Coherent neutrino scattering and sterile neutrino searches w/ a decay at rest source

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FNAL

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Outline

- Introduction to coherent neutrino scattering
- Detection techniques and neutrino sources
- Sensitivity to oscillations
- A new decay at rest neutrino oscillation idea

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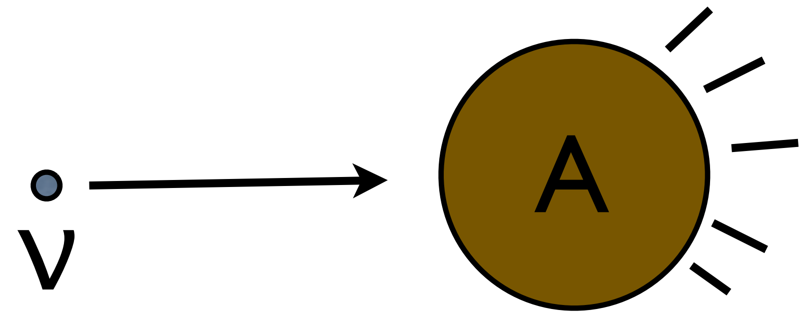
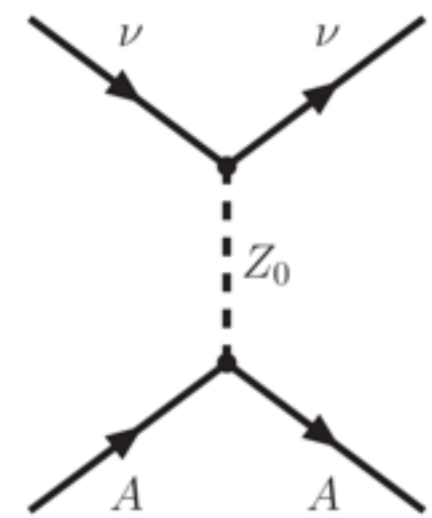
Coherent neutrino-nucleus scattering



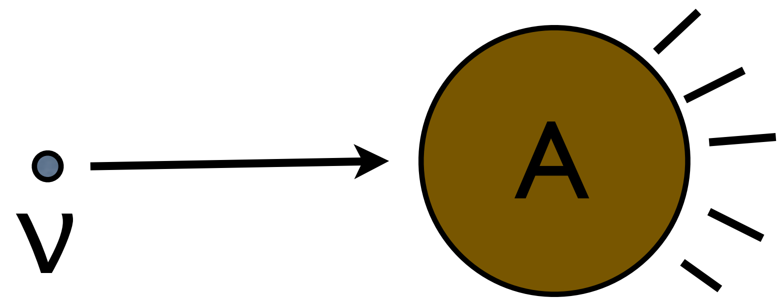
Coherent ν-A elastic

$$\frac{d\sigma}{dE} = \frac{G_F^2}{2\pi}\frac{Q_w^2}{4}F^2(2ME)M(2-\frac{ME}{k^2})$$



A process well-predicted by the SM
with a small theoretical cross section uncertainty.

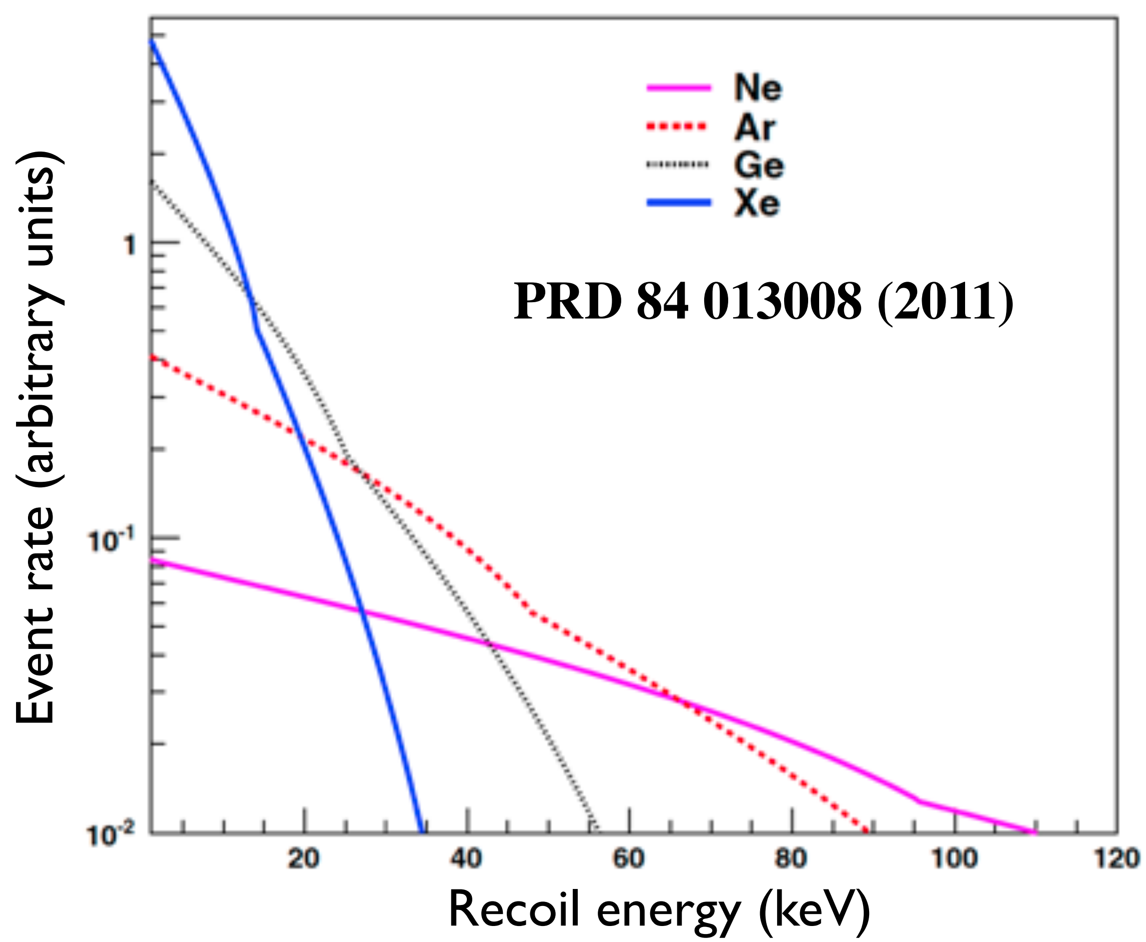
An unobserved process with a large cross section ...and a tiny signature



In the few-50 MeV range:

- Coherent ν-A elastic $\sigma \sim 10^{-39}$ cm^2
- ν-A charged current $\sigma \sim 10^{-40}$ cm^2
- ν-p charged current $\sigma \sim 10^{-41}$ cm^2
- ν-e elastic $\sigma \sim 10^{-43}$ cm^2

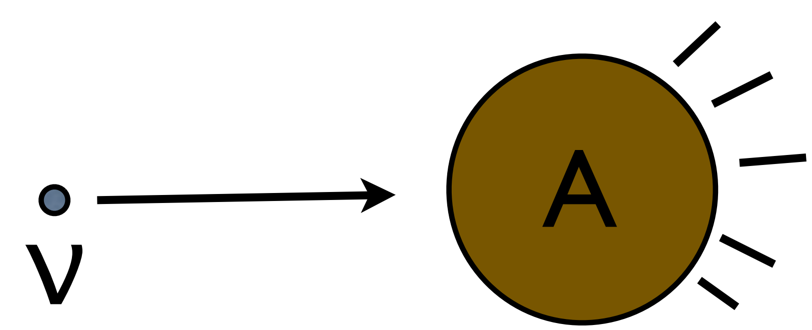
Recoil energies for stopped-pion neutrino source



Very low energy (WIMP-like) recoils

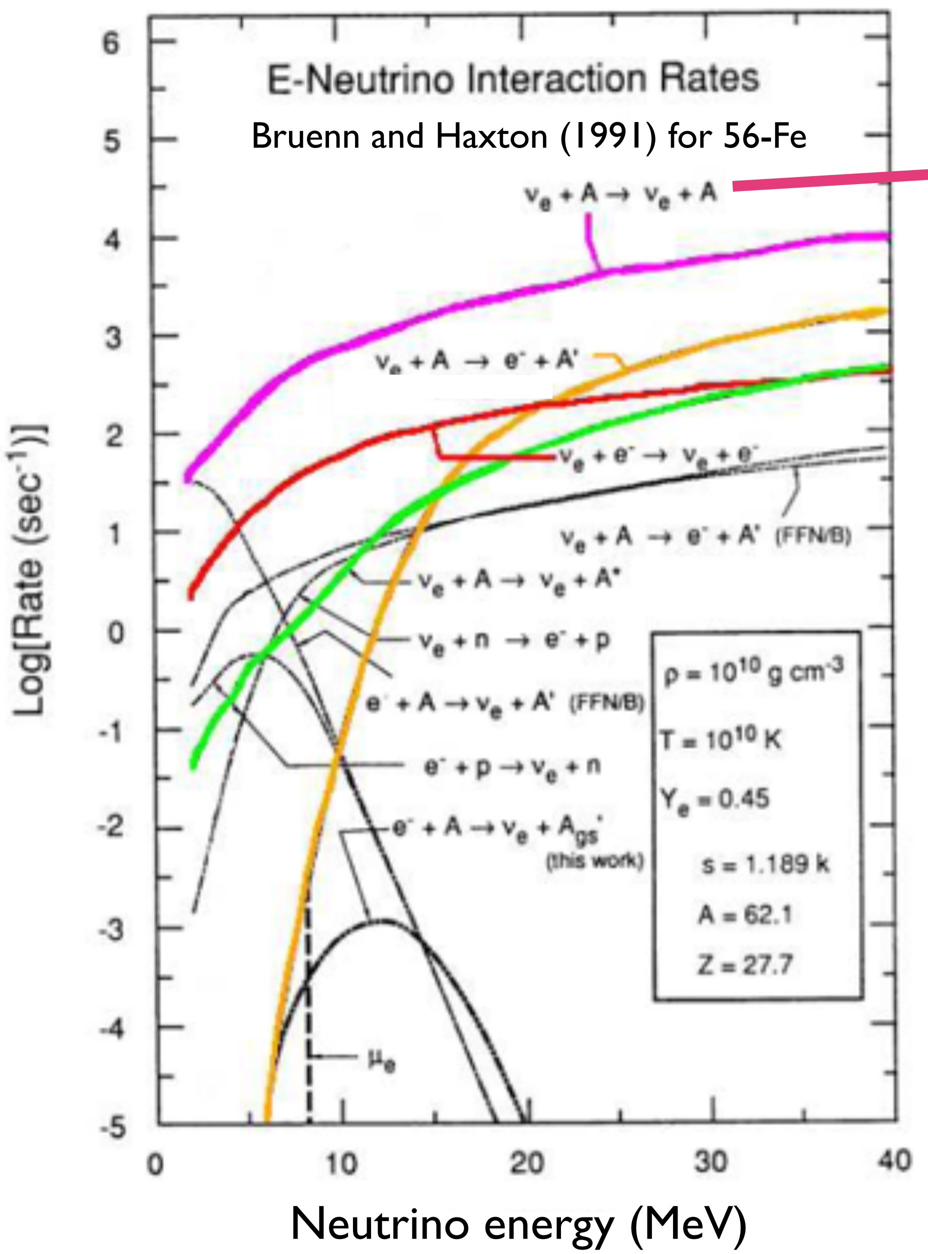
Why is coherent neutrino-nucleus scattering interesting?

