Beyond a PeV,
Paris, September 13 -6, 2016

How far are the sources of IceCube neutrinos? Constraints from the diffuse TeV gamma-ray background

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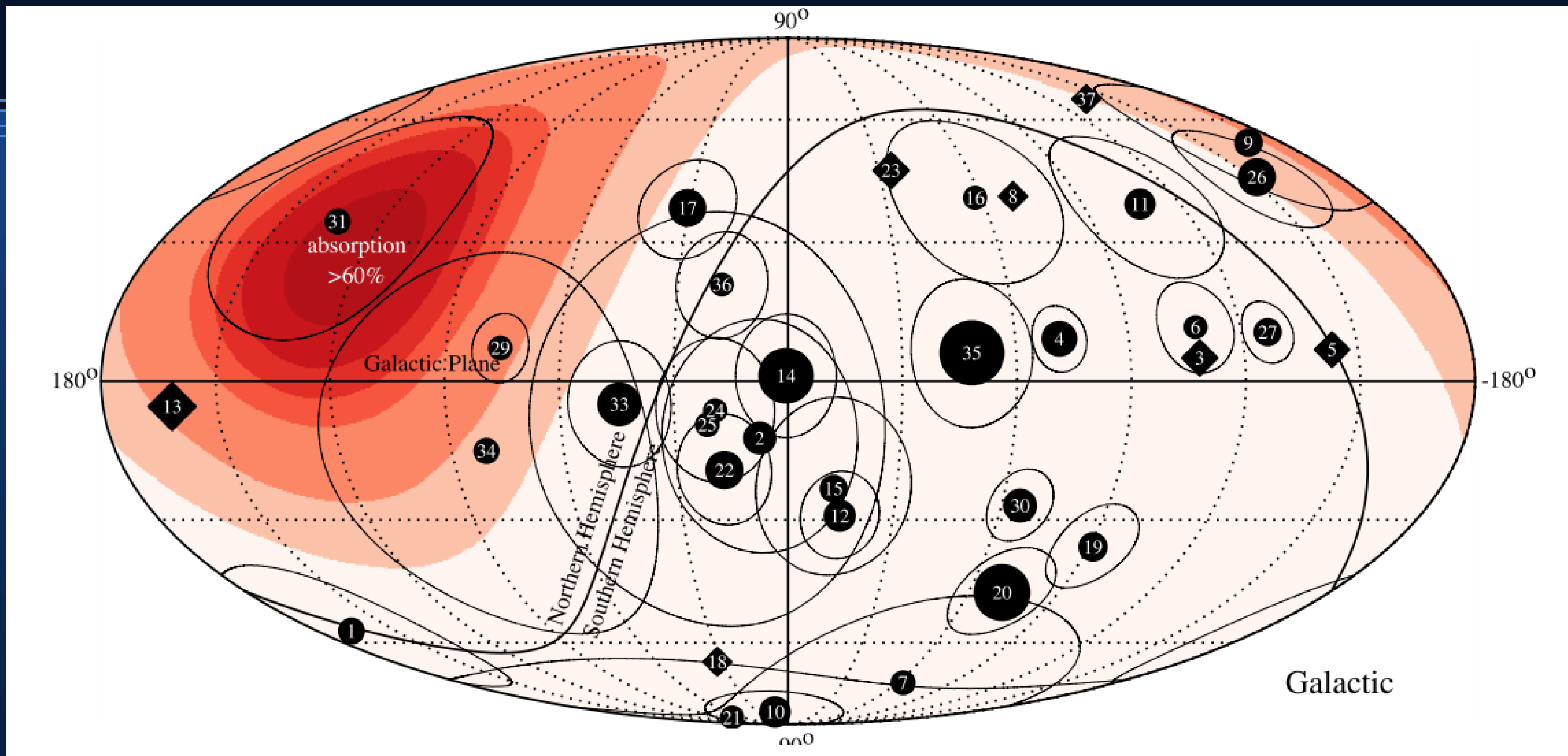
Outline

- Constraining the neutrino source distance with diffuse TeV background

- Some discussions on the starburst galaxy scenario

Arriving directions



- **28 "cascade events" (circles) and 7 "tracks events" (diamonds)**; size of symbols proportional to deposited energy (30 TeV to 2 PeV) [IceCube PRL 113 (2014)]

✘ **no significant spatial or temporal correlation of events**

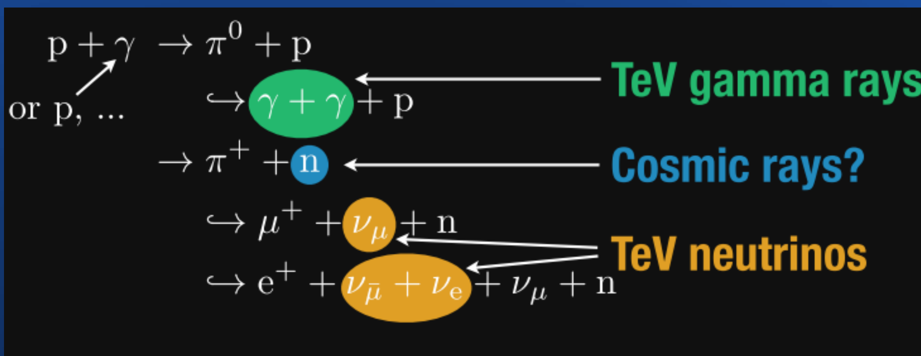
- **Isotropic distribution dominated**
- **Favor extragalactic origin**

How far are the sources of neutrinos

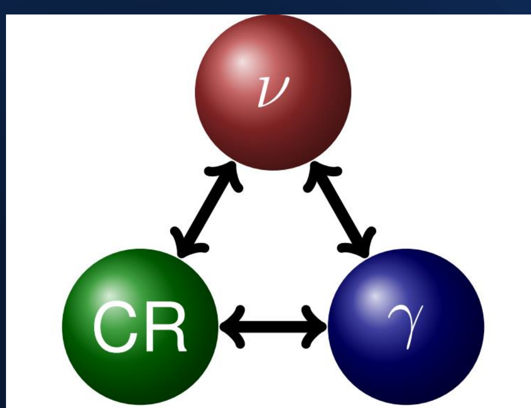
- ✓ The sources of neutrinos are unknown due to lack of associations
- ✓ Such an isotropic distribution could be produced as long as the distance to the source is significantly larger than the size of the Galactic plane
- ✓ There are claims of correlations between neutrinos and UHECRs

(Moharana & Razzaque 2015)

TeV gamma-ray connection



$$E_\gamma Q_\gamma(E_\gamma) \approx (2/3) E_\nu Q_\nu(E_\nu)|_{E_\nu = E_\gamma/2}$$



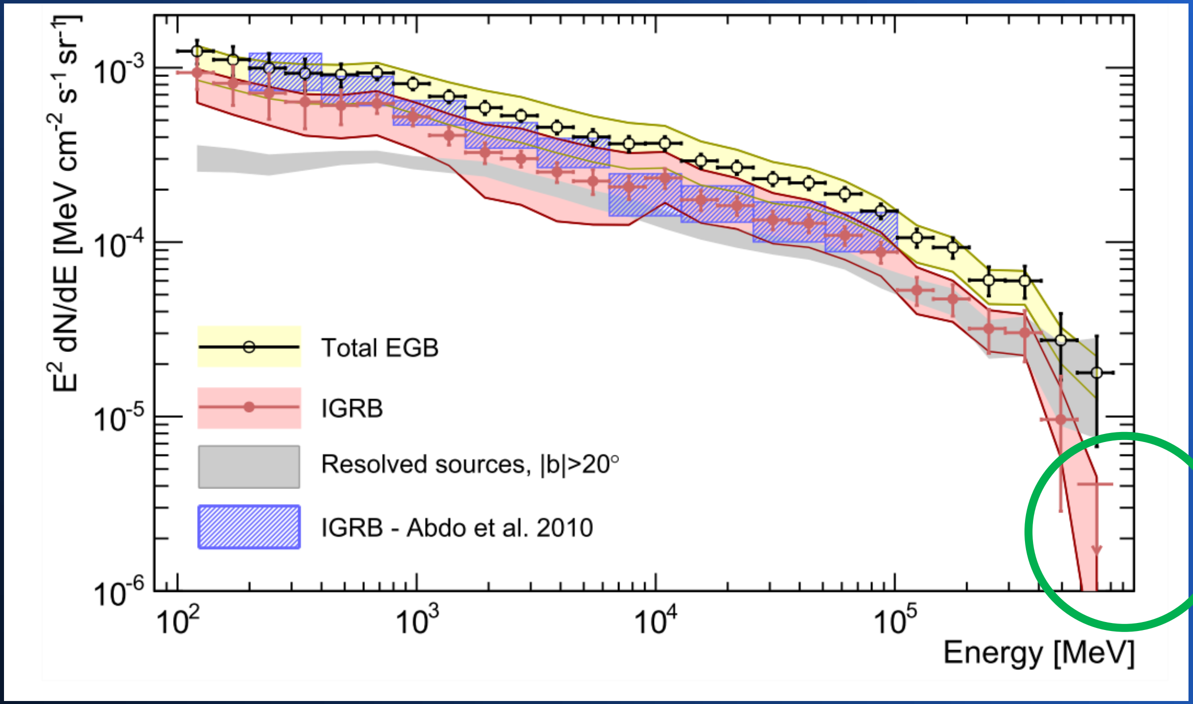
■TeV gamma-rays will be absorbed if they are too far from us.

