Neutrino Cross-Section Experiments at the Spallation Neutron Source

Kate Scholberg, Duke University
NuInt 2014, May 22, 2014

OUTLINE

Low-energy cross sections overview:
physics motivation

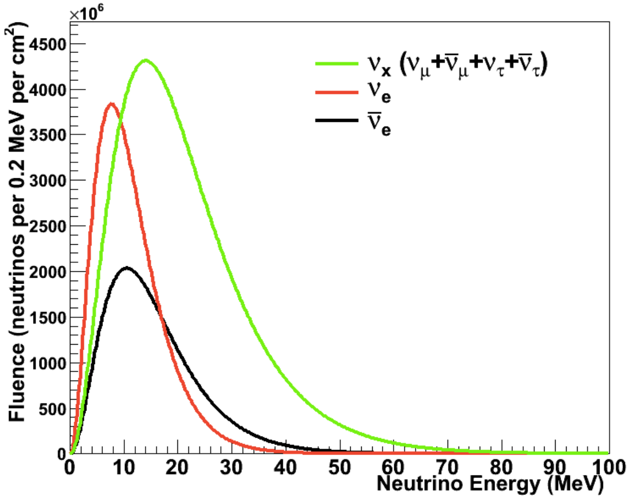
The SNS as a neutrino source

Cross-section experiments at the SNS

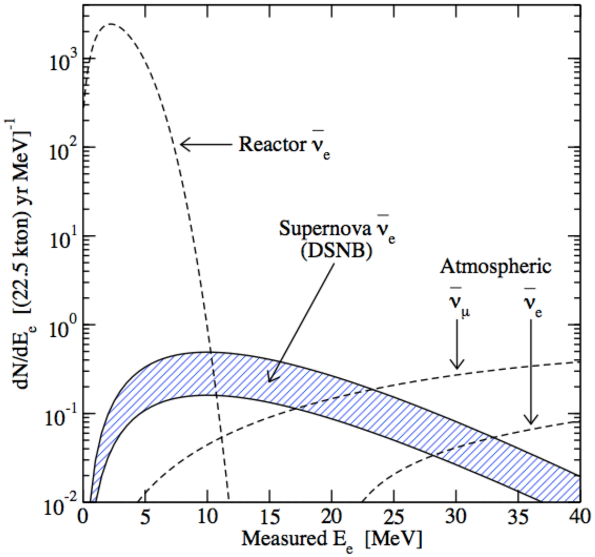
➔ Focus on the COHERENT experiment

Work underway and prospects

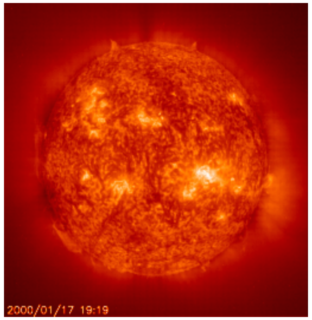
Neutrino interactions in the few-100 MeV range are relevant for:

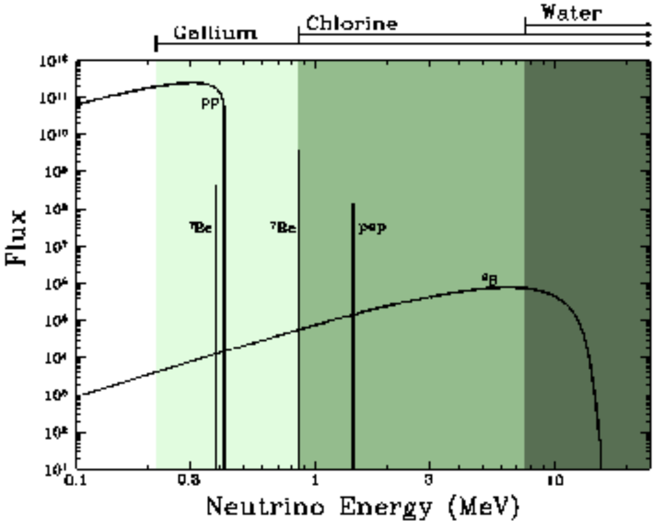


supernova neutrinos, burst & relic

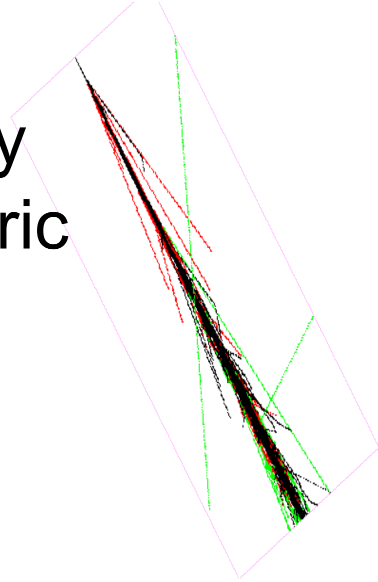


solar neutrinos



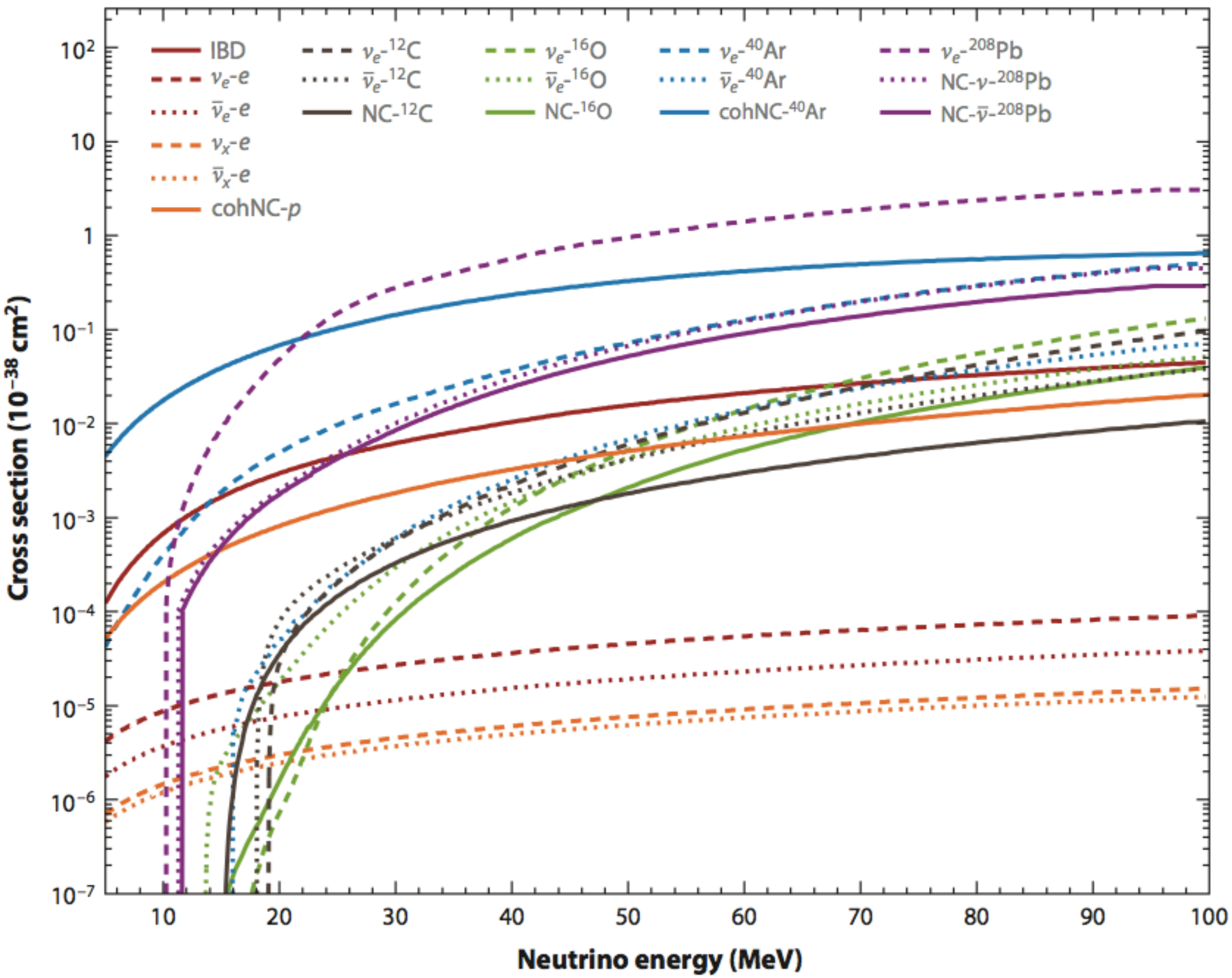


low energy atmospheric neutrinos



Physics: oscillation, SM tests, astrophysics

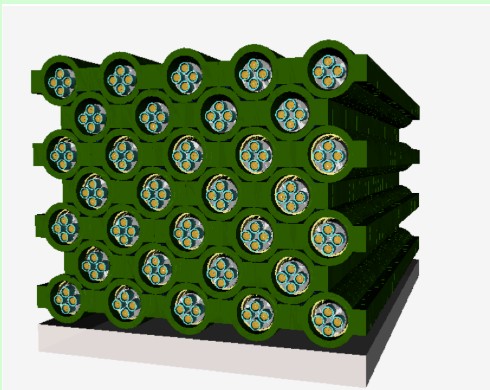
Cross-sections in this energy range



IBD and ES on electrons well understood... but so far only ^{12}C is the *only* heavy nucleus with ν interaction cross sections well (~10%) measured in the tens of MeV regime

Supernova-neutrino-relevant cross sections to understand in this energy range

Lead



HALO
at
SNOLAB

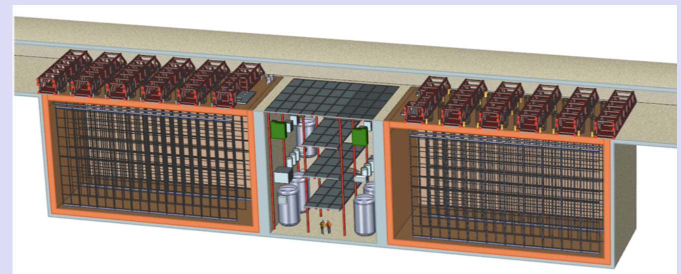
$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^-$

$\searrow$ 1n, 2n emission

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

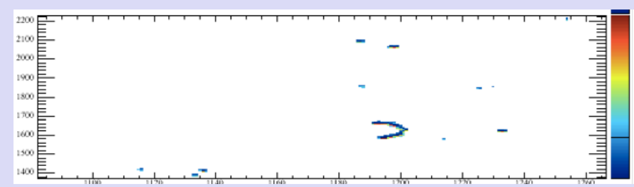
$\searrow$ 1n, 2n, γ emission

Argon

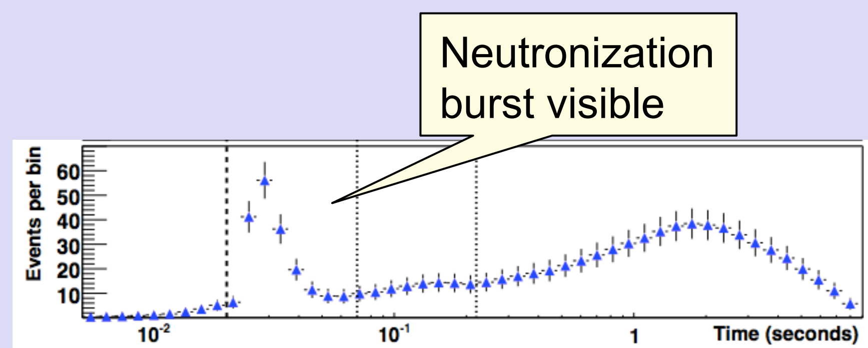


LBNE

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



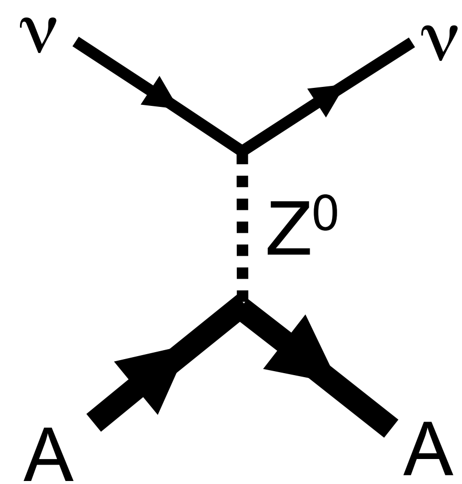
electron
+ γ's



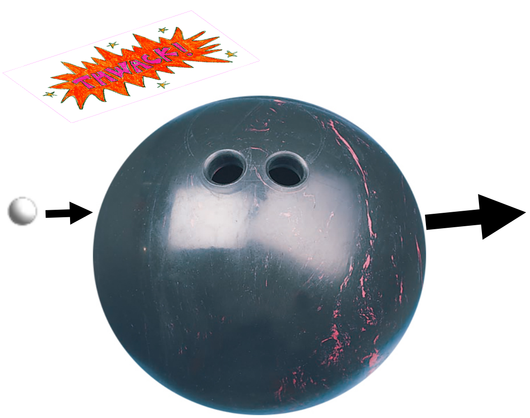
also: oxygen, iron, carbon,...

