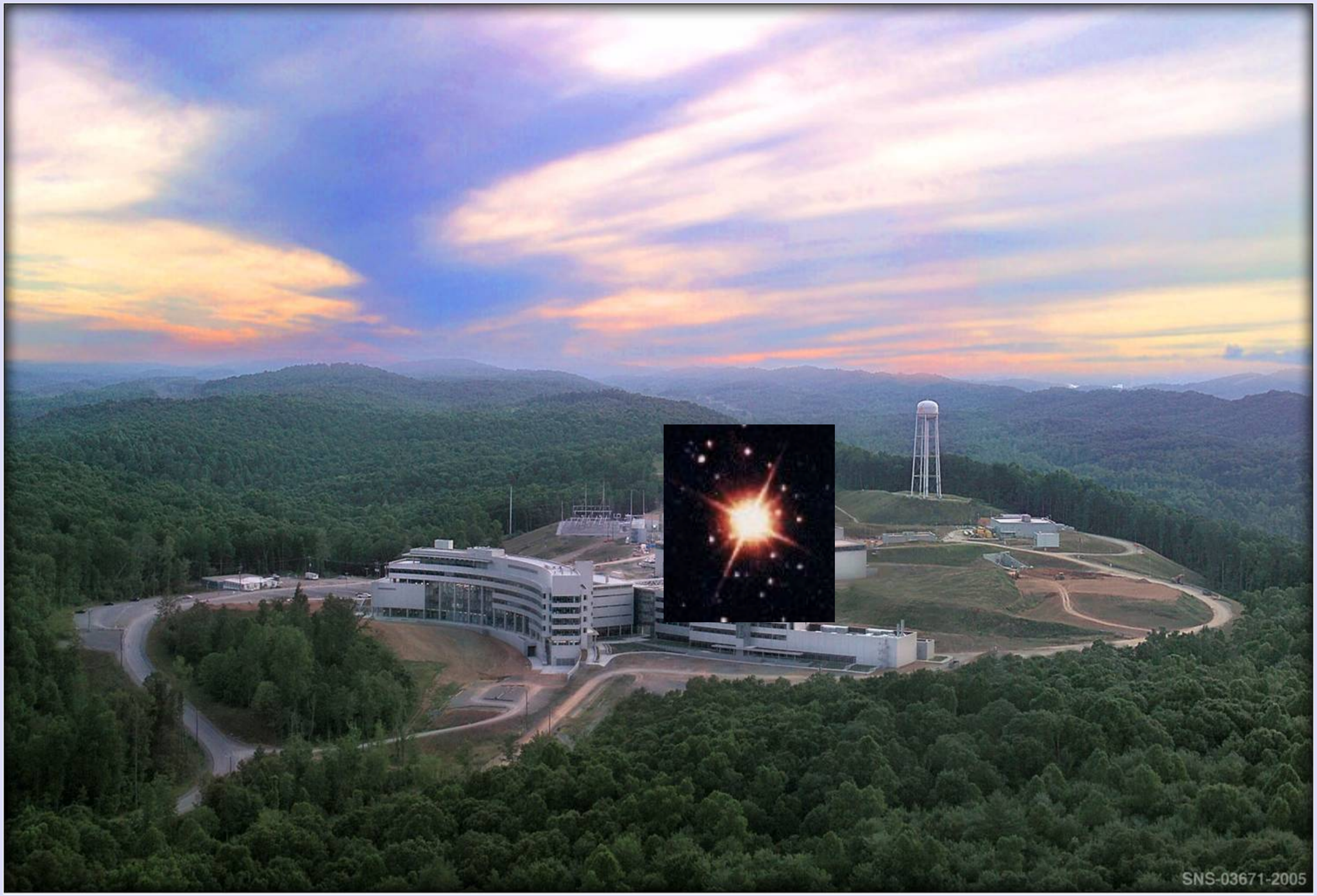
Liquid Argon Measurements for Understanding of Supernova Neutrino Sensitivity



Kate Scholberg, Duke University
Santa Fe, February 2013

Outline

-Supernova neutrinos

Supernova neutrino physics with LAr

-What do we need to know for LBNE?

Cross sections

Detector response

Backgrounds

-How to go after these

Stopped-pion sources

The Spallation Neutron Source

Measuring cosmogenics

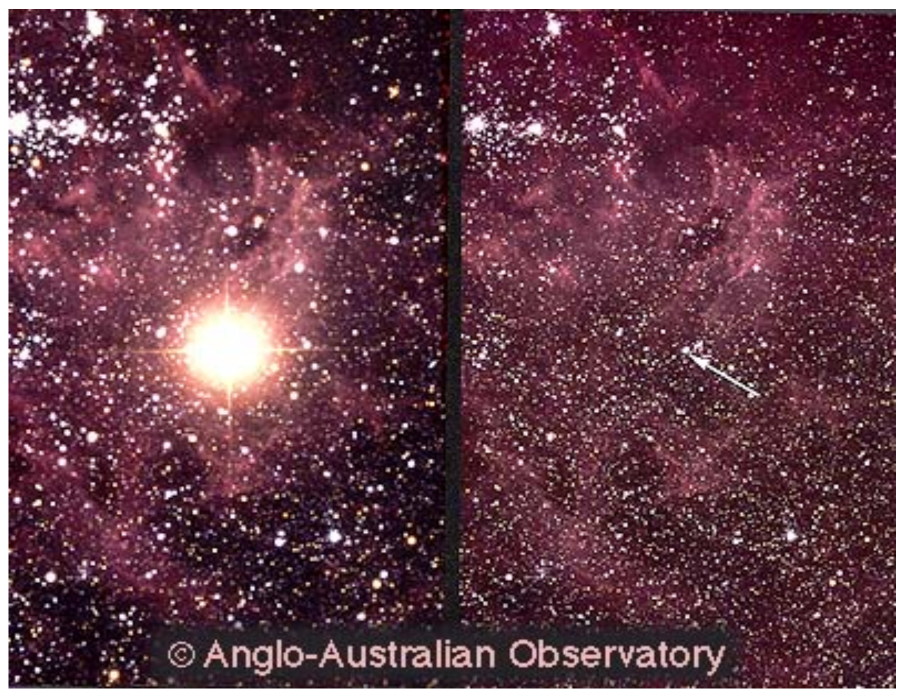
Neutrinos from core collapse

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)

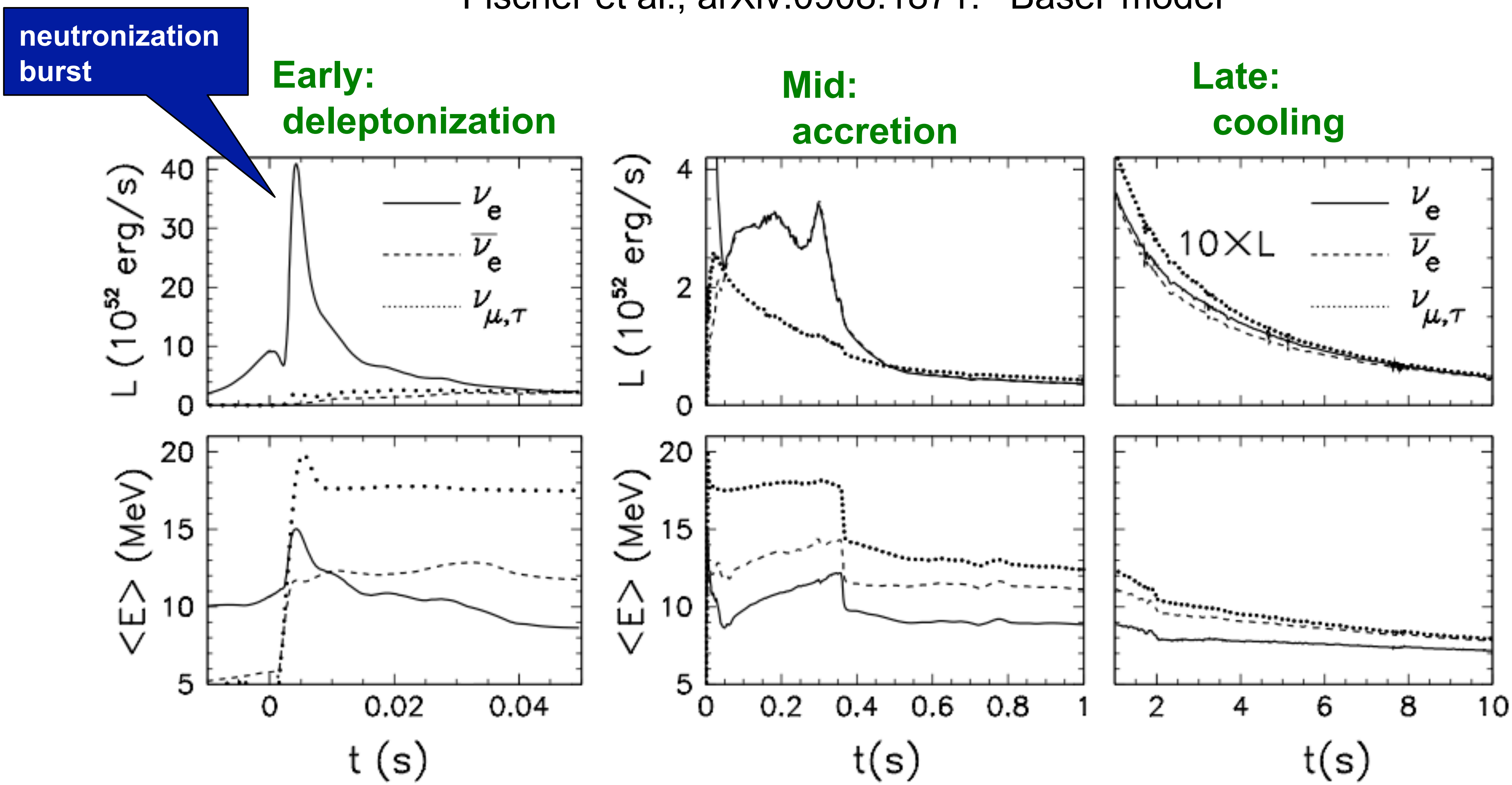
Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

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



Expected neutrino luminosity and average energy vs time

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

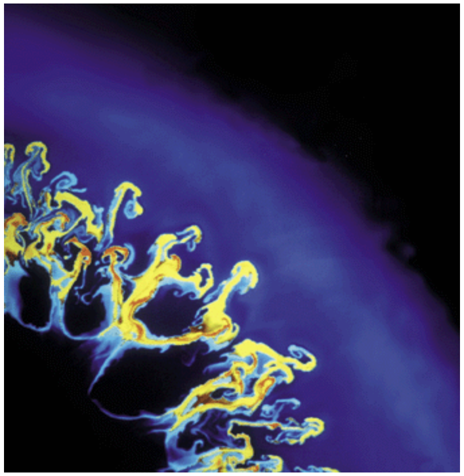


Generic feature:

(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

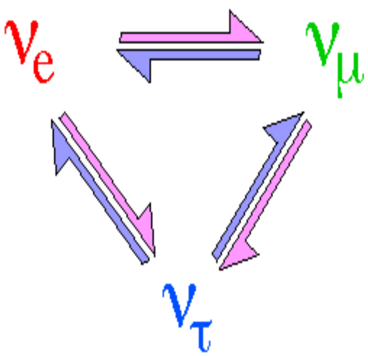


CORE COLLAPSE PHYSICS

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

from flavor, energy, time structure of burst

NEUTRINO/OTHER PARTICLE PHYSICS

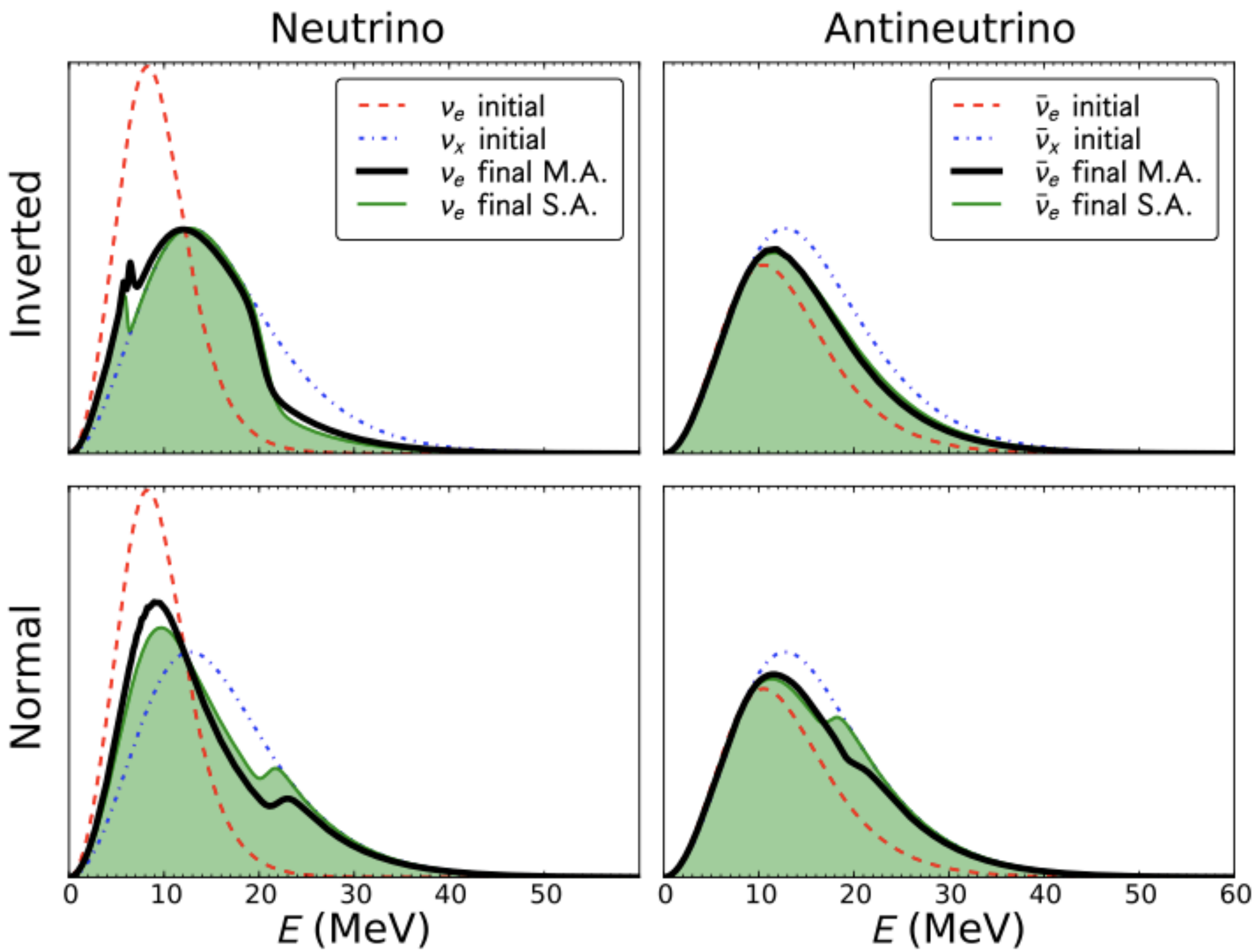


- ν absolute mass (not competitive)
- ν mixing from spectra: flavor conversion in SN/Earth
- other ν properties: sterile ν's, magnetic moment,...
- axions, extra dimensions, FCNC, ...

+ EARLY ALERT

Example: collective effects

Duan & Friedland, arXiv:1006.2359



***Distinctive spectral swap features depend on neutrino mass hierarchy*, for neutrinos vs antineutrinos**

Experimentally, can we tell the difference?

Low energy neutrino interactions in argon

Charged-current absorption

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

Dominant

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

Neutral-current excitation

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

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)...