■By comparing the cumulative TeV flux and neutrino background flux, one can obtain the information of the source distance

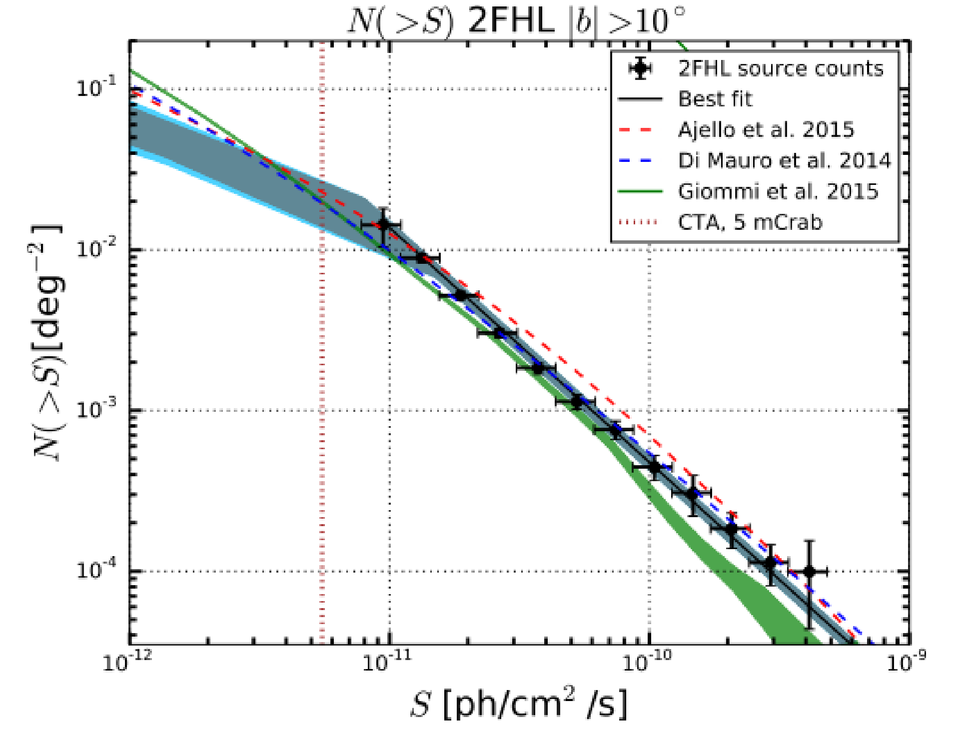
■One assumption: no internal absorption in the source

TeV gamma-ray background

- TeV background flux is significantly lower than the neutrino background
- Most of the TeV gamma-rays associated with neutrinos must be absorbed



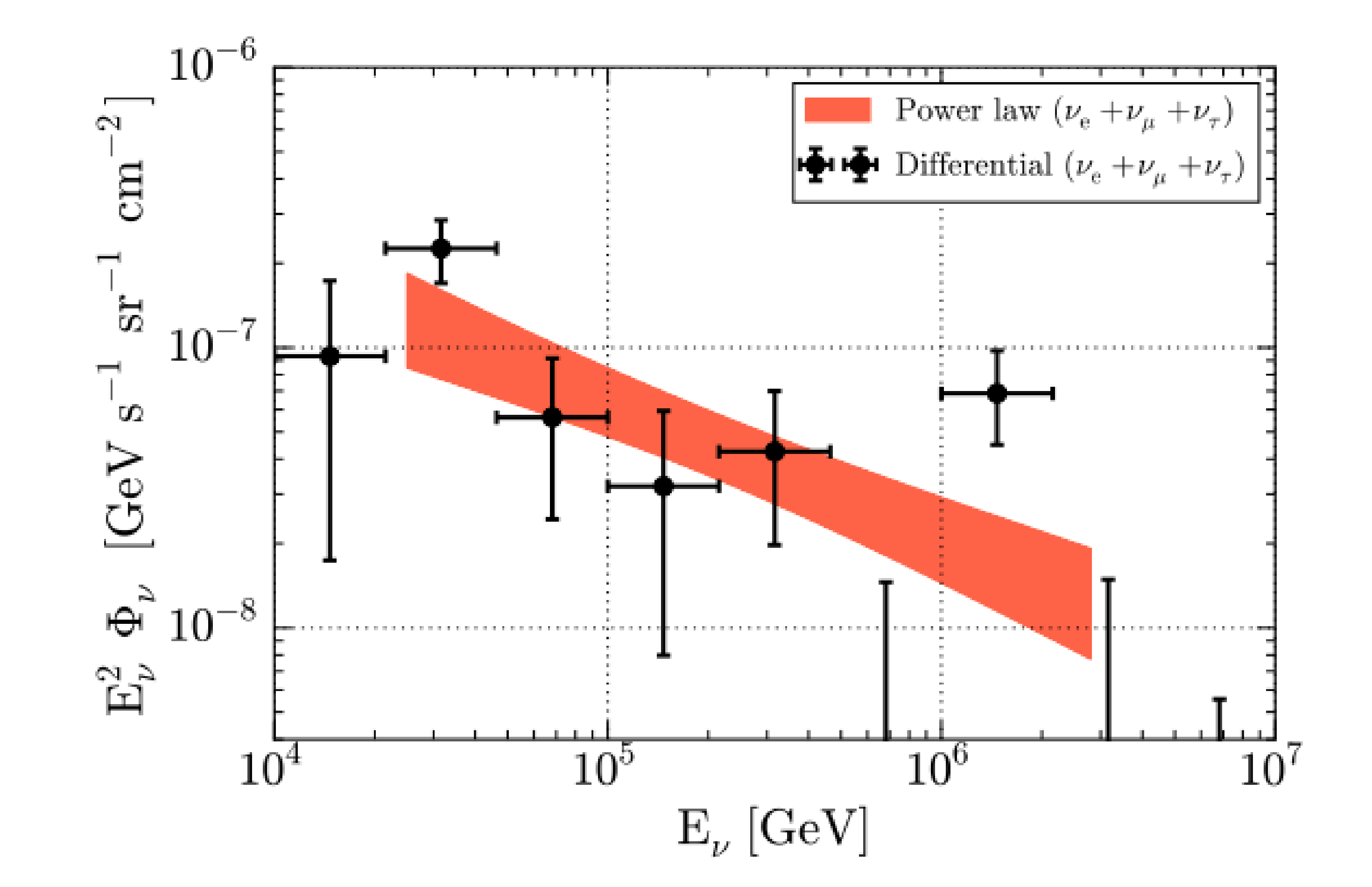
Blazar contribution to the extragalactic gamma-ray background



Ackermann+ 2016

- Above 50 GeV , blazars account for at least $86^{+16}_{-14}\%$ of the total extragalactic γ-ray background.
- The non-blazar EGB account for <14%

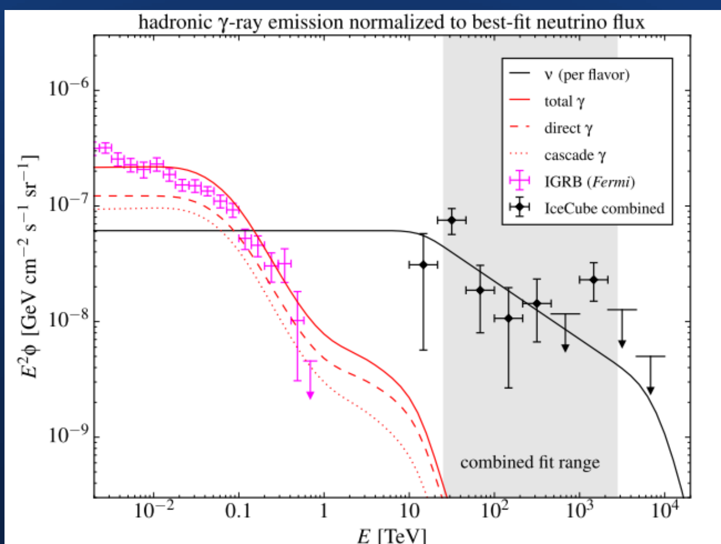
Combined maximum-likelihood analysis

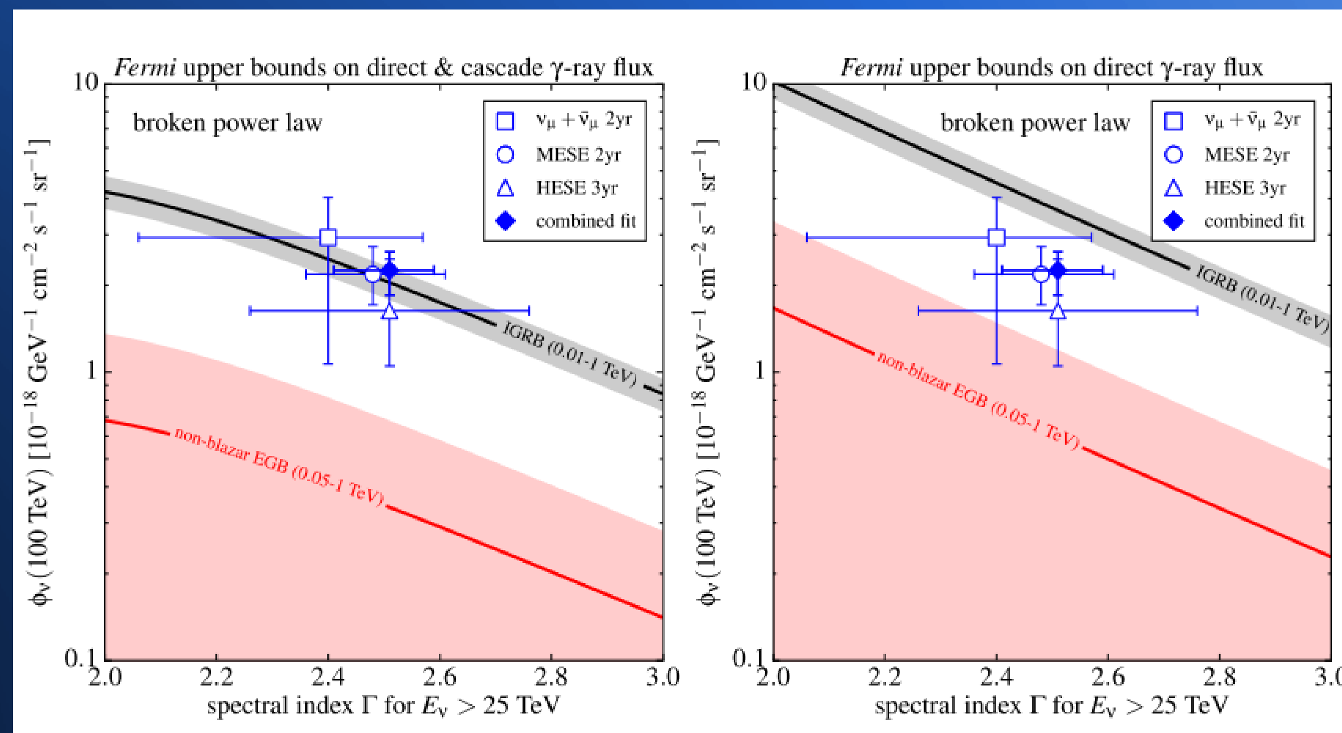


IceCube collaboration , 2015, ApJ

Tension with the gamma-ray background

arXiv:1511.00688





Possible scenarios：1）overestimate the neutrino flux at 10 TeV
2）hidden in gamma-rays (e.g. Choked jets)

