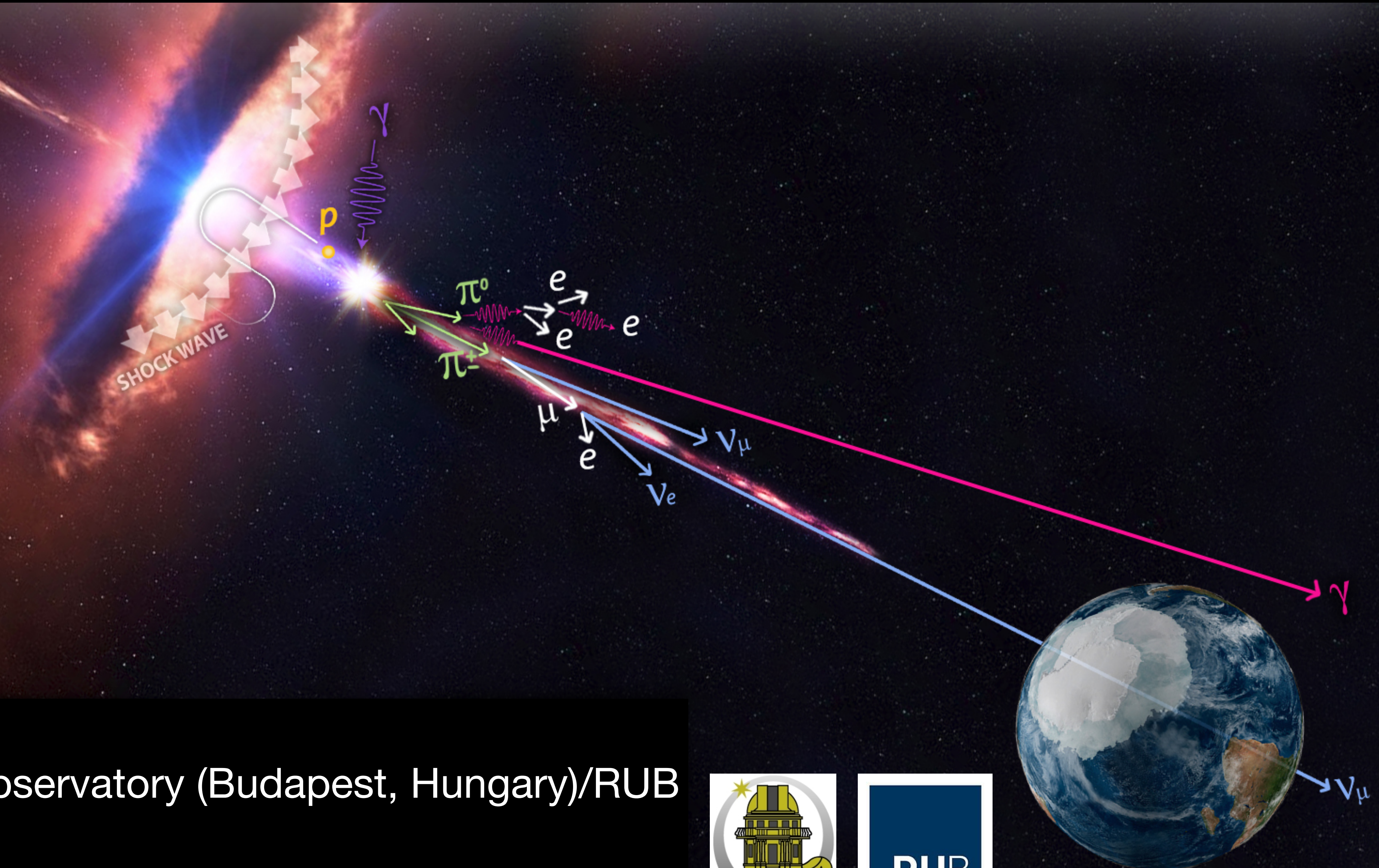
Multimessenger astronomy of cosmic particle accelerators



