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Diagnose the sources of IceCube neutrinos with *Fermi*

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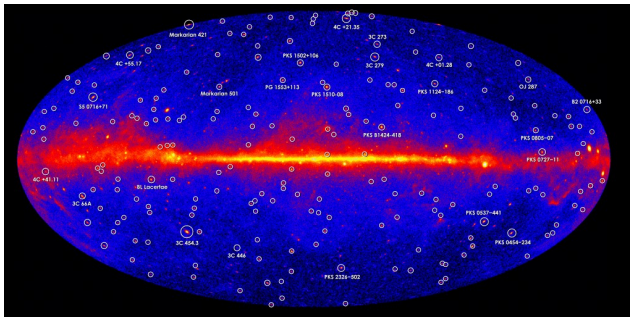
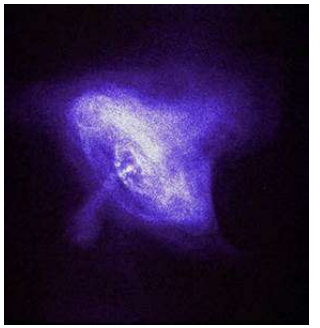
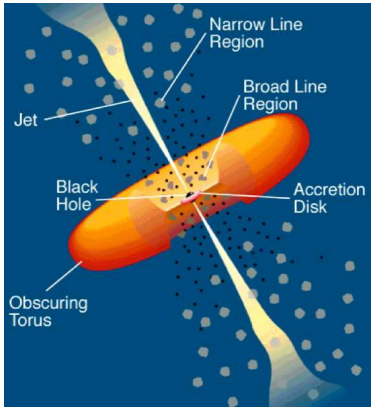
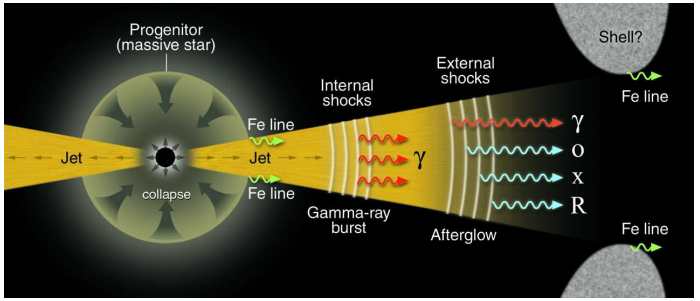
IceCube neutrino origin?

- Galactic origin
  - Diffuse emission (CR propagation)?
  - Galactic point sources?
- Extragalactic origin
  - Gamma ray bursts?
  - Blazars?
  - Star forming/starburst galaxies?