Tool for evaluating neutrino event rates

To evaluate sensitivity to different features of flux/physics, we need to fold

$$\text{flux} \otimes \text{xscn} \otimes \text{detector response}$$

Software package to make use of the GLoBES front-end rate engine (*not* the oscillation sensitivity part)

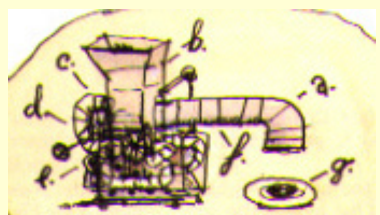
flux differential spectra w/physics

cross- sections for relevant channels

smearing matrix for given detector config: includes both interaction product distributions and detector response

post-smearing efficiency

SNOw GLoBES

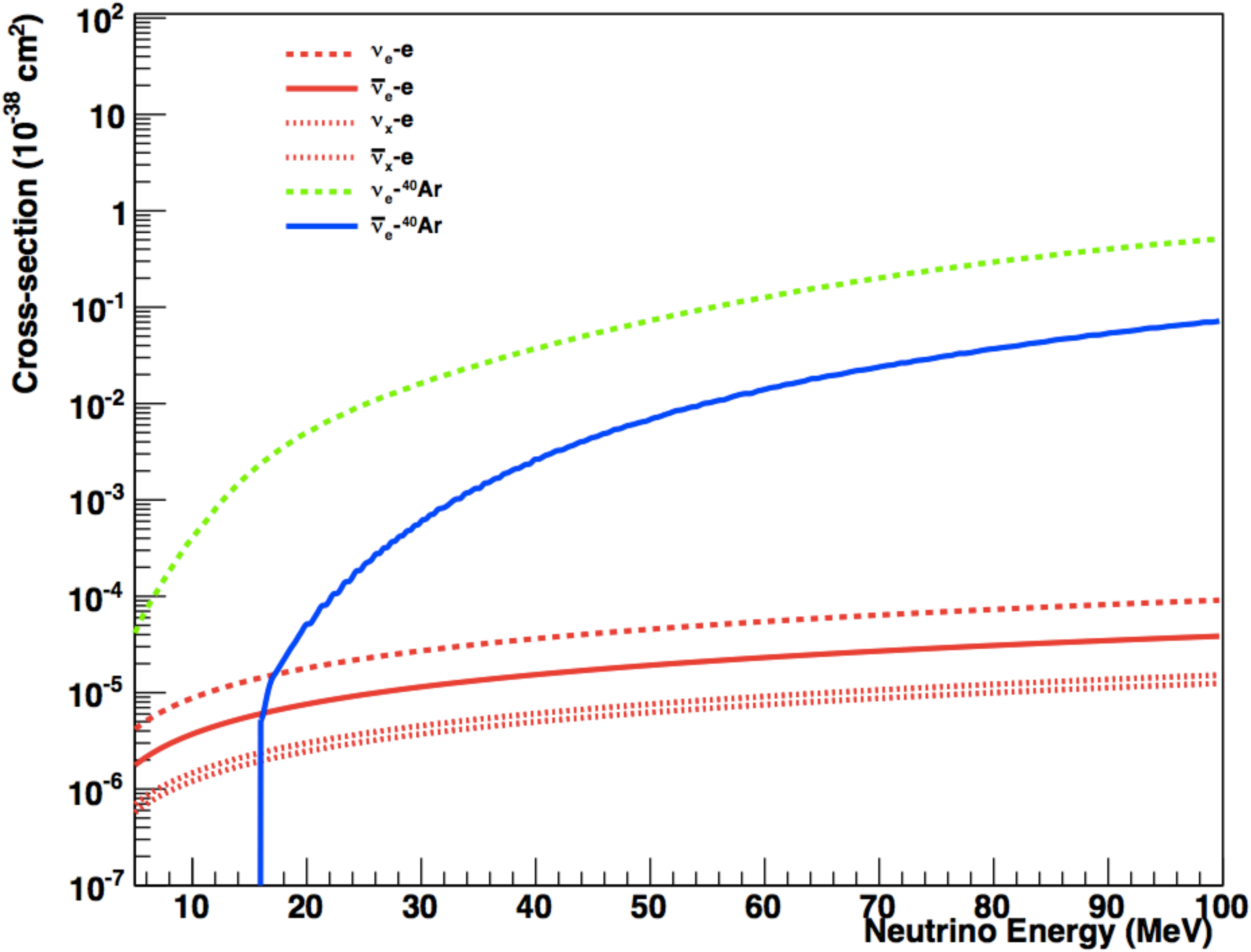


interaction rates, as a function of neutrino energy

'smeared' rates as a function of detected energy

what we're after

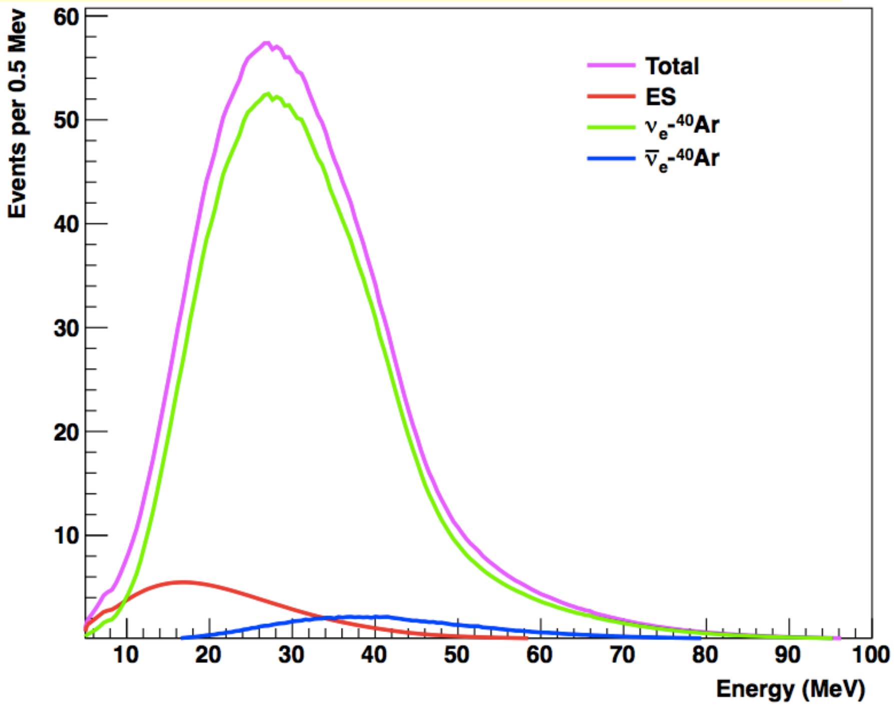
Cross-sections for interactions in argon



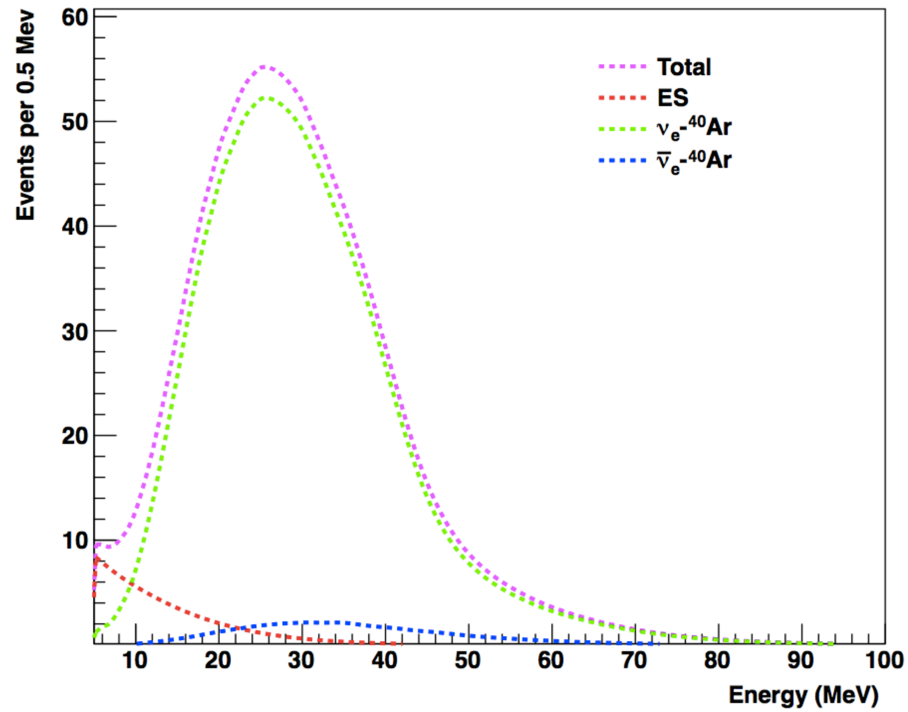
Supernova signal in LAr

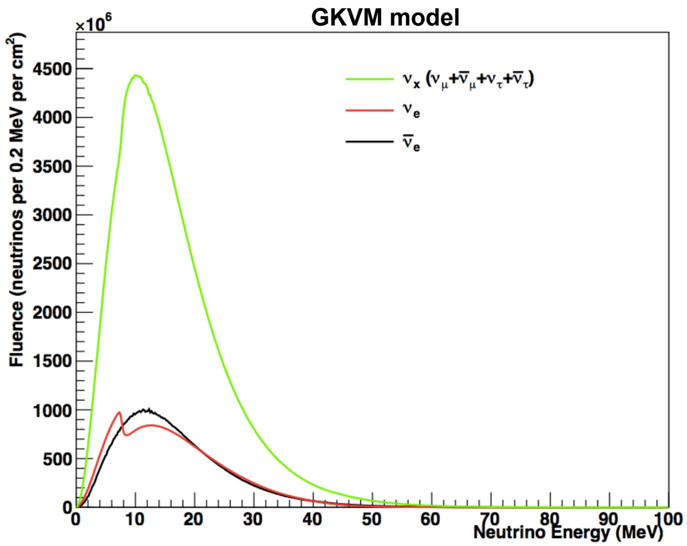
SN @ 10 kpc, 34 kton

Interactions, as a function of neutrino energy



Events seen, as a function of observed energy





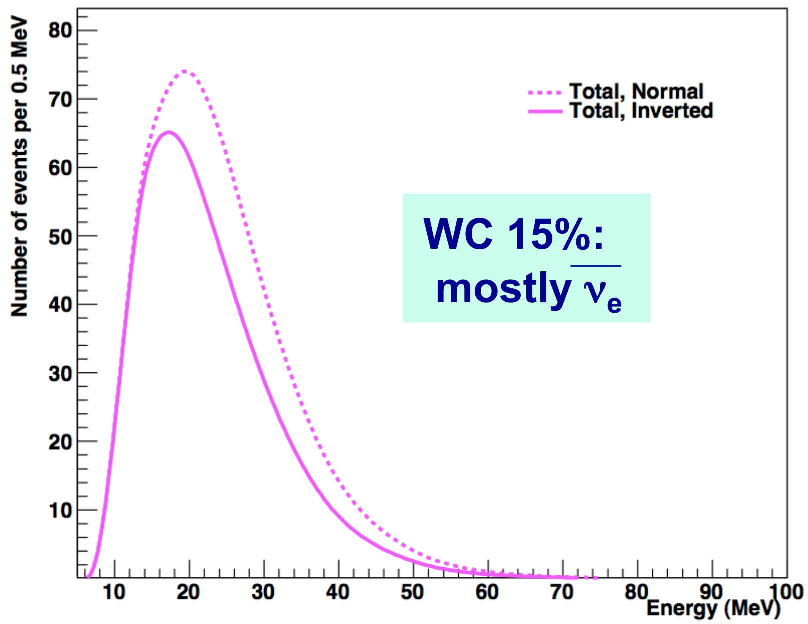
Channel	No of events (observed), GKVM	No. of events (observed), Livermore
Nue-Ar40	2848	2308
Nuebar-Ar40	134	194
ES	178	296
Total	**3160**	**2798**

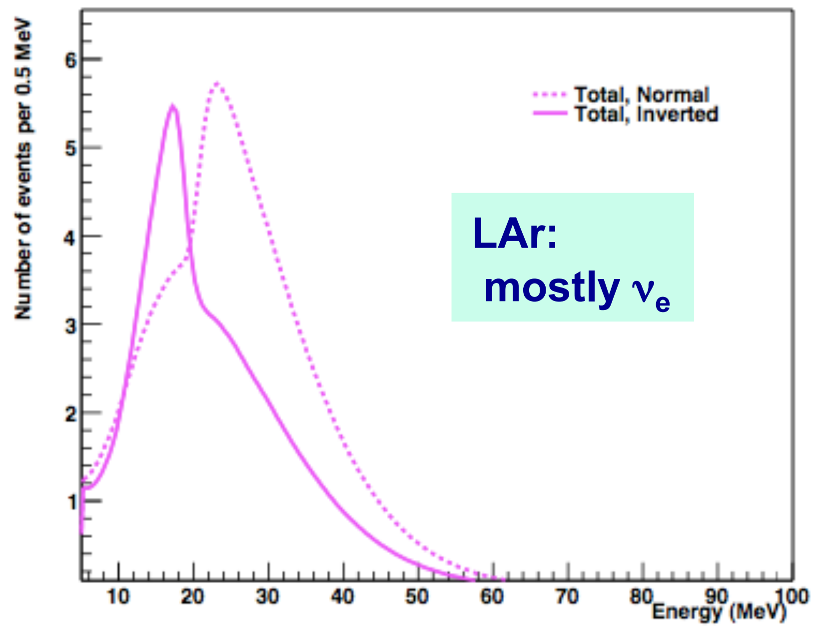
Dominated by ν_e

Observability of oscillation features: example

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

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



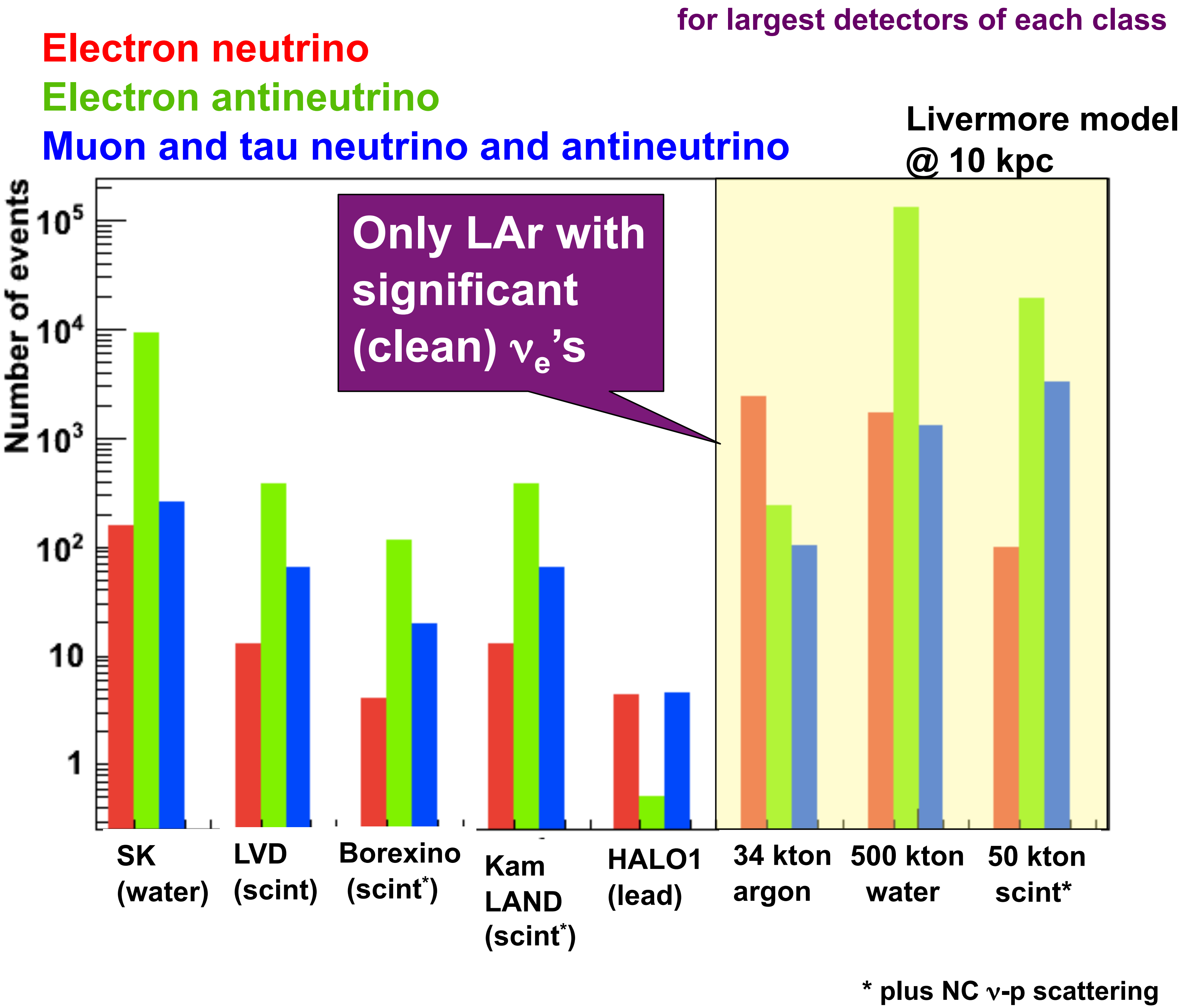


Differences, but no sharp features

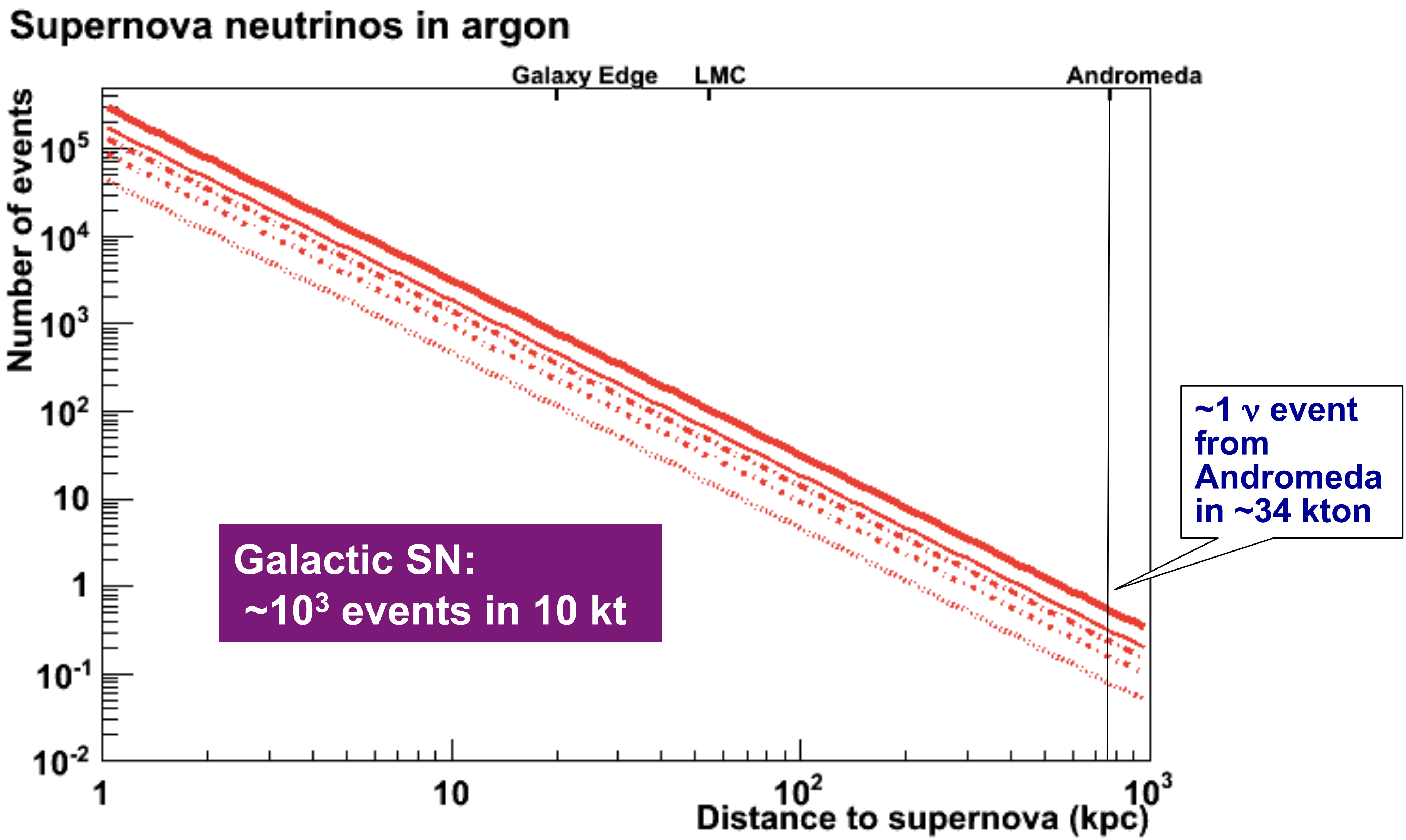
LAr shows dramatic difference

`Anecdotal' evidence is good...
systematic surveys underway

World SN flavor sensitivity



Signal rates vs distance for LBNE configurations



5, 10, 15, 20, 34 kton

What do we need to know to evaluate, and optimize, SN neutrino sensitivity in LBNE?

