北京大学
Peking University

Diagnose the sources of IceCube neutrinos with *Fermi*

Zhuo Li (黎卓)
Peking University

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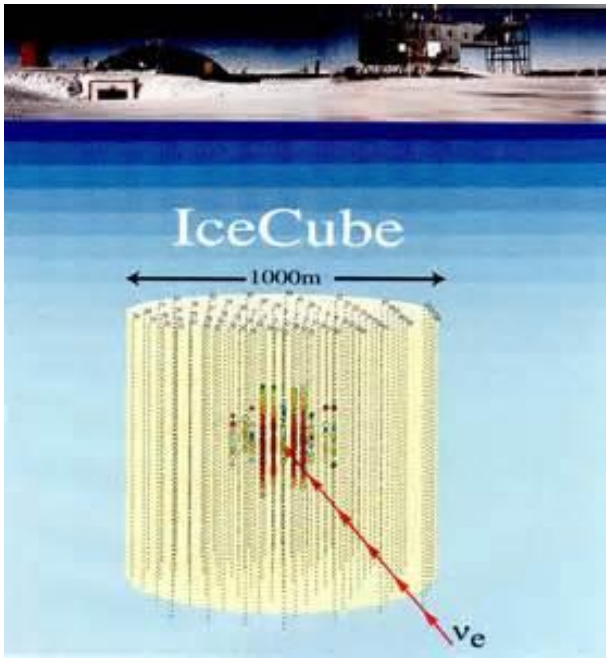
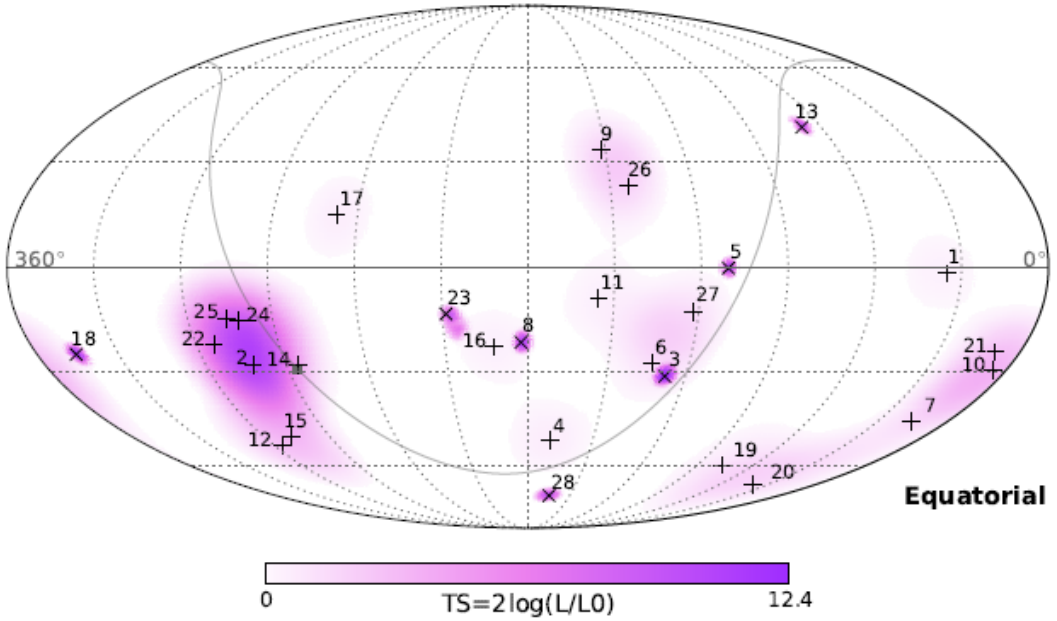
Diffuse neutrinos at IceCube

28 evnt, 30TeV-2PeV; background evnt 10.6, 4sigma signal





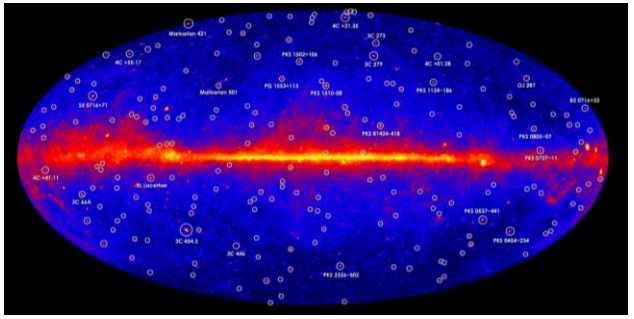
$$E_\nu^2 \Phi_\nu^{\text{total}}(E_\nu) = 3.6 \times 10^{-8}\ \text{GeV}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

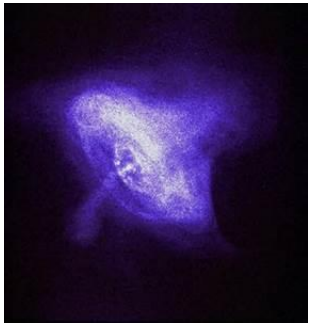
[IC 2013]

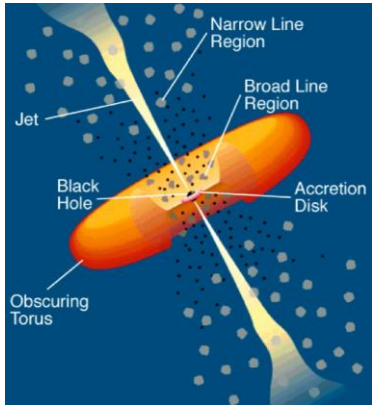
Consistent with isotropic, flat spectrum, and flavor ratio 1:1:1

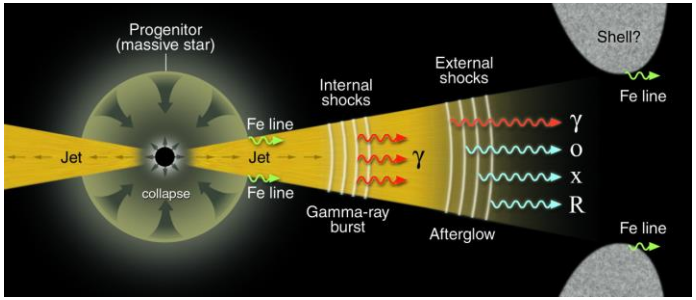
Where are they from?

