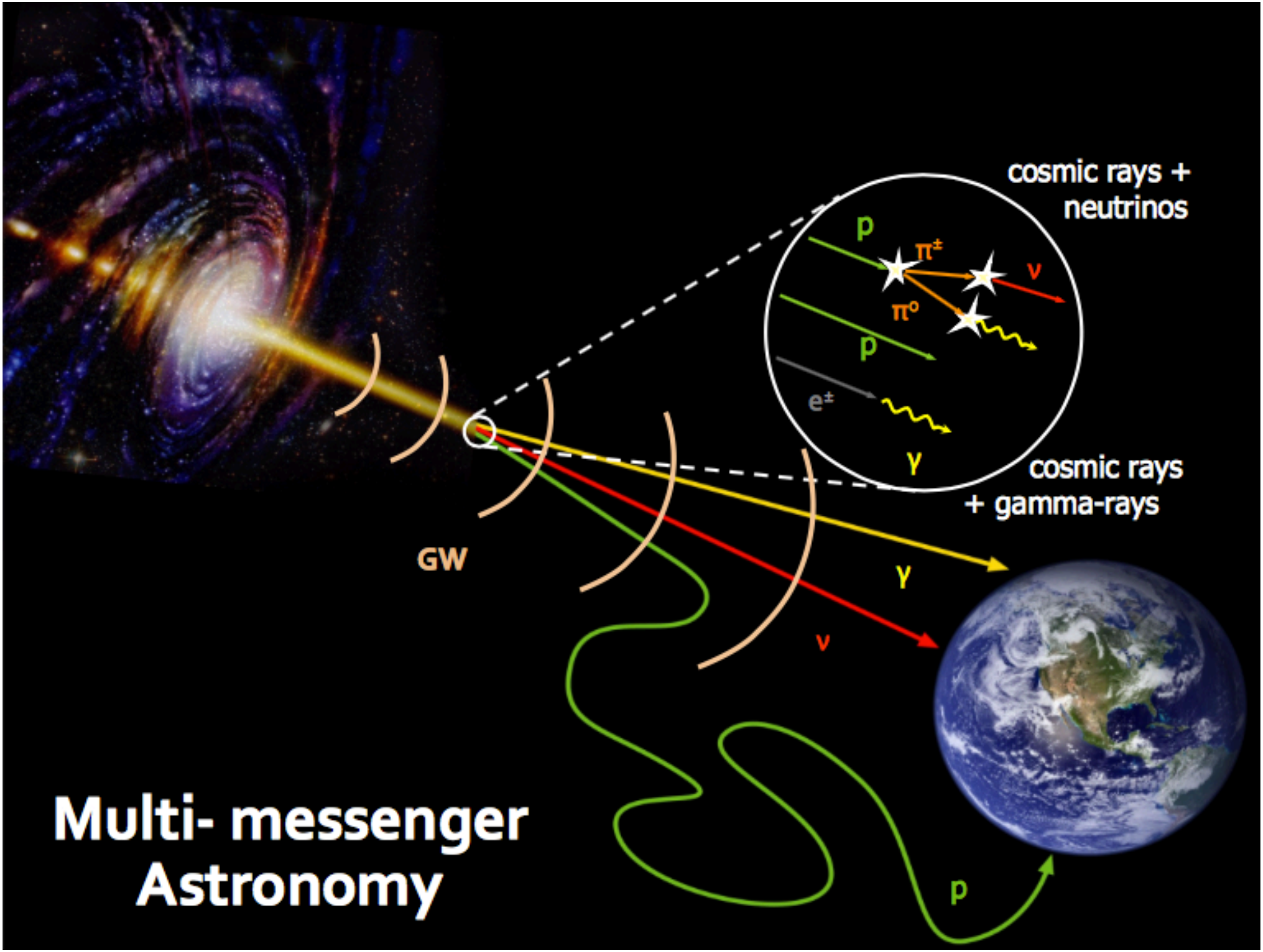
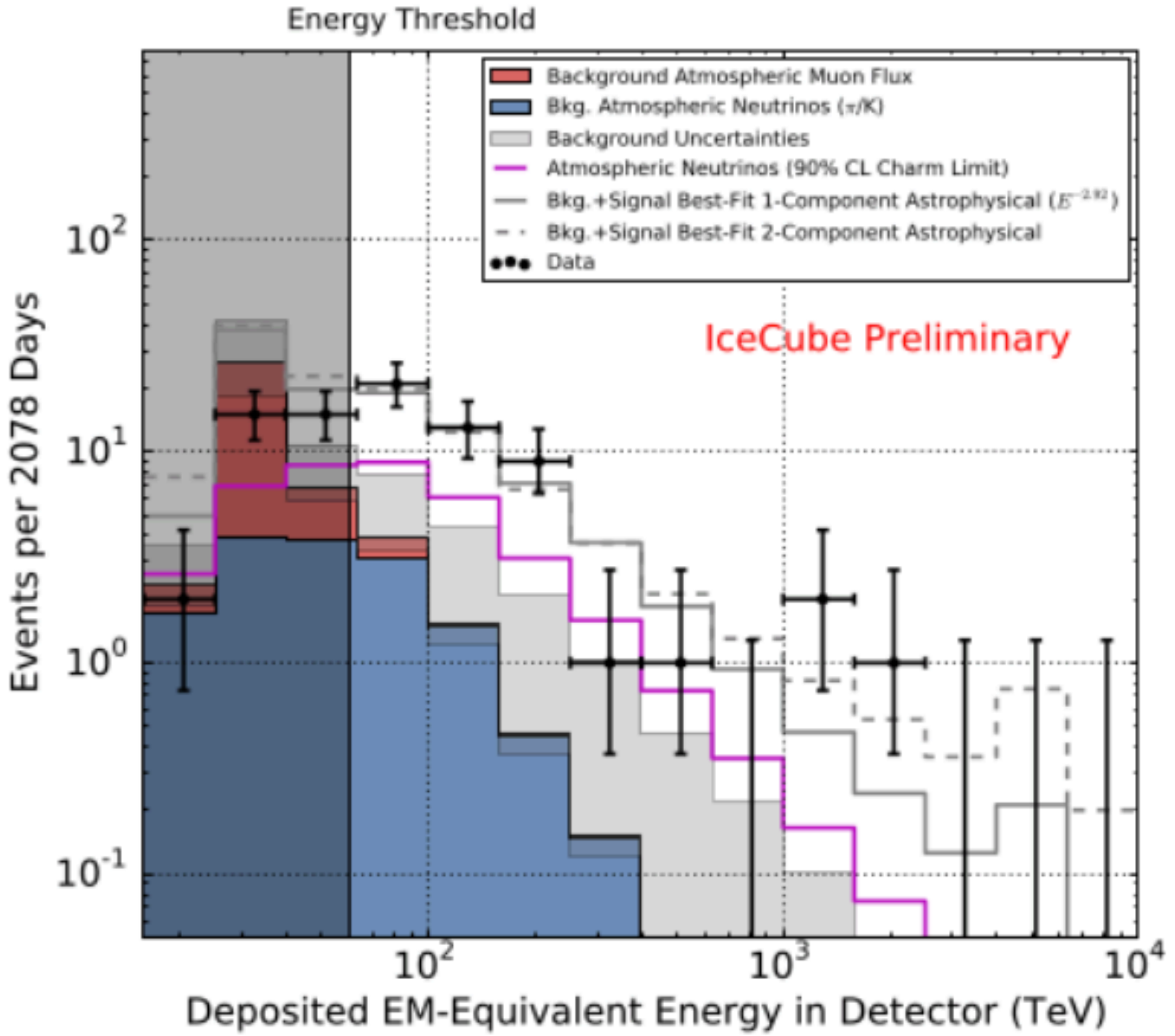
Gamma rays and neutrino connection

Dario Gasparrini
SSDC and INFN Roma 2
dario.gasparrini@ssdc.asi.it
Sara Buson
Wurzburg University
sara.buson@gmail.com


cosmic rays +
neutrinos
p
π±
ν
π°
p
e±
γ
cosmic rays
+ gamma-rays
GW
γ
ν
p
Multi- messenger
Astronomy

