Impact-2008@KICP, Chicago
October 28, 2008

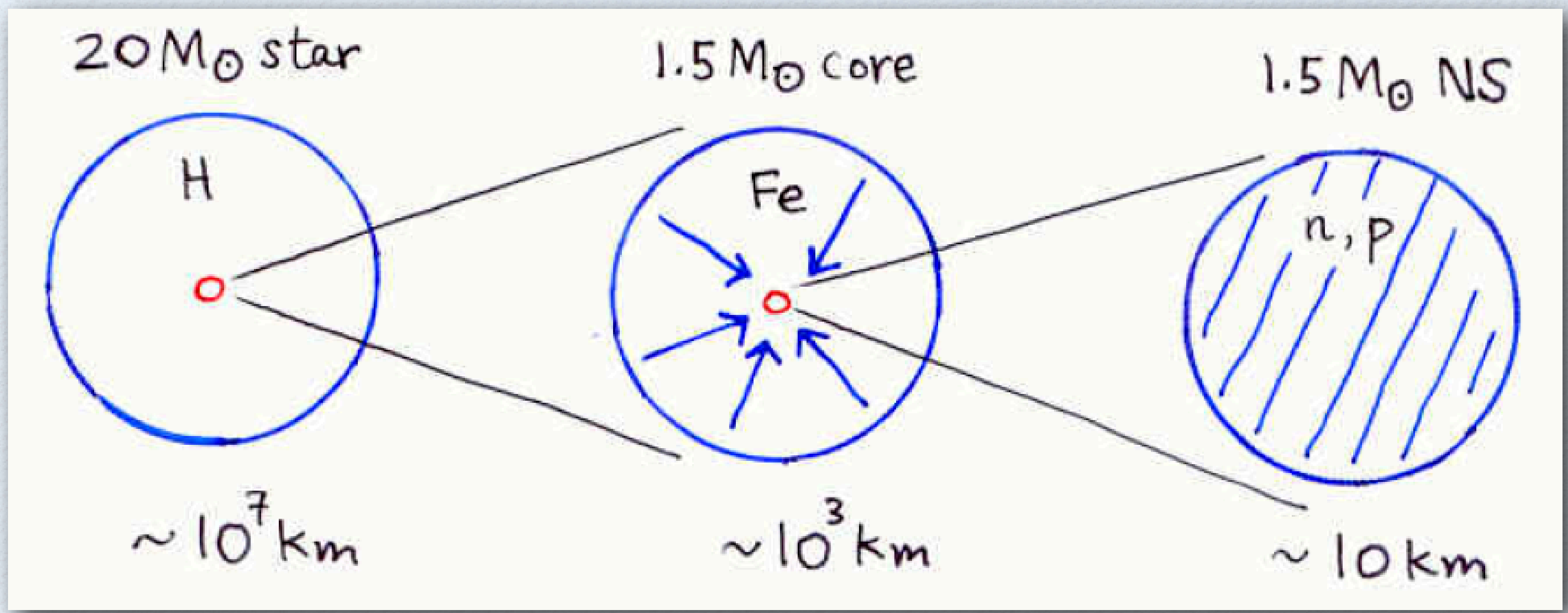
Cosmic Supernova Neutrino Background

Shin'ichiro Ando

California Institute of Technology

1. Introduction

Core-Collapse Supernova Explosion



- Last stage of the massive star evolution
- Released gravitational energy:

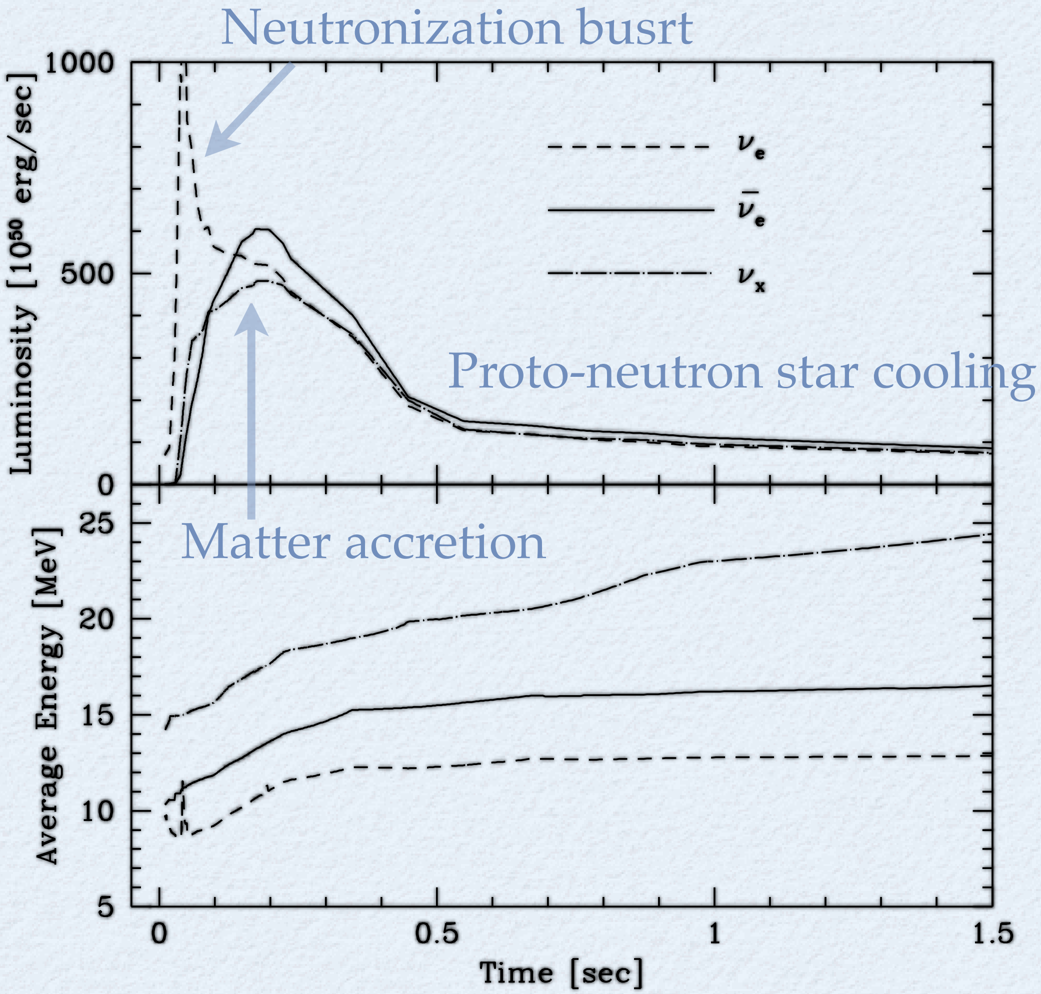
$$E_b = \frac{GM_{\rm NS}^2}{R_{\rm NS}} = 3 \times 10^{53} \text{ erg}$$

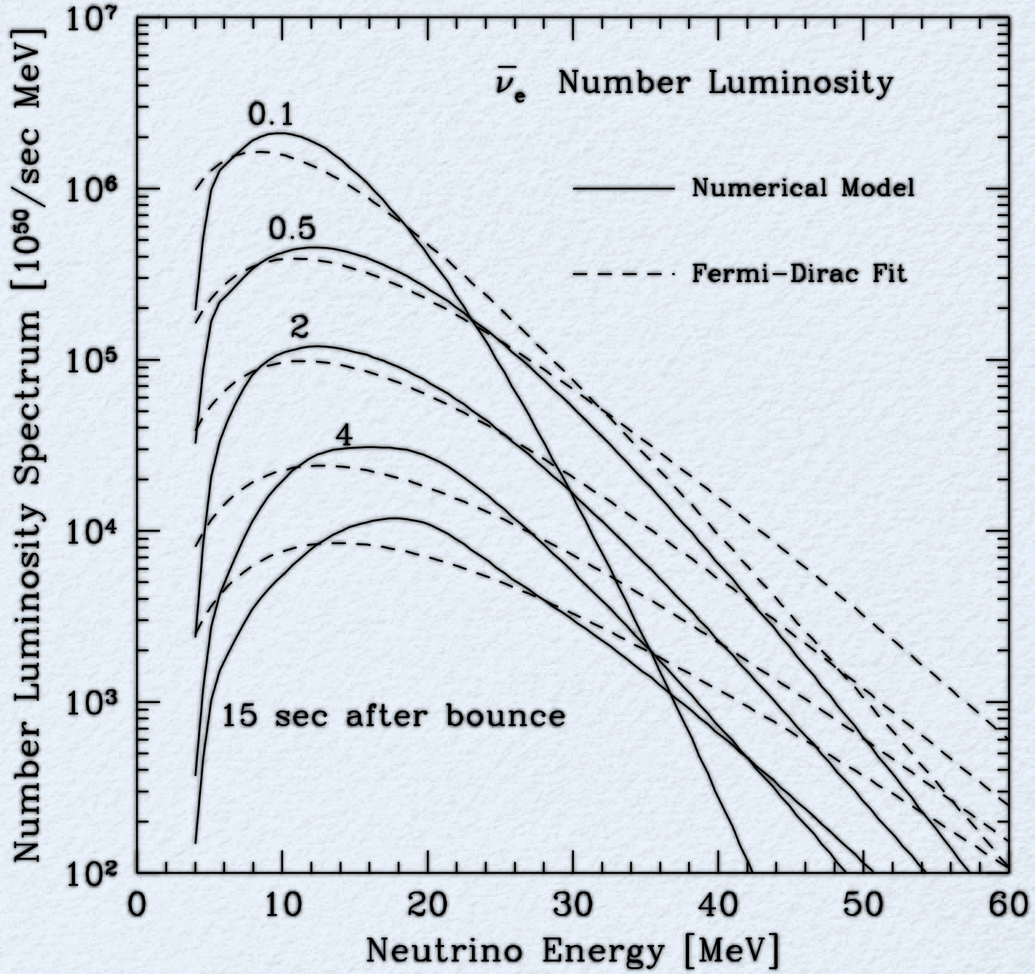
99%	MeV Neutrinos
1%	Shock Waves
0.01%	Photons

Supernova Neutrinos: General Characteristics

- They are trapped in the core due to coherent scattering, and diffuse out (e.g., Sato 1975)
  - Diffusion time scale ~ 10 sec
- Thermally distributed with a typical energy of 10 MeV, reflecting the core temperature
- Bring out almost all the gravitational energy (10^{53} erg) of a new-born neutron star, which is equipartitioned to each flavor

