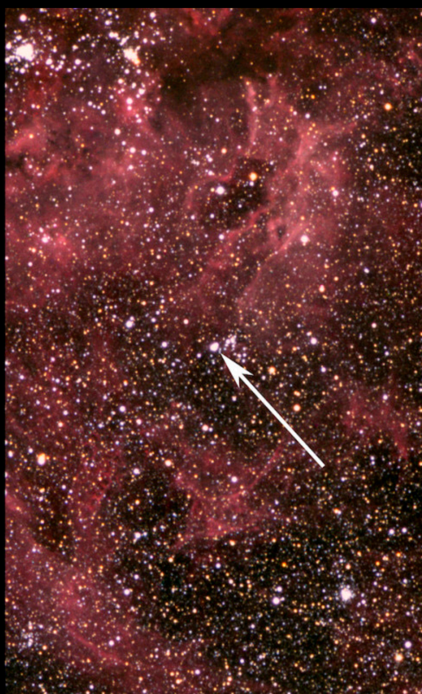
Astrophysical Neutrinos: Sources and Detection (SNe)

John Beacom, The Ohio State University



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

Unique Impacts of Neutrino Astronomy

To understand astrophysics,
only neutrinos can reveal extreme conditions

To understand neutrinos,
only extreme conditions can reveal particle properties

Neutrino Astronomy – How Possible?

Factors we can't control

Nature provides sources: luminous, high-energy, varied

Factors we can control

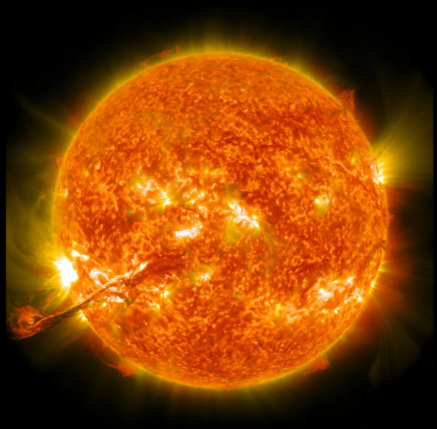
We provide detectors: big, sensitive, low-background

Factors that require wisdom

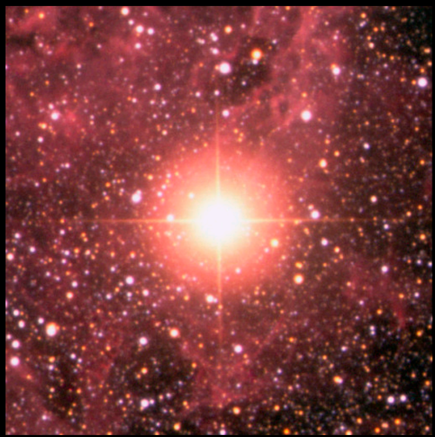
We provide leverage: power of SM data, EM observations

Neutrino Astronomy is Real

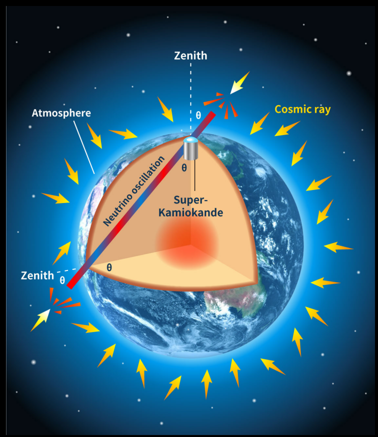
Sun



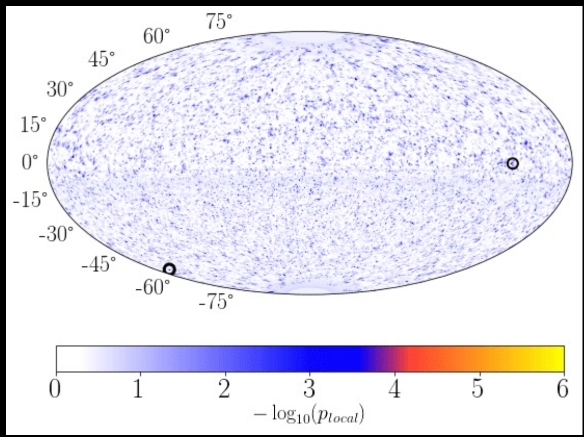
SN 1987A



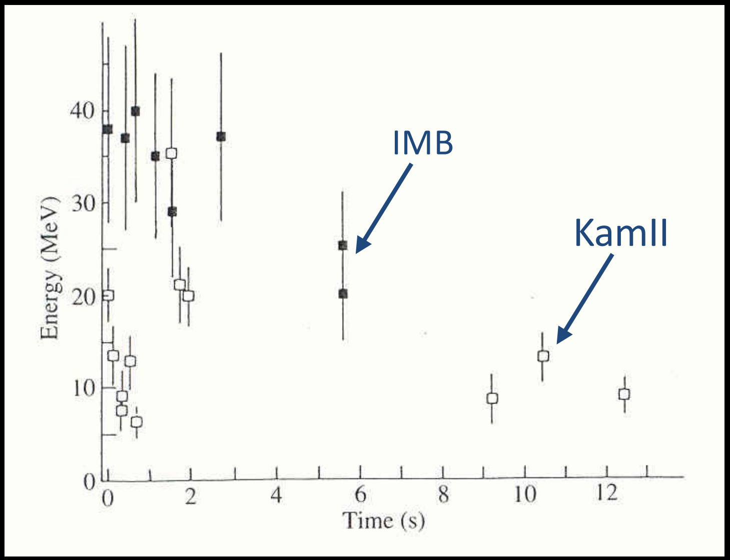
Atmosphere



Extragalactic Sources



SN 1987A — A Rosetta Stone



Observation: Type II supernova progenitors are massive stars

Observation: The neutrino precursor is very energetic

Theory: Core collapse makes a proto-neutron star and neutrinos

What Does This Leave Unknown?

