Origin of IceCube Astrophysical Neutrinos

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Recent detection of high-energy neutrinos (approximately 30 TeV – 2 PeV range), most likely from astrophysical sources, by IceCube neutrino observatory ushers the era of Neutrino Astronomy. Poor angular resolutions of the dominantly cascade-type events prohibit identification of the sources, however. A cluster of 5 cascade events near the Galactic Center, although statistically not significant with current data, and an additional 3 cascade events correlated with the Fermi Bubbles hint plausible Galactic origin of a subset of the neutrino events detected by IceCube. An additional, most likely extragalactic, flux component is required to explain the full published data set. Together with neutrino fluxes from the Galactic Center activity and the resulting Fermi Bubbles it will be shown that an extragalactic neutrino flux, most likely from relativistic blast waves of exploding stars, could explain IceCube detection in a multi-source-class scenario.

Extragalactic Path

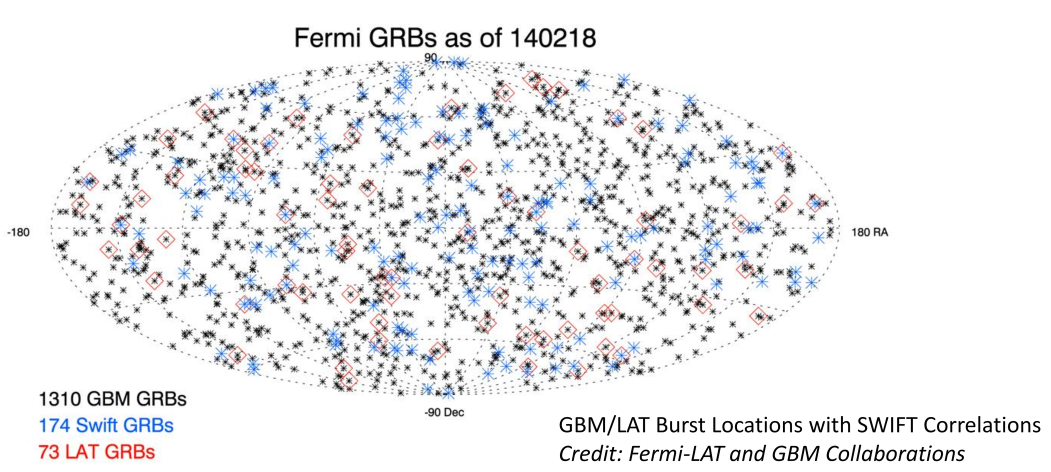
Gamma Ray Bursts

The most powerful explosion in the universe!

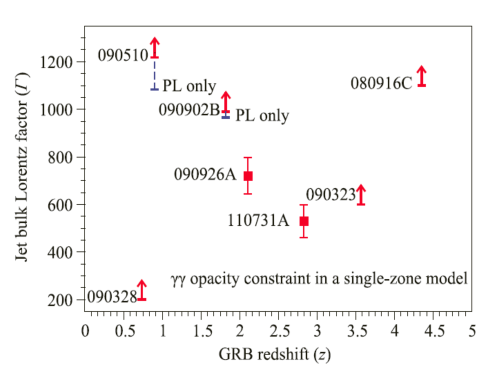
- Long duration (>2 s) and short duration (<2 s) GRBs
- Observed rate: ≈2 per day for long GRBs
- Typical redshift: z=1-2 (detected up to z~9)
- Isotropic-equivalent γ-ray power: 10^{52} erg/s

Powerful sources are required to produce >10^18 eV energy/nucleon. GRBs are potential sources of UHECRs
- Waxman 1995, Vietri 1995

Fermi GRBs as of 140218



GBM/LAT Burst Locations with SWIFT Correlations
Credit: Fermi-LAT and GBM Collaborations



Waxman-Bahcall GRB ν flux calculations is based on photopion interactions of UHECRs with prompt γ rays

