The Supernova Relic Neutrinos

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Collaborators:

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A supernova is the transition of an ordinary star into a body of considerably smaller mass… Baade and Zwicky (1934).

Energetics of a supernova explosion

- The binding energy of a neutron star ~ GM^2/R ~ 5×10^{53} ergs is liberated in a type II supernova event
  - Total energy emitted in neutrinos ~ 99% of binding energy
  - Kinetic energy of ejecta ~ 10^{51} ergs (Woosley and Weaver, ApJS 1995)
  - Light output ~ 10^{49} ergs (SN 1987a)
- Average neutrino energy is of $\mathcal{O}$(10 MeV)
- Time scale for radiating away binding energy is of $\mathcal{O}$(secs)

Flux of supernova relic neutrinos at earth

$$j_\nu(E) = \int_0^{z_{max}} dz\, |dt/dz|\, R_{SN}(z) \times (1+z)\, \langle \mathcal{N}_\nu(E(1+z)) \rangle$$

j_ν is the differential flux at earth: number per unit area per unit time per unit energy interval

R_{SN} is the SNII rate per unit comoving volume

$\mathcal{N}_\nu$ is the number of neutrinos emitted per unit energy interval at source

<…> denotes averaging over the IMF

Outline

- Supernova and the associated neutrino signal.
- Supernova relic neutrinos: a cosmological background of O(MeV) neutrinos from all the supernovae that have occurred.
  - Detection at earth
  - Neutrino spectrum (Initial Mass function & ν Mixing)
  - Supernova rate (SDSS, Metal Enrichment Rate)
  - Backgrounds to detection
  - Future prospects and forecasts

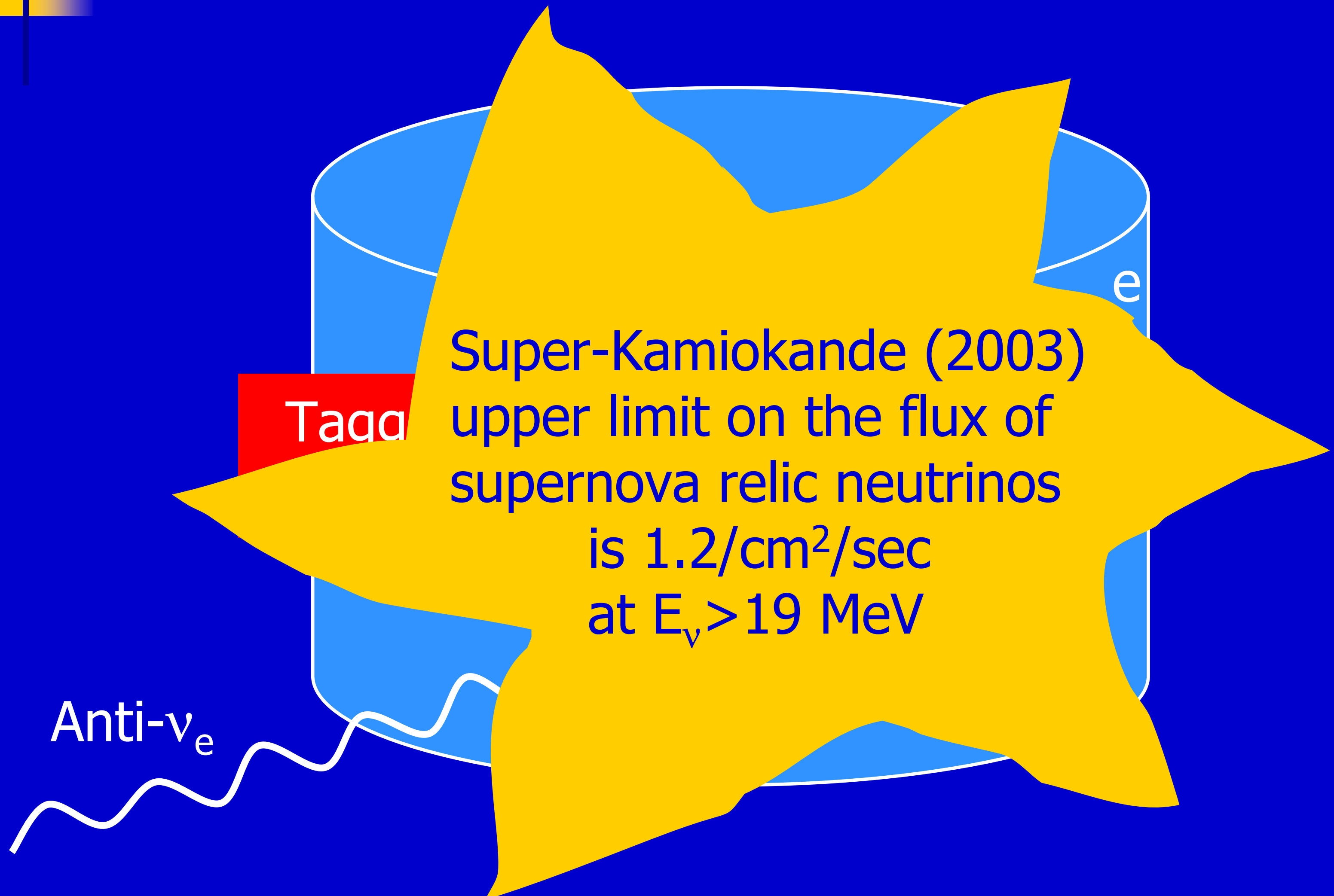
Current detectors to observe the relic neutrinos

