Coherent Neutrino Scattering with Cryogenic Semiconductor Detectors

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Moriond EW 2012

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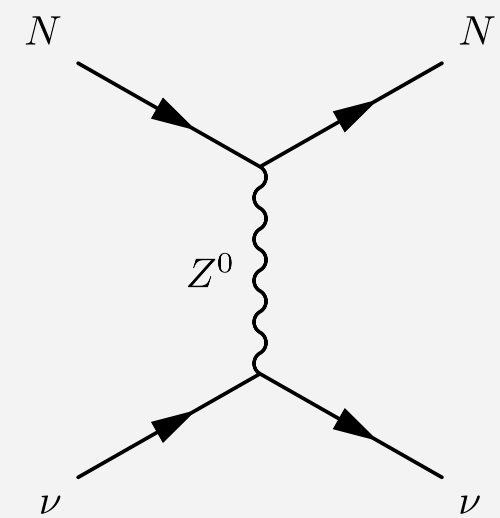
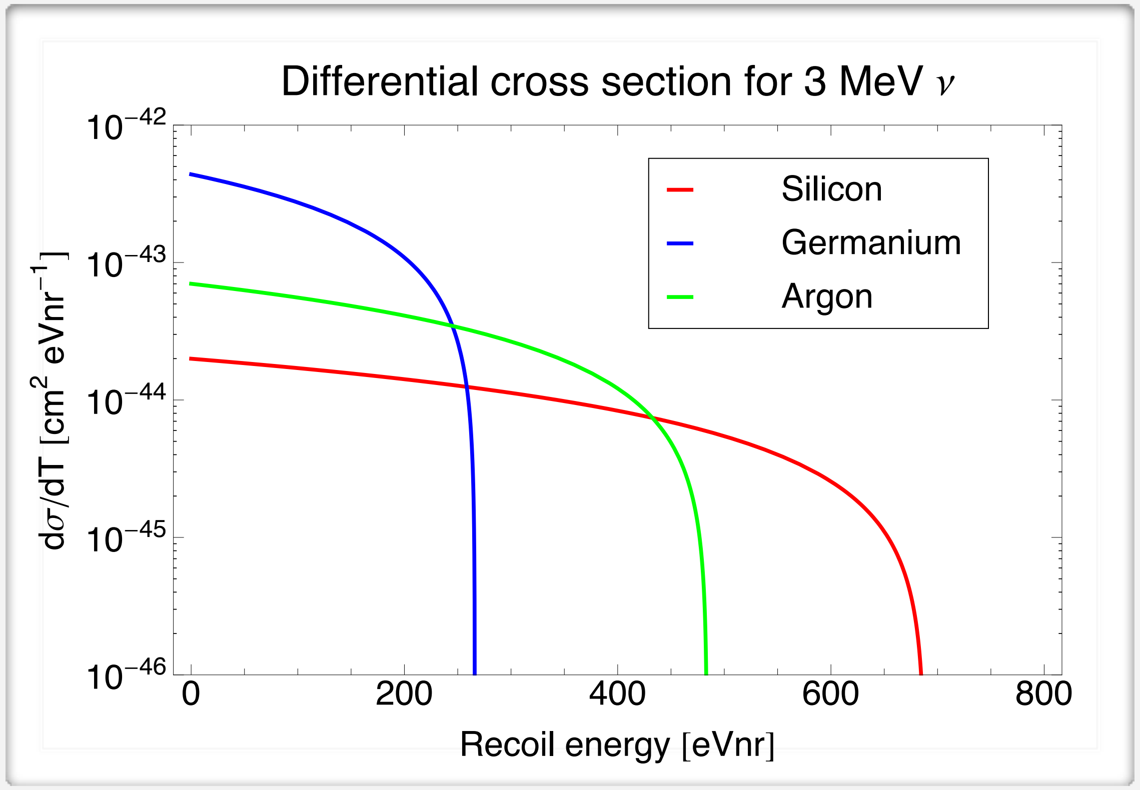
Coherent Neutrino-Nucleus Scattering (CNS)

- Unmeasured flavor-independent SM process
- Elastic neutrino scattering that is coherent on the entire nucleus: cross section scales as A^2
- Signature is nuclear recoil: very low energies
- CNS cross section dominates other neutrino cross sections in the 10-50 MeV neutrino energy range