- Galactic origin
  - Diffuse emission (from CR propagation)?
  - Galactic point sources?
- Extragalactic origin
  - (Diffuse emission from CR propagation?)
  - Gamma ray bursts?
  - Active galactic nuclei jets/cores?
  - Star forming/starburst galaxies?



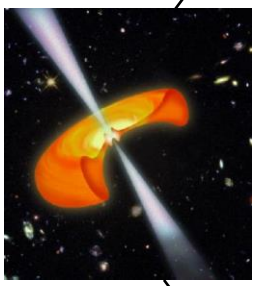






- Observation: low statistics & poor location
- Question: which population of sources can produce the all-sky integrated flux?
- Method: other messenger – gamma-rays

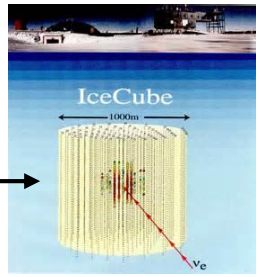
Photon – neutrino connection



$p + \gamma(p) \rightarrow$

$N + \pi^{\pm}$

$\pi^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_e + \nu_\mu + \bar{\nu}_\mu$

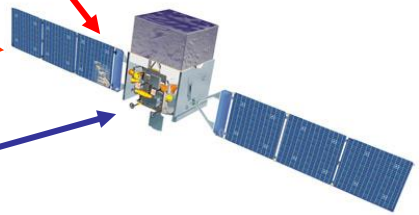


$e^{\pm} \rightarrow$ syn/IC radiation

$N + \pi^0$

$\pi^0 \rightarrow \gamma + \gamma$

I



$e^{-}(p) \rightarrow$ synch/IC radiation

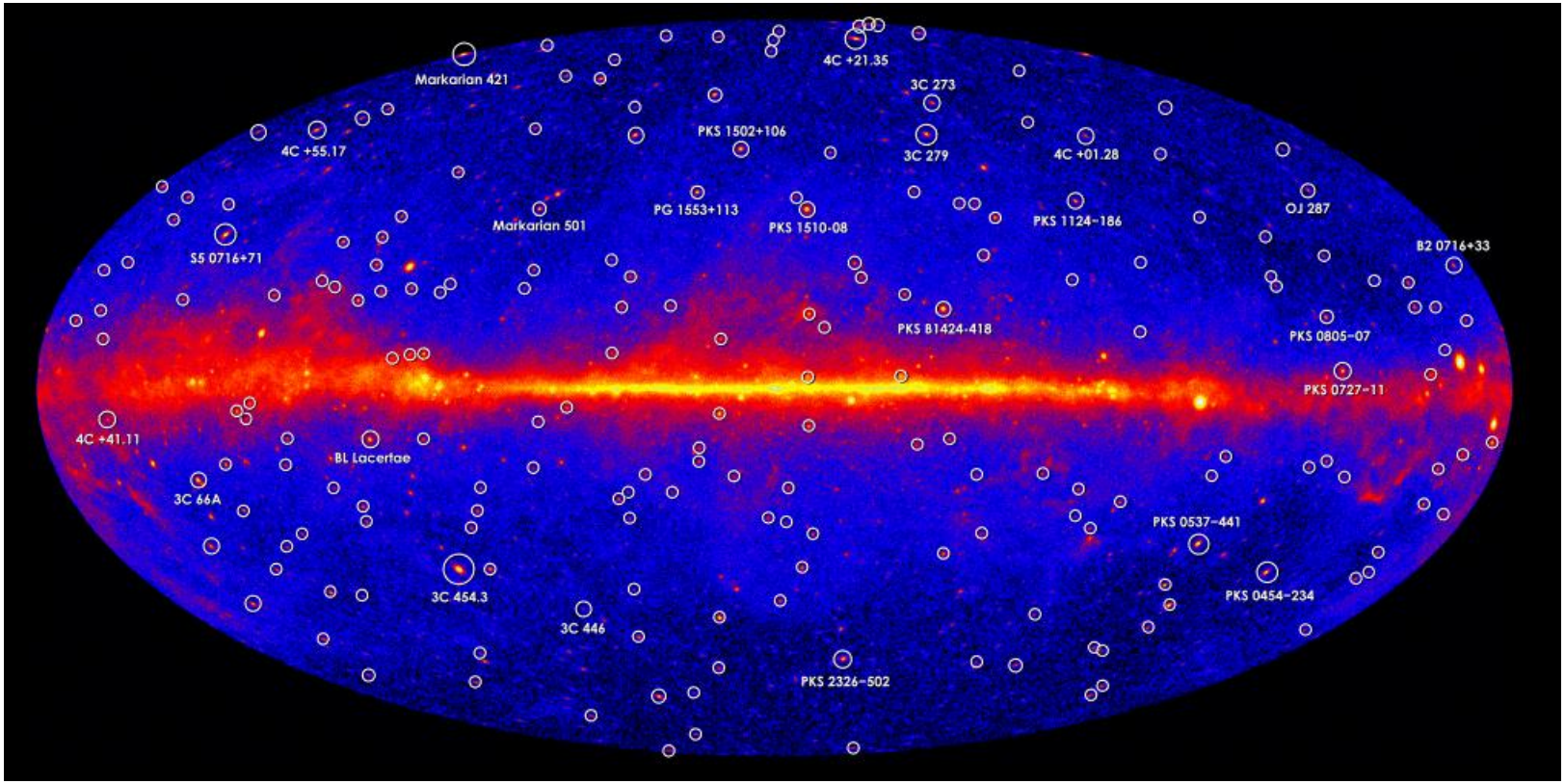
II

Connections:

I. neutrino – secondary electron/gamma-ray

II. neutrino – primary electron/proton

Fermi-LAT probes neutrino origin



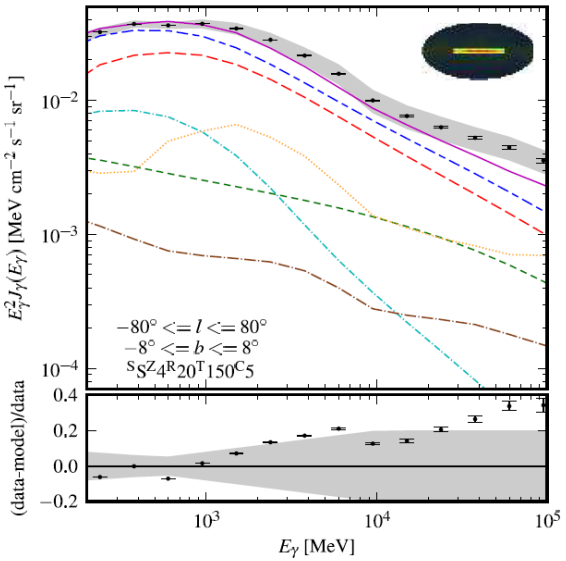
Whether various candidate sources can produce the all-sky neutrino flux?

$$E_\nu^2 J_{\nu,\mathrm{IC}} \approx 1.2 \times 10^{-7} \mathrm{GeV cm^{-2} s^{-1}}$$

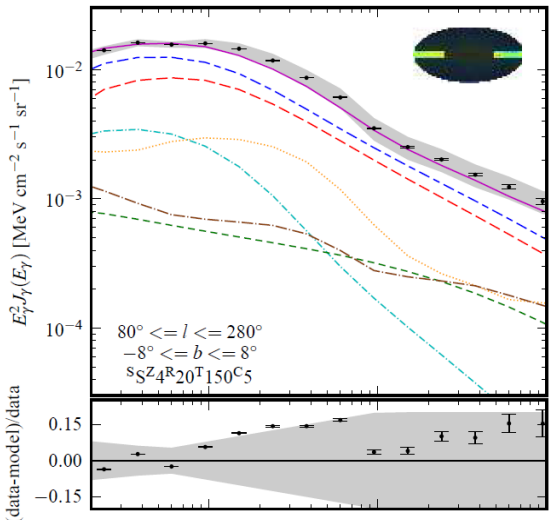
(single flavor)

Diffuse Galactic emission

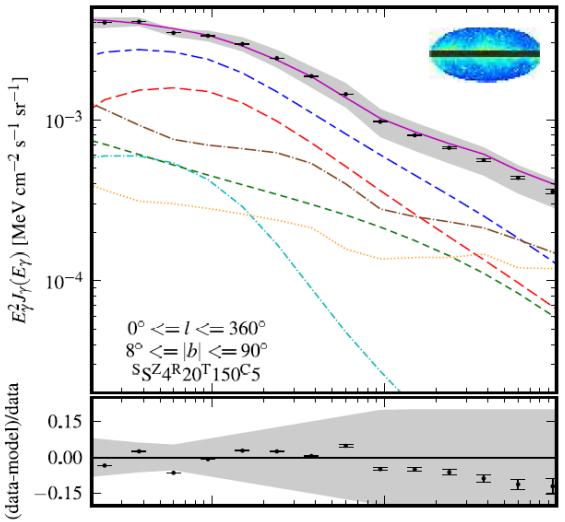
Inner galaxy



Outer galaxy



Local galaxy



100GeV

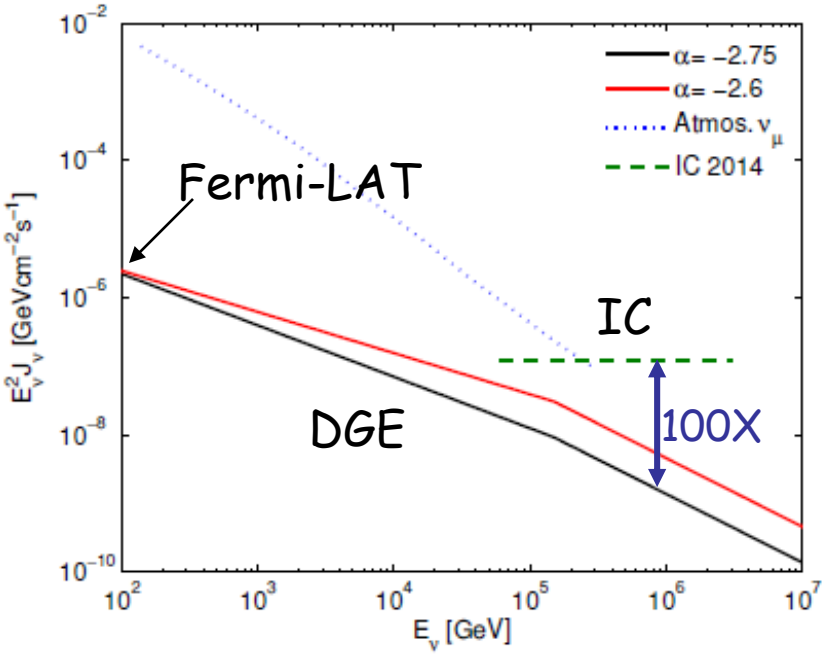
[Fermi-LAT, Ackermann+ 12]