We are interested in the anti-ν_e part of the flux

Super-Kamiokande
Energy window for detecting SRN: $E_\nu > 19$ MeV

KamLAND
Energy window for detecting SRN: $E_\nu > 6$ MeV

Detecting the relic neutrinos



Super-Kamiokande (2003)
upper limit on the flux of
supernova relic neutrinos
is 1.2/cm^2/sec
at E_ν>19 MeV

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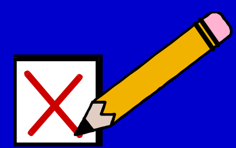
  - Detection at earth 
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Neutrino spectrum

- Common assumption: Fermi-Dirac with a temperature characteristic of the neutrino-sphere.

$$\mathcal{N}_\nu(E) = \mathcal{E}_\nu \frac{120}{7\pi^4} \frac{E^2/T_\nu^4}{\exp\left(E/T_\nu - \eta\right) + 1}$$

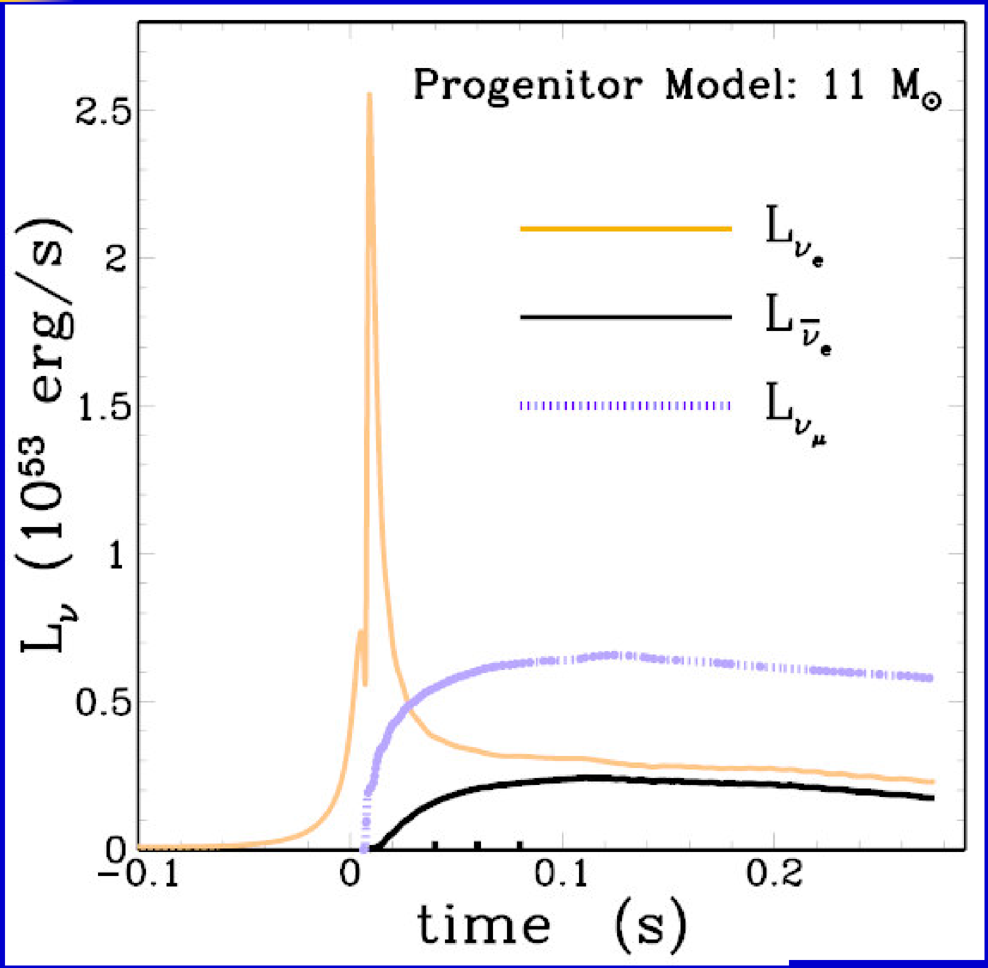
where $\mathcal{E}_\nu$ is total energy released in a family

Is this the correct form?
Is equipartion valid?
Keil, Raffelt and Janka, Astrophys.J.590:971-991,2003

Degeneracy η is not a well known quantity.
It could depend on the progenitor mass.

SRN may offer an opportunity to learn more.

Neutrino luminosity



Use this keeping in mind that this is an open question.

