Super-Kamiokande with Gadolinium: Supernova Detection and More

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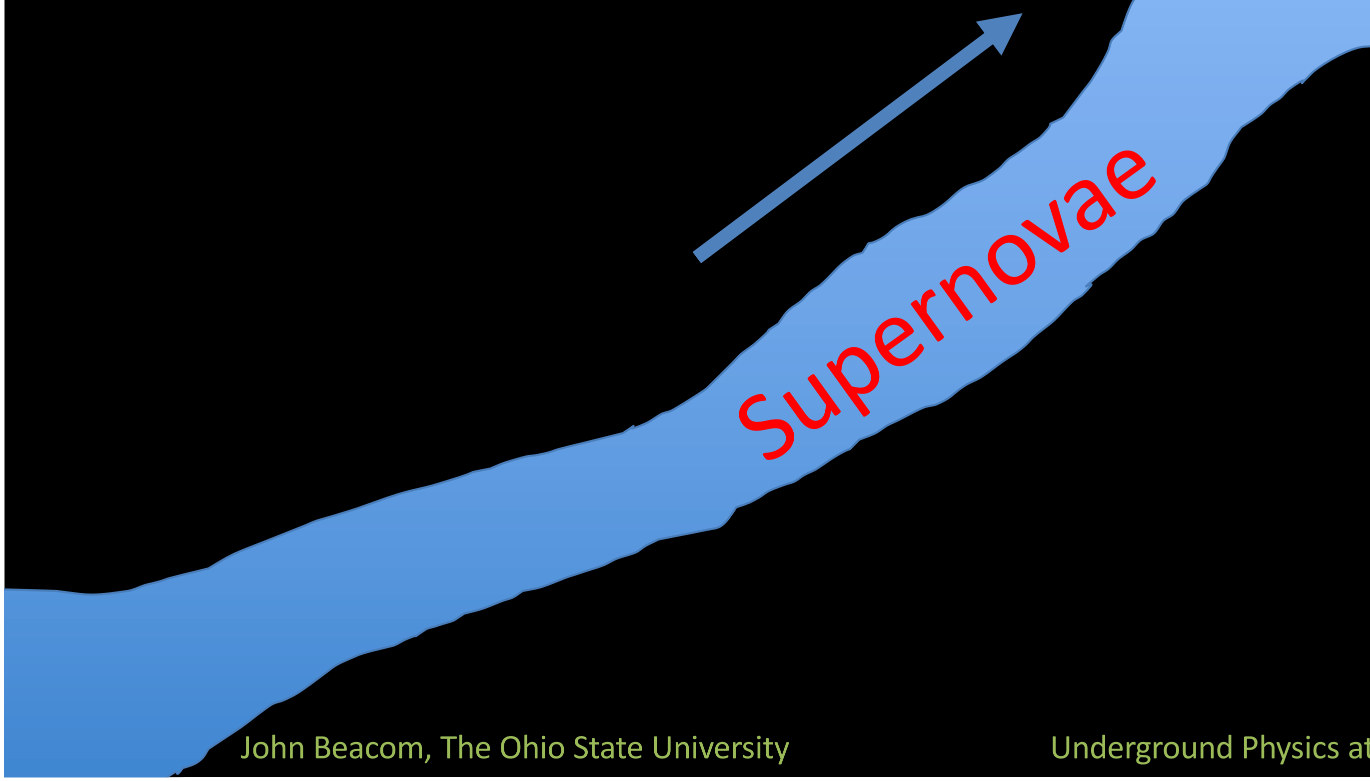
CCAPP

NSF

Gateway: Astrophysics

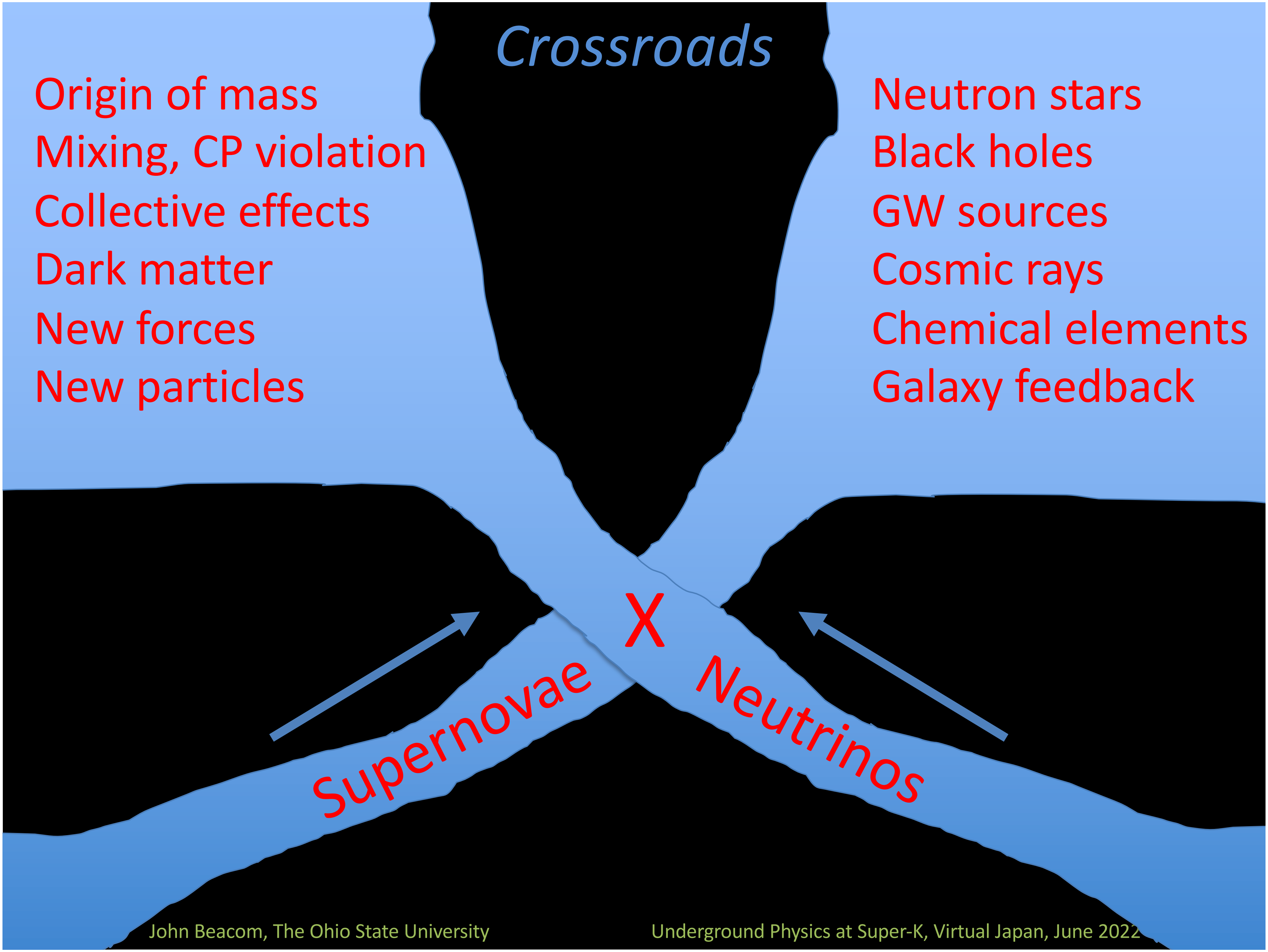
- Neutron stars
- Black holes
- GW sources
- Cosmic rays
- Chemical elements
- Galaxy feedback