How far are the neutrino sources

Chang, Liu & Wang 2016

$$\Phi_{\gamma,\mathrm{un}}(E_\gamma) = \sum_{F_n<F_{\mathrm{sens}}}^{n} F_n(E_\gamma) \leqslant \Phi_{\mathrm{IGRB}}(E_\gamma),$$

$$\Phi_{\gamma,\mathrm{tot}}(E_\gamma) = \sum^{n} F_n(E_\gamma) \leqslant \Phi_{\mathrm{EGB}}(E_\gamma)$$

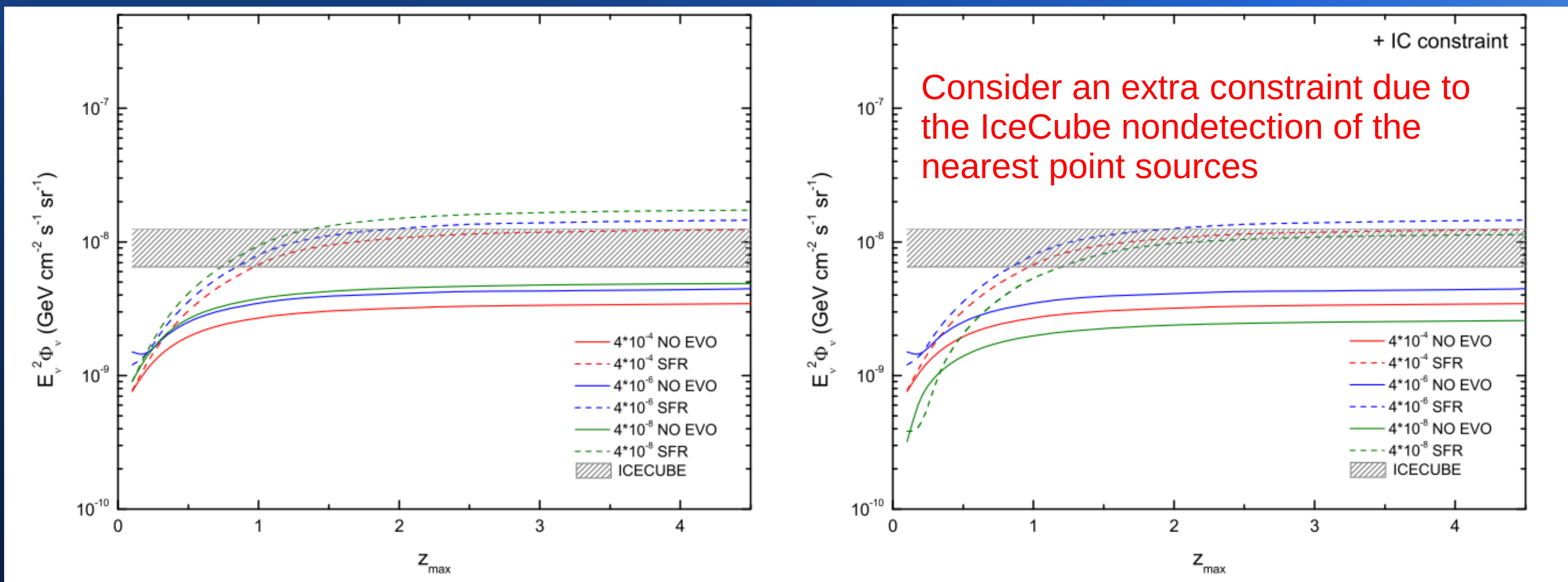
$$F(E_\gamma) = \{Q'_\gamma[(1+z)E_\gamma]e^{-\tau(E_\gamma)} + Q_{\gamma,\mathrm{cas}}(E_\gamma)\}/4\pi\bar{r}^2,$$

$$\rho = \rho(z)$$

- high-density source case (e.g. 4×10^{-4} Mpc^{-3}; starburst galaxies)
- middle-density case (e.g., 4×10^{-6} Mpc^{-3}; cluster of galaxies)
- low-density case (e.g. 4×10^{-8} Mpc^{-3} blazars)

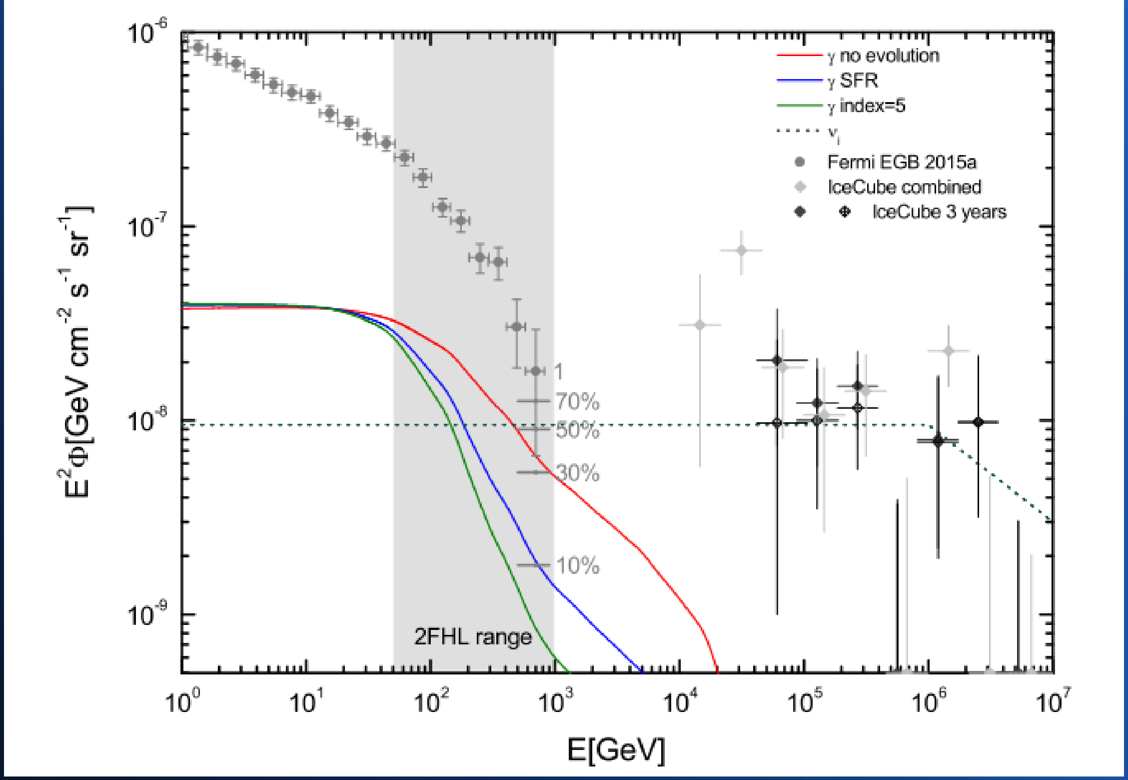
1) Non-blazar EGB Case

Assume that EGB and IGRB are only relevant to >100 TeV neutrinos



1) We find that above 80% of the IceCube neutrinos should come from sources at redshift z > 0.5.

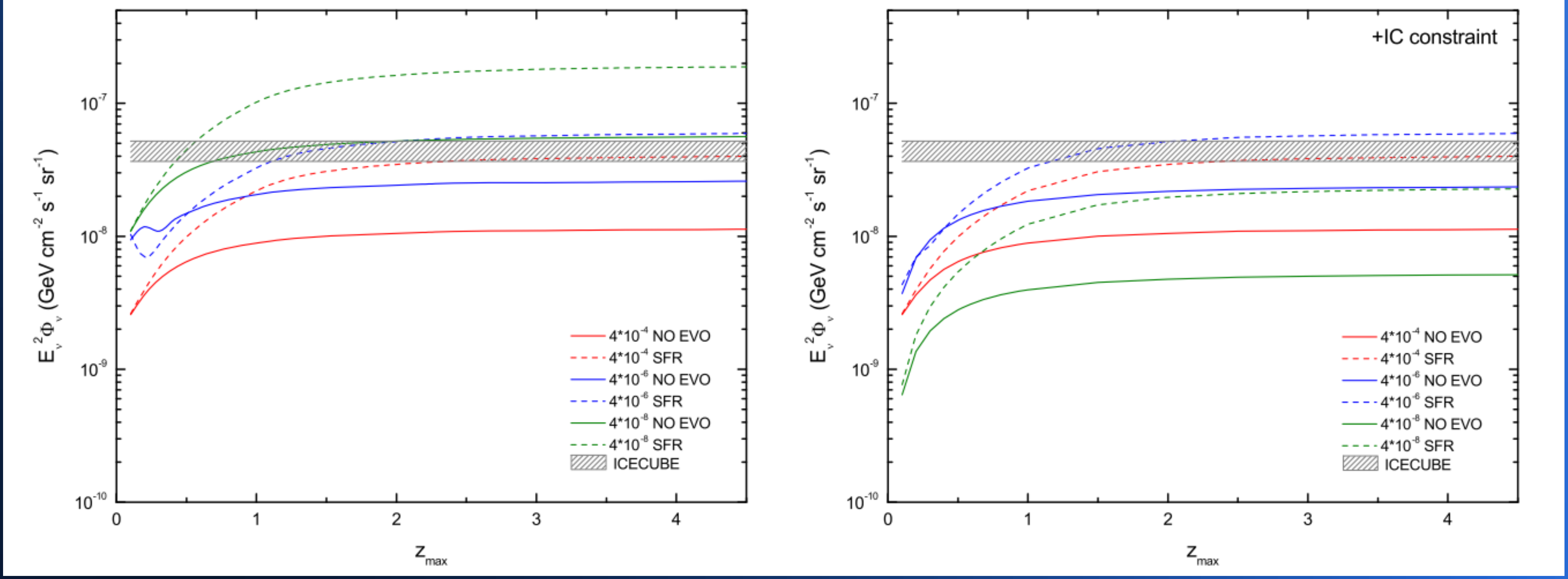
2) the redshift evolution of neutrino source density must be at least as fast as SFR



