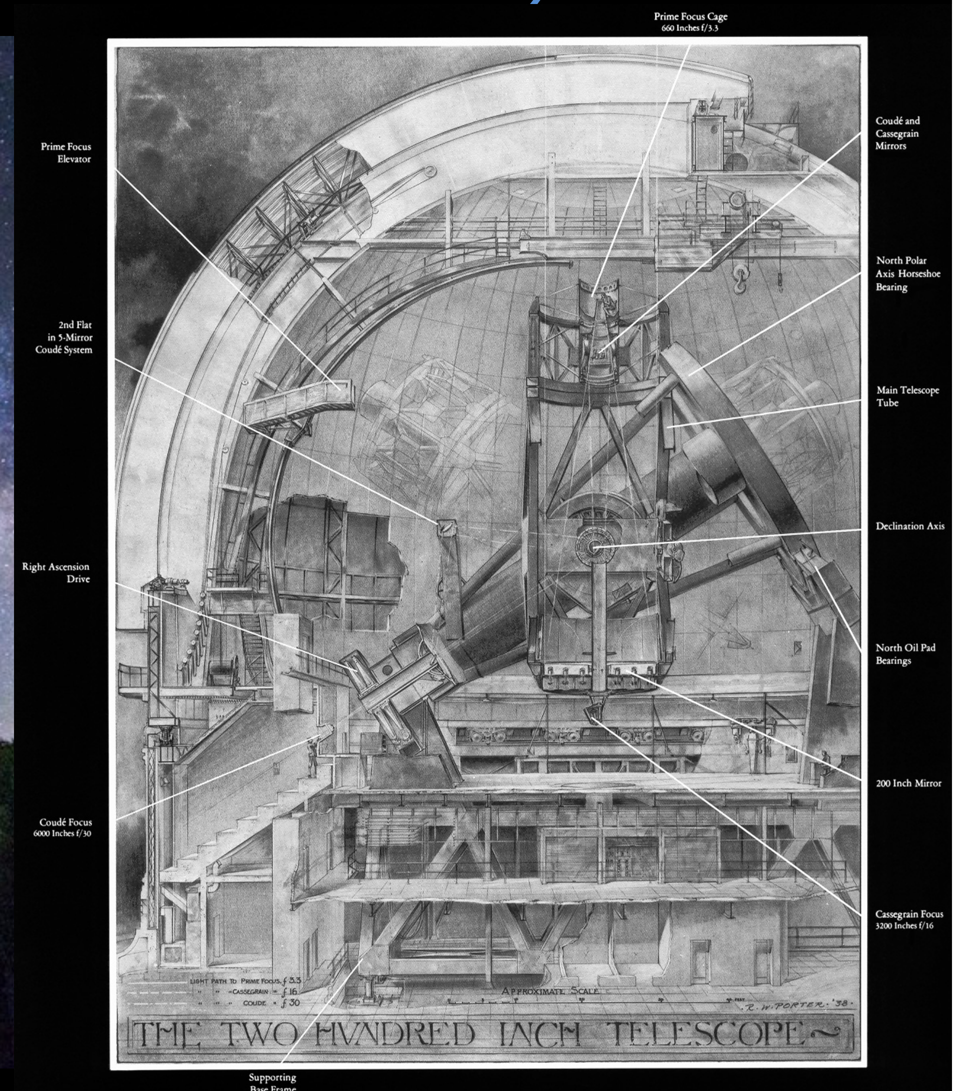
Diffuse Supernova Neutrino Background: Theory

John Beacom, The Ohio State University



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

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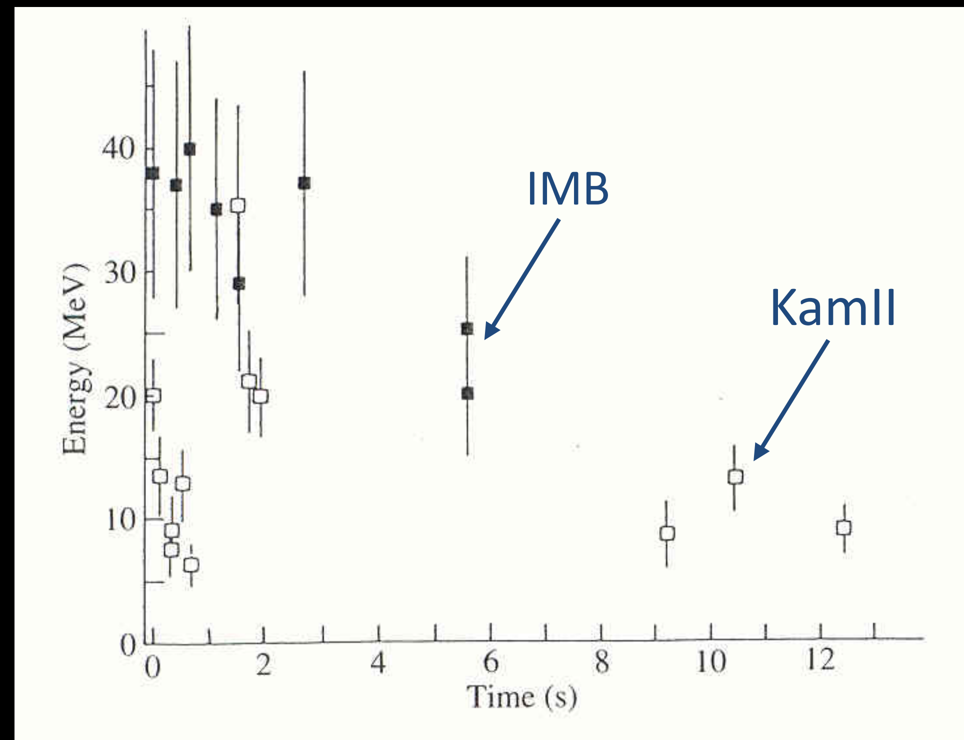
SN 1987A: Our Rosetta Stone



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?

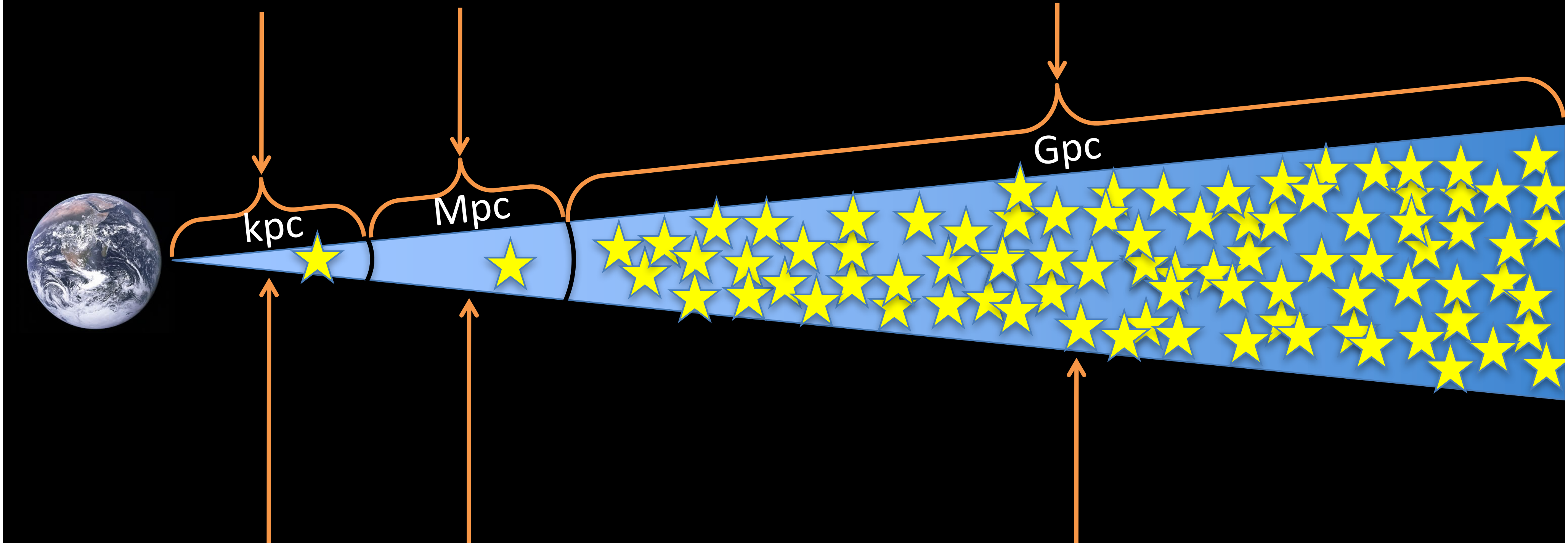
Total energy emitted in neutrinos?
Partition between flavors?
Emission in other particles?
Spectrum of neutrinos?
Neutrino mixing effects?
⋮
Supernova explosion mechanism?
Nucleosynthesis yields?
Neutron star or black hole?
Electromagnetic counterpart?
Gravitational wave counterpart?
⋮
and much more!

