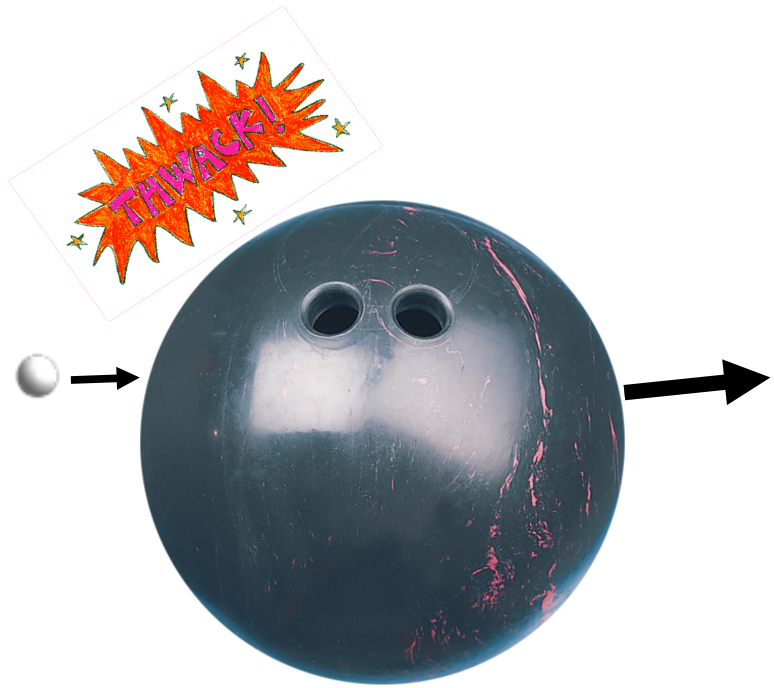
Prospects for measuring coherent elastic neutrino-nucleus scattering



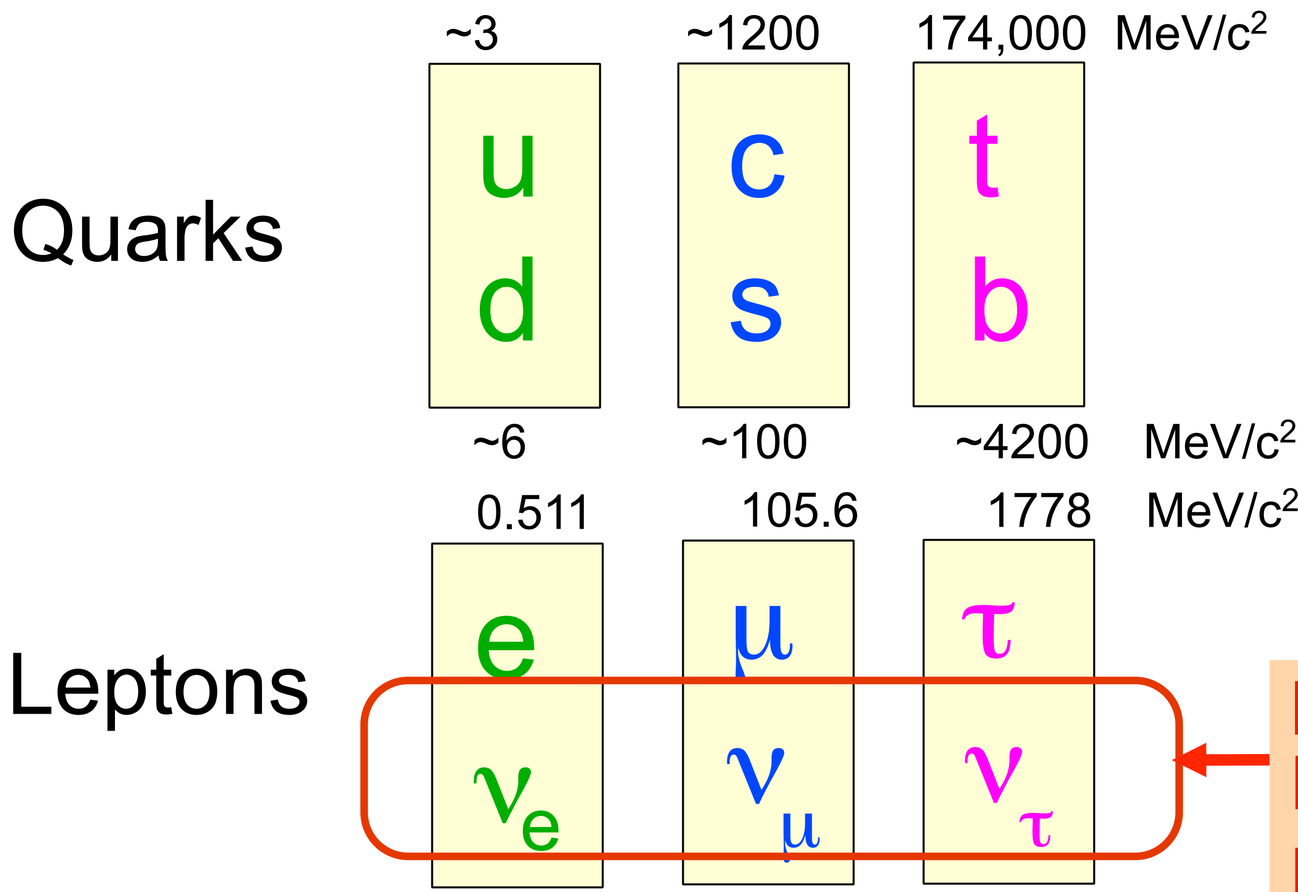
Kate Scholberg, Duke University

ORNL Seminar, November 14 2013

Outline

- Neutrinos
- Coherent elastic neutrino-nucleus scattering
- Possible sources and detectors;
  focus on stopped-pion neutrinos
- Some physics that could be explored
- Prospects for near-future measurements
  (SNS & FNAL BNB)

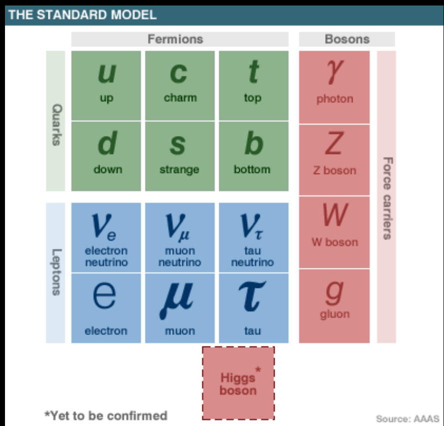
NEUTRINOS



In the Standard Model of particle physics, neutral partners to the charged leptons

- **Spin 1/2**
- **Zero charge**
- **3 flavors (families)**
- **Interact *only* via *weak interaction* (& gravity)**
- **Tiny mass (< 1 eV)**

Why do neutrinos matter?



fundamental particles and interactions

astrophysical systems

cosmology

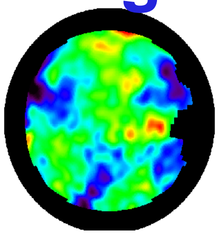
nuclear physics

Neutrinos make up a ~few % of dark matter, but are important in understanding of history of structure formation

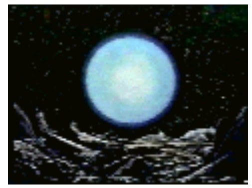
Sources of wild neutrinos

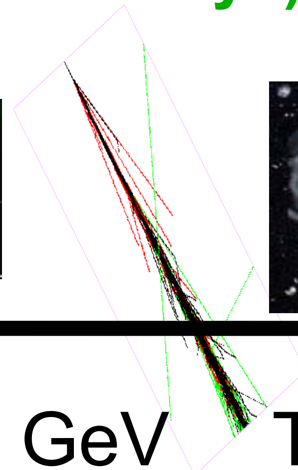
The Atmosphere (cosmic rays)

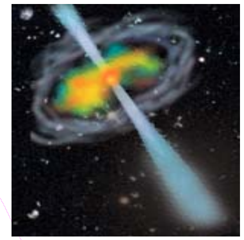
The Big Bang



Super novae



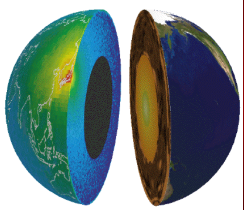


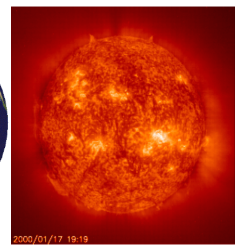


AGN's, GRB's

meV eV keV MeV GeV TeV PeV EeV

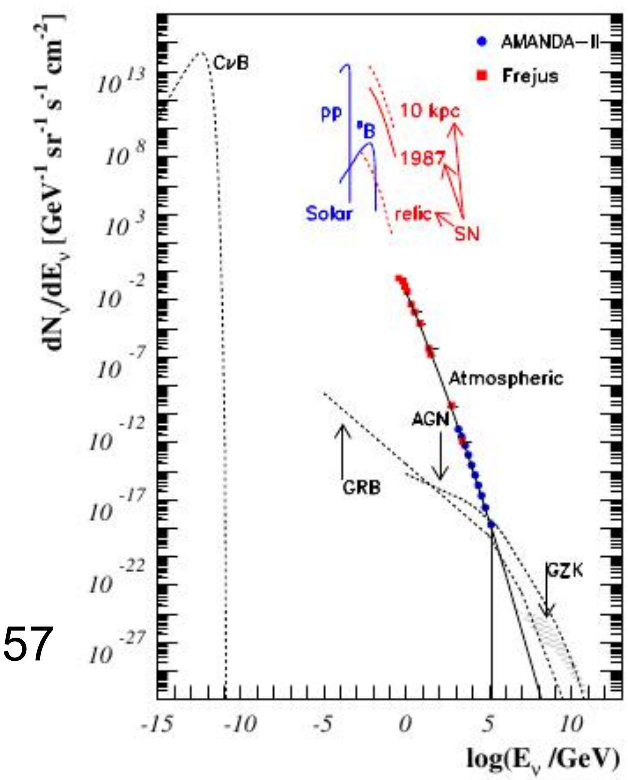
Radioactive decay in the Earth





The Sun

J. Becker, arXiv:0710.1557

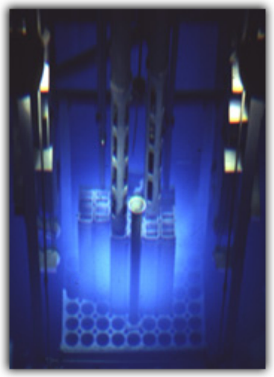


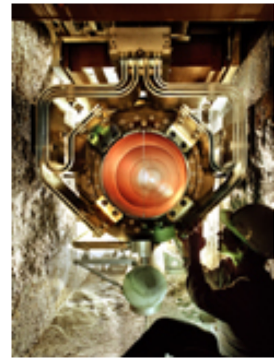
Sources of 'tame' neutrinos

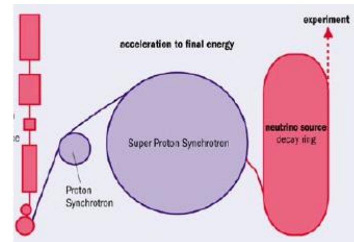
Proton accelerators

Beta beams

Nuclear reactors

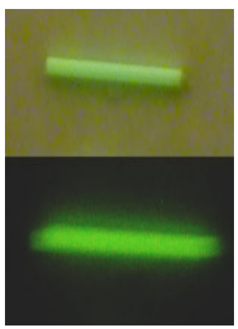


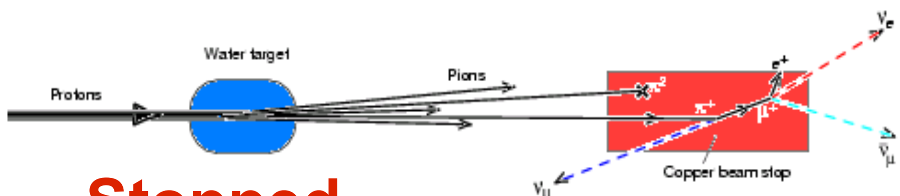




eV keV MeV GeV TeV

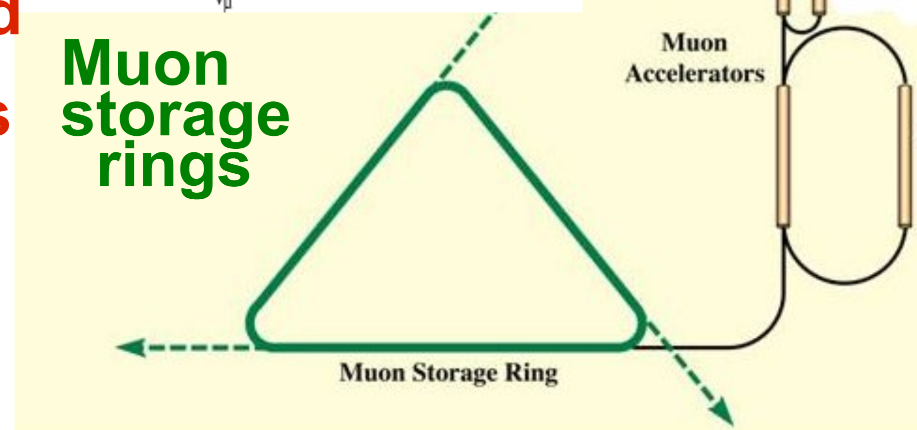
Artificial radioactive sources





Stopped pion sources

Muon storage rings

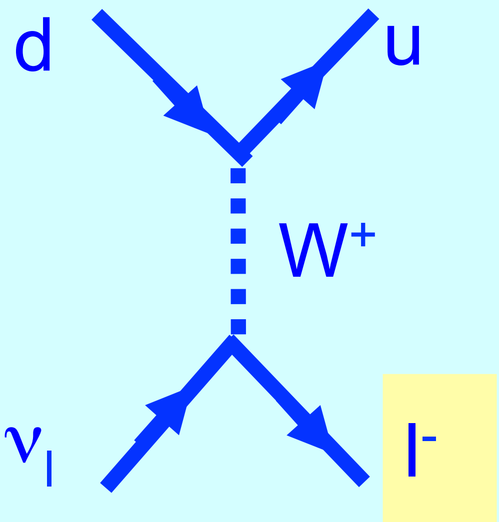


Usually (but not always) better understood...

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

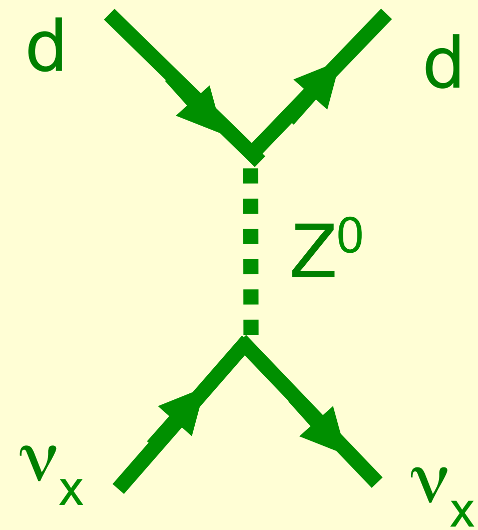


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton with flavor corresponding to neutrino flavor

(must have enough energy to make lepton)

Neutral Current (NC)

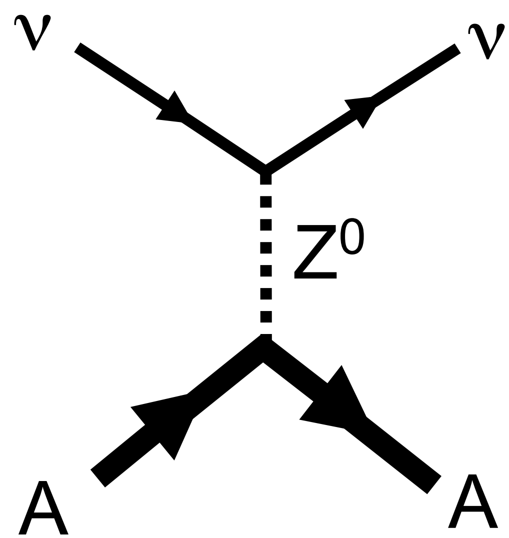


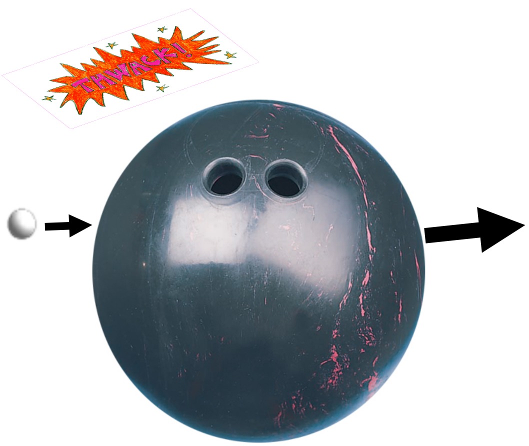
Flavor-blind

Coherent Elastic (neutral-current) Neutrino-Nucleus Scattering (CENNS)

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

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils; coherent for Q<~1/R up to E_ν~ 50 MeV for mid-size A





Well-calculable cross-section in SN:

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

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

Why try to measure this?

- It's never been done!

- Important in supernova processes
- Important for supernova ν detection

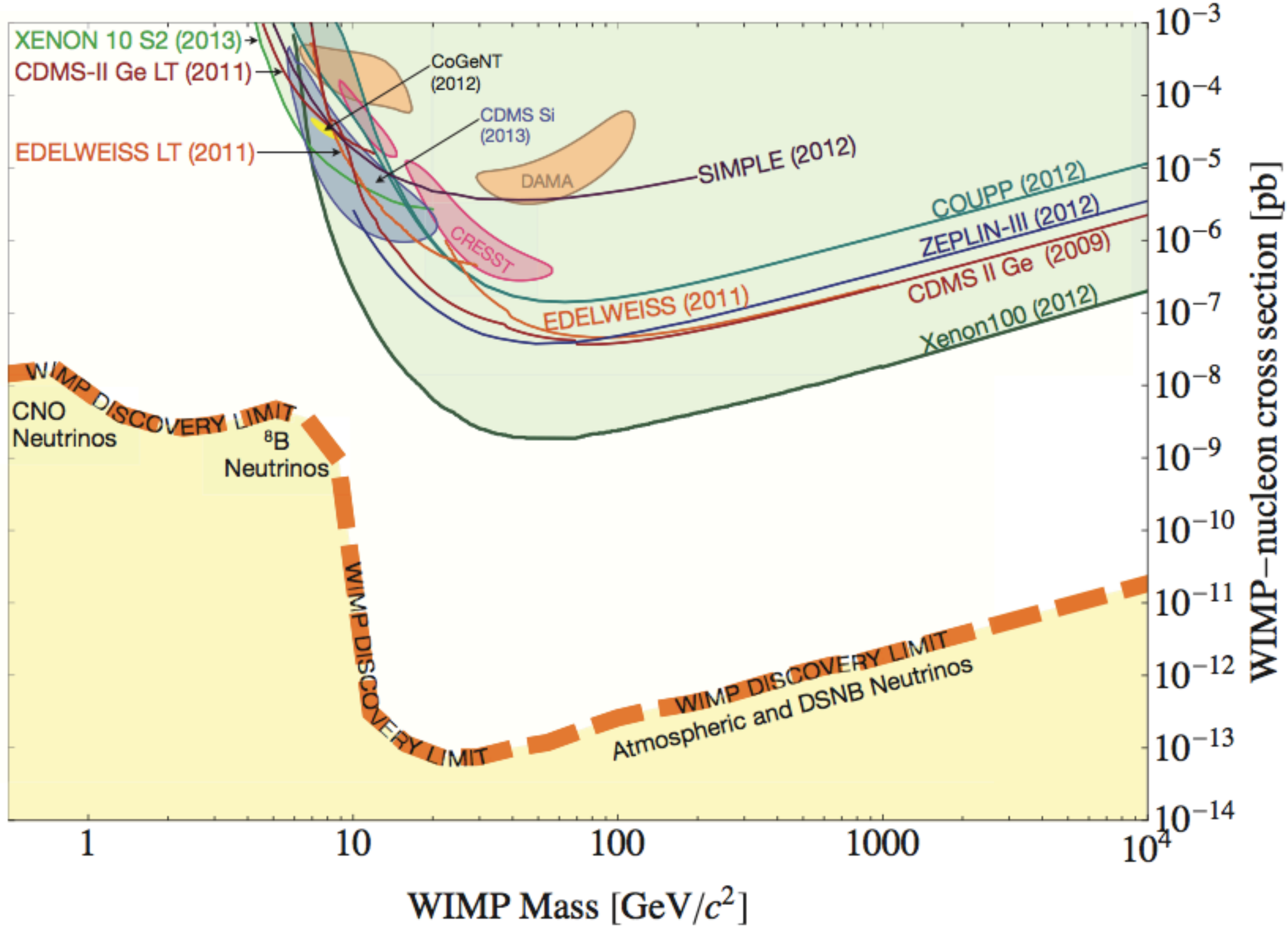
- Deviations from expected x-scn may indicate non-SM processes

???

