Diffusive shock acceleration with regular electric fields

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Outline

- Acceleration of particles at forward and reverse shocks in SNRs
- Amplification of magnetic fields
- Modeling of DSA with regular electric fields
- IIn supernova as the sources of high energy astrophysical neutrinos

Diffusive Shock Acceleration

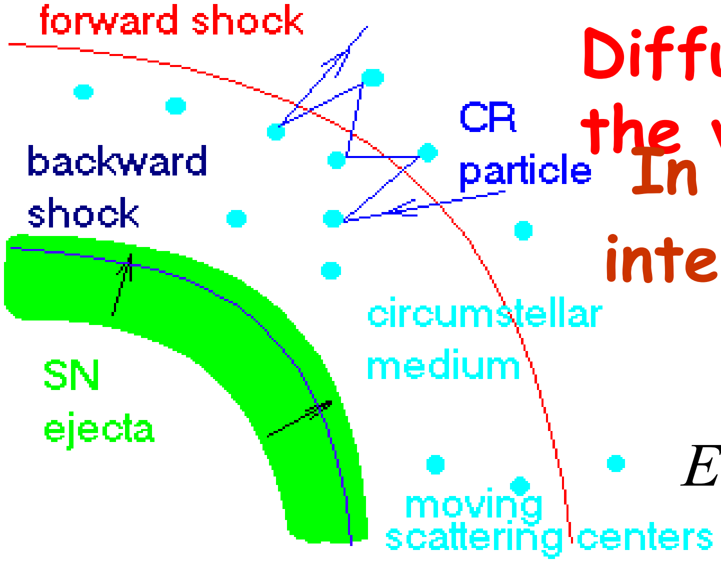
Krymsky 1977; Bell 1978; Axford et al.1977; Blandford & Ostriker 1978

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 $< D_{gal}$

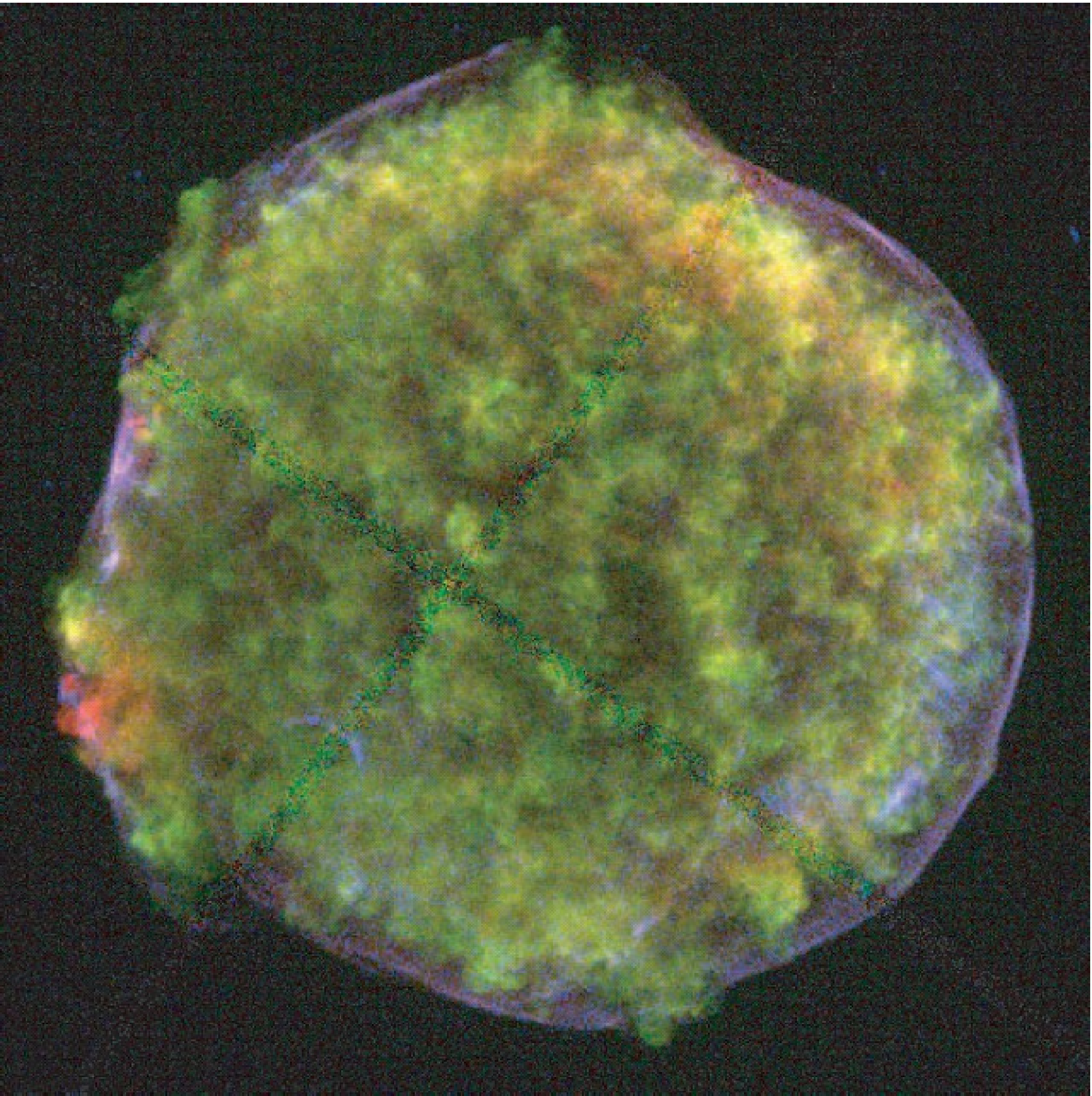
Diffusion coefficient should be small in the vicinity of SN shock

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



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

X-ray image of Tycho SNR (from Warren et al. 2005)



1. CD is close to the forward shock – evidence of the shock modification by CR pressure.
2. Thin non-thermal X-ray filaments at the periphery of the remnant – evidence of electron acceleration and of magnetic amplification.

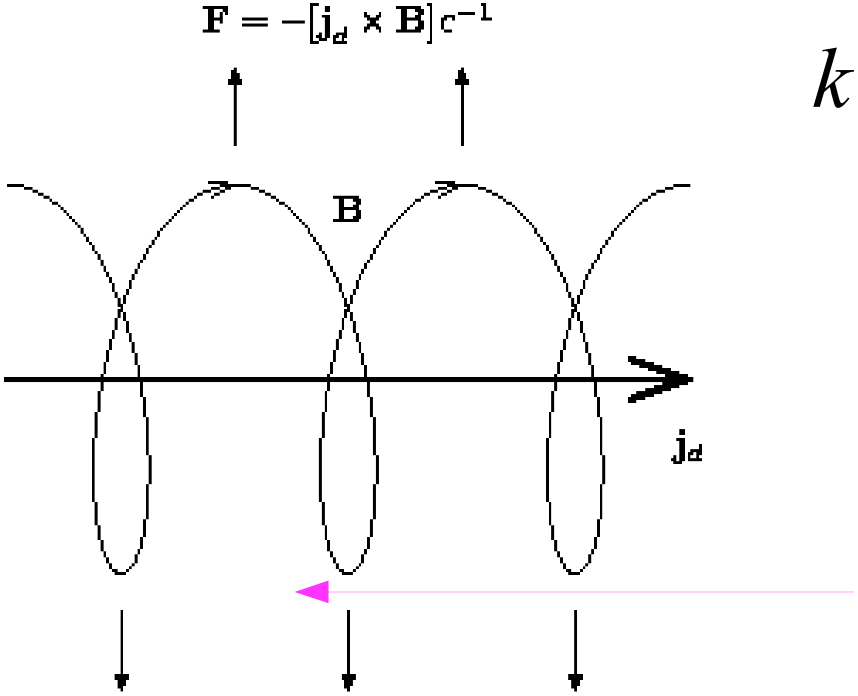
Magnetic field amplification by non-resonant streaming instability

Bell (2004) used Achterberg's results (1983) and found the regime of instability that was overlooked

$$F_{CR} = -\frac{1}{c}\left[j_d \times B\right]$$

$$\omega^2 = V_a^2 k^2 - j_d \frac{B_0 k}{c\rho_0}$$

$$k\, r_g >> 1,\ \gamma_{max} = j_d B_0 / 2c\rho V_a$$



Since the CR trajectories are weakly influenced by the small-scale field, the use of the mean j_d is well justfied