Discovery of an astrophysical flux of ν

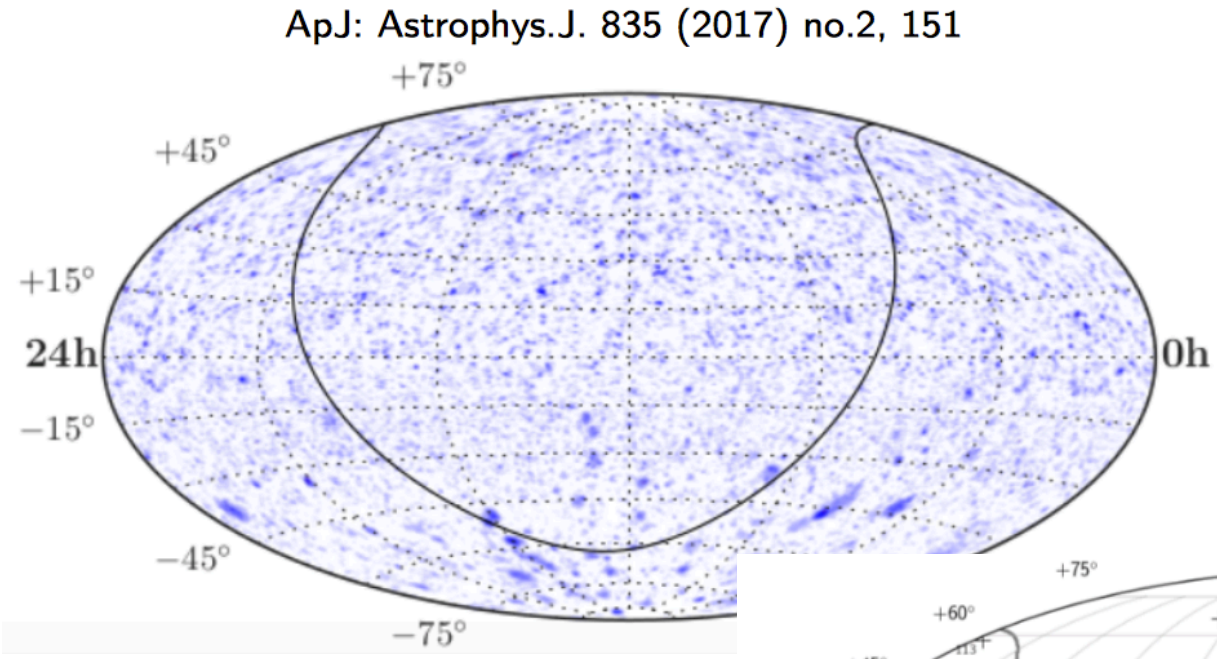


PoS (ICRC 2017) 981 and Science 342, 2013

Preliminary considerations

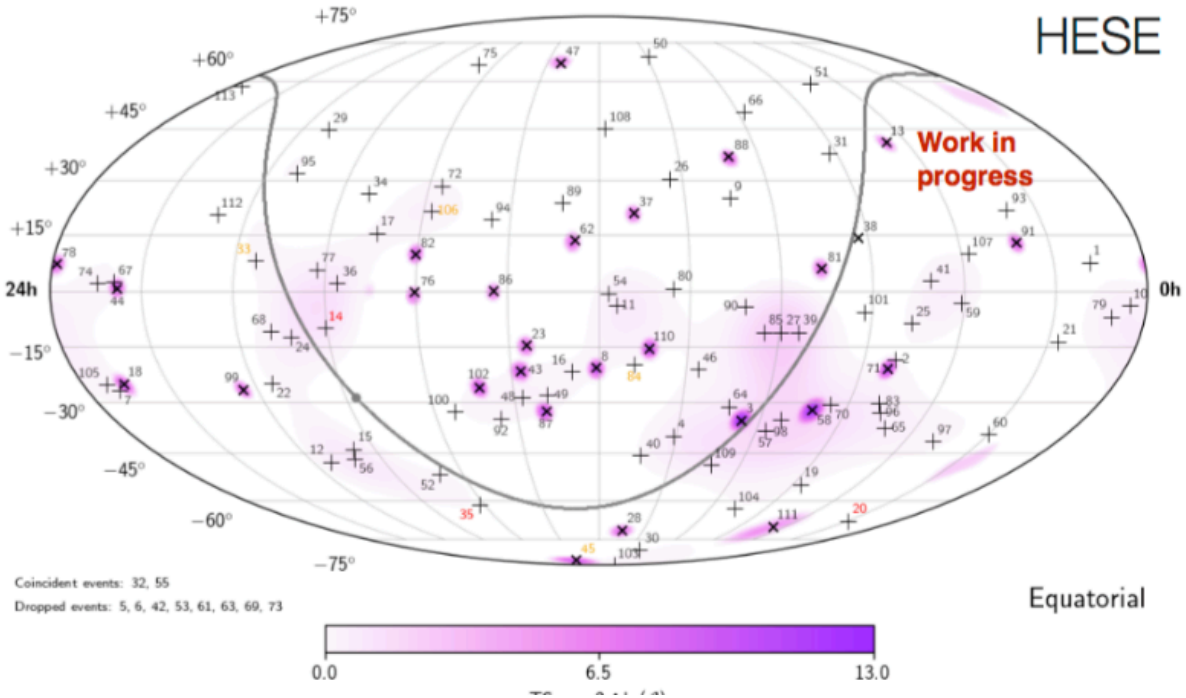
- A pre-condition for likely astrophysical VHE neutrino sources is that they are also sources of VHE cosmic rays
- Such sources could also be naturally related to the sources of ultra-high energy cosmic rays (UHECRs) observed by the Auger and TA cosmic ray arrays
- We still cannot prove those energies. 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

Looking for astrophysical ν sources



- **The isotropic distribution is a hint of dominant extragalactic origin.**
- **Looking for Neutrino clustering in other wavelength**

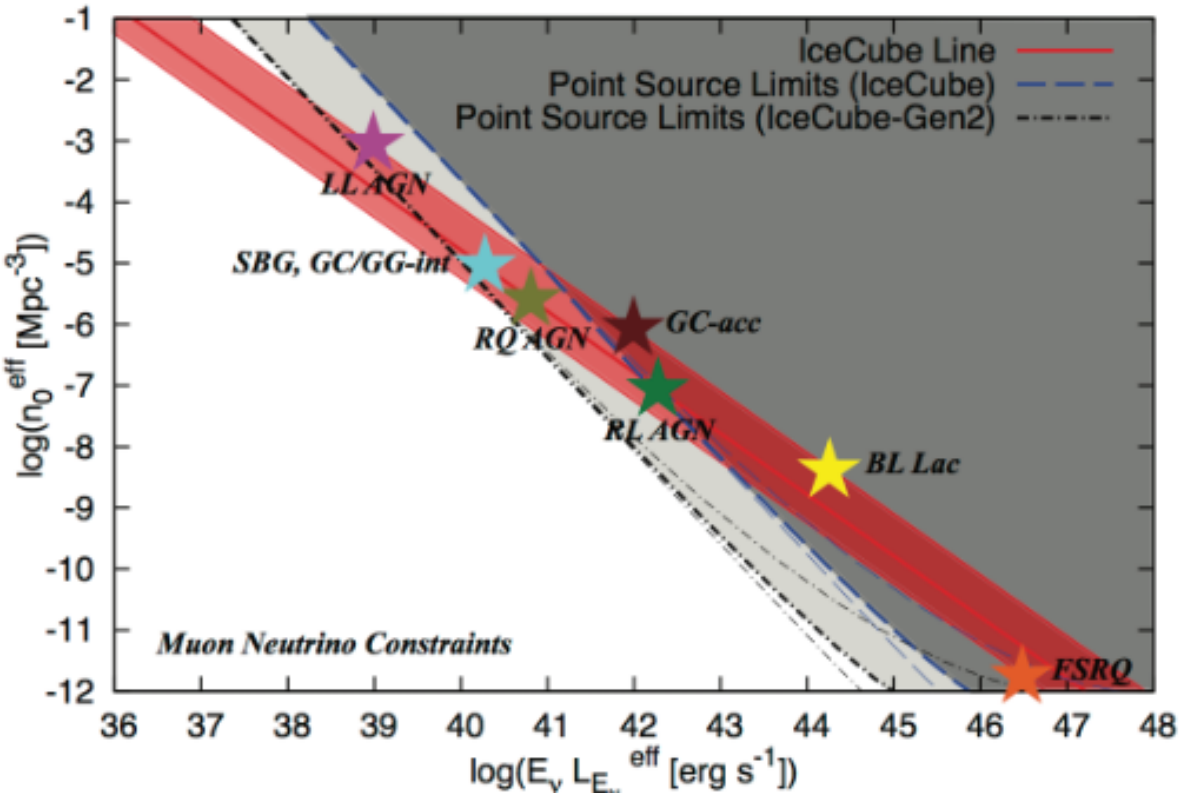
- **Start from HESE (High energy starting track Event) to reduce contamination from backgrounds**



Who is responsible of ν emission?

- **Cosmic ray accelerators**
  - **Neutrino produced within CR source, radiation interaction**
    - **Gamma ray burst** (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**
  - **Neutrino produced in the surroundings of CR source, inelastic hadronuclear collisions:**
    - **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 Clusters** (e.g., Berezinsky+ 97, KM et al. 08, Kotera+ 09 // Murase, Ahlers & Lacki 13, Fang & Olinto 16)