Diffuse Galactic emission

- Connection I
- $\pi^+ : \pi^- : \pi^0 = 1:1:1$

  $E_\nu = \frac{1}{2} E_\gamma$

  $E_\nu{}^2 J_\nu(E_\nu) = \frac{1}{2} E_\gamma{}^2 J_\gamma(E_\gamma)$
- Extrapolation 100GeV to PeV
  - Neutrinos follow CR spectrum
- DGE accounts for <1% IC flux



Diffuse Galactic emission unlikely

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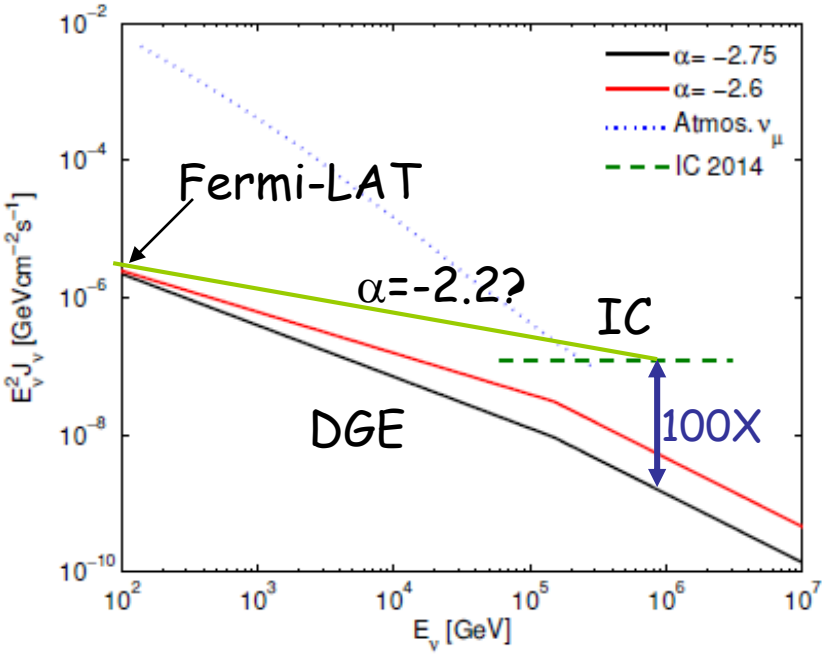


- Hard CR spectrum?
  - -2.2 index at >100 GeV
  - 10PeV CR loses most energy

Diffuse Galactic emission unlikely

Note on extended Galactic halo

- IC events require a total Galactic halo neutrino luminosity

  $L \sim R_{halo}^2 E^2 J \sim 10^6 L_{sun}$; $R_{halo} \sim 100$kpc
- Local galaxy number density

  $n_{gal} \sim 10^{-2} Mpc^{-3}$
- All-sky neutrino flux from all galaxies is

  $I = \xi_z (c/4\pi) L n_{gal} t_{Hubble} = 3.10^{-7} GeV cm^{-2} s^{-1} sr^{-1}$

  ($\xi_z \sim 3$ accounts for z-evolution)
- Overproduce: 10 time IC flux

halo contribution unlikely

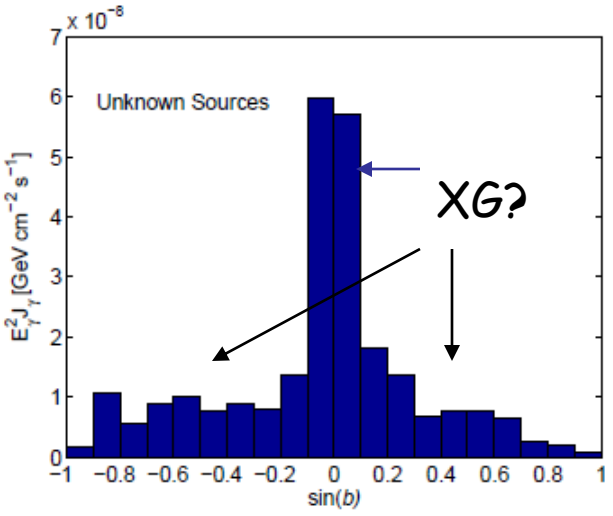
Galactic point sources

- Connection I; extrapolated as E^{-2}
- Known Galactic sources lower than IC flux by orders of magnitude
- Unknown sources match, but
  - USs, at both low and high Galactic latitudes, are more likely extragalactic
  - High-latitude USs contribute not enough flux for high-latitude IC nuetrinos

Source type	$E_\gamma^2 J_\gamma(100\mathrm{GeV})/\mathrm{GeV cm^{-2} s^{-1}}$
Galactic total	1.29×10^{-7}
spp	5.77×10^{-8}
pwn	4.04×10^{-8}
psr	1.39×10^{-8}
snr	1.21×10^{-8}
glc	4.01×10^{-9}
hmb	5.06×10^{-10}
nov	1.60×10^{-13}
US	2.58×10^{-7}

LAT point source catalog

Latitude distribution

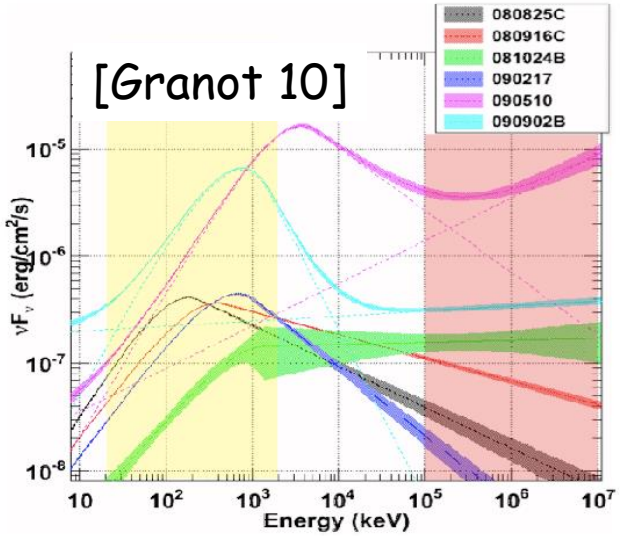


GRBs

- Fermi-LAT observes the GBM-triggered GRBs, and gives upper limits to gamma-ray flux (0.1-100GeV)
- Translated to neutrino flux upper limit by connection I

