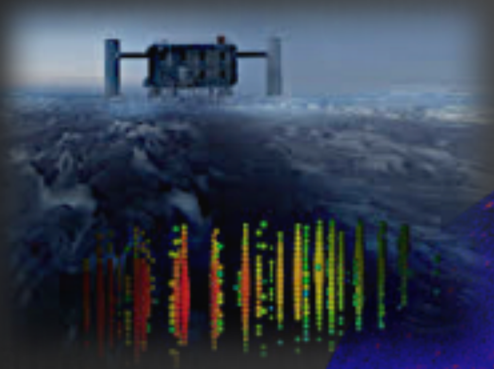
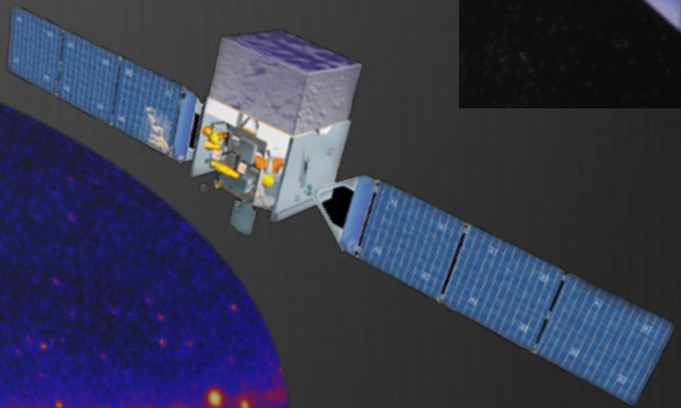
Linking Electromagnetic Observations to Neutrino Astrophysics






Sara Buson

Würzburg Univesität

University of Maryland, Baltimore County

12th INTEGRAL Conference, 1st AHEAD Gamma-ray Workshop

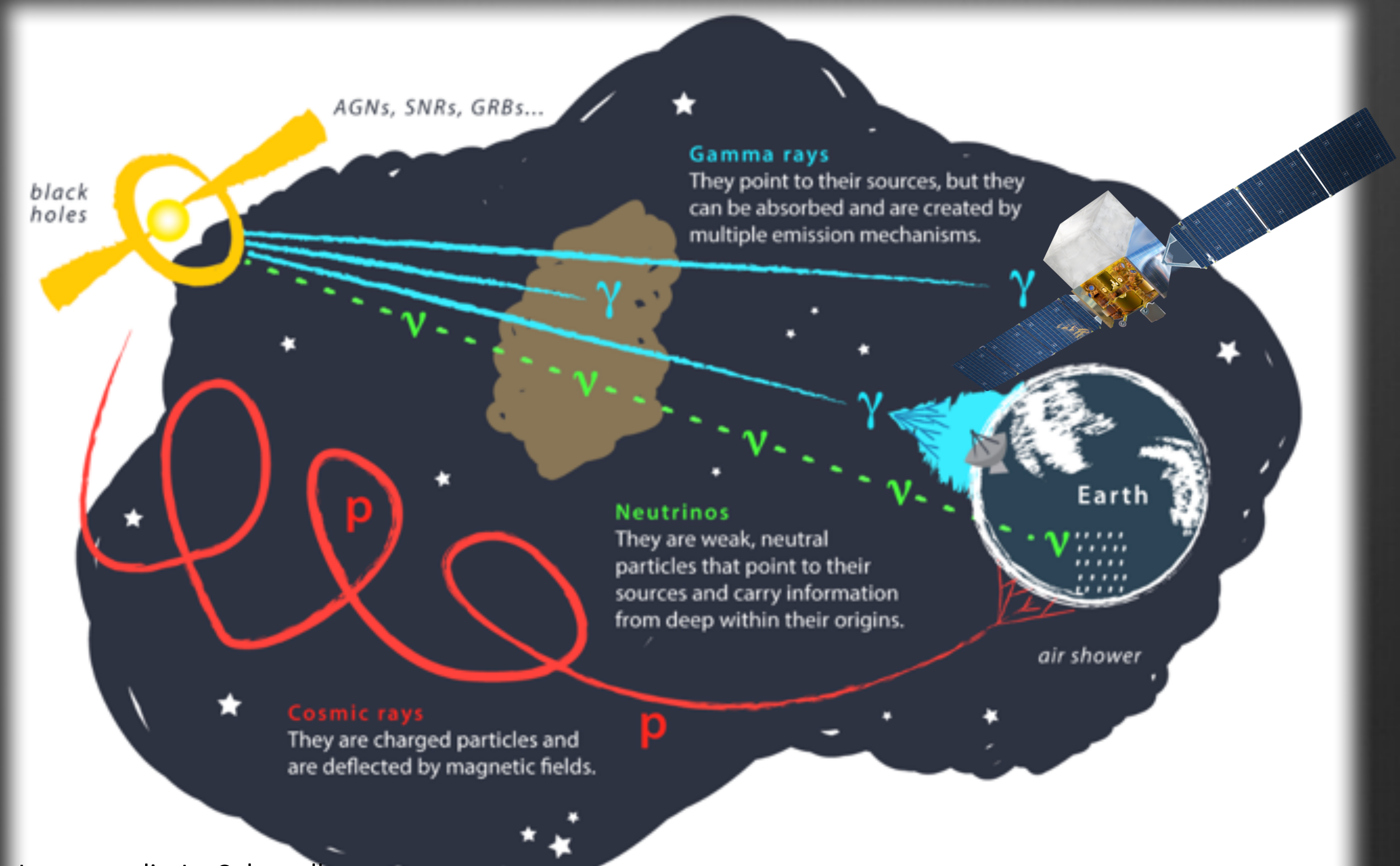
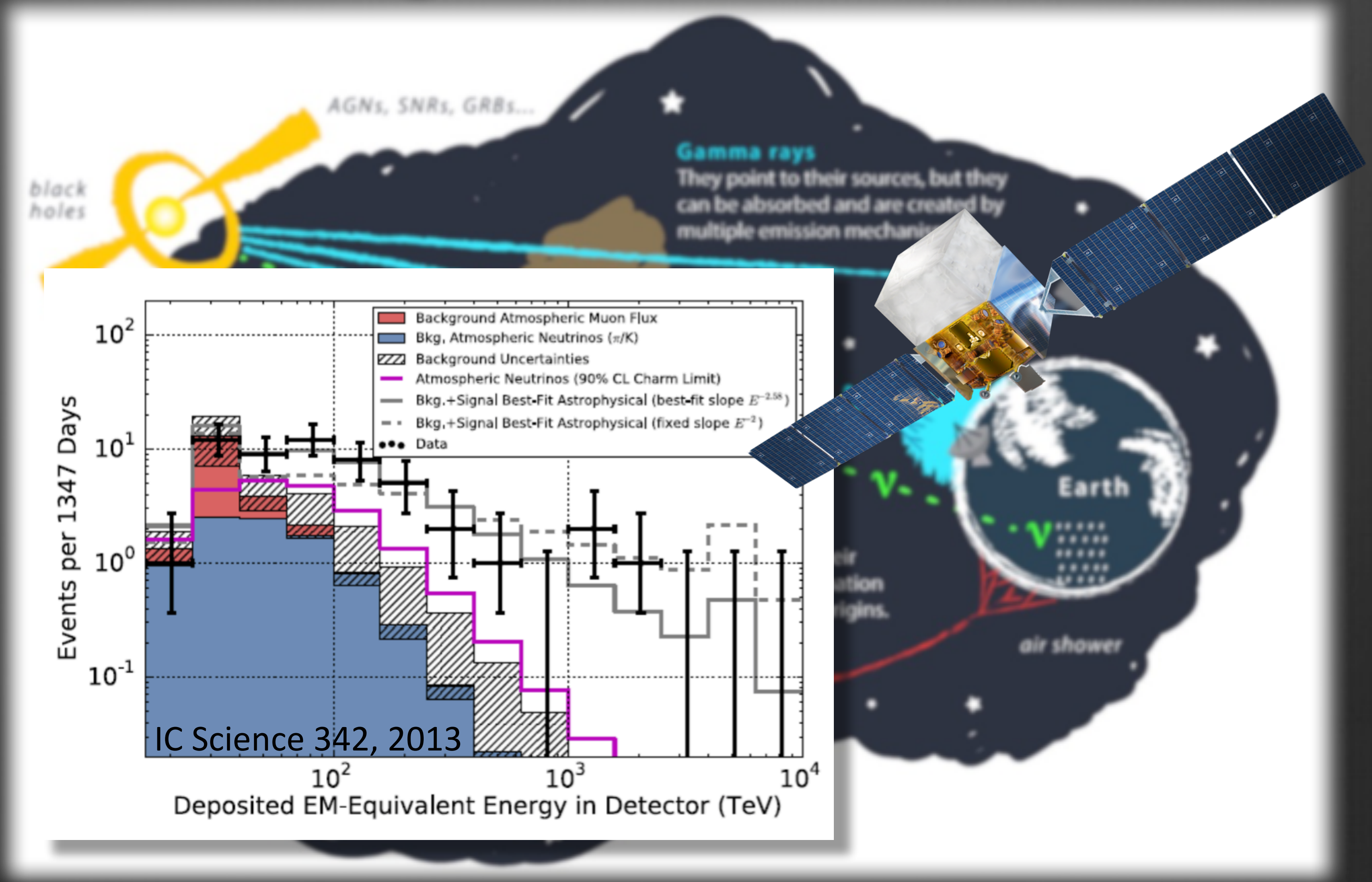


Image credit: IceCube coll.

Hunting Cosmic Neutrinos

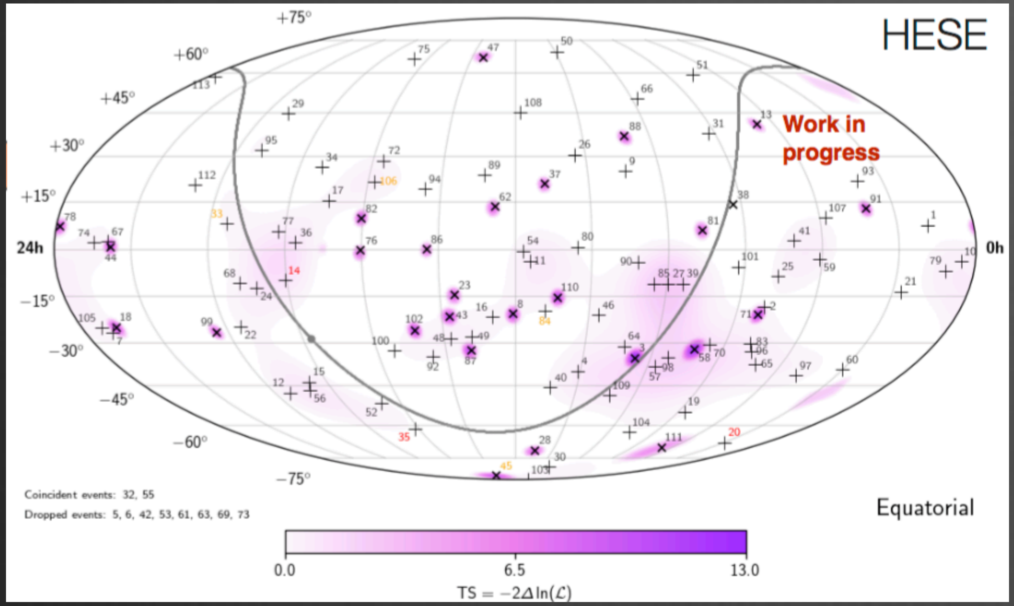


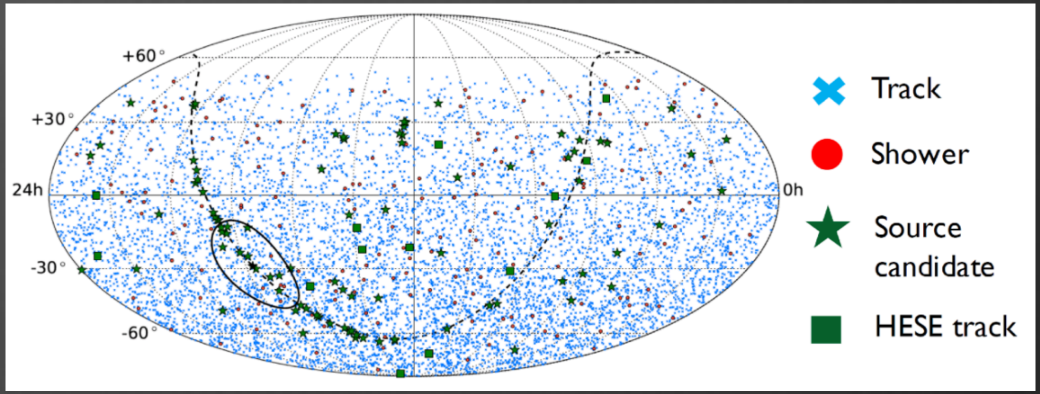
Astrophysical Sources of High Energy Neutrinos

