Supernova and Solar Neutrinos

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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 the Sun

Detection of Neutrinos from SN 1987A

What Do We Want to Find Out?

Supernovae in the Milky Way

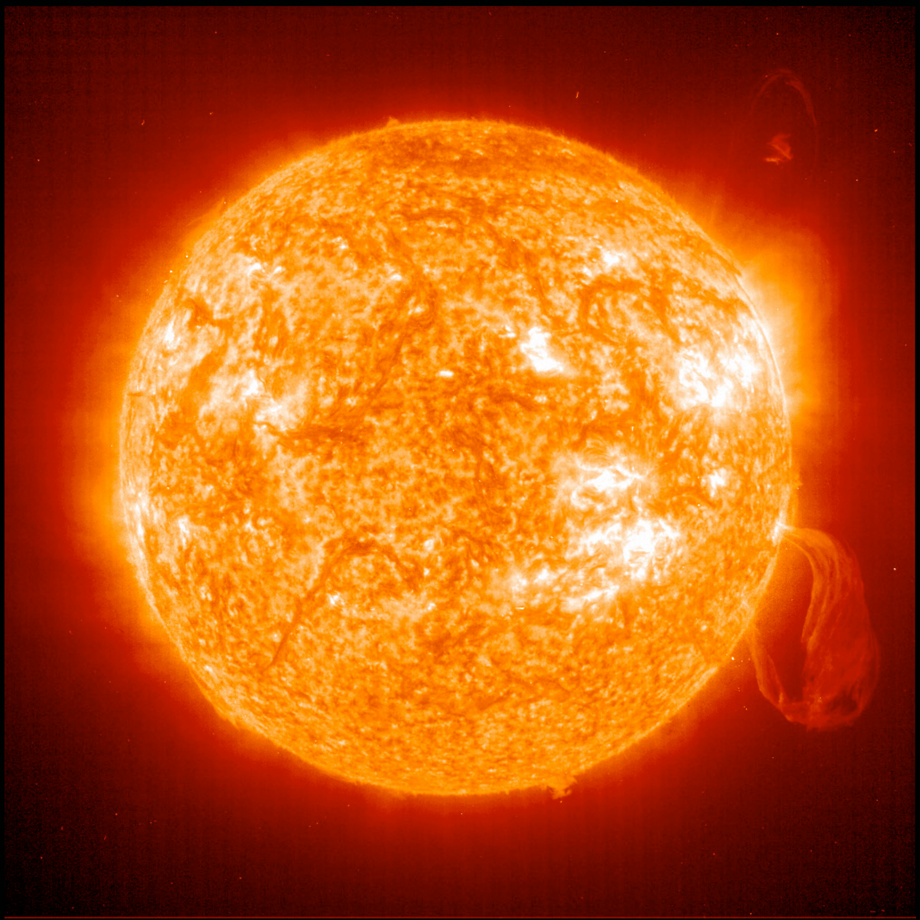
Supernovae in the Nearby Galaxies

Diffuse Supernova Neutrino Background

Concluding Perspectives

Birth of Neutrino Astronomy: Detection of Neutrinos from the Sun

The Sun Observed



Luminosity ~ 4×10^{33} erg/s

Temperature ~ 5500 K

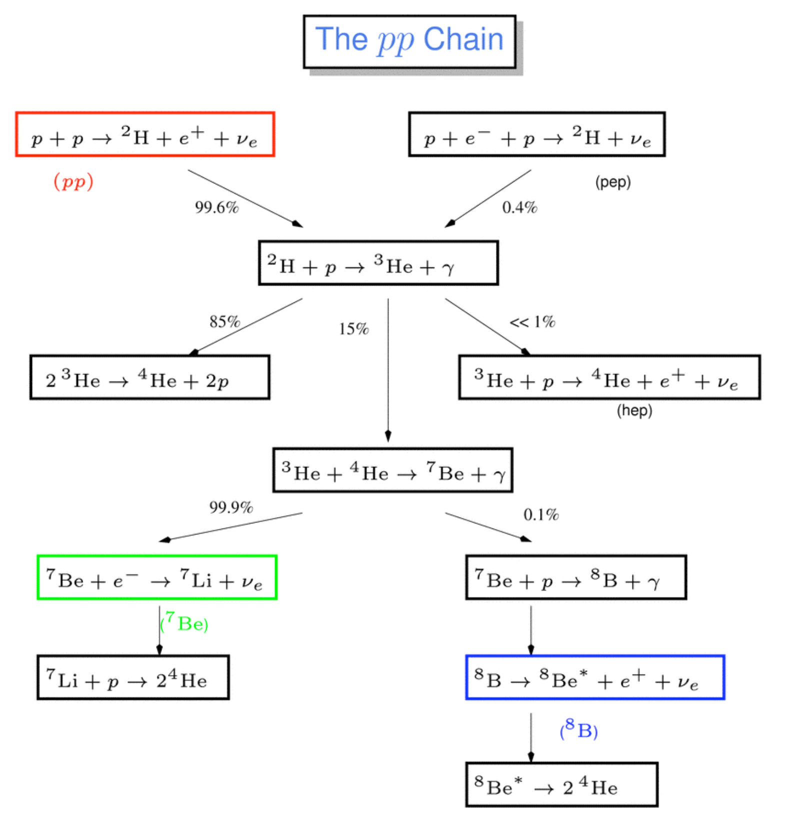
Radius ~ 7×10^{10} cm

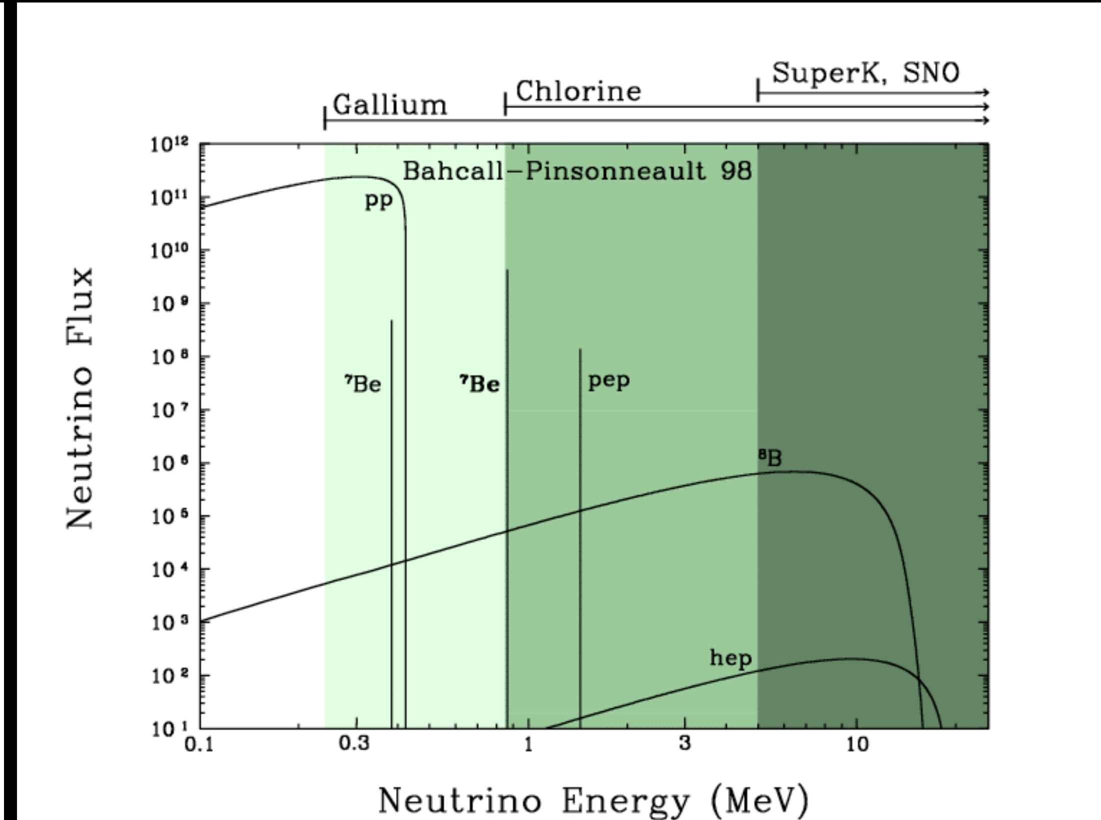
$L \sim 4\pi R^2 \sigma_{SB} T^4$ works

Age ~ 4.5 Gyr puzzling for this high luminosity

Question: What is the time-integrated energy output?

Solar Neutrino Reactions and Spectrum





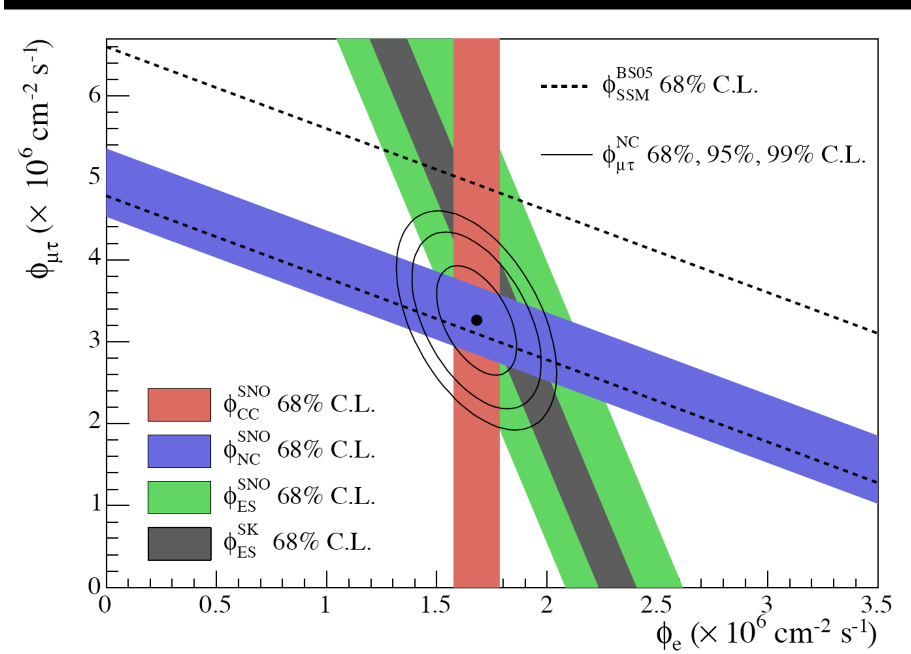
Question: What is L_ν compared to L_{photon}?

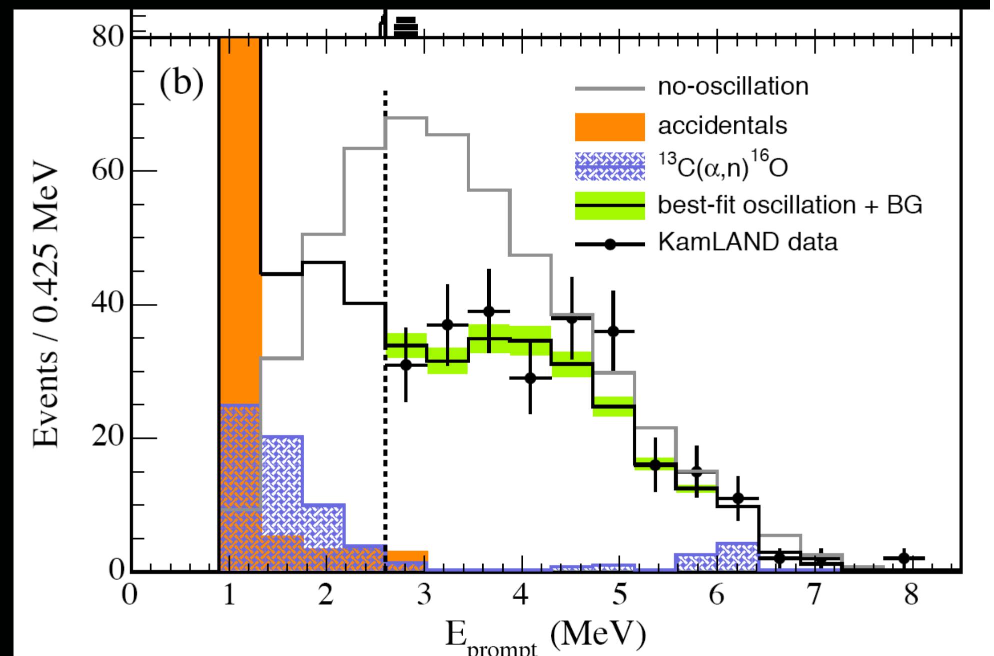
Successes of Solar Neutrino Research

From 40 years of hard work, we learned that:

