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Supernova Burst and Relic Neutrino

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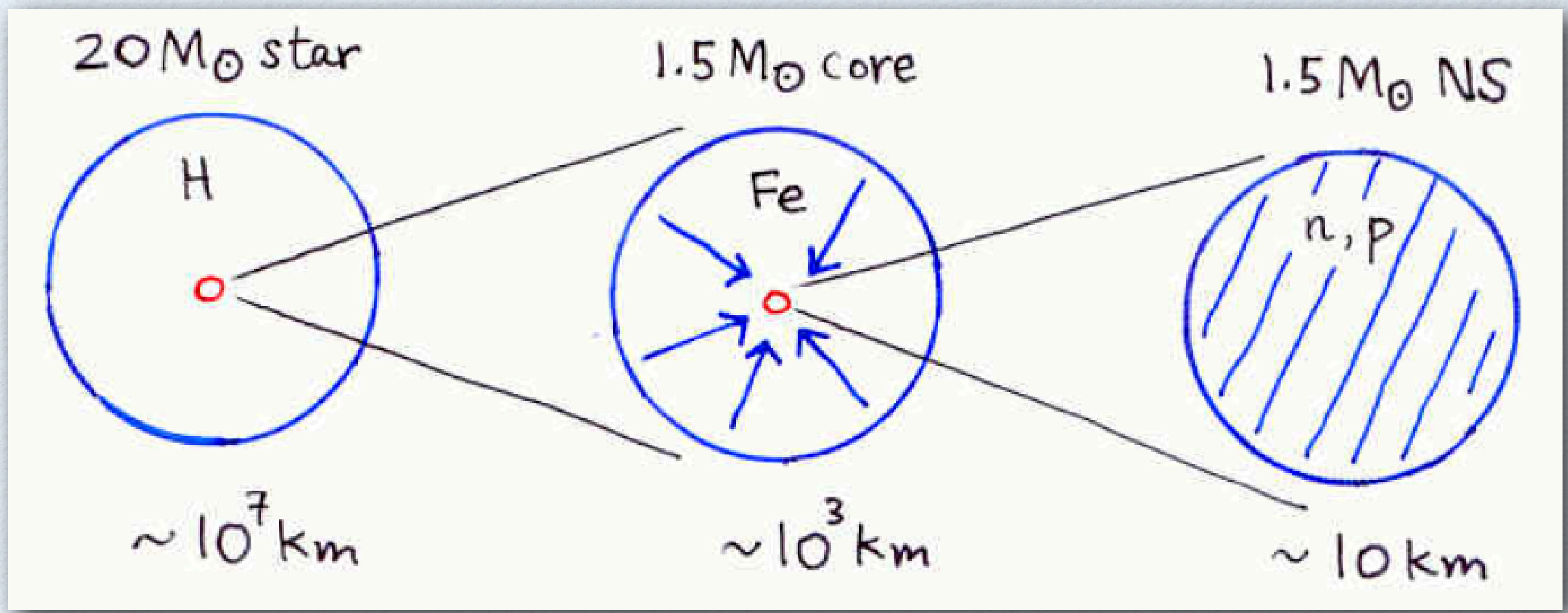
3. Supernova Rate in the Milky Way
4. Diffuse Neutrino Background from Cosmological Supernovae

1. Introduction

Core-Collapse Supernova Explosion



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

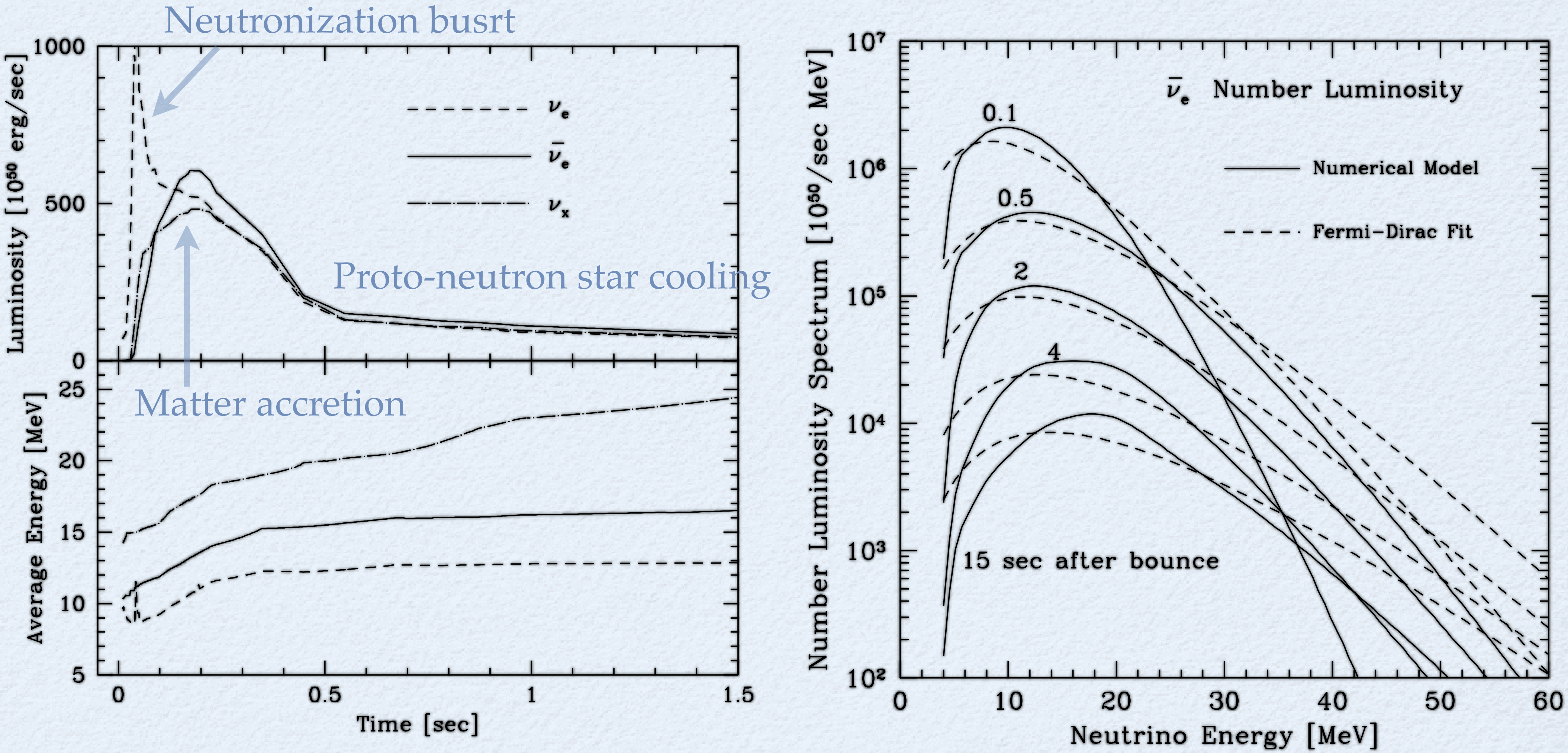
$$E_b = \frac{GM_{\rm NS}^2}{R_{\rm NS}} = 3 \times 10^{53} \text{ erg}$$

