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Hypernova remnants as a source of UHCRs and high-energy neutrinos

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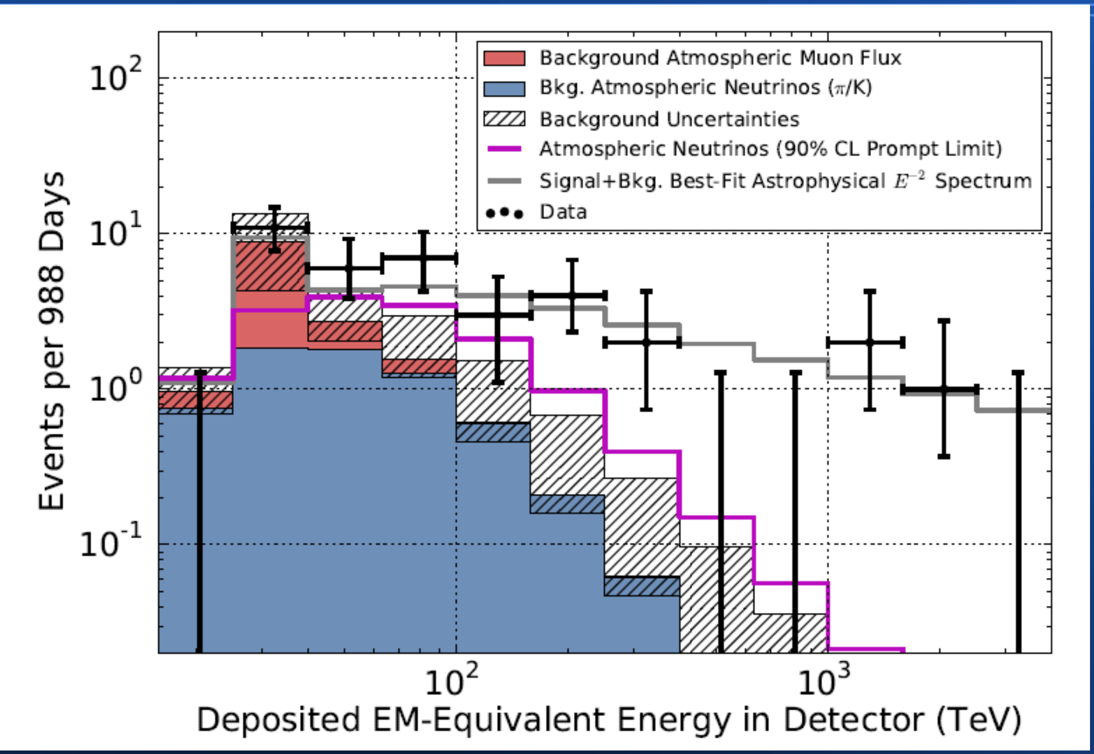
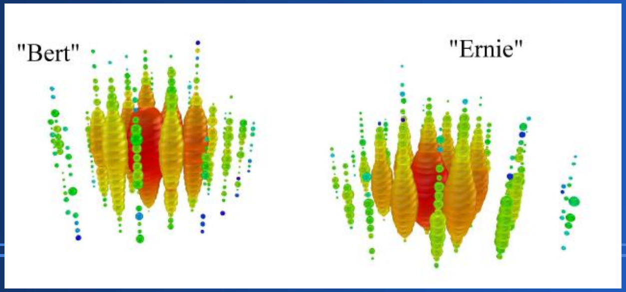
IceCube: diffuse PeV neutrinos detected

IceCube collaboration , 2014, 2015



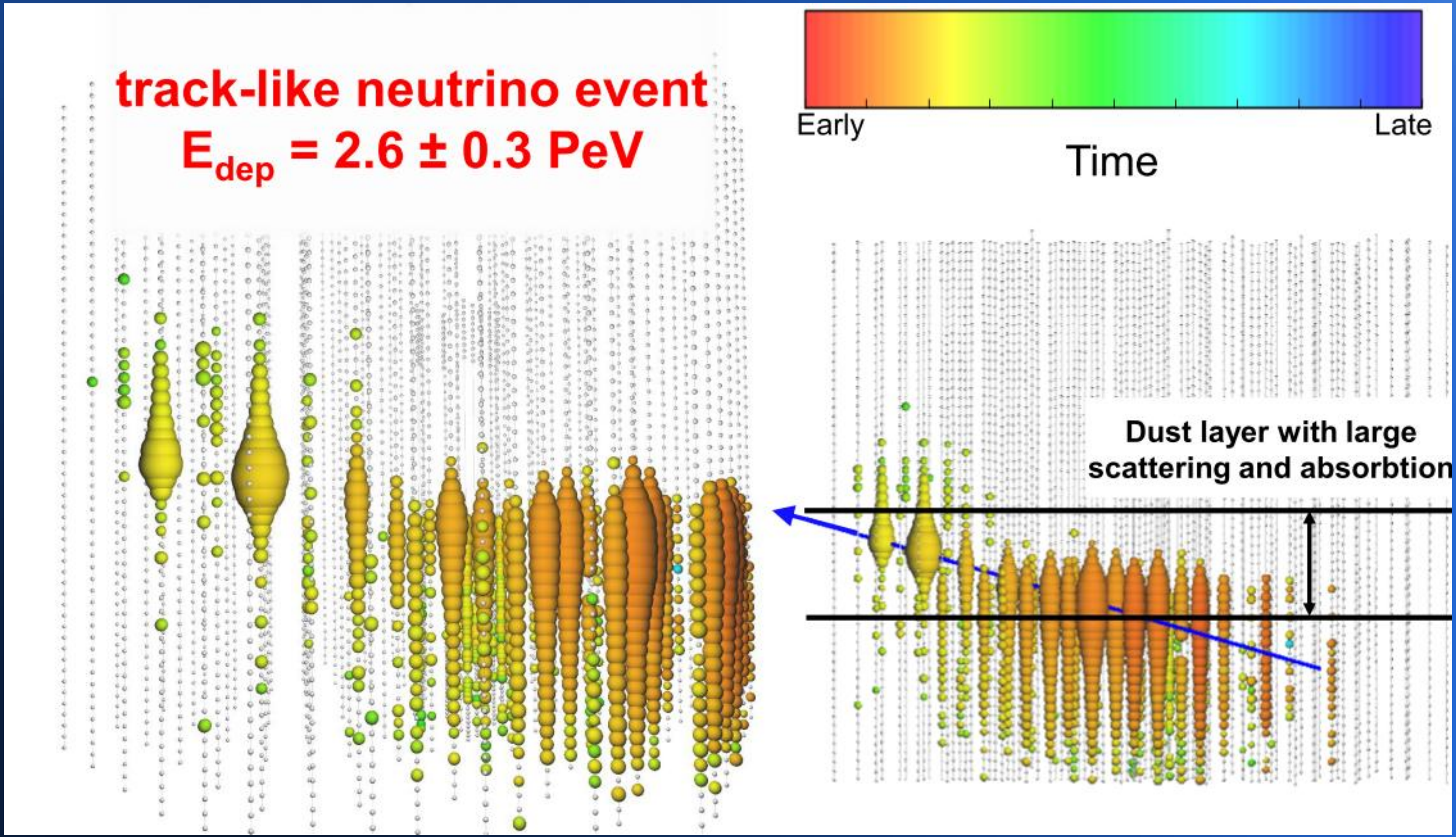
- 54 events in 60 TeV-PeV
- 7 σ rejection of atmospheric-only hypothesis
- PeV neutrinos: mostly induced cascade events



