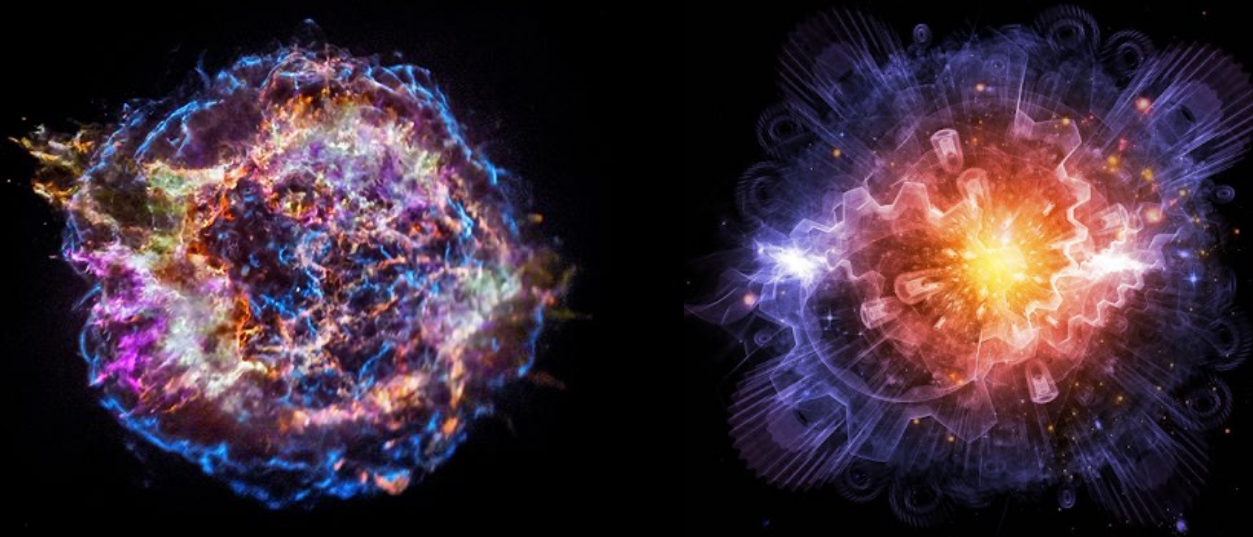


# *Supernova Neutrinos (Theory)*

*John Beacom, The Ohio State University*



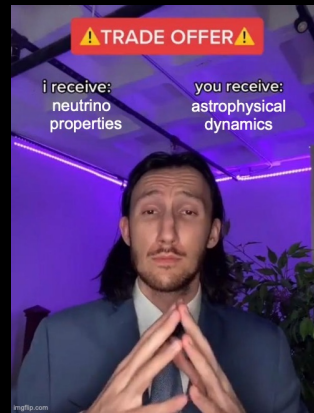
The Ohio State University's Center for Cosmology and AstroParticle Physics



# Supernovae and Neutrinos

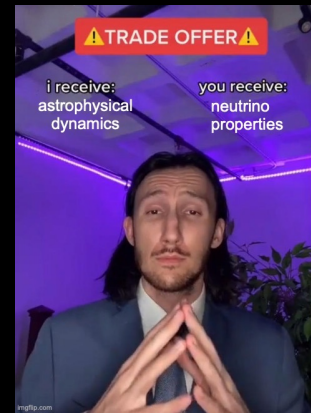
To an astronomer, a supernova is:

- 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)

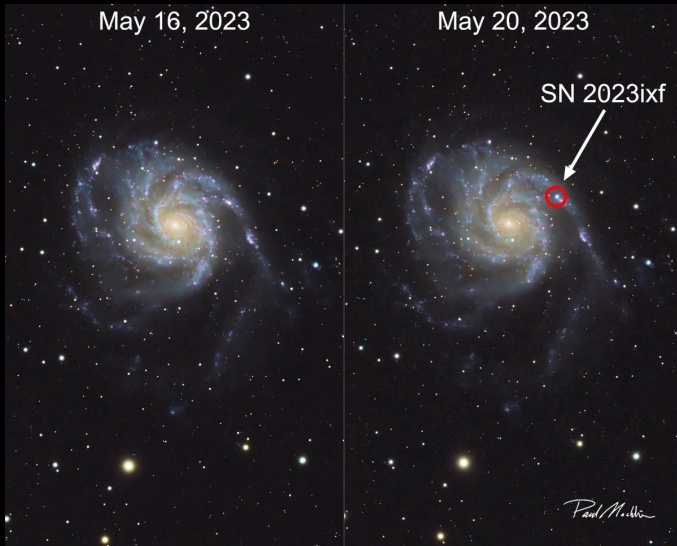
Diffuse Supernova Neutrino Background (DSNB)

## Long-Term Strategy

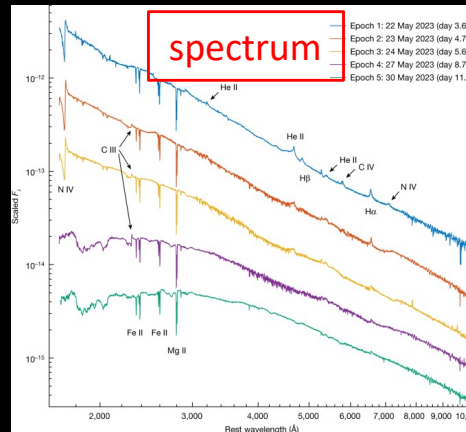
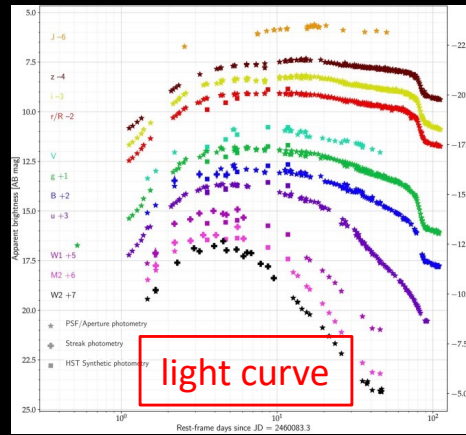
# Theoretical Overview