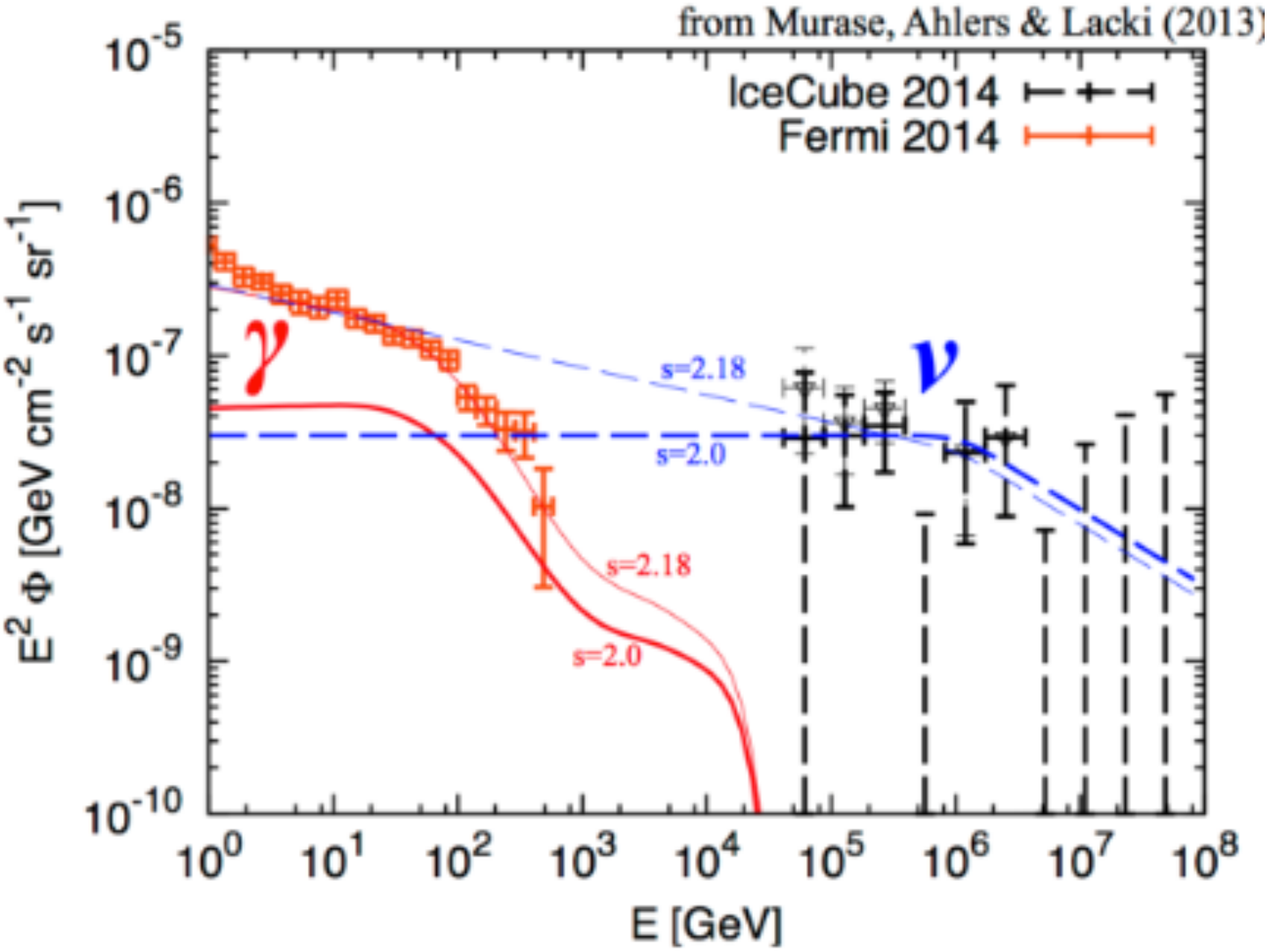
Searching strategies: steady emission



Murase, Waxman, 2016

Limits on source density inferred by non- observation of neutrino multiplets
It seems that blazar jets are unlikely to dominate the IceCube flux
Waiting for IceCube-Gen2 to investigate other classes

Study of the background



γ – ν connection: strategy

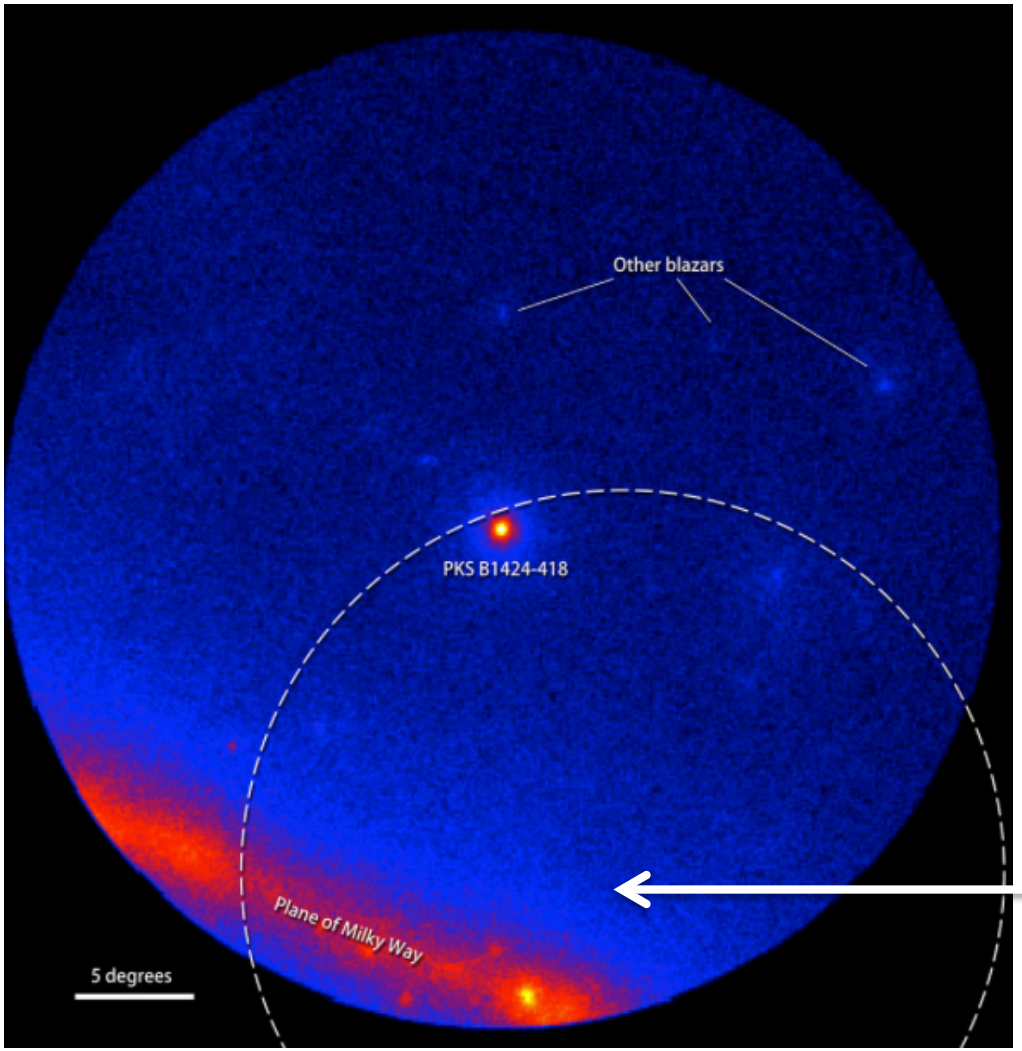
- **Correlation with known catalogs**
  - **3LAC (>100MeV, 4years); 2FHL (>50 GeV, 6years); 2WHSP (most complete list of High Synchrotron Peaked blazars)**
- **None of the three blazar catalogs tested showed any significant evidence for a neutrino signal above background expectations.**
- **All the outcomes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

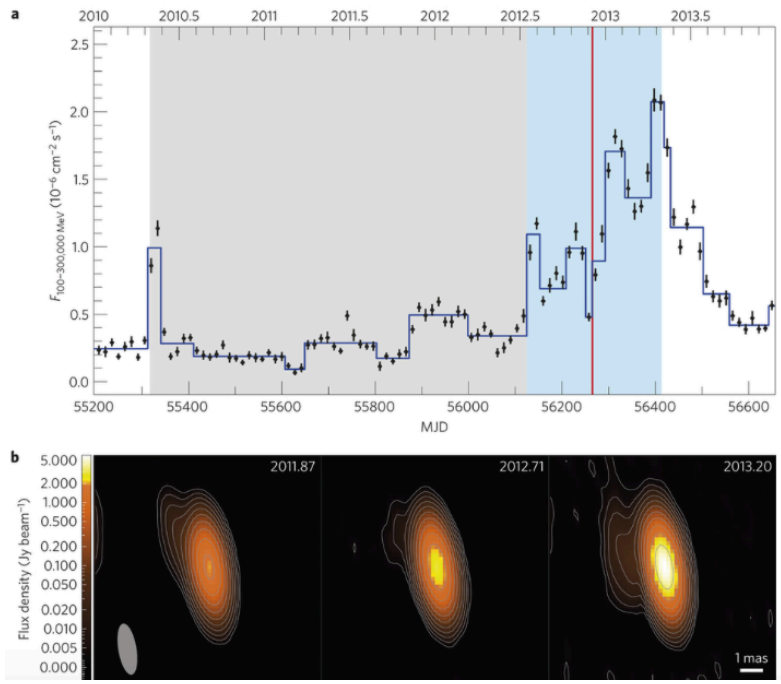
IceCube - PoS(ICRC2017)994

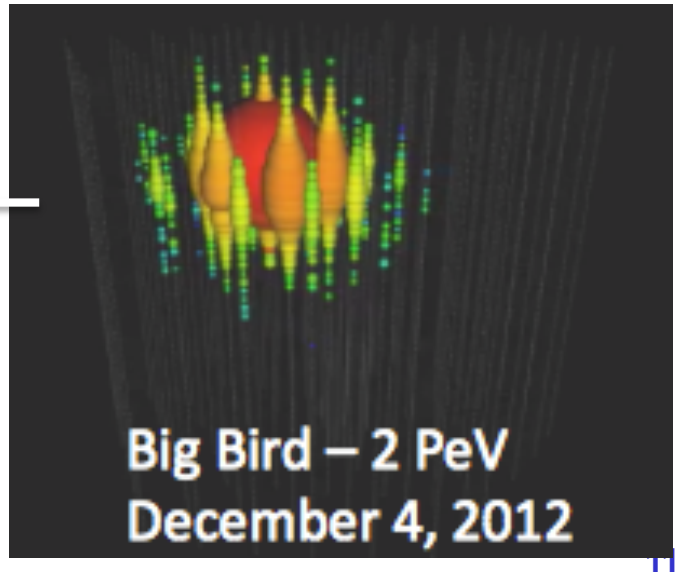
Neutrino emission consistent with gamma-ray flares

- **Search for neutrino emission temporally consistent with a gamma ray flare of a blazar (ApJ 807, 46 2015)**
  - **Enhanced status reported by Fermi-LAT monitoring programs**
  - **TeV Orphaned flares**
  - **In both cases no evidence has been found for neutrino emission**
- **There were a previous suspect: blazar 1ES1959+650:**
  - **Seen by Whipple in 2002**
  - **3 neutrinos from AMANDA during the VHE flare**
  - **Even If flared again during Fermi observations, no significant emission detected by IceCube**

A little hint: PKS 1424-418 (~2-3 σ)







