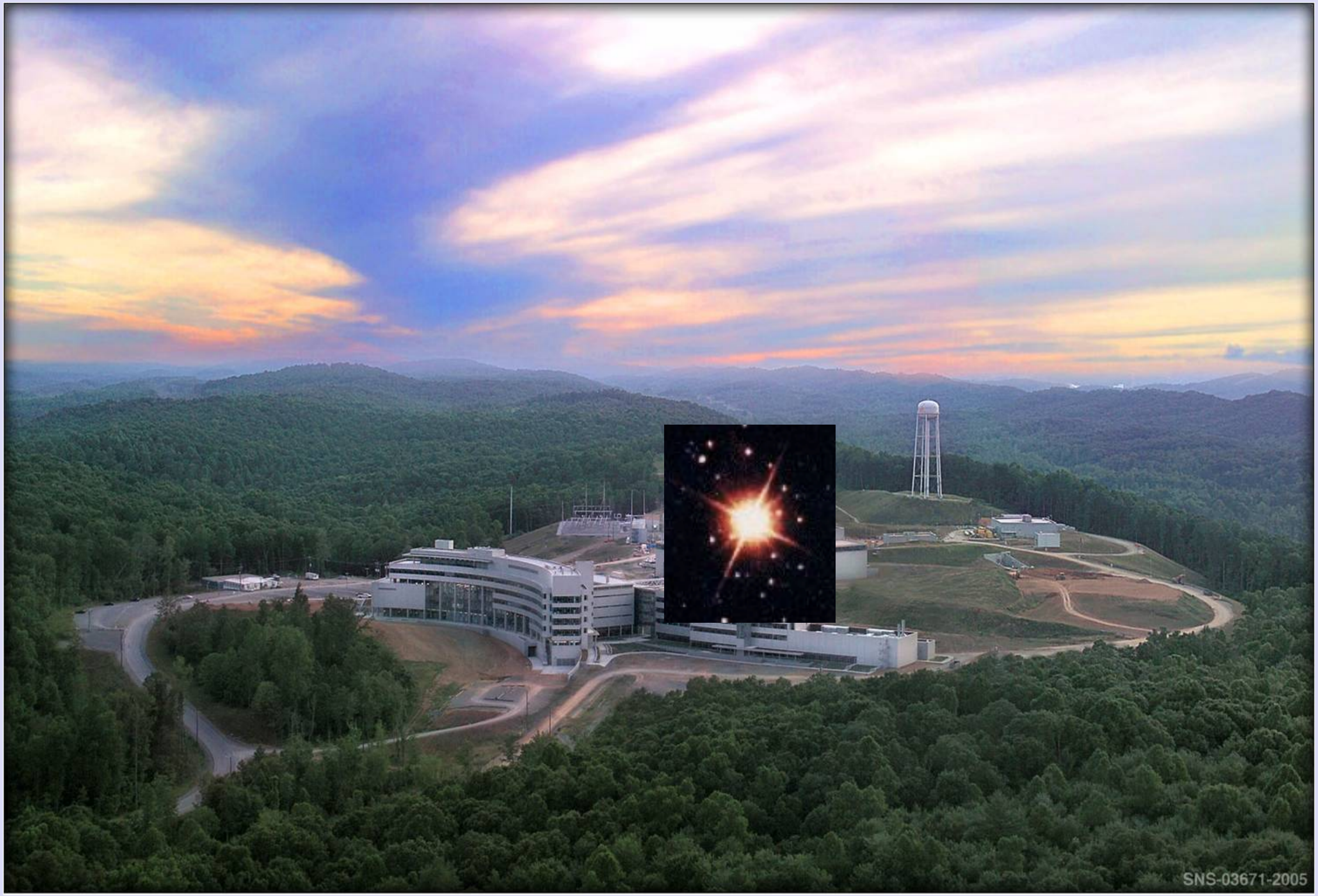
Stopped-Pion Neutrino Sources: Physics Capabilities and Needs



Kate Scholberg, Duke University

BNL, April 2013

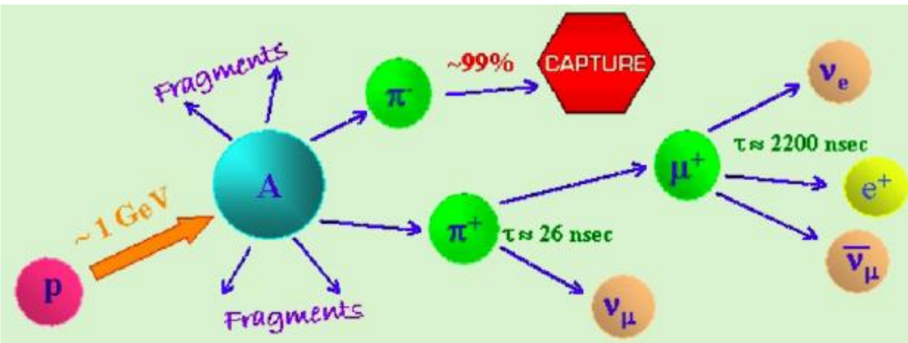
Outline

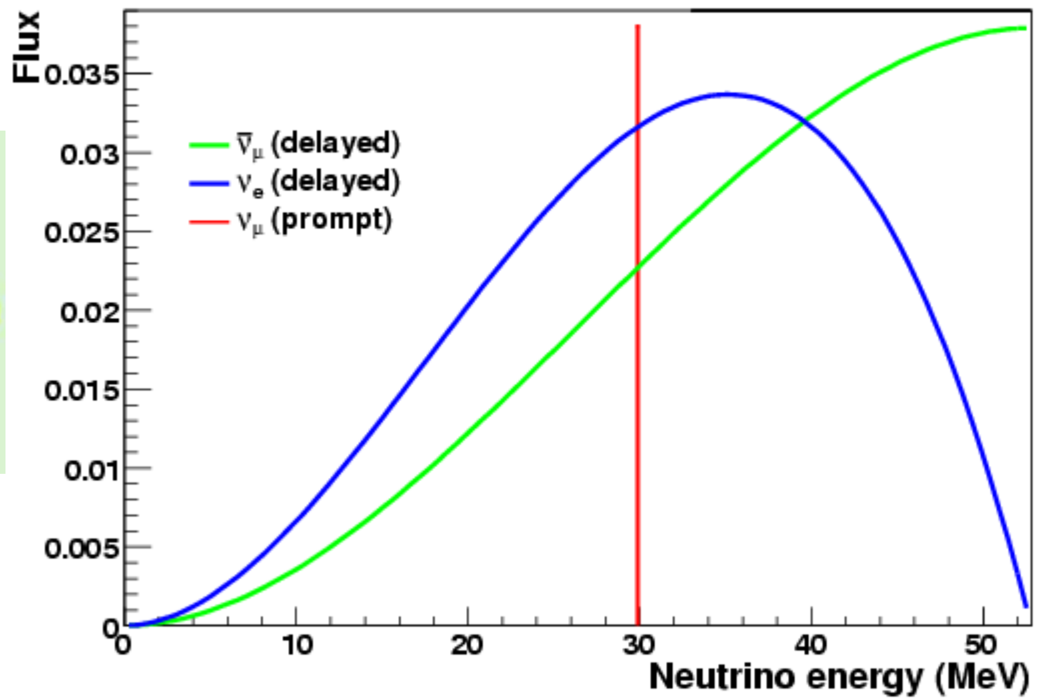
- Stopped pion (DAR) neutrinos

- Physics with Stopped Pion Neutrinos
  - Supernova-relevant cross-sections
  - Coherent elastic νA scattering
  - Sterile neutrino oscillations

- Needs and desirables for sources

Stopped-Pion (DAR) Neutrinos





$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ PROMPT

$$\downarrow$$

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

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

Typical flux: ~0.13 per flavor per proton at the SNS

Opportunities for Neutrino Physics at the Spallation Neutron Source: A White Paper

A. Bolozdynya, F. Cavanna, Y. Efremenko, G. T. Garvey, V. Gudkov,
A. Hatzikoutelis, R. Hix, J. M. Link, W. C. Louis,
D. Markoff, G. B. Mills, K. Patton, K. Scholberg, R. G. Van de Water,
C. Virtue, D. H. White, J. Yoo

arXiv:1211.5199

Contents

Many diverse opportunities...
I will cover the highlights

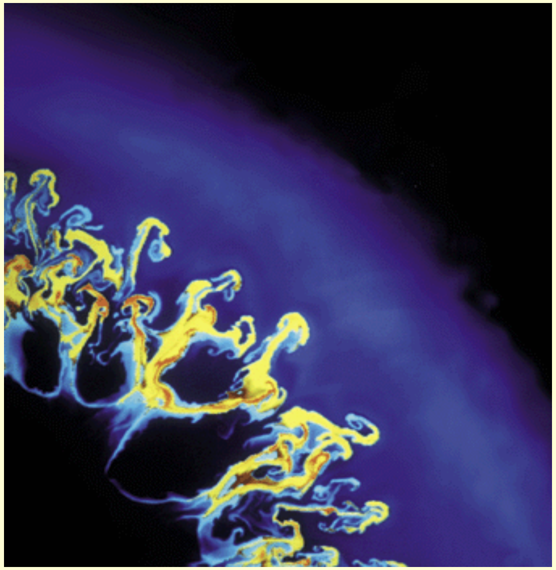
Neutrinos from core collapse

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

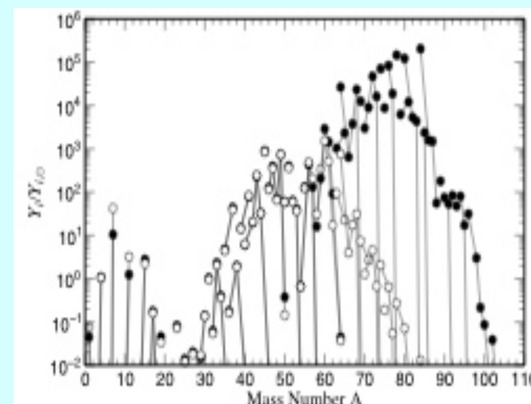


Supernova explosion

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

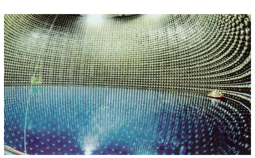


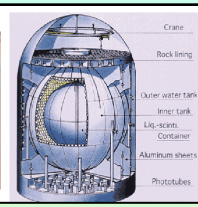
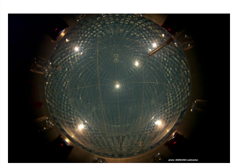
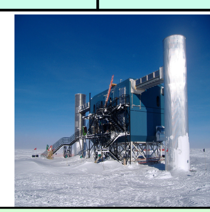
Fröhlich *et al*., Astrophys. J. 637 (2006) 415-426

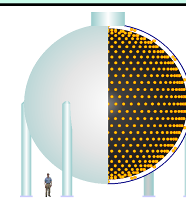
Understanding of neutrino interactions with matter is crucial!

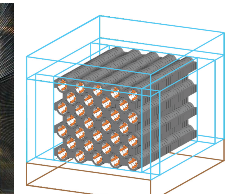
Supernova neutrino detectors, current & future

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



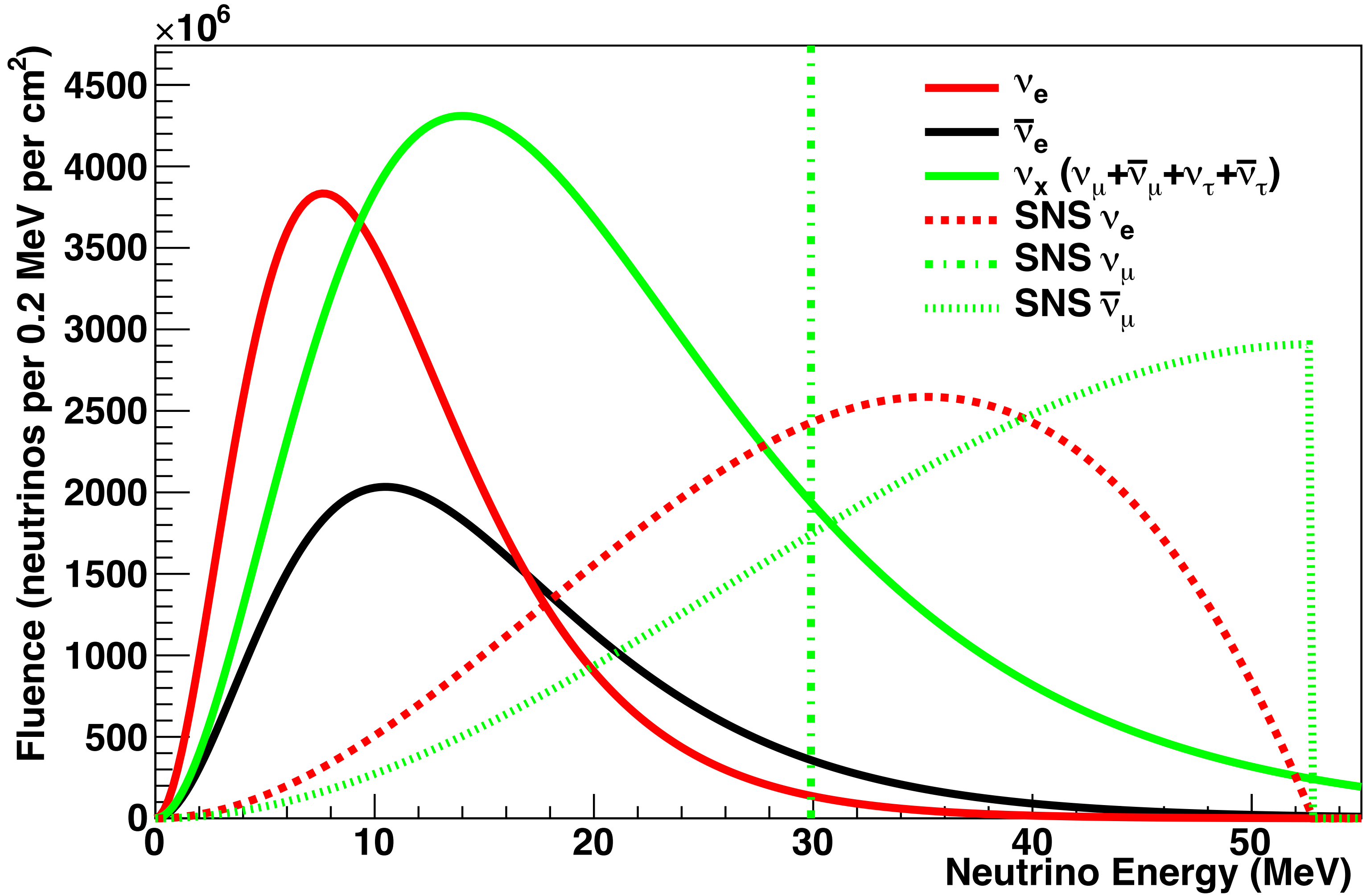








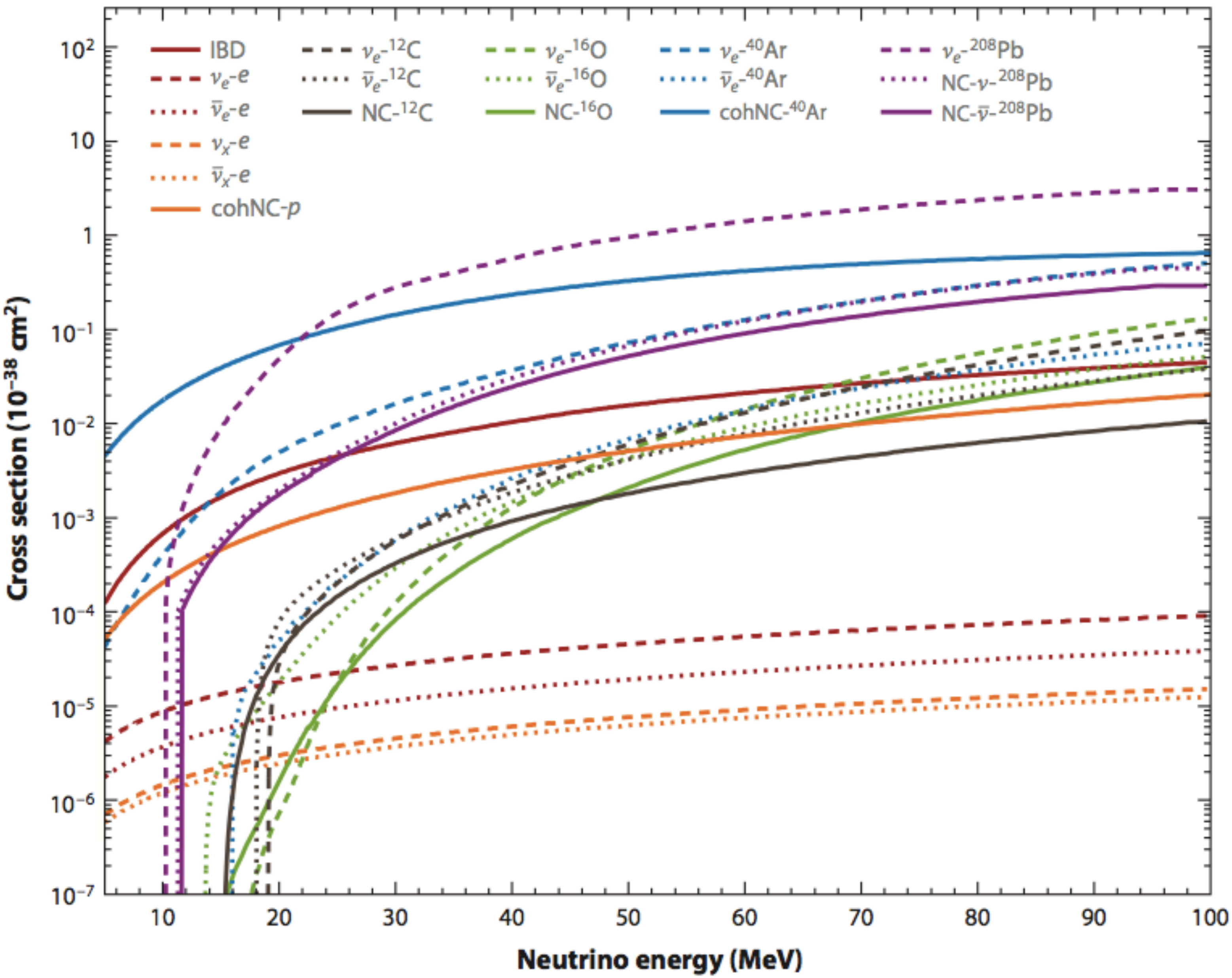
To make the most of a Galactic SN neutrino detection, we need to understand how the neutrinos interact with detector materials

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

SN-relevant cross sections in this energy range



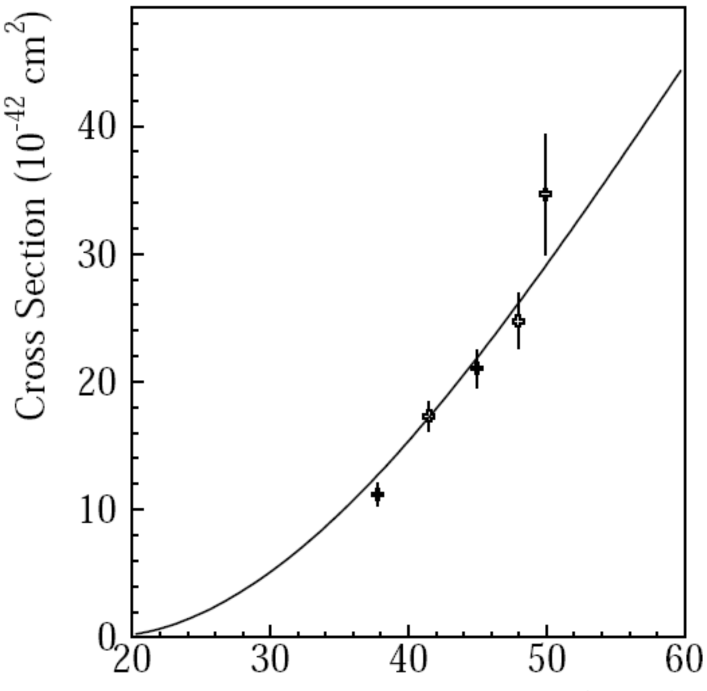
Of these, only IBD, ν-e ES are known at the few % level

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

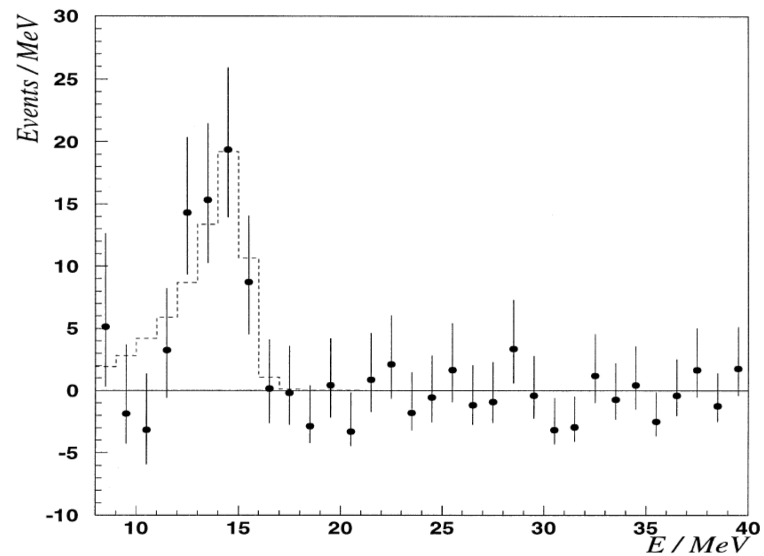
Phys. Rev. C 66 (2002) 015501



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

Karmen

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



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

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

Highlight: low energy neutrino interactions in argon:
relevant for MicroBooNE, LBNE

Charged-current absorption

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

Dominant

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

Neutral-current excitation

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

Insufficient info in literature; ignoring for now

Elastic scattering

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

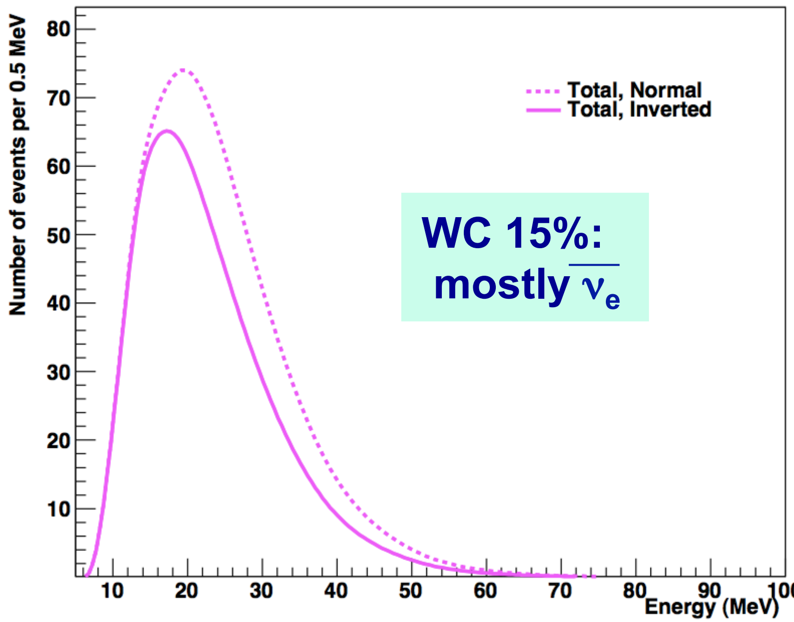
Can use for pointing

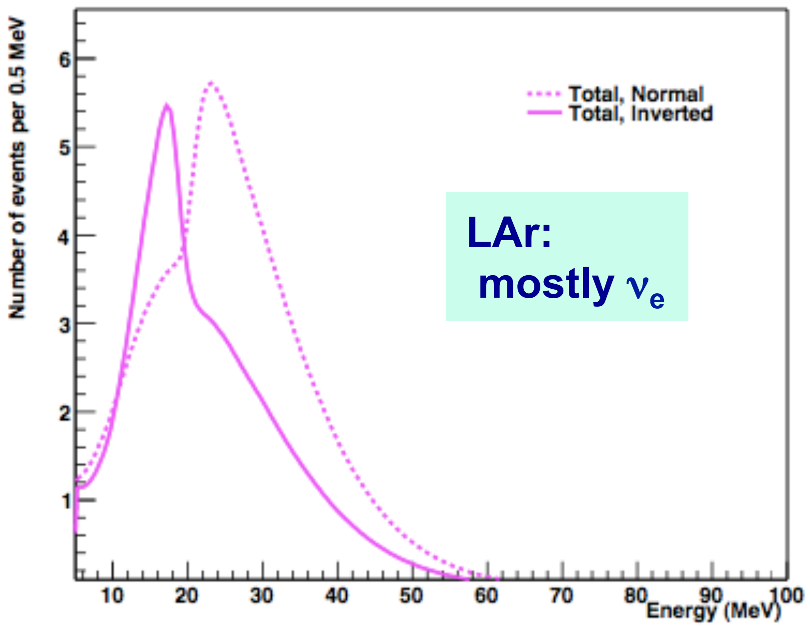
- In principle can tag modes with
- deexcitation gammas (or lack thereof)...

