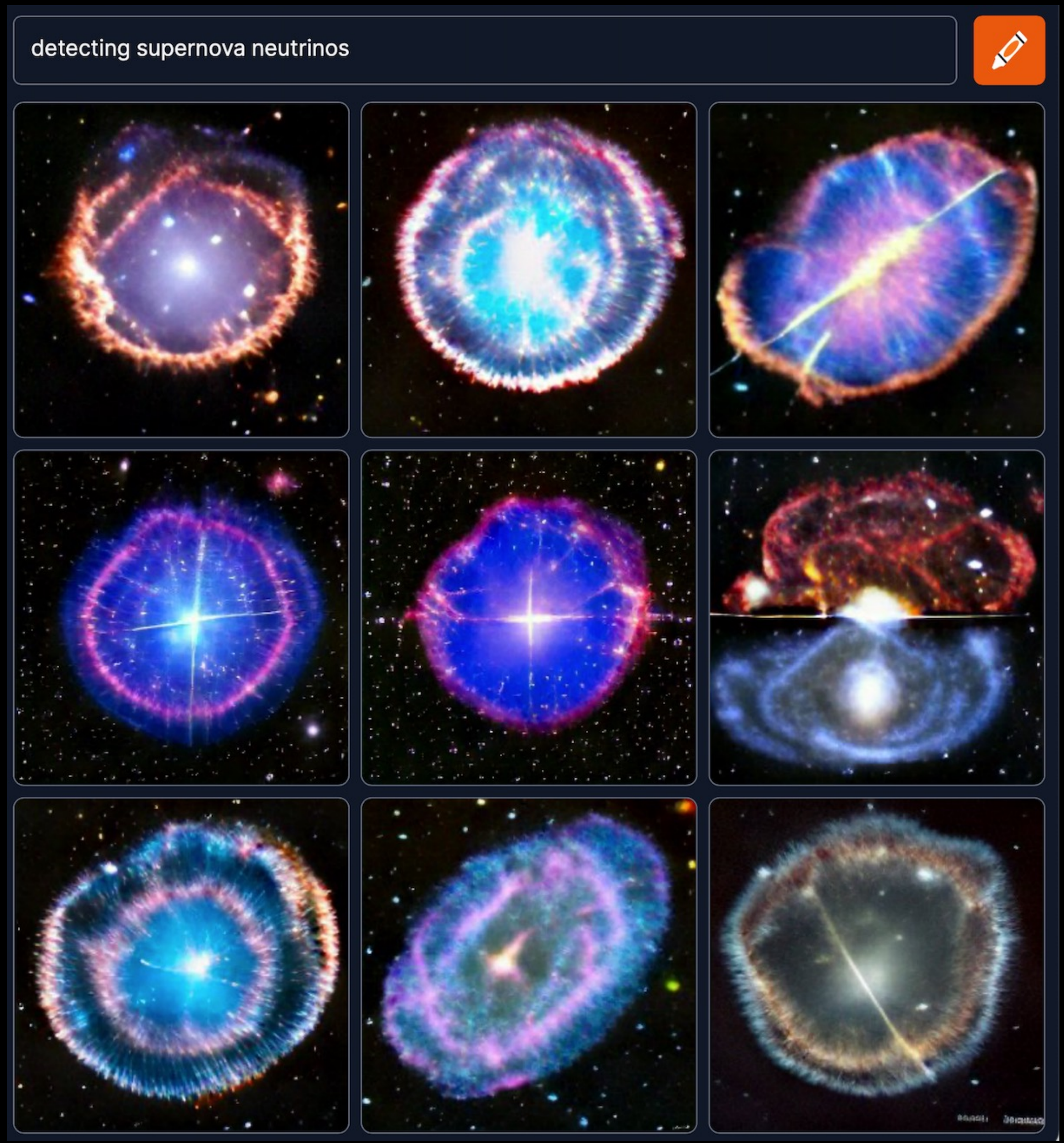
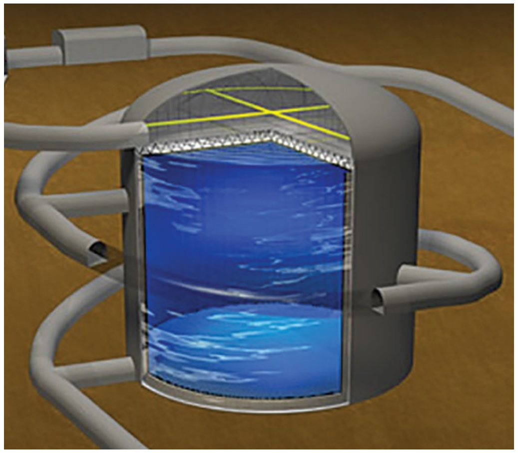
Measuring Artifical Supernova Neutrinos in Neutrino Alley

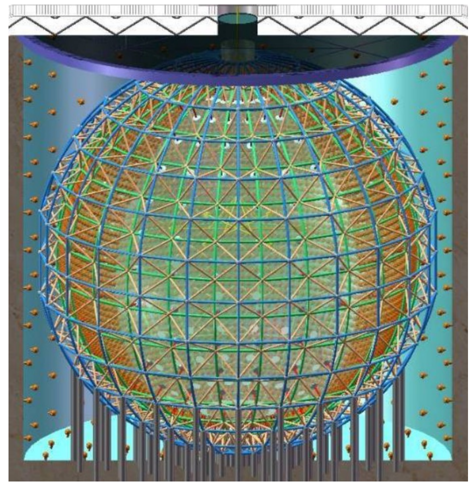


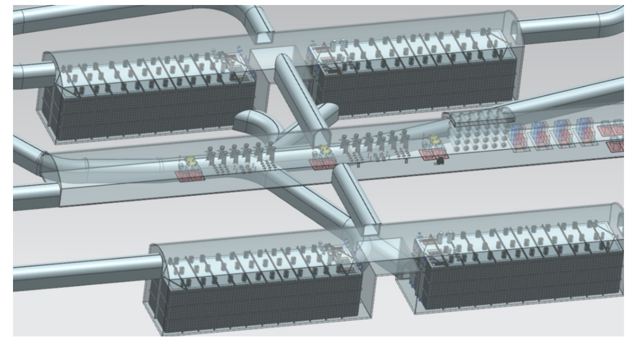
Kate Scholberg,
Duke University

10th Supernova Neutrino Workshop
Okayama
March 1, 2024

Future Large Supernova-Burst-Sensitive Neutrino Detectors







Hyper-Kamiokande
260 kton water
Japan

JUNO
20 kton scintillator
(hydrocarbon)
China

DUNE
40 kton argon
USA

- Hyper-K /JUNO are primarily sensitive to **nuebar**

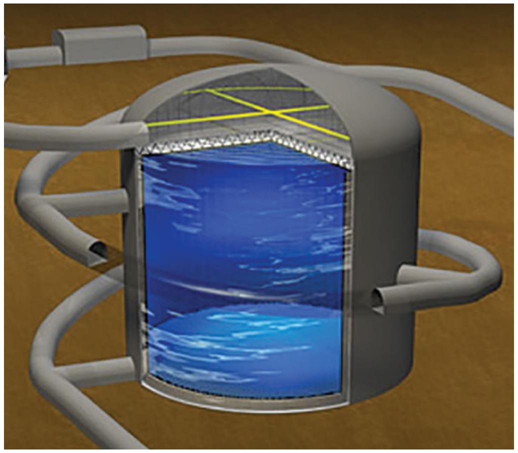
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- DUNE is primarily sensitive to **nue**

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

extreme complementarity

Future Large Supernova-Burst-Sensitive Neutrino Detectors



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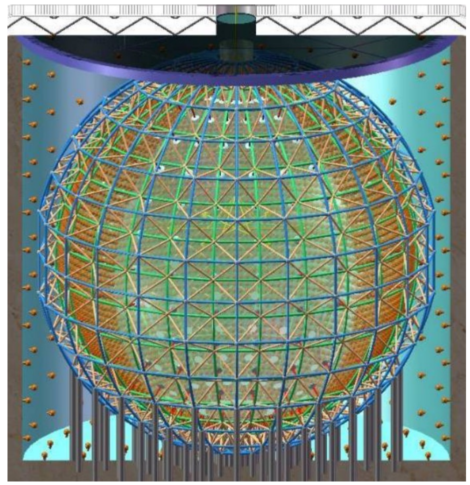

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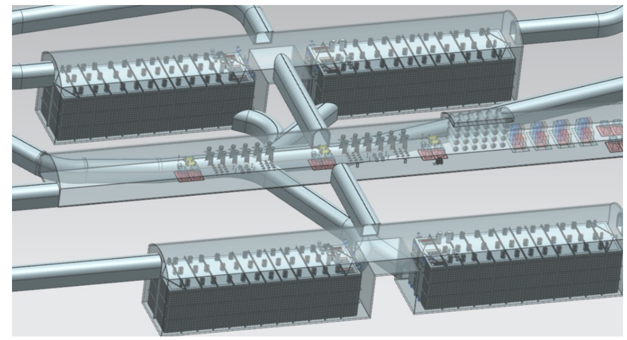

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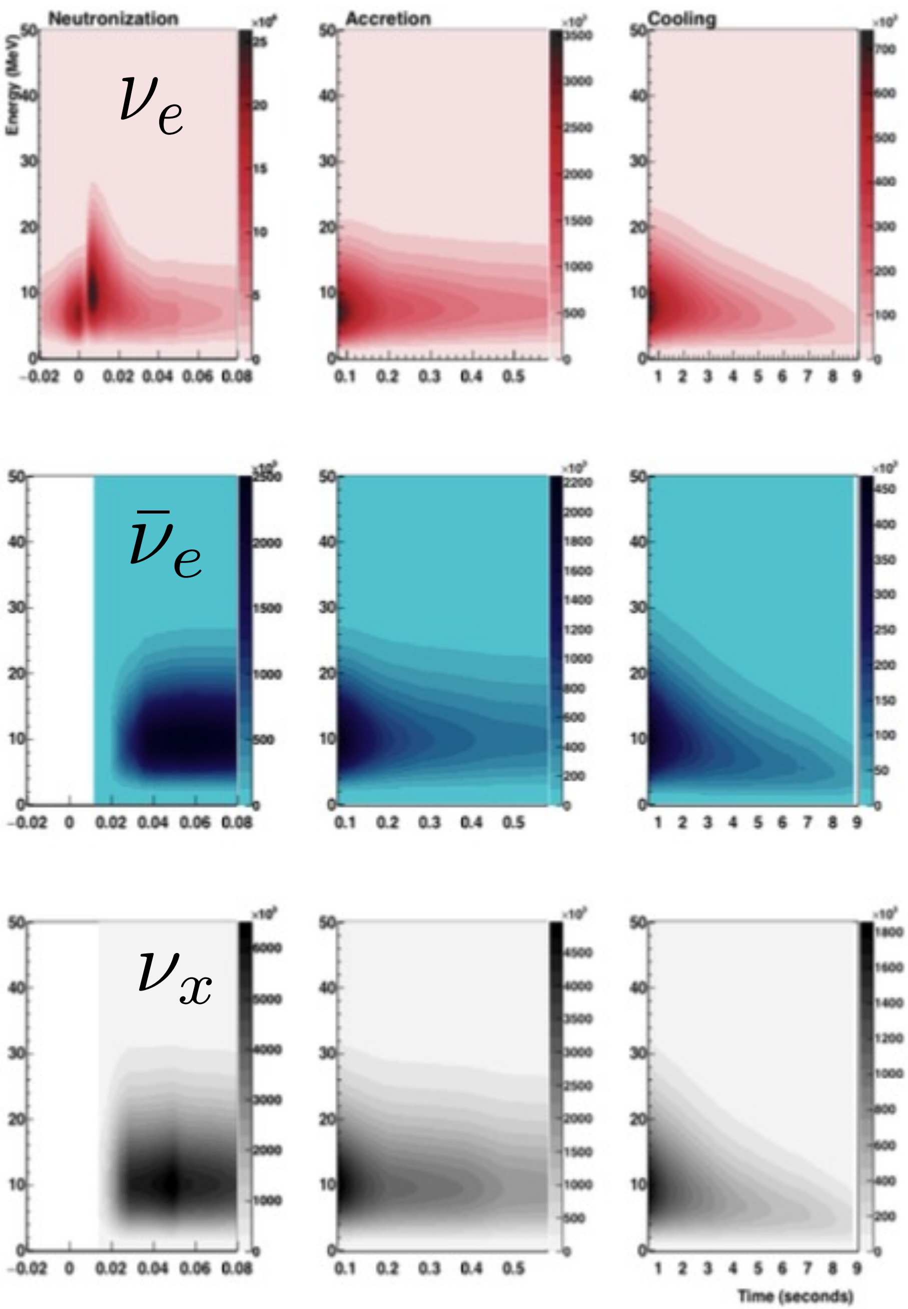
extreme complementarity