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 up to $E_\nu \sim 50$ MeV

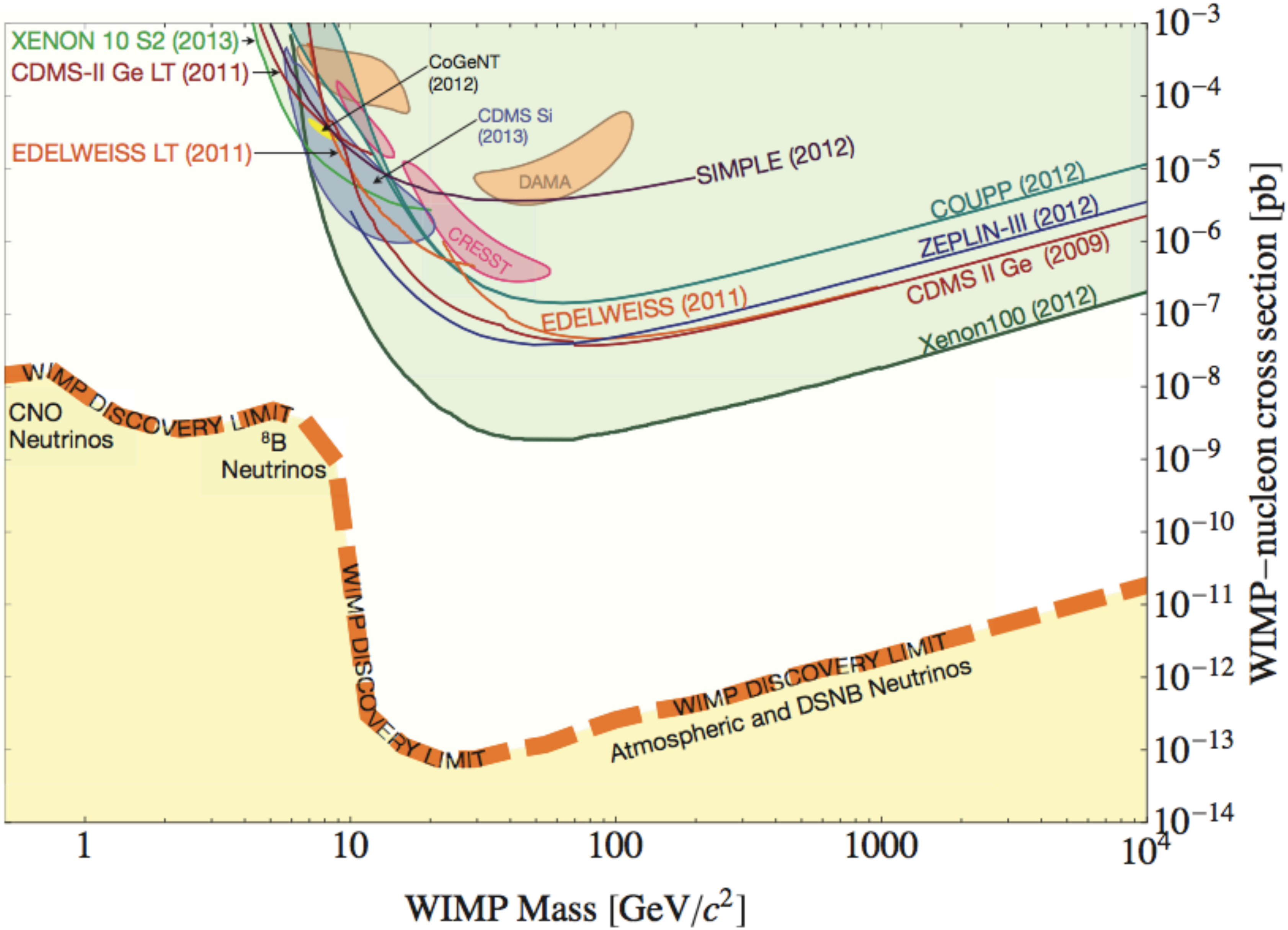


- Important in SN processes & detection
- Well-calculable cross-section in SM: SM test, probe of neutrino NSI
- Possible applications (reactor monitoring)

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

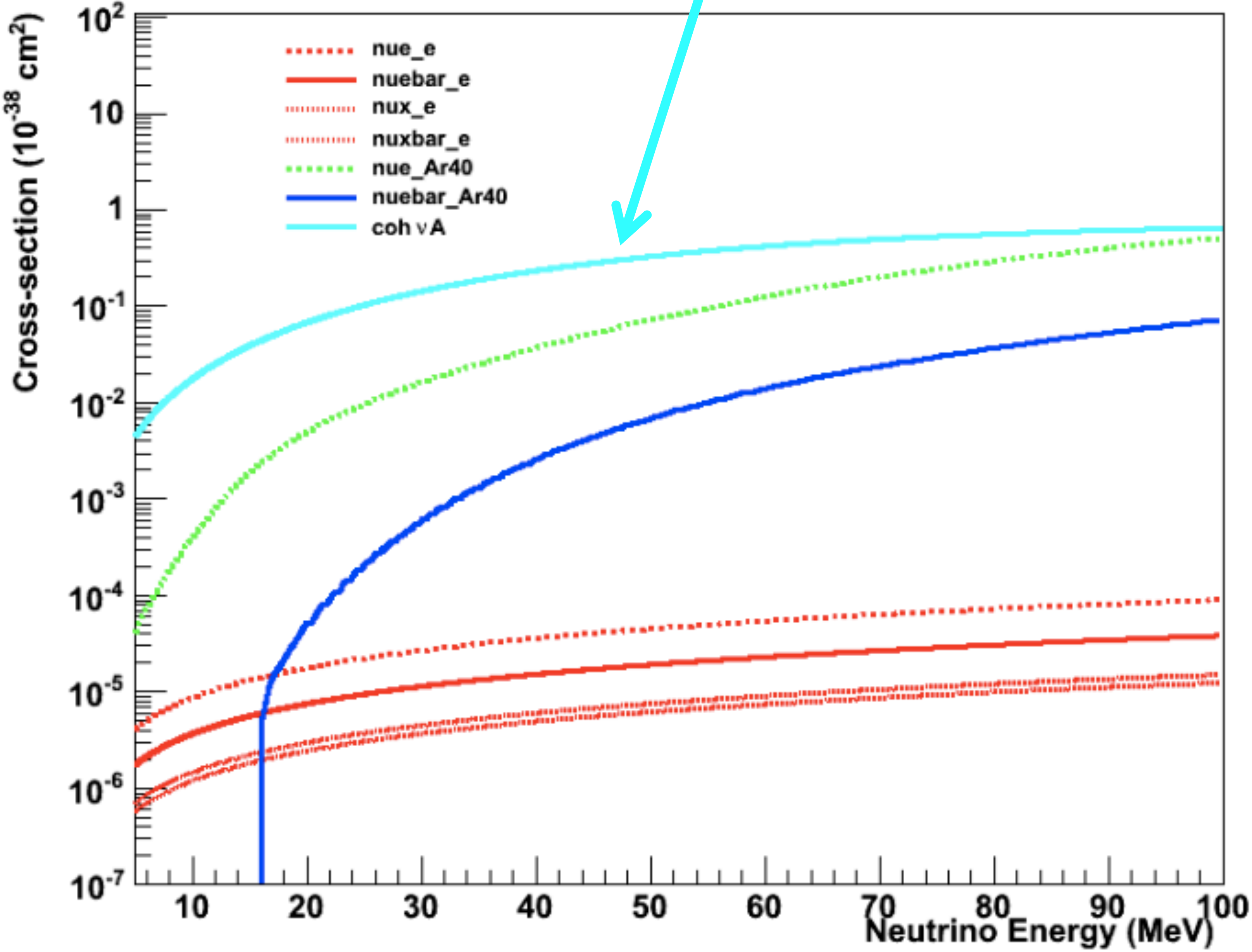
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

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



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

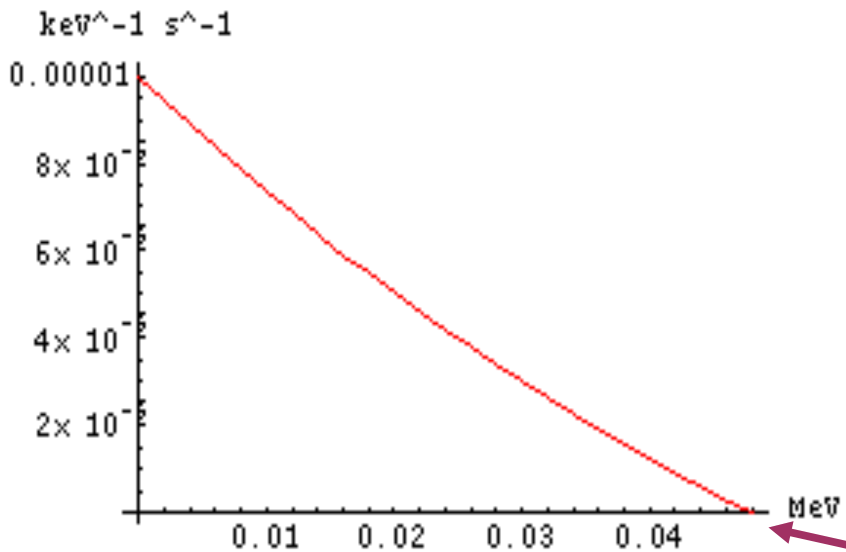
The cross-section is *large*



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...

➔ but WIMP detectors developed over the last ~decade are sensitive

Physics reach for CENNS experiments

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

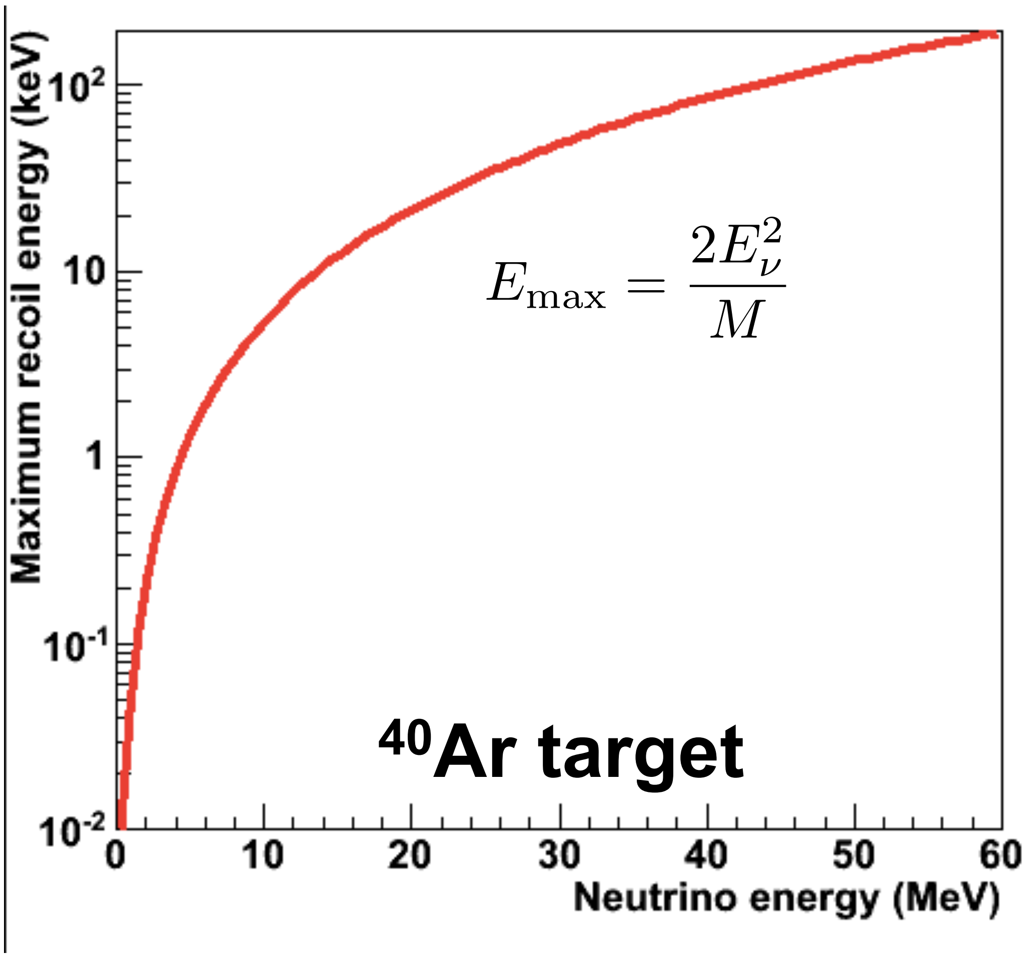
At a level of experimental precision better than that on the nuclear form factors:

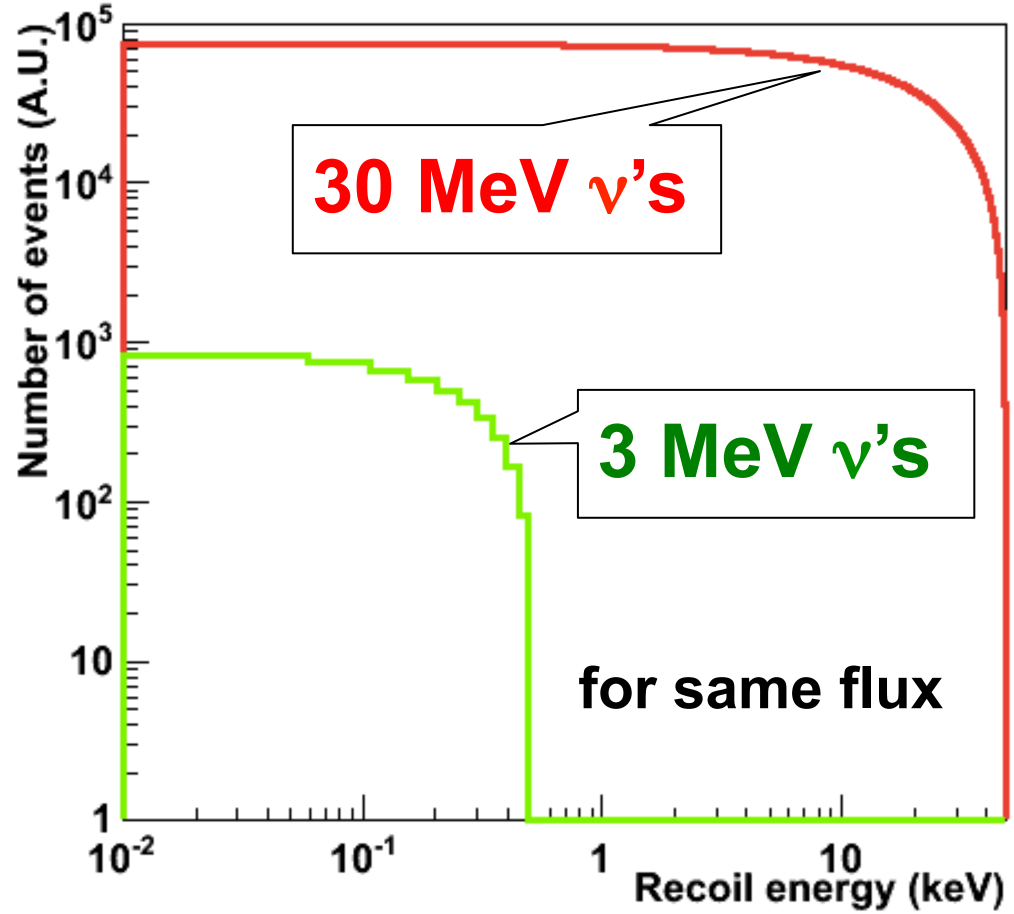
- Neutron form factor:

hard but conceivable; need good energy resolution,
control of systematics

What do you want to detect CENNS?