- This process has never been detected
- Differences from Standard Model prediction could be a sign of new physics
- Non-standard neutrino interactions
- Supernova process and burst/diffuse neutrino detection
- Weak mixing angle
- Neutron radius
- Sensitivity to sterile neutrino(s)

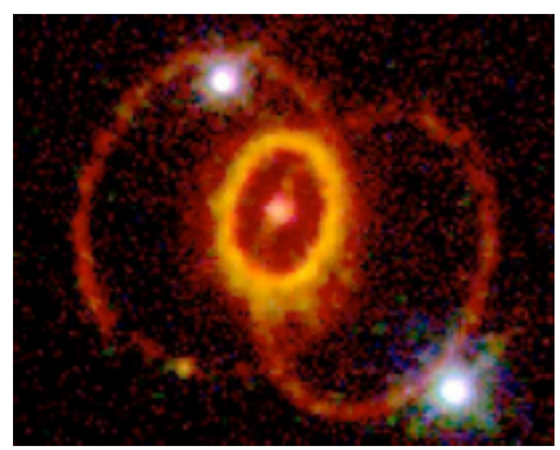


Core-collapse Supernova

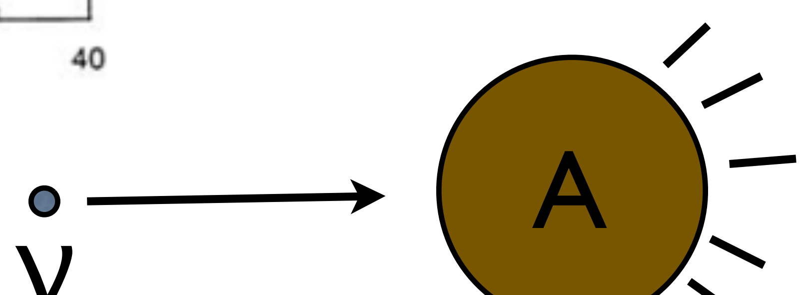
Neutrinos carry energy (10^{53} ergs, 99% of total) out of the star before anything else.



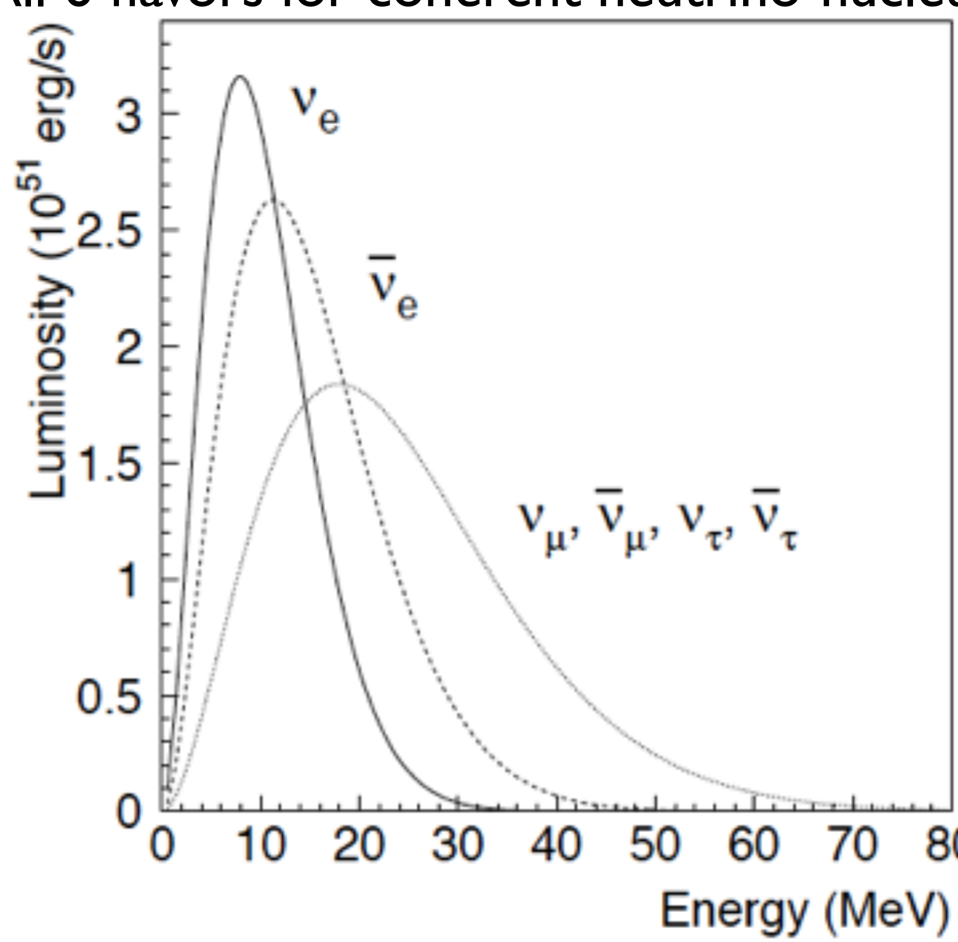
The dominant interaction, coherent neutrino-nucleus scattering, has never even been measured before!



SN1987a



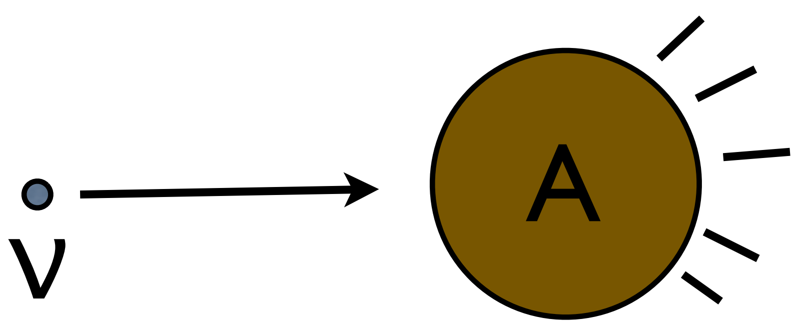
Core-collapse supernova neutrino spectra
All 6 flavors for coherent neutrino-nucleus!



Non-Standard Neutrino Interactions

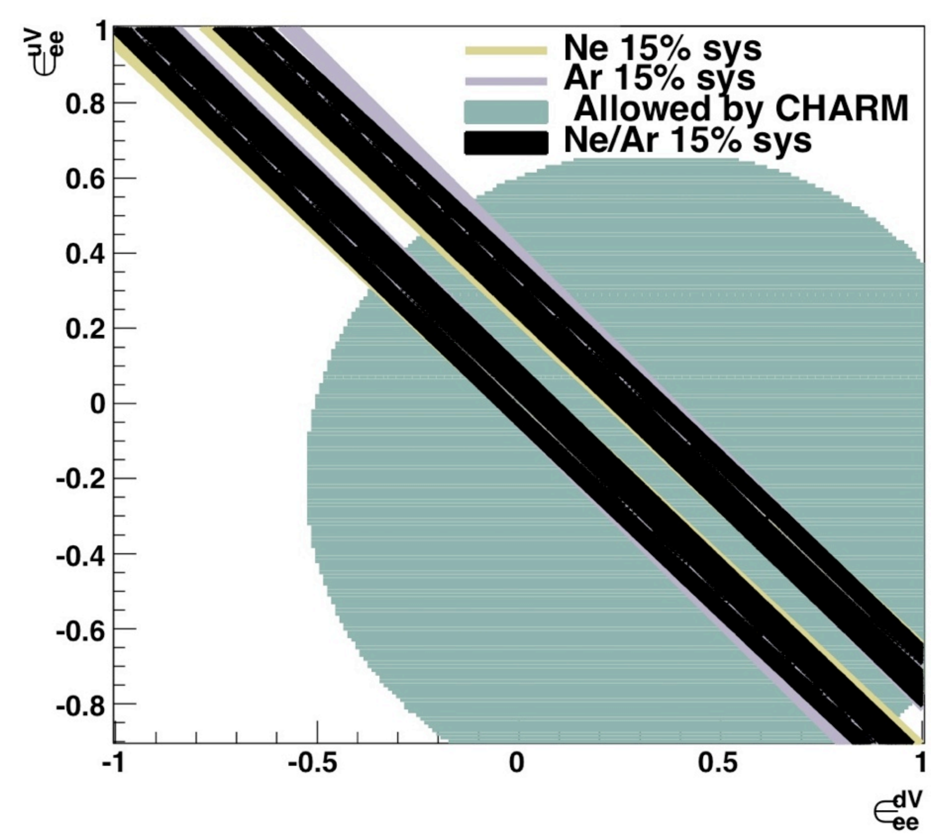
Planned and existing precision experiments are not sensitive to new physics specific to neutrino-nucleus interactions.

The signature of NSI is a deviation from the expected cross section



Non-standard interactions are often poorly constrained:

A coherent neutrino measurement (with just 100 kg-year exposure at SNS) on argon/neon consistent with the SM would provide an order of magnitude improvement on existing limits.



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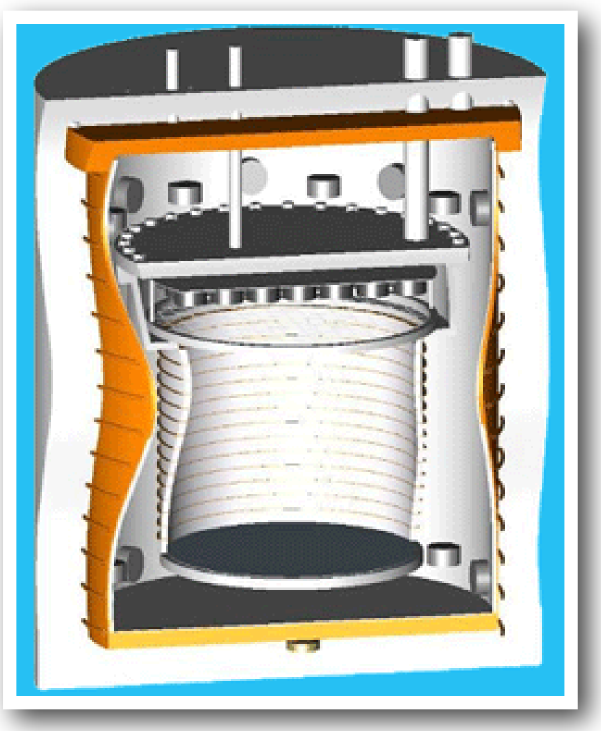
Low energy detection techniques

WIMP detectors are sensitive to keV-scale recoils...
and pretty much any technology will do.



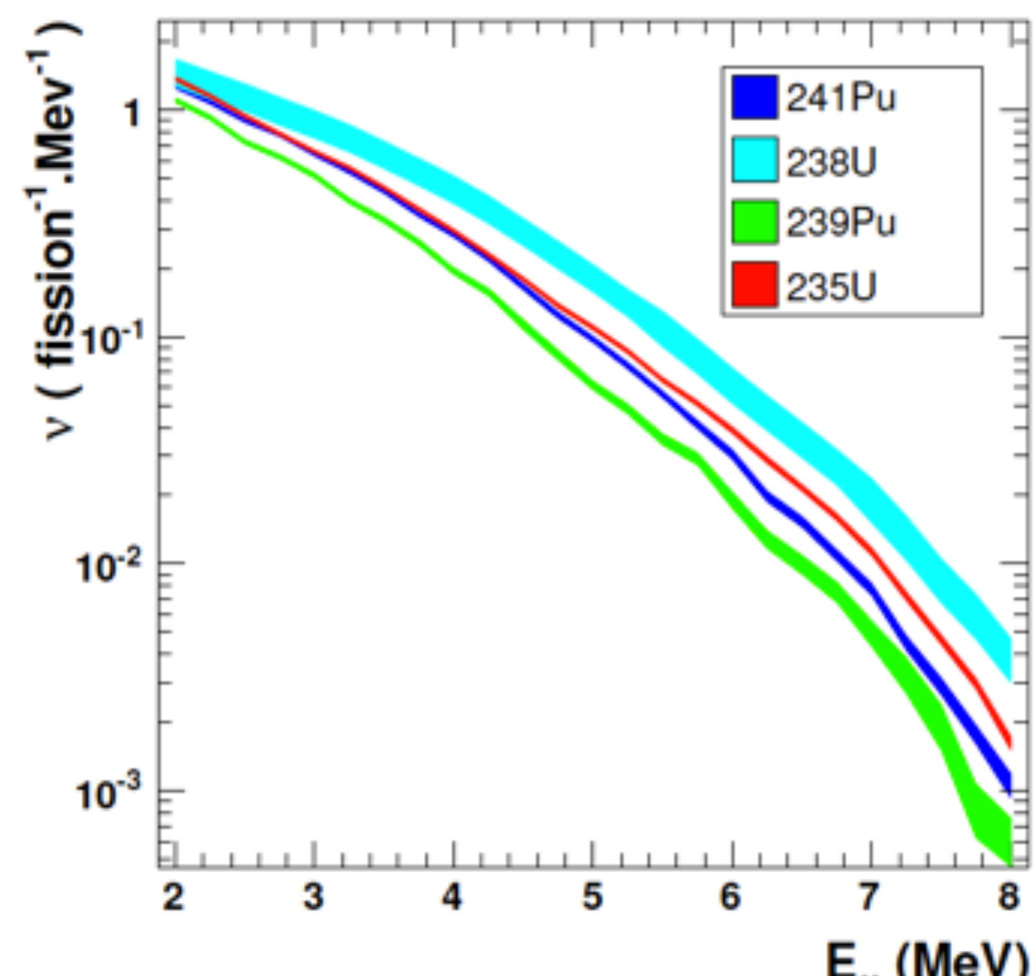
XENON (~3 keV)

