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Coherent elastic neutrino nucleus scattering at a stopped pion source

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Coherent Elastic Neutrino Nucleus Scattering at a Stopped Pion Source

Kate Scholberg, Duke University

Nutech '09

OUTLINE

- Coherent νA scattering

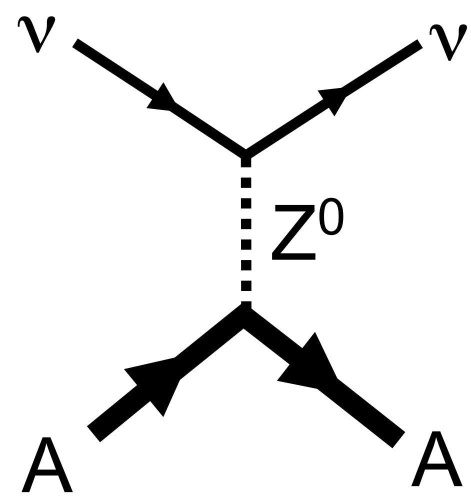
- Measurement in a stopped pion beam
  - Possible detectors
  - Rate calculations

- Physics that could be explored

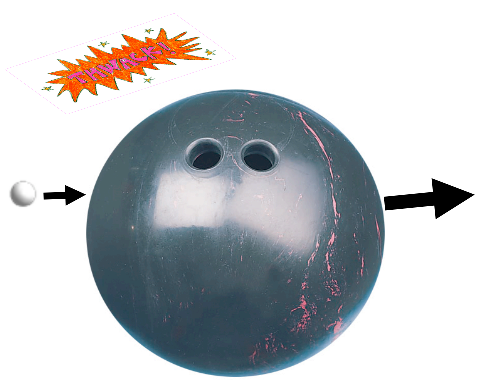
- The CLEAR Experiment

Coherent neutral current neutrino-nucleus elastic scattering

$$\nu + A \rightarrow \nu + A$$



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils



- Neutral current, so flavor-blind
- Coherent up to $E_\nu \sim 50$ MeV
- Important in SN processes & detection

This process has a cross-section easily calculable in the Standard Model:

A. Drukier & L. Stodolsky, PRD 30:2295 (1984)
Horowitz et al. , PRD 68:023005 (2003) astro-ph/0302071

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

k: neutrino energy

N: no. of neutrons; Z: no of protons

θ: scattering angle of ν

F: form factor (depends on nucleus);

Q: 4-mom transfer

G: Fermi constant; θ_w: Weinberg angle

And the cross-section is *large!*

Typical cross-sections for other neutrino interaction processes in the few-50 MeV range:

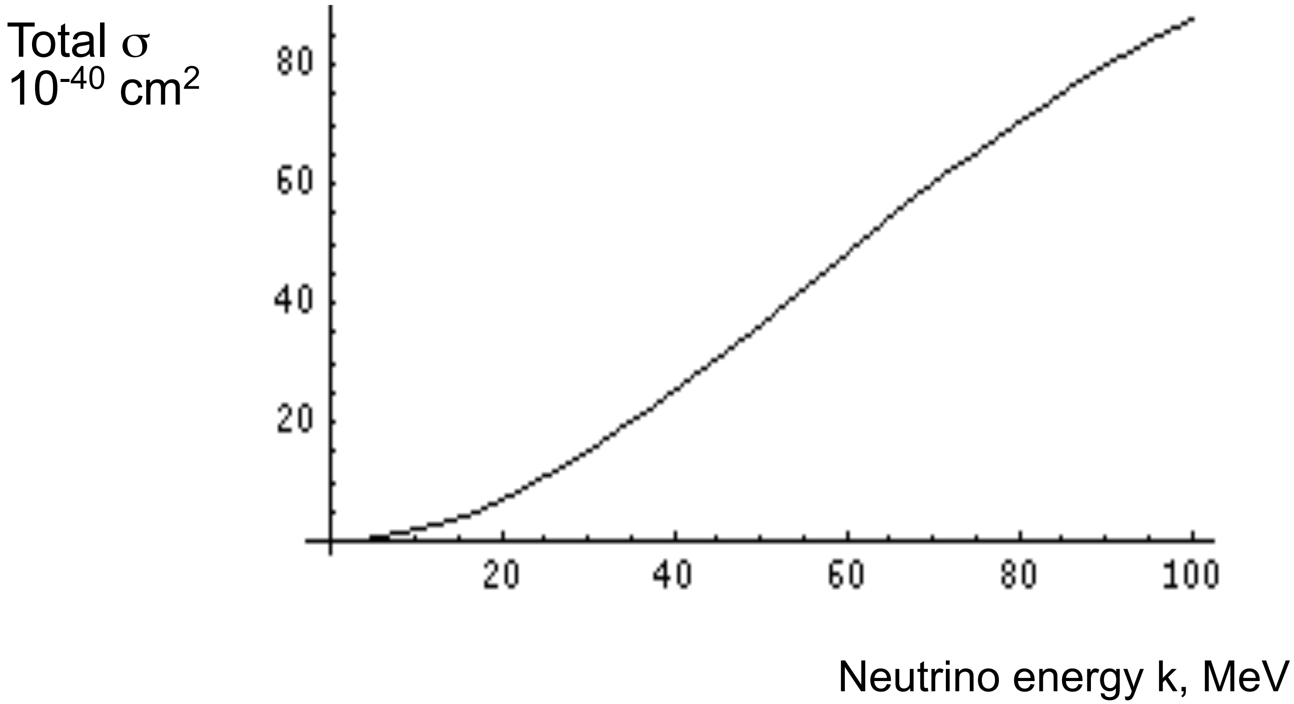
Coherent ν-A elastic: $\sim 10^{-39}$ cm^2 very large

ν-A charged current: $\sim 10^{-40}$ cm^2

$\bar{\nu}$-p charged current: $\sim 10^{-41}$ cm^2

ν-e elastic : $\sim 10^{-43}$ cm^2

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

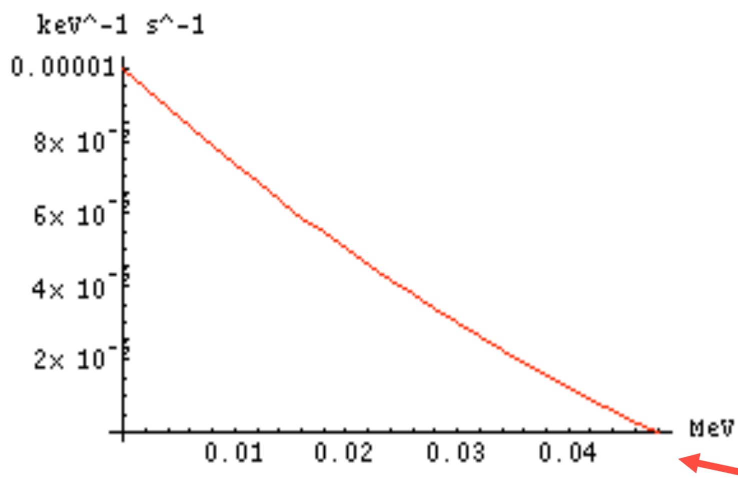


Total cross-section increases with ν energy, and scales approximately as N²

But this coherent ν A elastic scattering has never been observed!

Why not?

Nuclear recoil energy spectrum for 30 MeV ν



Max recoil energy is $2E_\nu^2/M$ (48 keV for Ar)

Recoil energies are tiny!

Most neutrino detectors (water, gas, scintillator) have thresholds of at least ~MeV: so these interactions are hard to see

Why try to measure this?

- It's never been done!

- Important in supernova processes
- Important for supernova ν detection

- Deviations from expected x-scn
  may indicate non-SM processes

???

- Possibly even applications..

e.g. Barbeau et al., IEEE Trans. Nucl. Sci. 50: 1285 (2003)
C. Hagmann & A. Bernstein, IEEE Trans. Nucl. Sci 51:2151 (2004)

Attempts so far to measure ν-A elastic scattering:
(COGENT, TEXONO)

Ultra-low energy detectors, e.g. germanium (~ keV thresholds) near reactor neutrino source

- Reactor ν flux is huge, but ~ few MeV, so recoil energies are tiny (~few keV or less)

- Detectors with ~ keV thresholds are hard to make large (>kg) and clean

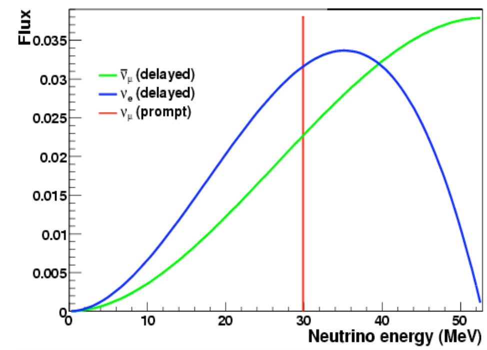
- Hard to get 'beam-off' time for background measurement

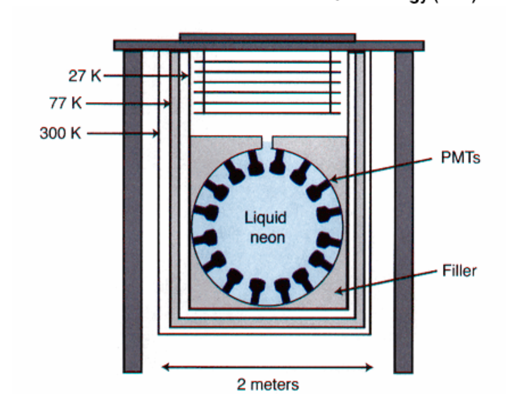
- Electron antineutrino flavor only

Another approach: use *stopped pion ν beam* with low threshold detector

Stopped pion beam: 10-50 MeV energies

- cross-section higher and recoil energies higher at higher energy
- high ν flux available
- background rejection for pulsed beam
- several flavors





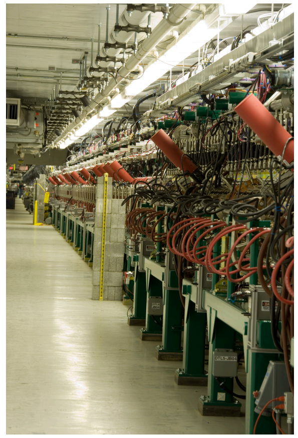
New detector technologies now (or will soon be) available!

- large, low background, low threshold detectors for pp solar neutrinos or WIMPs
- up to ton scale detectors with <~10 keV thresholds

Spallation Neutron Source

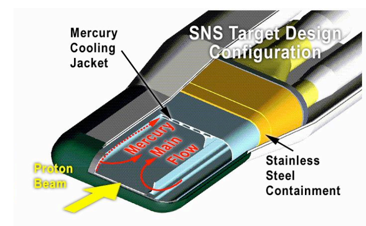
$1B facility for neutron science: most intense pulsed neutron beams in the world for chemistry, materials science, engineering, structural biology...

Proton linear accelerator, initial operation at 1.0 GeV; upgrade to 1.3 GeV planned



Accumulator ring, 400 ns pulse width

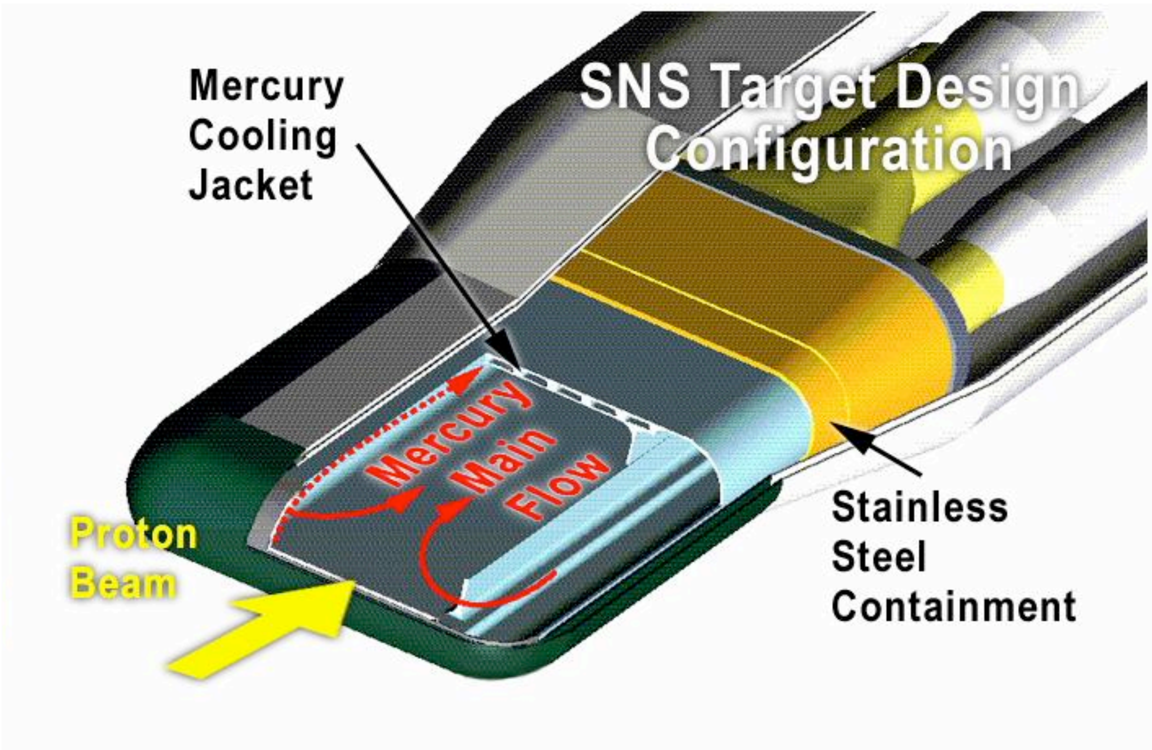
Proton beam bombards liquid Hg target

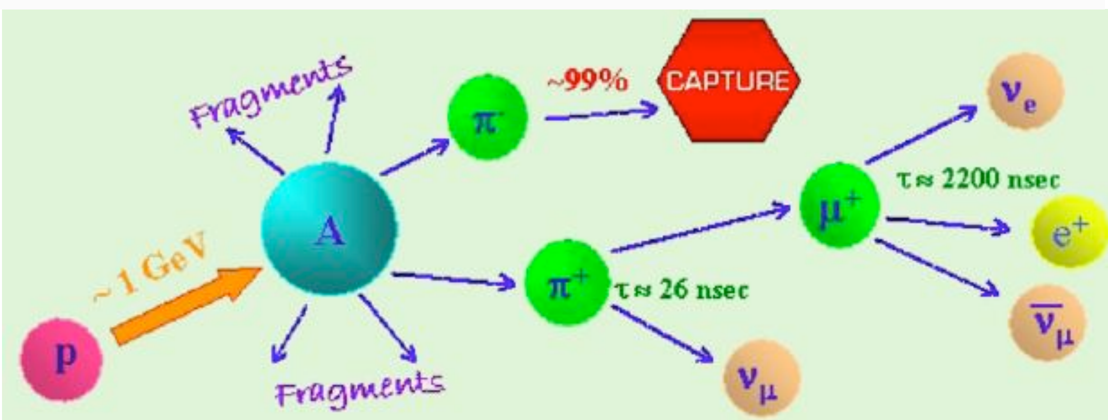


24 μC/pulse at 60 Hz $\Rightarrow$ 1.4 MW power

Full power in early 2010

Neutrinos are a free by-product!





