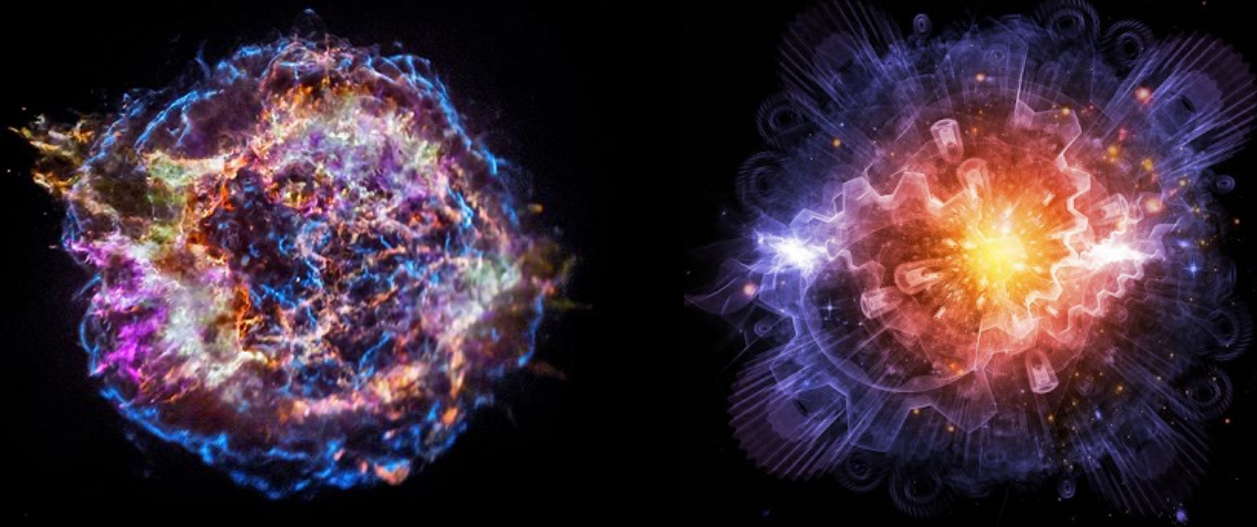


Challenges in Supernova Neutrino Detection

John Beacom, The Ohio State University



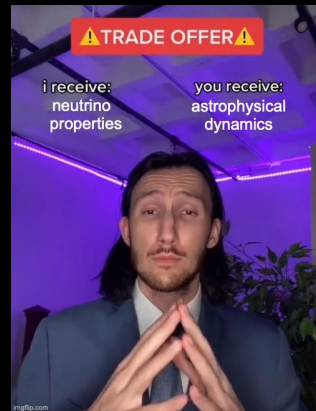
The Ohio State University's Center for Cosmology and AstroParticle Physics



Supernovae and Neutrinos

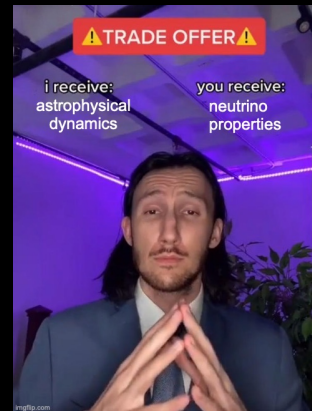
To an astronomer, a supernova is:

- An essential astrophysical process
- Gateway to MMA (multi-messenger astronomy)
- Dominated by and complicated by neutrino physics



To a physicist, a supernova is:

- An unmatched source of neutrinos
- Gateway to BSM (beyond standard model) physics
- Dominated by and complicated by astrophysics



Huge discovery opportunities if we can do both

Outline

Theoretical Overview

Milky Way Burst

Nearby Galaxies Mini-Bursts (in bonus slides)

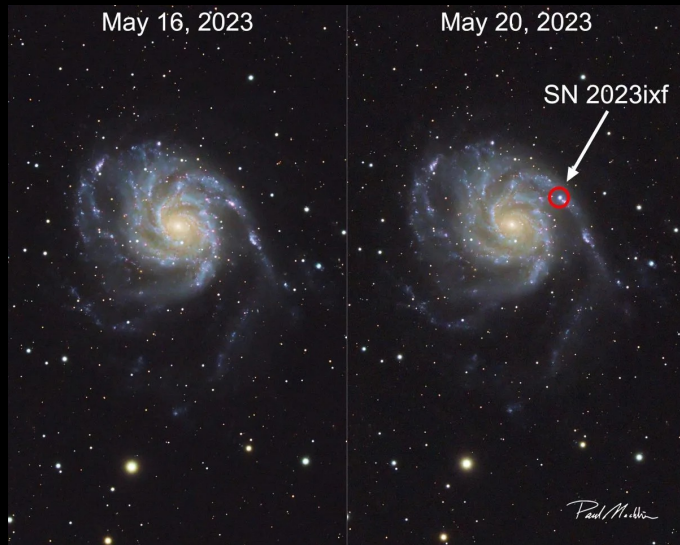
Diffuse Supernova Neutrino Background (DSNB)

Long-Term Strategy

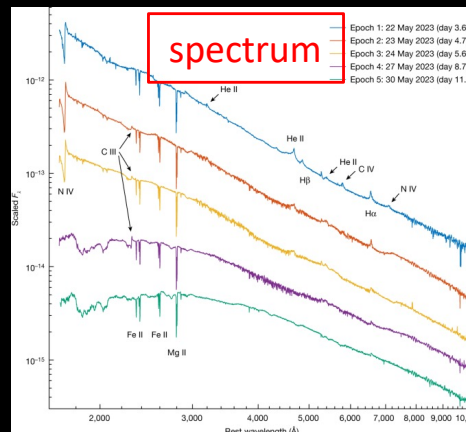
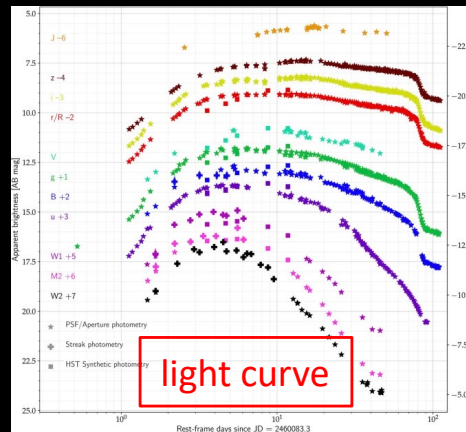
Theoretical Overview

Supernova!

SN 2023ixf in M101 galaxy
~7 Mpc distance



Macklin (2023)



Zimmerman (2024)

Key characteristics of SNe:
Rare (~1/century/galaxy)
Energetic (often $>10^{49}$ erg)
Transient (~months)
Observable (peaks in optical)
Resolvable (eventually)

But SNe are complex, with details of their power sources shrouded by dense matter

Why Are Supernovae Interesting?

What happens?

What do they create?

What do they destroy?

What do they reveal?

What reach beyond the lab?