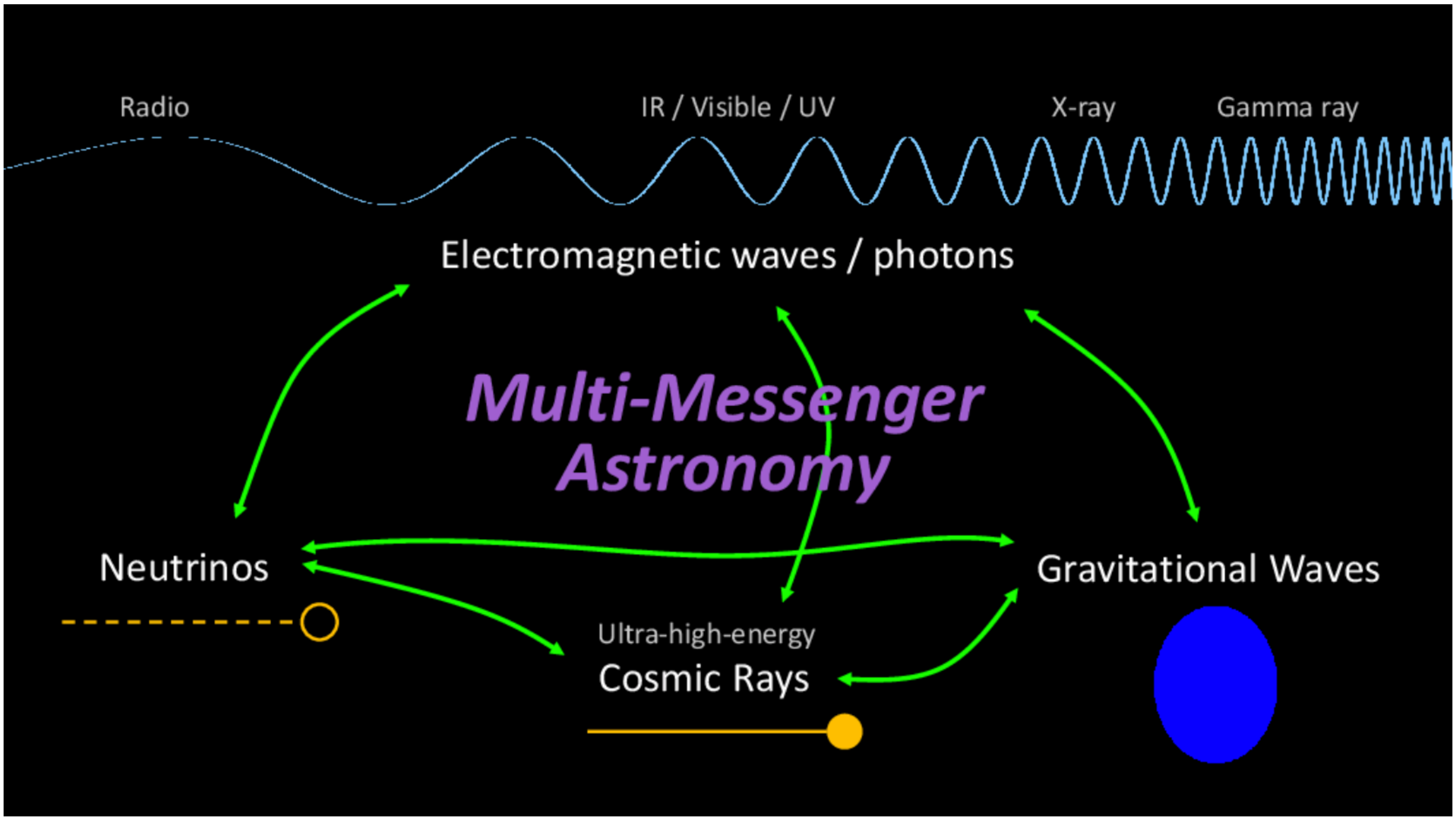
Emma Kun
Konkoly Observatory (Budapest, Hungary)/RUB