- Possibly even applications..

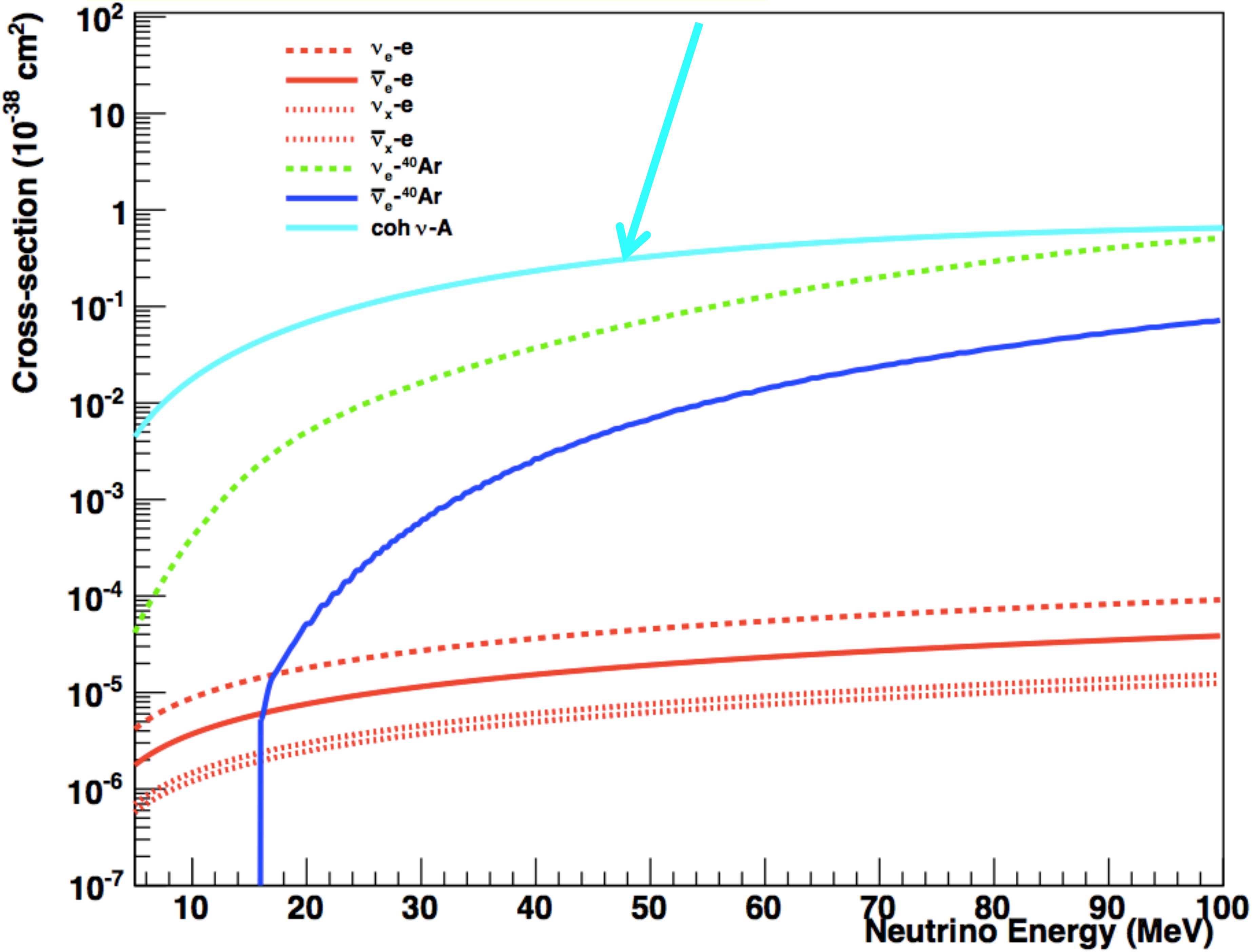
e.g. Barbeau et al., IEEE Trans. Nucl. Sci. 50: 1285 (2003)
C. Hagmann & A. Bernstein, IEEE Trans. Nucl. Sci 51:2151 (2004)

CENNS from natural neutrinos creates ultimate background for direct DM search experiments



J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

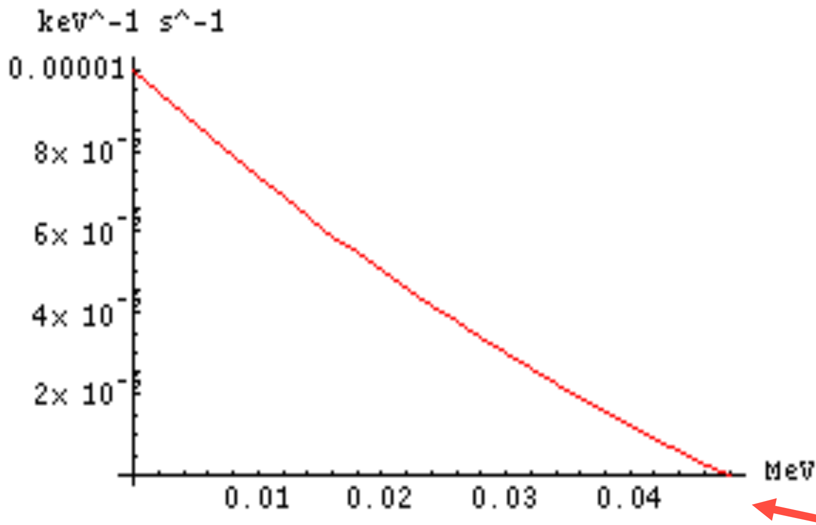
The cross-section is *large*



But CENNS has never been observed...

Why not?

Nuclear recoil energy spectrum for 30 MeV ν



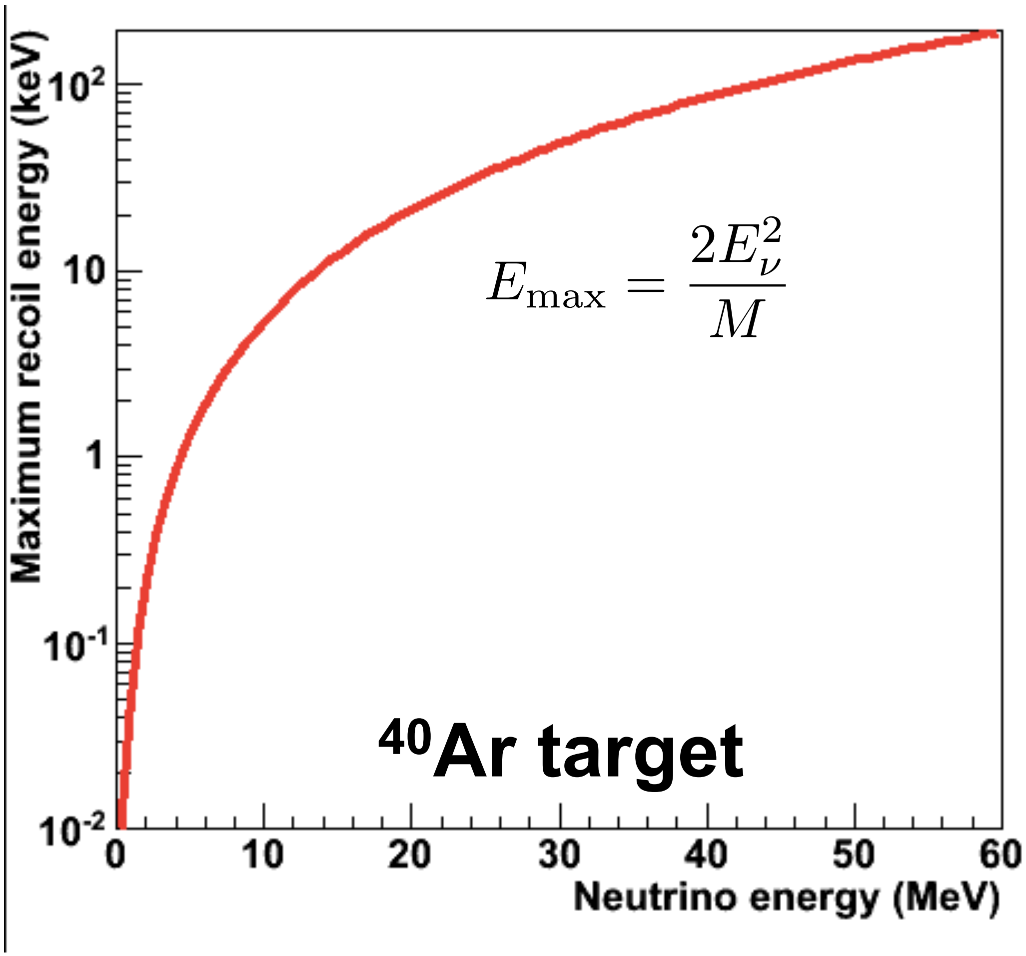
Max recoil energy is $2E_\nu^2/M$ (48 keV for Ar)

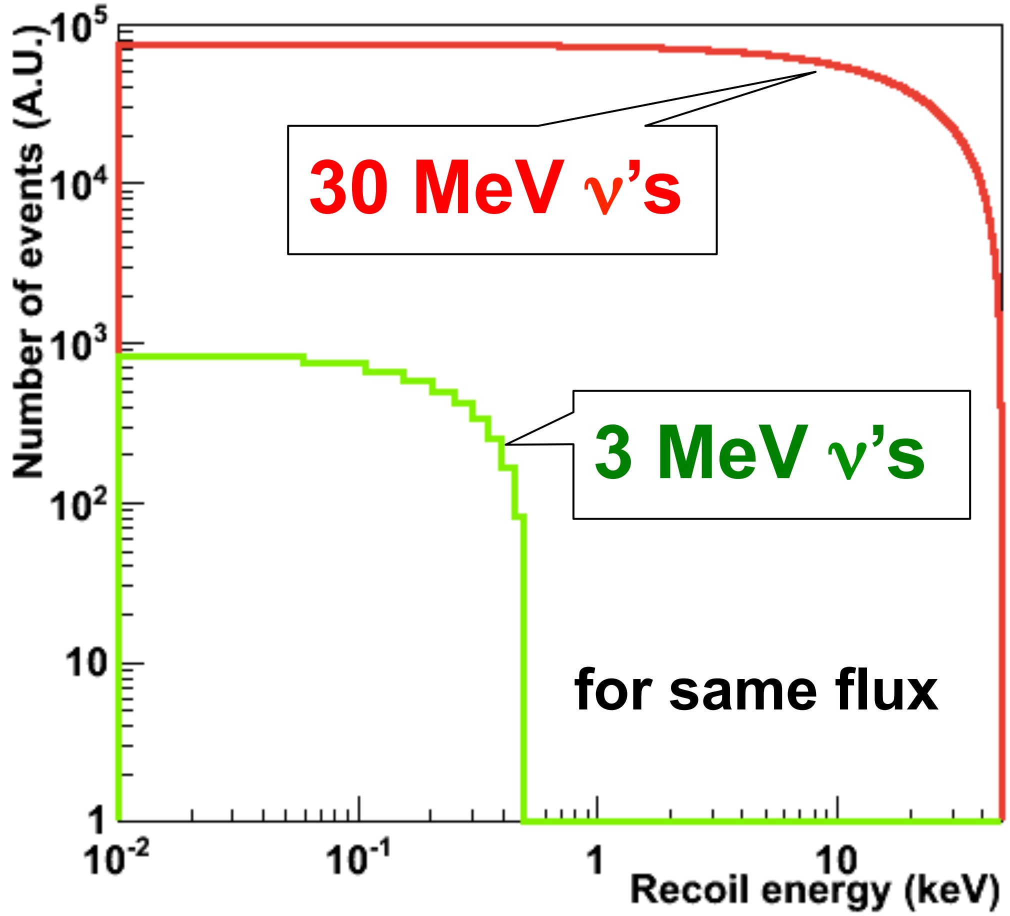
Recoil energies are tiny!

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

What do you want in order to detect CENNS?

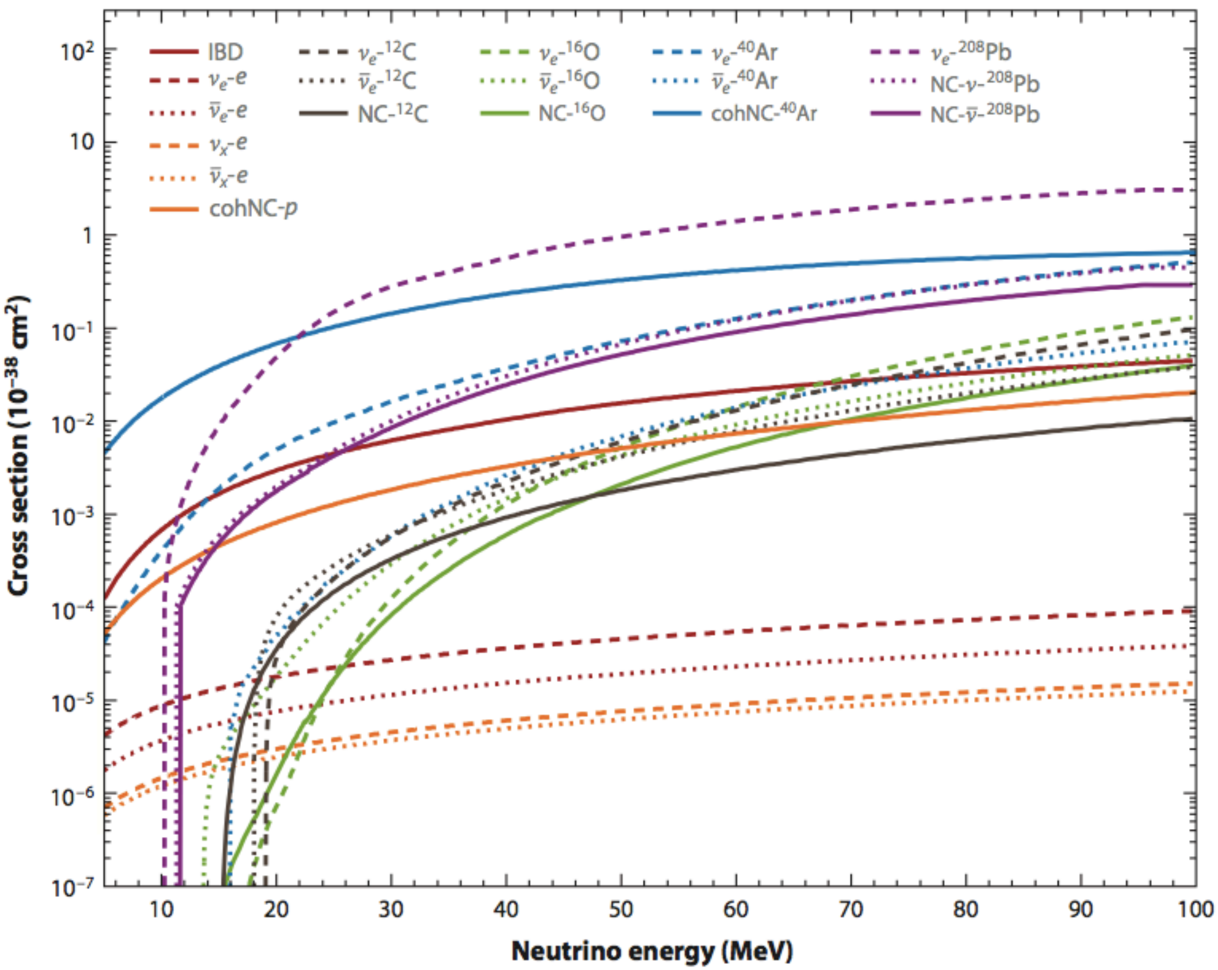
High-energy neutrinos, because both cross-section and maximum recoil energy increase with neutrino energy





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

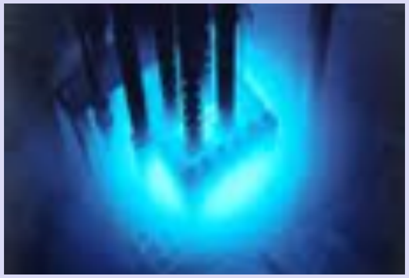
What do you want in a neutrino source for CENNS detection (and physics)?

