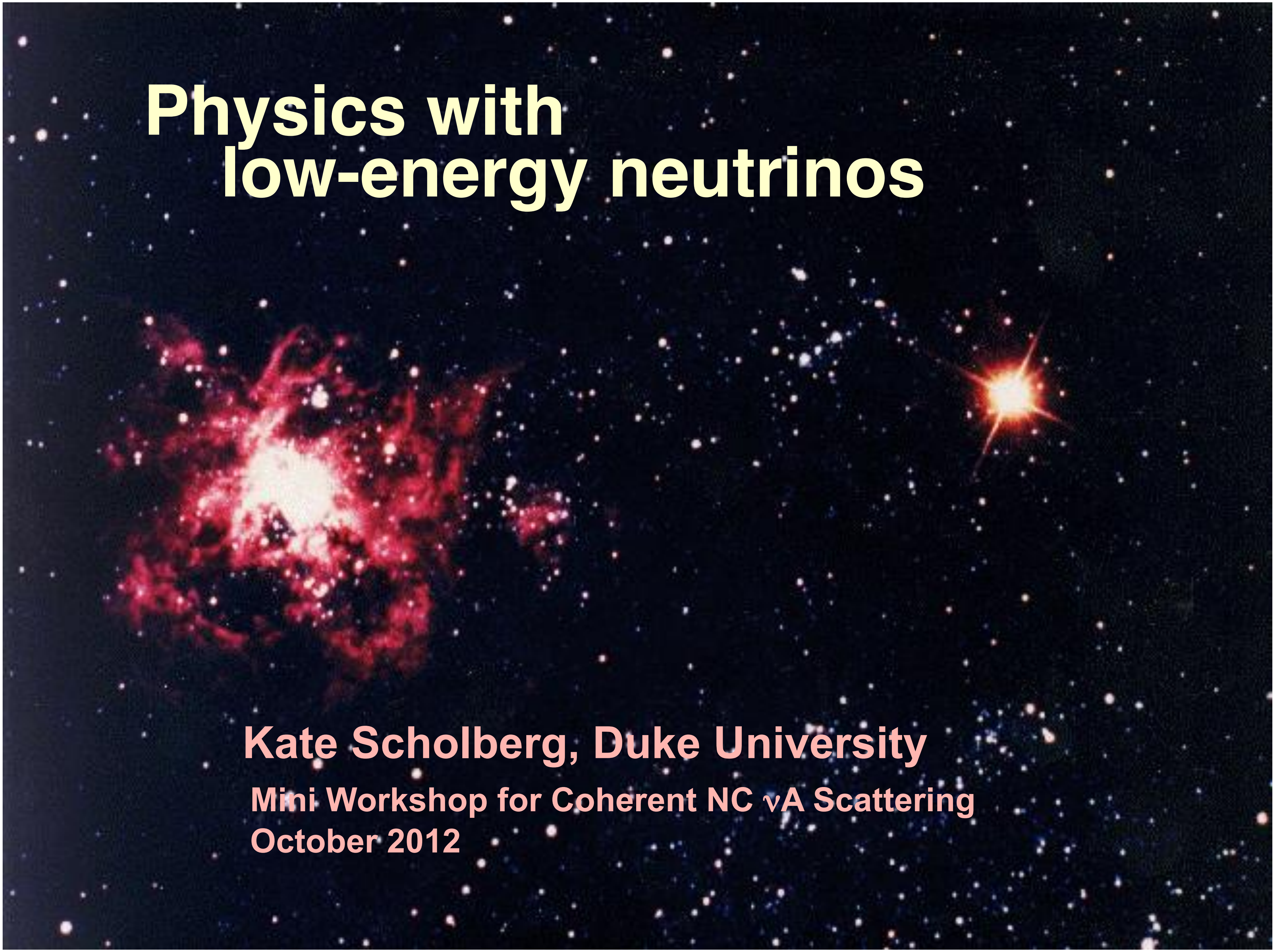


Physics with low-energy neutrinos

Kate Scholberg, Duke University

Mini Workshop for Coherent NC νA Scattering
October 2012

Outline

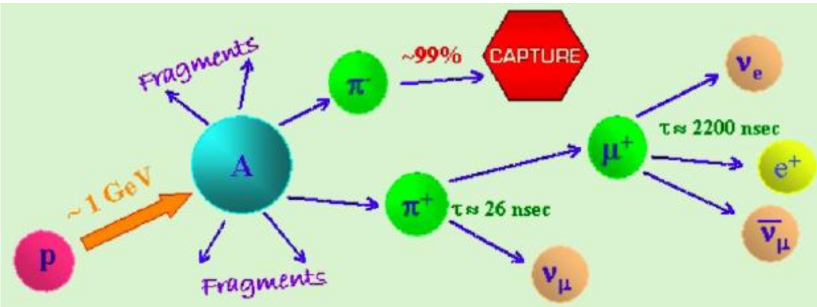
- Stopped-pion (DAR) neutrinos

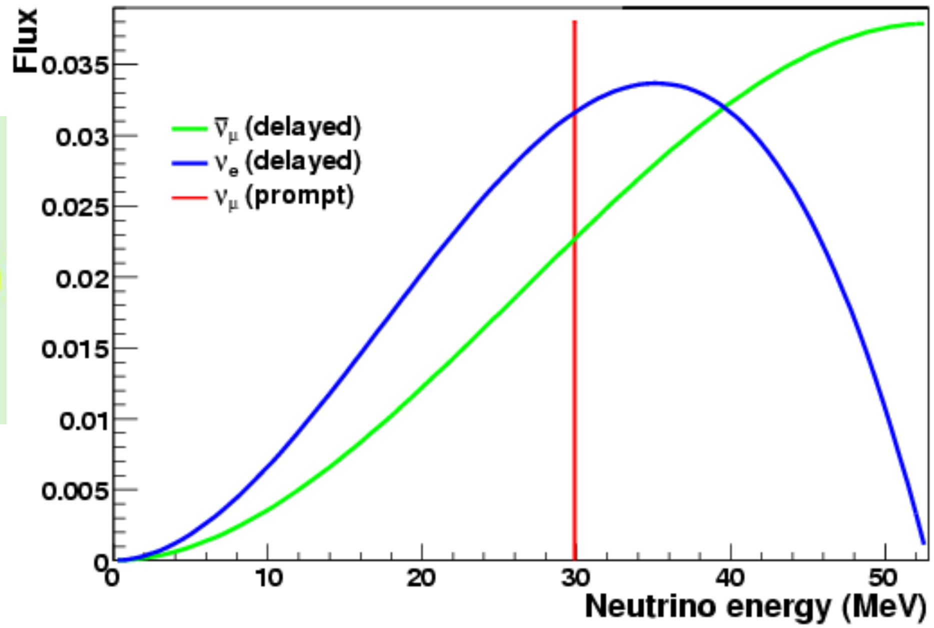
- Physics that could be explored
    - CC/NC interactions w/ standard detectors
    - coherent elastic νA scattering

- What do we want in a DAR source?
  ...some comments on phasing

The SNS as a Stopped-Pion Neutrino Source

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





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

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

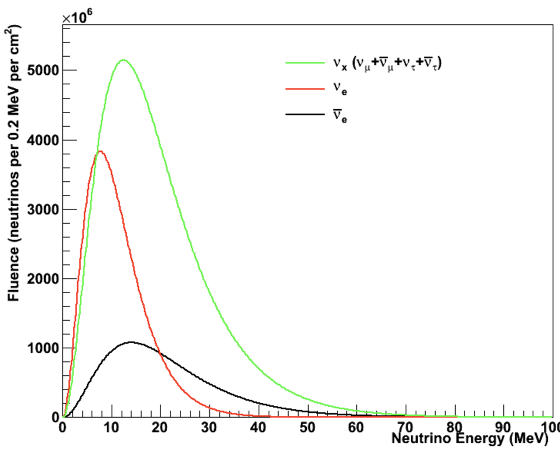
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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

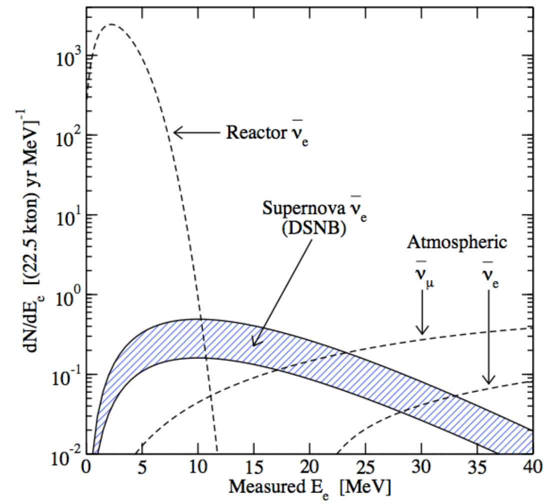
Neutrino flux: few times 10^7 /s/cm^2 at 20 m

~0.13 per flavor per proton

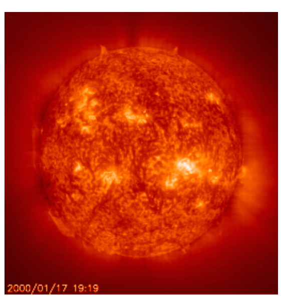
Neutrino interactions in the few-100 MeV range are relevant for neutrinos from various natural sources

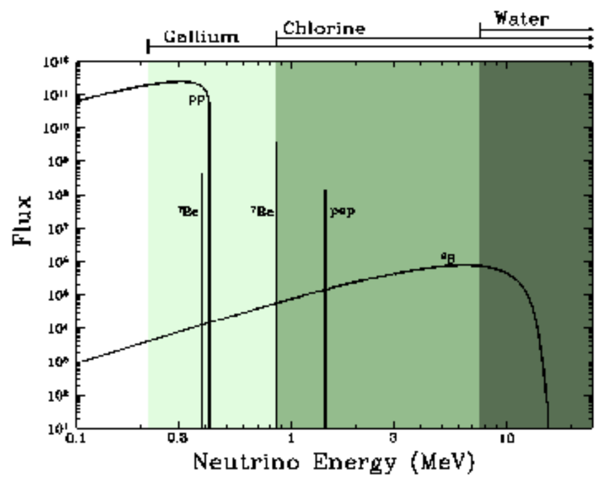


supernova neutrinos, burst & relic

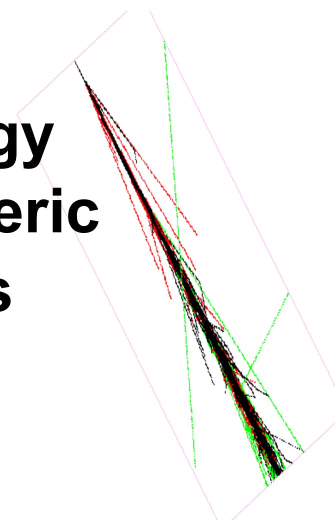


solar neutrinos





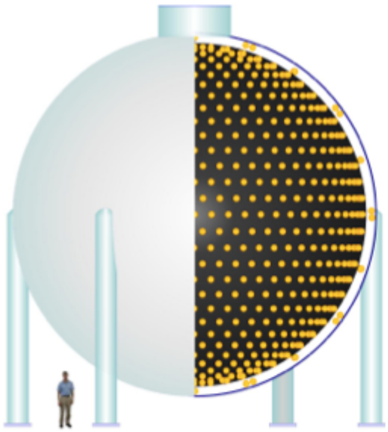
low energy atmospheric neutrinos

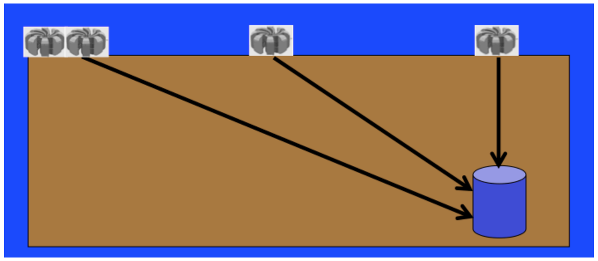


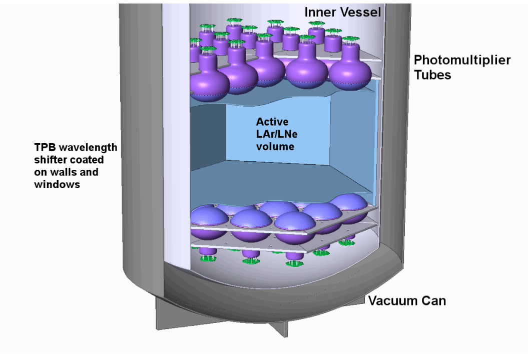
oscillation, astrophysics

... as well as terrestrial experiments

Neutrino oscillation, Standard Model tests, searches for BSM physics







Workshop on Neutrinos at the Spallation Neutron Source

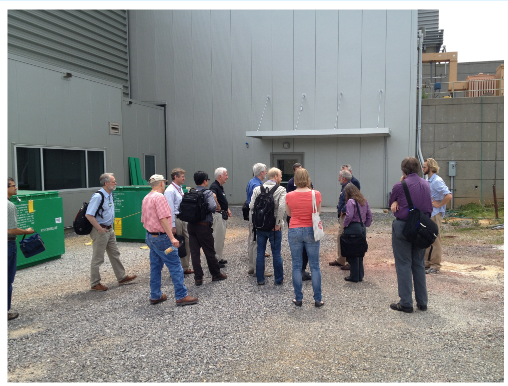
An informal workshop will be held on **May 3-4, 2012** at the Spallation Neutron Source at Oak Ridge National Laboratory, to explore future possibilities for neutrino measurements at the SNS. The discussion will be primarily on cross-section measurements in the few tens of MeV range. The aim for this workshop is to solicit from the community ideas for small-scale first-generation experiments that could be done on a relatively short time scale. Farther-future possibilities will also be discussed.

We expect that the workshop will generate a white paper that could guide future developments.

Whitepaper in soon on arXiv

Topics for discussion:

- Supernova neutrino physics
- Supernova neutrino detection
- Short baseline neutrino oscillations
- Standard model tests
- Measurements of cross-sections on nuclear targets relevant for existing and future supernova detectors
- Detector technologies for coherent elastic neutrino-nucleus scattering
- Potential experiment sites and needs



http://www.phy.duke.edu/~schol/sns_workshop

Categorization of possible experiments

see Heather’s talk

3 Physics Motivations

will discuss some physics for these

although main focus on physics here

CC/NC ν-nucleus cross sections in the tens-of-MeV range

- typical thresholds few to few 10's of MeV
- standard detector technologies can work

Physics motivations:

Core collapse supernovae, process & detection

Standard Model tests (CC spectrum)

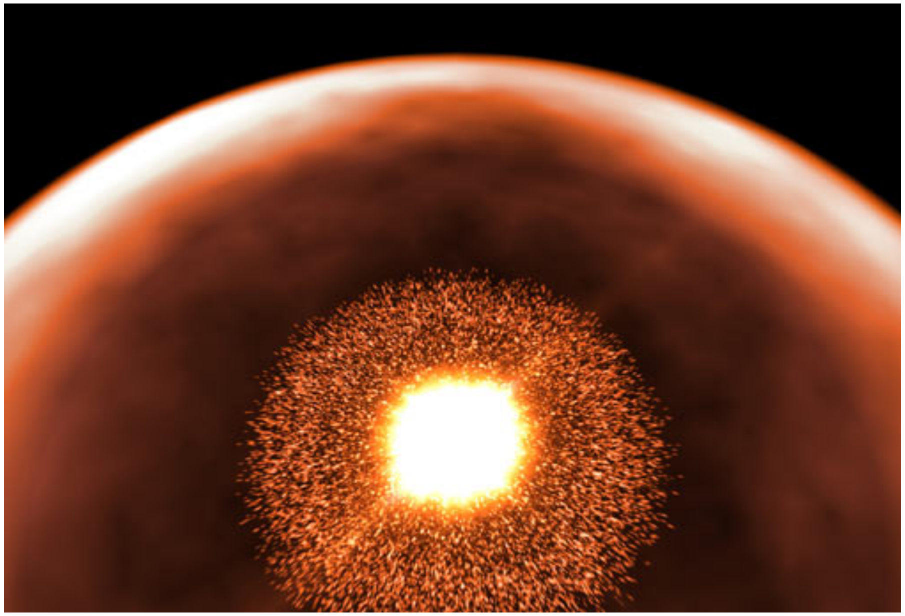
NEUTRINOS FROM CORE COLLAPSE

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of *all flavors* with ~MeV energies

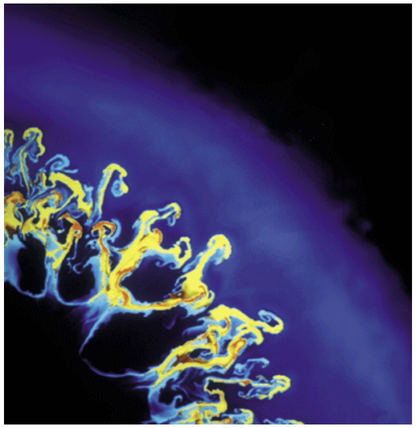
(Energy *can* escape via ν's)

Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

Timescale: *prompt* after core collapse, overall Δt~10's of seconds



What We Can Learn

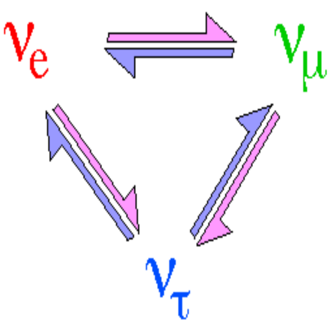


CORE COLLAPSE PHYSICS

- explosion mechanism
- proto nstar cooling, quark matter
- black hole formation
- accretion disks
- nucleosynthesis

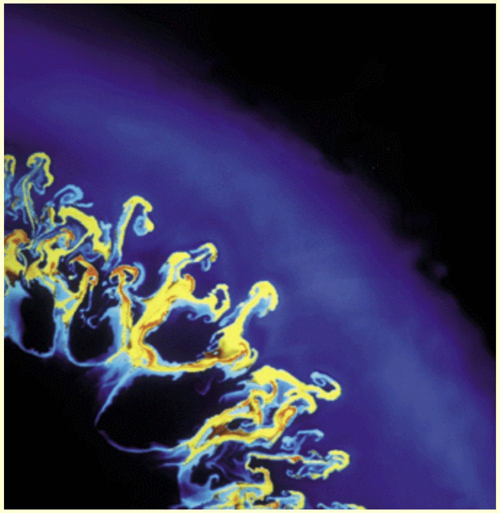
from flavor, energy, time structure of burst

NEUTRINO/OTHER PARTICLE PHYSICS



- ν absolute mass (not competitive)
- ν mixing from spectra: flavor conversion in SN/Earth
  mass hierarchy, collective oscillations
- other ν properties: sterile ν's, magnetic moment,...
- axions, extra dimensions, FCNC, ...

+ EARLY ALERT

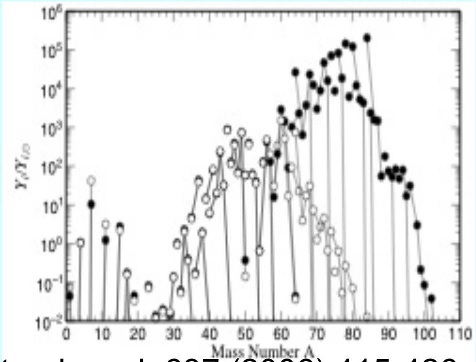


Supernova explosion

Neutrinos are intimately involved in the post-collapse explosion, which is not fully understood

Supernova nucleosynthesis

Neutrino reactions affect the distribution of SN-produced elements, and may produce rare isotopes

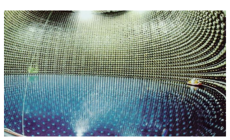


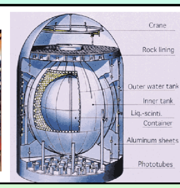
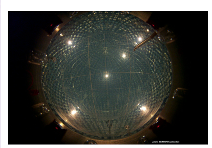
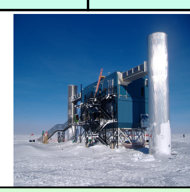
Fröhlich *et al*., Astrophys. J. 637 (2006) 415-426

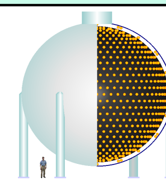
Understanding of neutrino interactions with matter is crucial!