SFB 1491 kick-off meeting, 02/06/2022

SFB 1491 kick-off meeting, 02/06/2022

Multimessenger astronomy

A tool to observe the highest-energy phenomena in the Nature



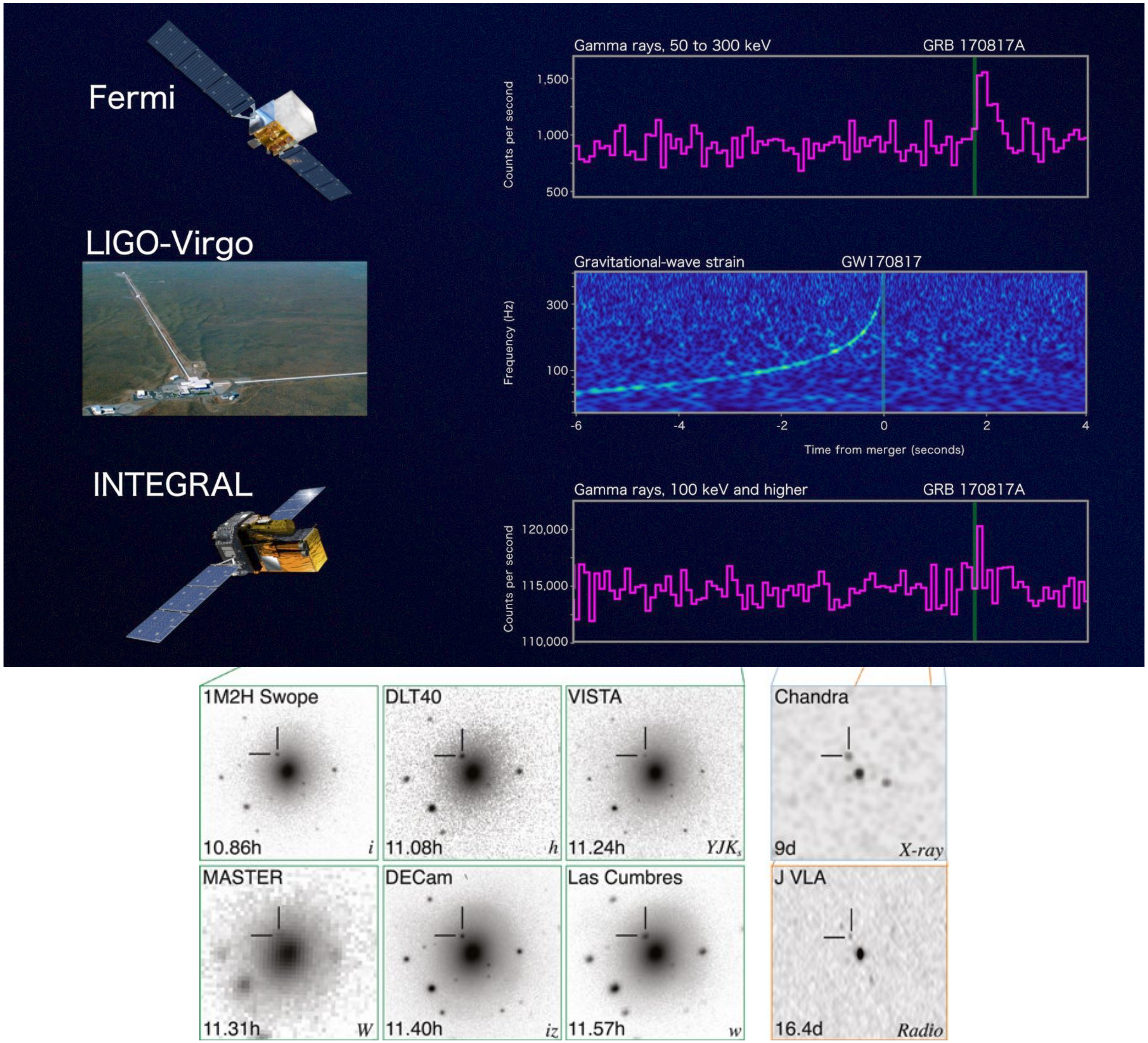
Multi-messenger observations of a binary neutron star merger

