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High-Fluence Blazars as Possible Sources of the IceCube PeV Neutrinos

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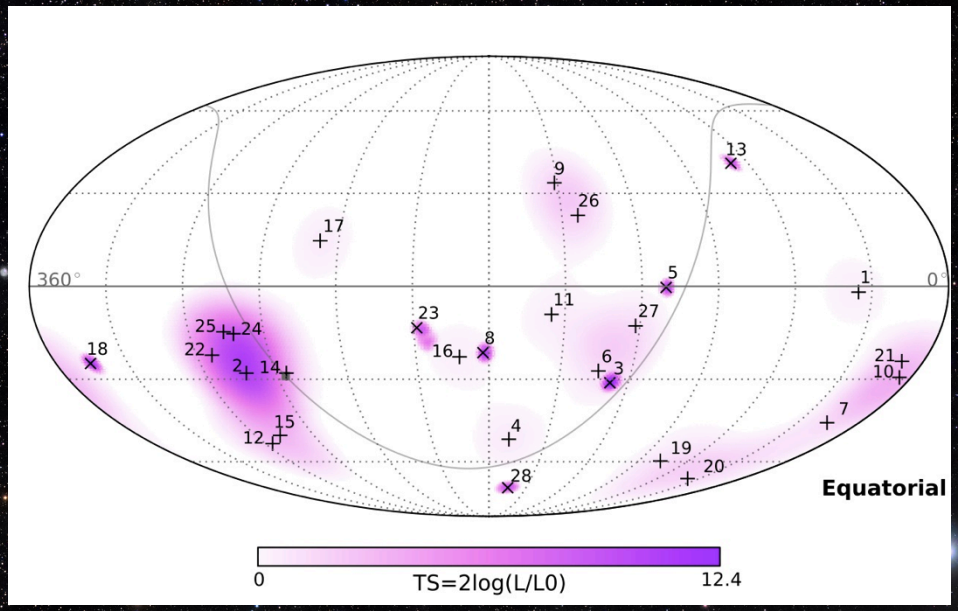
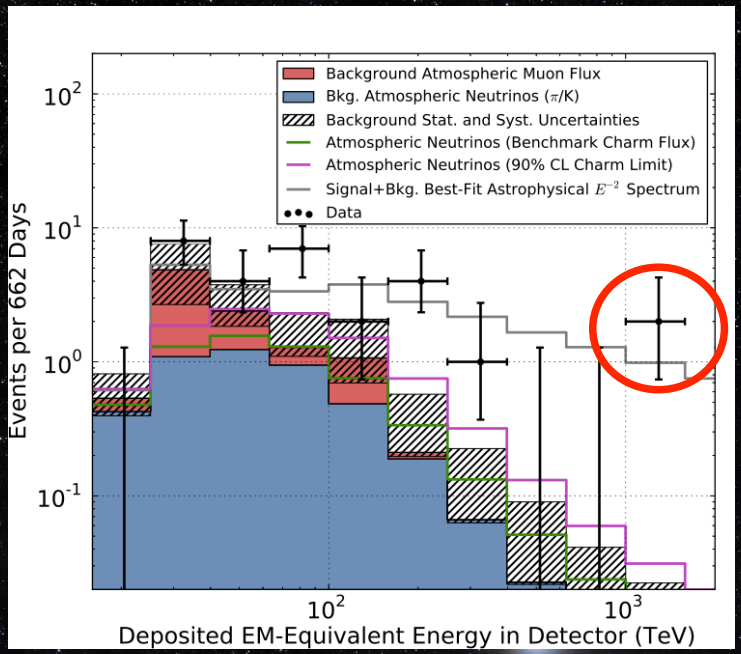
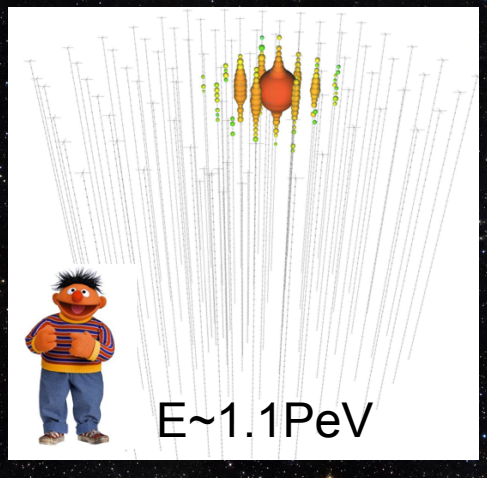
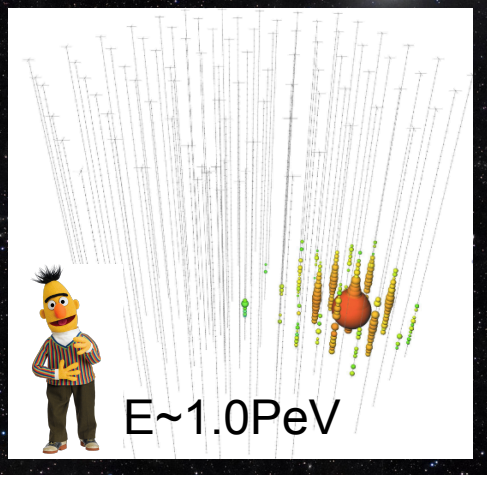
What are the Sources of the IceCube Neutrino Signal?

