Neutrinos from Extragalactic Jets under Scrutiny

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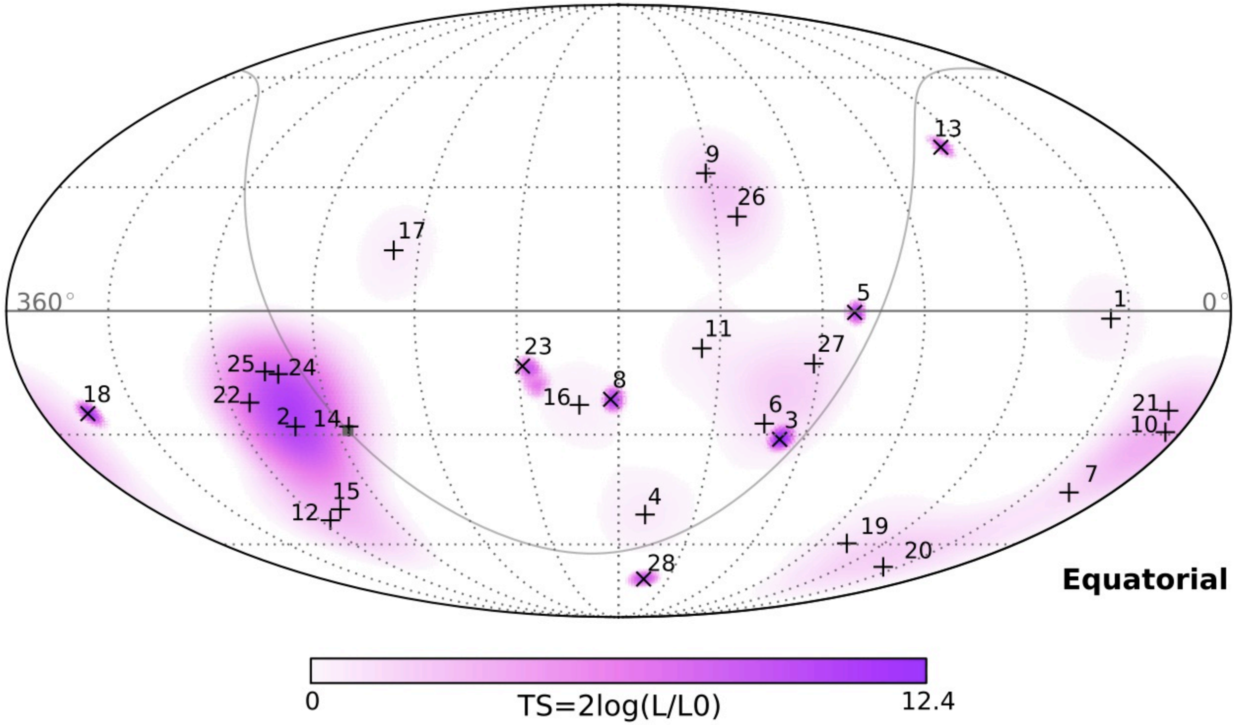
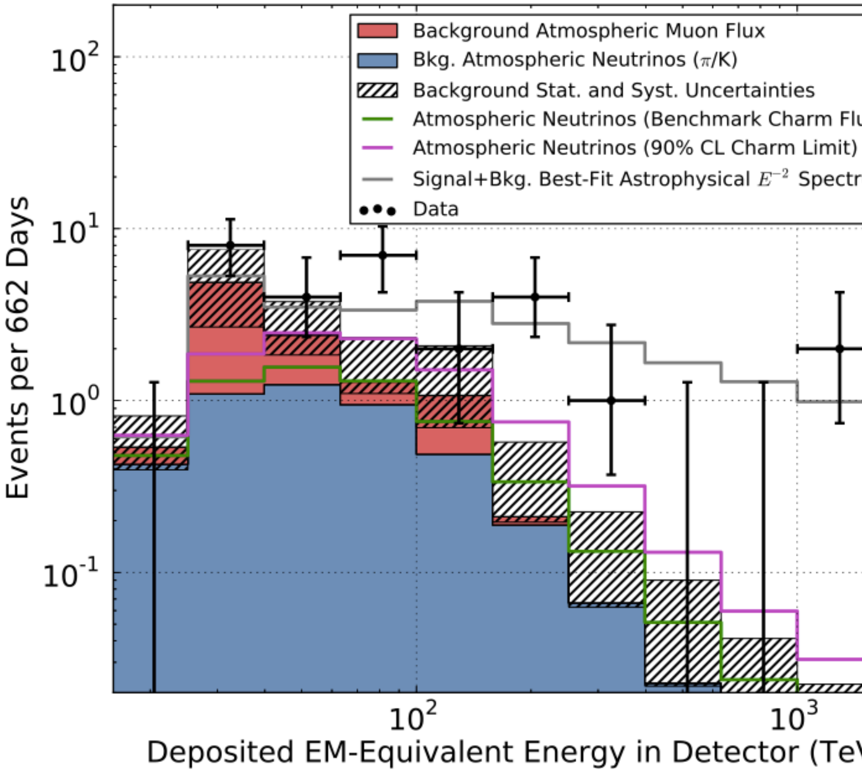
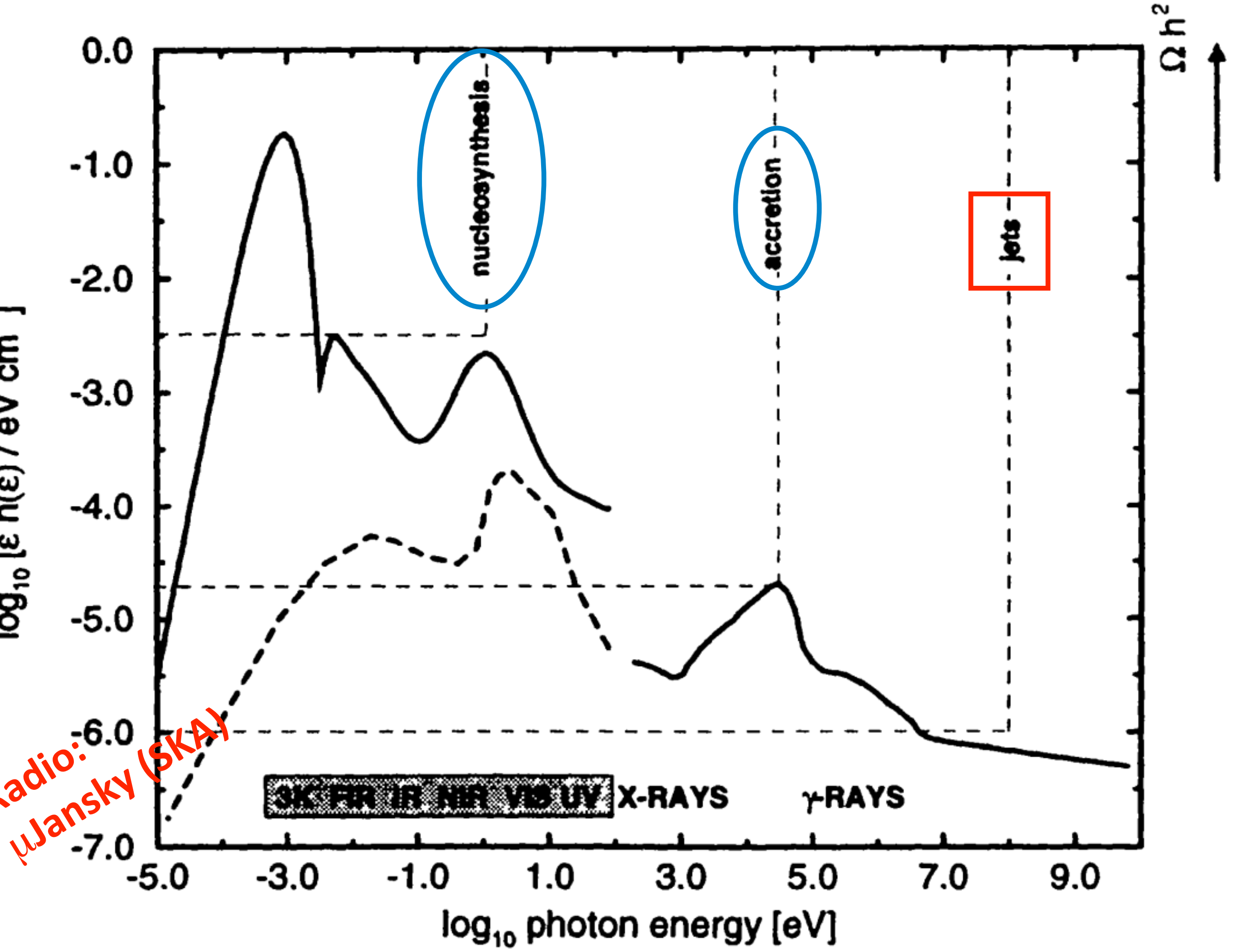