Abbott et al., 2017, ApJL, 848,12

GW170817

short GRB

Kilonova



@LIGO, NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA

Multi-messenger observations of a binary neutron star merger

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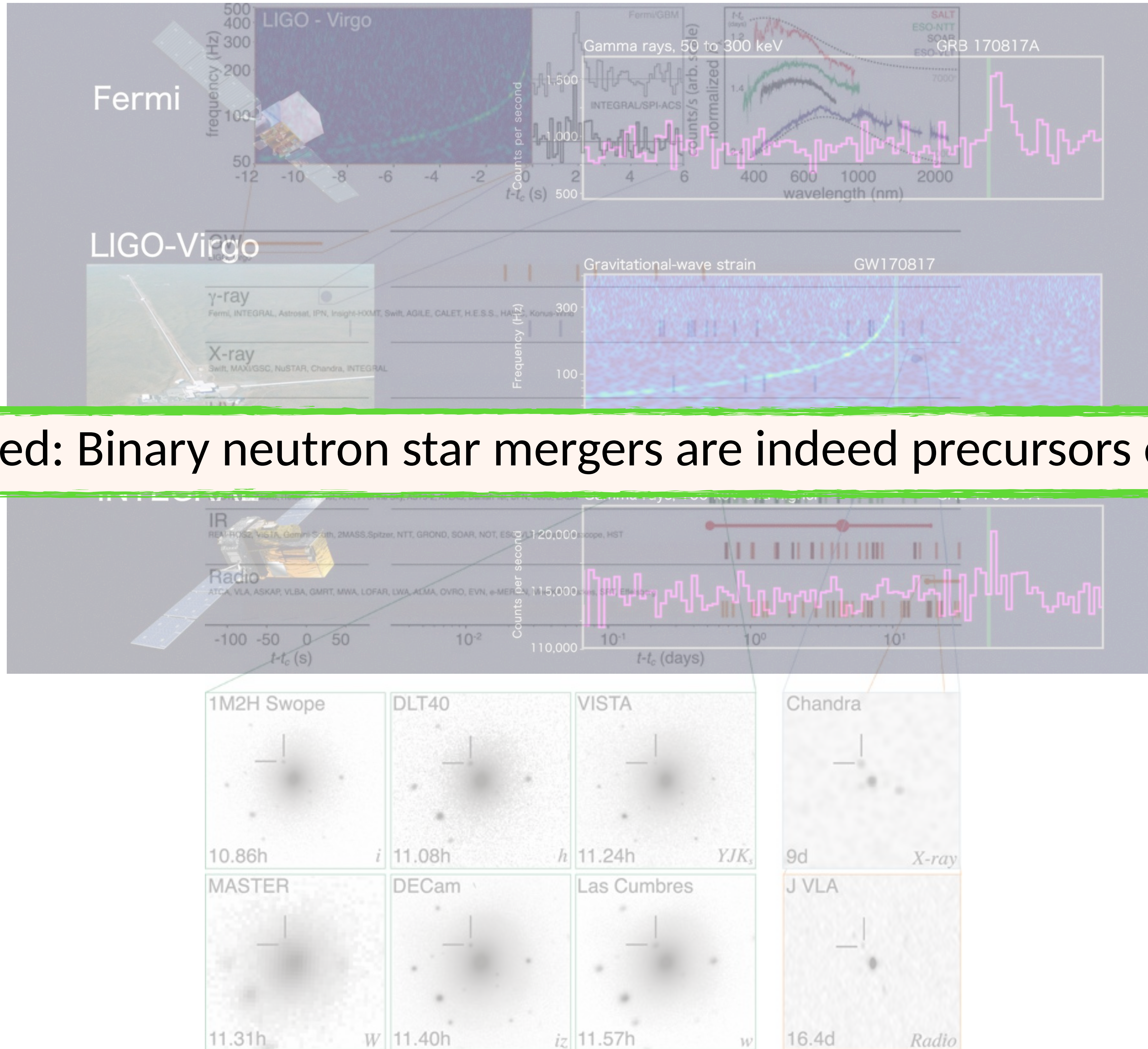
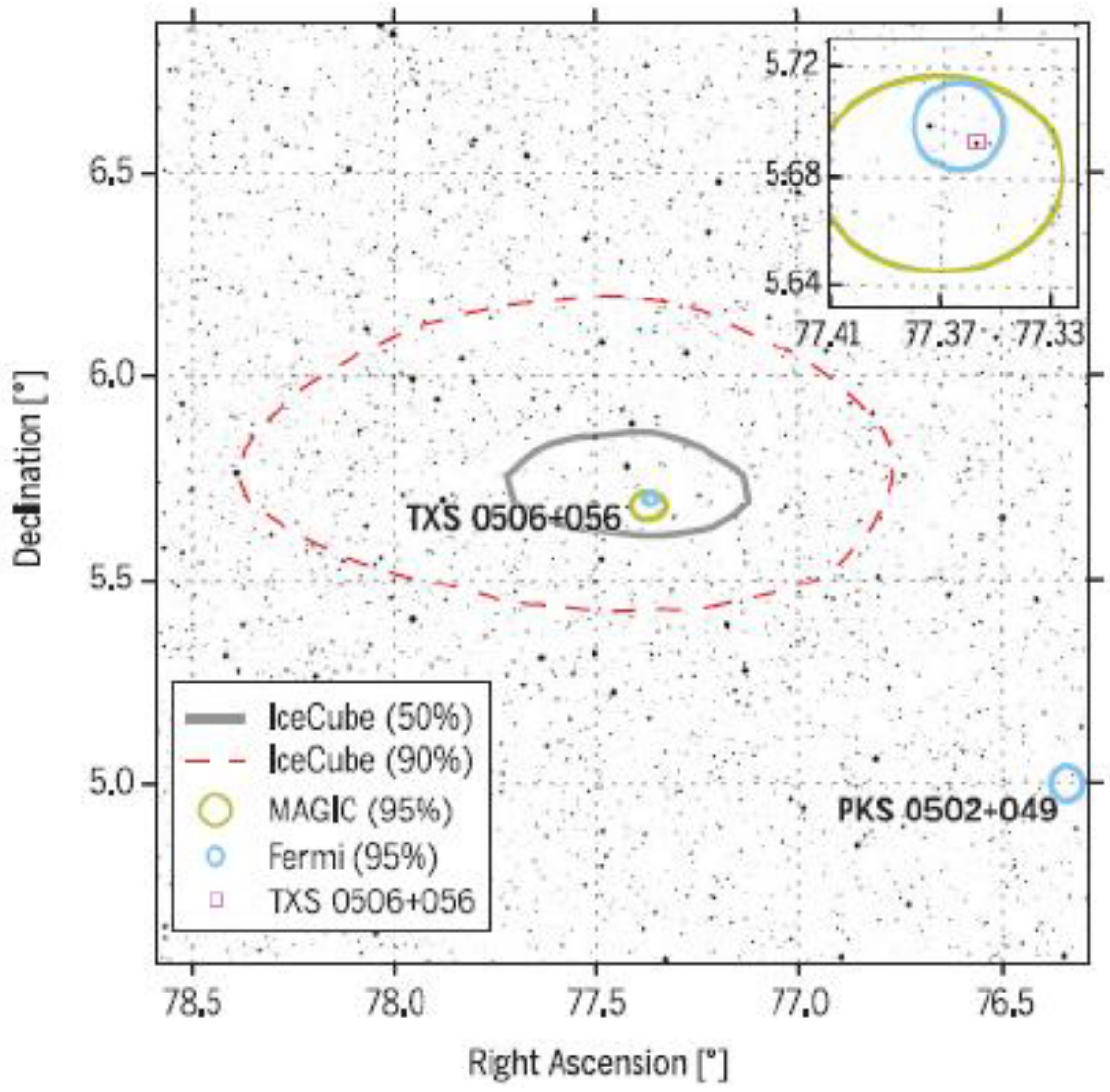


