Type IIn supernovae as the sources of high energy neutrinos

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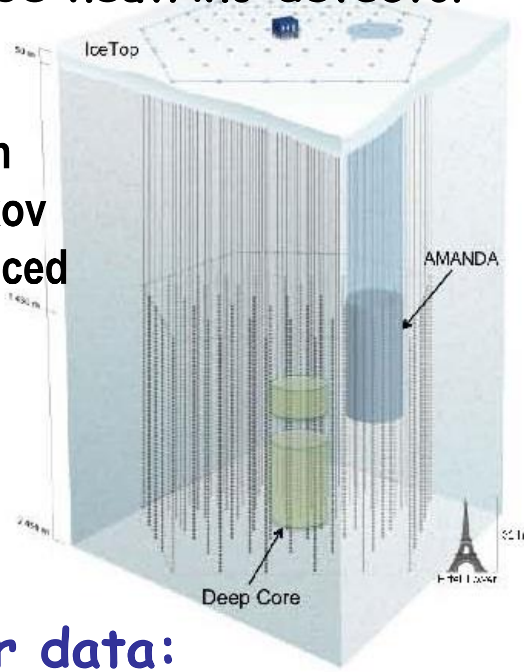
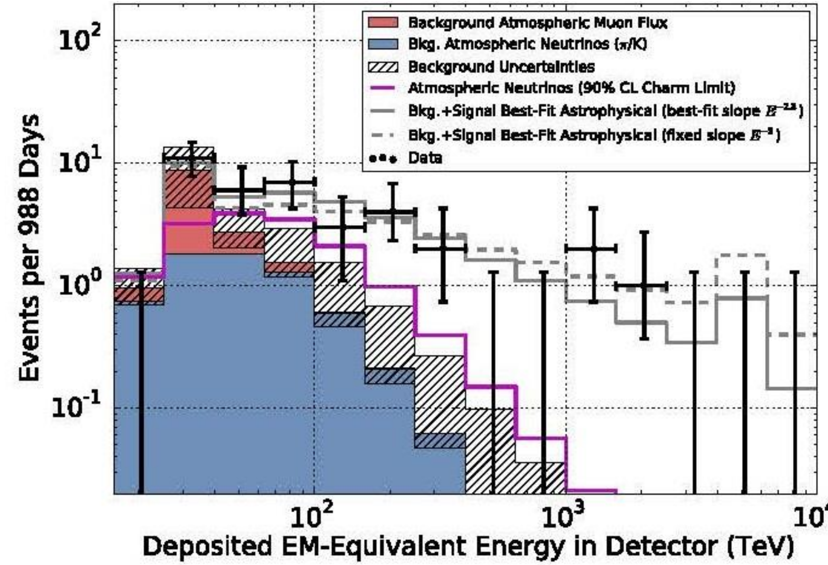
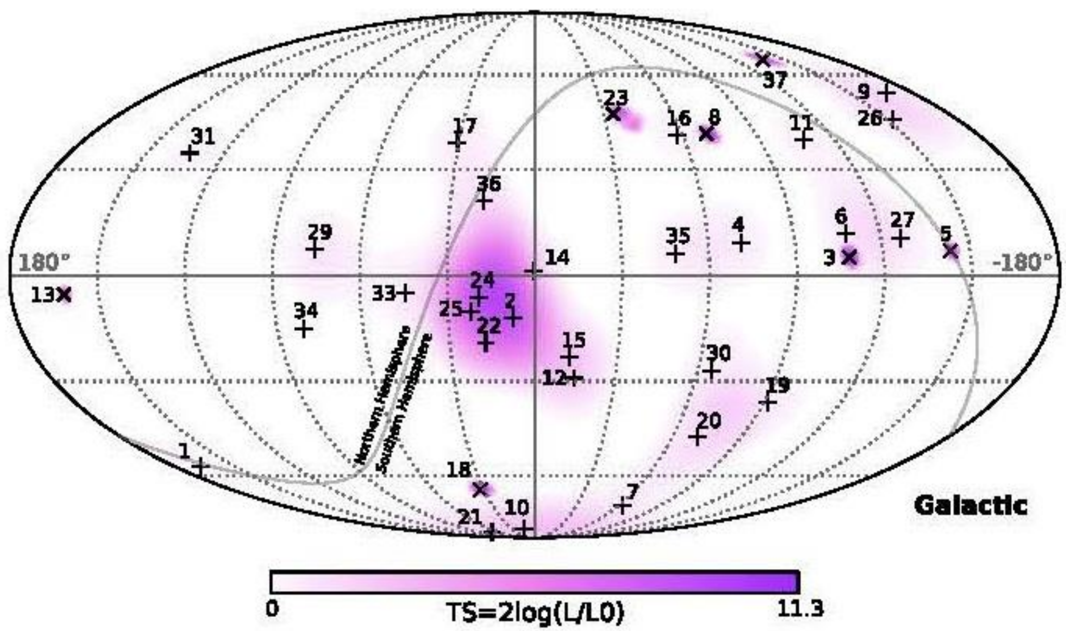
high energy neutrinos of cosmic origin

