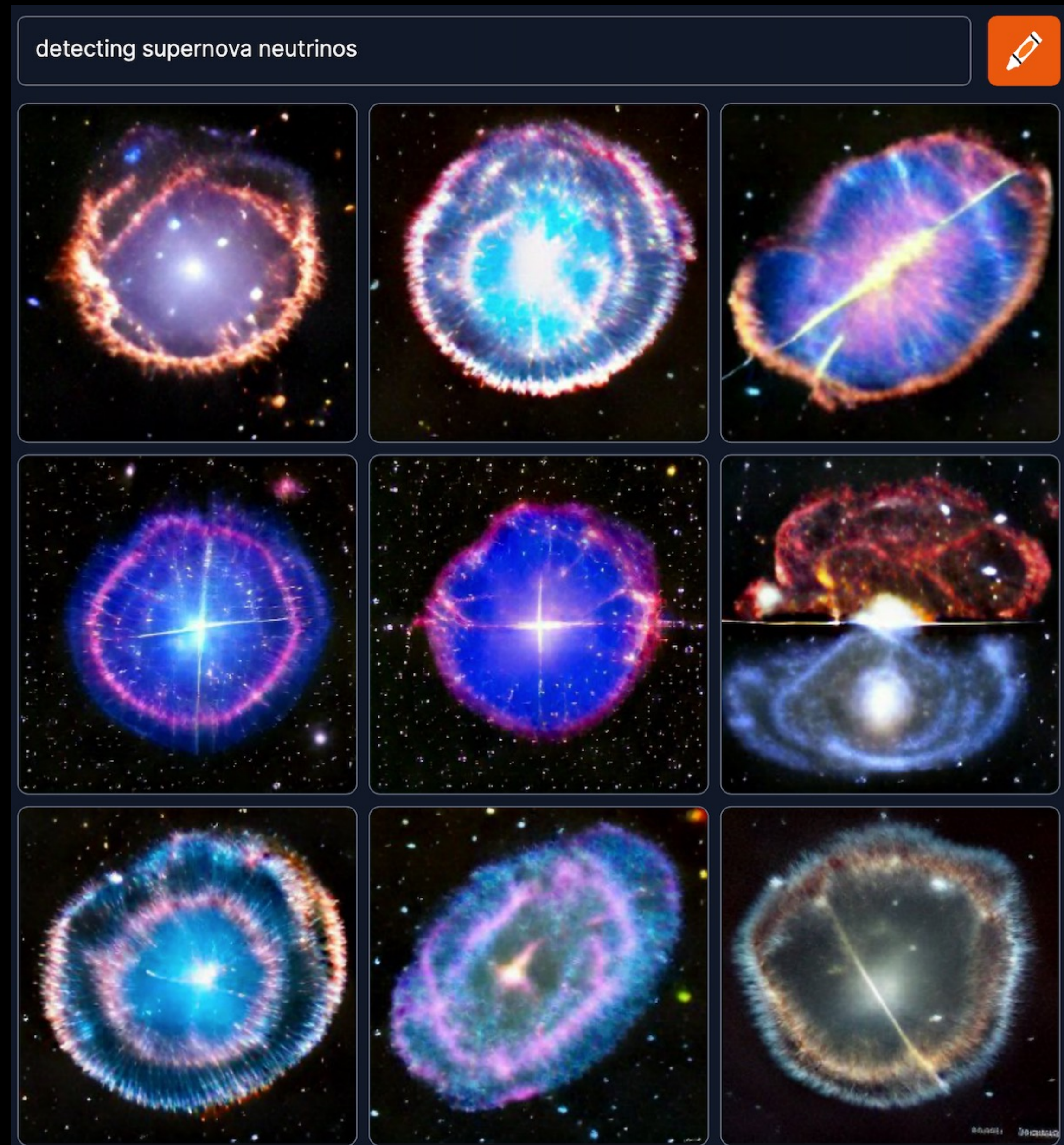
Measuring Artificial Supernova Neutrinos in Neutrino Alley

Kate Scholberg,
Duke University

Unraveling the History of the Universe and Matter Evolution with Underground Physics
Sendai, Japan
March 6, 2024



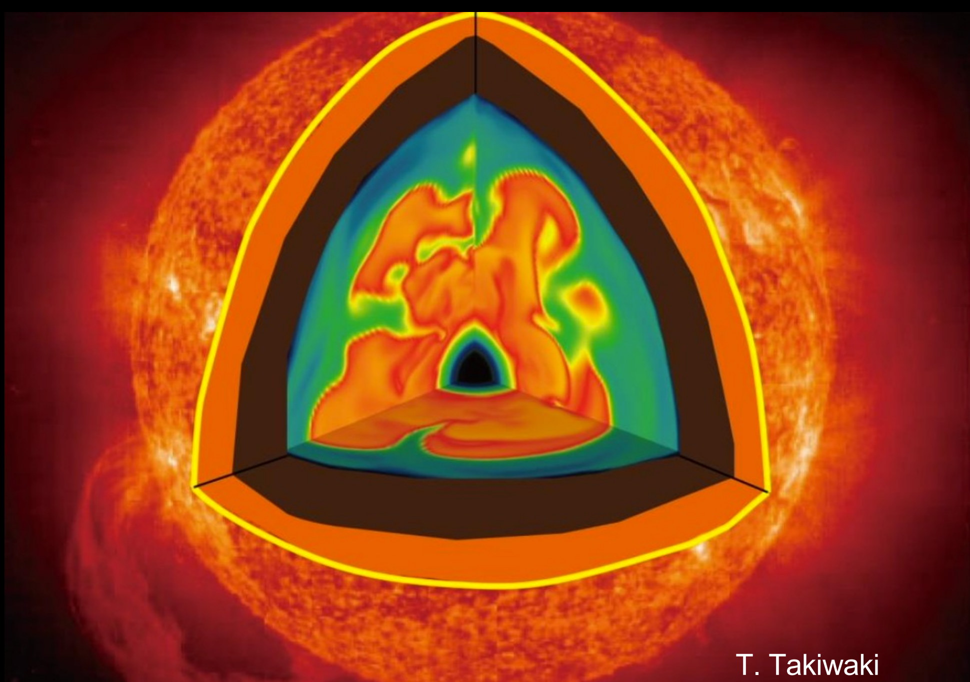
Neutrinos from core-collapse supernovae

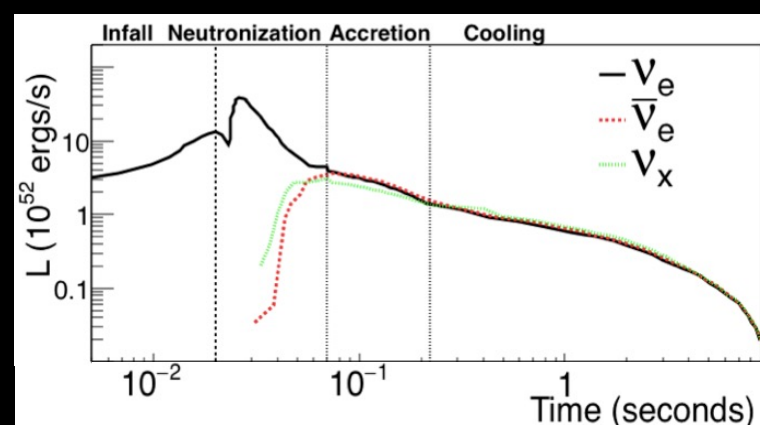
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

(Energy *can* escape via ν's)

Mostly ν-νbar pairs from proto-nstar cooling

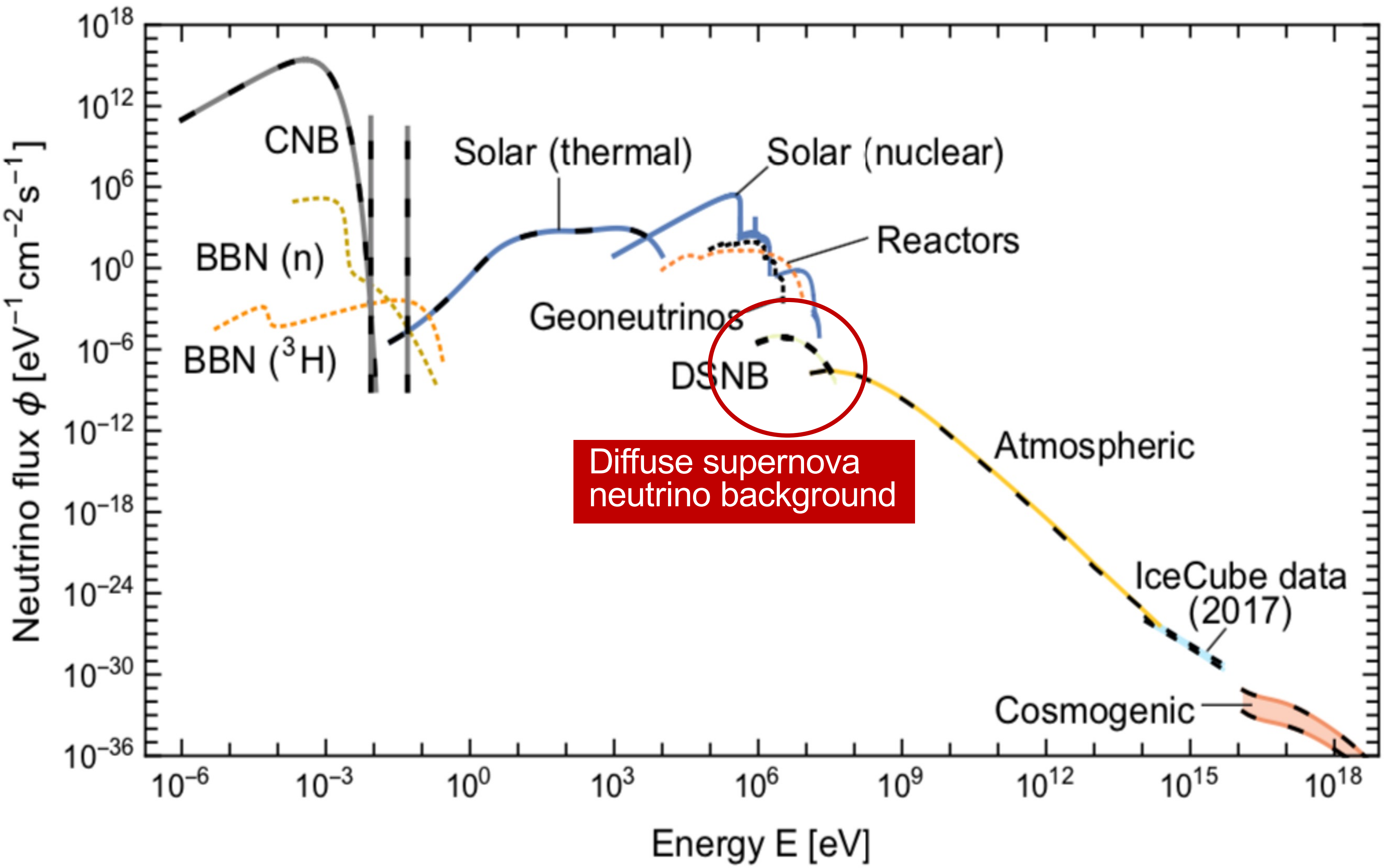
Timescale: *prompt* after core collapse, overall Δt~10's of seconds





The Steady State Neutrino Spectrum @ Earth

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF



During a ~10s Galactic burst, SN flux can increase 9-10 orders of magnitude

Grand Unified Neutrino Spectrum at Earth
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MPP-2019-205
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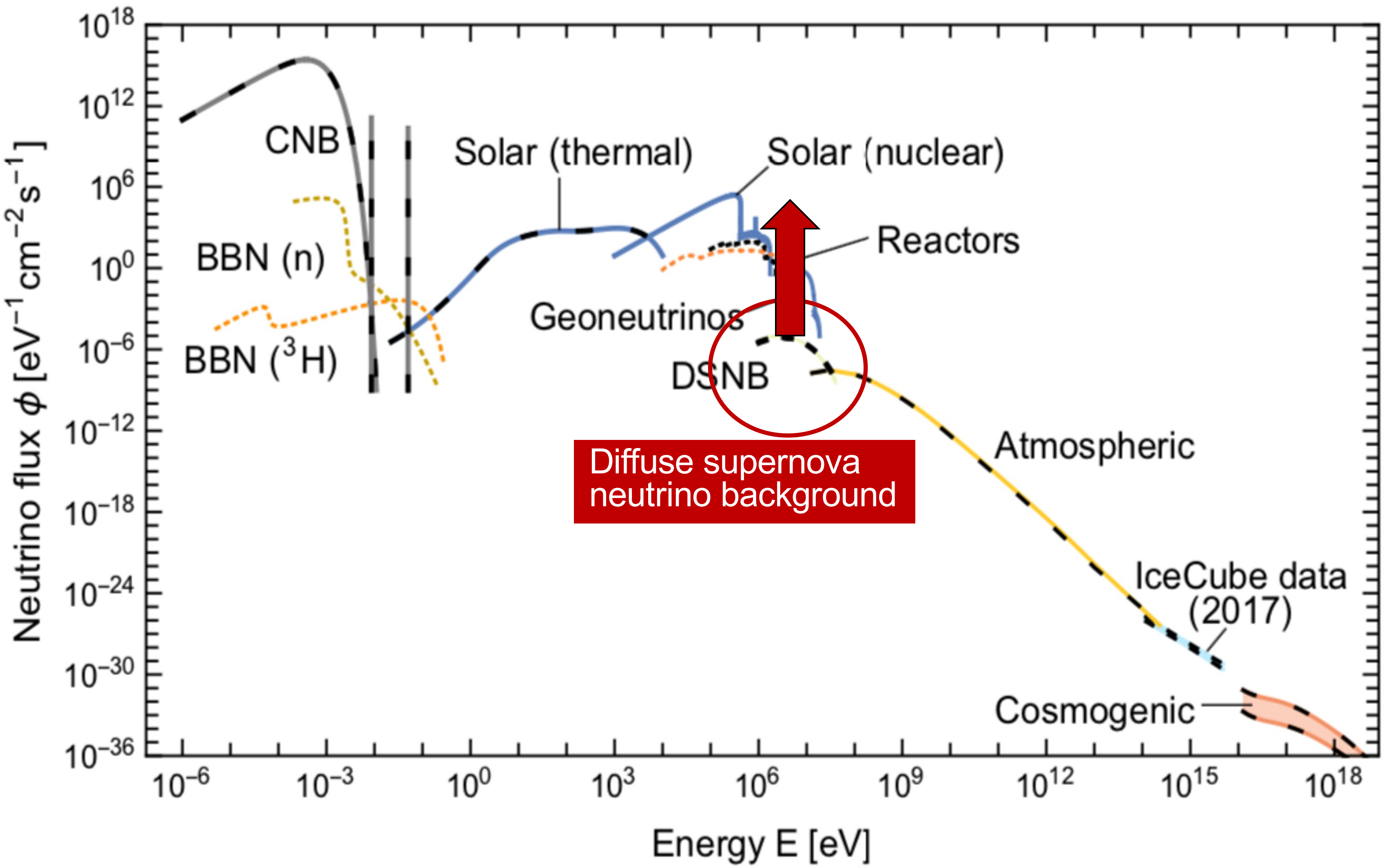
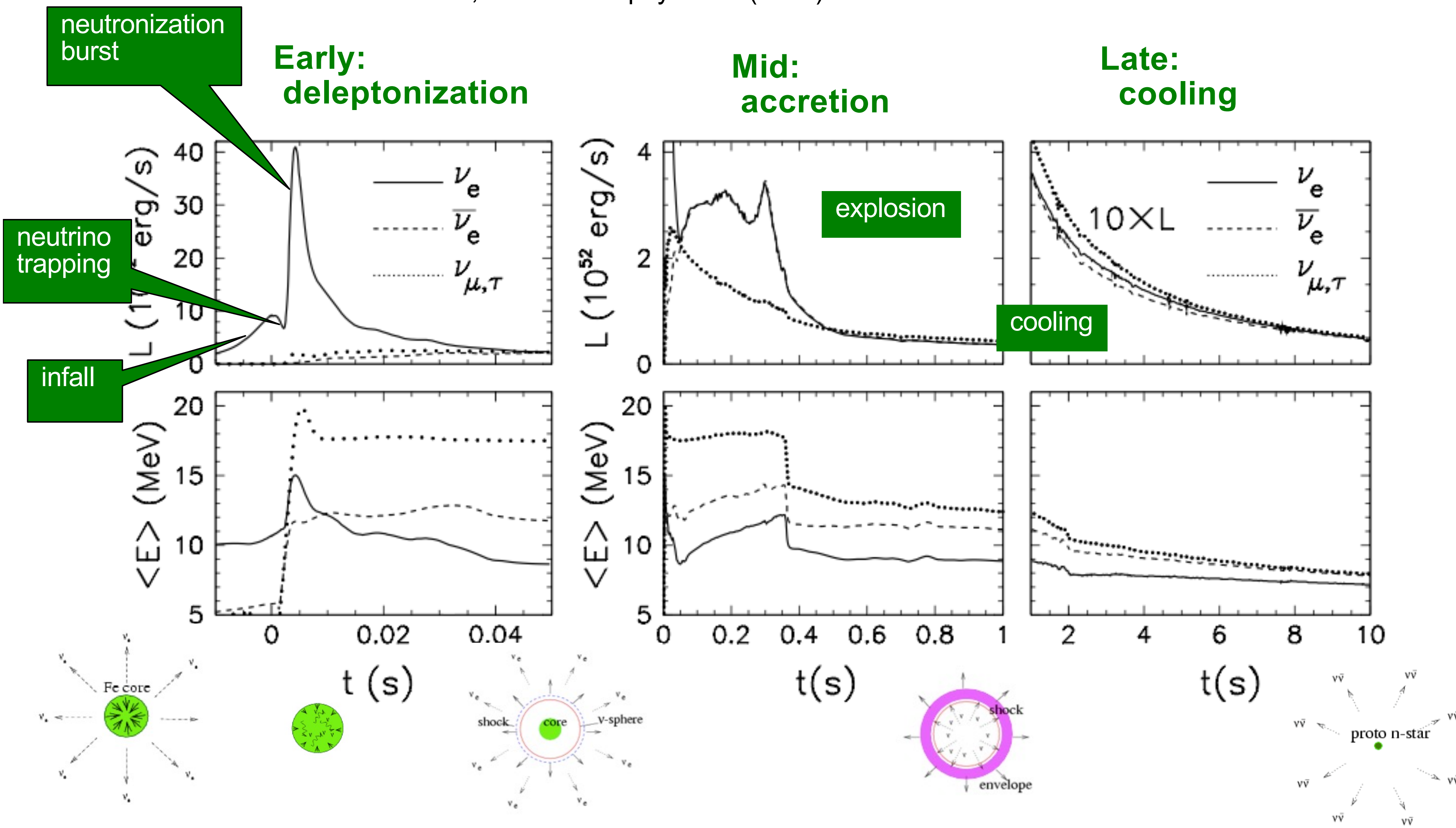


