Detecting Supernova Neutrinos: Frontiers

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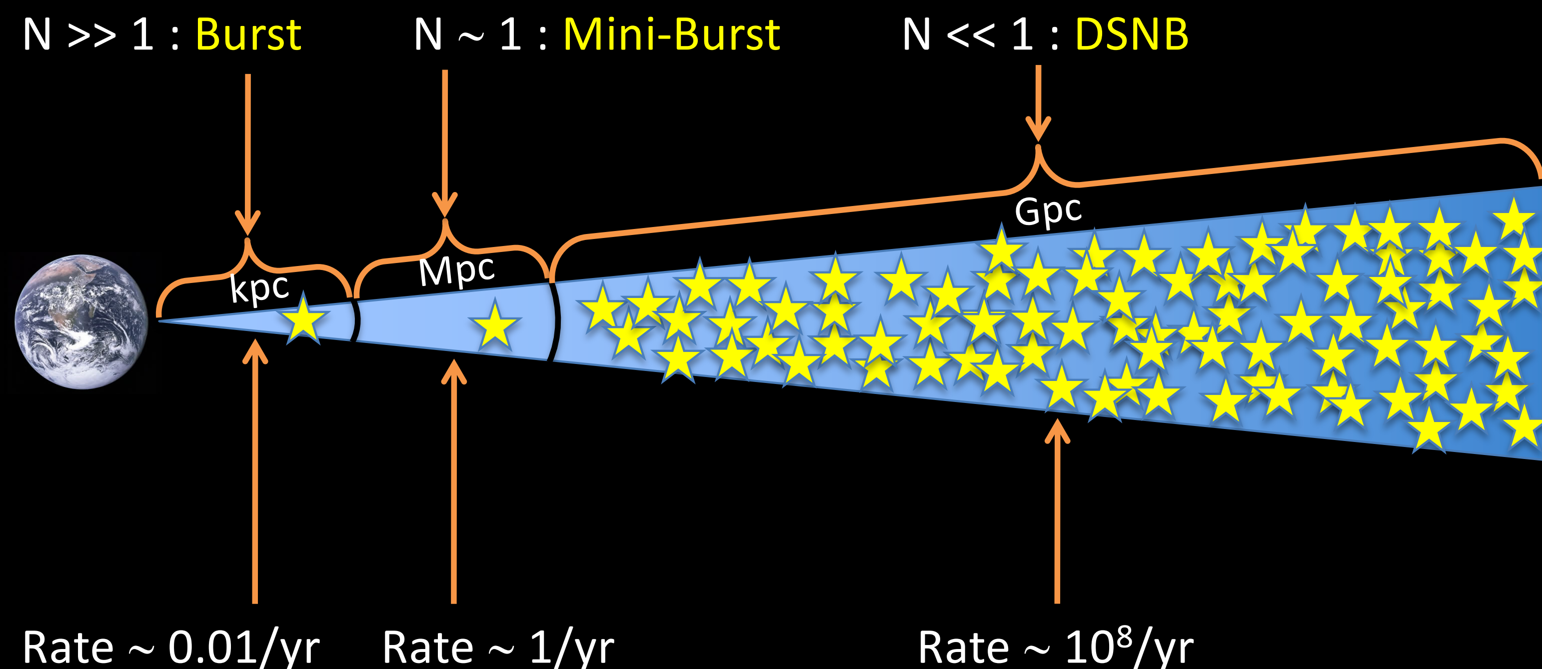
How Do We Find Core Collapses With Neutrinos?



high statistics,
all flavors

object identity,
burst variety

cosmic rate,
average emission

Outline

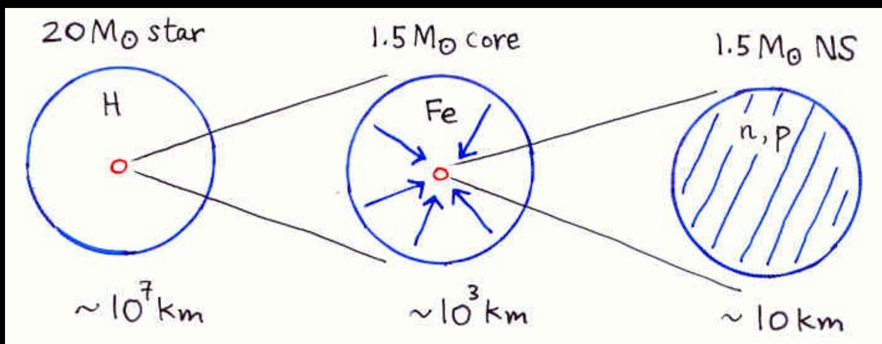
First lecture: Basics

Second lecture: Frontiers
Milky Way
Nearby Galaxies
DSNB

Milky Way

What Are the Mechanisms of Core Collapse?