Total energy emitted in neutrinos?
Partition between flavors?
Emission in other particles?
Spectrum of neutrinos?
Neutrino mixing effects?

…

Supernova explosion mechanism?
Nucleosynthesis yields?
Neutron star or black hole?
Electromagnetic counterpart?
Gravitational wave counterpart?

…

and much more!

Outline

Openings
Neutrino astronomy
Supernova neutrinos

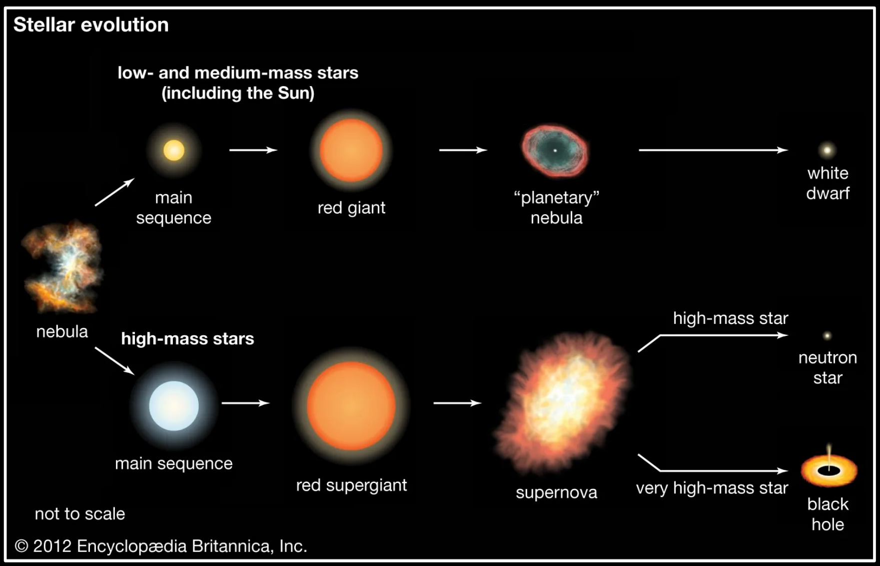
How it works
Neutrino production
Neutrino propagation
Neutrino detection

Discovery Frontiers
DSNB

Bonus Material
Career skills

Neutrino Production

What is a Core-Collapse Supernova?



"Massive" stars: above about $8M_{sun}$

Luminous, rare, short-lived

Early idea:
"Neutrino Theory of Stellar Collapse,"
Gamow and Schoenberg (1941)

Core collapses (emitting neutrinos)
Envelope expands (emitting light)

Group discussion on the board:

What is the total energy release?

Further Details

Group discussion on the board:

What is the density?

What is the column density?

What does this imply?

Other key estimates:

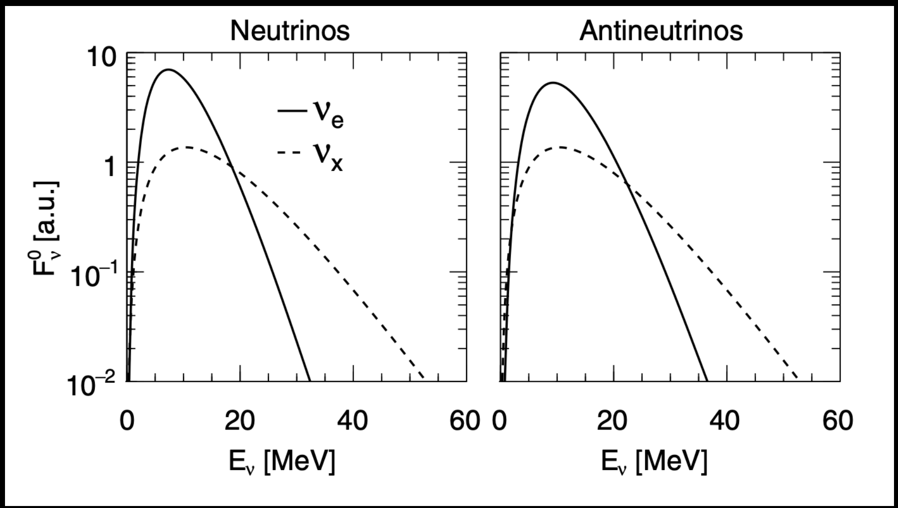
<E_ν> ~ 100 MeV in core

<E_ν> ~ 10 MeV at surface

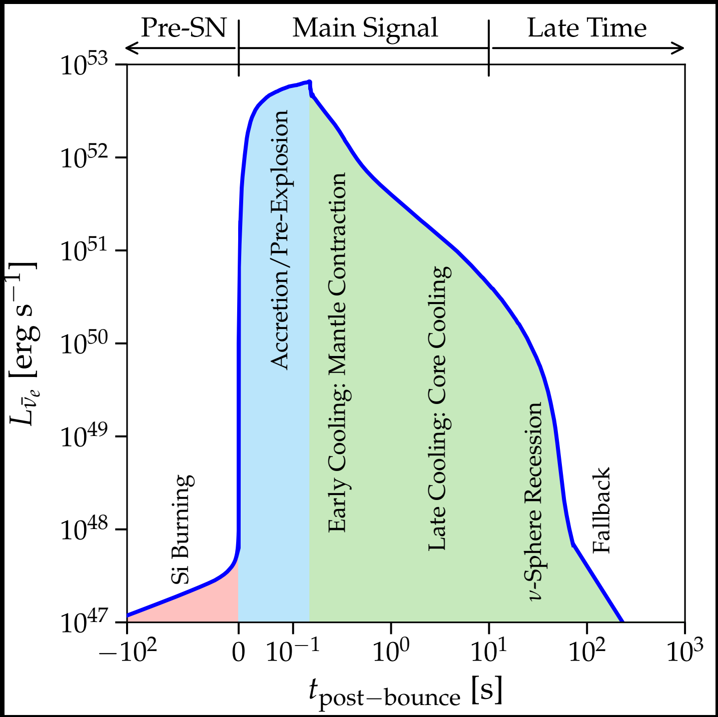
Diffusion over seconds

See Chang et al., 2206.12426

Spectra and Time Profiles



Capozzi, Dasgupta, Mirizzi (2018)

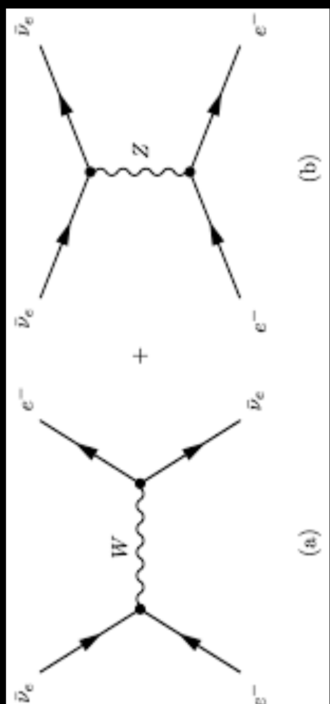


Li, Roberts, and Beacom (2021)

Neutrino Propagation

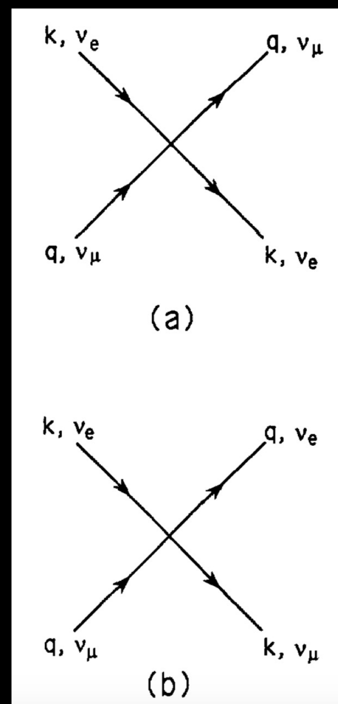
Neutrino Mixing

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

Is This Uncertainty a Problem?

Yes

If we want to compare neutrino data to theory

If we want to precisely test new physics

No

If we want to compare neutrino data to data

If we want to roughly test new physics

Why?

Nothing happens to the neutrinos en route!