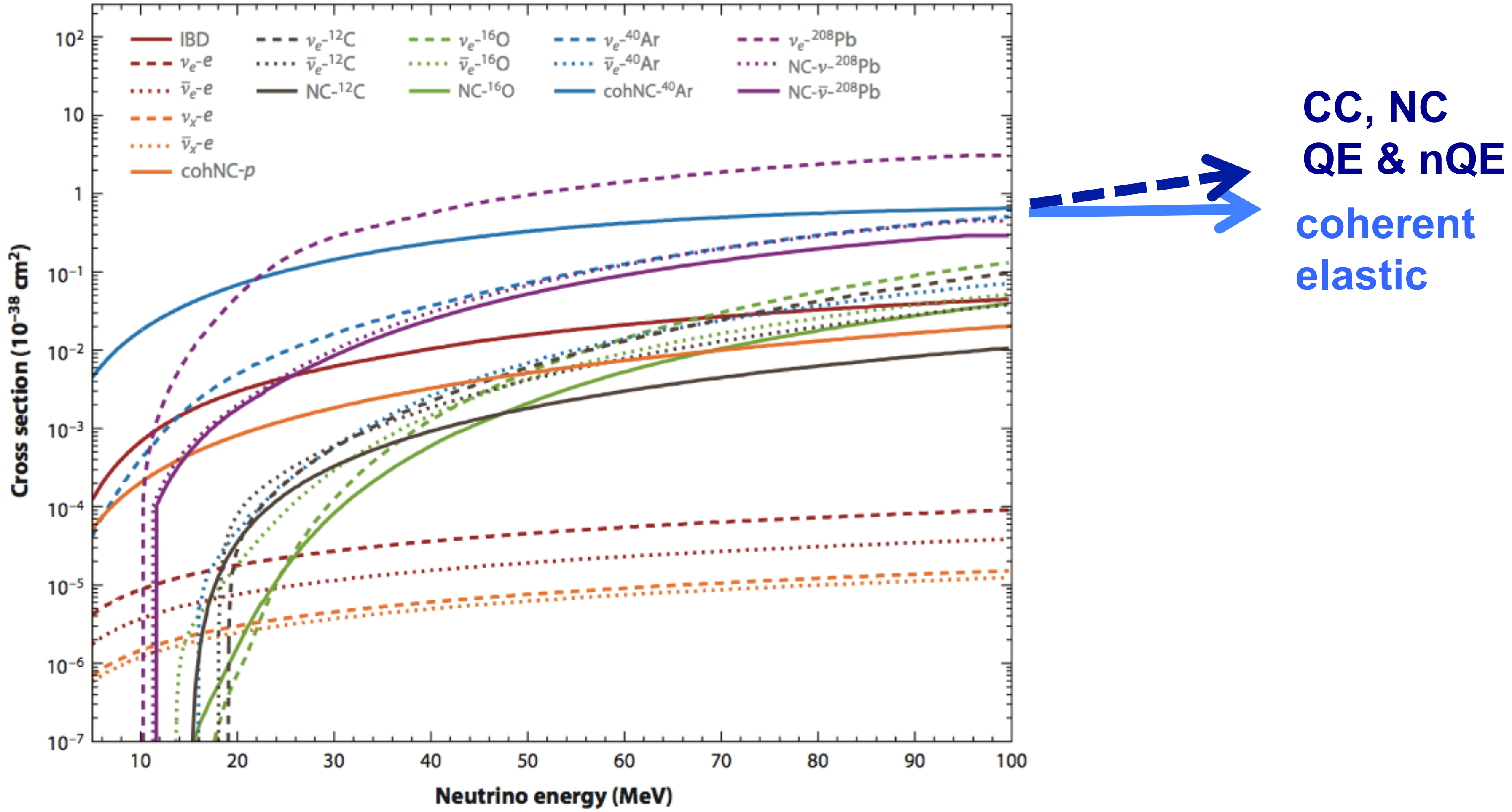
High-energy neutrinos, because both cross-section and maximum recoil energy increase with neutrino energy





... but...

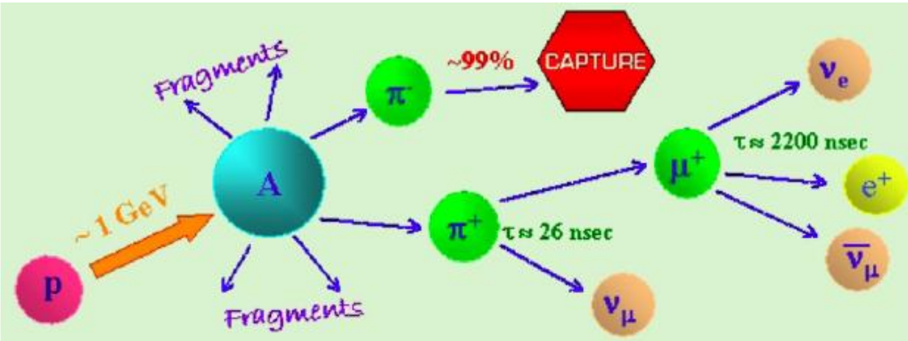
... neutrino energy should not be *too* high...

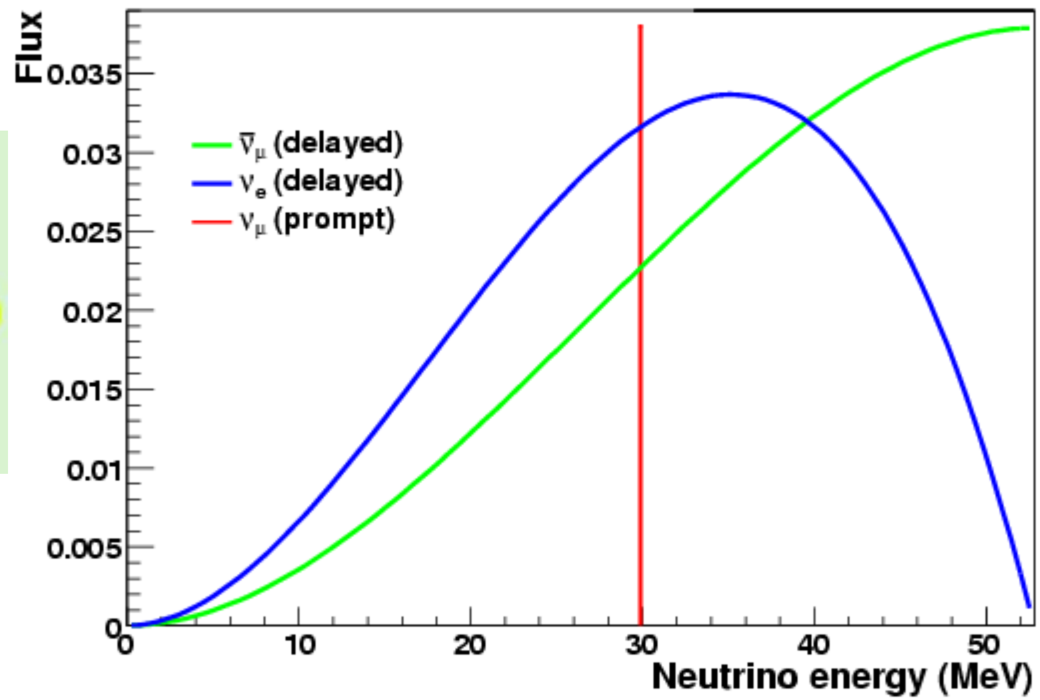


The coherent cross-section flattens, but
inelastic cross-section increases
(eventually start to scatter off *nucleons*)

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

Stopped-Pion (DAR) Neutrinos





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

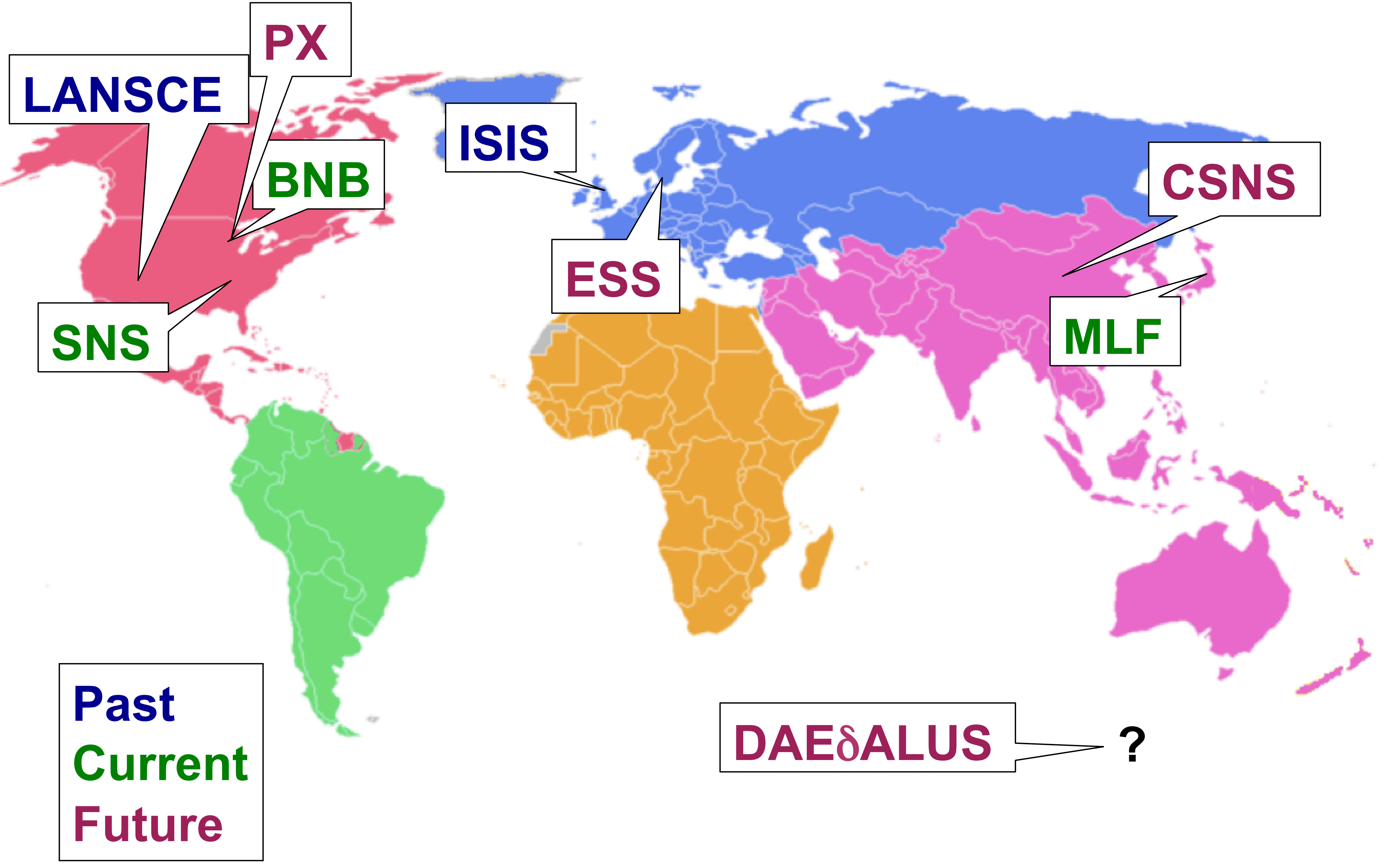
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

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

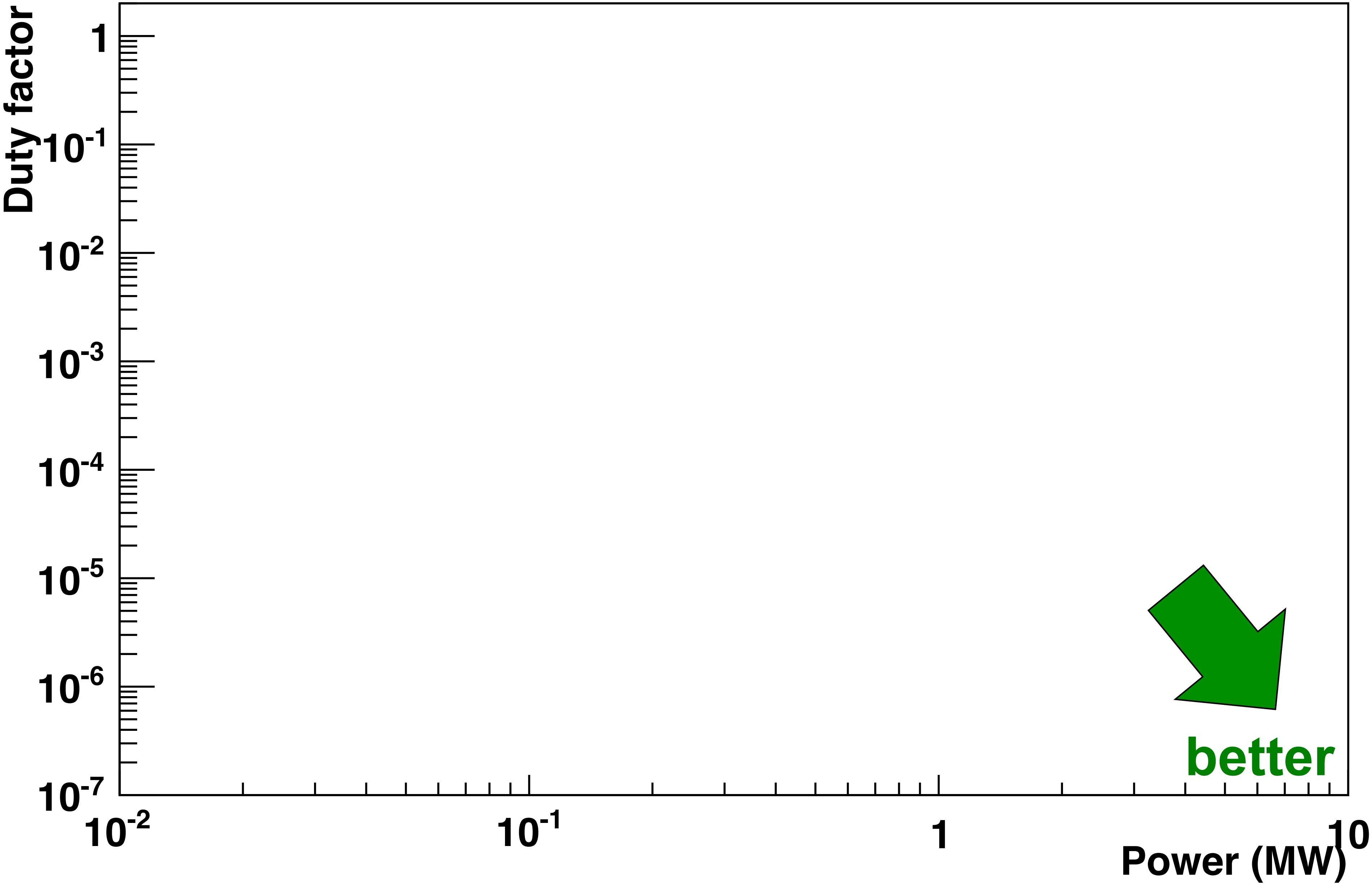
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Stopped-Pion Sources Worldwide

