Diffuse Supernova Neutrino Background

John Beacom
The Ohio State University

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, <u>Neutrino Astrophysics</u> (1989)

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

Plan of the Talk

Detection of Neutrinos from SN 1987A

What Do We Want to Find Out?

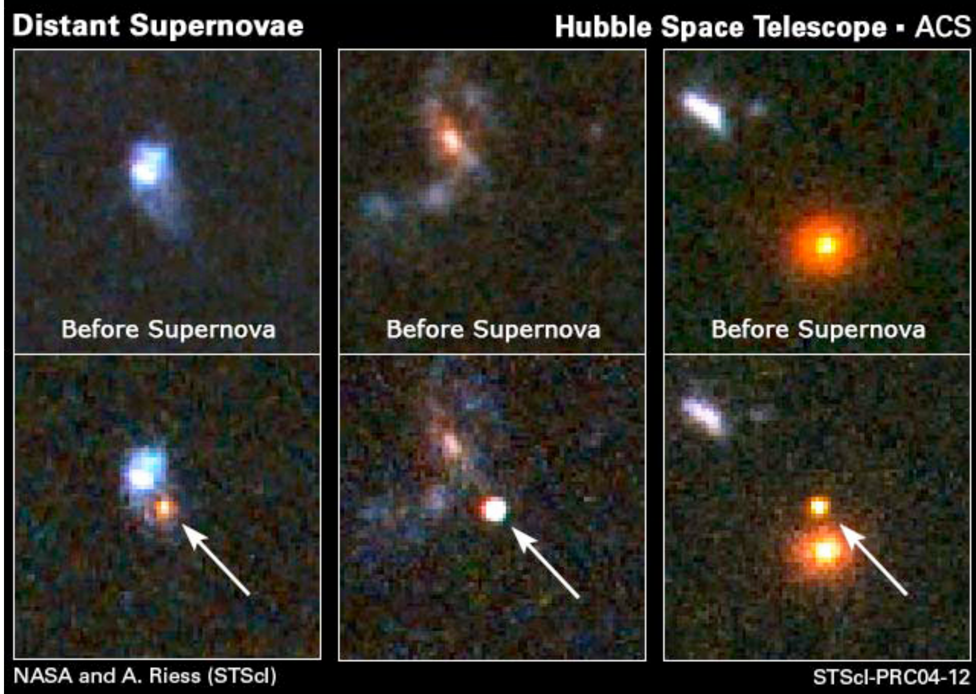
Diffuse Supernova Neutrino Background

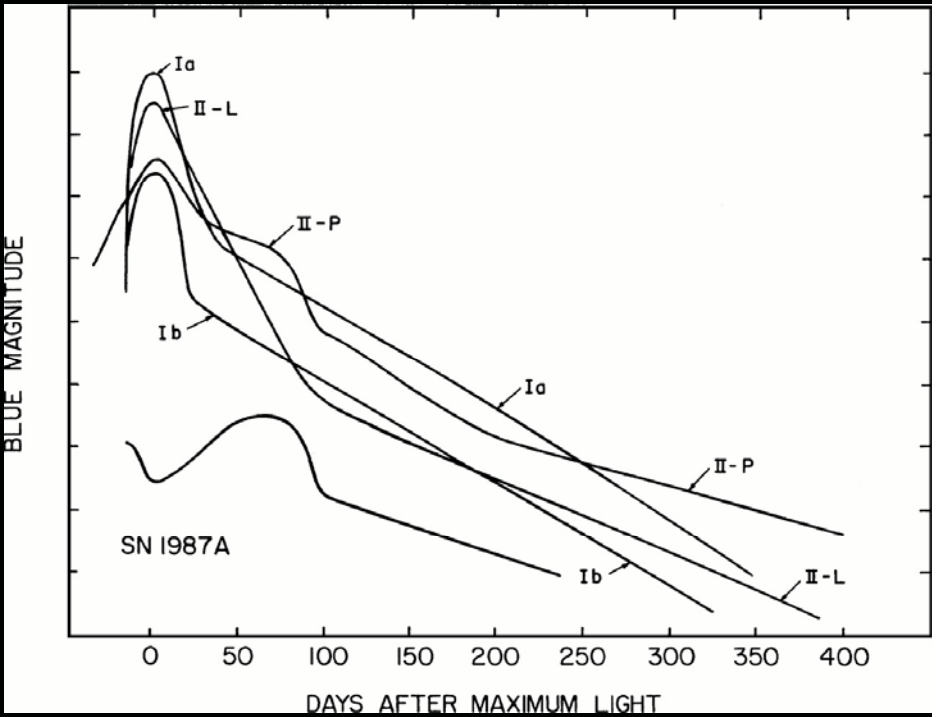
R&D Update from Vagins

Concluding Perspectives

Birth of Neutrino Astronomy: Detection of Neutrinos from SN1987A

Supernovae Are Optically Bright





Question: By how what factor does the supernova outshine its host galaxy in neutrinos?

Products of Stars and Supernovae

light

TeV-PeV-EeV
neutrinos and
gamma rays

winds

cosmic rays

gas, dust

neutron stars,
black holes
(gravity waves?)

MeV neutrinos
and gamma rays

nucleosynthesis
yields

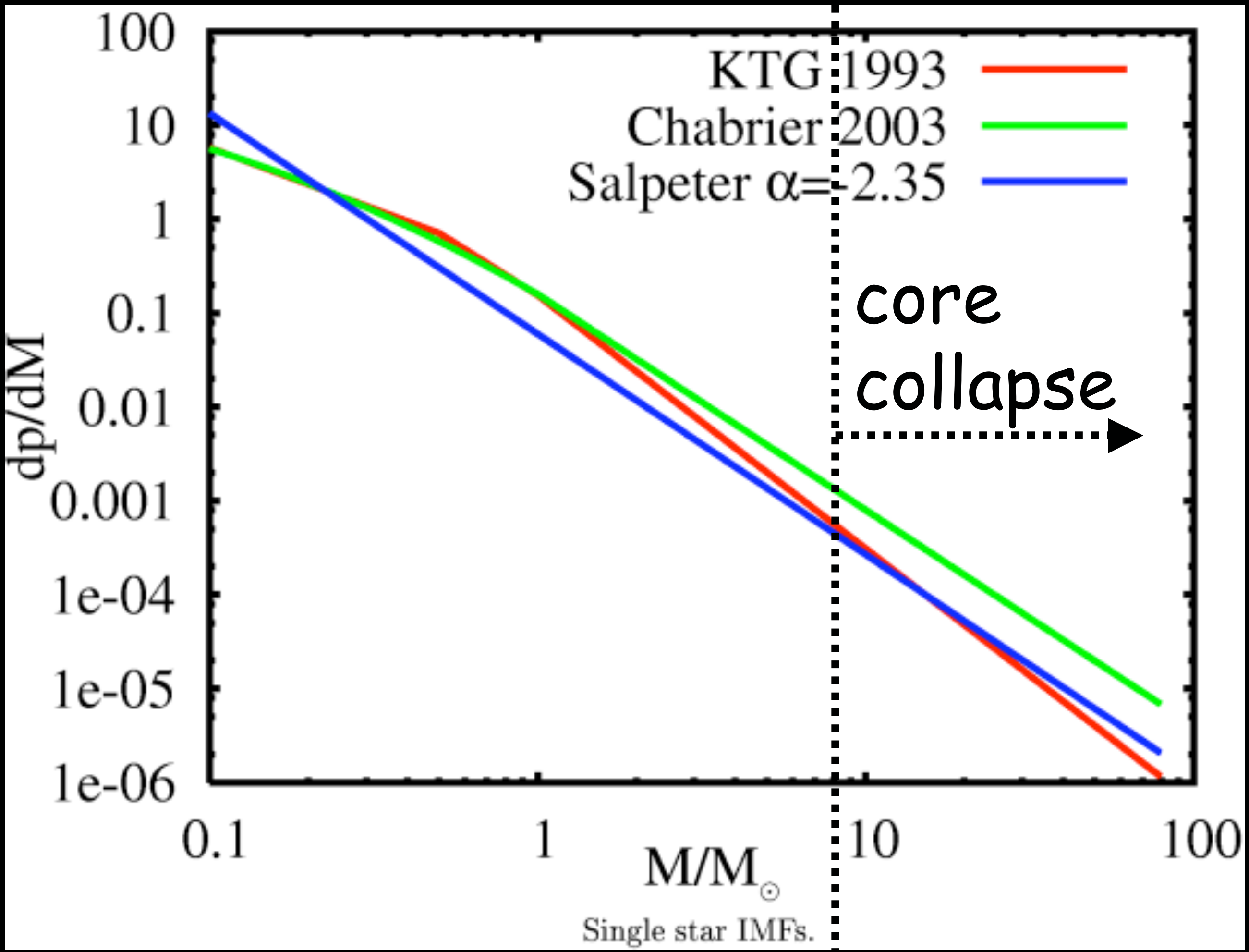
Mechanisms of Supernovae

Thermonuclear supernova: type Ia (3 < M < 8)
runaway burning initiated by binary companion
MeV gamma rays from ^{56}Ni, ^{56}Co decays

Core-collapse supernova: types II, Ib, Ic (M > 8)
collapse of iron core in a massive star
MeV neutrinos from proto-neutron star

Gamma-ray burst: long-duration type (M > 30?, spin)
collapse of iron core in a very massive star
significant angular momentum, jet formation
keV gamma rays from fireball
very high energy gamma rays and neutrinos?

Stellar Initial Mass Function

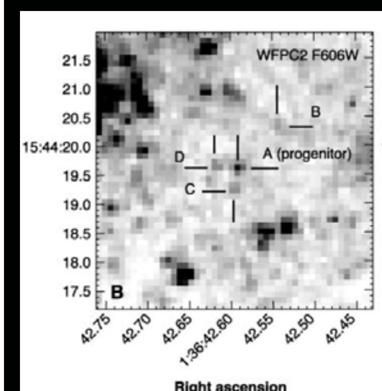


short lives

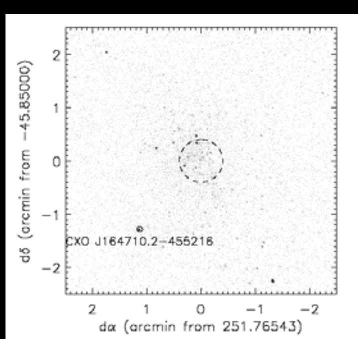
Which Progenitors Lead to SNII?