IceCube neutrino detector



registration of Cherenkov light produced in ice by charged secondary particles



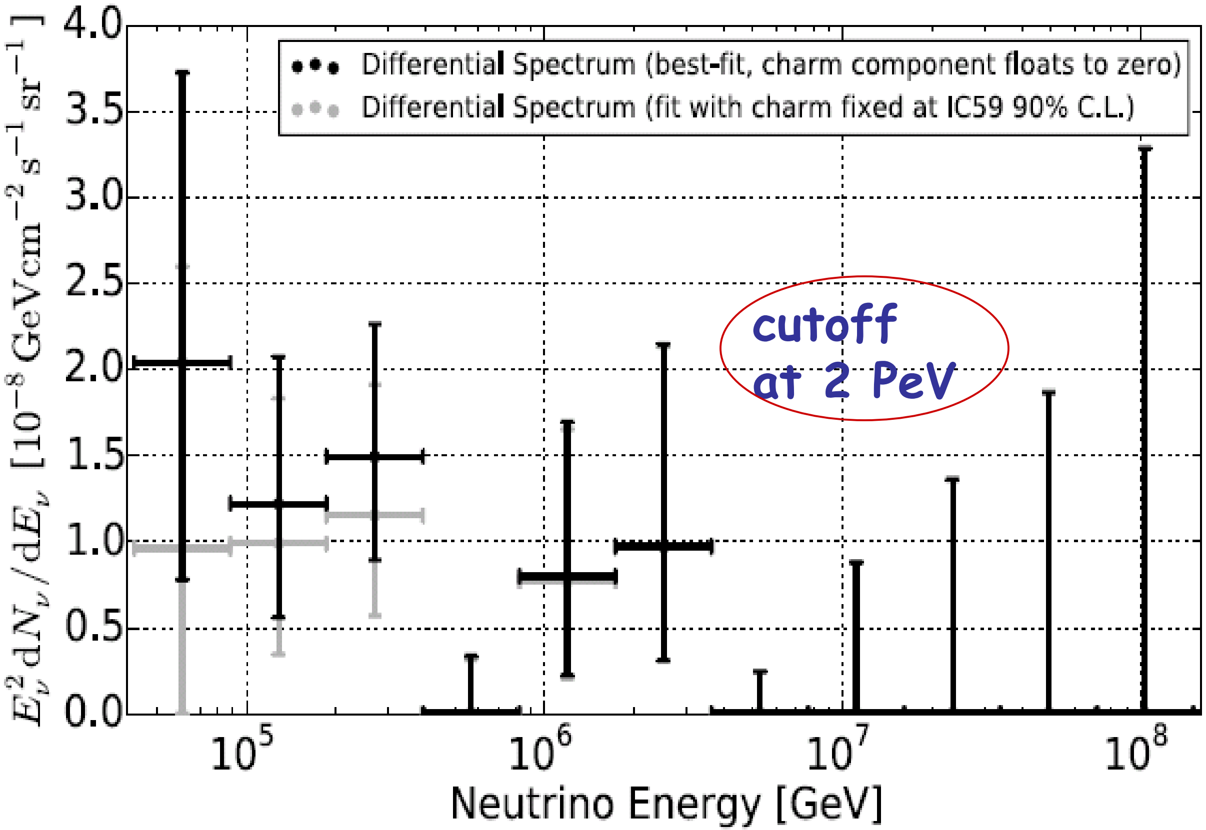


3-year data:
excess of 37 neutrinos above background (>5.7 sigma) at 3.10^{13} to 2.10^{15} eV

$$E_\nu^2 \left(dN / dE_\nu \right) = (0.95 \pm 0.3) \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Aartsen et al. 2014

spectrum of high-energy astrophysical neutrinos E^{2}xN



neutrino production in cosmos is possible via interactions $p\gamma, pp$ and decay chains

$$\pi^+ \rightarrow \mu^+ \nu_\mu,\ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu,$$

$$E_\nu \approx 0.05 \times E_p$$

- no correlation with any types of astrophysical objects was found
- Galactic sources may account only for a minority of events
- cosmogenic neutrino production is inefficient
- can be produced in extragalactic sources of UHE cosmic rays
  Waxman-Bahcal bound?