[....but each also has subdominant channels.
at few to ~10% level, e.g. ν_e+^{16}O]

What we *want* to measure

Neutrino fluxes vs E, t



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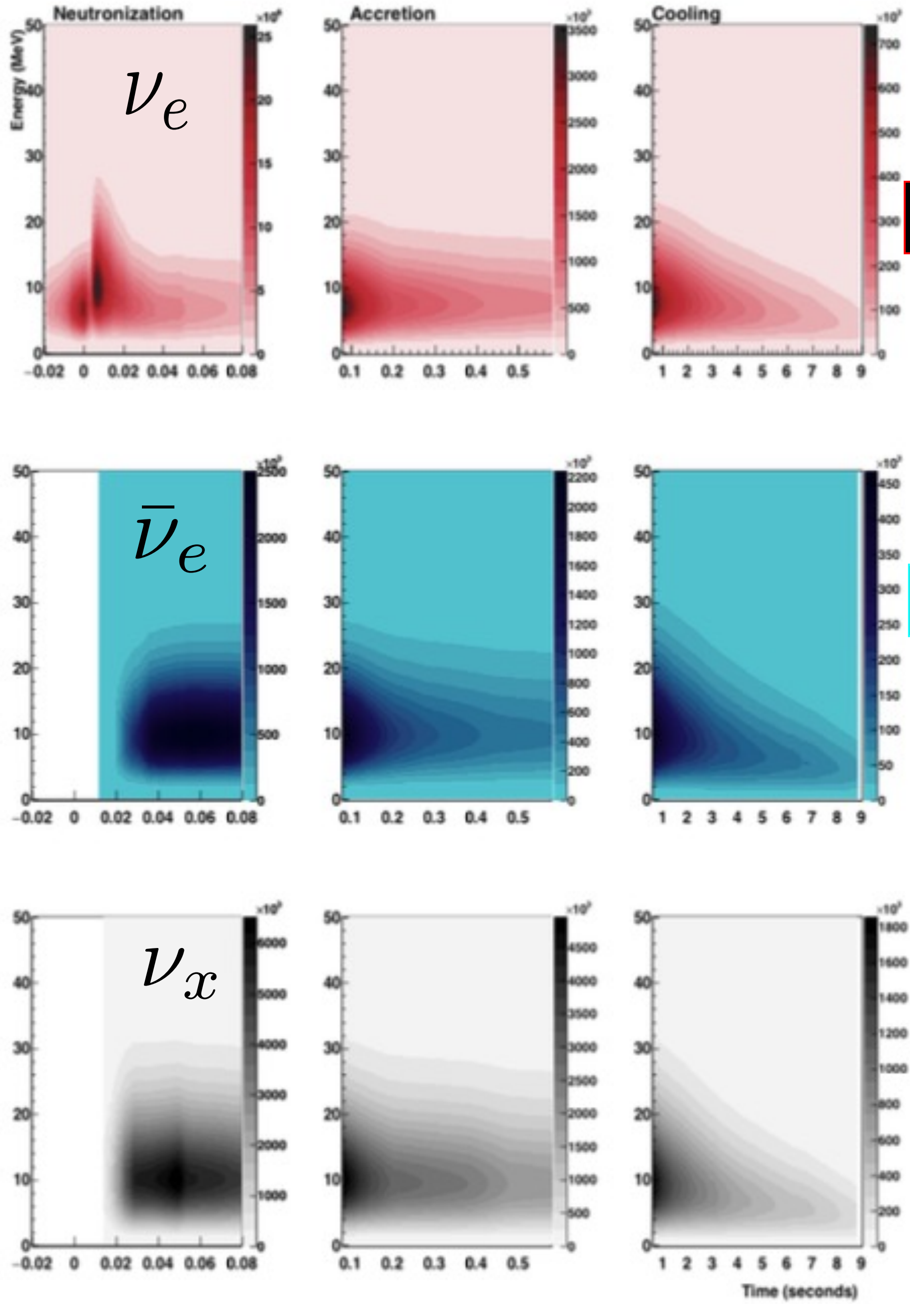


What we *can* measure

Event rates in different interaction channels vs E, t (with imperfect tagging & resolution)

ν_eCC

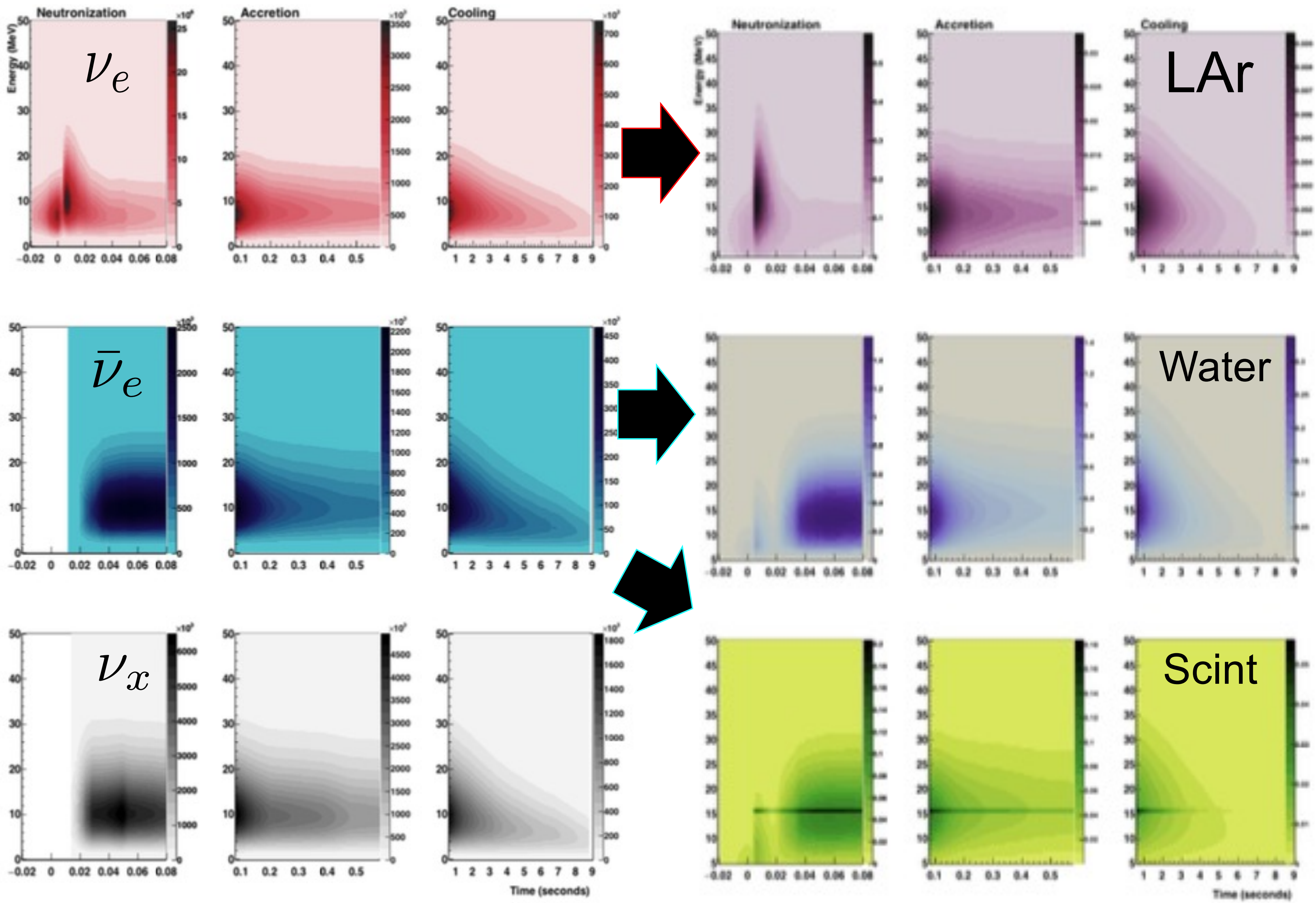
$\bar{\nu}_e$CC

NC

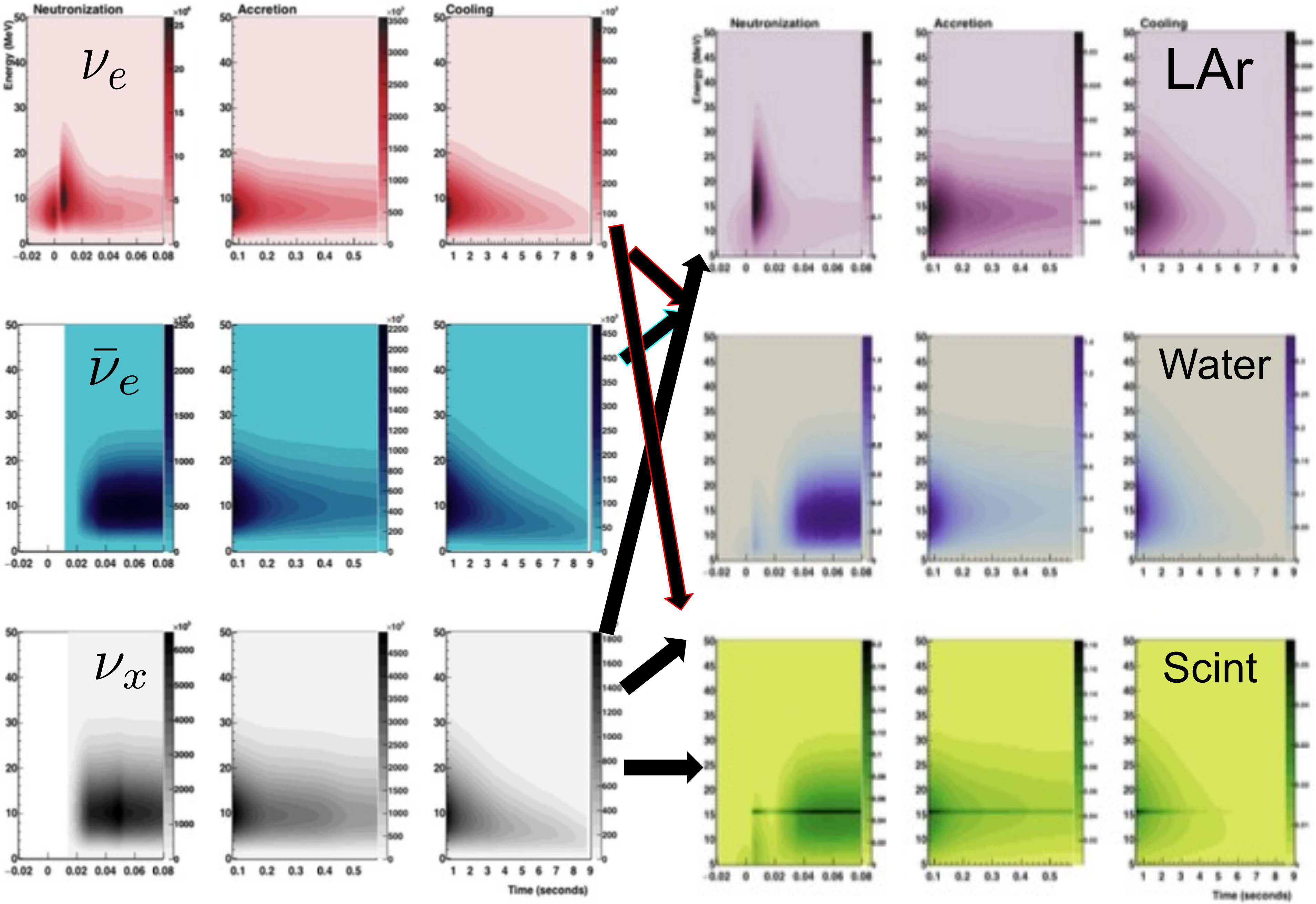
Neutrino fluxes vs E, t

Dominant channels

Event rates vs E, t



Subdominant channels are in the mix too,
and not always easily taggable... may be hard to disentangle!