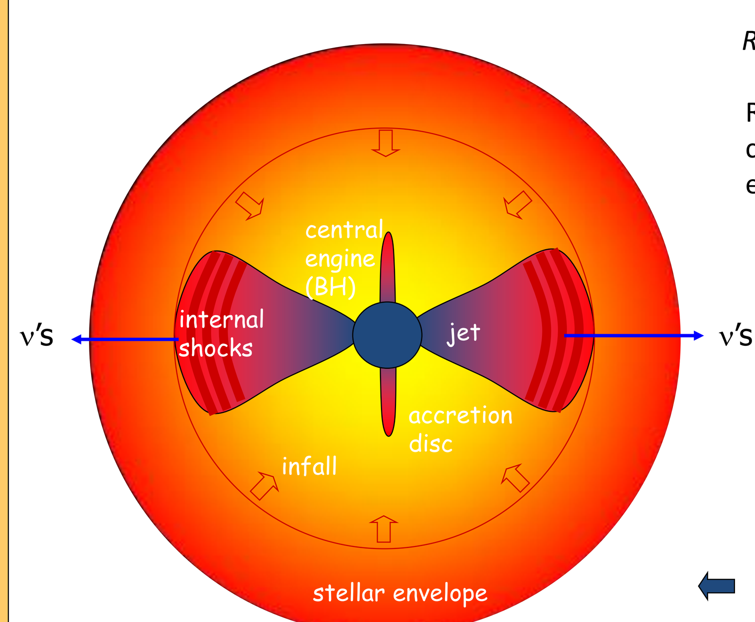
Photopion production efficiency scales with GRB bulk Lorentz factor as ~ $1/\Gamma^4$
- Razzaque+08, Ackermann+11, Crumley+Kumar12

Large Γ>>100 inferred from Fermi-LAT data can reduce ν flux and explain lack of GRB neutrinos

Gehrels & Razzaque 2013

ν's precursor to GRBs / choked GRBs

Razzaque, Meszaros & Waxman 2003



Relativistic jets formed inside the collapsing star may break through the envelope (GRB) or choke inside

→ Optically thick shocks in jet
→ High density of thermal γ-rays and target protons

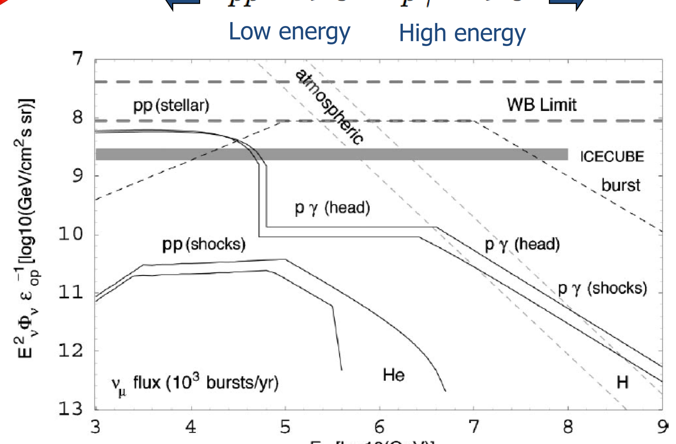
Neutrino production takes place dominantly by *pp* interactions in the shocks and by *p*γ interactions in the head of the jet

$pp \to \nu' s$ Low energy
$p\gamma \to \nu' s$ High energy

Diffuse neutrino flux

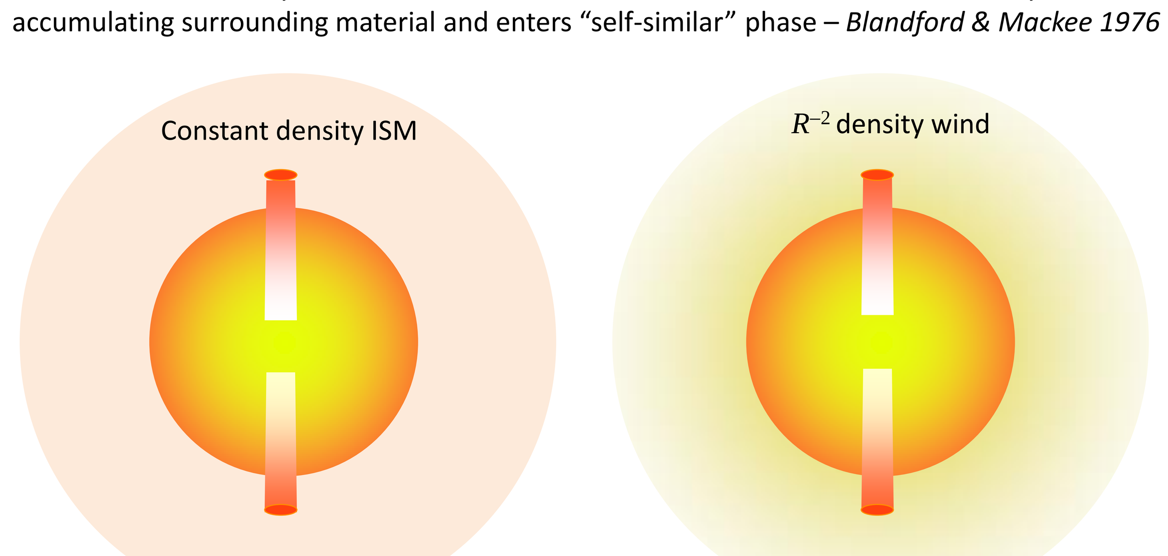
- Depends on the progenitor star
- No. of choked jets can be larger than the no. of obs. GRBs
- Choked GRB flux is not constrained by IceCube
- Can contribute to the IceCube cosmological ν flux