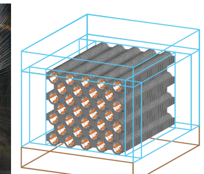
Supernova neutrino detectors, current & future

Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BOONE	Scintillator	USA	0.7	200	Running
HALO	Lead	Canada	0.079	20	Running
Icarus	Liquid argon	Italy	0.6	(60)	(Running)
NOνA	Scintillator	USA	15	3000	Under construction
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction



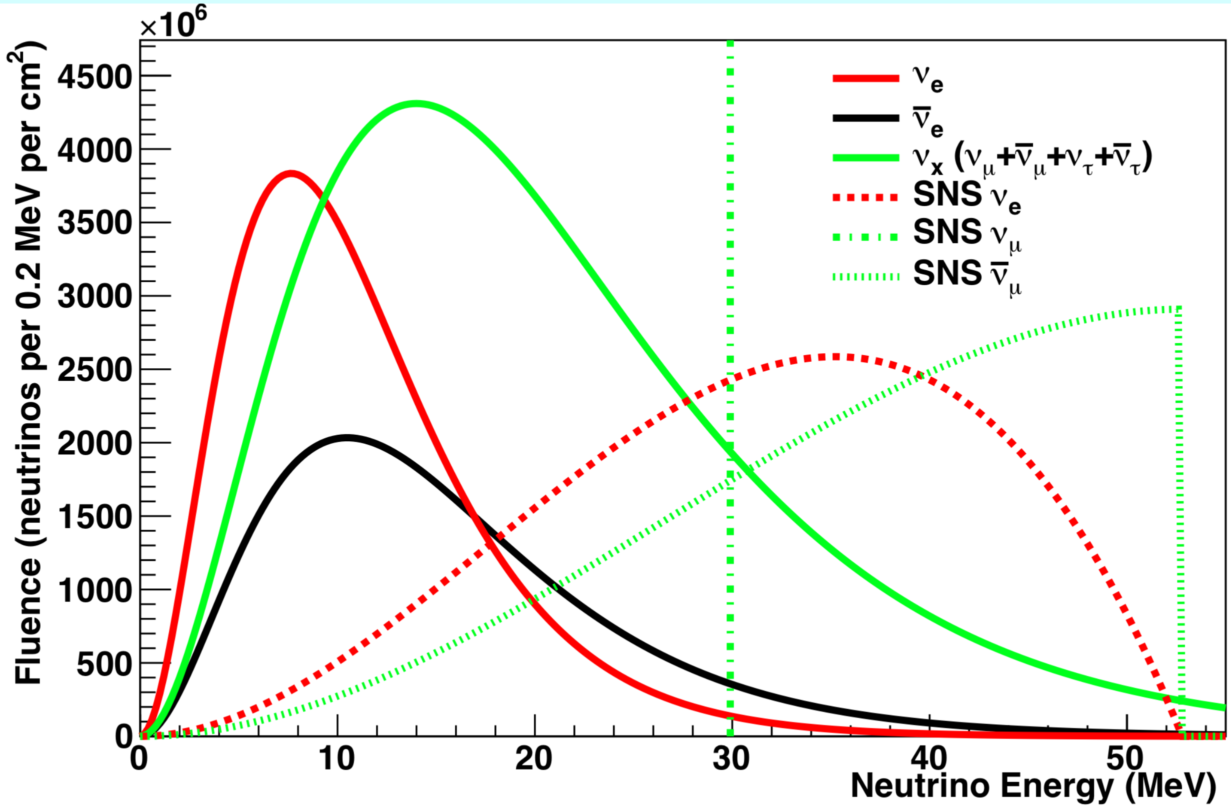








To make the most of a Galactic SN neutrino detection, we need to understand how the neutrinos interact with detector materials

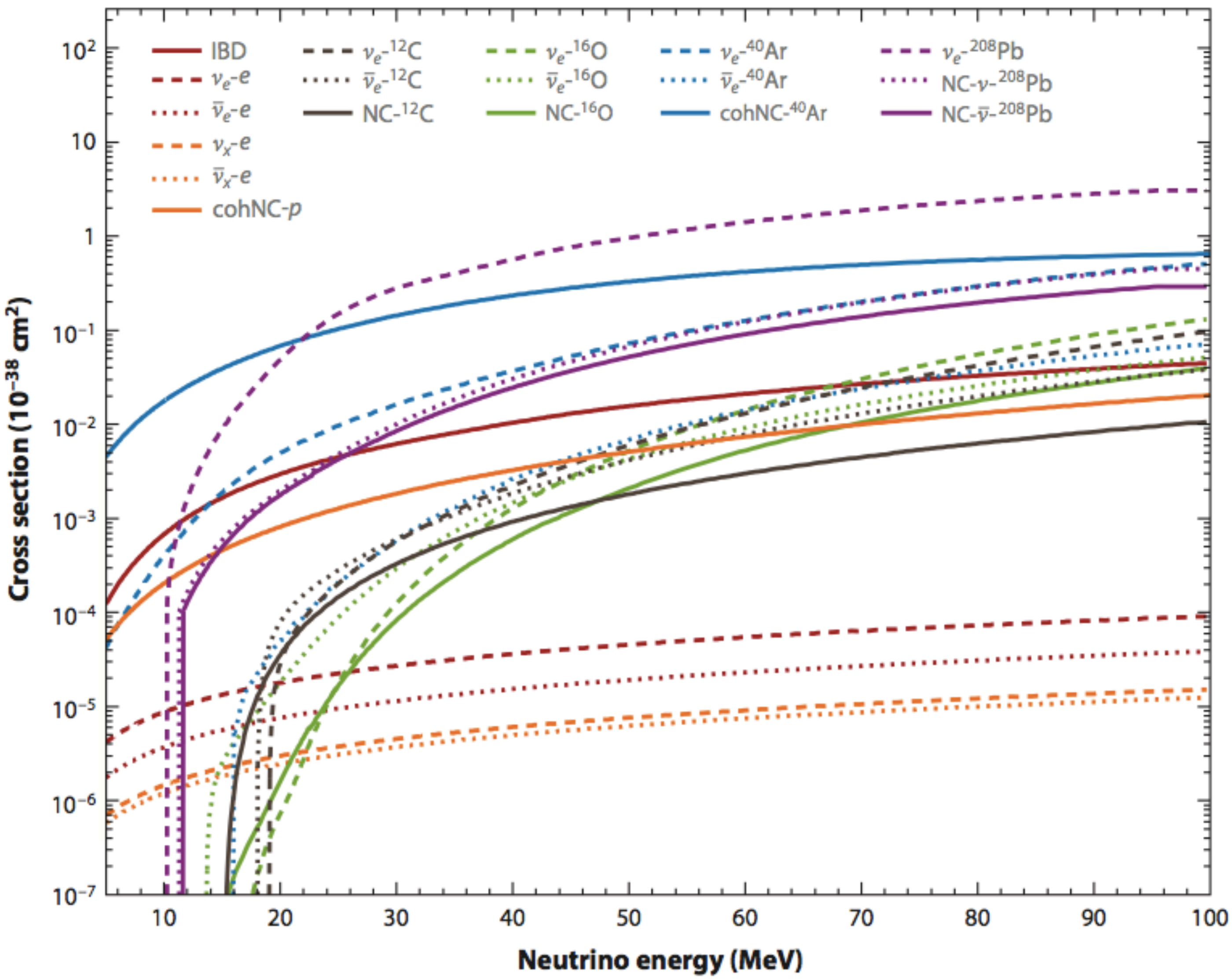
Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum



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

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

SN-relevant cross sections in this energy range



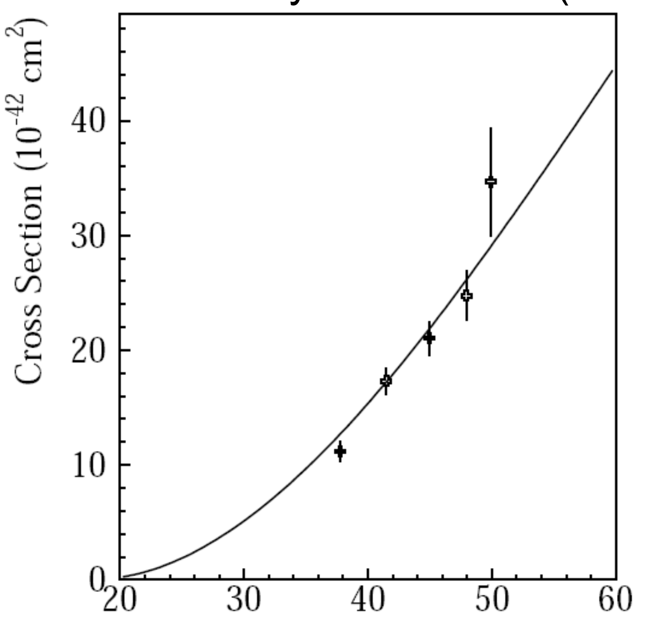
Of these, only IBD, ν-e ES are known at the few % level

So far only ^{12}C is the *only* heavy nucleus with ν interaction x-sections well (~10%) measured in the tens of MeV regime

e.g.

LSND

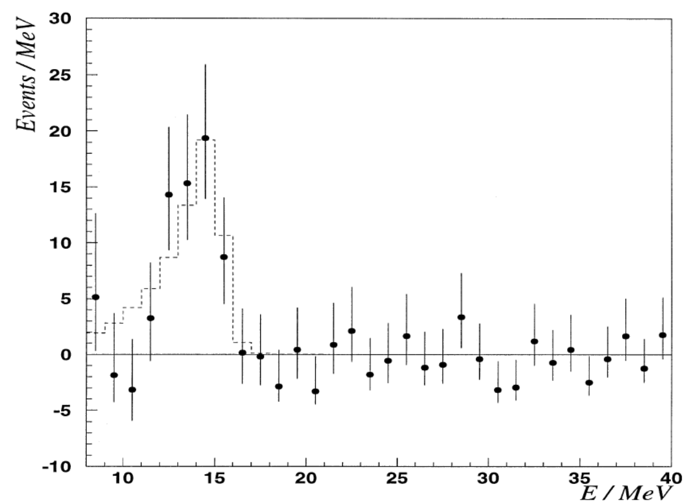
Phys. Rev. C 66 (2002) 015501



$$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$$

Karmen

Phys. Lett. B 423 (1998) 15-20



$$^{12}C(\nu_\mu \nu_\mu')\,^{12}C^*(1^+,1;15.1\,\mathrm{MeV})$$

Need: oxygen (water), lead, iron, argon...

Low energy neutrino interactions in argon

Charged-current absorption

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Not much known

Elastic scattering

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

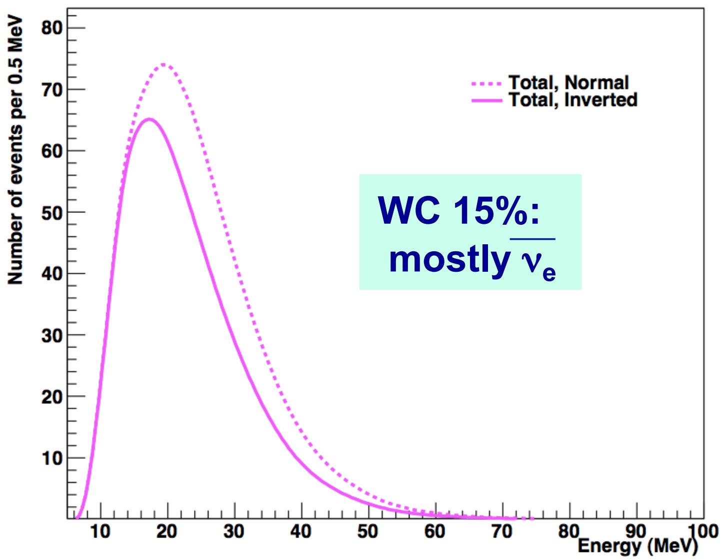
Can use for pointing

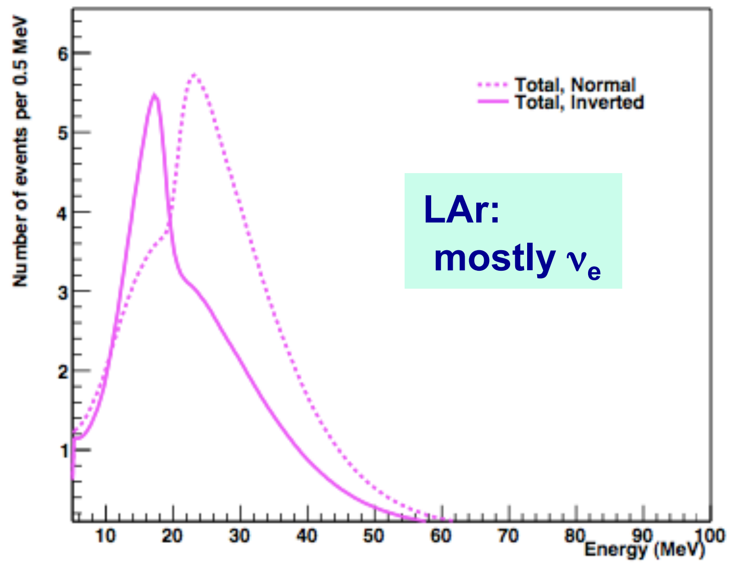
- In principle can tag modes with
- deexcitation gammas (or lack thereof)...
- however no assumptions made about this so far

Observability of oscillation features: example

Can we tell the difference between normal and inverted mass hierarchies?

(1 second late time slice, flux from H. Duan w/collective effects)



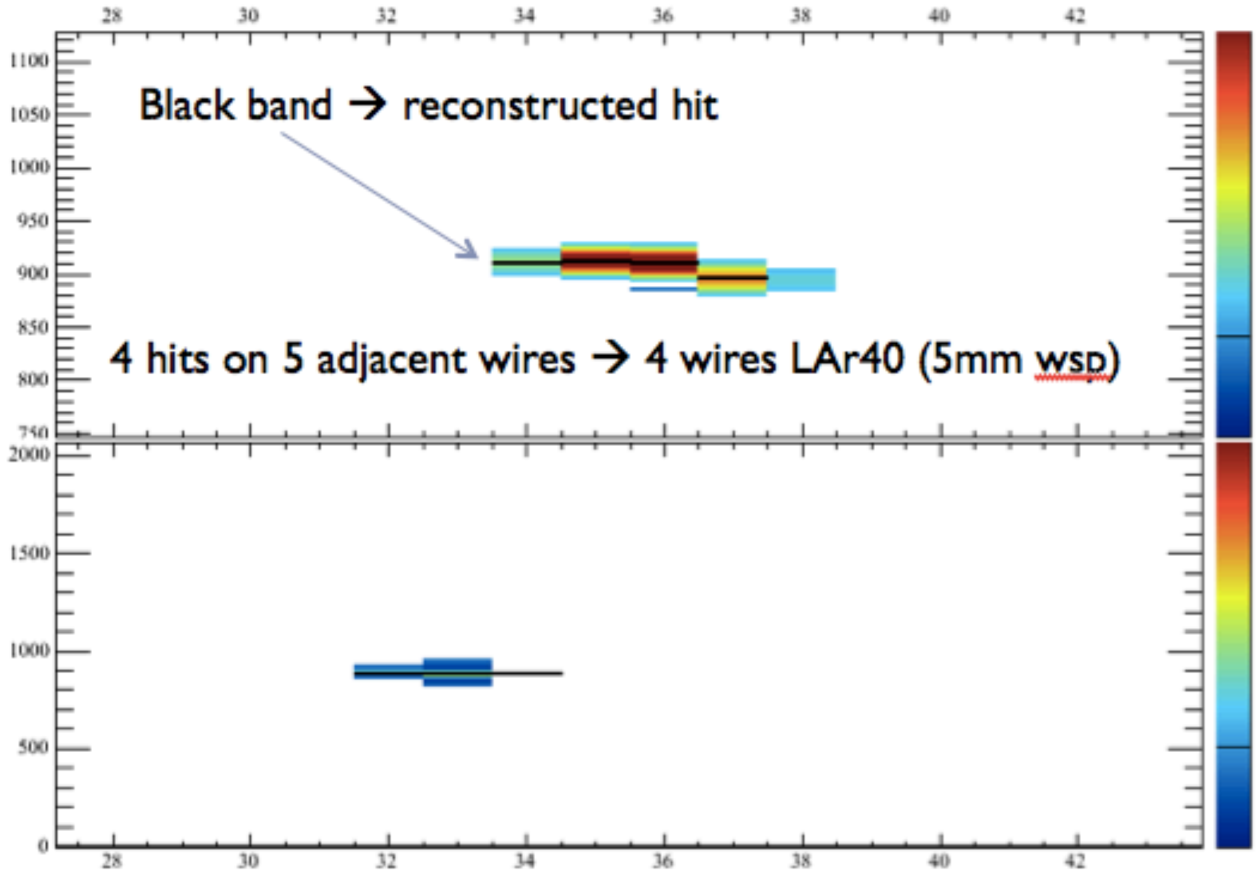


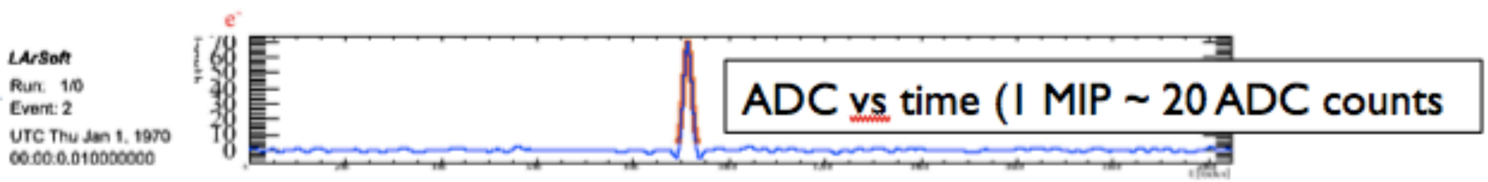
Differences, but no sharp features

LAr shows dramatic difference

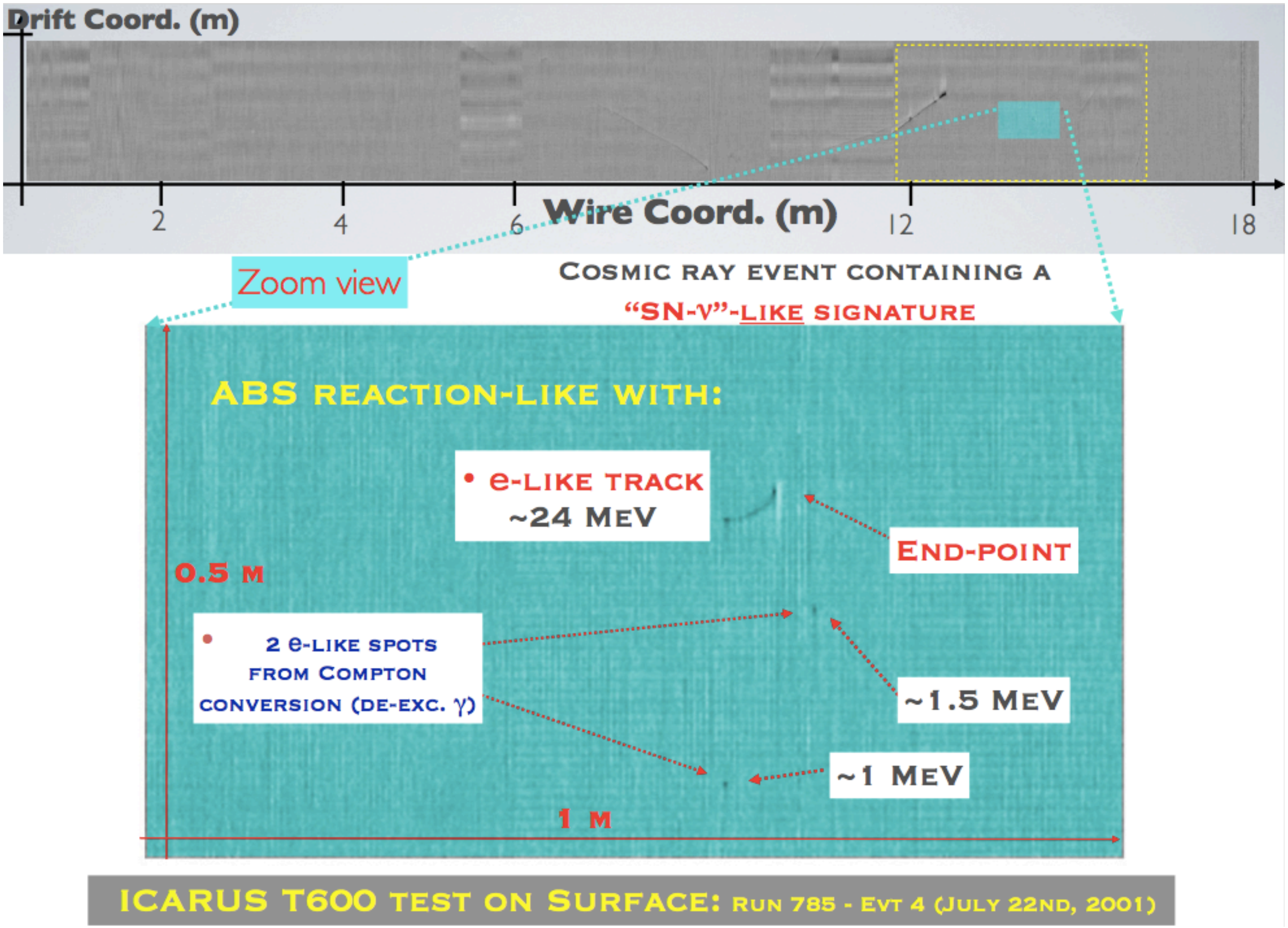
But need to understand the cross-section!