The Sun works just as expected

But neutrinos have mass and mixing



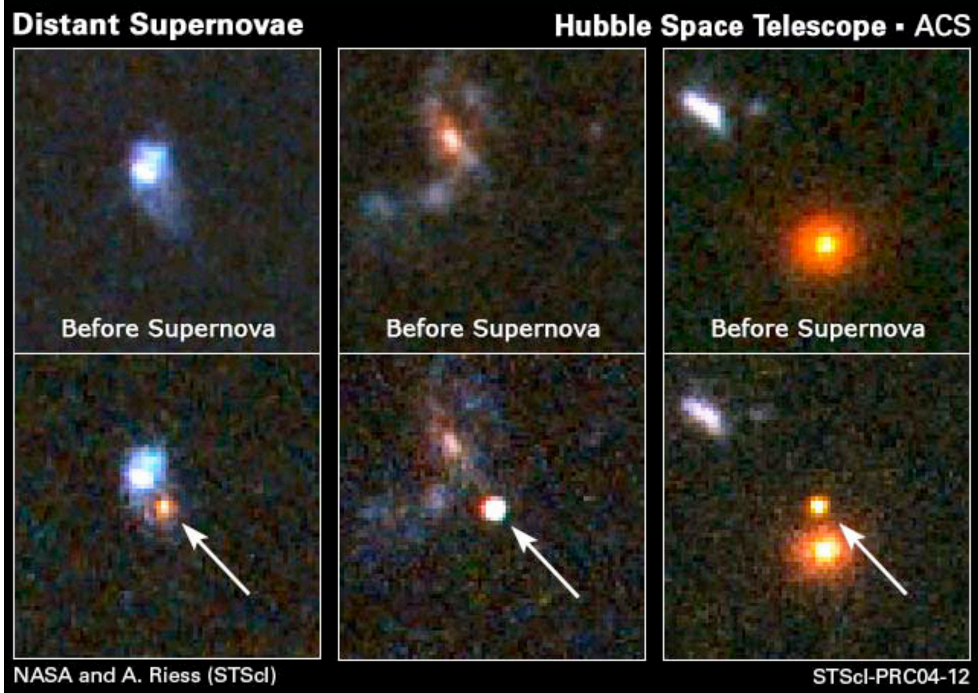


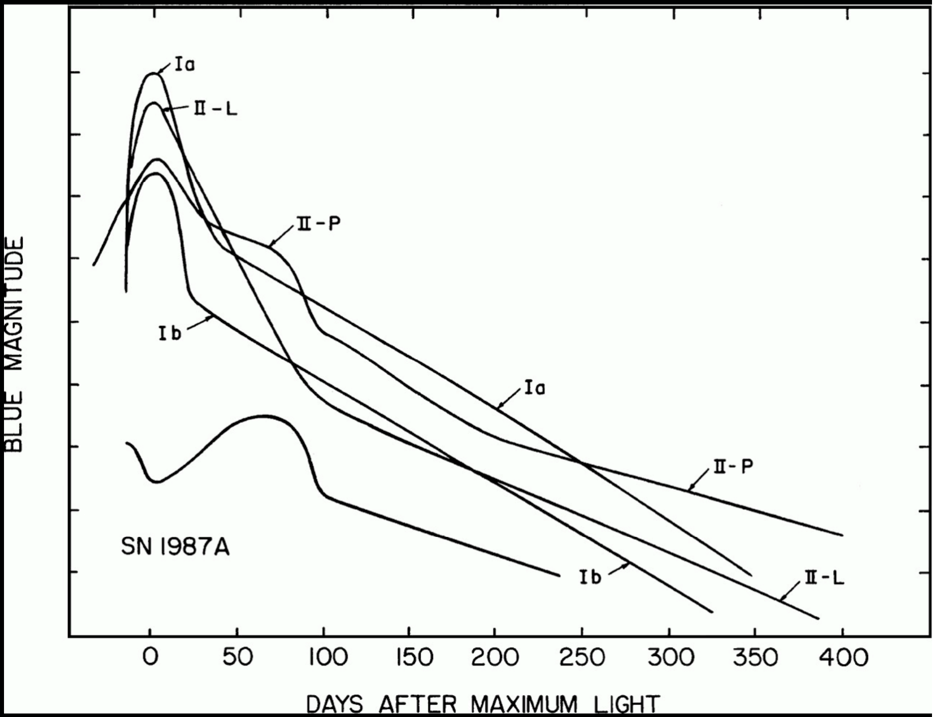
SNO, PRC 72, 055502 (2005)

KamLAND, PRL 94, 081801 (2005)

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

TeV-PeV-EeV neutrinos and gamma rays

light

winds

cosmic rays

gas, dust

neutron stars, black holes (gravity waves?)

MeV neutrinos and gamma rays

nucleosynthesis yields

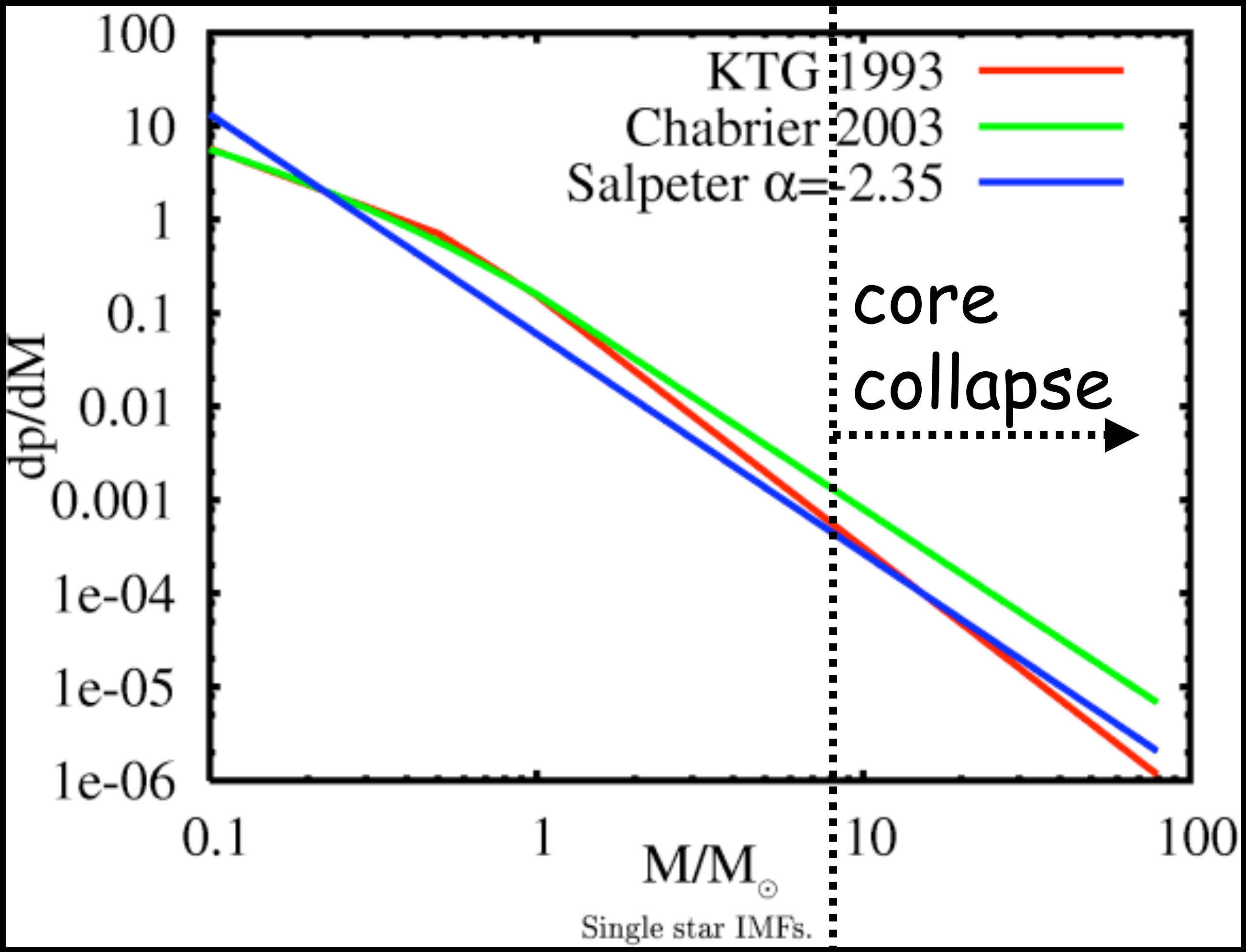
Mechanisms of Supernovae

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

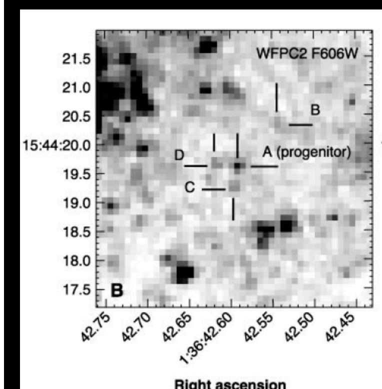


short lives

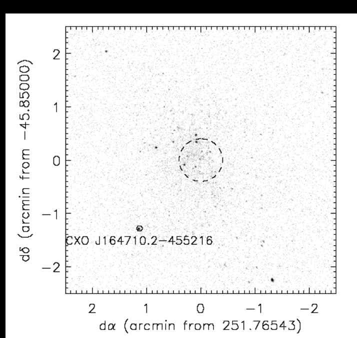
Which Progenitors Lead to SNII?

From ~ 8 M_{sun} to ?

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

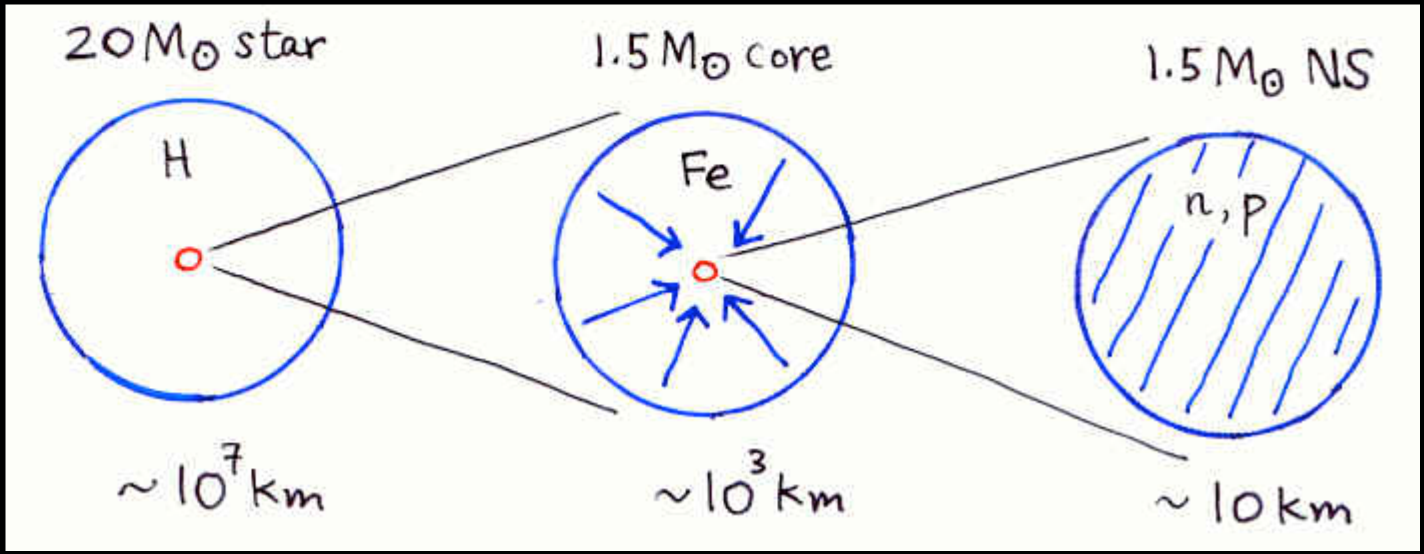


SN 2005cs: initial mass 9 +3/-2 M_{sun}
initial mass 10 +3/-3 M_{sun}
SN 2003gd: initial mass 8 +4/-2 M_{sun}
initial mass ~ 8-9 M_{sun}
from the Smartt and Filippenko groups



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

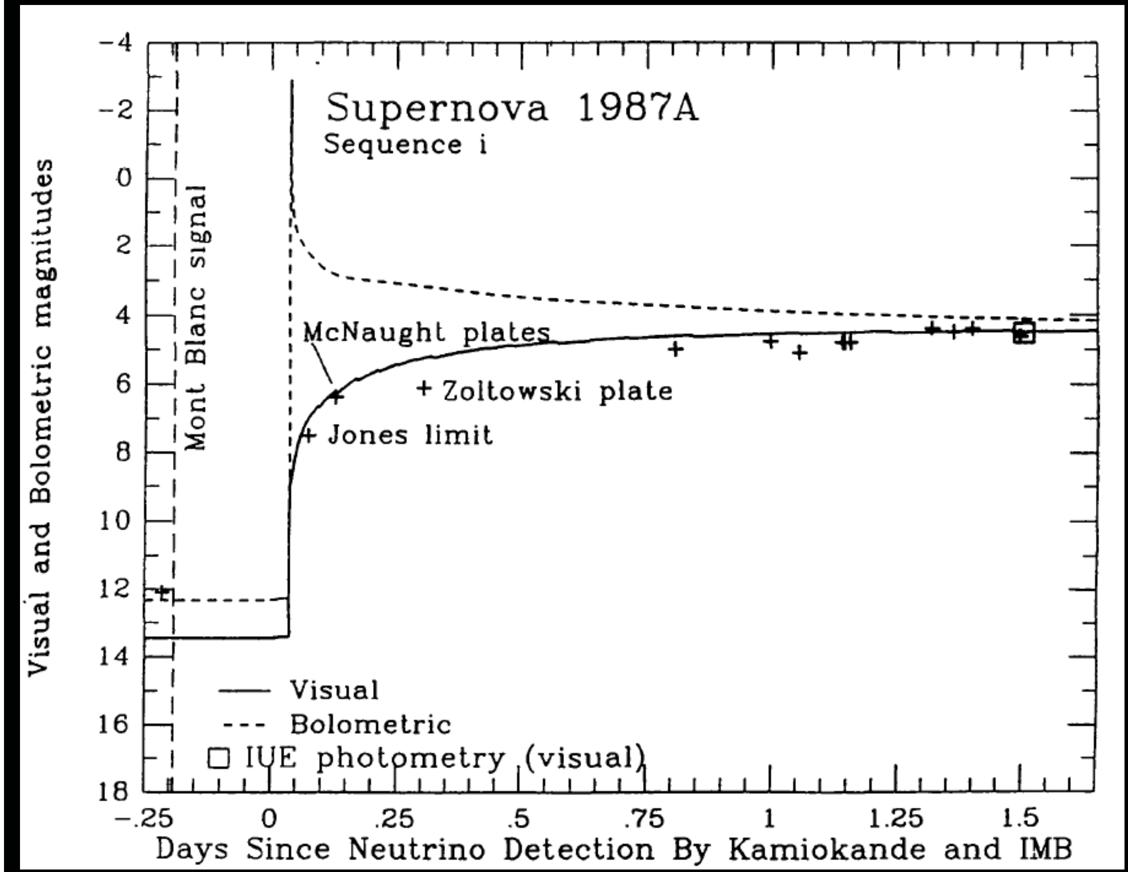
- The diffusion timescale is $\tau \sim (\lambda/c)\,(R/\lambda)^2 \sim 1$ s