CDMS (~7 keV)

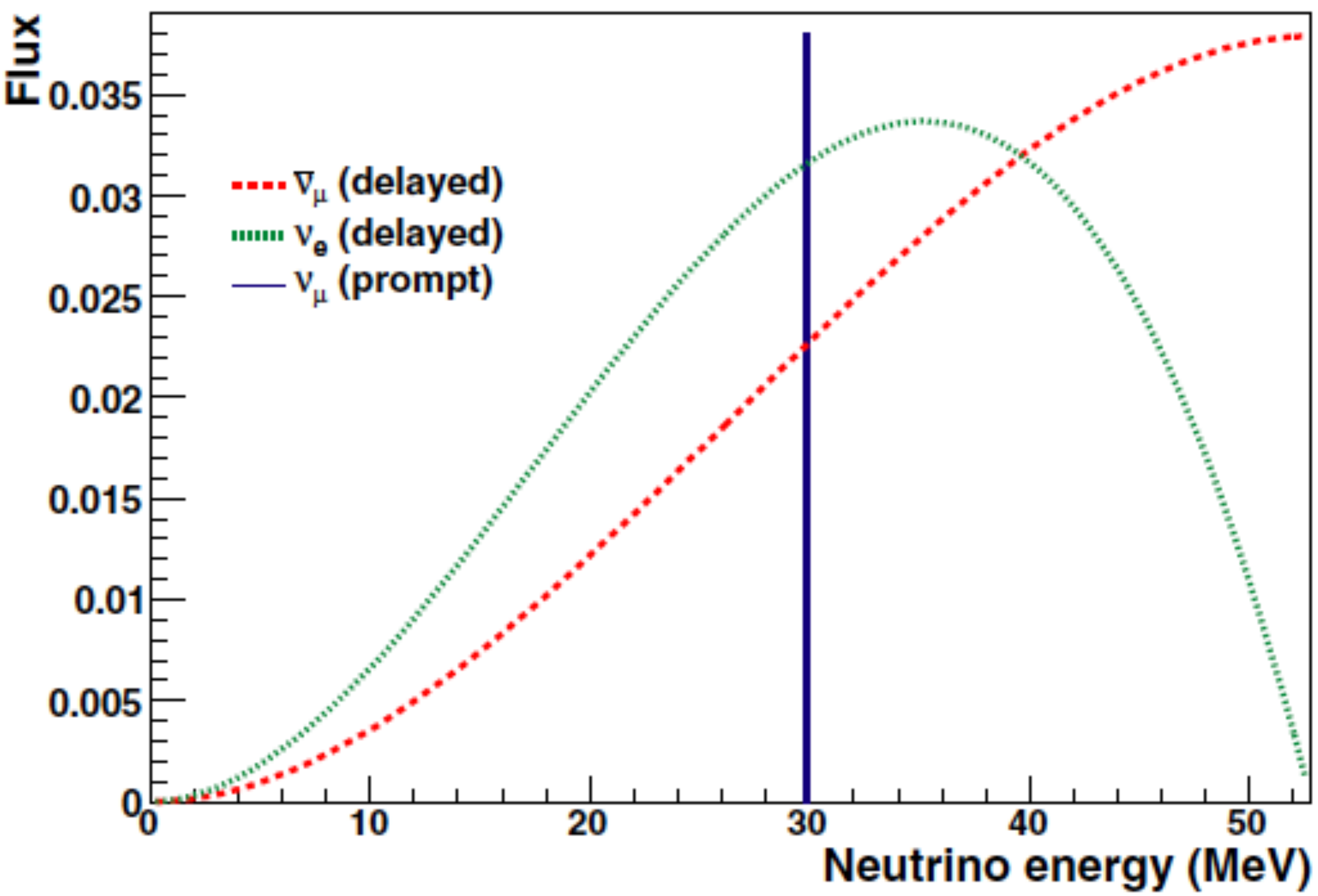
COUPP (~5-10 keV)

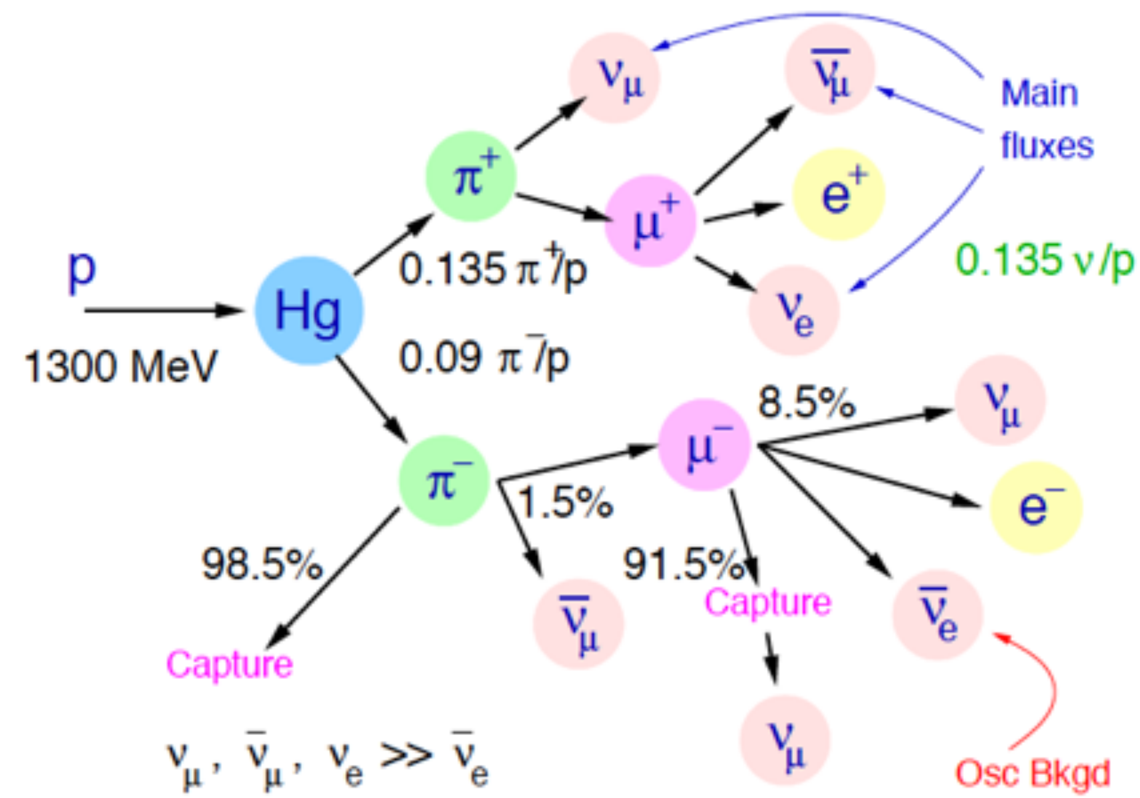
Coherent scattering with a reactor source

- Nuclear reactors are intense sources of neutrinos, producing 2E20 ν/second/GW.
- Reactor off time is often rare and steady state background is a main issue. Also, lower energy than a decay at rest source.



Opportunities with a decay-at-rest source



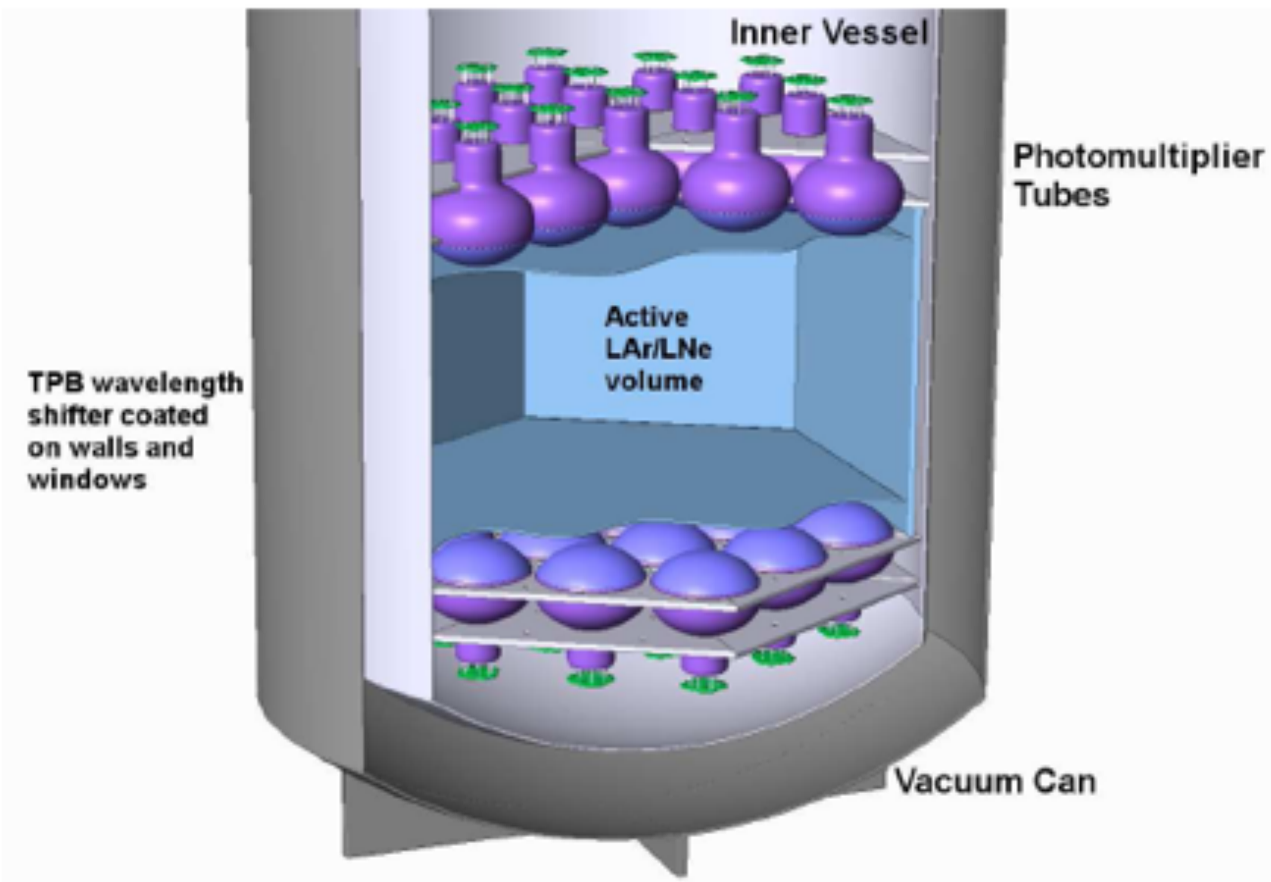


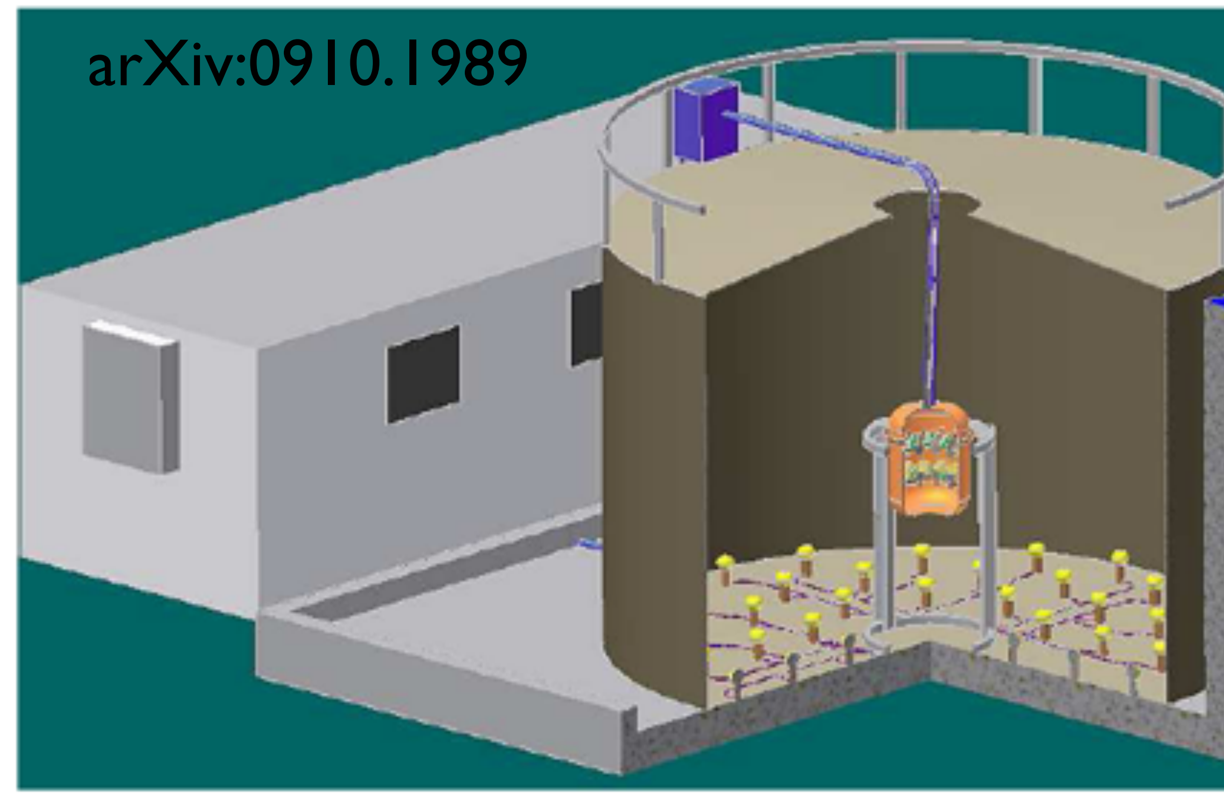
For 1300 MeV protons on Hg (nucl-ex/0309014)