Lesson learned: Binary neutron star mergers are indeed precursors of short GRBs

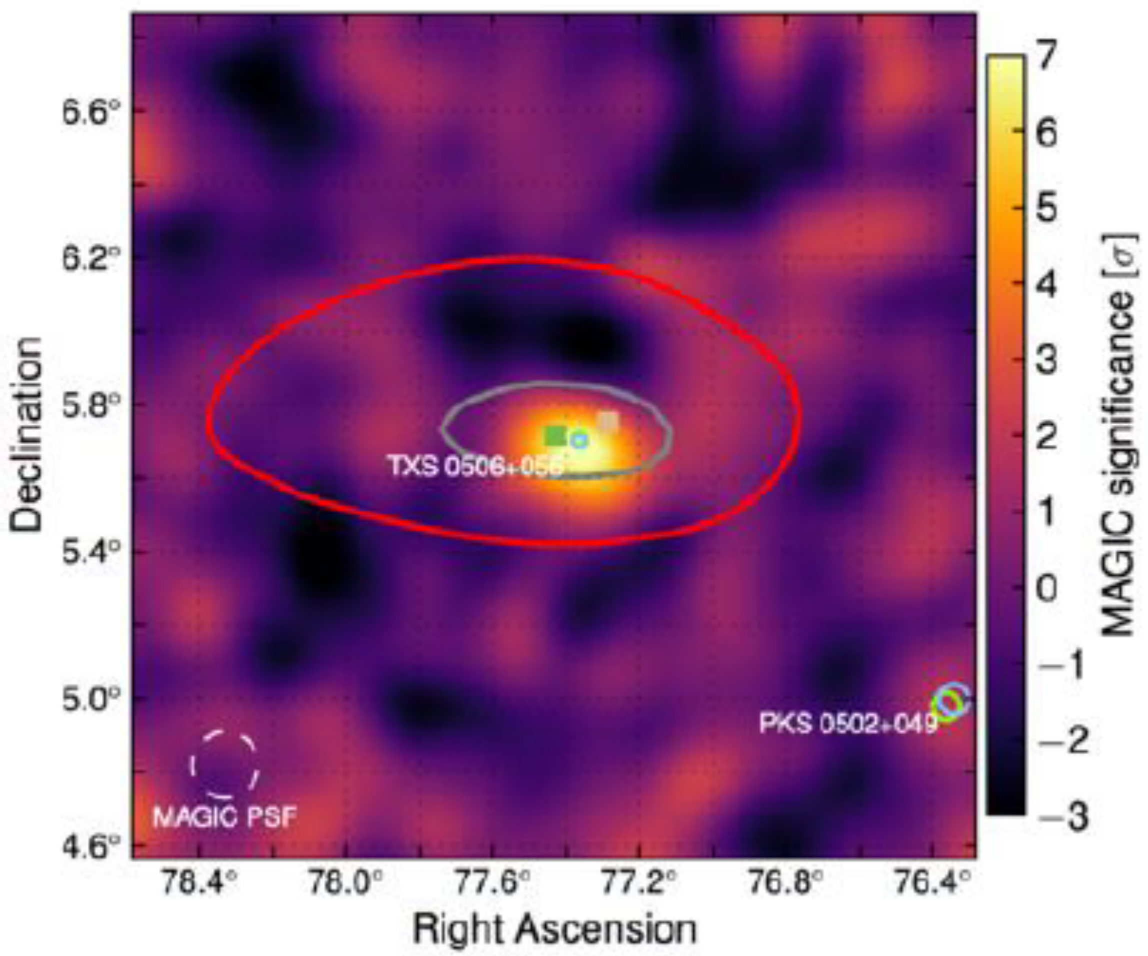
@LIGO, NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA

TXS 0506+056 — identified high-energy neutrino source (3.5 σ) IceCube-170922A

The IceCube Collaboration, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams, 2018, Science, 361, 6398