- Cross sections for ν-Ar interactions at low energy

- Realistic LAr TPC detector response:

  Efficiency, resolution, tagging

- Backgrounds:

  especially cosmogenics

What do we need to know to evaluate, and optimize, SN neutrino sensitivity in LBNE?

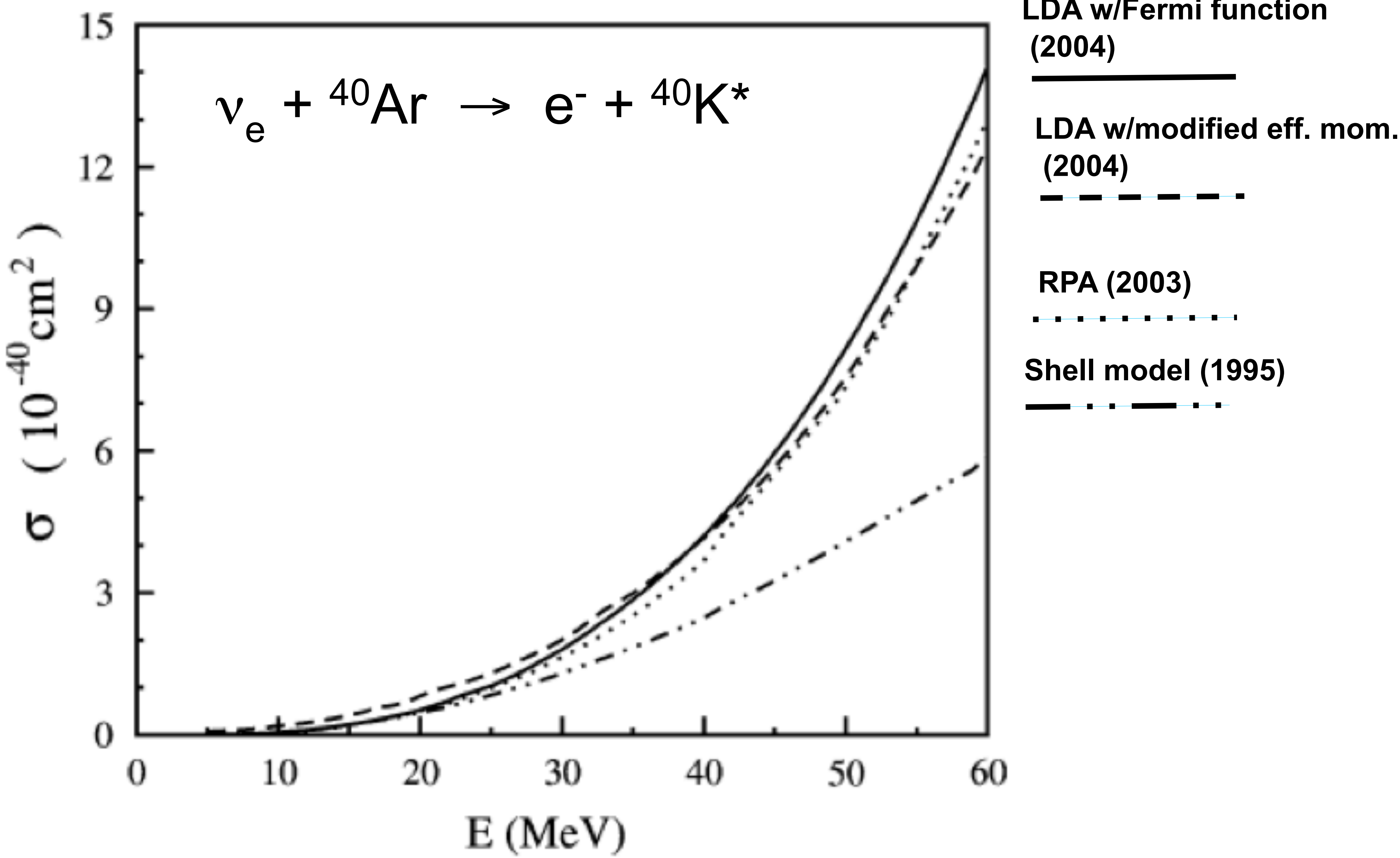
- Cross sections for ν-Ar interactions at low energy

- Realistic LAr TPC detector response:

  Efficiency, resolution, tagging

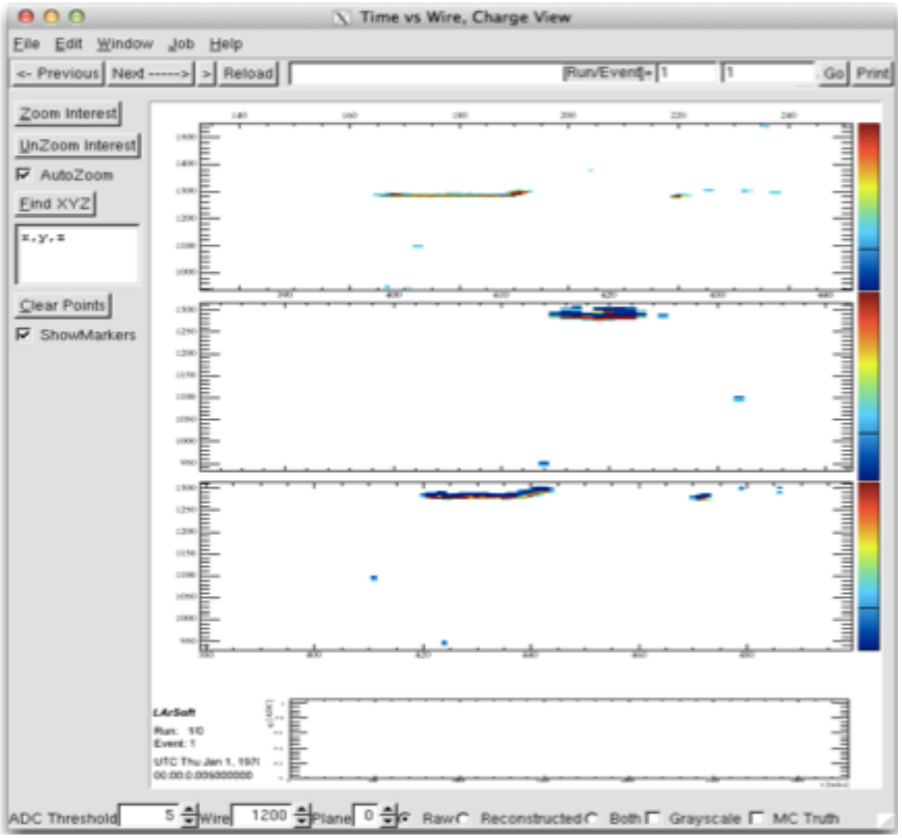
Cross sections for CC electron neutrino absorption

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

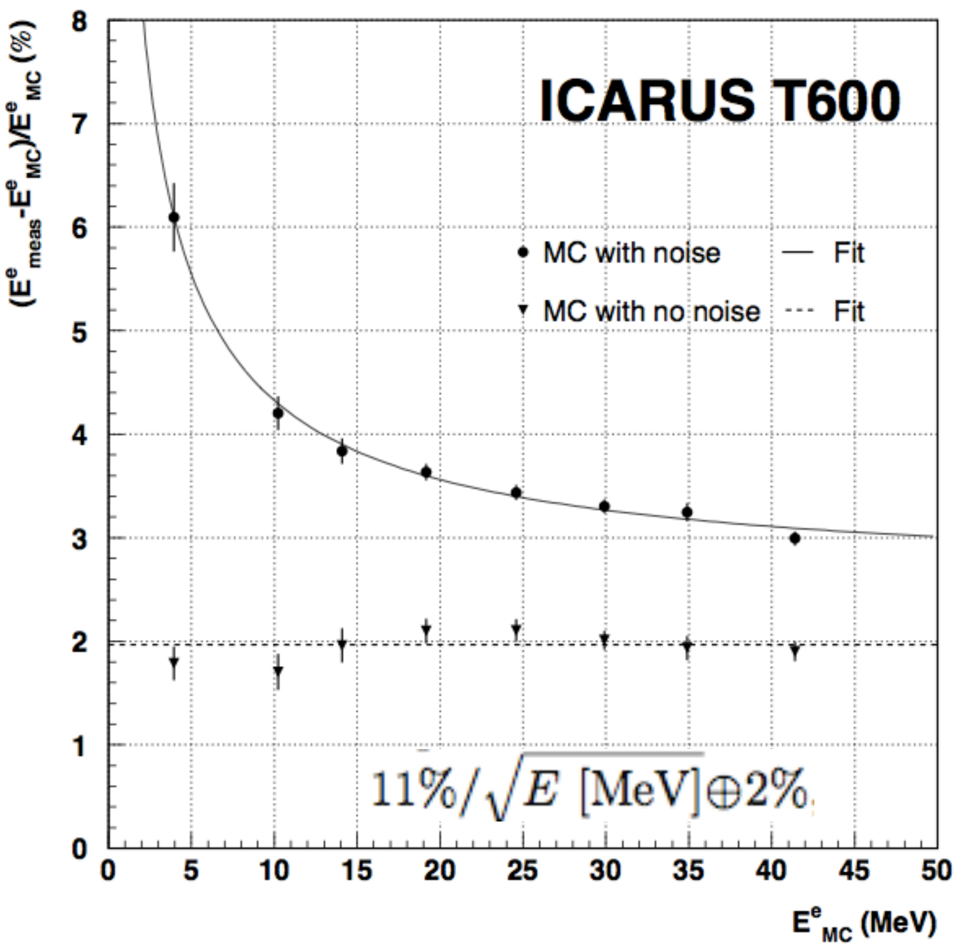
(μBooNE geometry)

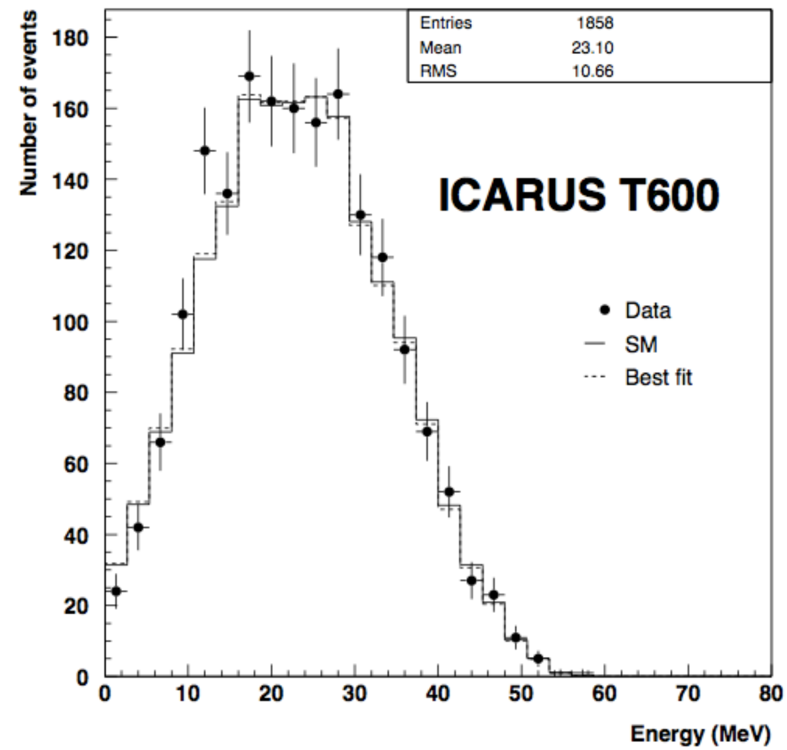
- **energy resolution?**
- **vertex resolution?**
- **directional resolution?**
- **detection & reconstruction efficiency?**

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

ICARUS resolution
(what's in SNOwGLoBES)

Amoruso et al., hep-ex/0311040



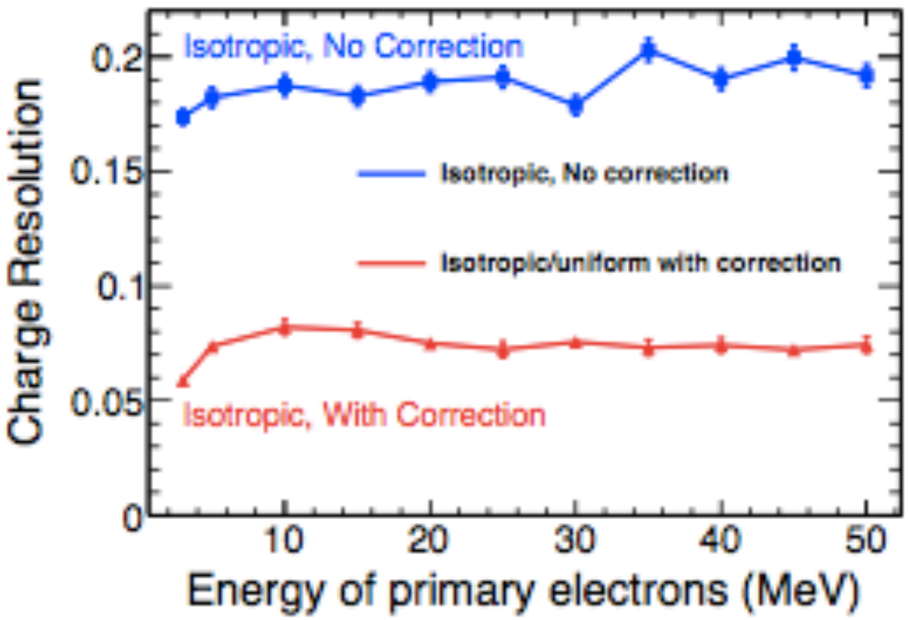


uses MC tuned to measured Michel electrons

Does not include "calorimetric" correction from drift time (~5%?)

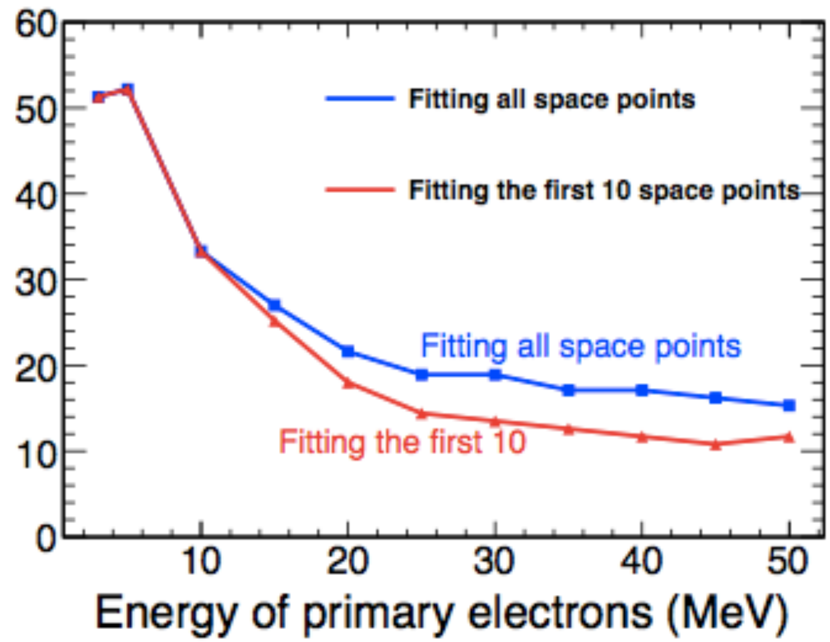
LArSoft Low-Energy Event studies (Z. Li)