Thomson, Burrows and Pinto (2003)
Bethe, Applegate and Brown (1980)

Neutrino spectrum and the Initial Mass Function

$$\langle \mathcal{N}_\nu(E) \rangle \simeq \langle \mathcal{E}_\nu \rangle \frac{120}{7\pi^4} \frac{E^2/\langle T_\nu \rangle^4}{\exp\left(E/\langle T_\nu \rangle\right)+1}$$

Approximation accurate to 10%
in the energy range of interest.

$$\begin{aligned} \langle \mathcal{E}_\nu \rangle &= 0.5 \times 10^{53} \mathrm{ergs} \\ \langle T_{\nu_e} \rangle &= 5 \mathrm{MeV} \\ \langle T_{\nu_\mu} \rangle &= 8 \mathrm{MeV} \end{aligned}$$

Woosley and Weaver, ApJS (1995)
Rausher, Heger, Hoffman and Woosley, ApJ (2002)

Neutrino mixing inside the supernova

- Neutrino mixing inside the supernova depends on the hierarchy of neutrino masses. Two hierarchies allowed.
  - Normal $m_3 > m_2 > m_1$
  - Inverted $m_2 > m_1 > m_3$

- SN has two resonant layers. *For normal hierarchy, neither of them are in the anti-neutrino channel.*
  - The anti-ν_e deep inside the SN core are anti-ν_1.
  - At the surface we have an incoherent mixture of anti-ν_1, anti-ν_2 and anti-ν_3 (with fluxes F_e, F_μ and F_τ)
  - At earth, the anti-ν_e flux $\simeq \cos^2\theta_\odot F_e + \sin^2\theta_\odot F_\mu$.

(Dighe and Smirnov, PRD 62 (2000) 033007.)

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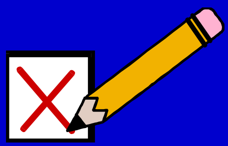
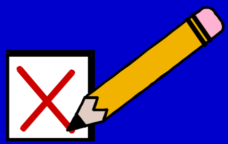
  - Detection at earth 
  - Neutrino spectrum 
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Supernova rate: Parameterization

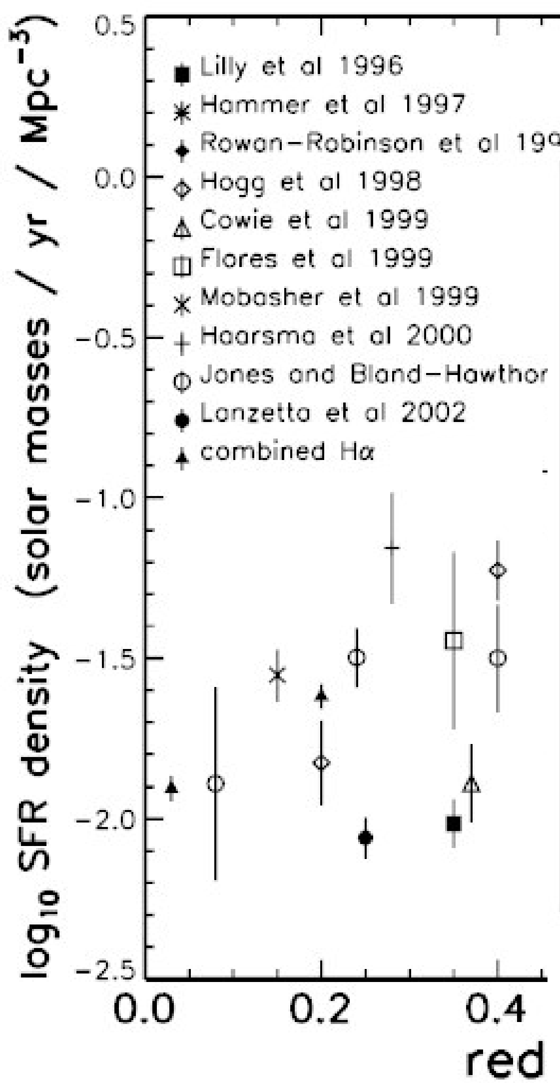
$$\mathrm{R_{SN}} \propto (1+z)^{\beta} \quad \forall \quad z < 1$$
$$\propto (1+z)^{\alpha} \quad \forall \quad z > 1$$