IceCube Collaboration 2013, Science 342, 1

F ~ 2 10^{-8} GeV cm^{-2} s^{-1} st^{-1}
u ~ 4π/c F ~ 10^{-8} eV cm^{-3}

Extragalactic radiation background



adio:
μJansky (SKA)

$$u_{\rm ns} \sim \frac{\rho_* Z \epsilon c^2}{1+z_{\rm f}}$$ Peebles!

$$u_{\rm ns} \sim 6\times 10^{-3} \left(\frac{\Omega_* h^2}{0.01}\right)\left(\frac{1+z_{\rm f}}{3}\right)^{-1} \ \text{eV cm}$$

$$u_{\rm accr} \sim \frac{\epsilon_{\rm accr} M_{\rm bh}}{Z\epsilon M_*}\frac{t_{\rm agn}}{t_*}u_{\rm ns} \sim 1.4\times 10^{-4} \ \text{eV c}$$

AGN average SED (Elvis et al.): u_X~ 0.2 u_a

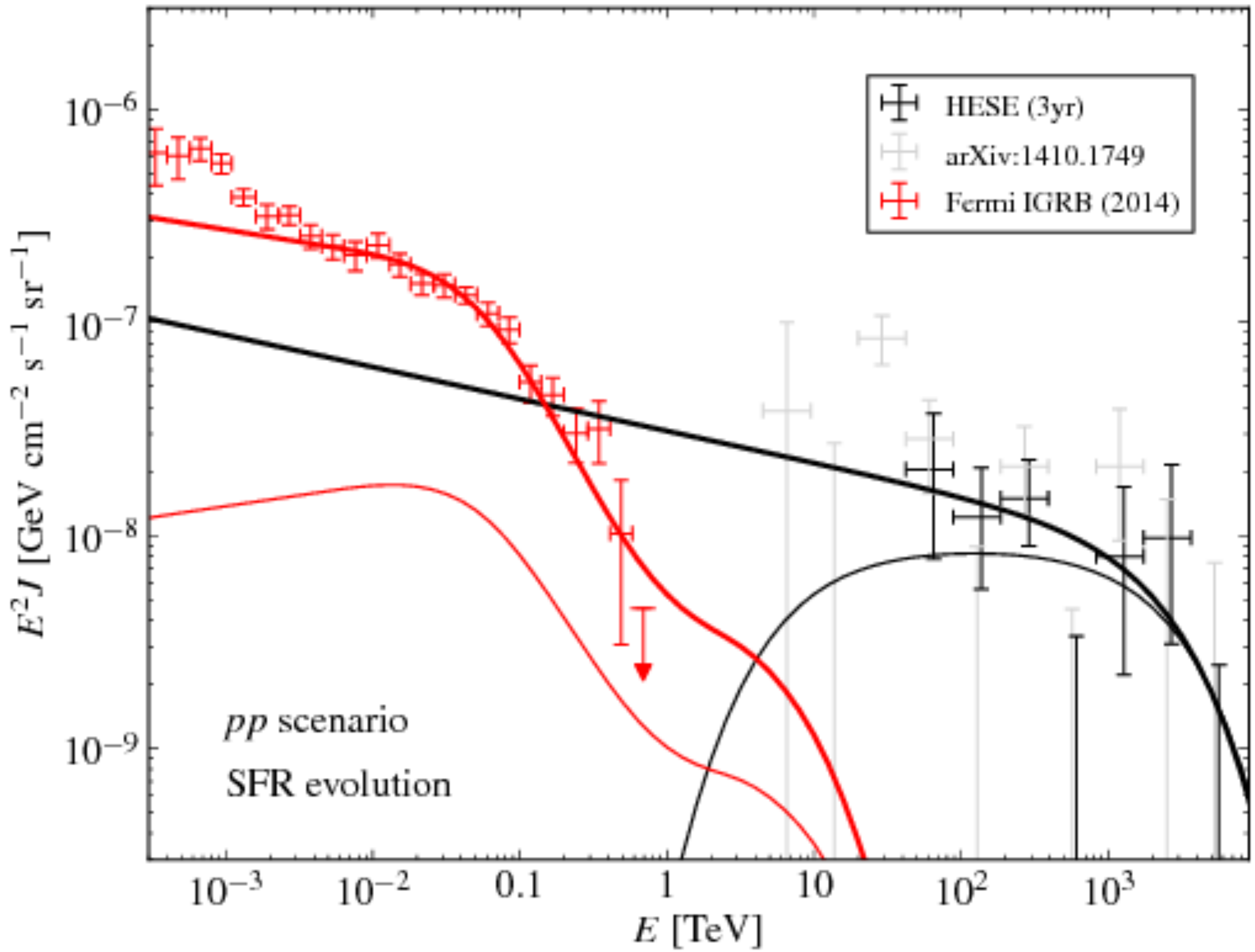
$$u_{\rm x} \sim 2.8\times 10^{-5} \ \text{eV cm}^{-3}$$

$$\xi_{\rm rl} \sim 20\,\%$$

$$u_{\rm j} = \left(\frac{\xi_{\rm rl}}{0.2}\right)u_{\rm accr} \sim \left(\frac{\xi_{\rm rl}}{0.2}\right) 2.8\times 10^{-5} \ \text{eV c}$$

$$\xi_{\rm acc} = \frac{u_{\rm acc}}{u_{\rm j}} = \frac{u_\gamma}{\xi_{\rm rad} u_{\rm j}}$$

$$\boxed{\xi_{\rm acc} \geq 0.18\,\xi_{\rm rad}^{-1}\left(\frac{\xi_{\rm rl}}{0.2}\right)^{-1}}$$

