Review of recent neutrino astronomy results

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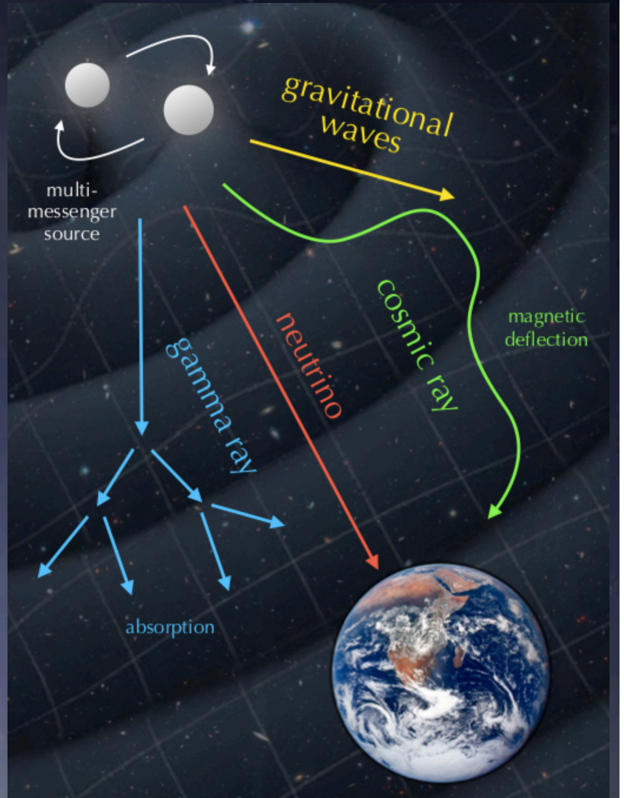
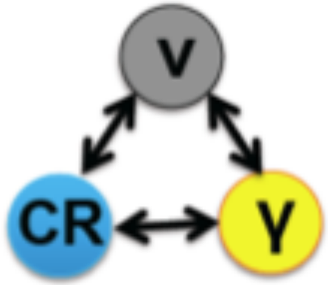
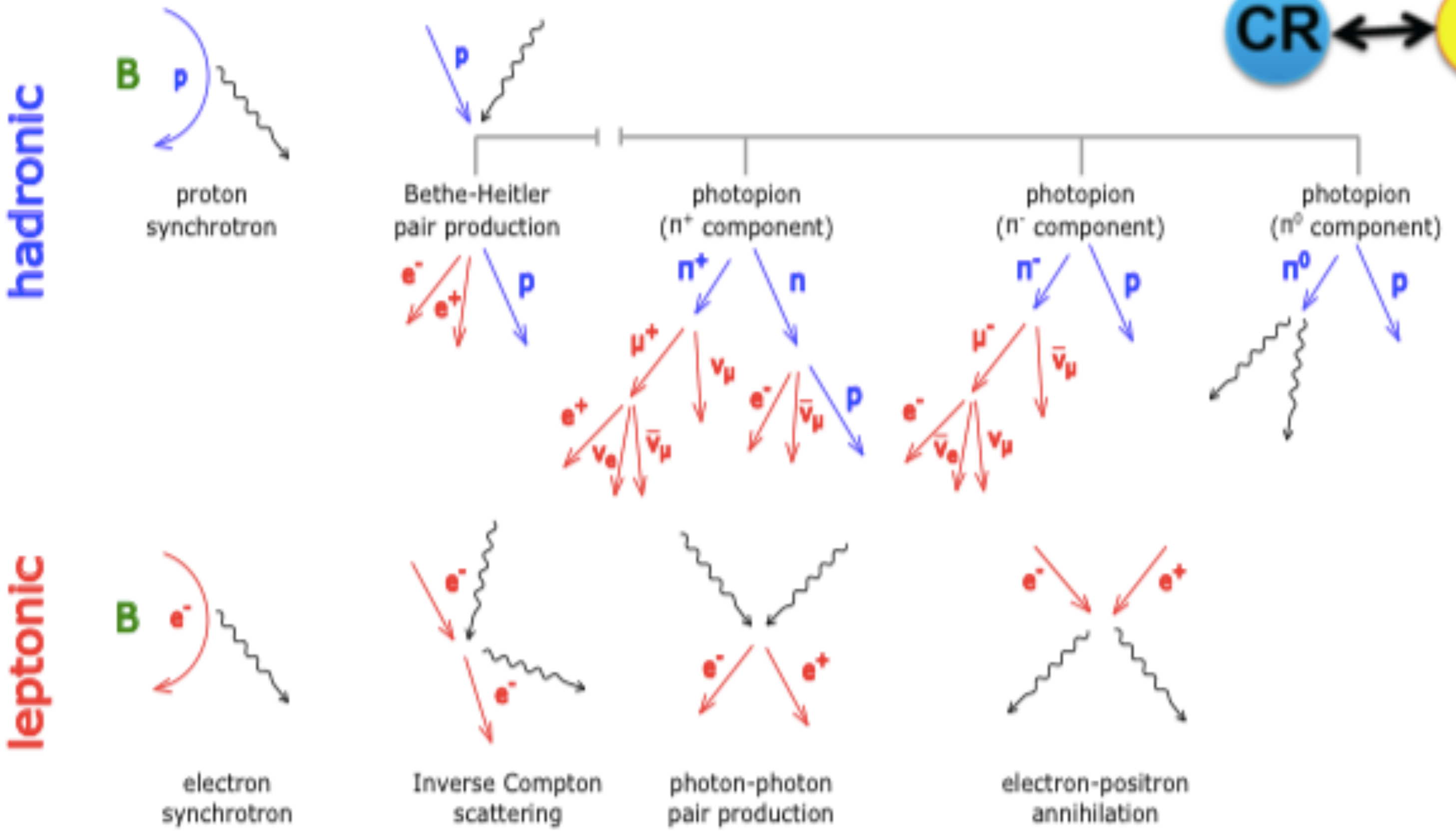
- The multi-messenger strategy and the TXS 0506+056 obervations
- Other results for point sources and diffuse searches
- Results on neutrino nature
- Future experiments

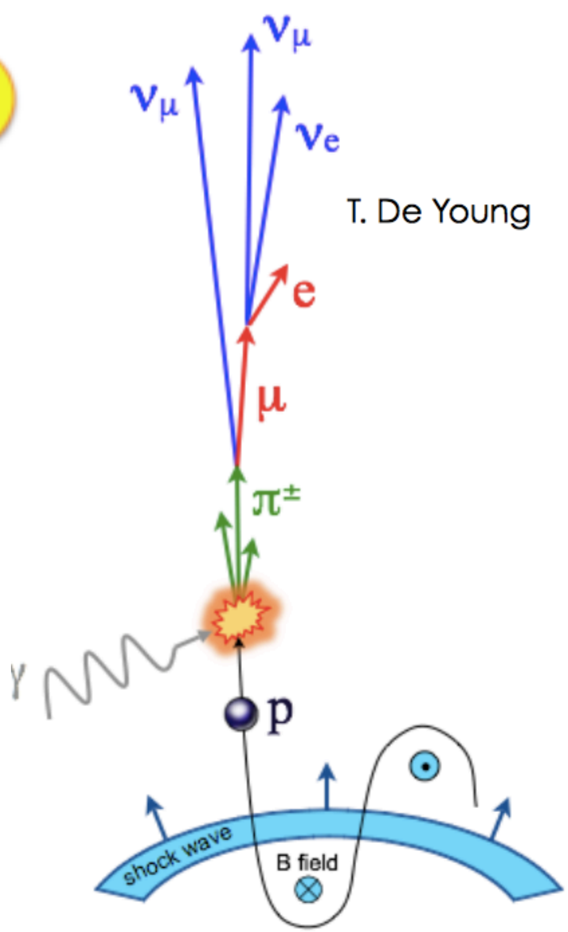


Cosmic ray sources

- accelerators (steady or variable) accelerating protons, nuclei, electrons and positrons to extreme energies
- The presence of neutrino is the smoking gun to trace matter in sources

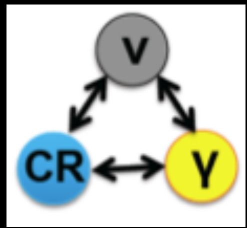


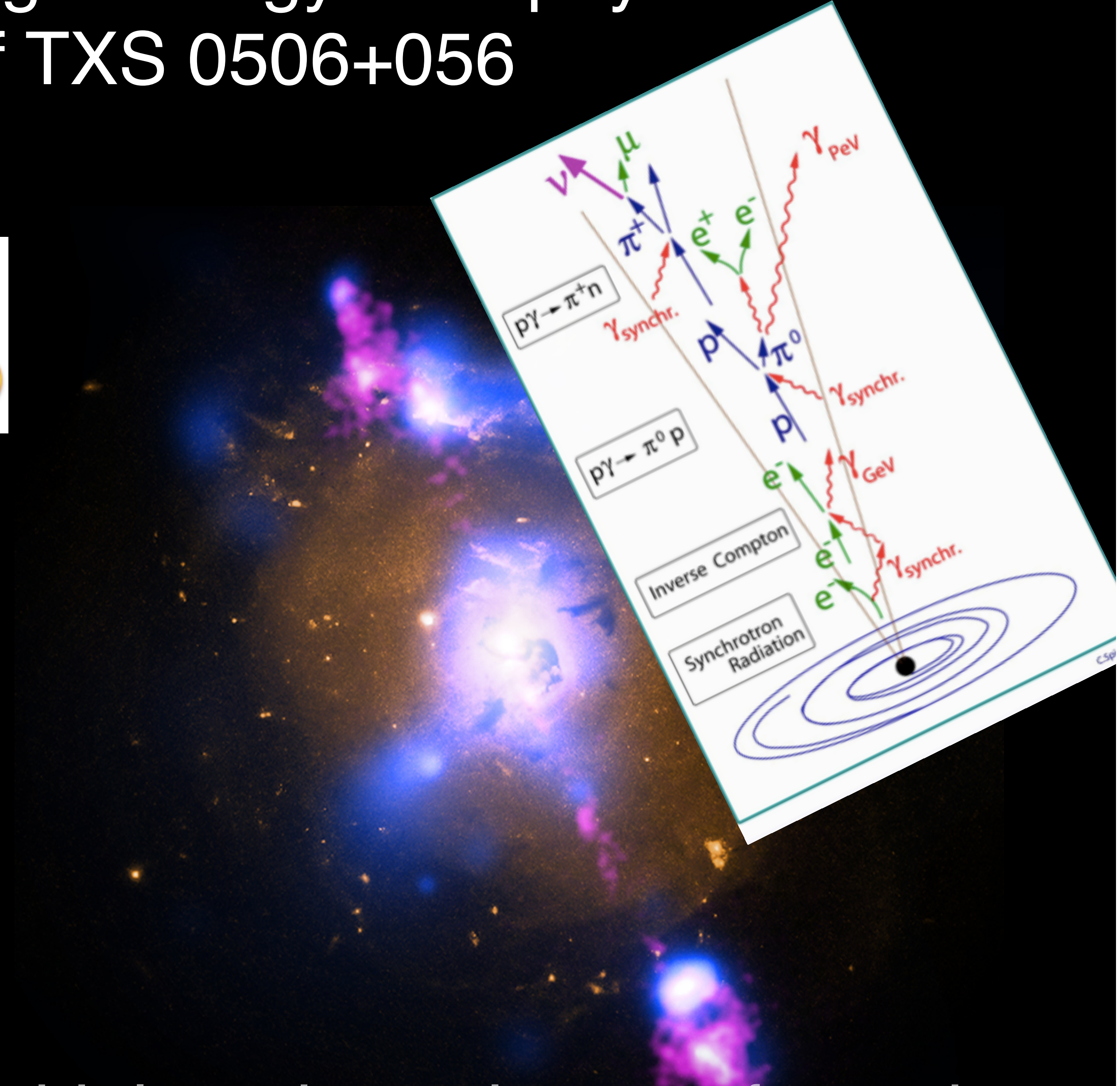




T. De Young

Multi-messenger High-Energy Astrophyiscs: the case of TXS 0506+056





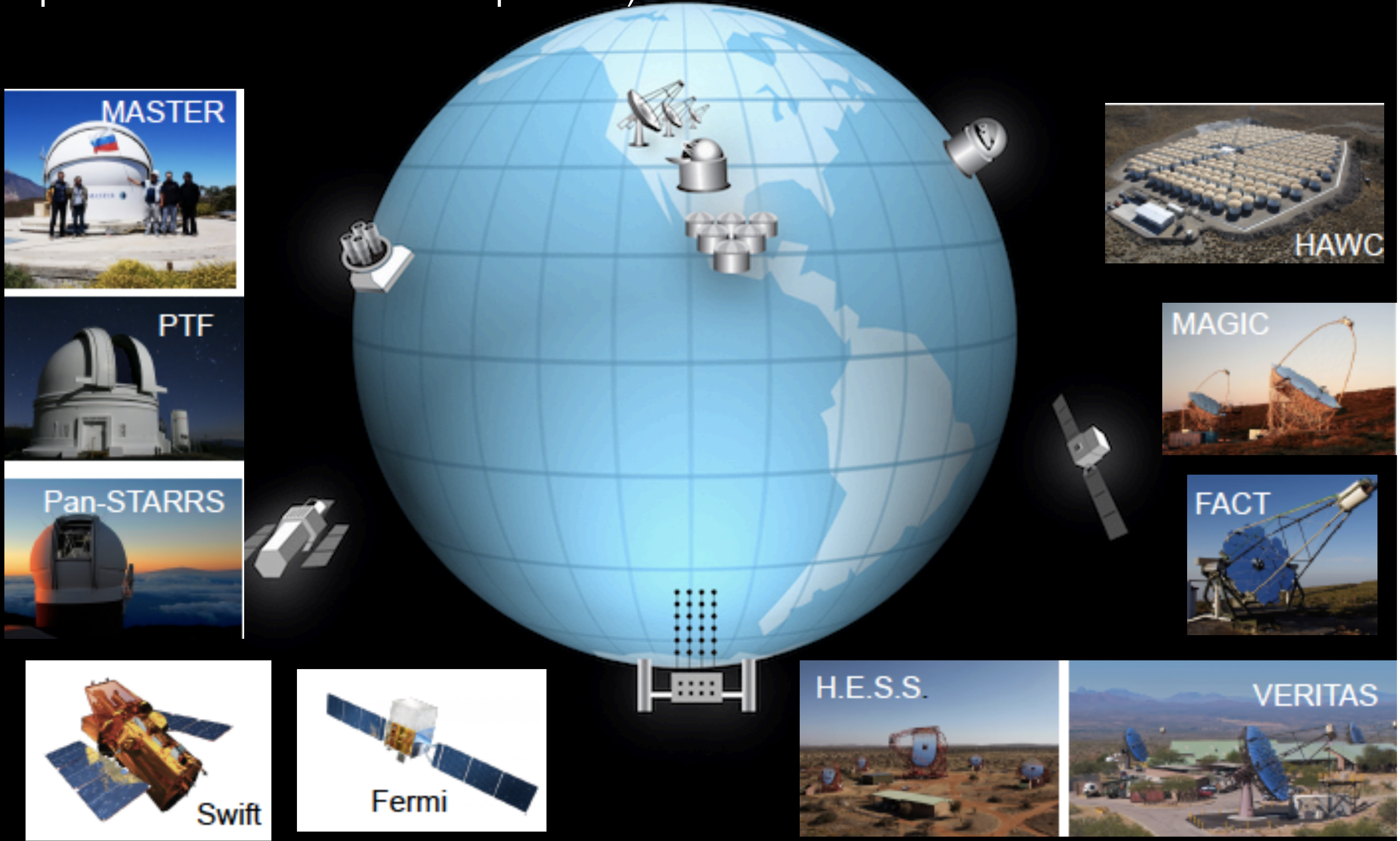
Science 361

DOI:10.1126/science.aat2890
DOI:10.1126/science.aat1378

Black holes are hungry devourers of matter that in part can be emitted under the form of jets of hot relativistic plasma departing from the region outside the horizon along the rotation axis.

The multi-messenger network

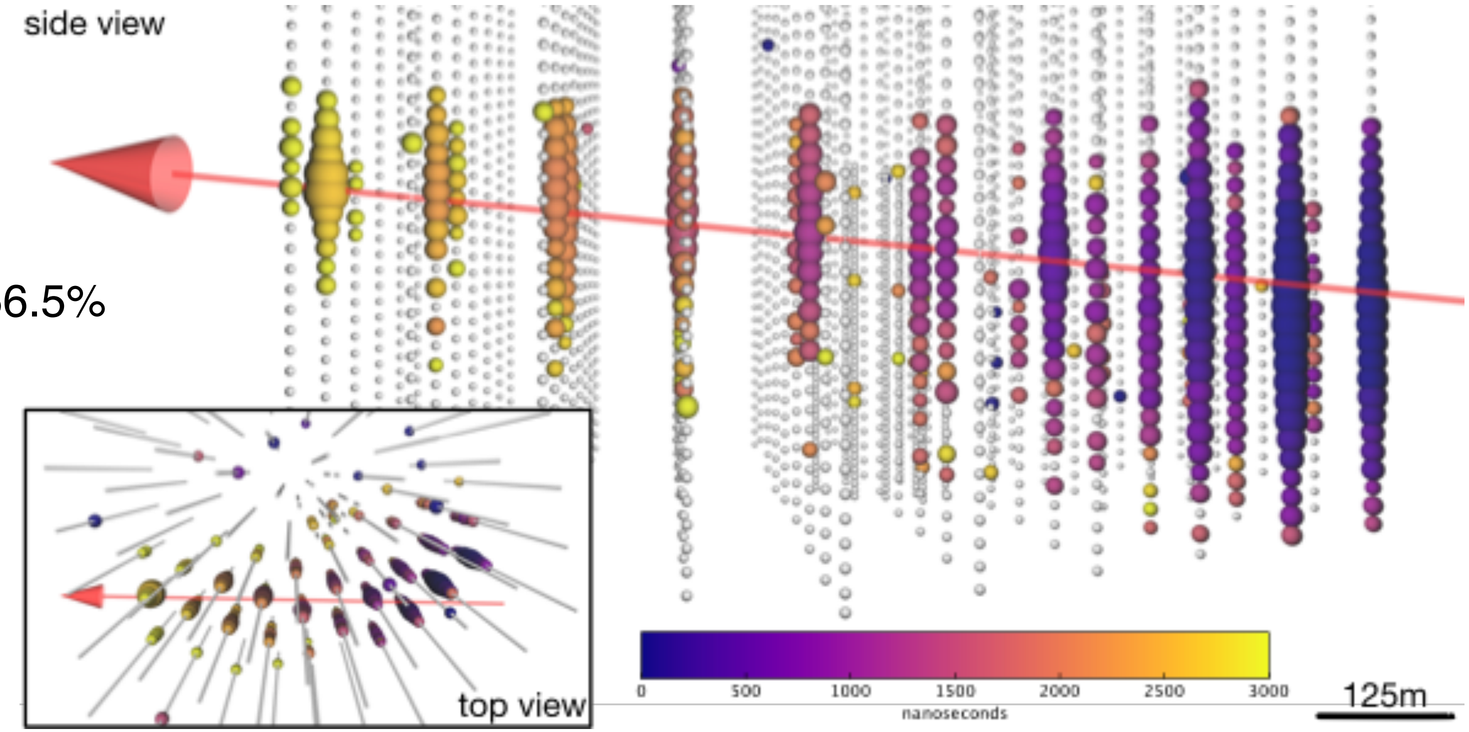
IceCube sends ~8 public alert/year of tracks with energy > 10^{14} eV since 04/2016 with median latency of 30 s. Around 3 have probability of being of cosmic origin > 50% (depends on assumed cosmic spectrum).



