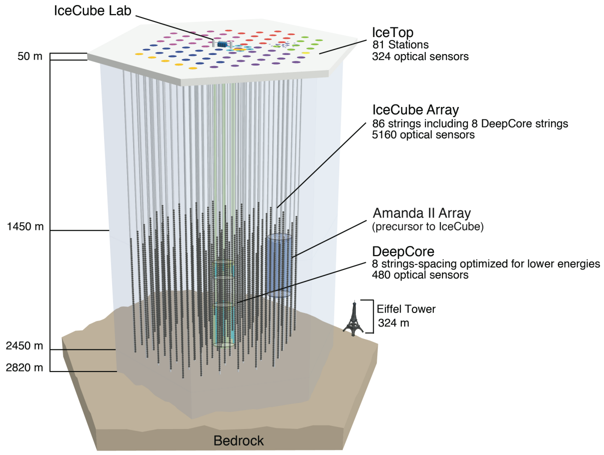


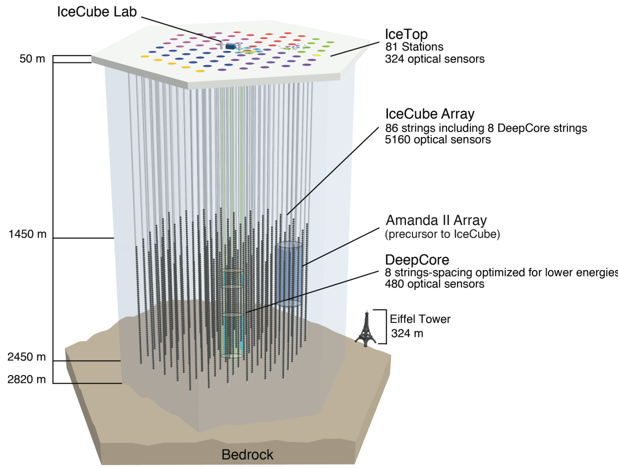
Neutrinos from a blazar jet and the birth of non-stellar neutrino astronomy

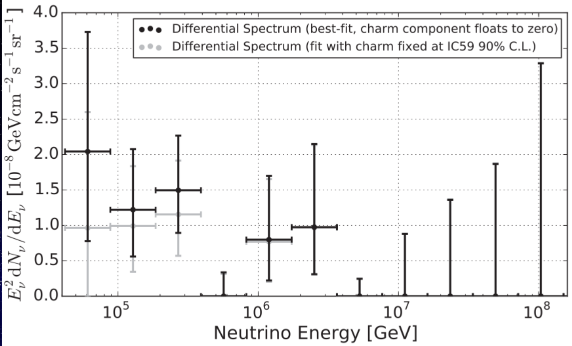
Paolo Padovani, ESO, Garching bei München

with Paolo Giommi, Elisa Resconi, Theo Glauch & Matthias Huber (Technische Universität München), Foteini Oikonomou (ESO), Maria Petropoulou (Princeton), Bruno Arsioli (UNICAMP, Brazil), Narek Sahakyan (ICRANET-Armenia), and others, plus the IceCube Collaboration and many others

SFB 1258 | Neutrinos Dark Matter Messengers

DFG Deutsche Forschungsgemeinschaft

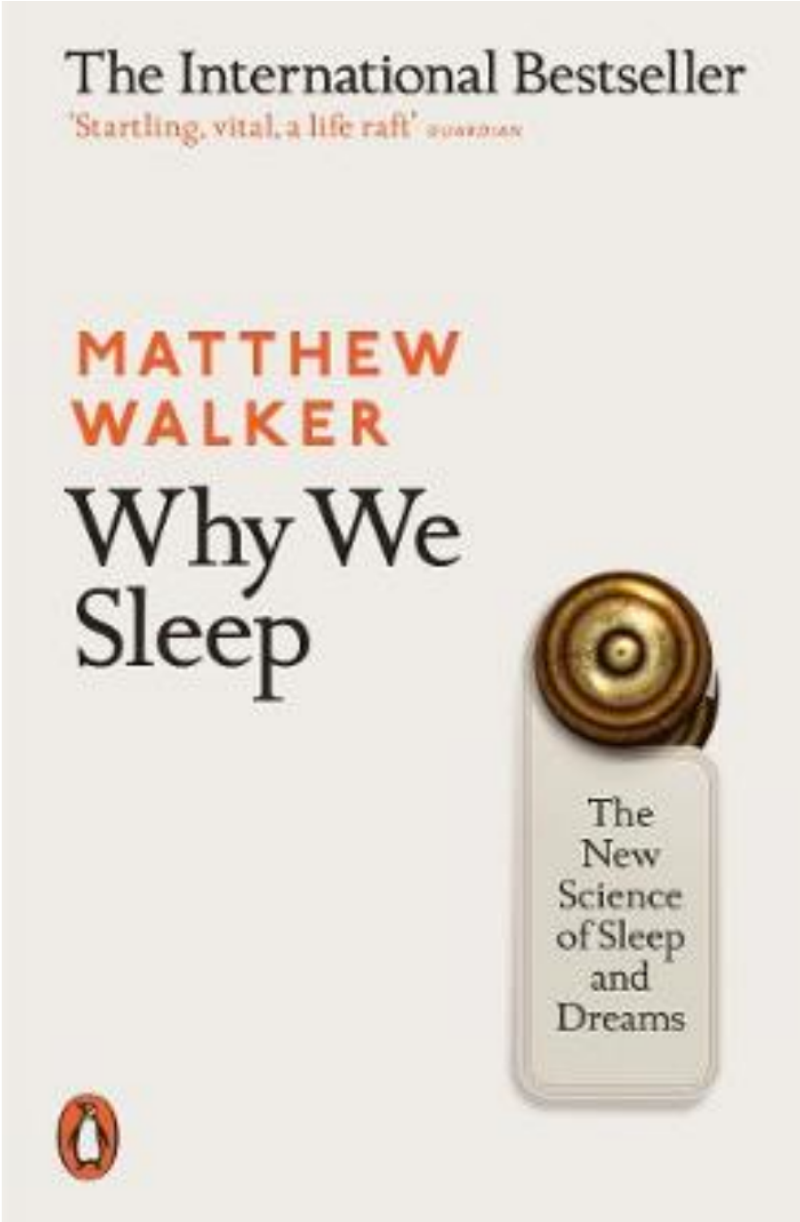


The birth of (non-stellar) neutrino Astronomy

Paolo Padovani, ESO, Garching bei München

with Elisa Resconi (Technische Universität München), Paolo Giommi (ASI, Rome), Maria Petropoulou (Purdue University, Indiana), and others



"All humans [...] have a genetically hardwired dip in alertness that occurs in the midafternoon hours."

"Should you ever have to give **a presentation at work**, for your own sake – and that of the conscious state of your listeners – if you can, **avoid the midafternoon slot**."

Talk outline:

- Neutrinos in a nutshell and neutrino astronomy
- The astrophysical problem and our approaches
- The blazar TXS 0506+056 as the first cosmic neutrino source
- The "big picture": why is this important?
- Recent results and outlook

Talk outline:

- Neutrinos i
- The astroph
- The blazar … rino source
- The "big pic
- Recent resu

Energy units

- 1 eV ≡ **2.42 10^{14}** Hz ≡ 12,400 Å
- 1 GeV (10^9) ≡ 2.42 10^{23} Hz (γ-rays) ≡ 1.24 10^{-5} Å
- 1 TeV (10^{12}) ≡ 2.42 10^{26} Hz (VHE γ-rays) ≡ 1.24 10^{-8} Å
- 1 PeV (10^{15}) ≡ 2.42 10^{29} Hz

- 1 TeV ≡ 1.602 erg
- 1 PeV ≡ 1.602 10^3 erg

Neutrinos in a nutshell

- Italian for "little neutral one"
- Tiny mass: < 1/2,000,000 m_e (= 9 10^{-28} g)
- Electrically neutral, weakly interacting elementary subatomic particle
- Three types: electron (ν_e), muon (ν_μ), and tau (ν_τ)
- Everywhere:
  - ✓ ~ 340 cosmic neutrinos/cm^3 in the Universe [E ~ 0.0002 eV]
  - ✓ ~ 10^{11} solar neutrinos/cm^2/s on Earth → ~ 10^{14} /s through our bodies [E $\lesssim$ 1 MeV]
- Probably the second most common particle in the Universe (dark matter?)

Neutrinos in a nutshell

- Italian for "little neutral one"
- Tiny r
- Electr ... entary
  subat
- Three ... u (ν_τ)
- Every
  - ✓ ... erse
  - ✓
  - V]
- Proba ... n the
  Unive

Neutrinos in a nutshell

500 parsec!

Neutrino Astronomy

- Only **two** astronomical neutrino sources known (until recently):
  - ✓ the Sun
  - ✓ SN 1987a

ARTICLE

28 AUGUST 2014 | VOL 512 | NATURE | 383

doi:10.1038/nature13702

Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*

In the core of the Sun, energy is released through sequences of nuclear reactions that convert hydrogen into helium. The primary reaction is thought to be the fusion of two protons with the emission of a low-energy neutrino. These so-called *pp* neutrinos constitute nearly the entirety of the solar neutrino flux, vastly outnumbering those emitted in the reactions that follow. Although solar neutrinos from secondary processes have been observed, proving the nuclear origin of the Sun's energy and contributing to the discovery of neutrino oscillations, those from proton–proton fusion have hitherto eluded direct detection. Here we report spectral observations of *pp* neutrinos, demonstrating that about 99 per cent of the power of the Sun, 3.84×10^{33} ergs per second, is generated by the proton–proton fusion process.

We have known for 75 years that the energy generated by stars comes from the fusion of light nuclei into heavier ones[1–3]. In the Sun, hydrogen is transformed into helium predominantly via the *pp* cycle[4,5], a chain of reactions releasing 26.73 MeV and electron neutrinos ν_e, and summarized as

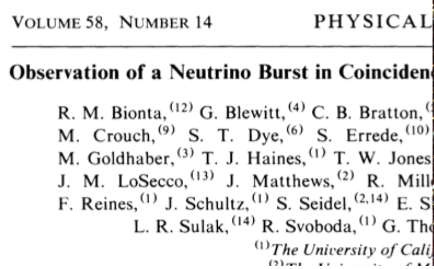
$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + \mathrm{E}$$

The cycle begins with the fusion of two protons into a deuteron, which occurs 99.76% of the time[6] by means of the primary reaction

$$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$$

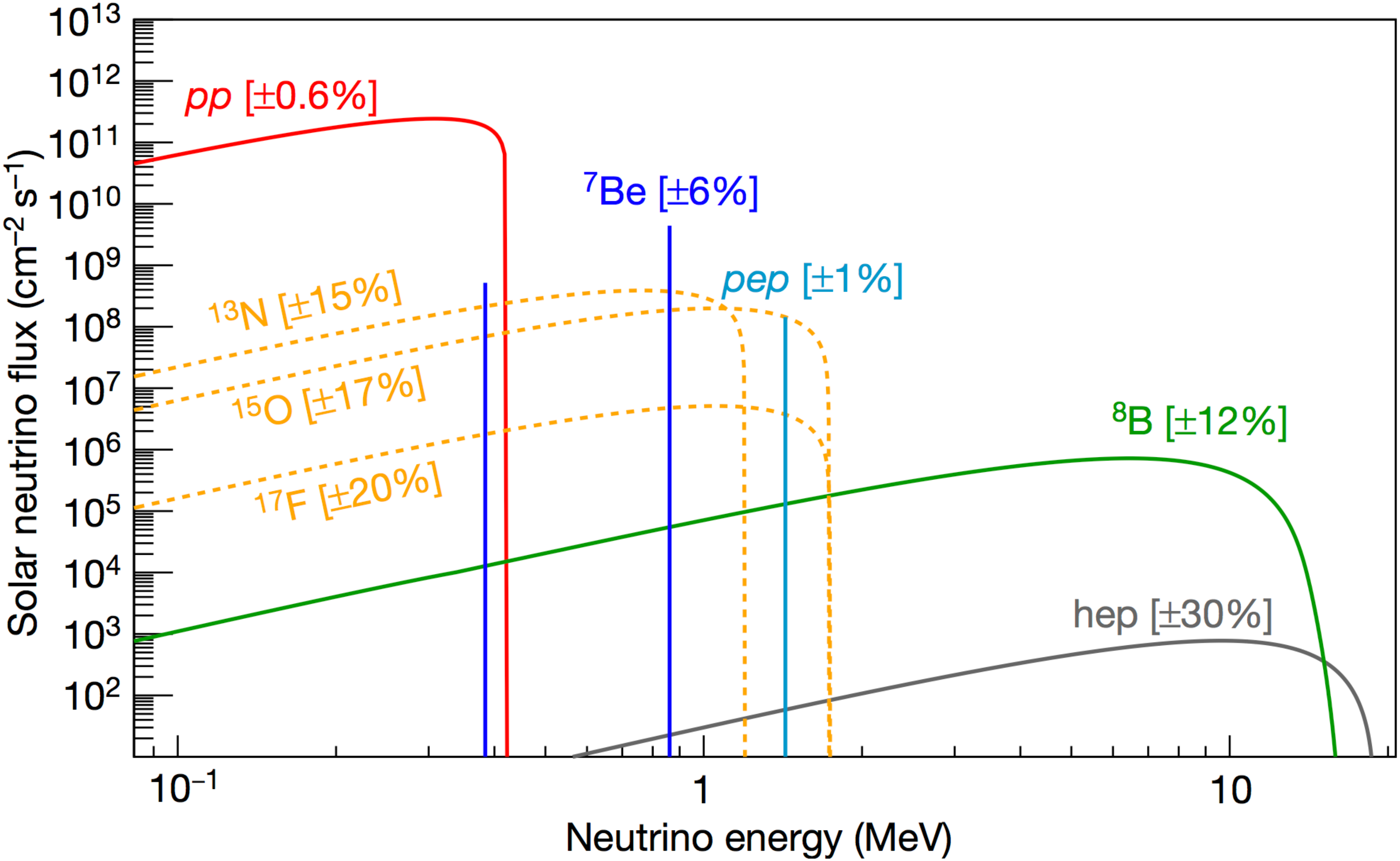
neutrinos. The measured solar *pp* neutrino flux is $(6.6 \pm 0.7) \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, in good agreement with the prediction of the standard solar model[9] (SSM) ($5.98 \times (1 \pm 0.006) \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$).

The observation of *pp* neutrinos provides us with a direct glimpse at the keystone fusion process that keeps the Sun shining and strongly reinforces our theories on the origin of almost the entirety of the Sun's energy. Their measured flux can also be used to infer the total energy radiated by the Sun, $3.84 \times 10^{33}\ \mathrm{erg\ s}^{-1}$. However, because photons produced in the Sun's core take a very long time (at least a hundred thousand years; ref. 21) to reach the surface, neutrino and optical observations in combination provide experimental confirmation that the Sun has been in thermodynamic equilibrium over such a timescale.


VOLUME 58, NUMBER 14 PHYSICAL

Observation of a Neutrino Burst in Coinciden

R. M. Bionta,(12) G. Blewitt,(4) C. B. Bratton,
M. Crouch,(9) S. T. Dye,(6) S. Errede,(10)
M. Goldhaber,(3) T. J. Haines,(1) T. W. Jones
J. M. LoSecco,(13) J. Matthews,(2) R. Mill
F. Reines,(1) J. Schultz,(1) S. Seidel,(2,14) E. S
L. R. Sulak,(14) R. Svoboda,(1) G. Th
(1)The University of Cali



VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst in Coincidence with Supernova 1987A in the Large Magellanic Cloud

R. M. Bionta,[12] G. Blewitt,[4] C. B. Bratton,[5] D. Casper,[2,14] A. Ciocio,[14] R. Claus,[14] B. Cortez,[16] M. Crouch,[9] S. T. Dye,[6] S. Errede,[10] G. W. Foster,[15] W. Gajewski,[1] K. S. Ganezer,[1] M. Goldhaber,[3] T. J. Haines,[1] T. W. Jones,[7] D. Kielczewska,[1,8] W. R. Kropp,[1] J. G. Learned,[6] J. M. LoSecco,[13] J. Matthews,[2] R. Miller,[1] M. S. Mudan,[7] H. S. Park,[11] L. R. Price,[1] F. Reines,[1] J. Schultz,[1] S. Seidel,[2,14] E. Shumard,[16] D. Sinclair,[2] H. W. Sobel,[1] J. L. Stone,[14] L. R. Sulak,[14] R. Svoboda,[1] G. Thornton,[2] J. C. van der Velde,[2] and C. Wuest[12]

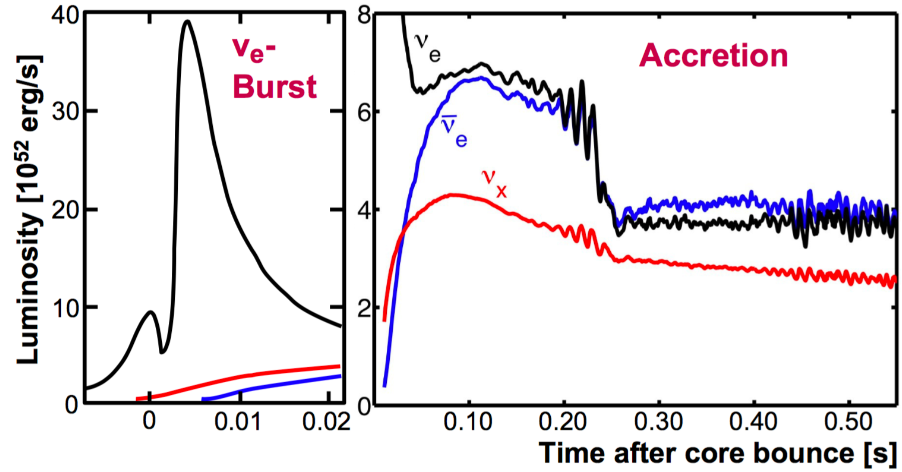
[1]*The University of California, Irvine, Irvine, California 92717*
[2]*The University of Michigan, Ann Arbor, Michigan 48109*
[3]*Brookhaven National Laboratory, Upton, New York 11973*
[4]*California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California 91109*
[5]*Cleveland State University, Cleveland, Ohio 44115*
[6]*The University of Hawaii, Honolulu, Hawaii 96822*
[7]*University College, London WC1E 6BT, United Kingdom*
[8]*Warsaw University, Warsaw, Poland*
[9]*Case Western Reserve University, Cleveland, Ohio 44106*
[10]*The University of Illinois, Urbana, Illinois 61801*
[11]*The University of California, Berkeley, California 94720*
[12]*Lawrence Livermore National Laboratory, Livermore, California 94550*
[13]*The University of Notre Dame, Notre Dame, Indiana 46556*
[14]*Boston University, Boston, Massachusetts 02215*
[15]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[16]*AT&T Bell Laboratories, Summit, New Jersey 07910*

(Received 13 March 1987)

A burst of eight neutrino events preceding the optical detection of the supernova in the Large Magellanic Cloud has been observed in a large underground water Cherenkov detector. The events span an interval of 6 s and have visible energies in the range 20–40 MeV.

Neutrino Emission from Supernovae

Janka 2017



$$e + p \rightarrow n + \nu_e$$

VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst from the Supernova SN1987A

K. Hirata,[a] T. Kajita,[a] M. Koshiba,[a,b] M. Nakahata,[b] Y. Oyama,[b] N. Sato,[c] A. Suzuki,[b] M. Takita,[b] and Y. Totsuka[a,c]
University of Tokyo, Tokyo 113, Japan

T. Kifune and T. Suda
Institute for Cosmic Ray Research, University of Tokyo, Tokyo 118, Japan

K. Takahashi and T. Tanimori
National Laboratory for High Energy Physics (KEK), Ibaraki 305, Japan

K. Miyano and M. Yamada
Department of Physics, University of Niigata, Niigata 950-21, Japan

E. W. Beier, L. R. Feldscher, S. B. Kim, A. K. Mann, F. M. Newcomer, R. Van Berg, and W. Zhang
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

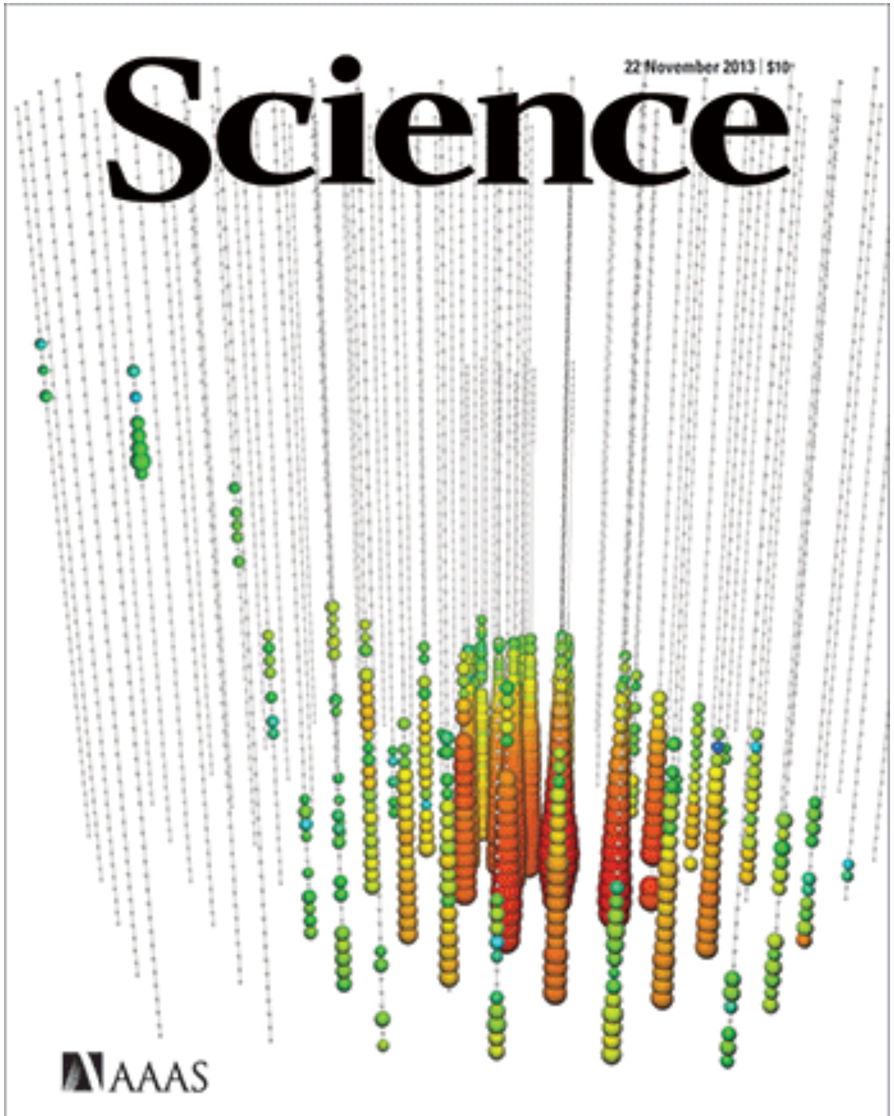
and

B. G. Cortez[d]
California Institute of Technology, Pasadena, California 91125

(Received 10 March 1987)

A neutrino burst was observed in the Kamiokande II detector on 23 February 1987, 7:35:35 UT (±1 min) during a time interval of 13 sec. The signal consisted of eleven electron events of energy 7.5 to 36 MeV, of which the first two point back to the Large Magellanic Cloud with angles 18° ± 18° and 15° ± 27°.

IceCube (2013)



Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

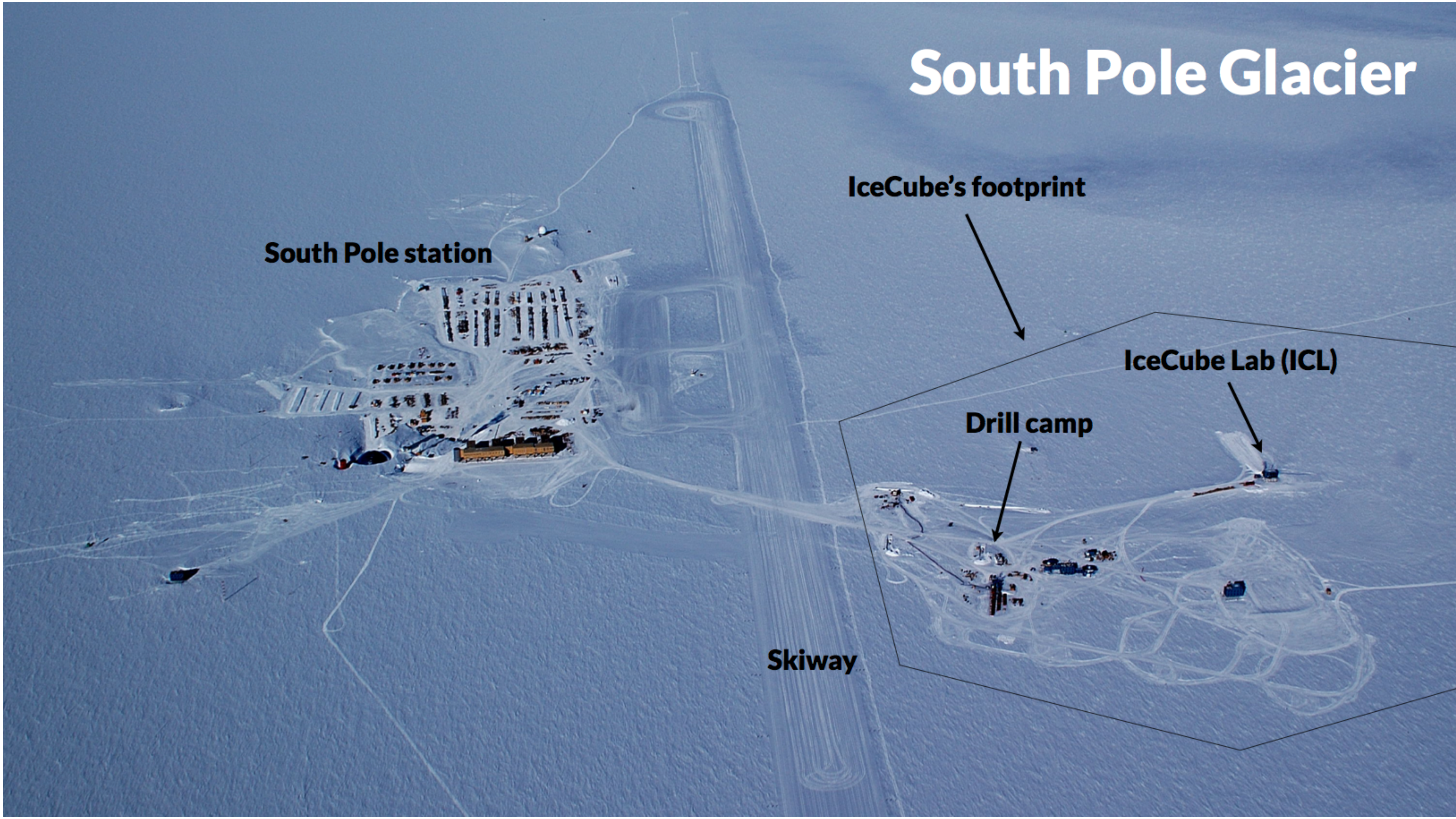
IceCube Collaboration*

Introduction: Neutrino observations are a unique probe of the universe's highest-energy phenomena: Neutrinos are able to escape from dense astrophysical environments that photons cannot and are unambiguous tracers of cosmic ray acceleration. As protons and nuclei are accelerated, they interact with gas and background light near the source to produce subatomic particles such as charged pions and kaons, which then decay, emitting neutrinos. We report on results of an all-sky search for these neutrinos at energies above 30 TeV in the cubic kilometer Antarctic IceCube observatory between May 2010 and May 2012.