Idealized; simple

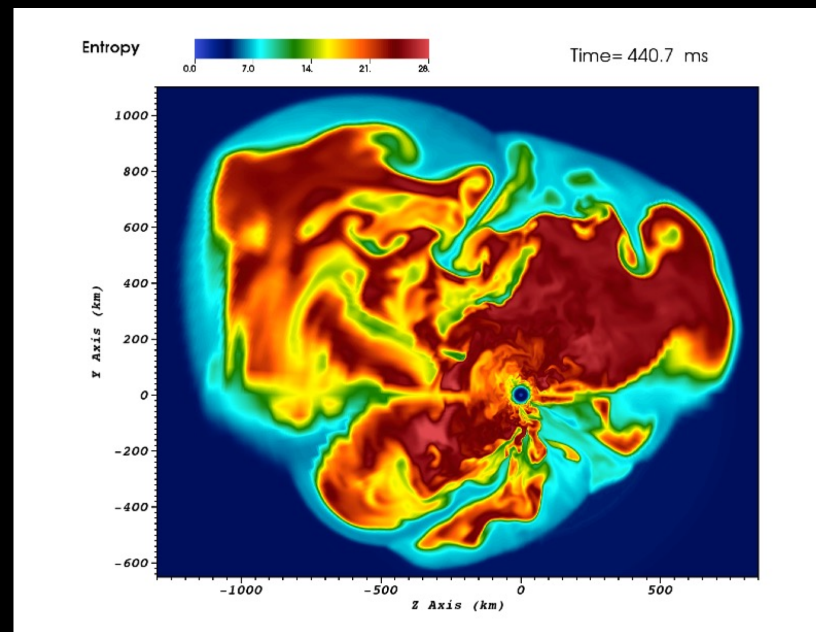


$$\Delta E_B \simeq \frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G M_{NS}^2}{R_{core}} \simeq 3 \times 10^{53}\text{ ergs} \simeq 2 \times 10^{59}\text{ MeV}$$

$$\text{K.E. of explosion} \simeq 10^{-2}\,\Delta E_B$$

$$\text{E.M. radiation} \simeq 10^{-4}\,\Delta E_B$$

Realistic; complex



Oak Ridge group (2015)

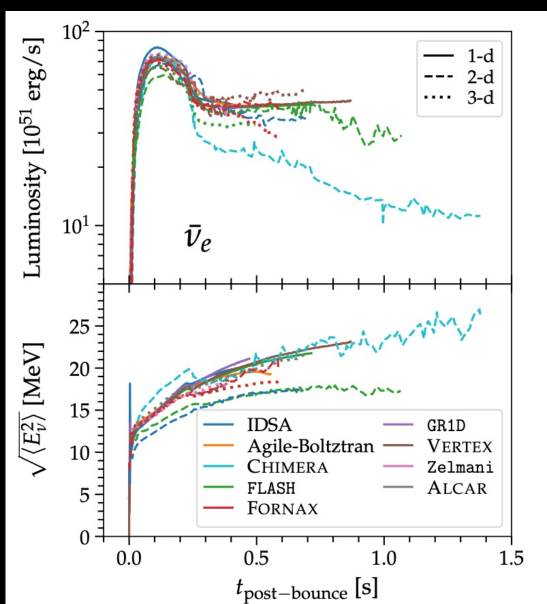
What Can We Learn From SN 1987A?

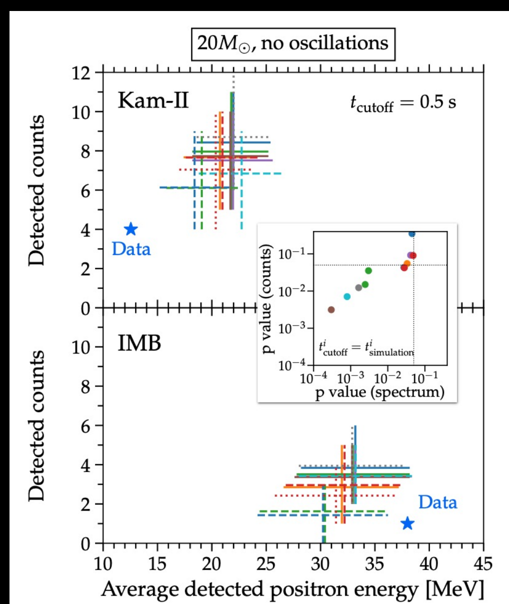
Old Data, New Forensics: The First Second of SN 1987A Neutrino Emission

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

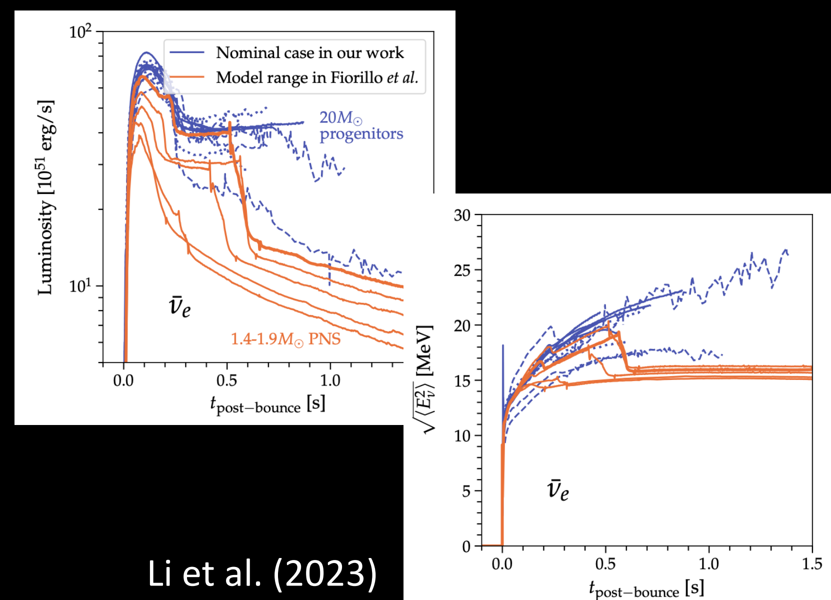
2023

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* realistic 2d and 3d models



Li et al. (2023)

Yields For a Milky Way Burst

Super-Kamiokande (32 kton water)

$\boxed{\sim 10^4 \text{ inverse beta decay on free protons}}$

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

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

Best for anti-ν_e

JUNO (20 kton mineral oil)

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

$\boxed{\sim 10^3 \text{ neutron-proton elastic scattering}}$

$\sim 10^2$ 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

DUNE (34 kton liquid argon)

$\boxed{\sim 10^3 \text{ CC and NC with argon nuclei}}$

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

Best for ν_e

How Do We Find the Supernova?