Observability of oscillation features: anecdoctal example

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

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



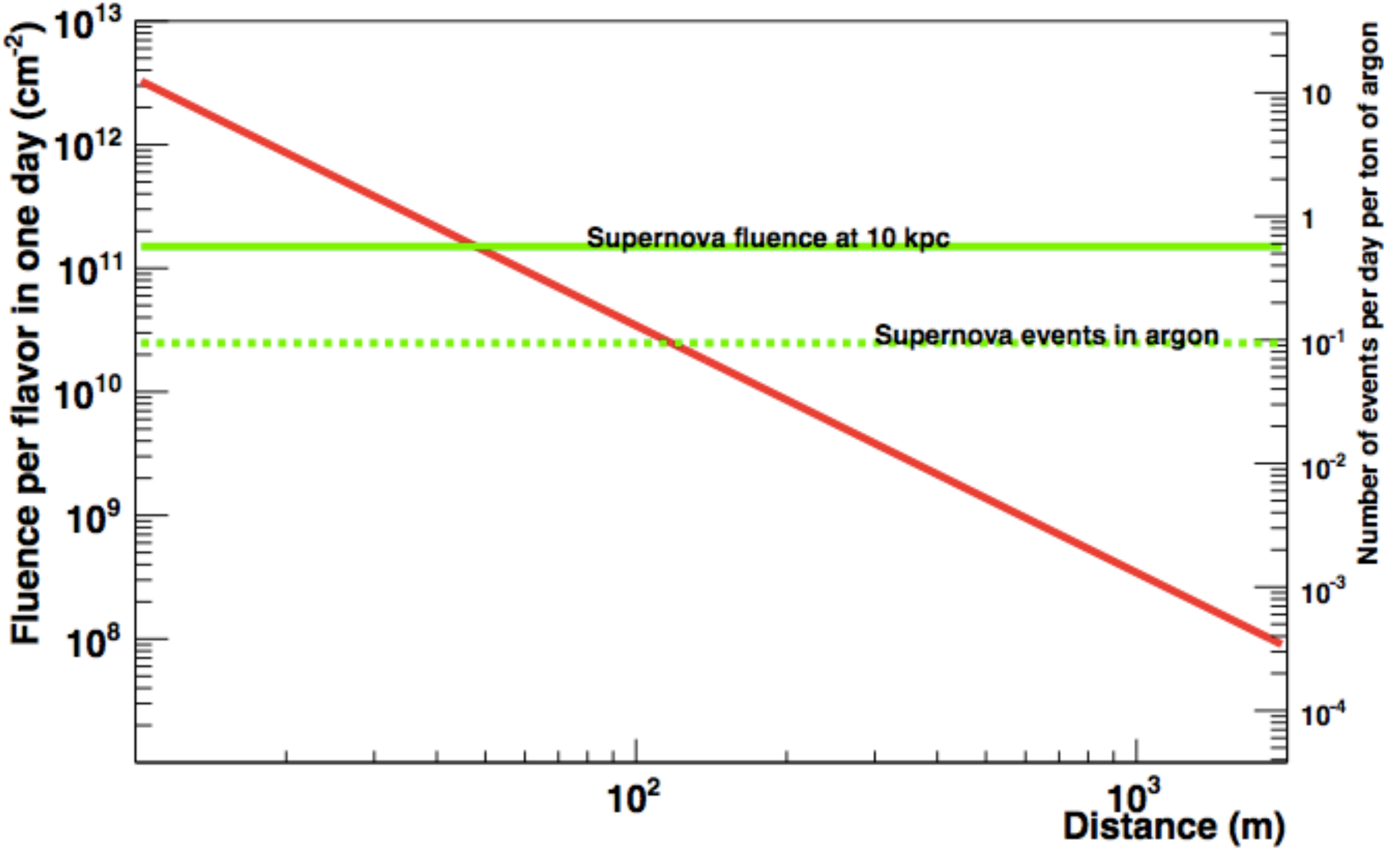


Differences, but no sharp features

LAr shows dramatic difference

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

(and effectively more events due to harder spectrum)



Another example: Interactions on lead nuclei

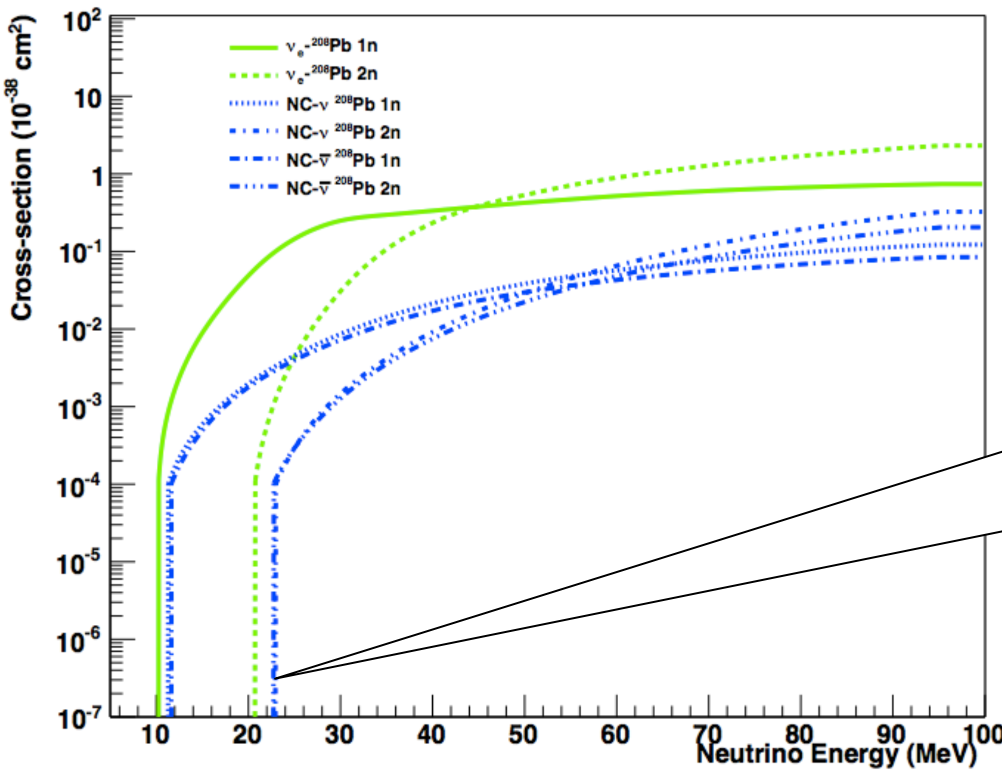
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↳ 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

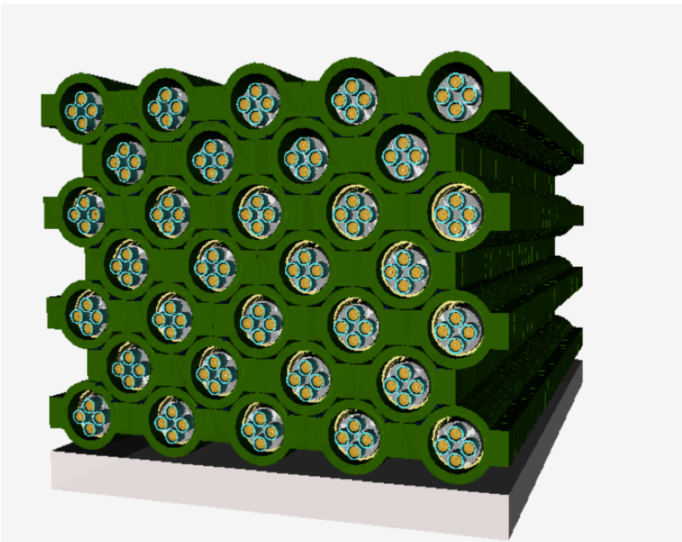


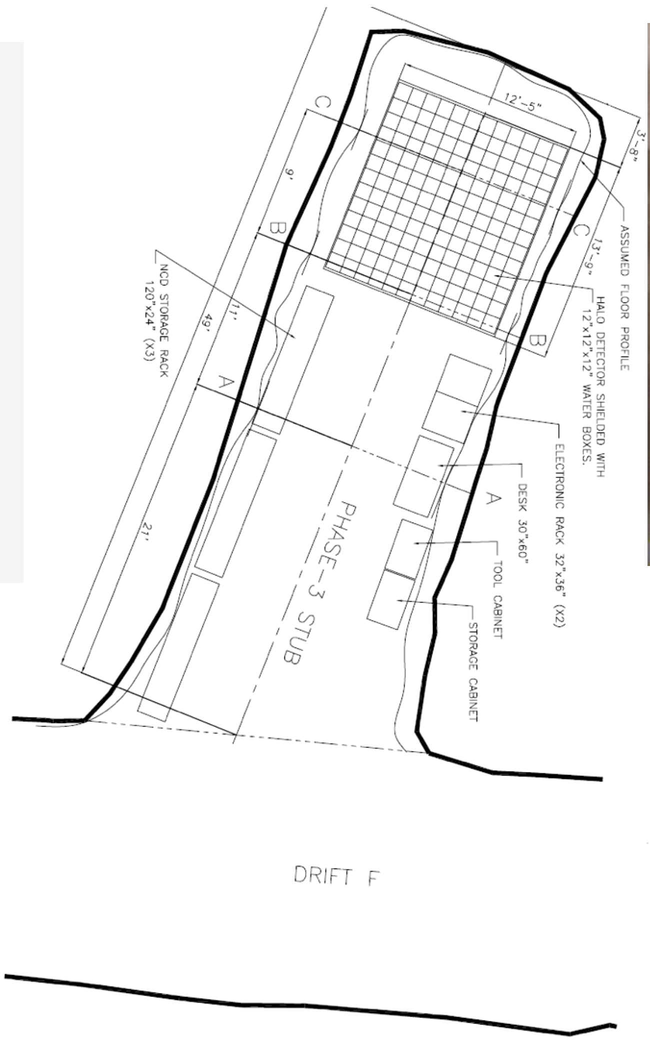
sharp thresholds, so 1n/2n relative rates are strongly dependent on the neutrino spectrum

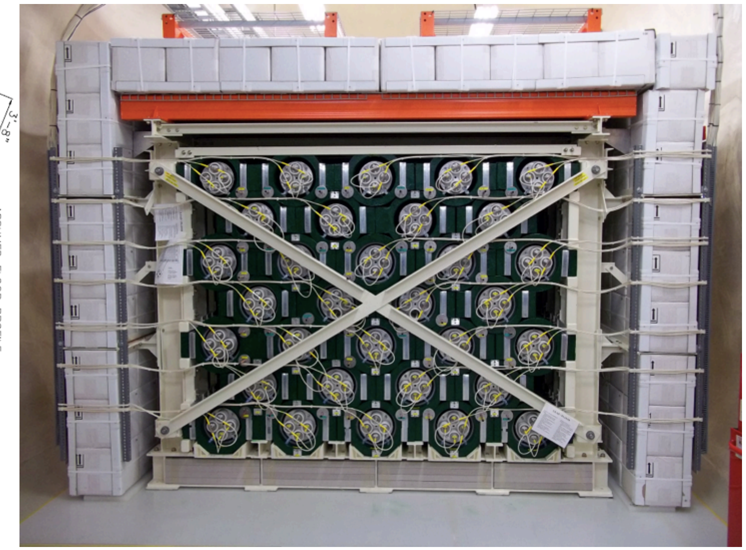
(similar for other lead isotopes)

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

HALO at SNOLAB





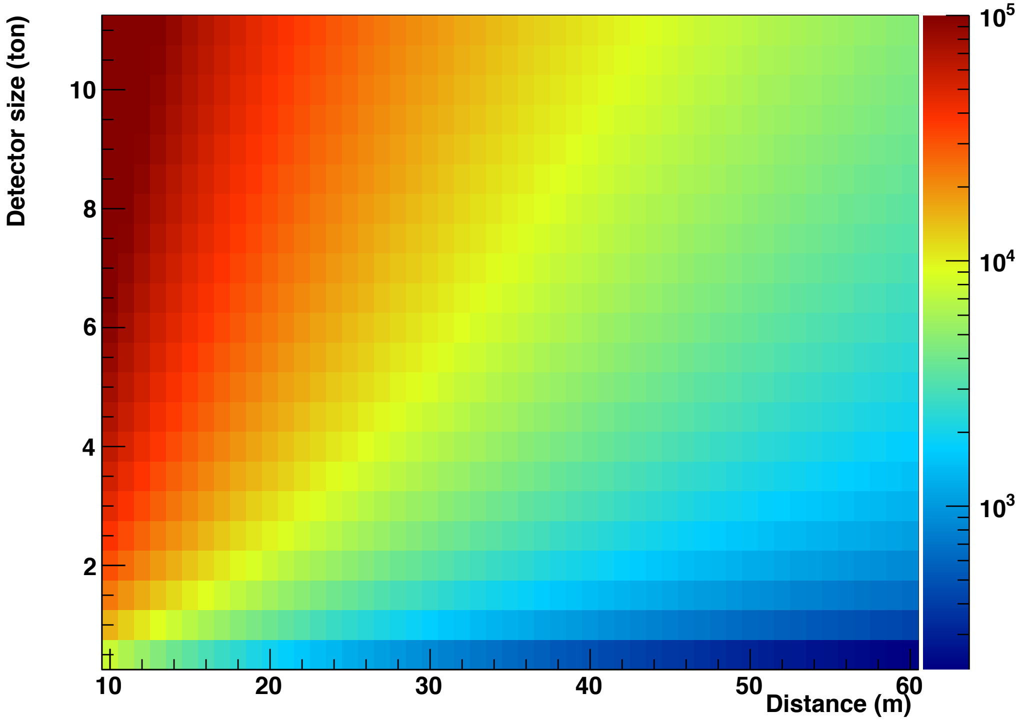


SNO ^{3}He counters + 79 tons of Pb: ~40 events @ 10 kpc

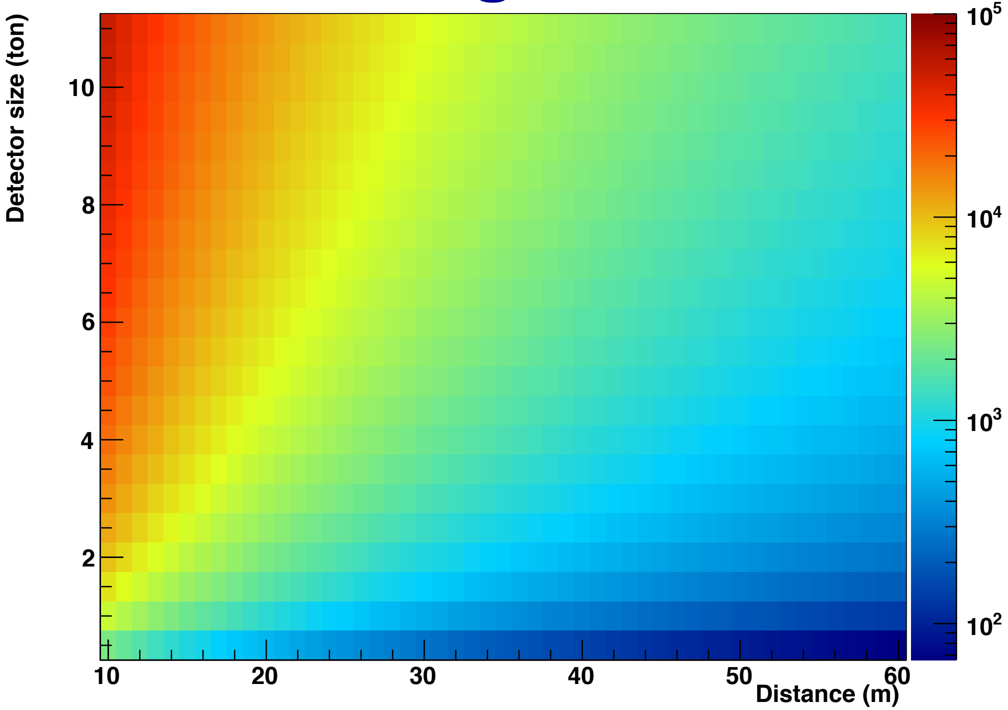
Total events per year at the SNS as a function of distance and mass

$$\propto 1/R^2, \propto M$$

lead



argon

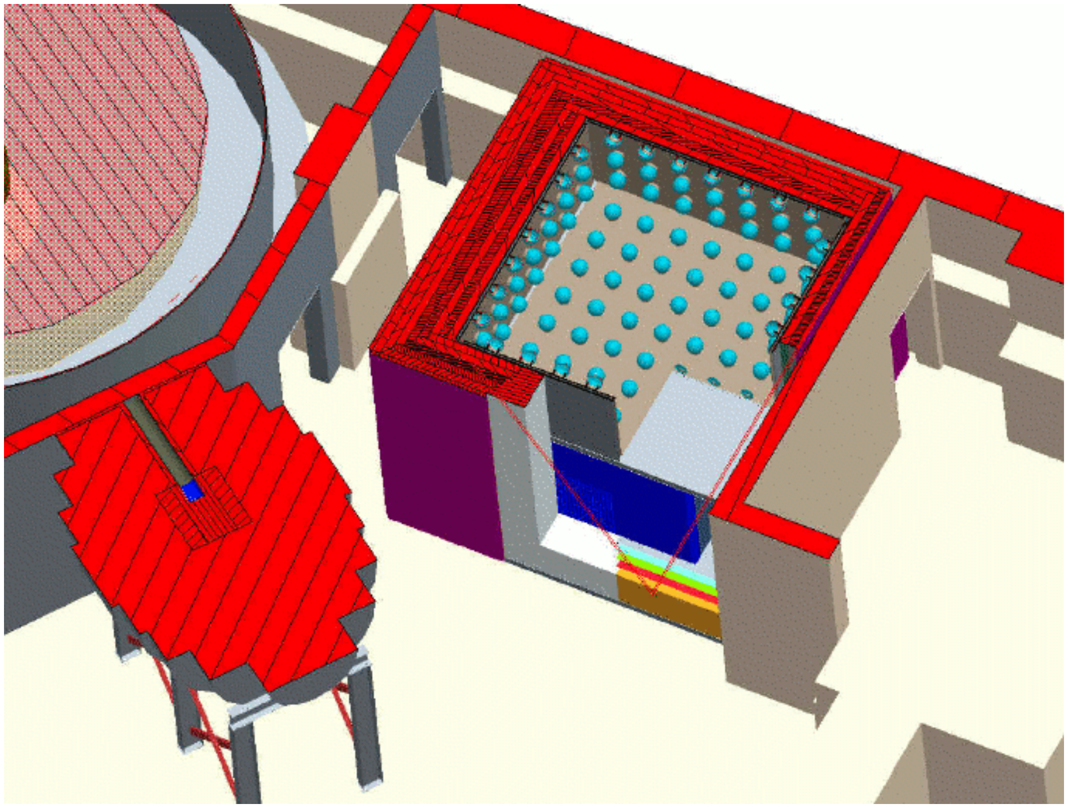


Scaling for another source: α power;
duty factor is critical for background rejection

Examples of detectors that could make these measurements:

NuSNS

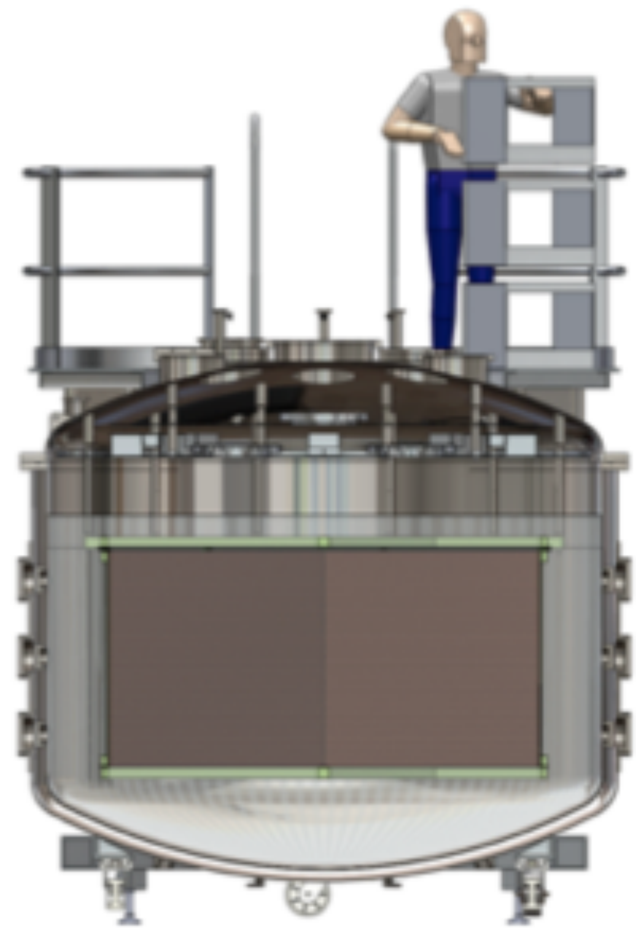
Neutrinos at the SNS



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

} changeable targets

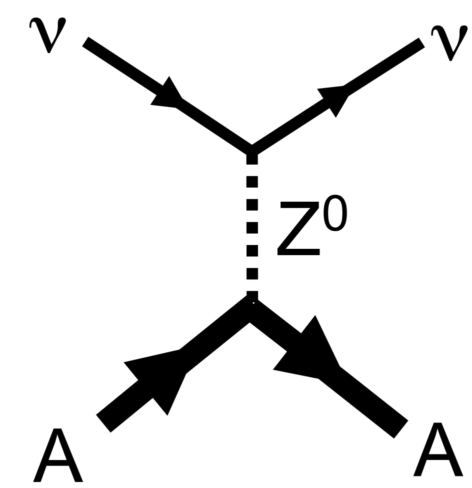
CAPTAIN



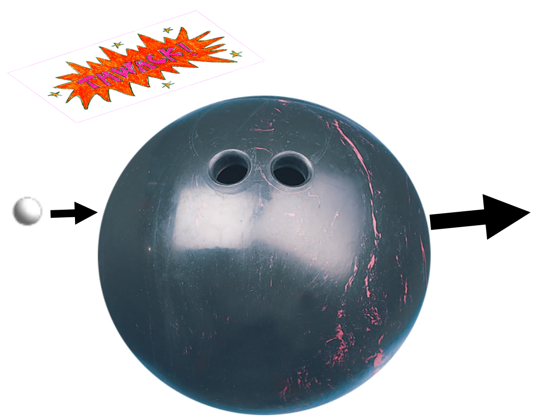
LArTPC

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_ν~ 50 MeV

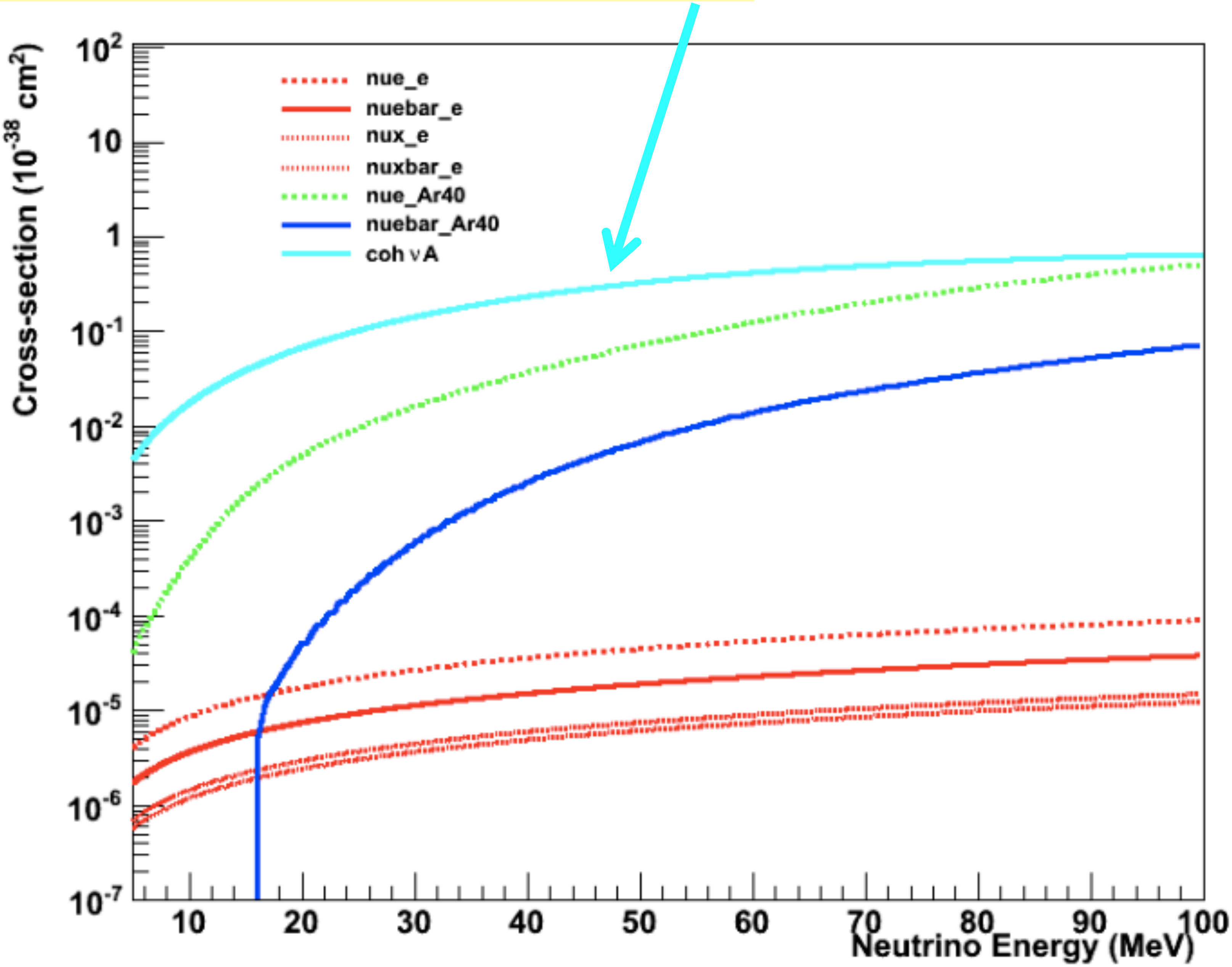


- **Important in SN processes & detection**
- **Well-calculable cross-section in SM: SM test, probe of neutrino NSI**
- **Possible applications** (reactor monitoring)

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

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

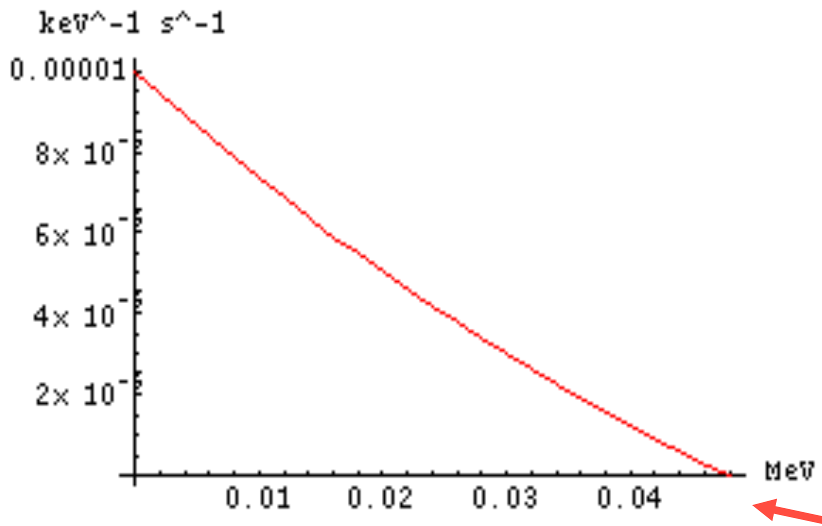
The cross-section is *large*



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

Why not?

Nuclear recoil energy spectrum for 30 MeV ν



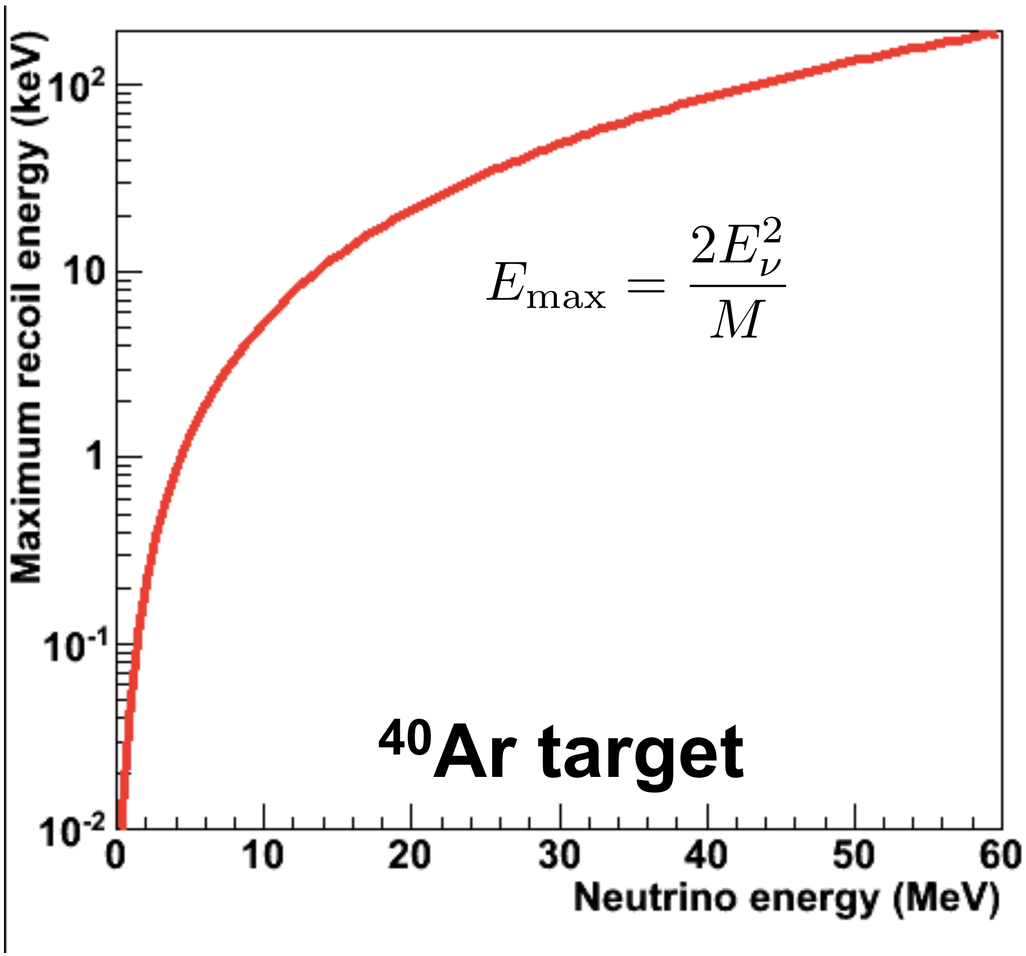
Max recoil energy is $2E_\nu^2/M$ (48 keV for Ar)

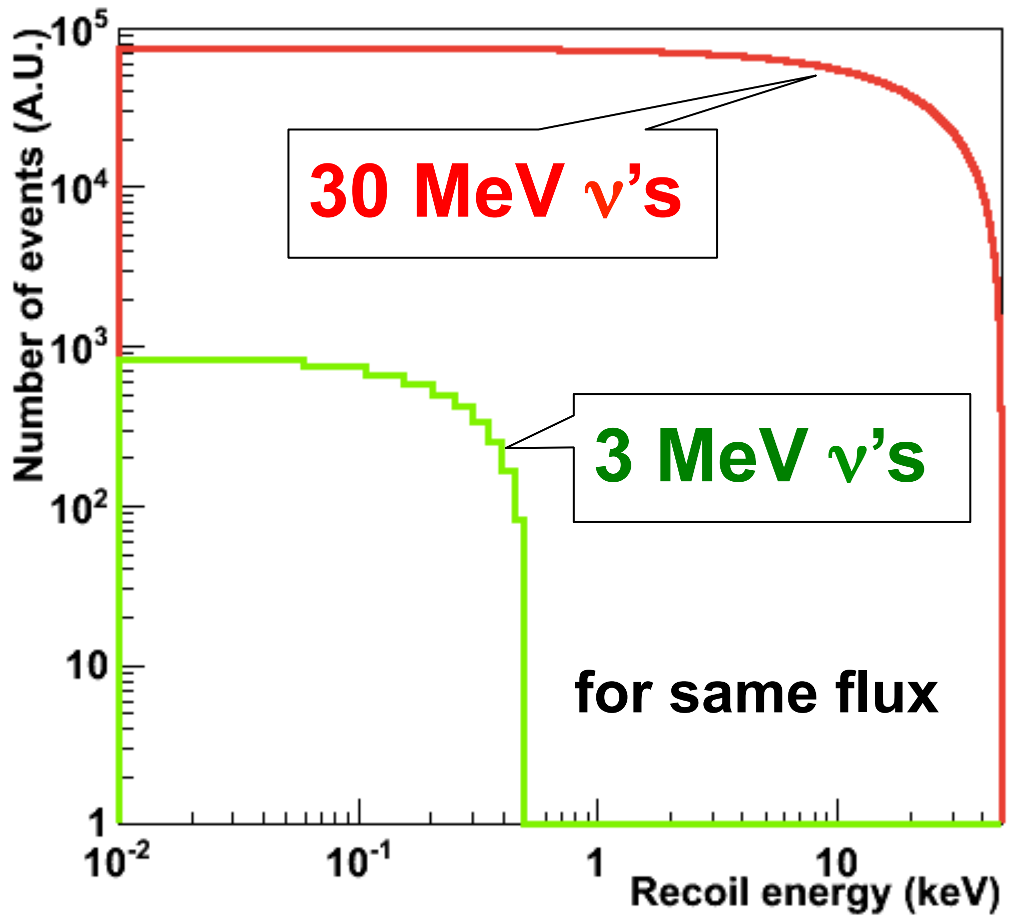
Recoil energies are tiny!