Glashow resonance

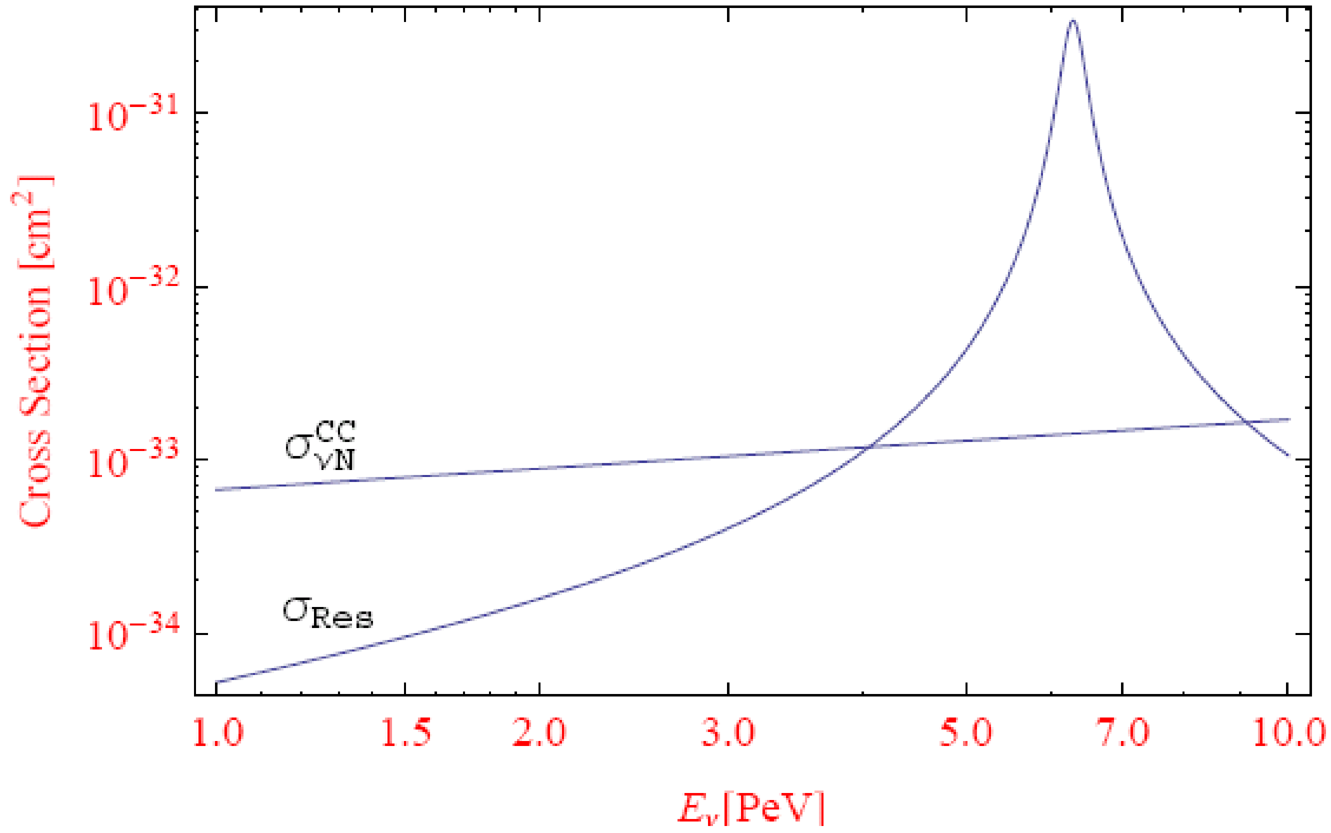
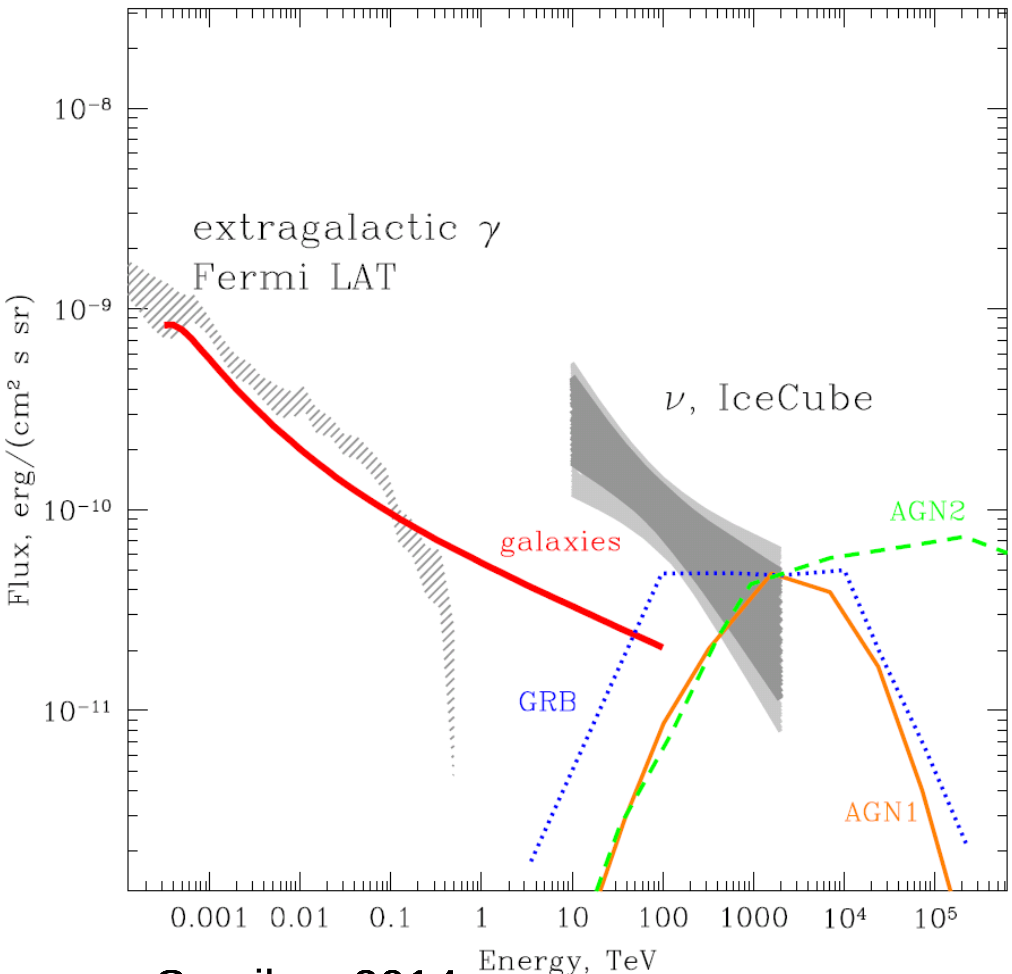


FIG. 1: Cross sections for the resonant process, $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ hadrons, and the non-resonant process, $\nu_e + N \rightarrow e^- +$ hadrons, in the 1–10 PeV region.

The most plausible mechanism pp interactions of high energy protons



Neronov, Semikoz 2014

$$pp \rightarrow \pi^+ \pi^- \pi^0 \rightarrow \nu_e + \bar{\nu}_e + 2\nu_\mu + 2\bar{\nu}_\mu + 2\gamma + e^+ + e^-$$

Hard proton spectrum ($\sim E^{-2}$) and cut-off at $E \sim 10^{17}$ eV

Acceleration in SNRs

Supernova remnants (SNRs) are the principal source of cosmic rays in the Galaxy up to "knee" energy ~3 PeV

Particles can be accelerated to higher energies in some rare SNRs produced by IIb, IIn supernovae

Supernovae IIn ~ 1-5% of core collapse supernovae. Dense stellar wind dM/dt=0.001-0.1 M_S per year – favorable conditions for particle acceleration and neutrino generation. Gamma-rays, neutrinos, nonthermal X-rays and radiowaves from nearest IIn supernova can be detected if effective DSA operates there (Murase et al. 2011, Kats et al. 2011)