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

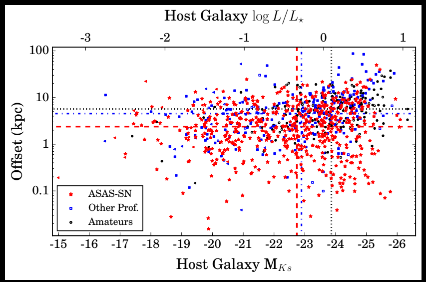
Yes by neutrino-electron scattering
No by triangulation timing

SNEWS
SUPERNOVA EARLY WARNING SYSTEM

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)



Multi-messenger characterization

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

Nearby Galaxies

Basic Idea of Mini-Bursts

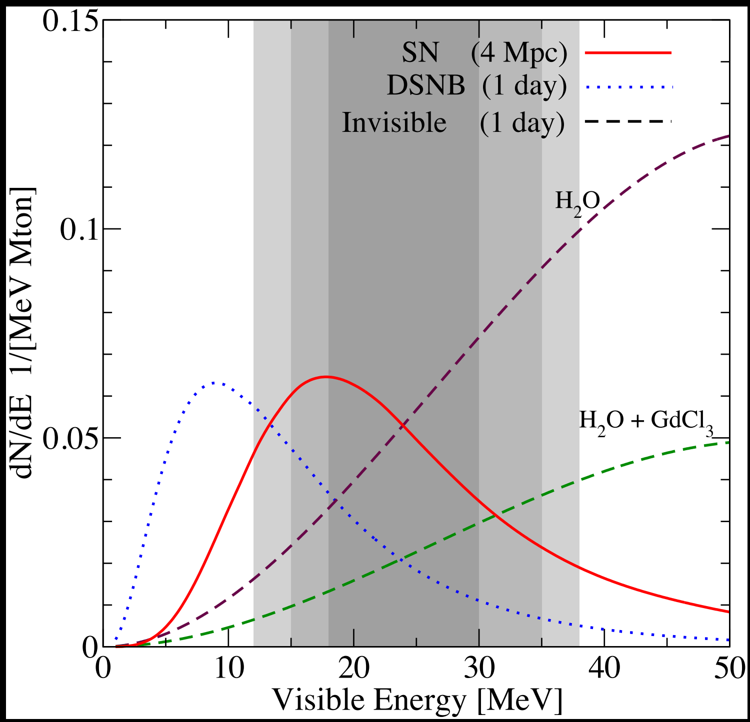
Super-K Milky Way burst (10 kpc)

- Detect ~ 10^4 events
- Backgrounds irrelevant
- Can detect even dark bursts

How about M31 (1000 kpc)?

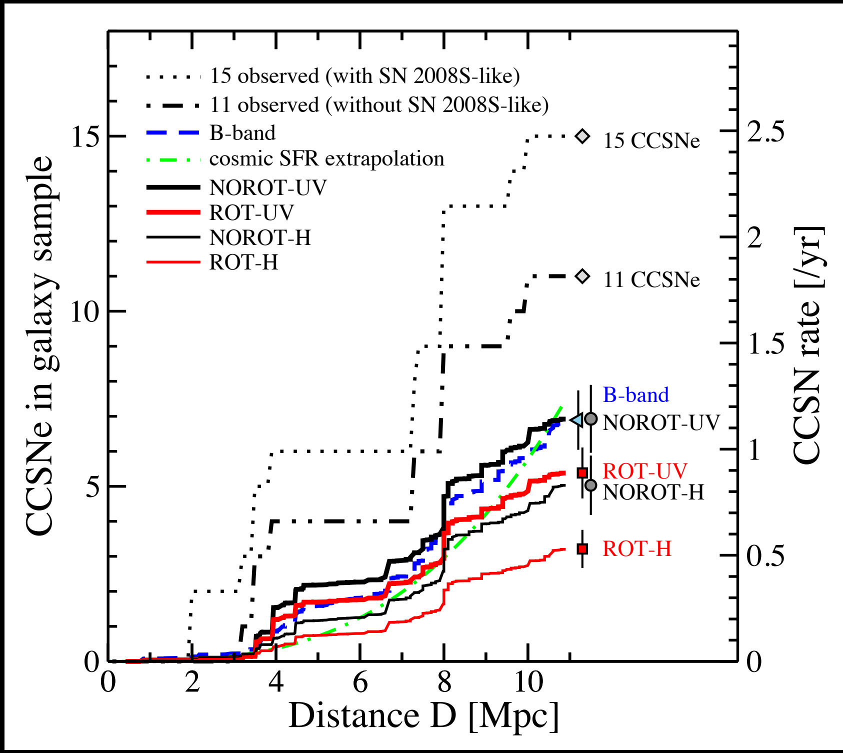
- Detect ~ 1 event
- Backgrounds large
- Optical signal needed for timing

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

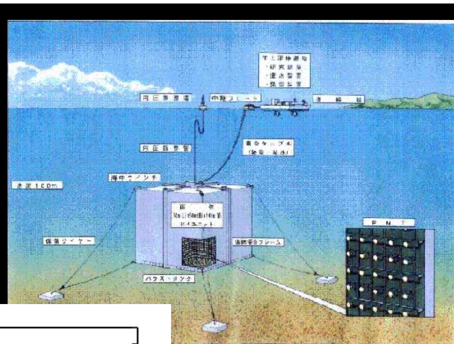
Neutrino dim, optically dim:
All the time!