1.1PeV

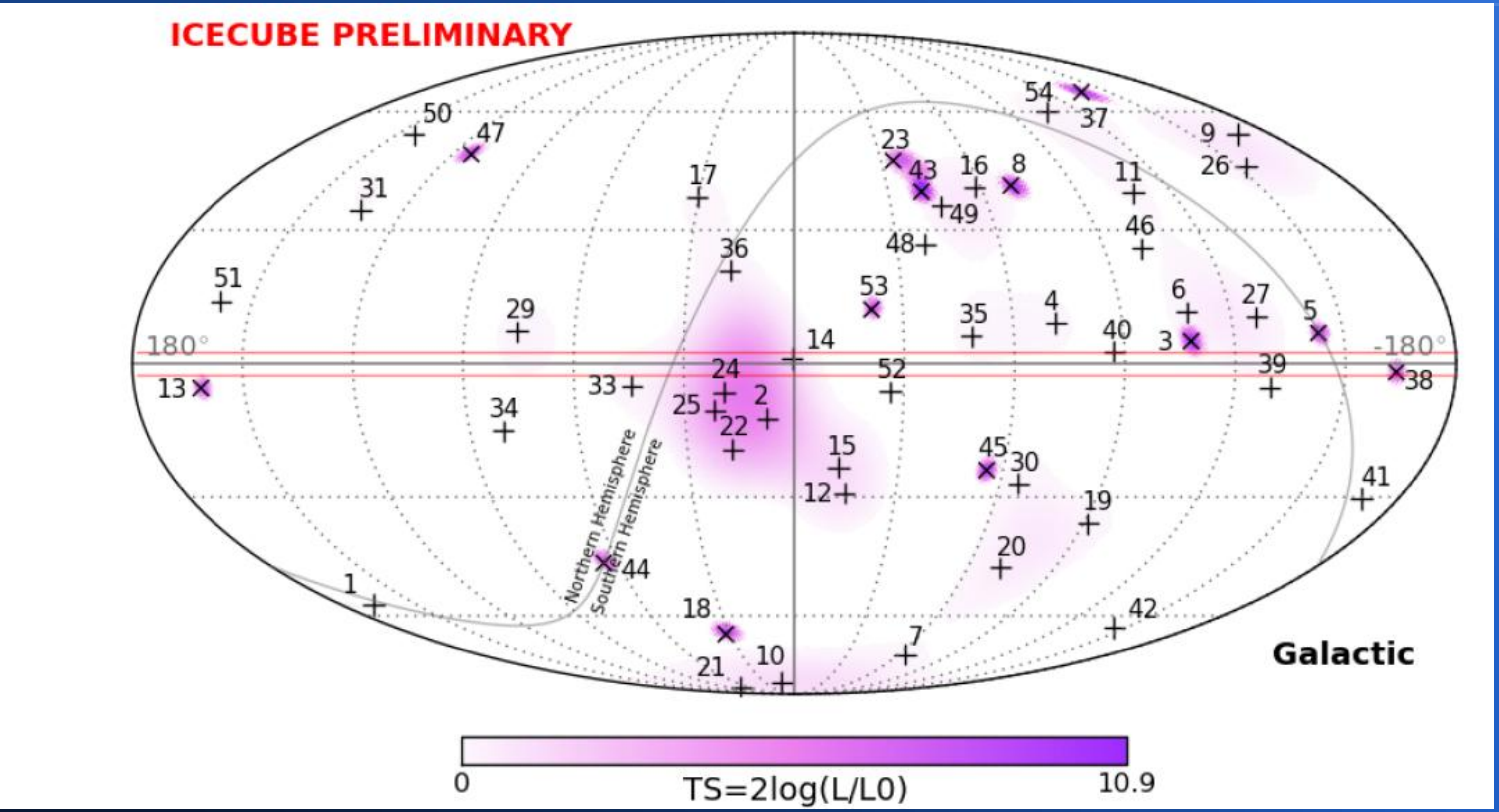
1PeV

A muon-track neutrinos with E>3 PeV



The energy of the neutrino is >2.6 PeV

Arriving directions



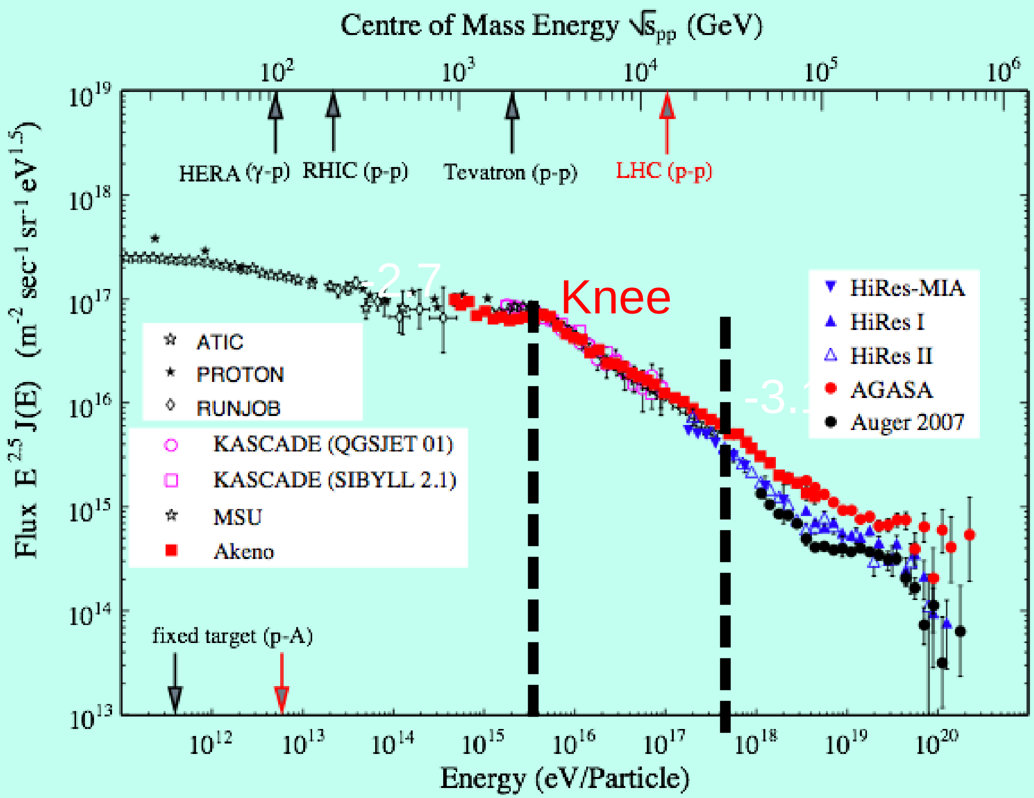
- Isotropic distribution dominantly→ extragalactic origin dominantly

Connection with extragalactic CRs

●Ev ~ 0.04 Ep:

>3 PeV ν ⇔ >100(1+z) PeV CR proton

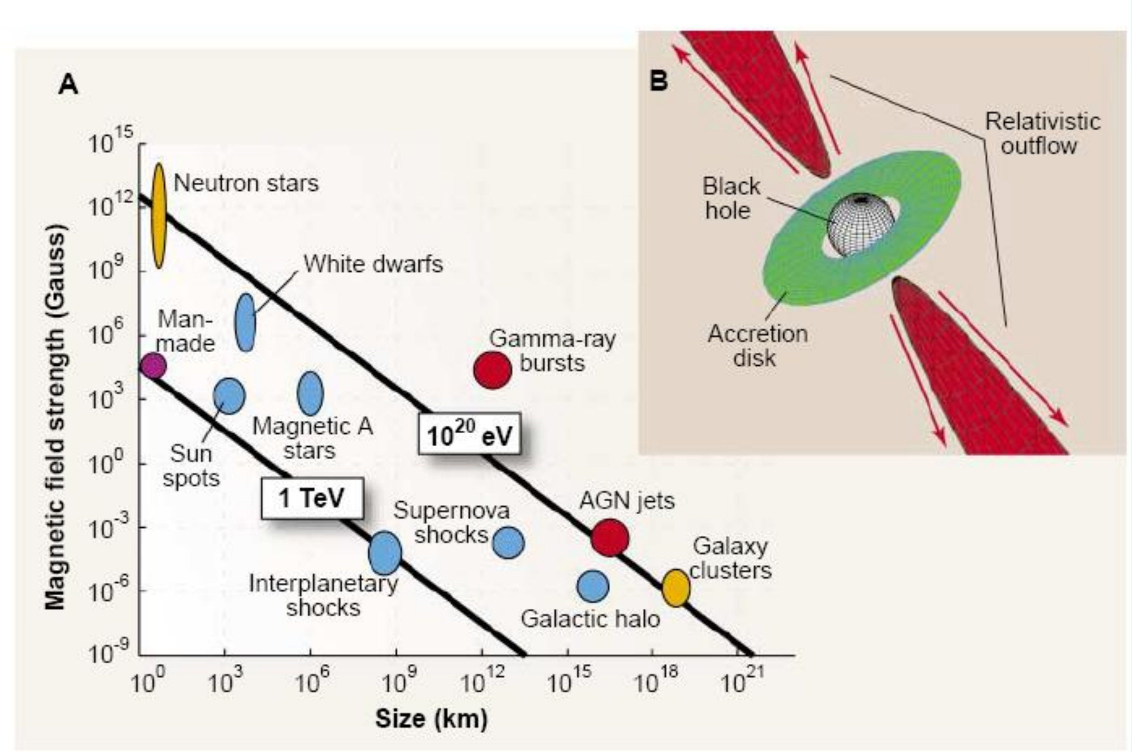
●HE neutrinos could be related with EeV CR sources



Second knee
Or ankle

Source of UHECRs ?