The extreme conditions give us a great lever arm

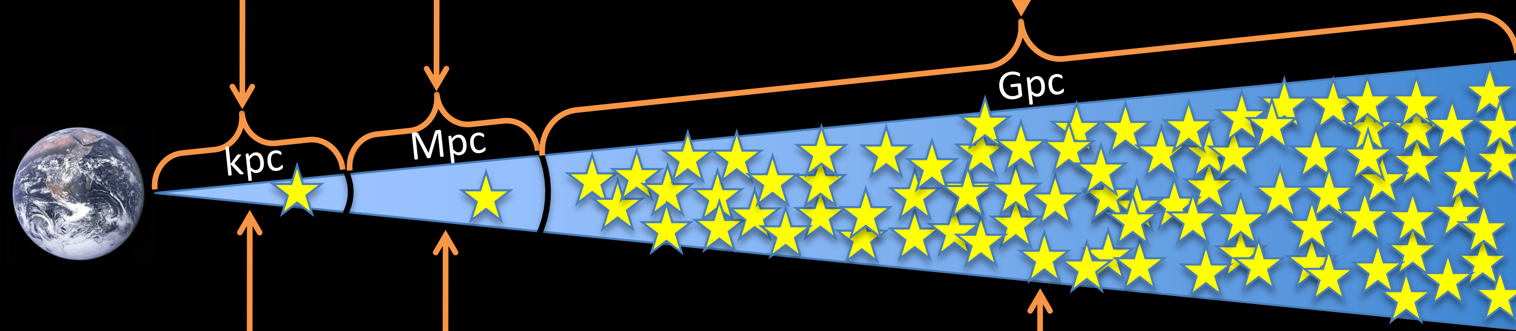
Neutrino Detection

Distance Scales and Detection Strategies

N >> 1 : Burst

N ~ 1 : Mini-Burst

N << 1 : DSNB



Rate ~ 0.01/yr

Rate ~ 1/yr

Rate ~ 10^8/yr

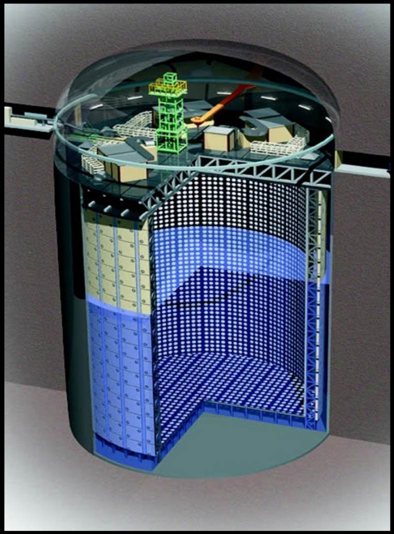
high statistics,
all flavors

object identity,
burst variety

cosmic rate,
average emission

New Multi-kton Neutrino Detectors

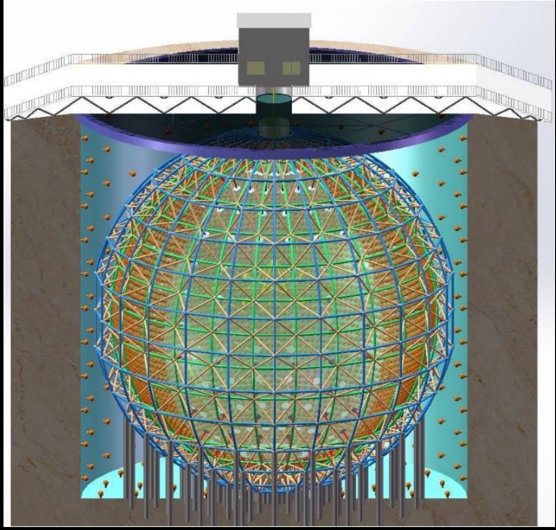
Super-K Gd



32 kton water+Gd
running (Japan)

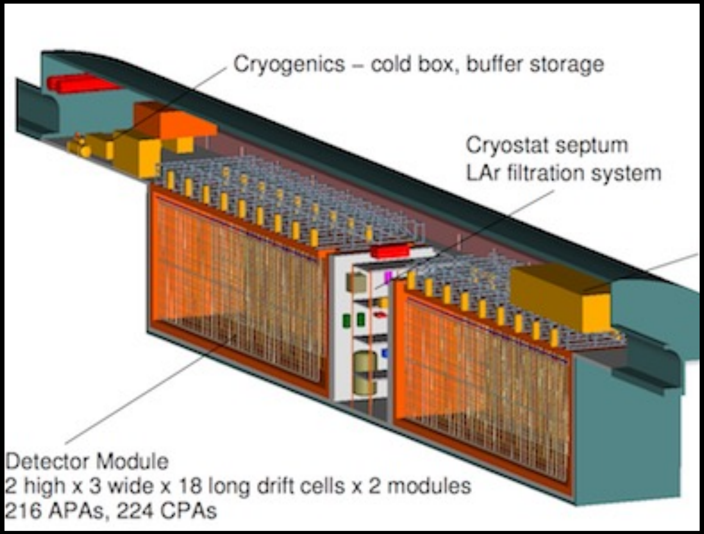
+
Hyper-K (260 kton) starts 2028

JUNO



20 kton scintillator
starts 2025 (China)

DUNE



34 kton liquid argon
starts ~2030 (United States)

Burst Detection Generalities

Group discussion on the board:

What are the neutrino fluences?

How many events do we expect?

Group discussion on the board:

What interactions are possible?

Why are multiple detectors important?

DSNB

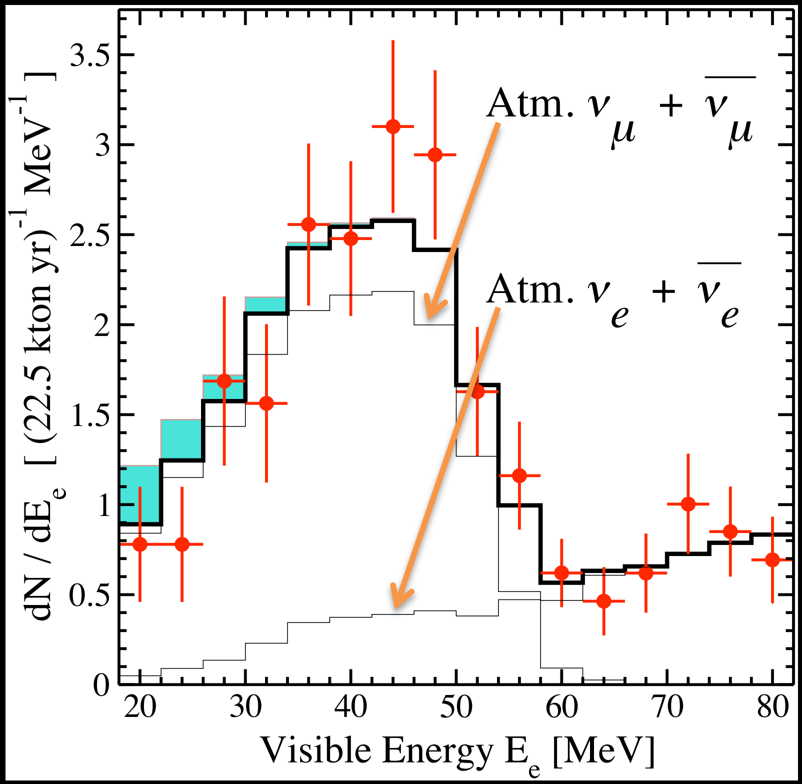
See my 2010 article in Annual Reviews of Nuclear and Particle Science

