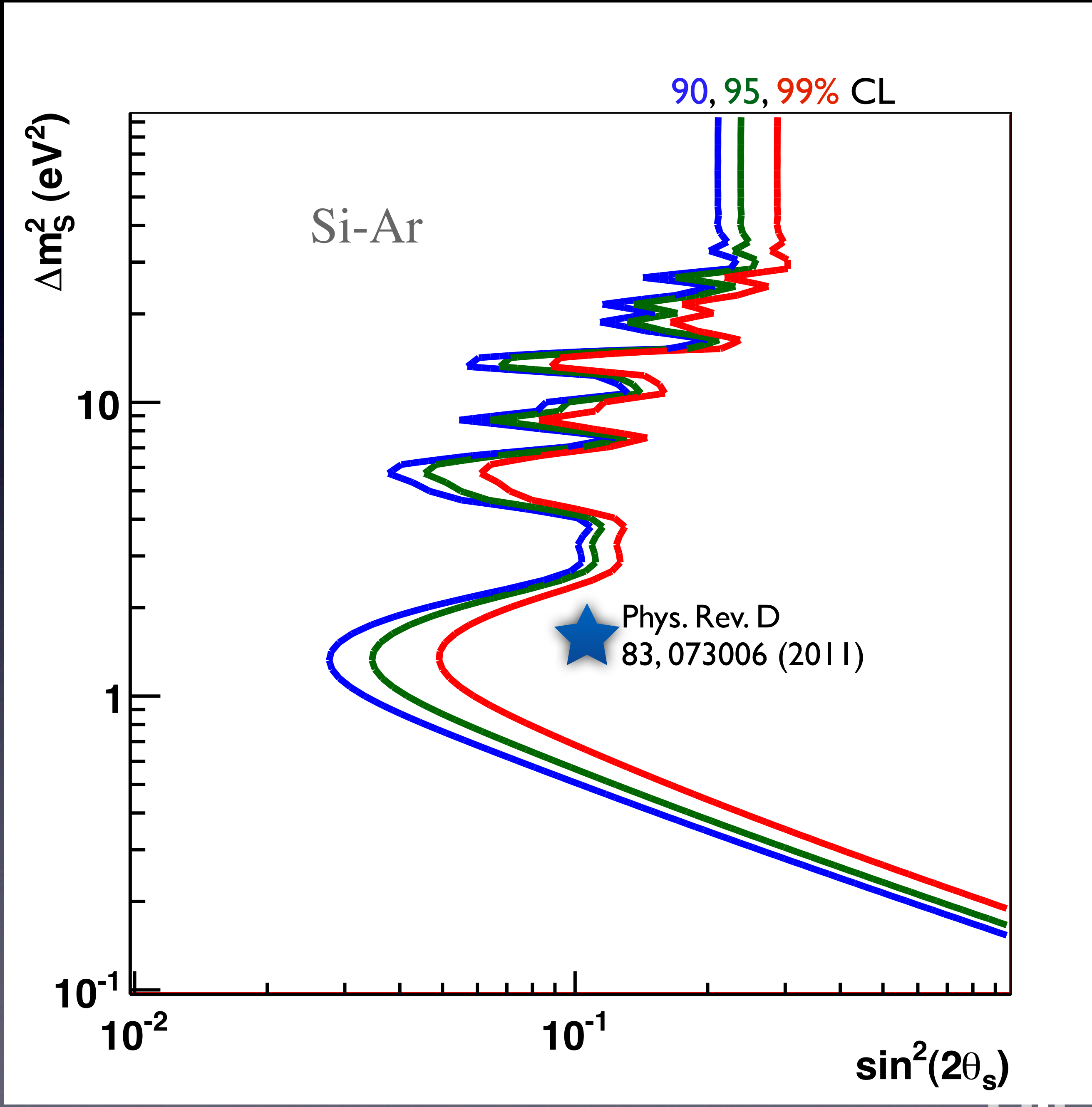


Design Issues...

- 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…)