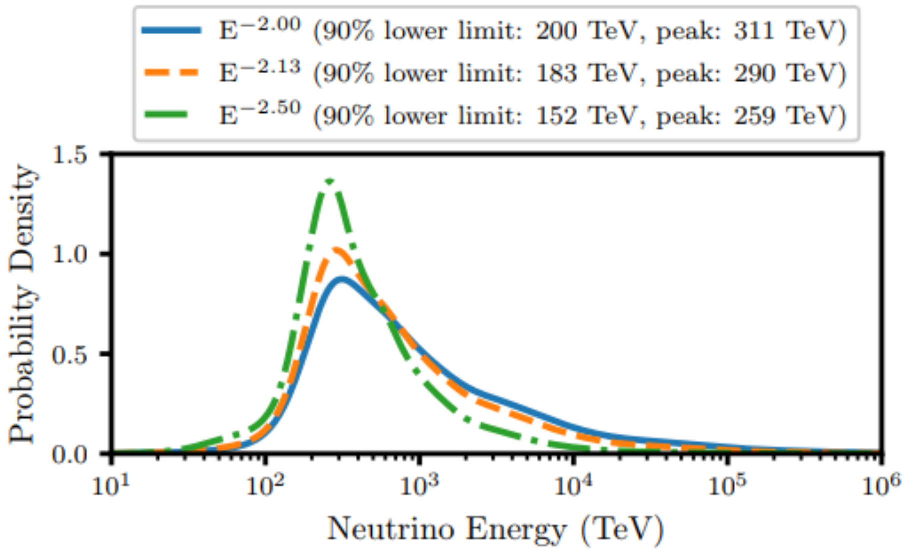
IC-170922A

23.7±2.8 TeV muon energy loss in the detector, 15 arcmin error (50% containment)

Signalness: 56.5%



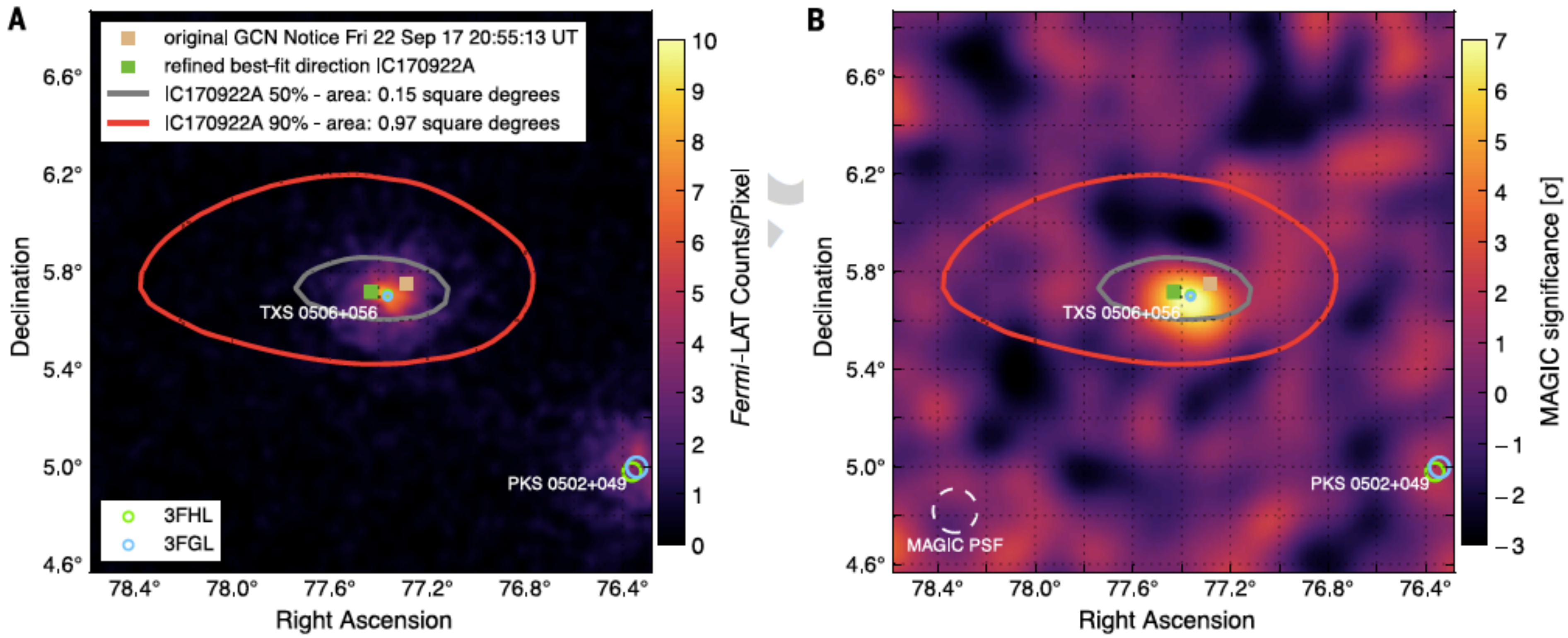
Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).



IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

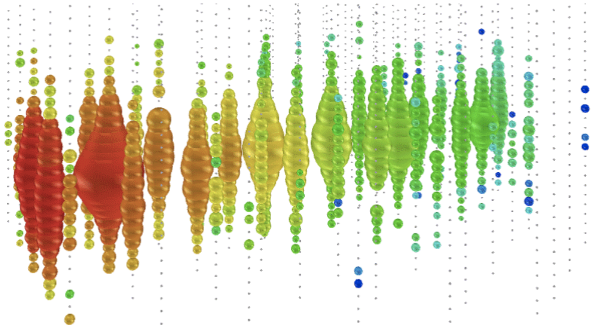
https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

The gamma-ray partner observations



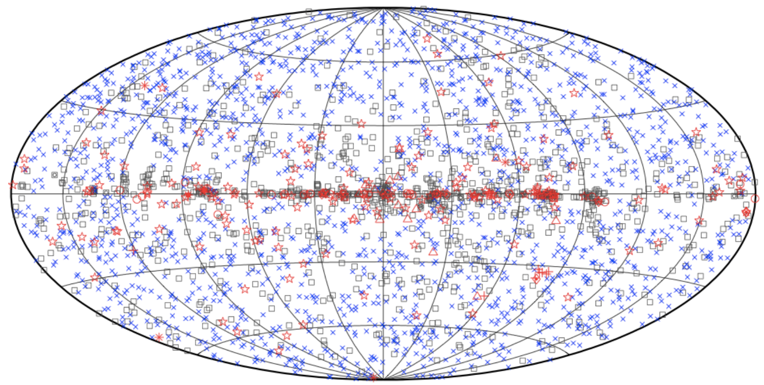
Shortly after, Fermi-LAT (20 MeV-300 GeV) detected a blazar in a high state at 0.06° from IceCube event (ATel#10791). MAGIC followed up and the blazar was observed at > 100 GeV energies with >6.2σ (ATel#10817, Ahnen, M. L., et al., ApJL 2018), later confirmed by VERITAS (Abeysekara et al, ApJL, 2018). **The probability that this coincidence happens by chance is excluded at 3σ level.**

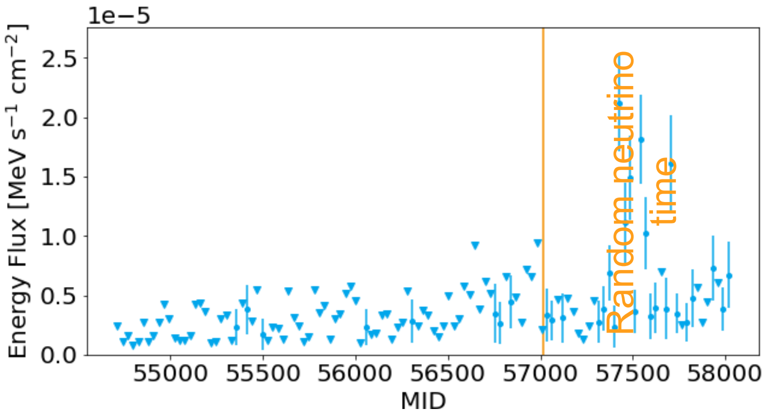
How Likely is it a Chance Probability?



Step I: Draw a random neutrino from a representative Monte-Carlo sample of high-energy muon-track events (EHE, 10 public alerts and 41 archival events)

Step II: Are there any extra-galactic Fermi sources close in space to the neutrinos?





Step III: What is the gamma-ray energy flux in the time bin when the neutrino arrives?

$$\boxed{\mathcal{S}(\vec{x},t) = \sum_s \underbrace{\frac{1}{2\pi\sigma^2} e^{-|\vec{x}_s - \vec{x}|^2/(2\sigma^2)}}_{\text{Spatial term}} w_s(t)\, w_{\mathrm{acc}}(\theta_s)}$$

acceptance

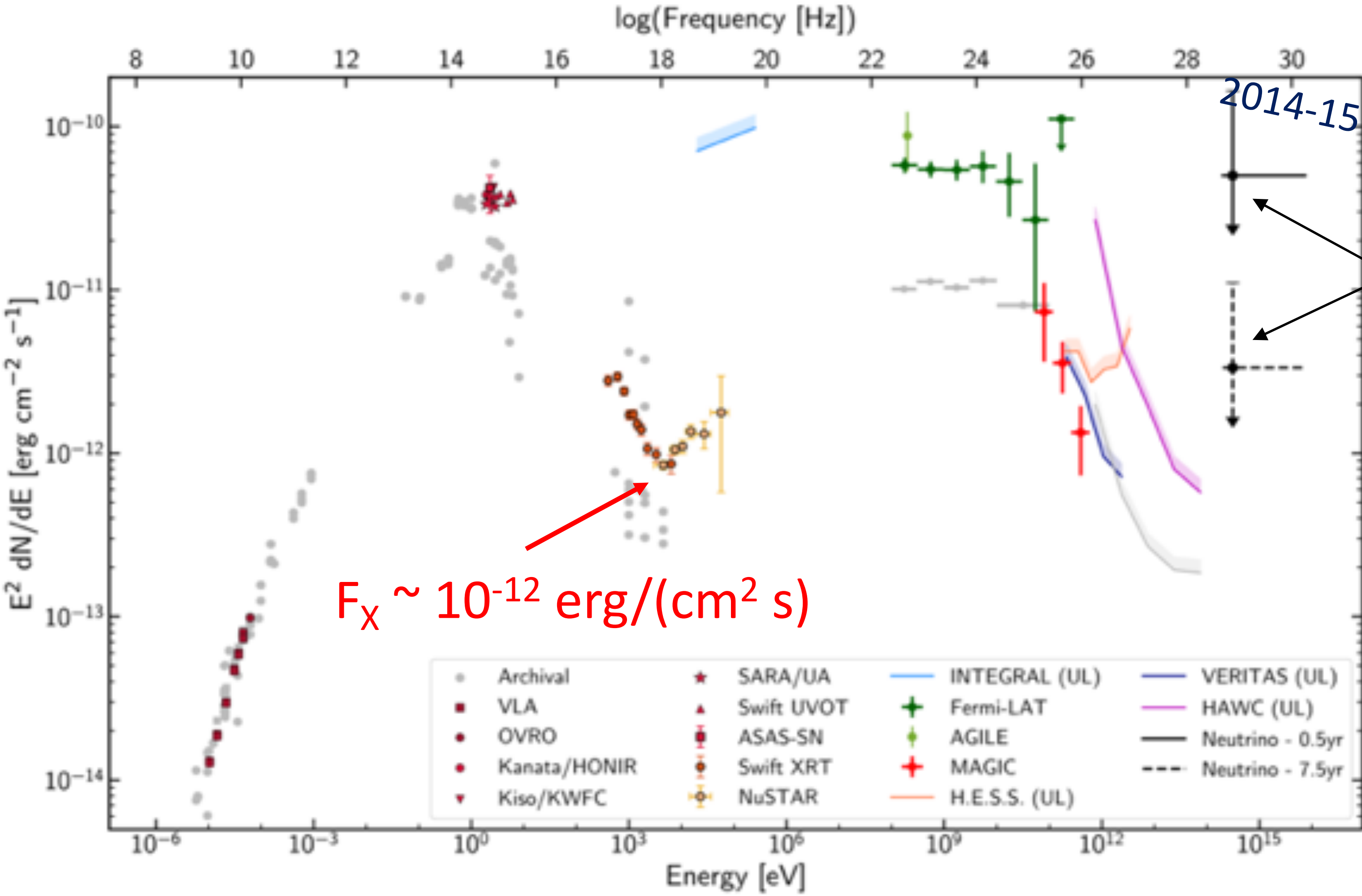
gamma-ray energy flux at time t

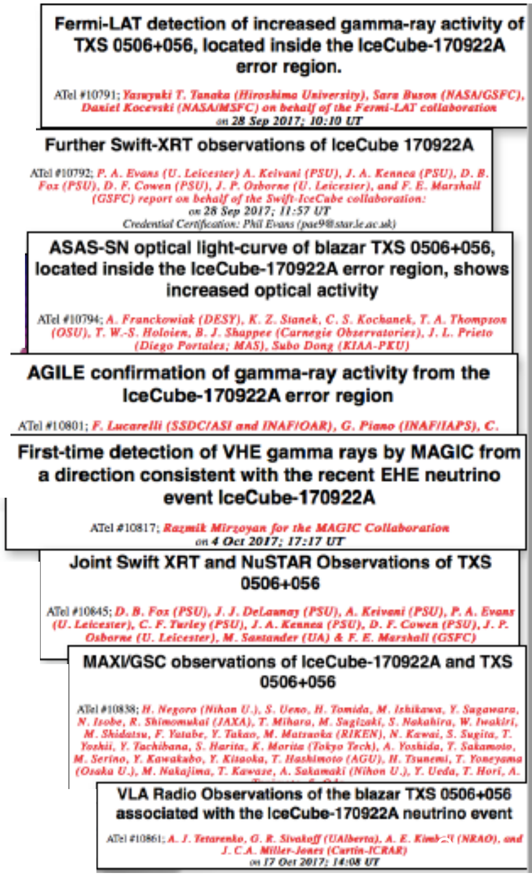
$$\mathcal{B}(\vec{x}) = \frac{\mathcal{P}_{BG}(\sin\theta)}{2\pi}$$

Post-trial p-value 3σ

$$TS = 2\log\frac{\mathcal{L}(n_s=1)}{\mathcal{L}(n_s=0)} = 2\log\frac{\mathcal{S}}{\mathcal{B}}$$

Spectral energy distribution of TXS 0506+056




Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

Further Swift-XRT observations of IceCube 170922A

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

MAXI/GSC observations of IceCube-170922A and TXS 0506+056

VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

How to reconcile the TXS 0506+056 observation with general consensus that BL Lac objects are inefficient neutrino emitters (Murase et al. 2014), due to the relatively low density of UV to soft X-ray synchrotron photons expected inside the jet?