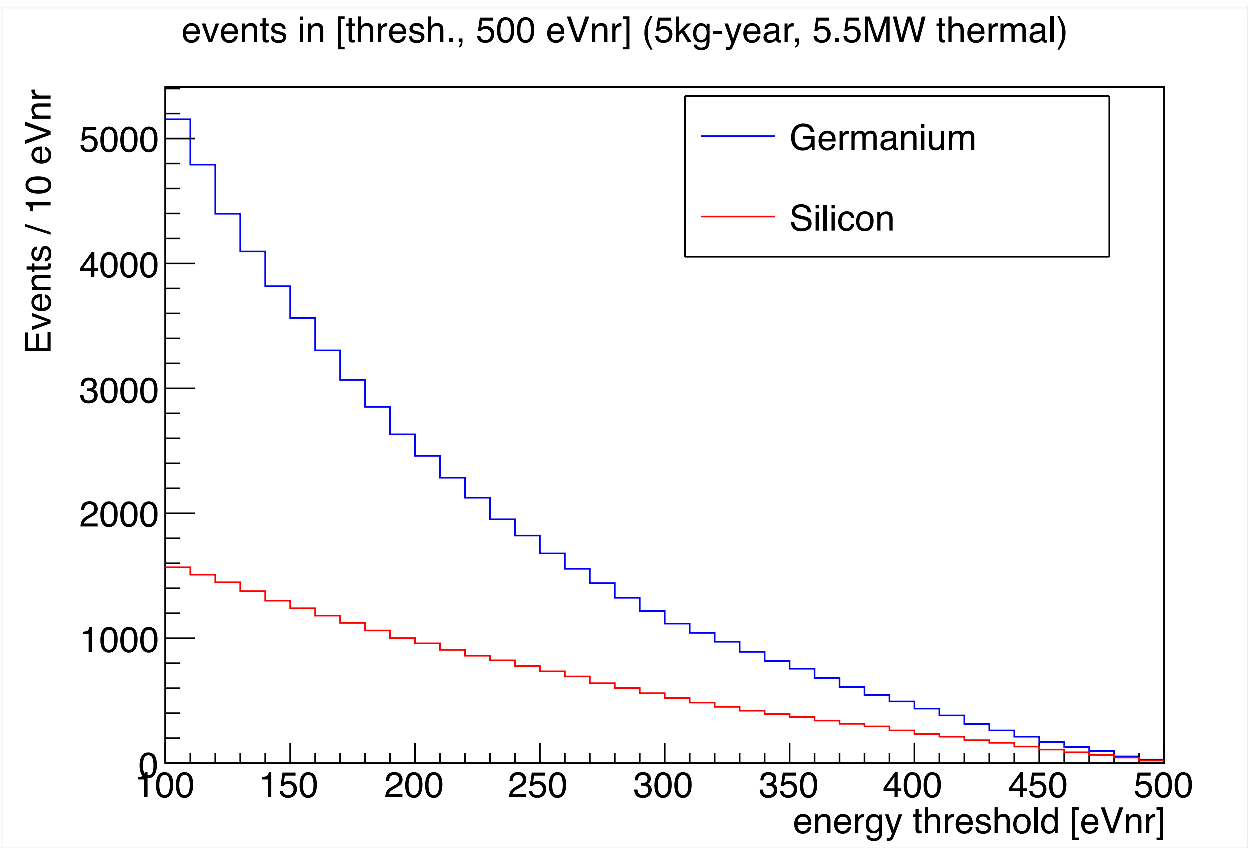
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} M_A Q_W^2 \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(q^2)^2$$

$$\begin{aligned}
T &= \text{recoil energy} \\
E_\nu &= \text{incident neutrino energy} \\
G_F &= \text{Fermi constant} \\
M_A &= \text{mass of target nucleus} \\
Q_W &= \text{weak charge of nucleus} \\
F(q^2) &= \text{form factor} \sim 1
\end{aligned}$$