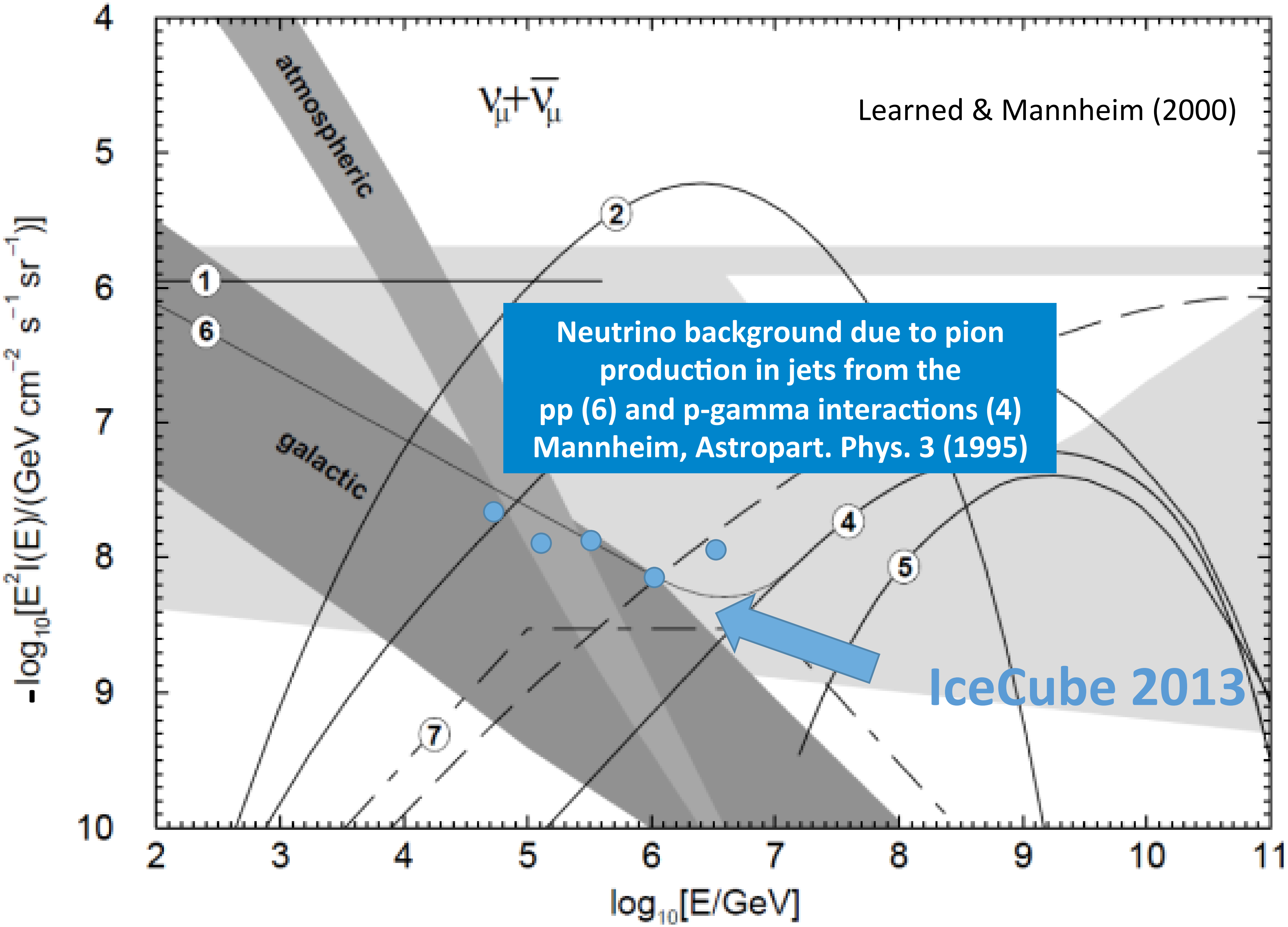

HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
E [TeV]
pp scenario
SFR evolution

Halzen (2014)

Conjecture of 1995

KM, Astroparticle Physics 3, 295-302 (1995):

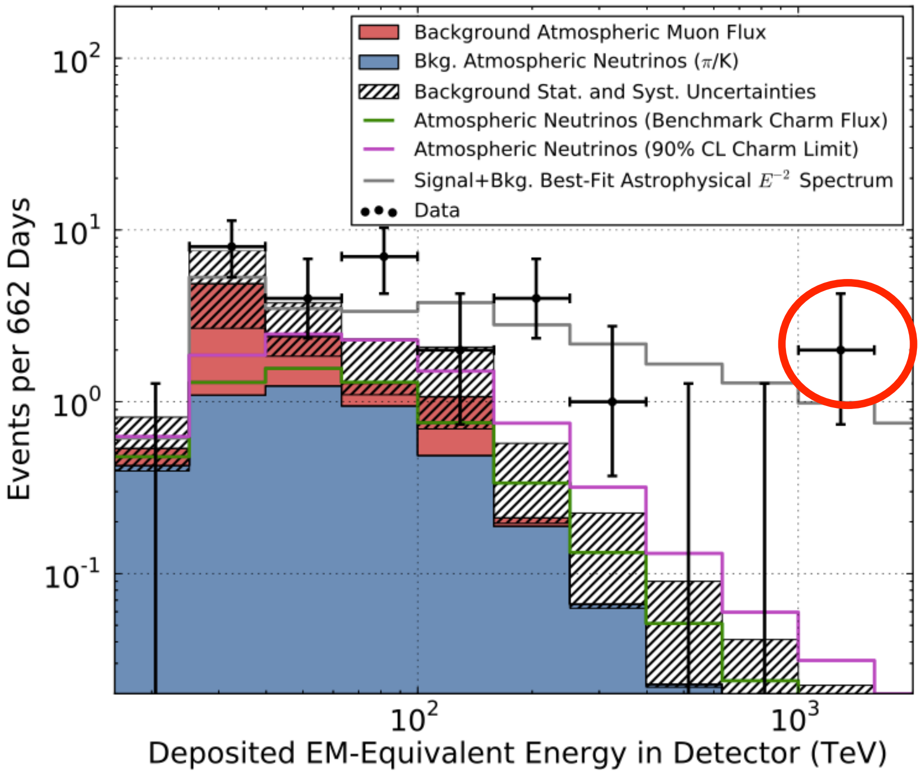
< *Abstract: … I calculate the diffuse background of high-energy neutrinos from extragalactic jets emerging from active galactic nuclei (AGN) … Recent γ-ray observations make it very plausible that the diffuse γ-ray background … above 100 MeV is due to radio-loud AGN. A striking similarity exists between the energy fluxes of diffuse y-rays above 100 MeV and cosmic ray protons above the ankle. This is an independent argument for proton acceleration in radio jets consistent with the explanation of the individual y-ray spectra by hadronically induced cascades. The corresponding prediction of a neutrino flux [model A: 10^{-8} GeV cm^{-2} s^{-1} st^{-1} @ 100 TeV - 1 PeV] therefore rests on a firm basis.* >



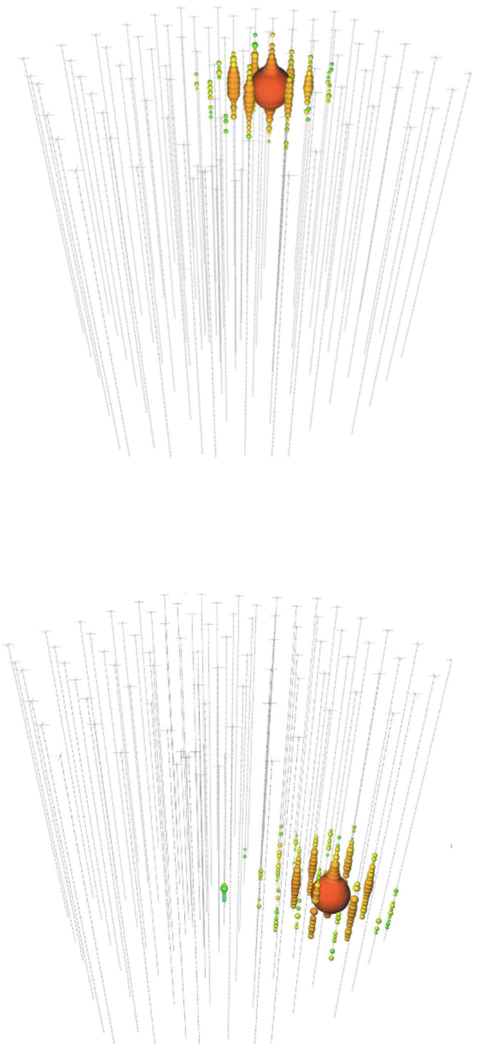
Learned & Mannheim (2000)

Neutrino background due to pion production in jets from the pp (6) and p-gamma interactions (4) Mannheim, Astropart. Phys. 3 (1995)