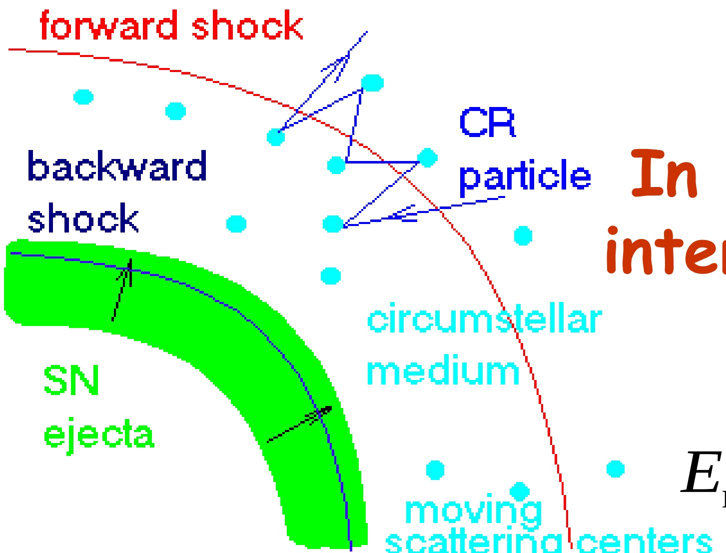
Diffusive Shock Acceleration

Krymsky 1977; Bell 1978

Very attractive feature: power-law spectrum of particles accelerated, $\gamma=(\sigma+2)/(\sigma-1)$, where σ is the shock compression ratio, for strong shocks $\sigma=4$ and $\gamma=2$

Maximum energy for SN: $D \sim 0.1 u_{sh} R_{sh} \sim 3 \cdot 10^{27}\ cm^2/s < D_{gal}$

Diffusion coefficient should be small in the vicinity of SN shock



In the Bohm limit $D=D_B=cr_g/3$ and for interstellar magnetic field

$$E_{max} = Z \cdot 10^{14} \mathrm{eV} \left(\frac{B}{10\mu\mathrm{G}}\right)\left(\frac{R_{sh}}{3\mathrm{pc}}\right)\left(\frac{u_{sh}}{3000\,\mathrm{kms}^{-1}}\right)$$

"Knee" energies for SNRs in different circumstellar media (Bohm diffusion in the amplified magnetic field)

Uniform medium

SNRs of Ia supernovae

$$E_{\mathrm{knee}} = 3Z\,\mathrm{PeV}\left(\frac{E_{SN}}{10^{51}\mathrm{erg}}\right)\left(\frac{M_{ej}}{M_{\mathrm{solar}}}\right)^{-2/3} n_H^{1/6}$$

Stellar wind

$$E_{\mathrm{knee}} = 80Z\,\mathrm{PeV}\left(\frac{E_{SN}}{10^{52}\mathrm{erg}}\right)\left(\frac{M_{ej}}{10M_{\mathrm{solar}}}\right)^{-1}\left(\frac{\dot{M}}{10^{-2}M_{\mathrm{solar}}\mathrm{yr}^{-1}}\right)^{1/2}\left(\frac{u_w}{100\ \mathrm{km/s}}\right)^{-1/2}$$

SNRs of IIP, IIb, IIn supernovae

quasi-parallel shocks, nonresonant instability (Bell 2004)

10 times lower energies

higher for oblique shocks

Estimate of neutrino flux from IIn supernova in the Universe

$$F(E)E^2 = \frac{\xi_{\mathrm{CR}} K_\nu \sigma_{pp} c^2 u_{SN} T_H \nu_{SN} \dot{M}^2}{(4\pi)^2 \mathrm{m} u_{\mathrm{w}}^2 \ln(\mathrm{E}_{\max}/\mathrm{m}c^2)} \ln\frac{R_{Sed}}{R_{\min}}$$

$$F(E)E^2 \approx 10^{-11} \frac{\mathrm{erg}}{\mathrm{cm}^2\mathrm{s\ sr}} \left(\frac{E_{SN}}{10^{52}\mathrm{erg}}\right)^{1/2} \left(\frac{M_{ej}}{10 M_{\mathrm{solar}}}\right)^{-1/2} \times$$

$$\left(\frac{\nu_{SN}}{10^{-6}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}}\right) \left(\frac{\dot{M}}{10^{-2} M_{\mathrm{solar}}\mathrm{yr}^{-1}}\right)^2 \left(\frac{u_w}{100\ \mathrm{km/s}}\right)^{-2}$$

Numerical model of nonlinear diffusive shock acceleration

(natural development of existing models of Berezhko et al. (1994-2006), Kang & Jones 2006)

Spherically symmetric HD equations + CR transport equation

$$\frac{\partial \rho}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r} r^2 u \rho \quad (1)$$

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial r} - \frac{1}{\rho}\left(\frac{\partial P_g}{\partial r} + \frac{\partial P_c}{\partial r}\right) \quad (2)$$

$$\frac{\partial P_g}{\partial t} = -u\frac{\partial P_g}{\partial r} - \frac{\gamma_g P_g}{r^2}\frac{\partial r^2 u}{\partial r} - (\gamma_g - 1)(w-u)\frac{\partial P_c}{\partial r} \quad (3)$$

$$\frac{\partial N}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r} r^2 D(p,r,t)\frac{\partial N}{\partial r} - w\frac{\partial N}{\partial r} + \frac{\partial N}{\partial p}\frac{p}{3r^2}\frac{\partial r^2 w}{\partial r}$$

$$+\frac{\eta_f \delta(p-p_f)}{4\pi p_f^2 m}\rho(R_f+0,t)(\dot{R}_f - u(R+0,t))\delta(r-R_f(t))$$

$$+\frac{\eta_b \delta(p-p_b)}{4\pi p_b^2 m}\rho(R_b-0,t)(u(R_b-0,t)-\dot{R}_b)\delta(r-R_b(t))$$

(4)

Spectra of accelerated particles and pp – neutrinos produced during 30 years after IIn supernova explosion

