NNN05

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Relic supernova neutrinos:

Current status and prospects of future detectors

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1. Introduction

- Potential of supernova neutrino burst for physics and astrophysics — talk by A. Dighe
- Galactic supernova rate: ~ 1 per century
  - It strongly depends on our luck
- Should we just wait for that lucky event?
  - No, because we have real chance to detect extragalactic supernova neutrinos!

Supernova Relic Neutrinos

Supernova Explosion

99% of its gravitational binding energy is released as neutrinos (supernova neutrino burst)

It is considered to trace the cosmic star formation rate (SFR).

There should be a diffuse background of neutrinos which were emitted from past supernova explosions.

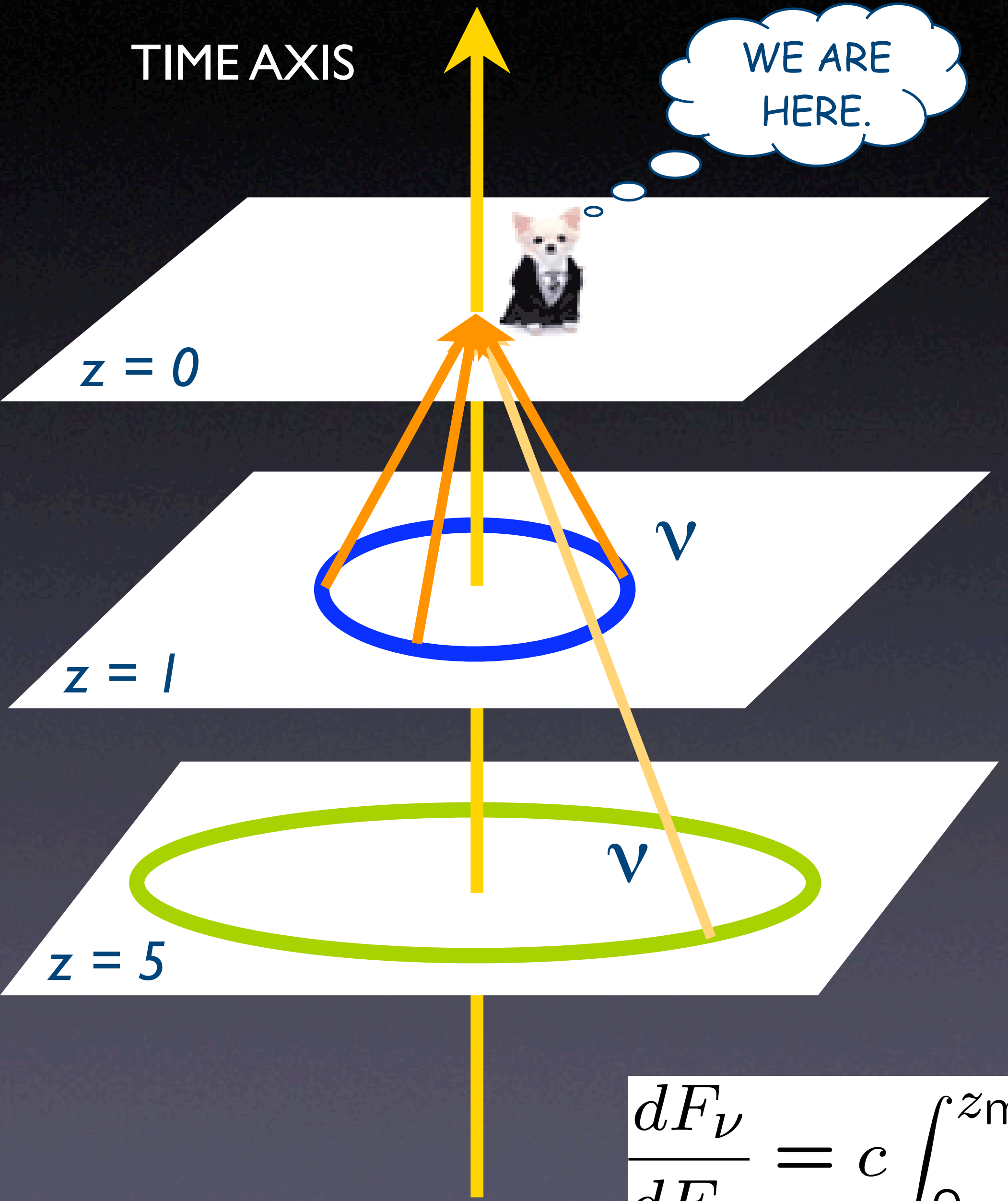
"Supernova Relic Neutrinos (SRN)"

Motivations — Involved Physics

- Detection of first extragalactic neutrinos
  - Precise rate and background estimates are essential
    - Kaplinghat, Steigman & Walker 2000; Ando, Sato & Totani 2003; Beacom & Vagins 2004; Strigari, Kaplinghat, Steigman & Walker 2004; Cocco et al. 2004
- Galaxy evolution and cosmic star formation rate
  - Complementary to observations using light
    - Fukugita & Kawasaki 2003; Ando 2004; Strigari et al. 2005
- Physics of supernova neutrinos
  - If we do not have any galactic supernovae...
- Neutrino properties as an elementary particle
  - Neutrino oscillation
    - Ando & Sato 2003
  - Neutrino decay (coupling with e.g. Majoron)
    - Ando 2003; Fogli, Lisi, Mirizzi & Montanino 2004

2. Formulation and Models

How to Calculate the SRN Flux

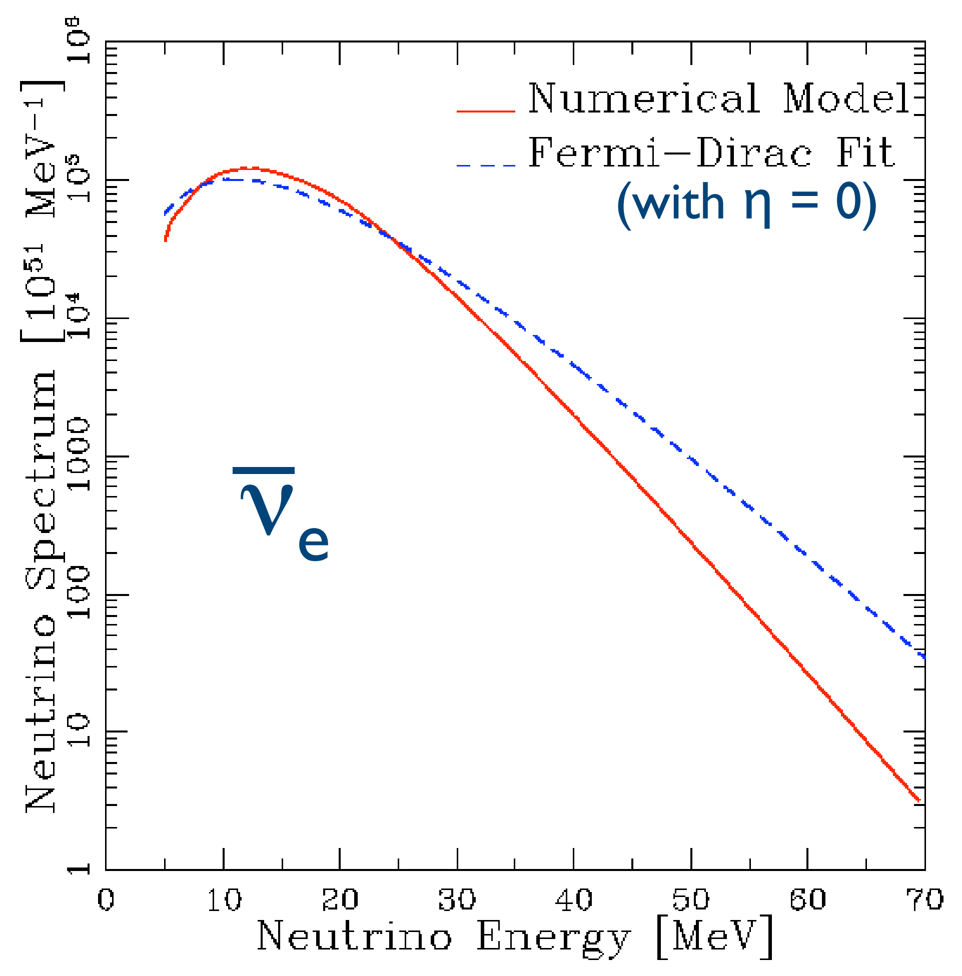


We need information concerning...

1. Neutrino spectrum emitted from each supernova explosion
2. Neutrino oscillation within supernovae and the Earth
3. Supernova rate

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

Original neutrino spectrum



Totani, Sato, Dalhed & Wilson (1998)

- Traditionally, Fermi-Dirac fit is used to represent neutrino spectrum.

$$\begin{aligned} \frac{dN_\nu}{dE_\nu} &\propto \frac{E_\nu^2}{\exp(E_\nu/T_\nu - \eta) + 1}, \\ T_{\nu_e} &= 3 \text{ MeV}, \\ T_{\bar{\nu}_e} &= 5 \text{ MeV}, \\ T_{\nu_x} &= 8 \text{ MeV} \end{aligned}$$

- Simulation by the Lawrence Livermore group (Totani et al. 1998) basically confirms this.