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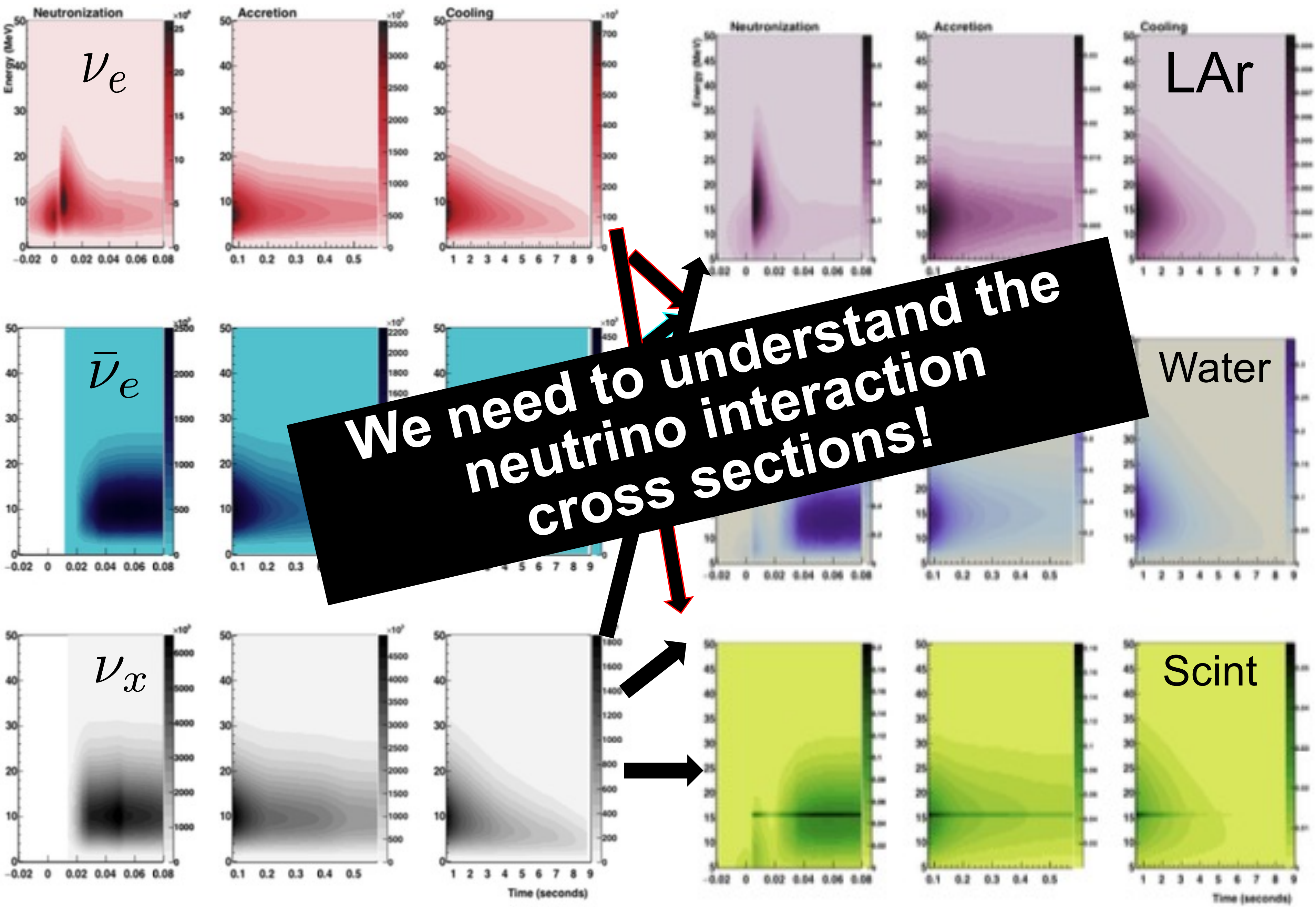
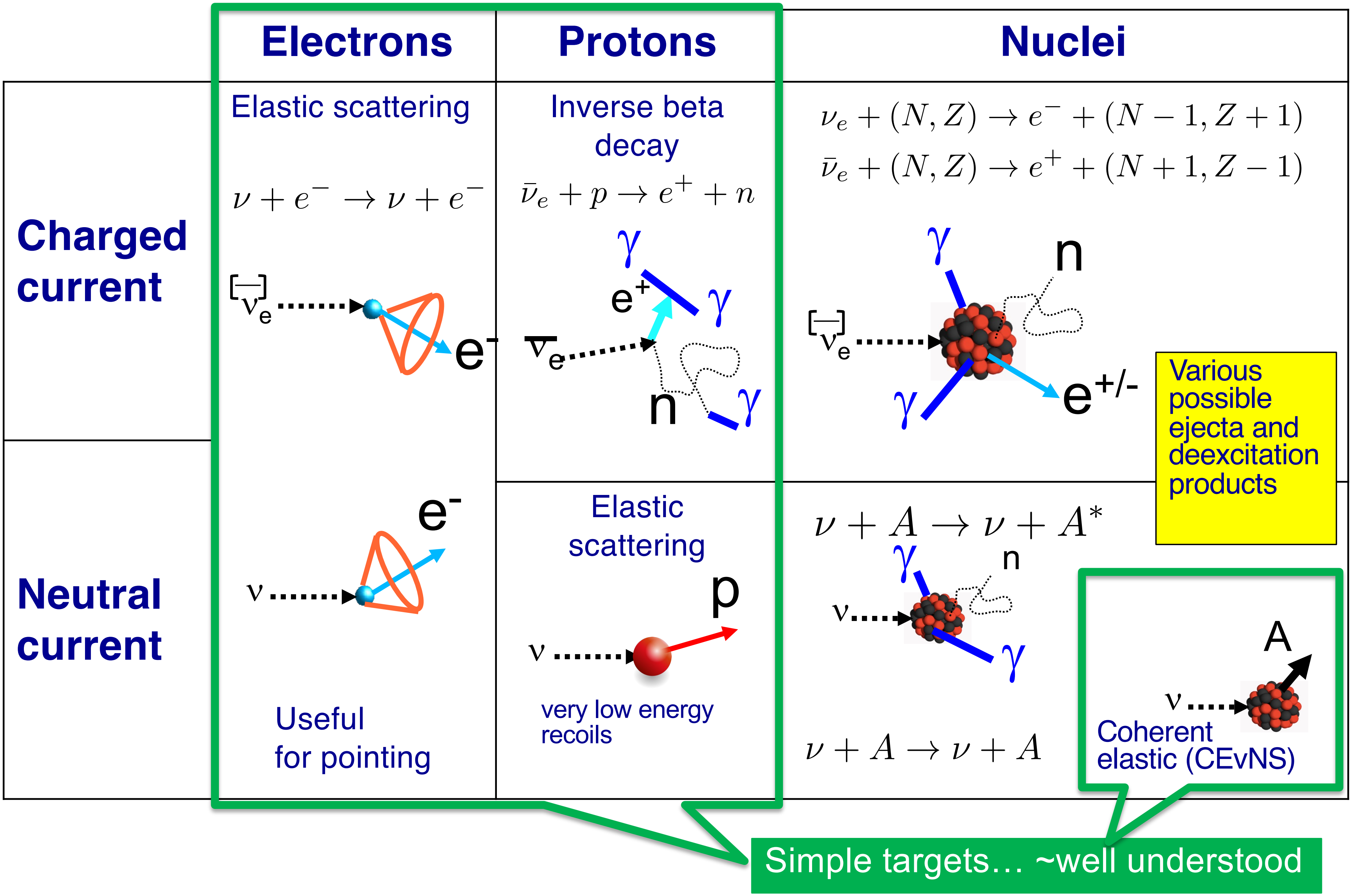
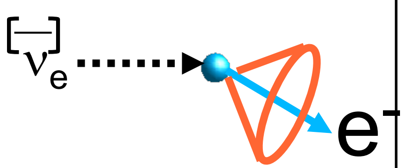
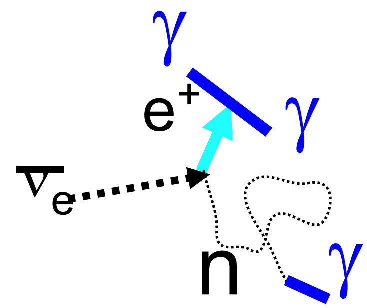
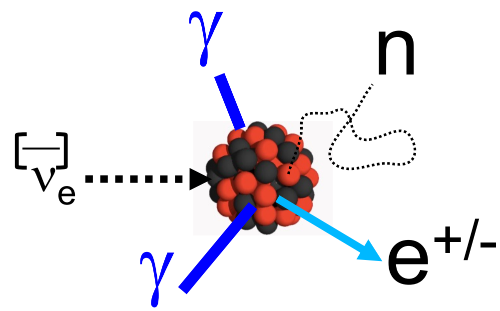
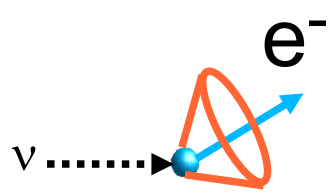
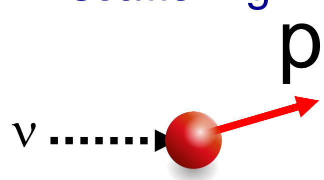
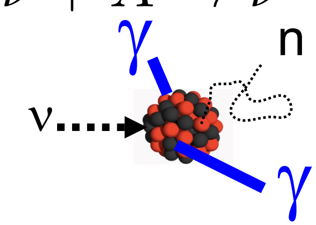
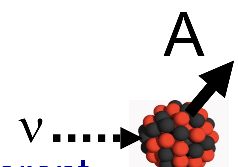


Neutrino interactions in the SNB energy range



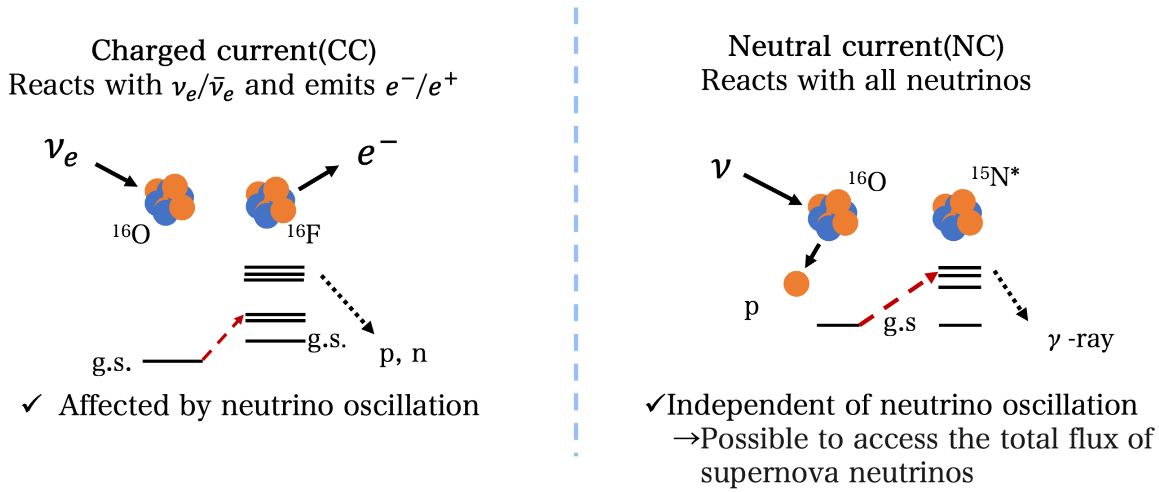
Neutrino interactions in the SNB energy range

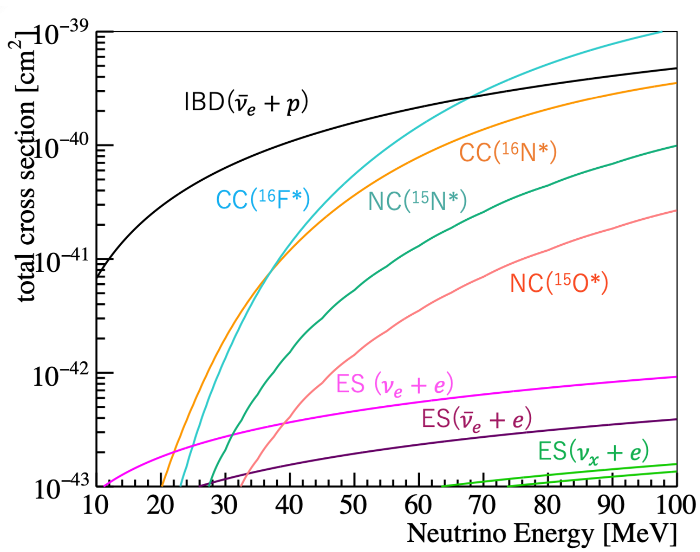
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \to \nu + A^*$  $\nu + A \to \nu + A$  Coherent elastic (CEvNS)

Generally poorly understood!