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

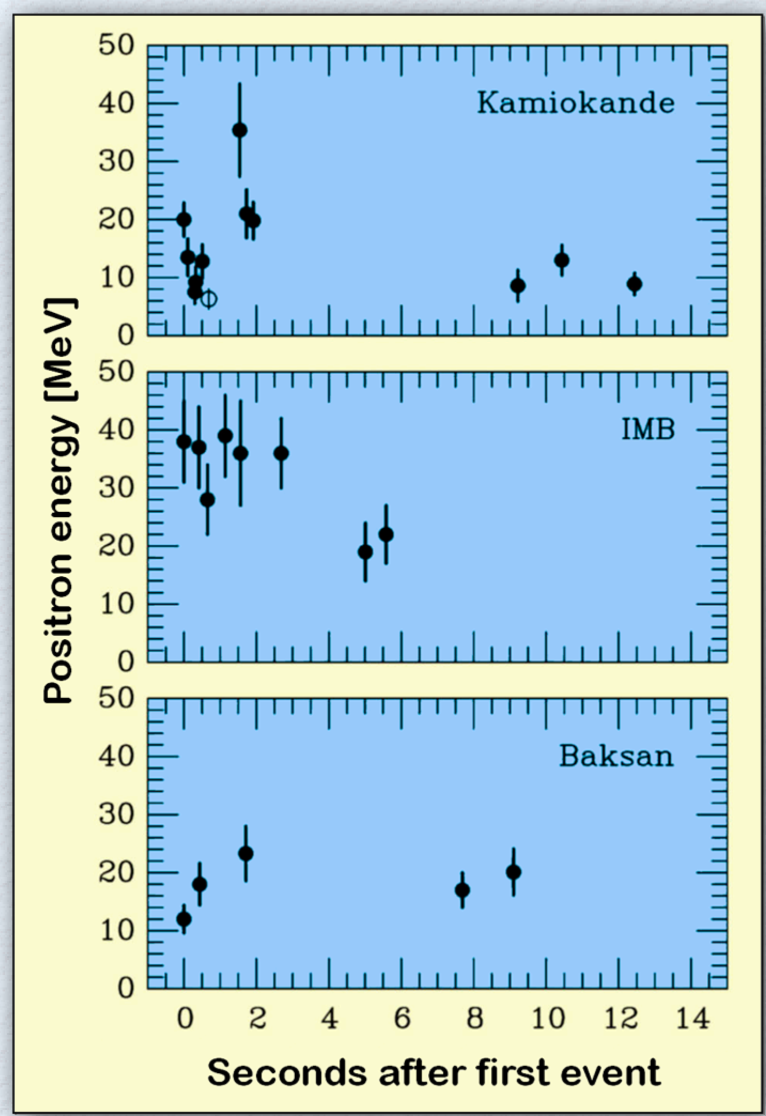
Supernova Neutrinos: Simulation



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

Supernova 1987A

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



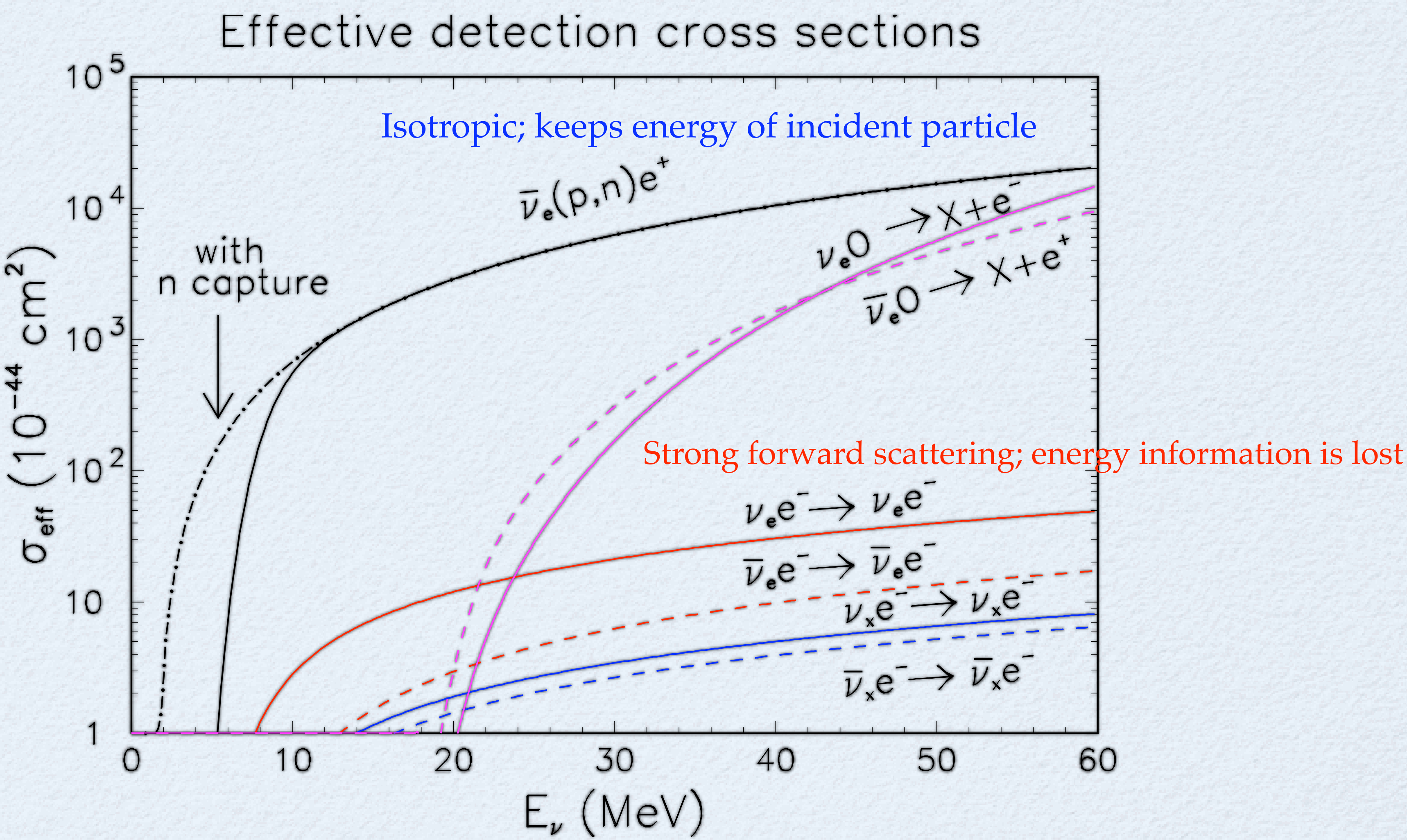
Hirata et al., *PRL* **58**, 1490 (1987); Bionta et al., *PRL* **58**, 1494 (1987)

2. Galactic Supernova Neutrino Burst

What Observation Tells Us

Supernova Physics	Neutrino Physics
Temperature and binding energy of proto-neutron stars, and EOS of high dense matter Jegerlehner et al. 1996; Kachelriess et al. 2001	Oscillation parameters, mass hierarchy Dighe & Smirnov 2000; Takahashi et al. 2001, 2003b,c; Fogli et al. 2002; Dighe et al. 2004
Explosion mechanism, shock propagation, and black hole formation Totani et al. 1998; Beacom et al. 2001; Takahashi et al. 2003a; Tomas et al. 2004; Fogli et al. 2003, 2005	Majorana magnetic moment Athar et al. 1995; Totani & Sato 1996; Nunokawa et al. 1997, 1999; Ando & Sato 2003a,b,c; Akhmedov & Fukuyama 2003
Locating supernova direction Beacom & Vogel 1999; Ando & Sato 2002; Tomas et al. 2003	Non-radiative neutrino decay Frieman et al. 1988; Raghavan et al. 1988; Ando 2004

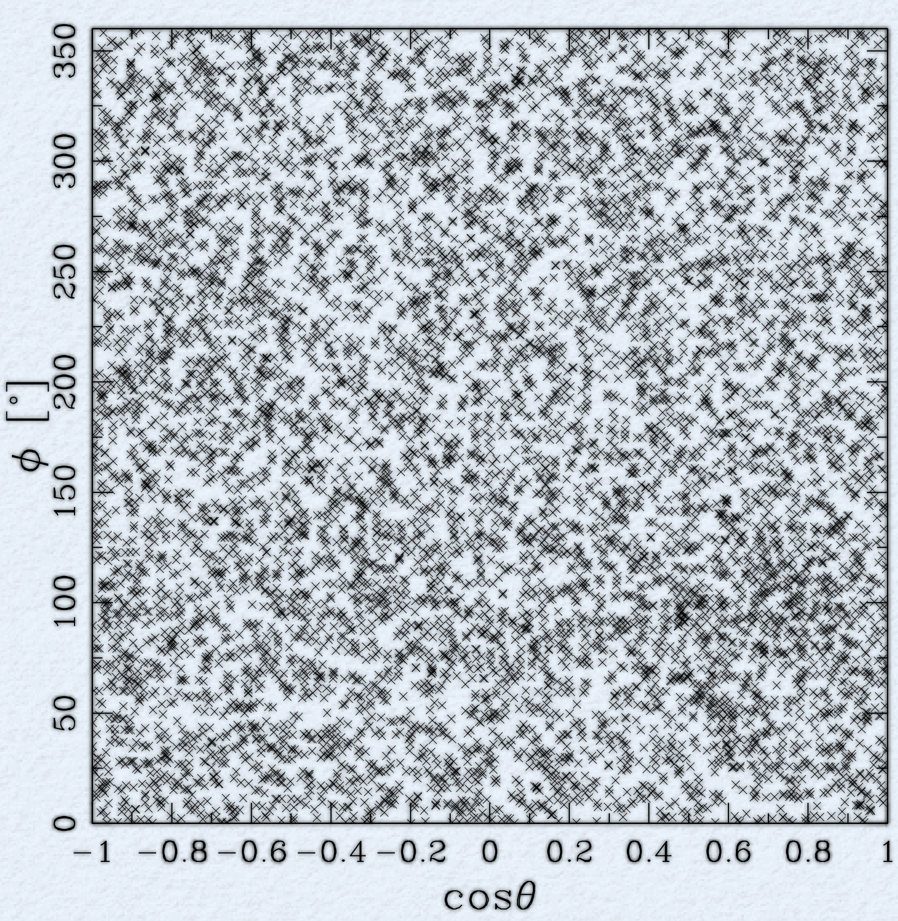
Reactions in Water Cerenkov Detectors

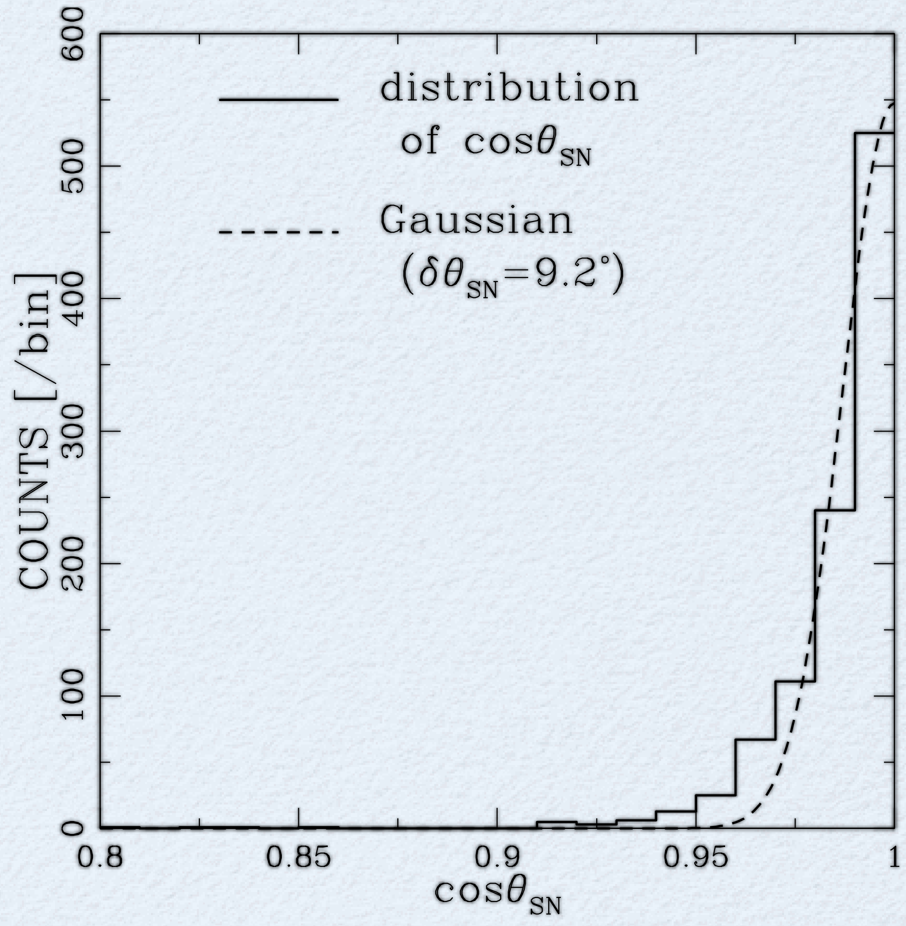


Fogli, Lisi, Mirizzi, Montanino, *JCAP* **0504**, 002 (2005)

Directional Distribution: Early Alert

Ando, Sato, *PTP* **107**, 957 (2002)