Conversion Probabilities

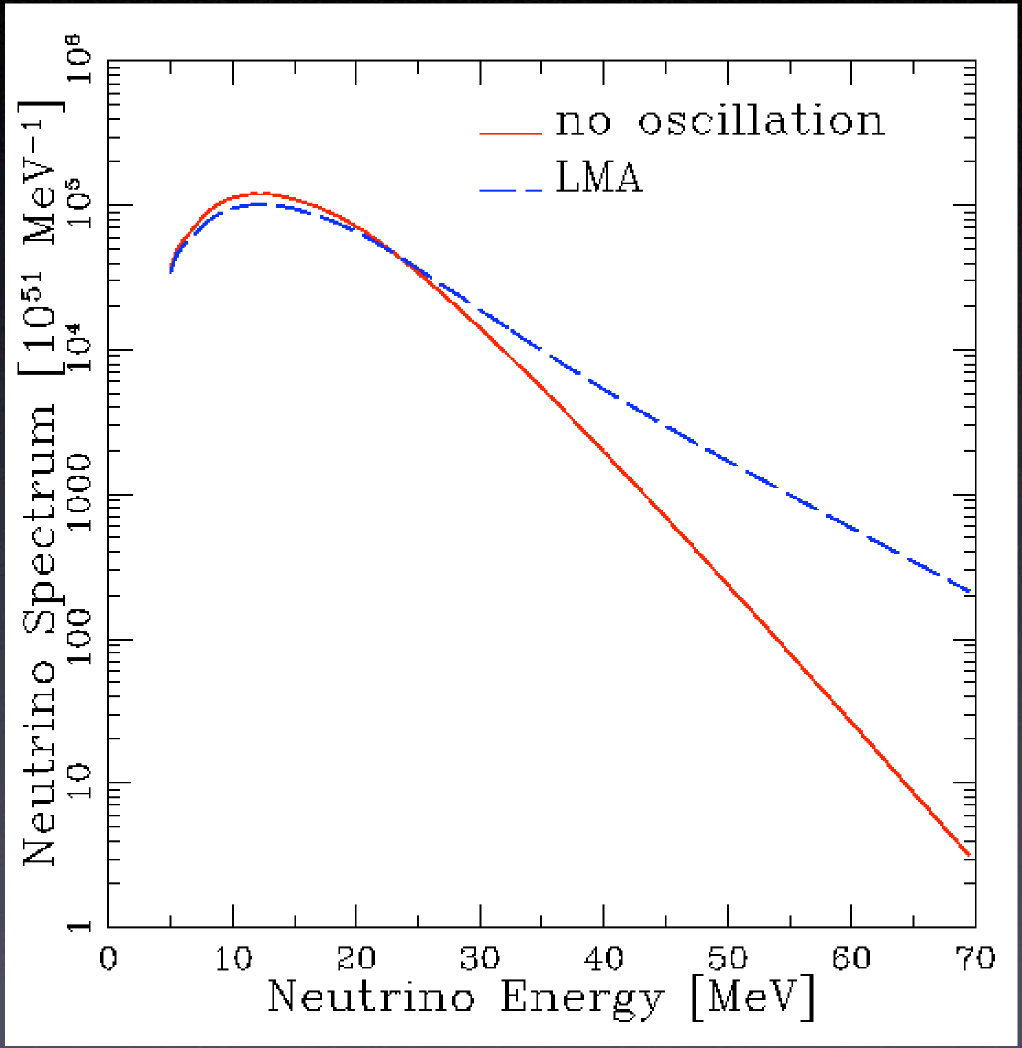
Probability of $\nu_e \Leftrightarrow \nu_x$ conversion

	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

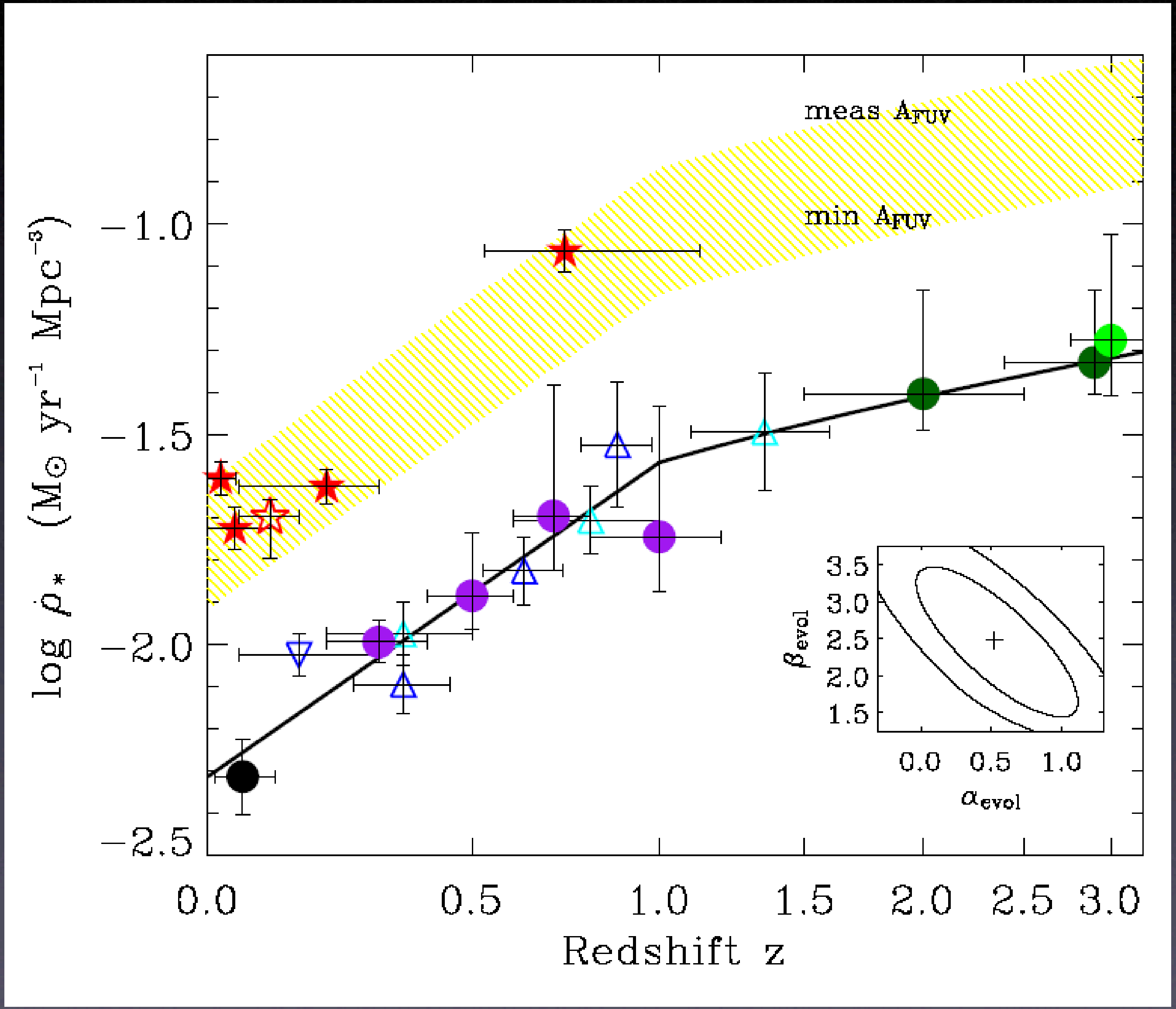
	Large θ_{13}	Small θ_{13}
Normal	30%	30%
Inverted	100%	30%

Spectrum after Oscillation



- Here, we only consider the case of normal mass hierarchy.
- Oscillation enhances the high-energy tail.
  - But not dramatically at detectable energy range (<30 MeV).

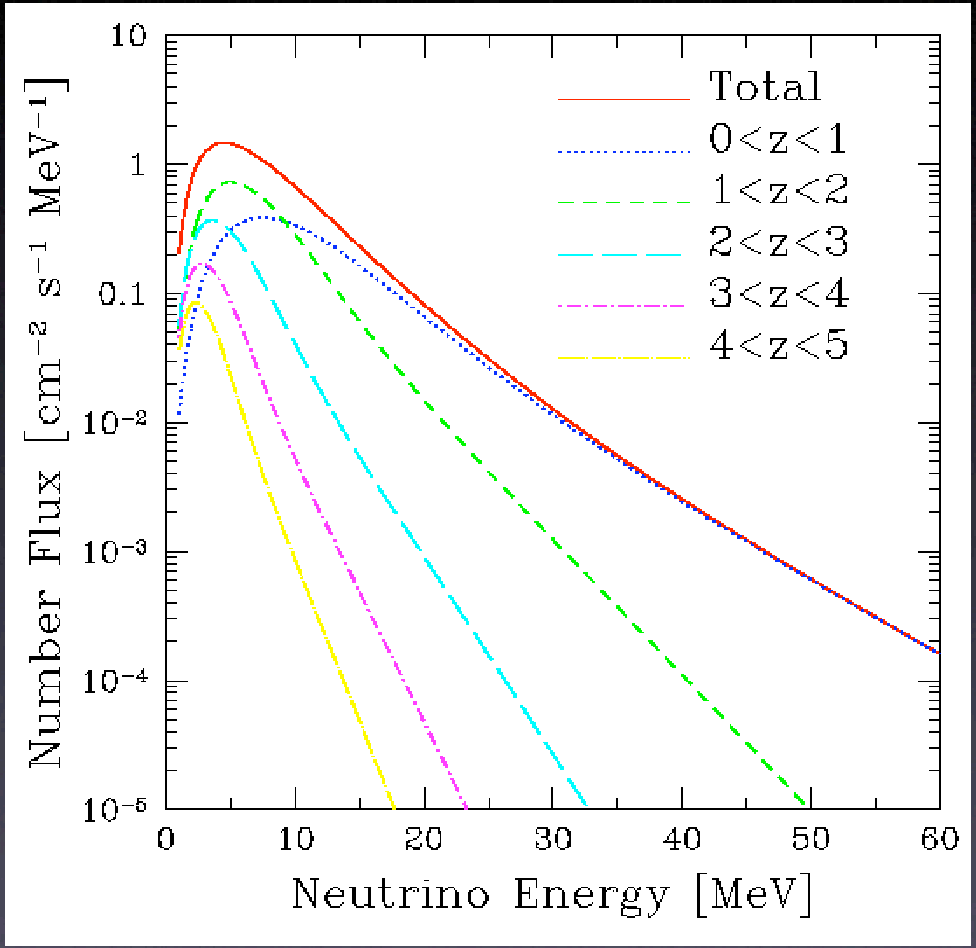
Recent GALEX Result



Schiminovich et al. 2005

- Recent GALEX determination of star formation rate (SFR)
- Supernova rate is inferred from SFR.