Gateway: Particle Physics

Origin of mass
Mixing, CP violation
Collective effects
Dark matter
New forces
New particles

Neutrinos


Crossroads
Origin of mass
Mixing, CP violation
Collective effects
Dark matter
New forces
New particles
Neutron stars
Black holes
GW sources
Cosmic rays
Chemical elements
Galaxy feedback
X
Supernovae
Neutrinos
John Beacom, The Ohio State University
Underground Physics at Super-K, Virtual Japan, June 2022

Why a Crossroads?

To understand supernovae

only neutrinos can reveal these extreme conditions

To understand neutrinos

only these extreme conditions can reveal particle properties

Crossroads: Past Versus Future

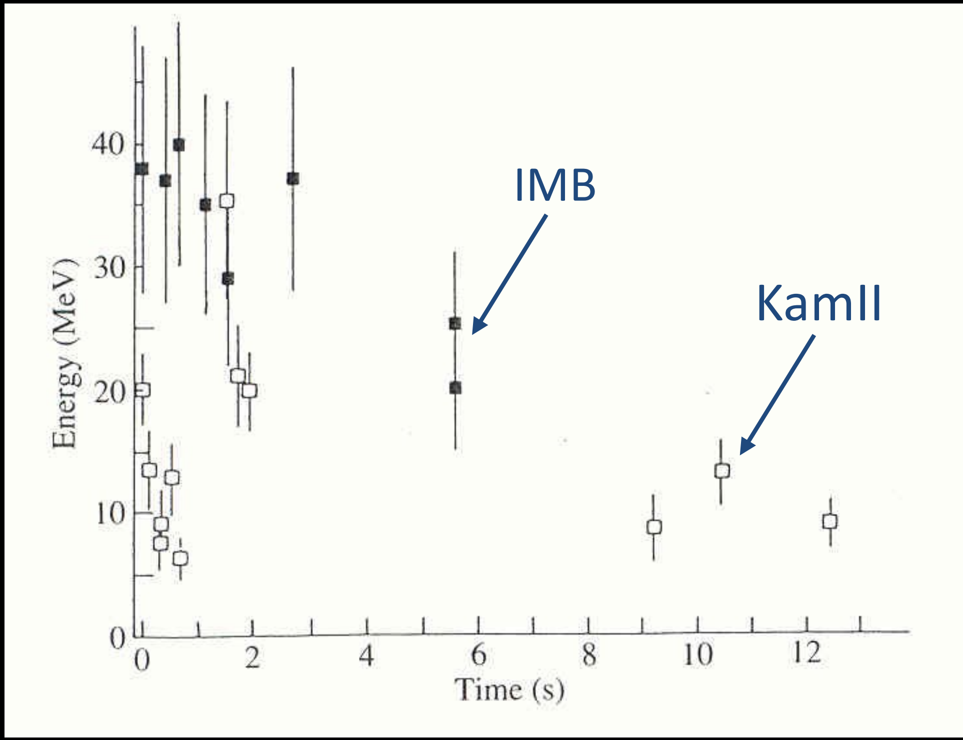
Are we ready?

For Milky Way burst detection?
To precisely detect the DSNB?
To detect extragalactic minibursts?

To advance multimessenger astrophysics?
To probe physics beyond the standard model?
To make neutrino astronomy real?

What should we do differently?

SN 1987A: Our Rosetta Stone



Observation: Type II supernova progenitors are massive stars

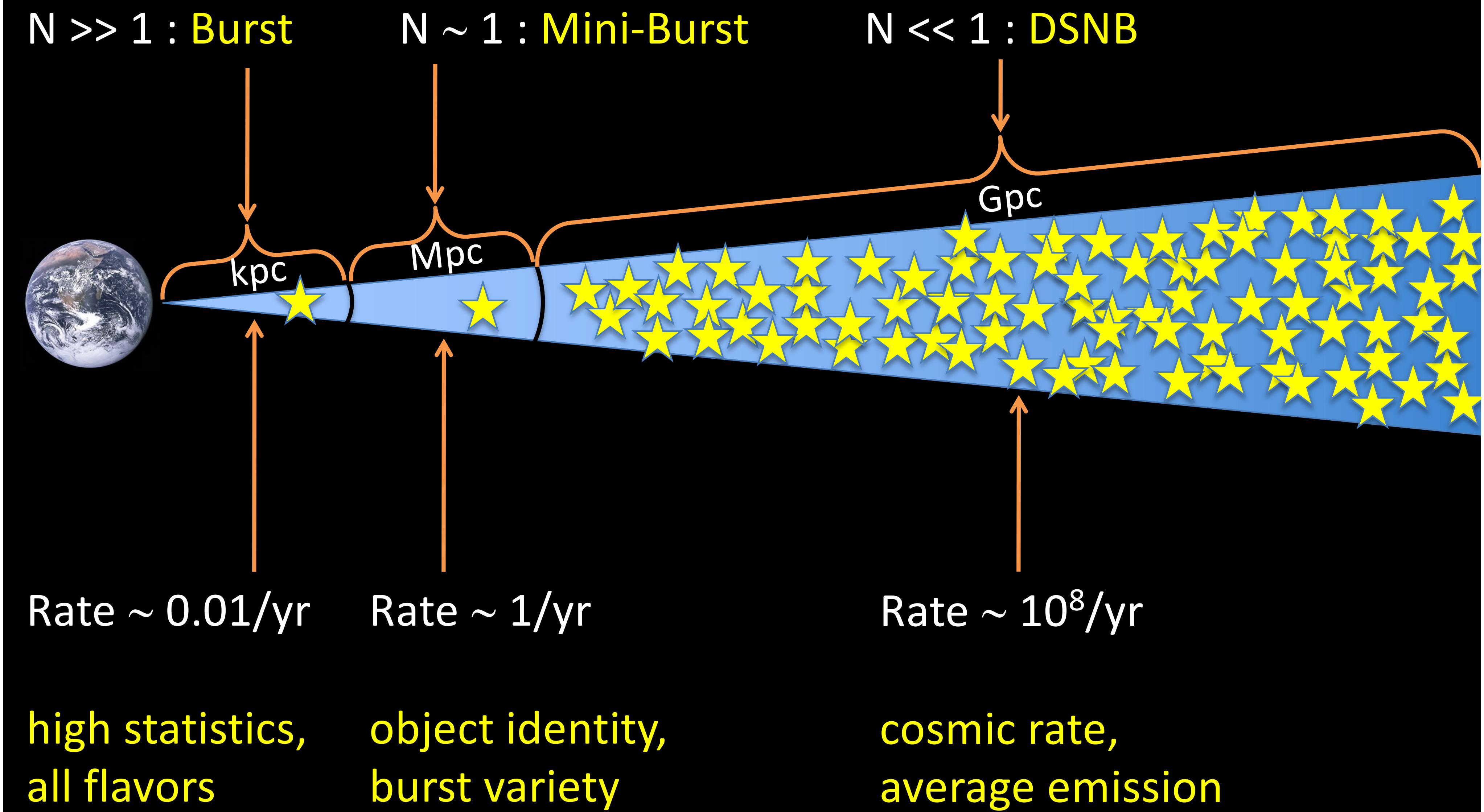
Observation: The neutrino precursor is very energetic

