Multimessenger studies of blazars

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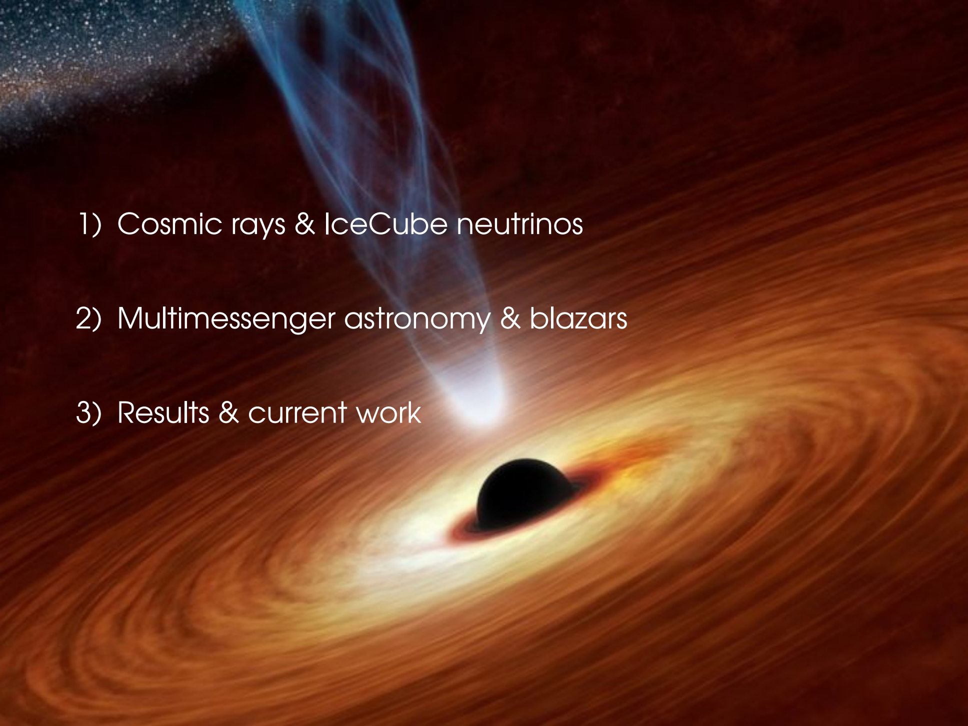
GRAPPA GRavitation AstroParticle Physics Amsterdam

