The Diffuse Supernova Neutrino Background

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

John Beacom
The Ohio State University

To Honor Professor Sato

Best wishes from your friends at Ohio State!

John Beacom
Gary Steigman
Todd Thompson
Terry Walker

Some Highlights

Neutrino trapping in supernovae (1975)

Analysis of SN 1987A burst (1987)

"Relic supernova neutrinos" (1995--)

And many more....

Dozens of students
and postdocs!

Two whom I worked with:

Ando

Horiuchi

The Impossible Dream of Neutrino Astronomy

"If [there are no new forces] -- one can conclude that there is no practically possible way of observing the neutrino."

Bethe and Peierls, Nature (1934)

"Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star..."

Bahcall, PRL (1964)

"The title is more of an expression of hope than a description of the book's contents....the observational horizon of neutrino astrophysics may grow...perhaps in a time as short as one or two decades."

Bahcall, Neutrino Astrophysics (1989)

Nobel Prizes: Reines (1995), Koshiba and Davis (2002)

Every Supernova Neutrino is Sacred

- MeV neutrinos

Core-collapse supernovae
How are neutron stars and black holes formed?

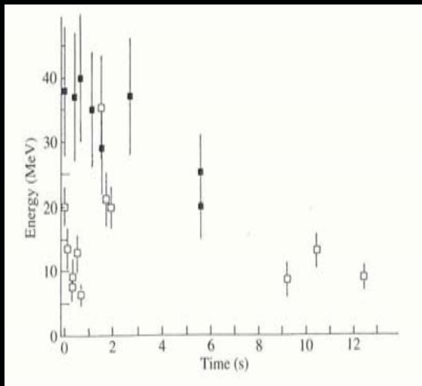
- TeV neutrinos

Supernova remnants and GRBs
Hadronic or leptonic origin for TeV gamma rays?

- EeV neutrinos

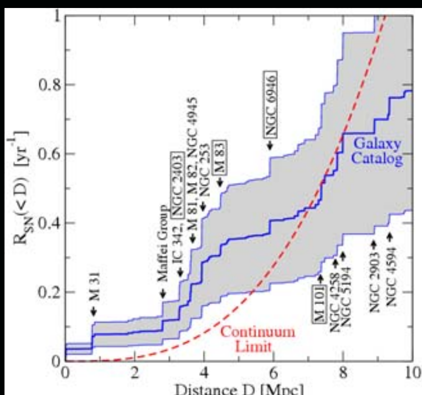
UHE cosmic rays (from GRBs?)
How are UHE cosmic rays accelerated?

Supernova Neutrino Detection Frontiers



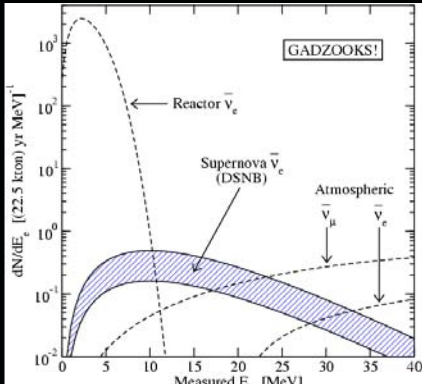
Milky Way

zero or at most one supernova
excellent sensitivity to details
one burst per ~ 40 years



Nearby Galaxies

one identified supernova at a time
direction known from astronomers
one "burst" per ~ 1 year



Diffuse Supernova Neutrino Background

average supernova neutrino emission
no timing or direction
(faint) signal is always there!

What are the Ingredients of the DSNB?

detector capabilities

supernova rate history

$$\psi(E_+) = \frac{c}{H_0} \sigma(E_\nu) N_t \int_0^{z_{max}} \phi(E_\nu[1+z]) \frac{R_{SN}(z)}{h(z)} dz \,,$$

positron spectrum (cf. detector backgrounds)

neutrino spectrum per supernova

Plan of the Talk

Supernova Basics

Star Formation and Supernova Rates

Detection of the DSNB

Constraints on Neutrino Emission

Concluding Perspectives

Supernova Basics

Products of Stars and Supernovae

Sato
TeV-PeV-EeV neutrinos and gamma rays

light Sato

for retirement?
winds

Sato
cosmic rays

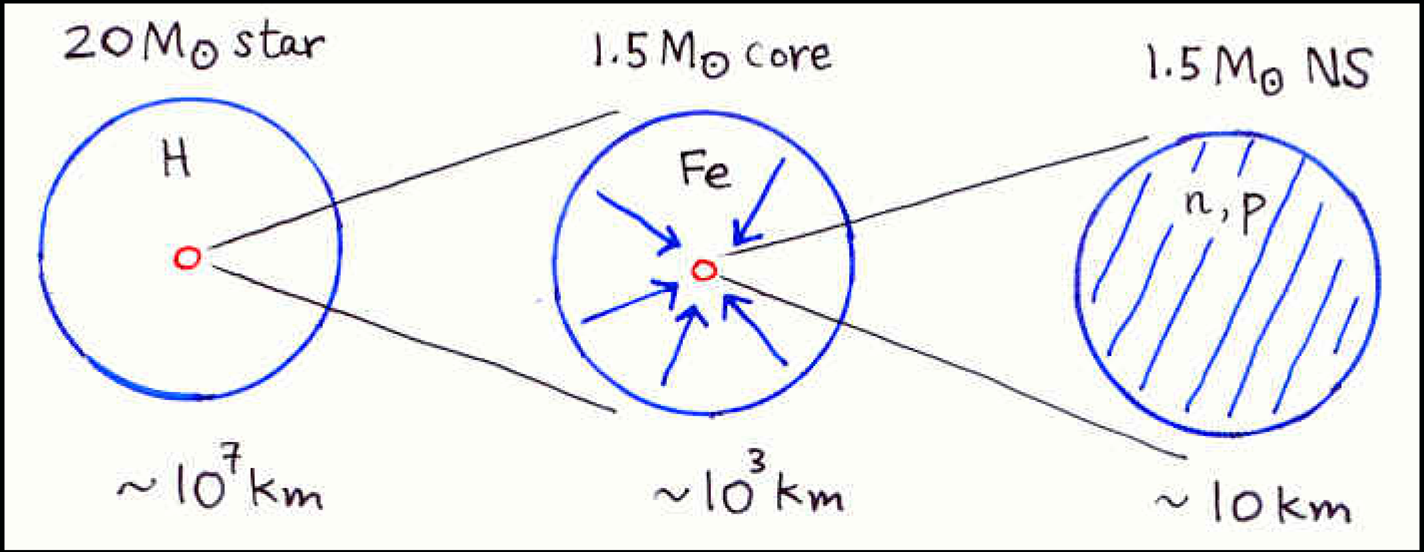
Sato
gas, dust

Sato
neutron stars, black holes (gravity waves?)