3. Flux and Event Rate

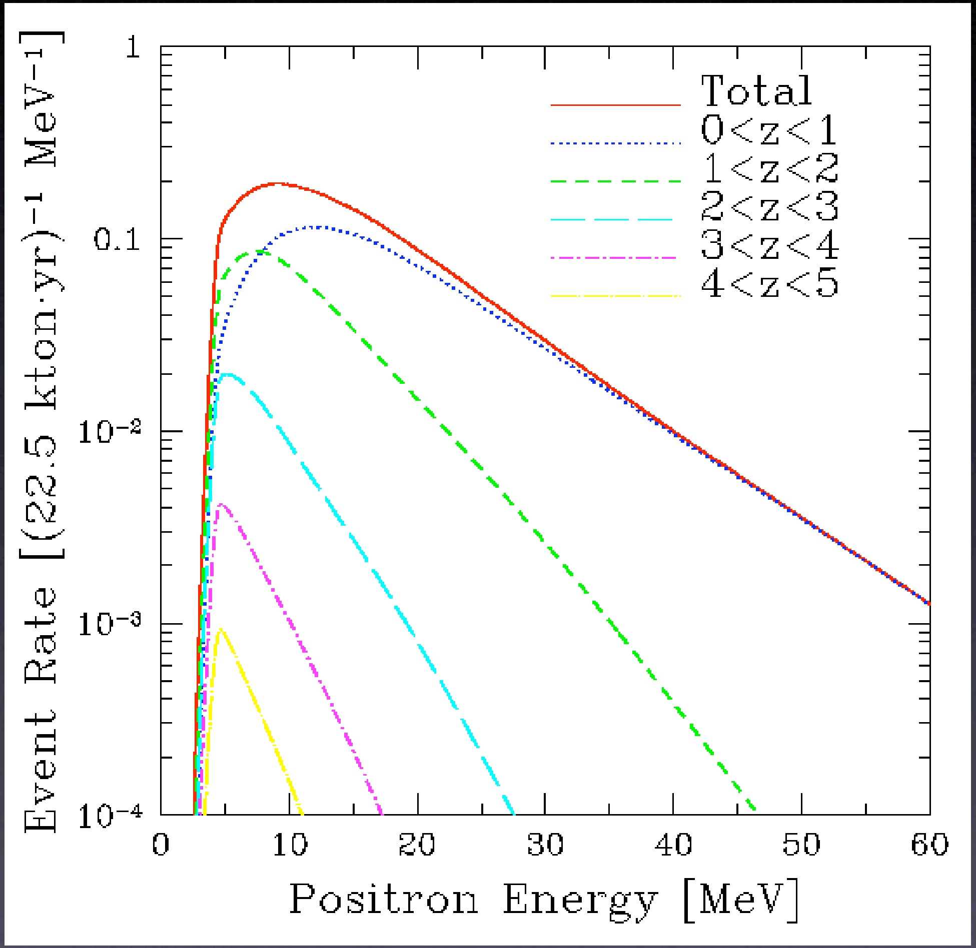


Ando, Astrophys. J. **607**, 20 (2004)

- Integrated flux (cm $^{-2}$ s $^{-1}$)

E_ν > 11.3 MeV	E_ν > 19.3 MeV
5.1	1.1

3. Flux and Event Rate



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

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

E_ν > 11.3 MeV	E_ν > 19.3 MeV
5.1	1.1

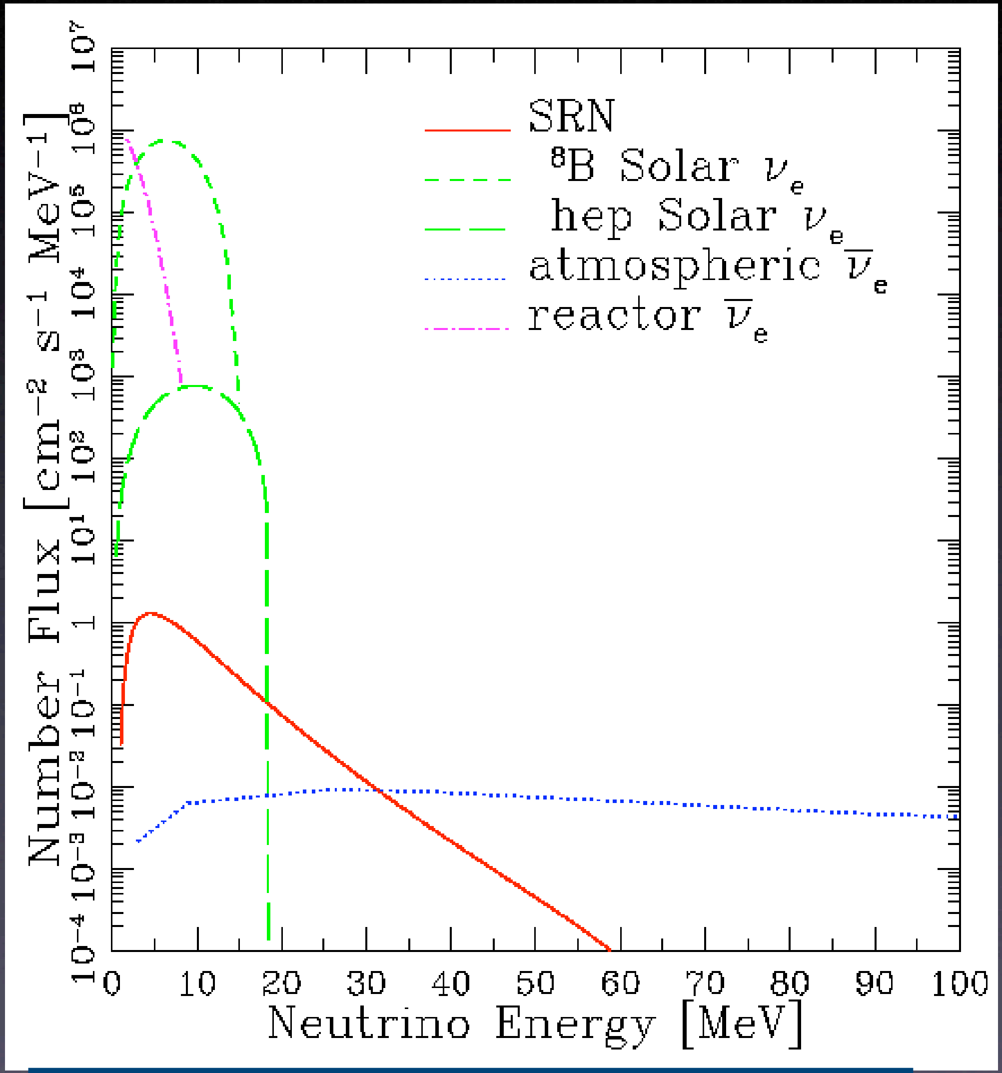
- Event rate at Super-K (yr^{-1})

E_e > 10 MeV	E_e > 18 MeV
5.2	2.5

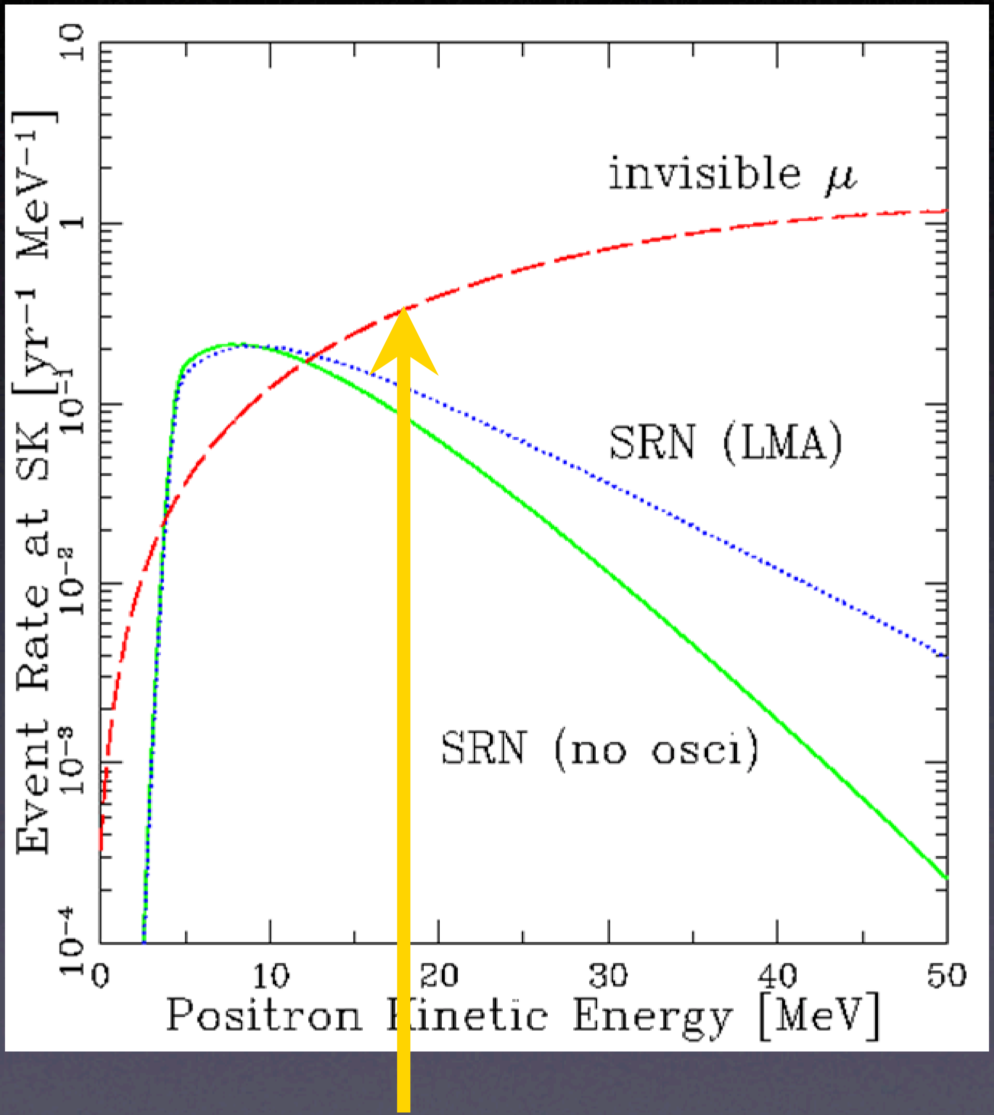
- Most of the event comes from the relatively nearby universe (z<1).