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



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

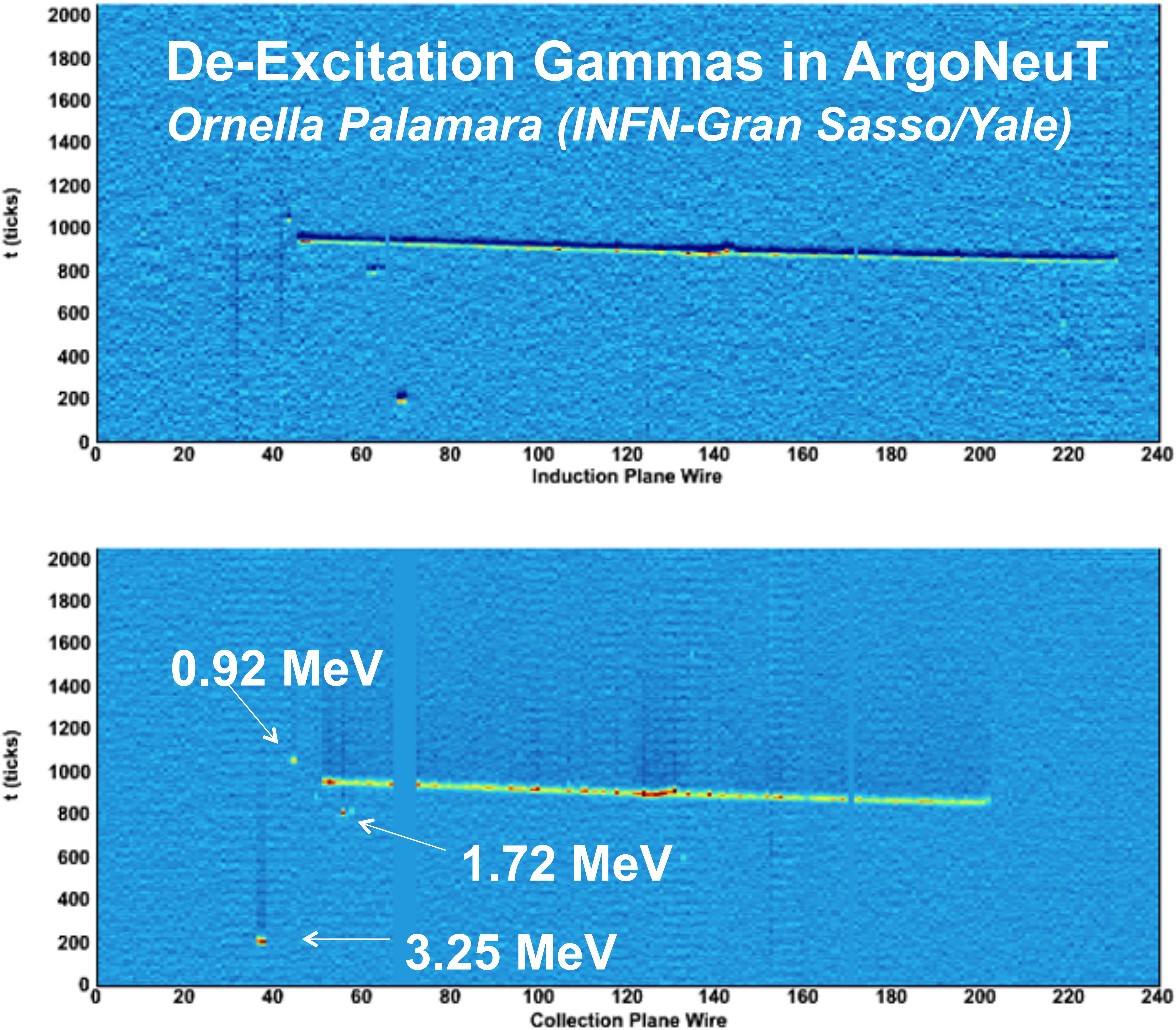
Direction resolution (degrees)



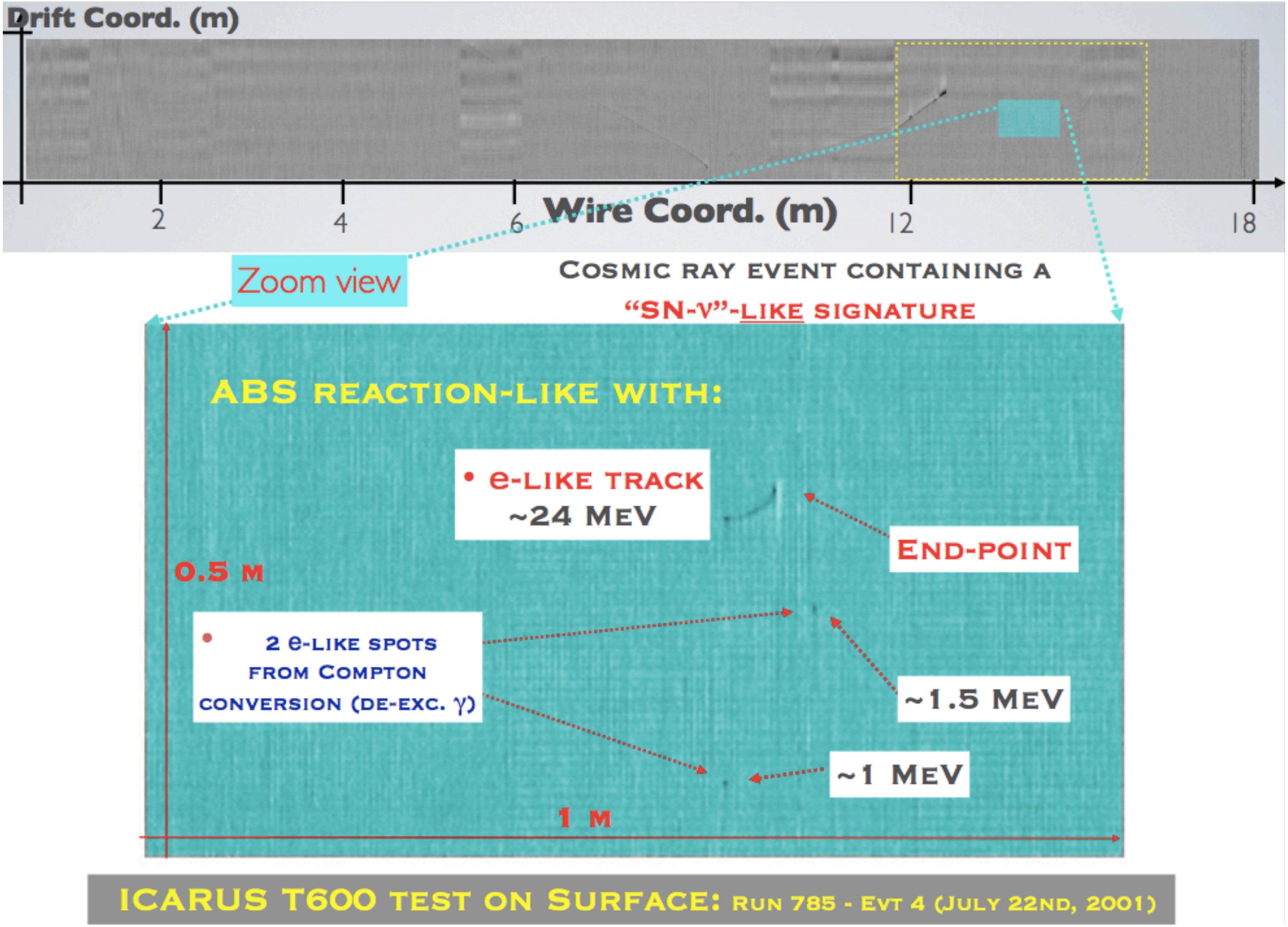
Preliminary

De-Excitation Gammas in ArgoNeuT

Ornella Palamara (INFN-Gran Sasso/Yale)



From Flavio Cavanna (SNS workshop, May 2012)



What do we need to know to evaluate, and optimize, SN neutrino sensitivity in LBNE?

- Cross sections for ν-Ar interactions at low energy

- Realistic LAr TPC detector response:

  Efficiency, resolution, tagging

How can we get at these?

What do we need to know to evaluate, and optimize, SN neutrino sensitivity in LBNE?

- Cross sections for ν-Ar interactions at low energy

- Realistic LAr TPC detector response:

  Efficiency, resolution, tagging

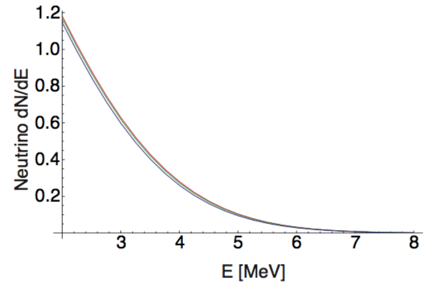
Need low-energy neutrinos of well-understood flux and spectrum

What do you want in a neutrino source?

- ✓ Neutrino spectrum ~matching supernova 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

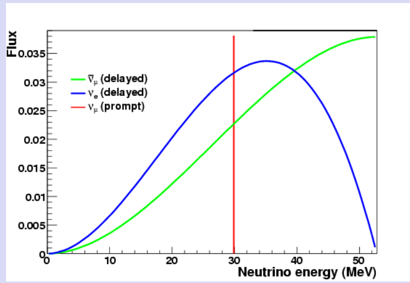
Reactors



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

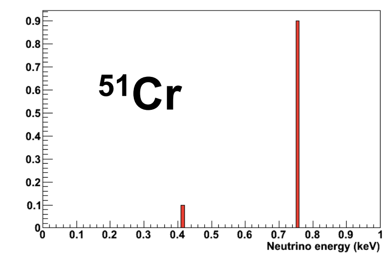
Too low energy

Stopped pions (decay at rest)



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

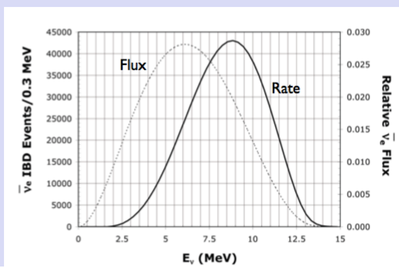
Radioactive sources



Portable; can get very short baseline

Too low energy

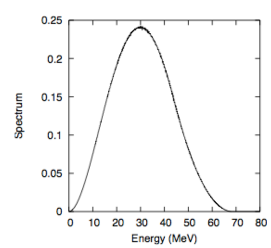
Beam-induced radioactive sources (IsoDAR)



Relatively compact, higher energy than reactor; not pulsed

Not main LAr sensitivity

Low-energy beta beams



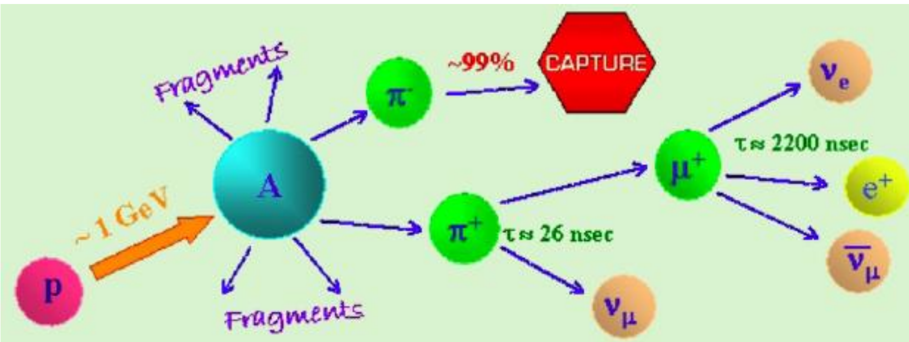
γ=10 boosted ^{18}Ne ν_e

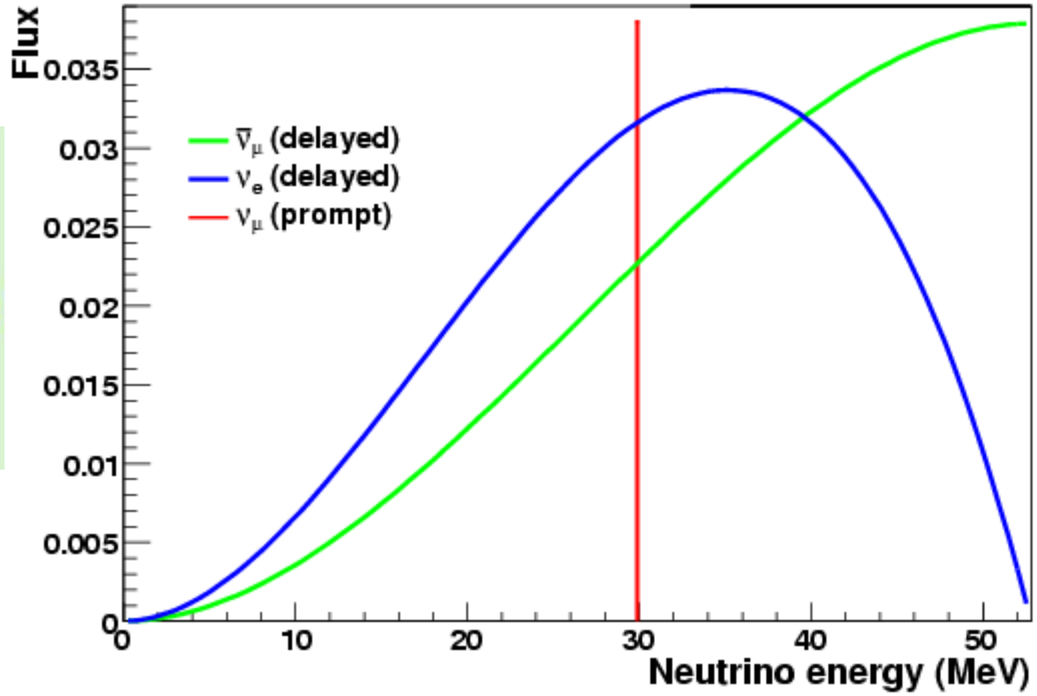
Tunable energy, but not pulsed

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 Neutrino Sources





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

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

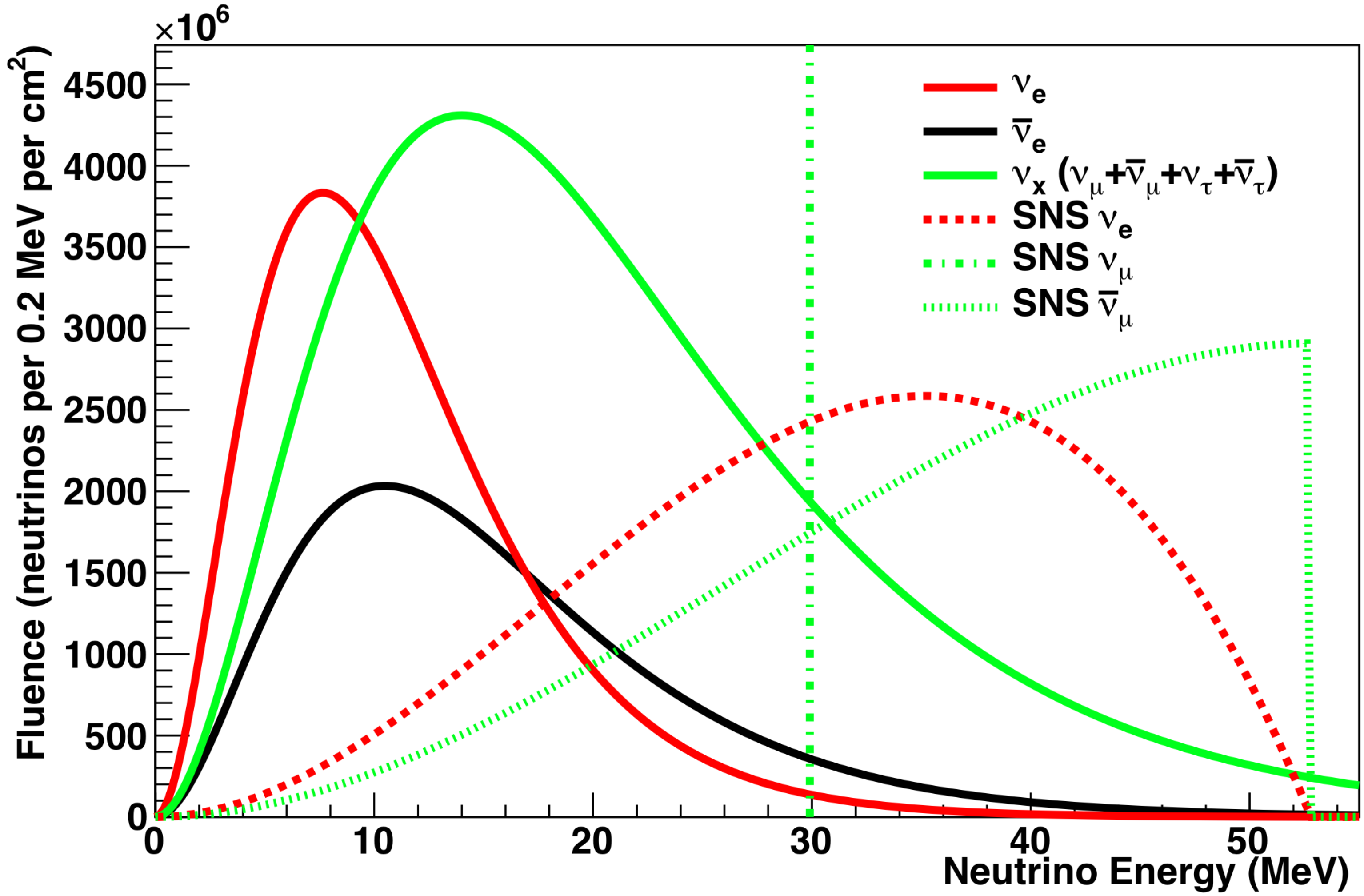
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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