Sato
MeV neutrinos and gamma rays

Sato
nucleosynthesis yields

Supernova Energetics

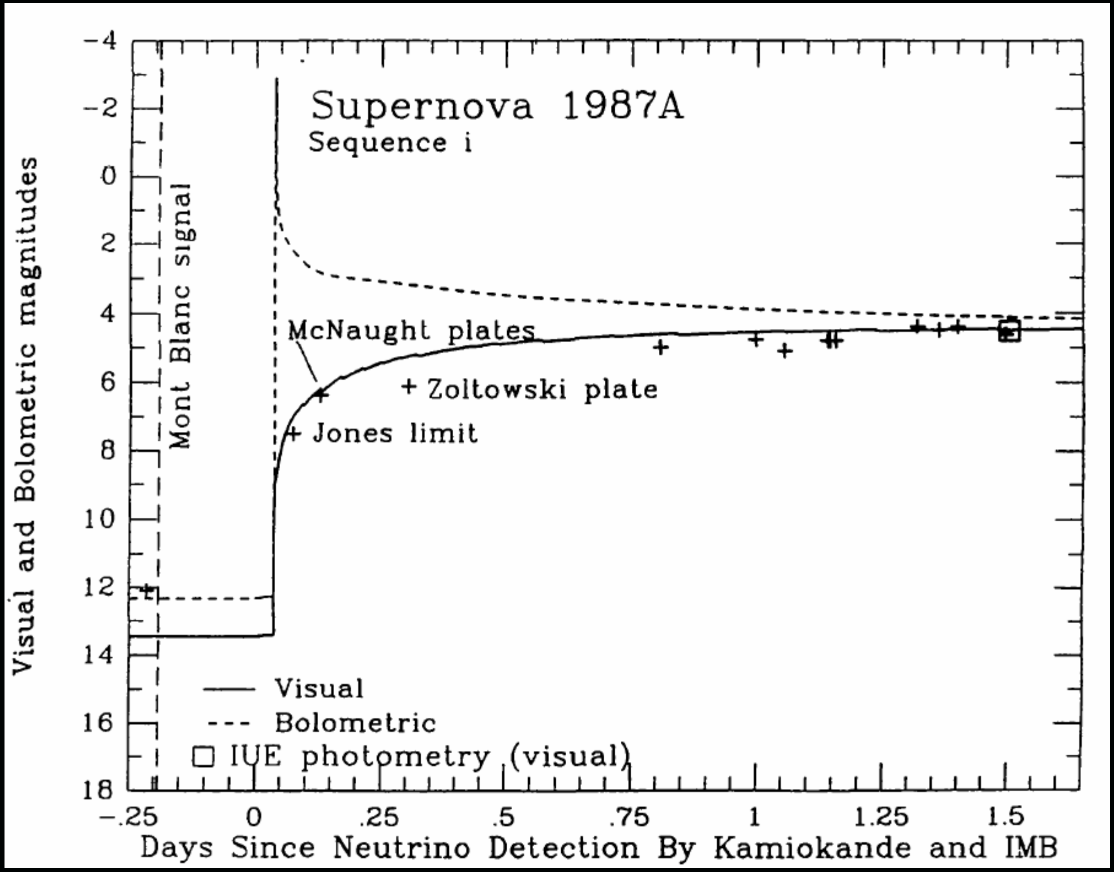


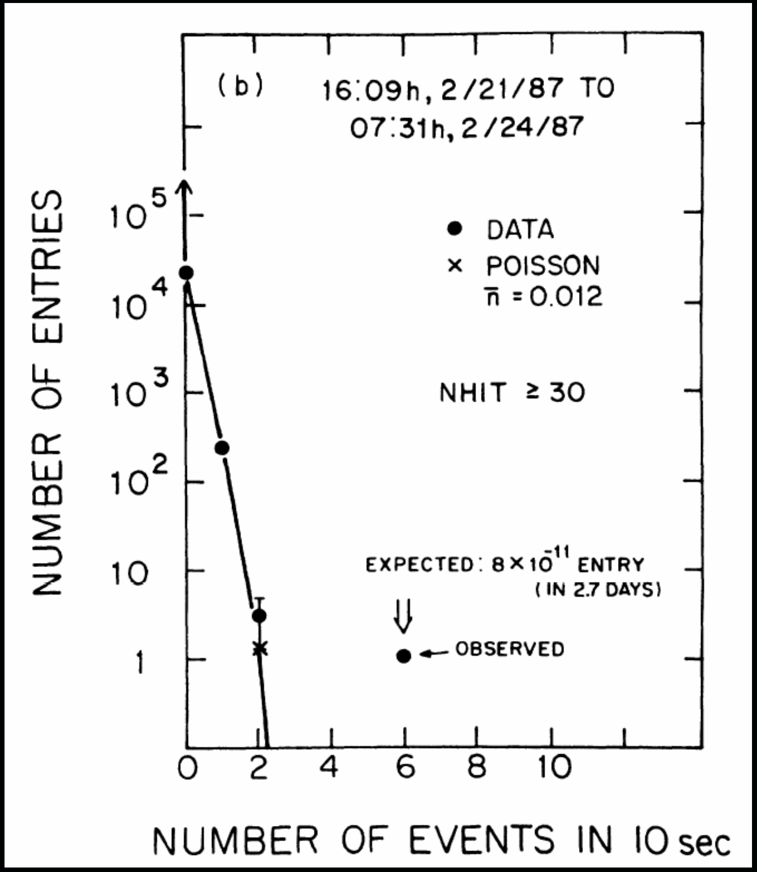
$$\Delta E_B \simeq \frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G M_{NS}^2}{R_{core}} \simeq 3 \times 10^{53} \text{ ergs} \simeq 2 \times 10^{59} \text{ MeV}$$

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

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

Type-II Supernovae Emit Neutrinos





The neutrino burst arrived before the light

SN 1987A was briefly more detectable than the Sun!

How Are Supernova Neutrinos Detected?

from SN

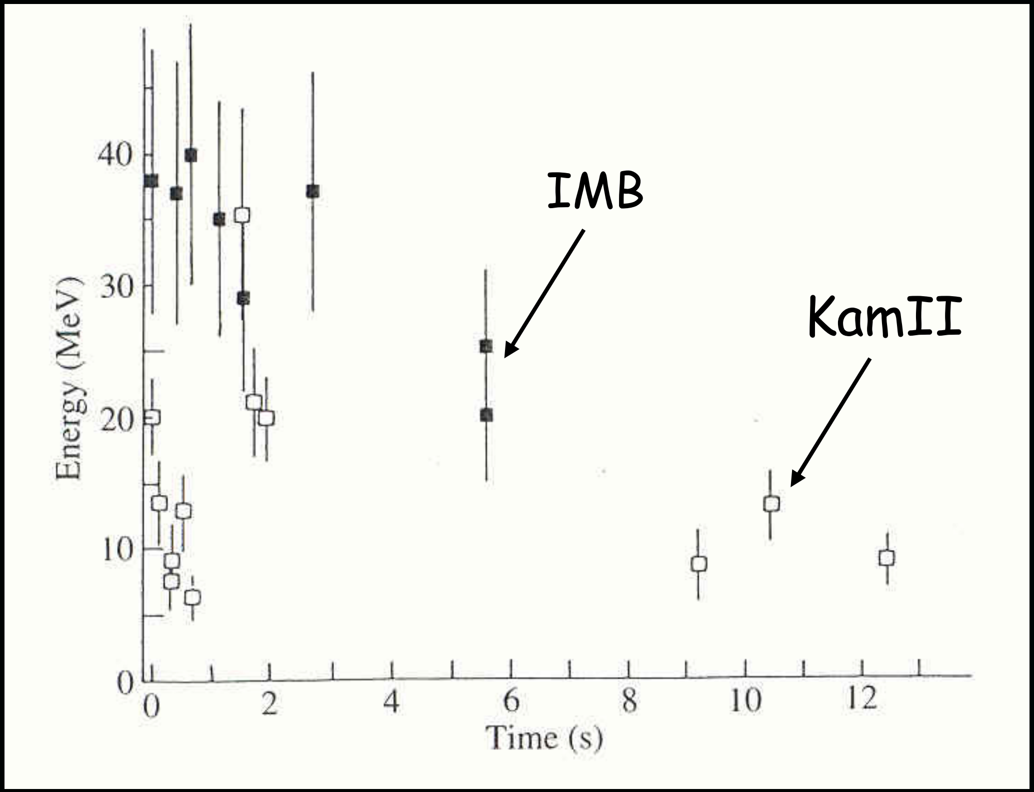
hydrogen nucleus

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

produces Cerenkov light

usually ignored (nota bene)

Neutrino Emission Due to NS/BH Formation



Neutrinos before light

Huge energy release
$E_B \sim GM^2/R \sim 10^{53}$ erg

Low average energy
$E_\nu \sim 10$ MeV

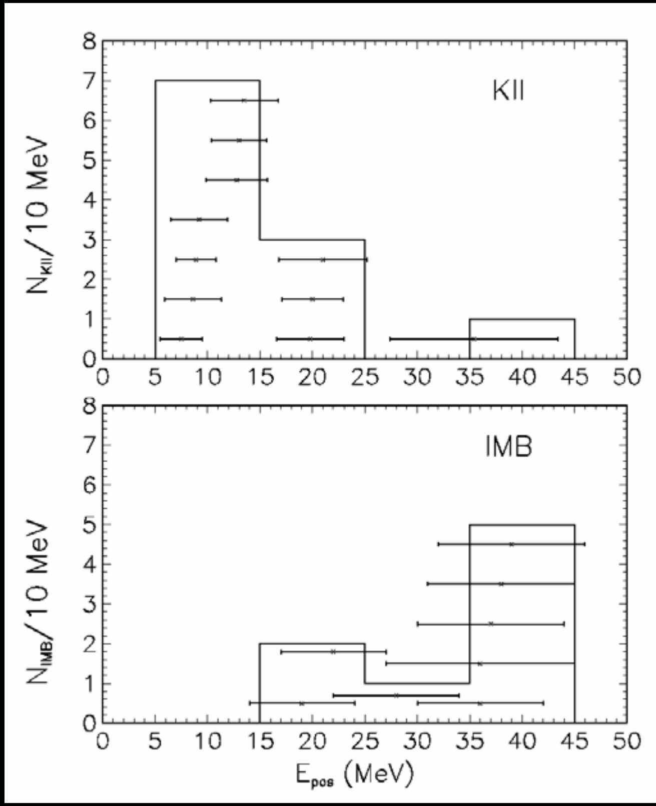
Very long timescale
$t \sim 10^4$ R/c

Sato

But still no direct observation of NS (or BH)

Do Data Agree with Each Other and Theory?