MC - 10 MeV Electron in ArgoNeuT/LArSoft 4 mm wire spacing *Bruce Baller*





From Flavio Cavanna (SNS workshop, May 2012)



Another example: Interactions on lead nuclei

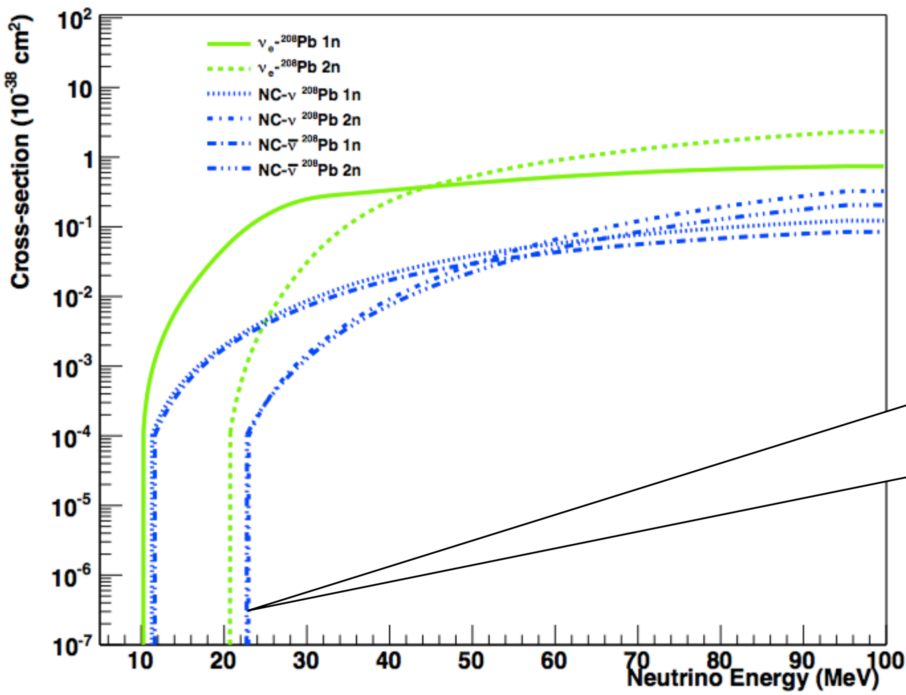
$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^-$ CC

↘ 1n, 2n emission

$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^* + \nu_x$ NC

↘ 1n, 2n, γ emission

Observe single and double ~few MeV neutron events in the ^{3}He counters

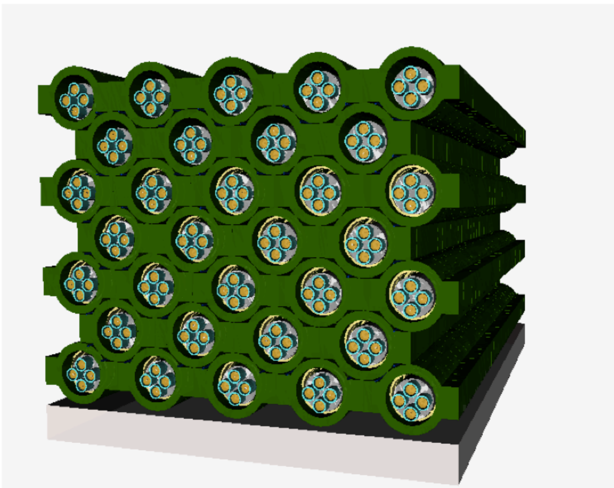


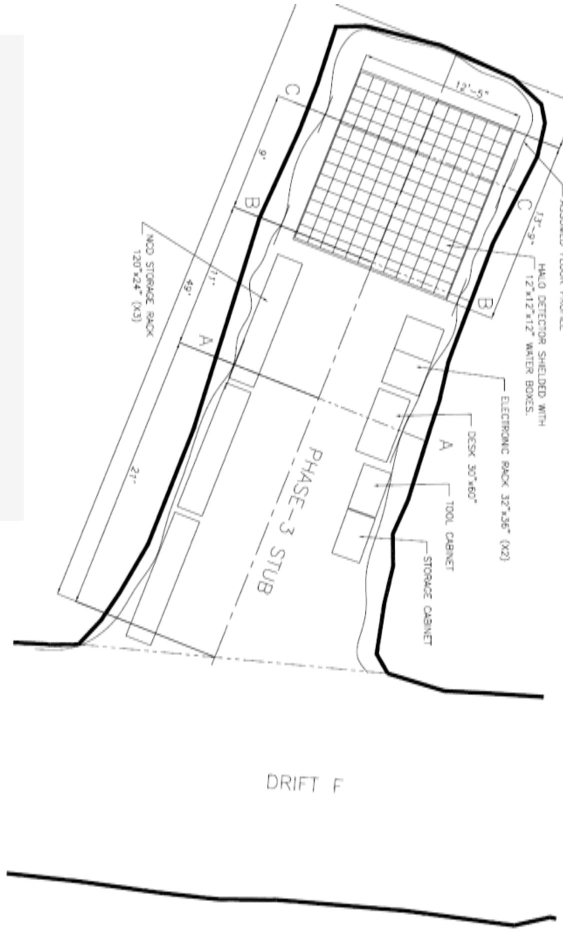
sharp thresholds, so 1n/2n relative rates are strongly dependent on the neutrino spectrum

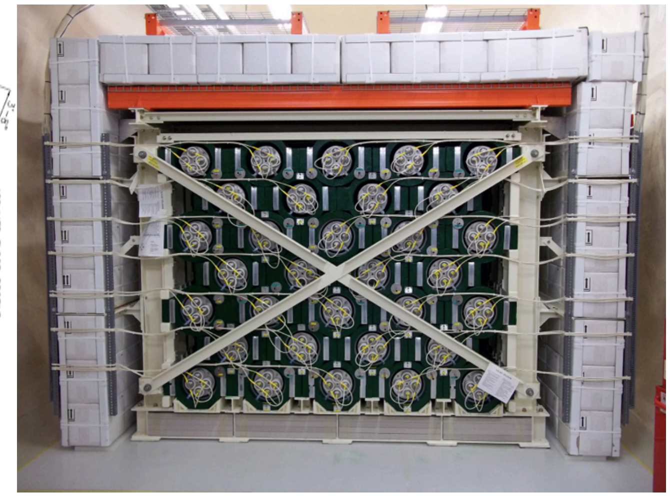
(similar for other lead isotopes)

*** Note: may need to worry about lead (or iron?) shielding for coherent νA !!**

HALO at SNOLAB







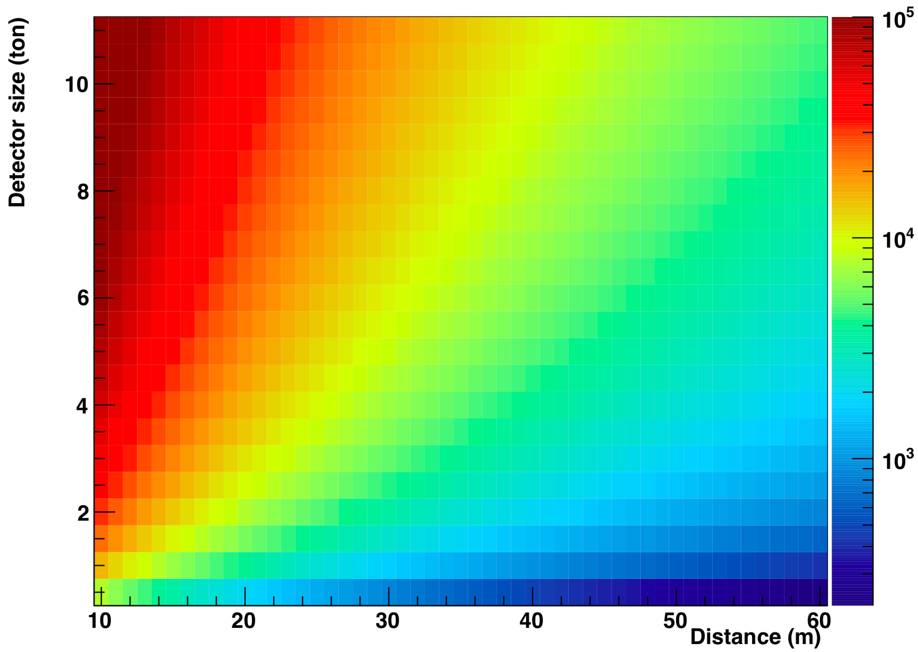
talk by Clarence Virtue tomorrow

SNO ^{3}He counters + 79 tons of Pb: ~40 events @ 10 kpc

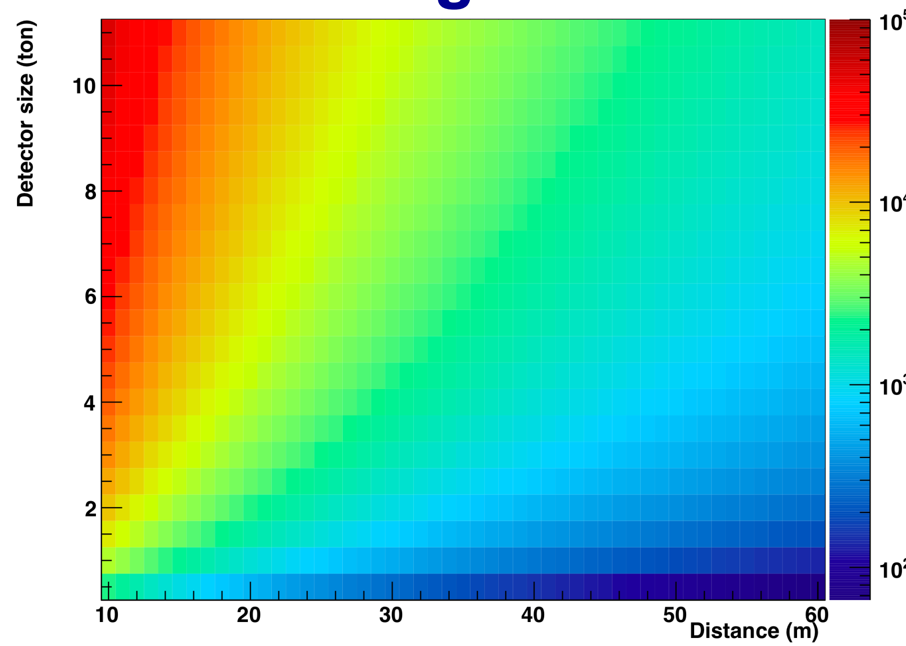
Total events per year at the SNS as a function of distance and mass

just scaling as α $1/R^2$, α M

lead



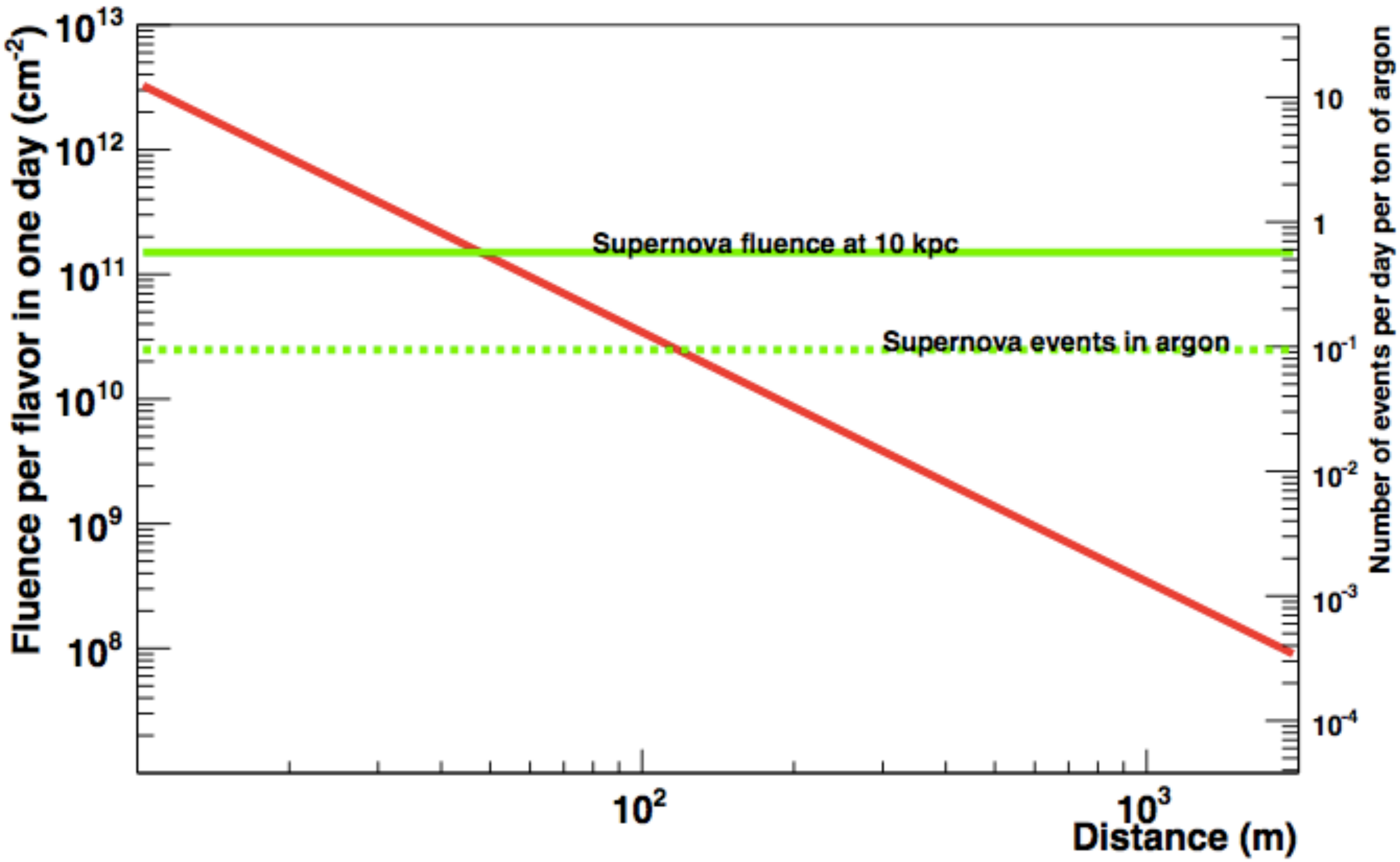
argon



~10^3 events per few tons at 30 m

Fluence at ~50 m from the SNS amounts to ~ a supernova a day!

(and effectively more events due to harder spectrum)

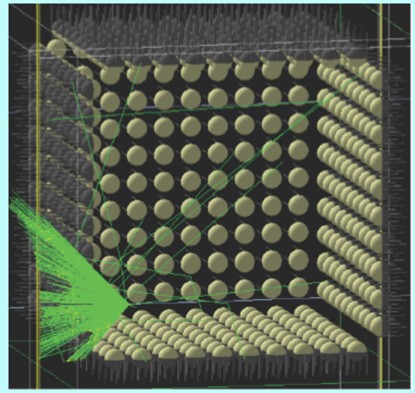


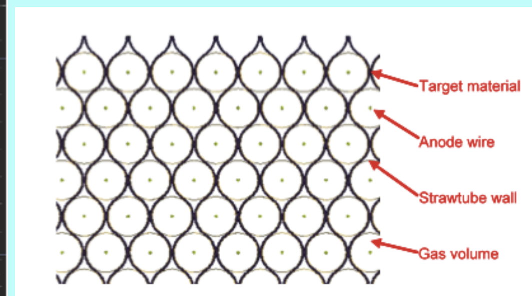
Possible Experiments for CC/NC Measurements

NuSNS:

interchangeable targets

- homogeneous detector for transparent liquids
- foils + strawtubes for metallic targets



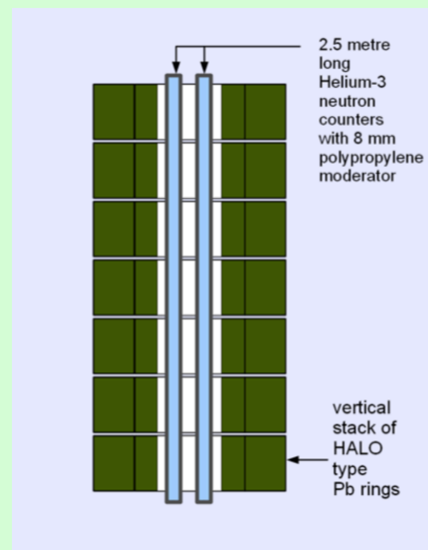


Small LAr TPC

ArgoNeut?
LBNE prototype?

Small lead + n detector

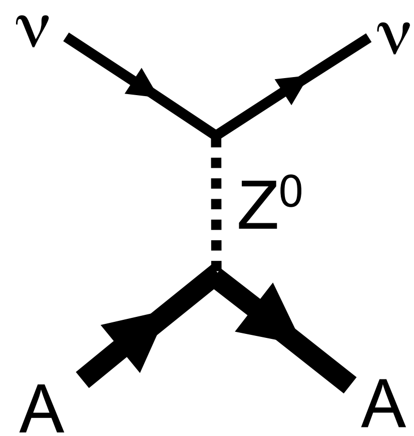
HALO-inspired

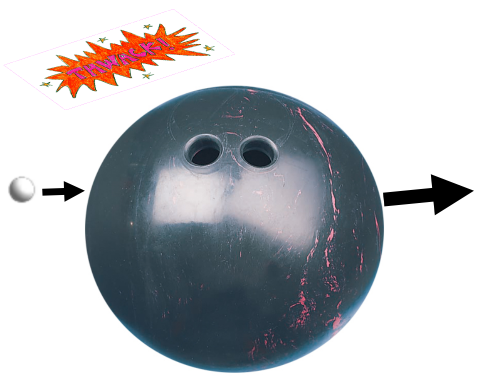


Coherent neutral current neutrino-nucleus elastic scattering

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

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils;
coherent up to $E_\nu \sim 50$ MeV



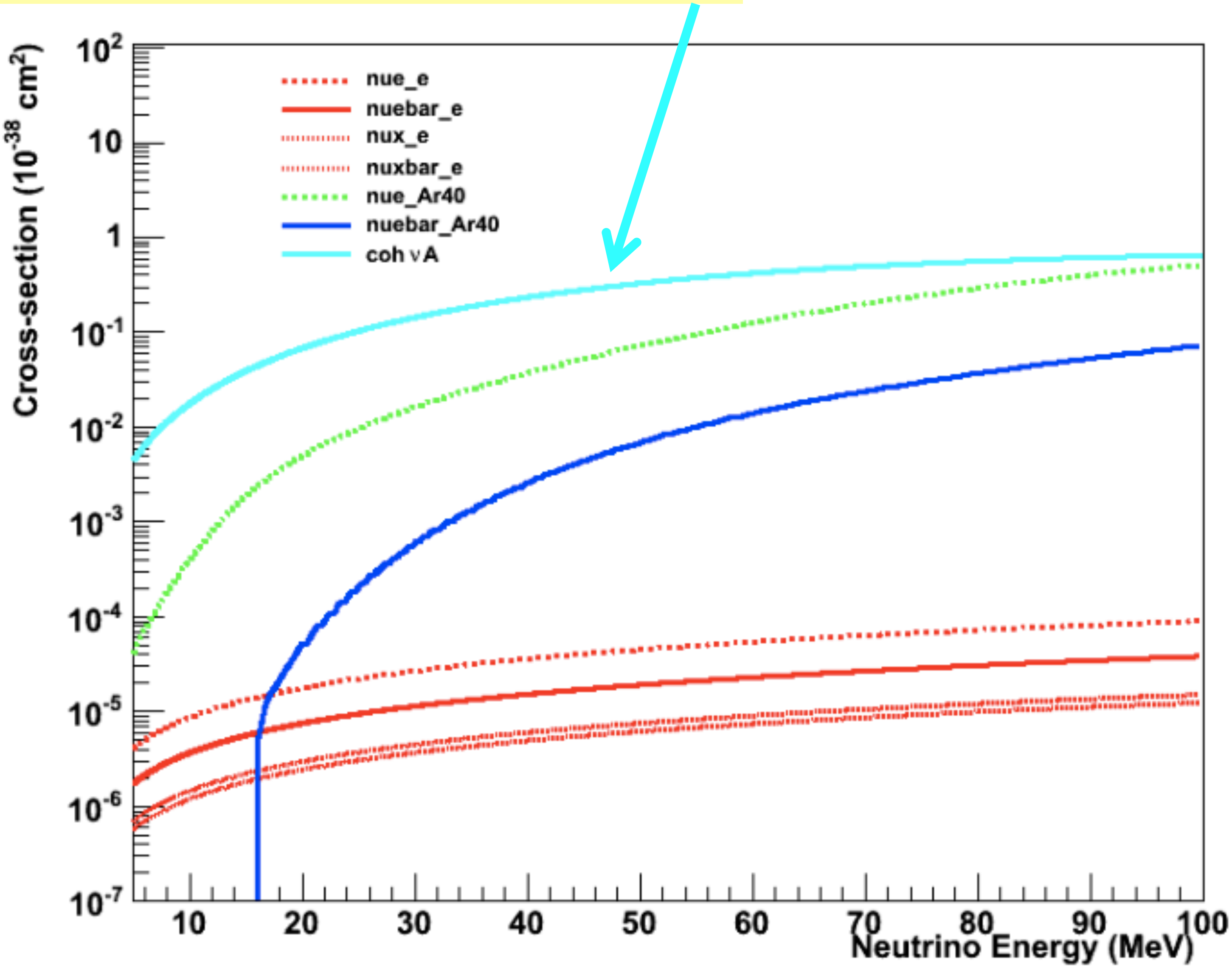


- Important in SN processes & detection
- Well-calculable cross-section in SM: SM test, probe of neutrino NSI
- Possible applications (reactor monitoring)

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

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

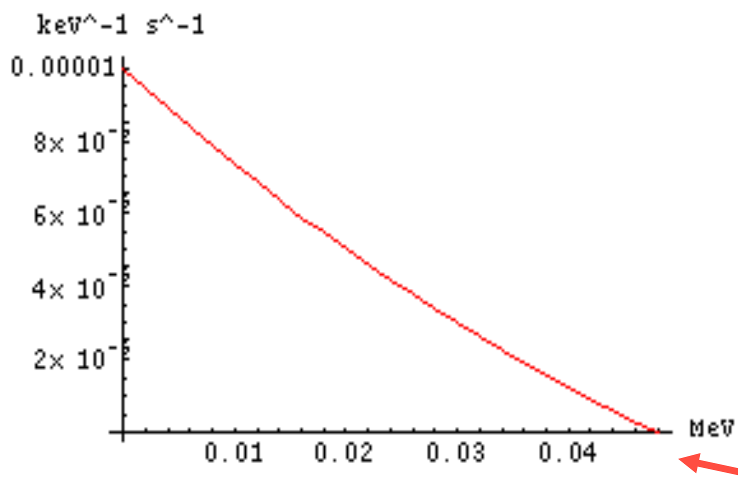
The cross-section is *large*



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

Why not?