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

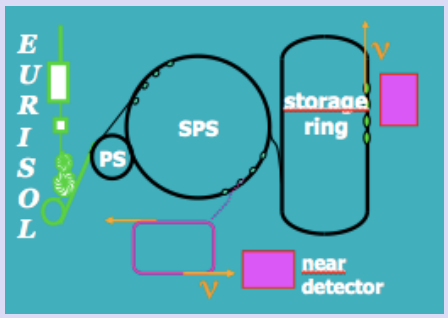
Potential sources for detection of coherent scattering

Artificial sources

reactor neutrinos

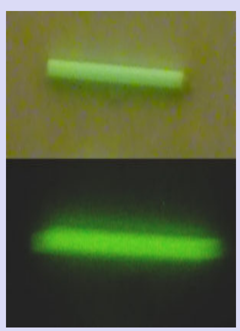


low energy beta beams



stopped pions

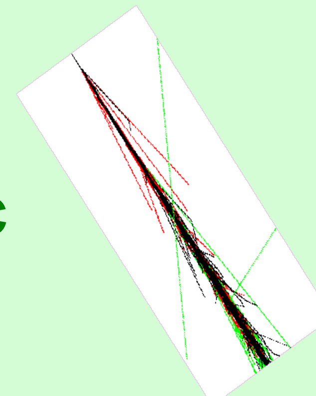
radioactive sources

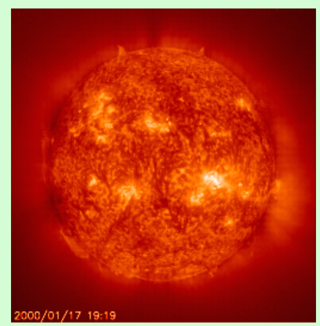


Natural sources

supernova neutrinos, burst & relic

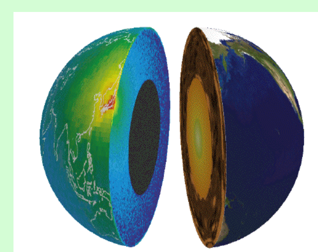
low energy atmospheric neutrinos



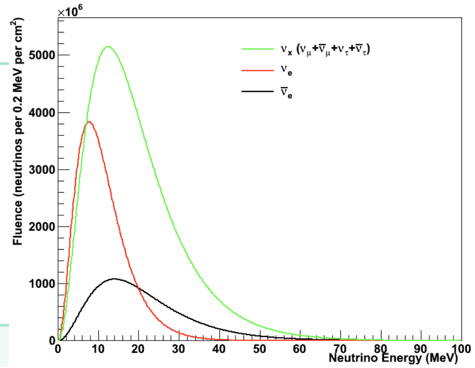


solar neutrinos

geo neutrinos

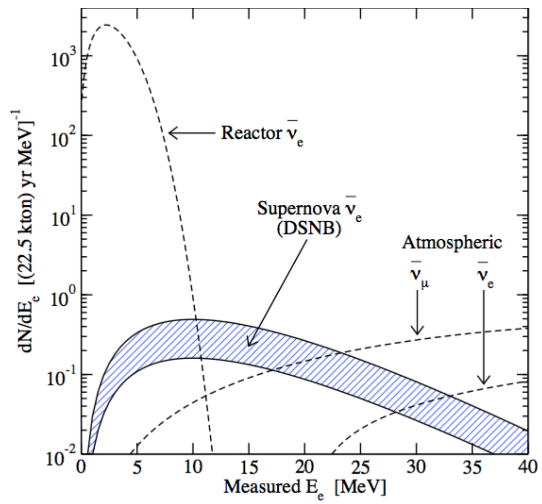


Supernova burst neutrinos



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

Supernova relic neutrinos

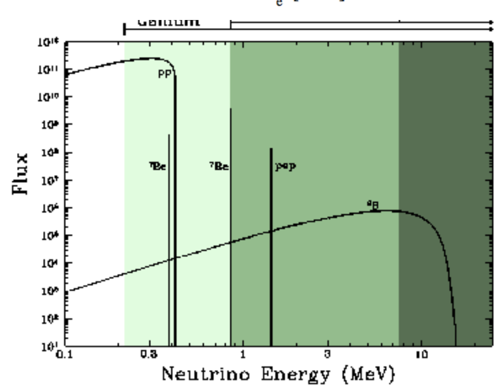


All flavors, low flux

Atmospheric neutrinos

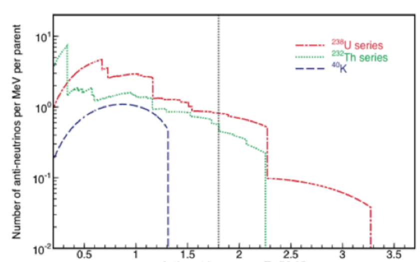
Some component at low energy

Solar neutrinos



Most flux below 1 MeV

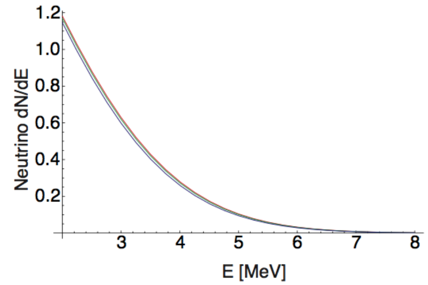
Geoneutrinos



Very low energy

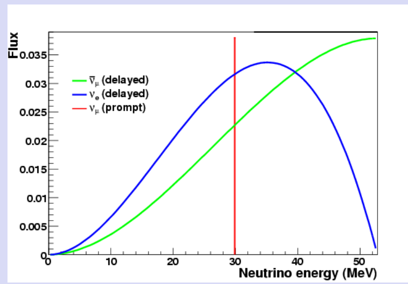
Coherent scattering eventually a bg for DM expts

Reactors



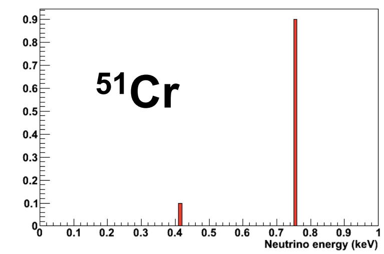
Low energy, but very high fluxes possible; ~continuous source good bg rejection needed

Stopped pions (decay at rest)



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

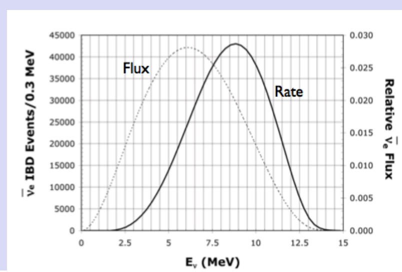
Radioactive sources



Portable; can get very short baseline

Too low energy

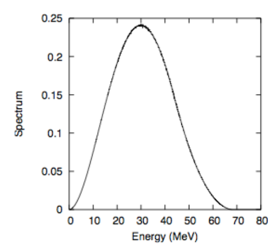
Beam-induced radioactive sources (IsoDAR)



Relatively compact, higher energy than reactor; not pulsed

Does not exist yet

Low-energy beta beams

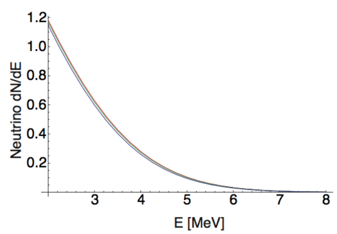
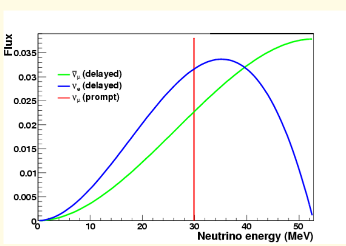


γ=10 boosted ^{18}Ne ν_e

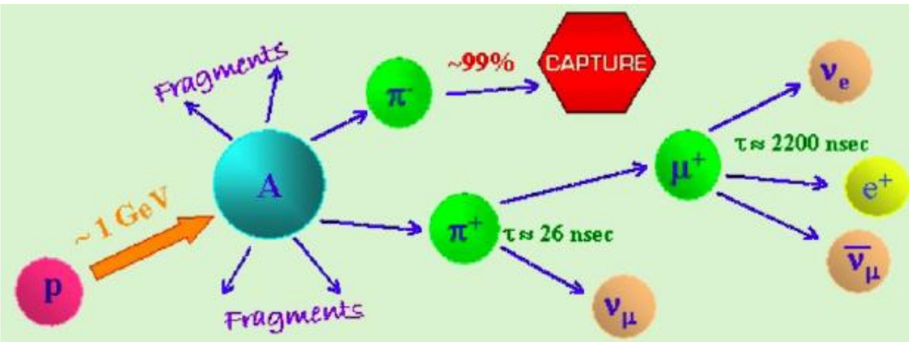
Tunable energy, but not pulsed

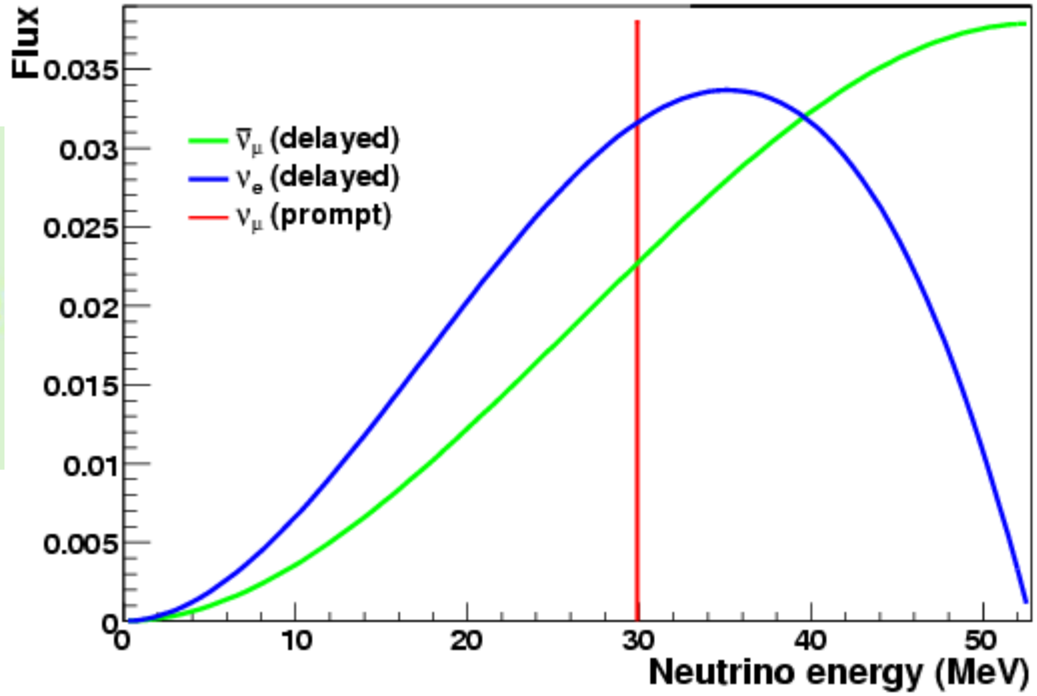
Does not exist yet

Reactor vs stopped-pion for CENNS

Source	Flux/ ν's per s	Flavor	Energy	Pros	Cons
Reactor 	2e20 s^{-1} per GW	nuebar	few MeV	• huge flux	• lower xscn • require very low threshold • CW
Stopped pion 	1e15 s^{-1}	numu/ nue/ nuebar	0-50 MeV	• higher xscn • higher energy recoils • pulsed beam for bg rejection • all flavors	• lower flux • potential fast neutron in-time bg

Stopped-Pion (DAR) Neutrinos





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

2-body decay: monochromatic 29.9 MeV ν_μ PROMPT

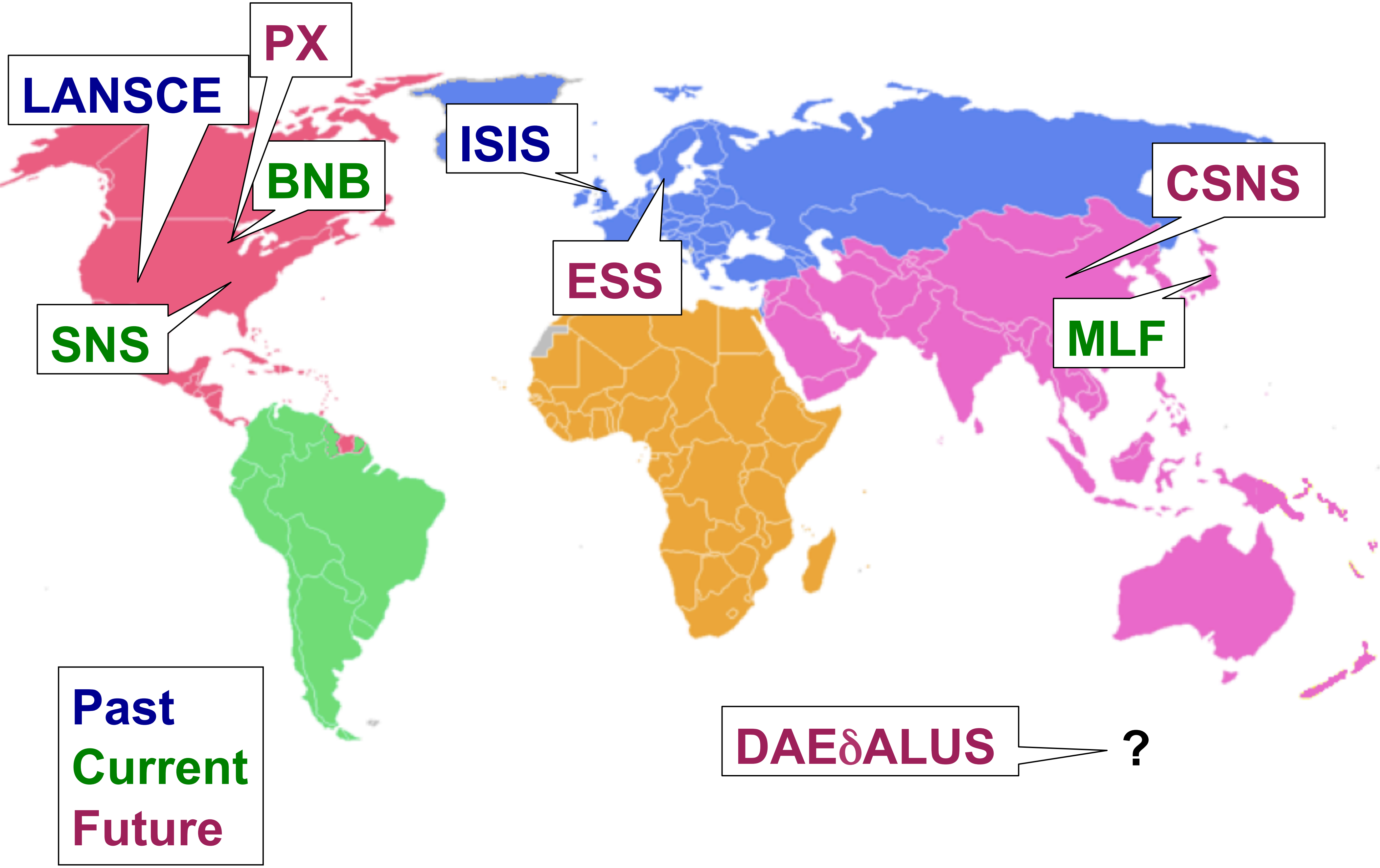
$$\downarrow$$

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

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

Stopped-Pion Sources Worldwide



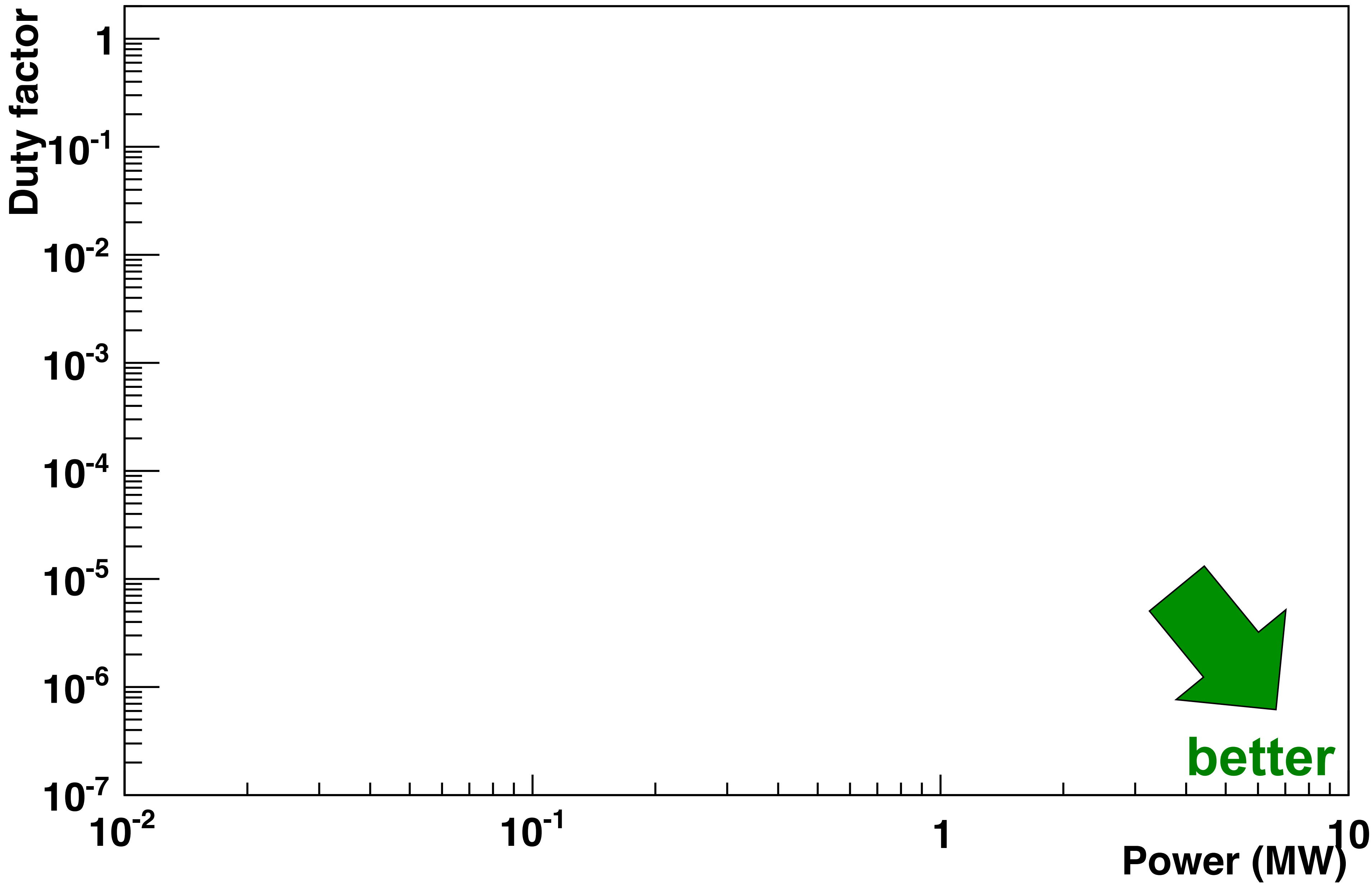
Comparison of stopped-pion neutrino sources

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 × 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 × 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)

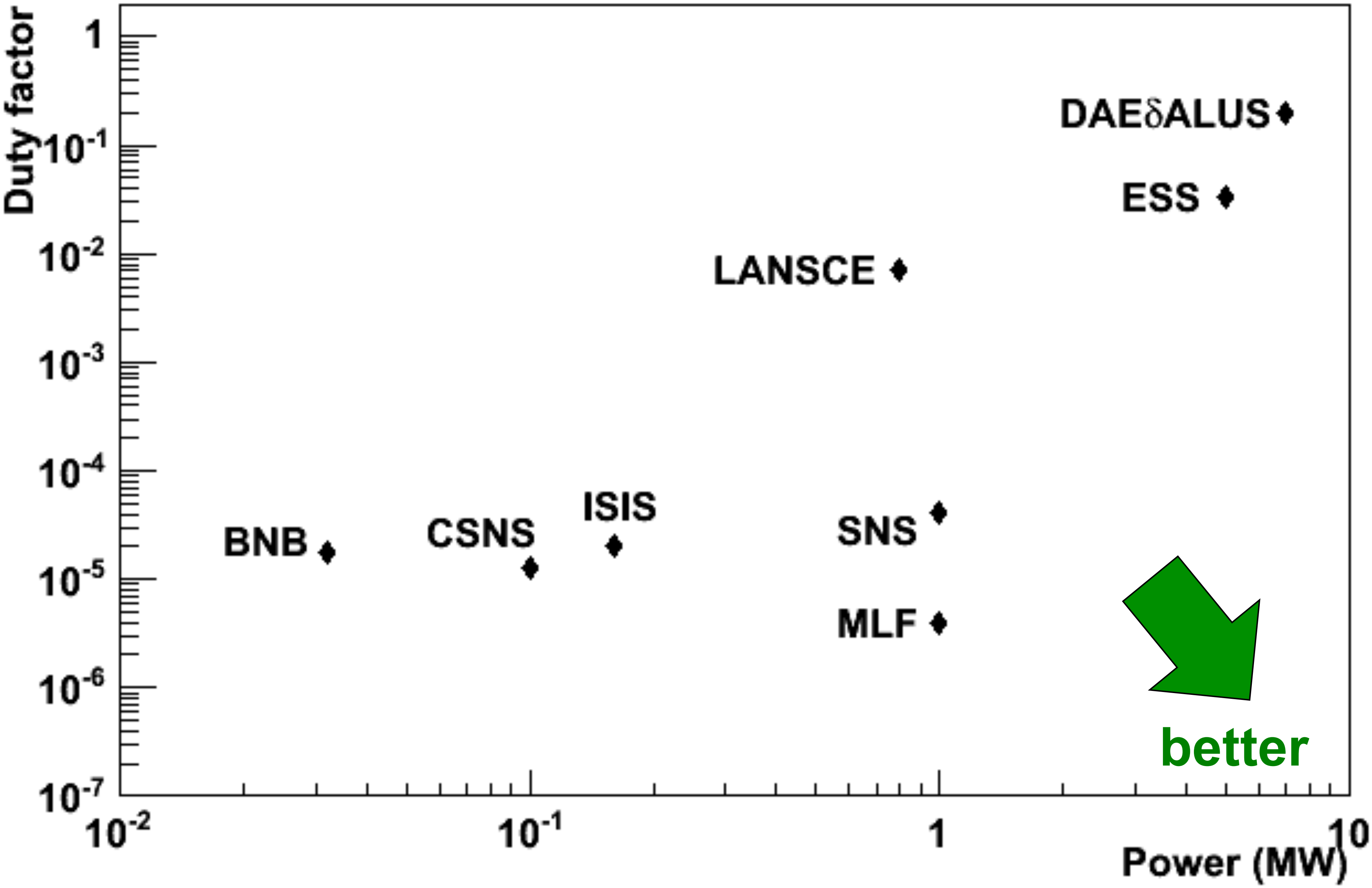
Flux $\propto$ power: want bigger!