IceCube 2013

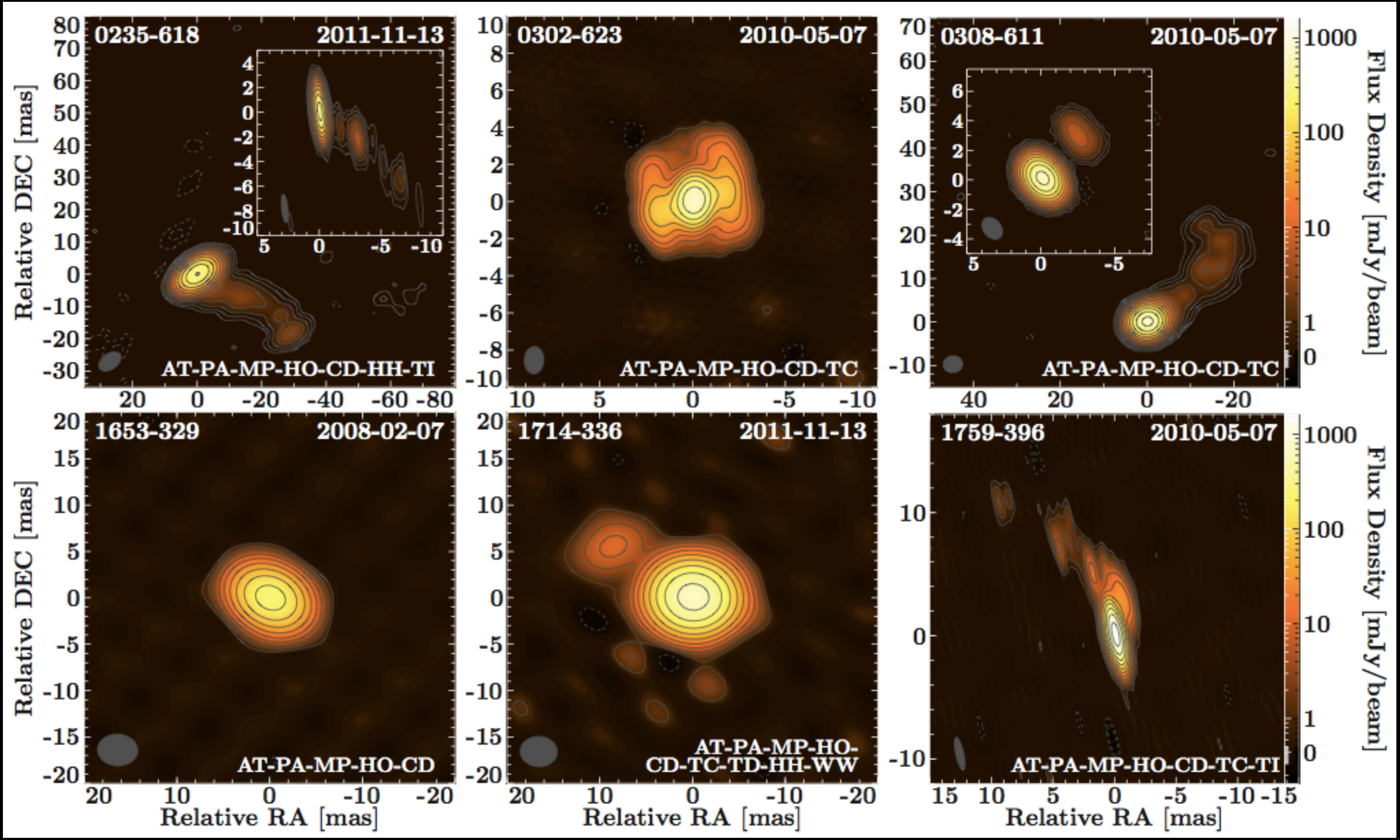


IceCube Collaboration 2013, Science 342, 1



E~1.0PeV

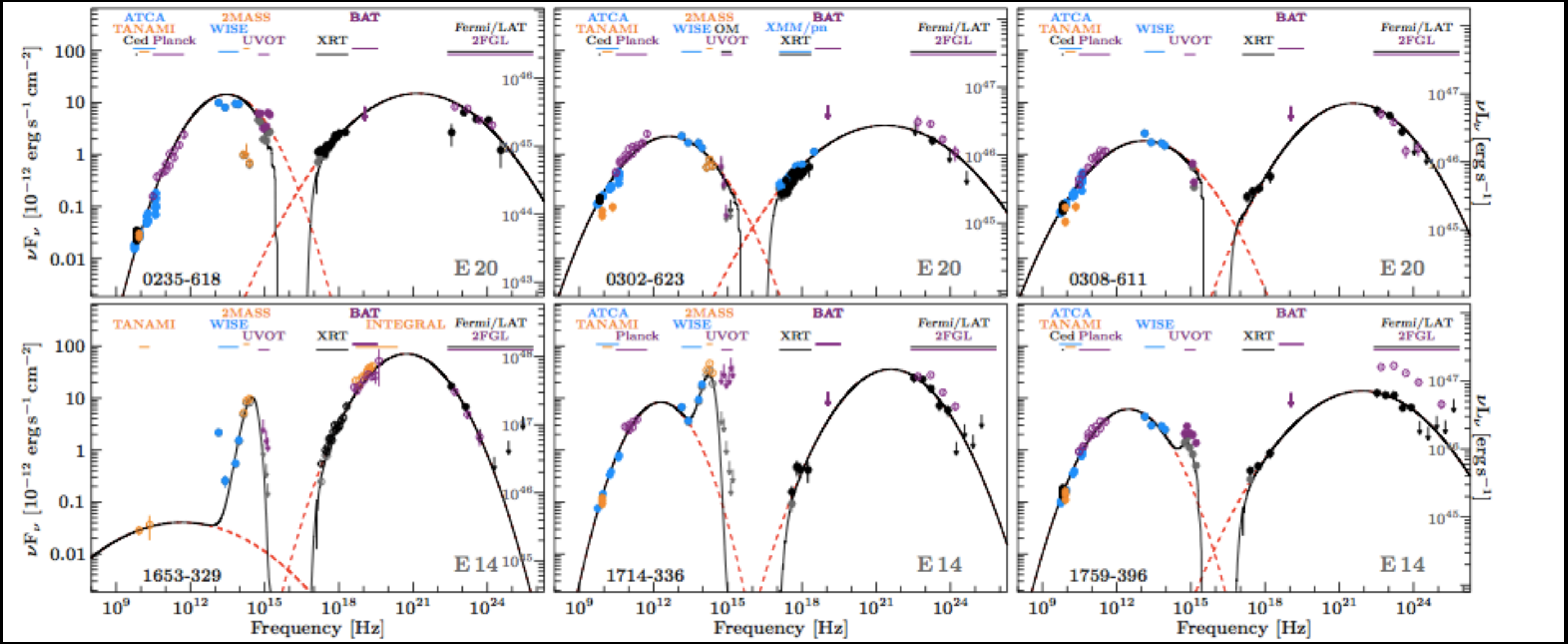
Blazars in the IceCube PeV Neutrino Fields observed by TANAMI



Krauß et al. 2014, A&A 566, L7

Blazars in the IceCube PeV Neutrino Fields

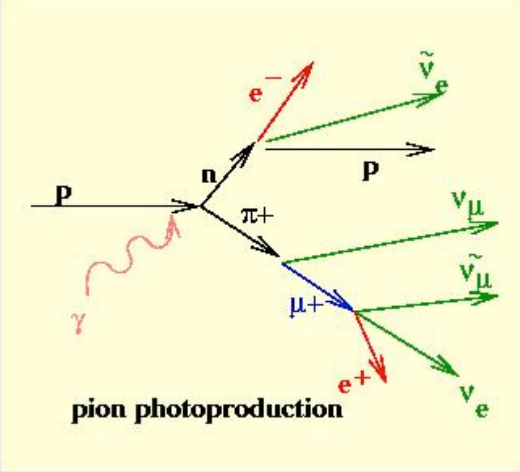
- Classical double-humped blazar SEDs
- Blue bumps in 3 sources



Krauß et al. 2014, A&A 566, L7

Estimate Maximum Neutrino Output

1. Assume presence of accelerated protons (hadronic jet models)
2. Pion photoproduction
3. Estimate neutrino flux from bolometric high-energy flux



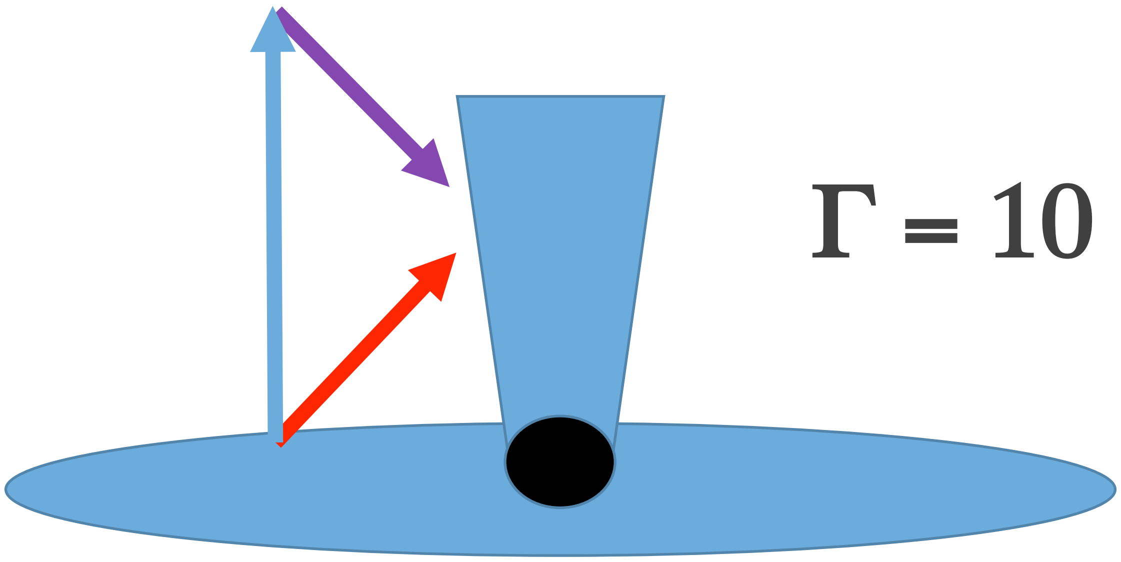
pion photoproduction

$$F_\gamma = 1/3 \cdot F_\pi + 1/4 \cdot 2/3 \cdot F_\pi = 1/2 \cdot F_\pi$$

$$F_\nu = 2/3 \cdot 3/4 \cdot F_\pi = 1/2 \cdot F_\pi$$

$$F_\nu = F_\gamma$$

$E_\nu = 0.05\ E_{p,th}$ = 100 TeV – 10 PeV



$$N^{\mathrm{max}}_{\nu,\,\mathrm{PeV}}(2\pi) = 13 \cdot \frac{2\pi}{\Omega^{R_{50}}_{\mathrm{HESE-35}}} \sim 336$$