Multimessenger observations



~300 TeV neutrino coincident with a γ-ray flare up to 400 GeV

TXS 0506-056 is a blazar (might be FSRQ), a class of the active galactic nuclei

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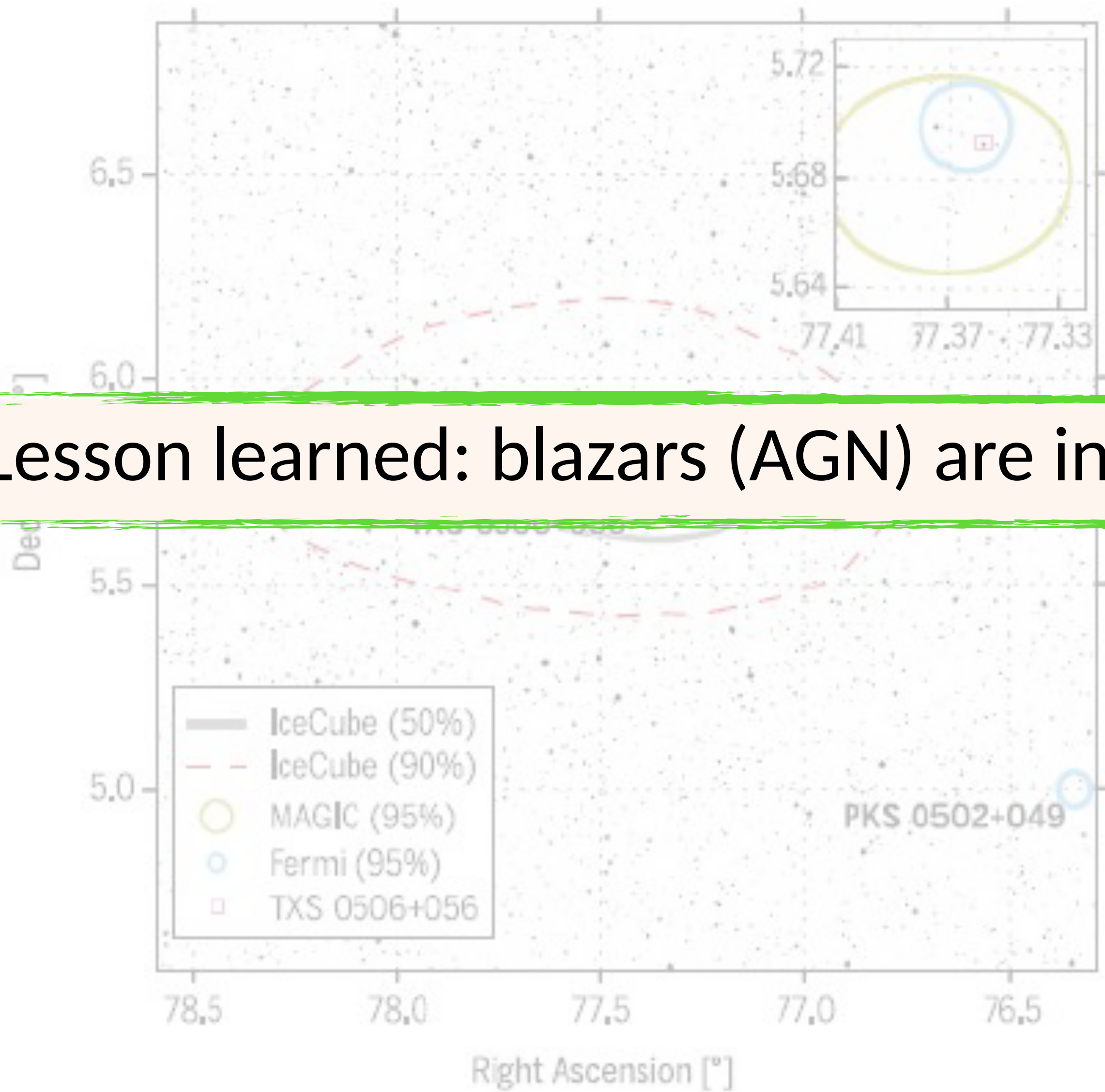
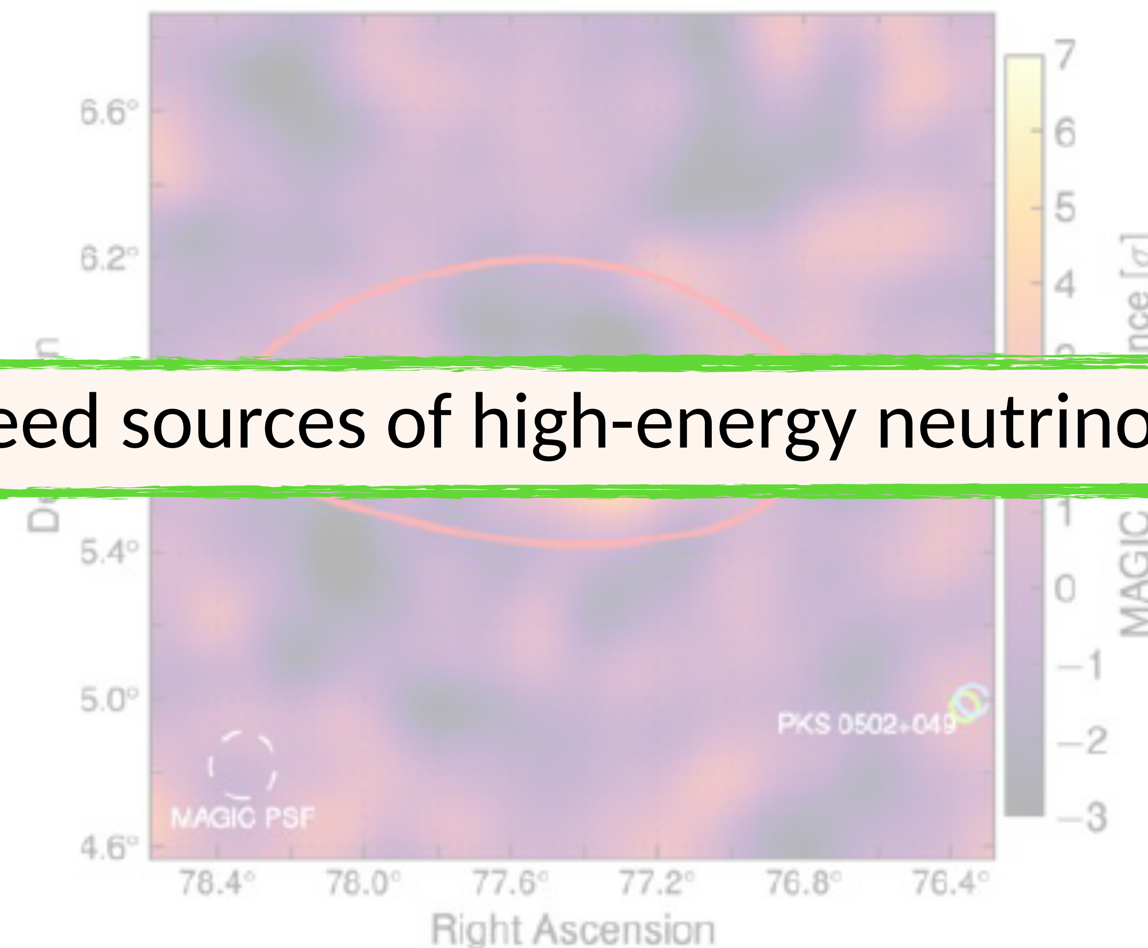