4. Detectability and Current Status

Background Events

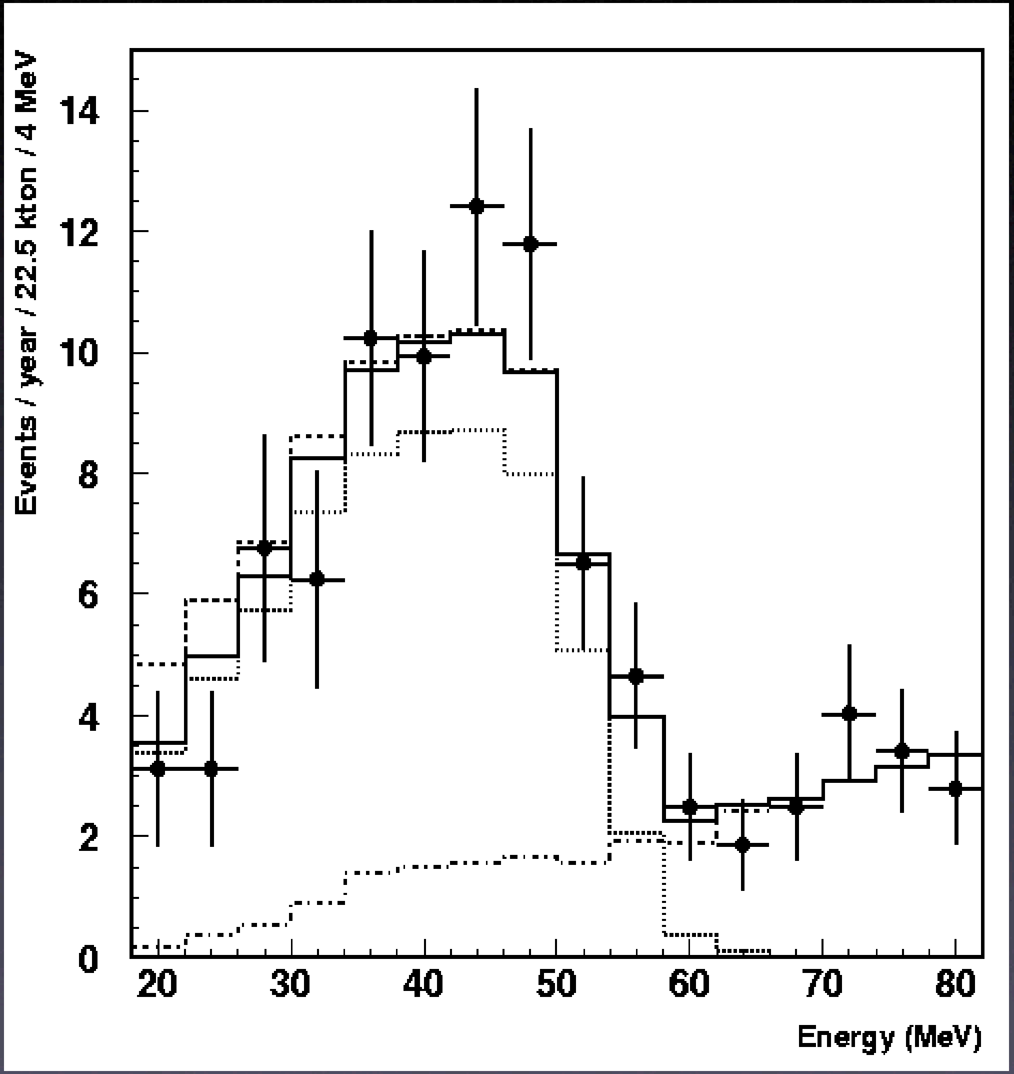


Ando, Sato & Totani, Astropart. Phys. 18, 307 (2003)



Atmospheric ν_μ → invisible μ → decay e

Observational Result by Super-K



Malek et al. 2003

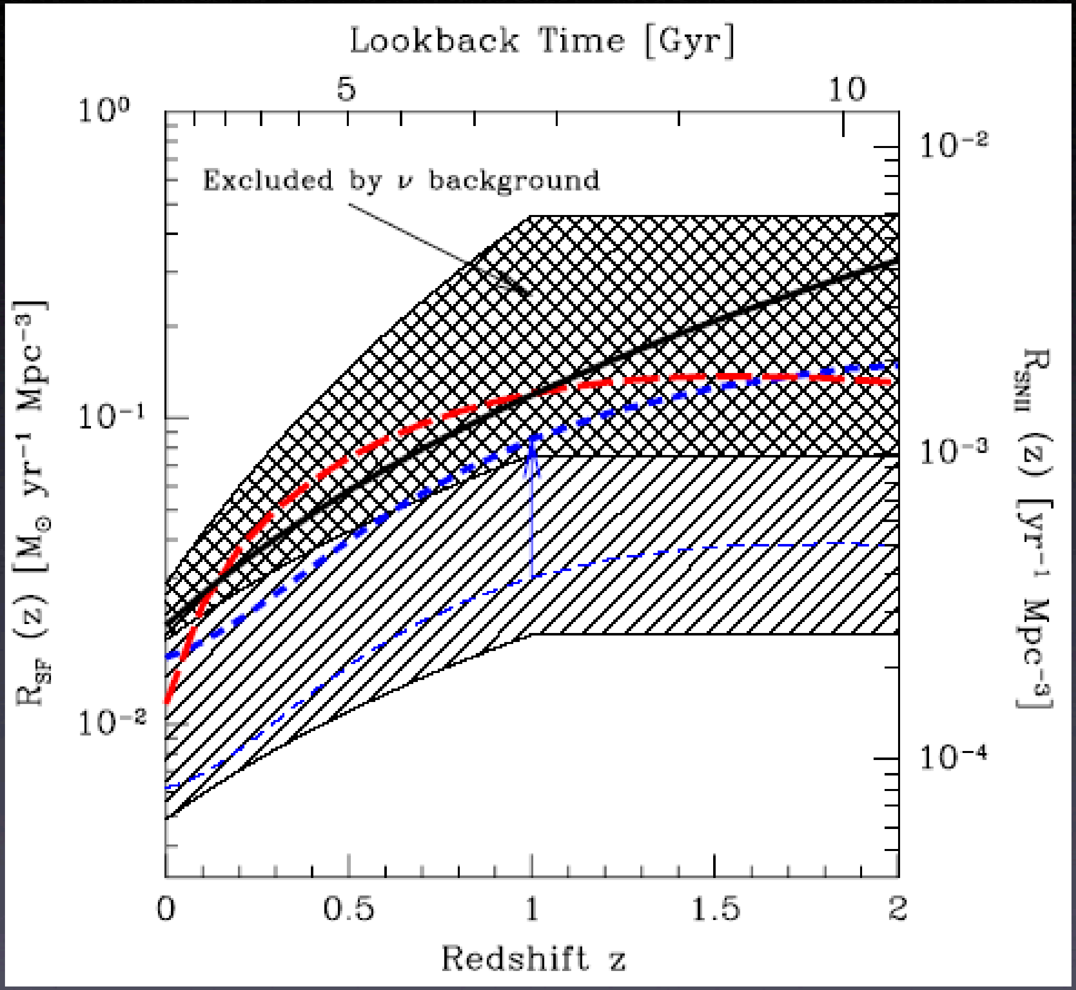
- Analysis using data for 1496 days (4.1 yr).
- As the result, they could not find positive signal.
- Upper limit on the SRN flux (E_ν > 19.3 MeV):

$$\boxed{1.2\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}}$$

(90% C.L.)

Just above the prediction ($1.1\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)

Implication from the Limit



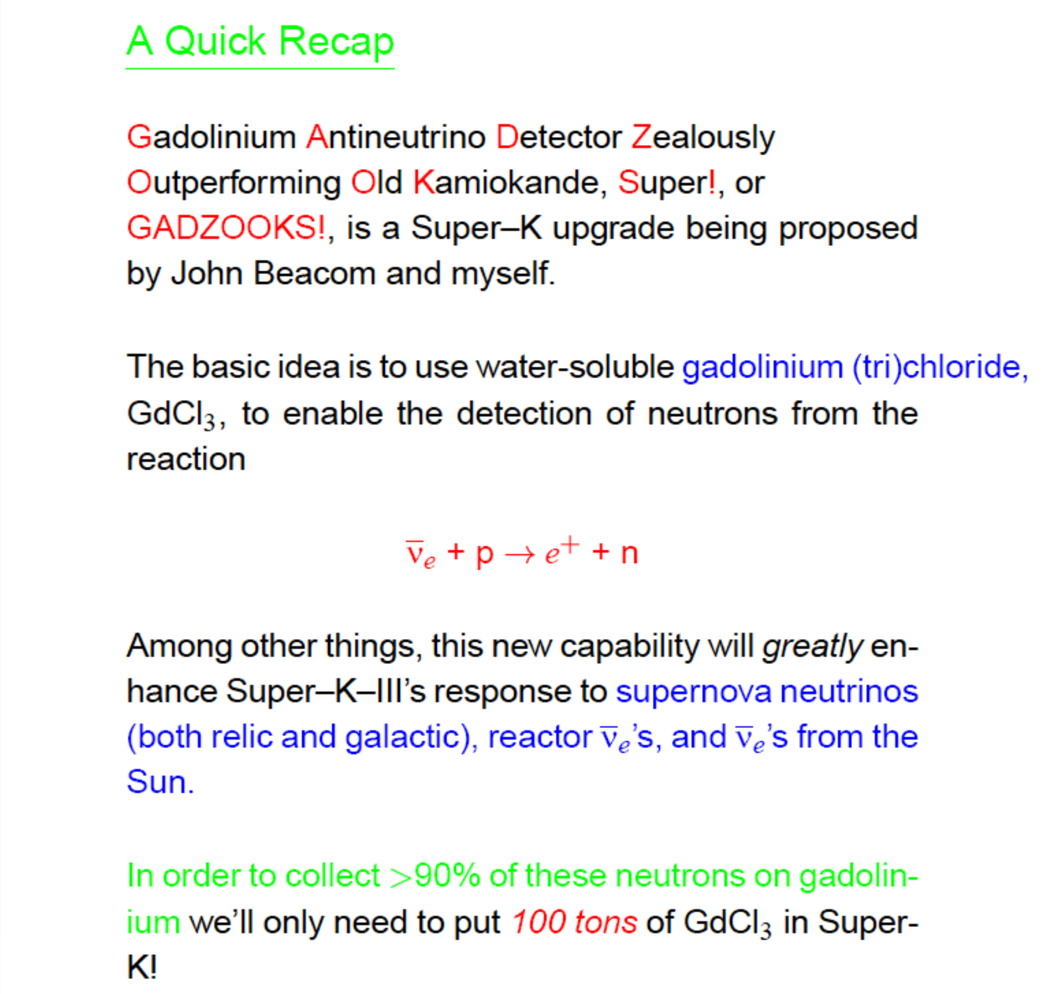
Strigari, Beacom, Walker & Zhang 2005

see also, Fukugita & Kawasaki 2003; Ando 2004

- Super-K limit can be used constrain the supernova rate.
  - It excludes some region, which is allowed by the astronomical observations.

5. Prospects of Future Detectors

GADZOOKS!



A Quick Recap

Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!, or GADZOOKS!, is a Super–K upgrade being proposed by John Beacom and myself.