- A pre-condition for likely astrophysical VHE neutrino sources is that they are also sources of VHE cosmic rays
- Such sources could also be naturally related to the sources of ultra-high energy cosmic rays (UHECRs) observed by the Auger and TA cosmic ray arrays
- NB: We still cannot prove those energies. For the currently detected maximum neutrino energies of ~< 3 PeV it is only necessary to have sources capable of accelerating CRs up to ~< 100 PeV

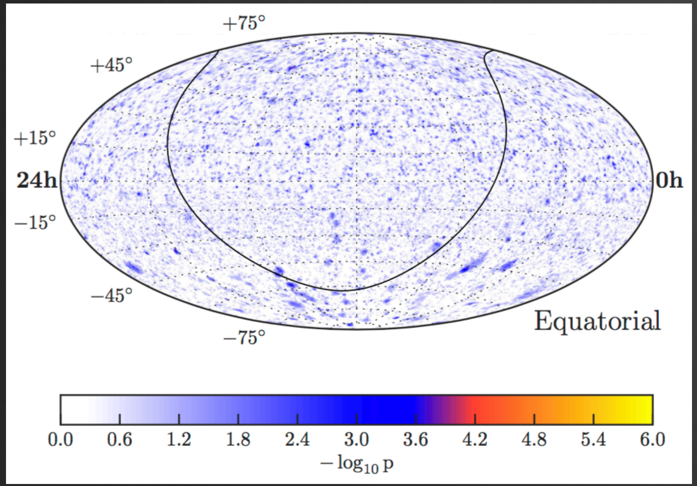
(e.g., Mészàros 2017, ARNPS, 67, 45;
Böttcher 2019 Galaxies, 7, 20 for a review)

Astrophysical ν point sources



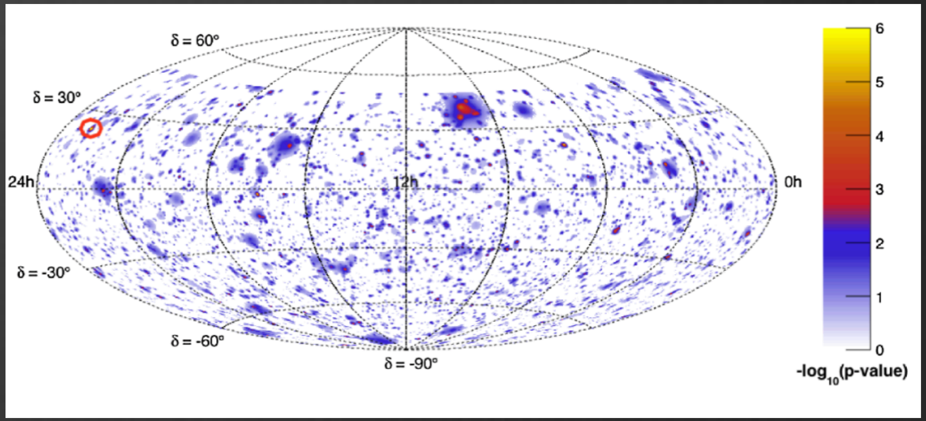


ANTARES Phys. Rev. D 96, 082001 (2017)



IceCube, ApJ, 835 (2017) no. 2, 151

Neutrinos are becoming a mature means to explore our Universe



Isotropically distributed: suggests a (dominant) extragalactic origin

Astrophysical Extragalactic Scenarios

▪ Cosmic-ray Accelerators

neutrinos produced within the CR source, mesons are typically produced by interactions of CRs with radiation

- **Gamma-ray bursts**
  (e.g. Waxman & Bahcall 97, Murase et al. 06, Cholis & Hooper 13, Liu & Wang 13, Murase & Ioka 13, Winter 13, Senno, Murase & Meszaros 16)

- **Active Galactic Nuclei**
  (e.g. Stecker et al. 91, Mannheim 93/95, Reimer 2012, Kalashev, Kusenko & Essey 13, Stecker 13, Murase, Inoue & Dermer 14, Dermer, KM & Inoue 14, Tavecchio et al. 14, Kimura, Murase & Toma 15, Padovani et al. 15, Wang & Li 1, Lamastra 2017)

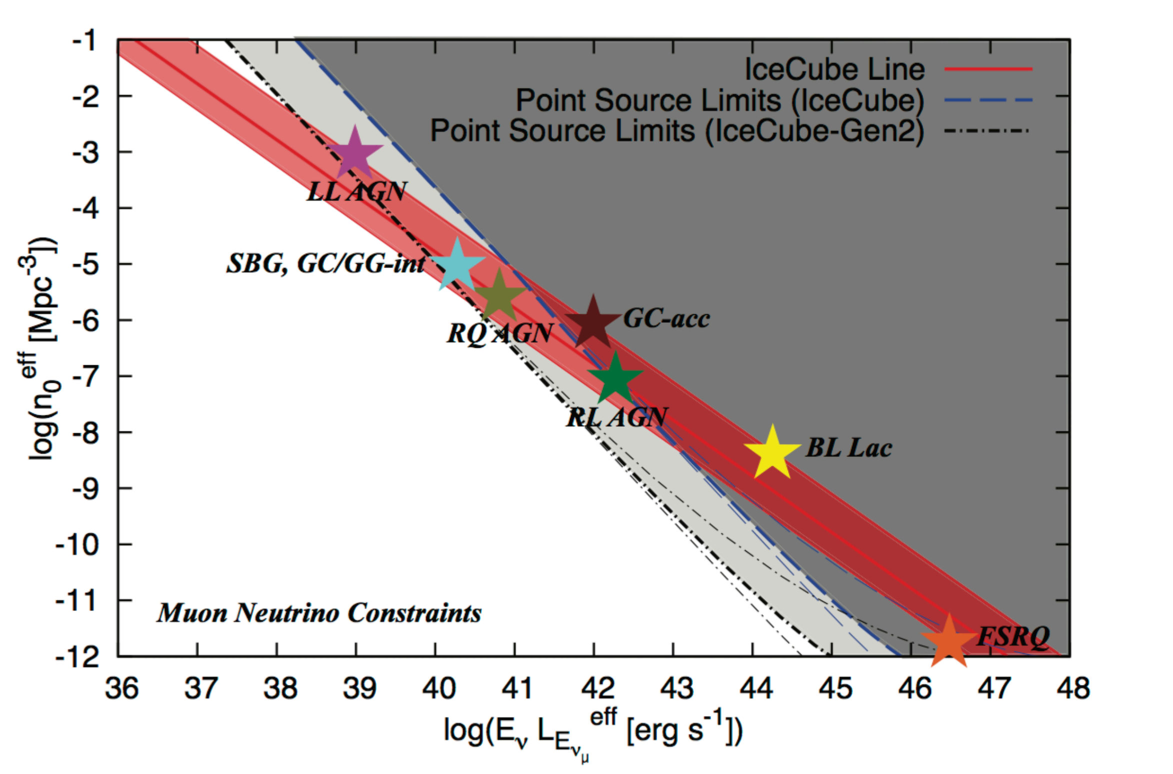
▪ Cosmic-ray Reservoirs

neutrinos produced by inelastic hadronuclear collisions while confined within the environment surrounding the CR source

- **Starburst galaxies**
  (e.g., Loeb & Waxman 06, Thompson+ 07; Murase, Ahlers & Lacki 13, Katz et al. 13, Liu+ 14, Tamborra, Ando & Murase 14, Anchordoqui+ 14, Senno+ 15

- **Galaxy groups/clusters**
  (e.g., Berezinsky+ 97, KM et al. 08, Kotera+ 09 // Murase, Ahlers & Lacki 13, Fang & Olinto 16)

γ - ν connection: strategies

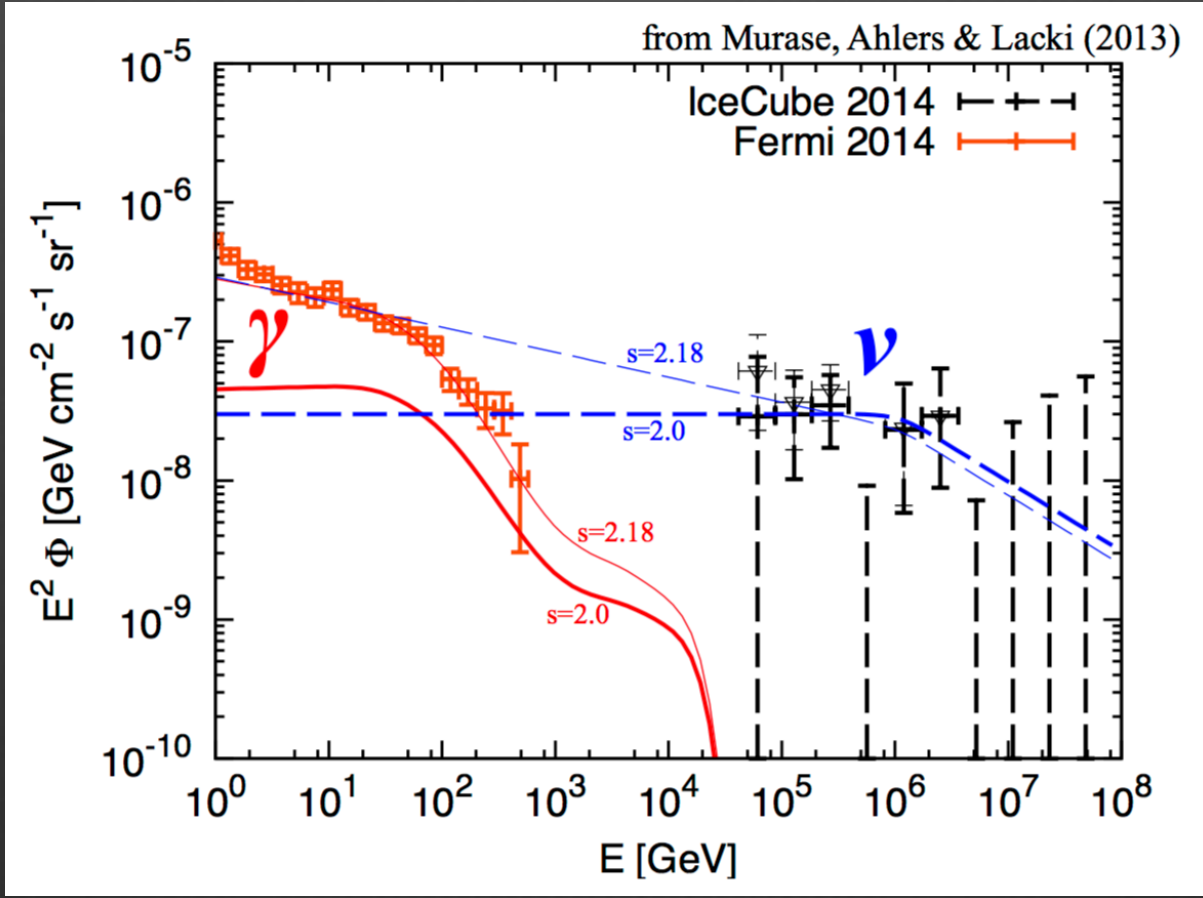


Kowalski, 2014; Ahlers, Halzen, 2014; Murase, Waxman, 2016

steady sources

- Limits on source density inferred by non-observation of neutrino multiplets

Tempting Neutrino/Gamma-rays connection



γ - ν connection: strategies

Correlation with known catalogs

- 3LAC (>100MeV, 4years); 2FHL (>50 GeV, 6years); 2WHSP (most complete list of HSP)
- None of the three blazar catalogs tested showed any significant evidence for a neutrino signal above background expectations.
- All the outcomes from the three catalog stacking analyses are fully compatible with background fluctuations.