Distance Scales and Detection Strategies

N >> 1 : Burst

N ~ 1 : Mini-Burst

N << 1 : DSNB



Rate ~ 0.01/yr

high statistics,
all flavors

Rate ~ 1/yr

object identity,
burst variety

Rate ~ 10^8/yr

cosmic rate,
average emission

Beacom-Vagins DSNB Pact (2002)

Founding principle: “We must detect the DSNB”

Founding document: GADZOOKS! paper (2003)

Since then:

Beacom and others work on theoretical aspects
Vagins and others work on experimental aspects
Constant collaboration on case for DSNB, GADZOOKS!

What’s next?:

New work on inputs, backgrounds, detector, methods
We’re optimistic about the next years and beyond

Talk Outline

Present: Theoretical Predictions

Present: Experimental Limits

Emerging: Enter GADZOOKS!

Future: Other Developments

Concluding Perspectives

Present: 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

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

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

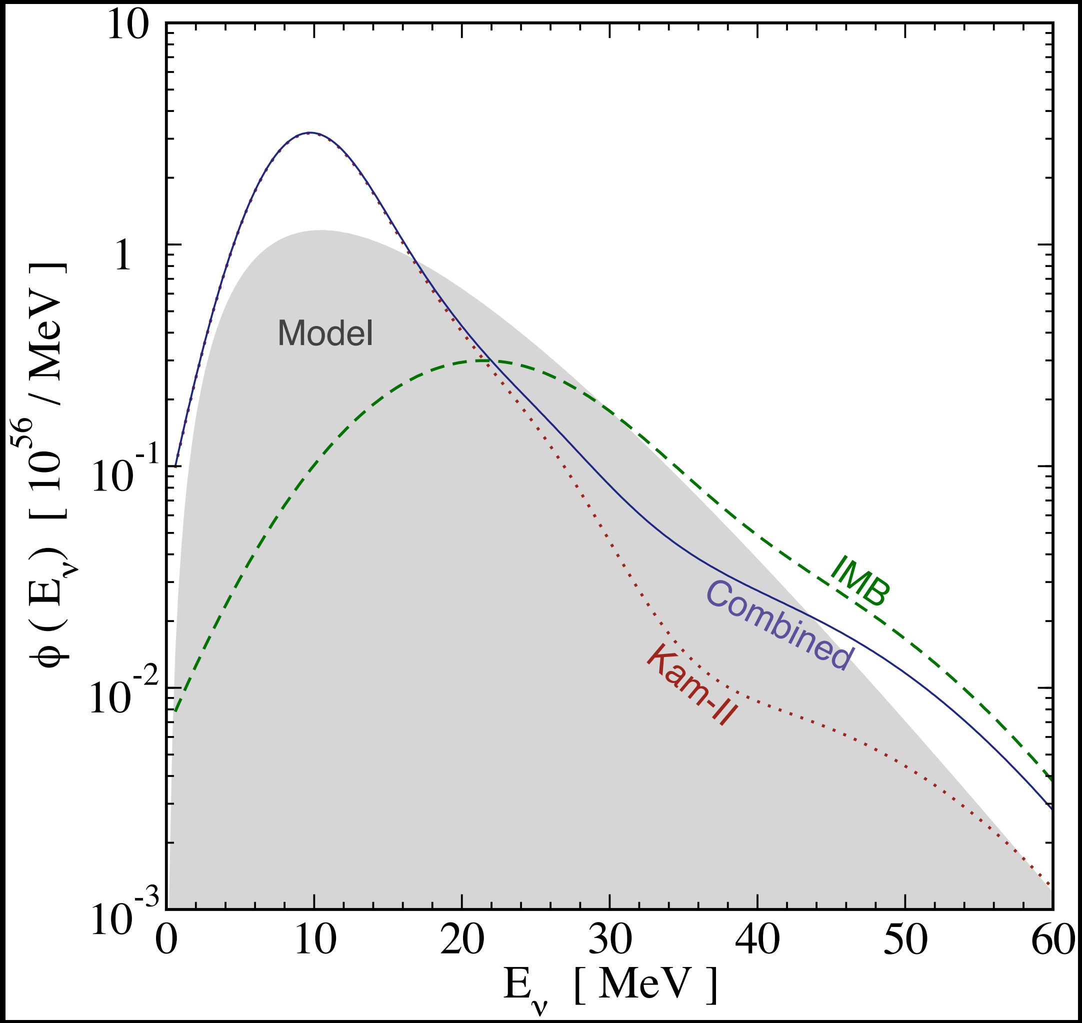
Core collapse releases ~ 3×10^{53} erg, shared by six flavors of neutrinos

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 2017mca 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

(now high precision)

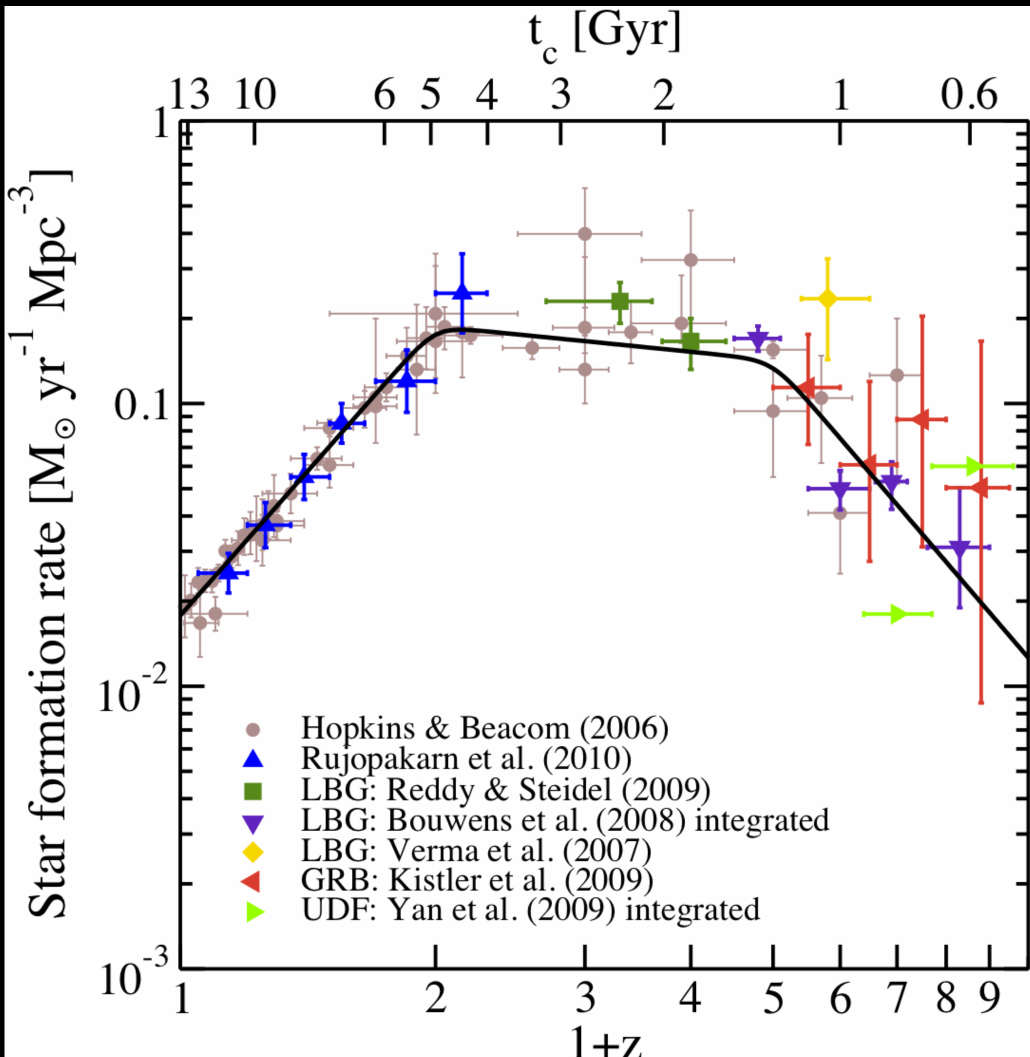
Measured from the core collapse supernova rate

(precision will improve rapidly)

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

(frontier research area)

Predictions from Cosmic Star Formation Rate



Horiuchi, Beacom (2010);
see also Hopkins, Beacom (2006)

Total star formation rate deduced from massive stars using initial mass function (IMF)