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 15D;   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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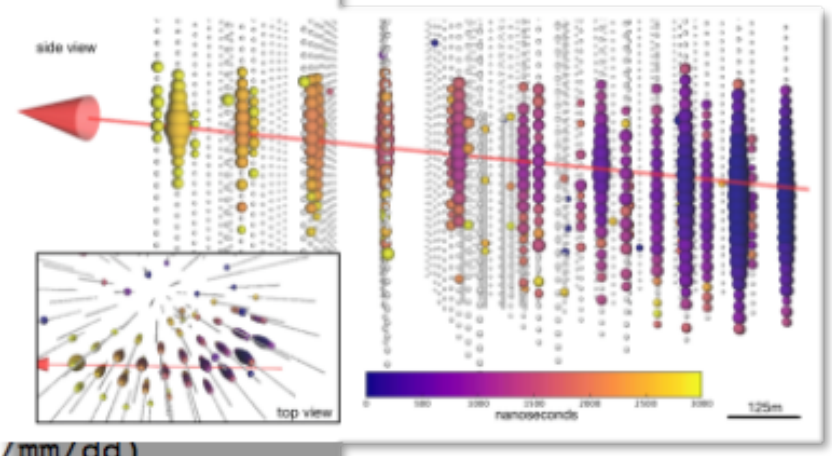
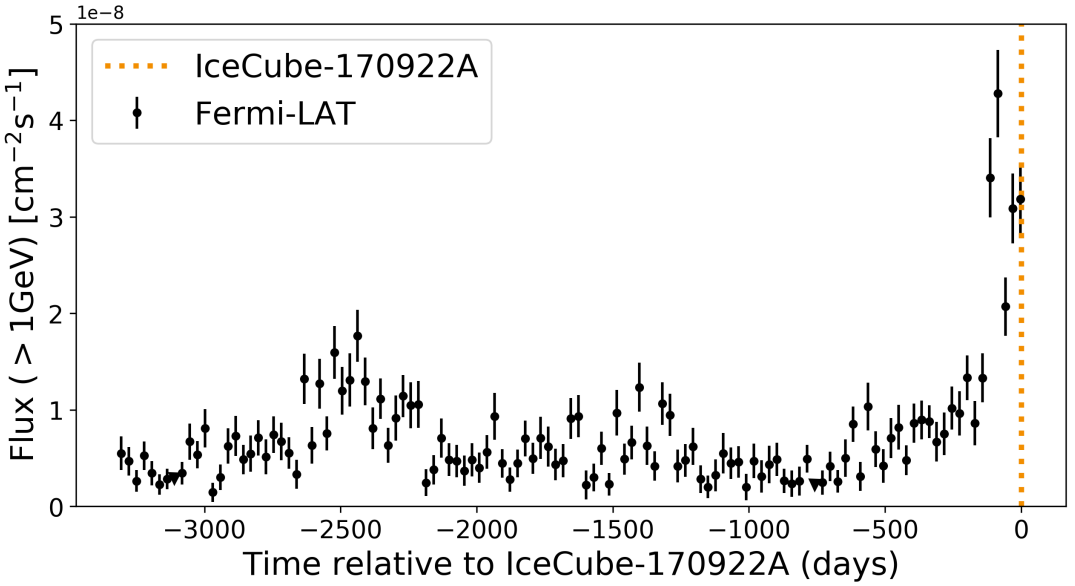
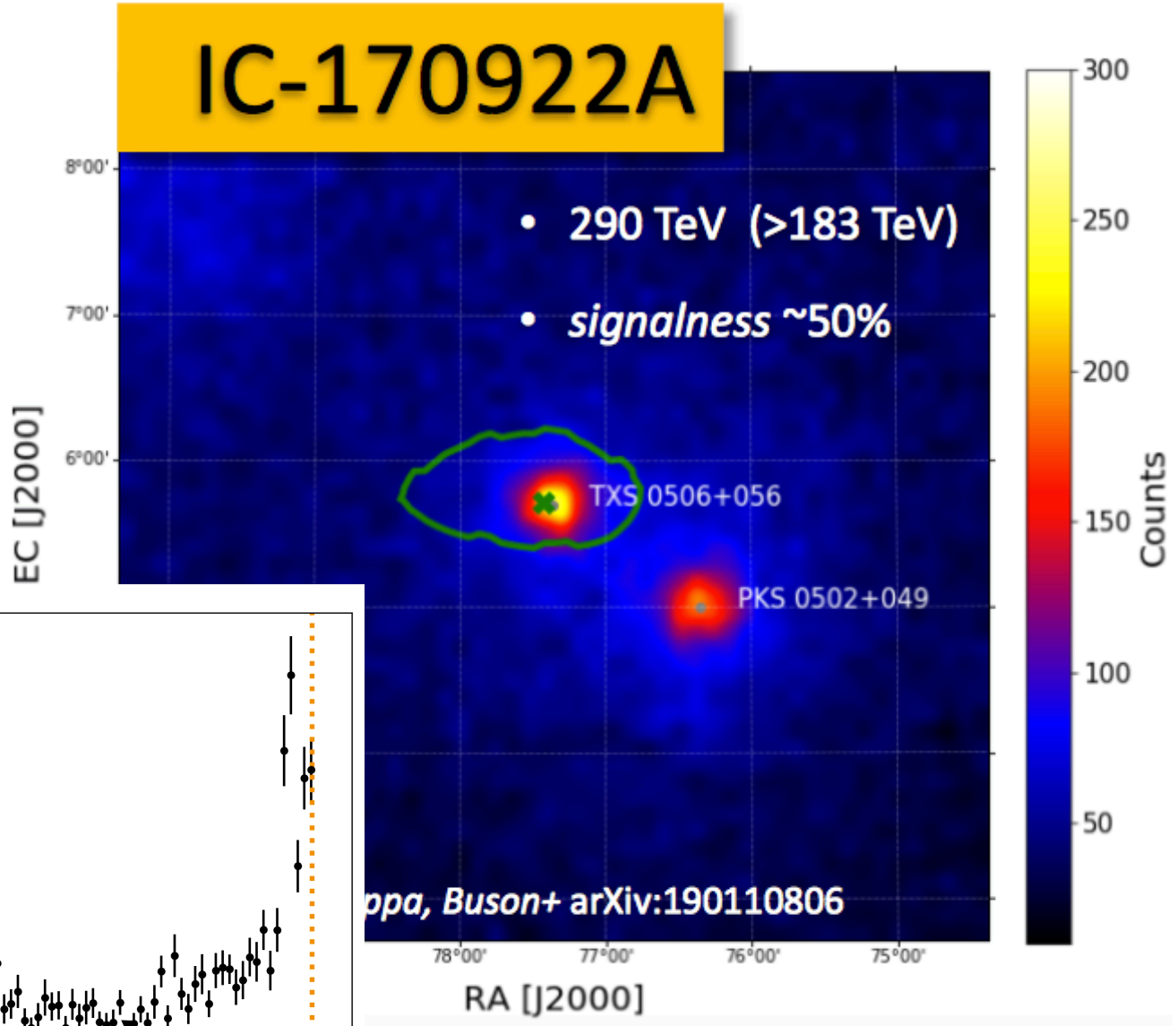


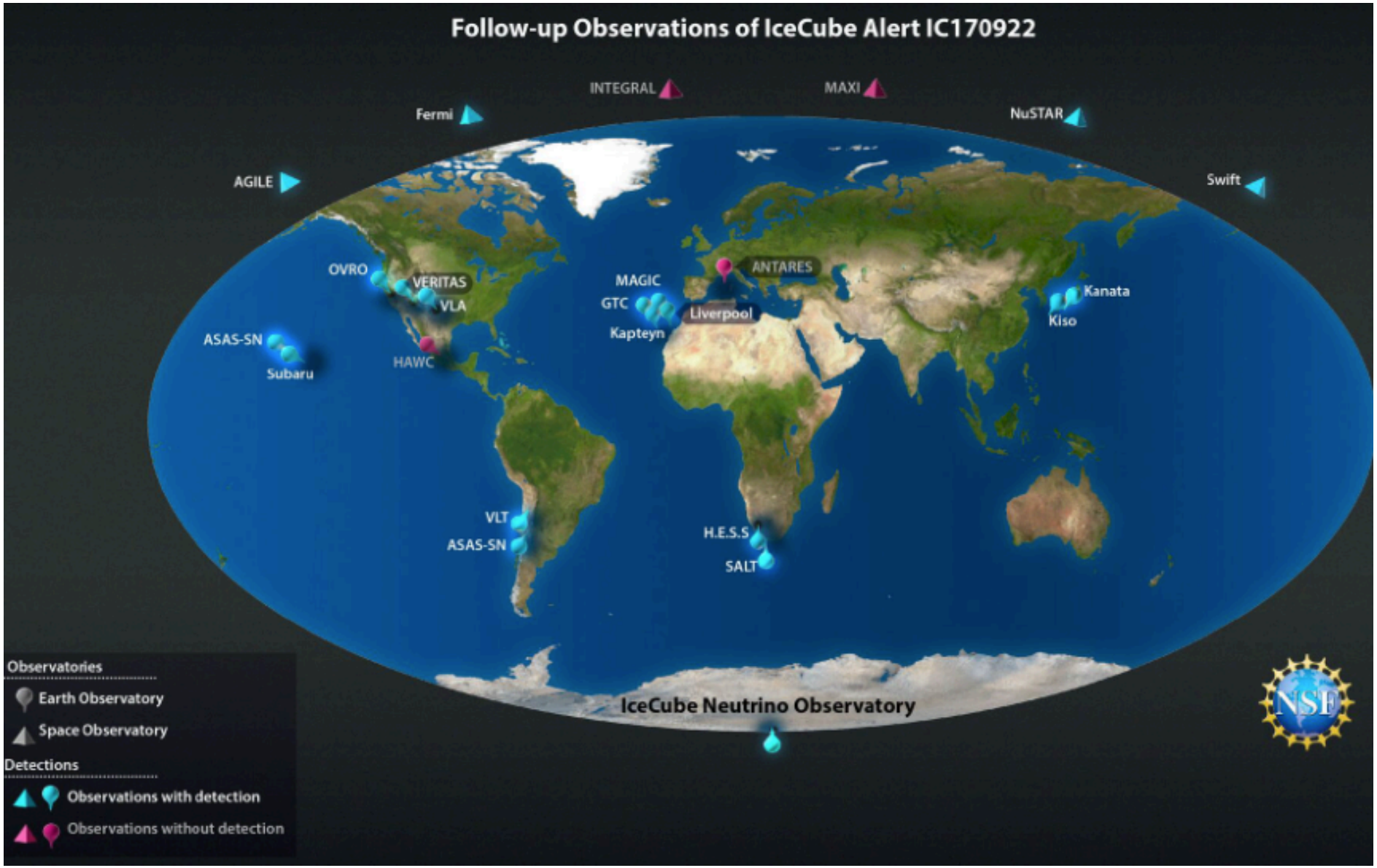
Fermi gamma-ray detection

- **Tanaka, Buson et al. Atel #10791**
- **Gamma-ray blazar at z = 0.3365 (Paiano+ 2018)**
- **Spatially correlated with the neutrino direction**
- **Ongoing gamma-ray flare during neutrino**