Also, explosions are cool

Basic Idea of Core Collapse

Early idea:

“Neutrino Theory of Stellar Collapse,”

Gamow and Schoenberg (1941)

Core collapses (emitting neutrinos)

~~Core forms white dwarf~~

Envelope expands (emitting light)

Modern idea:

Core forms neutron star or black hole

Always emits neutrinos

Usually emits light

Might emit gravitational waves

Simple estimates:

$$E_{\text{total}} \sim 3 \times 10^{53} \text{ erg}$$

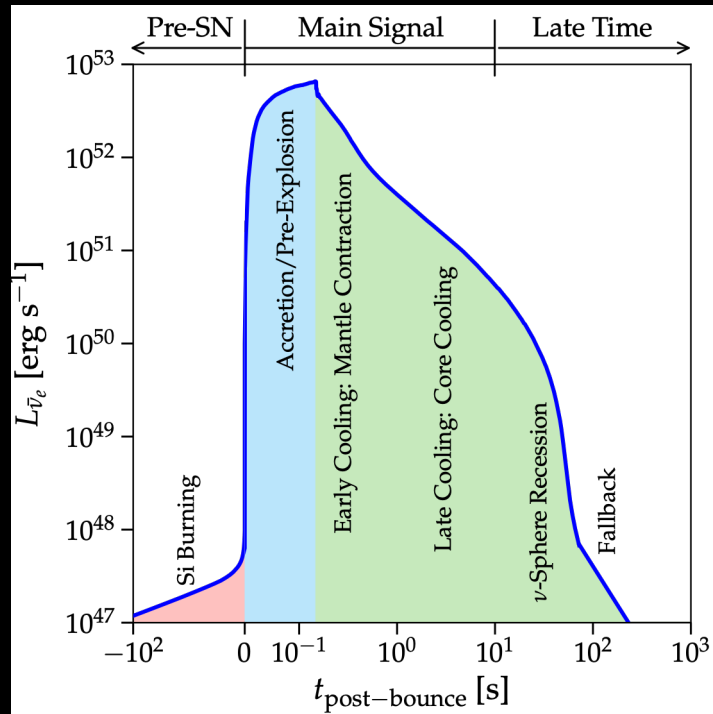
$$\langle E_{\nu} \rangle \sim 100 \text{ MeV in core}$$

$$\langle E_{\nu} \rangle \sim 10 \text{ MeV at surface}$$

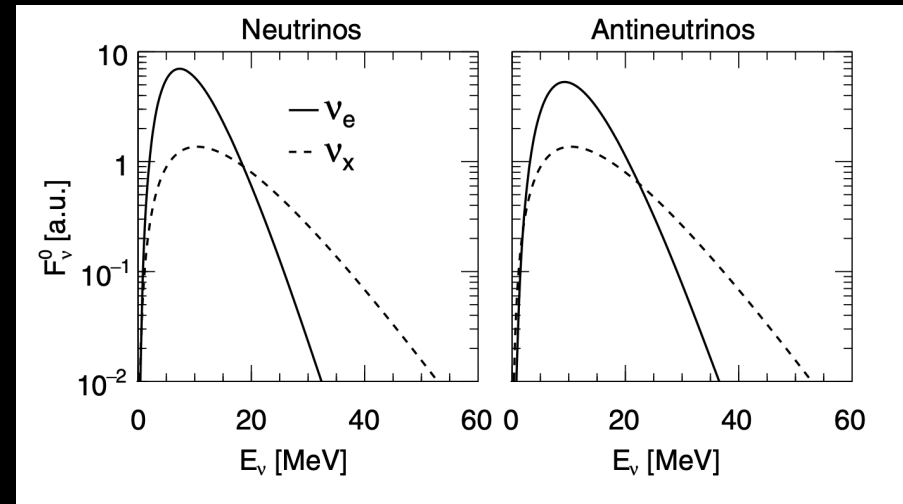
diffusion over seconds

Summarized in 2206.12426

Basic Neutrino Profiles and Spectra



Li, Roberts, and Beacom (2021)

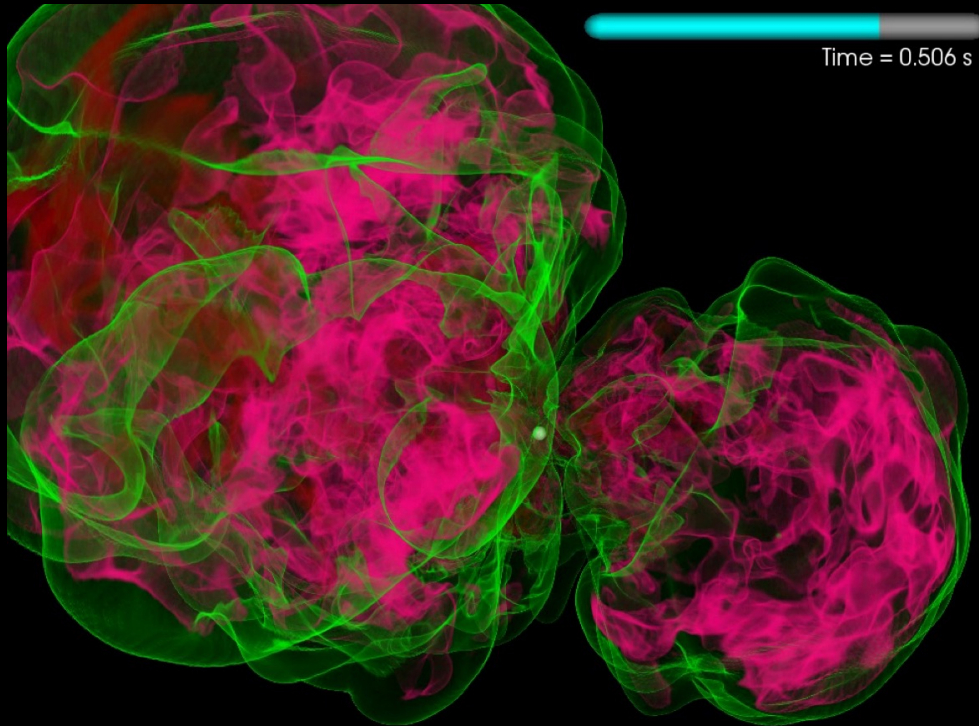


Capozzi, Dasgupta, Mirizzi (2018)

$\langle E \rangle$ increasing for ν_e , anti- ν_e , ν_x

Even moderate precision could be decisive for testing the astrophysics

Core-Collapse Simulations



Exploding 3d model, Burrows and Vartanyan (2021)

Extremely complicated problem

Higher dimensionality important for realism, explosions

Duration of calculated time profile is limited

Fraction of failed supernovae is likely appreciable

We do not yet have adequate models to compare with data

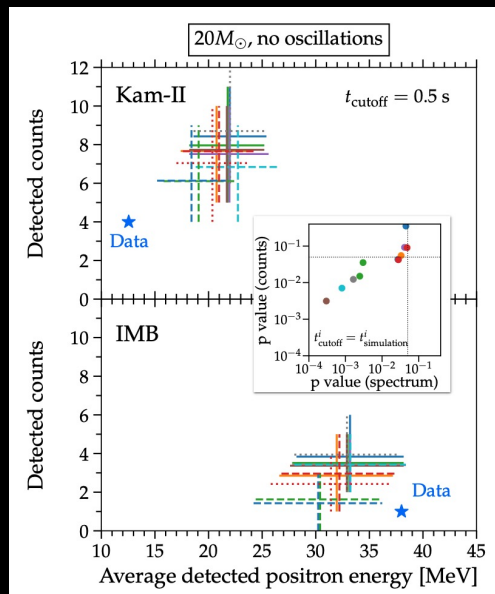
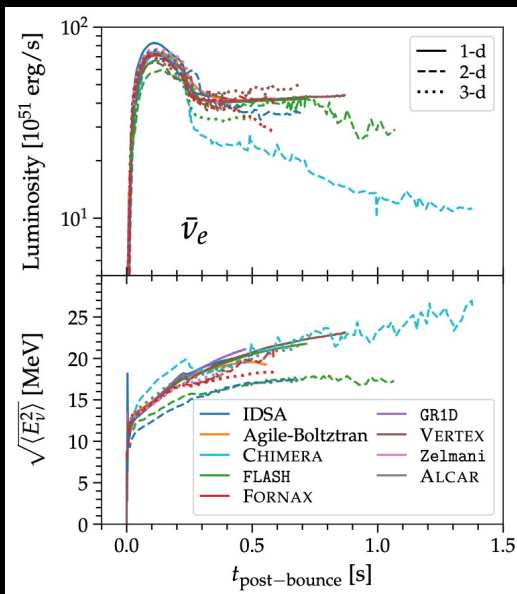
Comparison of Simulations to SN 1987A