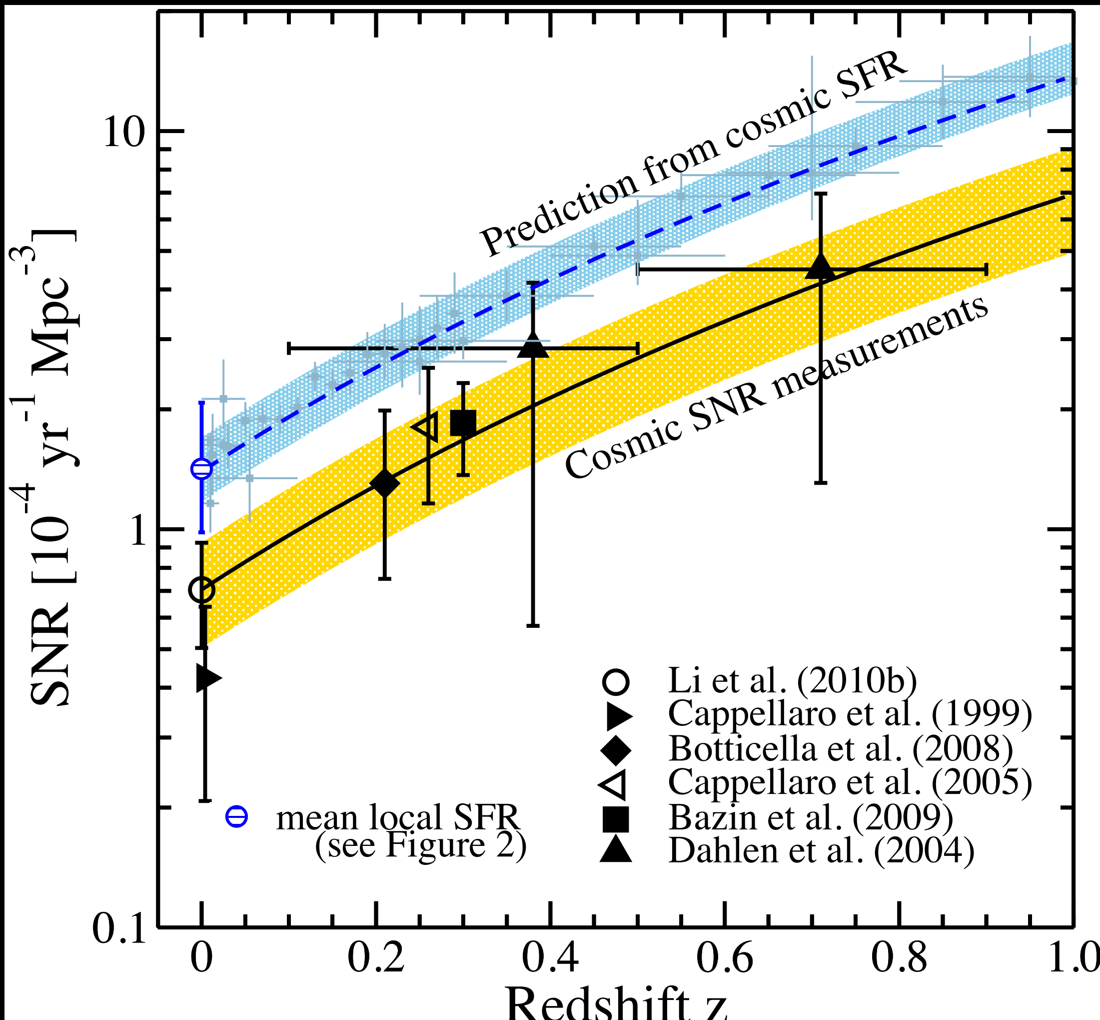
Impressive agreement among results from different groups, techniques, and wavelengths

Integral of R_{SF} agrees with EBL

$$R_{\rm SN}(z) \simeq \frac{R_{\rm SF}(z)}{143 M_\odot}$$

IMF uncertainty on R_{SN} small

Measured Cosmic Supernova Rate



Horiuchi et al. (2011);
see also Hopkins, Beacom (2006),
Botticella et al. (2008),
Mattila et al. (2012)

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?

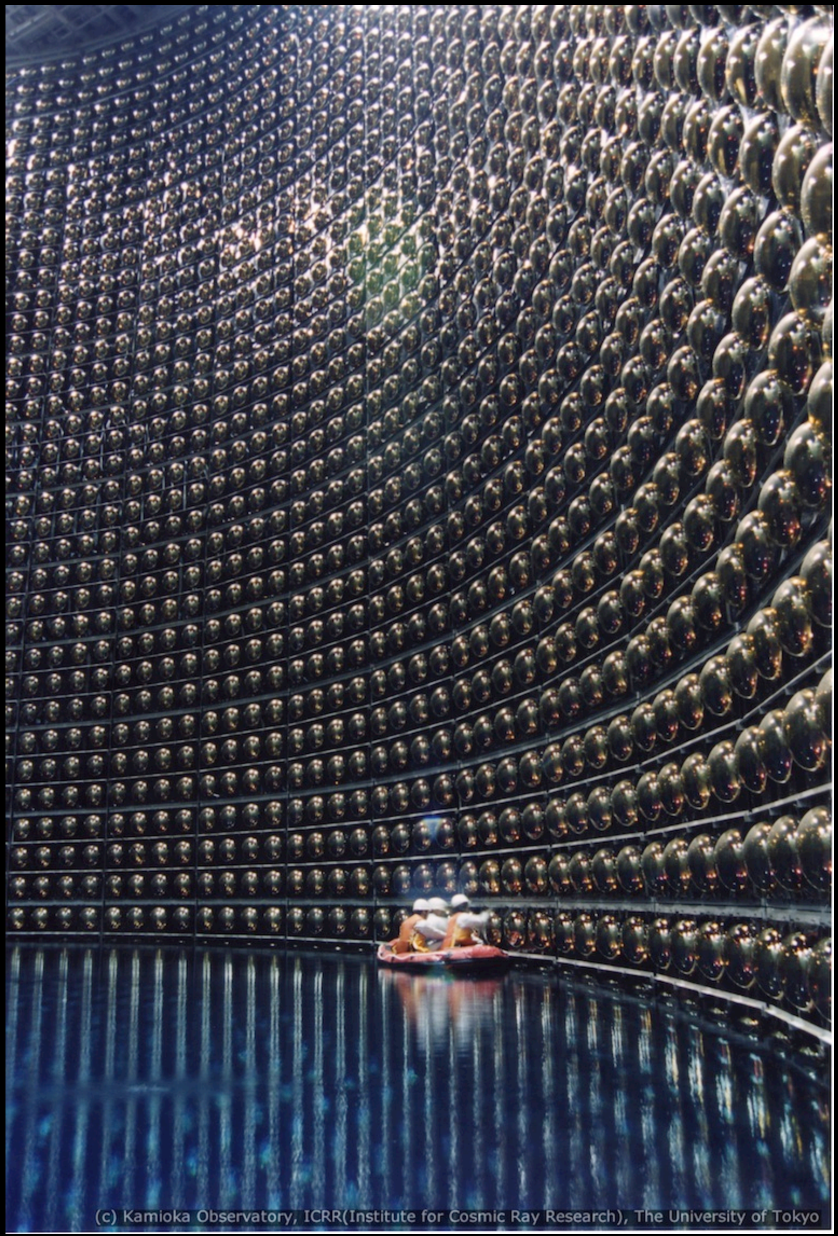
Third Ingredient: Neutrino Detection Capabilities