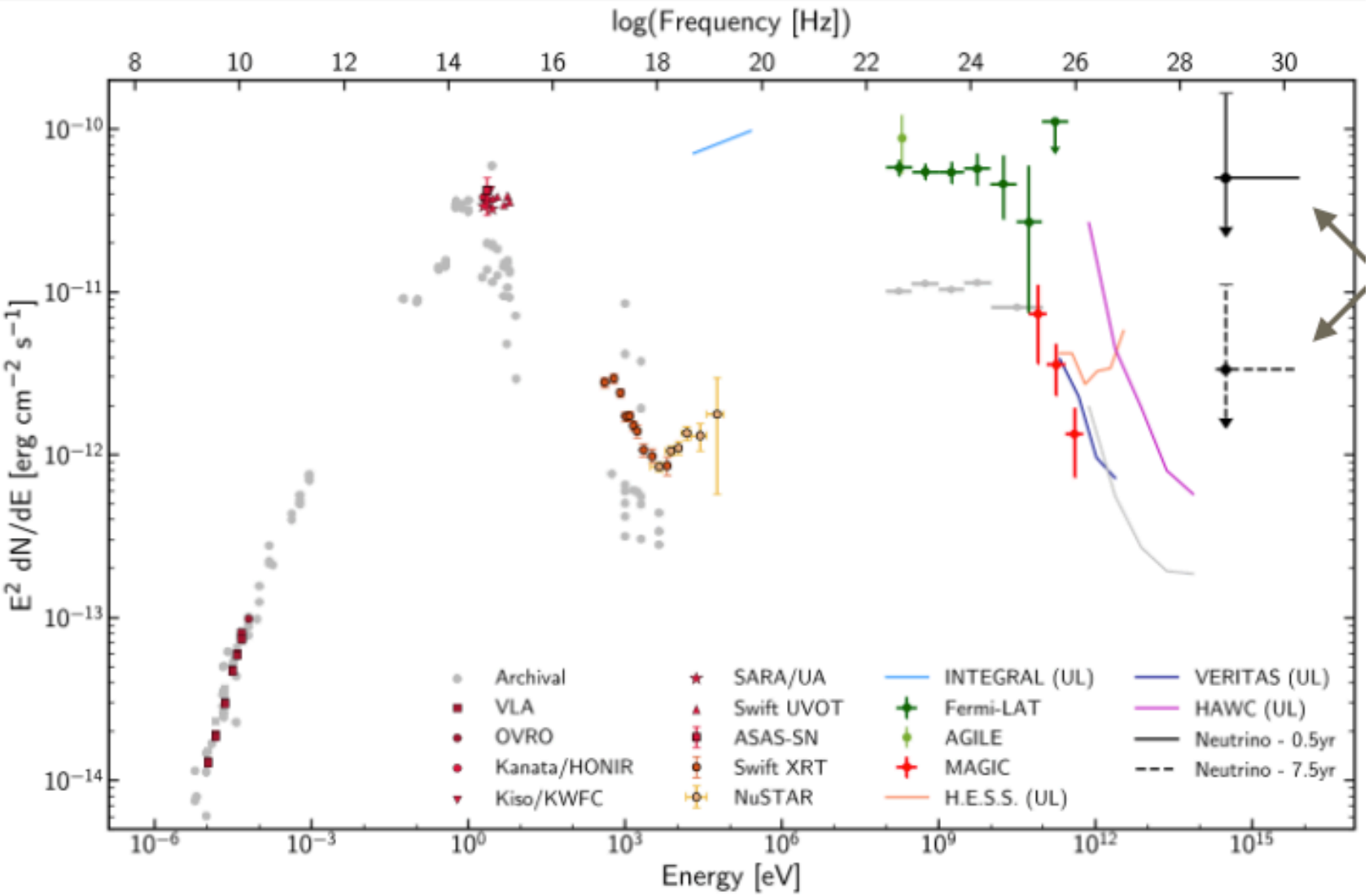




Multiwavelength followup of IC170922A



MWL SED of TXS 0506+056

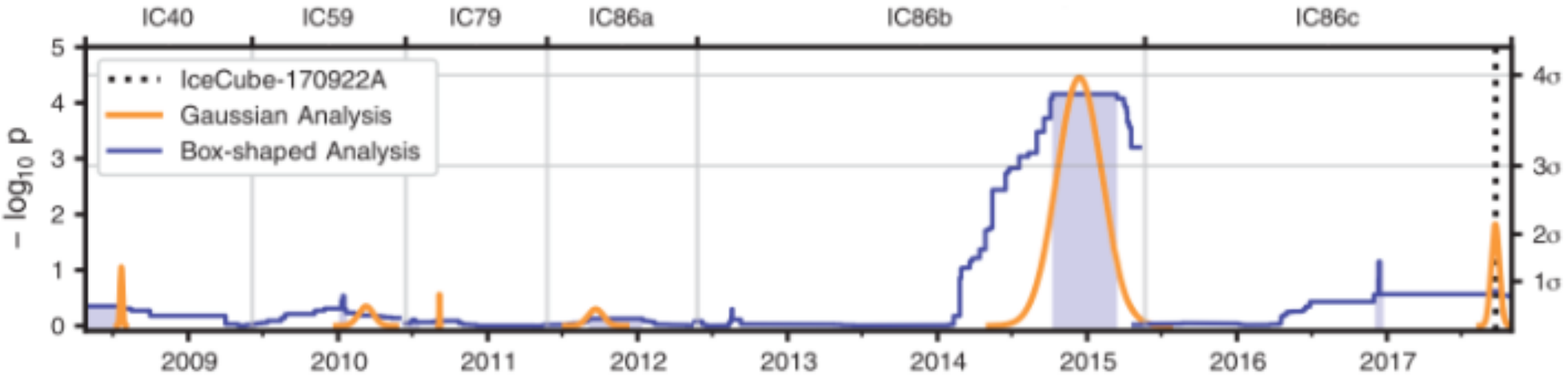


ν estimated flux

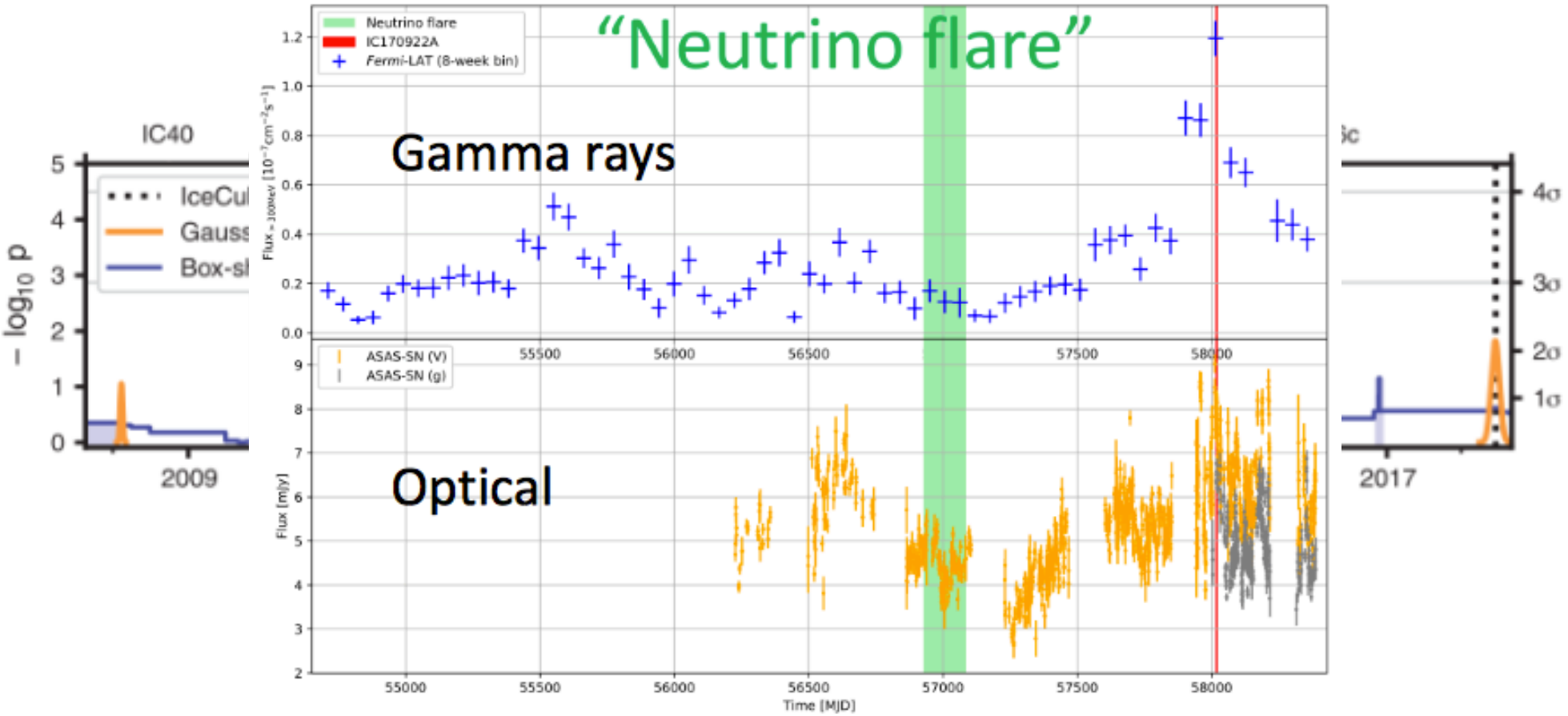
IceCube, Fermi, MAGIC+ Science 361, 146 2018