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

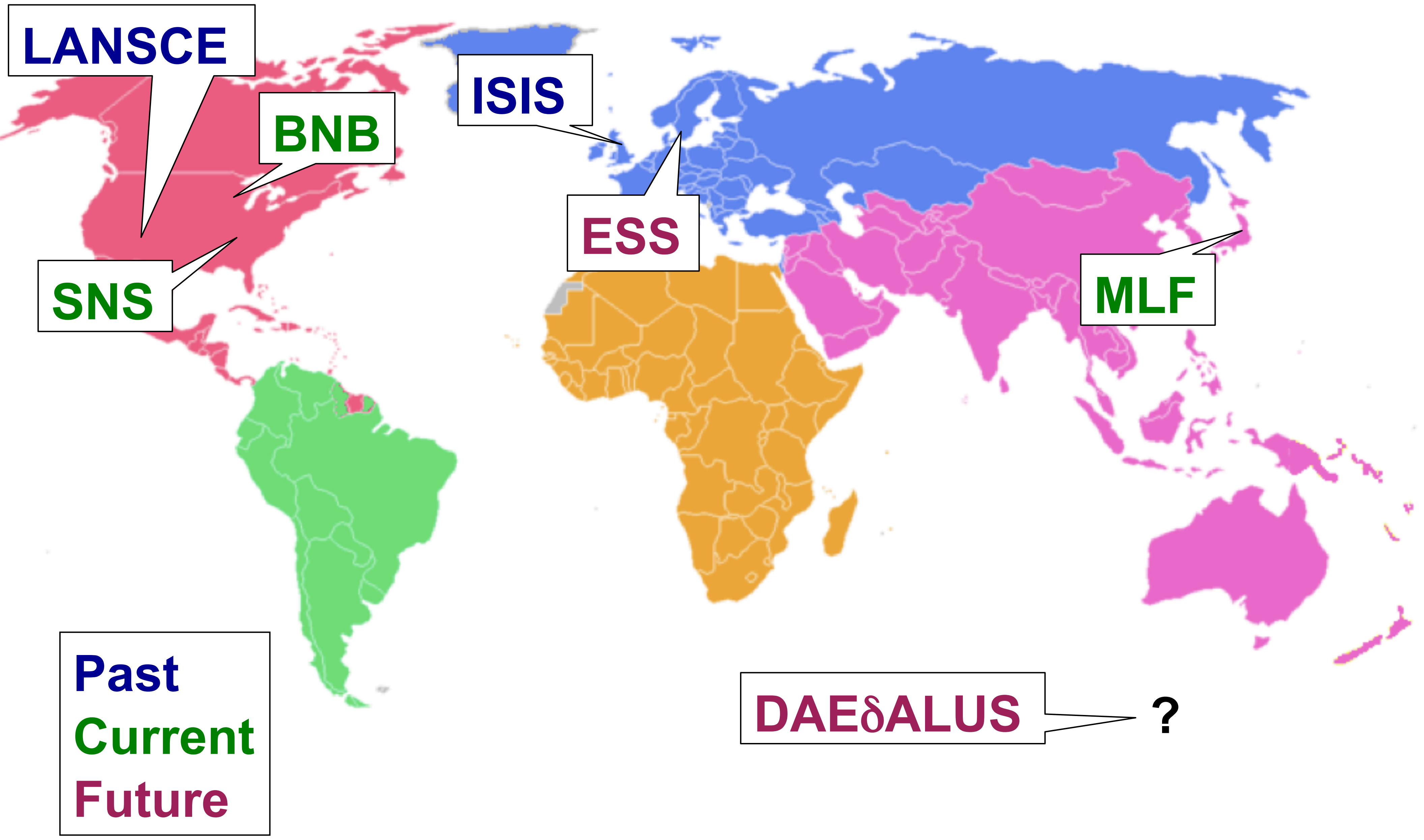
~0.13 per flavor per proton

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

Stopped-Pion Sources Worldwide



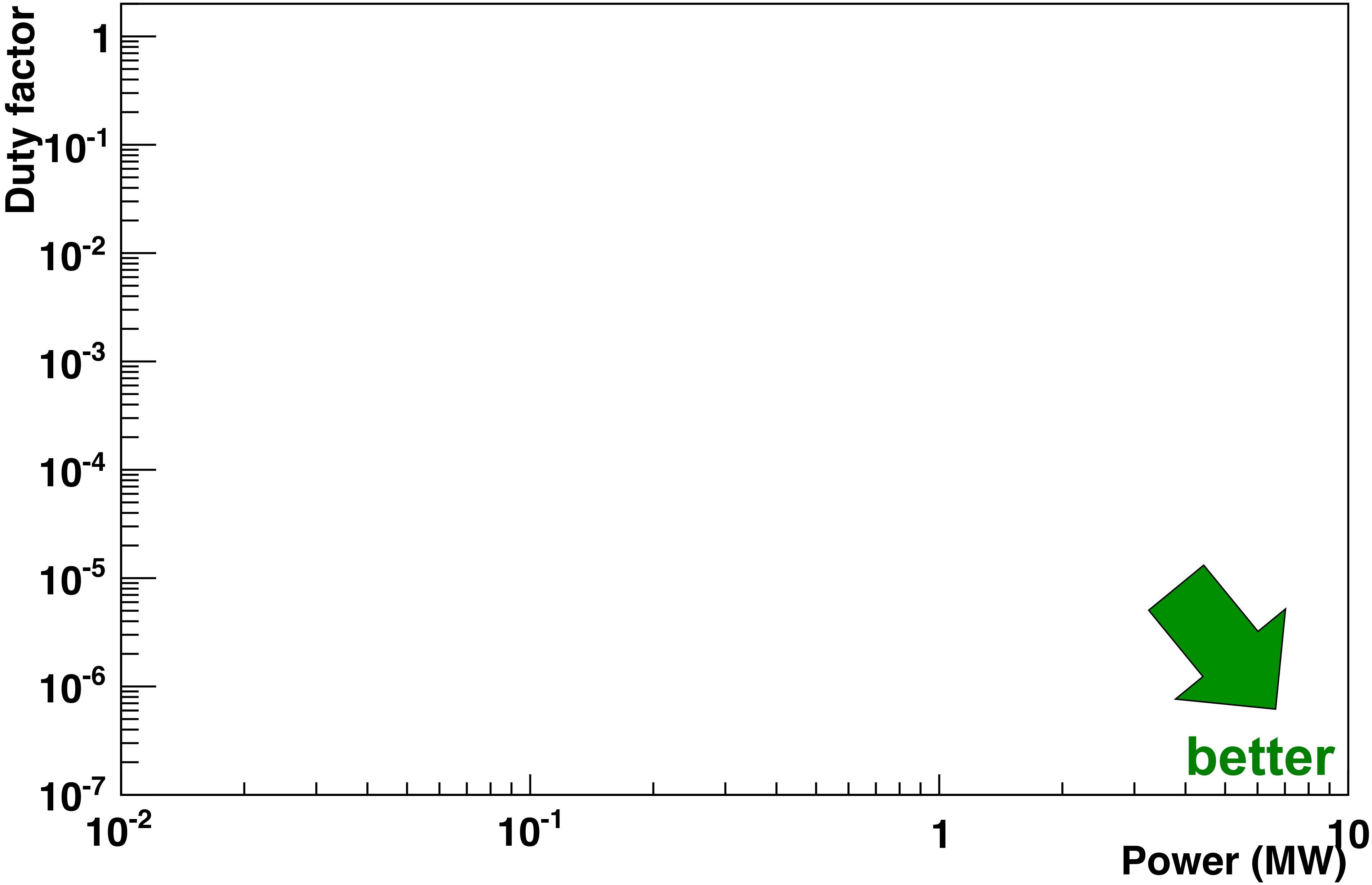
Comparison of stopped-pion neutrino sources

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)

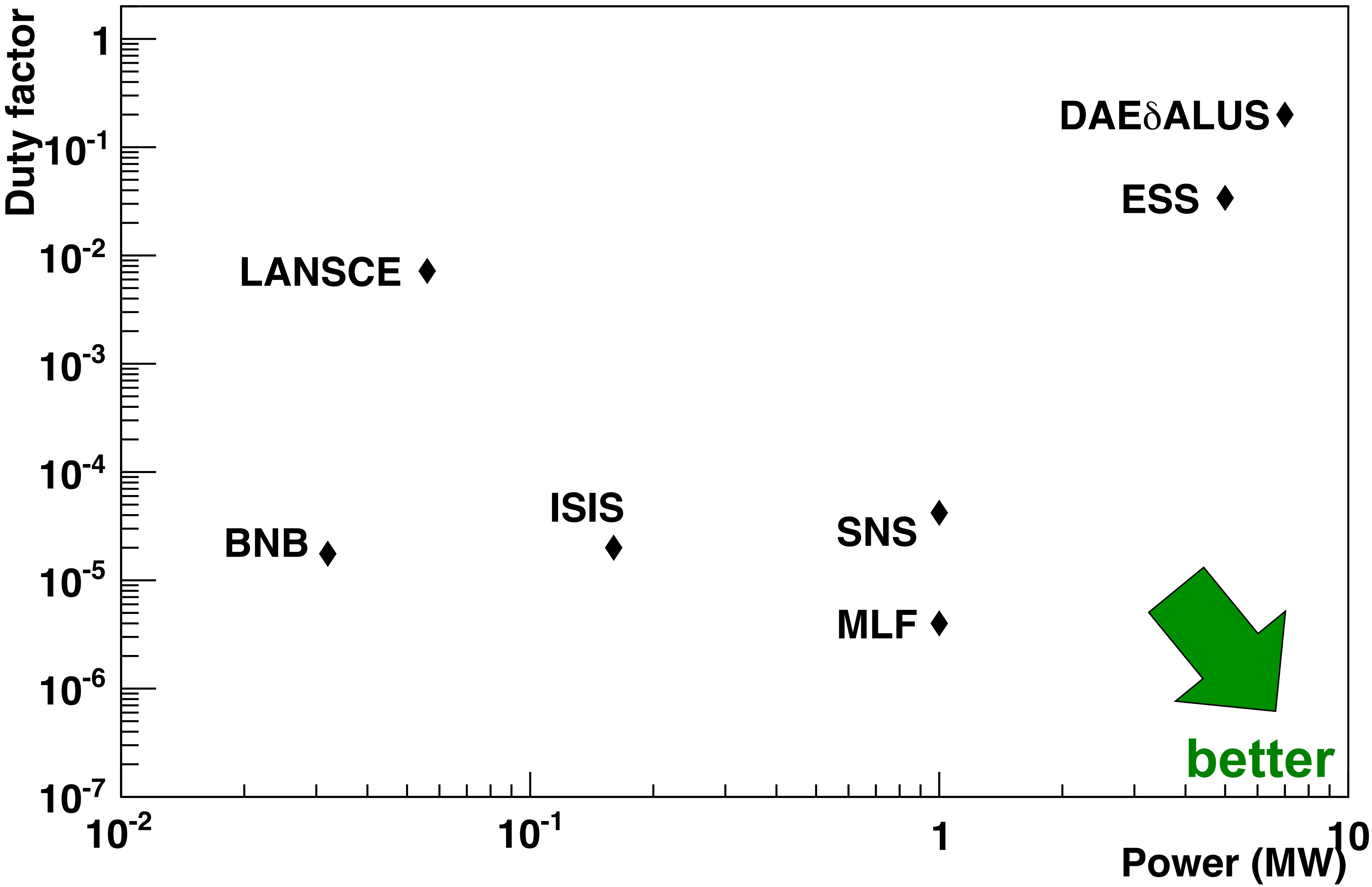
Flux $\propto$ power: want bigger!

Duty factor: want smaller!



Flux $\propto$ power

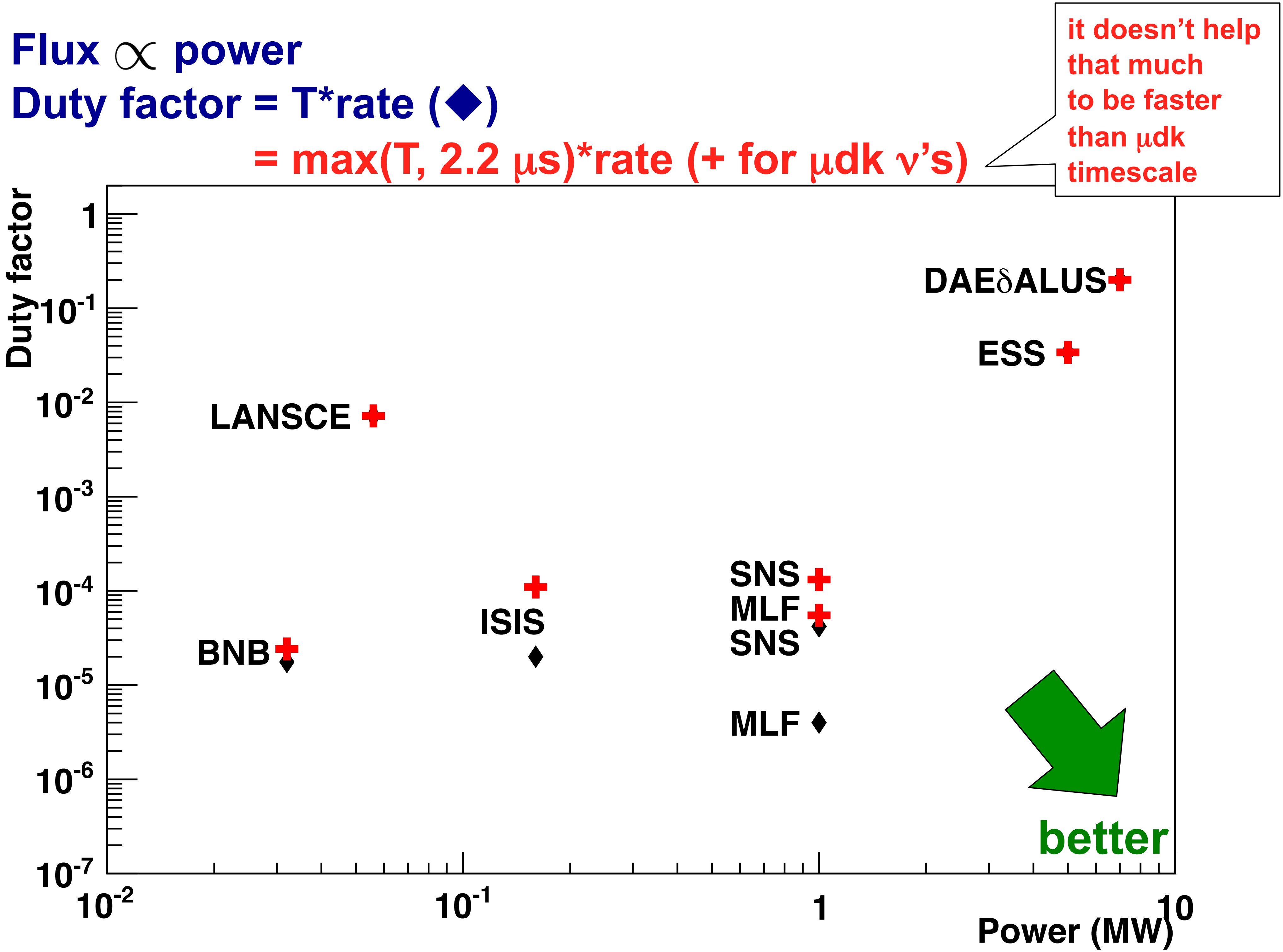
Duty factor = T*rate (◆)



Flux $\propto$ power

Duty factor = T*rate (◆)

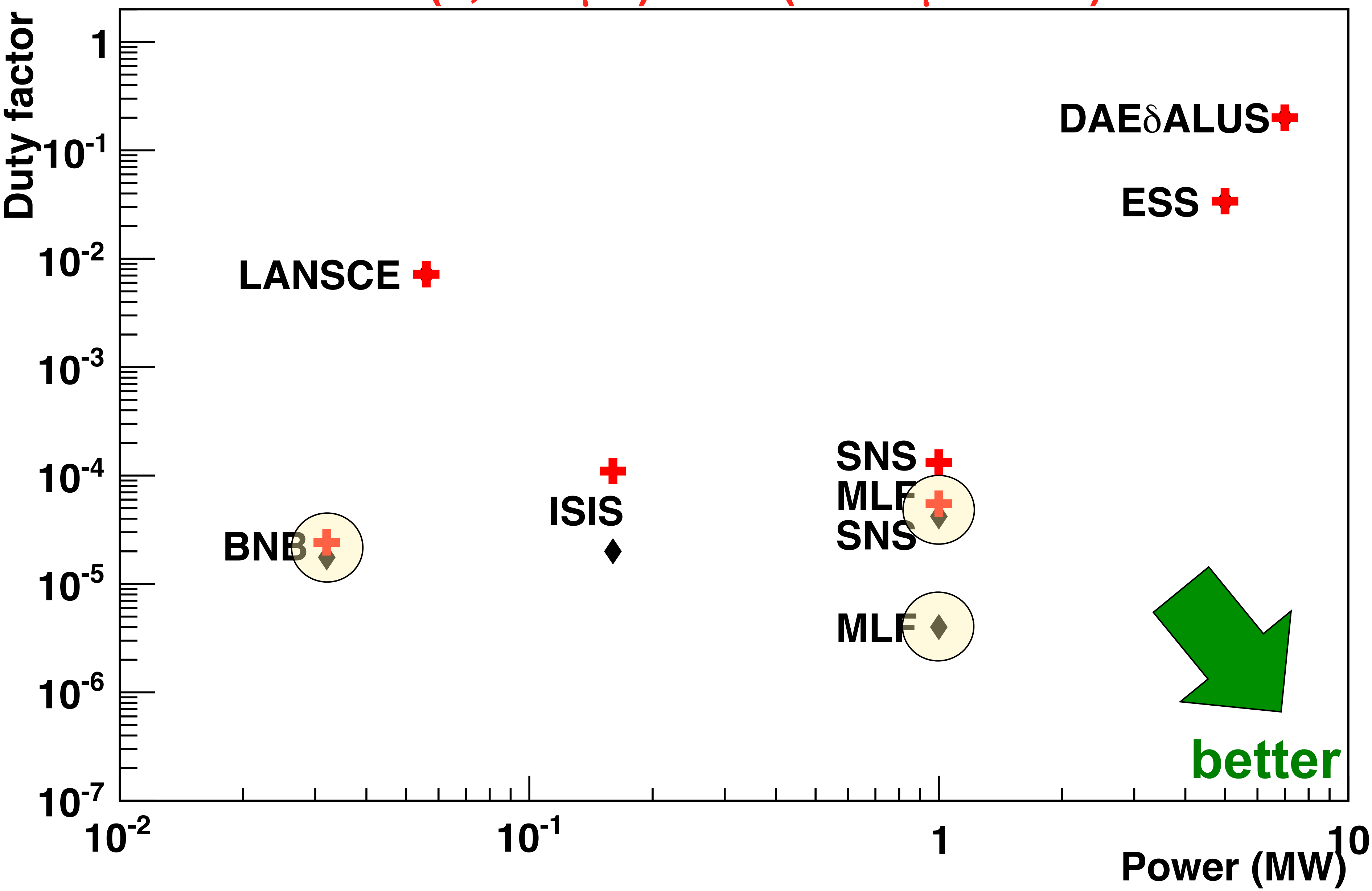
= max(T, 2.2 μs)*rate (+ for μdk ν's)