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

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

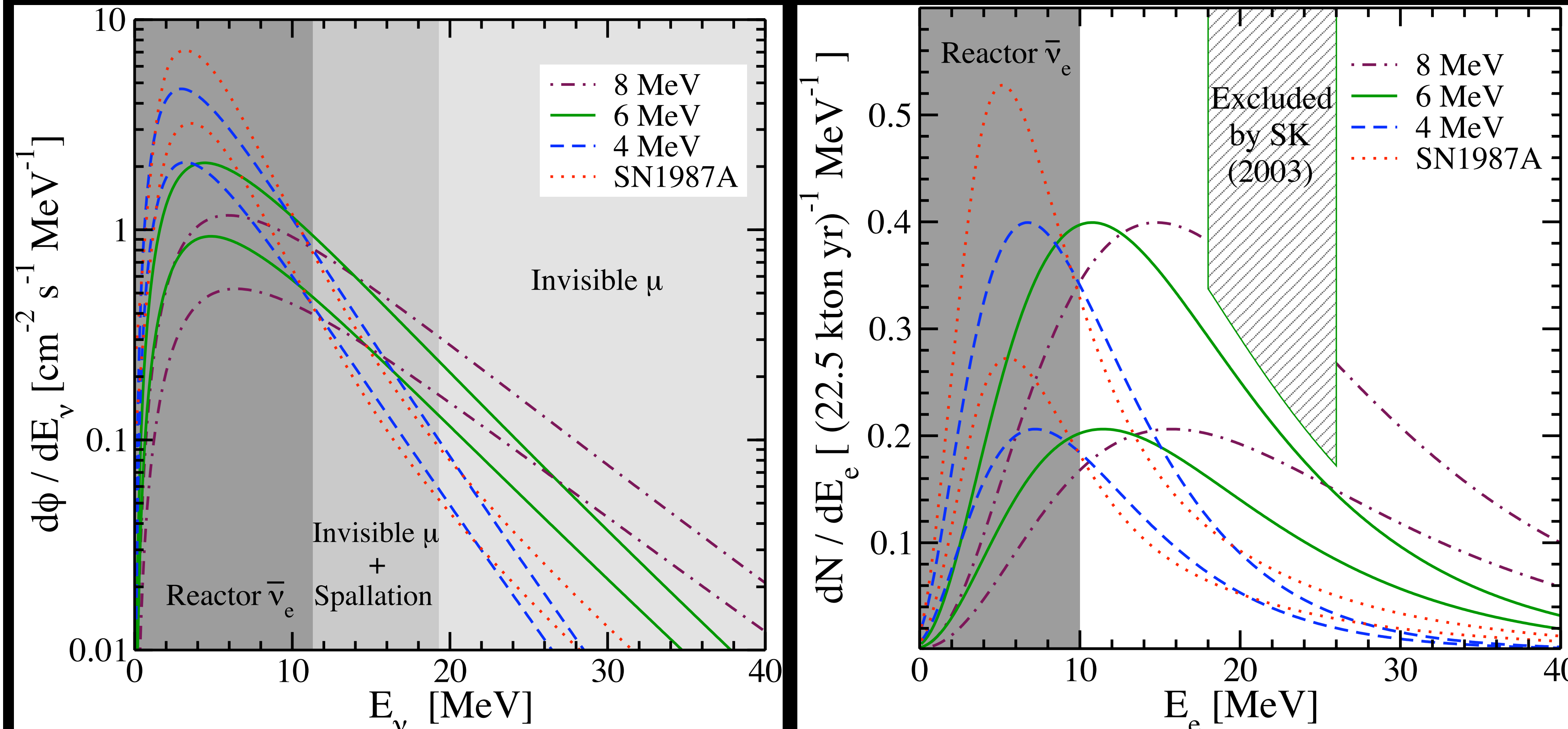
Free proton targets only
Cross section grows as $\sigma \sim E_\nu^2$
Kinematics good, $E_e \sim E_\nu$
Directionality isotropic

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



Super-Kamiokande

Predicted Flux and Event Rate Spectra



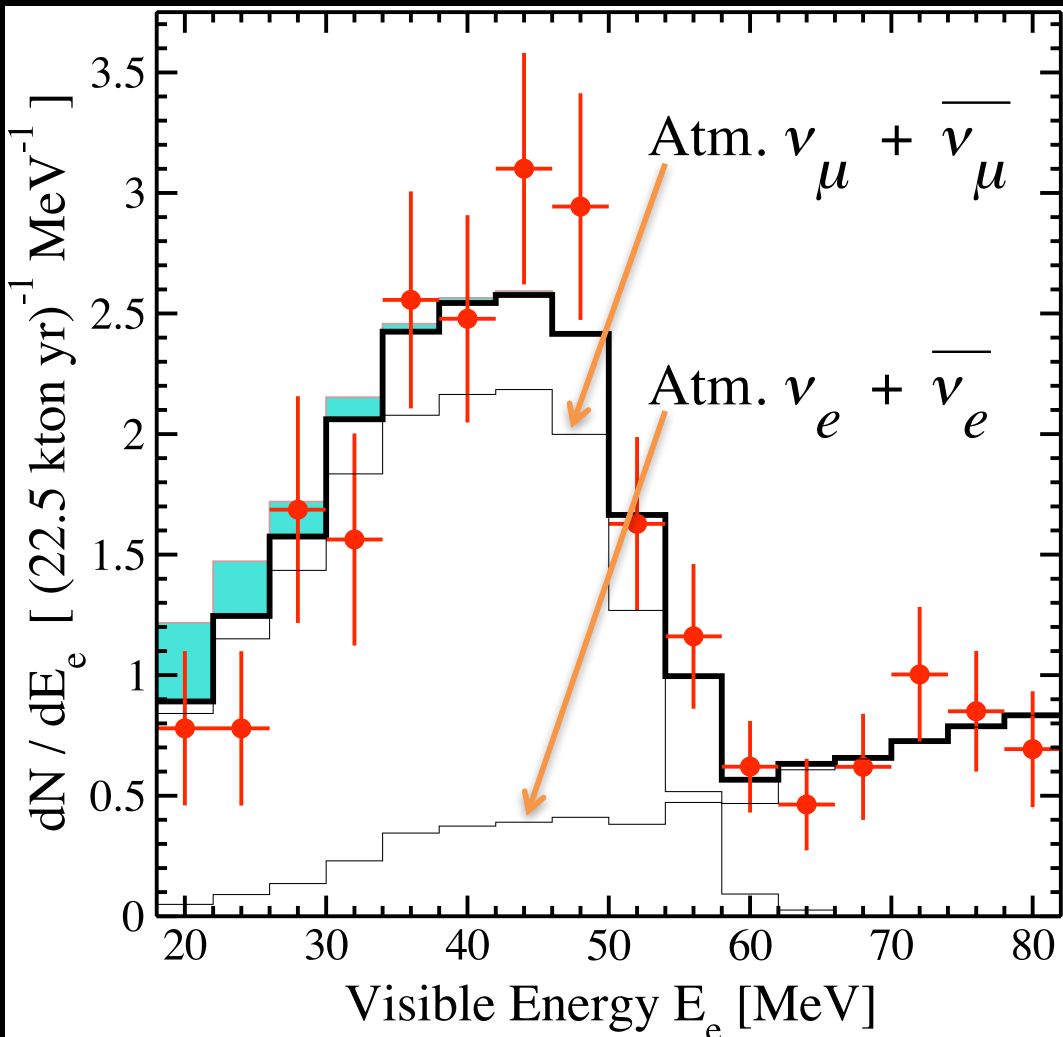
Horiuchi , Beacom, Dwek (2009)

Bands show full uncertainty range arising from cosmic supernova rate

Present: Limits from Super-Kamiokande

See Bays et al. [Super-Kamiokande] (2012)