Neutrino flare 2014/2015

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

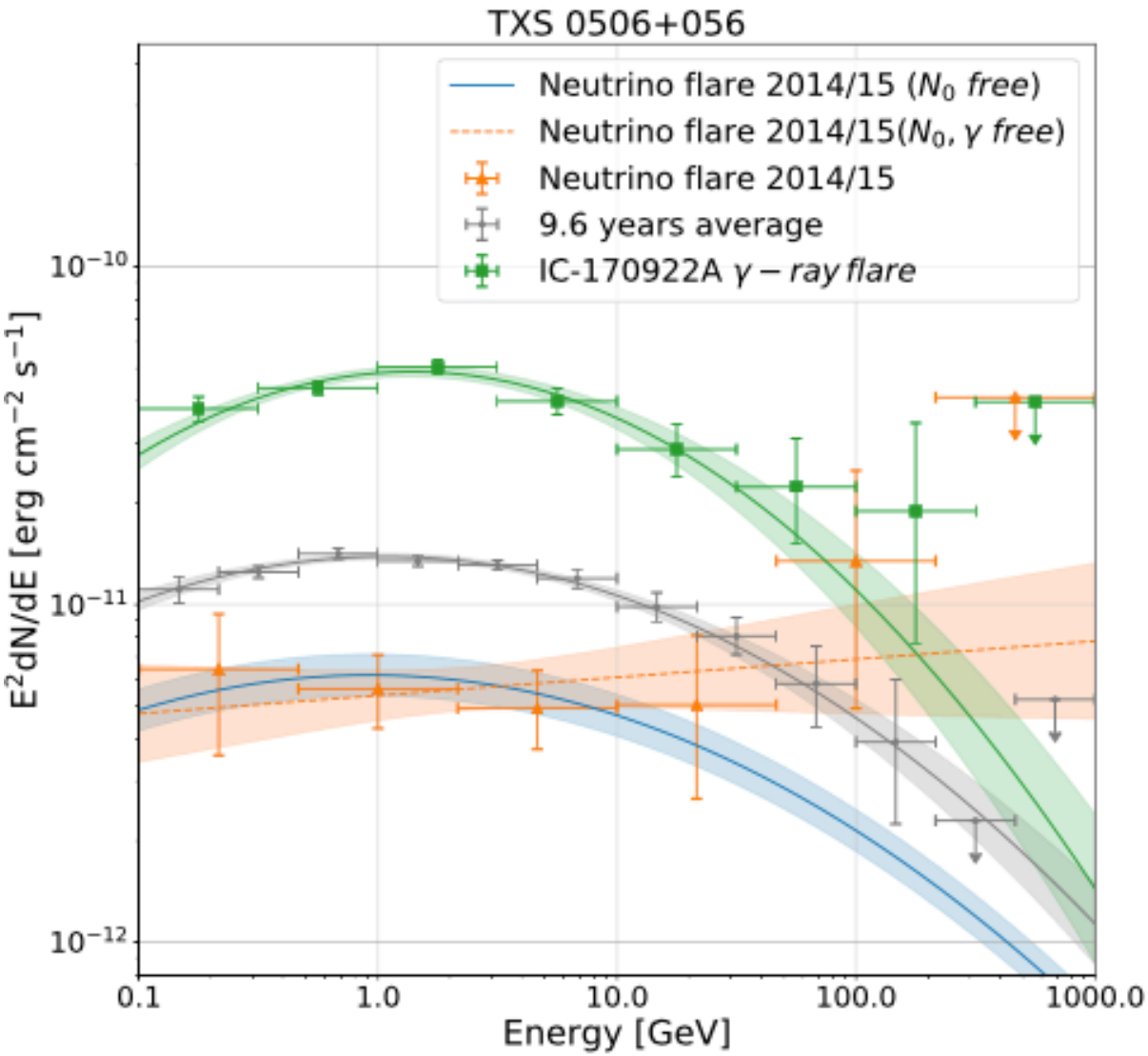


Neutrino flare 2014/2015



No Gamma rays flare or optical enhanced activity during the neutrino flare

Gamma ray SED for 2014/15 period



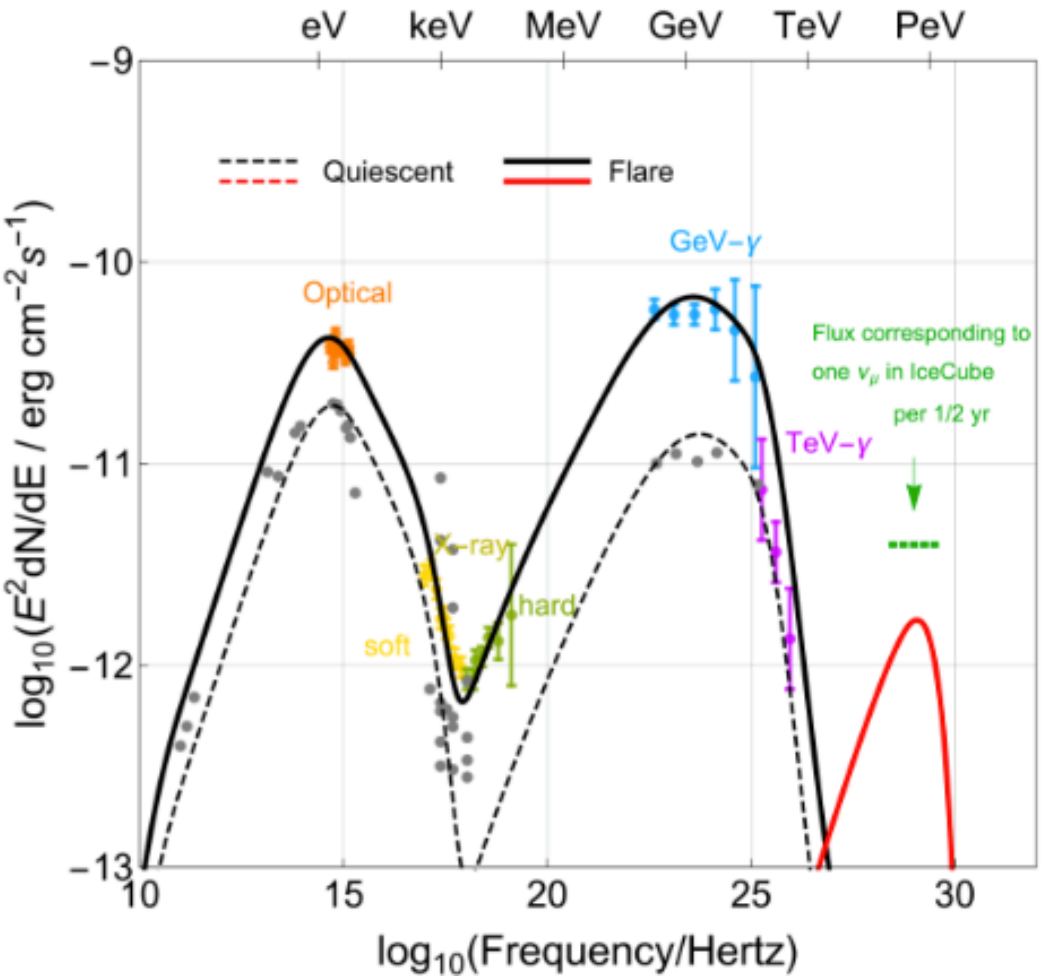
Spectral shape during the neutrino flare is compatible with quiescence (~ 2 sigma variation) (Garrappa+, arXiv:190110806)

Padovani+ 2018 shows an hardening of the spectrum (E>2GeV) during the neutrino flare indicating 2 behaviors :

- **large flux/soft spectrum**
- **small flux/hard spectrum**

Modelling TXS 0506+056

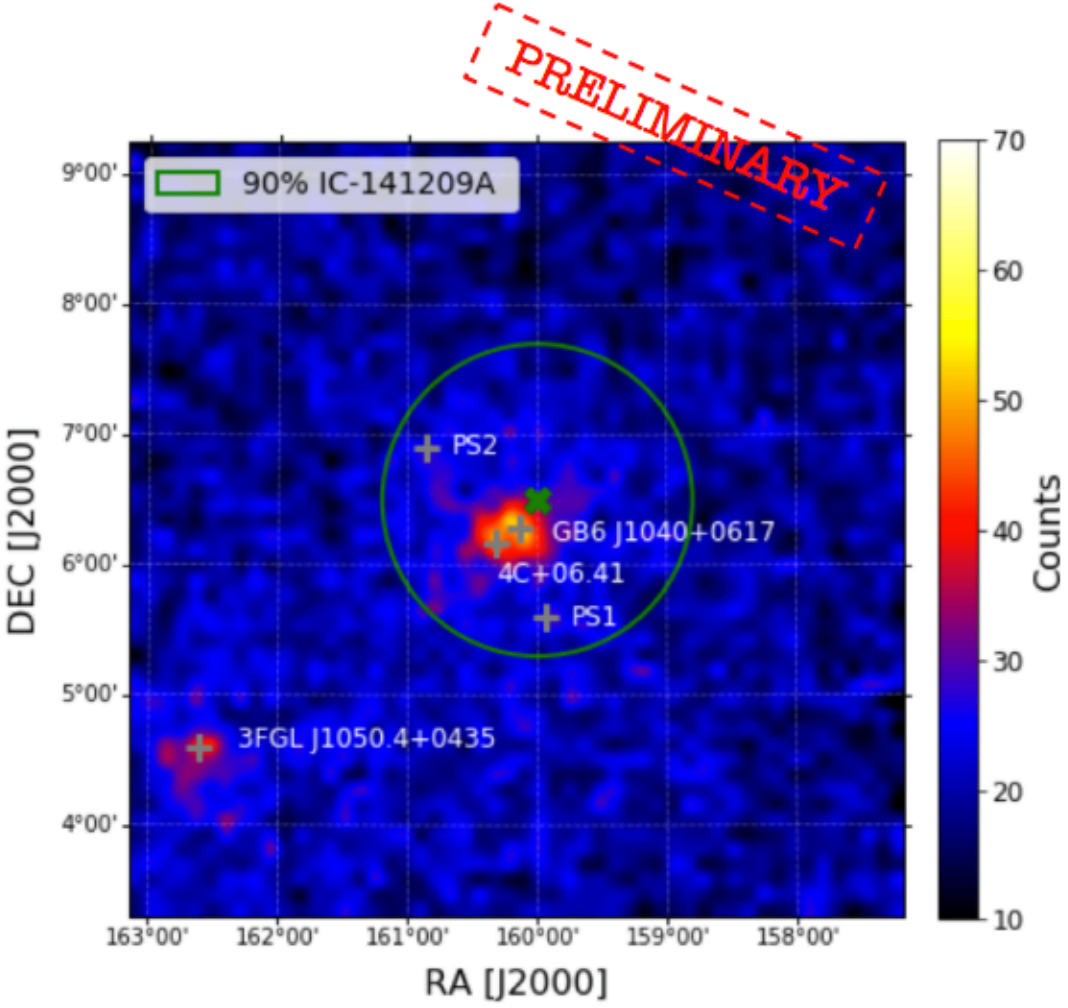
- **Pure leptonic models are excluded for the presence of neutrino**
- **TXS requires a more complex model with multiple zones, to avoid the above contraints (see Gao+ 2018)**
- **Lepto-hadronic signatures could be observable for nearby blazars in TeV as a break and hardening of the spectrum, coordinated with X-ray activity**
- **TXS alone is unfortunately not enough to understand why this blazar is a particular neutrino source**