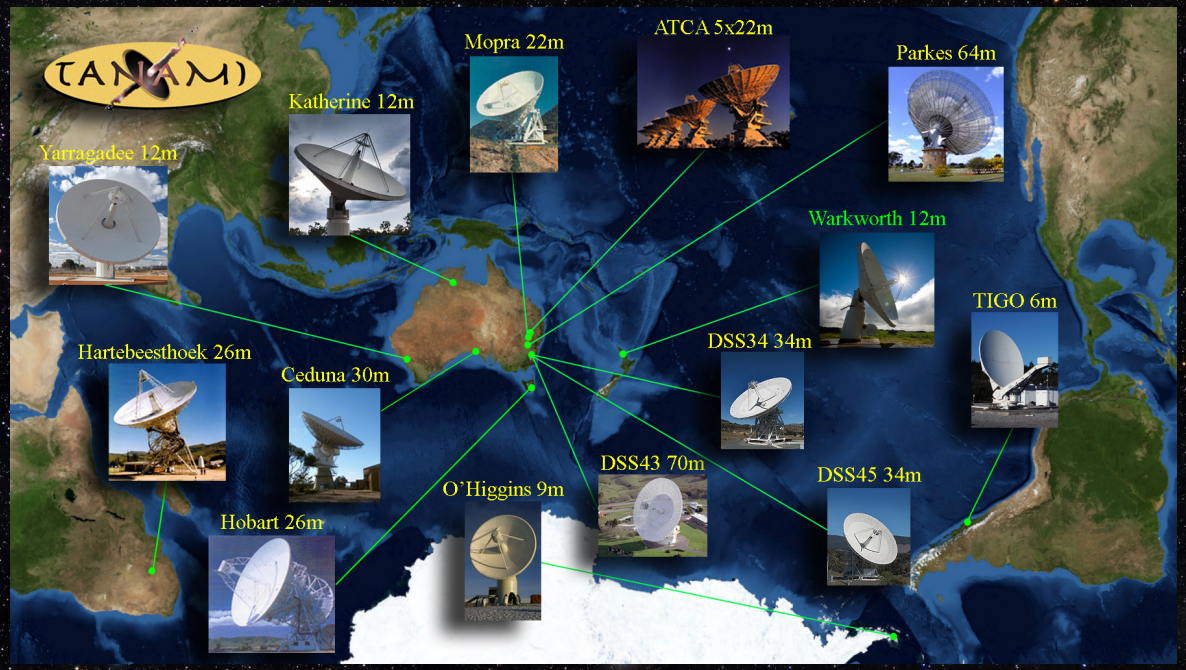


IceCube Collaboration 2013, Science 342, 1





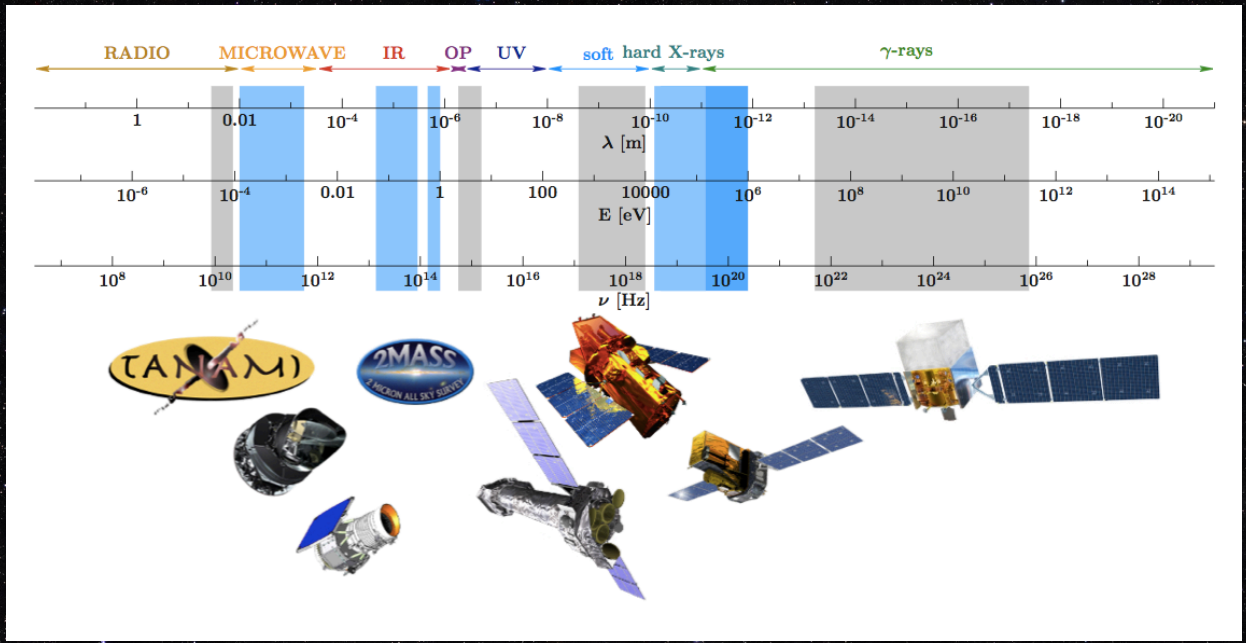




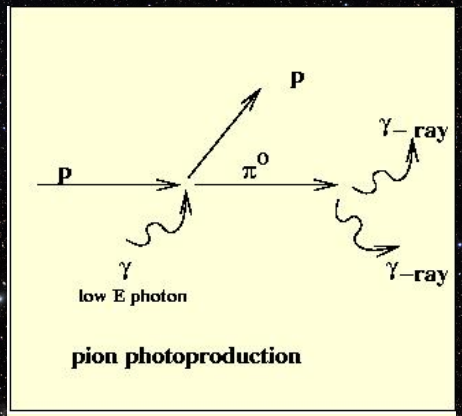
TANAMI

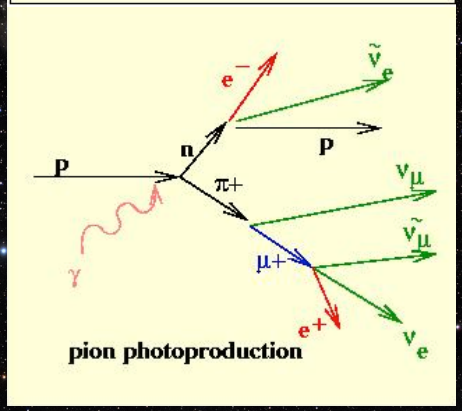
Multiwavelength Monitoring of ~90 AGN Jets South of -30°