See also, Murase & Ioka 2013



ν's from GRB Blast Waves

GRB blast wave initially coasts with a constant bulk Lorentz factor and slows down by accumulating surrounding material and enters "self-similar" phase – *Blandford & Mackee 1976*



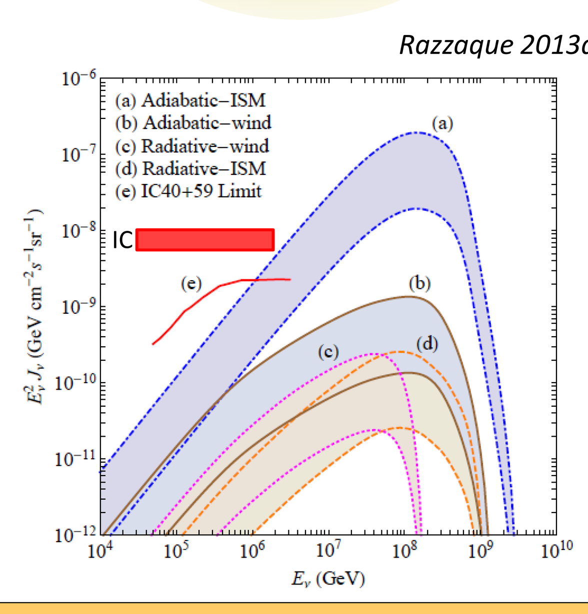
Razzaque 2013a

Time scale for BW deceleration (similar to non-relativistic "Sedov time") differs

GRB blast wave forward-shock model is highly successful in describing afterglow observation as synchrotron radiation

UHECR interactions with afterglow synchrotron photons in the blast wave produce PeV-EeV neutrinos

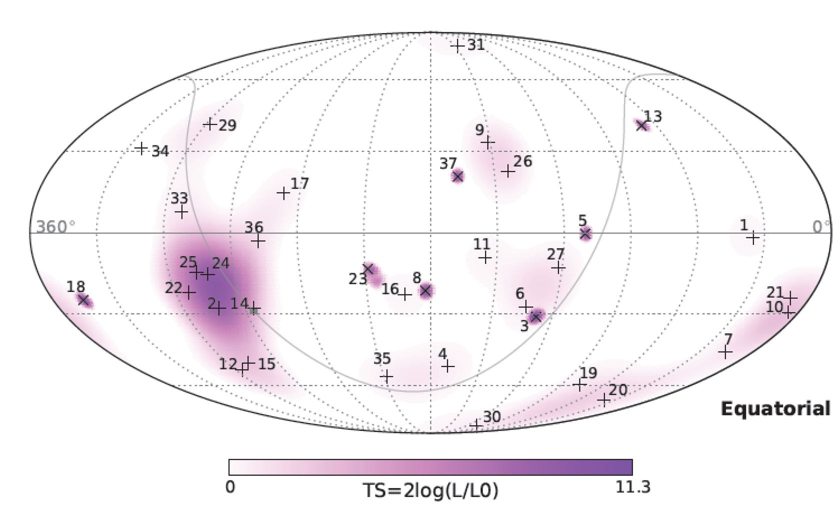
Long (day) time scale of blast wave neutrinos are not constrained by IC data