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

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

Coherent Low Energy A Recoils = CLEAR at the Spallation Neutron Source

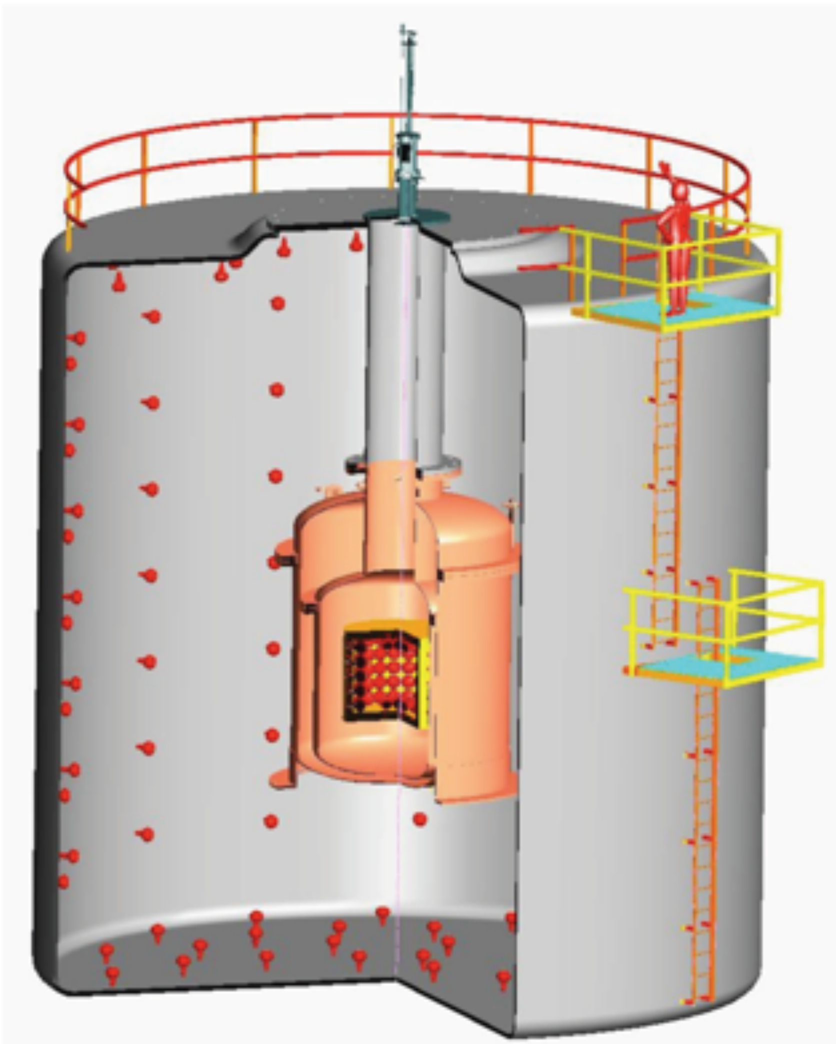




- CLEAR would be on the surface, 46 meters from the stopped-pion neutrino source at SNS.
- Active LAr (LNe) mass = 456 (391) kg.
- 200-1000 signal events expected per year, depending on analysis threshold and target.

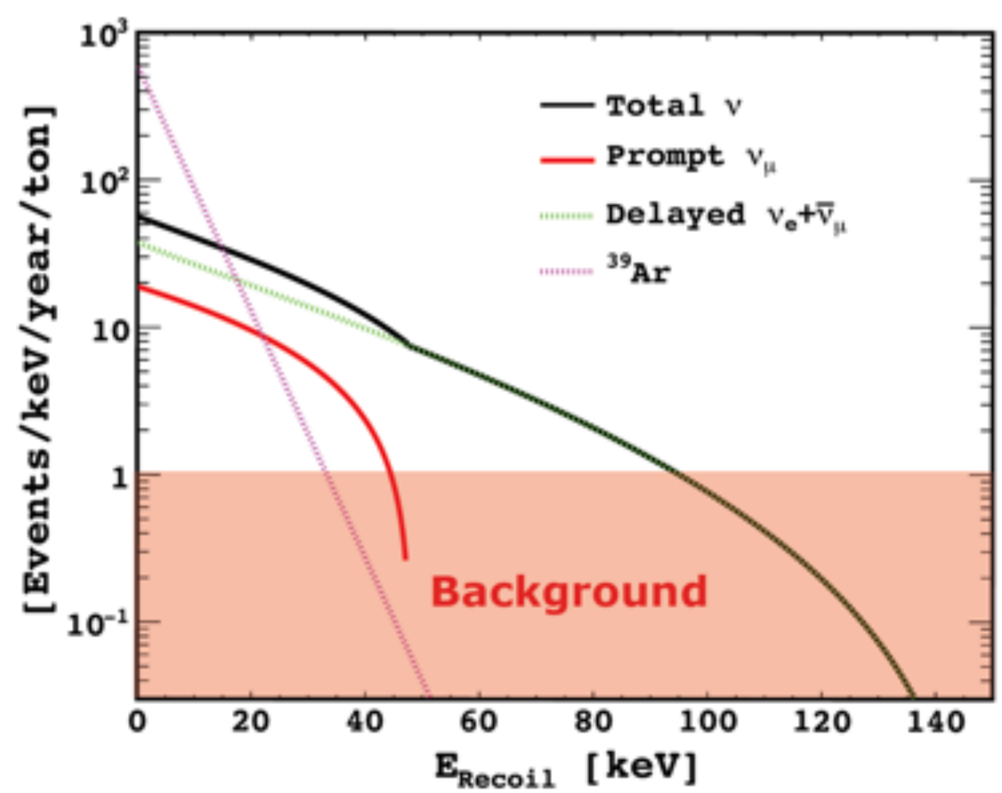
Coherent neutrino detection at Fermilab

A ton-scale LAr detector may perform the first ever observation of the coherent-NCνAS at Fermilab



Envisioned experimental setup

- There is a decay-at-rest neutrino component to the Booster Neutrino Beam, dominating at far-off-axis.
- A WIMP-detector-like single-phase Ar-based device could collect ~200 events/ton/yr at 20 m from the target.



Event rate 20 m from BNB target

Thanks to J. Yoo for plots and information!

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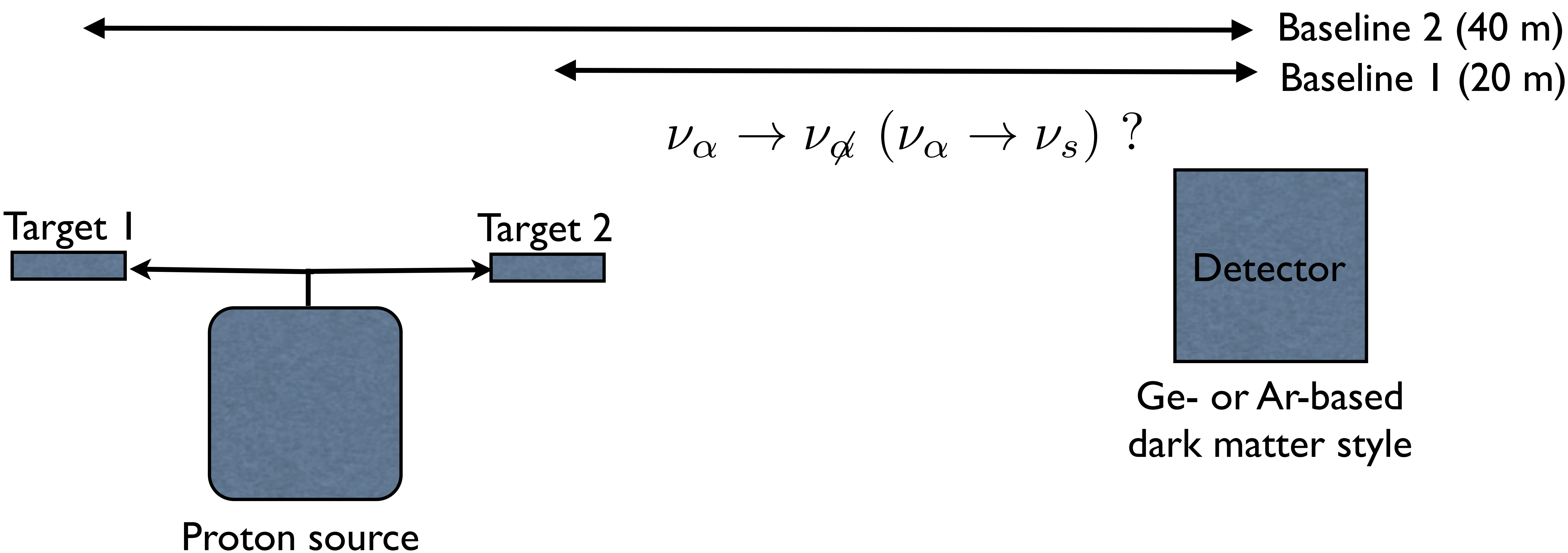
Advantage of the neutral current in a sterile search

- The disappearance of neutrinos interacting via the neutral current is a strict probe of active-to-sterile oscillations.
  - No complicating contributions from active-to-active disappearance.
- Could definitively establish the existence of the sterile neutrino, especially when considered in combination with charged-current-based searches.