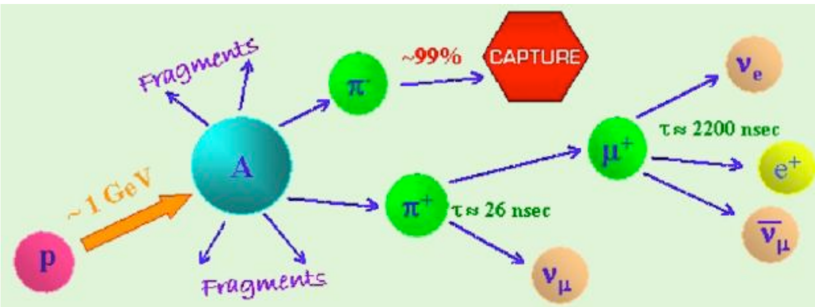
In addition to kicking out neutrons, protons on target create copious pions:

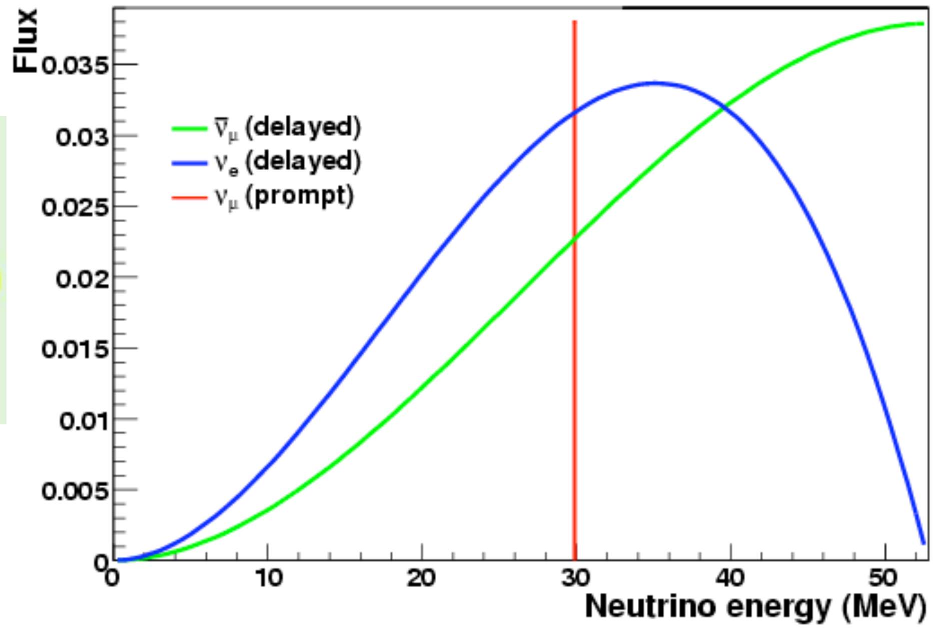
π^- get captured;

π^+ slow and decay at rest

Expected neutrino spectrum

F. Avignone and Y. Efremenko, J. Phys. G: 29 (2003) 2615-2628





$$\pi^+ \to \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

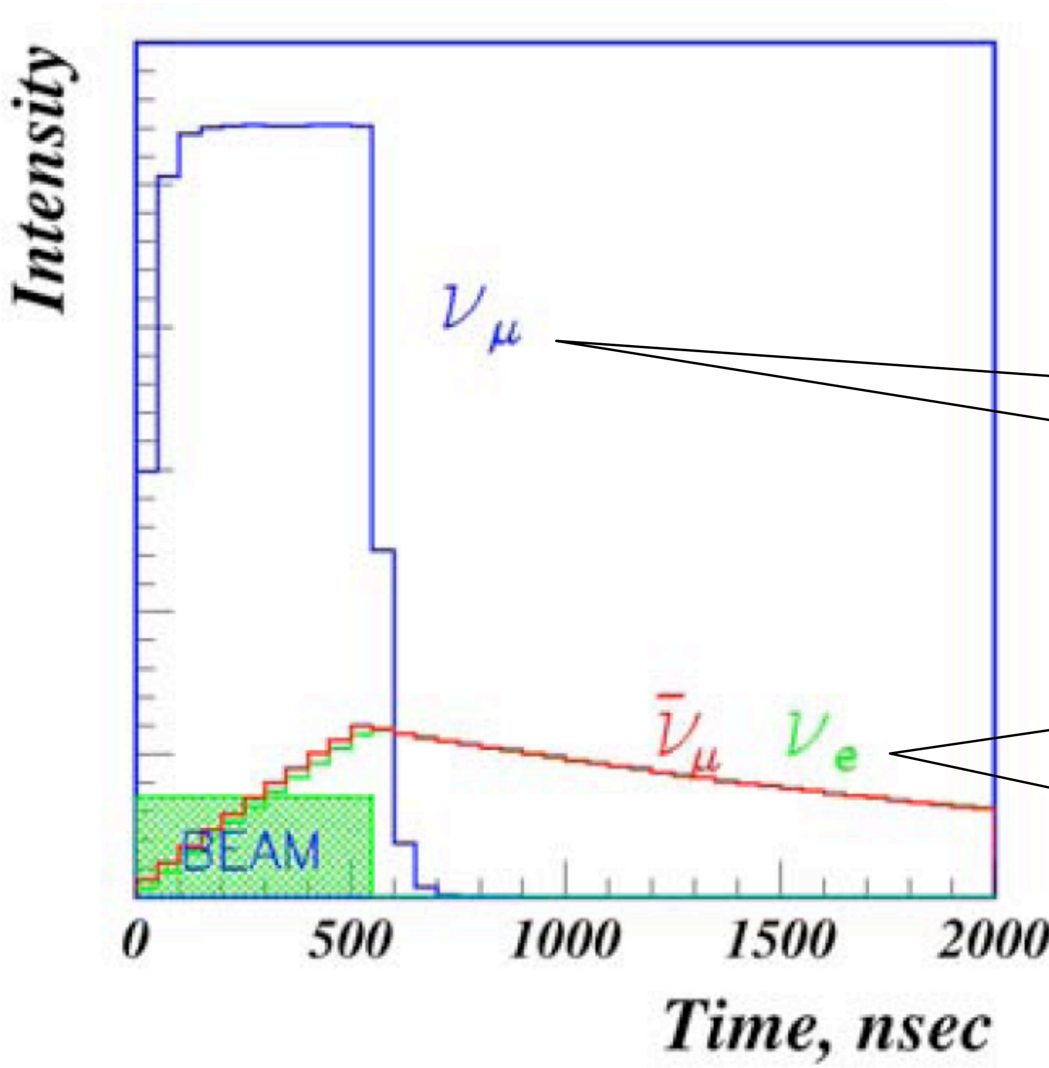
$$\downarrow$$

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

3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Neutrino flux: few times 10^7 /s/cm^2 at 20 m ~0.13 per flavor per proton

Time structure of the source



60 Hz *pulsed* source

in time with beam

delayed on μ decay timescale (2.2 μs)

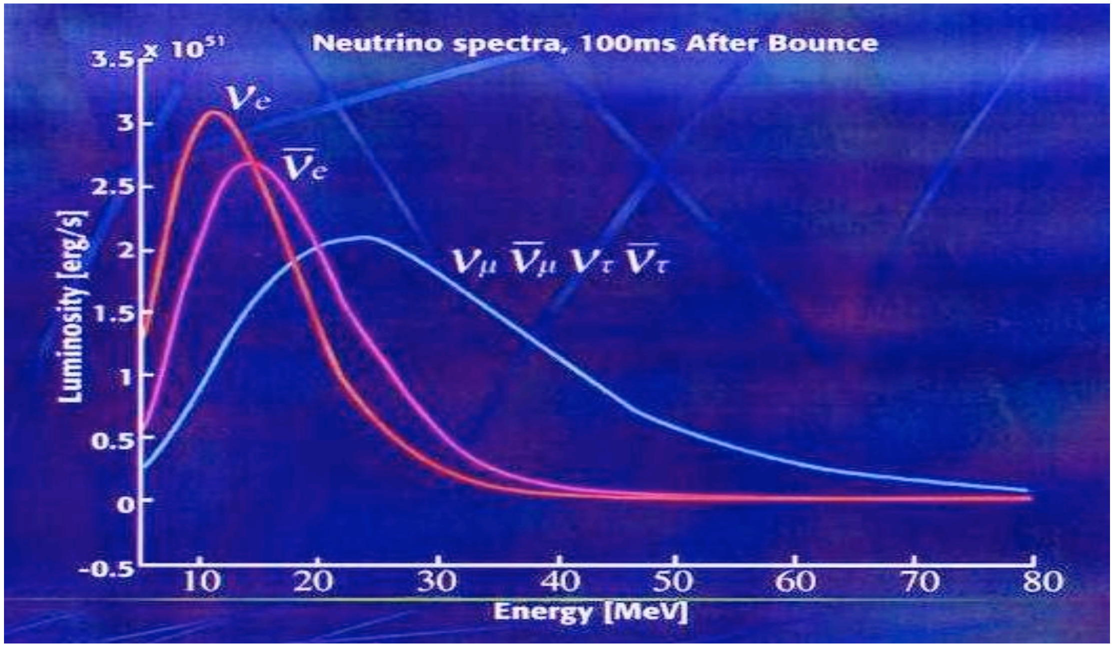
Background rejection factor ~few x 10^{-4}

Comparison of stopped-pion neutrino sources

	LANSCE	ISIS	SNS	JSNS
Location	USA (LANL)	UK (RAL)	US (ORNL)	Japan (J-PARC)
Proton energy	0.8 GeV	0.8 GeV	1 (1.3) GeV	3 GeV
Beam current	70 mA	0.2 mA	1.1 mA	0.33 mA
Time structure	Continuous	Two 200 ns bunches separated by 300 ns	380 ns FWHM	1 ms
Repetition rate	N/A	50 Hz	60 Hz	25 Hz
Power	56 kW	160 kW	> 1 MW	1 MW
Target	Various	Water-cooled tantalum	Mercury	Mercury

-very high intensity ν's
-~below kaon threshold
-nearly all decay at rest
-narrow pulses

Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum!



