Fossil Records of Star Formation: Supernova Neutrinos and Gamma Rays

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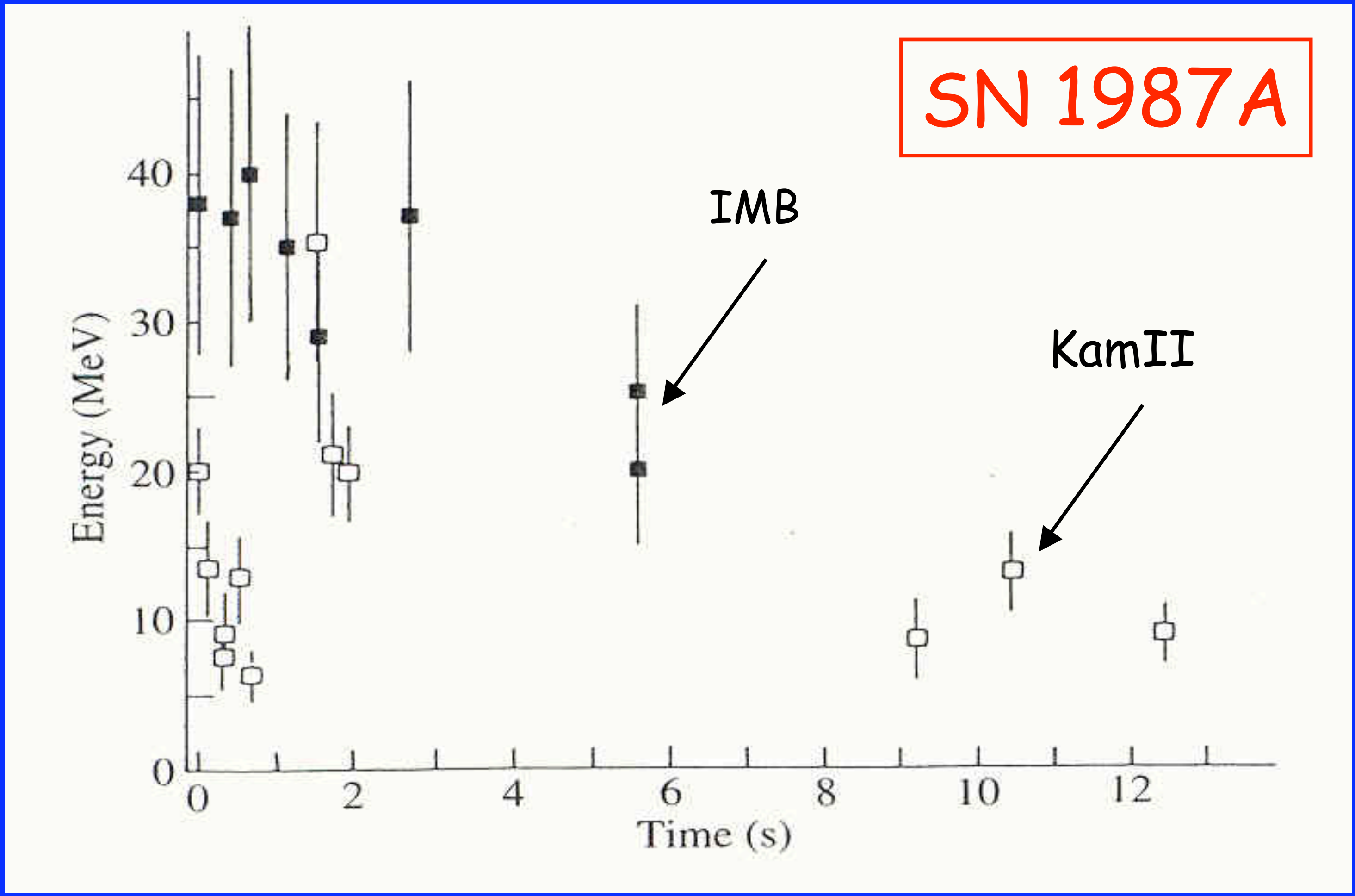
Basic Pitch

- Supernovae are of broad and fundamental interest
- Neutrinos and gamma rays are direct messengers
- Recent results show that detection soon is realistic
- Discovery science due to unprecedented reach

Strongly motivates a nuclear physics case to build a Mton-scale detector in an Underground Laboratory

A guaranteed signal while waiting for proton decay

Whisper from a Supernova



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

Fundamental Questions

nuclear physics: supernova explosion mechanism
production of the elements
neutron star equation of state

particle physics: new energy loss channels in SNII
neutrino properties
dark matter decay, annihilation

astrophysics: cycle of stellar birth, life, death
constraints on nonstellar sources

cosmology: supernova distance indicators
galaxy evolution

Microphysical Messengers

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

Type Ia SN:
$\sim$ 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:
$\sim$ 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 Status

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:

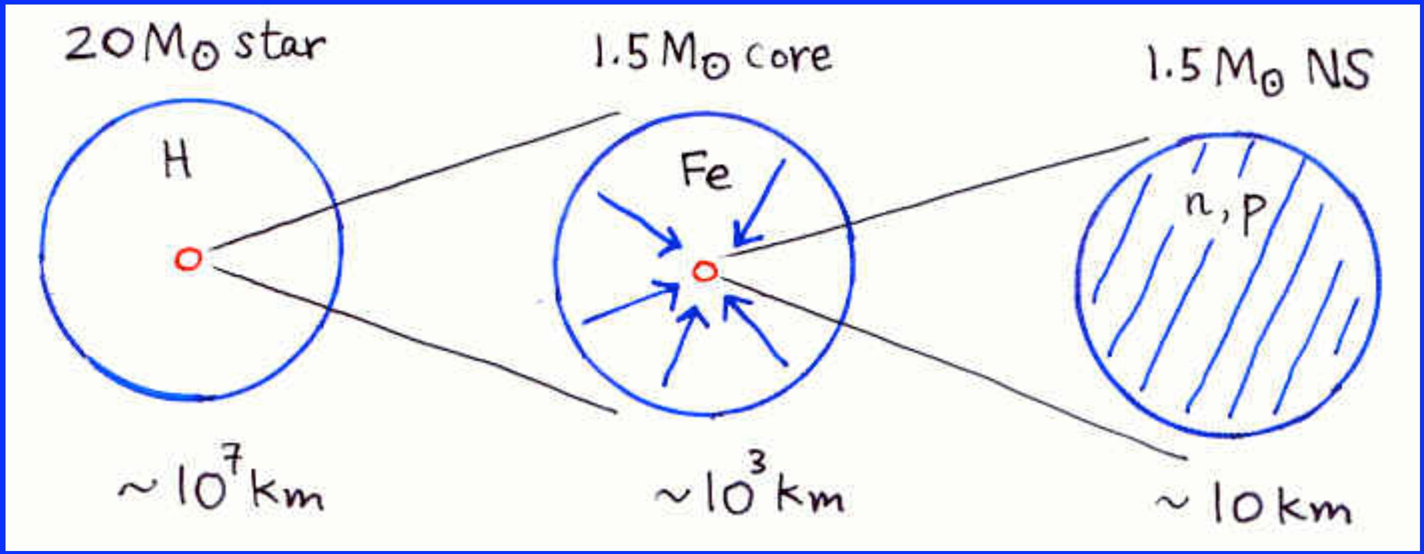
Seen once, from SN 1987A

But only ~ 20 events

Diffuse background from SNII not seen

Tight limit on MeV background from Super-K

Supernova Energetics

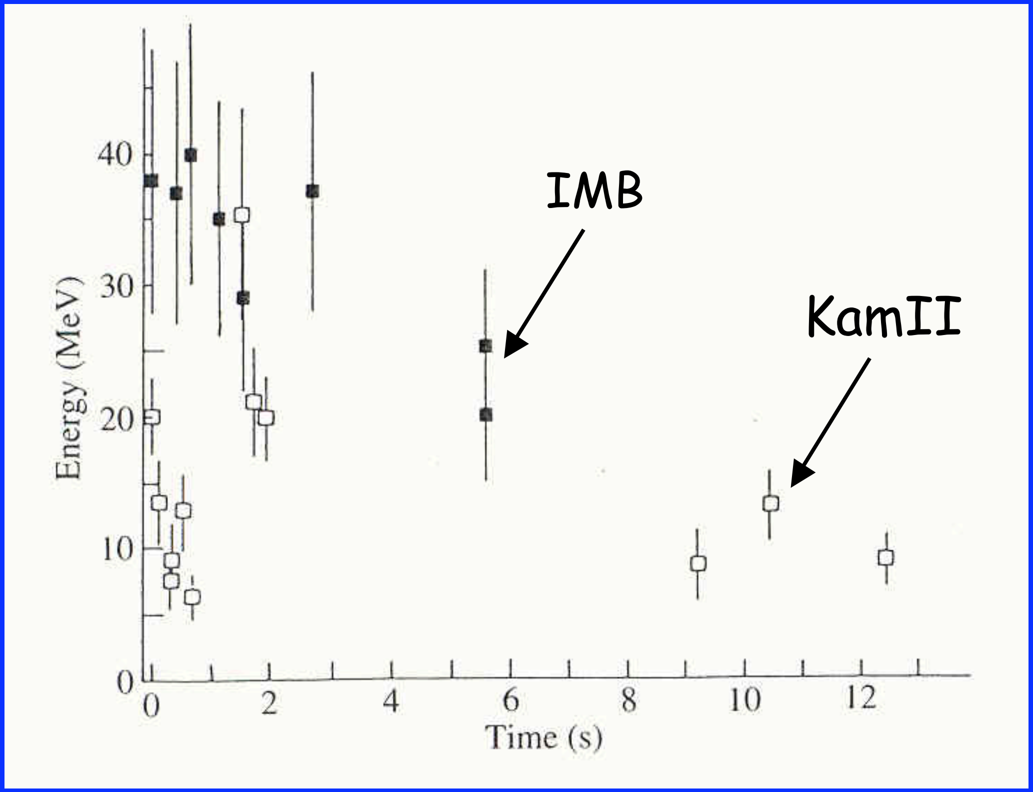


$$\Delta E_B \simeq \frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G M_{NS}^2}{R_{core}} \simeq 3 \times 10^{53} \text{ ergs} \simeq 2 \times 10^{59} \text{ MeV}$$

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

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

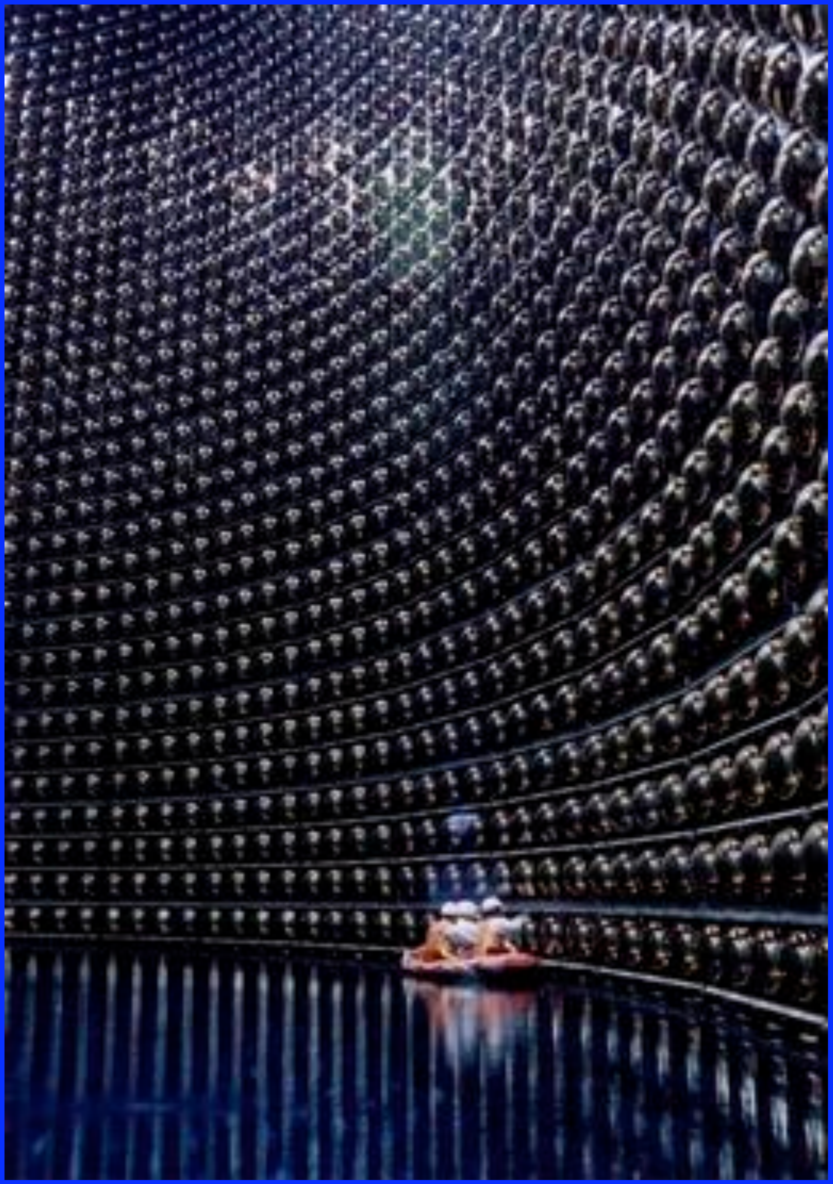
Supernova Neutrino Emission



Low average energy and long timescale indicate that the neutrinos diffuse out

All six flavors of neutrinos and antineutrinos are expected to take a comparable fraction of the total binding energy of 3×10^{53} erg

Super-Kamiokande



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

22.5 kton fiducial mass

Expect 10^4 events in SK from a Milky Way supernova at 10 kpc ... and 10^3 events in other detectors worldwide

But supernovae are rare!

DSNB: First Good Limit

Supernova Neutrino Background

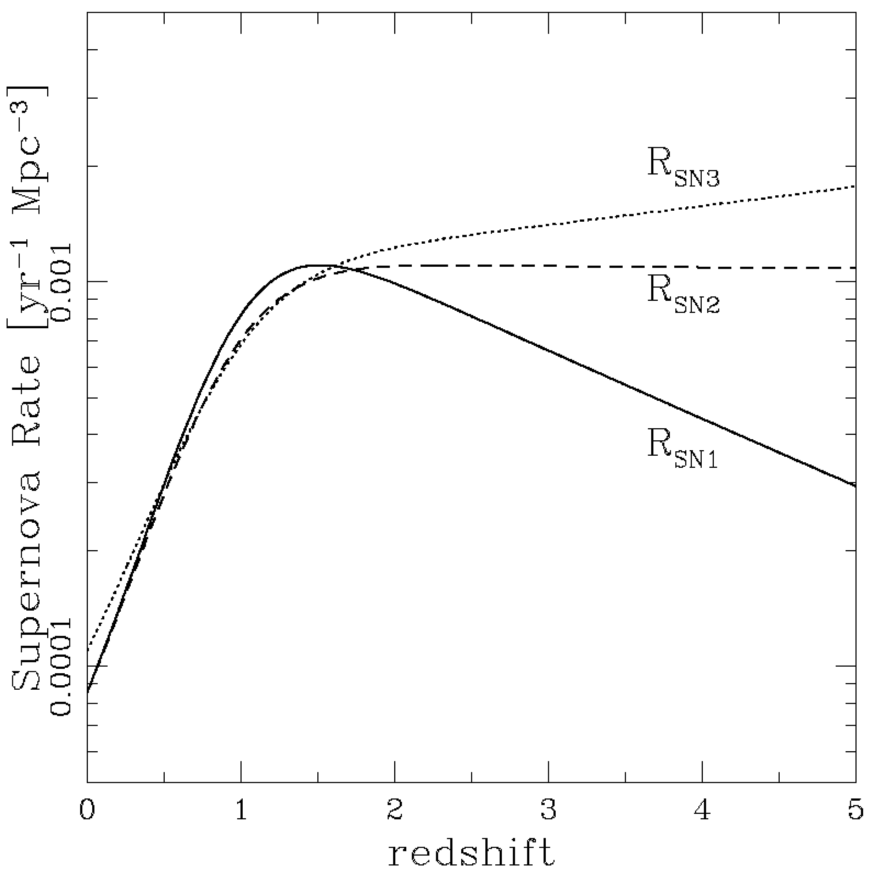


Fig. 2. Supernova rate evolution on the cosmological time scale. These lines are for a Λ-dominated cosmology ($\Omega_m = 0.3, \Omega_\lambda = 0.7$). The Hubble constant is taken to be 70 km s^{-1} Mpc^{-1}.