TANAMI

Fermi Gamma-ray Space Telescope

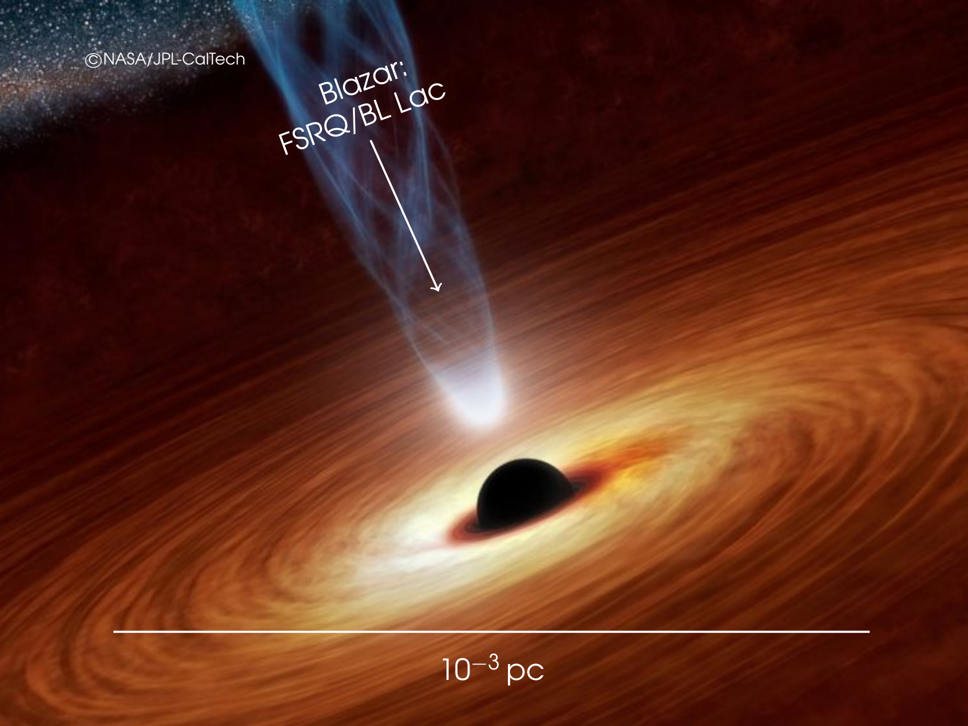
@FeKrauss

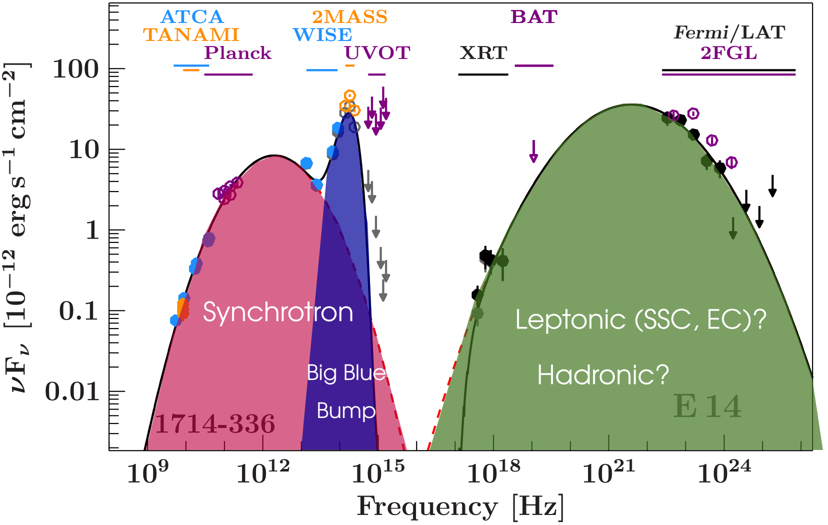


1) Cosmic rays & IceCube neutrinos

2) Multimessenger astronomy & blazars

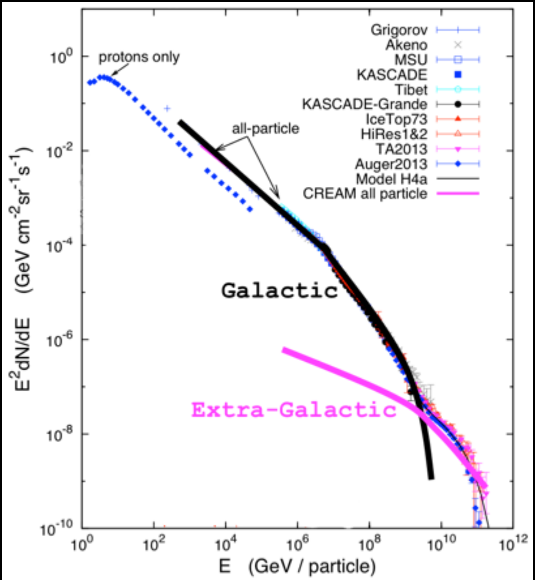
3) Results & current work


©NASA/JPL-CalTech
Blazar:
FSRQ/BL Lac
10^{-3} pc



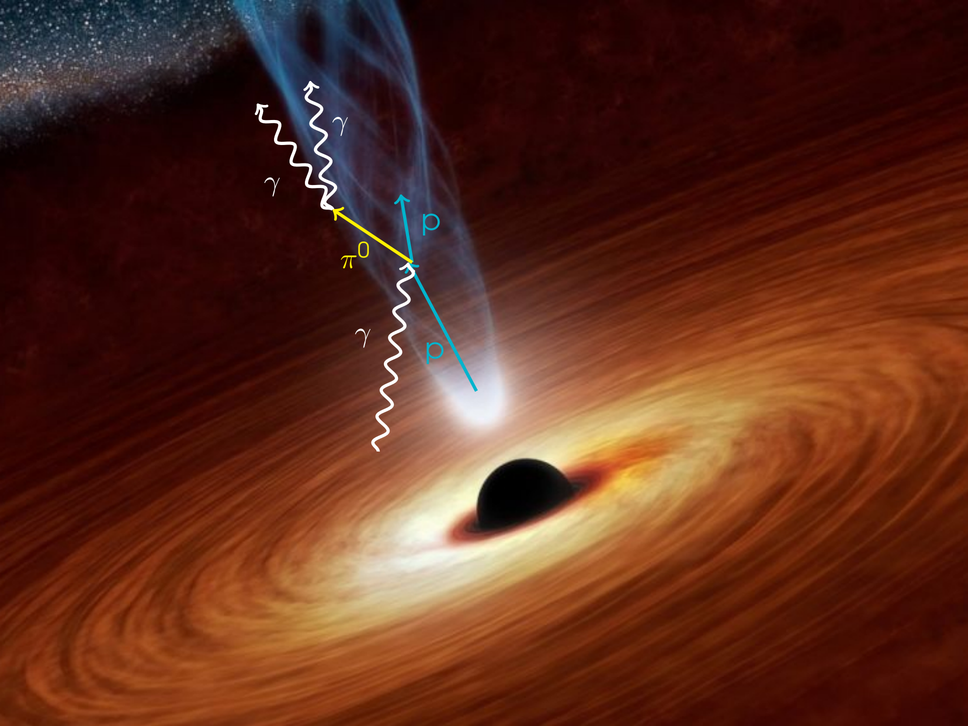
Krauß F., Kadler M., et al., A&A, 2014, 556, L7