Supernova Neutrinos: Simulation

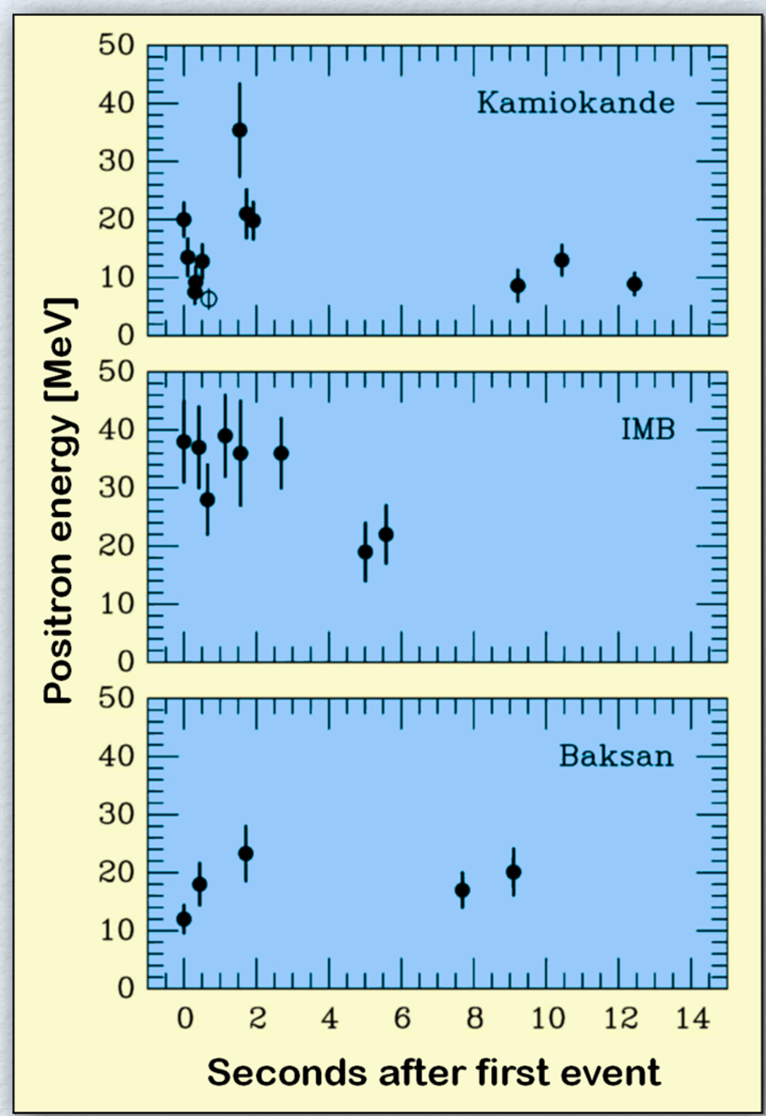




Totani, Sato, Dalhed, Wilson, *ApJ* **496**, 216 (1998)

Supernova 1987A

- A supernova neutrinos burst in LMC(@50 kpc)



Hirata et al., *PRL* **58**, 1490 (1987); Bionta et al., *PRL* **58**, 1494 (1987)

Diffuse Supernova Neutrinos

Core-collapse supernovae

99% of the gravitational energy is released as neutrinos

They occurred frequently, tracing the star formation rate

There should exist a diffuse background of neutrinos emitted from all the past supernovae

Classic Papers in 1980s

Medium-energy neutrinos in the universe

G. S. Bisnovatyĭ-Kogan and Z. F. Seidov

Institute for Space Research, USSR Academy of Sciences, Moscow

(Submitted April 13, 1981)

Astron. Zh. **59**, 213–223 (March–April 1982)

The number density and energy spectrum of 3–30 MeV neutrinos and their influence on a solar neutrino detector are calculated on the basis of recent theoretical estimates for supernova neutrino emission, supernova rate data, and the heavy-element abundance of galactic matter. The evolution of galaxies is taken into account. At present the mass density of such neutrinos in the universe should be $(2–10) \times 10^{-33}$ g/cm^3, greater than the equivalent density of the cosmic background radiation. But unlike matter and the microwave radiation, which probably were created at the start of the cosmological expansion, medium-energy neutrinos would have developed subsequent to star formation at epochs $z \lesssim 10$ and would still be produced today. About 20 neutrino pulses should reach the observer each second from supernovae within the volume $z < 1$; each pulse would last $\sim 10^2–10^6$ sec if the neutrino rest mass is 0–30 eV, and the relative pulsation amplitude would be $\sim 10^{-2}–10^{-4}$.

PACS numbers: 94.40.Te, 94.40.Cn, 97.60.Bw

Bisnovatyi-Kogan, Seidov,
Sov. Astron. **26**, 132 (1982)

NATURE VOL. 310 19 JULY 1984 REVIEW ARTICLE 191

Antineutrino astronomy and geophysics

Lawrence M. Krauss*, Sheldon L. Glashow† & David N. Schramm‡

* Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
† Department of Physics, Boston University, Boston, Massachusetts 02215, USA
‡ Department of Physics and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA

Radioactive decays inside the Earth produce antineutrinos that may be detectable at the surface. Their flux and spectrum contain important geophysical information. New detectors need to be developed, discriminating between sources of antineutrinos, including the cosmic-background. The latter can be related to the frequency of supernovas.

Krauss, Glashow, Schramm,
Nature **310**, 191 (1984)

Motivations

- Detectability—first detection of extragalactic neutrinos
  - Evaluation of event rate and backgrounds
    - Ando, Sato & Totani 2003; Beacom & Vagins 2004; Strigari, Kaplinghat, Steigman & Walker 2004; Cocco et al. 2004; Beacom & Strigari 2005; Lunardini 2006b
- Galaxy evolution and star formation history
  - Complementary to observations with the light
    - Totani, Sato & Yoshii 1996; Fukugita & Kawasaki 2003; Ando 2004; Strigari et al. 2005; Lunardini 2006a
- Supernova neutrino parameters
  - Yüksel, Ando & Beacom 2005; Lunardini 2006c; Yüksel & Beacom 2007
- Neutrino properties as elementary particles
  - Neutrino oscillation
    - Ando & Sato 2003; Volpe & Welzel 2007; Chakraborty et al. 2008
  - Neutrino decay (i.e., coupling with unknown particle)
    - Ando 2003; Fogli, Lisi, Mirizzi & Montanino 2004

2. Flux, Event Rate, Current Upper Limits

Order-of-Magnitude Estimate

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  - Combining these three ingredients, we get

$$\sim 3 \times 10^{53} \text{ erg} \times 10^{-4} \text{ yr}^{-1} \text{ Mpc}^{-3} \times 10^{10} \text{ yr} = 10^{-14} \text{ erg cm}^{-3}$$

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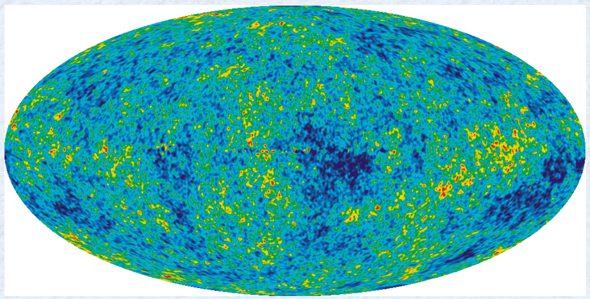
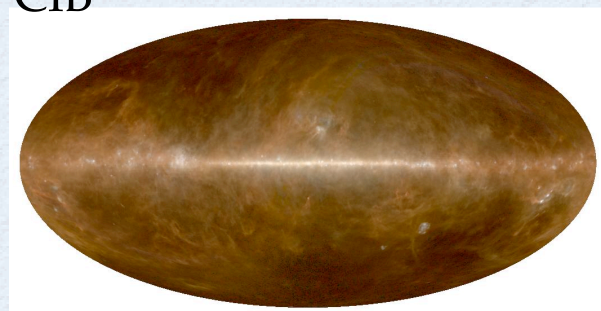
OK, how big is this 10^{-14} erg cm^{-3} ?

- Universe is filled with radiation

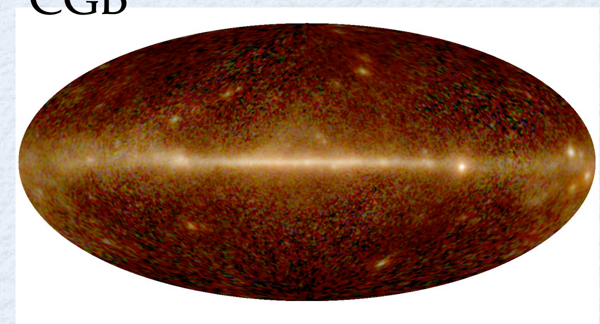
CMB



CIB

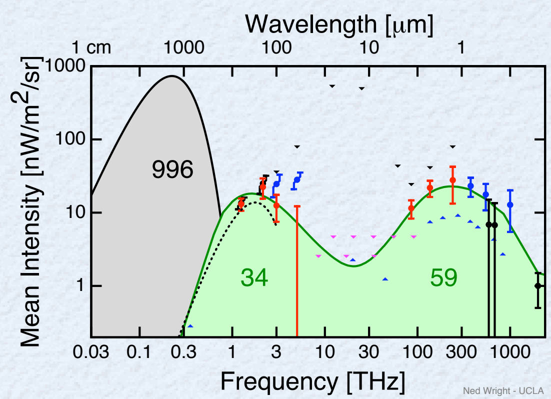


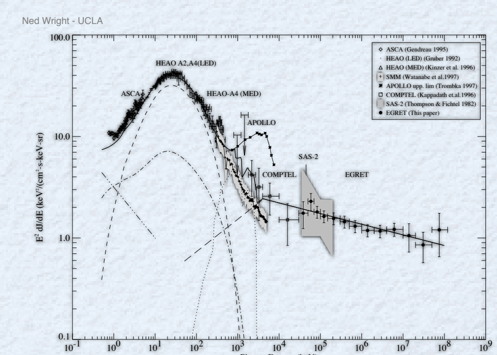
CGB



- Energy densities of background radiation are:

	Energy density
CMB	4×10^{-13} erg cm^{-3}
CIB / EBL	3×10^{-14} erg cm^{-3}
CXB	10^{-16} erg cm^{-3}
CGB	10^{-17} erg cm^{-3}





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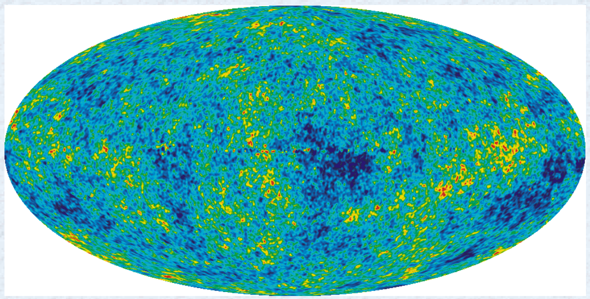

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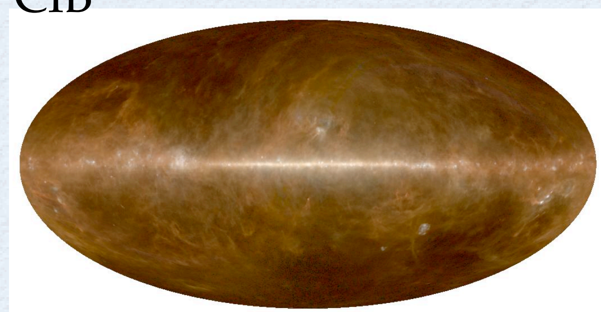

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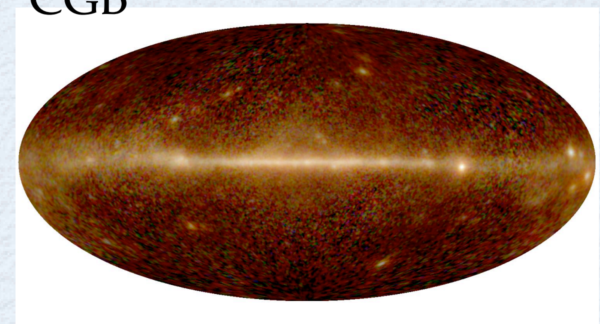

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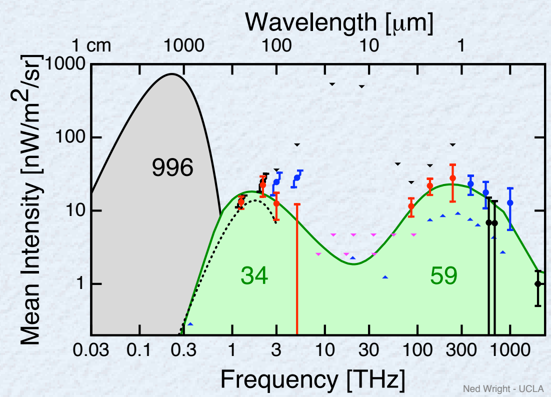

