Lecture 1: Supernova Neutrinos

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Stellar Masses and Fates

$dn/dm \sim m^{-2.35}$, $m = M_{star} / M_{sun}$ Salpeter (1955)

Type Ia SN:
~ 3 - 8 M_{sun} progenitor (~ Gyr);
carbon-oxygen white dwarf in binary;
gammas reveal (thermonuclear) explosion energy;
56Ni --> 56Co --> 56Fe with gammas (months)

Type II SN:
~ 8 - 40 M_{sun} progenitor (< 0.1 Gyr)
iron white dwarf in core of star;
neutrinos reveal (gravitational) explosion energy;
hot and dense --> nu + nubar (seconds)

Observational Scorecard

Gamma rays from SNIa:

Never seen from individual SNIa

Tight limits in three cases with COMPTEL

Diffuse background from SNIa not seen

COMPTEL *did* measure an MeV background

Neutrinos from SNII:

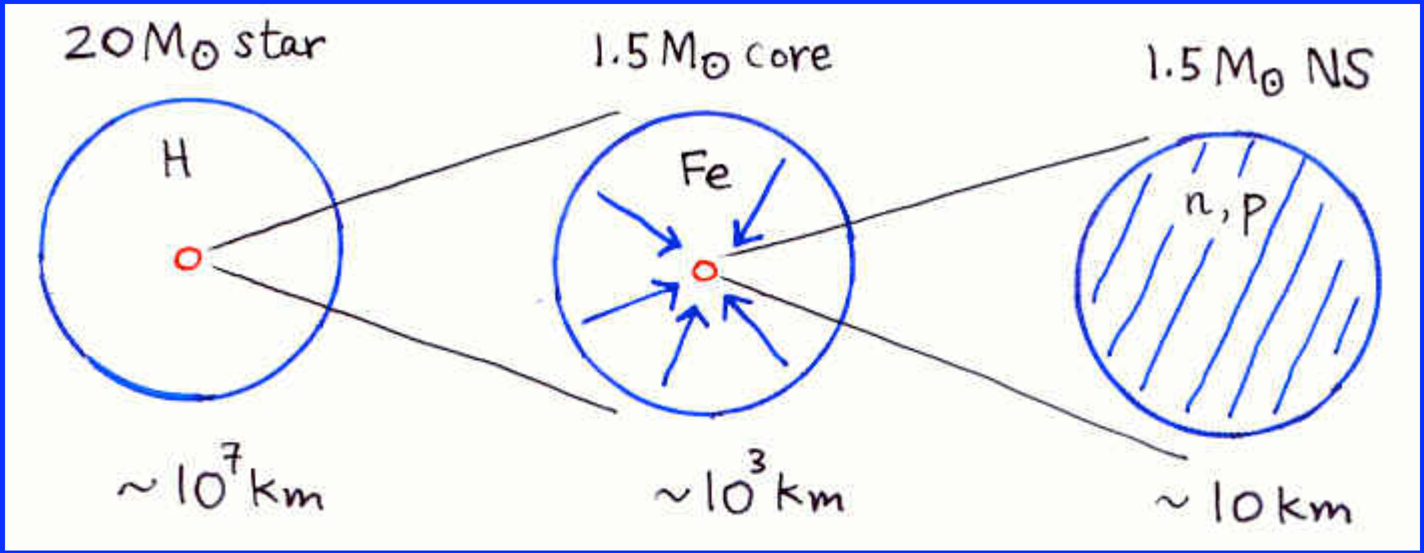
Seen once, from SN 1987A

But only ~ 20 events

Diffuse background from SNII not seen

Limits on MeV background from Super-K

Supernova Energetics

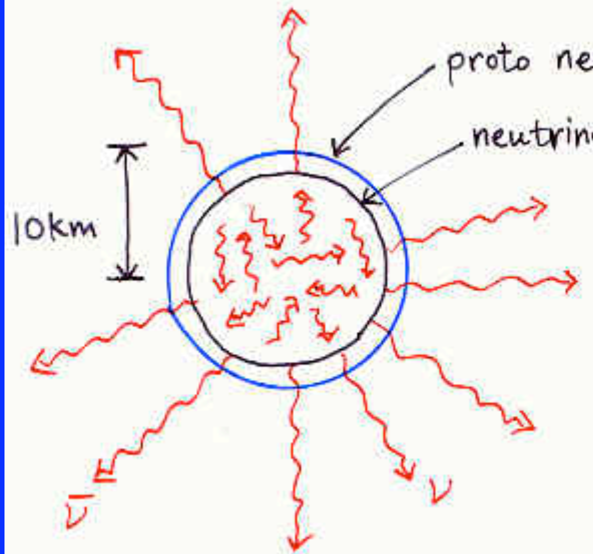


$$\Delta E_B \simeq \frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G M_{NS}^2}{R_{core}} \simeq 3\times 10^{53}\ \text{ergs} \simeq 2\times 10^{59}\ \text{MeV}$$

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

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

Supernova Neutrino Emission



"cooling" by neutrino emission :

$$p + e^- \longrightarrow n + \nu_e$$

$$e^+ + e^- \longrightarrow \nu_e + \bar{\nu}_e,\ \nu_\mu + \bar{\nu}_\mu,\ \nu_\tau + \bar{\nu}_\tau$$

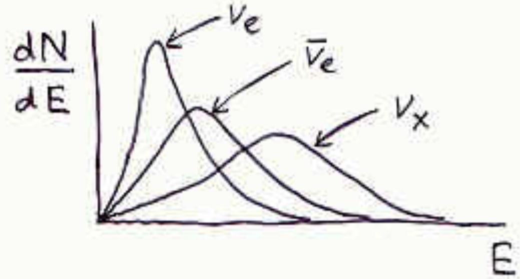
etc.

diffusion until $\lambda = 1/\rho\sigma$ from surface, then escape

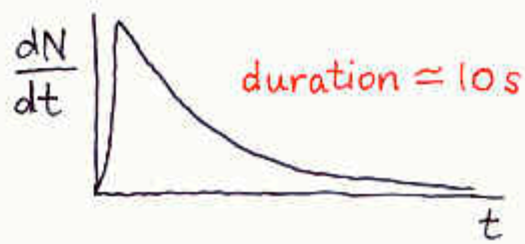
$$\langle E_{\nu_e} \rangle \simeq 11\ \text{MeV}$$

$$\langle E_{\bar{\nu}_e} \rangle \simeq 16\ \text{MeV}$$

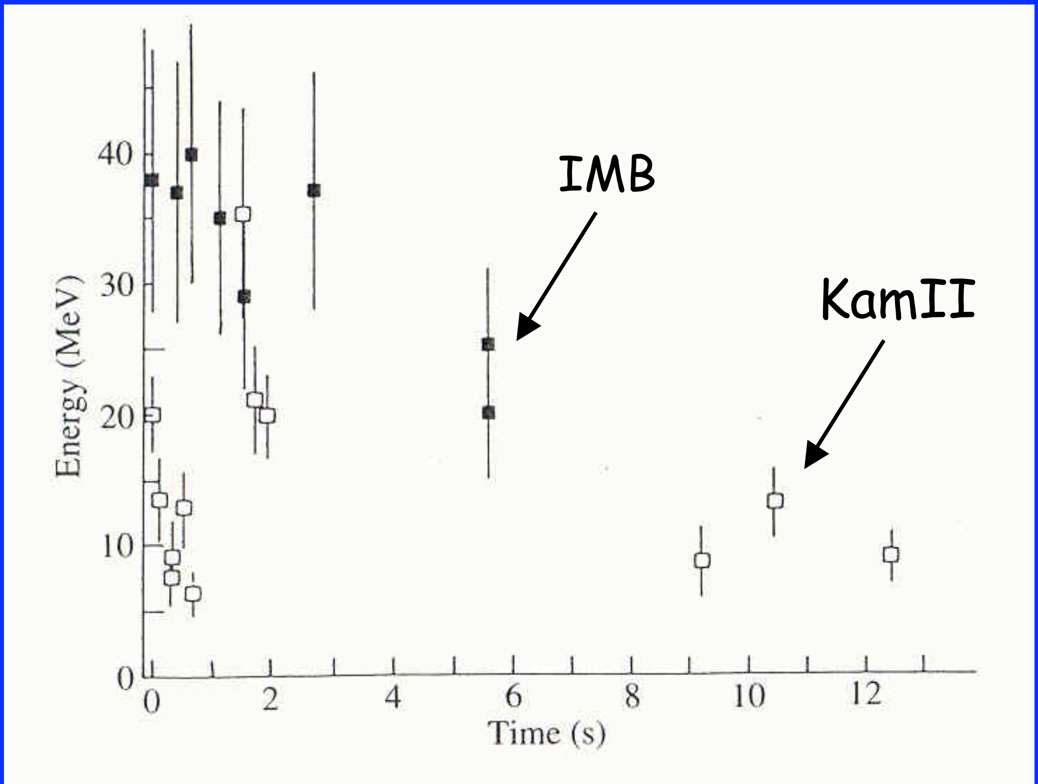
$$\langle E_{\nu_x} \rangle \simeq 25\ \text{MeV}$$



$$L_{\nu_e}(t) \simeq L_{\bar{\nu}_e}(t) \simeq L_{\nu_x}(t)$$



Supernova Neutrino Detection



SN1987A :

$\sim 20\ \ \bar{\nu}_e p \rightarrow e^+ n$ events

SN200?? :

$\sim 10^4$ CC events

$\sim 10^3$ NC events

Supernova physics (models, black holes, progenitors…)

Particle physics (neutrino properties, new particles, …)

Gathering Supernova Neutrinos

Milky Way (D ~ 10 kpc):

Expect ~ 10^4 events in Super-Kamiokande

Frequency is ~ 3/century

Very obvious when it happens

Nearby (D < 10 Mpc):

Expect ~ 1 event in Hyper-Kamiokande

Frequency is ~ 1/year

Requires two-neutrino or optical coincidence

Distant (z < 1):

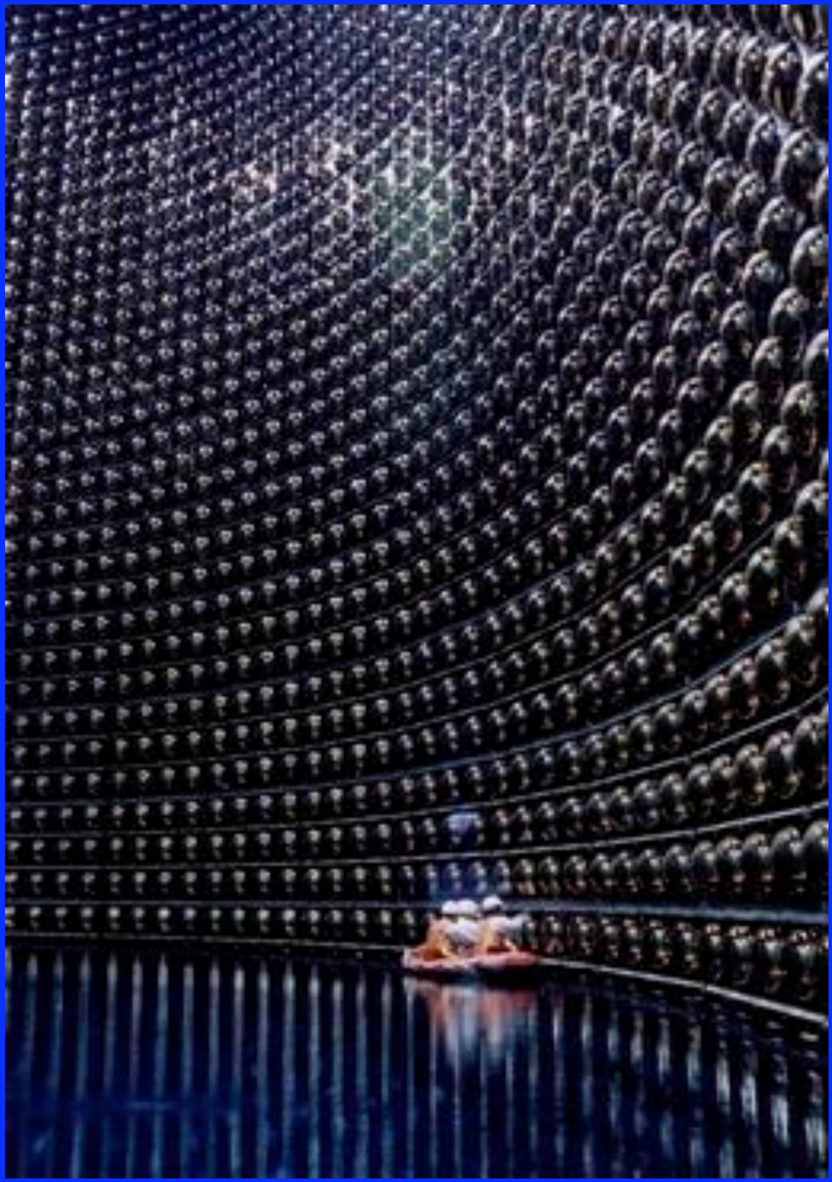
Expect ~ 5 events/year in Super-Kamiokande