IceCube – PoS(ICRC2017)994

Search for neutrino emission correlated with g-ray flares

A previous suspect

The high-peaked BL Lac object 1ES 1959+650:

- "Orphan" VHE flaring episode on June 4th, 2002 (WHIPPLE)
- Three neutrino events were found to arrive during the flaring episode (AMANDA); one within a few hours of the gamma ray observations
- Exhibited major flares in VHE gamma rays in the spring of 2016 (Buson+ Atel #9010, Fermi-LAT, FACT, MAGIC and VERITAS coll.)
- Test for time-clustering of neutrinos with IceCube
  - No significant emission neither by integrating over the whole flaring episode, nor by testing for clusters on shorter time scales

IC – PoS(ICRC2017)969

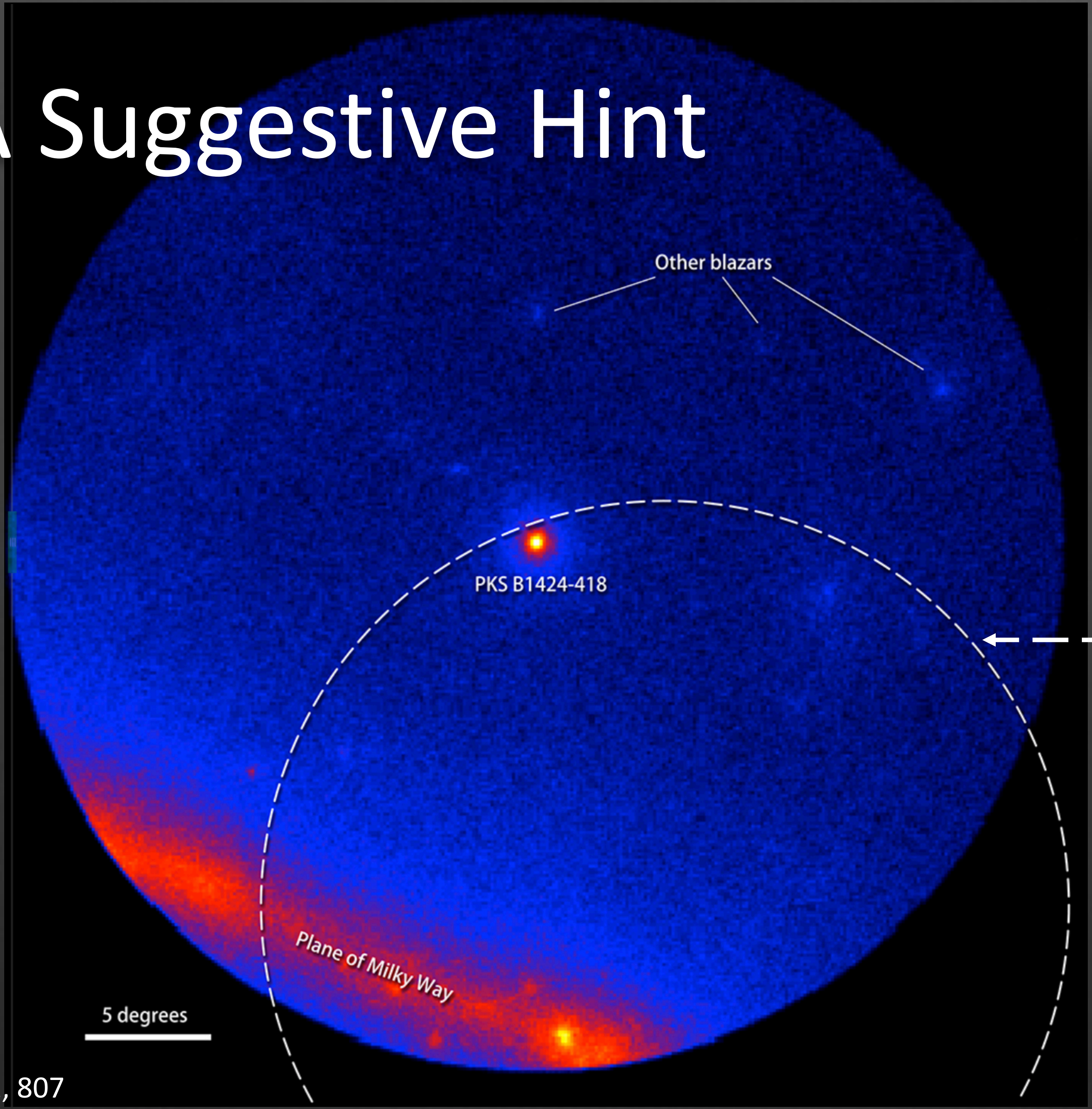
Search for neutrino emission temporally consistent with g-ray blazars:

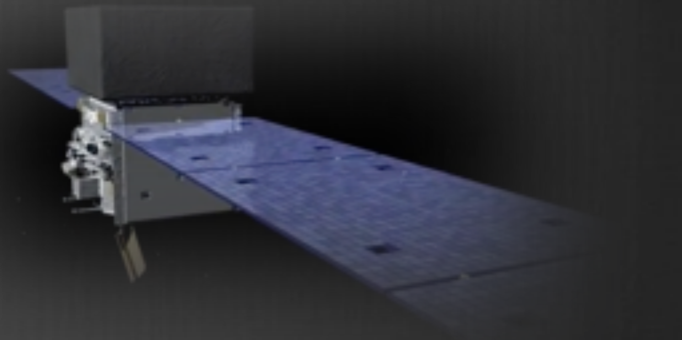
- Enhanced states pointed out by Fermi-LAT monitoring (IC ApJ, 807, 46 2015)
- TeV "orphaned" flares (IC ApJ, 744, 1 2012; ApJ, 807, 46 2015)

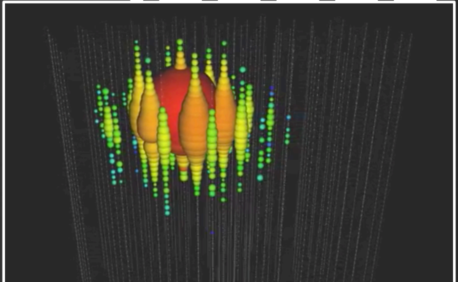
No compelling neutrino excess pointed out

A Suggestive Hint

PKS 1424-418
(FSRQ)
Fermi-LAT gamma-ray counts map (>100 MeV)







Big Bird – 2 PeV
December 4, 2012

Kadler+ 2016 *Nature Physics* 12, 807
(see also Gao+ ApJ, 2017)