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

What do you want to detect CENNS?

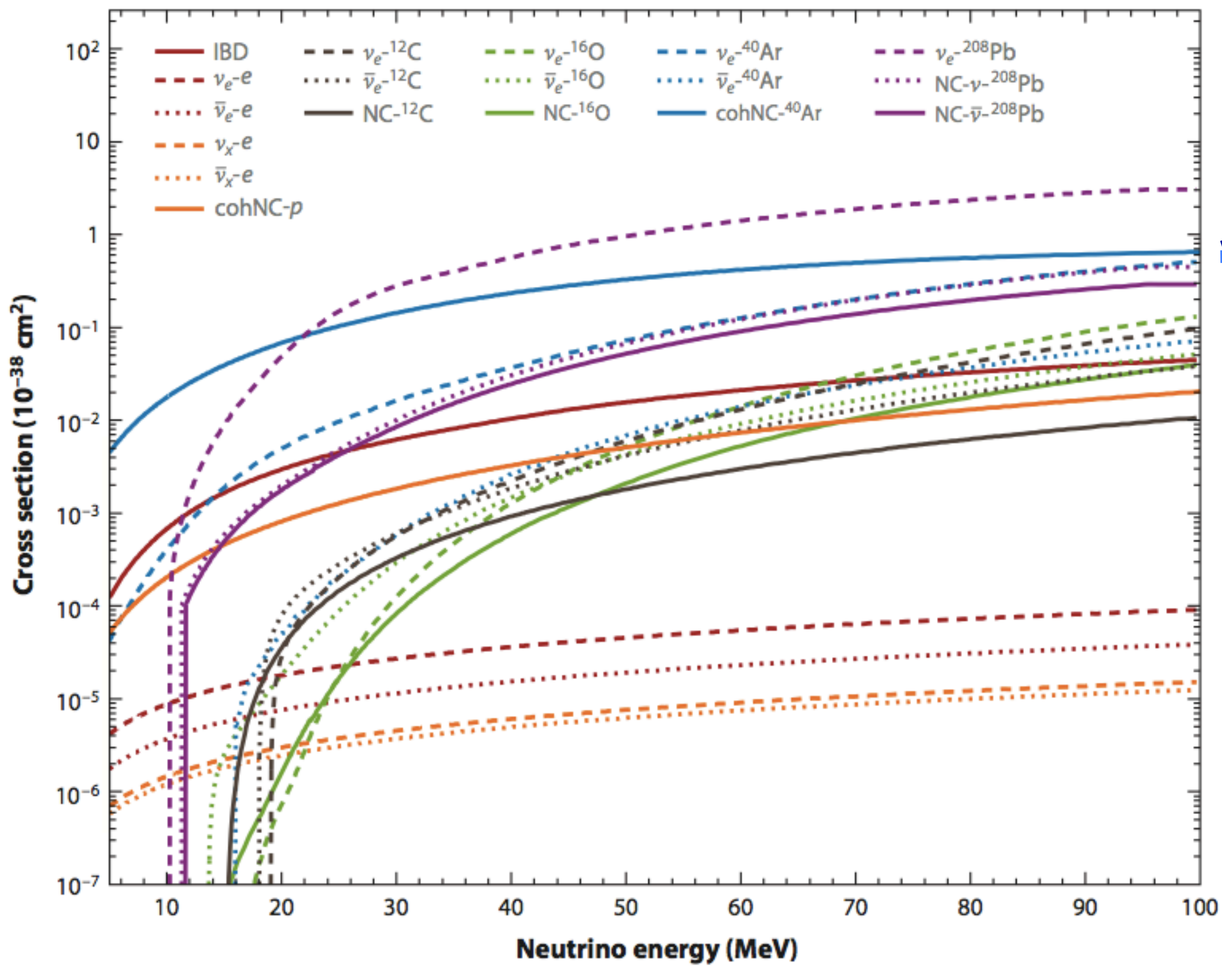
High-energy neutrinos, because both cross-section and maximum recoil energy increase with neutrino energy





... but...

... neutrino energy should not be *too* high...



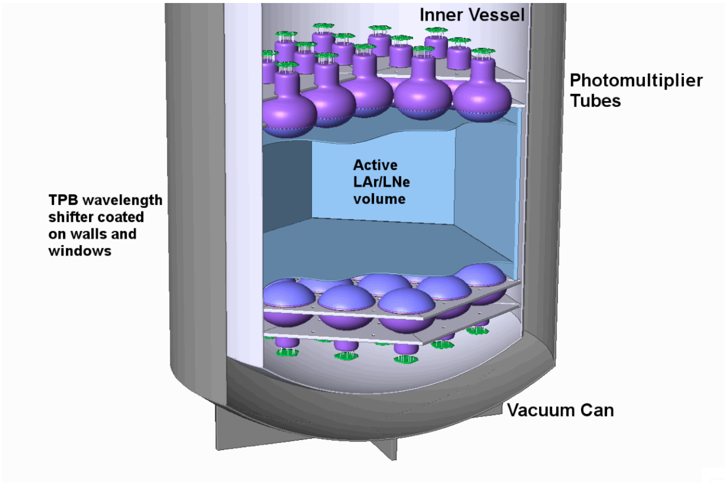
CC, NC QE & nQE

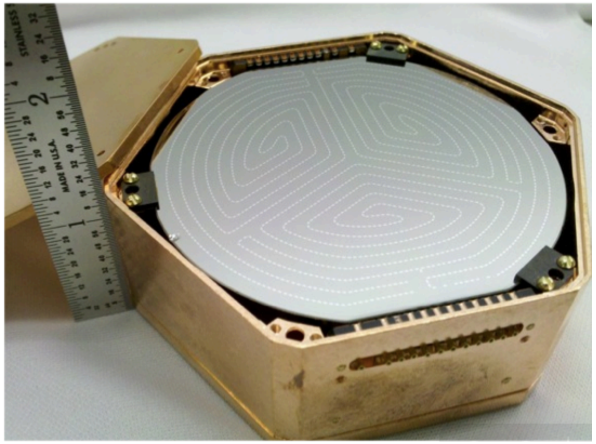
coherent elastic

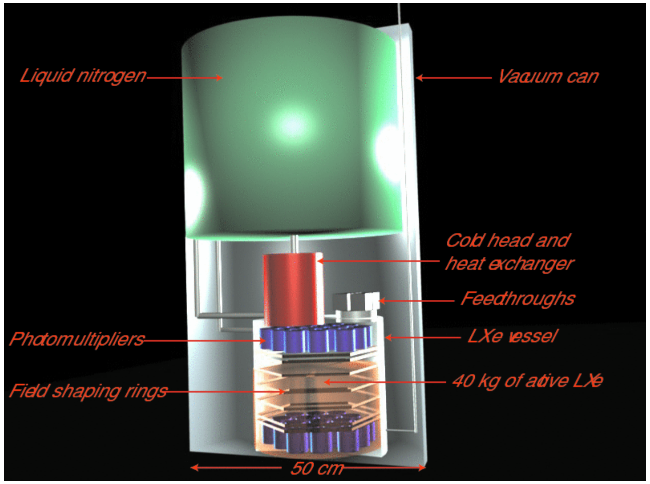
The coherent cross-section flattens, but inelastic cross-section increases (eventually start to scatter off *nucleons*)

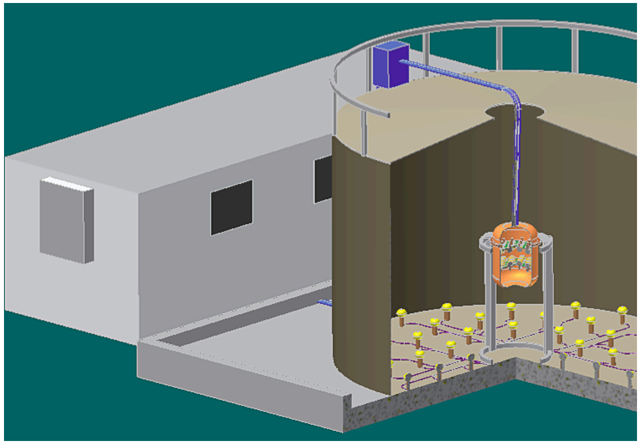
➔ want E_ν ~ 50 MeV to satisfy $Q \lesssim \frac{1}{R}$

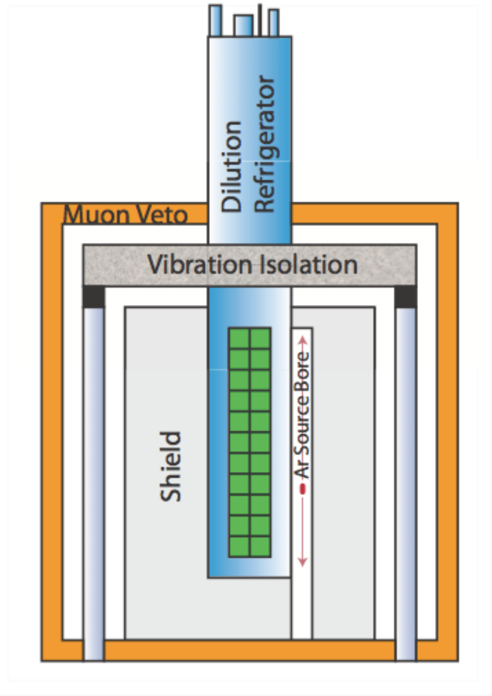
Detector possibilities: various DM-style strategies

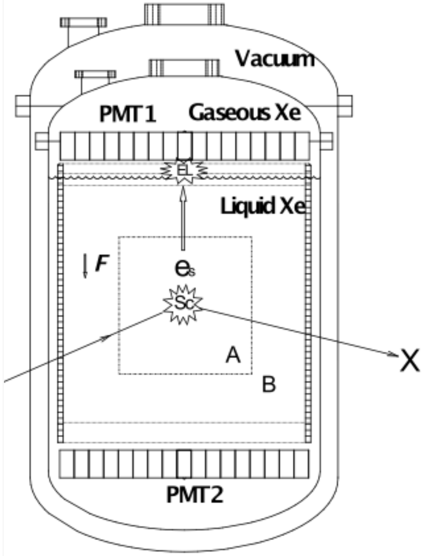


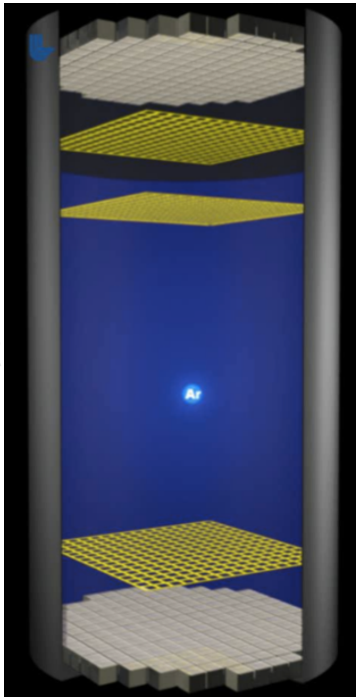




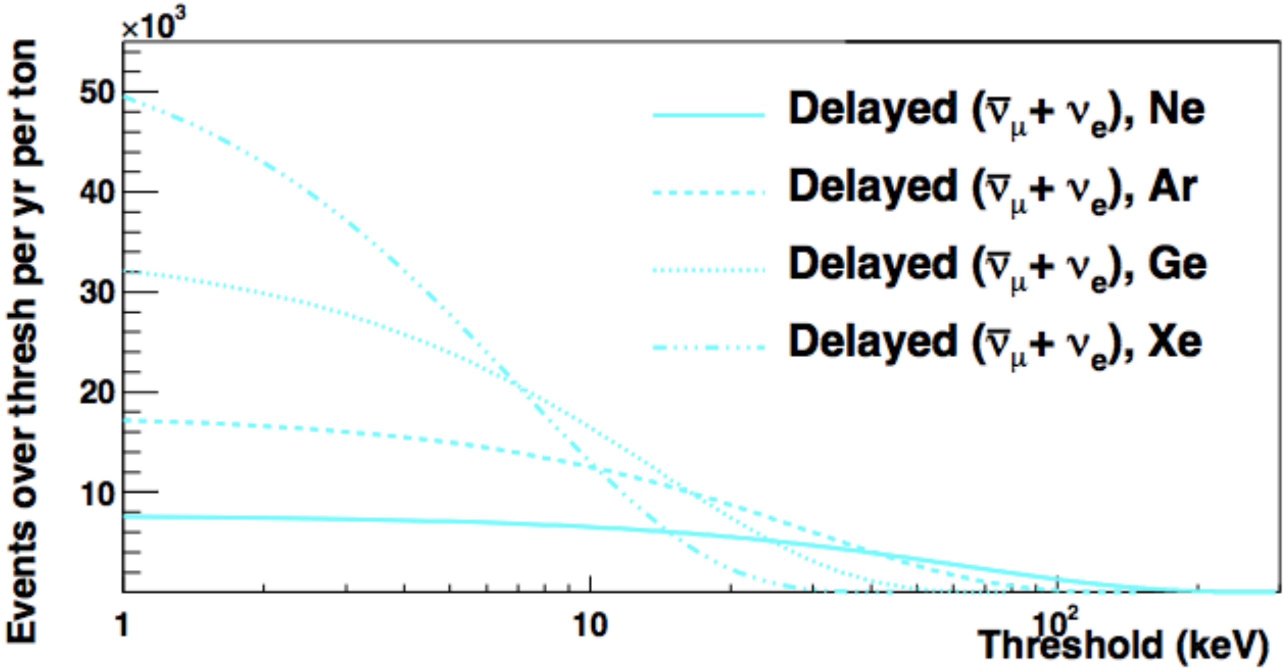


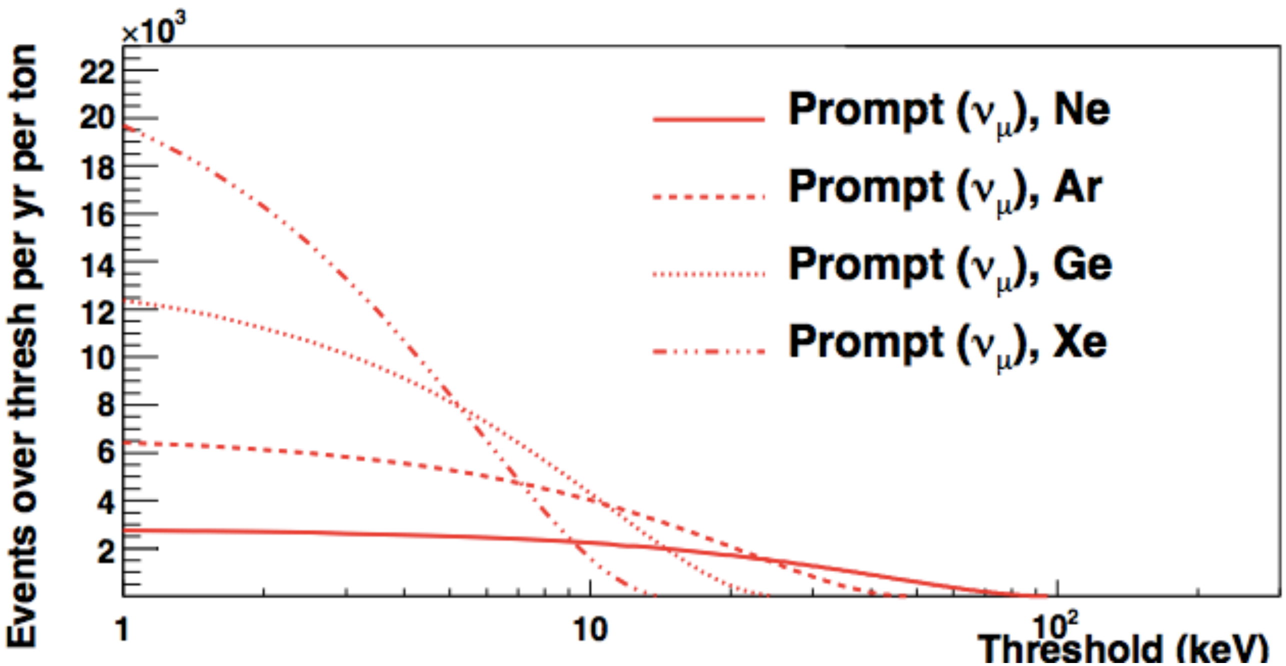






Integrated SNS yield for various targets





20 m

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
- Sterile oscillations
- ...
- Nuclear physics

Weak mixing angle

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

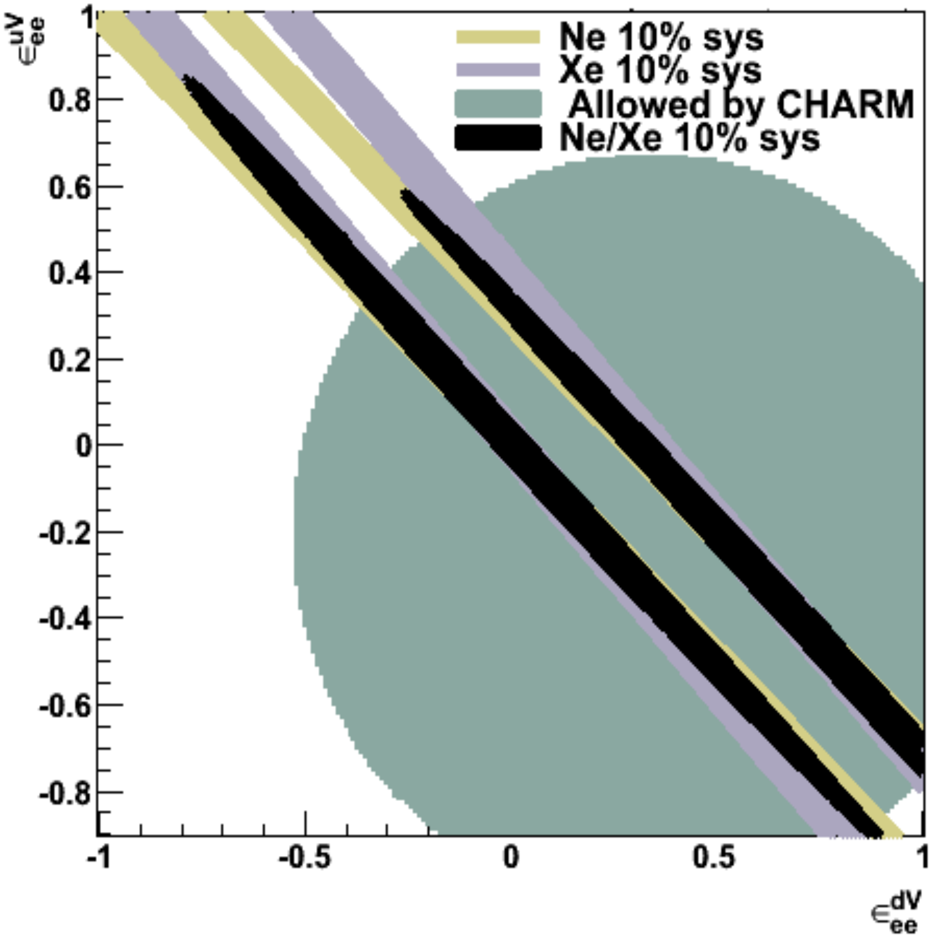
Absolute rate in SM is proportional to

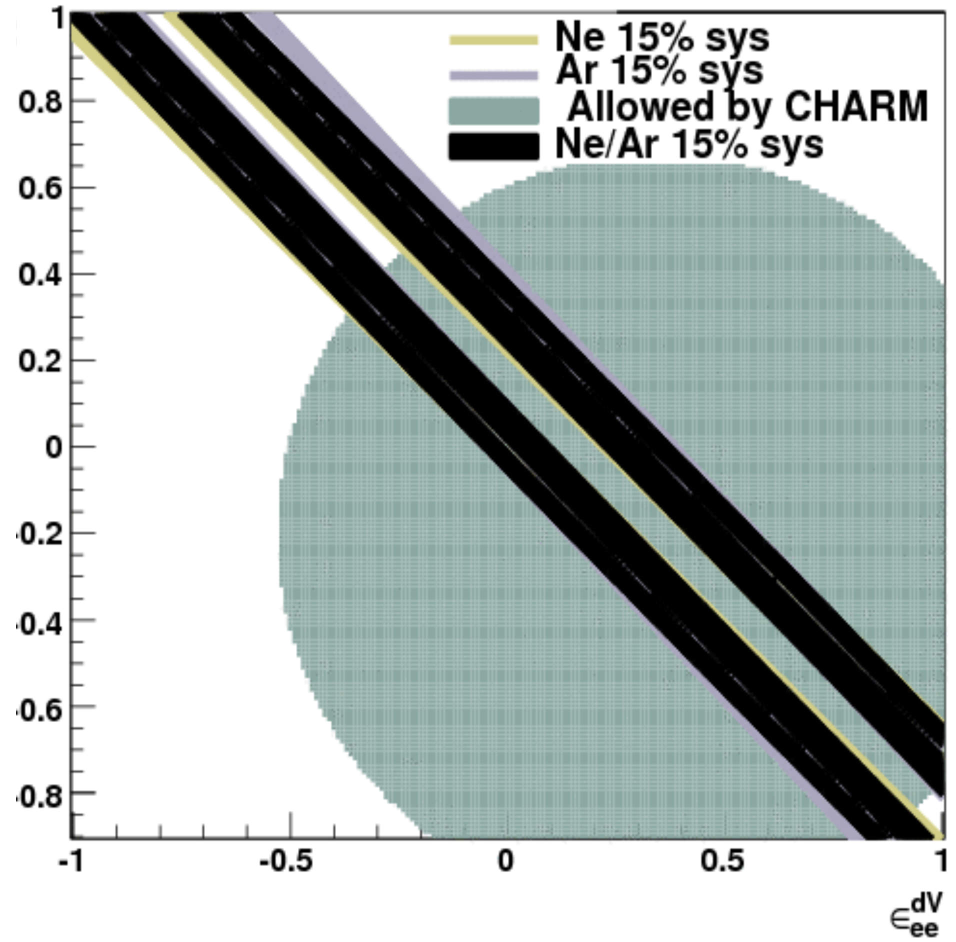
$$(N - (1 - 4\sin^2\theta_W)Z)^2$$

Momentum transfer at SNS is Q~ 0.04 GeV/c

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

Non-Standard Interactions of Neutrinos





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

(for best sensitivity, want multiple targets)

Nuclear physics with coherent elastic scattering

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

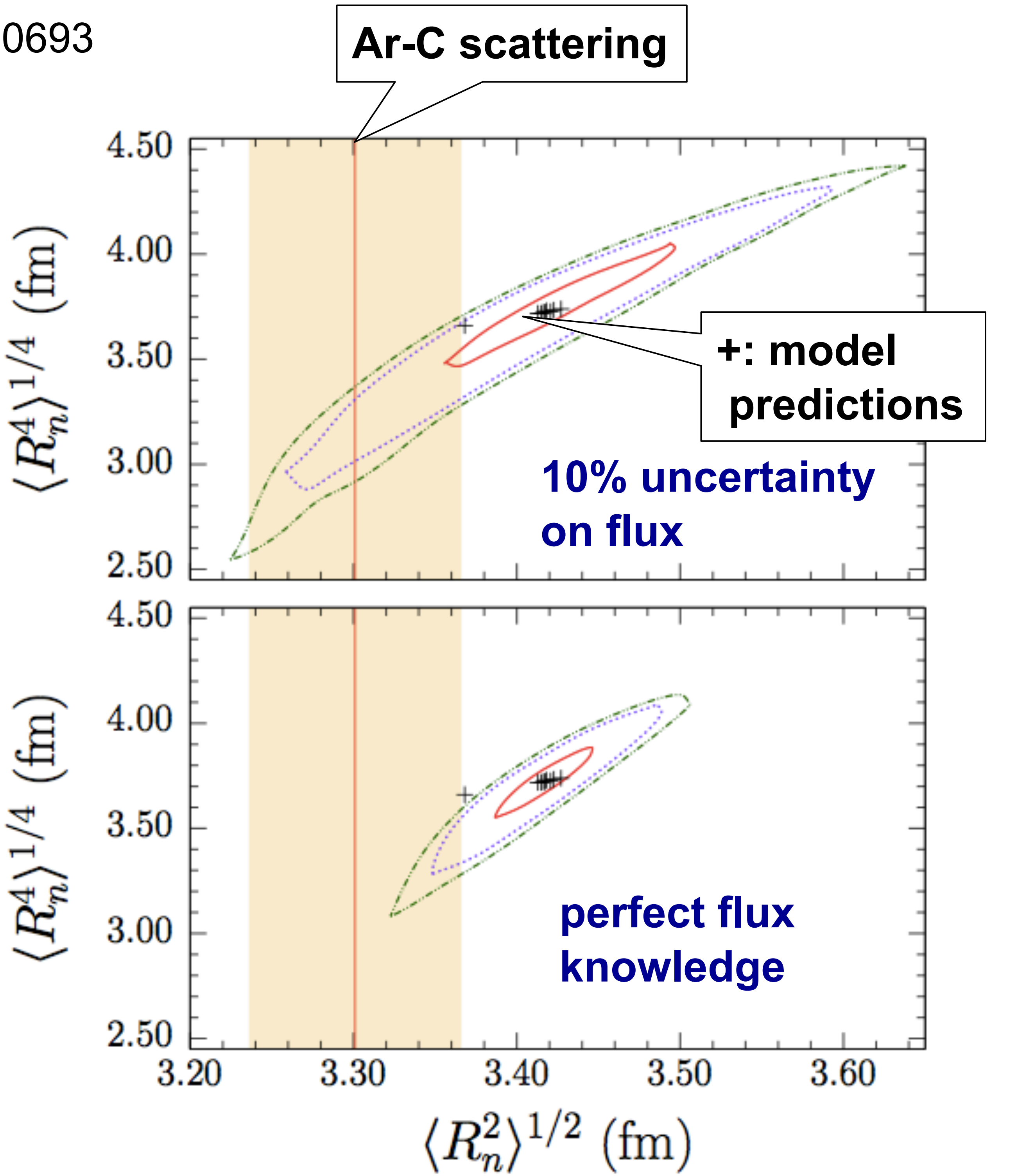
$$\begin{aligned} F_n(Q^2) &\approx \int \rho_n(r) \left(1 - \frac{Q^2}{3!} r^2 + \frac{Q^4}{5!} r^4 - \frac{Q^6}{7!} r^6 + \cdots \right) r^2 dr \\ &\approx N \left(1 - \frac{Q^2}{3!} \langle R_n^2 \rangle + \frac{Q^4}{5!} \langle R_n^4 \rangle - \frac{Q^6}{7!} \langle R_n^6 \rangle + \cdots \right).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

Fit recoil *spectral shape* to determine these moments

(requires very good energy resolution)

K. Patton et al., arXiv:1207.0693

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



Will require stringent control of uncertainties

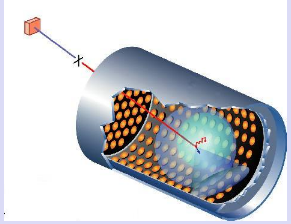
Possible phases of stopped-pion coherent νA scattering experiments

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, oscillations	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

Outstanding 'anomalies' in neutrino physics

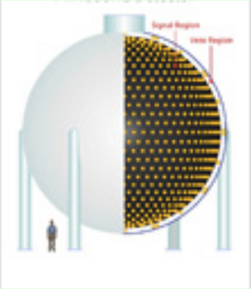
LSND @ LANL (~30 MeV, 30 m)

Excess of $\bar{\nu}_e$ interpreted as $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



➔ $\Delta m^2 \sim 1\ eV^2$: inconsistent with 3 ν masses

MiniBooNE @ FNAL ($\nu,\bar{\nu}$ ~1 GeV, 0.5 km)



- unexplained >3 σ excess for E < 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antineutrinos
  (~consistent with neutrinos)
- small excess for E > 475 MeV in antineutrinos
  (consistent w/ LSND)
- for E>200 MeV, both nu and nubar consistent with LSND

????