Includes the radio- and γ-ray brightest AGN in the IceCube PeV neutrino fields

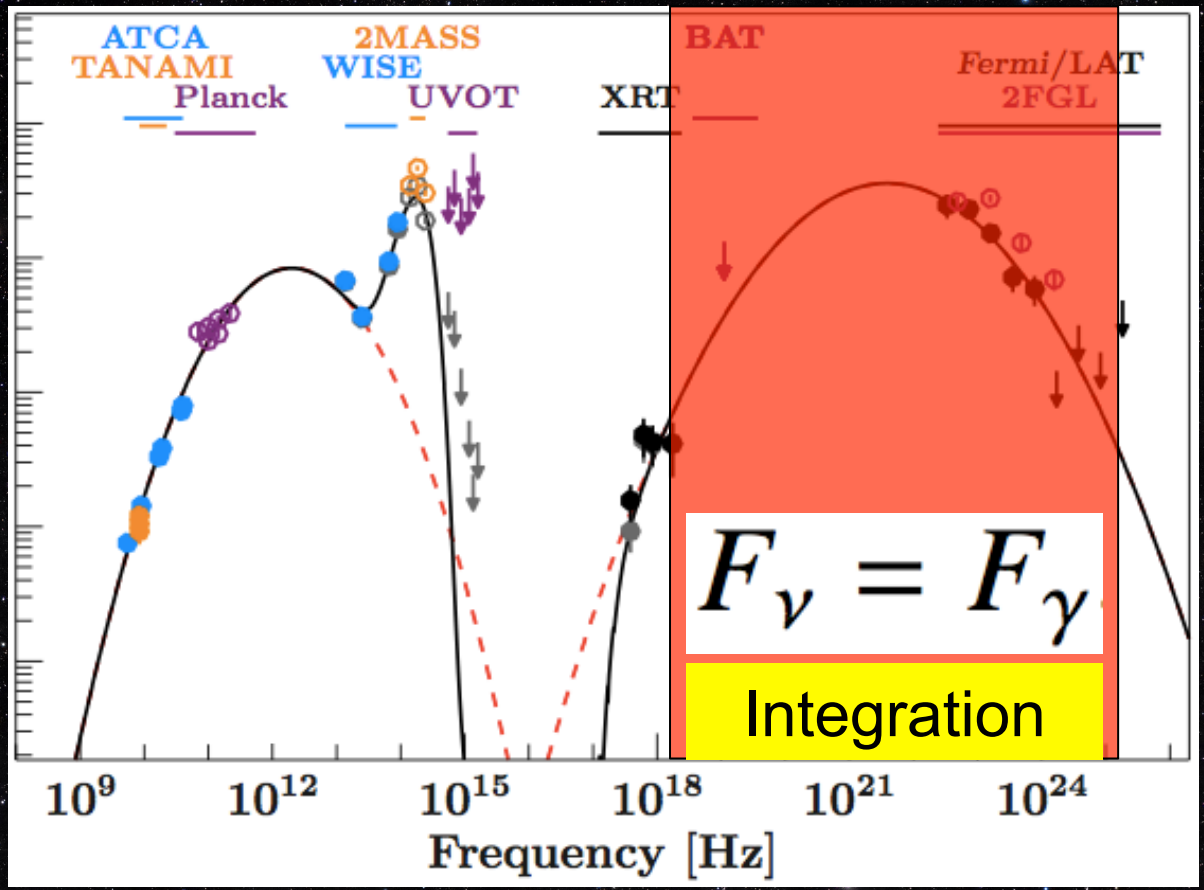


Maximum Neutrino Output in Photopion Production



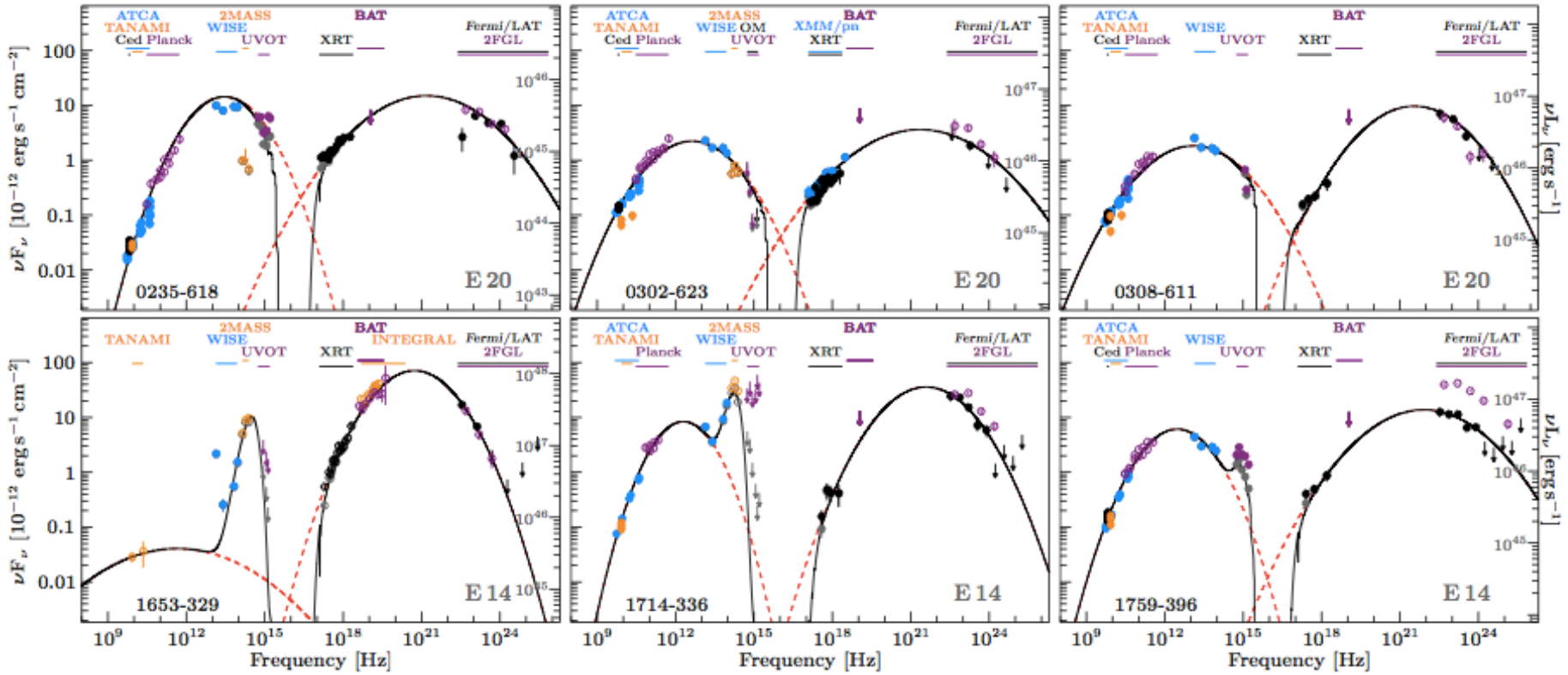


- UV seed photons
  - ➢ PeV peaked spectra



$$N^{\max}_{\nu,\mathrm{PeV}}(\Omega) = A_{\mathrm{eff},\nu_e} \cdot \left(\frac{F_\gamma}{E_\nu}\right) \cdot \Delta t \quad \rightarrow \quad \underline{\text{need high-fluence!}}$$

TANAMI Blazars in the First Two PeV-Neutrino Fields



Krauß et al. 2014, A&A 566, L7

TANAMI Blazars in the First Two PeV-Neutrino Fields

1. Maximum-possible neutrino flux from blazars can explain observed PeV events
2. Many(!) faint blazars hidden in the EGB ➔ more neutrinos

Source	F_γ(erg cm^{-2} s^{-1})	events
0235−618	$\left(1.0^{+0.5}_{-0.5}\right) \times 10^{-10}$	$0.19^{+0.04}_{-0.04}$
0302−623	$\left(3.4^{+0.7}_{-0.7}\right) \times 10^{-11}$	$0.06^{+0.01}_{-0.01}$
0308−611	$\left(7.5^{+2.9}_{-2.9}\right) \times 10^{-11}$	$0.14^{+0.05}_{-0.05}$
1653−329	$\left(4.5^{+0.5}_{-0.5}\right) \times 10^{-10}$	$0.86^{+0.10}_{-0.10}$
1714−336	$\left(2.4^{+0.5}_{-0.6}\right) \times 10^{-10}$	$0.46^{+0.10}_{-0.12}$
1759−396	$\left(1.2^{+0.3}_{-0.2}\right) \times 10^{-10}$	$0.23^{+0.50}_{-0.40}$
Total		1.9 ± 0.4