R_L<R → B*R>E/Zqv



1. **AGN (Berezinsky..)**
2. **GRB (Waxman, Vietri, …)**
3. **Pulsars (Fang+, Kotera+)**
4. **Galaxy clusters (Inoue+)**
5. **Hypernova remnants (XW+)**

TeV/PeV neutrino models?

AGNs: (e.g.Kalashev+13, Padovani + 15)

GRBs (e.g. Cholis & Hooper ; Liu & Wang 13)

Low-power GRBs (e.g. , Ioka & Murase 2013)

Pulsars (e.g. Fang+ 15)

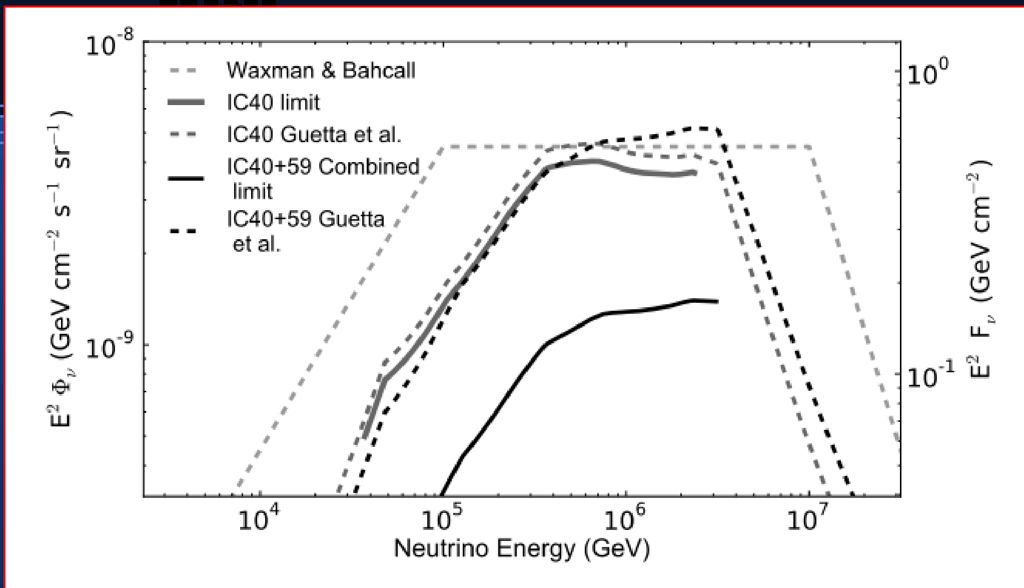
Starburst galaxy (e.g. Loeb & Waxman 2006)

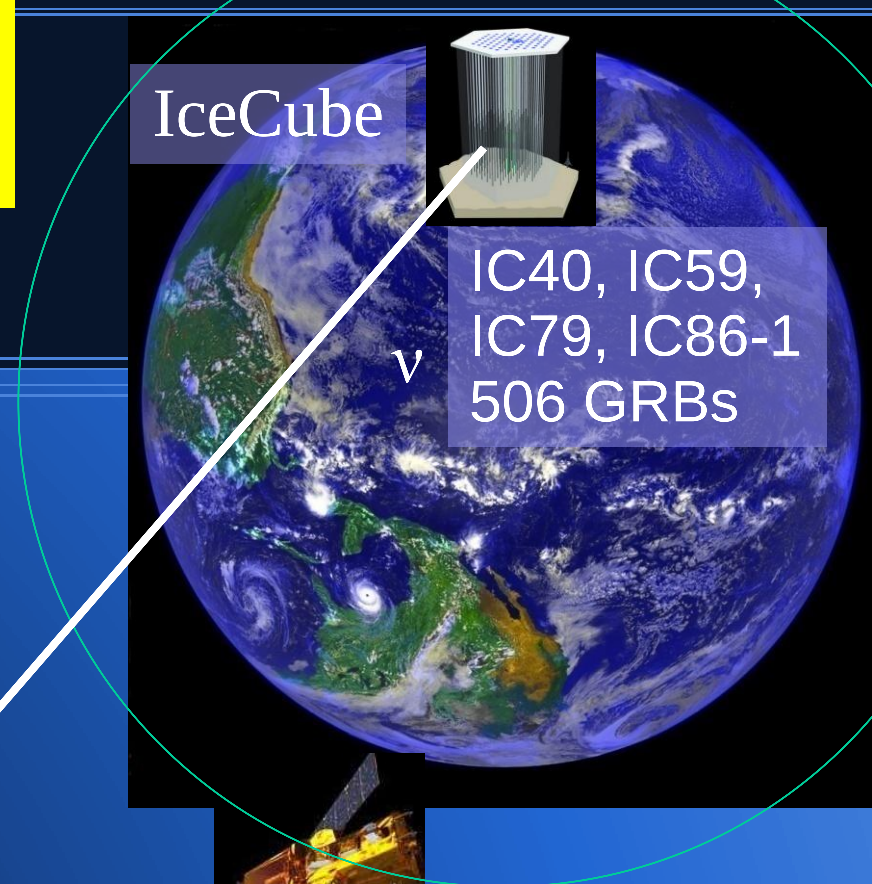
Hypernova in star-forming/starburst galaxies (Liu et al. 14)

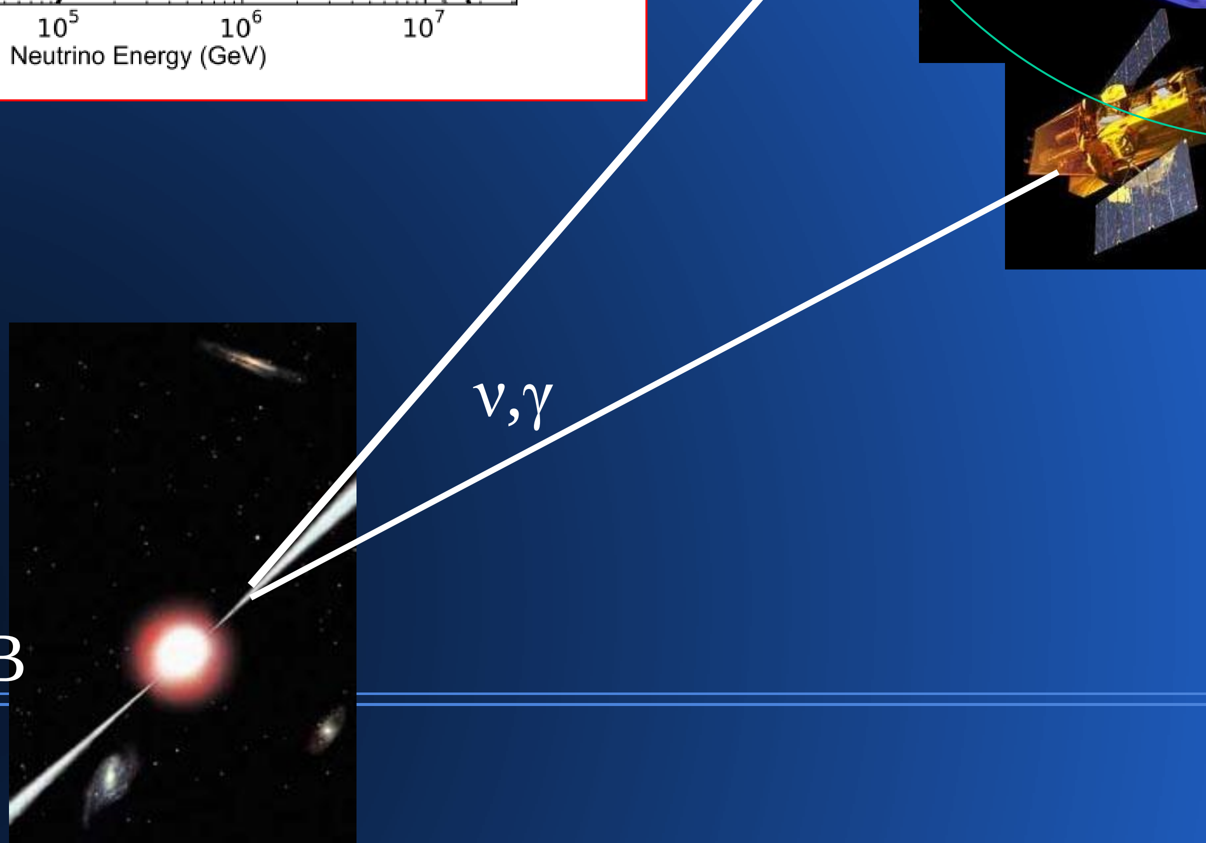
……

Neutrinos in coincidence with gamma-ray bursts?

