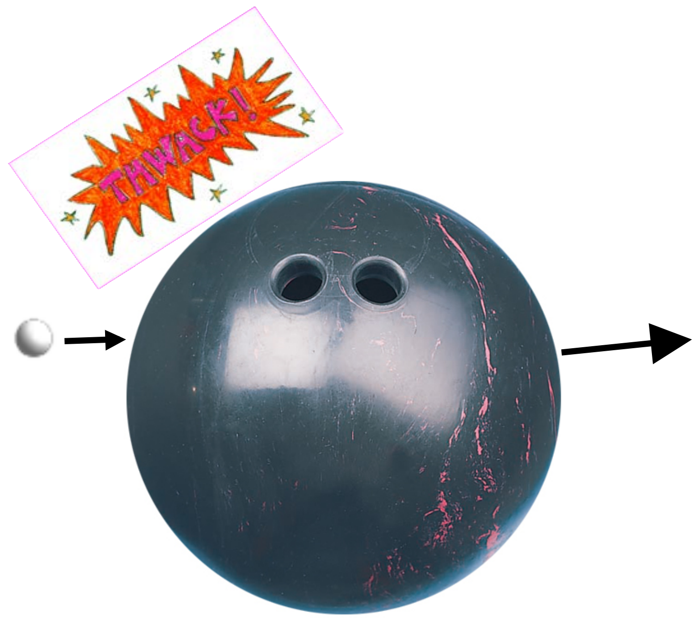
Coherent elastic neutrino-nucleus scattering at stopped-pion sources



Kate Scholberg, Duke University

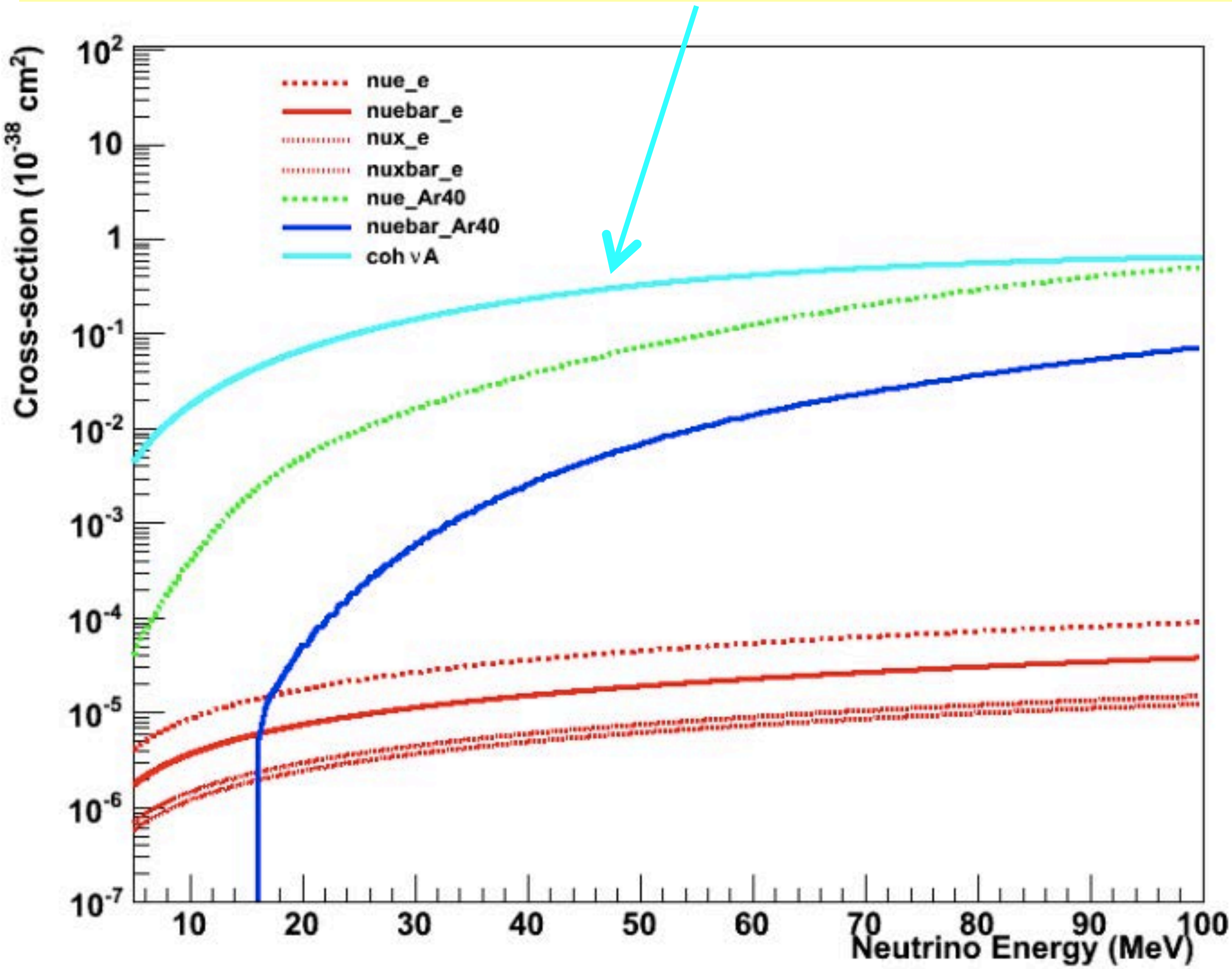
Coherent Scattering Workshop
Livermore, December 2012

Outline

- Possible sources and detectors for coherent elastic νA scattering;
  focus on stopped-pion neutrinos

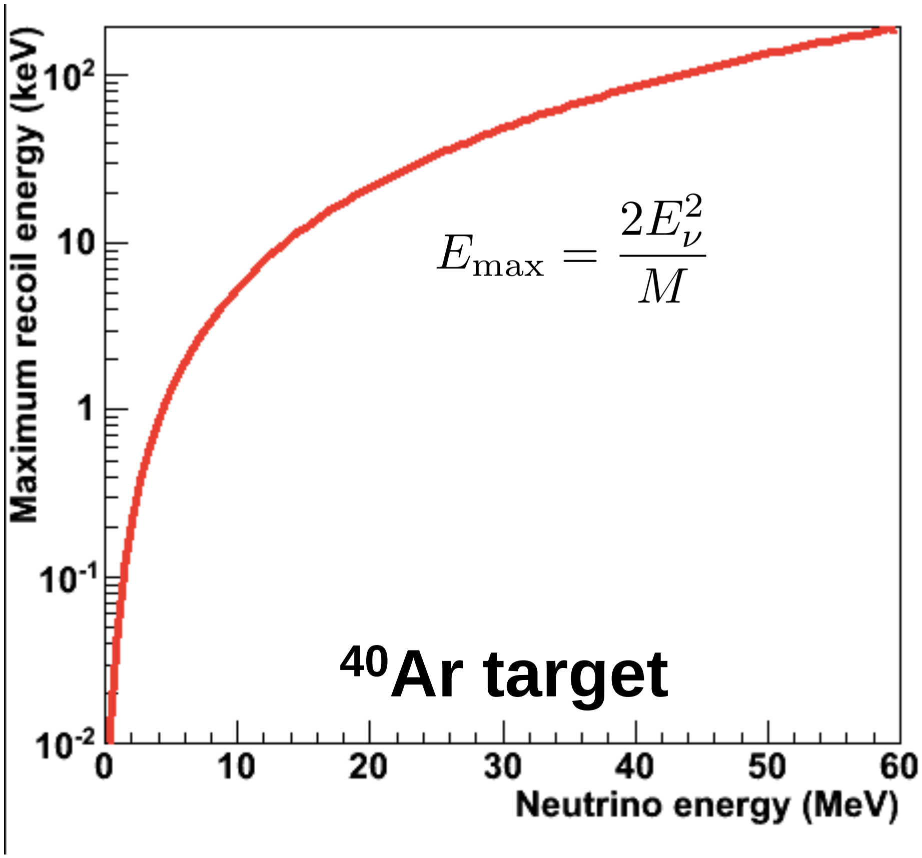
- Some physics that could be explored with stopped pion neutrinos

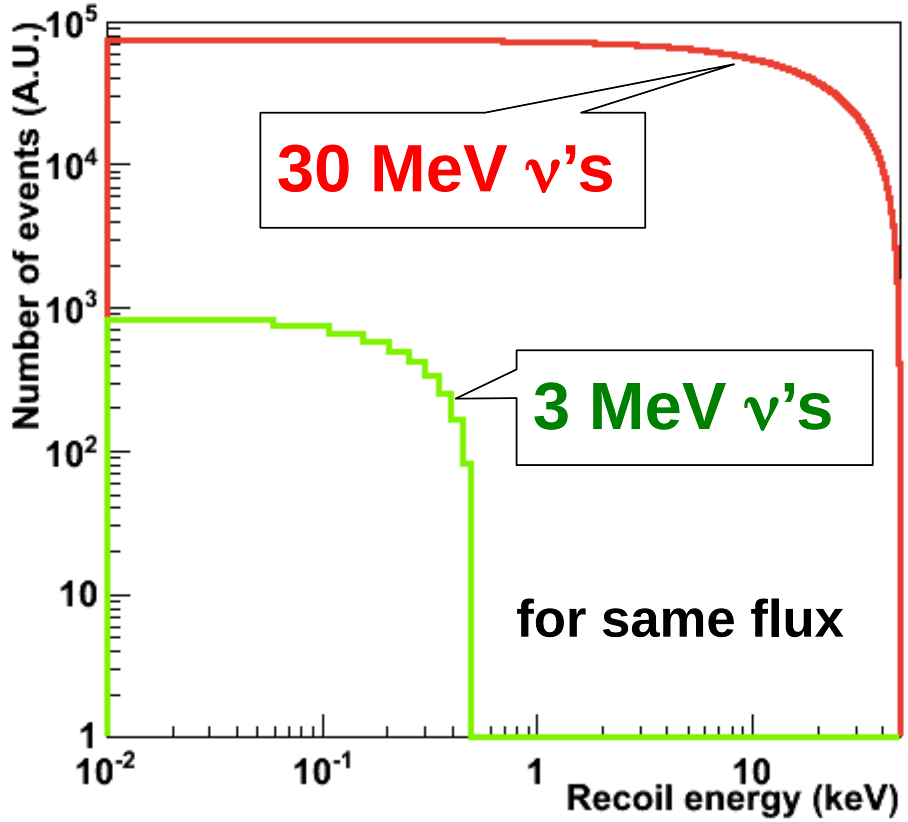
Large cross-section, increasing with energy



What do you want in a neutrino source?

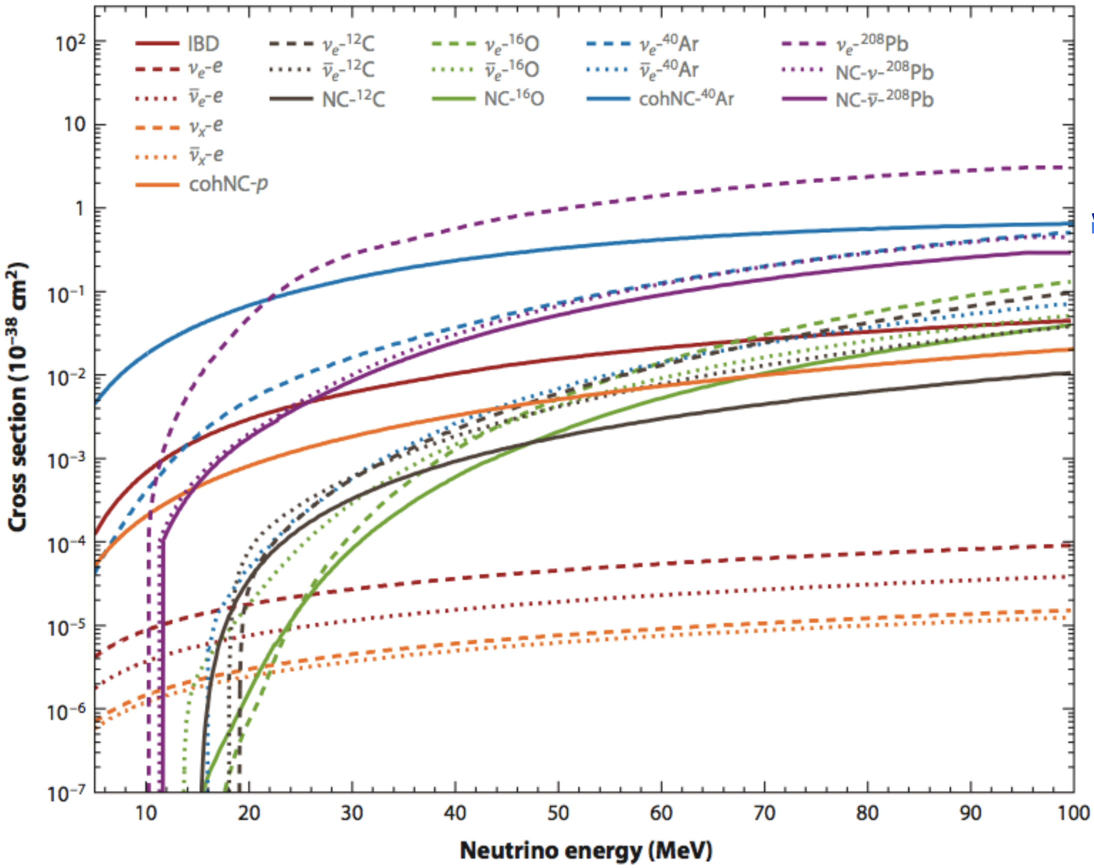
High-energy neutrinos, because both cross-section and maximum recoil energy increase with neutrino energy





... 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 $Q \lesssim \frac{1}{R}$

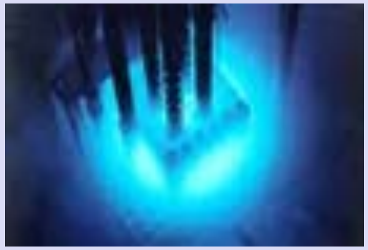
What do you want in a neutrino source?