But:

- No individual source bright enough for a direct association
  - ⇒ Highest flux from 1653-329 and 1714-336
- Scaling factor needs to be determined

Scaling Factor

Things to consider:

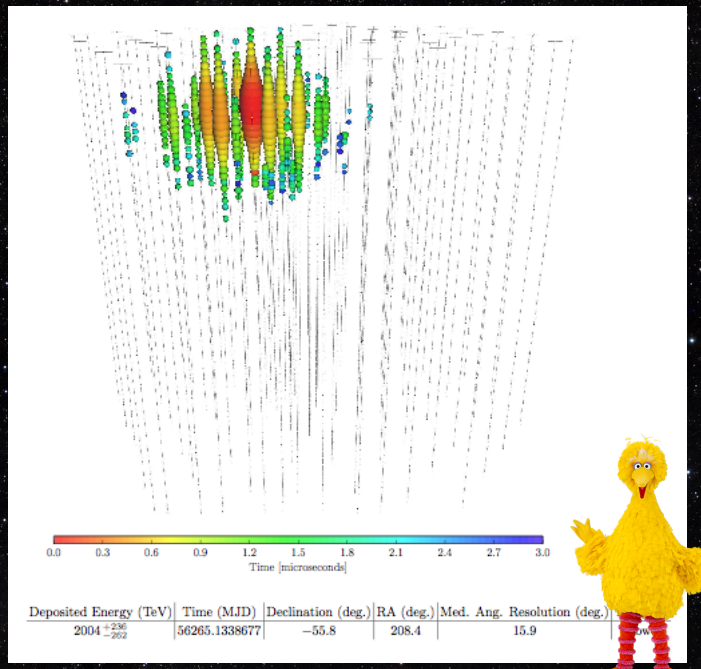
1. Different neutrino flavors
2. UV seed photons needed (FSRQs)
3. PeV peaks might be smeared out to ~(0.03-10)PeV (adopt measured $E^{-2.3}$ spectrum)

➢ $$N_{\nu,\mathrm{obs,PeV}} = f \cdot N_{\nu,\mathrm{max,PeV}}$$

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

2PeV event on Dec 4, 2012 (Big Bird):

- Median pos. uncertainty: 15.9deg
  ⇒ 17 gamma blazars (2LAC) + EGB
- Prediction: 13 events
- Use this field to determine scaling factor empirically:



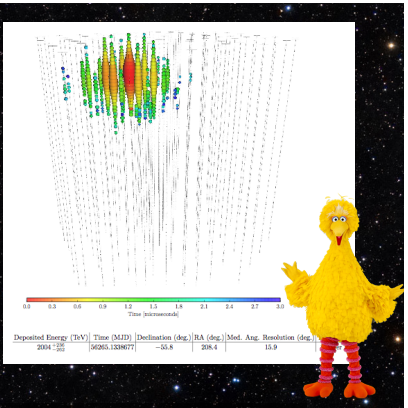
Aartsen et al. 2014

$$N^{\max}_{\nu,\,\mathrm{PeV}}(2\pi) = 13 \cdot \frac{2\pi}{\Omega_{\mathrm{IC\,35}}} \sim 336$$

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

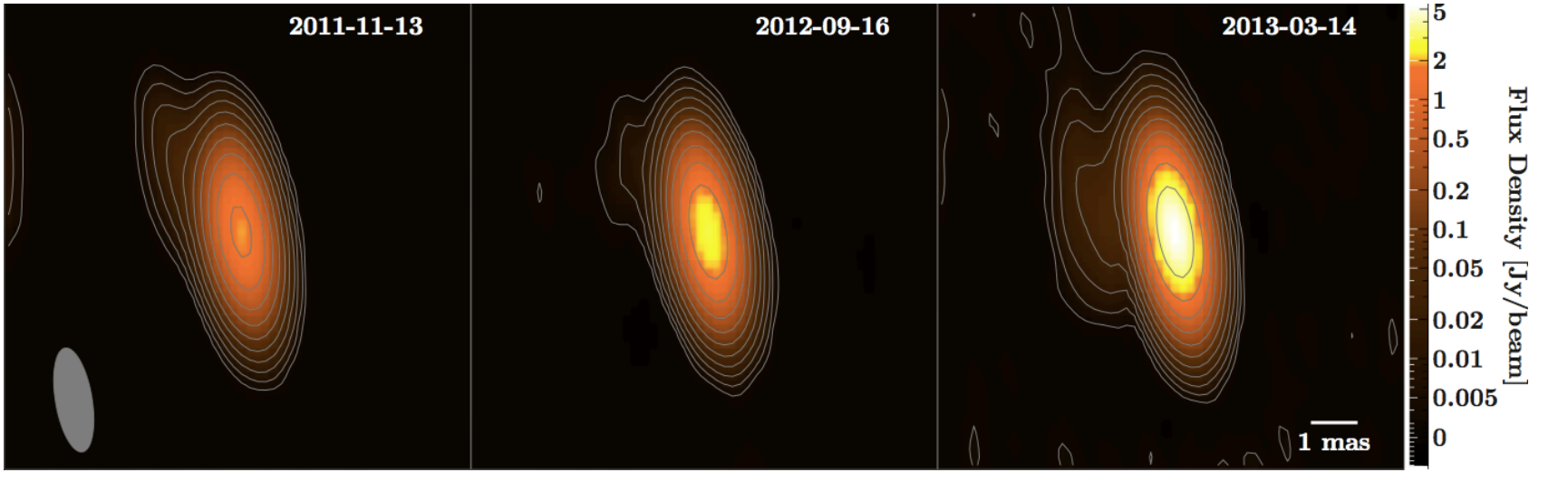
Calorimetric Output in BigBird field dominated by a single source:

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



Calorimetric Output in BigBird field dominated by a single source:

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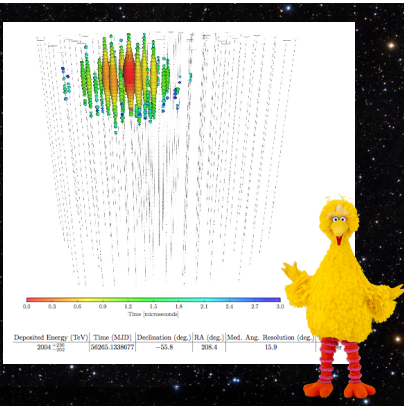
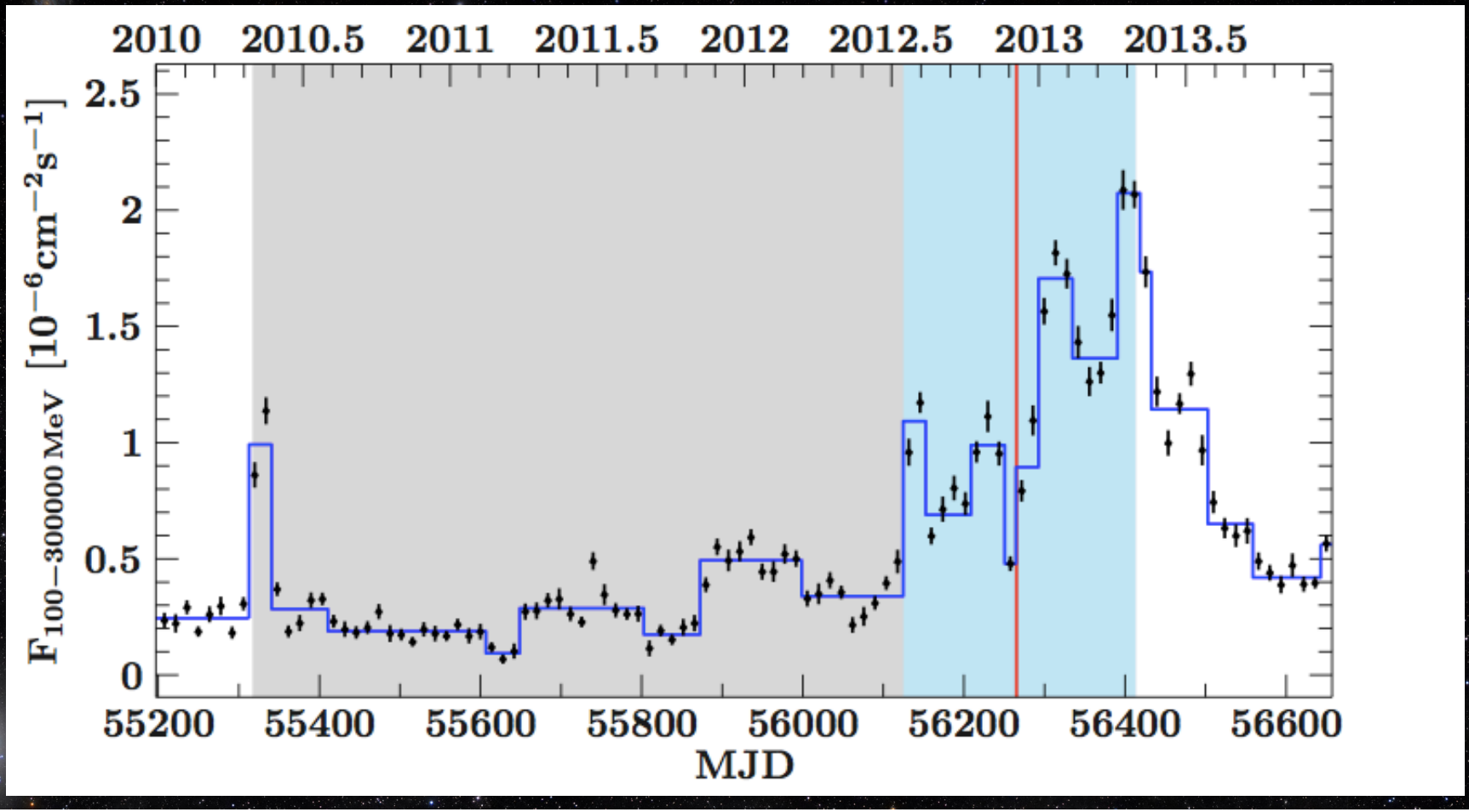
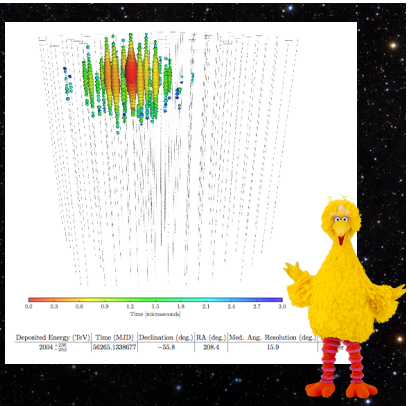