The cosmic ray spectrum

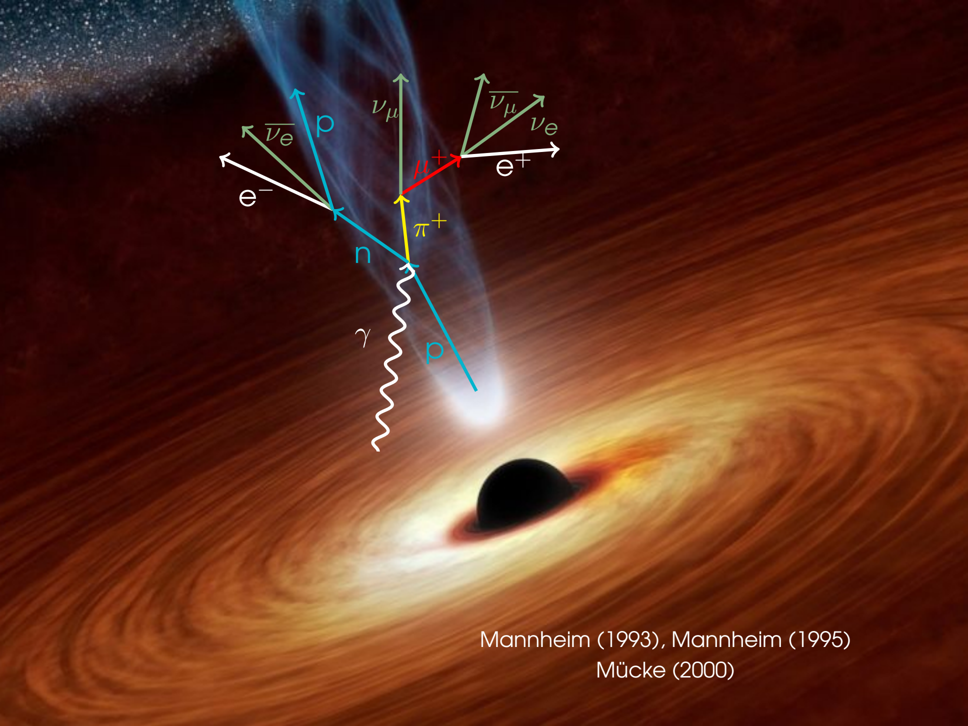


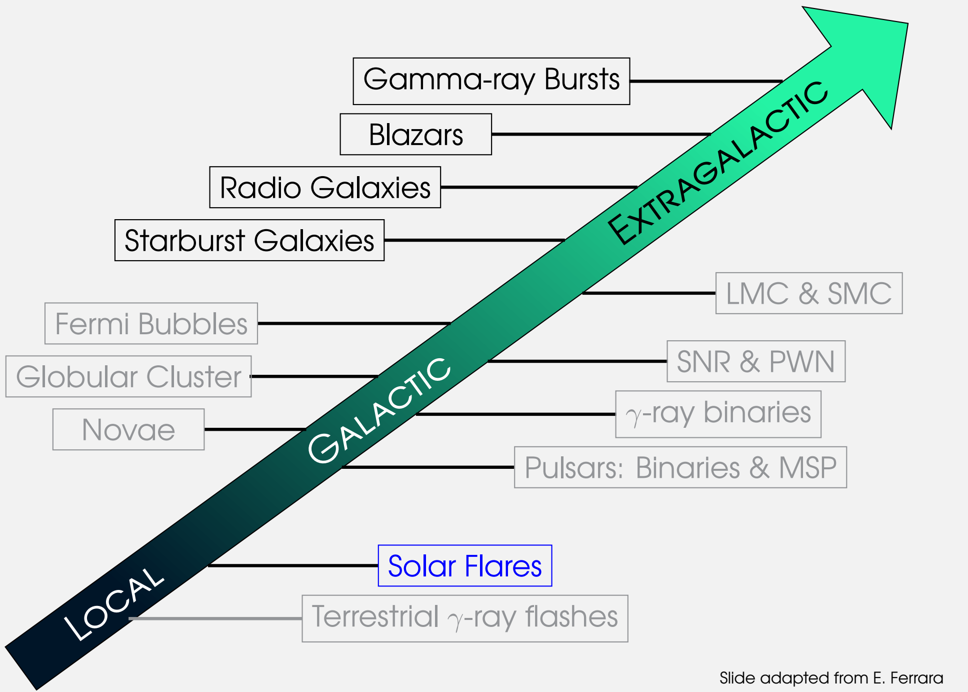
after Hillas 2006

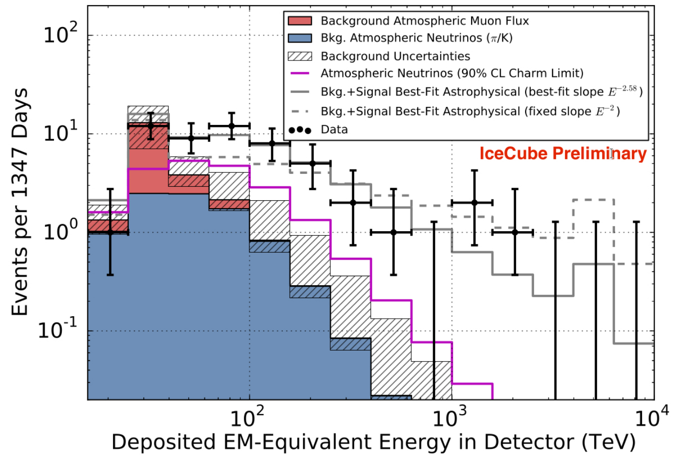
- ⋆ Which sources can accelerate particles to Ultra-High Energies and how?
- ⋆ How do we identify the sources of UHECR?