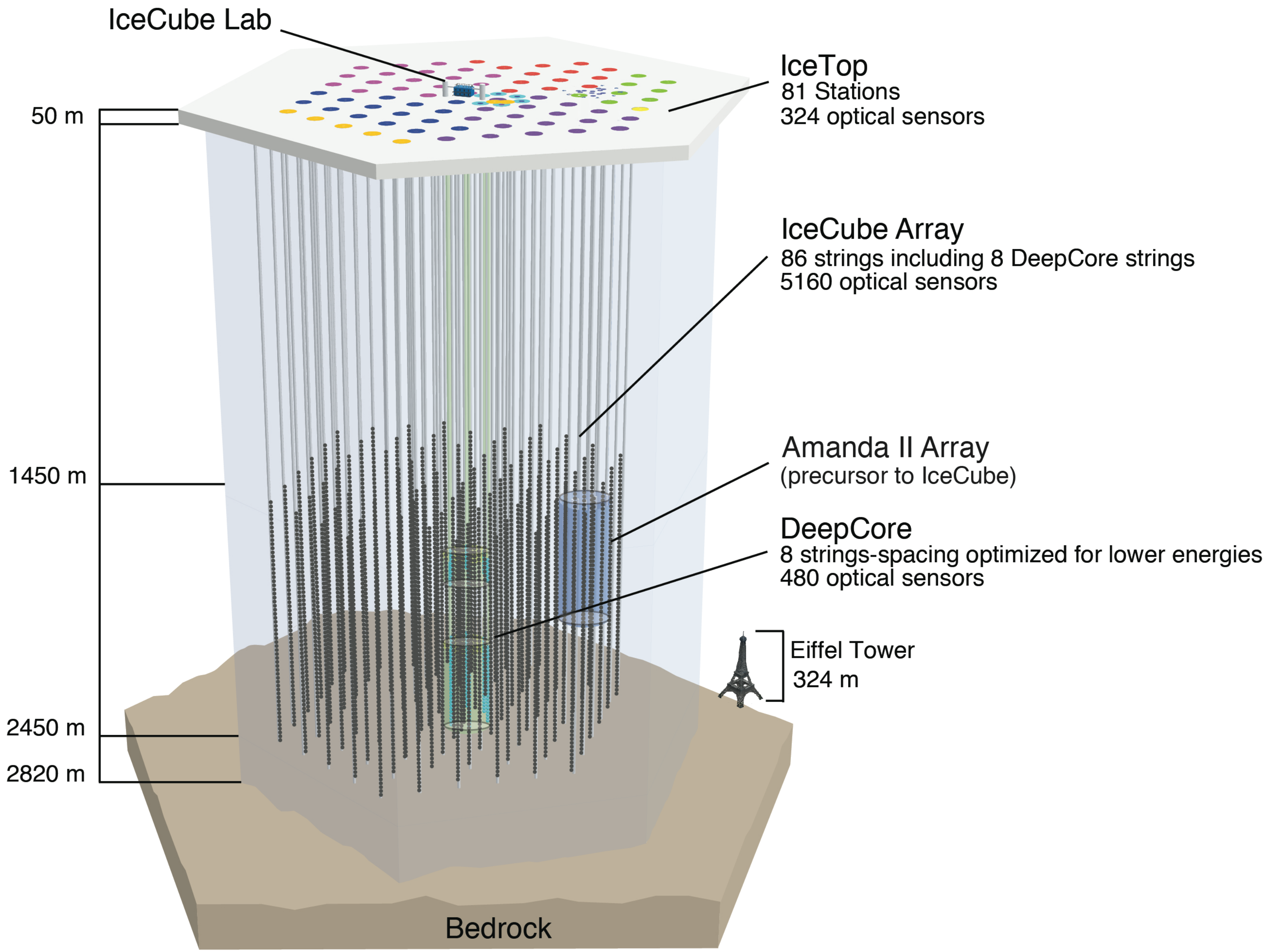
Methods: We have isolated a sample of neutrinos by rejecting background muons from cosmic ray showers in the atmosphere, selecting only those neutrino candidates that are first observed in the detector interior rather than on the detector boundary. This search is primarily sensitive to neutrinos from all directions above 60 TeV, at which the lower-energy background atmospheric neutrinos become rare, with some sensitivity down to energies of 30 TeV. Penetrating muon backgrounds were evaluated using an in-data control sample, with atmospheric neutrino predictions based on theoretical modeling and extrapolation from previous lower-energy measurements.

Results: We observed 28 neutrino candidate events (two previously reported), substantially more than the $10.6^{+5.0}_{-3.6}$ expected from atmospheric backgrounds, and ranging in energy from 30 to 1200 TeV. With the current level of statistics, we did not observe significant clustering of these events in time or space, preventing the identification of their sources at this time.

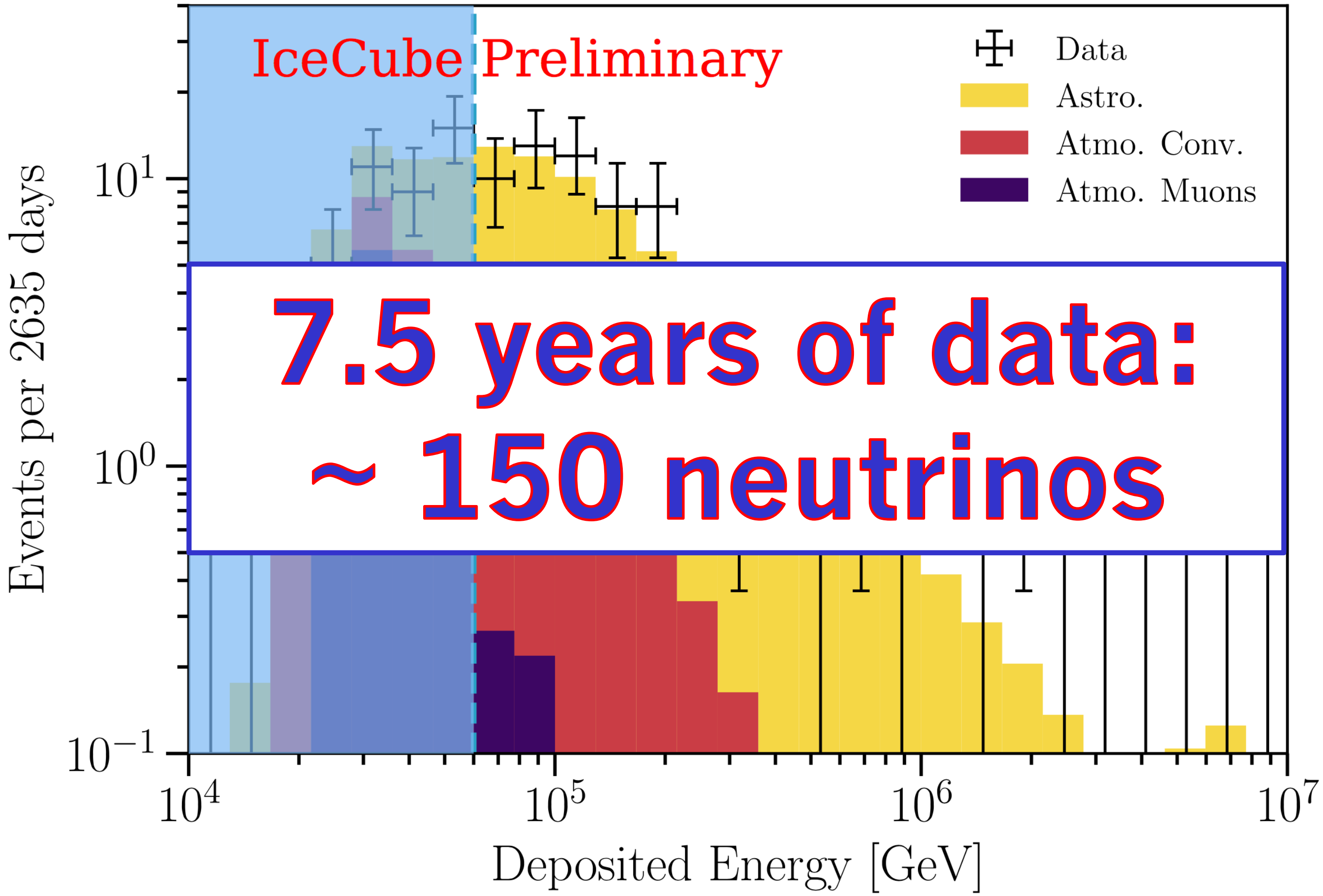
IceCube


South Pole Glacier
IceCube's footprint
South Pole station
IceCube Lab (ICL)
Drill camp
Skiway

IceCube


IceCube Lab
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
Amanda II Array
(precursor to IceCube)
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock

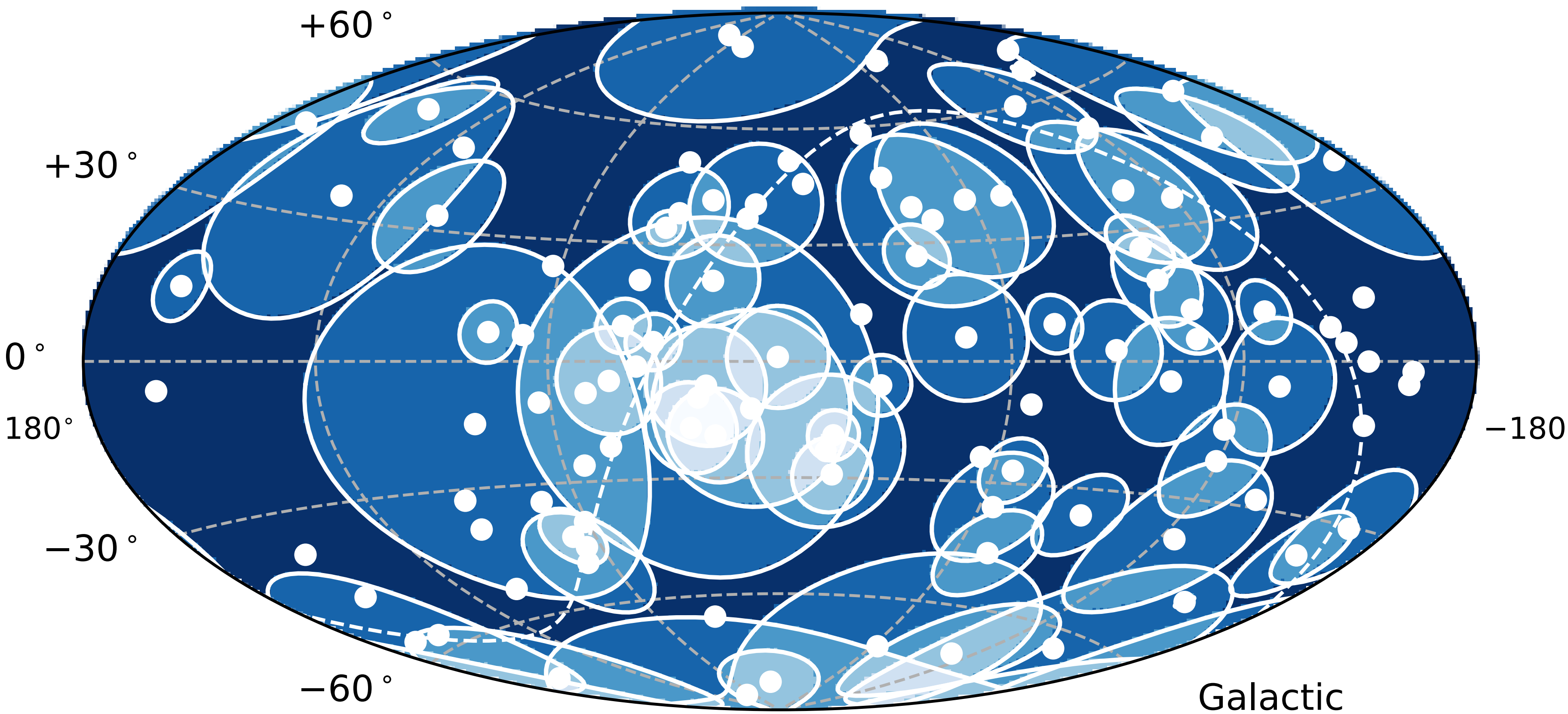
IceCube (2019) [7.5 years]



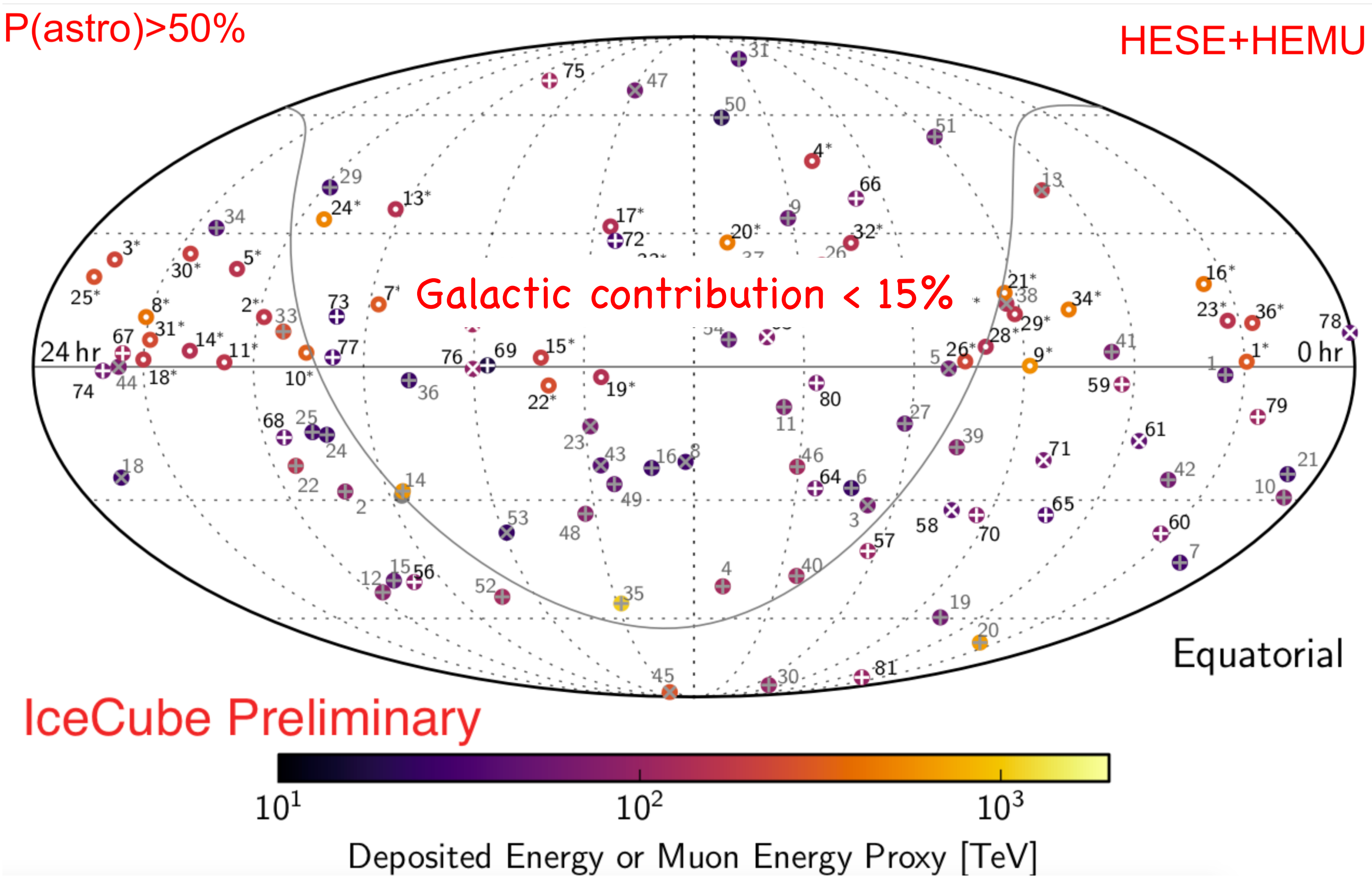
> 6.5σ detection

IceCube collaboration ICRC36 (2019)

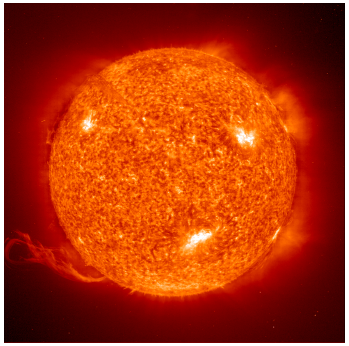
Sky distribution



Sky distribution

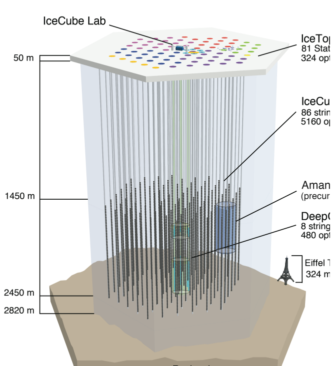


Neutrino energies



≲ 1 MeV (nuclear fusion)

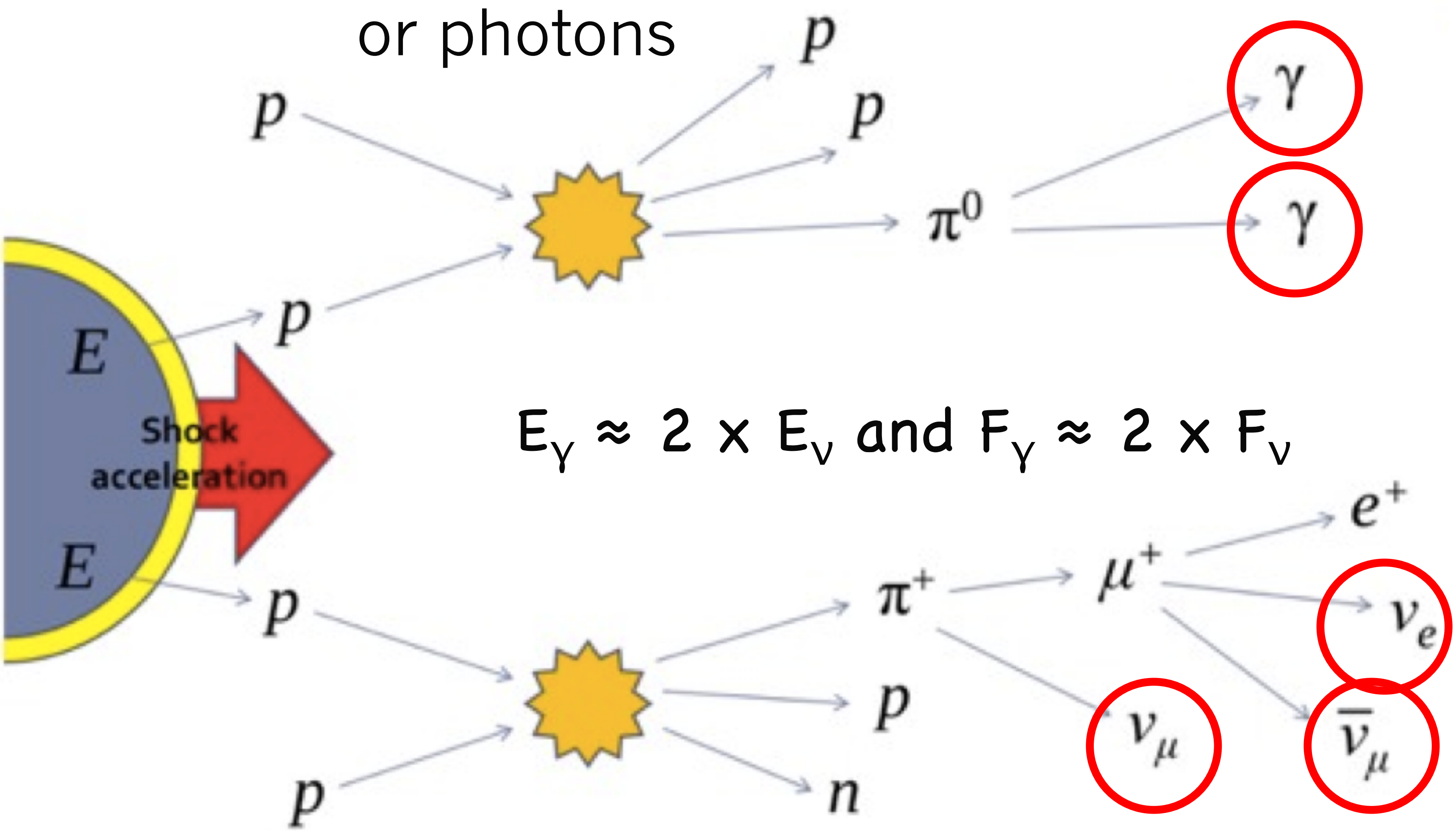
~ 10 MeV (Supernova explosion)



60 TeV – 4 PeV

?

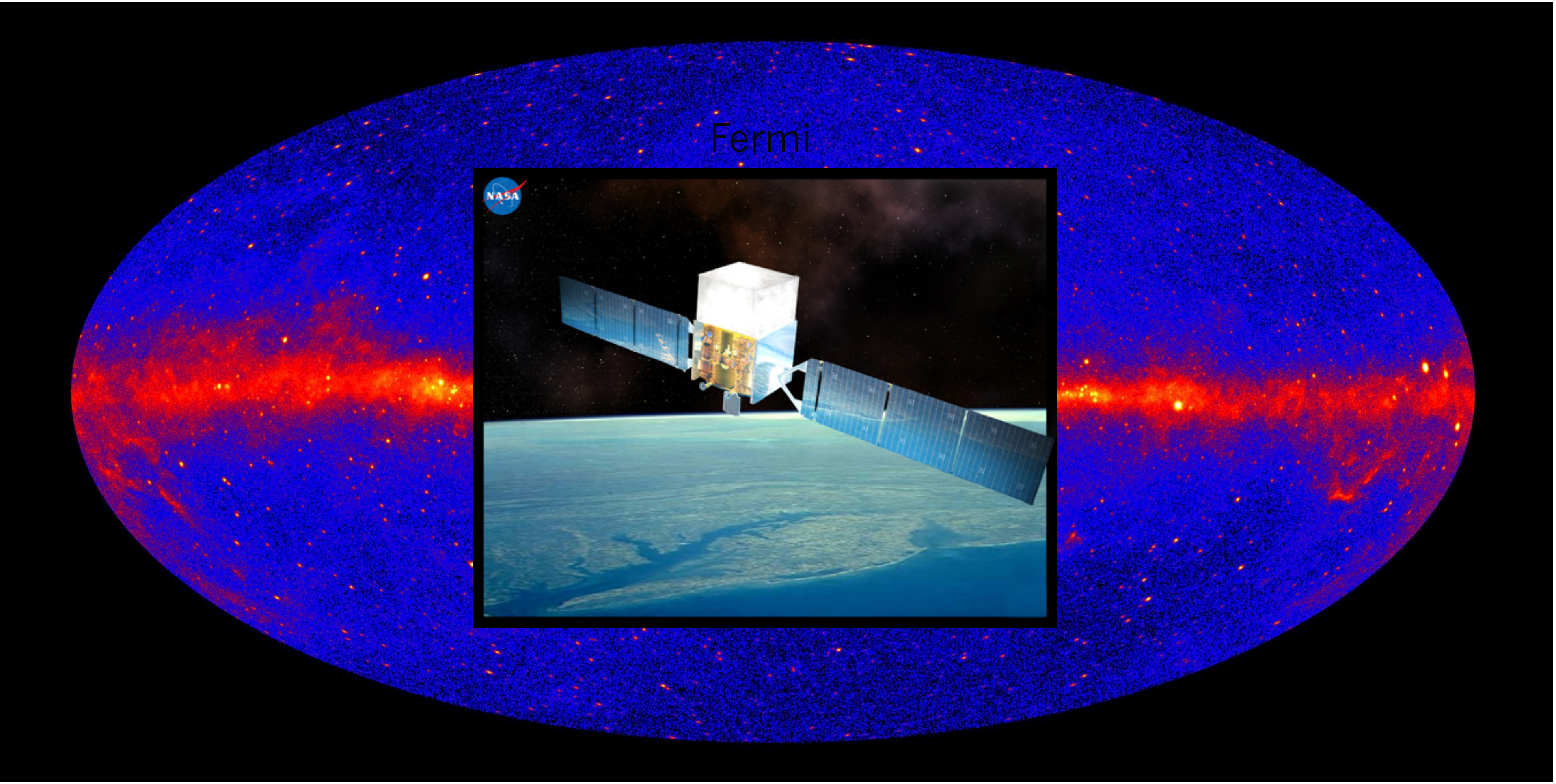
High-energy neutrino physics

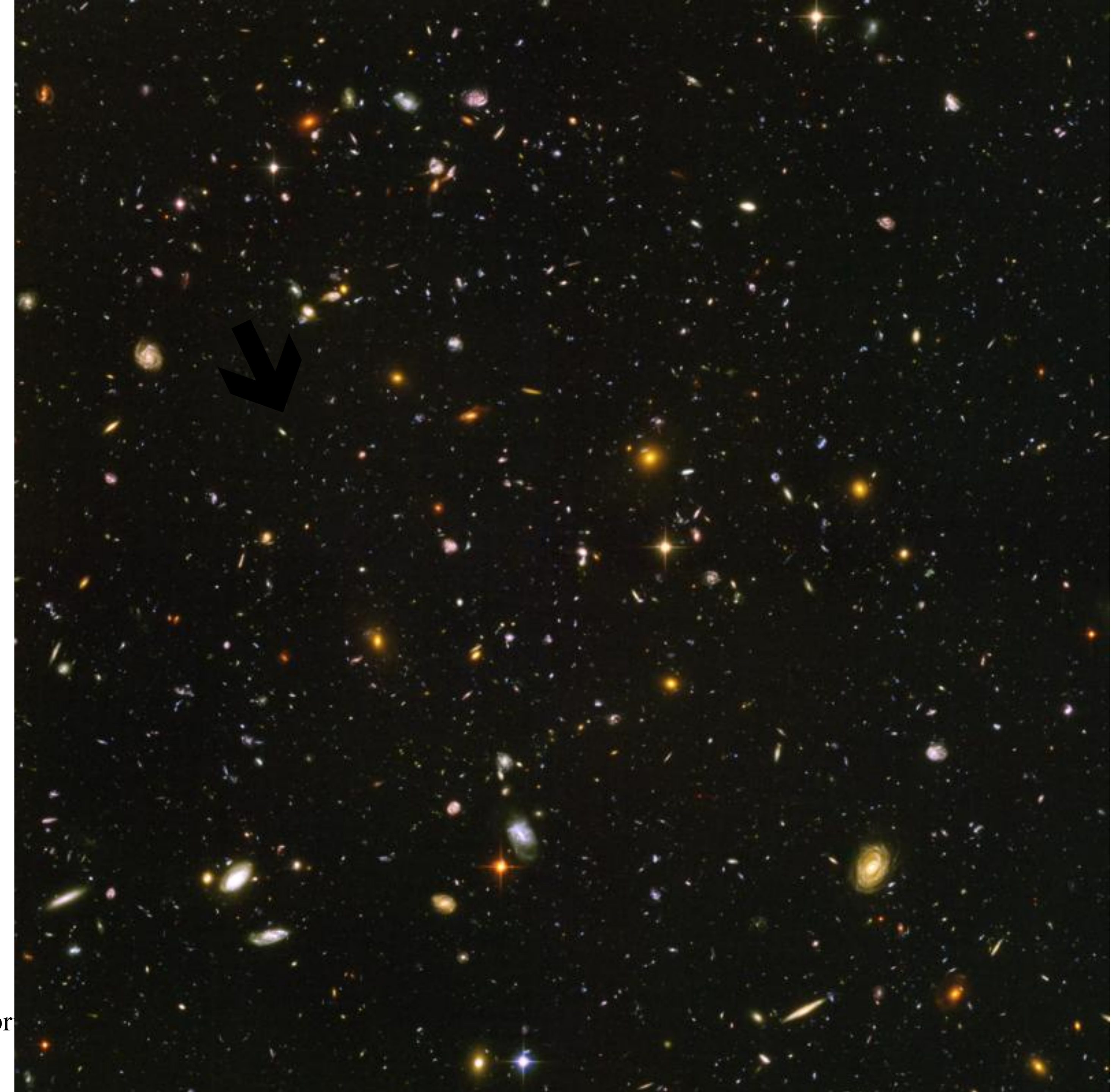


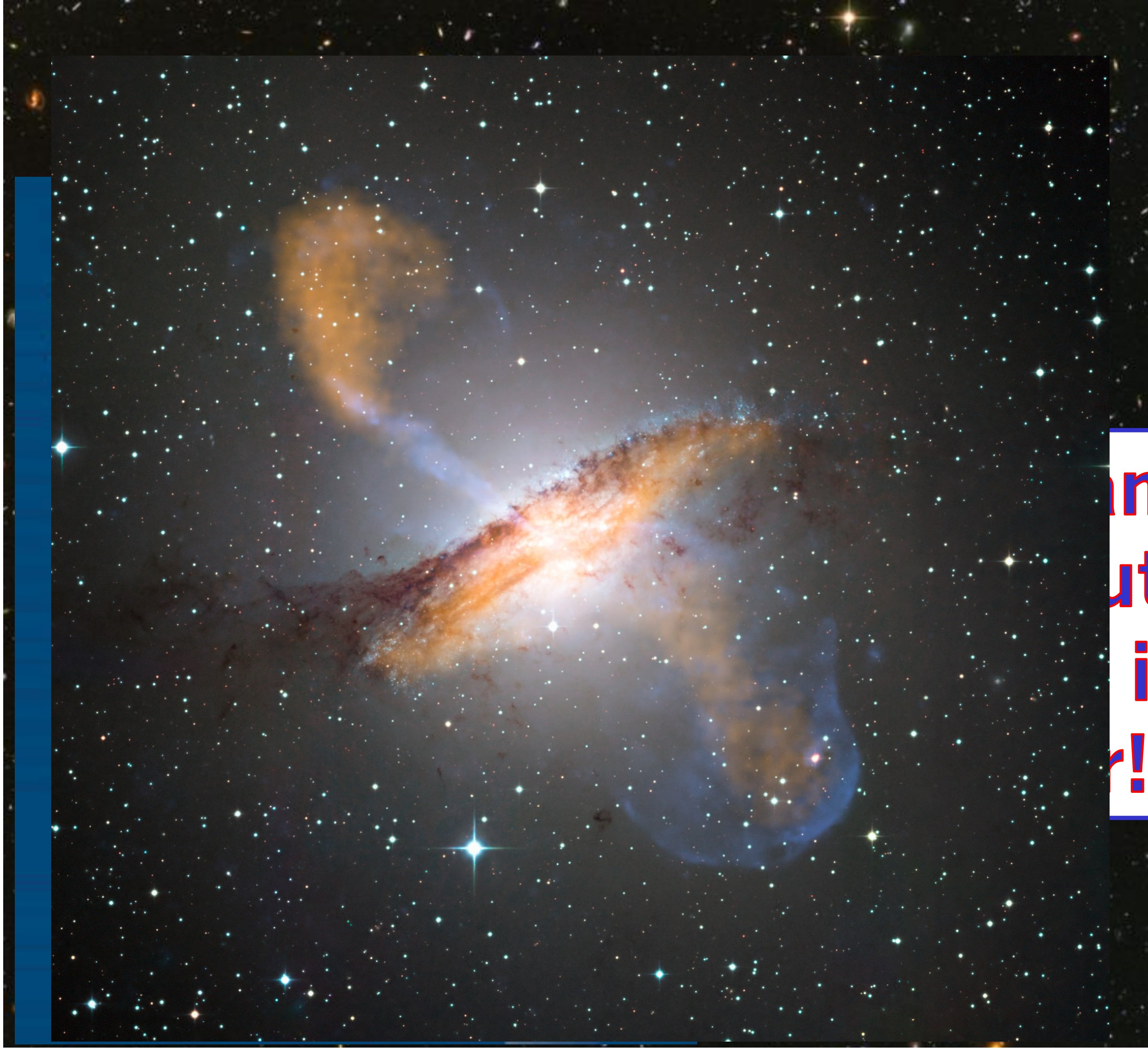
$E_\gamma \approx 2 \times E_\nu$ and $F_\gamma \approx 2 \times F_\nu$

All neutrino sources HAVE to be γ-ray sources!