25% of explosion energy goes into accelerated particles

$E_{SN}=10^{52}$ erg

$M_{ej}=10\ M_S$

Mass loss rate

$dM/dt=10^{-2}$

M_S per year

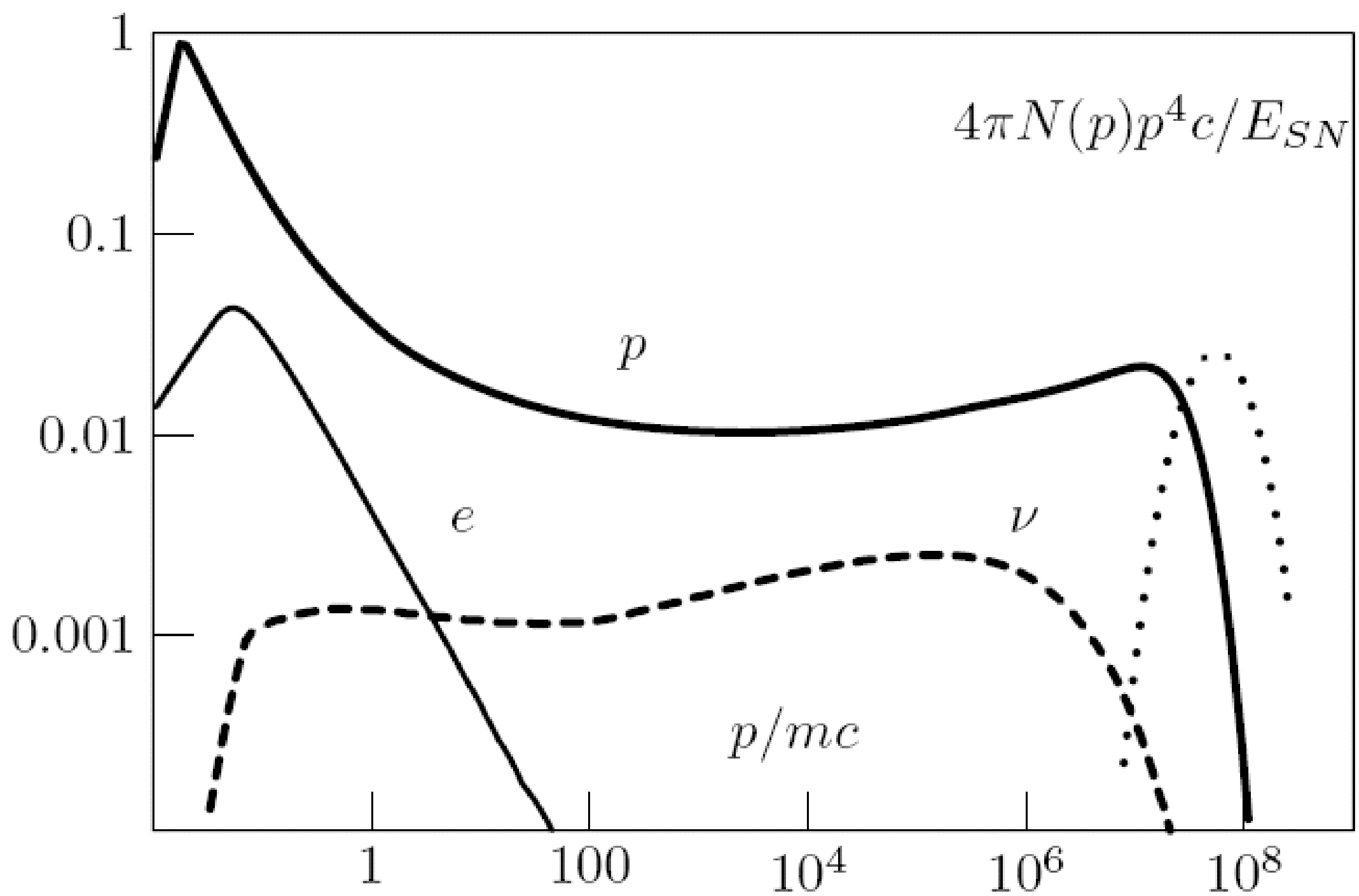
Stellar wind speed

$u_w=100$ km/s

parameters from

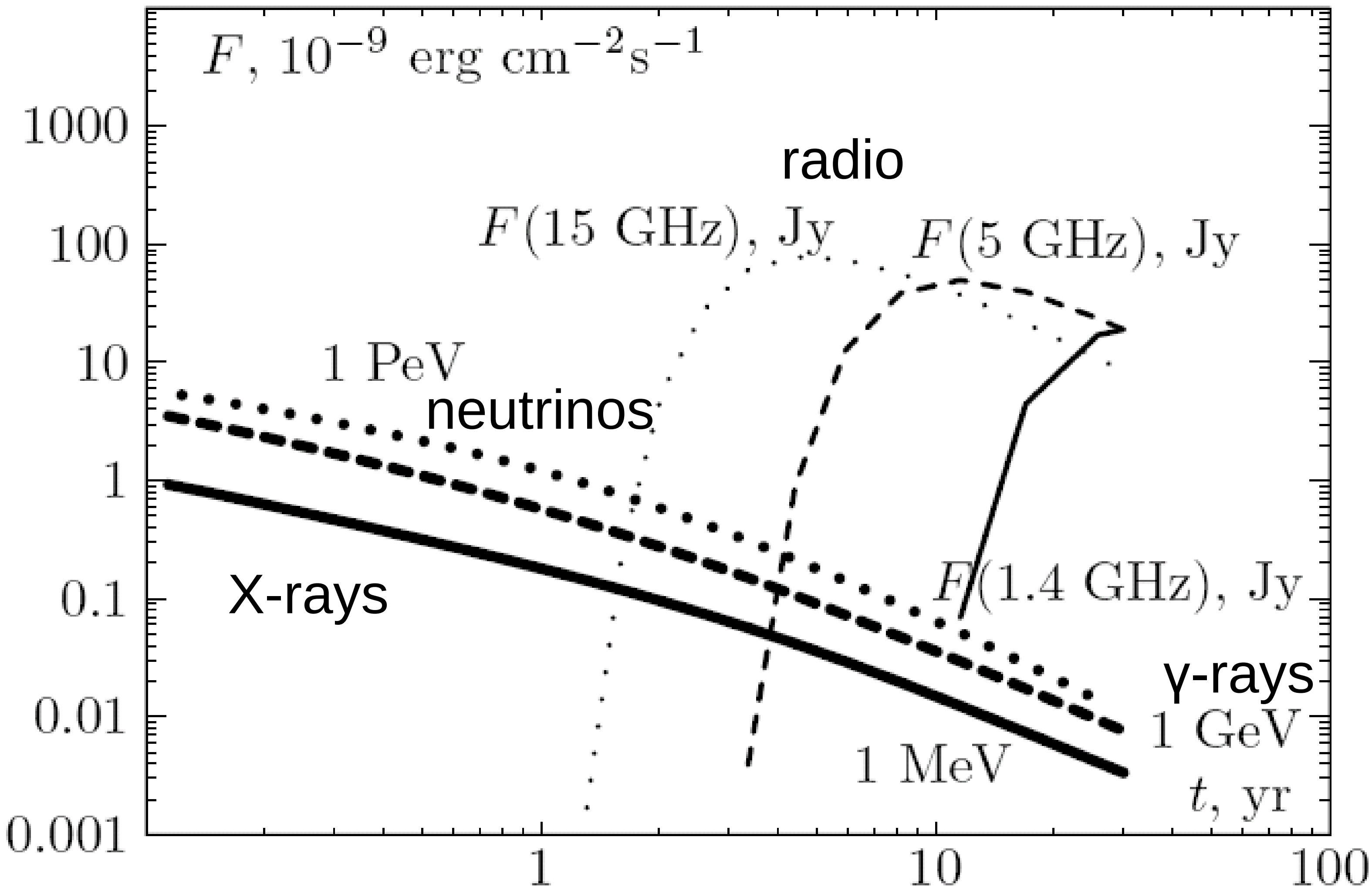
Moriya et al.