~ 20 events from $\bar{\nu}_e + p \longrightarrow e^+ + n$ in KamII, IMB



Mirizzi and Raffelt, PRD 72, 063001 (2005)

Simplest fits consistent with

$E_{tot} \sim 5 \times 10^{52}$ erg

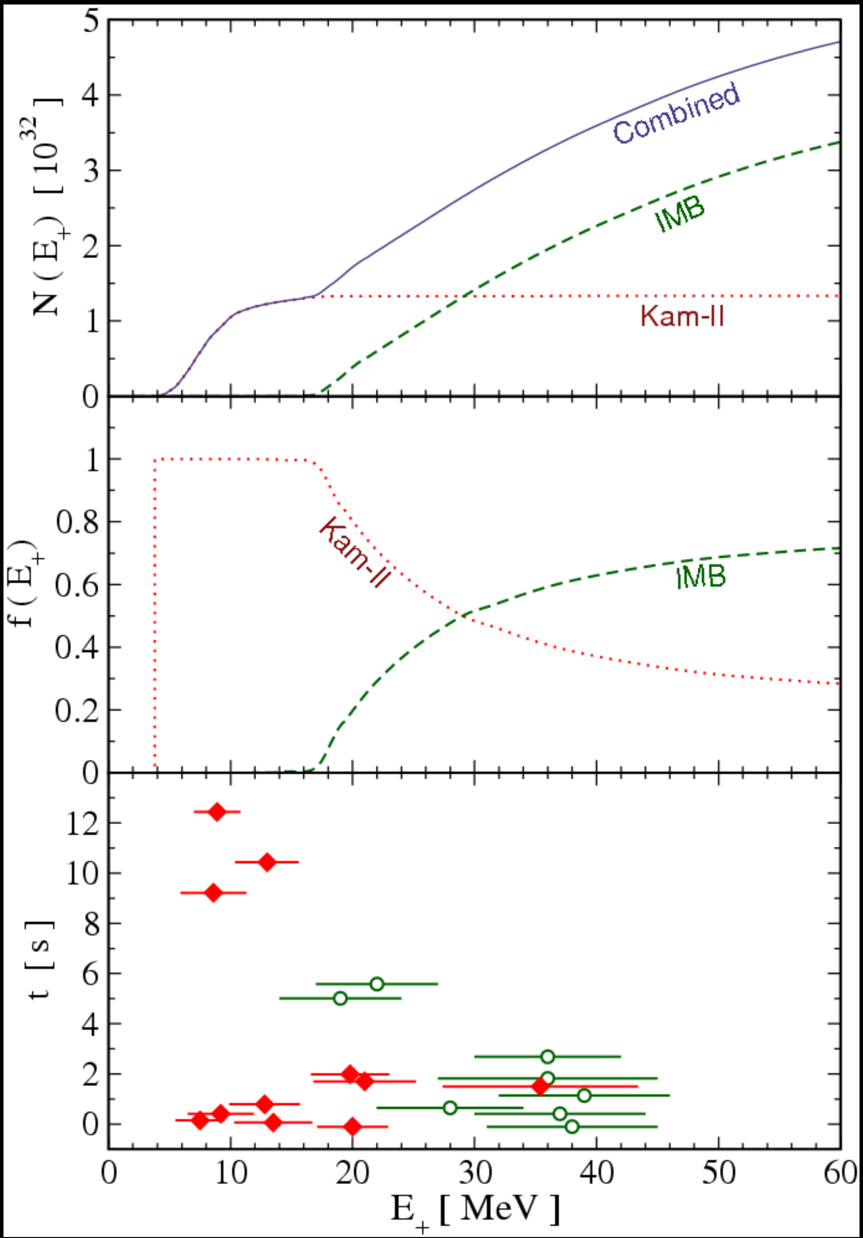
T ~ few MeV

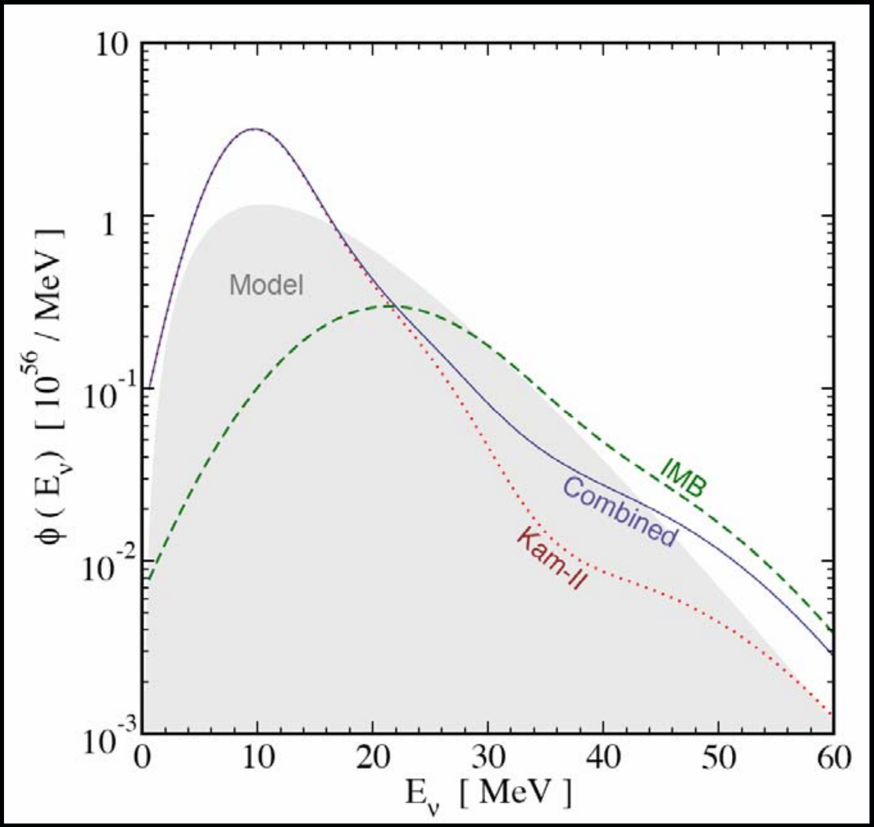
for the nuebar flavor

Sato

If the five unseen flavors were similar, then it fits expectations for NS formation in core collapse