with





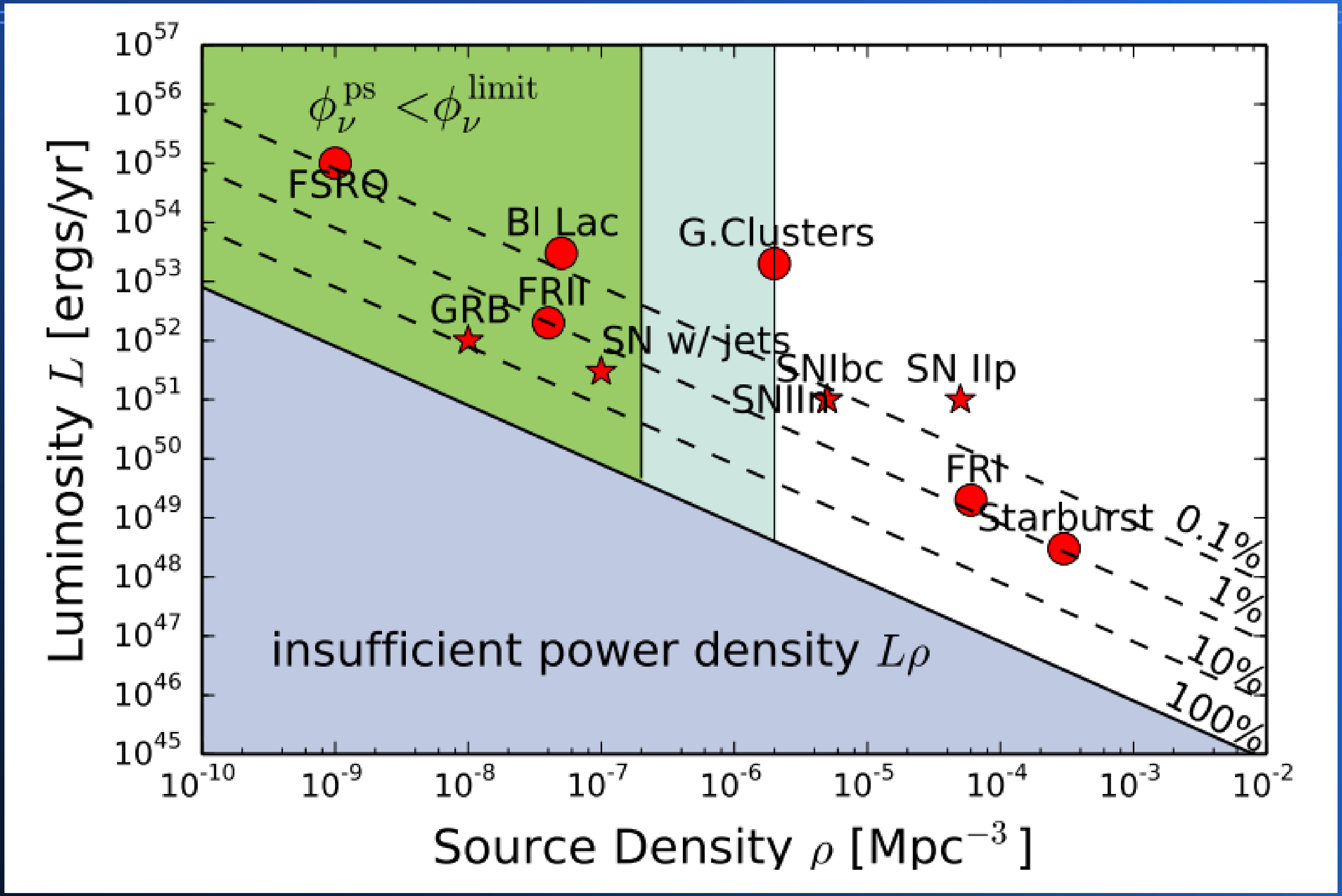


Gamma-ray satellites

distant GRB

Limit from point source observations

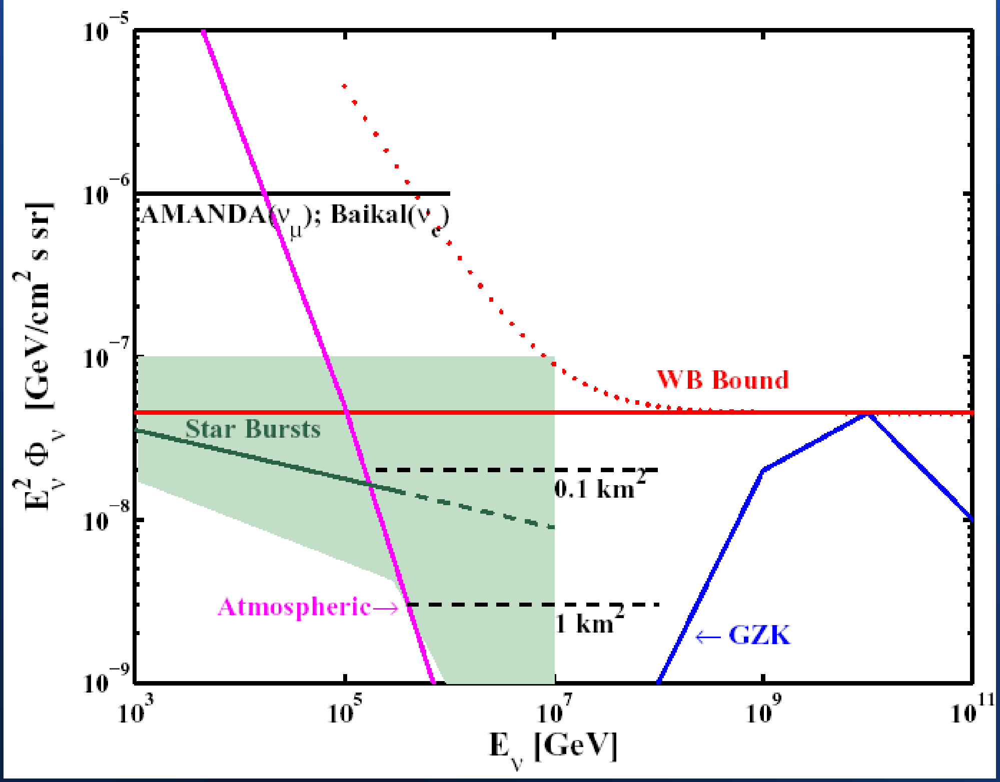
(Kowalski 2014)



- Favor high density, low-power sources,
- e.g. starbursts, SNe

Starburst galaxy scenario

Loeb & Waxman 2006



- Cosmic rays are accelerated by SNR shocks
- Normalized with the local 1.4 GHz energy production rate and extrapolate to HE with a simple PL