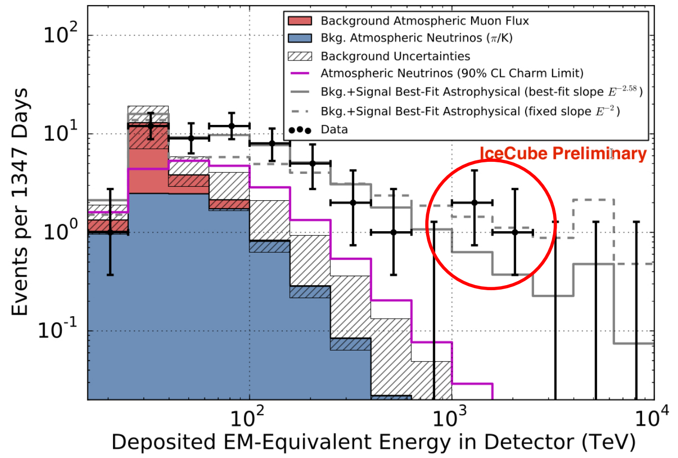
γ
γ
p
π0
γ
p


$\overline{\nu_e}$
p
ν_μ
$\overline{\nu_\mu}$
ν_e
μ^+
e^+
e^-
π^+
n
γ
p
Mannheim (1993), Mannheim (1995)
Mücke (2000)


Gamma-ray Bursts
Blazars
Radio Galaxies
Starburst Galaxies
EXTRAGALACTIC
LMC & SMC
Fermi Bubbles
SNR & PWN
Globular Cluster
GALACTIC
γ-ray binaries
Novae
Pulsars: Binaries & MSP
Solar Flares
LOCAL
Terrestrial γ-ray flashes
Slide adapted from E. Ferrara



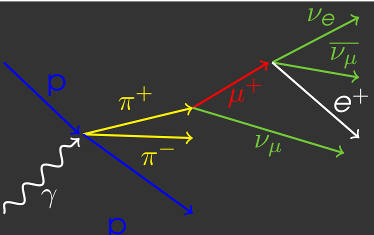
IceCube Collaboration 2013, 2013, 2014, 2015



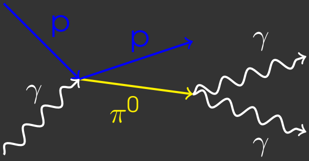
IceCube Collaboration 2013, 2013, 2014, 2015

Detection of high-energy photons is not proof for hadronic processes!

$\rightarrow$ Upscattering of Synchrotron photons by relativistic electrons via Inverse Compton



$$F_\nu = \frac{2}{3} \cdot \frac{3}{4} F_\pi = \frac{1}{2} F_\pi$$

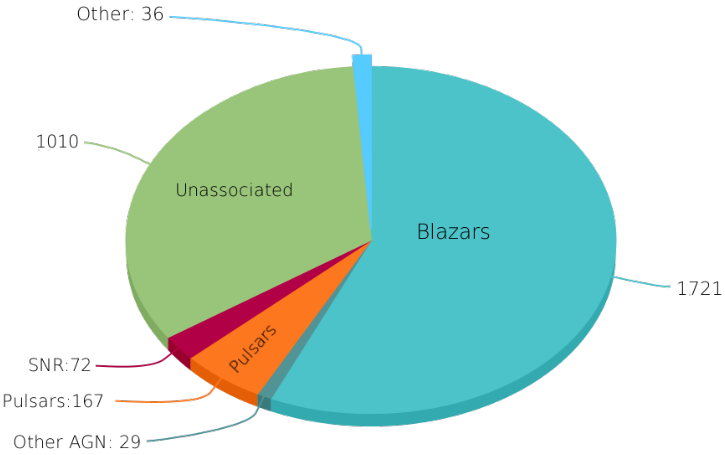


Mannheim 1993,1995
Mücke 2000

$$F_\gamma = \frac{1}{3} F_\pi + \frac{1}{4} \cdot \frac{2}{3} F_\pi = \frac{1}{2} F_\pi$$