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

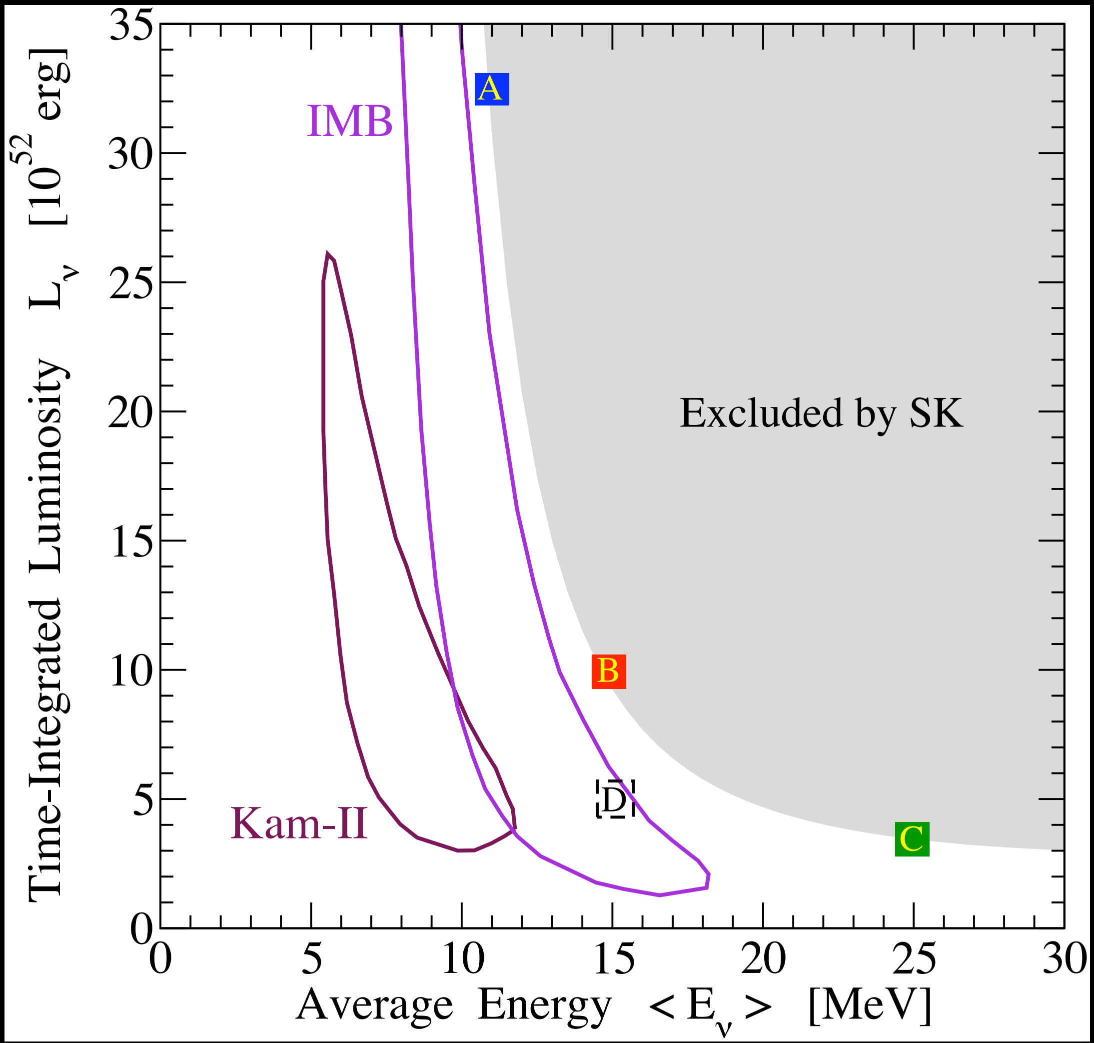
Limits on Supernova Neutrino Emission

2003 Super-Kamiokande limit:
$\Phi < 1.2\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (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)

2012 Analysis of Super-Kamiokande Data

2003: factor ~ 100 improvement over Kamiokande-II limit

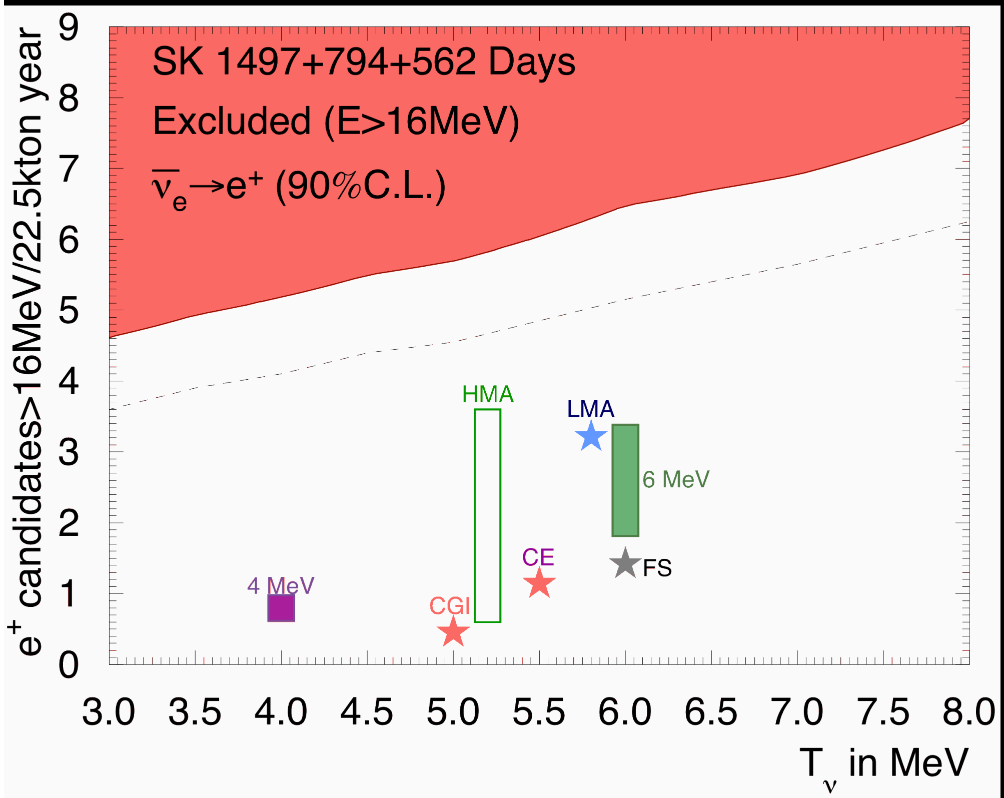
2012: all details down to ~ 10%
More data
Full reanalysis
Three detector periods
Backgrounds in more detail
New backgrounds included
Lowered energy threshold
Improved efficiency
Detailed systematics
Better treatment of statistics
Improved cross section
Conservative choices
….

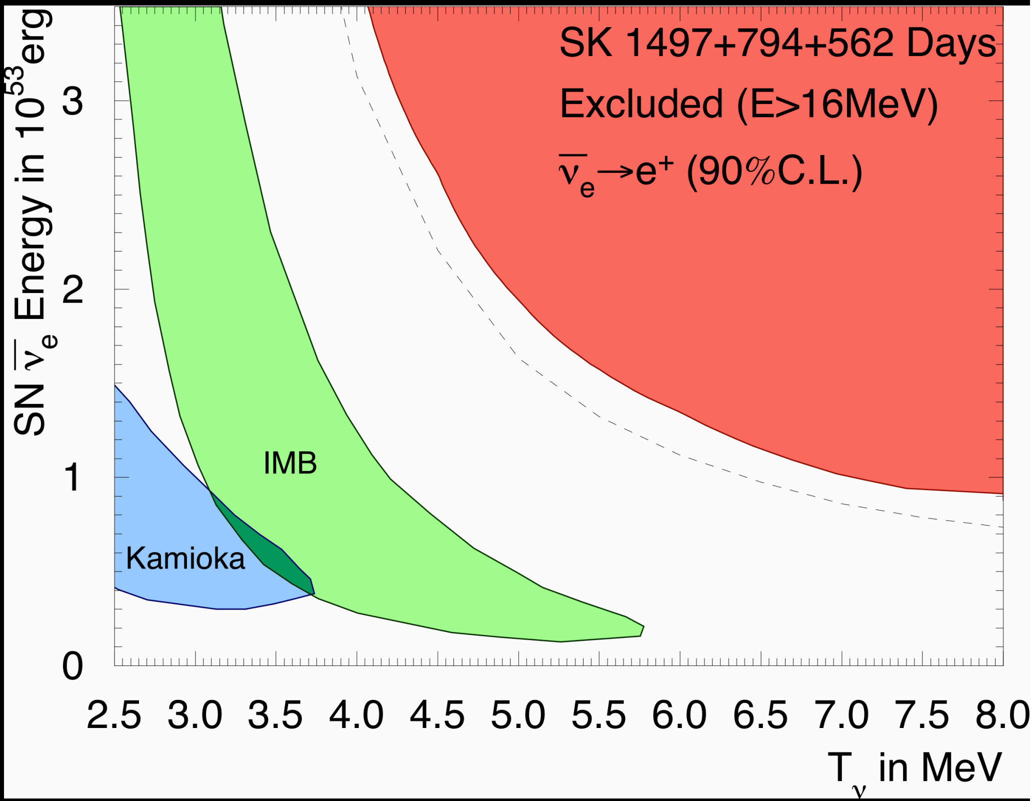
Who got the better Ph.D. thesis project?

2012 Super-Kamiokande Limits

Much improved analysis and more data

To be *conservative*, new limits are a factor ~ 2 worse than before





Bays et al. [Super-Kamiokande] (2012)