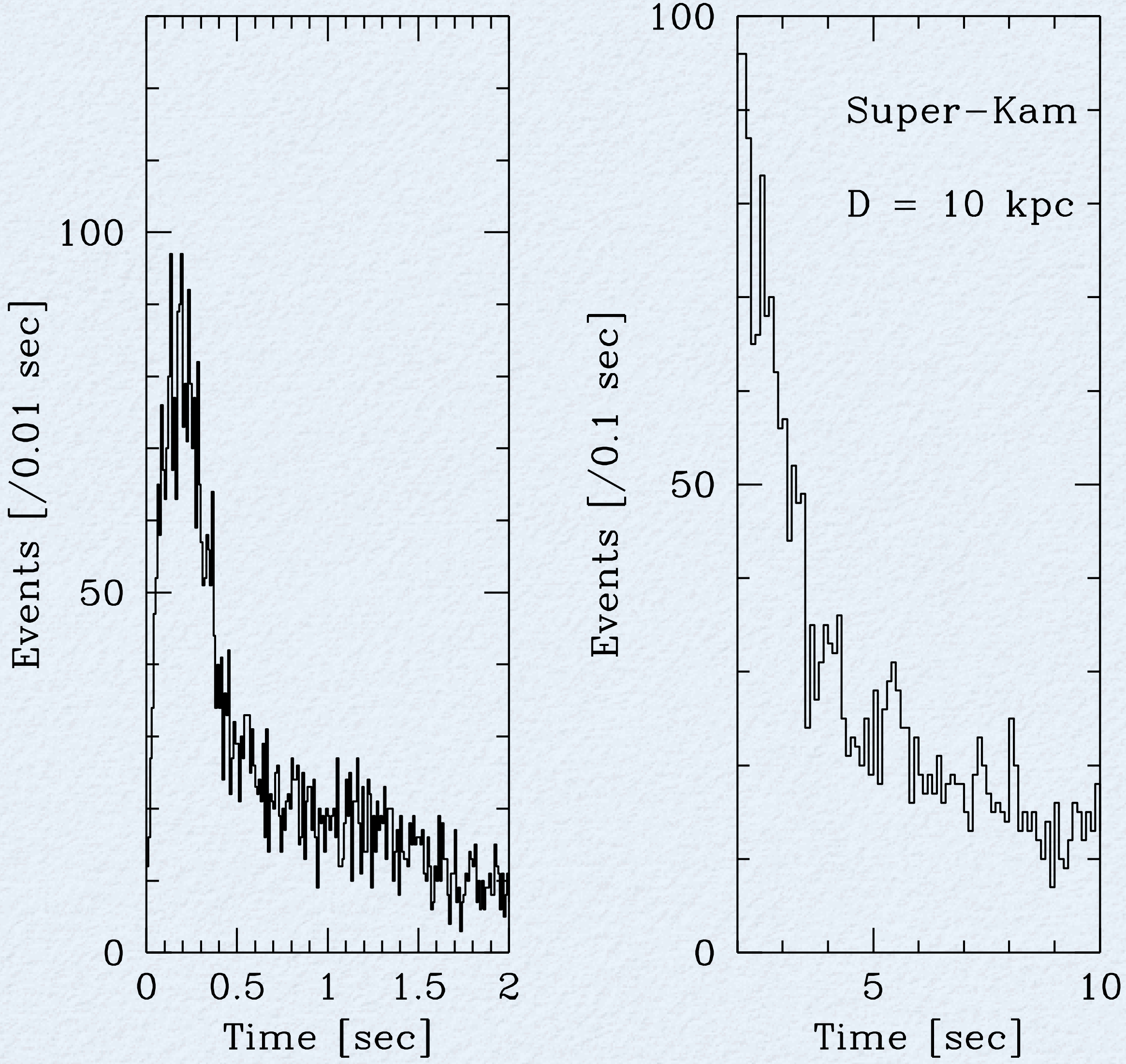


We can predict direction of optical explosion with accuracy of ~5–10 deg, *several hours in advance*

See also: Beacom, Vogel 1999; Tomas et al. 2003

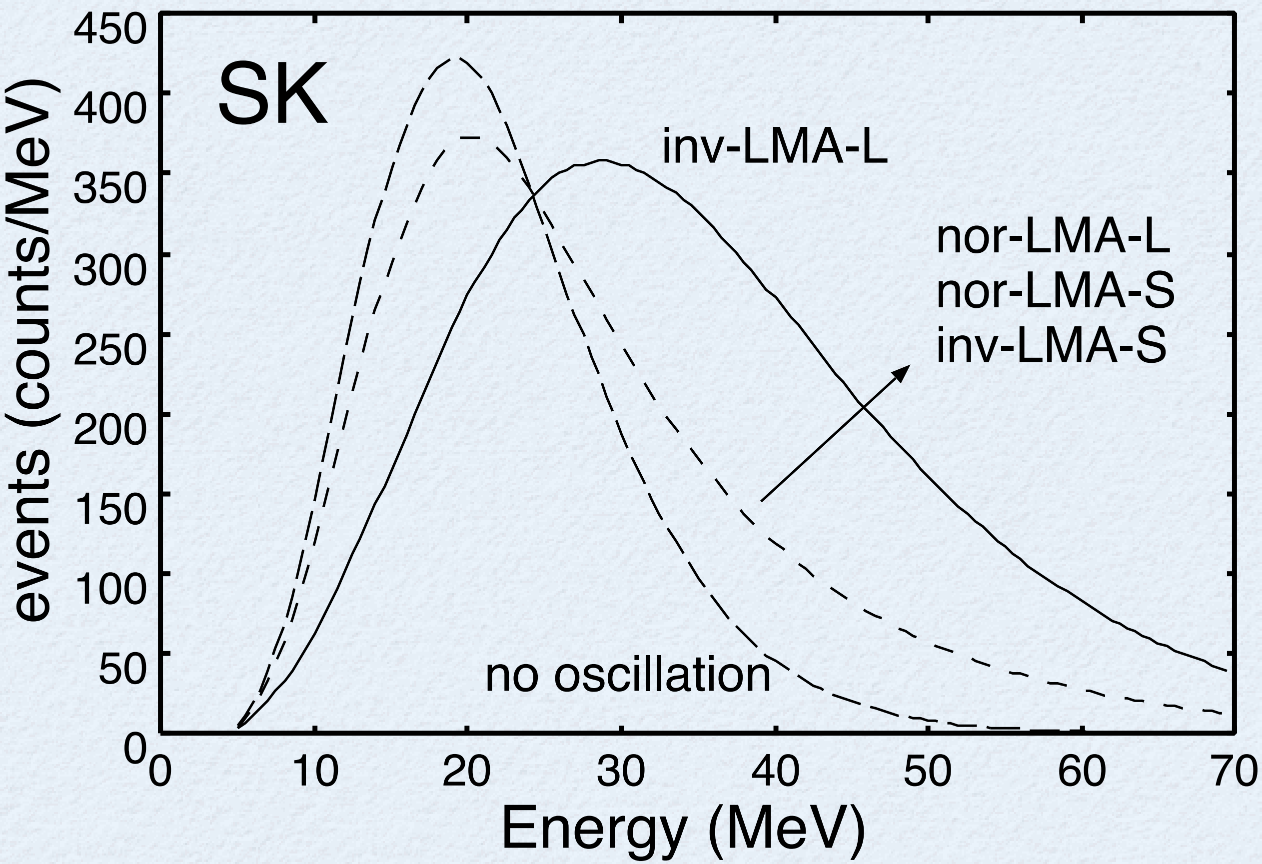
Time Distribution: Explosion Mechanism

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



- Evidence of accretion phase, in the case of delayed explosion
- Implication for explosion mechanism
- Black hole formation or shock wave propagation may also be probed

Energy Distribution: Core Temperature and Oscillation Models



Takahashi, Sato, *PTP* **109**, 919 (2003)

- Measurement of temperature of neutrinosphere
- Mixture of thermal distributions with different two temperatures
- Oscillation model can also be probed

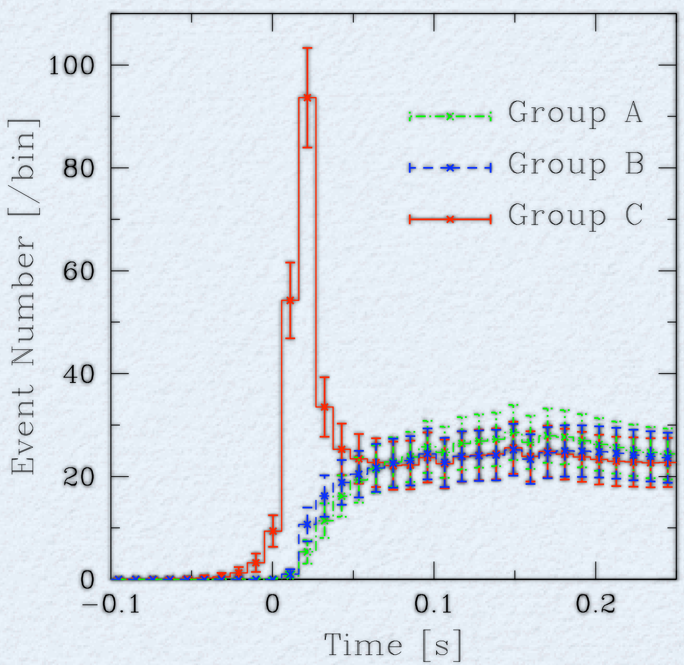
Advanced Topic: Magnetic Moment

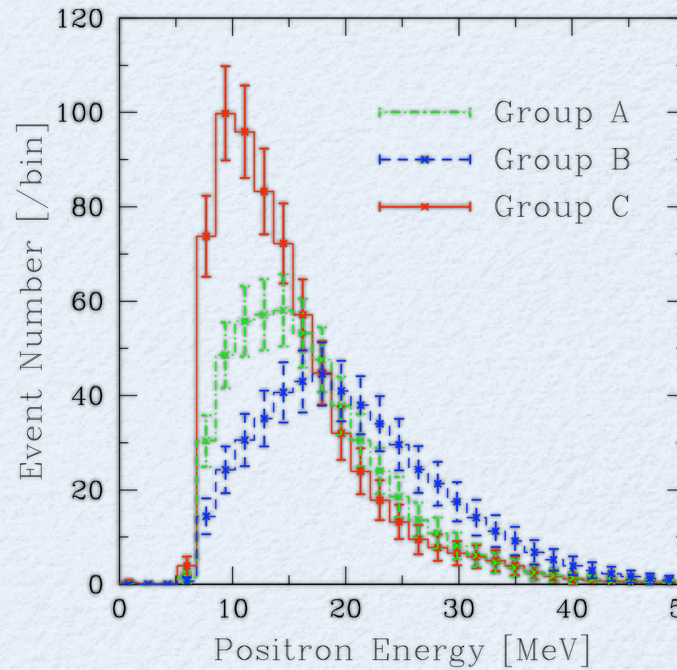
Ando, Sato, *JCAP* **0310**, 001 (2003)