The γ-ray sky (E > 0.1 GeV)







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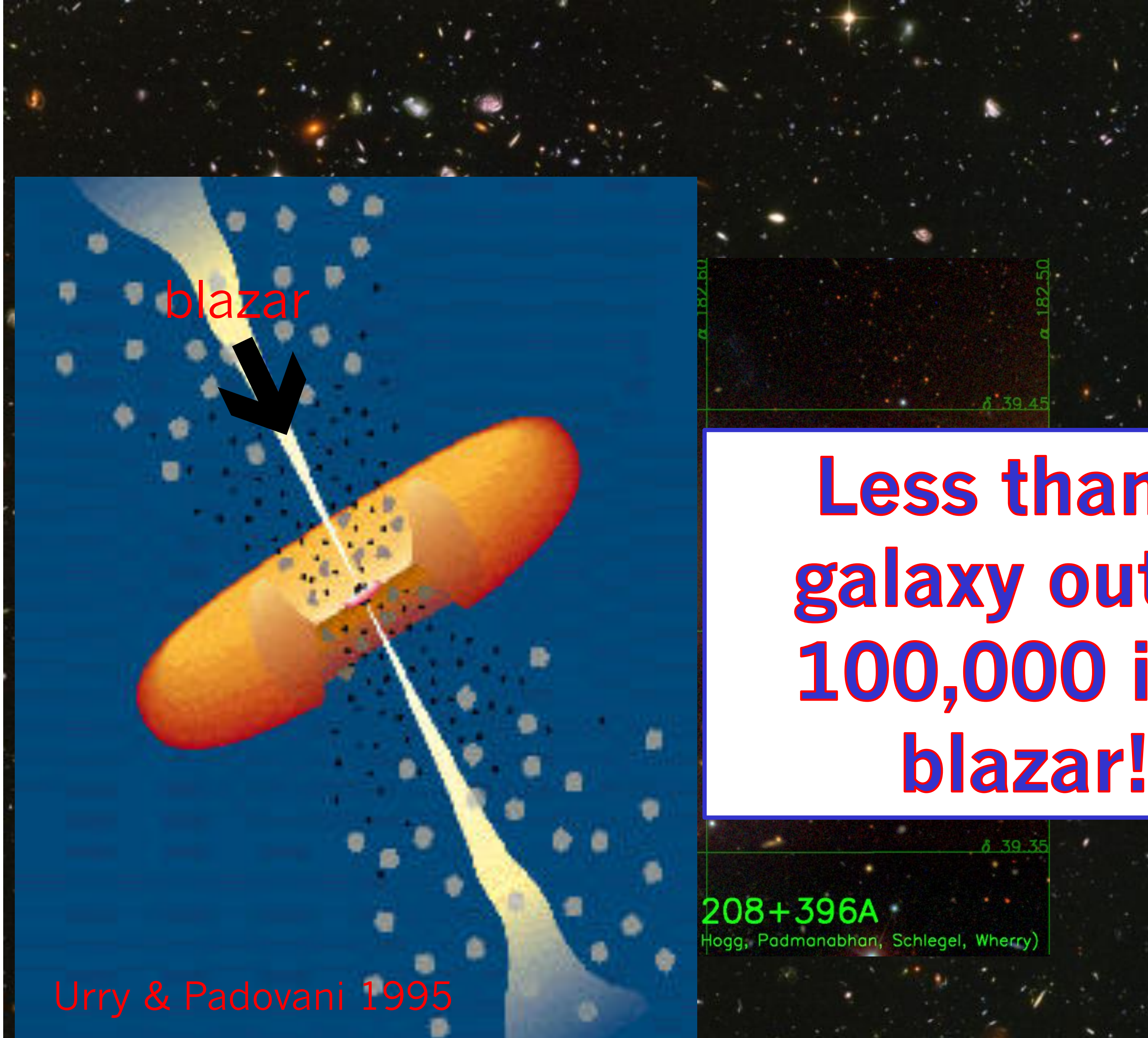
eso0903a. Credit: ESO/WFI (optical); MPIfR/ESO/APEX/A.Weiss et al. (submillimetre); NASA/CXC/CfA/R. Kraft et al. (X-ray)

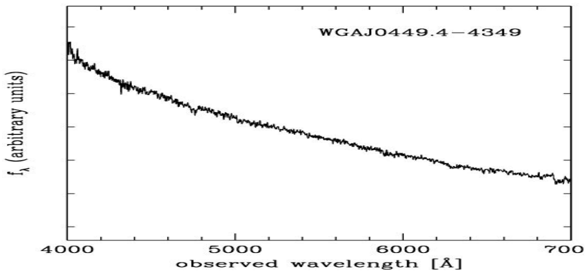


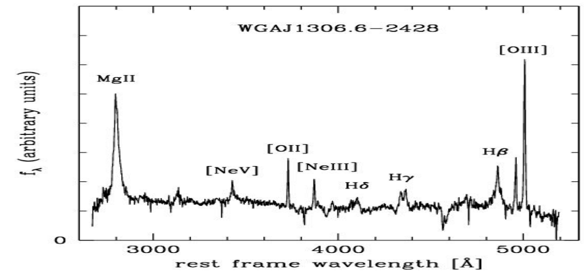
Less than 1 galaxy out of 100,000 is a blazar!

eso0903a. Credit: ESO/WFI (optical); MPIfR/ESO/APEX/A.Weiss et al. (submillimetre); NASA/CXC/CfA/R. Kraft et al. (X-ray)

Blazars

BL Lacertae objects and Flat-Spectrum Radio Quasars



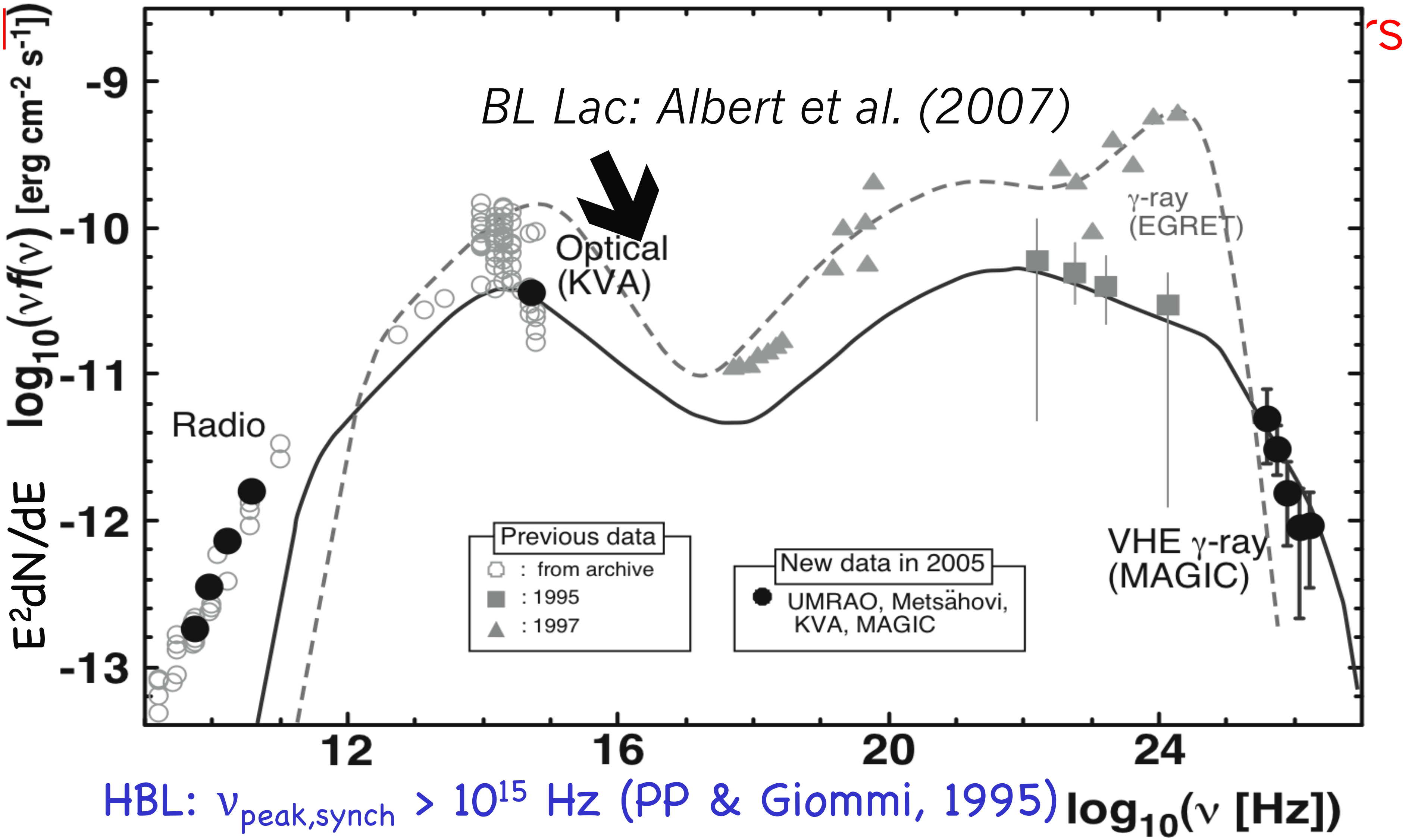


- Smooth, broad, non-thermal continuum (radio to γ-rays)

Sites of very high energy phenomena:
E_{max} ~ 20 TeV (5 x 10^{27} Hz) and v_{max} ~ 0.9998c

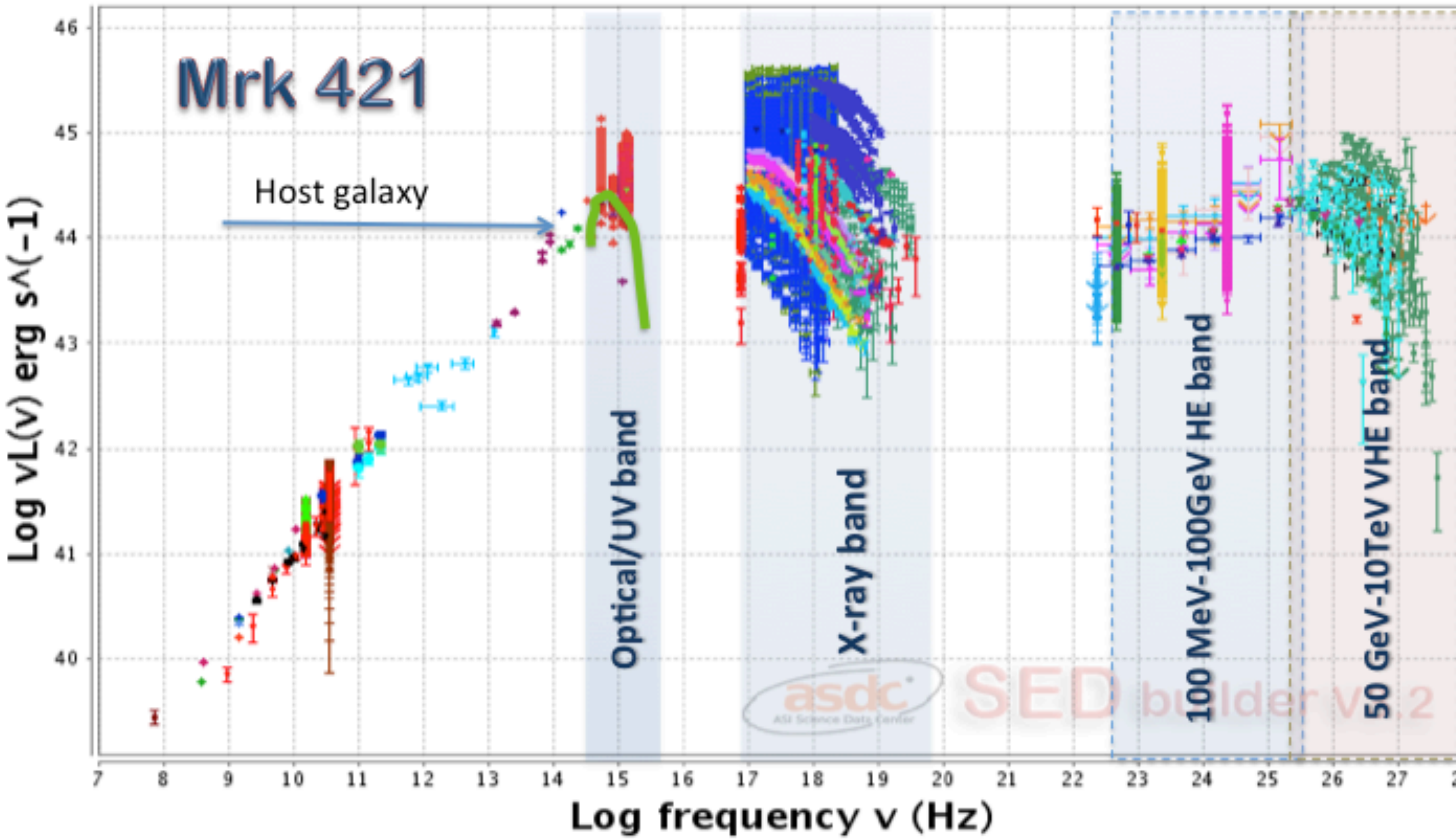
Nature's free accelerators

Blazars



HBL: $\nu_{peak,synch}$ > 10^{15} Hz (PP & Giommi, 1995)

Blazars



Mrk 421
Host galaxy
Optical/UV band
X-ray band
100 MeV-100GeV HE band
50 GeV-10TeV VHE band
Log νL(ν) erg s^(−1)
Log frequency ν (Hz)
46
45
44
43
42
41
40
7
8
9
10
11
12
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14
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asdc
SED builder v.2

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **457,** 3582–3592 (2016)
Advance Access publication 2016 January 27

doi:10.1093/mnras/stw228

Extreme blazars as counterparts of IceCube astrophysical neutrinos

P. Padovani,[1,2★] E. Resconi,[3] P. Giommi,[4,5] B. Arsioli[4,5,6] and Y. L. Chang[4,6]

[1]*European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany*
[2]*Associated to INAF – Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy*
[3]*Physik-Department, Technische Universität München, James-Frank-Str. 1, D-85748 Garching bei München, Germany*
[4]*ASI Science Data Center, via del Politecnico s.n.c., I-00133 Roma Italy*
[5]*ICRANet-Rio, CBPF, Rua Dr. Xavier Sigaud 150, 22290-180 Rio de Janeiro, Brazil*
[6]*ICRA, Dipartimento di Fisica, Piazzale Aldo Moro 5, Sapienza Università di Roma, I-00185 Roma, Italy*

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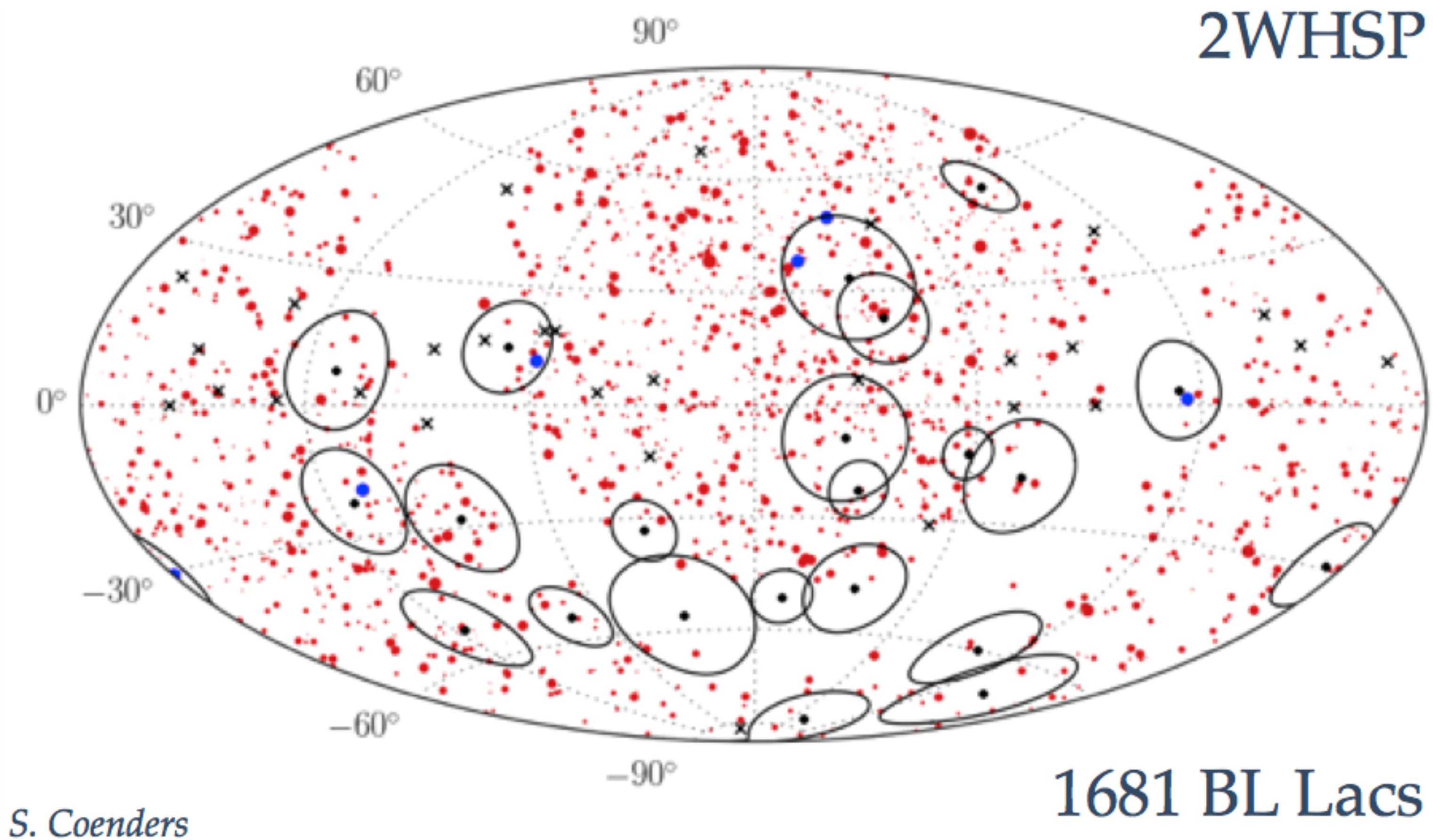
ABSTRACT

We explore the correlation of γ-ray emitting blazars with IceCube neutrinos by using three very recently completed, and independently built, catalogues and the latest neutrino lists. We introduce a new observable, namely the number of neutrino events with at least one γ-ray counterpart, N_ν. In all three catalogues we consistently observe a positive fluctuation of N_ν with respect to the mean random expectation at a significance level of 0.4–1.3 per cent. This applies only to extreme blazars, namely strong, very high energy γ-ray sources of the high energy peaked type, and implies a model-independent fraction of the current IceCube signal ~10–20 per cent. An investigation of the hybrid photon – neutrino spectral energy distributions of the most likely candidates reveals a set of ≈5 such sources, which could be linked to the corresponding IceCube neutrinos. Other types of blazars, when testable, give null correlation results. Although we could not perform a similar correlation study for Galactic sources, we have also identified two (further) strong Galactic γ-ray sources as most probable counterparts of IceCube neutrinos through their hybrid spectral energy distributions. We have reasons to believe that our blazar results are not constrained by the γ-ray samples but by the neutrino statistics, which means that the detection of more astrophysical neutrinos could turn this first hint into a discovery.

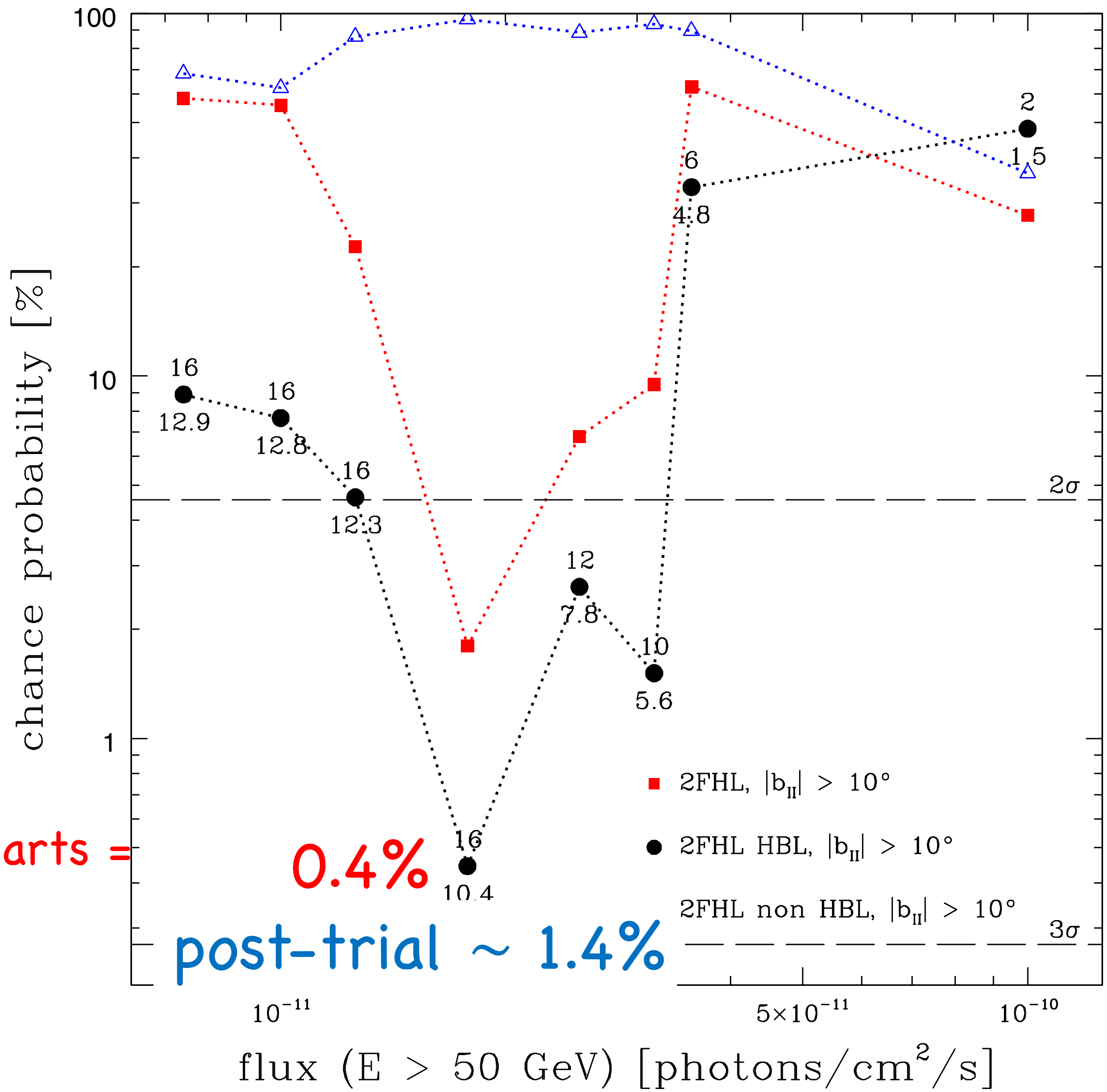
Key words: neutrinos – radiation mechanisms: non-thermal – pulsars: general – BL Lacertae objects: general – gamma-rays: galaxies.