- UV-photons from accretion disk in blazars
- delta-shaped PeV spectrum
- electron neutrinos

$$f_{\mathrm{emp}} = \frac{N^{\mathrm{obs}}_{\nu,\,\mathrm{PeV}}(2\pi)}{N^{\mathrm{max}}_{\nu,\,\mathrm{PeV}}(2\pi)} \sim \frac{3}{336} \sim \boxed{0.009}$$

Rescaling to observed three PeV events

$$N^{\mathrm{pred}}_{\nu,\mathrm{PeV}}(\Omega^{R_{50}}_{\mathrm{HESE-35}}) = f_{\mathrm{th}} \cdot N^{\mathrm{max}}_{\nu,\mathrm{PeV}}(\Omega^{R_{50}}_{\mathrm{HESE-35}})$$

Compare with theoretical scaling factor

$$f_{\mathrm{th}} = f_{\mathrm{I}} \cdot f_{\mathrm{II}} \cdot f_{\mathrm{III}}$$

$f_{\mathrm{I}} \sim 0.5$ Flavor ratio for cascades folded with HESE acceptance

$f_{\mathrm{II}} \sim 0.5$ FSRQ fraction Fermi-LAT

$f_{\mathrm{III}} = 0.05$ Bandwidth (2.3 spectrum, redshift, UV photon angular distribution)

$$f_{\mathrm{th}} = 0.5 \cdot 0.5 \cdot 0.05 \sim \boxed{0.0125}$$

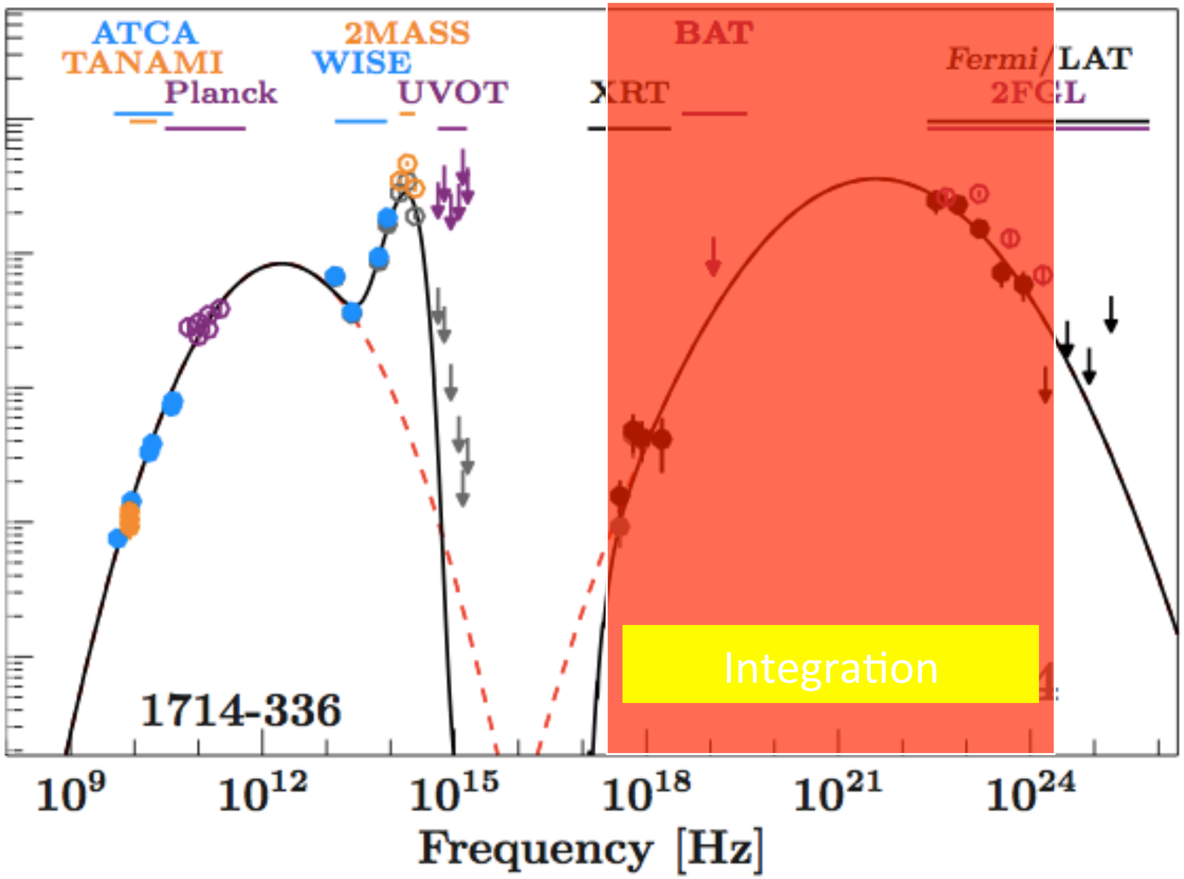
Estimate Maximum Neutrino Output

$$F_\nu = F_\gamma$$

- Fit SEDs with log-parabolas

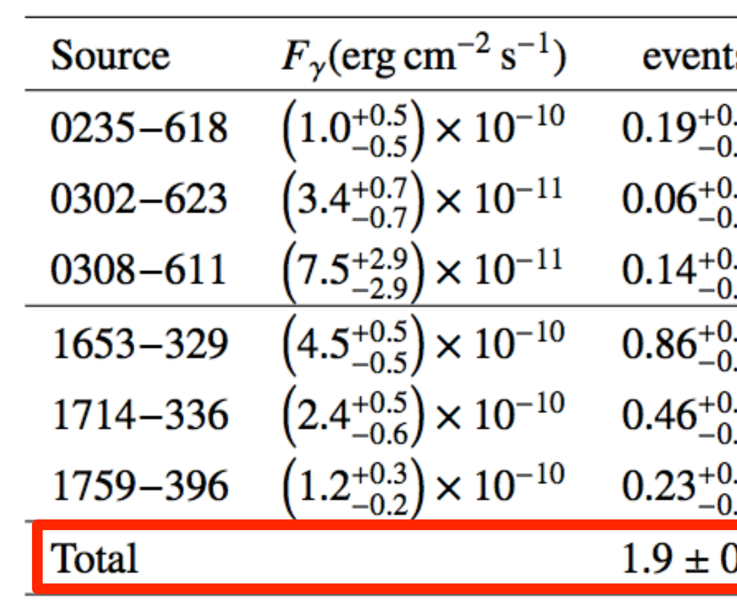
(plus BB component, absorption)