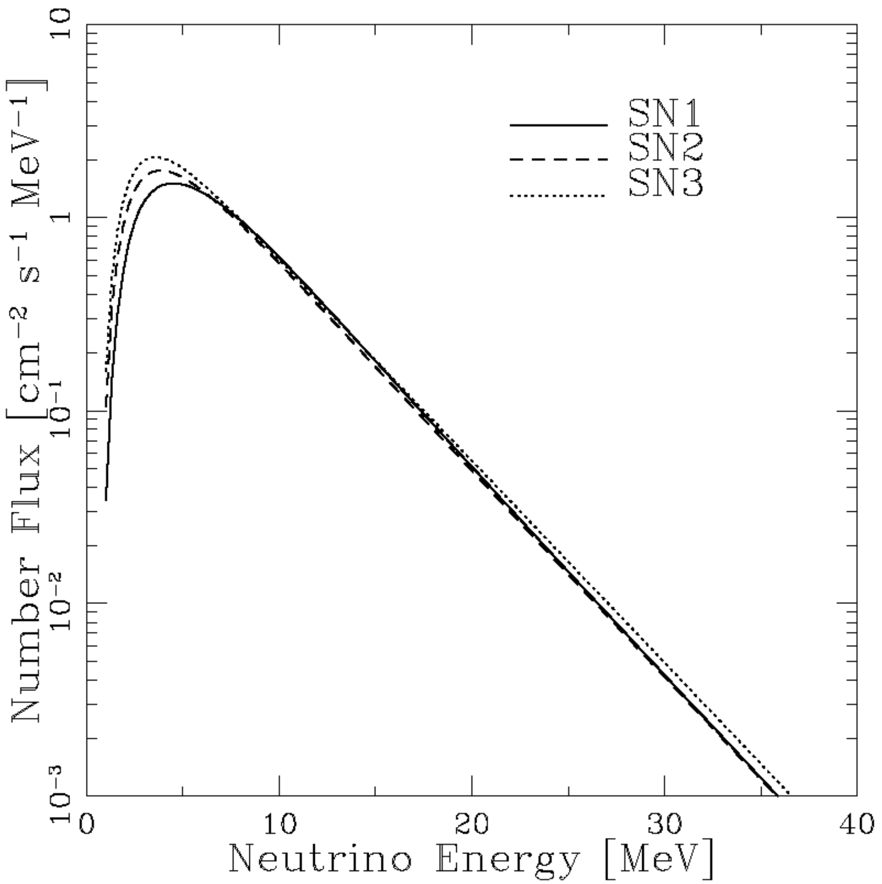
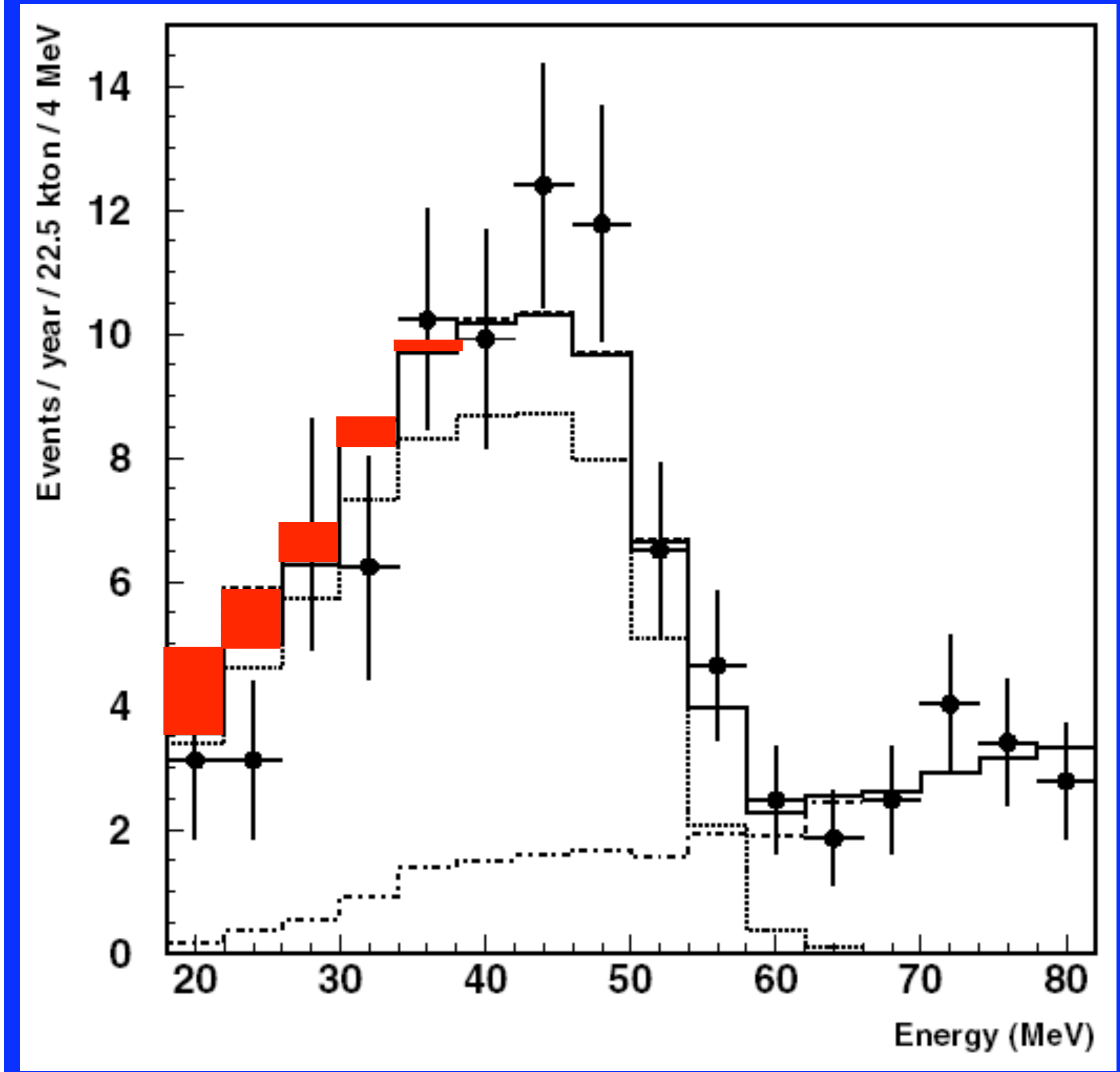


Fig. 3. Number flux of $\bar{\nu}_e$'s for the three supernova rate models, assuming "no oscillation" case.

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)

Encouraging, but there were two serious problems:
Search was background limited
Predictions were uncertain

Solving the Background Problem

Inverse Beta Decay

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

- Cross section is "large" and "spectral"

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

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

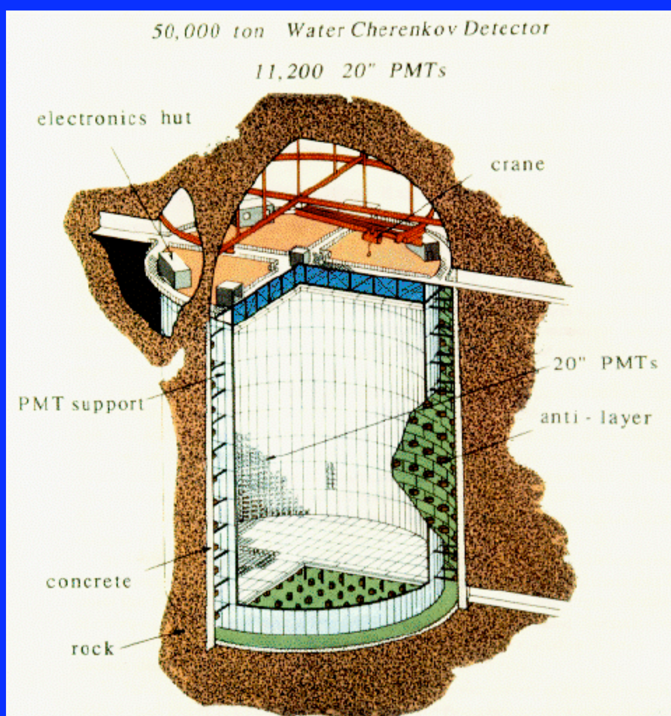
Corrections in Vogel and Beacom, PRD 60, 053003 (1999)

- We must detect the neutron, but how?