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)

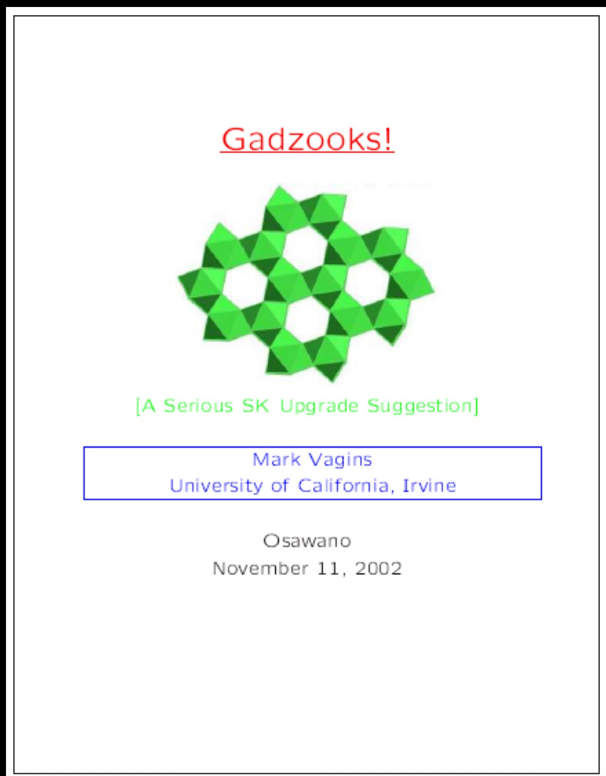
Amazing background rejection: nothing but neutrinos despite huge ambient backgrounds

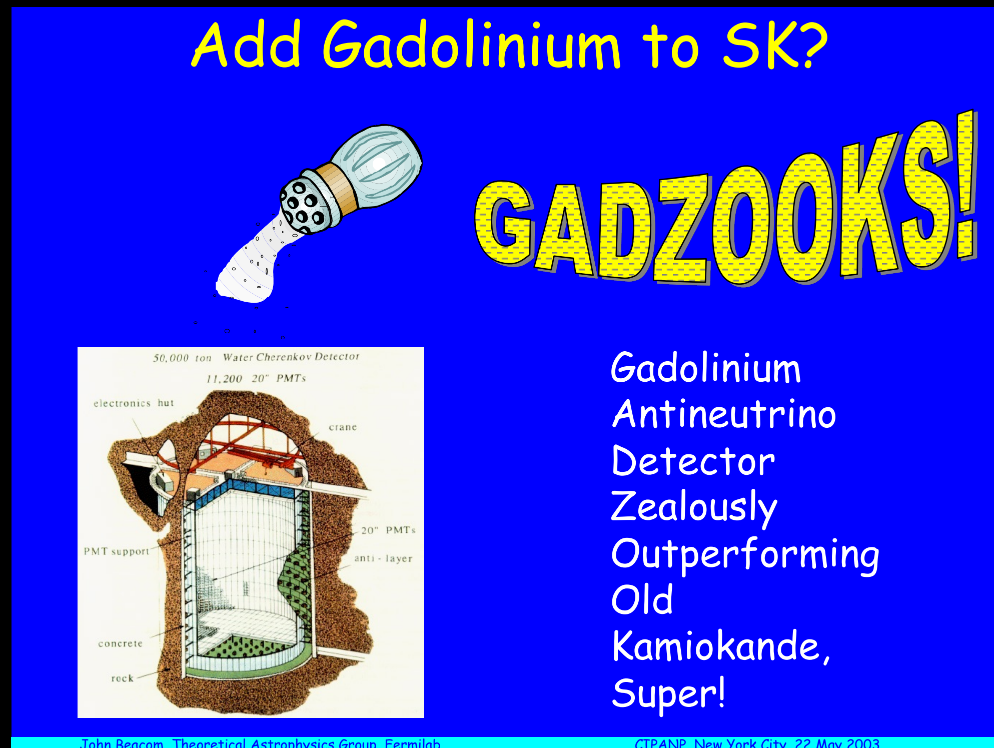
Amazing sensitivity: factor ~100 over Kamiokande-II limit and first in realistic DSNB range

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


Add Gadolinium to SK?
GADZOOKS!
50,000 ton Water Cherenkov Detector
11,200 20" PMTs
electronics hut
crane
20" PMTs
anti - layer
PMT support
concrete
rock
Gadolinium
Antineutrino
Detector
Zealously
Outperforming
Old
Kamiokande,
Super!
John Beacom, Theoretical Astrophysics Group, Fermilab
CIPANP, New York City, 22 May 2003