Sensitivity

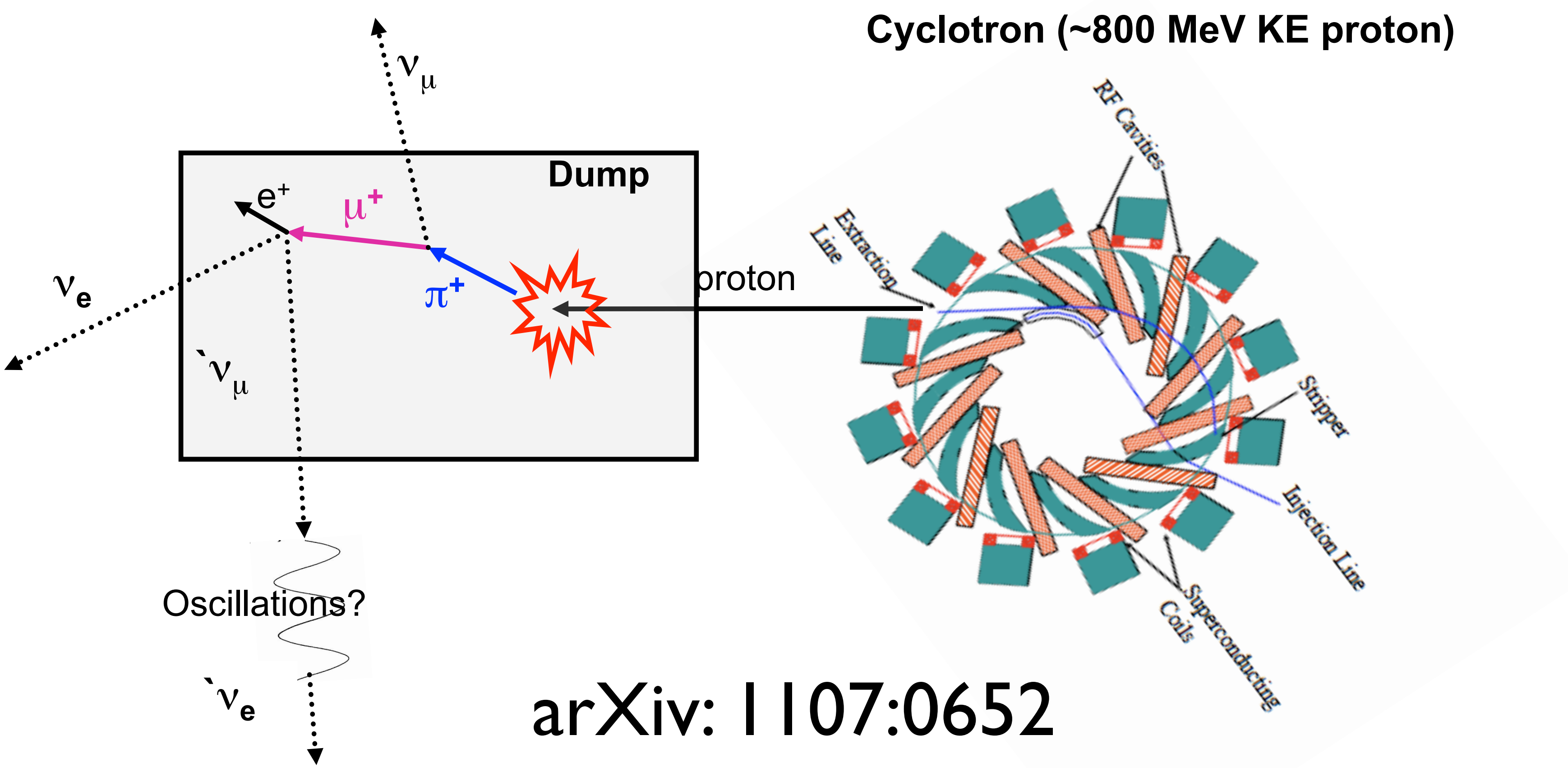
- 10 eV threshold
- 500 kg target
- 5 MCi ^{37}Ar source
- Background:
  1 event/kg/day in
  10 - 50 eV region
  of interest



Overview

- Hints of Sterile Neutrinos
- Coherent Scattering of Neutrinos
- E_{ν} ~ 1 MeV Search for Sterile Neutrinos
- E_{ν} ~ 40 MeV Search for Sterile Neutrinos

The ν Source: DAEδALUS

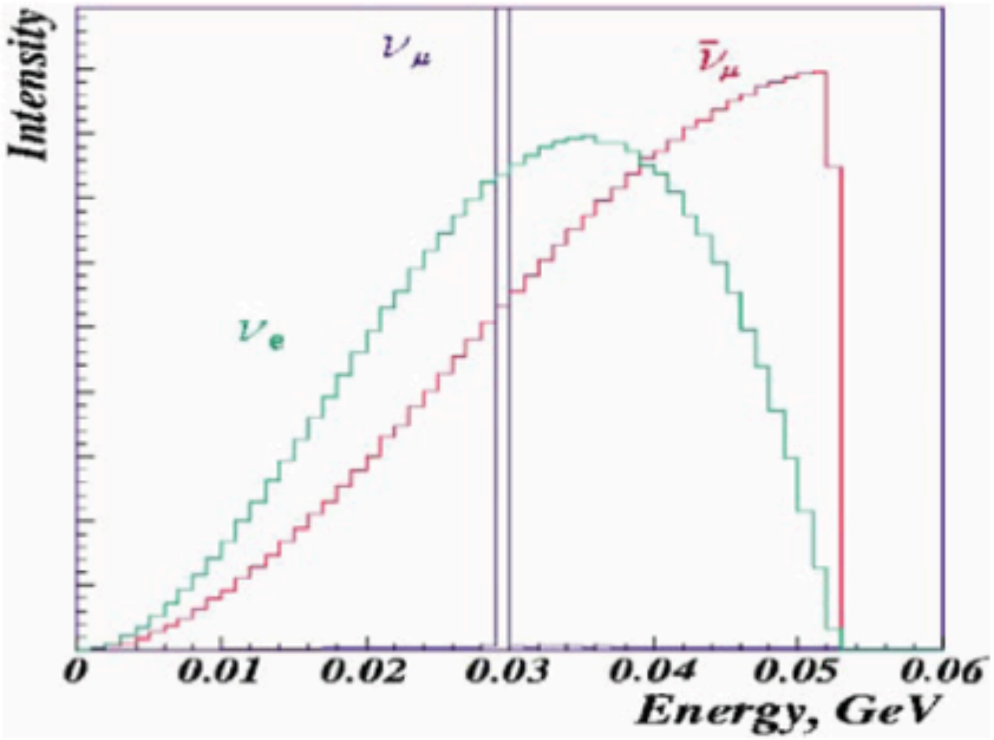


arXiv: 1107:0652

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)