Green: Group A
Blue: Group B
Red: Group C

Model	B_0 (G)	Mass hierarchy	$\sin^2 2\theta_{13}$
MSW-NOR-S	0	Normal	10^{-6}
MSW-NOR-L	0	Normal	0.04
MSW-INV-S	0	Inverted	10^{-6}
MSW-INV-L	0	Inverted	0.04
RSF-NOR-S	10^{10}	Normal	10^{-6}
RSF-NOR-L	10^{10}	Normal	0.04
RSF-INV-S	10^{10}	Inverted	10^{-6}
RSF-INV-L	10^{10}	Inverted	0.04

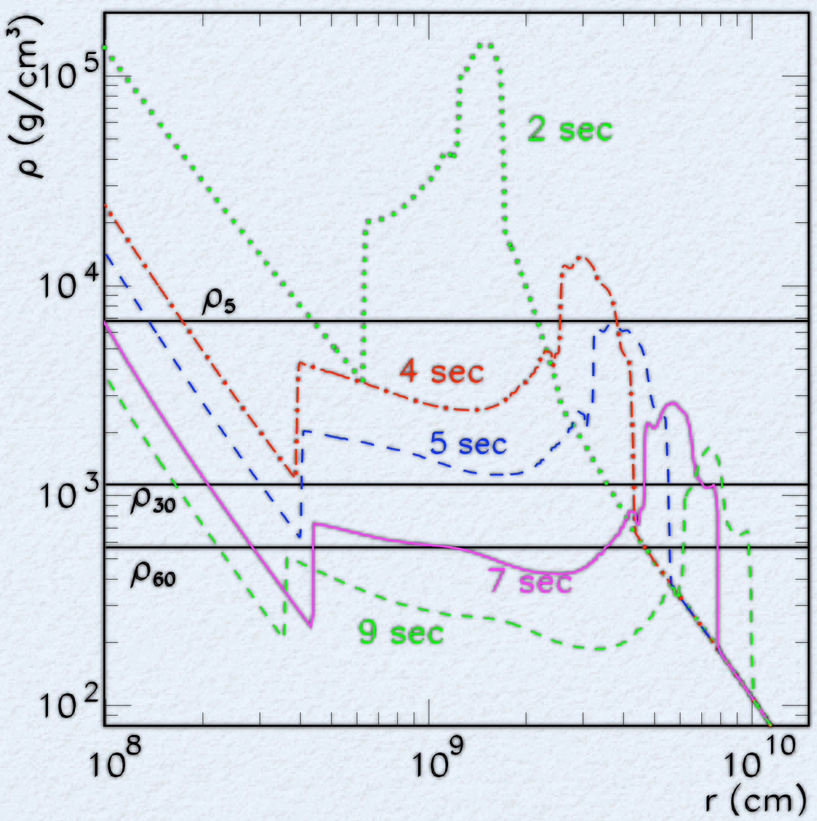
$\mu_\nu = 10^{-12}\,\mu_B$

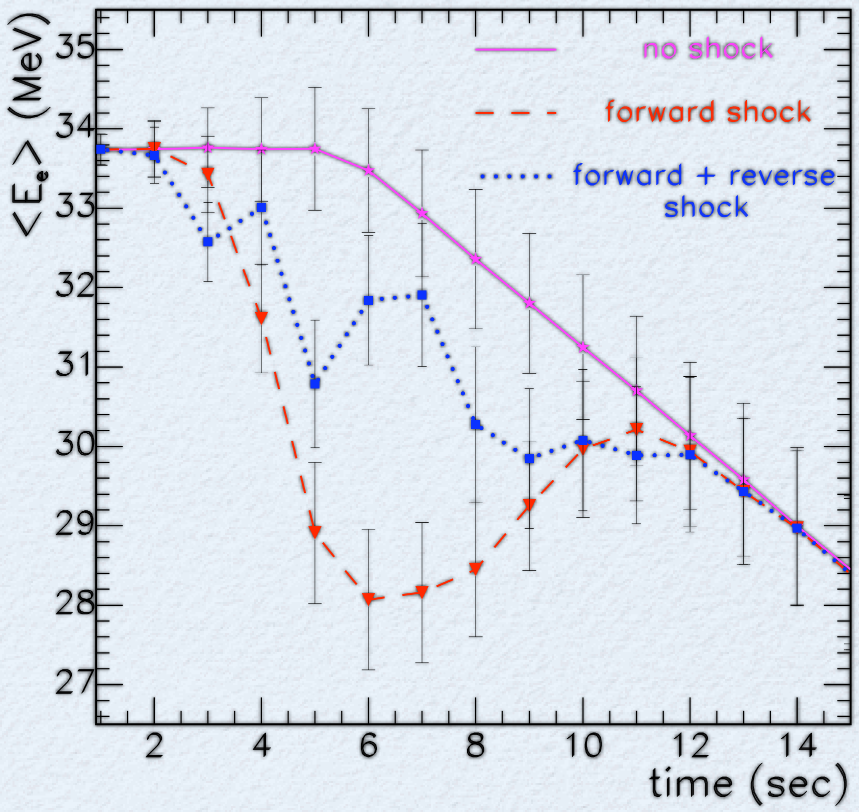




Advanced Topic: Shock Waves

Tomàs, Kachelriess, Raffelt, Dighe, Janka, Scheck, *JCAP* **0409**, 015 (2004)





This method is applicable *only* in the case of inverted hierarchy with large θ_{13} .

Galactic Supernova Neutrino Burst: Summary

- Super-K can detect 10,000 neutrino events
- We can locate a supernova in advance with accuracy of 5–10 degrees, using neutrino directional distribution
- Time evolution tells us explosion mechanisms, shock wave propagation, or black hole formation
- Energy distribution reflects core temperature and flavor conversion inside the supernova envelope

3. Supernova Rate in the Milky Way

Galactic Supernova Rate Estimates

- Extragalactic scaling
- Historic supernova record
- Galactic gamma-ray emission
- Neutrino burst
- And others...

Extragalactic Scaling

- Using supernova database
- Depends on type of supernovae and morphological types of galaxies

Cappellaro, Turatto, astro-ph/0012455

Table 1. The local SN rates. Units are $SNu = \mathrm{SN}/10^{10}\mathrm{L}_{\odot,\mathrm{B}}/100\mathrm{yr}$. $\mathrm{h}=\mathrm{H}_0/100$.

galaxy	SN type			
type	Ia	Ib/c	II	All
E-S0	$0.32 \pm .11\ h^2$	$< 0.02\ h^2$	$< 0.04\ h^2$	$0.32 \pm .11\ h^2$
S0a-Sb	$0.32 \pm .12\ h^2$	$0.20 \pm .11\ h^2$	$0.75 \pm .34\ h^2$	$1.28 \pm .37\ h^2$
Sbc-Sd	$0.37 \pm .14\ h^2$	$0.25 \pm .12\ h^2$	$1.53 \pm .62\ h^2$	$2.15 \pm .66\ h^2$
All	$0.36 \pm .11\ h^2$	$0.14 \pm .07\ h^2$	$0.71 \pm .34\ h^2$	$1.21 \pm .36\ h^2$

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- For Milky Way (Sb-Sbc), $L_B = 2.3\times10^{10}\ L_{sun,B}$, core-collapse SN rate is 1.5 / century

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- For Milky Way (Sb-Sbc), $L_B = 2.3\times10^{10}\ L_{sun,B}$, core-collapse SN rate is 1.5 / century
- Note, however, that this estimate completely neglects highly dust-extinguished SNe

Historic Supernova Record

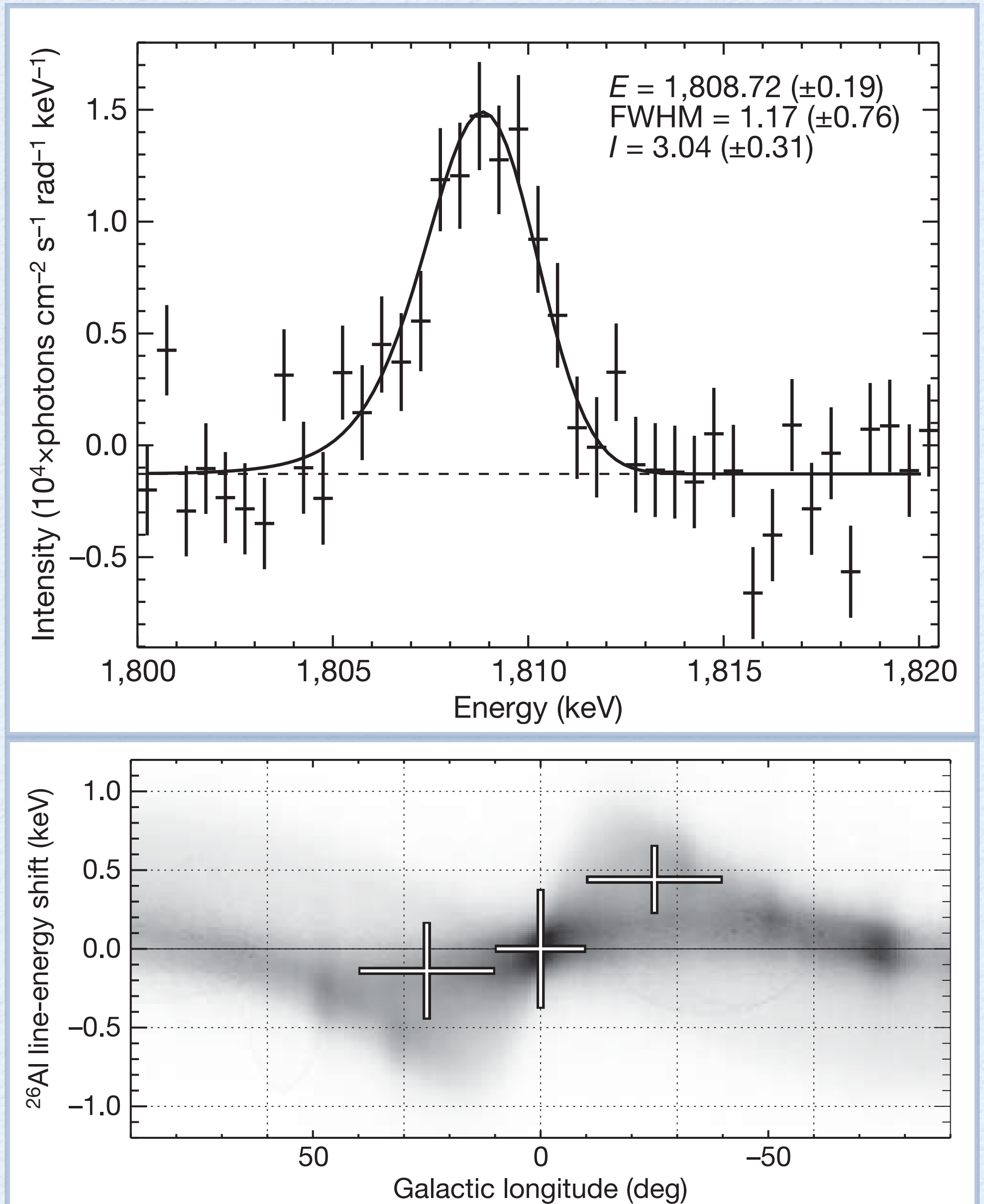
Strom, *A&A* **288**, L1 (1994)