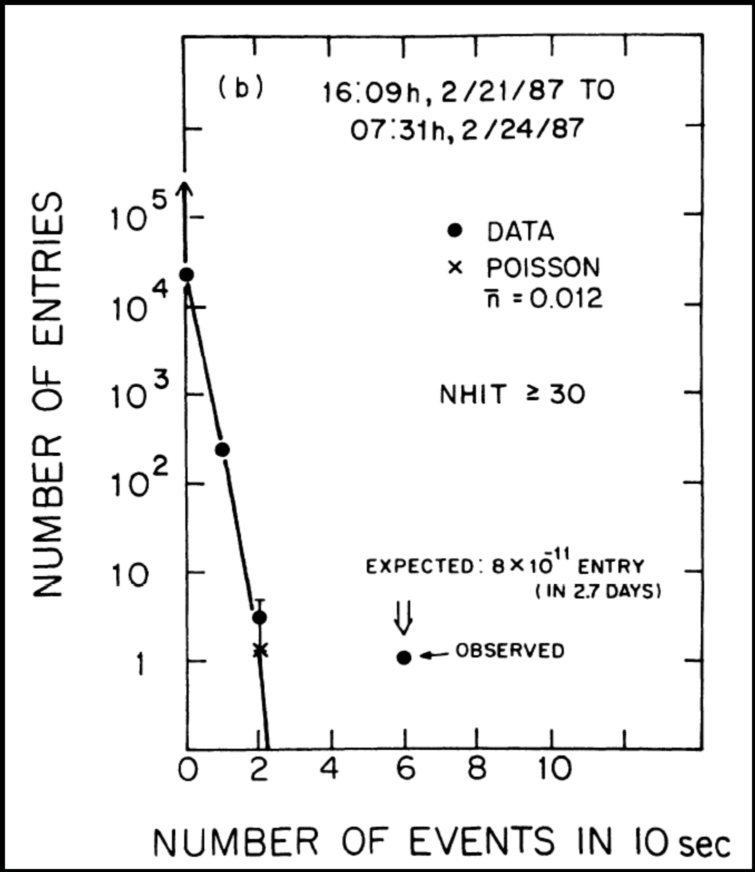
- The luminosity $L \sim E_{tot}/\tau \sim 4\pi R^2\, \sigma_{SB}\, T^4$

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

(Note that these numbers are very rough)

Type-II Supernovae Emit Neutrinos

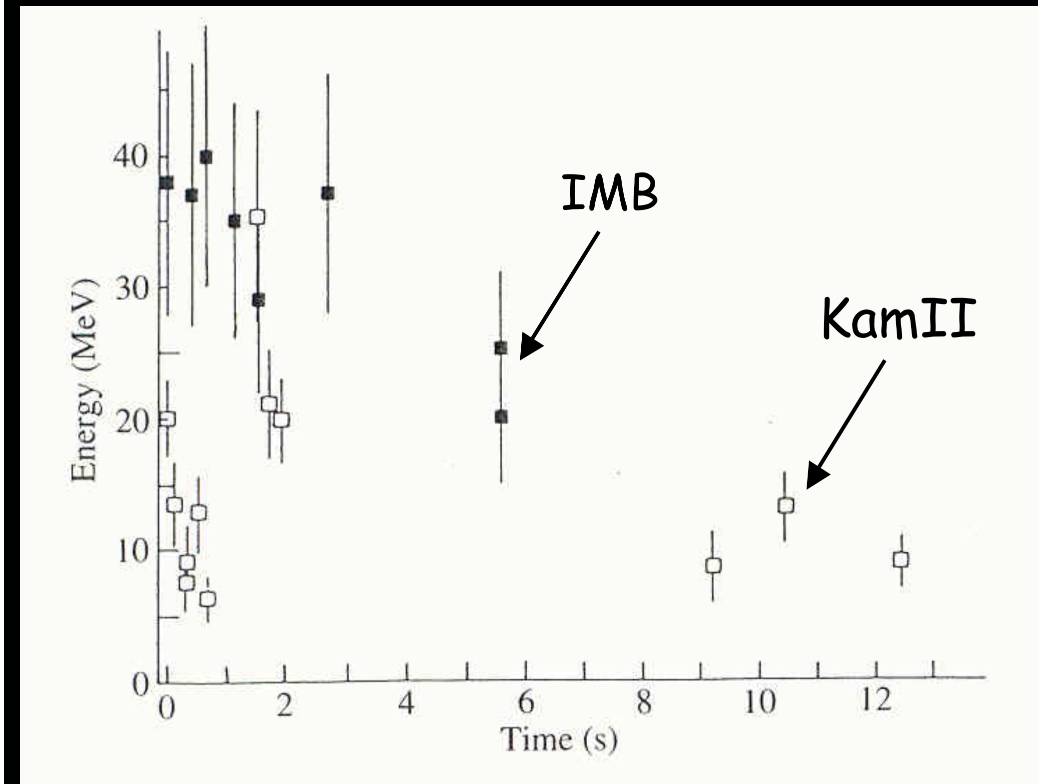




The neutrino burst arrived before the light

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

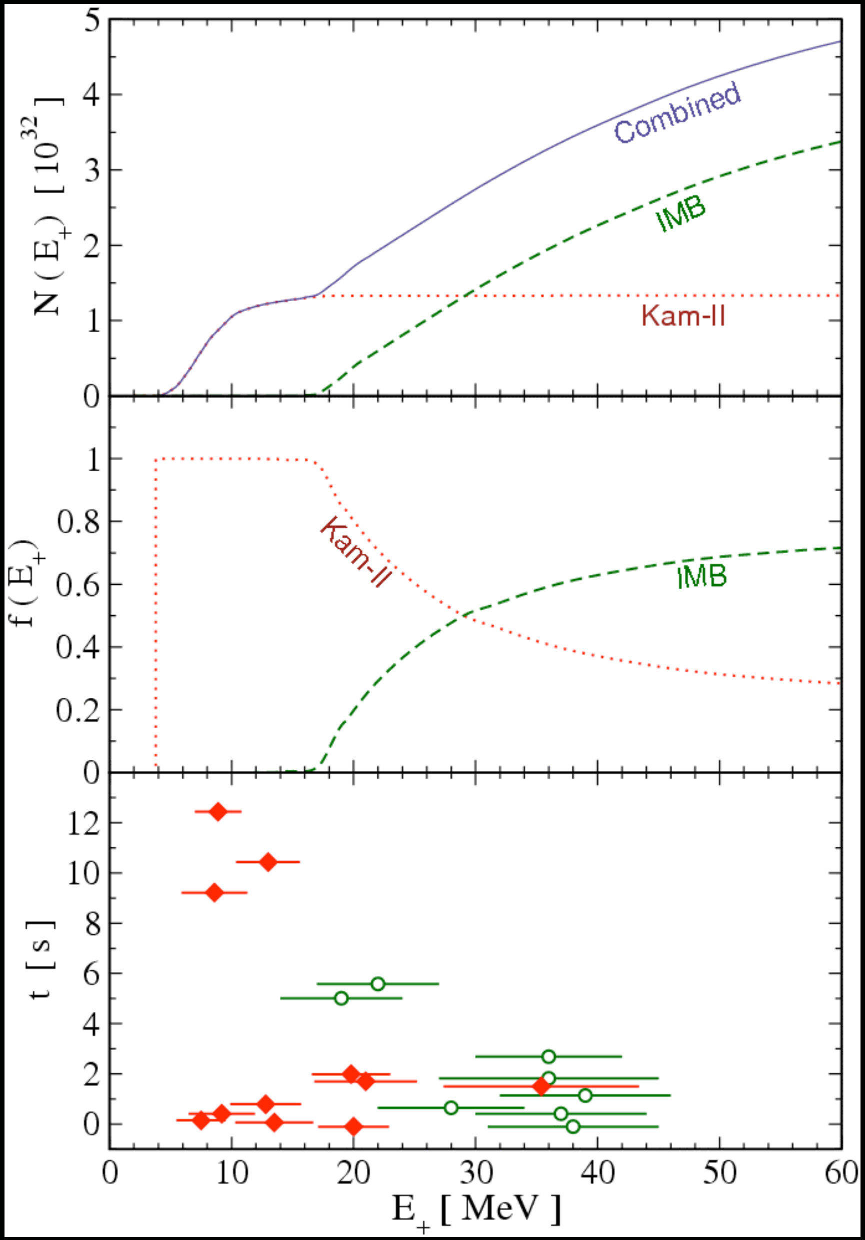
Low average energy
$E_\nu \sim 10$ MeV

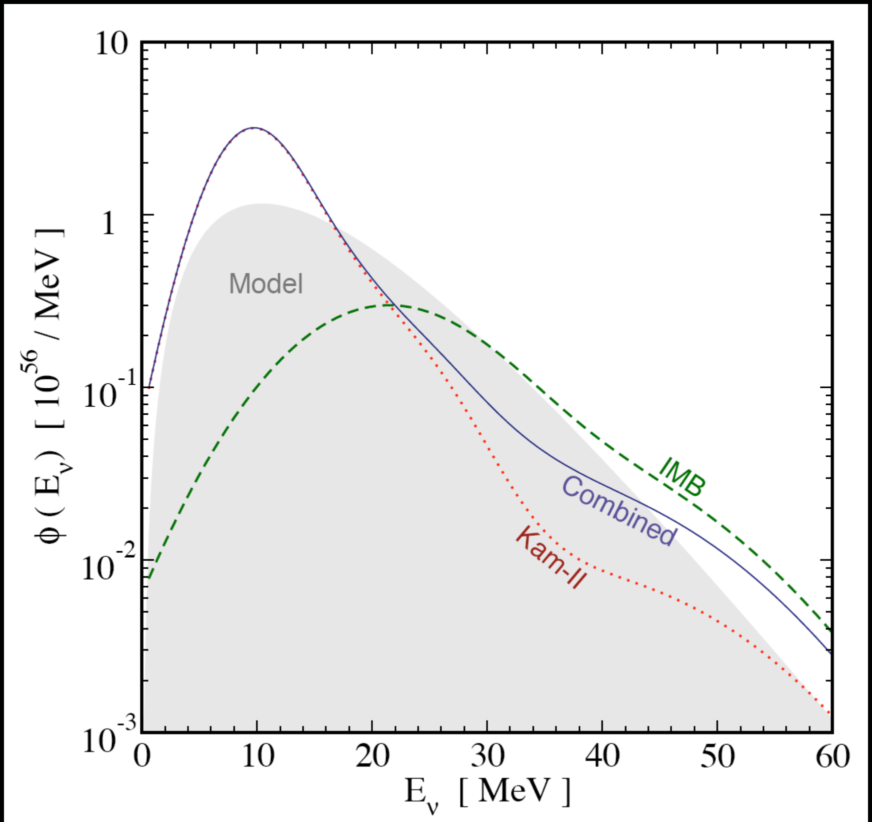
Very long timescale
$t \sim 10^4$ R/c

But still no direct observation of NS (or BH)

Question: How many detected neutrinos were expected?

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?

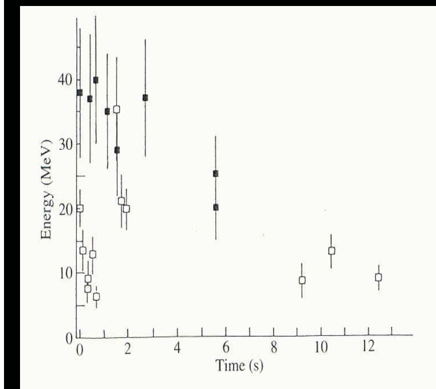
Multidisciplinary Aspects

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

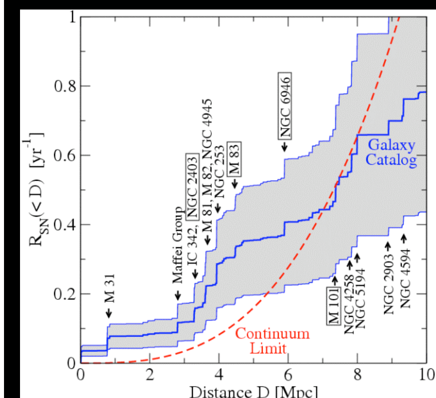


Milky Way

zero or at most one supernova

excellent sensitivity to details

one burst per ~ 40 years

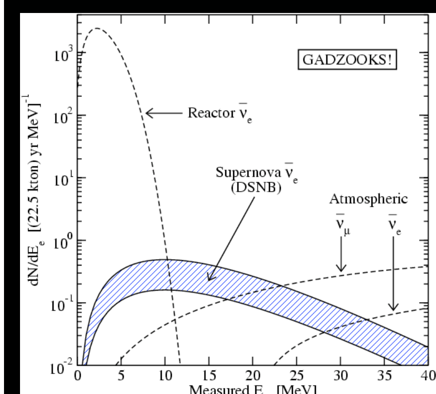


Nearby Galaxies

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?