No correlation to specific supernovae possible

Requires strong rejection of detector backgrounds

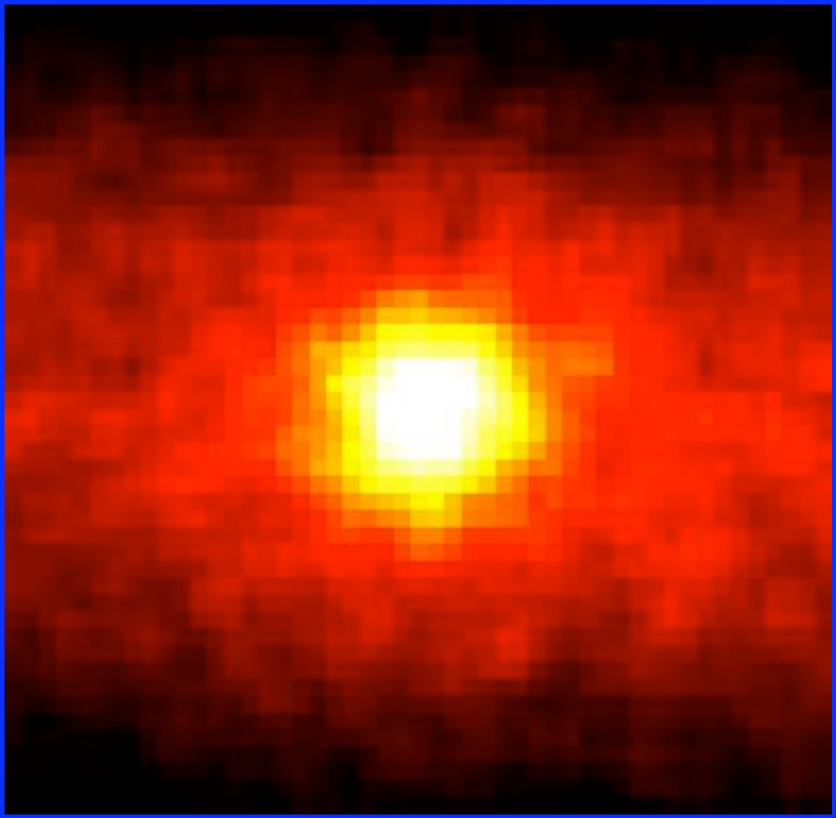
Supernovae in the Milky Way

Super-Kamiokande



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

22.5 kton fiducial mass



Yields in Super-Kamiokande

$\simeq 8000 \quad \bar{\nu}_e + p \to e^+ + n$

$\simeq 700 \quad \nu + {}^{16}O \to \nu + \gamma + X \quad (E = 5 - 10\ \text{MeV})$

$\simeq 300 \quad \nu + e^- \to \nu + e^- \quad (e^-\ \text{is forward})$

$\sim 100 \quad \nu_e + {}^{16}O \to e^- + X \quad (\text{buried})$

$\bar{\nu}_e + {}^{16}O \to e^+ + X$

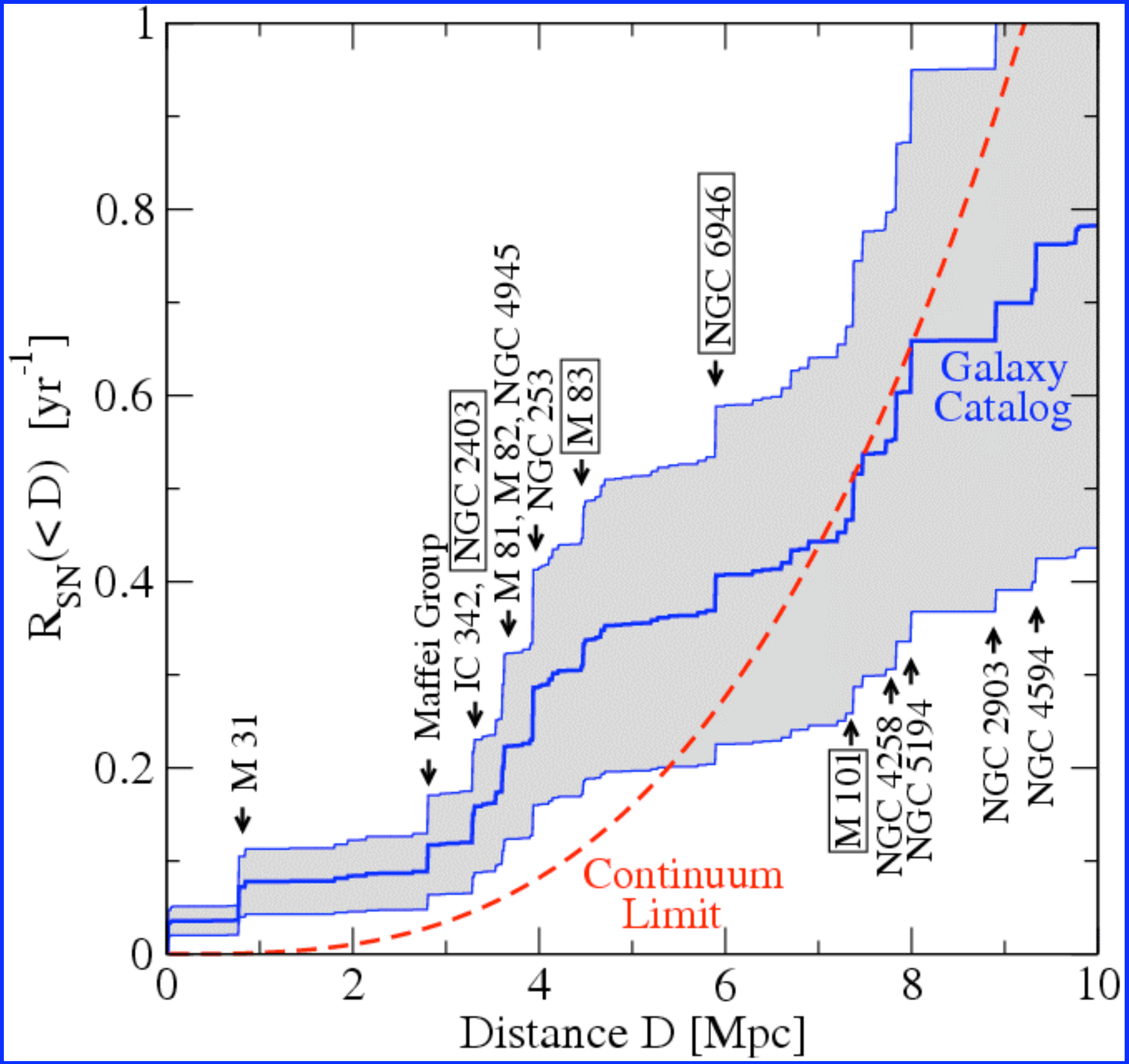
With neutron tagging, we can separate reactions

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

Other detectors worldwide smaller but important

Supernovae in Nearby Galaxies

Nearby Star Formation Rate



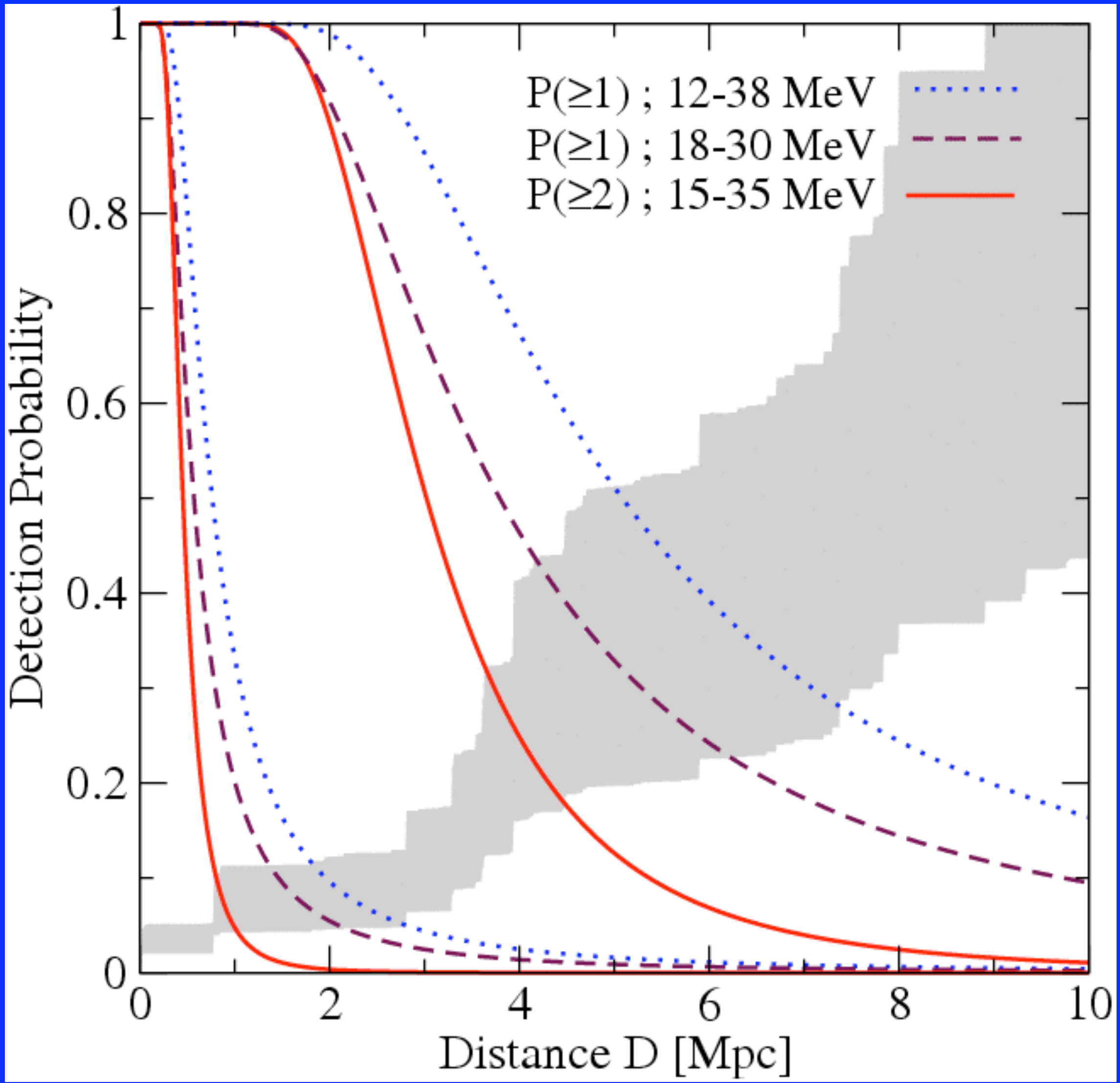
Ando, Beacom, and Yüksel, PRL 95, 171101 (2005)