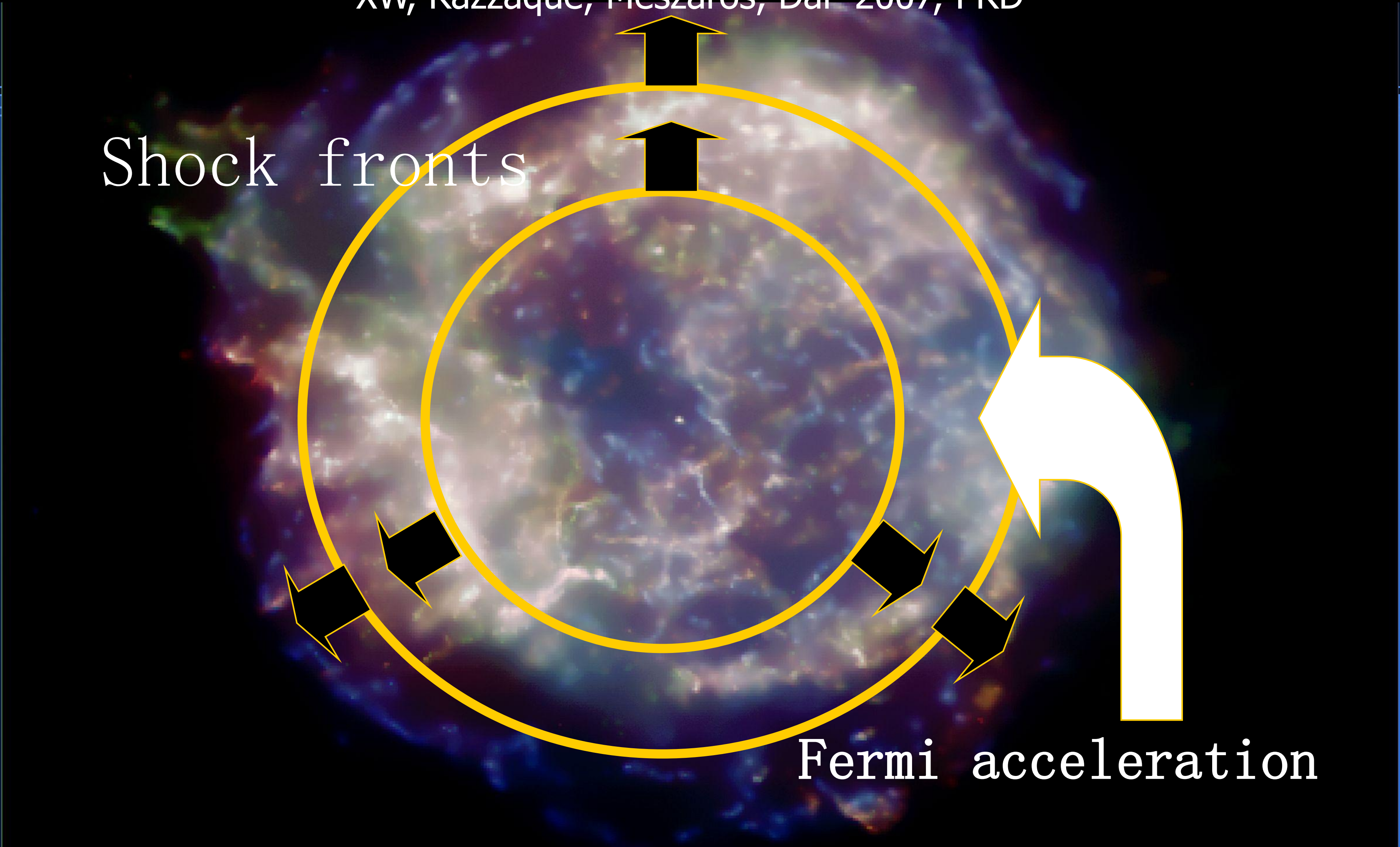
$$E_\nu^2 \Phi_\nu(E_\nu = 1\mathrm{GeV}) \approx \frac{c}{4\pi}\zeta t_H \left[4\nu(dL_\nu/dV)\right]_{\nu=1.4\mathrm{GHz}} = 10^{-7}\zeta_{0.5}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}. \quad (2)$$

$$E_\nu^2 \Phi_\nu^{\mathrm{SB}} \approx 10^{-7}(E_\nu/1\mathrm{GeV})^{-0.15\pm0.1}\mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

- But, Normal SNRs can accelerate CR to only PeV, while IceCube neutrinos need >100 PeV CRs ?

Hypernova remnant blast wave model

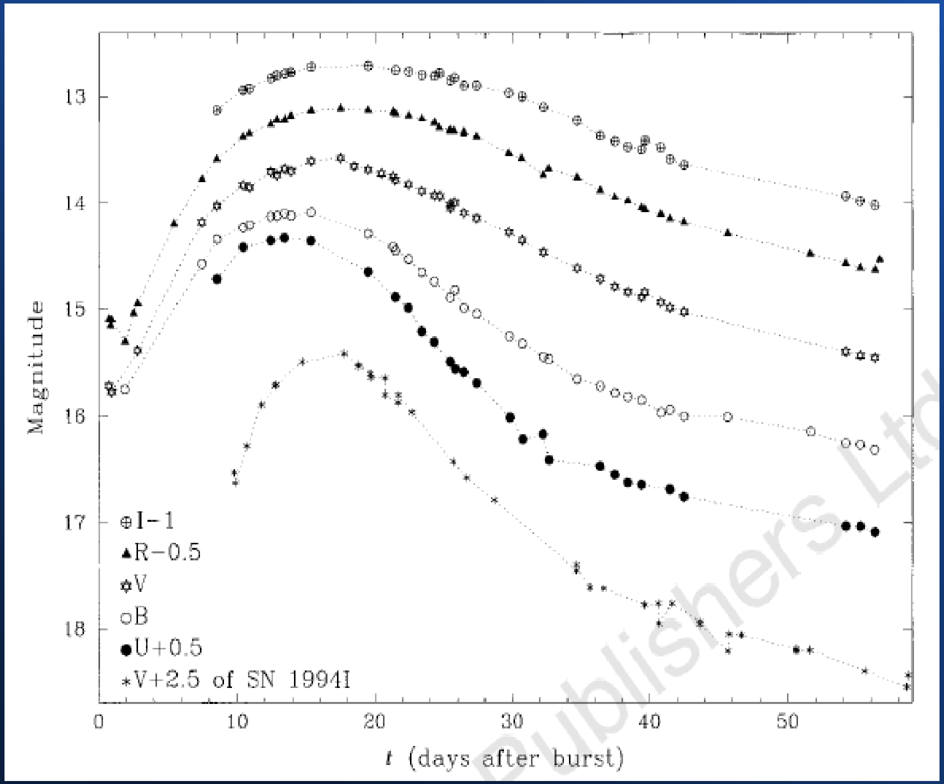
XW, Razzaque, Meszaros, Dai 2007, PRD

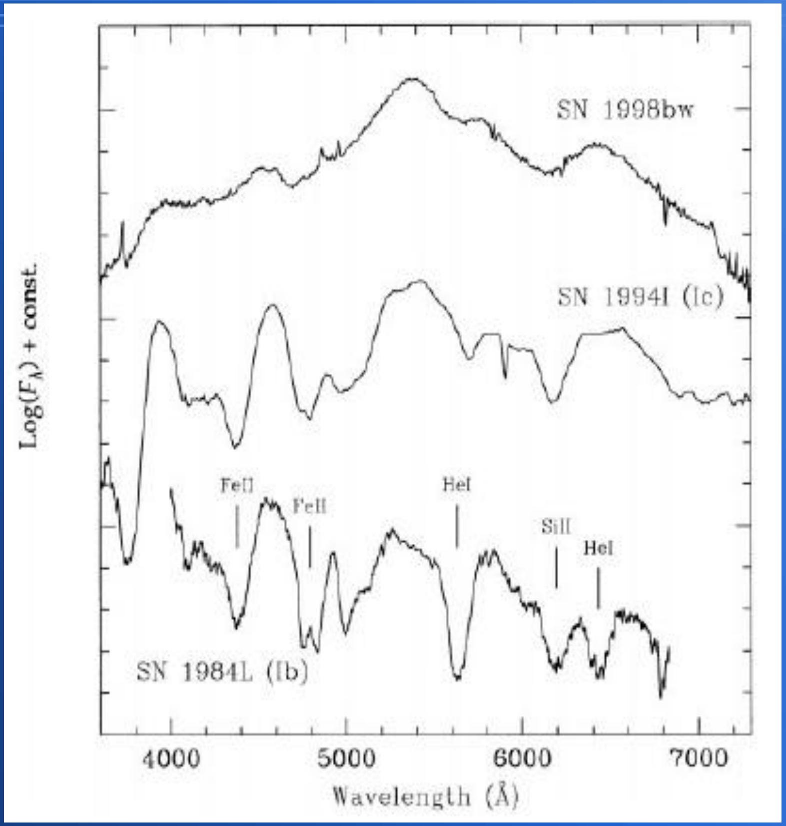


Scale-up of normal SNRs for Galactic CRs

Hypernova prototype – SN1998bw: an unusual SN

In the error box of GRB980425





1) Type Ic SN, Distance=38 Mpc
2) High peak luminosity, broad emission lines -> modelling require large explosion energy (E=3-5e52erg)