Nuclear recoil energy spectrum for 30 MeV ν



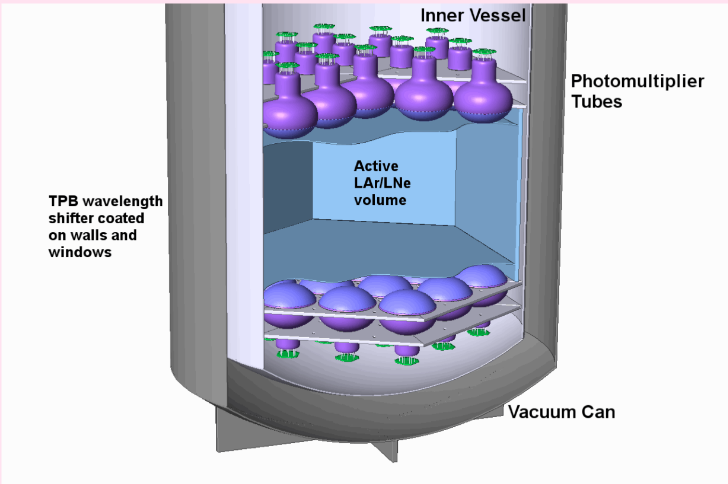
Max recoil energy is $2E_\gamma^2/M$ (48 keV for Ar)

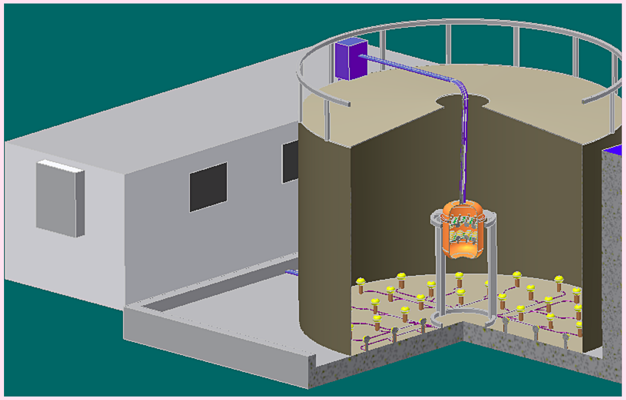
Recoil energies are tiny!

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

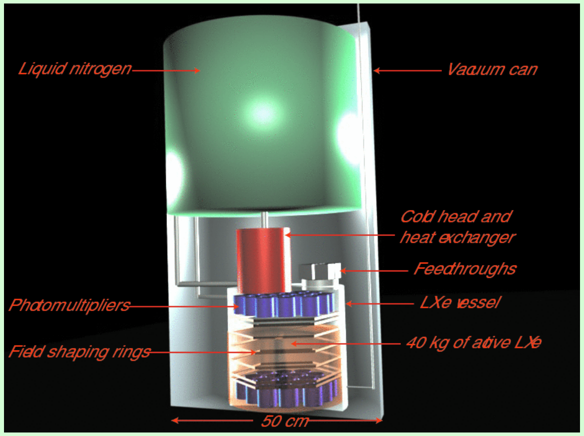
Detector possibilities: various DM-style strategies

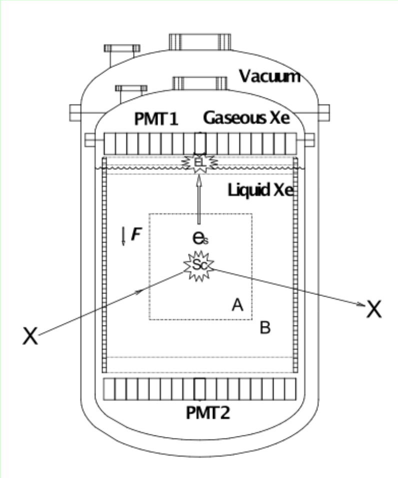
Single-phase Ar/Ne (CLEAR)



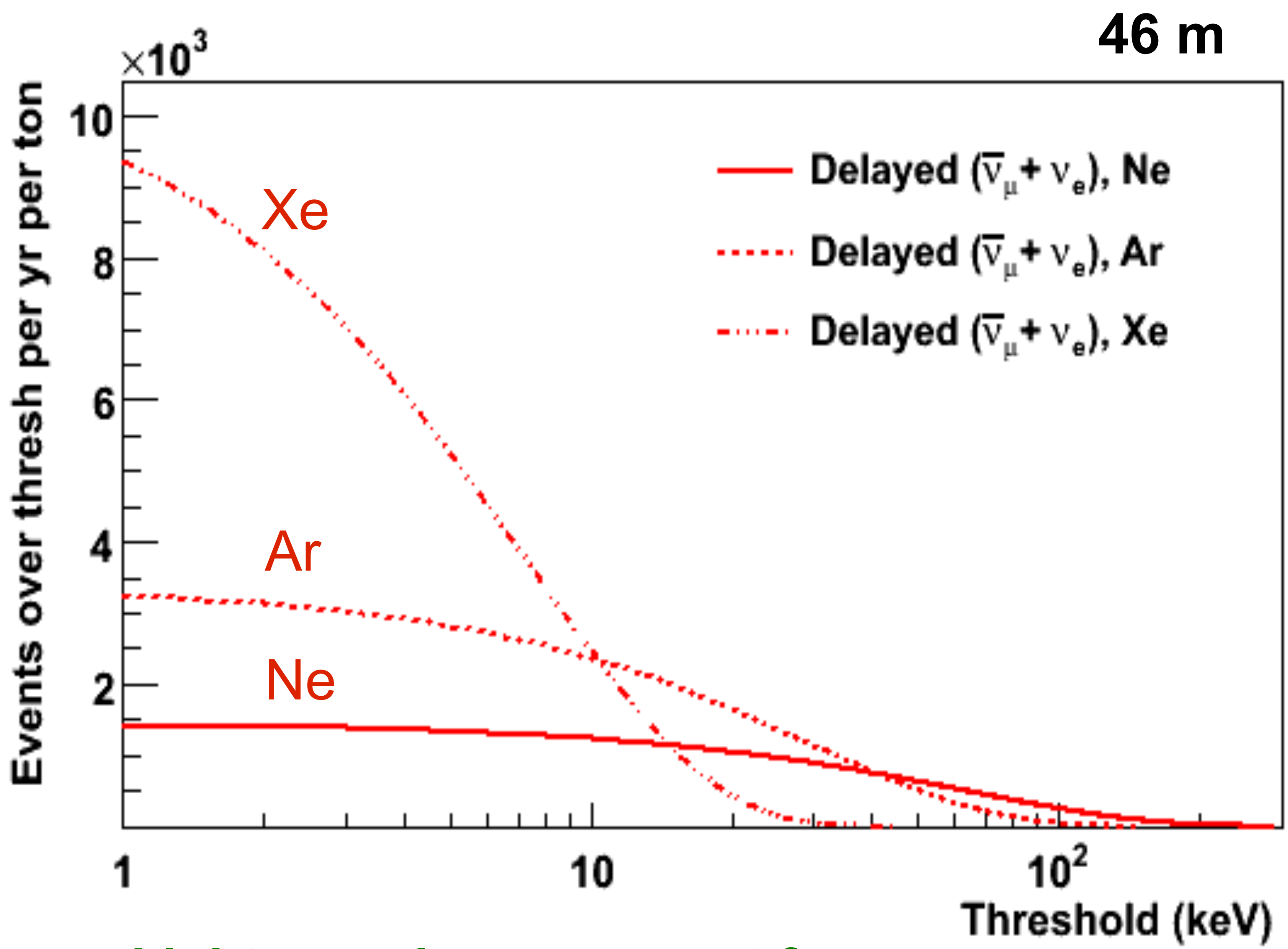


Xe dual-phase TPC





Integrated SNS yield for various targets



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

What physics could be learned from measuring this?

KS, 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

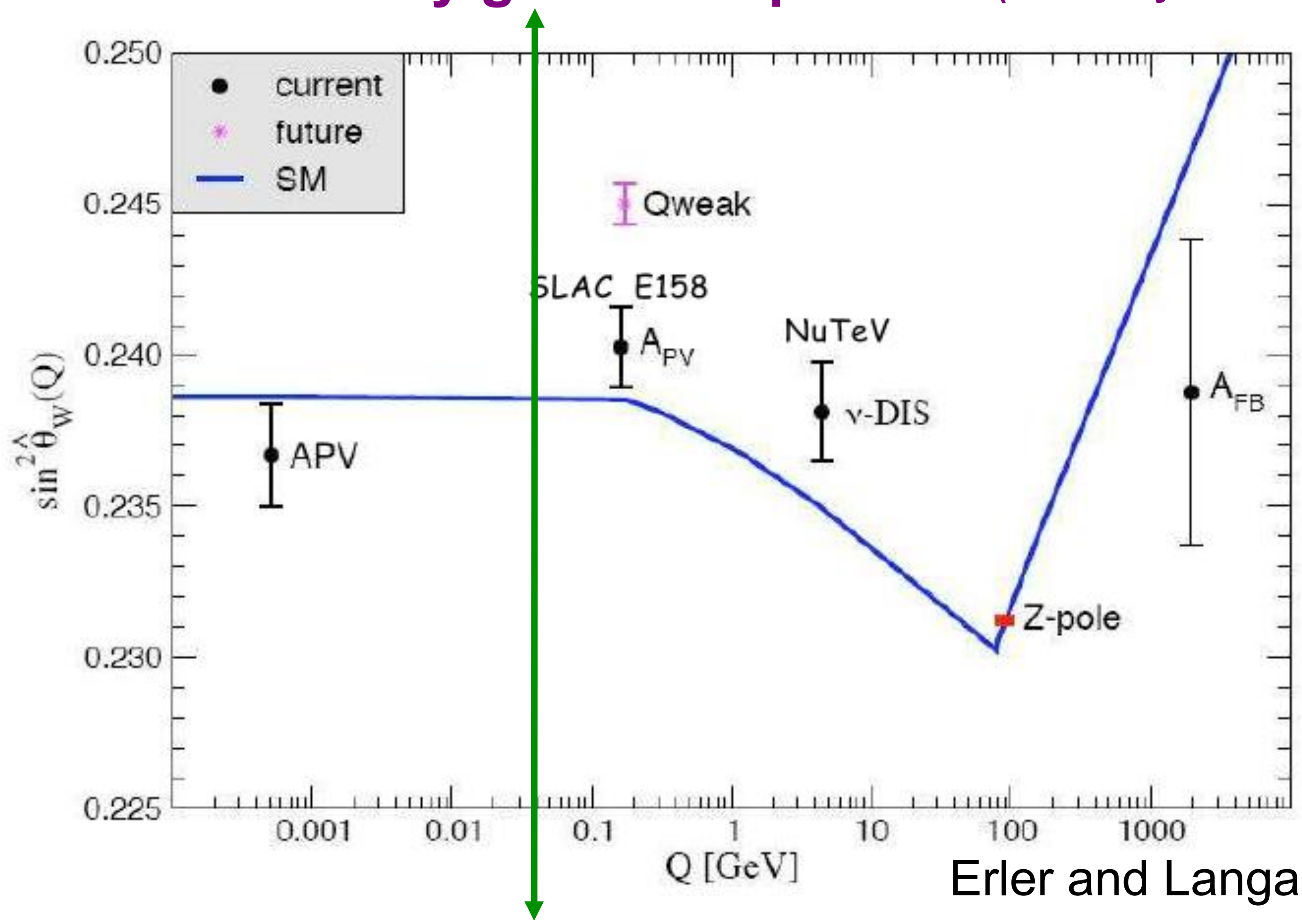
Absolute rate in SM is proportional to

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

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)
... could eventually get to few percent (limited by nuclear physics)



Erler and Langacker, PDG

However note it's a unique channel and independent test

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:

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

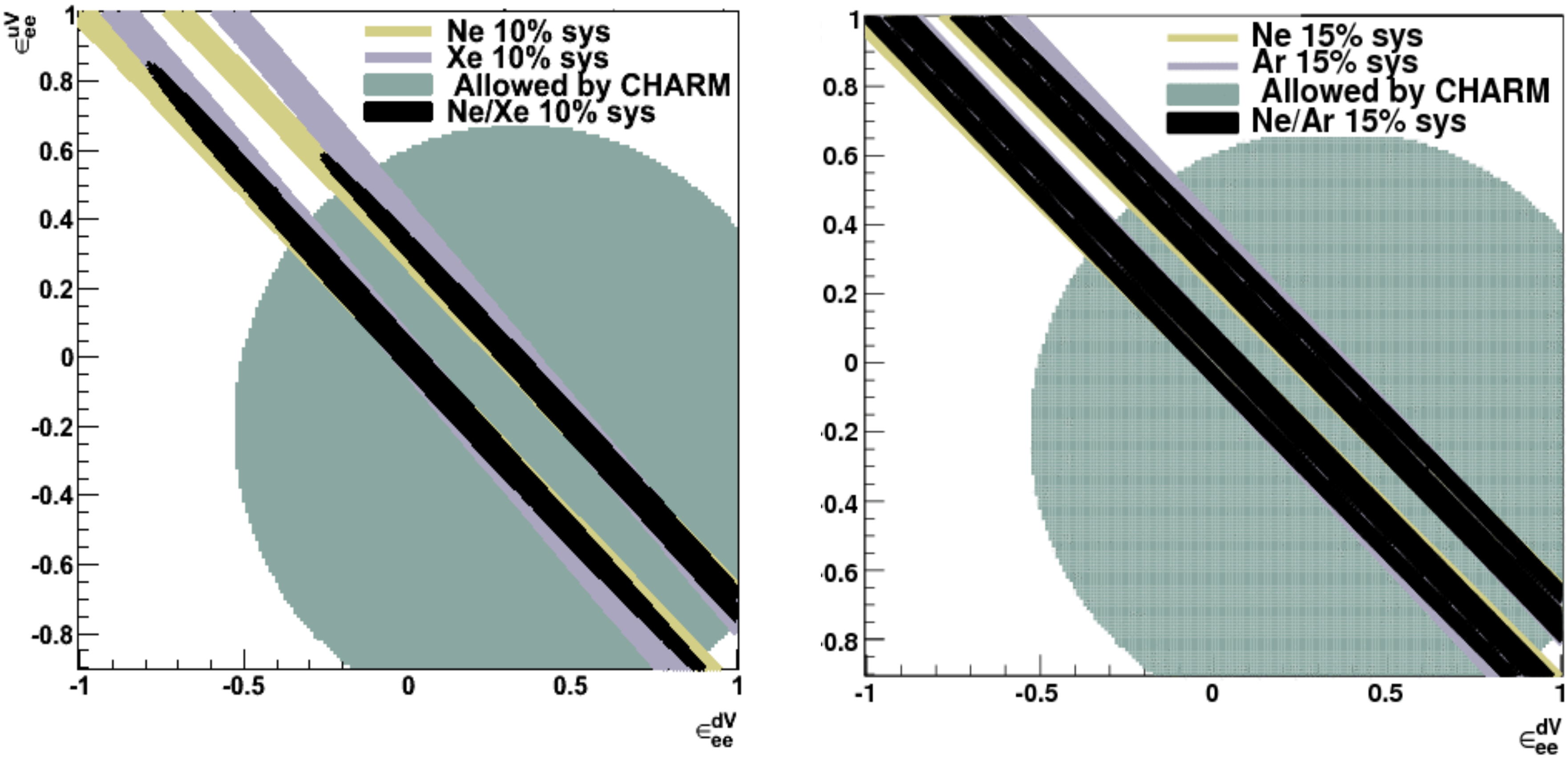
$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$ **non-universal**

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

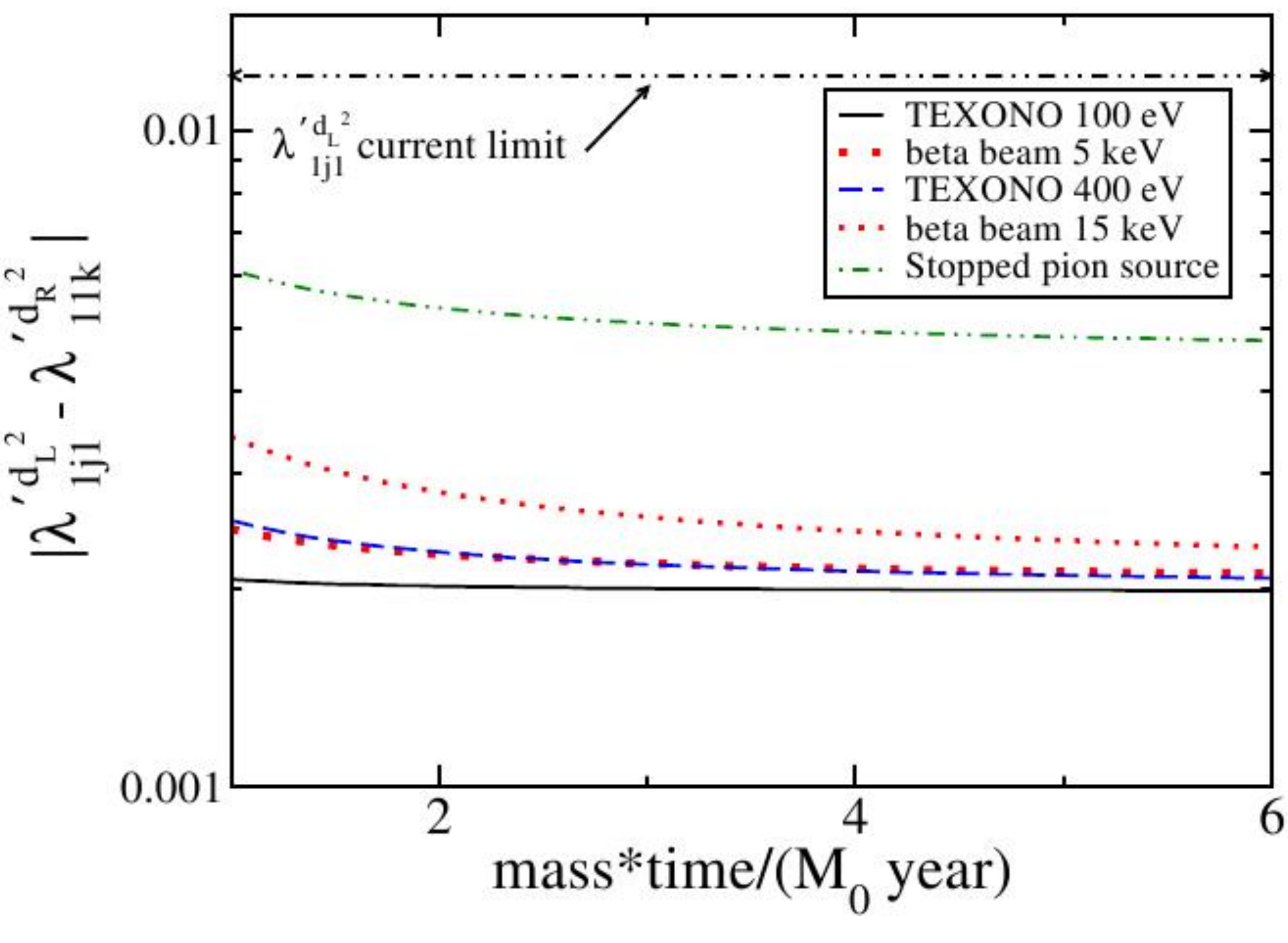


Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment

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



If systematics can be reduced to ~ few % level, we could start to explore nuclear form factors