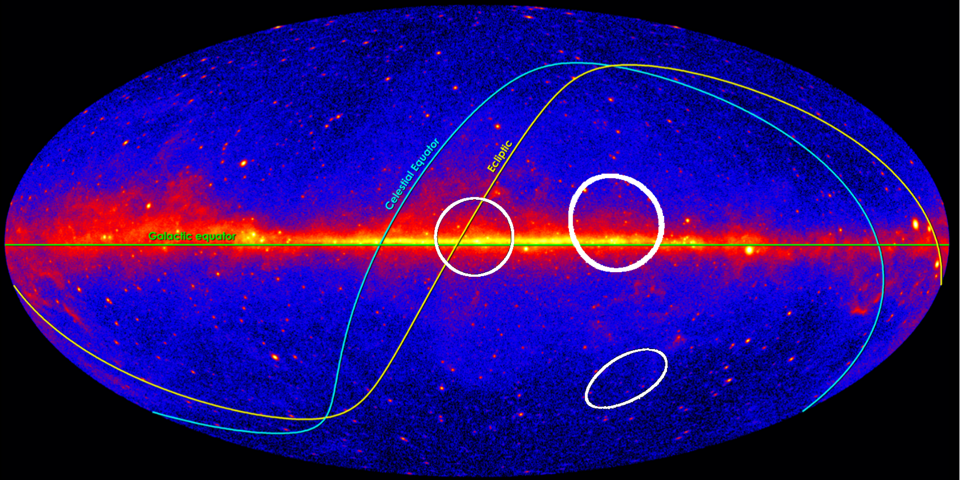
BUT: $F_{\gamma-\mathrm{ray}} \neq F_\nu$

HIGH ENERGY PHOTONS AS TRACERS OF NEUTRINO EMITTERS


Other: 36
1010
Unassociated
Blazars
1721
SNR:72
Pulsars
Pulsars:167
Other AGN: 29

HAS A NEUTRINO BEEN ASSOCIATED WITH A HIGH-ENERGY PHOTON EMITTER?

MAYBE!

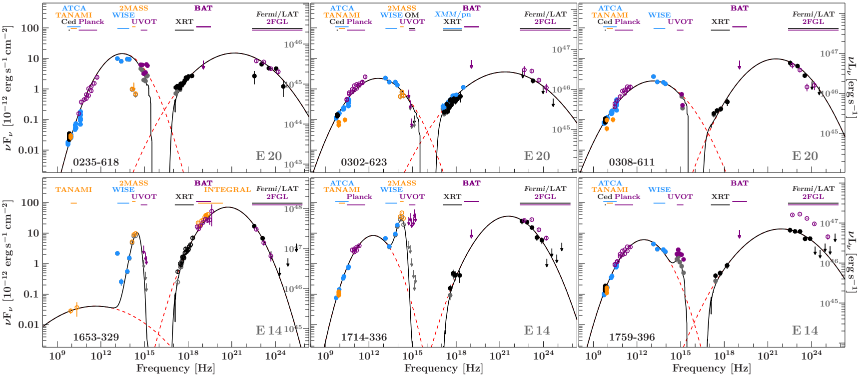

Celestial Equator
Ecliptic
Galactic equator

RESULTS

Cumulative search: no significant counterparts (Glüsenkamp et al. 2016)

Contribution from Blazars & Pulsar Wind Nebulae (PWNe; Padovani et al. 2014)?

Blazars as a class capable of producing observed neutrino flux (Krauss et al. 2014);



Krauss et al. 2014

Source	$F_\gamma(\mathrm{erg\,cm^{-2}\,s^{-1}})$	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