Statistical analysis



PP et al. (2016)

Results: *Fermi*-2FHL



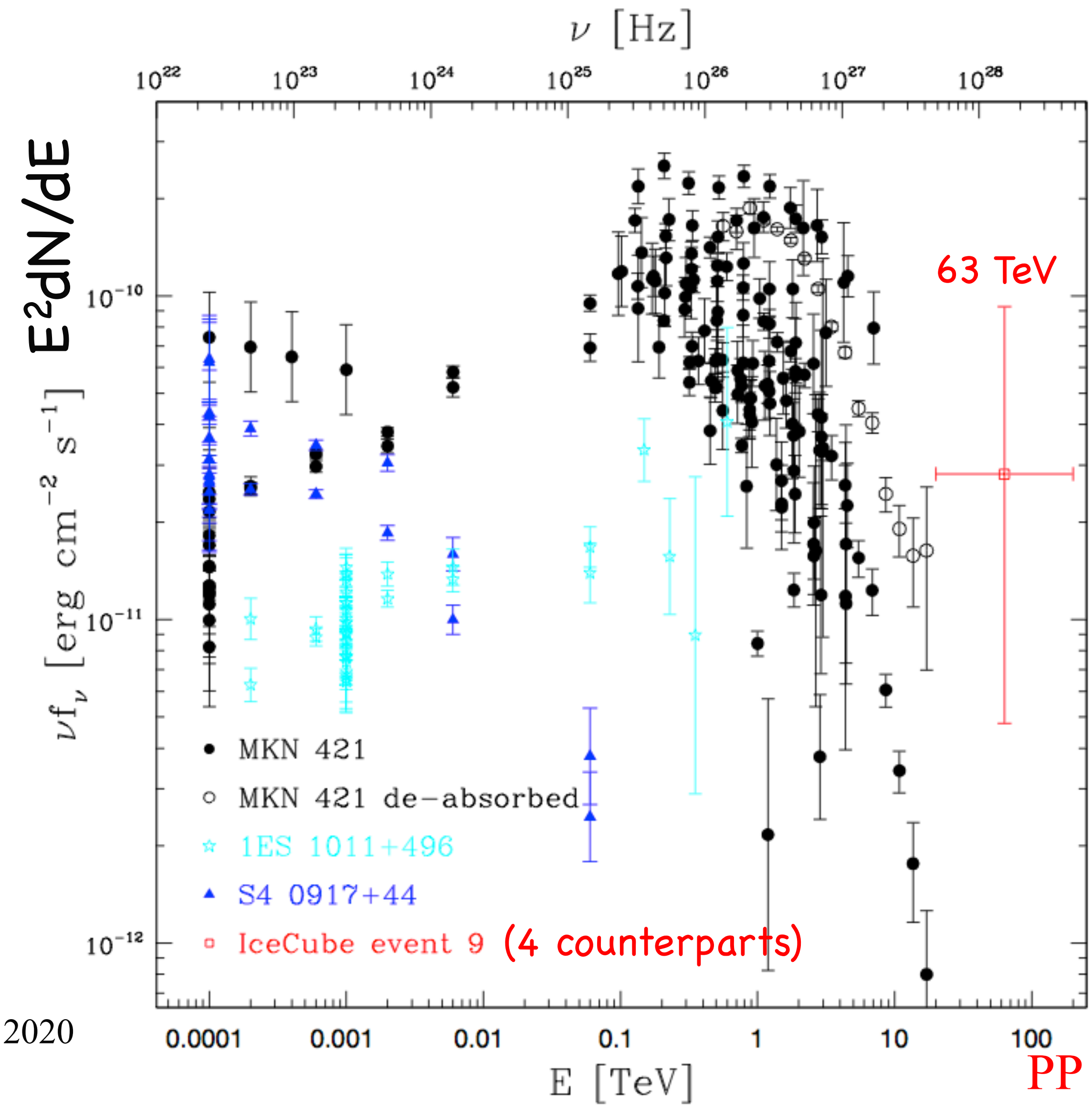
"real" counterparts = 16 – 10.4 ~ 5.6

0.4%

post-trial ~ 1.4%

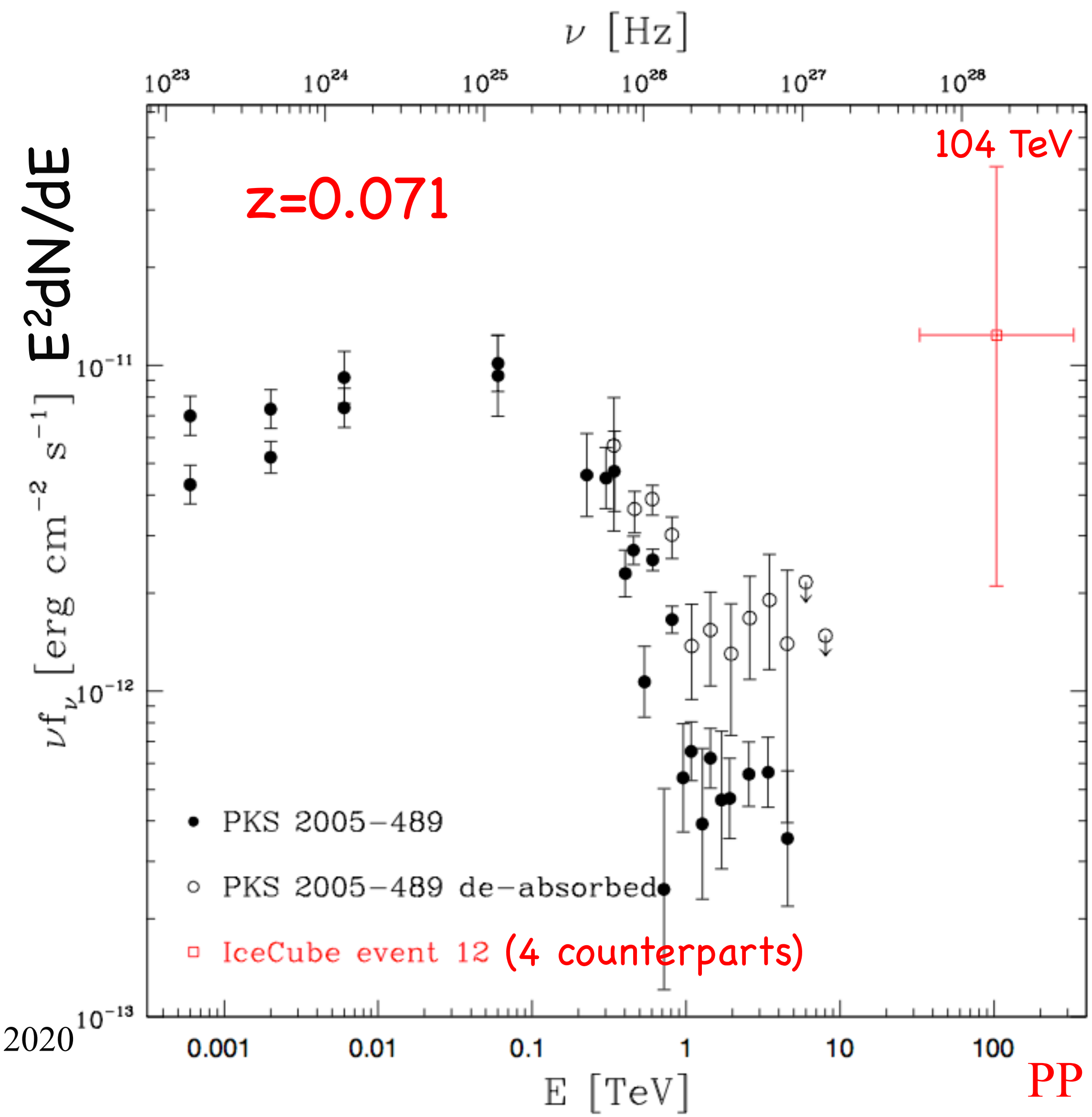
PP et al. (2016)

“Hybrid” spectral energy distribution (SED): MKN 421



PP & Resconi (2014)

"Hybrid" SED: PKS 2005-489



PP & Resconi (2014)

Table 2. 2FHL HBL sources with $F(>50\,\mathrm{GeV}) \geq 1.8 \times 10^{-11}$ photon cm^{-2} s^{-1} and 2WHSP sources with FoM ≥1.0 in one median angular error radius around the positions of the IceCube events. The counterparts of the most probable matches are indicated in boldface.

ID	2WHSP name	2FHL name	Common name	offset (deg)	z	FoM	flux[a]	Comments
9	J091037.0+332924	J0910.4+3327	Ton 1015	11.4	0.350	2.0	0.283	positional match (PR14)
	J091552.4+293324	J0915.9+2931	B2 0912+29	11.2	>0.19	2.5	0.324	positional match (PR14)
	J101504.1+492600	J1015.0+4926	**1ES 1011+496**	15.9	0.212	4.0	1.62	most probable match (PR14)
	J110427.3+381231	J1104.4+3812	**MKN 421**	12.8	0.031	57.5	12.4	most probable match (PR14)
10	J235907.8−303740		**H 2356−309**	4.7	0.165	2.0	0.69[b]	most probable match (PR14)
11	J095302.7−084018	J0952.9−0841	1RXS J095303.4−084003	7.0	–	0.8	0.385	positional match (PR14)
	J102243.7−011302	J1022.7−0112	1RXS J102244.2−011257	7.7	>0.36	1.3	0.171	positional match (PR14)
	J102658.5−174858	J1027.0−1749	1RXS J102658.5−174905	9.0	0.267	1.0	0.196	most probable match?
12	J193656.1−471950	J1936.9−4721	PMN J1936−4719	5.6	0.265	1.3	0.240	most probable match?[c]
	J195502.8−564028	J1954.9−5641	1RXS J195503.1−56403	4.2	–	1.0	0.127	positional match
	J195945.6−472519	J1959.6−4725	SUMSS J195945−472519	5.9	–	1.0	0.183	positional match
	J200925.3−484953	J2009.4−4849	PKS 2005−489	5.6	0.071	10.0	0.970	positional match (PR14)
14	J171405.4−202752	J1713.9−2027	1RXS J171405.2−202747	9.9	–	1.3	0.275	most probable match?
17	J155543.0+111124	J1555.7+1111	**PG 1553+113**	8.9	–	7.9	4.20	most probable match (PR14)
19	J050657.8−543503	J0506.9−5434	1RXS J050656.8−543456	5.1	>0.26	1.0	0.131	positional match (PR14)
	J054357.2−553207	J0543.9−5533	1RXS J054357.3−553206	6.4	–	2.5	0.527	positional match[d]
20	J014347.3−584551	J0143.8−5847	SUMSS J014347−584550	10.1	–	2.0	0.161	positional match[e]
	J035257.4−683117	J0352.7−6831	PKS 0352−686	7.6	0.087	2.0	0.228	positional match (PR14)
22	J191744.8−192131	J1917.7−1921	**1H1914−194**	4.8	0.137	1.6	0.814	most probable match (PR14)
		J1921.9−1607	PMN J1921−1607	6.7	–	–	0.397	most probable match?(PR14)[f]
	J195814.9−301111	J1958.3−3011	1RXS J195815.6−30111	9.7	0.119	1.3	0.282	most probable match?(PR14)[f]
39		J0622.4−2604	PMN J0622−2605	12.8	0.414	–	0.258	positional match
	J063059.5−240646	J0631.0−2406	1RXS J063059.7−240636	10.0	–	1.6	0.322	positional match
	J064933.6−313920	J0649.6−3139	1RXS J064933.8−31391	14.2	–	0.8	0.225	most probable match?
40	J102356.1−433601		SUMSS J102356−433600	9.7	–	2.5	2.08[b]	most probable match?
41	J041652.4+010523	J0416.9+0105	**1ES 0414+009**	2.9	0.287	3.2	0.269	most probable match
46	J094709.5−254100		1RXS J094709.2−254056	4.7	–	1.0		positional match
	J102658.5−174858[h]	J1027.0−1749	1RXS J102658.5−174905	7.4	0.267	1.0	0.196	most probable match?
48	J144037.8−384655	J1440.7−3847	1RXS J144037.4−38465	8.0	–	1.3	0.184	positional match
51	J054030.0+582338	J0540.5+5822	GB6 J0540+5823	4.8	–	1.6	0.187	positional match
	J060200.4+531600	J0601.9+5317	GB6 J0601+5315	1.3	–	1.0	0.101	positional match

≈ 5 "most probable" matches (plus ≈ 5 possible ones) out of 51 IceCube neutrinos → Blazar (HBL) component at 10-20%

Notes. [a]f (E >50 GeV) in units of 10^{-10} ph cm^{-2} s^{-1}.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **448,** 2412–2429 (2015) doi:10.1093/mnras/stv179

Photohadronic origin of γ-ray BL Lac emission: implications for IceCube neutrinos

M. Petropoulou,[1†] S. Dimitrakoudis,[2] P. Padovani,[3] A. Mastichiadis[4] and E. Resconi[5]

[1]*Department of Physics and Astronomy, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907, USA*
[2]*Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, GR 15236 Penteli, Greece*
[3]*European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany*
[4]*Department of Physics, University of Athens, Panepistimiopolis, GR 15783 Zografos, Greece*
[5]*Technische Universität München, James-Frank-Str. 1, D-85748 Garching bei München, Germany*

Accepted 2015 January 23. Received 2015 January 14; in original form 2014 December 4

ABSTRACT

The recent IceCube discovery of 0.1–1 PeV neutrinos of astrophysical origin opens up a new era for high-energy astrophysics. Although there are various astrophysical candidate sources, a firm association of the detected neutrinos with one (or more) of them is still lacking. A recent analysis of plausible astrophysical counterparts within the error circles of IceCube events showed that likely counterparts for nine of the IceCube neutrinos include mostly BL Lacs, among which Mrk 421. Motivated by this result and a previous independent analysis on the neutrino emission from Mrk 421, we test the BL Lac–neutrino connection in the context of a specific theoretical model for BL Lac emission. We model the spectral energy distribution (SED) of the BL Lacs selected as counterparts of the IceCube neutrinos using a one-zone leptohadronic model and mostly nearly simultaneous data. The neutrino flux for each BL Lac is self-consistently calculated, using photon and proton distributions specifically derived for every individual source. We find that the SEDs of the sample, although different in shape and flux, are all well fitted by the model using reasonable parameter values. Moreover, the model-predicted neutrino flux and energy for these sources are of the same order of magnitude

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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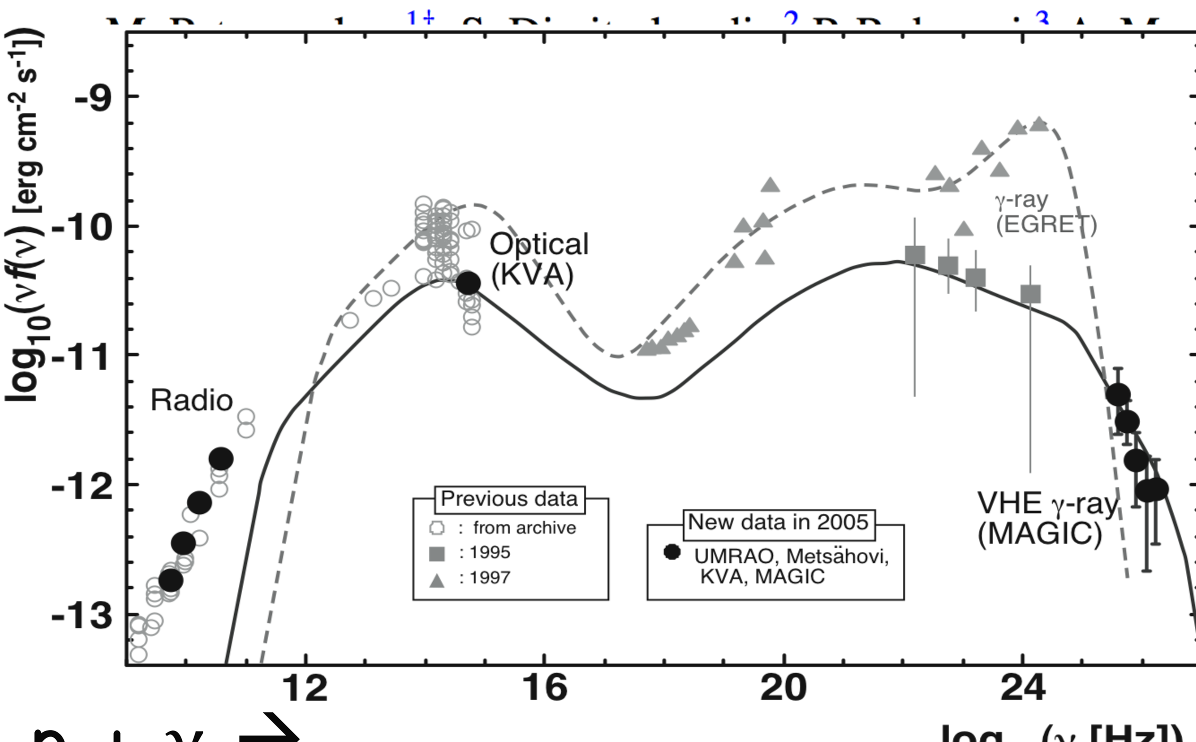
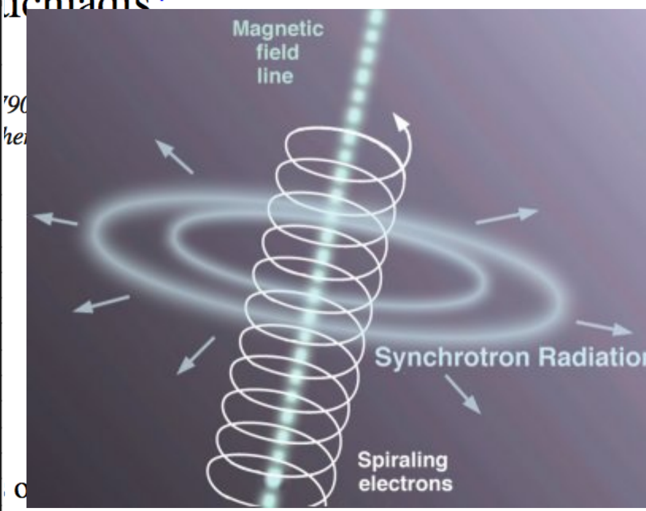
Photohadronic origin of γ-ray BL Lac emission: implications for IceCube neutrinos





$p + \gamma \rightarrow$

$\pi^0 \rightarrow 2\gamma$

(hadronic)

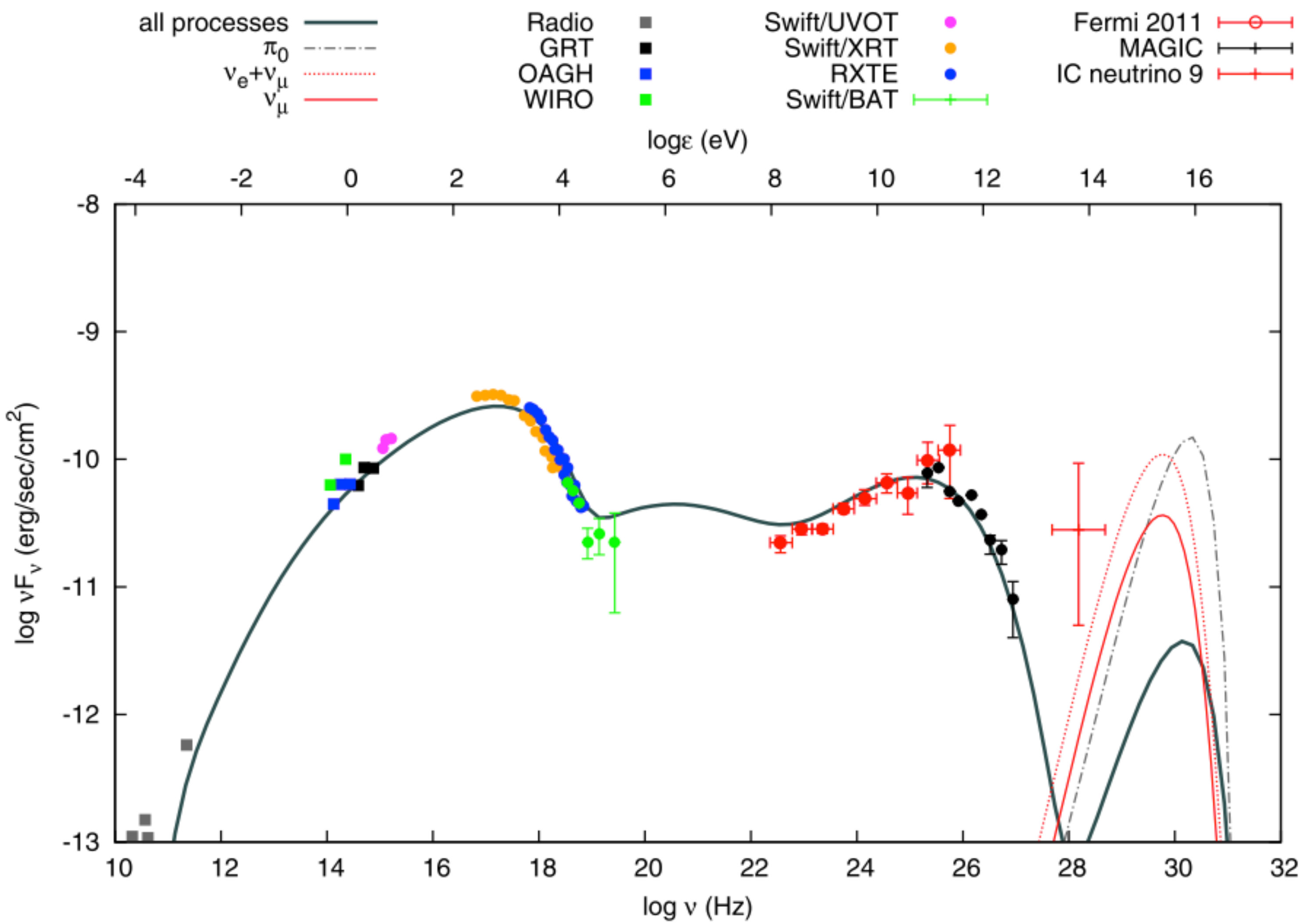
Inverse Compton emission:

$e^- + \gamma_{low\text{-}energy} \rightarrow \gamma_{high\text{-}energy}$

(leptonic)

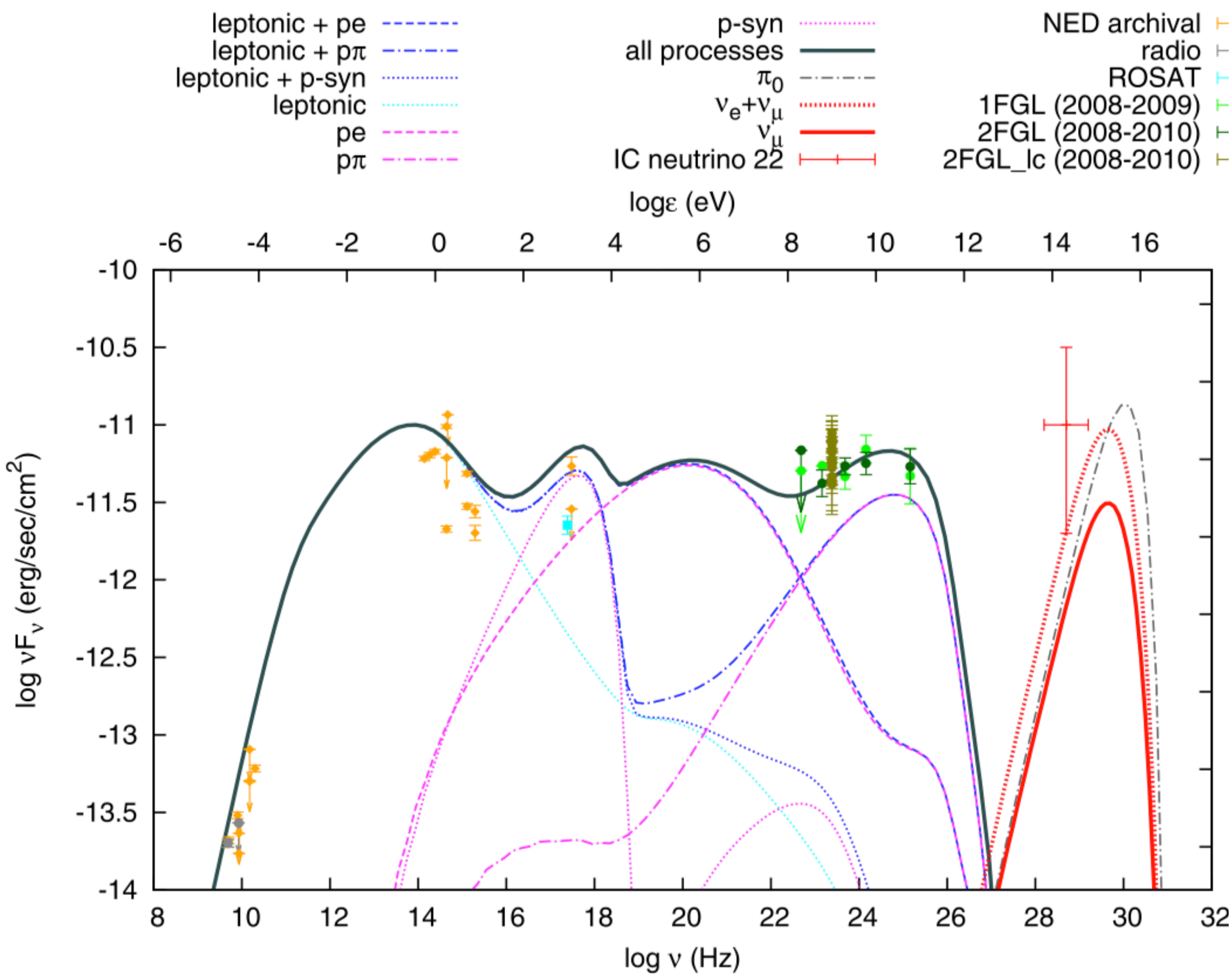
...various astrophysical candidate sources, ...r more) of them is still lacking. A recent ...in the error circles of IceCube events ...be neutrinos include mostly BL Lacs, ...a previous independent analysis on the ...-neutrino connection in the context of a specific theoretical model for BL Lac emission. We model the spectral energy distribution (SED) of the BL Lacs selected as counterparts of the IceCube neutrinos using a one-zone leptohadronic model and mostly nearly simultaneous data. The neutrino flux for each BL Lac is self-consistently calculated, using photon and proton distributions specifically derived for every individual source. We find that the SEDs of the sample, although different in shape and flux, are all well fitted by the model using reasonable parameter values. Moreover, the model-predicted neutrino flux and energy for these sources are of the same order of magnitude

MKN 421



all processes
π_0
$\nu_e+\nu_\mu$
ν_μ
Radio
GRT
OAGH
WIRO
Swift/UVOT
Swift/XRT
RXTE
Swift/BAT
Fermi 2011
MAGIC
IC neutrino 9
logε (eV)
-4 -2 0 2 4 6 8 10 12 14 16
-8 -9 -10 -11 -12 -13
log νF$_\nu$ (erg/sec/cm^2)
10 12 14 16 18 20 22 24 26 28 30 32
log ν (Hz)

1H 1914–194


leptonic + pe
leptonic + pπ
leptonic + p-syn
leptonic
pe
pπ
p-syn
all processes
π0
νe+νμ
νμ
IC neutrino 22
NED archival
radio
ROSAT
1FGL (2008-2009)
2FGL (2008-2010)
2FGL_lc (2008-2010)
logε (eV)
-6
-4
-2
0
2
4
6
8
10
12
14
16
-10
-10.5
-11
-11.5
-12
-12.5
-13
-13.5
-14
log νFν (erg/sec/cm2)
8
10
12
14
16
18
20
22
24
26
28
30
32
log ν (Hz)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **452,** 1877–1887 (2015) doi:10.1093/mnras/stv1467

A simplified view of blazars: the neutrino background

P. Padovani,[1,2★] M. Petropoulou,[3†] P. Giommi[4,5] and E. Resconi[6]

[1]*European Southern Observatory, Karl-Schwarzschild-Str 2, D-85748 Garching bei München, Germany*
[2]*Associated to INAF - Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy*
[3]*Department of Physics and Astronomy, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907, USA*
[4]*ASI Science Data Center, via del Politecnico s.n.c., I-00133 Roma, Italy*
[5]*ICRANet-Rio, CBPF, Rua Dr Xavier Sigaud 150, 22290-180 Rio de Janeiro, Brazil*
[6]*Technische Universität München, Physik-Department, James-Frank-Str 1, D-85748 Garching bei München, Germany*

Accepted 2015 June 30. Received 2015 June 26; in original form 2015 May 18

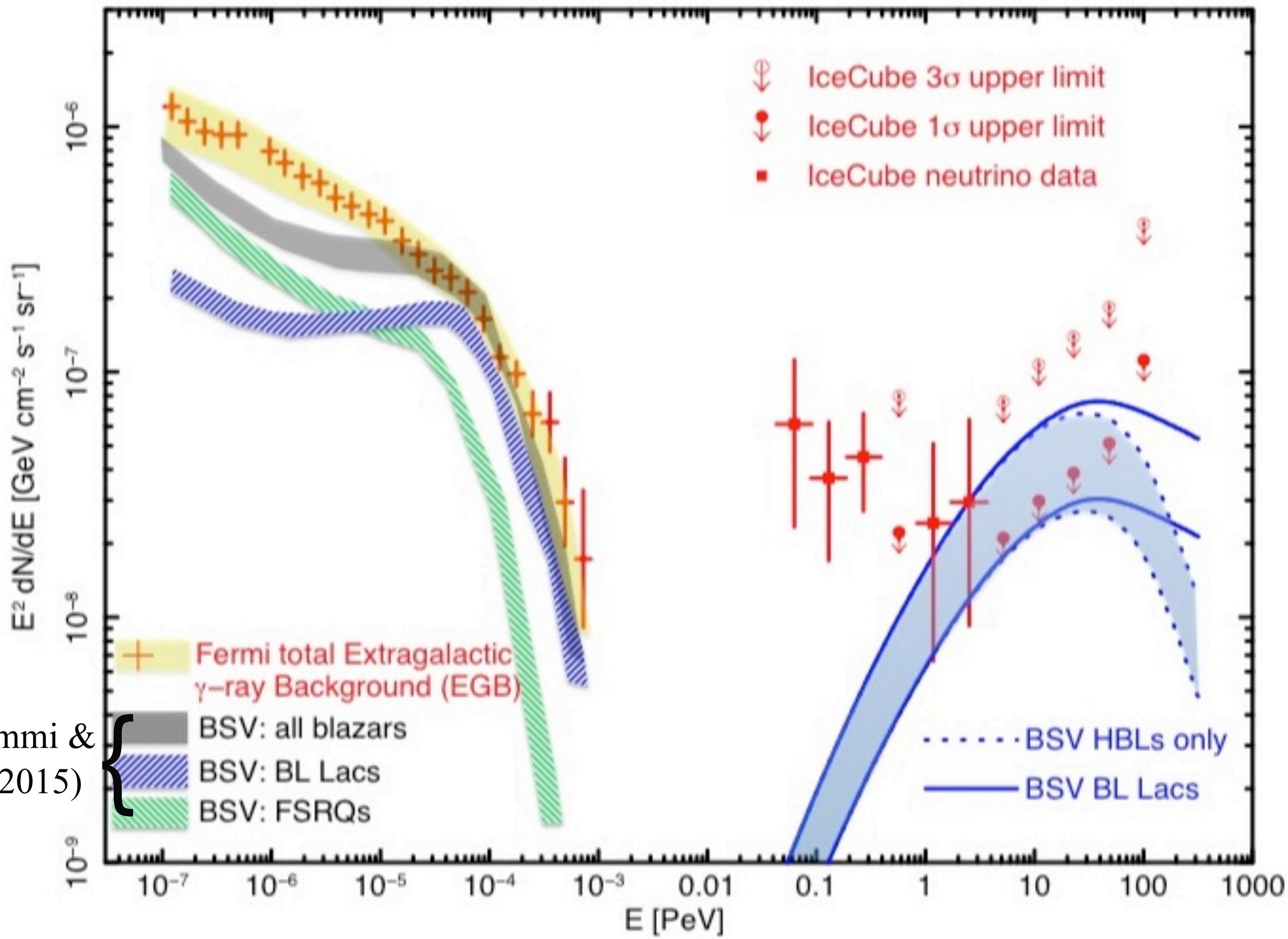
Can BL Lacs explain the neutrino background?