Use observed neutrino luminosity and limits on observed UV/X-ray flux of $F_x \sim 10^{-12}$ erg cm^{-2} s^{-1} for TXS 0506+056 to constrain the target photon luminosity and required proton power

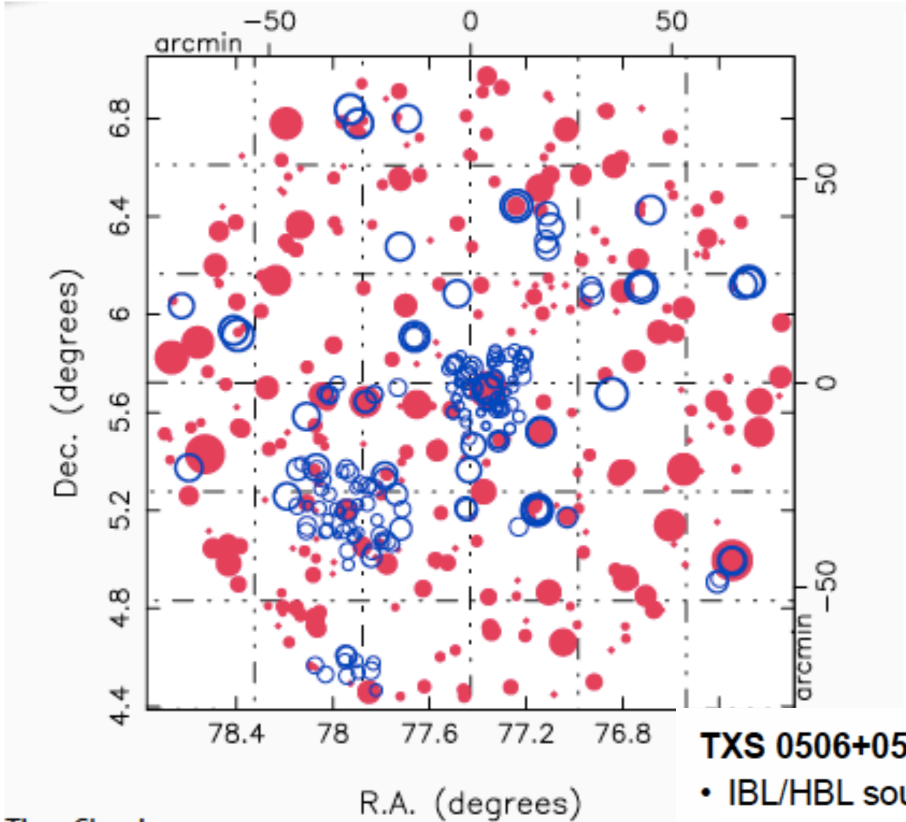
Source confusion

Sources in the Region
Radio: 637 (red)
X-Ray: 297 (open blue)

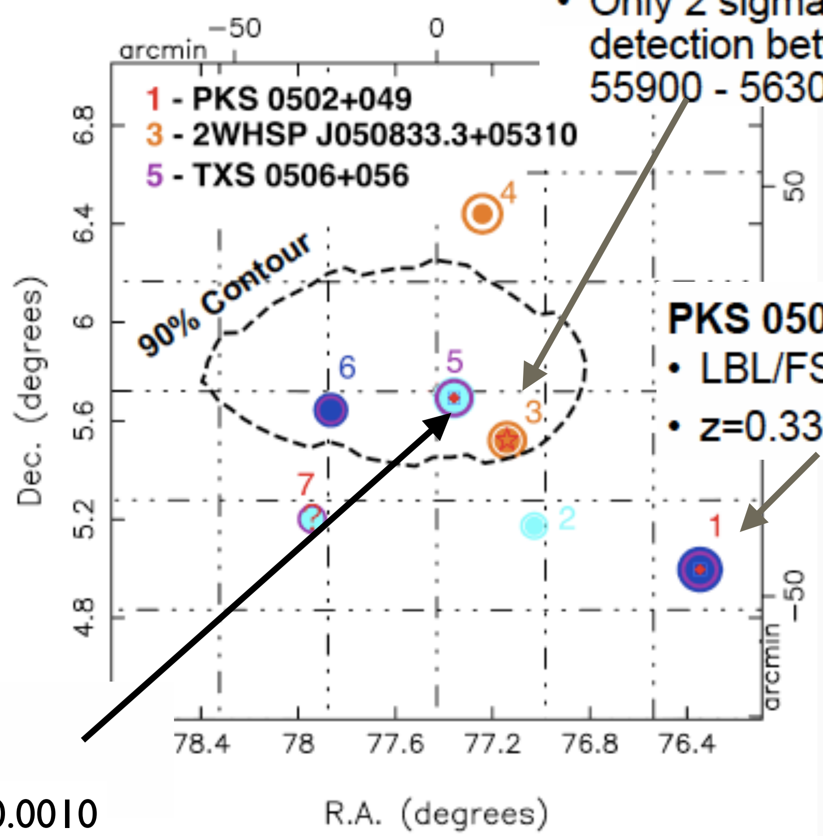
Identify **6** interesting objects with,
- Non-Thermal Emission
- Radio **and** X-Ray Emission
- A blazar-like ratio of x-ray/radio emission

Analysis is based on the VOU-Blazar tool developed by the United Nations Open Universe initiative http://www.openuniverse.asi.it/

- *Input data combines 28 radio and X-ray catalogs, as well as additional data points from Swift observations following IceCube-170922A*



Theo Glauch
TeVPA Berlin, August 2018



2WHSP J050833.3+05310
- HBL source
- Only 2 sigma gamma-ray detection between MJD 55900 - 56300

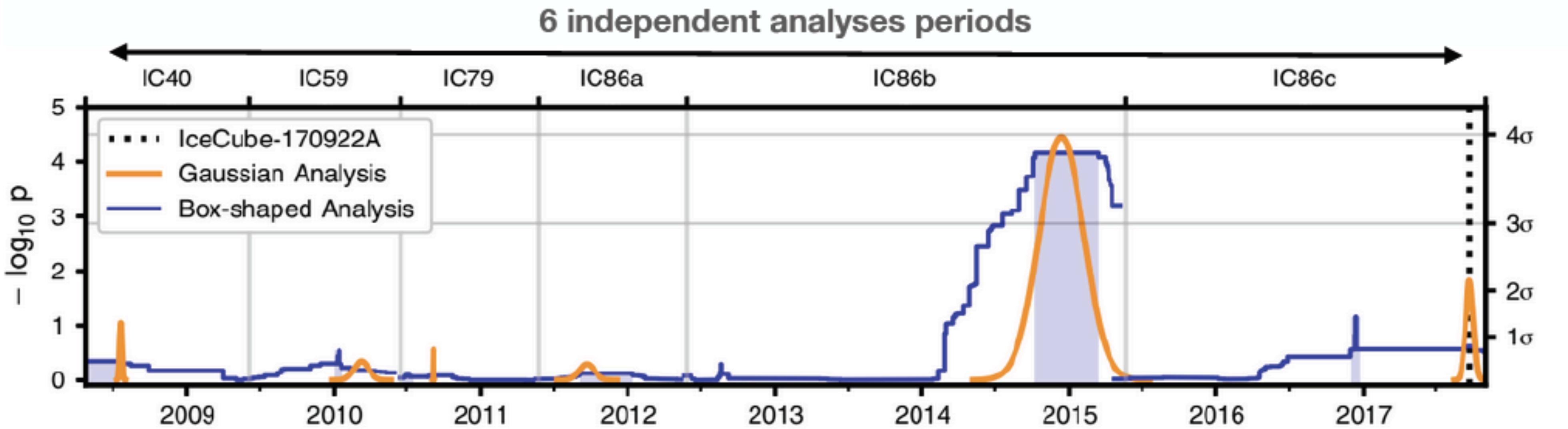
PKS 0502+049
- LBL/FSRQ source
- z=0.3366

TXS 0506+056
- IBL/HBL source
- z = 0.3365 ± 0.0010
- **Top 4%** brightest γ-ray objects in Fermi 3LAC
- Radio: 1Jy at 6cm, 537mJy at 20cm, **Top 0.3%** in NVSS

Padovani et al
MNRAS 480 (2018) 192

Solving the confusion: electromagnetic - neutrino flares

Analysis of 9.5 yr in 6 independent periods. An excess of 13 muon neutrino events in a period of ~5 months (2014-2015) in sample of 3yr is inconsistent with atmospheric neutrino origin at 3.5σ CL correcting for lifetime of IC86b: 9.5/3.



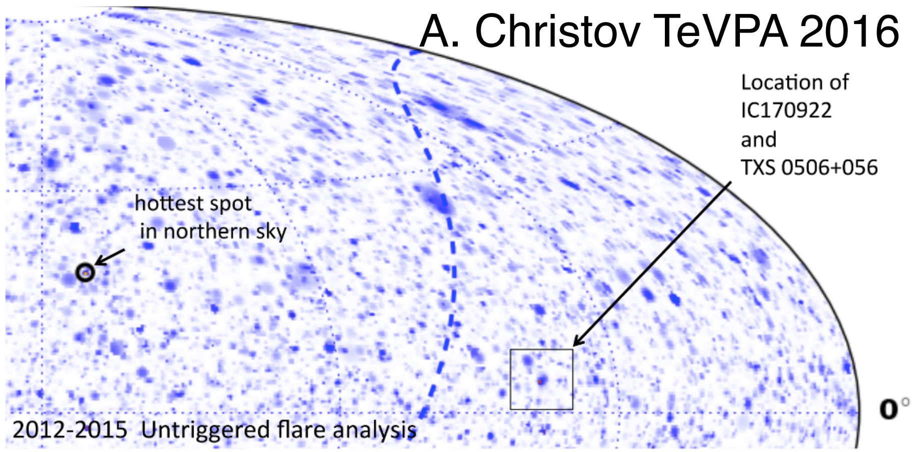
Best fit parameters of two flares:

DOI:10.1126/science.aat1378

2012-2015 period	Gaussian PDF	Box PDF
ns	13	14
γ	2.1	2.2
Width	110 days	158 days
Time	2014-12-26 2015-03-05	2014-12-13
Significance	3 x 10^{-5}	7×10^{-5}

ns	1.4 +2.5/- 1.0
γ	1.7 +/- 0.6
Width	19 days
Time	2017-09-22

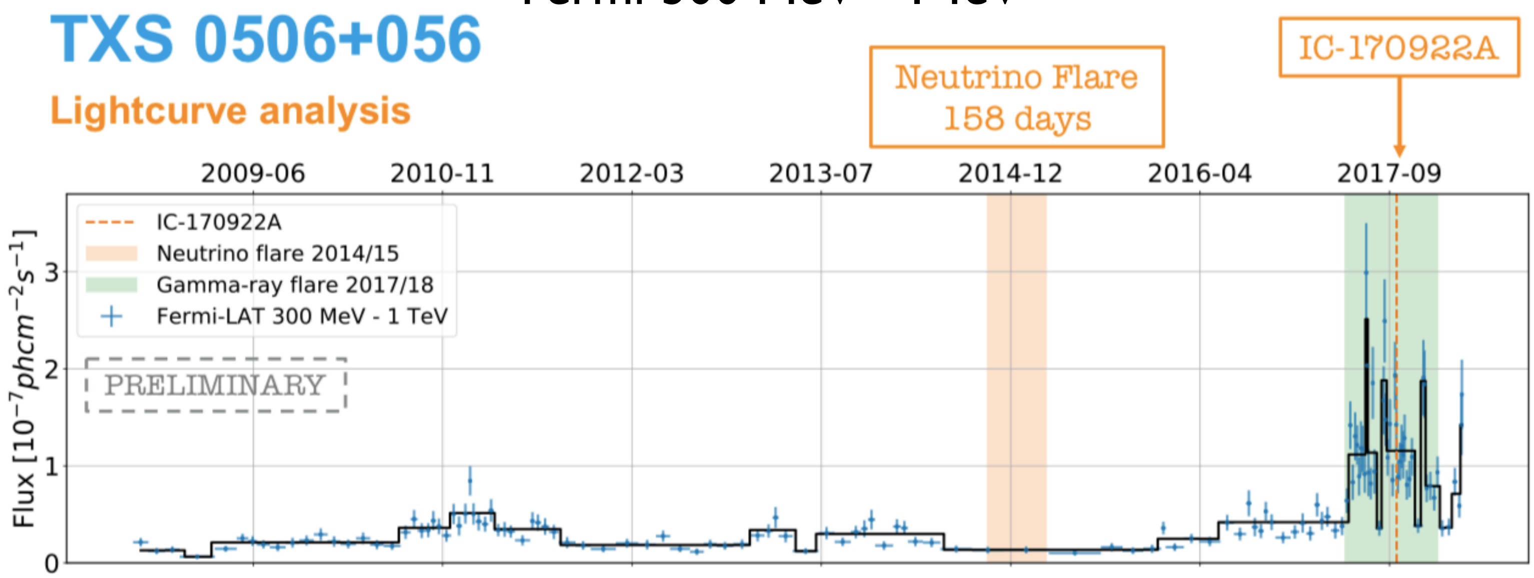
A. Christov TeVPA 2016



ν-γ time correlation analysis

Garrappa et al, TeVPA18

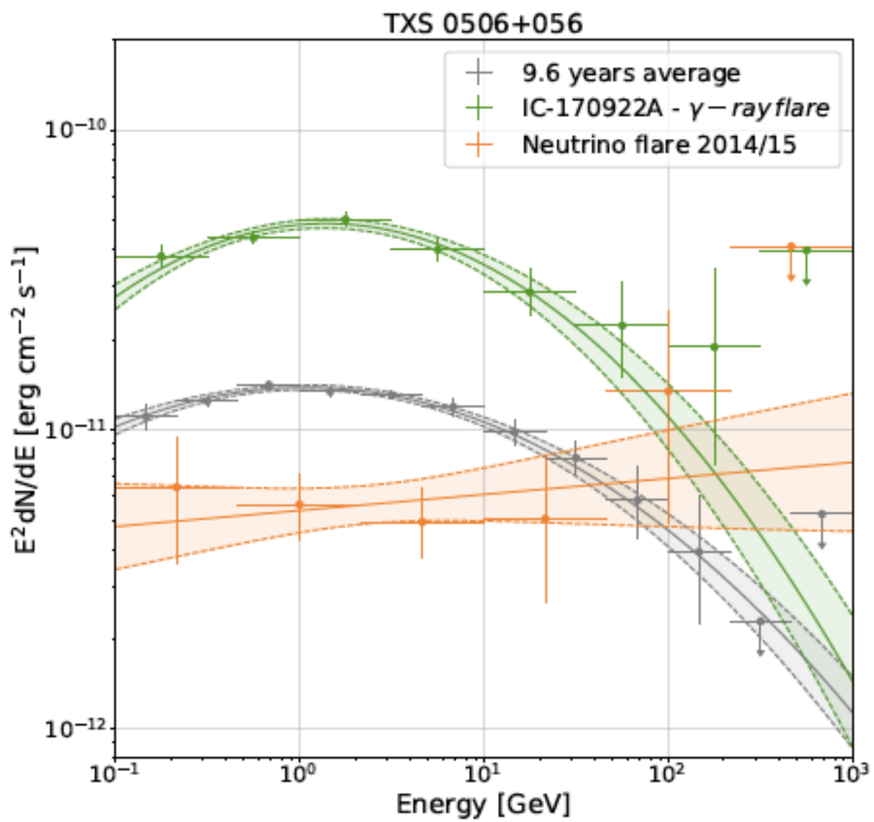
Fermi 300 MeV - 1 TeV



Among 50 brightest 3LAC sources

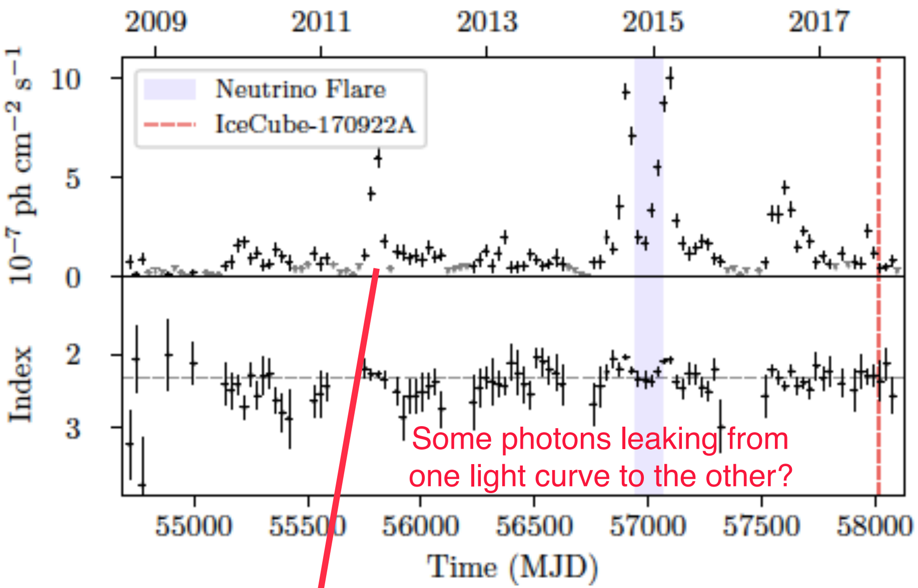
The bright 2017/18 gamma-ray flare shows fast variability on ~daily timescale, suggesting a compact emission region.

During 2014/15 neutrino flare no significant gamma-ray flaring activity or spectral change have been observed.

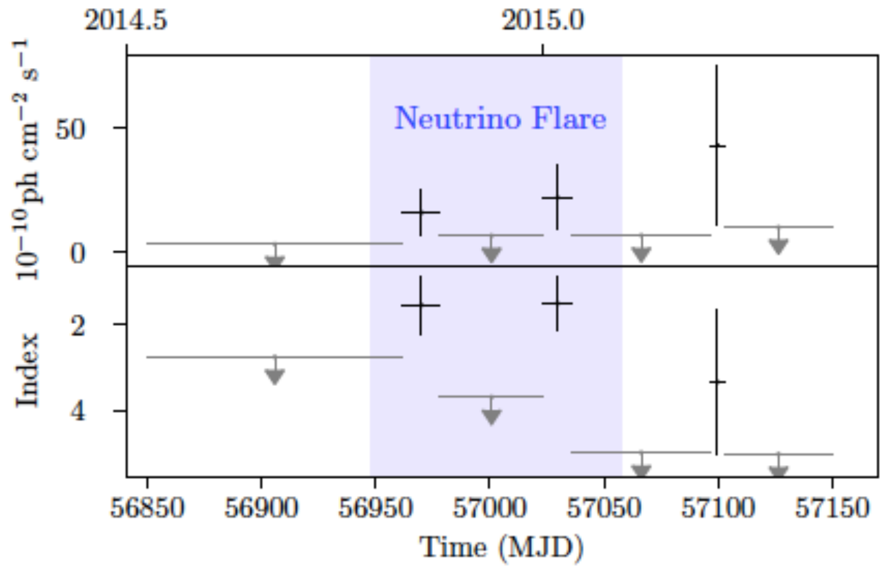


ν-γ time correlation analysis at higher energy

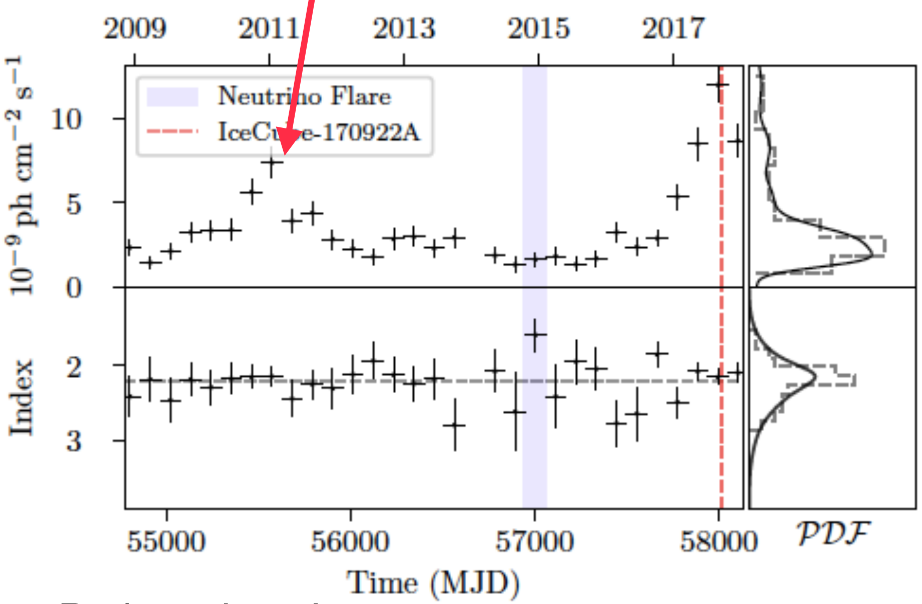
TXS 0506+056: 100 d lightcurve (55 d bin) > 2 GeV