Must further decrease detector backgrounds and energy threshold

Emerging: Gadolinium in Super-Kamiokande

See talk by Mark Vagins

GADZOOKS! Proposal

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

Beacom and Vagins (2004): 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

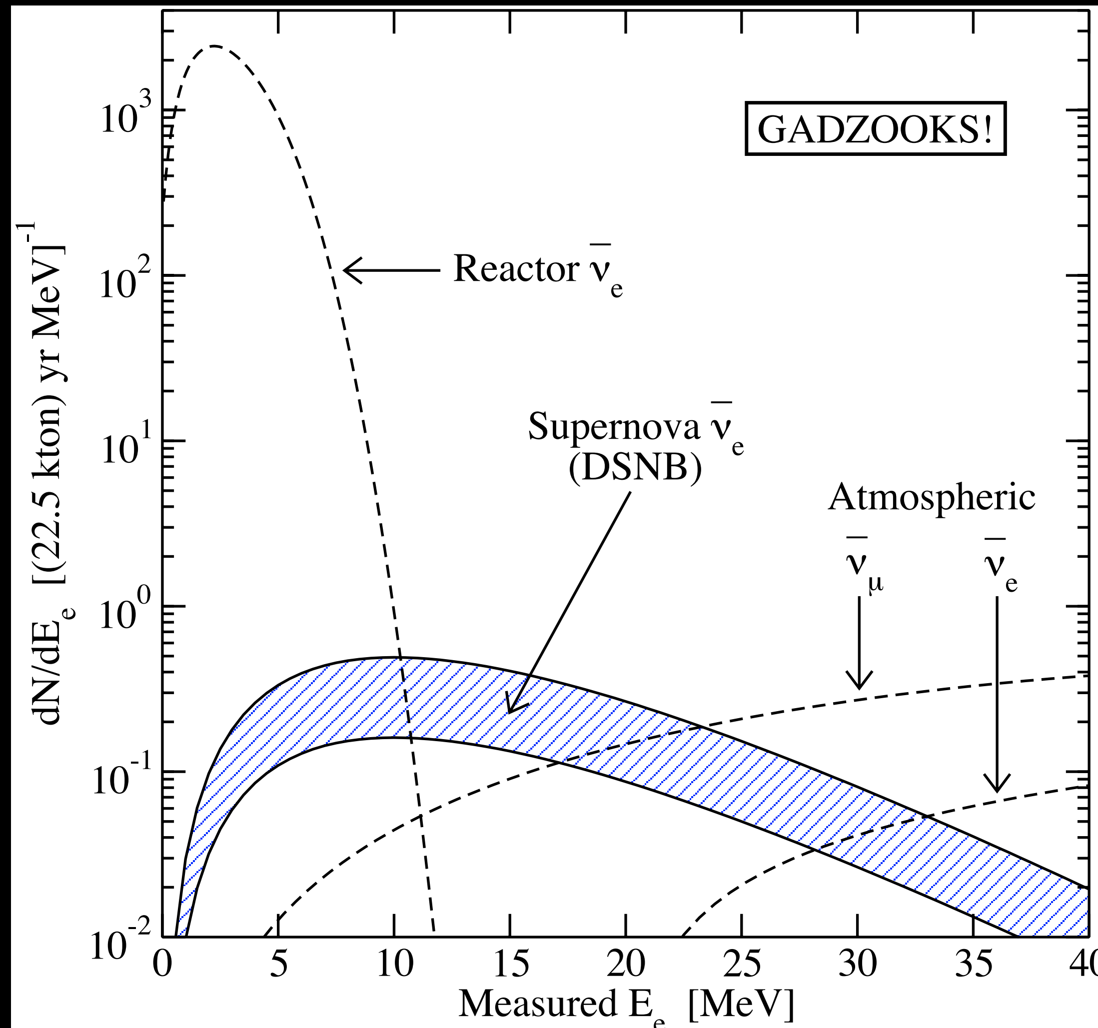
Solar neutrinos:
eliminated

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)

Fate of the GADZOOKS! Proposal

For about 10 years:

Vagins and colleagues developed experimental aspects

Beacom and colleagues developed theoretical aspects

Super-K 2015: Yes

[41] Ref. [4] proposed adding a 0.2% gadolinium solution into the SK water. After exhaustive studies, on June 27, 2015, the SK Collaboration formally approved the concept, officially initiating the SuperK-Gd project, which will enhance anti-neutrino detectability (along with other physics capabilities) by dissolving 0.2% gadolinium sulfate by mass in the SK water.

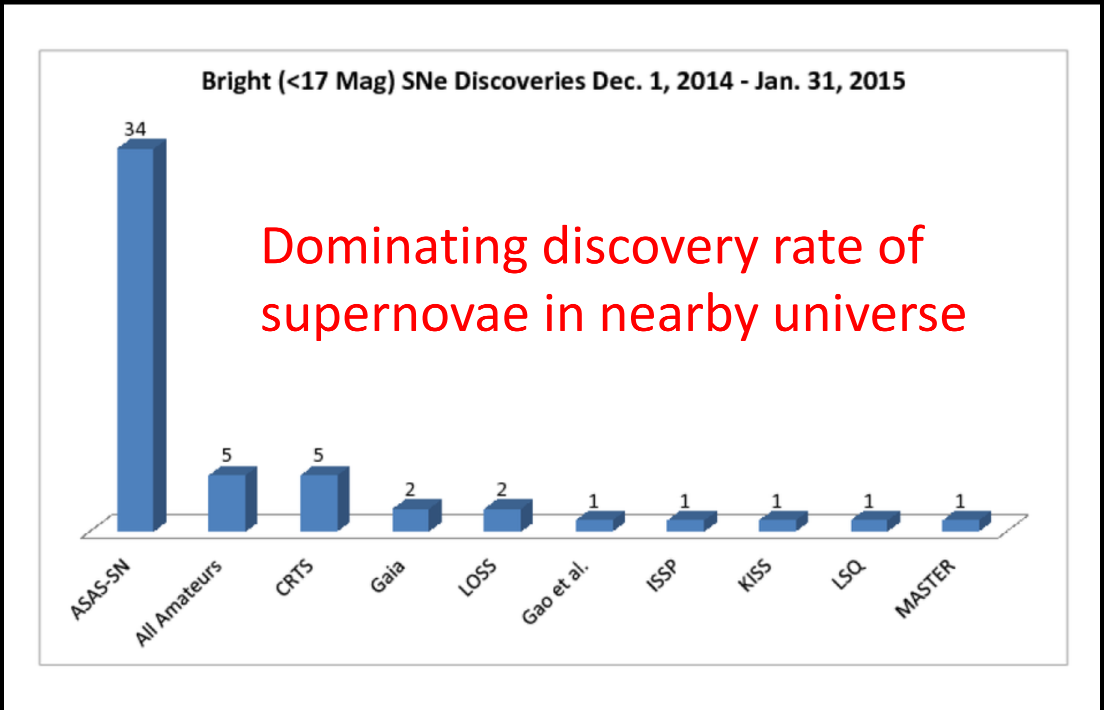
Will greatly increase sensitivity for many studies

Future: Other Developments

All-Sky Optical Monitoring to Leverage

Connection to astronomy crucial, but optical data are lacking

Enter OSU's "Assassin" (All-Sky Automated Survey for SN)



Discovering and monitoring optical transients to 17th mag.

See also Adams, Kochanek, Beacom, Vagins, Stanek (2013)

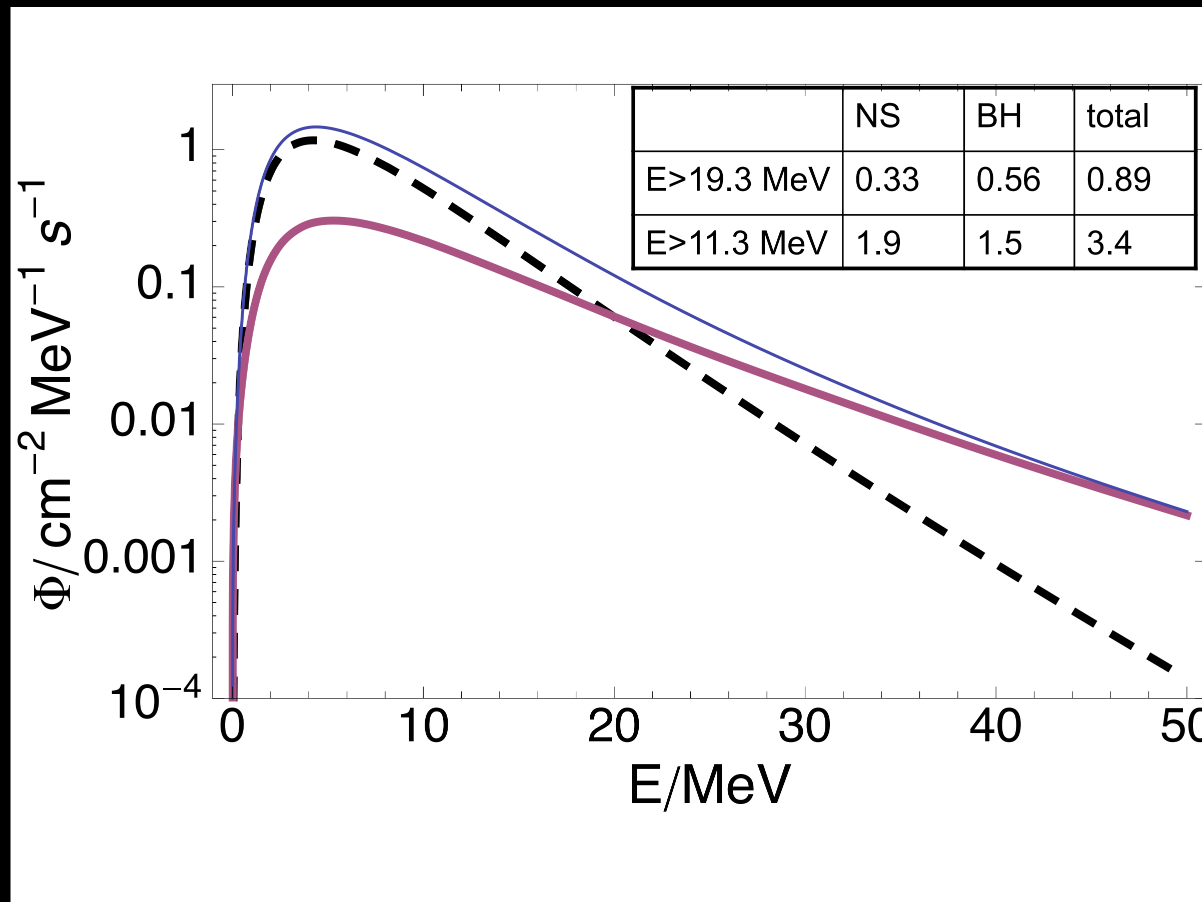
Neutrino Emission with Black Hole Formation