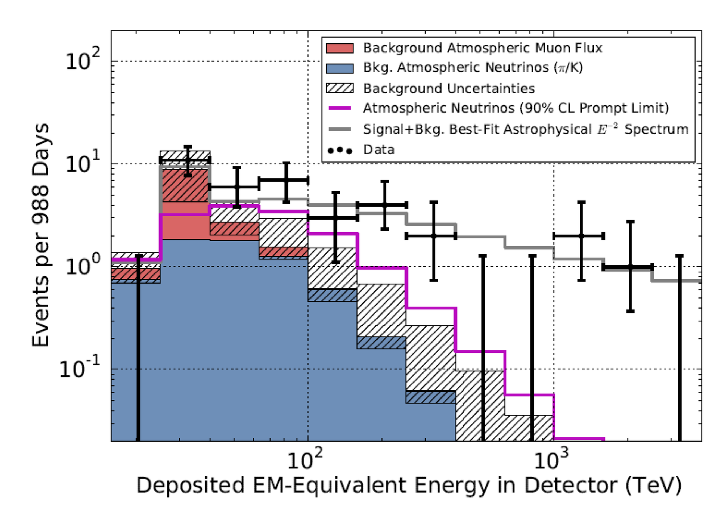


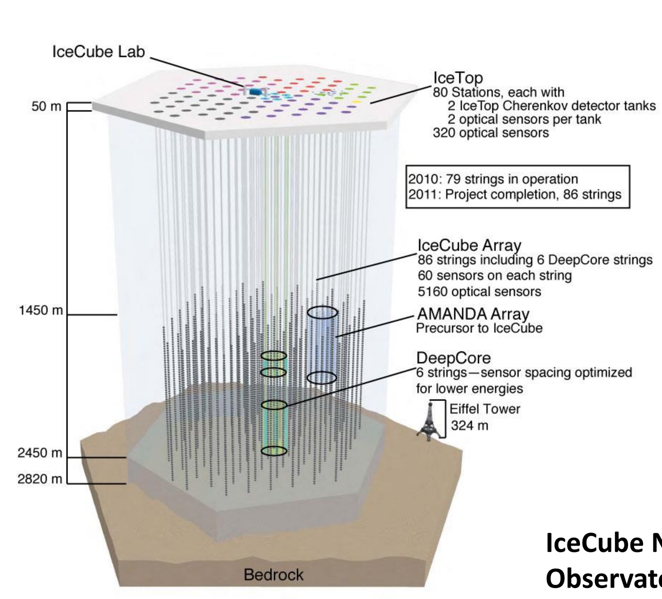
Discovery of Astrophysical ν's by IceCube

37 Events, 30 TeV – 2 PeV, 5.7σ above atmospheric ν background

IceCube Collaboration 2012, 2013, 2014



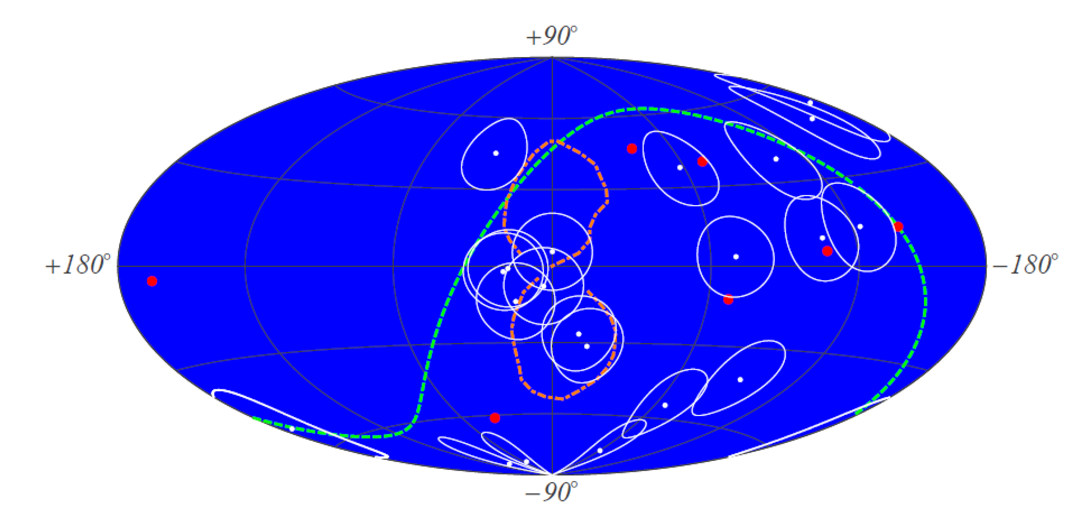




IceCube Neutrino Observatory

Milky Way

Galactic Center Region



5 shower-like events are concentrated at the Galactic Center region

Rather hard spectrum, $E^{-\Gamma}$, Γ≈2.0-2.3

Razzaque 2013
Ahlers & Murase 2013
Anchordoqui et al. 2014

Flux from within a 8° circle around the GC

[solid angle $\Omega_{GC} = 2\pi(1-\cos 8°) = 0.06$ sr]