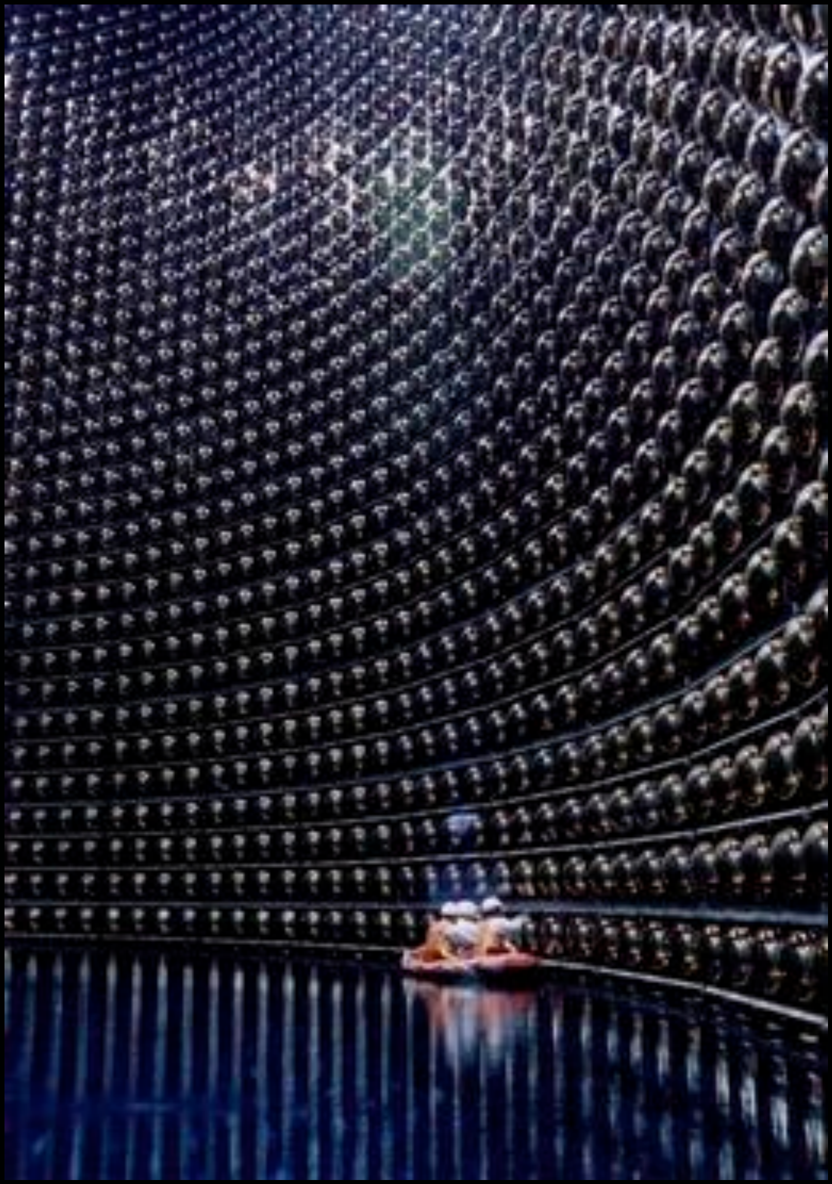
What is the average neutrino emission per supernova?

How much variation is there in the neutrino emission?

How does neutrino mixing affect the received signal?

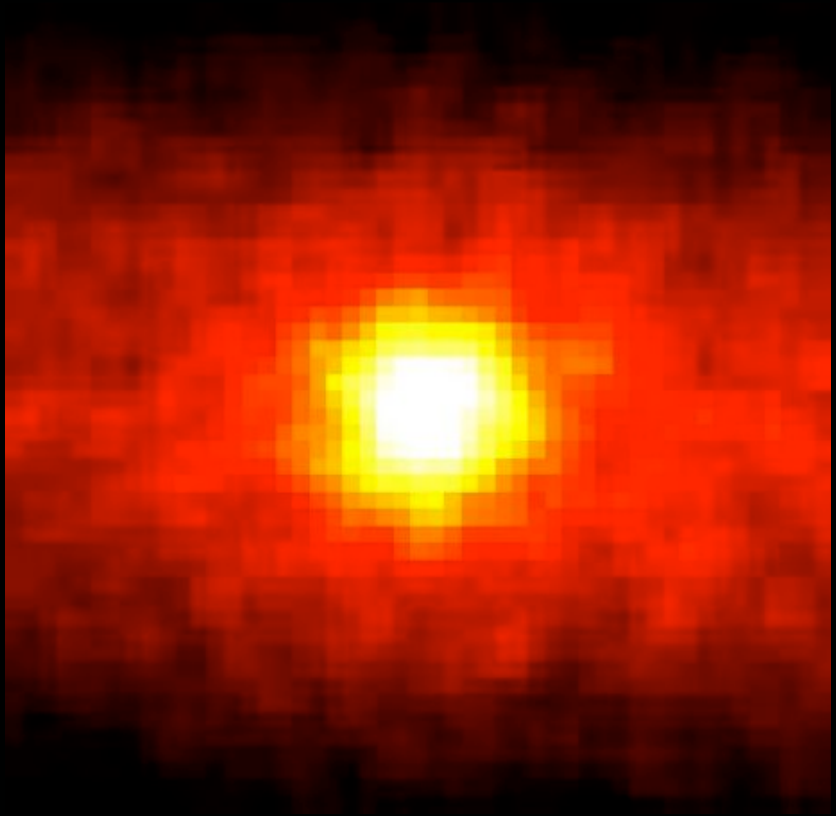
Future of Neutrino Astronomy: Supernovae in the Milky Way

Super-Kamiokande



e^- , e^+ , γ
convert to Cerenkov light

22.5 kton fiducial mass



Yields in Super-Kamiokande

$\simeq 8000$	$\bar{\nu}_e + p \rightarrow e^+ + n$	
$\simeq 700$	$\nu + {}^{16}O \rightarrow \nu + \gamma + X$	$(E = 5 - 10\ \mathrm{MeV})$
$\simeq 300$	$\nu + e^- \rightarrow \nu + e^-$	(e^- is forward)
~ 100	$\nu_e + {}^{16}O \rightarrow e^- + X$	(buried)
	$\bar{\nu}_e + {}^{16}O \rightarrow e^+ + X$	

With neutron tagging, we can separate reactions

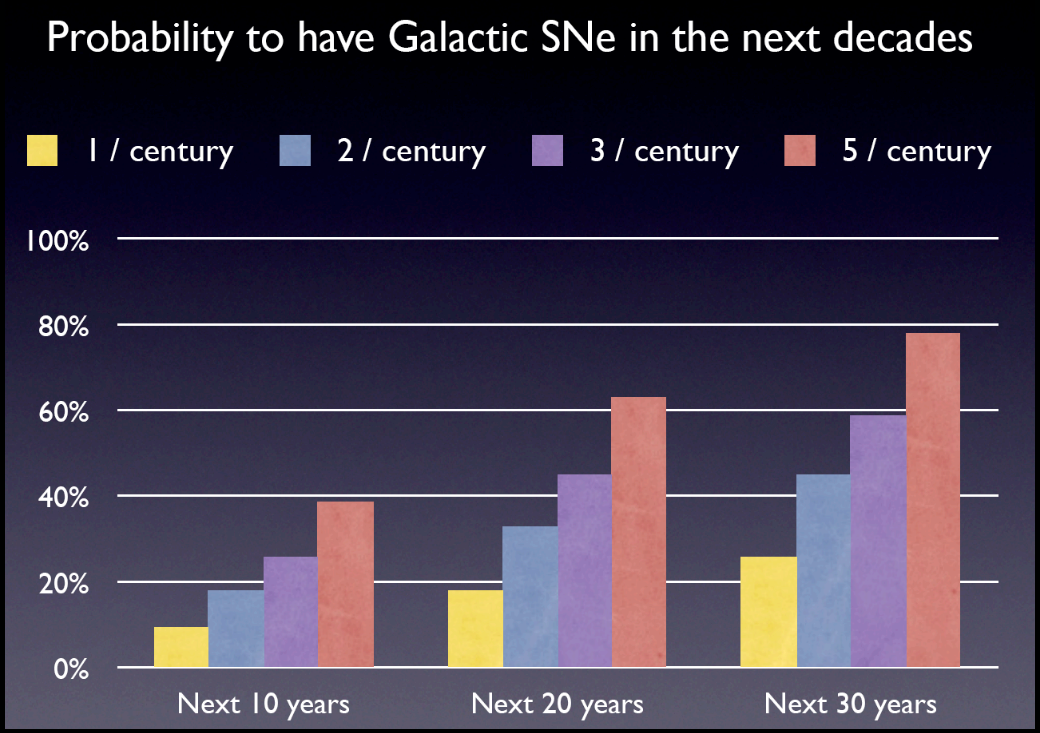
Real chance to see CC reactions on ^{16}O
Haxton, PRD 36, 2283 (1987)

Other detectors worldwide smaller but important

How Long to Wait for Next Milky Way SN?

Until we get one

Very good chances if we can wait for decades



Ando

What else can we do while we wait?

Are We Ready for Next Milky Way SN?

Yes, if we are

~ 10^4 events in Super-Kamiokande
~ 10^3 events in other detectors combined
significant background excess in IceCube
can point with SK, cross-check with SNEWS

NOOOO!!!!, if we aren't

It would be a tragedy if a burst is missed

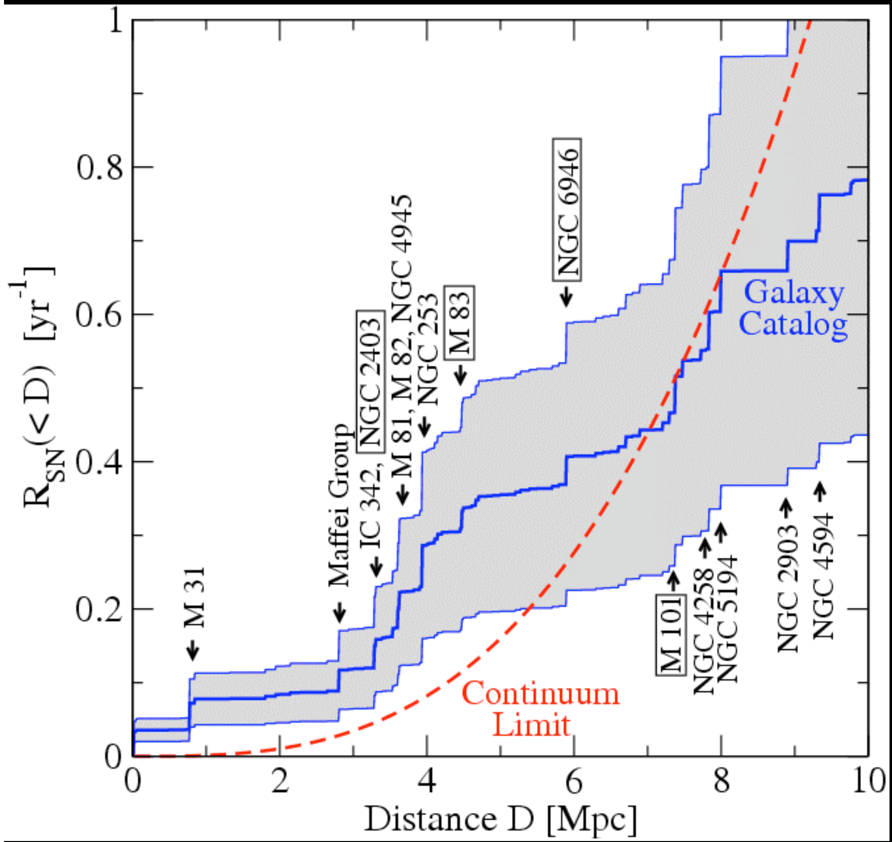
Early warning system?