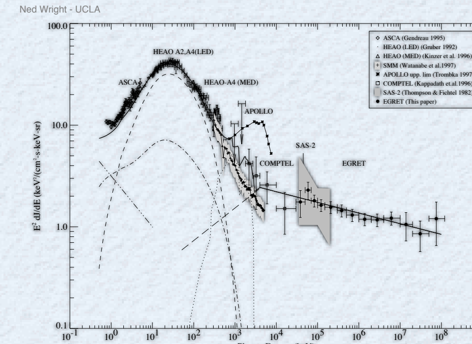

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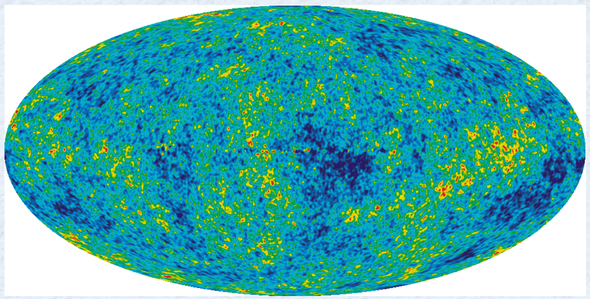

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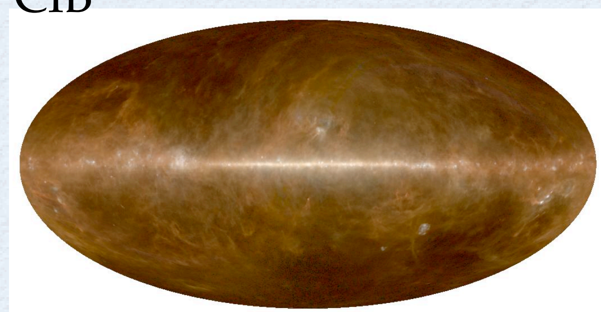

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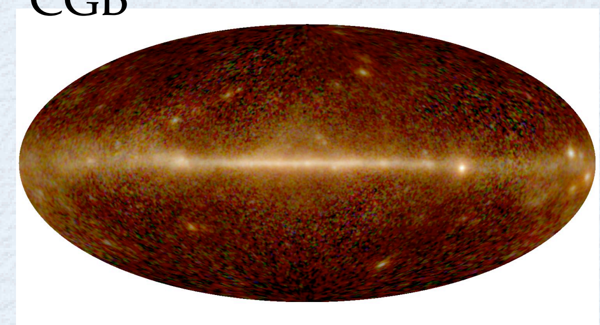

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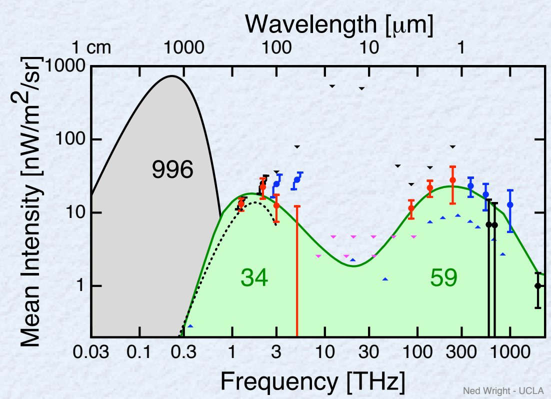
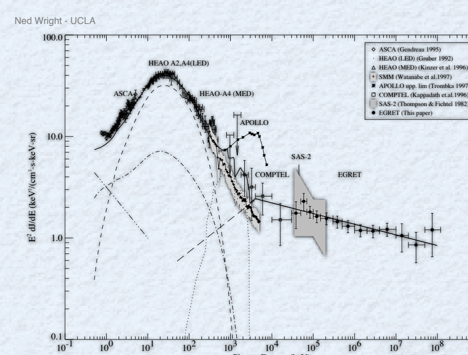
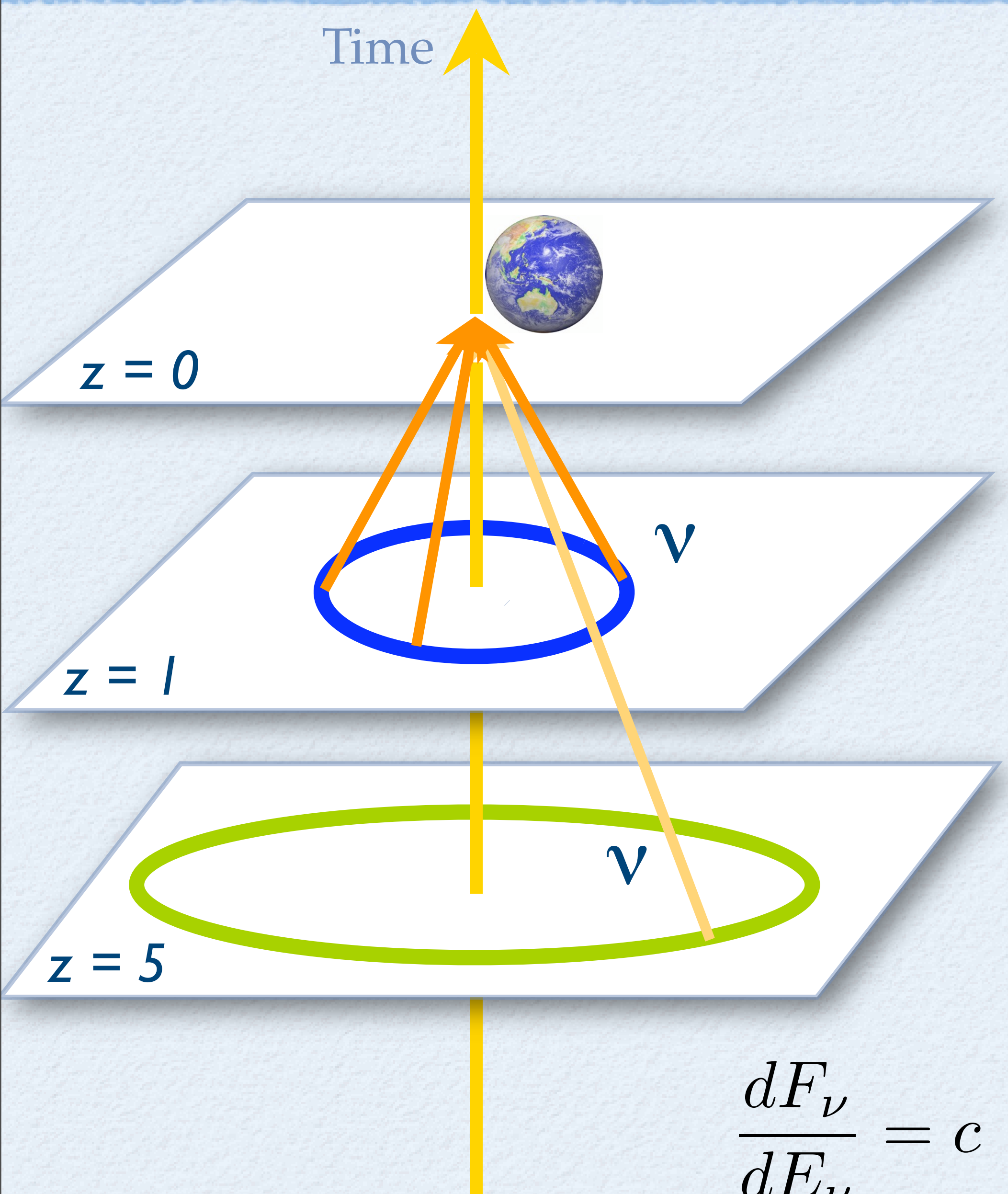
WB bound	$< 10^{-19}$ erg cm^{-3}





Formulation

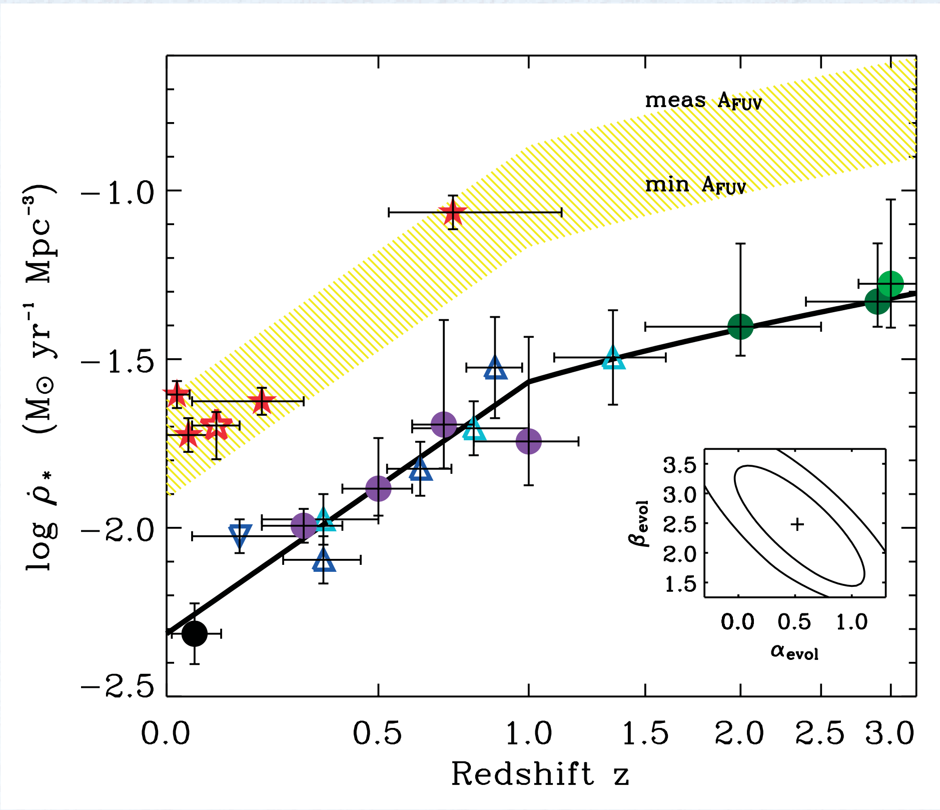


Required Physics:

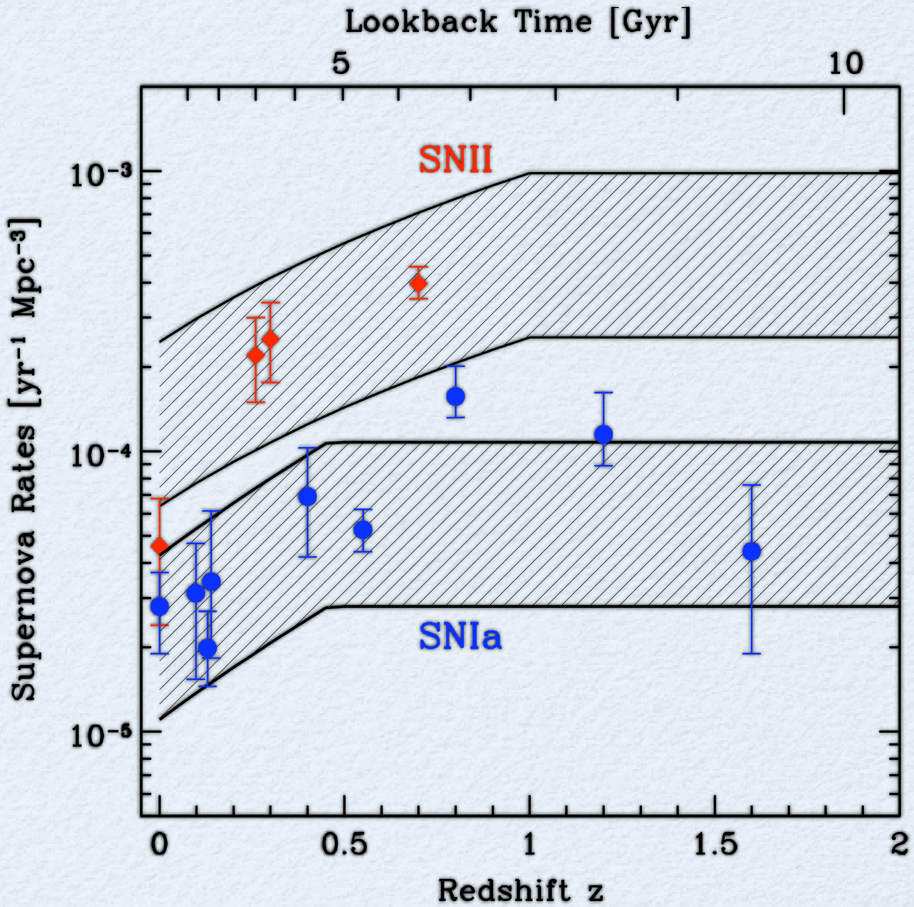
1. Neutrino spectrum from each supernovae
2. Neutrino oscillation during propagation in supernova envelope
3. Supernova rate

$$\frac{dF_\nu}{dE_\nu} = c \int_0^{z_{\max}} R_{\rm SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