Nearby Supernovae

Galaxy	D [Mpc]	Known Supernovae
NGC 2403	3.3	1954J, 2002kg, 2004dj
NGC 5236 (M 83)	4.5	1923A, 1945B, 1950B, 1957D, 1968L, 1983N
NGC 6946	5.9	1917A, 1939C, 1948B, 1968D, 1969P, 1980K, 2002hh, 2004et
NGC 5457 (M 101)	7.4	1909A, 1951H, 1970G

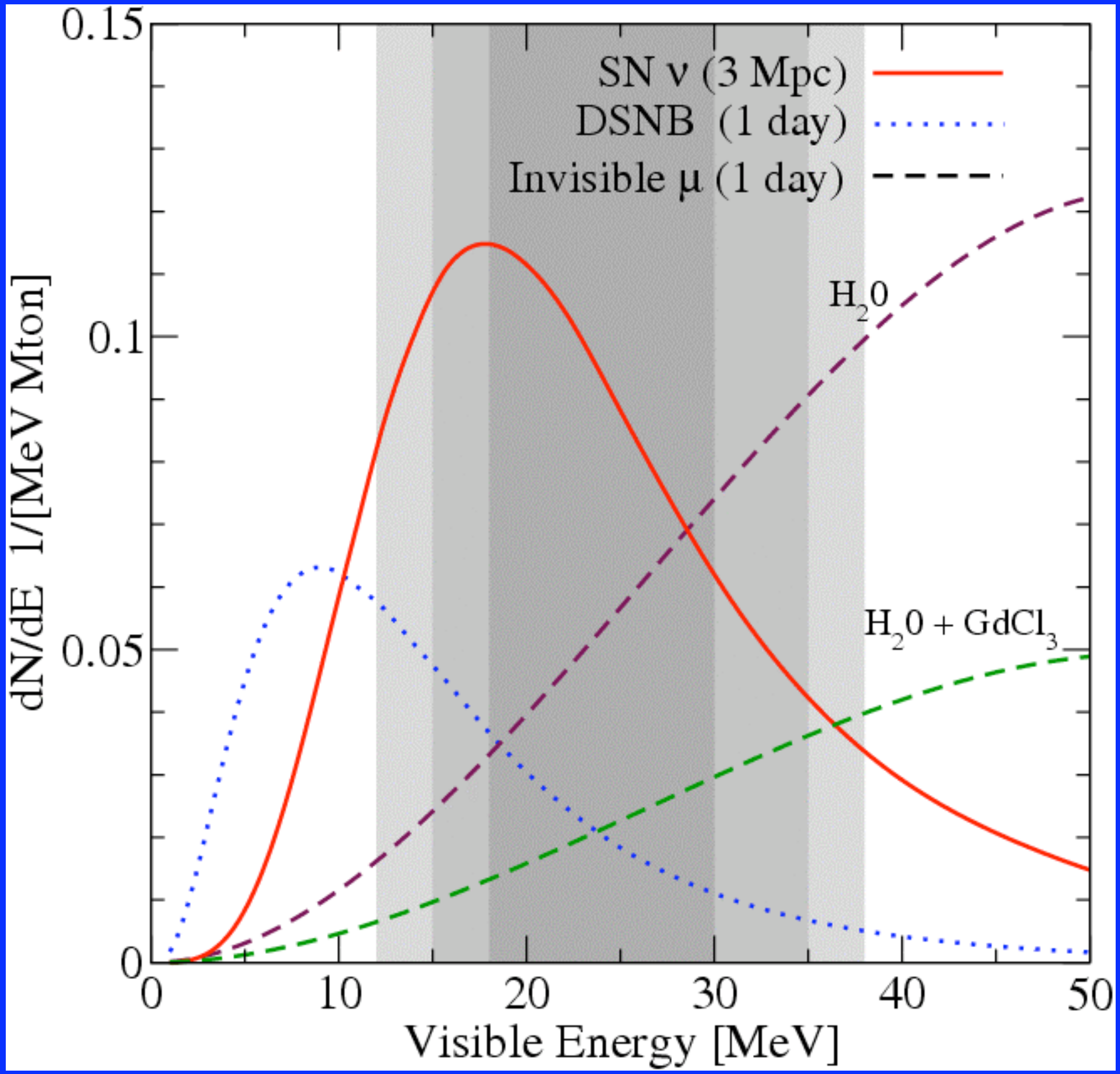
Supernova	Mag.	Host Galaxy	D [Mpc]	Discoverer
2002ap	14.5	M 74	7.3	Yoji Hirose
2002bu	15.5	NGC 4242	7.8	Tim Puckett
2002hh	16.5	NGC 6946	5.9	LOTOSS
2002kg	19	NGC 2403	3.3	LOTOSS
2003gd	13.2	M 74	7.3	Robert Evans
2004am	17	M 82	3.5	LOSS
2004dj	11.2	NGC 2403	3.3	Koichi Itagaki
2004et	12.8	NGC 6946	5.9	Stefano Moretti
2005af	12.8	NGC 4945	3.6	CEAMIG/REA

More Than a Snowball's Chance



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

Nearby Supernova Detection



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

New Optical Survey

NO SWEAT: Neutrino-Oriented Supernova
Whole-EArth Telescope

Monitor 12 large nearby galaxies nightly for SNe

Avishay Gal-Yam, et al.

http://www.astro.caltech.edu/~avishay/nosweat.html

Early behavior of light curves
Possible identification of progenitors
Correlation with neutrino experiments
Correlation with LIGO
Correlation with gamma-ray satellites
Etc.

DSNB, Take 1: First Good Limit

Supernova Neutrino Background

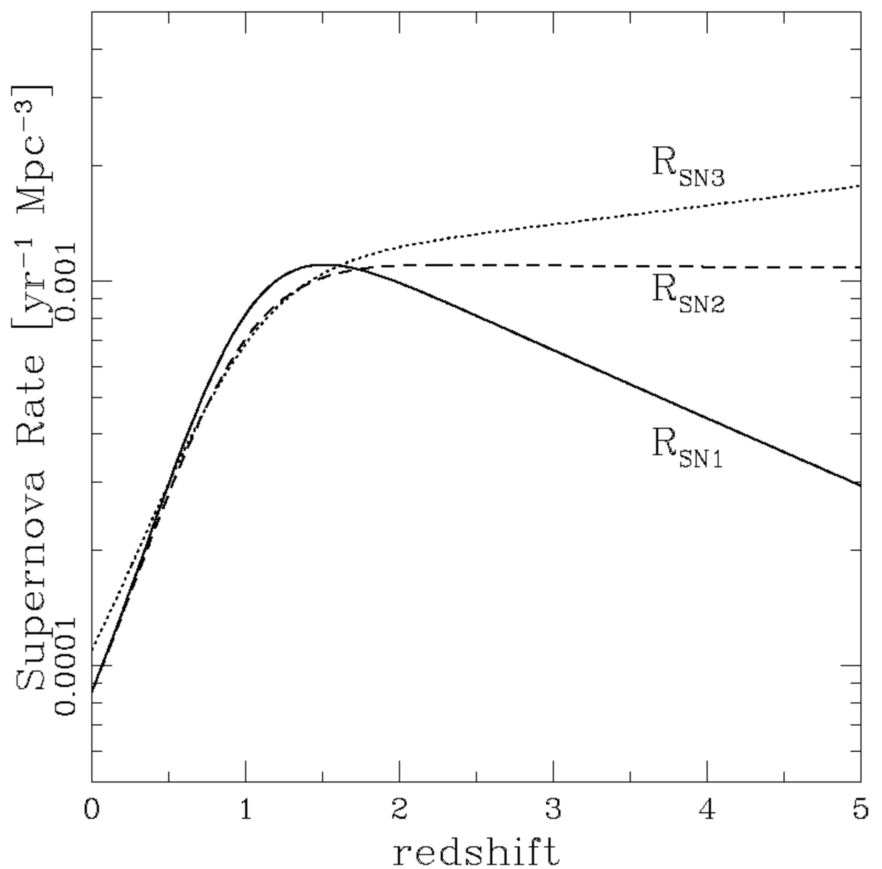


Fig. 2. Supernova rate evolution on the cosmological time scale. These lines are for a Λ-dominated cosmology ($\Omega_m = 0.3, \Omega_\lambda = 0.7$). The Hubble constant is taken to be 70 km s^{-1} Mpc^{-1}.

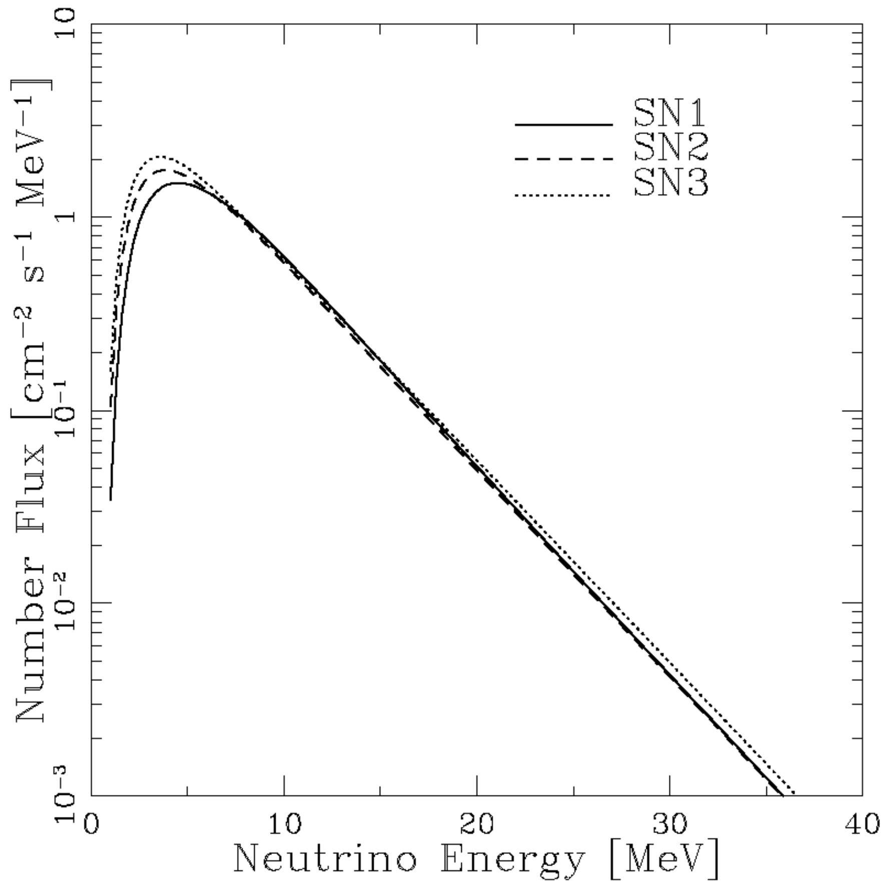
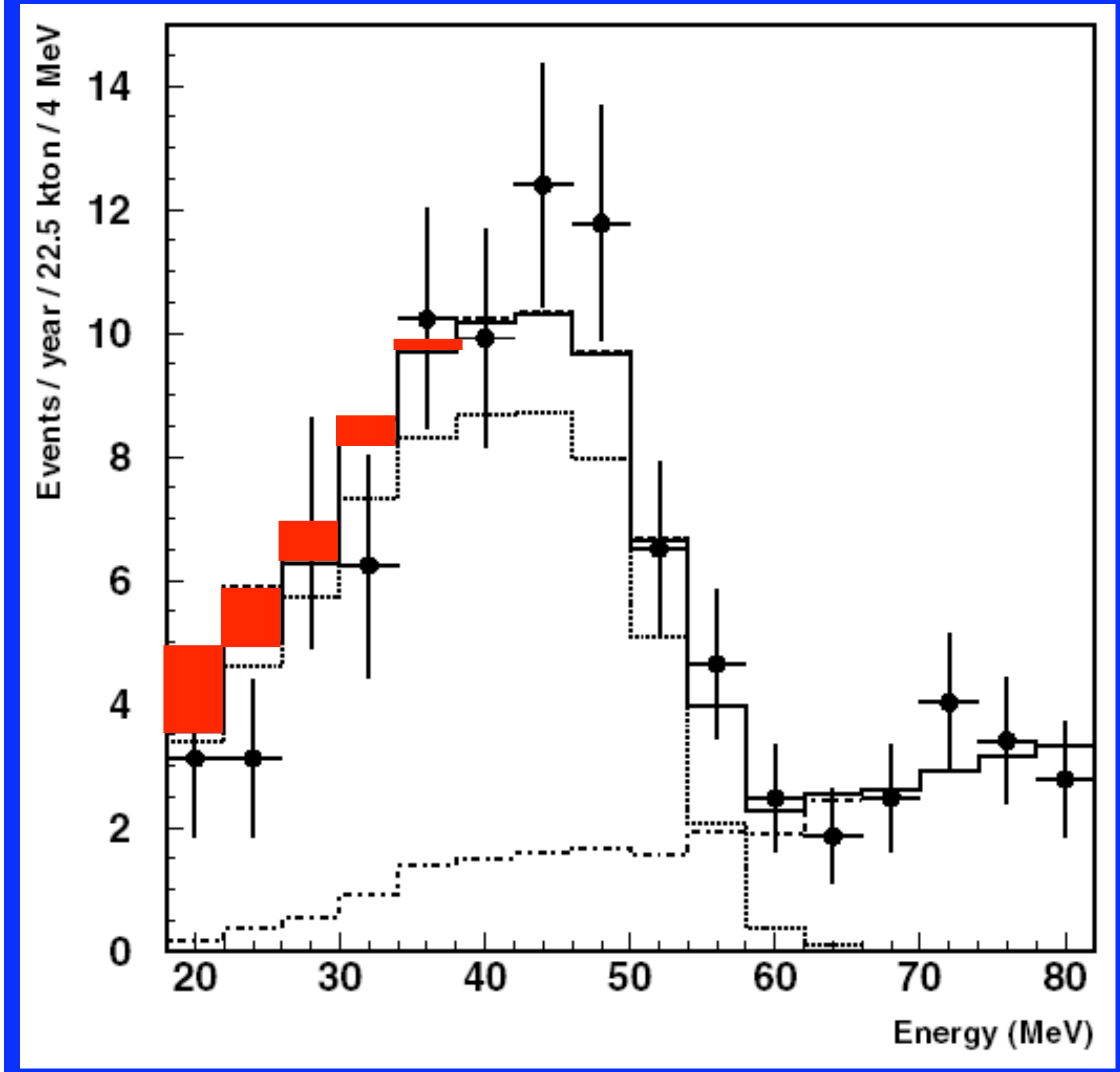