Gamma Outburst coincident with BigBird arrival time

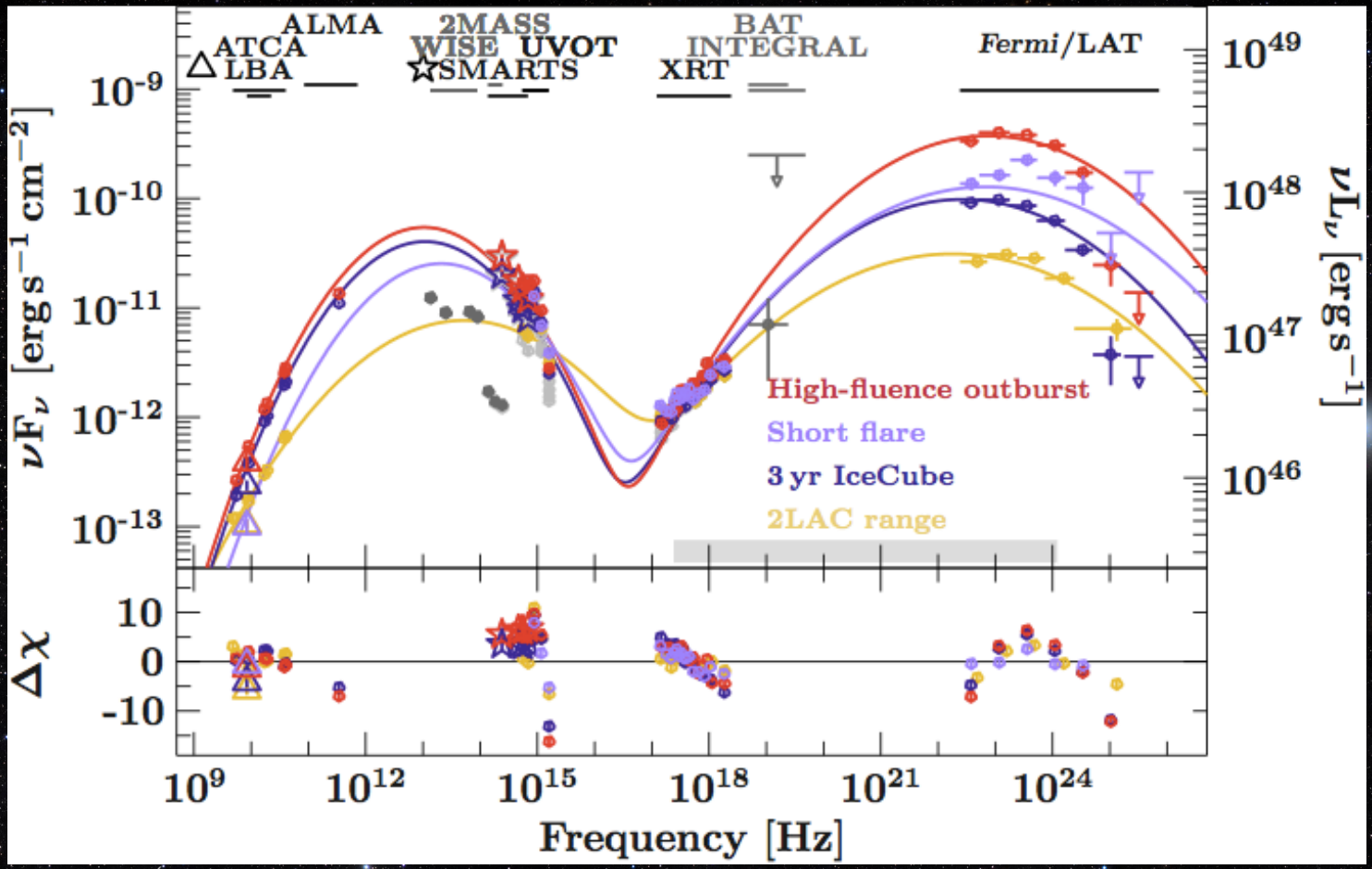


Calorimetric Output in BigBird field dominated by a single source:

PKS B1424-418

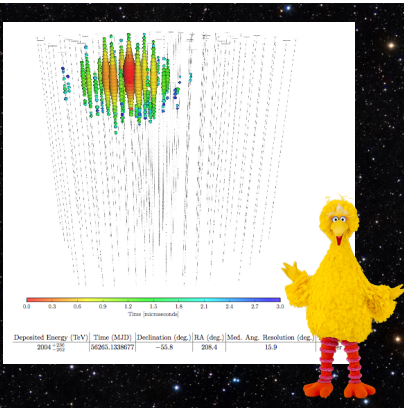


SED: High state over months ➔ High fluence



Calorimetric Output in BigBird field dominated by a single source:

PKS B1424-418



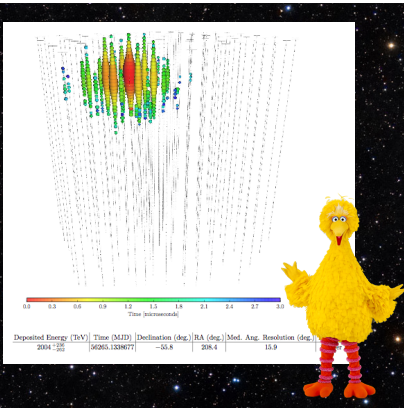
9-month outburst yields highest predicted neutrino count:

$$N^{\max}_{\nu,\mathrm{PeV}} \sim 4.5,\ N^{\mathrm{pred}}_{\nu,\mathrm{PeV}} \sim 0.11$$

Poisson probability: ~11%

Calorimetric Output in BigBird field dominated by a single source:

PKS B1424-418



Chance Coincidence?

~5%

Highest-energy neutrino (seen in the southern sky)

Most dramatic blazar outburst of the (far) southern sky

Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube

ATel #7856; *Sebastian Schoenen and Leif Raedel (III. Physikalisches Institut, RWTH Aachen University) on behalf of the IceCube Collaboration*
*on **29 Jul 2015; 20:47 UT***
Credential Certification: Marcos Santander (santander@nevis.columbia.edu)

Subjects: Neutrinos, Request for Observations

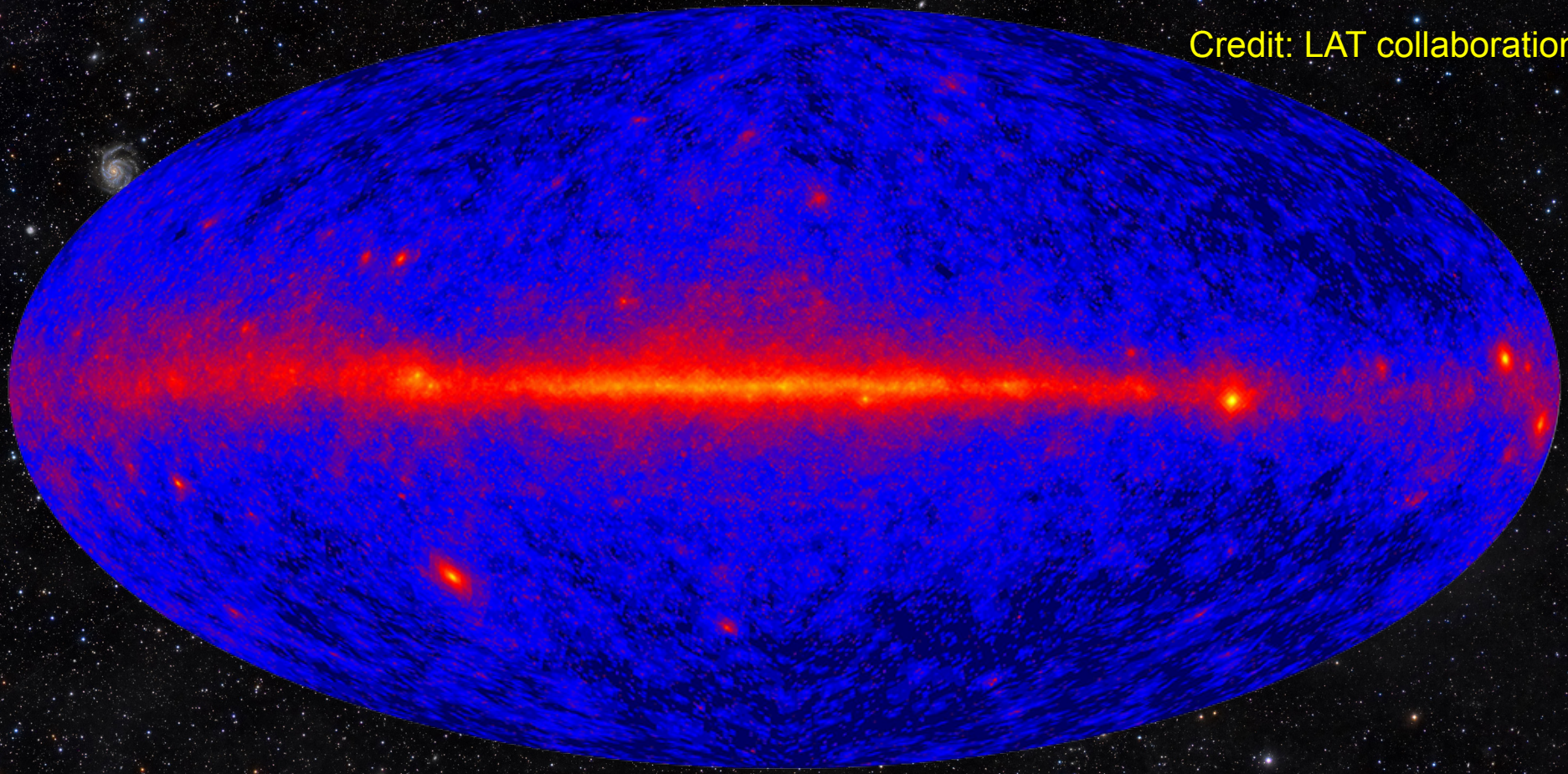
We observed a muon event with an energy of multiple PeV originating from a neutrino interaction in the vicinity of the IceCube detector. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole mostly sensitive to neutrinos in the TeV-PeV energy range. The event is the highest-energy event in a search for a diffuse flux of astrophysical muon neutrinos using IceCube data recorded between May 2009 and May 2015. It was detected on June 11th 2014 (56819.20444852863 MJD) and deposited a total energy of 2.6 +/- 0.3 PeV within the

- >2.6PeV muon track event
- Median Positional accuracy: 0.27°
- Closest Fermi blazar at ~3° offset

But:

- Only ~50% of all PeV events predicted to be associated with Fermi-catalog sources!