Fresh Look at the SN 1987A Spectrum



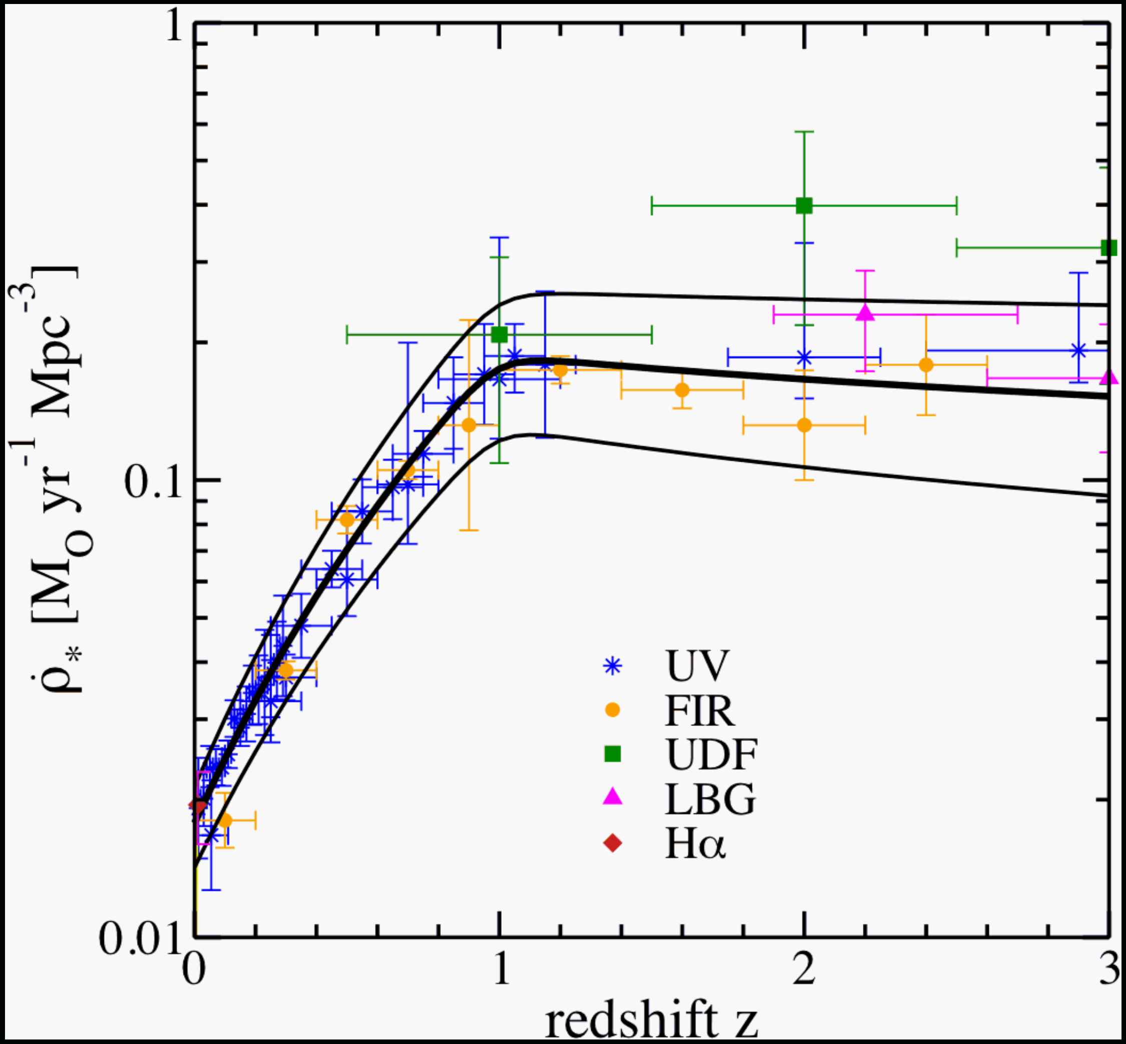


Yuksel and Beacom, astro-ph/0702613

No conflicts in data, only with assumed thermal spectrum

Star Formation and Supernova Rates

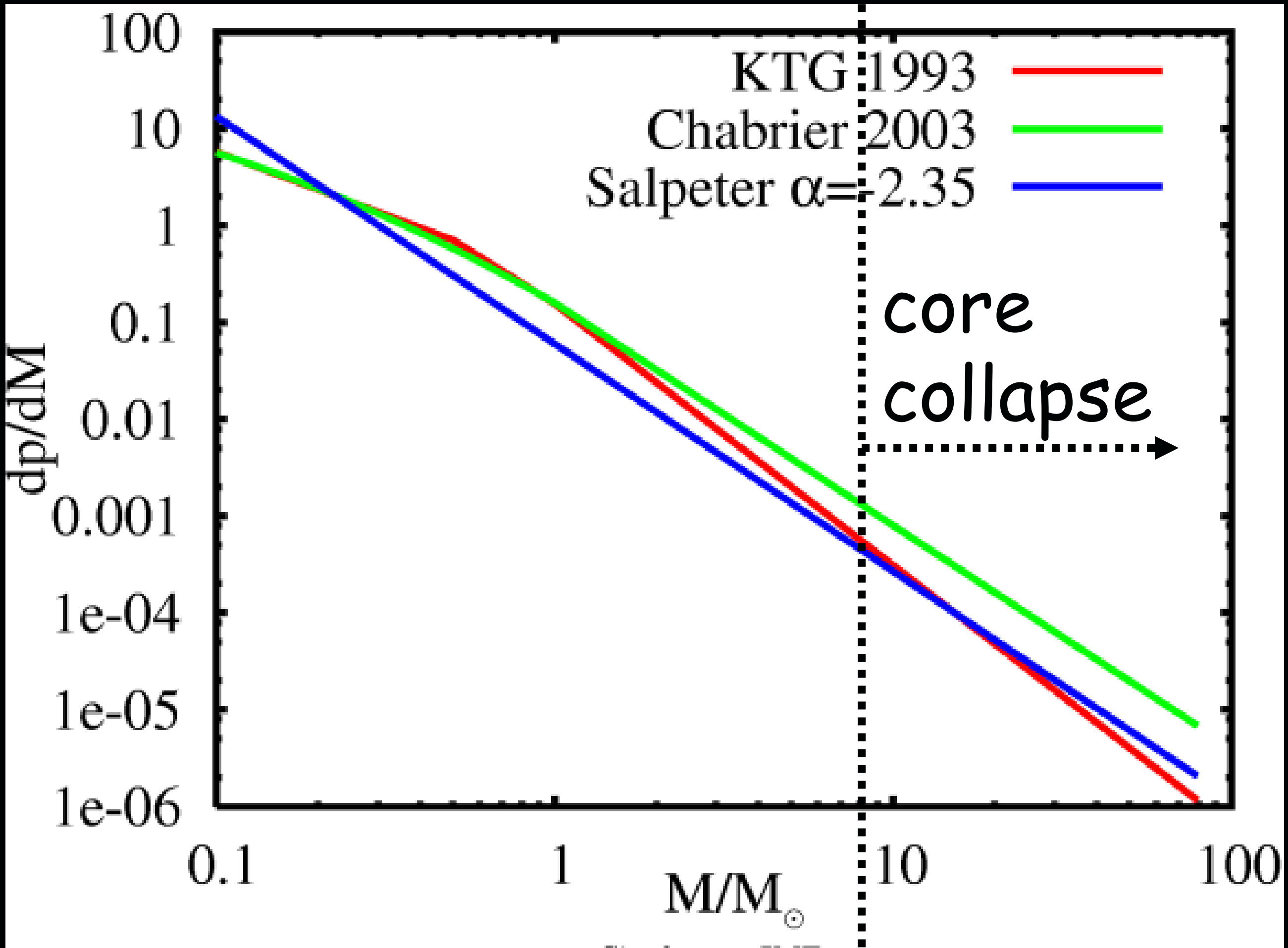
Star Formation Rate



Star formation rate is well known, but some concern about conversion to supernova rate

Horiuchi, Beacom, Dwek (in preparation)

Stellar Initial Mass Function

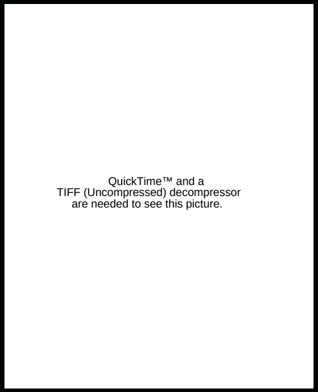


Single star IMFs.

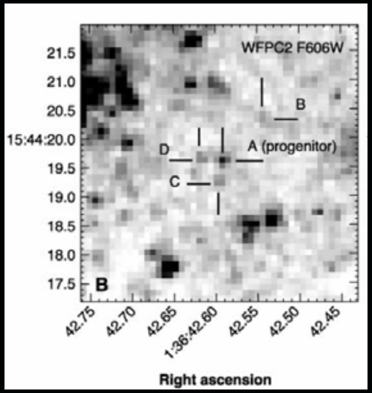
short lives

Which Progenitors Lead to Successful SNII?

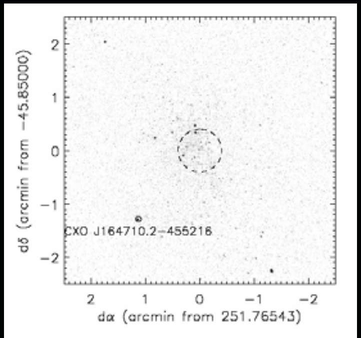
From ~ 8 M_{sun} to ?