Fig. 3. Number flux of $\bar{\nu}_e$'s for the three supernova rate models, assuming "no oscillation" case.

Ando, Sato, and Totani, Astropart. Phys. 18, 307 (2003)

SK Data Limit



- 4.1 years of SK data
- Background limited
- Some improvement is possible

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

DSNB Flux Limit

- Predictions roughly agree on spectrum shape

- Main question is normalization of

$$\bar{\nu}_e / cm^2 / s, \quad E_\nu > 19.3 \text{ MeV}$$

2.2 Kaplinghat, Steigman, Walker, PRD 62, 043001 (2000)

< 1.2 Malek et al. (SK), PRL 90, 061101 (2003)

0.4 Fukugita and Kawasaki, MNRAS 340, L7 (2003)

0.4 Ando, Sato, and Totani, Astropart. Phys. 18, 307 (2003)

1.0 Strigari, Kaplinghat, Steigman, Walker, JCAP 0403, 007 (2004)

SK + Gadolinium: DSNB Detection

Inverse Beta Decay

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

- Cross section is "large" and "spectral"

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

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

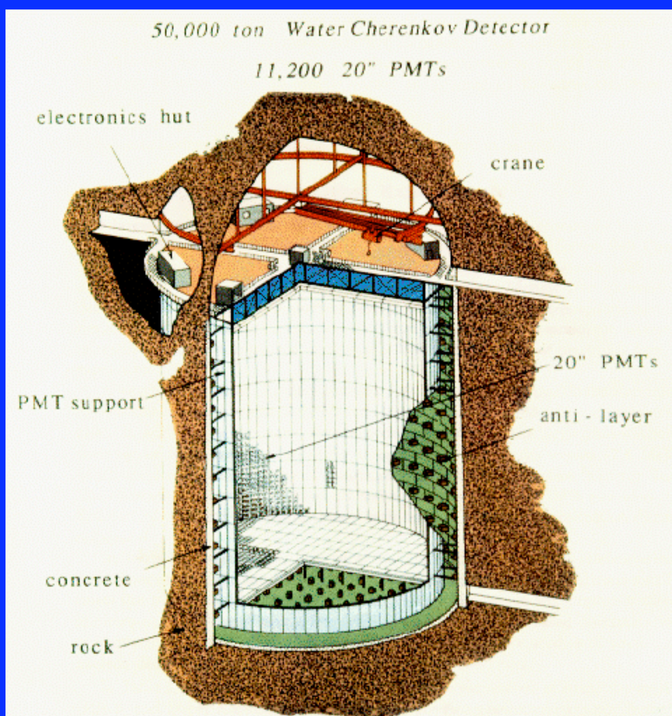
Corrections in Vogel and Beacom, PRD 60, 053003 (1999)

- 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% $GdCl_3$:

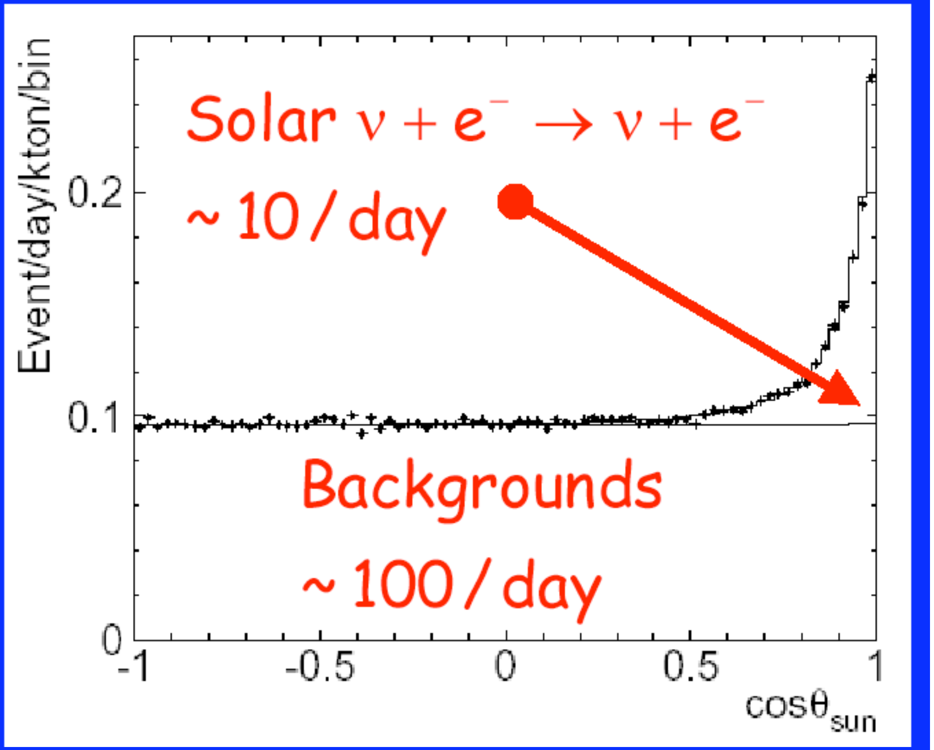
Capture fraction = 90%

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

Neutron Backgrounds in SK

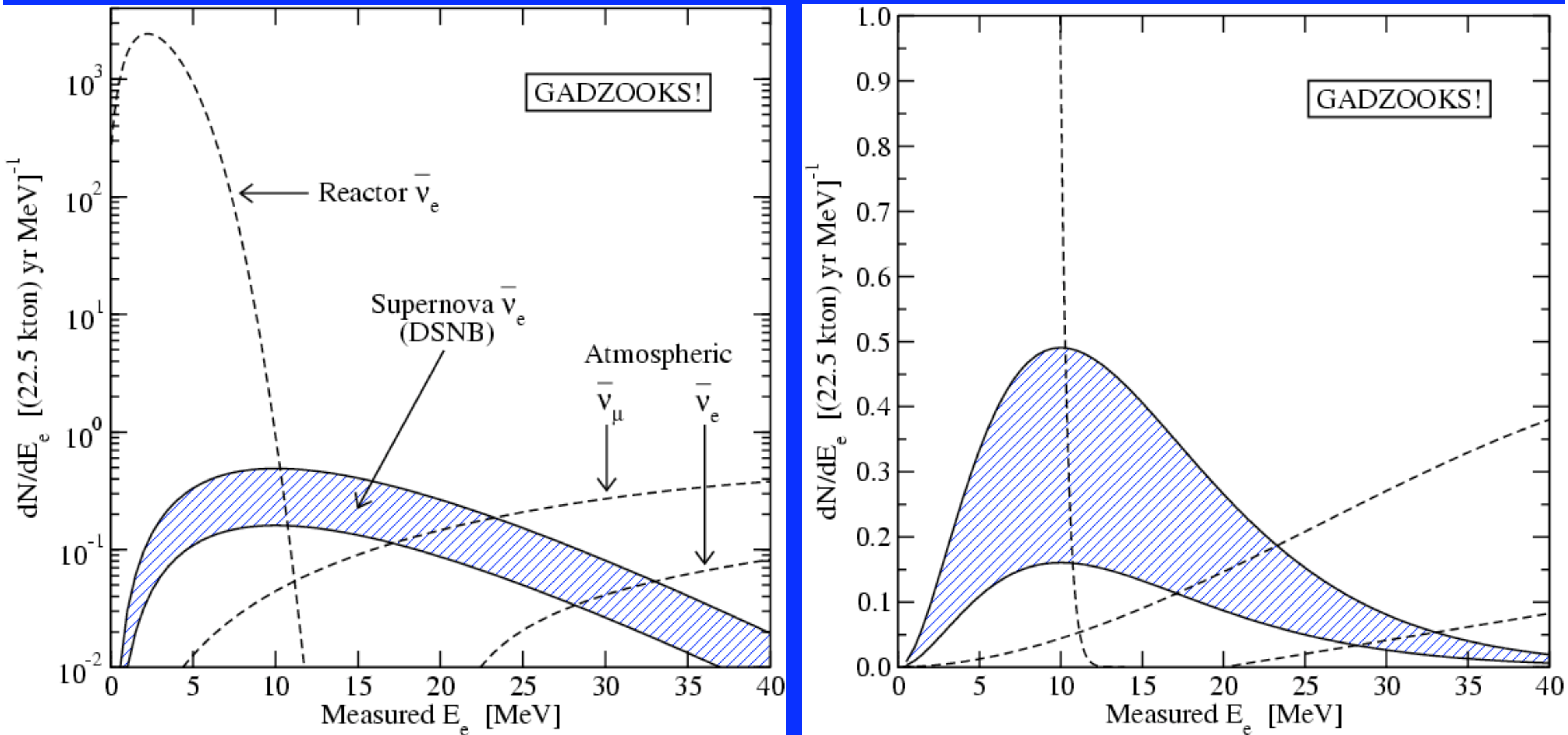
Don't want captures on Gd to dilute the solar signal

How many neutrons are in SK anyway?