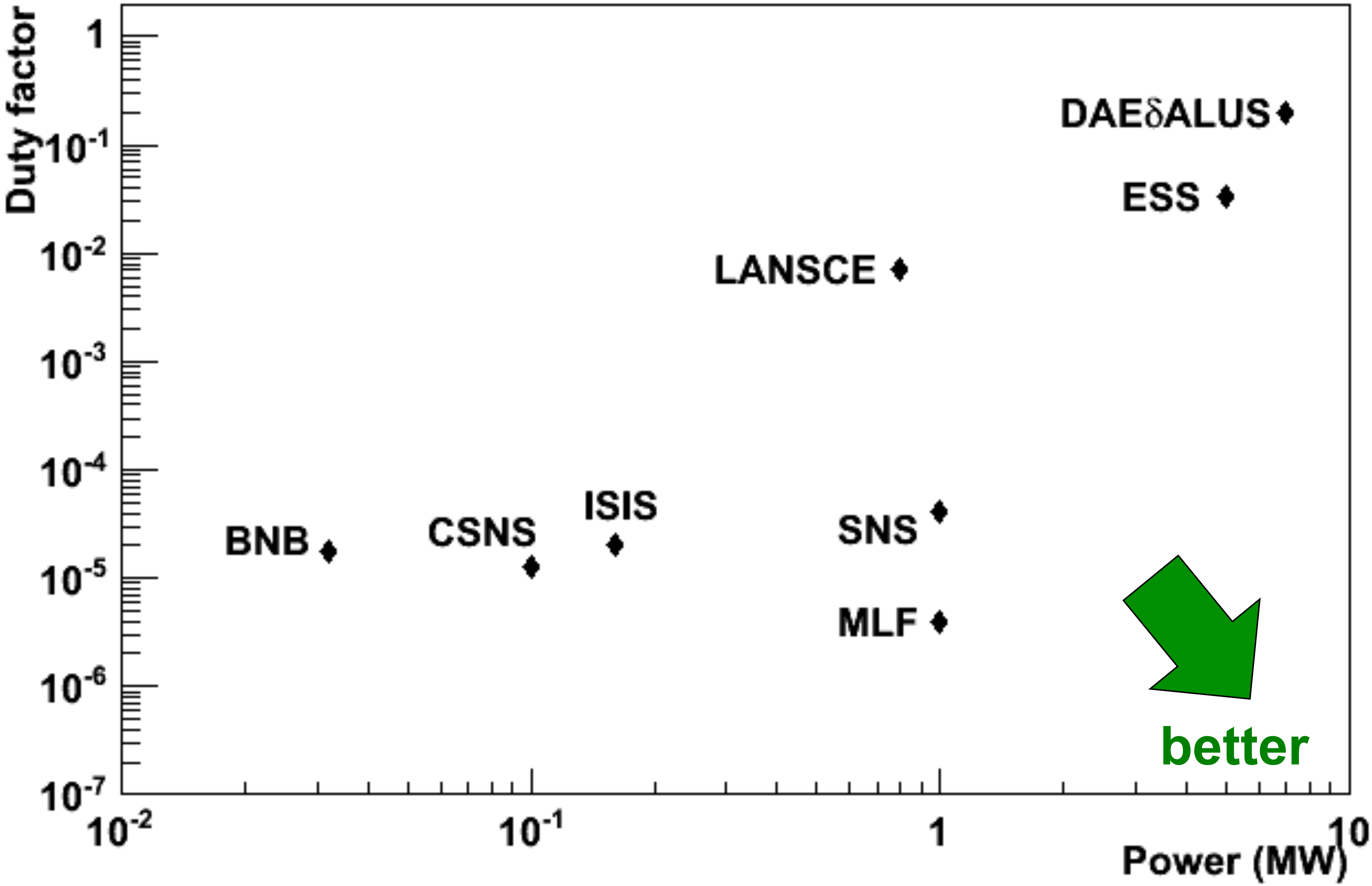


Flux $\propto$ power: want bigger!

Duty factor: want smaller!



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

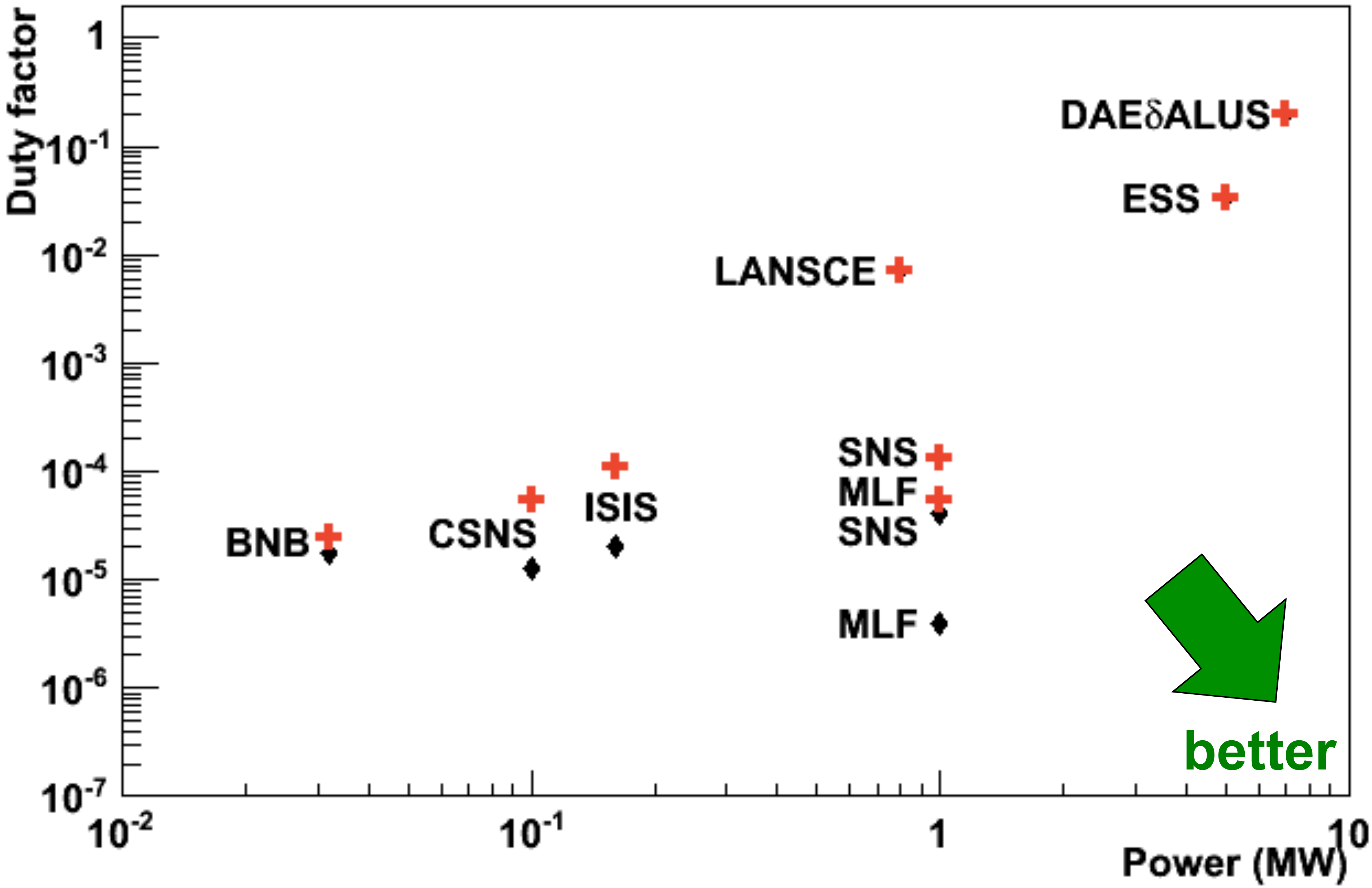


Flux $\propto$ power

Duty factor = T*rate (◆)

= max(T, 2.2 μs)*rate (+ for μdk ν's)

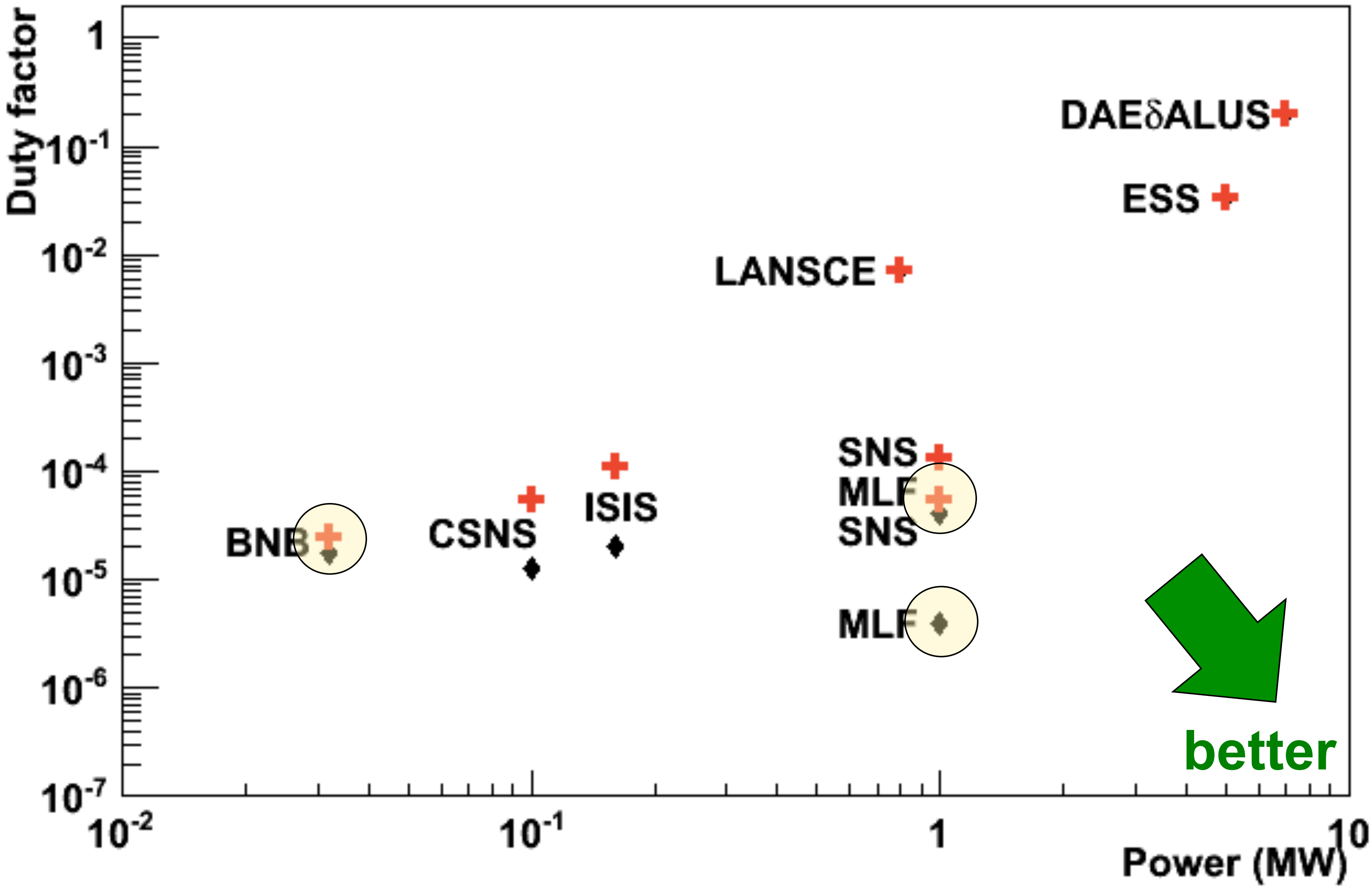
it doesn't help that much to be faster than μdk timescale



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

Duty factor = T*rate (◆)

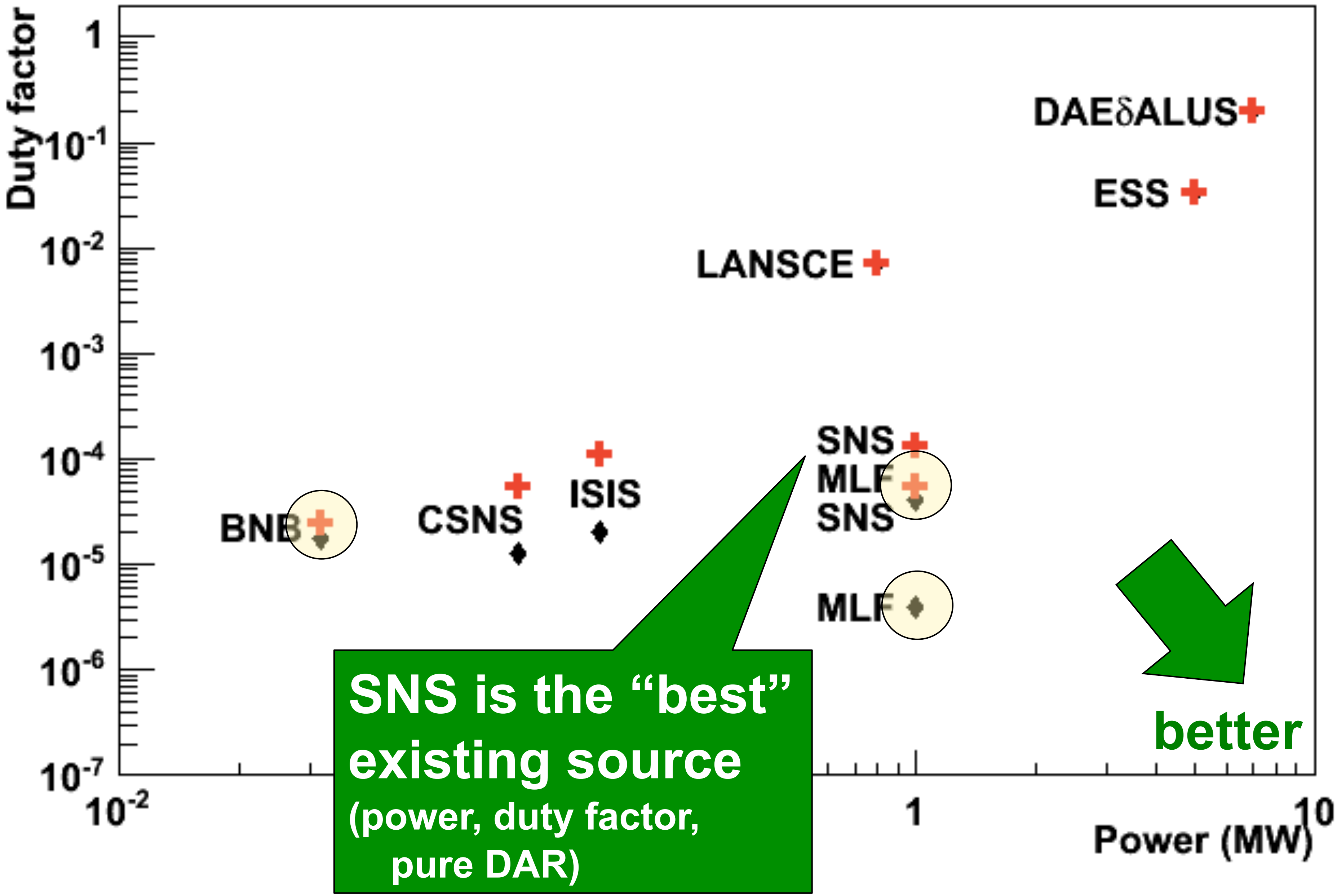
= max(T, 2.2 μs)*rate (+ for μdk ν's)



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!