Study CC and NC interactions with various nuclei, in few to 10's of MeV range

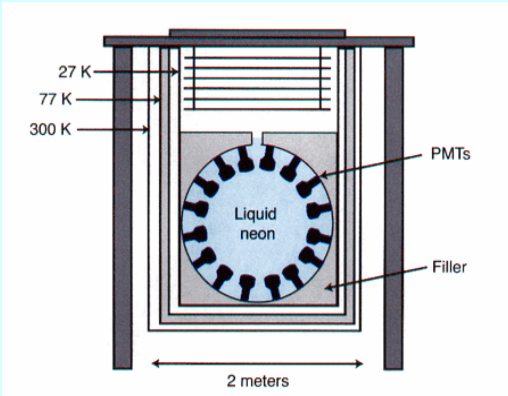
1. **Understanding of *core-collapse SN processes***
2. **Understanding of *SN ν detection* processes**

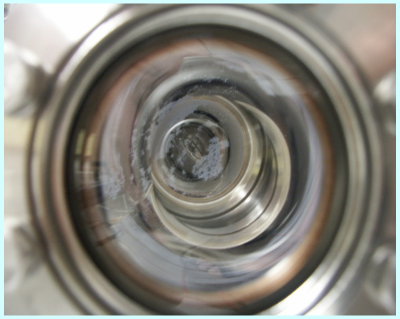
NuSNS (Neutrinos at the SNS)

Multi-target program: currently on hold

Detector technologies that might work: (WIMPs)

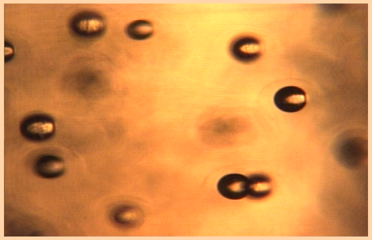
Noble gas/liquid, single or dual-phase (Ne, Ar, Xe)





Germanium

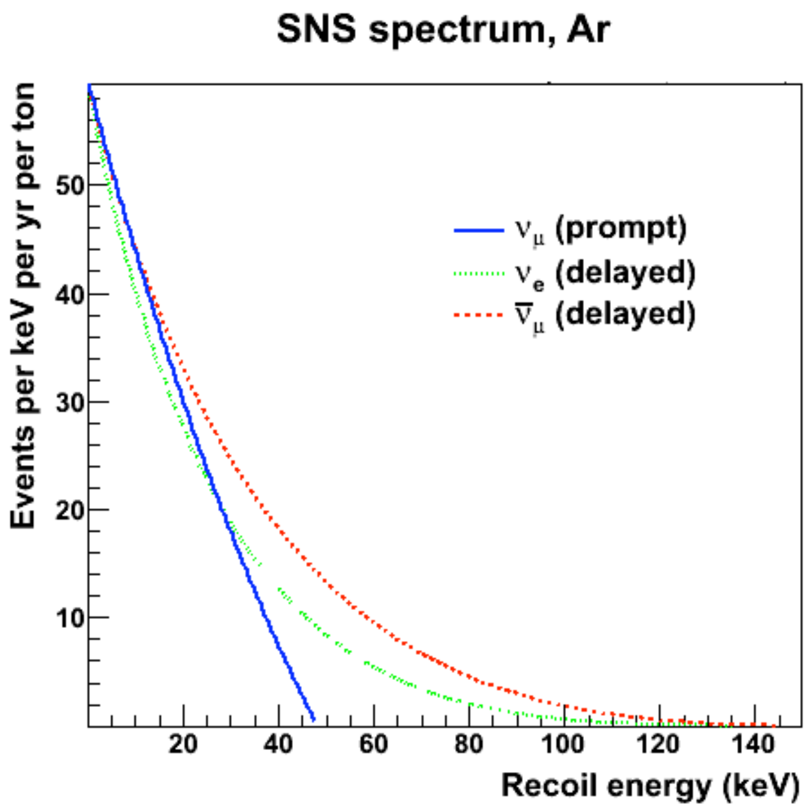
Warm liquid/bubble



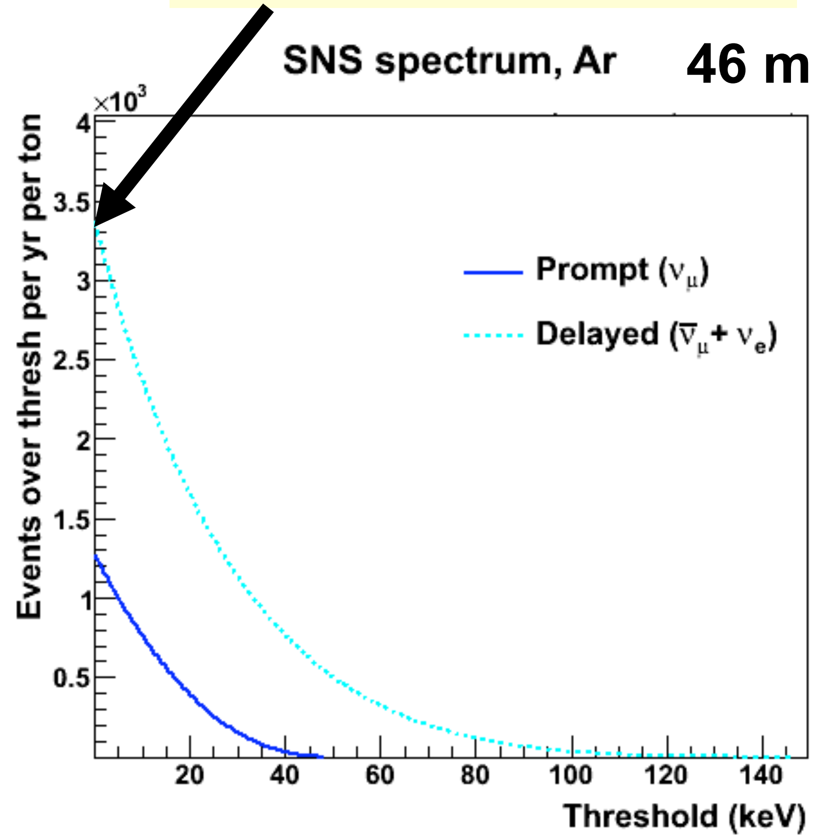
- <10 keV threshold achievable, good recoil selection
- large target masses may be possible
- bg requirements less stringent than for WIMPs

Rates for Ar at the SNS

1000's of
events per ton-year

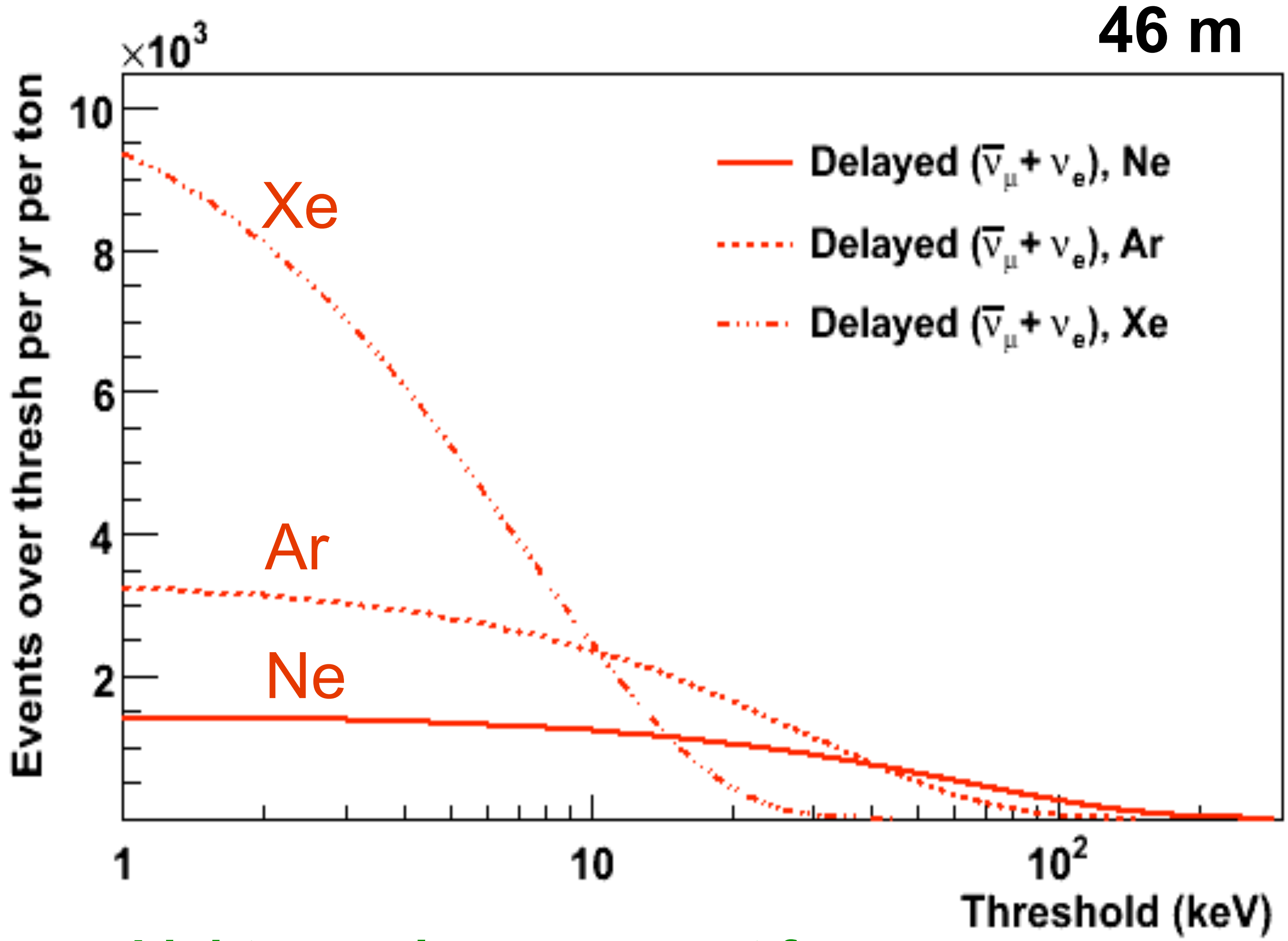


Differential nuclear recoil spectrum



Integrated yield over threshold

Integrated SNS yield for various targets



Lighter nucleus ⇒ expect fewer interactions, but more at higher energy

So, the 'sanitized' rates look good...

What physics could be learned?

K. Scholberg, Phys. Rev D 73 (2006) 033005

Basically, any deviation from SM cross-section is interesting...

- **Weak mixing angle**
- **Non Standard Interactions (NSI) of neutrinos**
- **Neutrino magnetic moment**
- **Nuclear physics**

Weak mixing angle?

L. M. Krauss, Phys. Lett. B 269 (1991) 407-411

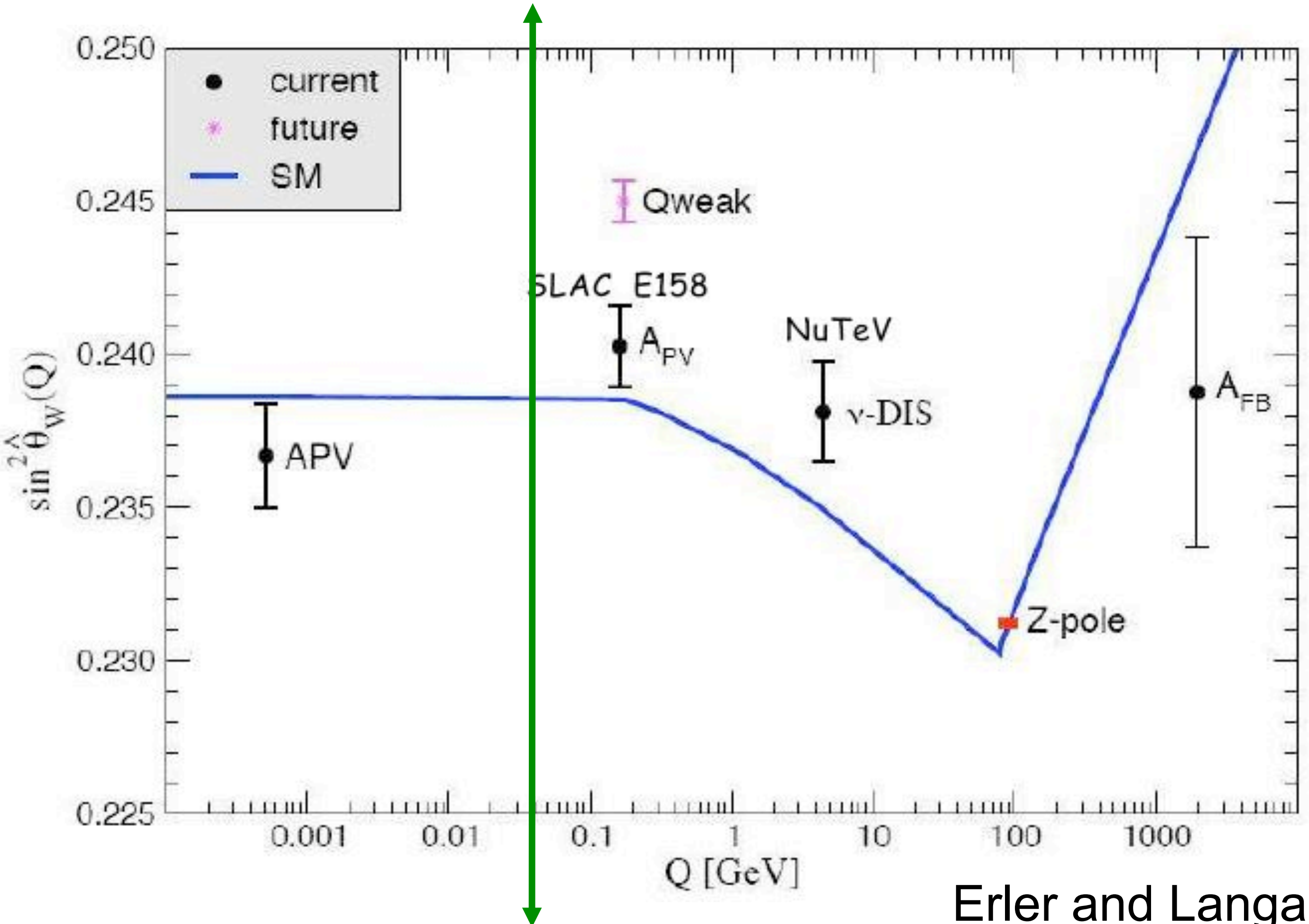
Absolute rate in SM is proportional to

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

Momentum transfer is Q~ 0.04 GeV/c

If absolute cross-section can be measured to ~10%, Weinberg angle can be known to ~5%

First-generation measurement not competitive:
(assuming ~10% systematic error on rate)



Erler and Langacker, PDG

However this could get interesting as we learn to reduce uncertainties...

(normalize with a well-known rate? multiple targets?)