# 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:

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

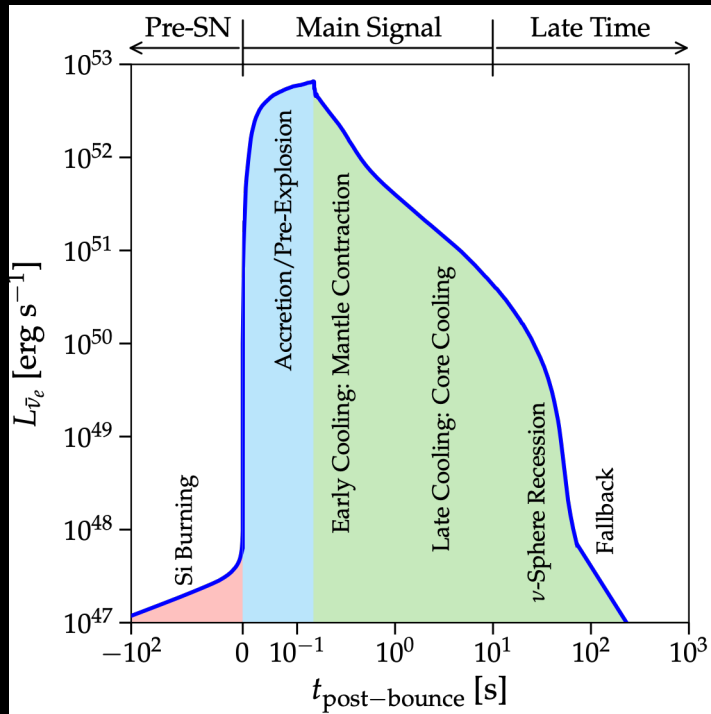
$$\langle E_{\nu} \rangle \sim 100 \text{ MeV in core}$$

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

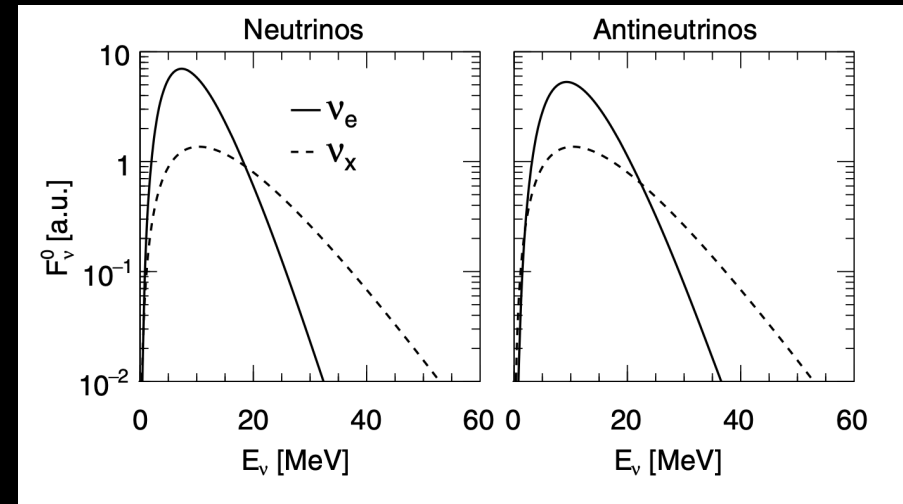
diffusion over seconds

Summarized in 2206.12426

# Basic Neutrino Profiles and Spectra



Li, Roberts, and Beacom (2021)

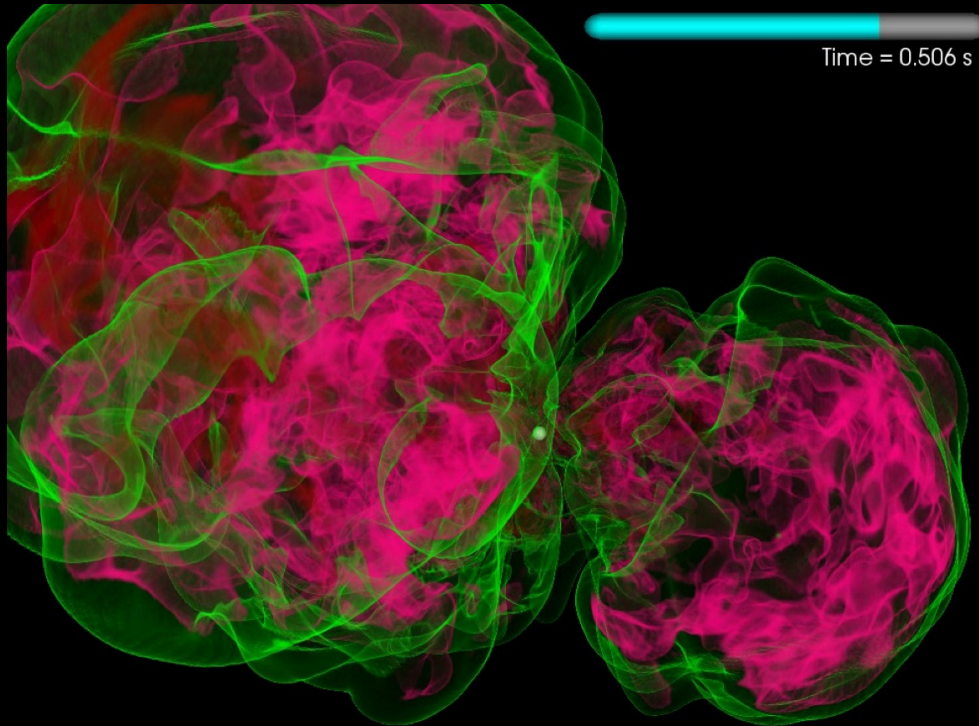


Capozzi, Dasgupta, Mirizzi (2018)

$\langle E \rangle$  increasing for  $\nu_e$ , anti- $\nu_e$ ,  $\nu_x$

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**

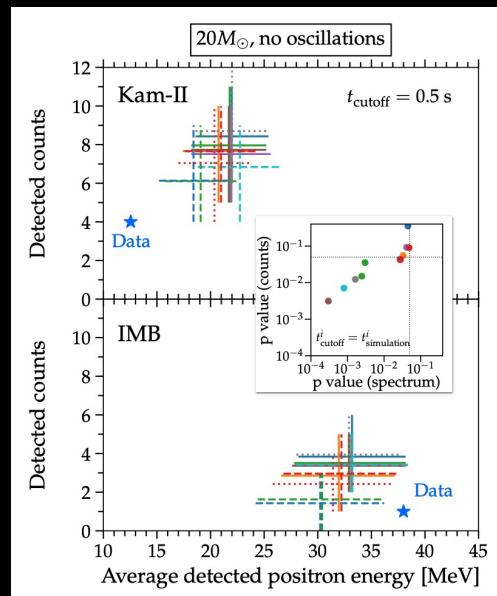
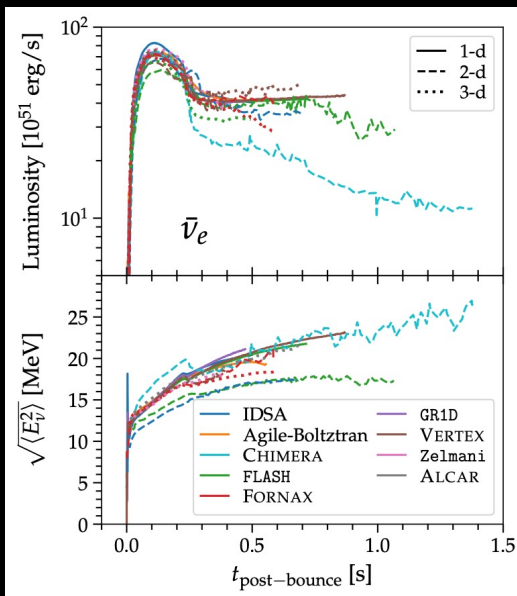
# Comparison of Simulations to SN 1987A