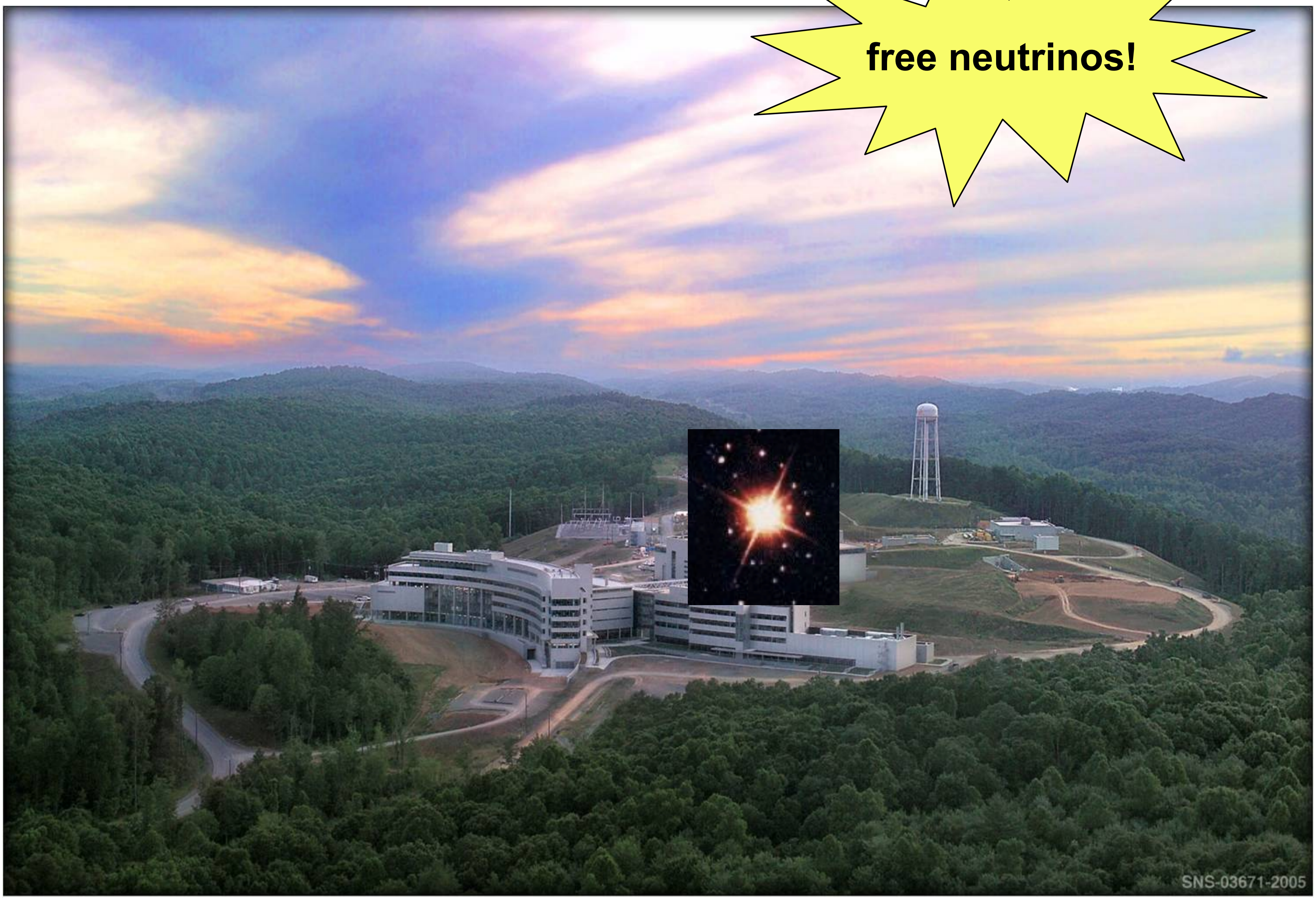
Flux ∝ power, ◯ high energy protons (non-DAR contamination)

Duty factor = T*rate (◆)

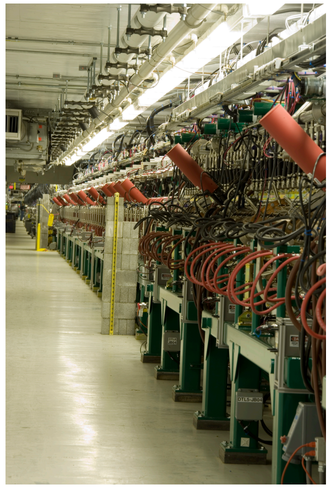
= max(T, 2.2 μs)*rate (+ for μdk ν's)



The Spallation Neutron Source
Oak Ridge, TN

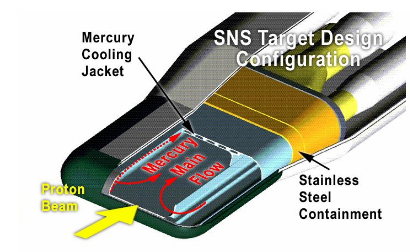


Proton linear accelerator, operation at 1.0 GeV

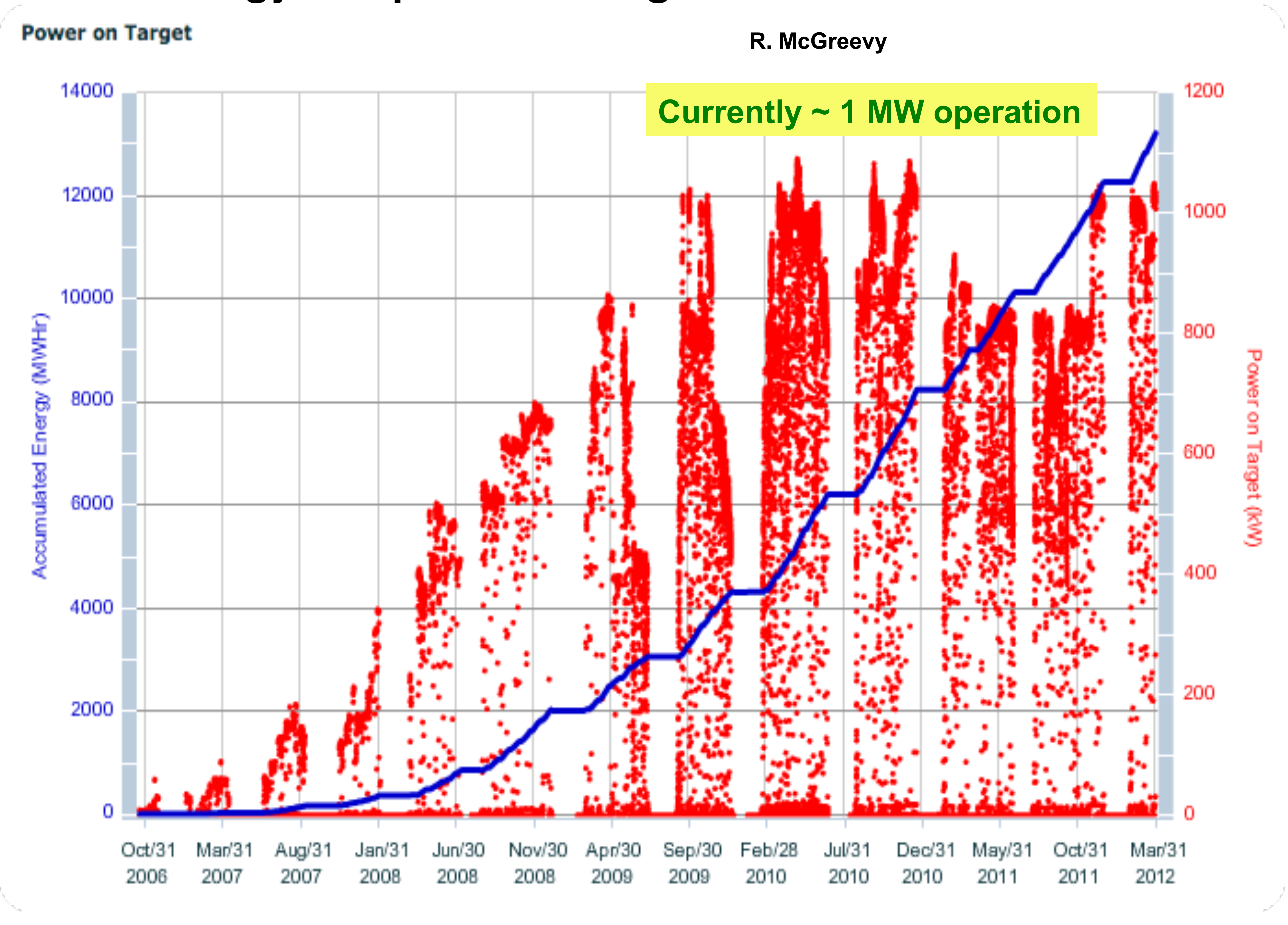


Accumulator ring, 700 ns pulse width

Proton beam bombards liquid Hg target



Energy and power on target from October 2006



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

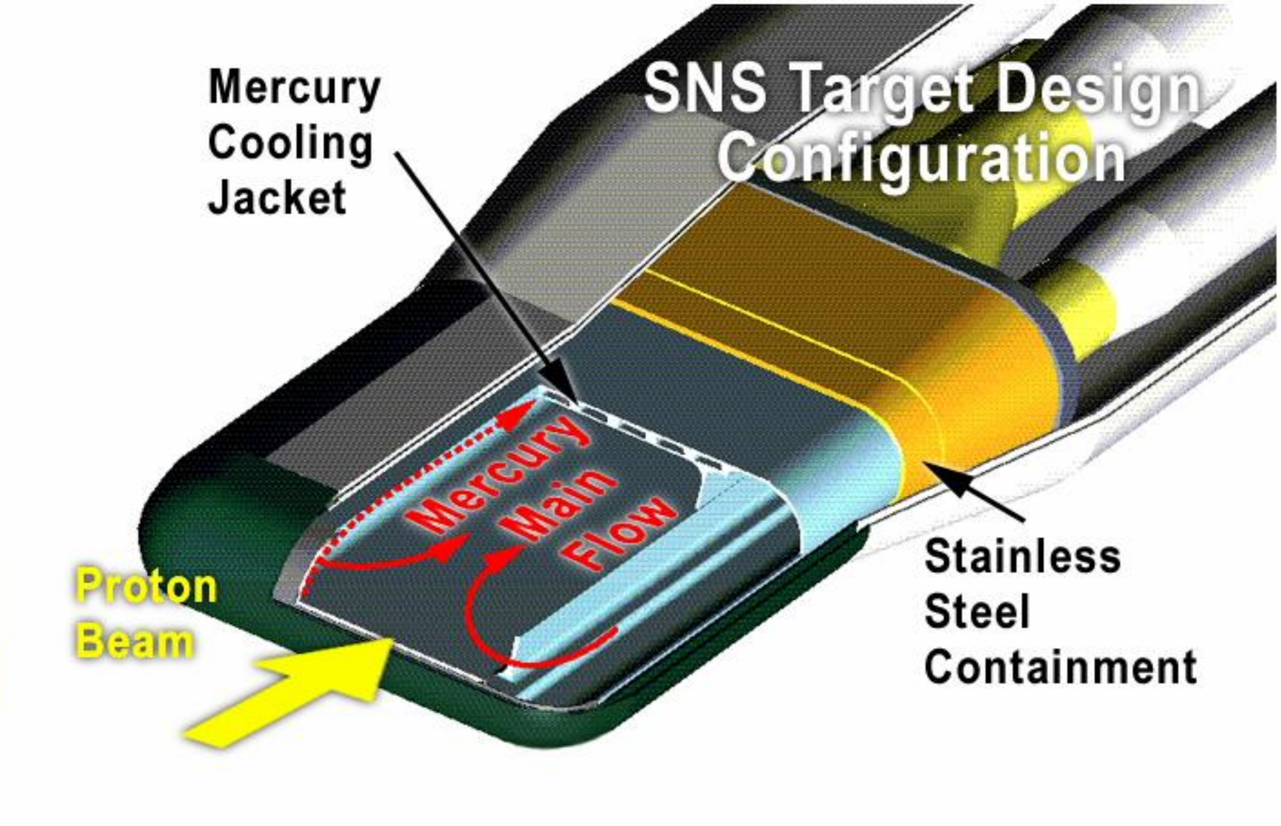
A. Bolozdynya, F. Cavanna, Y. Efremenko, G. T. Garvey, V. Gudkov,
A. Hatzikoutelis, R. Hix, J. M. Link, W. C. Louis,
D. Markoff, G. B. Mills, K. Patton, K. Scholberg, R. G. Van de Water,
C. Virtue, D. H. White, J. Yoo

arXiv:1211.5199

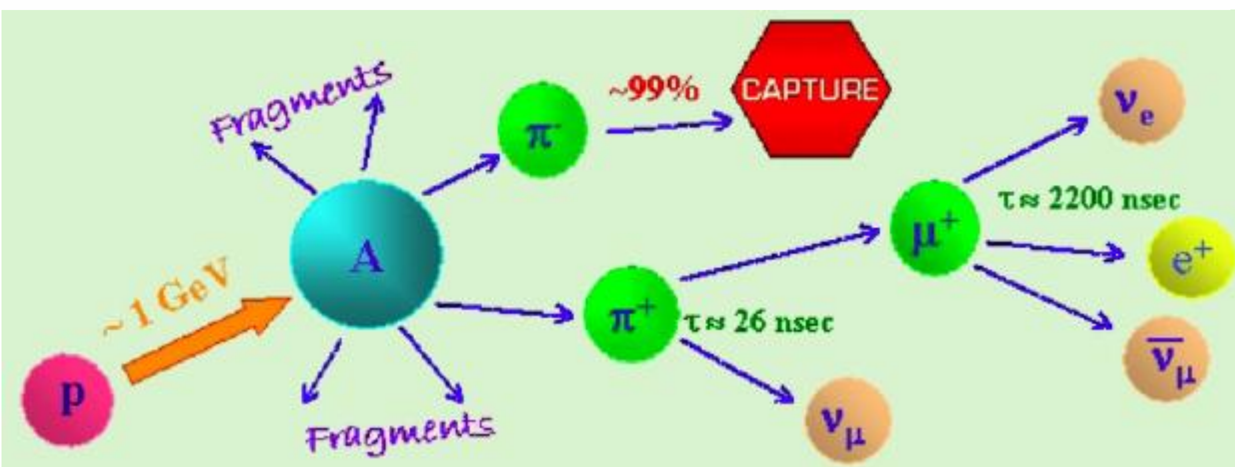
Contents

Actually many diverse opportunities! This is just one of them

The SNS as a Stopped-Pion Neutrino Source

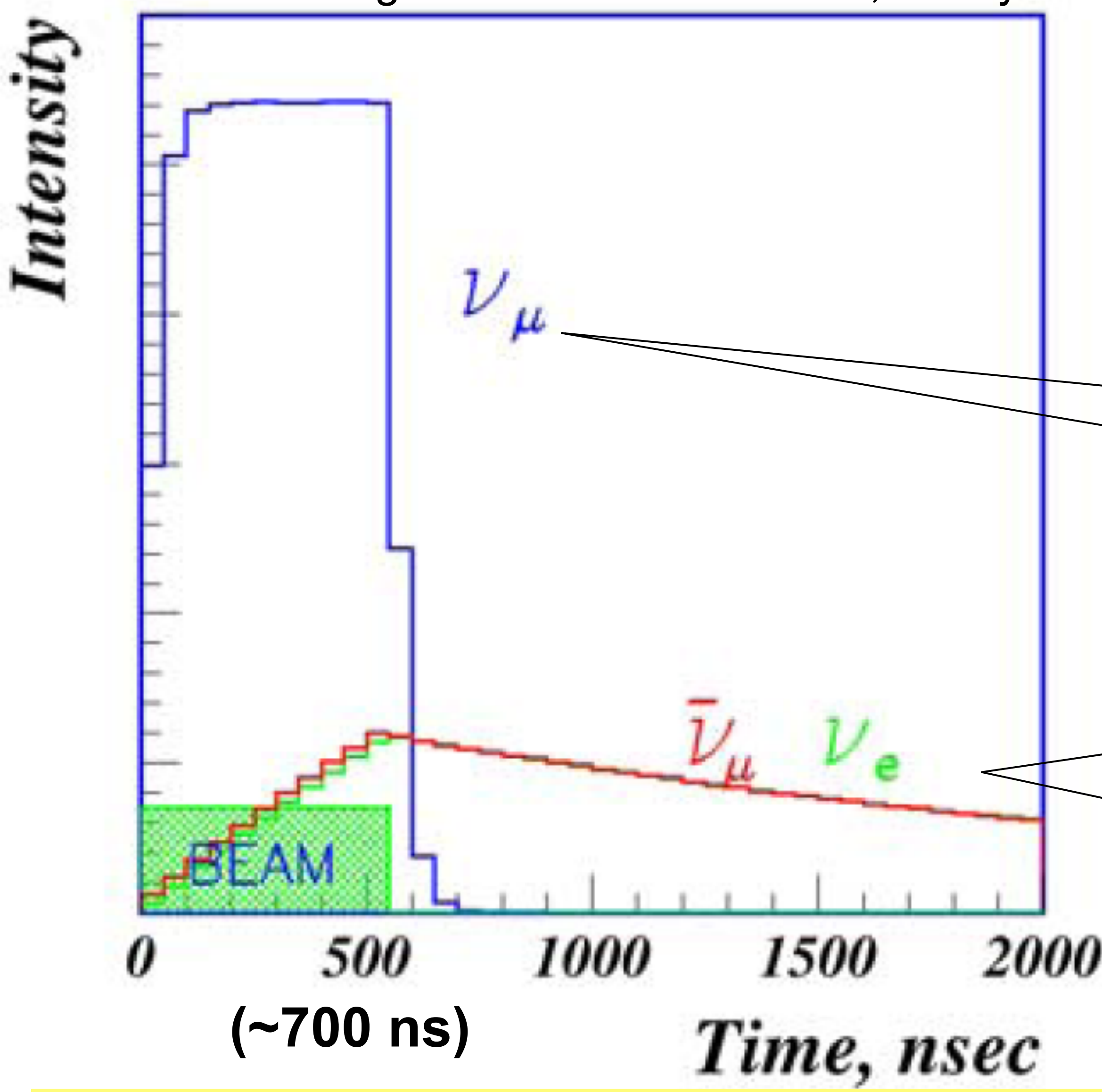


In addition to kicking out neutrons, protons on target create copious pions:
π^- get captured;
π^+ slow and decay at rest



Time structure of the source

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



(~700 ns)

60 Hz *pulsed* source

in time with beam

delayed on μ decay timescale (2.2 μs)