➔average neutrino flux per GBM GRB

$$f_\nu < 2\times10^{-3}\,\mathrm{GeV\,cm^{-2}}$$ [ZL 2013]



- All-sky GRB MeV gamma-ray flux is measured/calculated
  - GRB redshift distribution $R_{GRB}(z)$ and MeV luminosity function $\Phi(L)$ are well measured
- Assume connection II: neutrino and MeV gamma-ray flux connected
- If GRBs can account for IC flux, then

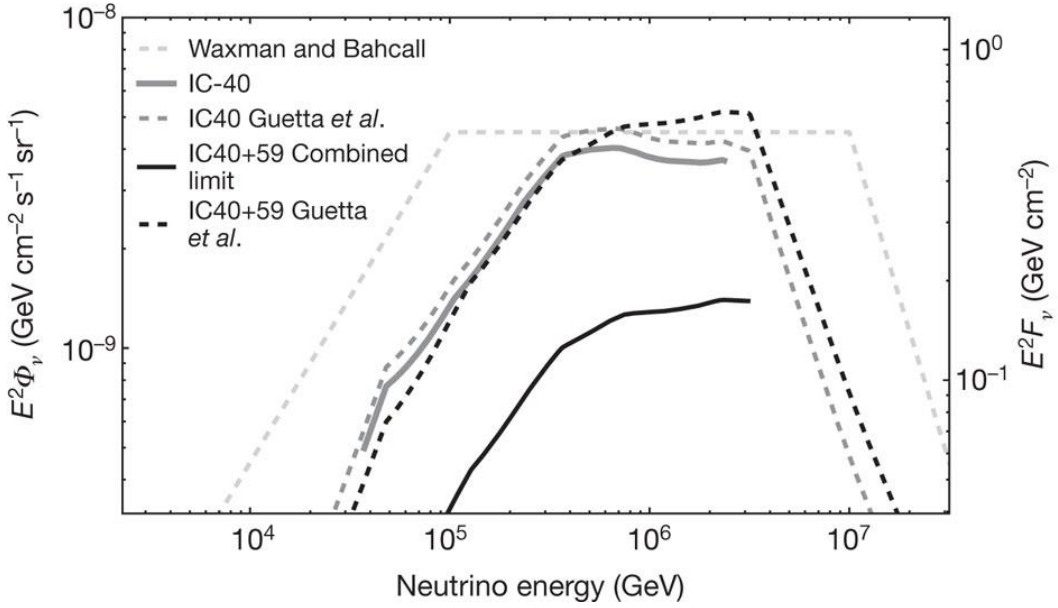
➔average neutrino flux per GBM GRB

$$f_\nu = 1.3\times10^{-2}\,\frac{\Phi_{\mathrm{trig}}}{0.7\Phi_{\mathrm{tot}}}\,\frac{400\,\mathrm{yr^{-1}}}{\dot{N}_{\mathrm{trig}}}\,\mathrm{GeV\,cm^{-2}}$$

GRB origin unlikely

Note on IC upper limit to GRBs

- IC stacking ~200 (~500 now) GRBs from various telescopes of different flux thresholds
  - Fermi/GBM, Swift …
- Derive “diffuse” GRB flux, assuming a detection rate of 666/yr
  - But not straight forward -- for what thresholds, what telescopes?

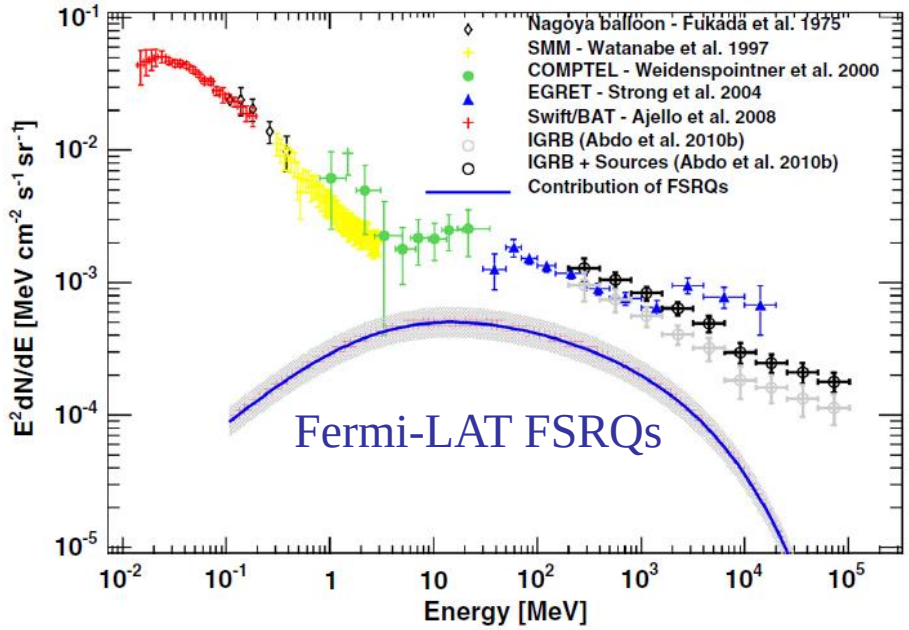


[IC 2012]