Normal SN: E=1e51 erg

Nearby hypernovae

■Radio and X-ray afterglow modeling suggest mildly relativistic ejecta with energy >1E50 erg (e.g. SN1998bw, SN2009bb)

—also called engine driven SNe

■Hypernova rate ~500 Gpc^-3 yr^-1, a few per cent of core-collapse Sne, leading to enough CR flux

Name	Distance	comments
SN1998bw	**38 Mpc**	GRB980425
SN2006aj	**120 Mpc**	GRB060218
SN 2010bh	**260 Mpc**	GRB100316D
SN2009bb	**40 Mpc**	No GRB associated

The maximum energy of accelerated particles by HNR

(Wang, Razzaque, Meszaros, Dai 2007, PRD)

1) Type Ib/c SN expanding into the stellar wind, Wolf-Rayet star

2) equipartition magnetic field B, both upstream and downstream

$$\rho_w(R) \propto R^{-2}$$

$$B^2/8\pi = 2\epsilon_B \rho_w(R) c^2 \beta^2$$

Maximum energy (shock acceleration):

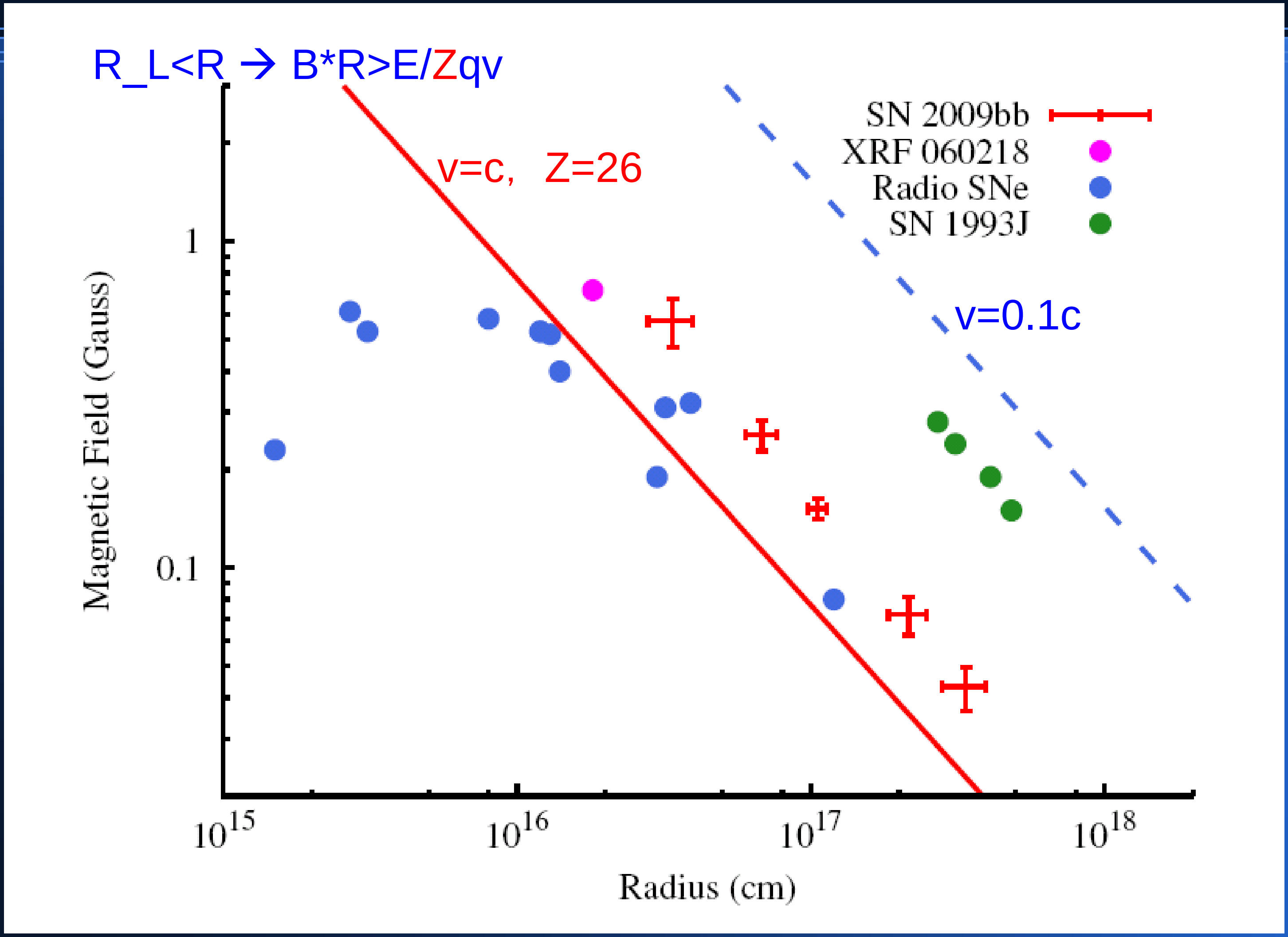
$$t_{\rm acc} \sim t_{\rm dyn}$$

$$\varepsilon_{\rm max} \simeq ZeBR\beta = 4 \times 10^{18} Z \times \epsilon_{B,-1}^{1/2} \left(\frac{v}{10^{10}{\rm cms^{-1}}}\right)^2 \left(\frac{\dot{M}}{3\times10^{-5}{\rm M_\odot yr^{-1}}}\right)^{1/2} v_{w,3}^{-1/2} {\rm eV}$$

Protons can be accelerated to ~1e19 eV

Iron can be accelerated to ~1e20 eV

Hillas plot for heavy nuclei CRs



Chakraborti et al. 2010

Energy spectrum from HNR

(Liu & XW 2012)