Year of SN	Land*	Duration (d)	Remnant	d (kpc)	D (pc)	b (°)	z (pc)	Age (yr)
1604 AD	C,K	330	Kepler	4.4	4.1	+6.8	525	375
386 AD	C	90	G 11.2−0.3	5	5.8	−0.3	26	1595
§	—	—	Cas A	2.8	4.1	−2.1	103	315
1572 AD	C,K	480	Tycho	2.3	5.6	+1.4	56	410
1181 AD	C,J	185	3C 58	2.6	6.8	+3.1	141	800
1054 AD	C,J	540	Crab	2	4.1	−5.8	203	930
—	—	—	G 292.0+1.8	3.6	12.6	+1.8	113	—
185 AD	C	$\geq$ 140	MSH 14−63	0.95	12.4	−2.3	38	1795
1006 AD	C,J,K?	240	PKS 1459−41	1.4	12.2	+14.6	365	975
—	—	—	RCW 103	3.3	8.6	−0.4	23	—
393 AD	C	210	—	—	—	$\lesssim$ 5	—	—

- Correcting for incompleteness of the record
- SN (I+II) rate of 5.7±1.7 / century

Galactic Gamma-Ray Emission

Diehl et al., *Nature* **439**, 45 (2006)



- 1.8 MeV ^{26}Al line by INTEGRAL
- Penetrating over the full Galaxy
- Snapshot of ***current*** massive star death
- This implies core-collapse SN rate of 1.9±1.1 / century

Some Other Methods

- Free-free radio emission from HII regions around massive stars
- Reprocessed FIR emission due to warm dust
- Radio supernova remnant statistics
- Number count of pulsars
- Number count of OB stars
- Etc...

Summary of Galactic Supernova Rate

Diehl et al., *Nature* **439**, 45 (2006)

Authors	SFR [$M_\odot y^{-1}$]	SNR [century^{-1}]	Comments
Smith et al. 1978	**5.3**	2.7	
Talbot 1980	**0.8**	0.41	
Guesten et al. 1982	**13.0**	6.6	
Turner 1984	**3.0**	1.53	
Mezger 1987	**5.1**	2.6	
McKee 1989	**3.6** (R) **2.4** (IR)	1.84 1.22	
van den Bergh 1990	2.9 ± 1.5	**1.5 ± 0.8**	„the best estimate“
van den Bergh & Tammann 1991	7.8	**4**	extragalactic scaling
Radio Supernova Remnants	6.5 ± 3.9	**3.3 ± 2.0**	very unreliable
Historic Supernova Record	11.4 ± 4.7	**5.8 ± 2.4**	very unreliable
Cappellaro et al. 1993	2.7 ± 1.7	**1.4 ± 0.9**	extragalactic scaling
van den Bergh & McClure 1994	4.9 ± 1.7	**2.5 ± 0.9**	extragalactic scaling
Pagel 1994	**6.0**	3.1	
McKee & Williams 1997	**4.0**	2.0	used for calibration
Timmes, Diehl, Hartmann 1997	5.1 ± 4	**2.6 ± 2.0**	based on ^{26}Al method
Stahler & Palla 2004	**4 ± 2**	2 ± 1	Textbook
Reed 2005	2-4	**1-2**	
Diehl et al. 2005	3.8 ± 2.2	**1.9 ± 1.1**	this work

Table 1: *Star formation and core-collapse supernova rates from different methods.*

- All methods converge at R_{SN} ~ a few / century, but could be even larger
- No neutrino burst in the last 25 years sets upper limit: < 9.2 / century (90% CL)

  Alekseev & Alekseeva 2002; Raffelt 2007
- Highly Poisson regime

Galactic Supernova Forecast

Probability to have Galactic SNe in the next decades

- 1 / century
- 2 / century
- 3 / century
- 5 / century

Galactic Supernova Forecast

Probability to have Galactic SNe in the next decades

Galactic Supernova Forecast

Probability to have Galactic SNe in the next decades

Galactic Supernova Forecast

Probability to have Galactic SNe in the next decades

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Galactic Supernova Forecast

Probability to have Galactic SNe in the next decades

4. Diffuse Neutrino Background from Cosmological Supernovae

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 $(2\text{–}10) \times 10^{-33}$ 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 $\sim 10^2\text{–}10^6$ sec if the neutrino rest mass is 0–30 eV, and the relative pulsation amplitude would be $\sim 10^{-2}\text{–}10^{-4}$.

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‡

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† Department of Physics, Boston University, Boston, Massachusetts 02215, USA
‡ Department of Physics and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA

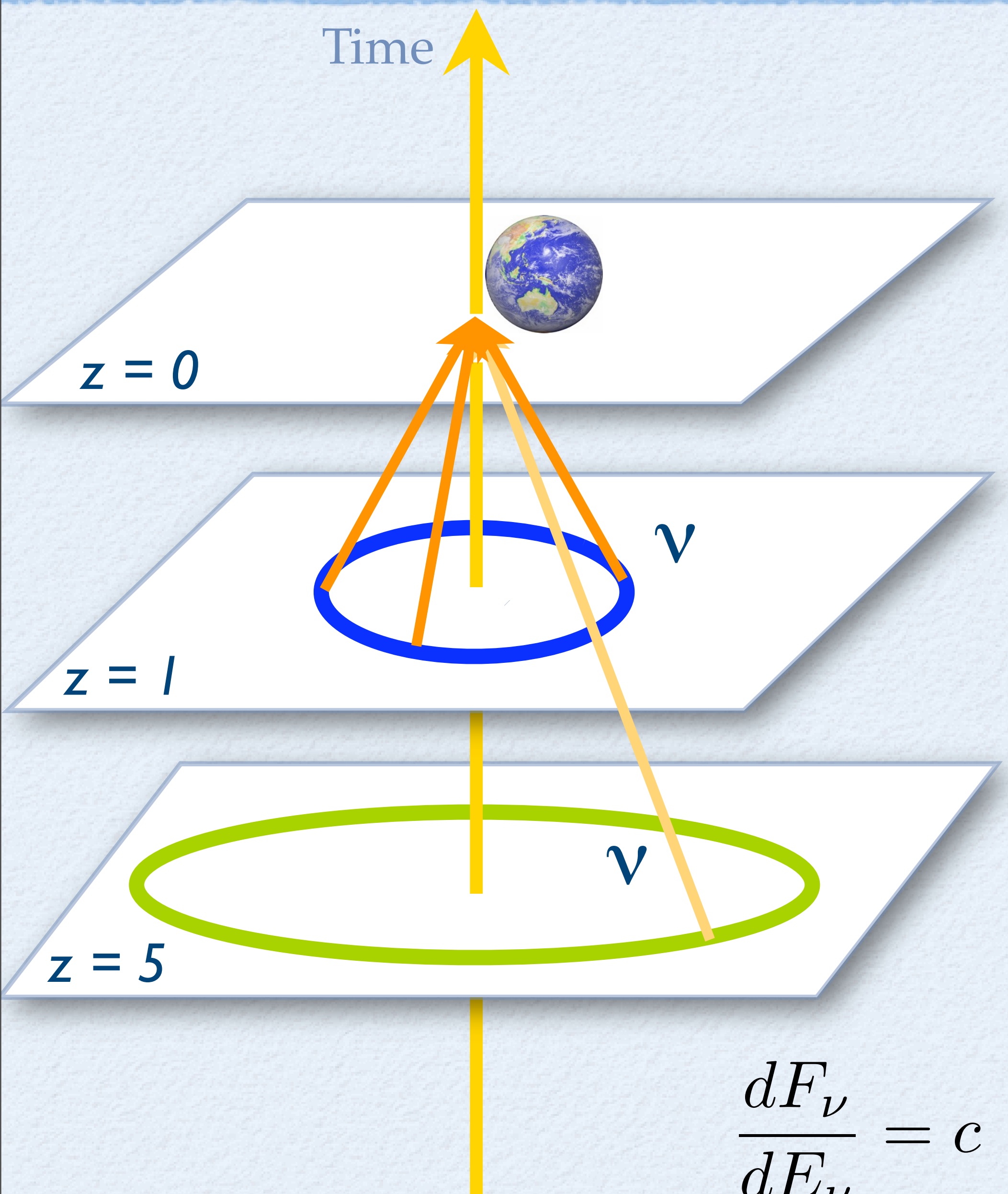
Radioactive decays inside the Earth produce antineutrinos that may be detectable at the surface. Their flux and spectrum contain important geophysical information. New detectors need to be developed, discriminating between sources of antineutrinos, including the cosmic-background. The latter can be related 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
- Neutrino properties as elementary particles
  - Neutrino oscillation
    - Ando & Sato 2003
  - Neutrino decay (i.e., coupling with unknown particle)
    - Ando 2003; Fogli, Lisi, Mirizzi & Montanino 2004