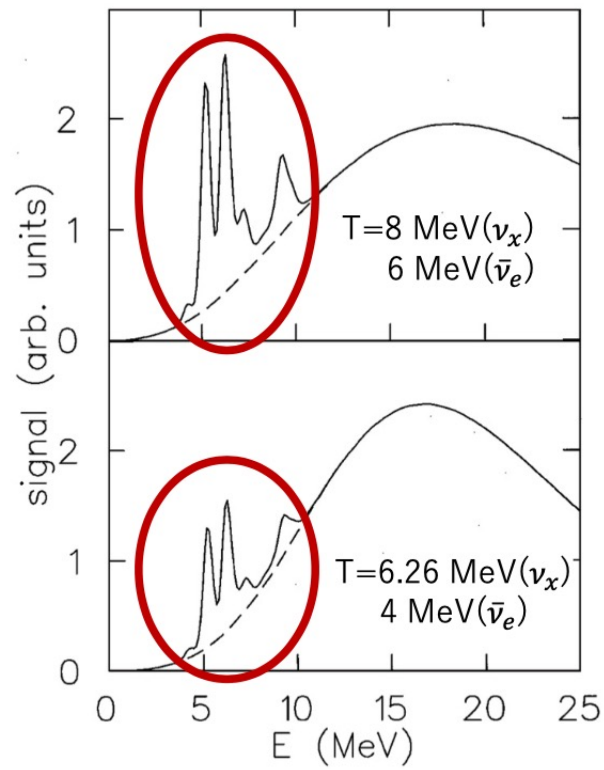
For example: **CC and NC interactions on oxygen**

F. Nakanishi, ORNL workshop 2023





Observables depend on nuclear structure

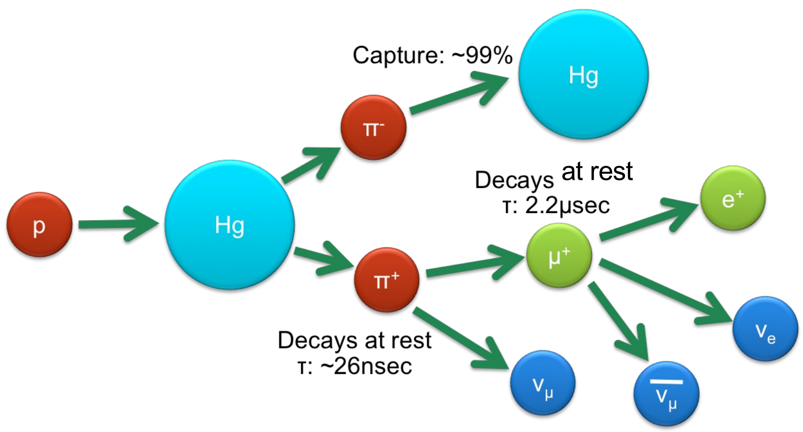


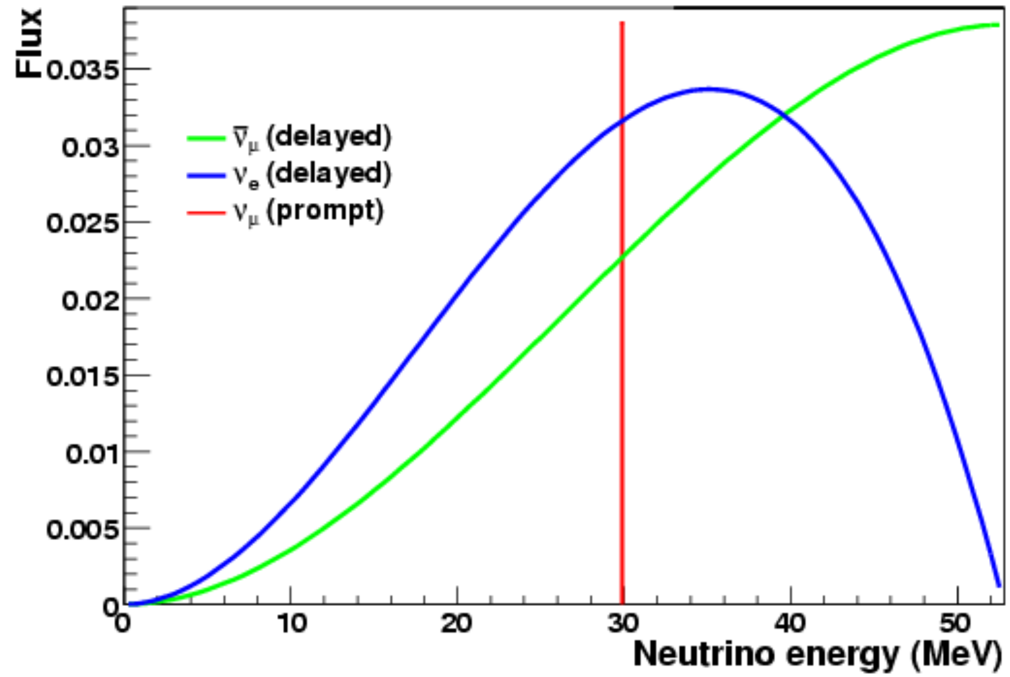
Expected energy spectrum in SK from K. Langanke et al.

Newer calcs by Nakazato et al.

Best to ***measure*** it!

Stopped-Pion (πDAR) Neutrinos





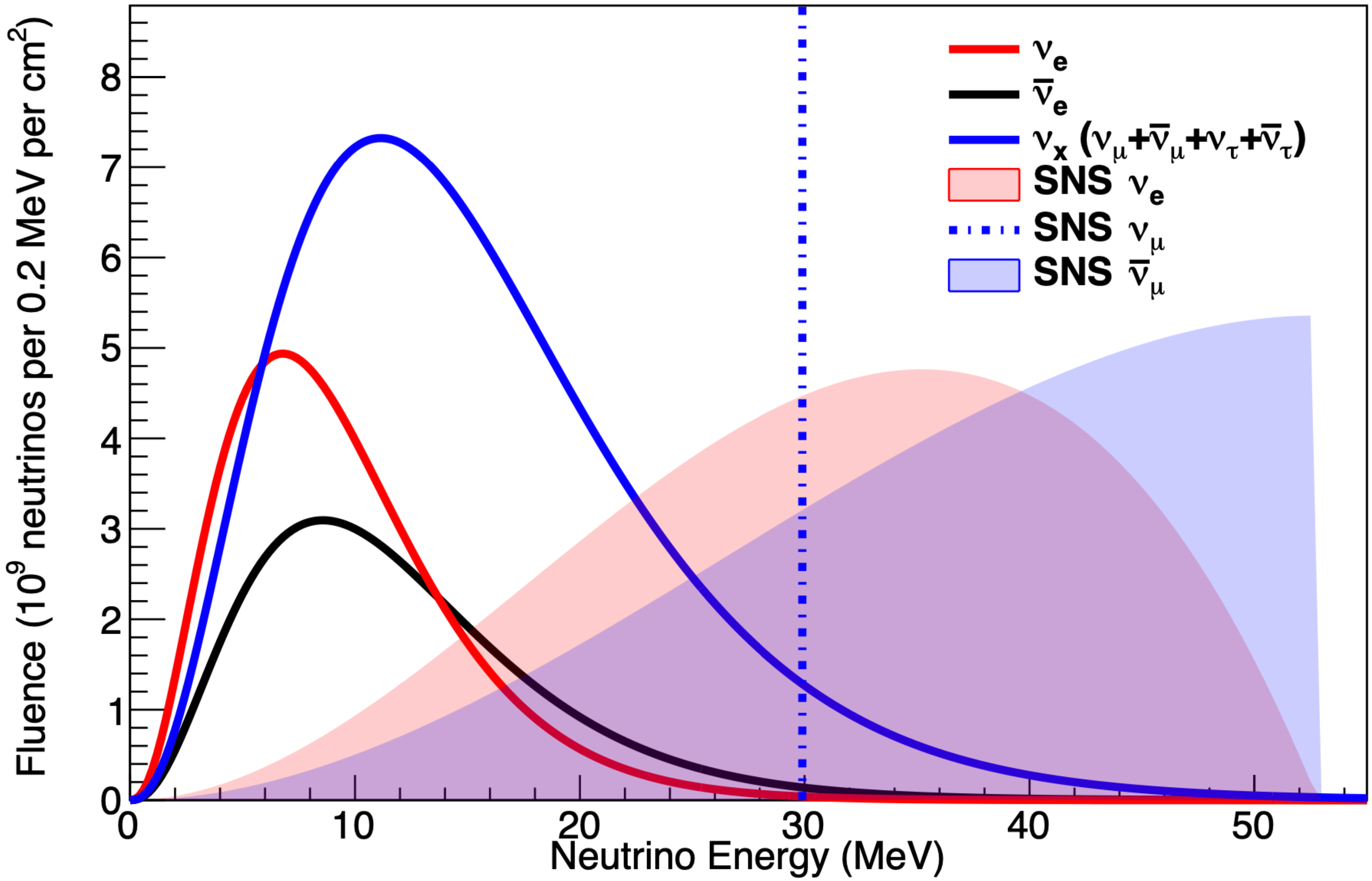
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

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

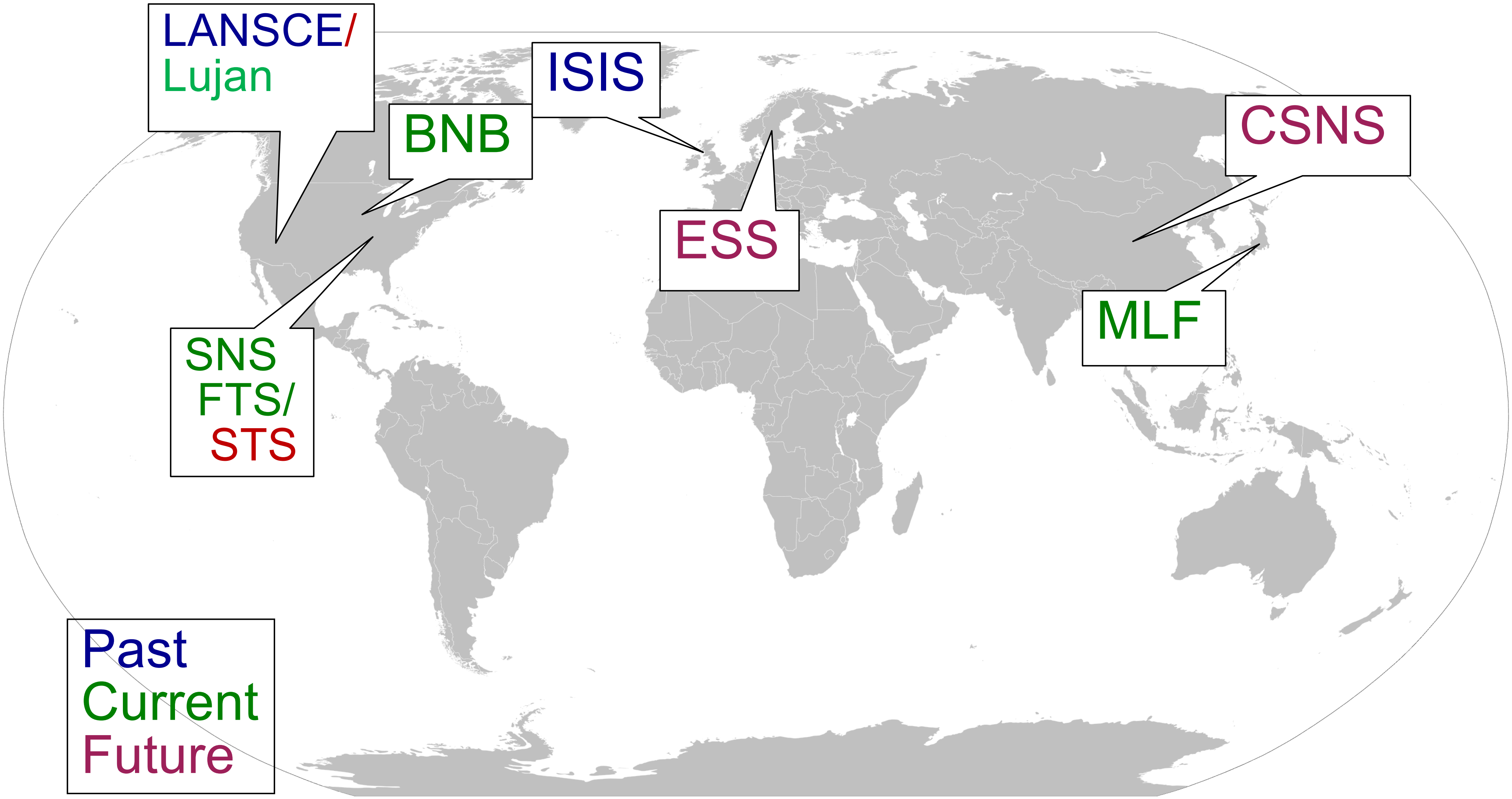
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Stopped-pion neutrinos are very supernova-esque...