Star Formation and Supernova Rate

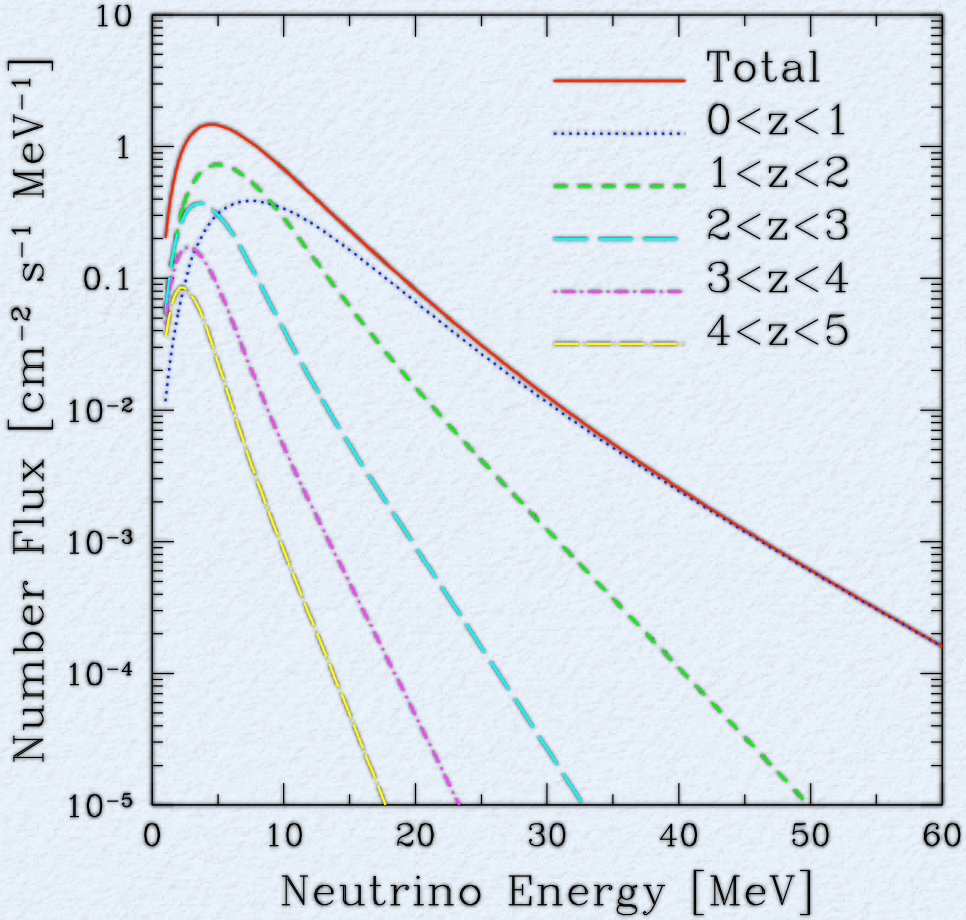


Schiminovich et al., *ApJ* **619**, L47 (2005)



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

Flux and Even Rate

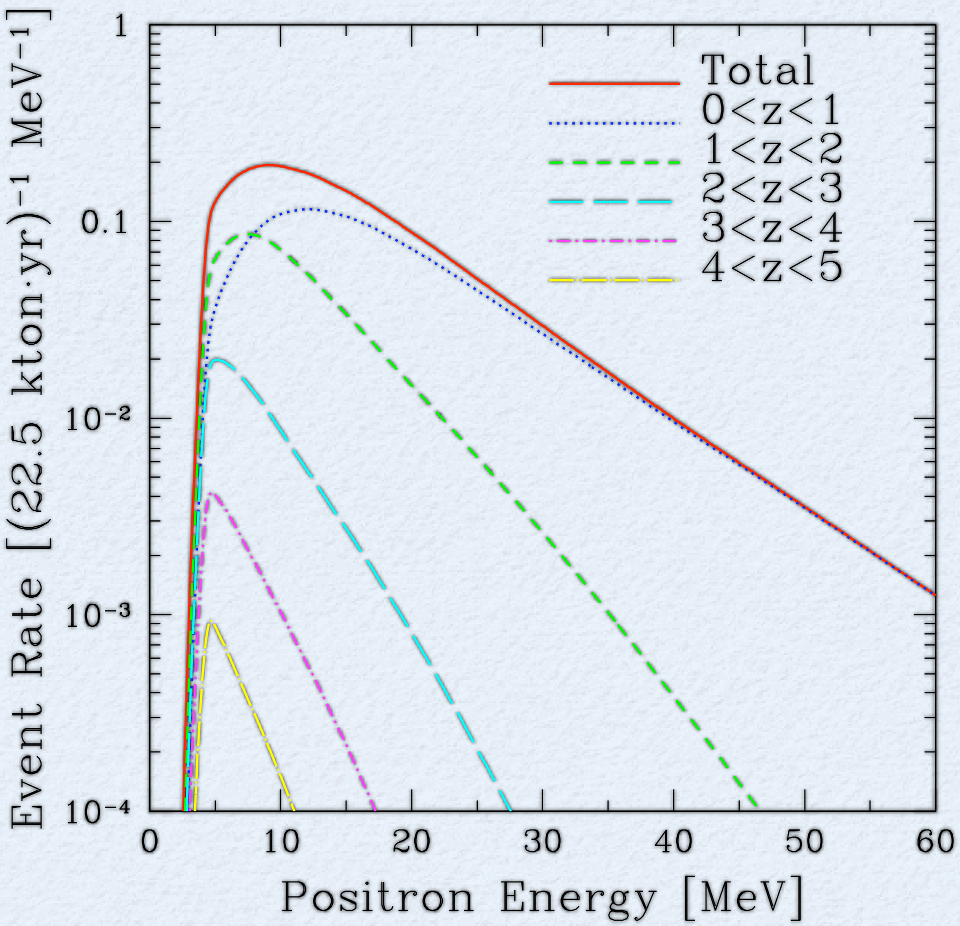


Ando, *Astrophys. J.* **607**, 20 (2004)

- Flux ($cm^{-2}\ s^{-1}$)

$E_\nu > 11.3$ MeV	$E_\nu > 19.3$ MeV
5.1	1.1

Flux and Even Rate



Ando, *Astrophys. J.* **607**, 20 (2004)

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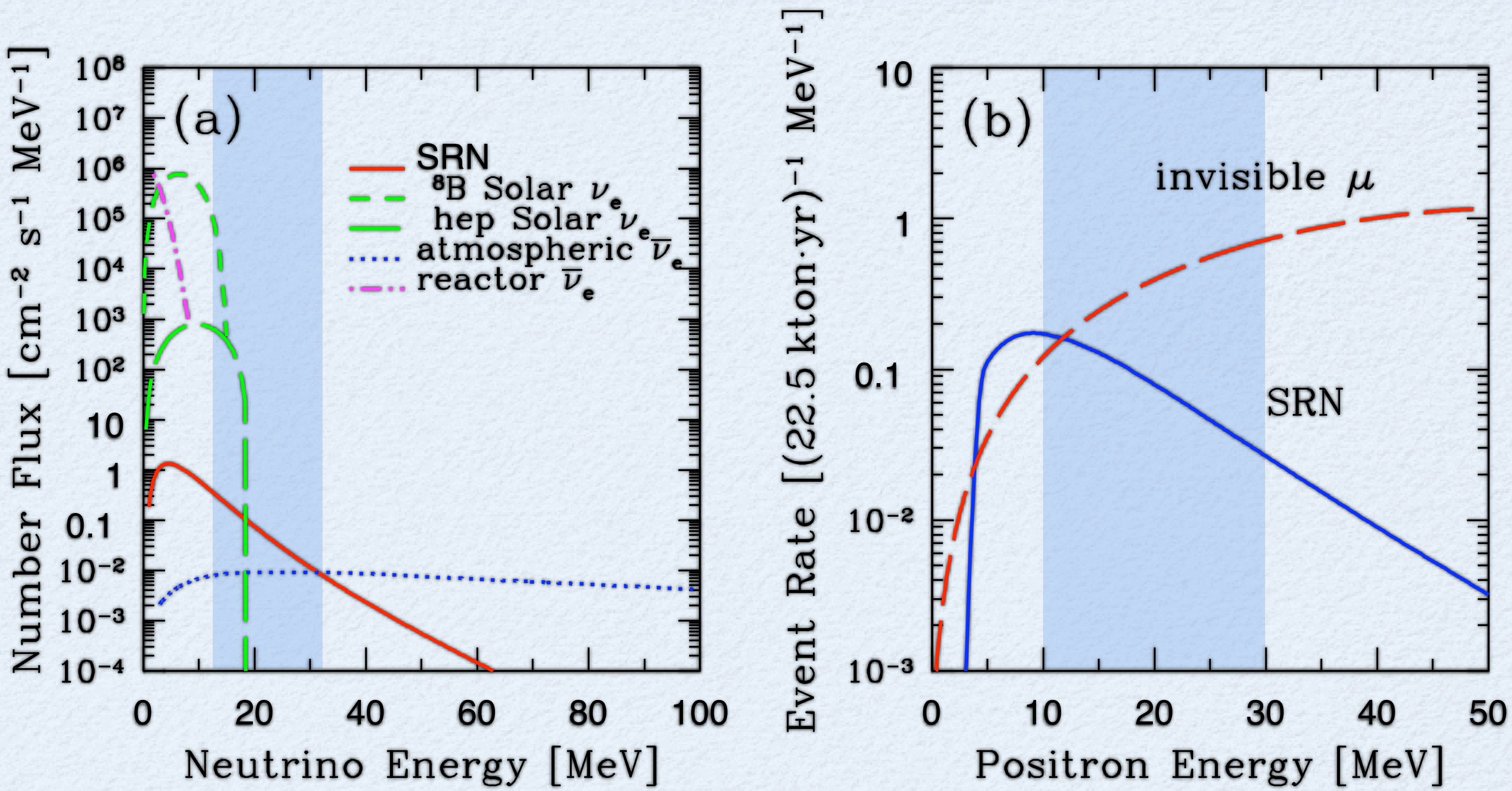
$E_\nu > 11.3$ MeV	$E_\nu > 19.3$ MeV
5.1	1.1

- Event rate at SK (yr^{-1})

$E_e > 10$ MeV	$E_e > 18$ MeV
5.2	2.5

Backgrounds against Detection



Ando, Sato, *NJP* **6**, 170 (2004)

- Flux: 1.1 cm^{-2} s^{-1} (E_ν > 19.3 MeV)
- There is no energy window at current water Cerenkov detectors
- Flux upper limit: 1.2 cm^{-2} s^{-1} (> 19.3 MeV, 90% C.L.; SK, Malek et al. 2003)
- In the future, 10–30 MeV can be a background-free energy region (with $GdCl_3$; Beacom & Vagins 2004)

Experimental Limit

Super-K, *PRL* **90**, 061101 (2003)

Theoretical model	Event rate limit (90% C.L.)	SRN flux limit (90% C.L.)	Predicted flux	Predicted flux ($E_\nu > 19.3$ MeV)
Galaxy evolution [4]	< 3.2 events/year	$< 130\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$44\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$0.41\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Cosmic gas infall [5]	< 2.8 events/year	$< 32\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$5.4\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$0.20\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Cosmic chemical evolution [6]	< 3.3 events/year	$< 25\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$8.3\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$0.39\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Heavy metal abundance [7]	< 3.0 events/year	$< 29\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$< 54\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$< 2.2\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Constant supernova rate [4]	< 3.4 events/year	$< 20\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$52\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$3.1\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Large mixing angle osc. [8]	< 3.5 events/year	$< 31\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$11\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$0.43\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Flux upper limit: 1.2 $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (> 19.3 MeV, 90% C.L.)