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

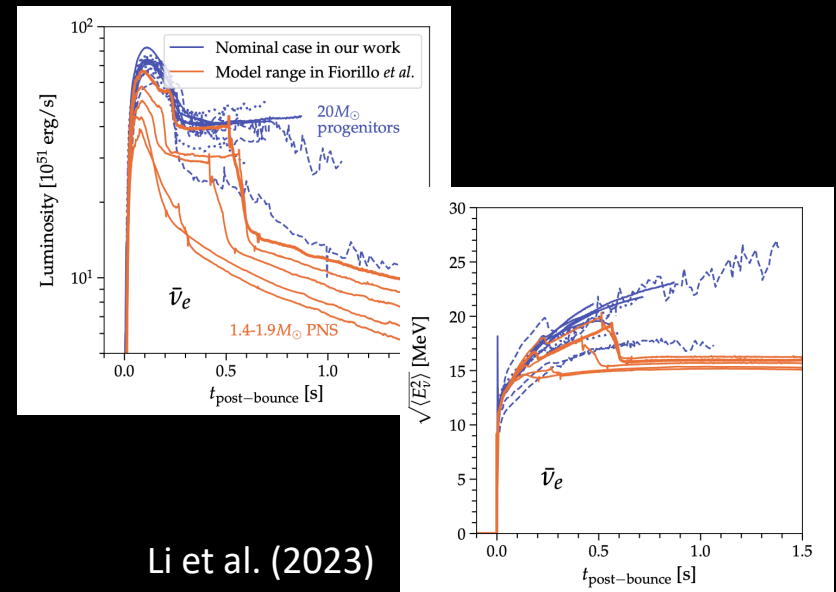
Shirley Weishi Li <sup>1,2,\*</sup>, John F. Beacom <sup>3,4,5,†</sup>, Luke F. Roberts <sup>6,‡</sup> and Francesco Capozzi <sup>7,8,§</sup>

2023

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



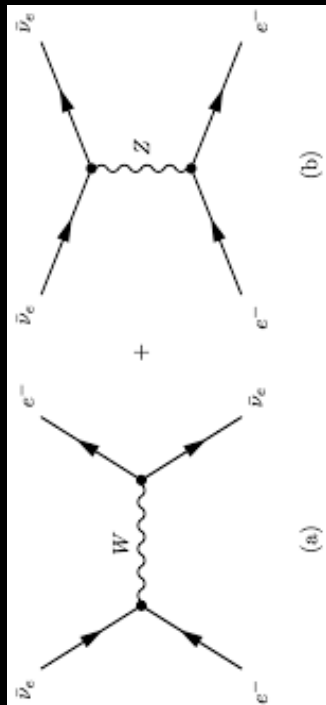
Criticized by Fiorillo et al. (2023),  
 but they use non-exploding 1d  
 models that fall *far below* more  
 realistic 2d and 3d models



Li et al. (2023)

# Neutrino Mixing in Matter

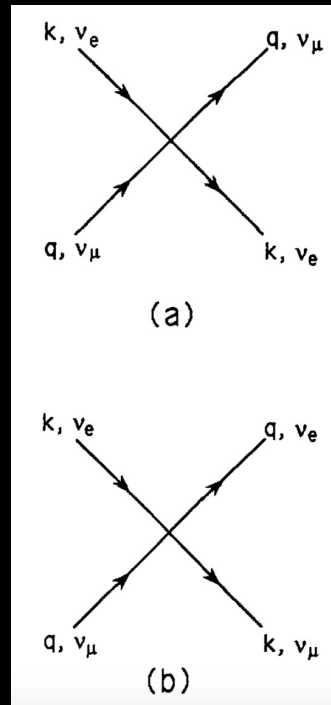
## Neutrino-Electron



MSW effect

+

## Neutrino-Neutrino



Pantaleone (1992)

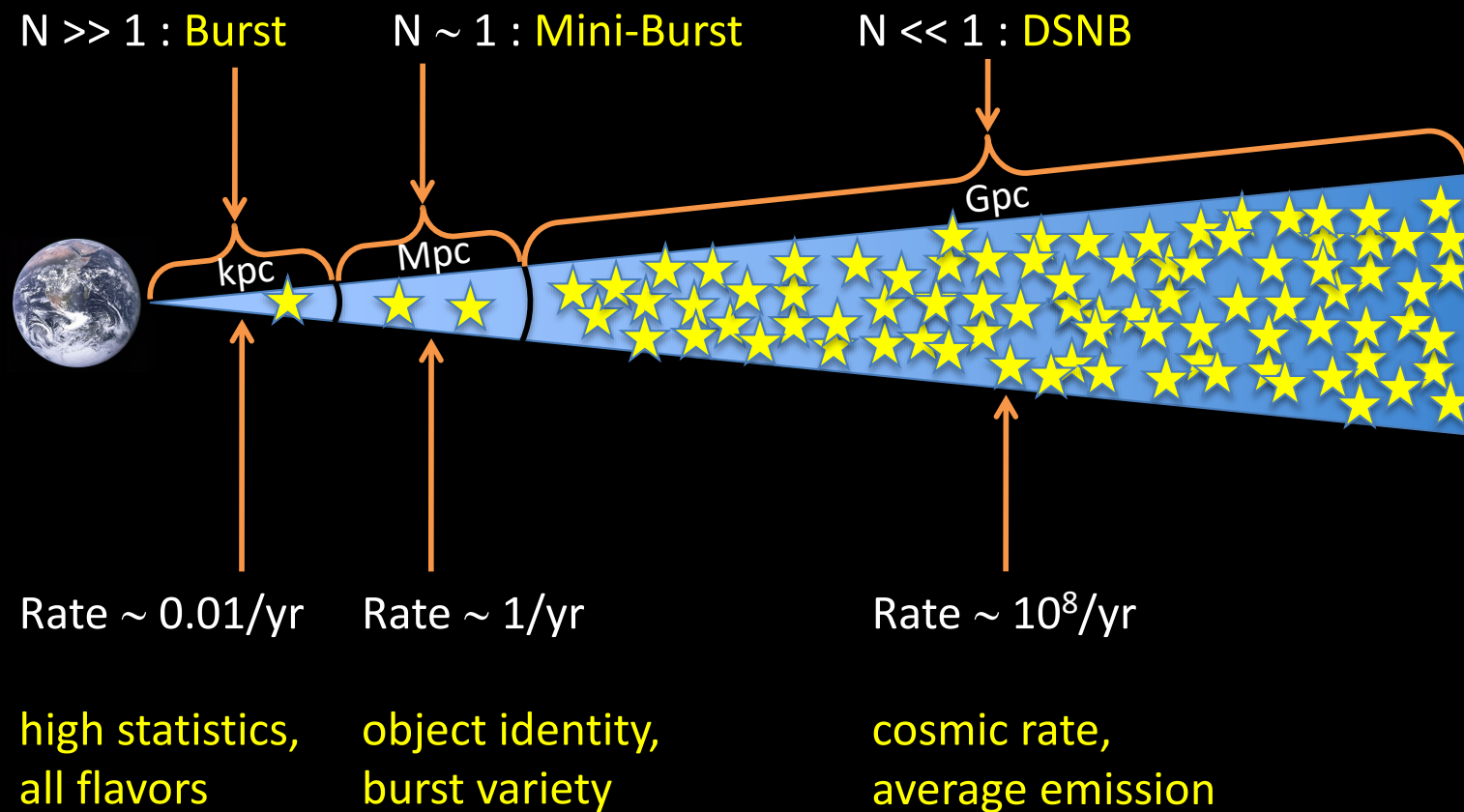


Very complex  
consequences for mixing  
and maybe for the  
supernova explosion!