From ~ 8 M_{sun} to ?

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

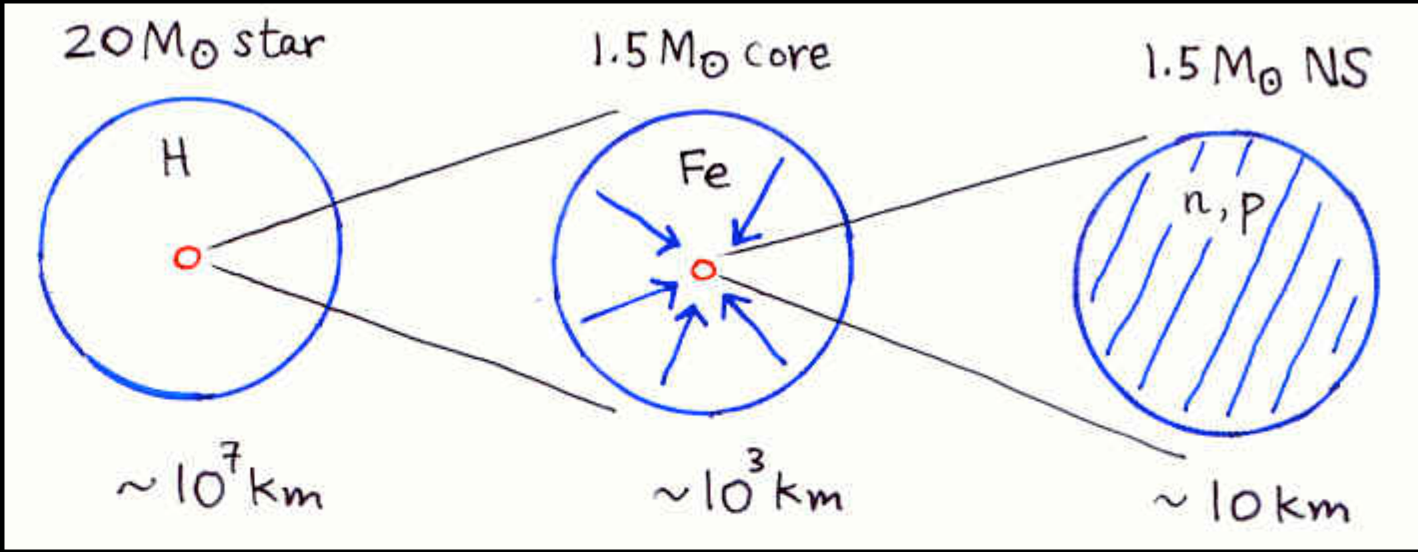


SN 2005cs: initial mass 9 +3/-2 M_{sun}
initial mass 10 +3/-3 M_{sun}
SN 2003gd: initial mass 8 +4/-2 M_{sun}
initial mass ~ 8-9 M_{sun}
from the Smartt and Filippenko groups



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

Supernova 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 $\simeq 10^{-4}\,\Delta E_B$

Cooling By Neutrinos

- Collapsed hot core produces thermal neutrino pairs of all flavors with average energy ~ 100 MeV

- At nuclear densities, the neutrinos are trapped with a mean free path of $\lambda \sim 1$ m

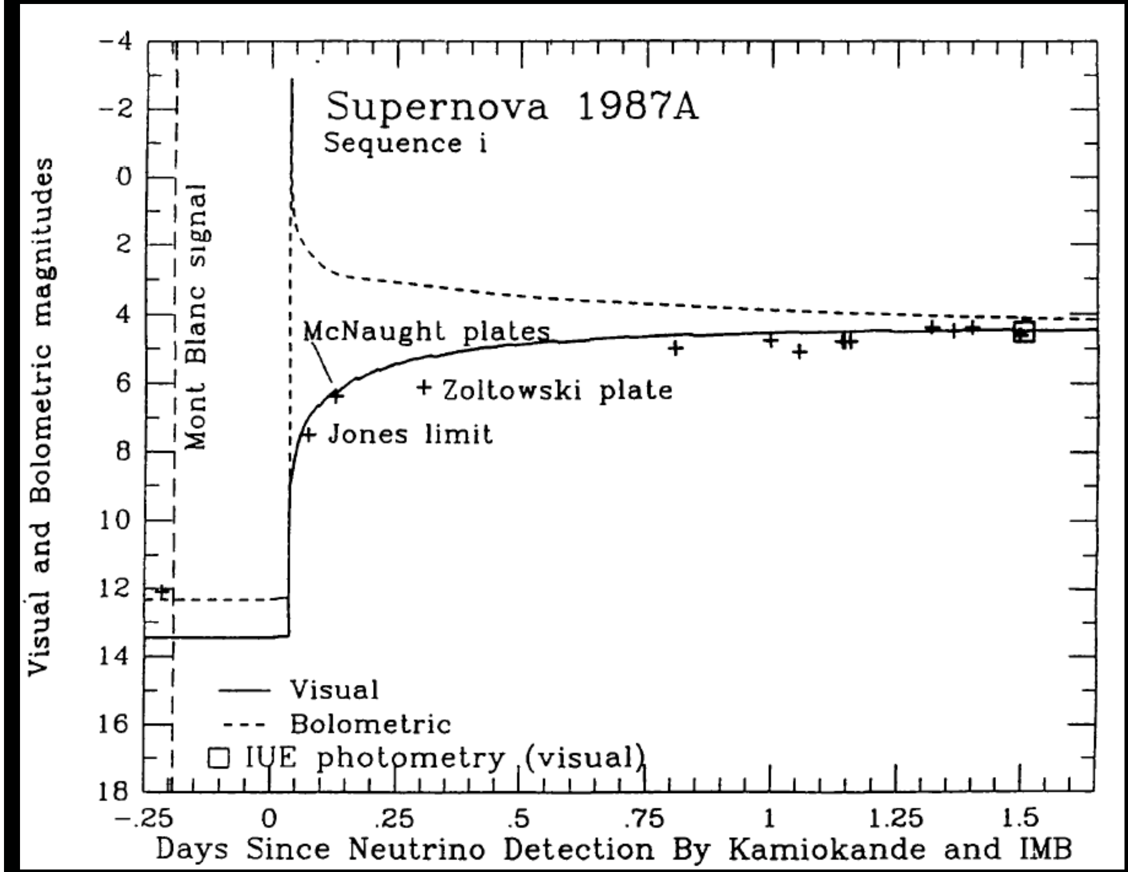
- The diffusion timescale is $\tau \sim (\lambda/c)\,(R/\lambda)^2 \sim 1$ s

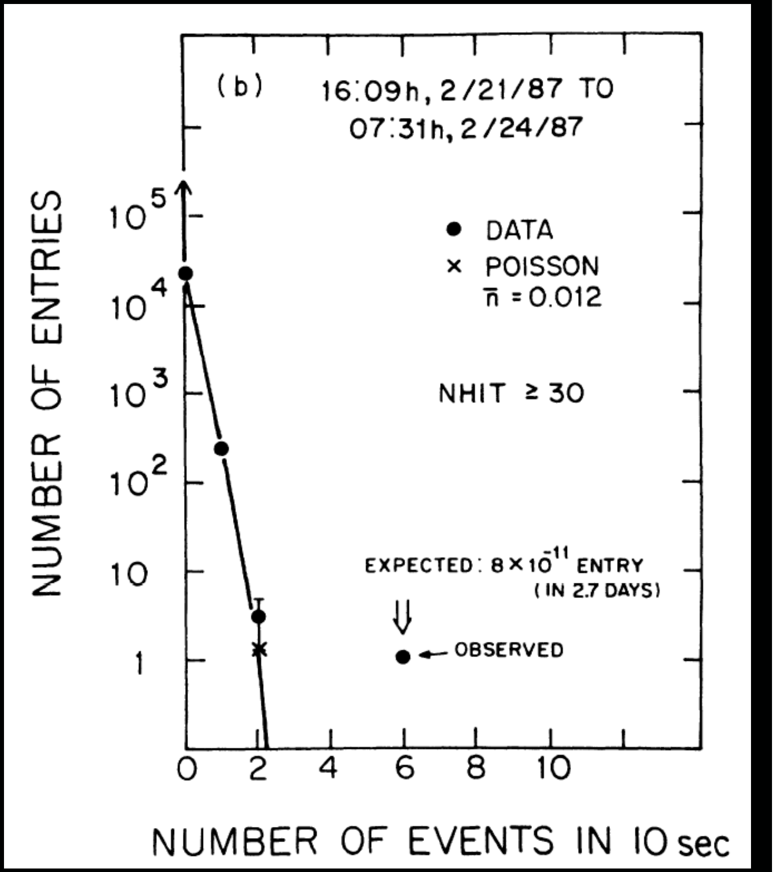
- The luminosity $L \sim E_{tot}/\tau \sim 4\pi R^2\, \sigma_{SB}\, T^4$

- Solve for T to get an average energy of ~ 10 MeV

(Note that these numbers are very rough)