Consider Non-Standard Interactions (NSI) specific to neutrinos + quarks

Model-independent parameterization

Davidson et al., JHEP 0303:011 (2004) hep-ph/0302093
Barranco et al., JHEP 0512:021 (2005) hep-ph/0508299

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

NSI parameters

'Non-Universal': ε_{ee}, $\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$

Flavor-changing: $\varepsilon_{\alpha\beta}$, **where** $\alpha \neq \beta$

$\Rightarrow$ **focus on poorly-constrained (~unity allowed)**

ε_{ee}^{uV}, ε_{ee}^{dV}, $\varepsilon_{\tau e}^{uV}$, $\varepsilon_{\tau e}^{dV}$

Cross-section for NC coherent scattering including NSI terms

For flavor α, spin zero nucleus:

$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times$$

$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$ **non-universal**

$$+ \sum_{\alpha\neq\beta} [Z(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + N(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})]^2\}$$ **flavor-changing**

$$g_V^p = (\frac{1}{2} - 2\sin^2\theta_W), \quad g_V^n = -\frac{1}{2}$$ **SM parameters**

$$\varepsilon_{\alpha\beta}^{qV} = \varepsilon_{\alpha\beta}^{qL} + \varepsilon_{\alpha\beta}^{qR}$$

- **NSI affect total cross-section, not differential shape of recoil spectrum**
- **size of effect depends on N, Z (different for different elements)**
- **ε's can be negative and parameters can cancel**

Experimental limits on non-universal couplings with quarks

Davidson et al., hep-ph/0302093

$\lvert\varepsilon^{uL}_{\tau\tau}\rvert < 1.4, \quad \lvert\varepsilon^{uR}_{\tau\tau}\rvert < 3$ $\lvert\varepsilon^{dL}_{\tau\tau}\rvert < 1.1, \quad \lvert\varepsilon^{dR}_{\tau\tau}\rvert < 6$	**LEP**
$\lvert\varepsilon^{dL}_{\mu\mu}\rvert < 0.003, \quad -0.008 < \varepsilon^{dR}_{\mu\mu} < 0.015$ $\lvert\varepsilon^{uL}_{\mu\mu}\rvert < 0.003, \quad -0.008 < \varepsilon^{uR}_{\mu\mu} < 0.003$	**NuTeV**
$-1 < \varepsilon^{uL}_{ee} < 0.3, \quad -0.4 < \varepsilon^{uR}_{ee} < 0.7$ $-0.3 < \varepsilon^{dL}_{ee} < 0.3, \quad -0.6 < \varepsilon^{dR}_{ee} < 0.5$	**CHARM**

$\varepsilon_{\mu\mu}$ **well-constrained**

ε_{ee}, $\varepsilon_{\tau\tau}$ **poorly constrained**

Experimental limits on flavor-changing couplings with quarks

$|\varepsilon^{uL,R}_{\tau\mu}| < 0.05$

$|\varepsilon^{dL,R}_{\tau\mu}| < 0.05$

NuTeV

$|\varepsilon^{uL,R}_{\mu e}| < 7.7 \times 10^{-4}$

$|\varepsilon^{dL,R}_{\mu e}| < 7.7 \times 10^{-4}$

flavor conversion in nuclei

$|\varepsilon^{uL,R}_{\tau e}| < 0.5$

$|\varepsilon^{dL,R}_{\tau e}| < 0.5$

CHARM

$\varepsilon_{\tau e}$ **poorly constrained**

$\varepsilon_{\mu e}$, $\varepsilon_{\tau\mu}$ **well-constrained**

Given

$\varepsilon_{\mu\mu}$ well-constrained

ε_{ee}, $\varepsilon_{\tau\tau}$ poorly constrained

$\varepsilon_{\tau e}$ poorly constrained

$\varepsilon_{\mu e}$, $\varepsilon_{\tau\mu}$ well-constrained

order unity allowed

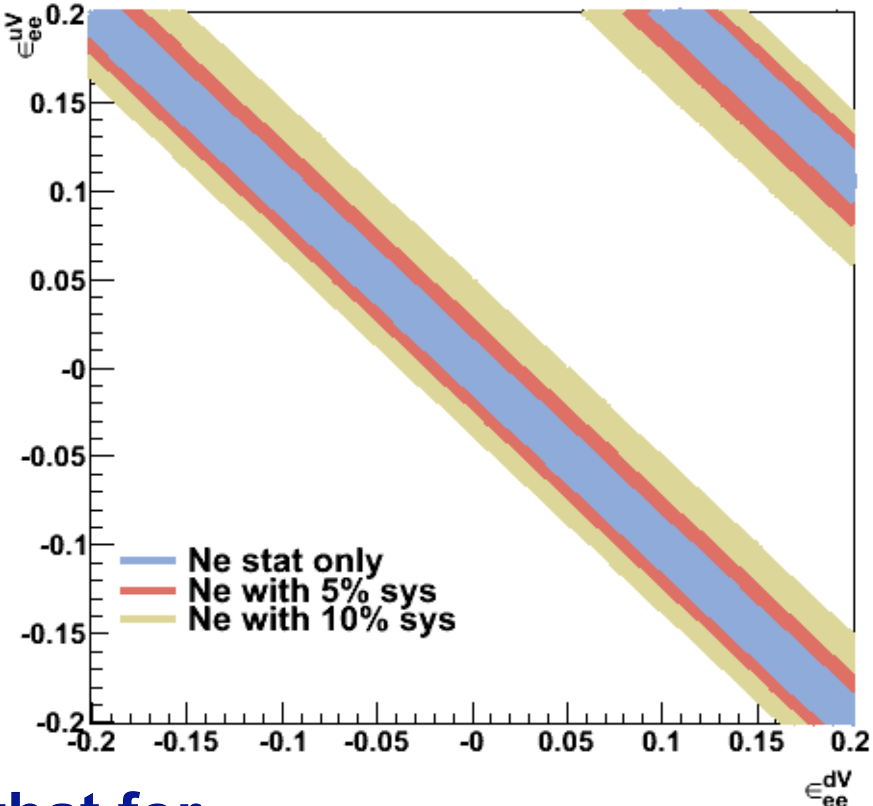
And, since at the SNS we have only μ and e neutrinos (assuming no oscillation), we have no access to $\varepsilon_{\tau\tau}$

$\Rightarrow$ focus on parameter space of

$$\varepsilon_{ee}^{uV},\ \varepsilon_{ee}^{dV},\ \varepsilon_{\tau e}^{uV},\ \varepsilon_{\tau e}^{dV}$$

Look at a few sample slices to estimate sensitivity employing electron flavor component of flux (delayed)

90% CL allowed region, assuming non-universal only for 100 kg-year at SNS, Neon



$$\varepsilon_{e\tau}^{qV} = 0$$

Assumes total delayed flux rate exactly matches SM

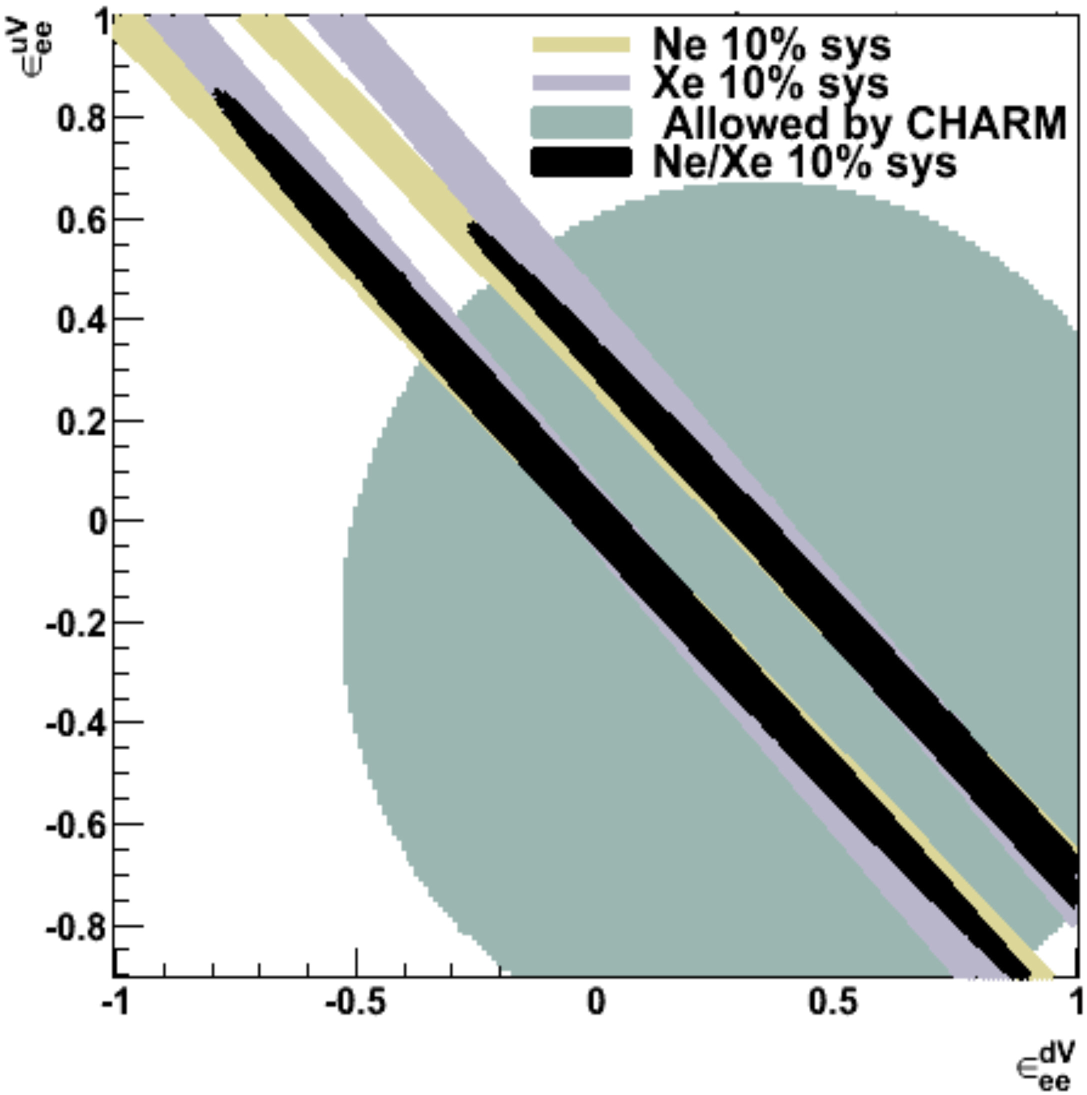
Note that for

$$Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) = \pm(Zg_V^p + Ng_V^n)$$

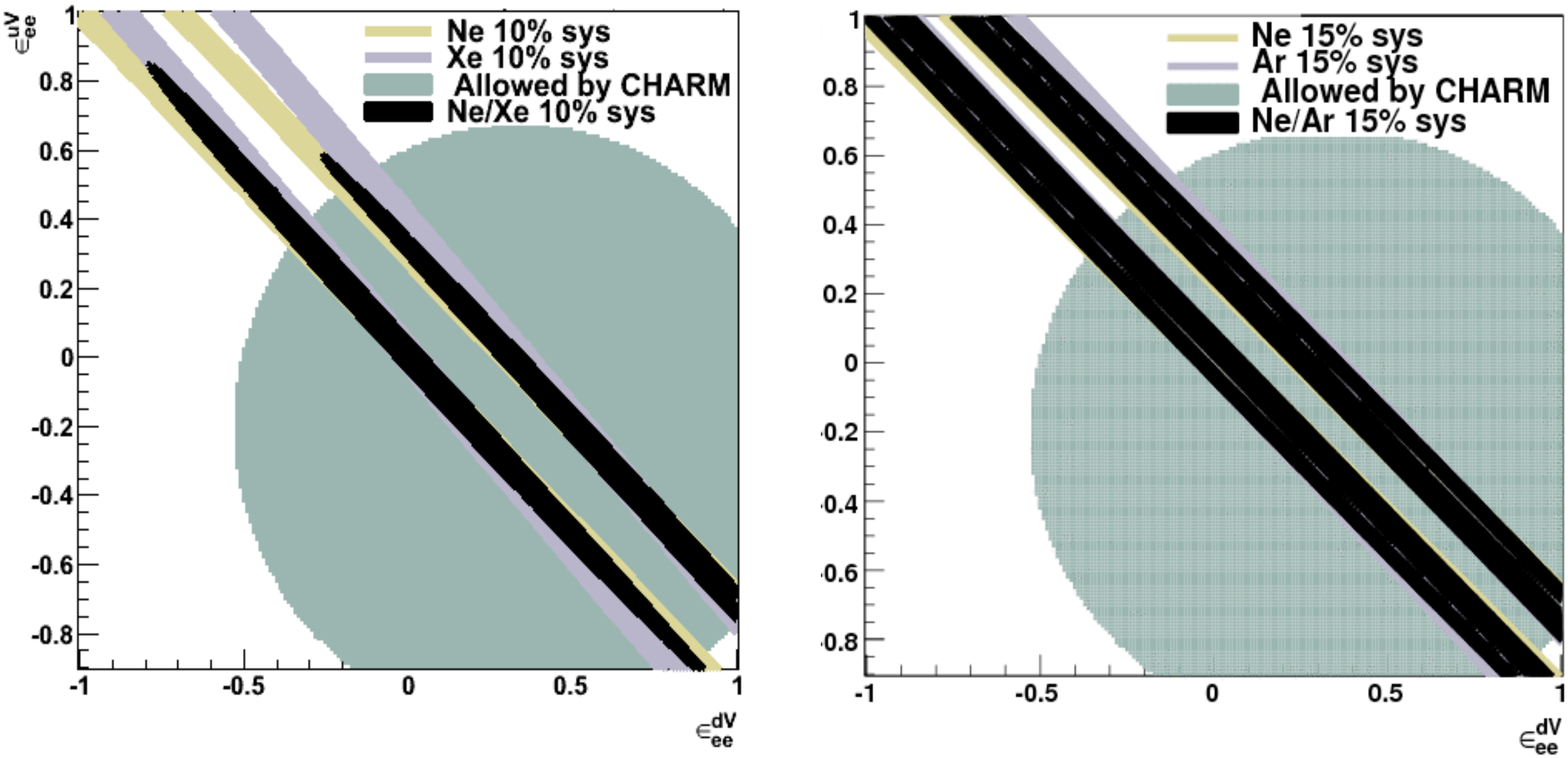
the rate is the same as for the SM, so parameters will be allowed