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

K. Patton et al., arXiv:1207.0693 NEW

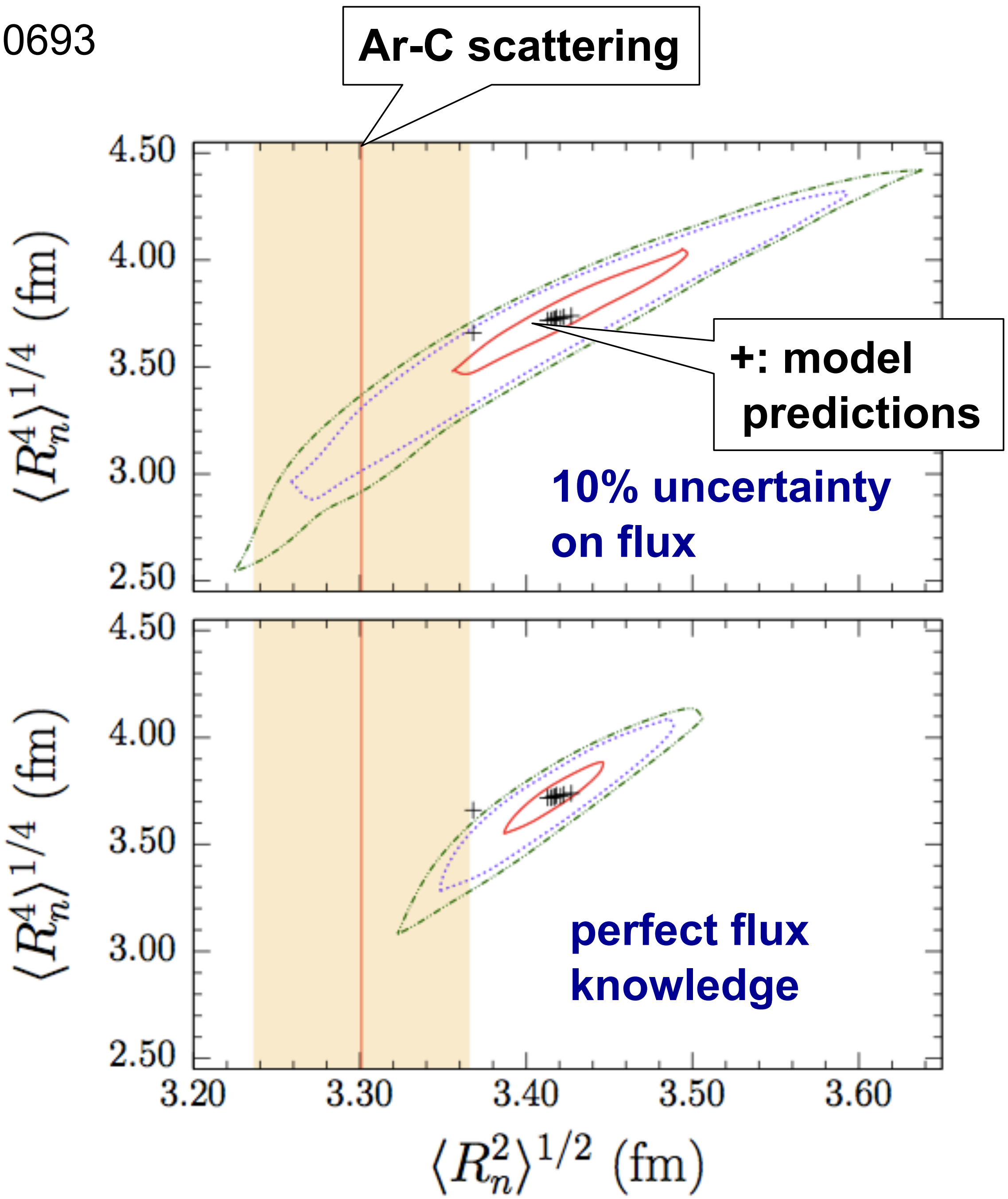
$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

Form factor, encodes information about nucleon (primarily neutron) distributions

$$\begin{aligned} F_n(Q^2) &\approx \int \rho_n(r) \left(1 - \frac{Q^2}{3!} r^2 + \frac{Q^4}{5!} r^4 - \frac{Q^6}{7!} r^6 + \cdots \right) r^2 dr \\ &\approx N \left(1 - \frac{Q^2}{3!} \langle R_n^2 \rangle + \frac{Q^4}{5!} \langle R_n^4 \rangle - \frac{Q^6}{7!} \langle R_n^6 \rangle + \cdots \right) . \end{aligned}$$

K. Patton et al., arXiv:1207.0693

Example: 3.5 tonnes of Ar at SNS (16 m)



Will require stringent control of uncertainties

Summary of physics reach for νA scattering

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

At a level of experimental precision better than that on the nuclear form factors:

- **Neutron form factor:**
  hard but conceivable

Comparison of stopped-pion neutrino sources

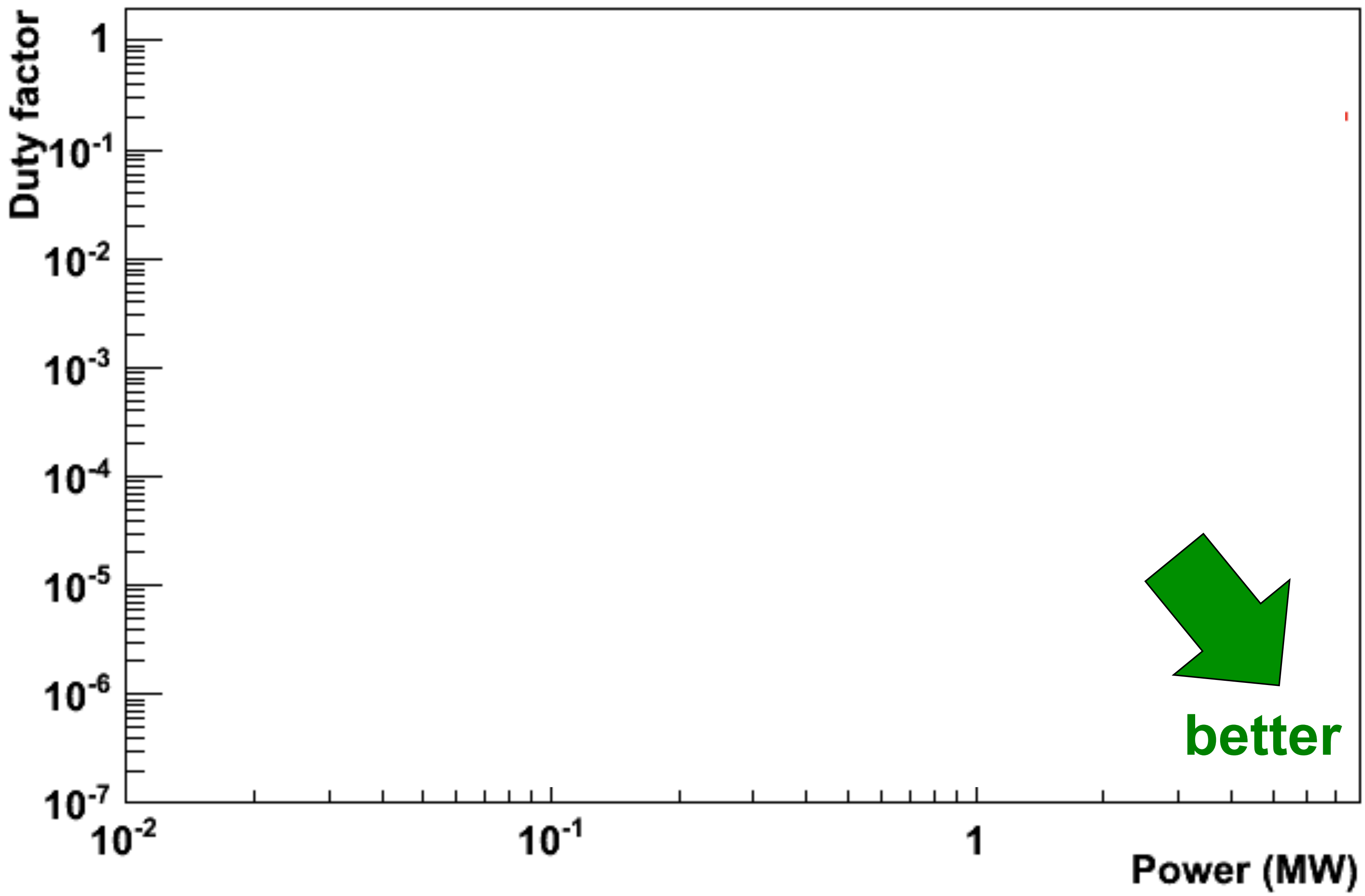
Facility	Location	Proton Energy (GeV)	Power (MW)	Bunch Structure	Rate	Target
LANSCE	USA (LANL)	0.8	0.056	Continuous	N/A	Various
ISIS	UK (RAL)	0.8	0.16	2×200 ns	50 Hz	Water-cooled tantalum
BNB	USA (FNAL)	8	0.032	1.6 μs	5-11 Hz	Beryllium
SNS	USA (ORNL)	1.3	1	700 ns	60 Hz	Mercury
MLF	Japan (J-PARC)	3	1	$2 \times$ 60-100 ns	25 Hz	Mercury
ESS	Sweden (planned)	1.3	5	2 ms	17 Hz	Mercury
DAEδALUS	TBD (planned)	0.7	$\sim 7 \times 1$	100 ms	2 Hz	Mercury

Want:
- very high intensity ν's
- ~below kaon threshold (low energy protons)
- nearly all decay at rest
- narrow pulses (small duty factor to mitigate bg)

Flux $\propto$ power

Duty factor = T*rate (◆)

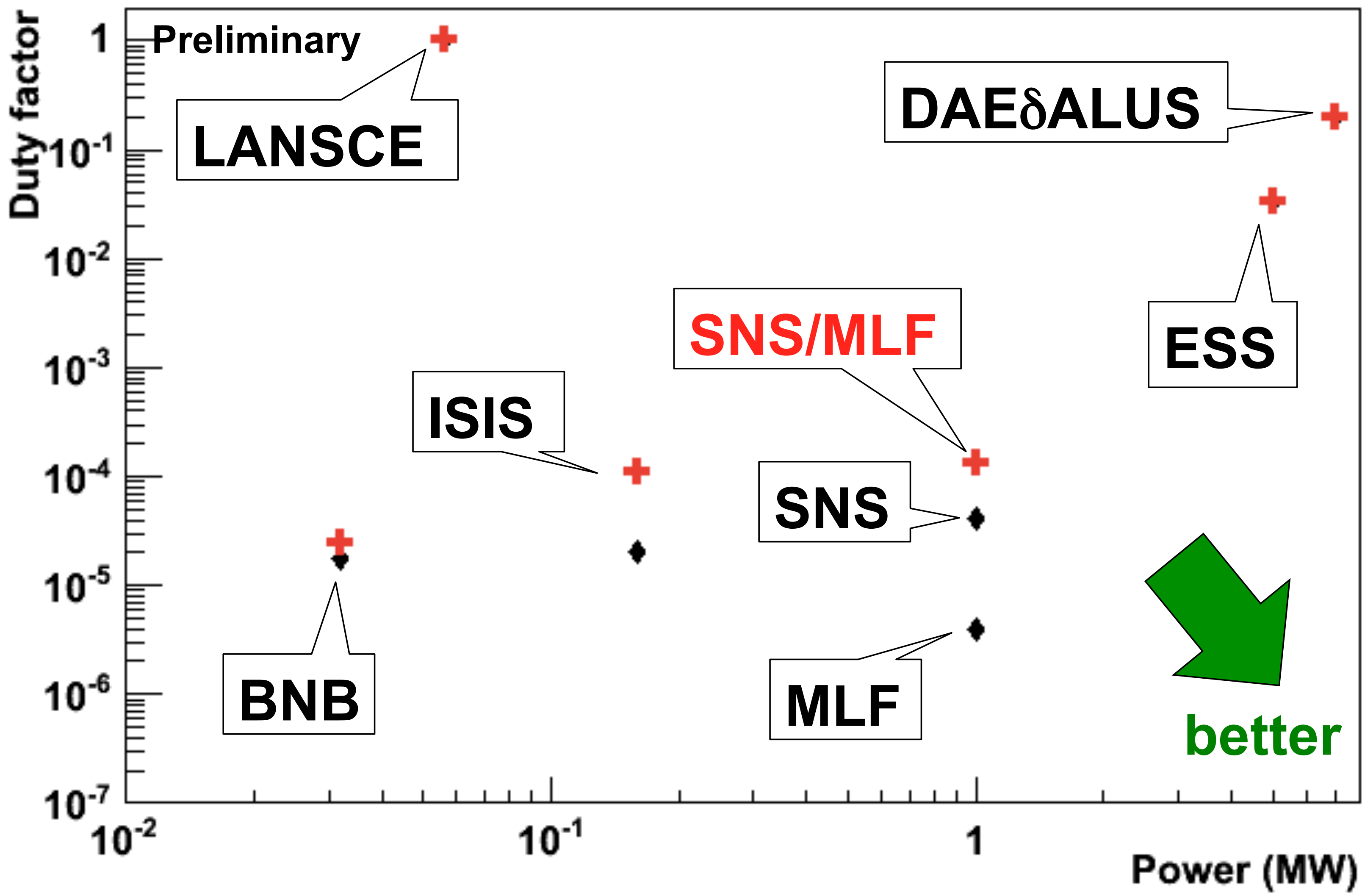
= max(T, 2.2 μs)*rate (+ for μdk ν's)



Flux $\propto$ power

Duty factor = T*rate (◆)

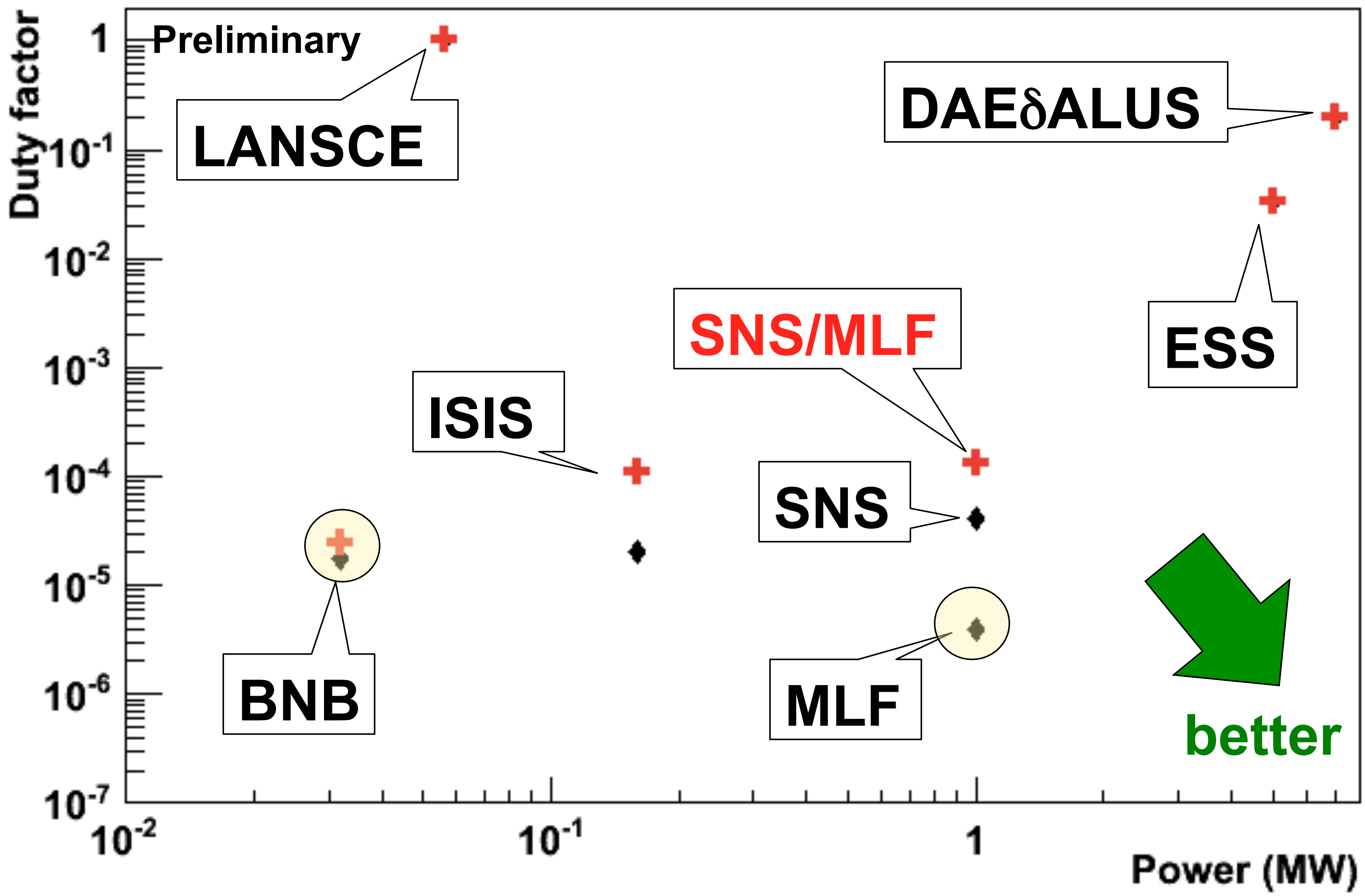
= max(T, 2.2 μs)*rate (+ for μdk ν's)



Flux ∝ power, ◯ high energy protons (non-DAR contamination)

Duty factor = T*rate (◆)

= max(T, 2.2 μs)*rate (+ for μdk ν's)



Possible Phases of Coherent νA Scattering Experiments

Phase	Detector Scale	Physics Goal	Comments
Phase I	Few to few tens of kg	First detection	Precision flux not needed
Phase II	Tens to hundreds of kg	SM test, NSI searches	Start to get systematically limited
Phase III	Tonne to multi-tonne	Neutron structure, neutrino magnetic moment	Control of systematics will be dominant issue; multiple targets useful

Summary

A stopped-pion neutrino source offers broad opportunities for physics with neutrinos in the tens of MeV range!

- **CC/NC cross-sections relevant for SN physics is almost completely unexplored**
- **Coherent elastic νA scattering:**
  - **SM tests, search for new physics, maybe nuclear physics**
- **Sterile oscillations**
- **(And more I didn't cover...)**

For first-generation measurements, requirements are not stringent;

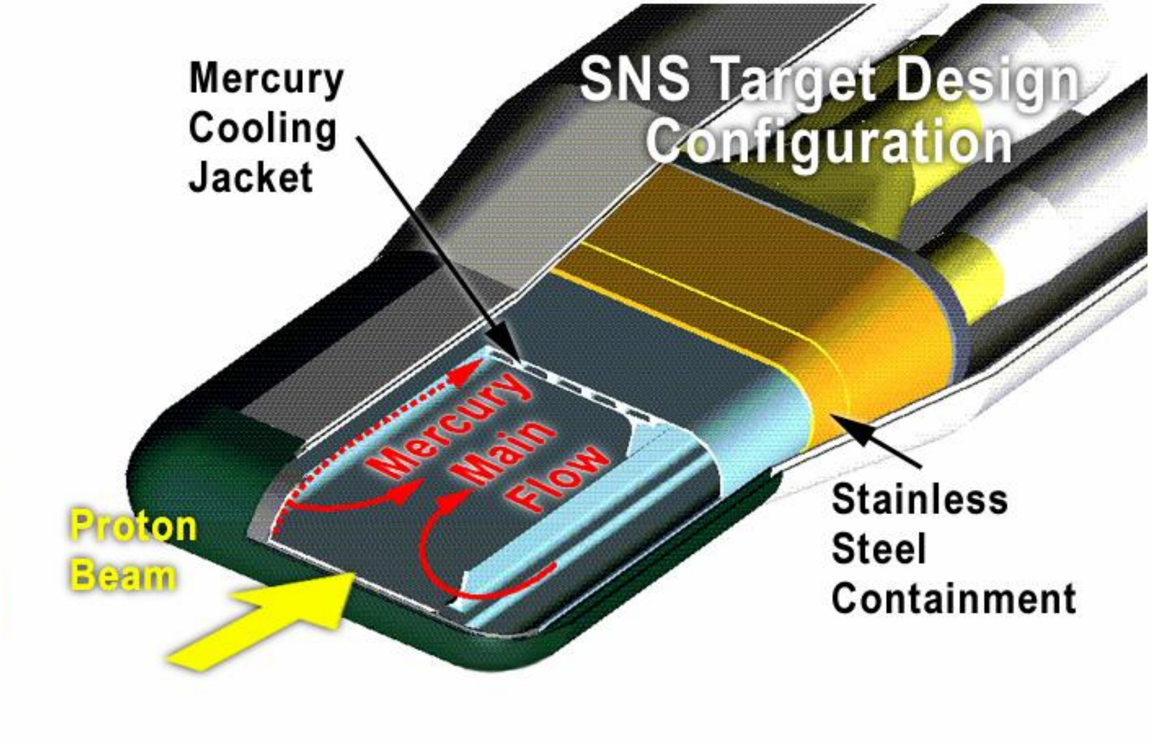
Systematic uncertainties may eventually become limiting