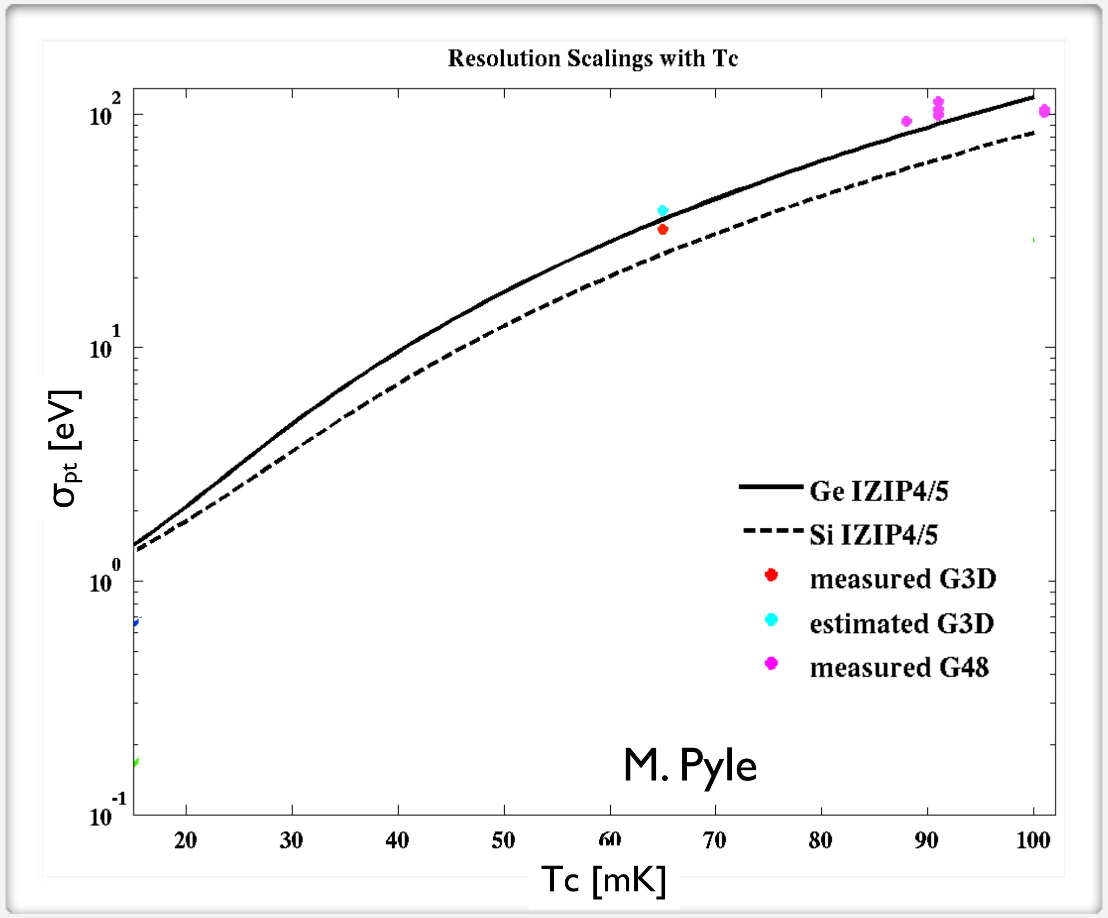
How to Measure?: Sources

- Multiple possibilities:
  - MCi electron capture sources (^{37}Ar, monoenergetic): ~800 keV (PRD **85**, 013009 (2012))
  - Reactors: 1-10 MeV (e.g. JHEP12 (2005) 021)
  - Decay-at-rest stopped-pion sources: 10-50 MeV (PRD **84**, 013008 (2011))
- Focus on nuclear reactors: high flux, very cheap, safe, well-understood
- MIT research reactor is convenient and has experimental site 4 m from reactor core
- ~14 events / day for 5 kg Ge detector 4 m from core of 5.5 MW (thermal) reactor



How to Measure?: Detectors

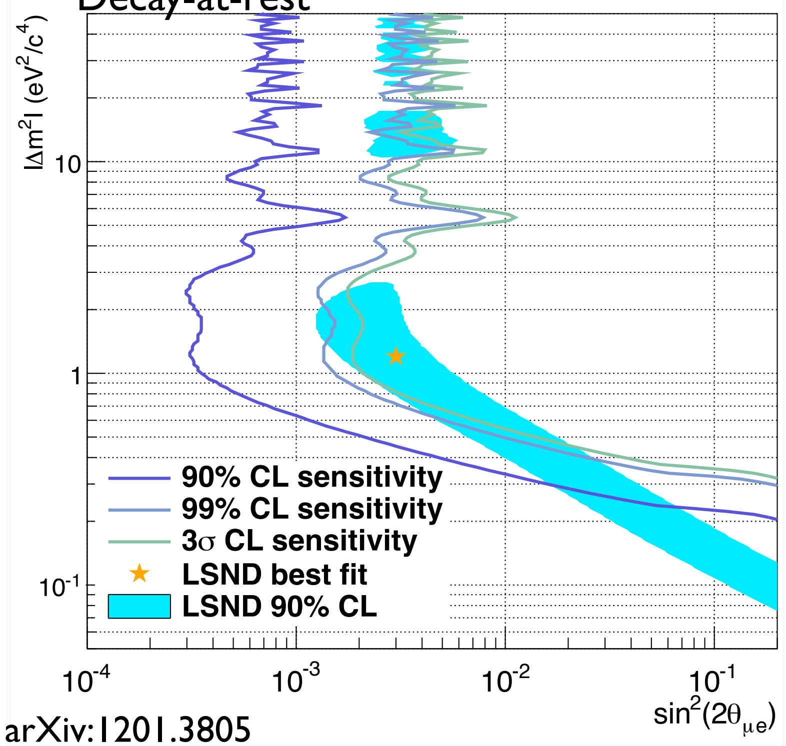
- Dark matter detectors are zero-background down to 5-10 keV for ~100 kg-day exposures
- Scheme:
  - Use CDMS-style cryogenic detectors: measure phonons with superconducting transition-edge sensors (TESs) on Ge or Si
  - Eliminate charge readout
  - Signal-to-noise improved by better matching of phonon pulse and TES bandwidths
  - Slow TES response by decreasing Tc of TES
  - Reactor-off data possible at research reactors for background subtraction



Sterile Neutrino Constraints

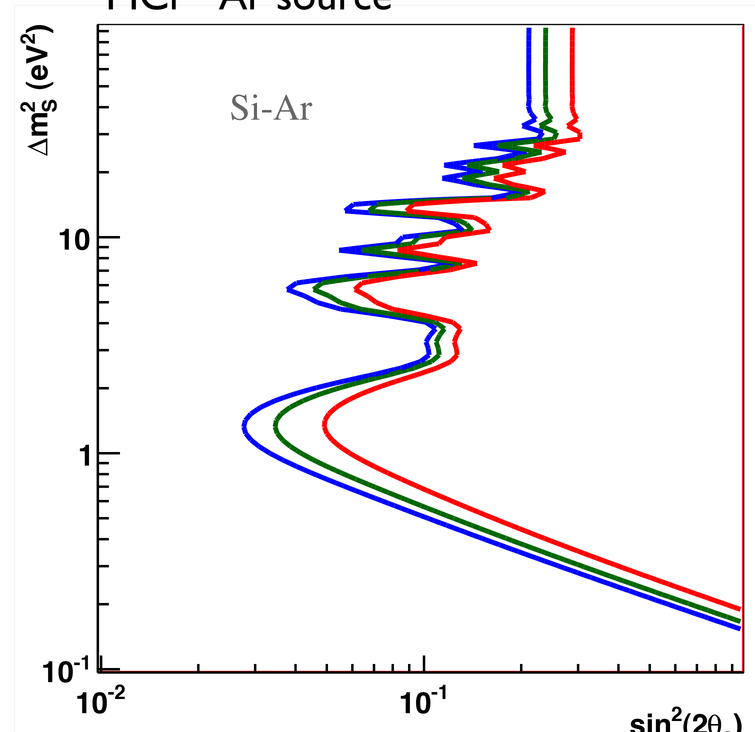
- Hints of 1 or 2 sterile neutrinos from cosmology, reactor neutrino anomaly, LSND, and MiniBooNE
- Reactors offer limited sensitivity to short-baseline neutrino oscillations from sterile neutrinos
- Electron capture sources and decay-at-rest sources with coherent neutrino scattering offer sensitivity to sterile states
- Neutral current is a direct probe of sterile neutrino hypothesis