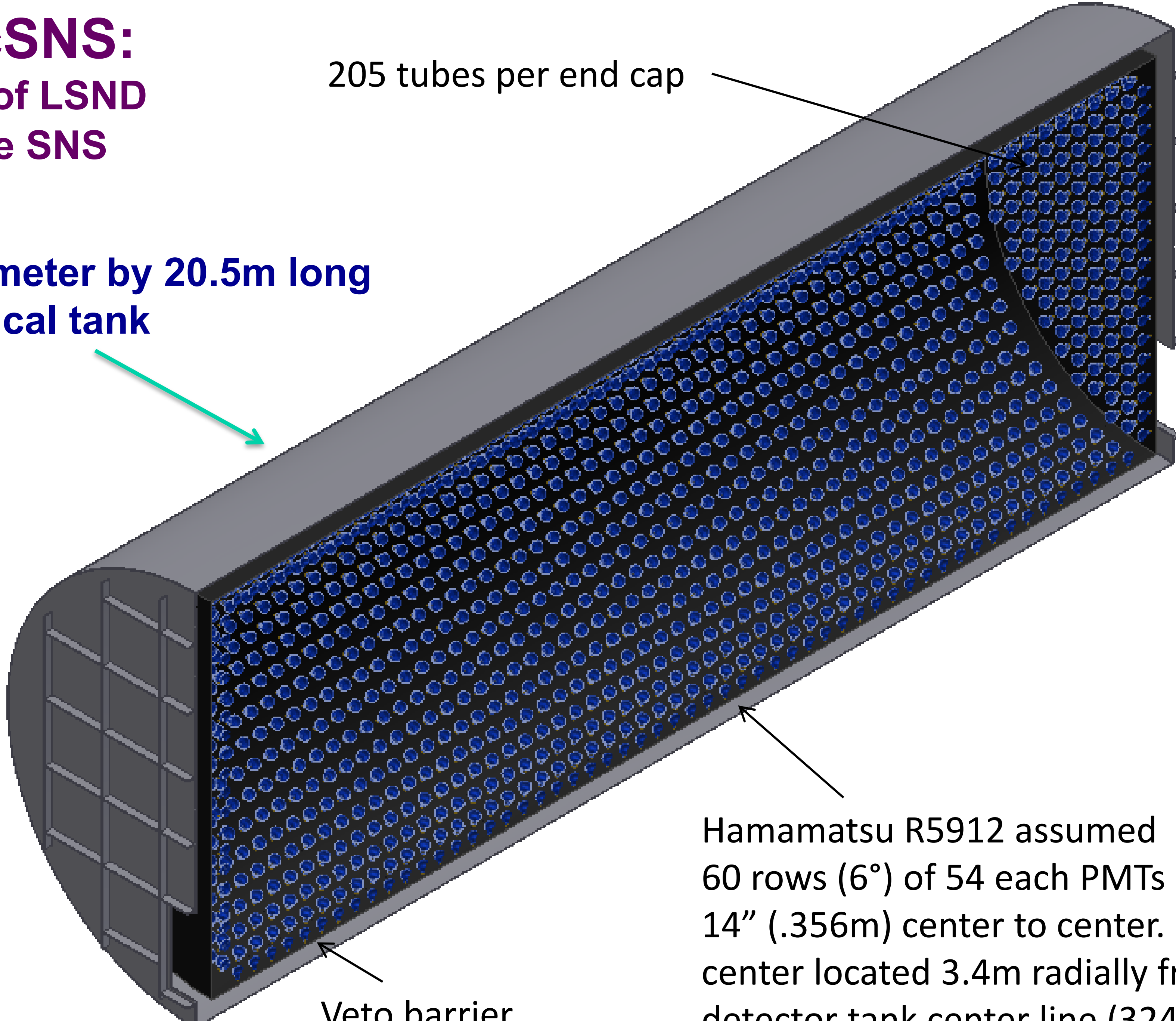
more data needed

Also: possible deficits of reactor $\bar{\nu}_e$ ('reactor anomaly') and source ν_e ('gallium anomaly')

Sterile neutrinos?? (i.e. no normal weak interactions)
Some theoretical motivations for this, both from particle physics & astrophysics. **Or some other new physics??**

OscSNS:
test of LSND at the SNS

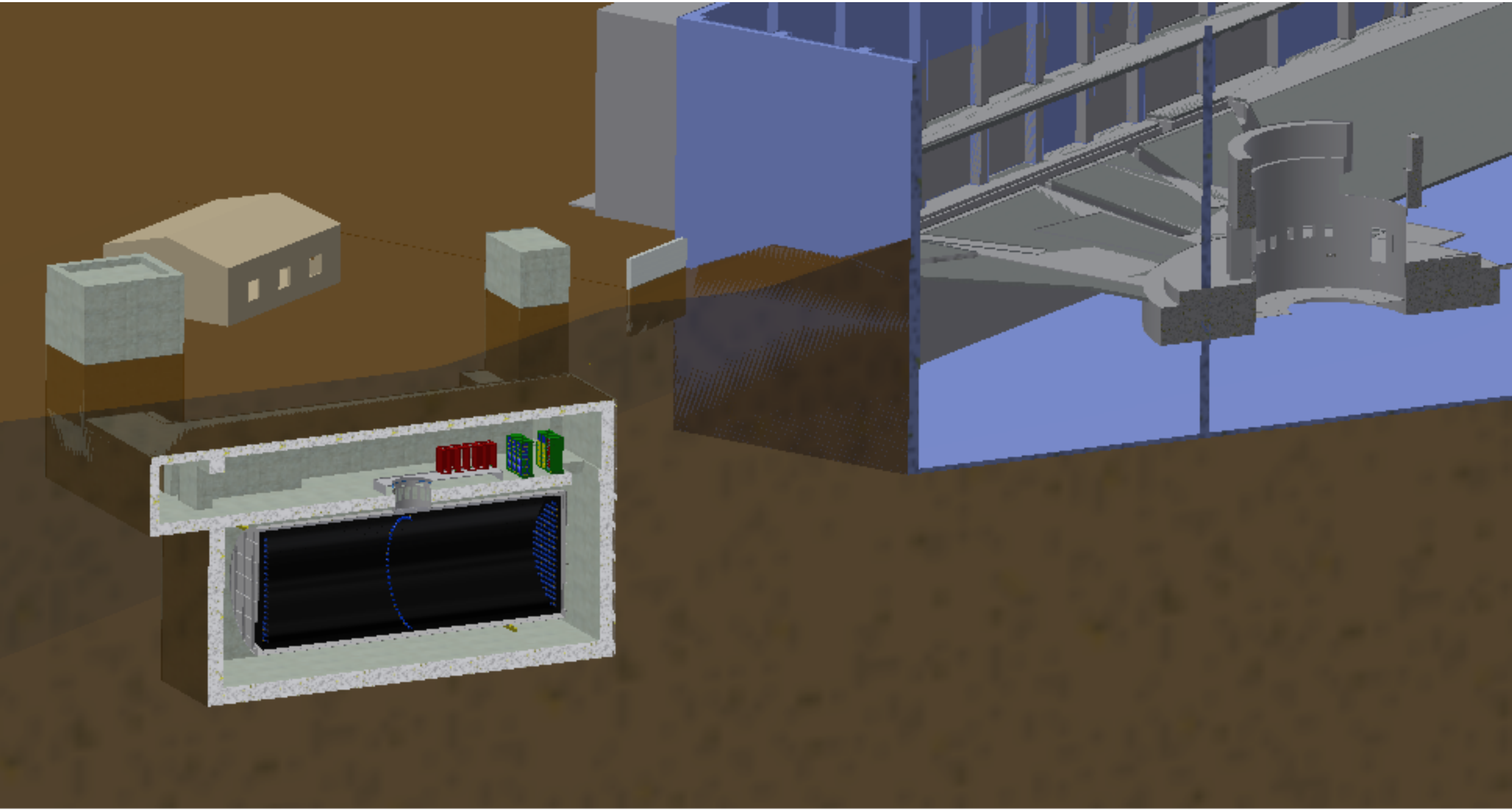
8m diameter by 20.5m long cylindrical tank



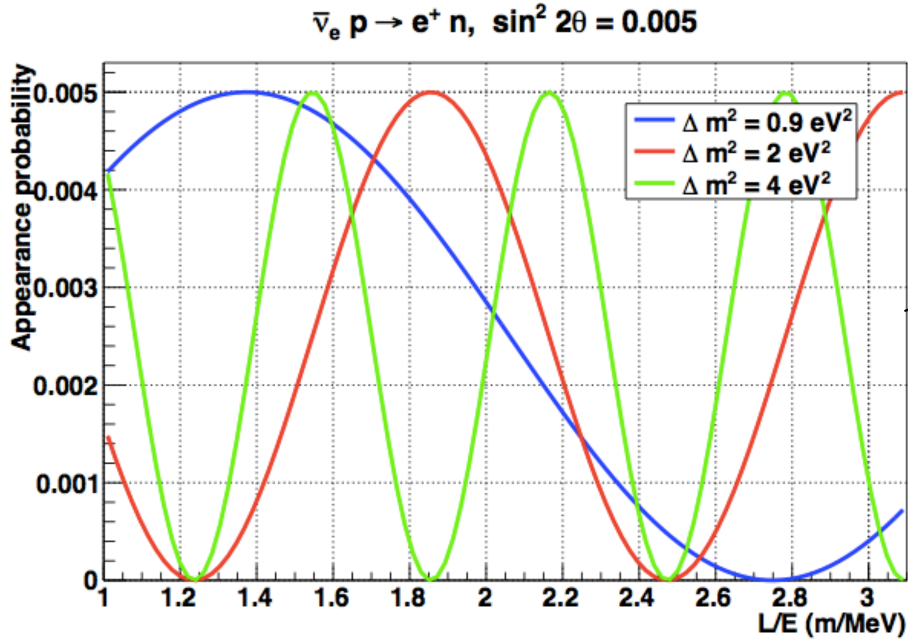
Hamamatsu R5912 assumed
60 rows (6°) of 54 each PMTs located 14” (.356m) center to center. Tube center located 3.4m radially from detector tank center line (3240 tubes)

From Bill Louis

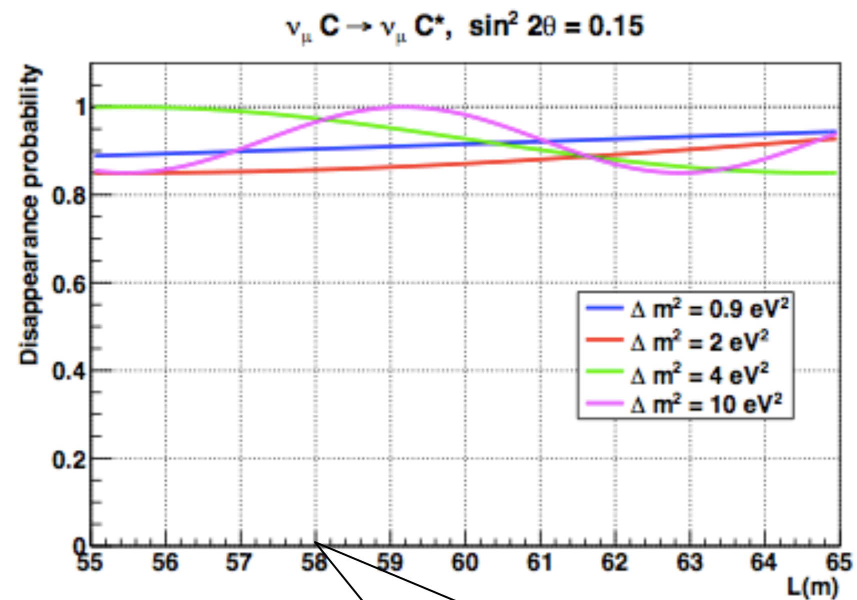
OscSNS location: 40-60 m



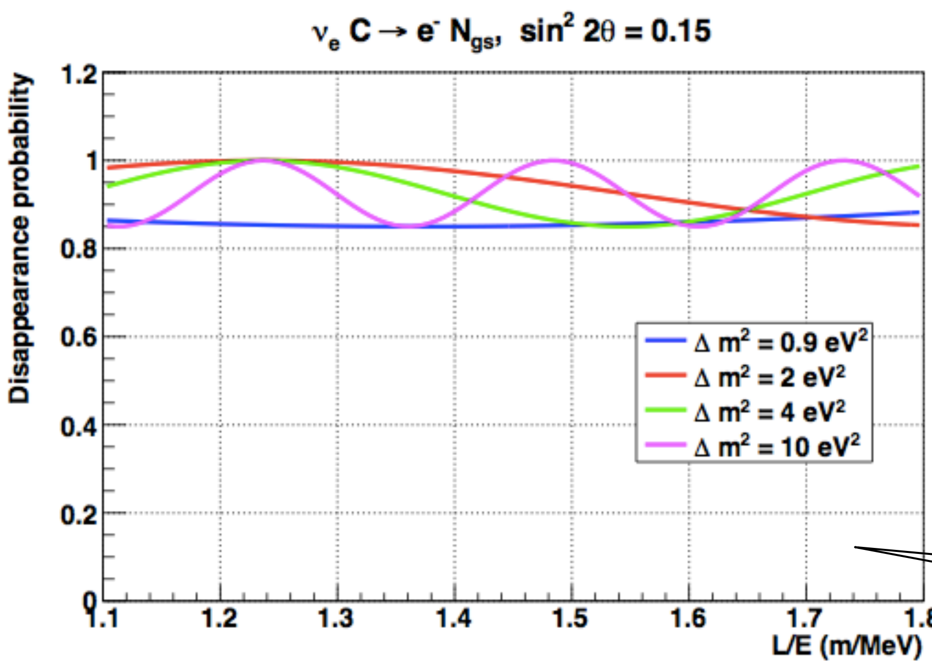
Look for wiggles along the length of the detector...



classic LSND appearance

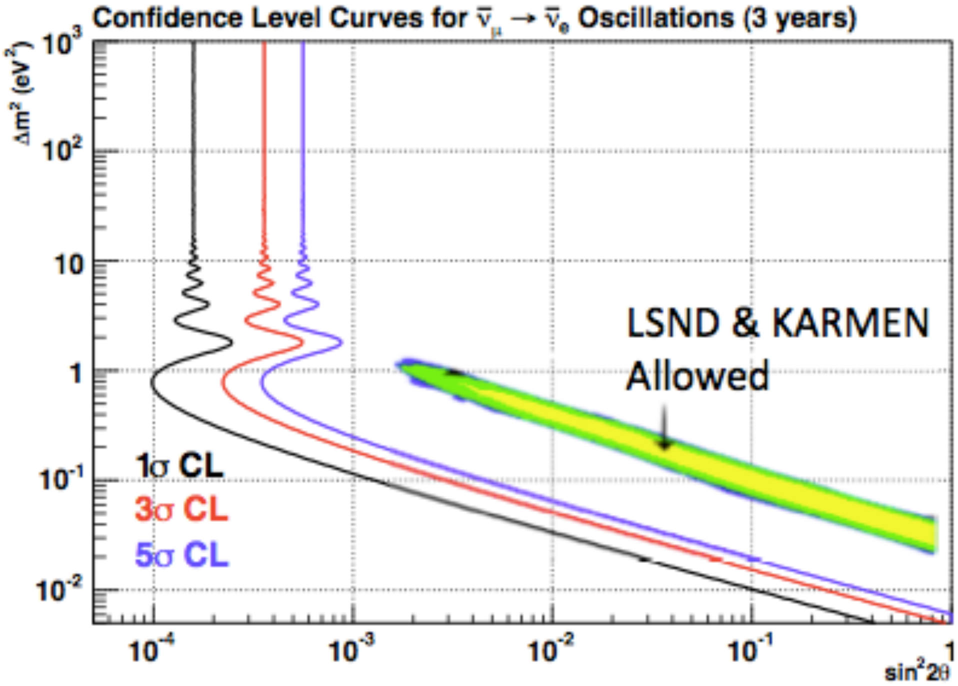


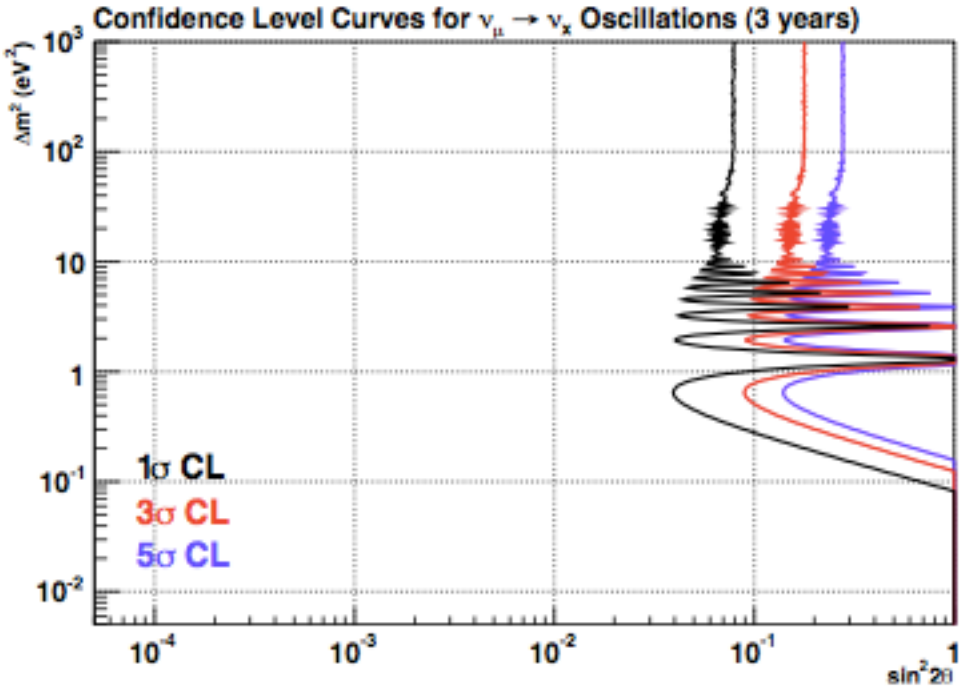
ν_μ disappearance



ν_e disappearance

OscSNS sensitivity curves





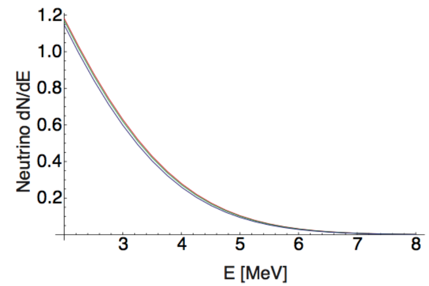
What do you want in a neutrino source for these physics goals?

(SN xscns, CENNS, sterile osc)

- ✓ For SN, ν spectrum ~matching SN spectrum
- ✓ High flux
- ✓ Well understood spectrum
- ✓ Multiple flavors
- ✓ Pulsed source if possible, for background rejection
- ✓ Ability to get close
- ✓ Practical things: access, control, ...

Low energy neutrino sources

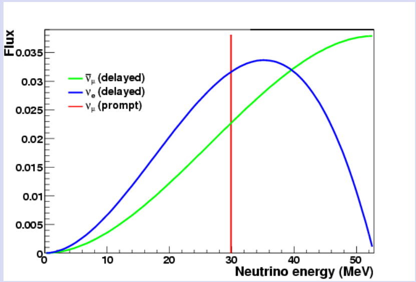
Reactors



Low energy, but very high fluxes possible; ~continuous source good bg rejection needed

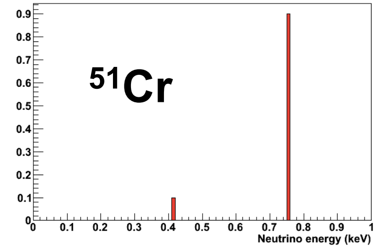
Too low energy

Stopped pions (decay at rest)



High energy, pulsed beam possible for good background rejection; possible neutron backgrounds

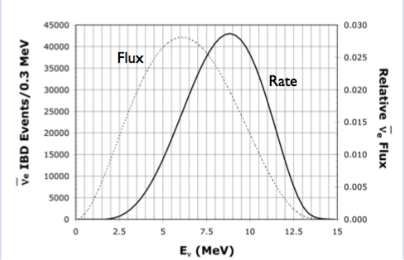
Radioactive sources



Portable; can get very short baseline

Too low energy

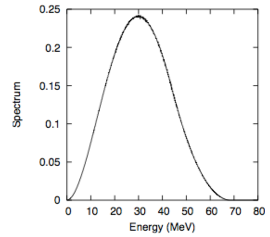
Beam-induced radioactive sources (IsoDAR)



Relatively compact, higher energy than reactor; not pulsed

Lowish energy

Low-energy beta beams



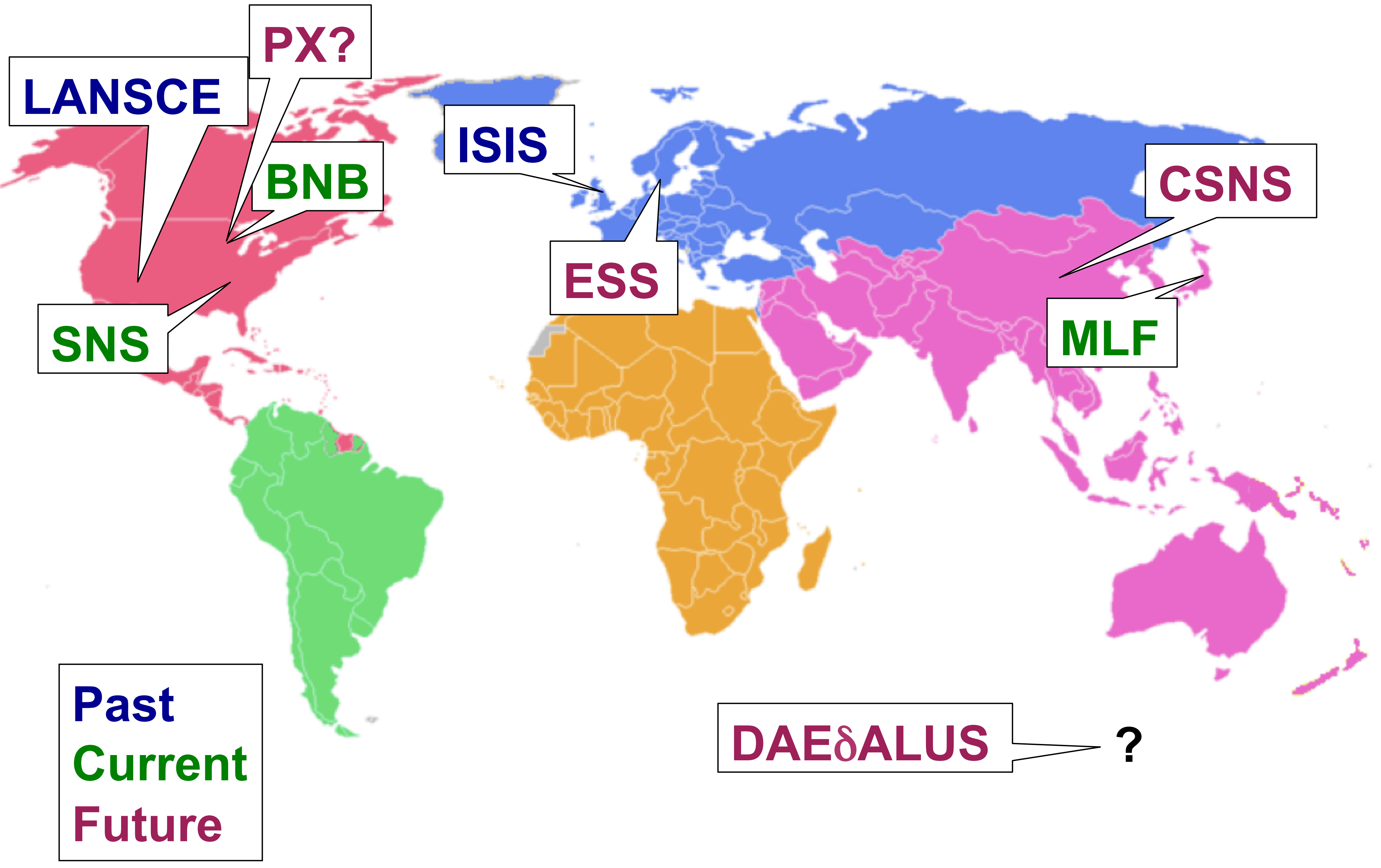
γ=10 boosted ^{18}Ne ν_e

Tunable energy, but not pulsed

Does not exist yet

Source	Flux/ ν's per s	Flavor	Energy	Background rejection	Access/ control?	Exists?
Reactor	2e20 s^{-1} per GW	nuebar	few MeV	Difficult: CW, low energy	Potentially yes	Yes, many possibilities
Stopped pion	1e15 s^{-1}	numu/ nue/ nuebar	0-50 MeV	Good: pulsed beam; high energy	Potentially yes	Yes, several possibilities
Low-energy beta beam	5e11 s^{-1} (?)	nue or nuebar	Tunable	Less: difficult: high energy, CW	Yes	No
Radioactive sources	3e16 s^{-1} per MCi	nue (or nuebar)	~<few MeV	Difficult: low energy, CW	Yes, portable	Yes, needs R&D
IsoDAR	9e14 s^{-1}	nuebar	5-12 MeV	Less difficult; higher energy, CW	Yes	No, seems feasible