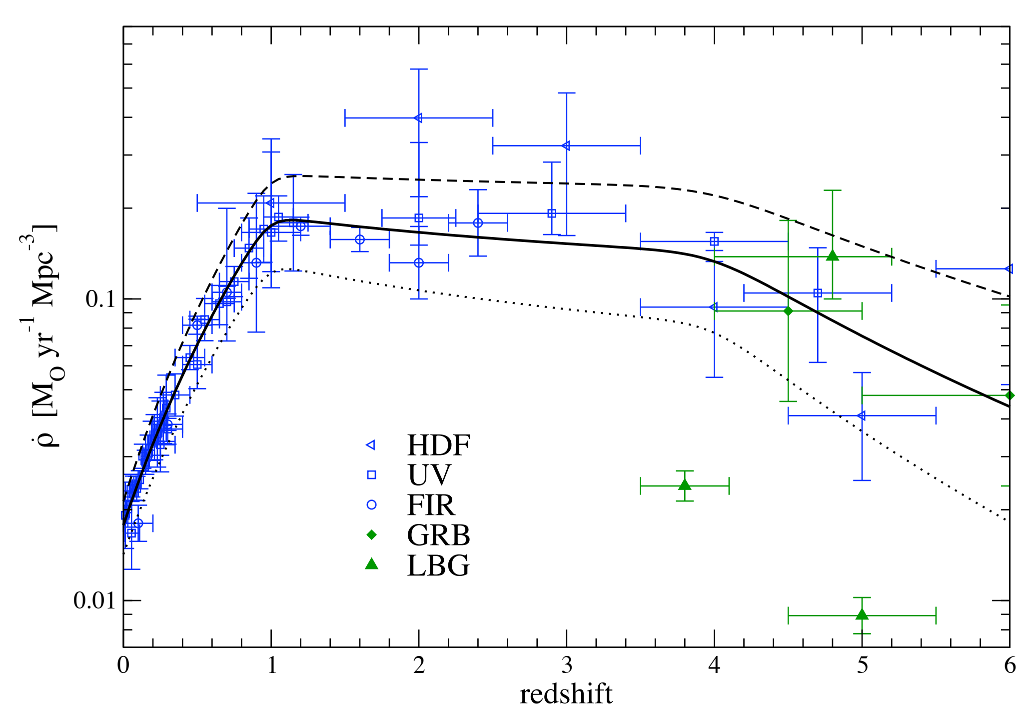
SNO, *ApJ* **653**, 1545 (2006)

	Integral Flux ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)		Flux 22.9 MeV $< E_\nu <$ 36.9 MeV ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	
Model	Prediction	Upper Limit	Prediction	Upper Limit
B&S : $T = 4$ MeV	21.1	1.1×10^4	0.19	93
B&S : $T = 6$ MeV	14.1	1.5×10^3	0.66	72
B&S : $T = 8$ MeV	10.5	6.0×10^2	1.08	61
A&S : NOR-L	28.5	1.3×10^3	1.49	69
A&S : NOR-S-INV	34.9	2.3×10^3	1.06	70

3. Implications: Constraining Supernova Neutrino Emission Parameters

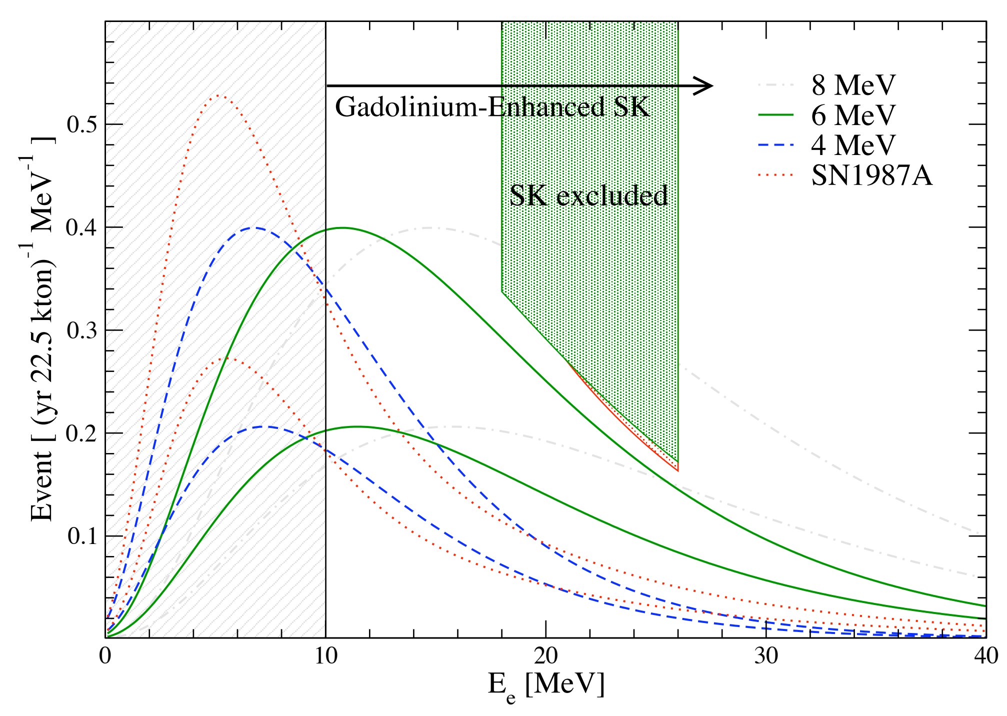
How Uncertain is Supernova Rate?

- Recent progress of astronomical observations constrains systematic uncertainty of star formation rate by a factor of ~2
- These star formation rate models are consistent with
  - direct supernova count
  - extragalactic background light
  - interstellar dust models, etc.
- Lowering by a factor of 2 will require fixing here and there in astronomy



Horiuchi, Beacom, Dwek, in preparation
Hopkins, Beacom 2006

Uncertainty of relic neutrino spectrum

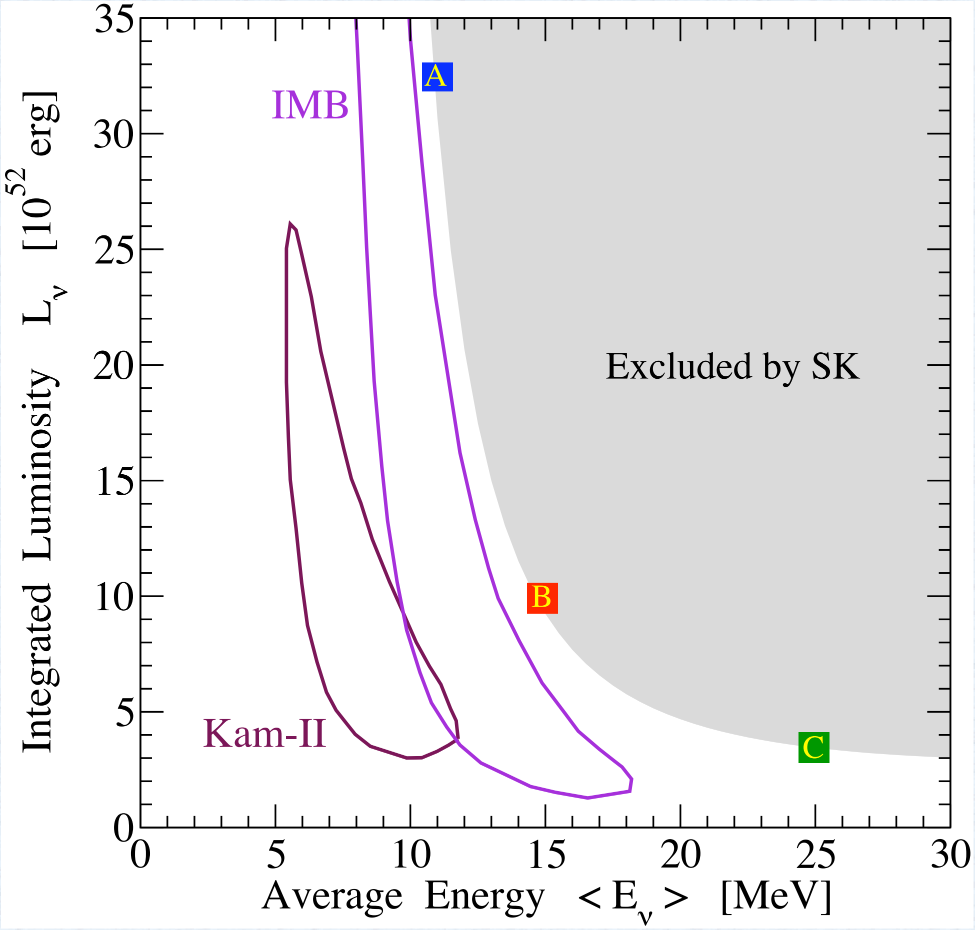


$\bar{\nu}_e$ spectrum	events [yr^{-1} 22.5 kton^{-1}]	
	$18 < E_e/\mathrm{MeV} < 26$	$10 < E_e/\mathrm{MeV} < 26$
8 MeV	$2.0^{+0.7}_{-0.6}$	$4.2^{+1.5}_{-1.2}$
6 MeV	$1.3^{+0.4}_{-0.3}$	$3.5^{+1.2}_{-1.0}$
4 MeV	$0.4^{+0.1}_{-0.1}$	$1.8^{+0.5}_{-0.5}$
SN1987A	$0.5^{+0.1}_{-0.1}$	$1.7^{+0.5}_{-0.4}$

Horiuchi, Beacom, Dwek, in preparation

- Uncertainty due to supernova rate is smaller than that due to supernova spectrum
- Relic neutrino spectrum with current astronomical knowledge could be used to constrain supernova neutrino parameters
- Lowering threshold down to 10 MeV (with Gd addition) would greatly help