$$P(\nu_\alpha \to \nu_{\text{active}}) = 1 - P(\nu_\alpha \to \nu_s)$$
$$= 1 - \sin^2 2\theta_{\alpha s} \sin^2(1.27 \Delta m^2 L/E)$$

$$\sin^2 2\theta_{\alpha s} = 4|U_{\alpha 4}|^2 |U_{s4}|^2$$

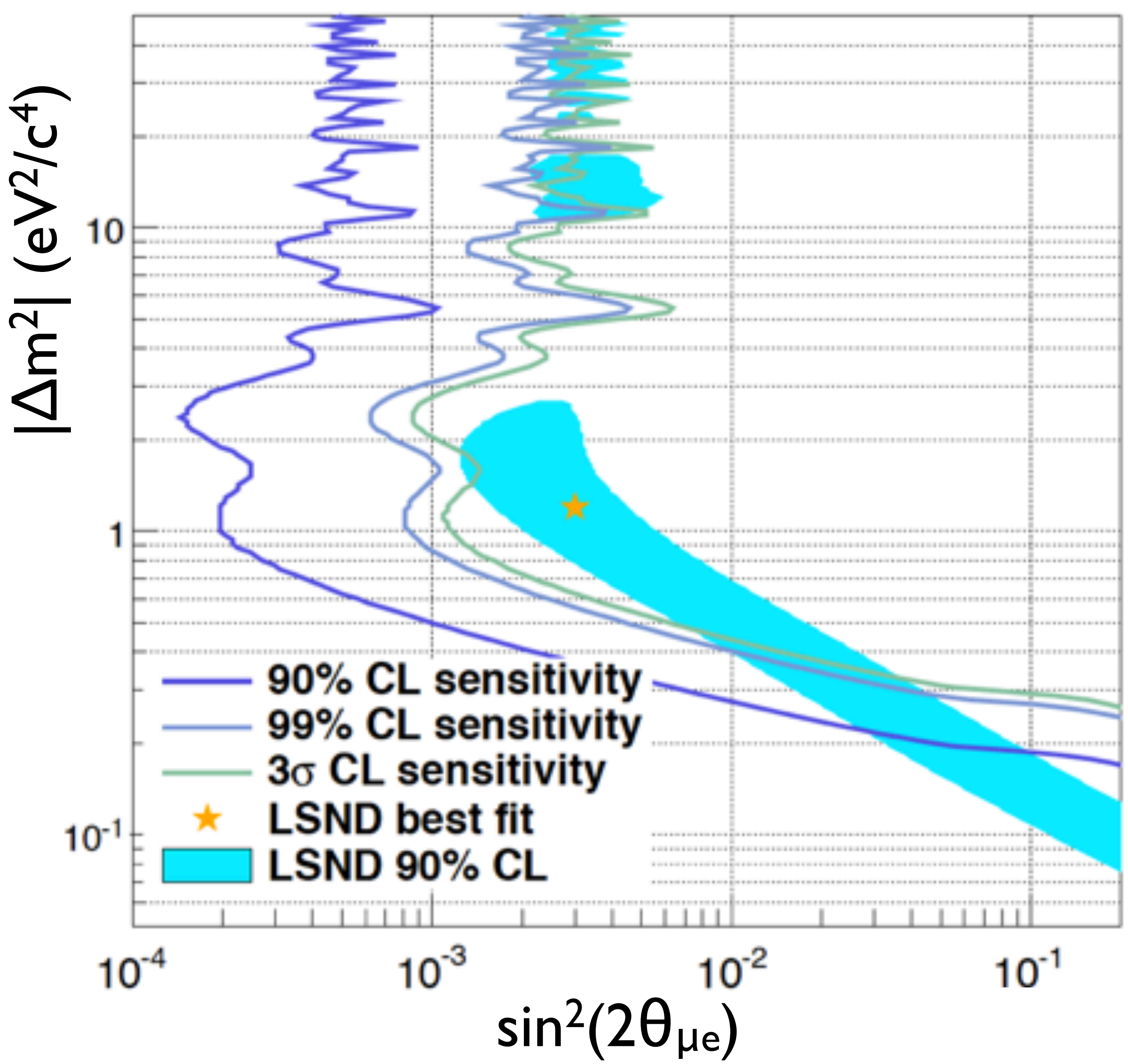
Sensitivity to oscillations w/ coherent scattering

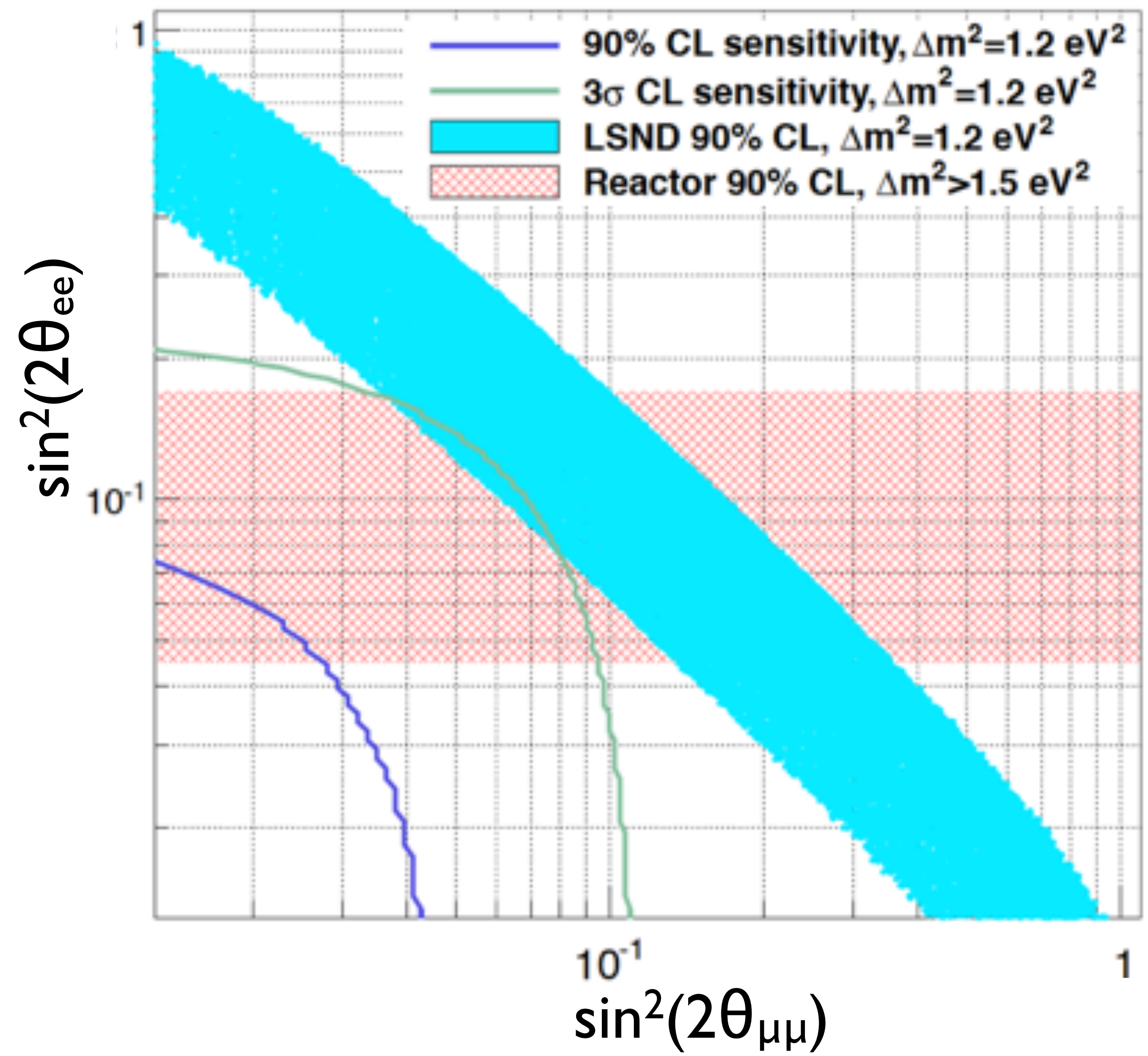


A dual-baseline oscillation search

arXiv:1201.3805 [hep-ph], accepted by Phys. Rev. D

Sensitivity to LSND and reactor/gallium anomalies





5 year run (1 MW, 0.8 GeV) w/ active Ge (LAr) mass = 100 (456) kg

arXiv:1201.3805 [hep-ph], accepted by Phys. Rev. D

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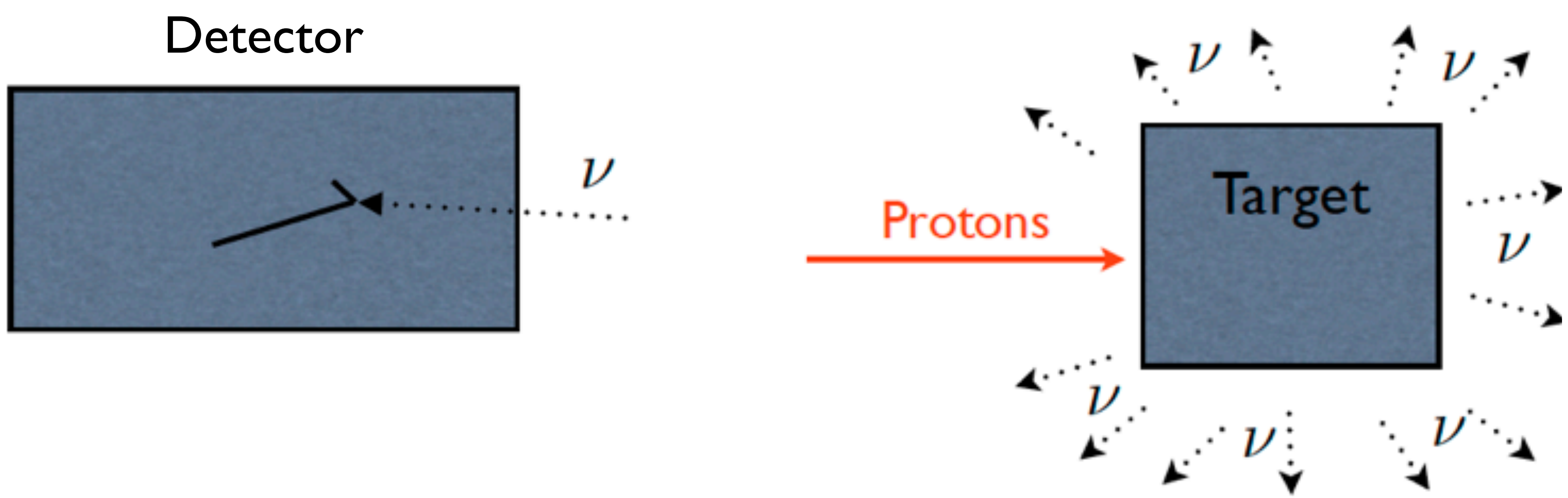
A sterile neutrino search w/ kaon decay at rest

$\nu_\mu \to \nu_e$?



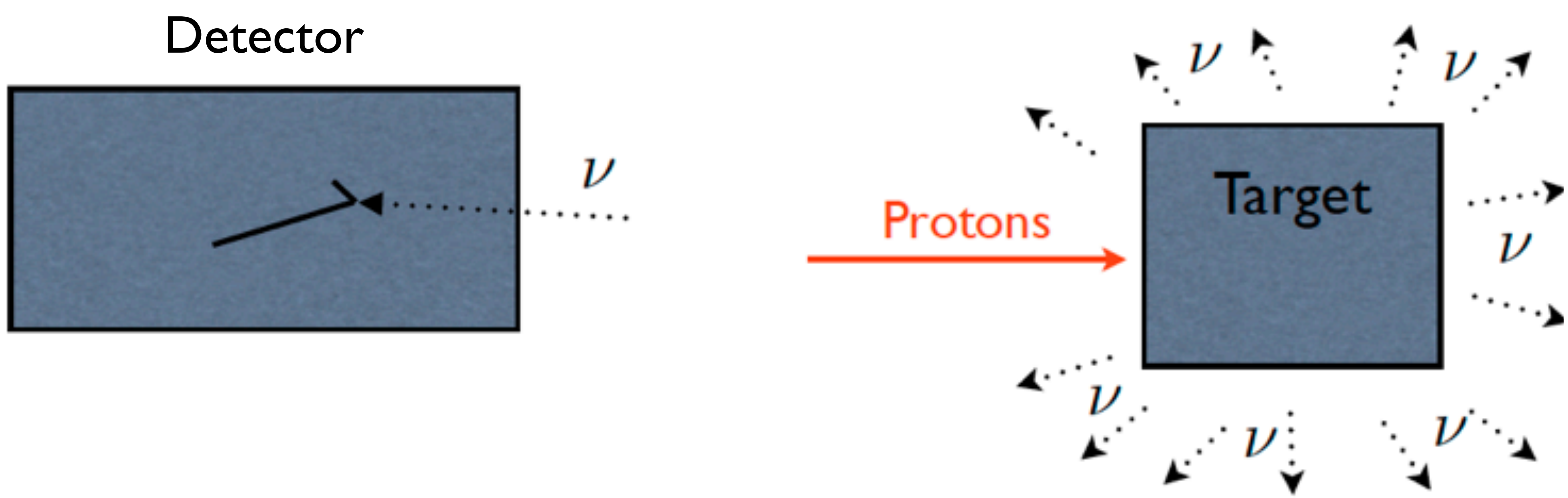
Monoenergetic (235 MeV) neutrino!