February 19, 2020

ABSTRACT

Blazars have been suggested as possible neutrino sources long before the recent IceCube discovery of high-energy neutrinos. We re-examine this possibility within a new framework built upon the *blazar simplified view* and a self-consistent modelling of neutrino emission from individual sources. The former is a recently proposed paradigm that explains the diverse statistical properties of blazars adopting minimal assumptions on blazars' physical and geometrical properties. This view, tested through detailed Monte Carlo simulations, reproduces the main features of radio, X-ray, and γ-ray blazar surveys and also the extragalactic γ-ray background at energies $\gtrsim$10 GeV. Here, we add a hadronic component for neutrino production and estimate the neutrino emission from BL Lacertae objects as a class, 'calibrated' by fitting the spectral energy distributions of a preselected sample of such objects and their (putative) neutrino spectra. Unlike all previous papers on this topic, the neutrino background is then derived by summing up at a given energy the fluxes of each BL Lac in the simulation, all characterized by their own redshift, synchrotron peak energy, γ-ray flux, etc. Our main result is that BL Lacs as a class can explain the neutrino background seen by IceCube above ~0.5 PeV while they only contribute ~10 per cent at lower energies, leaving room to some other population(s)/physical mechanism. However, one cannot also exclude the possibility that individual BL Lacs still make a contribution at the ≈20 per cent level to the IceCube low-energy events. Our scenario makes specific predictions, which are testable in the next few years.

The big picture



Giommi & PP (2015)

Towards an IceCube direct detection: IceCube-170922A

Various evidence (statistical, theoretical, and population-related) pointing to blazars as neutrino sources!
But no "smoking gun"

Towards an IceCube direct detection: IceCube-170922A

Gamma-ray Coordinates Network

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09:26 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of Maryland) report on behalf of the IceCube Collaboration (http://ic

On 22 Sep, … origin. T
event was … erating
state. EHE … ses the
detector v

After the
sophistica

Date: 22 S
Time: 20:5
RA: 77.43
Dec: 5.72

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu

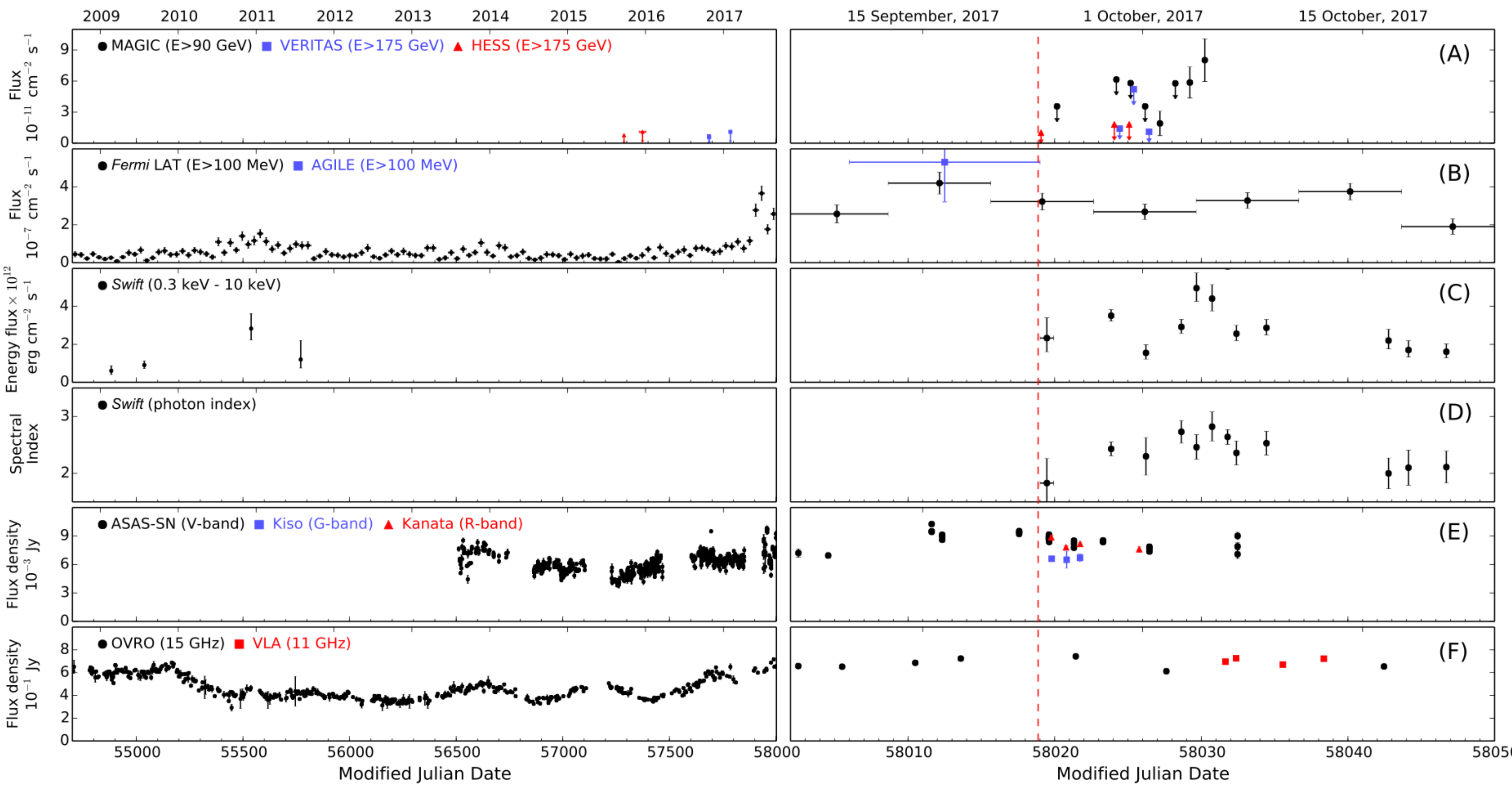
Various evidence (statistical, theoretical, and population-related) pointing to blazars as neutrino sources!

But no "smoking gun"

E ~ 290 TeV

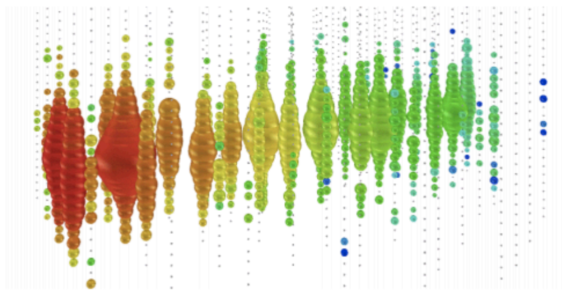
Towards an IceCube direct detection: IceCube-170922A

The neutrino–γ-ray connection. 1. the Sept. 2017 alert

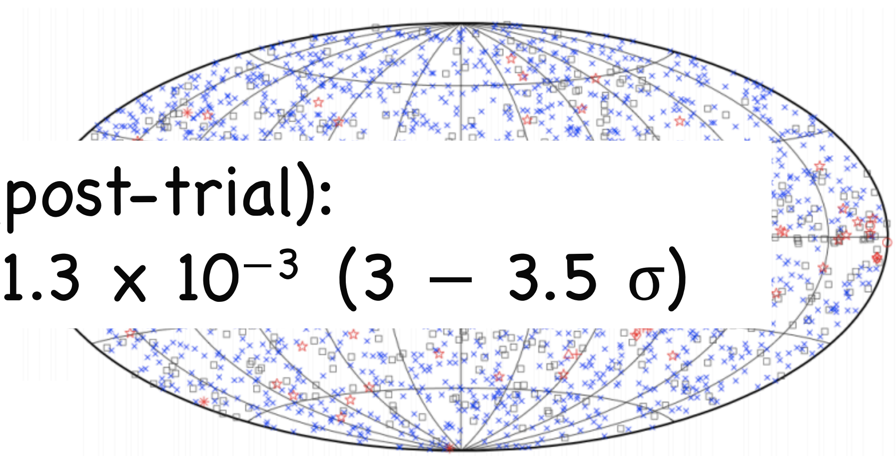


IceCube collaboration et al., 2018

The neutrino–γ-ray connection. 2. the Sept. 2017 alert

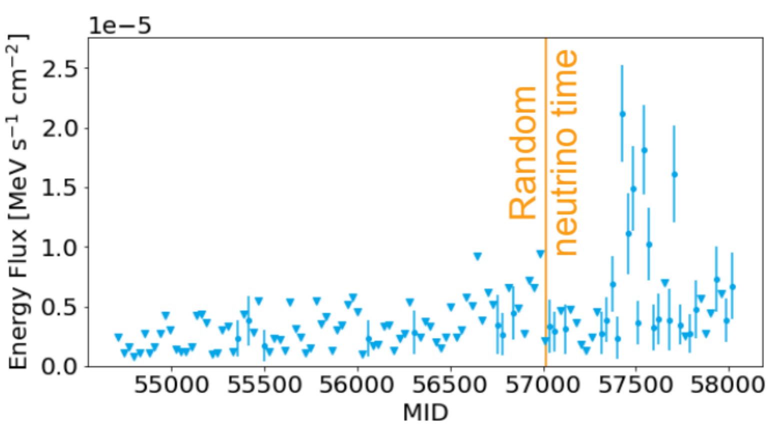


Step I: Draw a random neutrino from a representative sample of high-energy muon-track events



coincidence probability (post-trial):

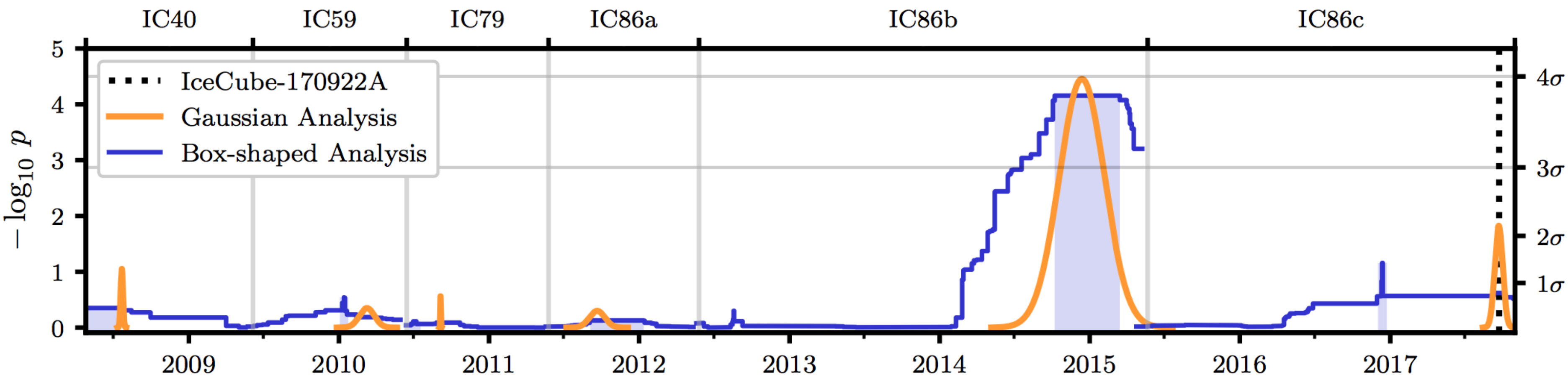
p–value ~ $2.5 \times 10^{-4} - 1.3 \times 10^{-3}$ (3 – 3.5 σ)



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

IceCube collaboration et al., 2018

The Oct. 2014 – Feb. 2015 neutrino flare



13±5 neutrinos over 110 (+35,−24) days

energy range (68%): 32 TeV - 3.6 PeV

coincidence probability (post-trial):
p−value ~ 2×10^{-4} (3.5 σ)

IceCube collaboration, 2018

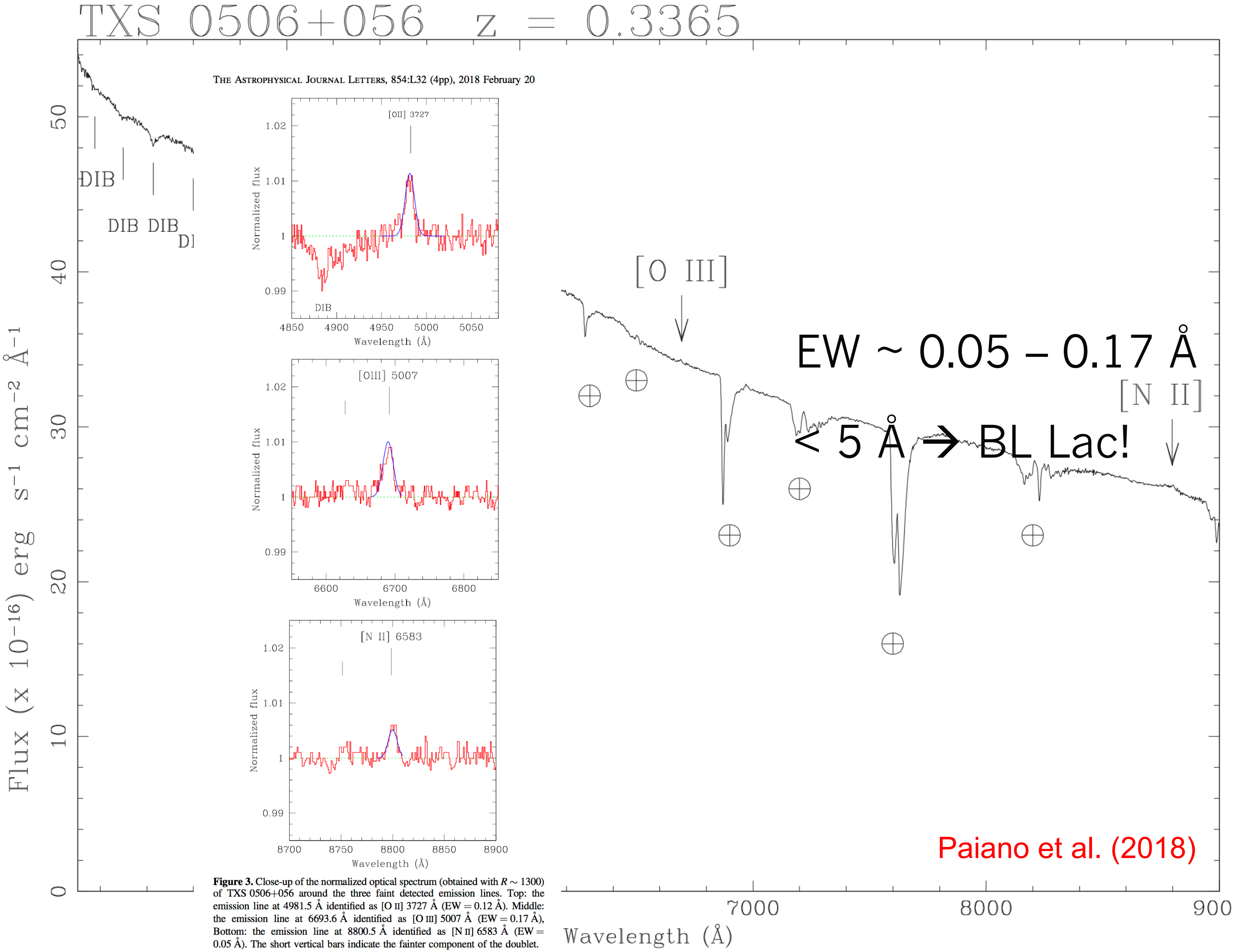
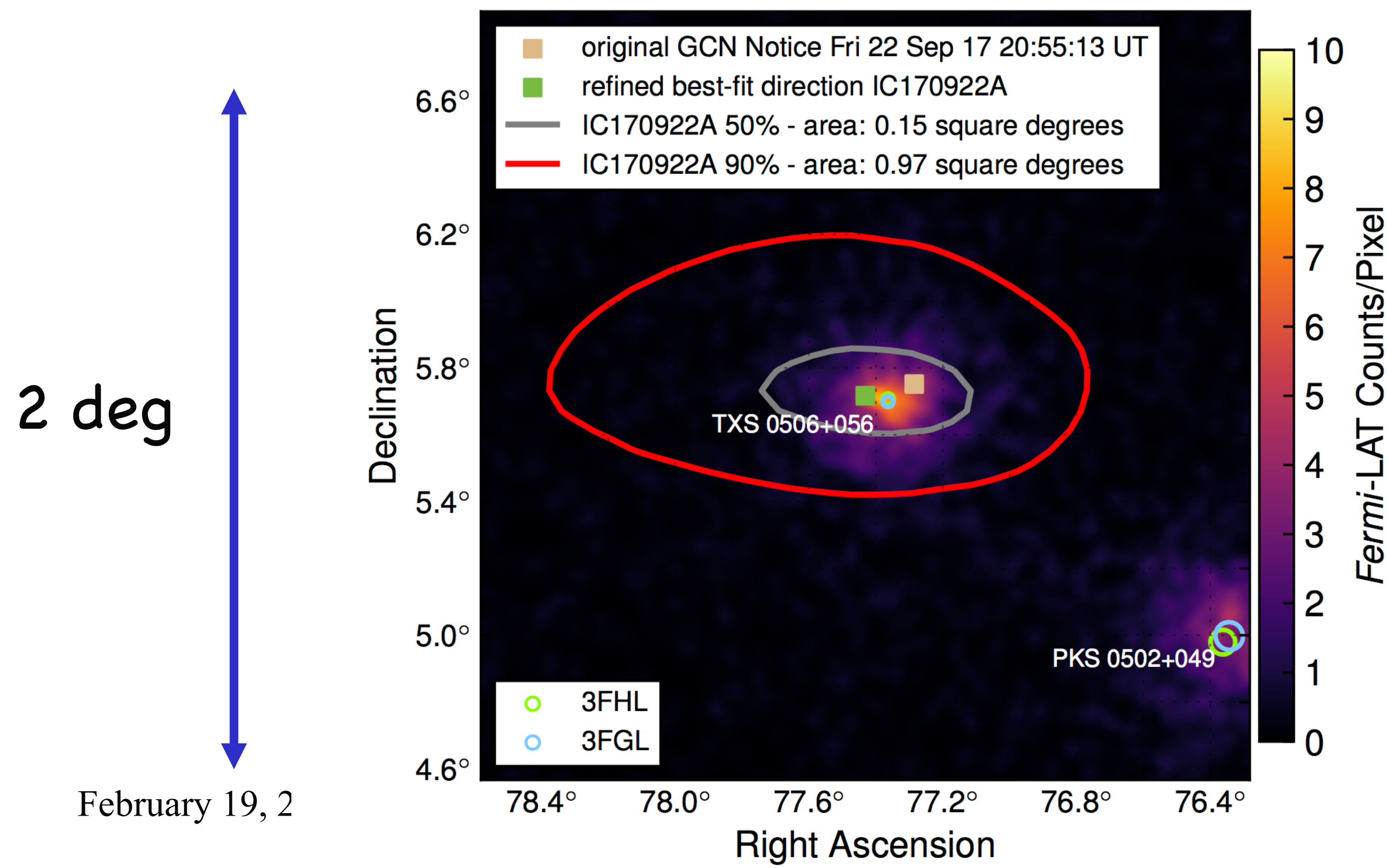


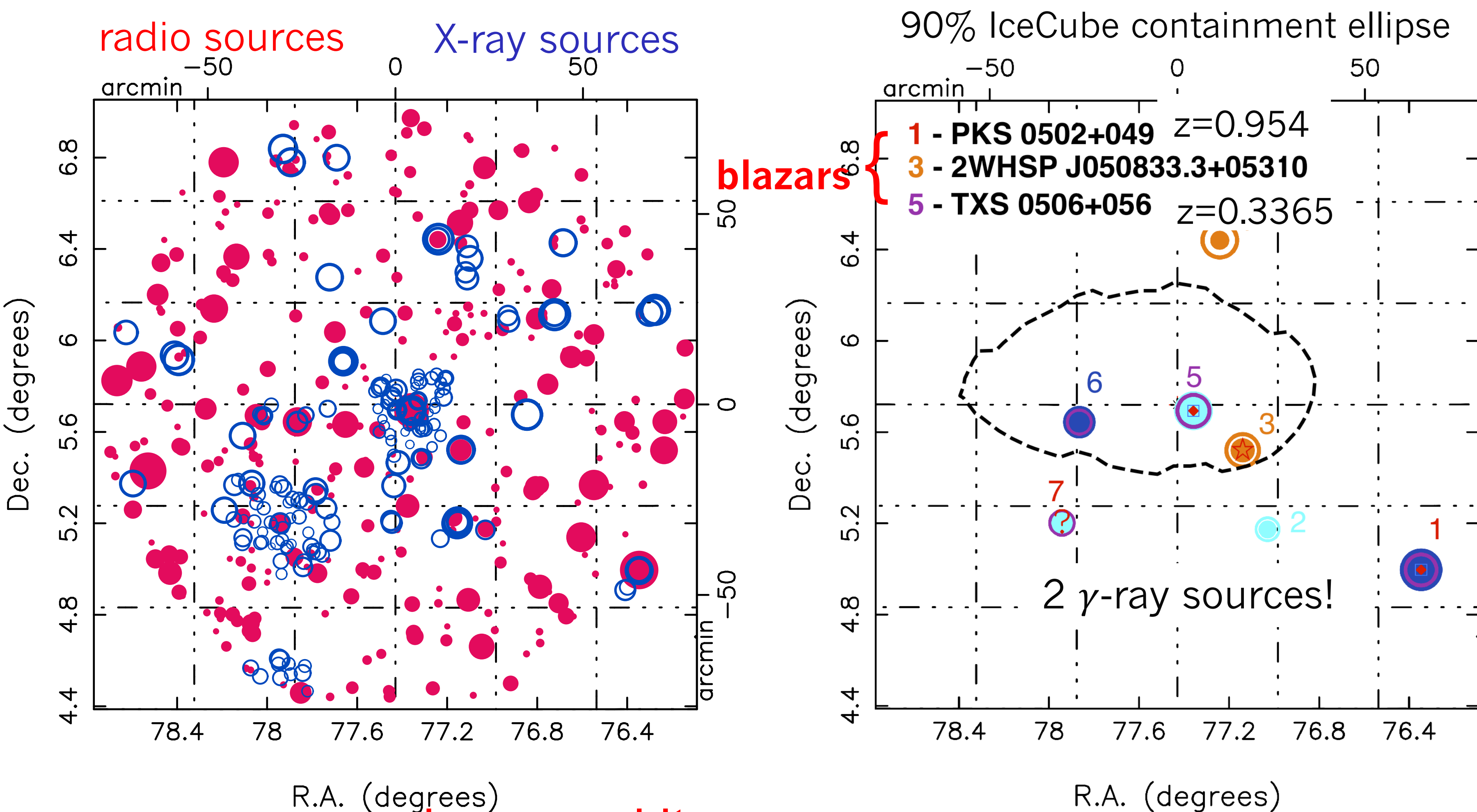
Figure 3. Close-up of the normalized optical spectrum (obtained with $R \sim 1300$) of TXS 0506+056 around the three faint detected emission lines. Top: the emission line at 4981.5 Å identified as [O II] 3727 Å (EW = 0.12 Å). Middle: the emission line at 6693.6 Å identified as [O III] 5007 Å (EW = 0.17 Å), Bottom: the emission line at 8800.5 Å identified as [N II] 6583 Å (EW = 0.05 Å). The short vertical bars indicate the fainter component of the doublet.

Open astronomical issues

Relatively large *Fermi* Point Spread Function (response to a point source): ~ 2.8 deg [95% containment] at E = 1 GeV



Dissecting the region around IceCube-170922A



www.openuniverse.asi.it

PP, Giommi, Resconi, et al. (2018)

γ-ray activity in the area. 1.

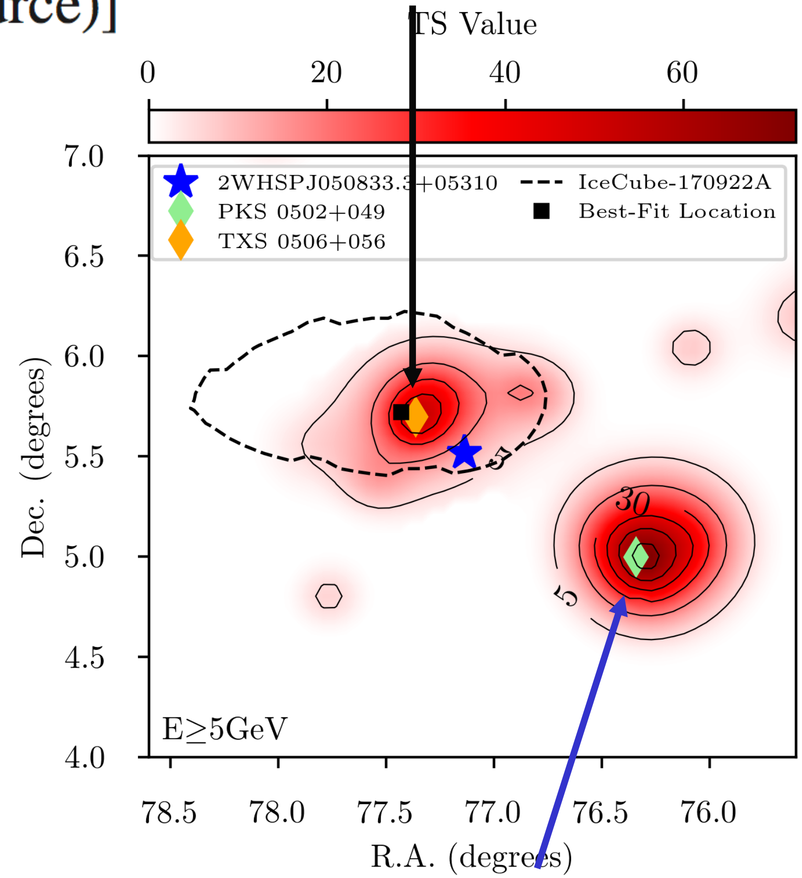
$$TS = 2 \times [\ln\mathcal{L}\,(\text{source}) - \ln\mathcal{L}\,(\text{no source})]$$

= "test statistic" map

TS = 30 ≡ 5 σ significance

July 20 – Oct. 8, 2011

TXS 0506+056

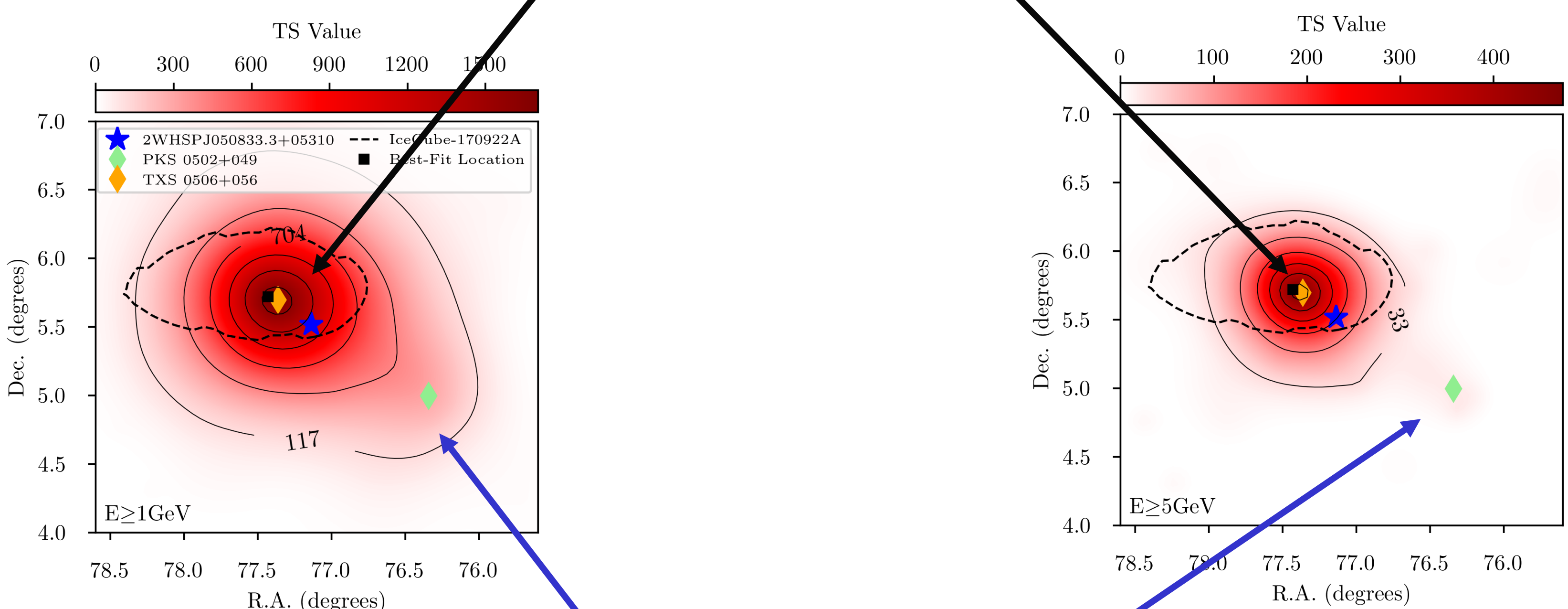


PKS 0502+049

PP, Giommi, Resconi, et al. (2018)