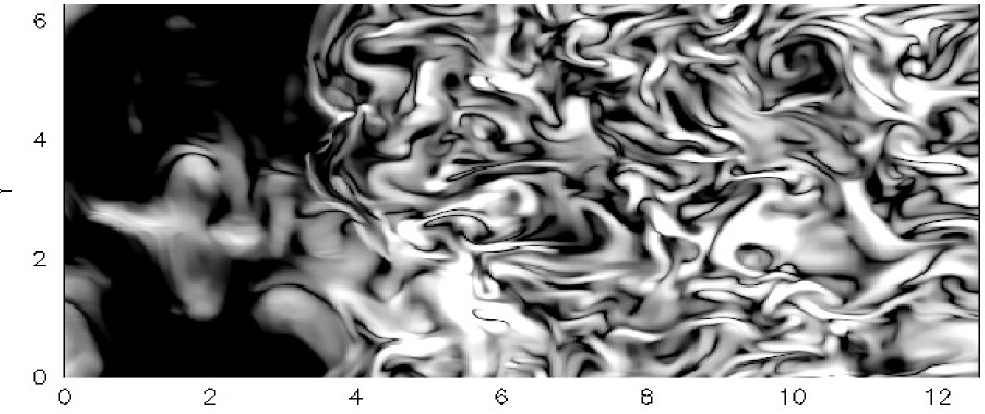
E= - [**u**X**B**]/c

Regular electric field

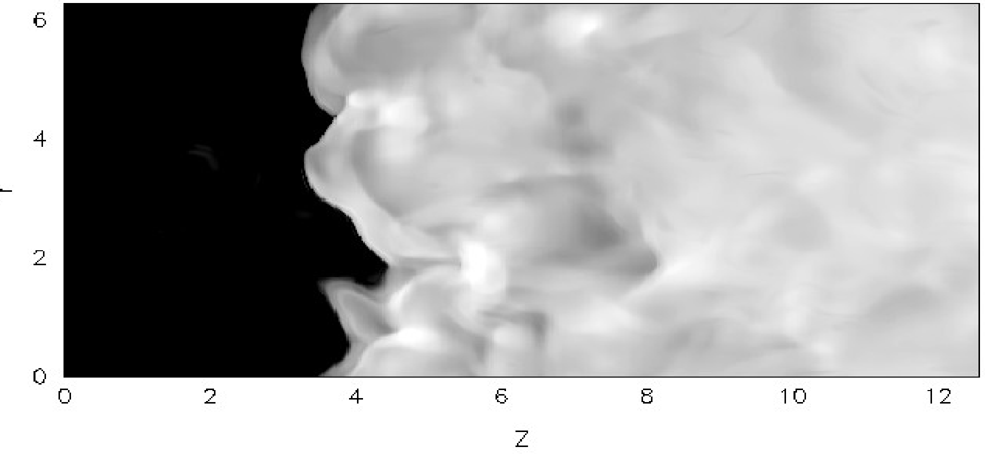
MHD modeling in the shock transition region and downstream of the shock

Zirakashvili & Ptuskin 2008

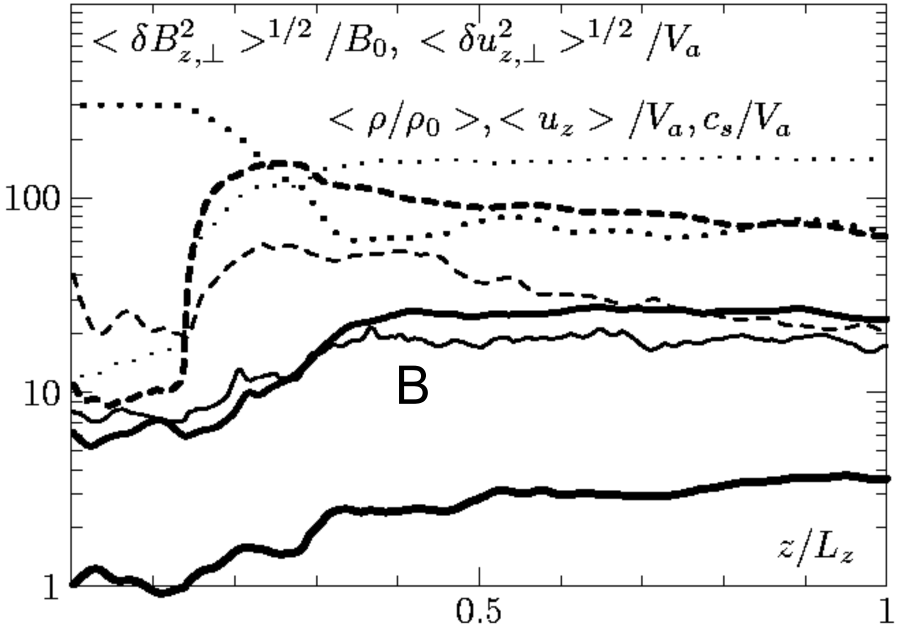
MAGNETIC FIELD



GAS PRESSURE



3D $256^2 \times 512$



u_1=3000 km/s V_a=10 km/s

η_{esc}=0.14

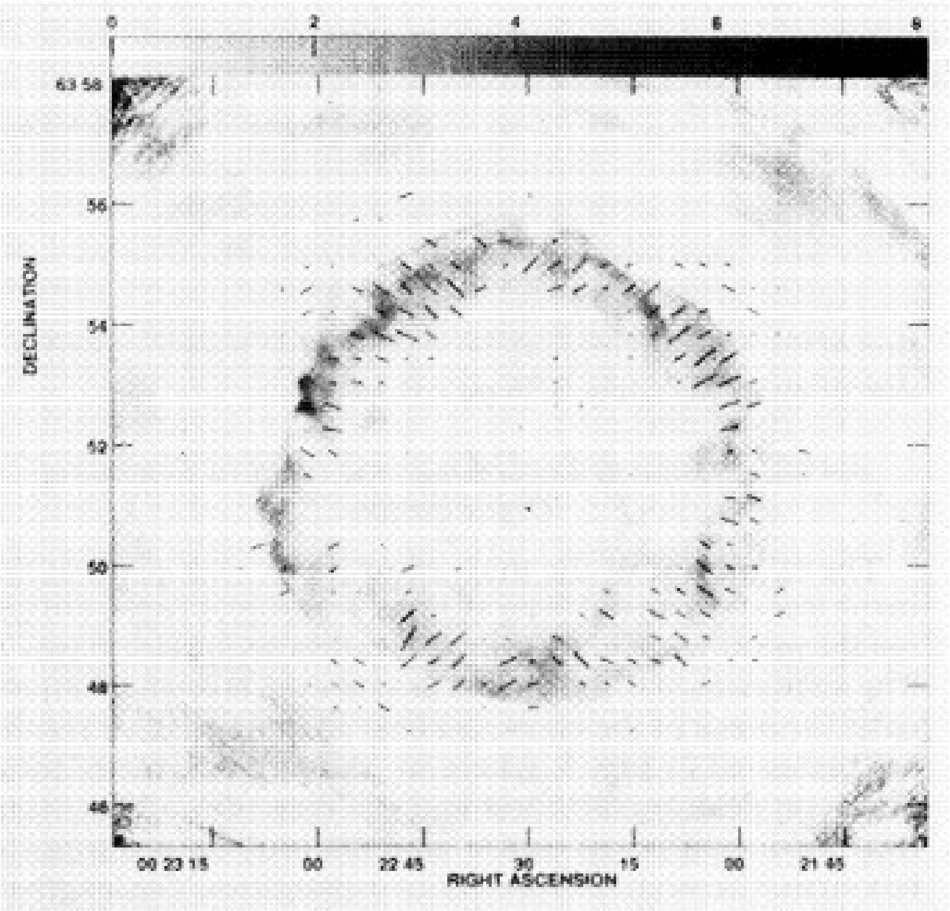
0.02L

Magnetic field is not damped and is perpendicular to the shock front downstream of the shock!

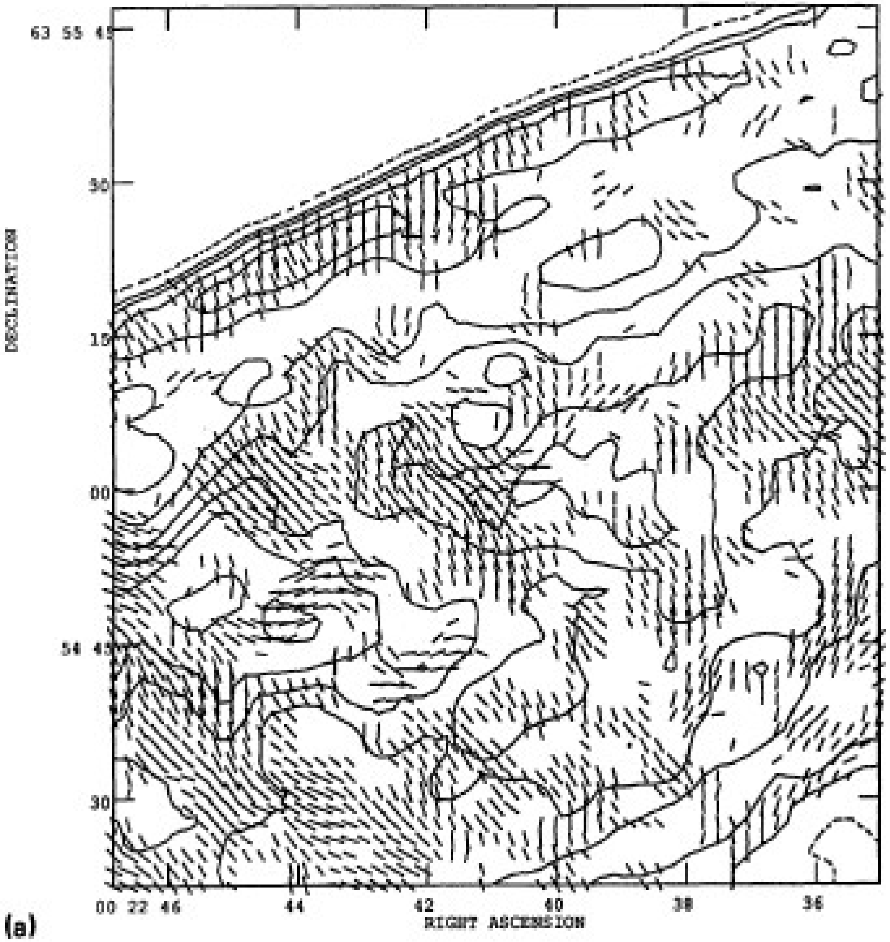
Ratio=1.4 σ_B=3

Wood & Mufson 1992

Dickel et al. 1991



(b)