TXS 0506+056: 100 d lightcurve > 10 GeV



PKS 0502+049: 28 d lightcurve > 100 GeV



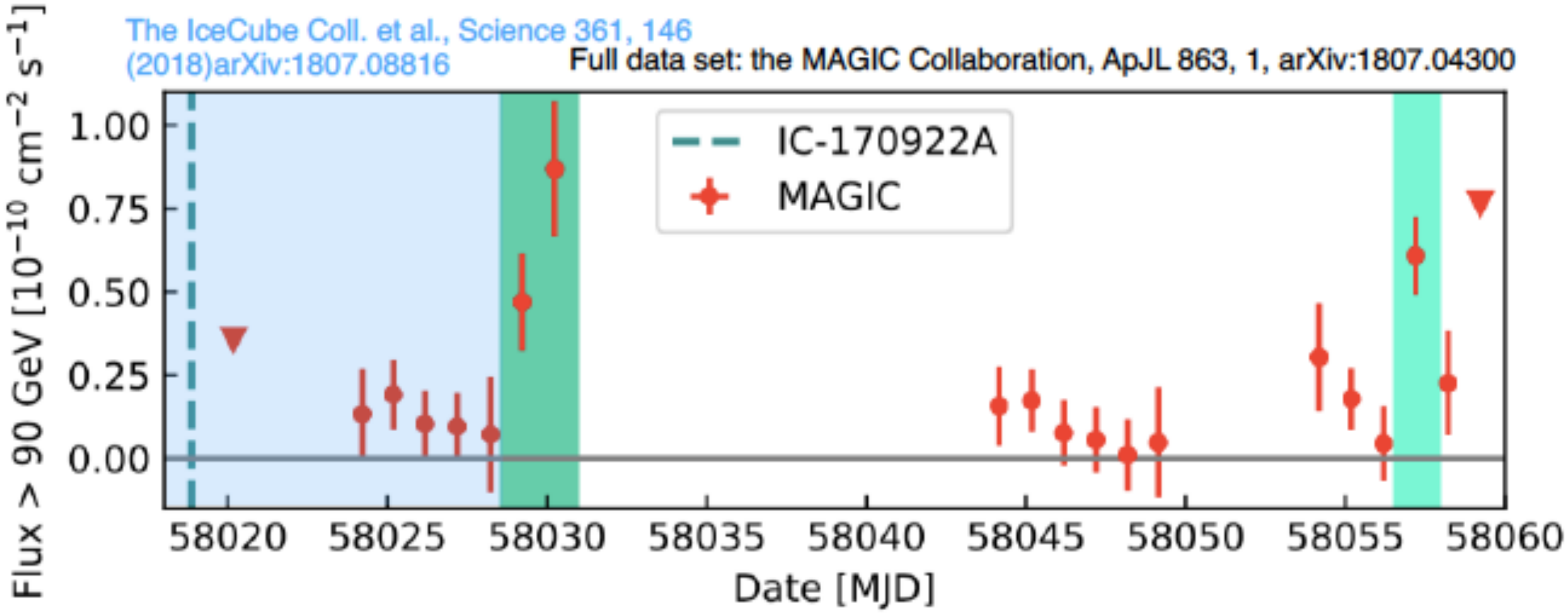
Padovani et al
MNRAS 480 (2018) 192

Selection of high energies maybe the key.

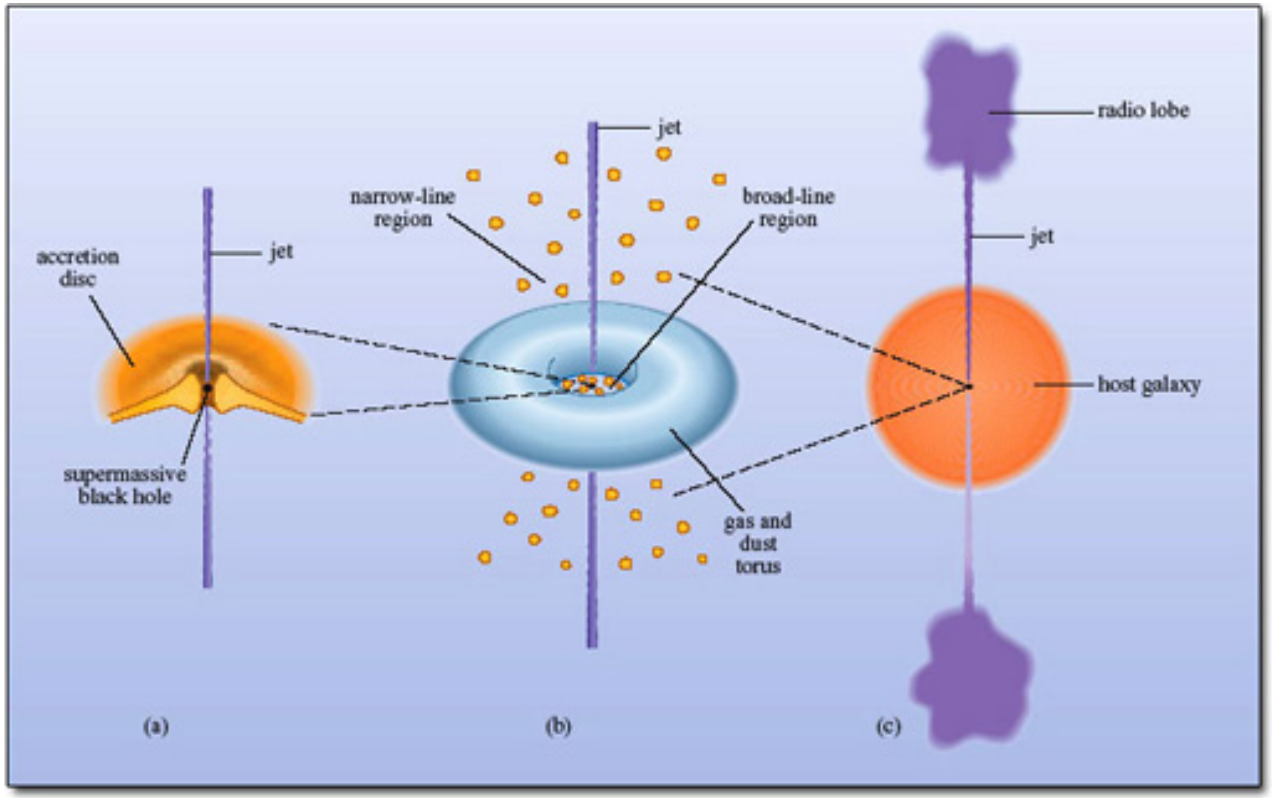
The light curve of TXS 0506+056 shows a large flux/soft spectrum state during the EHE event and an indication (at 2σ level) for a small flux/hard spectrum state during the ν - flare.

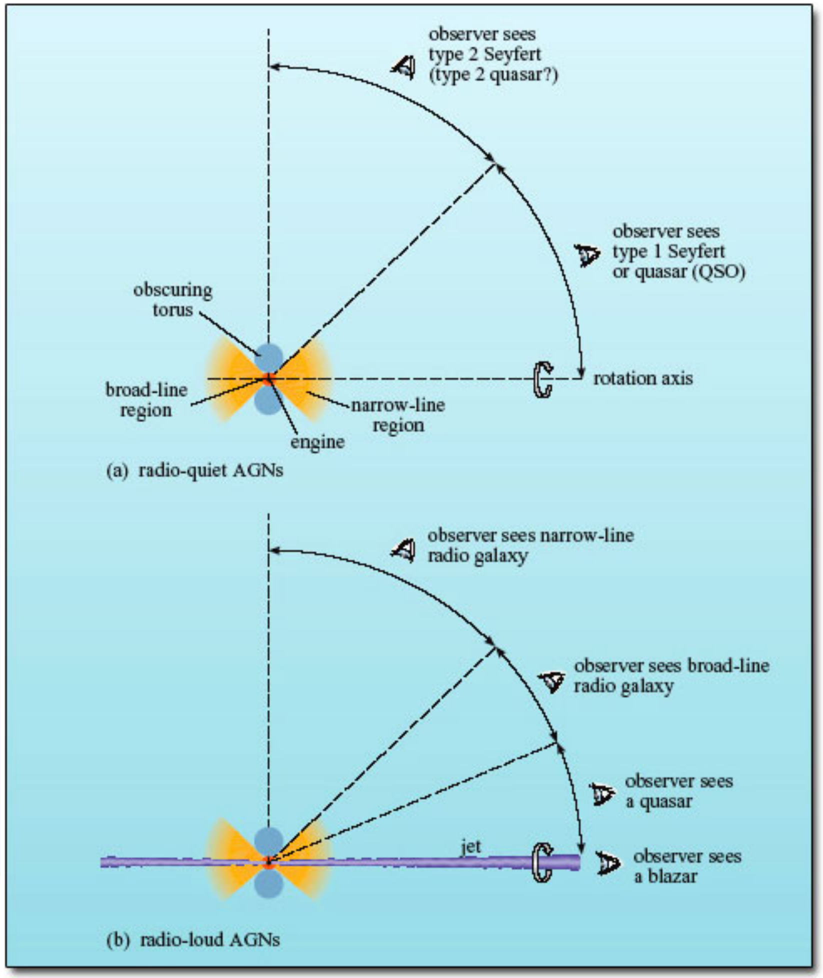
ν-γ time correlation analysis: MAGIC followup

41 hrs 24/9-2/11 Energy spectrum up to 400 GeV with spectral index between -3.5 ÷ -4
Two flares around Oct 3-4 and Oct 31, 2017.



AGN unified model





(a) The central engine is a supermassive black hole surrounded by an accretion disc with jets emerging perpendicular to the accretion disc.

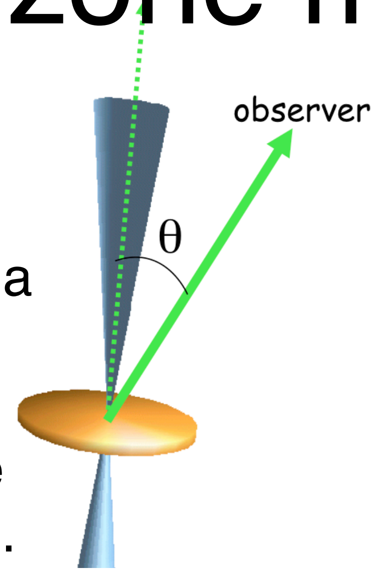
(b) The engine is surrounded by an obscuring torus of gas and dust. The broad-line region (BLR) occupies the hole in the middle of the torus and the narrow-line region lies further out.

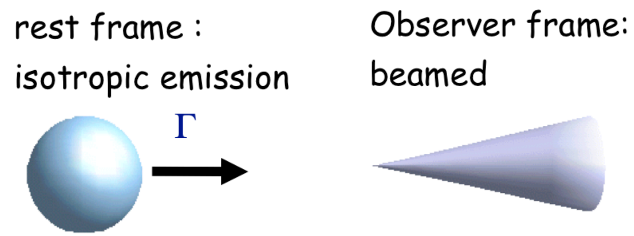
(c) The entire AGN appears as a bright nucleus in an otherwise normal galaxy. The jets extend to beyond the host galaxy and terminate in radio lobes

http://www.open.edu/openlearn/ocw/mod/oucontent/view.php?printable=1&id=2462

AGN one-zone model

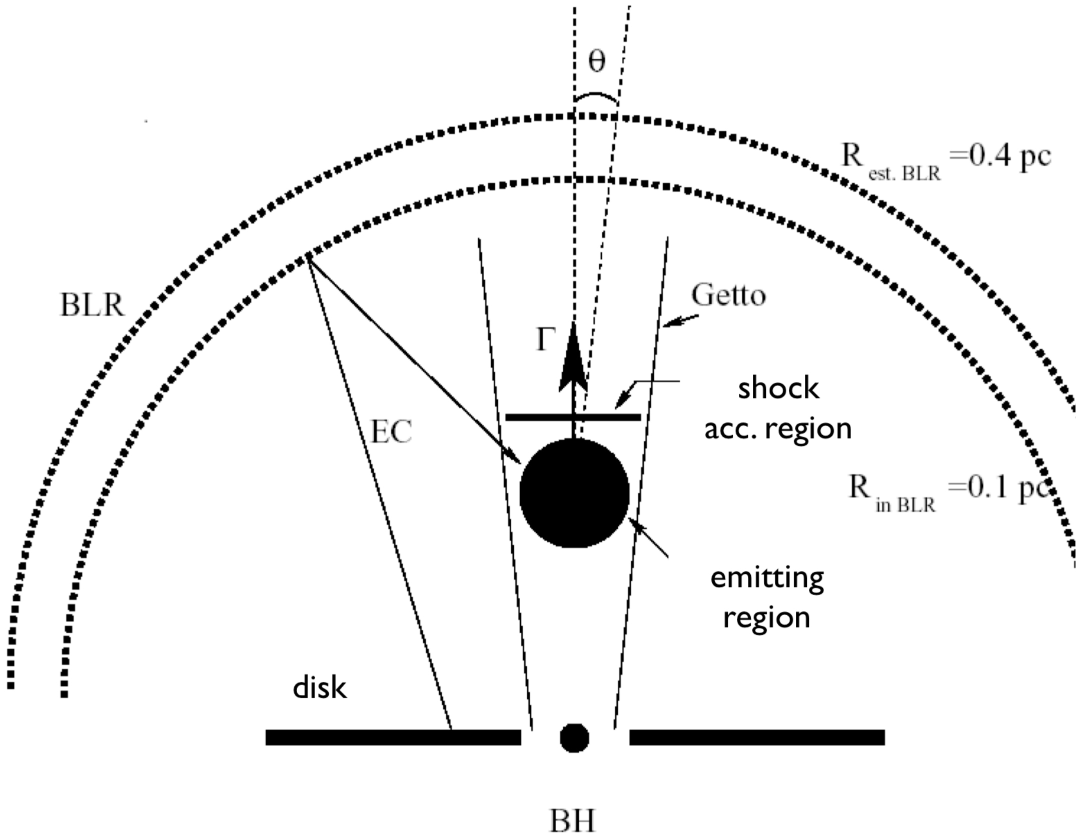
- Plasma of leptons (e+/-) distributed in a one-zone homogeneous spherical emitting region.
- Accelerated electrons interact with the B-field, and emit synchrotron radiation.
- Self Compton model (SSC, Jones et al 1974): synchrotron photons produced by these relativistic electrons seed photons for the Inverse Compton (IC).
- External Radiation Compton (EC, [Sikora et al. 1994](https://)): UV photons generated by the accretion disk are reflected toward the jet by the Broad Line Region (BLR) and seed IC.
-





Beaming factor:

- $\delta = \frac{1}{\Gamma(1-\beta cos(\theta))}$
- $\theta = 1/\Gamma$



https://www.isdc.unige.ch/sedtool/PROD/html_js/SED_Web_tool/Doc/test_doc/index.html

Connecting cosmic rays-neutrinos

Photopion production threshold: $E_p^{\rm thr} = \frac{m_p\, m_\pi\, c^4}{2\, E_{\rm ph}} \left(1 + \frac{m_\pi}{2\, m_p}\right)$ $\sim 10^{17}$ eV $E_{t,eV}^{-1}$

The photon field energy

$E_\nu^p \sim 1/3\ (m_p - m_\mu - m_e)\ c^2 \sim 10^7$ eV (in p rest frame - at threshold in CM frame)

$E_\nu' = E_\nu/\delta \sim 10^7\ \gamma'_p$ eV (in emission-region rest frame)

To produce IceCube neutrinos ~ 100 TeV → $\gamma'_p \sim \gamma'_e \sim \gamma'_\pi \sim 10^6\ E_{14}\ \delta_1^{-1} \equiv \gamma_6$

need protons with $E'_p \sim 10^{15}\ E_{14}\ \delta_1^{-1}$ eV (emission region rest frame, not UHECRs!)

and target photons with $E'_t \sim 170\ E_{14}^{-1}\ \delta_1$ eV (X-rays!)

Associated to this

- Proton synchrotron at $f_{p,sy} \sim 2\times10^{18}\ g_6^2\ B_2\ d_1$ Hz (~ 10 keV)
- Secondary electron synchrotron at $f_{esy} \sim 4\times10^{21}\ g_6^2\ B_2\ d_1$ Hz (~ 20 MeV)

Protons producing IceCube neutrinos do not produce > 300 MeV gamma-rays from proton or secondary electron synchrotron!