⇒ get linear allowed regions, slope = -(A+N)/(A+Z)

Different targets have different slopes

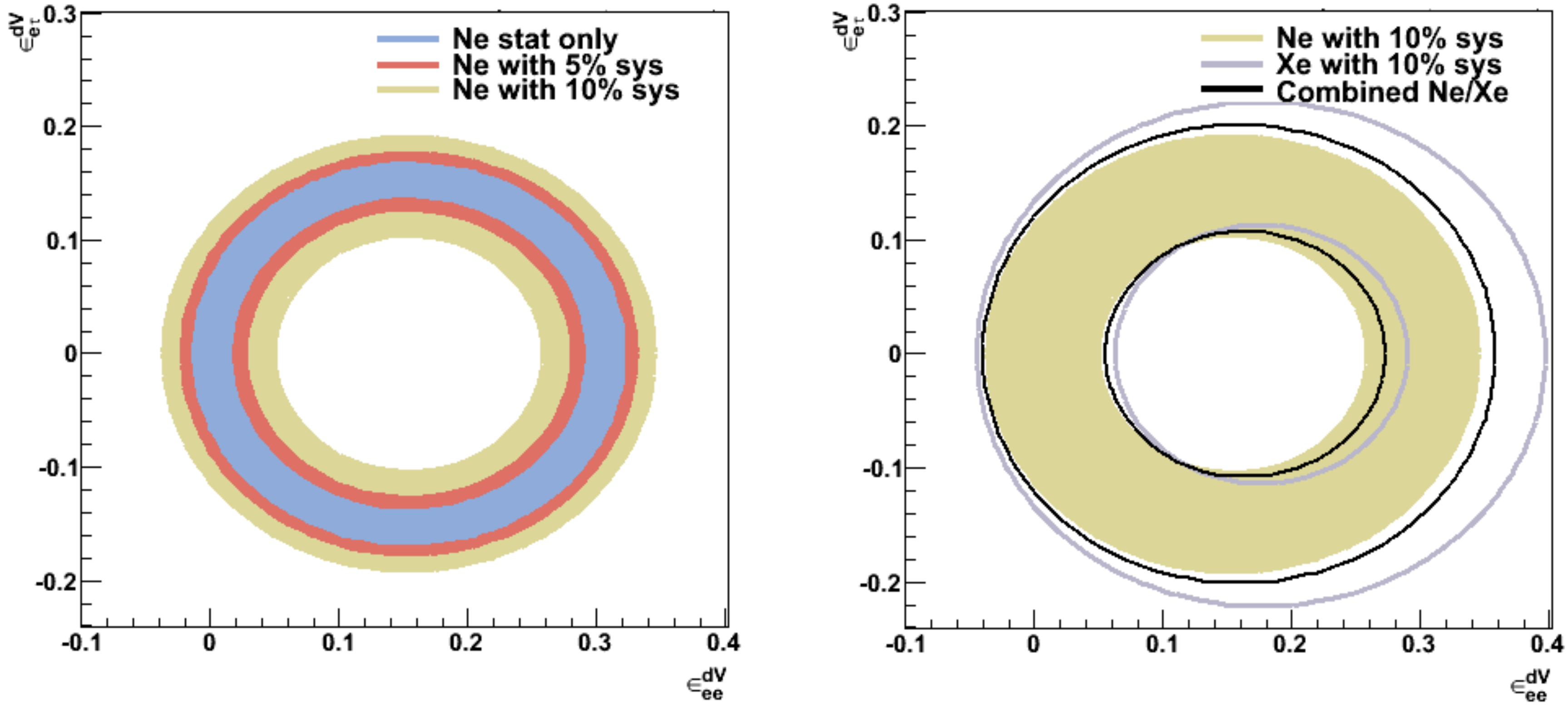


In principle, can further constrain if you measure in more than one element



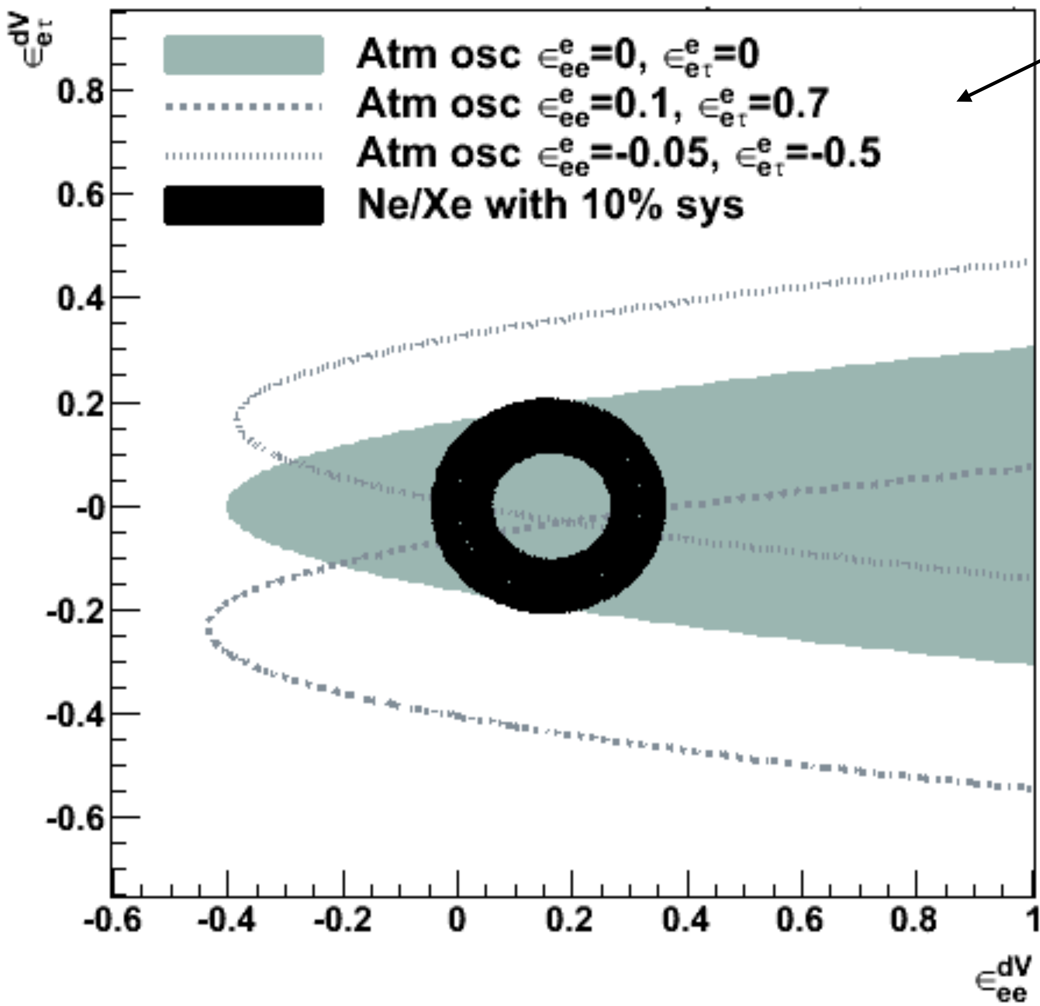
Can improve ~ order of magnitude beyond current limits with a first-generation experiment

$\varepsilon_{e\tau}^{dV}$ vs ε_{ee}^{dV} parameter space slice $\varepsilon_{e\tau}^{uV} = 0$



Significant constraint wrt current allowed parameters

Friedland & Lunardini et al., hep-ph/0506143

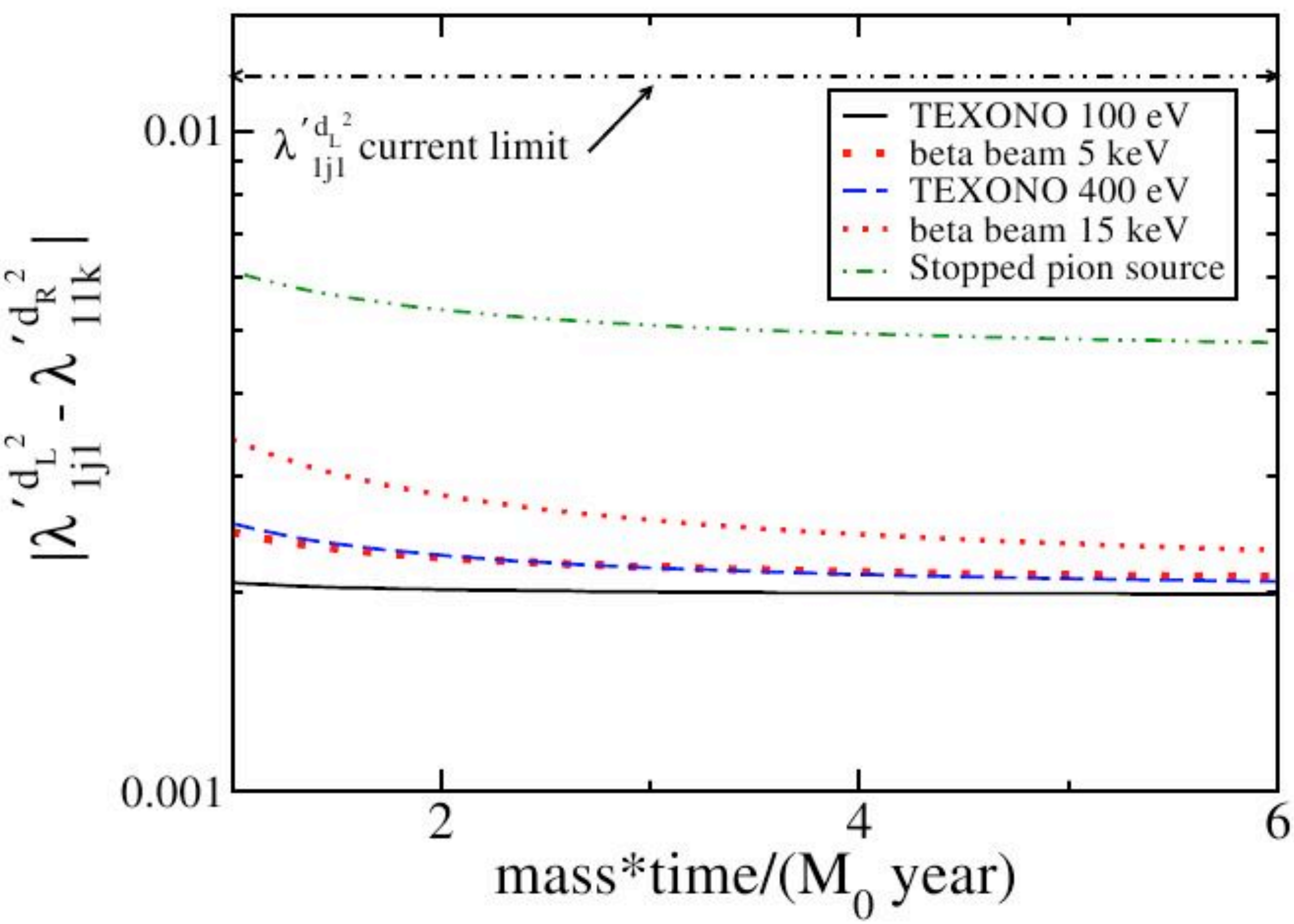


Note: may improve systematics by comparing prompt (ν_μ) and delayed ($\nu_\mu + \nu_e$) fluxes; may also use spectral info to separate

J. Barranco, O.G. Miranda, T.I. Rashba,
Phys. Rev. D 76: 073008 (2007) hep-ph/0702175:

Low energy neutrino experiments sensitivity to physics beyond the Standard Model

Specific NSI models: Z', leptoquark, SUSY with broken R-parity



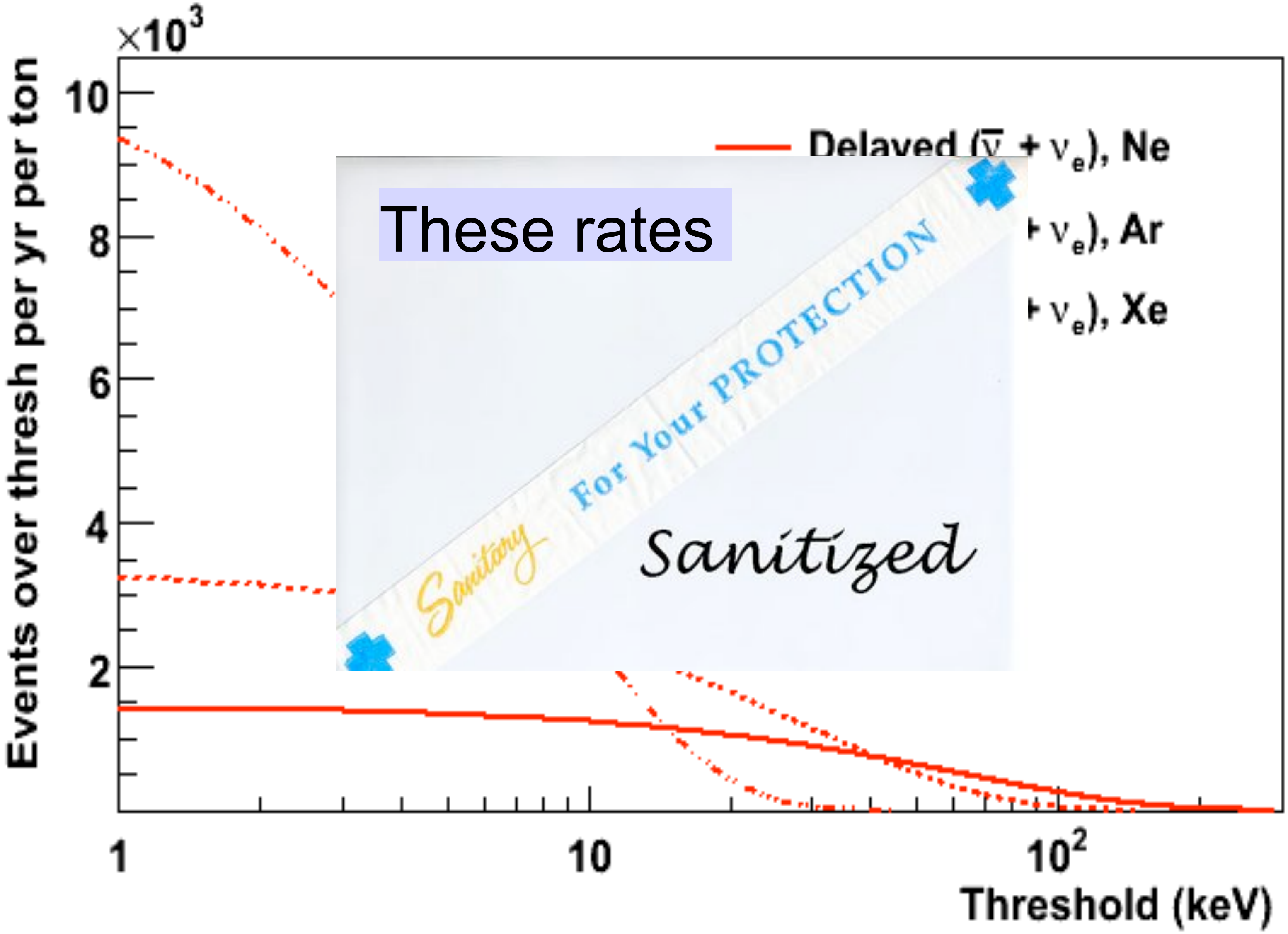
Summary of physics reach

Basically, any deviation from SM x-scn is interesting...