2014



Fluxes expected from IIn supernova

D=1Mpc

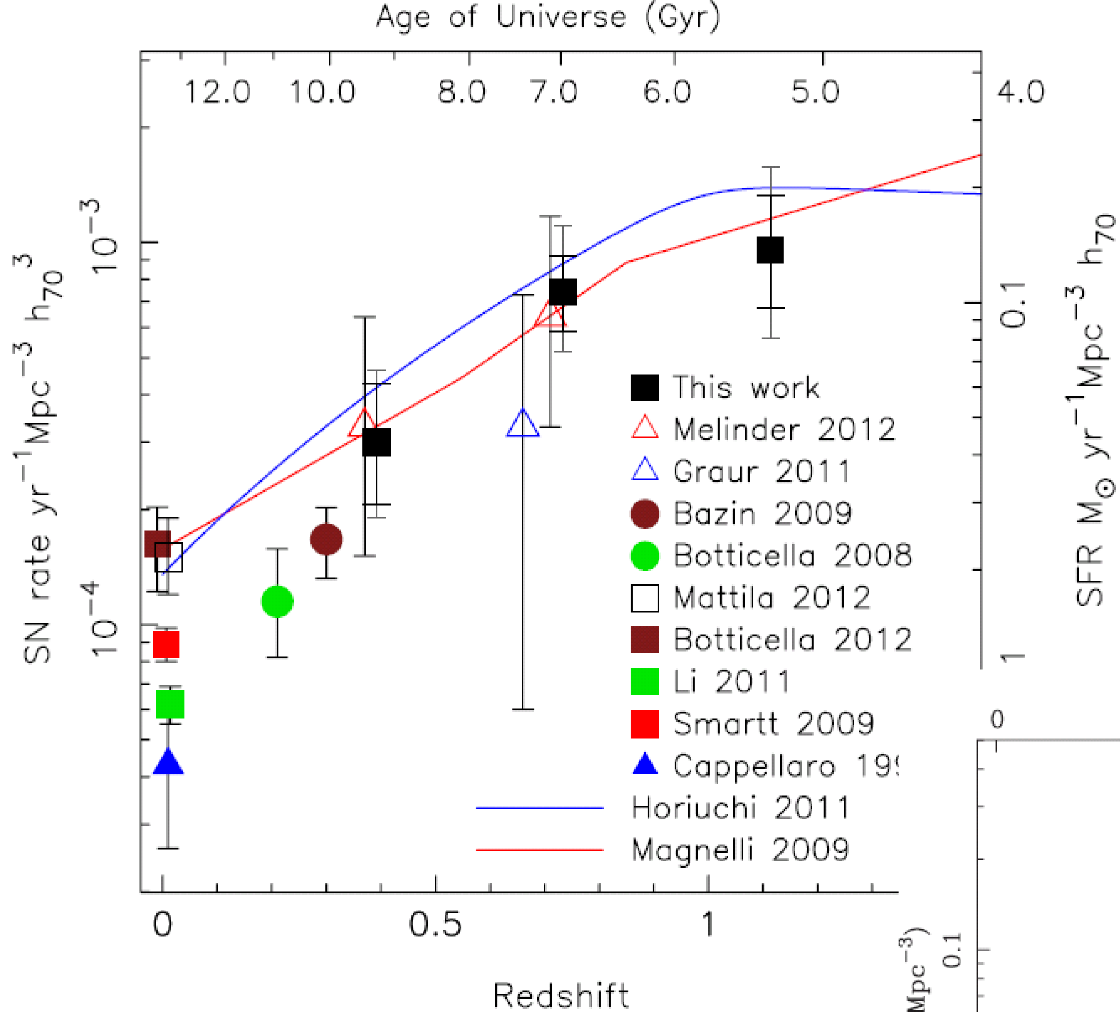


Background spectrum of astrophysical neutrinos

$$F(E) = H_0^{-1} \int_{E}^{E(1+z_{\max})} \frac{dE'}{E} \left(\frac{E'}{E} \right)^m \frac{q(E')}{\sqrt{\Omega_\Lambda + \Omega_M E'^3 / E^3}}$$