γ-ray activity in the area. 2. the neutrino alert period

TXS 0506+056

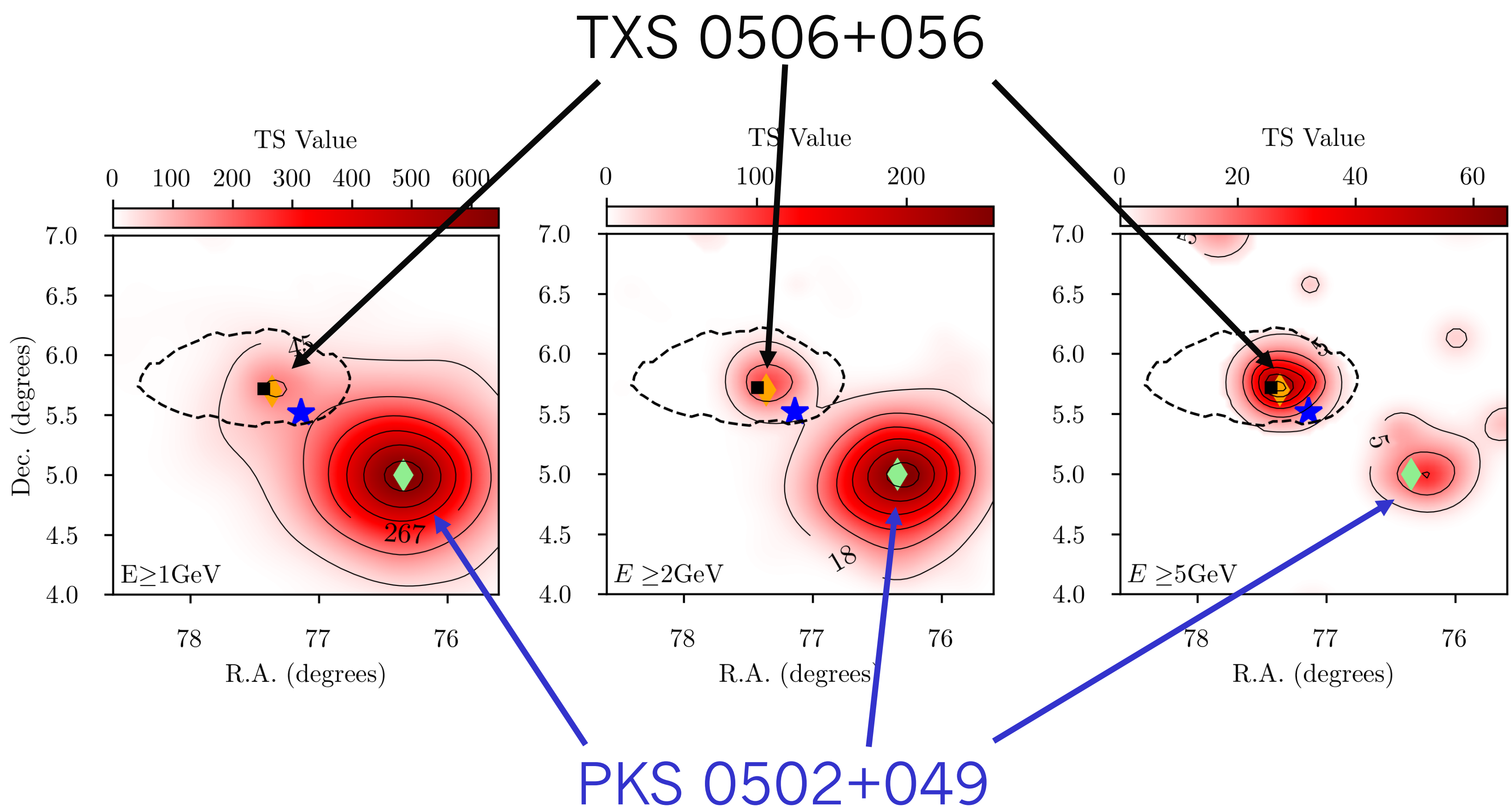


PKS 0502+049

June 4, 2017 – Sept. 22, 2017

PP, Giommi, Resconi, et al. (2018)

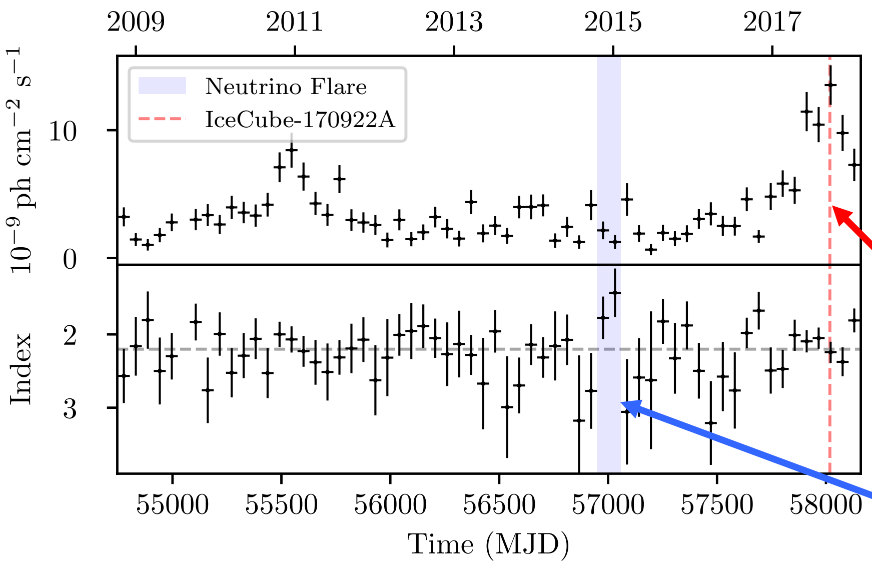
γ-ray activity in the area. 3. the neutrino flare period



Oct. 9, 2014 – Feb. 6, 2015

PP, Giommi, Resconi, et al. (2018)

Light and photon index curves



TXS 0506+056
(the BL Lac object)

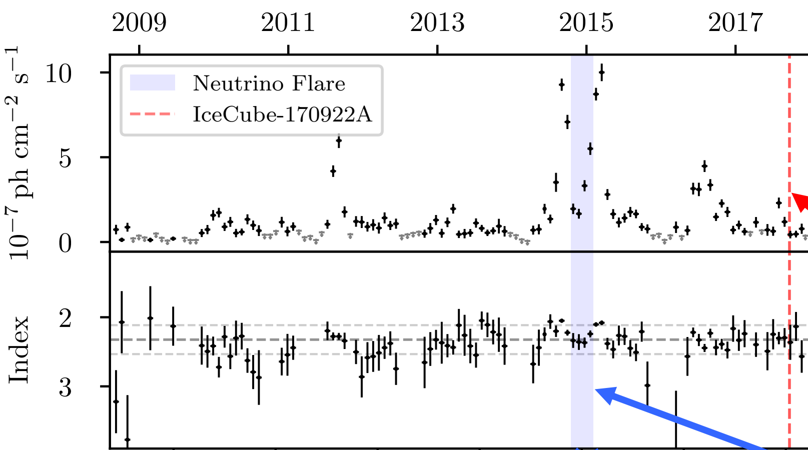
neutrino alert

neutrino flare

E > 2 GeV

PP, Giommi, Resconi, et al. (2018)

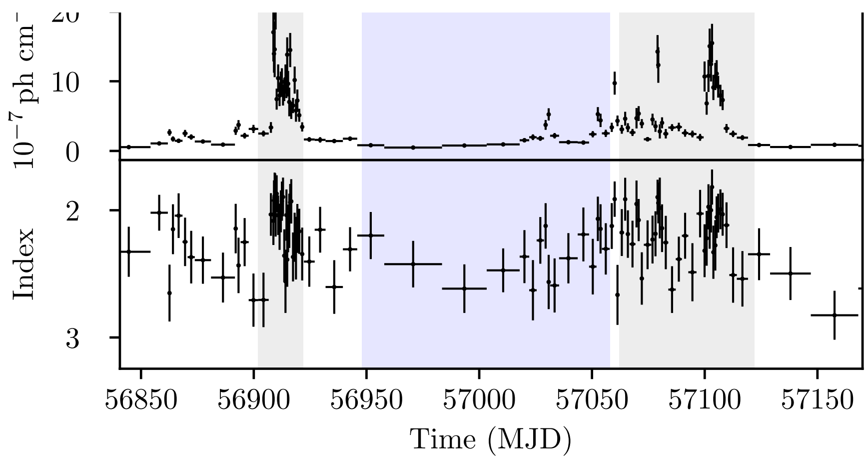
Light and photon index curves



PKS 0502+049
(the flat-spectrum radio quasar)

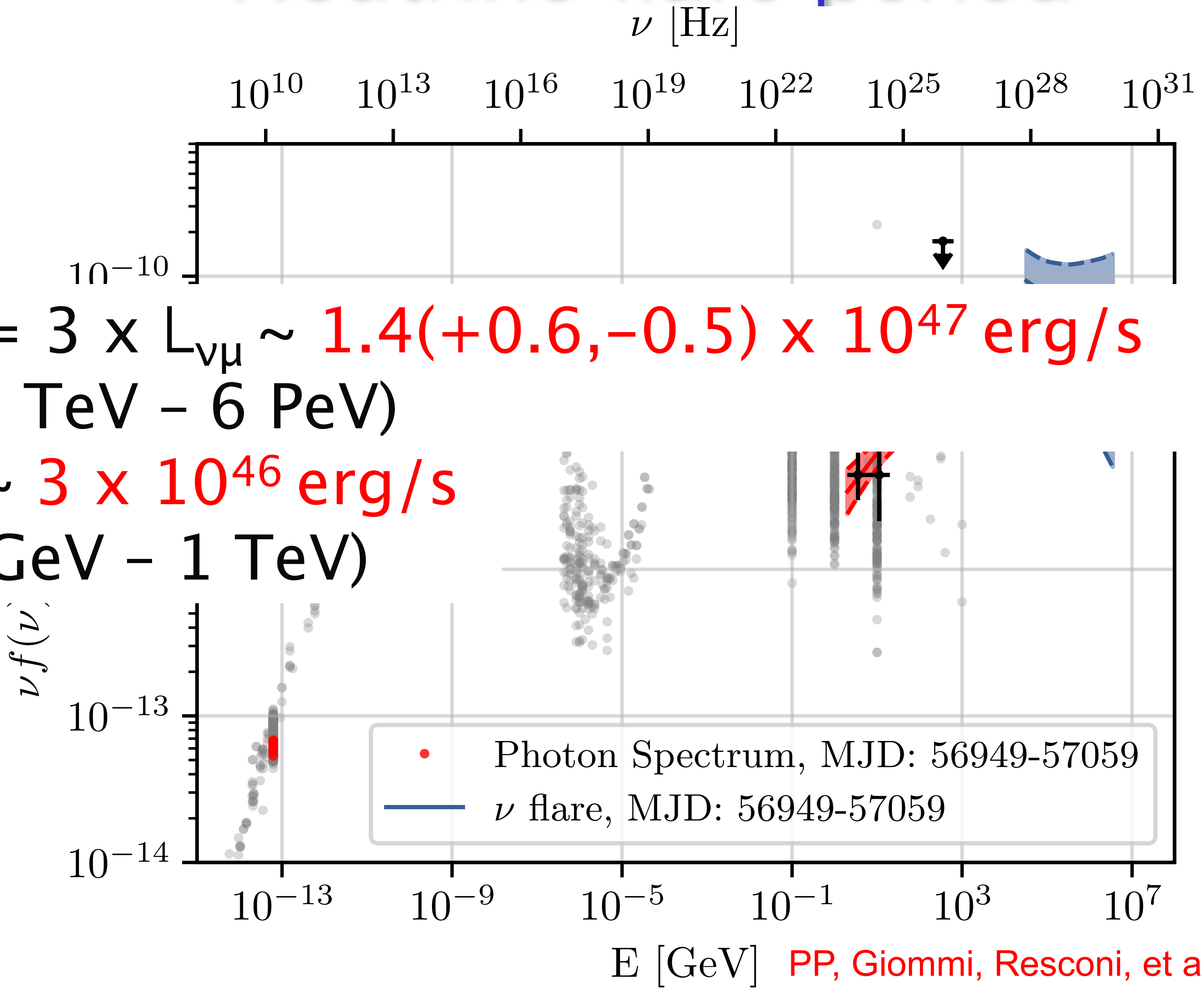
neutrino alert

All the high-energy (> 2 GeV) γ-ray activity in the area is related to TXS 0506+056!



PP, Giommi, Resconi, et al. (2018)

The hybrid SED of TXS 0506+056. Neutrino flare period



$L_\nu = 3 \times L_{\nu\mu} \sim$ 1.4(+0.6,−0.5) x 10^{47} erg/s
(32 TeV – 6 PeV)

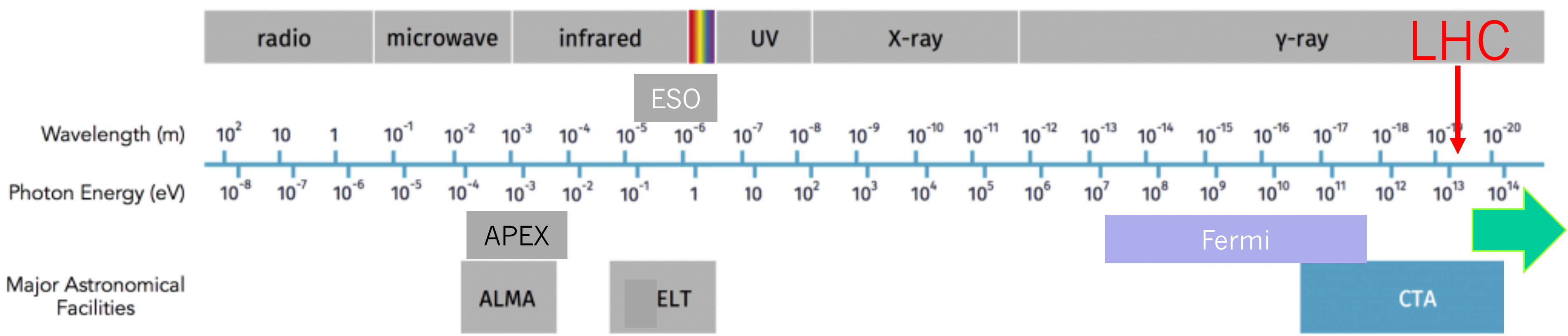
$L_\gamma \sim$ 3 x 10^{46} erg/s
(2 GeV – 1 TeV)

PP, Giommi, Resconi, et al. (2018)

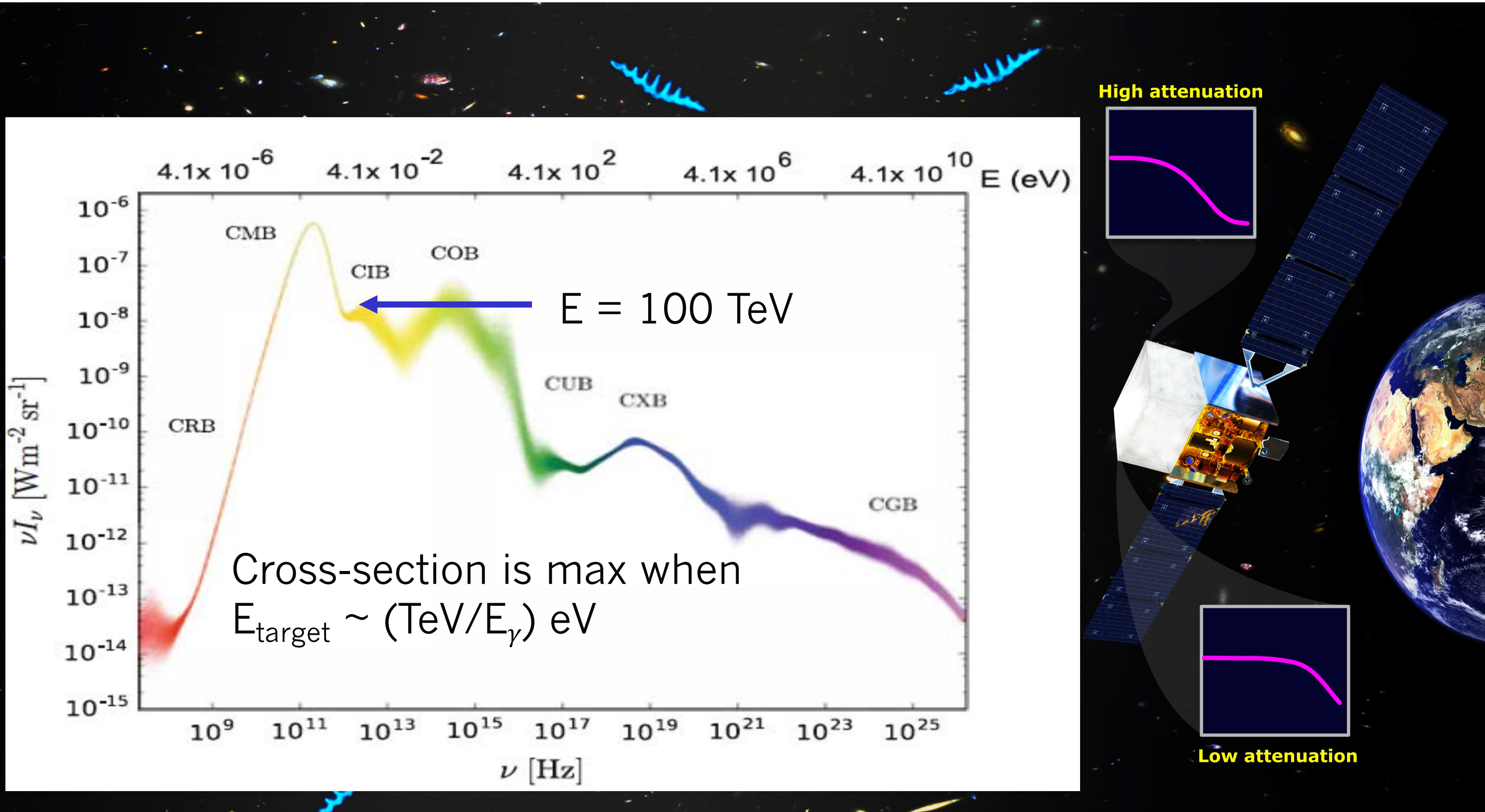
Astrophysical implications

1. with neutrinos we are now exploring an energy range which is, and will always be, **inaccessible** with photons at this (or any!) redshift
   → new window on blazar physics

Reaching the limits of “classical astronomy”



Extragalactic Background Light



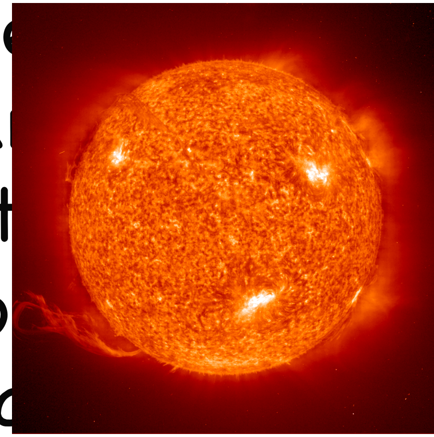
Credit: NASA's Goddard Space Flight Center

Astrophysical implications

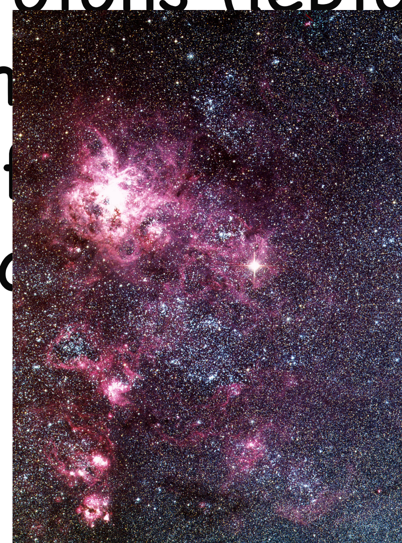
1. with neutrinos we are now exploring an energy range which is, and will always be, **inaccessible** with photons at this (or any!) redshift
   → new window on blazar jet physics
2. the SED of at least one blazar **has** to be modelled using protons (lepto-hadronic scenario)

Astrophysical implications

1. with neutrinos we … xploring an energy range which is, a … ys be, **inaccessible** with photons at t … redshift
   → new window o … physics



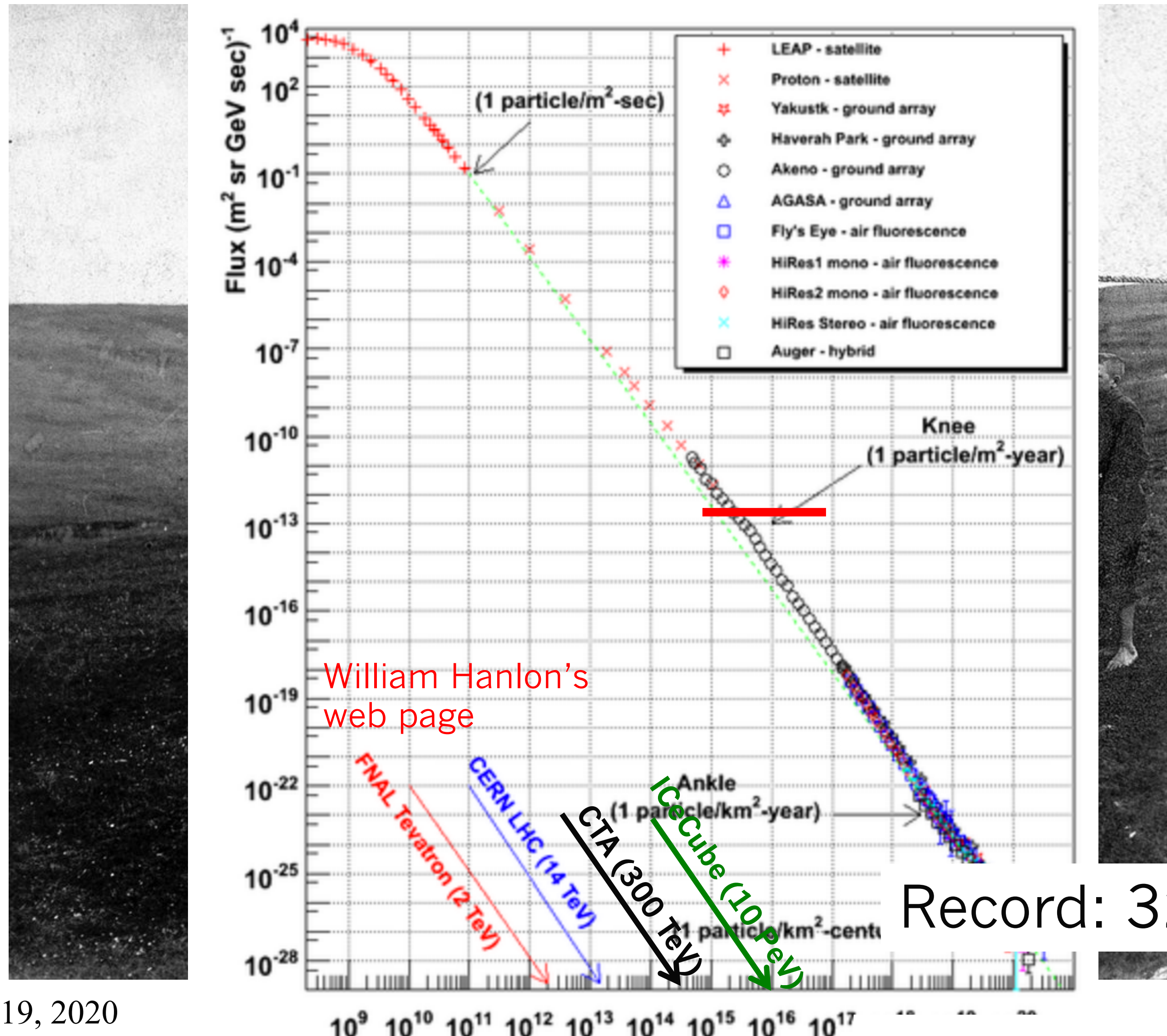
2. the SED of at lea … ar **has** to be modelled using protons (lepto-hadronic scenario)
3. the number of kn … no sources has just jumped by 50% (…)! And we have found the first n … eutrino source



Astrophysical implications

1. with neutrinos we are now exploring an energy range which is, and will always be, **inaccessible** with photons at this (or any!) redshift
   → new window on blazar jet physics
2. the SED of at least one blazar **has** to be modelled using protons (lepto-hadronic scenario)
3. the number of known neutrino sources has just jumped by 50% (from 2 to 3)! And we have found the first non-stellar neutrino source
4. at least one cosmic ray source has been identified

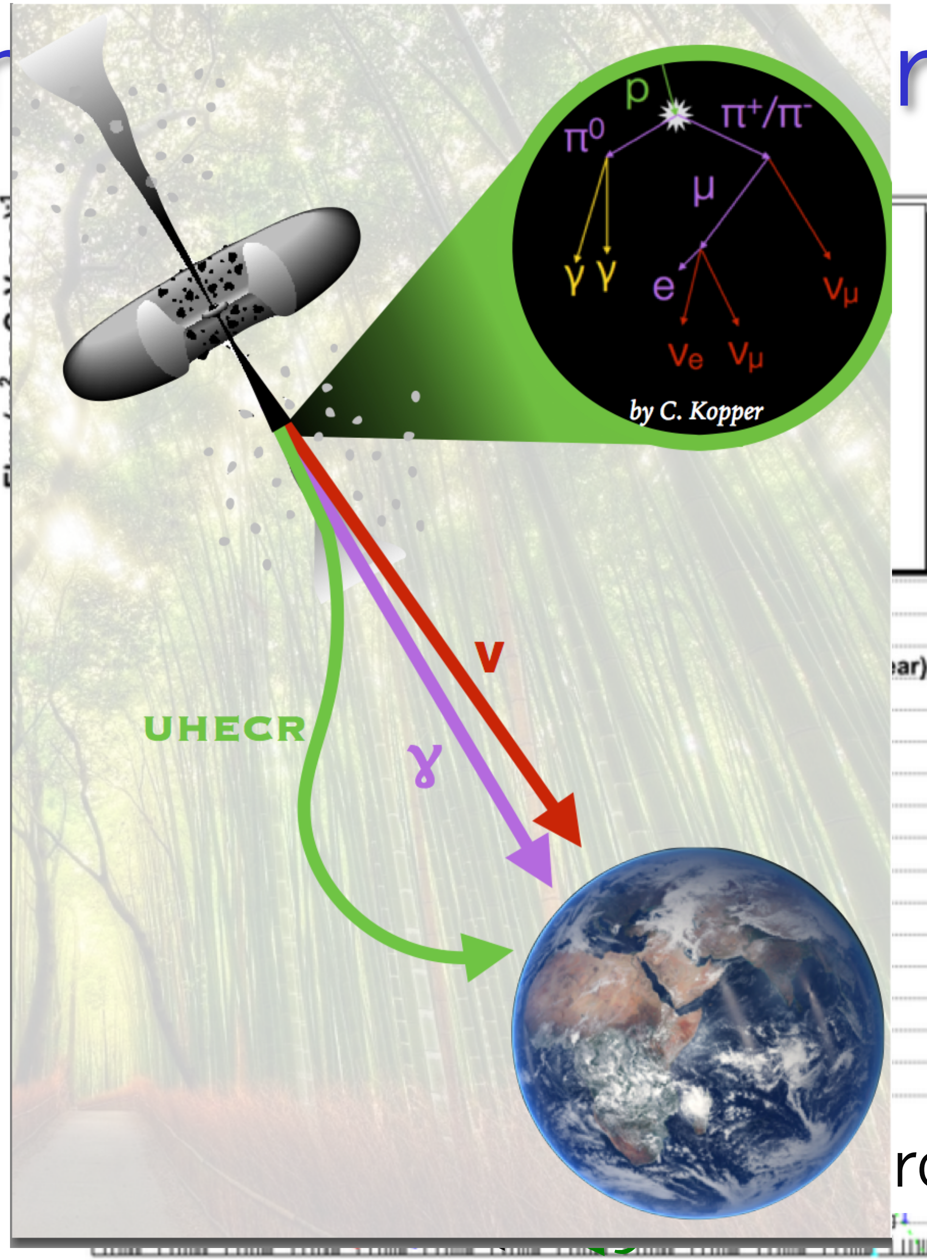
The mystery of cosmic rays

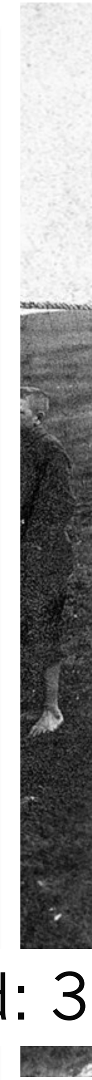


Record: 320 Exa eV!