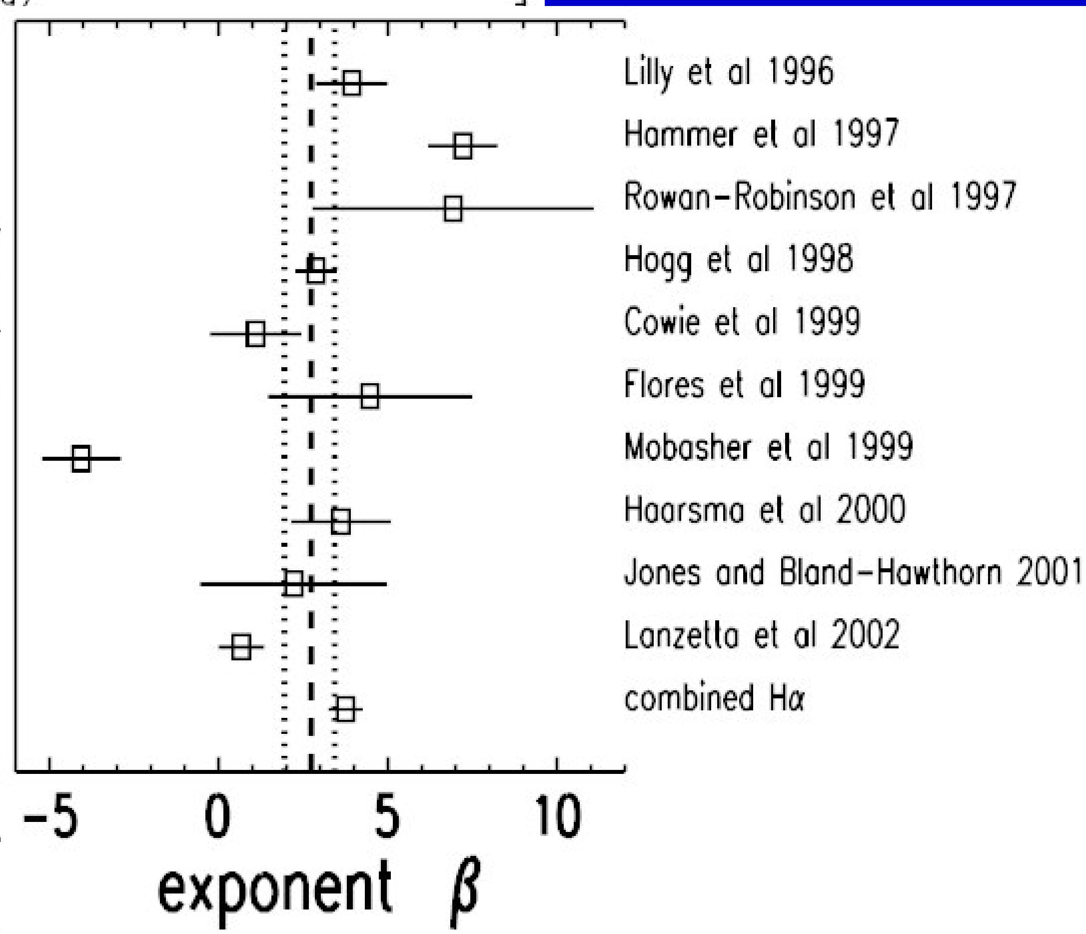
Different observational techniques point to the validity of the above parameterization.

α virtually unknown.