Decay-at-rest



arXiv:1201.3805

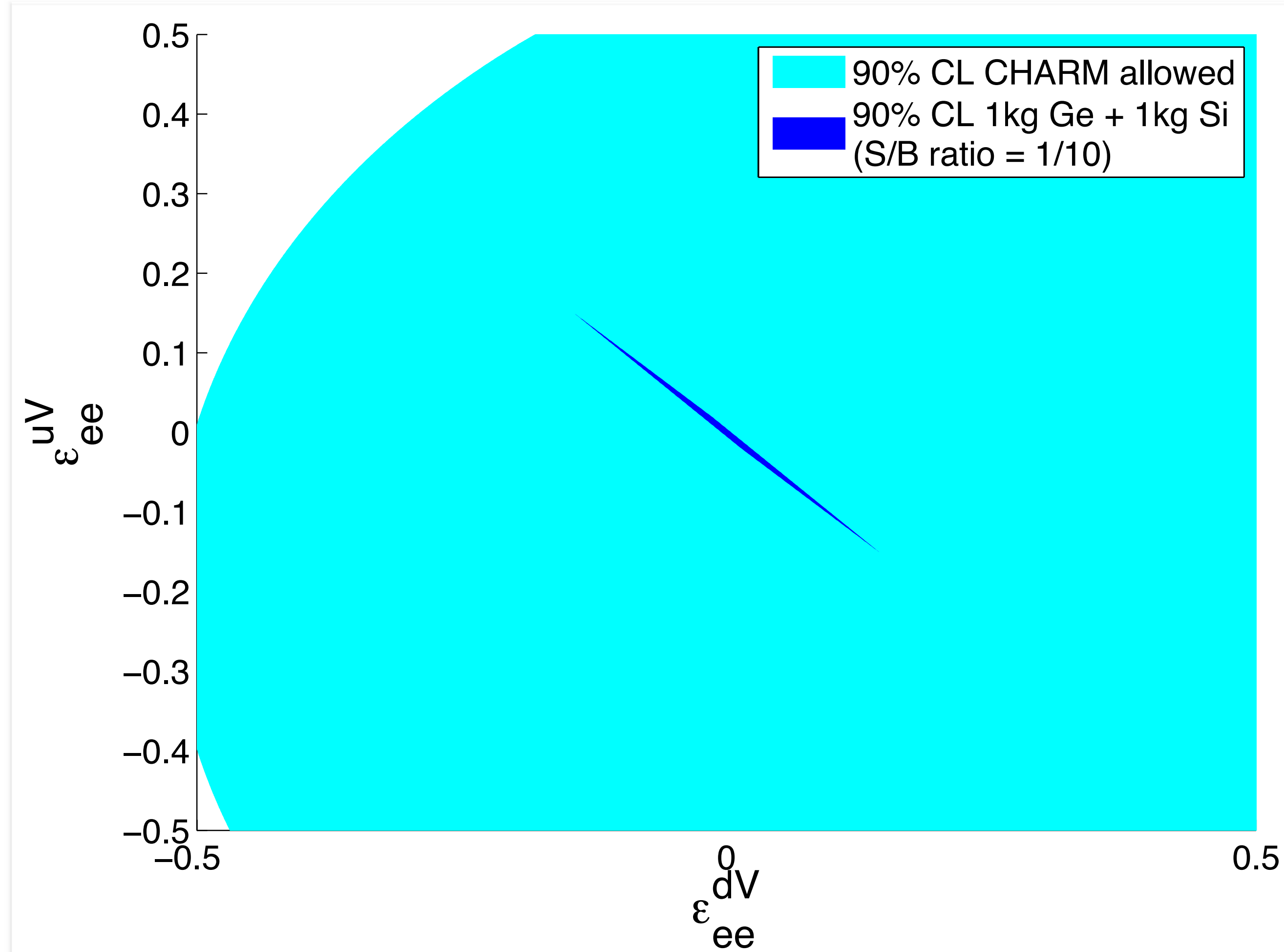
MCi ^{37}Ar source



PRD **85**, 013009 (2012)

Non-Standard Interaction Constraints

- Low-energy limit of dimension-6 operators can produce deviations from SM neutrino interactions
- Reactors yield very strong limits on non-standard interactions of electron neutrinos
- Parameterized by additional couplings in lagrangian, which modify overall normalization of cross section