The basic idea is to use water-soluble gadolinium (tri)chloride, $GdCl_3$, to enable the detection of neutrons from the reaction

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

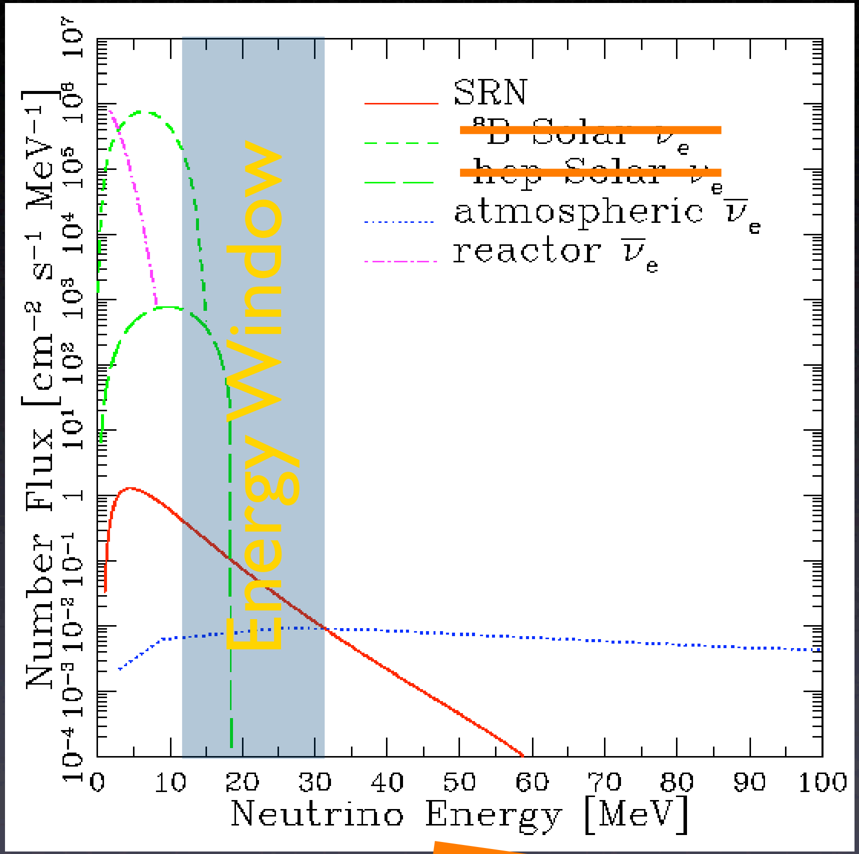
Among other things, this new capability will *greatly* enhance Super–K–III's response to supernova neutrinos (both relic and galactic), reactor $\overline{\nu}_e$'s, and $\overline{\nu}_e$'s from the Sun.

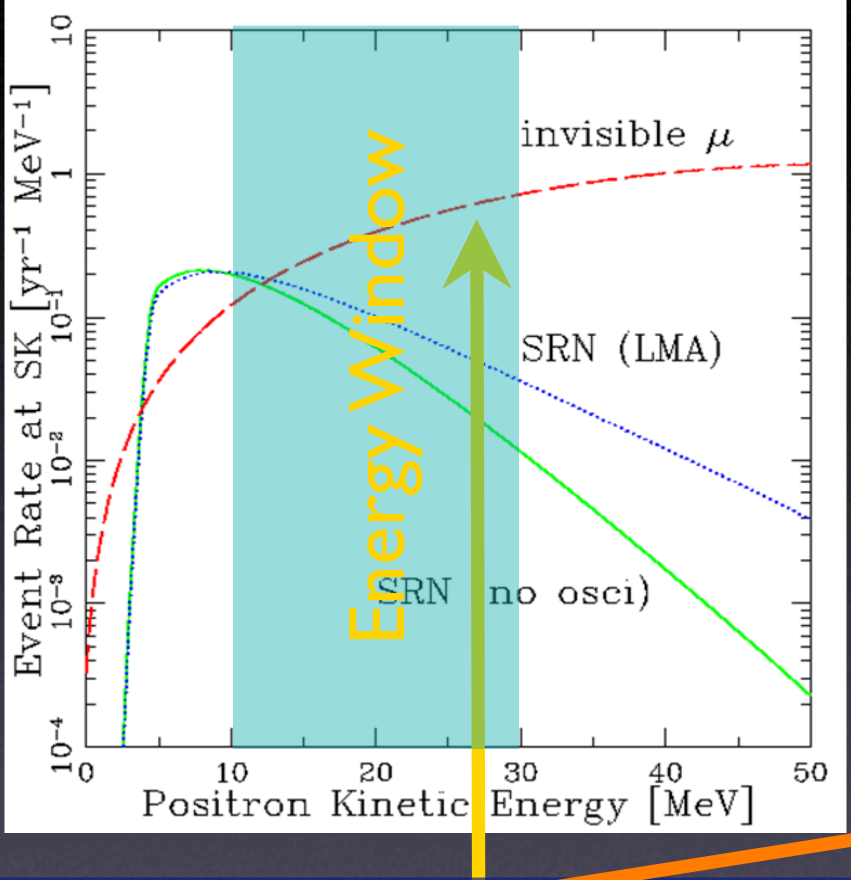
In order to collect >90% of these neutrons on gadolinium we'll only need to put *100 tons* of $GdCl_3$ in Super-K!

Beacom and Vagins 2004

- Delayed coincidence signal of neutrons tagged by Gd.
- It enables to distinguish $\overline{\nu}_e$ from other flavors or μ-induced events.
- It opens up energy window at 10-30 MeV for the SRN detection.