Gamma-rays from:

- π^0 decay ~700 TeV
- IC: ~5 TeV with intense IR-optical target photon field with $u'_{ph} \gg u'_B \sim 400\ B_2^2$ erg/cm^3

Origin of target photon field

(At least) two possible scenarios:

a) Target photons co-moving with the emission region

$\Rightarrow E_t^{obs} \sim 1.7\, E_{14}^{-1}\, \delta_1^{2}/(1+z)$ keV

$\Rightarrow$ Observed as X-rays

b) Target photons stationary in the AGN frame

$\Rightarrow E_t^{obs} \sim 17\, E_{14}^{-1}/(1+z)$ eV

$\Rightarrow$ Observed as UV

Use observed neutrino luminosity and limits on observed UV/X-ray flux of $F_x \sim 10^{-12}$ erg cm^{-2} s^{-1} for TXS 0506+056 to constrain the target photon luminosity and required proton power

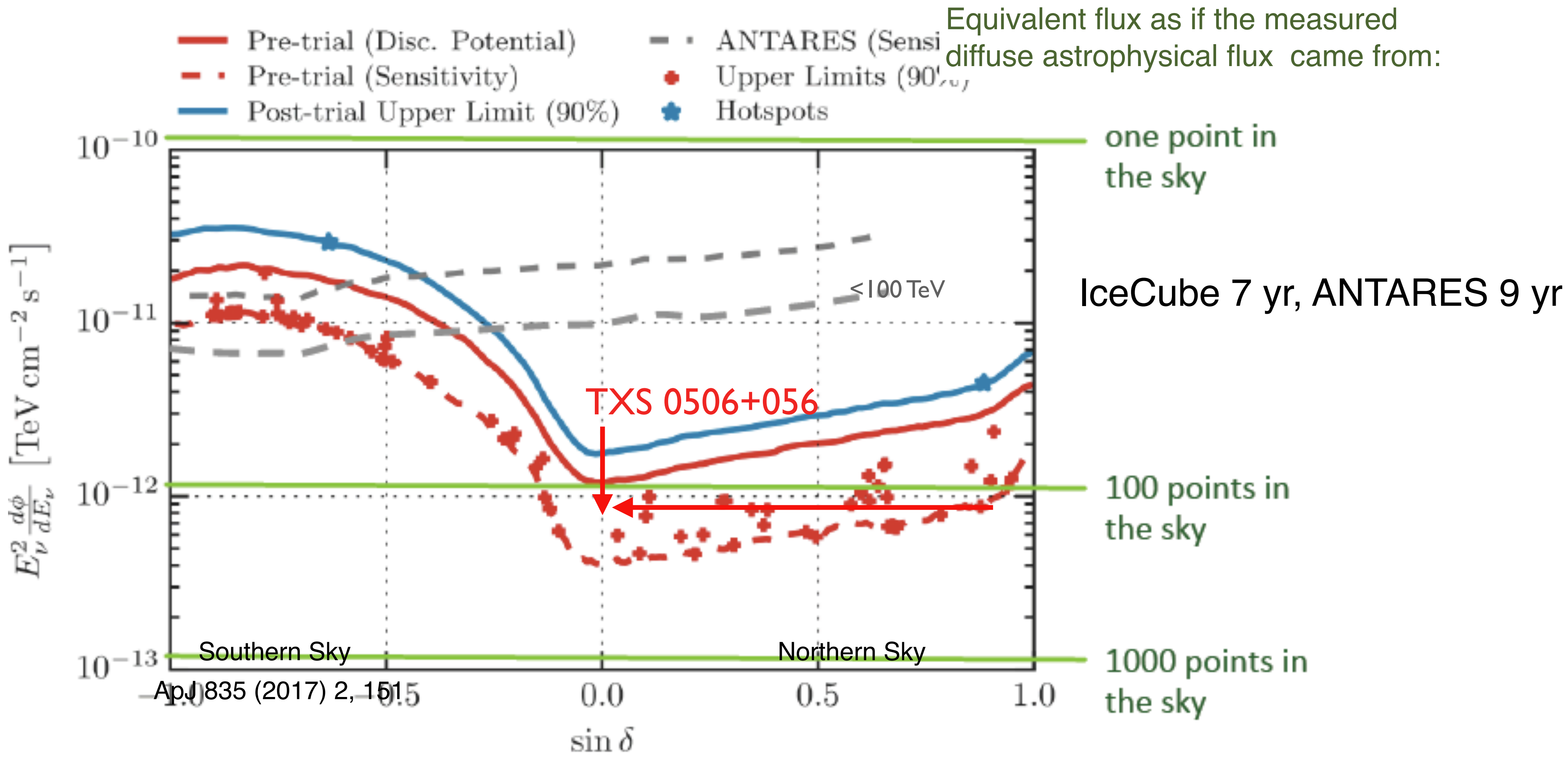
=> Unrealistically large kinetic power; Requires low B-field (< 1 G) to suppress p-synchrotron below X-ray flux limit of $F_X \sim 10^{-12}$ erg/(cm^2 s)

=> p-sy suppressed below UV/X-ray limit for B ~10G. IceCube 170922A / TXS 0506+056 favours UV / soft X-ray target photon field external to the jet.

The source maybe opaque with few photons coming out and a flux mostly produced during propagation in EBL.

M. Boettcher, TeVPA2018

Time-integrated Point source results

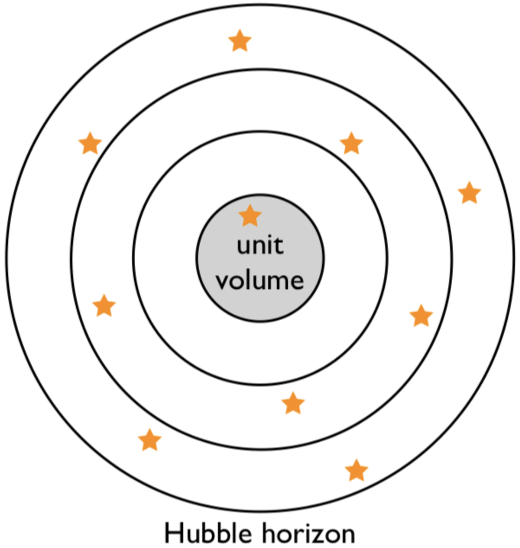


A dedicated time-integrated analysis for the region of TXS 0506+056 using 7 yr of data shows compatible results with the time dependent search.

The a-posteriori significance of the 2015-2017 period is 2.1σ (4σ if the EHE event period is included) and the total fluence is $E^2 J_{100} = 2 \times 10^{-4}$ TeV cm^{-2} at 100 TeV

DOI:10.1126/science.aat1378

Implications of Point-Source limits



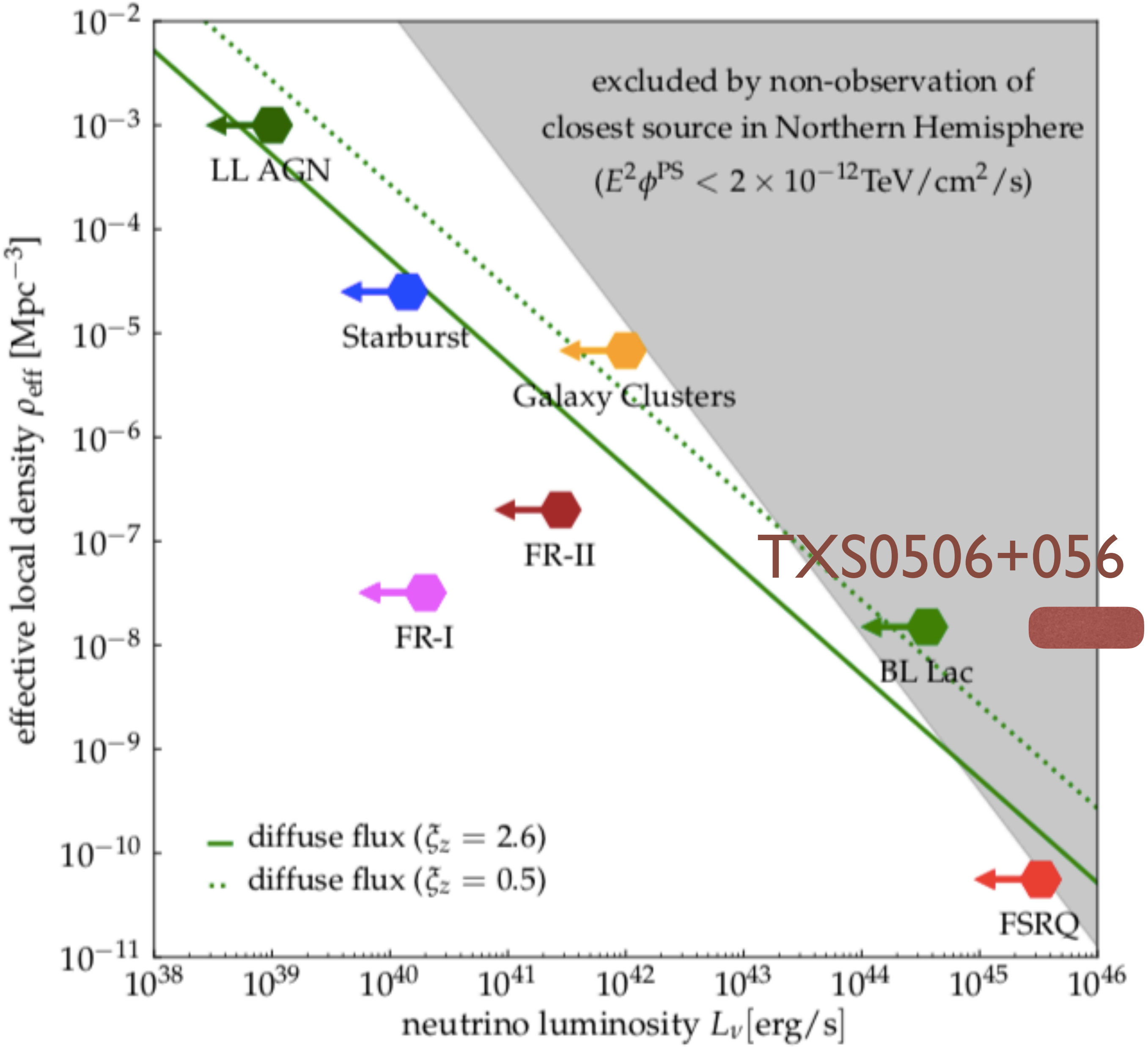
lower density (ρ)

$\Downarrow$

higher luminosity (L)

$\Downarrow$

brighter sources (ϕ)



Diffuse flux observed by IceCube is composed of many individual sources. Their non-observation constrains source populations

[MA & Halzen'18]

Murase & Waxman,2016

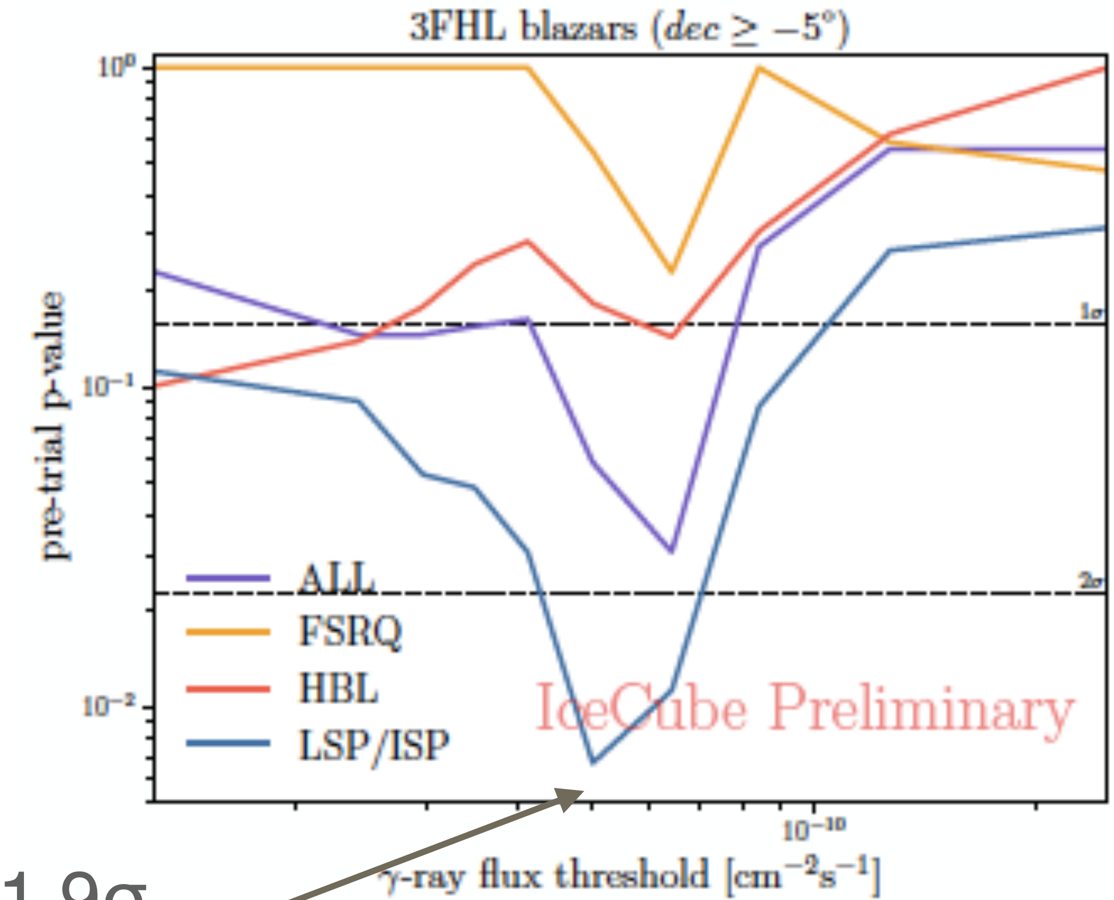
Stacking neutrinos from Fermi blazars

3FHL catalog (3rd catalog of hard Fermi LAT sources) [Ajello et al 2017, Chang et al 2017] : 1301 blazars with E >10GeV;
8 yr IceCube up-going muon neutrinos
Assumptions:

- all blazars are equally strong neutrino emitters
- all sources in a population follow a global spectral distribution

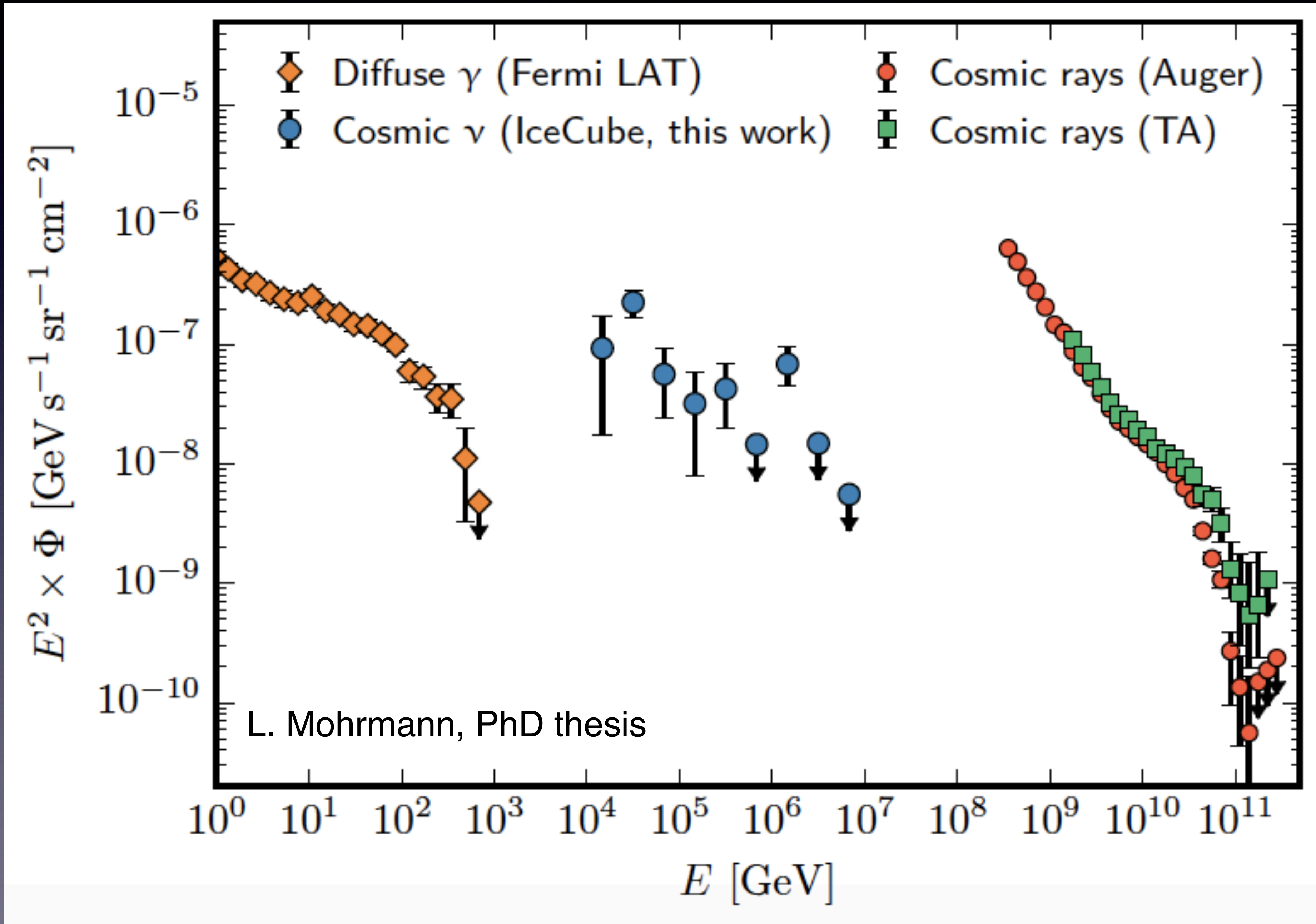
Huber et al TeV PA 2018

Previous result (ICRC2017): while blazars account for ~85% of the extragalactic gamma-ray background, IceCube neutrinos < 6% (but model dependent)