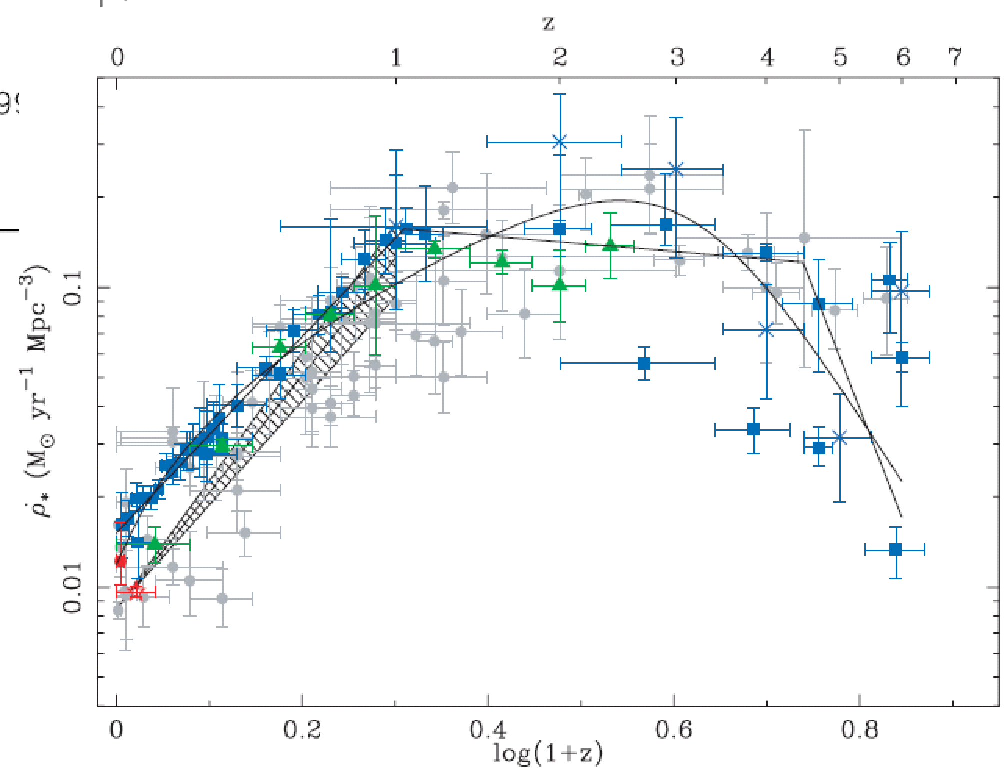
m describes evolution of sources $q \sim (1+z)^m$