Add Gadolinium to SK?

GADZOOKS!

Gadolinium
Antineutrino
Detector
Zealously
Outperforming
Old
Kamiokande,
Super!



Beacom and Vagins, PRL 93, 171101 (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)

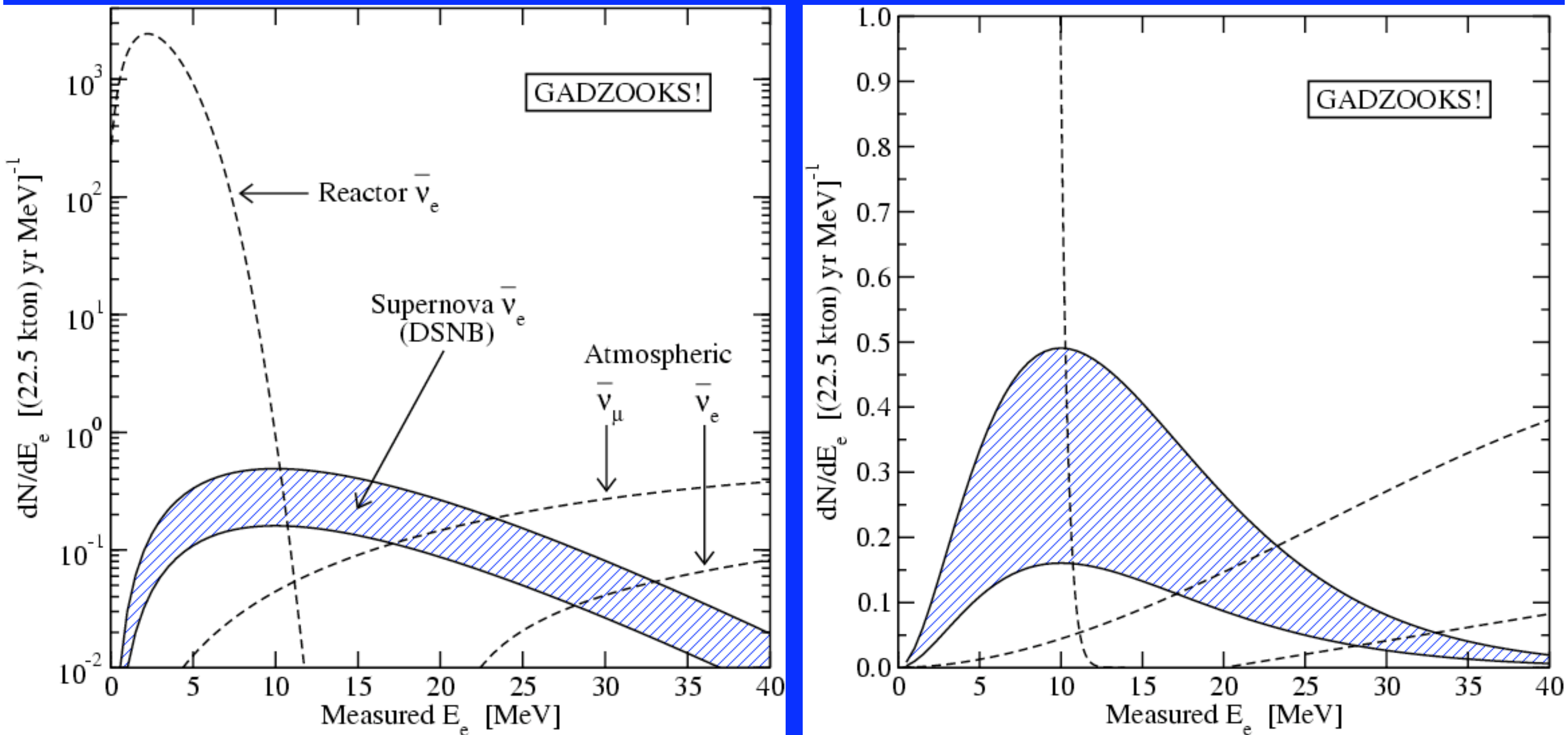
$$\frac{1}{\lambda_{total}} = \frac{1}{\lambda_H} + \frac{1}{\lambda_{Gd}} = n_H \sigma_H + n_{Gd} \sigma_{Gd}$$

At 0.2% $GdCl_3$:

Capture fraction = 90%

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

Spectrum With GADZOOKS!



Beacom and Vagins, PRL 93, 171101 (2004)

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

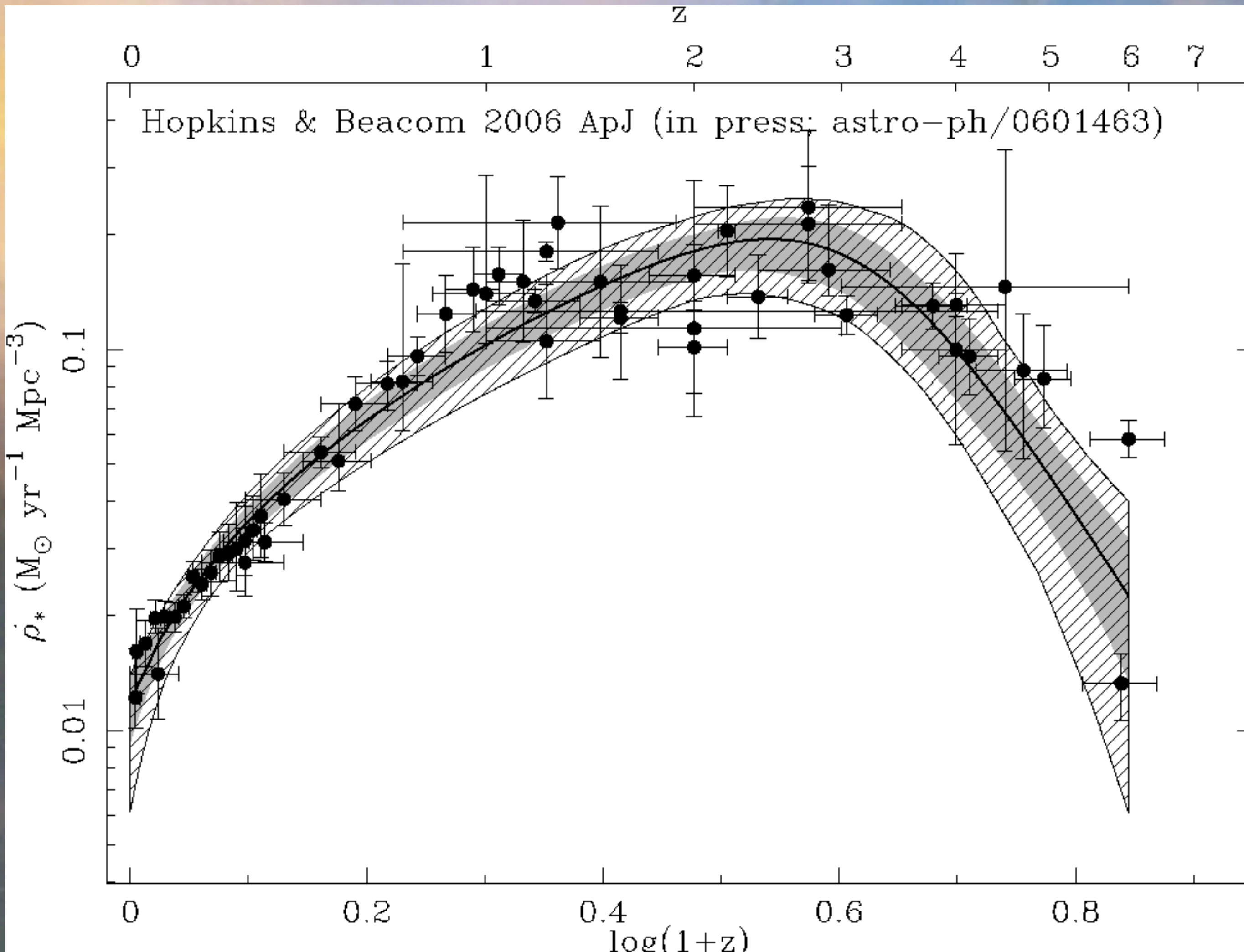
- Very high level of interest, based on the physics potential, for the DSNB, reactors, and more