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 (this is now the unknown)

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

First Ingredient: Supernova Neutrino Emission

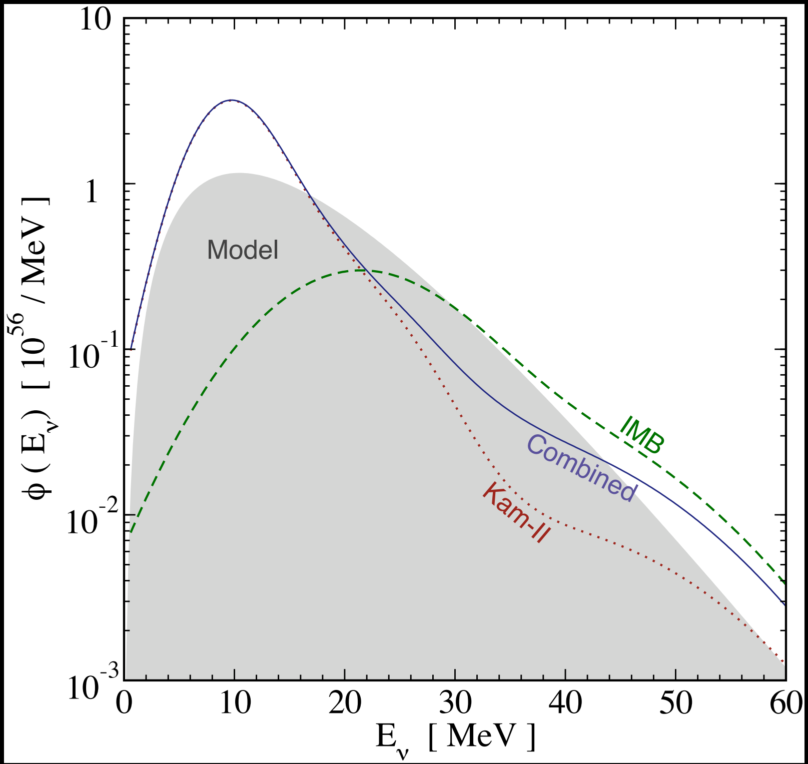
Core collapse releases ~ 3×10^{53} erg, shared by six flavors of neutrinos

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 2025zzz 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

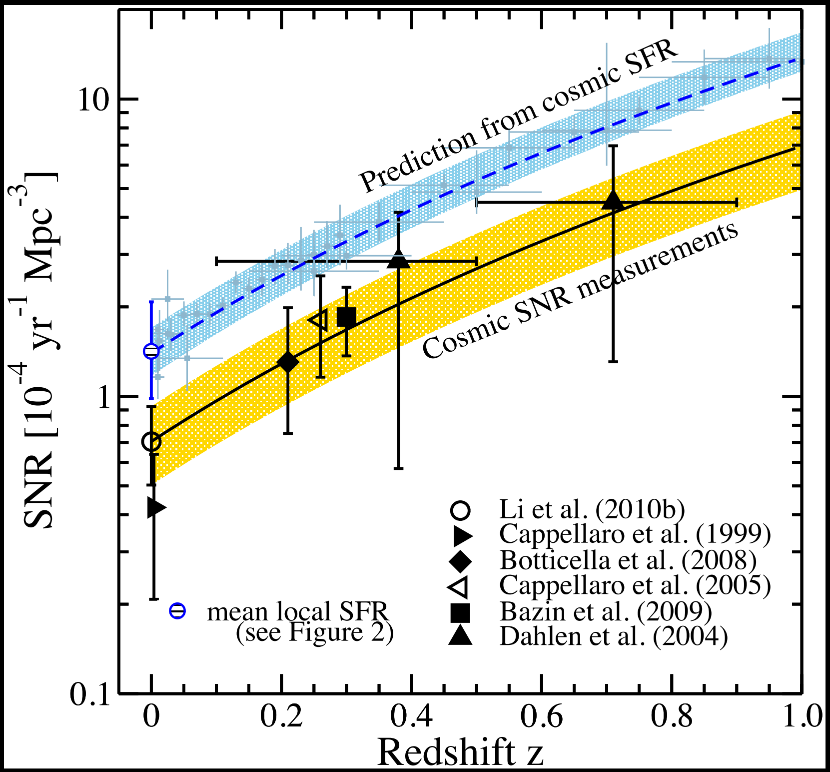
Inferred from mismatch; can be measured by star disappearance; contributes to the DSNB

(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?