When core collapse fails (no optical supernova), the neutrino emission can be *larger* in total and average energy

The collapse goes *farther* and *faster*, but must shed much thermal energy by neutrino emission

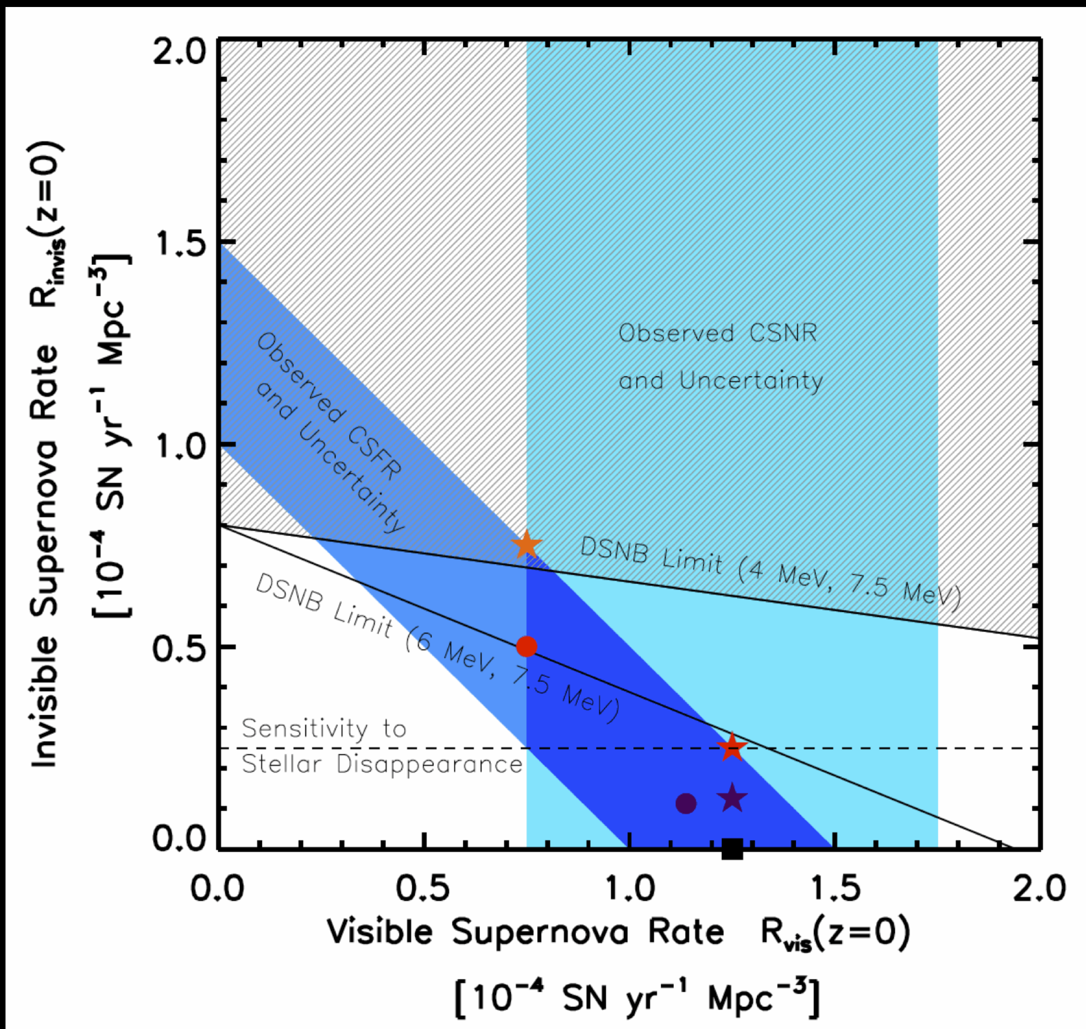
Sumiyoshi et al. (2007)
Nakazato et al. (2008)
Fischer et al. (2008)
O'Connor, Ott (2011)
....

DSNB spectrum could be *more* detectable



Lunardini (2009)

Limits on the Black Hole Formation Rate



Lien, Fields, Beacom (2010)

Low visible supernova rate would require large black hole fraction, up to ~ 50%

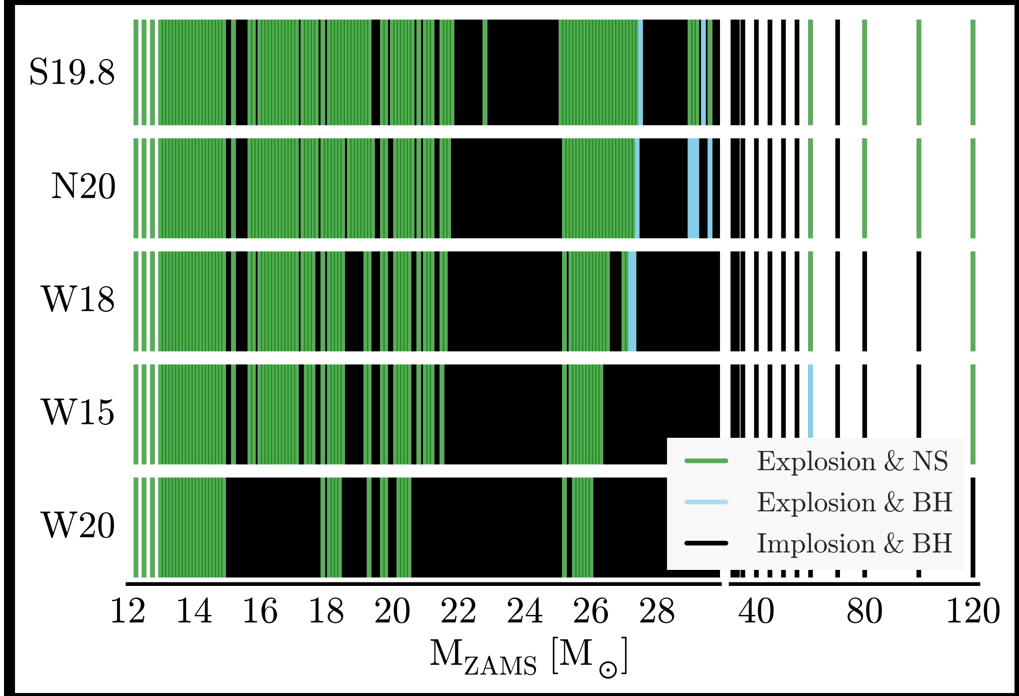
Standard models predict at least ~ 10% black holes