$K^+ \to \mu^+ \nu_\mu$

Phys. Rev. D 85 093020 (2012)

A sterile neutrino search w/ kaon decay at rest

$$\nu_\mu \rightarrow \nu_e \;?$$

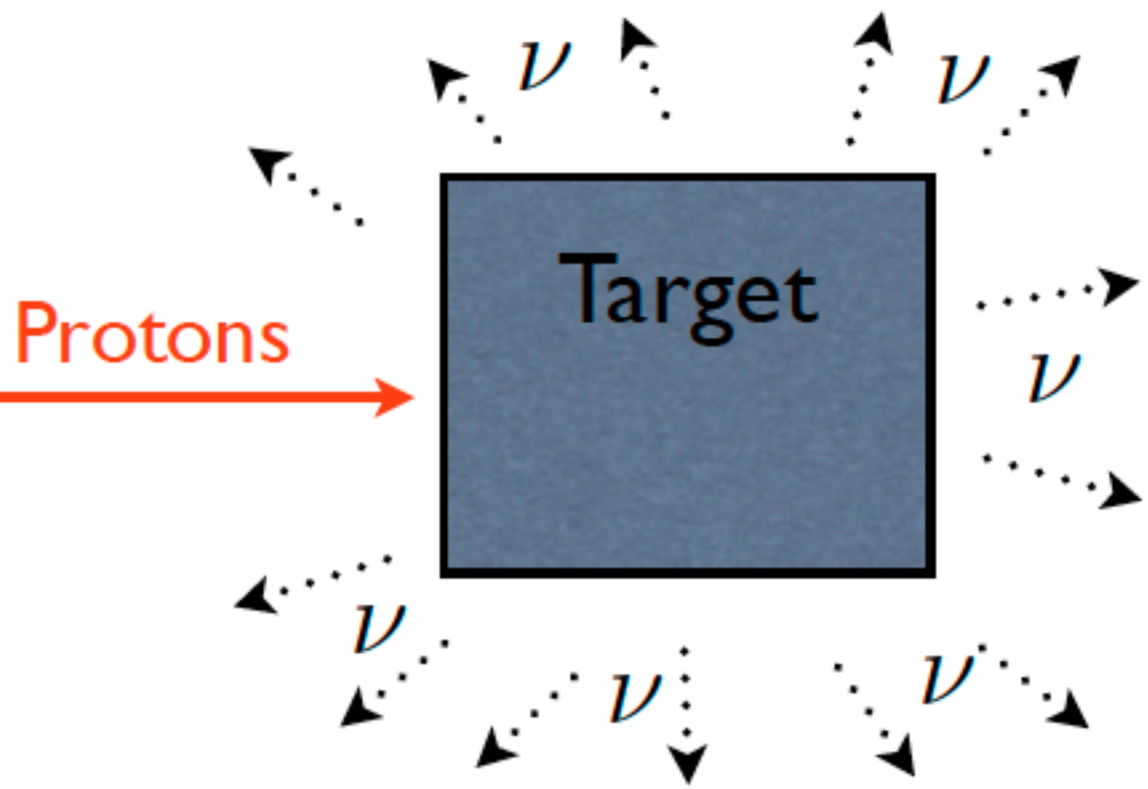


Monoenergetic (235 MeV) neutrino!

$$K^+ \rightarrow \mu^+ \nu_\mu$$

Backgrounds $\begin{cases} K^+ \rightarrow \pi^0 e^+ \nu_e \\ K^0_L \rightarrow \pi^\pm e^\mp \nu_e \end{cases}$

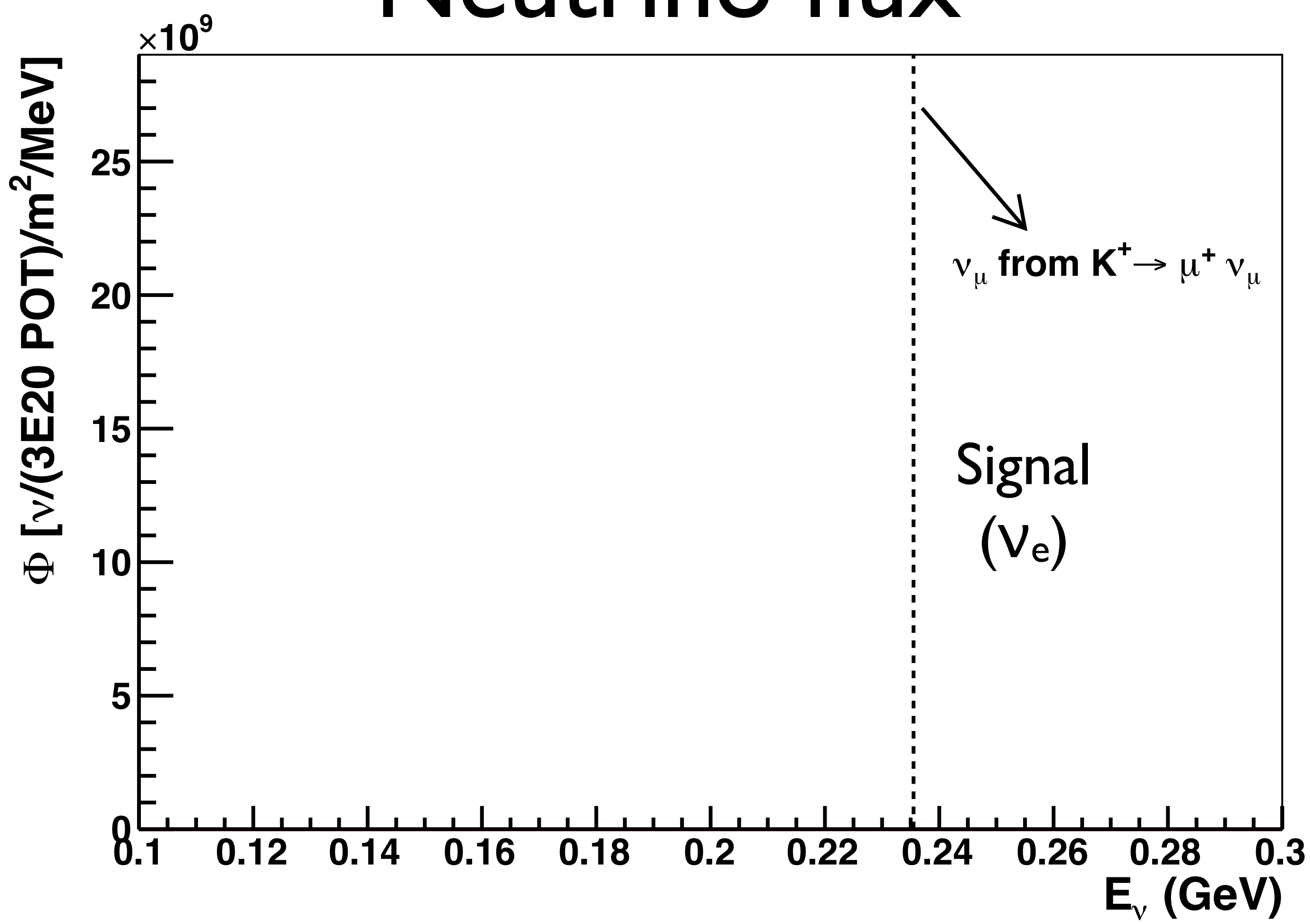
A sterile neutrino search w/ kaon decay at rest



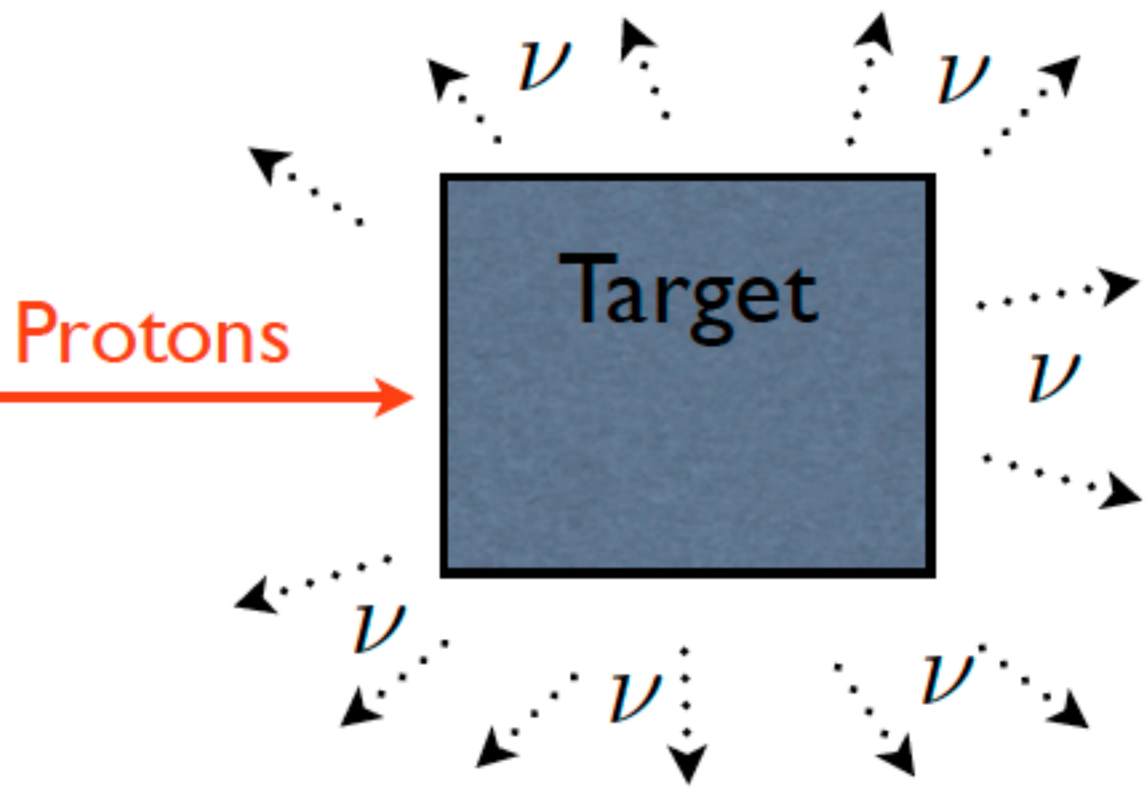
$$K^+ \rightarrow \mu^+ \nu_\mu$$

$$\nu_\mu \rightarrow \nu_e \quad ?$$

Neutrino flux



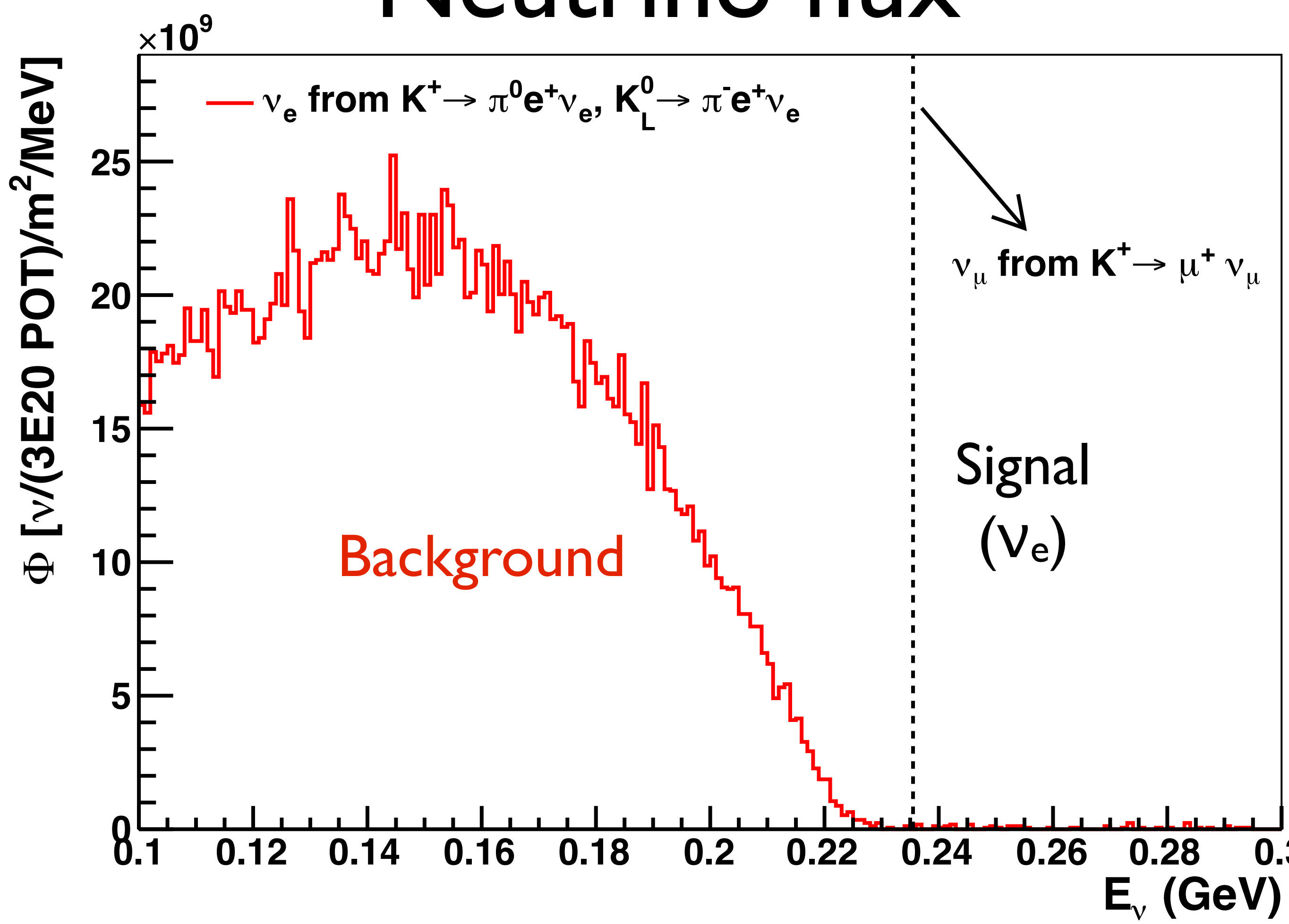
A sterile neutrino search w/ kaon decay at rest



$$K^+ \rightarrow \mu^+ \nu_\mu$$
$$K^+ \rightarrow \pi^0 e^+ \nu_e$$
$$K_L^0 \rightarrow \pi^\pm e^\mp \nu_e$$