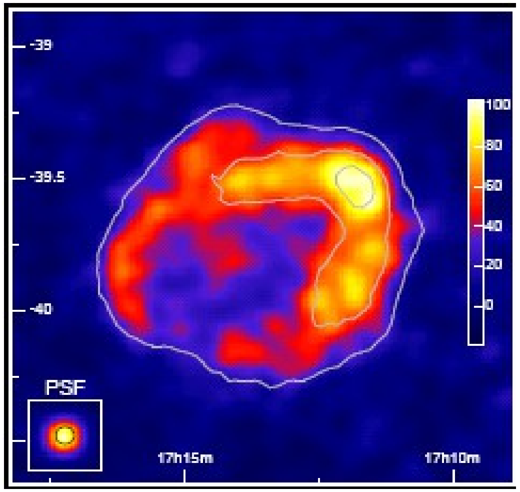
(a)

FIG. 5. Map of the remnant of Tycho's supernova showing local magnetic field organization and the direction of the mean local field averaged over boxes of various sizes, superposed on total intensity grey scale as shown in Dickel *et al.* 1991 (Paper I). The length of the vectors indicates the degree of organization in a box, and is proportional to Υ_{org}. The angle of the vector corresponds to the alignment of the mean magnetic field in a box. Positive values of the total intensity are represented with a peak of 8.1×10^{-3} Jy beam^{-1}; the grey scale is in units of 10^{-3} Jy beam^{-1}. (a) Box size of 30×30 pixels (0.55 pc $\times$ 0.55 pc). (b) Box size of 15×15 pixels (0.27 pc $\times$ 0.27 pc).

Radial magnetic fields were indeed observed in young SNRs

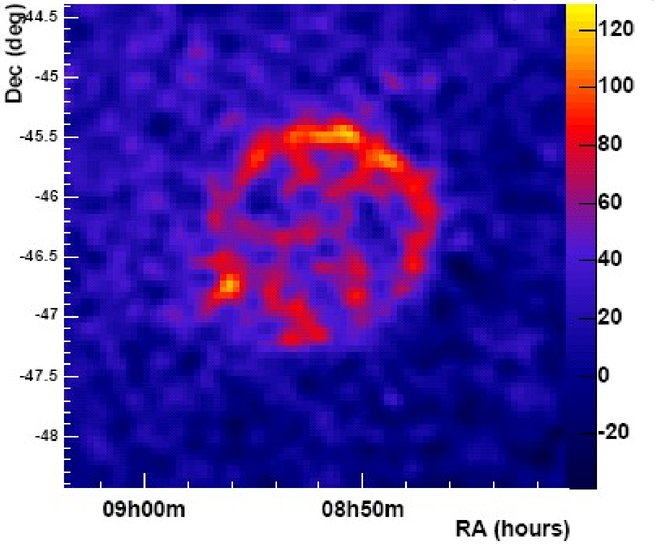
TeV gamma-rays from young SNRs

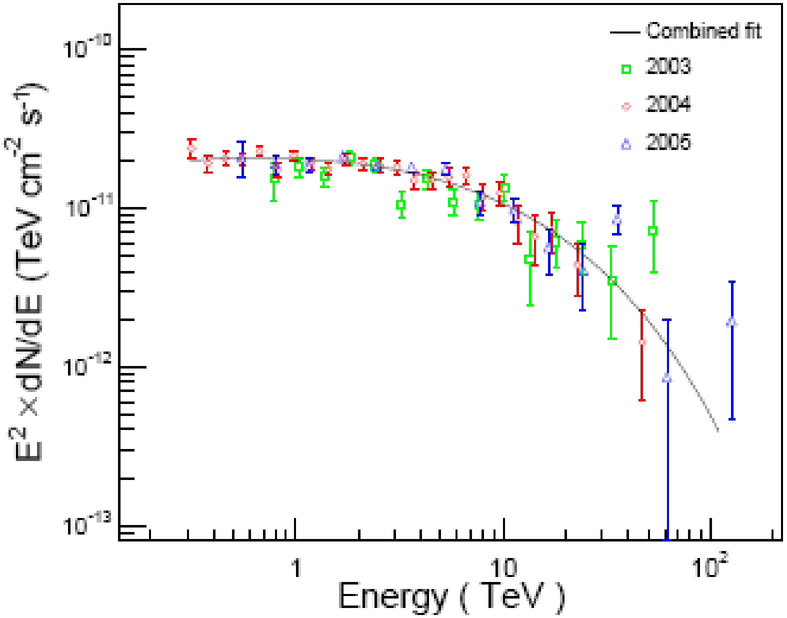
Aharonian et al 2008 (HESS)



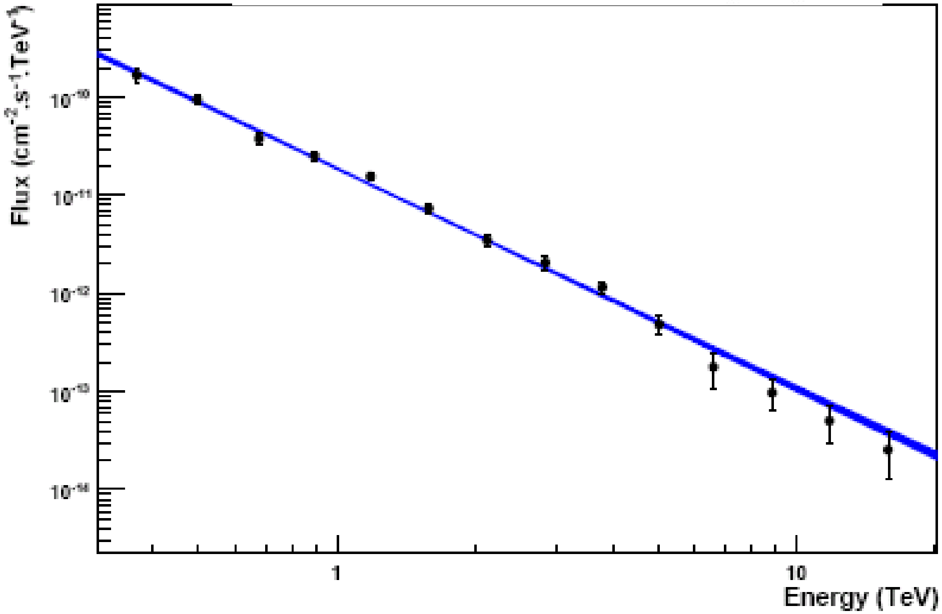
Particles accelerated up to100 TeV in these SNRs. Gamma-rays can be produced in pp collisions (hadronic models) or via the Inverse Compton scattering of IR and MWBR photons on the electrons accelerated (leptonic models)

Aharonian et al 2007 (HESS)