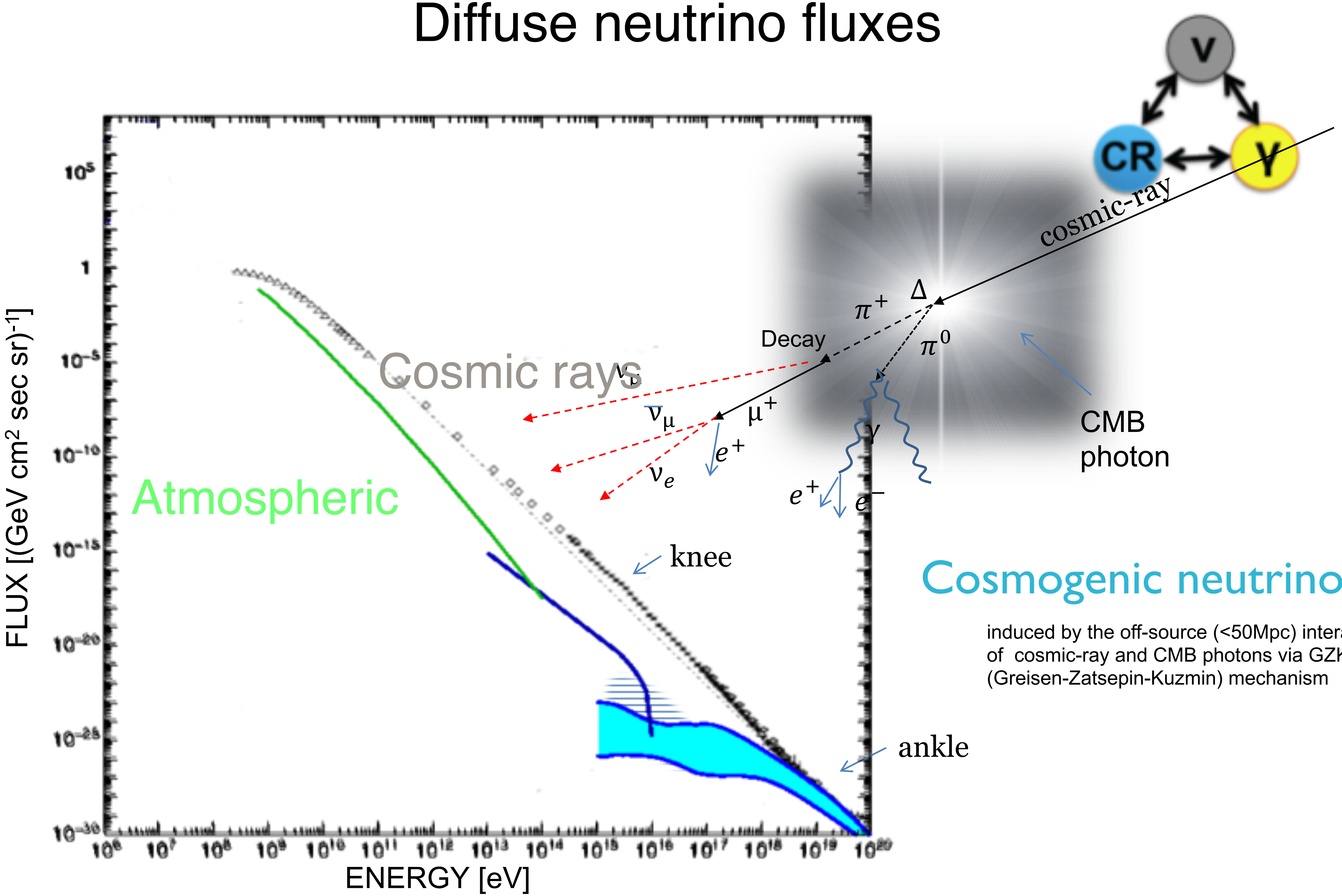


Post-trial 1.9σ

Energy in multi-messenger diffuse fluxes



Diffuse neutrino fluxes

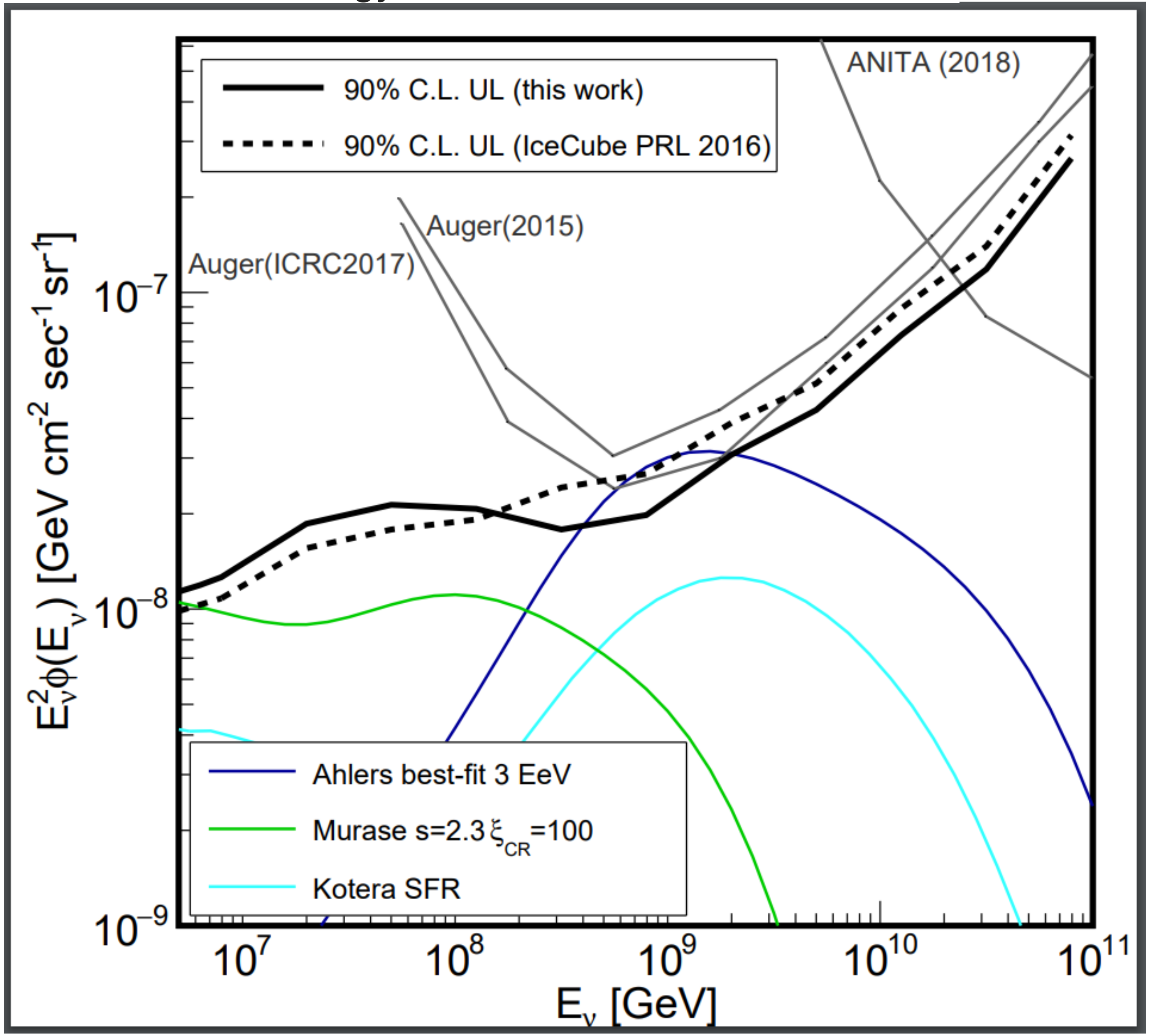


Cosmogenic neutrinos

induced by the off-source (<50Mpc) interact
of cosmic-ray and CMB photons via GZK
(Greisen-Zatsepin-Kuzmin) mechanism

Cosmogenic neutrinos

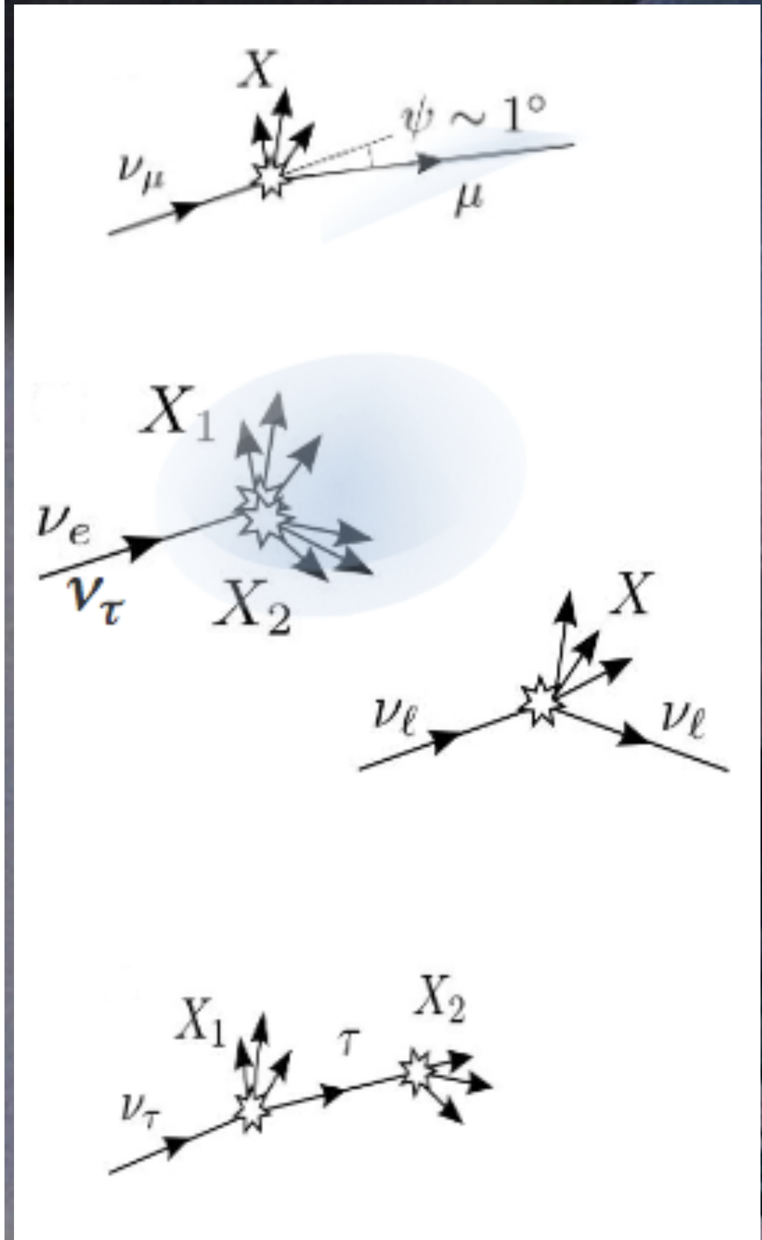
Limit for neutrino energy between 5×10^6 - 2×10^{10} GeV



9 years of iceCube data
Strong constraints proton dominated UHECR sources
Mildly evolving models (e.g. star formation rate) disfavoured

https://doi.org/10.1103/PhysRevD.98.062003

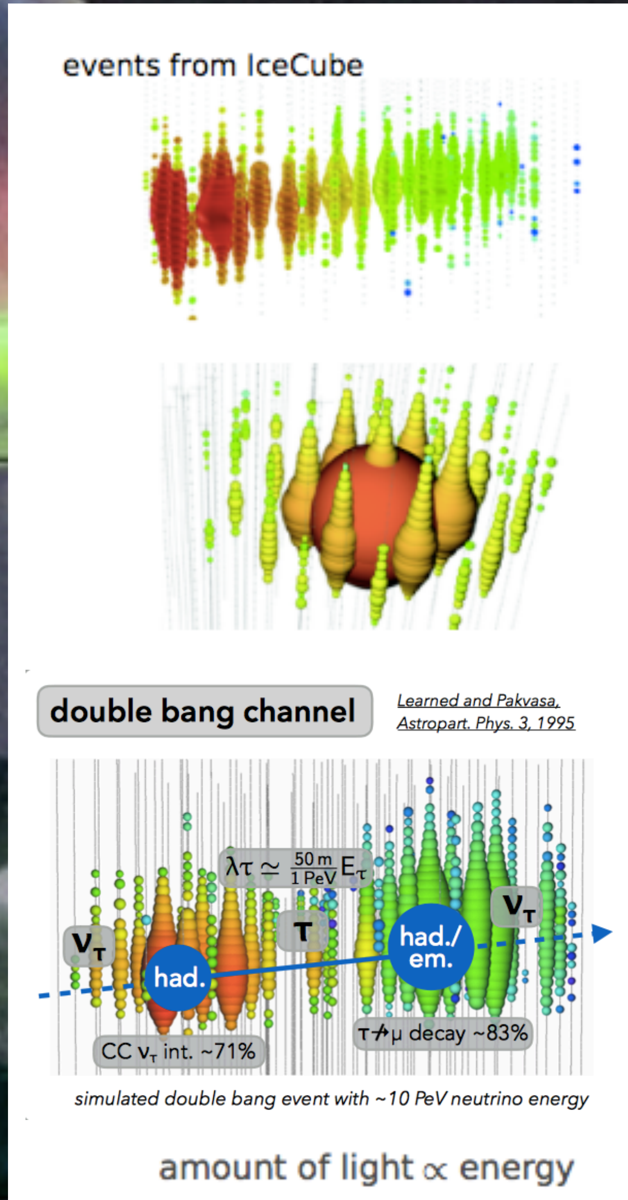
The neutrino flavour of events



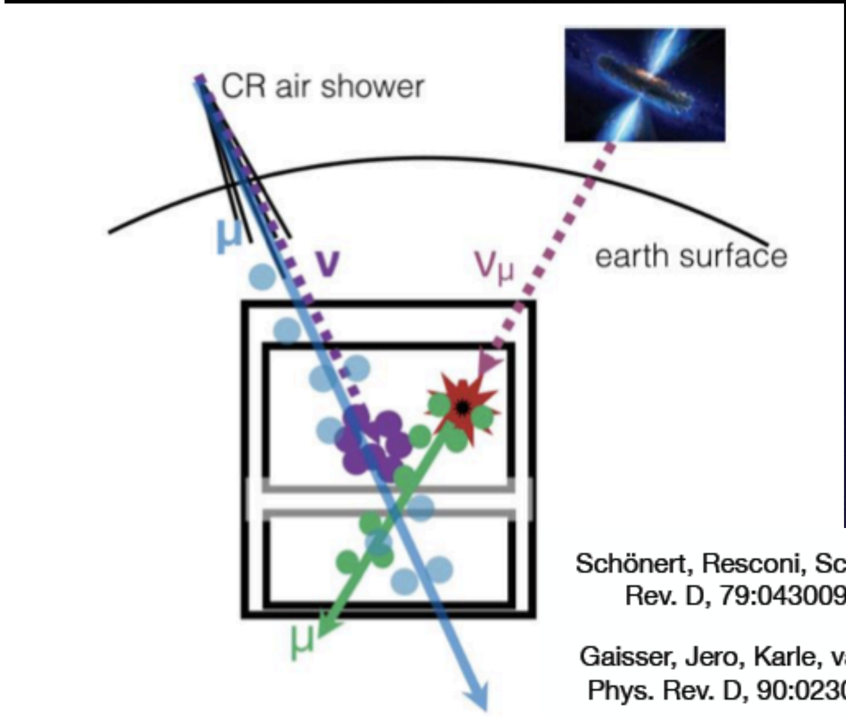
Track
Standard reconstruction;
about x2 energy resolution
Angular resolution ~0.5°
(0.3° for E > 100 TeV)

Cascade
10-15% energy resolution
for E > 100 TeV
Angular resolution O(10°)

Tau neutrino double bang
Decay length ~ 50 m/PeV



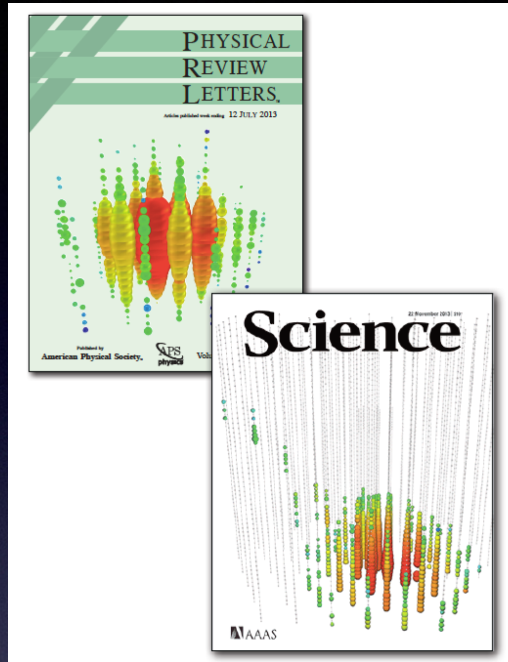
The biggest events (HESE)

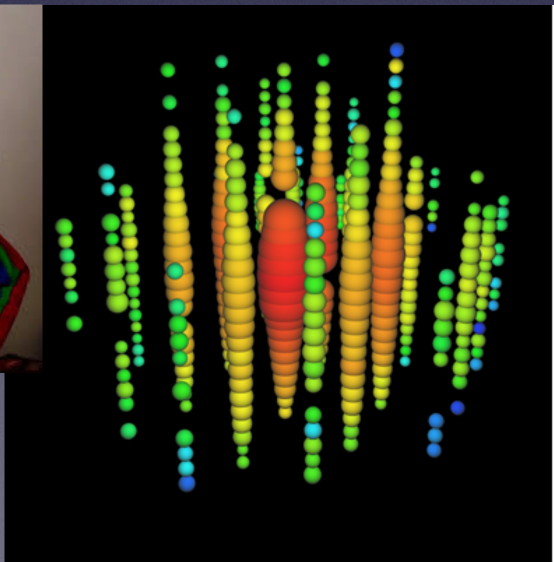


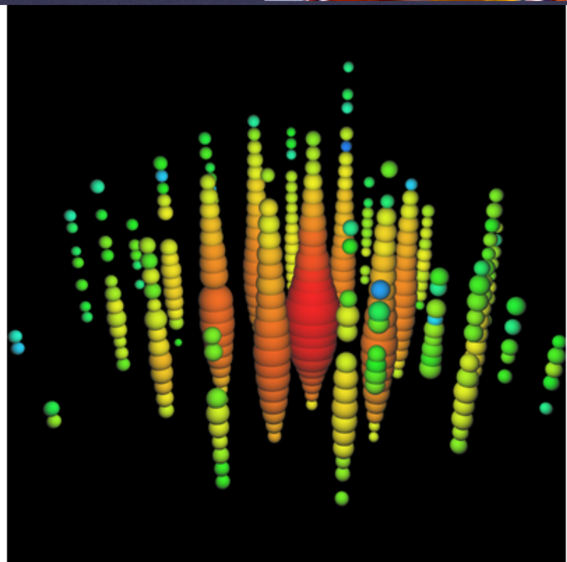
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

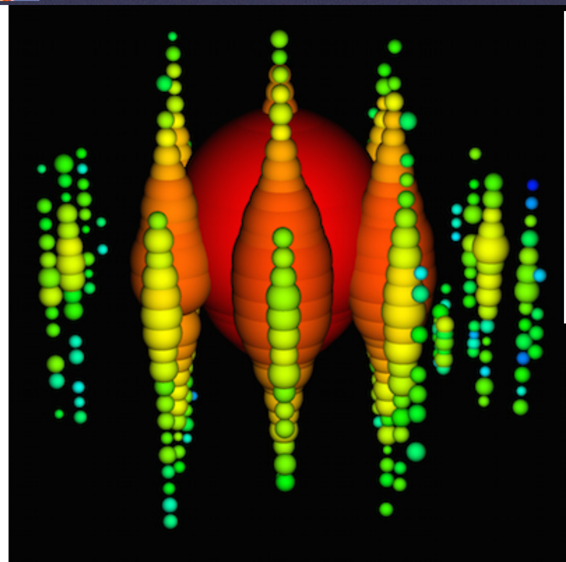
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Science di Novembre 2013: discovery of first astrophysical neutrinos in 4 yrs of data.