Expected neutrino luminosity and average energy vs time

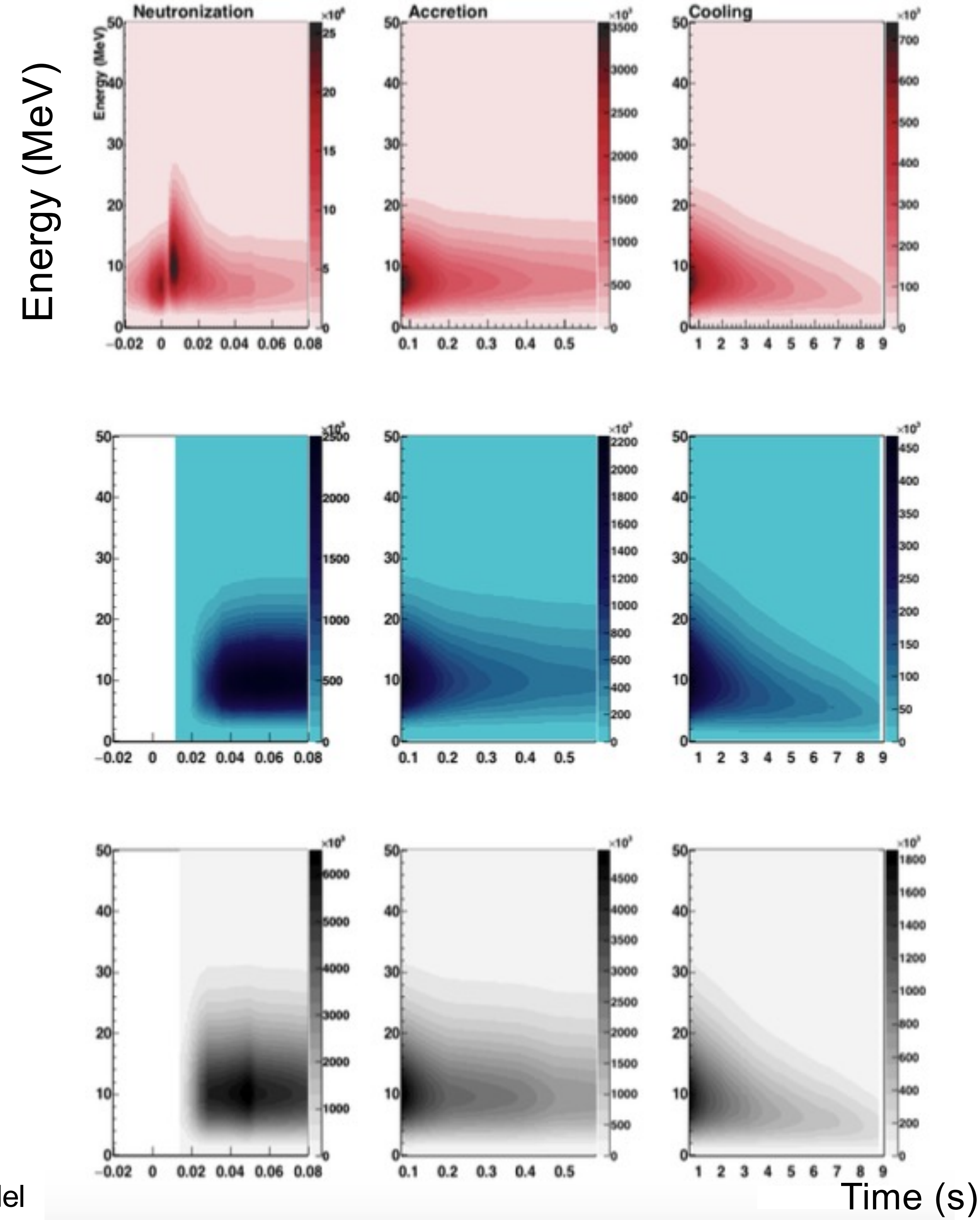
Vast information in the *flavor-energy-time profile*

Fischer et al., Astron.Astrophys. 517 (2010). arXiv:0908.1871: 'Basel' model



Visible supernova may not show up for hours or days

Fluxes as a function of time and energy



ν_e

$\bar{\nu}_e$

ν_x

$= \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$

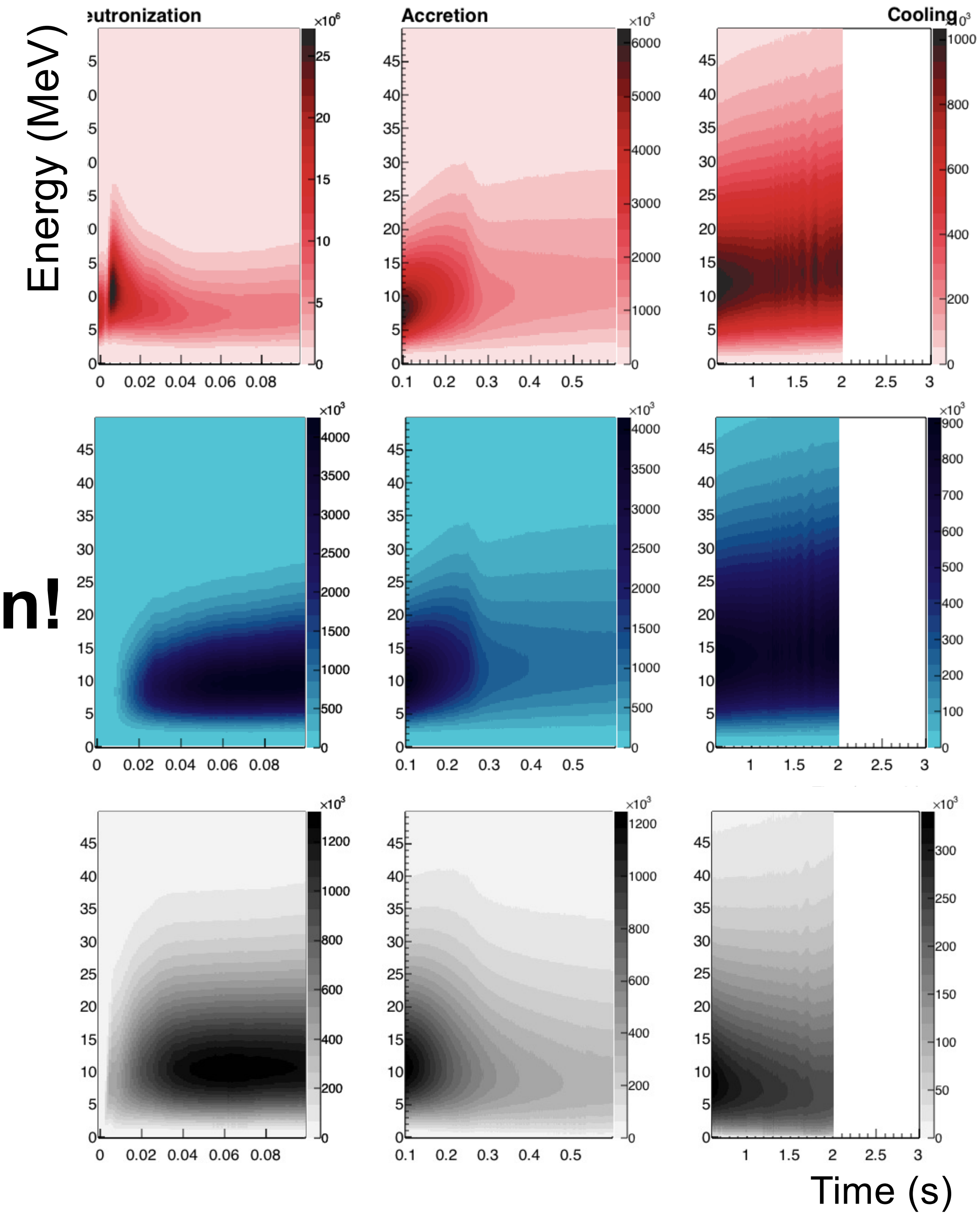
Neutrinos per cm^2 per bin (per ms per 0.5 MeV)

Huedepohl et al. model

Another example of a model

…

black hole formation!



ν_e

$\bar{\nu}_e$

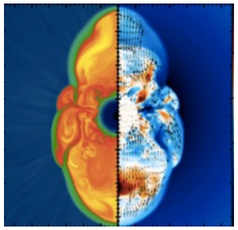
ν_x

$= \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$

Model by L. Huedepohl

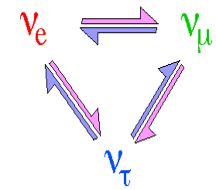
What can we learn from the next neutrino burst?

CORE COLLAPSE PHYSICS



explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....

input from neutrino experiments



from flavor, energy, time structure of burst

NEUTRINO and OTHER PARTICLE PHYSICS

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

input from **multimessenger** observations

+ EARLY ALERT

Supernova neutrino detector types

Water

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

$\overline{\nu}_e$

Water, long-string

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

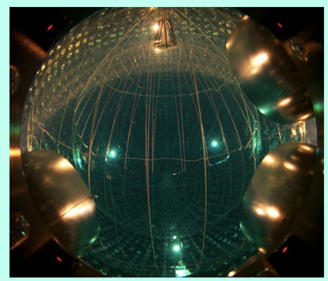
$\overline{\nu}_e$

Argon

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

ν_e

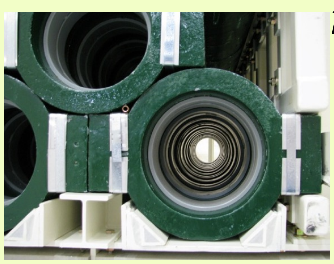
Scintillator



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

$\overline{\nu}_e$

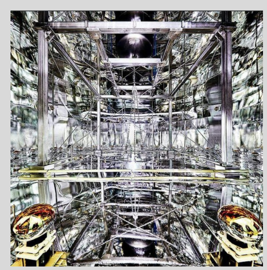
Lead



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

ν_e

DM (Noble liquid)



$$\nu_x + \mathrm{A} \rightarrow \nu_x + \mathrm{A}$$

ν_x

Summary of supernova neutrino detectors

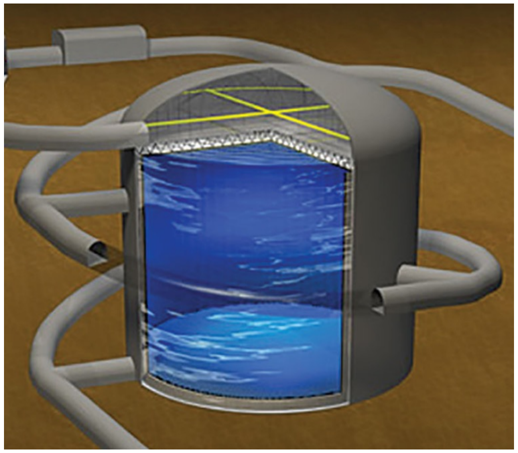
Galactic sensitivity

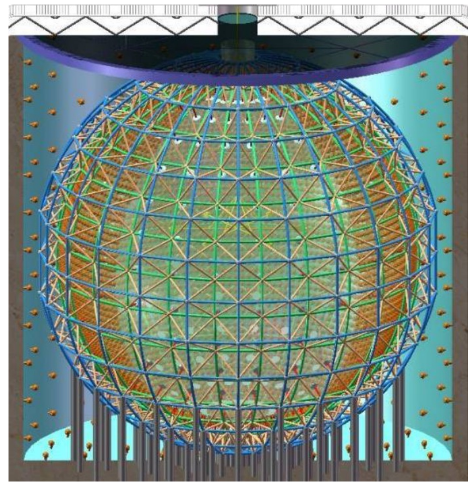
Extragalactic

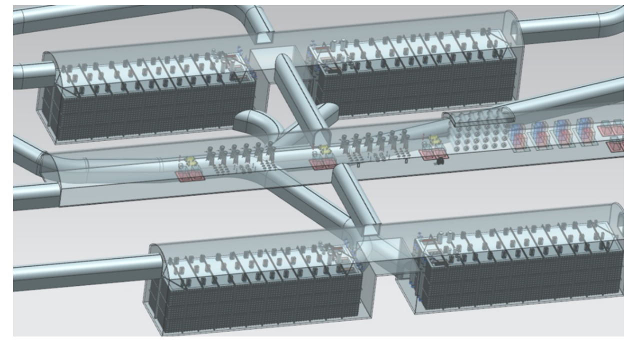
Detector	**Type**	**Location**	**Mass (kton)**	**Events @ 10 kpc**	**Status**
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Recently completed
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Recently completed
NOvA	Scintillator	USA	15	3000	Running
SNO+	Scintillator	Canada	1	300	Running
MicroBooNE	Liquid argon	USA	0.17	17	Running
DUNE	Liquid argon	USA	40	3000	Future
Hyper-K	Water	Japan	266	110,000	Future
JUNO	Scintillator	China	20	6000	Future
IceCube Gen-2	Long string	South pole			Future
KM3Net	Long string	Mediterranean			Future

plus reactor experiments, DM experiments...