- ✓ Neutrinos with as high energy as possible,
  but <~ 50 MeV to preserve coherence
- ✓ High flux
- ✓ Well understood spectrum
- ✓ Multiple flavors
- ✓ Pulsed source if possible, for background rejection
- ✓ Range of baselines if possible (ability to get close)
- ✓ Practical things: access, control, ...

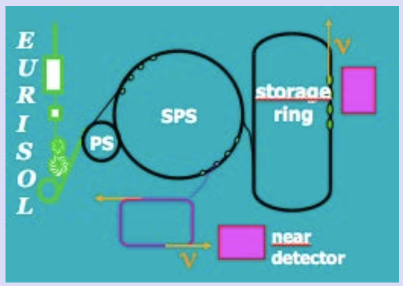
Potential sources for detection of coherent scattering

Artificial sources

reactors

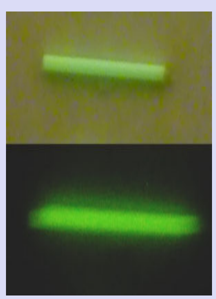


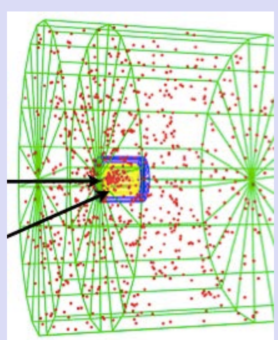
low-energy beta beams



stopped pions

radioactive sources

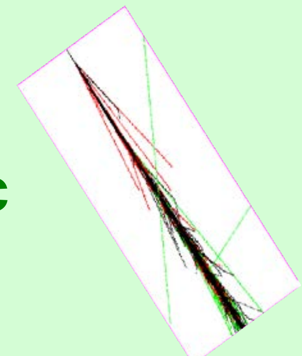


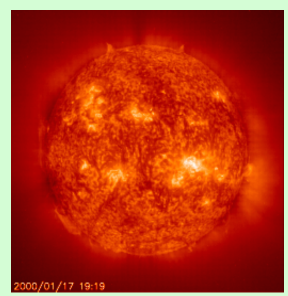


Natural sources

supernova neutrinos, burst & relic

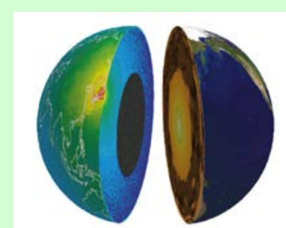
low energy atmospheric neutrinos



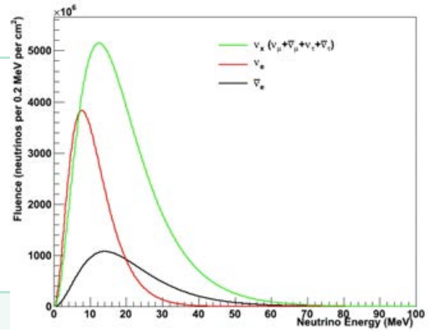


solar neutrinos

geo neutrinos

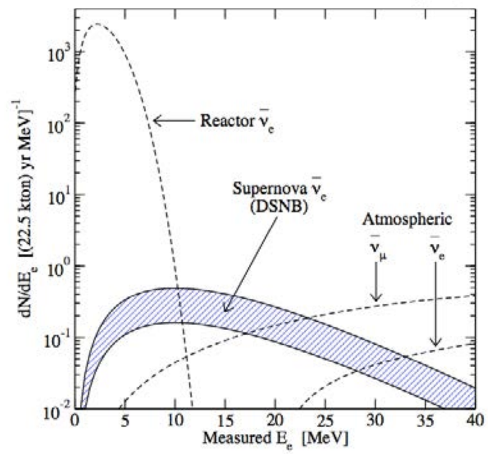


Supernova burst neutrinos



Every ~30 years in the Galaxy,~few 10’s of sec burst, all flavors

Supernova relic neutrinos

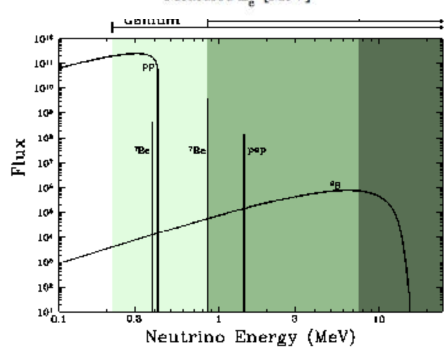


All flavors, low flux

Atmospheric neutrinos

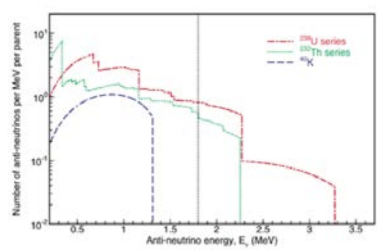
Some component at low energy

Solar neutrinos



Most flux below 1 MeV

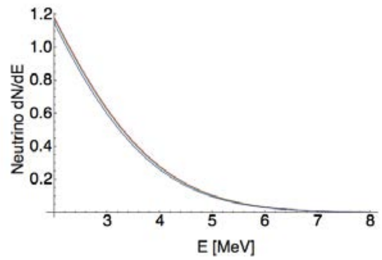
Geoneutrinos



Very low energy

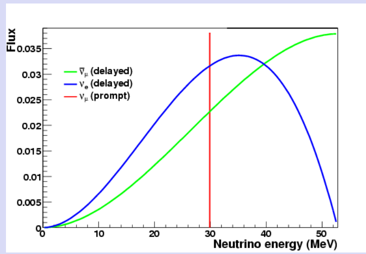
Coherent scattering eventually a bg for DM expts

Reactors



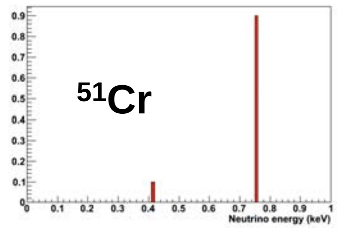
Low energy, but very high fluxes available; ~continuous source so good bg rejection needed

Stopped pions (decay at rest)



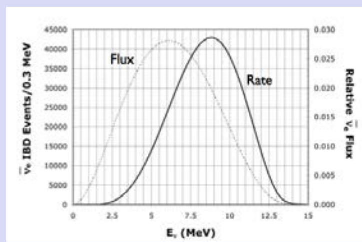
High energy, pulsed beam possible for good background rejection; possible neutron backgrounds

Radioactive sources



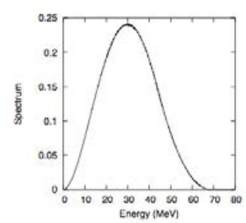
Portable; can get very short baseline; typically low energy

Beam-induced radioactive sources (IsoDAR)



Relatively compact, higher energy than reactor; not pulsed

Low-energy beta beams

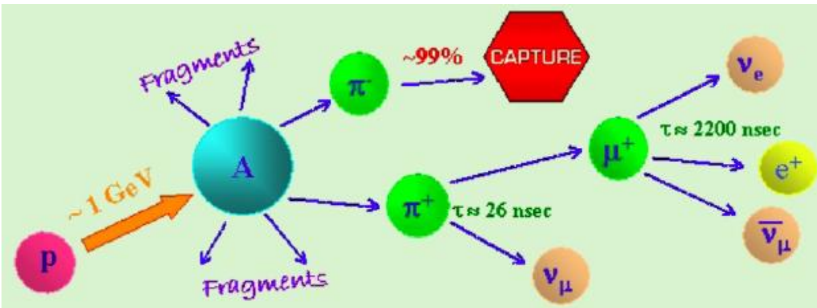


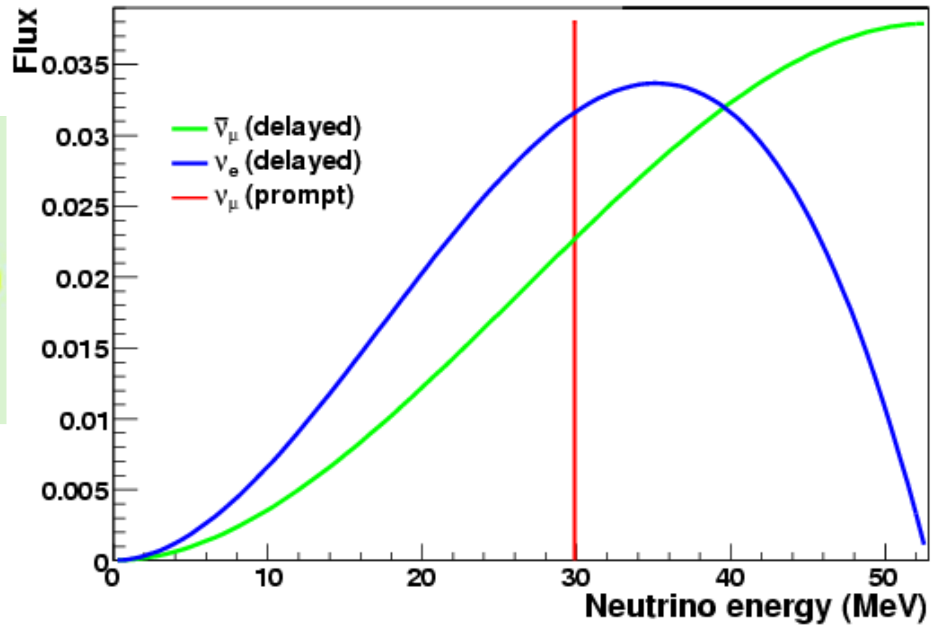
γ=10 boosted ^{18}Ne ν_e

Tunable energy, but not pulsed; does not exist yet

Source	Flux/ ν's per s	Flavor	Energy	Background rejection	Access/ control?	Exists?
Supernova	High	all	few-50 MeV	Good in burst (poor for relic)	No	Yes, ~1/30 years
Solar/geo	Low	nue/ nuebar	<15/ <few MeV	Difficult	No	Yes
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 Neutrino Sources