Duty factor: want smaller!



Flux $\propto$ power

Duty factor = T*rate (◆)

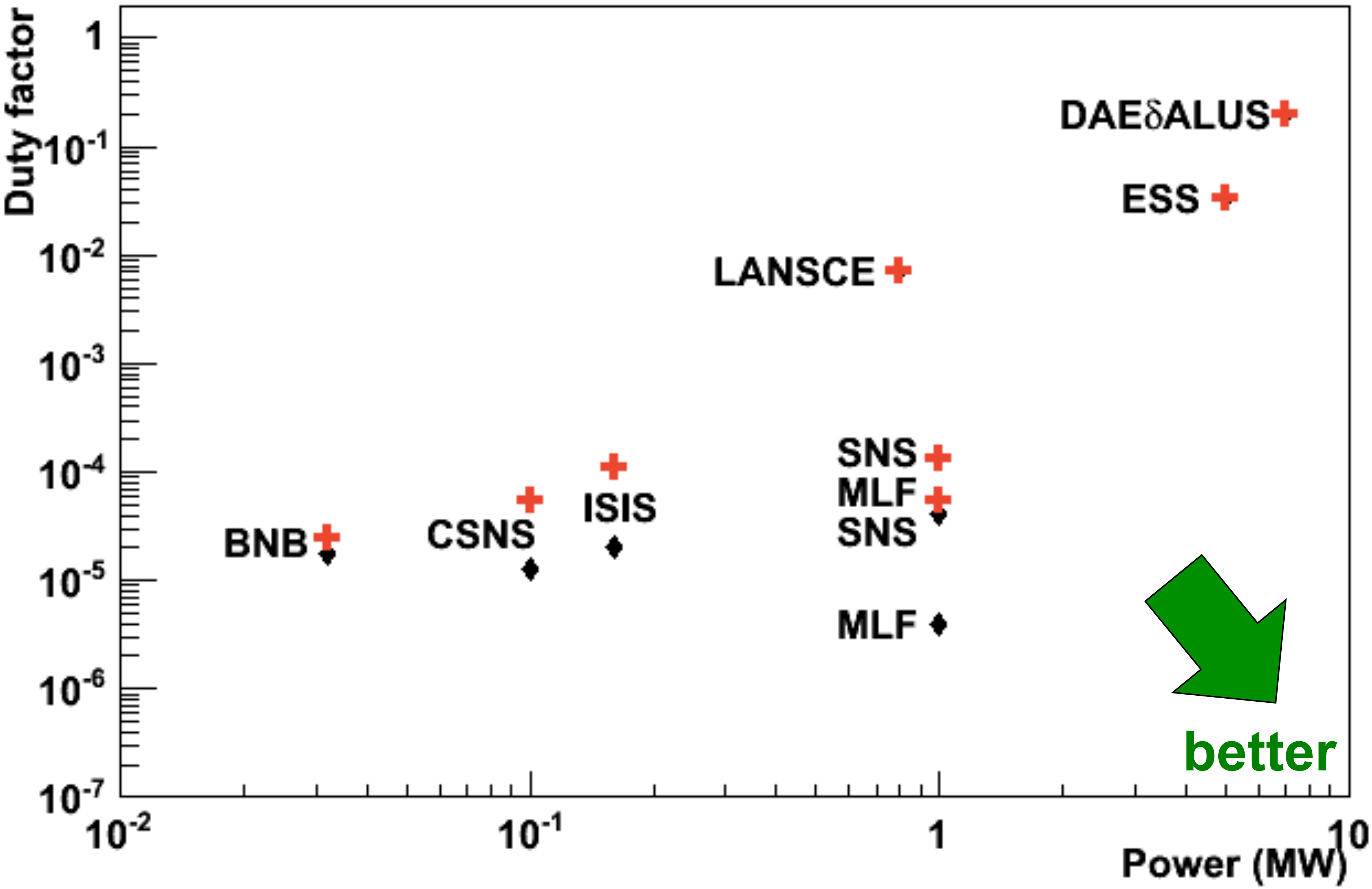


Flux $\propto$ power

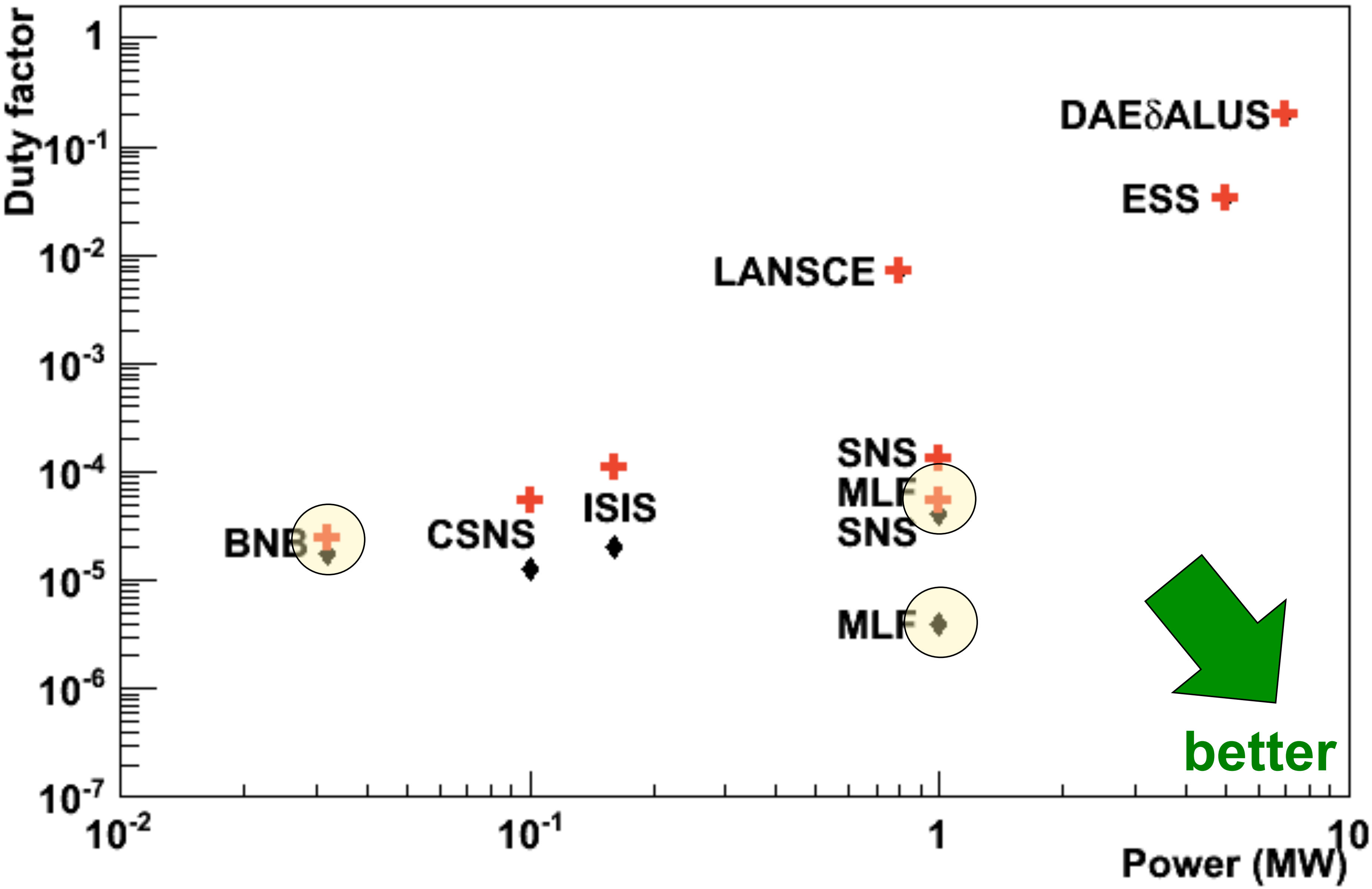
Duty factor = T*rate (◆)

= max(T, 2.2 μs)*rate (+ for μdk ν's)

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



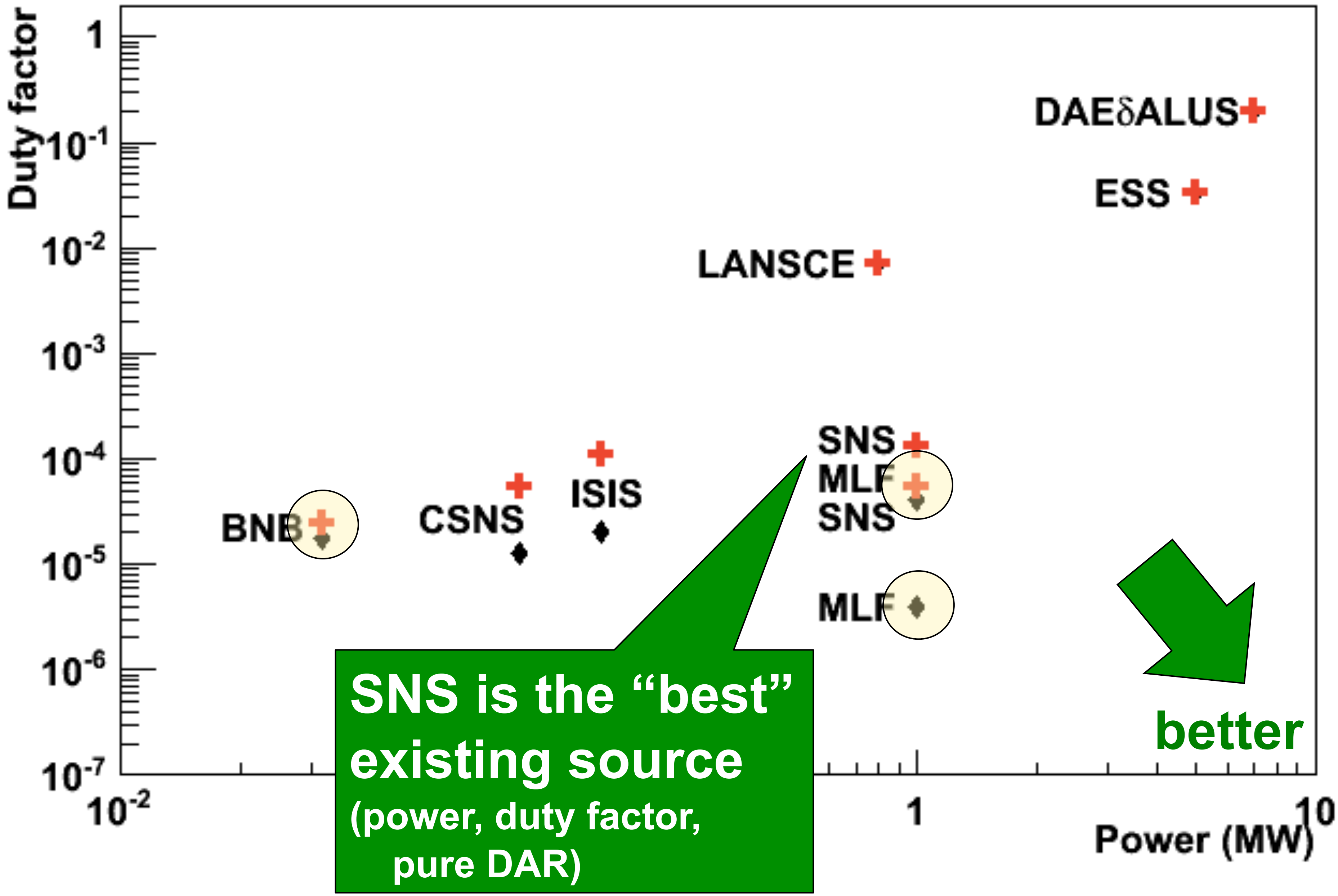
Flux ∝ power, (circle) high energy protons (non-DAR contamination)
Duty factor = T*rate (◆)
= max(T, 2.2 μs)*rate (+ for μdk ν's)



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

Duty factor = T*rate (◆)

= max(T, 2.2 μs)*rate (+ for μdk ν's)

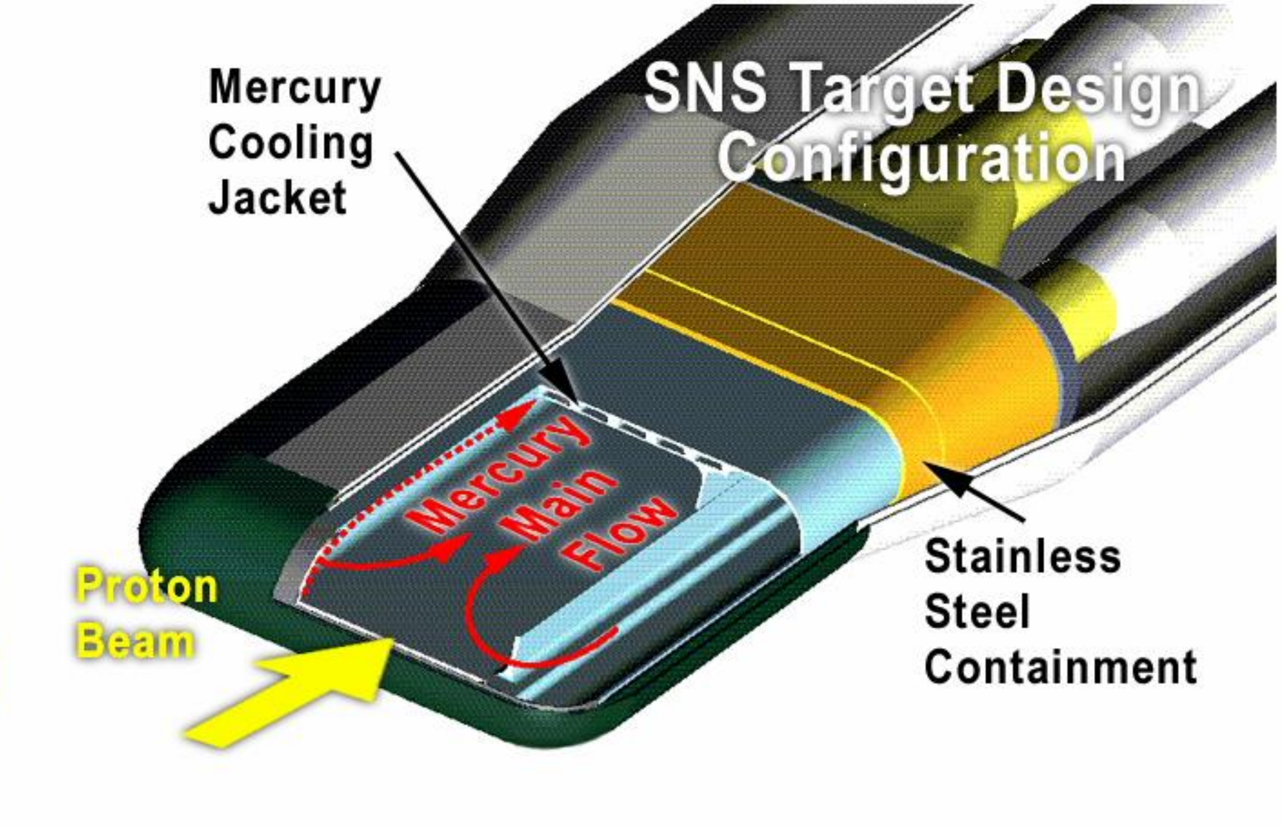


Prospects at the SNS: Free Neutrinos!

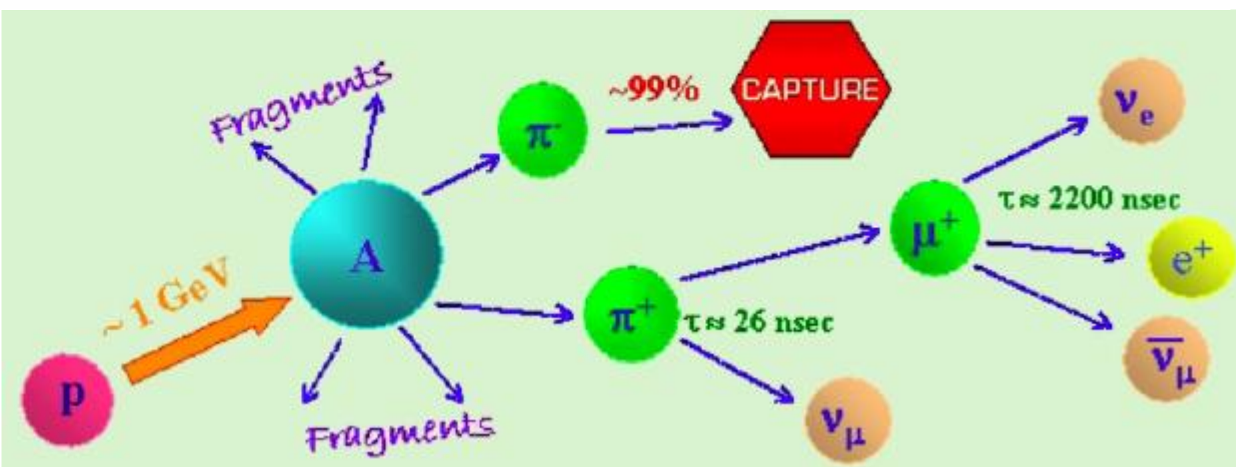

1.3 GeV proton linear accelerator
Accumulator ring
Front-End Building
Klystron Building
Central Helium Liquefaction Building
Linac Tunnel
Ring
Radio-Frequency Facility
Target
Future Target Building
Support Buildings
Central Laboratory and Office Complex
Center for Nanophase Materials Sciences
Joint Institute for Neutron Sciences
01-04517/arm
Main target

Y. Efremenko

The SNS as a Stopped-Pion Neutrino Source

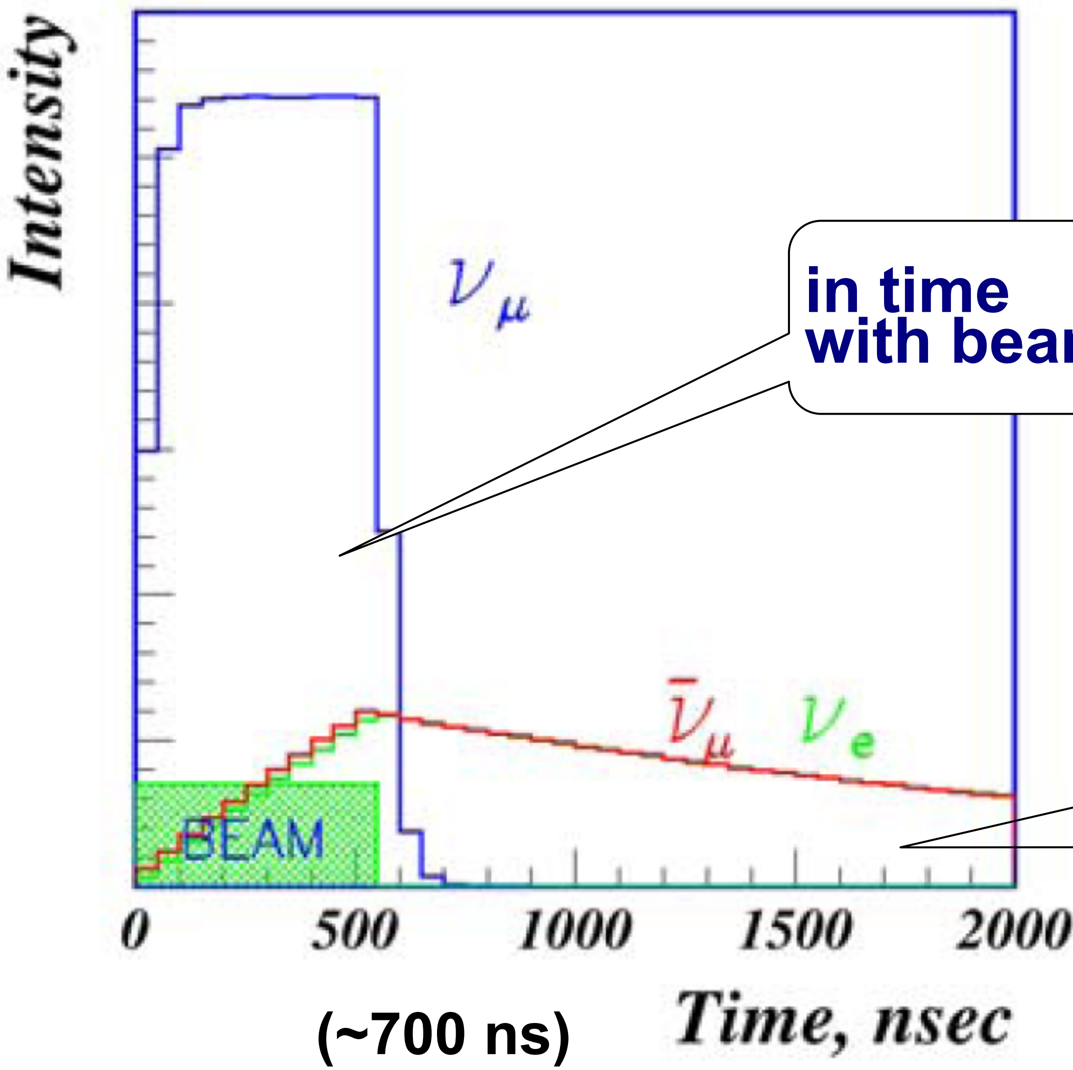


In addition to kicking out neutrons, protons on target create copious pions:
π^- get captured;
π^+ slow and decay at rest