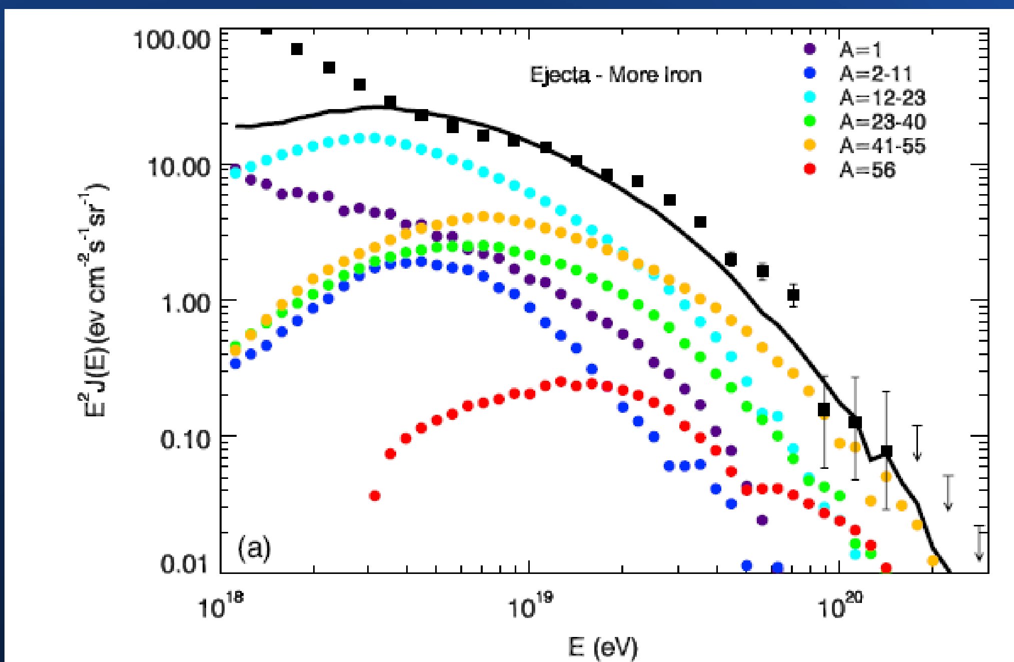
WR stellar wind

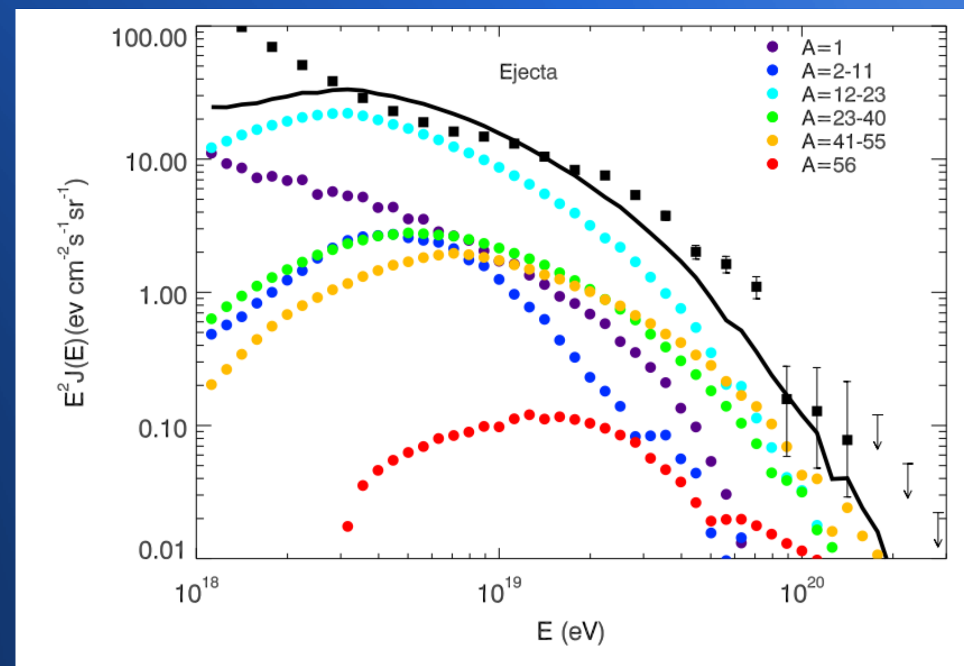
Hypernova ejecta (SN1998bw)

p=2

$$E_{\rm max,Fe} = 10^{20.5}(Z/26){\rm eV}$$

p=2





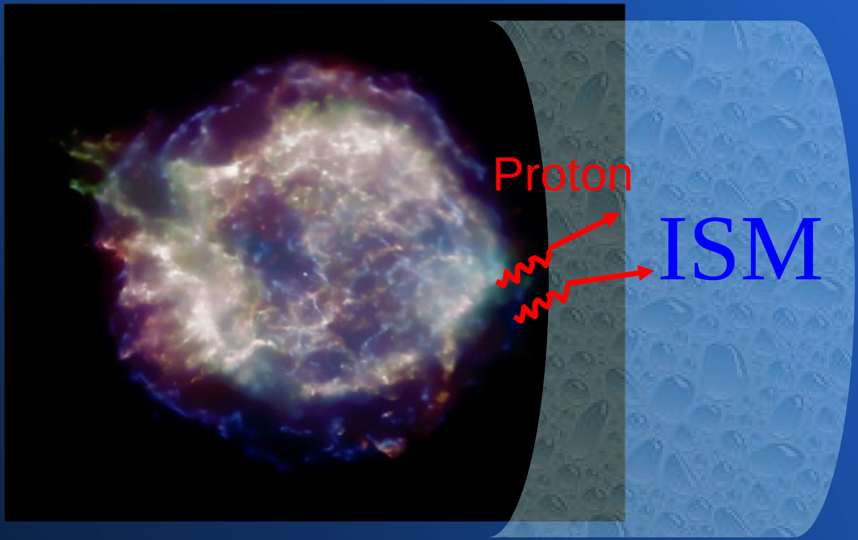
$$M_{\rm He} : M_{\rm C} : M_{\rm O} : M_{\rm X} = 0.32 : 0.39 : 0.25 : 0.04$$

of $M_{\rm C} : M_{\rm O} : M_{\rm Ne} : M_{\rm Mg} : M_{\rm Si} : M_{\rm S} : M_{\rm Ca} : M_{\rm Fe} = 0.006 : 0.71 : 0.037 : 0.034 : 0.083 : 0.041 : 0.007 : 0.09.$

Neutrino production

(Liu, XW, Inoue, Crocker & Aharonian 2014)

- Proton-proton collisions



$$pp/pn \rightarrow \pi^{\pm}/K^{\pm}$$

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

- pp efficiency in star-forming galaxies & starburst galaxies

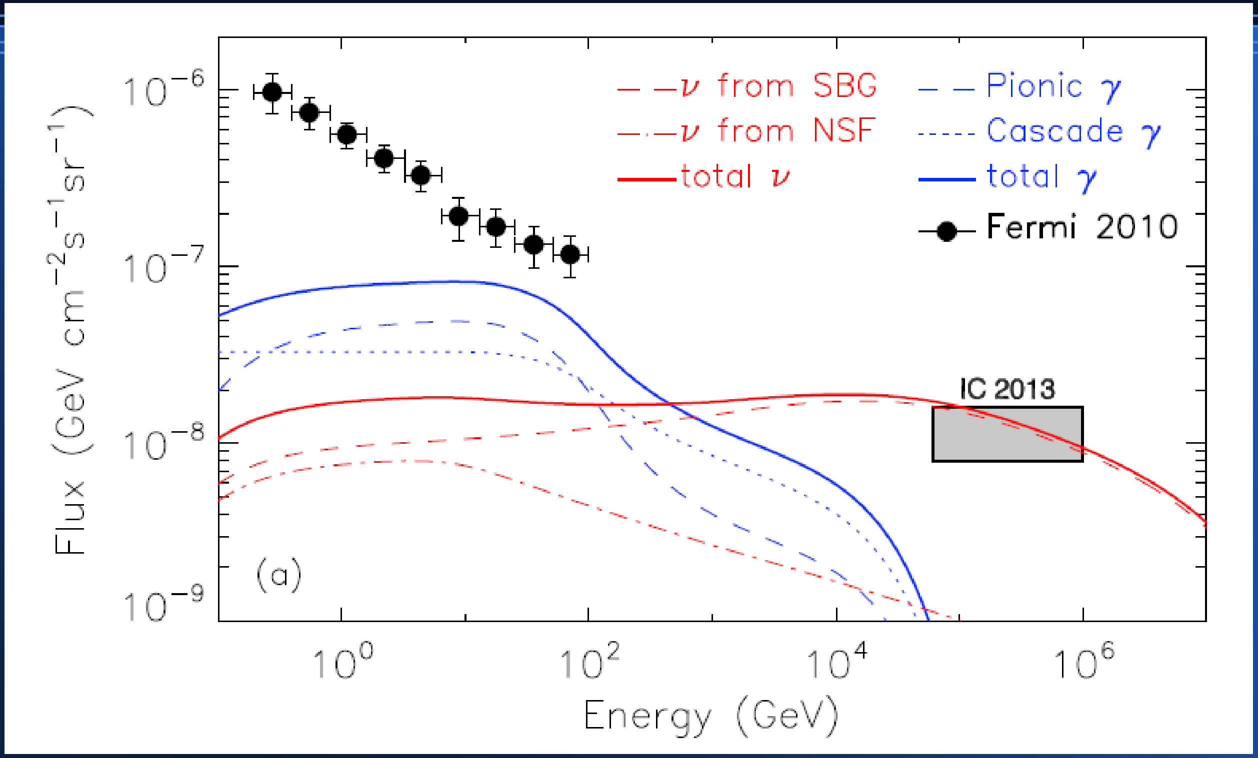
$$t_{\rm loss} = 7 \times 10^{4}\,{\rm yr} \frac{R}{500\,{\rm pc}} \left(\frac{\Sigma_g}{1\,{\rm g\,cm^{-2}}} \right)^{-1}$$

$$t_{\rm diff} = 10^{5}\,{\rm yr} \left(\frac{R}{500\,{\rm pc}} \right)^{2} \left(\frac{D_0}{10^{27}\,{\rm cm^2\,s^{-1}}} \right)^{-1} \left(\frac{E_p}{60\,{\rm PeV}} \right)^{-0.3}$$

$$f_{\pi}^{\rm N} = t_{\rm diff}^{\rm N}/\tau_{pp}^{\rm N} \simeq 0.01 \text{ and } f_{\pi}^{\rm B} = t_{\rm diff}^{\rm B}/\tau_{pp}^{\rm B} \simeq 0.4$$