This can be resolved

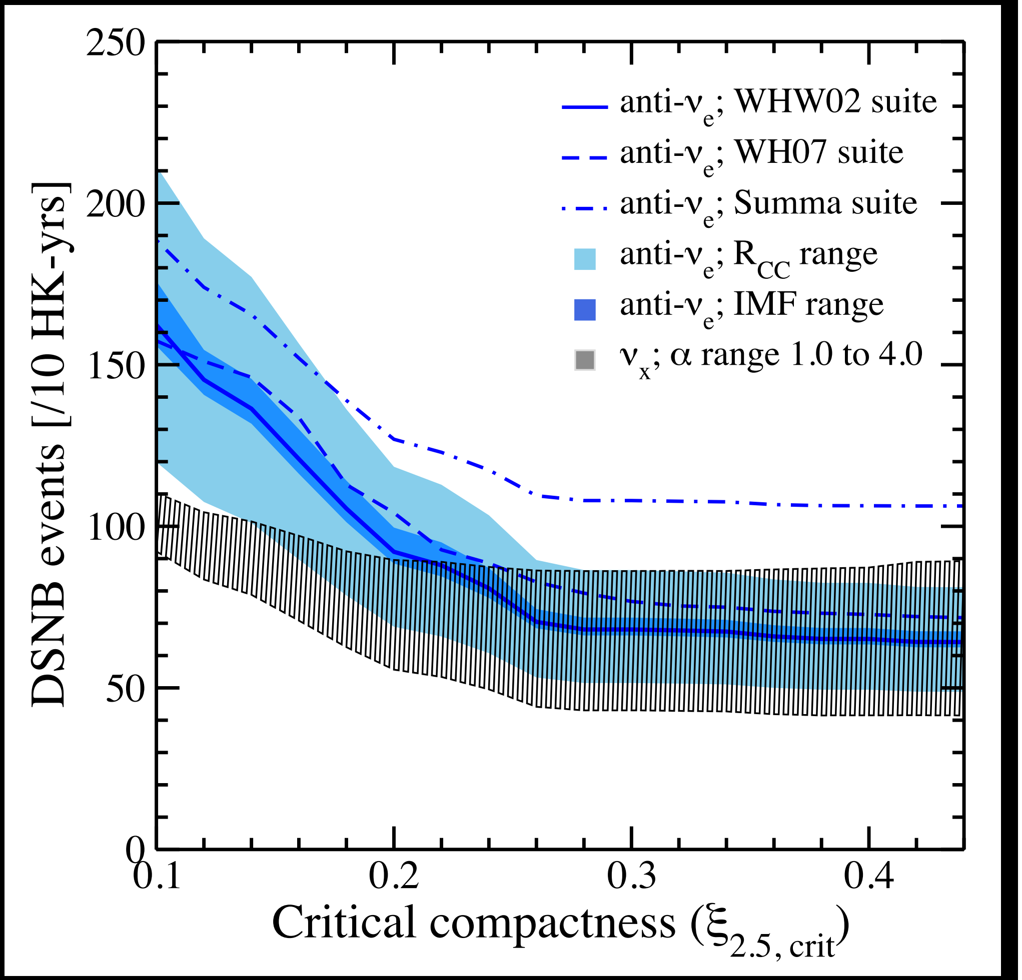
"Survey About Nothing" (Kochanek et al., 2008) can see massive stars disappear; ASAS-SN for nearby SN rate

Large DSNB a crucial test

DSNB with Black Hole Formation



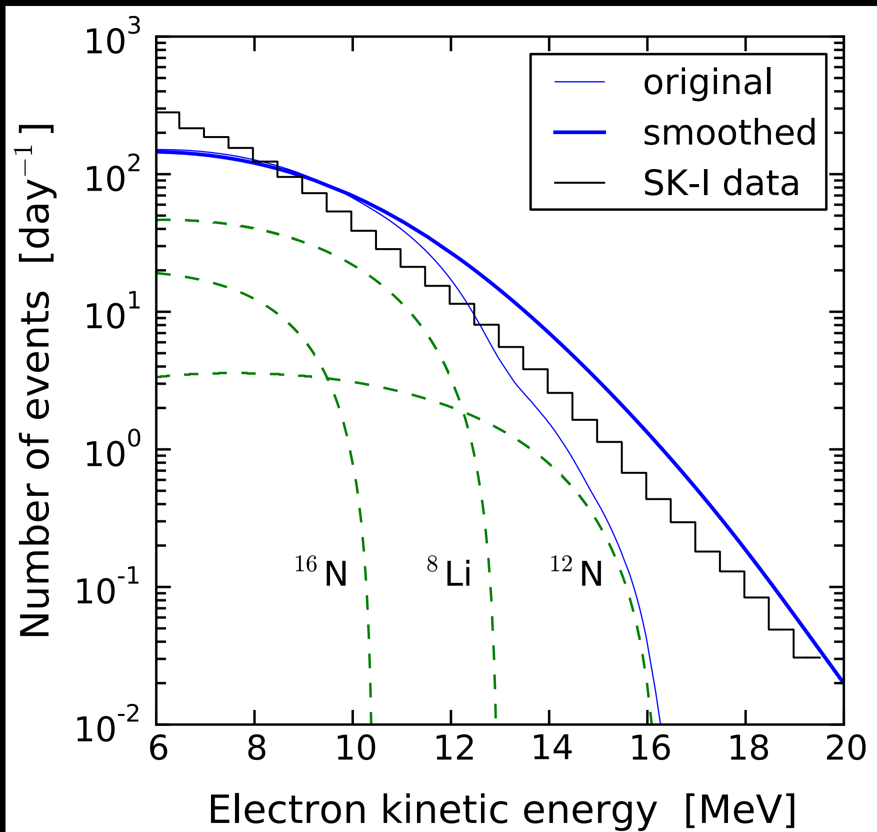
Sukhbold et al. (2015)



Horiuchi et al. (2017)

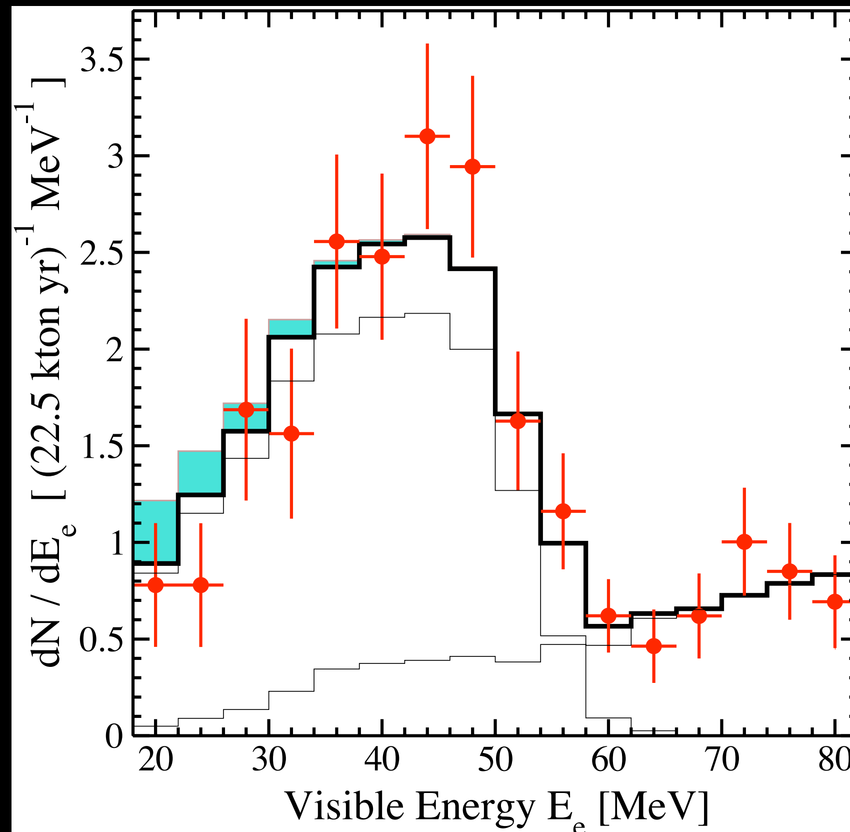
Back to the Backgrounds

Spallation Beta Decays



Li and Beacom: 3 papers so far
Zhu et al.: paper coming
Anticipate factor ~ 10 reduction

Atmospheric Neutrinos



Zhou and Beacom: paper coming
Anticipate significant reduction

Concluding Perspectives

Prospects for First Detection of the DSNB

Guaranteed signal:

SK has a few DSNB nuebar signal interactions per year

Astrophysical uncertainties are small and shrinking quickly

Super-Kamiokande upgrade:

Adding gadolinium is approved and under construction

Research and development work very promising so far

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

Types of Possible New Underground Detectors

We must go beyond even Super-Kamiokande with gadolinium

Large Liquid Scintillator:
DSNB nuebar
oil instead of water
neutron tagging
no invisible muons
new NC backgrounds

example is JUNO
~ 1 times rate of SK

Large Liquid Argon:
DSNB nue
σ/kton comparable
good event ID
no invisible muons
new backgrounds?

example is DUNE
~ 1 times rate of SK

Very Large Water:
DSNB nuebar
just like SK
could use Gd
some invisible muons
no new backgrounds

example is HK
> 10 times rate of SK

Center for Cosmology and AstroParticle Physics

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CCAPP

Columbus, Ohio: 1 million people (city), 2 million people (city+metro)
Ohio State University: 56,000 students
Physics: 55 faculty, Astronomy: 20 faculty
CCAPP: 20 faculty, 10 postdocs from both departments
Placements: *In 2014 alone, 12 CCAPP alumni got permanent-track jobs*

Recent faculty hires: Antonio Boveia, Linda Carpenter, Chris Hirata, Adam Leroy, Laura Lopez, Annika Peter
Recent PD hires: Ami Choi, Alexia Lewis, Niall MacCrann, Tuguldur Sukhbold, Michael Troxel, Ying Zu, Francesco Capozzi, Heidi Wu

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