Direct measures of high redshift supernova rate

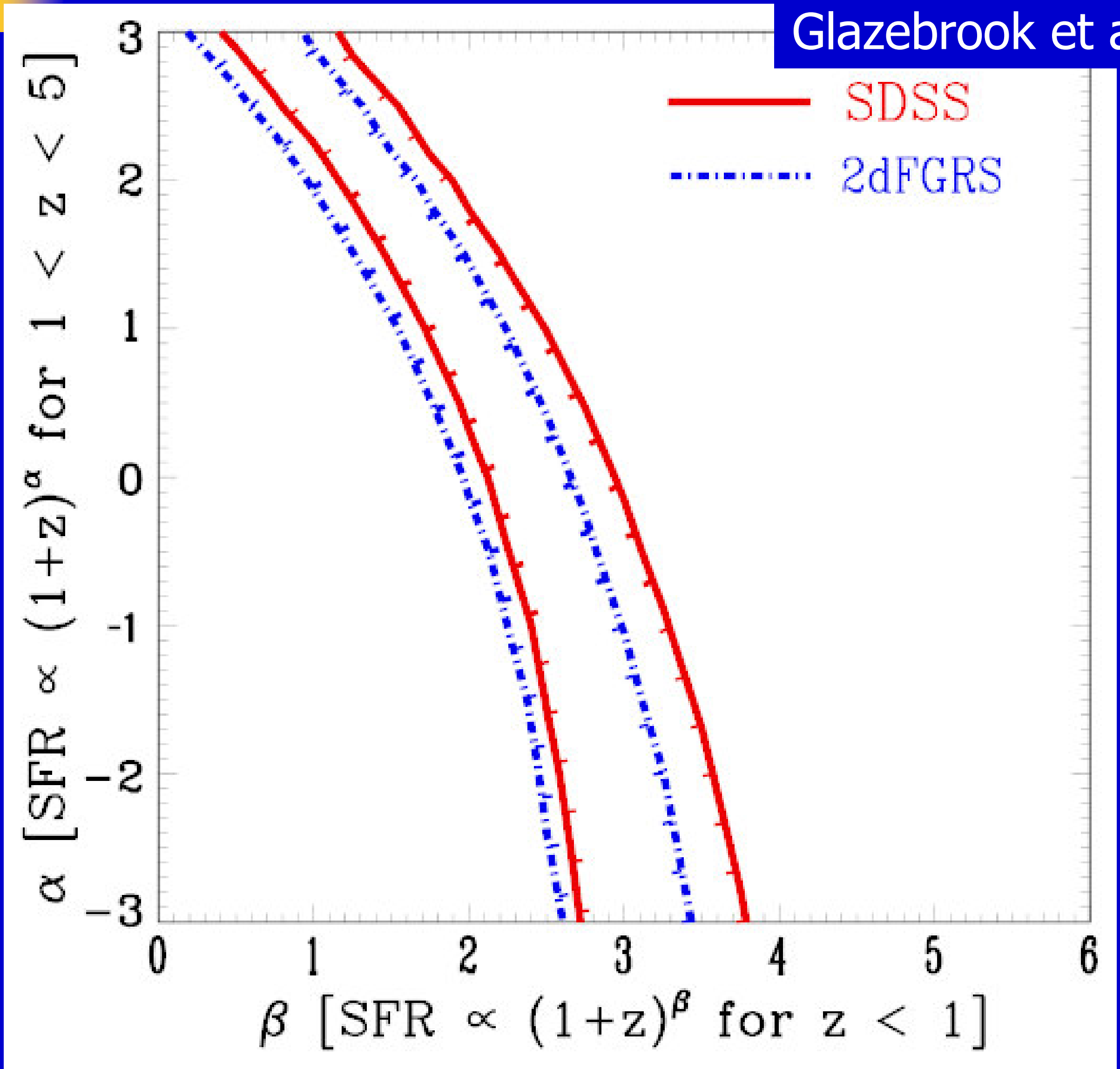
Hogg (2001) astro-ph/0105280





SDSS constraints on supernova rate

Glazebrook et al, astro-ph/0301005



A check: SN rate from metal enrichment history

$$R_{SN}(t) = \dot{\rho}_Z(t)/\langle M_Z \rangle$$

Kaplinghat, Steigman and Walker (2002)

$\langle M_Z \rangle$ is the average yield of metals.

$\dot{\rho}_Z(t)$ is the metal enrichment rate calculated from the UV luminosity density evolution.

Lilly et al, ApJL (1996), Madau et al, MNRAS (1996)
Sullivan et al, MNRAS (2000), Gallego et al, ApJL (1995)

Reduced sensitive to the IMF.

Adopted models for supernova rate

A. Best fit model from SDSS star formation history analysis (this model comes close to saturating the SK upper bound).

B. Reasonable lower limit to the flux based on the SDSS results for the star formation history.

$$\dot{\rho}_*(0) = 0.7 \times 10^{-2} h \mathrm{M}_\odot \mathrm{yr}^{-1} \mathrm{Mpc}^{-3}$$