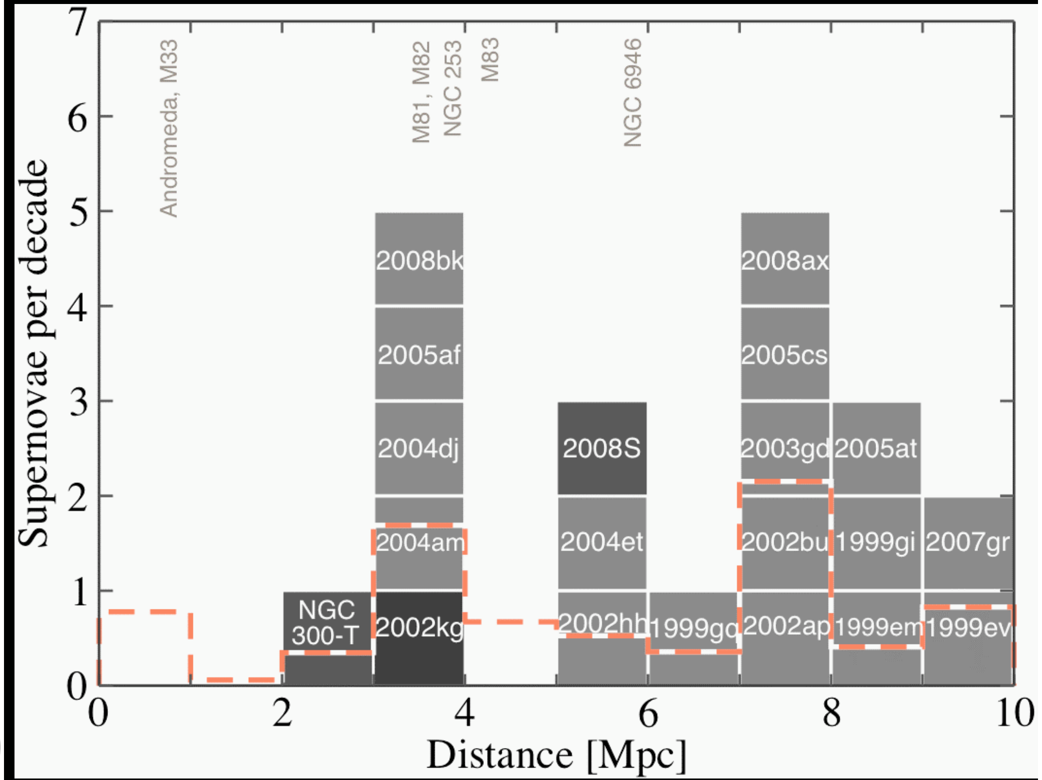
Maybe detect pre-supernova signal! (Odrzywolek et al.)

Future of Neutrino Astronomy: Supernovae in Nearby Galaxies

Question: How do the prospects depend on distance?

Nearby Supernova Rate

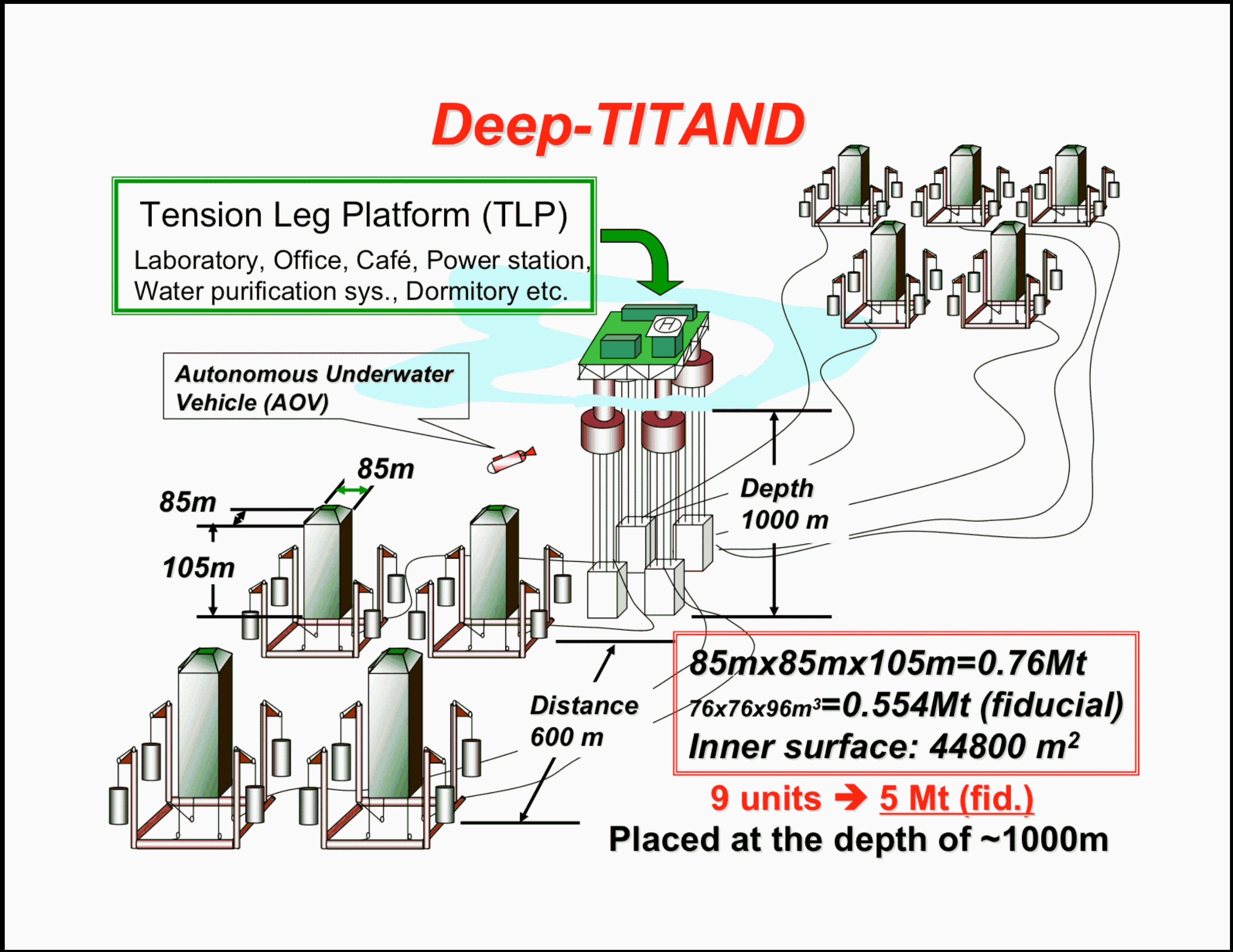




Ando, Beacom, and Yüksel, PRL 95, 171101 (2005)

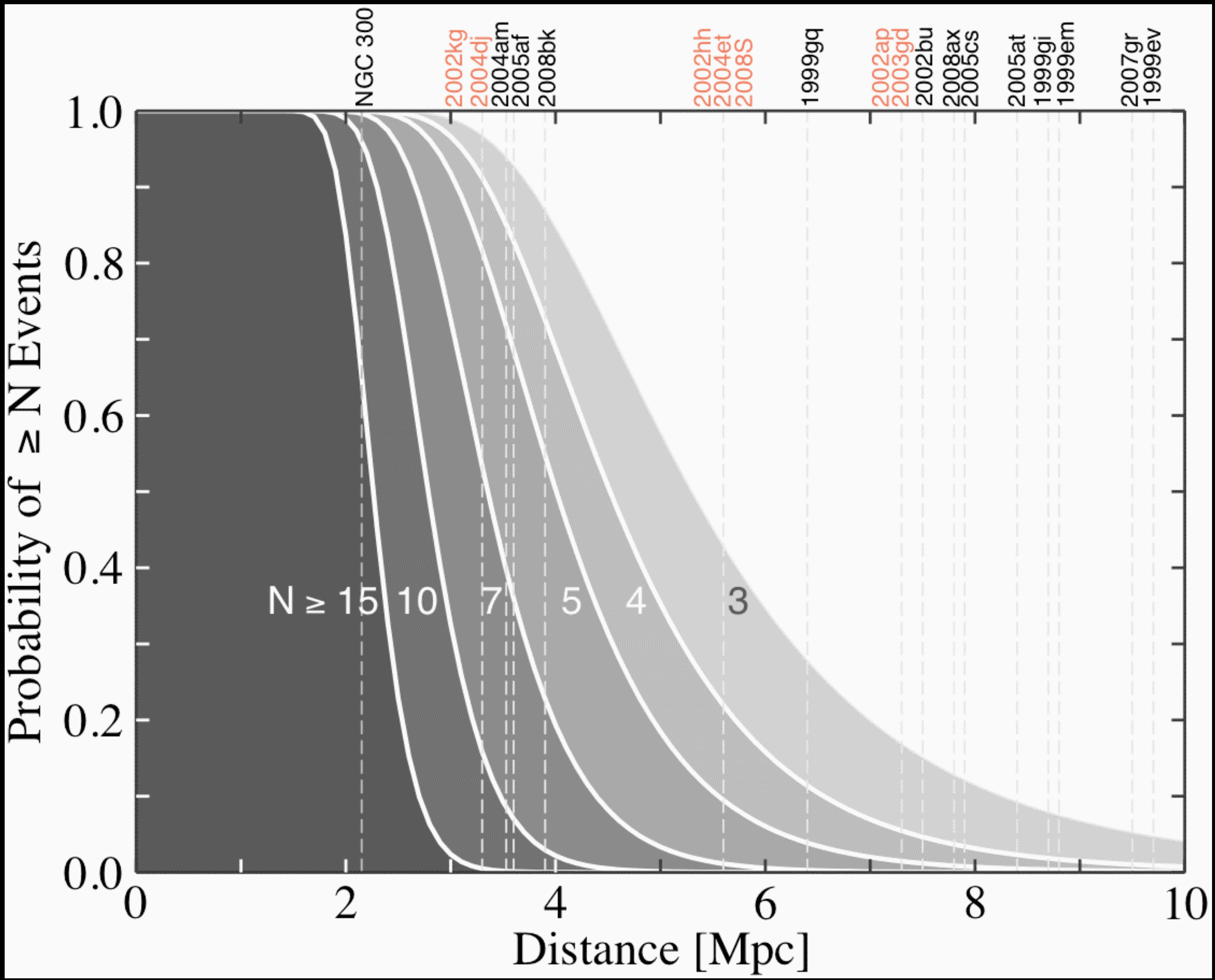
Kistler, Yuksel, Ando, Beacom, Suzuki, arXiv:0810.1959

A Five-Megaton Detector



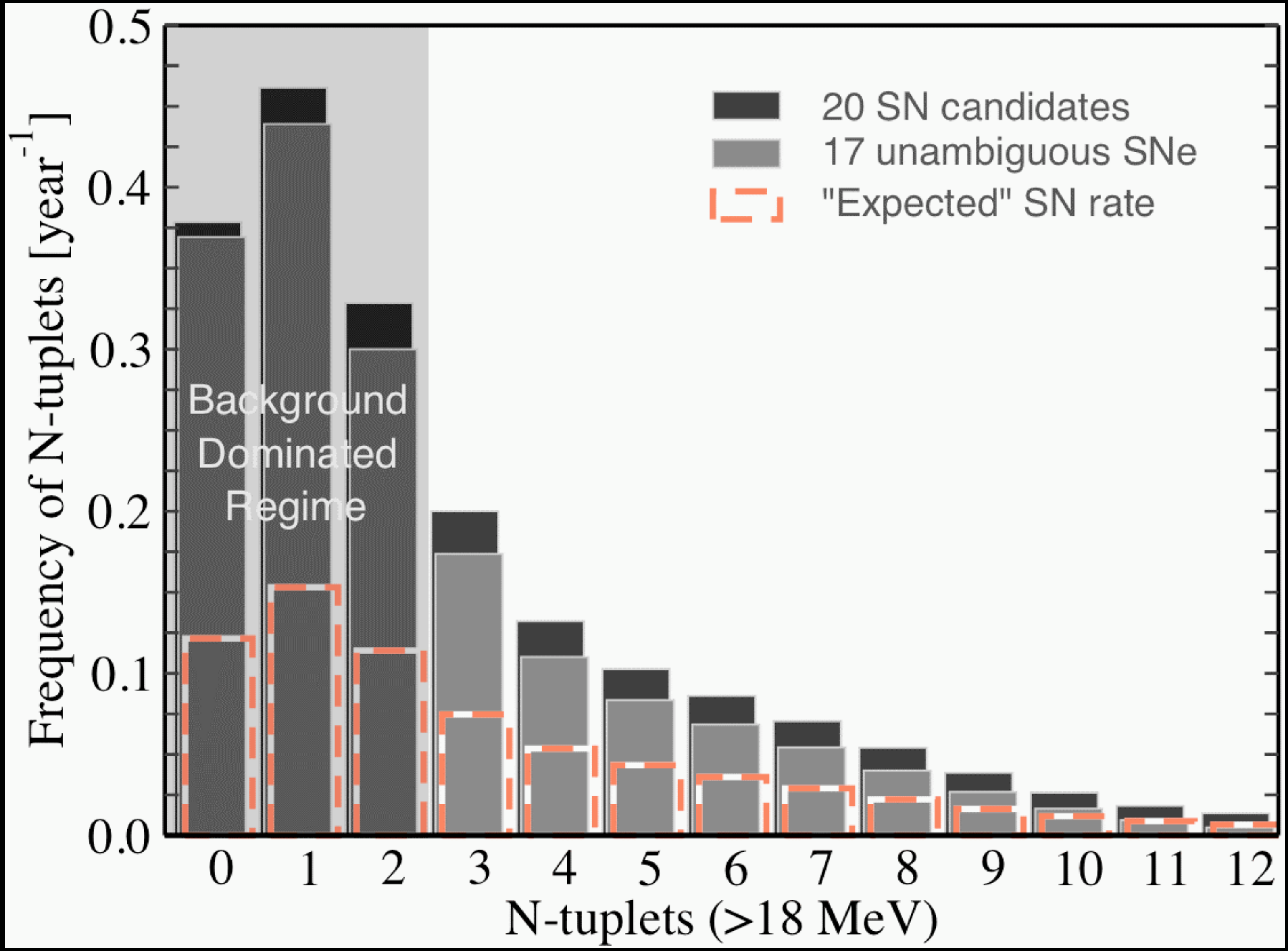
Proposed Deep-TITAND detector (Yoichiro Suzuki)

Yields in a Huge Detector



Kistler, Yuksel, Ando, Beacom, Suzuki, arXiv:0810.1959

Burst Rates in a Huge Detector



Kistler, Yuksel, Ando, Beacom, Suzuki, arXiv:0810.1959

Future of Neutrino Astronomy: Diffuse Supernova Neutrino Background

Question: Can you estimate the DSNB flux?