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**

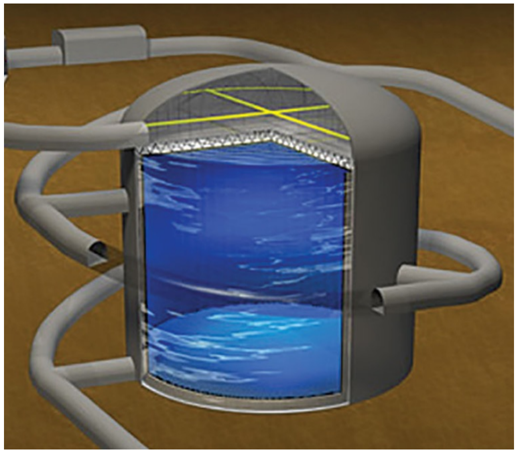
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- DUNE is primarily sensitive to **nue**

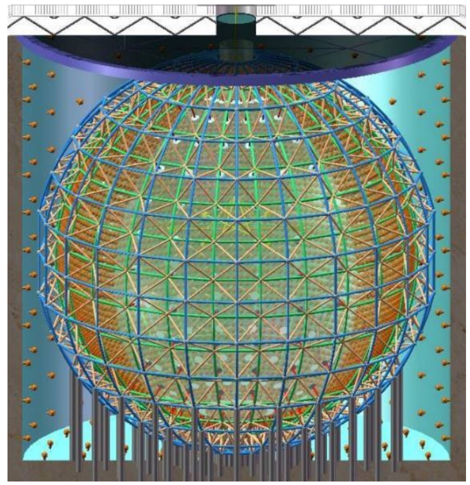
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

extreme complementarity

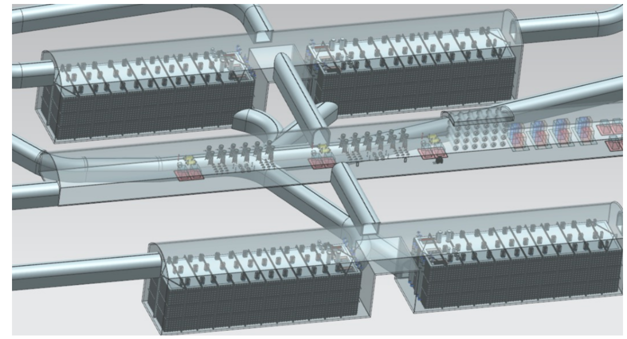
Future Large Supernova-Burst-Sensitive Neutrino Detectors



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**

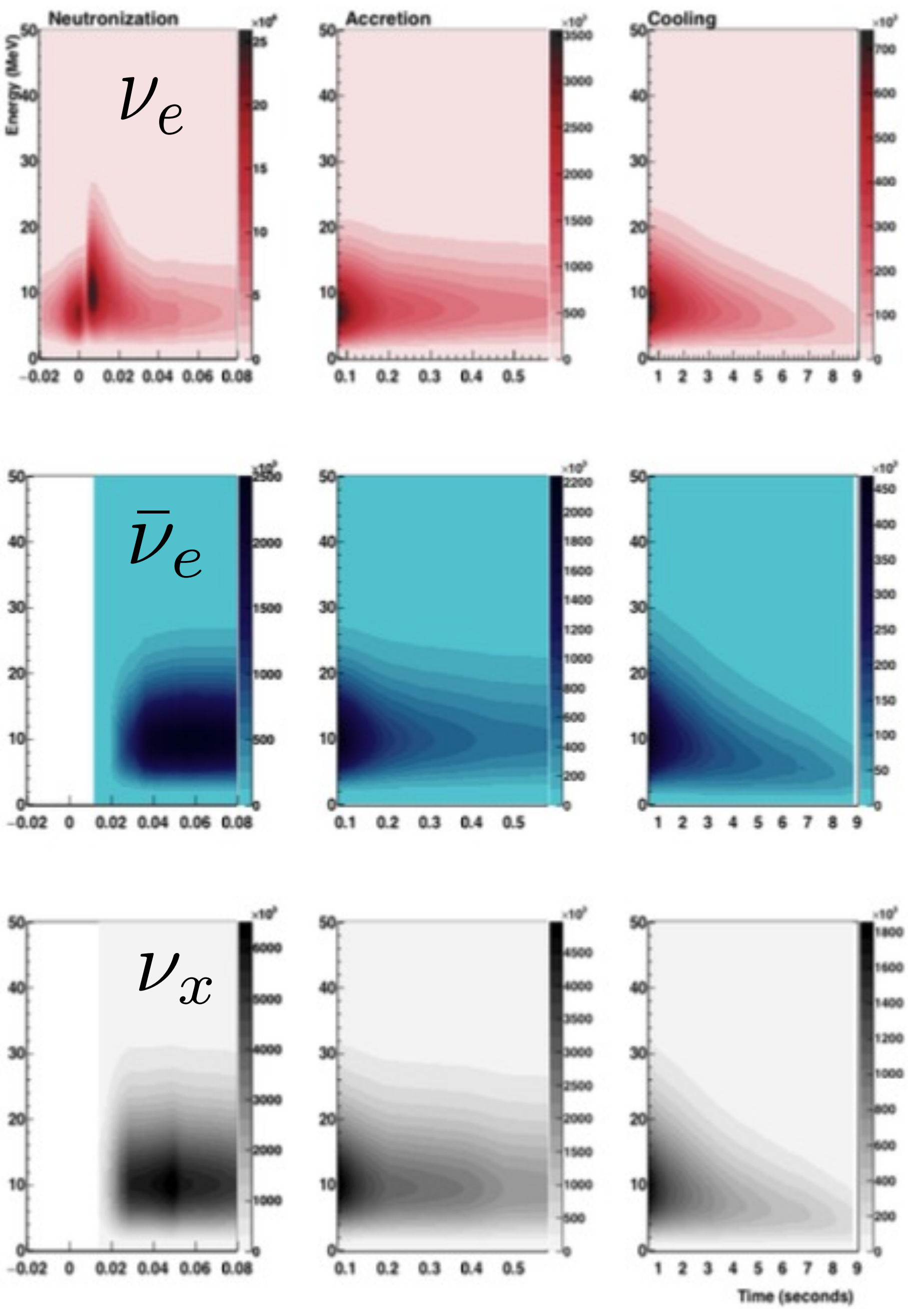
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

extreme complementarity

[....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

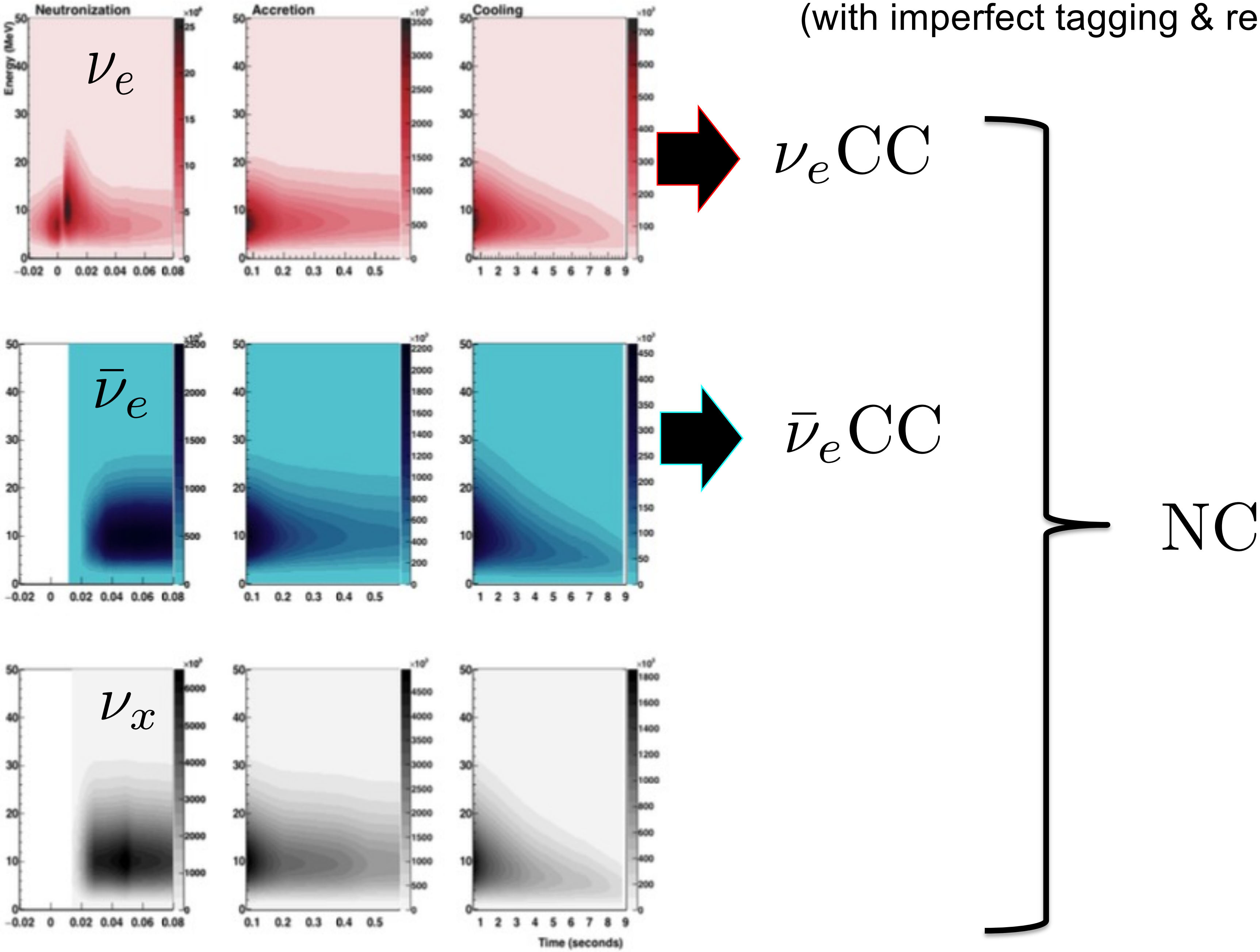


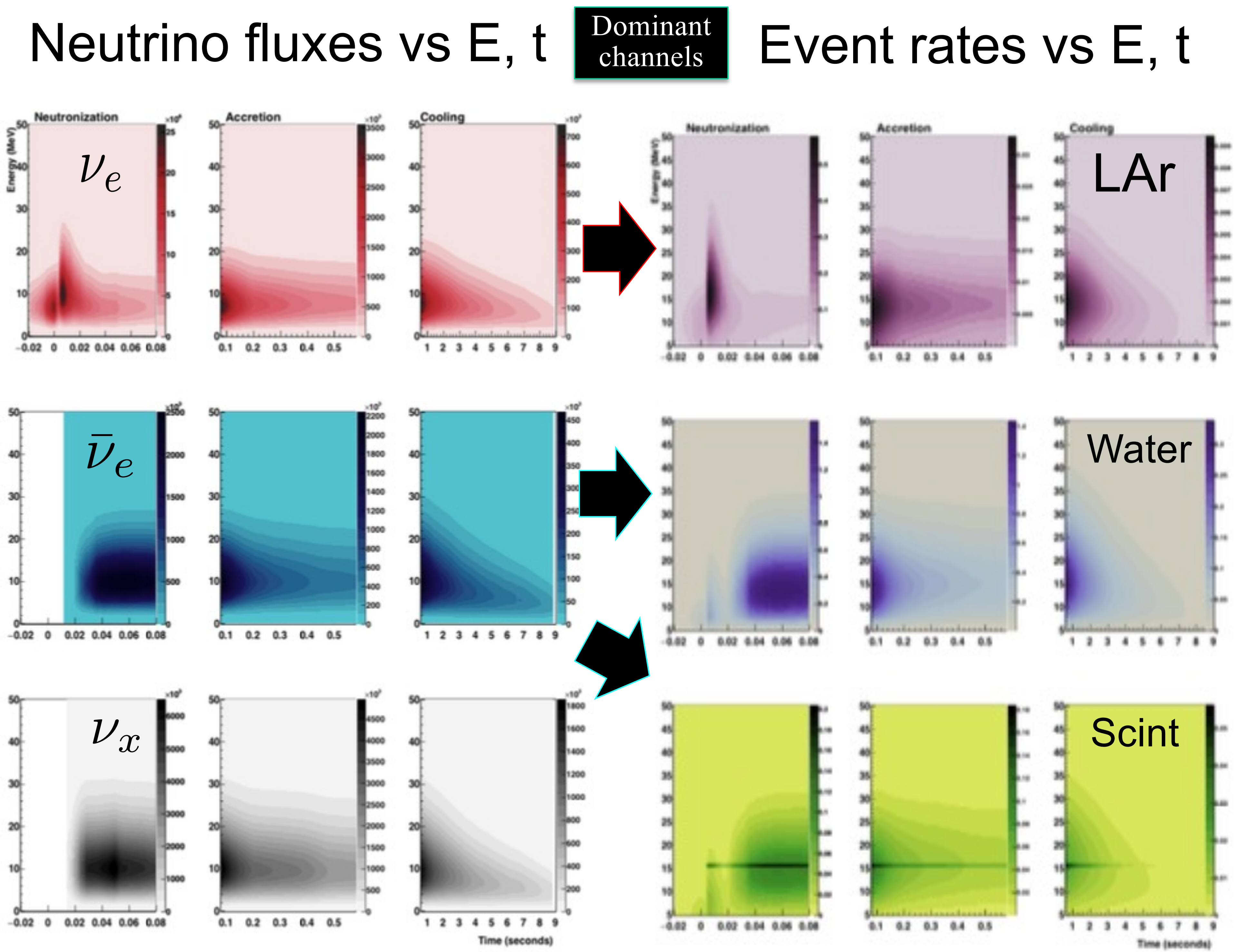
What we *want* to measure

Neutrino fluxes vs E, t

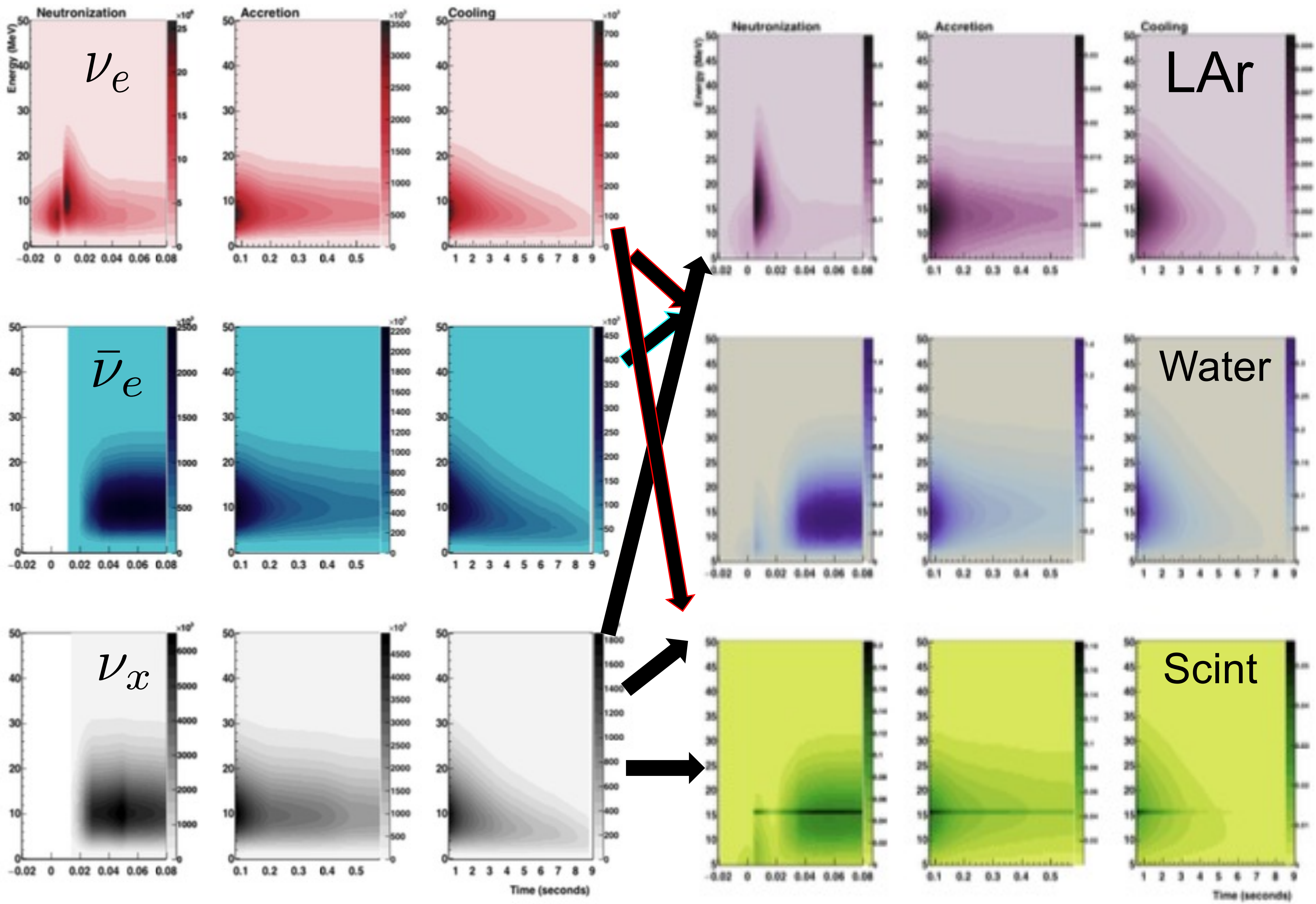
What we *can* measure

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




Neutrino fluxes vs E, t
Dominant channels
Event rates vs E, t
ν_e
$\bar{\nu}_e$
ν_x
LAr
Water
Scint
Neutronization
Accretion
Cooling
Energy (MeV)
Time (seconds)