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!

Distance Scales and Detection Strategies



Cosmic Deep Fields

Stellar Photons (~ eV)

energy density ~ 0.01 eV / cm^3

Supernova Neutrinos (~ MeV)

energy density ~ 0.01 eV / cm^3

DSNB Goals in 2002

Beacom and Vagins:

We must detect the DSNB

Standard Model of Predicted DSNB

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

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

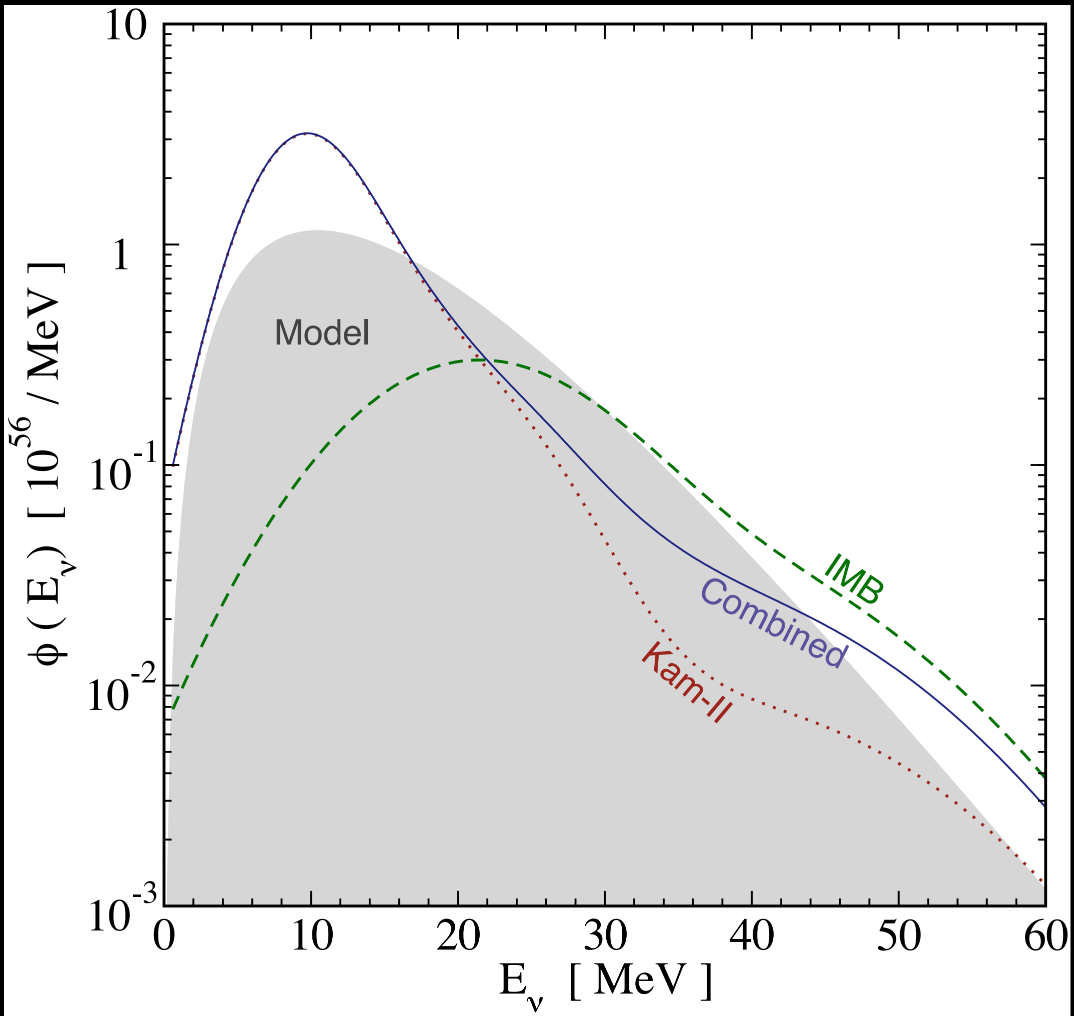
Core collapse releases ~ 3×10^{53} erg, shared by six flavors of neutrinos

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)

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

(now high precision)

Measured from the core collapse supernova rate

(precision will improve rapidly)

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

(frontier research area)