- Super-Kamiokande internal technical design review to be completed in 2008

Solving the Prediction Problem

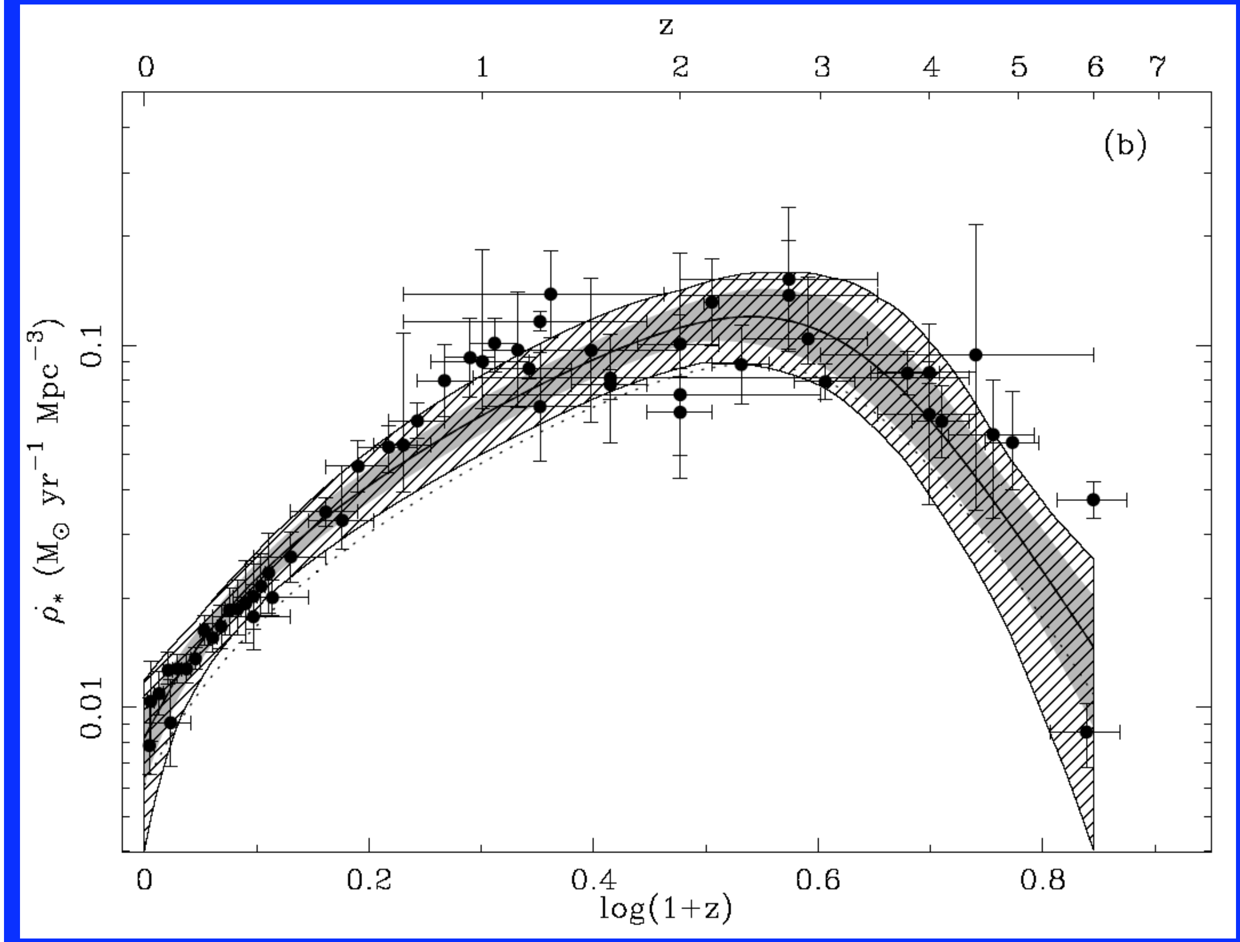
Comoving space density of SFR

SFR density



Redshift

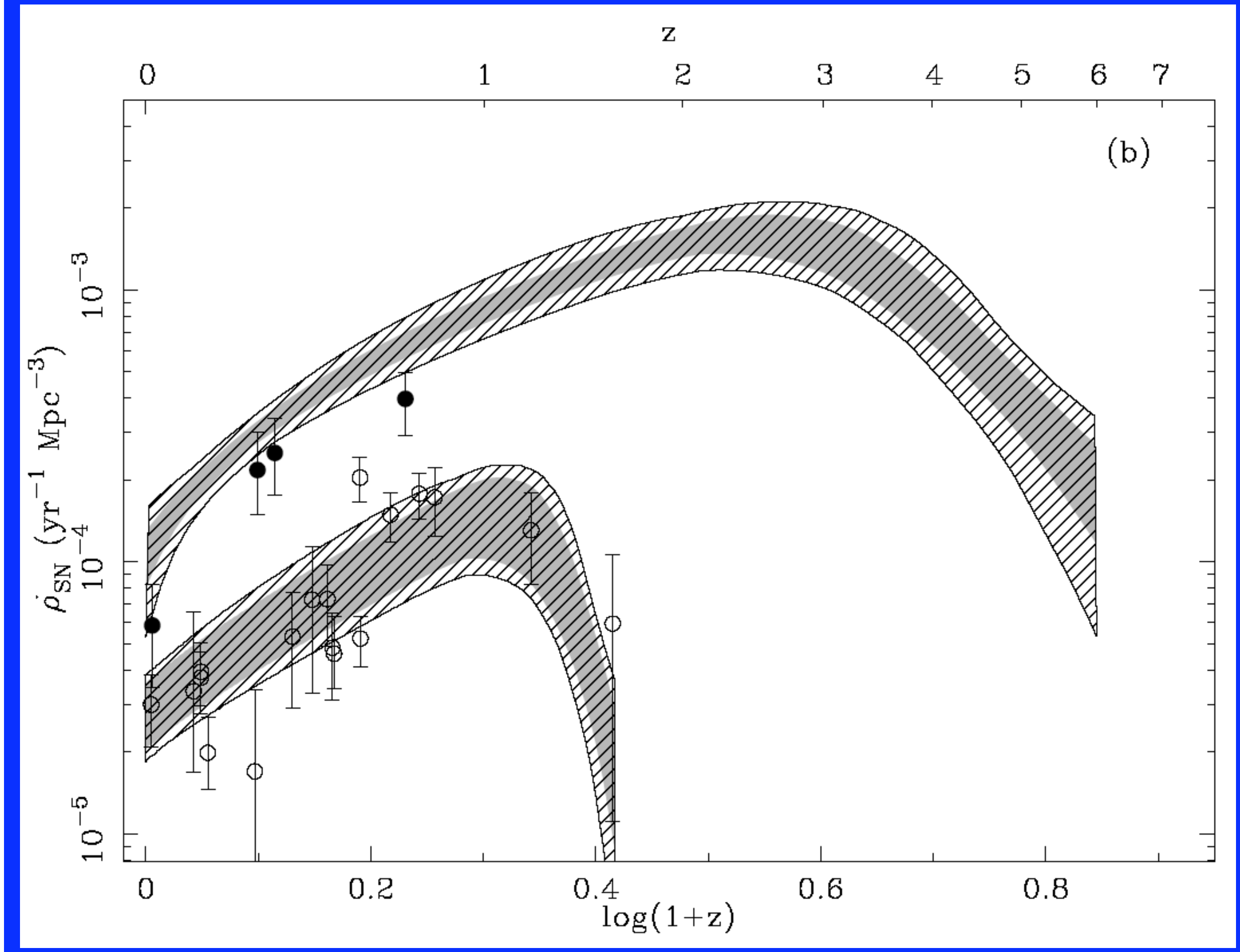
New Precision in the SFR



Hopkins, Beacom, ApJ [astro-ph/0601463]