Multimessenger observations



~300 TeV neutrino coincident with a γ-ray flare up to 400 GeV

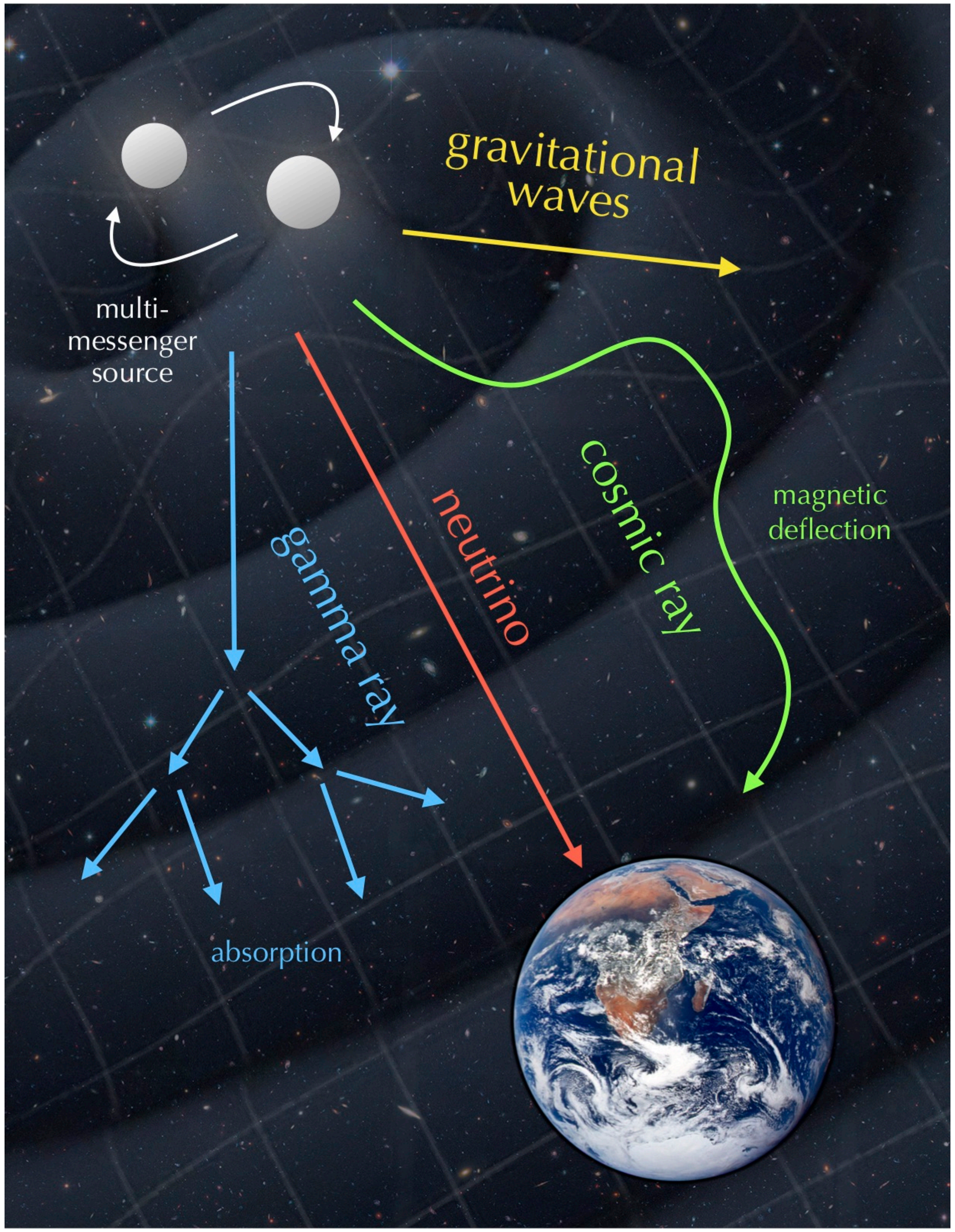
Lesson learned: blazars (AGN) are indeed sources of high-energy neutrinos