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

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

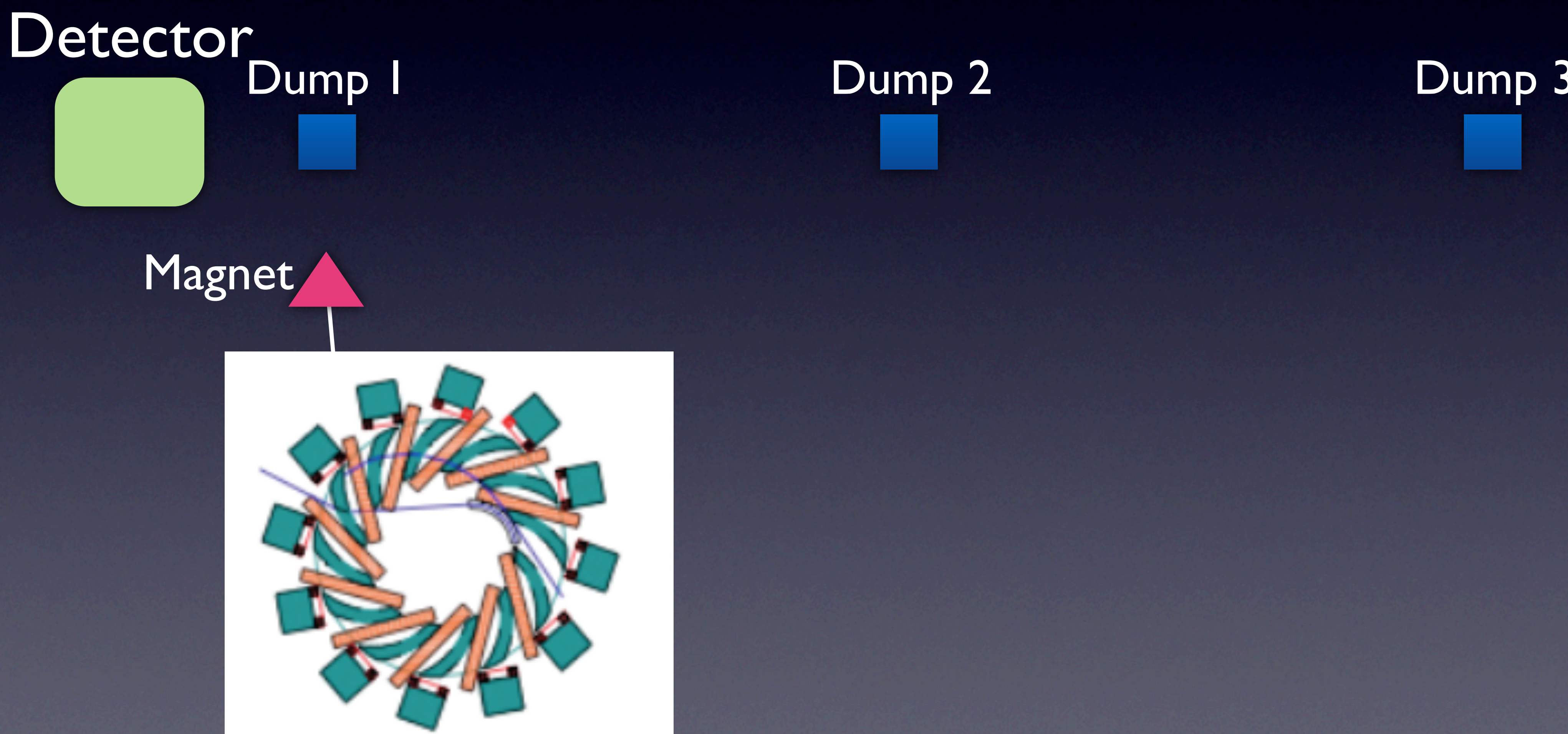
- NO electron anti-neutrinos!
  - $\bar{\nu}_e$ contribution (π^- decay) is insignificant: $<10^{-2}\%$