Basic Picture

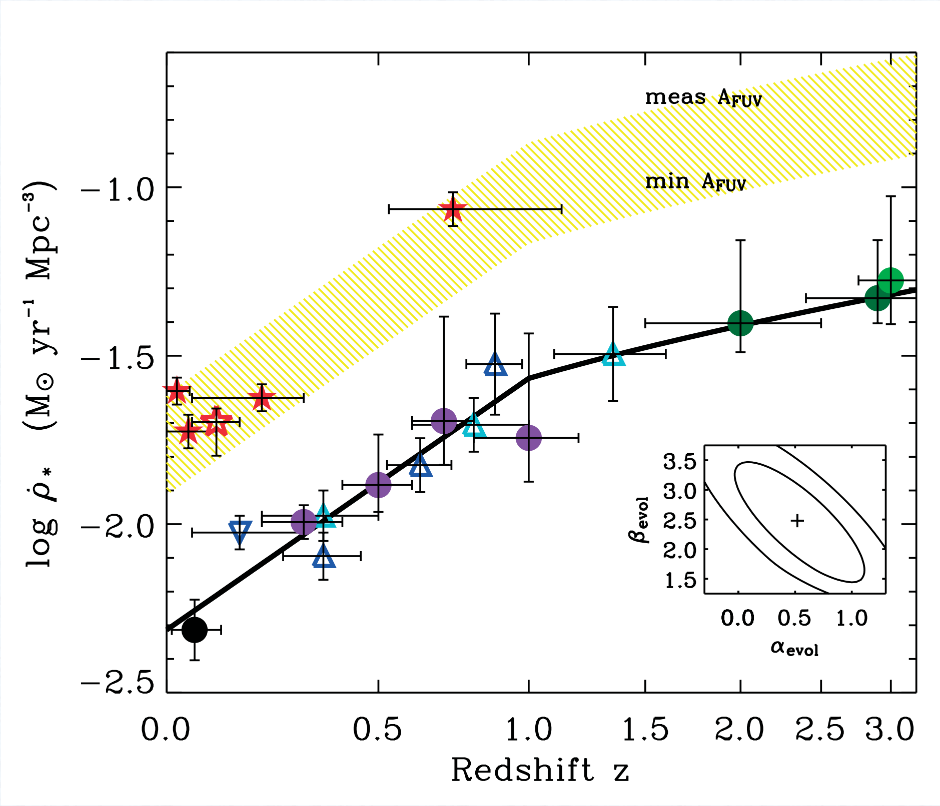


Required Physics:

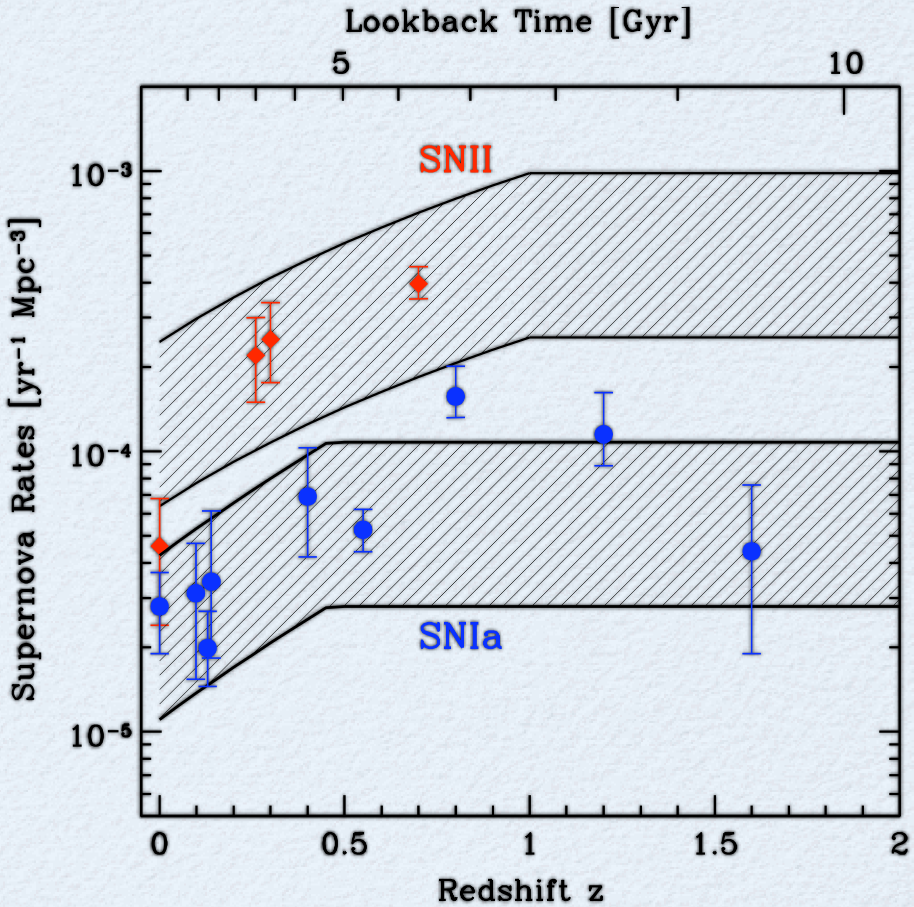
1. Neutrino spectrum from each supernovae
2. Neutrino oscillation during propagation in supernova envelope
3. Supernova rate

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

Star Formation and Supernova Rate

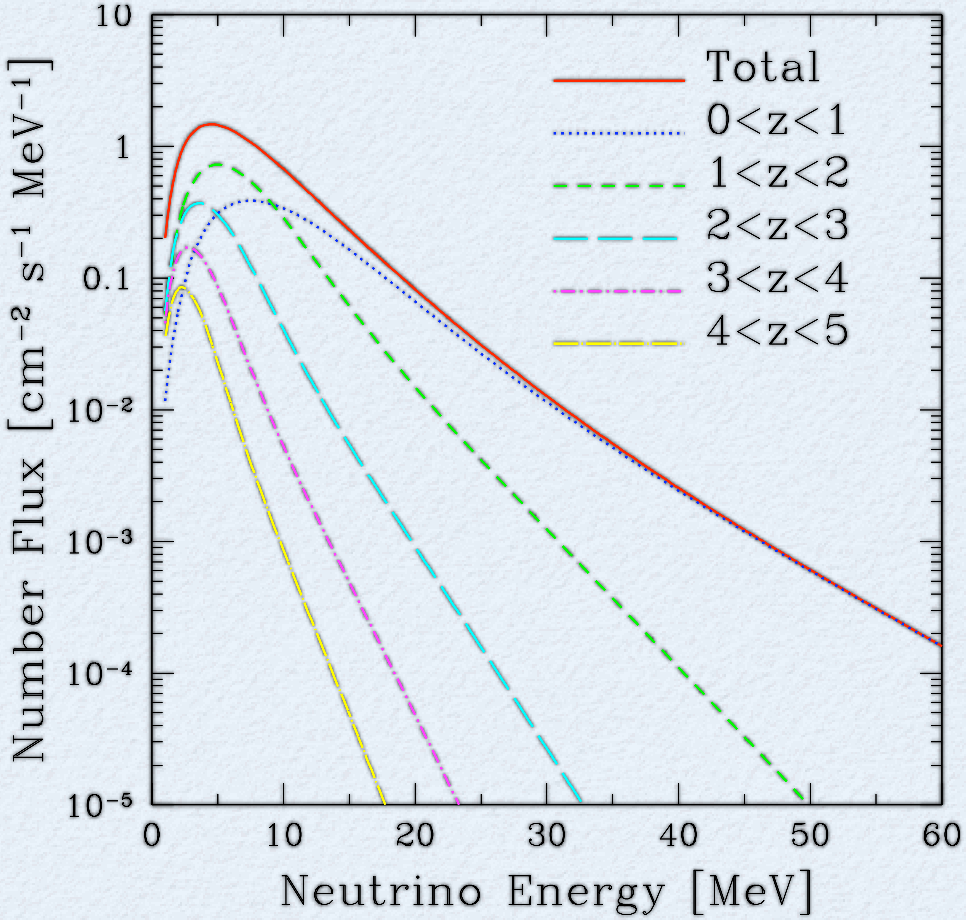


Schiminovich et al., *ApJ* **619**, L47 (2005)



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

Flux and Even Rate

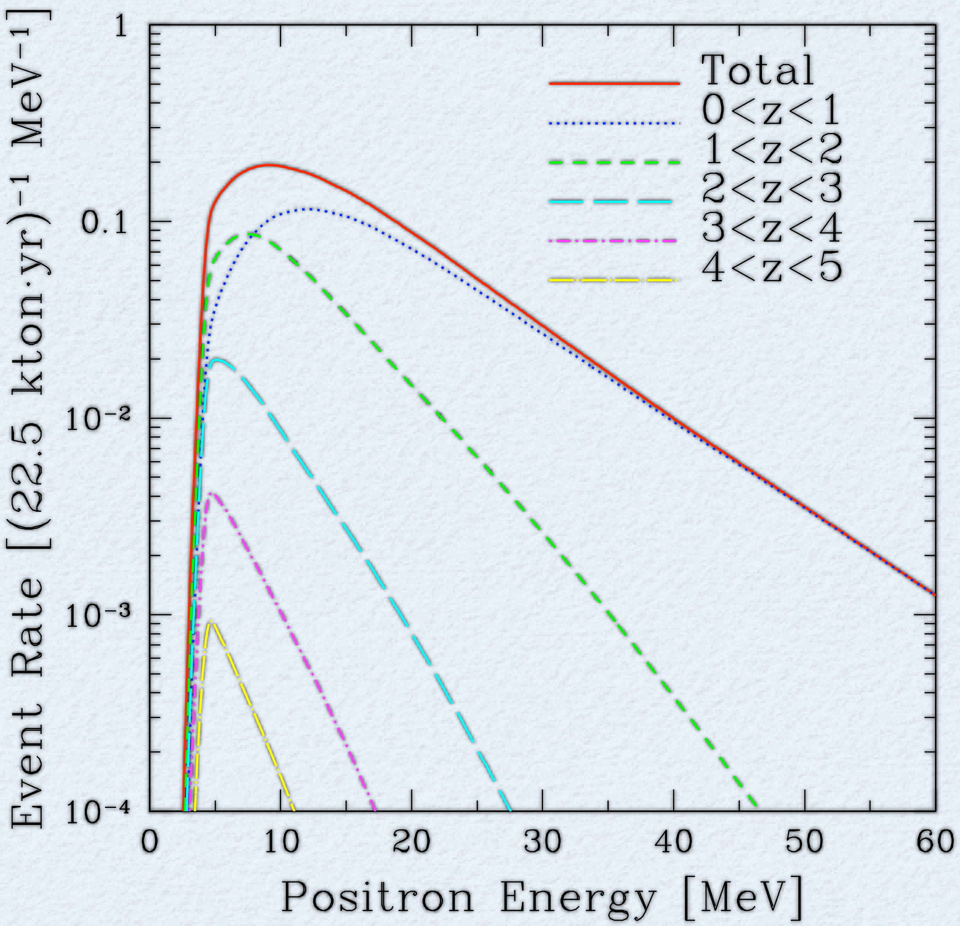


Ando, *Astrophys. J.* **607**, 20 (2004)