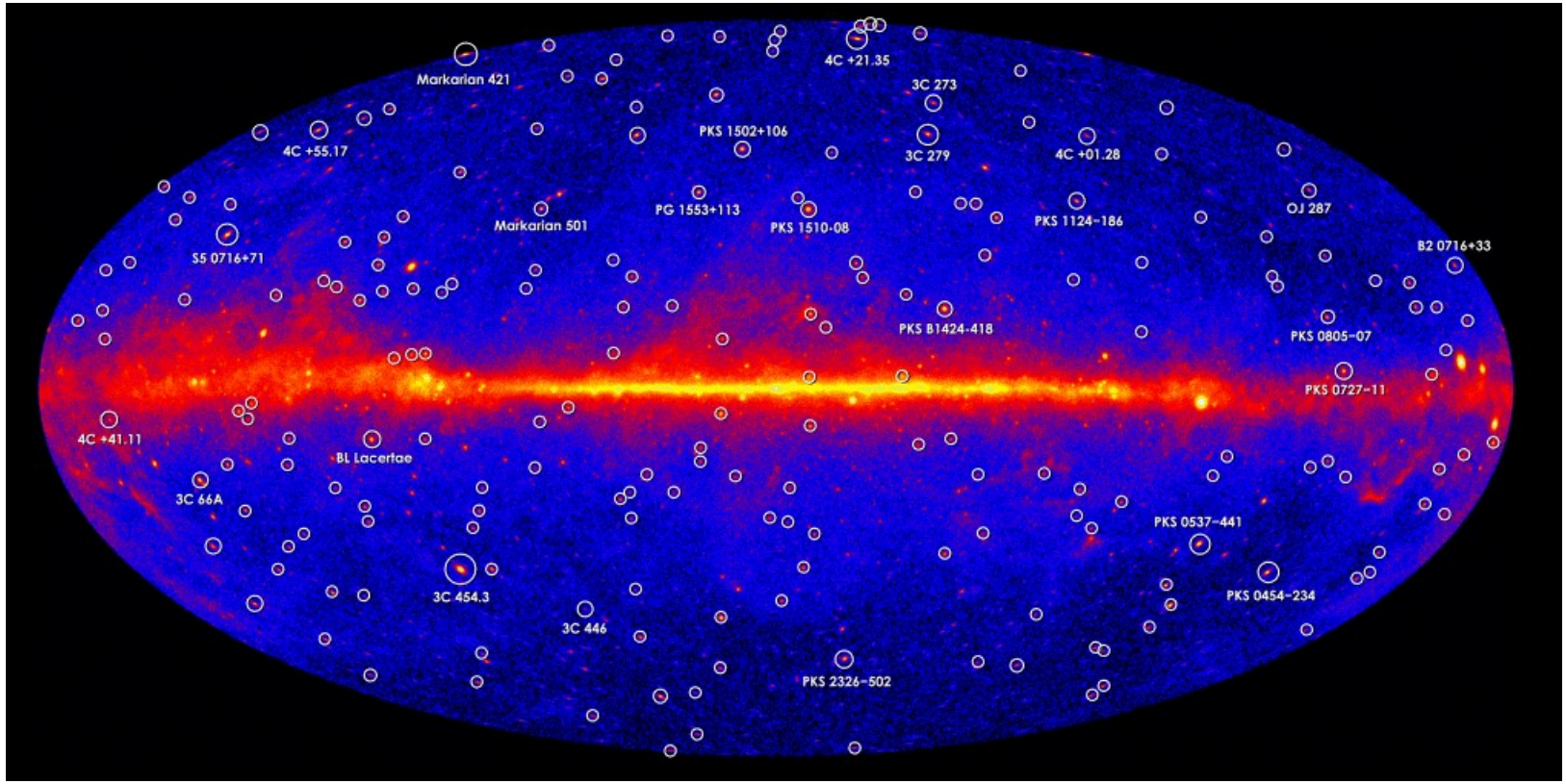








Fermi-LAT sky survey

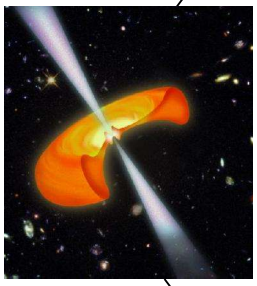


Whether various candidate sources can produce the all-sky IceCube flux?

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

(single flavor)