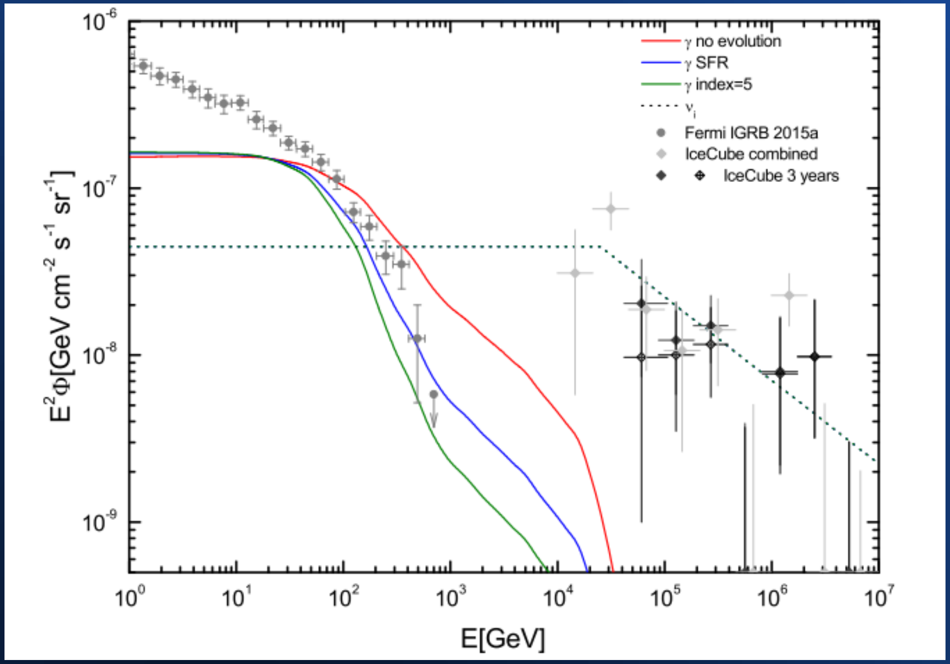
the redshift evolution of neutrino source density must be at least as fast as SFR

2) Blazar EGB case

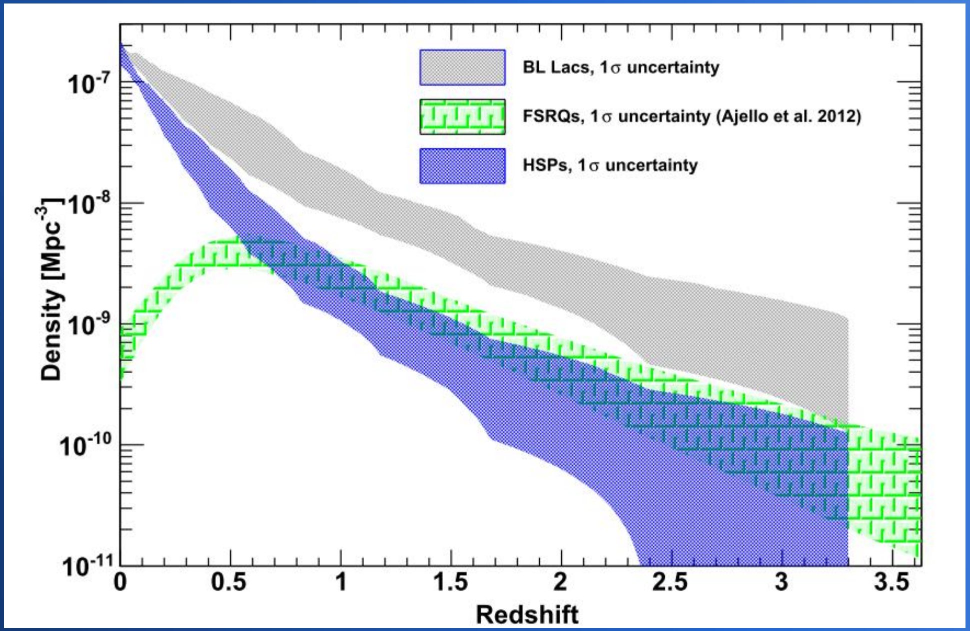
Allow blazars to contribute to IceCube neutrinos (10-100TeV) and use the full EGB as the upper limit



However, in conflict with BL Lacs distribution



Chang, Liu & Wang 2016



Ackermann 2014

Summary (I)

- >80% of the IceCube neutrinos should come from sources at redshift $z > 0.5$.
- To explain the flux of neutrinos under the TeV gamma-ray emission constraint, the redshift evolution of neutrino source density must be at least as fast as the cosmic SFR.
- Future better measurements of TeV background will put more stringent constraints.

TeV/PeV neutrino models?

GRB (Cholis & Hooper 13)

AGNs: (Stecker et al. 91; Kalashev et al. 13)

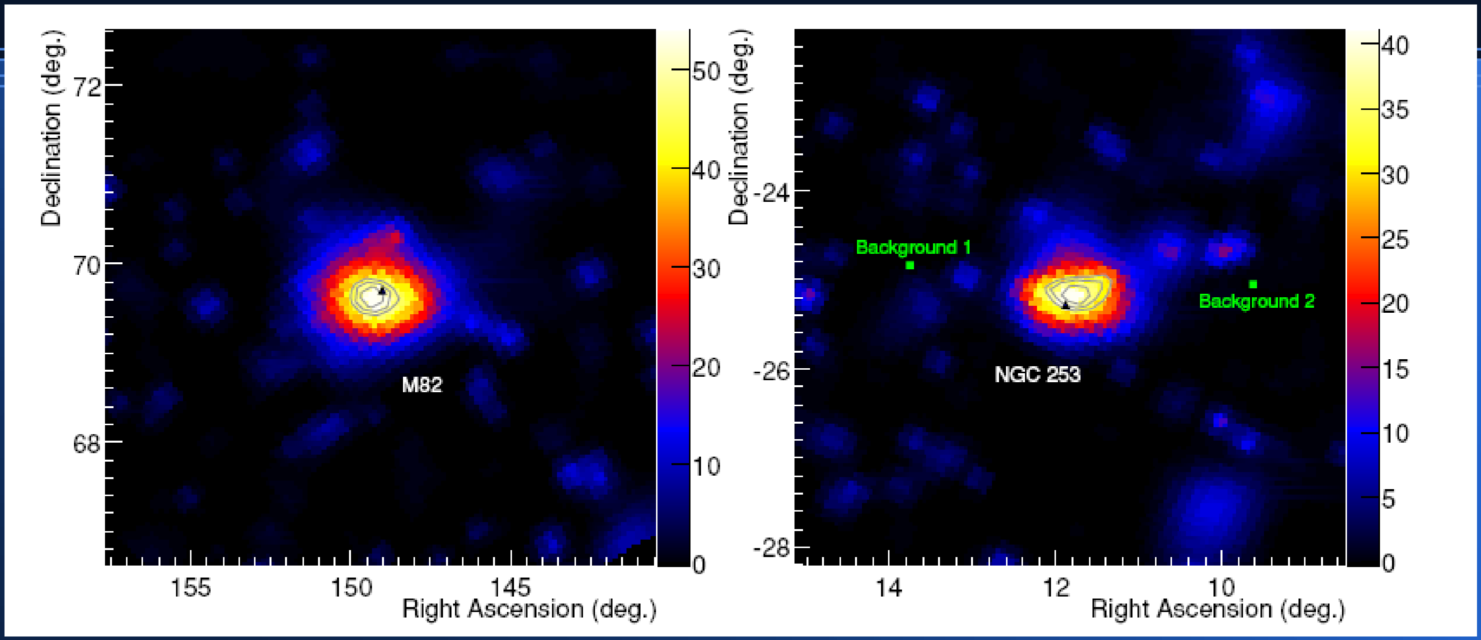
Starburst galaxy (Loeb & Waxman 2006)

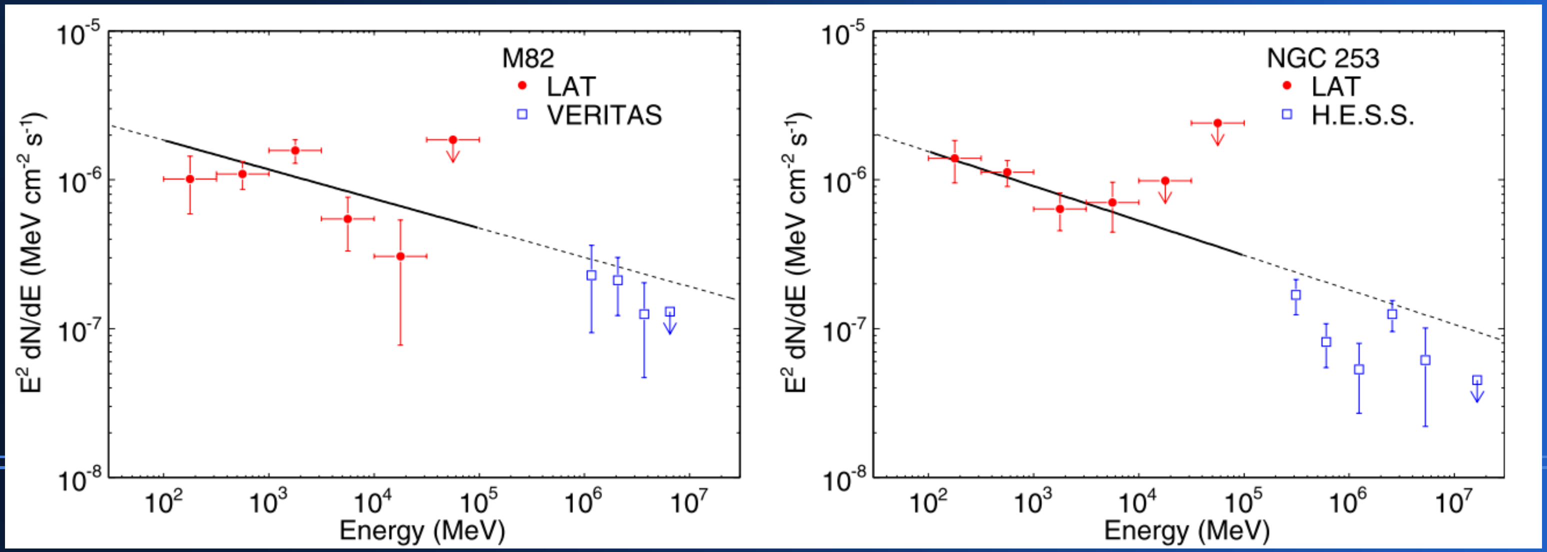
Hypernova in star-forming galaxies (Liu et al. 14)