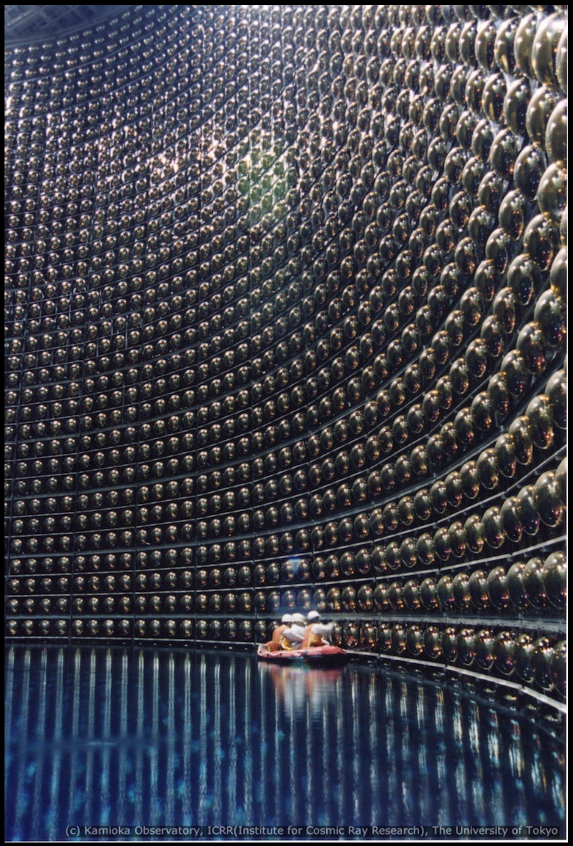
Third Ingredient: Detector Capabilities

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

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

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

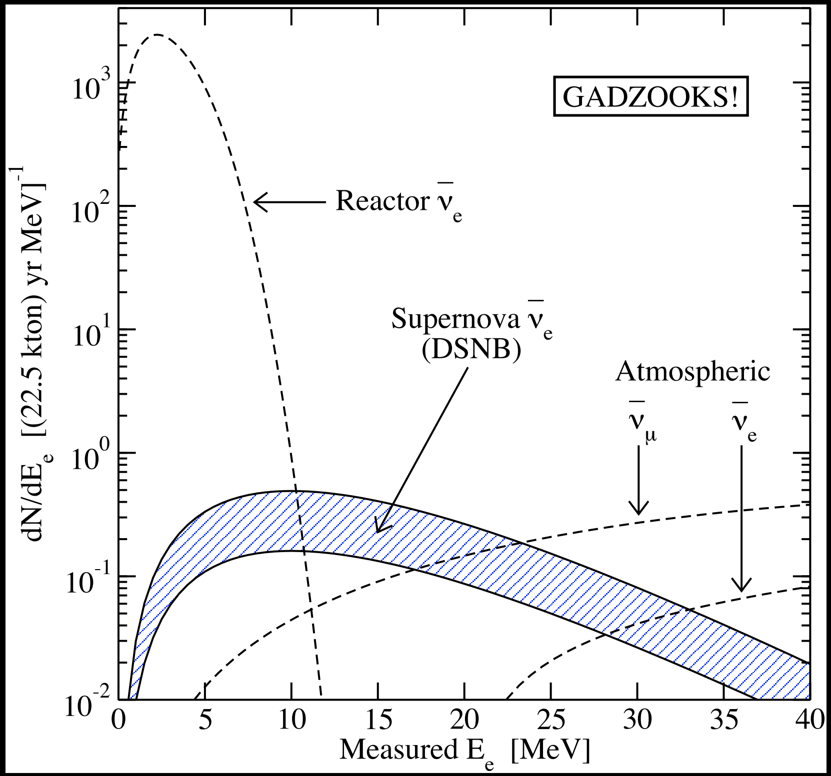
Solar neutrinos:
eliminated

Spallation daughter decays:
essentially eliminated

Reactor neutrinos:
now a visible signal

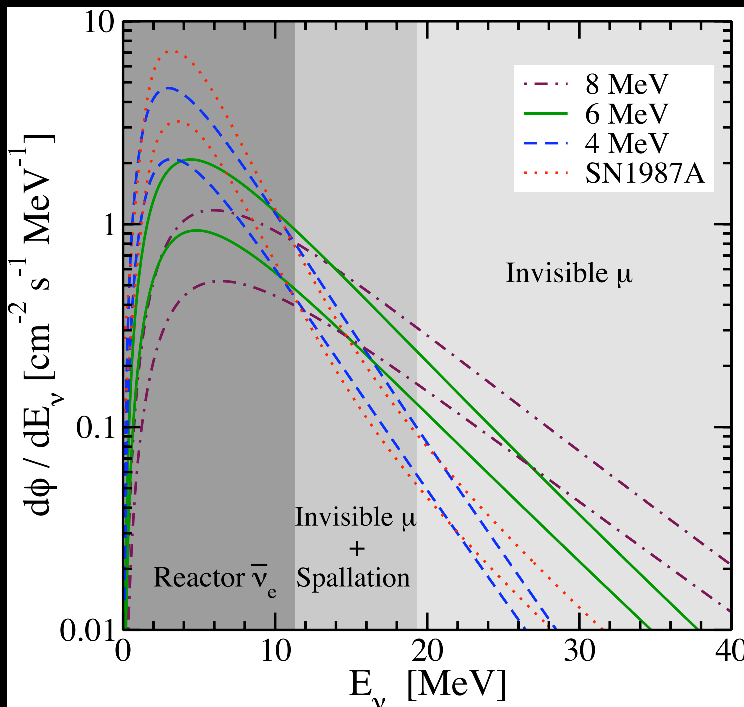
Atmospheric neutrinos:
significantly reduced