AGN jets

- neutrino/gamma flux ratio for diffuse emission from FSRQs
  - ν(20TeV-2PeV)/γ(0.1-100GeV)=3.8%
- Gamma-rays (>0.1GeV) less likely pion production induced EM cascade emission
  - where ν/γ flux ratio = O(1) is expected
- Gamma-rays more likely leptonic or p-synch origin

[Wang & ZL 15]



[Fermi-LAT, Ajello+ 2012]

IceCube flux

AGN jets: connection II

expected to be = if AGN jet origin

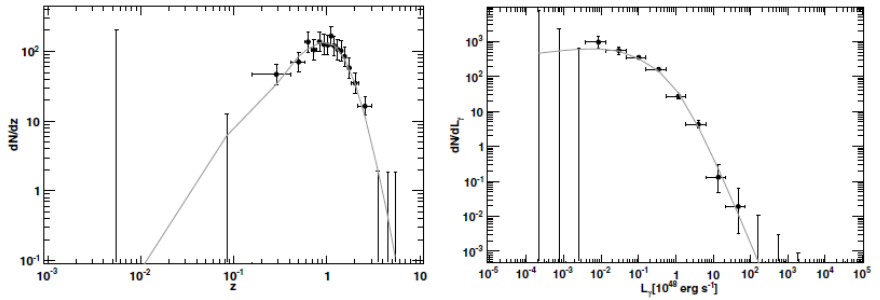
IC upper limits to individuals

IC detection

$$\frac{\nu \text{ flux (point)}}{\gamma \text{ flux (point)}} \text{ vs } \frac{\nu \text{ flux (all-sky)}}{\gamma \text{ flux (all-sky)}}$$

Fermi-LAT detections of individuals

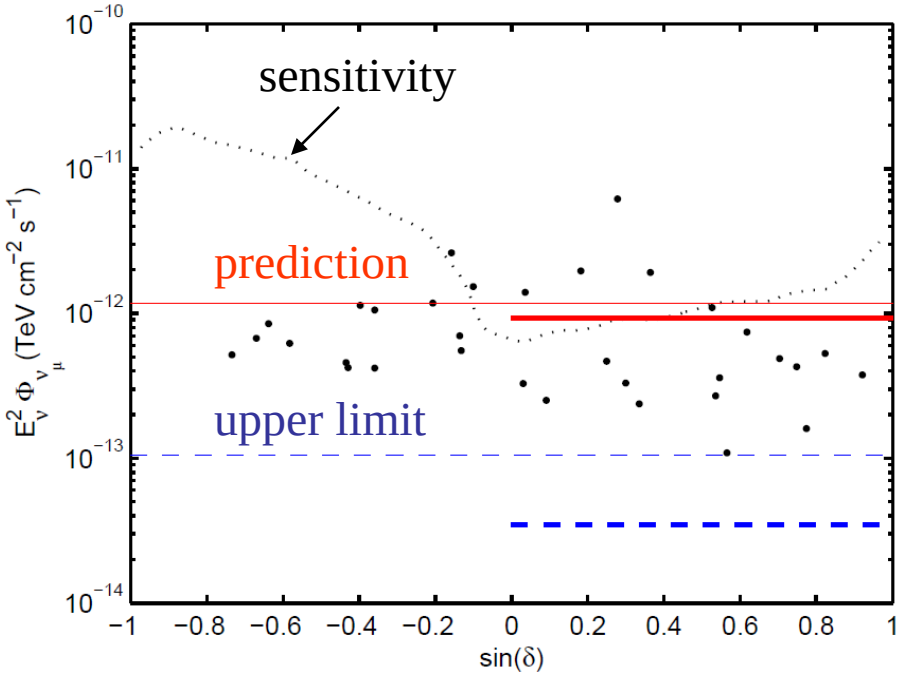
Derived from Fermi-LAT measured LF and their z-distribution:



Stacking search

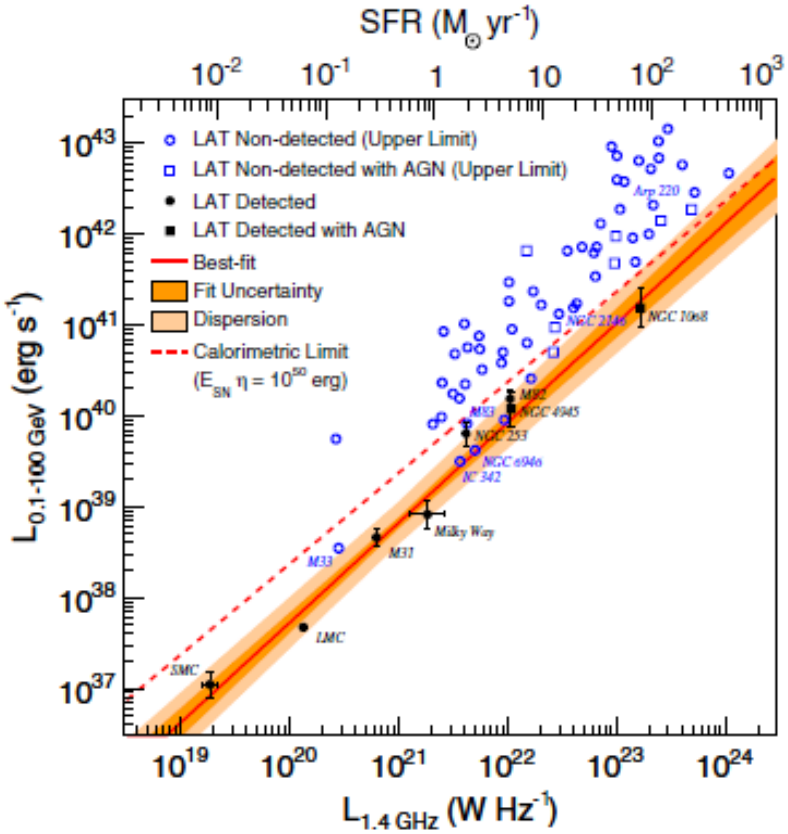
- 33 bright FSRQs, selected based on gamma flux
- FSRQs can only account for <10% (<3%) IC neutrinos