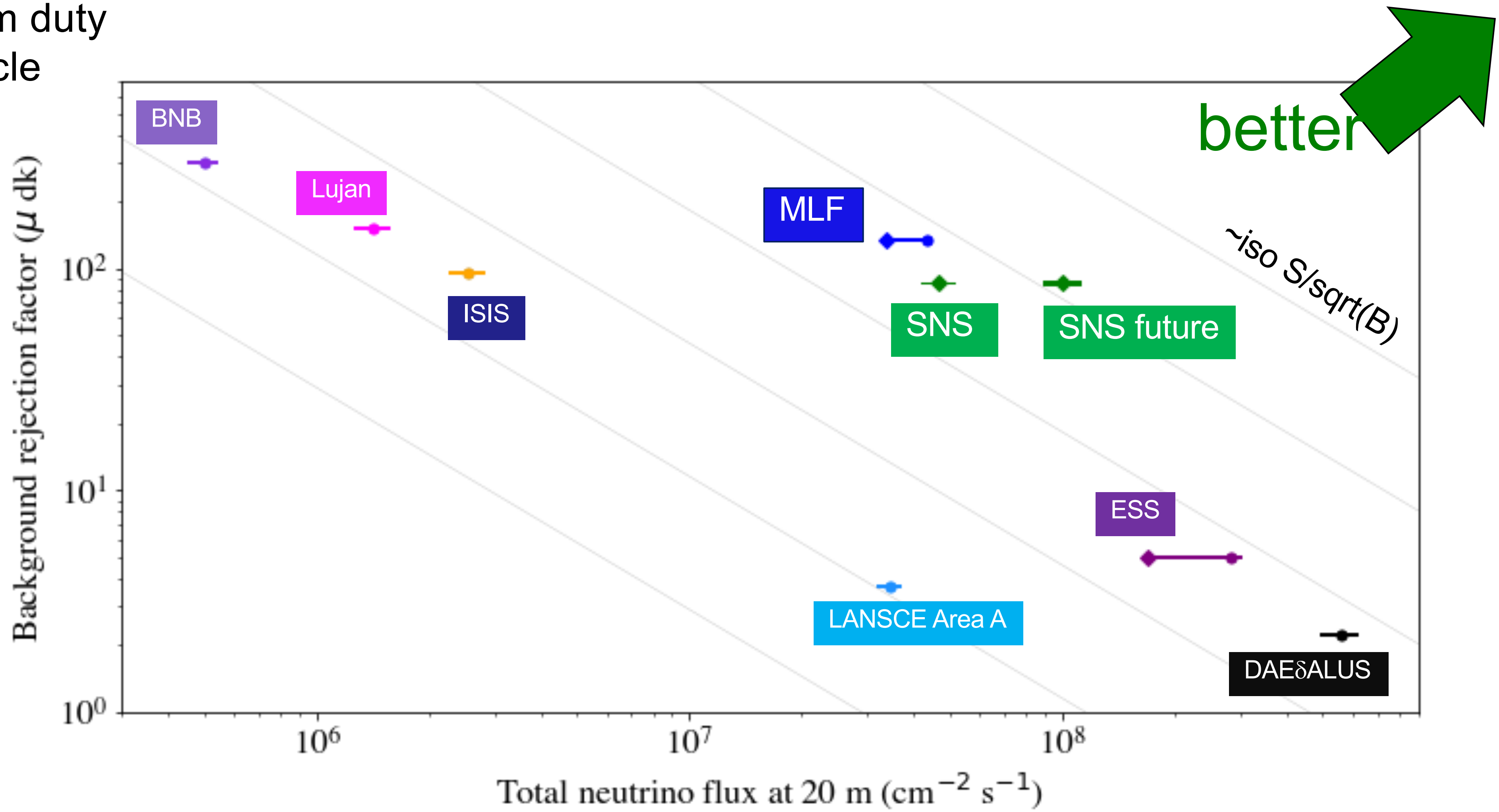
- understanding of SN processes & detection
- understanding of weak couplings (g_A quenching) & nuclear transitions

Stopped-Pion Neutrino Sources Worldwide

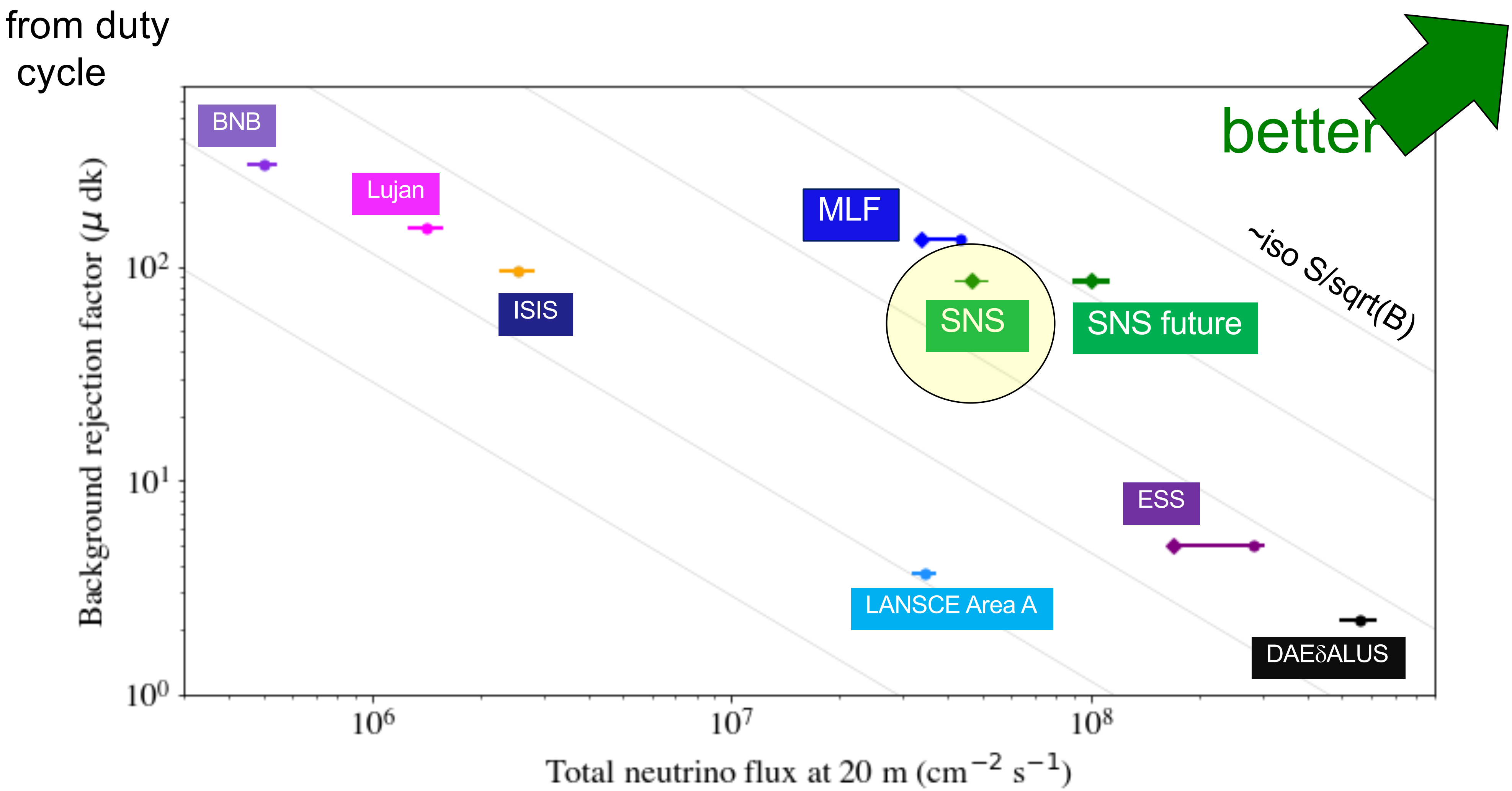


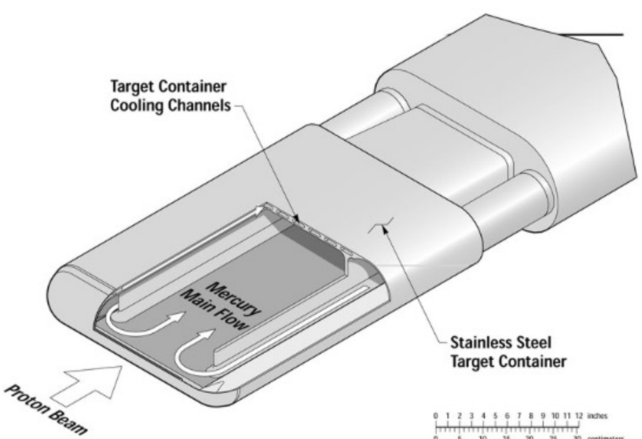
Comparison of pion decay-at-rest ν sources

from duty cycle



Comparison of pion decay-at-rest ν sources





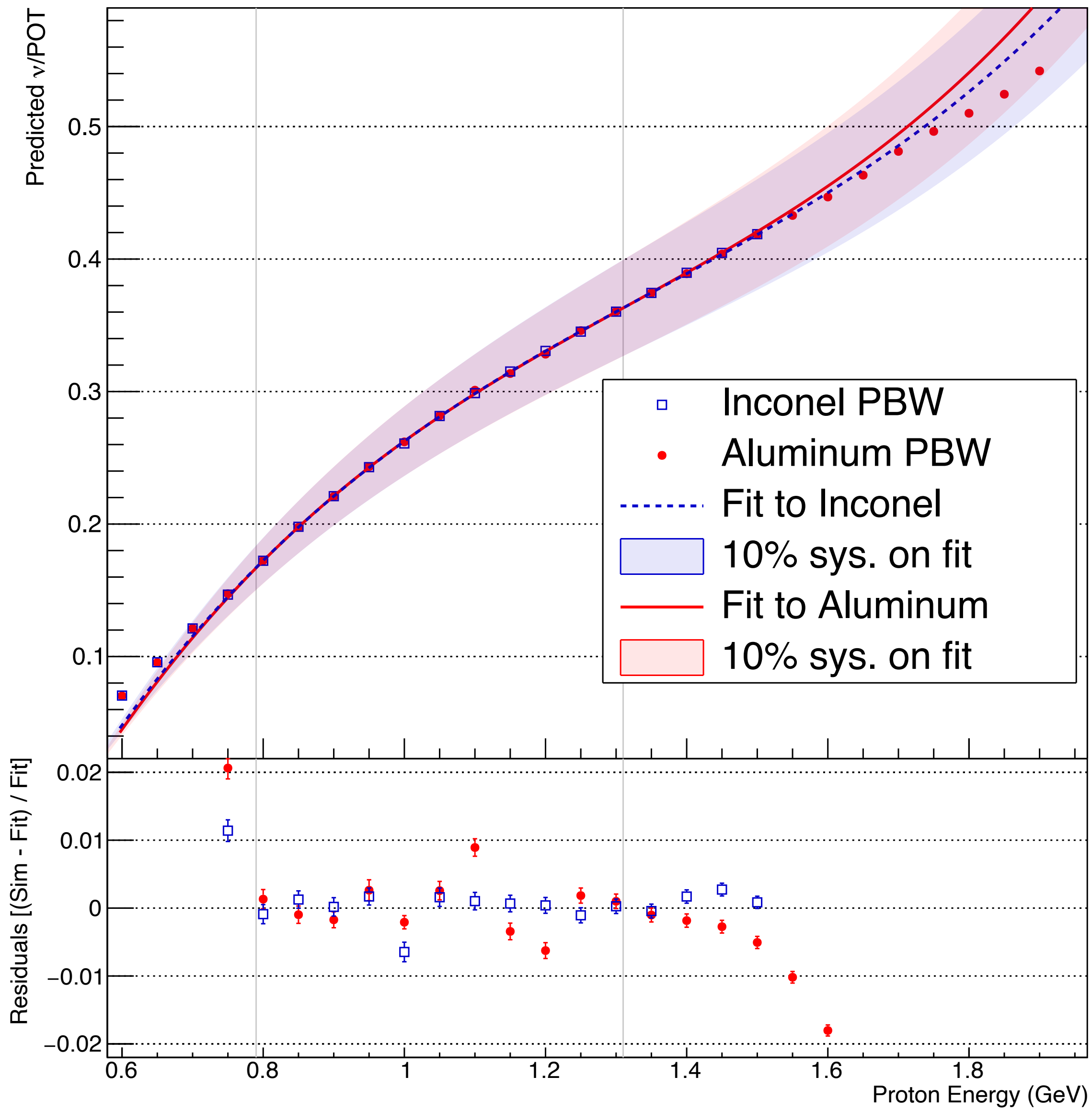
Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Fluxes depend on proton energy as well as power