GB6 J1040+0617 and IC-141209A ?

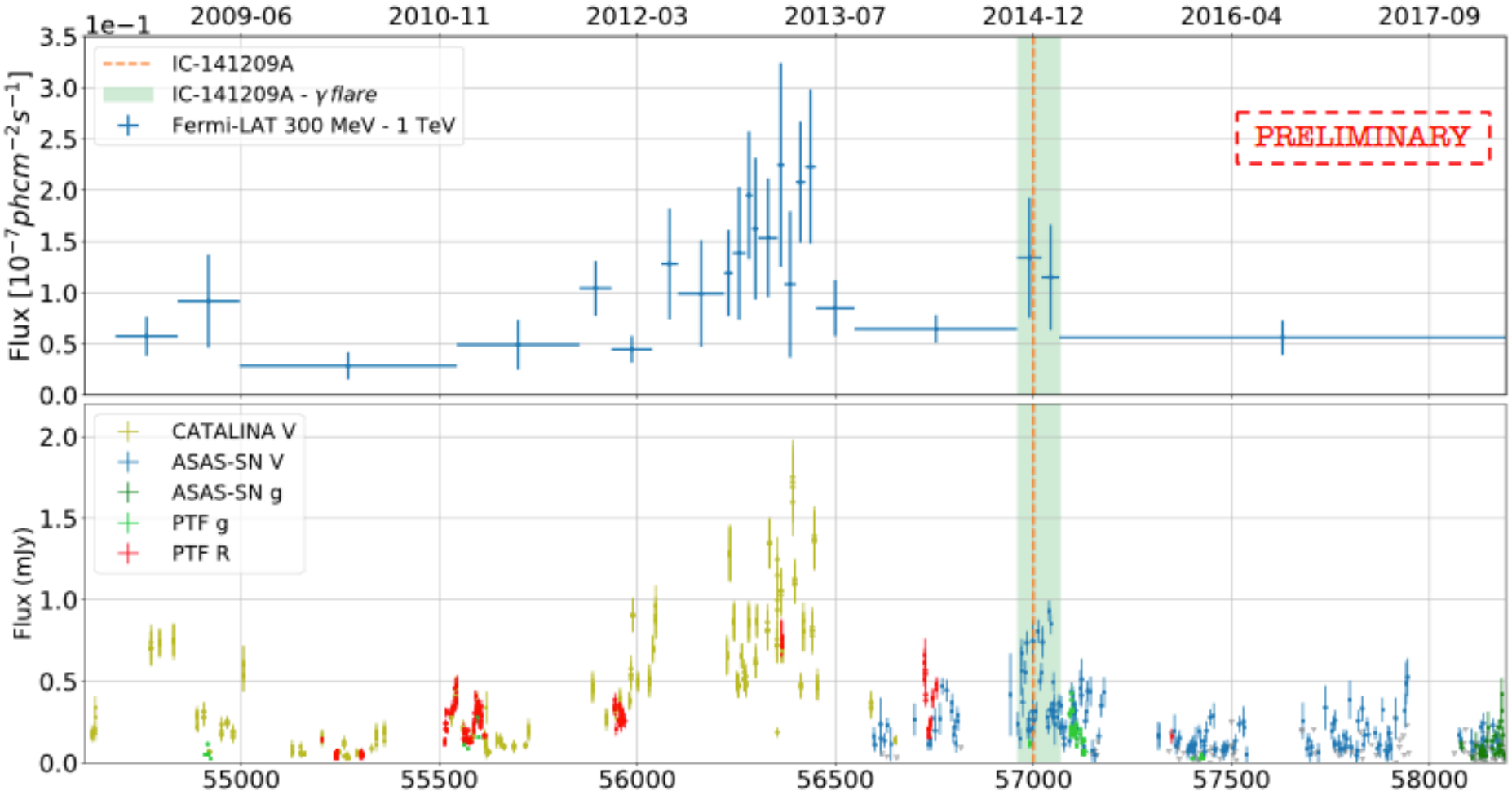
- **GB6 J1040+0617 is a BL Lac with z~0.73**
- **Dist. from IC-141209A: 0.27°**

- **The gamma-ray sky inside the IC error region is pretty crowded:**
  - **4C+06.41 (QSO)**
  - **Two additional sources (PS1 and PS2) found using 9.6 years of data**
  - **PS2 also included in FL8Y as FL8Y J1043.3+0651**



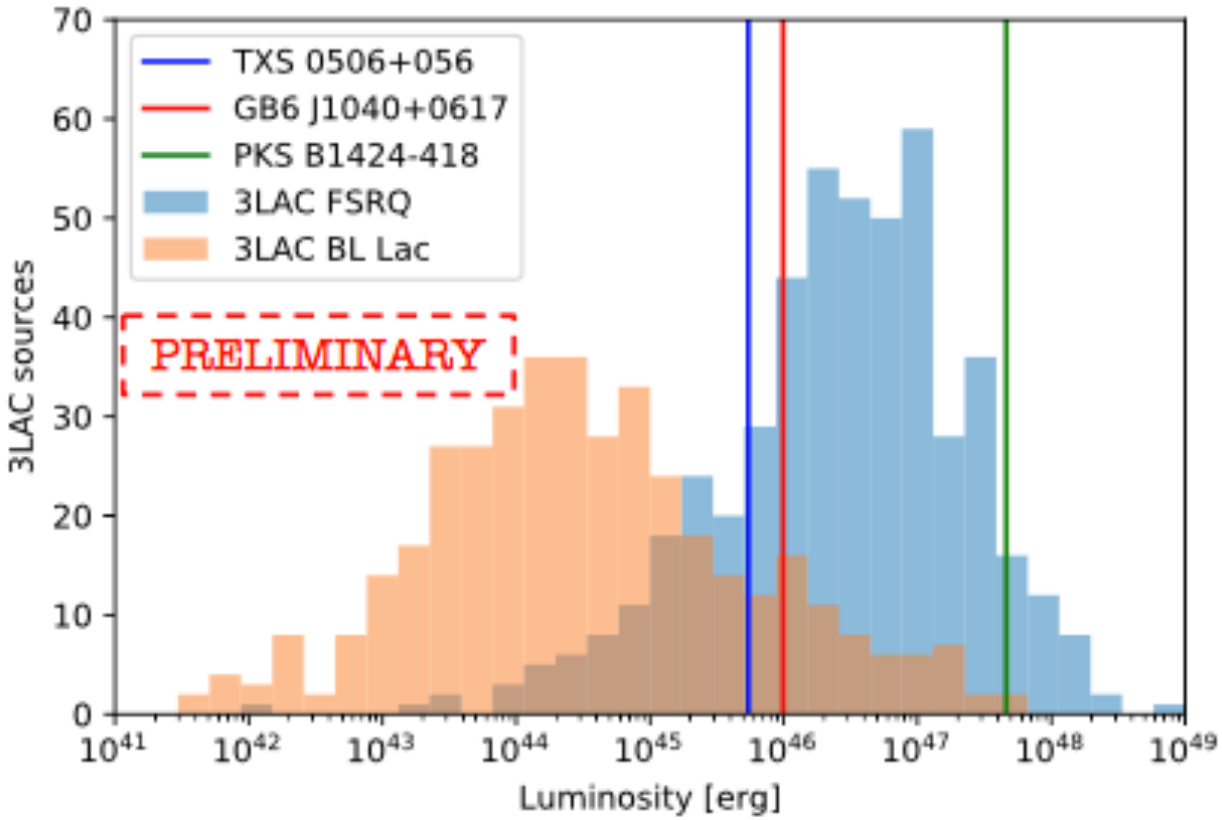
Garrappa+ 2019 submitted

Gamma Ray and optical light curve



Garrappa+ 2019 submitted

Another good candidate



Assuming the redshift of 0.73 the obtained gamma-ray luminosity for GB6 is comparable to that of TXS and so we consider it a potential counterpart to the high-energy neutrino event IC-141209A.