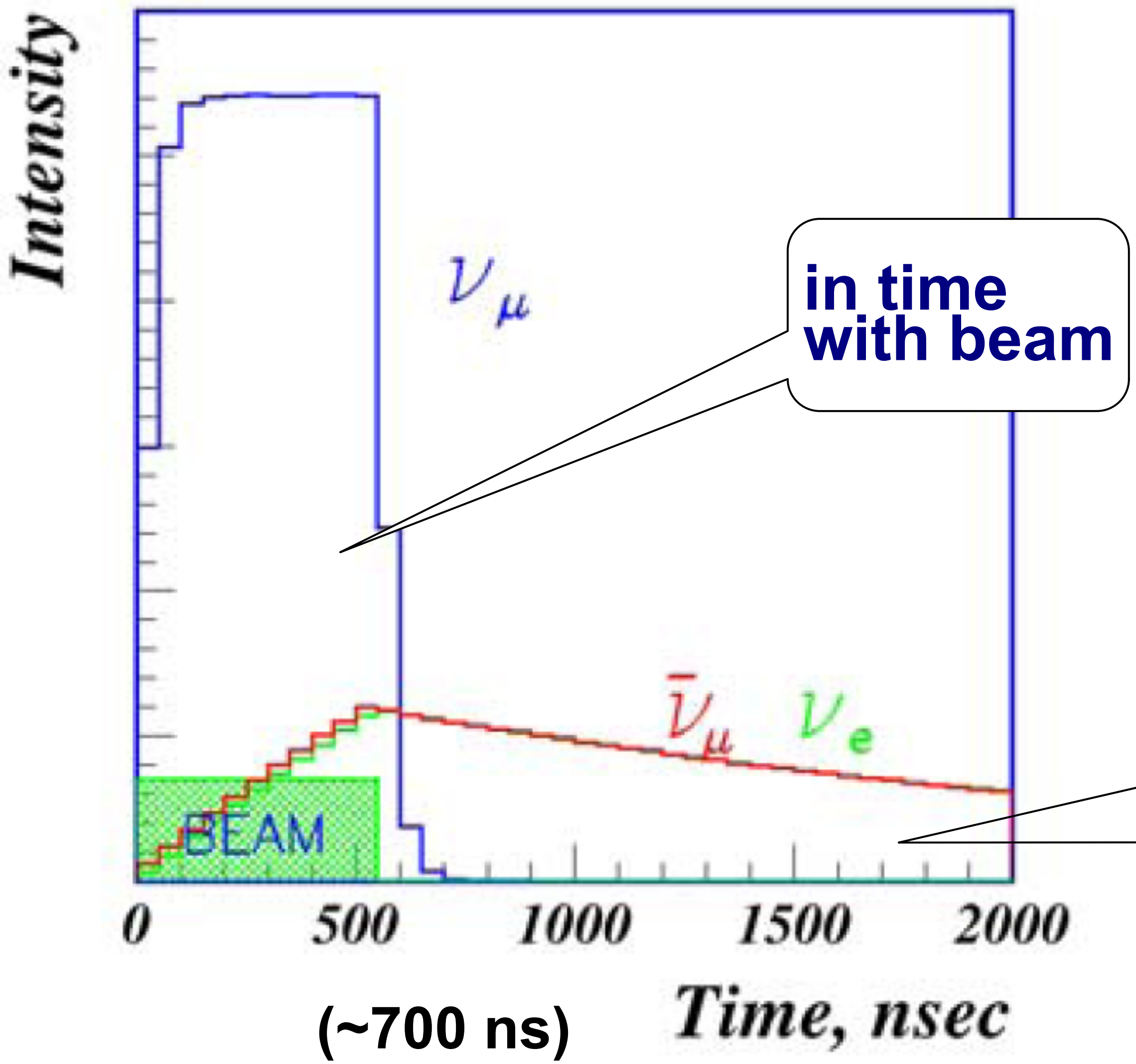
These are *not* crummy old cast-off neutrinos...

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

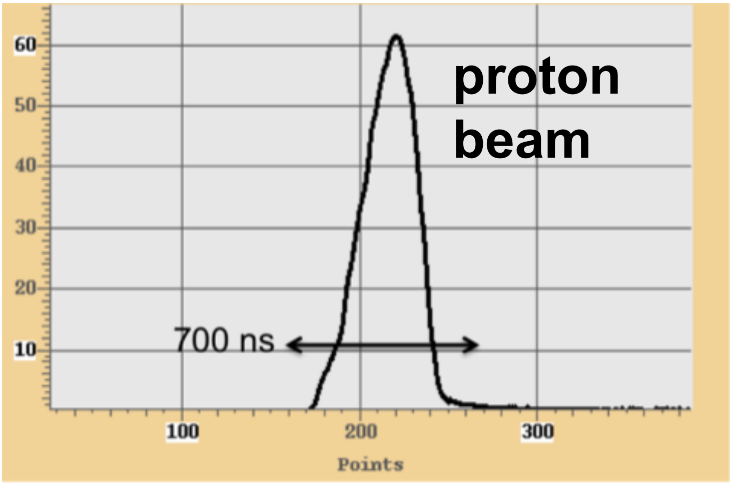
They are of the highest quality!

Time structure of the SNS source

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



60 Hz *pulsed* source



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

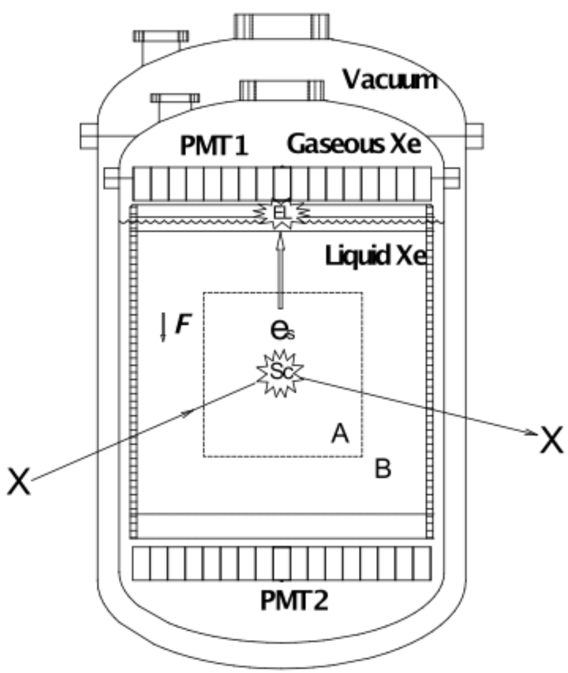
Neutrino flux: few times 10^7 /s/cm^2 at 20 m

~0.13 per flavor per proton

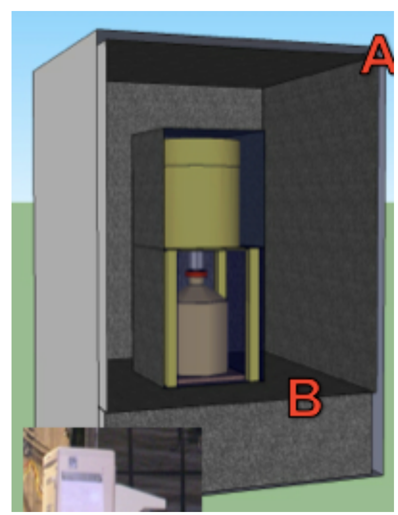
Newly-formed COHERENT collaboration

Three possible technologies under consideration for short-term deployment

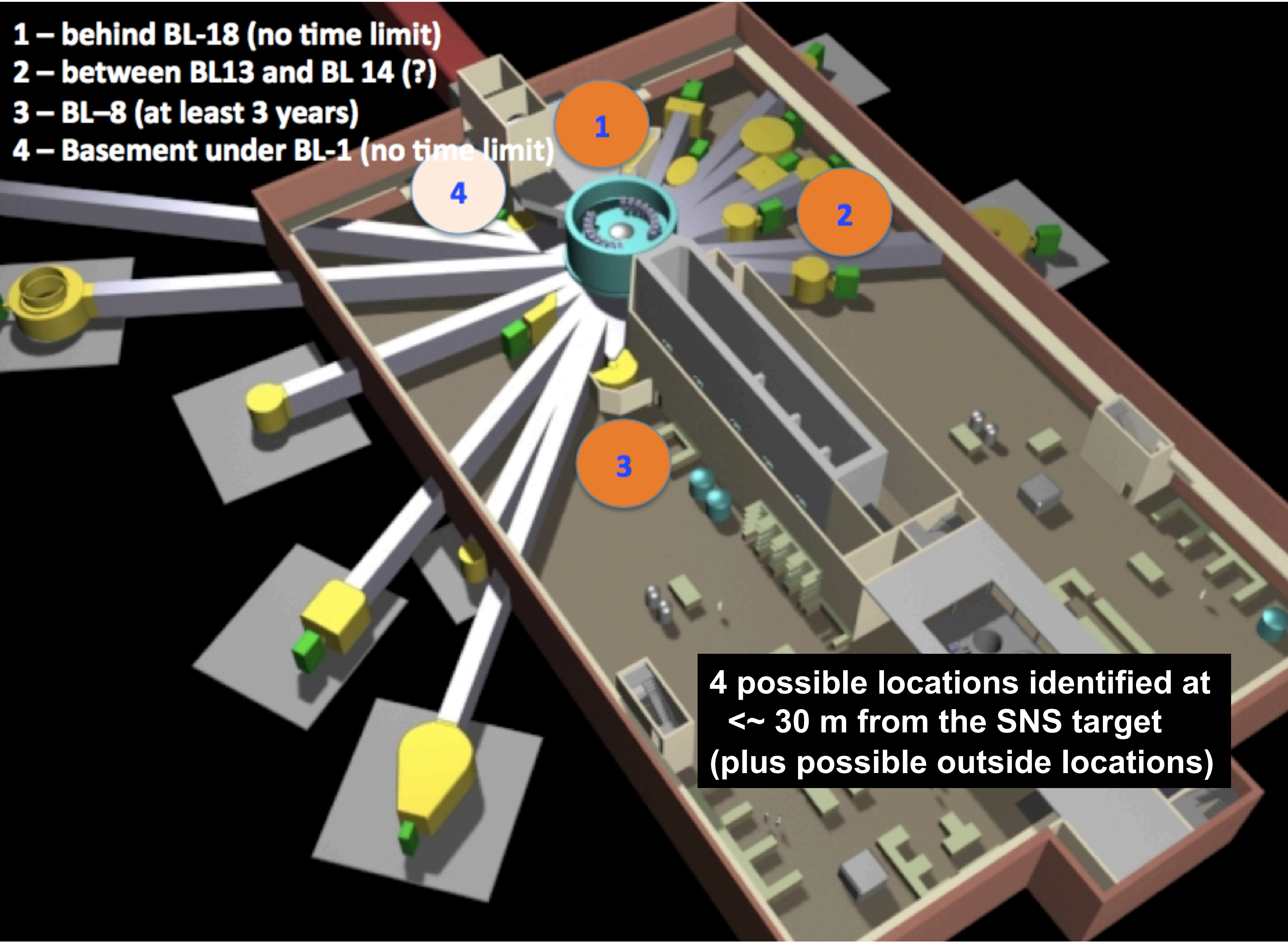
Two-phase LXe



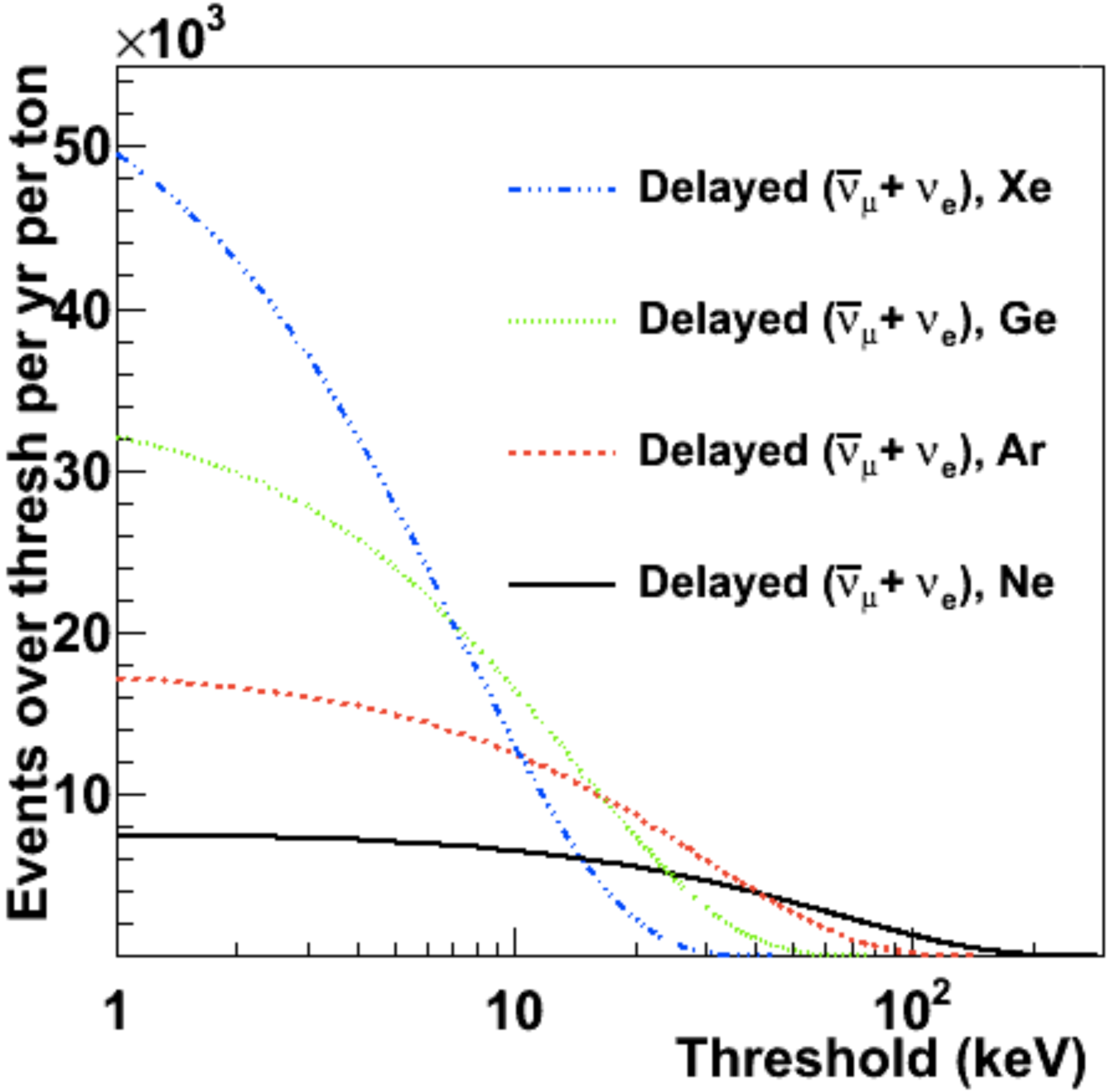
CsI



HPGe PPC


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)