Type-II Supernovae Emit Neutrinos

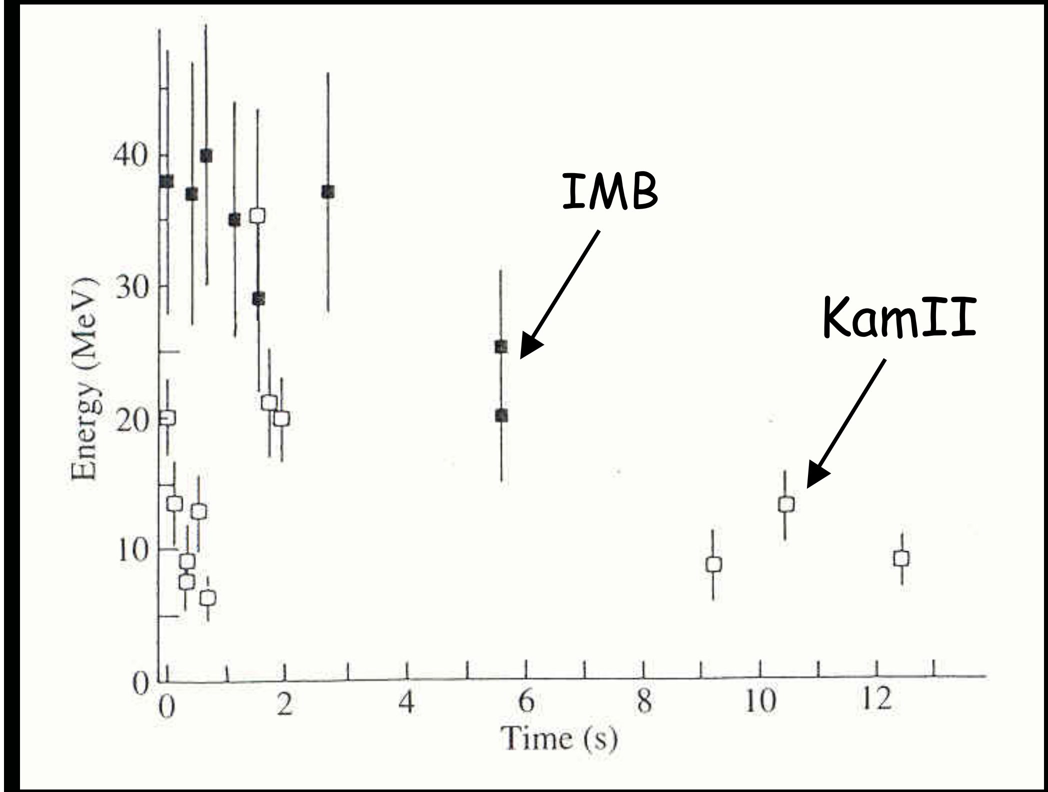




The neutrino burst arrived before the light

SN 1987A was briefly more detectable than the Sun!

Neutrino Emission Due to NS/BH Formation



Neutrinos before light

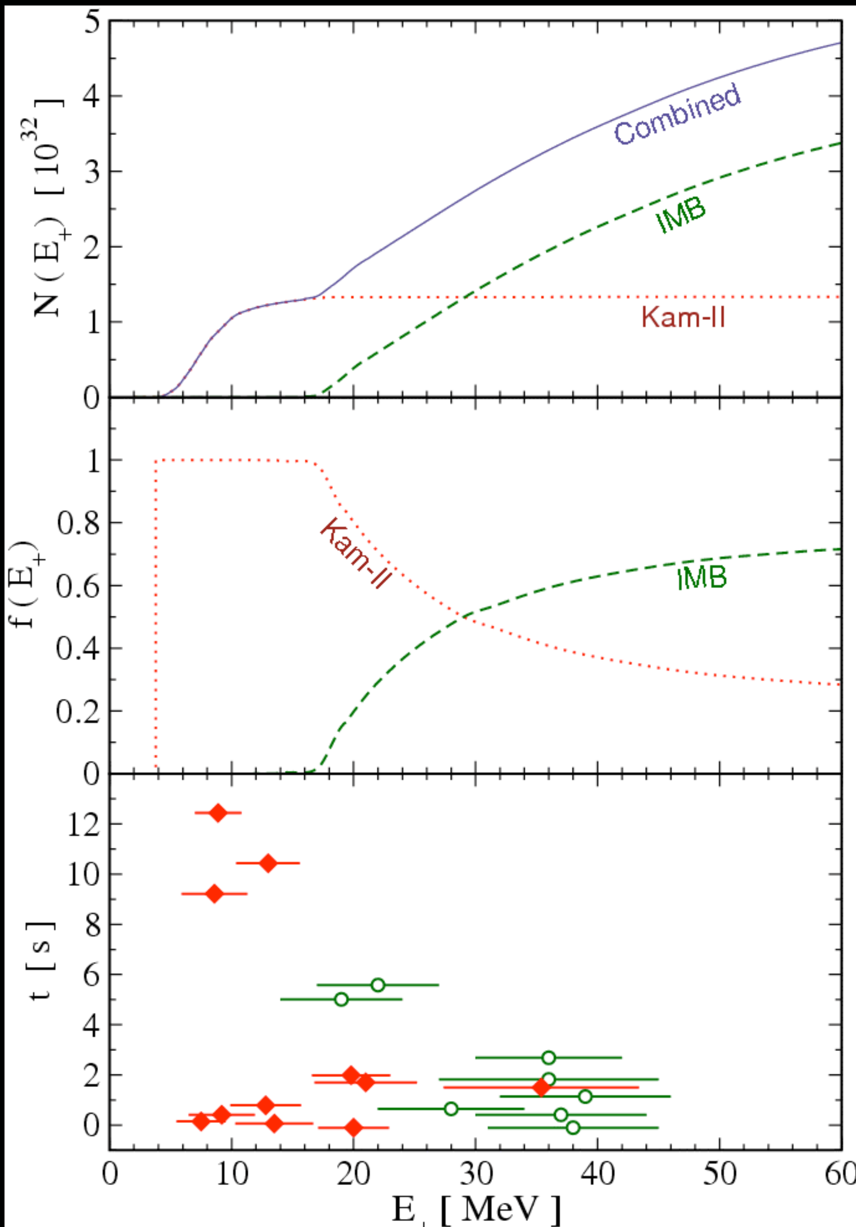
Huge energy release
$E_B \sim GM^2/R \sim 10^{53}$ erg

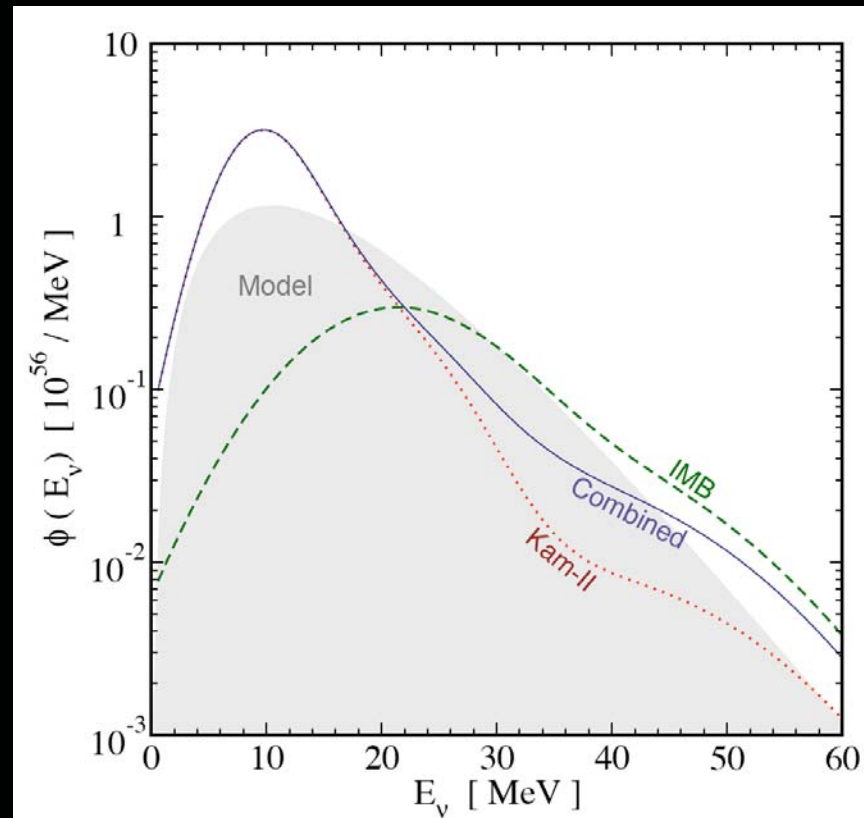
Low average energy
$E_\nu \sim 10$ MeV

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

But still no direct observation of NS (or BH)

Fresh Look at the SN 1987A Spectrum





Yuksel and Beacom, PRD 76, 083007 (2007)

No conflicts in data, only with assumed pure thermal spectrum

Progress in Neutrino Astronomy: What Do We Want to Find Out?

Lessons So Far

- Dream big

Ask questions that astronomers can't answer

- Build big

Neutrino cross sections are small

- Wait big

Technical challenges require patience

- Win big

Important results for astronomy and physics

Why continue now?

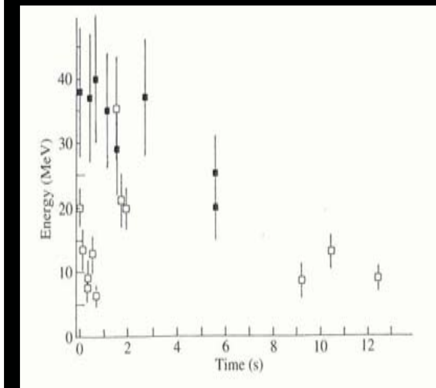
Multidisciplinary Aspects

Understanding supernovae is essential for:

particle physics:	SNII energy loss channels
	neutrino properties
nuclear physics:	production of the elements
	neutron star equation of state
astrophysics:	cycle of stellar birth, life, death
	constraints on new sources
cosmology:	supernova distance indicators
	dark matter decay, annihilation

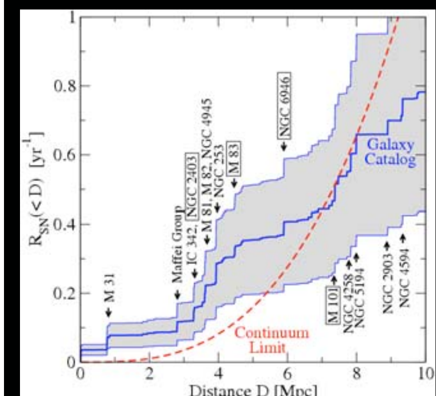
There are very good chances for collecting new supernova neutrinos within the next five years

Supernova Neutrino Detection Frontiers



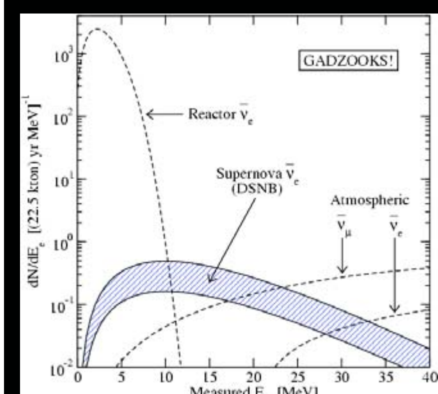
Milky Way

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!

Some Key Open Questions

What is the true rate of massive star core collapses?

What is the average neutrino emission per supernova?