Energy Window for the SRN Detection

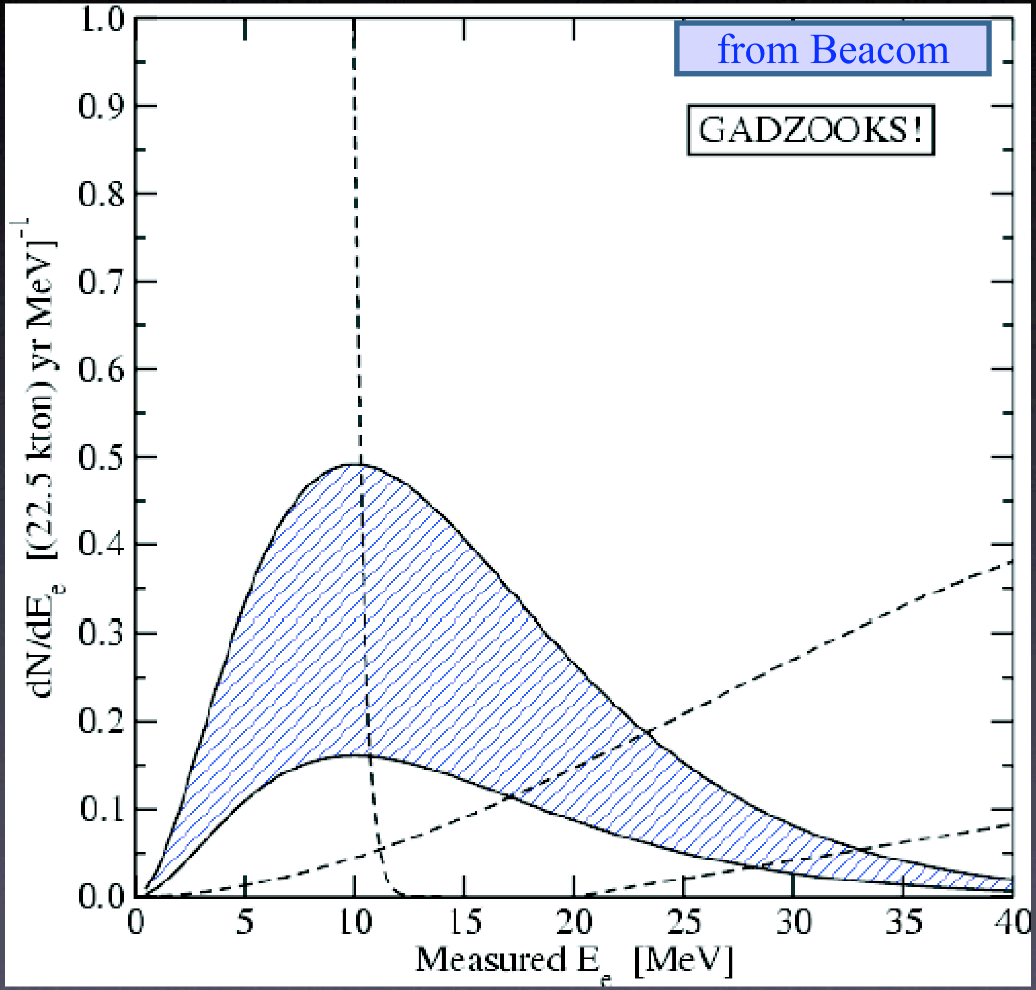


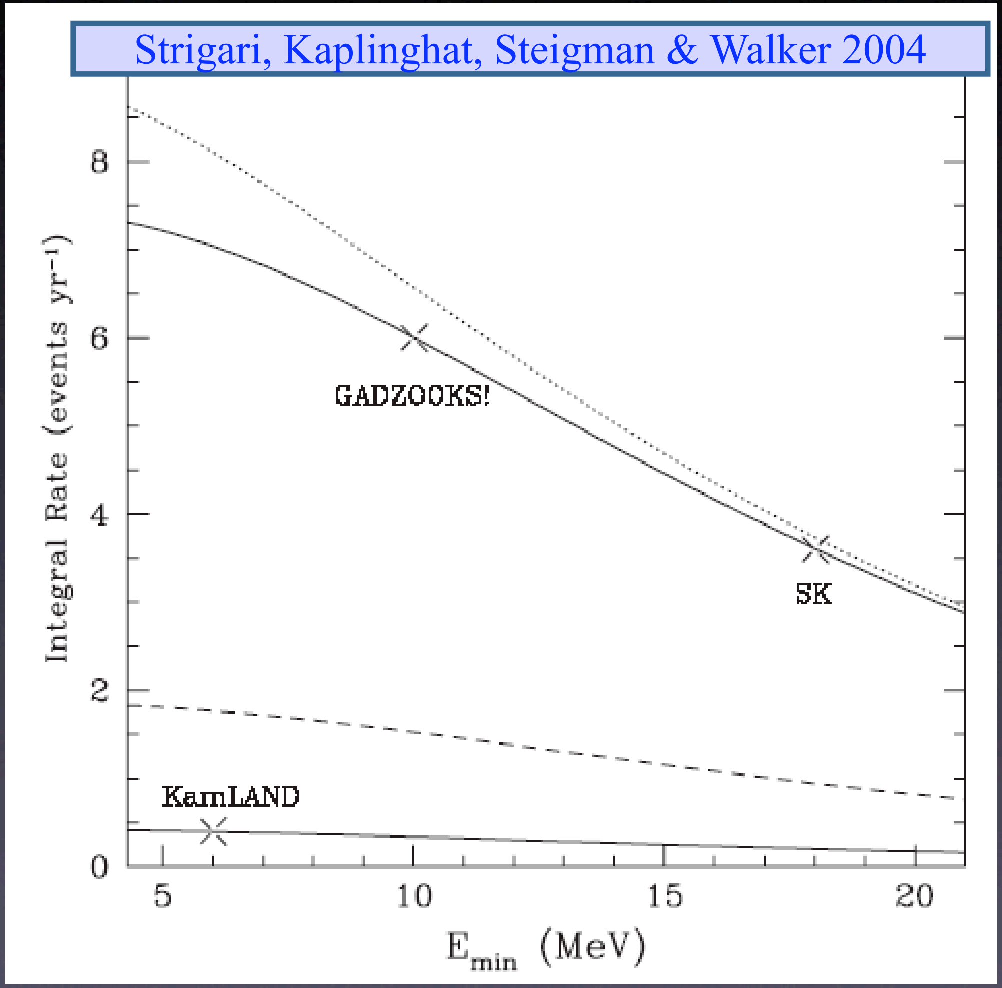


~~Atmospheric ν_μ → invisible μ → decay e~~

- Solar ν_e or invisible μ events become reducible!!

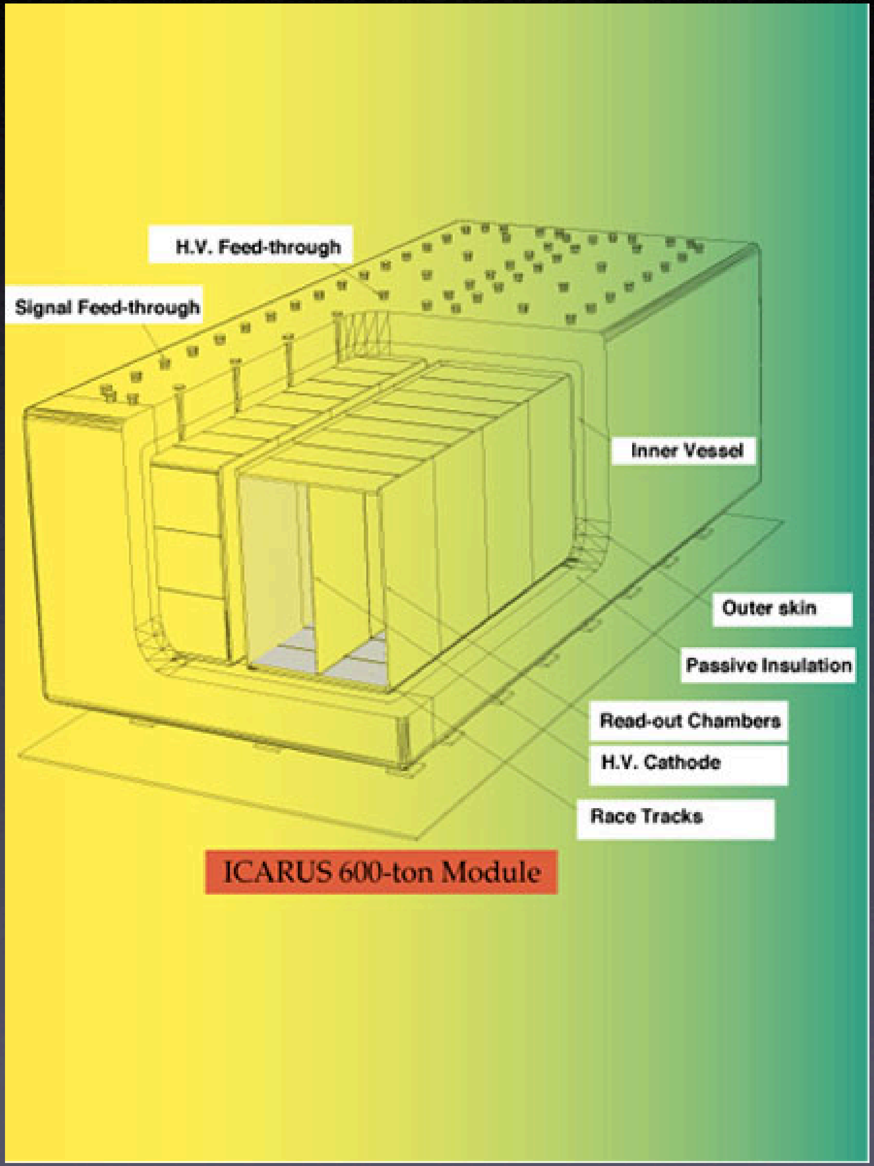
SRN Event at Gd-H_2O Detectors


from Beacom


Strigari, Kaplinghat, Steigman & Walker 2004

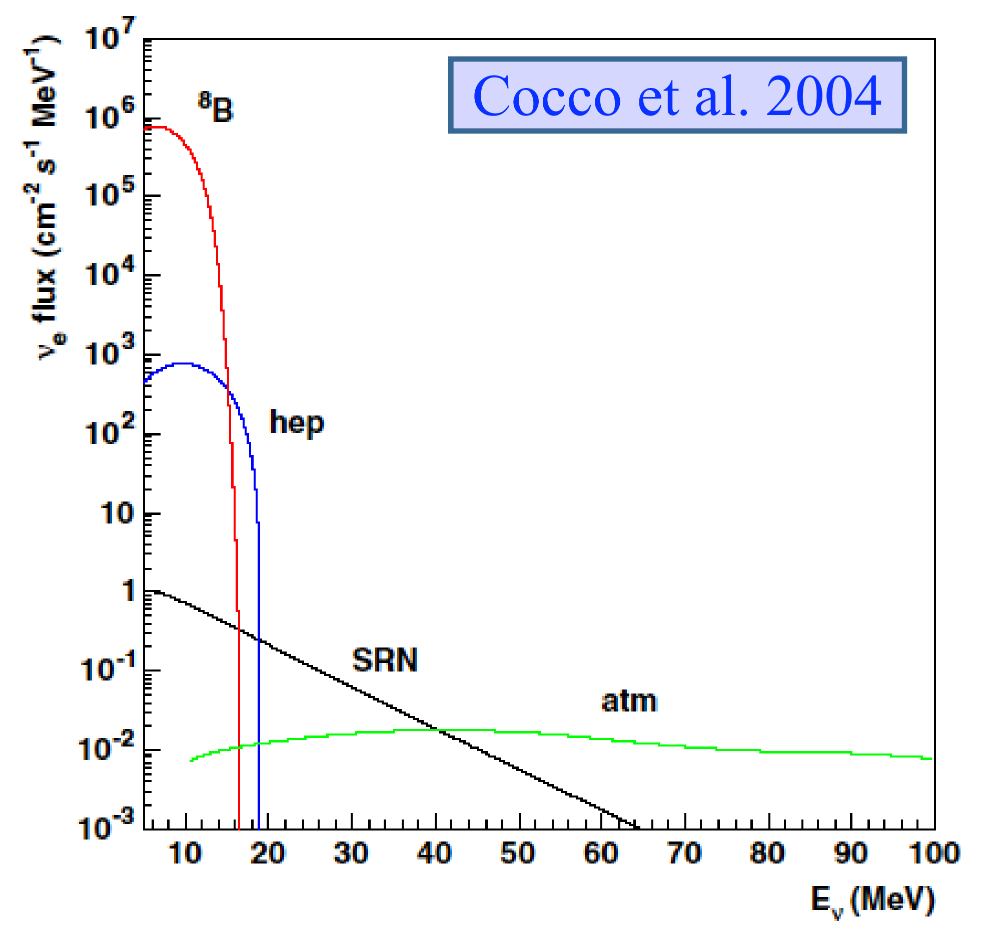
SRN at Liquid Argon Detector

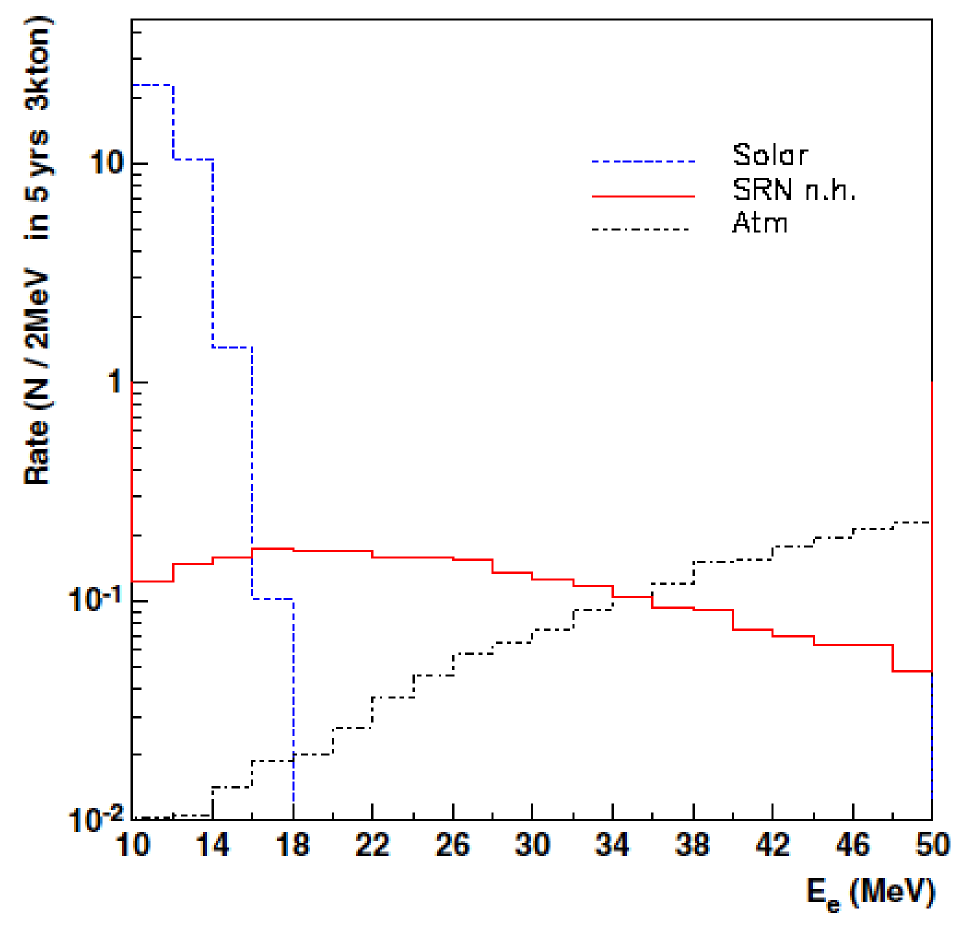
Cline 1990s; Cocco et al. 2004



- Liquid argon detectors are sensitive to ν_e.
- $\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e$
- Detectors:
  - ICARUS (3 kton)
  - Large mass TPC detector (100 kton)
- Several advantages compared with water Cerenkov.