SN 1987A progenitor was ~ 20 M_{sun}
It clearly exploded and emitted neutrinos

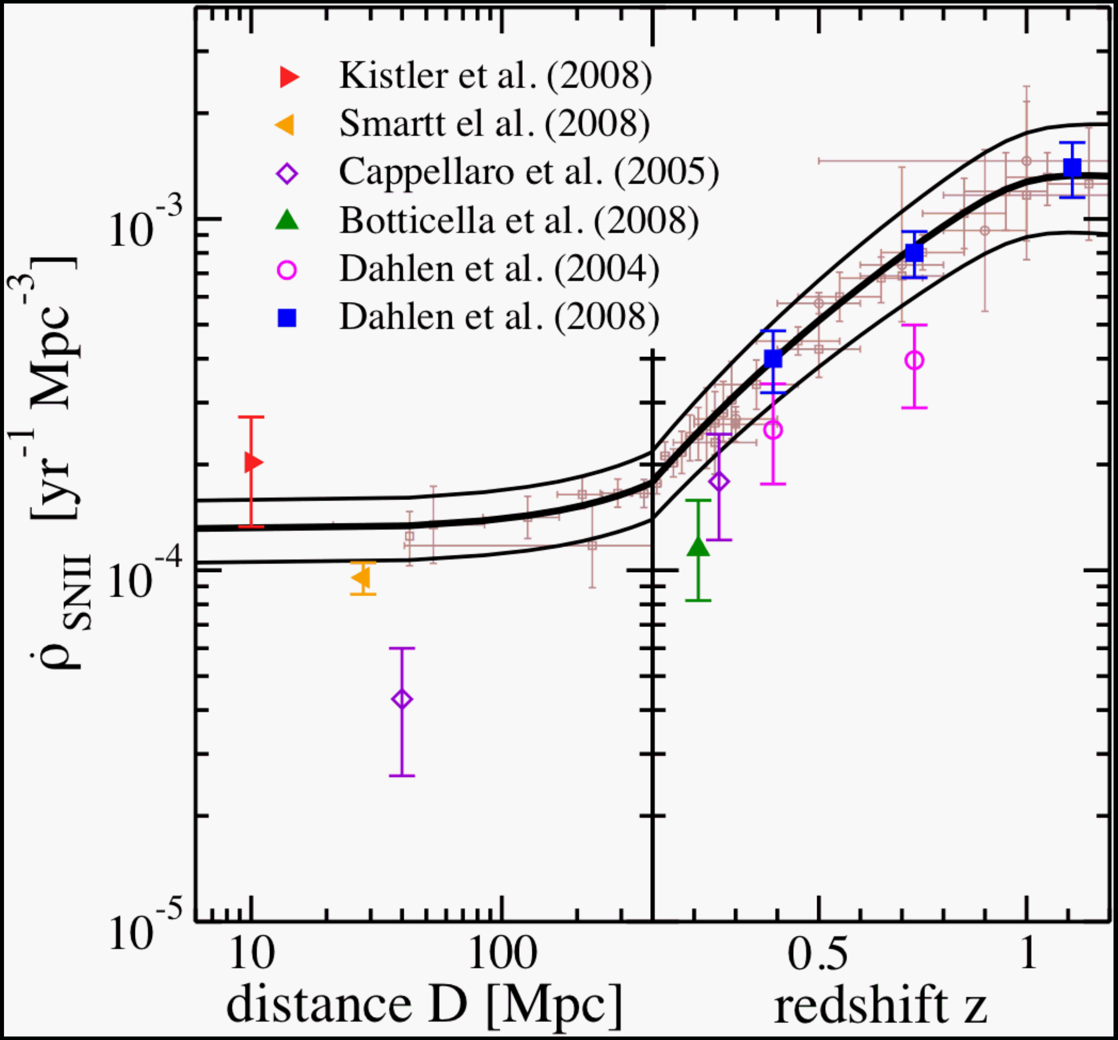


SN 2005cs: initial mass 9 +3/-2 M_{sun}
initial mass 10 +3/-3 M_{sun}
SN 2003gd: initial mass 8 +4/-2 M_{sun}
initial mass ~ 8-9 M_{sun}
from the Smartt and Filippenko groups



Muno et al. (2006) argue for a neutron star made by a ~ 40 M_{sun} progenitor

Supernova Rate

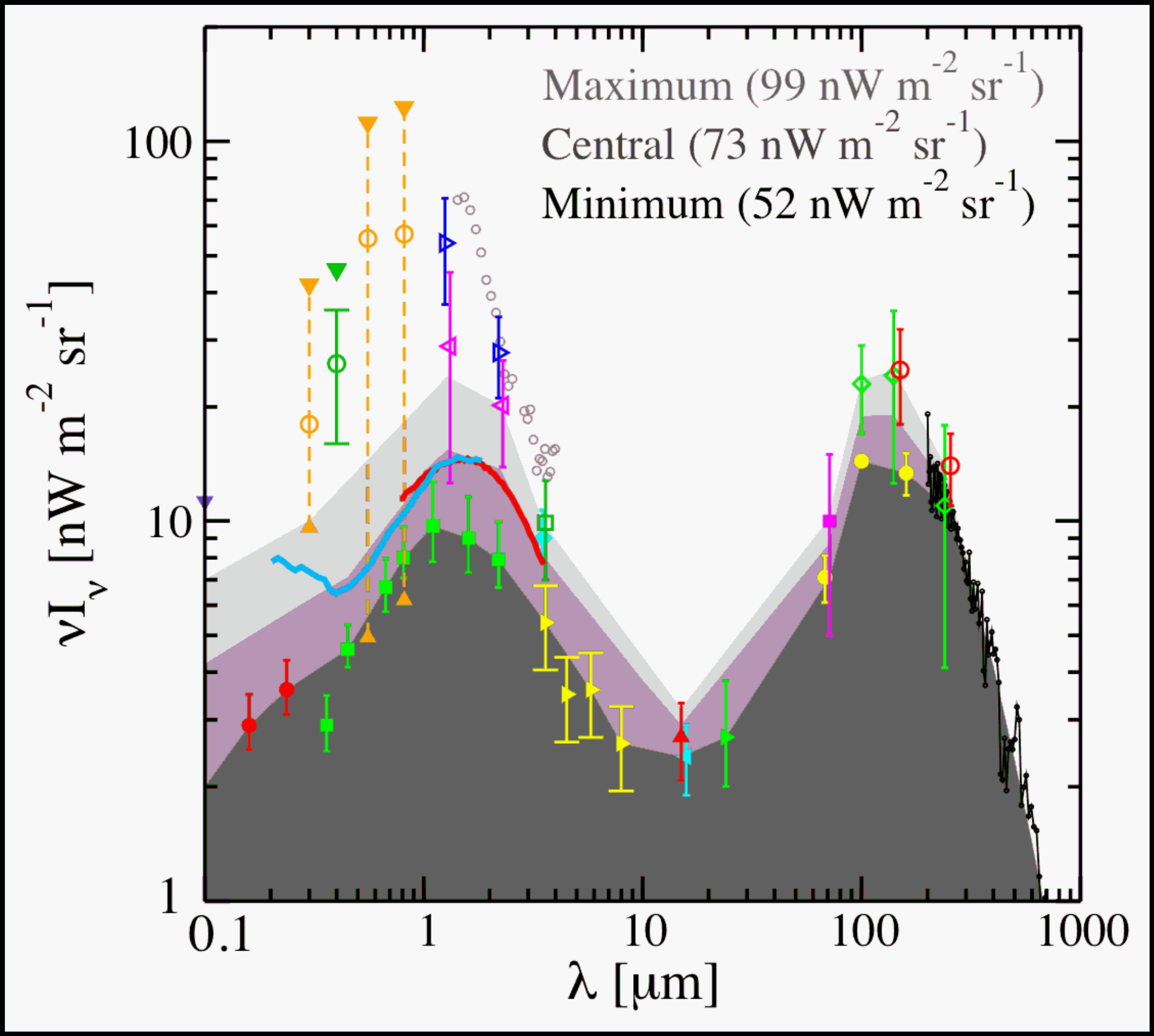


Provides direct normalization of the DSNB

Supernova rate *must* follow the shape of the star formation rate

Horiuchi, Beacom, Dwek (in preparation)

Extragalactic Background Light



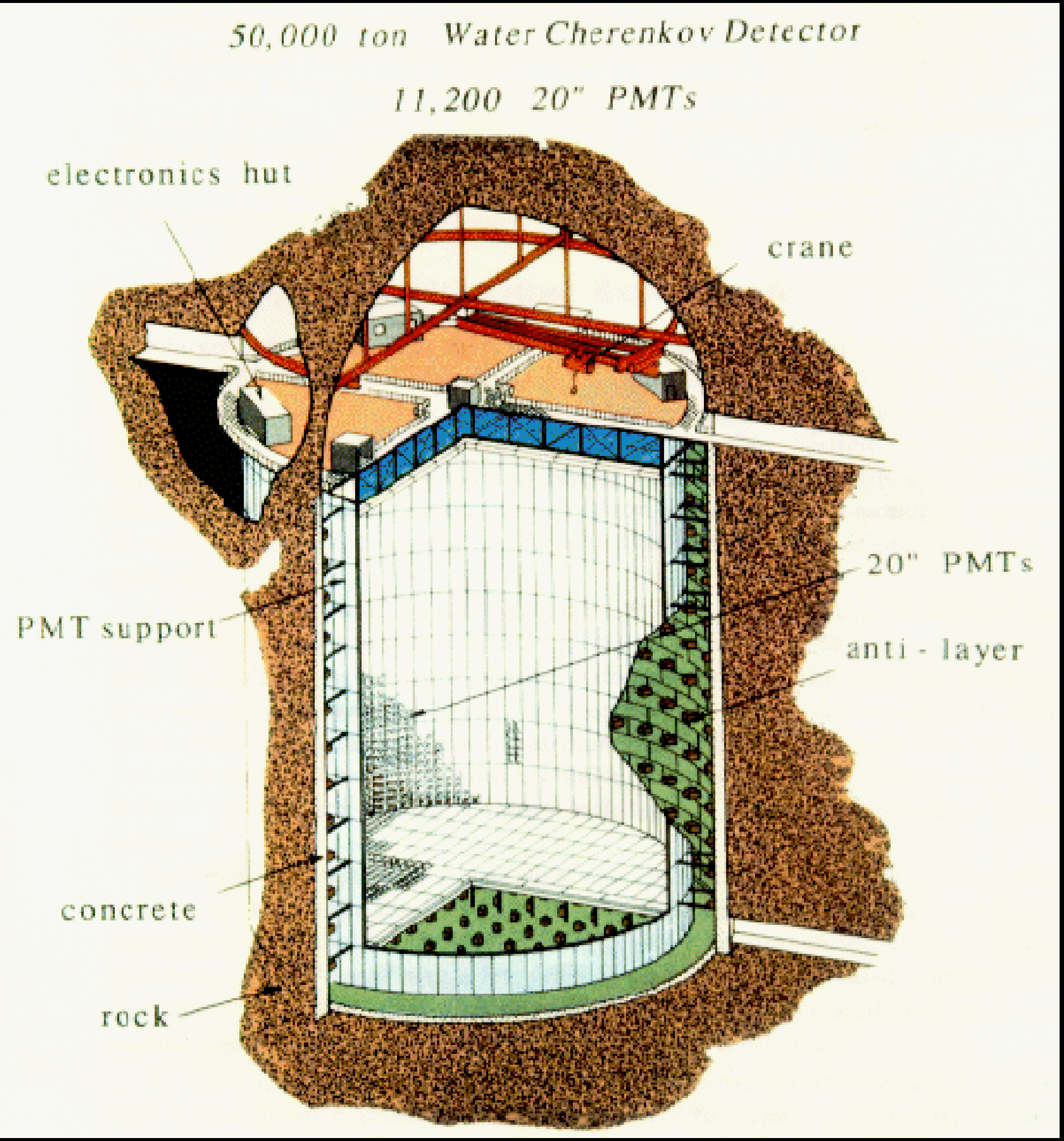
Using HB06 CSFH, our calculated result is 78--95, depending on IMF