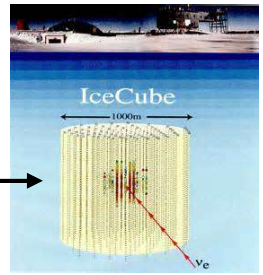
Photon – neutrino connection



$p + \gamma(p) \rightarrow$

$N + \pi^{\pm}$

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



$e^{\pm} \rightarrow$ 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

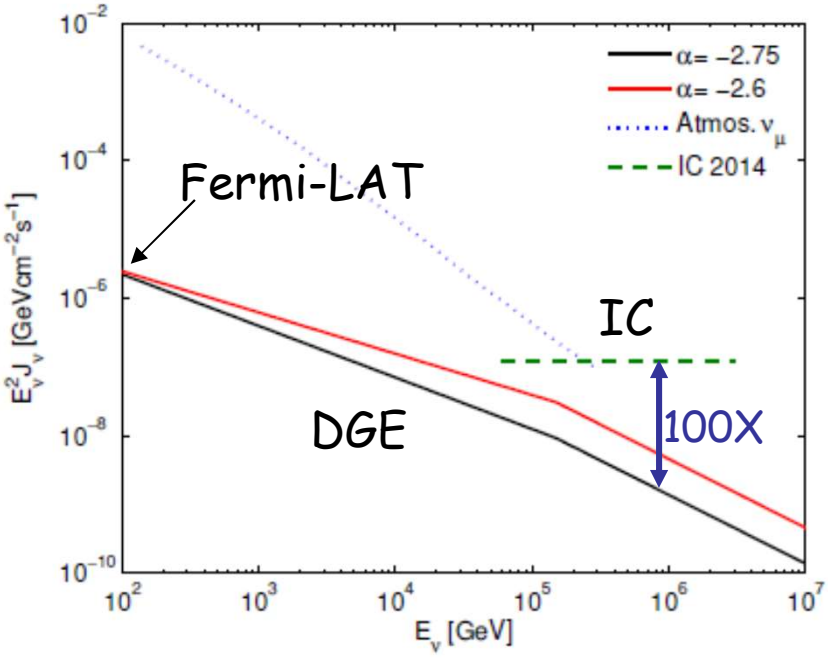
II. neutrino – primary electron/proton

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



[Wang, Zhao, ZL 14]

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: 10X IC flux

[Wang, Zhao, ZL 14]

Blazars

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

IC upper limits to individuals

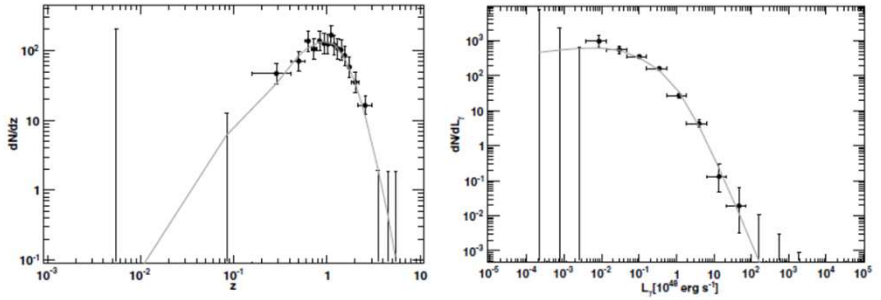
IC detection

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

[Wang & ZL, 2016]

Fermi-LAT detections of individuals

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



[Fermi-LAT, Ajello+ 2012]

Blazar: specific model

- Total flux: $J_\nu \sim \iint L_\nu(L_\gamma)\rho(L_\gamma, z)\mathrm{d}L_\gamma \mathrm{d}z$
- Per source

$$E_\nu L_{E_\nu} \approx \frac{1}{8} f_{p\gamma} E_p L_{E_p} \approx \frac{1}{8} f_{p\gamma} \hat{\xi}_{\rm cr} L_{\rm rad}$$

- Stacking search constrains CR loading

$$E_\nu^2 \Phi_{\nu,i} = \frac{1}{8} f_{p\gamma}(L_{\gamma,i}) \frac{L_{\rm rad}(L_{\gamma,i})}{L_{\gamma,i}} \hat{\xi}_{\rm cr} S_{\gamma,i}$$

$$\sum_i E_\nu^2 \Phi_{\nu,i} < E_\nu^2 \Phi_{\nu_\mu+\bar{\nu}_\mu}^{90\%} \Rightarrow \hat{\xi}_{\rm cr} < 0.062 f_{\rm cov,-1}^{-1} \zeta^{-1}$$

- Blazars account for <10% IC neutrinos

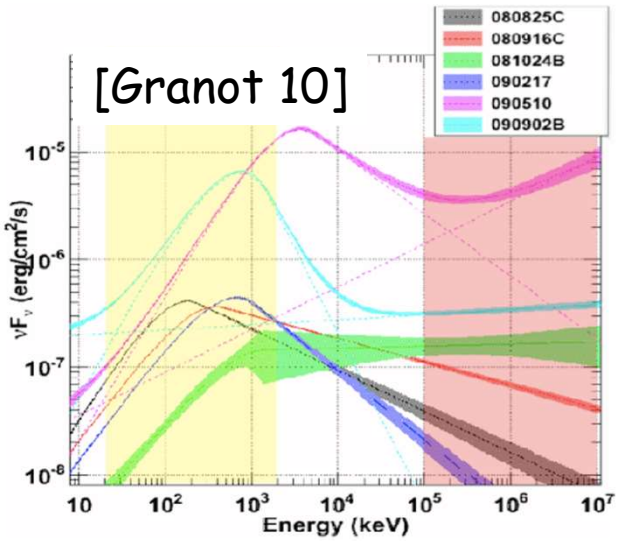
[Zhang, ZL 2017]