IceCube Alert – IC170922A

"EHE" through-going track selection in the real-time alert system

```
////////////////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50%
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
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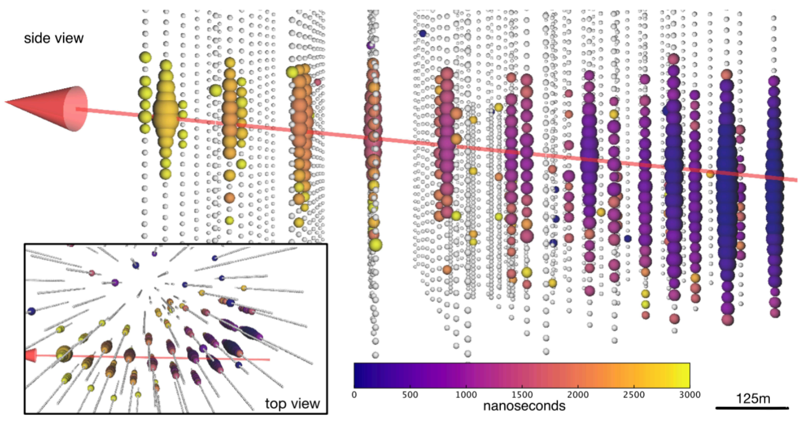
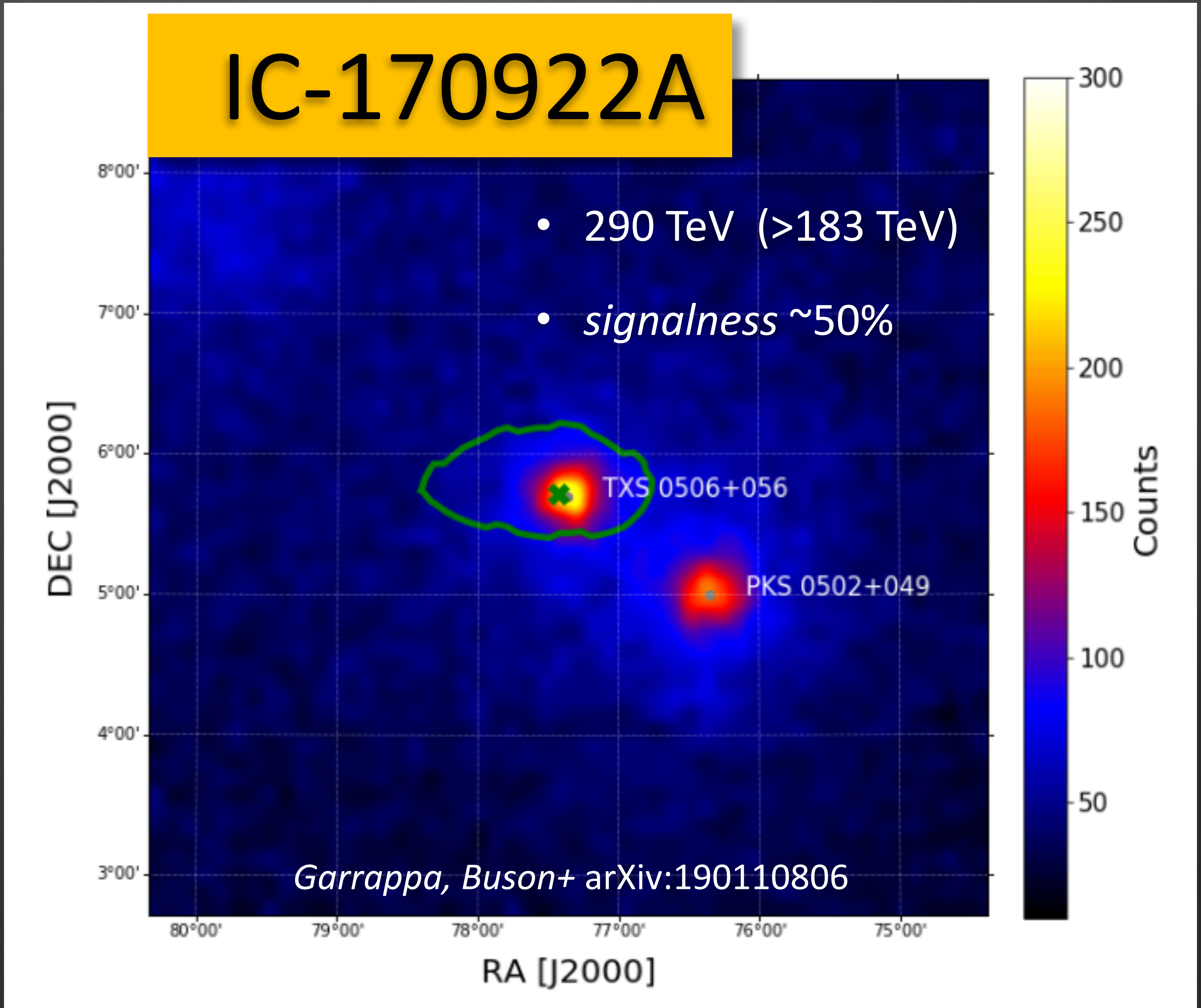
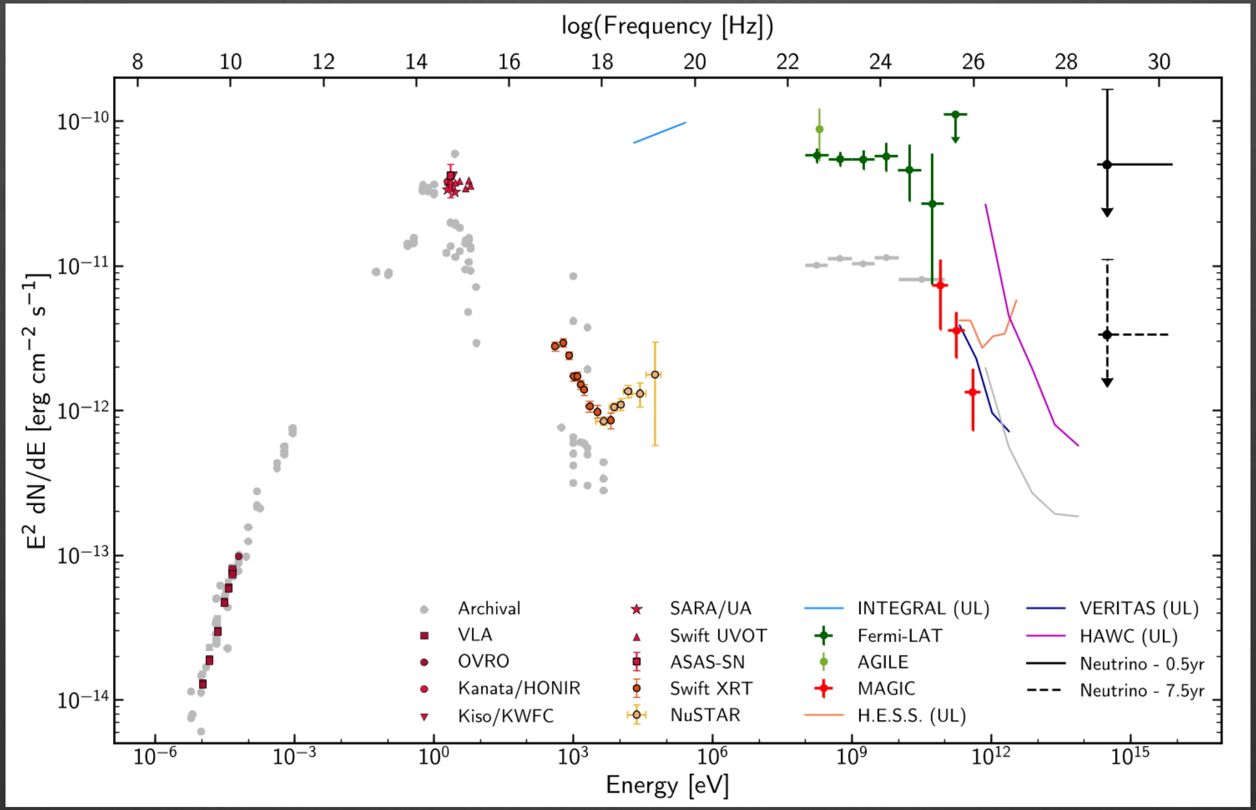


Fermi-LAT detection of candidate counterpart

Tanaka, Buson+
Atel #10791

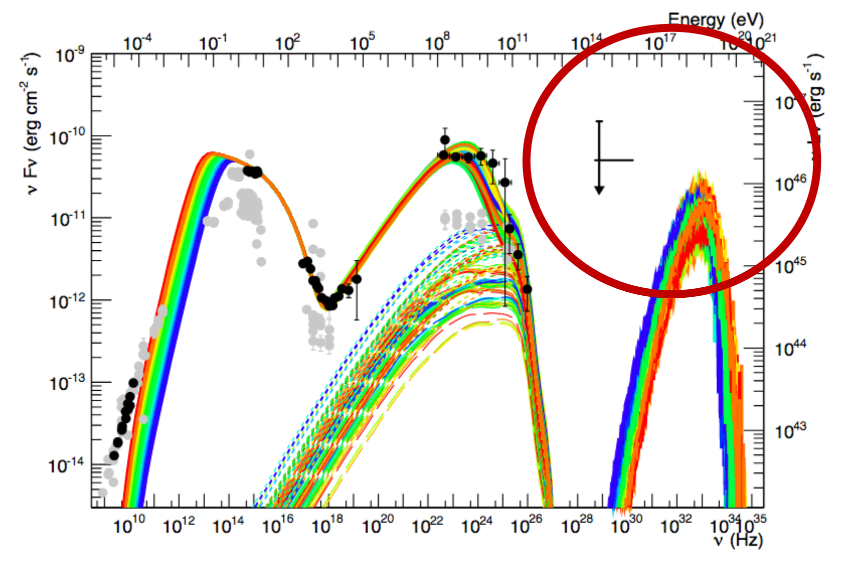


What can we learn from IC170922A?

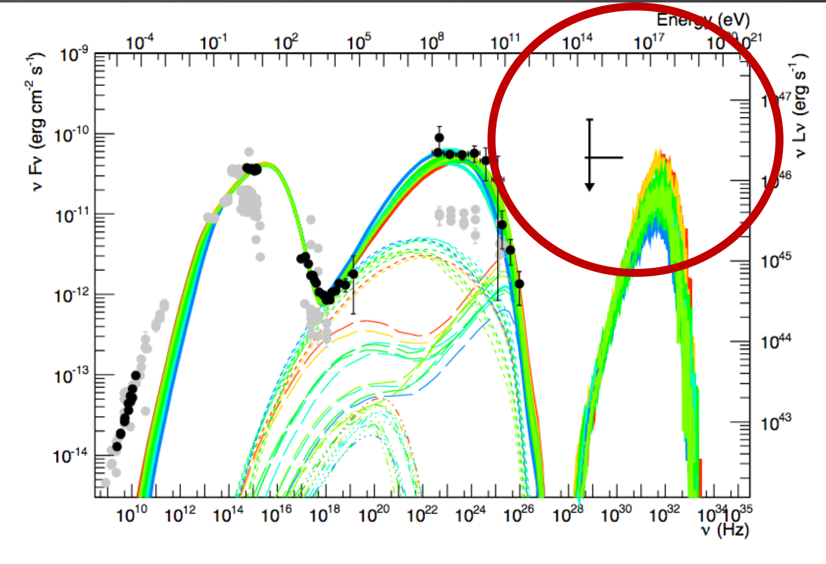


IceCube, Fermi, MAGIC+ Science 361, 146 2018

Multi-Messenger SED



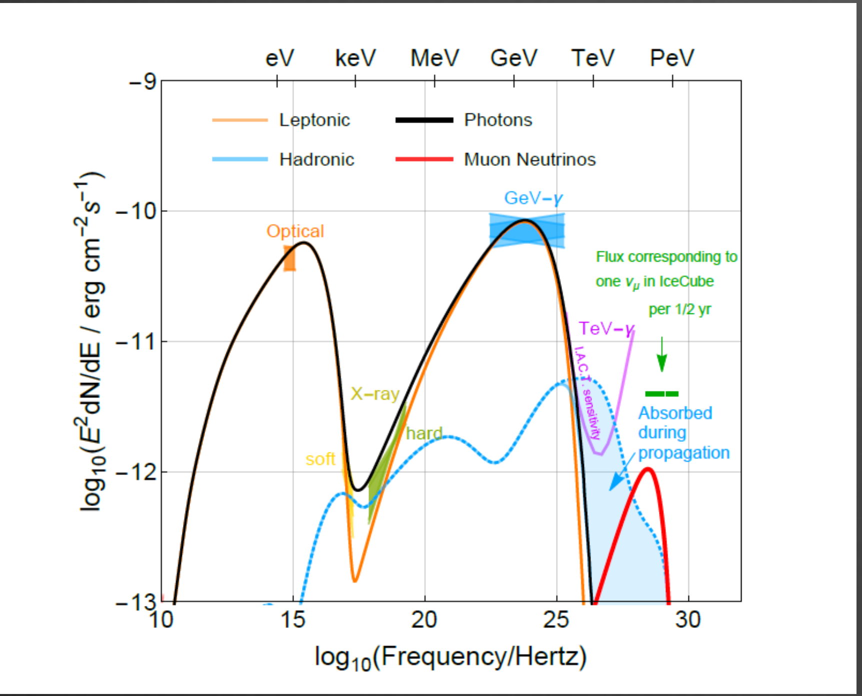
(a) Proton synchrotron modeling of TXS 0506+056



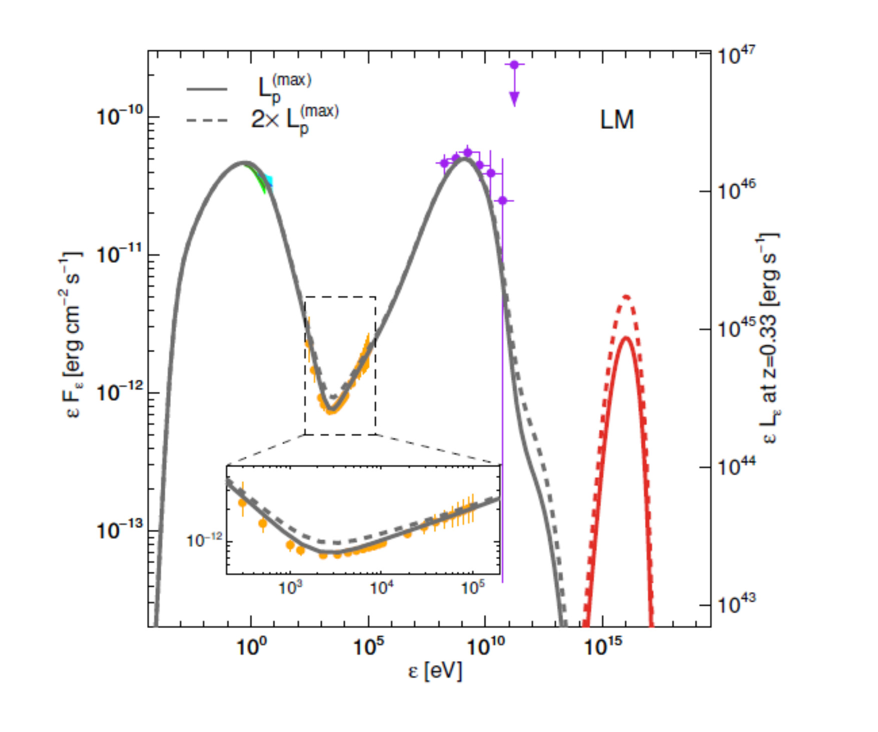
(Cerruti et al.: 1807.04335)

Models producing neutrinos and gamma-rays through the same proton population, predict too high neutrino energies!

Photo-pion Models for TXS 0506+056



(Gao et al., 2018, Nature Astron., arXiv: 1807.04275)

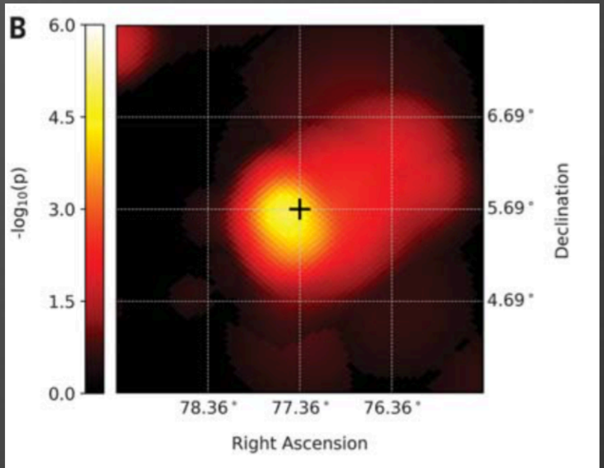


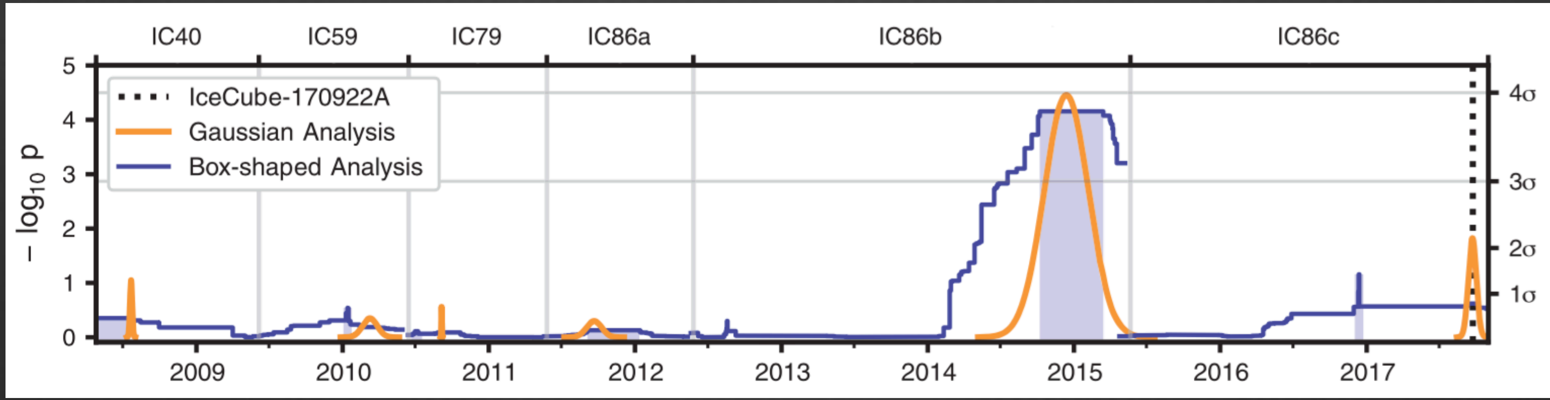
(Keivani et al.:, 2018, ApJ, 864, 84; arXiv: 1807.04537)

Models producing neutrinos and gamma-rays require leptonic-dominated gamma-ray production!

“Neutrino flare” 2014/2015