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

Confirmation by SN Rates

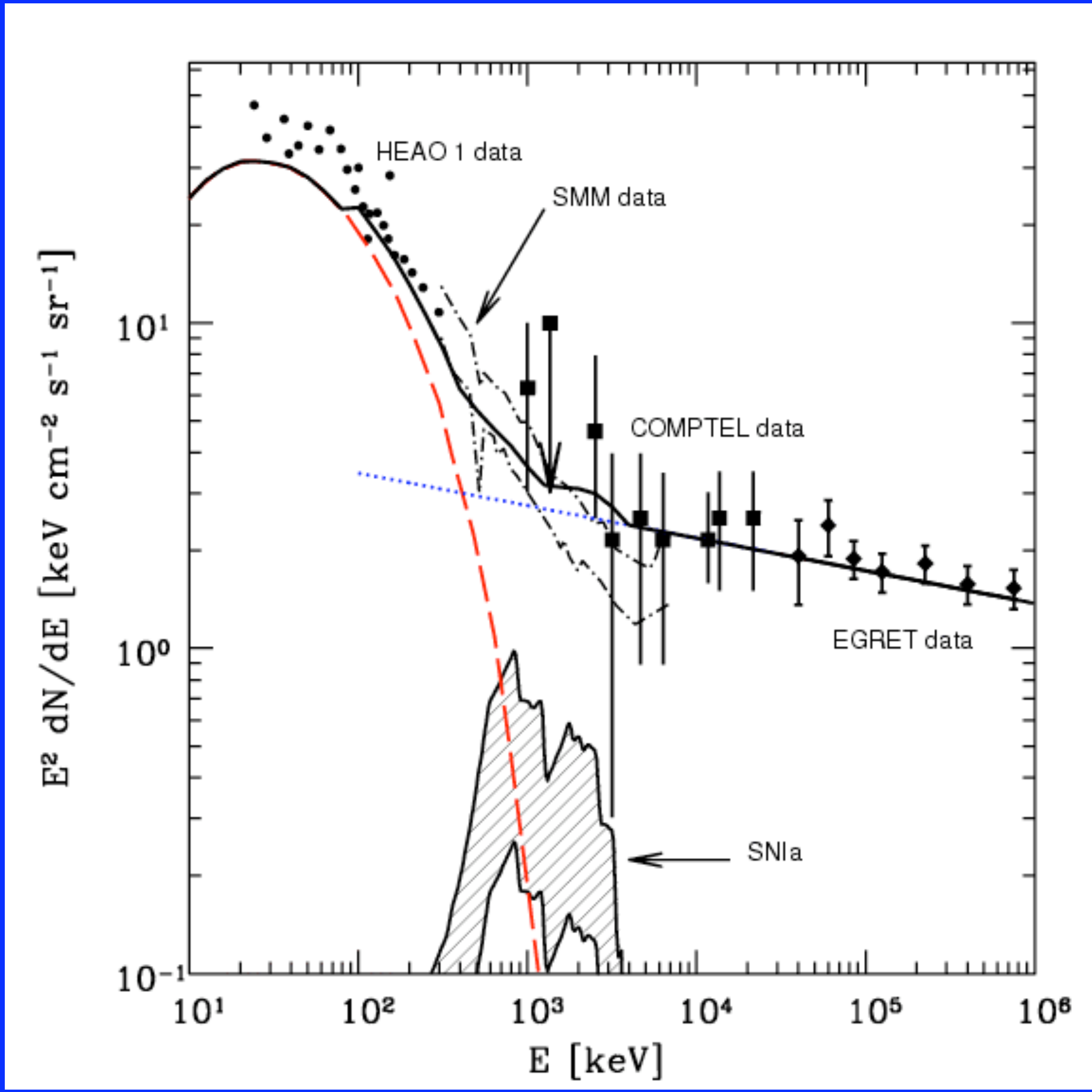


The z = 0 data point is likely an underestimate

Hopkins, Beacom, ApJ [astro-ph/0601463]