need multiple targets, well-understood neutrino source

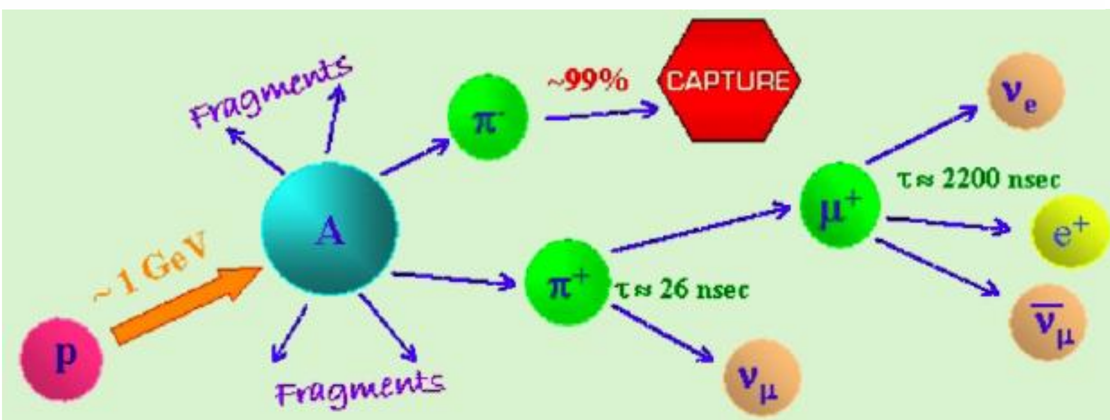
We need to strategize a phased program

Extras/Backups

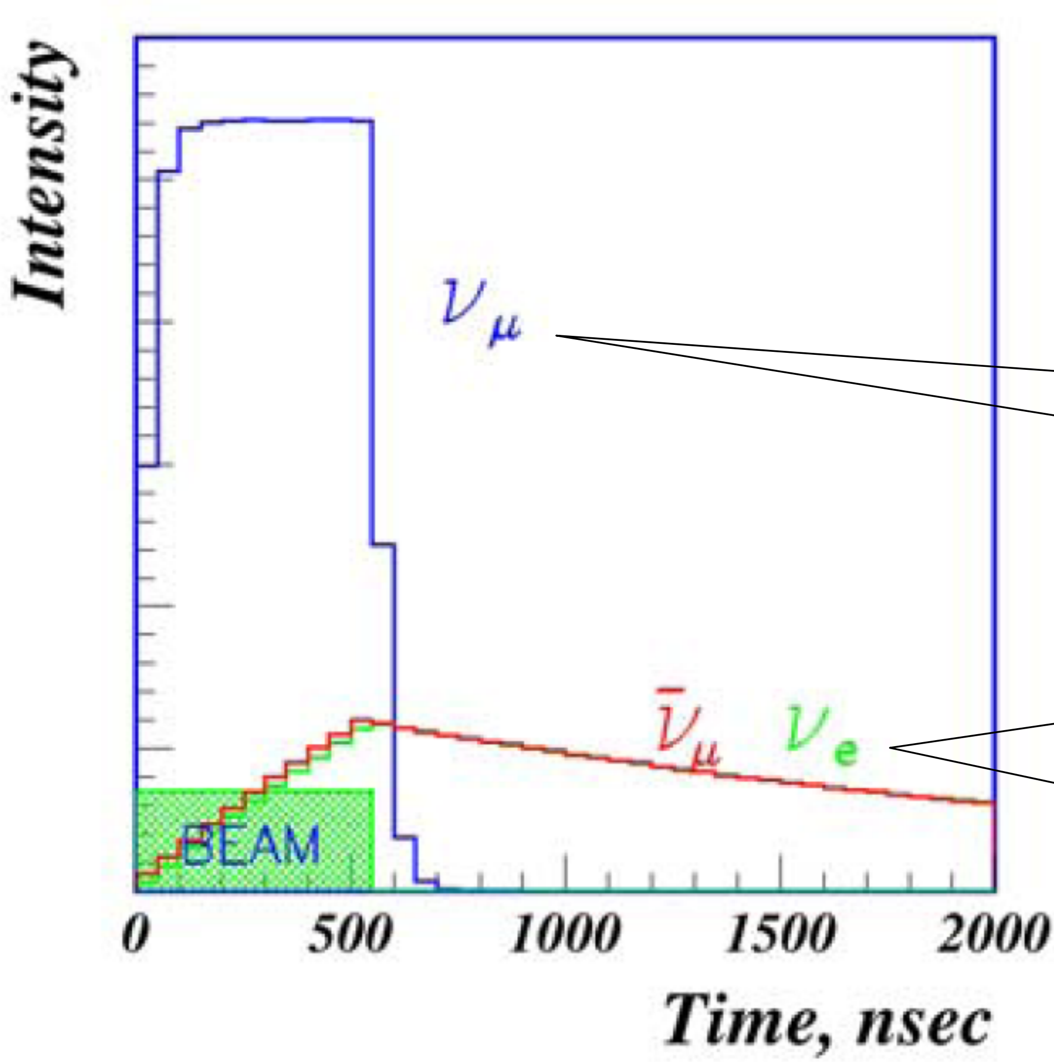
Neutrinos are a free by-product!



In addition to kicking out neutrons, protons on target create copious pions: π^- get captured; π^+ slow and decay at rest



Time structure of the source



60 Hz *pulsed* source

in time with beam

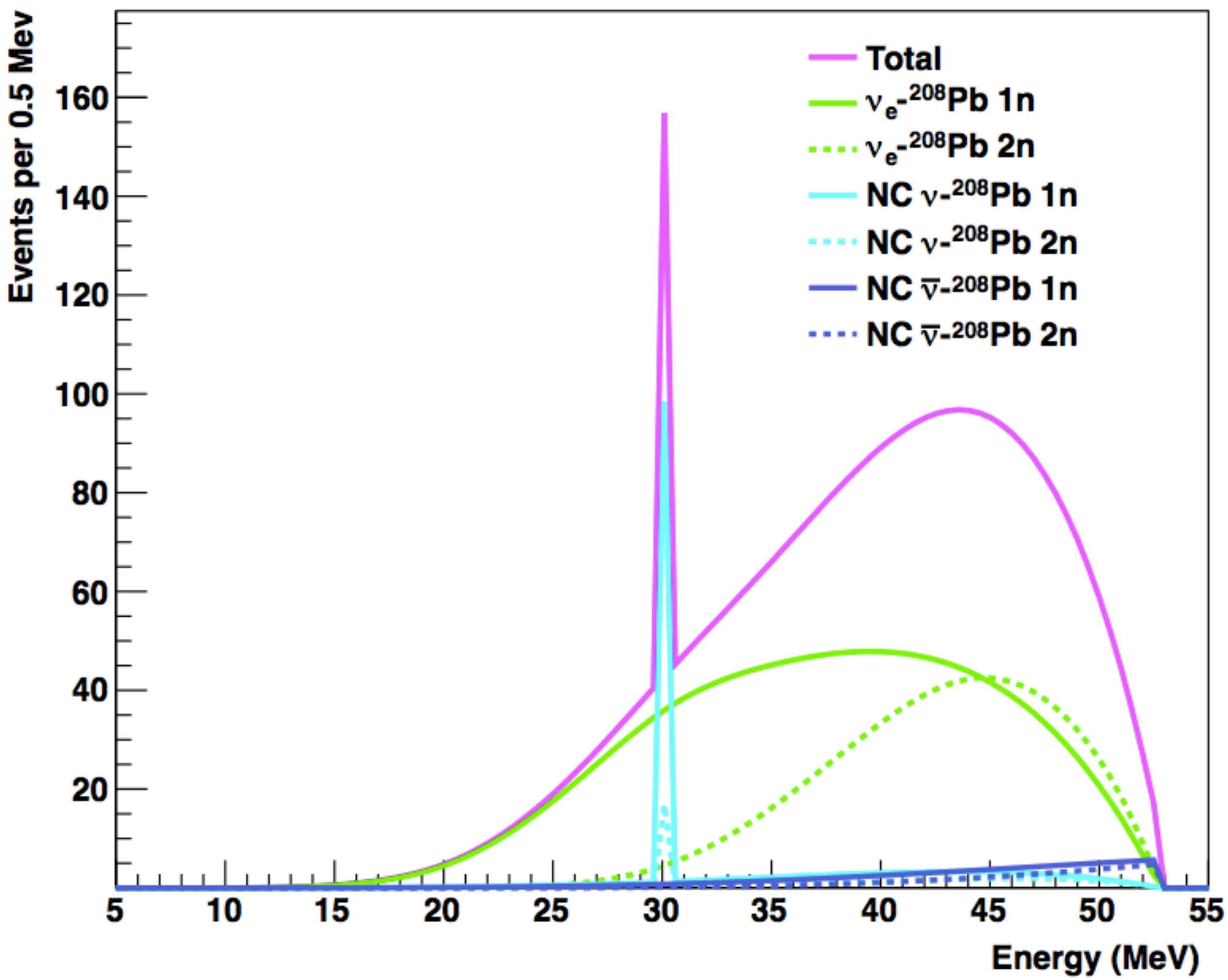
delayed on μ decay timescale (2.2 μs)

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

Event rates for lead

per ton per year at 20 m

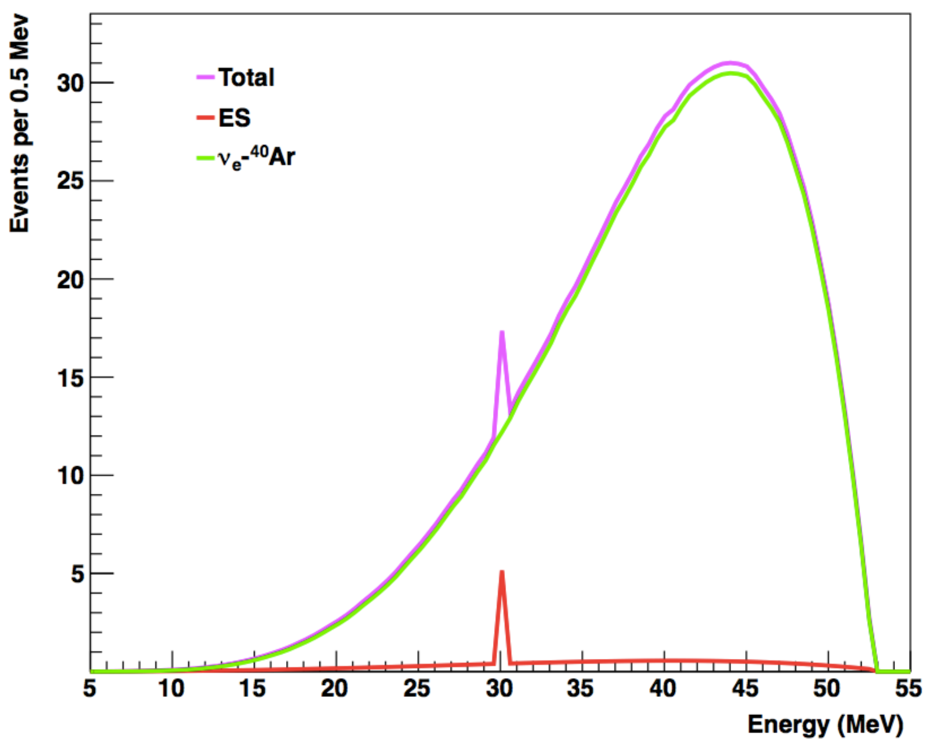
Interactions, as a function of neutrino energy



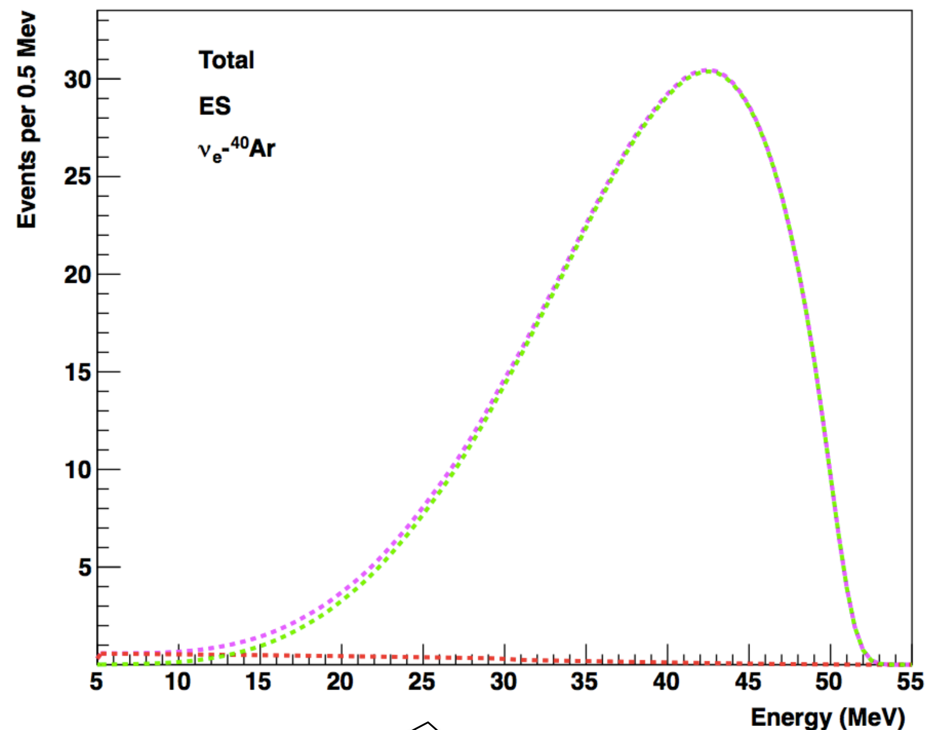
Event rates for argon

per ton per year at 20 m

Interactions, as a function of neutrino energy



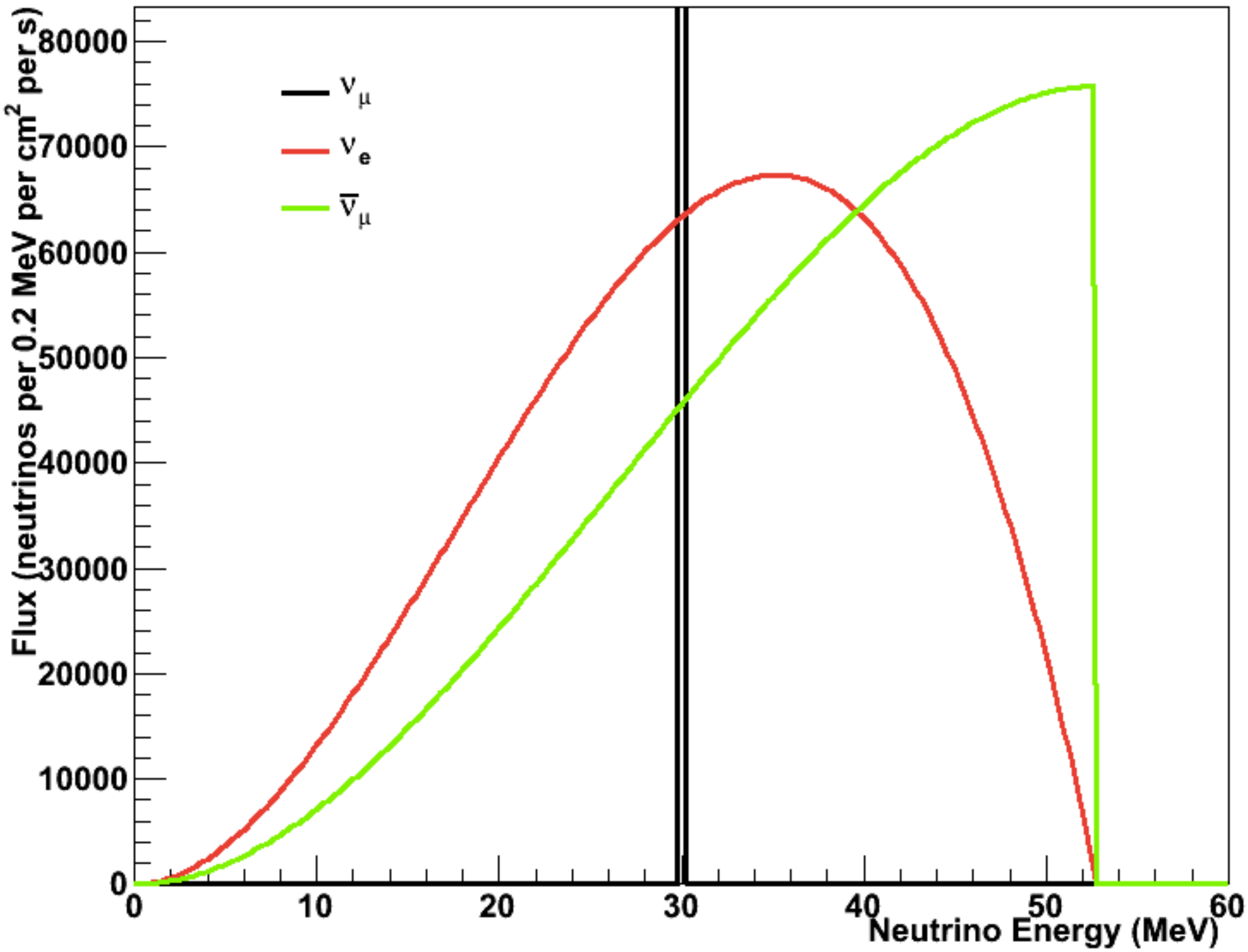
Events seen, as a function of observed energy



Assumes 100% efficiency,resolution from Amoruso et. al. (ICARUS)

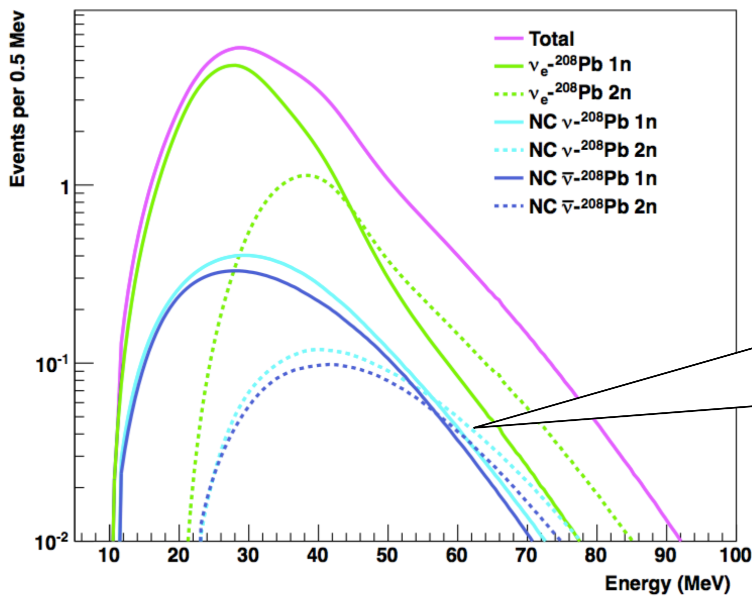
SNS Flux for SNOwGLoBES

Normalized to 10^7 per cm^2 per s per flavor at 20 m



Example of event rates for particular models

`http://www.phy.duke.edu/~schol/snowglobes`



2n events sample higher neutrino energies

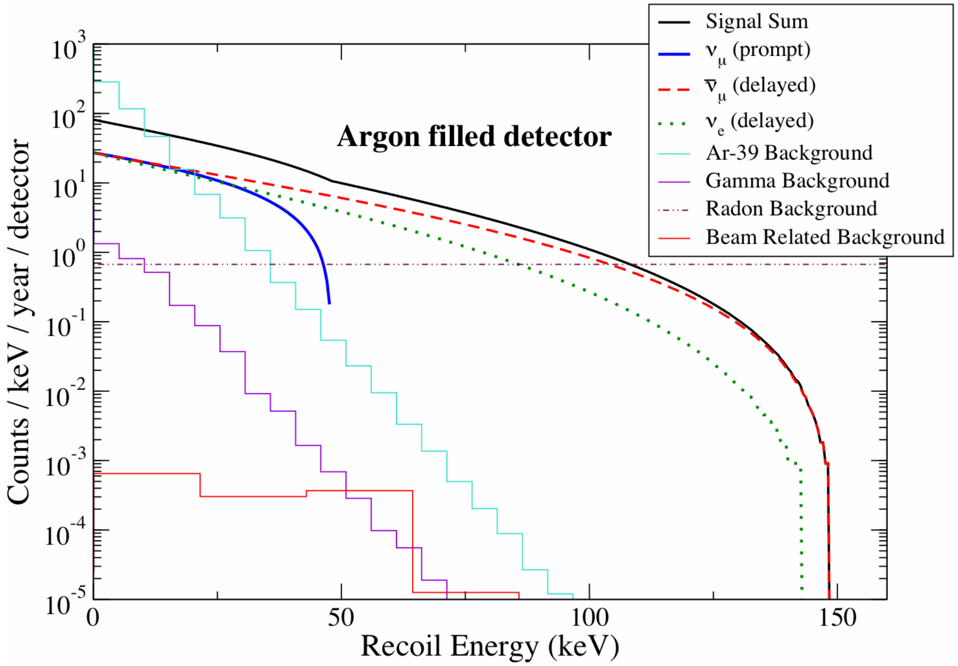
Channel	Events, "Livermore" model	Events, "GKVM" model
$\nu_e + ^{208}\text{Pb} \to e^- + ^{207}\text{Bi} + n$	124	173
$\nu_e + ^{208}\text{Pb} \to e^- + ^{206}\text{Bi} + 2n$	14	45
$\nu_x + ^{208}\text{Pb} \to \nu_x + ^{207}\text{Pb} + n$	53	23
$\nu_x + ^{208}\text{Pb} \to \nu_x + ^{206}\text{Pb} + 2n$	27	7
$\bar{\nu}_x + ^{208}\text{Pb} \to \bar{\nu}_x + ^{207}\text{Pb} + n$	48	19
$\bar{\nu}_x + ^{208}\text{Pb} \to \bar{\nu}_x + ^{206}\text{Pb} + 2n$	23	6
Total 1n events	225	215
Total 2n events	64	58
Total events	289	272