Gamma-ray bursts

- Fermi-LAT constrains 0.1-100GeV flux of GBM-triggered GRBs
- Translated to neutrino flux upper limit

➔average neutrino flux per GBM GRB

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



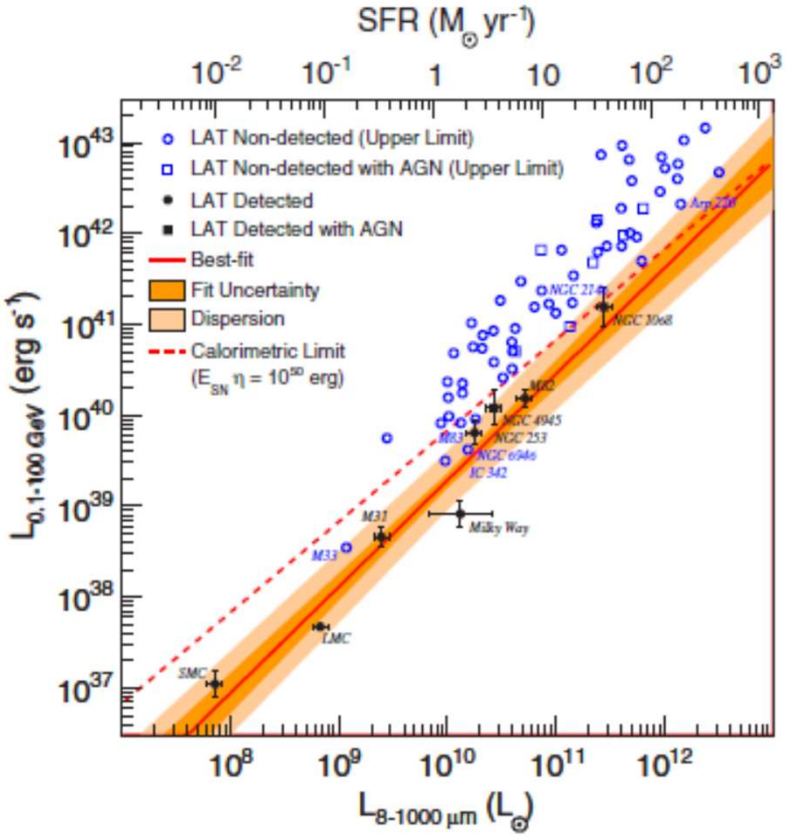
- All-sky GRB MeV gamma-ray flux is measured/calculated
  - GRB redshift distribution $R_{GRB}(z)$ and MeV luminosity function $\Phi(L)$ are well measured
- Assume neutrino/gamma~const.
- IC flux requires

➔average neutrino flux per GBM GRB

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

[Wang, Zhao, ZL 14]

Starburst galaxies

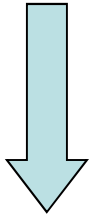


$$\nu L_\nu(\mathrm{GeV})/\mathrm{SFR} \approx 10^{46}\mathrm{erg}/M_\odot$$

[Fermi-LAT, Ackermann+12]

GeV neutrino ~ GeV gamma

$$\sim \int \frac{\nu L_\nu}{SFR}\rho_{SFR}(z)\mathrm{d}z$$



extrapolated to PeV ~$E_p^{-2.2}$

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

Consistent with observed flux and spectrum at >60TeV

[Wang, Zhao, ZL 14]