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

2-body decay: monochromatic 29.9 MeV ν_μ PROMPT

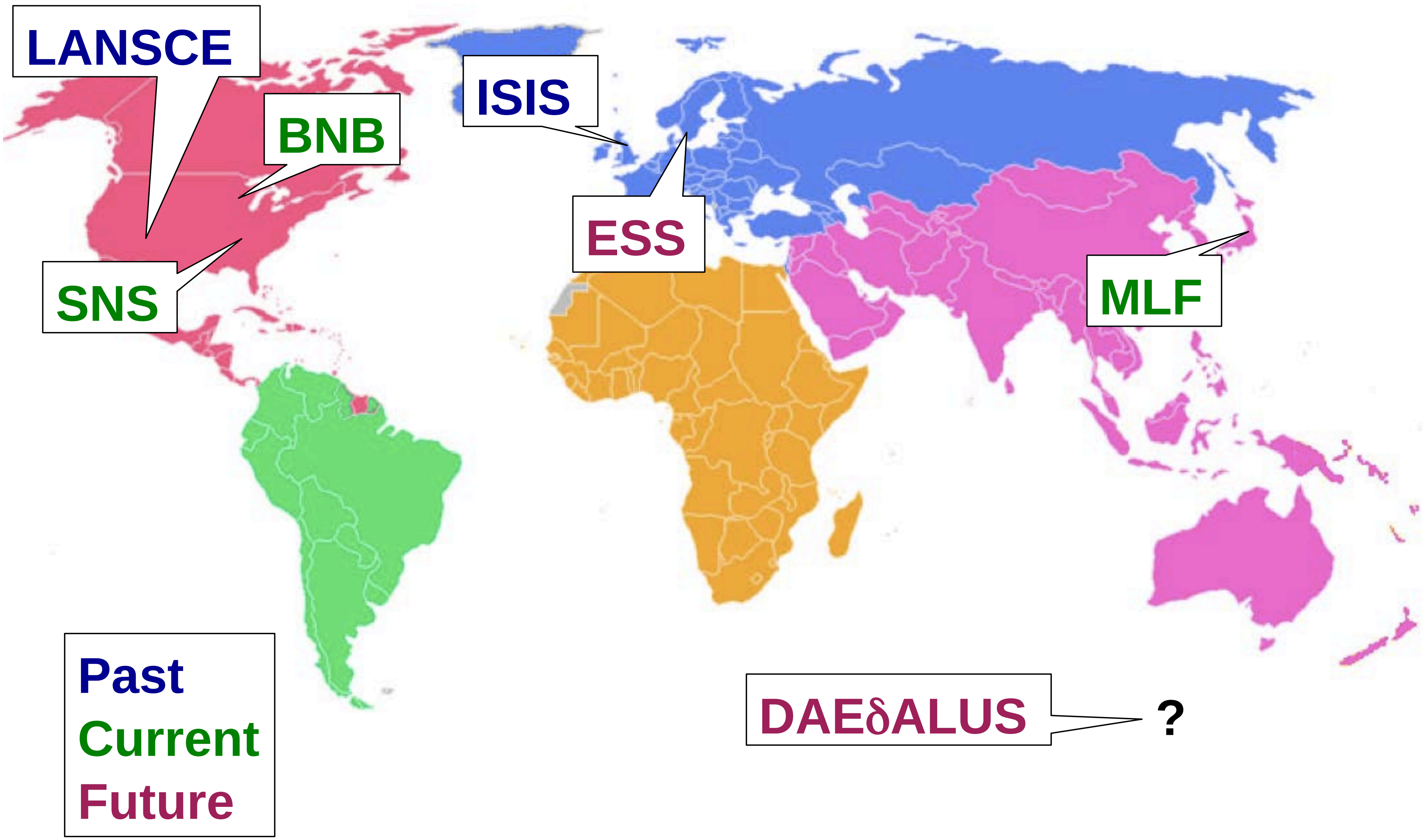
$$\downarrow$$

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

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

Stopped-Pion Sources Worldwide

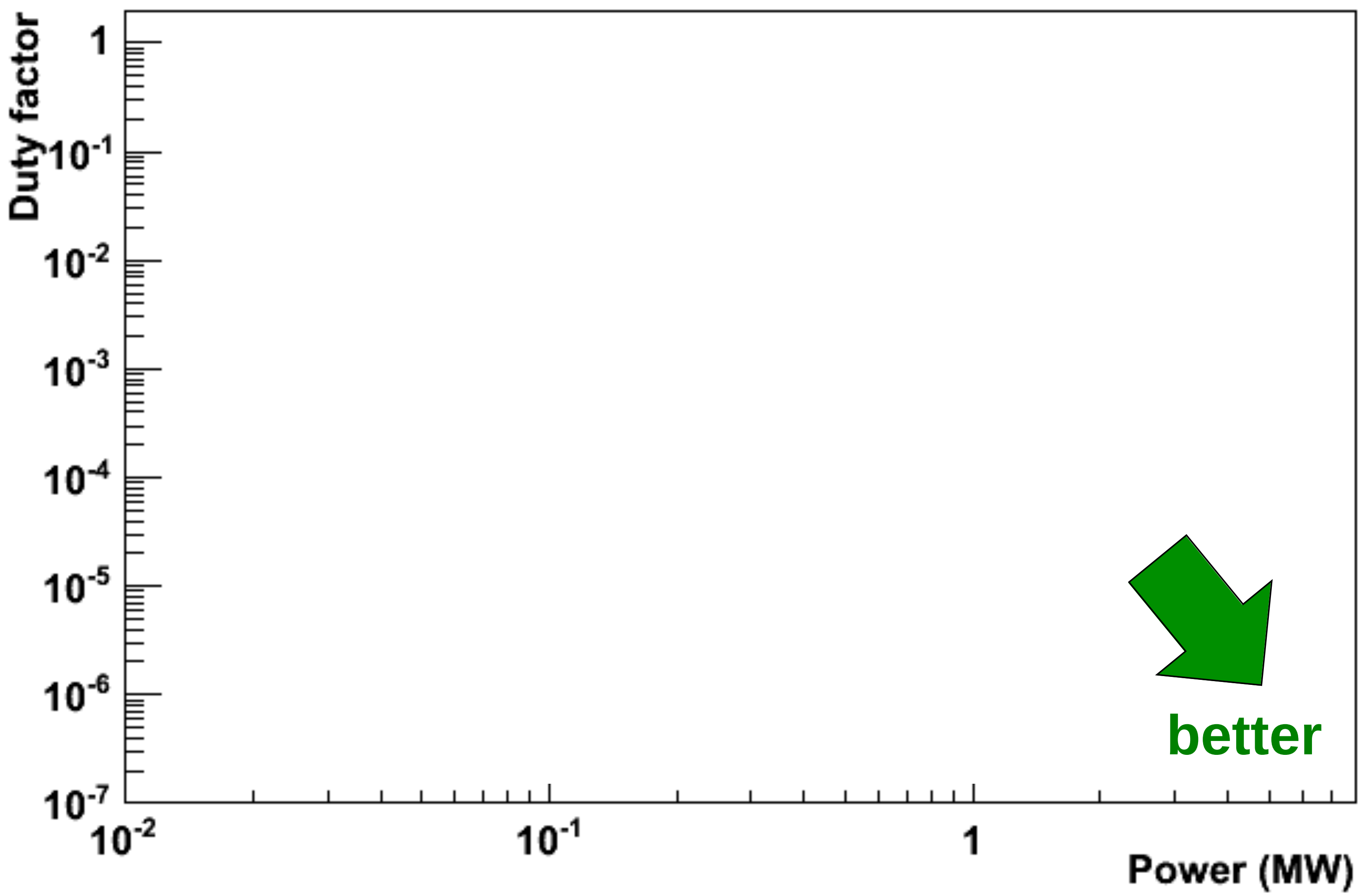


Comparison of stopped-pion neutrino sources

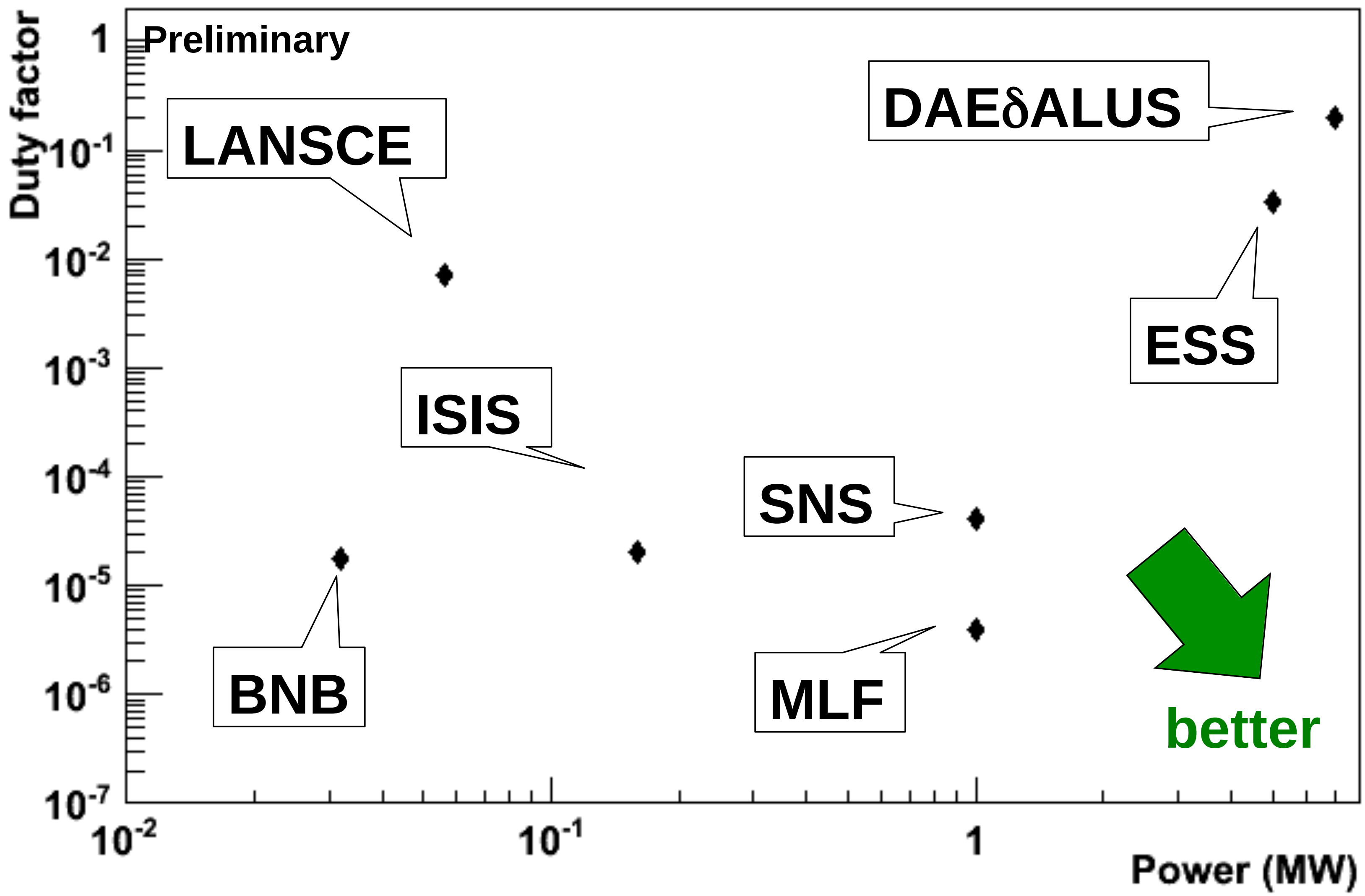
Facility	Location	Proton Energy (GeV)	Power (MW)	Bunch Structure	Rate	Target
LANSCE	USA (LANL)	0.8	0.056	600 μs	120 Hz	Various
ISIS	UK (RAL)	0.8	0.16	2×200 ns	50 Hz	Water-cooled tantalum
BNB	USA (FNAL)	8	0.032	1.6 μs	5-11 Hz	Beryllium
SNS	USA (ORNL)	1.3	1	700 ns	60 Hz	Mercury
MLF	Japan (J-PARC)	3	1	$2 \times$ 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: want bigger!
Duty factor: want smaller!



Flux ∝ power
Duty factor = T*rate (◆)