*Unsolved problem,  
beyond reach of the lab*

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

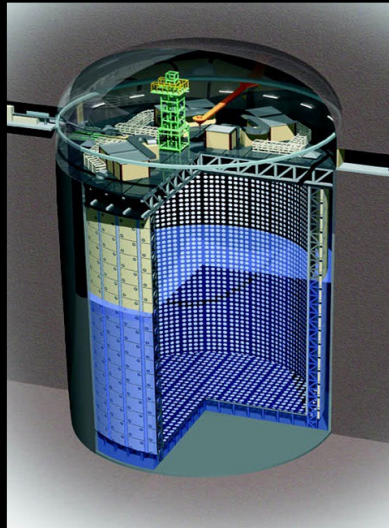
# How Can We Detect Core Collapse Neutrinos?



# Milky Way Burst

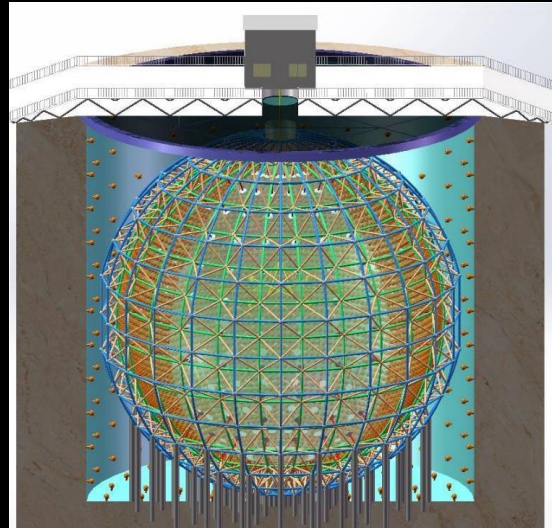
# Primary Detectors

Super-K Gd



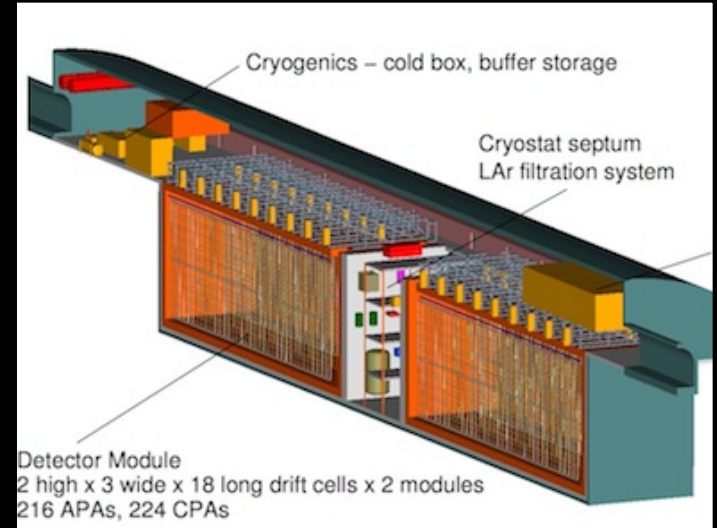
32 kton water+Gd  
*running* (Japan)

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

$\sim 10x$  for HK

Best for  $\bar{\nu}_e$

### 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  $\nu_x$

### IceCube ( $10^6$ kton water)

- Burst is increase over background rate
- Possibility of precise timing information

And many other detectors

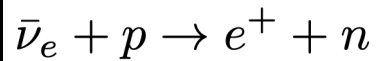
### DUNE (34 kton liquid argon)

- $\sim 10^3$  CC and NC with argon nuclei
- $\sim 10^2$  neutrino-electron elastic scattering

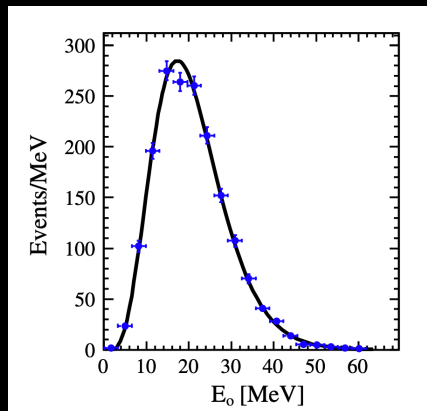
Best for  $\nu_e$

# Spectrum Measurements

Best for anti- $\nu_e$

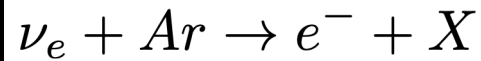


Vogel, Beacom (1999)  
Strumia, Vissani (2003)

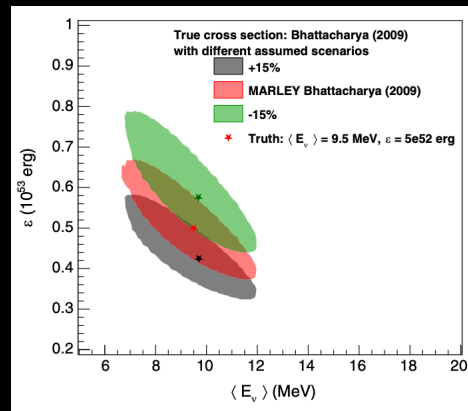


Li et al. (2019)

Best for  $\nu_e$

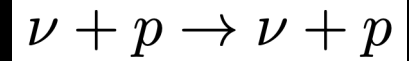


MARLEY (Gardiner)

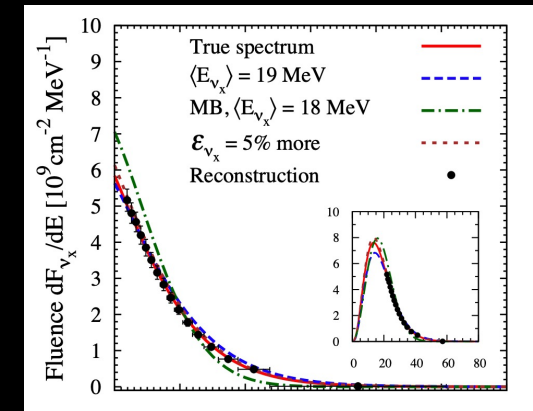


DUNE (2023)

Best for  $\nu_x$



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)

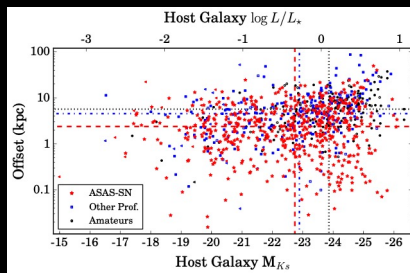
Yes by neutrino-electron scattering  
No by triangulation timing



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.