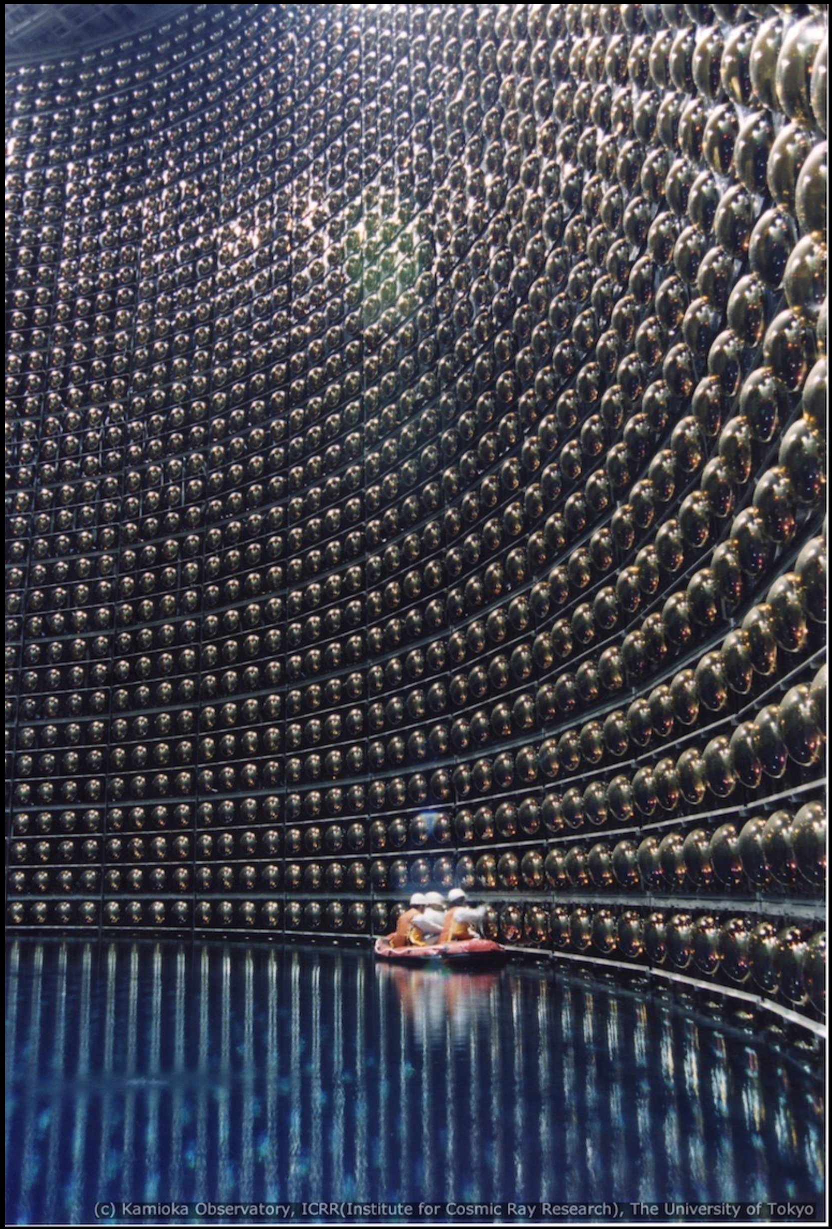
Third Ingredient: Neutrino Detection Capabilities

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

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

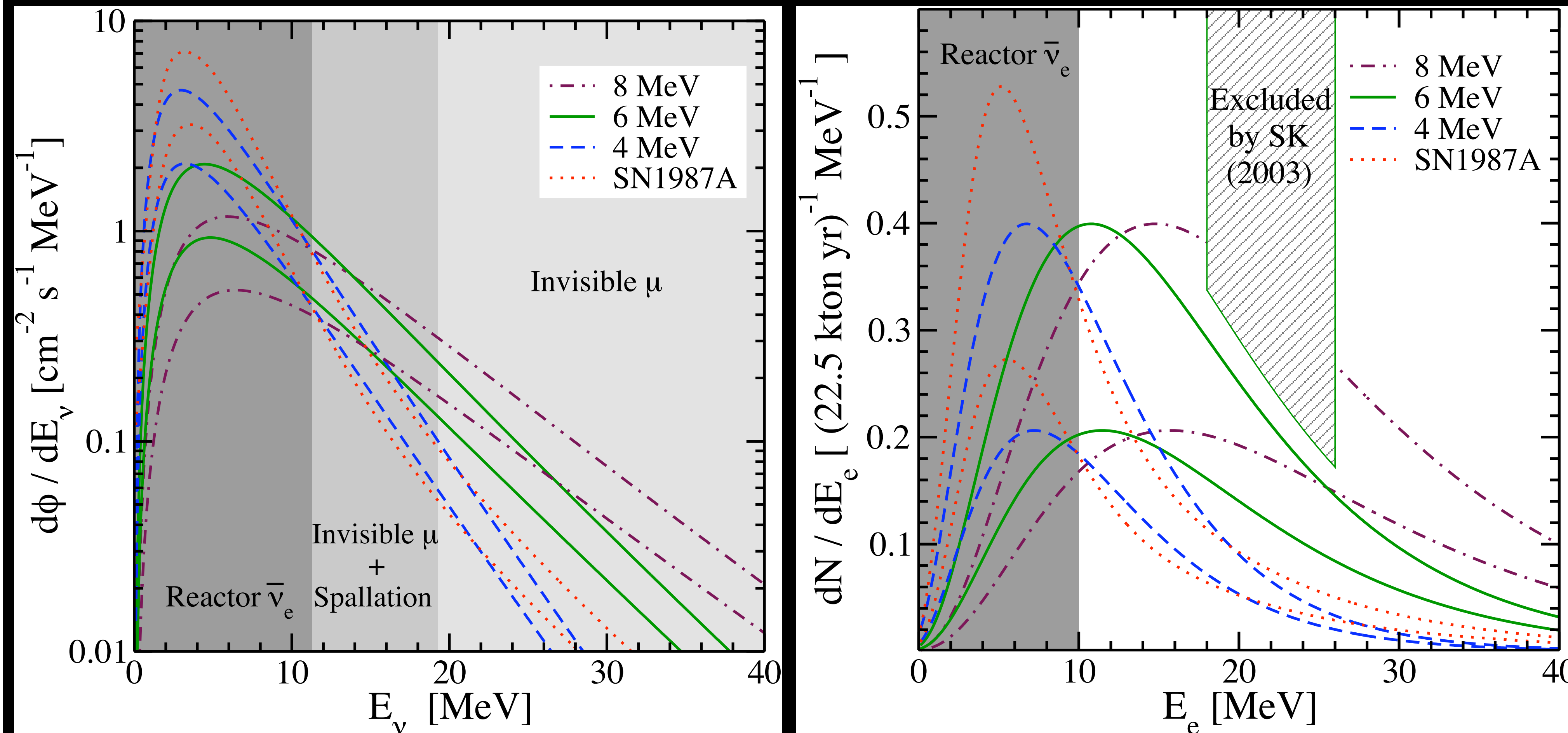
Free proton targets only
Cross section grows as $\sigma \sim E_\nu^2$
Kinematics good, $E_e \sim E_\nu$
Directionality isotropic