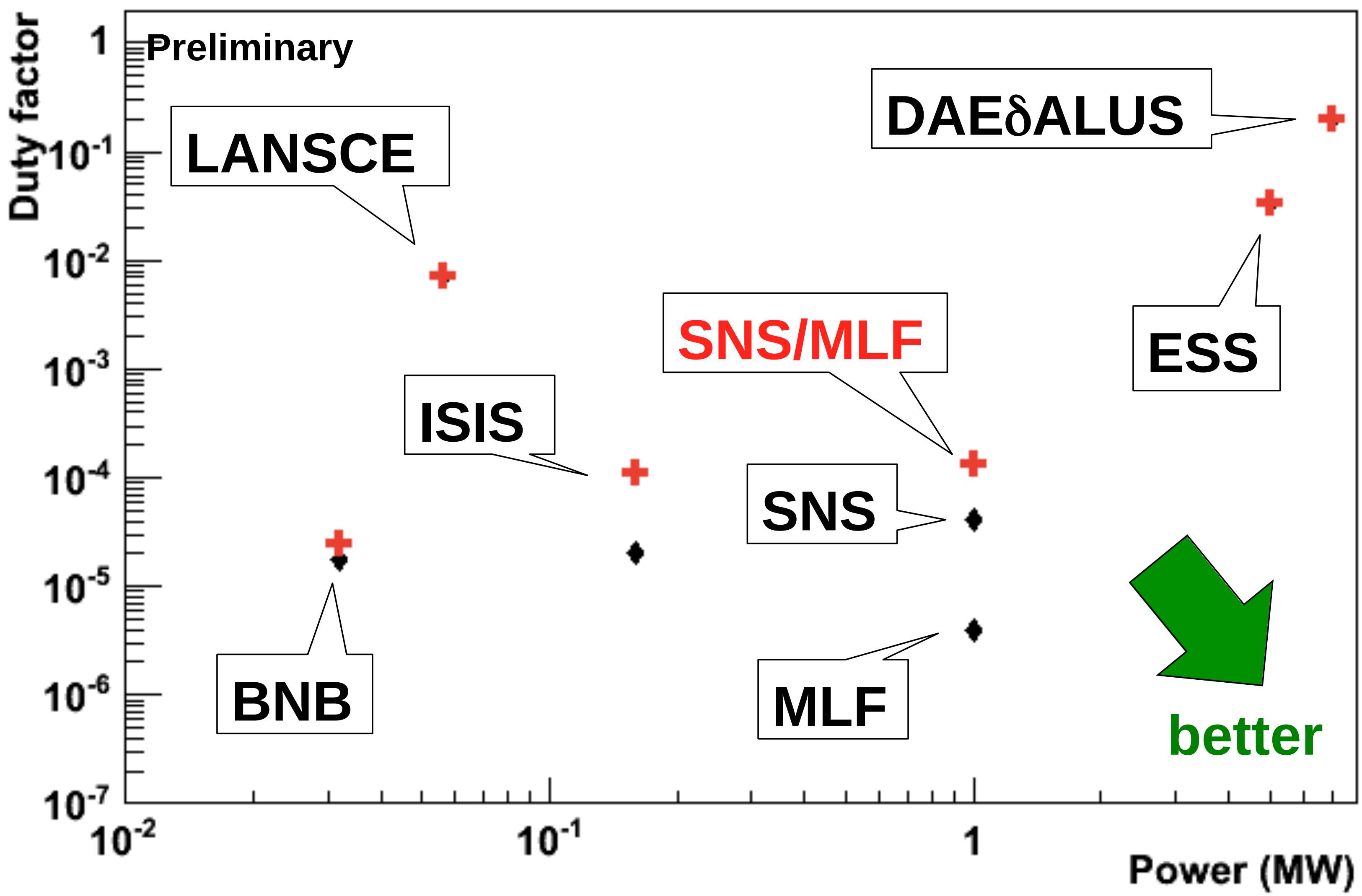


Flux $\propto$ power

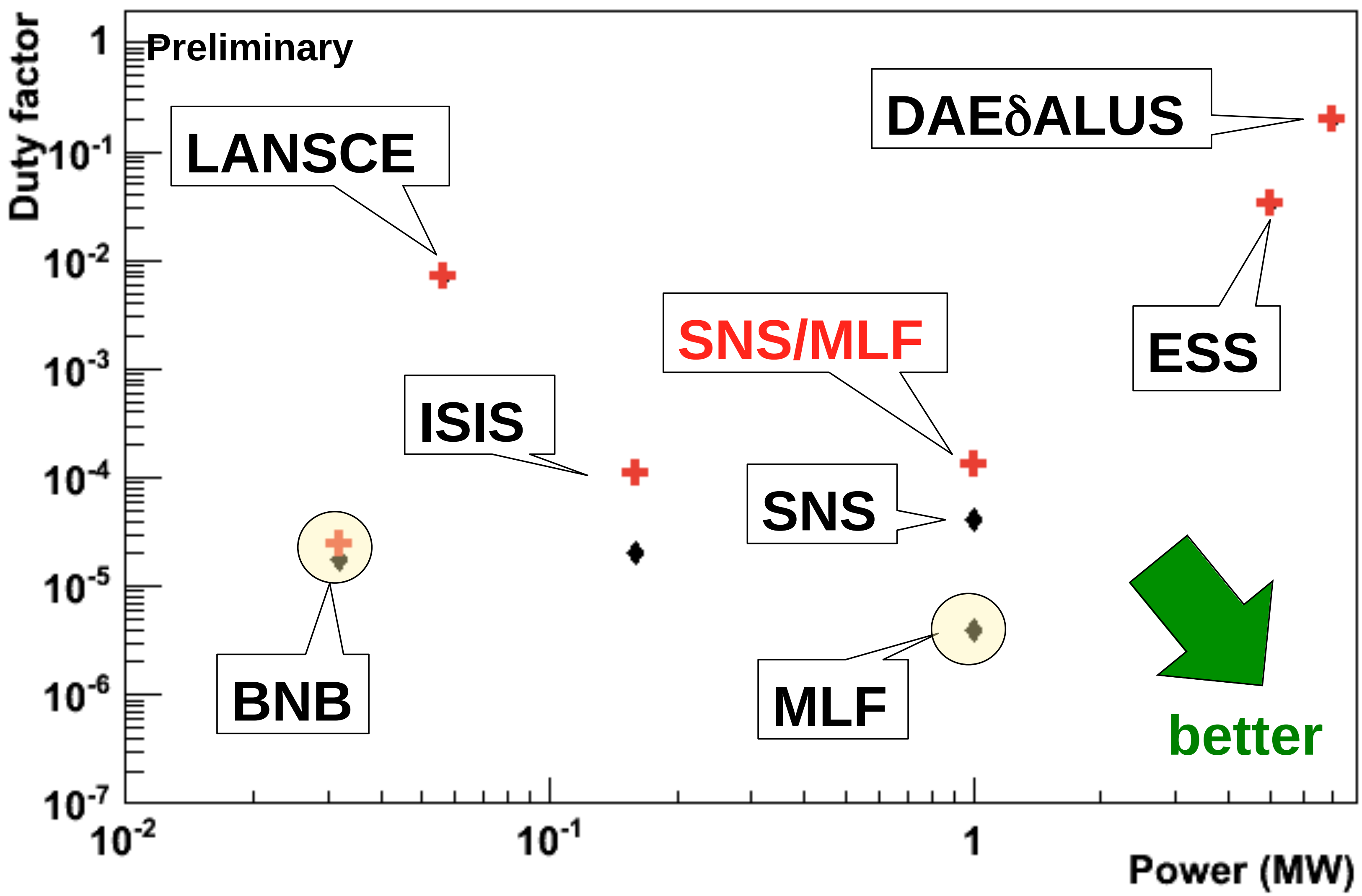
Duty factor = T*rate (◆)

= max(T, 2.2 μs)*rate (+ for μdk ν's)

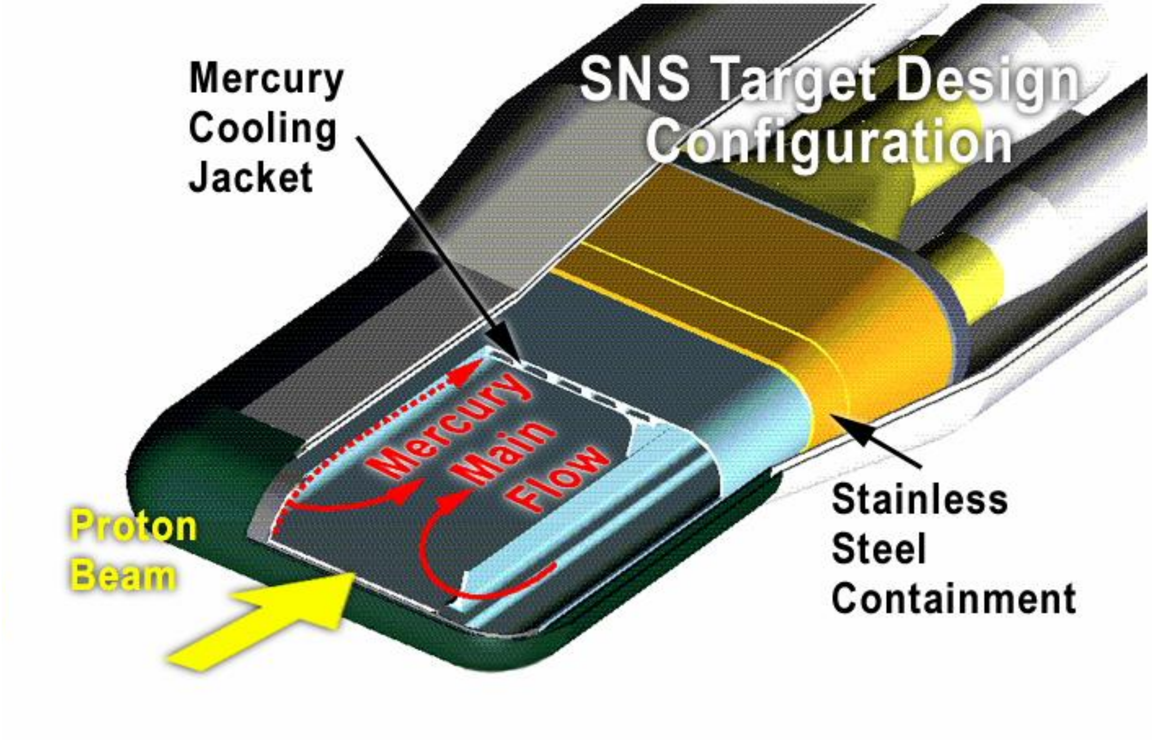
it doesn't help that much to be faster than μdk timescale



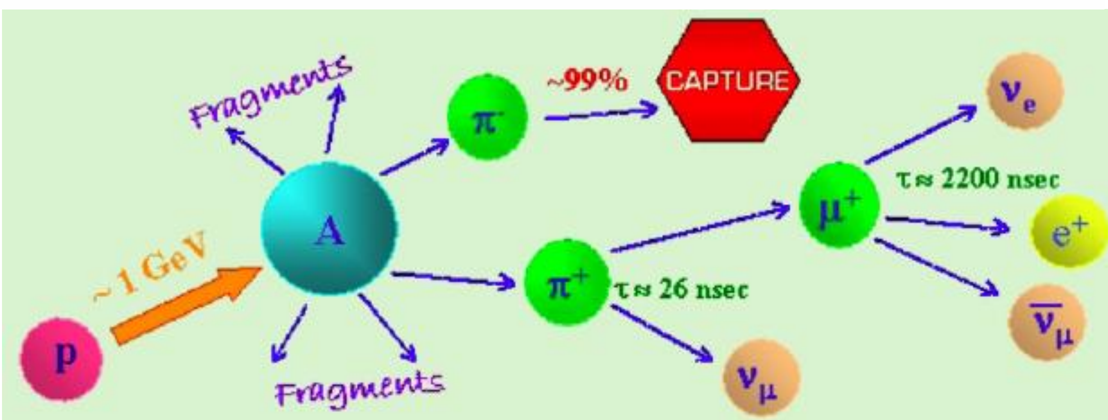
Flux ∝ power, ◯ high energy protons (non-DAR contamination)
Duty factor = T*rate (◆)
= max(T, 2.2 μs)*rate (+ for μdk ν's)



The SNS as a Stopped-Pion Neutrino Source

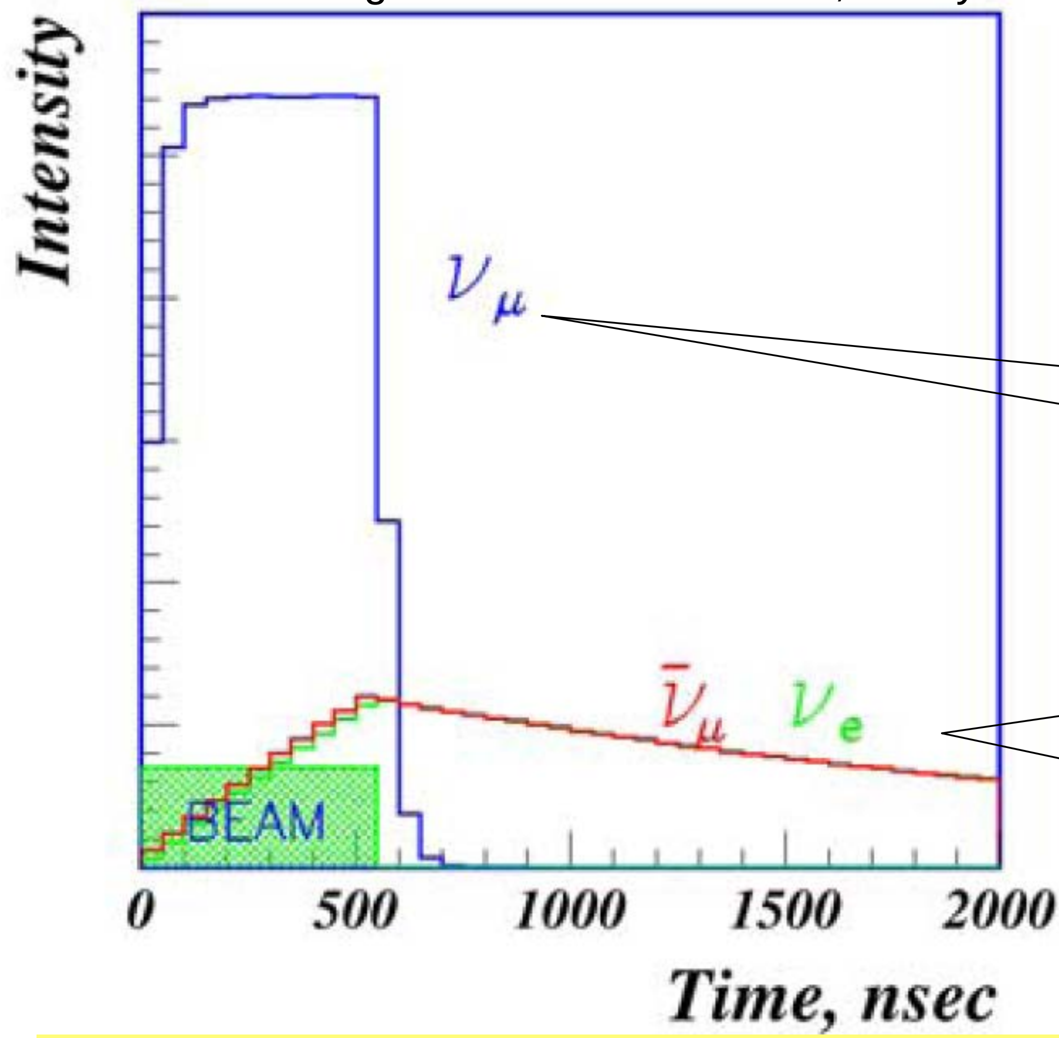


In addition to kicking out neutrons, protons on target create copious pions:
π^- get captured;
π^+ slow and decay at rest