Old Data, New Forensics: The First Second of SN 1987A Neutrino Emission

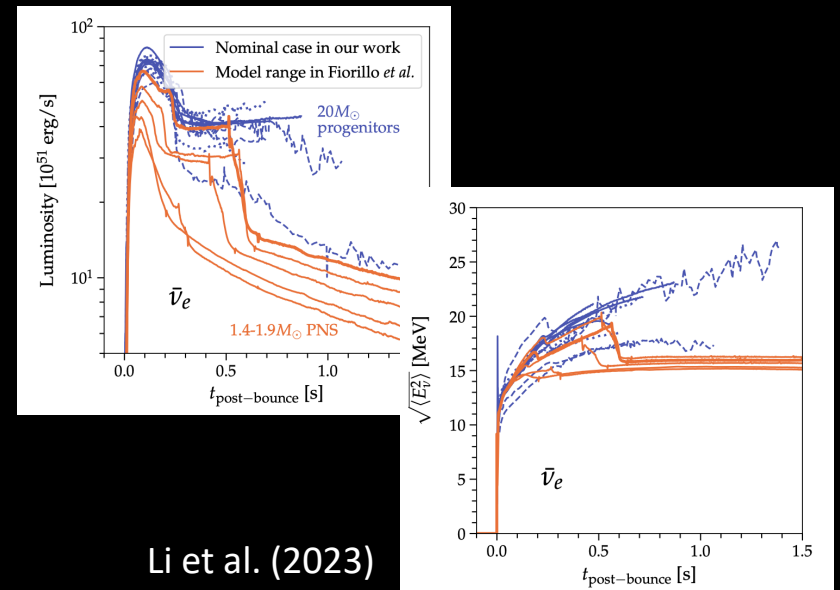
Shirley Weishi Li ^{1,2,*}, John F. Beacom ^{3,4,5,†}, Luke F. Roberts ^{6,‡} and Francesco Capozzi ^{7,8,§}

2023

Models *generally agree* with each other
Models *generally disagree* with data



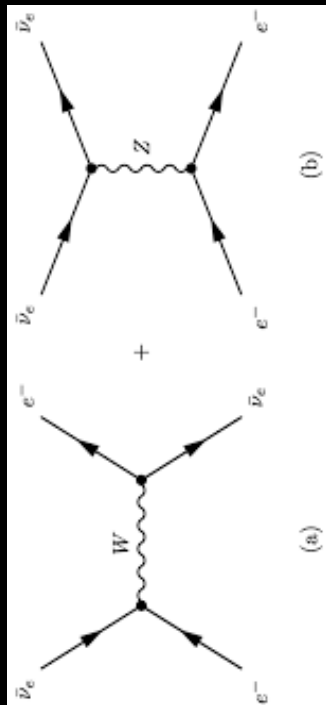
Criticized by Fiorillo et al. (2023), but they use non-exploding 1d models that fall *far below* more realistic 2d and 3d models



Li et al. (2023)

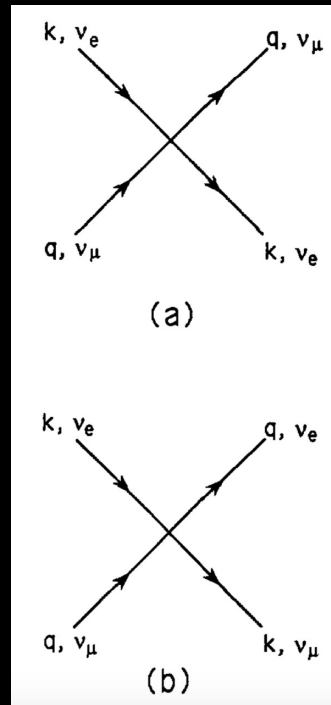
Neutrino Mixing in Matter

Neutrino-Electron



MSW effect

Neutrino-Neutrino



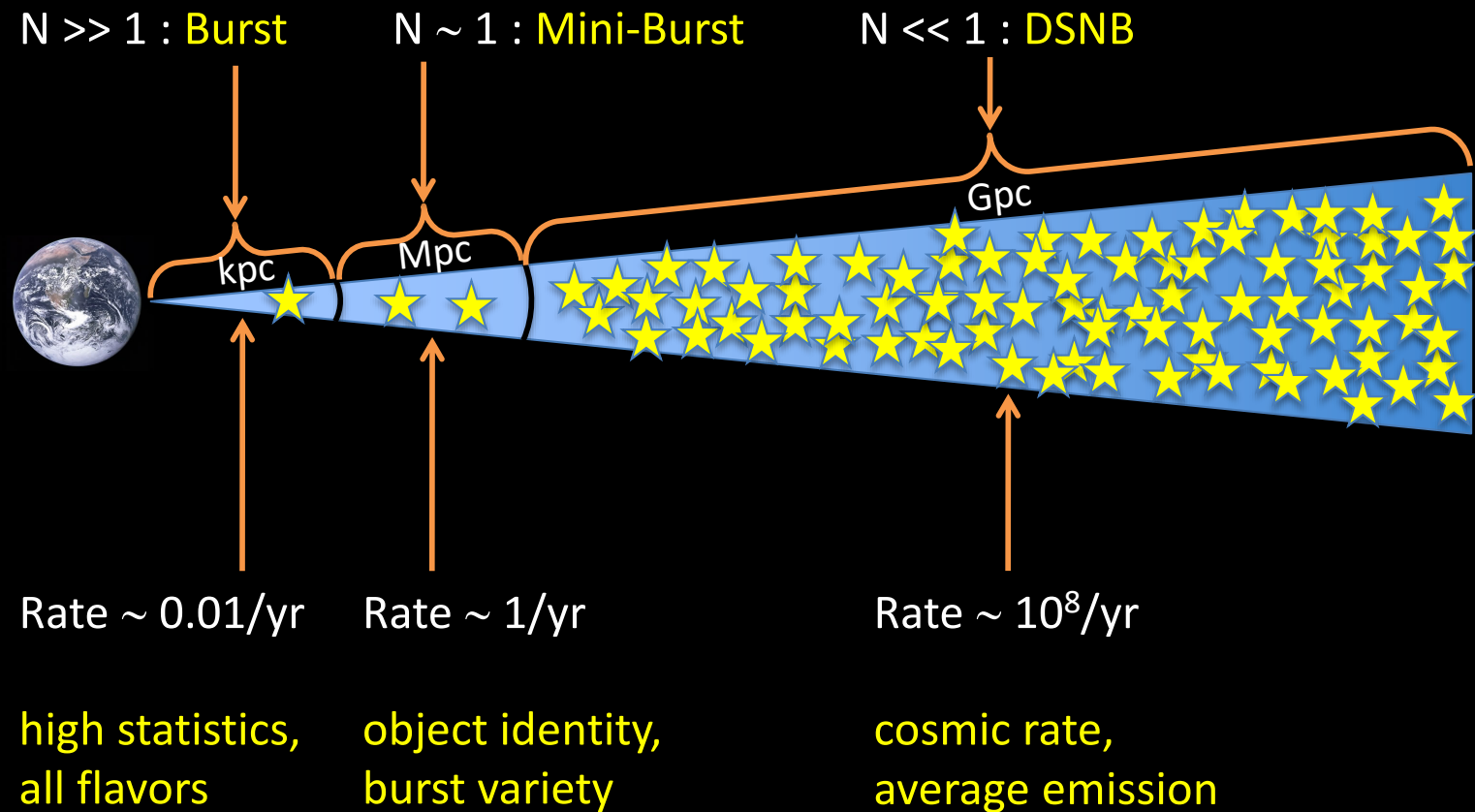
Pantaleone (1992)

Very complex
consequences for mixing
and maybe for the
supernova explosion!