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



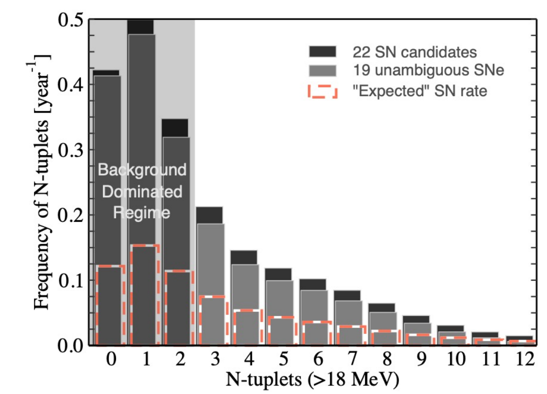
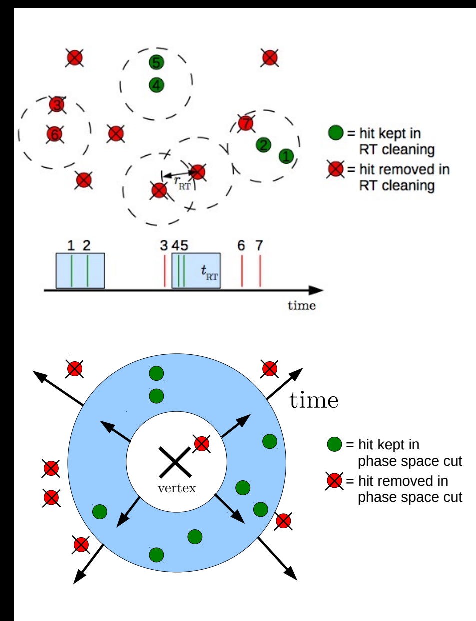


FIG. 4: Frequency of neutrino mini-bursts expected with a 5 Mton detector. The bins with $N = 3$ or more can be used for burst detection because the background rate is small enough. Three different estimates of the supernova rate are shown, as labeled.

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



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

Greatly lowers backgrounds

DSNB

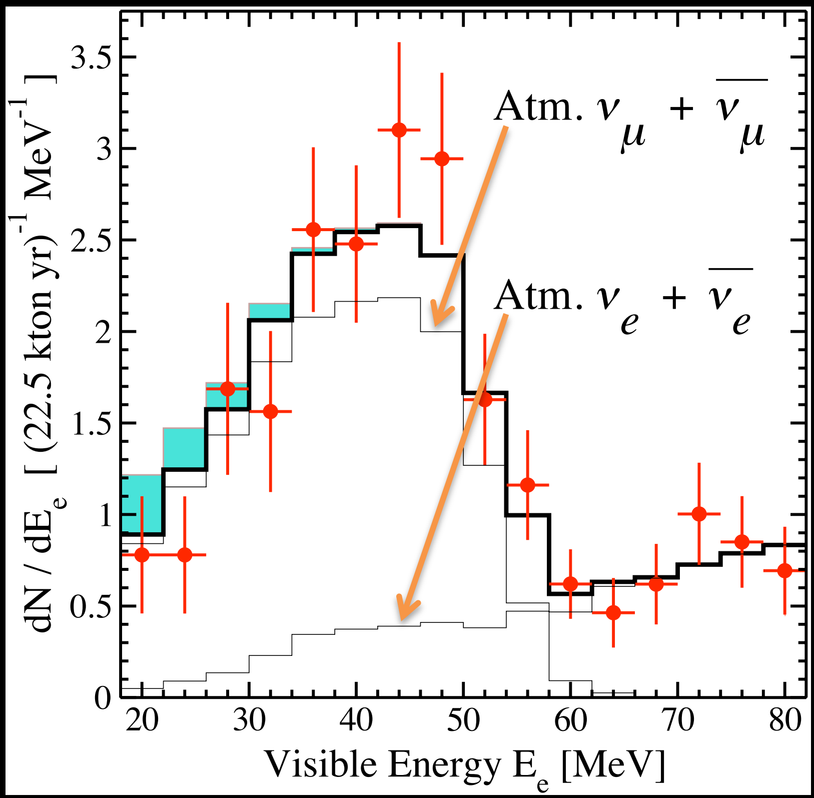
See my 2010 article in Annual Reviews of Nuclear and Particle Science

DSNB Goals in 2002

Beacom and Vagins:

We must detect the DSNB

Measured Spectrum — All Backgrounds



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

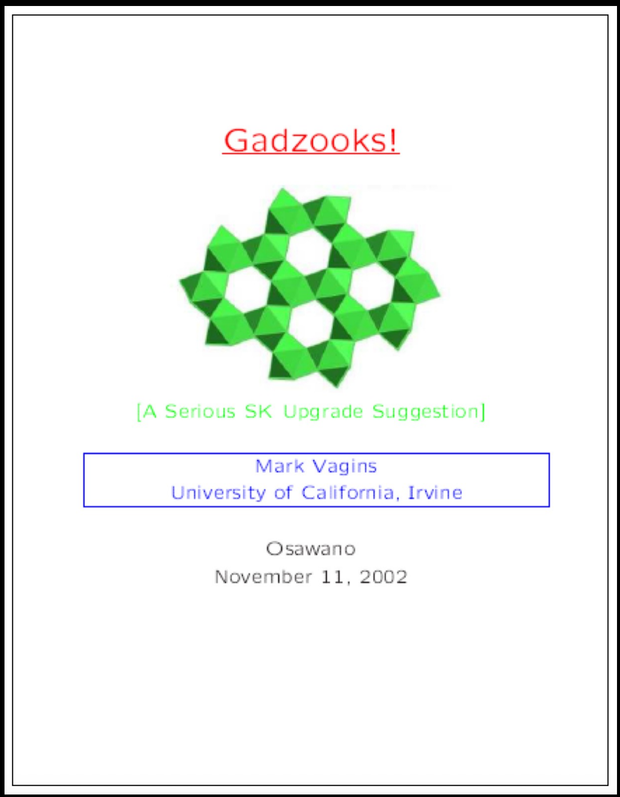
Amazing background rejection: nothing but neutrinos despite huge ambient backgrounds

Amazing sensitivity: factor ~100 over Kamiokande-II limit and first in realistic DSNB range

No terrible surprises

Challenges: *Decrease* backgrounds and energy threshold and *increase* efficiency and particle ID

GADZOOKS!


Gadzooks!

[A Serious SK Upgrade Suggestion]

Mark Vagins
University of California, Irvine

Osawano
November 11, 2002

Theoretical Framework

Signal rate spectrum in detector in terms of measured energy

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

Third ingredient: Detector Capabilities (well understood)

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

First ingredient: Neutrino spectrum (this is now the unknown)

Cosmology? Solved. Oscillations? Included. Backgrounds? See below.

First Ingredient: Supernova Neutrino Emission

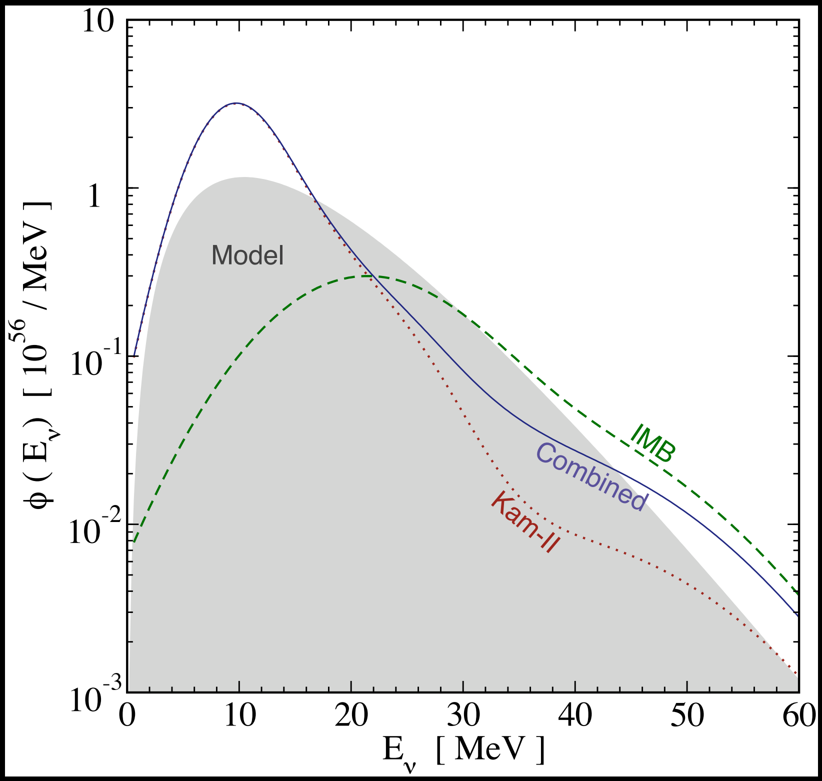
Core collapse releases ~ 3×10^{53} erg, shared by six flavors of neutrinos

Spectra quasi-thermal with average energies of ~ 15 MeV

Neutrino mixing surely important but actual effects unknown

Goal is to measure the received spectrum

Nonparametric reconstruction from SN 1987A data



Yuksel, Beacom (2007)

Importance of the Spectrum

Experiment

SN 1987A data

Experiment

DSNB data

Experiment

SN 2025gw data

?

=

¿

Theory

Supernova simulations
(*initial spectra*)
Several groups

+

Neutrino flavor change
(*effects of mixing*)
Several groups

Second Ingredient: Cosmic Supernova Rate

Number of massive stars unchanging due to short lifetimes

$$\left(\frac{dN}{dt}\right) = 0 = +\left(\frac{dN}{dt}\right)_{\substack{\text{star}\\\text{birth}}} - \left(\frac{dN}{dt}\right)_{\substack{\text{bright}\\\text{collapse}}} - \left(\frac{dN}{dt}\right)_{\substack{\text{dark}\\\text{collapse}}}$$