RX J1713.7-3946



Vela Jr

Transport equation with electric field

(Zirakashvili et al. 2008)

$$\frac{\partial N}{\partial t}+\mathbf{u}_0\nabla N-\frac{p}{3}\frac{\partial N}{\partial p}\nabla\mathbf{u}_0=\left(\nabla_i+\frac{1}{p^2}\frac{\partial}{\partial p}\frac{p^2 q}{v}E_{0i}\right)D_{ij}\left(\nabla_j N+\frac{q}{v}E_{0j}\frac{\partial N}{\partial p}\right)$$

$$J_i=-D_{ij}\left(\nabla_j N+E_{0j}\frac{q}{v}\frac{\partial N}{\partial p}\right)-u_{0i}\frac{p}{3}\frac{\partial N}{\partial p}$$

$$D_{ij}=(D_{\|}-D_{\perp})b_i b_j+D_{\perp}\delta_{ij}+D_A e_{ijk}b_k$$

$$D_{\|}=\frac{v^2}{3\nu},\ D_{\perp}=\frac{v^2\nu/3}{\Omega^2+\nu^2},\ D_A=\frac{v^2\Omega/3}{\Omega^2+\nu^2}$$

$$\nu(p)=\frac{\pi}{4}\frac{q^2 v}{p^2 c^2}\int d^3k B(k)/k$$

Dolginov & Toptygin 1967

Scattering by small-scale isotropic random magnetic field

$$<\delta B^2>=\int d^3k B(k)$$

Simple estimate of electric effects

$$W = q\mathbf{E}\mathbf{J}_d = -4\pi \int p^2 dp q \mathbf{E} D \nabla N =$$

Energy losses

$$-\frac{4\pi}{3}\mathbf{V_{A0}} \int p^2 dp v p (r_{g0} k) \nabla N$$

$$\mathbf{E} = \frac{\mathbf{V_{A0}}}{c}\frac{\delta B^2}{B_0}$$

$$D = D_{B0} k r_{g0} \frac{B_0^2}{\delta B^2}$$

Small-scale scattering

Effective CR velocity is higher than Alfven velocity in the amplified field

$$V_{eff} = V_{A0} r_{g0} k = r_{g0}\gamma \sim \frac{10}{T} r_{g0} \sim 10u\frac{r_{g0}}{R}$$

$$r_{g0} < 0.1R$$

Limitation of maximum energy

Modeling of DSA with electric field at the plane shock (Zirakashvili & Ptuskin 2015)

$$\frac{\partial N}{\partial t} = \left(\frac{\partial}{\partial z} + \frac{1}{p^2}\frac{\partial}{\partial p} p^2 \frac{qE_{el}}{\mathrm{v}}\right) D \left(\frac{\partial N}{\partial z} + \frac{qE_{el}}{\mathrm{v}}\frac{\partial N}{\partial p}\right) - u\frac{\partial N}{\partial z} + \frac{p}{3}\frac{\partial N}{\partial p}\frac{\partial u}{\partial z}$$

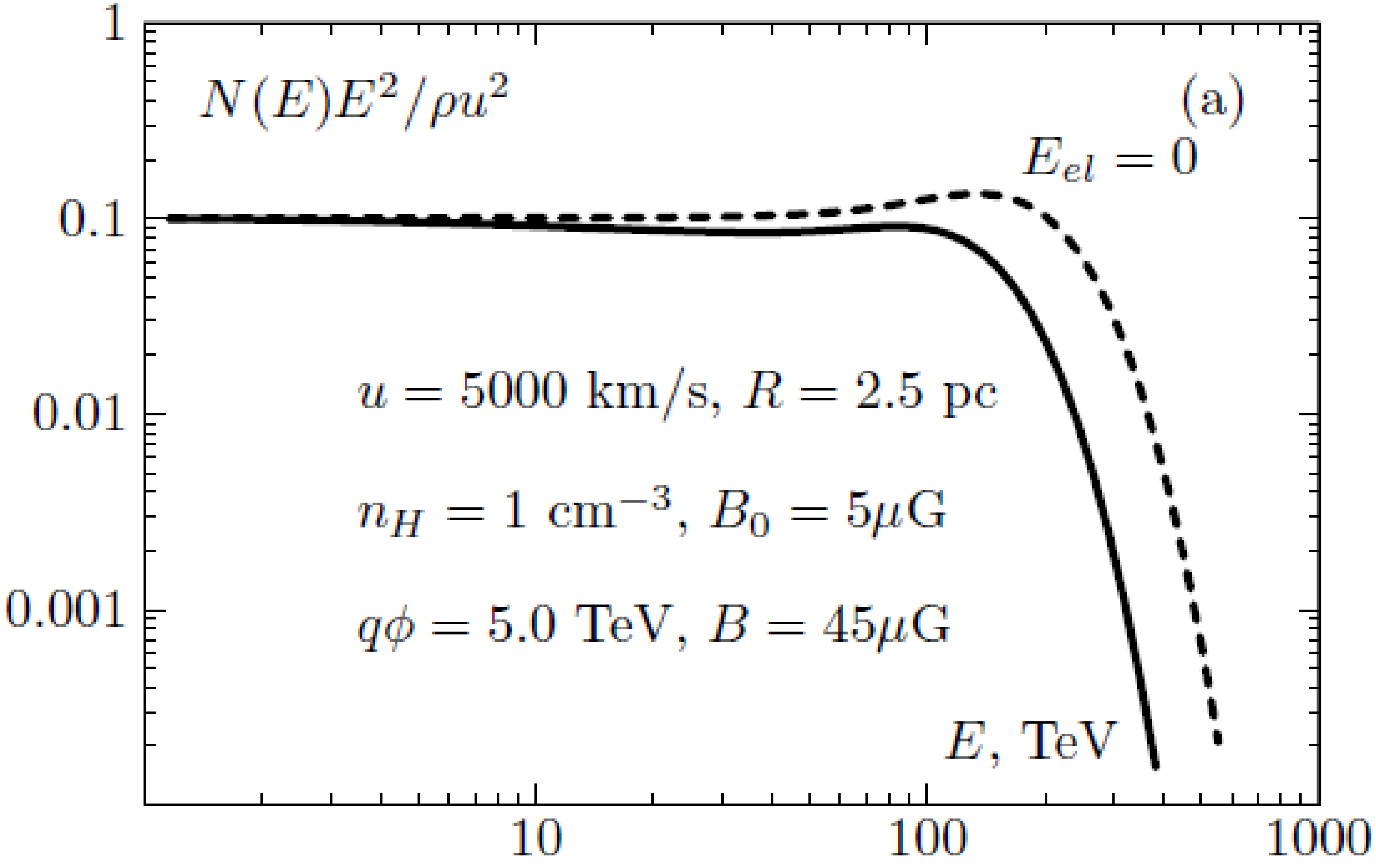
$$D = \frac{\mathrm{v}p^2c^2}{12\pi q^2} \Big/ \int W(k)dk/k$$

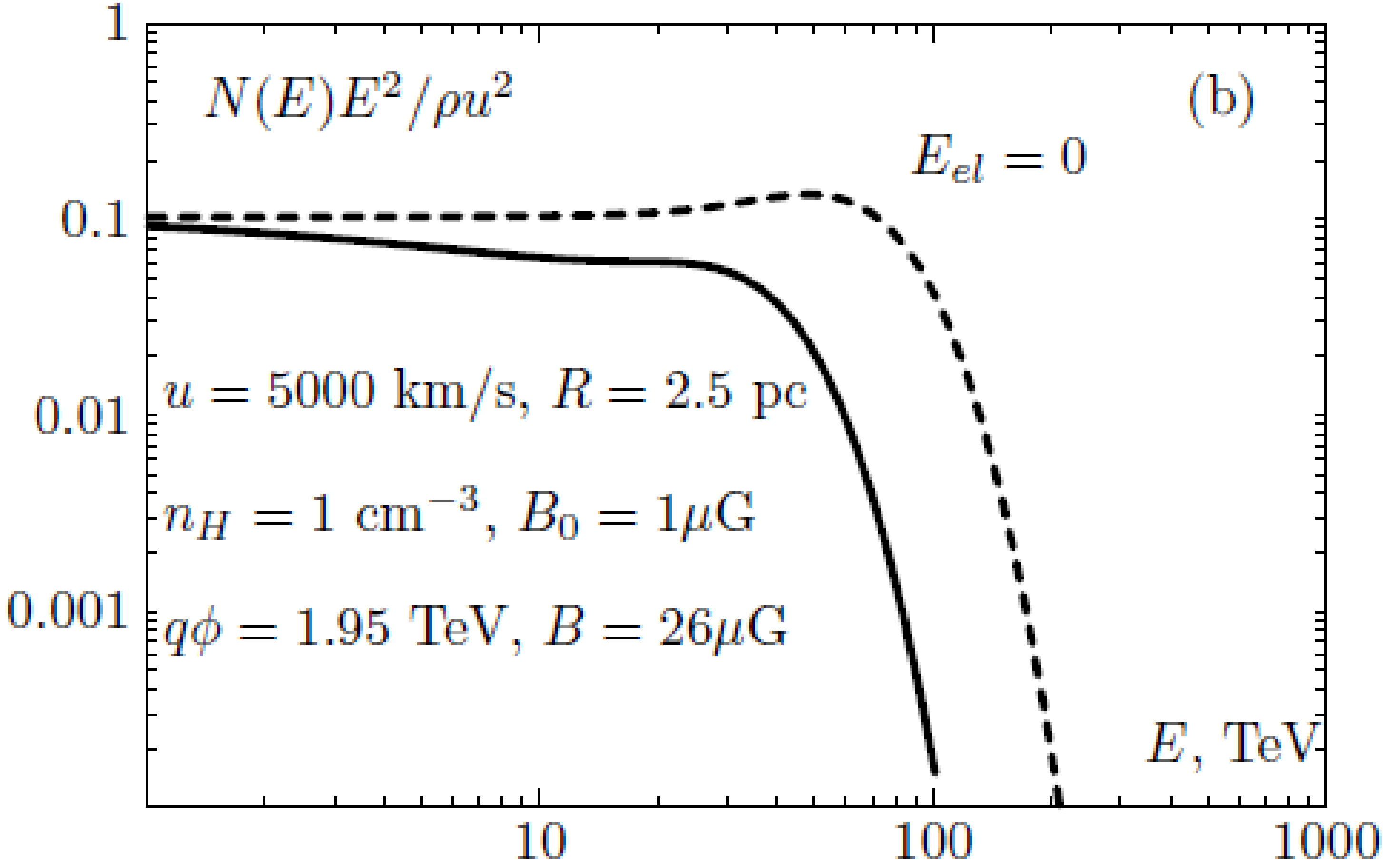
$$\frac{\partial W}{\partial t} + u\frac{\partial W}{\partial z} = 2(\Gamma_B - \Gamma_{NL})W$$