…

Gamma-ray emission from starburst galaxies

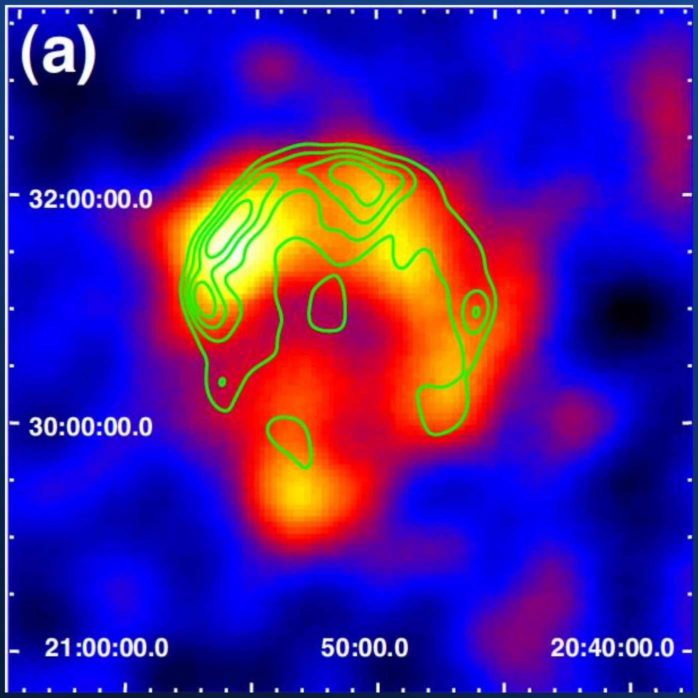
Abdo et al. 2010





Cosmic rays accelerated by SNRs

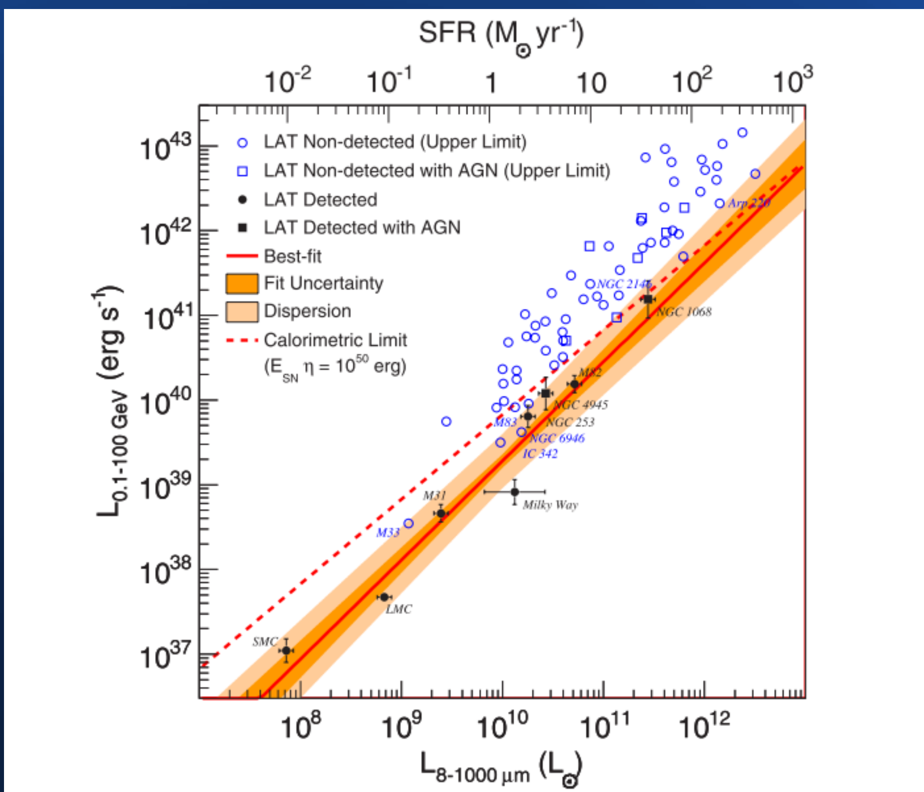
Cygnus Loop (0.5-10 GeV)



- Supernova explosions induce shocks (SNRs)
- Cosmic rays are accelerated across these shock fronts
- GeV Gamma-rays are produced by Cosmic rays

$$p^{+}_{CR} + p^{+}_{ISM} \rightarrow p^{+} + p^{+} + \pi^{0}, \pi^{0} \rightarrow \gamma + \gamma$$

Correlation between gamma-ray and infrared luminosities



Ackermann et al. 2012

- Several nearby star-forming galaxies detected
- Gamma-ray and infrared luminosity well correlated
- Naturally expected if more CR energy is converted into gamma-rays in more luminous galaxies

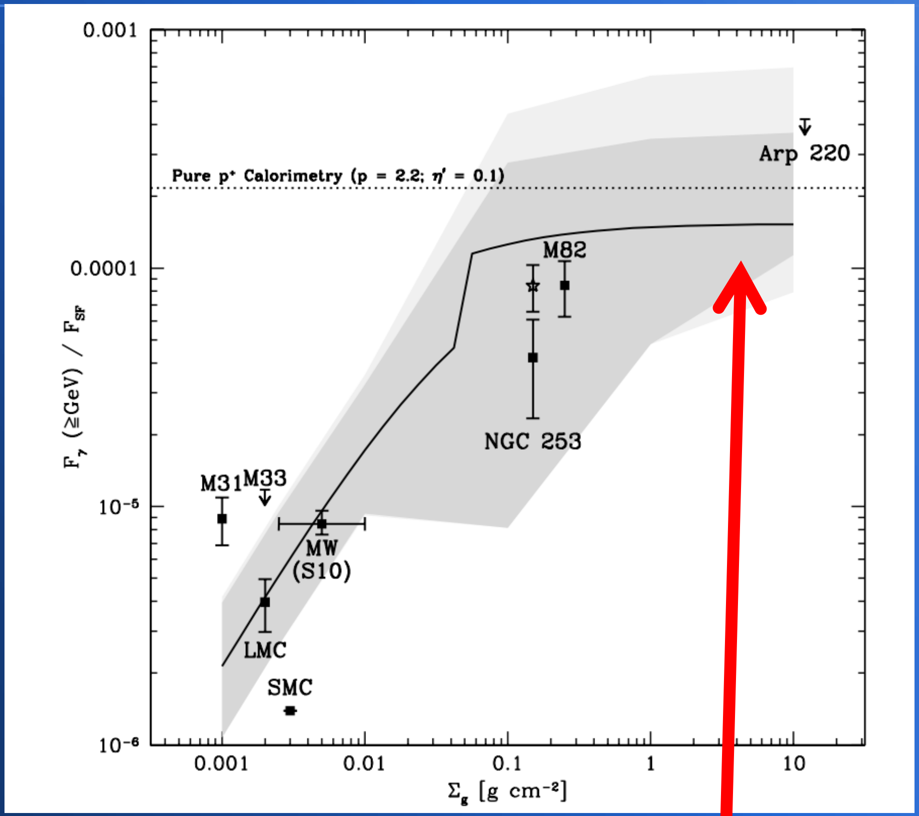
CR calorimeter ?

- Calorimeter: high gas density galaxy

$t_{pp} < t_{escape}$

- "calorimetry fraction limit"