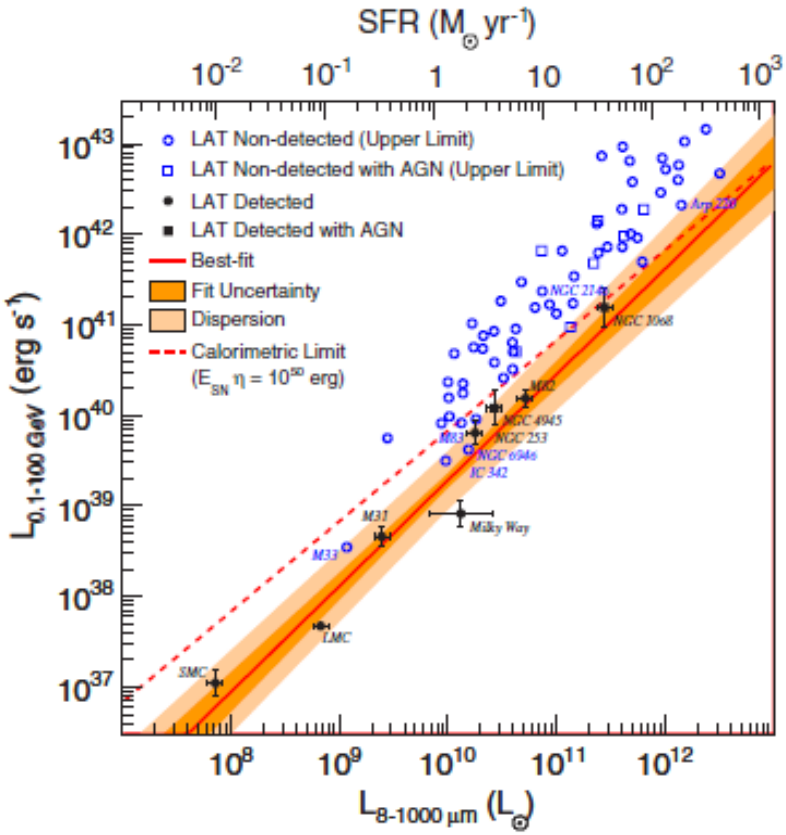
$$\frac{\nu \text{ flux (stack)}}{\gamma \text{ flux (stack)}} < \frac{\nu \text{ flux (all-sky)}}{\gamma \text{ flux (all-sky)}} \times 10\%\,(3\%)$$



[Wang & ZL, 2015]

Starburst galaxies





$$\nu L_\nu(\mathrm{GeV})/\mathrm{SFR} \approx 10^{46}\mathrm{erg}/M_\odot$$

[Fermi-LAT, Ackermann+12]

SFR(z) → production $Q_\gamma(z)$ → gamma flux $\Phi(\gamma)$ → neutrino flux $\Phi(\nu)$

Starburst galaxies

- Local-universe (z=0) gamma-ray production rate density

$$E_\gamma^2 Q_\gamma(\mathrm{GeV}) = \rho_{\mathrm{SFR}}(\nu L_\nu(\mathrm{GeV})/\mathrm{SFR})$$

- Gamma-ray flux from SBGs from whole universe

$$E_\gamma^2 \Phi_\gamma(\mathrm{GeV}) = \xi_z t_{\mathrm{H}} (c/4\pi) E_\gamma^2 Q_\gamma(\mathrm{GeV})$$

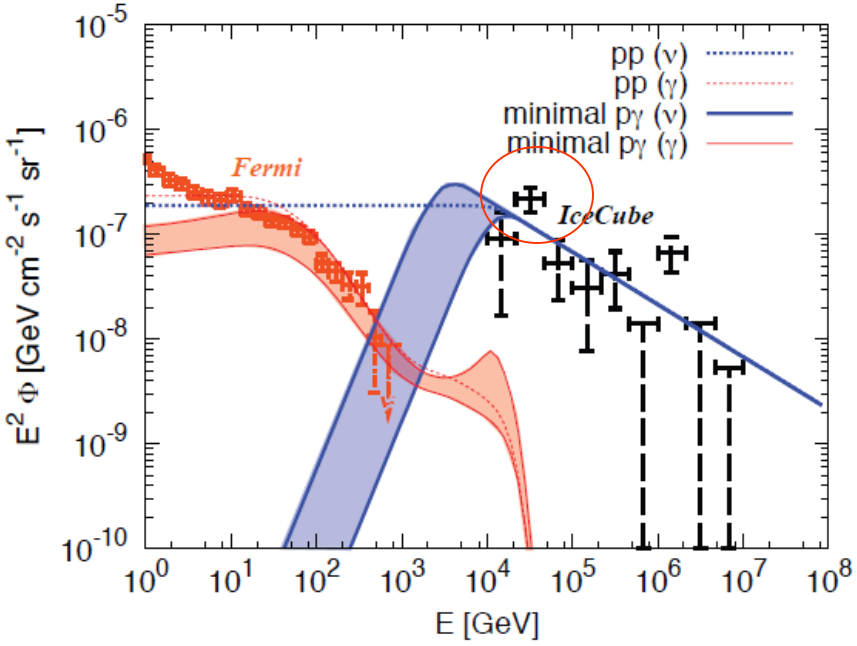
- Assume connection I for SBGs
  - if CRs injected with ~$E_p^{-2.2}$
  - if <100PeV CRs lose energy significantly as expected in SBGs
  - Neutrino flux extrapolated from GeV to PeV:

$$E_\nu^2 \Phi_\nu \approx 10^{-8} \frac{\xi_z}{3} \left(\frac{E_\nu}{1\mathrm{PeV}} \right)^{-0.2} \mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$$