DAEδALUS

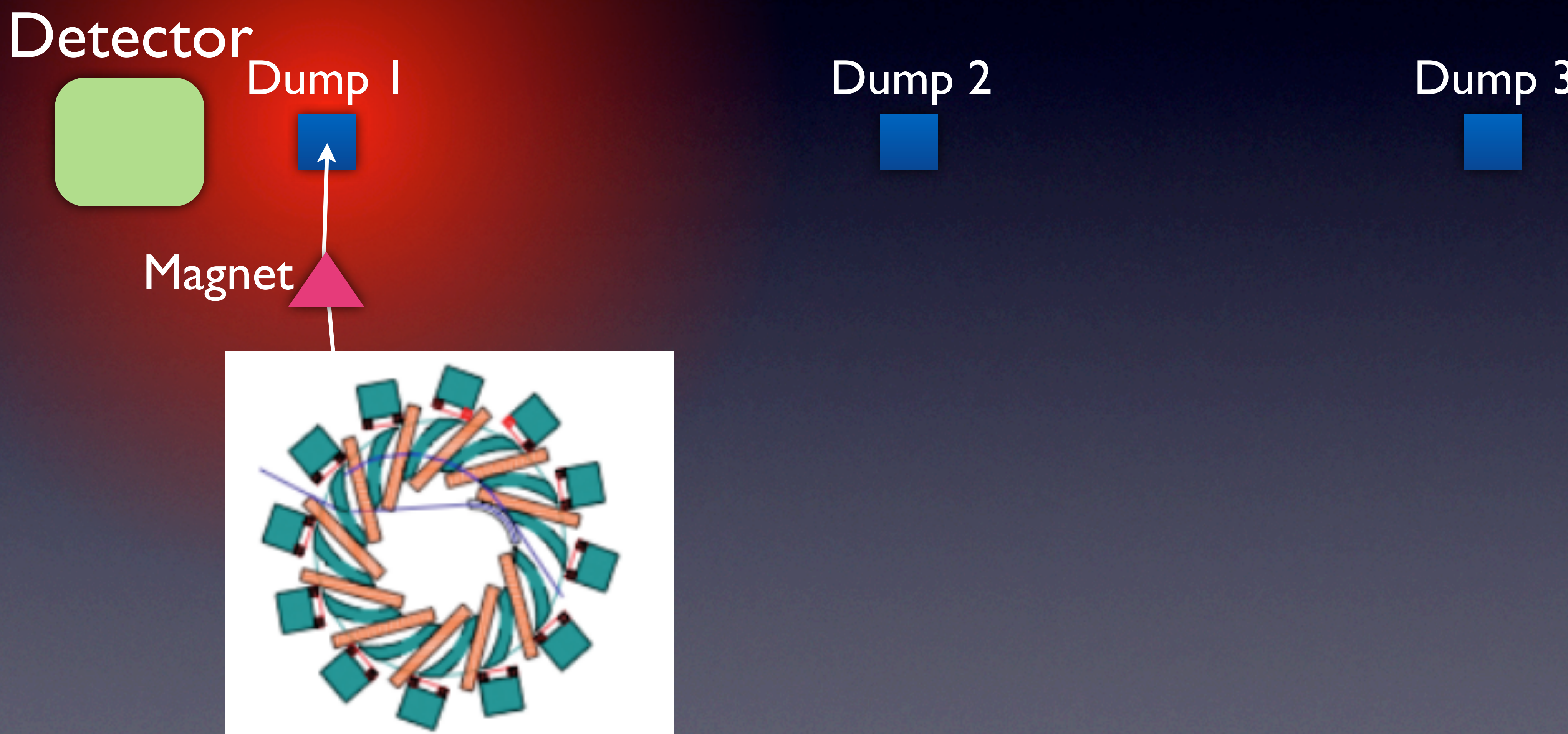
Look For Oscillations at 10's of Meters

- 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 (see arXiv: 1103.4894)