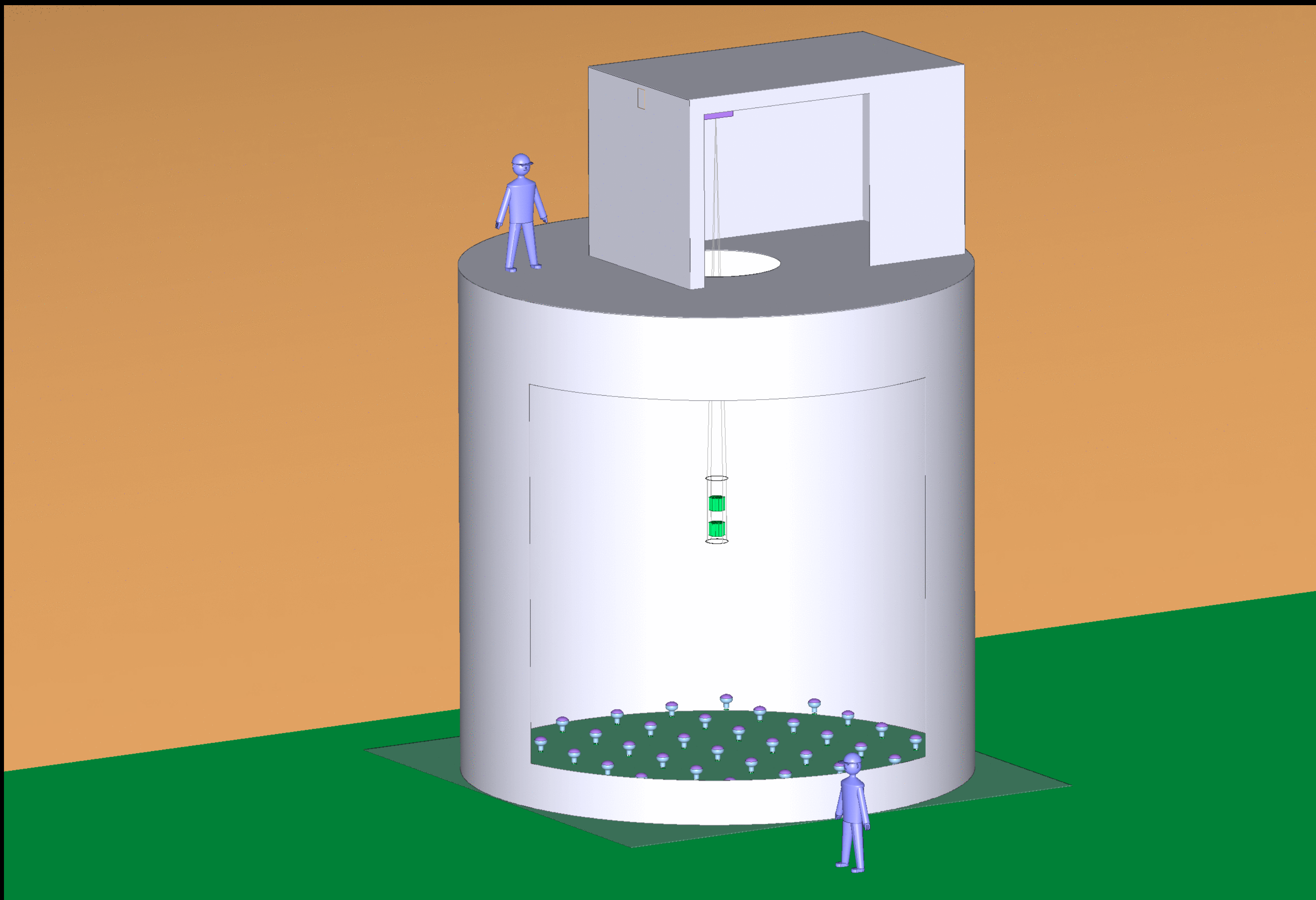
- **Standard Model weak mixing angle:**
  could measure to ~5% (new channel)
- **Non Standard Interactions (NSI) of neutrinos:**
  could significantly improve constraints
- **Neutrino magnetic moment:**
  hard, but conceivable
- **Neutron form factor:**
  also hard but conceivable

P. S. Amanik and G. C. McLaughlin, J. Phys. G 36:015105, 2009 hep-ph.0707.4191

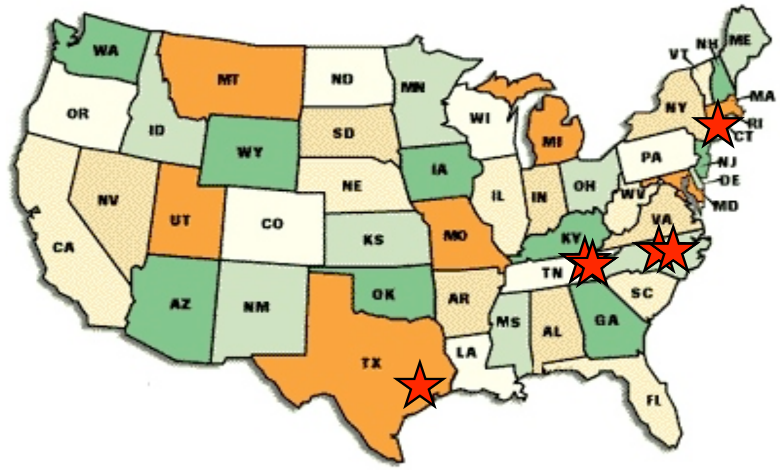
Measurement looks promising... but...



The CLEAR (Coherent Low Energy A Recoils) Experiment



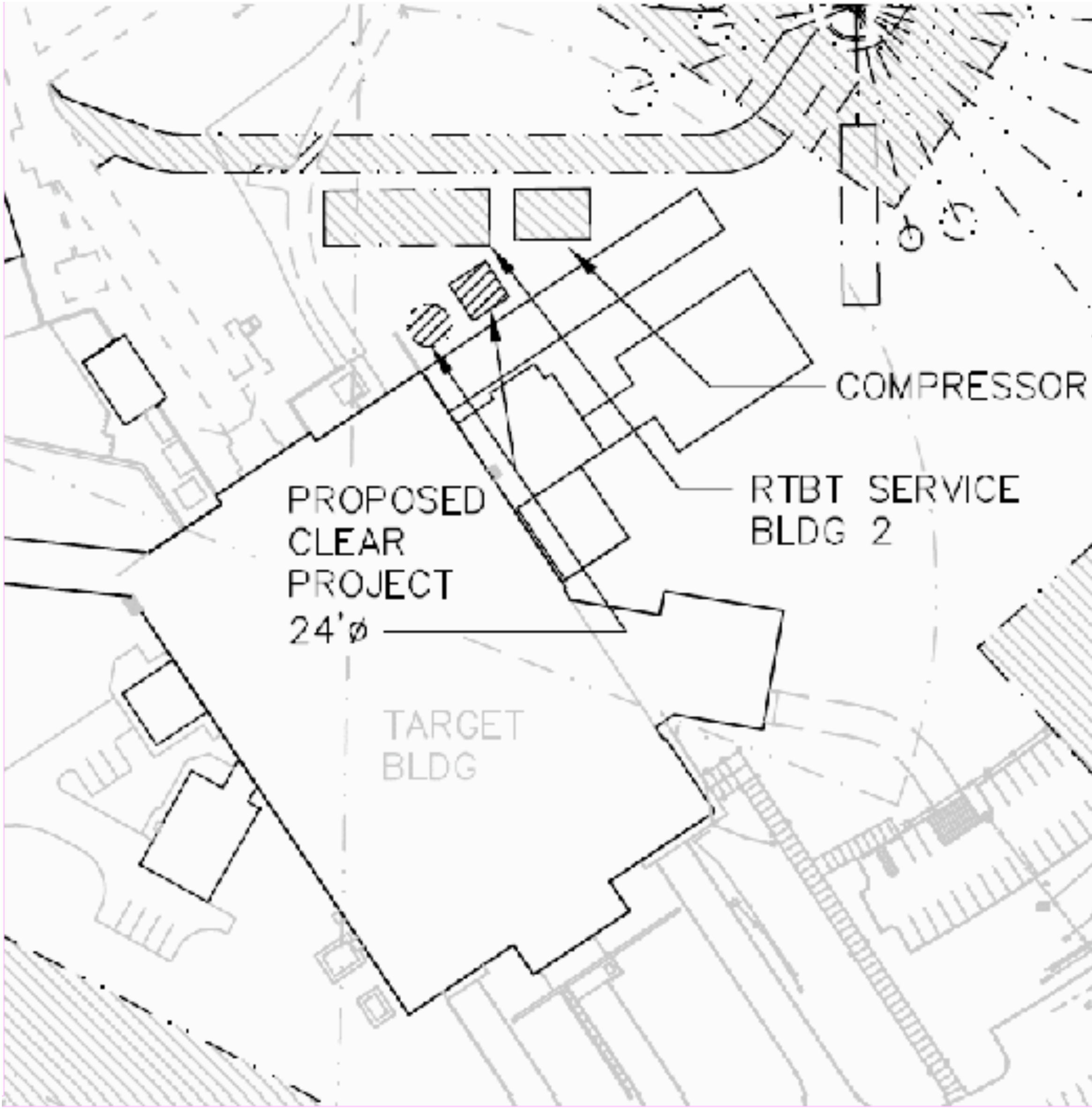
CLEAR Collaboration



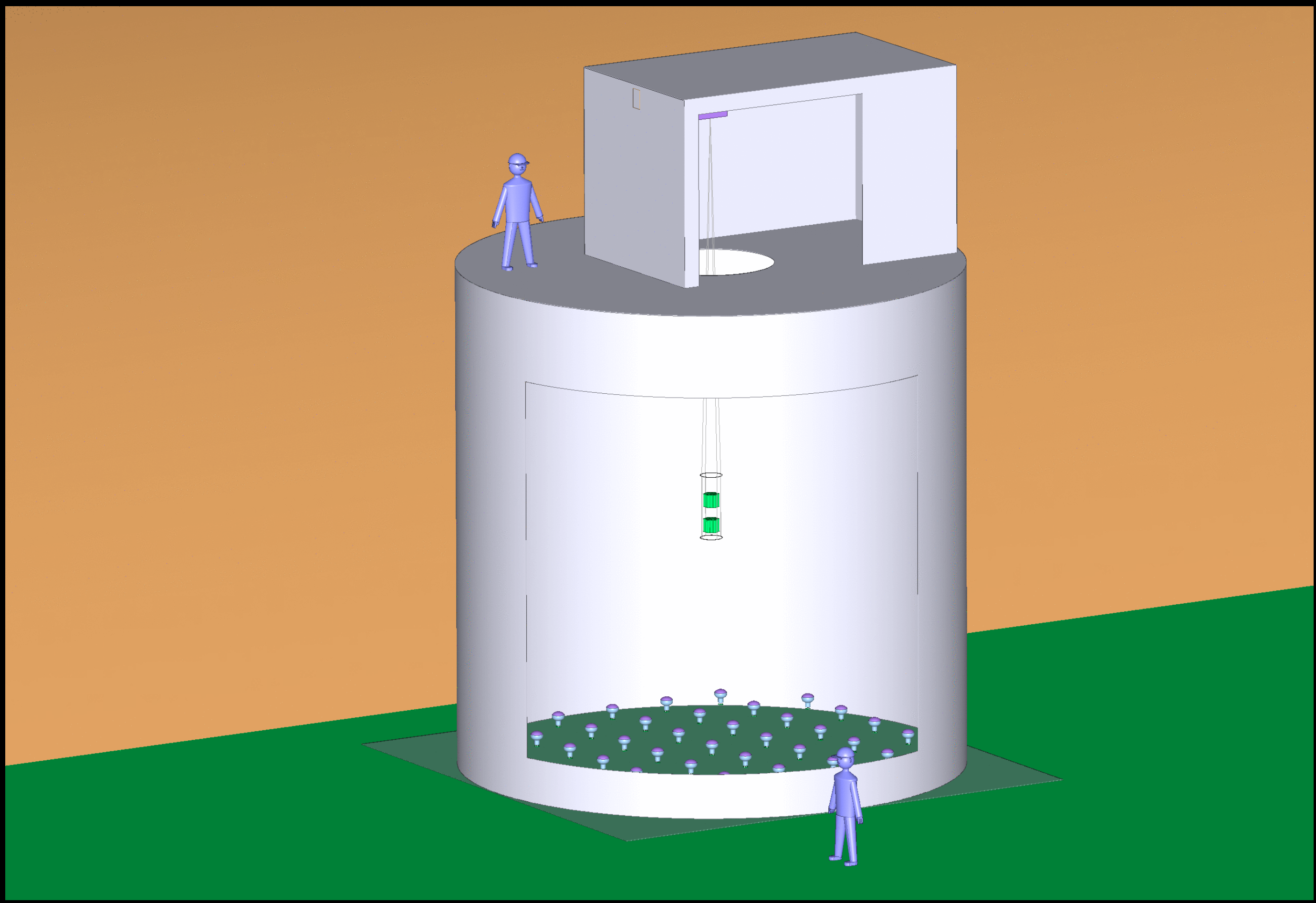
Duke: Kate Scholberg
Taritree Wongjirad
Houston: Ed Hungerford
Toni Empl
NCCU: Ben Crowe
Diane Markoff