$$\beta = 2 \quad \alpha = 0$$

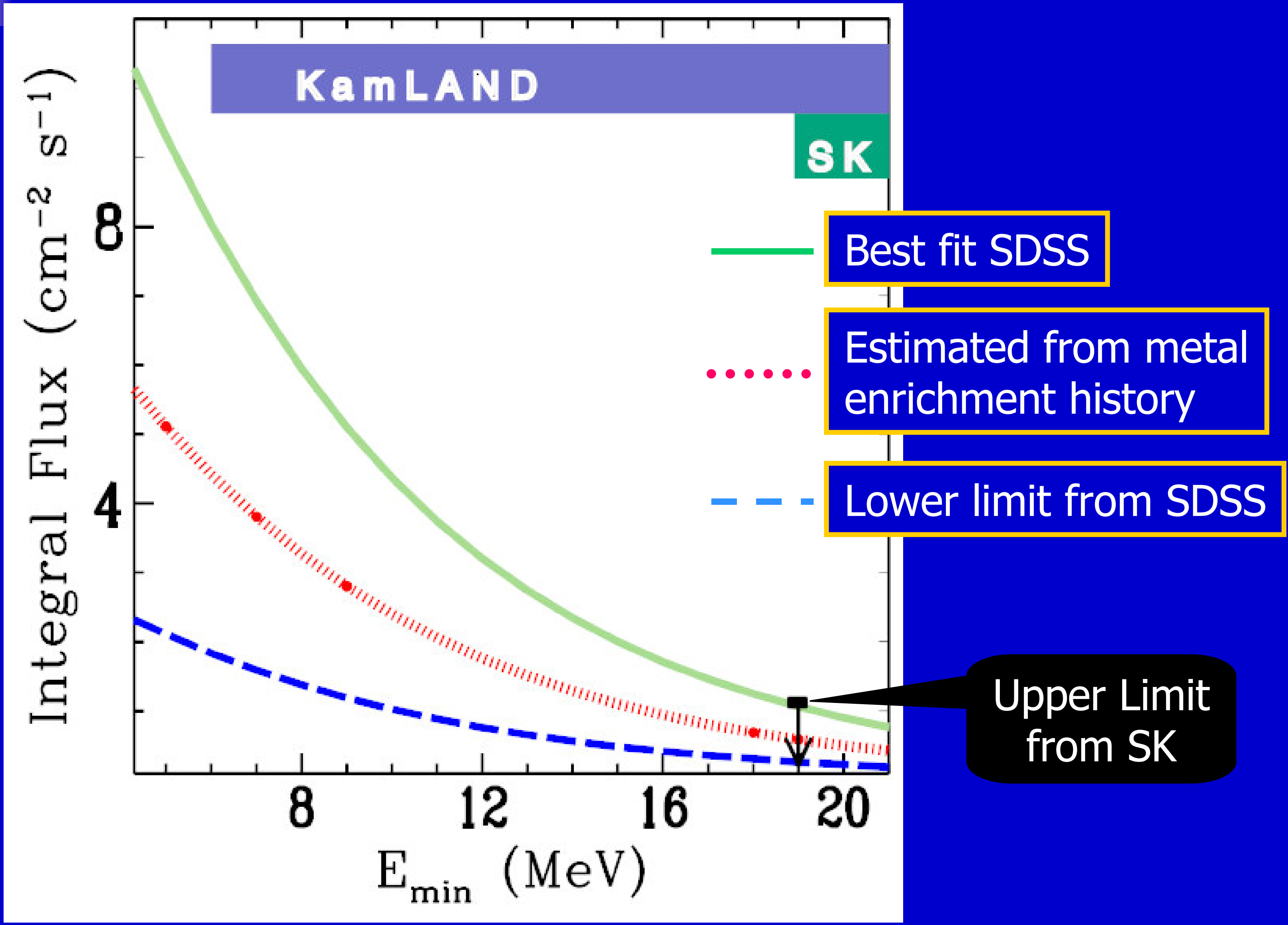
Baldry and Glazebrook, astro-ph/0304423

C. Derived from the metal enrichment history and is consistent with the SDSS results.

$$\mathrm{R}_{\mathrm{SN}}(0) = 1.2 \times 10^{-4} \mathrm{yr}^{-1} \mathrm{Mpc}^{-3}$$