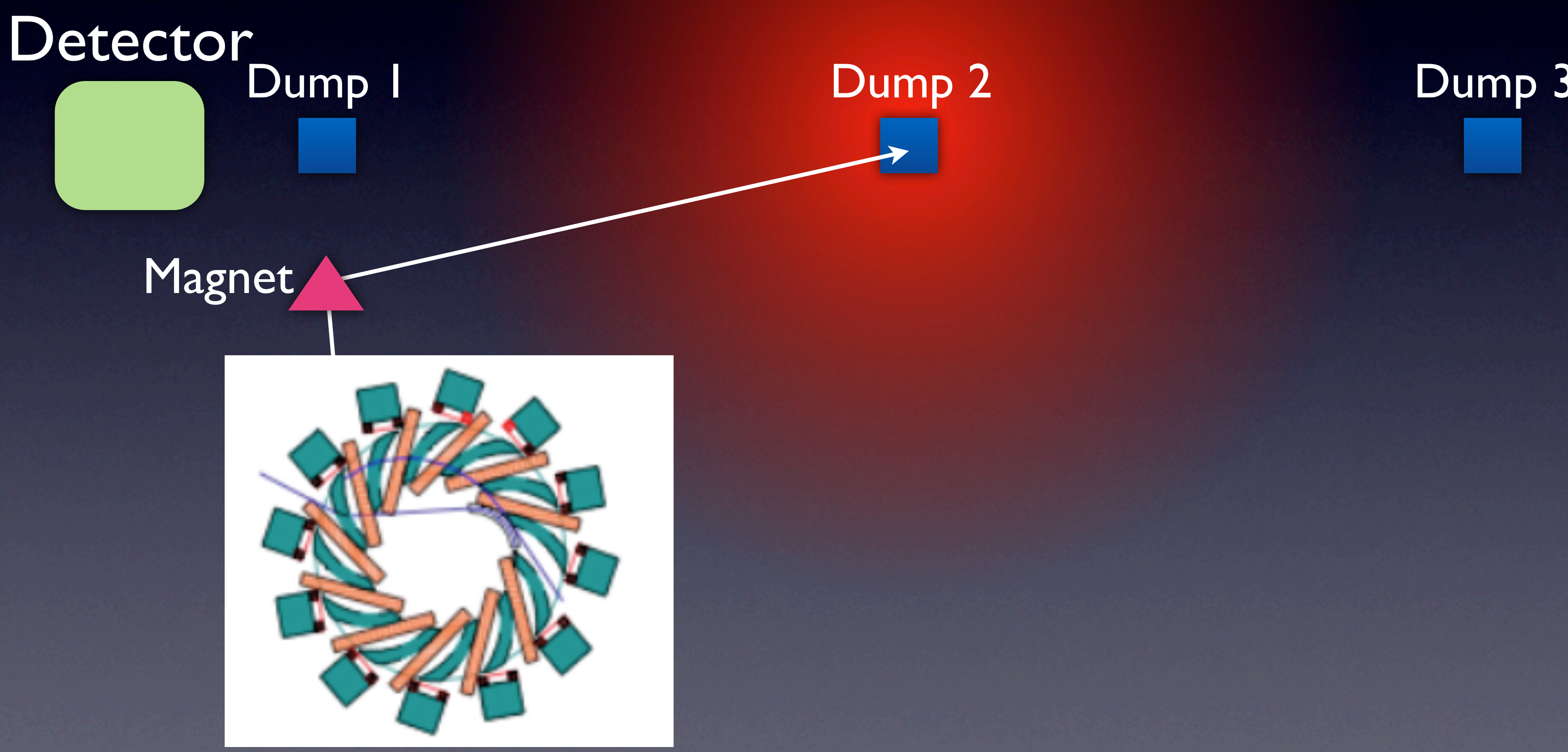
Multiple Dumps, Multiple Baselines



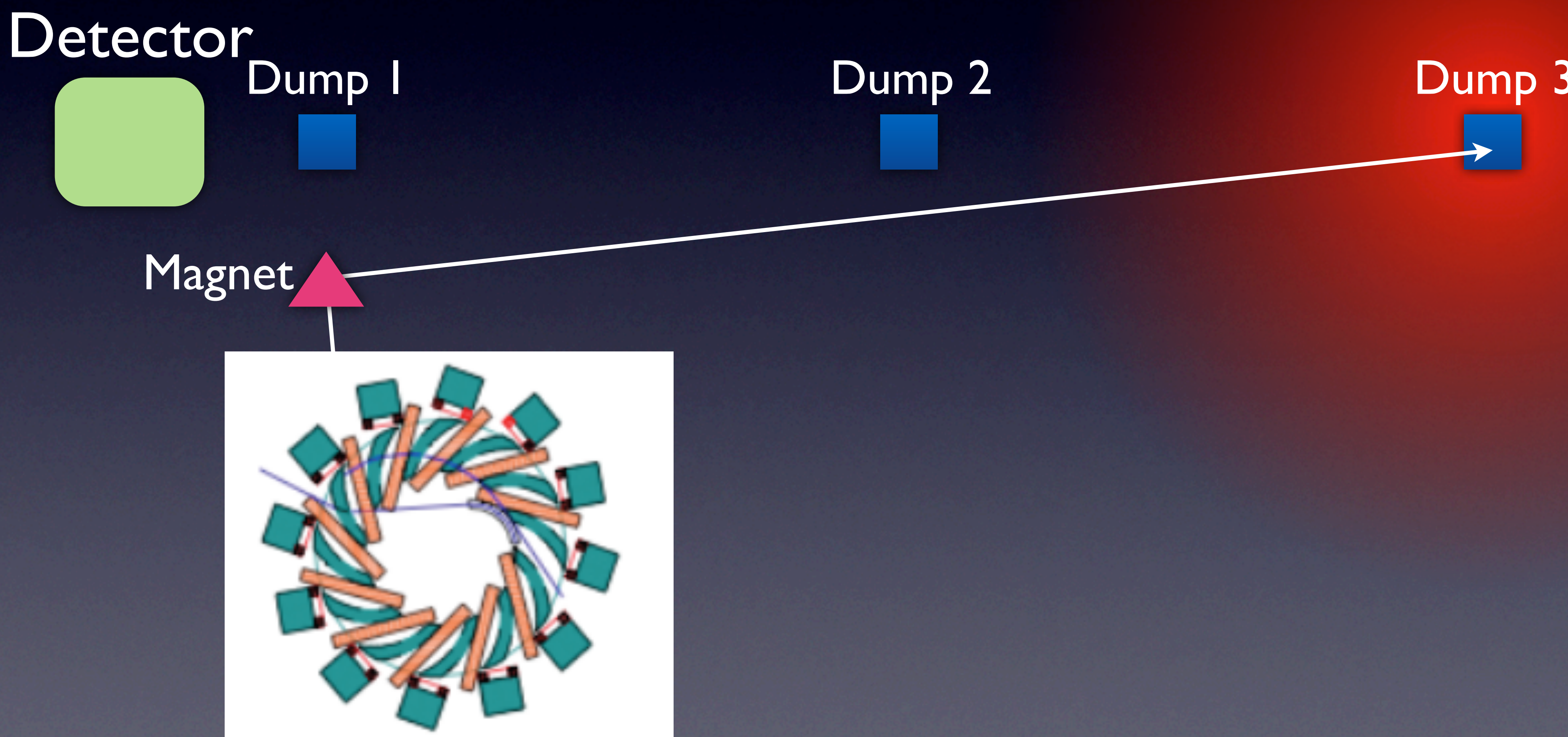
Multiple Dumps, Multiple Baselines



Multiple Dumps, Multiple Baselines

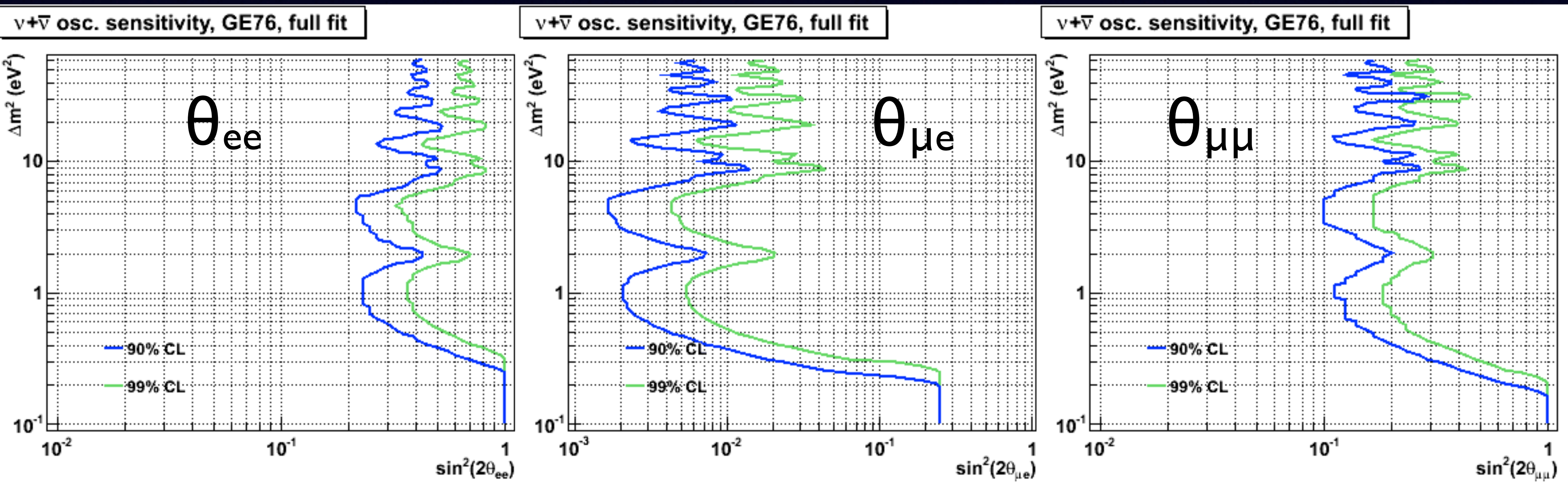


Multiple Dumps, Multiple Baselines



Work in Progress...

Sensitivity for 5 years, 100 kg Ge detector



Preliminary!

Conclusions

- A 10 eV threshold, 500 kg detector could have a great science program:
  - Detection of Neutrino Coherent Scattering
  - Sterile Neutrino Search
  - Limits on Neutrino Magnetic Moment (you get it for free during sterile ν search)
  - Dark Matter Search at Low Masses (Sensitivity Down to 150 MeV/c^2)