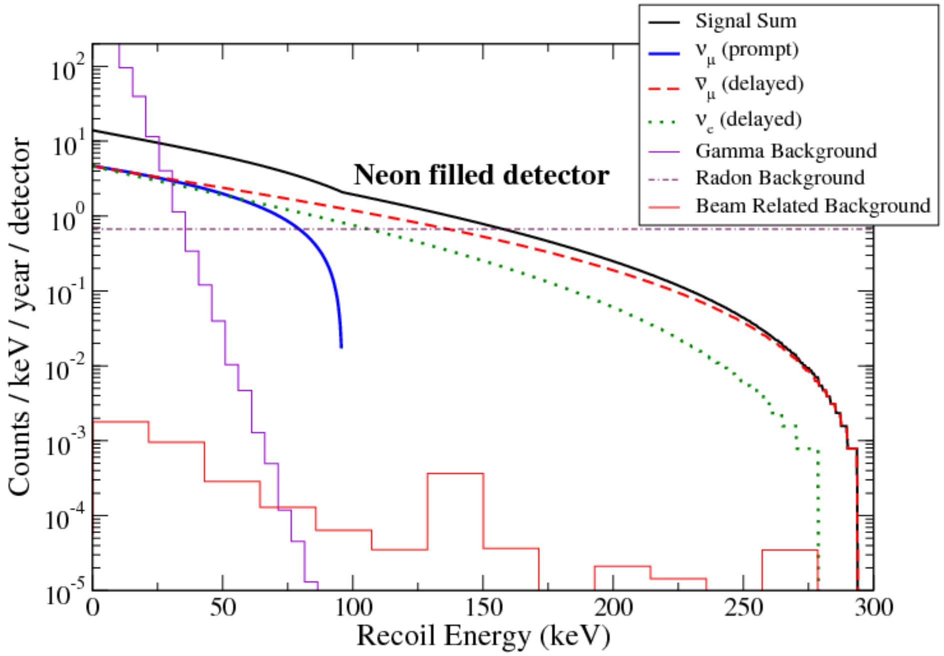
expect a few hundred events per kton @ 10 kpc

Bottom line signal and background for CLEAR

Signal events/year: ~1100 in 456 kg of Ar >20 keVr
~450 in 391 kg of Ne >30 keVr

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



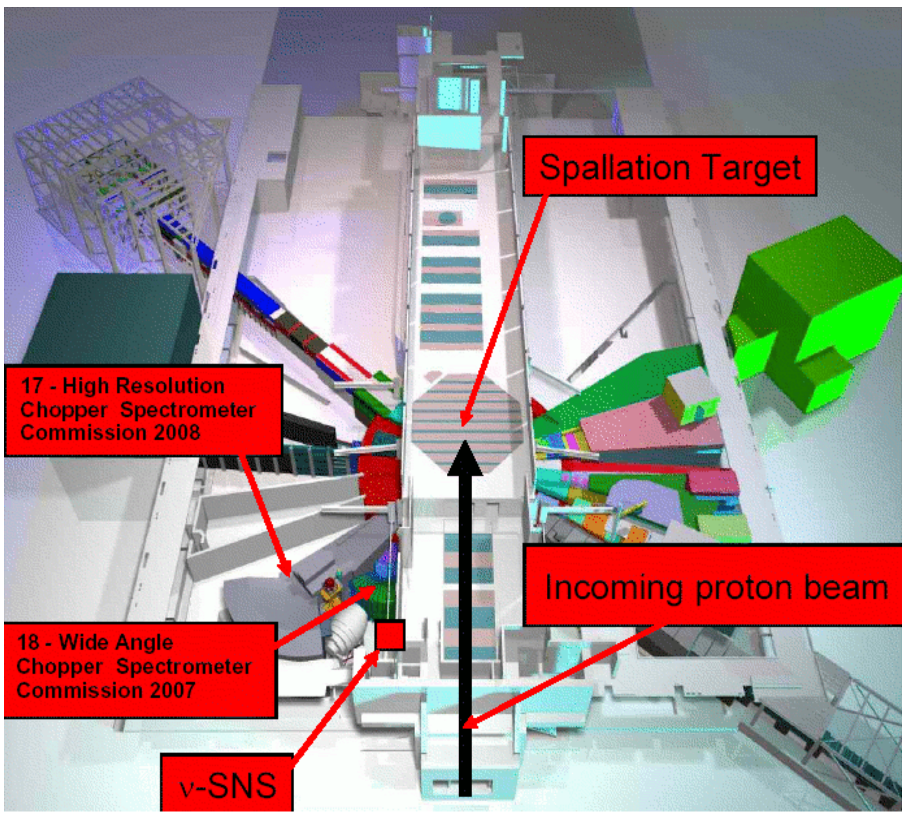


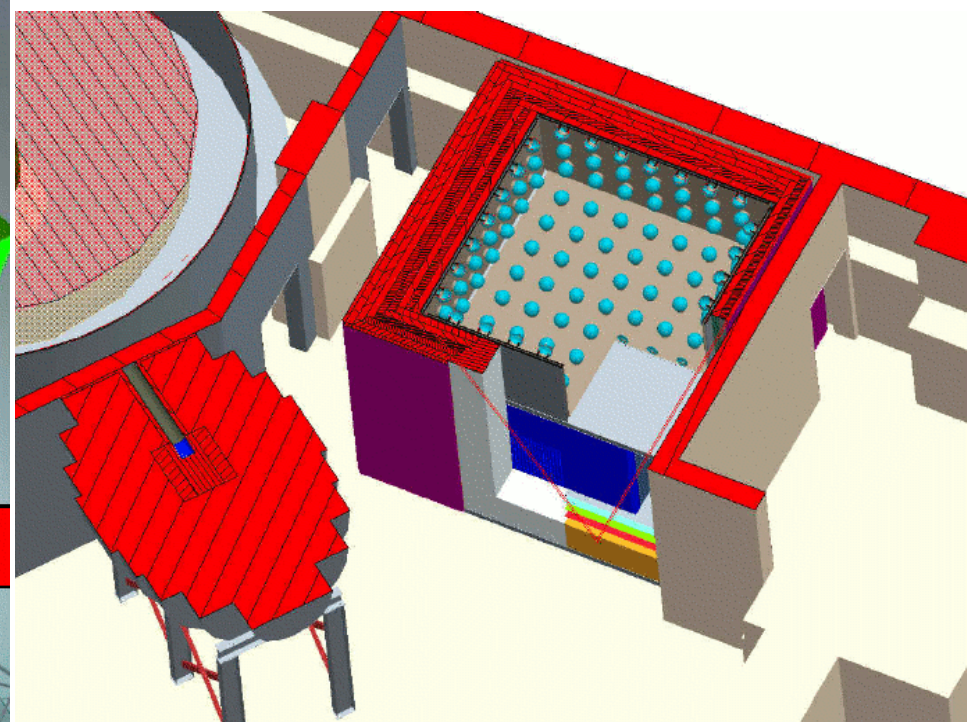
NuSNS (Neutrinos at the SNS)

Conventional ~10 ton detectors w/ few MeV thresholds:

- liquid target + PMTs
- strawtube gas tracker+ target sheets
- cosmic ray veto

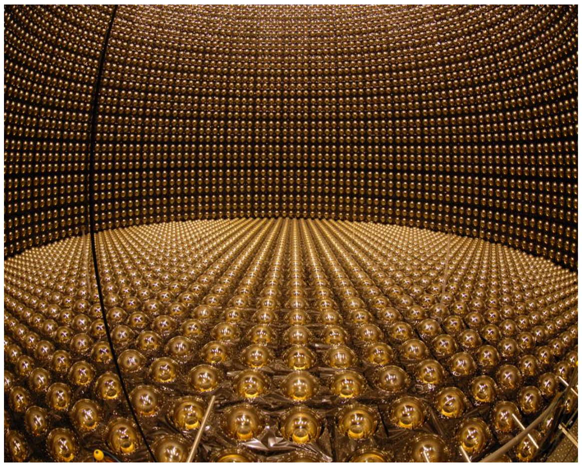
} changeable targets





Example 1: interactions on oxygen nuclei

CC interactions



few % of SN signal

Kolbe, Langanke, Vogel: PRD 66, (2002) 013007

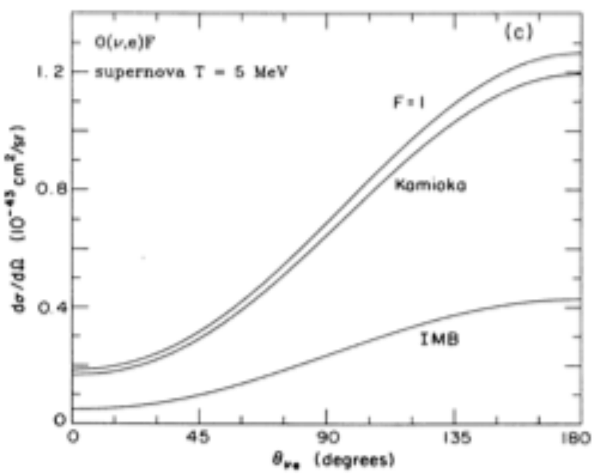
TABLE III. Partial cross sections for charged-current neutrino-induced reactions on ^{16}O. Fermi-Dirac distributions with $T=4$ MeV and $T=8$ MeV and zero chemical potential have been assumed. The cross sections are given in units of 10^{-42} cm^2, exponents are given in parentheses.

Neutrino reaction	$\sigma, T=4$ MeV	$\sigma, T=8$ MeV
total	1.91 (−1)	1.37 (+1)
$^{16}O(\nu_e, e^- p)^{15}O(g.s.)$	1.21 (−1)	6.37 (+0)
$^{16}O(\nu_e, e^- p\gamma)^{15}O^*$	4.07 (−2)	3.19 (+0)
$^{16}O(\nu_e, e^- np)^{14}O^*$	3.92 (−4)	1.76 (−1)
$^{16}O(\nu_e, e^- pp)^{14}N^*$	2.61 (−2)	3.26 (+0)
$^{16}O(\nu_e, e^- \alpha)^{12}N^*$	1.16 (−3)	1.31 (−1)
$^{16}O(\nu_e, e^- p\alpha)^{11}C^*$	2.17 (−3)	5.66 (−1)
$^{16}O(\nu_e, e^- n\alpha)^{11}N(p)^{10}C^*$	1.11 (−6)	3.28 (−3)

TABLE IV. Partial cross sections for charged-current antineutrino-induced reactions on ^{16}O. Fermi-Dirac distributions with $T=5$ MeV and $T=8$ MeV and zero chemical potential have been assumed. The cross sections are given in units of 10^{-42} cm^2, exponents are given in parentheses.

Neutrino reaction	$\sigma, T=5$ MeV	$\sigma, T=8$ MeV
total	1.05 (+0)	9.63 (+0)
$^{16}O(\bar{\nu}_e, e^+)^{16}N(g.s.)$	3.47 (−1)	2.15 (+0)
$^{16}O(\bar{\nu}_e, e^+ n)^{15}N(g.s.)$	5.24 (−1)	4.81 (+0)
$^{16}O(\bar{\nu}_e, e^+ n\gamma)^{15}N^*$	1.47 (−1)	1.90 (+0)
$^{16}O(\bar{\nu}_e, e^+ np)^{14}C^*$	4.56 (−3)	1.38 (−1)
$^{16}O(\bar{\nu}_e, e^+ nn)^{14}N^*$	5.50 (−3)	1.81 (−1)
$^{16}O(\bar{\nu}_e, e^+ \alpha)^{12}B^*$	1.07 (−2)	1.91 (−1)
$^{16}O(\bar{\nu}_e, e^+ n\alpha)^{11}B^*$	6.20 (−3)	2.16 (−1)

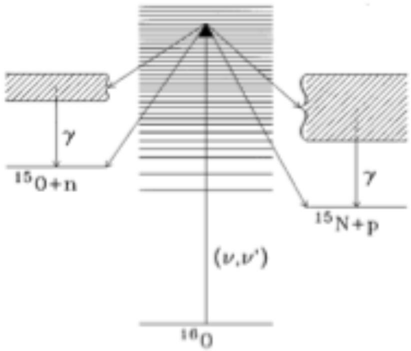
Angular distributions are interesting



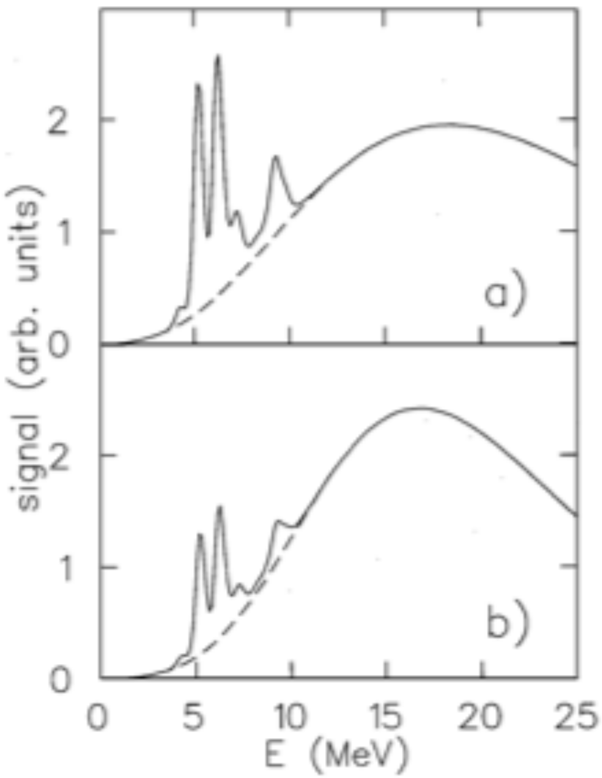
Haxton: PRD 36, (1987) 2283

NC interactions on oxygen nuclei

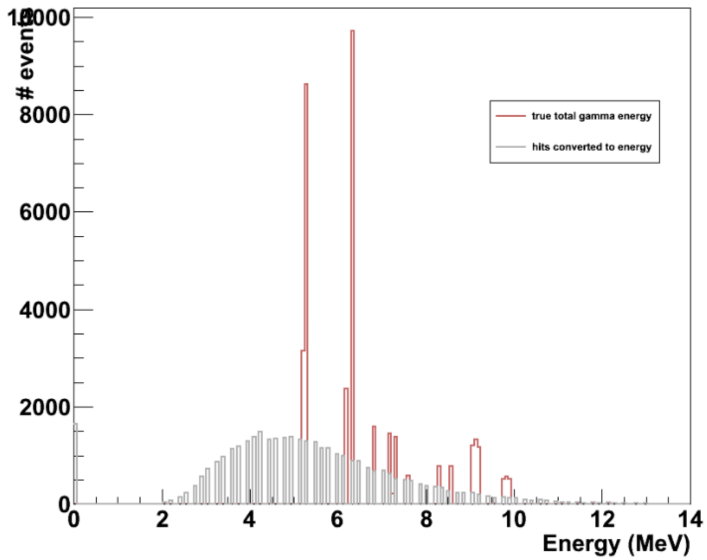
Final states from NC excitation



Langanke, Vogel, Kolbe: PRL 76, (1996) 2629

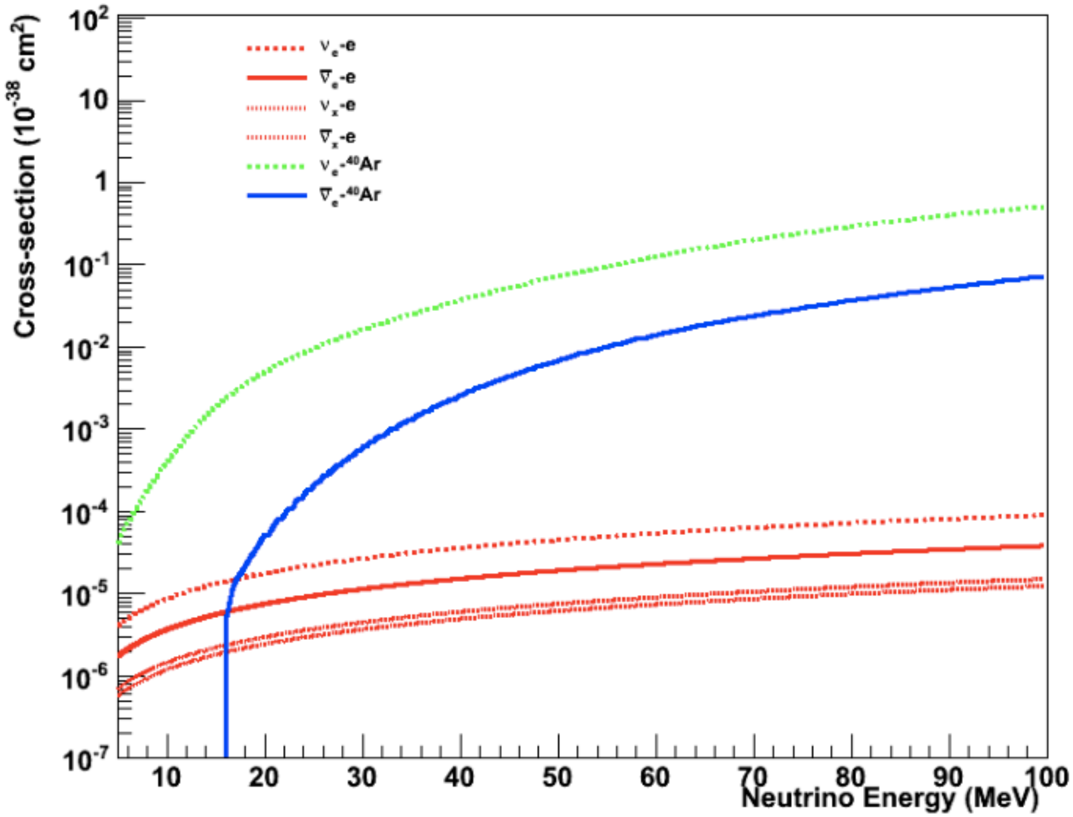


Observed γ energy per event



large fraction of the γ energy is lost in Compton scatter

Example 2: interactions on argon nuclei



M. Sajjad-Athar & S.K. Singh,
Phys. Lett. B 591 (2004) 69

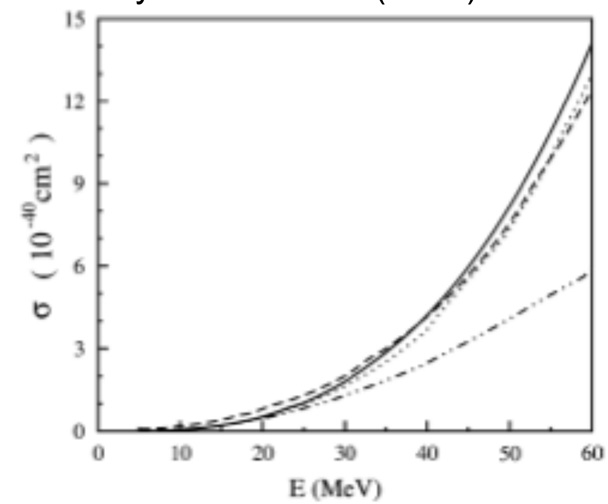


Fig. 3. Total cross section σ vs. E for $\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$ reaction with Fermi function (solid line), modified effective momentum approximation (dashed line), Ormand et al. [12] (dashed-double dotted line) and Bueno et al. [13] (dotted line).

$$\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$$
$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \to e^+ + {}^{40}\mathrm{Cl}^*$$
$$\nu_x + {}^{40}\mathrm{Ar} \to \nu_x + {}^{40}\mathrm{Ar}^*$$

Again, final states include ejected nucleons and deexcitation γ's
... are these observable?