Fermi implication to IceCube

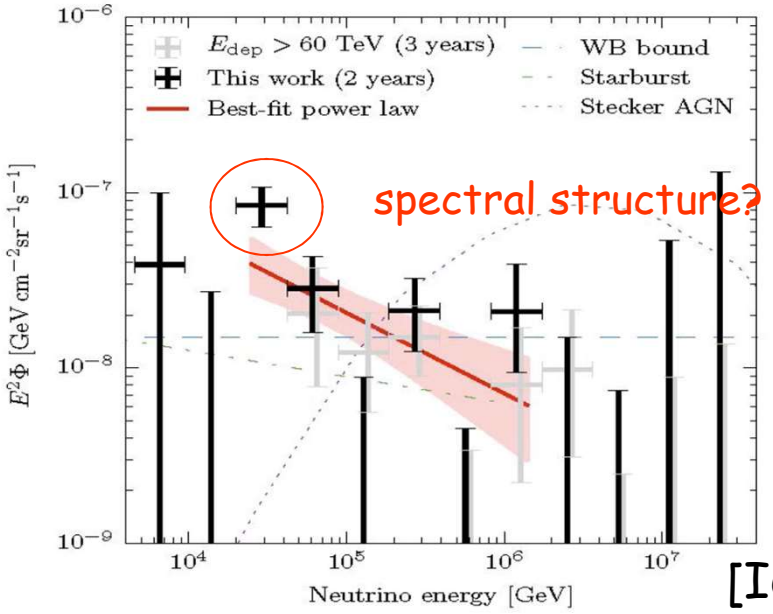
- ☹diffuse Galactic emission, <1%
- ☹Galactic point sources
- ☹GRBs, <10%
- ☹AGN jets, <10%
- ☺starburst galaxies

[Wang, Zhao, ZL 2014 JCAP;
Wang, ZL 2016 SCPMA;
Zhang, ZL 2017 JCAP]

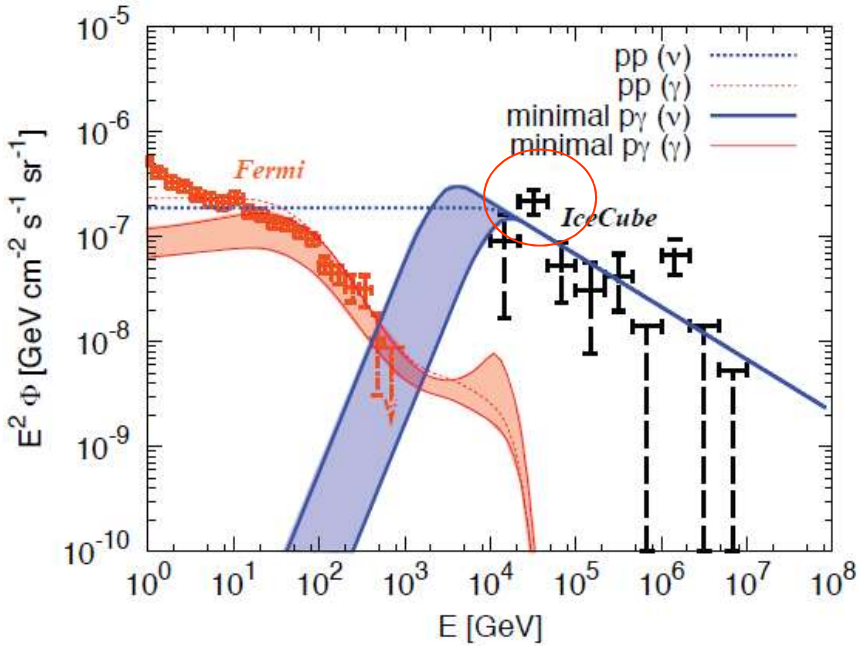
- AGN core? TDE? Galaxy cluster?...

Tension of low energy neutrinos with gamma background?

excess at 30TeV?



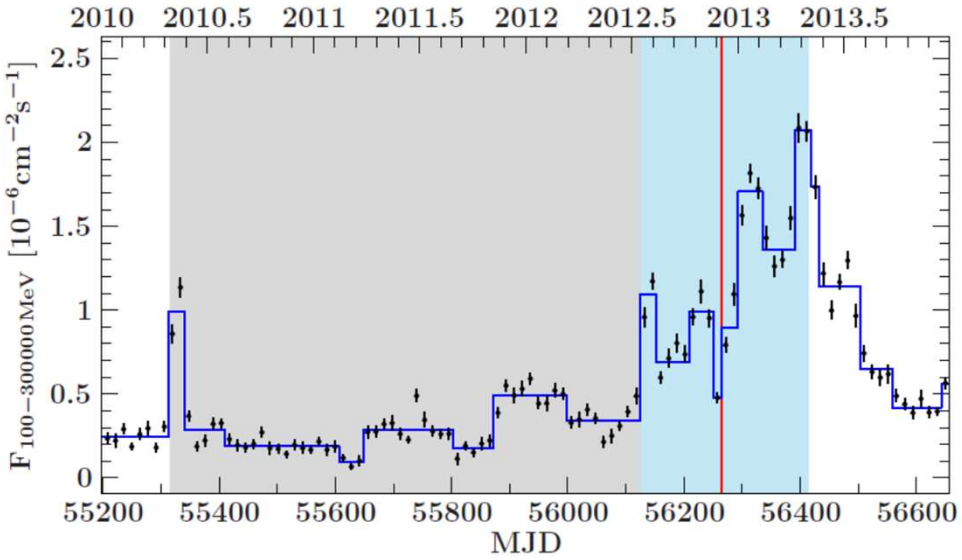
[IC 15a]