Stopped-Pion Sources Worldwide



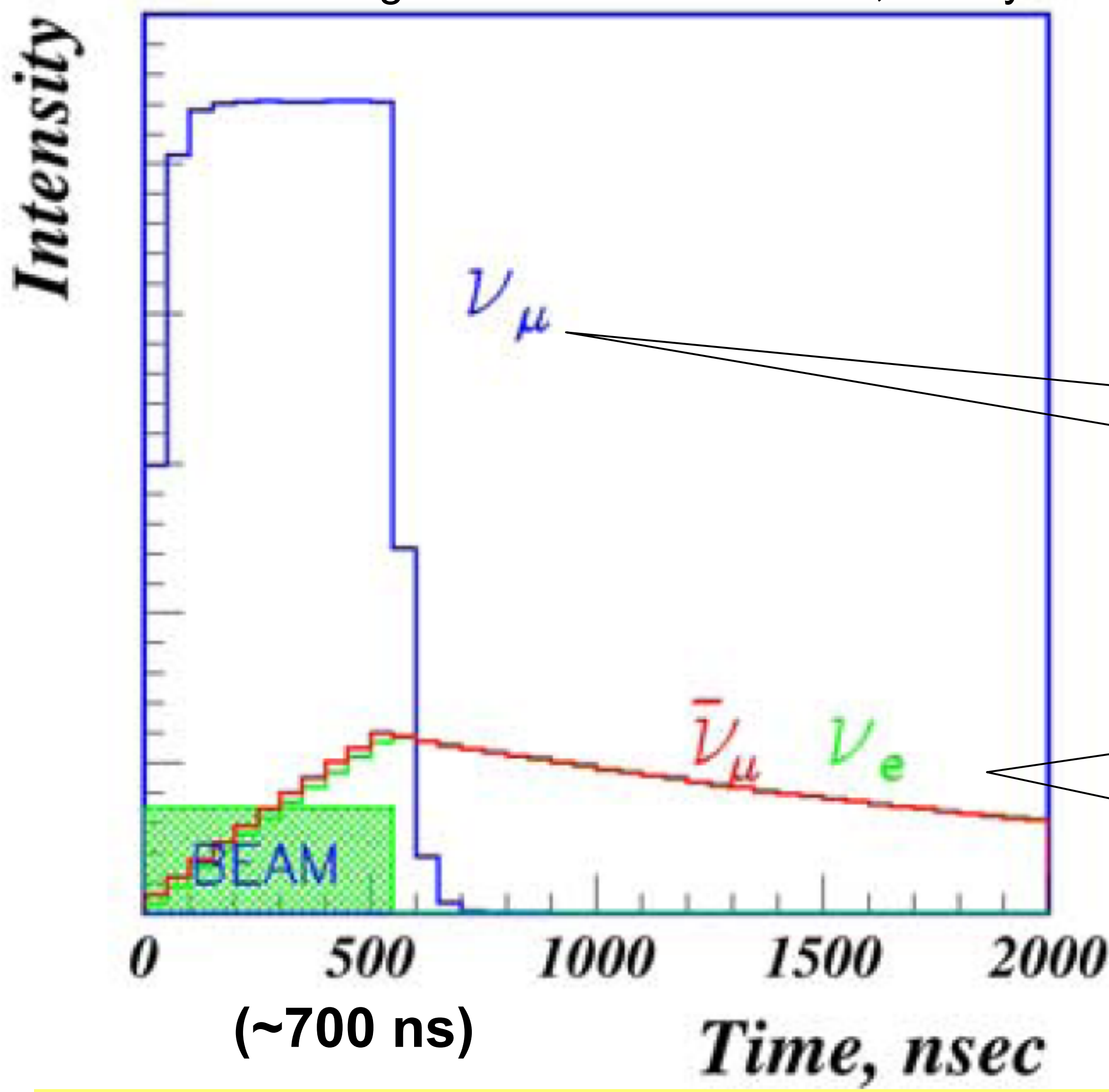
Comparison of stopped-pion neutrino sources

Facility	Location	Proton Energy (GeV)	Power (MW)	Bunch Structure	Rate
LANSCE	USA (LANL)	0.8	0.8	600 μs	120 Hz
ISIS	UK (RAL)	0.8	0.16	2 $\times$ 200 ns	50 Hz
BNB	USA (FNAL)	8	0.032	1.6 μs	5-11 Hz
SNS	USA (ORNL)	1.3	1	700 ns	60 Hz
MLF	Japan (J-PARC)	3	1	2 $\times$ 60-100 ns	25 Hz
CSNS	China (planned)	1.6	0.1	<500 ns	25 Hz
ESS	Sweden (planned)	1.3	5	2 ms	17 Hz
DAEδALUS	TBD (planned)	0.7	$\approx 7 \times 1$	100 ms	2 Hz

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)

Time structure of the source

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



(~700 ns)

60 Hz *pulsed* source

in time with beam

delayed on μ decay timescale (2.2 μs)

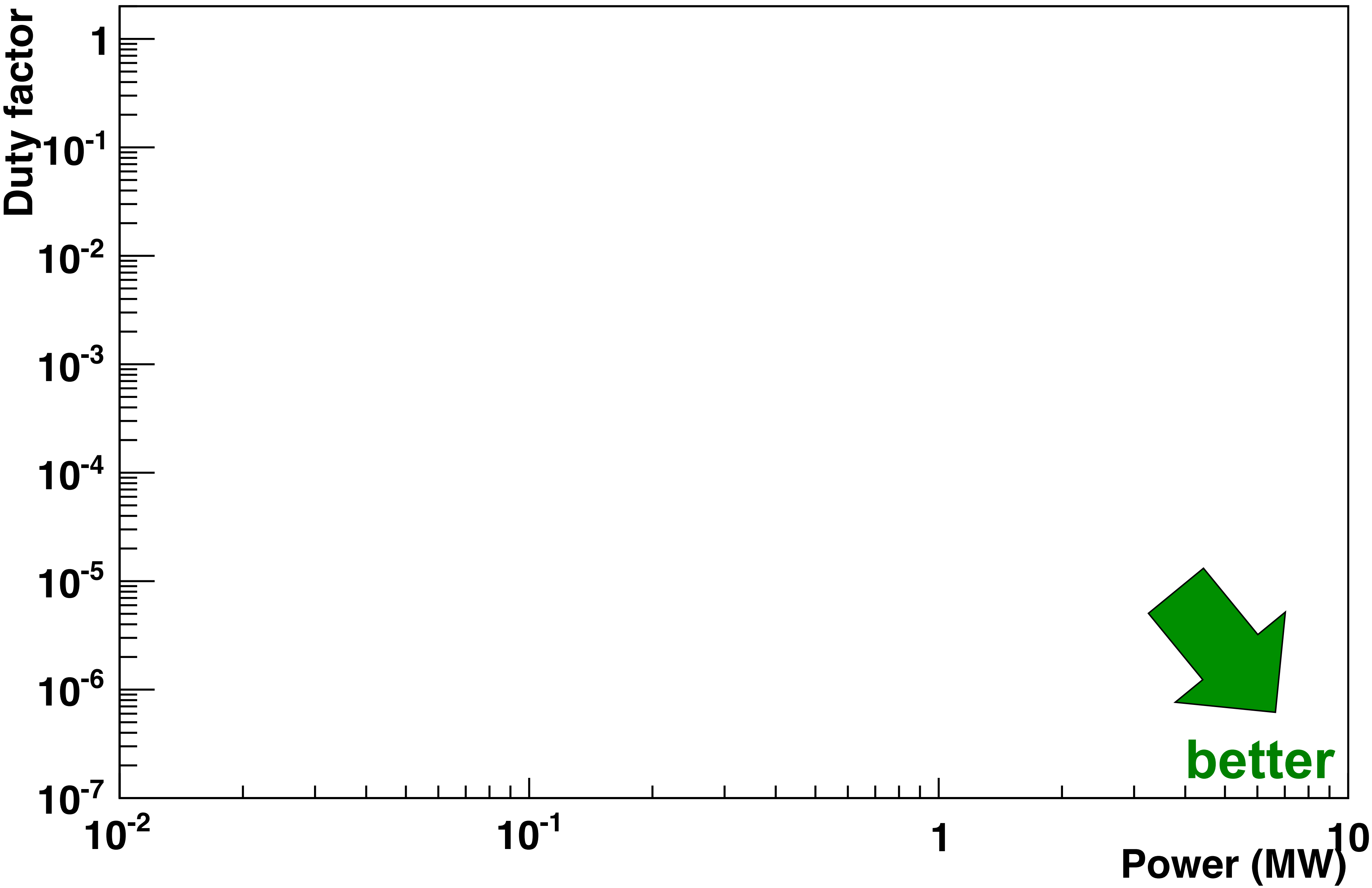
Background rejection factor ~few x 10^{-4}

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

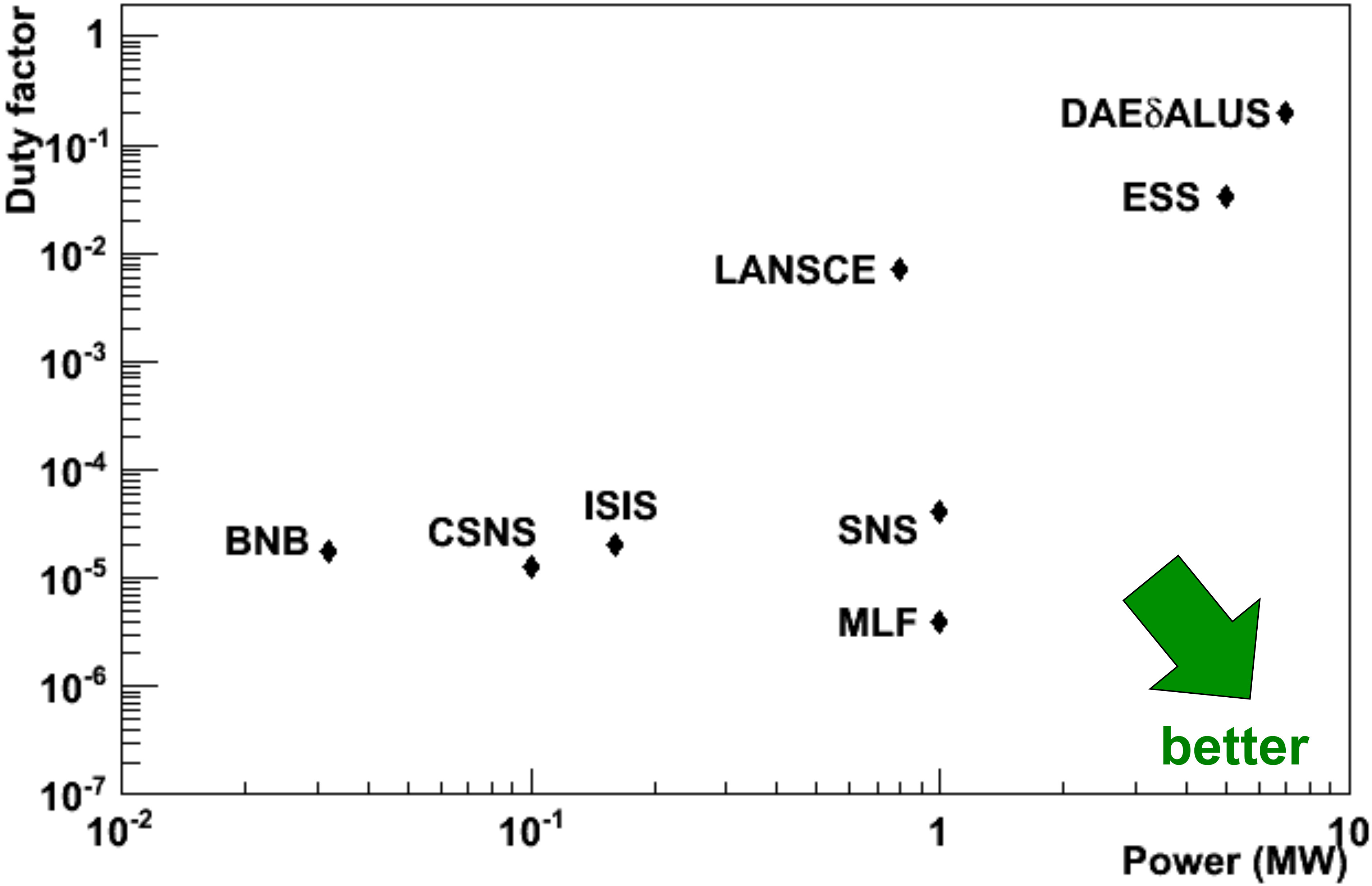
~0.13 per flavor per proton

Flux $\propto$ power: want bigger!

Duty factor: want smaller!



Flux $\propto$ power
Duty factor = T*rate (◆)

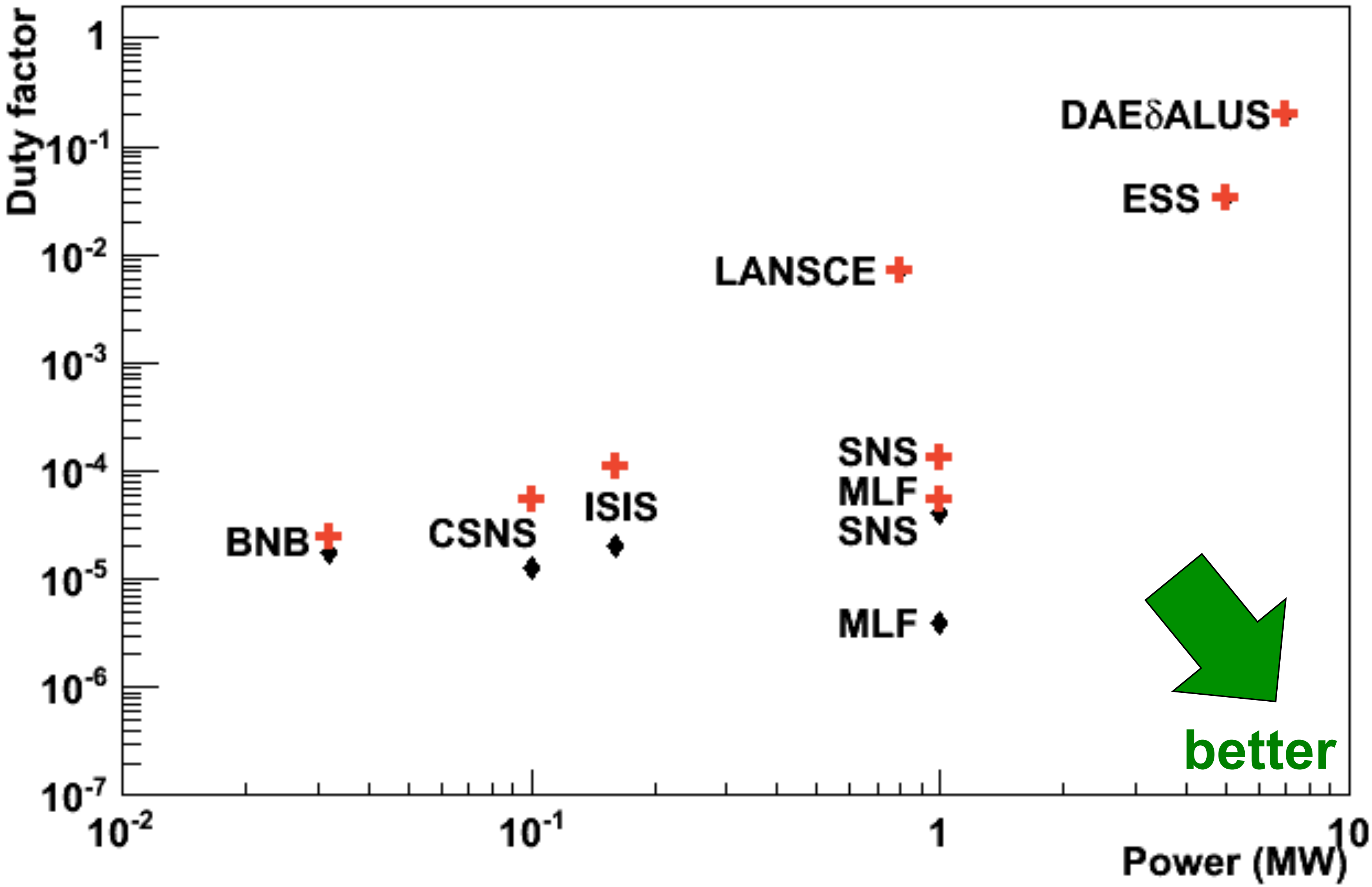


Flux $\propto$ power

Duty factor = T*rate (◆)

= max(T, 2.2 μs)*rate (+ for μdk ν's)

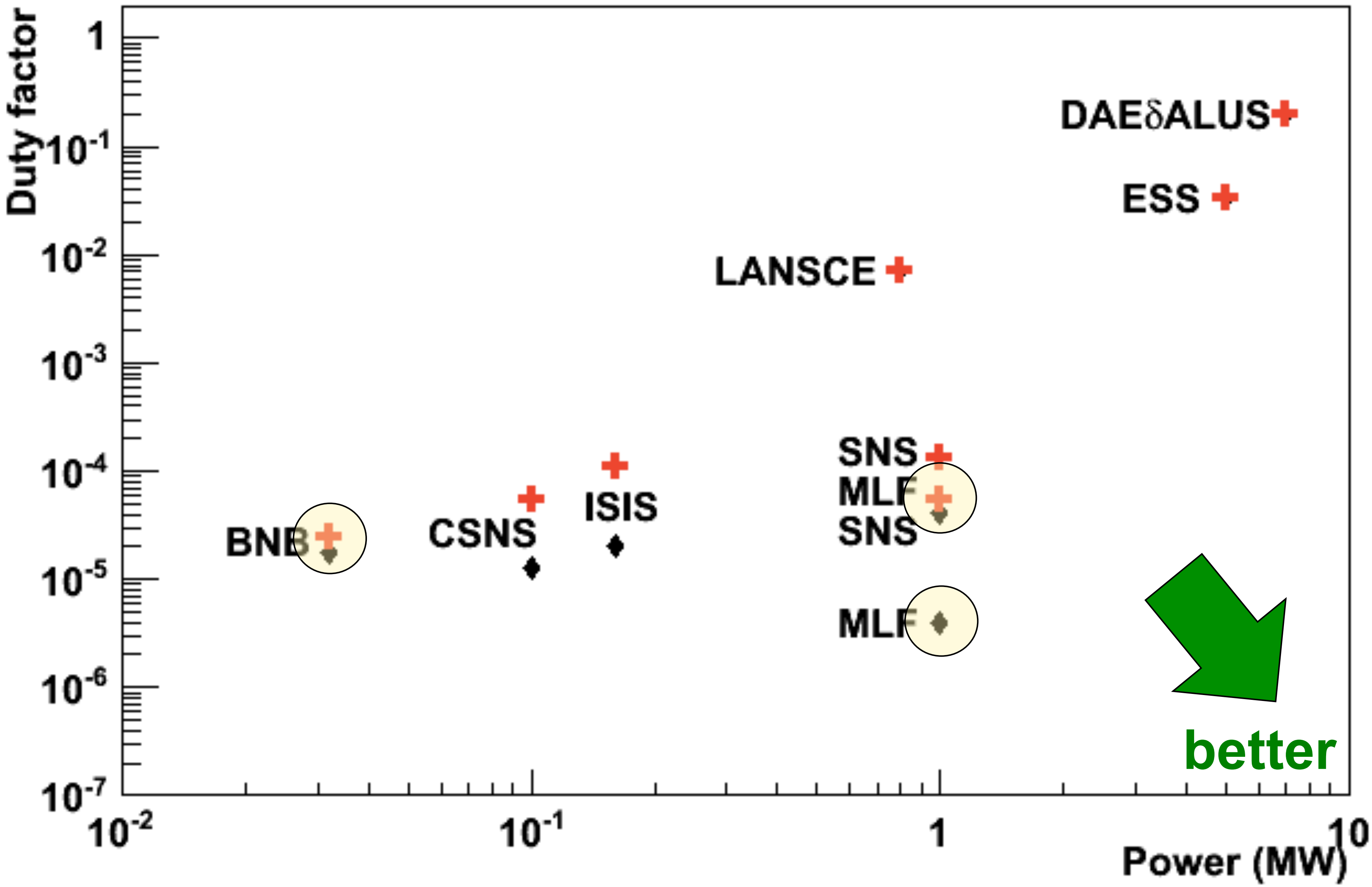
it doesn't help that much to be faster than μdk timescale



Flux $\propto$ power, ◯ high energy protons (non-DAR contamination)

Duty factor = T*rate (◆)

= max(T, 2.2 μs)*rate (+ for μdk ν's)



Summary

Stopped-pion (DAR) neutrinos:
few tens of MeV,   well understood spectrum

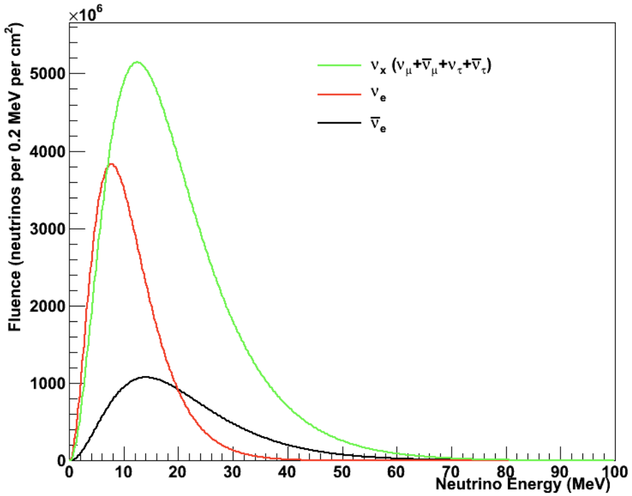
Many possible physics applications:

- SN-relevant cross-sections
  - understanding of SNae
  - interpretation of detected SN neutrinos
- CENNS: never before observed
  - SM test
  - nuclear physics
- Sterile oscillations
  - could be a priority for neutrino physics if anomalies hold up

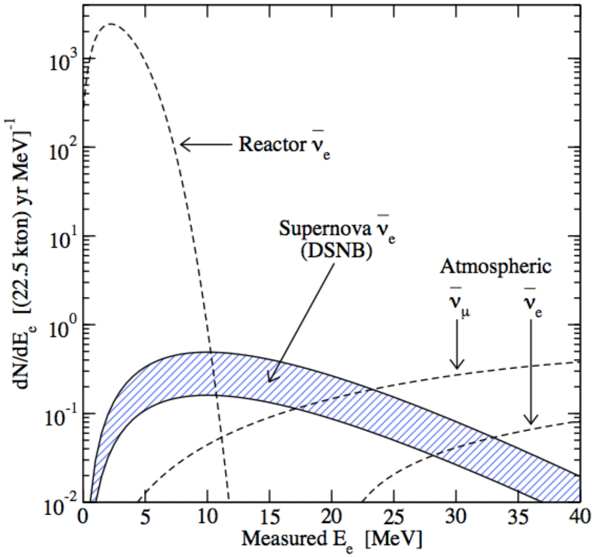
Want high power, narrow pulses:
a dedicated source would be very welcome

Extras/Backups

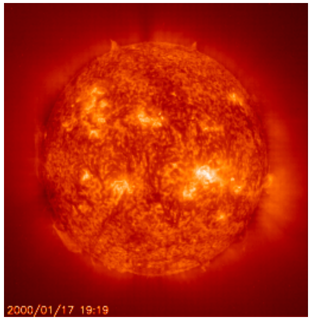
Neutrino interactions in the few-100 MeV range are relevant for neutrinos from various natural sources

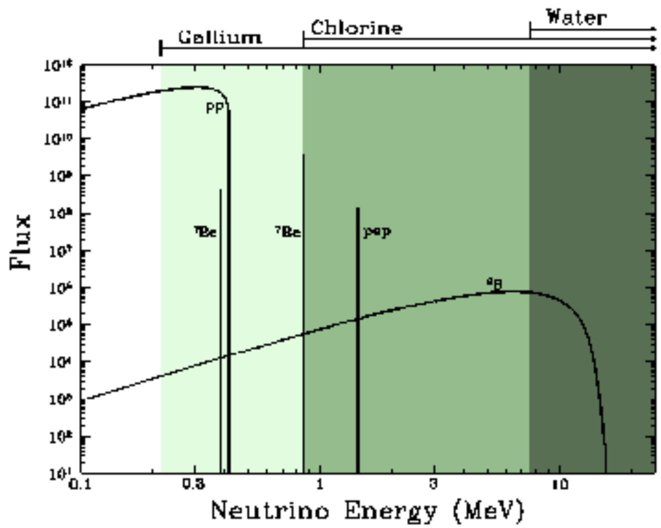


supernova neutrinos, burst & relic

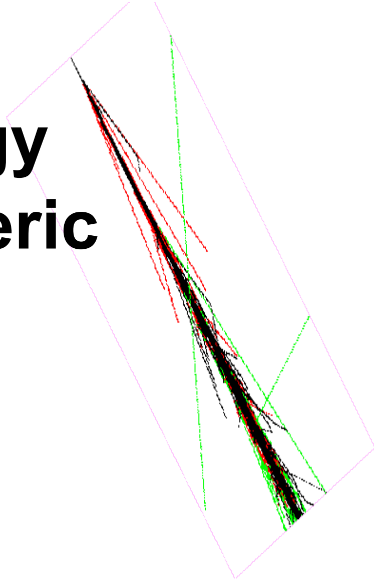


solar neutrinos





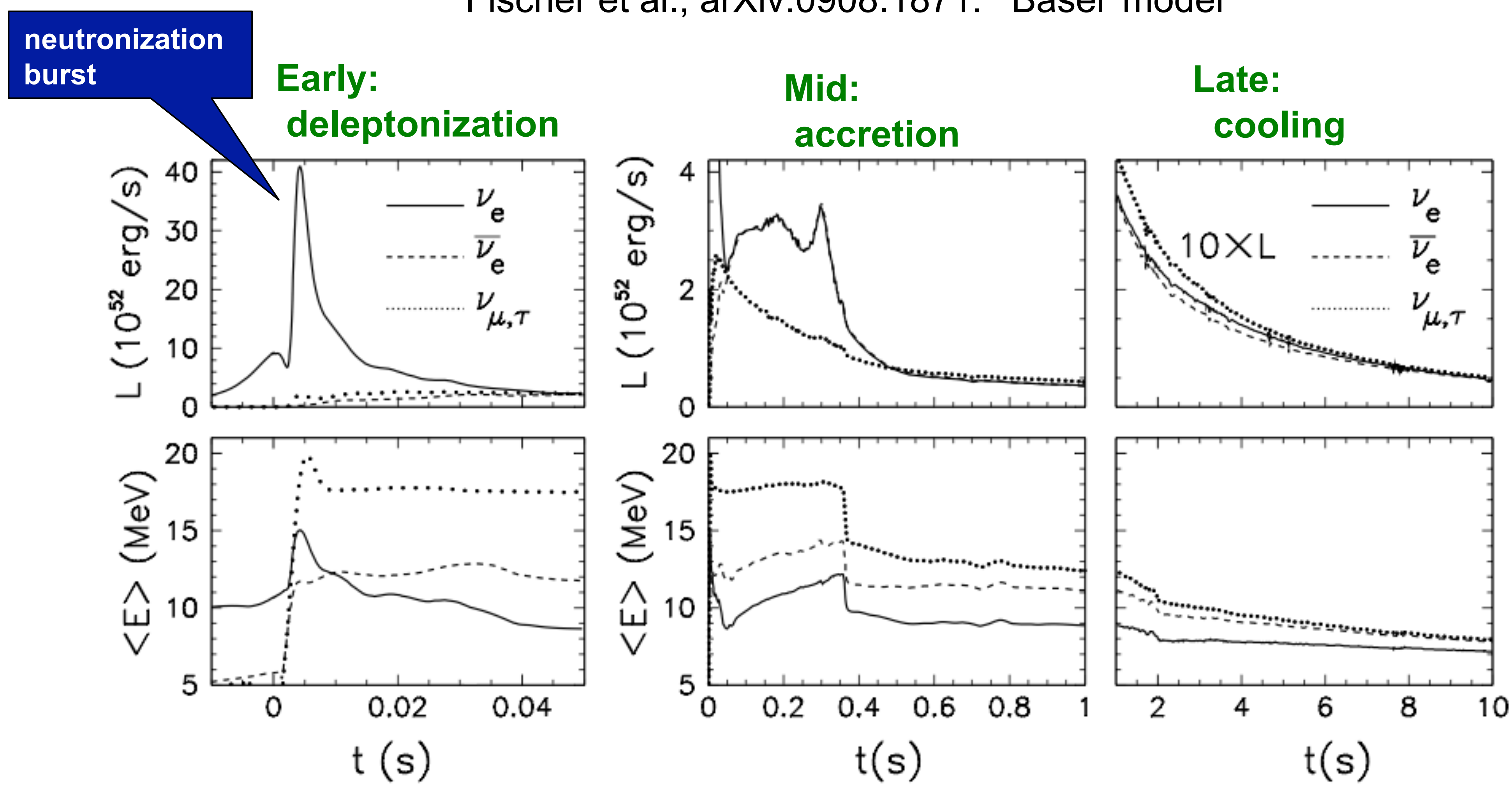
low energy atmospheric neutrinos



oscillation, astrophysics

Expected neutrino luminosity and average energy vs time

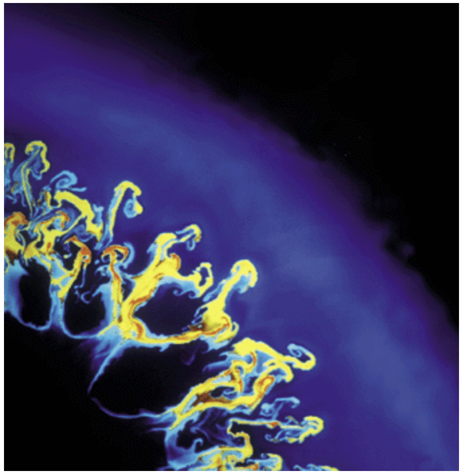
Fischer et al., arXiv:0908.1871: 'Basel' model