SRN at Liquid Argon Detector





Flux sensitivity: 1.6 $cm^{-2}\,s^{-1}$ (for > 16 MeV; 3 kton 5 yr)

Complementary to Super-K, since it is mainly sensitive to ν_e.

Large Volume Detectors

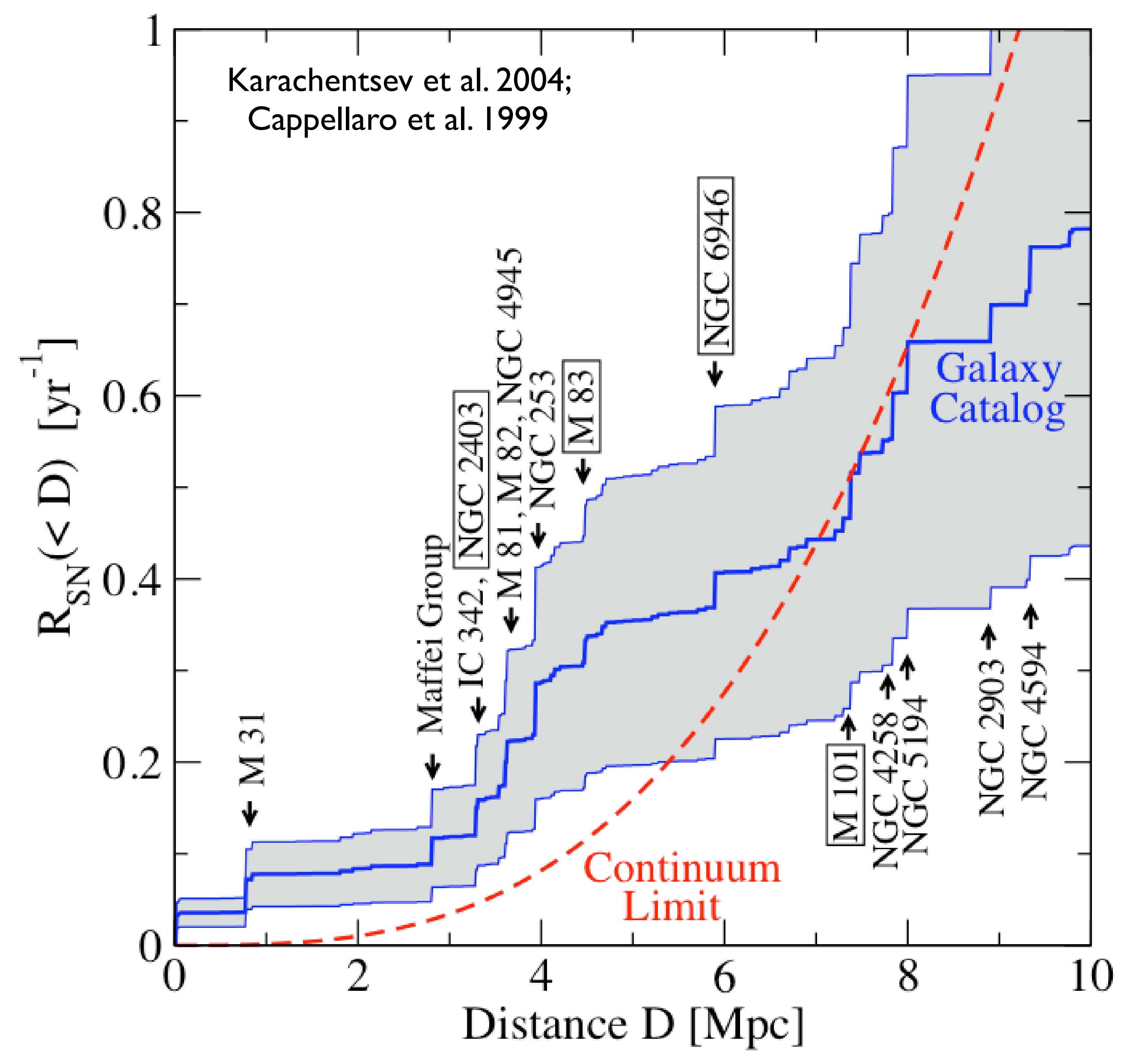
- Megaton water Cerenkov detectors
  - 5σ detection would be possible for a couple of years (pure water).
  - Detection rate: ~ 300 /yr (Gd-loaded)
- 100 kton liquid argon detectors
  - N_{SRN} = 57 +/- 12 for 16-40 MeV (100 kton 5 yr; Cocco et al. 2004)

Neutrino Detection from Supernovae in Nearby Galaxies

S. Ando, J. F. Beacom & H. Yüksel, astro-ph/0503321

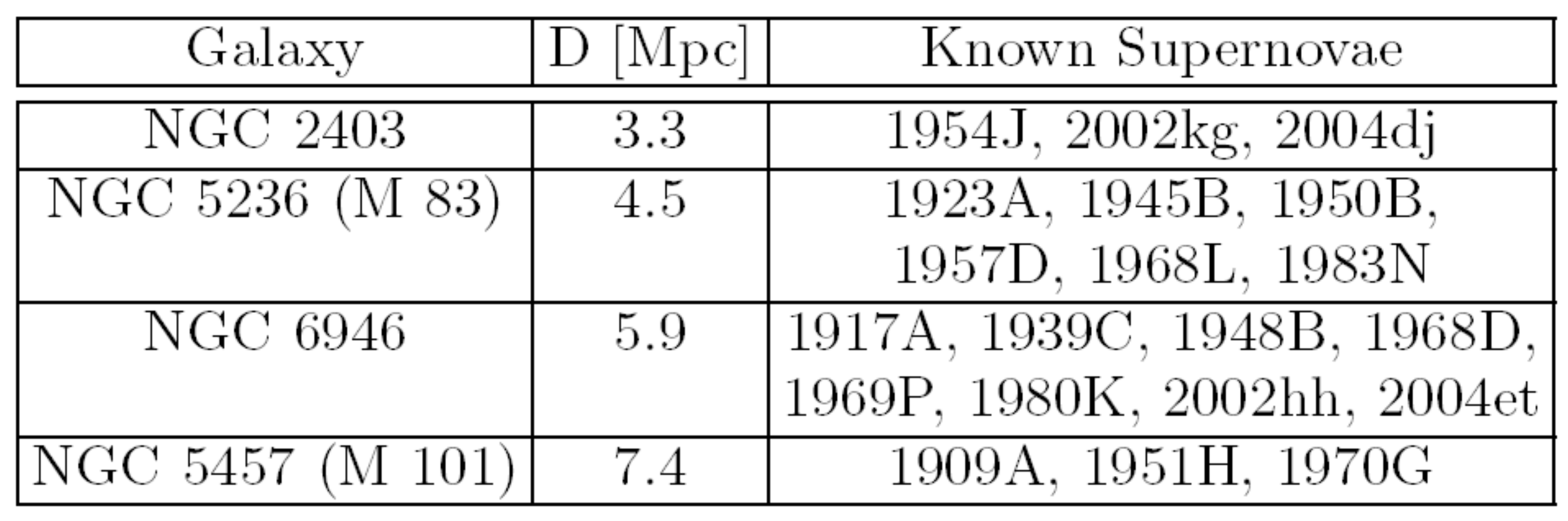
If I don’t have enough time, click here to jump to conclusions...