*Unsolved problem,
beyond reach of the lab*

This makes the predictions
much more uncertain but is
a huge scientific opportunity

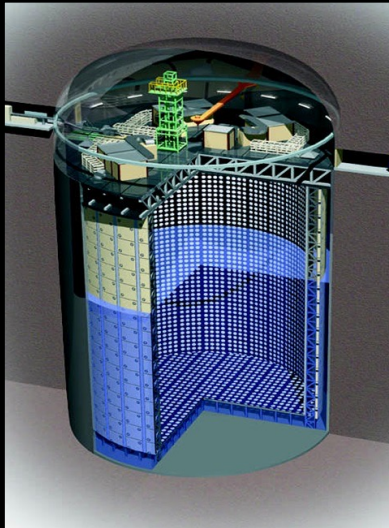
How Can We Detect Core Collapse Neutrinos?



Milky Way Burst

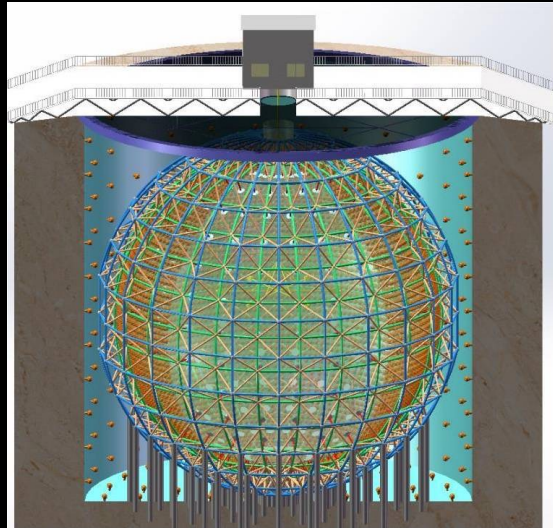
Primary Detectors

Super-K Gd



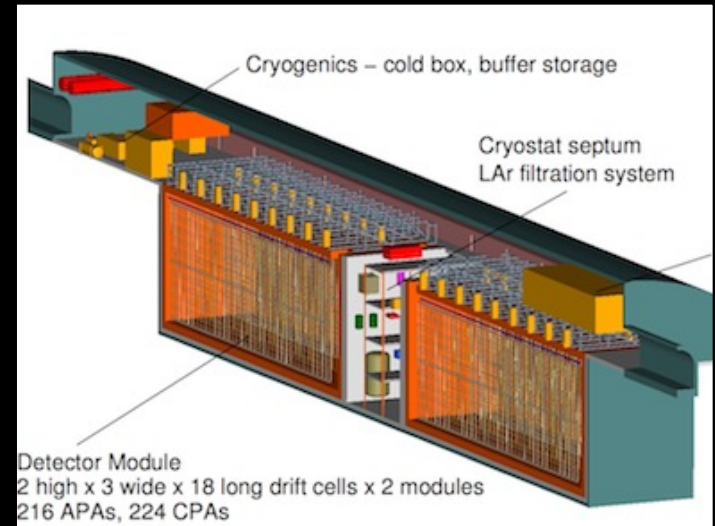
32 kton water+Gd
running (Japan)

JUNO



20 kton scintillator
started 2025 (China)

DUNE



34 kton liquid argon (first stage)
starts ~2030 (United States)

+

Hyper-K (260 kton) starts 2028

Yields for a Milky Way Burst

Super-Kamiokande (32 kton water)

$\sim 10^4$ inverse beta decay on free protons

$\sim 10^2$ CC and NC with oxygen nuclei

$\sim 10^2$ neutrino-electron elastic scattering

Best for $\bar{\nu}_e$

$\sim 10\times$ for HK

JUNO (20 kton mineral oil)

$\sim 10^4$ inverse beta decay on free protons

$\sim 10^3$ neutron-proton elastic scattering

$\sim 10^2$ CC and NC with carbon nuclei

$\sim 10^2$ neutrino-electron elastic scattering

Best for ν_x

IceCube (10^6 kton water)

Burst is increase over background rate

Possibility of precise timing information

And many other detectors

DUNE (34 kton liquid argon)

$\sim 10^3$ CC and NC with argon nuclei

$\sim 10^2$ neutrino-electron elastic scattering

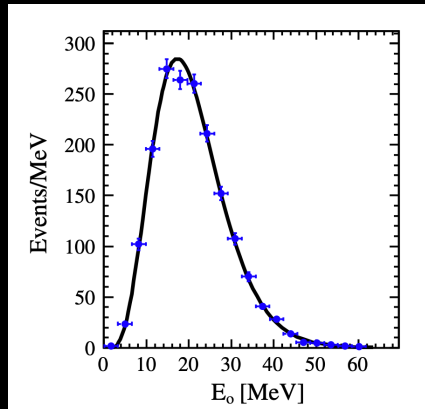
Best for ν_e

Spectrum Measurements

Best for anti- ν_e

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

Vogel, Beacom (1999)
Strumia, Vissani (2003)

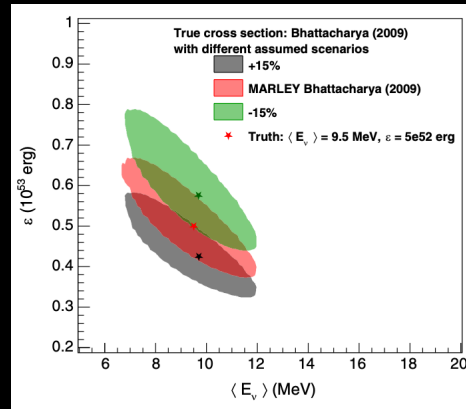


Li et al. (2019)

Best for ν_e

$$\nu_e + Ar \rightarrow e^- + X$$

MARLEY (Gardiner)

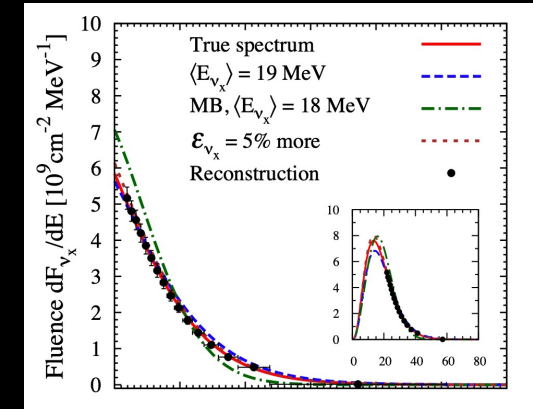


DUNE (2023)

Best for ν_x

$$\nu + p \rightarrow \nu + p$$

Beacom, Farr, Vogel (2002)



Dasgupta, Beacom (2011)

Without spectra on all flavors, we are severely limited in probing physics and astrophysics

Finding the Supernova

“Can a supernova be located by its neutrinos?” Beacom and Vogel (1999)

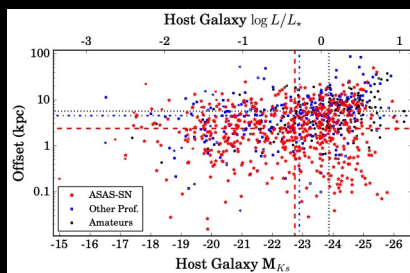
Yes by neutrino-electron scattering
No by triangulation timing



Al Kharusi et al. (2021)

Provides robust alerts by multi-detector
Does not provide directionality

Ohio State’s “ASAS-SN” (All-Sky Automated Survey for SN)



John Beacom, The Ohio State University

Multi-messenger characterization

Adams et al., 1306.0559
Nakamura et al., 1602.03028
Etc.