Time structure of the source

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



60 Hz *pulsed* source

in time with beam

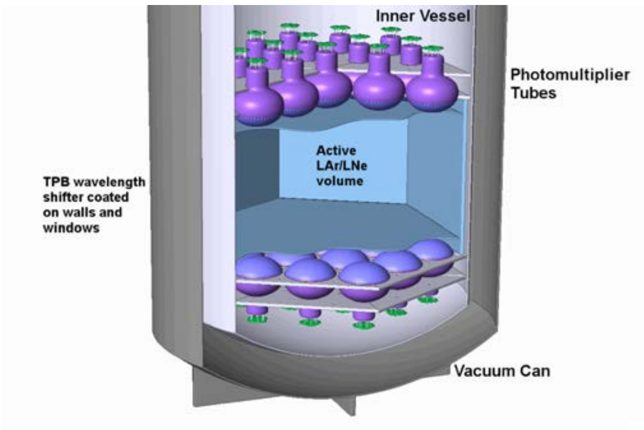
delayed on μ decay timescale (2.2 μs)

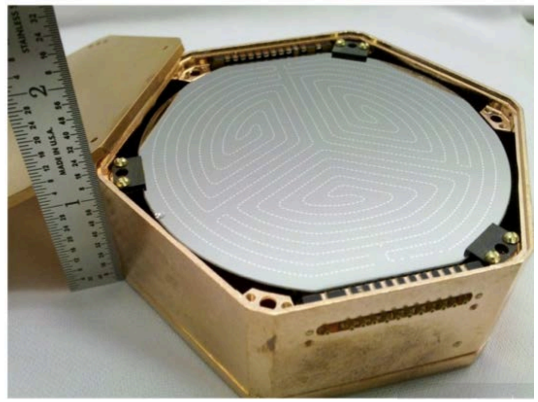
Background rejection factor ~few x 10^{-4}

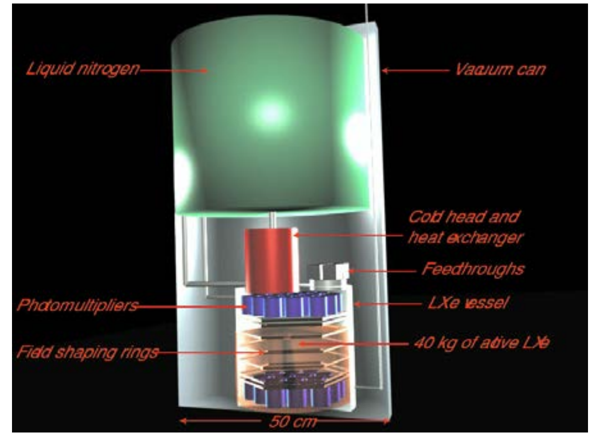
Neutrino flux: few times 10^7 /s/cm^2 at 20 m

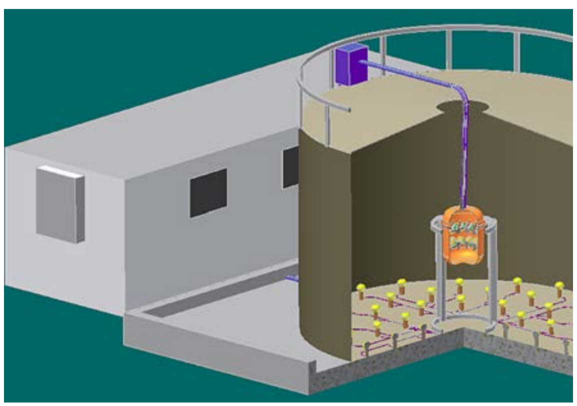
~0.13 per flavor per proton

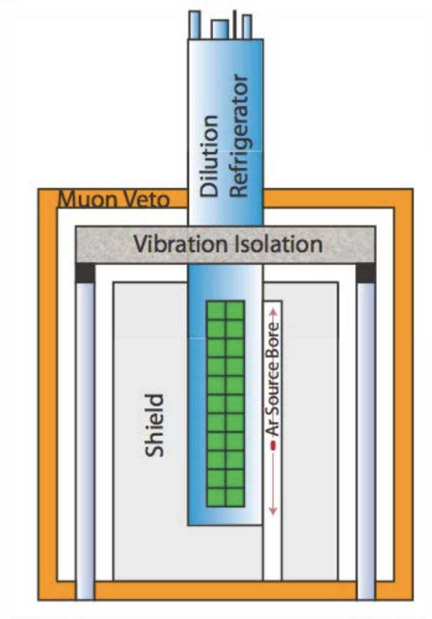
Detector possibilities: various DM-style strategies

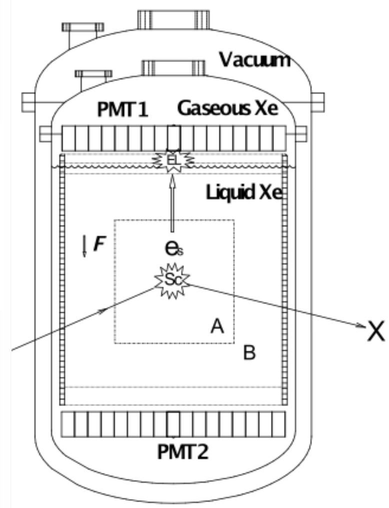




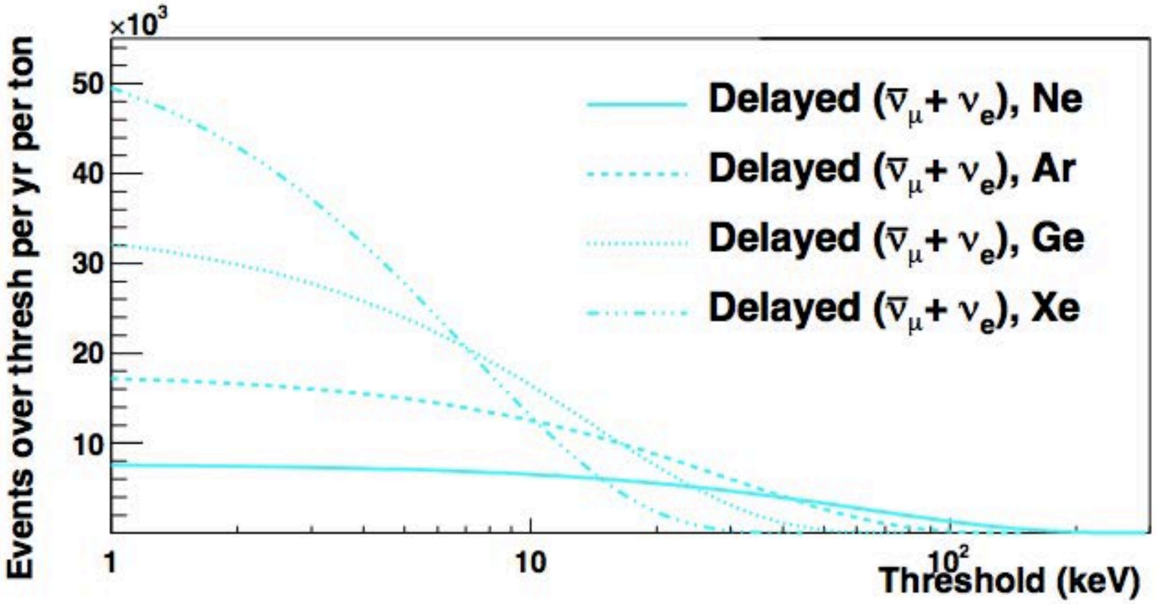




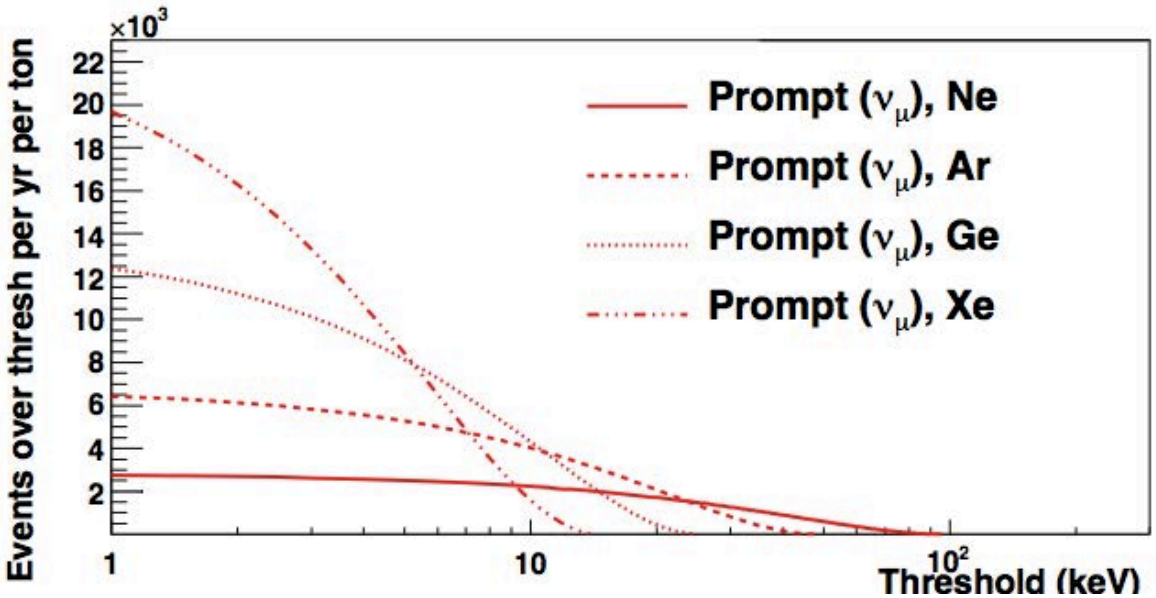




Integrated SNS yield for various targets



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

See also: arXiv.org > hep-ex > arXiv:1211.5199

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, W. R. Hix, W. C. Louis, J. M. Link, D. M. Markoff, G. B. Mills, K. Patton, H. Ray, K. Scholberg, R. G. Van de Water, C. Virtue, D. H. White, S. Yen, J. Yoo

(includes more than CENNS)

Weak mixing angle

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

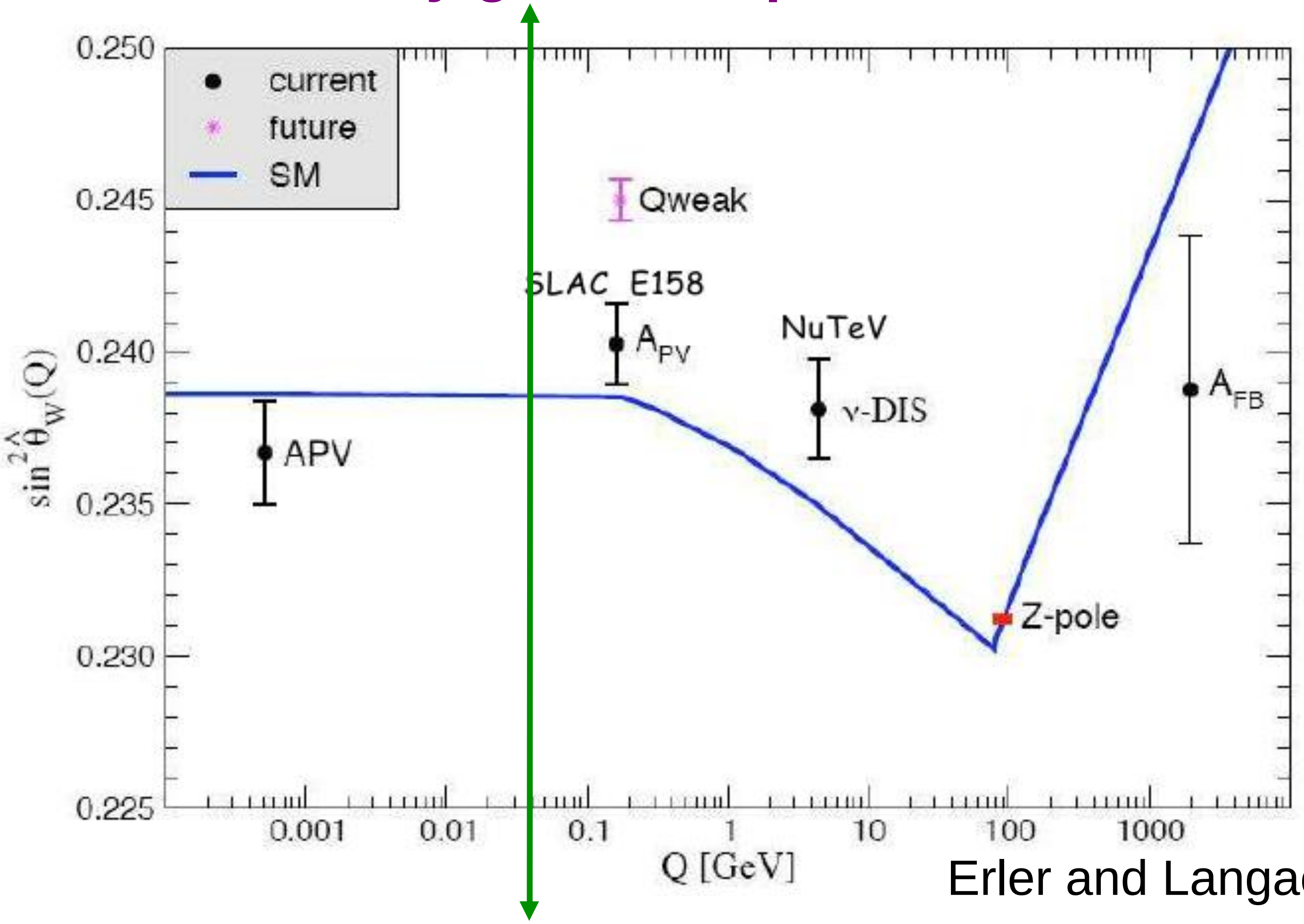
Absolute rate in SM is proportional to

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

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%

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

Combination of targets will help

(idea from Yuri Efremenko)