Supernova Rate in Nearby Galaxies

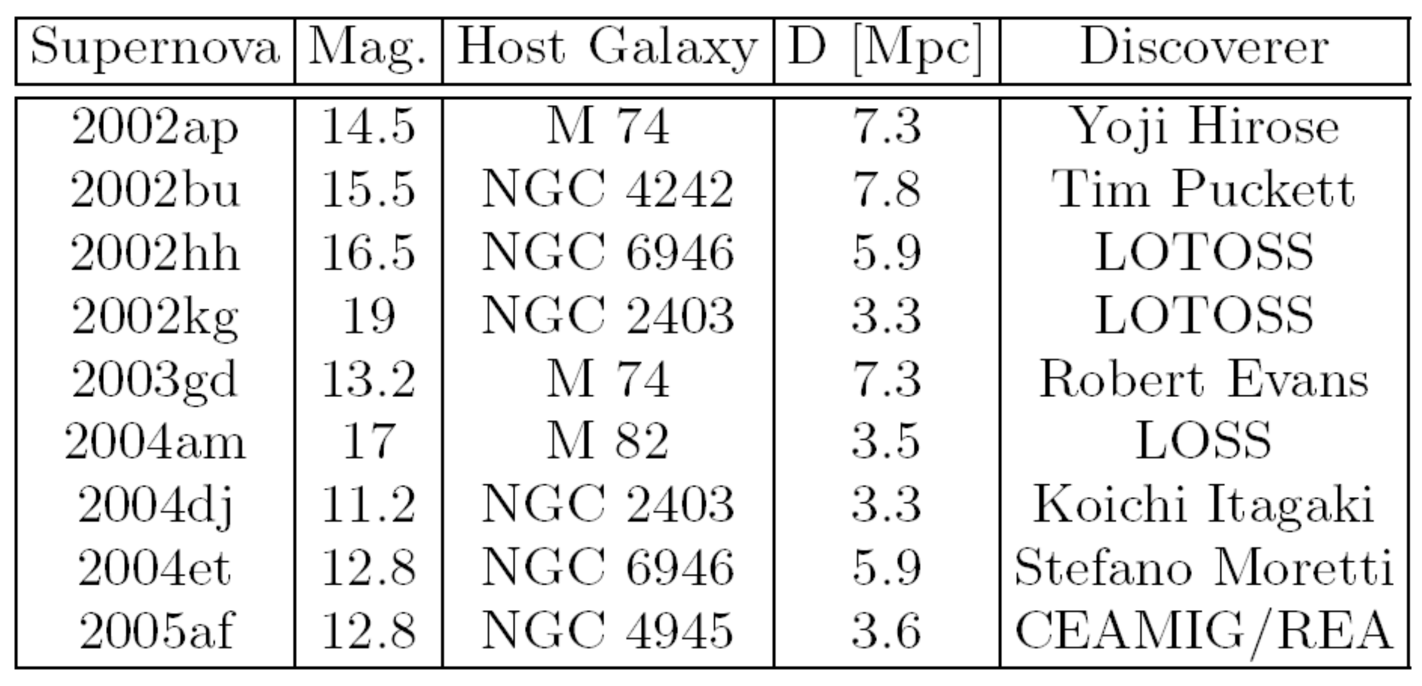


Karachentsev et al. 2004; Cappellaro et al. 1999

Nearby Supernovae

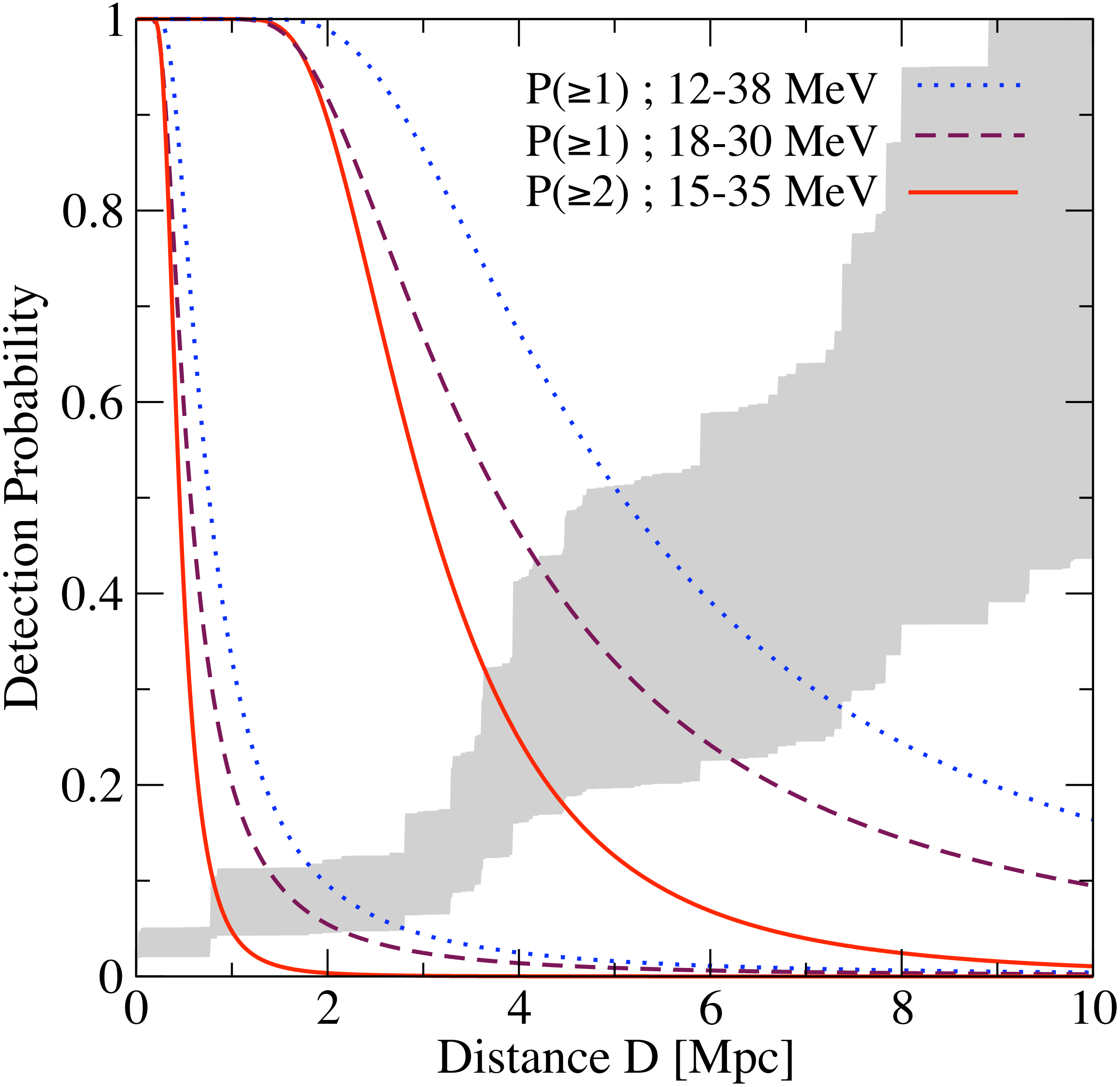


Galaxy	D [Mpc]	Known Supernovae
NGC 2403	3.3	1954J, 2002kg, 2004dj
NGC 5236 (M 83)	4.5	1923A, 1945B, 1950B, 1957D, 1968L, 1983N
NGC 6946	5.9	1917A, 1939C, 1948B, 1968D, 1969P, 1980K, 2002hh, 2004et
NGC 5457 (M 101)	7.4	1909A, 1951H, 1970G



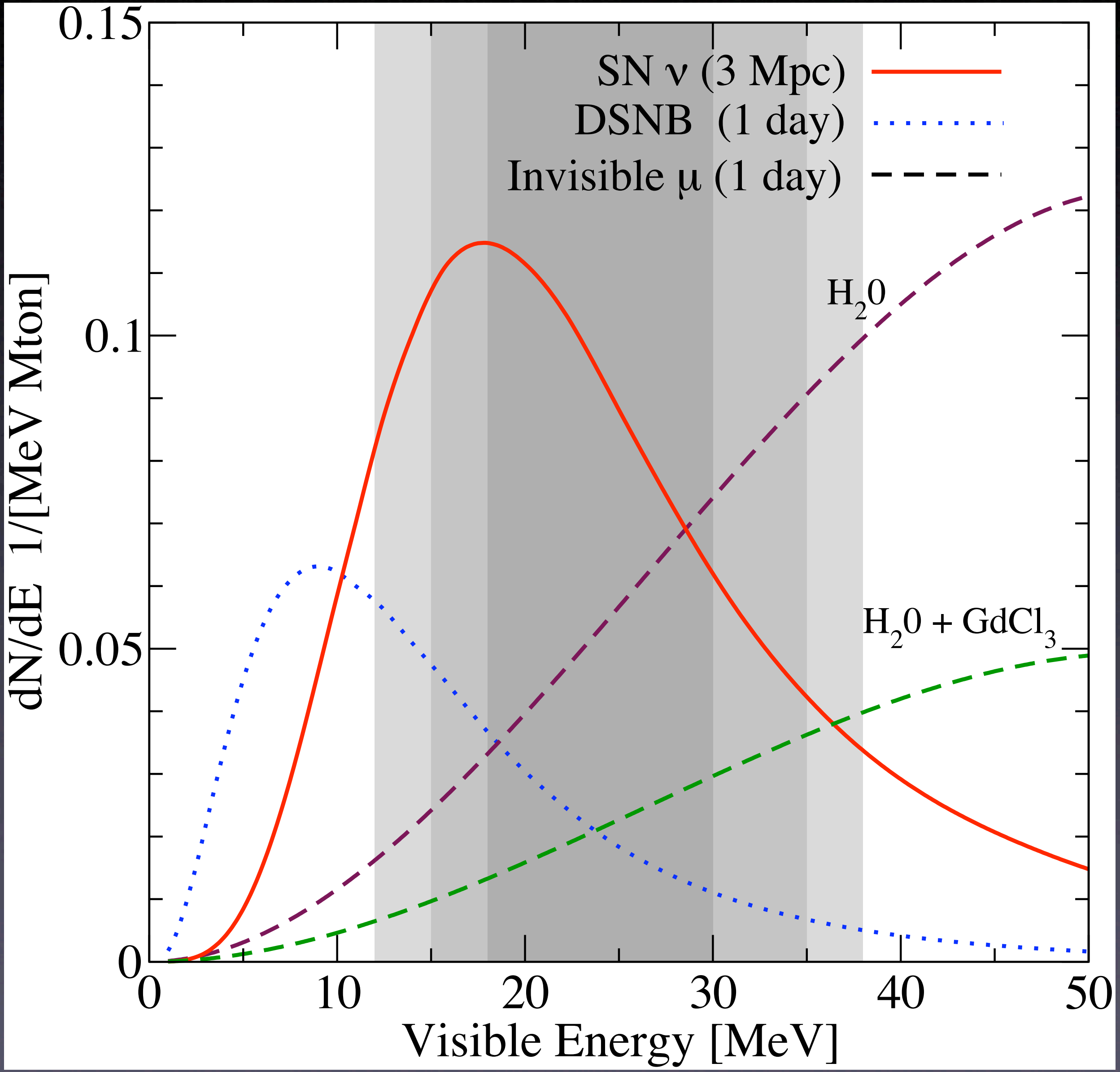
Supernova	Mag.	Host Galaxy	D [Mpc]	Discoverer
2002ap	14.5	M 74	7.3	Yoji Hirose
2002bu	15.5	NGC 4242	7.8	Tim Puckett
2002hh	16.5	NGC 6946	5.9	LOTOSS
2002kg	19	NGC 2403	3.3	LOTOSS
2003gd	13.2	M 74	7.3	Robert Evans
2004am	17	M 82	3.5	LOSS
2004dj	11.2	NGC 2403	3.3	Koichi Itagaki
2004et	12.8	NGC 6946	5.9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

Detection Probabilities



- Real chance to detect more than 1 or 2 events
- More than 2-event detection
  - Essentially background-free
  - Accidental coincidence rate: ~ 0.1 /yr
- 1-event detection
  - Need astronomers' help to restrict time-bin.

Event and Background Spectra (in 1 day)



6. Conclusions

- SRN is a diffuse background of neutrinos emitted from past (cosmological) supernovae.
- Current Super-K limit just above theoretical predictions.
- The detection would be within reach if we use observational data for 5-10 years.
- Future larger volume detectors have a good chance to detect them!

6. Conclusions (continued)

- Supernova neutrinos from nearby galaxies could be detectable with megaton detectors.
- Doubles are robust; singles can also be used with the optical information.
- Physical implications are:
  - construction of supernova neutrino spectrum;
  - exact timing of the core collapse, which helps gravitational wave searches.