- 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)

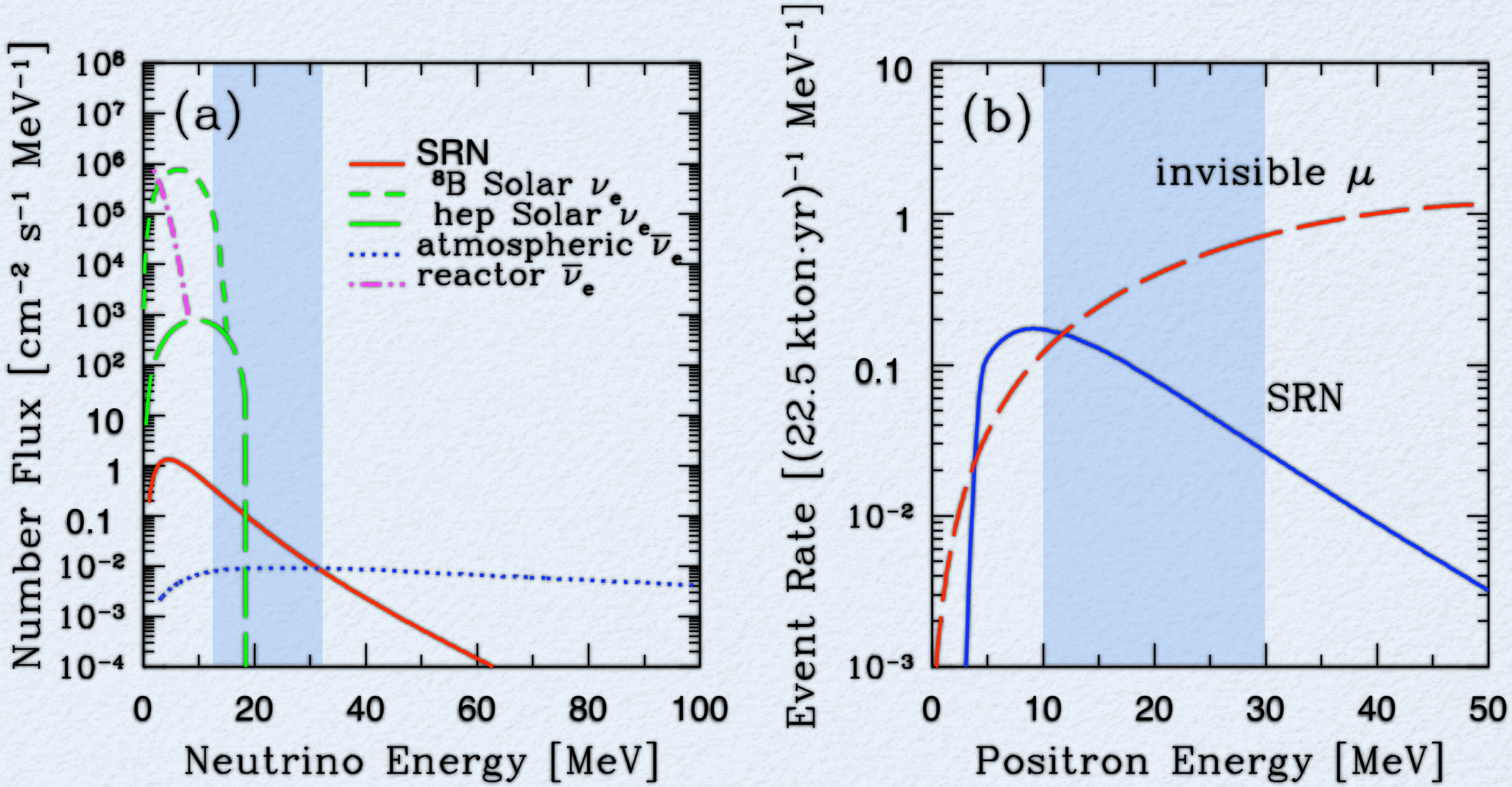
- Flux ($cm^{-2}\ s^{-1}$)

$E_\nu > 11.3$ 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	$< 31\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$11\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	$0.43\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

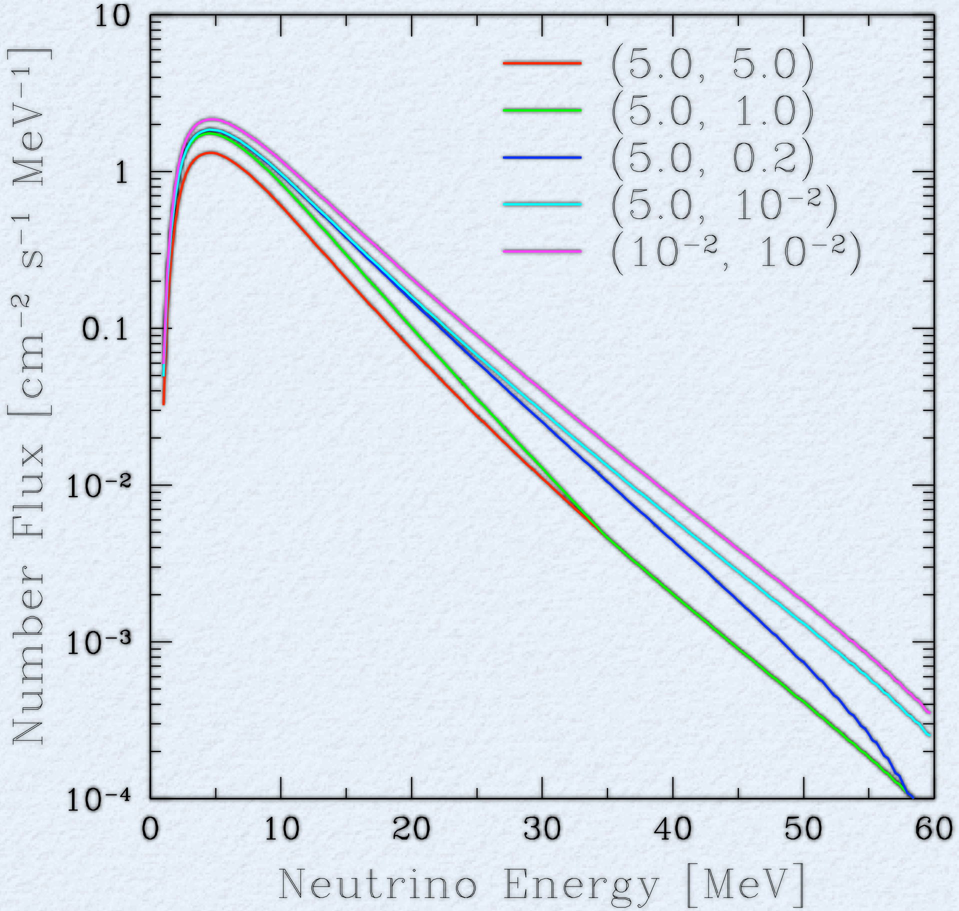
Flux upper limit: 1.2 $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (> 19.3 MeV, 90% C.L.)

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

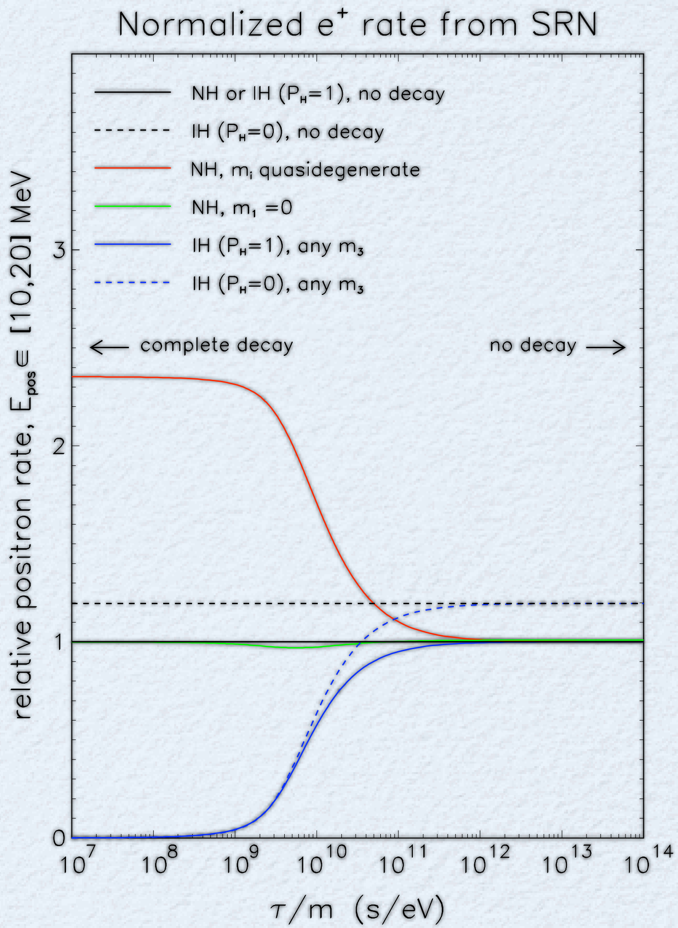
	Integral Flux ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)		Flux 22.9 MeV $< E_\nu <$ 36.9 MeV ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	
Model	Prediction	Upper Limit	Prediction	Upper Limit
B&S : $T = 4$ MeV	21.1	1.1×10^4	0.19	93
B&S : $T = 6$ MeV	14.1	1.5×10^3	0.66	72
B&S : $T = 8$ MeV	10.5	6.0×10^2	1.08	61
A&S : 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