Could We Prove Blazar Population from 22(+15) Gamma Photons?

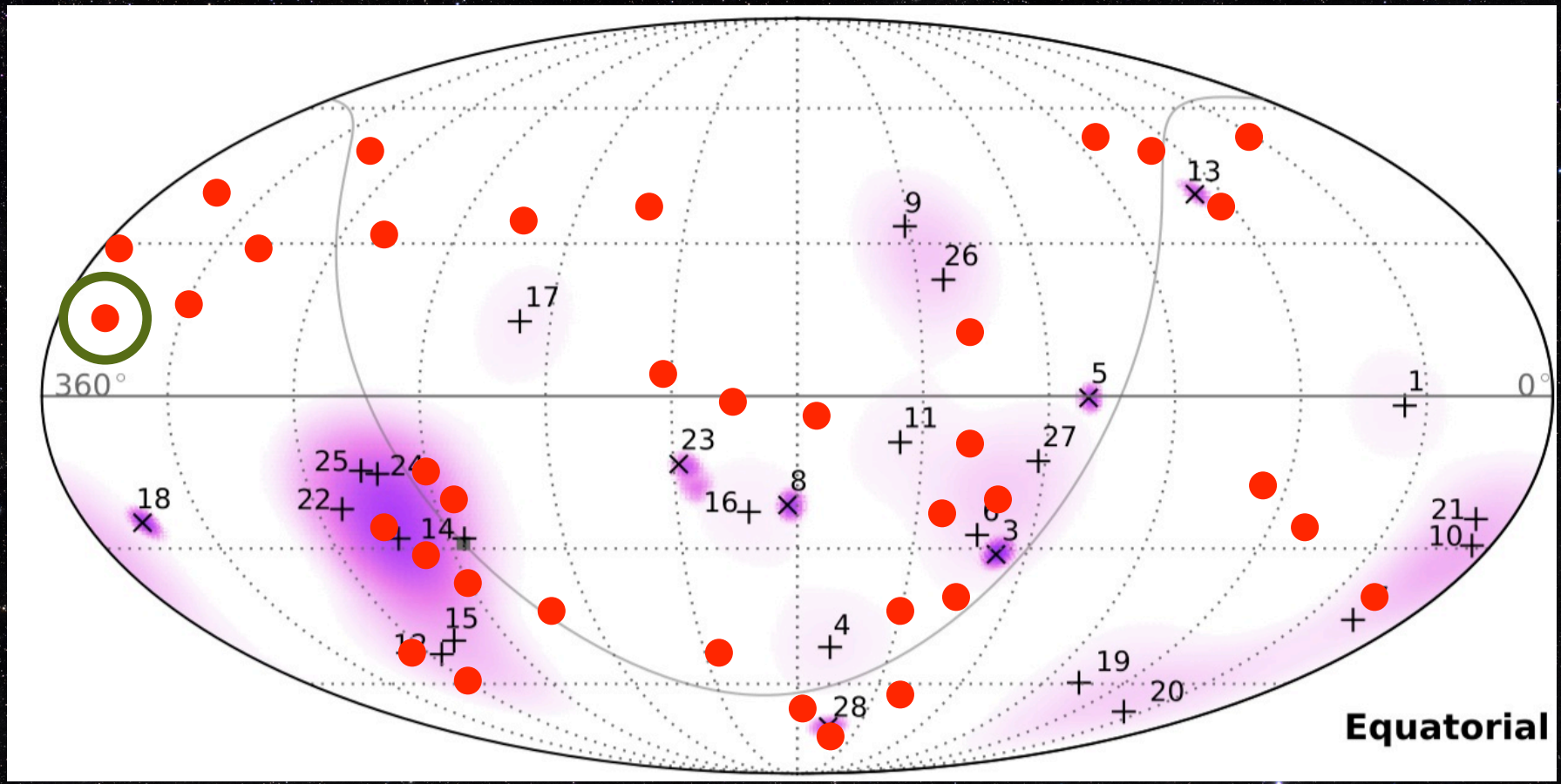


Credit: LAT collaboration

- Pick 22 photons from LAT's first 3 days (134.000 events)
- Add 15 random-position fake events

Could We Prove Blazar Population from 22(+15) Gamma Photons?

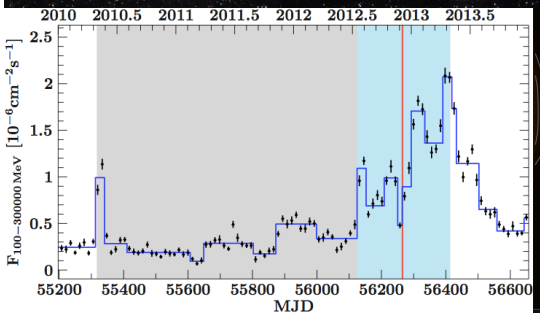
Aartsen et al. 2014

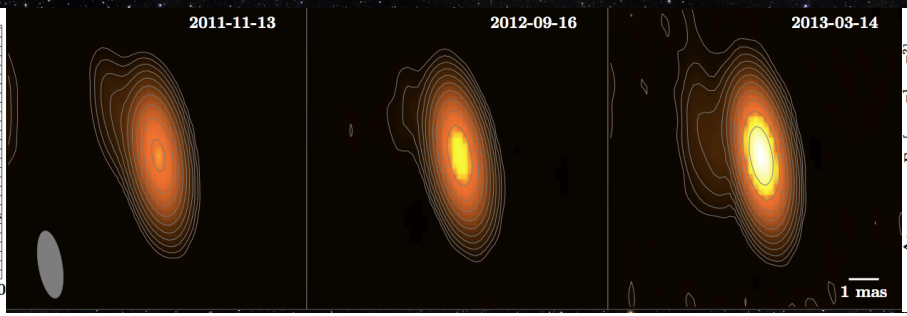


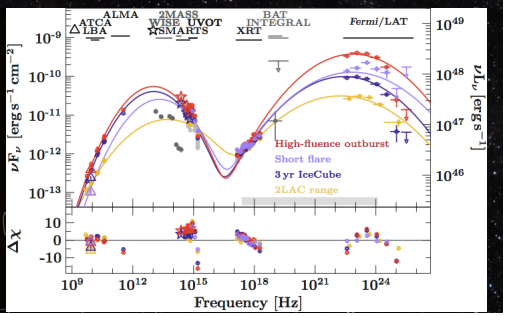
- Merge events and treat them like IceCube events (with appropriate LAT PSF for each event's energy)
  - ➢ Only one coincidence with bright source list: 3C454.3