$$E^2\Phi(\nu_e+\nu_\mu+\nu_\tau) \sim \begin{cases} 1.3\times 10^{-9}\ \mathrm{GeV\,cm^{-2}\,s^{-1}}; & (100\ \mathrm{TeV}) \\ 1.1\times 10^{-9}\ \mathrm{GeV\,cm^{-2}\,s^{-1}}; & (1\ \mathrm{PeV}), \end{cases}$$

Atmospheric flux from within a 8° circle around the GC is negligible at PeV

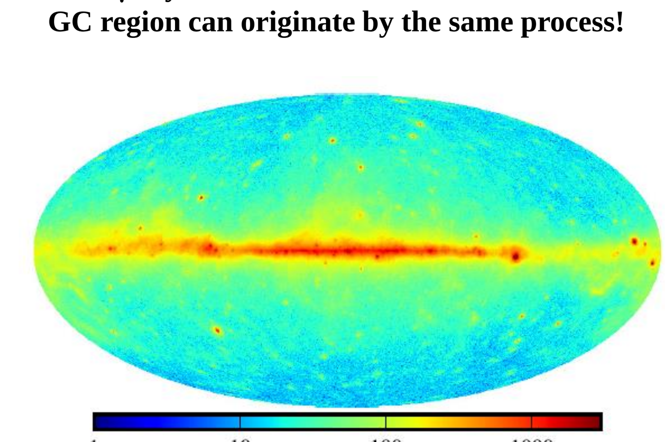
$$E^2\Phi(\nu_\mu) = 5.0\times 10^{-11}(E/\mathrm{PeV})^{-1.6}\ \mathrm{GeV\,cm^{-2}\,s^{-1}}$$

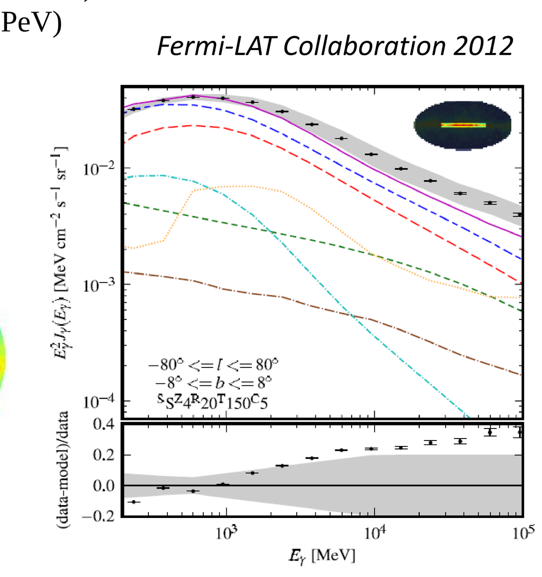
Intriguingly, neutrino flux from the GC region is consistent with an extrapolation of the π^0 decay γ-ray flux detected by Fermi-LAT at up to 100 GeV

$E^2\,\Phi_\gamma \approx 7.6\times 10^{-9}$ GeV cm – 2 s $^{-1}$ (100 TeV)
$E^2\,\Phi_\gamma \approx 7.6\times 10^{-9}$ GeV cm – 2 s $^{-1}$ (1 PeV)

Fermi-LAT Collaboration 2012

Both γ ray and ν detected from the GC region can originate by the same process!