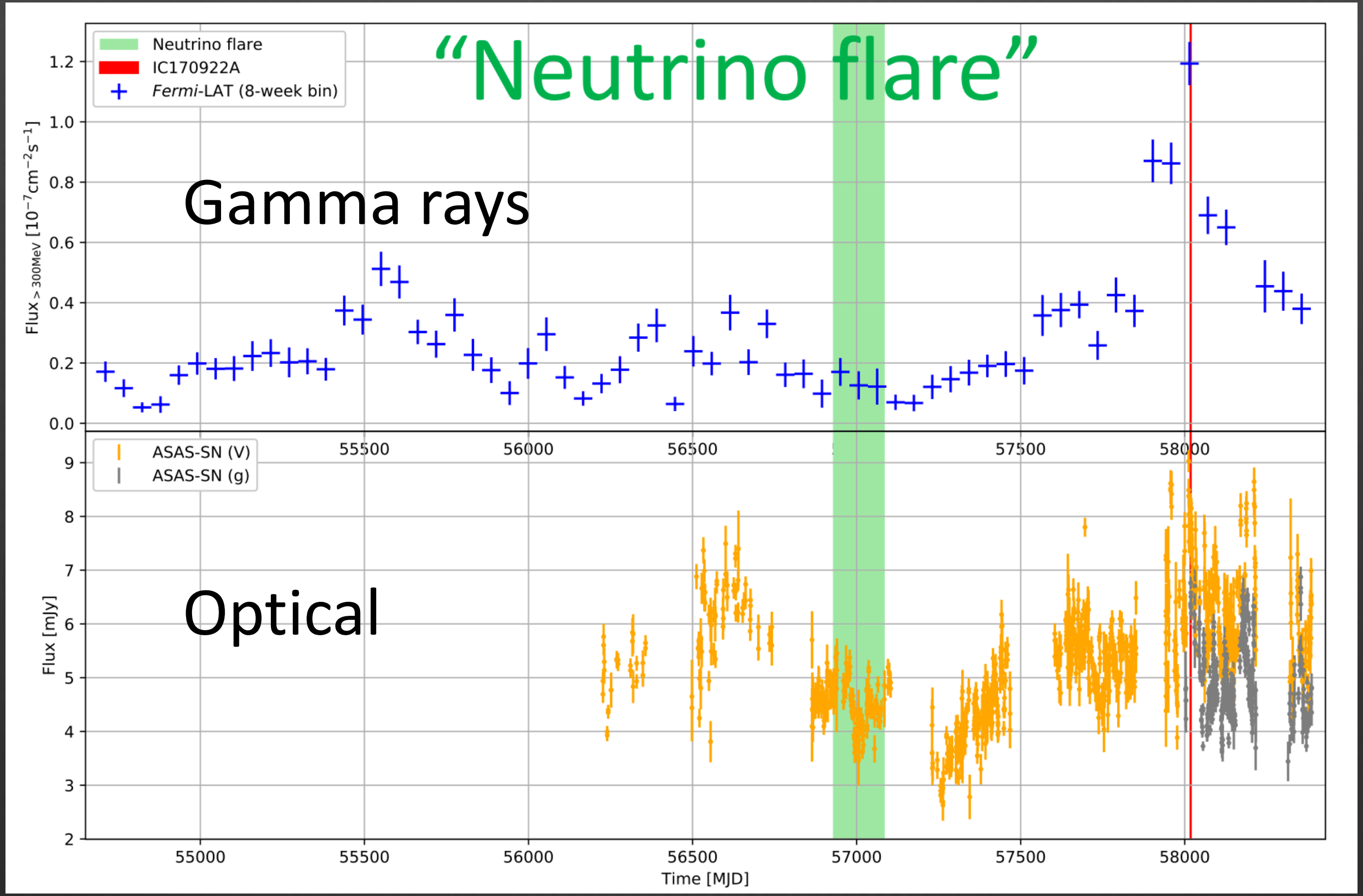
- IceCube archival search found 3.5sigma excess positionally consistent with the same blazar





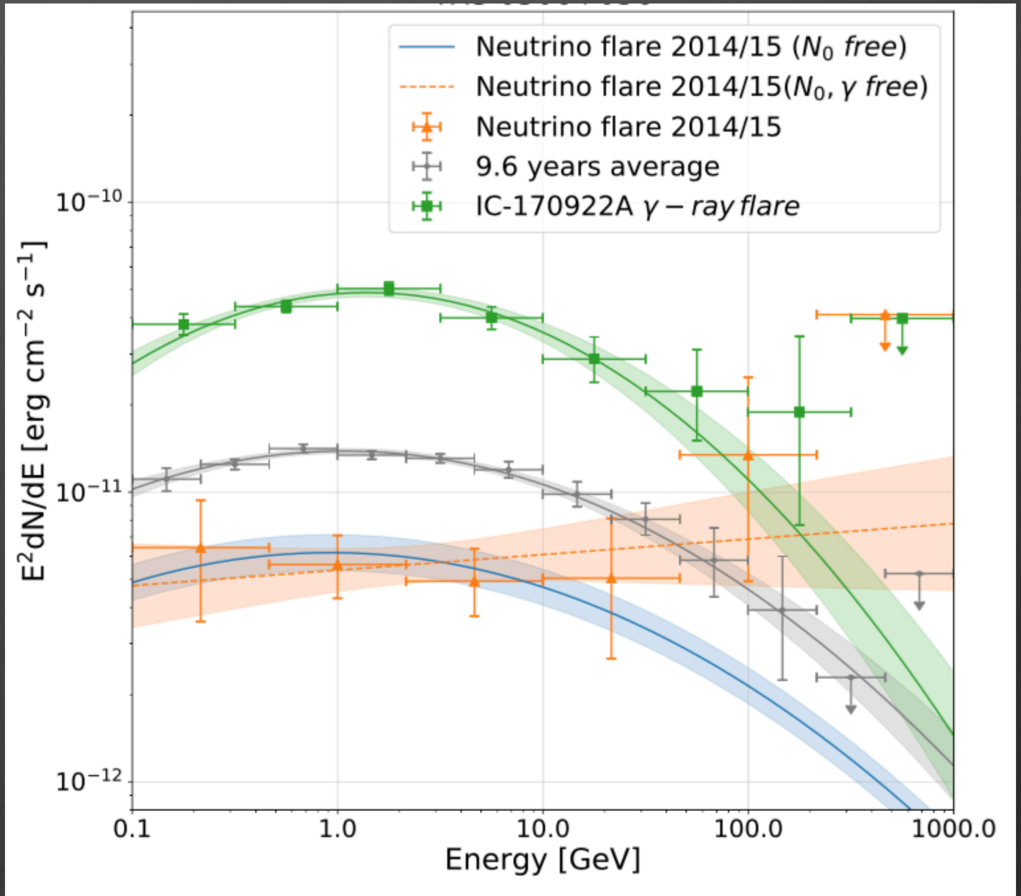
IC coll. 2018

TXS 0506+056 Light Curve

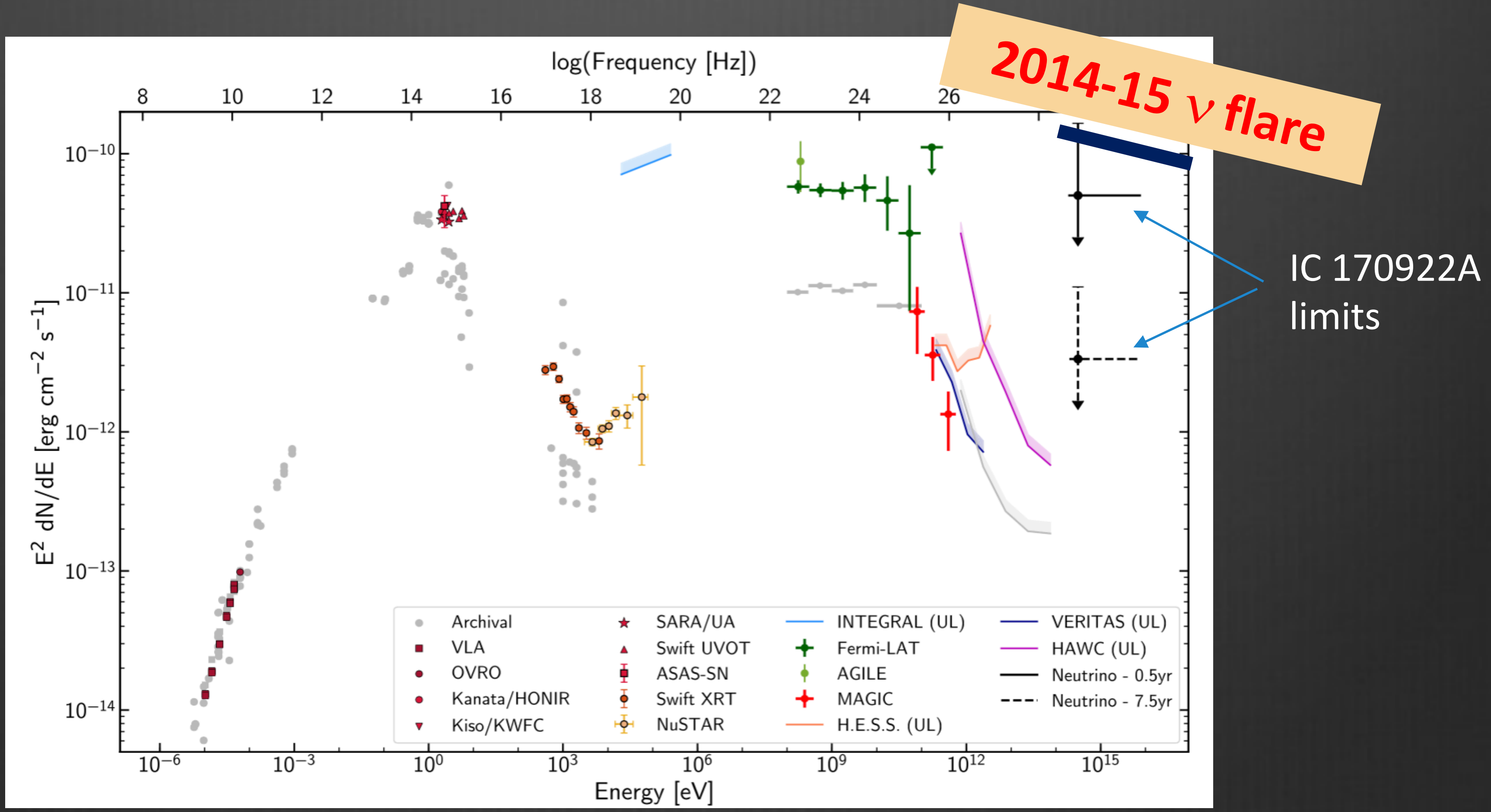


γ-ray SED for 2014/15 period

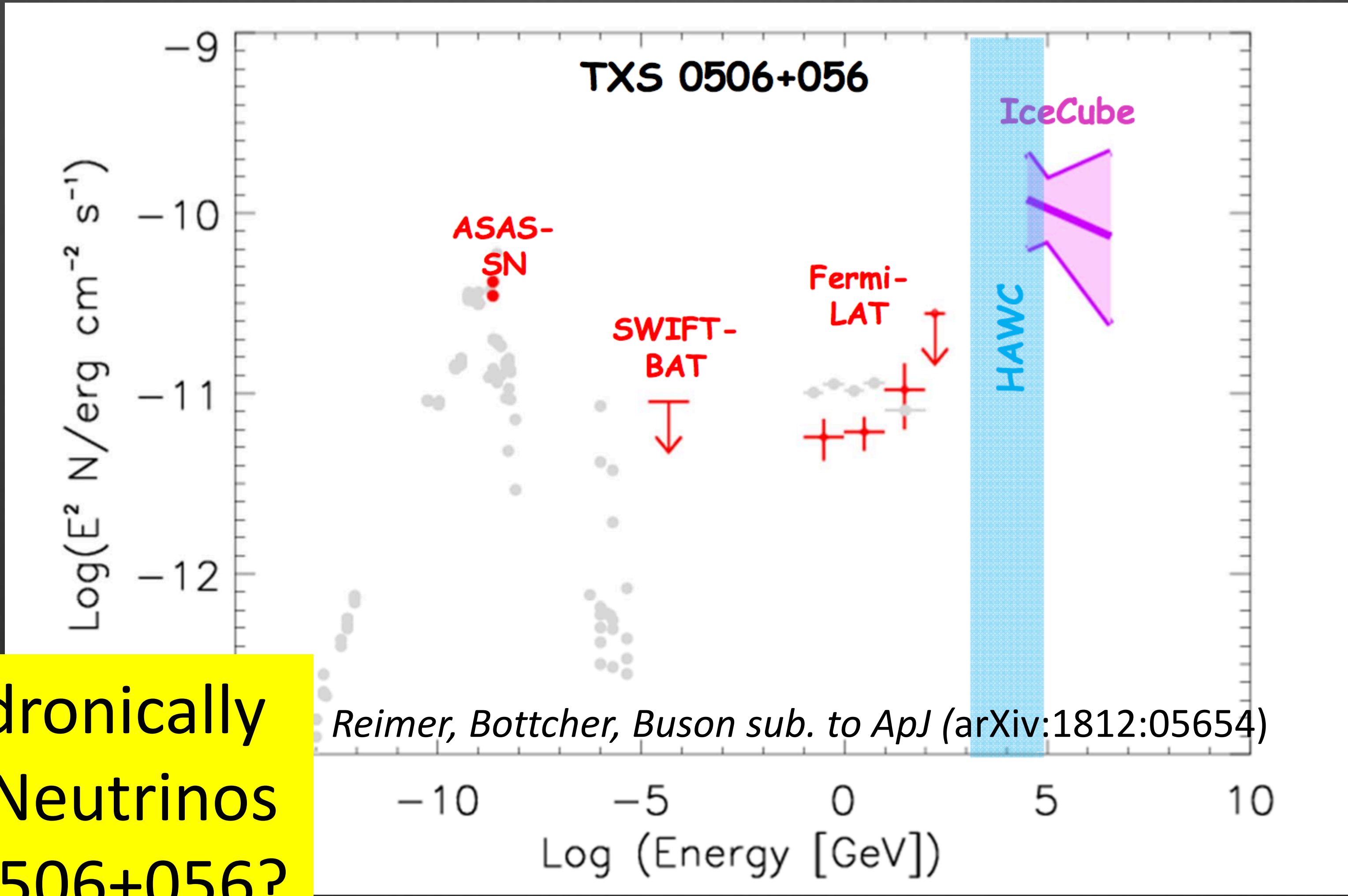
- Compatible with quiescence (Garrappa, Buson, Franckowiak, ASAS-SN, IceCube coll. 2019)
- but see also Padovani+2018



MWL SED – TXS 0506+056



Simultaneous Multi-Messenger SED (TXS 0506+056 “neutrino flare”)



Reimer, Bottcher, Buson sub. to ApJ (arXiv:1812:05654)

Photo-Hadronically Produced Neutrinos from TXS 0506+056?

Photo-Pion Production / Energetics

pγ interactions are strongly dominated by single-pion production through the Δ^+ resonance at an energy of $E_{\Delta+}$ =1232MeV

At Δ^+ resonance energy, the γ and *p* energies obey the relation:

$$s = E'_p E'_t (1 - \beta_p' \mu) \sim E'_p E'_t \sim E_{\Delta^+}{}^2 = (1232\ \mathrm{MeV})^2$$

and $E'_\nu \sim 0.05\ E'_p$

$\Rightarrow$ To produce IceCube neutrinos (~ 100 TeV $\rightarrow E_\nu = 10^{14} E_{14}$ eV):

(i.e., $E'_\nu = 10\ E_{14}\ \delta_1^{-1}$ TeV)

Need protons with $E'_p \sim 200\ E_{14}\ \delta_1^{-1}$ TeV (< UHECRs energy)

and target photons with $E'_t \sim 1.6\ E_{14}^{-1}\ \delta_1$ keV (X-ray band)