Time structure of the SNS source

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

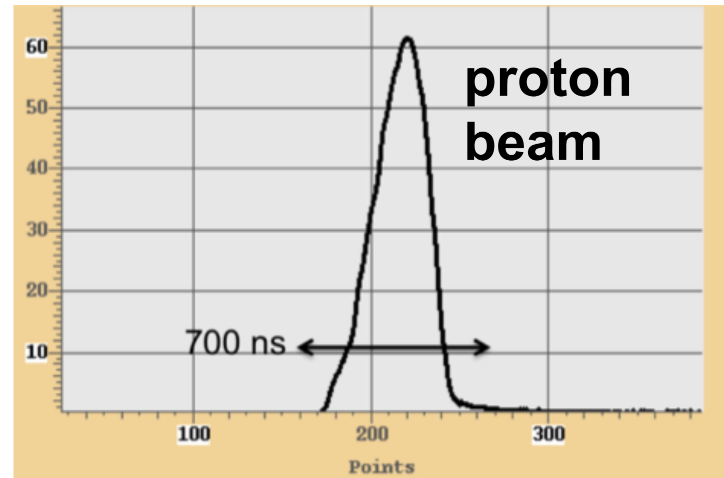


in time with beam

(~700 ns)

delayed on μ decay timescale (2.2 μs)

60 Hz *pulsed* source



proton beam

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

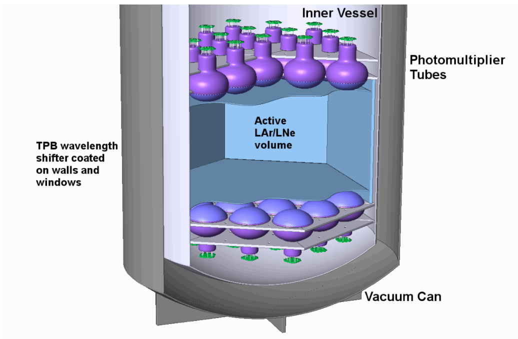
Neutrino flux: few times 10^{7} /s/cm^{2} at 20 m

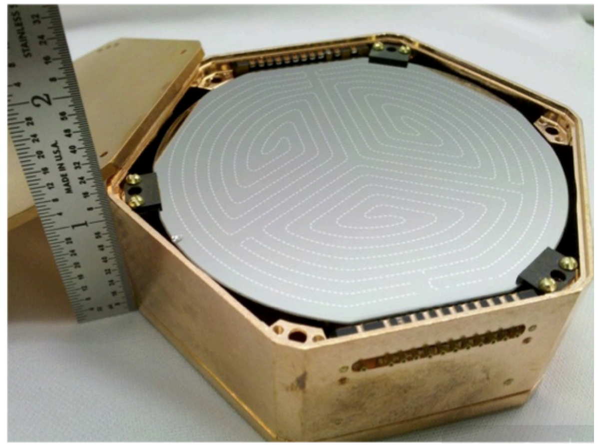
~0.13 per flavor per proton

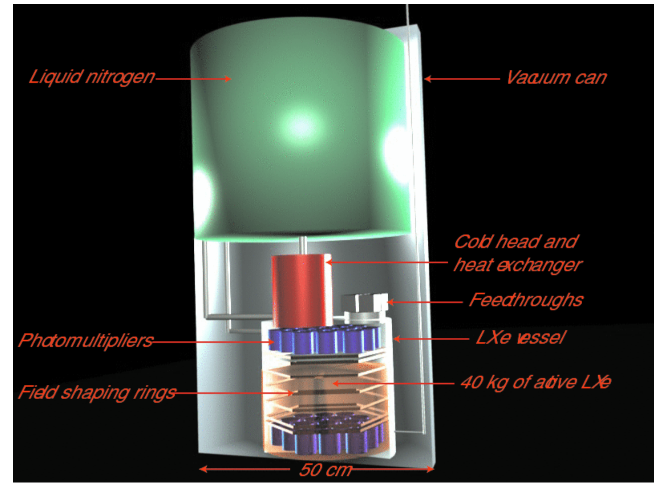
These are *not* crummy old cast-off neutrinos...

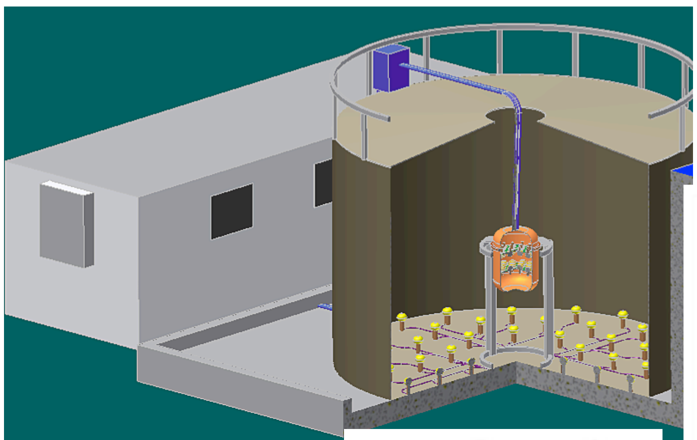
They are of the highest quality!

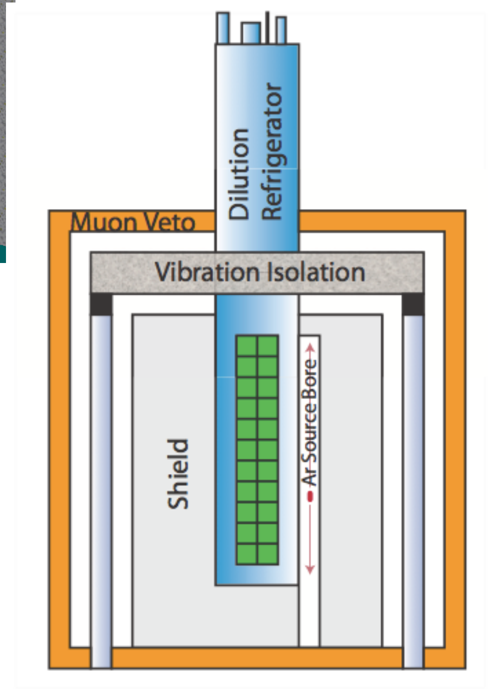
Detector possibilities: various DM-style strategies

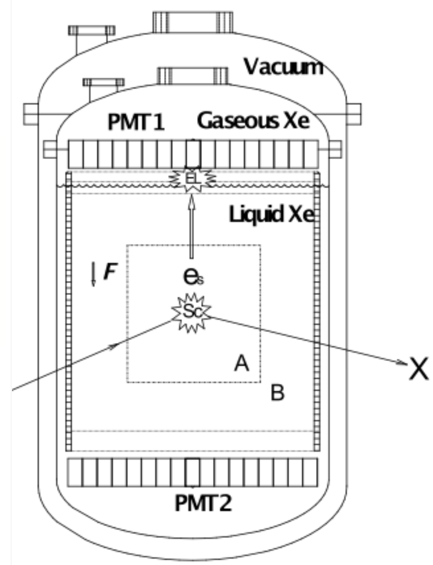


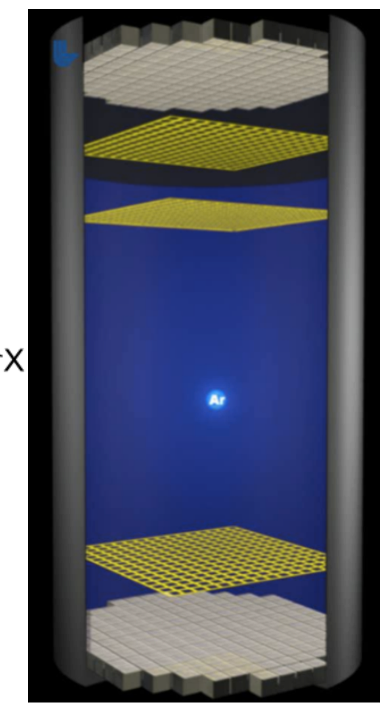




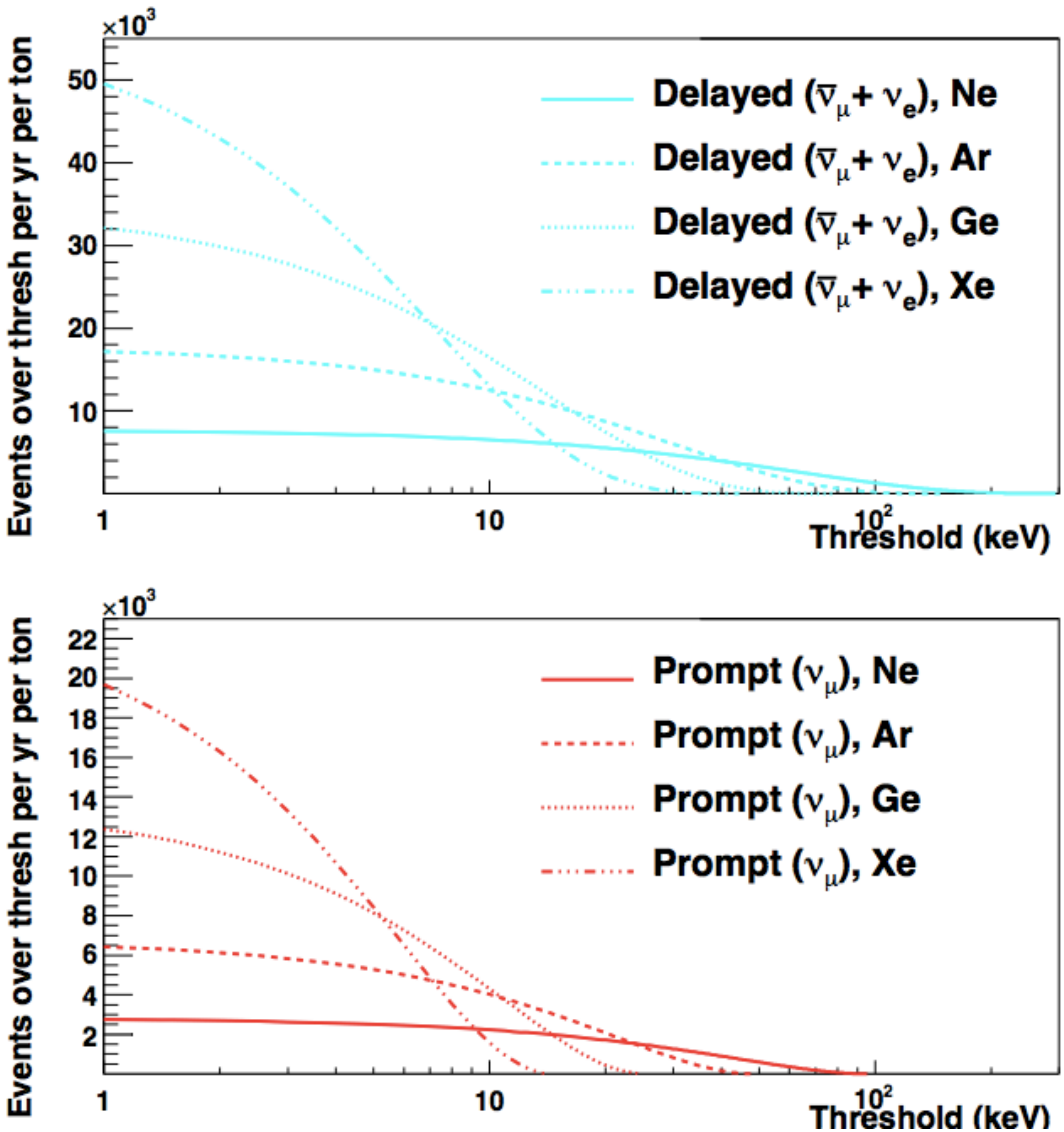








Integrated SNS yield for various targets



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

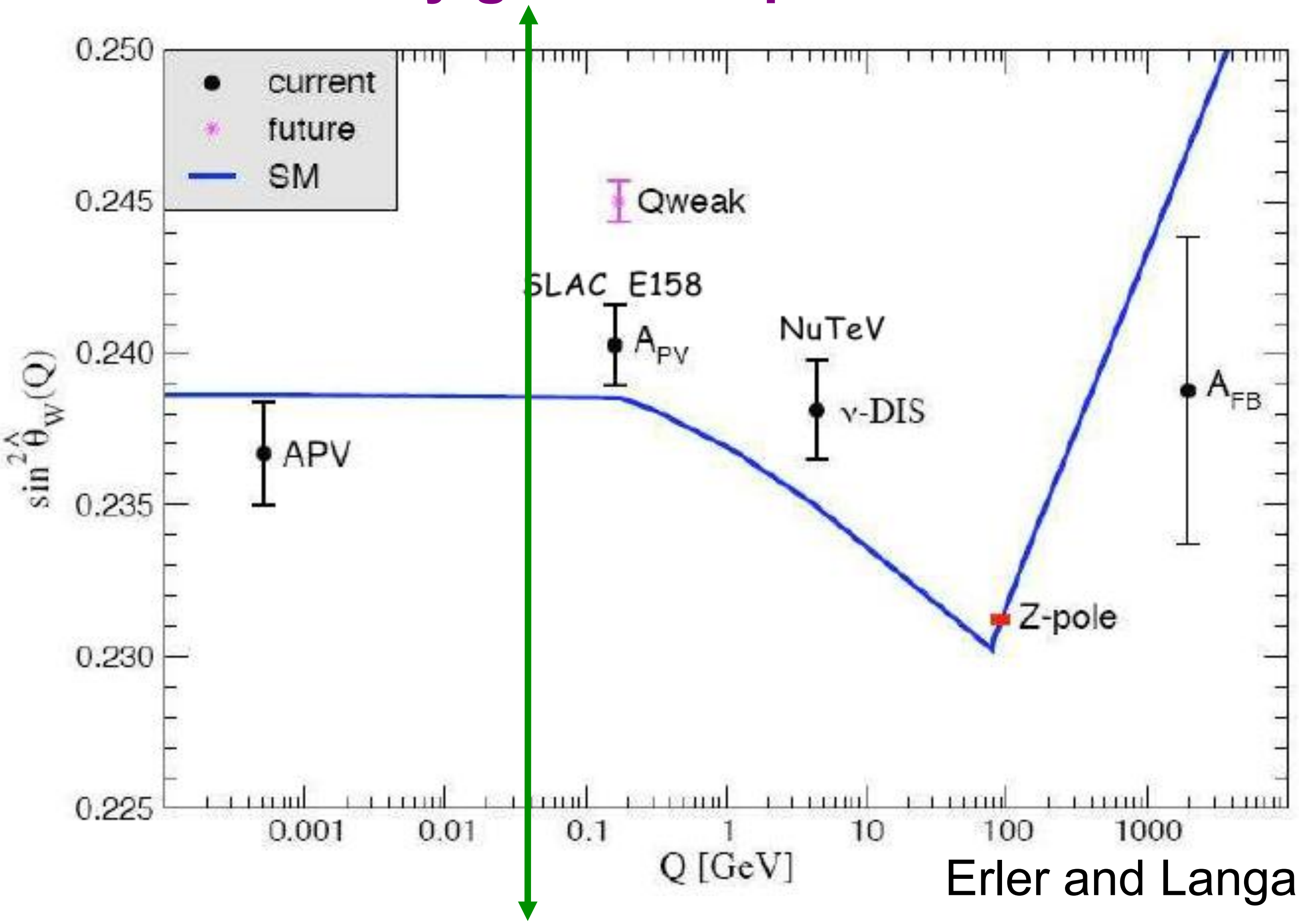
Absolute rate in SM is proportional to

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

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%

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** $\alpha \neq \beta$

⇒ focus on poorly-constrained (~unity allowed)

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

Cross-section for CENNS 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

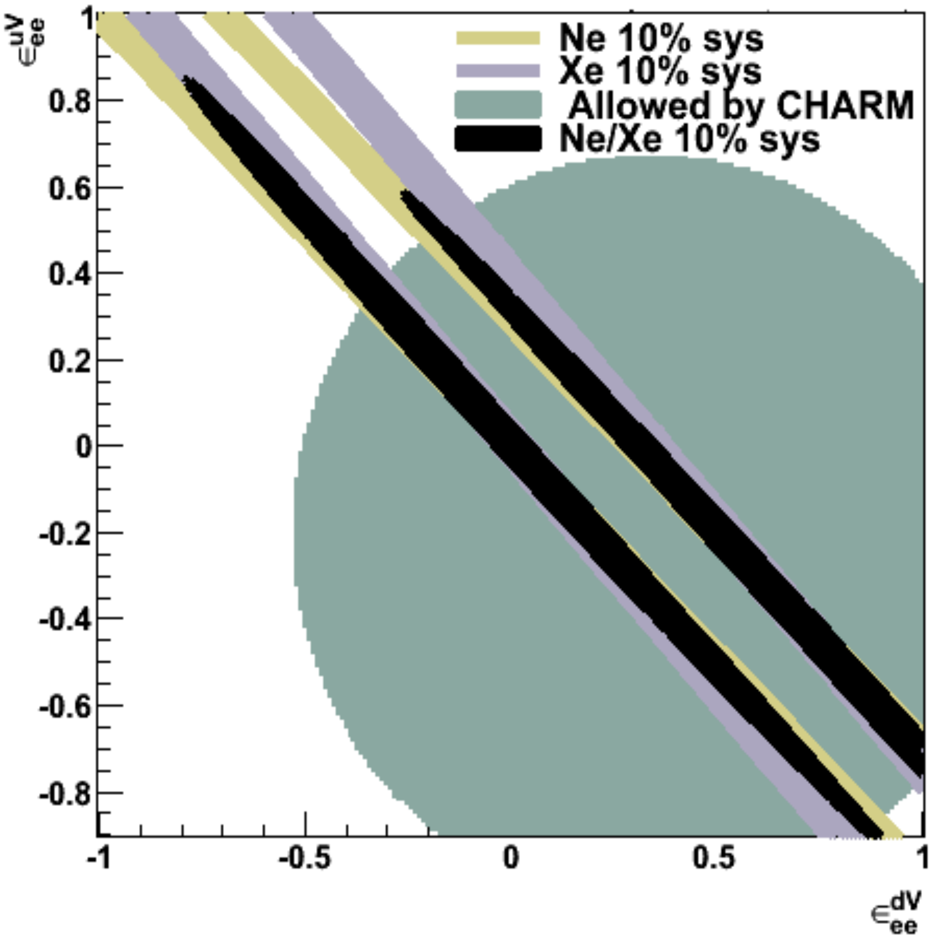
$$g_V^p = (\frac{1}{2} - 2\sin^2\theta_W), \quad g_V^n = -\frac{1}{2}$$