GeV TeV PeV Exa eV = 1000 PeV

The r… rays



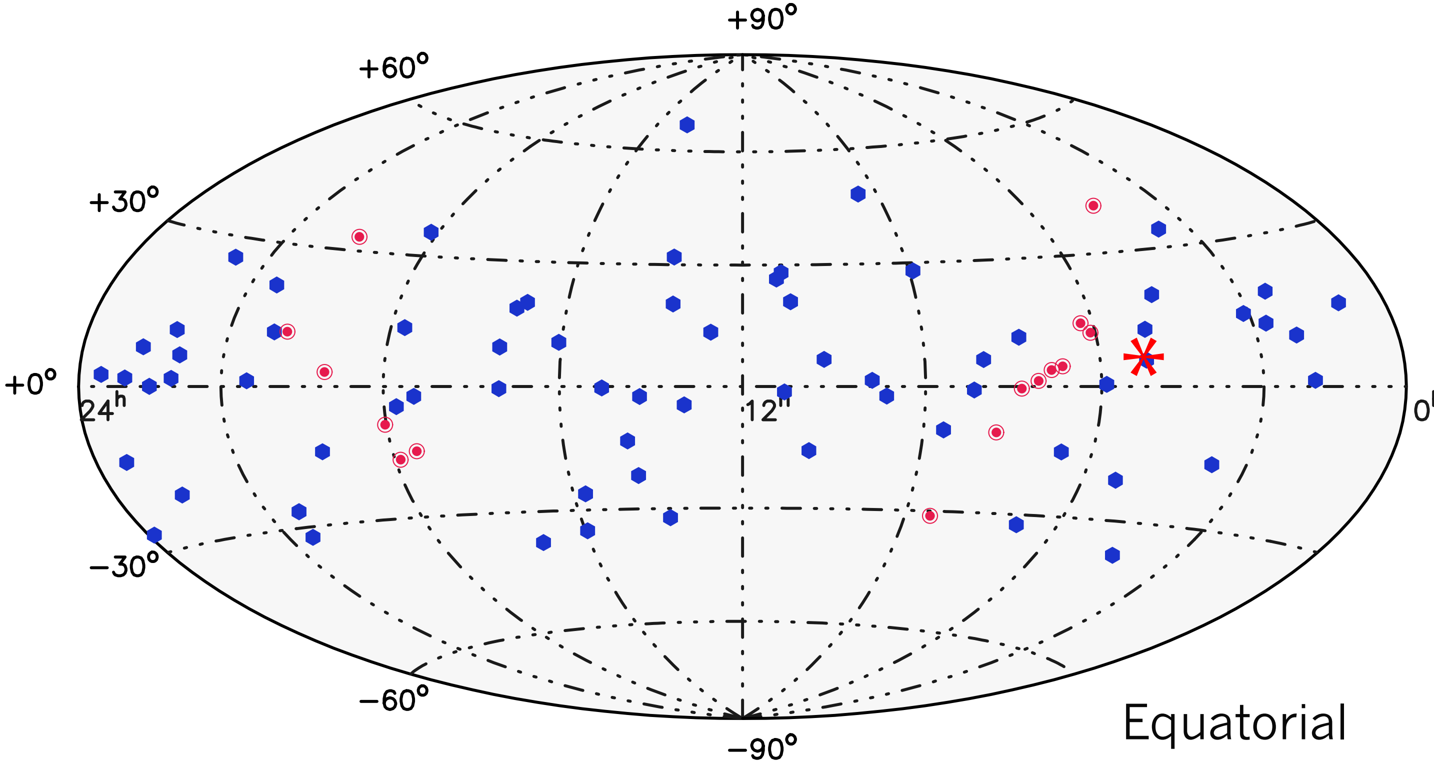


…rd: 320 Exa eV!

10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17}

GeV TeV PeV Exa eV = 1000 PeV

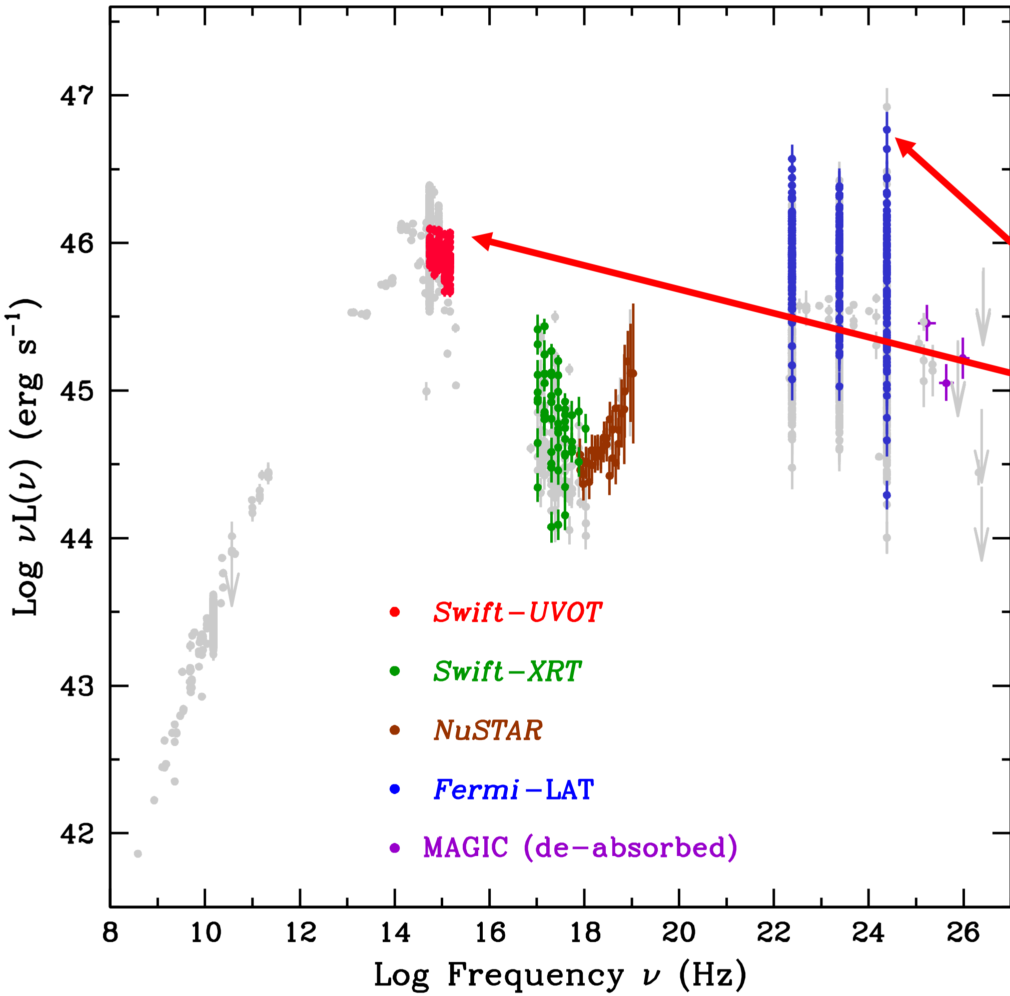
Why TXS 0506+056?



Giommi, PP, et al., 2020 (arXiv:2001.09355)

Why TXS 0506+056?

z=0.3365



Top 4% *Fermi* 3LAC

Top 0.3% *NVSS* (radio)

One of the most powerful BL Lacs known

PP, Giommi, Resconi, et al. (2018)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **00**, L1 (2019) doi:10.1093/mnrasl/slz011

TXS 0506+056, the first cosmic neutrino source, is not a BL Lac

P. Padovani ,[1,2★] F. Oikonomou,[1] M. Petropoulou,[3] P. Giommi[4,5,6] and E. Resconi[7]

[1] *European Southern Observatory, Karl-Schwarzschild-Str 2, D-85748 Garching bei München, Germany*
[2] *Associated to INAF - Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy*
[3] *Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*
[4] *Agenzia Spaziale Italiana, ASI, via del Politecnico s.n.c., I-00133 Roma, Italy*
[5] *Institute for Advanced Studies, Technische Universität München, Lichtenbergstr 2a, D-85748 Garching bei München, Germany*
[6] *ICRANet, Piazzale della Repubblica 10, I-65122 Pescara, Italy*
[7] *Physik-Department, Technische Universität München, James-Franck-Str 1, D-85748 Garching bei München, Germany*

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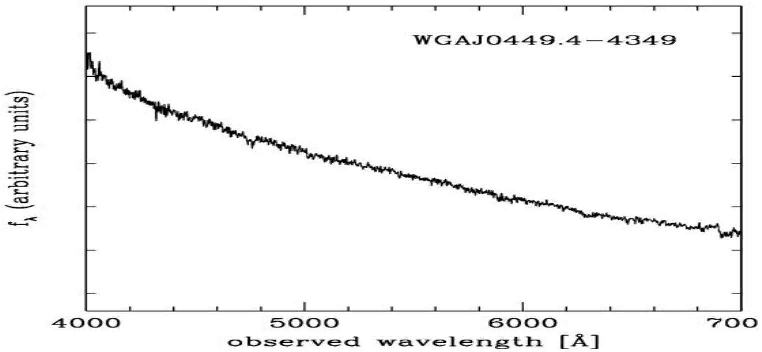
ABSTRACT

We present evidence that TXS 0506+056, the first plausible non-stellar neutrino source, despite appearances, is *not* a blazar of the BL Lac type but is instead a masquerading BL Lac, i.e. intrinsically a flat-spectrum radio quasar with hidden broad lines and a standard accretion disc. This reclassification is based on: (1) its radio and O II luminosities; (2) its emission line ratios; (3) its Eddington ratio. We also point out that the synchrotron peak frequency of TXS 0506+056 is more than two orders of magnitude larger than expected by the so-called 'blazar sequence', a scenario which has been assumed by some theoretical models predicting neutrino (and cosmic ray) emission from blazars. Finally, we comment on the theoretical implications this reclassification has on the location of the γ-ray emitting region and our understanding of neutrino emission in blazars.

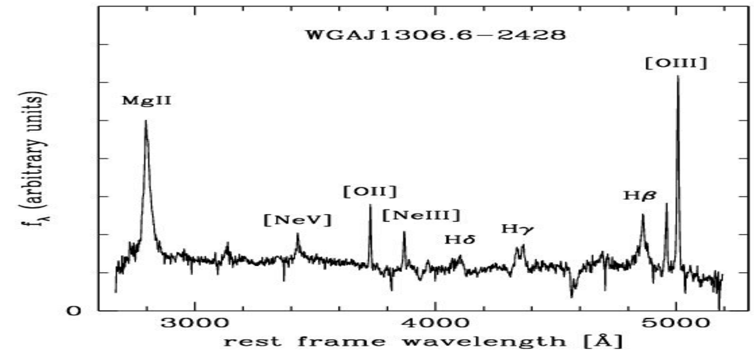
Key words: neutrinos – radiation mechanisms: non-thermal – galaxies: active – BL Lacertae objects: general – gamma-rays: galaxies.

Why TXS 0506+056?

BL Lacs



Flat-Spectrum Radio Quasars



- Real BL Lacs: lines are intrinsically weak (EW low because line weak) → low-excitation galaxies (radiatively inefficient accretion)
- Masquerading BL Lacs*: lines are intrinsically strong but swamped by the jet (EW low because continuum high) → intrinsically FSRQs, hence high-excitation galaxies (radiatively efficient accretion)

* Giommi, PP, et al. (2012)

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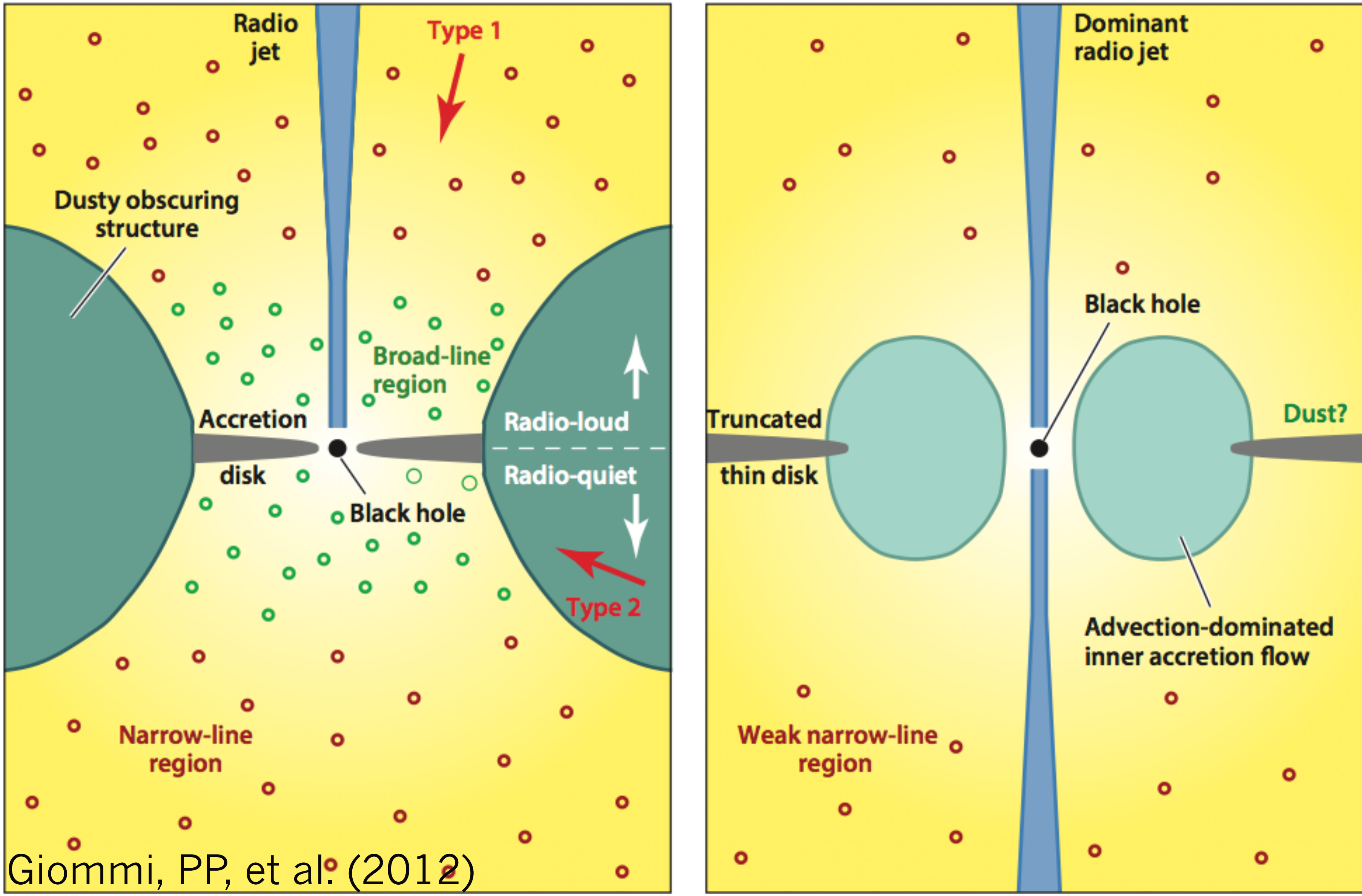
MNRAS 00, L1 (2019) doi:10.1093/mnrasl/slz011

Bl … Radio Quasars

Heckman & Best 2014



* Giommi, PP, et al. (2012)

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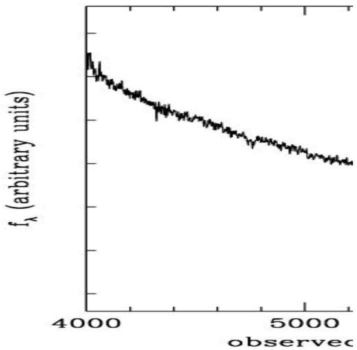
Bl ... Radio Quasars



[7] Physik-Department, Tech

Accepted 2019 January 19

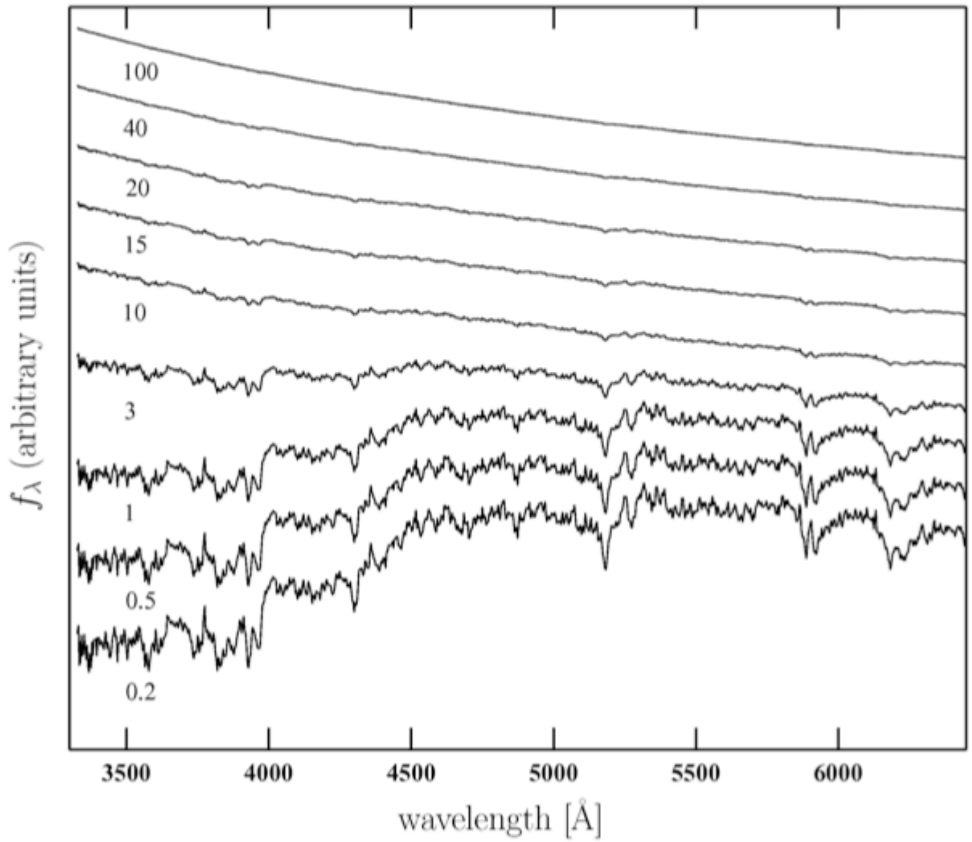
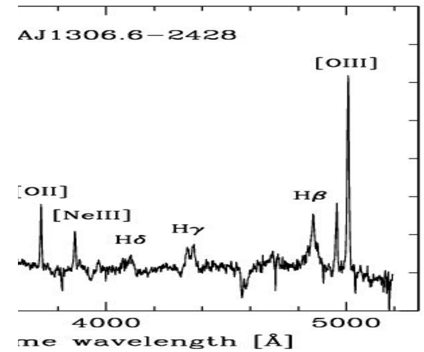


Figure 1. Simulated BL Lac spectra f_λ versus λ for a jet of optical spectral slope $\alpha_\lambda = \alpha_\nu = 1$ and of increasing flux relative to the underlying host galaxy. The assumed jet/galaxy ratios (defined at 5500 Å) are from bottom to top: 0.2, 0.5, 1, 3, 10, 15, 20, 40 and 100.



neutrino source, despite
querading BL Lac, i.e.
d a standard accretion
sities; (2) its emission
tron peak frequency of
pected by the so-called
tical models predicting
nent on the theoretical
mitting region and our
understanding of neutrino emission in blazars.

Landt, PP, & Giommi (2002)

Key words: neutrinos – radiation mechanisms: non-thermal – galaxies: active – BL Lacertae objects: general – gamma-rays: galaxies.

* Giommi, PP, et al. (2012)

TXS 0506+056 is a masquerading BL Lac!

1. it has quasar-like radio and OII/OIII powers ($P_{1.4GHz}$ ~ 1.8 x 10^{26} W/Hz, L_{OII} ~ 2 × 10^{41} erg/s)
2. its line ratios are Seyfert/quasar-like (Paiano et al. 2018)
3. it has L/L_{Edd} > 0.01 (and L_{BLR}/L_{Edd} > 5 x 10^{-4}) → high-excitation source

→ more target photons for neutrino production!

More associations*

- *AGILE* detections of 3 *transient* γ-ray sources:
  - ✓ within 1.5 deg from IceCube positions
  - ✓ within 2 days from the neutrino event time
- Recovery of TXS 0506+056 plus two new associations, still unidentified
- Joint post-trial p-value ~ 4.7 σ

*Lucarelli et al. (2019)

• AGI... es:

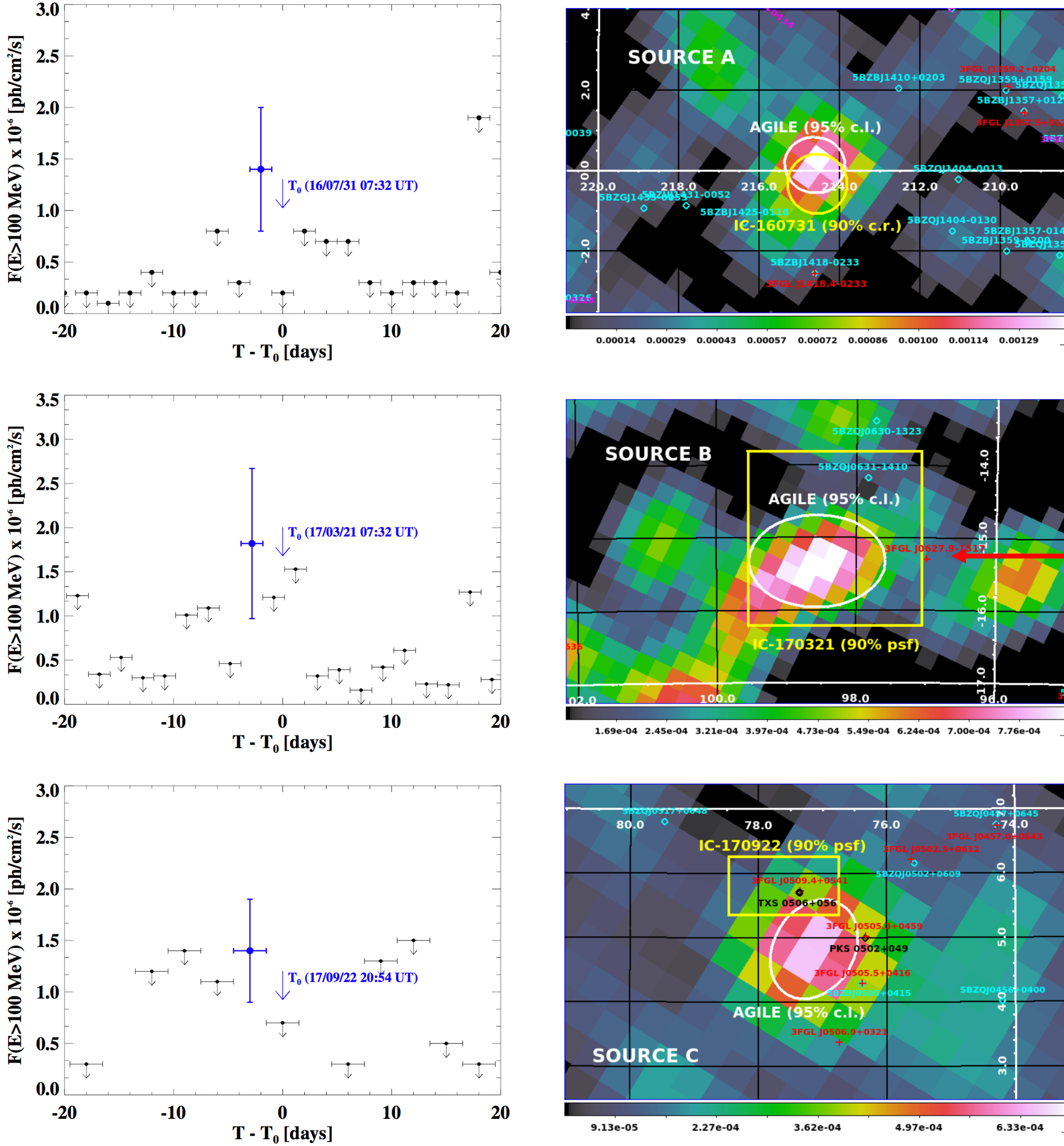
✓ v

✓ v ... ne

• Rec...

asso...

• Join...



BL Lac (HBL),
z =0.31
ATEL #12269

*Lucare...

Dissecting the regions around IceCube high-energy neutrinos: growing evidence for the blazar connection

P. Giommi[1,2,3], T. Glauch[1,4], P. Padovani[5,6], E. Resconi[4], A. Turcati[4], Y.L. Chang[3,7]
[1] Institute for Advanced Study, Technische Universität München, Lichtenbergstrasse 2a, D-85748 Garching bei München, Germany
[2] Associated to Agenzia Spaziale Italiana, ASI, via del Politecnico s.n.c., I-00133 Roma Italy
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[5] European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany
[6] Associated to INAF - Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy
[7] Tsung-Dao Lee Institute, Shanghai Jiao Tong University, 800 Dongchuan RD. Minhang District, Shanghai, China

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The association of two IceCube detections, the IceCube-170922A event and a neutrino flare, with the blazar TXS 0506+056, has paved the way for the multimessenger quest for cosmic accelerators. IceCube has observed many other neutrinos but their origin remains unknown. To better understand the reason for the apparent lack of neutrino counterparts we have extended the comprehensive dissection of the sky area performed for the IceCube-170922A event to all the 70 public IceCube high-energy neutrinos that are well reconstructed and off the Galactic plane. Using the multi-frequency data available through the Open Universe platform, we have identified numerous candidate counterparts of IceCube events. We report here the classification of all the γ-ray blazars found and the results of subsequent statistical tests. In addition, we have checked the 4LAC, 3FHL and 3HSP catalogues for potential counterparts. Following the dissection of all areas associated with IceCube neutrinos, we evaluate the data using a likelihood-ratio test and find a 3.23 σ (post-trial) excess of HBLs and IBLs with a best-fit of 15 ± 3.6 signal sources. This result, together with previous findings, consistently points to a growing evidence for a connection between IceCube neutrinos and blazars, the most energetic particle accelerators known in the Universe.

Key words: neutrinos — radiation mechanisms: non-thermal — galaxies: active — BL Lacertae objects: general — gamma-rays: galaxies

1 INTRODUCTION

The IceCube Neutrino Observatory at the South Pole[1] has reported in the past few years on the detection of tens of high-energy neutrinos of likely astrophysical origin (Aartsen et al. 2013, 2015, 2016; IceCube Collaboration 2013, 2014, 2015a, 2017a,b; Schneider 2019; Stettner 2019). This result, together with the recent association in space and time between the bright blazar TXS 0506+056 and one IceCube neutrino detected in Sept. 2017 and a neutrino flare in 2014-2015 (IceCube Collaboration et al. 2018a; IceCube Collaboration 2018b; Padovani et al. 2018), is triggering a large interest in the nature of the electromagnetic counterparts of astrophysical neutrinos.

High-energy neutrinos in a cosmic context are thought to be generated when very high-energy (VHE) cosmic rays interact with matter or radiation creating charged and neutral mesons, which then decay into neutrinos, γ-rays and other particles. Neutrinos and γ-rays are the "messengers" that can travel cosmological distances and reach the Earth undeflected, thus providing information on the VHE physical processes that generated them.

Blazars, the most abundant type of γ-ray sources in the extra-galactic sky (e.g. Ackermann et al. 2015), have long been suspected to be capable of accelerating cosmic rays to sufficiently large energies to produce astrophysical neutrinos (e.g. Mannheim 1995; Halzen & Zas 1997; Mücke et al. 2003). Blazars are a rare type of Active Galactic Nuclei (AGN; see Padovani et al. 2017, for a review) characterised by the emission of strong and highly variable non-thermal radiation across the entire electromagnetic spectrum. This radiation is generated by energetic charged particles moving in a magnetic field within a relativistic jet that is seen at a small angle with respect to the line of sight (Urry & Padovani 1995; Padovani et al. 2017).