How much variation is there in the neutrino emission?

How does neutrino mixing affect the received signal?

Future of Neutrino Astronomy: Diffuse Supernova Neutrino Background

What are the Ingredients of the DSNB?

detector capabilities

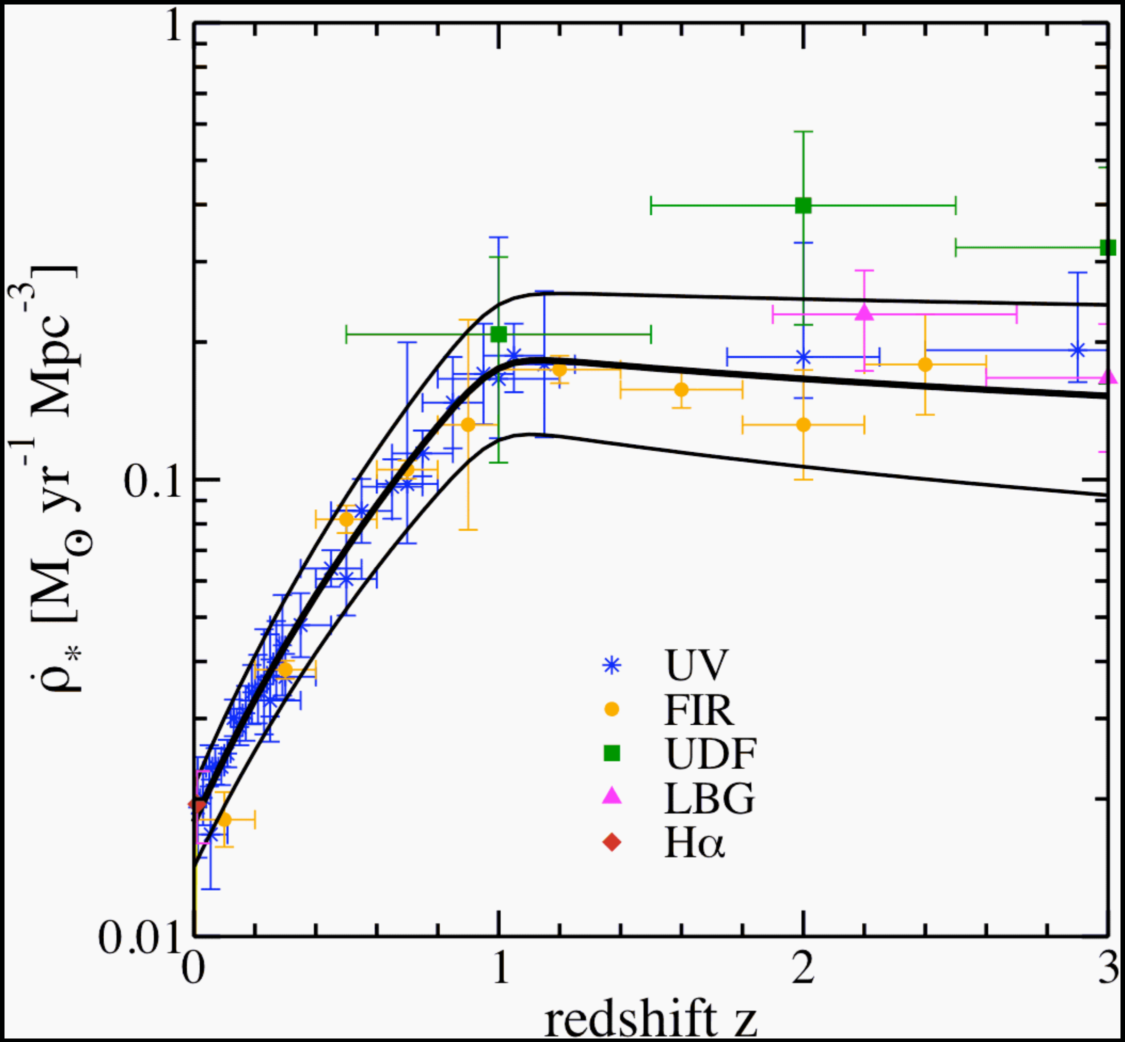
supernova rate history

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

positron spectrum
(cf. detector backgrounds)

neutrino spectrum
per supernova

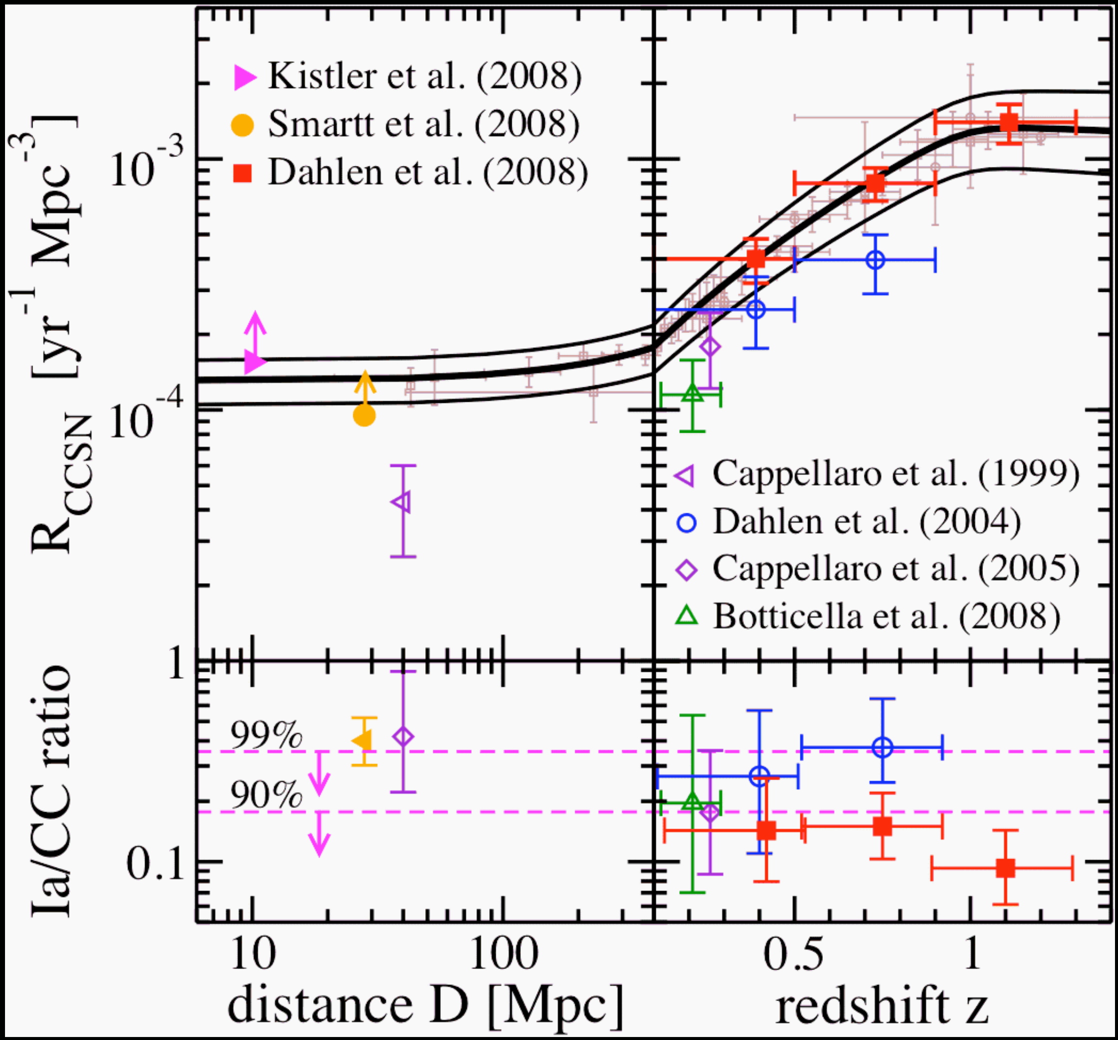
Star Formation Rate



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

Horiuchi, Beacom, Dwek, PRD 79, 083013 (2009)