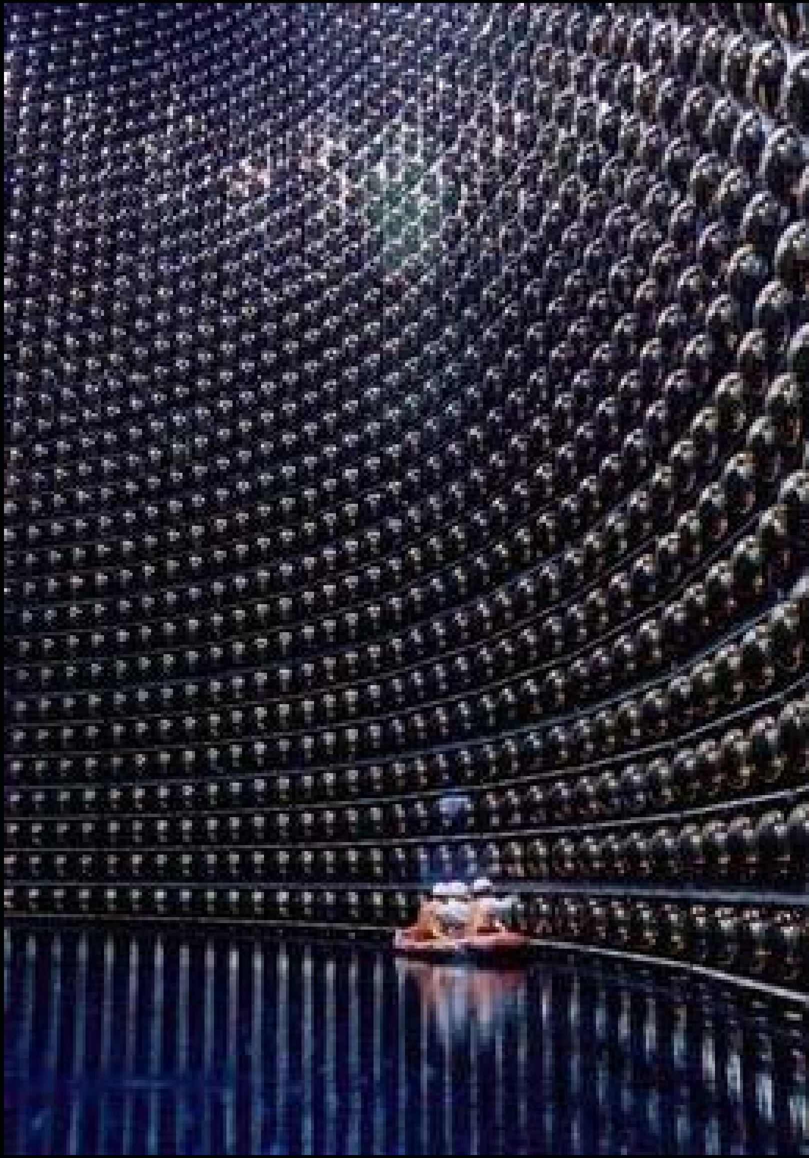
Provides another confirmation of the adopted CSFH

Horiuchi, Beacom, Dwek (in preparation)

Detection of the DSNB

Super-Kamiokande

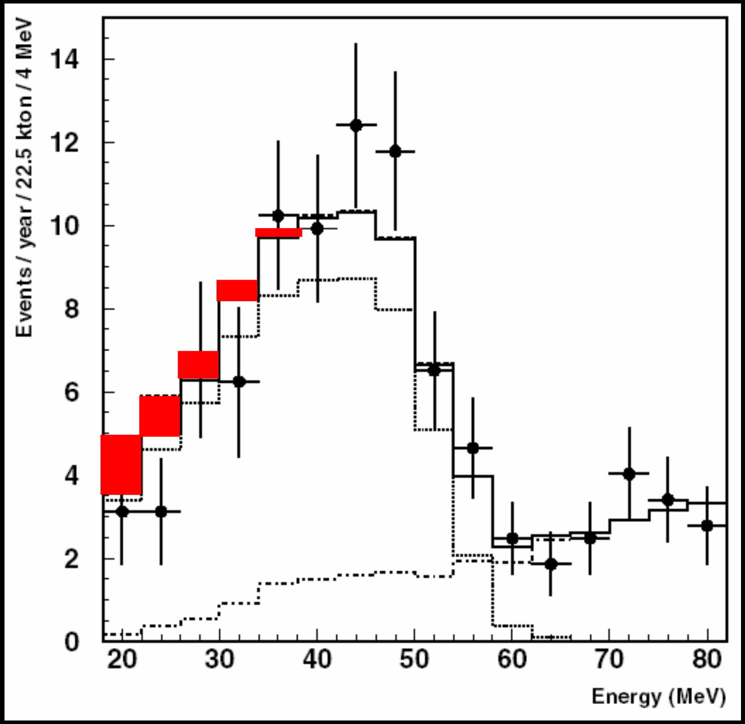




Might the DSNB be Detectable?

~20 years ago: early theoretical predictions
weak limit from Kamiokande, Zhang et al. (1988)

Sato et al., 1995-- : predictions for flux



Malek et al. (SK), PRL 90, 061101 (2003)

Kaplinghat, Steigman, Walker (2000)
flux < 2.2/cm^2/s above 19.3 MeV

SK limit is flux < 1.2/cm^2/s

This might be possible!

Two serious problems:
Predictions uncertain
Backgrounds daunting

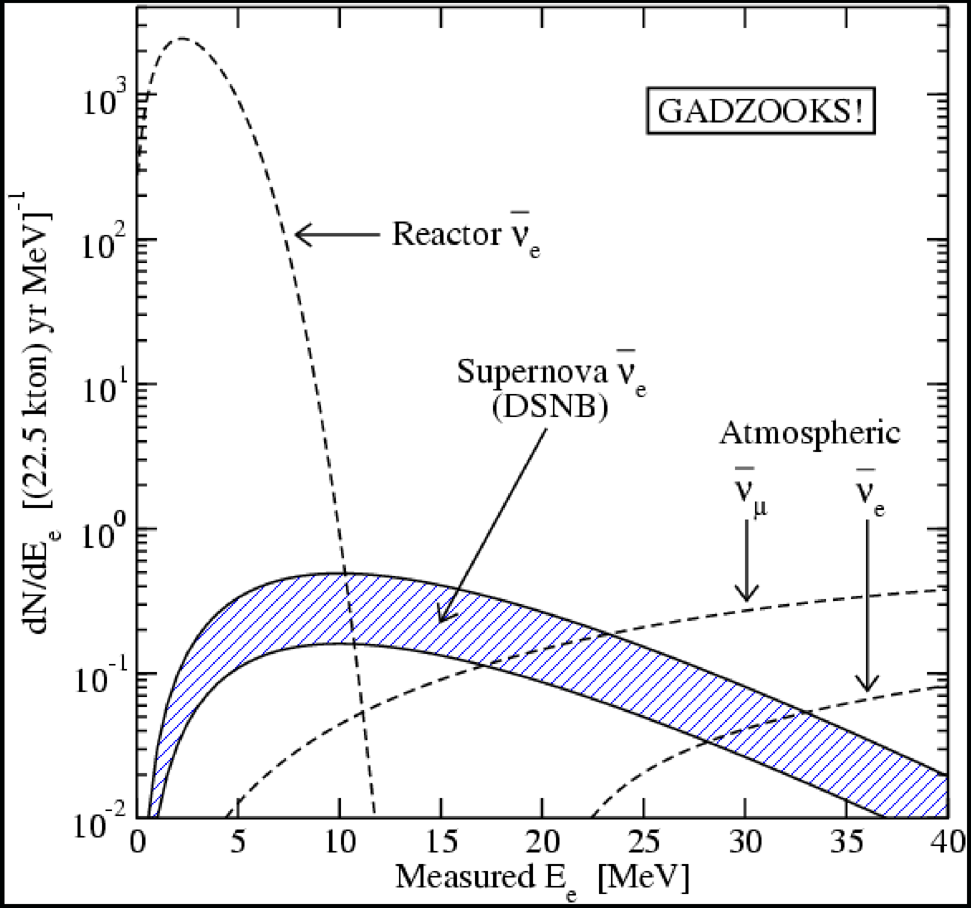
Now solved or solvable

Can We Beat the Backgrounds?

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

Beacom, Vagins, PRL 93, 171101 (2004)

GADZOOKS!