IceCube Particle Astrophysics Symposium, U. Wisconsin, October 2026

DSNB

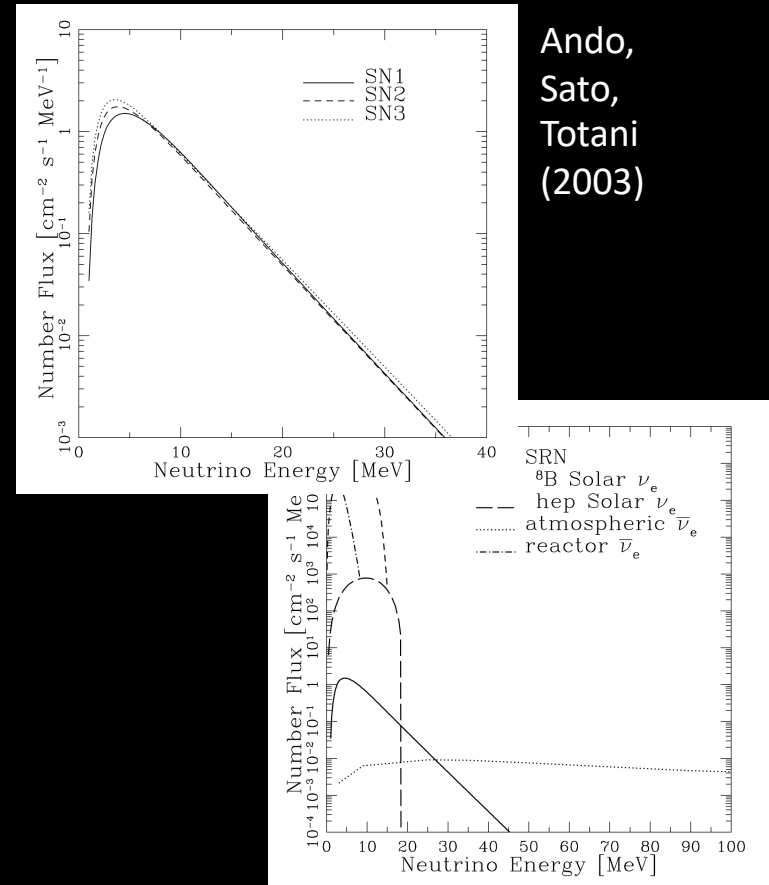
Prehistory: DSNB Signal

- First discussed in the 1960s, *with very high fluxes* (Ruderman; Zel'dovich, Guseinov)
- Reasonable predictions starting in late 1990s
- Overall flux robustly estimated as

$$\Phi \sim 10 \text{ cm}^{-2} \text{ s}^{-1} \sim \int_{\text{LOS}} d\ell N_\nu \cdot \Gamma_{\text{SN}} \cdot n_{\text{gal}}$$

10^{58} neutrinos SN^{-1} , 10^{-2} SNe galaxy $^{-1}$ year $^{-1}$
 10^{-2} galaxies Mpc^{-3} , integrate LOS out to c/H_0

Guaranteed flux, but the details must be measured



Ando,
Sato,
Totani
(2003)

Prehistory: DSNB Backgrounds

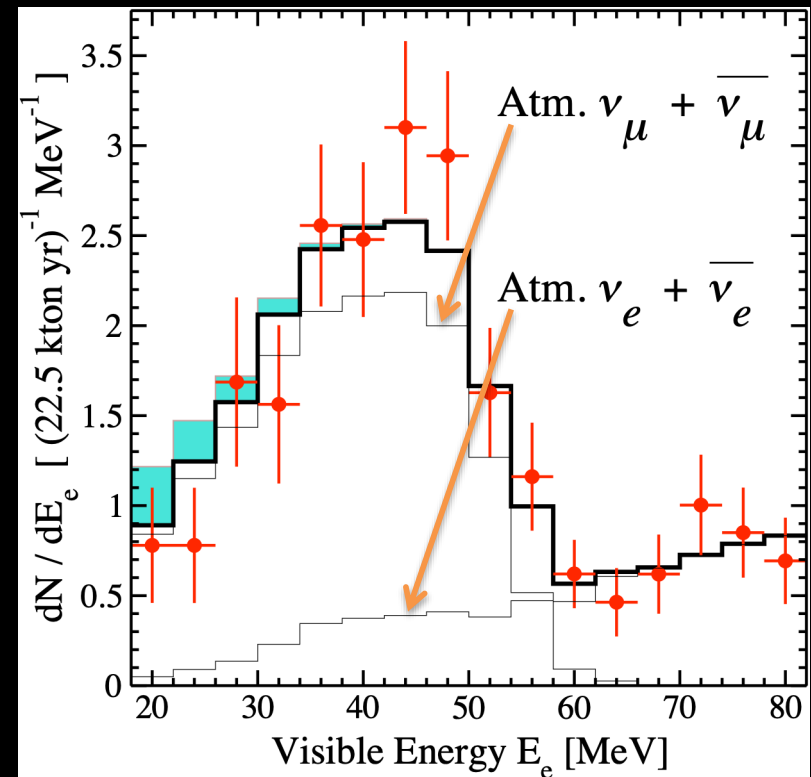
- Super-K (2003): first competitive search
Better by orders of magnitude
Focused on nuebar

High threshold, ~ 20 MeV

Backgrounds high, $\sim 50+$ events/year

But signal is only $\sim$ few events/year
And is concentrated at low energies

Discovery requires a new approach



Malek et al. [Super-Kamiokande] (2003);
energy units adjusted in Beacom (2011)

First Thing, Let's Kill All the Backgrounds

GADZOOKS! Antineutrino Spectroscopy with Large Water Čerenkov Detectors

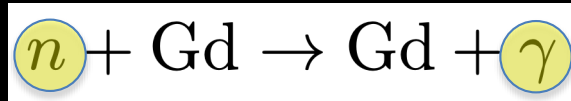
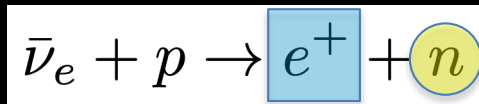
John F. Beacom¹ and Mark R. Vagins²

¹NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500

²Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697

(Dated: 25 September 2003)

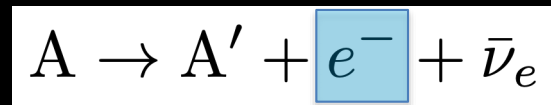
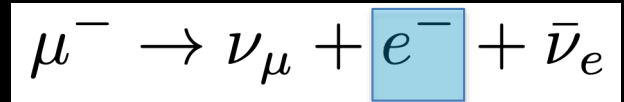
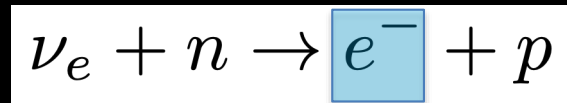
Example signal



delayed gamma

Gd detects neutrons!

Example backgrounds (noise)



No neutrons!