Supernova Rate

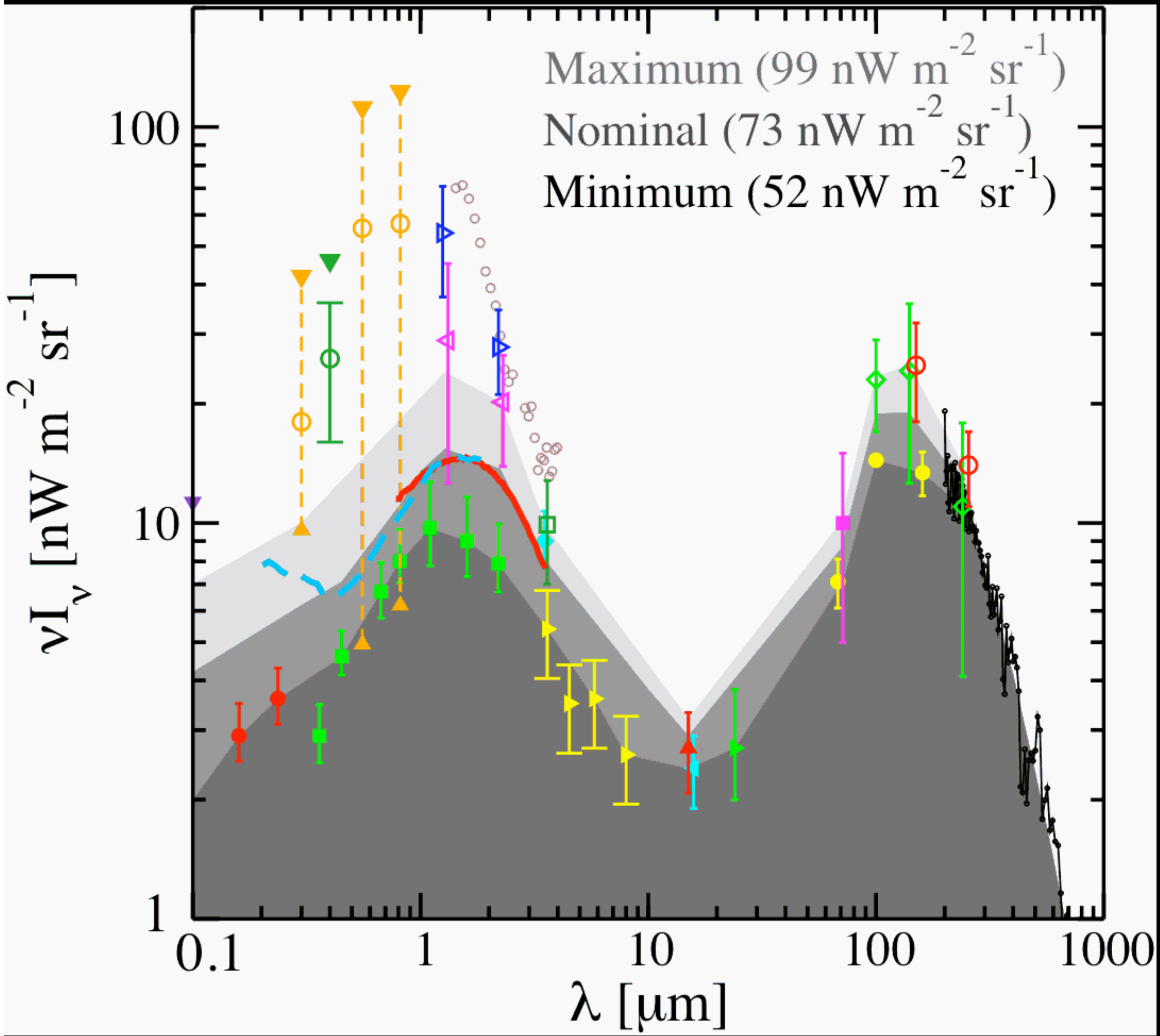


Provides direct normalization of the DSNB

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

Horiuchi, Beacom, Dwek, PRD 79, 083013 (2009)

Extragalactic Background Light

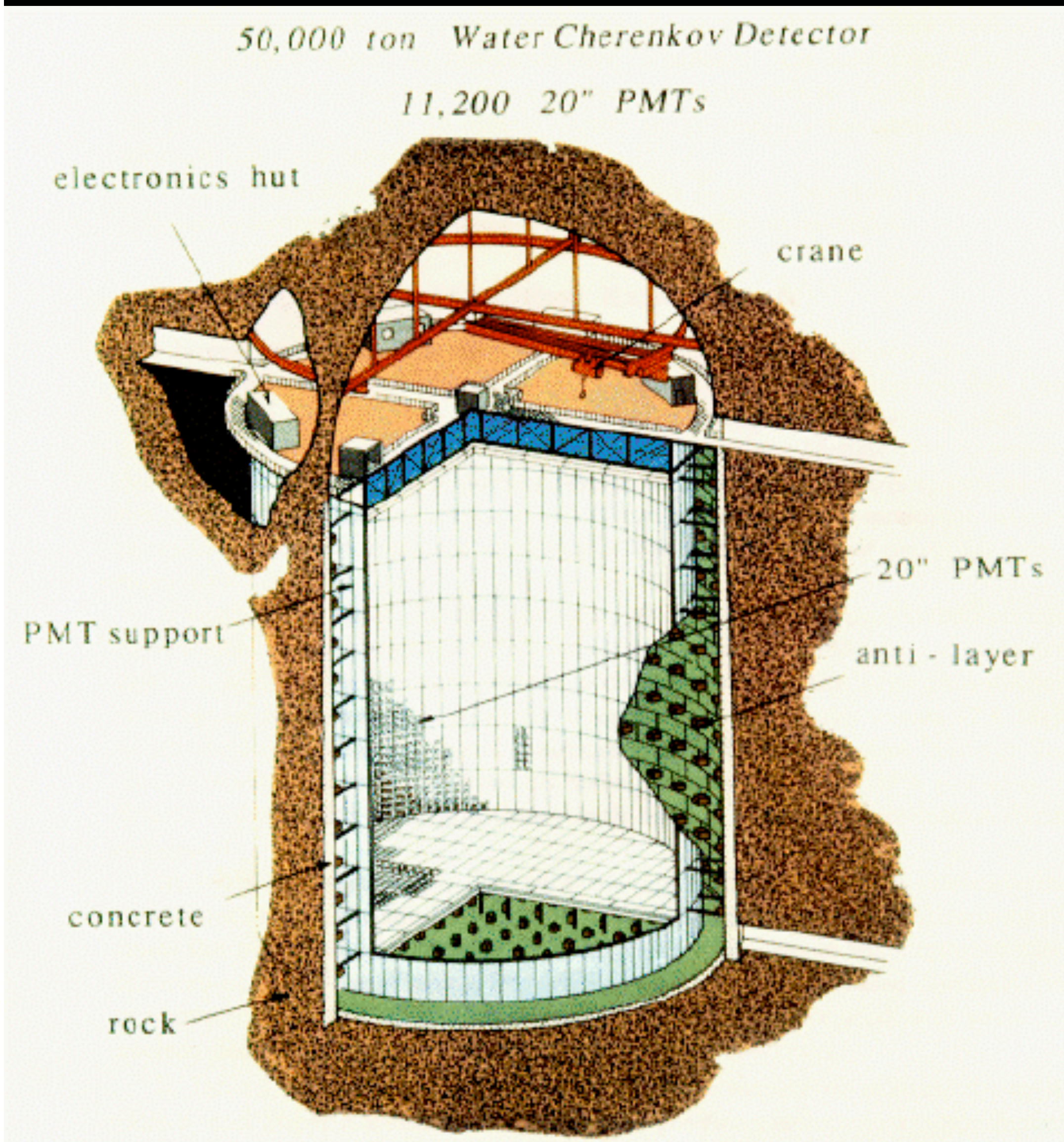


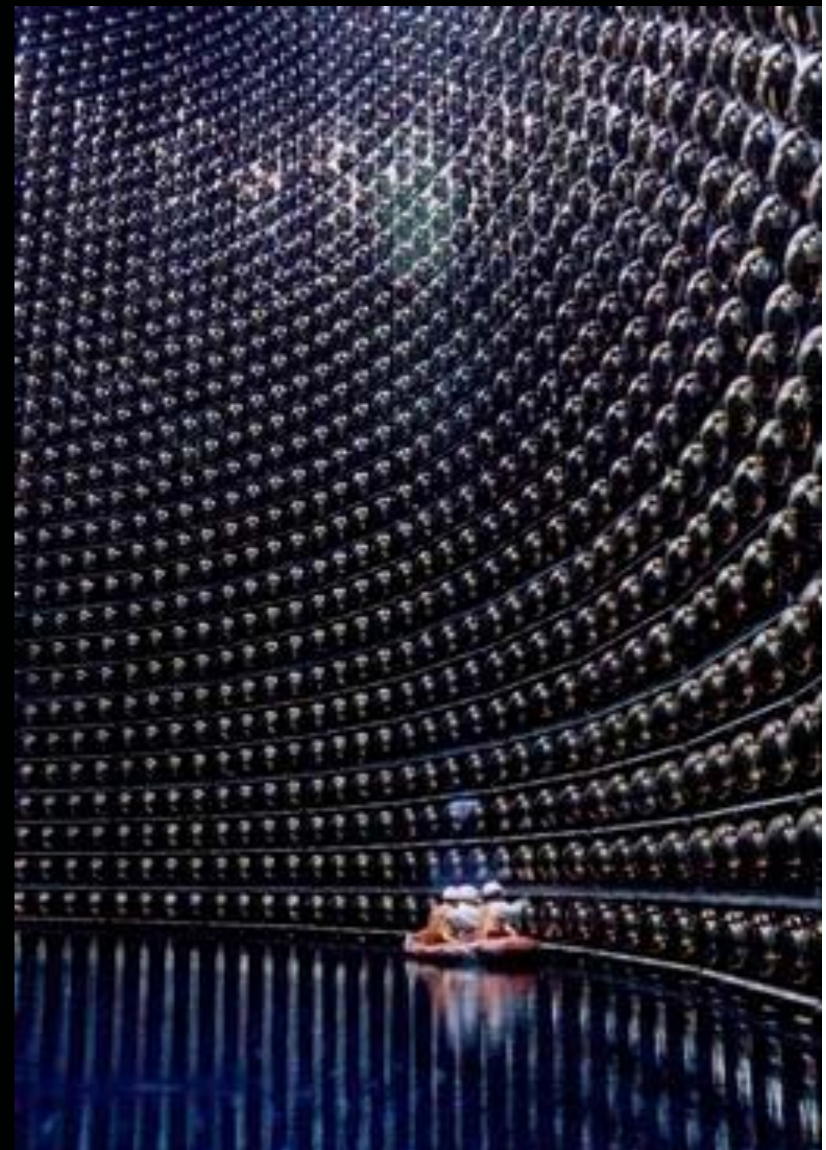
Using HB06 CSFH, our calculated result is 78--95, depending on IMF

Provides another confirmation of the adopted CSFH

Horiuchi, Beacom, Dwek, PRD 79, 083013 (2009)

Super-Kamiokande

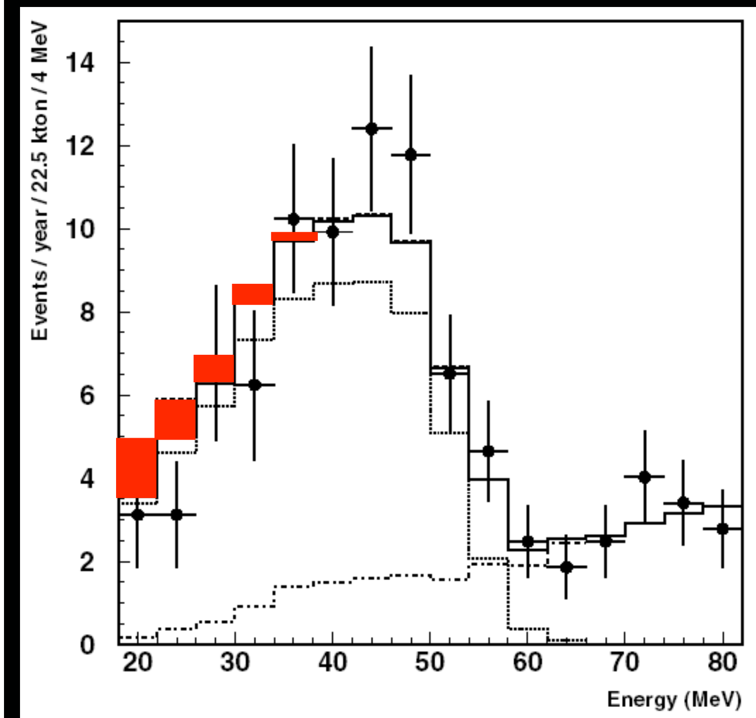




Might the DSNB be Detectable?