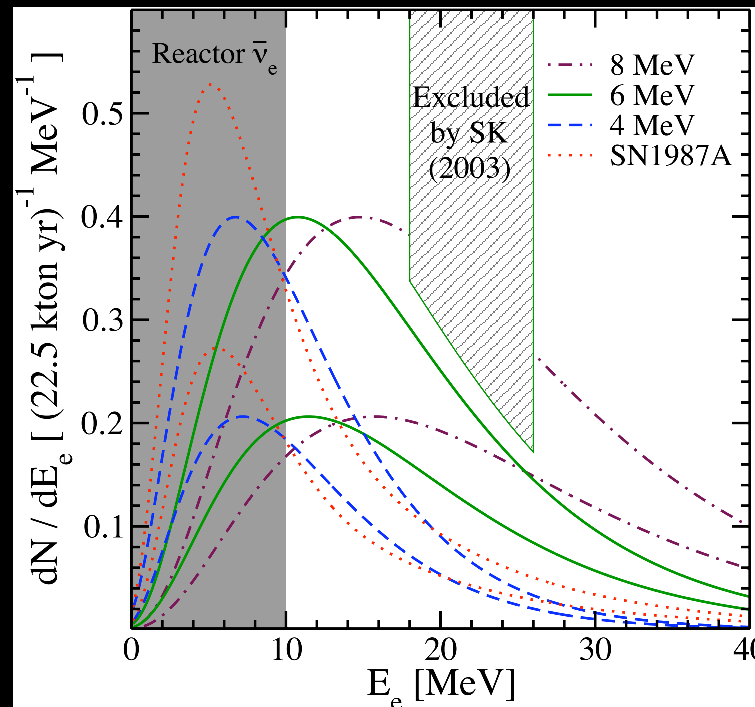
DSNB:
More signal, less background!



Beacom, Vagins (2004)

Predicted Flux and Event Rate Spectra





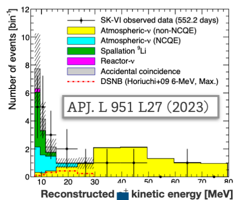
Horiuchi , Beacom, Dwek (2009)

Bands show full uncertainty range arising from cosmic supernova rate

Recent Super-Kamiokande Results

Results

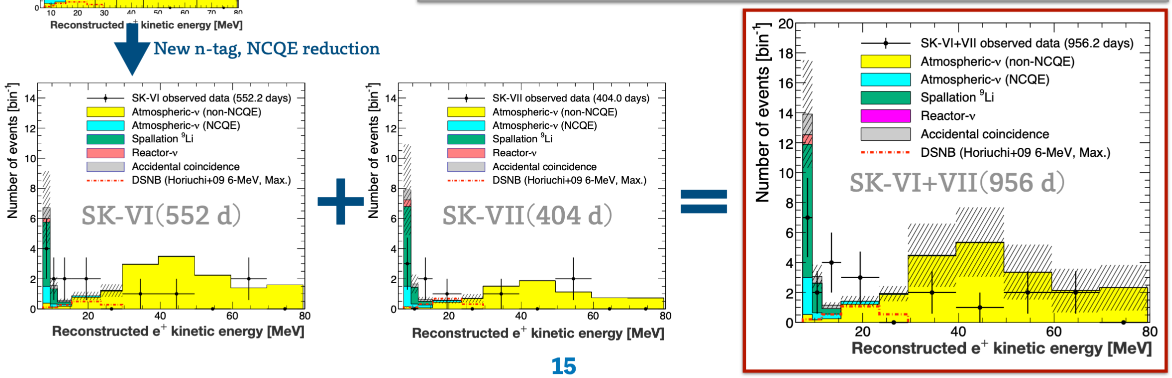
SK-Gd energy spectrum



New n-tag, NCQE reduction

Highlight:

- Additional 404 days with 0.03% Gd ➡ Totally 956 days SK-Gd data
  - Select only $N_n = 1$
  - New neutron ID and background reduction
- No signal obvious excess, but indicates (min. p-value=0.04)



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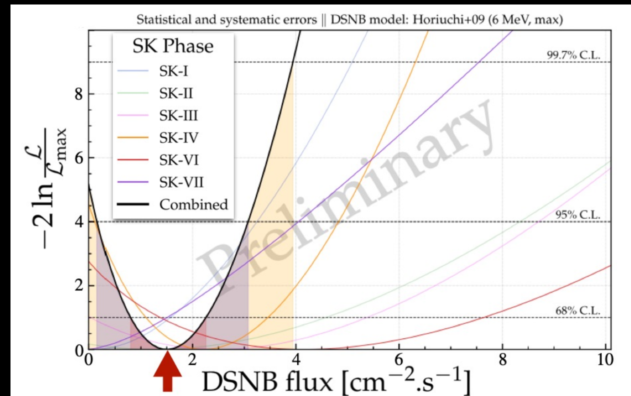

Best fit: 1.4

(Rogly, poster 79)

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 $\mathbf{1.4^{+0.8}_{-0.6}}$ **cm^{-2} s^{-1}** for $E_\nu > 17.3$ MeV

➡ **exhibit ~2.3 σ excess!!**

Super-Kamiokande (2024)

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 take patience, but they reward it richly

Bonus Material: Career Skills

Group Discussion at the Board:

1. Increasing visibility (ORCID, webpage, LinkedIn)
2. Building work skills (Erdos Institute, LinkedIn)
3. Building AI skills within ethical guidelines
4. Strategy, selection, and happiness
5. [Discussion topics following audience interest]

For more: YouTube, “John Beacom mentoring matters” (starts around 00:20:00)