SFR history concordant with these and other data

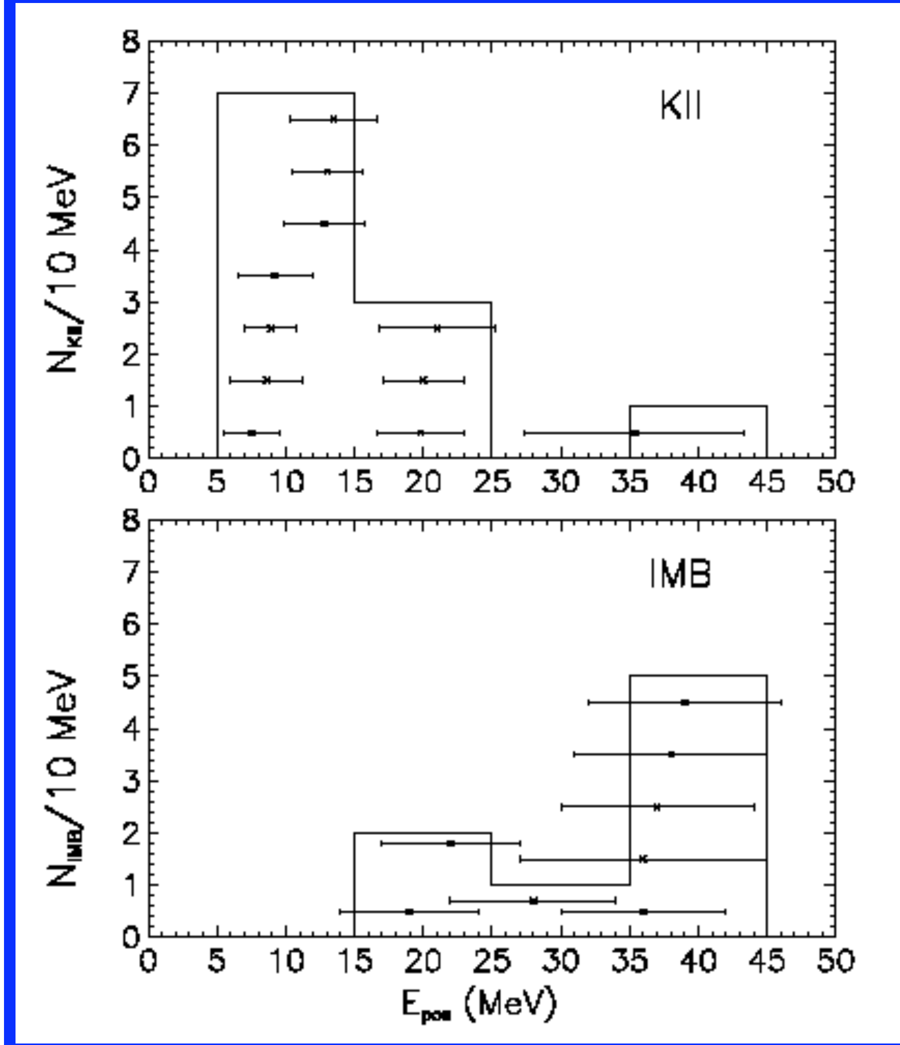
SNIa Gamma Ray Background

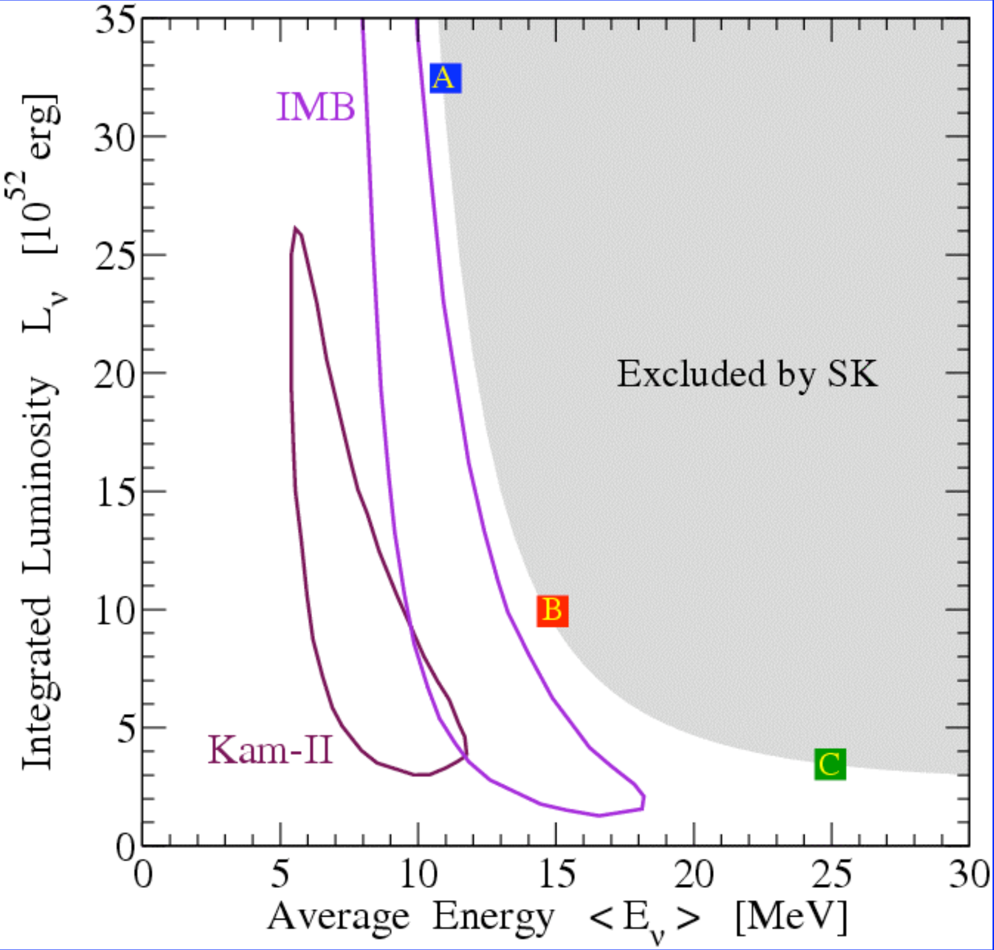


Strigari, Beacom, Walker, Zhang, JCAP 0504, 017 (2005)

Tests of Neutrino Emission

Cold Case File: 87A Spectrum

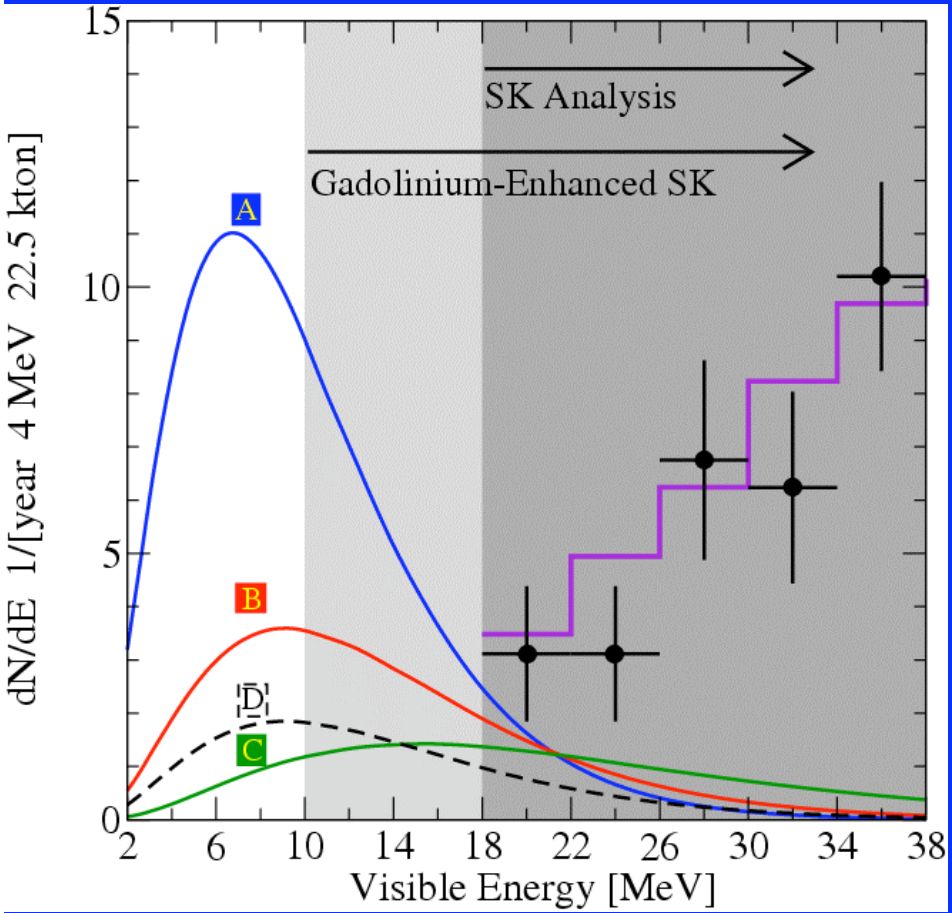


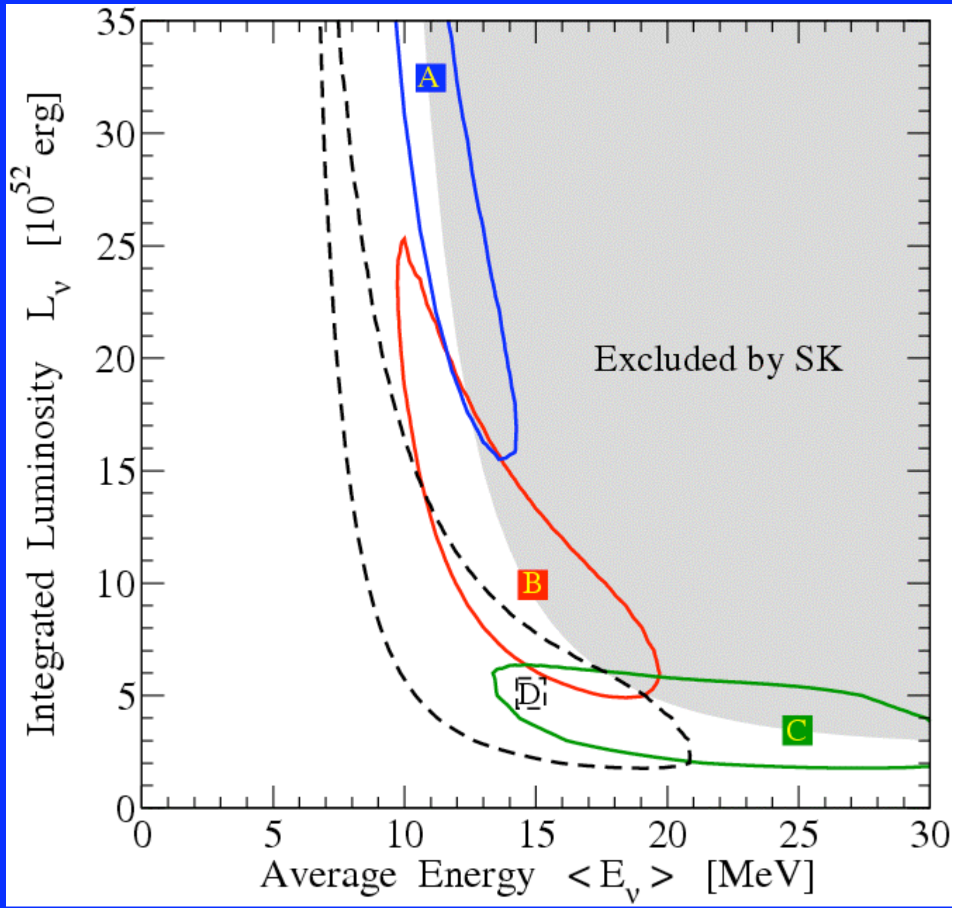


Yuksel, Ando, Beacom, PRC 74, 015803 (2006)

Mirizzi, Raffelt, PRD 72, 063001 (2005)