G4 QGSP_BERT, validated vs HARP/HARP-CDP

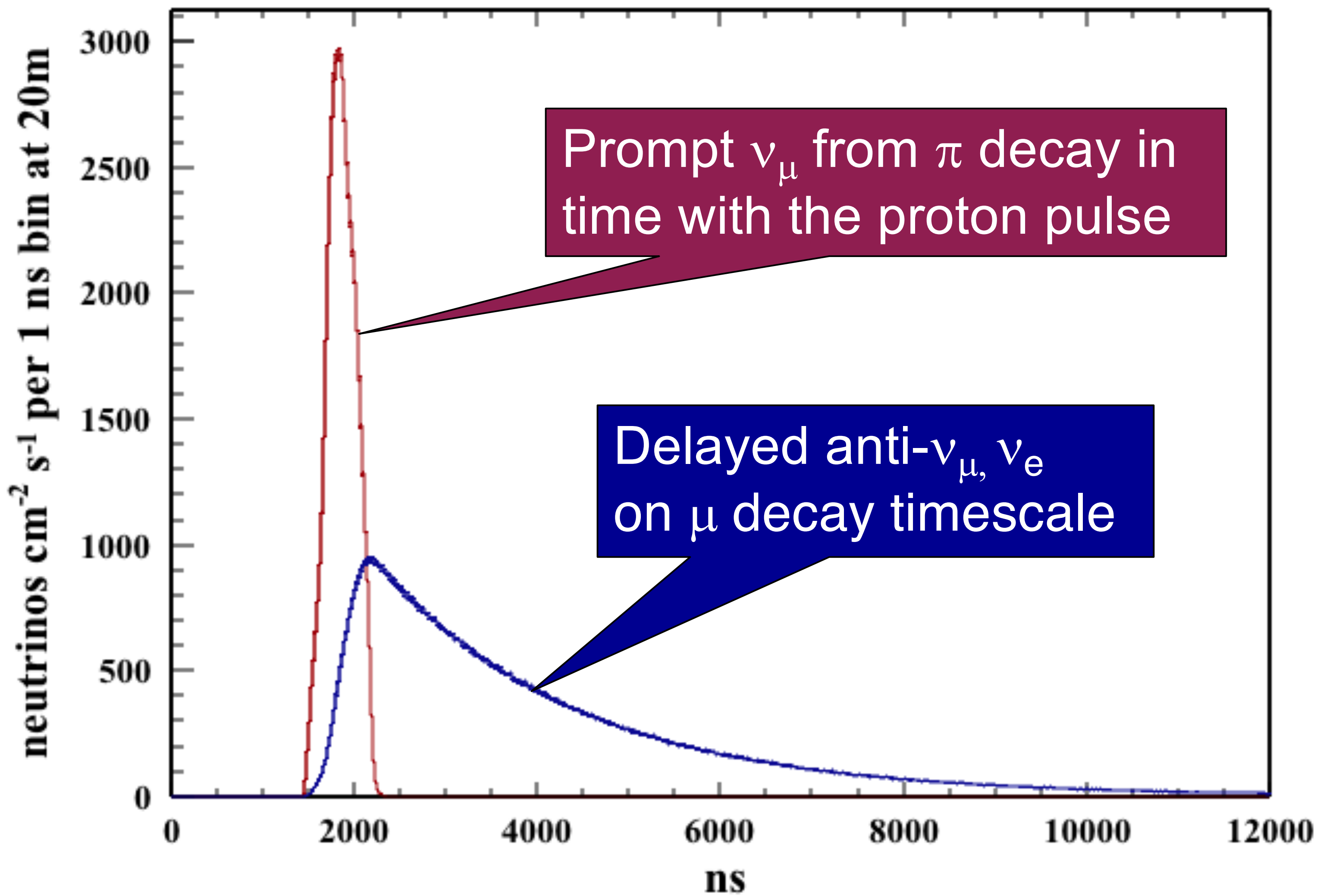
Total neutrinos per proton (all 3 flavors)



Phys.Rev.D 106 (2022) 3, 032003 arXiv:2109.11049 [hep-ex]

Time structure of the SNS source

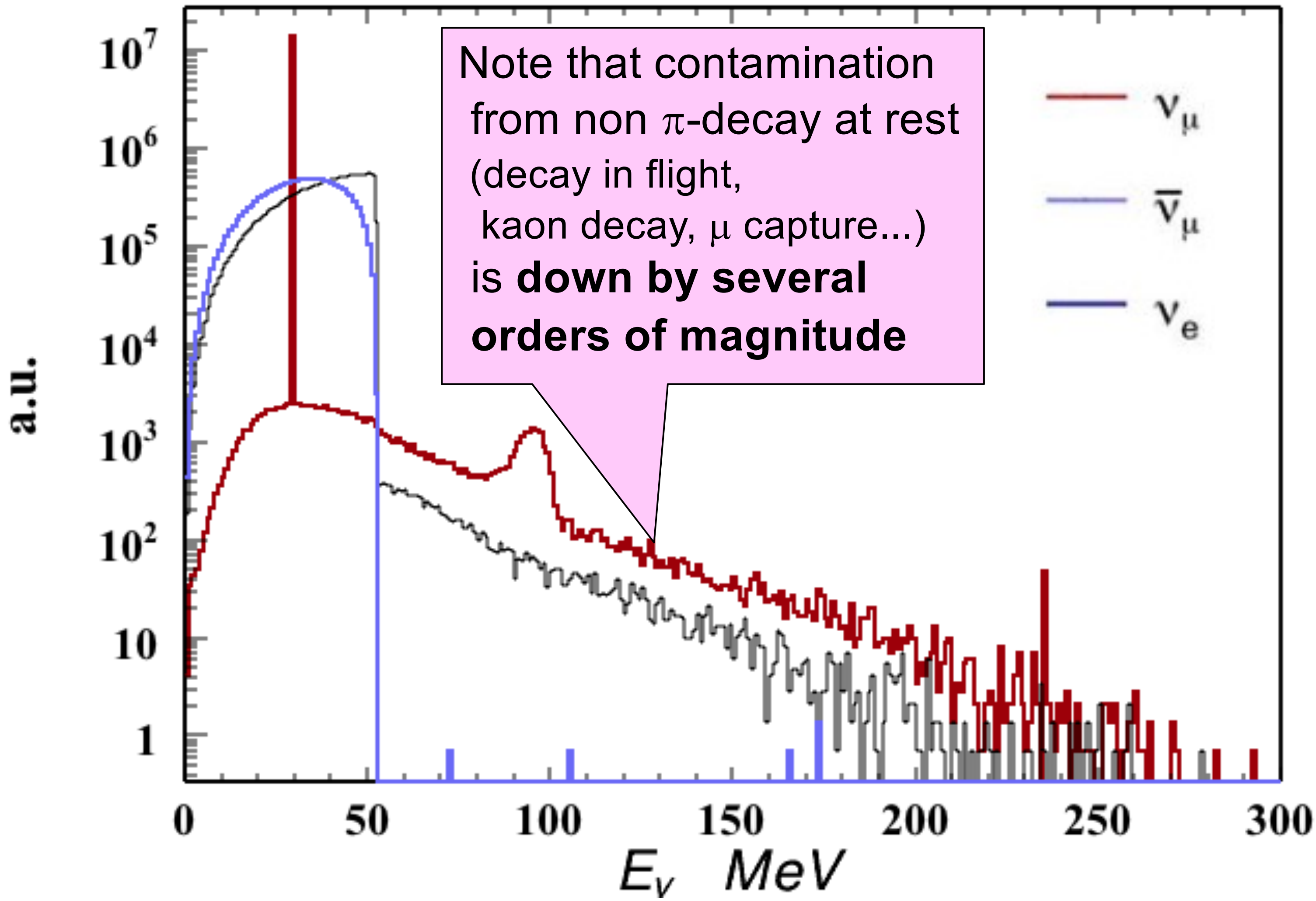
60 Hz *pulsed* source



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

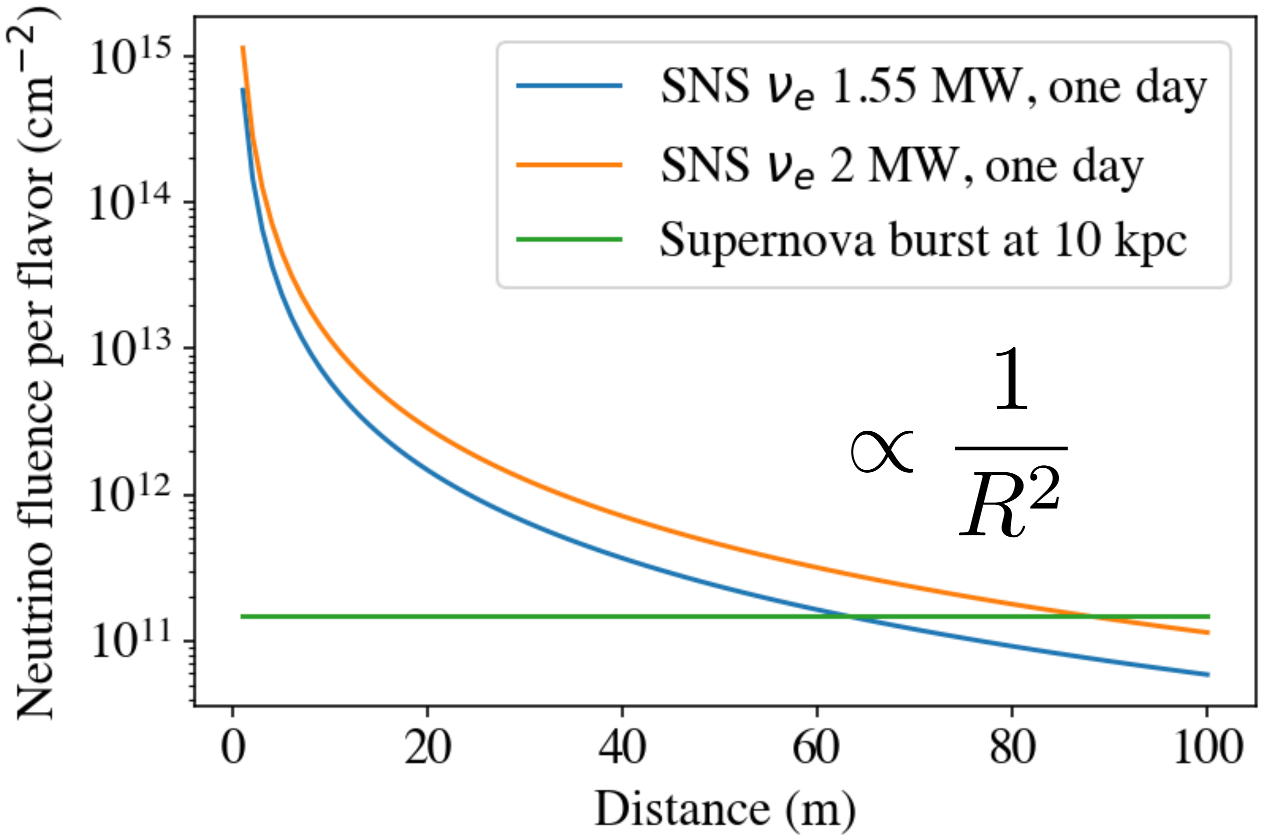
The SNS has **large, extremely clean** stopped-pion ν flux

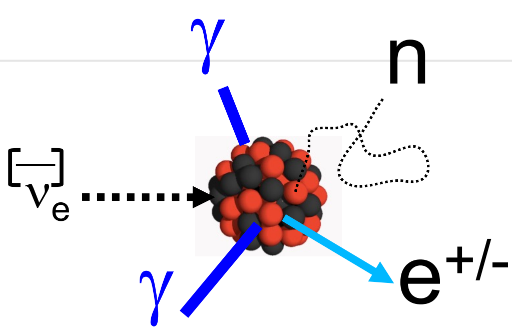
0.08 neutrinos per flavor per proton on target



SNS flux (1.4 MW):
430 x 10^5 ν/cm²/s
@ 20 m

Neutrino flux at ~20-30 m from the SNS amounts to ~ 2 SNe per day! (and will be twice that soon)