What are the Ingredients of the DSNB?

detector capabilities

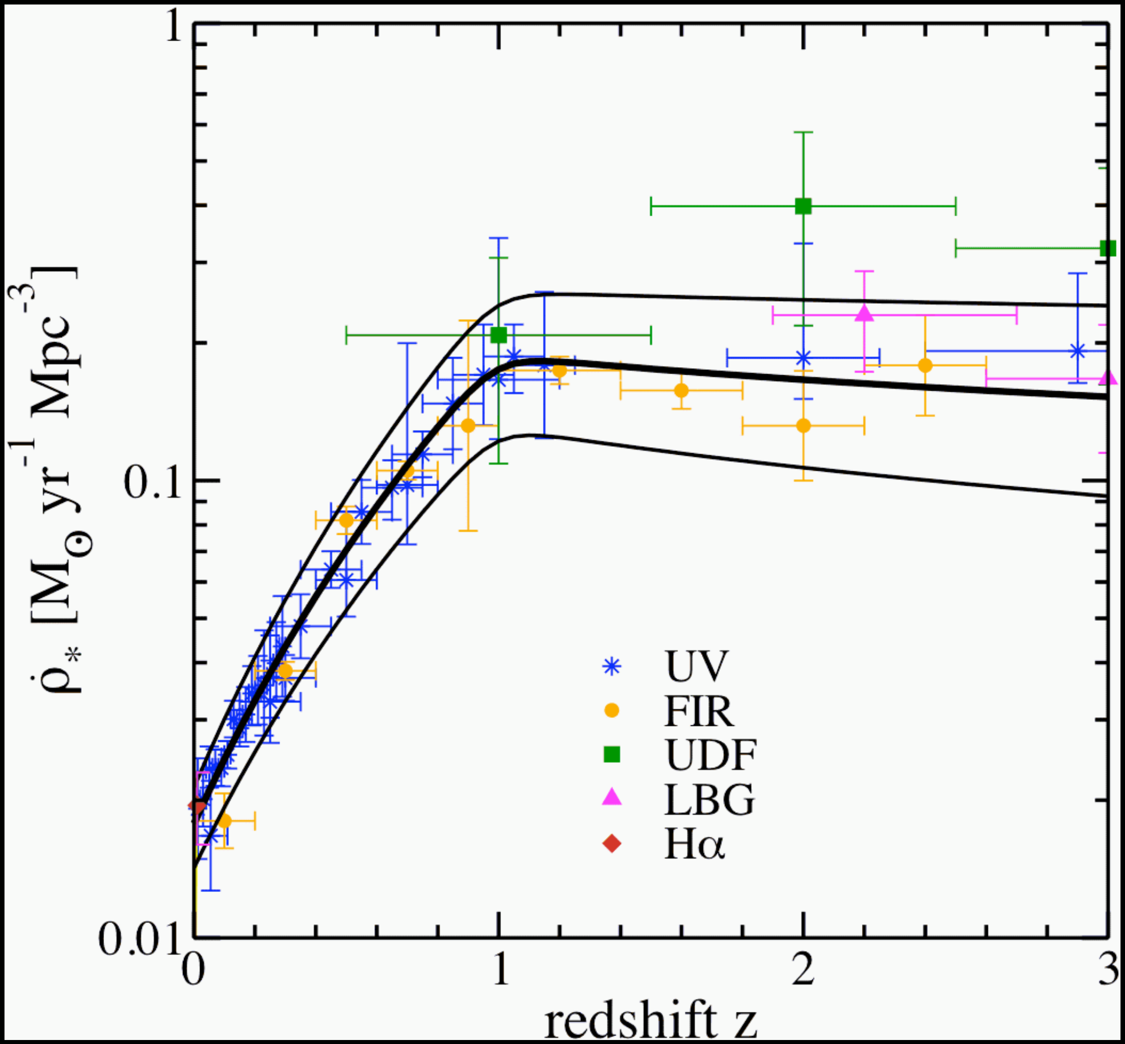
supernova rate history

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

positron spectrum (cf. detector backgrounds)