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



Subdominant channels are in the mix too,
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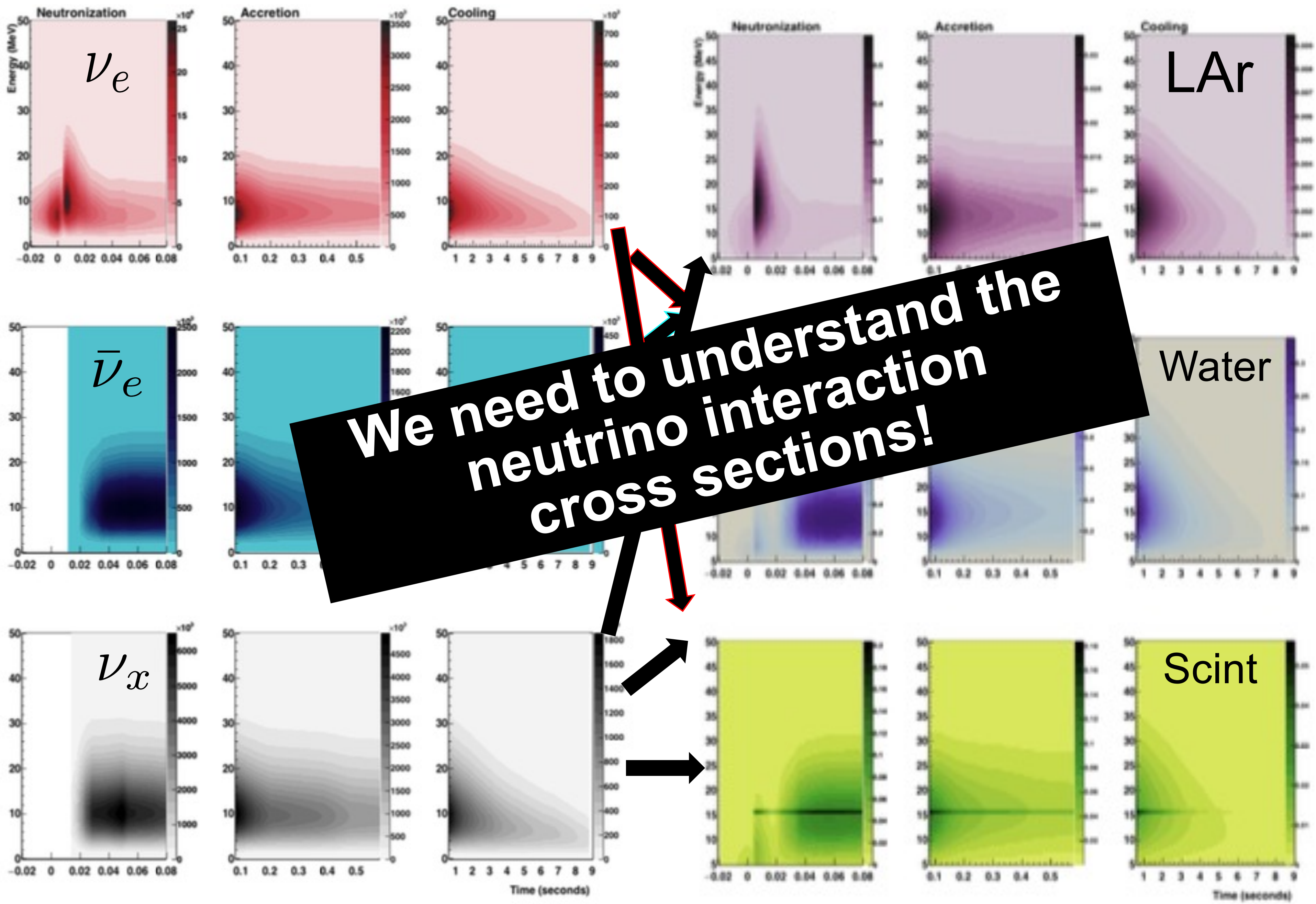
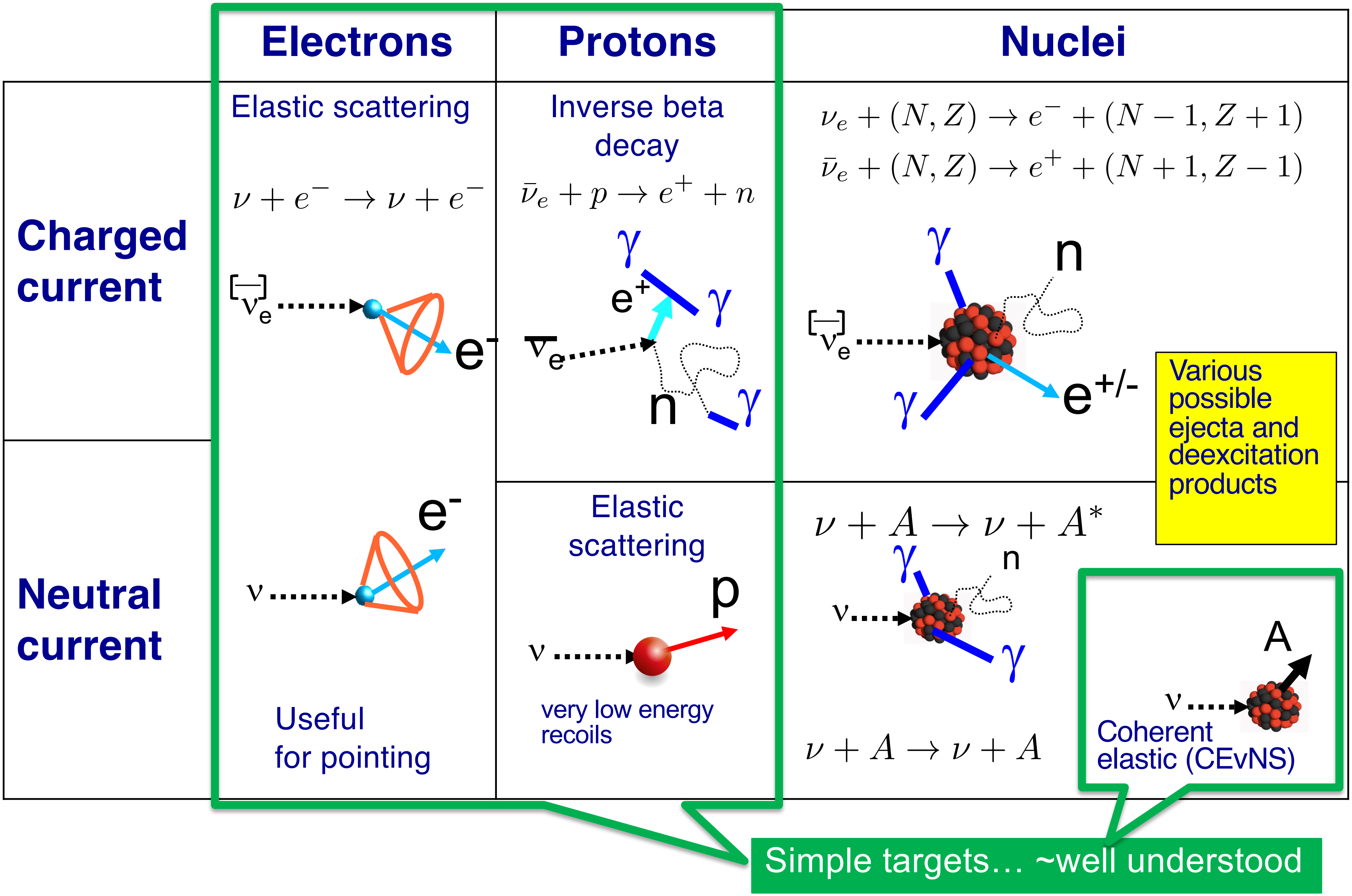
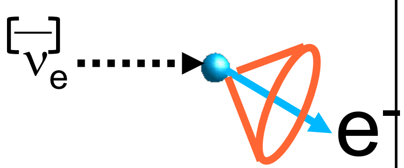
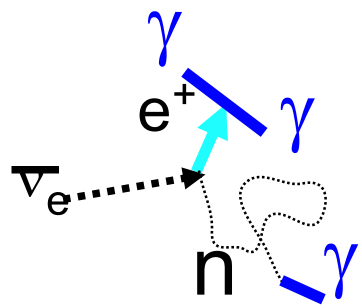
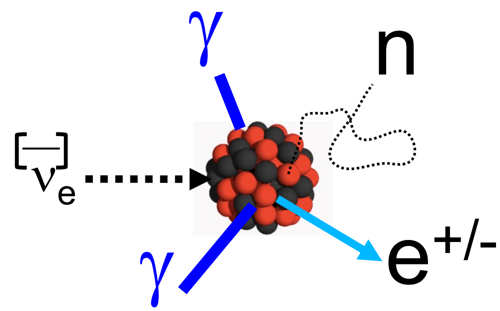
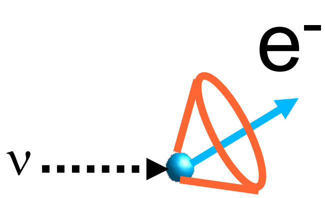
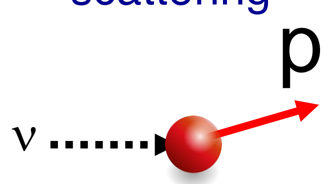
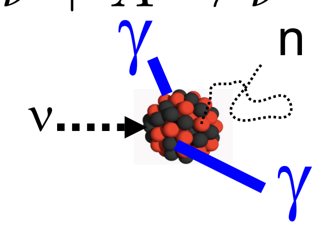
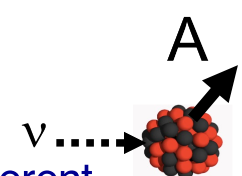


Neutrino interactions in the SNB energy range



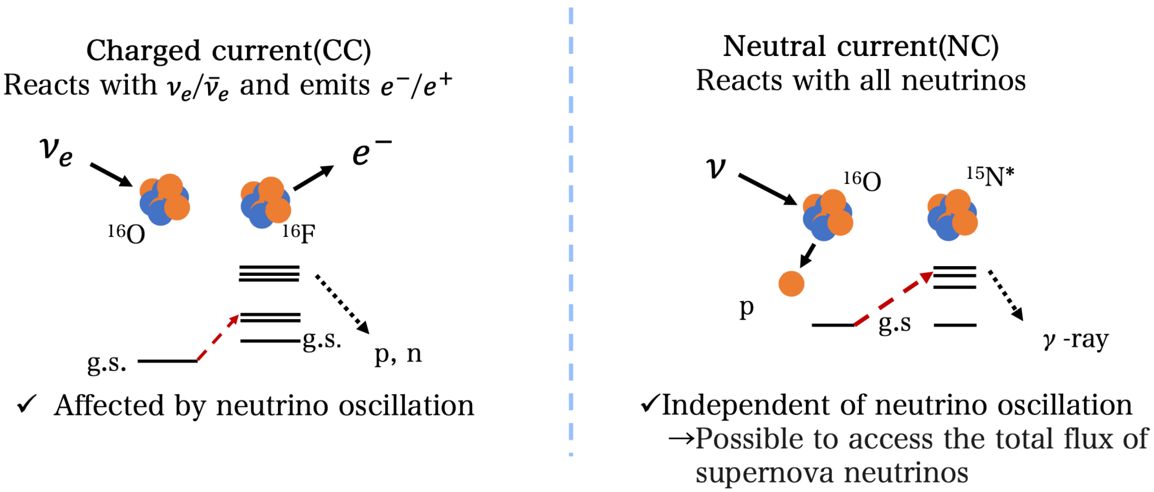
Neutrino interactions in the SNB energy range

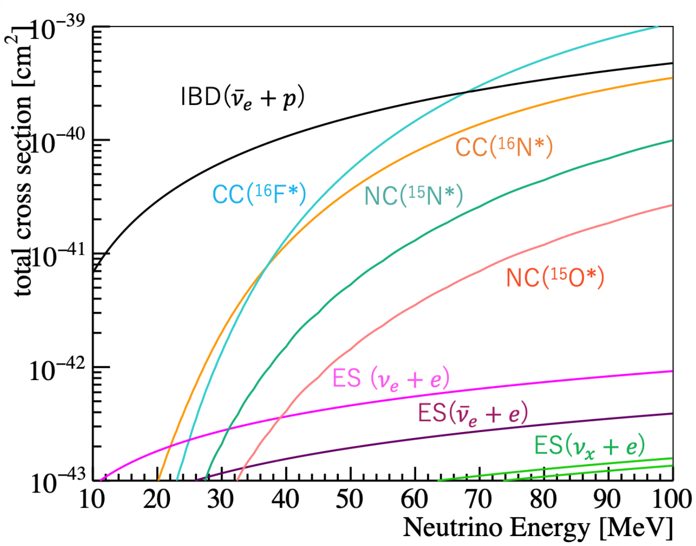
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing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

Generally poorly understood!