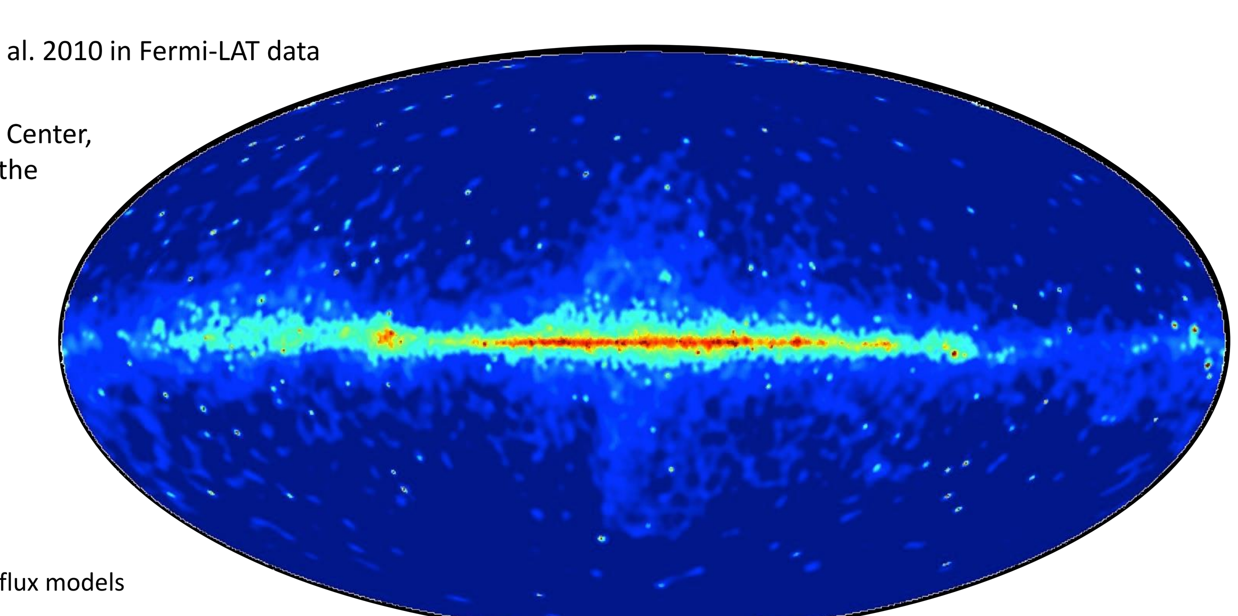


Fermi Bubbles at the Galactic Center

Discover by Finkbeiner et al. 2010, Su et al. 2010 in Fermi-LAT data

Giant globular structures at the Galactic Center, extending up to 9 kpc below and above the Galactic plane.

Fermi Bubbles are better visible at high energies → Hard spectrum
Seem to have well-defined boundary → sharp edges
Uniform projected intensity over the whole bubble surface



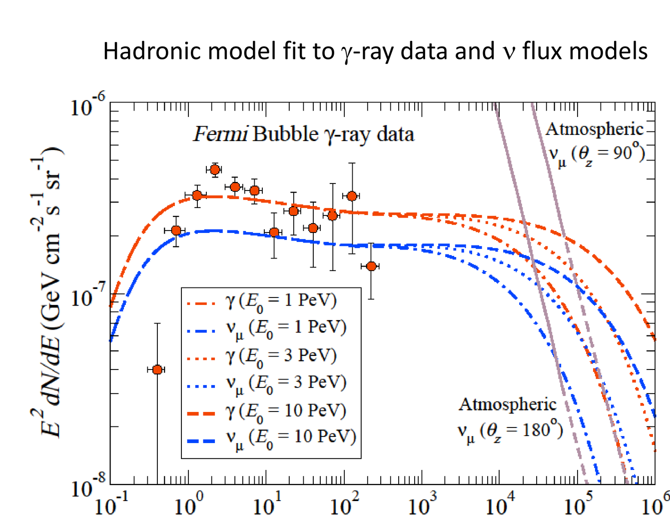
A hadronic or a leptonic mechanism of γ ray production from Fermi Bubbles has profound implications for its age and origin.

Intense supernova activity near the Galactic Center inflates the Fermi Bubbles by a bipolar wind in the hadronic model

Hadronic model predicts ν emission from Fermi Bubbles

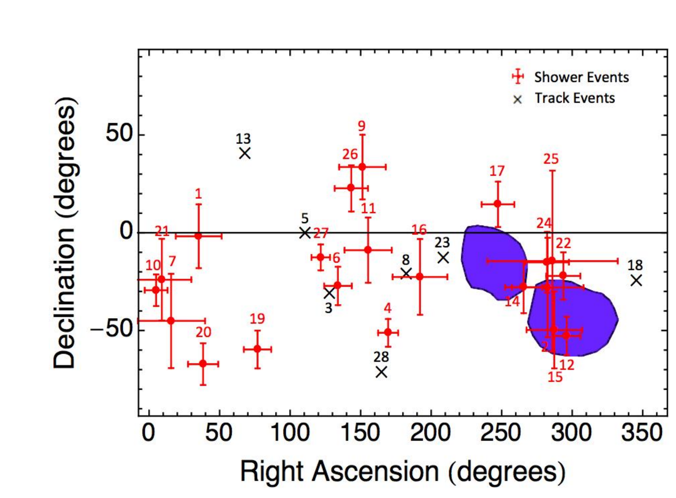
Crocker & Aharonian 2011
Lunardini & Razzaque 2012