- Spallation ~ 10^5/day but can be easily cut
- Reactor ~ 20/day (more likely a signal!)
- ^{152}Gd decay 10^{10} alpha/day, P(alpha,n) on ^{17}O is 10^{-10}
- U/Th contamination in $GdCl_3$ must be controlled

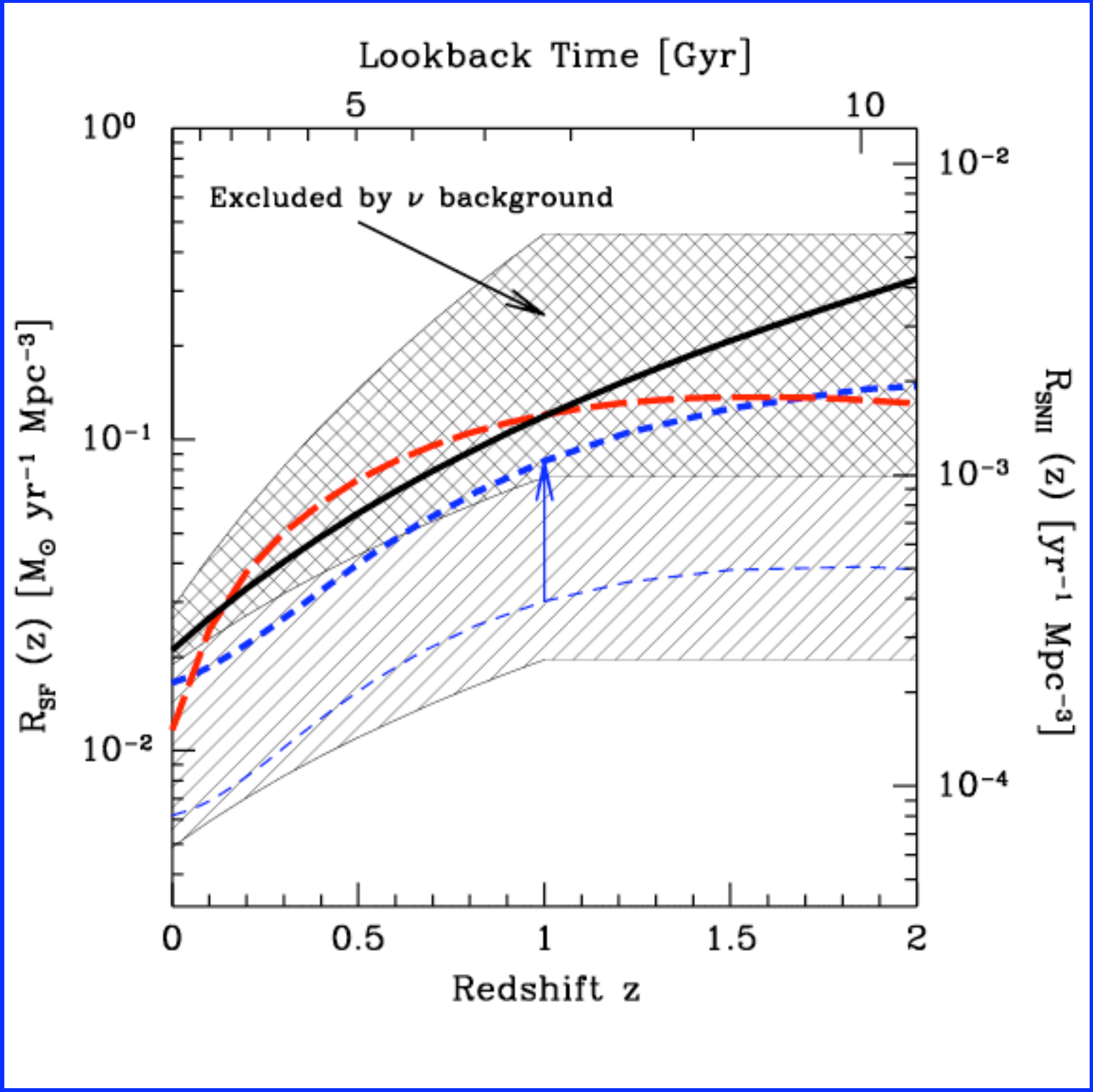
Spectrum With GADZOOKS!



Beacom and Vagins, PRL (2004) [hep-ph/0309300]

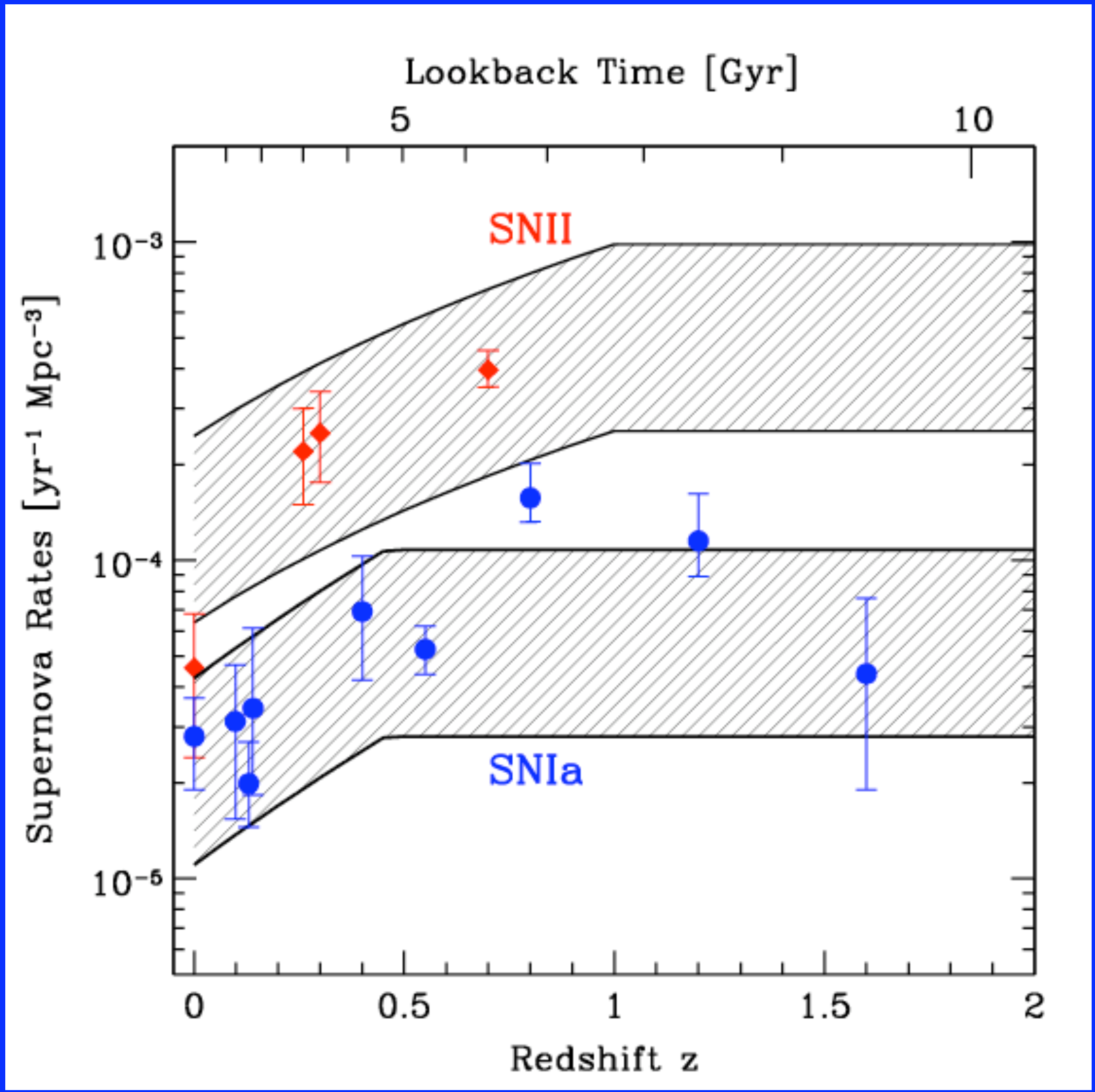
DSNB, Take 2: Astrophysics

New Constraint on SFR



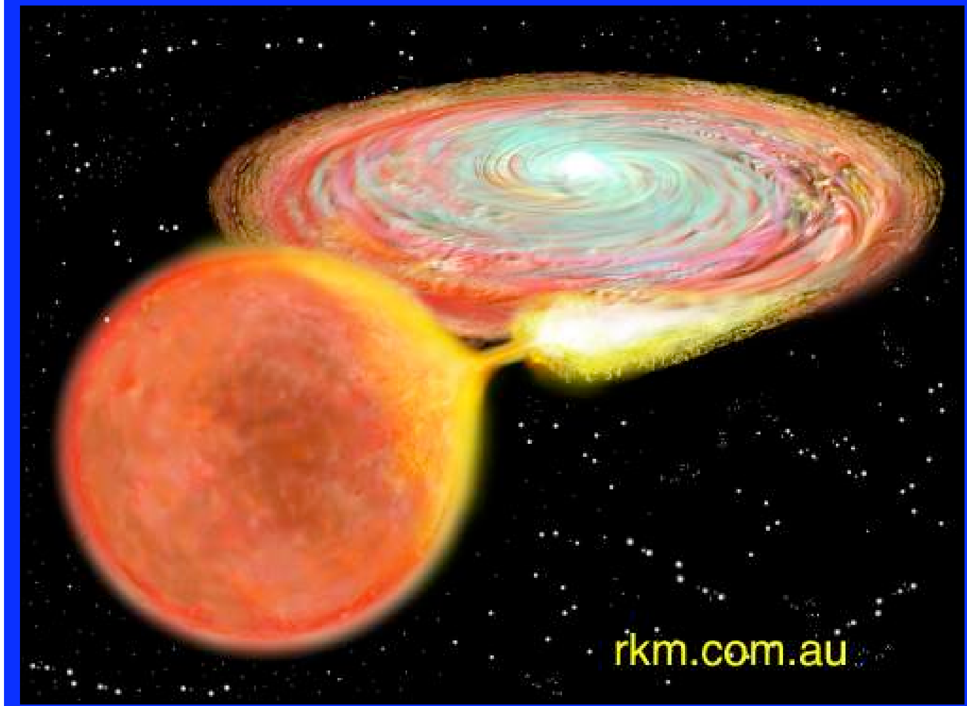
Strigari, Beacom, Walker, Zhang, JCAP 0504, 017 (2005)

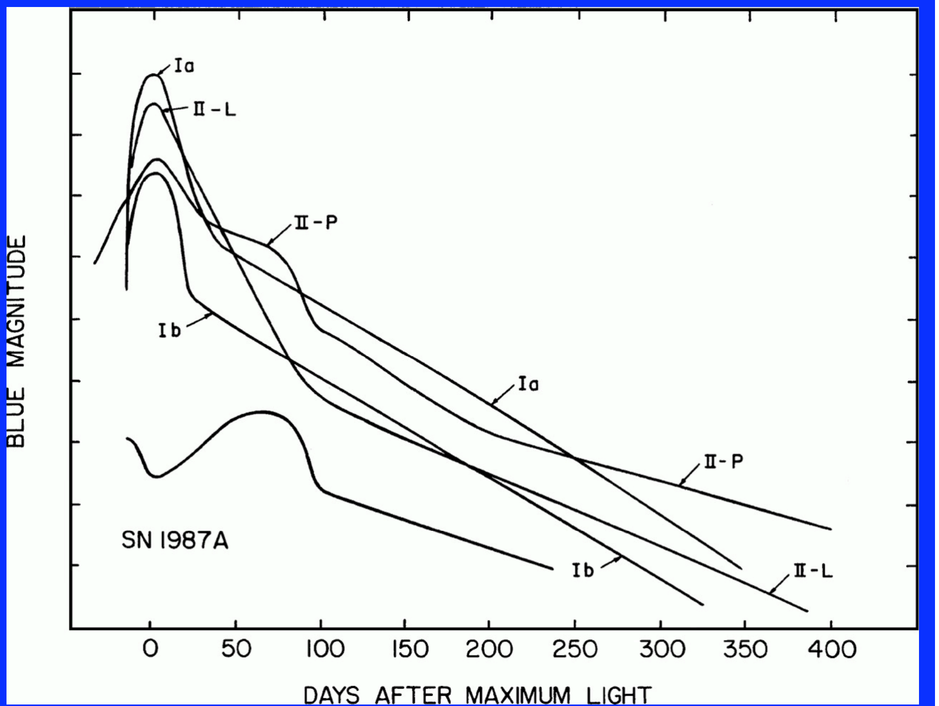
Corresponding Supernova Rates



Strigari, Beacom, Walker, Zhang, JCAP 0504, 017 (2005)