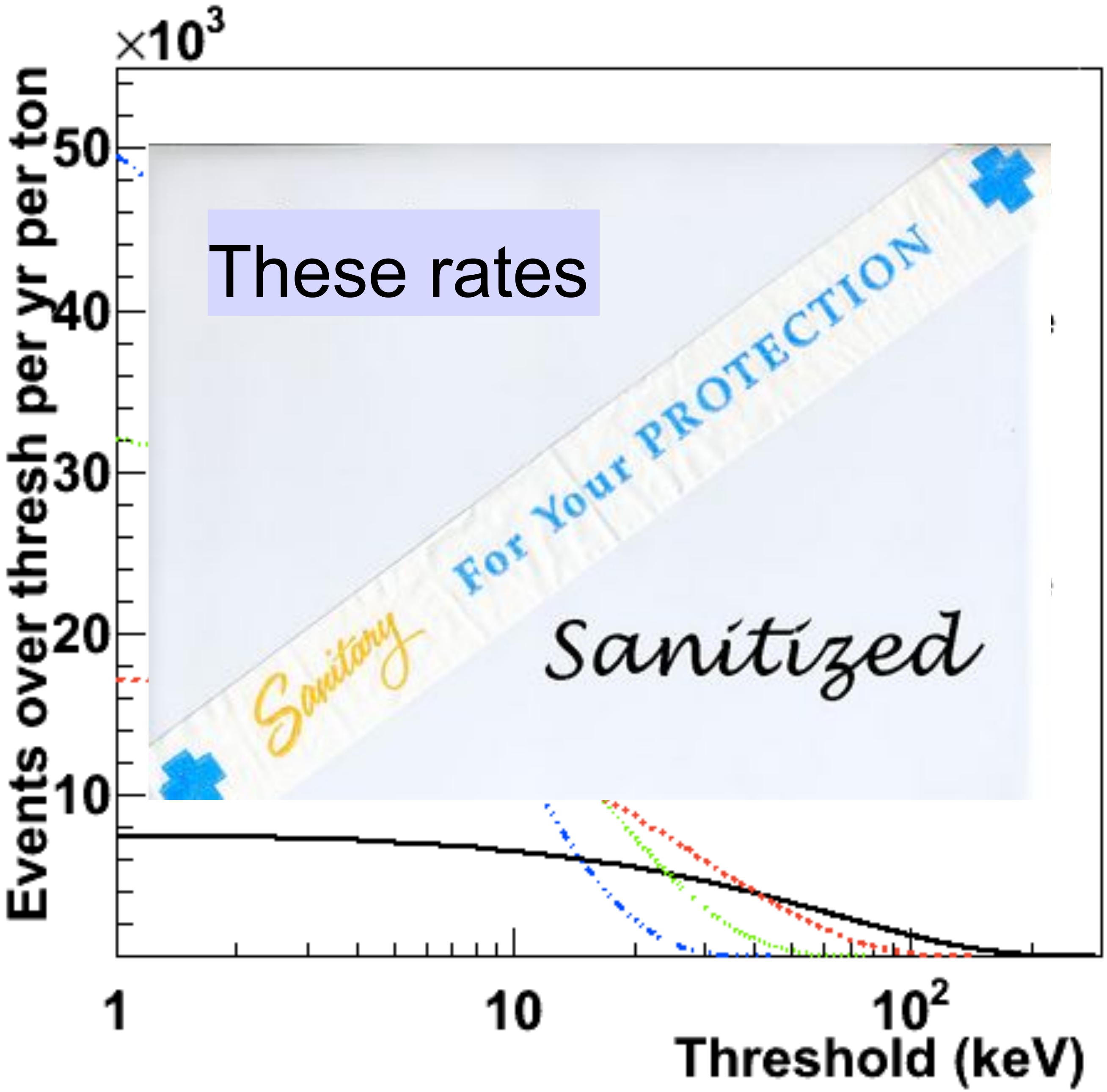
Integrated SNS CENNS yield for various targets



20 m

Lighter nucleus
$\Rightarrow$ expect fewer interactions, but more at higher energy

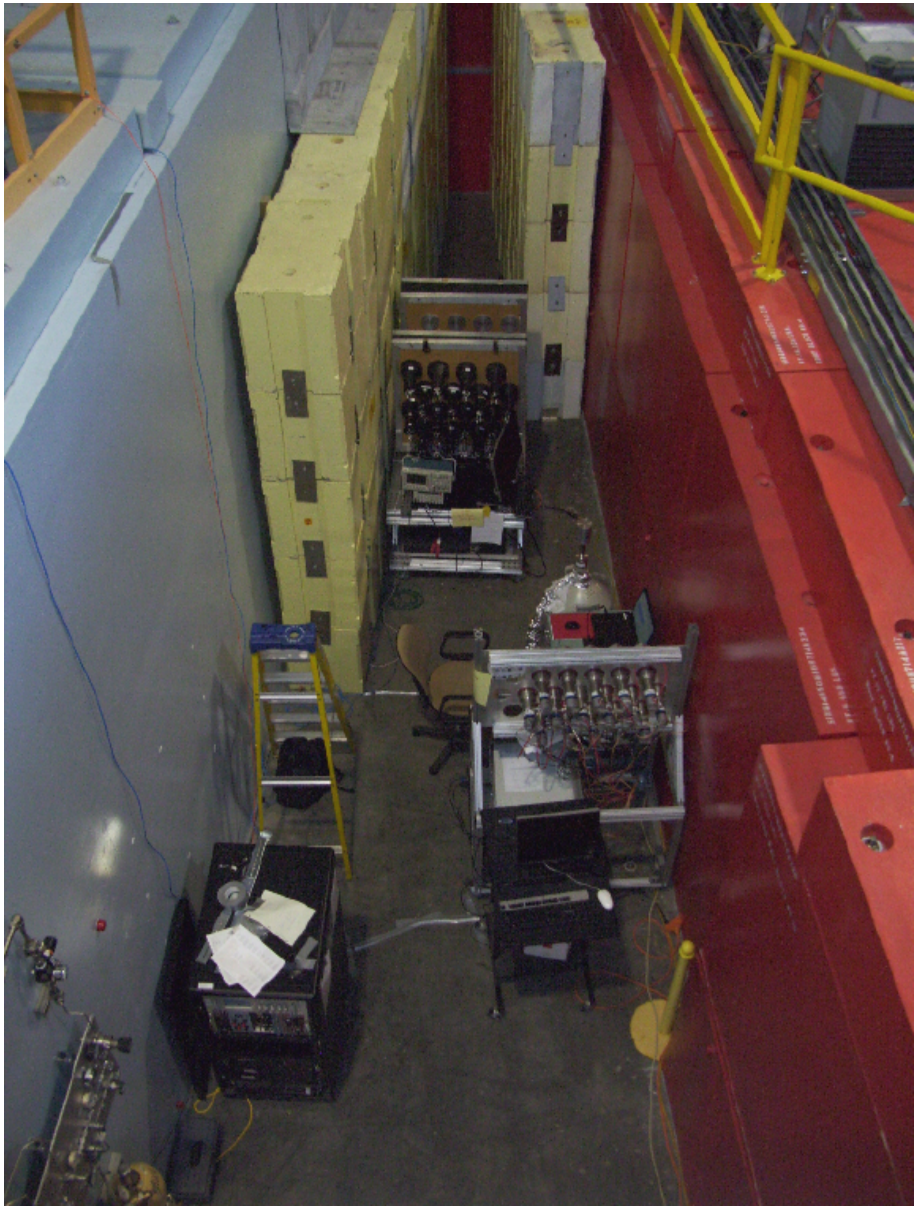
Integrated SNS CENNS yield for various targets



20 m

➔Neutron background is a serious concern...

Neutron background measurements underway inside the SNS target building: so far sites 2, 4



- Scintillator array (ORNL)
- Neutron scatter camera (Sandia)
- BEGe (LBNL)

Data under analysis... preliminary results show site 4 is promising

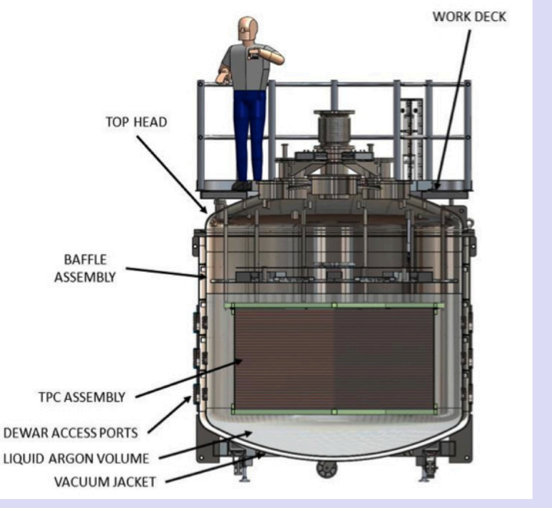
Proposal planned for fall

Other neutrino experiments proposed for the SNS

OscSNS

- 800-ton, 10-m long scintillator detector @ 60 m
- primary goal is direct test of LSND anomaly
- cross sections on ^{12}C also possible

CAPTAIN



- 5-ton LArTPC
- SN-relevant cross sections on argon
- current run plan is far off-axis @FNAL BNB before SNS

Common concerns with COHERENT (flux, background)

More information

Comprehensive white paper on neutrino physics opportunities at the SNS

arXiv.org > hep-ex > arXiv:1211.5199

Search or Articl

High Energy Physics – Experiment

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

(Submitted on 22 Nov 2012)

Snowmass white paper on CENNS measurements

arXiv.org > hep-ex > arXiv:1310.0125

Search or Artic

High Energy Physics – Experiment

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

"CSI" is now "COHERENT"

Summary

Cross sections on nuclei in the few tens-of-MeV regime
are very poorly understood
... measurements especially relevant for SN neutrinos

CENNS also never before measured, and now within reach with WIMP detector technology

Stopped-pion neutrinos offer opportunities for these measurements

The SNS is the current "best" facility

Background measurements for COHERENT underway;
multiple detector technologies under consideration

Extras/Backups

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, ...

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	$2 \times$ 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)