$$F_{\rm cal} \equiv \frac{L_\pi}{L_{\rm CR}(K \geqslant K_{\rm th})}$$

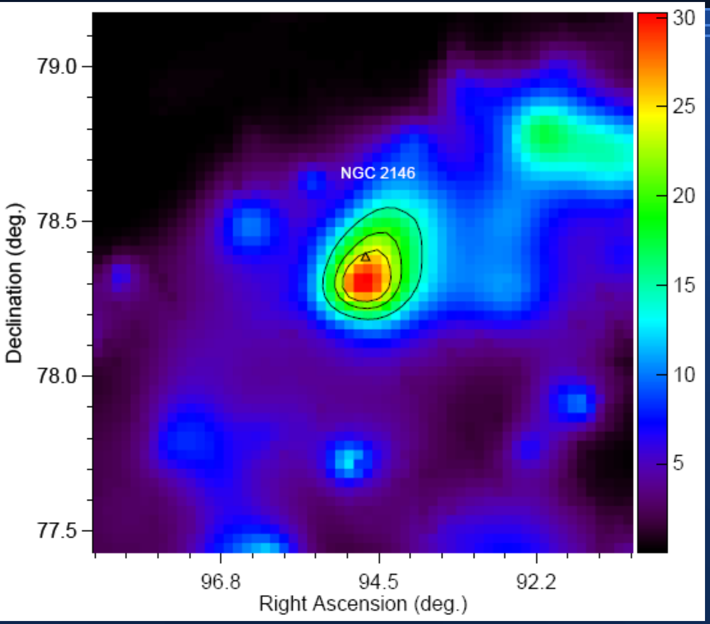


Best target: (ultra) luminous infrared galaxies

Lacki et al. 2011

GeV emission from LIRG NGC 2146

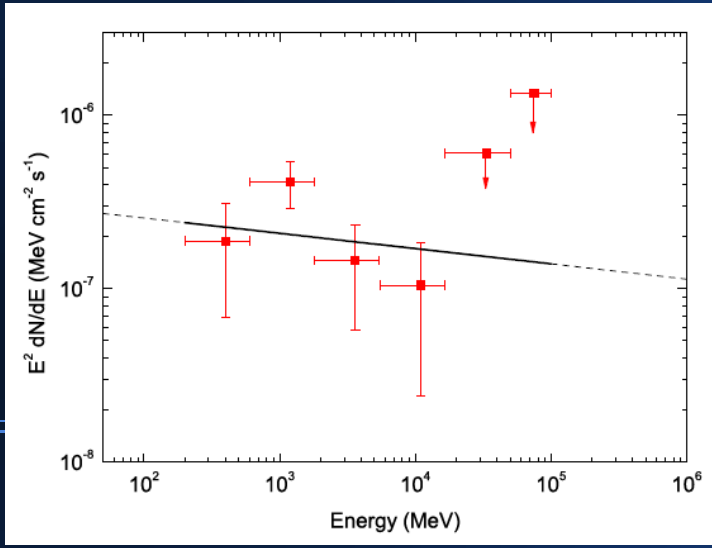
Tang, Wang & Tam 2014

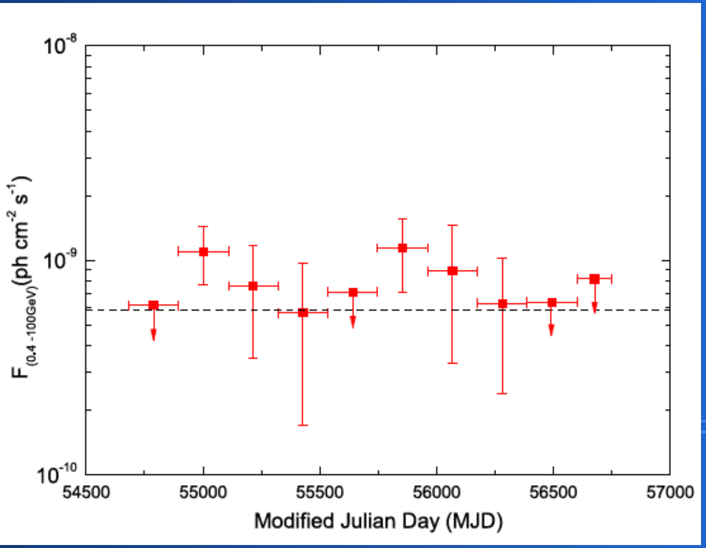


- A luminous infrared galaxy at d=15Mpc

$$L_{8-1000\,\mu m} \simeq 10^{11}\,L_{\odot}$$

- using the 68 month Fermi data
- 5.5σ detection of gamma-ray emission above 200 MeV

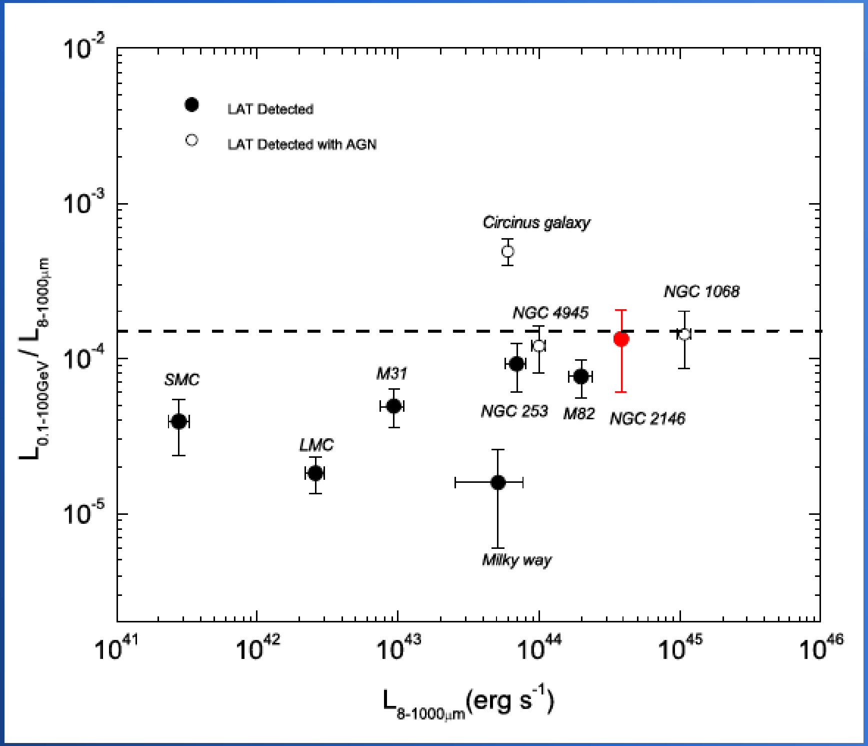




NGC2146—a likely calorimeter ?

$$\xi \equiv \frac{L_\gamma(>0.1\ \mathrm{GeV})}{L_{8-1000\,\mu\mathrm{m}}} = 1.5 \times 10^{-4} E_{51}\eta_{0.05}\beta_{17}$$

- assuming $E_{SN,51}\ \eta_{0.05}$=1, for proton calorimeter limit : $L_{0.1\text{-}100GeV}/L_{8\text{-}100\mu m}$=1.5e-4.
- NGC 2146 is likely a proton calorimeter !
- Cosmic rays accelerated in NGC 2146 lose most of their energy into secondary pions



Tang, Wang & Tam 2014

Arp 220- the nearest ULIRG: must be calorimeter!

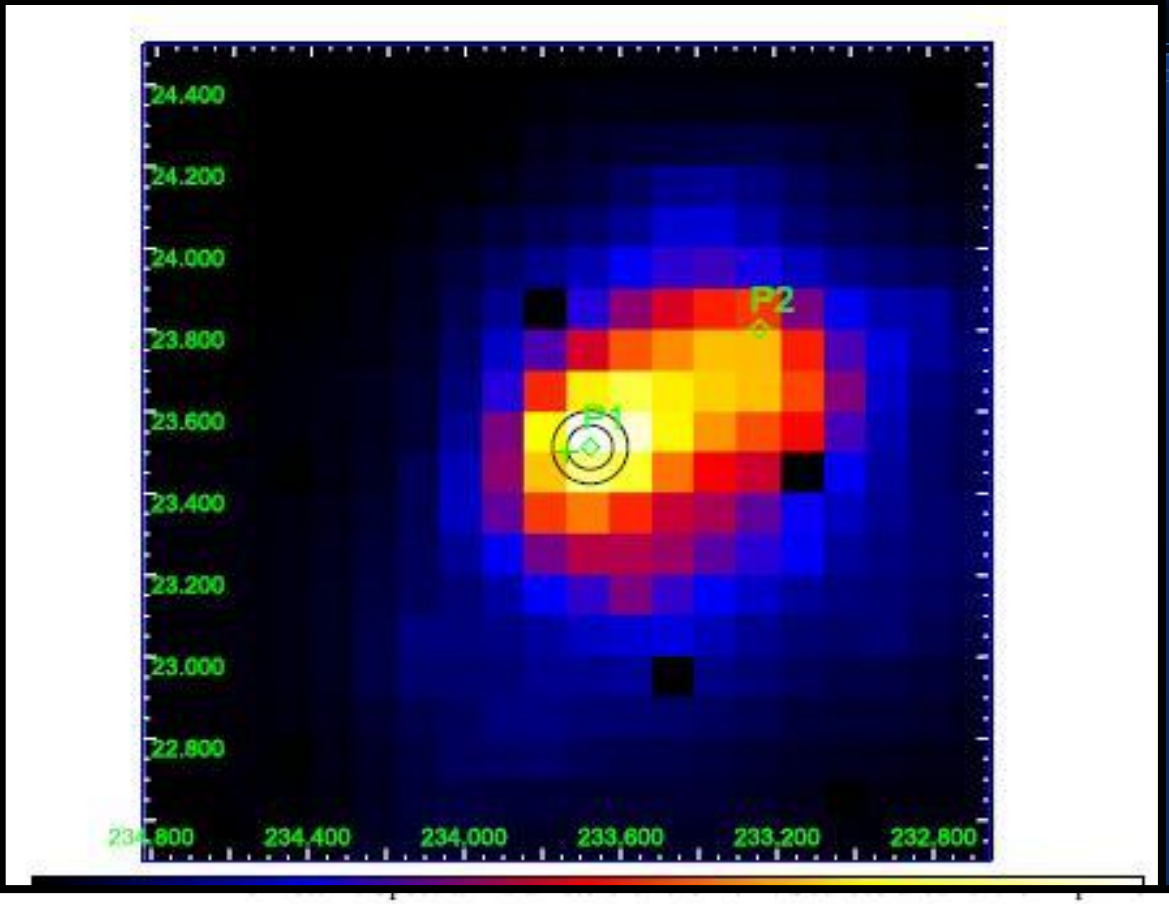
- A prototype of ULIRG: $L_{IR}=1.4*10^{12}L_{sun}$
- D=78Mpc
- $n\sim10^4cm^{-3}$

  $t_{pp}<t_{escape}$

- Possible AGN
- SN rate: 4+-2/yr
- Long predicted to be GeV sources

(e.g.,Torres 2004; Lacki+ 2011; Yoast-Hull+2015)