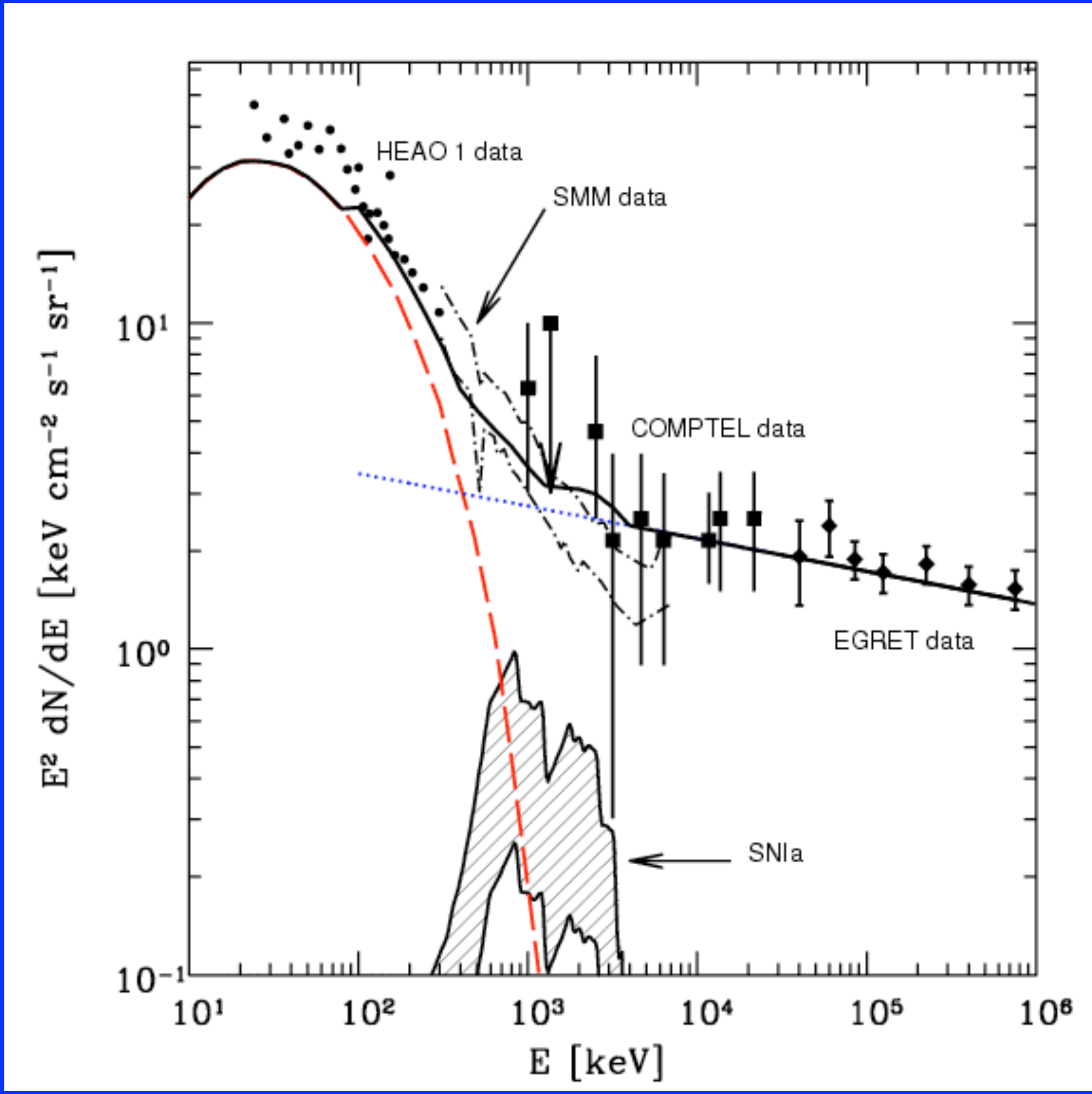
Thermonuclear Supernovae





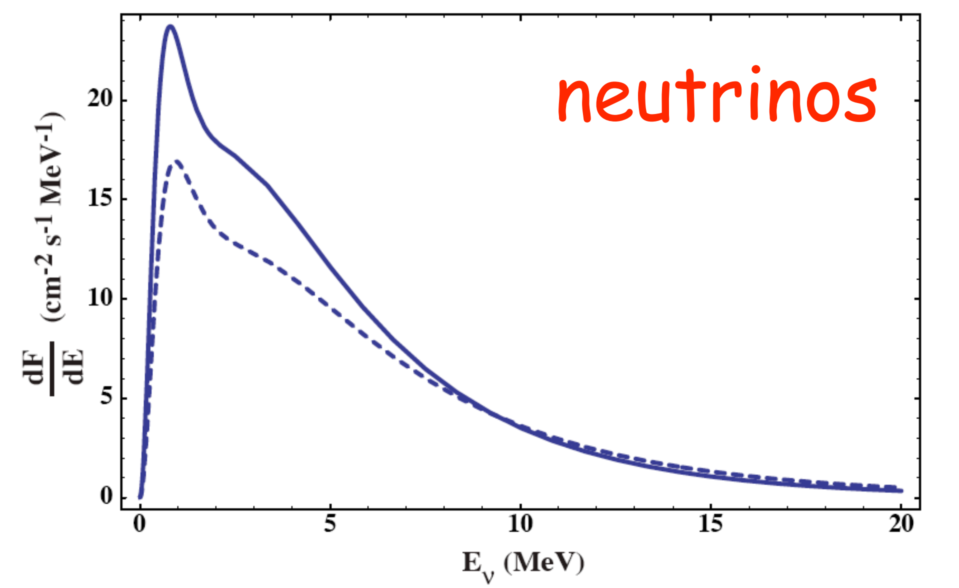
Explosion energy from production of 0.6 M_{sun} of ^{56}Ni

Supernova Gamma Ray Background



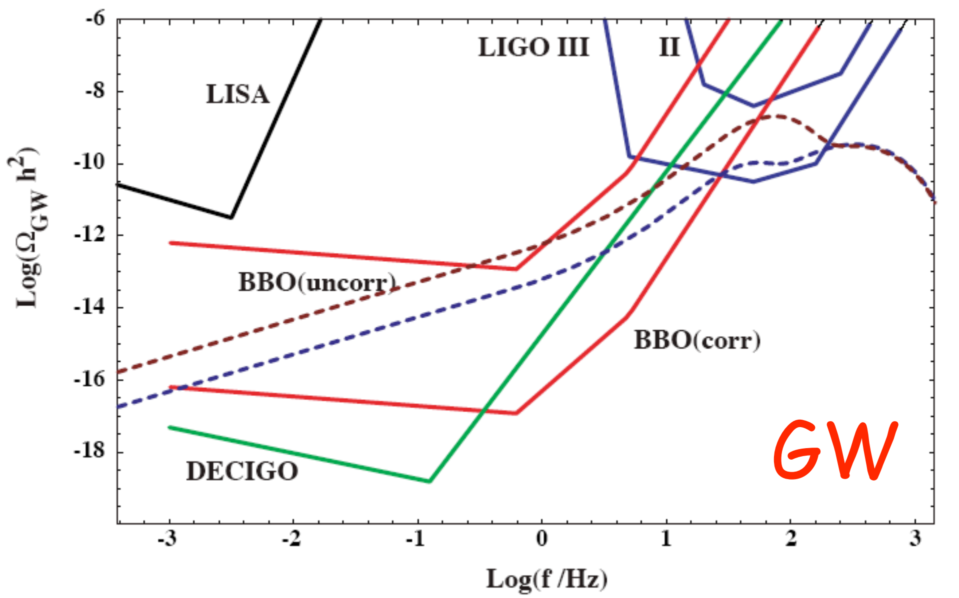
Strigari, Beacom, Walker, Zhang, JCAP 0504, 017 (2005)

SN Gravity Wave Background



(SNII on right, PopIII on left)

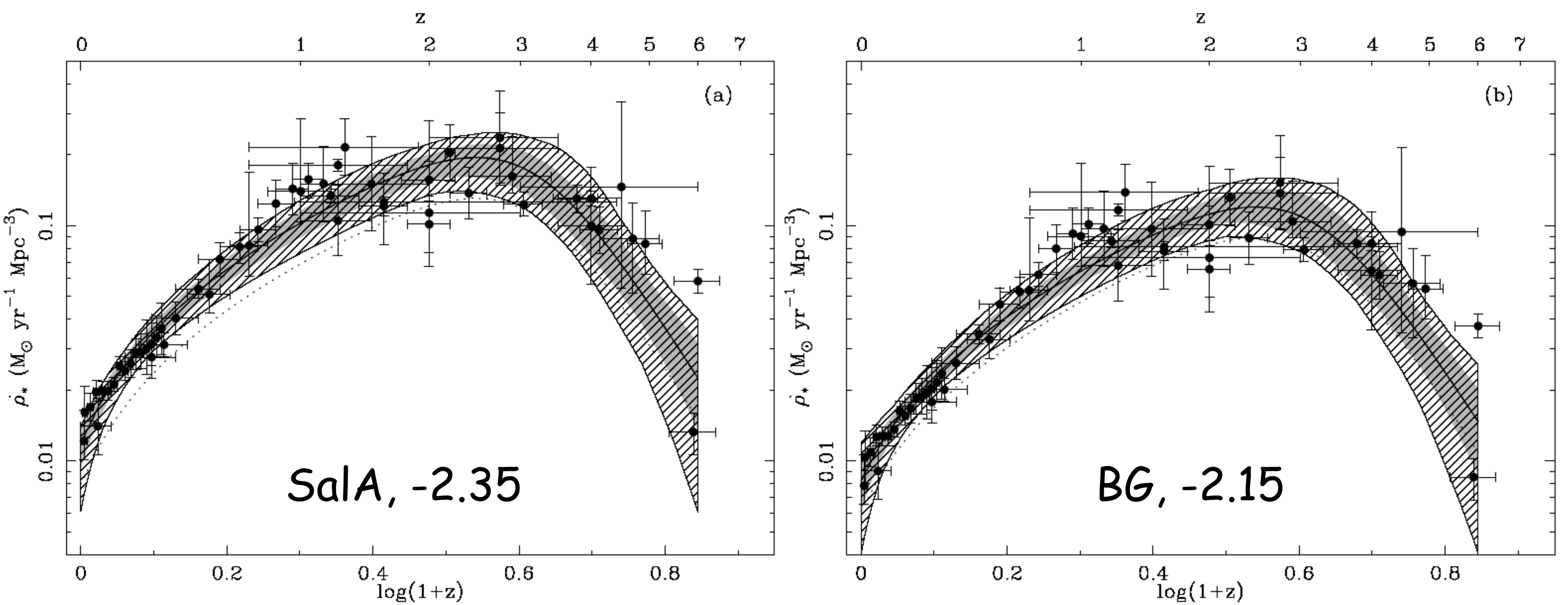
Daigne, Olive, Sandick, Vangioni,
PRD 72, 103007 (2005)



(SNII on left, PopIII on right)

Sandick, Daigne, Olive, Vangioni,
PRD 73, 104024 (2006)