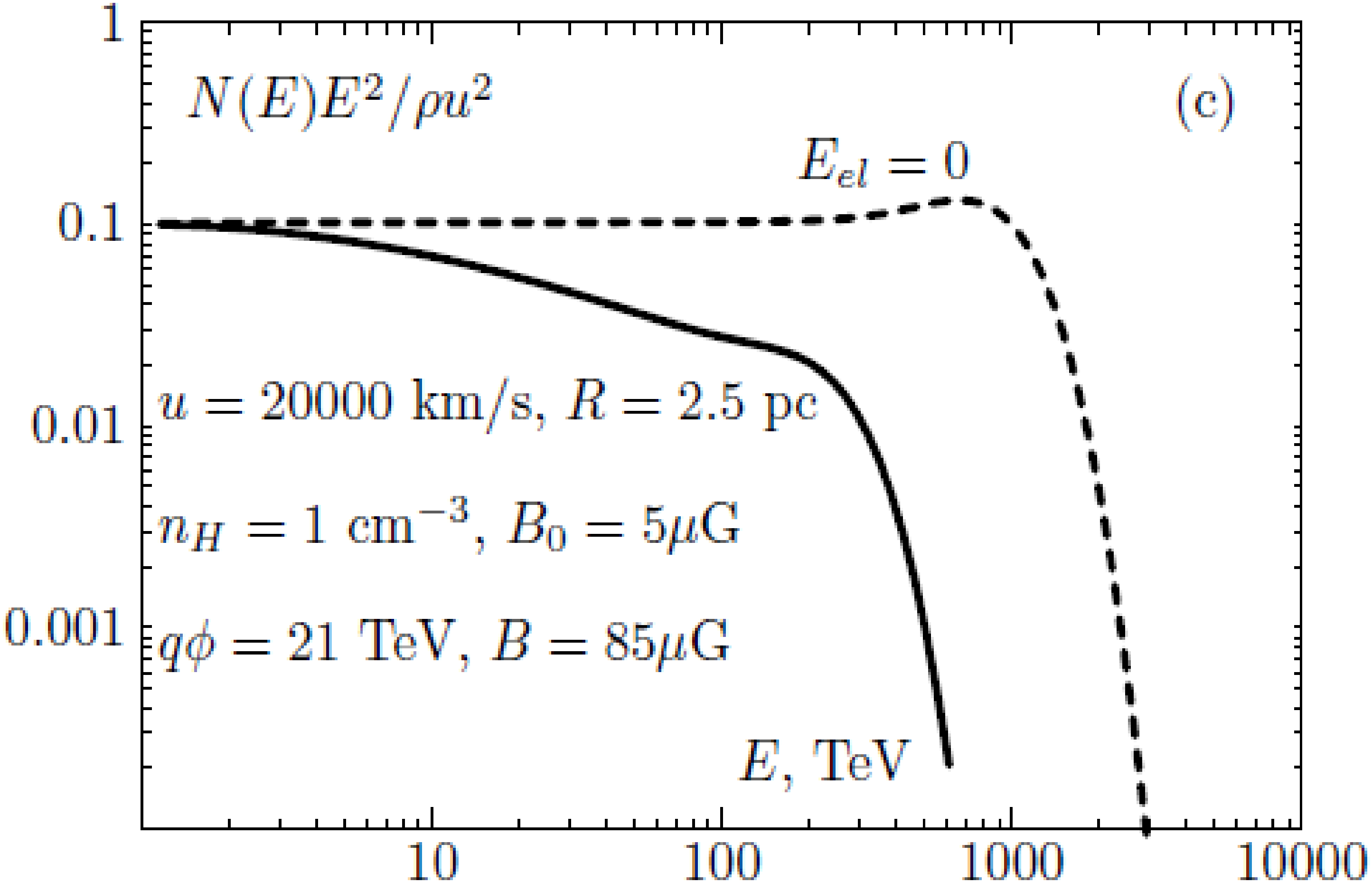
$$\Gamma_B = \sqrt{\frac{j_d B_0 k}{c\rho} - V_A^2 k^2} \qquad \Gamma_{NL} = 0.2\, V_A k \left(\frac{kW(k)}{B_0^2/4\pi}\right)^{1/2}$$

$$j_d = q\int 4\pi p^2 dp J_d(p) \qquad E_{el} = \frac{4\pi}{cB_0}\int dk\left(\Gamma_B - \Gamma_{NL}\right)W(k)/k$$

Numerical results

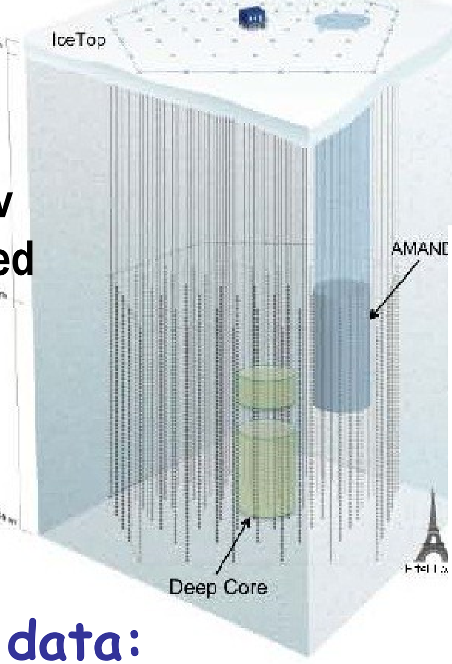



1
0.1
0.01
0.001
10
100
1000
$N(E)E^2/\rho u^2$
(b)
$E_{el} = 0$
$u = 5000$ km/s, $R = 2.5$ pc
$n_H = 1$ cm^{-3}, $B_0 = 1\mu$G
$q\phi = 1.95$ TeV, $B = 26\mu$G
E, TeV

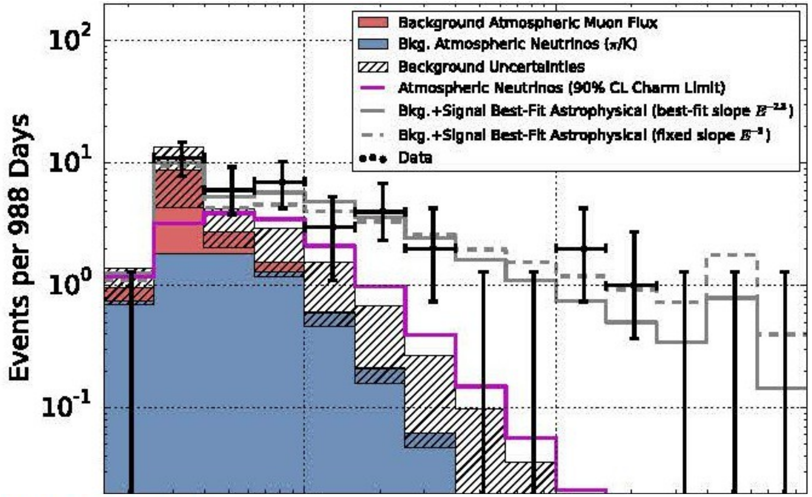

$N(E)E^2/\rho u^2$
(c)
$E_{el} = 0$
$u = 20000$ km/s, $R = 2.5$ pc
$n_H = 1$ cm^{-3}, $B_0 = 5\mu$G
$q\phi = 21$ TeV, $B = 85\mu$G
E, TeV
1
0.1
0.01
0.001
10
100
1000
10000