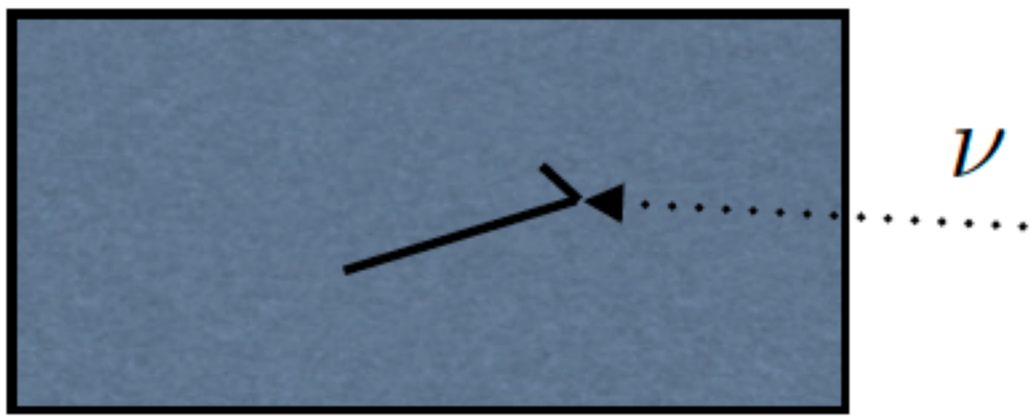
$$\nu_\mu \rightarrow \nu_e \quad ?$$

Neutrino flux



A sterile neutrino search w/ kaon decay at rest

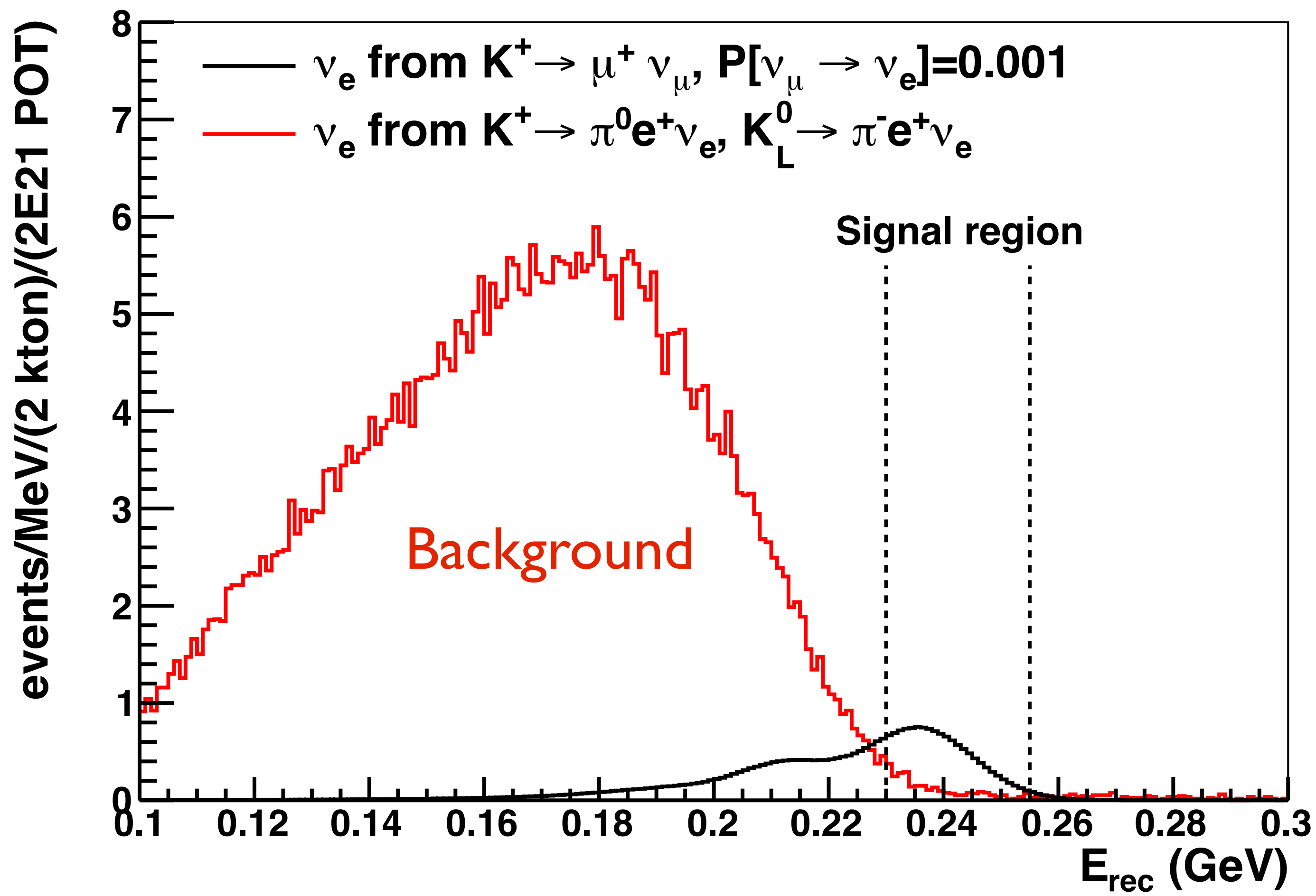
Detector



$$\nu_e n \rightarrow e^- p$$

$$\nu_\mu \rightarrow \nu_e \quad ?$$

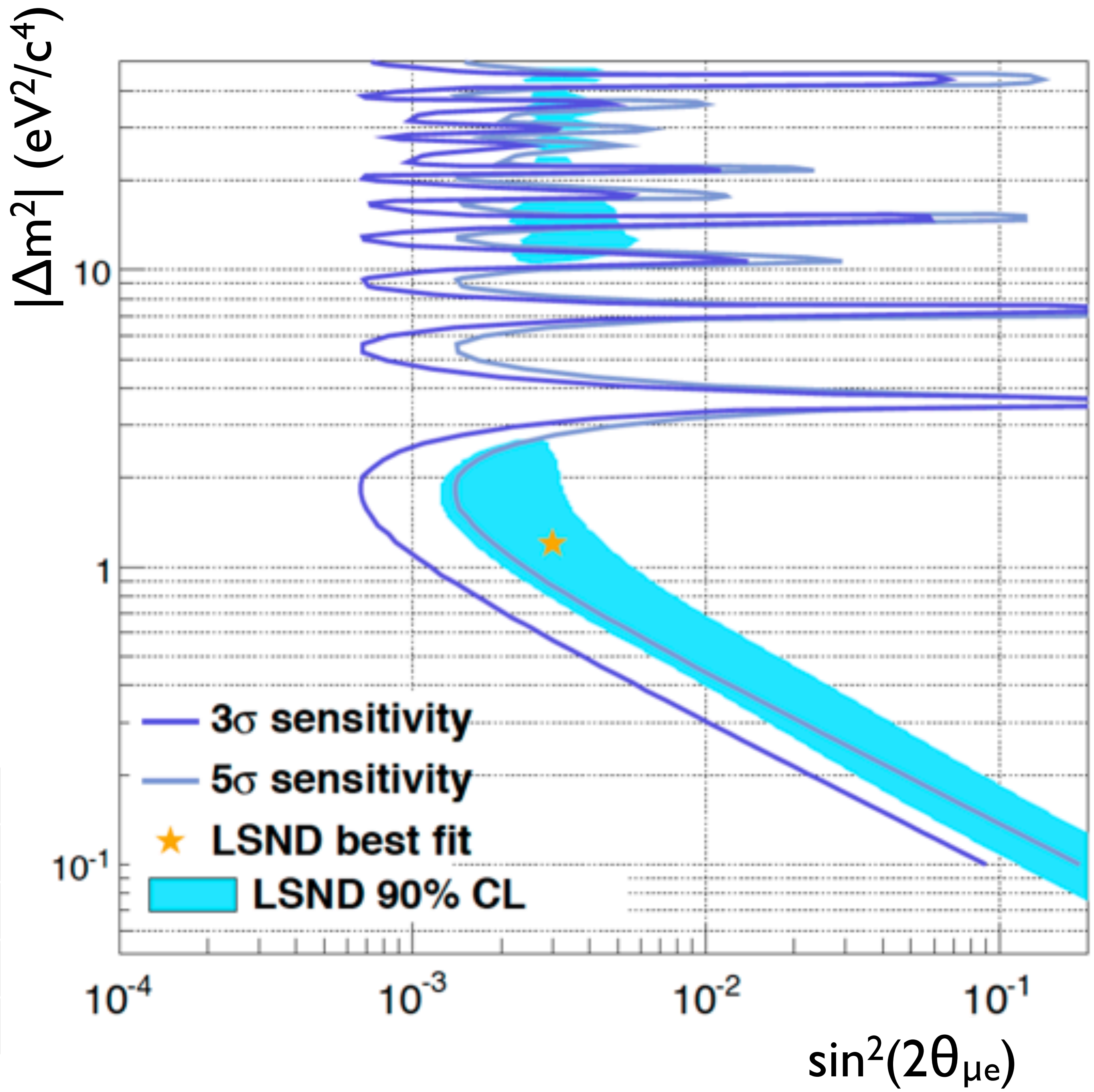
Neutrino rate



- The concept is analogous to a neutrinoless double beta decay search.
- You look for an excess near the endpoint of a well understood and measured background distribution.

A sterile neutrino search w/ kaon decay at rest

- This experiment can be accomplished at a number of intense >3 GeV proton facilities around the world.
- Gives >5σ sensitivity to most of the LSND allowed region.



Proton target	Copper
Exposure	2×10^{21} protons on target
Baseline	160 m
Neutrino target	^{40}Ar (22 neutrons)
Neutrino target mass	2 kton

Phys. Rev. D 85 093020 (2012)

Conclusions

- There is a lot of physics in coherent neutrino-nucleus scattering. The process hasn't even been observed before!

- A definitive probe of the sterile neutrino can be provided by a coherent oscillation search.

- A kaon-based neutrino source is a new idea to search for the sterile neutrino.

- A decay-at-rest source created via an intense proton beam provides an enormous opportunity for a lot of physics.