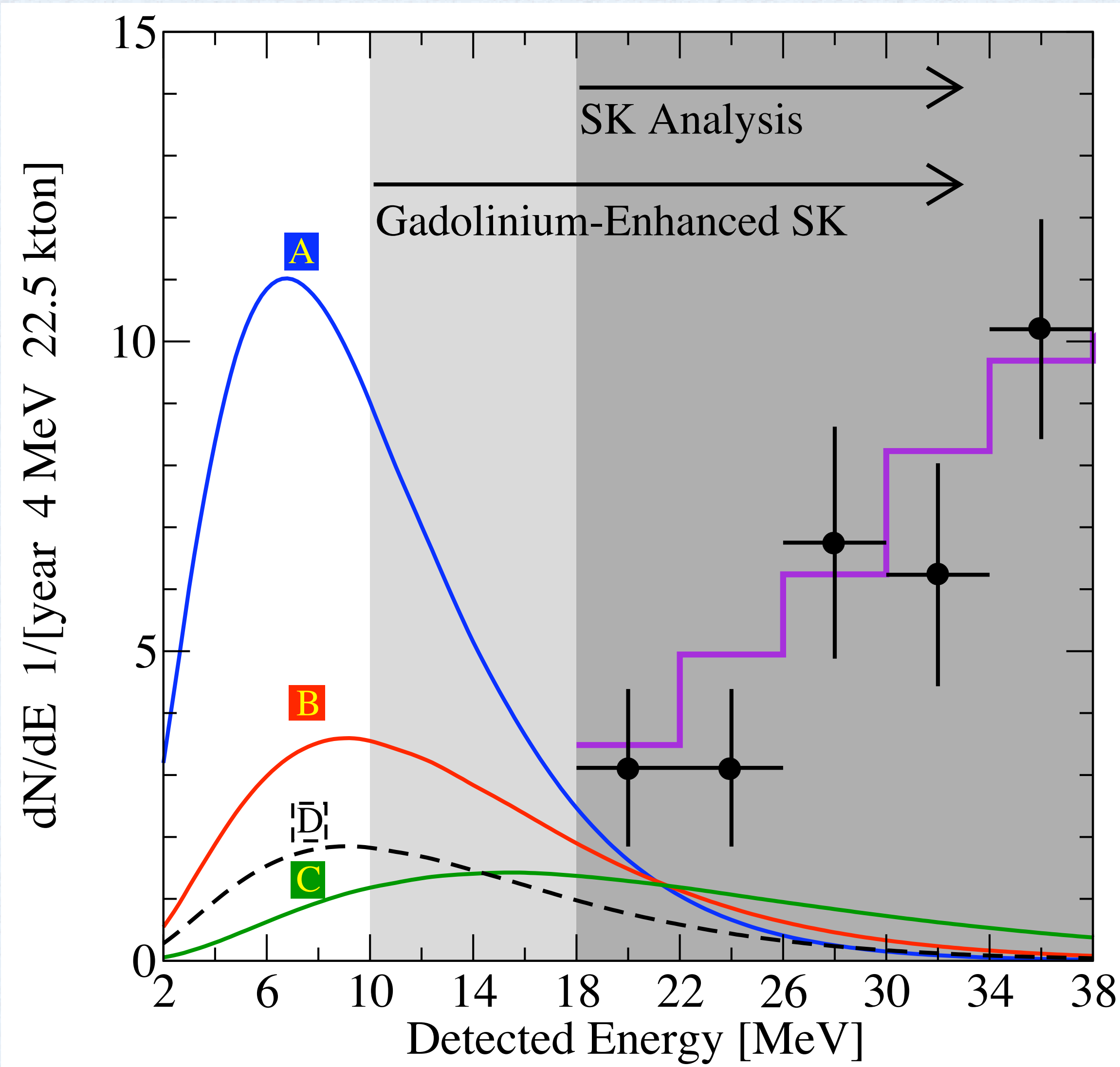
Constraining Supernova Parameters



Yüksel, Ando, Beacom, *PRC* **74**, 015803 (2006)

- Reinterpreting the SK flux limit (Malek et al. 2003) in terms of physical parameters
- Very close to the SN 1987A region (especially IMB)
- The result of Super-K 4-yr data accumulation
  - This still includes backgrounds

Parameter Constraint by SK Data

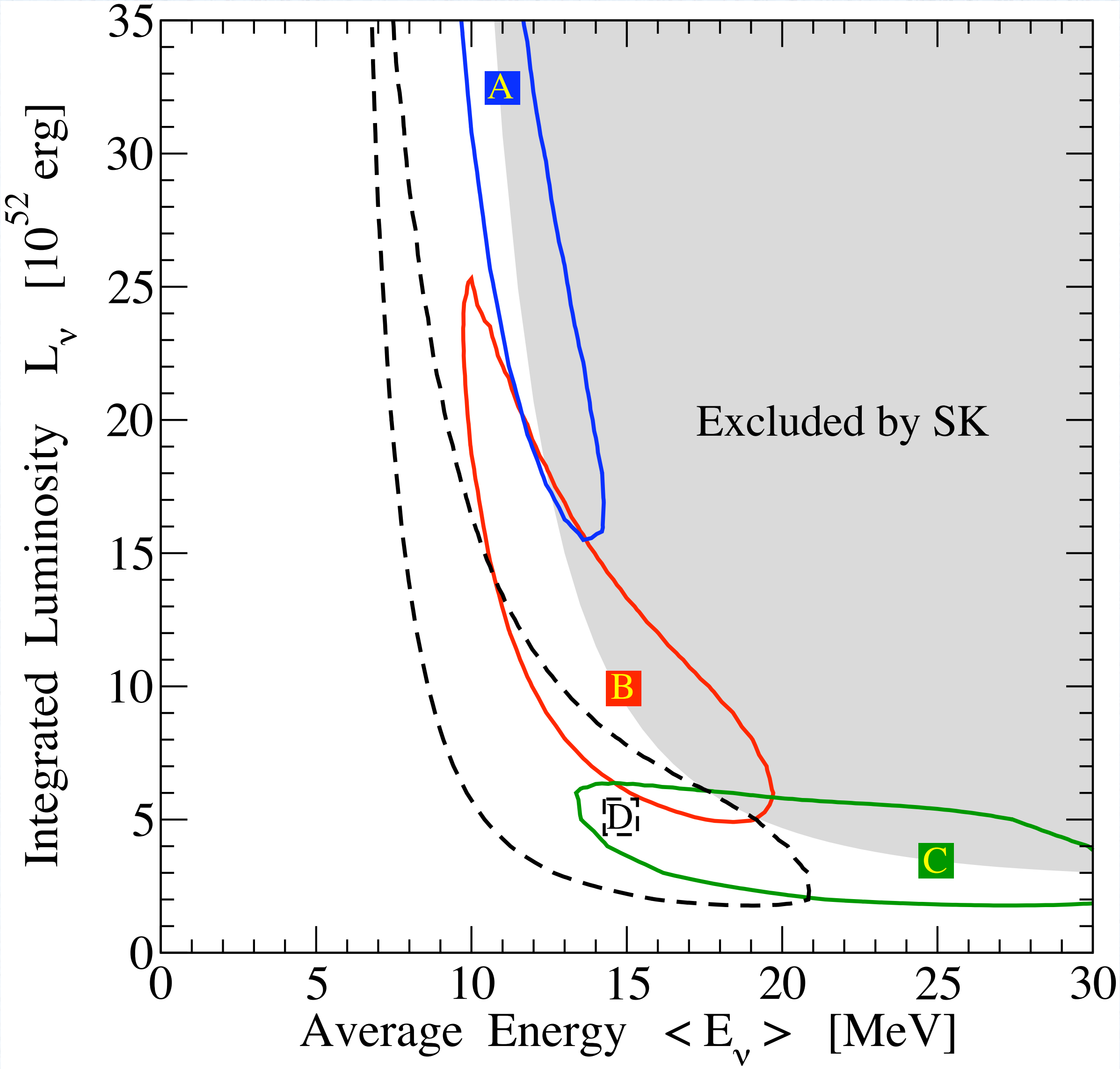


Yüksel, Ando, Beacom, *PRC* **74**, 015803 (2006)

- Current data are dominated by background
- Future Gd-loaded detectors enables background-free neutrino search above 10 MeV
- This enables to distinguish models

Parameter Constraint by SK Data

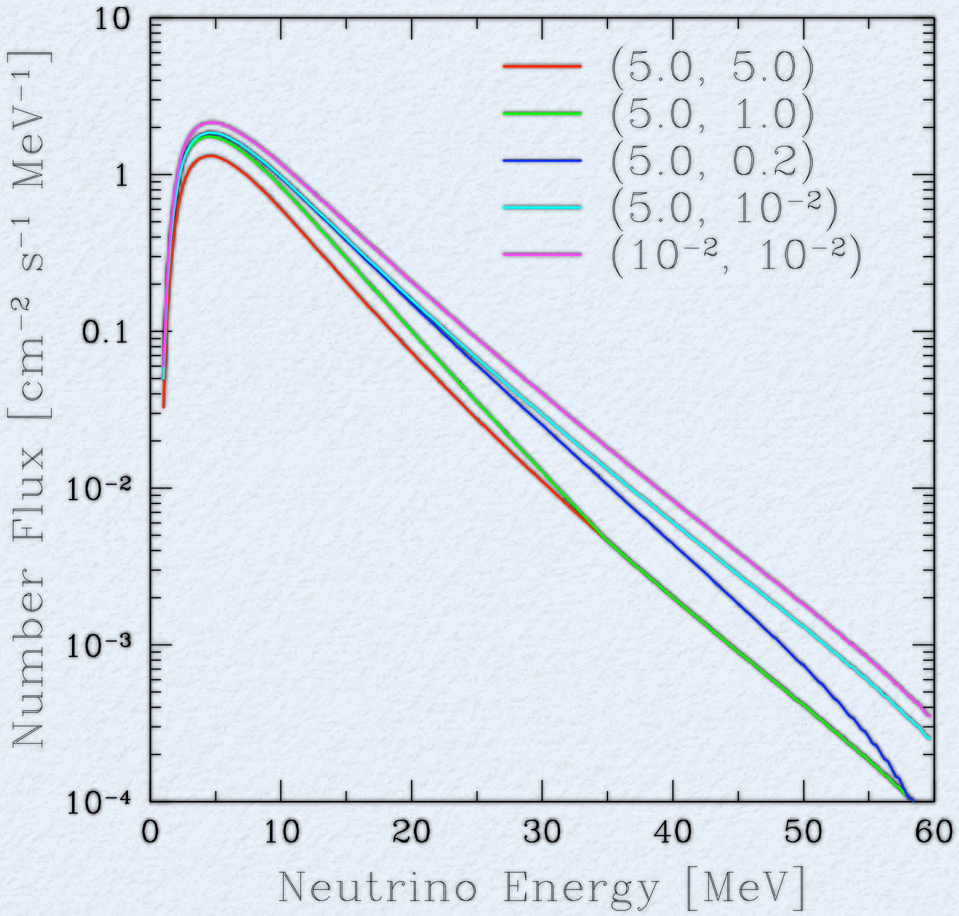
Gd-SK
5 yr



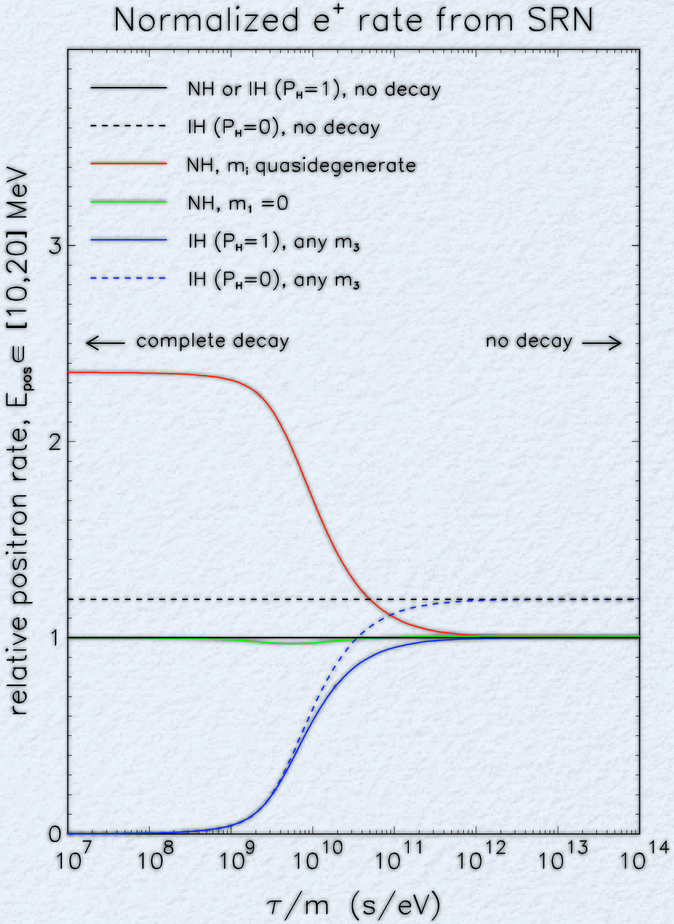
Yüksel, Ando, Beacom, *PRC* **74**, 015803 (2006)

Another implication: Longest baseline experiment

- One can provide strongest limits on secret interaction of neutrinos
- E.g., neutrino decay: $\nu_i \rightarrow \nu_j + \phi$



Ando, *PLB* **570**, 11 (2003)



Fogli et al., *PRD* **70**, 013001 (2004)

4. Conclusions

- A diffuse supernova neutrino background filling the entire universe
- Theory predicts its flux *just below* the current upper limit by the Super-K
  - The excluded region on the (E_{b}, T) plane is promisingly approaching the SN 1987A region
- Future Gd-doped Super-K or Mton detectors enables determination of these parameters
  - The systematic uncertainty of supernova rate is now within a factor of 2

Appendix

Galactic Supernova Neutrino Burst

- Expected event number by galactic supernova (10 kpc)

Detector	Type	Mass (kton)	Event #
Super-K	Water Cerenkov	32	~ 10,000
SNO	Heavy Water	1.4 (D_2O)	~ 500
KamLAND; LVD	Scintillatior	1	~ 300
ICARUS	Liquid Argon	3 (planned)	~ 300

How lucky are we?