Measured from N/τ using luminosity and spectrum of galaxies

Measured from the core collapse supernova rate

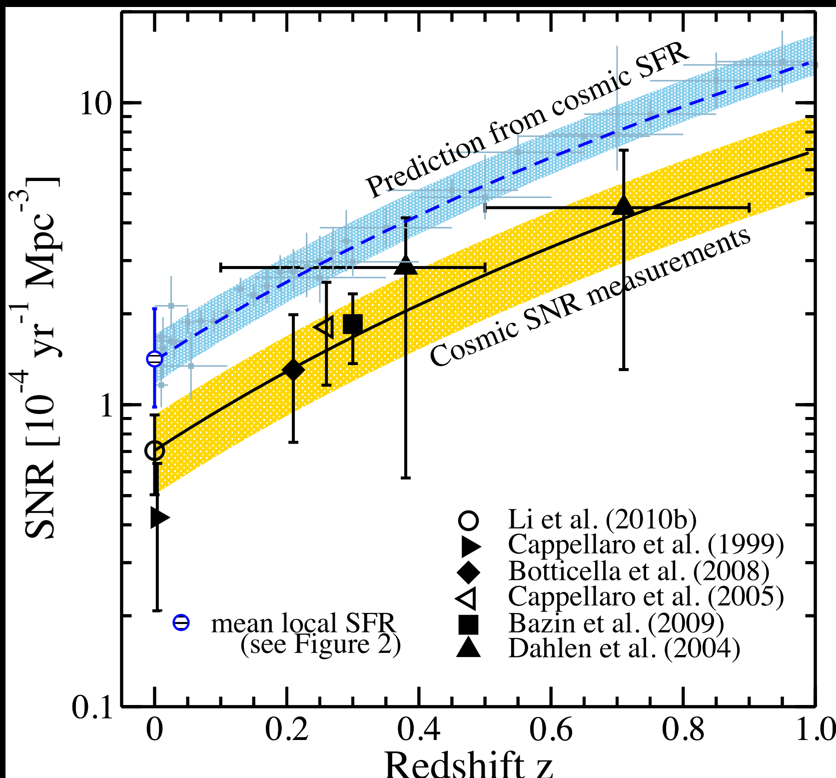
Inferred from mismatch; can be measured by star disappearance; contributes to the DSNB

(now high precision)

(improving rapidly)

(frontier topic)

Cosmic SFR and SNR



Horiuchi et al. (2011)

Measured cosmic supernova rate is half as big as expected, a greater deviation than allowed by uncertainties

Why?

There must be missing supernovae – are they faint, obscured, or truly dark?

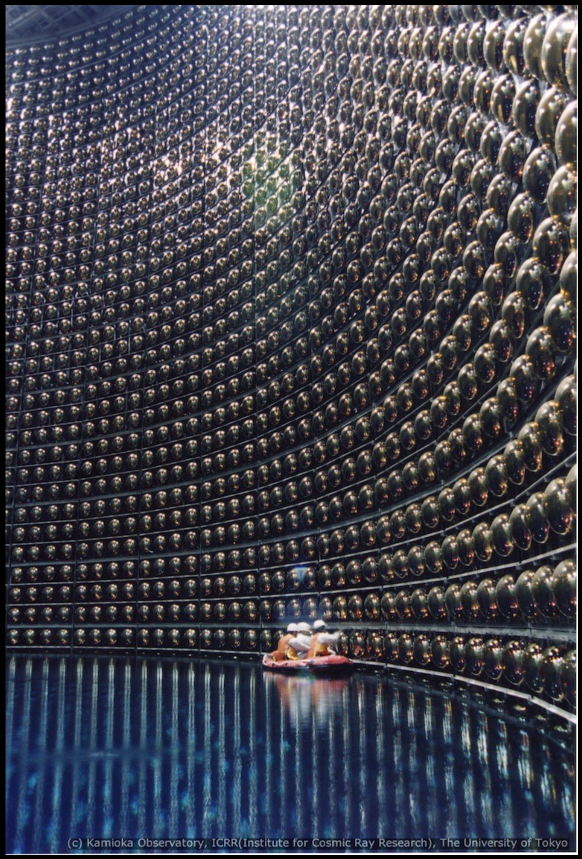
Third Ingredient: Detector Capabilities

Super-Kamiokande has large enough mass AND (nearly) low enough backgrounds

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

Free proton targets only
Cross section grows as $\sigma \sim E_\nu^2$
Kinematics good, $E_e \sim E_\nu$
Directionality isotropic

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



Super-Kamiokande

GADZOOKS! Proposal

The signal reaction produces a neutron, but most backgrounds do not

Beacom and Vagins (2003): First proposal to use dissolved gadolinium in large light water detectors showing it could be practical and effective

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

SK

Neutron capture on protons
Gamma-ray energy 2.2 MeV
Hard to detect in SK

SK+Gd

Neutron capture on gadolinium
Gamma-ray energy ~ 8 MeV
Easily detectable coincidence
separated by ~ 4 cm and ~ 20 μs