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



Super-Kamiokande

Predicted Flux and Event Rate Spectra

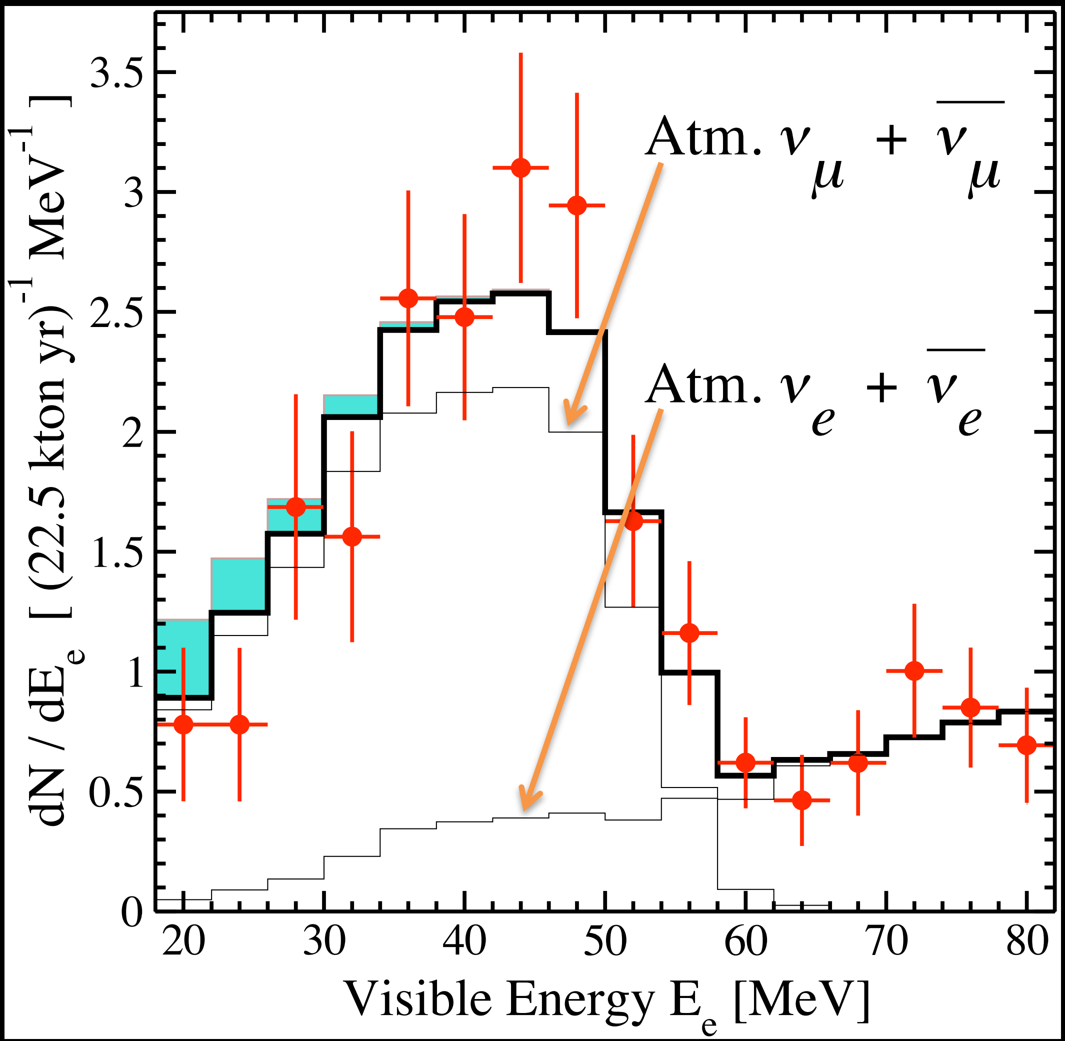


Horiuchi , Beacom, Dwek (2009)

Bands show full uncertainty range arising from cosmic supernova rate

Limits from Super-Kamiokande

Measured Spectrum Including Backgrounds



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

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

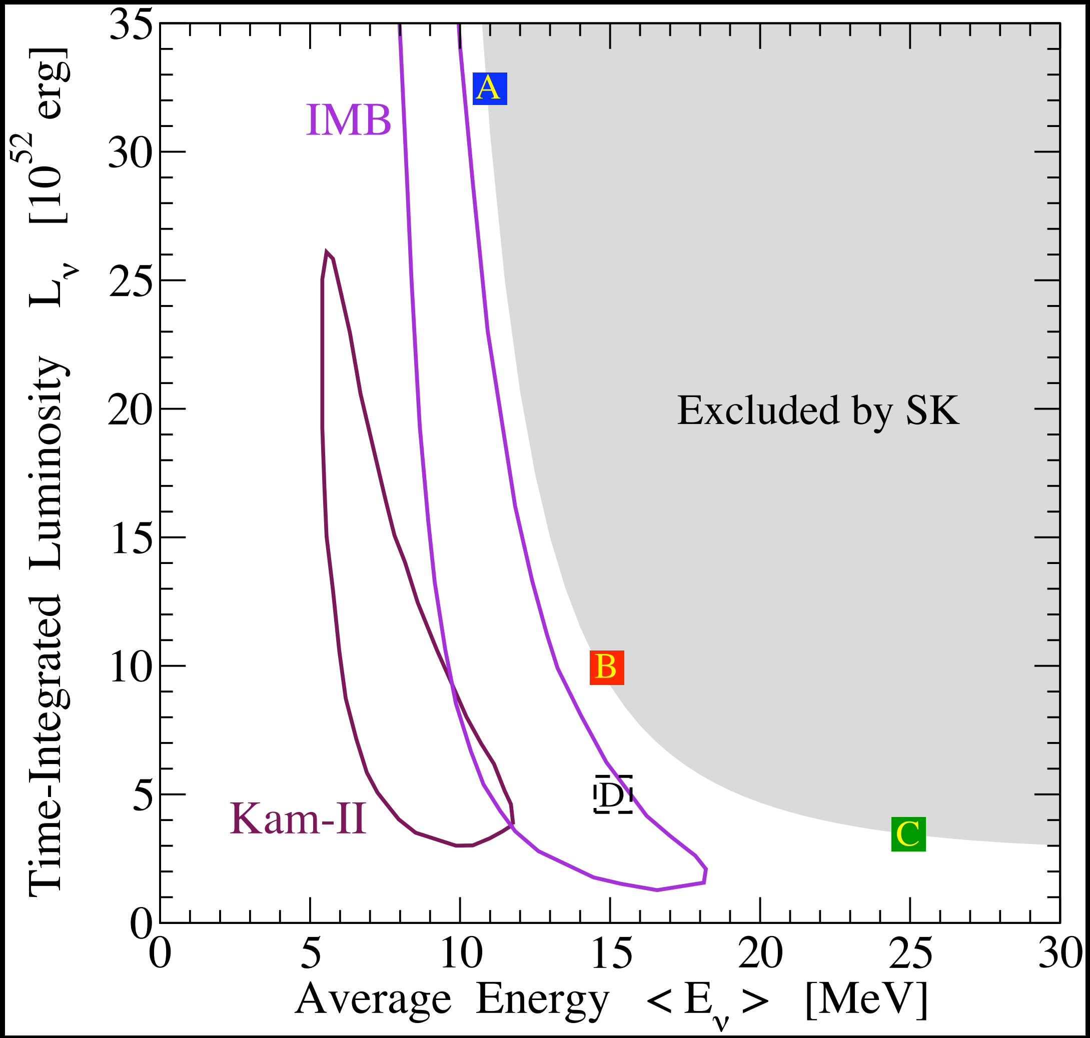
Limits on Supernova Neutrino Emission

2003 Super-Kamiokande limit:
$\Phi < 1.2\ cm^{-2}\ s^{-1}$ (90% CL)
for nuebar with $E_\nu > 19.3$ MeV

Supernova rate uncertainty is now subdominant; this limits the effective nuebar spectrum that includes mixing effects