- Athermal phonon sensors could potentially reach these thresholds for larger masses without the dependence on the crystal heat capacity.
- A more traditional detector could have enhanced sensitivity to sterile neutrinos at a DAR ν source like DAEδALUS or the SNS by using multiple dumps

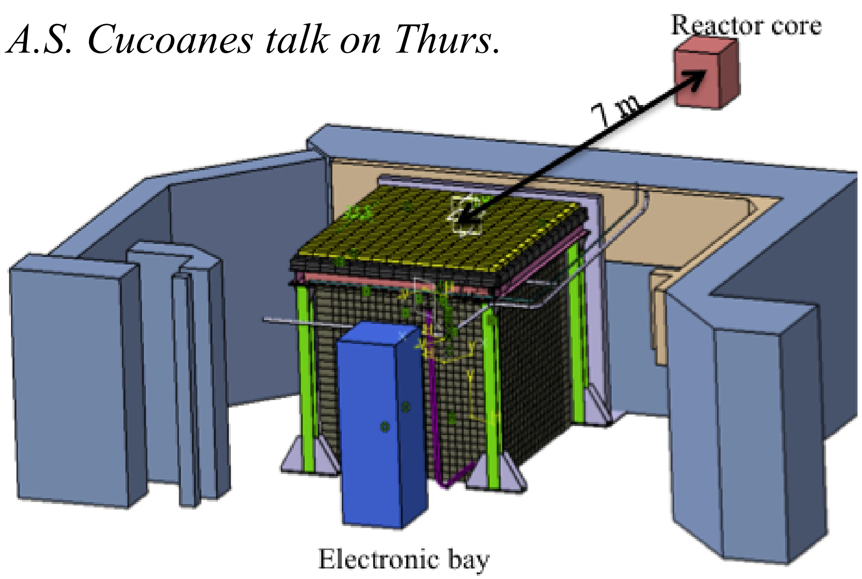
J. Formaggio, EFF, A. Anderson arxiv:1107.3512

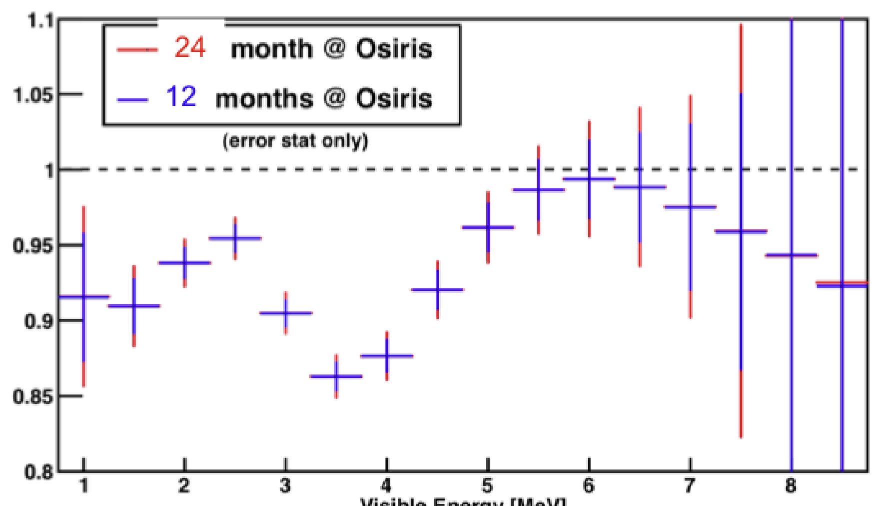
Backup Slides

Examples: Very-short Baseline Exps

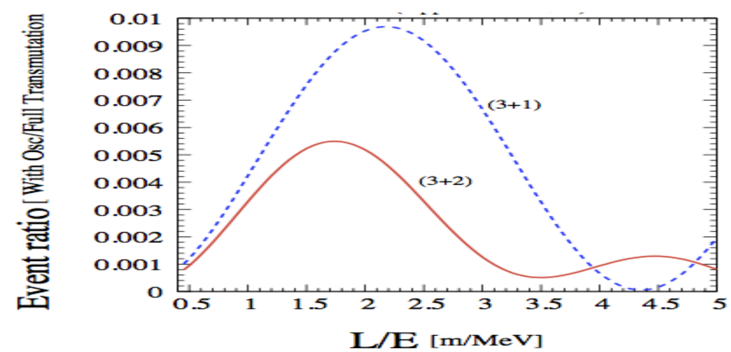
- NUCIFER Proposed Experiment
  - Osiris Research Reactor: Core Size: 57x57x60 cm
  - 1.2m x 0.7m detector 7m distance from core