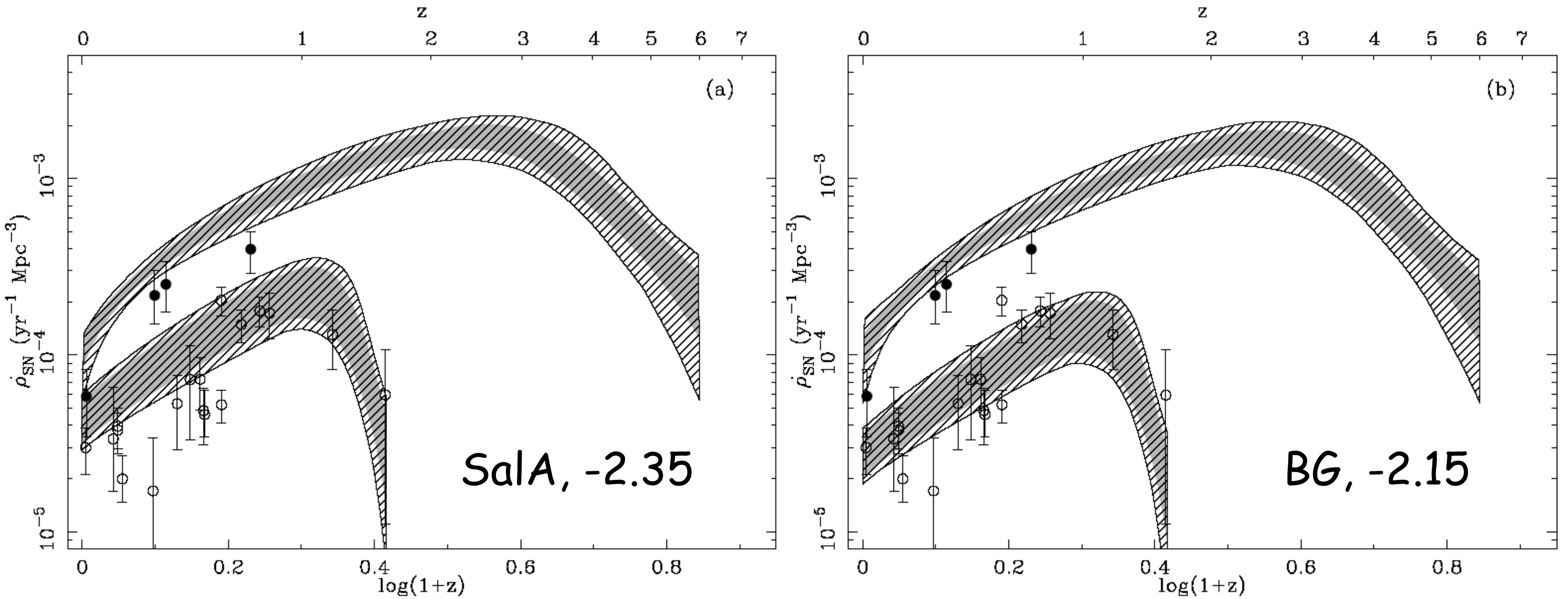
Towards Higher Precision



Cosmic SFR normalization depends on dust corrections, stellar initial mass function, and SN neutrino emission -- with reasonable choices, they saturate the SK limit!

Hopkins, Beacom, astro-ph/0601463

Corresponding SN Rates

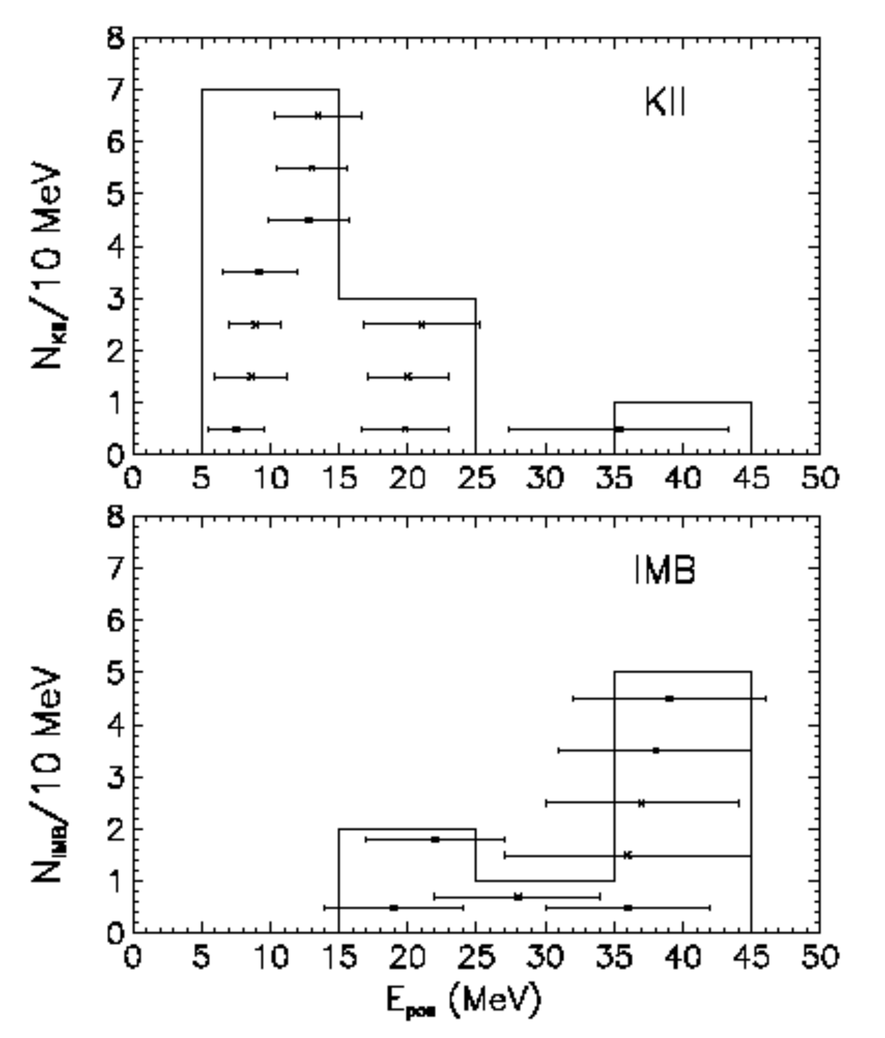


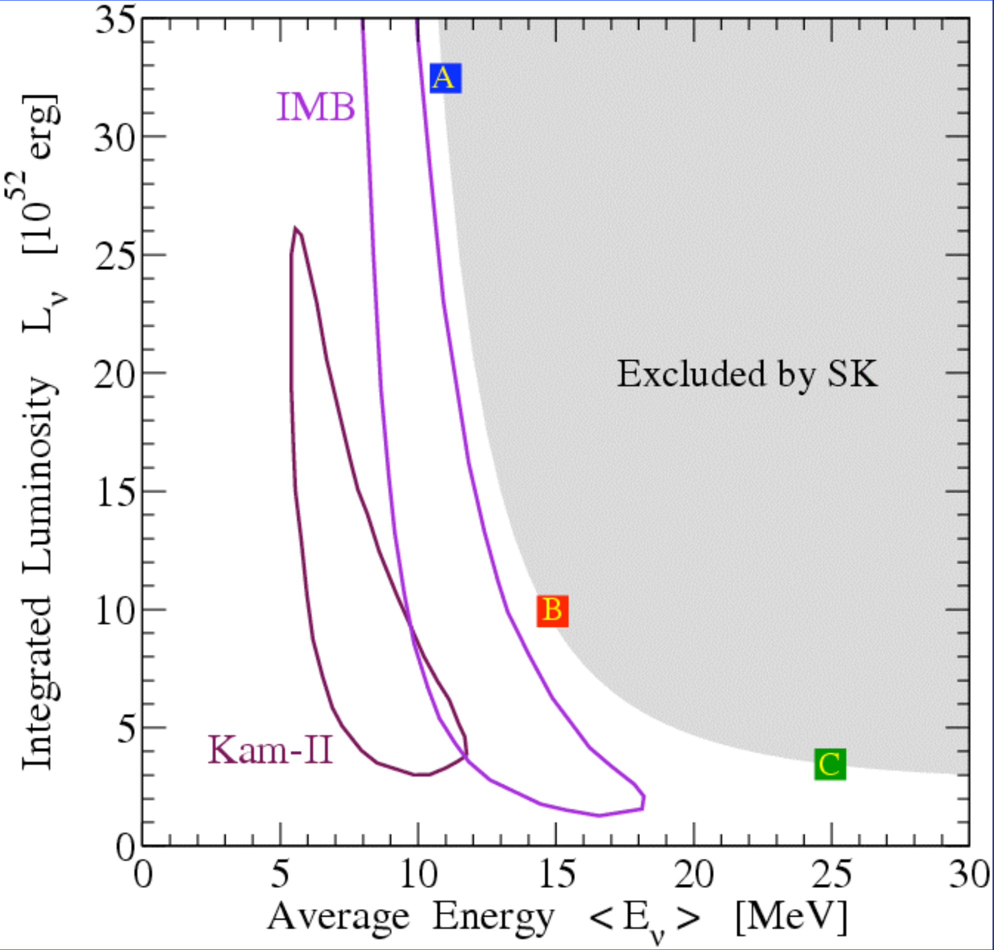
SNII rate data are a *lower* limit on the SFR