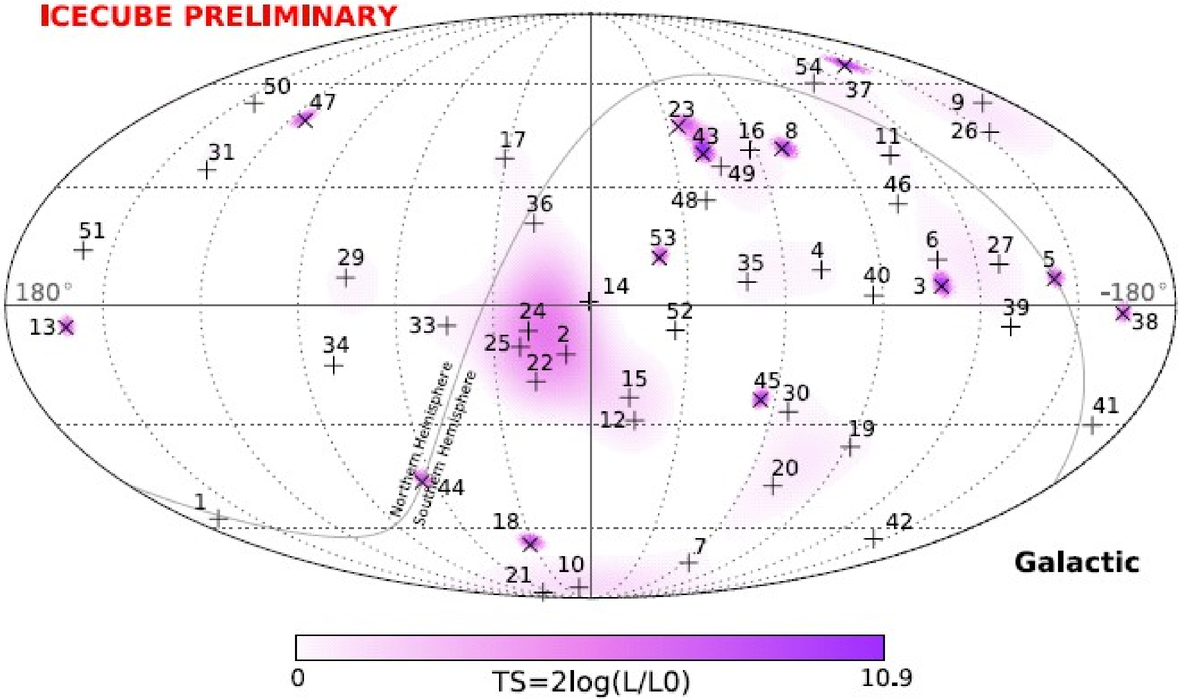
high energy neutrinos of cosmic origin

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

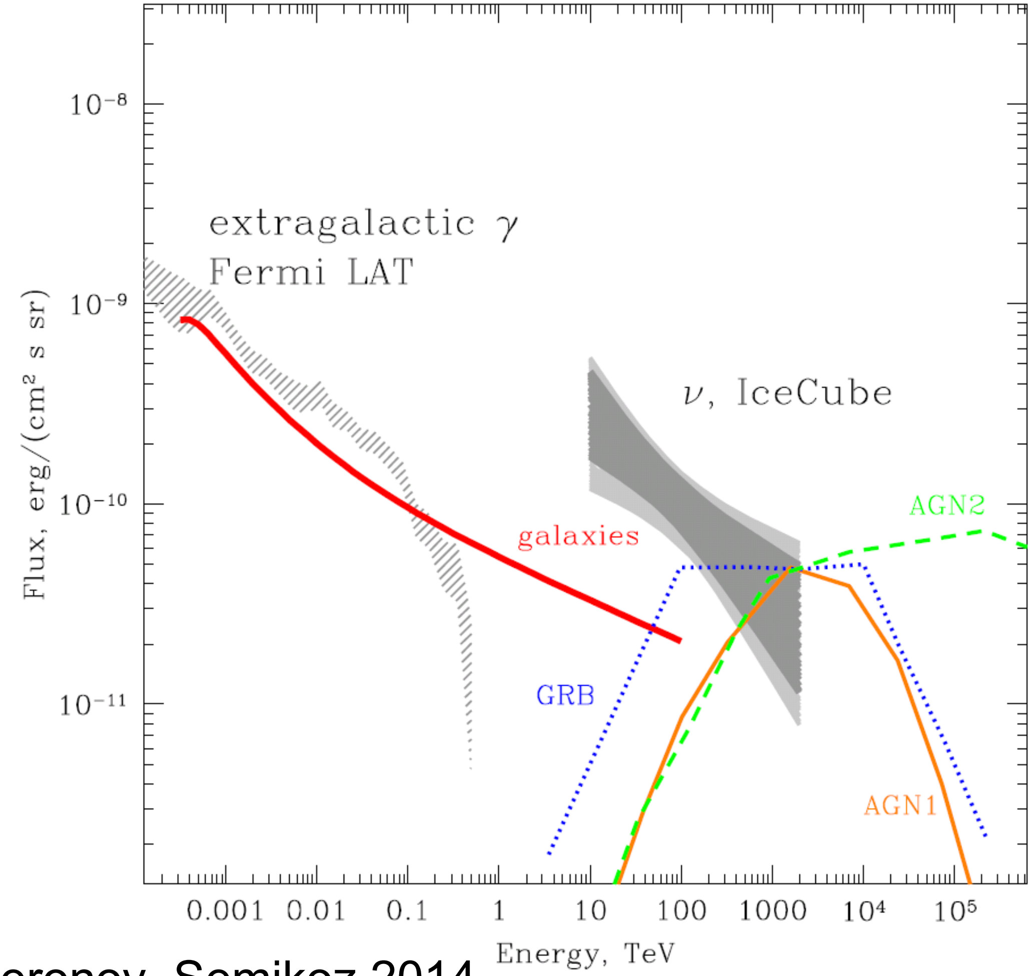
4th year - 17 neutrinos

$$E_\nu^2\left(dN/dE_\nu\right)=(0.95\pm0.3)\times10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

Aartsen et al. 2014

IceCube Coll. 2015

The most plausible mechanism pp interactions of high energy protons



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

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

Neronov, Semikoz 2014

“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

Maximum energies for protons in IIn SNRs (Bohm diffusion in the amplified magnetic field)

$$E_{\max} = \frac{3qV_f^2}{10M_A c}\sqrt{\frac{\dot{M}}{u_w}}\min\left(1, \frac{t}{t_{pp}}\right) =$$

$$80\ \mathrm{PeV}\min\left(1, \frac{t}{t_{pp}}\right)\left(\frac{M_A}{10}\right)^{-1}\left(\frac{\dot{M}}{10^{-2}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{1/2}\times$$

$$\left(\frac{u_w}{100\ \mathrm{km\ s}^{-1}}\right)^{-1/2}\left(\frac{E_{SN}}{10^{52}\ \mathrm{erg}}\right)\left(\frac{M_{ej}}{10\ M_\odot}\right)^{-1}$$

$$t_{pp} = \frac{0.5c\sigma_{pp}\dot{M}}{\pi u_w m V_f^2} = 0.2\ \mathrm{yr}\left(\frac{\dot{M}}{10^{-2}\ M_\odot\ \mathrm{yr}^{-1}}\right)\times$$

$$\left(\frac{u_w}{100\ \mathrm{km\ s}^{-1}}\right)^{-1}\left(\frac{E_{SN}}{10^{52}\ \mathrm{erg}}\right)^{-1}\left(\frac{M_{ej}}{10\ M_\odot}\right).$$

Estimate of neutrino flux produced by IIn supernova in the Universe

$$F(E_\nu)E_\nu^2 = \frac{3\xi_{CR}K_\nu}{16\pi^2\ln(E_{\max}/mc^2)}\frac{\nu_{sn}c^2V_f\sigma_{pp}\dot{M}^2}{H_0 m u_w^2}\times$$

$$\ln\left(1+\frac{t_{\rm S}}{t_{pp}}\right) = 10^{-11}\xi_{CR}\frac{\rm erg}{\rm cm^2 s\ sr}\ln\left(1+\frac{t_{\rm S}}{t_{pp}}\right)\times$$

$$\left(\frac{\dot{M}}{10^{-2}\ M_\odot\ {\rm yr}^{-1}}\right)^2\left(\frac{u_w}{100\ {\rm km\ s}^{-1}}\right)^{-2}\left(\frac{M_{ej}}{10\ M_\odot}\right)^{-1/2}\times$$

$$\left(\frac{E_{SN}}{10^{52}\ {\rm erg}}\right)^{1/2}\left(\frac{\nu_{sn}}{10^{-6}{\rm Mpc}^{-3}{\rm yr}^{-1}}\right),$$

$$t_{\rm S} = \frac{M_{ej}u_w}{\dot{M}V_f} = 10\ {\rm yr}\left(\frac{\dot{M}}{10^{-2}\ M_\odot\ {\rm yr}^{-1}}\right)^{-1}\times$$

$$\left(\frac{u_w}{100\ {\rm km\ s}^{-1}}\right)\left(\frac{E_{SN}}{10^{52}\ {\rm erg}}\right)^{-1/2}\left(\frac{M_{ej}}{10\ M_\odot}\right)^{3/2}$$

$$t_{pp} = \frac{0.5c\sigma_{pp}\dot{M}}{\pi u_w m V_f^2} = 0.2\ {\rm yr}\left(\frac{\dot{M}}{10^{-2}\ M_\odot\ {\rm yr}^{-1}}\right)\times$$

$$\left(\frac{u_w}{100\ {\rm km\ s}^{-1}}\right)^{-1}\left(\frac{E_{SN}}{10^{52}\ {\rm erg}}\right)^{-1}\left(\frac{M_{ej}}{10\ M_\odot}\right).$$