Generic feature:
(may or may not be robust)

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

What We Can Learn

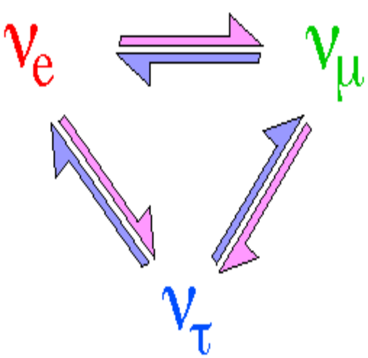


CORE COLLAPSE PHYSICS

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

from flavor, energy, time structure of burst

NEUTRINO/OTHER PARTICLE PHYSICS

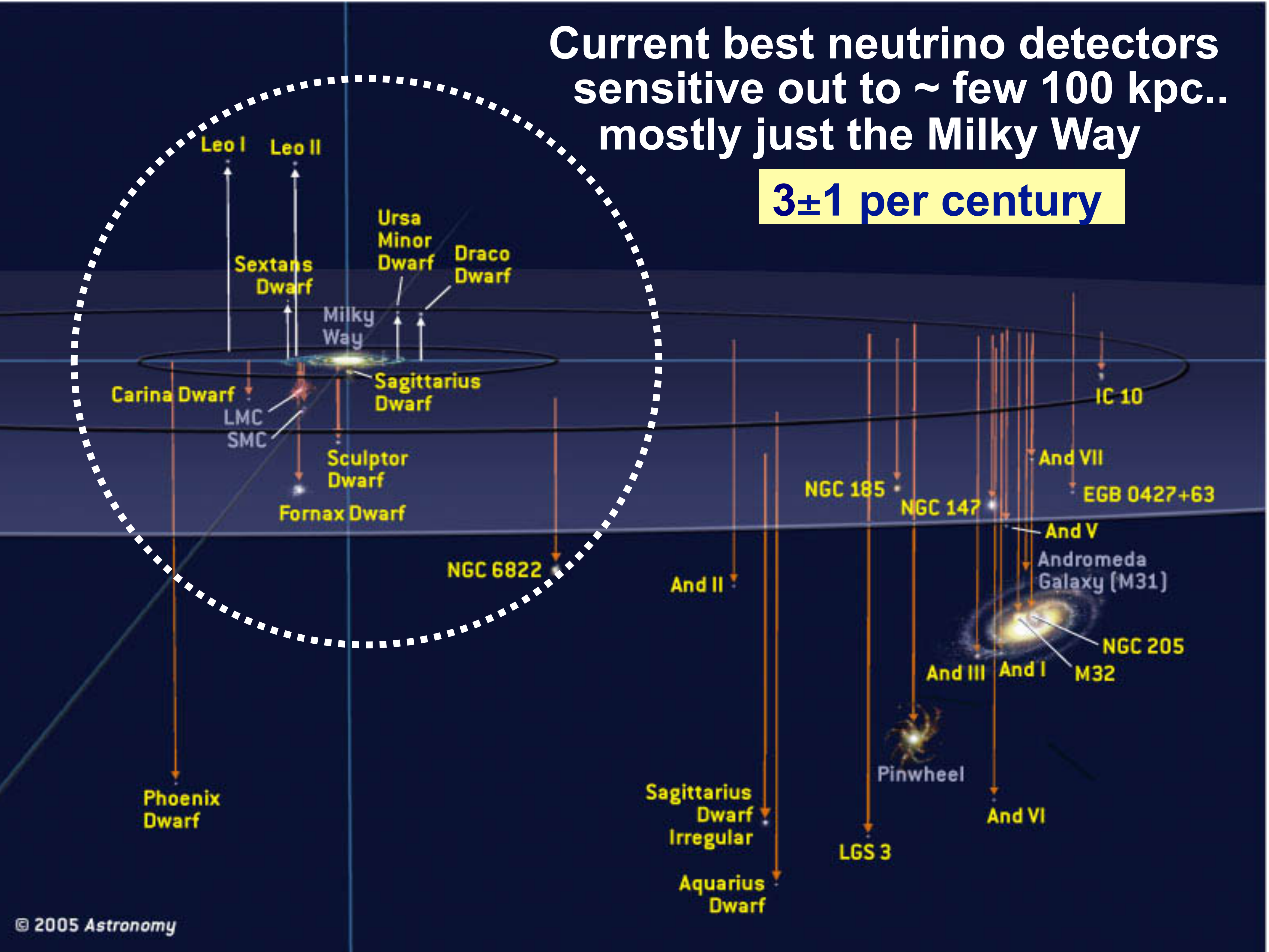


- ν absolute mass (not competitive)
- ν mixing from spectra: flavor conversion in SN/Earth
- other ν properties: sterile ν's, magnetic moment,...
- axions, extra dimensions, FCNC, ...

+ EARLY ALERT

Current best neutrino detectors sensitive out to ~ few 100 kpc.. mostly just the Milky Way

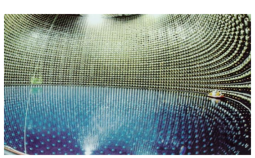
3±1 per century

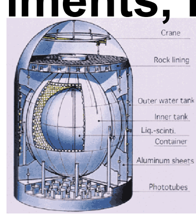


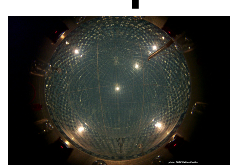
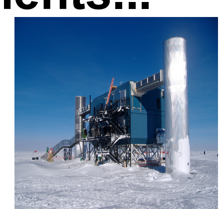
Current & near-future supernova neutrino detectors

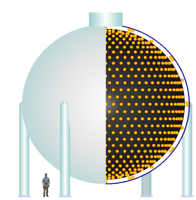
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	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

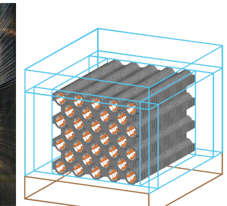
plus reactor experiments, DM experiments...









Primary sensitivity is to electron antineutrinos via inverse beta decay

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

Summary of supernova neutrino detectors

Galactic sensitivity

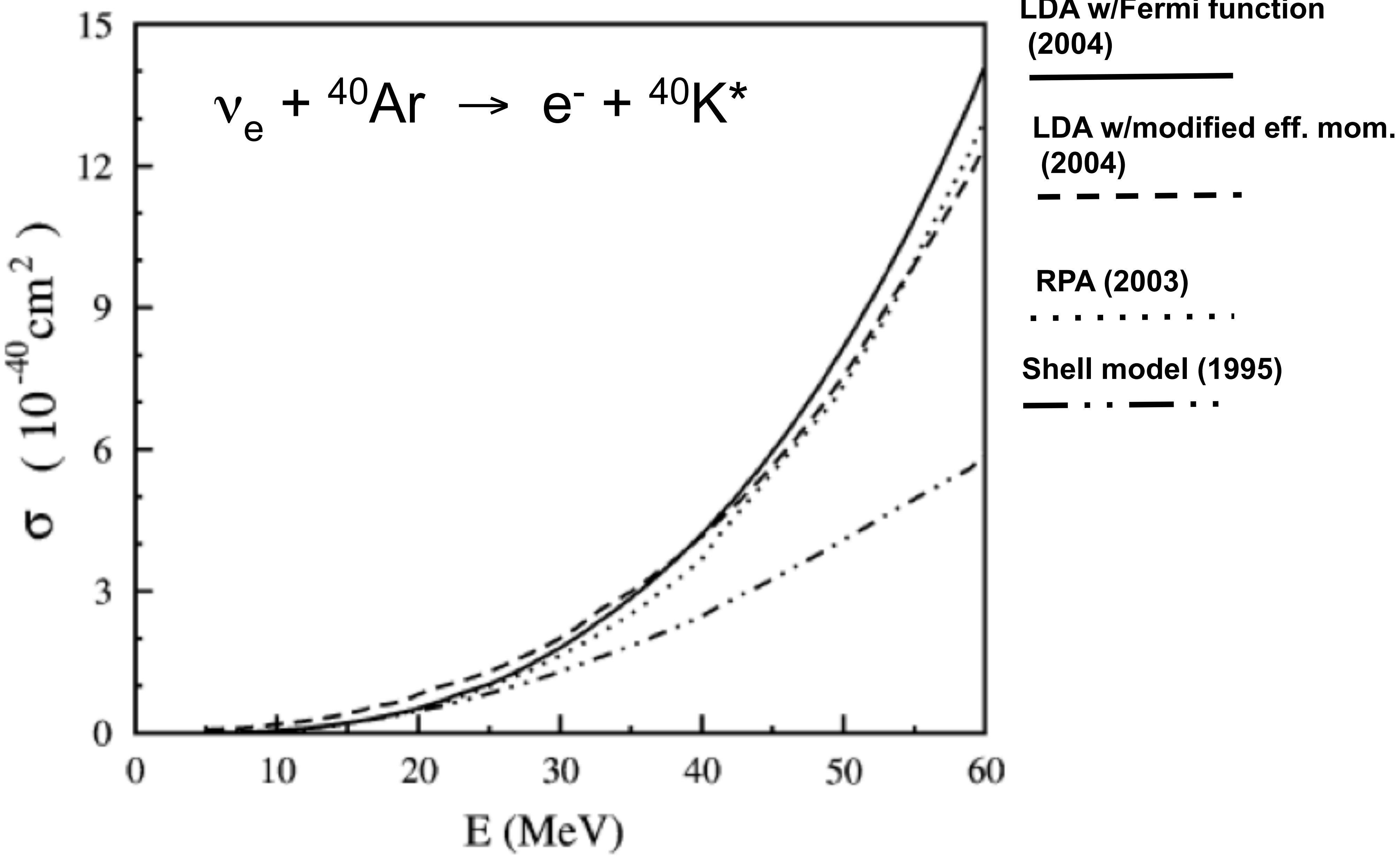
Extragalactic

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)
NOvA	Scintillator	USA	15	3000	Under construction
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction
LBNE LAr	Liquid argon	USA	34	3000	Proposed
(LBNE WC)	Water	USA	200	44,000	Proposed
MEMPHYS	Water	Europe	440	88,000	Proposed
Hyper-K	Water	Japan	540	110,000	Proposed
LENA	Scintillator	Europe	50	15,000	Proposed
GLACIER	Liquid argon	Europe	100	9000	Proposed

plus reactor experiments, DM experiments...

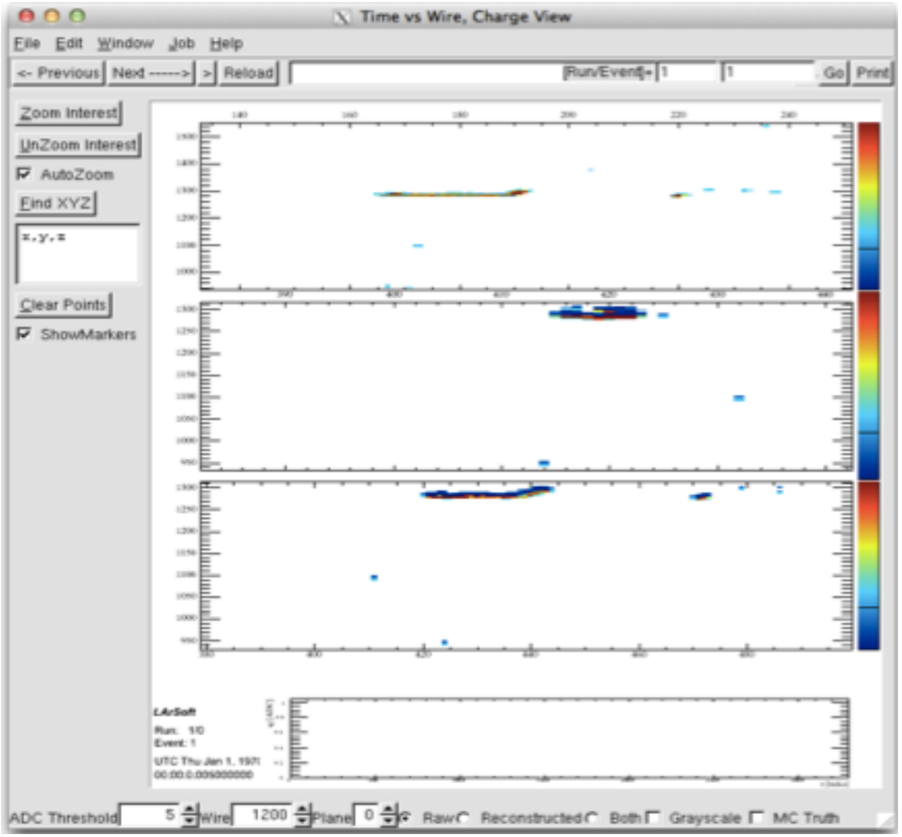
Cross sections for CC electron neutrino absorption

M. Sajjad Athar and S.K. Singh, Phys. Lett. B591, 69 (2004)



Need to measure deexcitation γ's!

LArTPC Detector Response



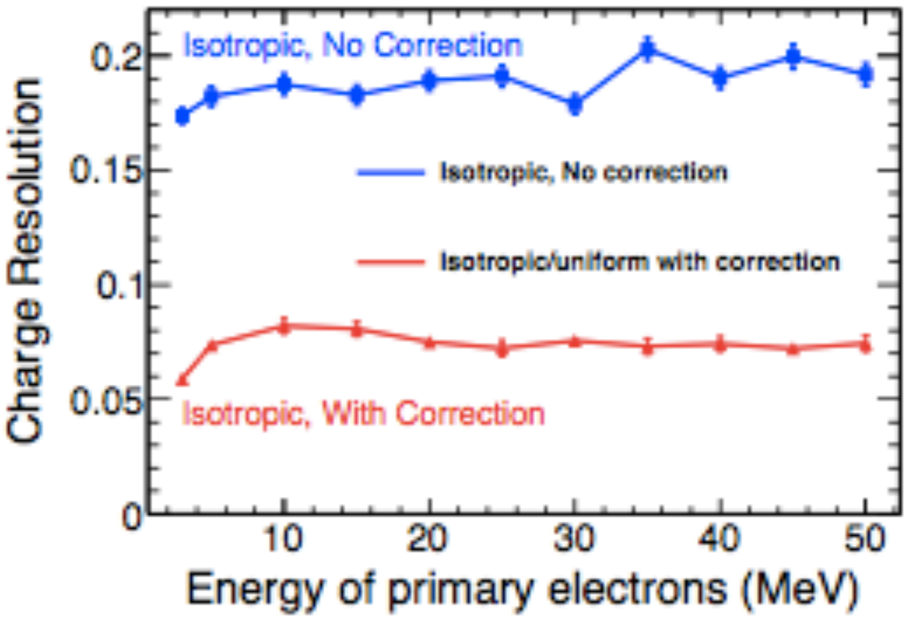
Example event display for 30 MeV electron
(μBooNE geometry)

- energy resolution?
- vertex resolution?
- directional resolution?
- detection & reconstruction efficiency?

much of this can be addressed at some level with simulation... but simulation needs to be *validated* with data

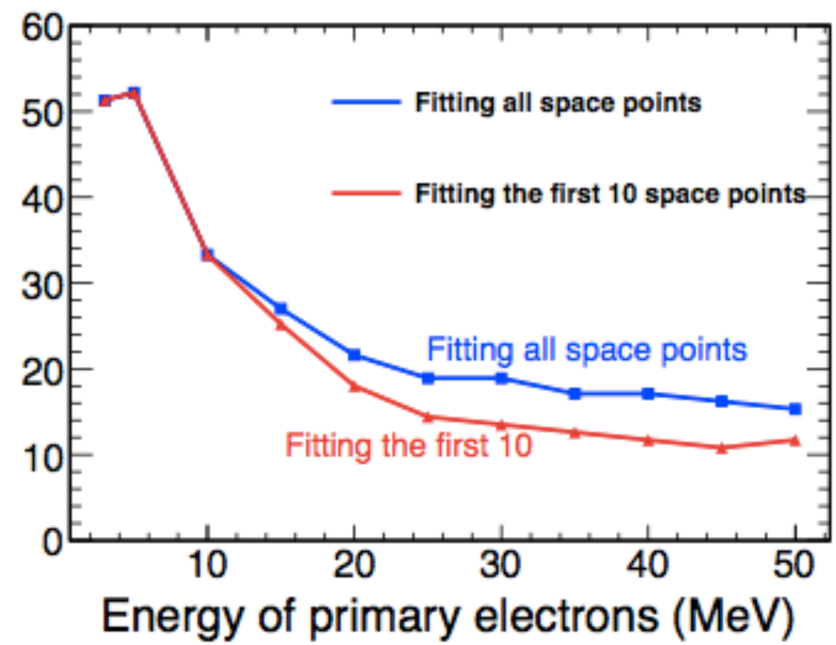
LArSoft Low-Energy Event studies (Z. Li)

Preliminary studies w/MicroBooNE geometry: looks somewhat worse than Icarus paper



using charge in the collection plane; drift correction using MC truth

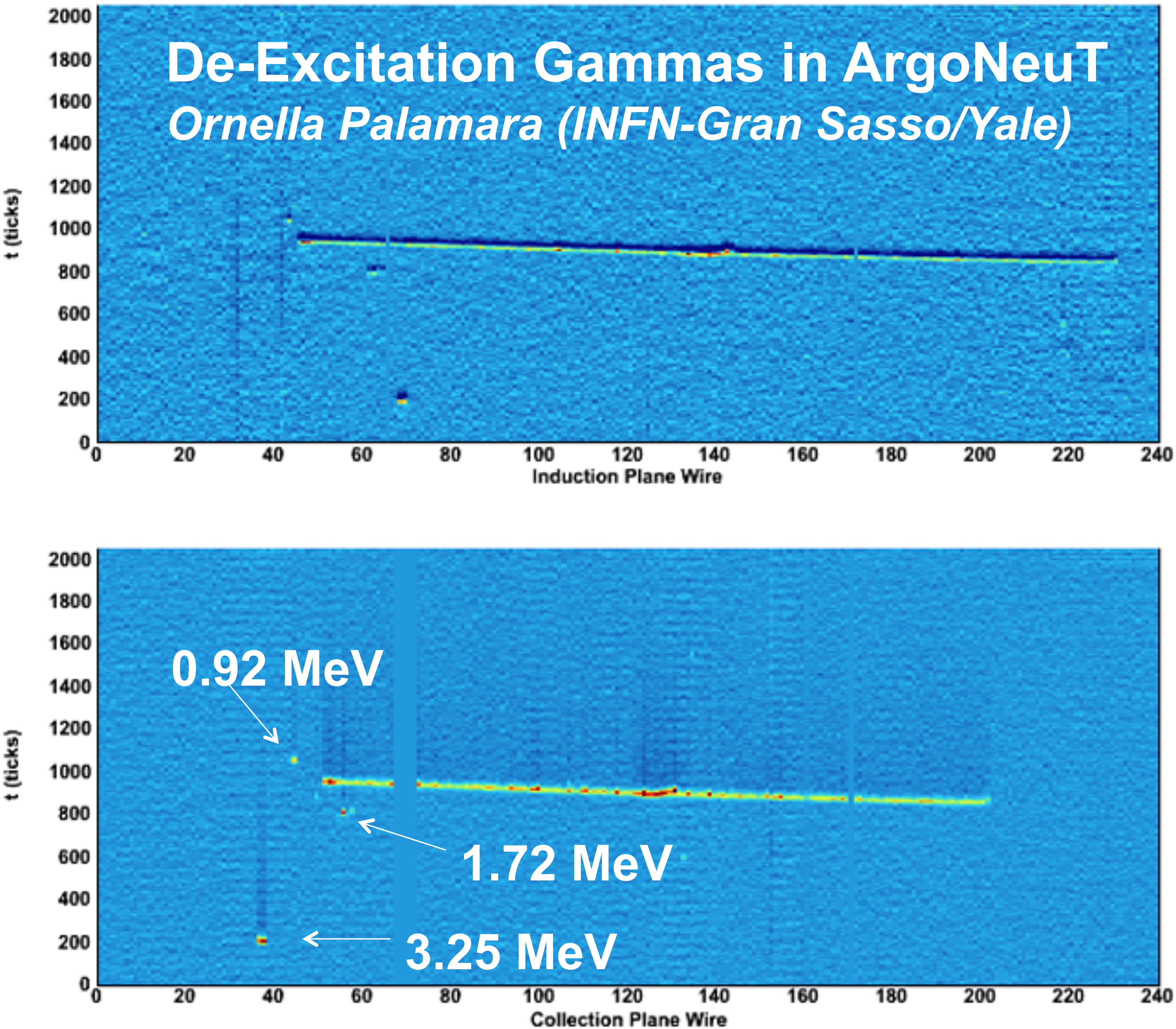
Direction resolution (degrees)



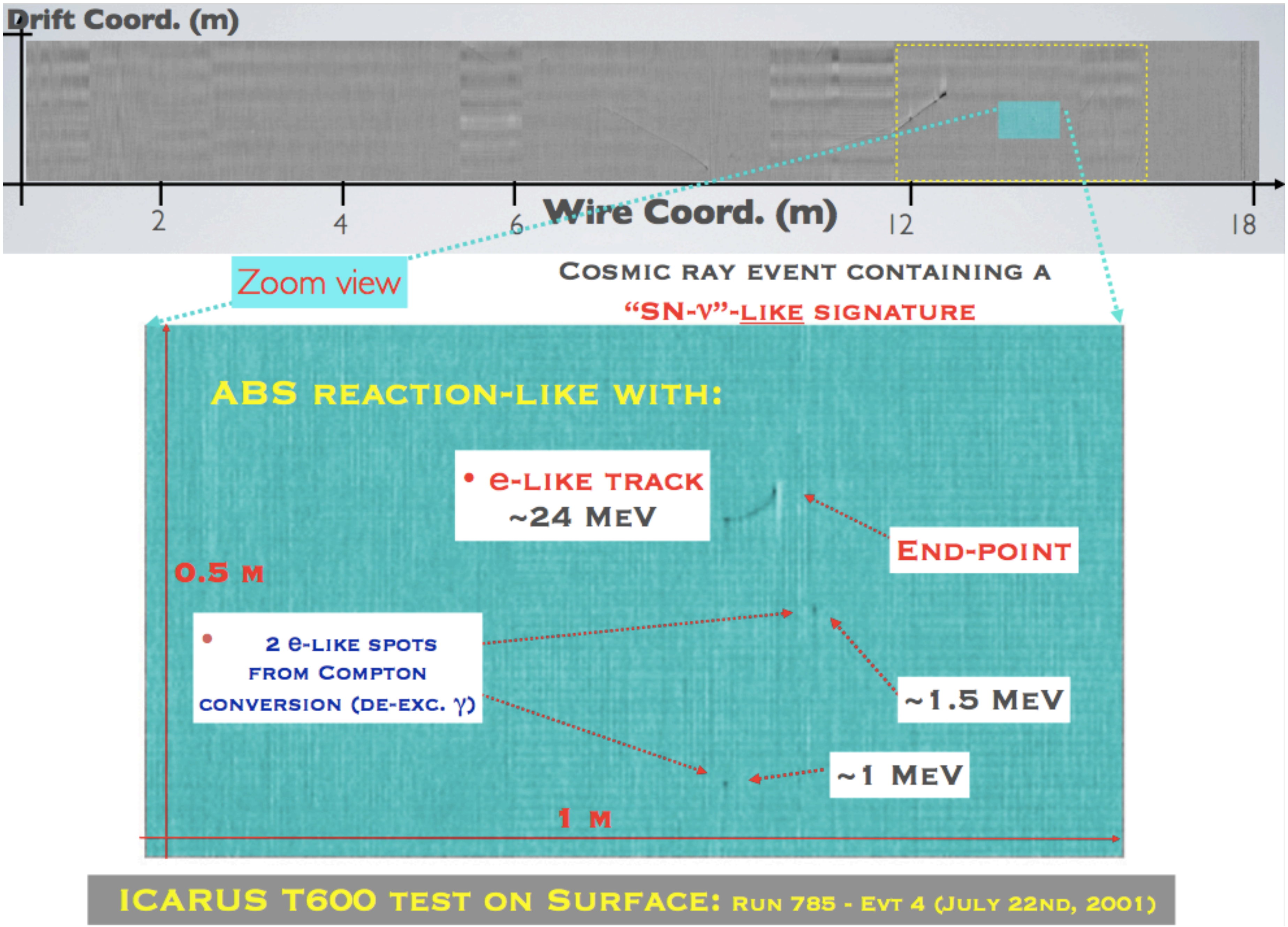
Preliminary

De-Excitation Gammas in ArgoNeuT

Ornella Palamara (INFN-Gran Sasso/Yale)



From Flavio Cavanna (SNS workshop, May 2012)



SNOwGLoBES package contents

- **driving script**
- **data files:**
  - cross-section files for O, Ar, C, Pb (+...)
  - smearing and efficiency files for several detector configurations (100kt, LAr, scint, HALO)
  - example flux file(s)
- **example plotting scripts**
- **documentation w/refs**

A. Beck, F. Beroz, R. Carr, KS, W. Johnson, A. Moss, D. Reitzner, D. Webber, R. Wendell
A. Dighe, H. Duan, A. Friedland, J. Kneller