Krauss et al. 2014

Blazars & AGN

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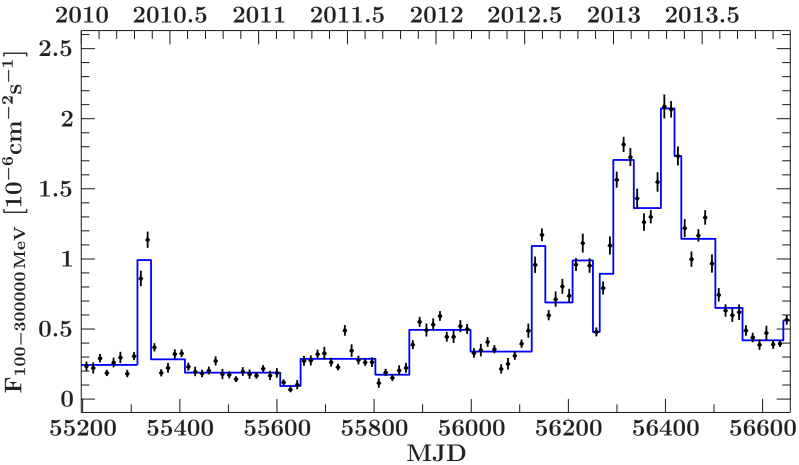
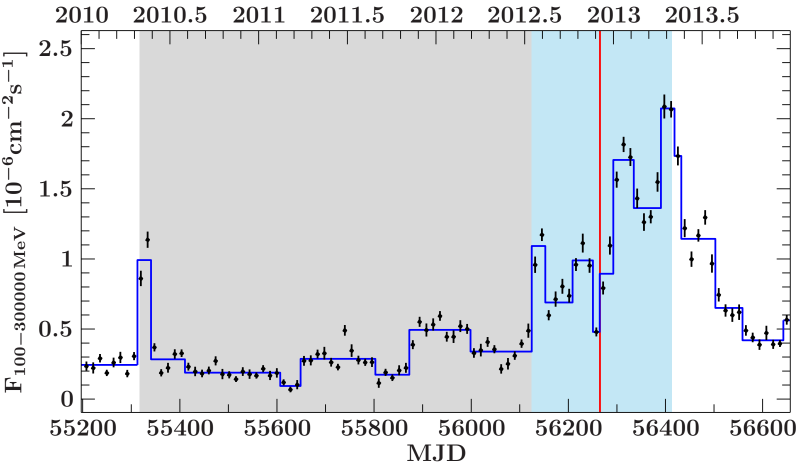
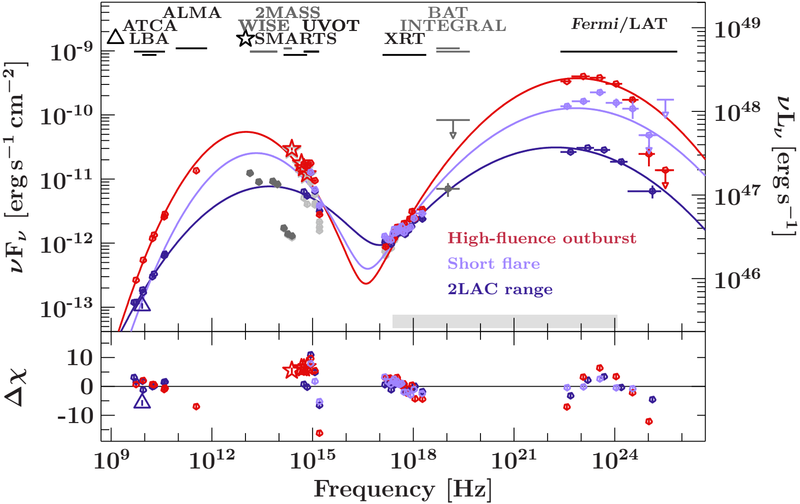
- Constraints on neutrino spectrum (ANTARES&TANAMI collaborations 2015)
- Coincidence of blazar outburst and high-energy neutrino event (Kadler, Krauss et al. 2016)


2010
2010.5
2011
2011.5
2012
2012.5
2013
2013.5
2.5
2
1.5
1
0.5
0
$F_{100-300000\,\mathrm{MeV}}$ $[10^{-6}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
55200
55400
55600
55800
56000
56200
56400
56600
MJD



2010
2010.5
2011
2011.5
2012
2012.5
2013
2013.5
2.5
2
1.5
1
0.5
0
$F_{100-300000\,\mathrm{MeV}}\ [10^{-6}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
55200
55400
55600
55800
56000
56200
56400
56600
MJD



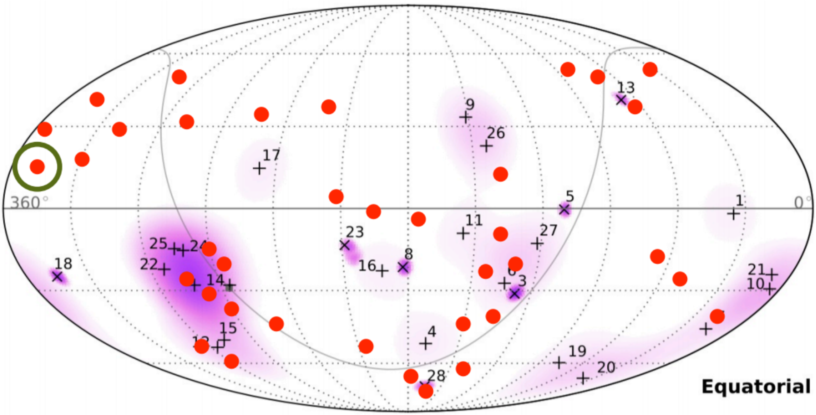
Variability as indicator for association!

Conclusions

- ⋆ Association not expected for each HE neutrino
- ⋆ Connection between high-energy (**not LAT!**) flux and neutrino flux
- ⋆ Blazars & AGN are the most promising candidates
- ⋆ Currently extending study to 100 TeV
- ⋆ Track events are promising for direct association
- ⋆ Further blazar flares promising for ruling out/confirming blazar hypothesis