Fermi observation- PASS 8

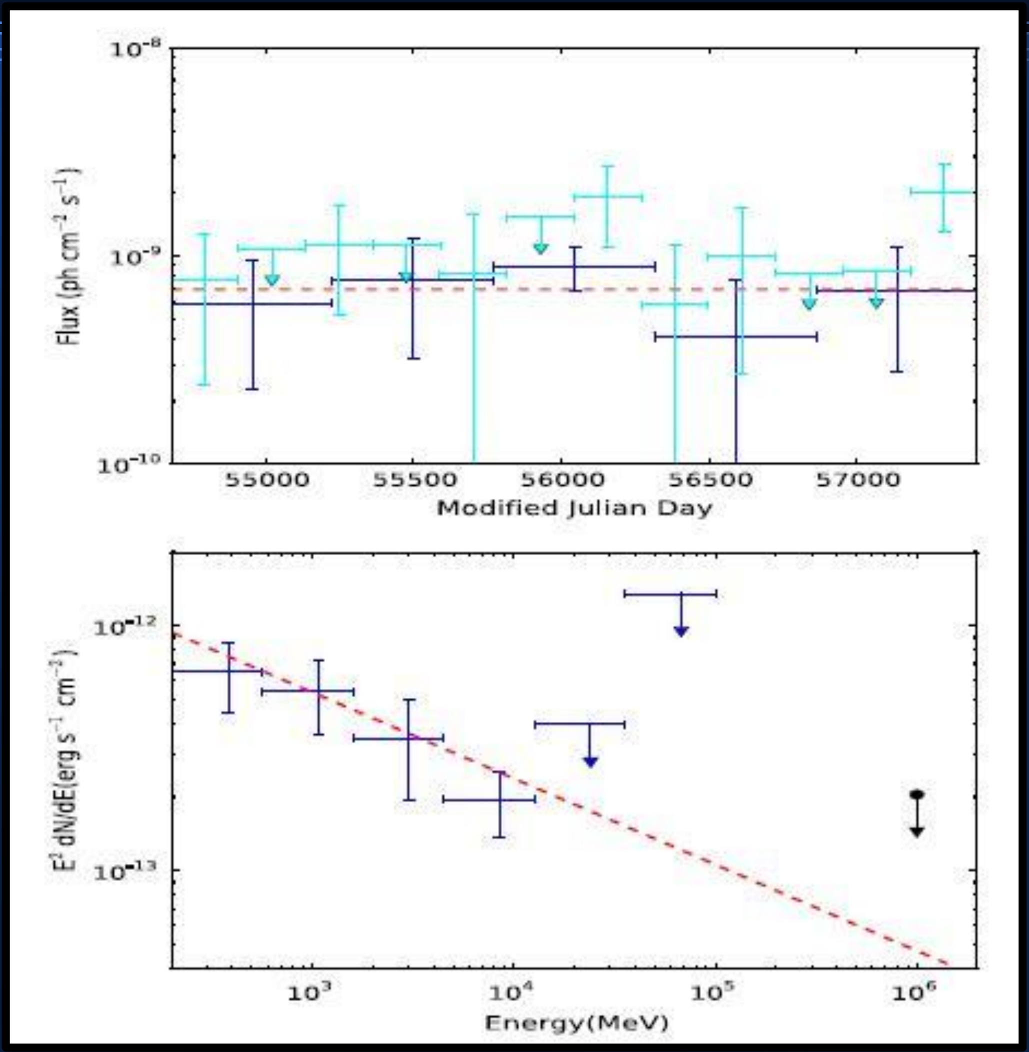


Peng, Wang et al. 2016, ApJL

See also Griffin et al. 2016

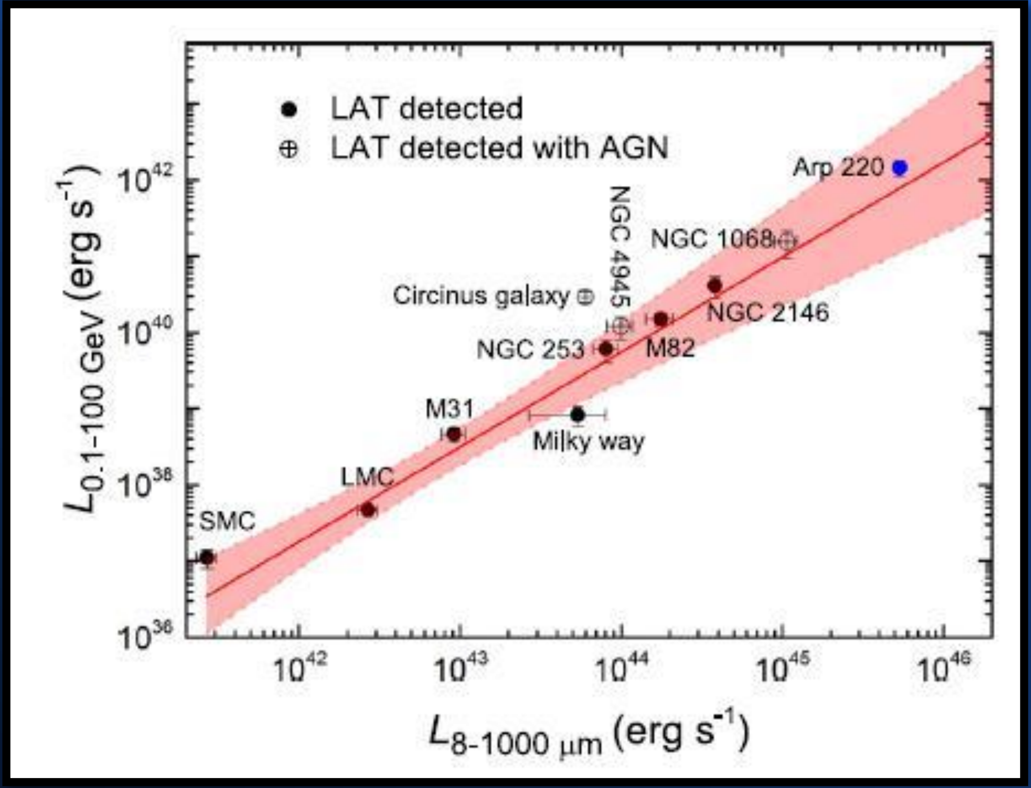
Point	Position (degree)	r_{95} (degree)	Separation (degree)	Photon Flux (10^{-9} ph cm^{-2} s^{-1})	Energy Flux (10^{-12} erg cm^{-2} s^{-1})	Γ	TS	Association
P1	(233.677, 23.5163)	0.090	0.058	1.76 ± 0.52	1.92 ± 0.43	2.35 ± 0.16	40	Arp 220
P2	(233.239, 23.8049)	0.279	0.547	1.45 ± 0.52	1.39 ± 0.40	2.45 ± 0.19	22	...

Light curve and SED of Arp 220



- Consistent with a constant flux
- Γ=-2.35+-0.16
- VERISTAS upper limit

Correlation



- Favor cosmic-ray origin for the gamma-ray emission !

Efficiency of powering CRs

- Cosmic Rays injection power (SN rate is known)

$$L_{CR}(>1\ \mathrm{GeV}) = 1.3 \times 10^{44}\ \mathrm{erg\ s^{-1}} E_{51} \eta \left(\frac{\Gamma_{SN}}{4\ \mathrm{yr}^{-1}}\right)$$

Γ_{SN}=4+-2 SN/yr

- GeV emission luminosity from CRs

The factor Γ-1 arises from the fact that a fraction (Γ−2)/(Γ−1) of the energy of CRs above 1 GeV is transferred to lower energy CRs.

$$L_{CR}(>1\ \mathrm{GeV}) = 3L_\gamma(>1\ \mathrm{GeV})(\Gamma - 1)\beta_\pi^{-1}$$

A fraction β_π of the pionic gamma-rays produced by CRs have energies above 1 GeV

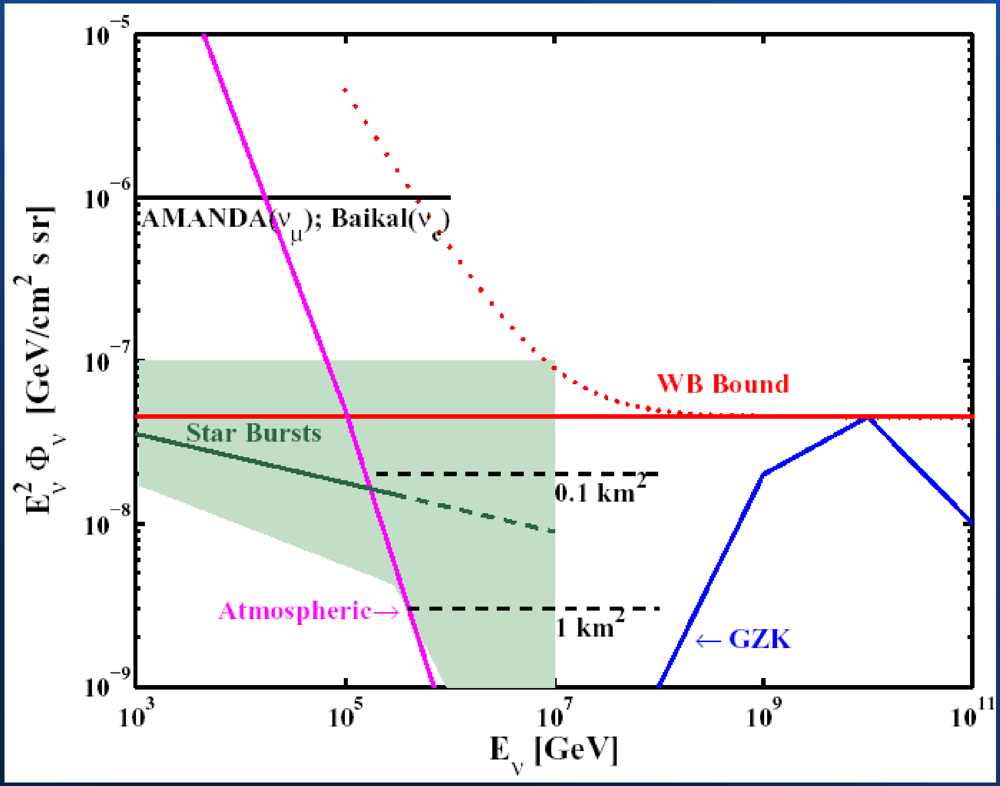
- Efficiency of powering CRs of SNRs

$$\eta \simeq (4.2 \pm 2.6)\% E_{51}^{-1} \left(\frac{\beta_\pi}{0.6}\right)^{-1} \left(\frac{\Gamma_{SN}}{4\ \mathrm{yr}^{-1}}\right)^{-1}$$

3%–10% efficiency in the Milky Way (Strong et al. 2010).

Starburst galaxy scenario

Loeb & Waxman 2006



- Cosmic rays are accelerated by SNR shocks
- Normalized with the local 1.4 GHz energy production rate
- But, Normal SNRs can only accelerate CR to PeV, while IceCube neutrinos need 100 PeV CRs ?