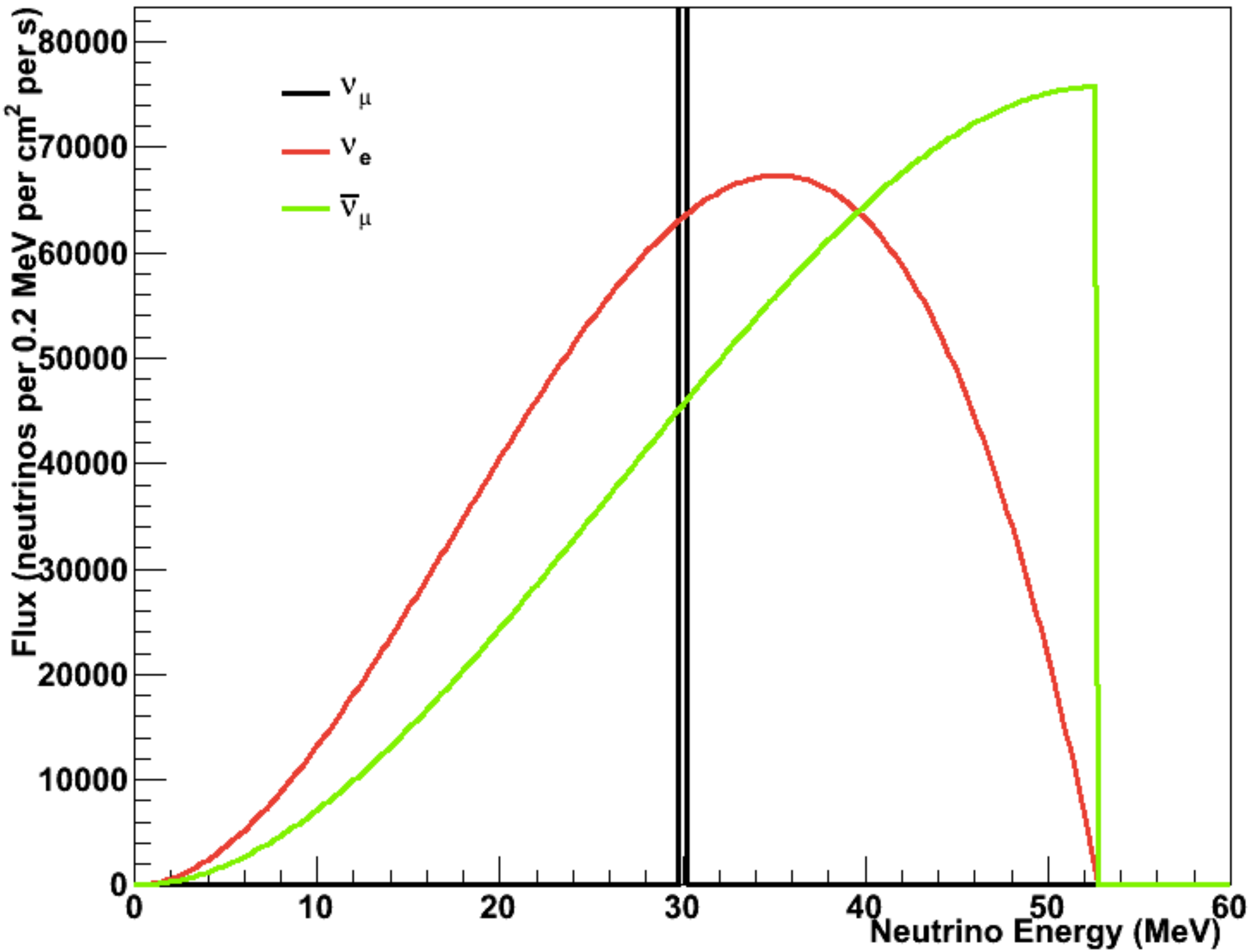
- **Smearing and efficiency files provided are based on:**
  - published information (resolutions etc.), reasonable assumptions, simulation output where available
- **Users (typically) would provide their own fluxes**
- **Users could use the packaged detector smearing datafiles, or provide their own**

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

- **Test version available**

SNS Flux for SNOwGLoBES

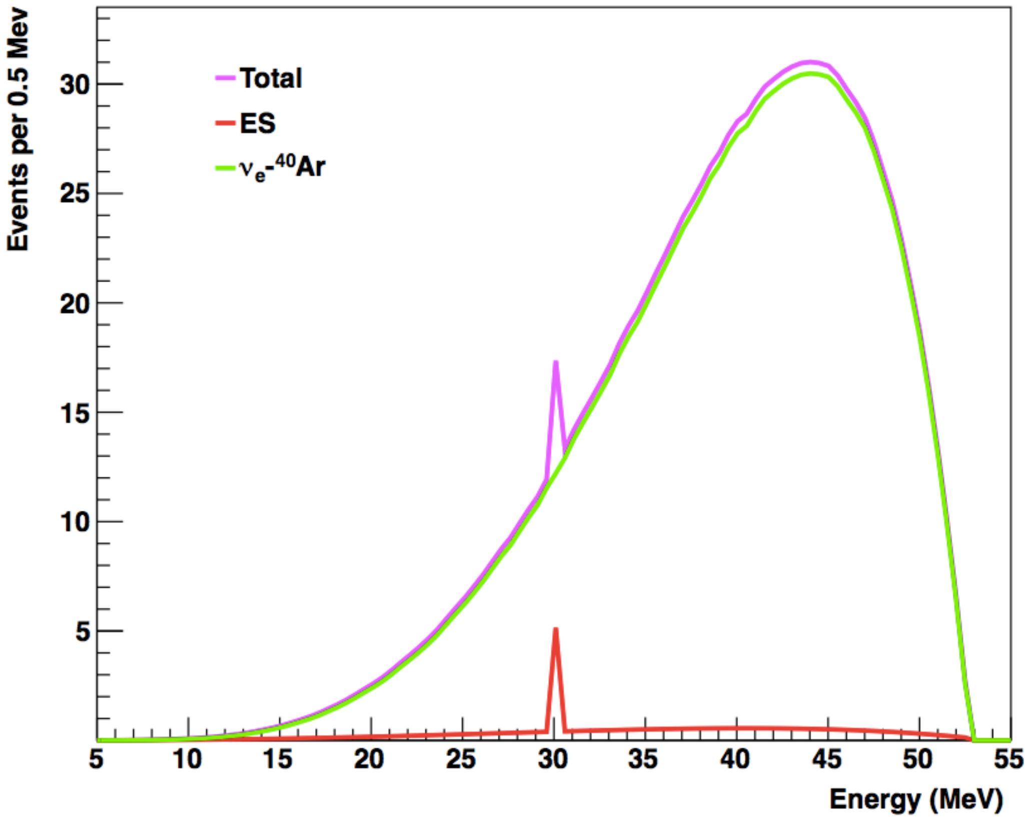
Normalized to 10^7 per cm^2 per s per flavor at 20 m



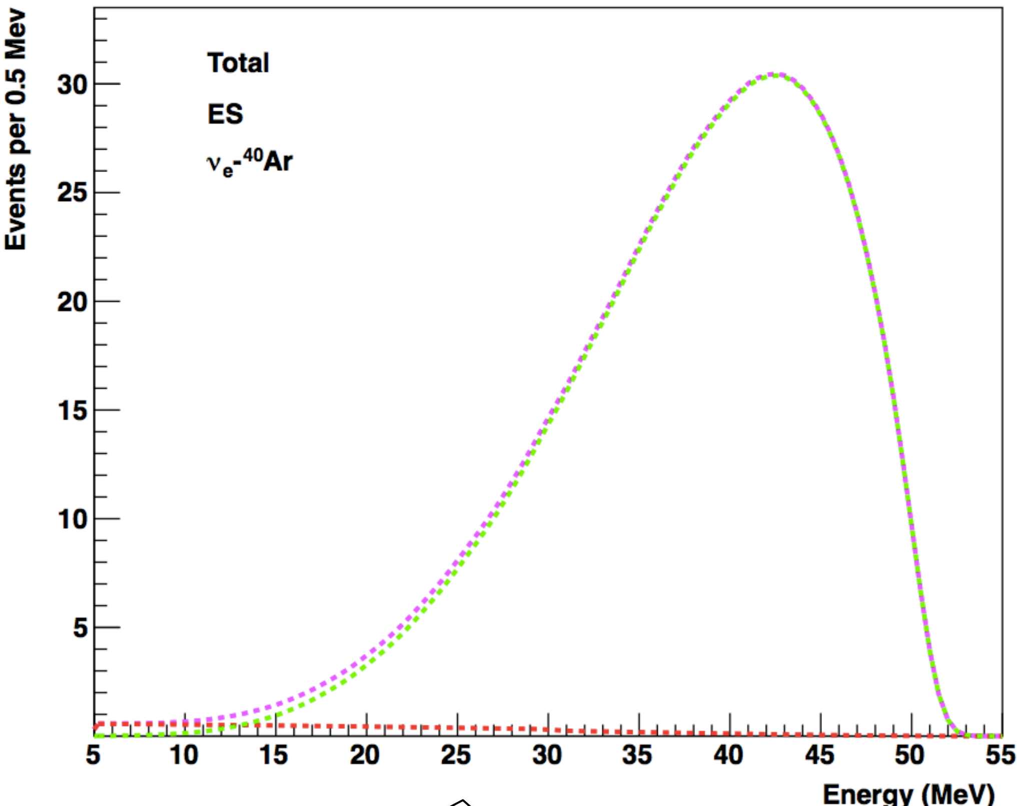
Event rates for argon at the SNS

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)

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 $\alpha \neq \beta$

⇒ 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

Combination of targets will help

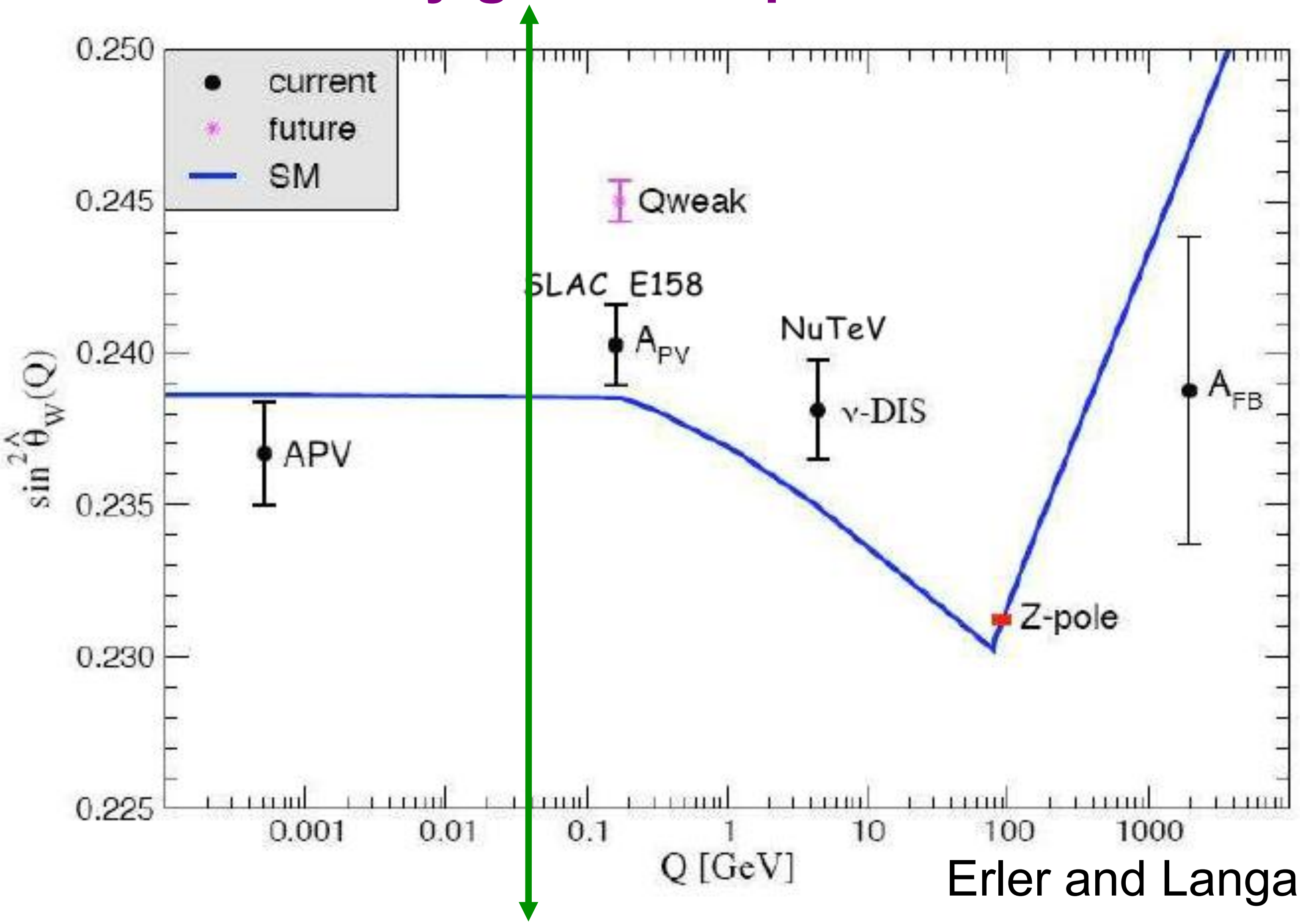
(idea from Yuri Efremenko)

$$\text{rate} \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

For 1% uncertainty on the *ratio* of rates in two different targets, get:

^{40}Ar/^{20}Ne	2.6%
^{132}Xe/^{20}Ne	1.5%
^{132}Xe/^{40}Ar	3.9%

First-generation measurement not competitive:
(assuming ~10% systematic error on rate)
... could eventually get to few percent **(limited by nuclear physics)**



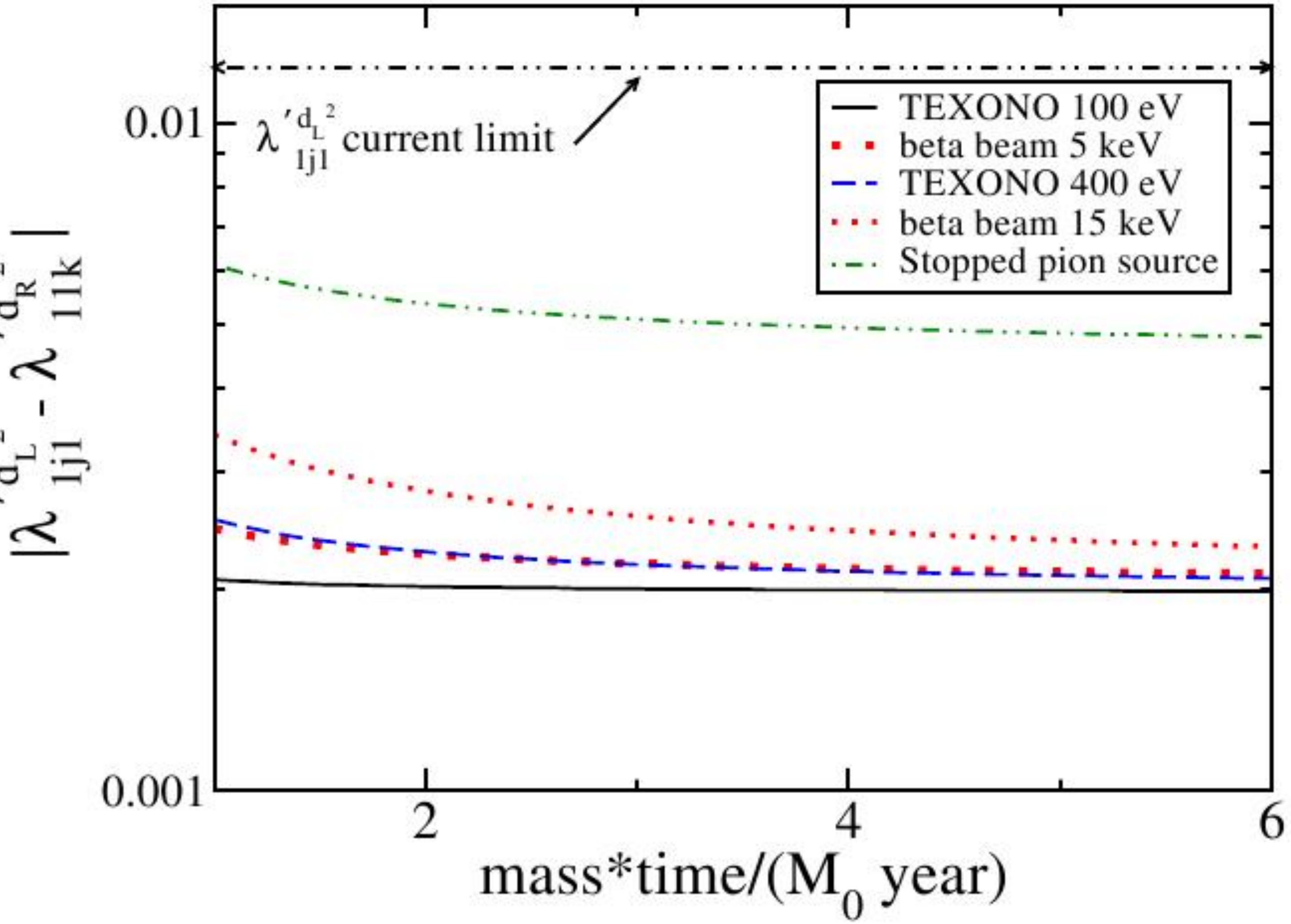
Erler and Langacker, PDG

However note it's a unique channel and independent test

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



Neutrino magnetic moment

Prediction of Standard Model: $\mu_\nu \sim 10^{-19} \mu_B \left(\frac{m_\nu}{1 \text{ eV}} \right)$

but extensions predict larger ones

Current best experimental limits:

Best limit from lack of distortion of ν-e elastic scattering x-scn , for reactor anti-ν_e's (GEMMA)

For ν_μ, best limit is from LSND ν_μ-e scattering

VALUE (10^{-10} μ_B)	CL%	DOCUMENT ID		TECN	COMMENT
< **0.32**	90	[122] BEDA	10	CNTR	Reactor $\overline{\nu}_e$
< **6.8**	90	[123] AUERBACH	01	LSND	$\nu_e e$, $\nu_\mu e$ scattering
< **3900**	90	[124] SCHWIENHO...	01	DONU	$\nu_\tau e^- \rightarrow \nu_\tau e^-$

Astrophysical limits:
(red giant cooling, SN1987A) $\mu_\nu < 10^{-10} - 10^{-12} \mu_B$

Magnetic moment effect on the coherent NC scattering rate

P. Vogel & J. Engel, PRD 39 (1989) 3378

SM cross-section:

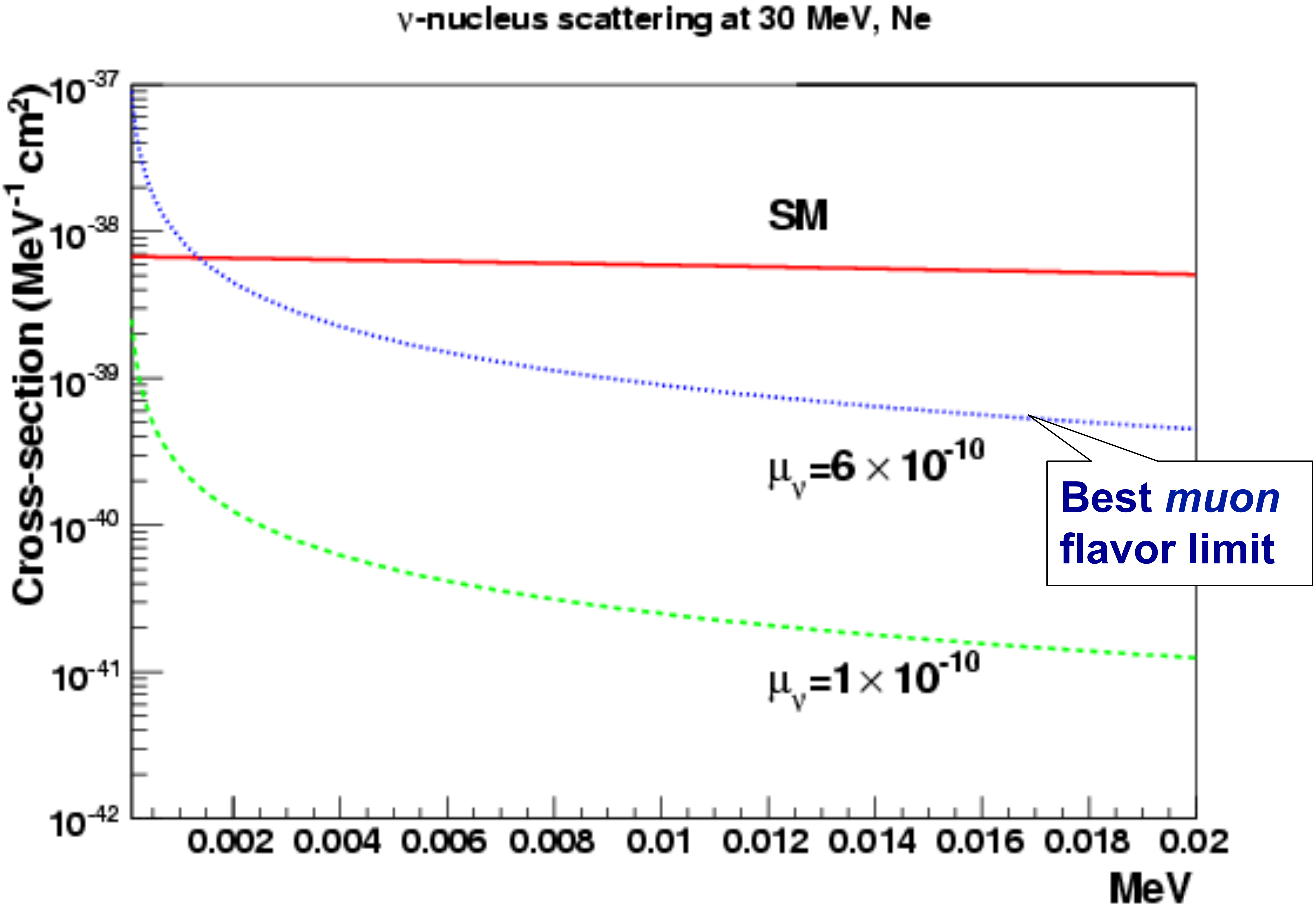
$$\frac{d\sigma}{dE} = \frac{G^2}{\pi} M \left(1 - \frac{ME}{2k^2}\right) \frac{N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

Magnetic cross-section:

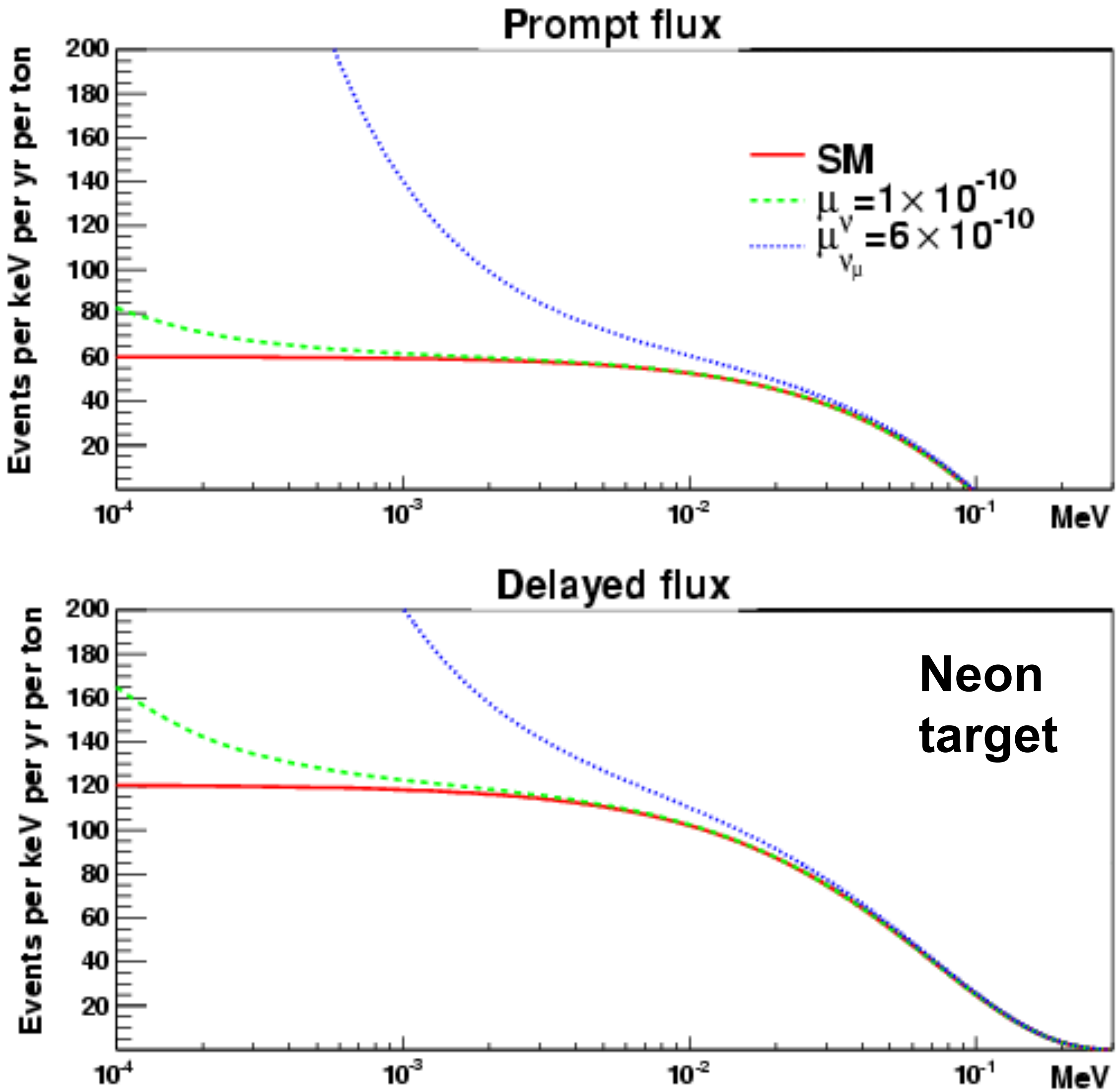
$$\frac{d\sigma}{dE} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2} \left(\frac{1 - E/k}{E} + \frac{E}{4k^2}\right)$$

(factor Z^2 instead of Z for electrons)

Cross-sections for 30 MeV ν



Differential yield at the SNS: muon and electron flavors



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

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

Experimentally hard! But maybe doable

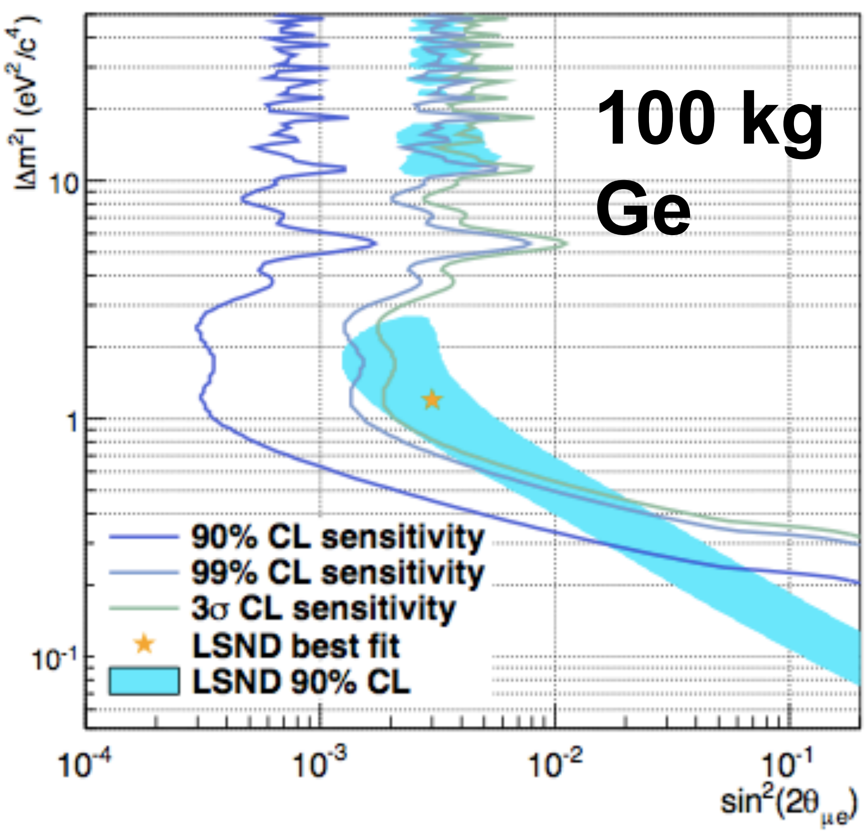
Oscillations to sterile neutrinos w/CENNS