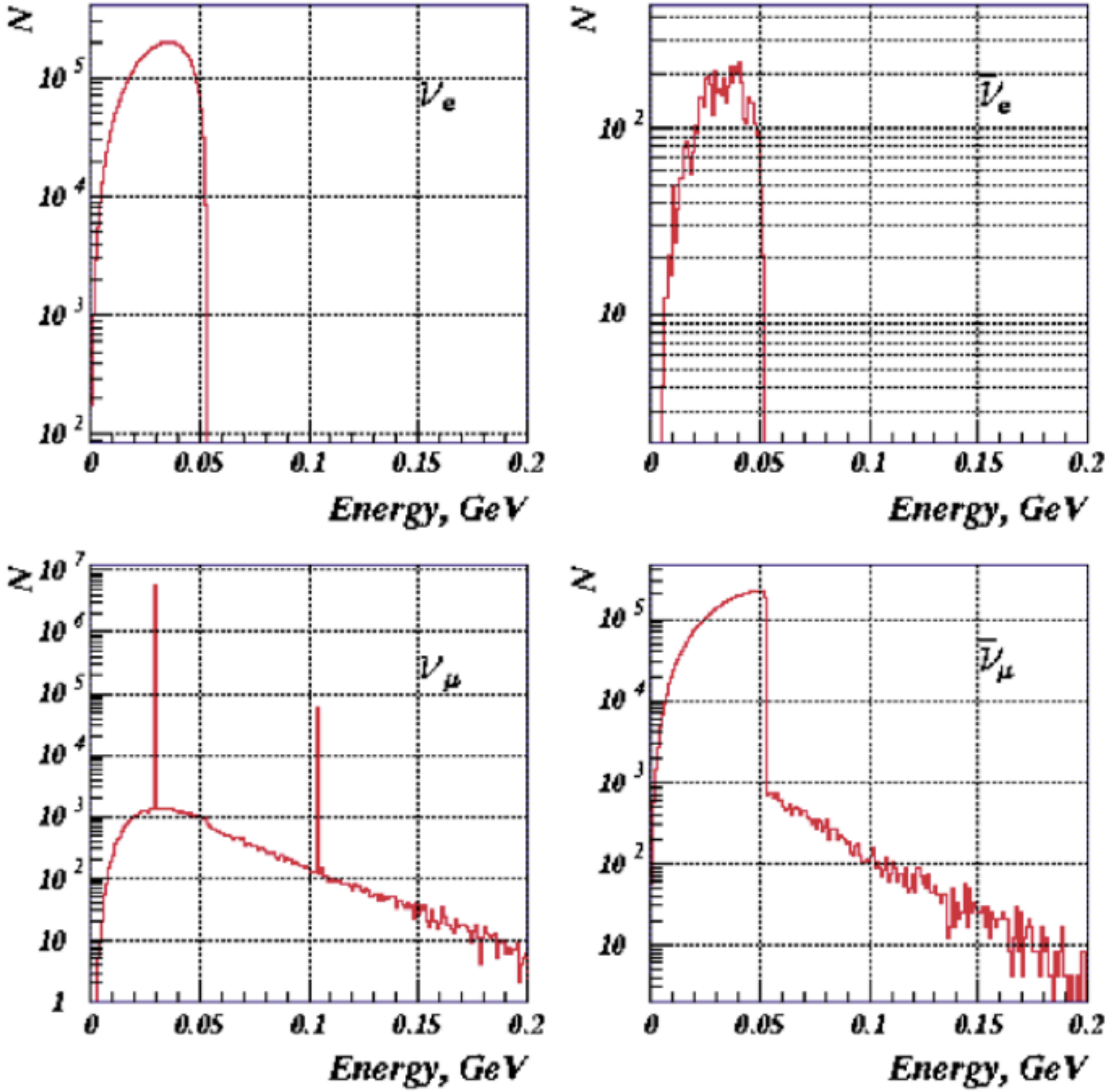
Background rejection factor ~few x 10^{-4}

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

~0.13 per flavor per proton

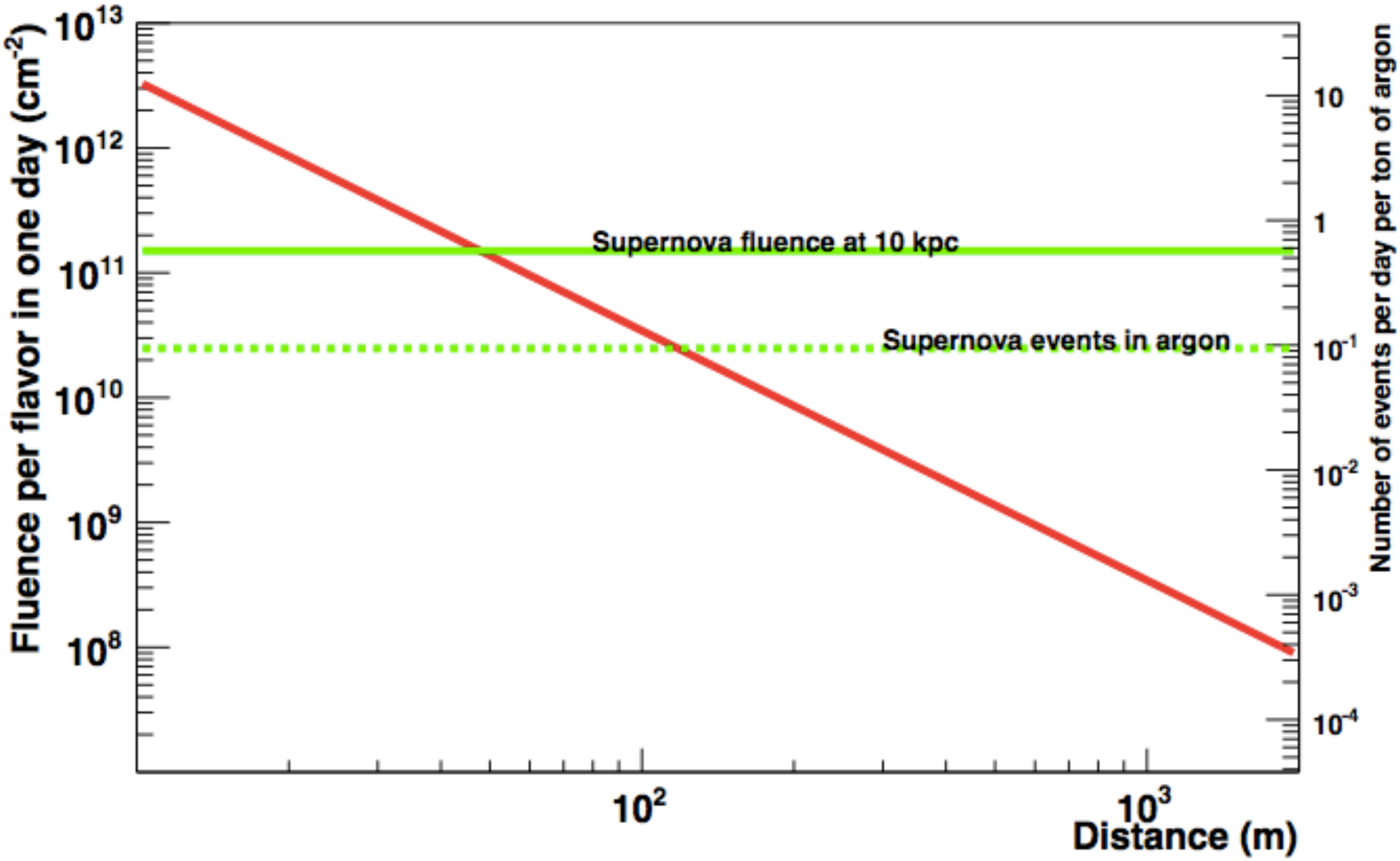
Flux calculation: clean spectrum

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



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

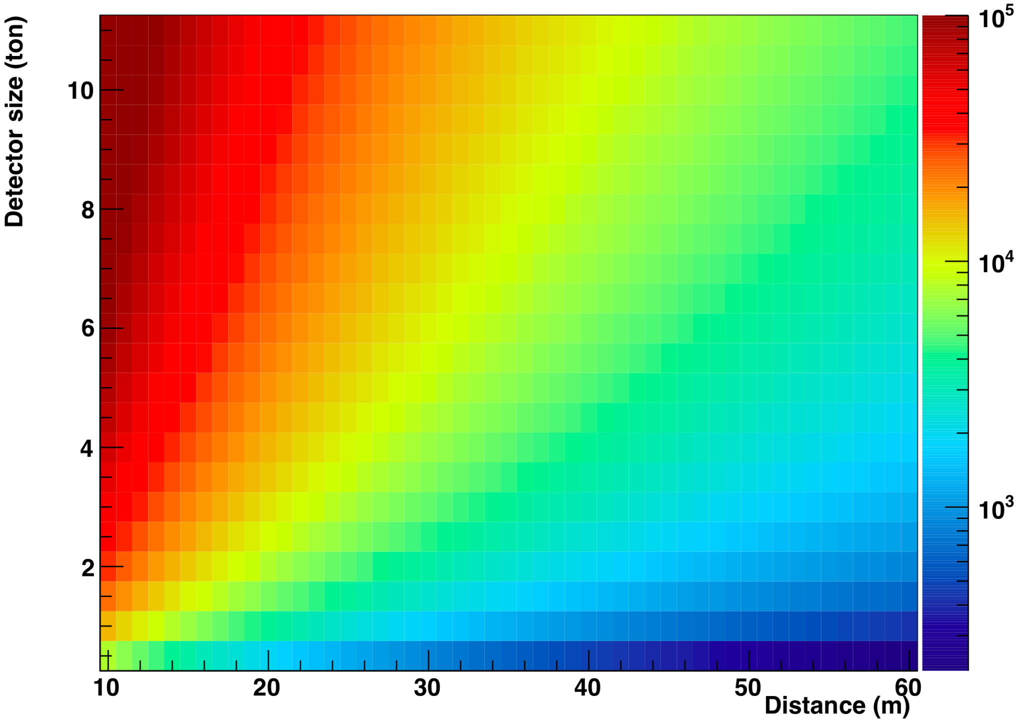
(and effectively more events due to harder spectrum)



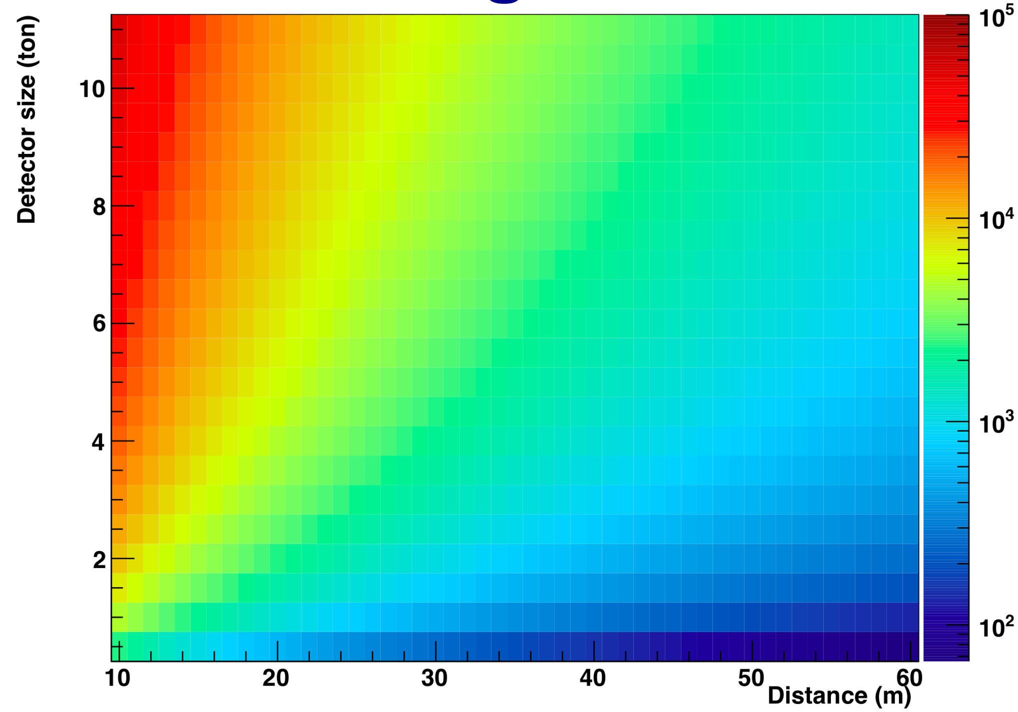
Total events per year at the SNS as a function of distance and mass

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

lead



argon

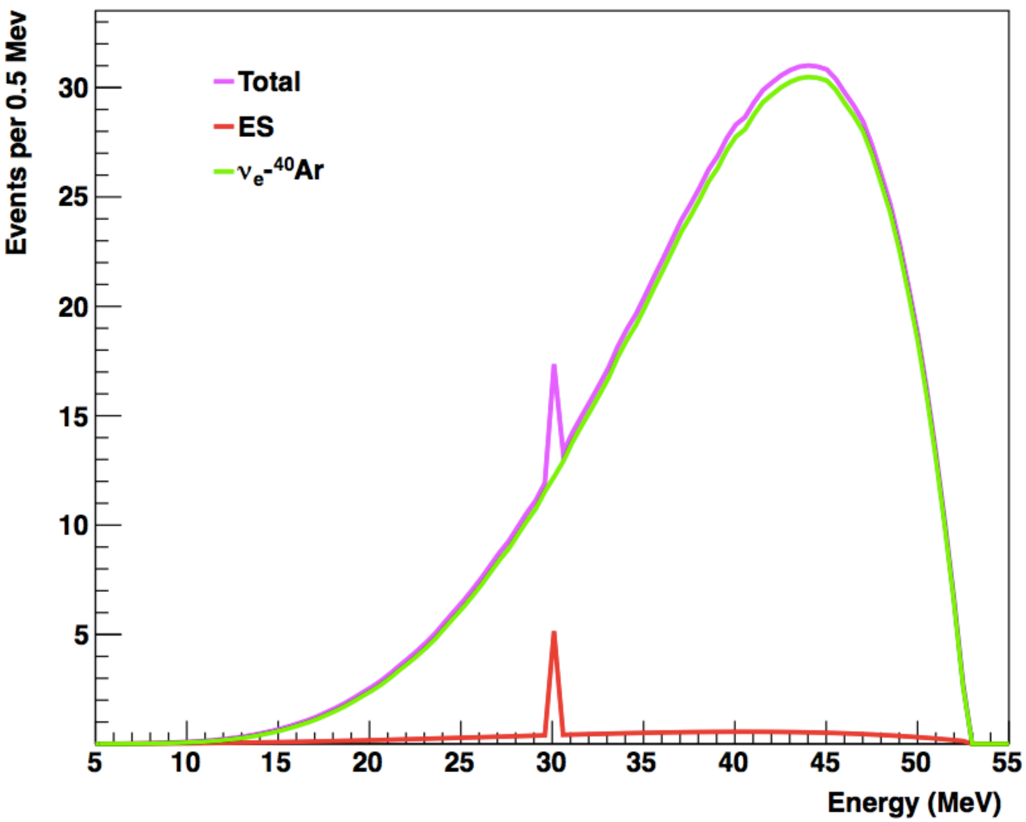


Scaling for another source: α power; duty factor is critical for background rejection