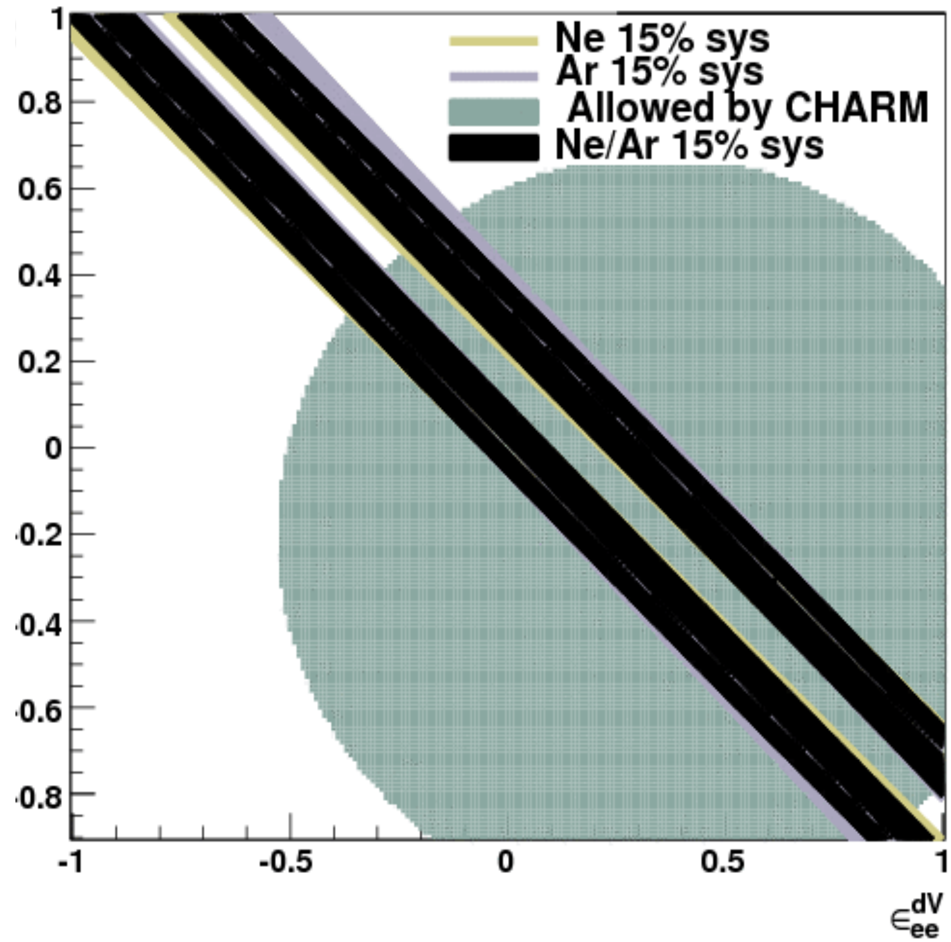
SM parameters

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

- **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**

Non-Standard Interactions of Neutrinos





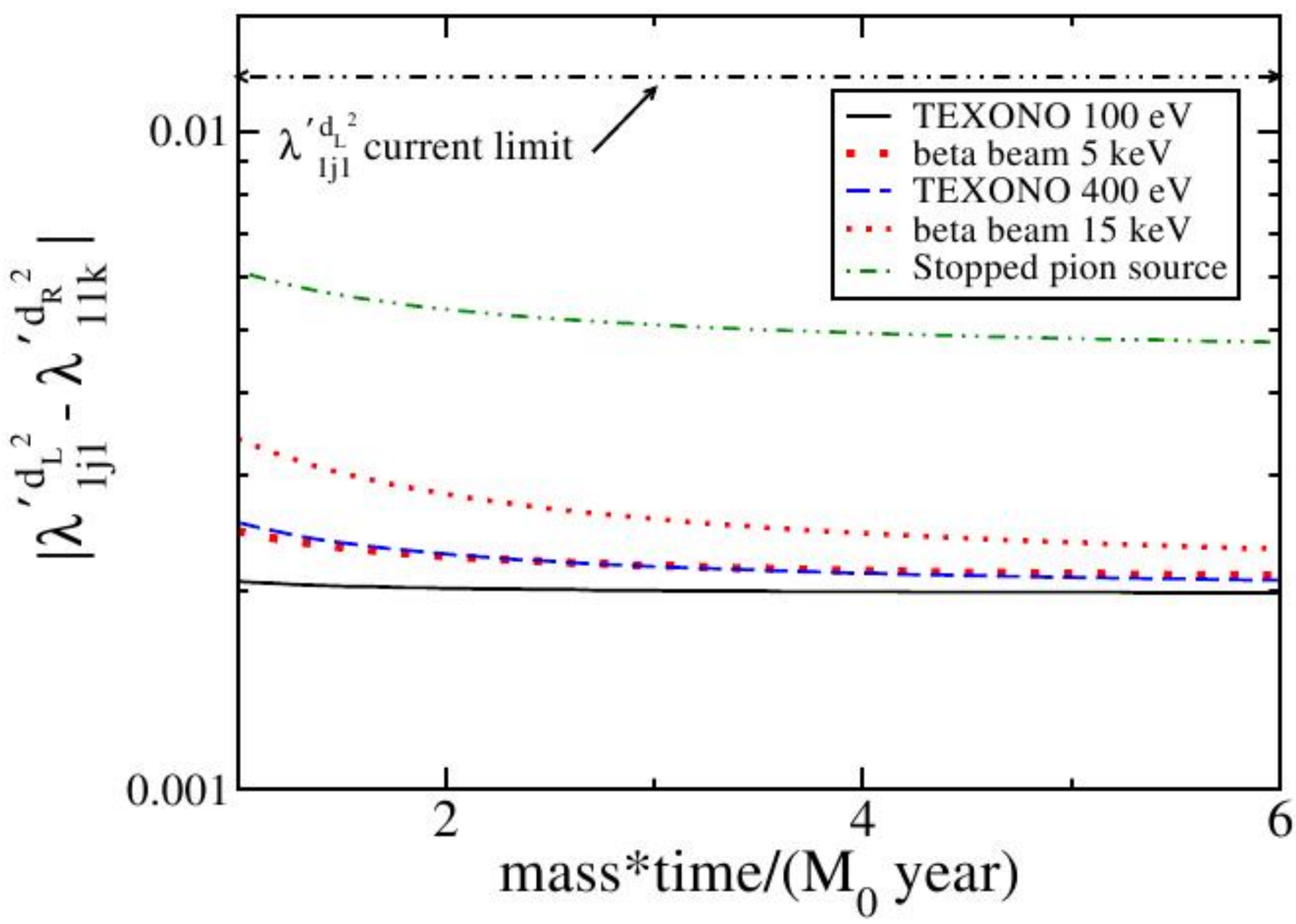
Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment

(for best sensitivity, want *multiple targets*)

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



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 uncertainty on $\sin^2\theta_W$:

Ar/Ne	**2.6%**
Xe/Ne	**1.5%**
Xe/Ar	**3.9%**

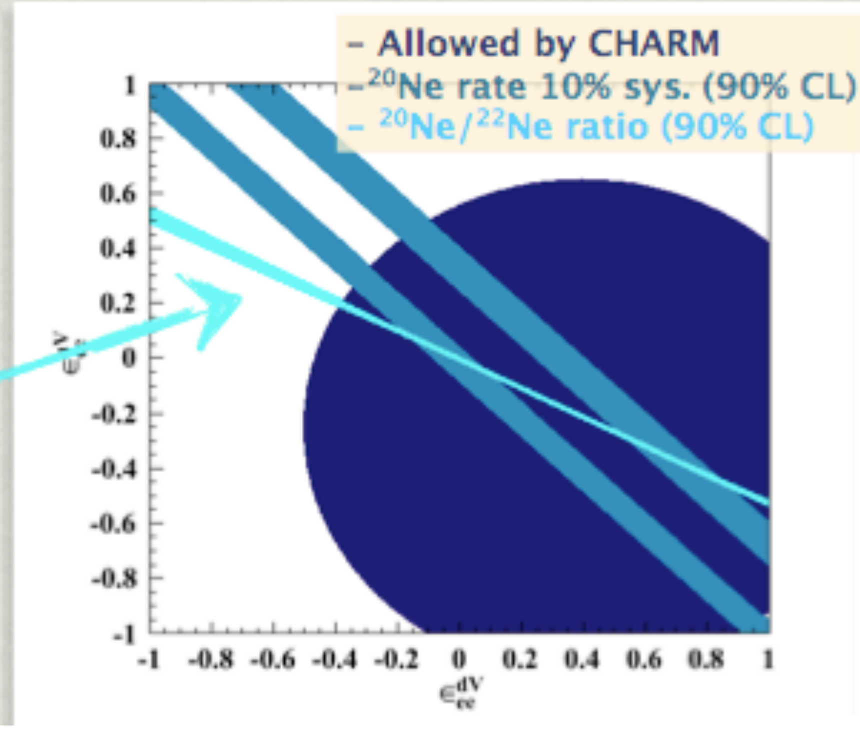
Phil Barbeau

NSI Search with ^{20}Ne-^{22}Ne

$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi} = G_V^2(1 + (1 - \frac{T}{E_\nu})^2 - \frac{MT}{E_\nu})$$

$$G_V = ((g_v^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_v^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N)F_{nucl}^V(Q^2)$$

- We take advantage of the precision in the ^{20}Ne/^{22}Ne system (^{132}Xe/^{136}Xe system less sensitive)
- If we include the SM radiative corrections, as well as statistical & systematic uncertainties, the ratio of the interaction rates for ^{20}Ne/^{22}Ne gives (For several tons of Ne)



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 CENNS scattering rate

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

SM cross-section:

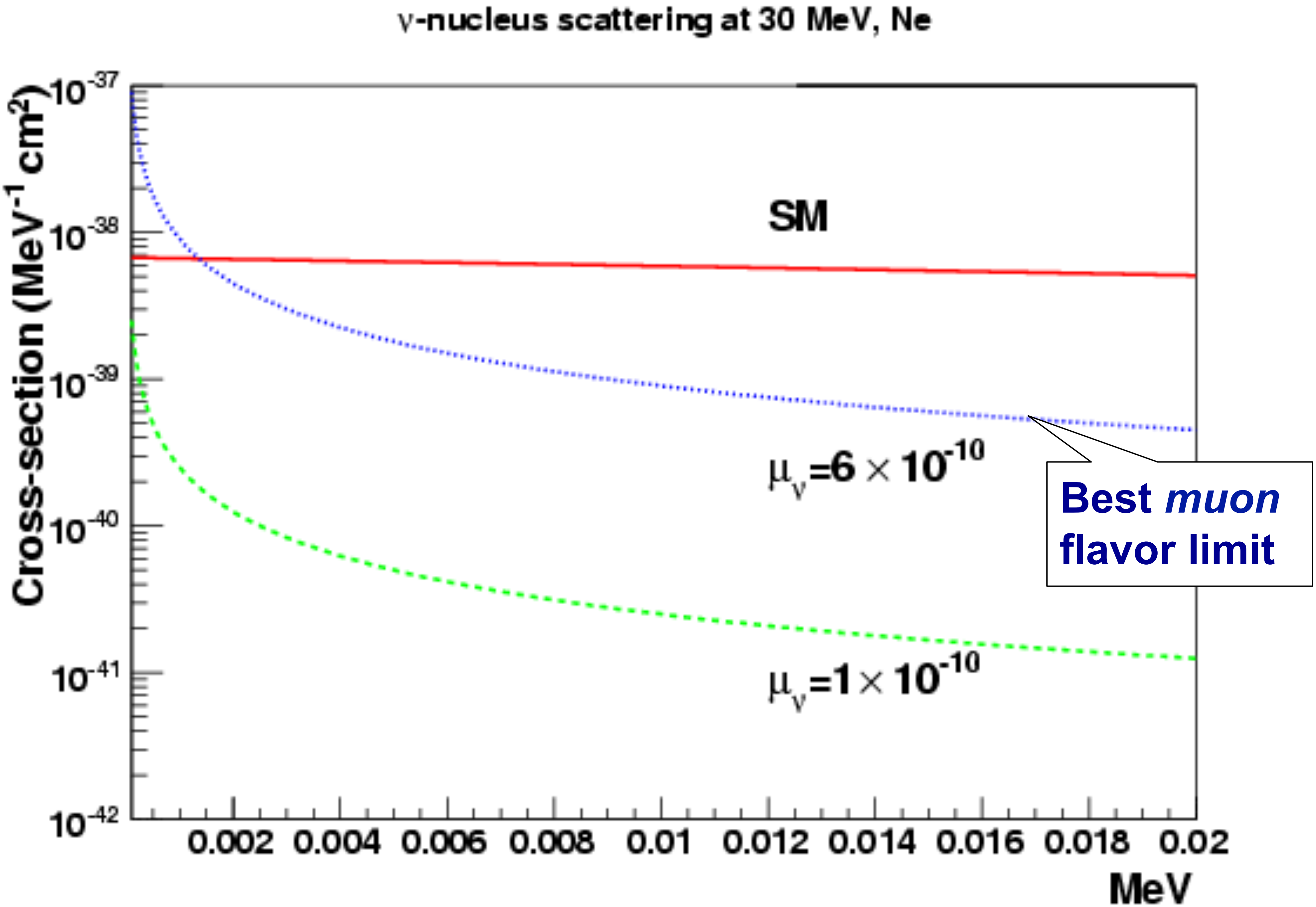
$$\frac{d\sigma}{dE} = \frac{G^2}{\pi} M \left(1 - \frac{ME}{2k^2}\right) \frac{N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

Magnetic cross-section:

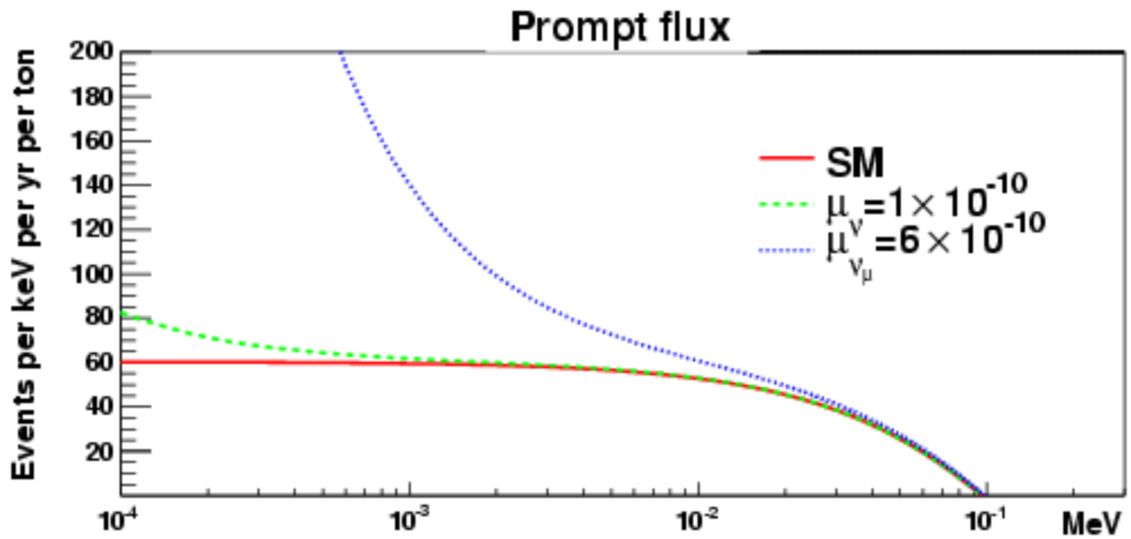
$$\frac{d\sigma}{dE} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2} \left(\frac{1 - E/k}{E} + \frac{E}{4k^2}\right)$$

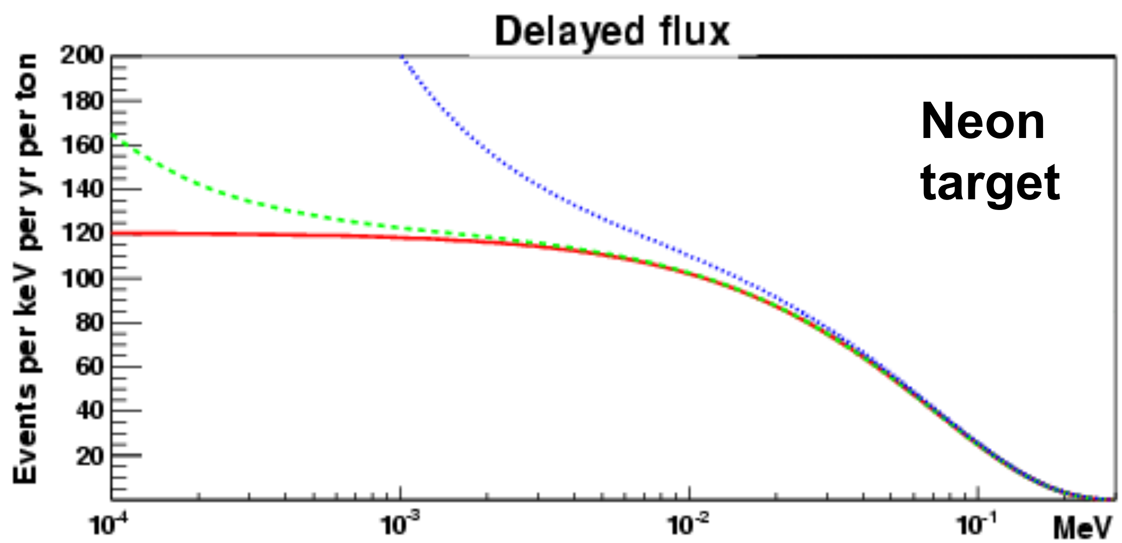
(factor Z^2 instead of Z for electrons)

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 $\mu_\nu=6\text{x}10^{-10}$ μ_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,

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

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

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

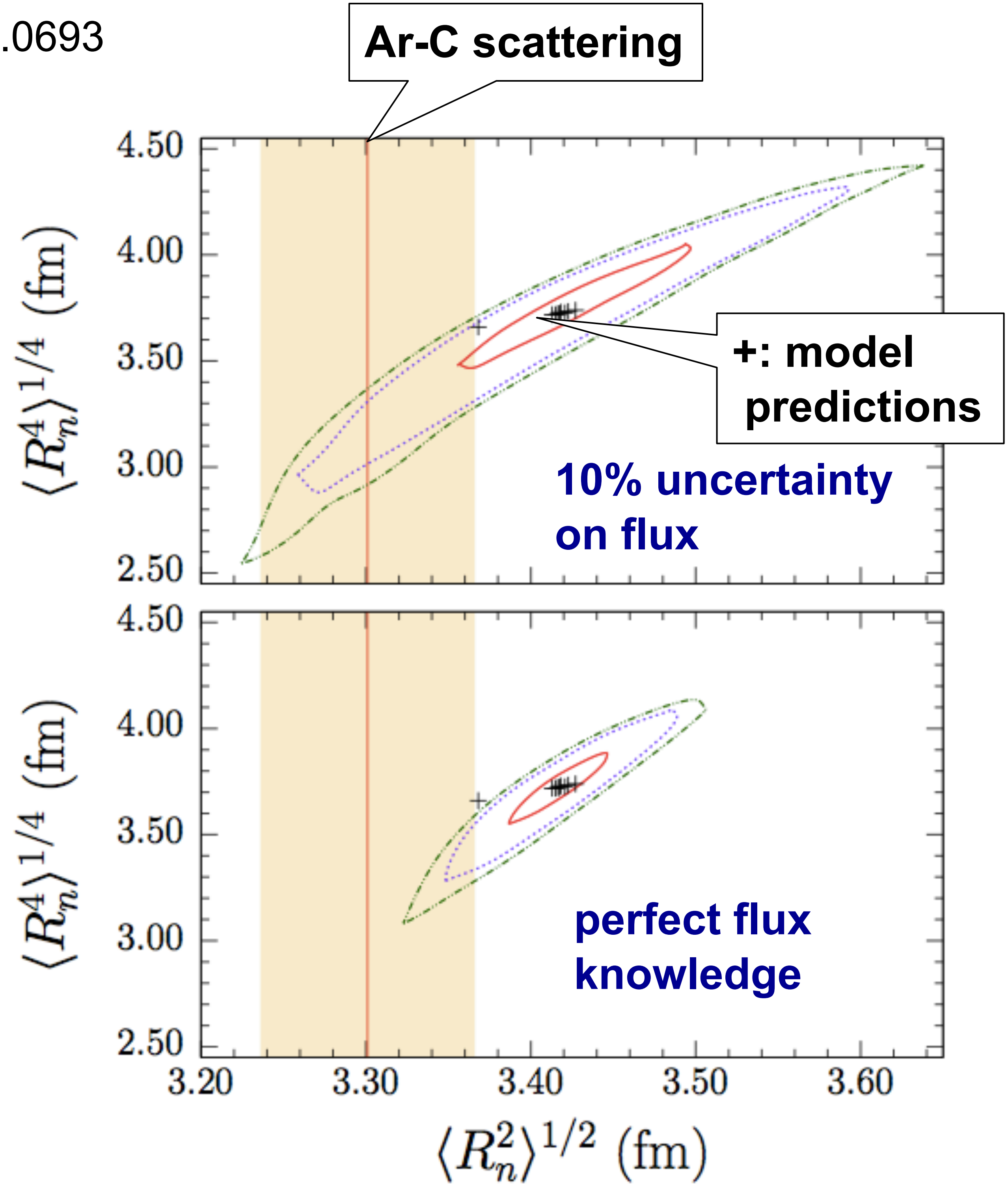
Fit recoil *spectral shape* to determine these moments