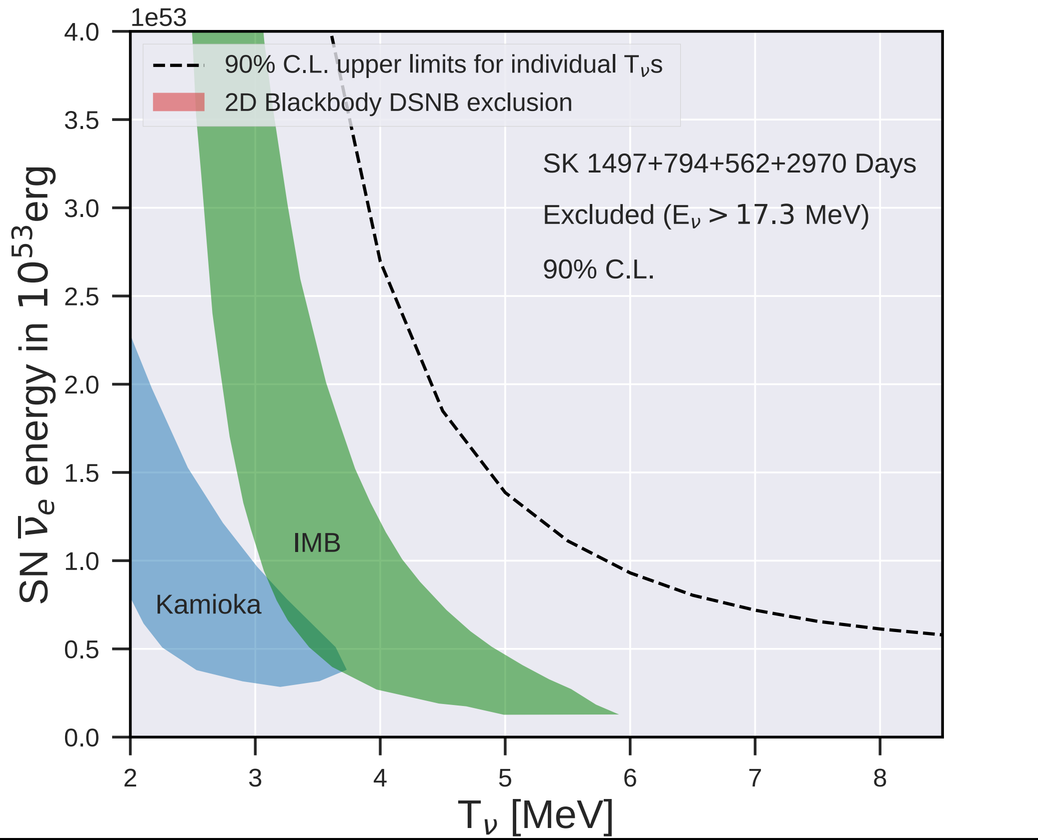
Within range of expectations from theory and SN 1987A!

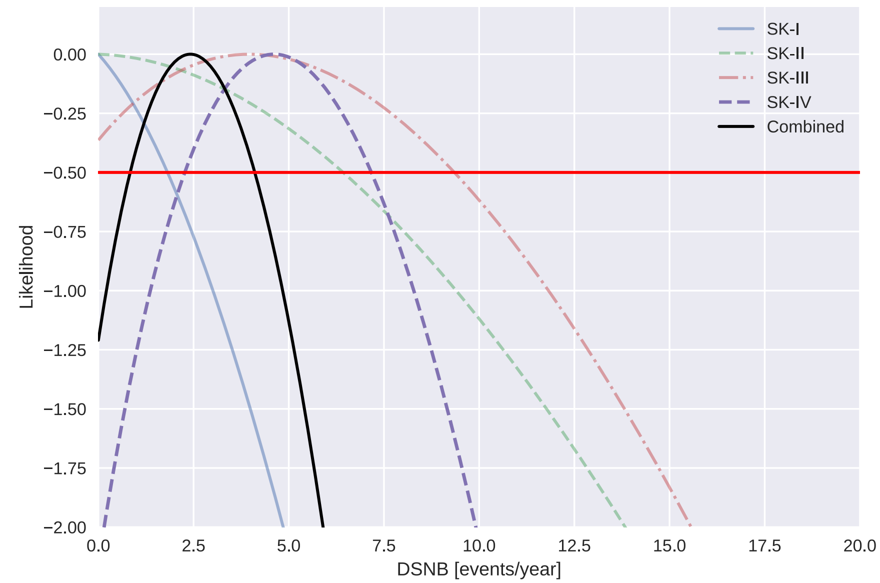
Also limits from KamLAND (lower energy) and SNO (nue)



Yuksel, Ando, Beacom (2006);
SN 1987A fits from Jegerlehner, Neubig, Raffelt (1996)

New Super-Kamiokande Analysis



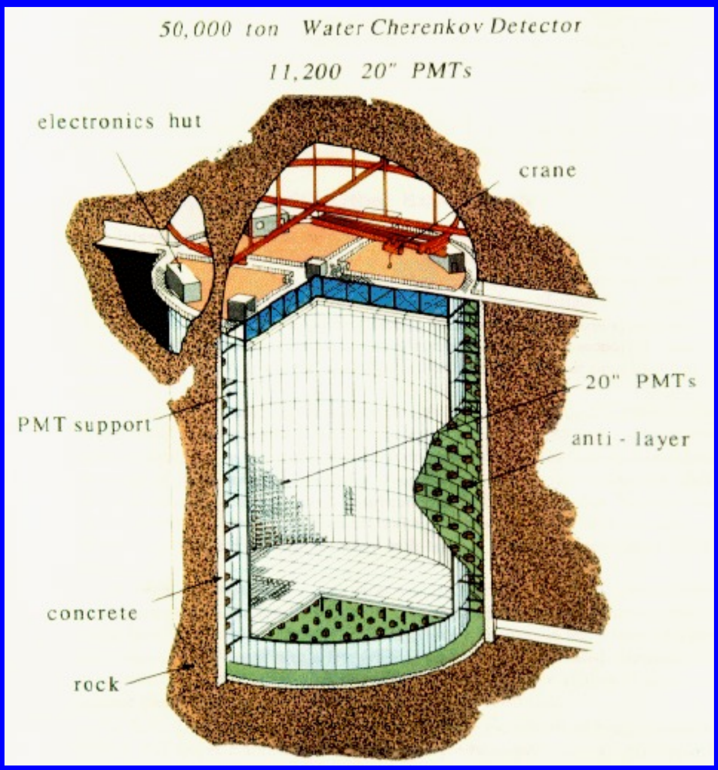


Abe et al. [Super-Kamiokande] (2021)

Towards Discovery of the DSNB

Add Gadolinium to SK?