This is an excellent opportunity to study poorly understood neutrino-nucleus interactions in the supernova energy range

The COHERENT collaboration

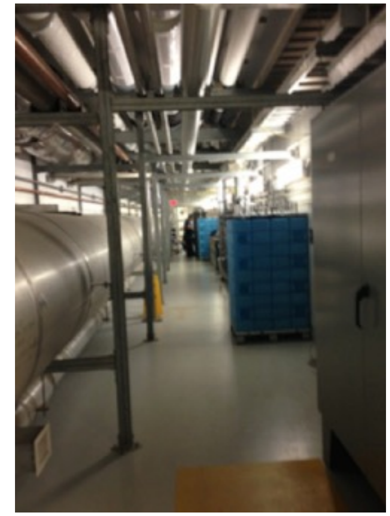
http://sites.duke.edu/coherent

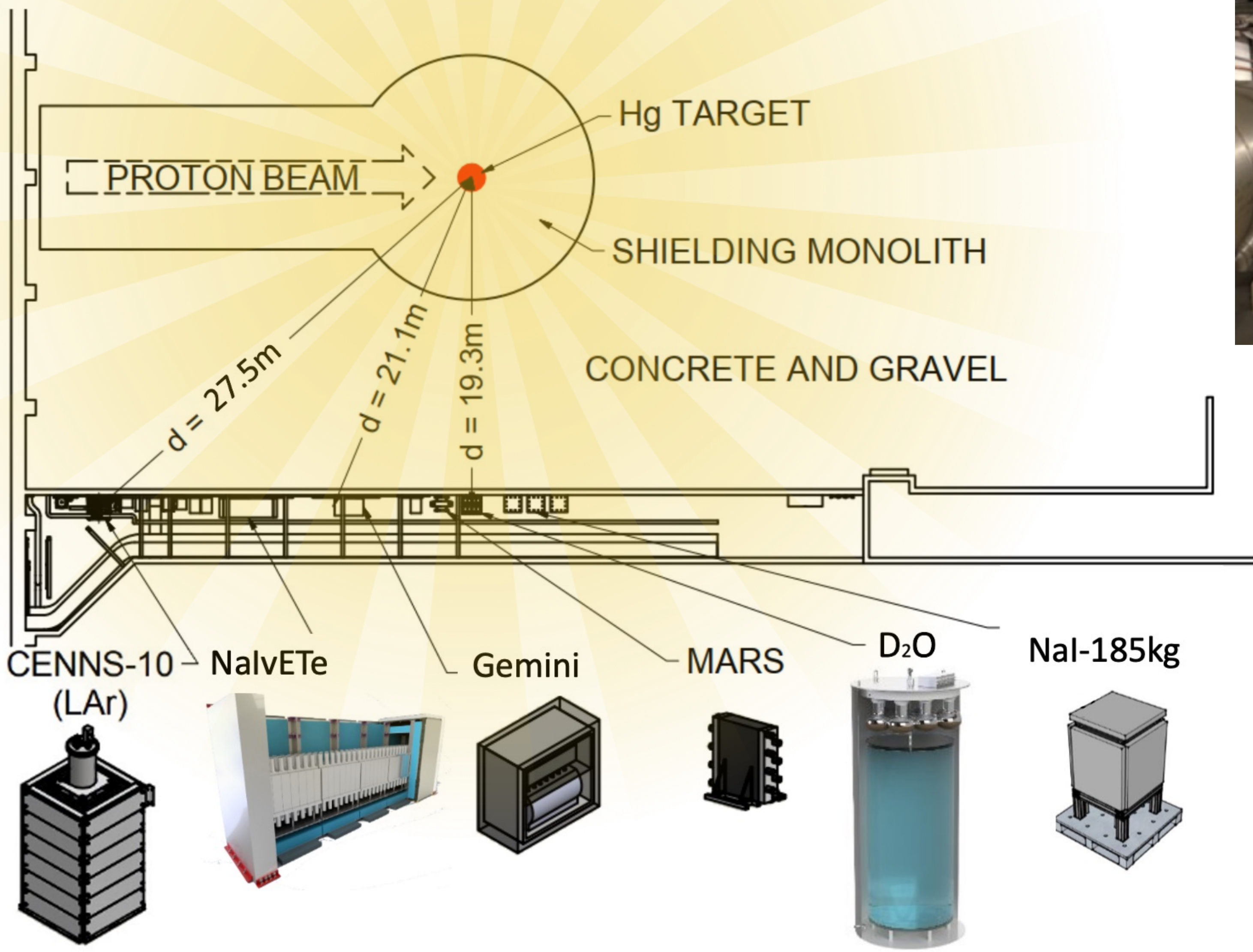
~100 members,
25 institutions
5 countries

Siting for deployment in SNS basement

(measured neutron backgrounds low, ~ 8 mwe overburden)

View looking down “Neutrino Alley”



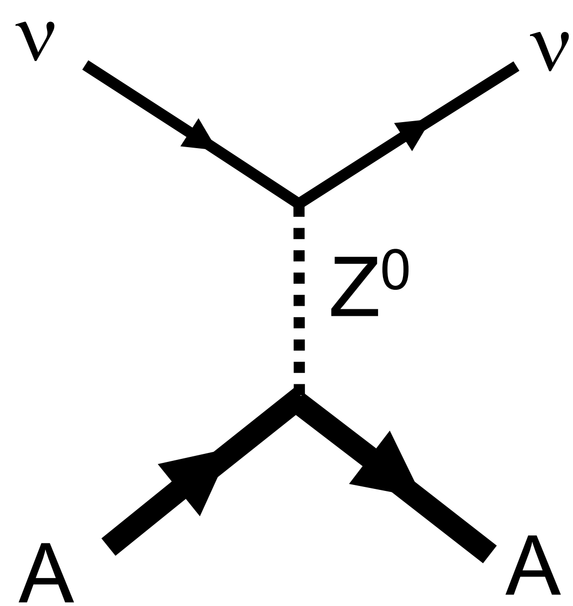


Isotropic ν glow from Hg SNS target

Future:
large LAr
LArTPC
light water
CryoCsI
neon
...

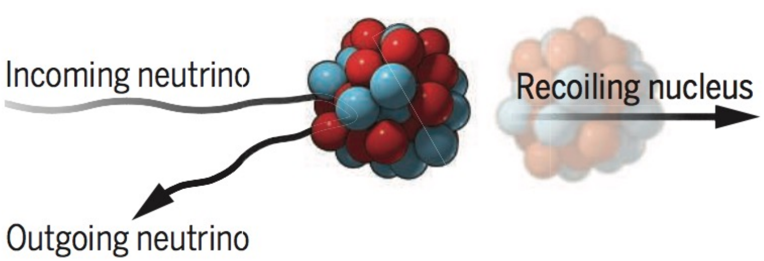
Coherent elastic neutrino-nucleus scattering (CEvNS)

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



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV

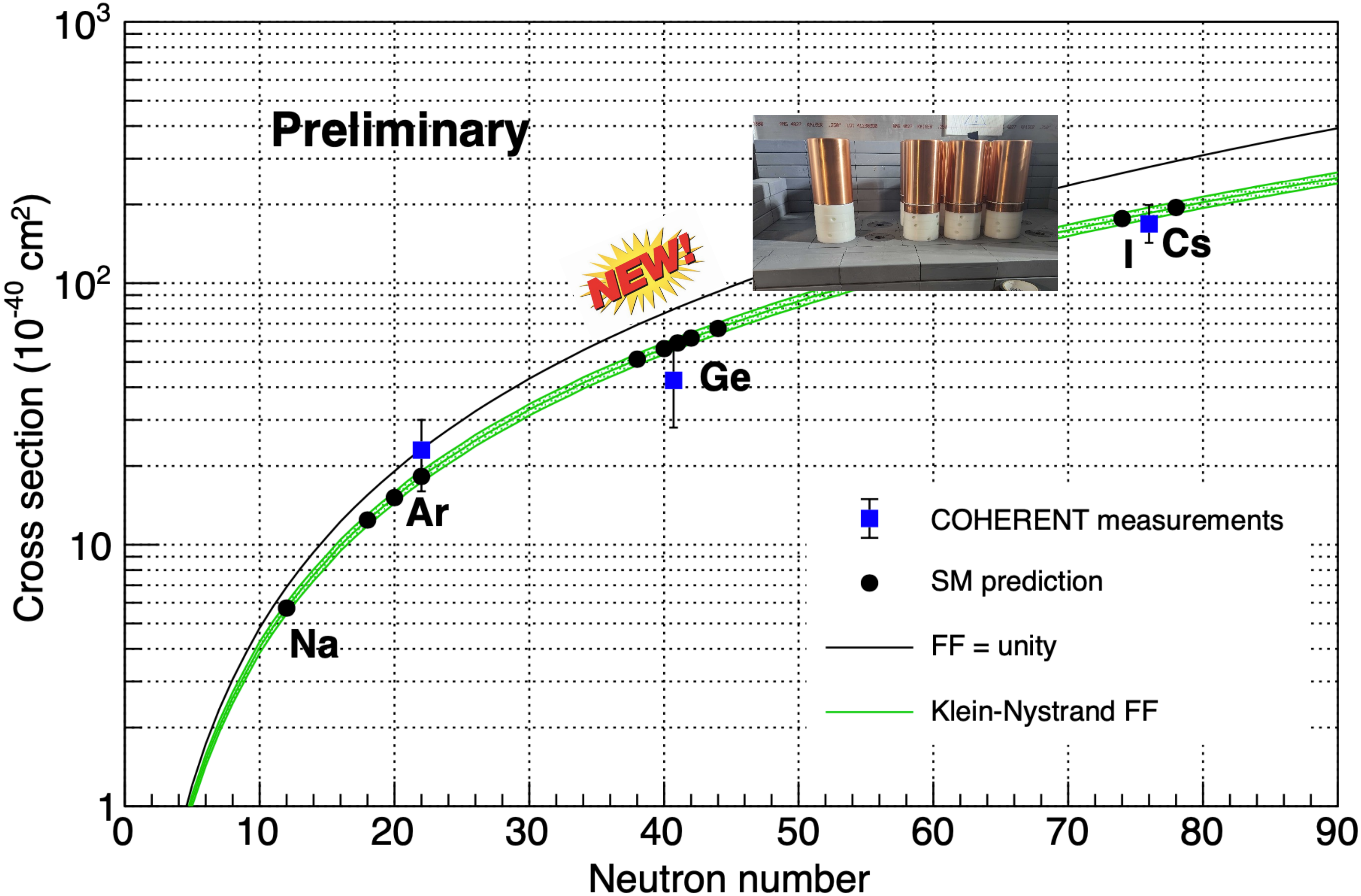
Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer



For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

A: no. of constituents

Image: J. Link *Science* Perspectives



(FNAL Wine & Cheese today!)