Benefits of Neutron Tagging for DSNB

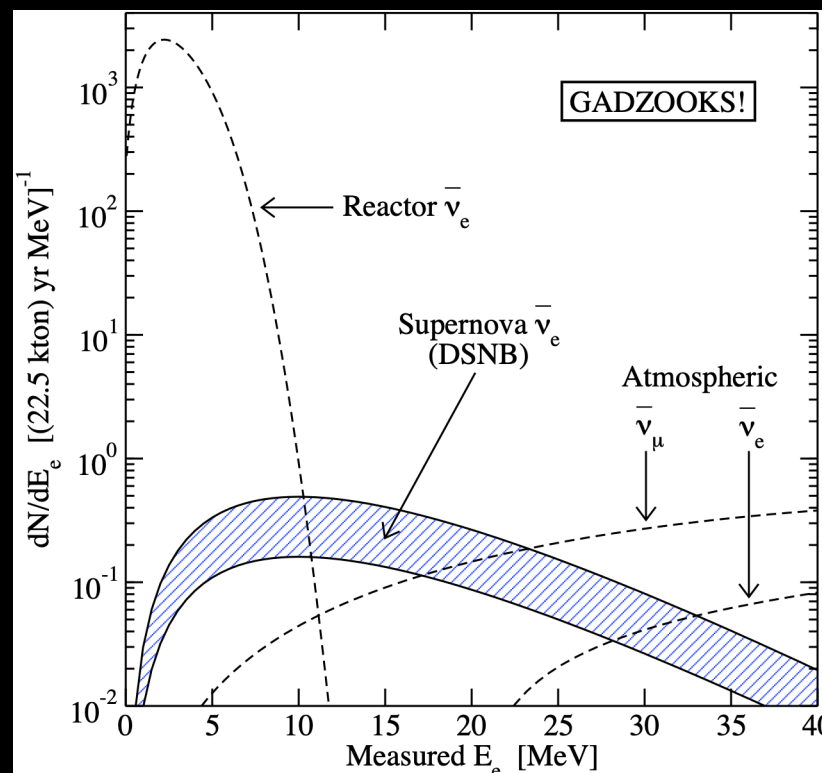
Solar neutrinos:
eliminated

Spallation daughter decays:
mostly eliminated

Reactor neutrinos:
now a visible signal

Atmospheric neutrinos:
significantly reduced

More signal, less background



Beacom, Vagins (2004)

How To Advance This Proposal?

Vagins and others,
experimental work



Beacom and others,
theoretical work



Some major actions by Super-K:

Started first Gd loading in 2020

Started second loading in 2022

Since then, using “SK-Gd” name

Big review article by Koshio,
Nakahata, Sekiya, Vagins (2025)



Now many Super-K papers — on
many topics — using power of Gd

DSNB Signal: Theoretical Framework

Signal rate spectrum in detector in terms of measured energy

$$\frac{dN_e}{dE_e}(E_e) = N_p \sigma(E_\nu) \int_0^\infty \left[(1+z) \varphi[E_\nu(1+z)] \right] \left[R_{SN}(z) \right] \left[\left| \frac{c dt}{dz} \right| dz \right]$$

Third ingredient: Detector Capabilities
(well understood)

Second ingredient: Core-collapse
rate (formerly very uncertain, but
now known with good precision)

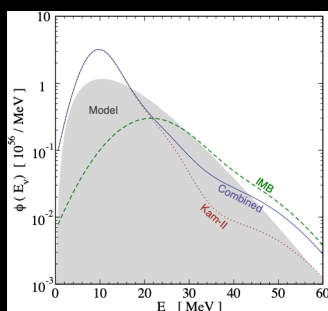
First ingredient: Neutrino spectrum
per core collapse (this is the unknown)

These and other details in my 2010 review article

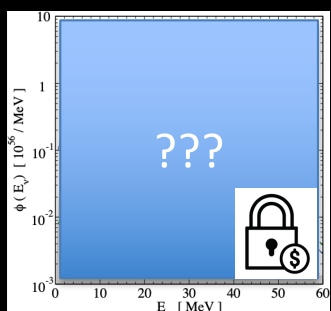
Why Is the Spectrum the Central Goal?

Of central importance to astrophysics — but only neutrino experiments can measure it

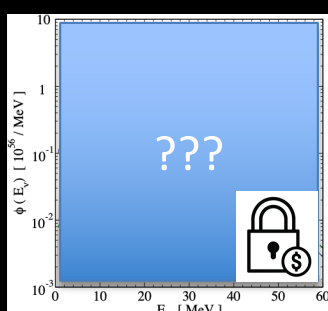
SN 1987A



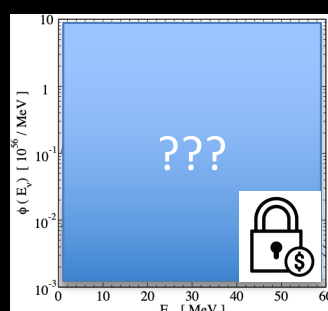
DSNB



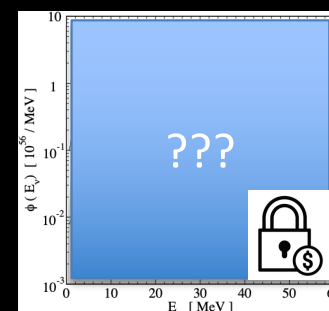
SN 2031xyz



Summed
mini-bursts



Simulation



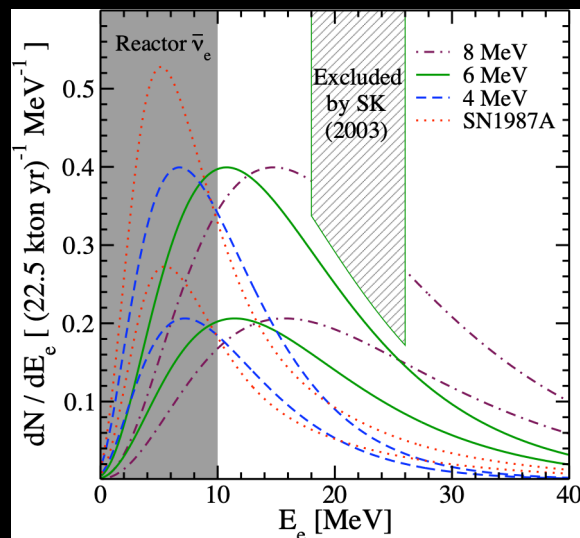
All include neutrino mixing, *which happens inside the supernova*

Needs mixing

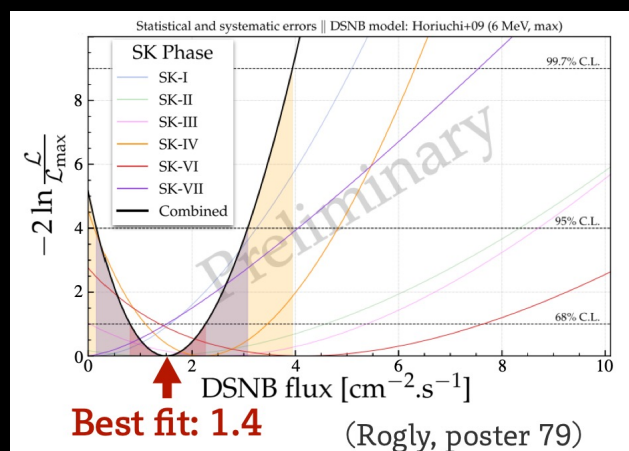
Separate opportunities to compare data to data and data to theory

Progress Towards Discovery

Horiuchi, Beacom, Dwek (2009)



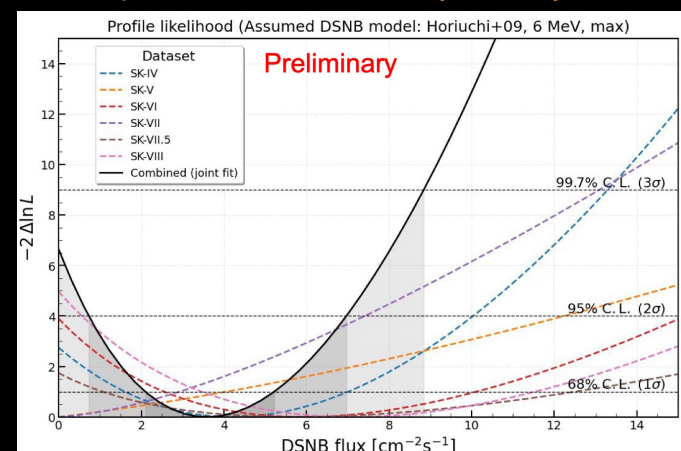
Super-Kamiokande (2024)



Highlight:

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
 - Best fit of whole SK observation is $1.4^{+0.8}_{-0.6} \text{ cm}^{-2} \text{ s}^{-1}$ for $E_\nu > 17.3 \text{ MeV}$
- exhibit ~2.3 σ excess!!