Hadronic model fit to γ-ray data and ν flux models

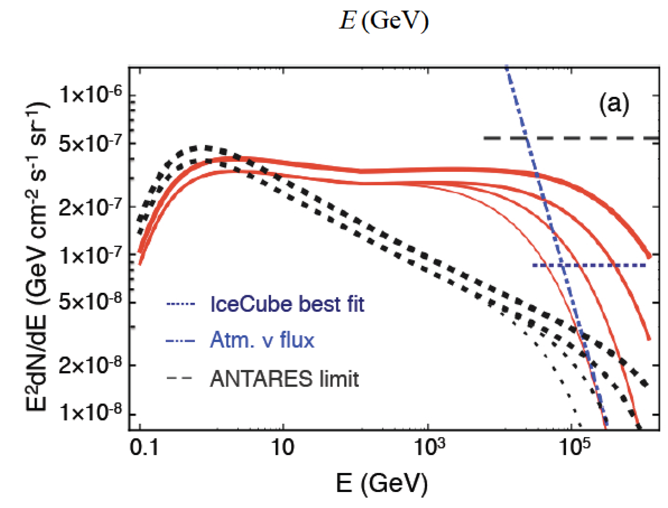


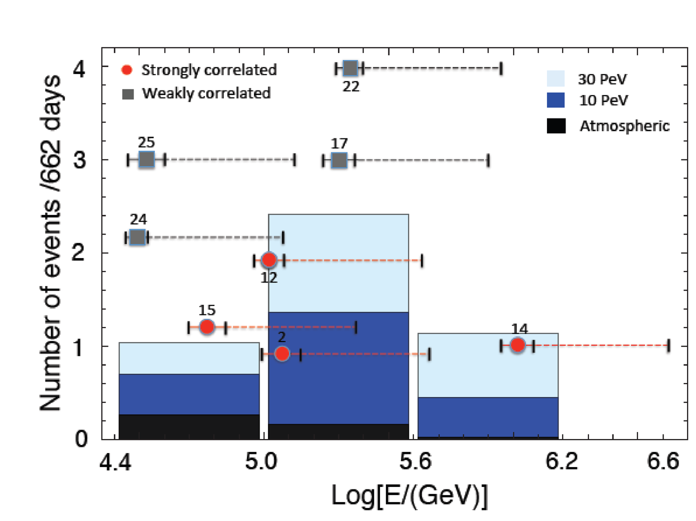
Some of the IceCube ν's can be explained with FB ν flux
- Lunardini, Razzaque, Theodoseau & Yang 2014

4 strongly correlated events (central coordinate values within FB)
4 weakly correlated events (error ellipses touching FB contours)



IceCube events correlated with FB and expected events





	log(E/GeV)			total
	4.4 – 5	5 – 5.6	5.6 – 6.2	
E_0/PeV = 1	0.23 [0.02]	0.19 [0.03]	0.01 [0]	0.43 [0.05]
E_0/PeV = 3	0.46 [0.04]	0.64 [0.1]	0.11 [0.02]	1.2 [0.16]
E_0/PeV = 10	0.7 [0.07]	1.37 [0.21]	0.44 [0.09]	2.51 [0.37]
E_0/PeV = 30	1.03 [0.1]	2.42 [0.38]	1.14 [0.24]	4.59 [0.72]
Background	0.25 [0.07]	0.16 [0.06]	0.02 [0.01]	0.43 [0.14]

References: *S. Razzaque 2013a, Phys. Rev. D88, 103003*
S. Razzaque 2013b, Phys. Rev. D88, 081302(R)
C. Lunardini & S. Razzaque 2012, Phys. Rev. Lett. 108, 221102
C. Lunardini, S. Razzaque, T. Theodoseau & L. Yang 2014, Phys. Rev. D, in press
S. Razzaque, P. Meszaros & E. Waxman 2003, Phys. Rev. D68, 083001

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