Benefits of Neutron Tagging for DSNB

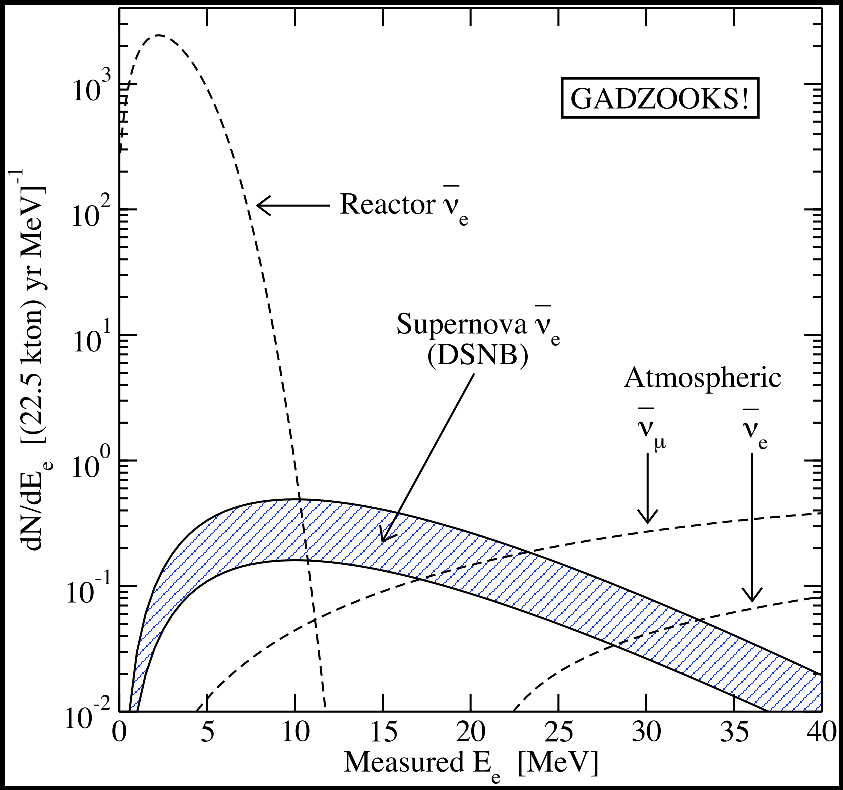
Solar neutrinos:
eliminated

Spallation daughter decays:
essentially eliminated

Reactor neutrinos:
now a visible signal

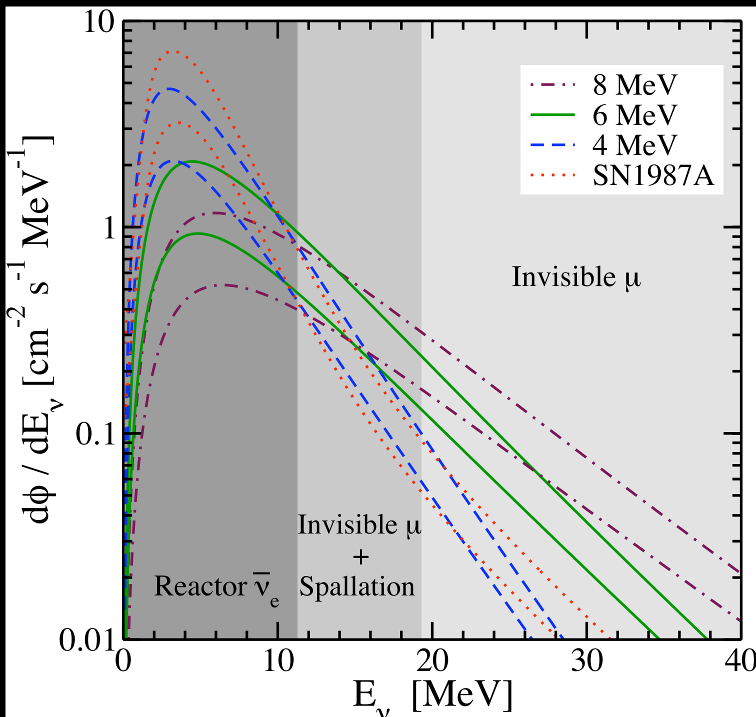
Atmospheric neutrinos:
significantly reduced

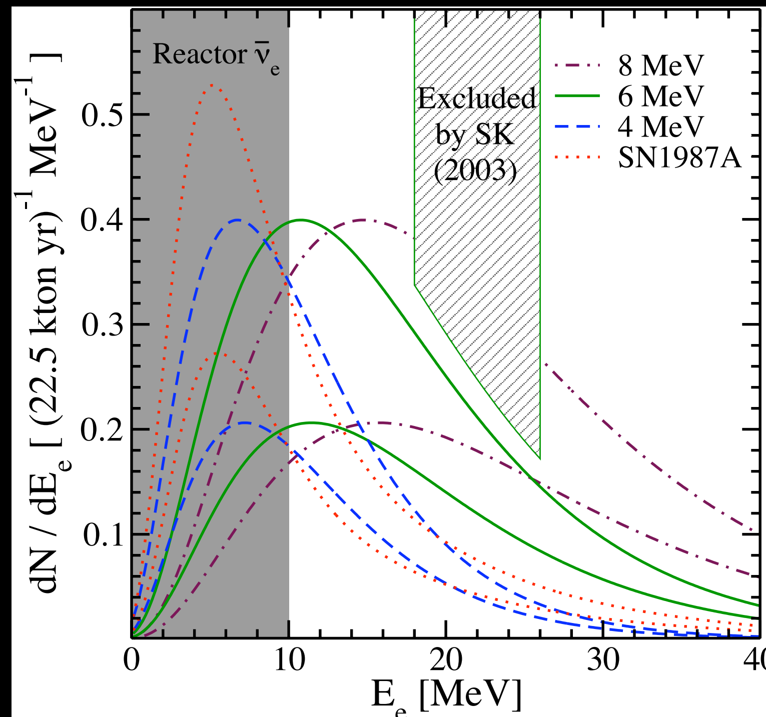
DSNB:
More signal, less background!