Super-Kamiokande (2026)



Joint fit significance = **2.6 σ** 99.5% CL

We must further reduce detector backgrounds

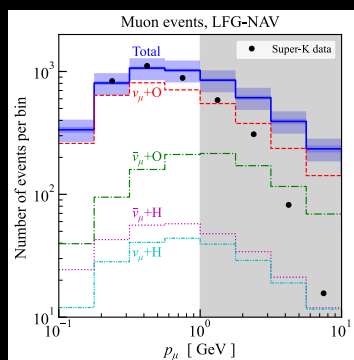
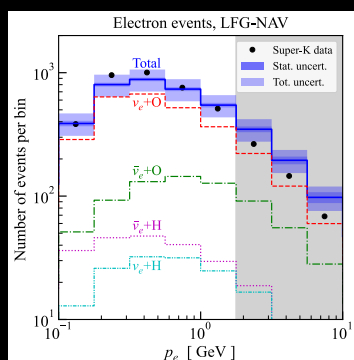
New Ideas to Reduce Backgrounds Further

First Detailed Calculation of Atmospheric Neutrino Foregrounds to the Diffuse Supernova Neutrino Background in Super-Kamiokande

Bei Zhou ^{1,2,*} and John F. Beacom ^{3,4,5,†}



Still the only theoretical study in this energy range



New bases for cutting these backgrounds

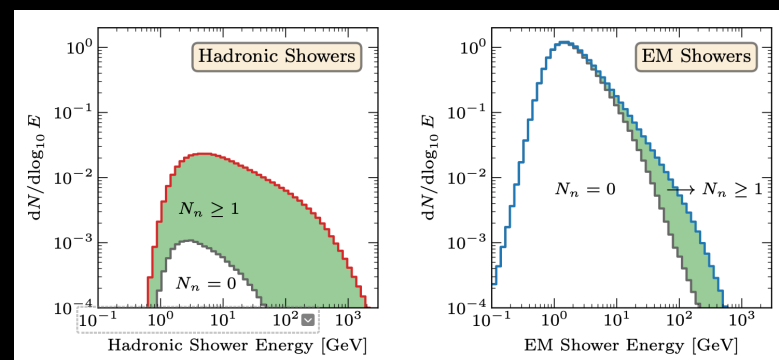
John Beacom, The Ohio State University

Neutron Tagging Can Greatly Reduce Spallation Backgrounds in Super-Kamiokande

Obada Nairat ^{1,2,*}, John F. Beacom ^{1,2,3,†} and Shirley Weishi Li ^{4,†}



Most isotopes produced by hadronic showers that also produce neutrons



Gd can help cut spallation by factor ~4

IceCube Particle Astrophysics Symposium, U. Wisconsin, October 2026

Long View on the DSNB

Guaranteed but uncertain signal, essential for neutrino astronomy and physics

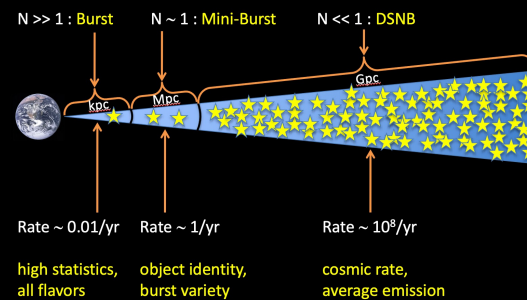
If we find it, we probe the neutrino emission of the average core collapse

If we find it with precision, we probe this in detail, including the black hole fraction (Lunardini, 2009), neutrino physics, and possible surprises

If we don't find it,



Long-Term Strategy



The Future Is Almost Now

Best of times?

Better detectors

SK-Gd, JUNO, Hyper-K, DUNE, others

Better theory

Simulations, mixing, BSM

Better astrophysics

Transient surveys, deep multiwavelength followup, gravitational waves

Approaching the end times?

Potential loss of SK-Gd

Nominal end within a few years!!!

Hyper-K

Not yet planned to have Gd and thus have the capabilities needed

Potential last generation of detectors

Maybe last chance for a Milky Way burst

The community must develop an overall strategy

What Should We Aim For?

Some principles:

- Critical quantities must be measured multiple ways
- Detectors must be designed to have broad capabilities
- We must unite laboratory, astrophysics, and cosmology studies

Some recommendations:

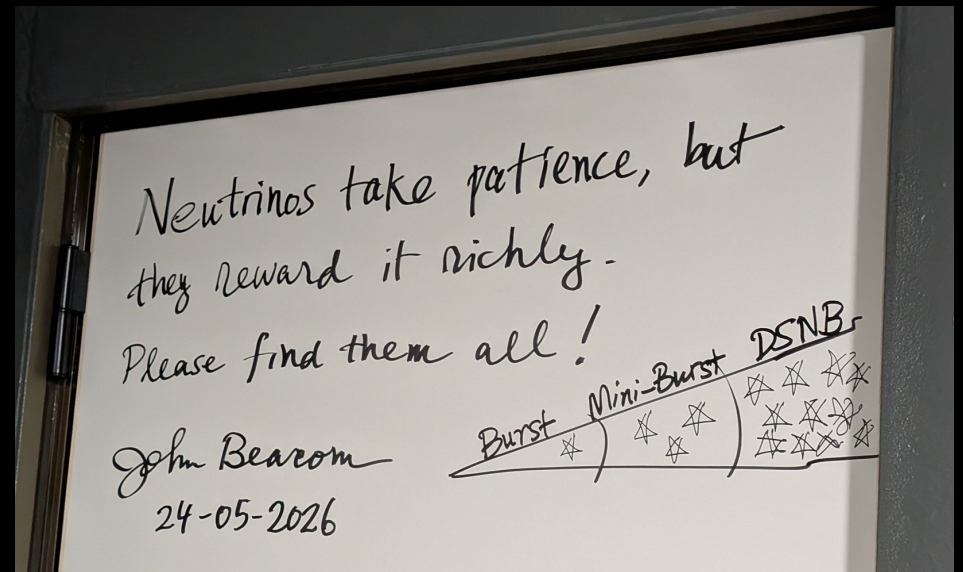
- The community should help define broad sets of expanded goals
- SK-Gd should run until it discovers the DSNB
- All detectors should run as long as possible for a Milky Way burst
- DUNE should keep developing MeV capabilities (see 1808.08232, 1811.07912)
- **Aim towards HK-Gd, which would be the greatest neutrino detector ever built:**
Gd would enable DSNB with high precision, new probe of CPV with atmospheric (2605.16721), Milky Way burst with ultimate precision

Closing Messages

Reines and Cowen (1956):

The neutrino is the smallest bit of material reality ever conceived of by man; the largest is the universe. To attempt to understand something of one in terms of the other is an attempt to span the dimension in which lie all physical manifestations of natural law....