Neutrino 2026 Conference, UC Irvine, June 2026

DSNB

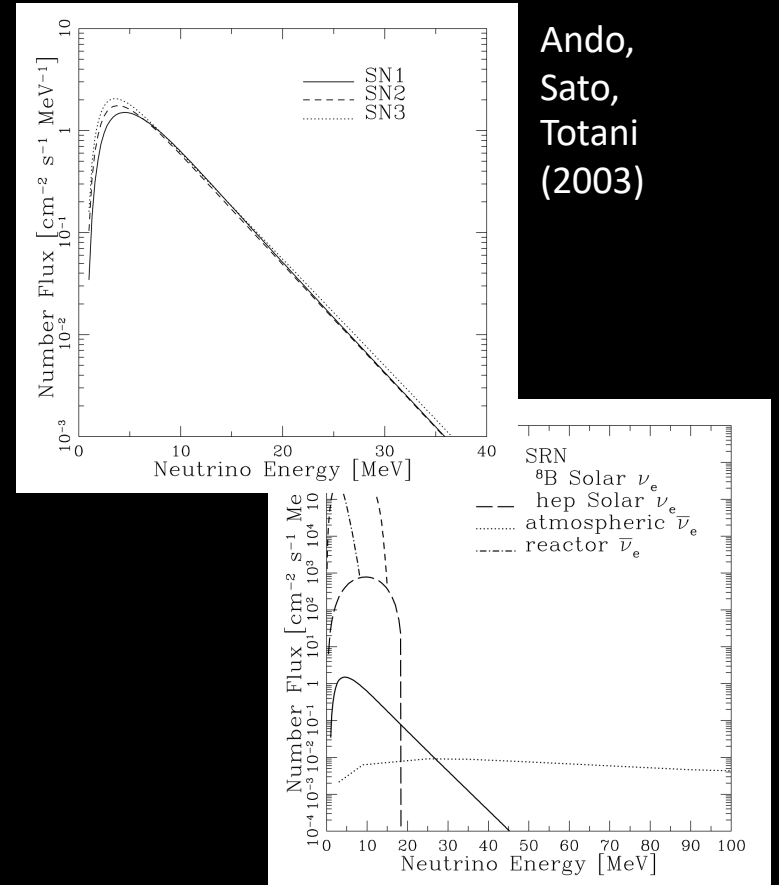
## Prehistory: DSNB Signal

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

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

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

**Guaranteed flux, but the details must be measured**



## Prehistory: DSNB Backgrounds

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

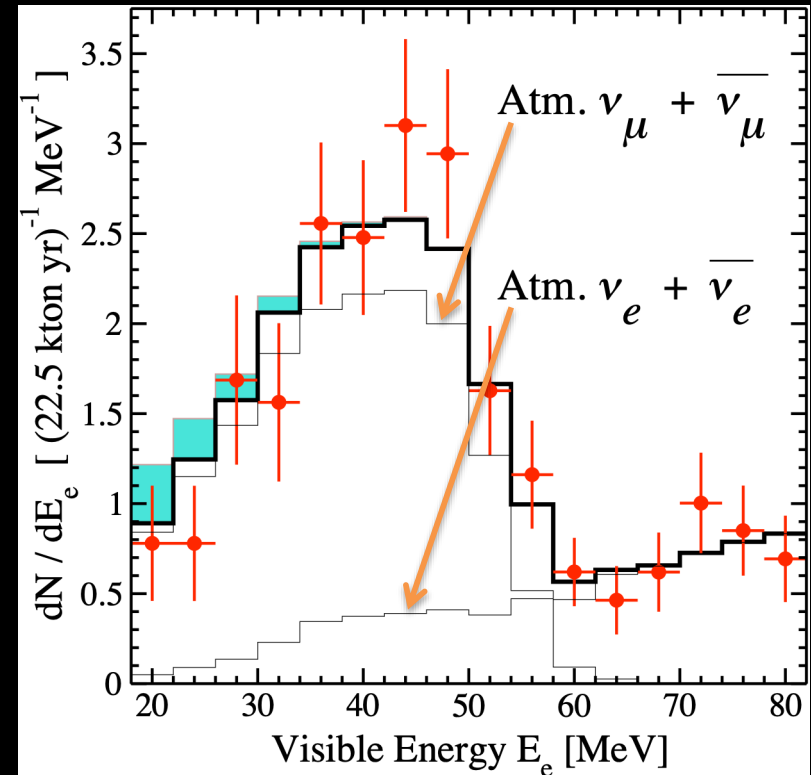
High threshold,  $\sim 20$  MeV

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

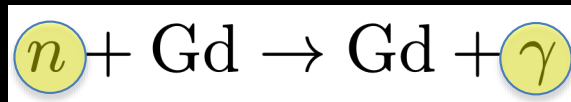
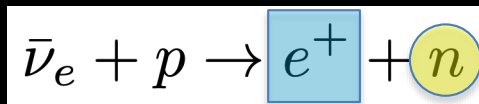
John F. Beacom<sup>1</sup> and Mark R. Vagins<sup>2</sup>

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

<sup>2</sup>Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697

(Dated: 25 September 2003)

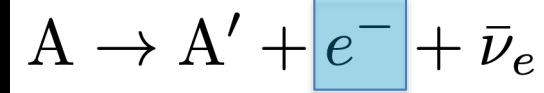
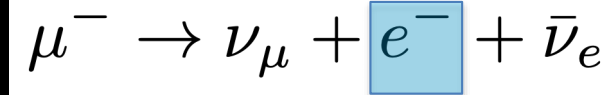
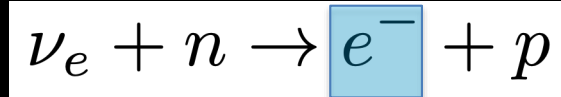
### Example signal



delayed gamma

Gd detects neutrons!

### Example backgrounds (noise)



No neutrons!