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

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%

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:

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

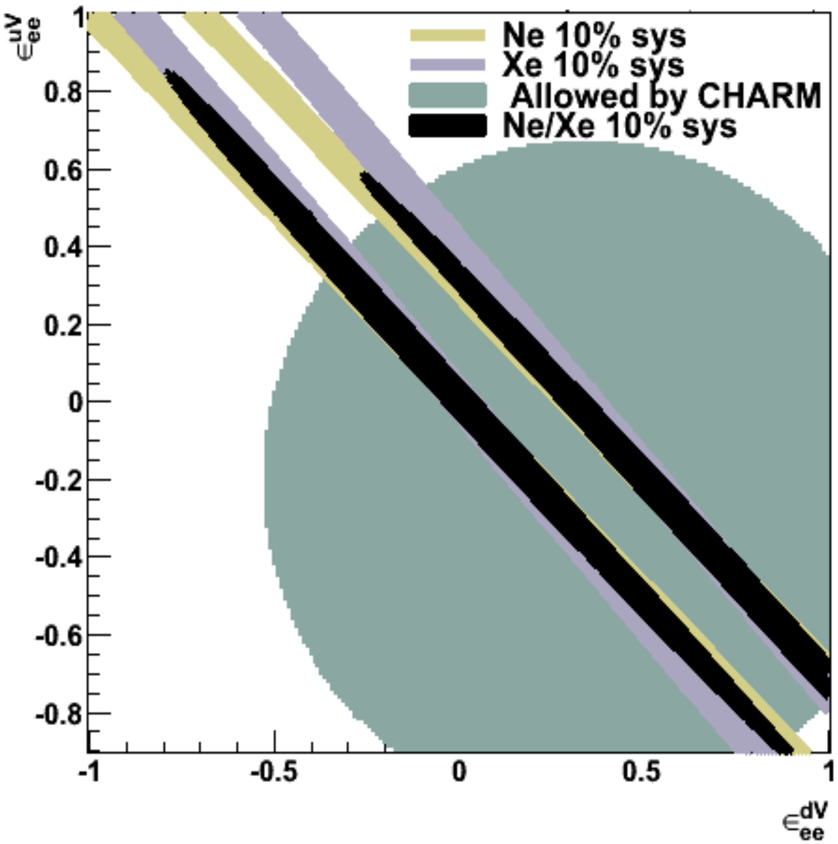
$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$ **non-universal**

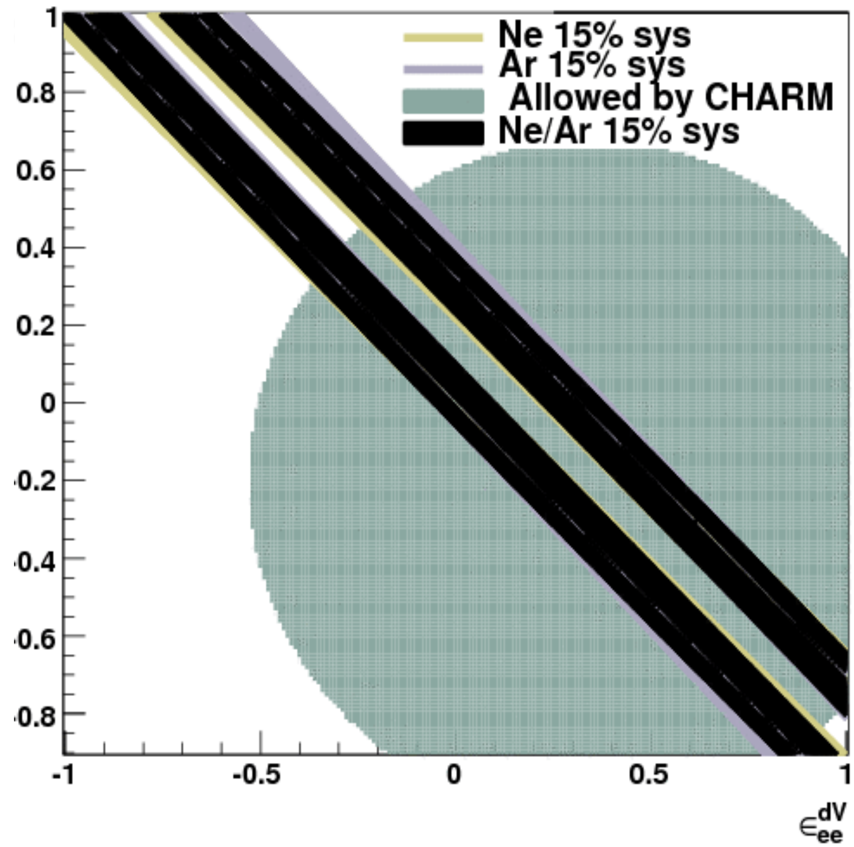
$$+\sum_{\alpha\neq\beta}[Z(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + N(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})]^2\}$$ **flavor-changing**

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



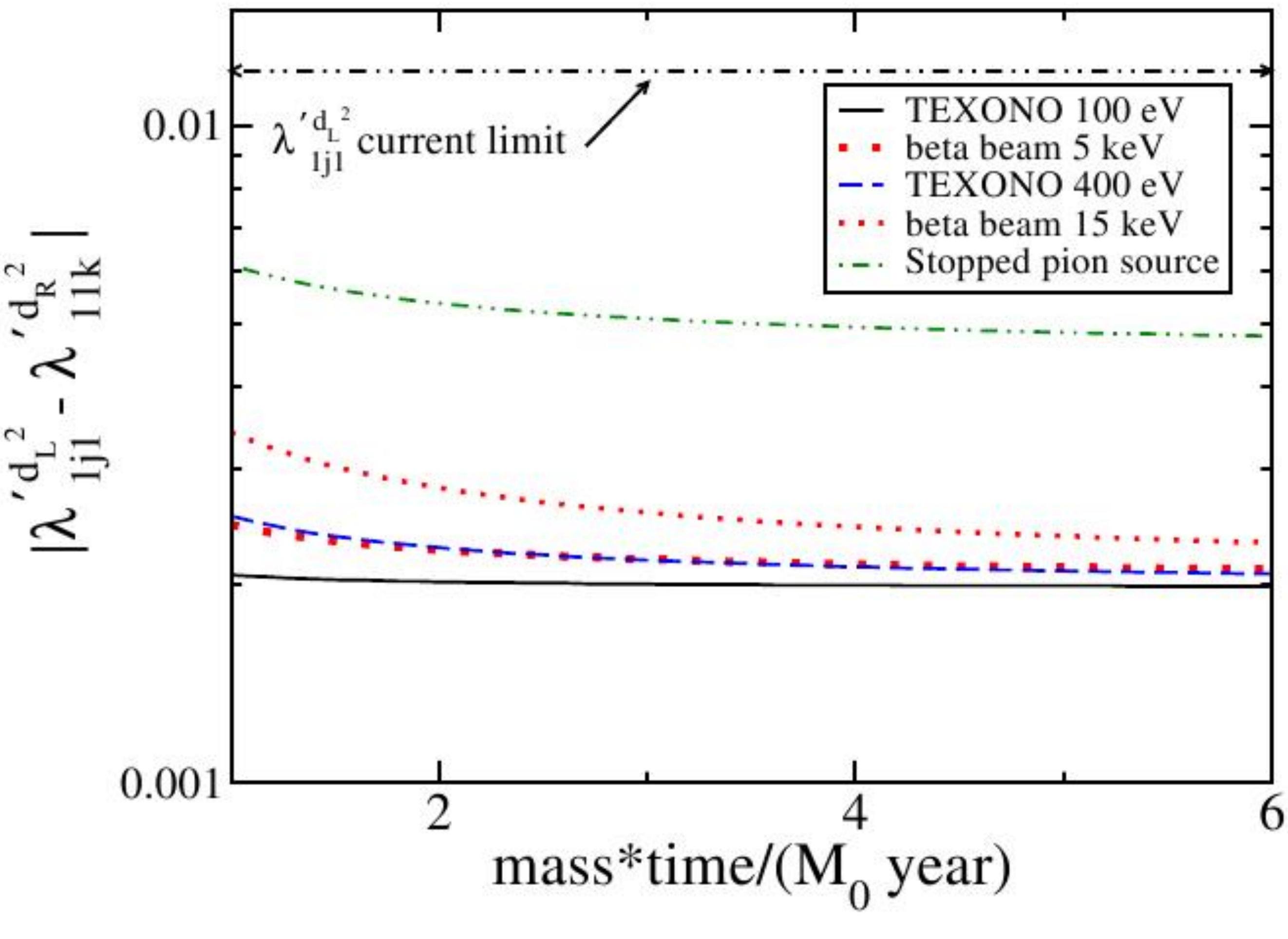


Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment

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



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 $\bar{\nu}_e$
< **6.8**	90	[123] AUERBACH 01	LSND	$\nu_e e$, $\nu_\mu e$ scattering
< **3900**	90	[124] SCHWIENHO...01	DONU	$\nu_\tau e^- \to \nu_\tau e^-$

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:

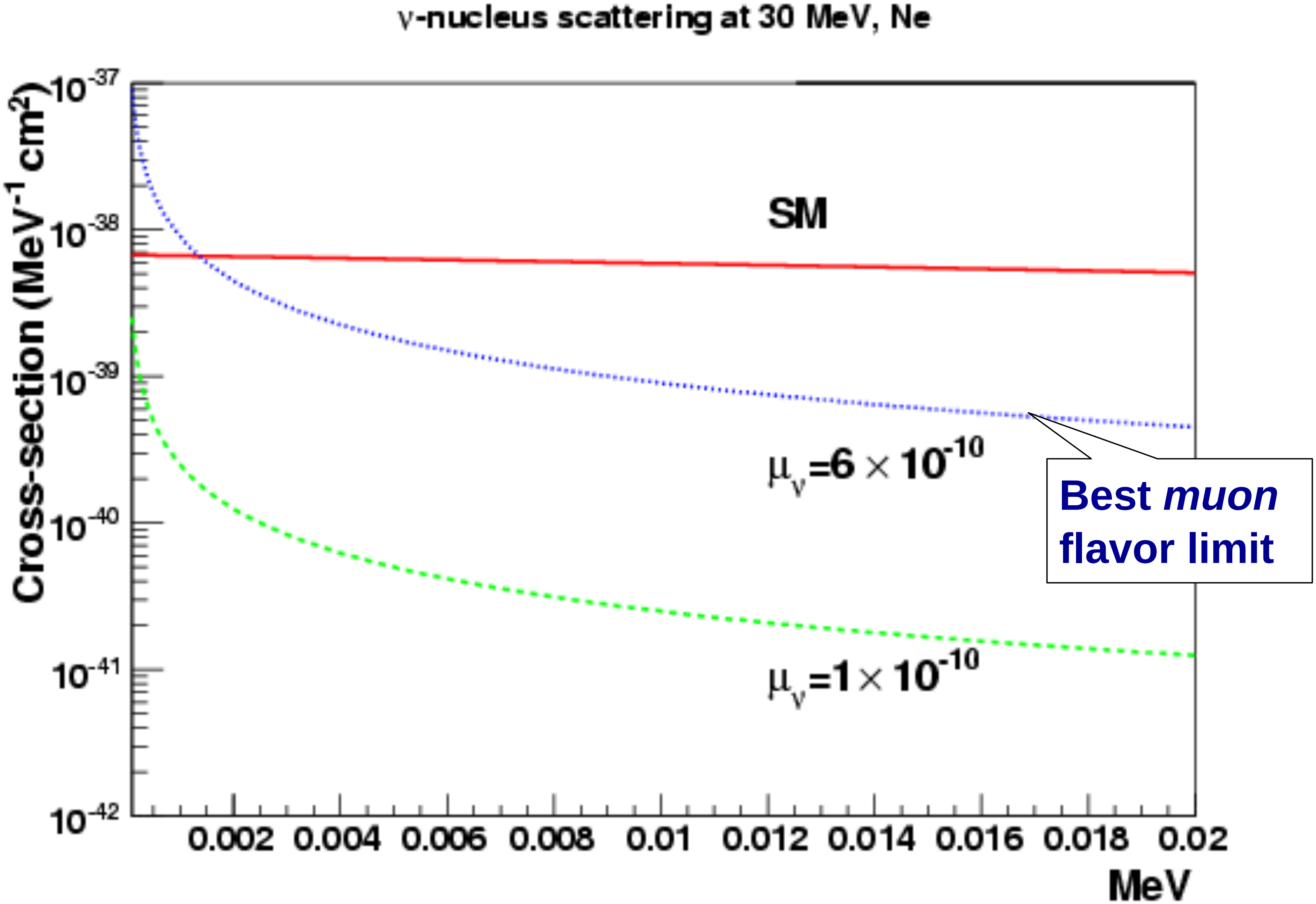
$$\frac{d\sigma}{dE} = \frac{G^2}{\pi} M \left(1 - \frac{ME}{2k^2}\right) \frac{N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