Blazars come in two flavours depending on the presence and on the strength of their optical emission lines, namely Flat Spec-

[1] http://icecube.wisc.edu

MNRAS 000, 1–15 (2020) Preprint 28 January 2020 Compiled using MNRAS LaTeX style file v3.0

Dissecting the regions around IceCube high-energy neutrinos: growing evidence for the blazar connection

P. Giommi[1,2,3], T. Glauch[1,4], P. Padovani[5,6], E. Resconi[4], A. Turcati[4], Y.L. Chang[3,7]
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[3] ICRANet, Piazzale della Repubblica,10 - 65122, Pescara, Italy
[4] Technische Universität München, Physik-Department, James-Frank-Str. 1, D-85748 Garching bei München, Germany
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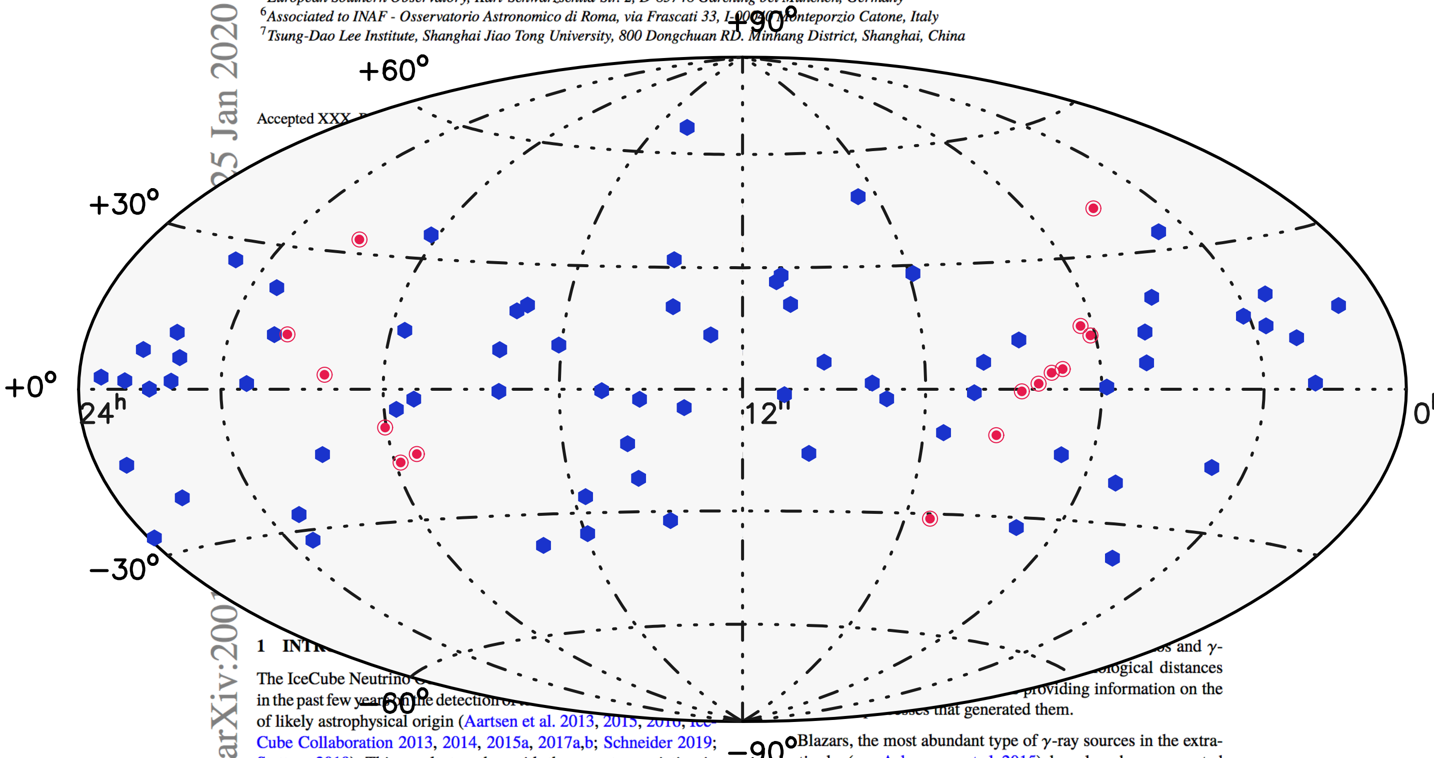
[7] Tsung-Dao Lee Institute, Shanghai Jiao Tong University, 800 Dongchuan RD. Minhang District, Shanghai, China

Accepted XXX. R...



1 INTR...

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High-energy neutrinos in a cosmic context are thought to be generated when very high-energy (VHE) cosmic rays interact with matter or radiation creating charged and neutral mesons, which then ... and γ- ... cosmological distances ... providing information on the ... that generated them.

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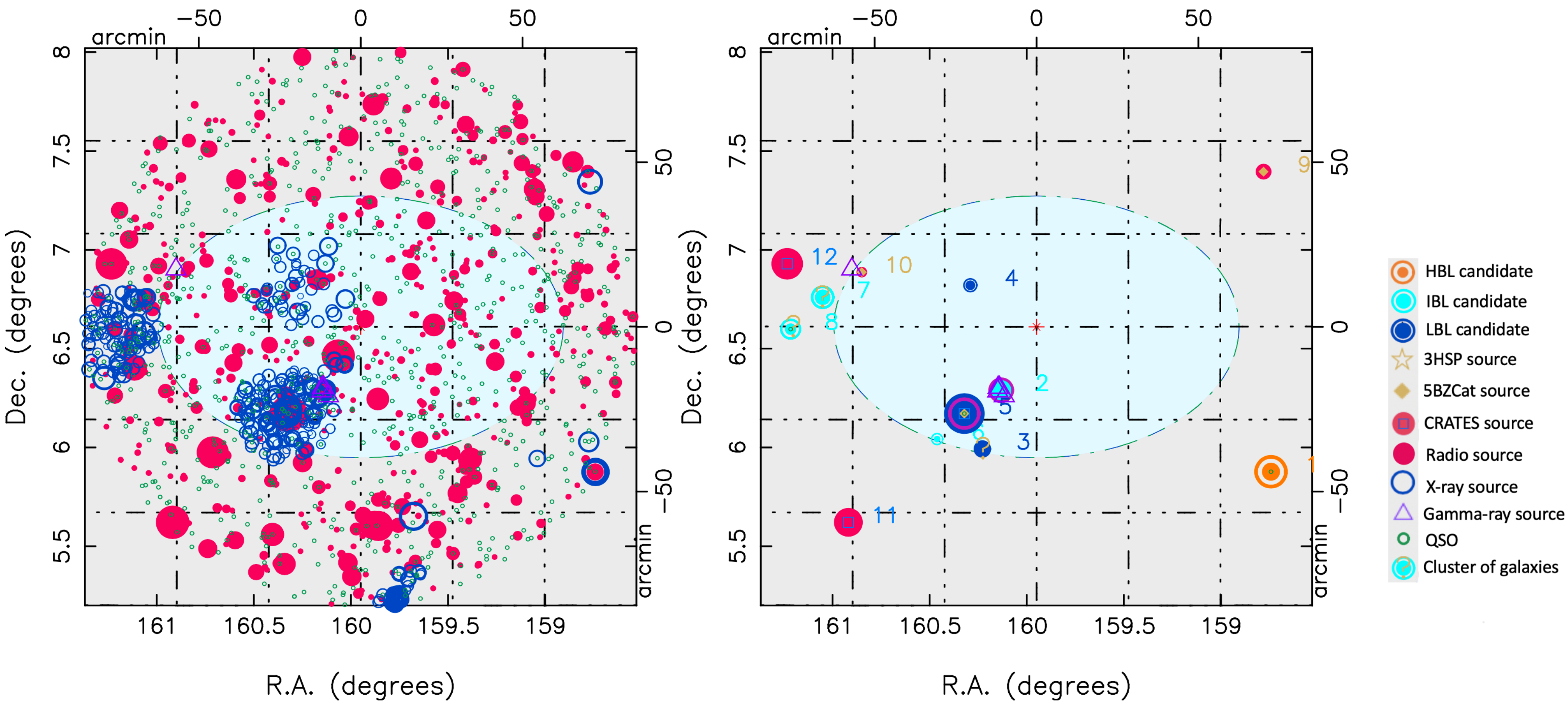
New results


arcmin
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8
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6.5
6
5.5
Dec. (degrees)
161
160.5
160
159.5
159
R.A. (degrees)
arcmin
12
10
4
7
8
2
5
3
9
1
11
HBL candidate
IBL candidate
LBL candidate
3HSP source
5BZCat source
CRATES source
Radio source
X-ray source
Gamma-ray source
QSO
Cluster of galaxies

New results

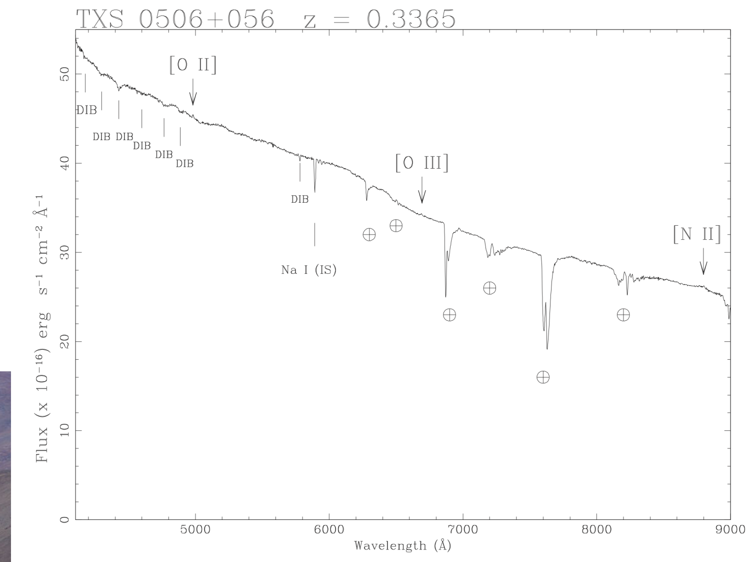
$\nu_{peak,synch} > 10^{14}$ Hz $\nu_{peak,synch} < 10^{14}$ Hz

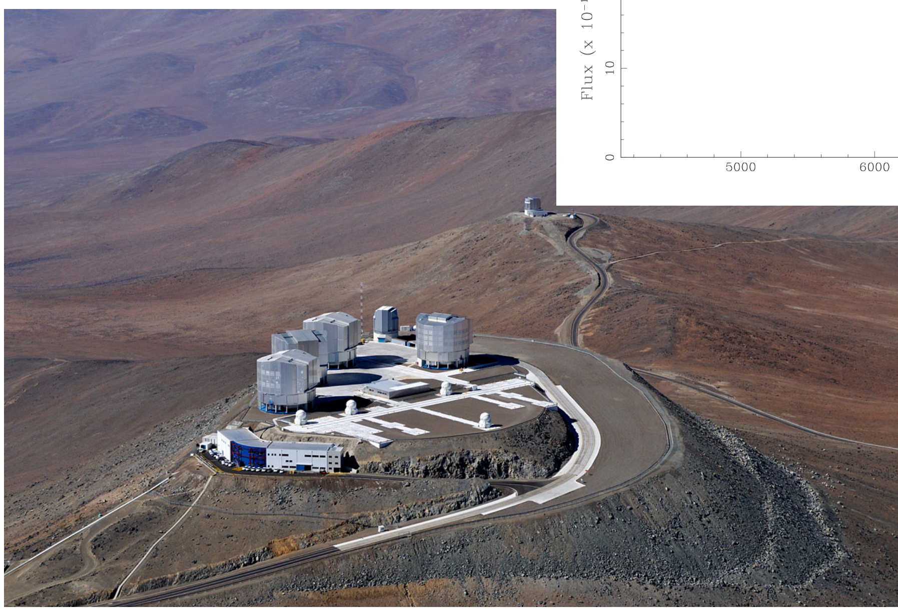
Table 6. Results on the occurrence of γ-ray blazars within the 70 IceCube high Galactic latitudes ($|b| > 10°$) neutrino with error radii $\leq 3.0°$ and comparison with the expectations due to random coincidences as estimated from the control sample.

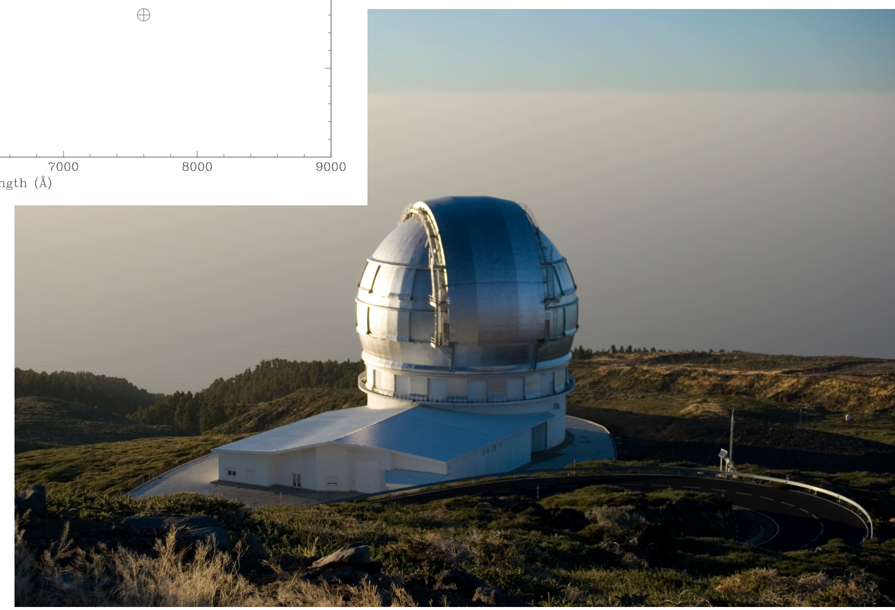
Area searched (1)	γ-ray IBL/HBL found in neutrino error region (2)	Expectation from control sample (3)	Likelihood-test p-value (4)	γ-ray LBL found in neutrino error region (5)	Expectation from control sample (6)	Likelihood-test p-value (7)
Ω_{90}	20	11.9	7.4×10^{-3}	9	11.9	0.43
$\Omega_{90\times1.1}$	24	14.4	1.4×10^{-2}	15	14.4	0.44
$\Omega_{90\times1.3}$	35	20.1	1.9×10^{-4}	17	20.1	0.48
$\Omega_{90\times1.5}$	47	26.8	2.0×10^{-4}	24	26.8	0.33
Post trial p-value: 6.2×10^{-4} ($3.23\,\sigma$)						

Excess of 15 γ-ray blazars (some TXS 0506+056-like)

ESO and GTC meet IceCube







ESO VLT

Gran Telescopio CANARIAS

Outlook

- looking for more neutrino sources
  - ✓ why TXS 0506+056?
- stacking for selected astronomical catalogues (IceCube)
- other classes of sources
- dedicated funding
- more neutrinos

SFB 1258 | Neutrinos Dark Matter Messengers

DFG Deutsche Forschungsgemeinschaft

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MNRAS **477**, 3469–3479 (2018) doi:10.1093/mnras/sty877

Key words: neutrinos – radiation mechanisms: non-thermal – ISM: kinematics and dynamics – galaxies: active.

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Advance Access publication 2018 April 6

AGN outflows as neutrino sources: an observational test

P. Padovani,[1,2★] A. Turcati[3] and E. Resconi[3]

[1] *European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany*
[2] *Associated to INAF – Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy*
[3] *Physik-Department, Technische Universität München, James-Frank-Str. 1, D-85748 Garching bei München, Germany*

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ABSTRACT

We test the recently proposed idea that outflows associated with Active Galactic Nuclei (AGN) could be neutrino emitters in two complementary ways. First, we cross-correlate a list of 94 'bona fide' AGN outflows with the most complete and updated repository of IceCube neutrinos currently publicly available, assembled by us for this purpose. It turns out that AGN with outflows matched to an IceCube neutrino have outflow and kinetic energy rates, and bolometric powers larger than those of AGN with outflows not matched to neutrinos. Secondly, we carry out a statistical analysis on a catalogue of [O III] λ5007 line profiles using a sample of 23 264 AGN at $z < 0.4$, a subsample of which includes mostly possible outflow sources. We find no significant evidence of an association between the AGN and the IceCube events, although we get the smallest p-values (∼6 and 18 per cent, respectively, pre-trial) for relatively high velocities and luminosities. Our results are consistent with a scenario where AGN outflows are neutrino emitters but at present do not provide a significant signal. This can be tested with better statistics and source stacking. A predominant role of AGN outflows in explaining the IceCube data appears in any case to be ruled out.

Key words: neutrinos – radiation mechanisms: non-thermal – ISM: kinematics and dynamics – galaxies: active.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
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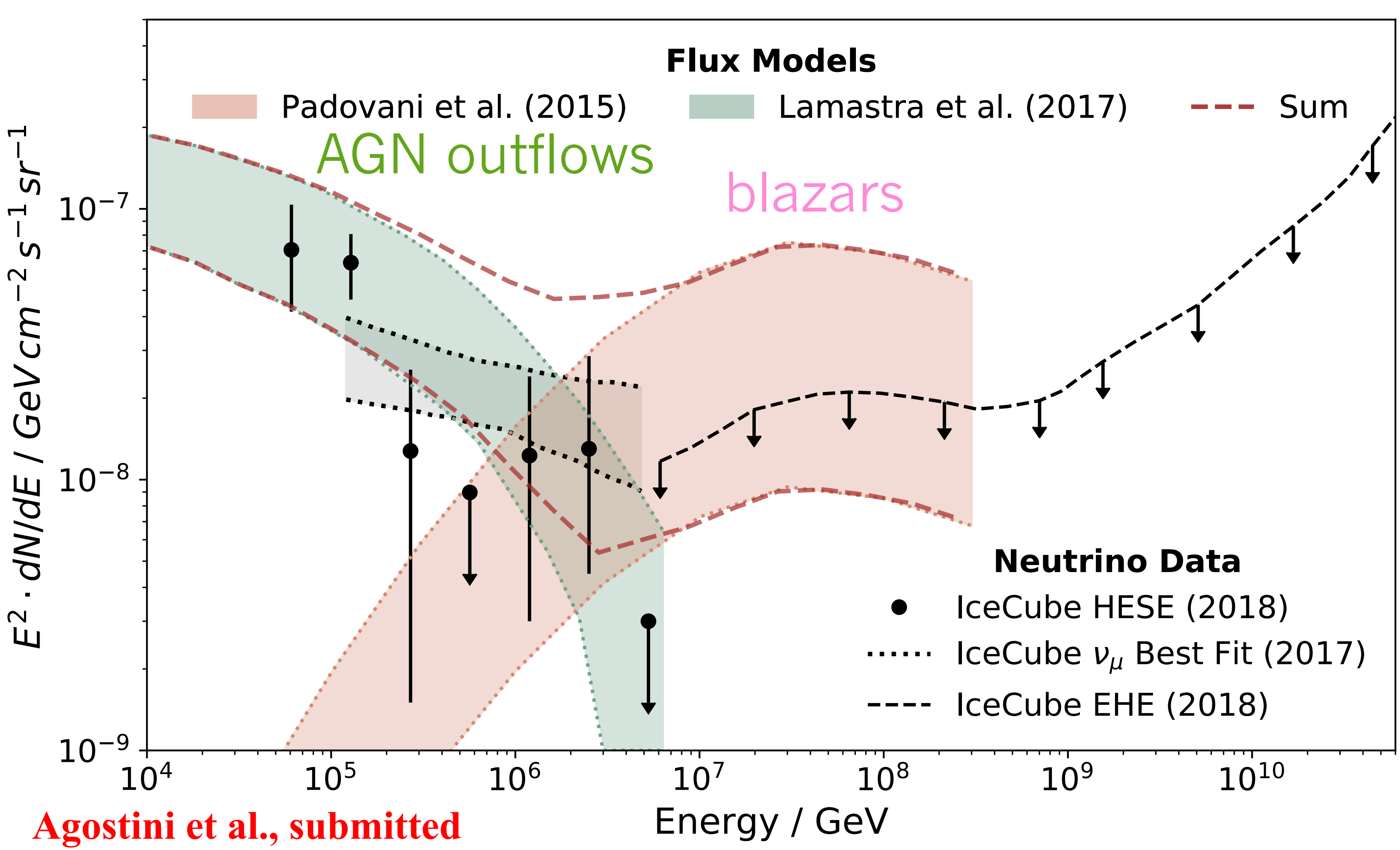

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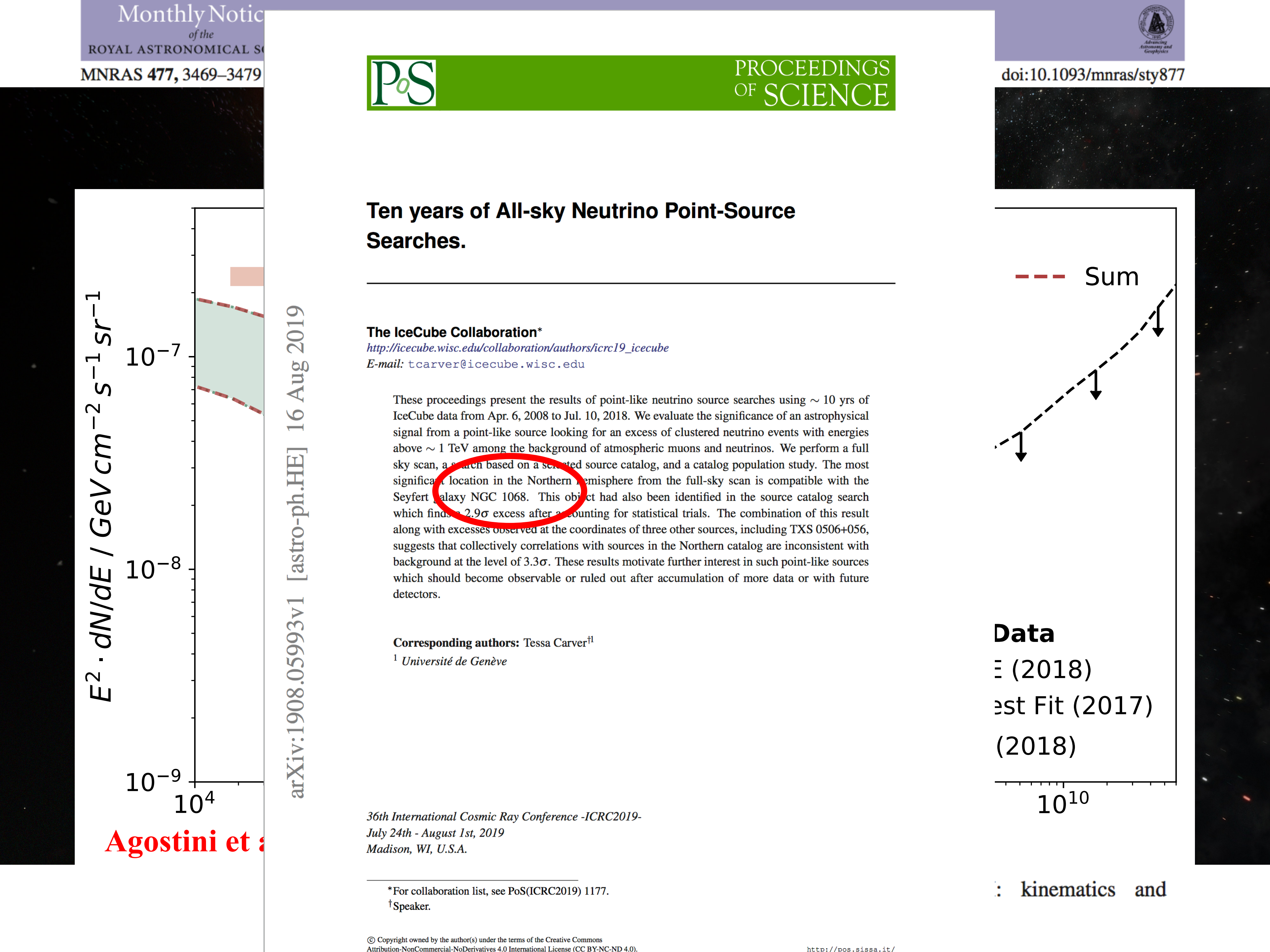


PROCEEDINGS OF SCIENCE

Ten years of All-sky Neutrino Point-Source Searches.

The IceCube Collaboration*
http://icecube.wisc.edu/collaboration/authors/icrc19_icecube
E-mail: tcarver@icecube.wisc.edu

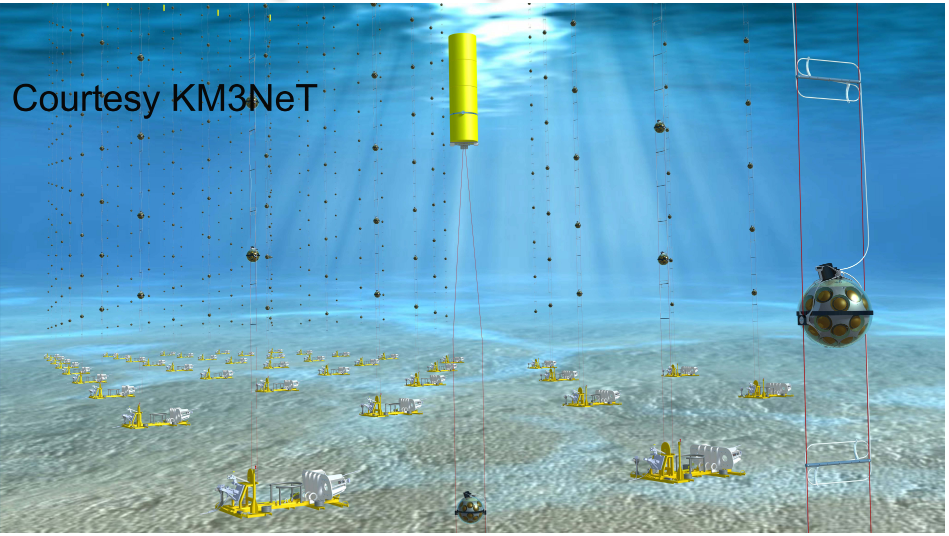
These proceedings present the results of point-like neutrino source searches using ∼ 10 yrs of IceCube data from Apr. 6, 2008 to Jul. 10, 2018. We evaluate the significance of an astrophysical signal from a point-like source looking for an excess of clustered neutrino events with energies above ∼ 1 TeV among the background of atmospheric muons and neutrinos. We perform a full sky scan, a search based on a selected source catalog, and a catalog population study. The most significant location in the Northern hemisphere from the full-sky scan is compatible with the Seyfert galaxy NGC 1068. This object had also been identified in the source catalog search which finds a 2.9σ excess after accounting for statistical trials. The combination of this result along with excesses observed at the coordinates of three other sources, including TXS 0506+056, suggests that collectively correlations with sources in the Northern catalog are inconsistent with background at the level of 3.3σ. These results motivate further interest in such point-like sources which should become observable or ruled out after accumulation of more data or with future detectors.

Corresponding authors: Tessa Carver[†1]
[1] *Université de Genève*

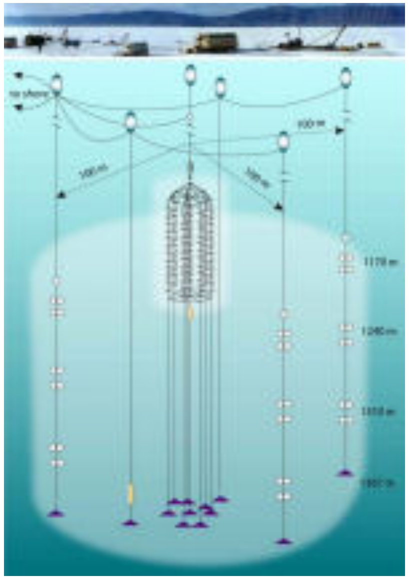
36th International Cosmic Ray Conference -ICRC2019-
July 24th - August 1st, 2019
Madison, WI, U.S.A.

*For collaboration list, see PoS(ICRC2019) 1177.
†Speaker.

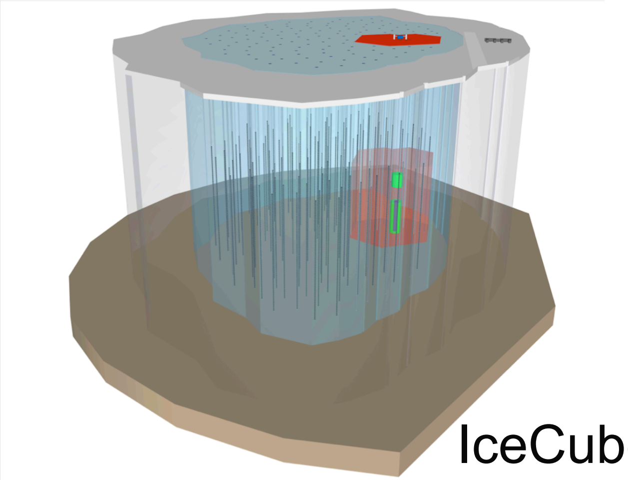
The (near) future of Neutrino Astronomy



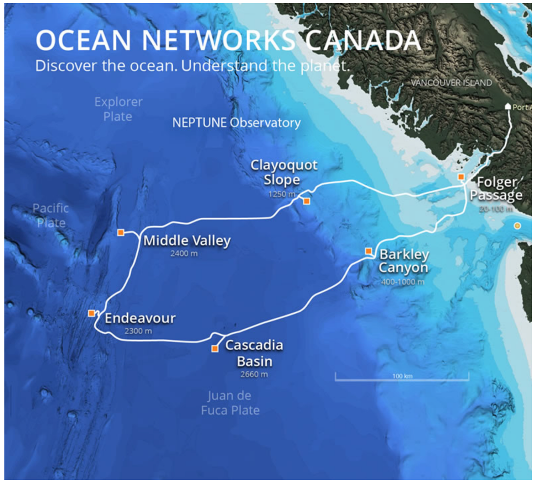
KM3NeT



Baikal Gigaton Volume Detector



IceCube-Gen2



Pacific Ocean Neutrino Experiment

Summary

- Blazars were thought to be very likely neutrino sources from various points of view: statistically, theoretically, and population-wise (but could not explain the whole IceCube signal)
- The IceCube-170922A event (1 neutrino) and the neutrino flare (~ 13 neutrinos) have been linked to the same source, TXS 0506+056, a blazar (BL Lac object) at $z = 0.3365$
- We have carefully studied the complex area around it and ruled out any other possible sources

Summary

Astrophysical Implications

1. Neutrinos are providing a new window on blazar jet physics at energies forever inaccessible with photons!

2. Hadronic (high-energy proton) emission is present in at least one blazar jet

3. The first source of cosmic rays has been found

4. The number of neutrino sources in the Universe has increased by 50%!

Summary

- Why this source? Perhaps because TXS 0506+056 is not what it looks like …
- We are looking for more such sources using ESO and GTC
- The case for blazars with $\nu_{peak,synch}$ > 10^{14} Hz as neutrino sources is growing!
- More neutrinos are coming