neutrino spectrum per supernova

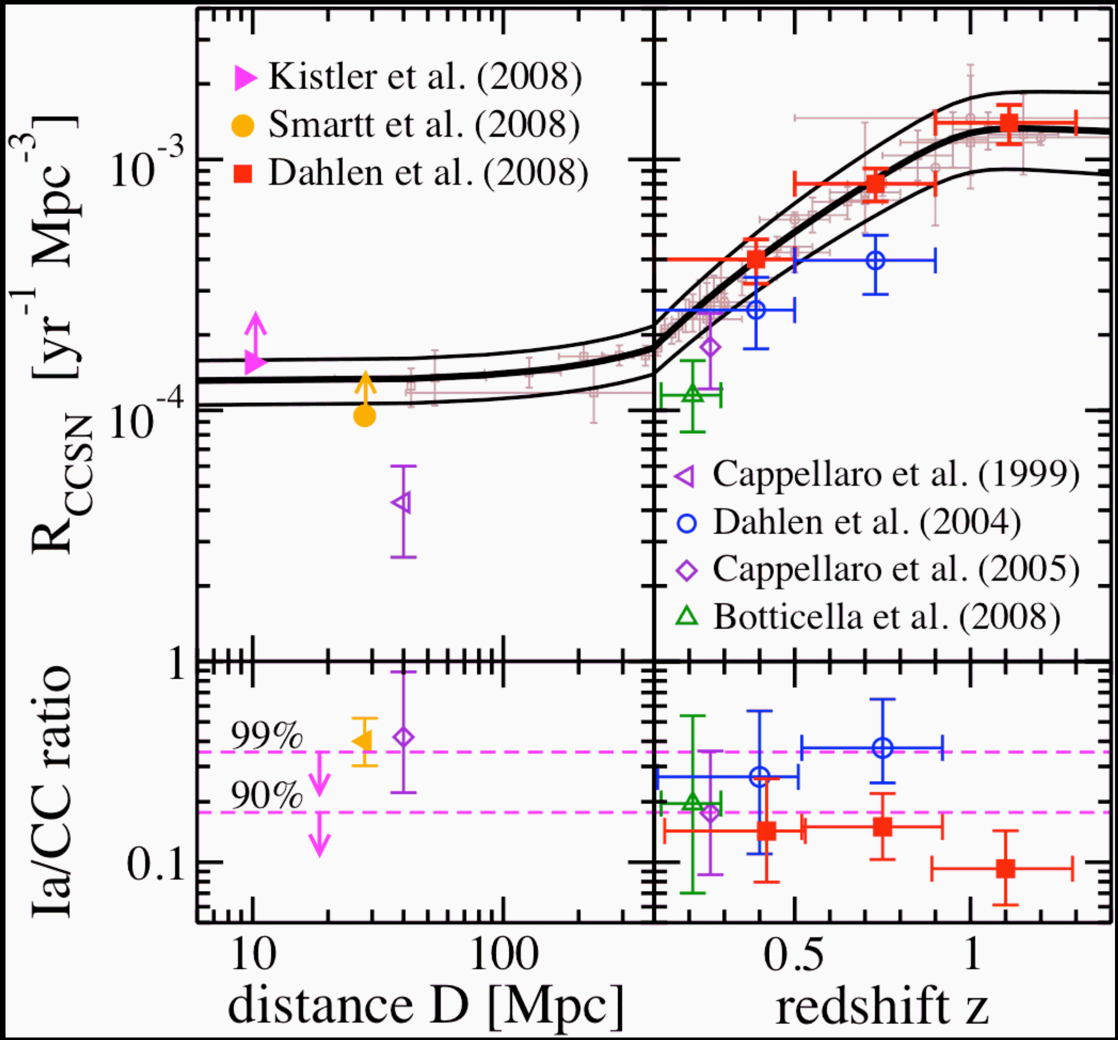
Star Formation Rate



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

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

Supernova Rate

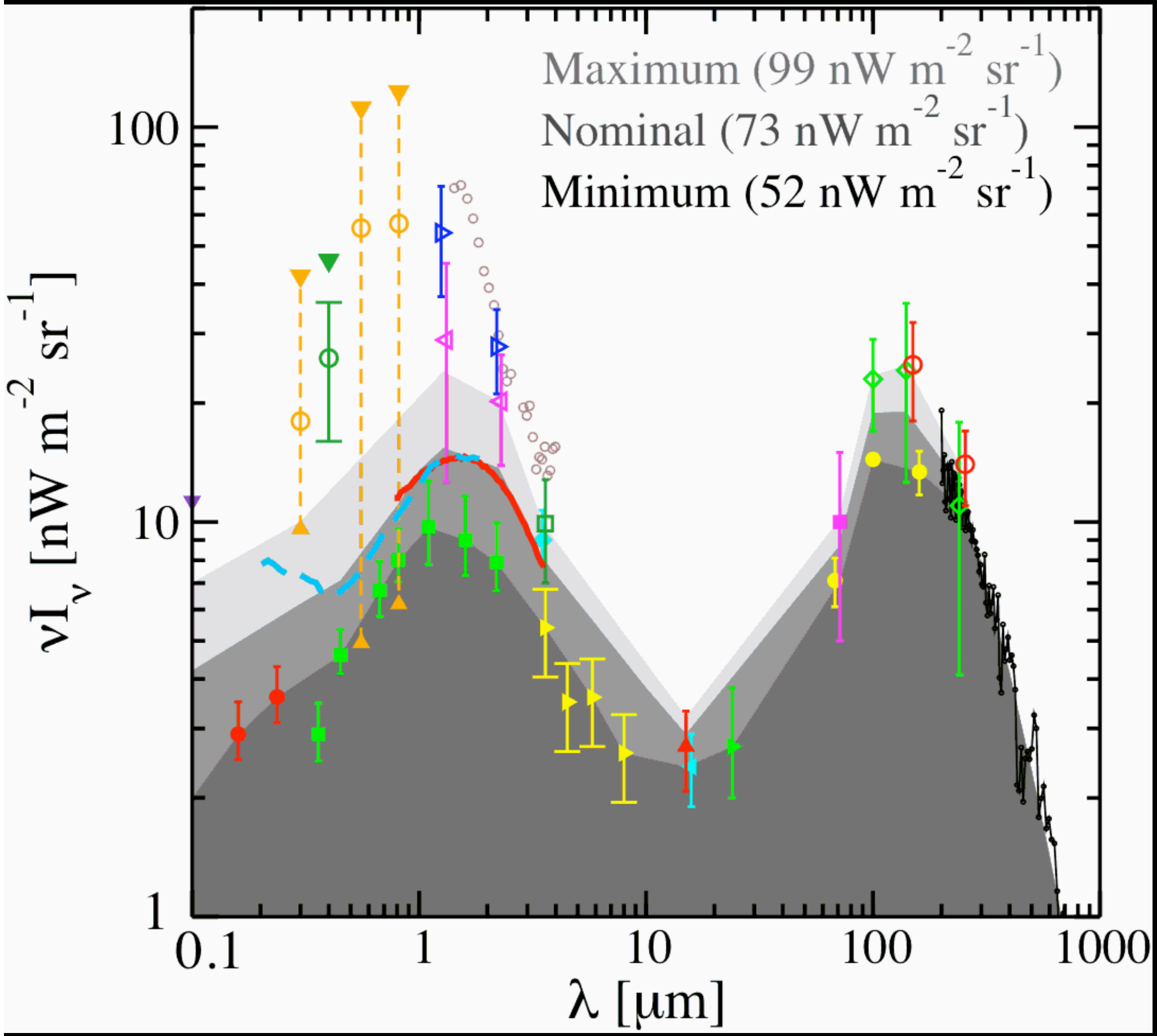


Provides direct normalization of the DSNB

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

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

Extragalactic Background Light

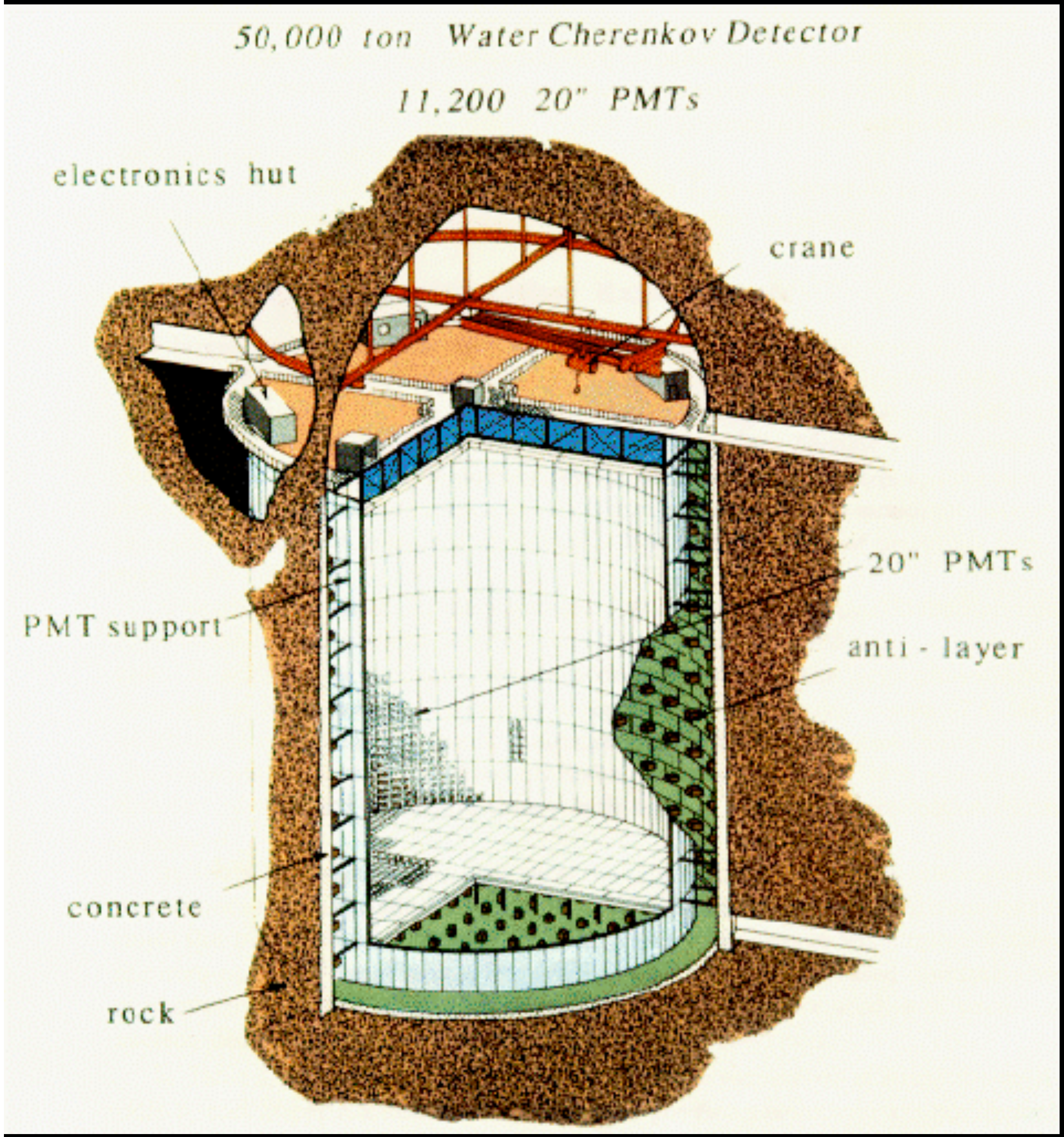


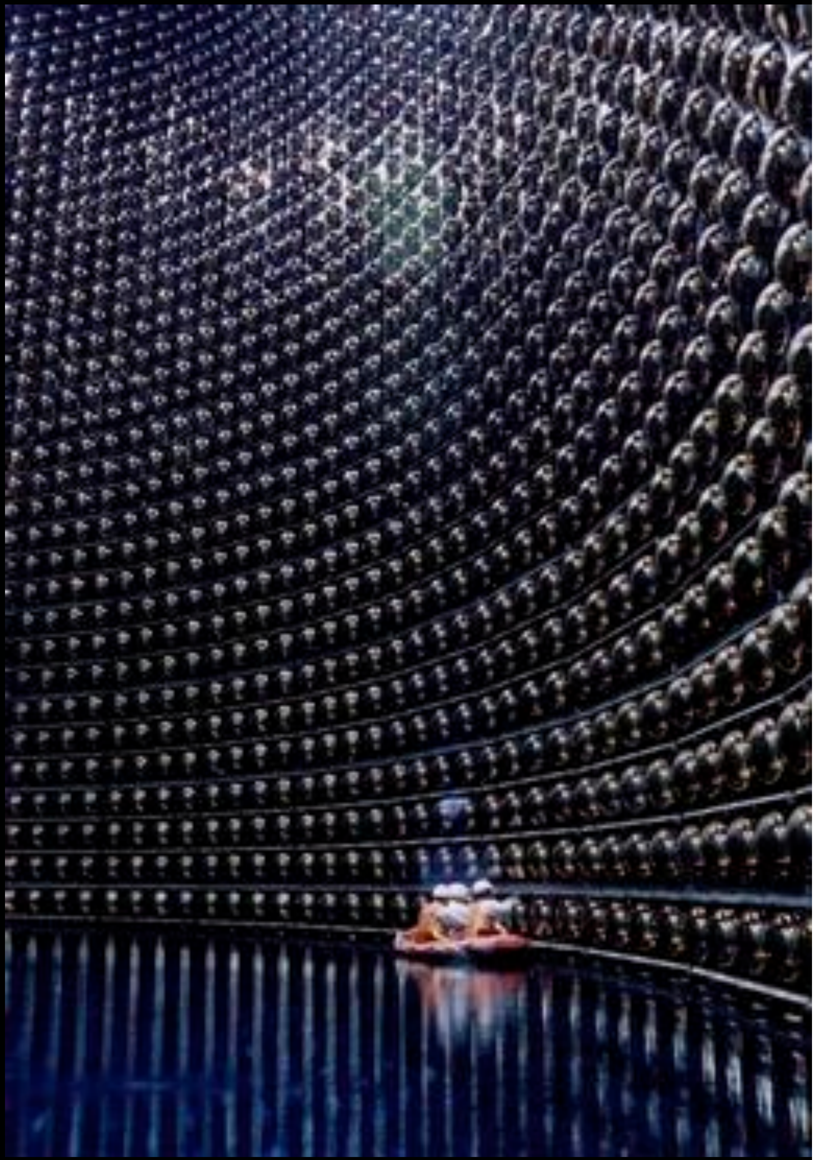
Using HB06 CSFH, our calculated result is 78--95, depending on IMF

Provides another confirmation of the adopted CSFH

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

Super-Kamiokande

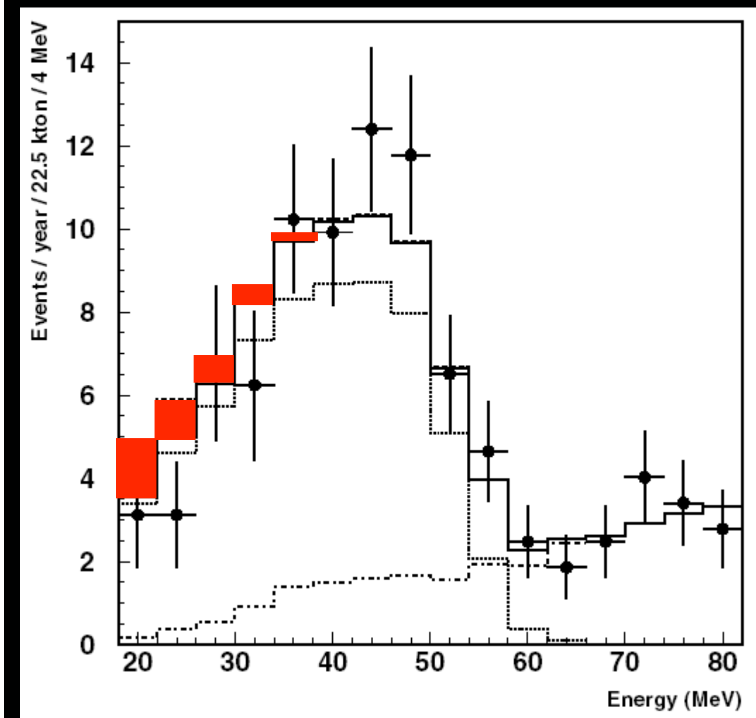




Might the DSNB be Detectable?

~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"

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

$$E_e \simeq E_\nu - 1.3\,\text{MeV}$$

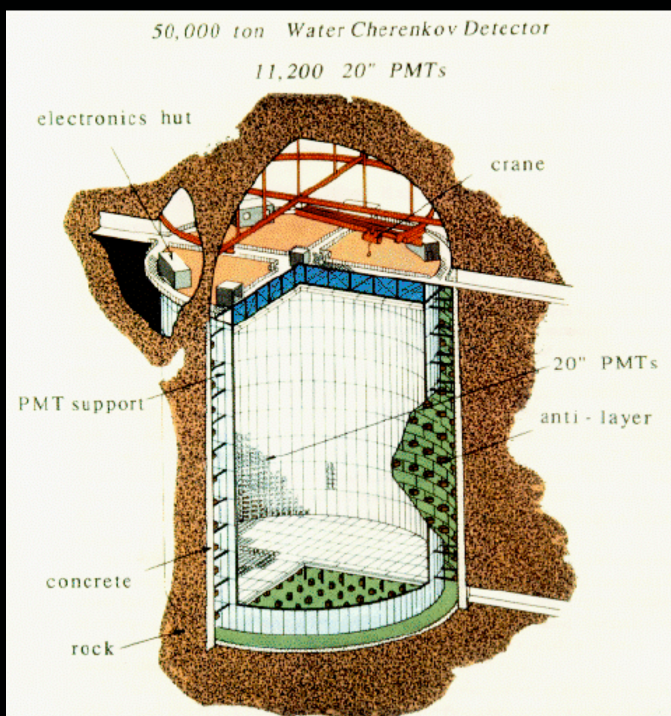
Corrections in Vogel and Beacom, PRD 60, 053003 (1999)

- 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?

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

GADZOOKS!

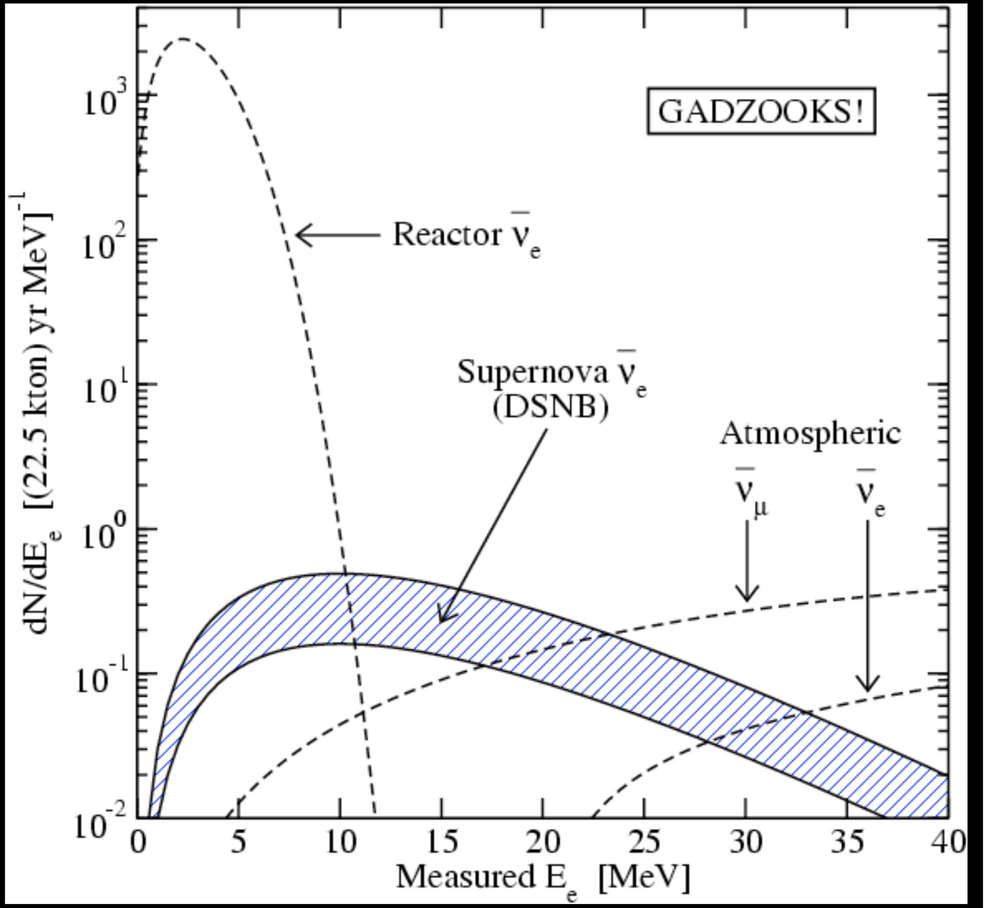
At 0.2% $GdCl_3$:

Capture fraction = 90%

λ = 4 cm, τ = 20 μs

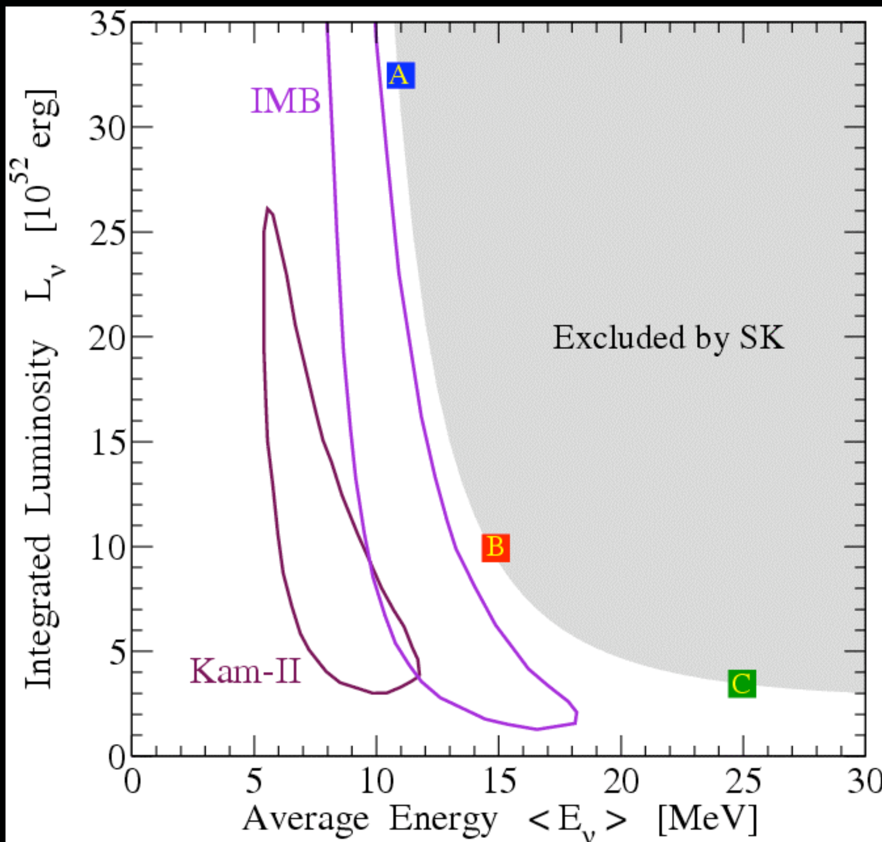
active R&D program
in US and Japan

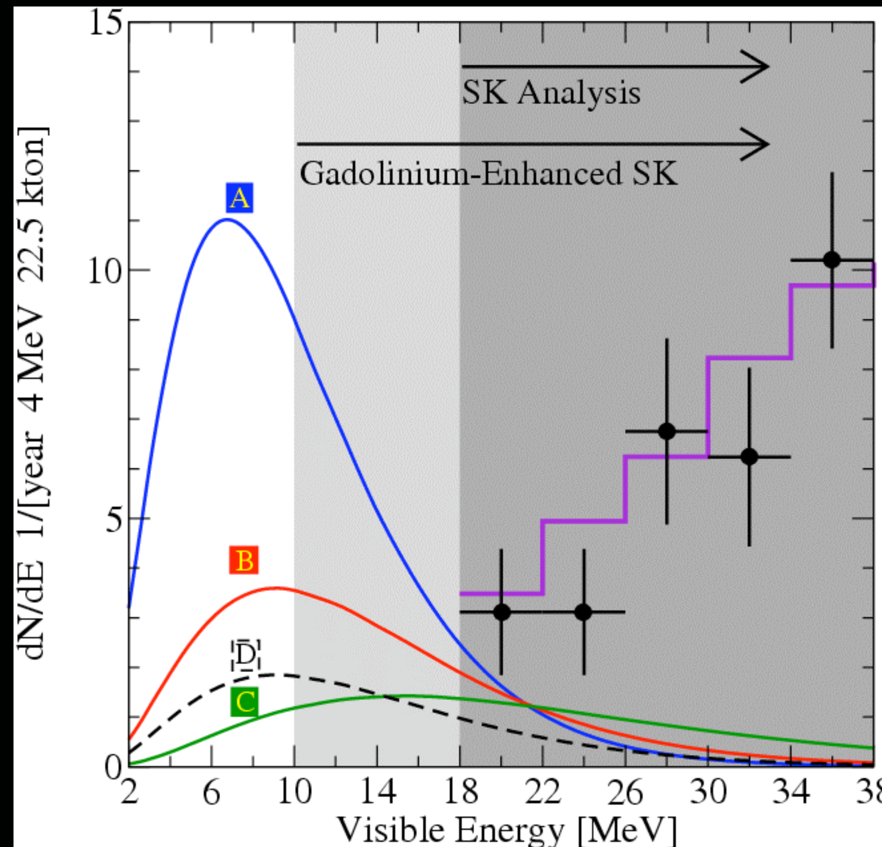
Beacom, Vagins, PRL 93, 171101 (2004)



Neutron tagging means lower backgrounds, thresholds

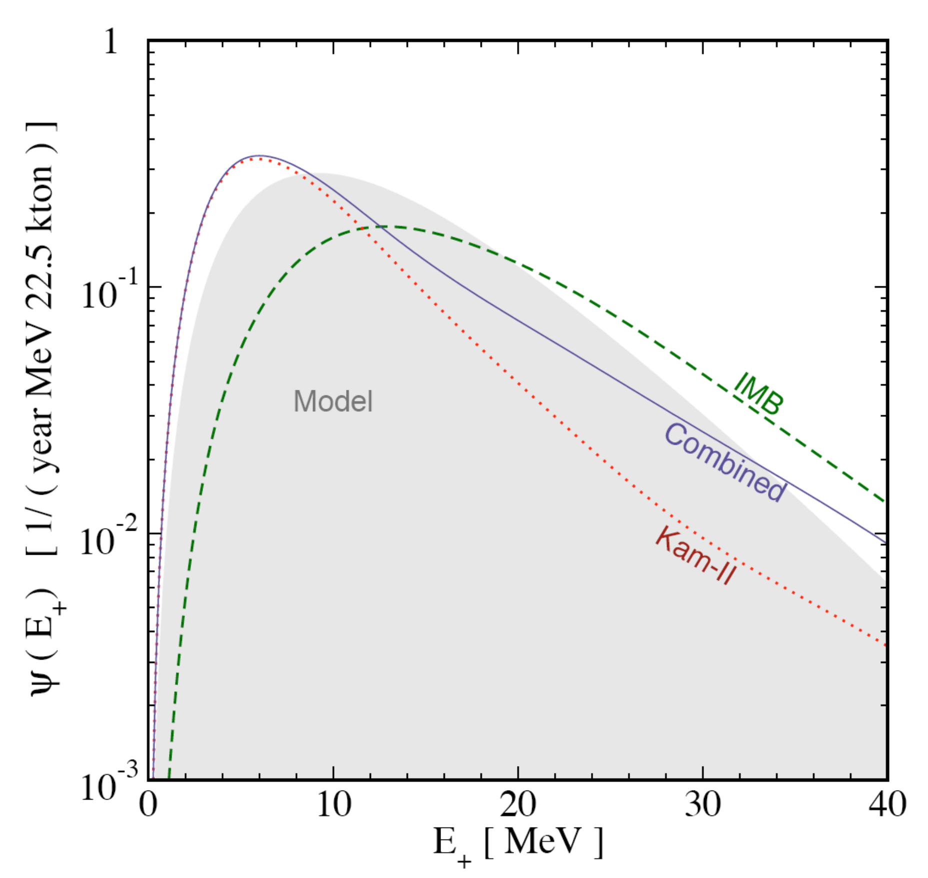
What is the Neutrino Emission per Supernova?

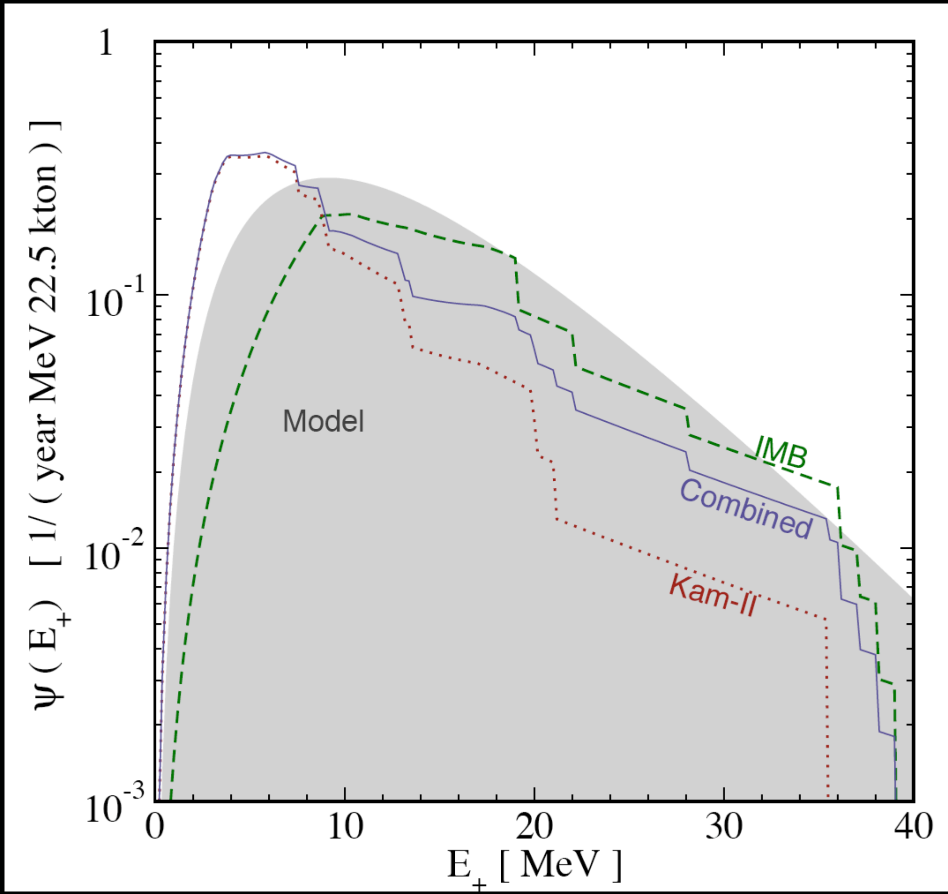




Yuksel, Ando, Beacom, PRC 74, 015803 (2006)

DSNB Spectra Based on SN 1987A Data

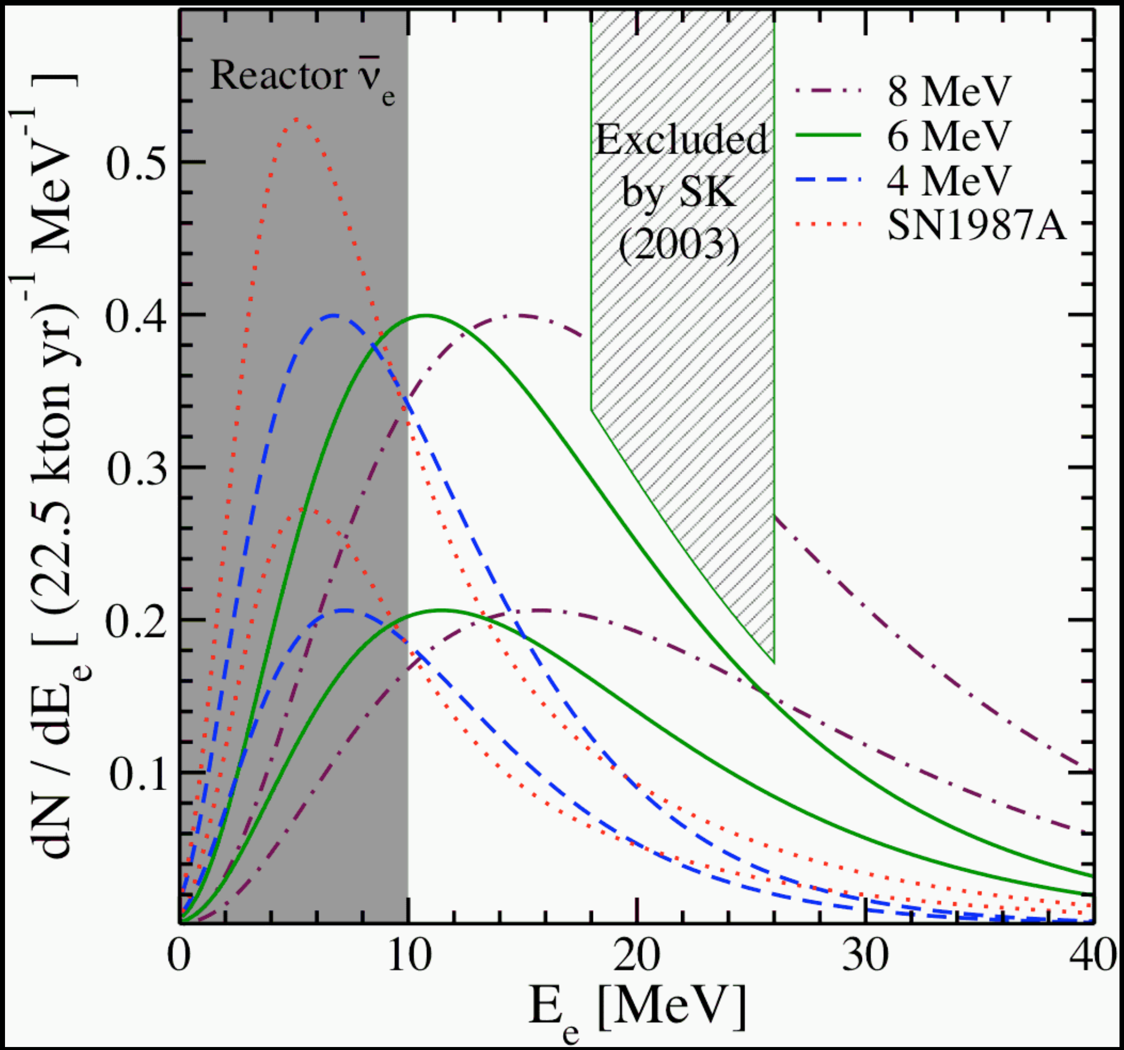




Yuksel and Beacom, PRD 76, 083007 (2007)

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

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

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