$$\beta = 2.5 \quad \alpha = 0$$

Flux at the detectors



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Observable energy window

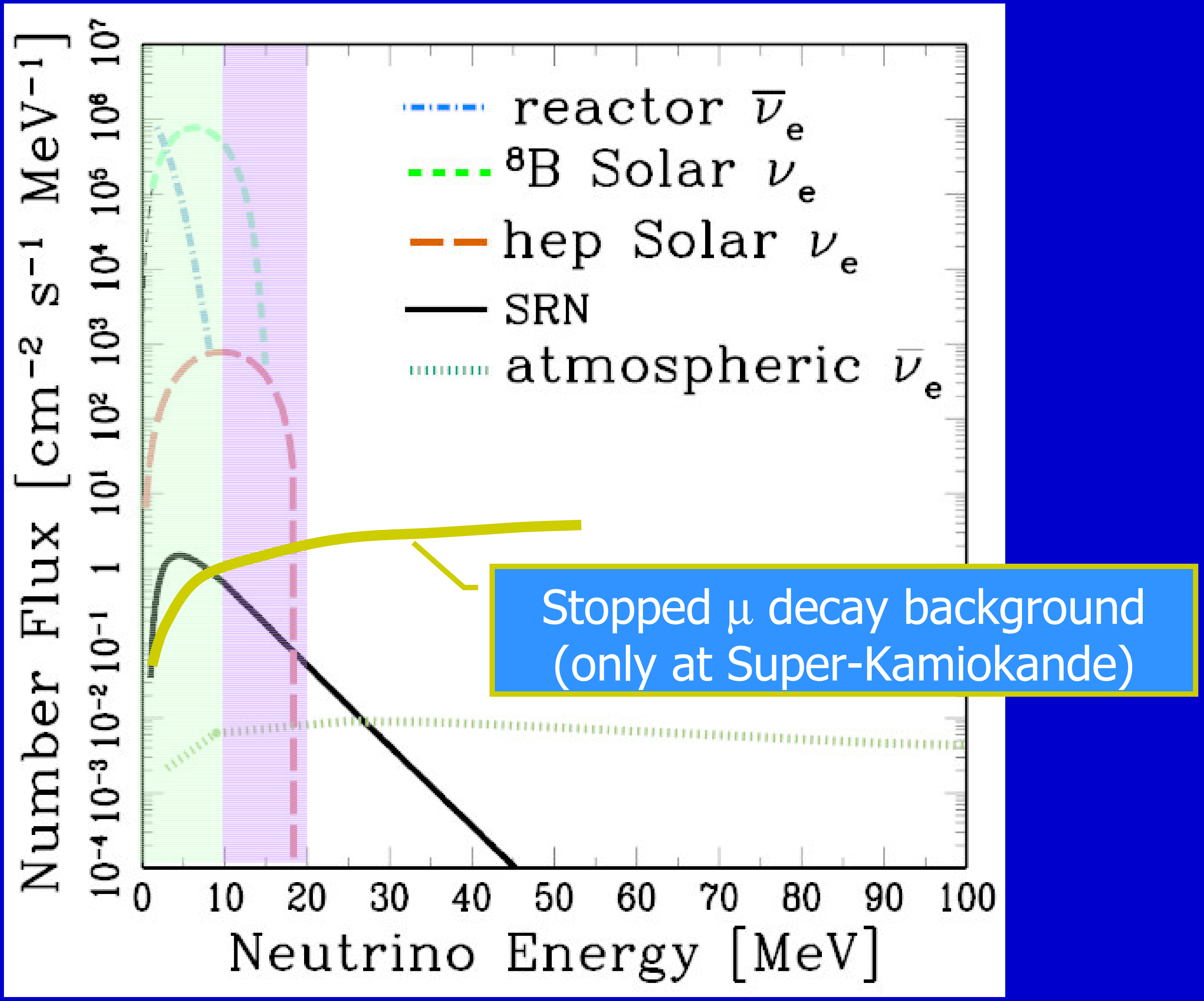
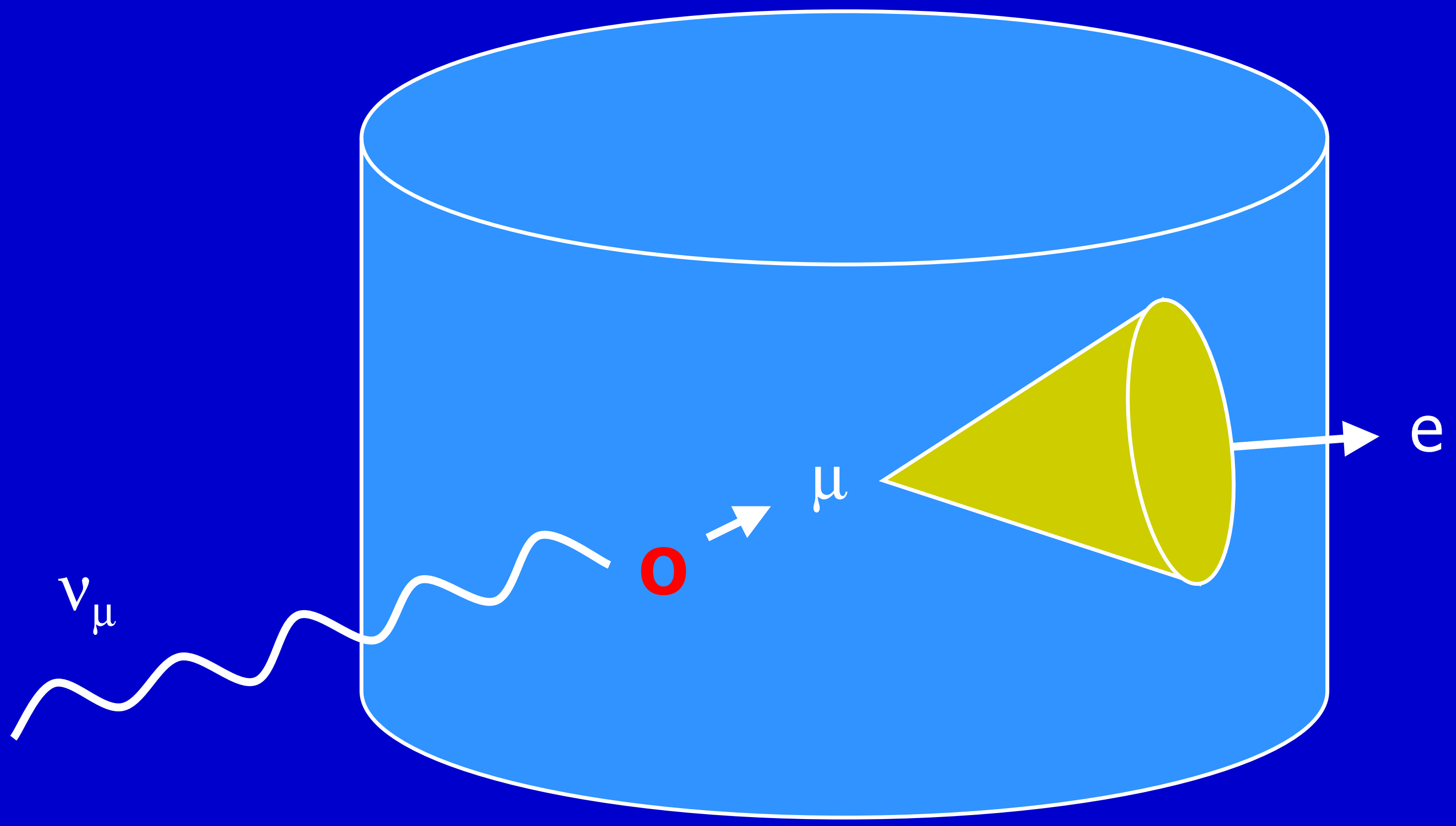