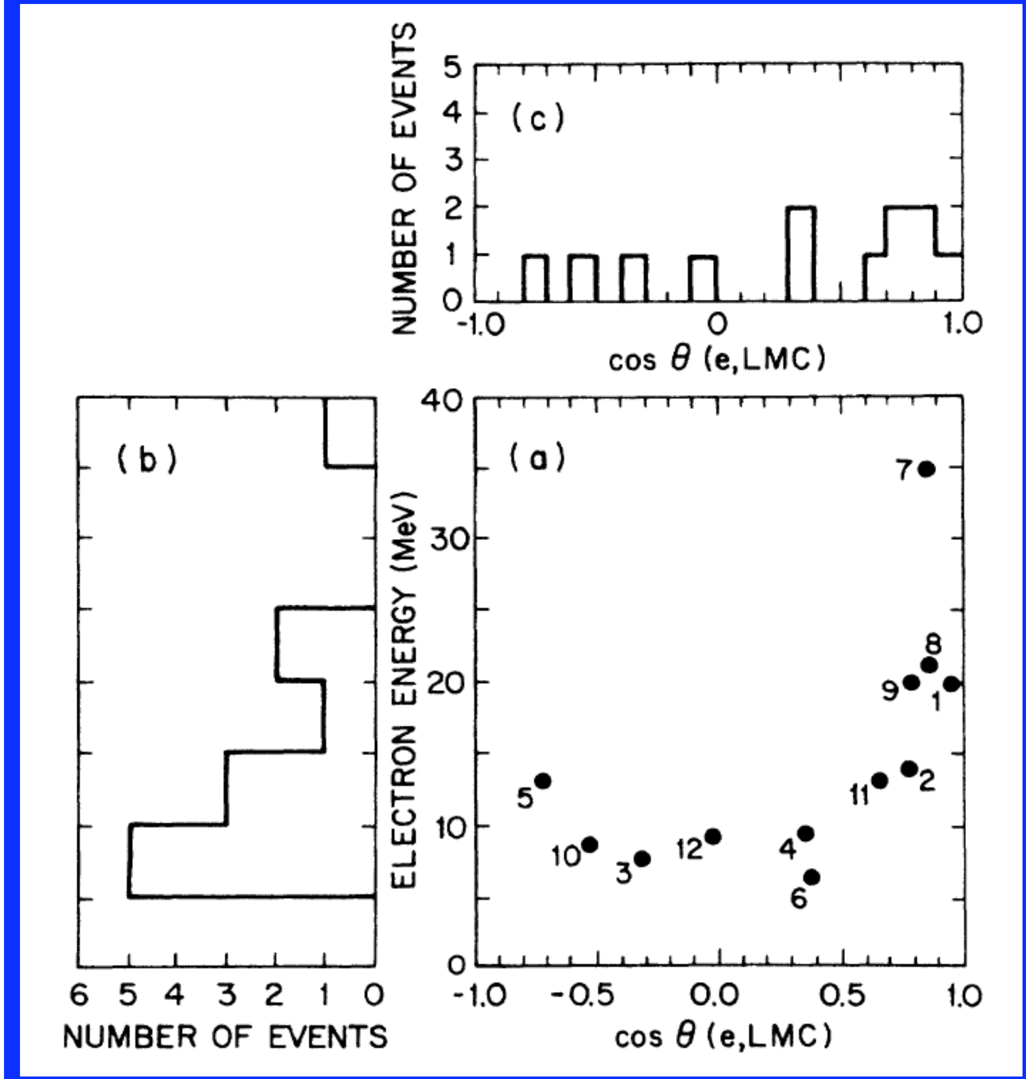
Supernova Emission Parameters





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

Cold Case File: 87A Electron Nu



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

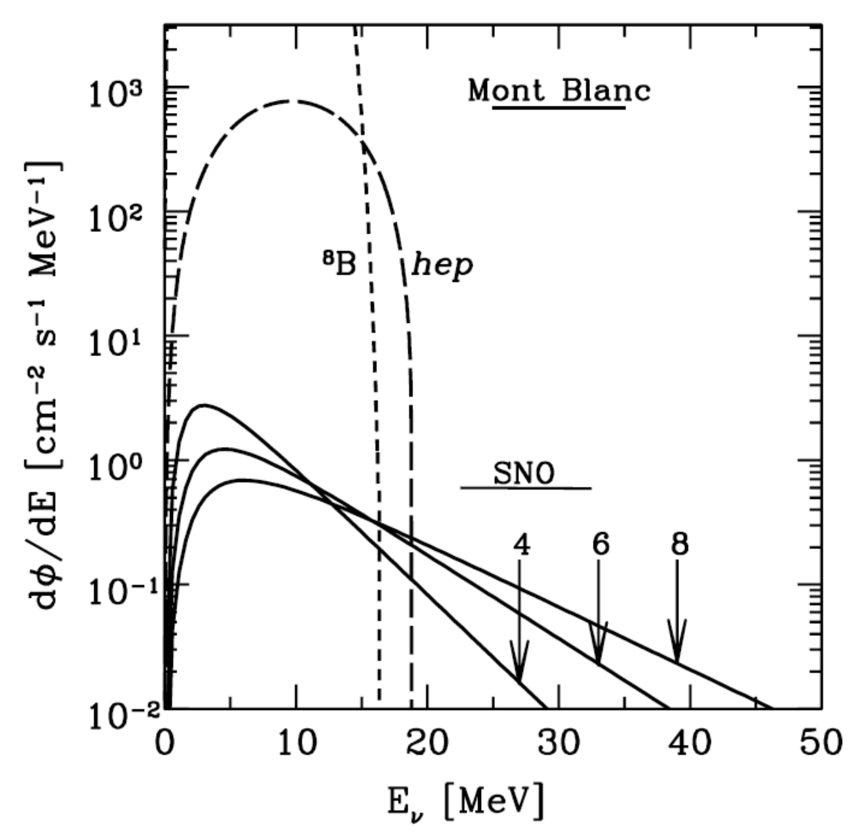
Dominant yield should be the nearly isotropic inverse beta decays

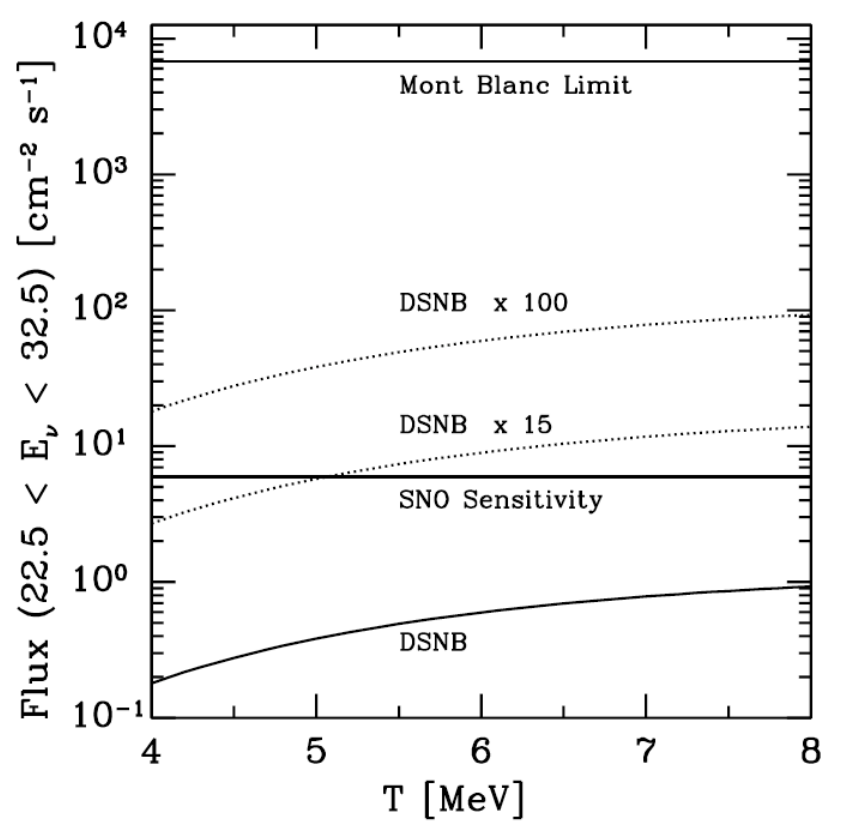
But both Kam-II and IMB had too-forward angular distributions

And the first event in Kam-II was forward

Were there some neutrino-electron scattering events?

Electron *Neutrino* DSNB





Beacom, Strigari, PRC 73, 035807 (2006)

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

This flux can be enhanced [Lunardini, PRD 73, 083009 (2006)]

Conclusions

• The diffuse flux of nuebar from all past type II supernovae has been strongly limited by existing data from Super-Kamiokande

• SNO has an interesting limit on the nue flux, and with all of their data, can be quite constraining

• If gadolinium is added to SK in 2008, we expect first detection of the nuebar flux

• Very exciting science will follow

Strongly motivates a nuclear physics case to build a Mton-scale detector in an Underground Laboratory