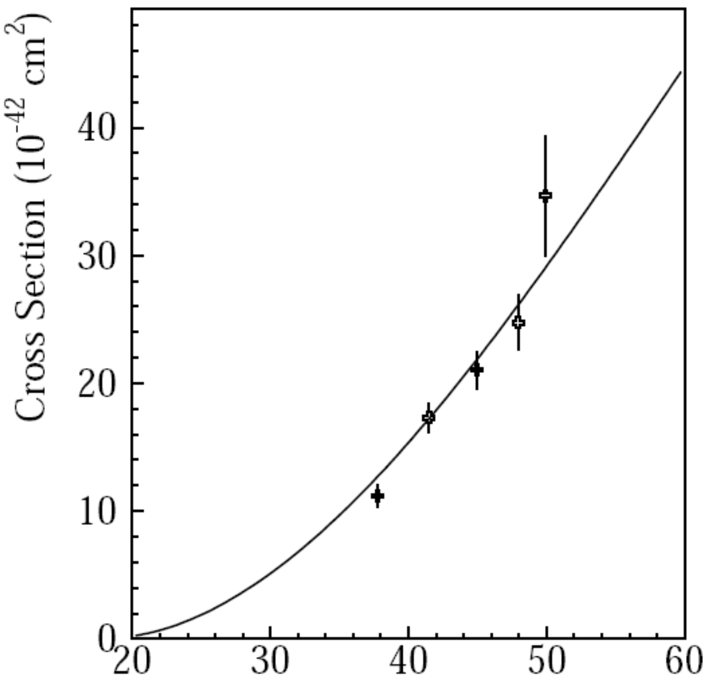
IBD and ν-e ES well understood... but

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

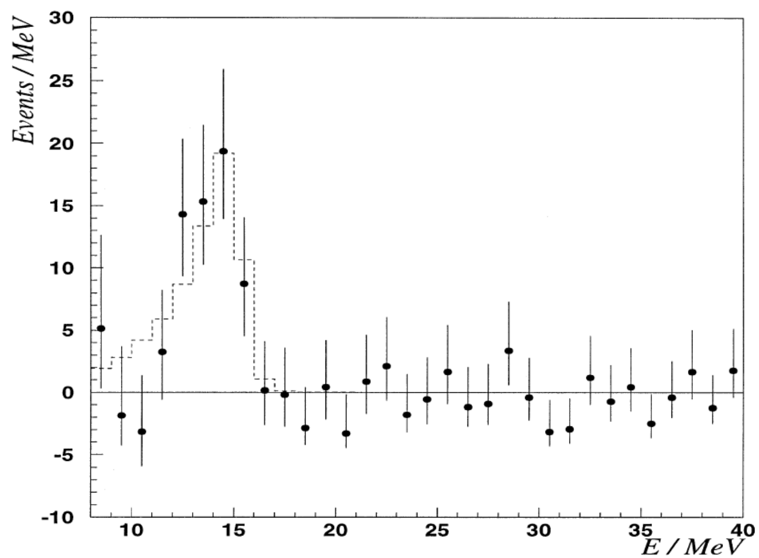
Phys. Rev. C 66 (2002) 015501



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

Karmen

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



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

1.3 GeV proton linear accelerator

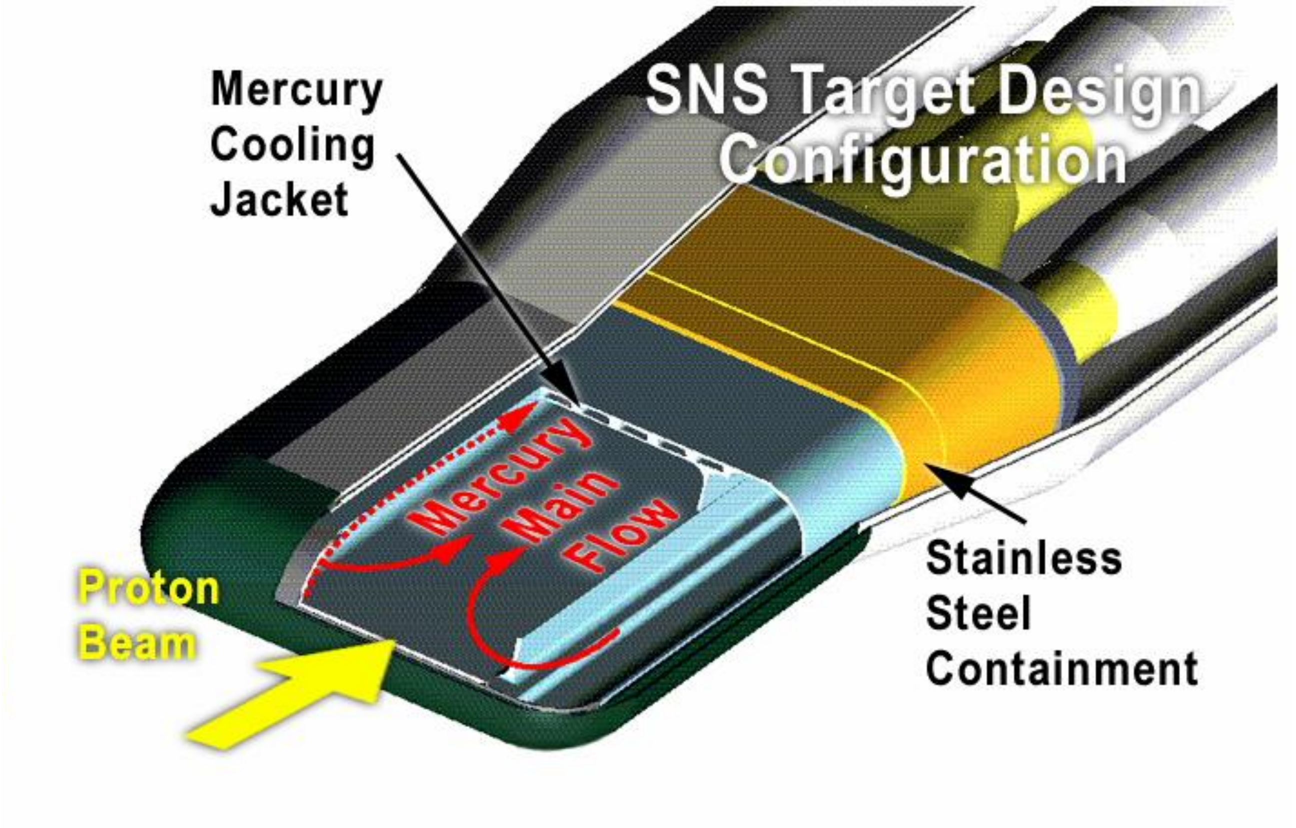
Accumulator ring

Main target

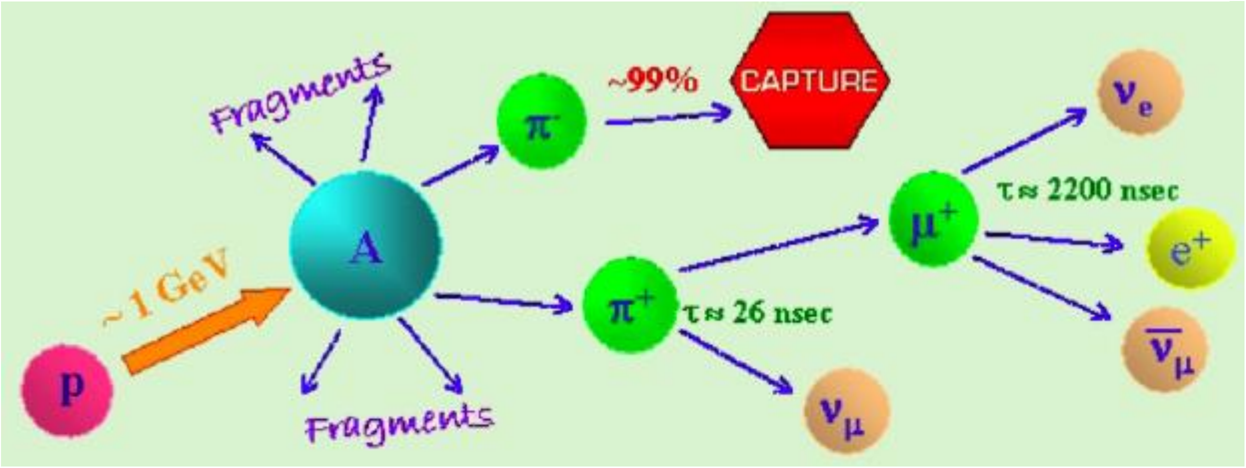
4

Y. Efremenko

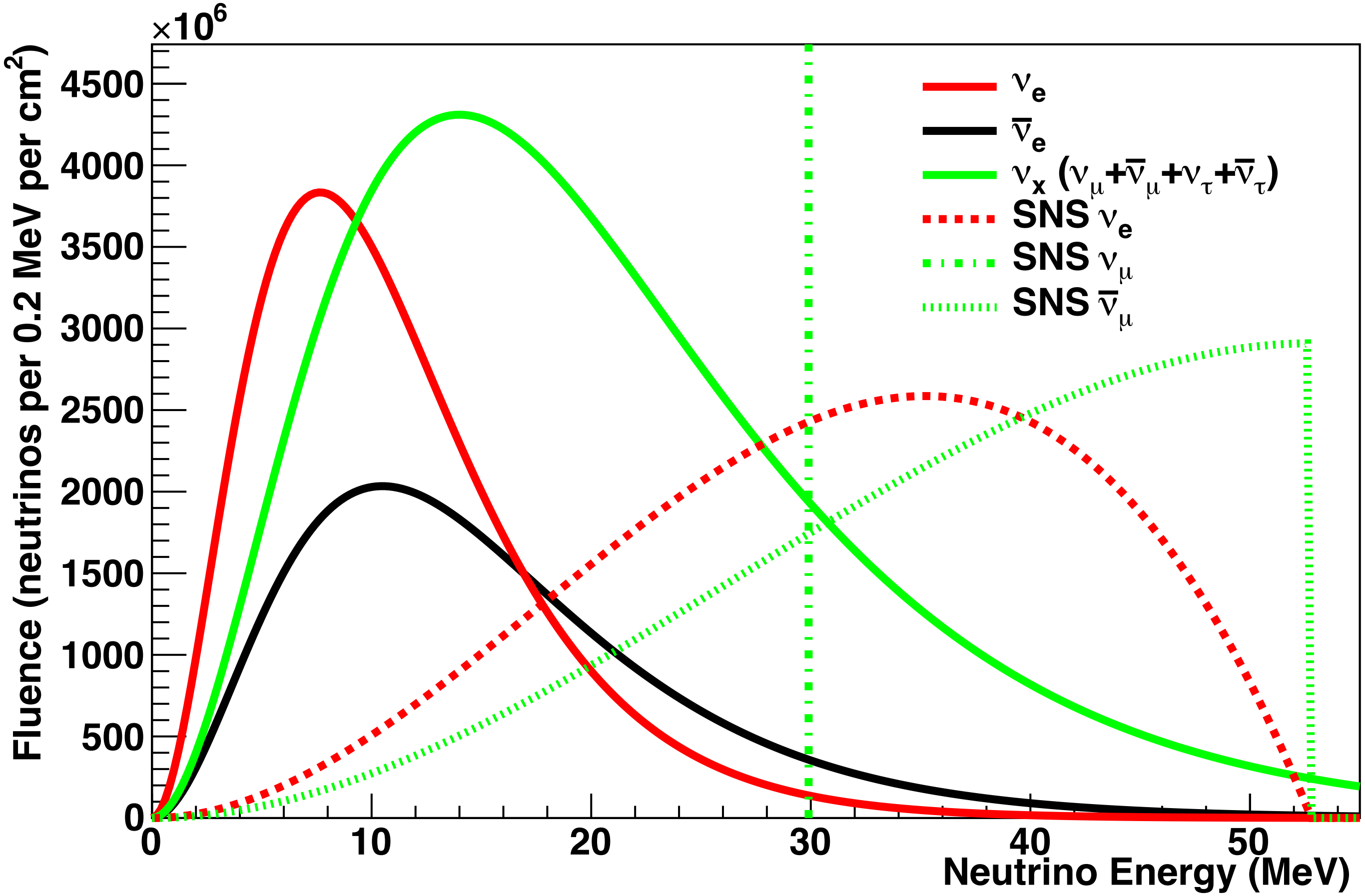
The SNS as a Stopped-Pion Neutrino Source



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

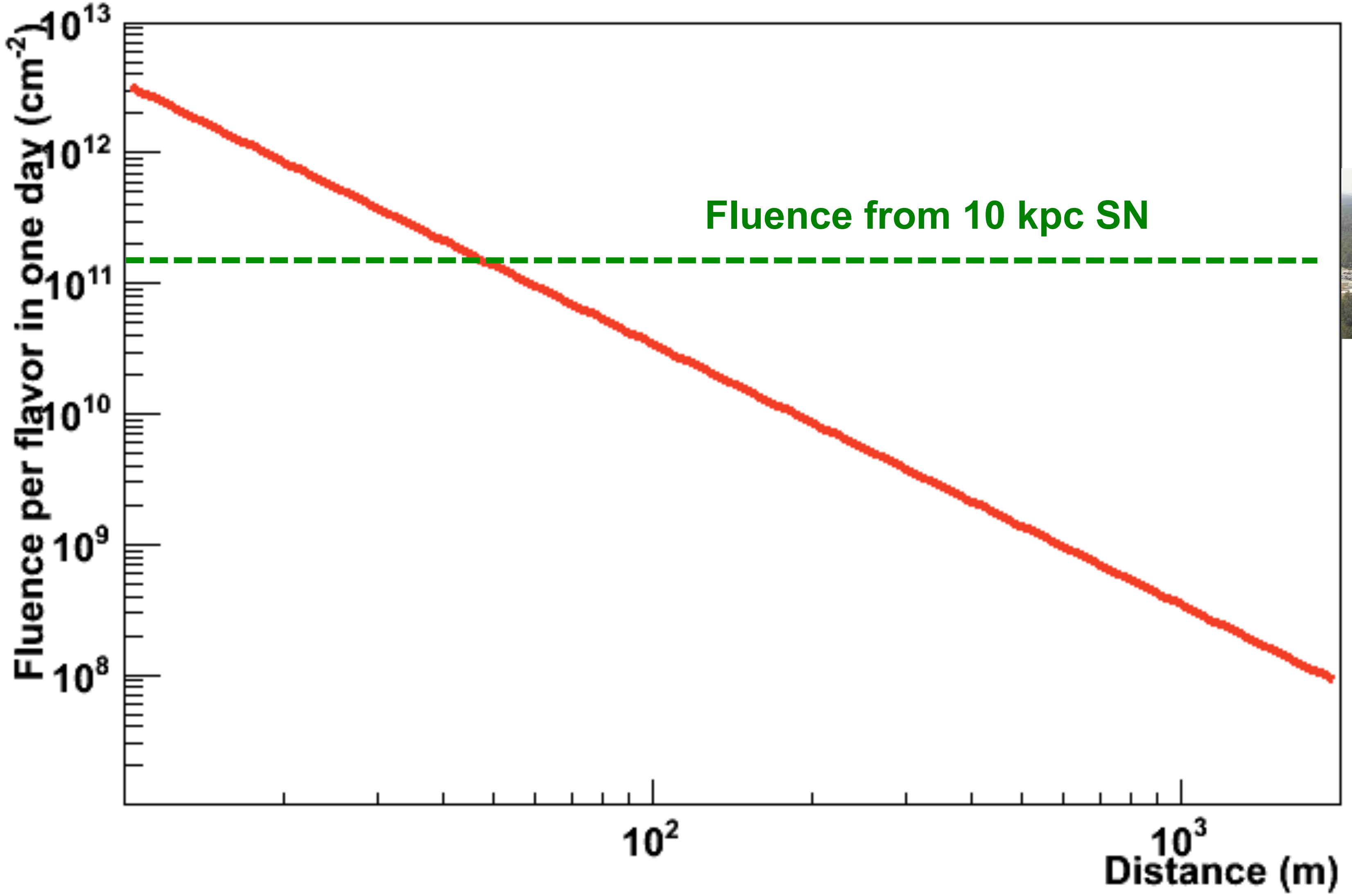


Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum



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

Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!