COHERENT also measures **inelastics** ("in-COHERENT")

Material	Mass (tons)	Detector type	Channel	Status
Pb	1	Neutrons	CC/NC NINs	Published
Fe	1	Neutrons	CC/NC NINs	Data taken
Ar	0.024	Single-phase scint	CEvNS/CC/NC	Data taken
Ar	0.75	Single-phase scint	CEvNS/CC/NC	Under construction
Ar	0.25	LArTPC	CC/NC	Proposed
D_2O/H_2O	0.67 x 2	Cherenkov	CC/NC	Data-taking/construction
NaI	0.185	Scint crystal	CC on 127I	Published
NaI	2.2+	Scint crystal	CEvNS/CC 127I	Construction
Th	0.052	Neutrons	CC fission	Data taking
(H_2O)	7	Cherenkov	CC/NC	Proposed

Workshop on Neutrino Interaction Measurements for Supernova Neutrino Detection

6–10 Mar 2023
America/New_York timezone

Enter your search term

https://indico.phy.ornl.gov/event/217/

Scientific Organizing Committee:

Marcel Demarteau
Yuri Efremenko
Motoyasu Ikeda
Yota Hino
Yusuke Koshio
Yasuhiro Nakajima
Jason Newby
Diana Parno
Kate Scholberg
Hiroyuki Sekiya
Roger Wendell

Workshop sponsors:

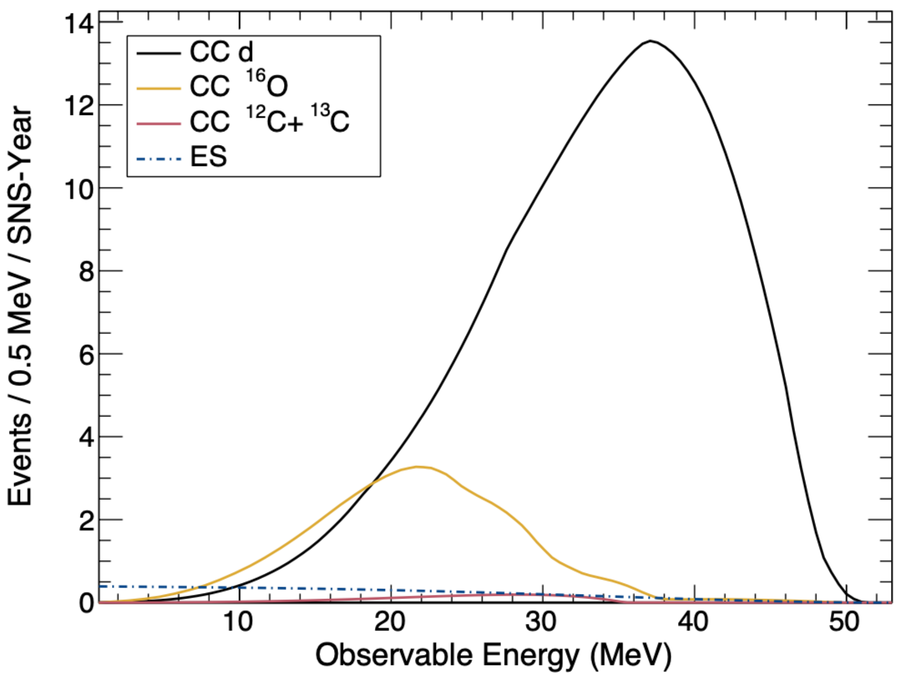
Department of Energy HEP US-Japan program
ORNL

Heavy water detector in Neutrino Alley

Dominant current uncertainty is ~10%, on neutrino flux from SNS

$$\nu_e + \mathrm{d} \longrightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$$

cross section known to ~1-2%

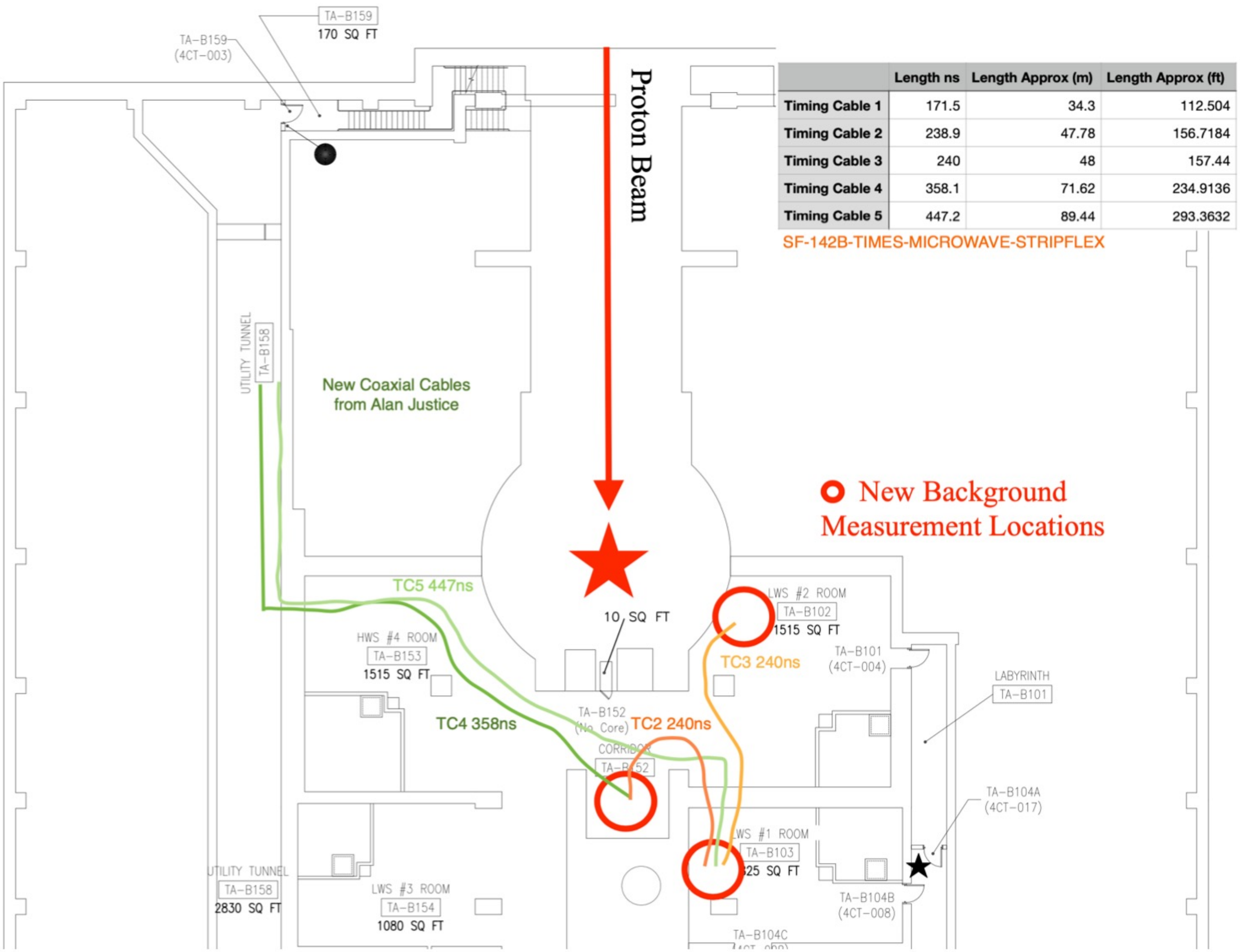


Measure electrons to determine flux normalization
Currently one heavy water module deployed, 2nd soon

Possible new water detector @ ORNL

	Length ns	Length Approx (m)	Length Approx (ft)
Timing Cable 1	171.5	34.3	112.504
Timing Cable 2	238.9	47.78	156.7184
Timing Cable 3	240	48	157.44
Timing Cable 4	358.1	71.62	234.9136
Timing Cable 5	447.2	89.44	293.3632

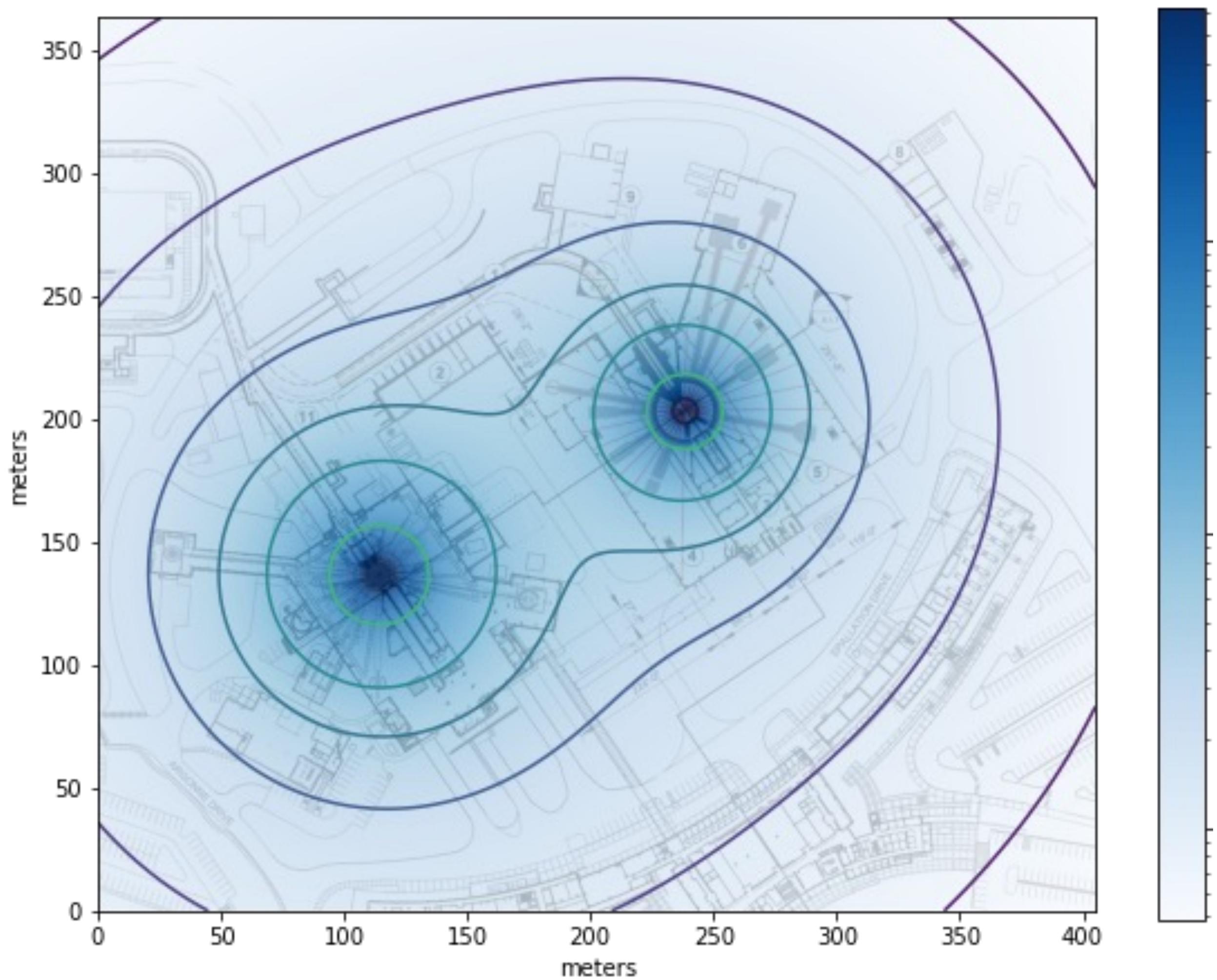
SF-142B-TIMES-MICROWAVE-STRIPFLEX



Jason Newby

SNS power upgrade to 2 MW underway

Second Target Station upgrade to 2.8 MW in 2030's



¾ bunches to FTS
¼ bunches to STS

Many exciting possibilities for ν's + DM!

Take-Away Messages

Core-collapse neutrinos

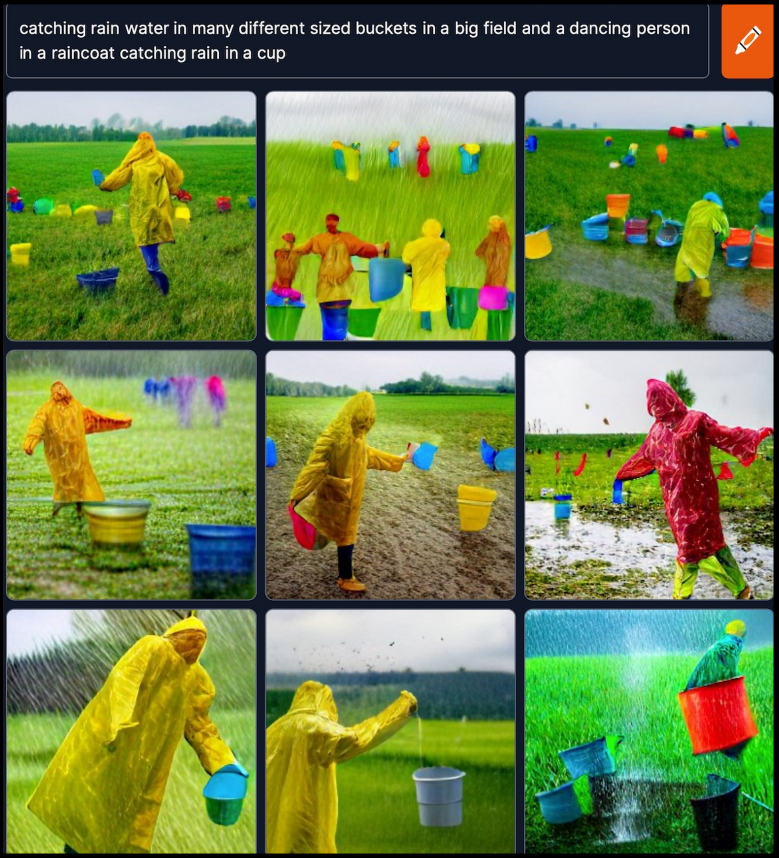
- vast science to be gained!
- we need to understand ν interactions to get the most out of a CCSN observation

Stopped-pion neutrinos are a "calibration source"

- SNS is nearly ideal!
- COHERENT in Neutrino Alley is exploiting these for CEvNS & **inelastics**

Future opportunities

- many materials, including CC/NC on ^{16}O



We want to catch them all!

(and measure xscns)