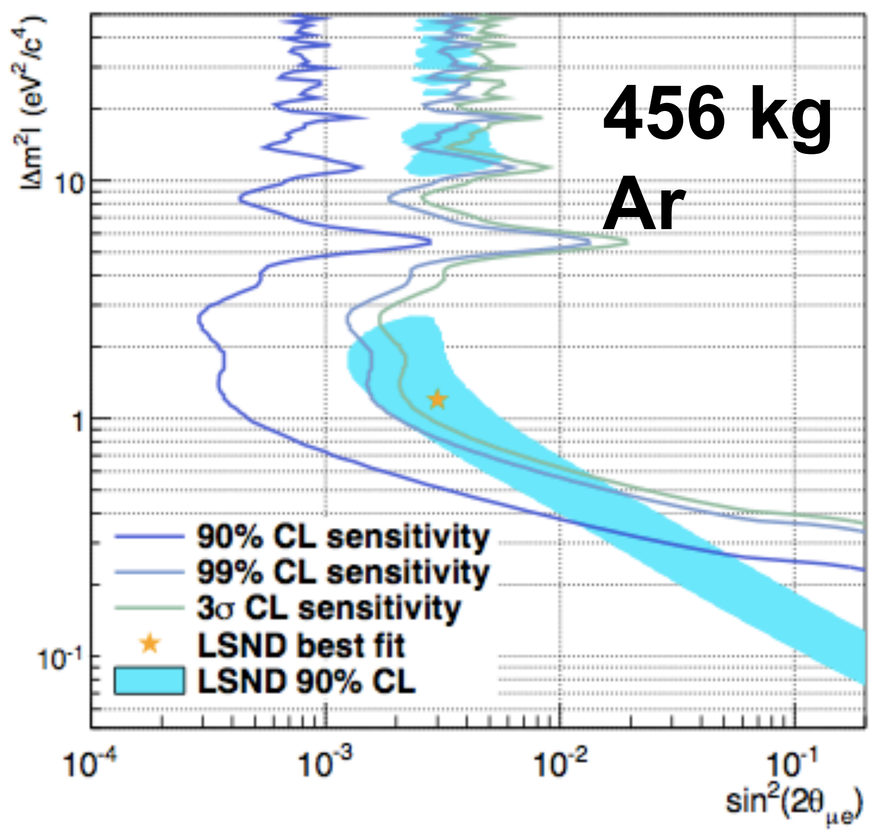
(NC is flavor-blind)

A. Anderson et al., PRD86 (2012) 013004, arXiv:1201.3805

Multi-cyclotron sources at different baselines (20 & 40 m)

look for deficit and spectral distortion





Summary of physics reach for νA scattering

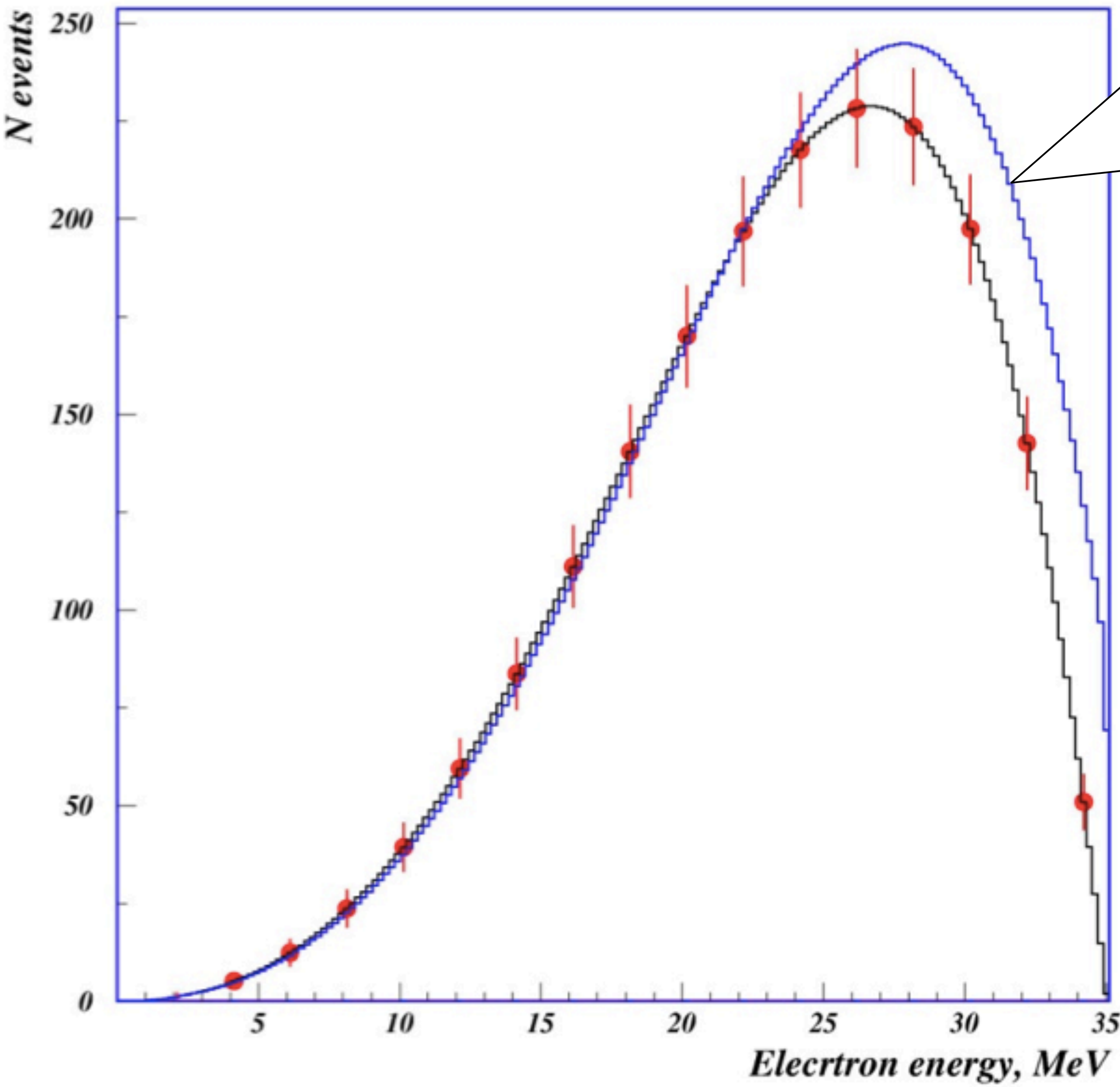
Basically, any deviation from SM x-scn is interesting...

- 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; need low energy sensitivity
- (Sterile oscillations):
  hard, but also conceivable

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

- Neutron form factor:
  hard but conceivable; need good energy resolution, control of systematics

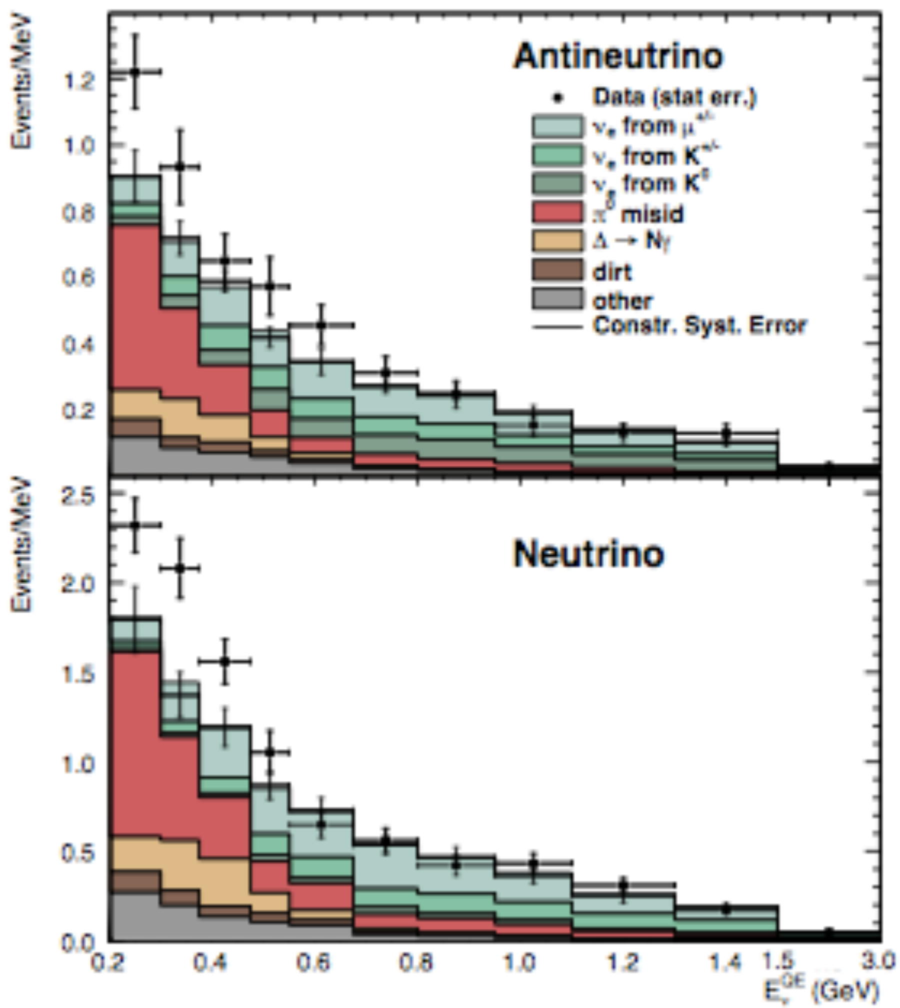
SM test from CC ν interaction on carbon

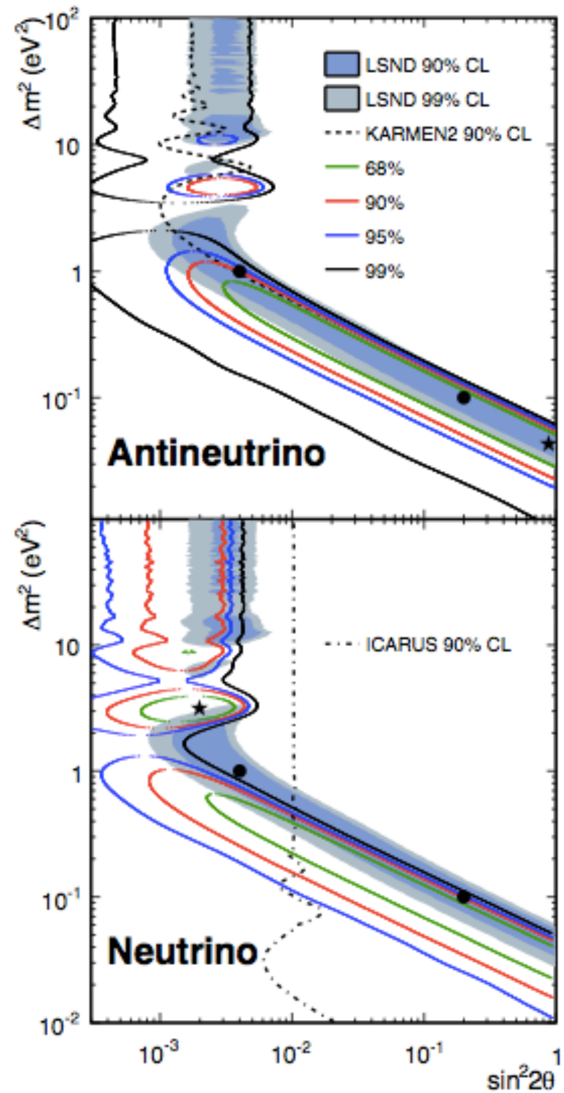


scalar & tensor admixture to V-A allowed by KARMEN

From NuSNS proposal

Latest MiniBooNE results



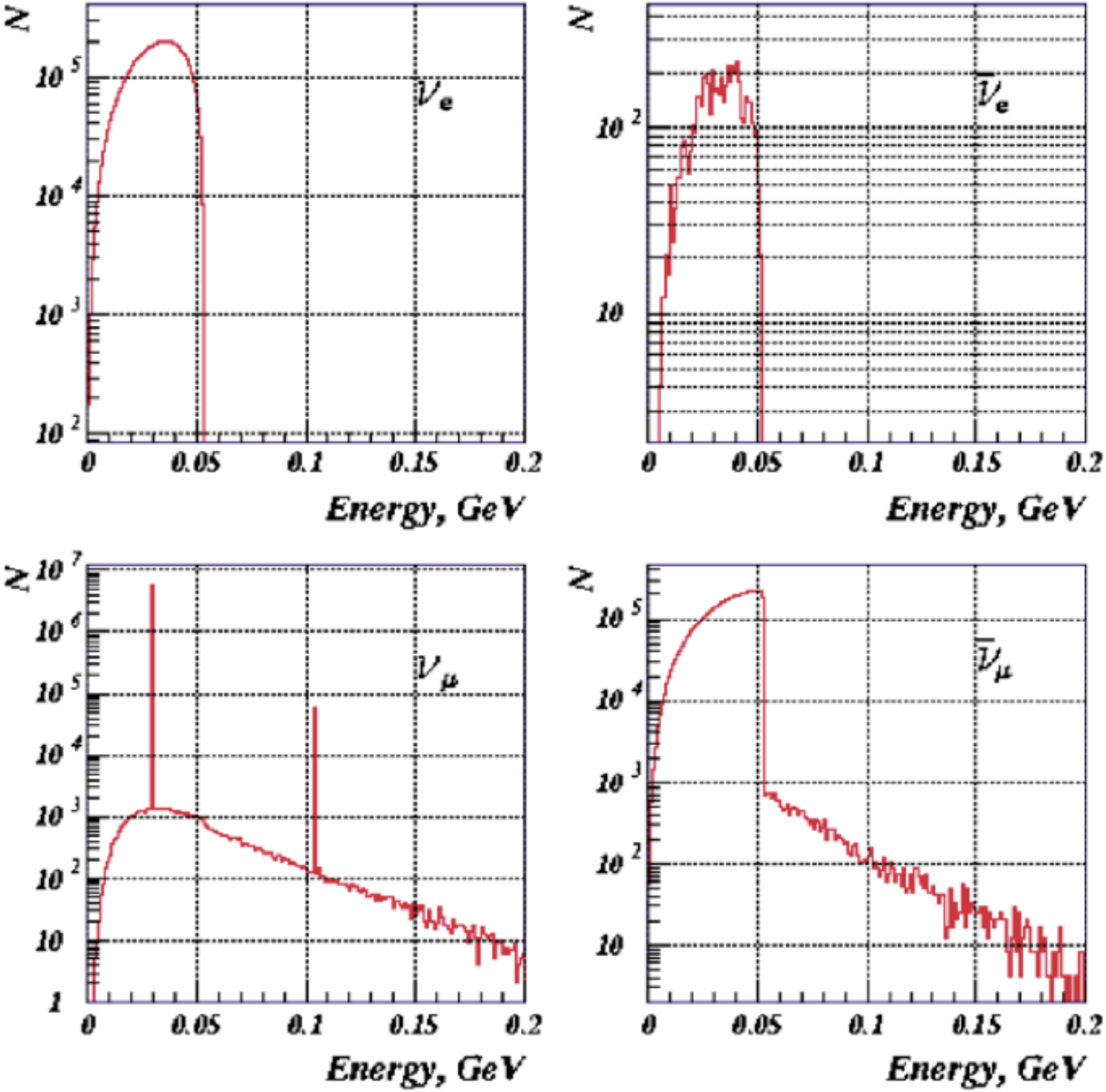


arXiv:1303.2588

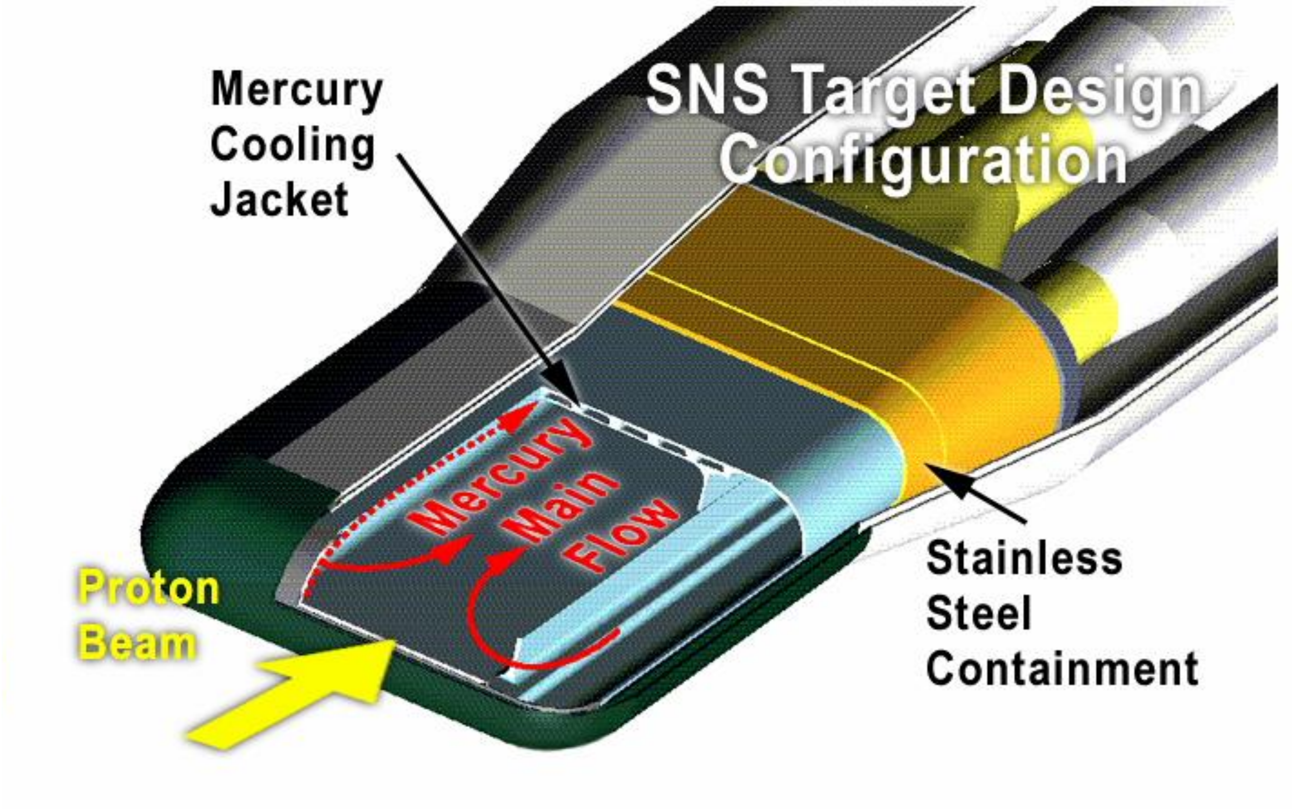
E_ν^{QE}>200 MeV

Flux calculation: clean spectrum

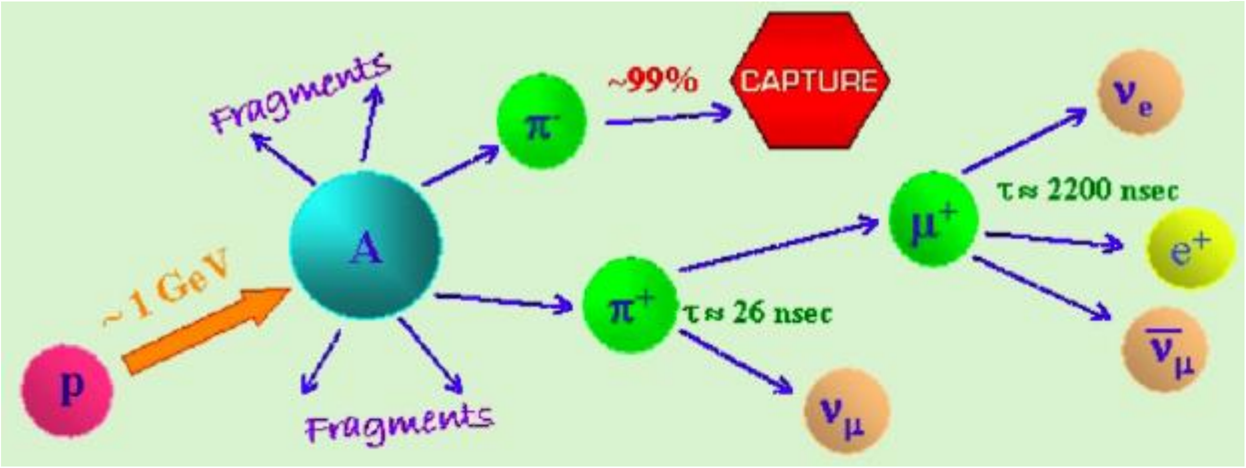
F. Avignone and Y. Efremenko, J. Phys. G: 29 (2003) 2615-2628



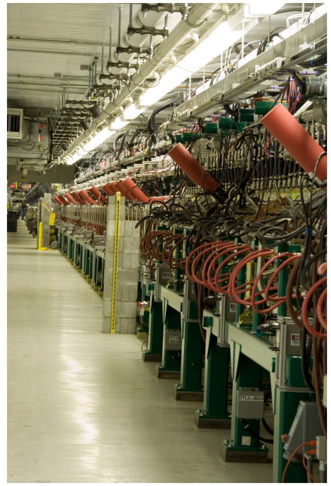
The SNS as a Stopped-Pion Neutrino Source



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



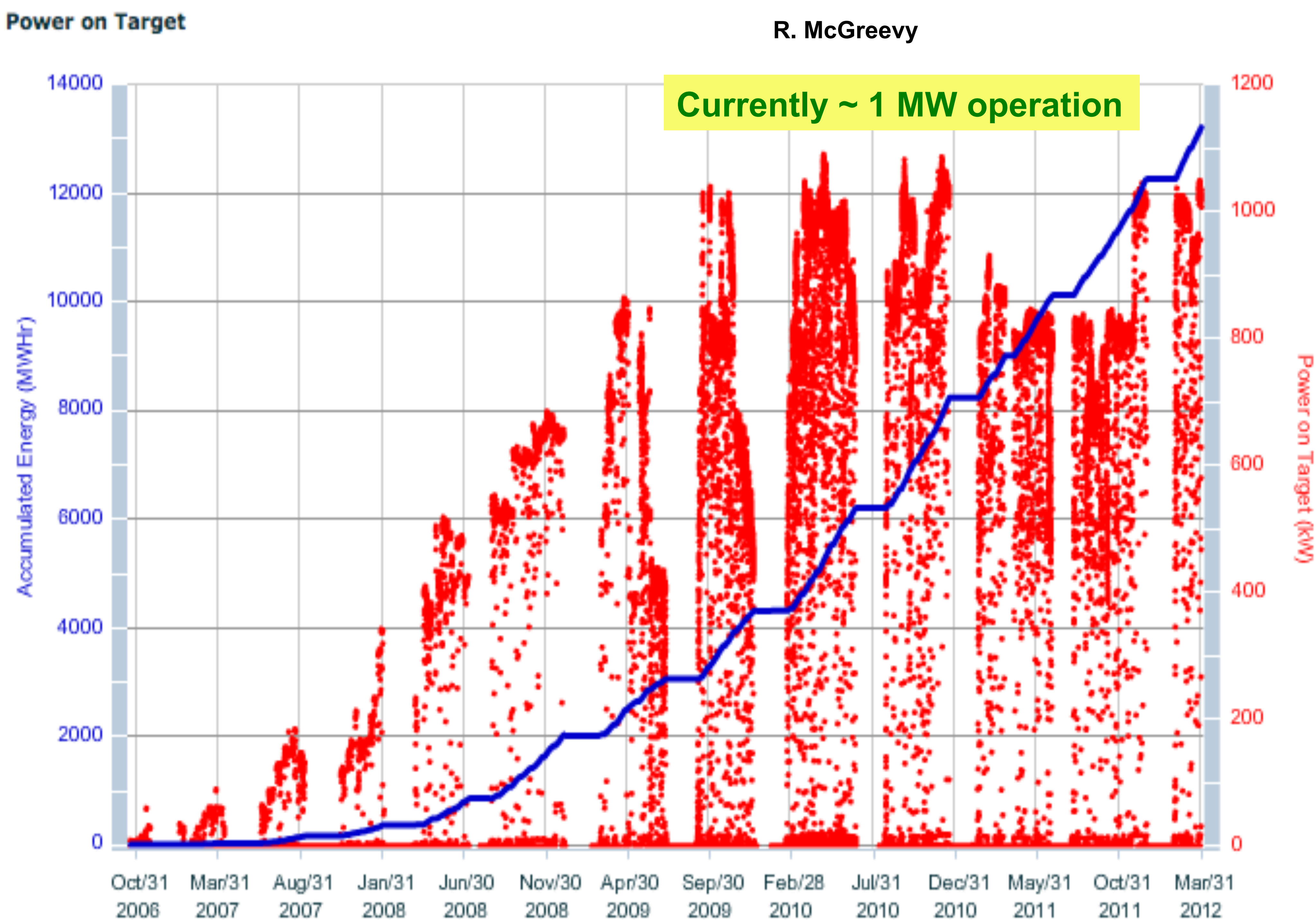
Proton linear accelerator, operation at 1.0 GeV



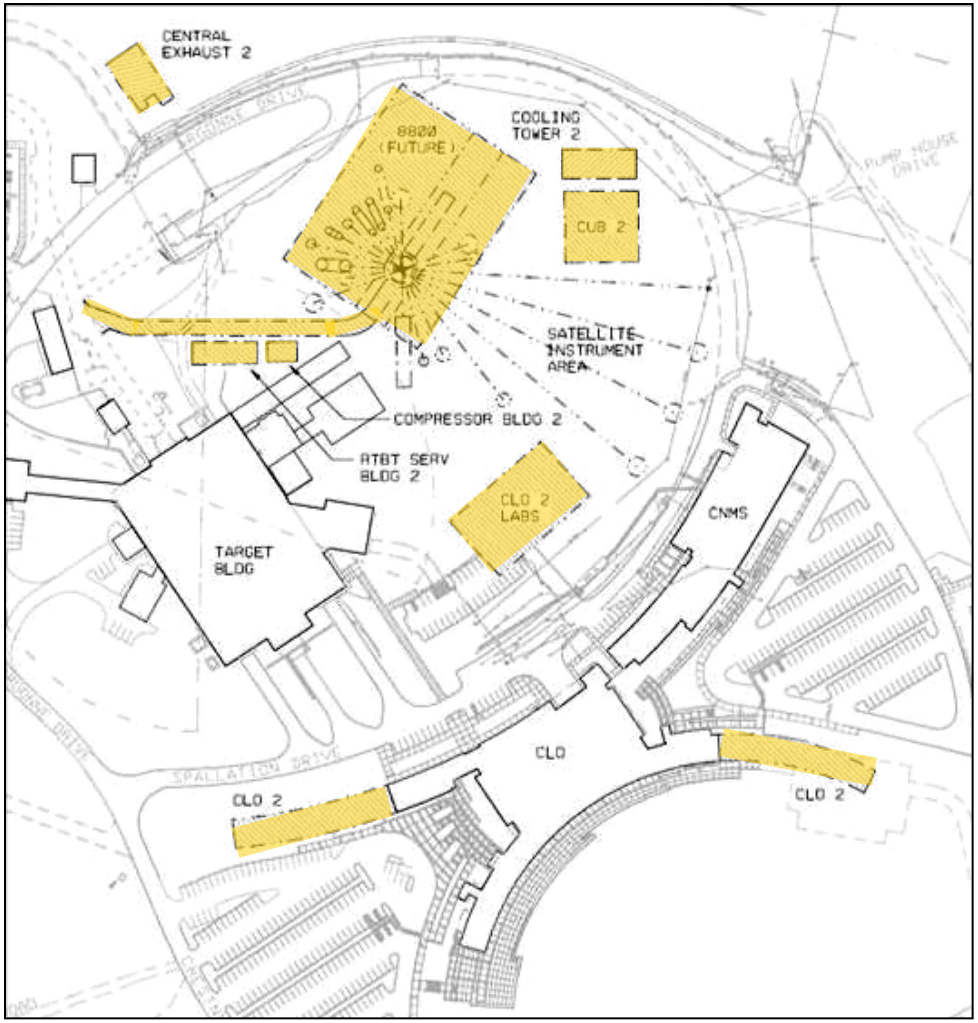
Accumulator ring, 700 ns pulse width

Proton beam bombards liquid Hg target

Energy and power on target from October 2006



SNS Second Target Station



R. McGreevy