Example 3: Interactions on lead nuclei

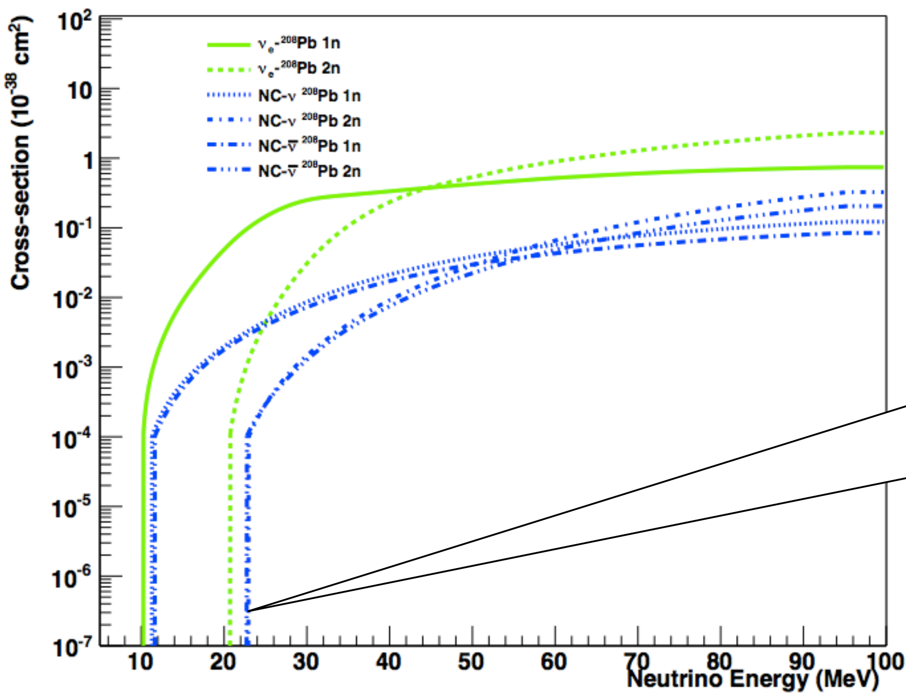
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

↘ 1n, 2n, γ emission

Observe single and double ~few MeV neutron events in the ^3He counters



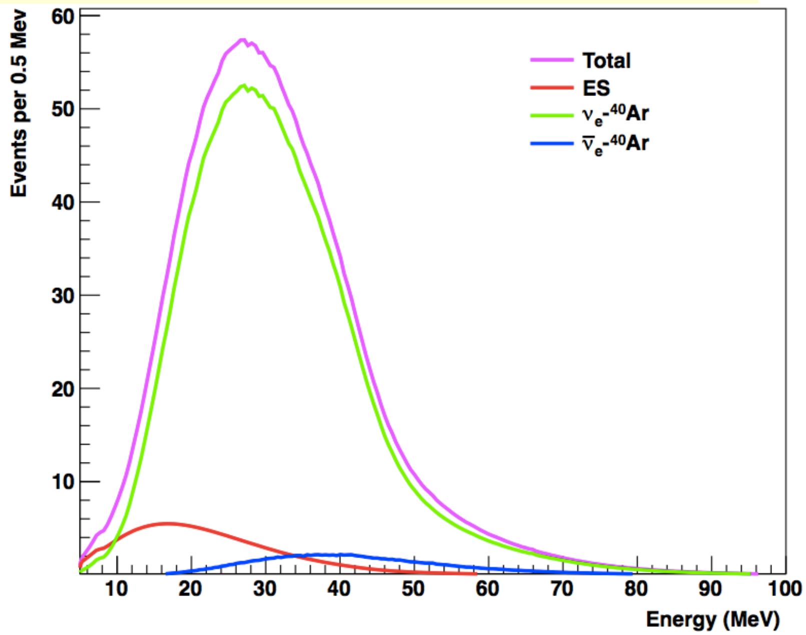
sharp thresholds, so 1n/2n relative rates are strongly dependent on the neutrino spectrum

(similar for other lead isotopes)

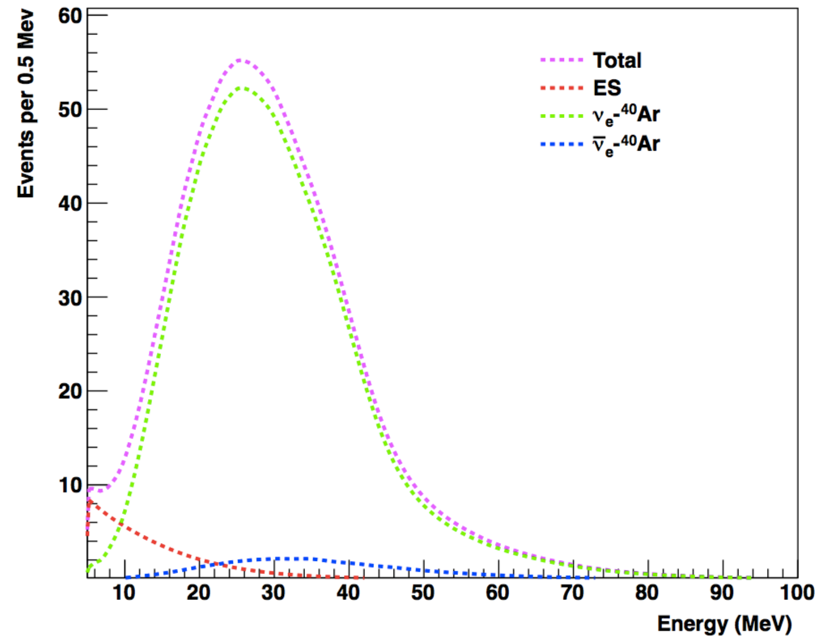
Supernova signal in LAr

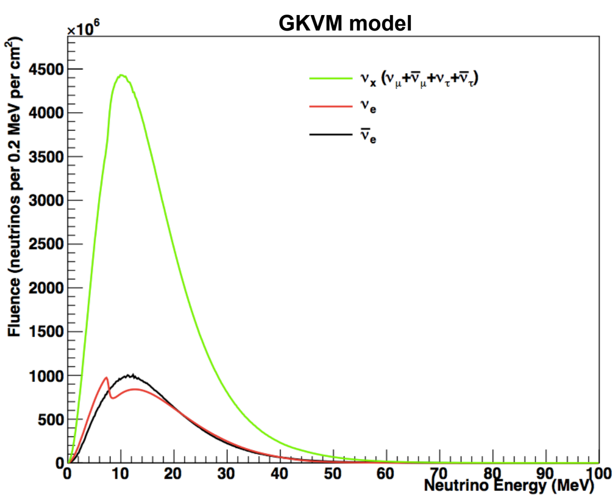
SN @ 10 kpc

Interactions, as a function of neutrino energy



Events seen, as a function of observed energy



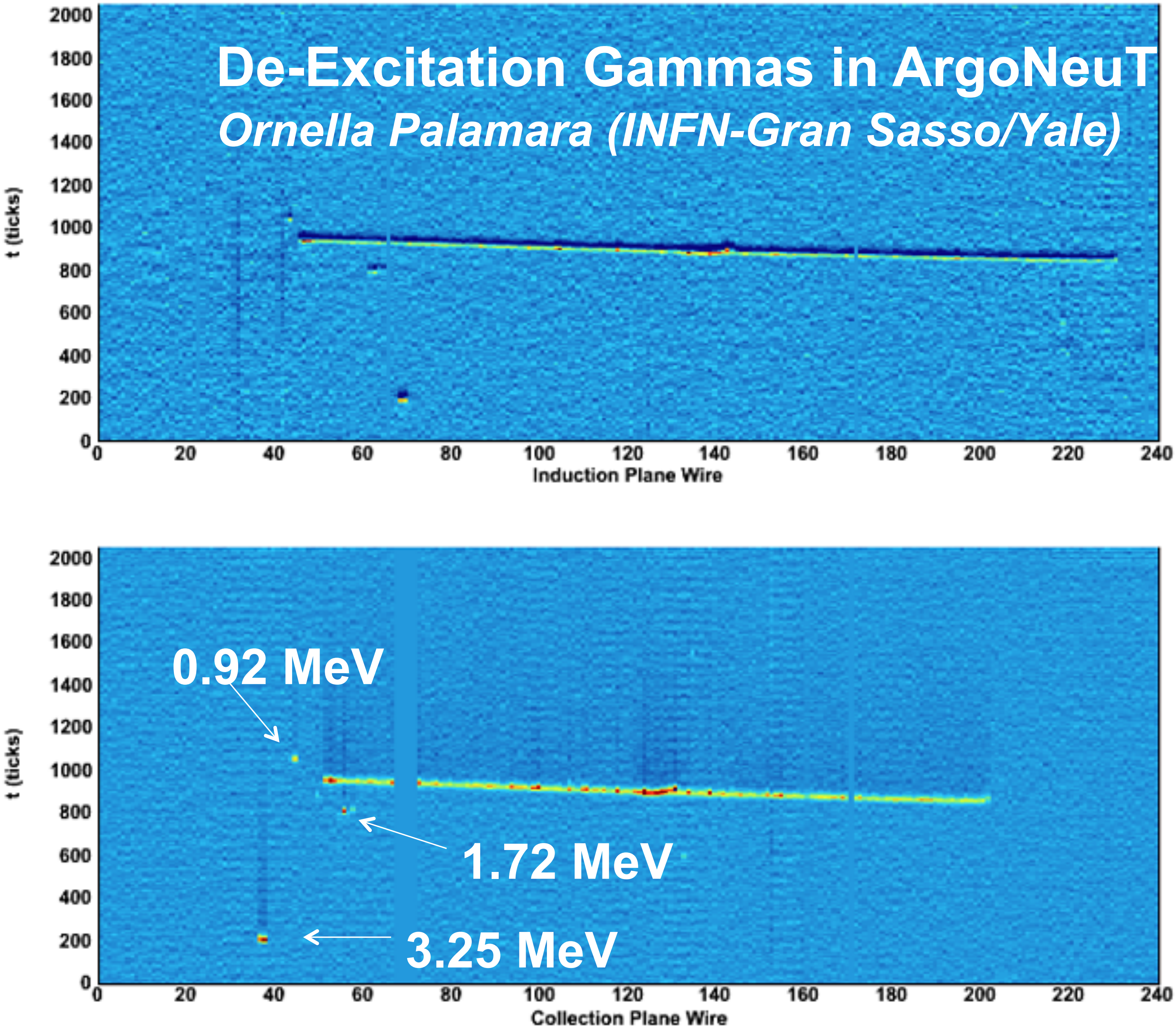


Channel	No of events (observed), GKVM	No. of events (observed), Livermore
Nue-Ar40	2848	2308
Nuebar-Ar40	134	194
ES	178	296
Total	**3160**	**2798**

Dominated by ν_e

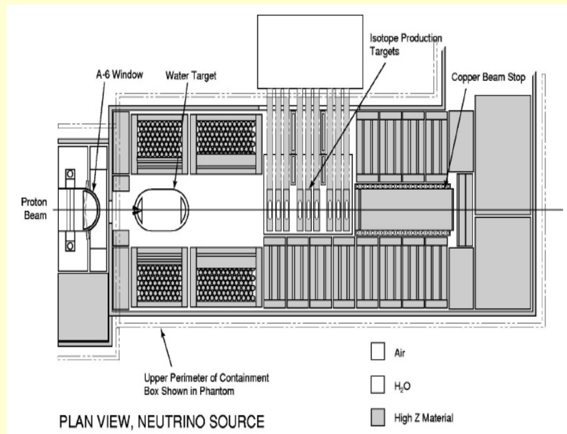
De-Excitation Gammas in ArgoNeuT

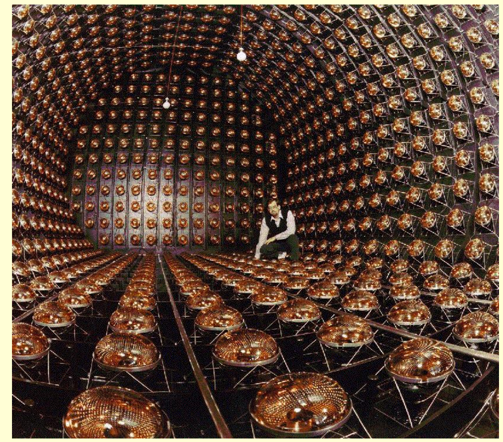
Ornella Palamara (INFN-Gran Sasso/Yale)



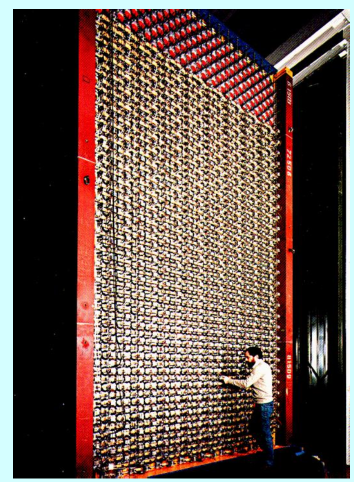
Previous neutrino experiments at stopped-pion neutrino sources

LSND at LANSCE (LANL)

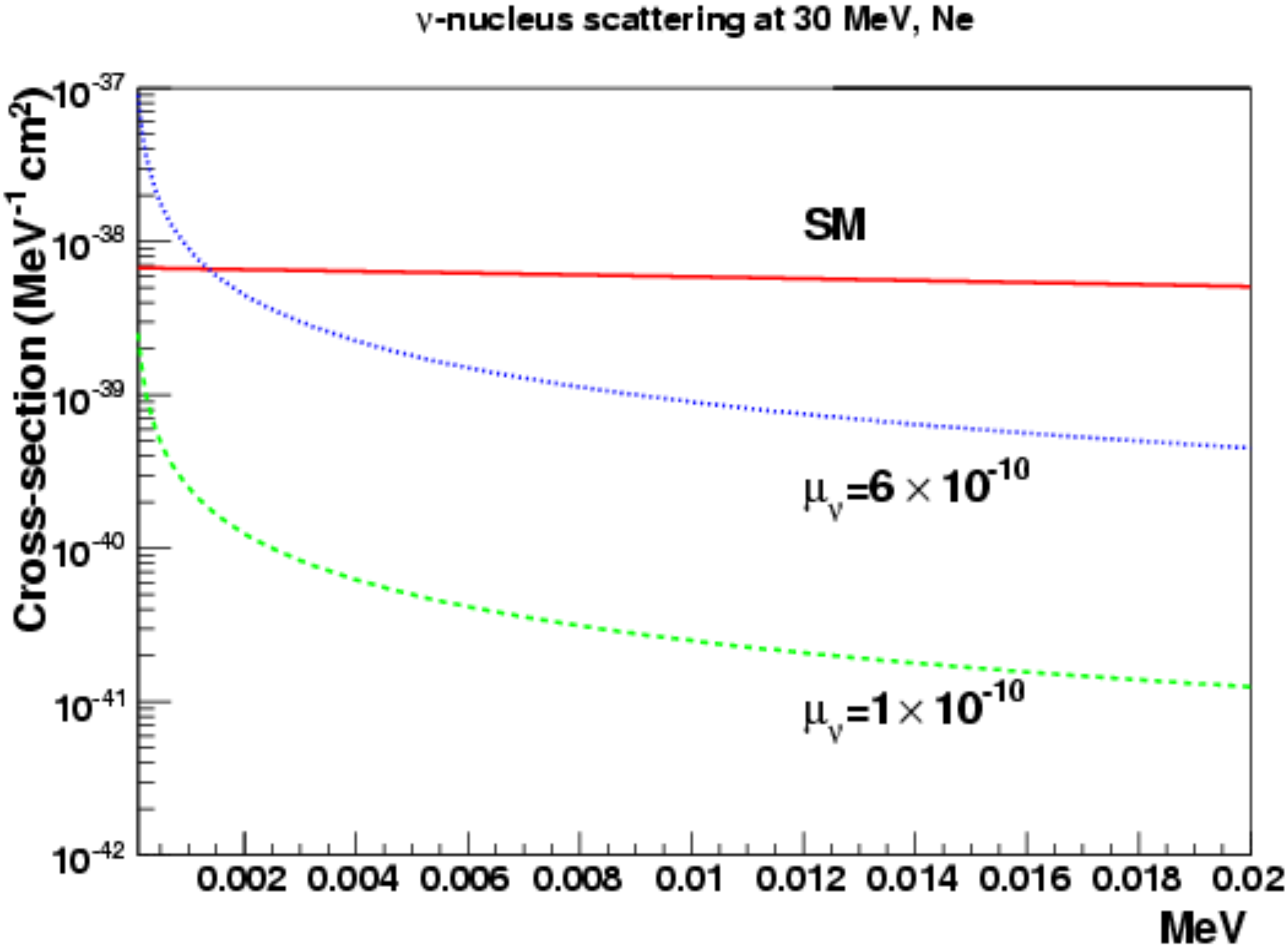




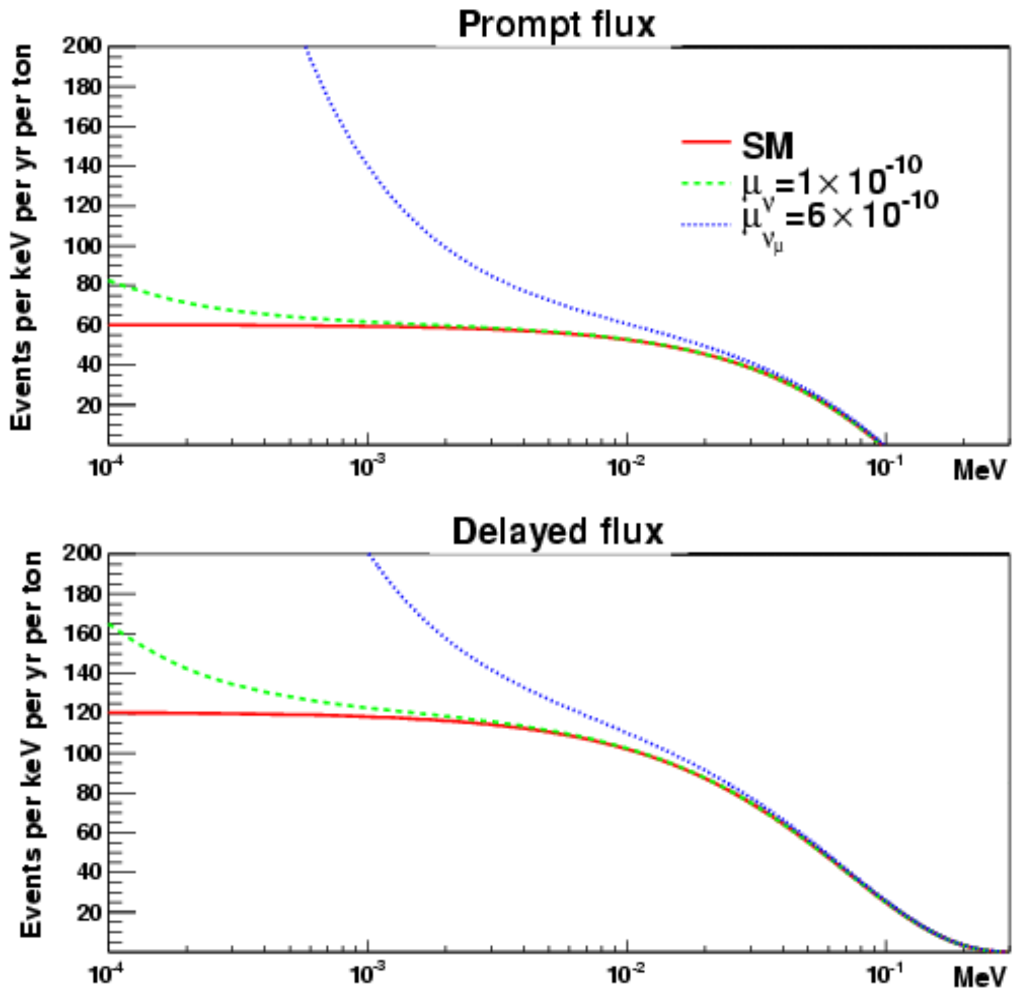
KARMEN at ISIS (RAL)



Cross-sections for 30 MeV ν



Differential Yield at the SNS

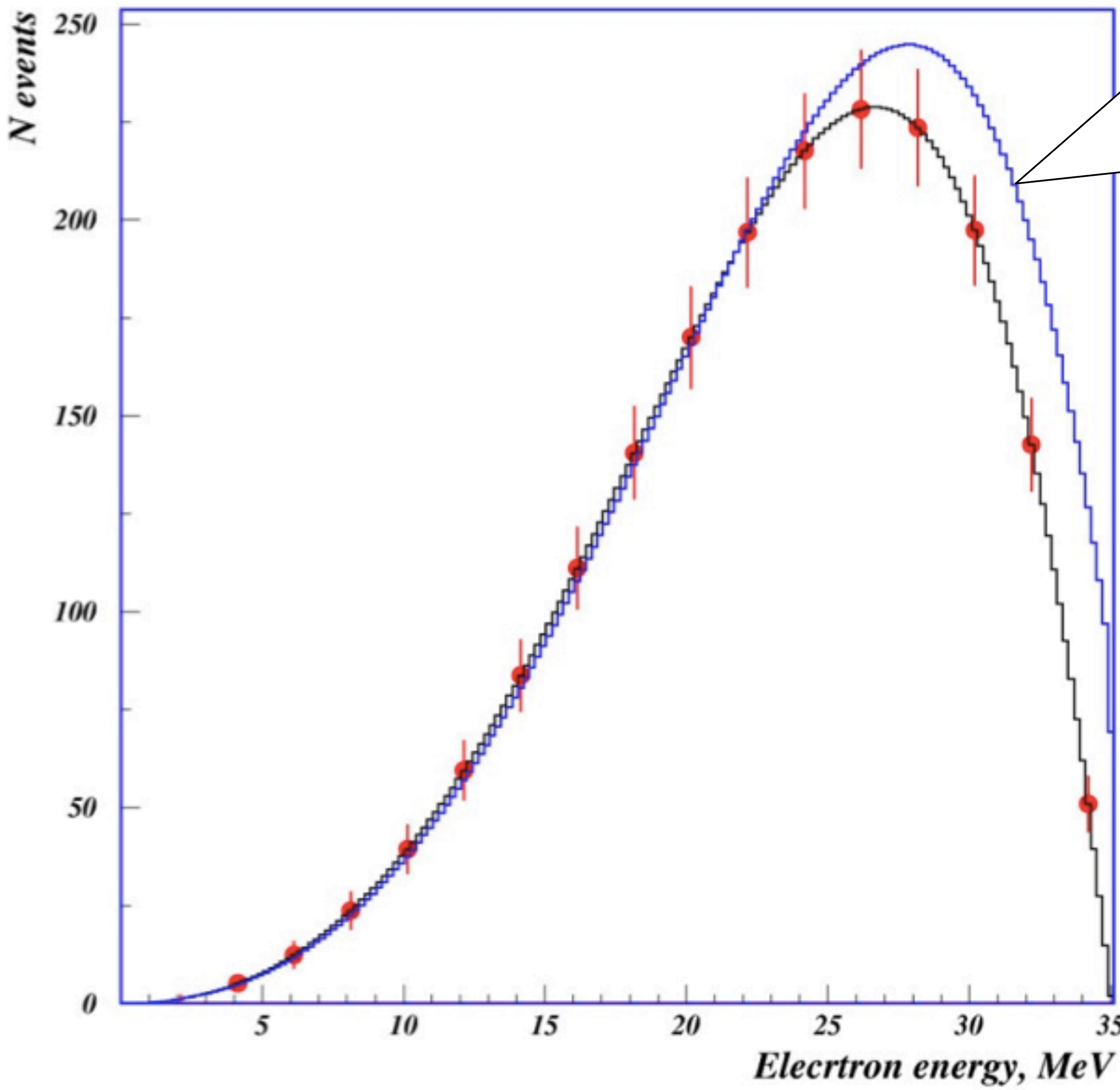


Impossible to see excess for $\mu_\nu=10^{-10}$ for 10 keV threshold

....but several % excess over SM background at ~10 keV for $\mu_\nu=6\text{x}10^{-10}$

Experimentally hard! But maybe doable

SM test from CC ν interaction on carbon



scalar & tensor admixture to V-A allowed by KARMEN

From NuSNS proposal