(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 on recoil energy



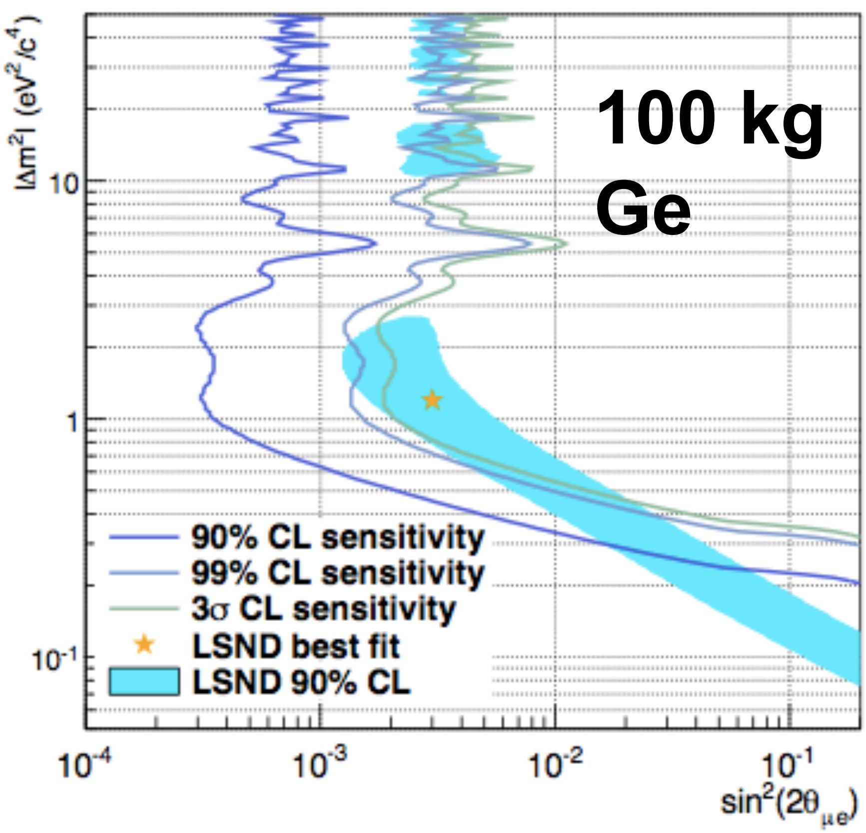
Oscillations to sterile neutrinos w/CENNS

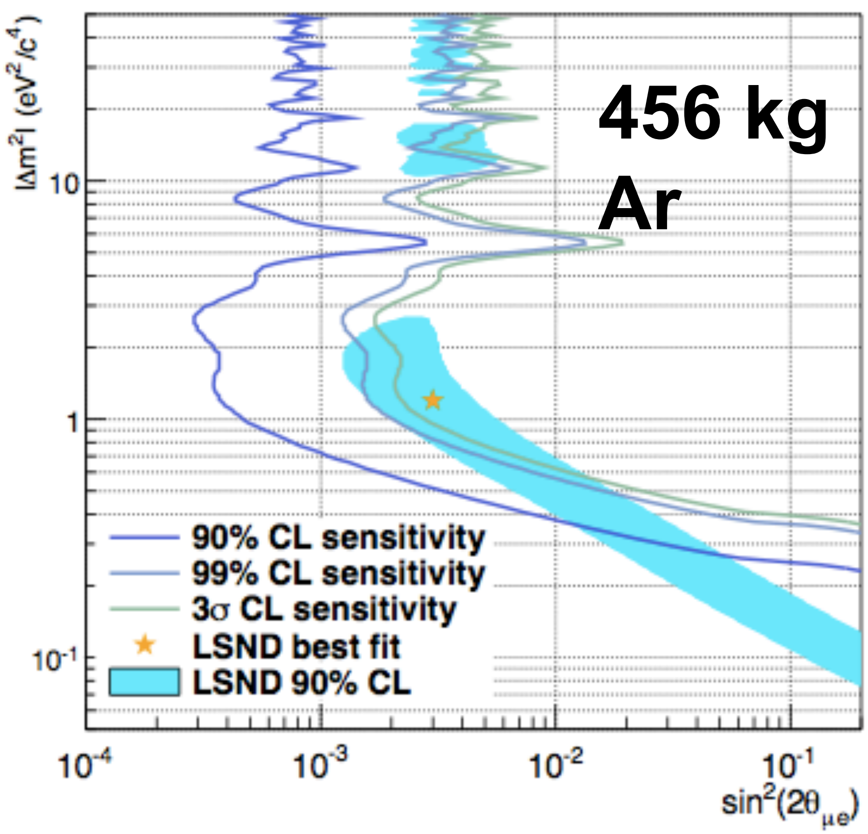
(NC is flavor-blind)

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): *muon* flavor**
  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 distributions:**
  hard but conceivable; need good energy resolution, control of systematics

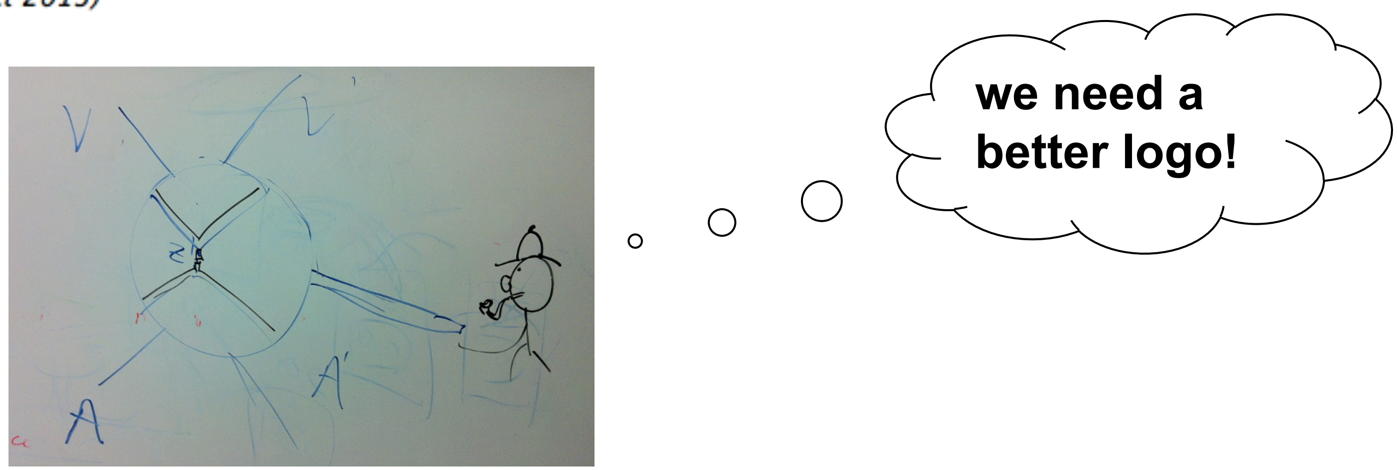
Possible phases of stopped-pion CENNS scattering experiments

Phase	Detector Scale	Physics Goal	Comments
Phase I	Few to few tens of kg	First detection	Precision flux/ systematics 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

Coherent Scattering Investigations at the Spallation Neutron Source: a Snowmass White Paper

D. Akimov, A. Bernstein, P. Barbeau, P. Barton, A. Bolozdynya, B. Cabrera-Palmer, F. Cavanna, V. Cianciolo, J. Collar, R.J. Cooper, D. Dean, Y. Efremenko, A. Etenko, N. Fields, M. Foxe, E. Figueroa-Feliciano, N. Fomin, F. Gallmeier, I. Garishvili, M. Gerling, M. Green, G. Greene, A. Hatzikoutelis, R. Henning, R. Hix, D. Hogan, D. Hornback, I. Jovanovic, T. Hossbach, E. Iverson, S.R. Klein, A. Khromov, J. Link, W. Louis, W. Lu, C. Mauger, P. Marleau, D. Markoff, R.D. Martin, P. Mueller, J. Newby, J. Orrell, C. O'Shaughnessy, S. Pentilla, K. Patton, A.W. Poon, D. Radford, D. Reyna, H. Ray, K. Scholberg, V. Sosnovtsev, R. Tayloe, K. Vetter, C. Virtue, J. Wilkerson, J. Yoo, C.H. Yu

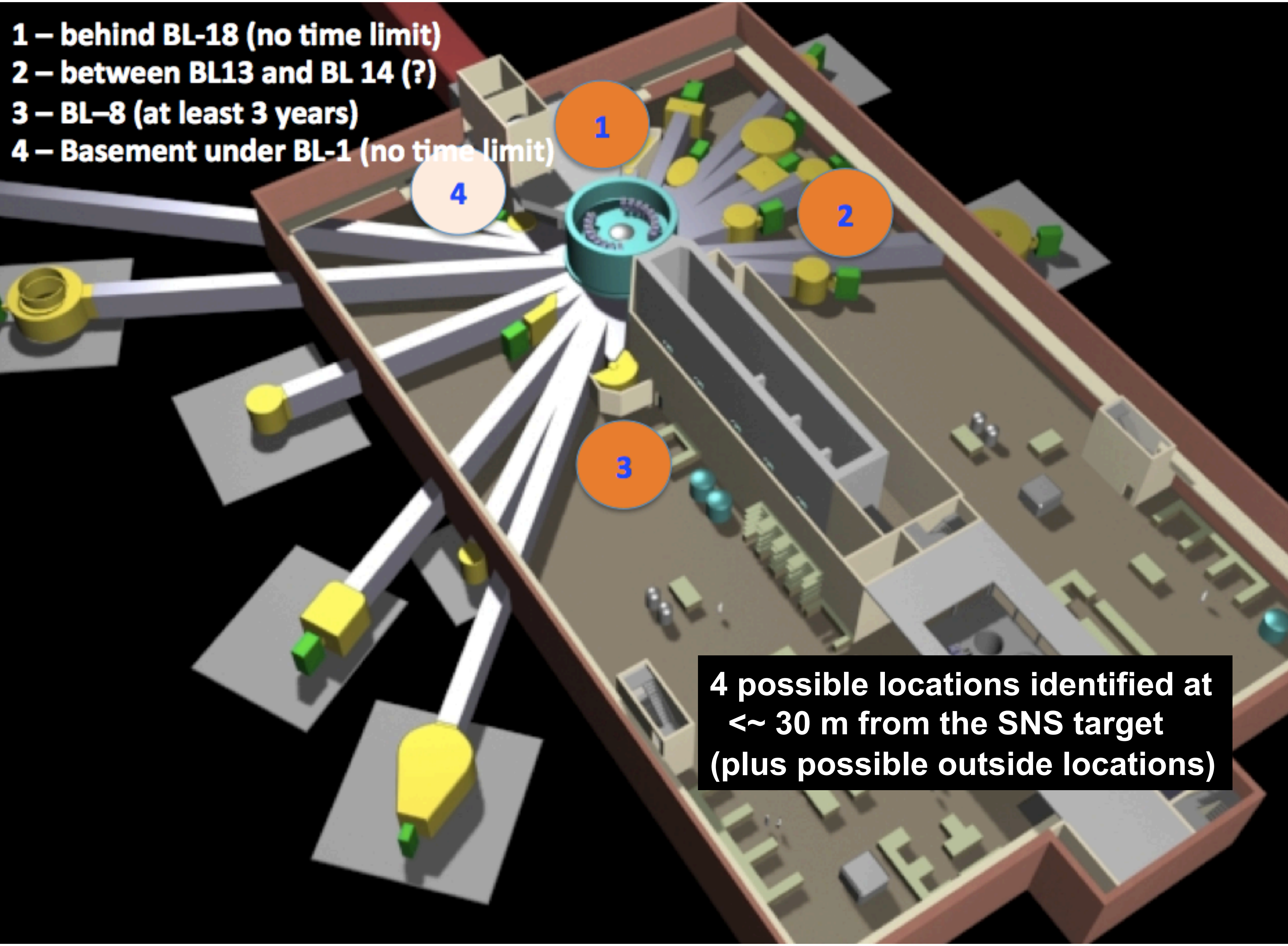
(Submitted on 1 Oct 2013)



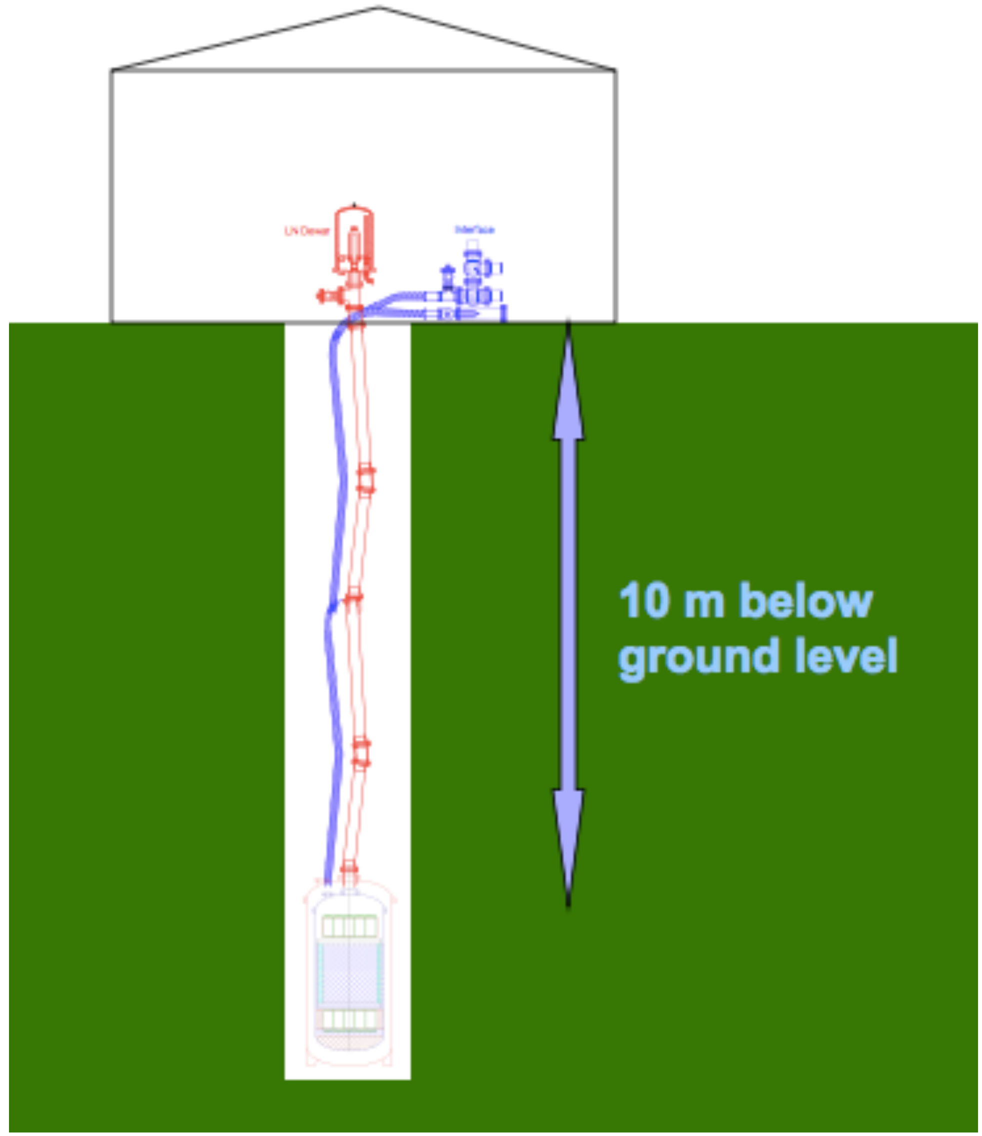
- **collaboration forming now**
- **detector technology choice:**

  must be inexpensive, ready on fast timescale:

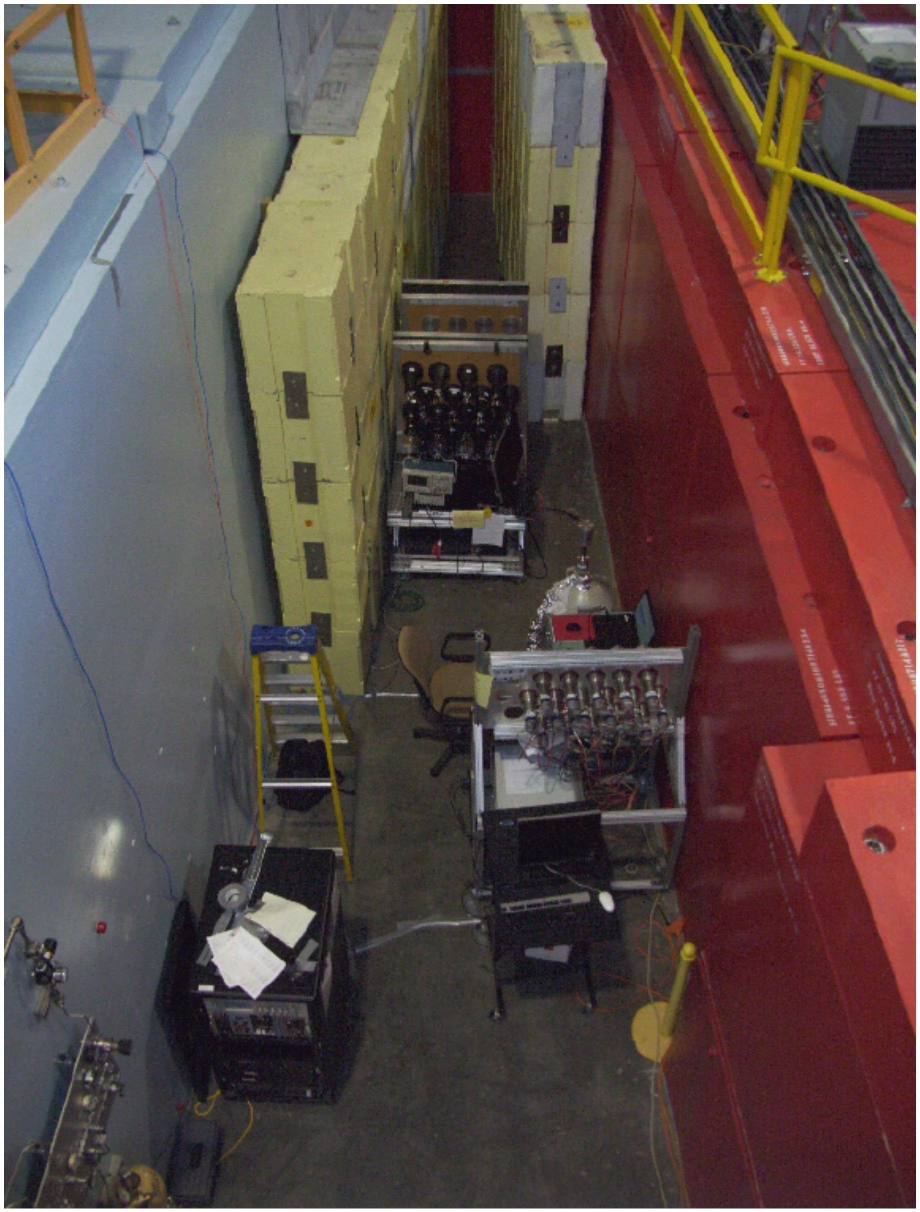
  ➔ CsI, Ge PPC or Xe 2-phase


1 – behind BL-18 (no time limit)
2 – between BL13 and BL 14 (?)
3 – BL–8 (at least 3 years)
4 – Basement under BL-1 (no time limit)
1
2
3
4
4 possible locations identified at
<~ 30 m from the SNS target
(plus possible outside locations)