# Benefits of Neutron Tagging for DSNB

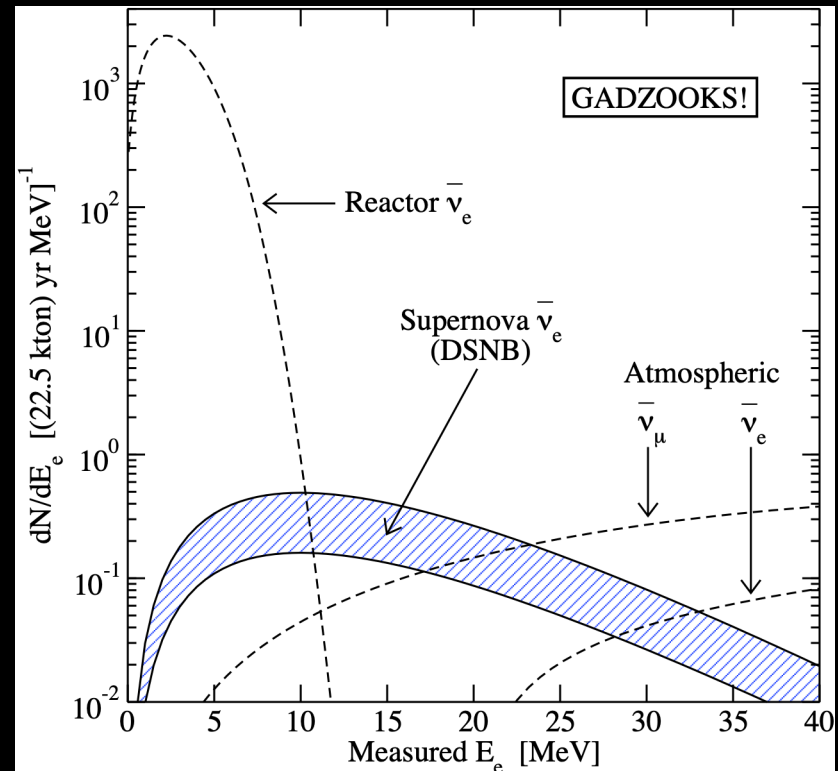
Solar neutrinos:  
eliminated

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

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

Third ingredient: Detector Capabilities  
(well understood)

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

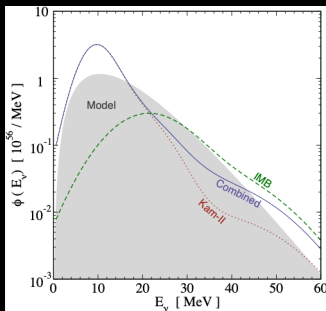
First ingredient: Neutrino spectrum  
per core collapse (this is the unknown)

These and other details in my 2010 review article

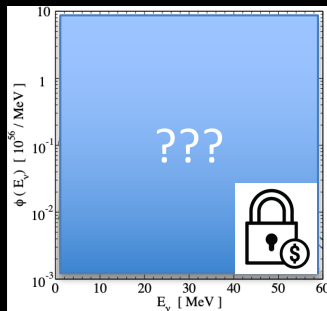
# Why Is the Spectrum the Central Goal?

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

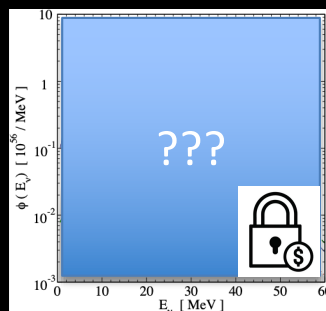
SN 1987A



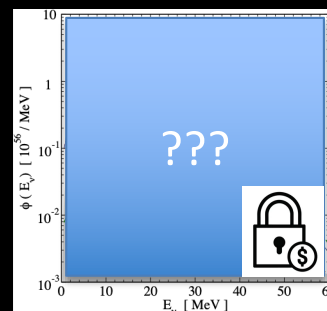
DSNB



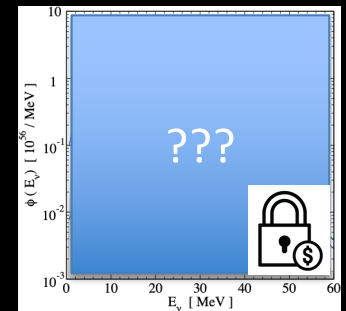
SN 2031xyz



Summed  
mini-bursts



Simulation



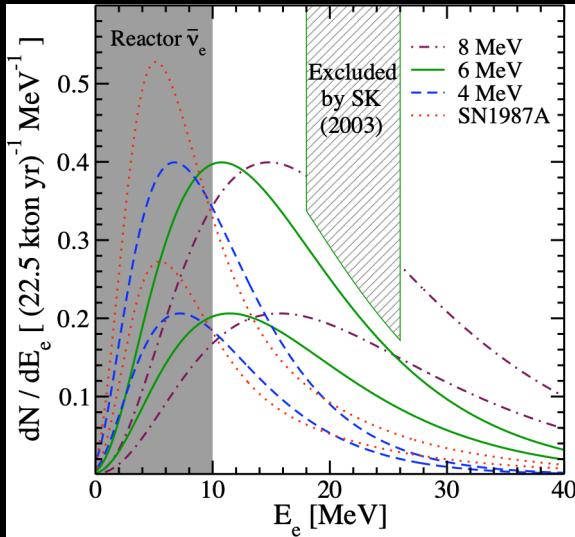
All include neutrino mixing, *which happens inside the supernova*

Needs mixing

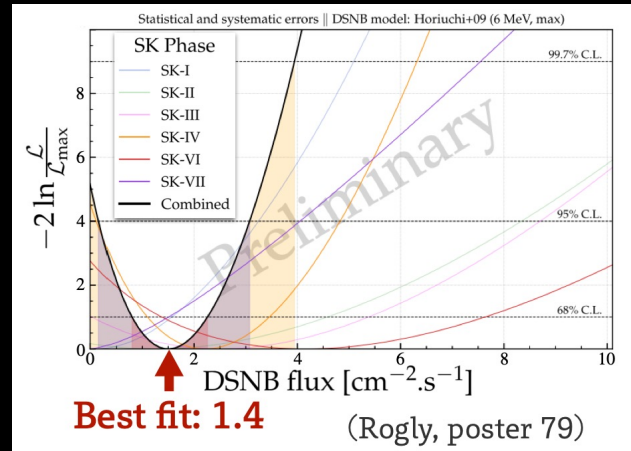
Separate opportunities to compare data to data and data to theory

# 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  $\sim 2.3 \sigma$  excess!!

Super-Kamiokande (next talk!)