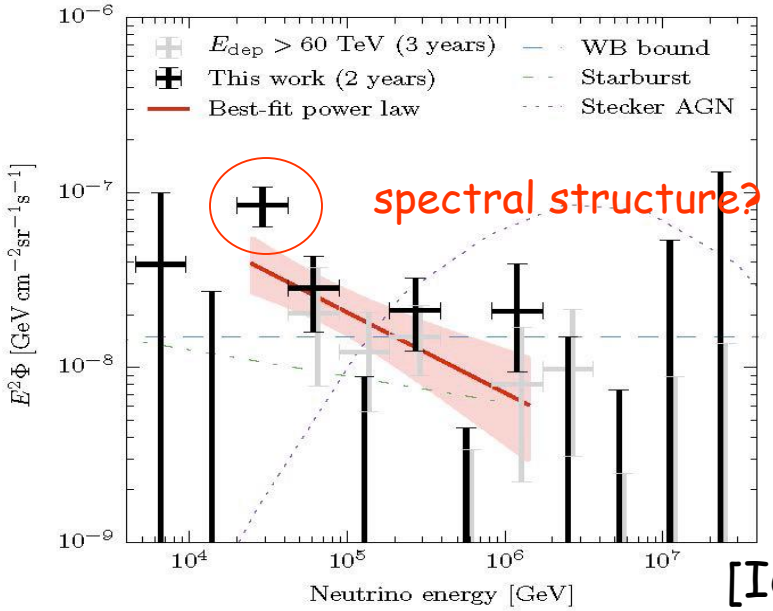
Consistent with IC measurement in both flux and spectrum at >60TeV

Fermi gamma background limit?

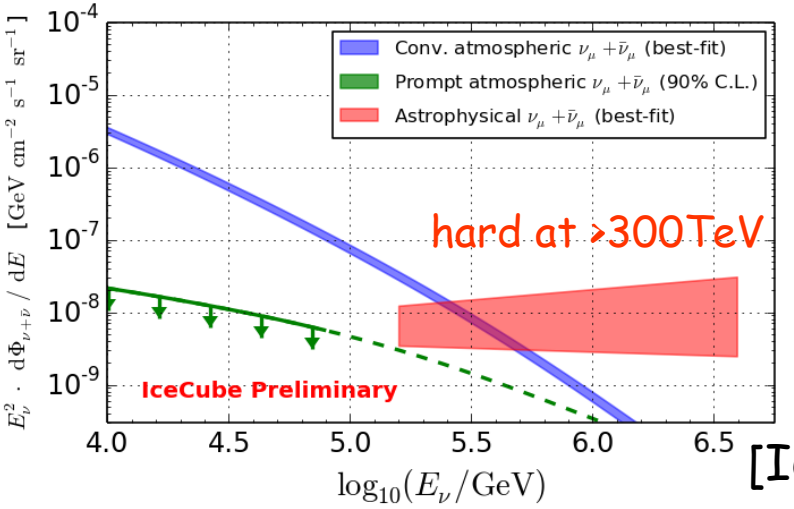
excess at 30TeV



[Murase+15]



[IC 15a]



[IC 15b]

Fermi informs IceCube

Assuming photon-neutrino connection:

- ☹diffuse Galactic emission, <10%
- ☹Galactic point sources
- ☹GRBs, <10%
- ☹AGN jets, <10%
- ☺Starburst galaxies

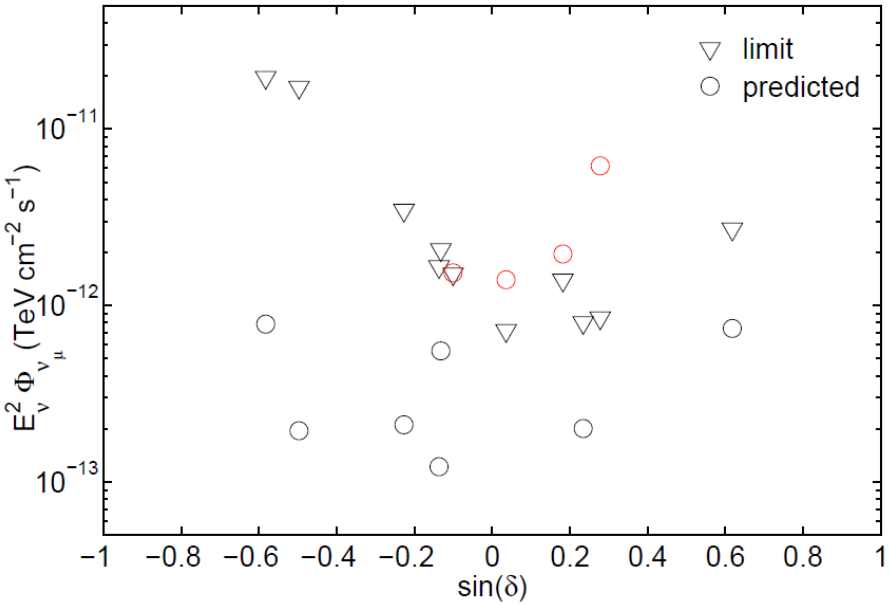
Wang, B., Zhao, X.H. & ZL, JCAP, 2015
Wang, B & ZL, Science China, 2015

Candidate FSRQs

- apply the all-sky ratio to individuals

→

- several sources in northern sky exceed IC upper limits



[Wang & ZL, 2015]