- Expected SN rate per galaxy: ~ 0.03 yr^{-1}
  - Small probability while detectors are running
  - Expected event number from SN in M31 (700 kpc): ~ 1
- What happens if we extend the distance scale further?
  - We cannot resolve each supernova, but still can detect neutrinos as <u>diffuse background</u>
  - It doesn't matter how lucky we are; only depends on the detector sensitivity!

Galactic SN vs Background

- Galactic burst
  - Many events! (~10,000@ Super-K)
  - We can do precise physics
    - Explosion mechanism
    - Shock wave propagation
    - Neutrino physics

- Diffuse background
  - Our efforts rewarded
  - Only a method to measure supernova neutrinos, if there is no galactic burst (which may be likely)
  - Unique physics (SN rate, neutrino decay, etc.)

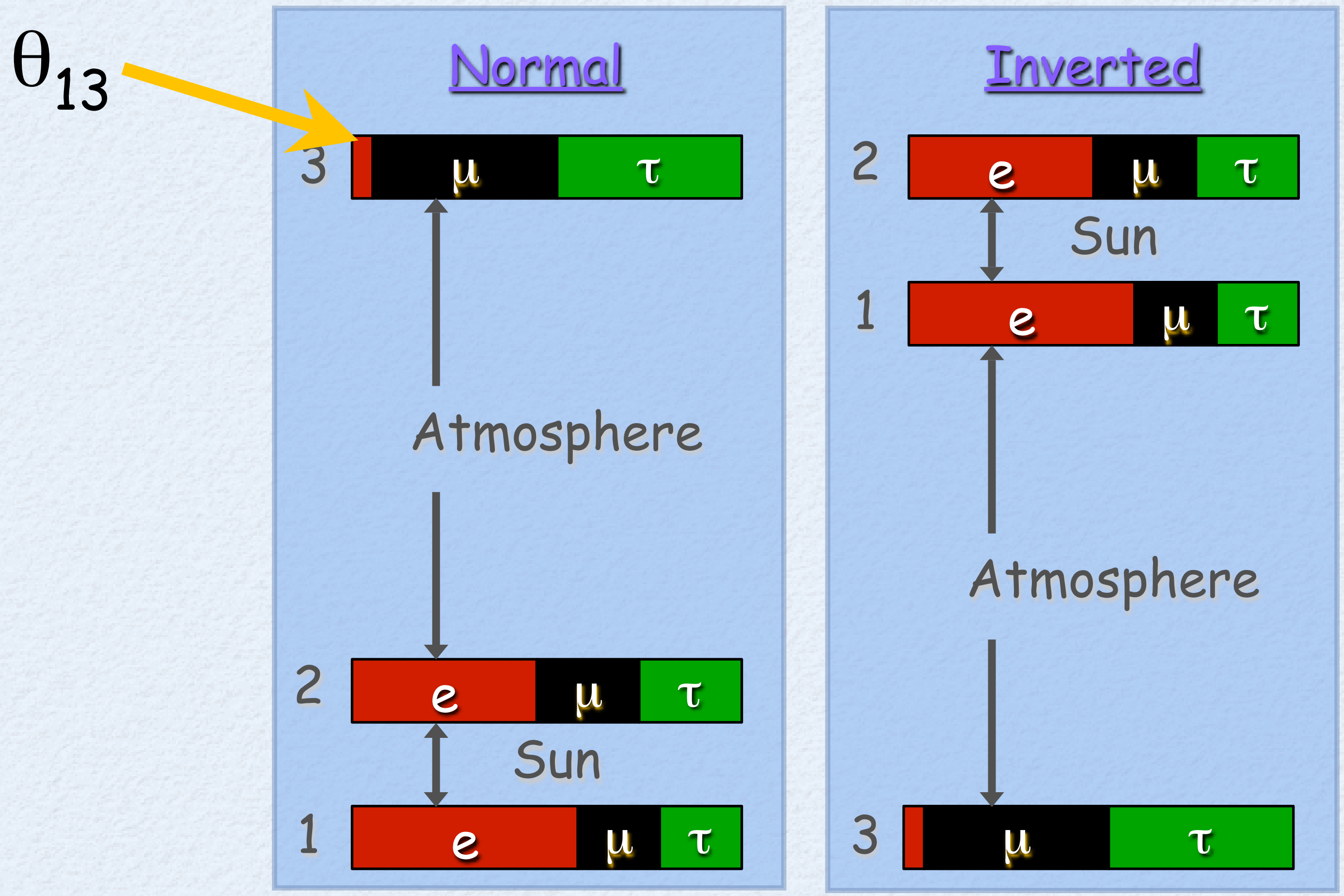
Neutrino Oscillation

- 5 parameters
  - two mass squared differences, three mixing angles

	Mass squared difference	Mixing angle
Atmospheric	$\lvert \Delta m_{23}^2 \rvert = 2.5\times10^{-3}\ \mathrm{eV}^2$	$\sin^2 2\theta_{23} = 1$
Solar	$\Delta m_{12}^2 = 8\times10^{-5}\ \mathrm{eV}^2$	$\tan^2\theta_{12} = 0.45$
Reactor	$\lvert \Delta m_{13}^2 \rvert = 2.5\times10^{-3}\ \mathrm{eV}^2$	$\sin^2\theta_{13} < 0.1$