Either way, we must further reduce detector backgrounds

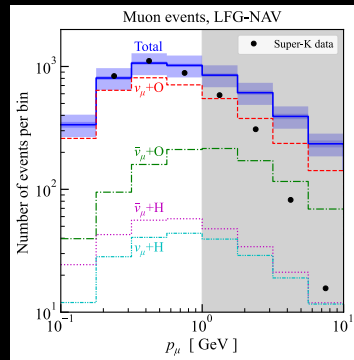
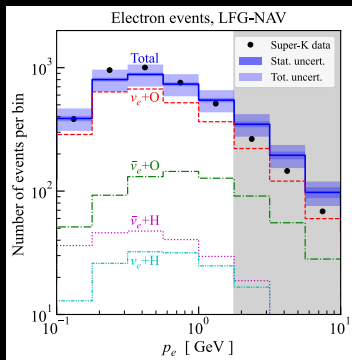
# New Ideas to Reduce Backgrounds Further

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

Bei Zhou <sup>1,2,\*</sup> and John F. Beacom <sup>3,4,5,†</sup>



Still the only theoretical study in this energy range

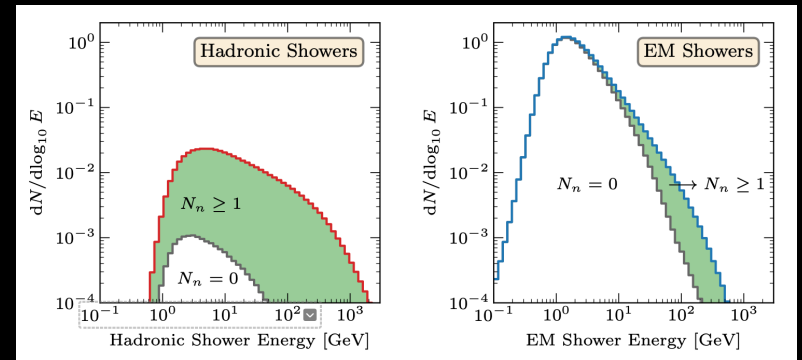


Neutron Tagging Can Greatly Reduce Spallation Backgrounds in Super-Kamiokande

Obada Nairat <sup>1,2,\*</sup>, John F. Beacom <sup>1,2,3,†</sup> and Shirley Weishi Li <sup>4,‡</sup>



Most isotopes produced by hadronic showers that also produce neutrons



New bases for cutting these backgrounds

Gd can help cut spallation by factor ~4

## *Long View on the DSNB*

Guaranteed but uncertain signal, essential for neutrino astronomy and physics

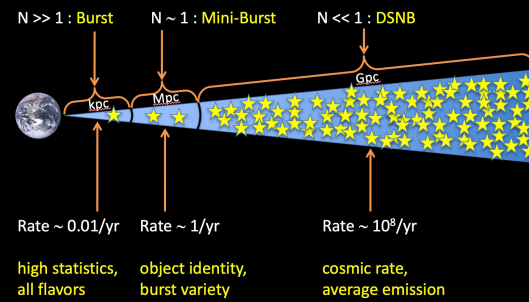
If we find it, we probe the neutrino emission of the average core collapse

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:

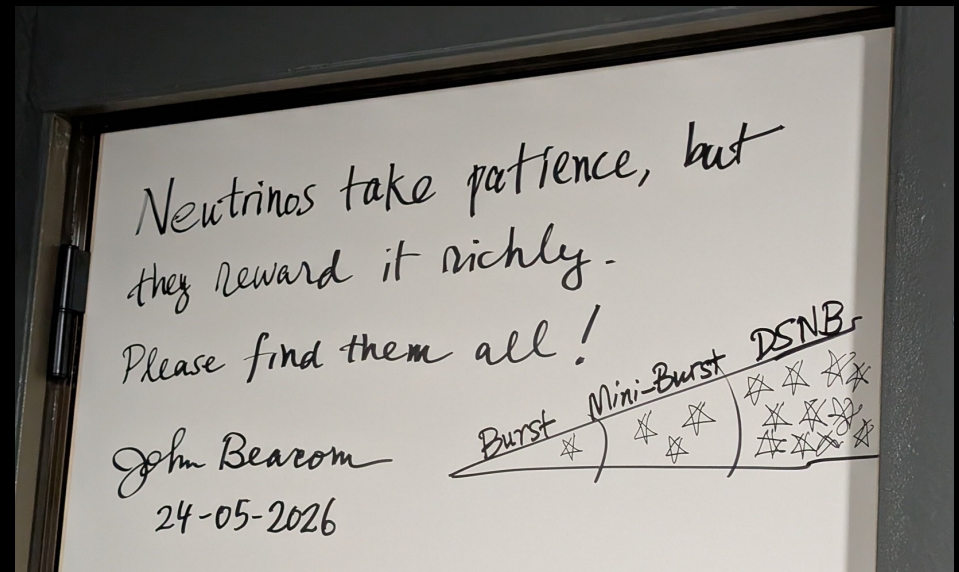
- The community should help define broad sets of expanded goals
- SK-Gd should run until it discovers the DSNB
- All detectors should run as long as possible for a Milky Way burst
- DUNE should keep developing MeV capabilities (see 1808.08232, 1811.07912)
- **Aim towards HK-Gd, which would be the greatest 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

## Please See Related Posters

Presenters	Title	Room	Easel
Binyu Pang	GPS-Synchronized Monitoring of Super	Doheny Beach A	3
Yosuke Ashida	Developing a spectral analysis code for	Doheny Beach A	14
Yota Hino	Modification on thermal motion in Gea	Doheny Beach A	15
Alex Rojewski	The Stochastic Gravitational Wave Back	Doheny Beach A	22
Veronika Shalam	Real-Time Supernova Neutrino Triggers	Doheny Beach A	26
Guillaume Pronc	Super-Kamiokande's Supernova monito	Doheny Beach A	31
Mao Nishigami	Neutron Tagging Efficiency Evaluation in	Doheny Beach A	40
Keigo Kadota	New experiment, BISCOTTEE, to measu	Doheny Beach A	42
Seon-Hee (Sunny	AI/ML-based Real-time Anomaly Detecte	Doheny Beach CD	4
Segev BenZvi	SNEWS 2.0: The Status of the SuperNov	Doheny Beach CD	12
Yufeng Li	Realization of Core-Collapse Supernova	Doheny Beach CD	17
Fumi Nakanishi	Search for Neutrinos Associated with a	Emerald Bay A	7
shishen xian	The Multi-messenger Trigger System fo	Emerald Bay A	24
Masayuki Harada	Evaluation of spallation background for	Emerald Bay C	4
Jiabao Liu	Fast Neutrino Flavor Conversions and T	Doheny Beach B	16
Saki Fujita	New Results from the Diffuse Supernov	Emerald Bay C	9
Geting Qin	Improved Supernova Pointing for DUNE	Emerald Bay C	22
Amanda Weinste	Astrophysical neutrino searches with th	Emerald Bay C	25
Sudipta Das	Probing the impact of scalar-mediated	Emerald Bay C	26
Geraint Clash	JUNO Sensitivity to DSNB Signal	Emerald Bay DE	8
Meghna Bhattach	Scalable Low-Energy Event Reconstruct	Emerald Bay DE	10
Andrew Santos	Hyper-Kamiokande Sensitivity to the Di	Crescent Bay AB	1
Chinami Kato	Comprehensive Neutrino Light Curves	Crescent Bay AB	5
Anson Kost	"Once-in-a-lifetime encounter" (OILE) n	Crescent Bay AB	8