Backup

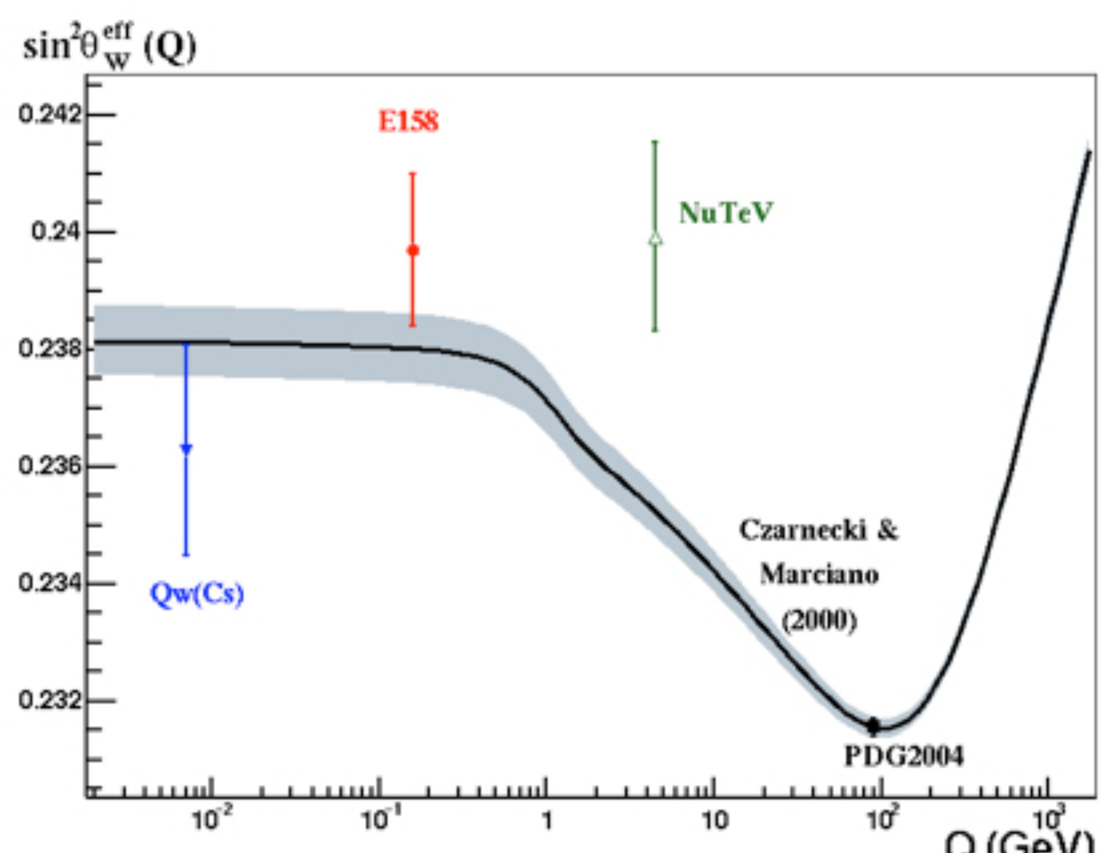
Coherent scattering and the weak mixing angle

$$\left(\frac{d\sigma}{dE}\right)_{\nu A} = \frac{G_F^2}{2\pi}\frac{Q_w^2}{4}F^2(2ME)M[2 - \frac{ME}{k^2}]$$

$$Q_w = N - (1 - 4\sin^2\theta_W)Z$$

where Z is the number of protons, N is the number of neutrons, and θ_W is the weak mixing angle.

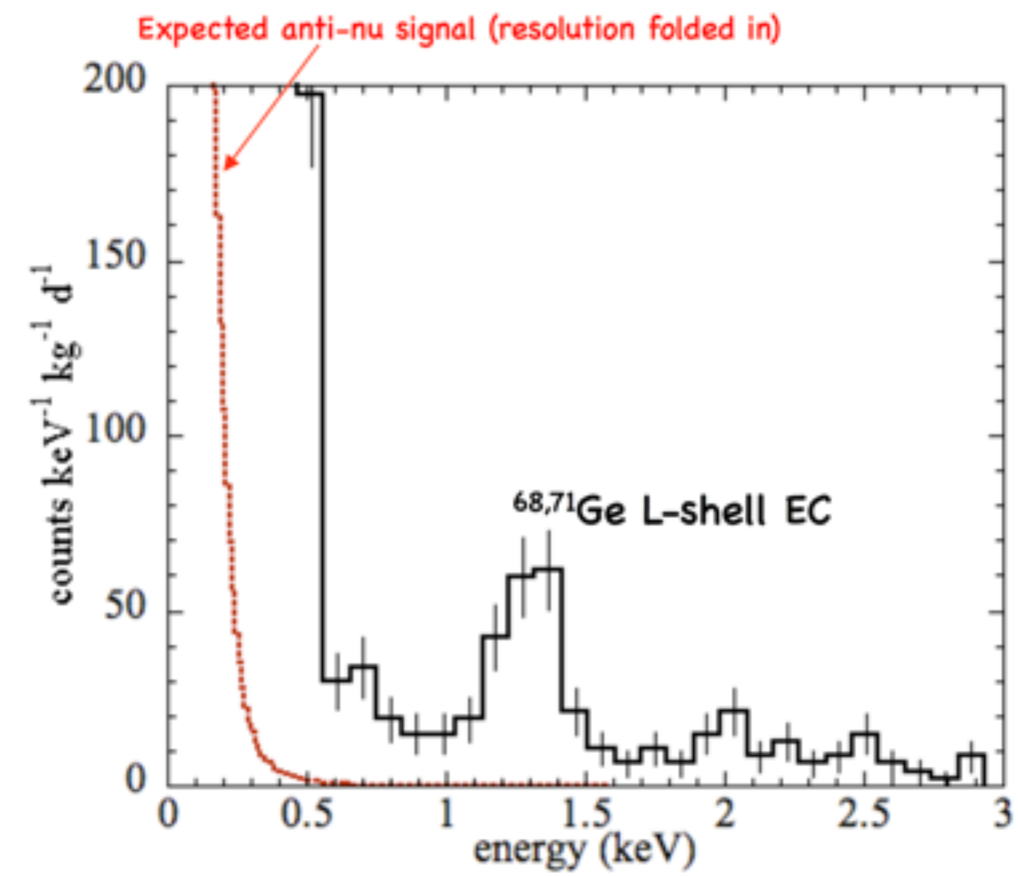
The weak mixing angle can be found by measuring the absolute cross-section.



There are no neutrino measurements near Q~0.04 GeV/c.

COGENT
and coherent neutrinos

- COGENT (Ge-based) is an experiment with applications in $0\nu\beta\beta$ decay (MAJORANA), light dark matter direct, and coherent neutrino detection.
- Prototype detector ran 20 m from ~1GW reactor core (SONGS).
- Need energy threshold and noise improvements for coherent neutrino detection.
- Improvements may allow coherent detection soon!

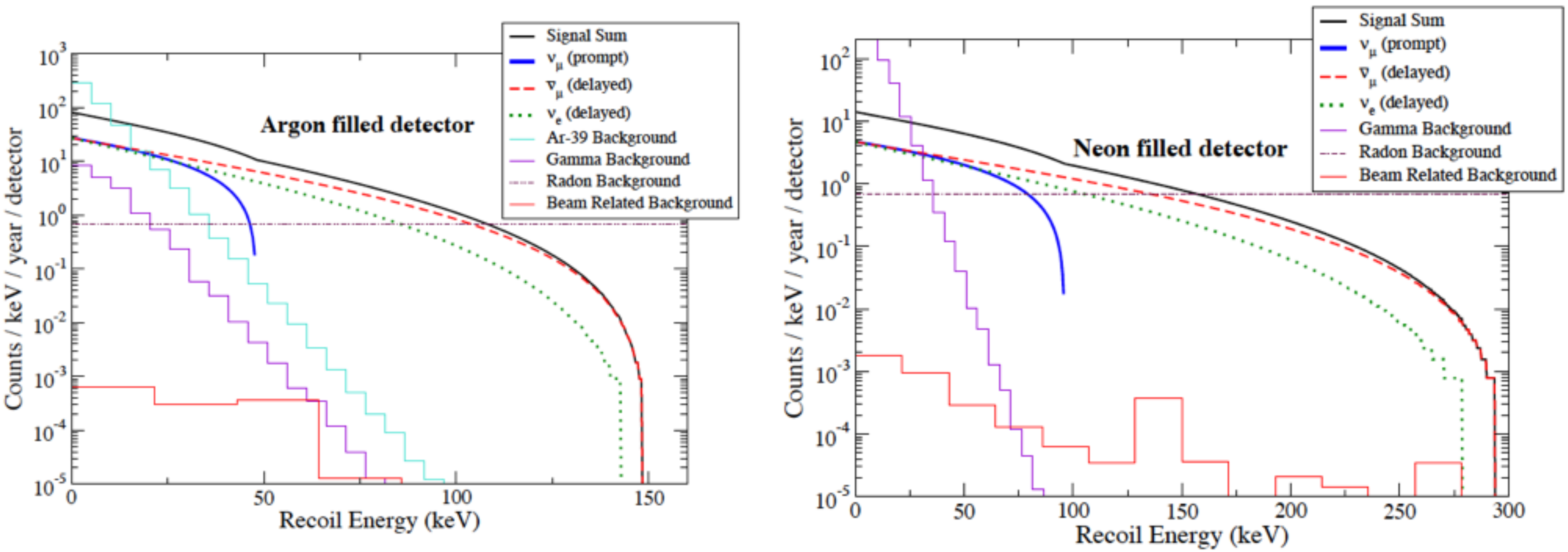


Observed spectrum by COGENT

Thanks to J. Collar!

Backgrounds for CLEAR

Intrinsic, steady-state backgrounds are the main worry for CLEAR.
Nuclear recoils due to neutrons look like signal.



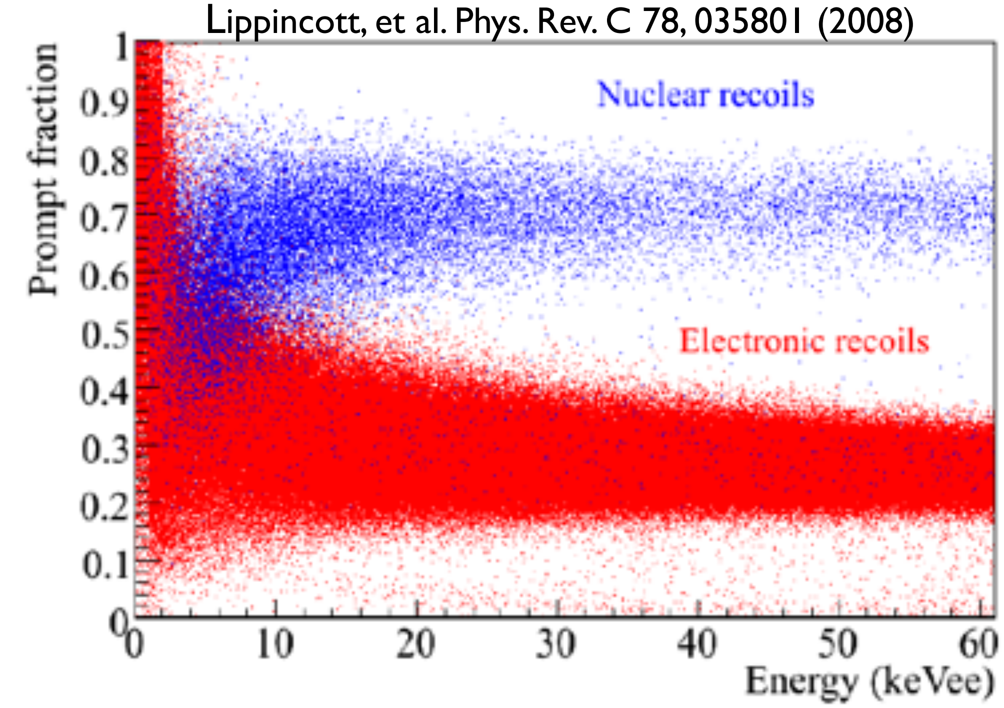
hep-ex: 0910.1989, with credit to K. Scholberg, J. Nikkel, T. Empl, and T. Wongjirad

Note that CR-related backgrounds are not plotted here.
They can be measured quite well during the beam dead time. However, the CR rate drove the CLEAR single-phase design (see: dead time for a two-phase).

Background mitigation

- A repetition frequency of 2000 Hz with a 100 microsec window gives a rejection of steady state background of 0.2 and knowledge of the steady-state rate. Fast scintillation signal from individual events can be known to within ~10ns
- Mitigation of backgrounds (see: WIMP-detection):
  - **Ar-39 (beta) background:** Neon, Xenon, or depleted Argon and Pulse Shape Discrimination (PSD), charge-to-light ratio in time in a dual phase detector.
  - **Radon background:** Mechanical scrubbing, HEPA filters, and radon-impermeable plastic.
  - **Gamma backgrounds (238-U, 232-Th, 40-K):** PSD, charge-to-light ratio in time in a dual-phase detector.
  - **Beam- and cosmic ray-related:** Shielding. Underground, these backgrounds will be much lower as compared to SNS. Expensive shielding/veto is probably not necessary with 150 mwe overhead.

Lippincott, et al. Phys. Rev. C 78, 035801 (2008)



PSD in argon

Singlet (short lifetime) and triplet (long lifetime) states are populated differently for nuclear and electronic recoils