Ev ~ 0.04 Ep: PeV neutrino ⇔ 20-30(1+z) PeV CR proton

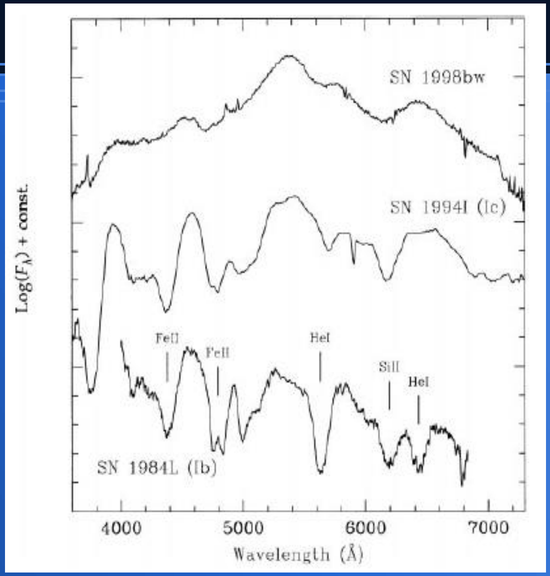
Hypernova remnant scenario

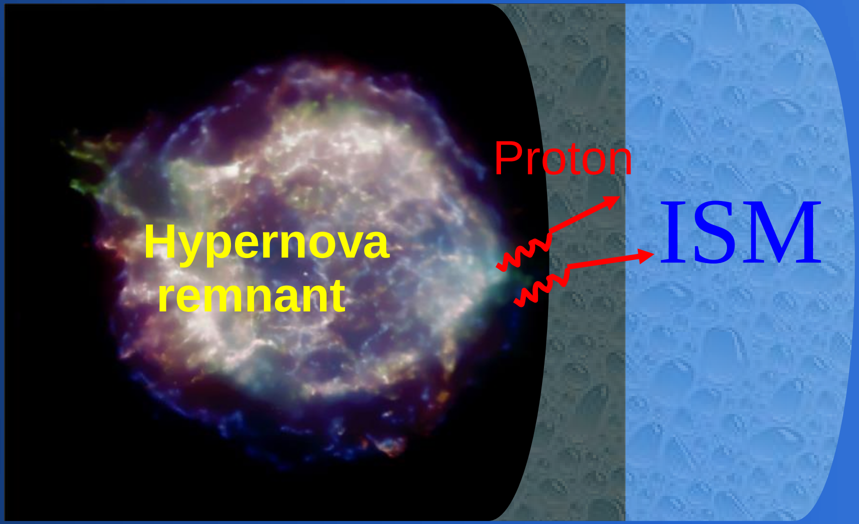
(Liu, Wang, Inoue, Crocker & Aharonian 2014)

- Hypernova prototype: SN 1998bw: faster ejecta and greater kinetic energy
- Hypernovae can accelerate CR protons to 10^18 eV (Wang et al. 2007)

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

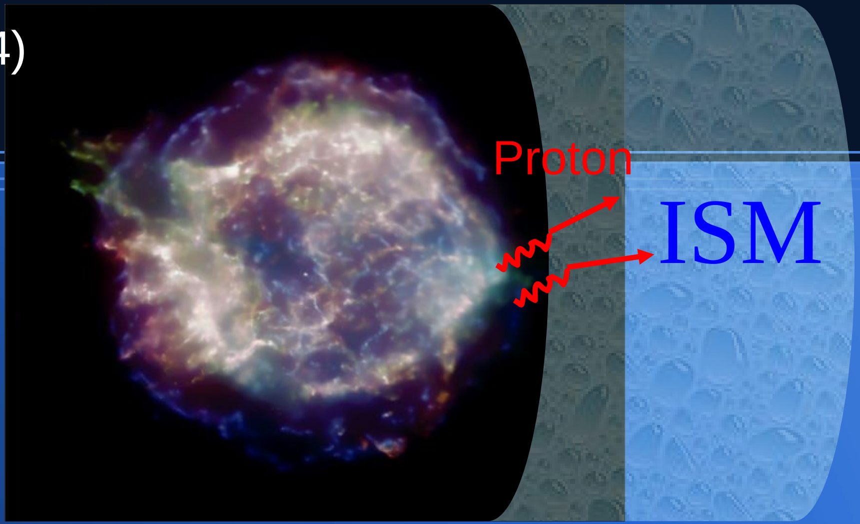
- CR protons collide with the surrounding gas and produce neutrinos





Neutrino production efficiency

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



- pp efficiency

$$f_\pi = \min\left(1, t_{\rm esc}/\tau_{pp}\right)$$

$$\tau_{pp}(\varepsilon_p) = [\kappa\sigma_{pp}(\varepsilon_p)nc]^{-1}$$

- Two escape ways: 1) diffusion 2) advection

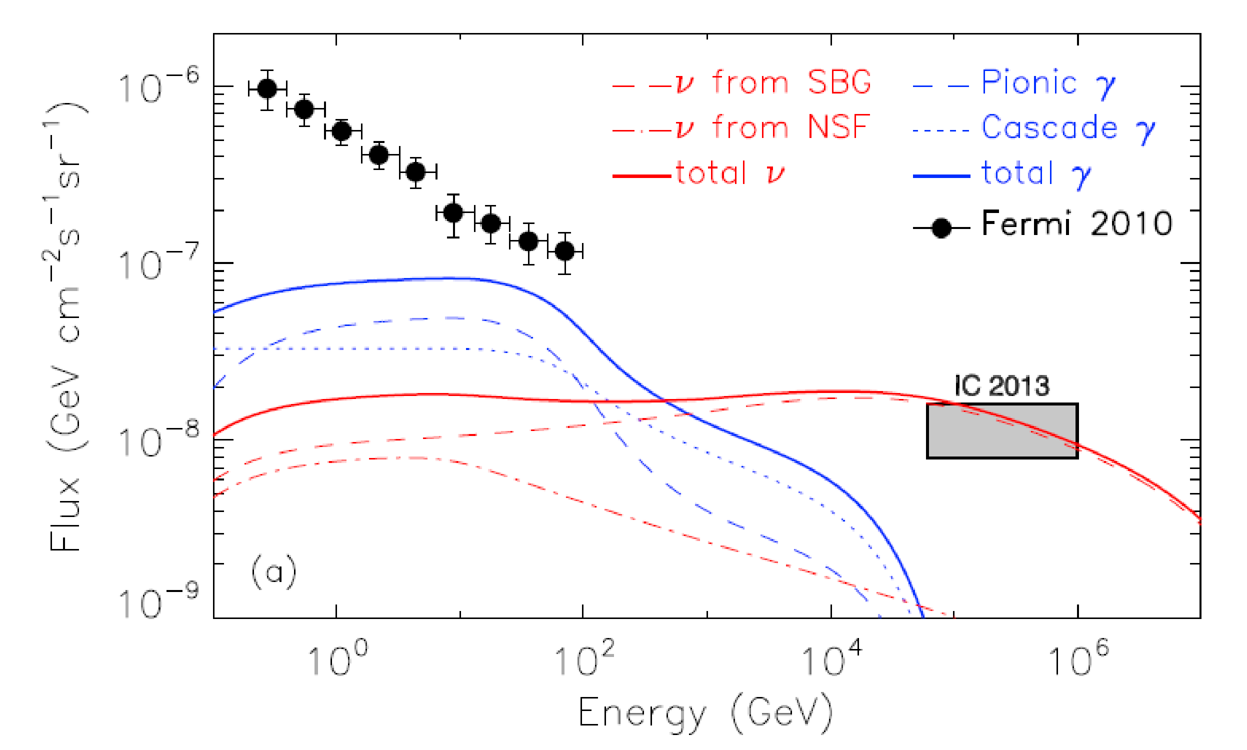
$$t_{\rm diff} = h^2/4D \qquad t_{\rm adv} = h/V_w$$

- pp efficiency in star-forming galaxies & starburst galaxies

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

Neutrino spectrum

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



SBG: star-burst galaxies

NSF: normal star-forming galaxies

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

$$\varepsilon_{p,\rm b}^{\rm B} = 1.6\,{\rm PeV}\left(\frac{h}{1\,{\rm kpc}}\right)^{3.3}\left(\frac{V_w}{1500\,{\rm km\,s^{-1}}}\right)^{3.3}\left(\frac{D_0}{10^{27}\,{\rm cm^2\,s^{-1}}}\right)^{-3.3}$$

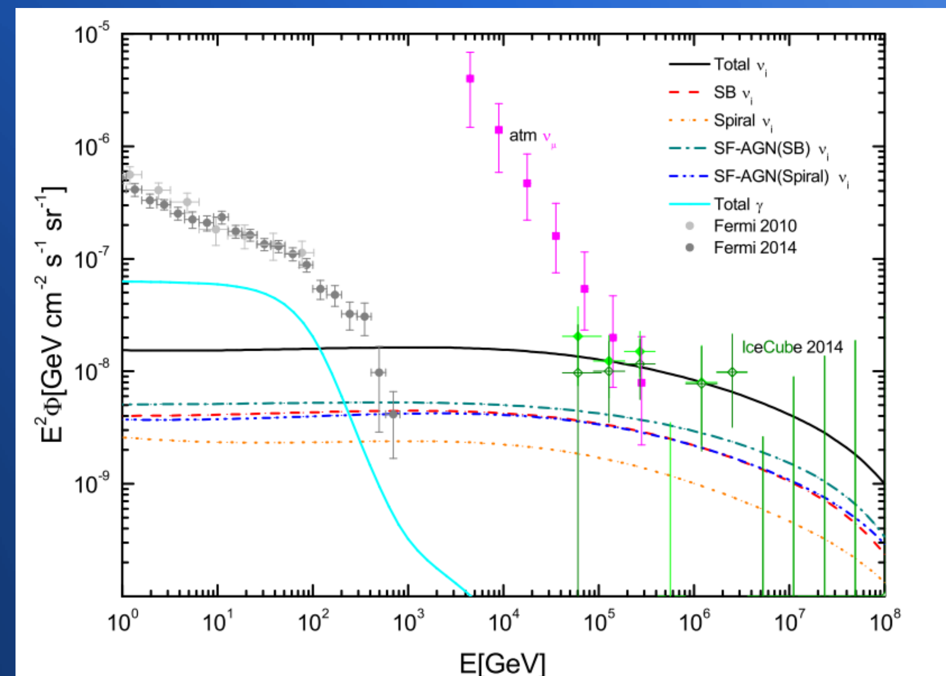
Detailed calculation

Chang, Liu & Wang 2015

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

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

- Normal star-forming galaxies also contribute significantly to the diffuse gamma-ray background



Summary (II)

- GeV emission from Arp 220 has been detected– calorimeter !
- Star-forming/starburst galaxies are one of the best candidates for >100 TeV neutrinos observed by IceCube