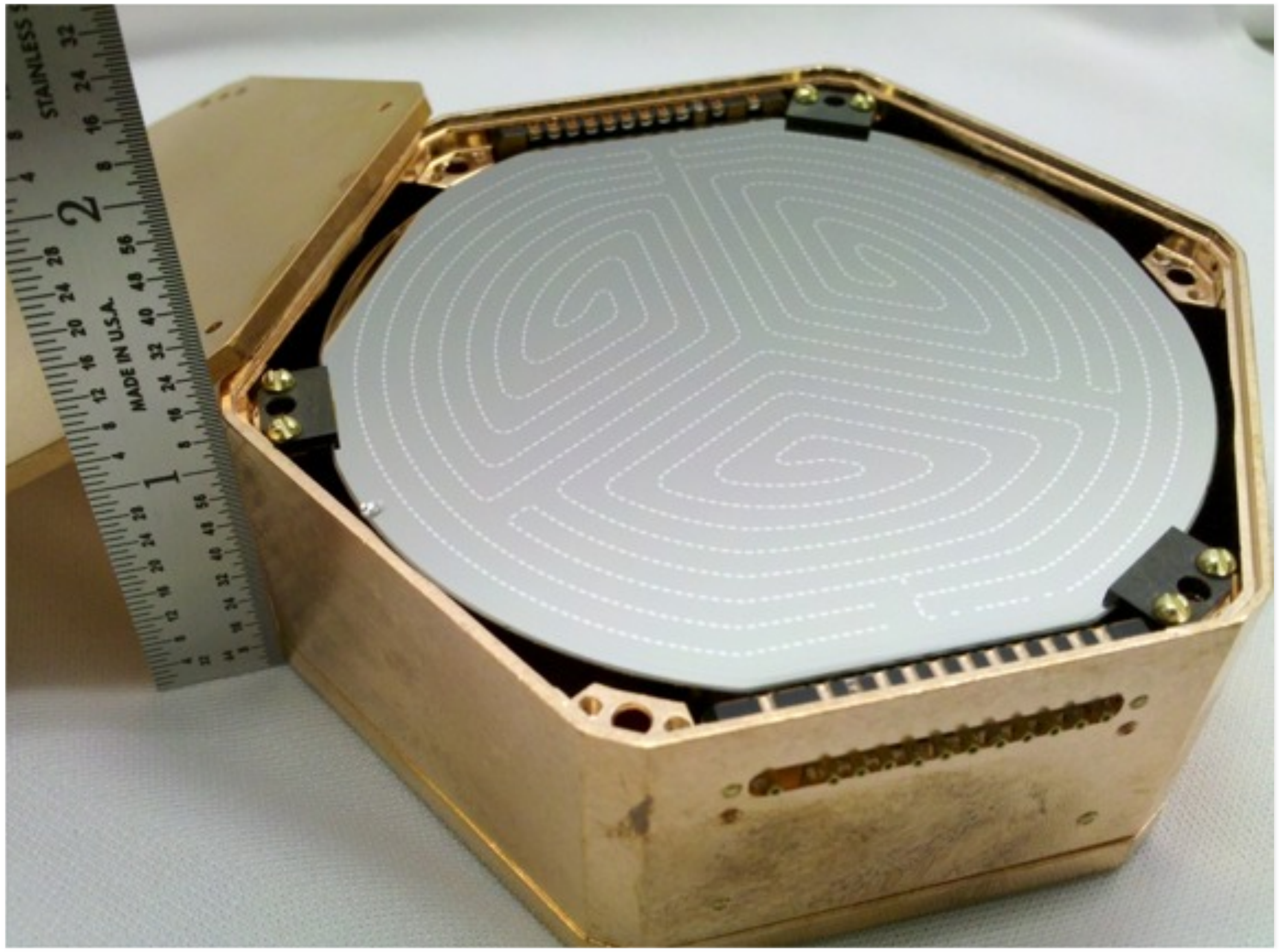
$$\mathcal{L}_{\nu\text{Hadron}}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} \left[\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta\right] \left(\epsilon_{\alpha\beta}^{qL}\left[\bar{q}\gamma_\mu(1-\gamma^5)q\right] + \epsilon_{\alpha\beta}^{qR}\left[\bar{q}\gamma_\mu(1+\gamma^5)q\right]\right)$$