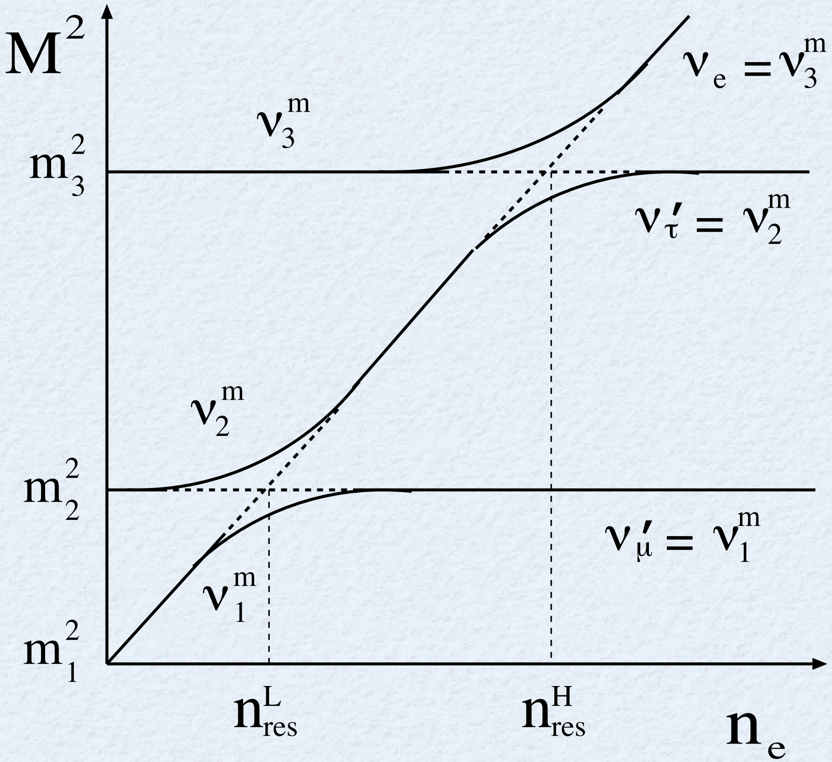
Mass hierarchy and θ_{13}

- Remaining uncertainty: mass hierarchy, θ_{13}

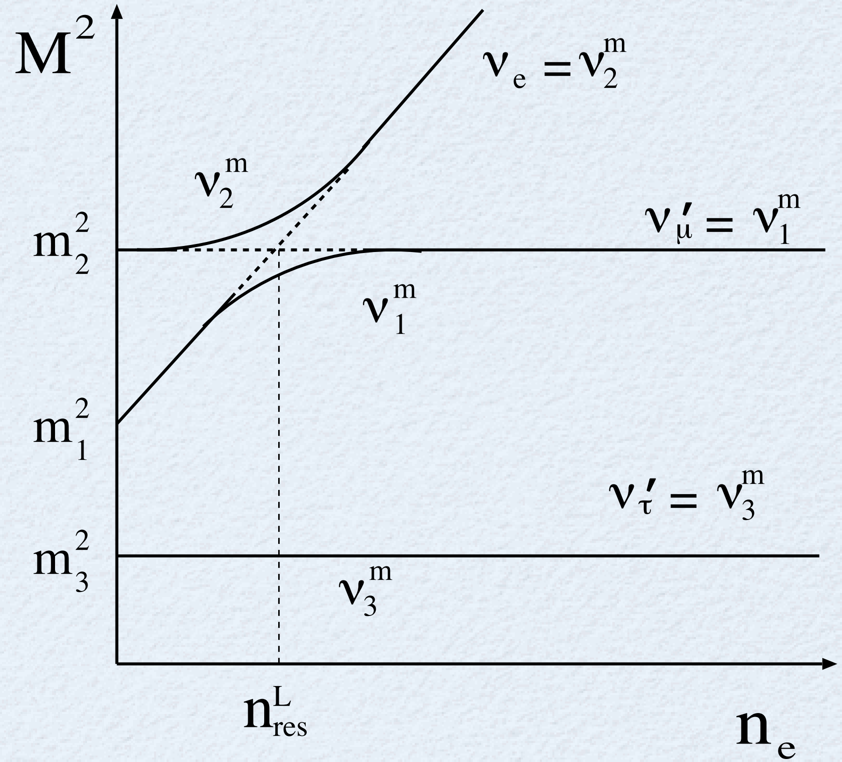


Supernova Neutrino Oscillation

Normal hierarchy



Inverted hierarchy



Supernova Neutrino Osillation: Summary

Probability of $\nu_e \Leftrightarrow \nu_x$ conversion

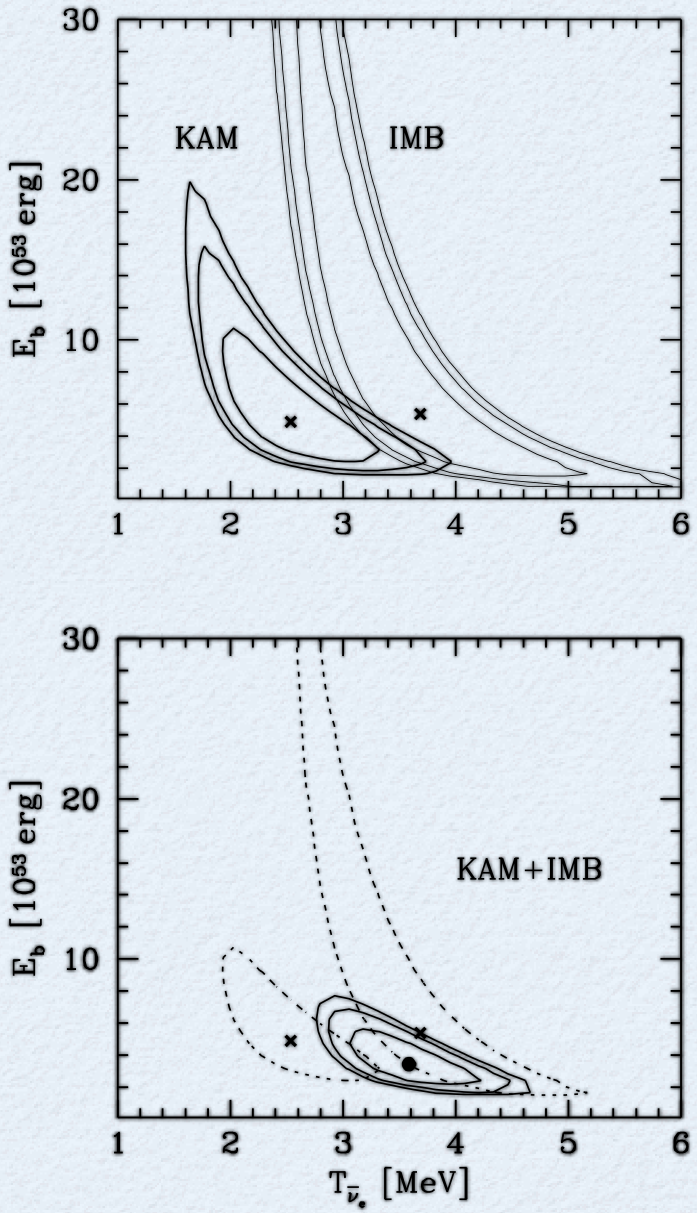
	Large θ_{13}	Small θ_{13}
Normal ($m_1 < m_3$)	100%	70%
Inverted ($m_1 > m_3$)	70%	70%

Probability of $\overline{\nu}_e \Leftrightarrow \overline{\nu}_x$ conversion

	Large θ_{13}	Small θ_{13}
Normal	30%	30%
Inverted	100%	30%

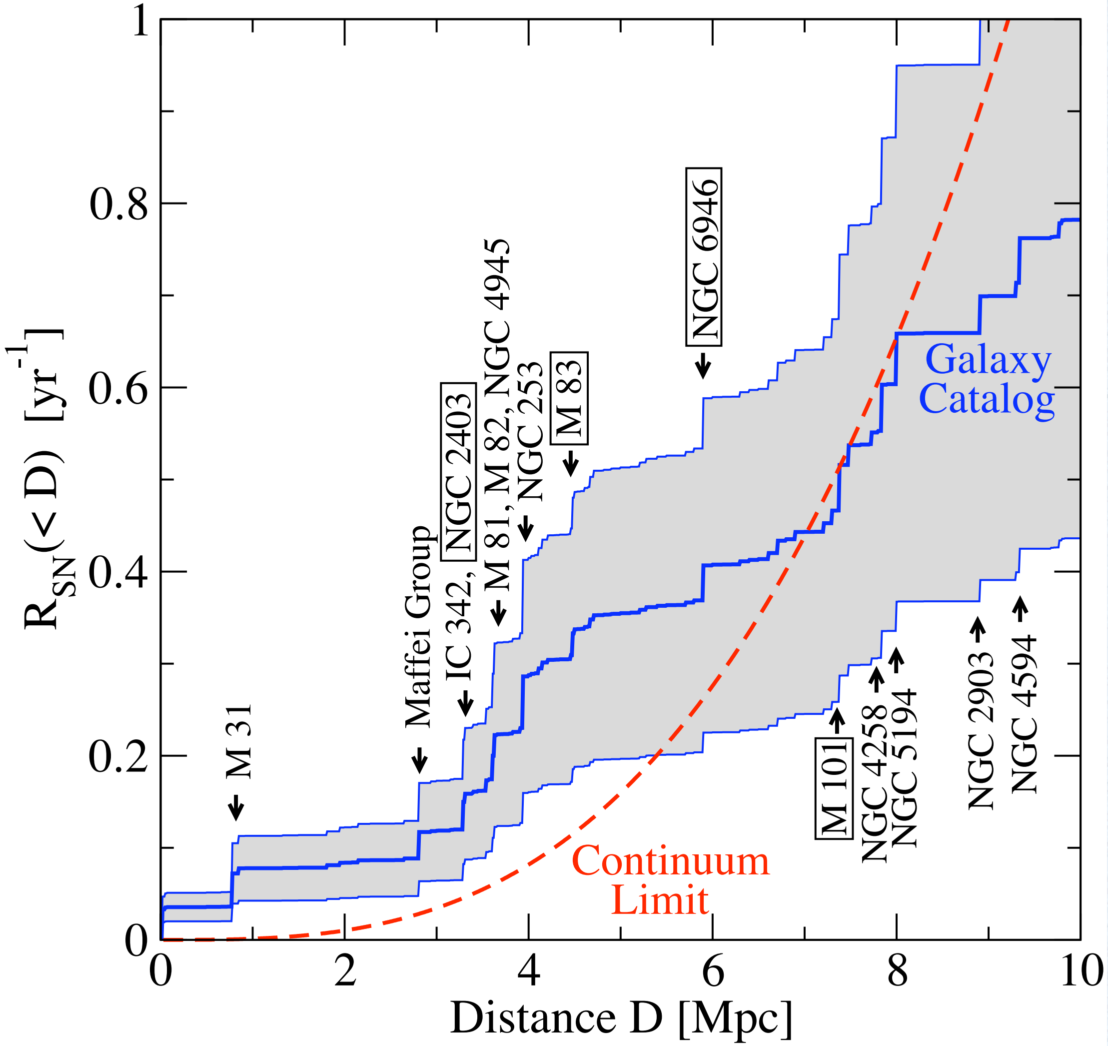
Implication: Constraining Supernova Parameters

Jegerlehner, Neubig, Raffelt, *PRD* **54**, 1194 (1996)



- Constraint on binding energy E_b and temperature T, from neutrino observation from SN 1987A
- Results of two detectors are not consistent with each other
- Numerical simulation predicts: $E_b = 3\times10^{53}$ erg, $T = 5$ MeV

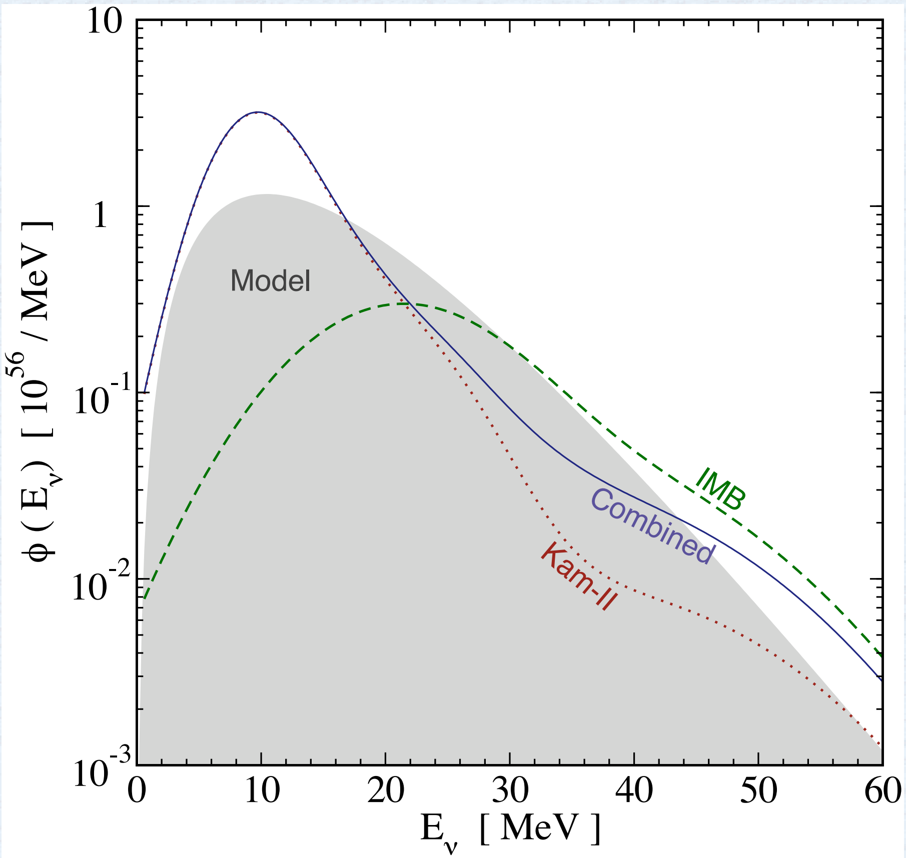
Nearby Supernova Rate



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

Estimate from SN 1987A

Yüksel, Beacom, astro-ph/0702613



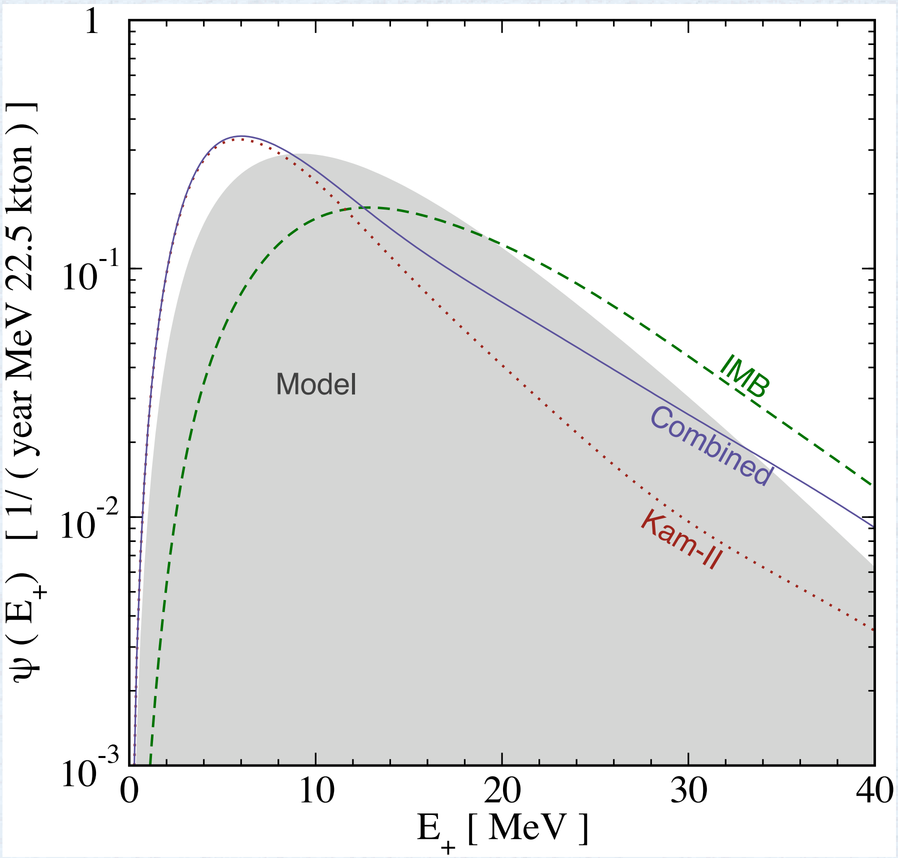


FIG. 2: The inferred neutrino emission spectra from either the Kam-II or IMB data sets alone or their combination, as discussed in the text (taking into account the corresponding effective number of targets and cross section). The shaded shape is a Fermi-Dirac spectrum with canonical neutrino emission parameters (average energy $E_0 = 15$ MeV and time-integrated luminosity $L = 5 \times 10^{52}$ erg).

FIG. 3: The DSNB detection spectra based on the neutrino spectra inferred from either the Kam-II or IMB data sets alone or their combination as in Fig. 2, compared to a model (shaded shape) with canonical neutrino emission parameters (the assumed core-collapse SN history is described in the text).