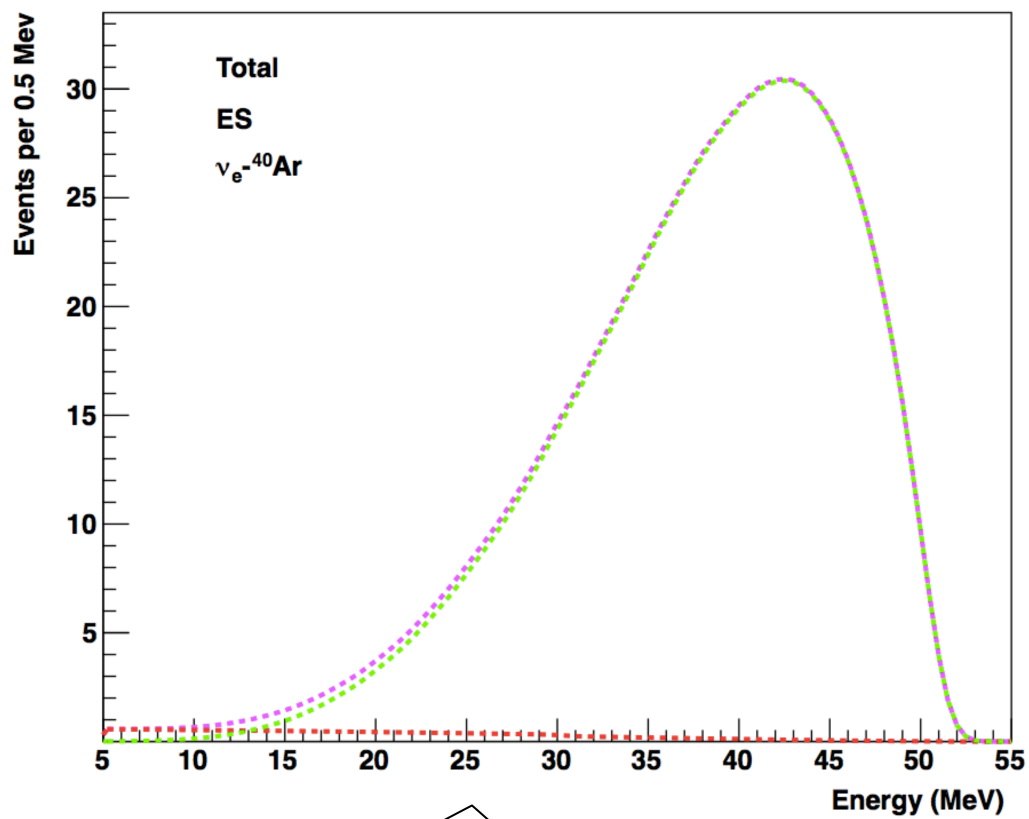
Event rates for argon at the SNS

per ton per year at 20 m

Interactions, as a function of neutrino energy

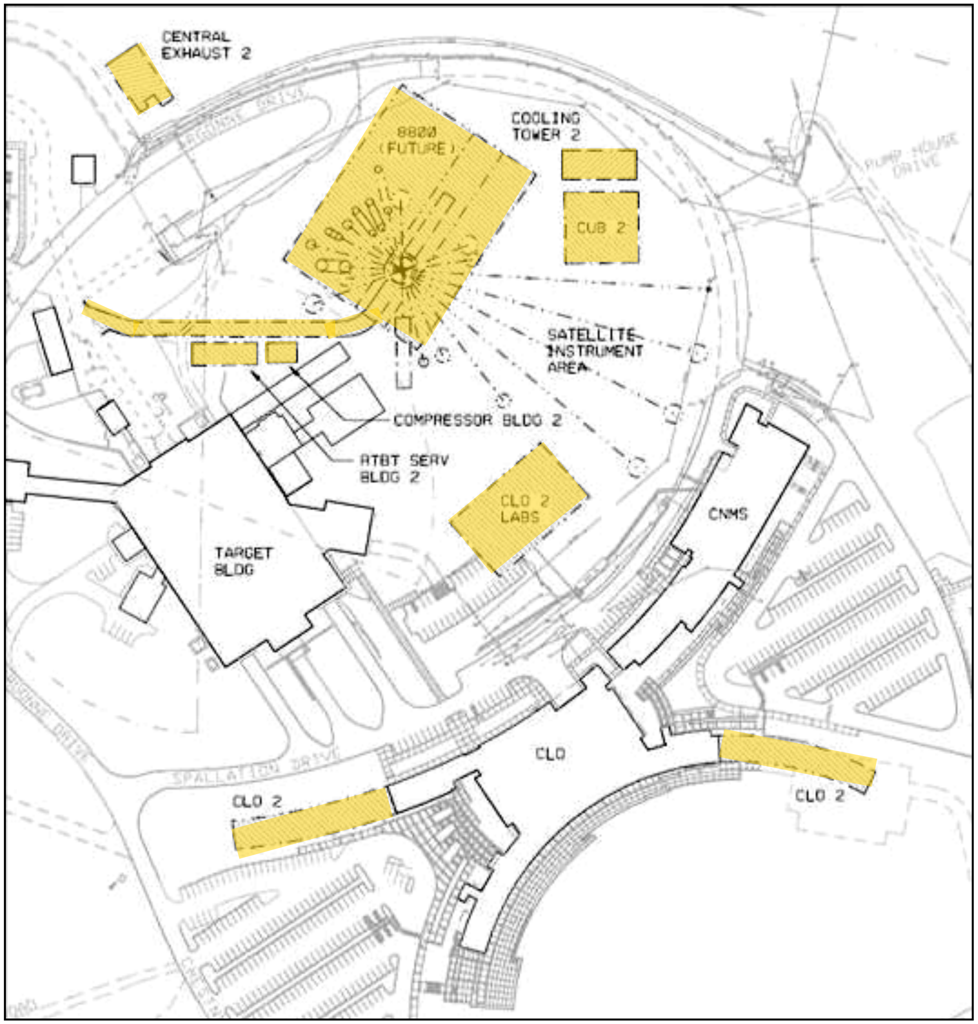


Events seen, as a function of observed energy



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

SNS Second Target Station



R. McGreevy

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

They are of the highest quality!

What do we need to know to evaluate, and optimize, SN neutrino sensitivity in LBNE?

- **Cross sections for ν-Ar interactions at low energy**

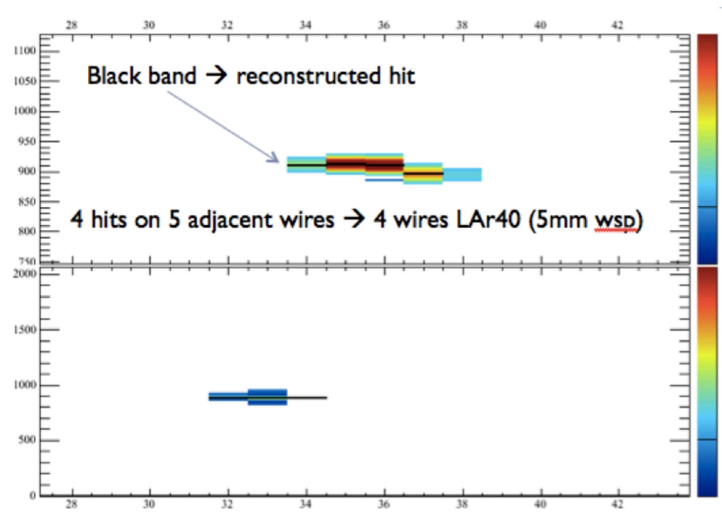
- **Realistic LAr TPC detector response:**

  Efficiency, resolution, tagging

- **Backgrounds:**

  especially cosmogenics

Background for supernova ν's in LAr

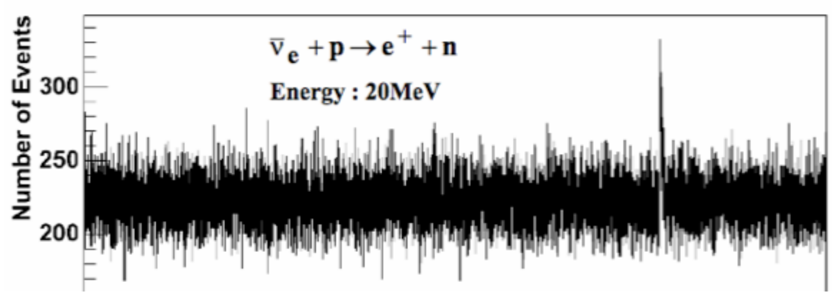


Signal is
"crummy little stubs"
and vulnerable to bg
(γ tagging could help)

- **muons & associated Michels: should be identifiable**
- **radioactivity: mostly < 5 MeV**
- **cosmogenics**

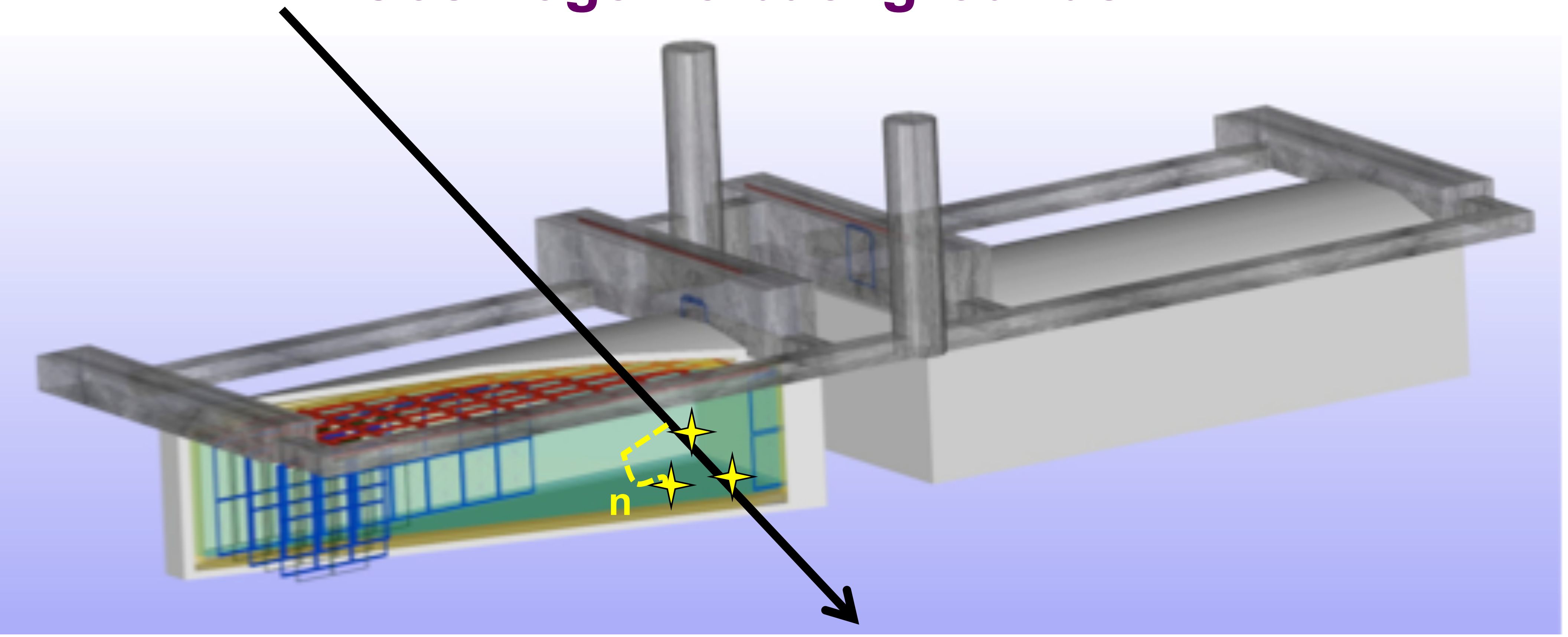
How shallow is OK?

NOνA, MiniBooNE, μBooNE
get *something*,
if background-ridden
(and bg can be *known*)



NOνA

Cosmogenic backgrounds in LAr



- cosmic rays can rip apart nuclei, leaving radioactive products that can decay on ms-hour (day, year..) timescales
- neutrons, muon capture can also be problematic
- fairly well understood in water & scintillator, but few studies in argon

- in principle can be associated with parent muons (need photons...)
- in principle mitigation strategies exist (e.g. γ tagging) but efficiency currently unknown

Cosmogenic products

From Barker, Mei & Zhang, arXiv:1202.5000 **(are G4 cross-sections OK??)**

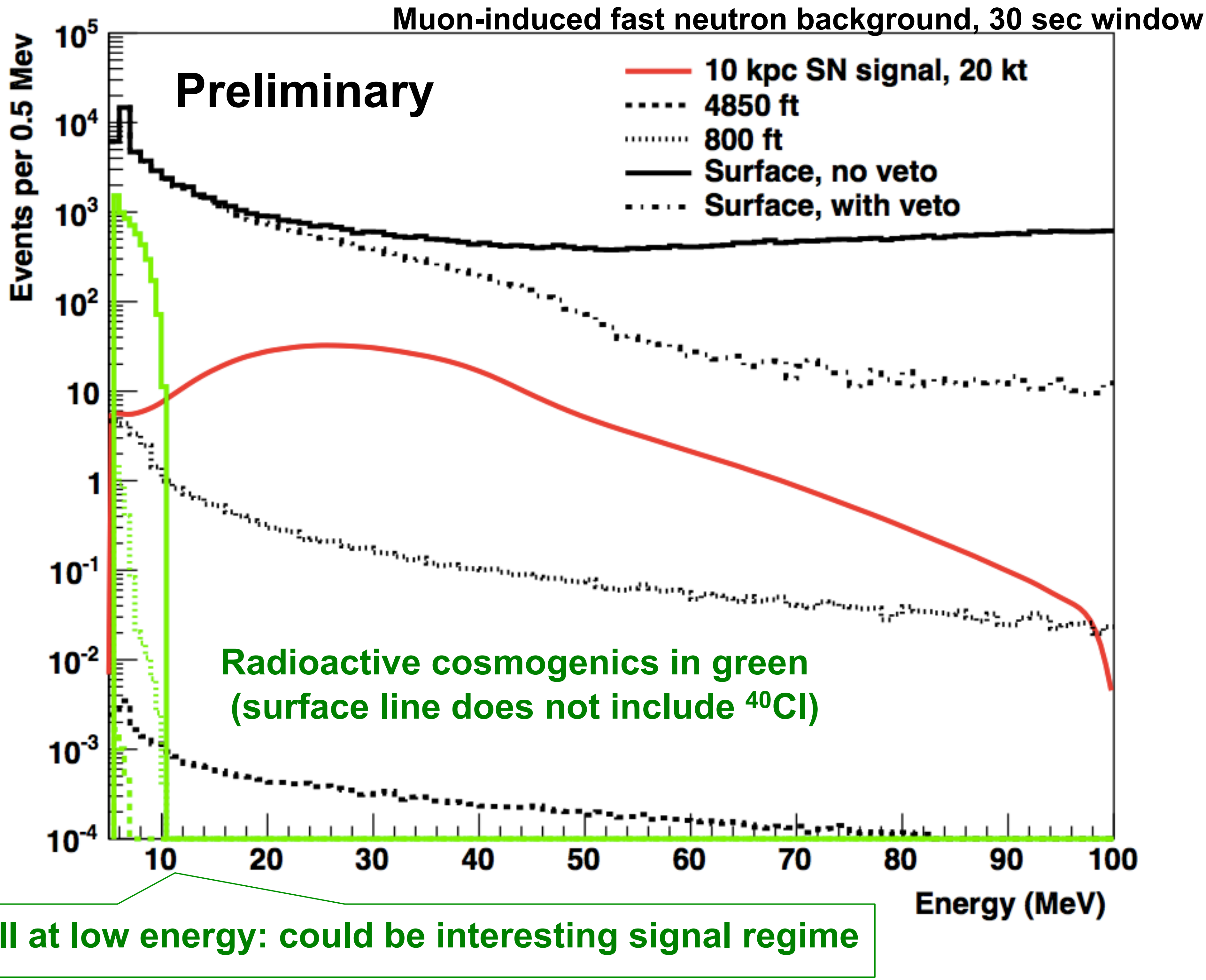
TABLE II: Additional significant cosmogenic production rates in the detector (20 kton) at the 800-ft level.

Isotope	Produced by	Rate per day	Q (MeV)	$t_{1/2}$
^{30}P	Spallation	9020	4.23	2.5 m
^{32}P	Spallation	20900	1.71	14. 3 d
^{33}P	Spallation	30100	0.25	25.3 d
^{34}P	Spallation	12090	5.4	12.4 s
^{35}P	Spallation	7500	4.0	47. 2 s
^{36}P	Spallation	1190	10.4	5.6 s
^{37}P	Spallation	550	7.9	2.3 s
^{31}S	Spallation	5500	5.4	2.6 s
^{35}S	Spallation	215500	0.17	87.5s
^{37}S	(n,α)	31500	4.9	5.1 m
^{38}S	Spallation	11500	2.9	170 m
^{39}S	Spallation	850	6.6	11.5 s
^{33}Cl	Spallation	670	5.6	2.5 s
^{34}Cl	Spallation	8700	5.6	32 m
^{36}Cl	Spallation	1005000	0.7	3.1×10^5 y
^{38}Cl	Spallation	110000	4.9	37.24 m
^{35}Ar	$(n,6n')$	7100	6.0	1.8 s
^{37}Ar	$(n,4n')$	21000	0.8	35 d
^{39}Ar	$(n,2n')$	91000	0.57	269 y
^{41}Ar	capture	45100	2.5	109 m
^{38}K	Spallation	650	5.9	7.6 m
^{40}K	(p,n)	6500	1.3	1.28×10^9 y
Total		1641920		

TABLE IV: Additional significant cosmogenic production rates in the detector (20 kton) at the 4850-ft level.

Isotope	Produced by	Rate per day	Q (MeV)	$t_{1/2}$
^{30}P	Spallation	9.6	4.23	2.5 m
^{32}P	Spallation	22.2	1.71	14. 3 d
^{33}P	Spallation	31.9	0.25	25.3 d
^{34}P	Spallation	12.8	5.4	12.4 s
^{35}P	Spallation	8.0	4.0	47. 2 s
^{36}P	Spallation	1.3	10.4	5.6 s
^{37}P	Spallation	0.6	7.9	2.3 s
^{31}S	Spallation	5.8	5.4	2.6 s
^{35}S	Spallation	228.5	0.17	87.5s
^{37}S	(n,α)	33.4	4.9	5.1 m
^{38}S	Spallation	12.2	2.9	170 m
^{39}S	Spallation	0.9	6.6	11.5 s
^{33}Cl	Spallation	0.7	5.6	2.5 s
^{34}Cl	Spallation	9.2	5.6	32 m
^{36}Cl	Spallation	1065.7	0.7	3.1×10^5 y
^{38}Cl	Spallation	116.6	4.9	37.24 m
^{35}Ar	$(n,6n')$	7.5	6.0	1.8 s
^{37}Ar	$(n,4n')$	22.3	0.8	35 d
^{39}Ar	$(n,2n')$	96.5	0.57	269 y
^{41}Ar	capture	47.8	2.5	109 m
^{38}K	Spallation	0.69	5.9	7.6 m
^{40}K	(p,n)	6.9	1.3	1.28×10^9 y
Total		1741		

- assume β-decay spectral form for given Q value
- normalize by rate per day from table
- add all contributions
- smear with LAr resolution from Amoruso paper


Muon-induced fast neutron background, 30 sec window
Preliminary
10 kpc SN signal, 20 kt
4850 ft
800 ft
Surface, no veto
Surface, with veto
Events per 0.5 Mev
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10
20
30
40
50
60
70
80
90
100
Energy (MeV)
Radioactive cosmogenics in green
(surface line does not include ^{40}Cl)
all at low energy: could be interesting signal regime

A detector that could measure backgrounds as a function of depth could be helpful

See Bob Svoboda's talk re: neutrons

A muon test beam to measure spallation products?
(appropriate energy is problematic)

Summary

Liquid argon has unique sensitivity to SN physics thanks to electron neutrino sensitivity

No measurements of low-energy ν-Ar cross-sections & interaction products exist

Need to understand detector response

SNS = Supernova Neutrino Substitute (for free! just need the detector)

Need to understand backgrounds; measurements could help

If interested...

Please sign the Snowmass whitepaper

Note no commitment implied... just potential interest

Opportunities for Neutrino Measurements at the Spallation Neutron Source

A. Bolozdynya, B. Cabrera-Palmer, F. Cavanna, G. Greene, Y. Efremenko, A. Hatzikoutelis, R. Hix, J. M. Link, W. C. Louis, D. Markoff, C. Mauger, P. Mueller, K. Patton, H. Ray, D. Reyna, K. Scholberg, C. Virtue, J. Yoo

(Also one on coherent elastic neutrino-nucleus scattering)

`http://www.phy.duke.edu/~schol/sns_neutrinos_onepage.pdf`
`http://www.phy.duke.edu/~schol/sns_coherent_onepage.pdf`