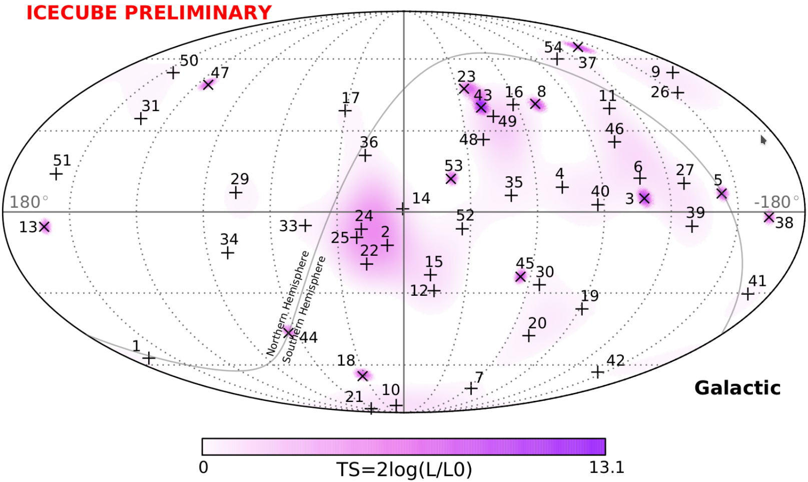
BACKUP

37 LAT photons



(after IceCube Collaboration 2014)

→ Only 1 photon associated with a resolved source, a blazar


ICECUBE PRELIMINARY
Galactic
180°
-180°
Northern Hemisphere
Southern Hemisphere
0
TS=2log(L/L0)
13.1

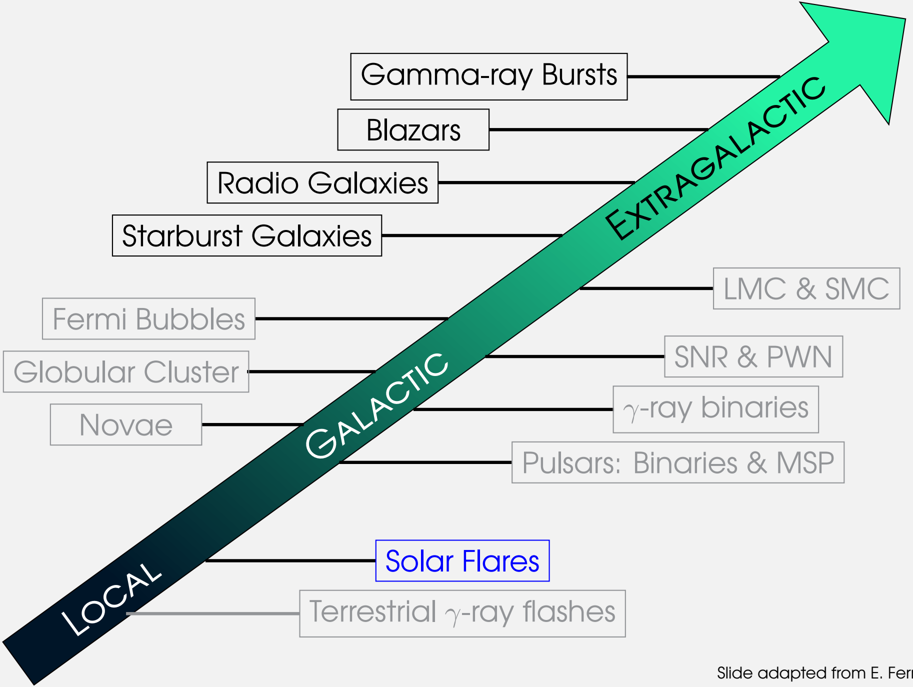
Galactic sources are not capable of producing PeV neutrinos

Pulsars: Eichler 1978, Harding et al. 1990, Anchordoqui et al. 2003, Link & Burgio 2005, 2006, Bhadra et al. 2008

Binaries: Gaisser et al. 1985, Eichler et al. 1993, Levinson 2001, Bednarek et al. 2005, Razzaque et al. 2010, Sitarek et al. 2012, 2014

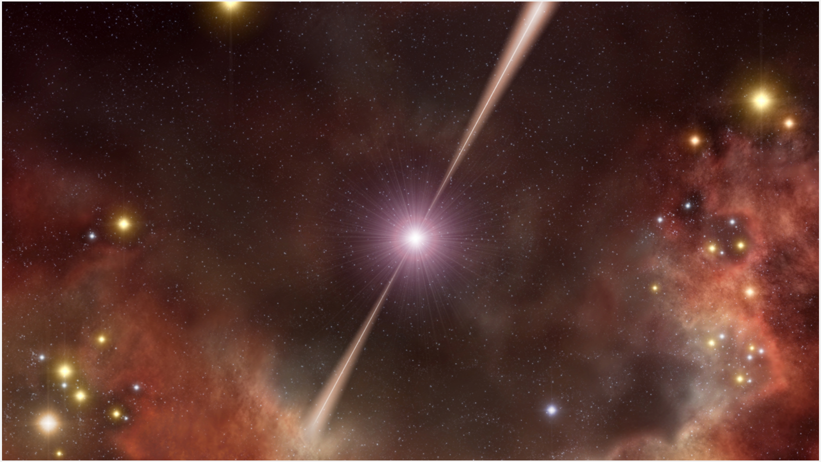
SNR & PWNe: Cheng et al. 1990, Aharonian & Atoyan 1996, Protheroe et al. 1998, Bednarek & Bartosik 2003, Mandelartz et al. 2015, Di Palma et al. 2016