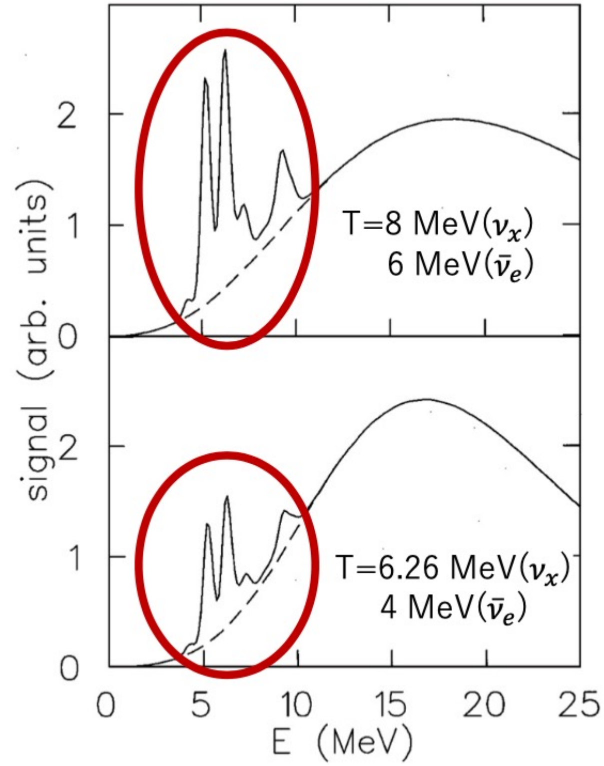
For example: **CC and NC interactions on oxygen**

F. Nakanishi, ORNL workshop 2023





Observables depend on nuclear structure

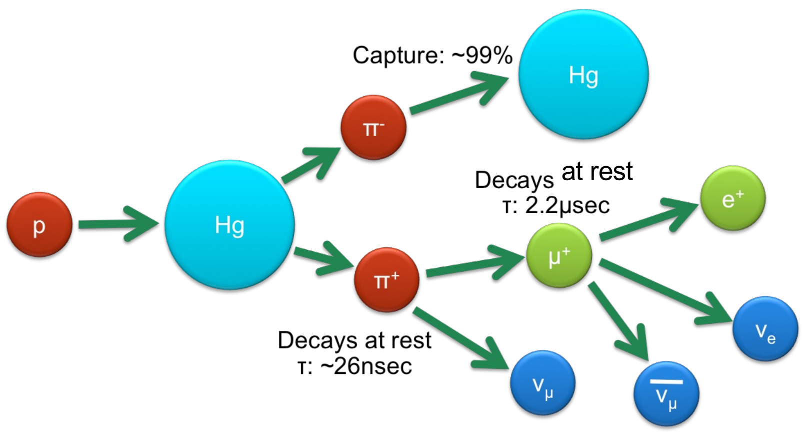


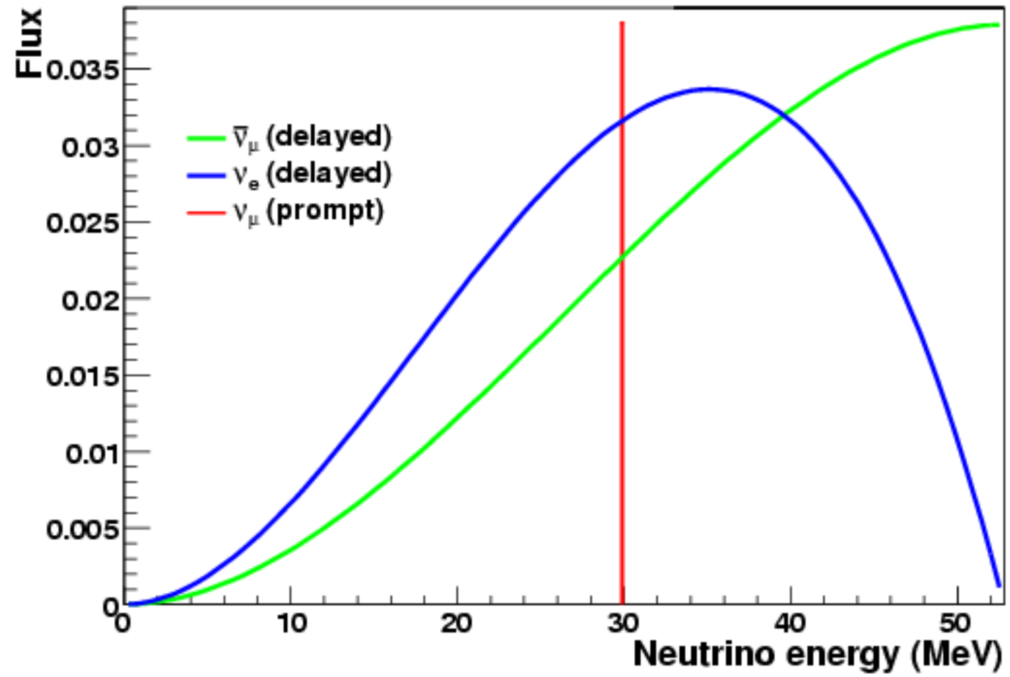
Expected energy spectrum in SK from K. Langanke et al.

Newer calcs by Nakazato et al.

Best to ***measure*** it!

Stopped-Pion (πDAR) Neutrinos





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

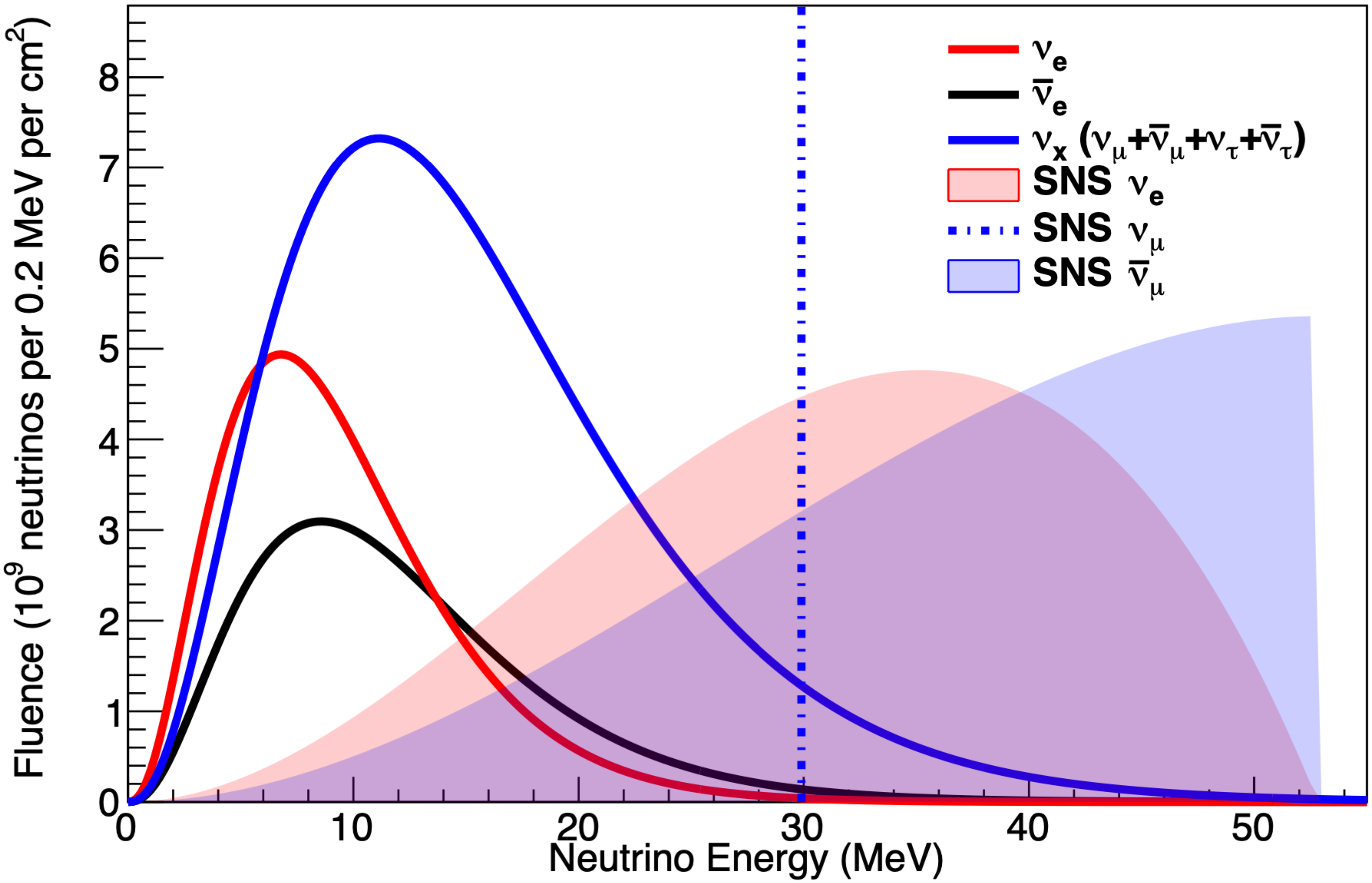
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

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

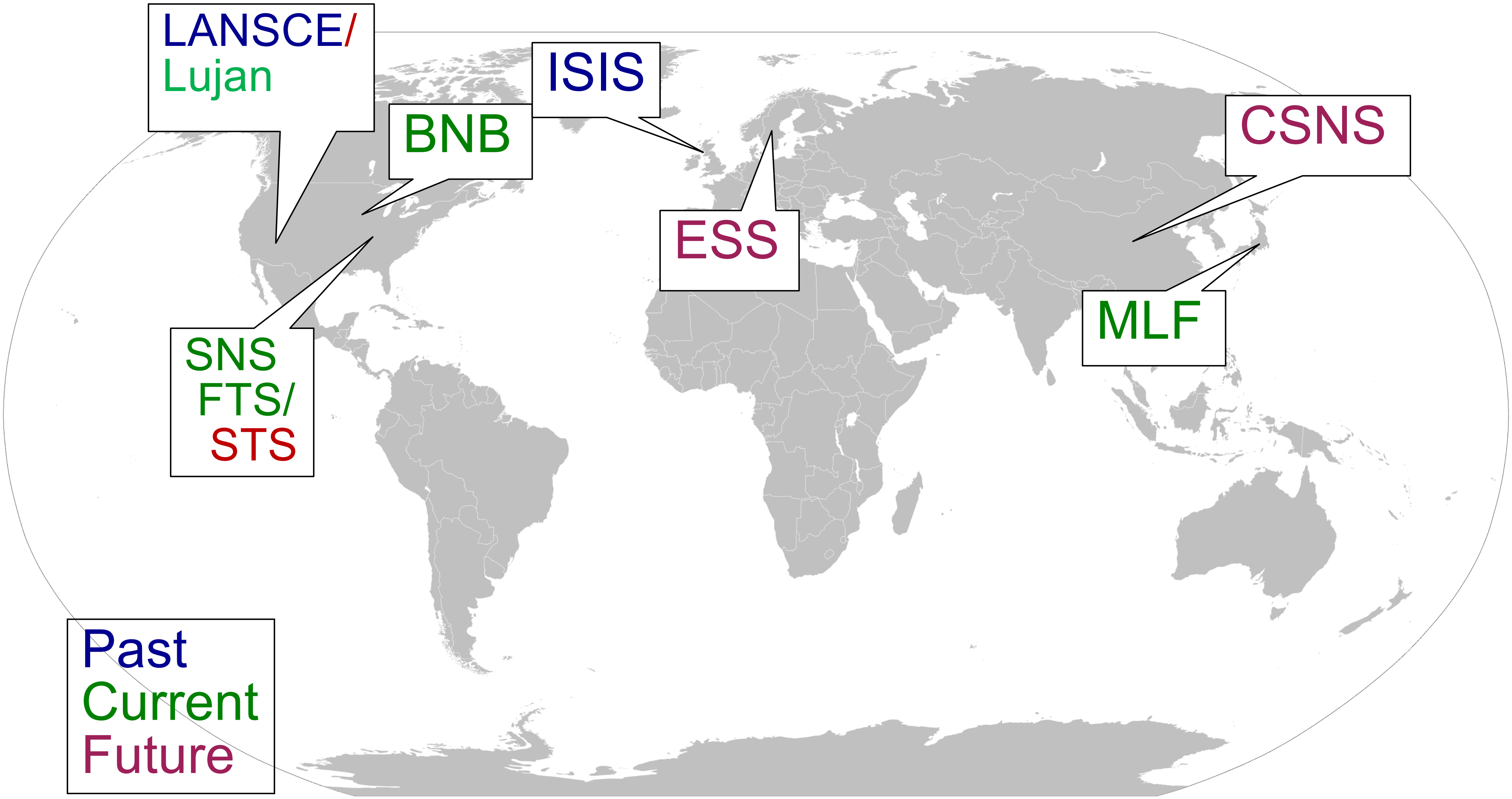
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

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



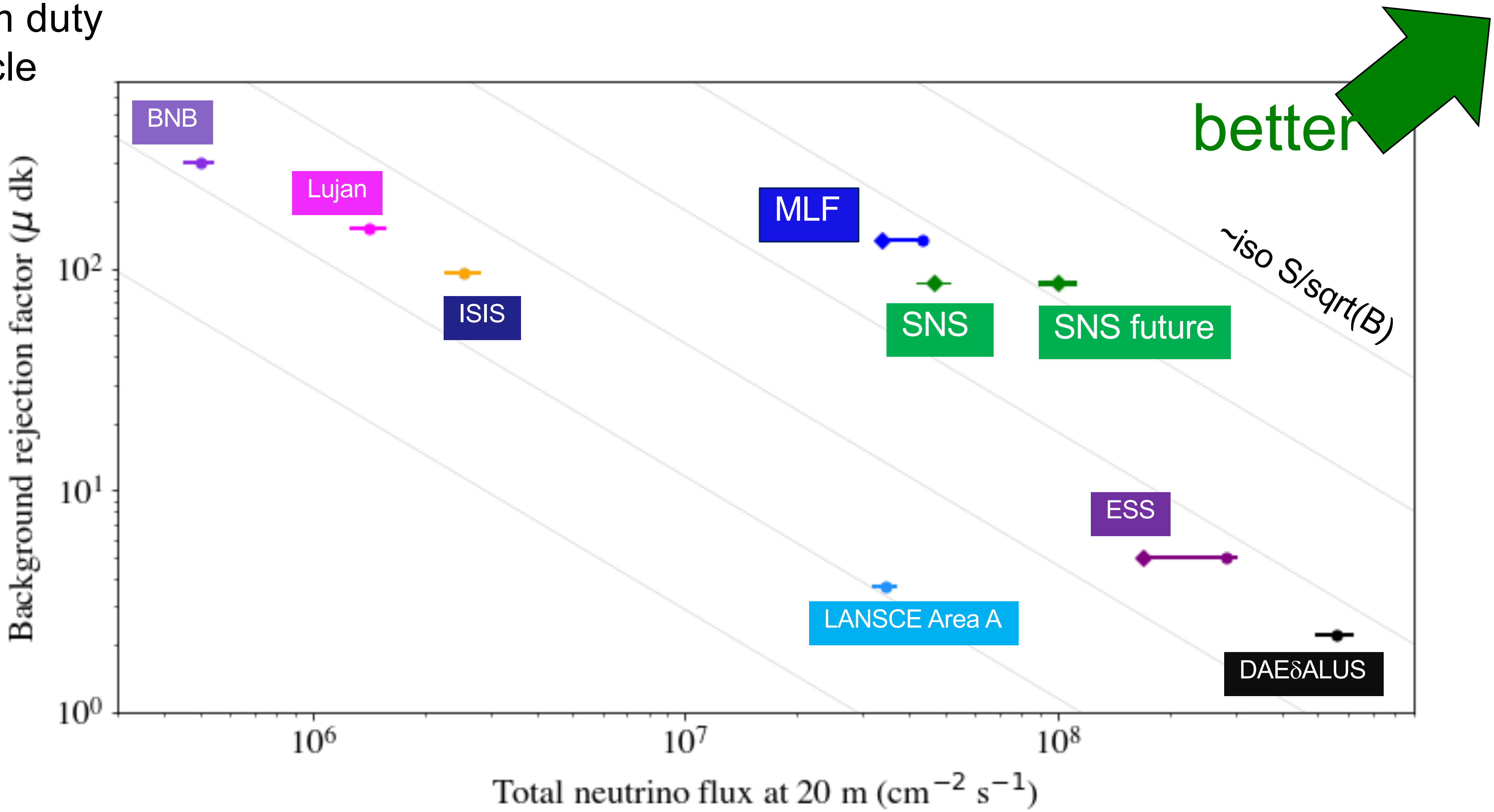
- understanding of SN processes & detection
- understanding of weak couplings (g_A quenching) & nuclear transitions