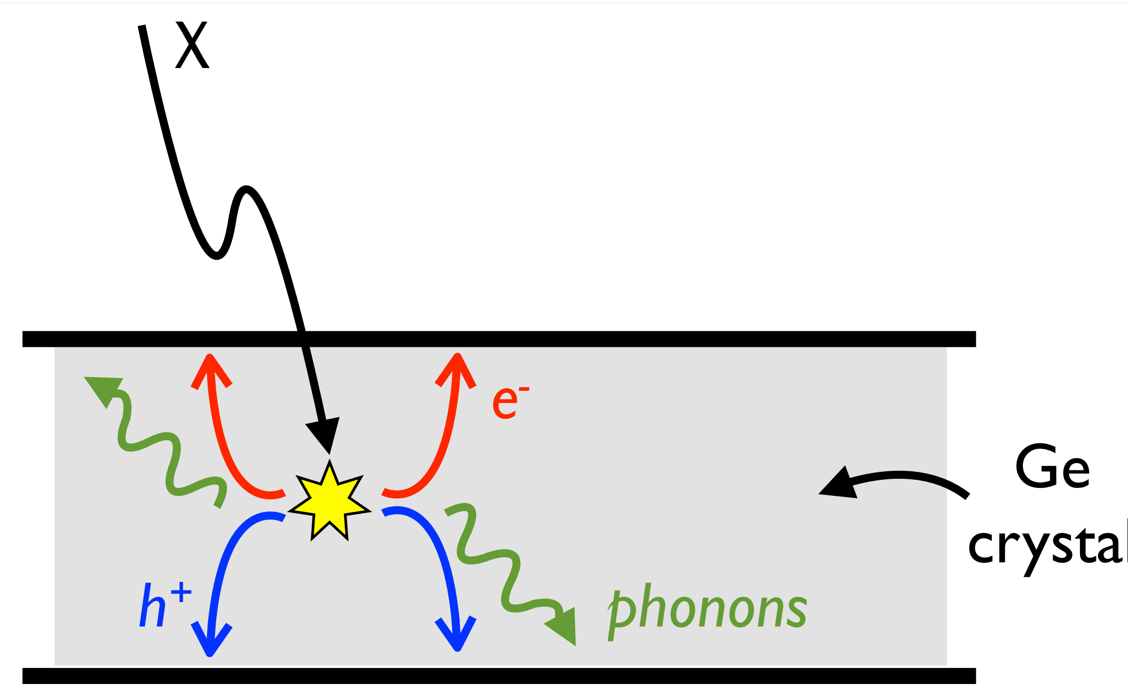
Conclusions

- CNS is difficult to detect, but possible with phonon-based low-threshold detector technologies
- Strong constraints on NSI possible with reactors
- Direct neutral-current probe of sterile neutrinos
- Experimental program underway to modify CDMS detectors for reactor neutrino physics