Dependence of supernova rate and star formation rate on z



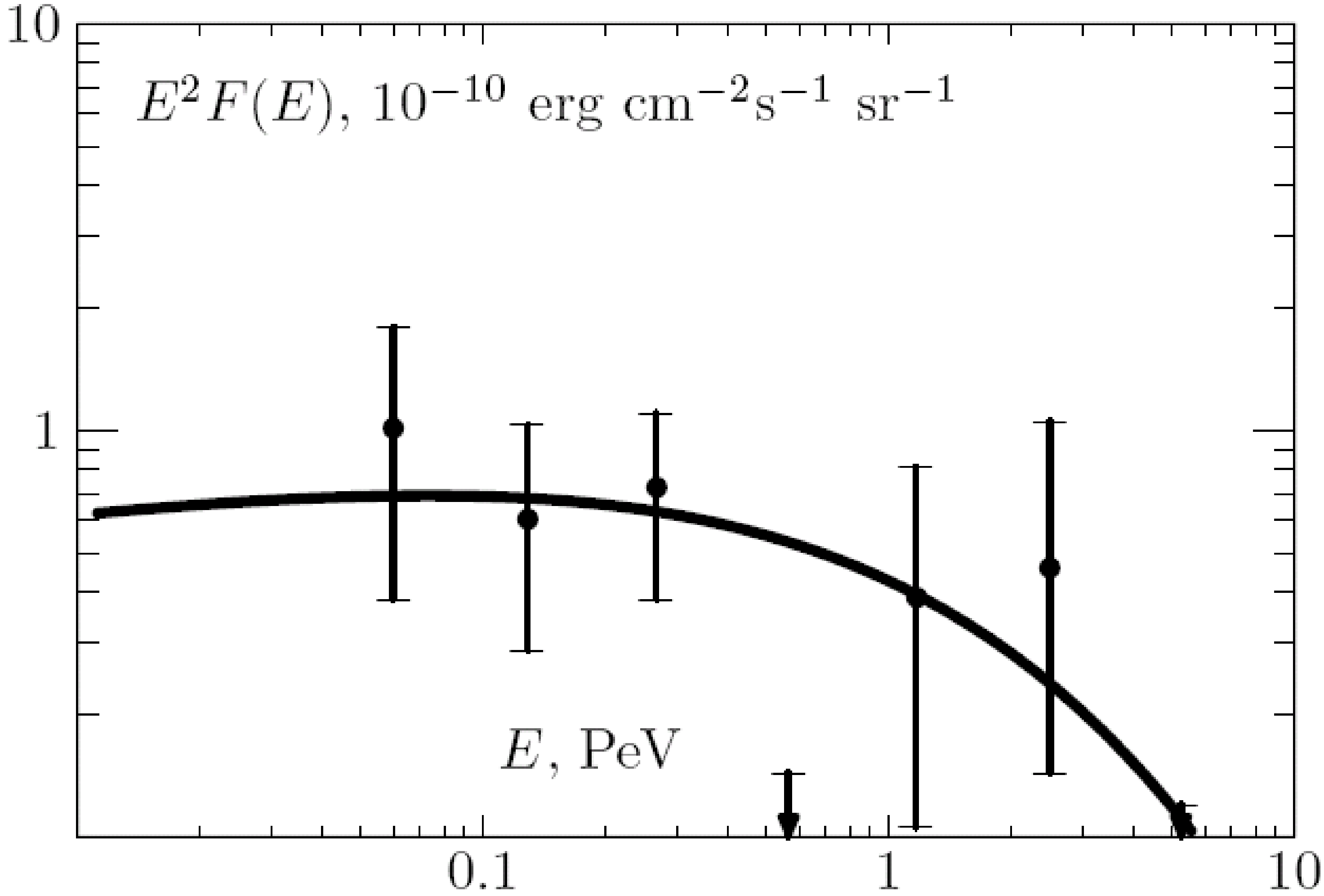
Dahlen et al. 2012

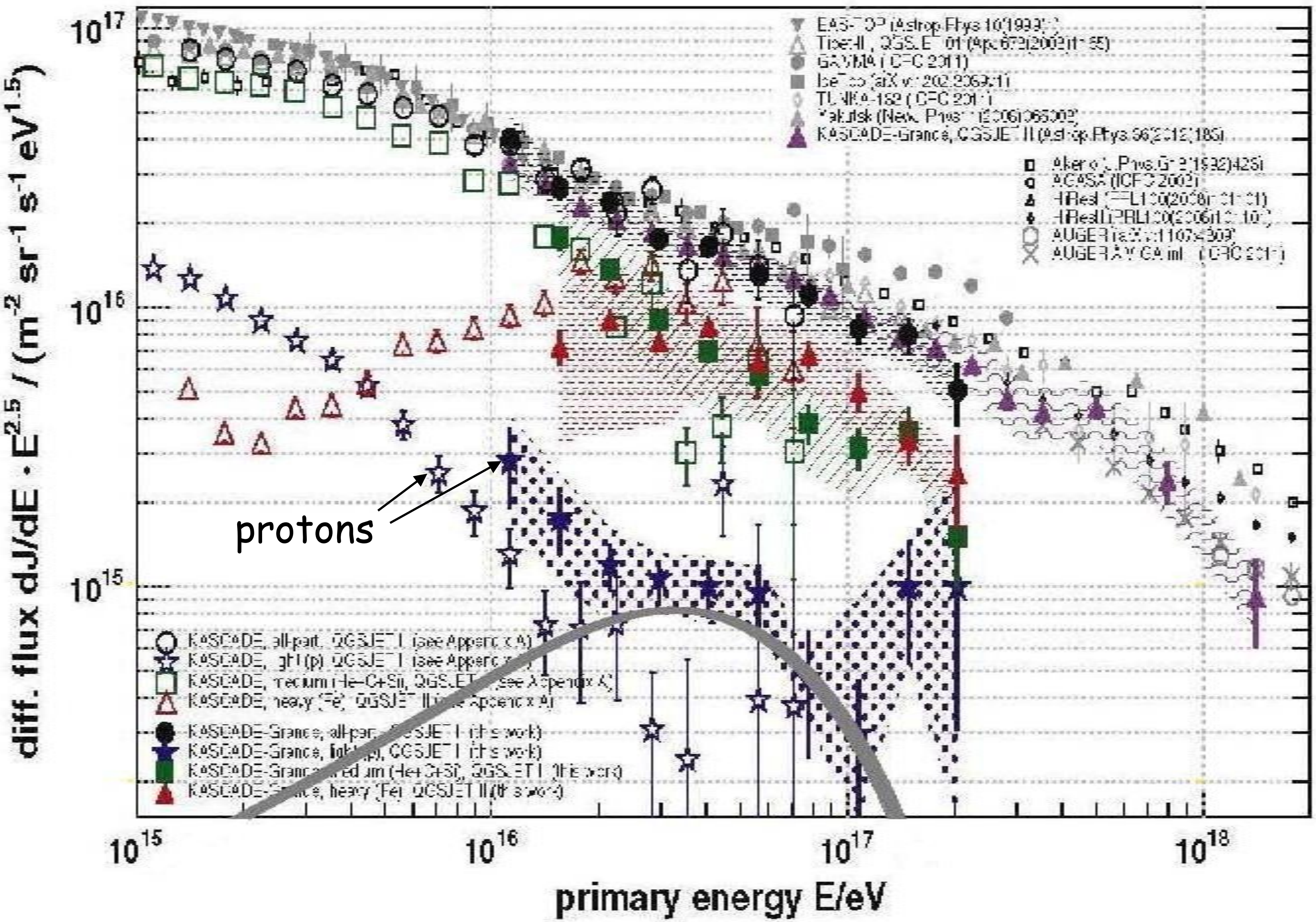
Hopkings & Beacom 2006



Neutrino spectrum produced by IIn supernovae

10^{-6} $(1+z)^{3.3}$ Mpc^{-3} per year at z<1 - 1% of core collapse SNe





solid line - calculated extragalactic proton background produced by SNIIn (without possible magnetic horizon effect); data on cosmic ray protons and nuclei from Apel et al 2013

Correlations of IIn SNe and IceCube neutrinos

1. No correlations with 8 track events (expected number 0.3)
2. ~5 correlations with 28 shower events (expected number 1)

Probably coincident

The arrival direction of PeV neutrino 20 is within 5 degrees from IIn SN 1978K – the nearest IIn supernova in the galaxy NGC 1313 at D=4Mpc

The arrival direction of PeV neutrino 35 is within 10 degrees from IIn SN 1996cr – the nearest IIn supernova in the Circinus galaxy at D=4Mpc

These supernovae were detected in X-rays, radio and optics. Circinus galaxy is the source of GeV gamma-rays (Hayashida et al. 2013).

Conclusions

1. Supernovae IIn can be the sources of high energy neutrinos. The main contribution comes from z~1.
2. Maximum energies of accelerated protons can reach 10^{17} eV. This is related with high density of circumstellar medium.
3. IIn supernova can give a significant contribution to the observed CR spectrum.
4. Nonthermal X-rays, gamma-rays and radiowaves from nearest IIn supernovae can be detected.
5. Further IceCube operation can detect the correlation between arrival directions of IceCube track events and IIn supernovae.