Stopped-Pion Neutrino Sources Worldwide



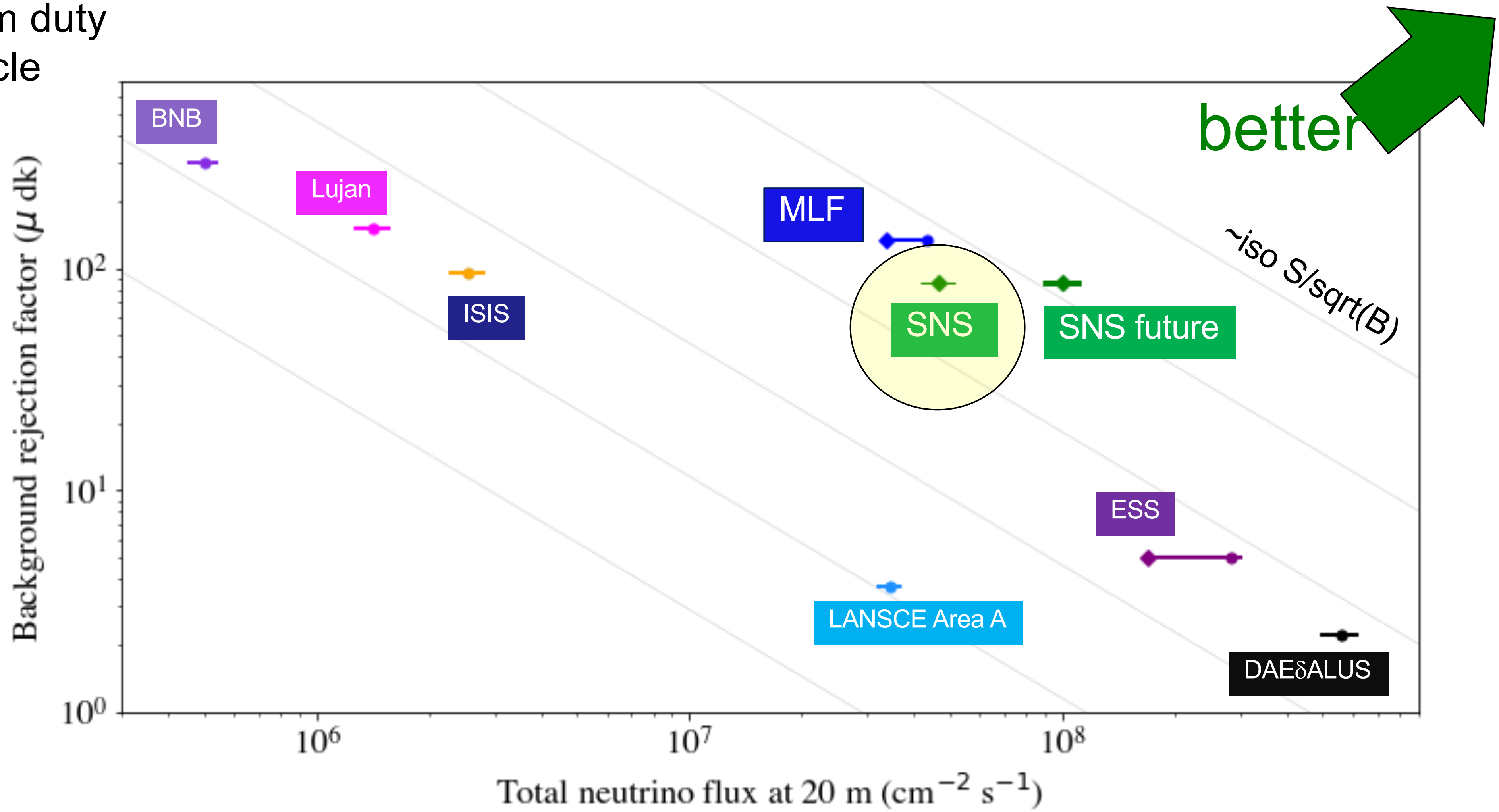
Comparison of pion decay-at-rest ν sources

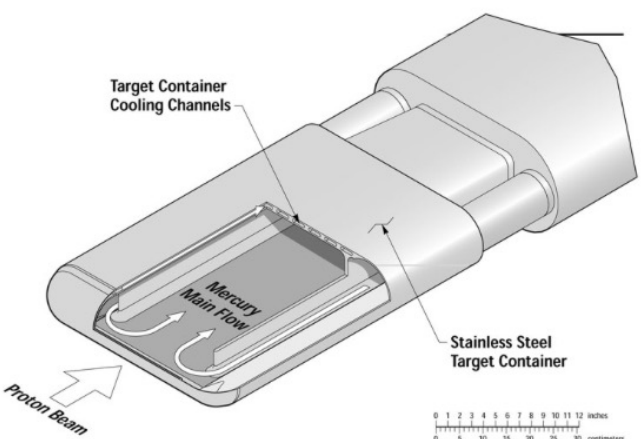
from duty cycle



Comparison of pion decay-at-rest ν sources

from duty cycle





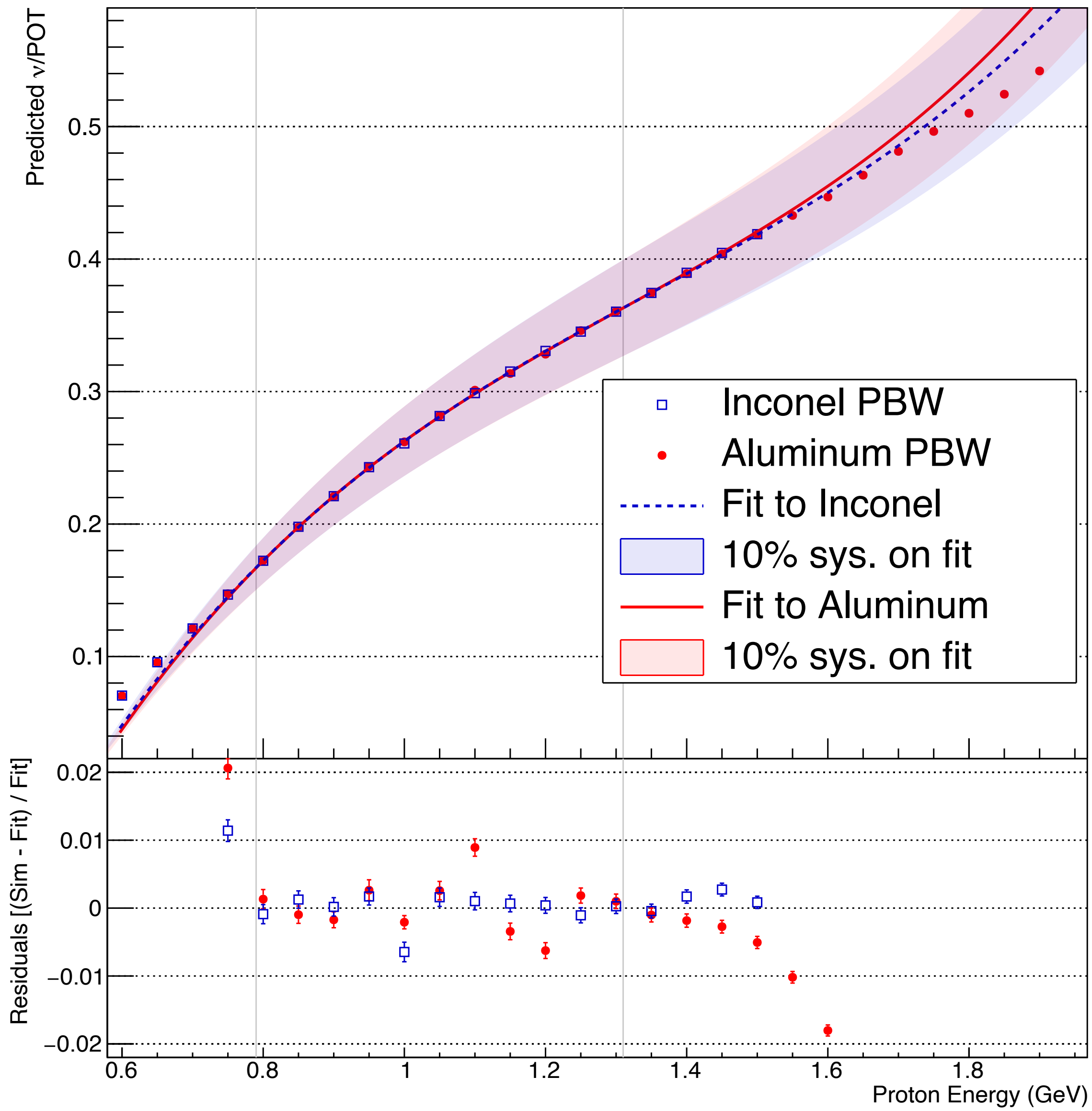
Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

Fluxes depend on proton energy as well as power

G4 QGSP_BERT, validated vs HARP/HARP-CDP

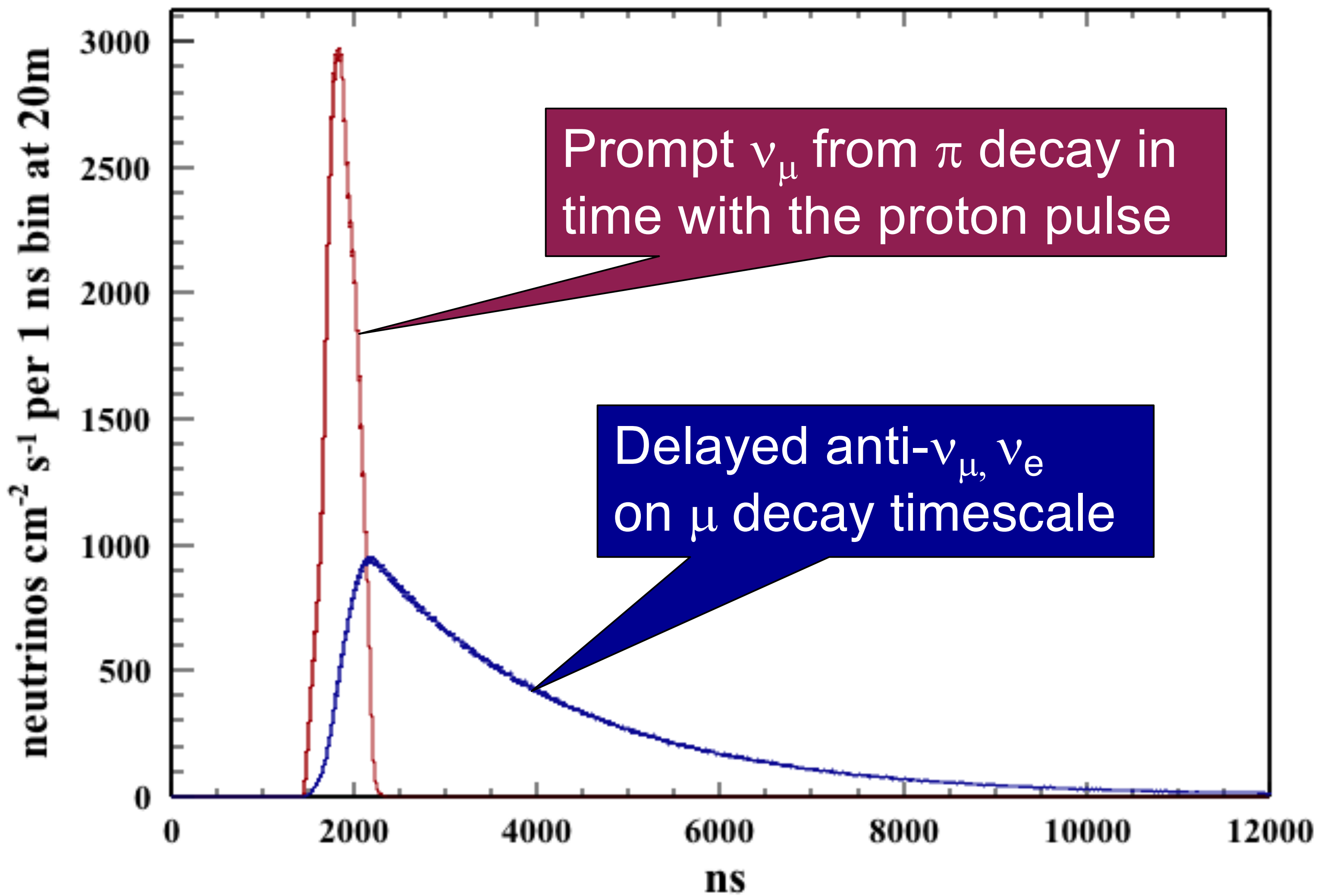
Total neutrinos per proton (all 3 flavors)