Neutrino spectrum from HNR

(Liu, XW, Inoue, Crocker & Aharonian 2014)



SBG: star-burst galaxies

NSF: normal star-forming galaxies

Normalized with EeV CR flux

- Two escape ways: 1) diffusion 2) advection

$t_{\rm diff} \propto \varepsilon^{-0.3}$ → S=-2.2-2.3

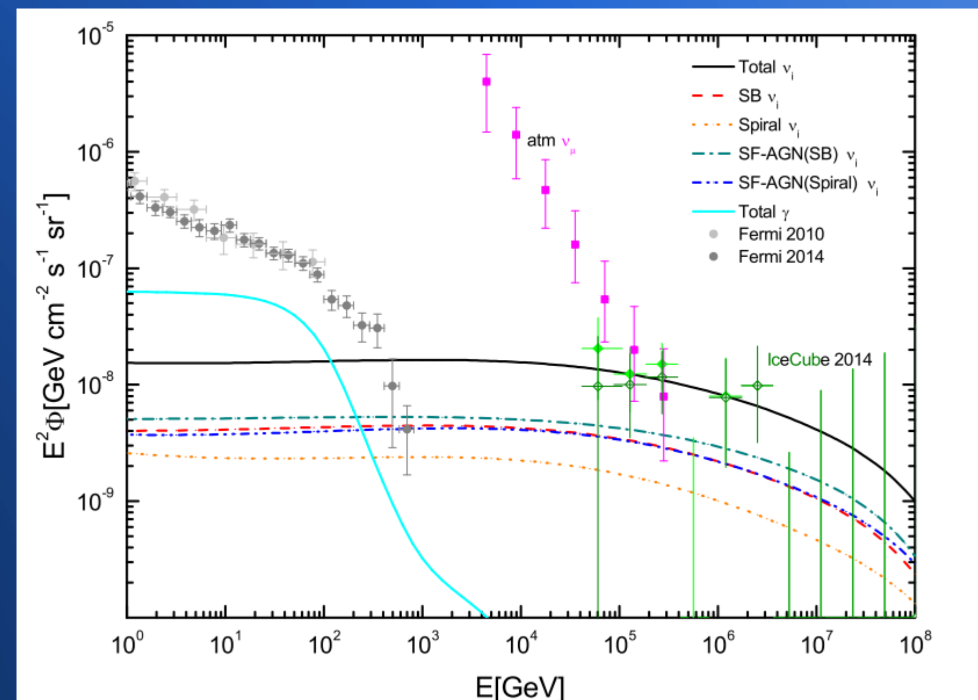
CR diffusion leads to a softer neutrino spectrum !

Cumulative neutrino spectrum

Chang, Liu & XW 2015

- Use infrared luminosity function obtained by Herschel PEP/HerMES (Gruppioni et al. 2013)
- Sum up contributions by different galaxy populations

$$E_\nu^2 \Phi_{\nu_i}^{\rm accu} = \frac{E_\nu^2 c}{4\pi} \int_0^{z_{\rm max}} \int_{L_{\rm TIR,min}}^{L_{\rm TIR,max}} \frac{\sum_i \phi_i(L_{\rm TIR}, z) L_{\nu_i}[(1+z)E_p, L_{\rm TIR}]}{H_0\sqrt{(1+z)^3\Omega_M + \Omega_\Lambda}} dL_{\rm TIR} dz.$$

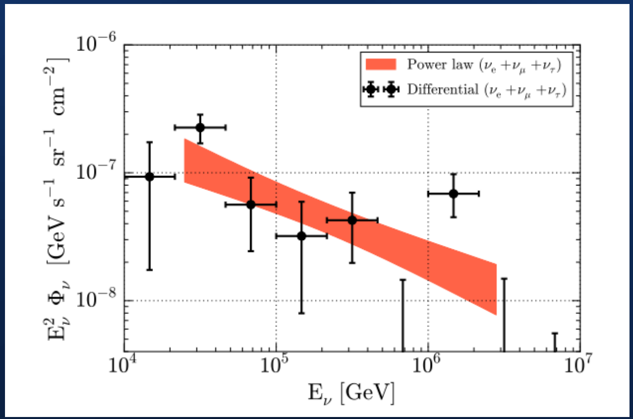


- Soft spectrum of the cumulative neutrino emission (see also Bartos+ 15)

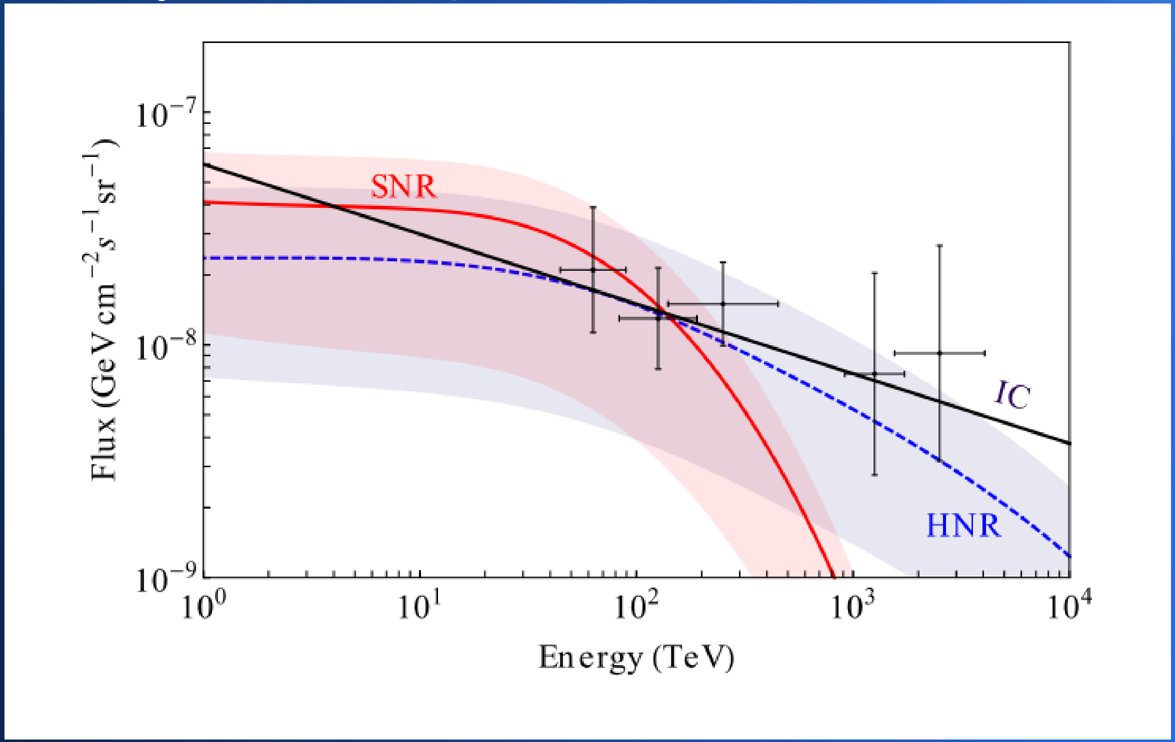
Normal SNRs + HNR

(Chakraborty and Izaguirre 15; Senno+ 15)

With normal SNRs, can explain the low energy IceCube data (softer spectrum)



IceCube



(Chakraborty and Izaguirre 15)

Summary

- HE neutrinos could come from the same sources of UHECRs
- Hypernova remnants, among other sources, are candidates of IceCube PeV neutrinos & UHECRs
- To identify the source, we need IceCube G-2 and multi-messenger approches