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

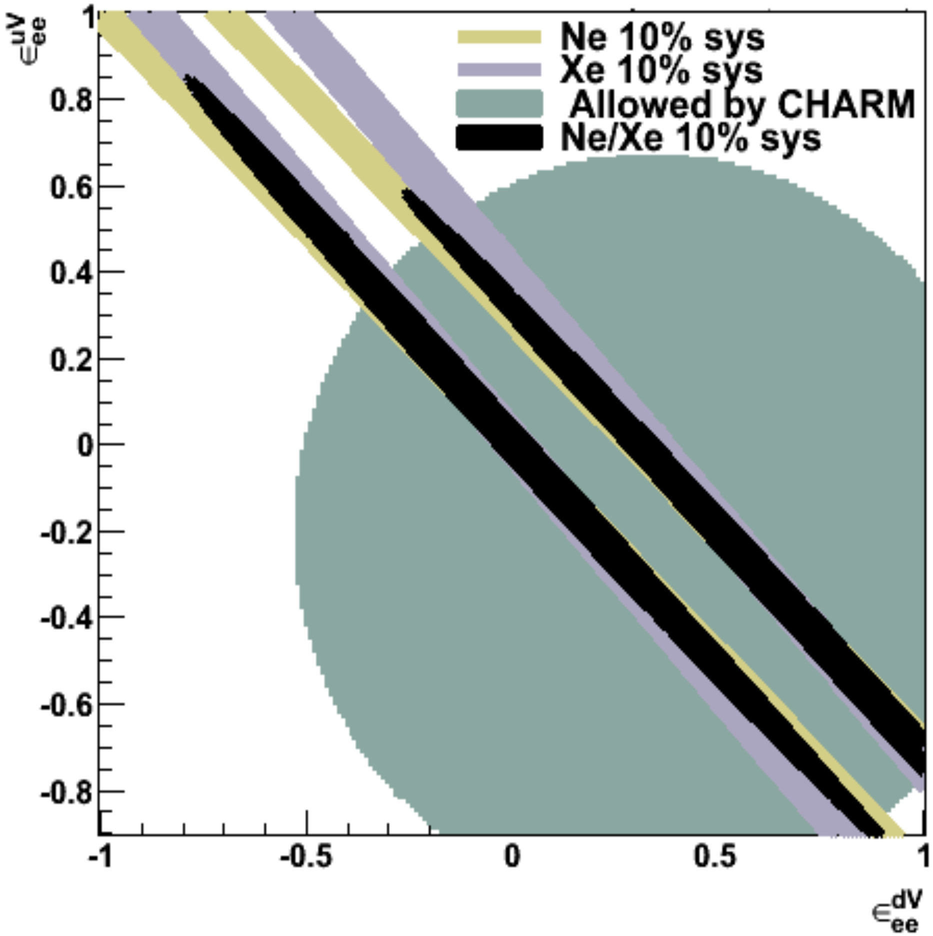
Absolute rate in SM is proportional to

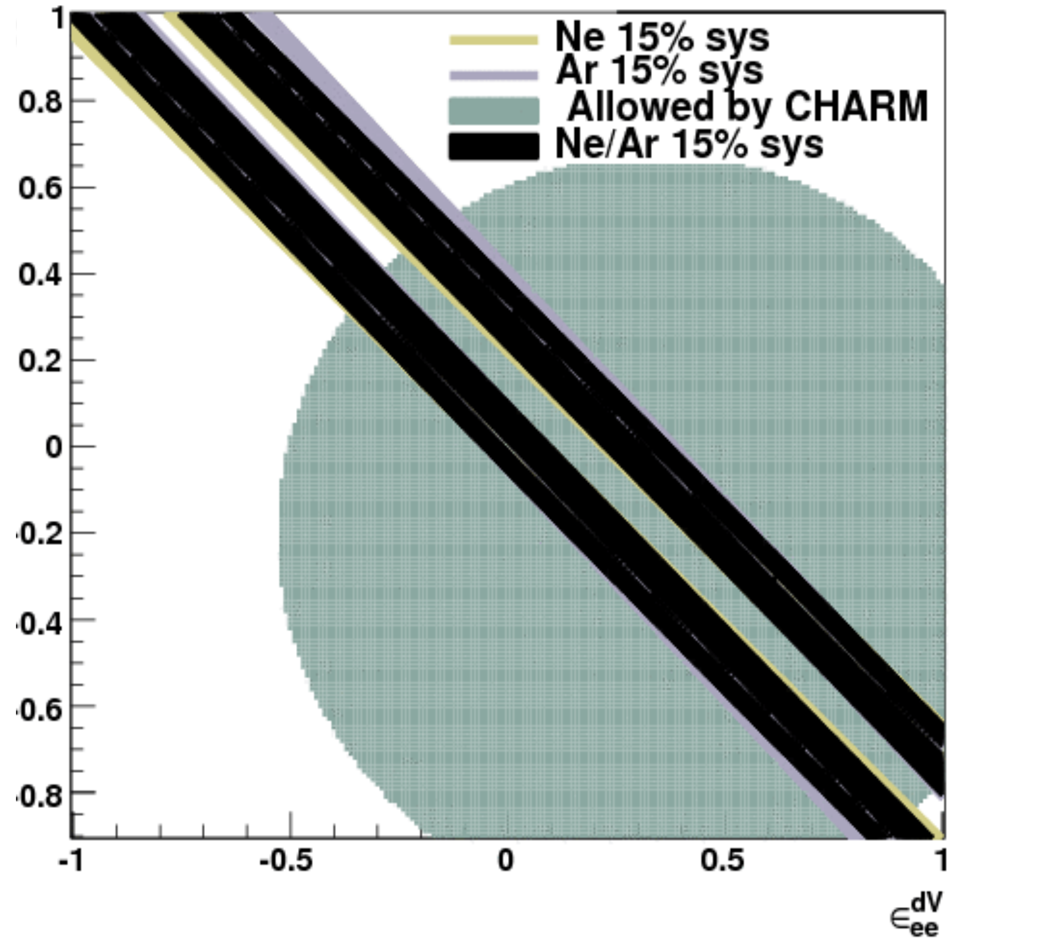
$$(N - (1 - 4\sin^2\theta_W)Z)^2$$

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

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

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

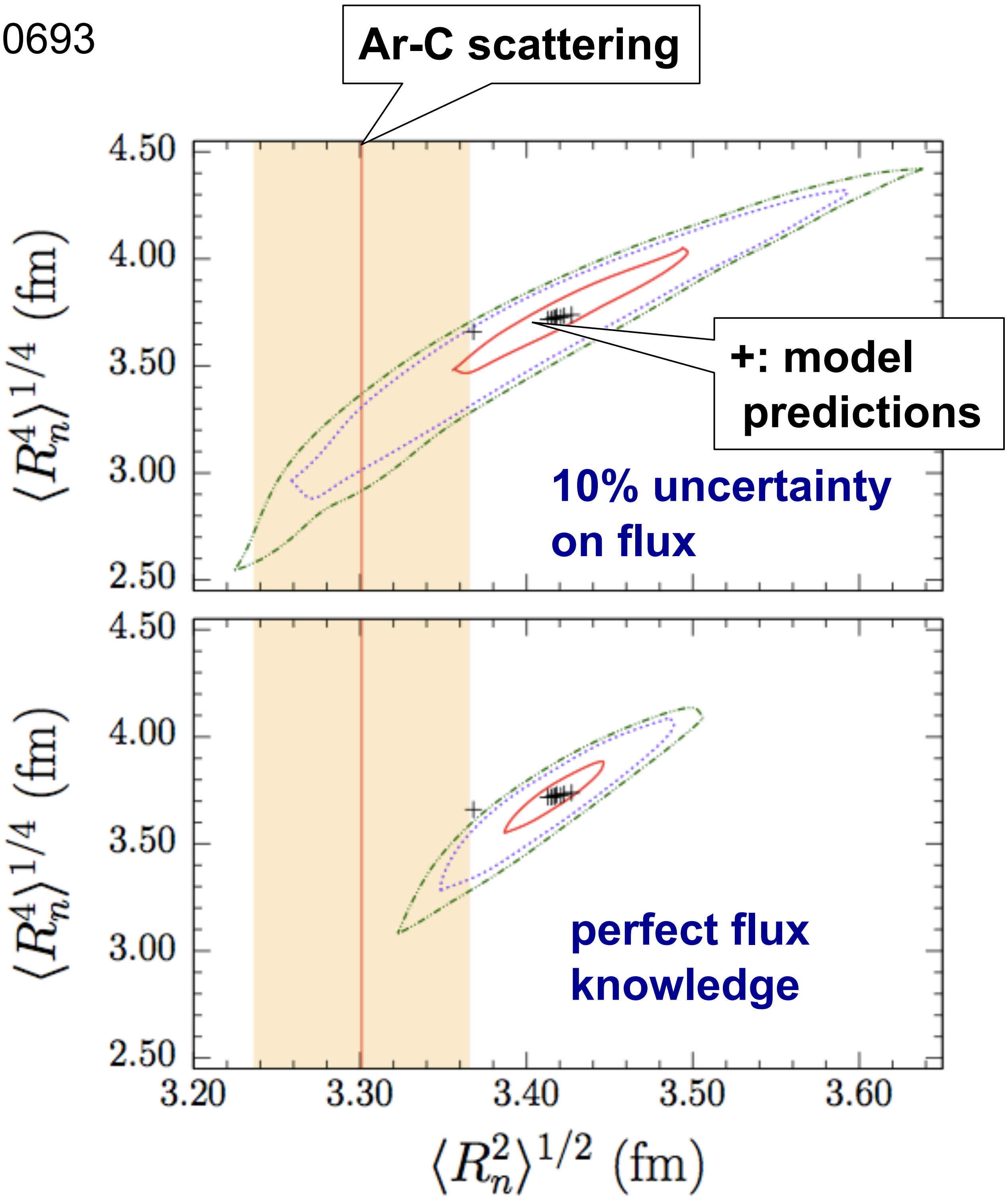
$$\begin{aligned} F_n(Q^2) &\approx \int \rho_n(r) \left(1 - \frac{Q^2}{3!} r^2 + \frac{Q^4}{5!} r^4 - \frac{Q^6}{7!} r^6 + \cdots \right) r^2 dr \\ &\approx N \left(1 - \frac{Q^2}{3!} \langle R_n^2 \rangle + \frac{Q^4}{5!} \langle R_n^4 \rangle - \frac{Q^6}{7!} \langle R_n^6 \rangle + \cdots \right)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

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

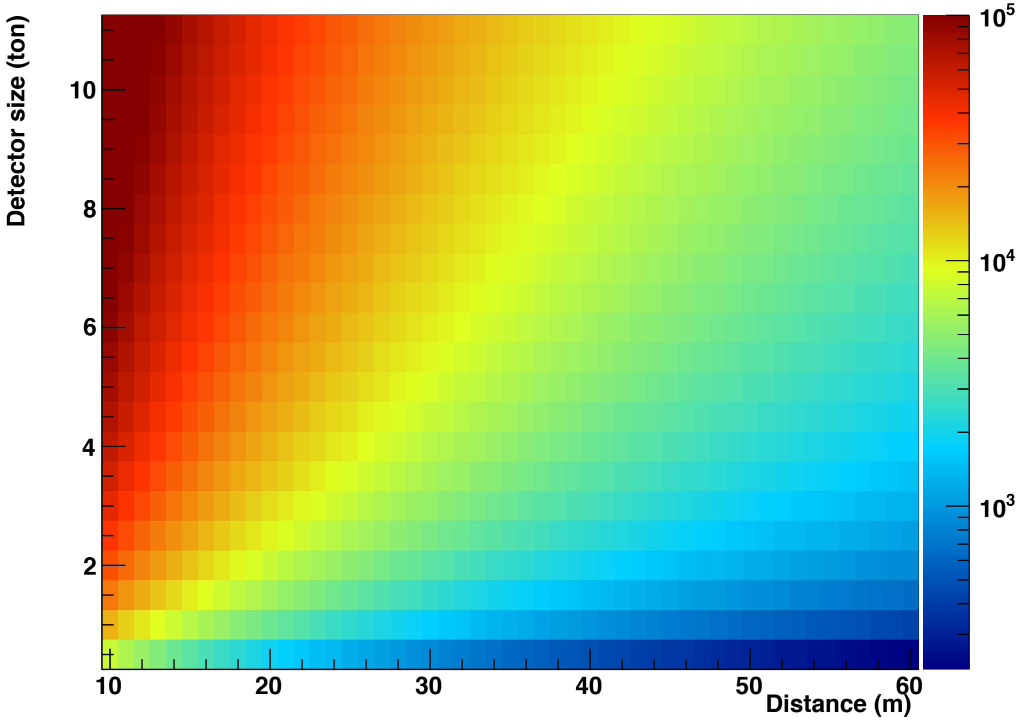
Possible phases of stopped-pion coherent νA scattering experiments

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

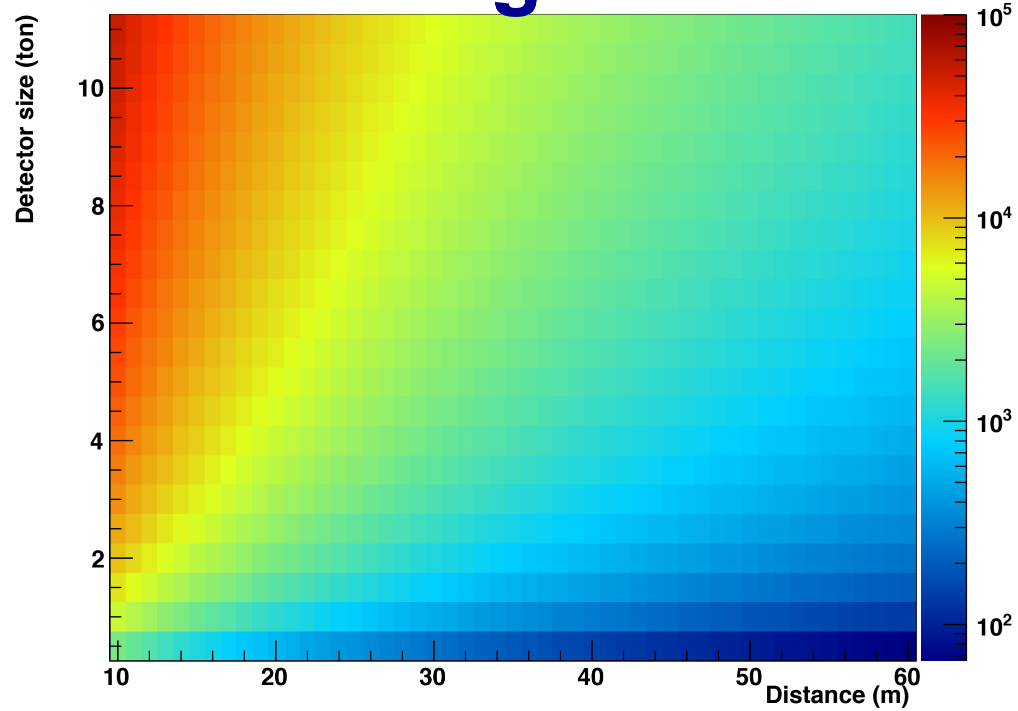
Total events per year at the SNS as a function of distance and mass

just scaling as α $1/R^2$, α M

lead



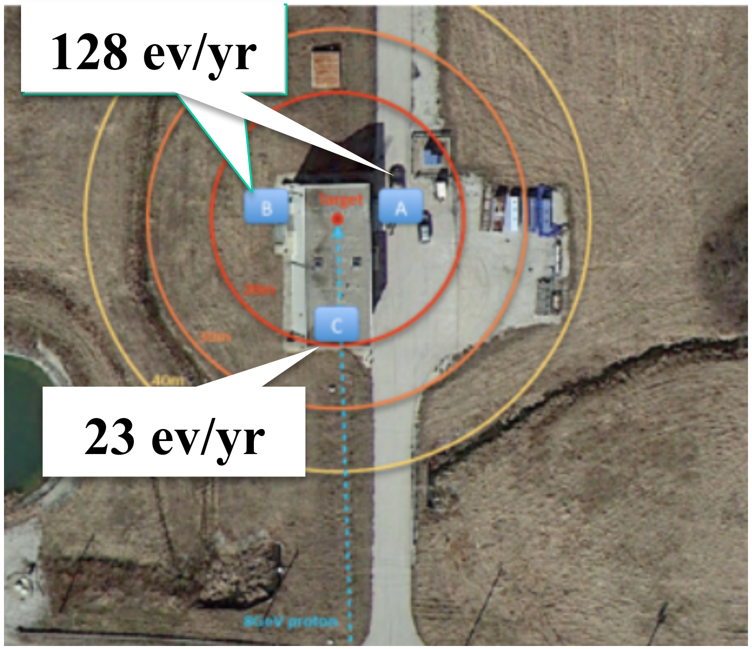
argon

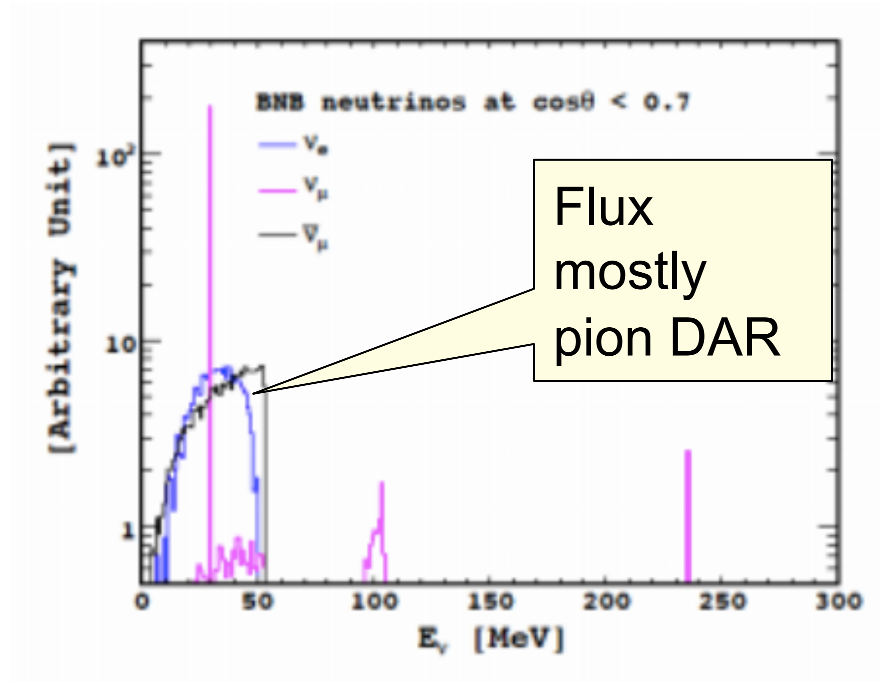


~10^3 events per few tons at 30 m

Low-energy neutrino running

Far-off-axis neutrinos at the FNAL Booster Neutrino Beam





Also considered:

Lujan (LANL), Spallation Neutron Source (ORNL)

➔ SNS gives higher event rate by ~10^2, but CAPTAIN has selected BNB due to easier installation

Further S/B studies for possible sites/shielding are needed