At 0.2% $GdCl_3$:

Capture fraction = 90%

λ = 4 cm, τ = 20 μs

active R&D program in US and Japan

Neutron tagging means lower backgrounds, thresholds

But Will it Work?

- Beacom and Vagins demonstrated plausibility of many aspects based on available data and estimates

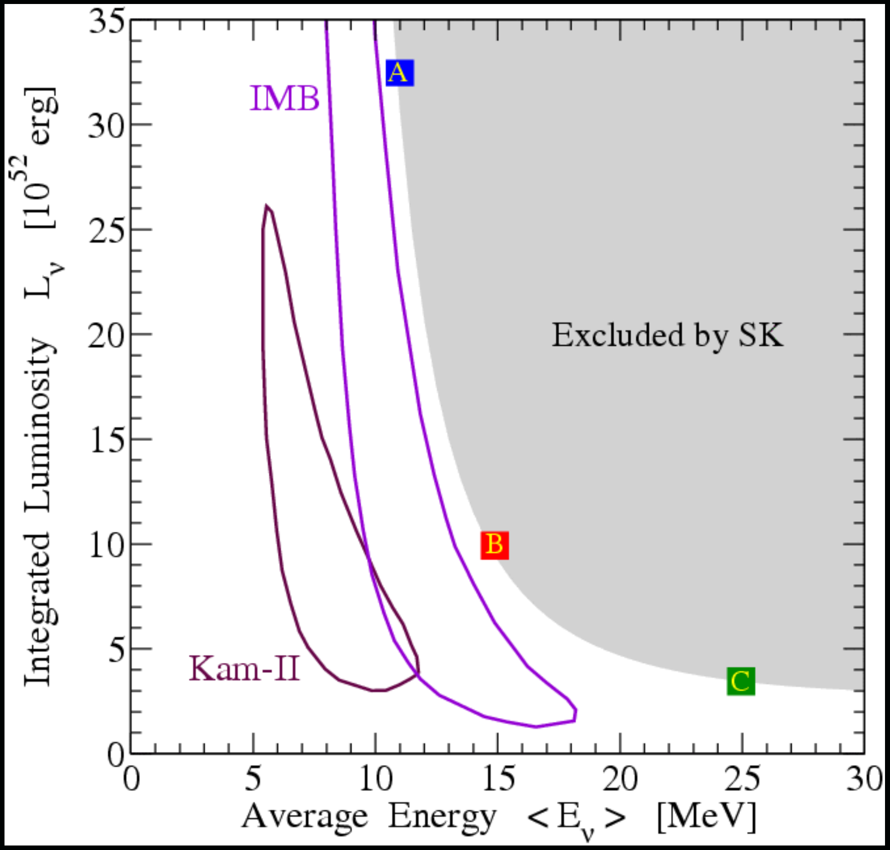
- Vagins is leading an intense R&D effort, funded by the DOE and Super-Kamiokande, to test all aspects ...and so far, so good

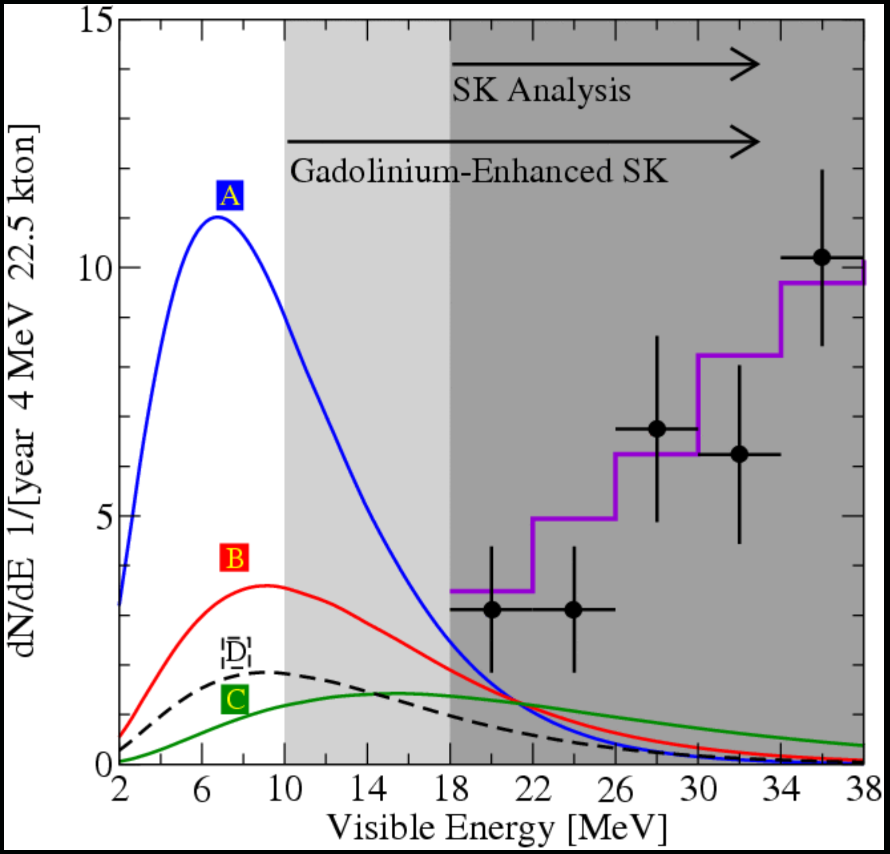
- Very high level of interest, based on the physics potential, for the DSNB, reactors, and more

- Super-Kamiokande internal technical design review ongoing; important new developments at site

Constraints on Neutrino Emission

What is the Neutrino Emission per Supernova?