The $p\gamma$ Efficiency Problem

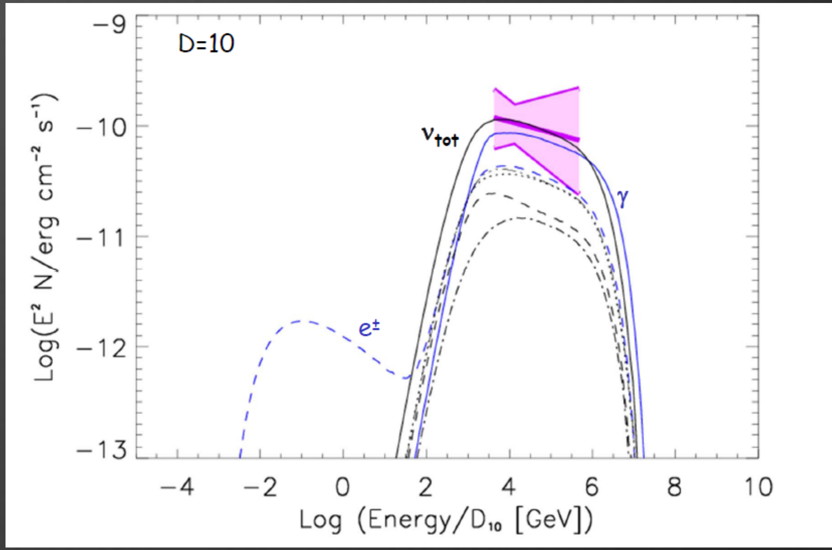
- Same target photon field for photo-pion production can also **absorb** any co-spatially produced γ-rays via $\gamma\gamma$ absorption.
- The $p\gamma$ cross section is several orders of magnitude smaller than the $\gamma\gamma$ absorption cross section.
- Efficient $p\gamma$ neutrino (and γ-ray) production requires that the optical depth for relativistic protons to interact with the target photon field, $\tau_{p\gamma} \sim 1$,

=> optical depth of the emission region to ~ GeV photons is $\tau_{\gamma\gamma} \sim 310\, \tau_{p\gamma} >> 1$

$\Rightarrow$ Photons with E_γ ~ GeV – TeV are heavily absorbed
$\Rightarrow$ EM cascade emission at lower energies

Photo-Hadronically Produced Neutrinos From TXS 0506+056?

- Hypothesis:
  - Neutrino (0.3-3 PeV range) flux at a similar level of the observed gamma-ray flux
- Aims: Constraining the neutrino production parameters as much model-independent as possible
  - ***No assumptions on the origin of the target photon field for particle-photon interactions***
- Primers:
  - Neutrinos and photons originate photo-hadronically in the Jet
  - Target radiation field in the jet is isotropic
  - Linear cascades