~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

Inverse Beta Decay

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

- Cross section is "large" and "spectral"

$$\sigma \simeq 0.095(E_\nu - 1.3\,MeV)^2\, 10^{-42}\, cm^2$$

$$E_e \simeq E_\nu - 1.3\,MeV$$

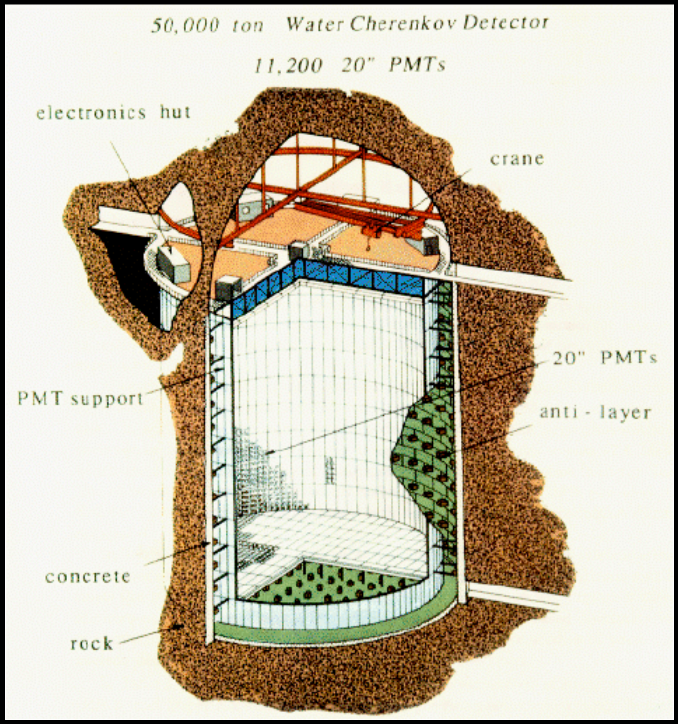
Corrections in Vogel and Beacom, PRD 60, 053003 (1999)

- We must detect the neutron, but how?

Add Gadolinium to SK?

GADZOOKS!

Gadolinium
Antineutrino
Detector
Zealously
Outperforming
Old
Kamiokande,
Super!



Beacom and Vagins, PRL (2004)

Neutron Capture

Capture on H: sigma = 0.3 barns
E_{gamma} = 2.2 MeV

Capture on Gd: sigma = 49100 barns
E_{gamma} = 8 MeV
(Equivalent E_e ~ 5 MeV)

$$\frac{1}{\lambda_{total}} = \frac{1}{\lambda_H} + \frac{1}{\lambda_{Gd}} = n_H \sigma_H + n_{Gd} \sigma_{Gd}$$

At 0.2% $GdCl_3$:

Capture fraction = 90%

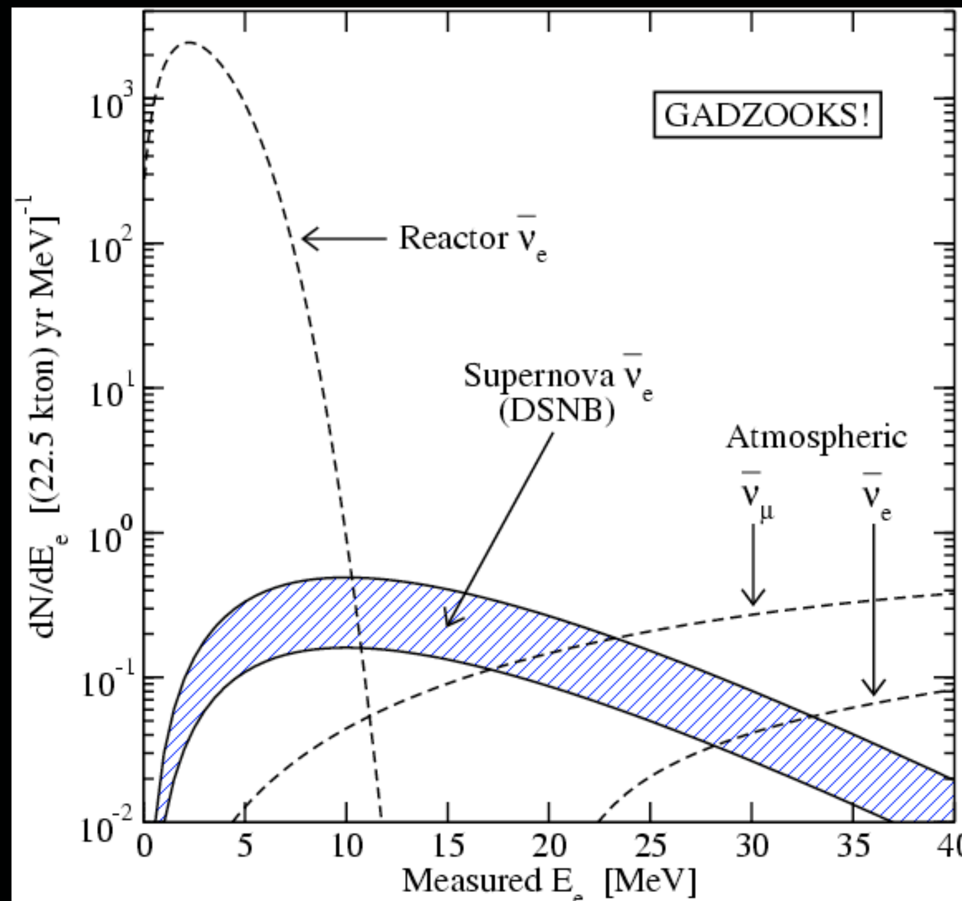
$\lambda = 4\,\mathrm{cm}, \tau = 20\ \mu s$

Can We Beat the Backgrounds?

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

Beacom, Vagins, PRL 93, 171101 (2004)

GADZOOKS!



At 0.2% $GdCl_3$:

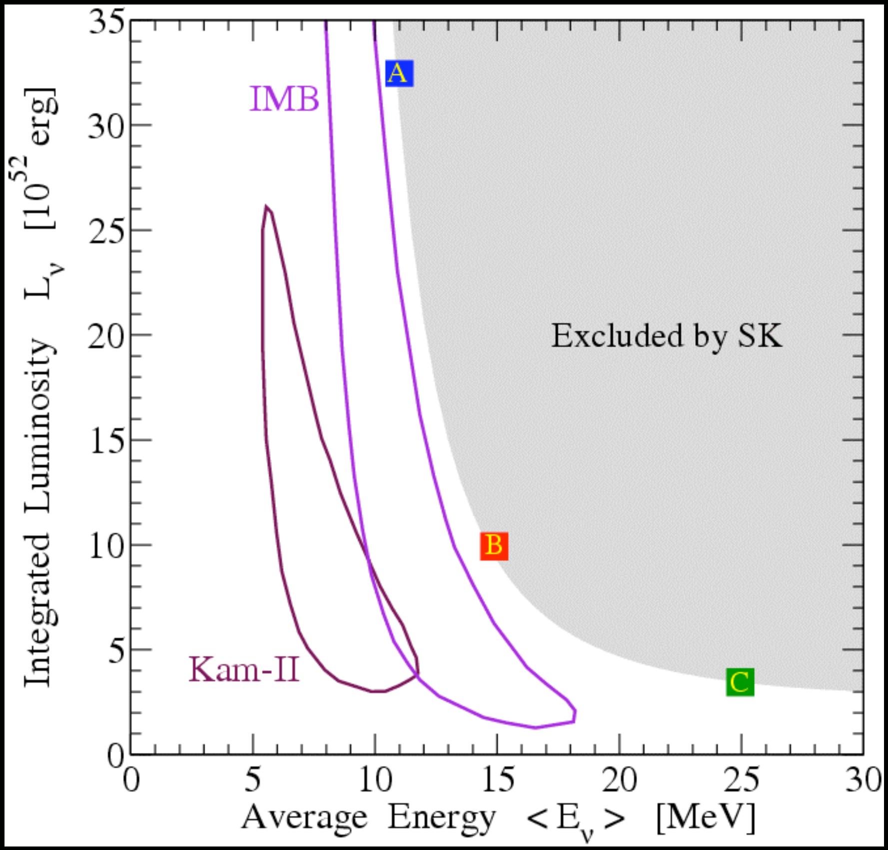
Capture fraction = 90%

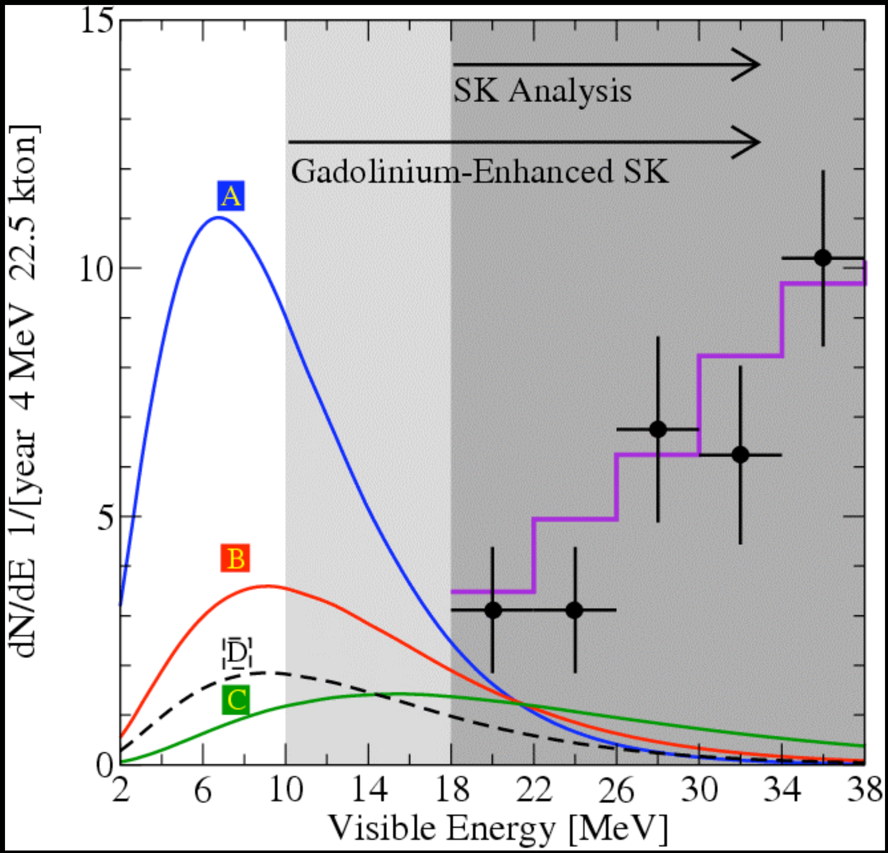
λ = 4 cm, τ = 20 μs

active R&D program in US and Japan

Neutron tagging means lower backgrounds, thresholds

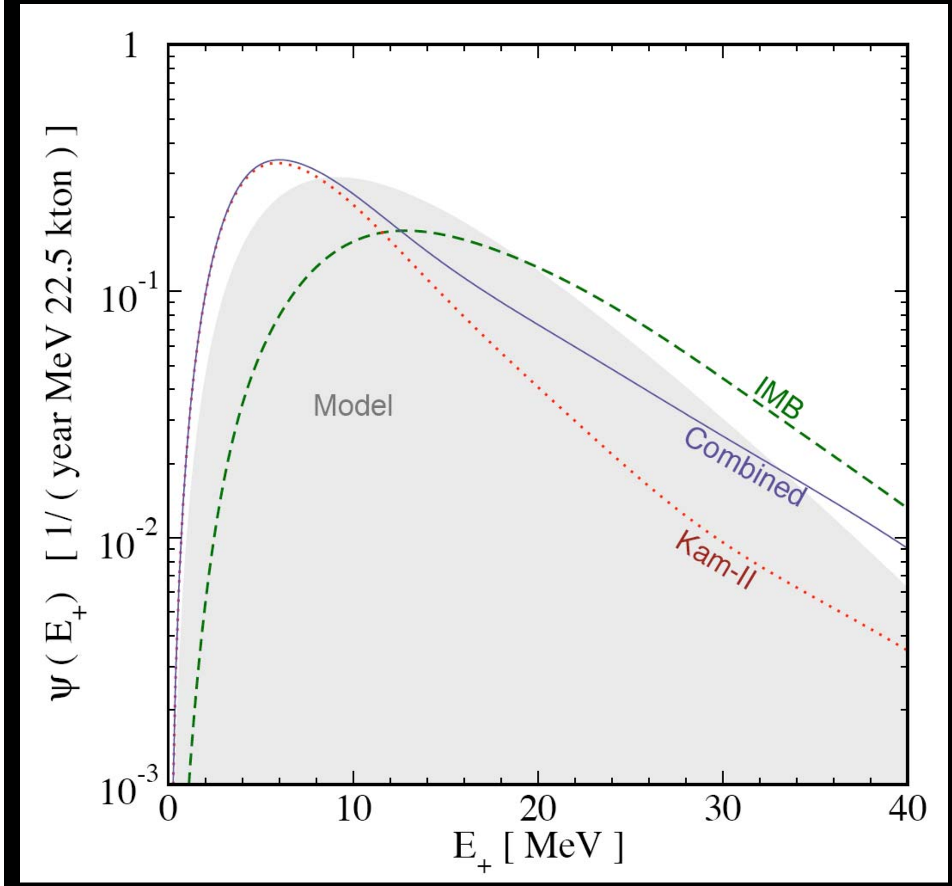
What is the Neutrino Emission per Supernova?

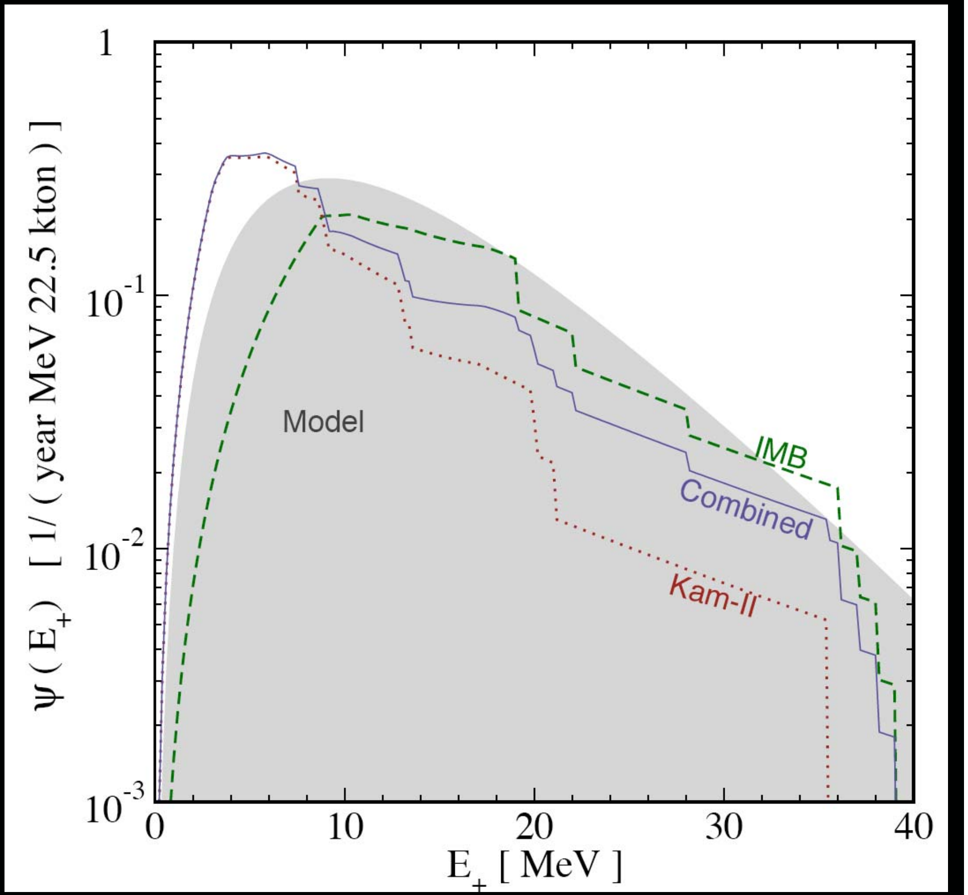




Yuksel, Ando, Beacom, PRC 74, 015803 (2006)

DSNB Spectra Based on SN 1987A Data

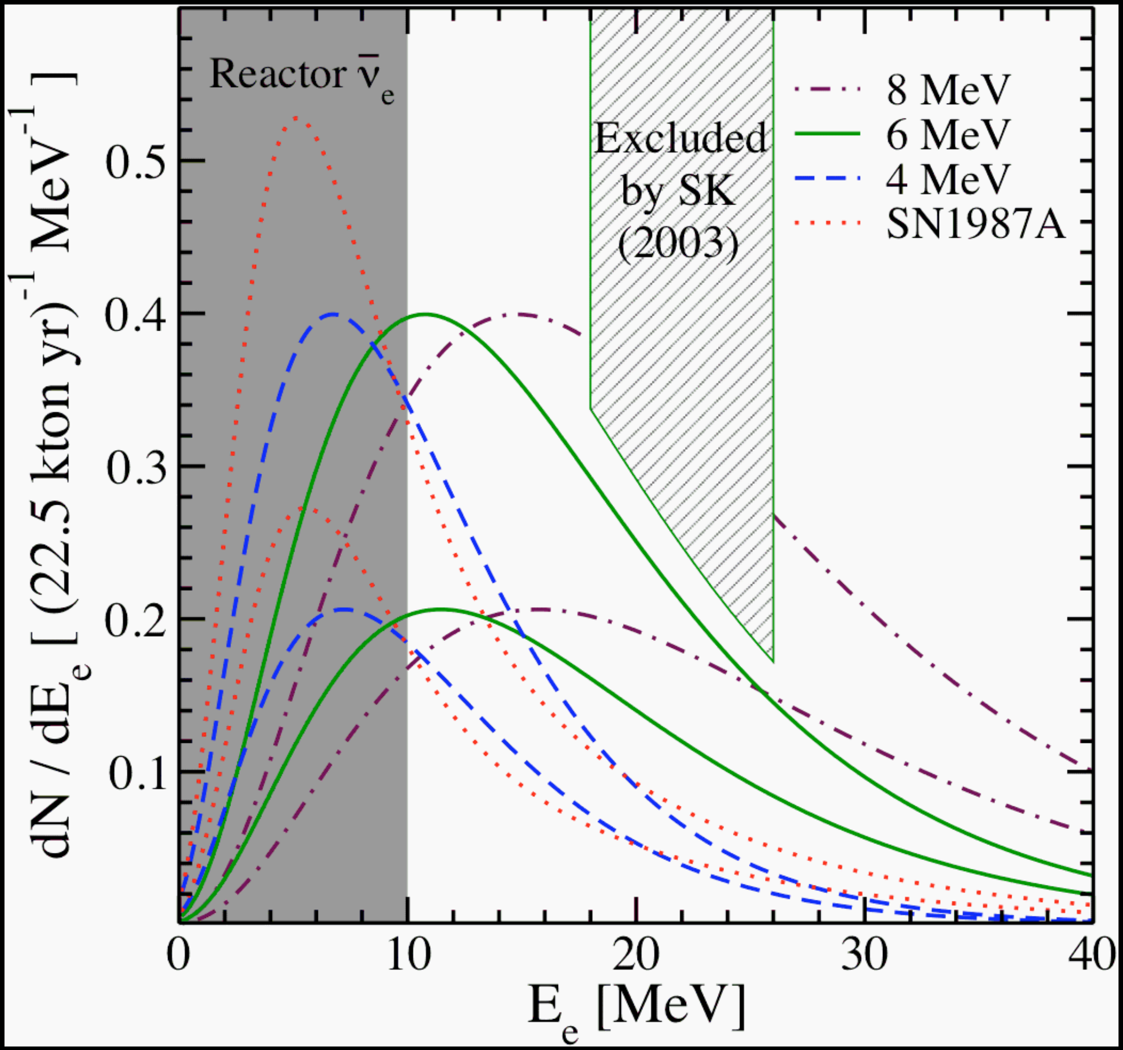




Yuksel and Beacom, PRD 76, 083007 (2007)