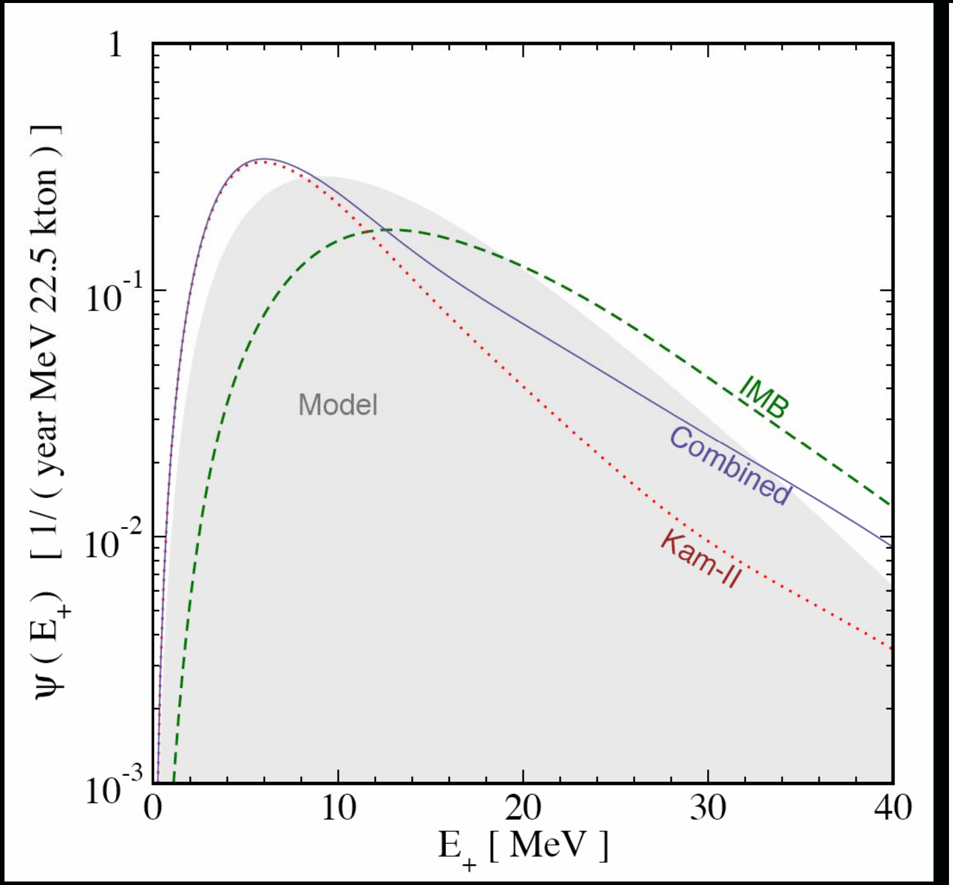


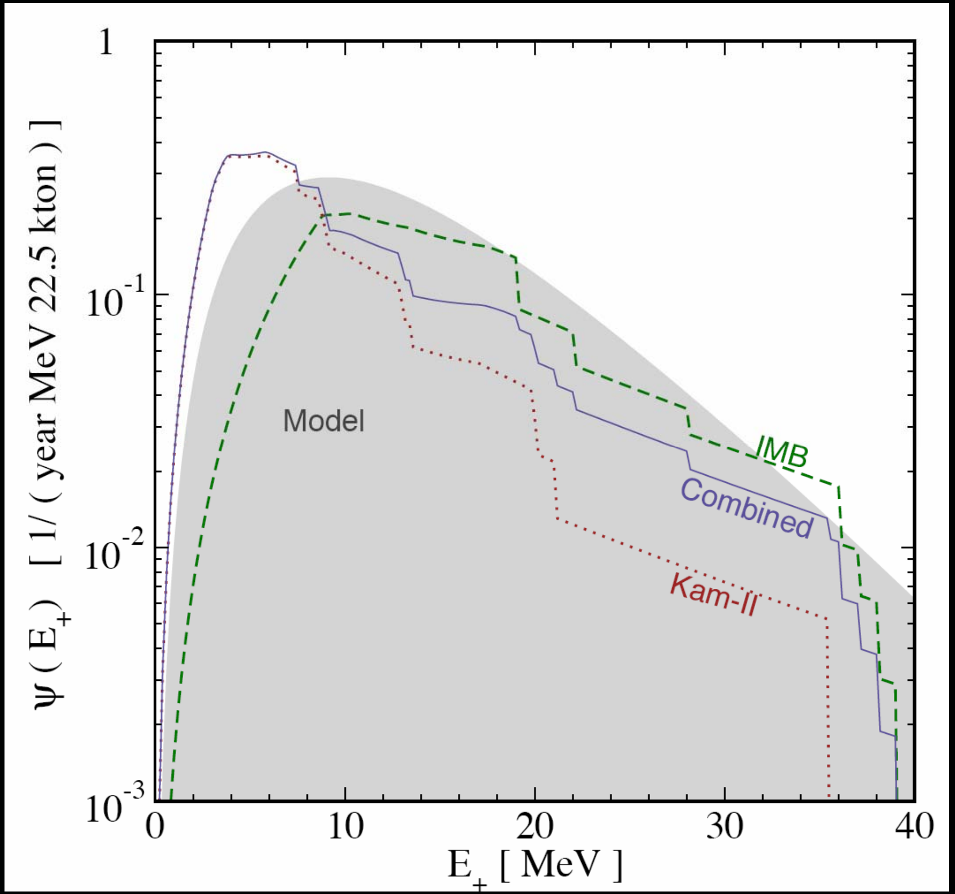


Yuksel, Ando, Beacom, PRC 74, 015803 (2006)

Yoshida et al. (2008): nucleosynthesis constraints on emission

DSNB Spectra Based on SN 1987A Data

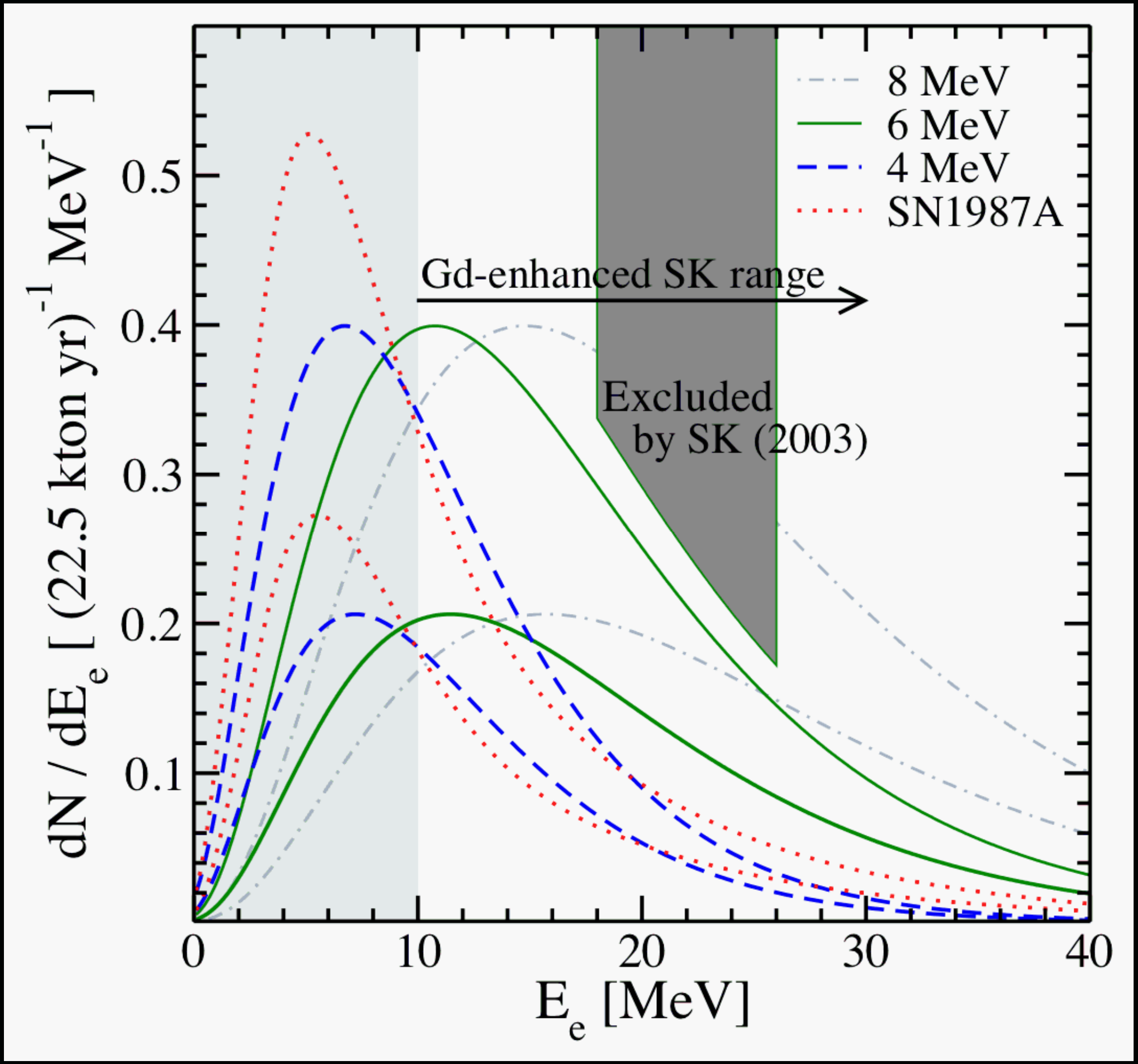




Yuksel and Beacom, astro-ph/0702613

DSNB robust, primarily depends on IMB data

Range of Reasonable DSNB Spectra



DSNB is easily within reach of detection

New test of supernova and neutrino physics

General agreement with e.g., Daigne et al., Ando and Sato

Horiuchi, Beacom, Dwek (in preparation)

What are the Ingredients of the DSNB?

detector capabilities

supernova rate history

$$\psi(E_+) = \frac{c}{H_0} \sigma(E_\nu) N_t \int_0^{z_{max}} \phi(E_\nu[1+z]) \frac{R_{SN}(z)}{h(z)} dz \,,$$

positron spectrum (cf. detector backgrounds)

neutrino spectrum per supernova

Three Main Results

Astrophysical (core collapse rate) uncertainties cannot be pushed to get a substantially lower DSNB flux

Emission (supernova neutrino yield) uncertainties also cannot be pushed to get a substantially lower DSNB flux

Prospects for Super-Kamiokande are excellent, and the results will provide a new and powerful probe of supernova and neutrino physics

Horiuchi, Beacom, Dwek (in preparation)

Concluding Perspectives

Open Questions

What is the average neutrino emission per supernova?
Measure this with the DSNB

What is the true rate of massive star core collapses?
Partially degenerate with the above

How much variation is there in the neutrino emission?
Requires detecting multiple individual supernovae

How does neutrino mixing affect the received signal?
Requires working supernova models, detailed inclusion of neutrino mixing effects, AND neutrino detection!

Future Plans

Short-Term

- Experimentalists develop Gd plans for Super-K
- SN modelers calculate time-integrated emission
- Astronomers better measure supernova rates

Long-Term

- Detect a Milky Way supernova (Super-K or ...)
- Detect the DSNB with high statistics (Hyper-K)
- Detect supernovae in nearby galaxies (5-Mton)

Conclusions

Understanding supernovae is crucial for astrophysics:
- How do supernovae work and what do they do?
- What is the history of stellar birth and death?

Detecting neutrinos is crucial for supernovae:
- What is the neutrino emission per supernova?
- How are neutron stars and black holes formed?

Neutrino astronomy has a very bright future:
- Already big successes with the Sun and SN 1987A!
- DSNB could be the first extragalactic detection!

Detection of the DSNB is very important:
- Crucial data for understanding supernova explosions!
- New tests of neutrino properties!

CCAPP at Ohio State

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

CCAPP

Center for Cosmology and AstroParticle Physics

Mission: To house world-leading efforts in studies of dark energy, dark matter, the origin of cosmic structure, and the highest energy particles in the universe, surrounded by a highly visible Postdoc/Visitor/Workshop Program.

ccapp.osu.edu

Postdoctoral Fellowship applications welcomed in Fall

We also welcome visiting students in the tradition of Ando and Horiuchi