- Target photons: $n_{ph}(\varepsilon) \sim \varepsilon^{-\alpha}$, ε_{min} = 10 keV, ε_{max} = 60 keV, α = 1
- Proton spectrum: n_p (E) ~ $E^{-\alpha_p}$, E_{max} = 30 PeV, α_p = 2.0

Reimer, Bottcher, Buson sub. to ApJ

Simulate pair cascades initiated by secondary γ-rays and electrons/positrons

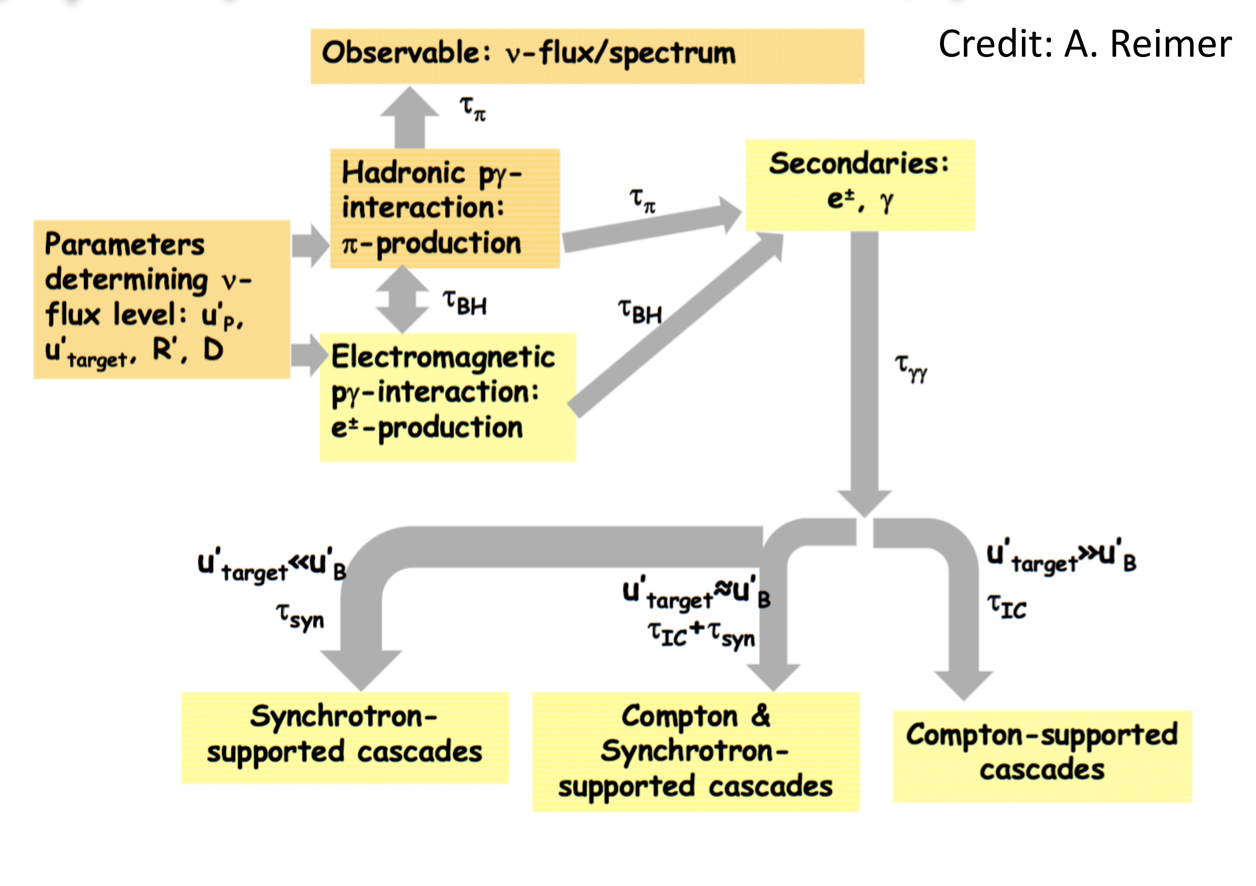
Cascade Drivers

Energy density of the target photon field

Energy density of the protons

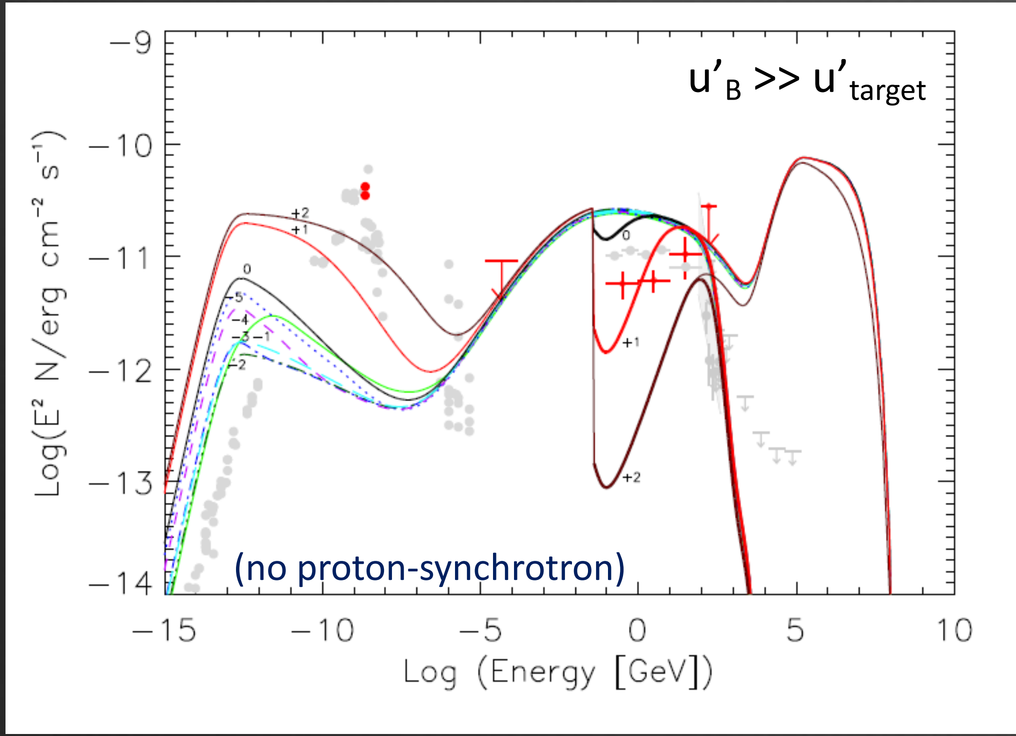
Size of the emitting region

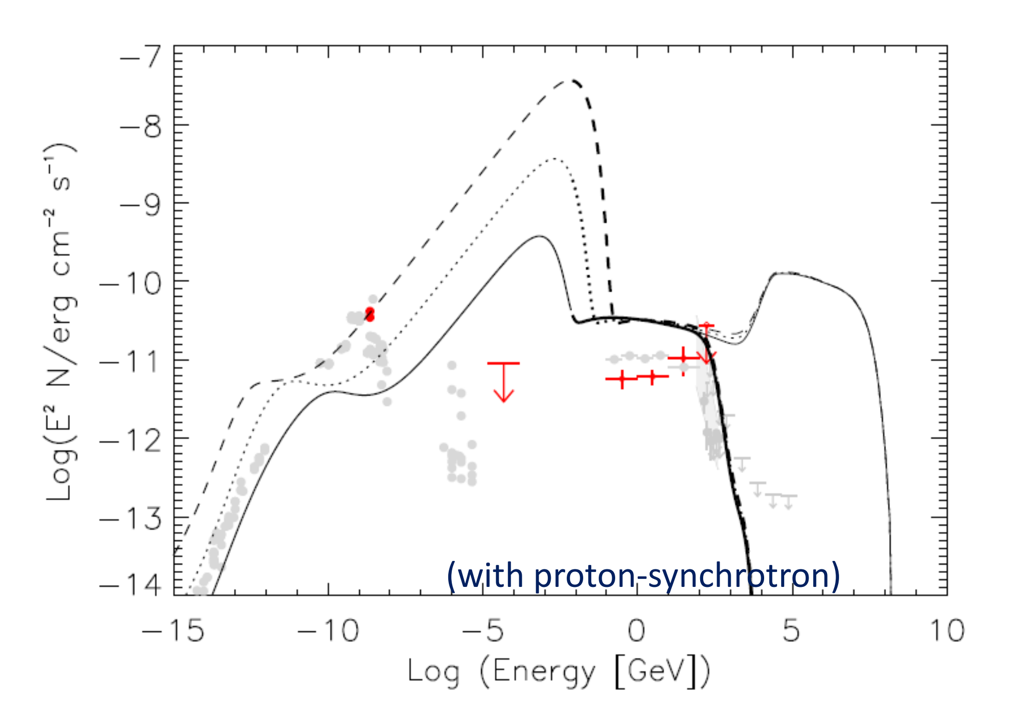
Doppler factor



Changes in the doppler factor shift in energy the distribution; and one needs to change a bit the target photon field. Good thing is that for any choice of doppler factor, one can always find a combination of parameters that works

Synchrotron-supported Cascades





Ruled out by MWL spectra

(over-predicting either Fermi-LAT or X-ray / radio fluxes)

Reimer, Bottcher, Buson sub. to ApJ

Feasible scenario

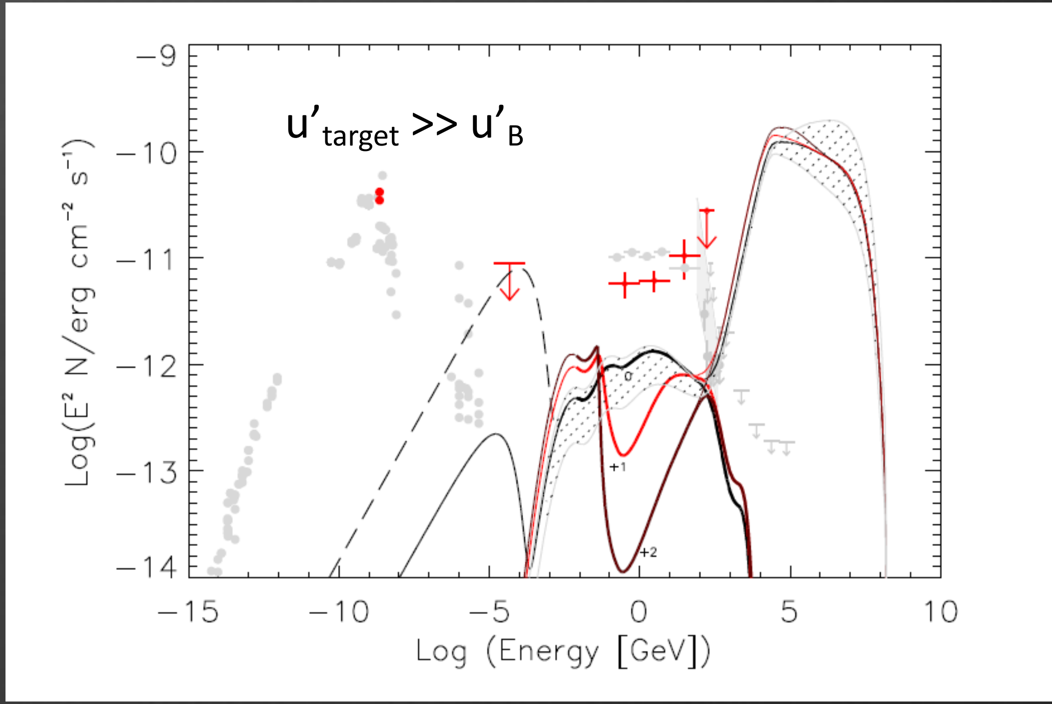
- $\tau_{\gamma\gamma}$ << 1 : minimal photon flux produced along with the gamma-flux co-spatially
- $\tau_{\gamma\gamma}$ >> 10: significant internal absorption in > GeV/VHE energy range
- Bulk of LAT-flux can not be produced co-spatially with neutrino-flux

In principle, allowed by MWL spectra:

Significantly below observed fluxes