The problem of detecting these cosmic end-products of all nuclear energy generation processes and the measurement of their characteristics presents a great challenge to the physics of to-day.



Super-K control room door

Bonus Slides

Nearby Galaxies Mini-Bursts

Basic Idea of Mini-Bursts

Super-K Milky Way burst (10 kpc)

Detect $\sim 10^4$ events

Backgrounds irrelevant

Can detect even dark bursts

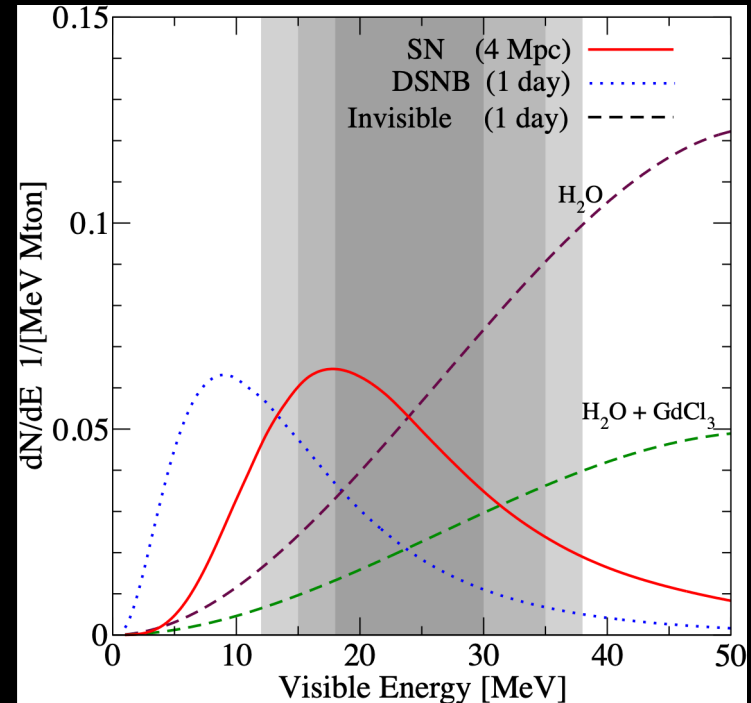
How about M31 (1000 kpc)?

Detect ~ 1 event

Backgrounds large

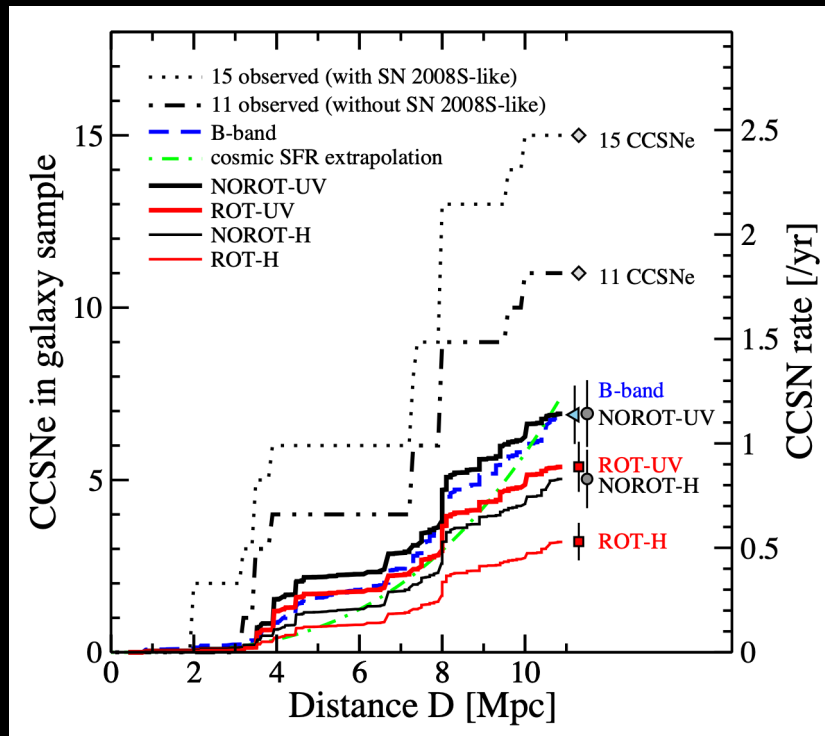
Optical signal needed for timing

With larger detectors, could see further, collect multiplets, and build the supernova neutrino spectrum



Ando, Beacom, Yuksel (2005)

Rates in Nearby Galaxies



Horiuchi et al. (2013)

Neutrino bright, optically bright:
Core-collapse supernova

Neutrino bright, optically dim:
Core-collapse to black hole

Neutrino dim, optically bright:
Type Ia supernova
Supernova impostor

Neutrino dim, optically dim:
All the time!

Possible Future Detectors

Core-Collapse Astrophysics with a Five-Megaton Neutrino Detector

Matthew D. Kistler,^{1,2} Hasan Yüksel,^{1,2} Shin'ichiro Ando,³ John F. Beacom,^{1,2,4} and Yoichiro Suzuki^{5,6}

2011

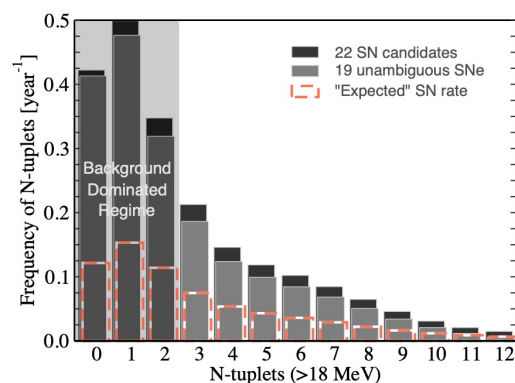
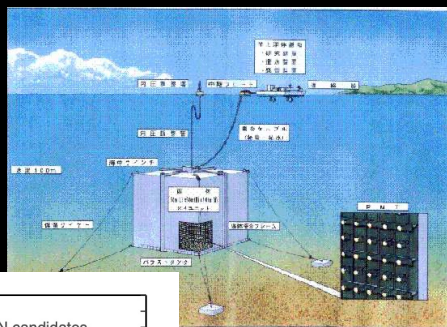


FIG. 4: Frequency of neutrino mini-bursts expected with a 5 Mton detector. The bins with $N = 3$ or more can be used for burst detection because the background rate is small enough. Three different estimates of the supernova rate are shown, as labeled.

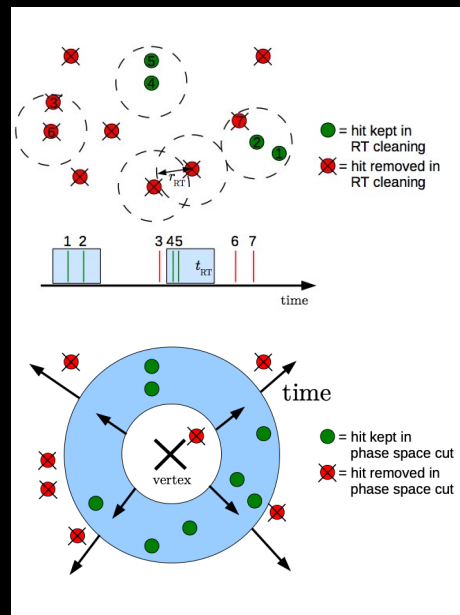
John Beacom, The Ohio State University

Detecting extra-galactic supernova neutrinos in the Antarctic ice

Sebastian Böser*, Marek Kowalski, Lukas Schulte, Nora Linn Strotjohann, Markus Voge

Physikalisches Institut, Universität Bonn, D-53115 Bonn, Germany

2014



IceCube Particle Astrophysics Symposium, U. Wisconsin, October 2026

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