Backup

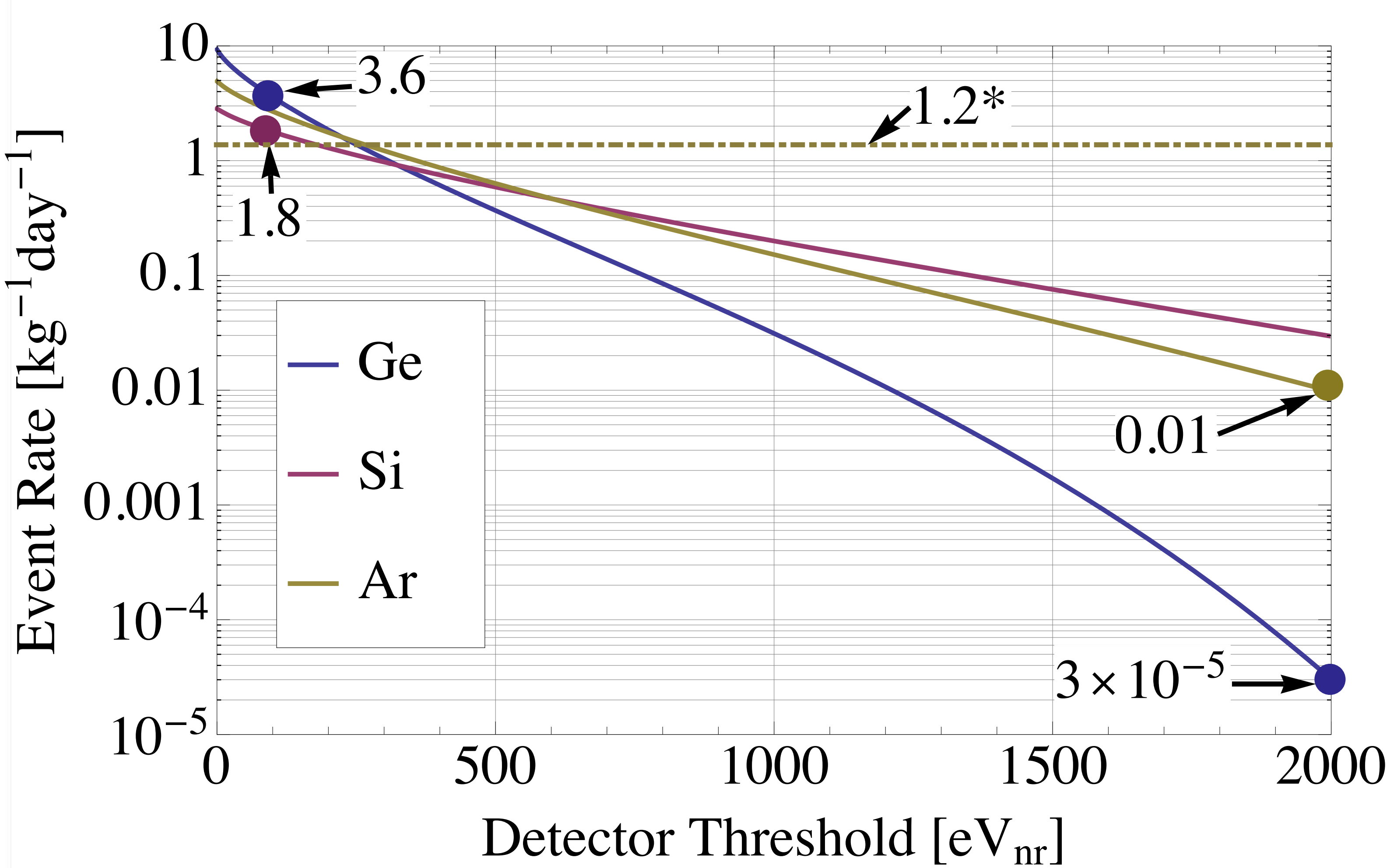
Existing CDMS Detectors



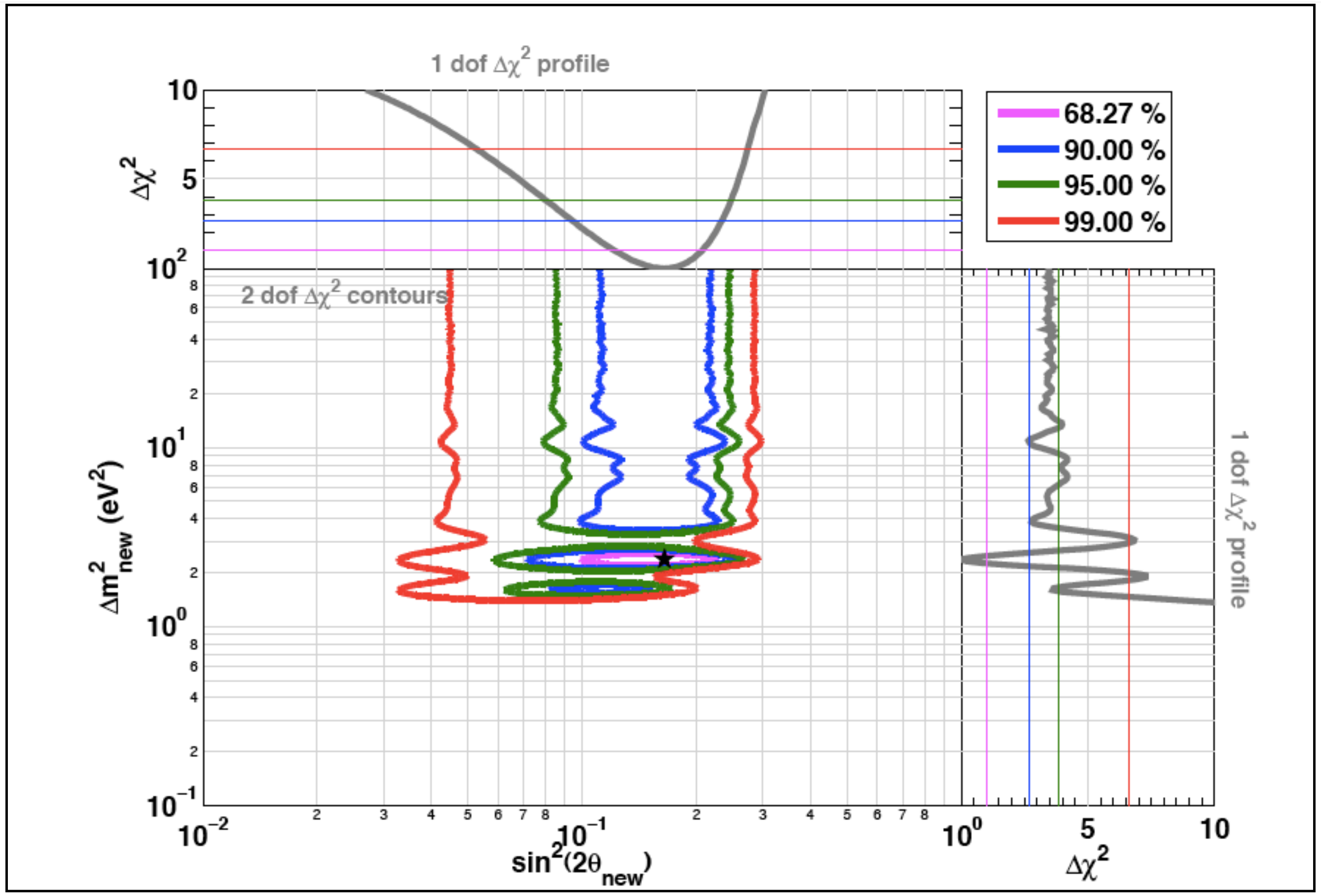


Comparison with Ionization Detectors

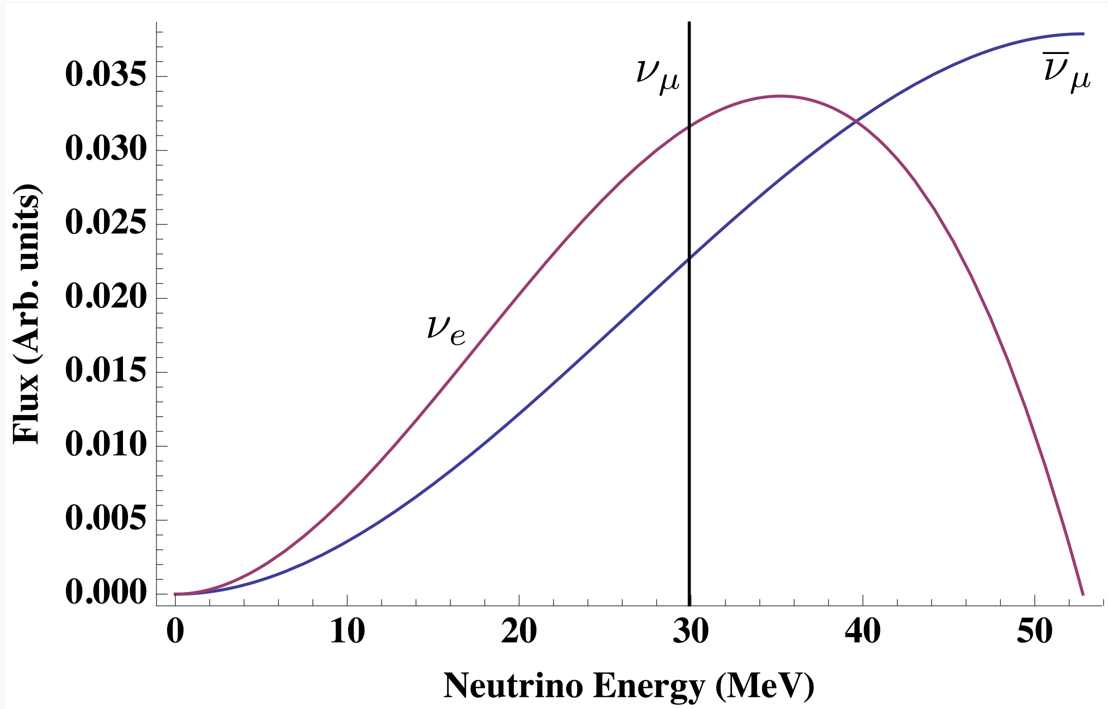
- Quenching factor is ~0.2 in Ge
- Ionization-only detectors must achieve significantly lower energy threshold in “electron-equivalent” units