Magnetic cross-section:

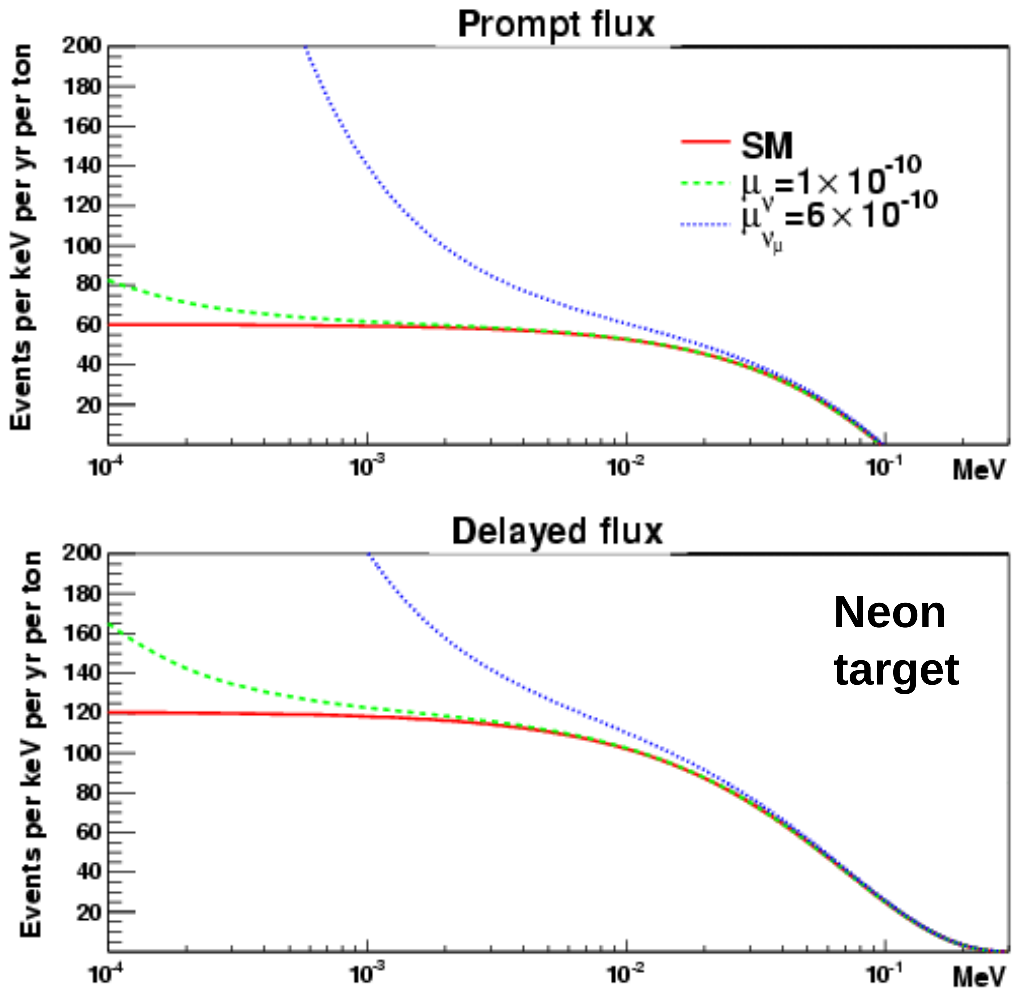
$$\frac{d\sigma}{dE} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2} \left(\frac{1 - E/k}{E} + \frac{E}{4k^2}\right)$$

(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 $\mu_\nu=6\times10^{-10}\ \mu_B$

Experimentally hard! But maybe doable

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

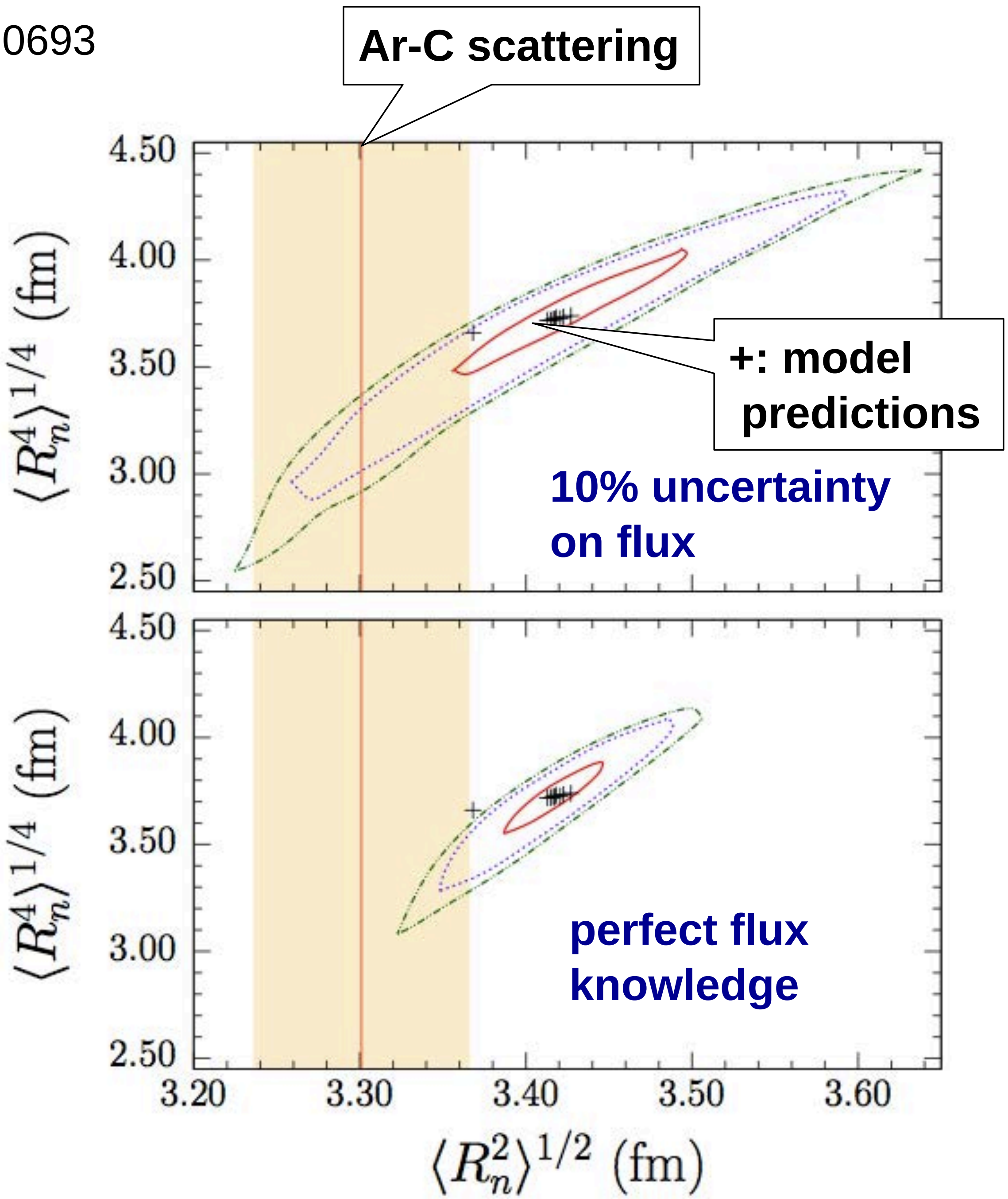
$$\begin{aligned} F_n(Q^2) &\approx \int \rho_n(r) \left(1 - \frac{Q^2}{3!} r^2 + \frac{Q^4}{5!} r^4 - \frac{Q^6}{7!} r^6 + \cdots \right) r^2 dr \\ &\approx N \left(1 - \frac{Q^2}{3!} \langle R_n^2 \rangle + \frac{Q^4}{5!} \langle R_n^4 \rangle - \frac{Q^6}{7!} \langle R_n^6 \rangle + \cdots \right)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

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)



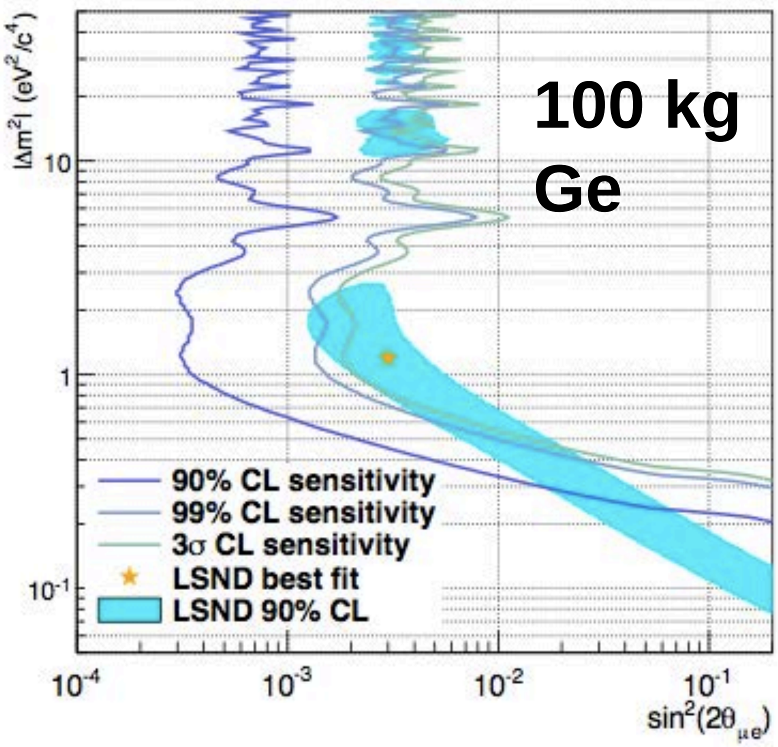
Will require stringent control of uncertainties

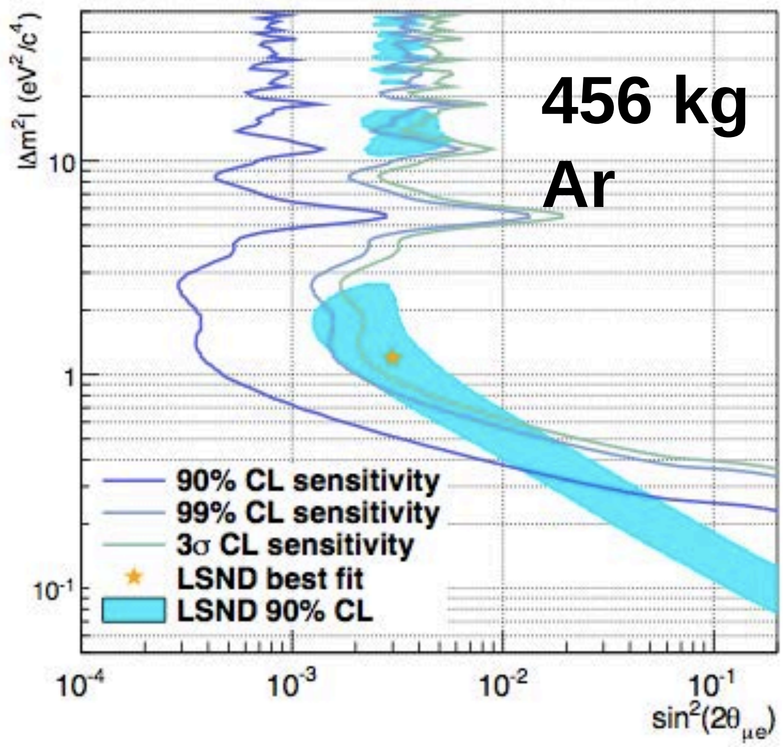
Last topic: oscillations to sterile neutrinos
(NC is flavor-blind)

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

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

Summary

Coherent elastic neutrino-nucleus scattering offers many physics prospects!