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

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

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

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

$$\begin{aligned}
\frac{\partial N}{\partial t} &= \frac{1}{r^2}\frac{\partial}{\partial r} r^2 D(p,r,t)\frac{\partial N}{\partial r} - w\frac{\partial N}{\partial r} + \frac{\partial N}{\partial p}\frac{p}{3r^2}\frac{\partial r^2 w}{\partial r} \\
&+ \frac{\eta_f \delta(p - p_f)}{4\pi p_f^2 m}\rho(R_f + 0, t)(\dot{R}_f - u(R + 0, t))\delta(r - R_f(t)) \\
&+ \frac{\eta_b \delta(p - p_b)}{4\pi p_b^2 m}\rho(R_b - 0, t)(u(R_b - 0, t) - \dot{R}_b)\delta(r - R_b(t))
\end{aligned} \qquad (4)$$

Evolution of supernova remnant during 30 years after IIn supernova explosion (Zirakashvili & Ptuskin 2016)

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

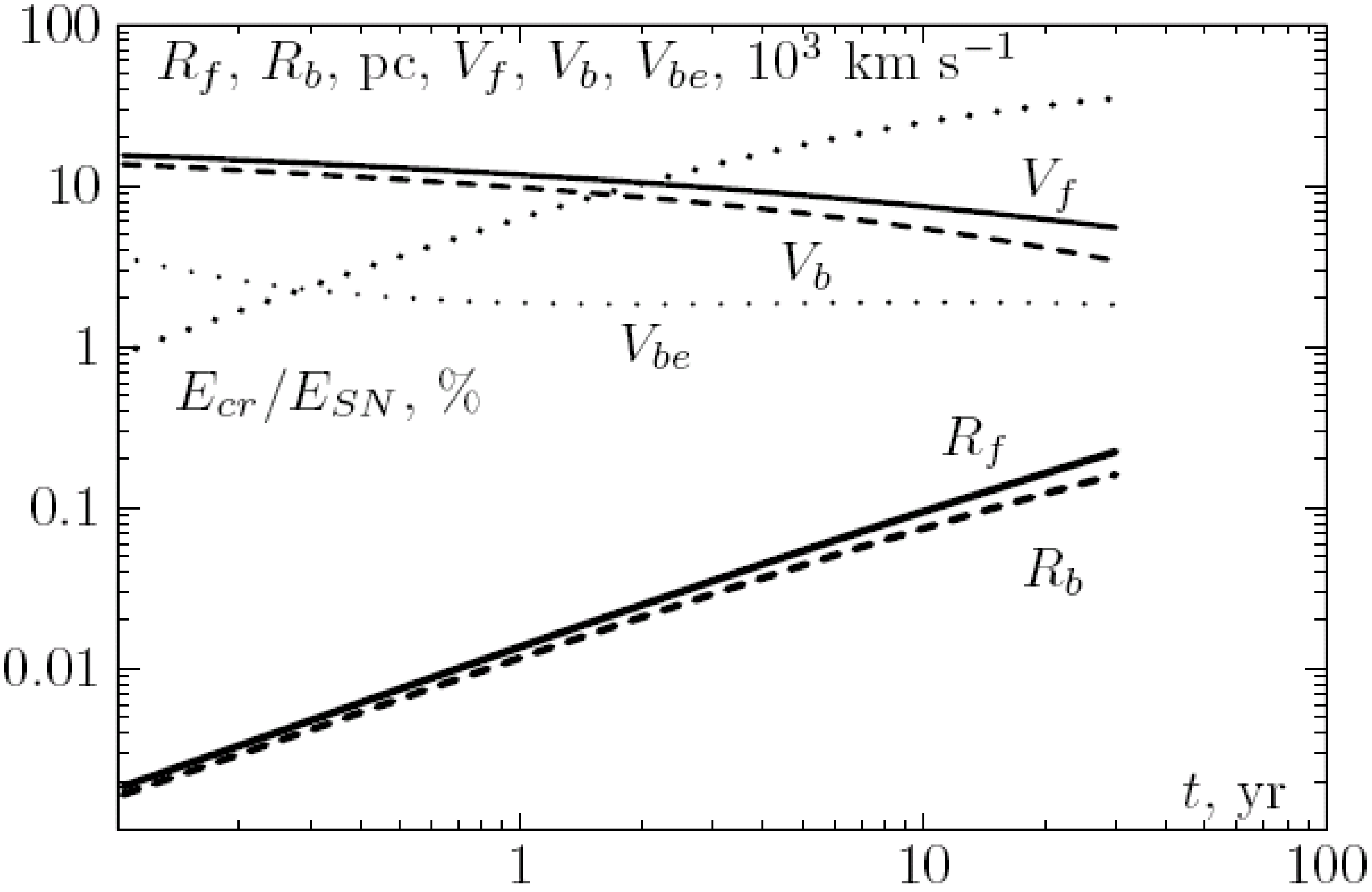
Stellar wind speed

$u_w=100$ km/s

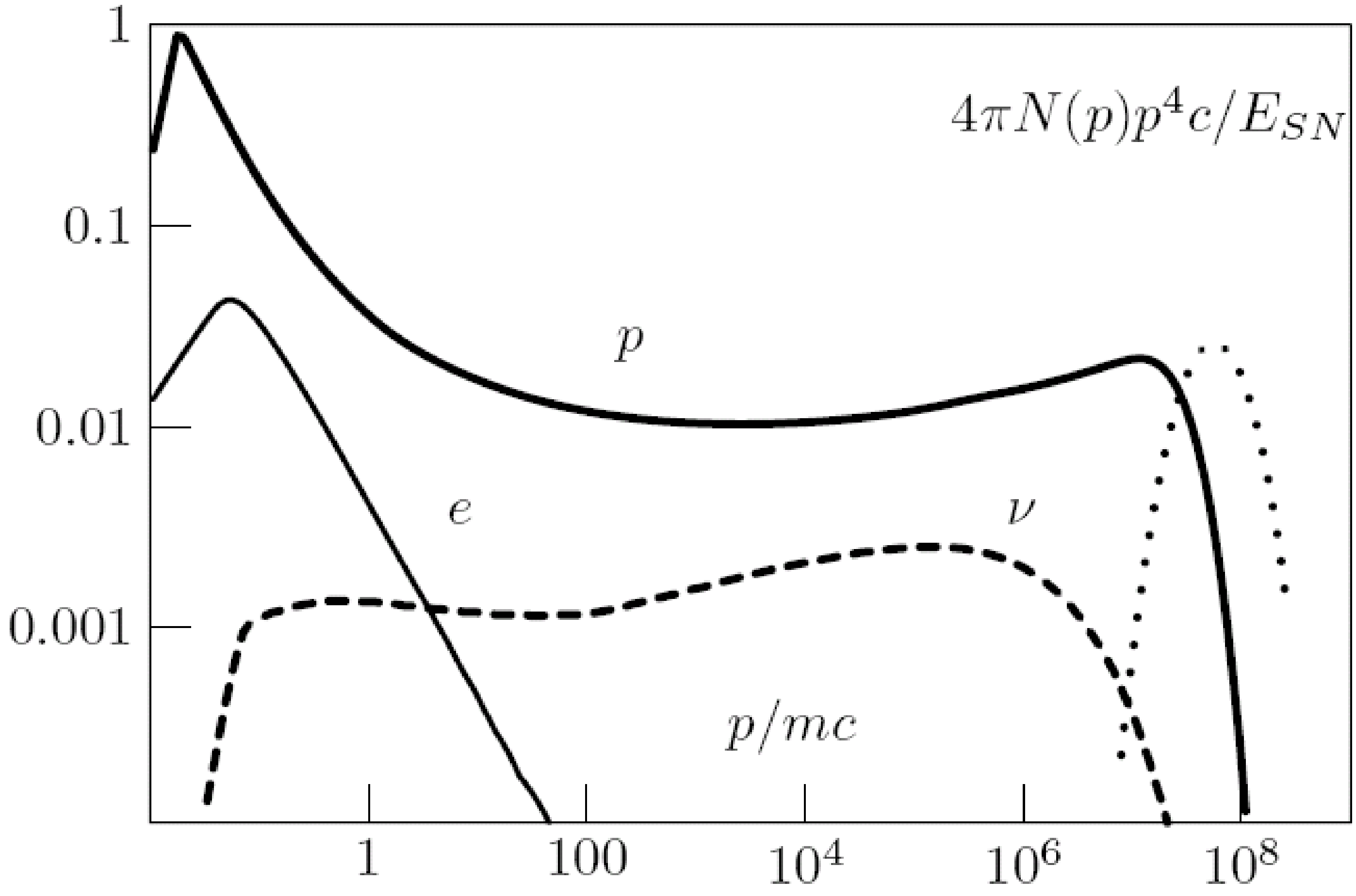
parameters from

Moriya et al.