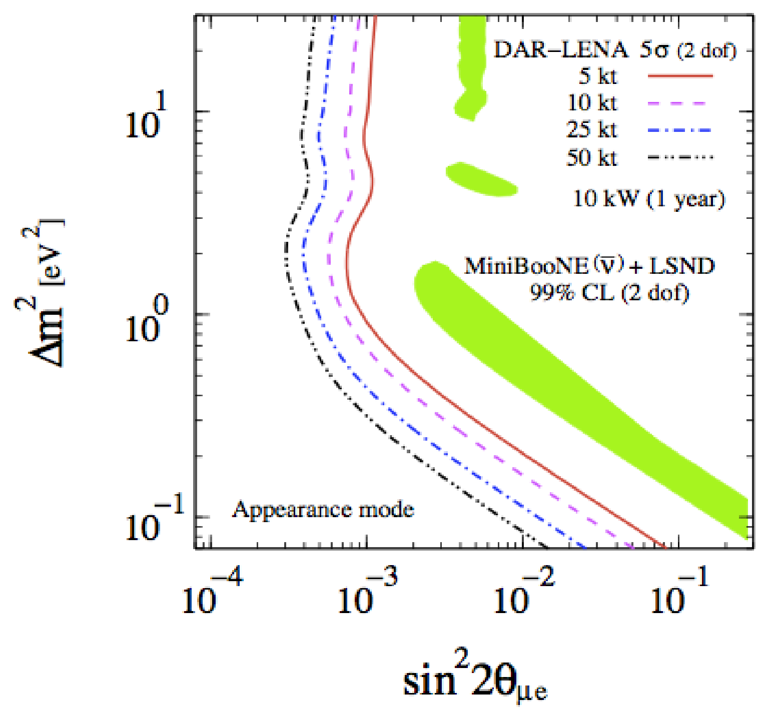
See A.S. Cucoanes talk on Thurs.





- Small (10 kW) decay-at-rest source (like Daedalus) near a large liquid scintillator detector (ala LENA)
  - Detect $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance





Agarwalla, Conrad, and Shaevitz,1105.4984 [hep-ph]