- Integrate from 1keV to 5GeV



Blazars in the two IceCube 1.0 PeV Neutrino Fields

The six TANAMI blazars are capable of explaining the observed IceCube signal



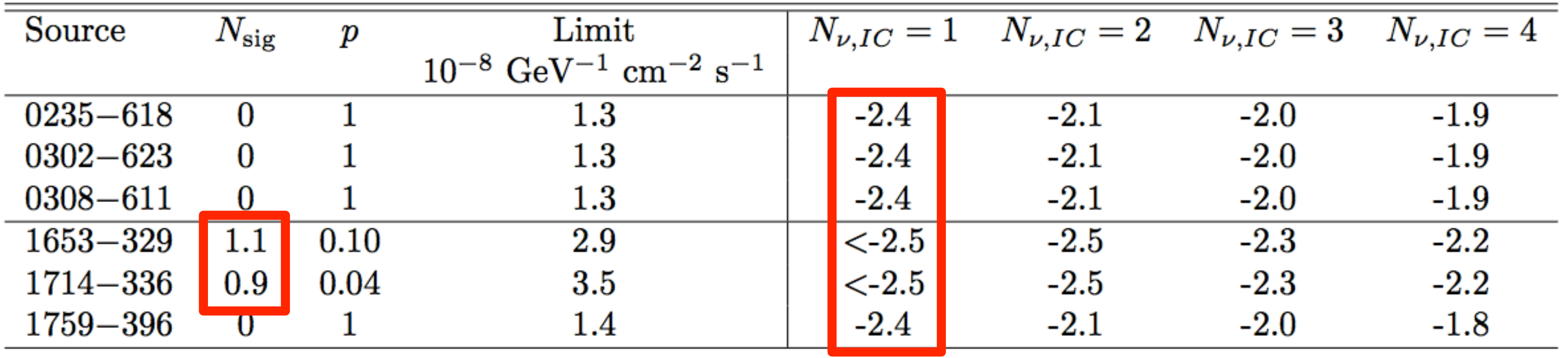
Source	F_γ(erg cm^{-2} s^{-1})	event
0235−618	$\left(1.0^{+0.5}_{-0.5}\right) \times 10^{-10}$	$0.19^{+0.}_{-0.}$
0302−623	$\left(3.4^{+0.7}_{-0.7}\right) \times 10^{-11}$	$0.06^{+0.}_{-0.}$
0308−611	$\left(7.5^{+2.9}_{-2.9}\right) \times 10^{-11}$	$0.14^{+0.}_{-0.}$
1653−329	$\left(4.5^{+0.5}_{-0.5}\right) \times 10^{-10}$	$0.86^{+0.}_{-0.}$
1714−336	$\left(2.4^{+0.5}_{-0.6}\right) \times 10^{-10}$	$0.46^{+0.}_{-0.}$
1759−396	$\left(1.2^{+0.3}_{-0.2}\right) \times 10^{-10}$	$0.23^{+0.}_{-0.}$
Total		1.9 ± 0

But:

1. No individual source bright enough for a direct association
   ⇒ Highest flux from 1653-329 and 1714-336
2. Blazar γ-ray luminosity function ~$F^{-2.4}$
   ⇒ Substantial contribution of faint, remote sources
   ⇒ Substantial fudge factor needed

ANTARES Results

ANTARES Collaboration and TANAMI Collaboration 2015, A&A, 576, L8



Source	$N_{\rm sig}$	p	Limit 10^{-8} GeV^{-1} cm^{-2} s^{-1}	$N_{\nu,IC} = 1$	$N_{\nu,IC} = 2$	$N_{\nu,IC} = 3$	$N_{\nu,IC} = 4$
0235−618	0	1	1.3	-2.4	-2.1	-2.0	-1.9
0302−623	0	1	1.3	-2.4	-2.1	-2.0	-1.9
0308−611	0	1	1.3	-2.4	-2.1	-2.0	-1.9
1653−329	1.1	0.10	2.9	<-2.5	-2.5	-2.3	-2.2
1714−336	0.9	0.04	3.5	<-2.5	-2.5	-2.3	-2.2
1759−396	0	1	1.4	-2.4	-2.1	-2.0	-1.8

- 1653-329 and 1714-336: one event, each.
  - ⇒ Consistent with blazar-source hypothesis, but also with background
- Zero events for the other four blazars.

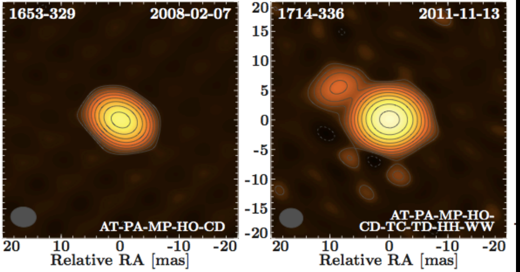
Either:

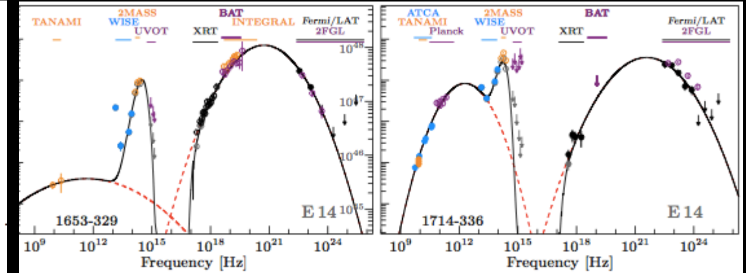
⇒ Not the sources of the PeV neutrinos, or

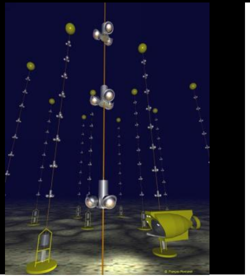
⇒ Neutrino spectra flatter than -2.4

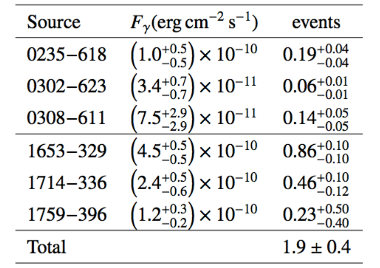
Conclusions from First Two PeV Events

- Integrated flux of blazars can explain the IceCube signal
- Note: Spectrum of each source can be different from global spectrum
- Follow-up with ANTARES finds two neutrinos coincident with the two brightest candidates (still consistent with background)
- Assume an association ⇒ Rather flat neutrino spectra









Source	$F_\gamma(\mathrm{erg\,cm^{-2}\,s^{-1}})$	events
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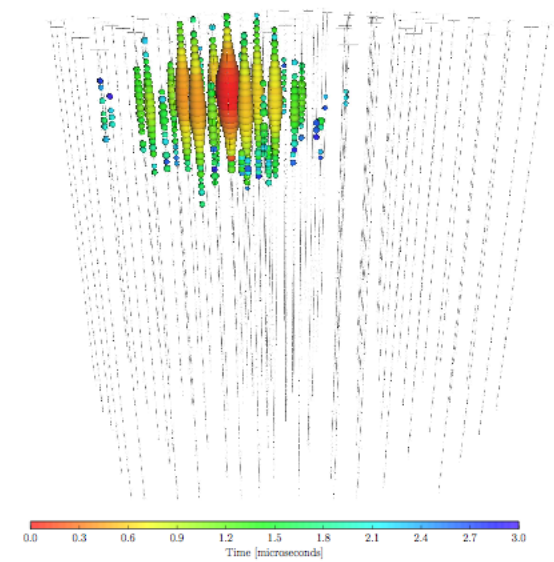
0308−611	$\left(7.5^{+2.9}_{-2.9}\right)\times10^{-11}$	$0.14^{+0.05}_{-0.05}$
1653−329	$\left(4.5^{+0.5}_{-0.5}\right)\times10^{-10}$	$0.86^{+0.10}_{-0.10}$
1714−336	$\left(2.4^{+0.5}_{-0.6}\right)\times10^{-10}$	$0.46^{+0.10}_{-0.12}$
1759−396	$\left(1.2^{+0.3}_{-0.2}\right)\times10^{-10}$	$0.23^{+0.50}_{-0.40}$
Total		1.9 ± 0.4

Big Bird

- 2PeV event on Dec 4, 2012 (Aartsen et al. 2014)
- RA = 208.4°, Dec = −55.8° (J2000)
- Median pos. uncertainty: 15.9deg

  ⇒ 17 gamma blazars (2LAC)
- Again: integral flux sufficient to explain the signal, but this time:

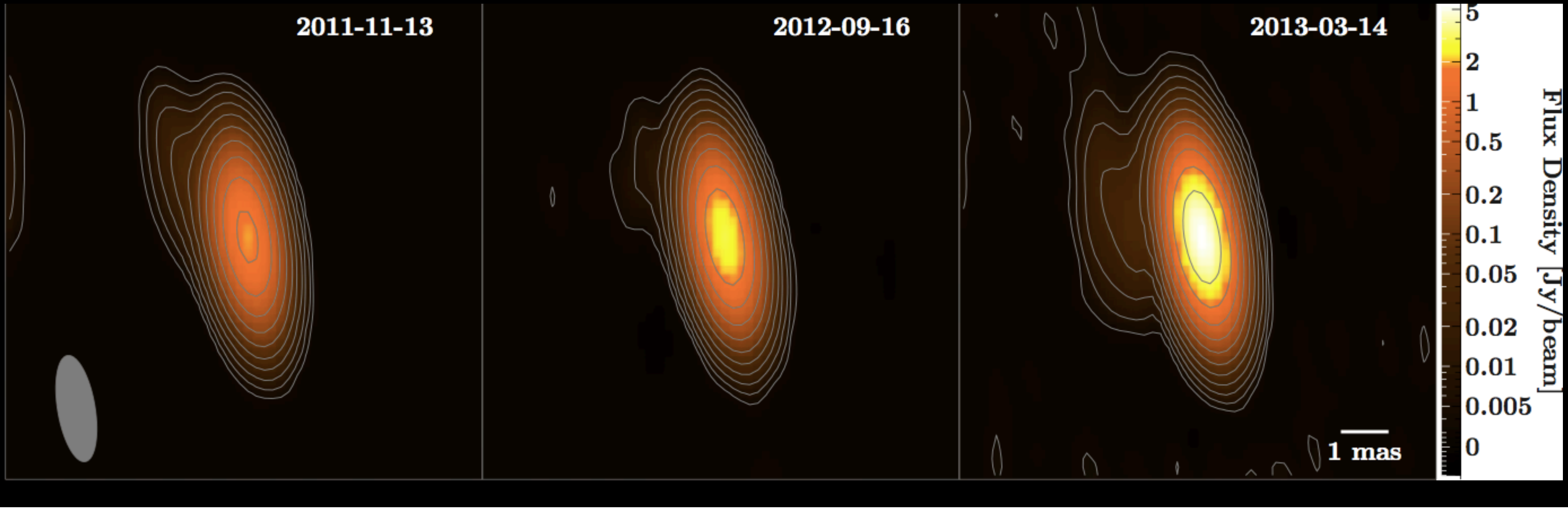


Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
2004^{+236}_{-262}	56265.1338677	−55.8	208.4	15.9	Shower

Output dominated by a single source: PKS B1424-418

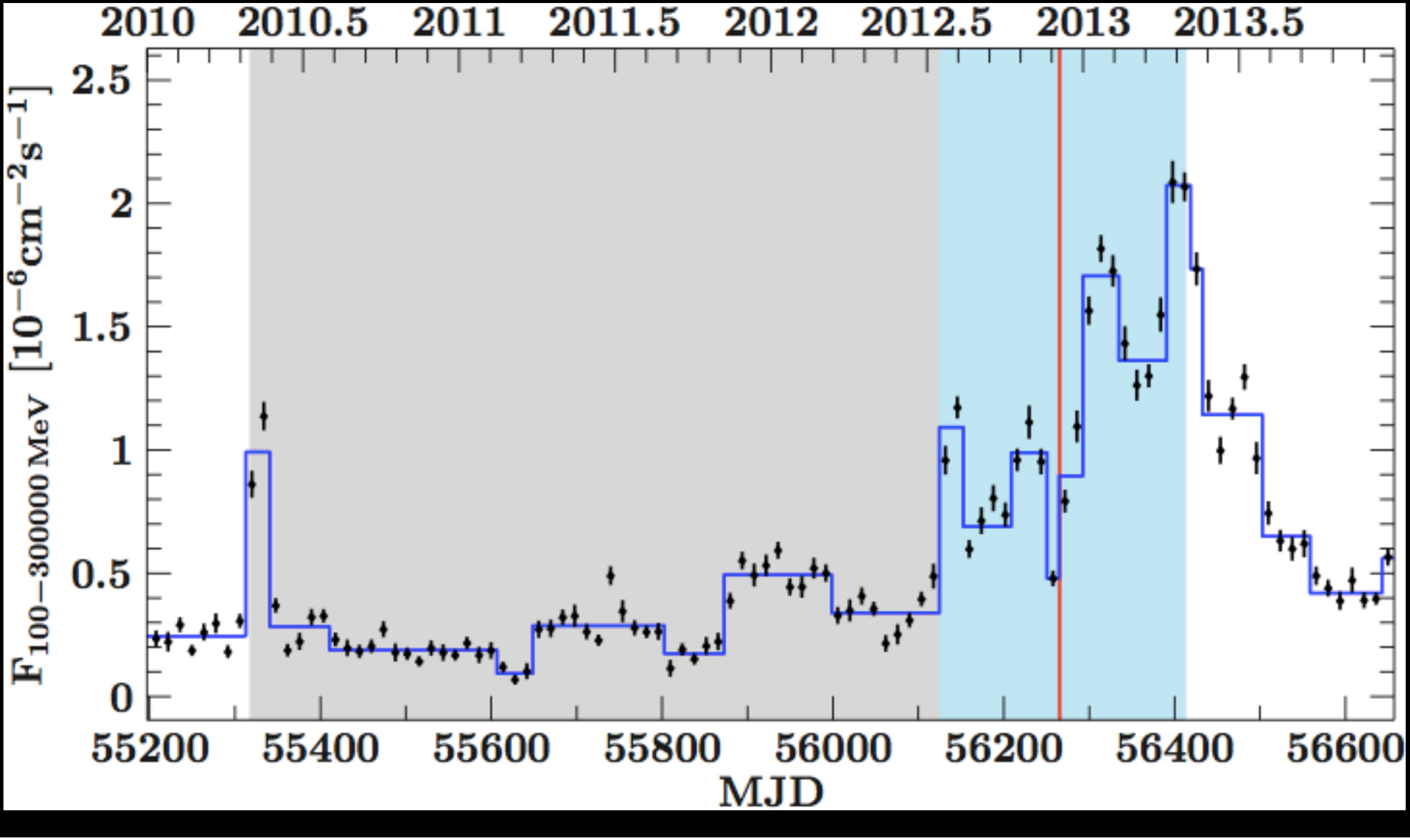
PKS B1424-418: Radio Outburst

- Radio core flux density increased from 1.5Jy to 6Jy in late 2012 to early 2013
- Strongest outburst ever seen by TANAMI