Figure from Ando, Totani and Sato 2003

Muon decay background



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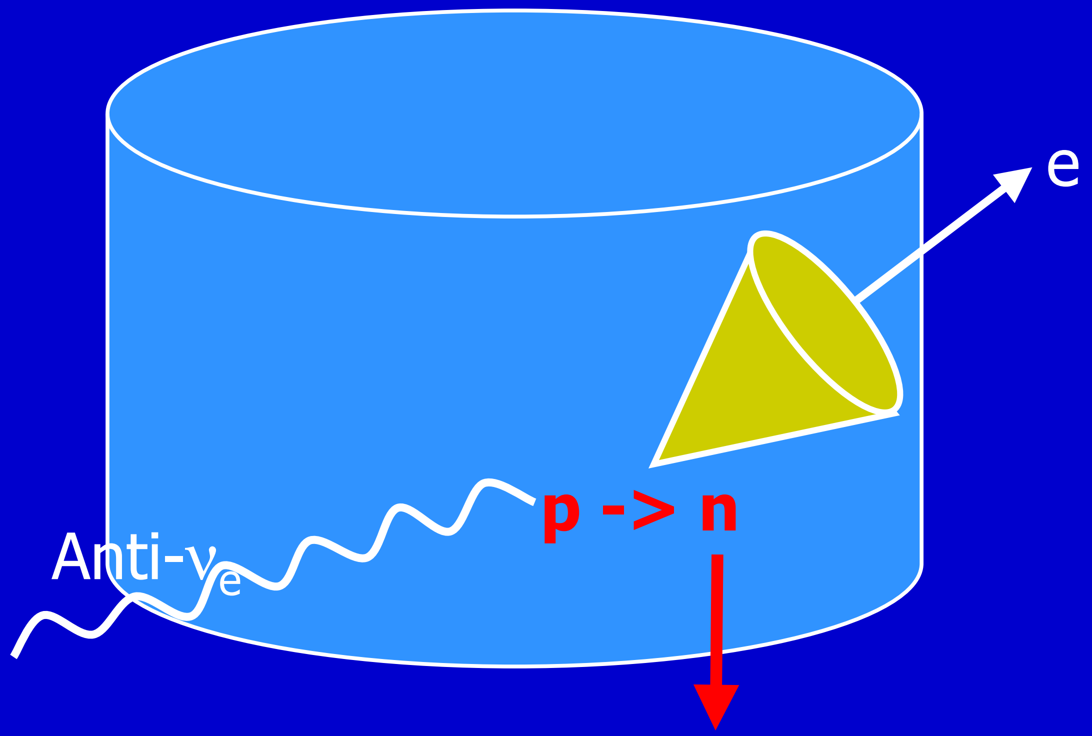
Forecasts

- We predict

$$1.8 \quad < \quad F(E > 6\text{MeV}) < 8\,\bar{\nu}_e\,/\text{cm}^2/\,\text{s}$$
$$0.3 \quad < \quad F(E > 19\text{MeV}) < 1.2\,\bar{\nu}_e\,/\text{cm}^2/\,\text{s}$$

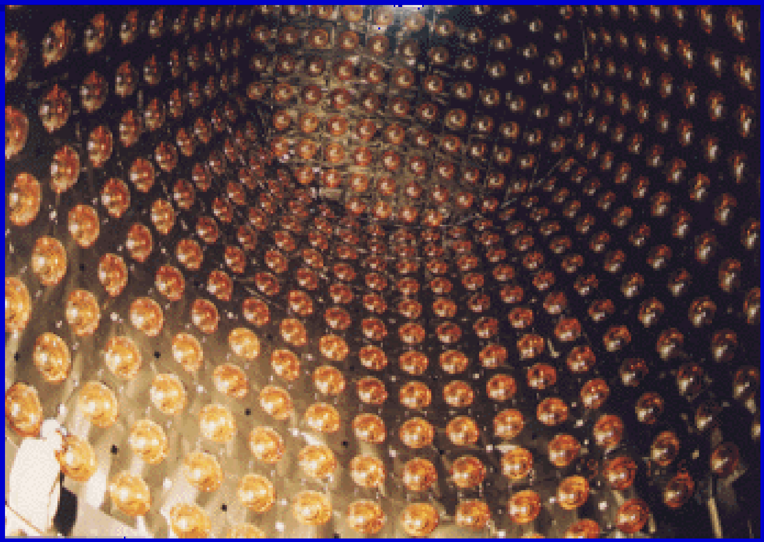
- 3.6 events per year in 22 kton of water (SK).
- 0.4 events per year in 1 kton of LS (KamLAND).

Exciting prospects for the future



GADZOOKS – Tag the neutron by adding $GdCl^3$ to water (Beacom and Vagins, 2003).
Can reduce the muon background by a factor of 5!
Go down to energies of order 10 MeV.

GADZOOKS: Spring 2005



K2K's 1 kiloton tank might be available for large-scale studies of

- Gd Water Filtering – UCI built and maintains this water system
- Gd Light Attenuation – using real 20" PMTs
- Gd Materials Effects – many similar detector elements as in SK

2006: $GdCl_3$ doped SK-III?

Bottomline

- Detection of supernova relic neutrino will verify the basic picture of star formation and death.
- Powerful constraints on the star formation history. The presents constraints already rule out a large region of parameter space allowed by SDSS data.

- Gd doping can reduce the time to detection by a factor of 10.
- Sensitivity to star formation history at $z > 1$.
- It might be possible to disentangle fundamental supernova physics from star formation history.

- EVEN NO DETECTION IS INTERESTING !