Implication: Longest Baseline Experiment

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

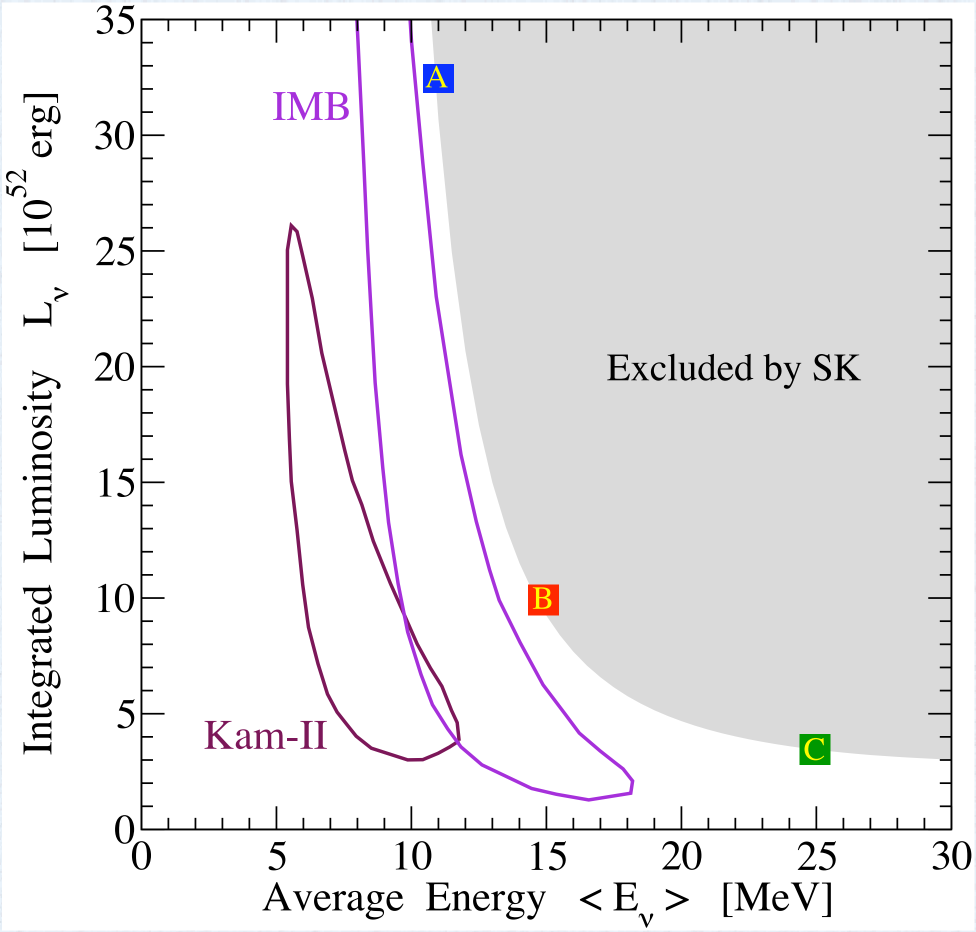


Ando, *PLB* **570**, 11 (2003)



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

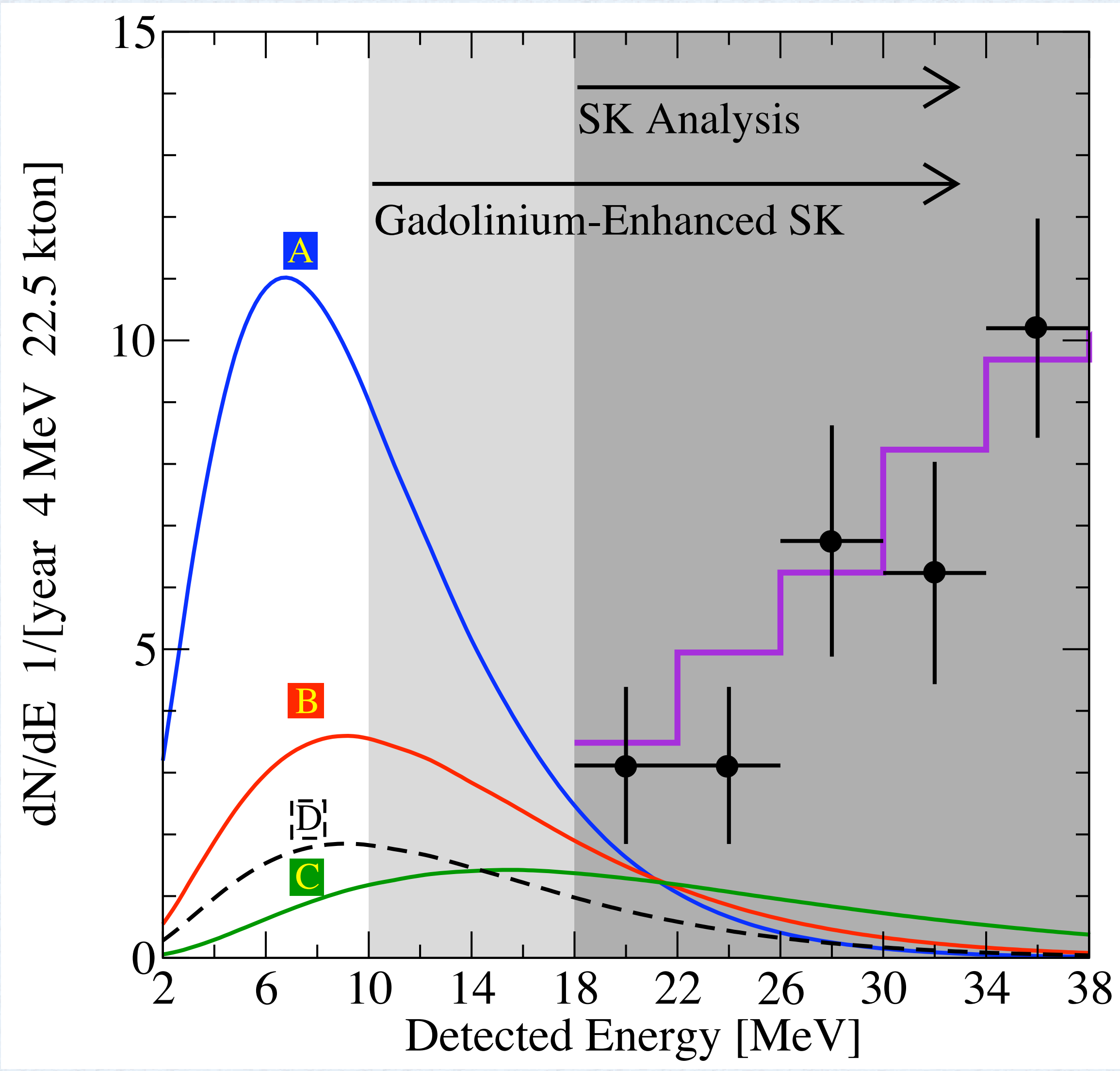
Implication: Constraining Supernova Parameters



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

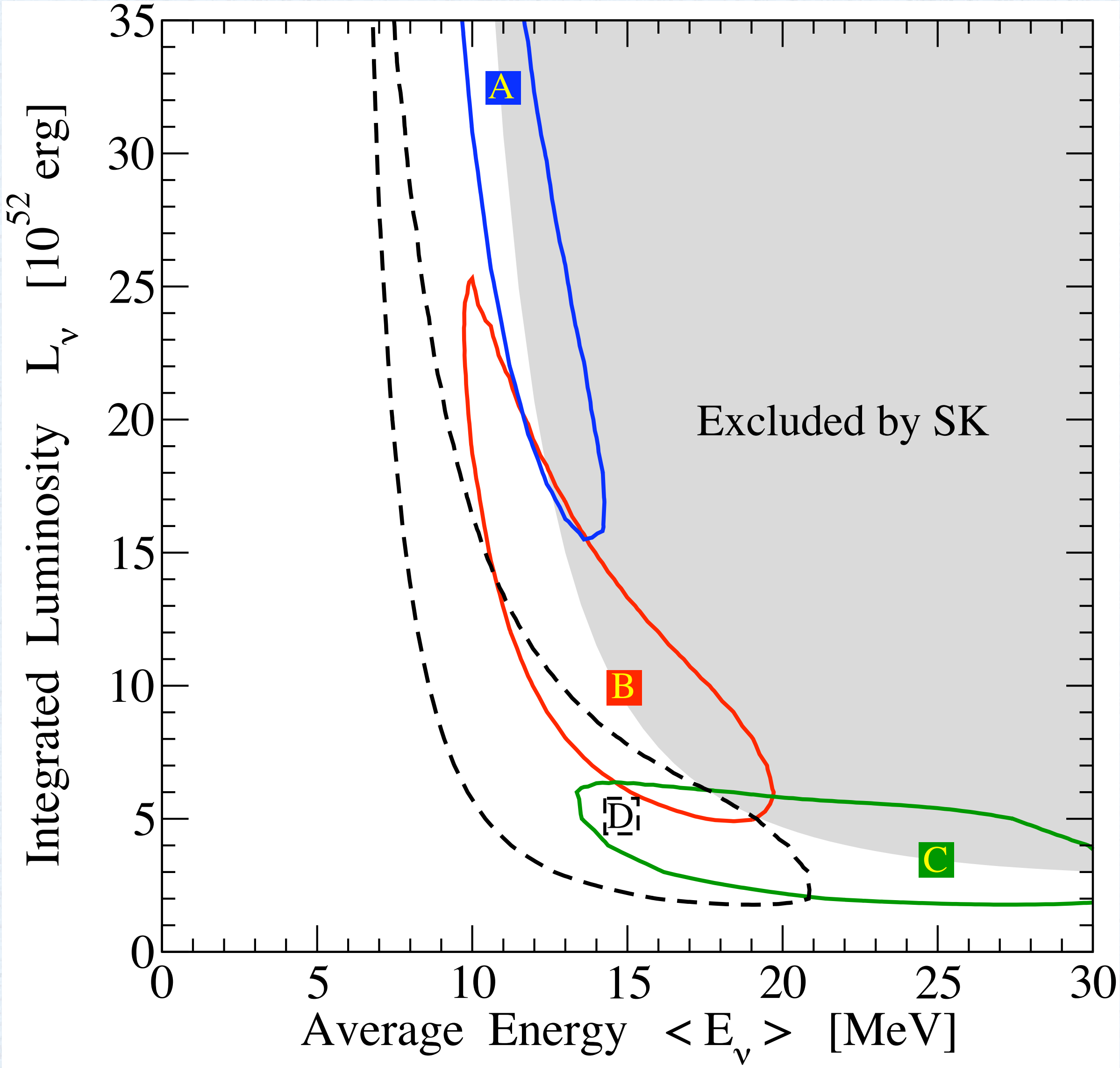


Yüksel, Ando, Beacom, *PRC* **74**, 015803 (2006)

- 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)

Diffuse Supernova Neutrinos: Summary

- A diffuse supernova neutrino background filling the entire universe
- Theory predicts its flux *just below* the current upper limit by the Super-K
- This provides longest baseline neutrino experiment, testing, e.g., neutrino decay
- 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