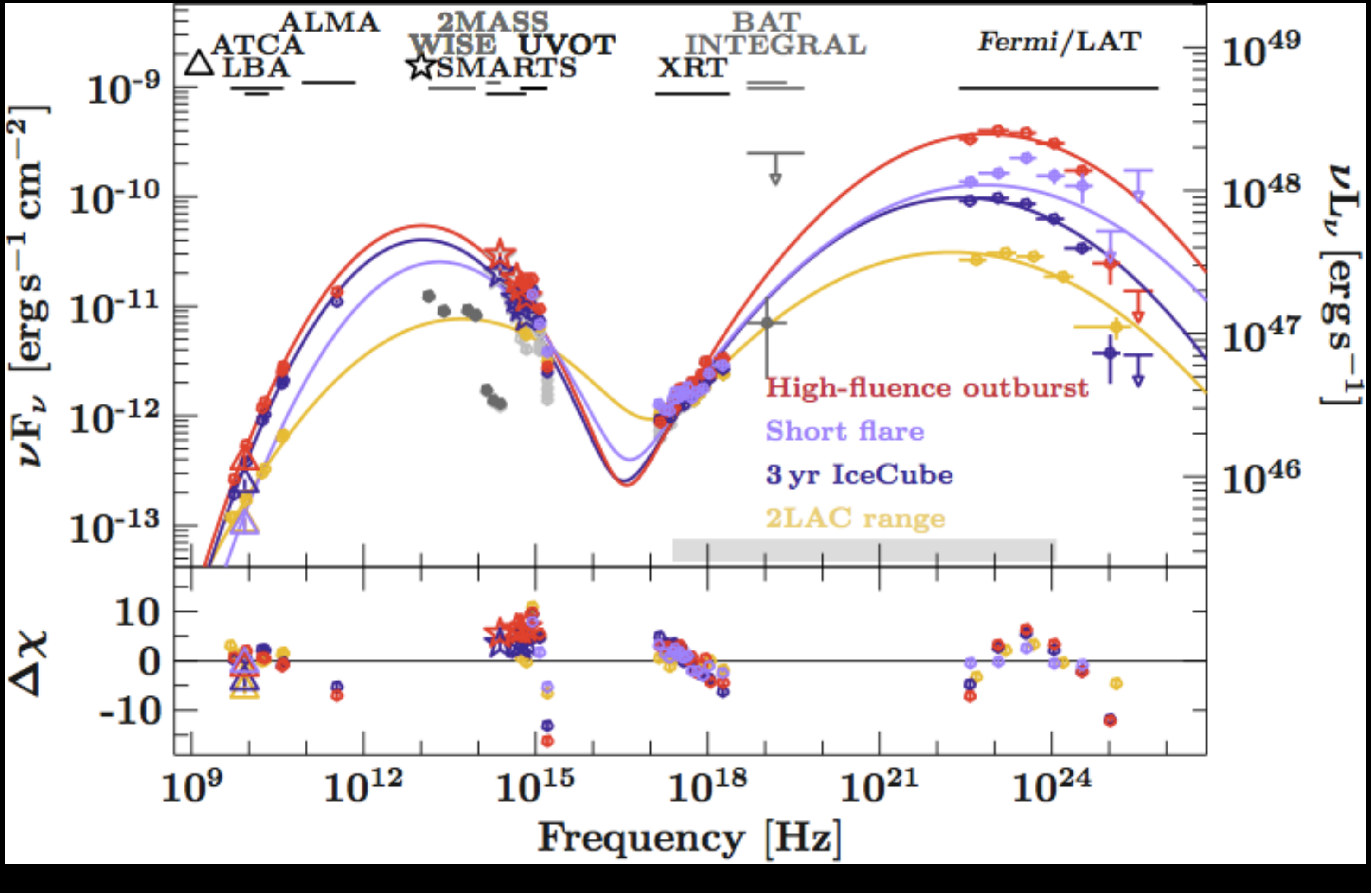
PKS B1424-418: Gamma Outburst

Outburst coincident with BigBird arrival time

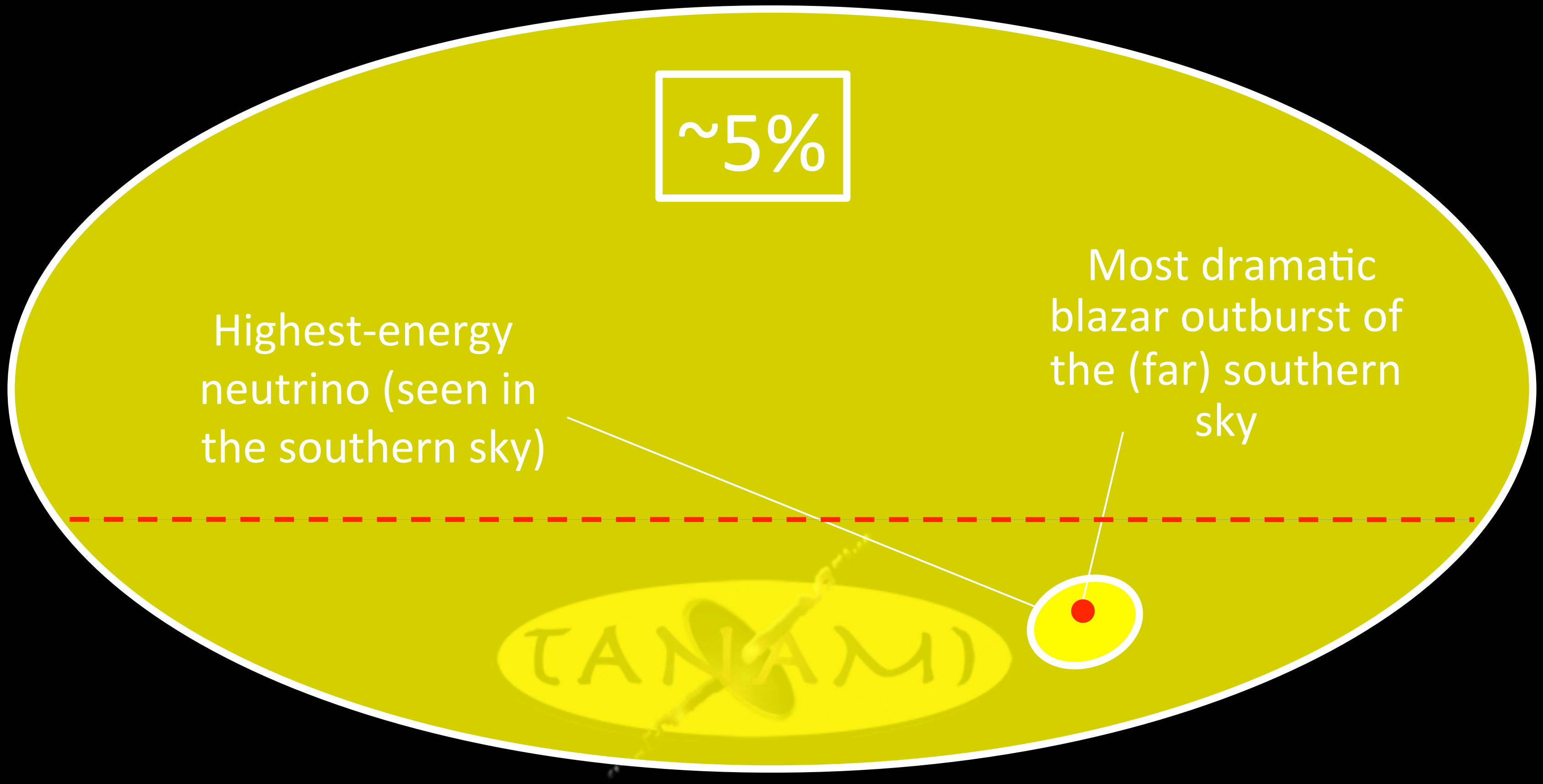


PKS B1424-418: Outburst SED

Predicted Neutrino Output: 2.2 Events



Chance Coincidence?



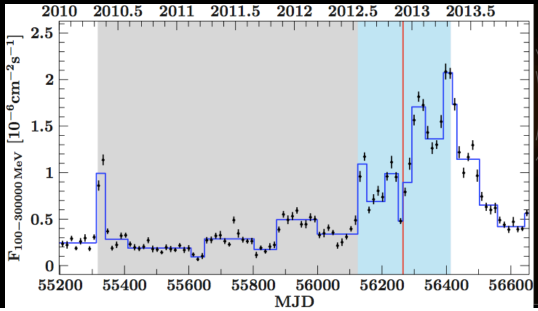
~5%

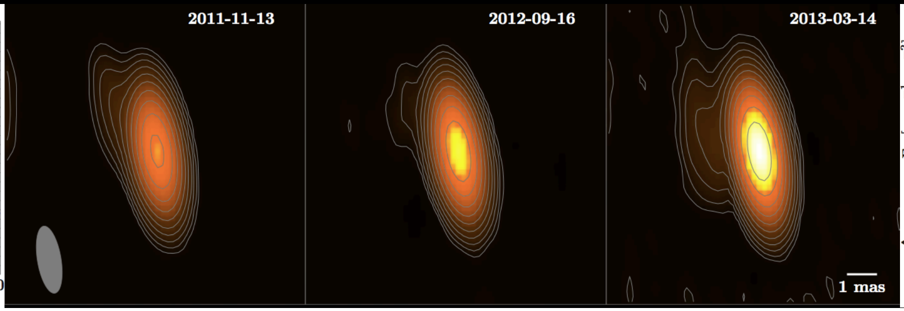
Highest-energy neutrino (seen in the southern sky)

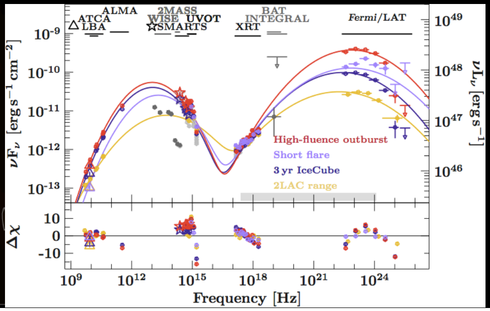
Most dramatic blazar outburst of the (far) southern sky

Conclusions from Third PeV Event

- Single blazar can explain an individual PeV neutrino
- Comparable blazar outbursts had substantially lower-sensitivity IceCube coverage
- Conservative estimate of ~5% chance coincidence







Questions

- **Consistency with Glüsenkamp et al. analysis of blazar contribution to IceCube flux above 10 TeV (less than 30% to EGRB) ?**
  - FSRQ spectra peak between 100 TeV and 10 PeV (Γ=10)
  - Unknown heavy quark contribution to pN scattering hardens atmospheric neutrino spectrum and pollutes excess flux
  - Beamed jet emission only be half or less than the total energy dissipated by jets through unbeamed emission (lower power – larger number → diffuse)
  - Possible Galactic Population of Pevatrons (100 TeV neutrinos)
- **Absence of Glashow resonance evence → steepening of spectrum ?**
  - Statistical limitations
  - Rise towards EeV expected due to HBLs (optically thin for protons up to UHE)
  - Ultimately, hit GZK neutrino flux (z-evolution, progagation)
  - New physics?