ORNL: Dan Bardayan
Raph Hix
Paul Mueller
Tennessee: Yuri Efremenko
TUNL: Alex Crowell
Yale: Dan McKinsey
James Nikkel

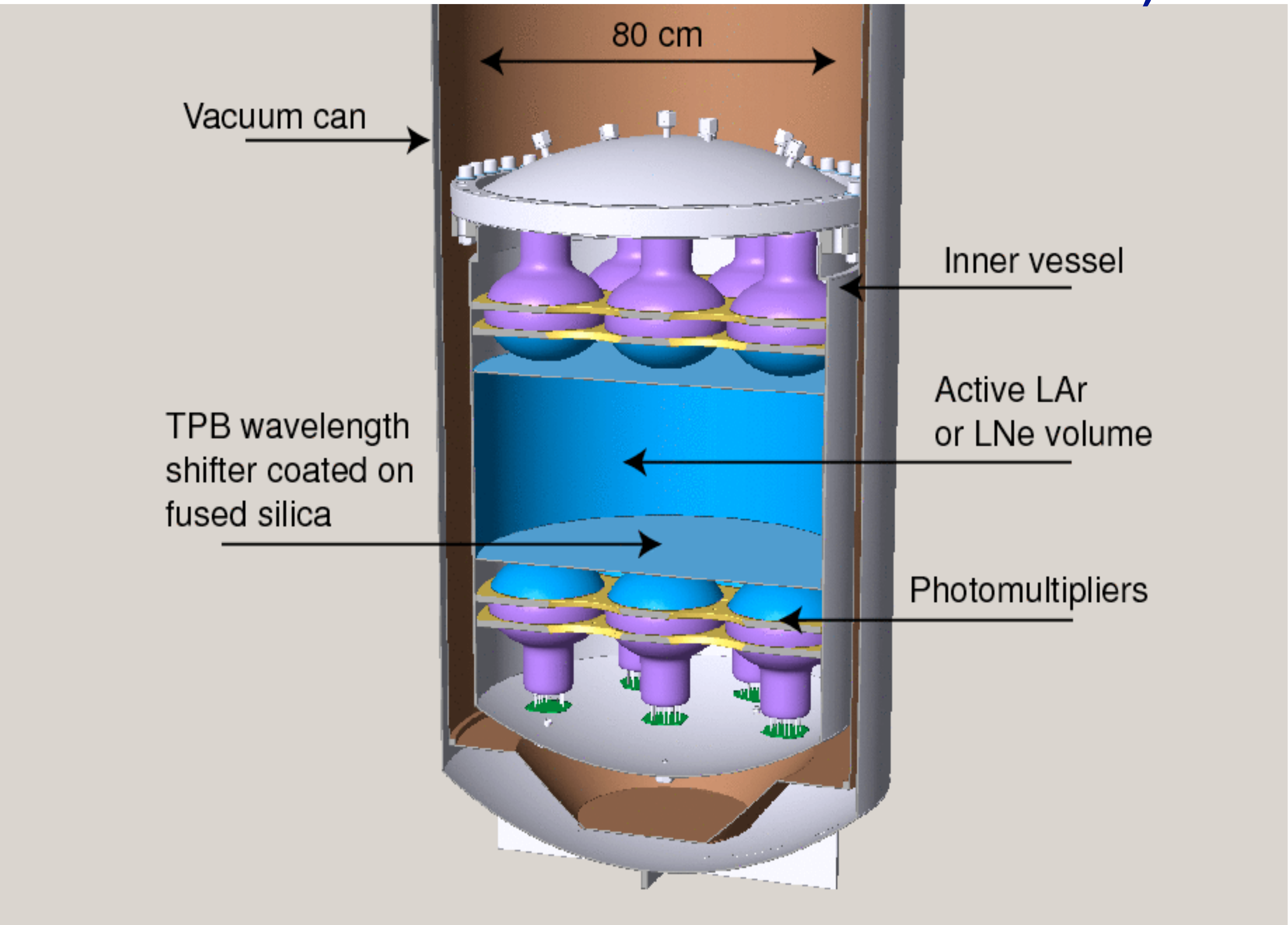
Detector site 46 meters from the SNS target



Shielding: 8 m diameter bolted steel water tank
66 cm steel (Duratek blocks, not shown)
Water tank instrumented with PMTs for cosmic veto

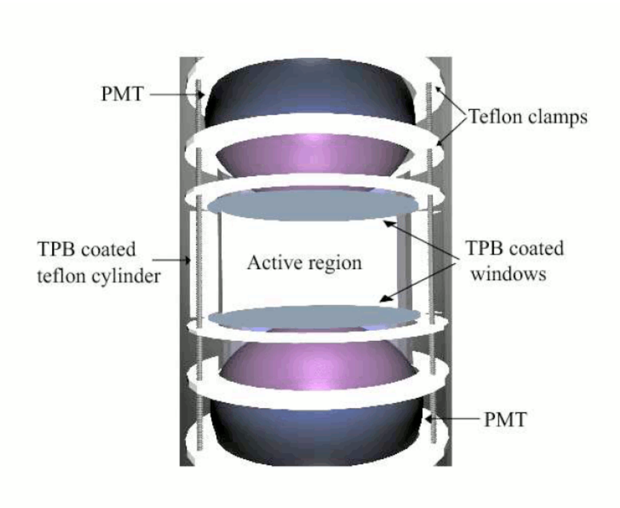


Single phase scintillation (like CLEAN/DEAP DM detectors)



Pulse-shape discrimination for recoil selection in Ar/Ne

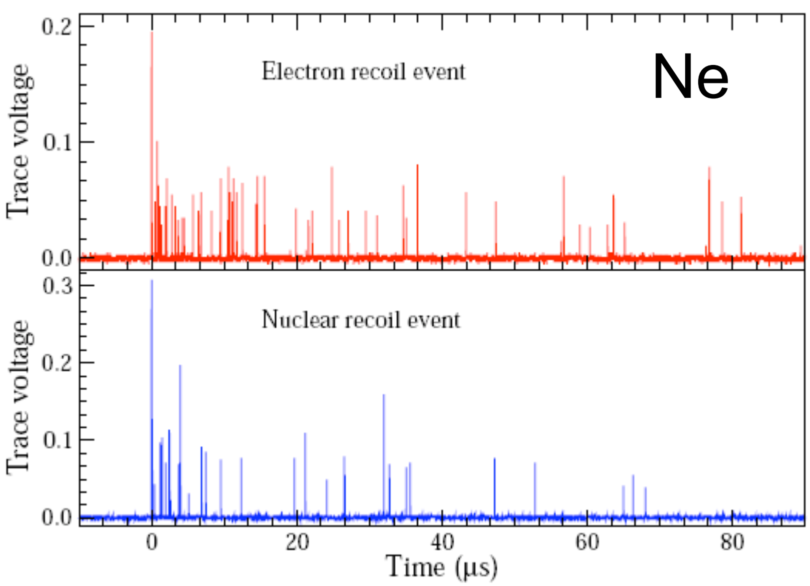
W. H. Lippincott et al., PRC 78:035801 (2008) arXiv:0801.1531
J. A. Nikkel et al., Astropart. Phys. 29:161 (2008), astro-ph/0612108

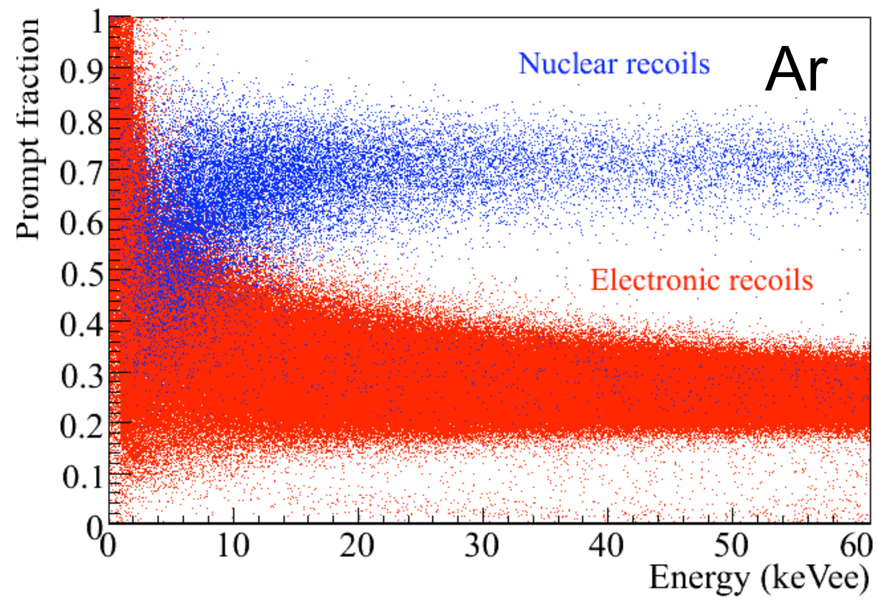


Yale test cell

- different n/e ionization density leads to different scintillation pulse shapes

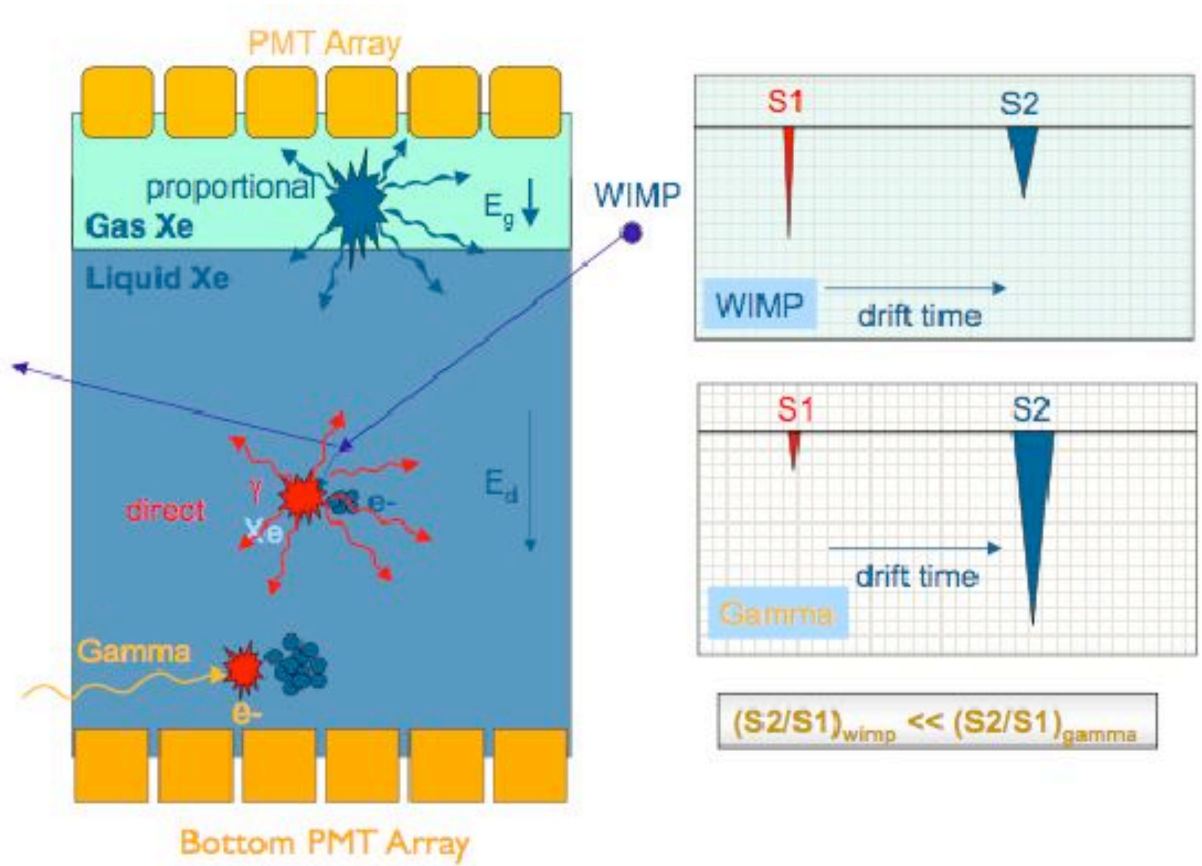
- >10^6 rejection (threshold-dependent)