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

Time structure of the SNS source

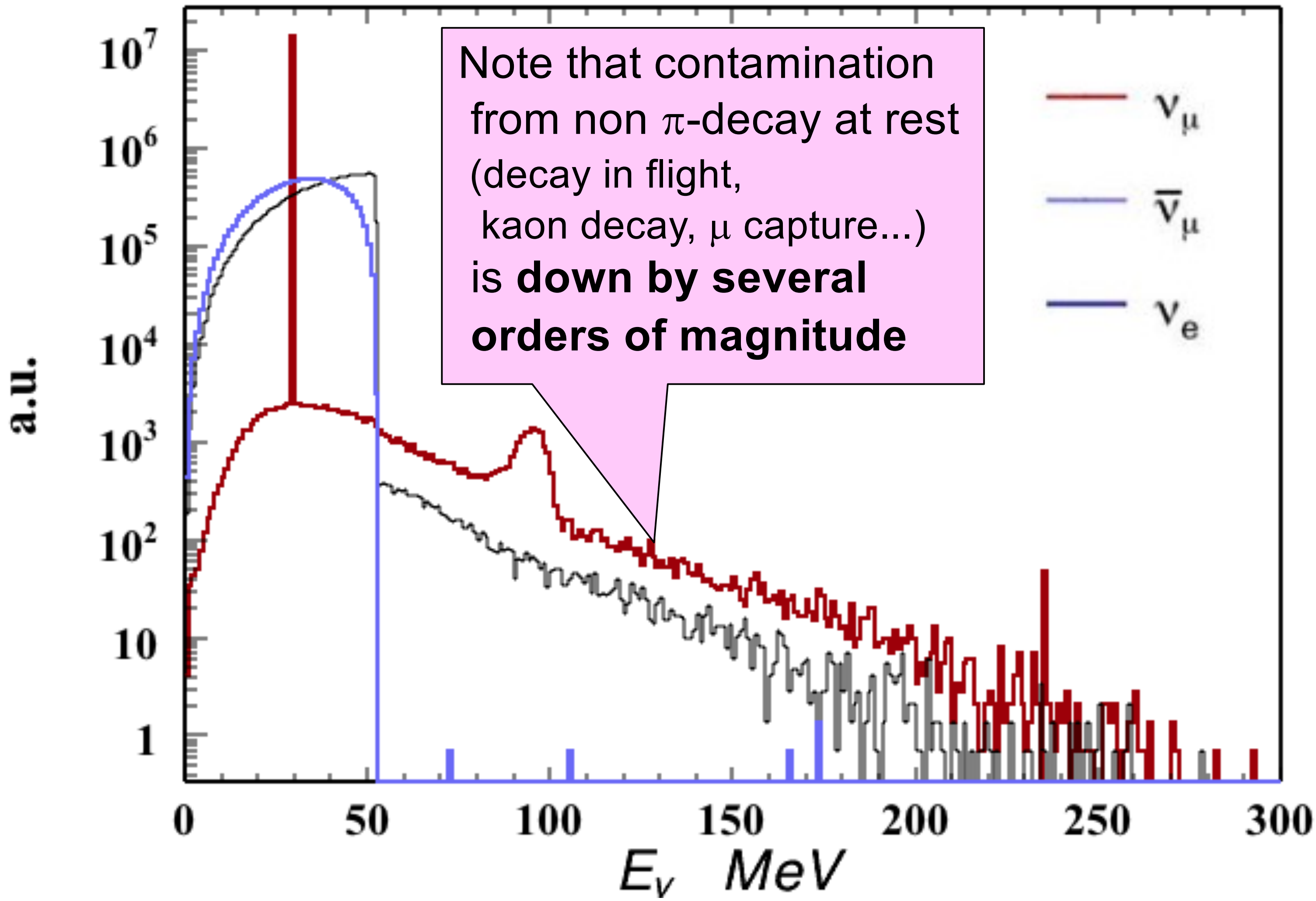
60 Hz *pulsed* source



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

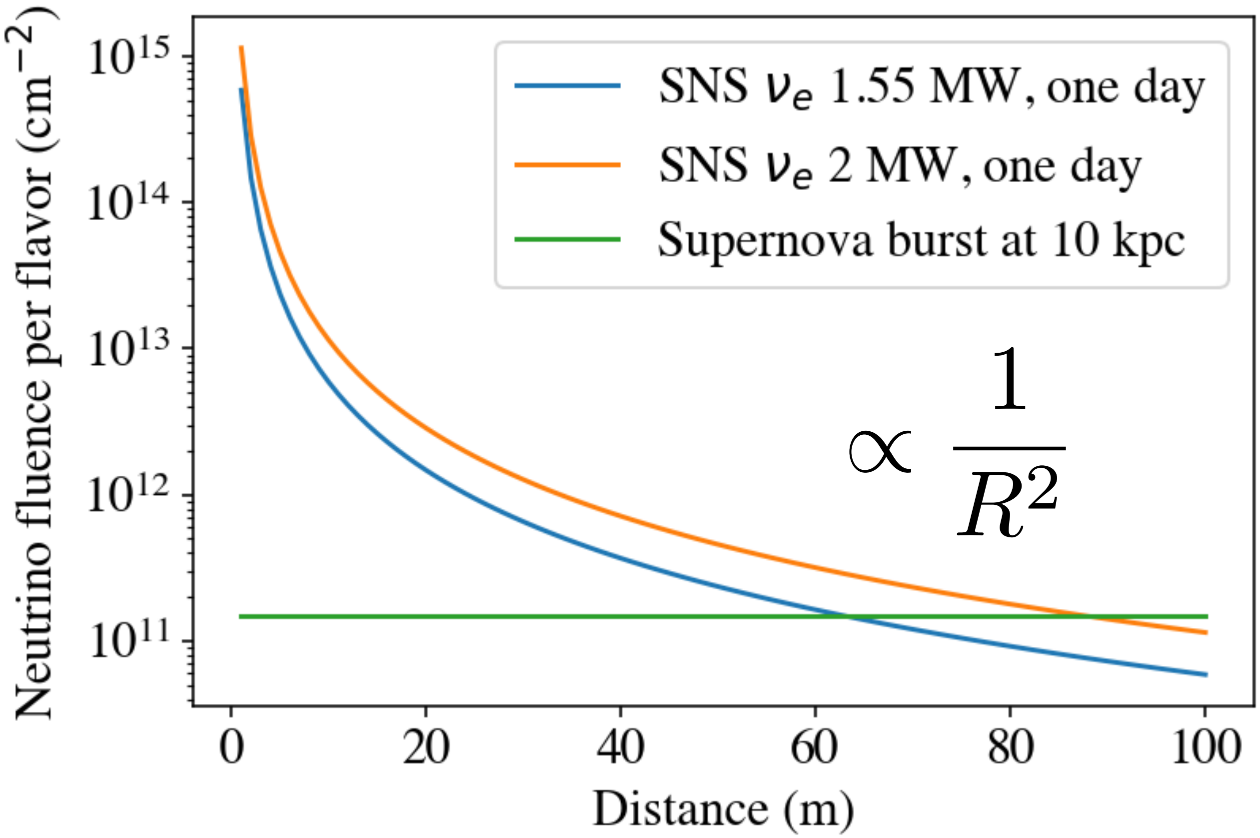
The SNS has **large, extremely clean** stopped-pion ν flux

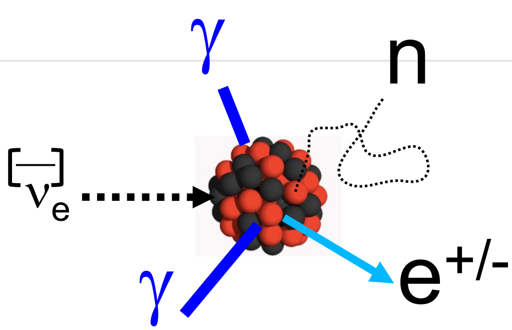
0.08 neutrinos per flavor per proton on target



SNS flux (1.4 MW):
430 x 10^5 ν/cm^2/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

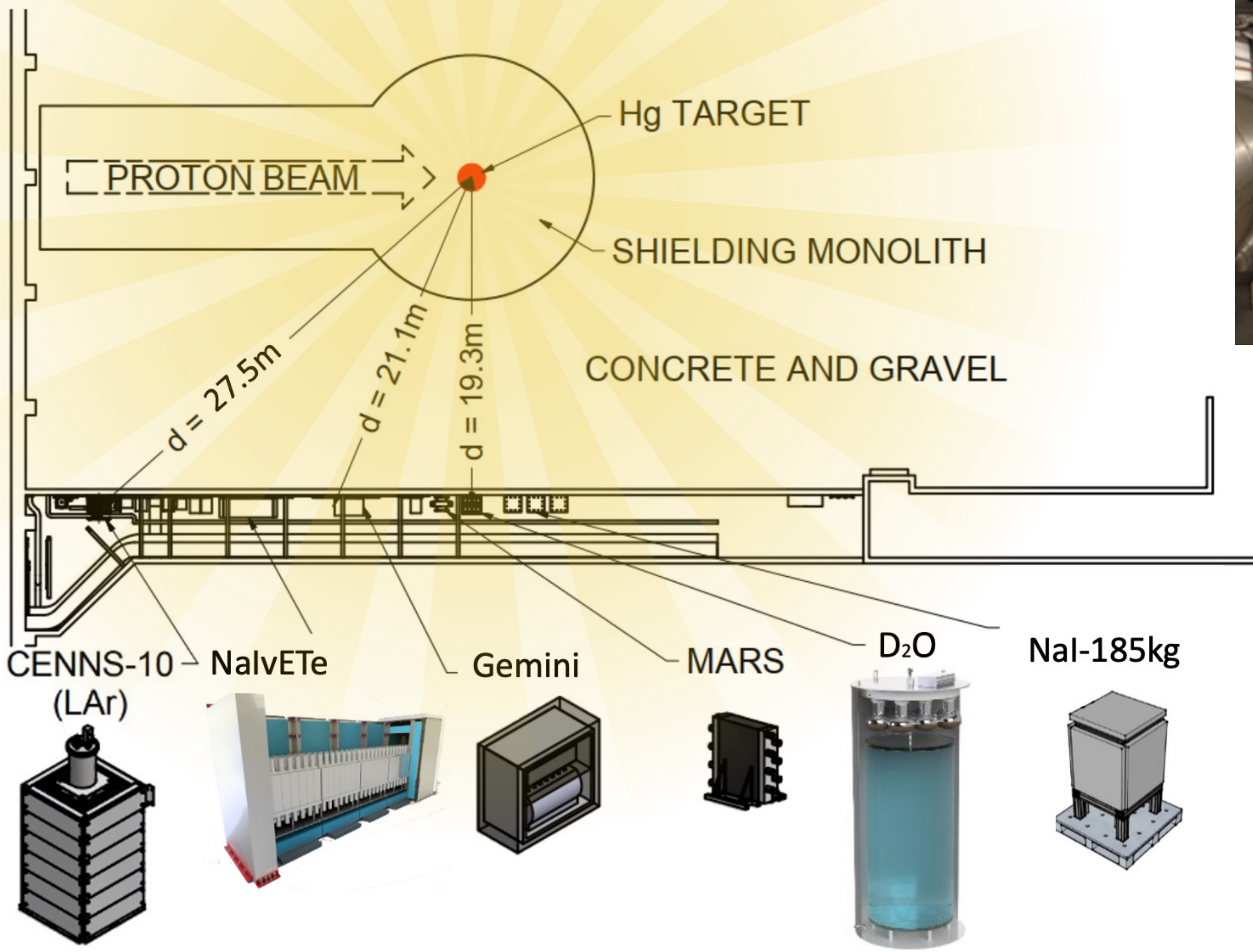
The COHERENT collaboration

http://sites.duke.edu/coherent

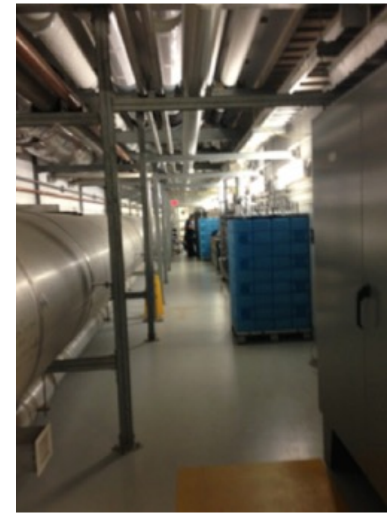
~100 members,
25 institutions
5 countries

Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)



View looking down "Neutrino Alley"

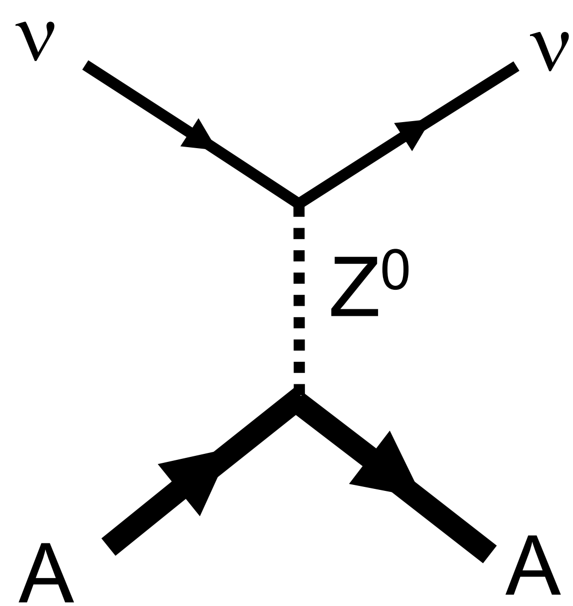


Future:
large LAr
LArTPC
light water
CryoCsI
neon
...

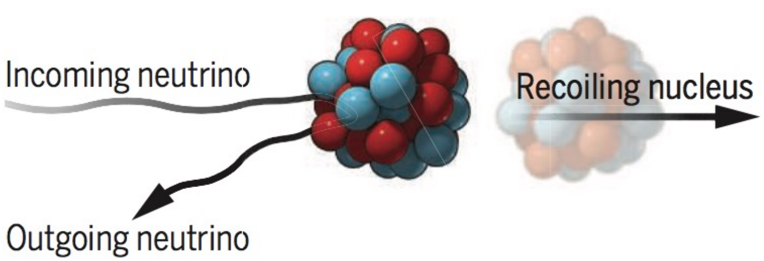
Isotropic ν glow from Hg SNS target

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

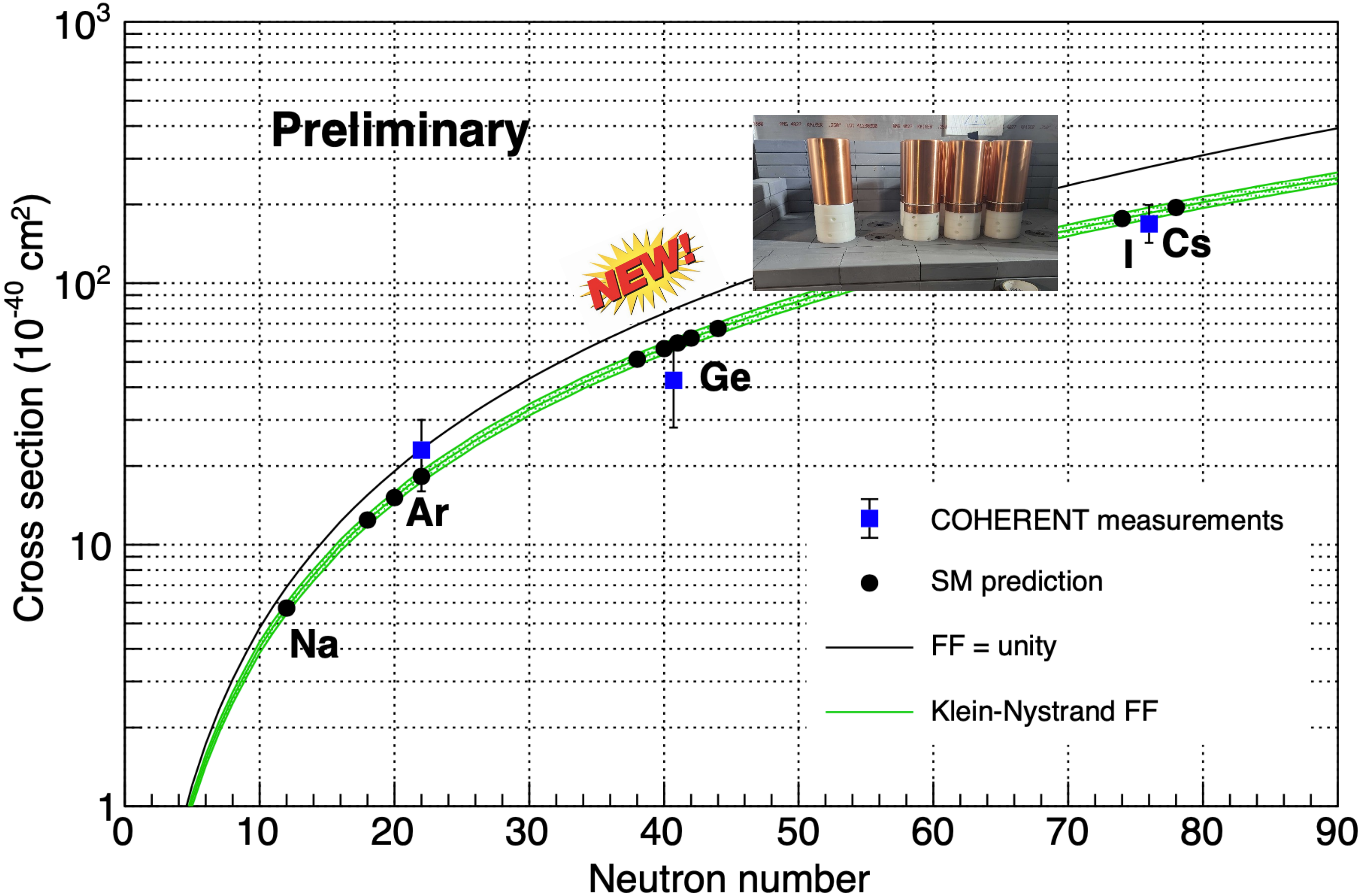


Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

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:

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Jason Newby
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Kate Scholberg
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Workshop sponsors:

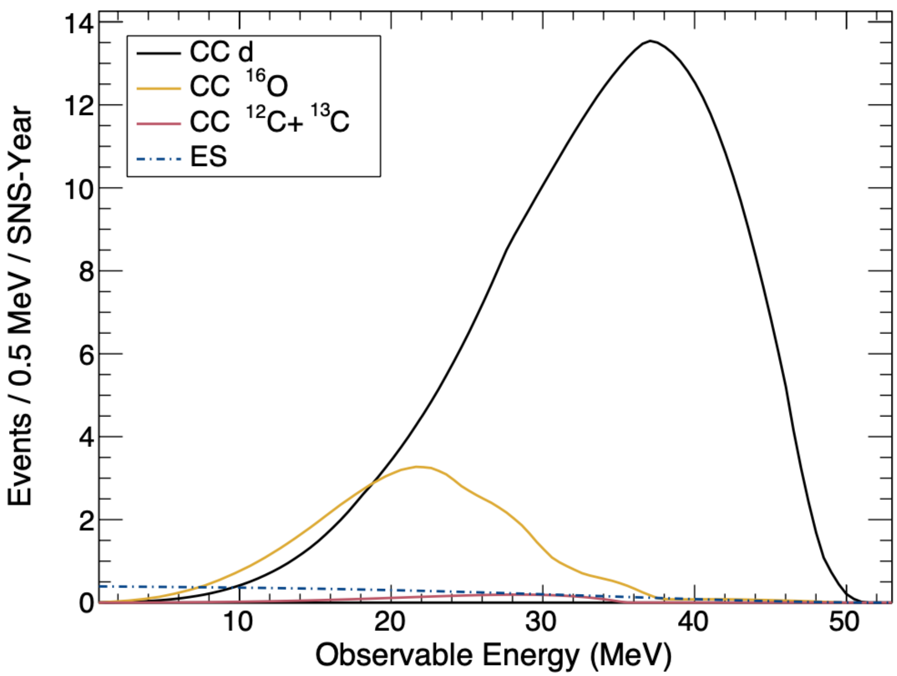
Department of Energy HEP US-Japan program
ORNL

Heavy water detector in Neutrino Alley

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

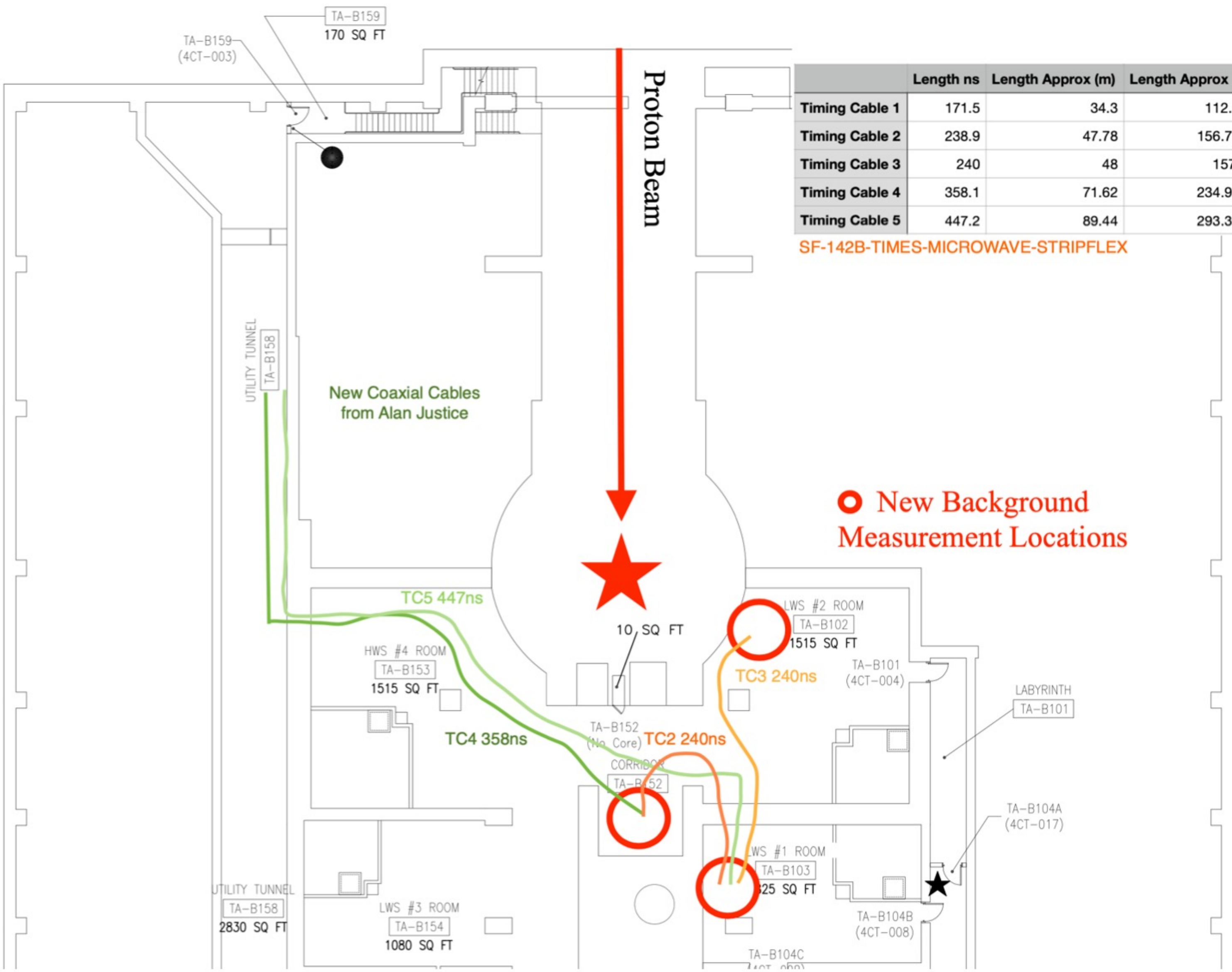
$$\nu_e + \mathrm{d} \longrightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$$

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



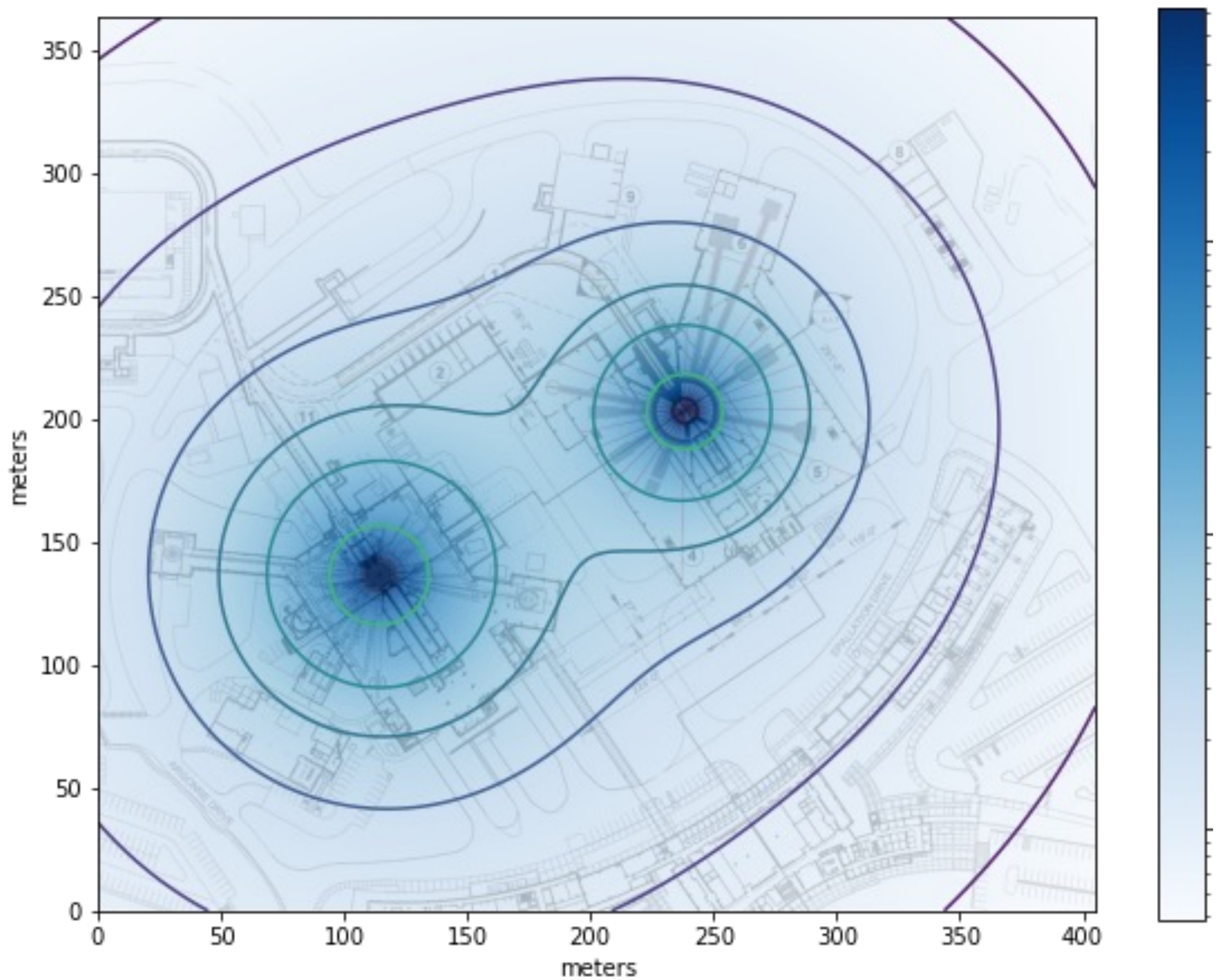
	Length ns	Length Approx (m)	Length Approx (ft)
Timing Cable 1	171.5	34.3	112.504
Timing Cable 2	238.9	47.78	156.7184
Timing Cable 3	240	48	157.44
Timing Cable 4	358.1	71.62	234.9136
Timing Cable 5	447.2	89.44	293.3632

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

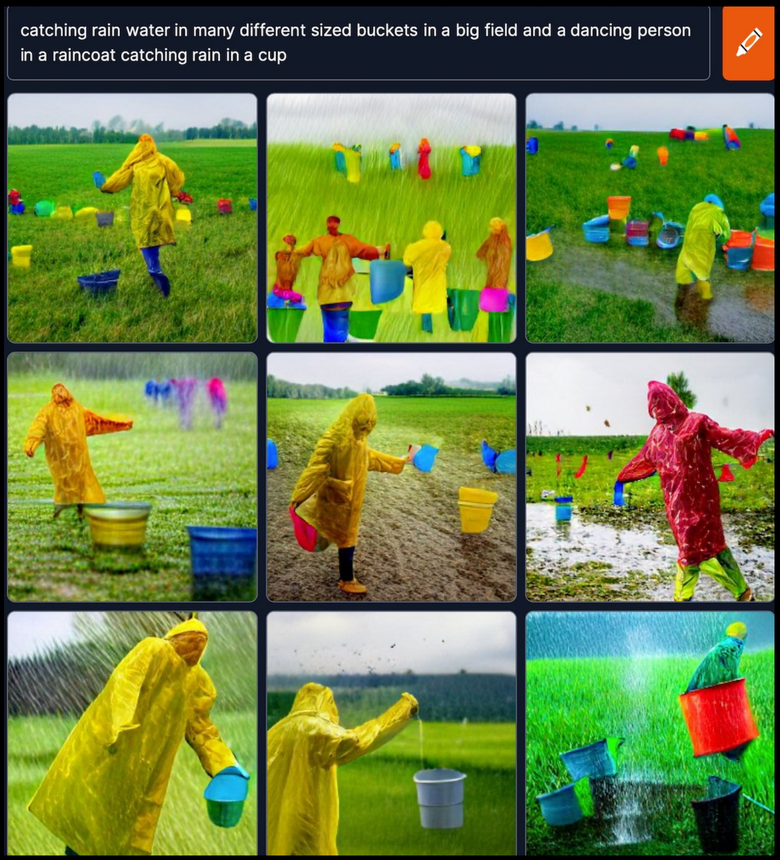
- vast science to be gained!
- we need to understand ν interactions to get the most out of a CCSN observation

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!

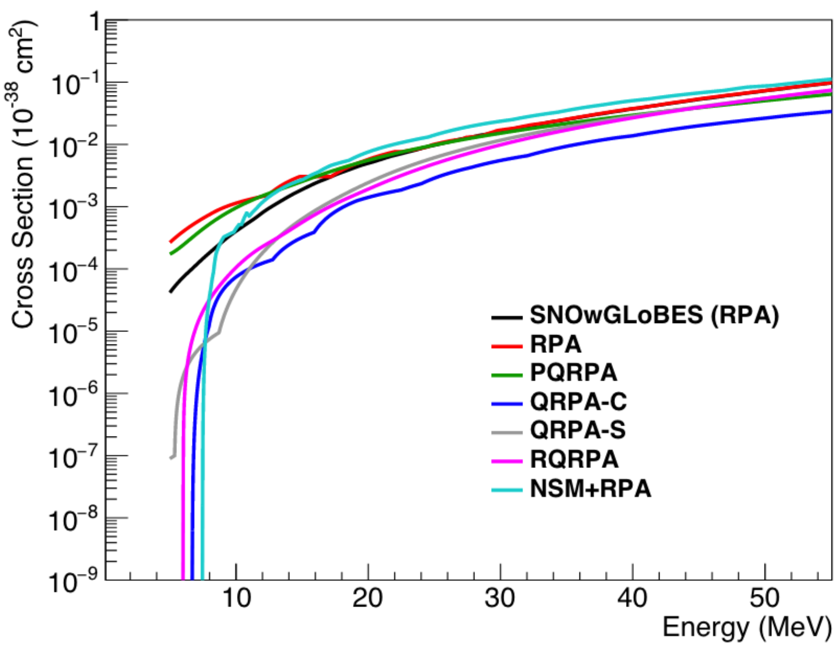
(and measure xscns)

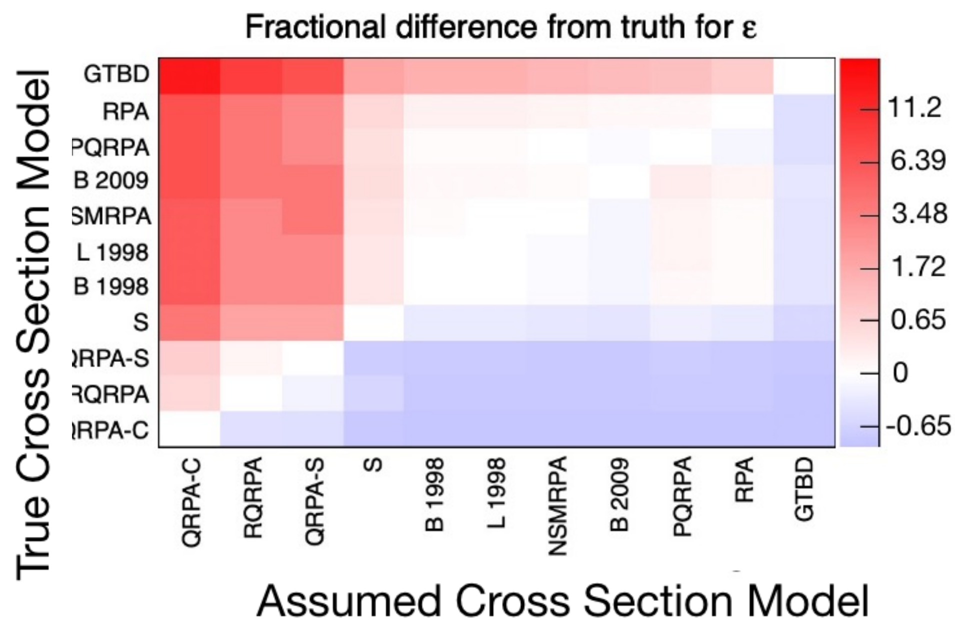
Especially interesting to measure **electron neutrino interactions on on argon in the few tens of MeV range**

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

$$\text{NC} \quad \nu_x + {}^{40}\text{Ar} \rightarrow \nu_x + {}^{40}\text{Ar}^*$$

- critical to understand (differential) cross sections for supernova physics in DUNE
- large theoretical uncertainties on cross sections
- **no** existing measurements





Impact of cross-section uncertainties on supernova neutrino spectral parameter fitting in the Deep Underground Neutrino Experiment

DUNE Collaboration • A. Abed Abud (CERN) et al. (Mar 29, 2023)

Published in: *Phys.Rev.D* 107 (2023) 11, 112012 • e-Print: 2303.17007 [hep-ex]

More soon from COHERENT!