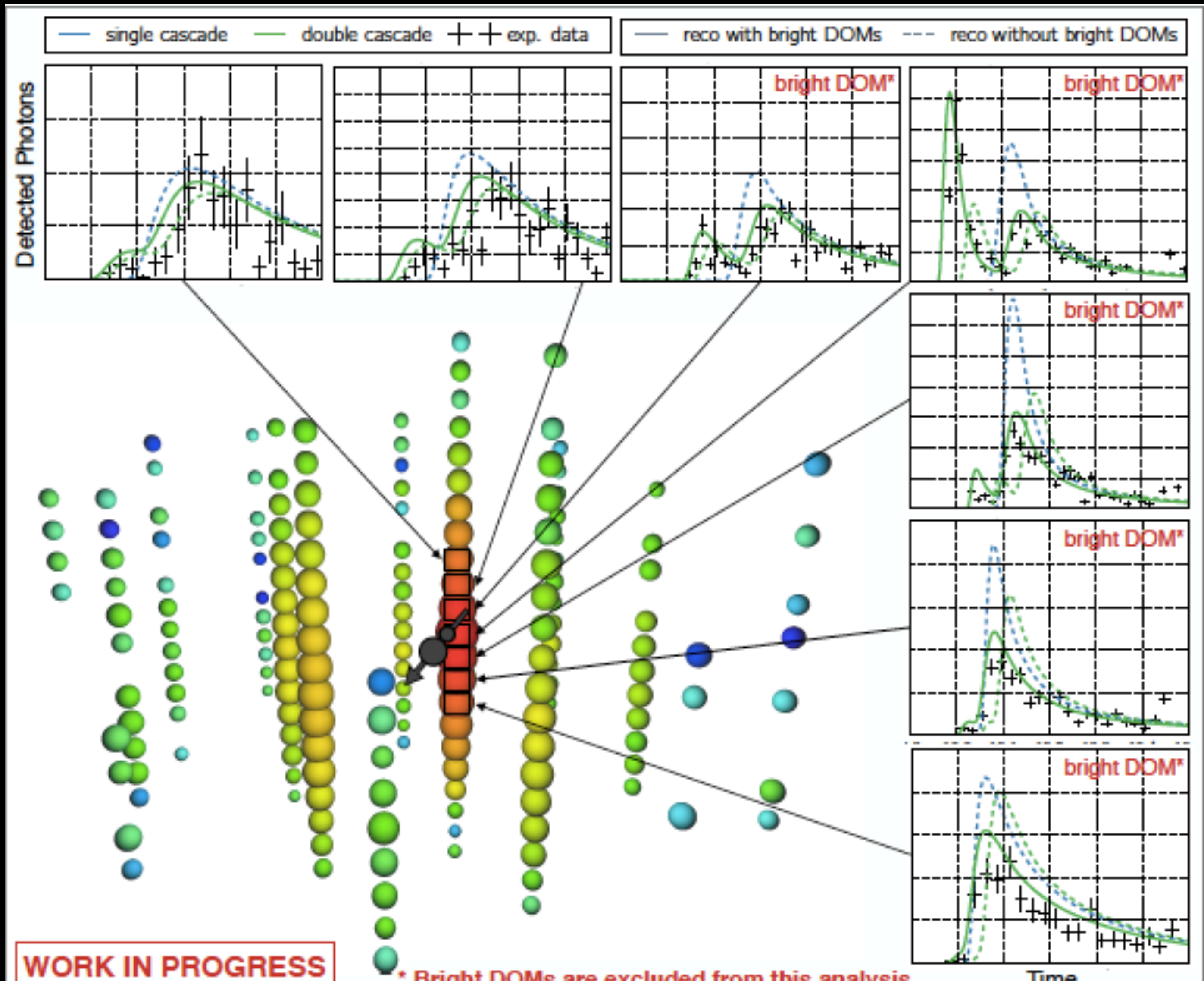




A tau neutrino from oscillations in the cosmos?

J. Stachurska, TeVPA2018

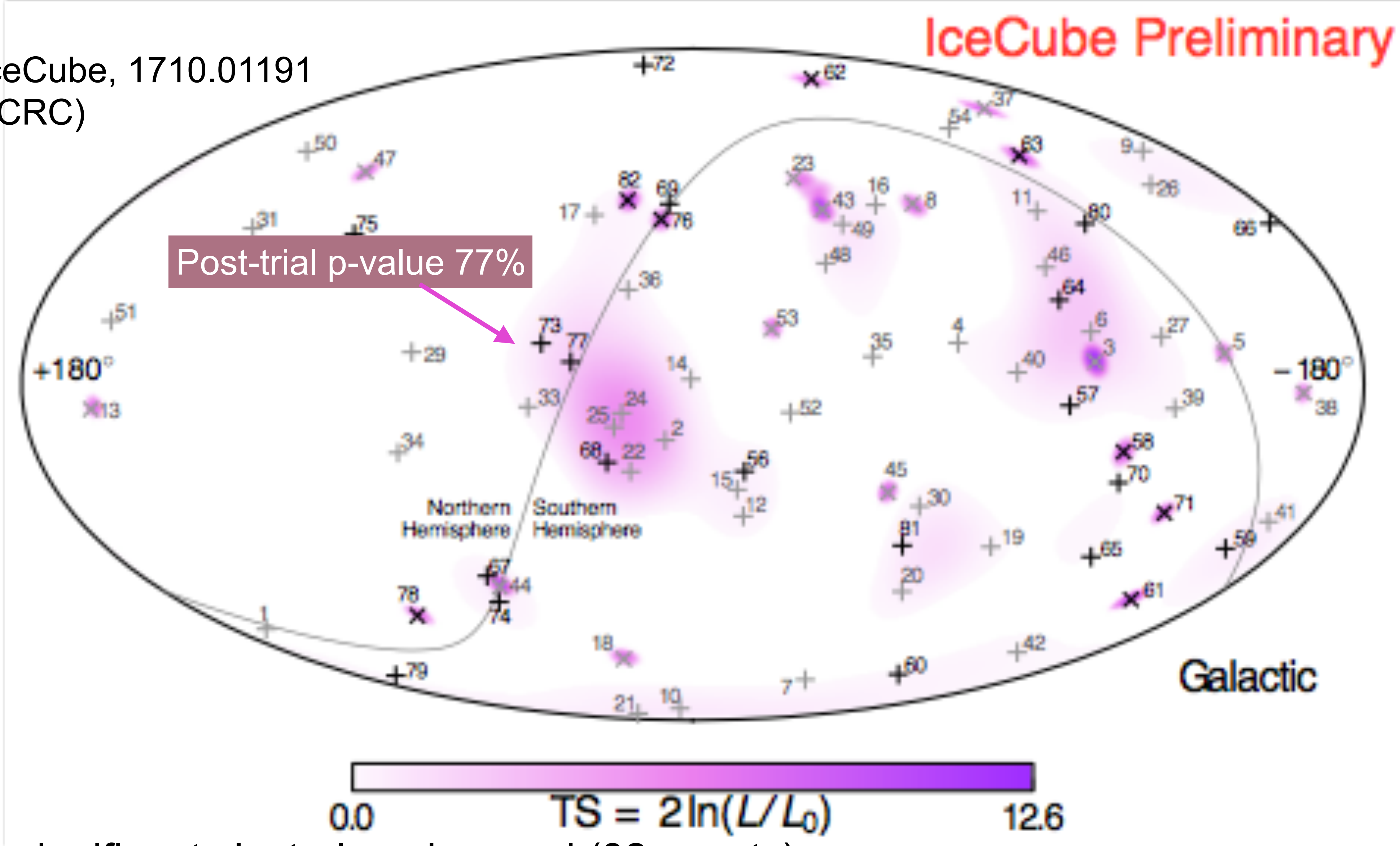
High probability to be a double bang event.
Still to do: evaluation of p-value for not being of prompt origin



IceCube high-energy starting events (6 years)

IceCube, 1710.01191
(ICRC)

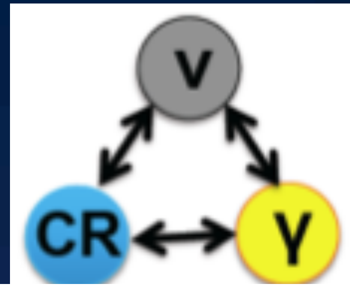
Post-trial p-value 77%



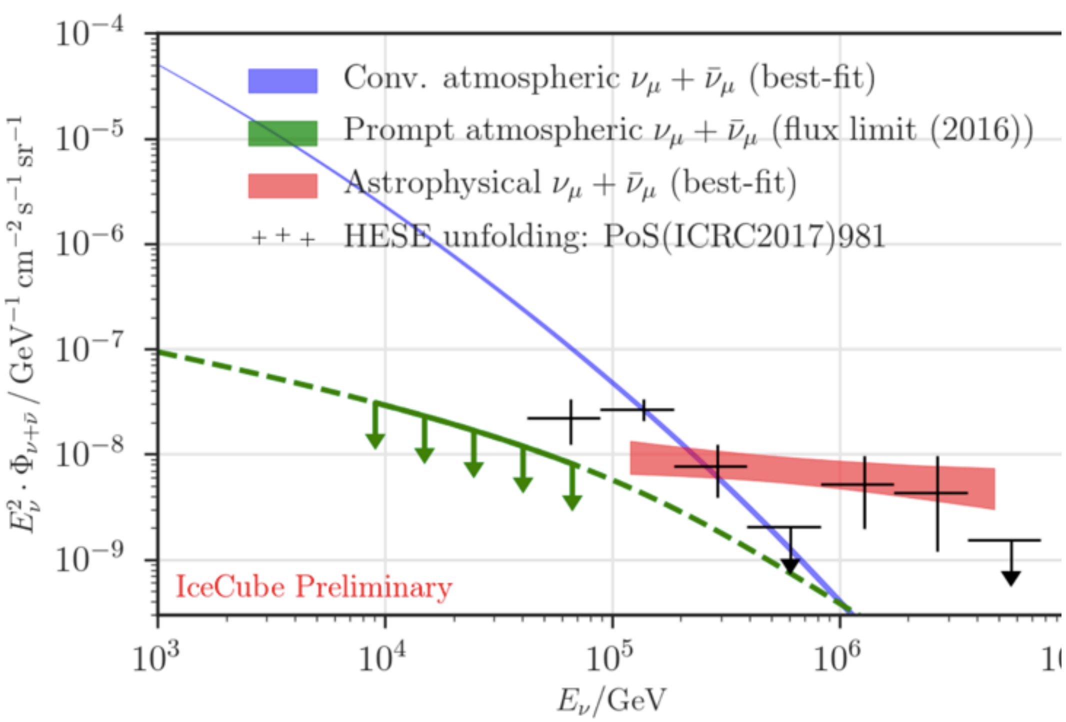
No significant clustering observed (82 events)

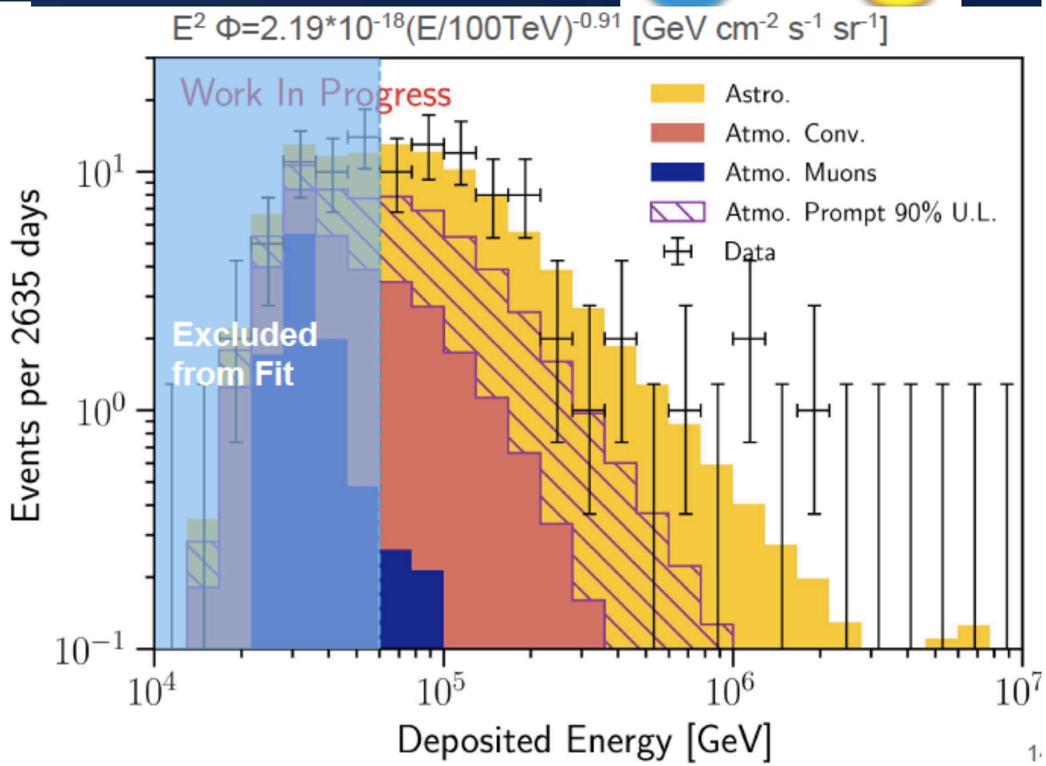
Arrival directions compatible with isotropy. => dominance of extragalactic sources?

Diffuse fluxes in IceCube



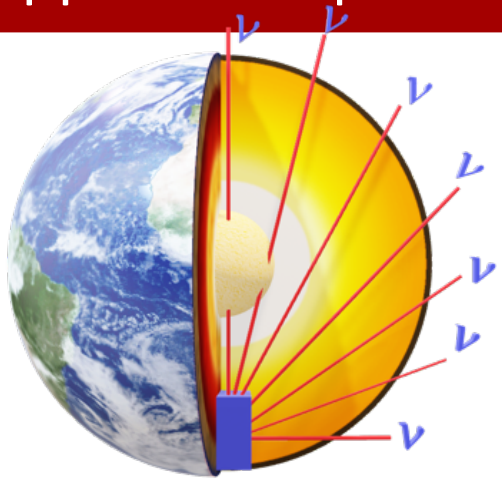
8 years of muon tracks



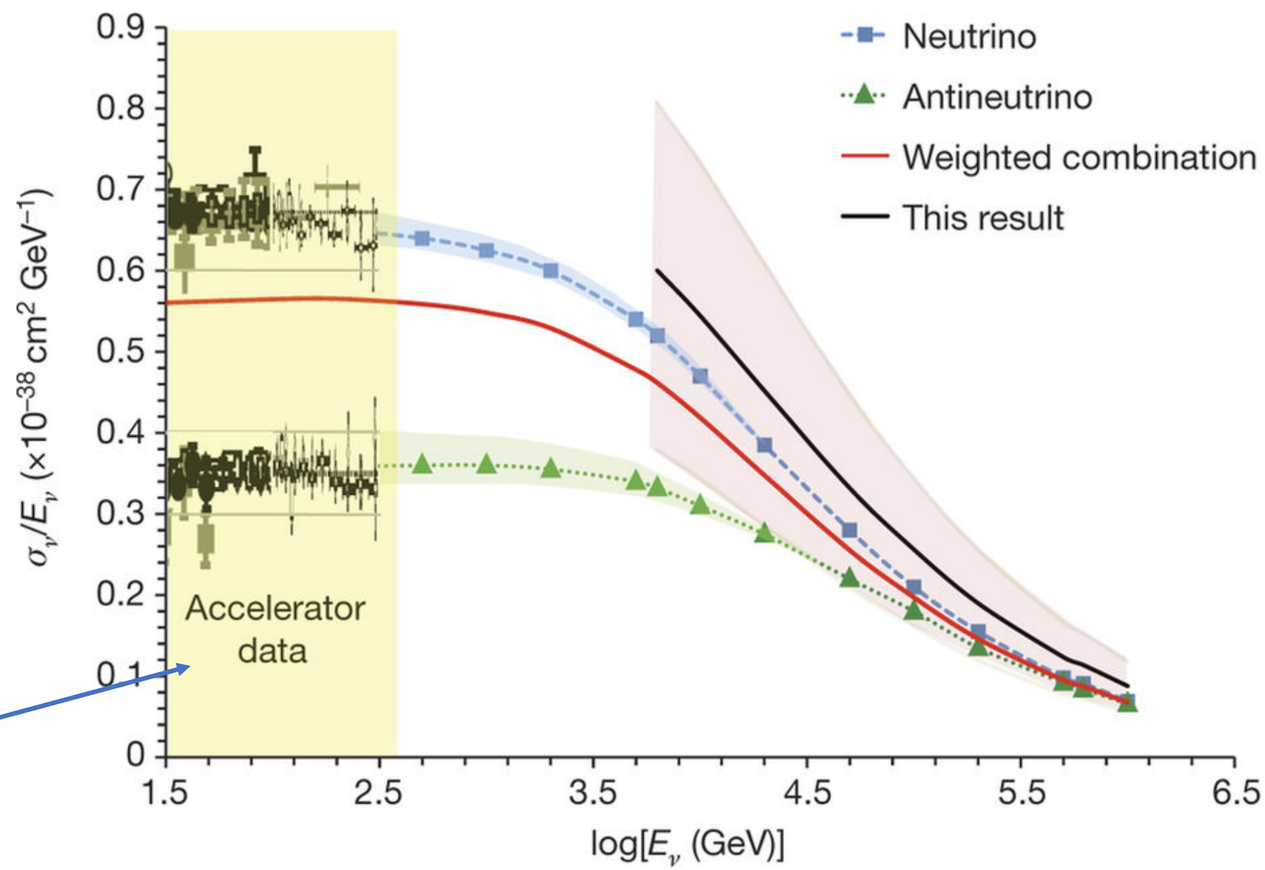


Preliminary: 102 High-Energy Starting Events (HESE) in 7.5 yr , 60 with E_{vis}>60 TeV
Background: 0.65±0.2 (atm.μ) , $14.5^{+10.1}_{-8.1}$ (atm.ν, incl. prompt)
Best Fit: -2.91 spectral index A, Schneider,TeVPA2018

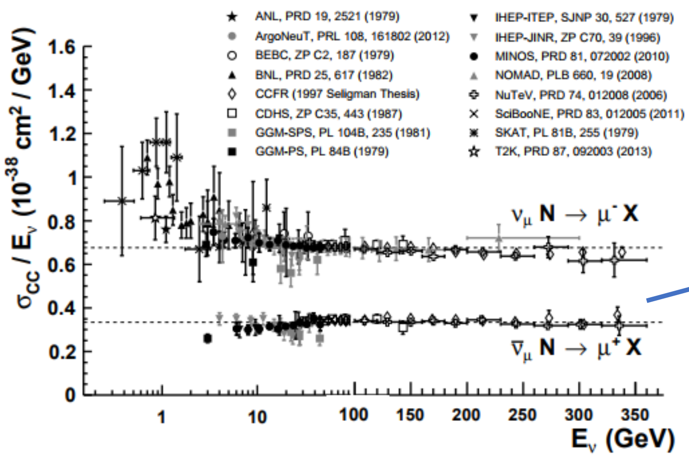
$\nu_\mu \rightarrow \nu_\mu$ disappearance probes high energy (TeV scale) neutrino cross-section