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

Horiuchi, Beacom, Dwek, PRD 79, 083013 (2009)

Three Main Results on the DSNB

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

R&D Update from Vagins

Last year I underwent a significant transformation…

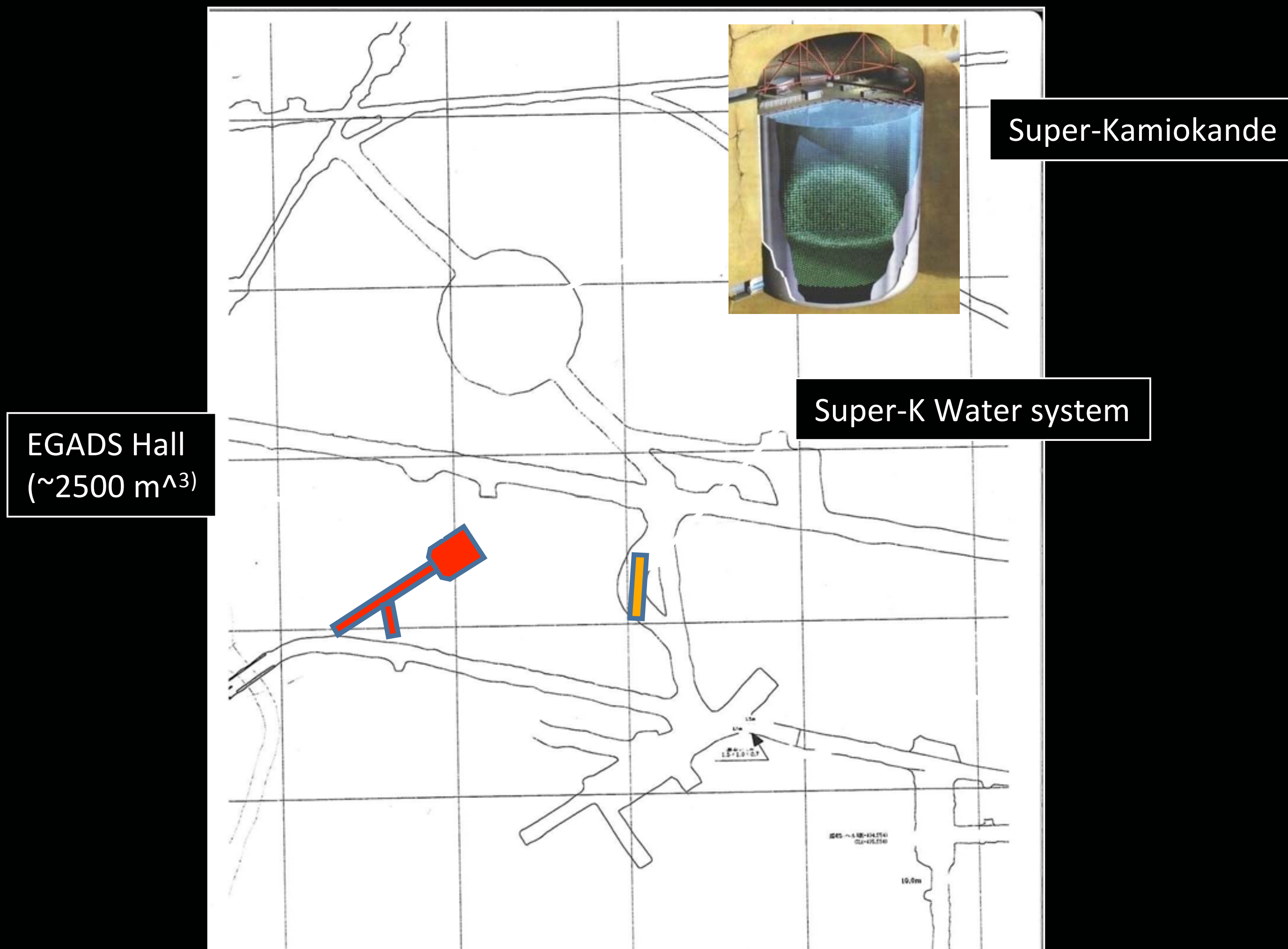
I joined UTokyo's newly-formed IPMU as their first full-time *gaijin* professor, though I still retain a "without salary" position at UC Irvine and continue Gd studies there.

I was explicitly hired to make gadolinium work in water!

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Now, we're building a dedicated Gd test facility, complete with its own water filtration system, 50-cm PMT's, and DAQ electronics.

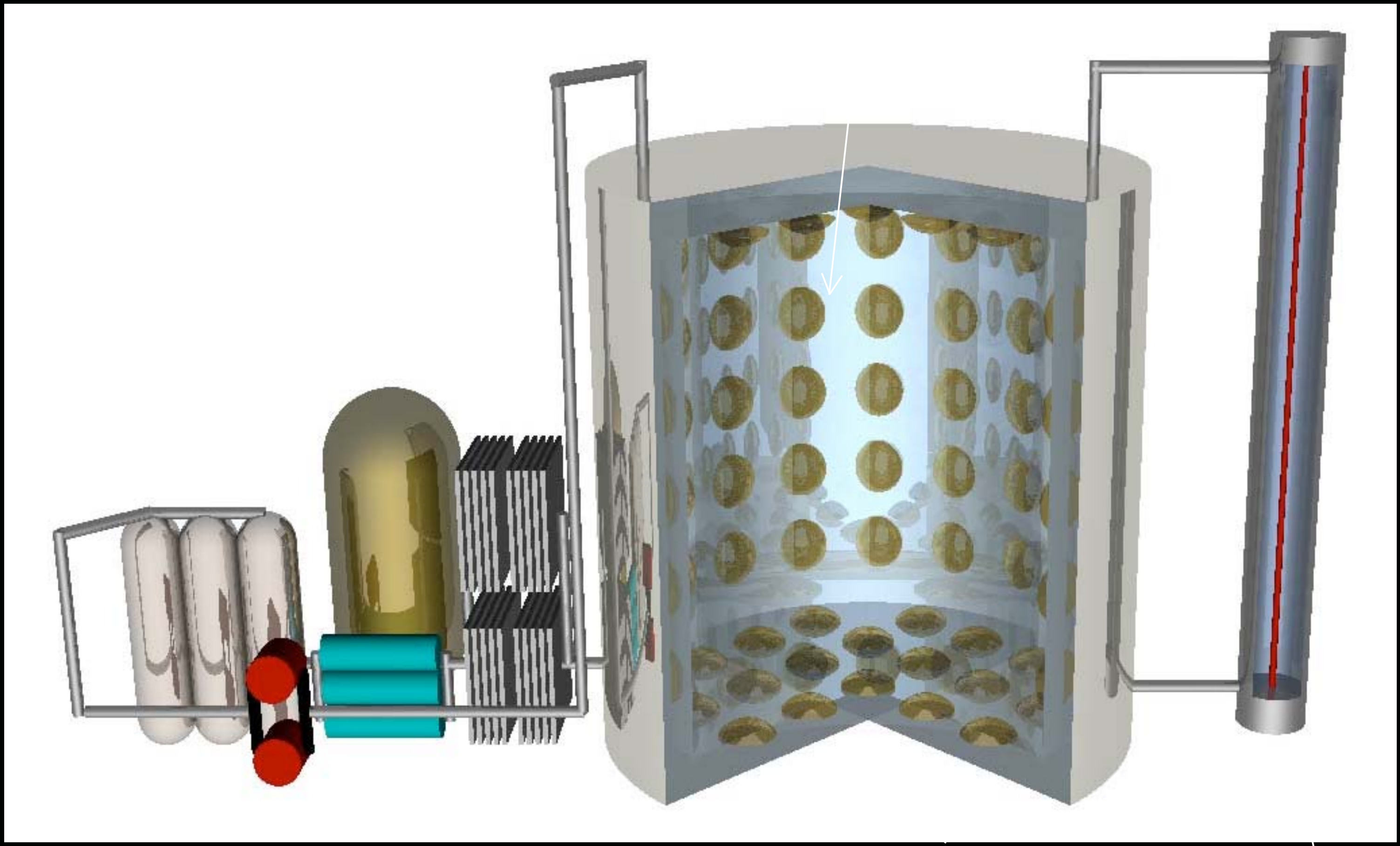
This 200 ton-scale R&D project will be called EGADS – Evaluating Gadolinium's Action on Detector Systems.



EGADS Facility

Last month we received ~$4,000,000 for this effort.

240 50-cm PMT's



[graphic by A. Kibayashi]

Selective Water+Gd Filtration System

200 ton (6.5 m X 6.5 m) water tank (SUS304)

Transparency Measurement

What are the goals of EGADS?

A large-scale test tank will allow us to conclusively address the following questions:

1. How fast can a Gd compound be added to the water? We will find out by dissolving the most promising Gd compound(s).
2. Will the dissolved Gd distribute itself uniformly in a large volume? Resistivity probes mounted throughout the volume will tell us.
3. How quickly/economically/completely can the Gd be removed? We will remove the compound(s) with different methods and assess the effectiveness via the *in situ* resistivity probes and water samples.
4. Are there any materials effects to worry about? Examination of the tank components and water system over time will augment sample soaking tests. Also, any variations in water transparency will be closely monitored.
5. Does selective filtering work, i.e., can we keep the water clear over extended periods of time? Water quality will be continuously checked with 理想 ("risou").
6. Will ambient neutron backgrounds cause trouble? Event rates throughout the volume will be measured and compared with expectations.

These are issues which must be conclusively studied before introducing Gd into Super-K.

What's the schedule for EGADS?

EGADS is fully funded, and the schedule is now fixed as follows:

2009-10: Excavation of new underground experimental hall, construction of stainless steel test tank and PMT-supporting structure (completion March 2010)

2010-11: Assembly of main water filtration system, tube prep, mounting of PMT's, installation of electronics and DAQ computers

2011-12: Experimental program to address technical issues on previous slide

At the same time, material aging studies will be carried out in Japan, and transparency and water filtration studies will continue in Irvine.

If all goes well we should be prepared to enrich Super-K with gadolinium early in the coming decade!

Concluding Perspectives

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

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.

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Postdoctoral Fellowship applications welcomed in Fall