2014



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

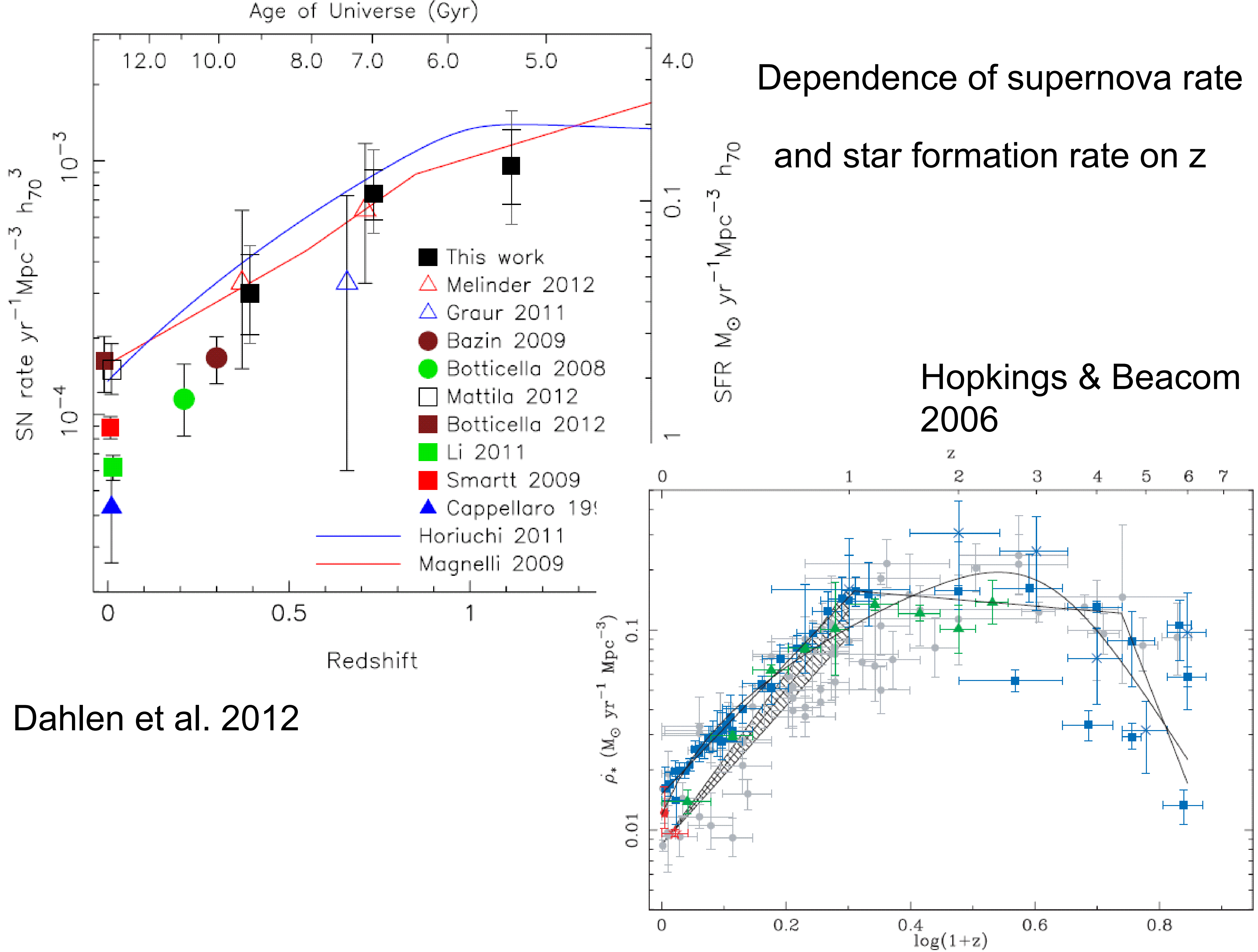


Background spectrum of astrophysical neutrinos

$$F(E) = cH_0^{-1} \int_{E}^{E(1+z_{\max})} \frac{dE'}{E} \left(\frac{E'}{E} \right)^m \frac{q(E')}{\sqrt{\Omega_\Lambda + \Omega_\mathrm{M} E'^3 / E^3}}$$

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

Dependence of supernova rate and star formation rate on z

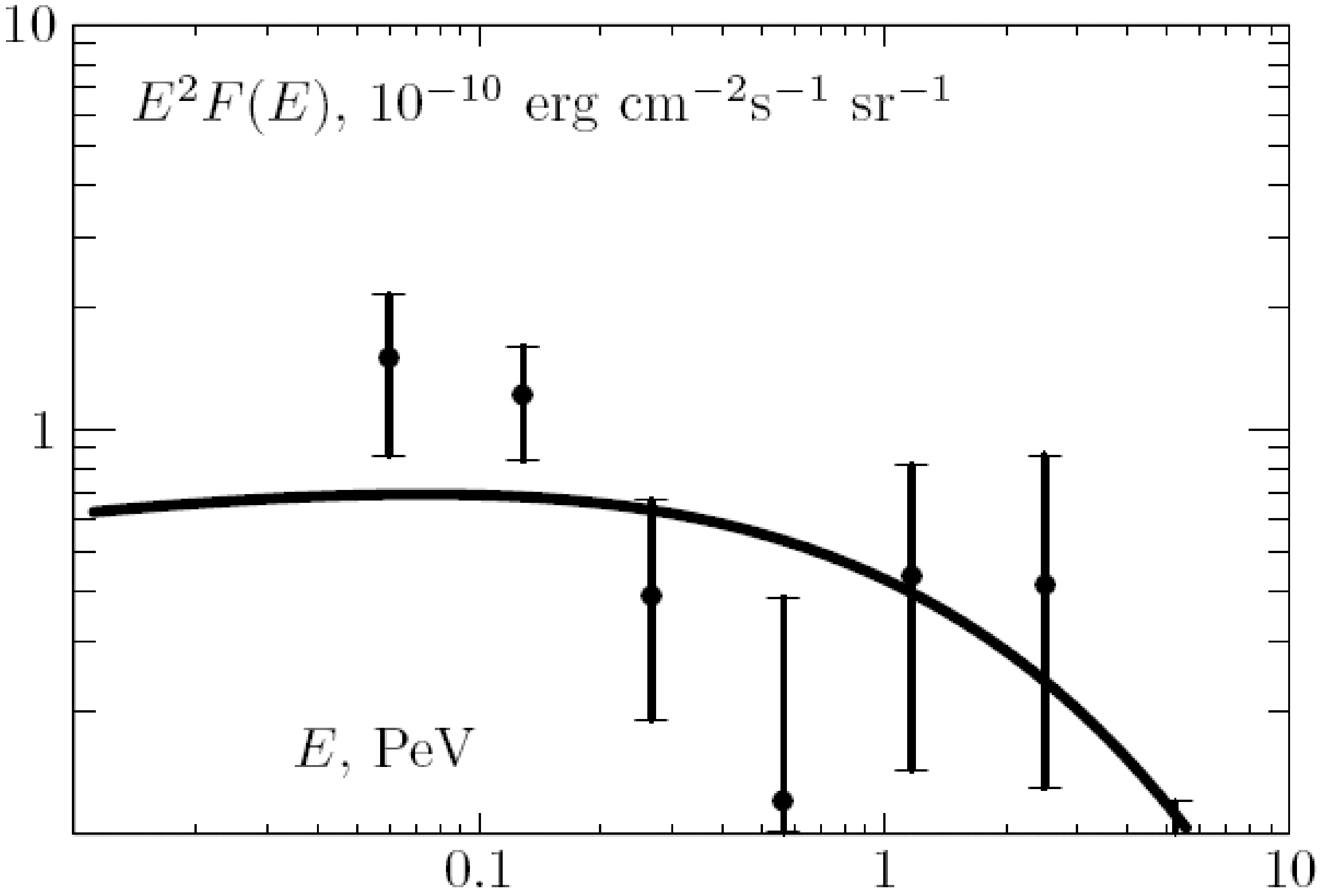


Hopkings & Beacom 2006

Dahlen et al. 2012

Neutrino spectrum produced by IIn supernovae

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



Correlations of IIn SNe and IceCube neutrinos (1-2 real correlations are expected)

1 correlation with 14 track events

SN 2005bx at 1.35 degree from the direction of track event 47

(chance probability 0.25)

1 correlation with 29 new track events (Aartsen et al. 2016)

SN 2005jq at 0.28 degree from the direction of track event 11

(chance probability 0.07)

Summary

1. Non-resonant streaming instability produced by the electric current of run-away CR particles results in the significant magnetic amplification at fast SNR shocks.

2. Regular electric fields generated in the course of non-resonant instability suppress very efficient acceleration of particles producing the instability (protons). The acceleration of electrons is more efficient.

3. This effect is significant for shocks with velocities > 10000 km/s propagating in the interstellar medium or for slower shocks propagating in the medium with weak magnetic fields.

4. Supernovae IIn can be the sources of high energy neutrinos. The main contribution comes from z~1. Maximum energies of accelerated protons can reach 10^{17} eV. This is related with high density of circumstellar medium.