Fermi Bubbles: Crocker 2012, Lunardini & Razzaque 2012, Razzaque 2013, Lunardini et al. 2015



Slide adapted from E. Ferrara

Gamma-ray Bursts (GRBs)



✓ 0.1-10 PeV (Waxman 1995; Waxman & Bahcall 1997, 1999; Dermer 2002, 2003, Murase & Ioka 2013)

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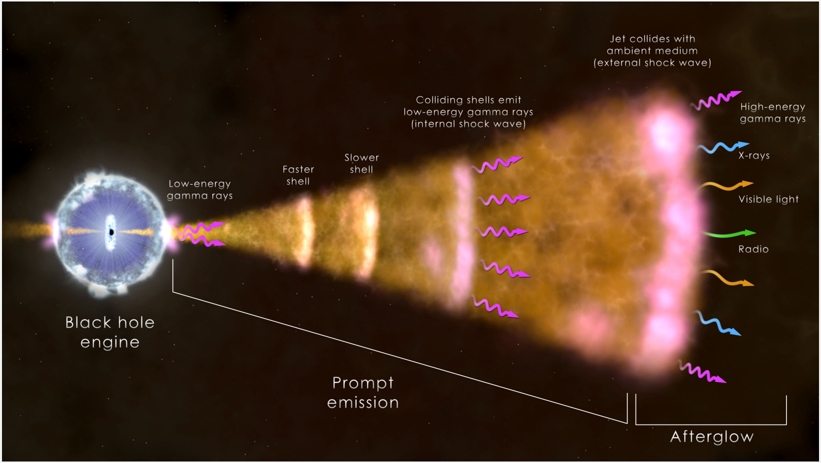
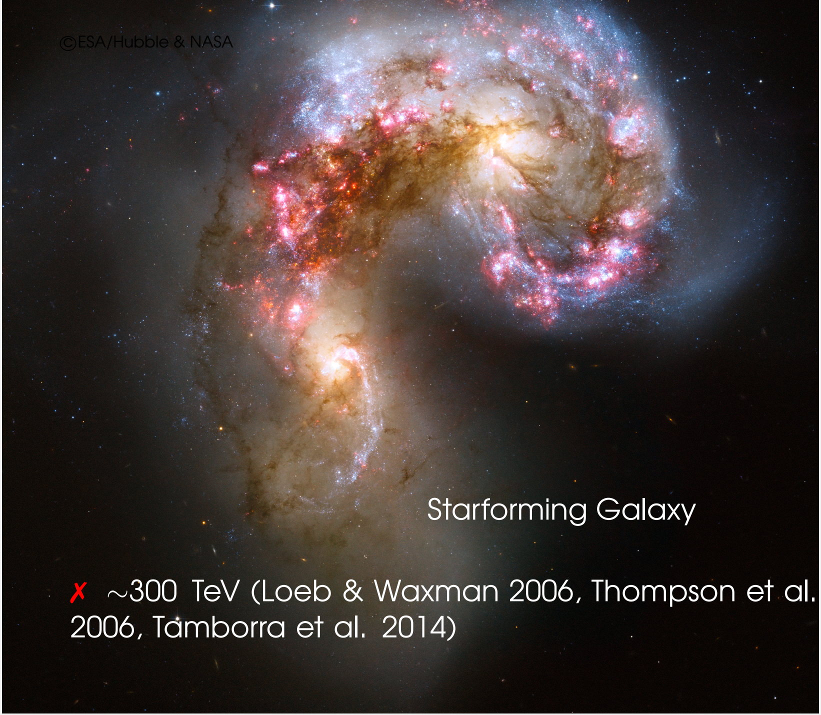
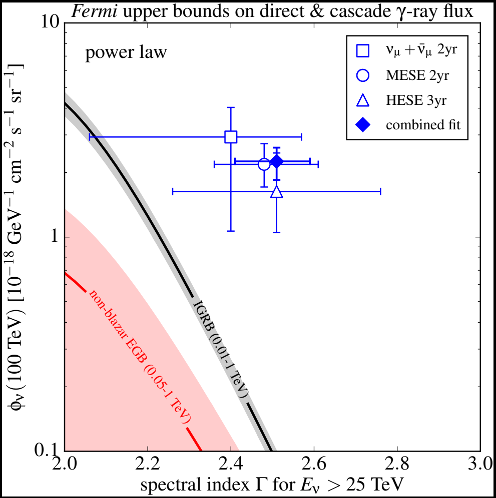




✗ $\sim$300 TeV (Loeb & Waxman 2006, Thompson et al. 2006, Tamborra et al. 2014)

Starforming Galaxies

- ⋆ LAT evidence against star-forming galaxies as dominant source of IC neutrinos (Bechtol et al. 2016)



Bechtol et al. 2016

GRBs

- ⋆ If large number of hypernovae vs. supernovae (Senno et al. 2016)
- ⋆ Low flux of ν from GRBs (Becker 2010)

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- ⋆ But: choked jets and low luminosity GRBs (Senno et al. 2016)