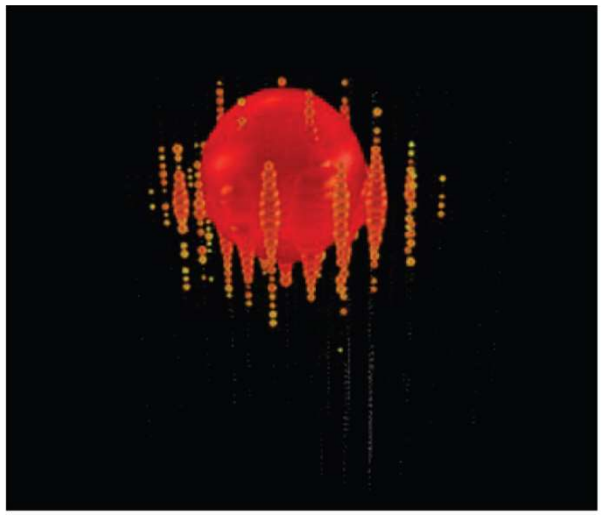
[Murase+15]

Blazar outburst origin?

PKS B1424-418



big bird



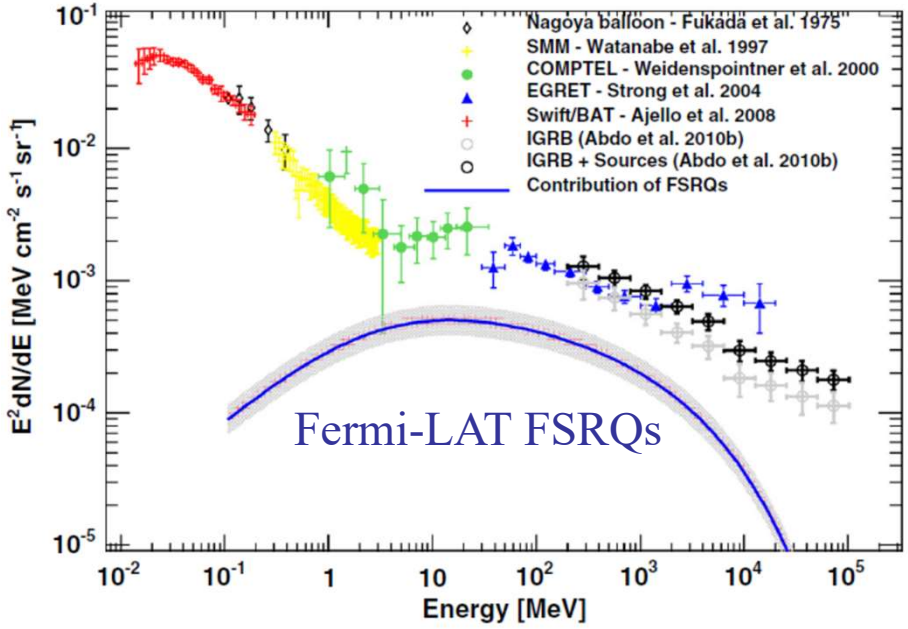
Blazar outburst: ~1yr, 15-30X flux enhance (high fluence); ~1/yr/sky
Neutrinos: 2PeV, ~1/yr; 15° error circle
Coincidence: ~5%

Require: gamma flux~=neutrino flux?! [Kadler etal 2016]

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 16]



[Fermi-LAT, Ajello+ 2012]

IceCube flux