Another possibility: detector principle similar to that of xenon dark matter search TPCs

The key is to select nuclear-recoil-like signals from gammas and electrons (different ionization energy loss)

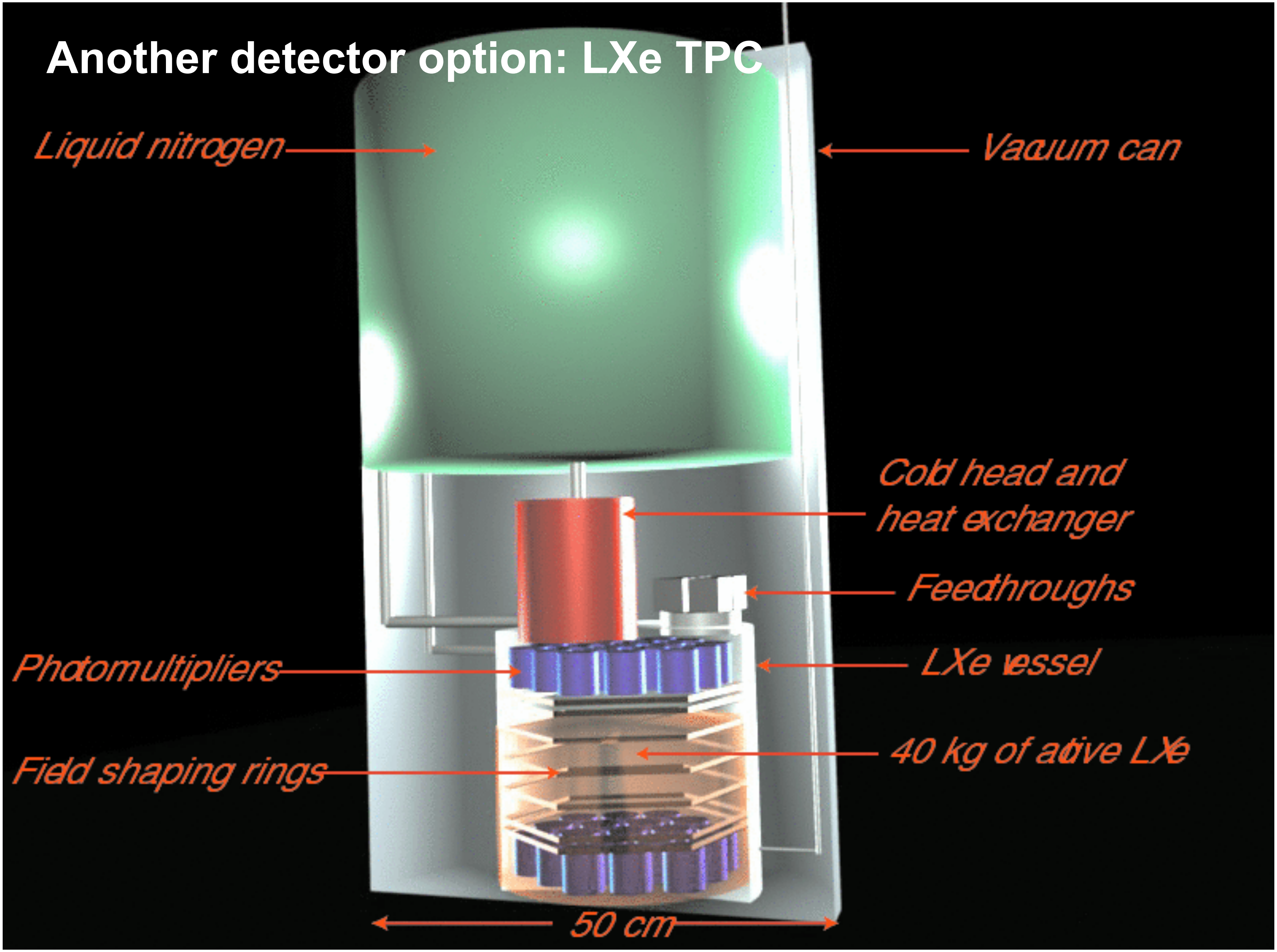


nuclear recoil

electronic recoil

E. Aprile

Another detector option: LXe TPC



Backgrounds

Most backgrounds mitigated by pulsed beam rejection factor (10^{-4}-10^{-3})

- **Radioactivity**

  - cosmogenic ^{39}Ar intrinsic to argon
  - radon
  - other radioactivity in detector materials
  - non-recoils suppressed by PSD
  - depleted argon may be available

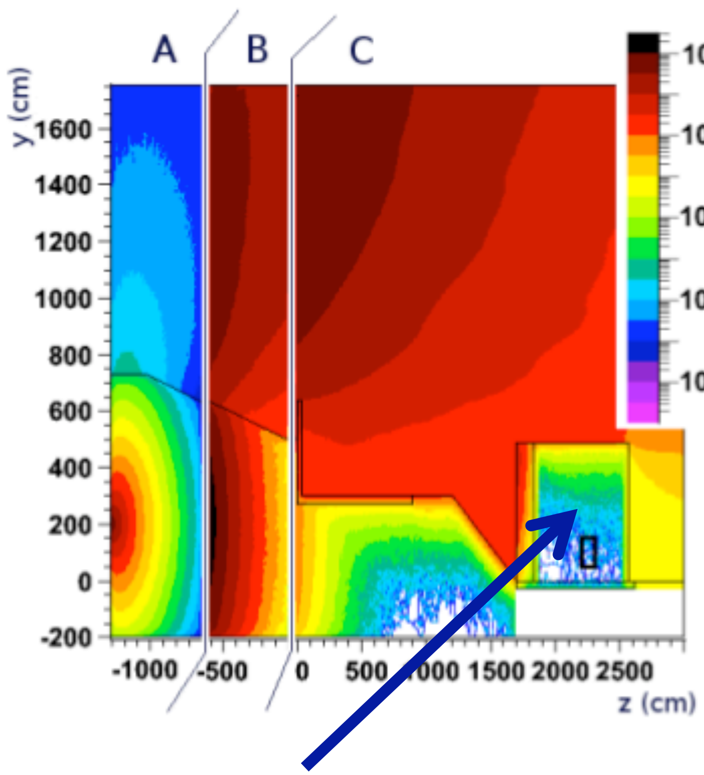
- **Cosmic-ray related**

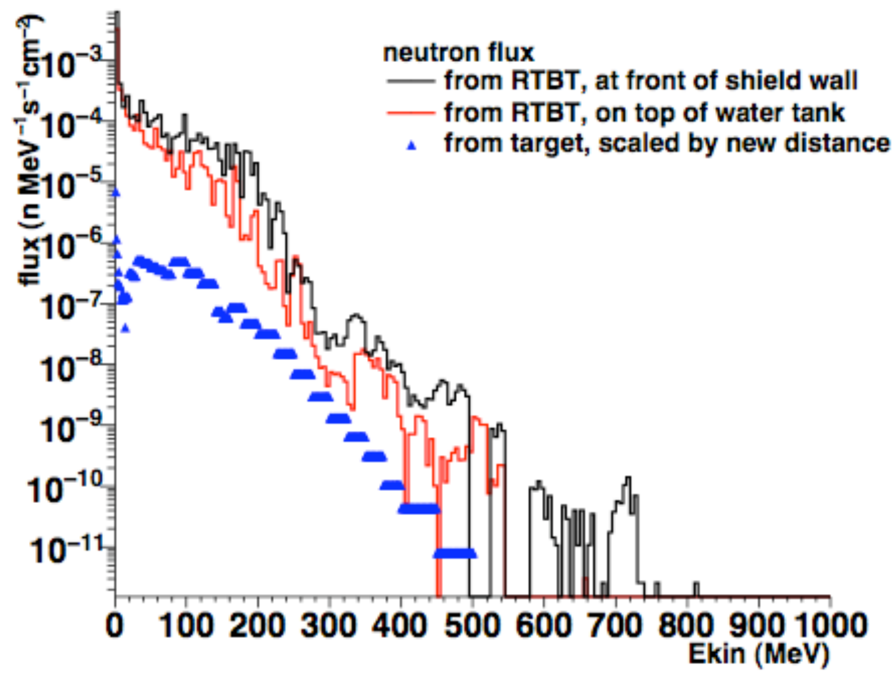
  - muons, muon-induced neutrons
  - reduced by shielding
  - tagged by veto

Beam-related neutrons

Few-MeV neutrons make 10's of keV recoils

SNS neutronics group calculation of neutron spectrum
+ Fluka sim through shielding (T. Empl, Houston)
+ noble liquid detector sim (J. Nikkel, Yale)

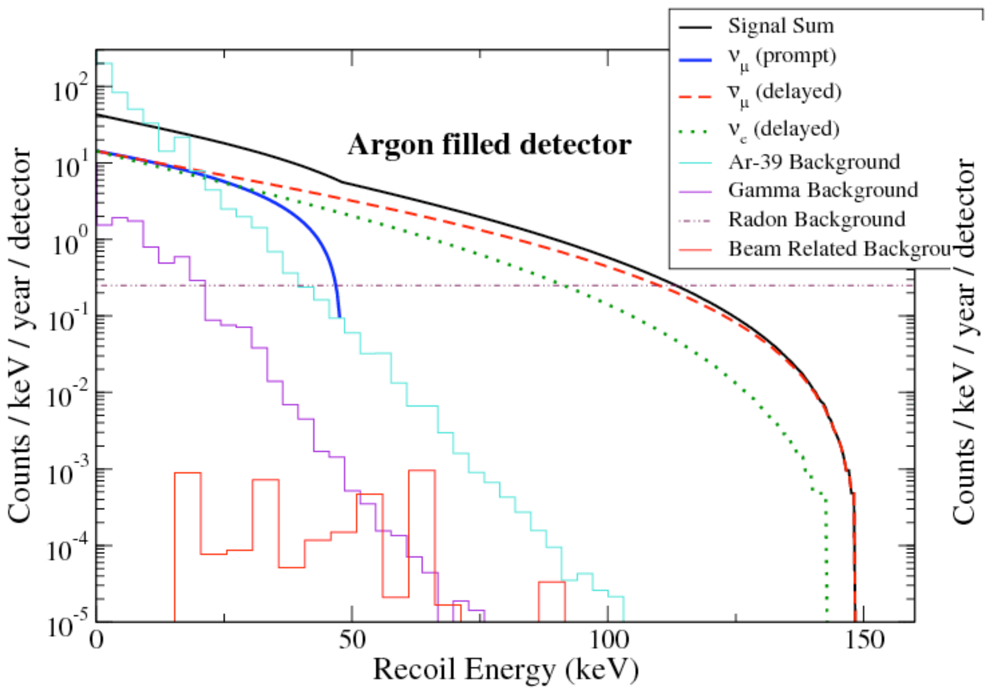


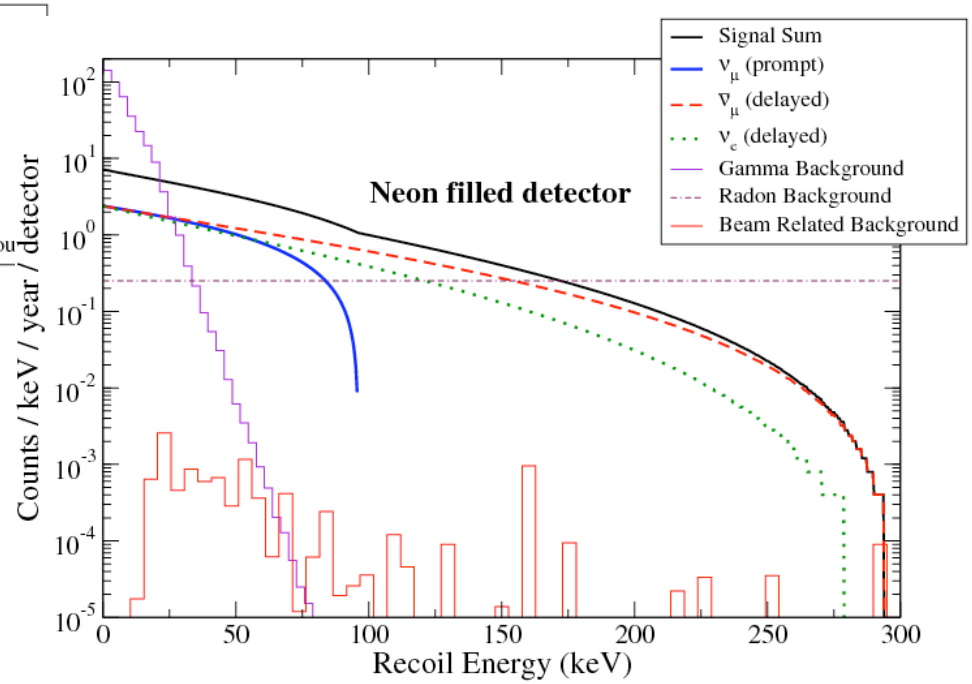


worst is 'skyshine': can optimize shielding configuration

Bottom line signal and background

Signal events/year: ~500 in 240 kg of Ar >20 keVr
~160 in 200 kg of Ne >30 keVr





First version of CLEAR has
initial goal of detection of the process

Nearer future:
- larger detectors
- multiple targets
  (cancel flux normalization systematics)
- reduction of systematics for ~ %-level Weinberg angle

Farther future:
- directional detection?
  (technology in R&D phase)
- polarization? (very hard...)
- high intensity flux w/beta beams?

Conclusion

Coherent neutral current elastic neutrino nucleus scattering is observable using a high intensity stopped-pion neutrino source:
recoil energies are few to tens of keV, which is observable with WIMP detectors

The CLEAR experiment aims to measure the rate and recoil spectrum with a noble liquid detector at the SNS