Summary

- Integrated flux of FSRQs can explain the IceCube PeV signal
- First time that a single blazar can explain an individual PeV neutrino (~11% detection probability; 5% chance coincidence)
- Association expected for ~50% of all PeV events

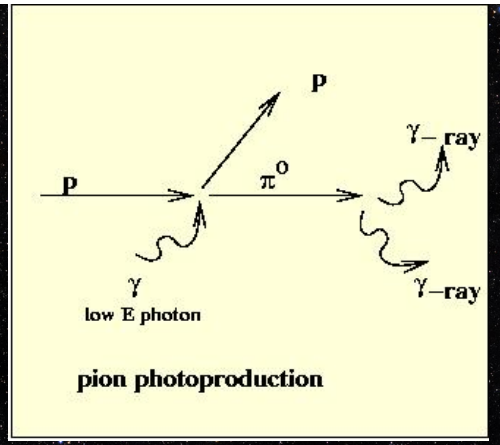


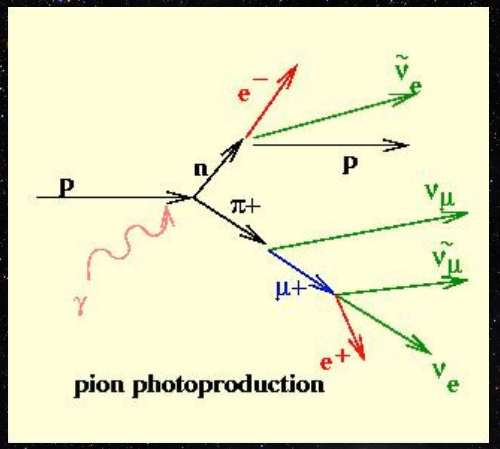




Pion Photoproduction

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





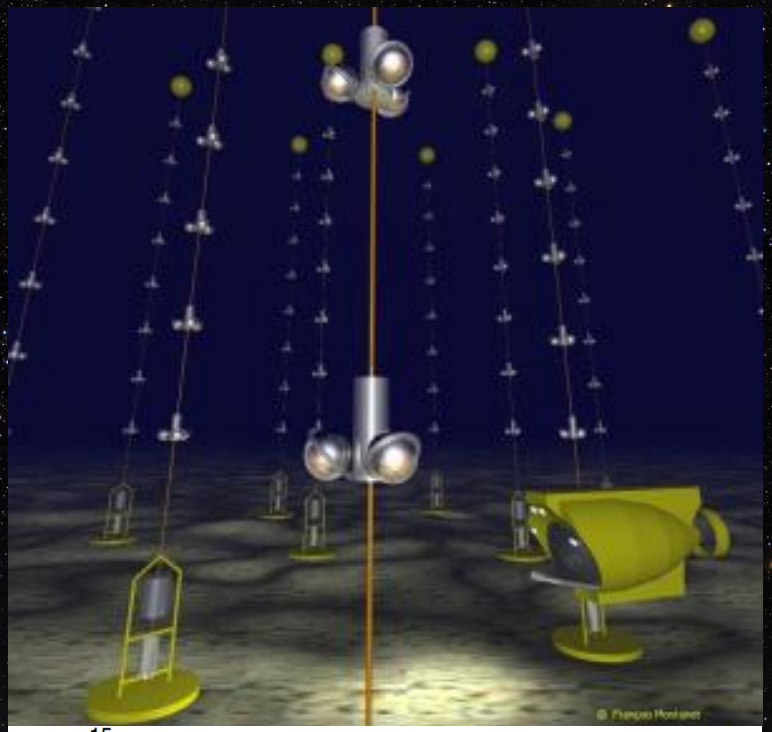
$$F_\gamma = 1/3 \cdot F_\pi + 1/4 \cdot 2/3 \cdot F_\pi = 1/2 \cdot F_\pi$$

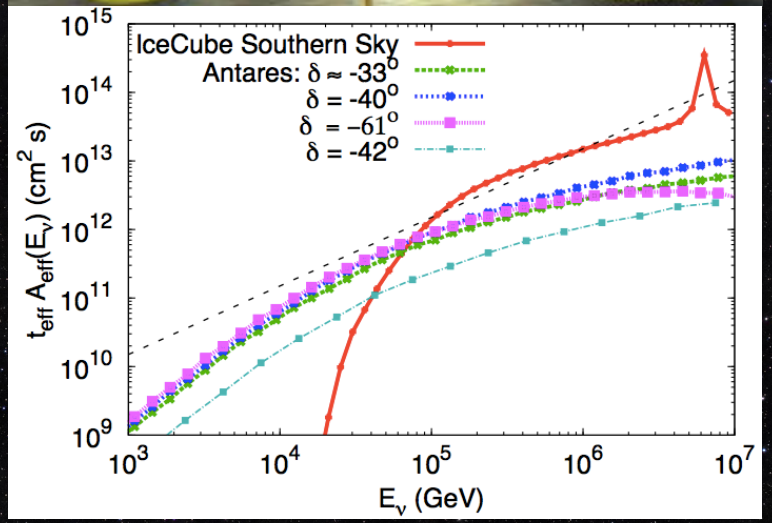
$$F_\nu = 2/3 \cdot 3/4 \cdot F_\pi = 1/2 \cdot F_\pi$$

$$F_\nu = F_\gamma$$

Follow-Up with ANTARES

- Neutrino Telescope in the Mediterranean (Water Ćerenkov Detector)
- In operation since 2008
- Angular resolution: 0.4°
- Highest sensitivity in TANAMI sky region for TeV neutrinos





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

ANTARES Results 1

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

Source	N_{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

ANTARES Results 2

- ANTARES detects zero events from PKS B1424-418 between Jul 2012 and Dec 2013
- E^{-2} Flux limit: 4.2×10^{-8} GeV $cm^{-2}s^{-1}$

- Positional coincidence with 3 IceCube neutrinos: IC35 (BigBird), IC16, IC25
- Similar to situation for 1759-396 in the Bert field

If PKS B1424-418 is associated with the 2PeV neutrino:

⇒ Association with IC16 and IC25 very unlikely

⇒ Neutrino spectrum flat or even peaked