Could also site outside the target building if backgrounds inside are too high



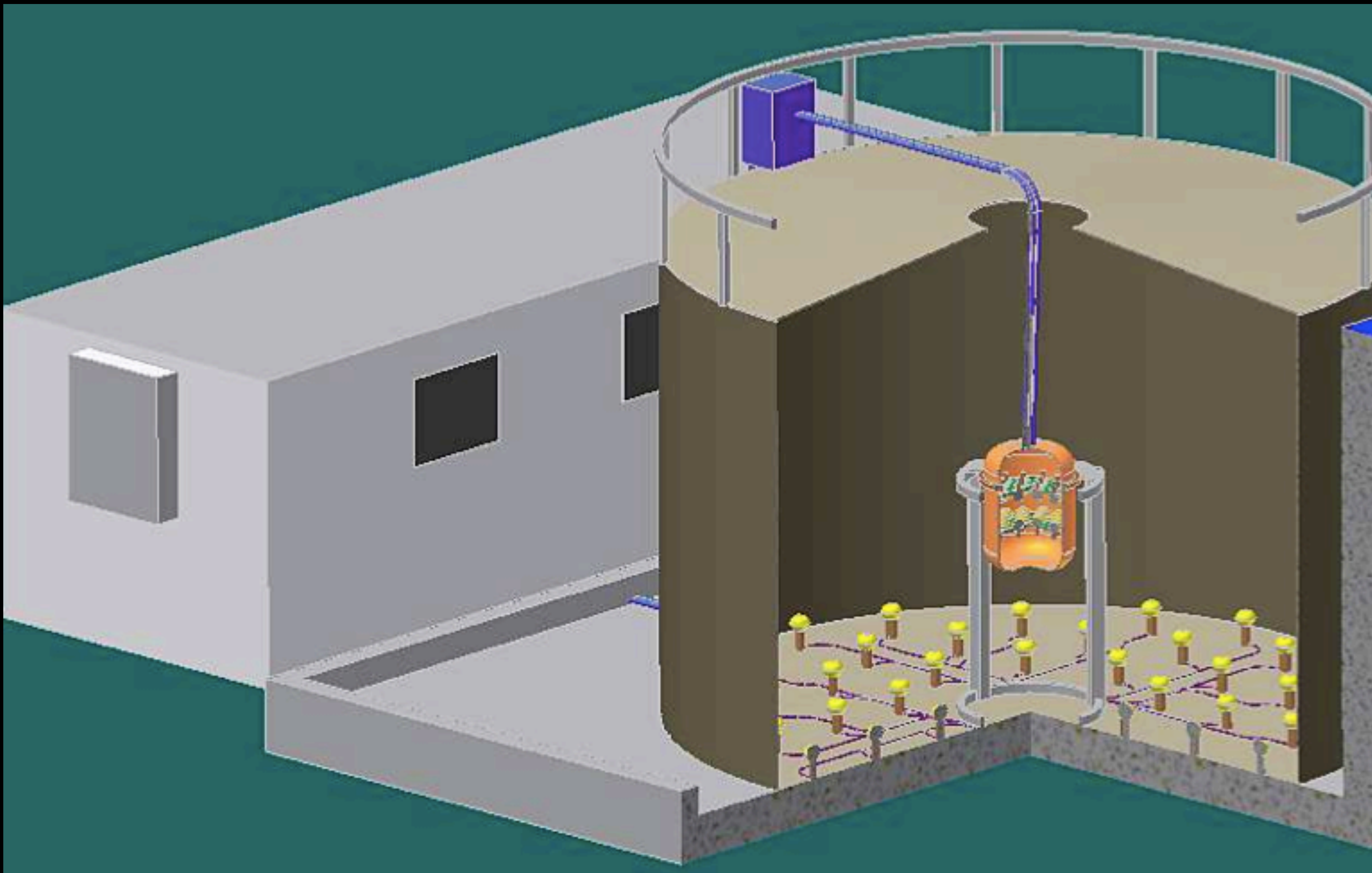
Neutron background measurements underway inside the SNS target building



- Scintillator array (ORNL)
- Neutron scatter camera (Sandia)
- BEGe (LBNL)
- More to come...

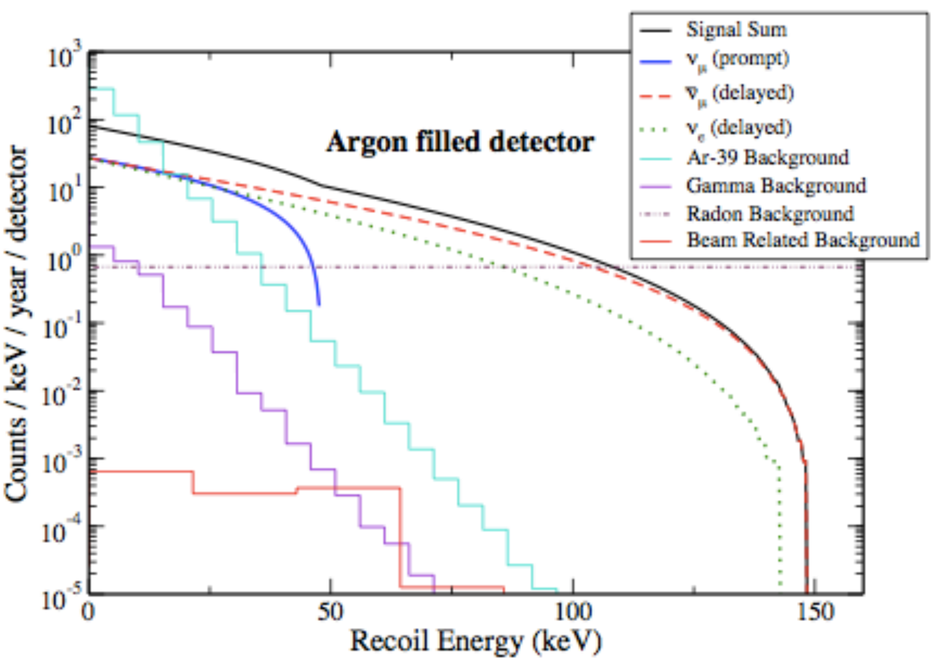
Example Phase 2 Experiment (CLEAR):
~1/2 ton Ar/Ne @ 46 m

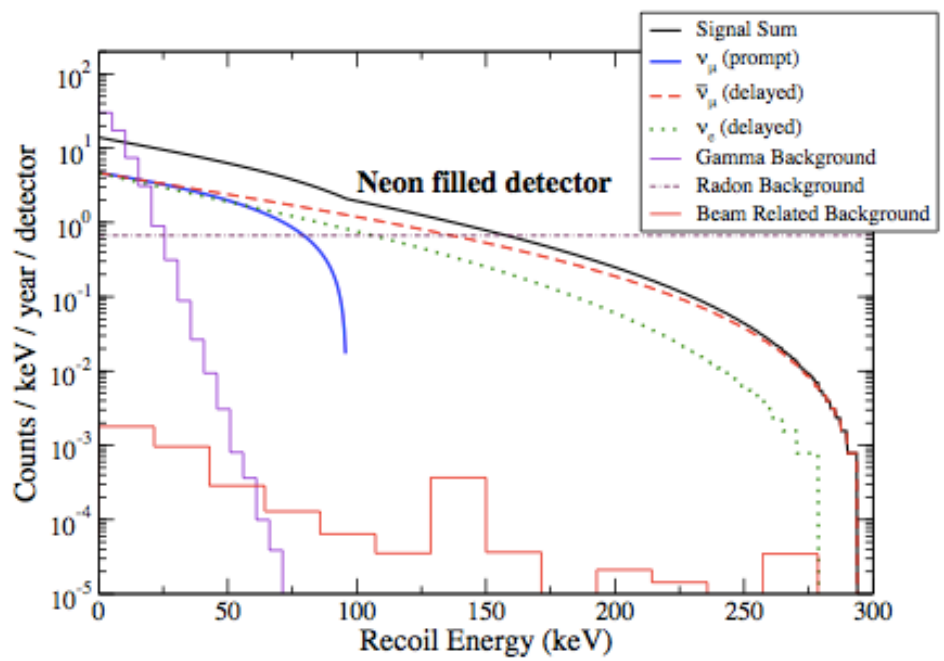
Water tank instrumented with PMTs for cosmic veto + iron shielding



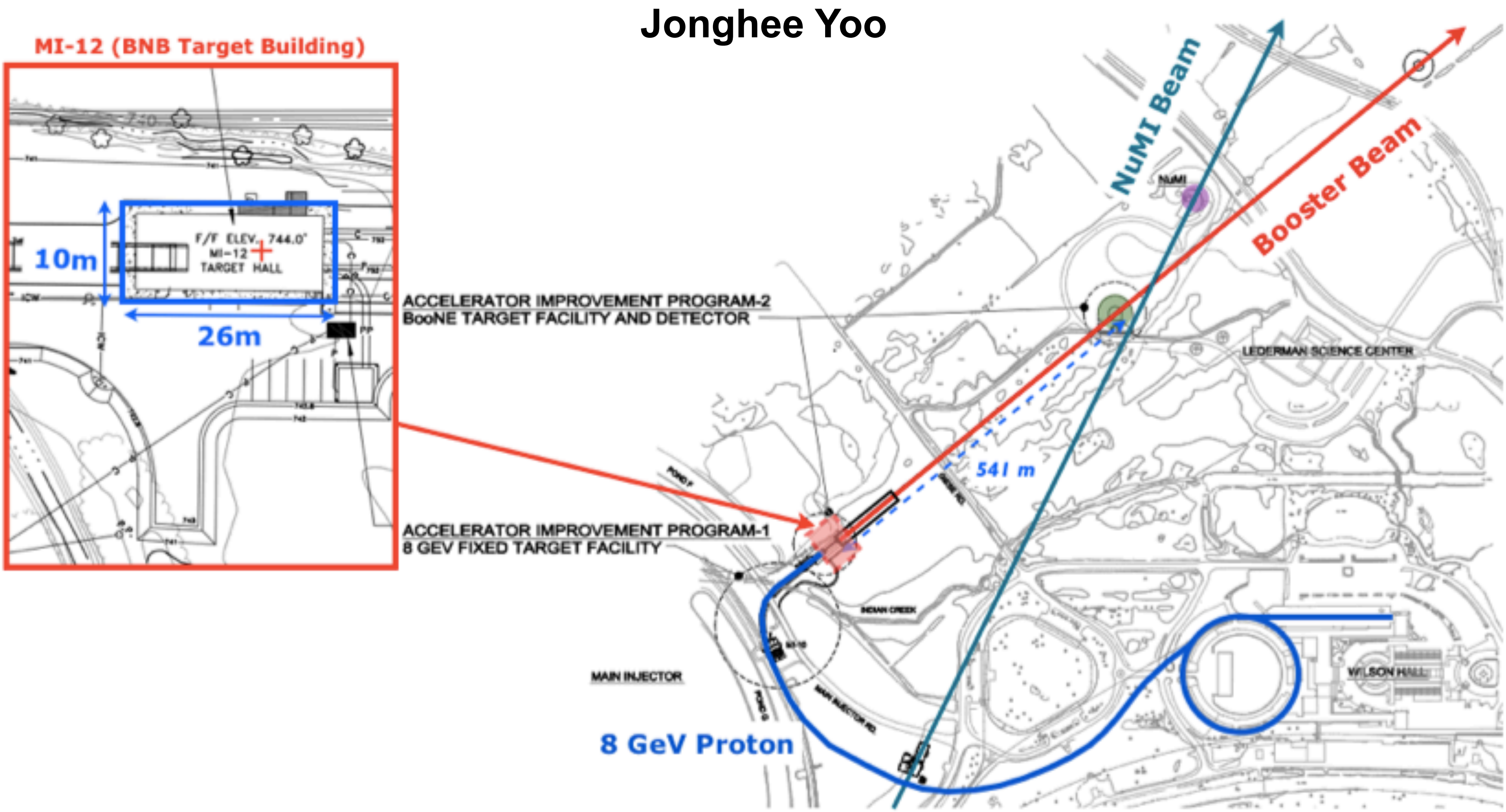
Signal events/year: ~1100 in 456 kg of Ar >20 keVr
~450 in 391 kg of Ne >30 keVr

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

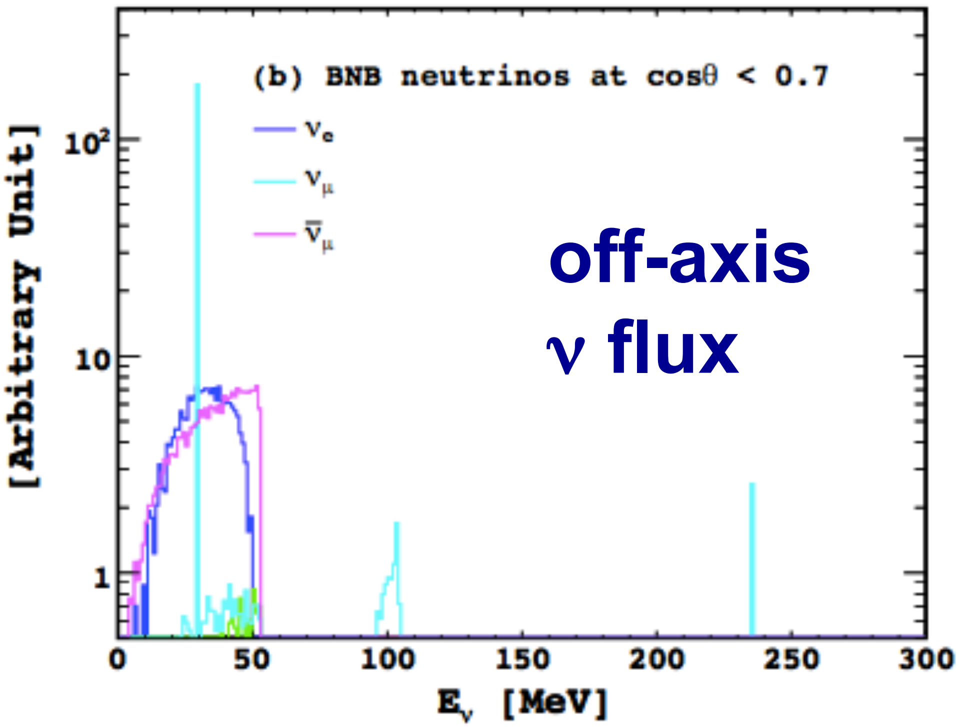


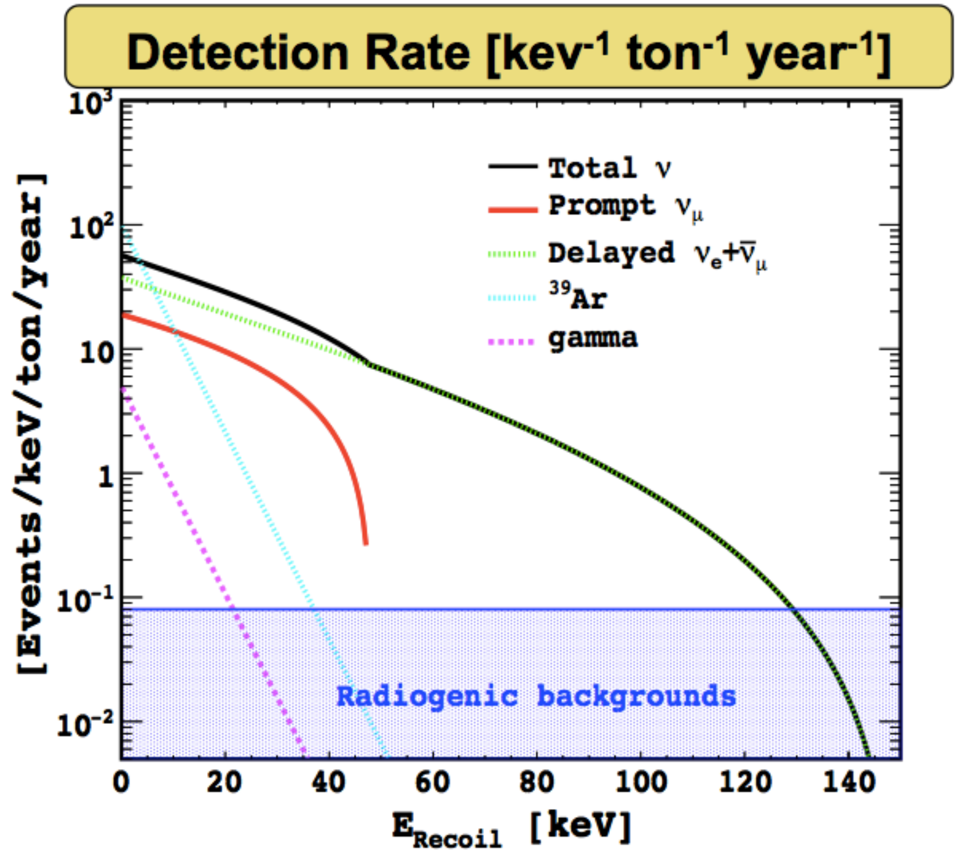


Another interesting possibility: BNB at Fermilab

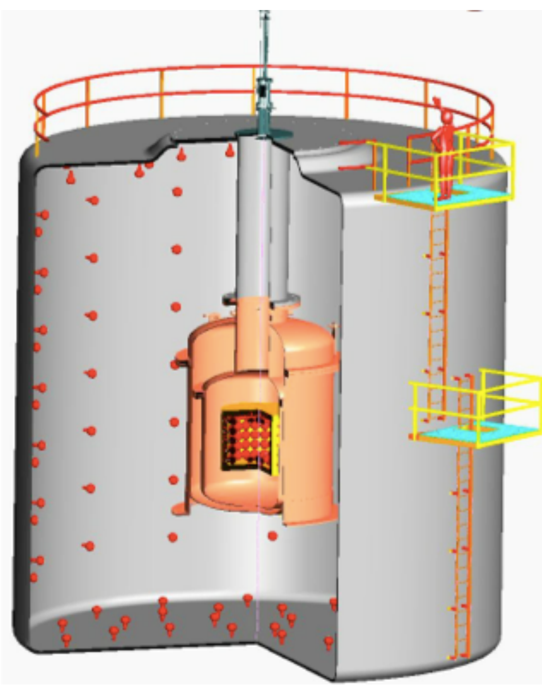


High-energy (~GeV) neutrinos for beam experiments are boosted forward... very far off-axis experiment sees isotropic stopped-pion flux





J. Yoo at Coherent NCvAS mini-workshop at FNAL



- 1 kt single-phase argon detector concept
- neutron bg measured w/ SciBath detector

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 for high energy neutrinos, good background rejection

First measurement may be possible on a short timescale

A "coherent" strategy is coming together