DSNB flux is an upper *limit* on the SFR

Hopkins, Beacom, astro-ph/0601463

Cold Case File: 87A Spectrum

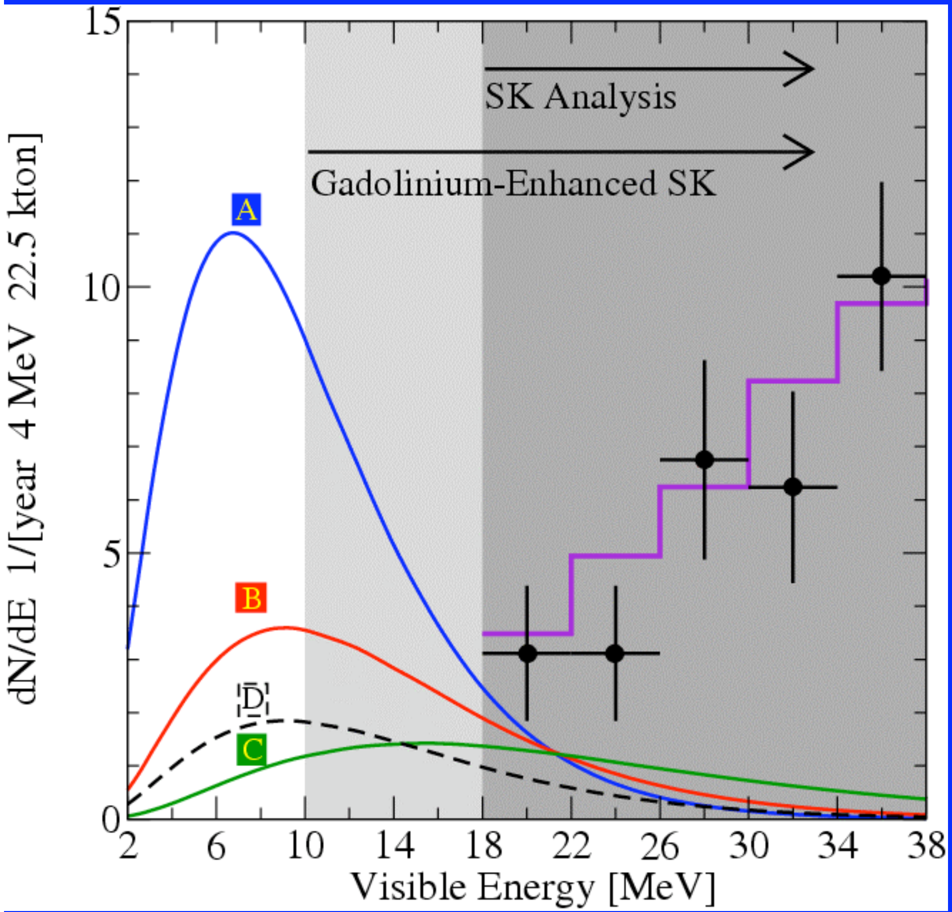


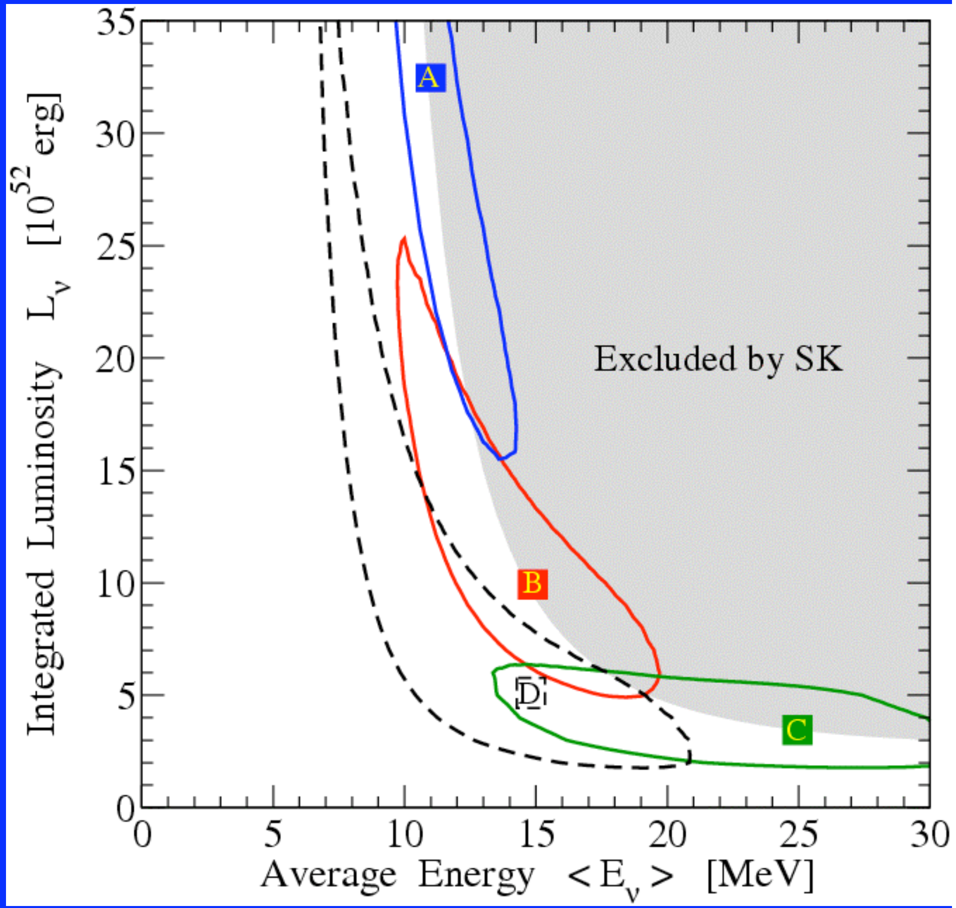


Yuksel, Ando, Beacom, astro-ph/0509297

Mirizzi, Raffelt, PRD 72, 063001 (2005)

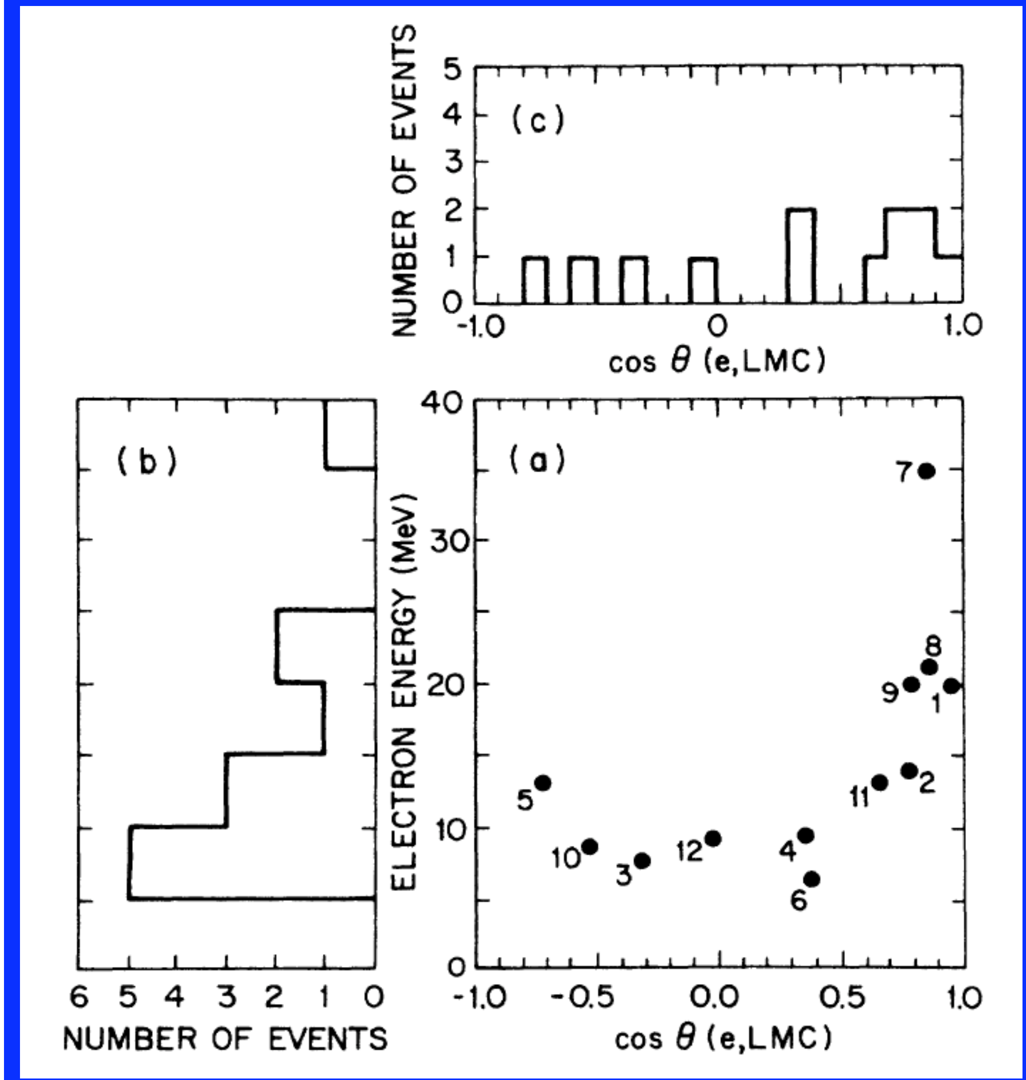
Supernova Emission Parameters





Yuksel, Ando, Beacom, astro-ph/0509297

Cold Case File: 87A Electron Nu



Hirata et al., PRD 38, 448 (1988)

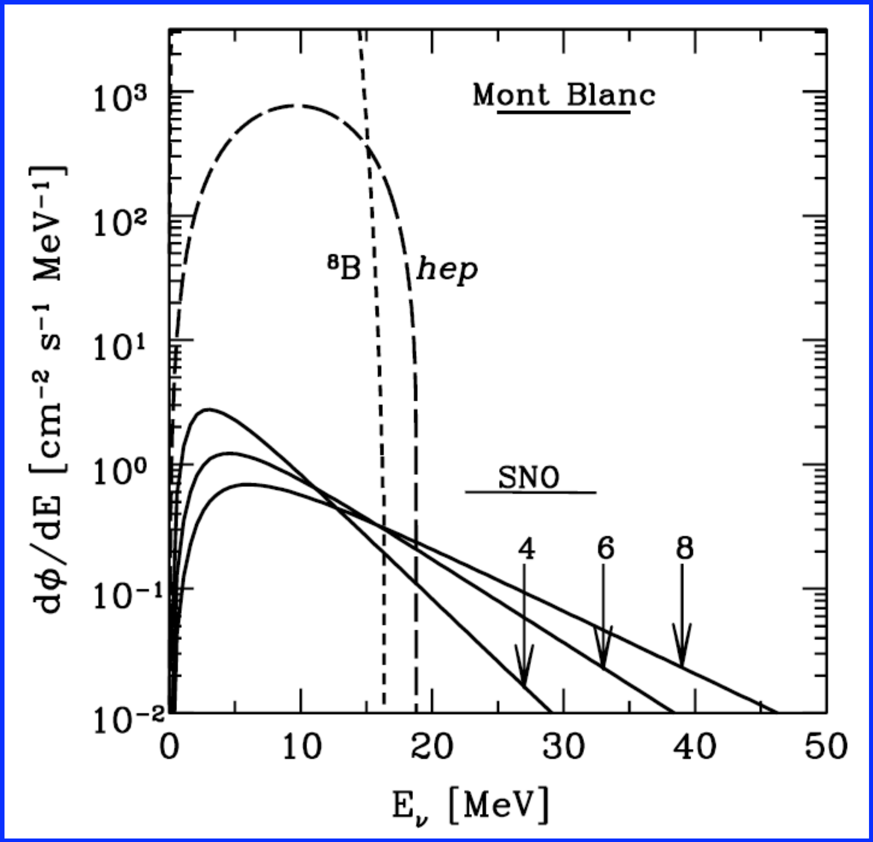
Dominant yield should be the nearly isotropic inverse beta decays

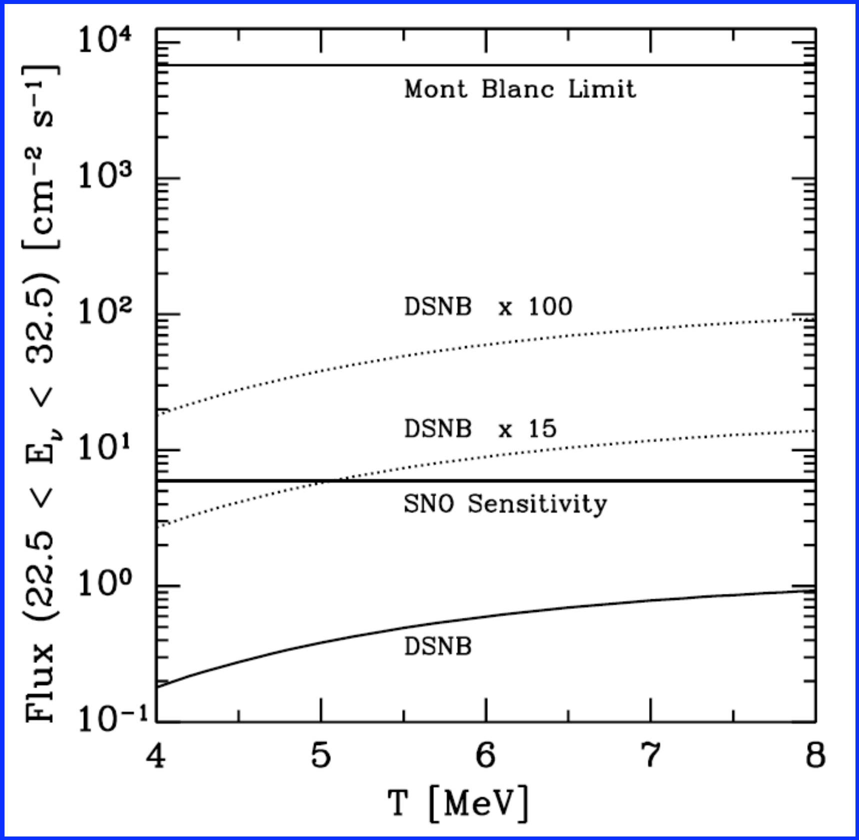
But both Kam-II and IMB had too-forward angular distributions

And the first event in Kam-II was forward

Were there some neutrino-electron scattering events?

Electron *Neutrino* DSNB





Beacom, Strigari, hep-ph/0508202 (PRC)

If there was a large electron neutrino flux in 87A
--> SNO can detect the electron neutrino DSNB

This flux can be enhanced (Lunardini, **hep-ph/0601054**)

Conclusions

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

Further Reading

• Georg Raffelt's online talks:
http://wwwth.mppmu.mpg.de/members/raffelt/

• "Identifying the Neutrino Mass Spectrum from the Neutrino Burst from a Supernova," Dighe & Smirnov, PRD 62, 033007 (2000)

• "Neutrinos as Astrophysical Probes," Cavanna, Costantini, Palamara, Vissani, astro-ph/0311256

• Mark Vagins' talk at Neutrino 2004 (video)
http://neutrino2004.in2p3.fr/

• "APS Neutrino Study: Report of the Neutrino Astrophysics and Cosmology Working Group,'' Barwick et al., astro-ph/0412544