+ Joachim Kopp, Detectable MeV ..., Crescent Bay AB, Easel 11

## Bonus Slides

# Nearby Galaxies Mini-Bursts

# Basic Idea of Mini-Bursts

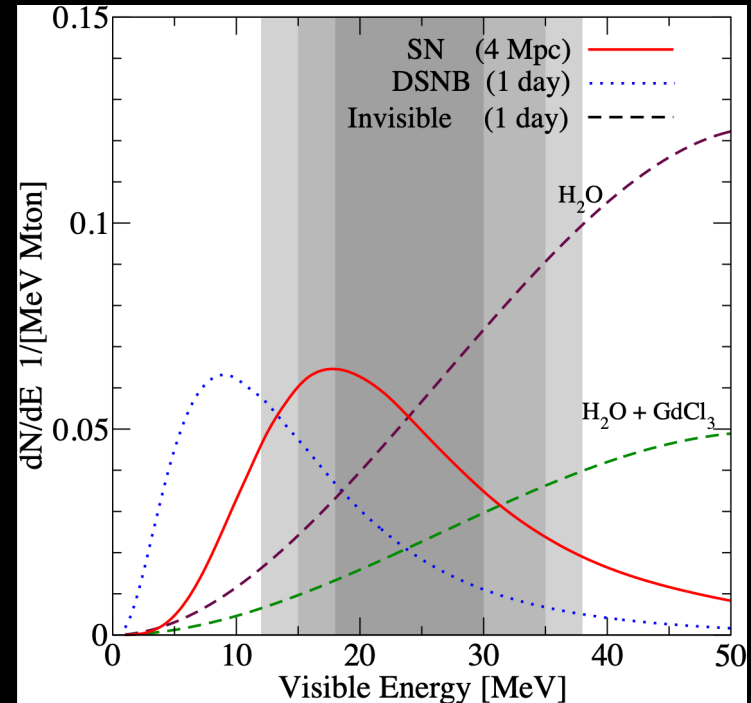
## Super-K Milky Way burst (10 kpc)

Detect  $\sim 10^4$  events  
Backgrounds irrelevant  
Can detect even dark bursts

## How about M31 (1000 kpc)?

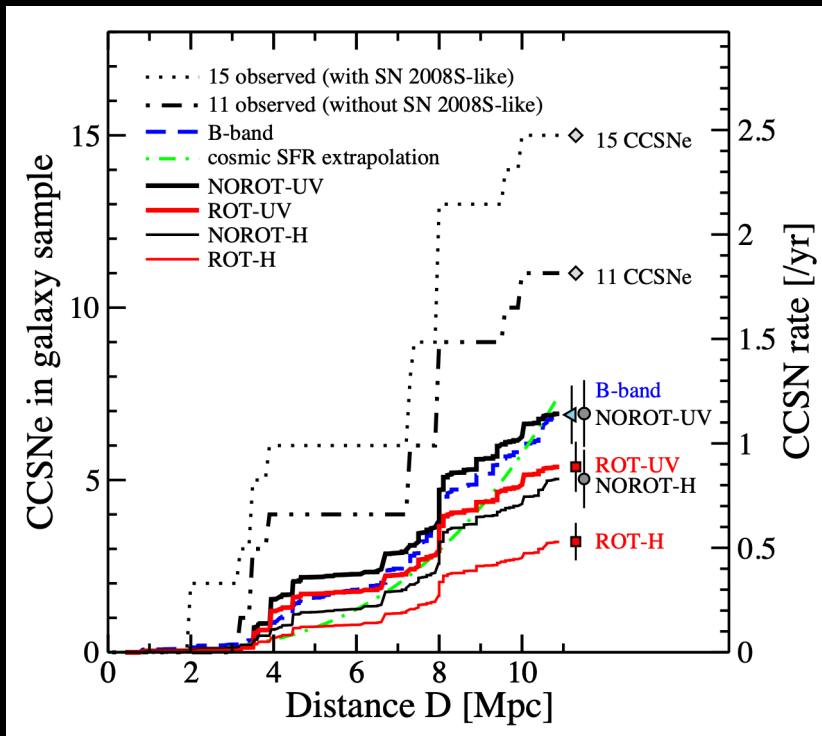
Detect  $\sim 1$  event  
Backgrounds large  
Optical signal needed for timing

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,<sup>1,2</sup> Hasan Yüksel,<sup>1,2</sup> Shin'ichiro Ando,<sup>3</sup> John F. Beacom,<sup>1,2,4</sup> and Yoichiro Suzuki<sup>5,6</sup>

2011

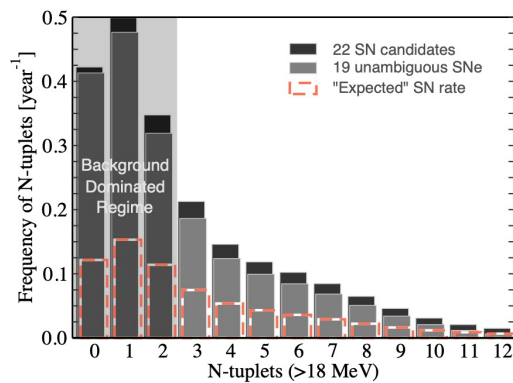
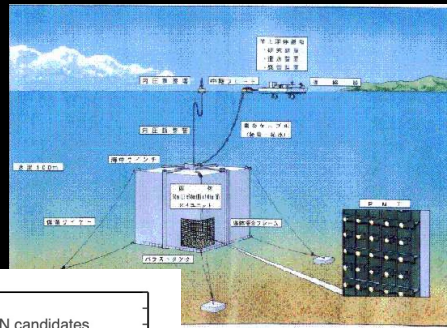


FIG. 4: Frequency of neutrino mini-bursts expected with a 5 Mton detector. The bins with  $N = 3$  or more can be used for burst detection because the background rate is small enough. Three different estimates of the supernova rate are shown, as labeled.

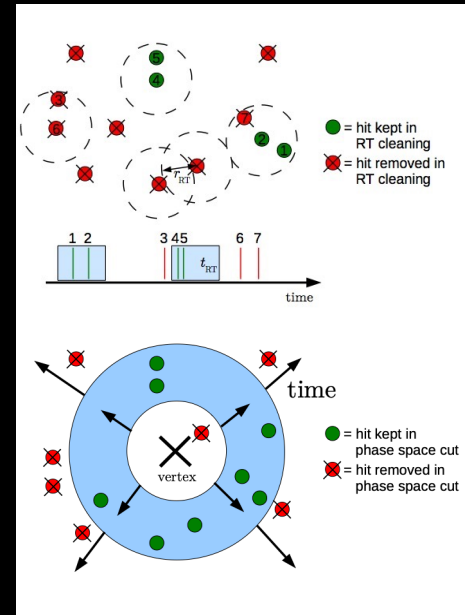
John Beacom, The Ohio State University

## Detecting extra-galactic supernova neutrinos in the Antarctic ice

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

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2014



Key idea is to detect multiple PMT hits per one neutrino event

Greatly lowers backgrounds

Neutrino 2026 Conference, UC Irvine, June 2026

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