Reactor Anomaly



DAR Source & Detector



	^{76}Ge
Active mass	100 kg
Efficiency	0.67 (flat)
Threshold	10 keV
$\frac{\Delta E}{E}$ at threshold	3%
Radiogenic background	2/year
Cosmogenic background	0.1/(10 kg·day)
Beam-related background	0/year

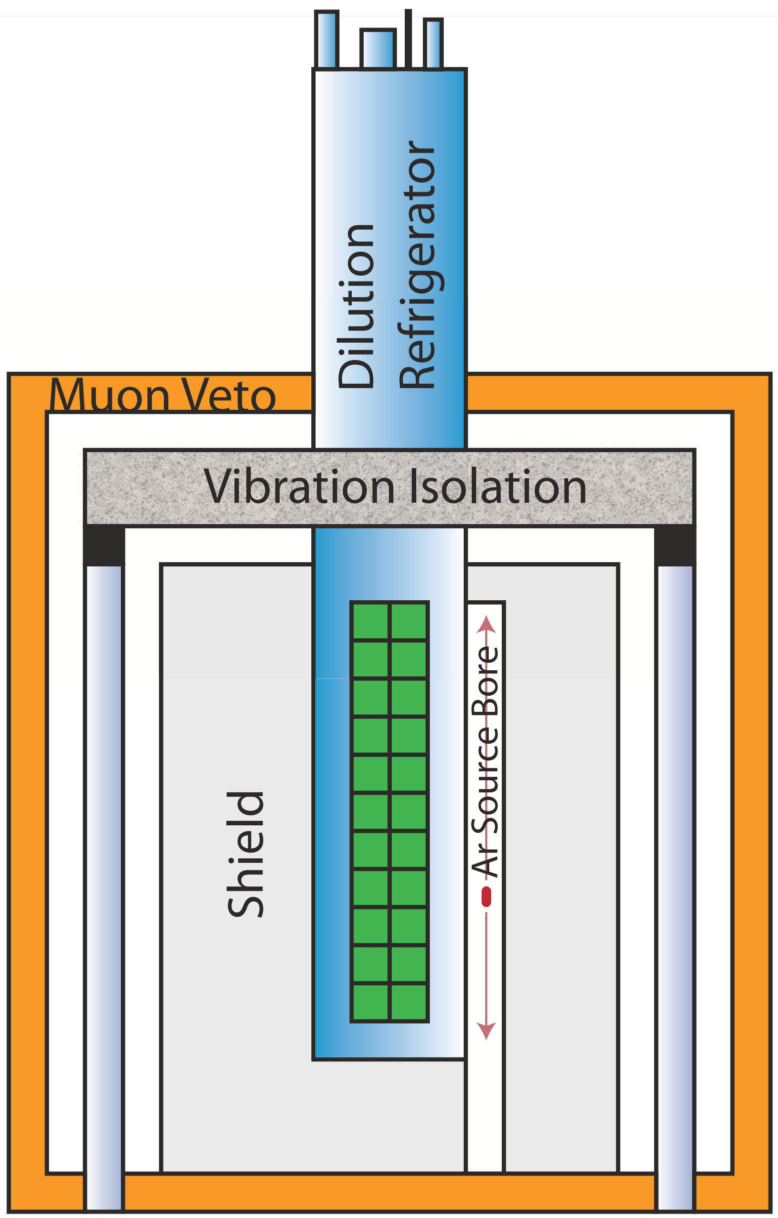
ν source	4×10^{22} ν/flavor/year
Duty factor	13%
Baseline correlation	0.99
ν flux norm. uncertainty	1.5%
Uncorr. sys. uncertainty	0.5%
Distances from ν source	20 m, 40 m
Exposure	5 years: 1 near, 4 far
Depth	300 ft

MCi Sources

- MCi ^{37}Ar sources used for calibration in SAGE experiment
- Difficult to manufacture: use ^{40}Ca(n,α)^{37}Ar reaction with fast (2 MeV) neutrons
- Monochromatic 811 keV line from electron capture

Source	Half-Life	Progeny	Production	E_ν	Gamma (?)
^{37}Ar	35.04 days	^{37}Cl	^{40}Ca(n,α)^{37}Ar	811 keV (90.2%), 813 keV (9.8%)	Inner Brem only
^{51}Cr	27.70 days	^{51}V	n capture on ^{50}Cr	747 keV (81.6%), 427 keV (9%), 752 keV (8.5%)	320 keV γ
^{65}Zn	244 days	^{65}Cu	n capture on ^{64}Zn	1343 keV (49.3%), 227 keV (50.7%)	1.1 MeV γ

Bolometer Detectors



Parameter	Detector Type	
Detector Material	Si	Ge
Atomic Number	28	72.6
$\sigma_0(E_\nu)$ (10^{-42} cm^2)	0.44	3.82
$T_{\rm max}$	50.3 eV	19.4 eV
Threshold	10 eV	
$f(E_\nu, T_0)$	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}