- neutrino NSI is the low-hanging fruit
- multi-tonne-scale experiments will have broad program

For first-generation measurements, requirements are not stringent;

systematic uncertainties may eventually become limiting;

need multiple targets, well-understood neutrino source

Stopped-pion sources are attractive:

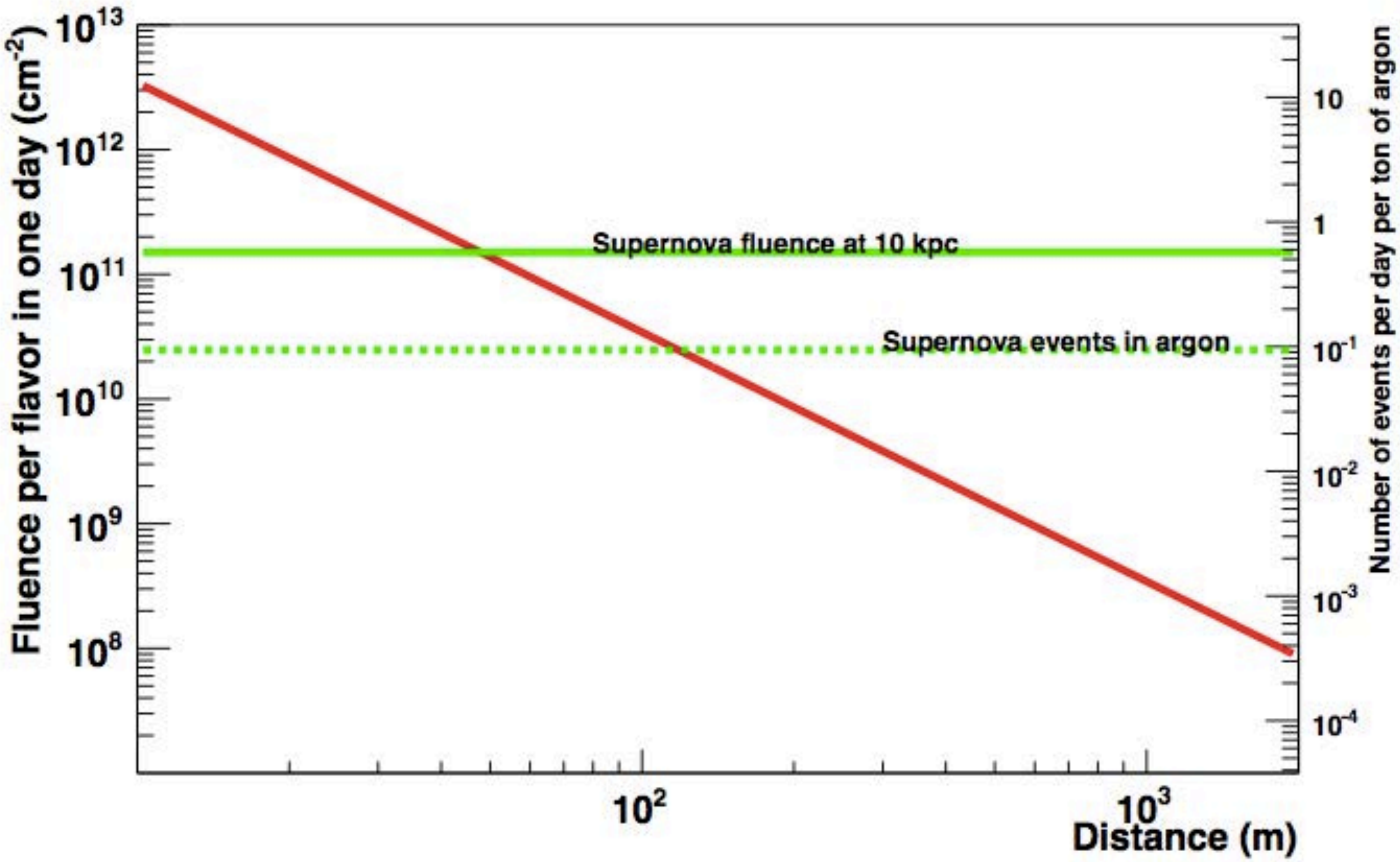
- high energy neutrinos ➔ higher rate for same flux;
  higher threshold OK
- multi-flavor, well-understood spectrum (muon flavor)
- good background rejection from time structure

We need a “coherent” strategy!

Extras/Backups

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

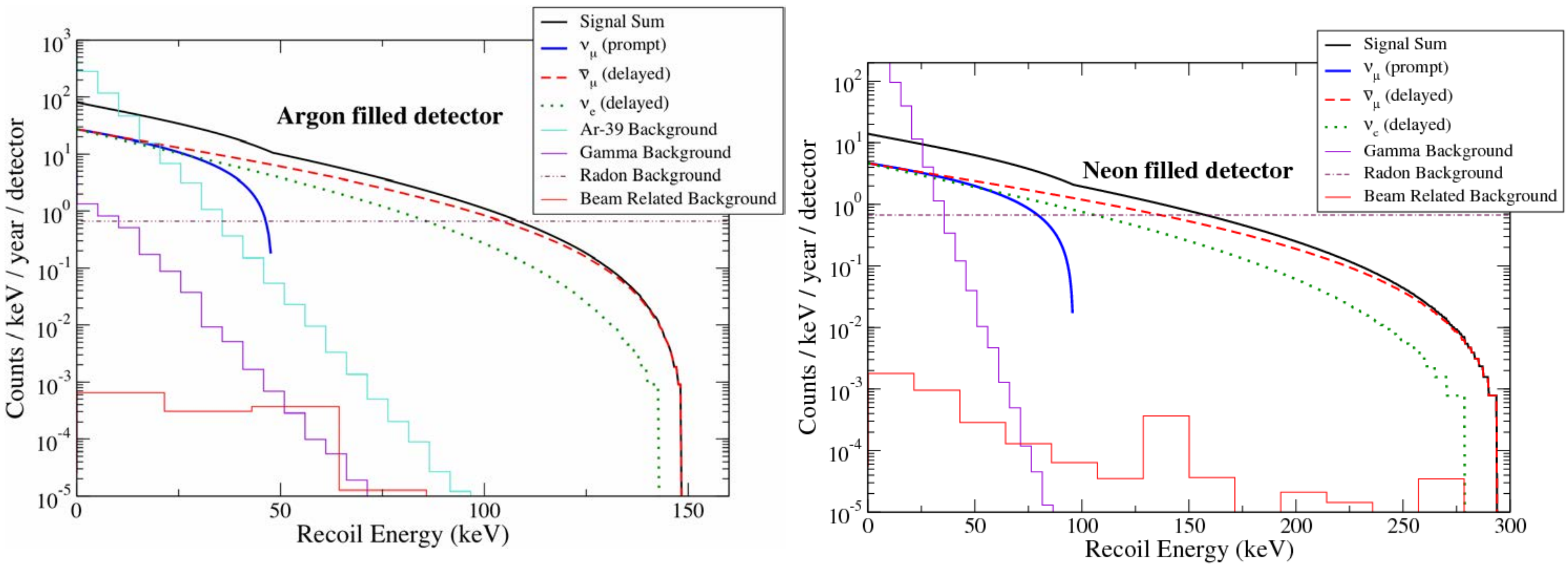
(and effectively more events due to harder spectrum)



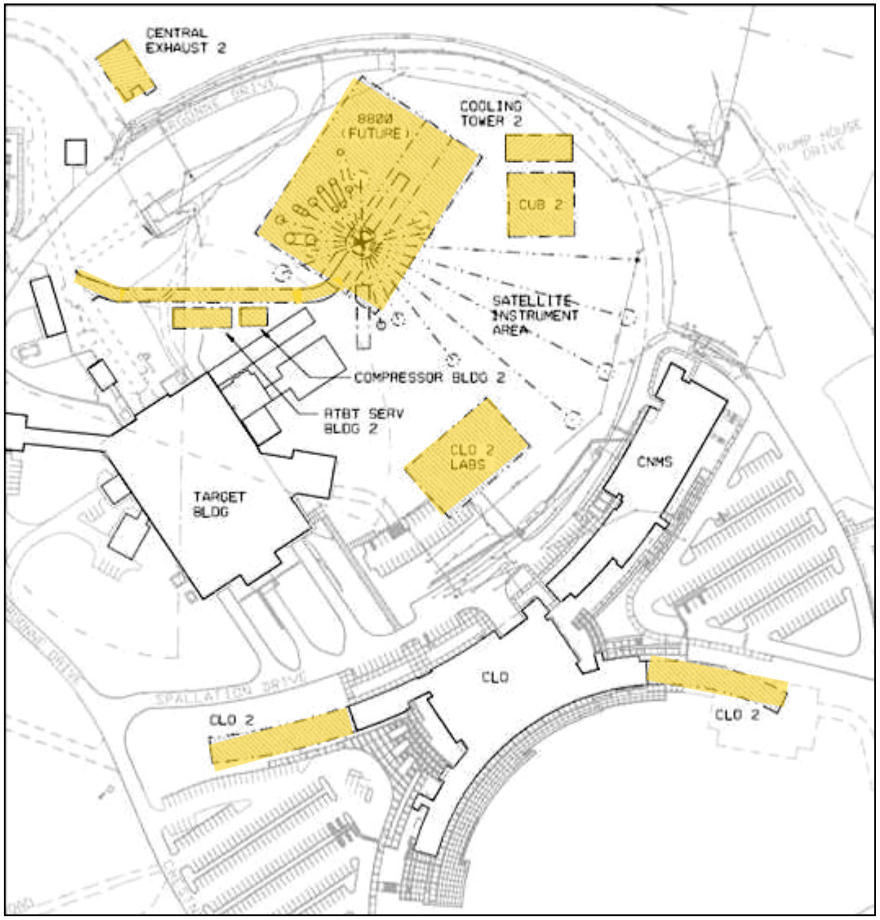
Bottom line signal and background for CLEAR

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

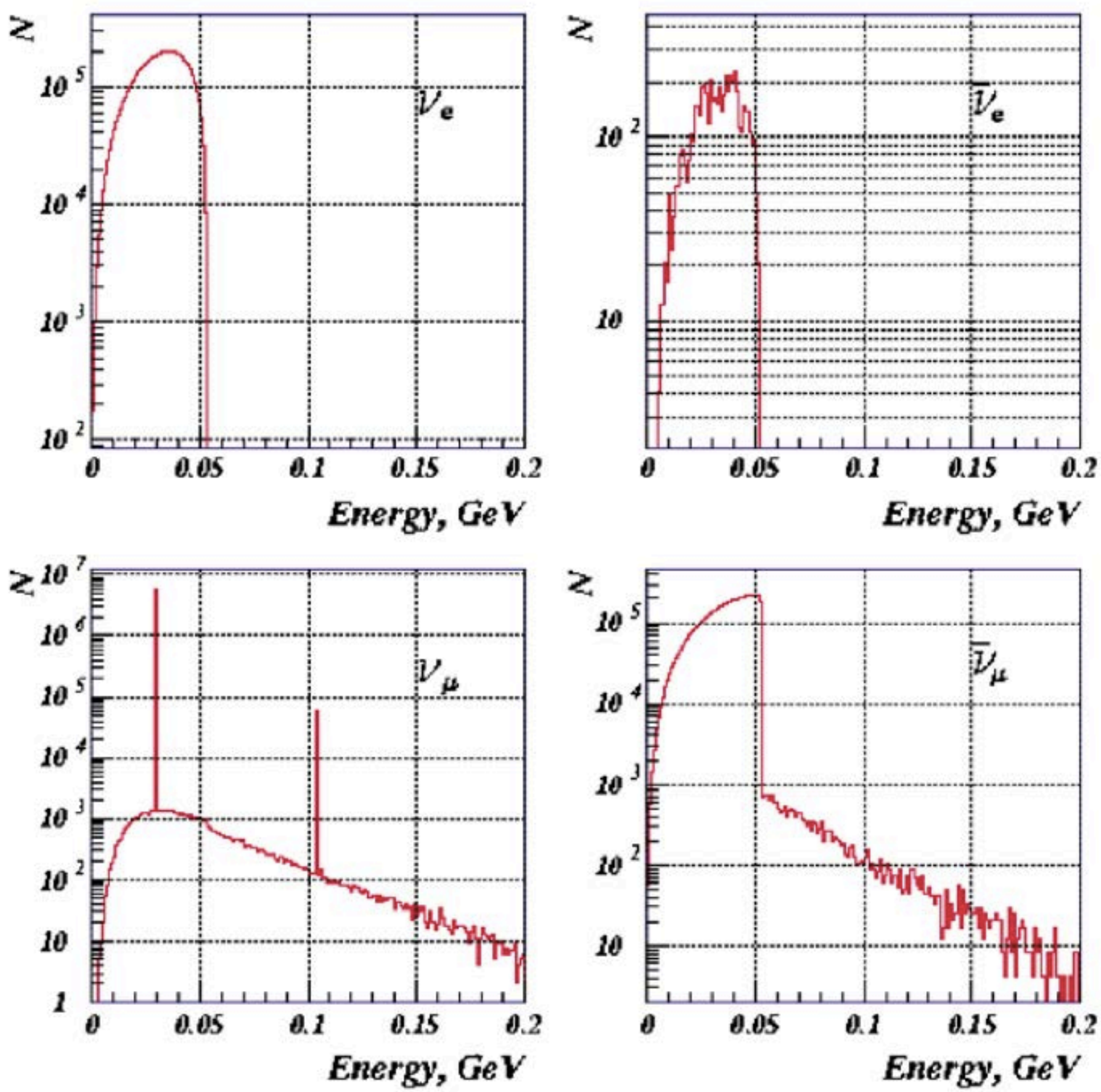
SNS neutronics group calculation of beam n spectrum
+ Fluka sim through shielding (T. Empl, Houston)
+ noble liquid detector sim (J. Nikkel, Yale)



SNS Second Target Station



R. McGreevy


N
ν_e
10^5
10^4
10^3
10^2
0
0.05
0.1
0.15
0.2
Energy, GeV
N
$\bar{\nu}_e$
10^2
10
0
0.05
0.1
0.15
0.2
Energy, GeV
N
ν_μ
10^7
10^6
10^5
10^4
10^3
10^2
10
1
0
0.05
0.1
0.15
0.2
Energy, GeV
N
$\bar{\nu}_\mu$
10^5
10^4
10^3
10^2
10
0
0.05
0.1
0.15
0.2
Energy, GeV