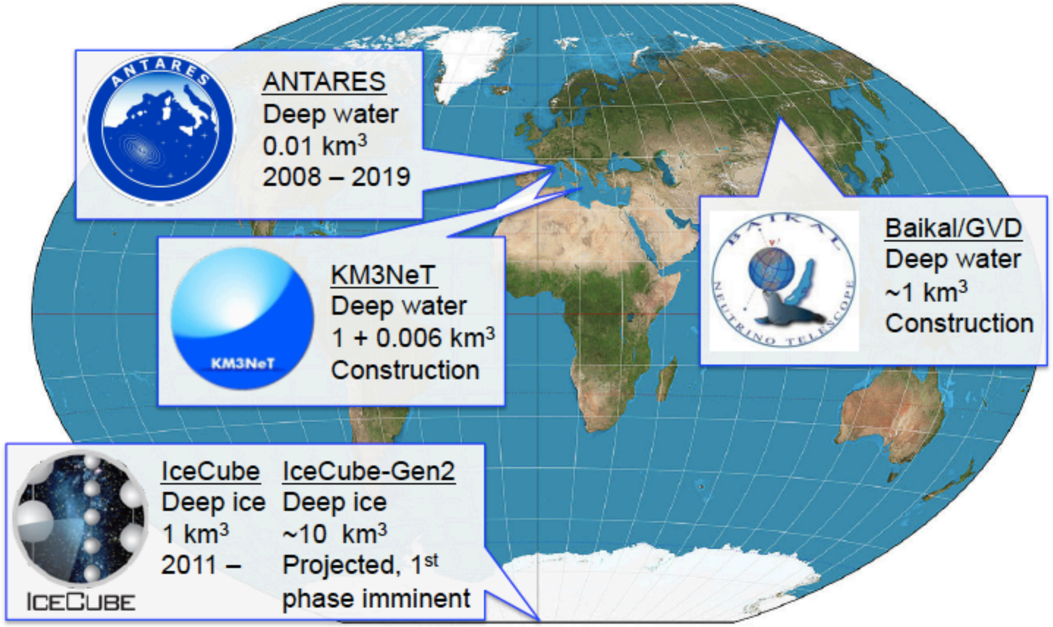
Nature ***551*** *596 (2017)*

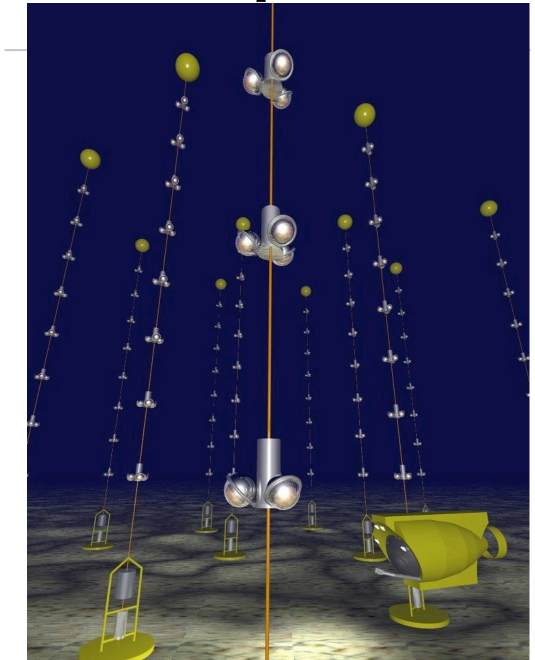


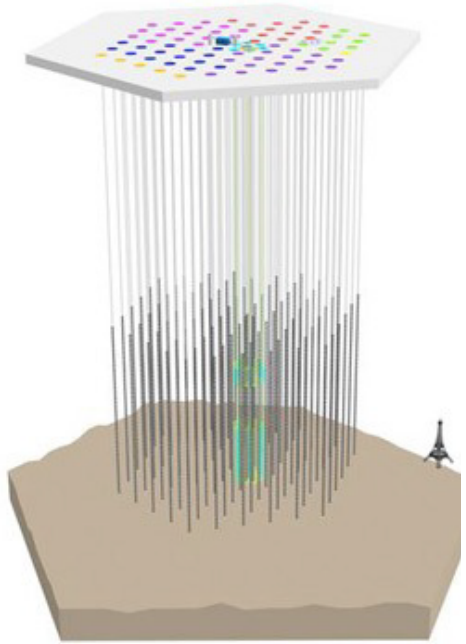
PDG



Current projects and experiments



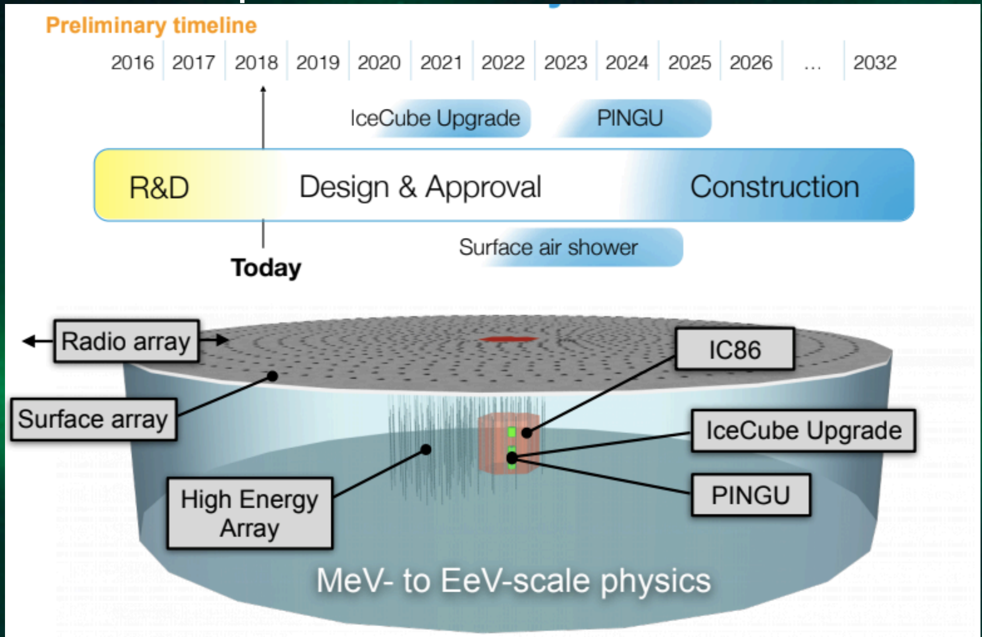


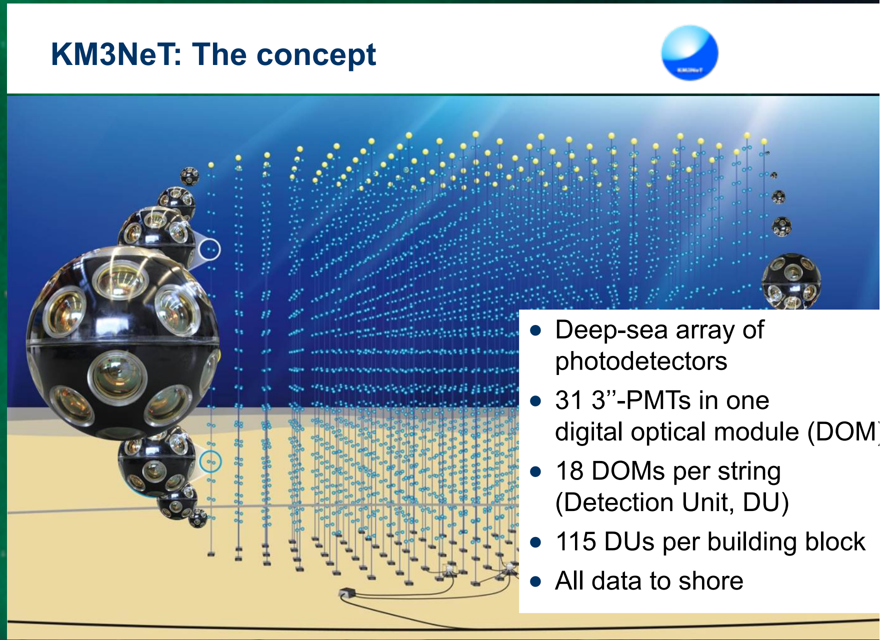


The Future

PINGU LoI: https://arxiv.org/pdf/1401.2046.pdf

update: arXiv:1607.02671

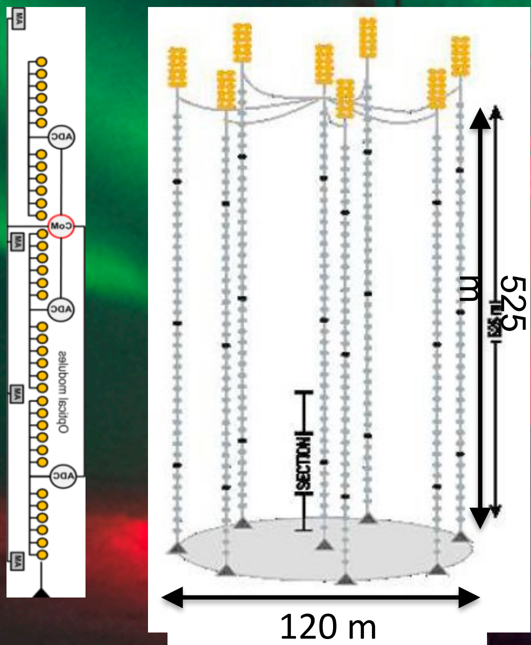


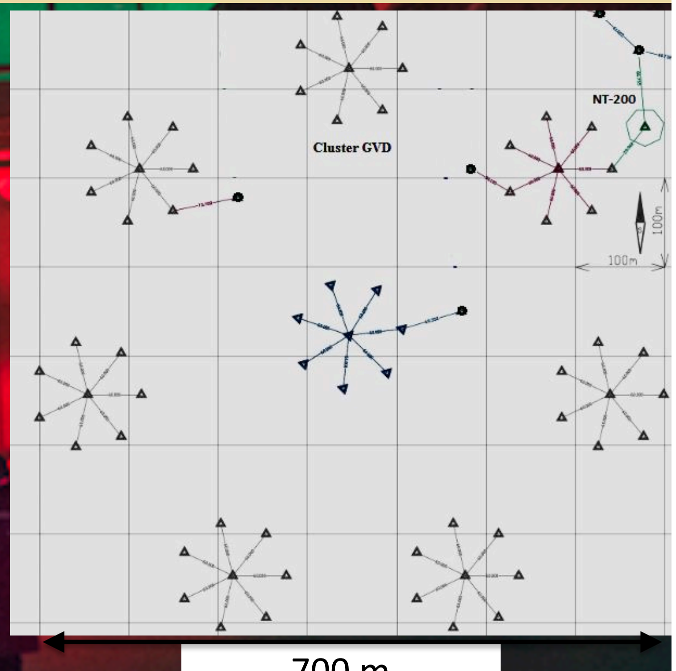


NSF initial funds just approved!

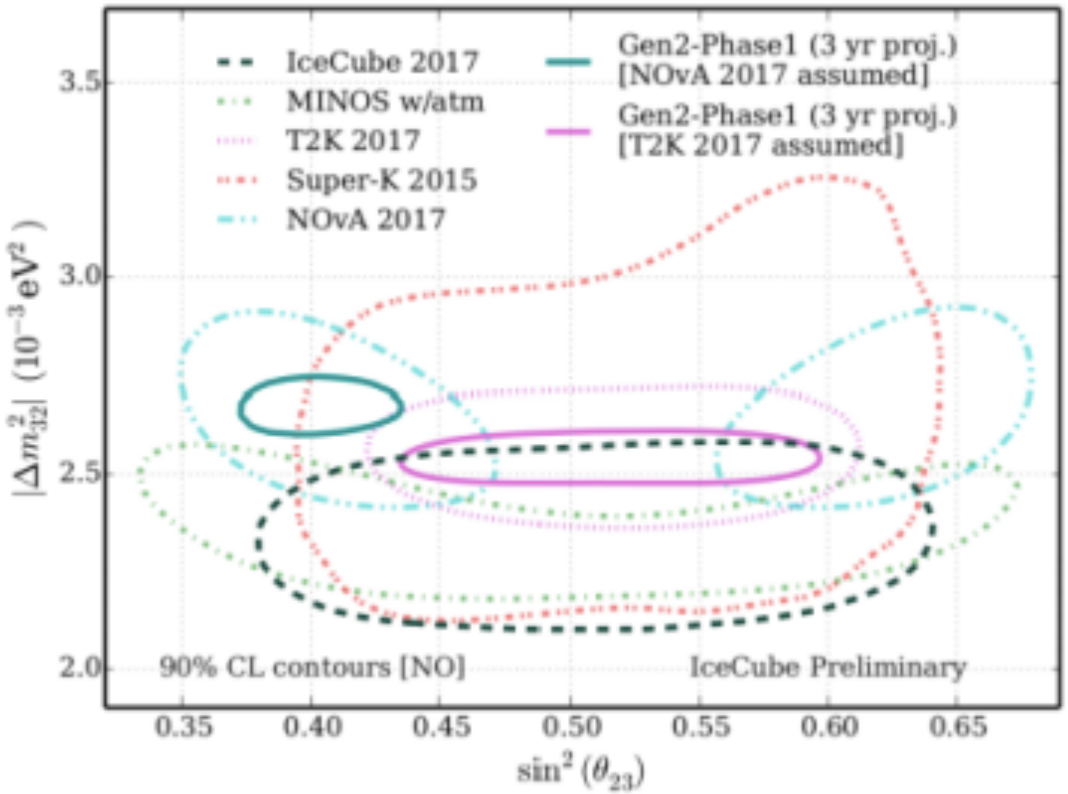
The Baikal GVD:

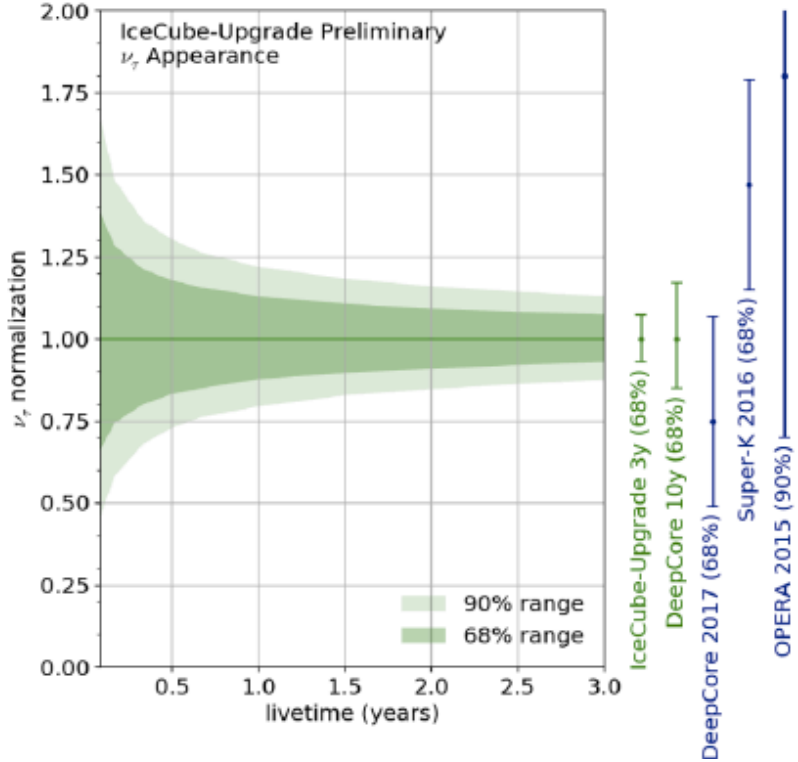
Final goal: 27 clusters, 1.5 km^3





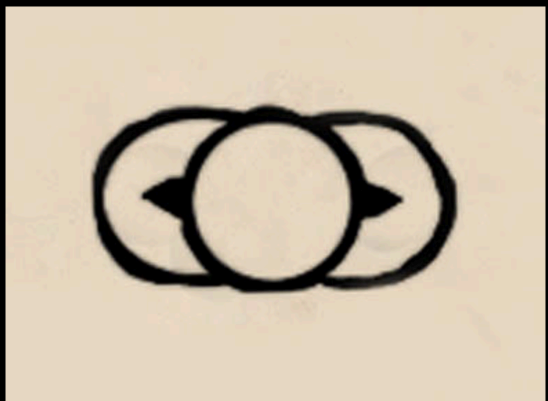
Neutrino oscillations

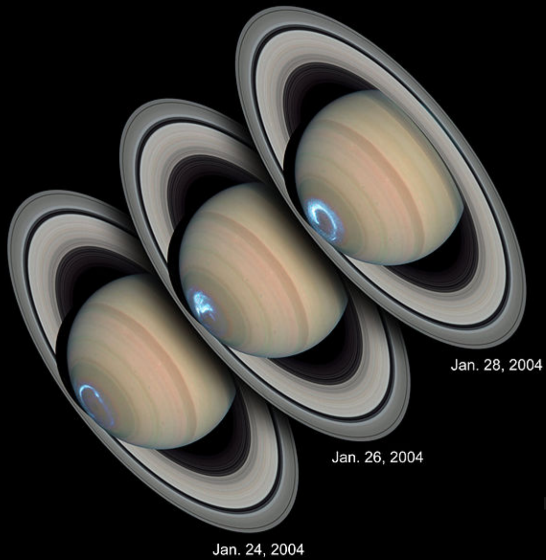


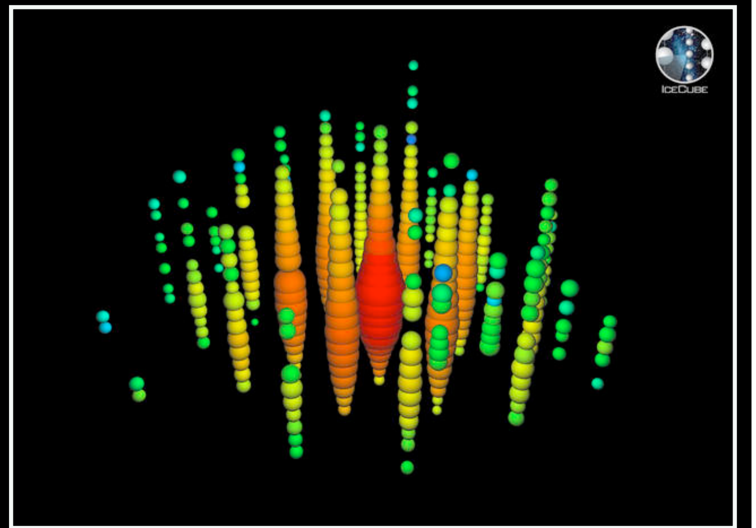


After 3 yr from upgrade with 7 compact strings, constraints on nutau normalisation are at 10% level.

CONCLUDING REMARK







Most of presented results are from IceCube Collaboration