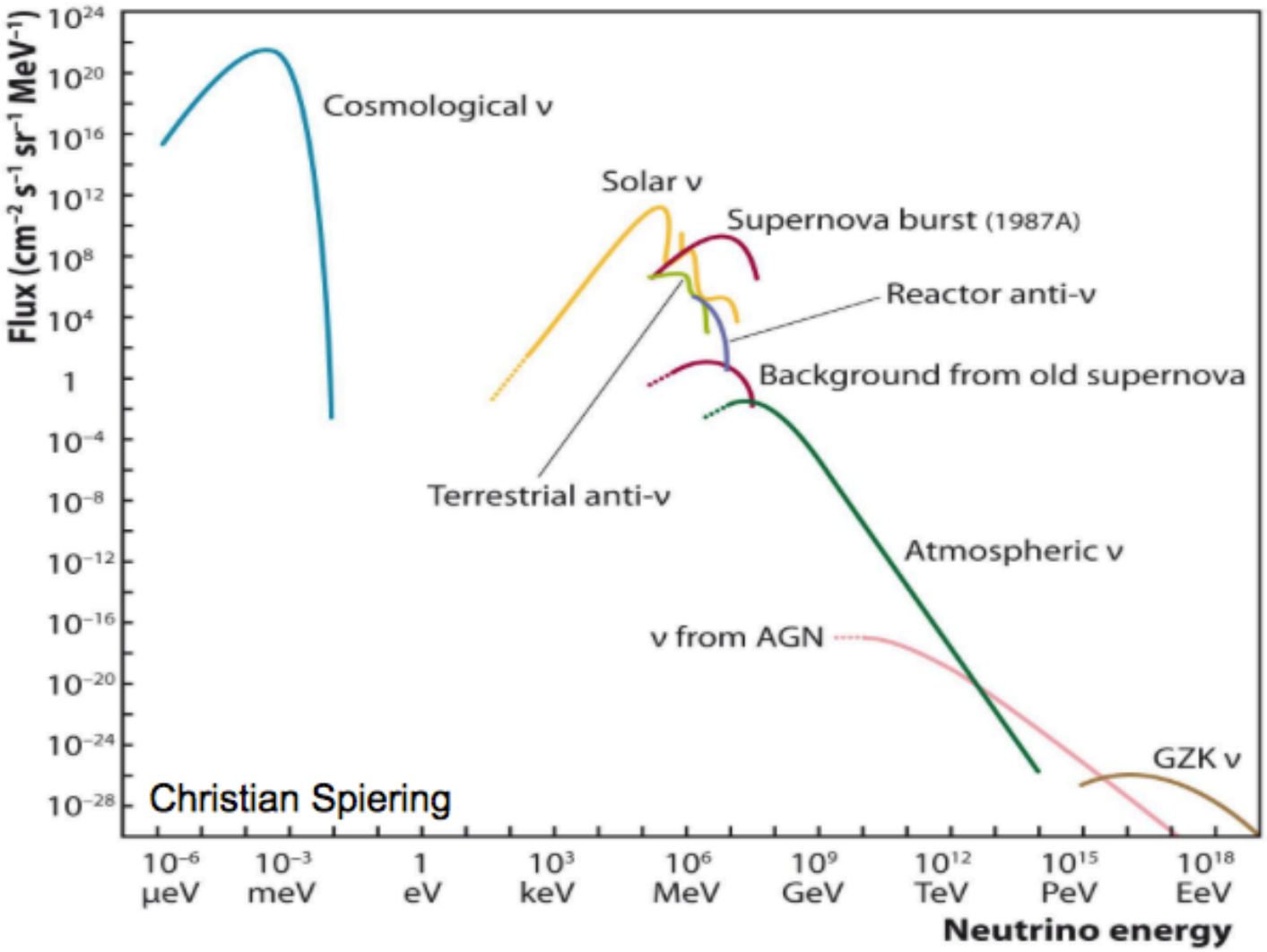
Conclusions

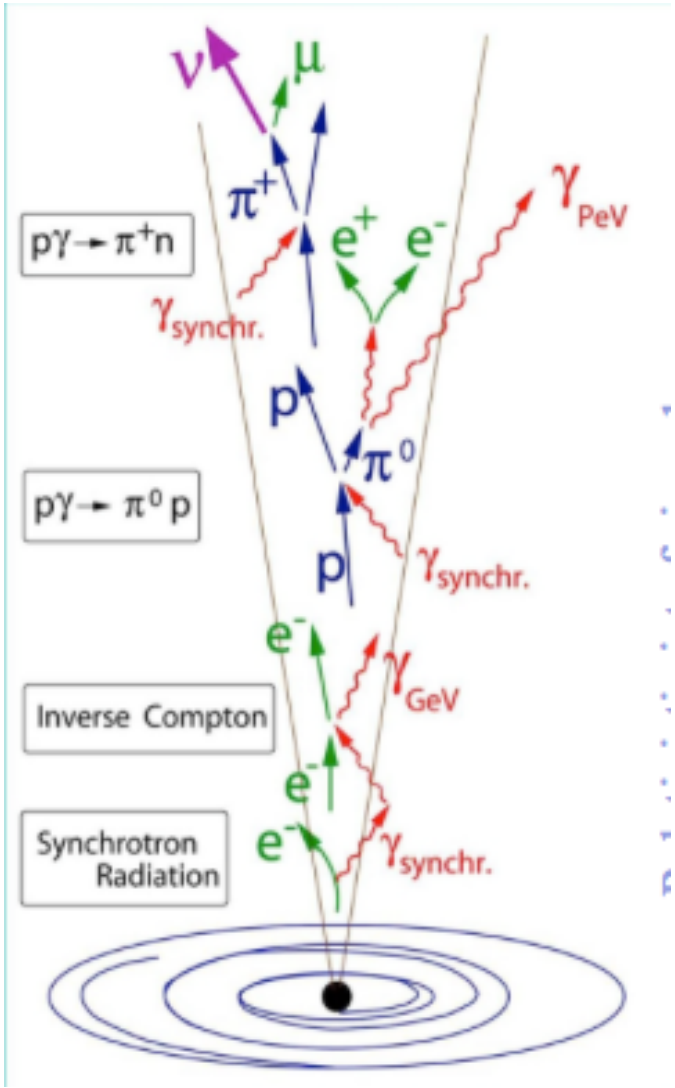
- This is just the beginning of neutrino/gamma ray astronomy
- Multi-messenger + time-domain is a promising path to reveal the origin of neutrinos (and potentially cosmic rays)
- Neutrino sample is growing year by year
- Future observatories will improve sensitivity and statistics, e.g., IceCube-Gen2, KM3NeT, AMEGO, ASTROGAM, CTA ...

Thanks!

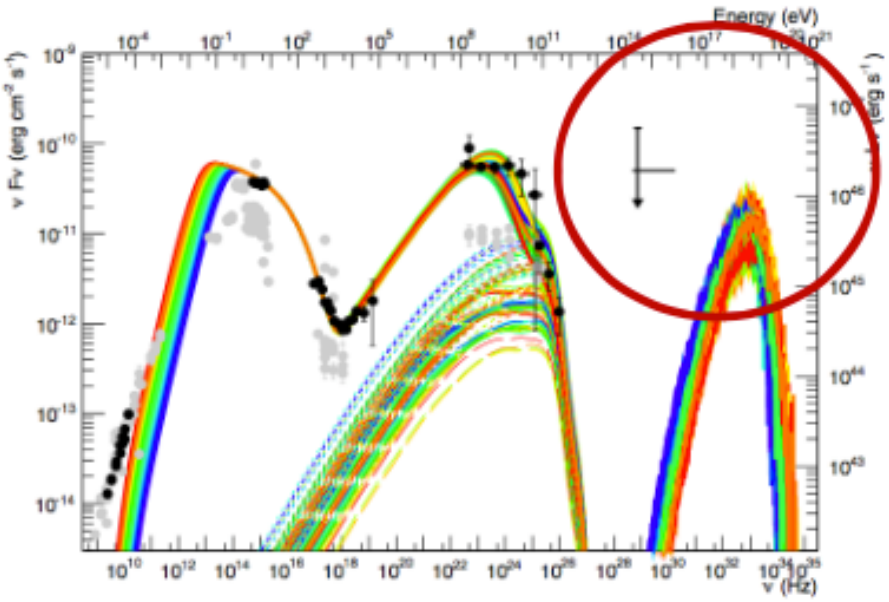
BACK UP

Neutrino source fluxes

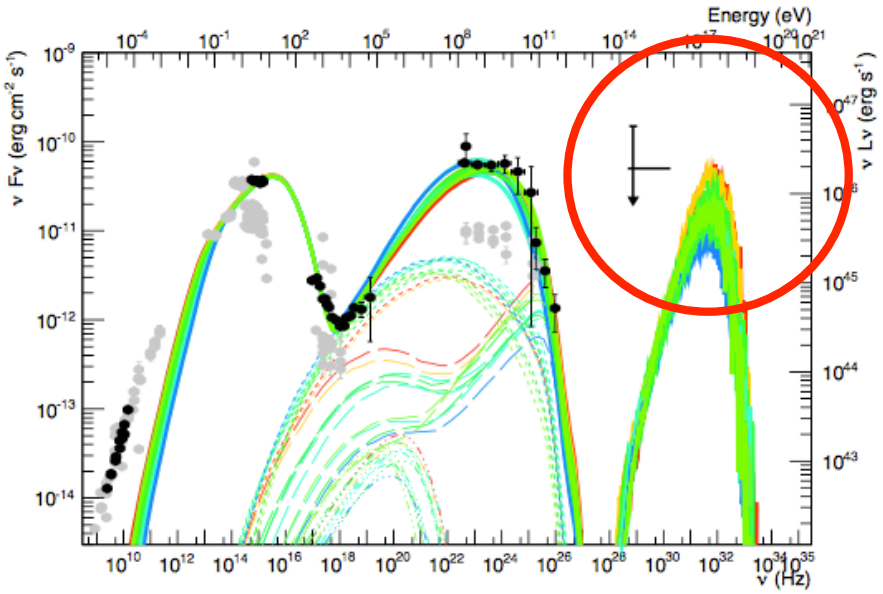



ν
μ
π+
pγ→π+n
e+
e-
γPeV
γsynchr.
p
π0
pγ→π0p
p
γsynchr.
e-
γGeV
Inverse Compton
e-
e-
γsynchr.
Synchrotron Radiation

Multi Messenger SED



(a) Proton synchrotron modeling of TXS 0506+056



(b) Lepto-hadronic 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!**