=> No neutrino – γ-ray correlation expected!

- Compton-Supported Cascades



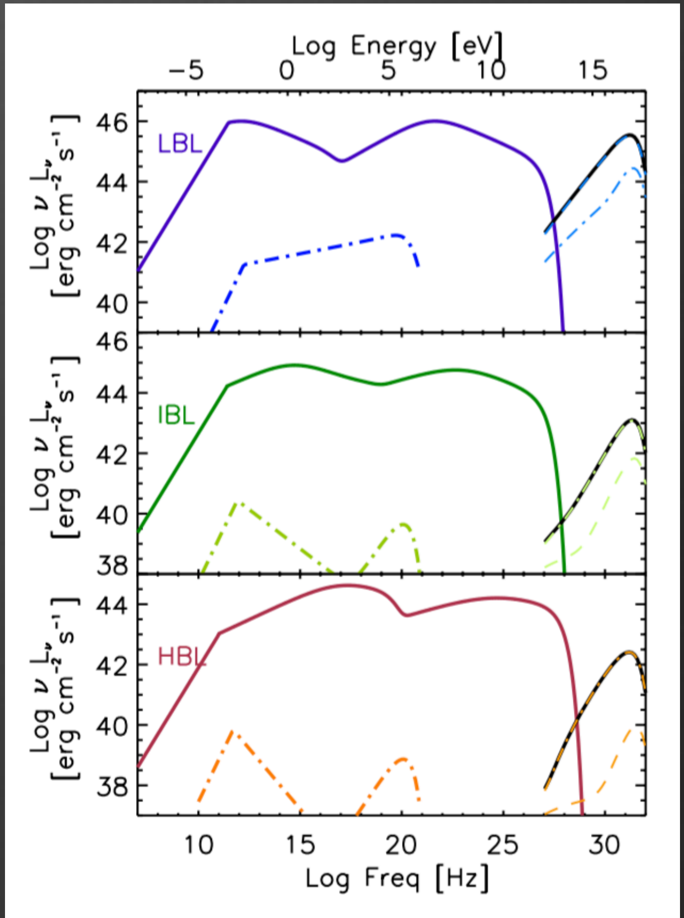
Reimer, Bottcher, Buson sub. to ApJ

pγ Production, Origin of Target Photons

Stationary UV / soft X-ray target photon field external to the jet is plausible

- Possible sources of external UV / soft X-ray target photons, e.g.,:

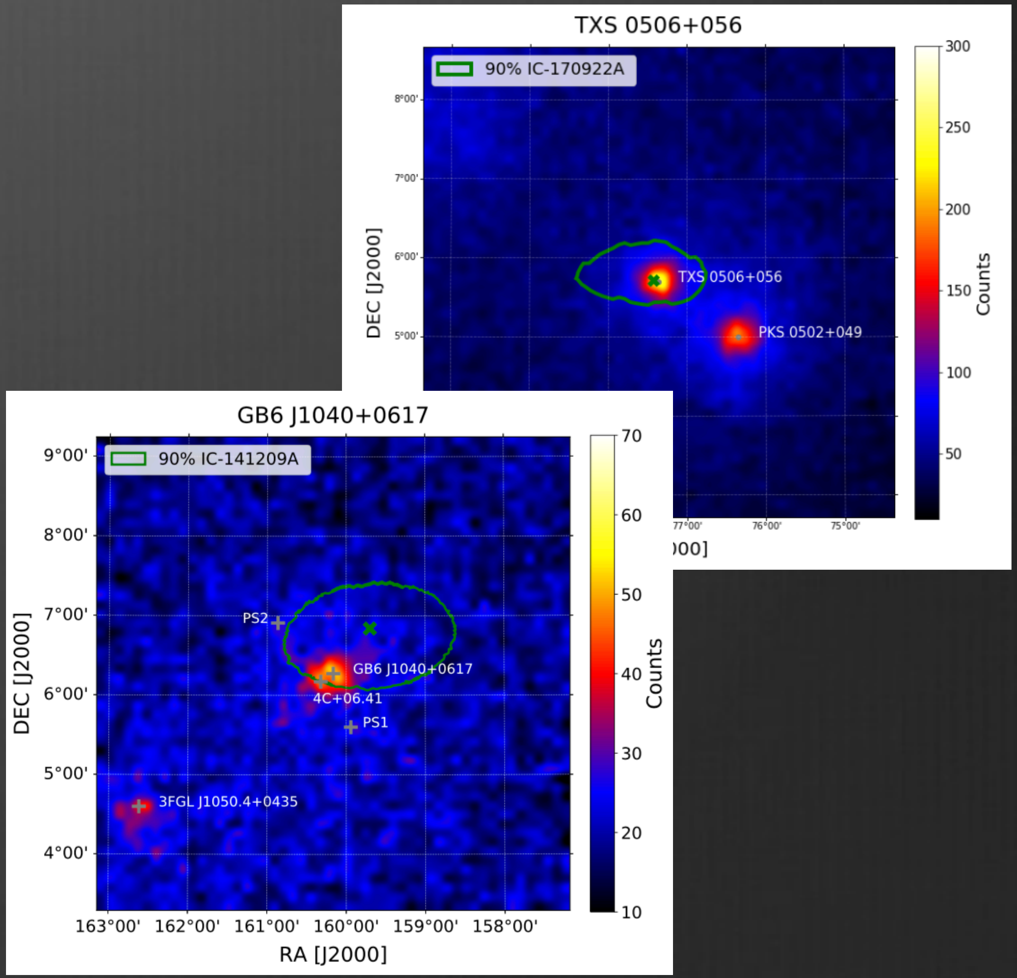
- BLR (Padovani+ 2019 MNRAS, 484, 104)
- Slow-moving sheath (Tavecchio & Ghisellini 2005)
- Accretion flow (ADAF, Righi+ 2019 MNRAS, 483, 127)



(see also Rodrigues+ 2018, arXiv:181205939)

Desiderata for Future Progresses

- Multi-messenger + time-domain is a promising path to reveal the origin of neutrinos (and potentially cosmic rays)
- More high-energy neutrinos! (IceCube increasing the event statistic)
- Future observatories will improve sensitivity and statistics, e.g., IceCube-Gen2, KM3NeT, AMEGO, ASTROGAM, CTA …



Garrappa, Buson, Franckowiak+ arXiv:190110806

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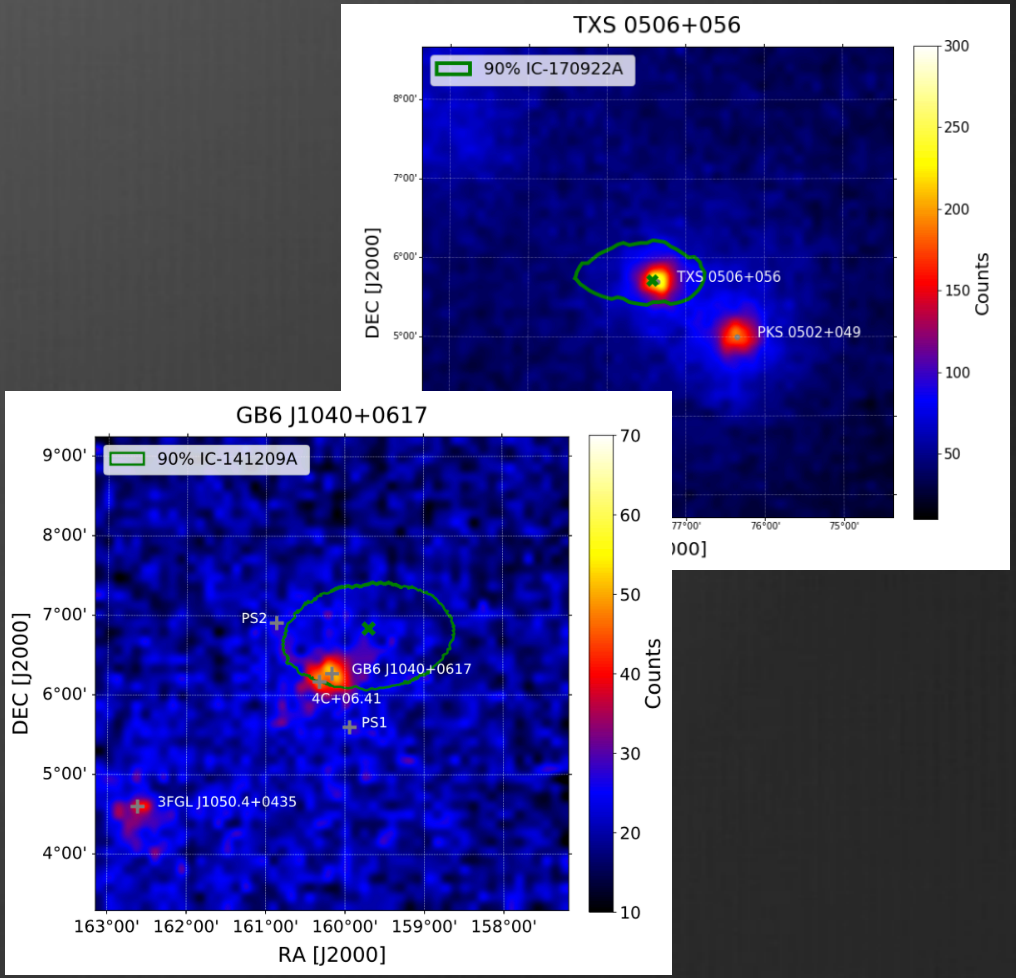
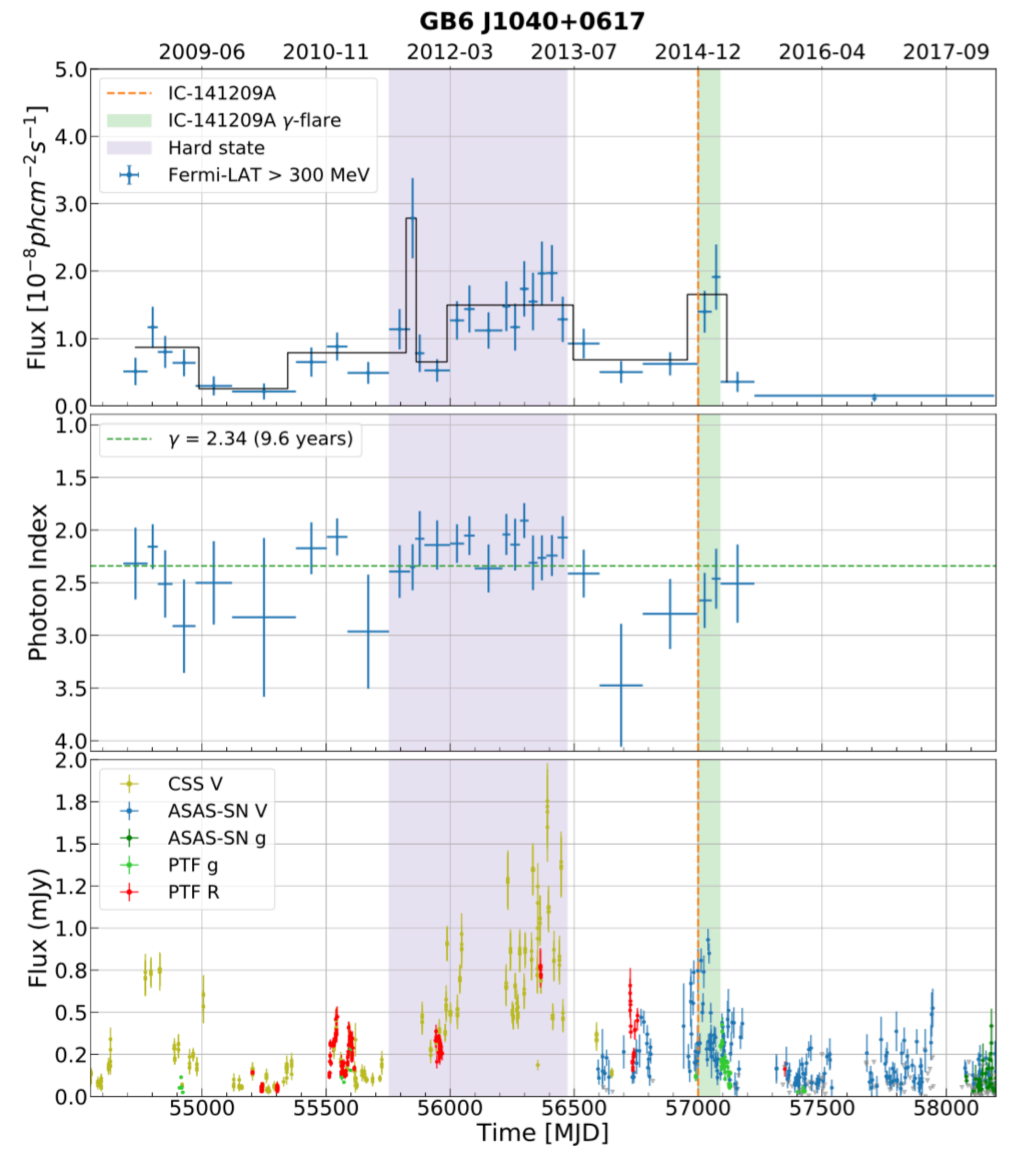
THANKS

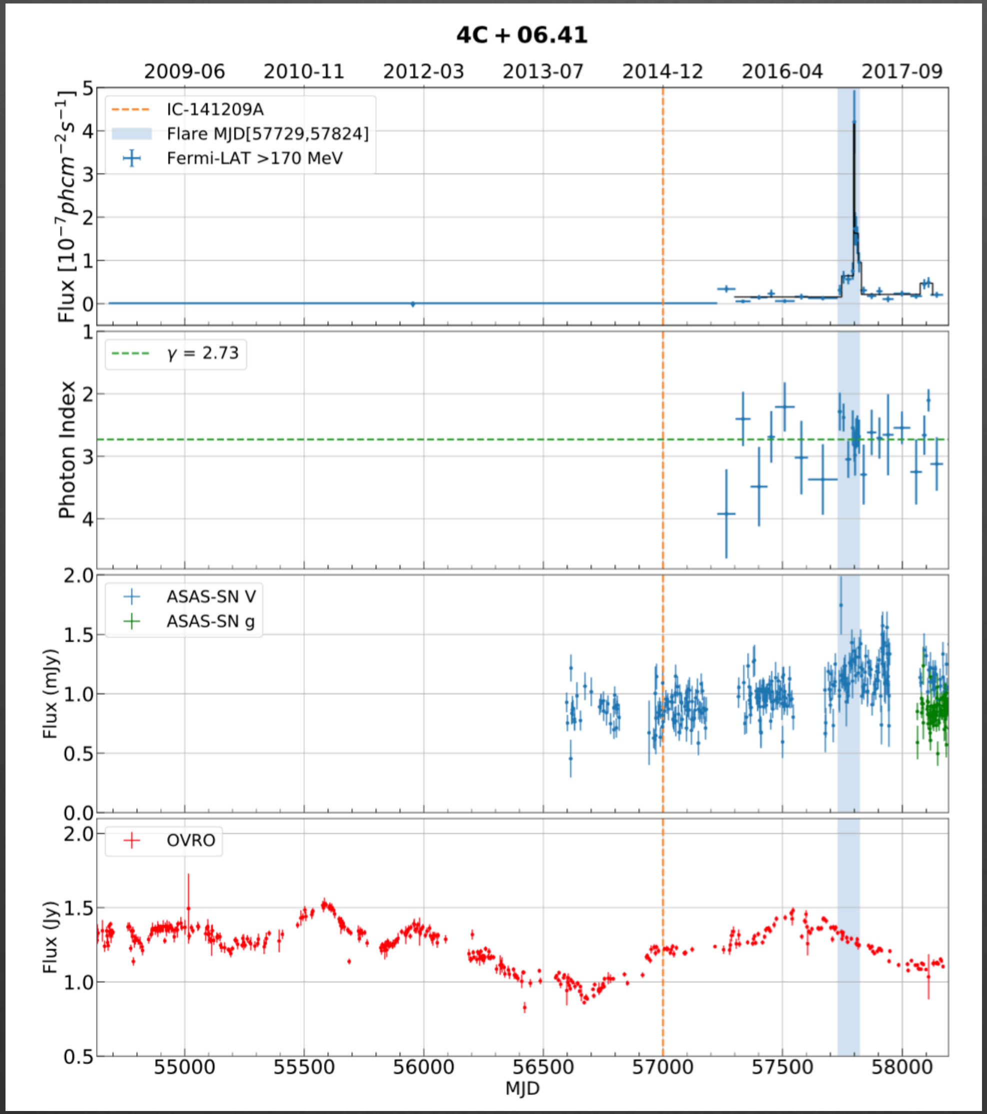


Garrappa, Buson, Franckowiak+ arXiv:190110806

BACK UP



Garrappa, Buson, Franckowiak+ arXiv:190110806



Garrappa, Buson, Franckowiak+ arXiv:190110806