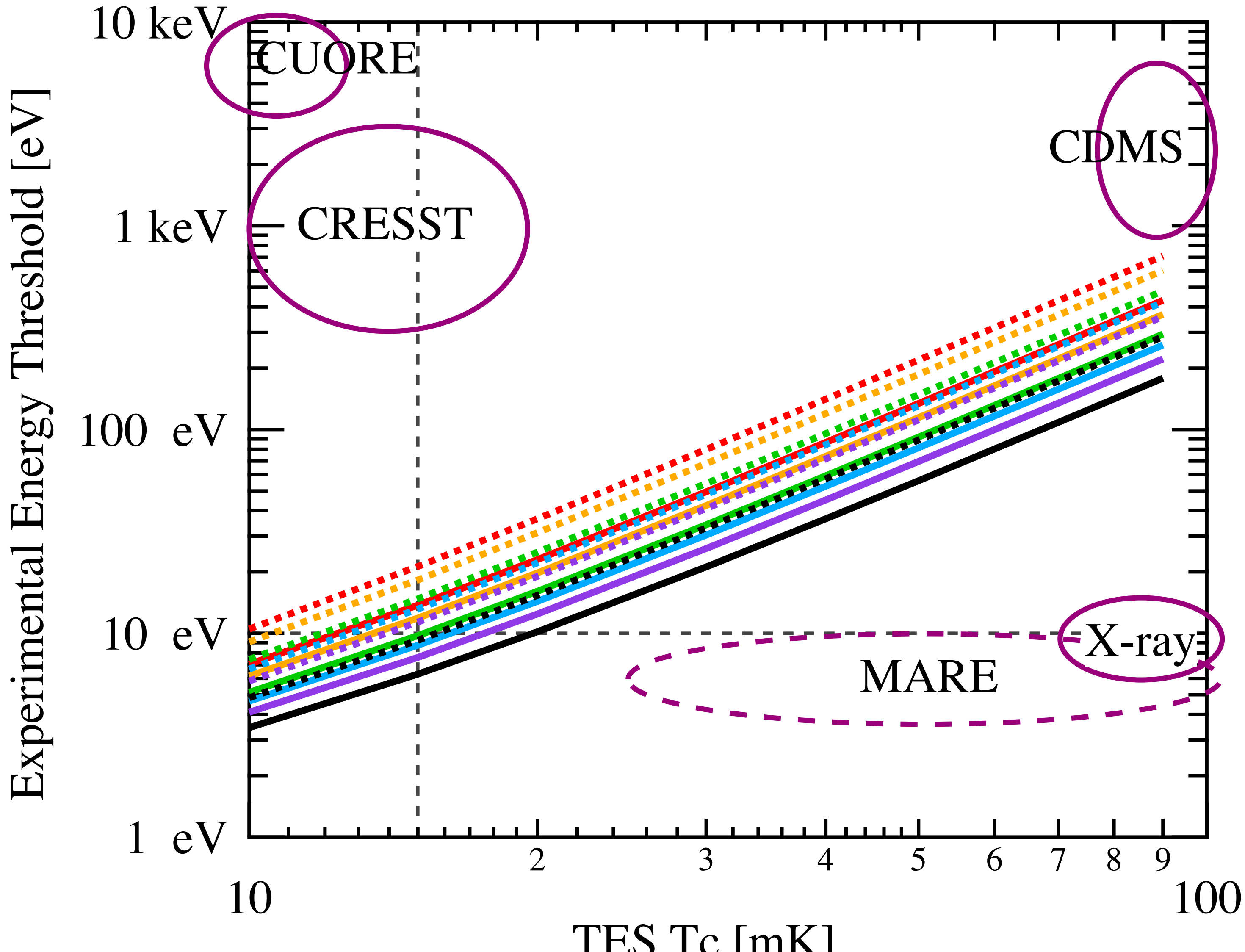
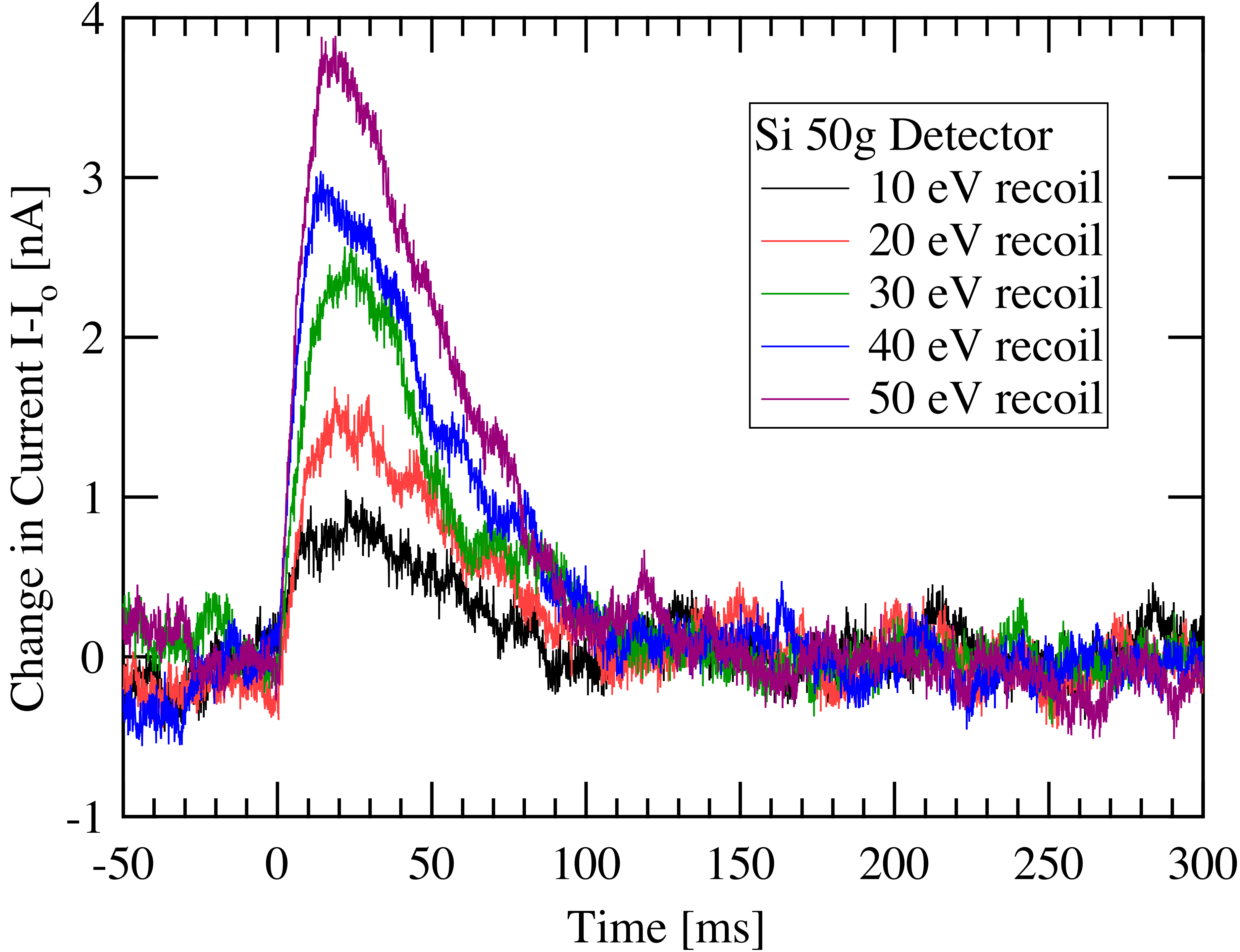

10 keV
1 keV
100 eV
10 eV
1 eV
Experimental Energy Threshold [eV]
CUORE
CRESST
CDMS
X-ray
MARE
2
3
4
5
6
7
8
9
10
100
TES Tc [mK]

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



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]
-1
0
1
2
3
4
-50
0
50
100
150
200
250
300

Backgrounds

- Radiogenic Impurities
- Compton Scattering
- Photoelectrons
- Photons from atomic relaxation transitions
- Neutrons
- Neutrino-electron scattering
- Dark matter