GADZOOKS!



Gadolinium
Antineutrino
Detector
Zealously
Outperforming
Old
Kamiokande,
Super!

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

New general tool for particle ID
Rich new physics program

Benefits of Neutron Tagging for DSNB

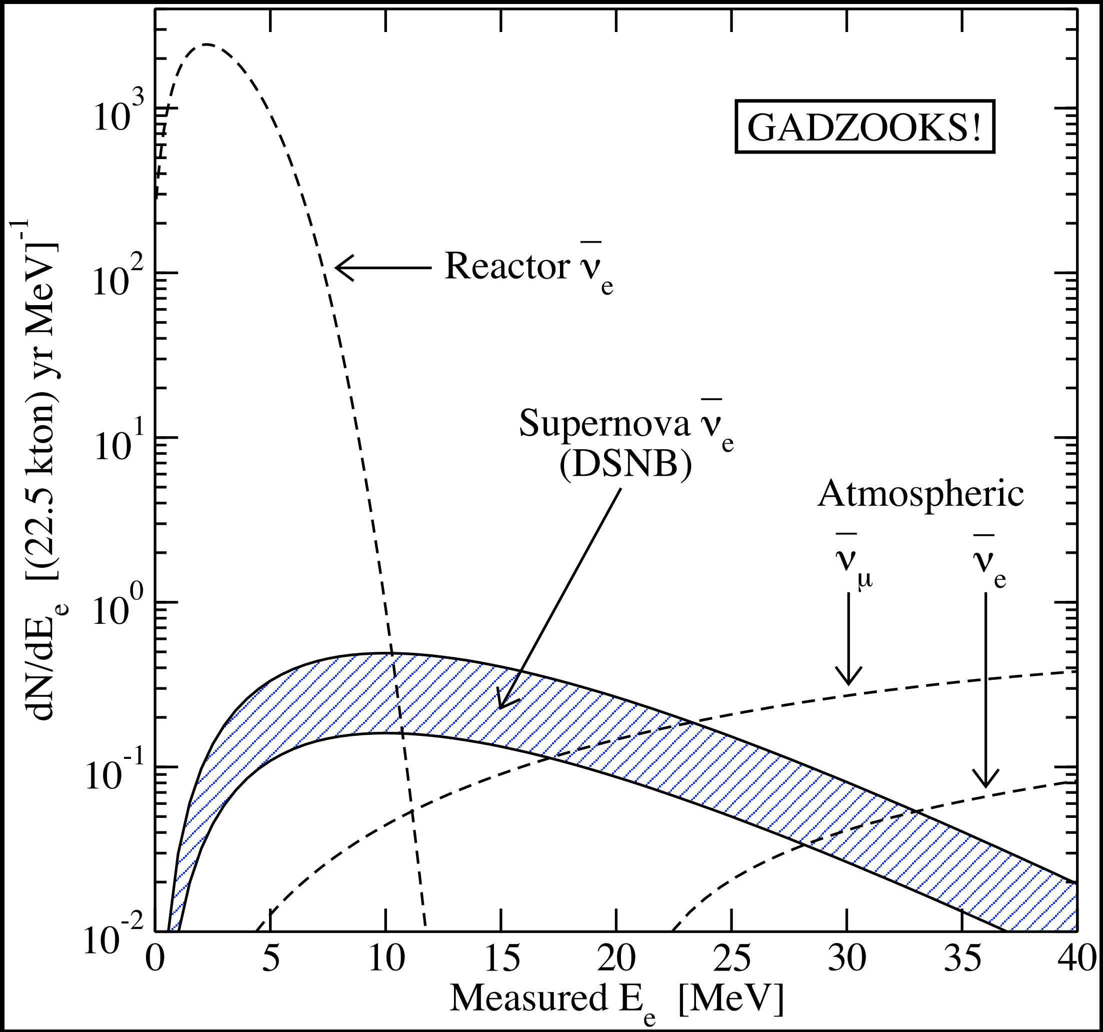
Solar neutrinos:
eliminated

Spallation daughter decays:
essentially eliminated

Reactor neutrinos:
now a visible signal

Atmospheric neutrinos:
significantly reduced

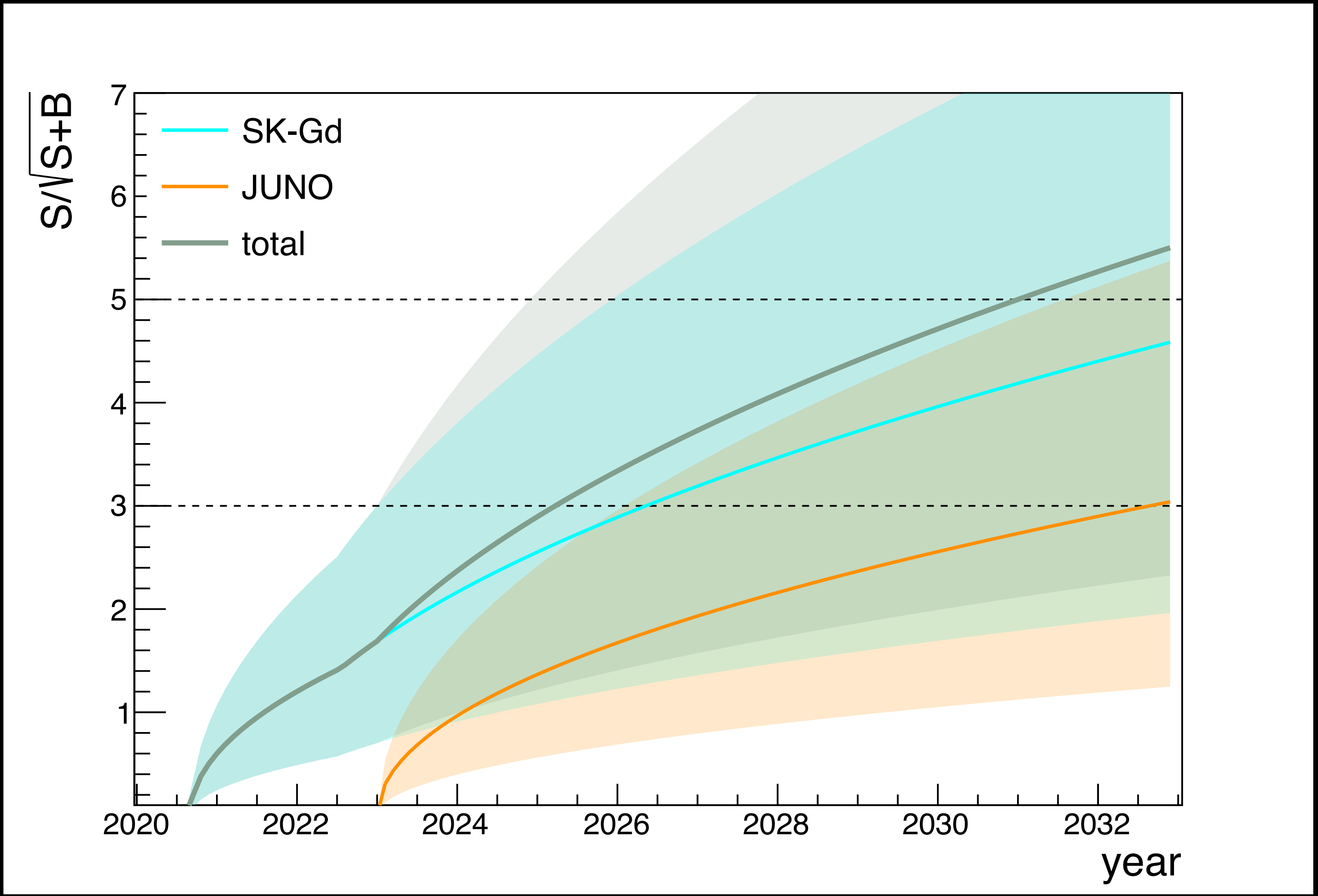
DSNB:
More signal, less background!



Beacom, Vagins (2004)

(DSNB predictions now at upper edge of band)

Prospects for DSNB Detection



Li, Vagins, and Wurm (2022)

Impact of DSNB Detection

Guaranteed signal:
SK has a few DSNB nuebar signal interactions per year
Astrophysical uncertainties are small and shrinking quickly

Super-Kamiokande upgrade:
Research and development work very promising so far
Adding gadolinium is approved and is being implemented

Supernova implications:
New measurement of cosmic core-collapse rate (and more?)
Direct test of the average neutrino emission per supernova

Broader context:
Possible first detections besides Sun and SN 1987A
Non-observation of a signal would require a big surprise

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

Concluding Perspectives

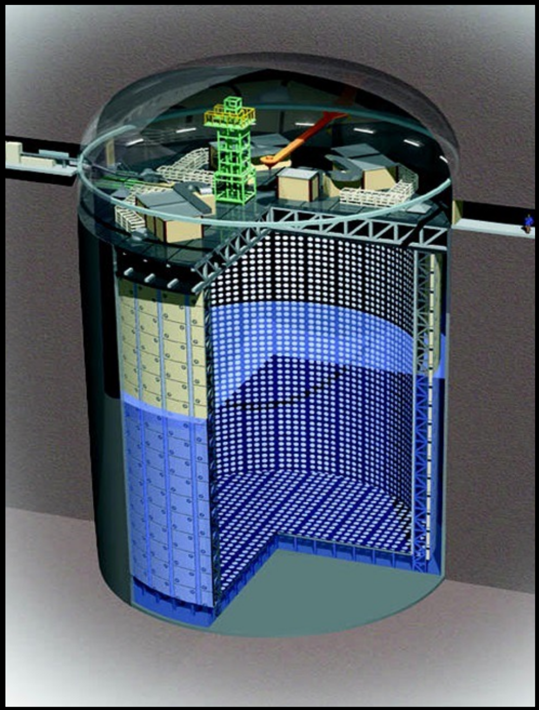
DSNB Goals in 2022

Super-Kamiokande:

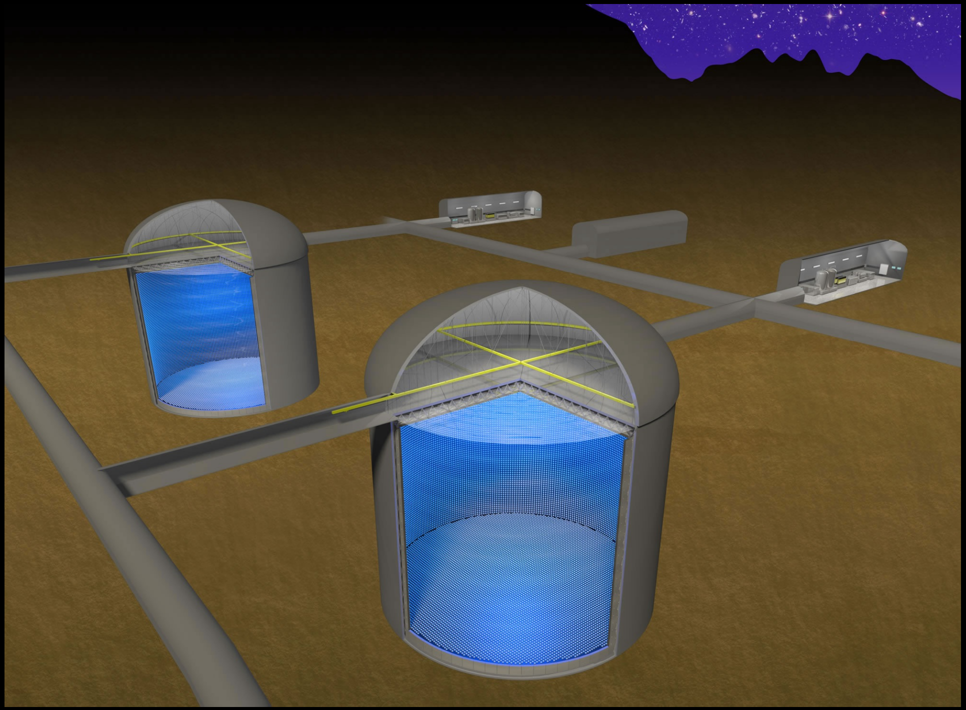
We will detect the DSNB

Hyper-Kamiokande

Super-K



Hyper-K



Hyper-K with Gd would be transformative for the DSNB

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Supernovae X Neutrinos

Special thanks to:

Mark Vagins

and the

Super-Kamiokande Collaboration