Beacom, Vagins (2004)

Predicted Flux and Event Rate Spectra

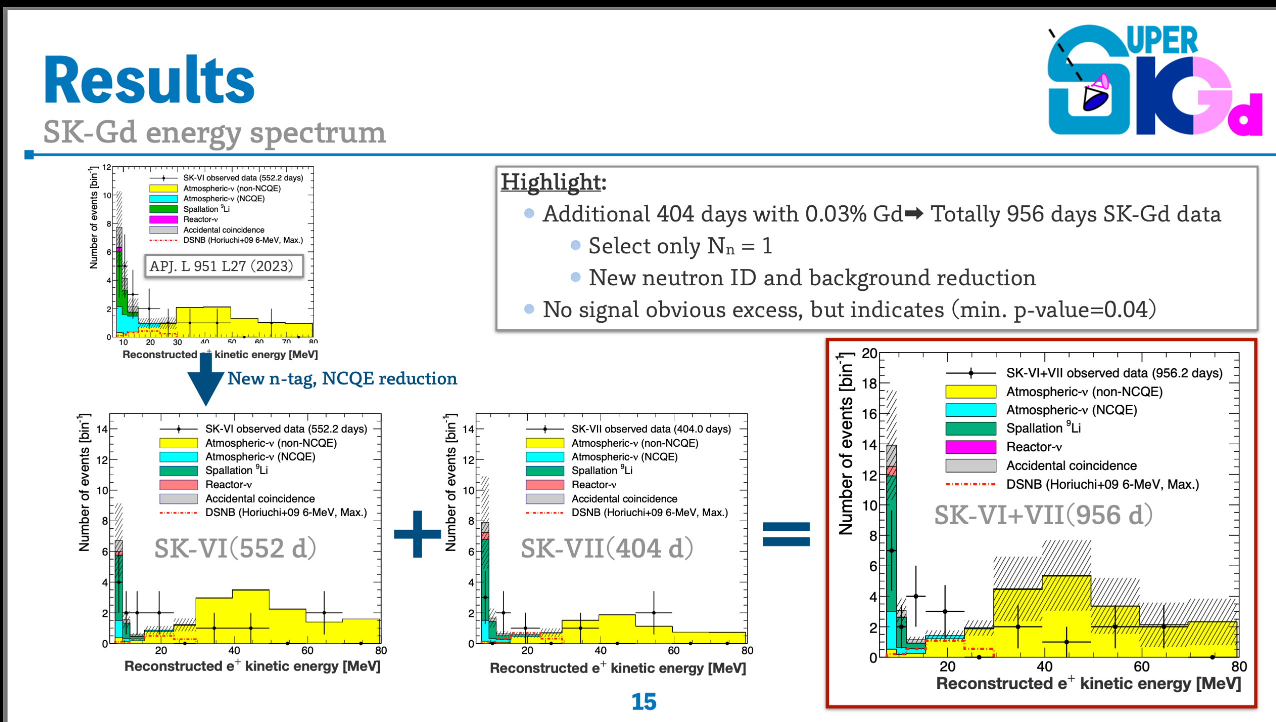




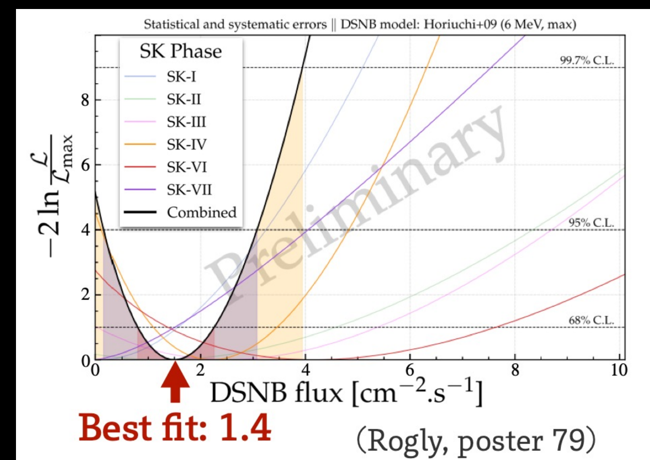
Horiuchi , Beacom, Dwek (2009)

Bands show full uncertainty range arising from cosmic supernova rate

Recent Super-Kamiokande Results



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 **$1.4^{+0.8}_{-0.6}$ cm^{-2} s^{-1}** for E_ν > 17.3 MeV

➡ **exhibit ~2.3 σ excess!!**

Impact of DSNB Detection

Guaranteed signal:
SK has a few DSNB nuebar signal interactions per year

Super-Kamiokande upgrade:
Gadolinium has been added and is causing no problems

Supernova implications:
Direct test of the average neutrino emission per supernova

Broader context:
Possible first detections besides Sun and SN 1987A

Other Physics Enabled by Gadolinium

Supernova burst detection:
Isolation of non-nuebar signals, early and late-time detection

Solar neutrinos:
Suppression of spallation backgrounds

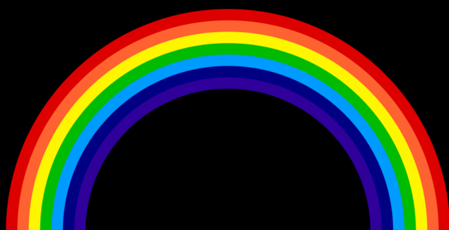
Reactor neutrinos:
New signal at low energies

Atmospheric neutrinos:
Separation of nu and nubar to test matter effects

Proton decay:
Reduction of backgrounds

Closing Message

Neutrinos

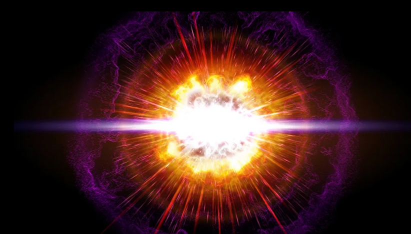


Electromagnetic

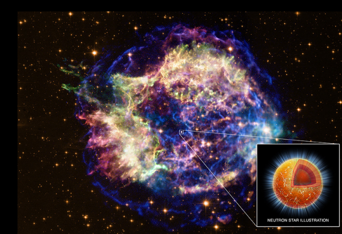
Gravitational Waves

Before

During



After



This is the only way to answer all the questions about supernovae