TXS 0506-056 is a blazar (might be FSRQ), a class of the active galactic nuclei

Violent phenomena in the Universe

- active galactic nuclei (AGN)
- starburst galaxies
- tidal disruption events
- gamma-ray bursts
- merger of compact objects
- pulsars
- collapse of stellar cores
- …etc

they are able to accelerate particles



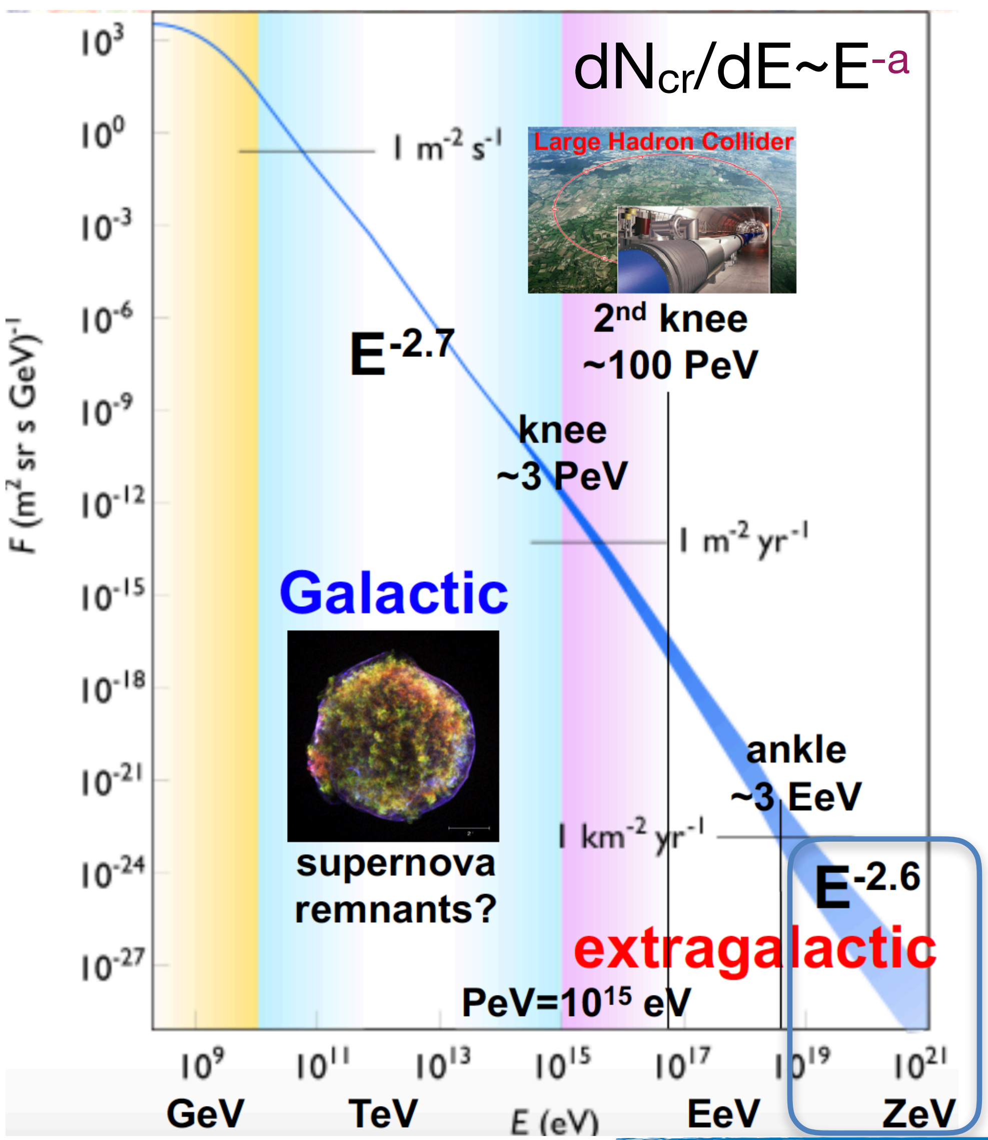
Cosmic-ray energy spectrum

Cosmic-rays

Charged particles (with intrinsic masses) from the Solar System, the Galaxy and beyond…

Protons (90%), heavier nuclei (9%), others (1%)

Oh-My-God particle (1991): 3×10^{11} GeV, 50 J



@Murase, 2018

1) How are cosmic rays accelerated?
bottom-up scenarios: *diffusive shock acceleration (a~2)*, Espresso models, acc. via induced electric field

2) How do they propagate?
diffusive, rectilinear

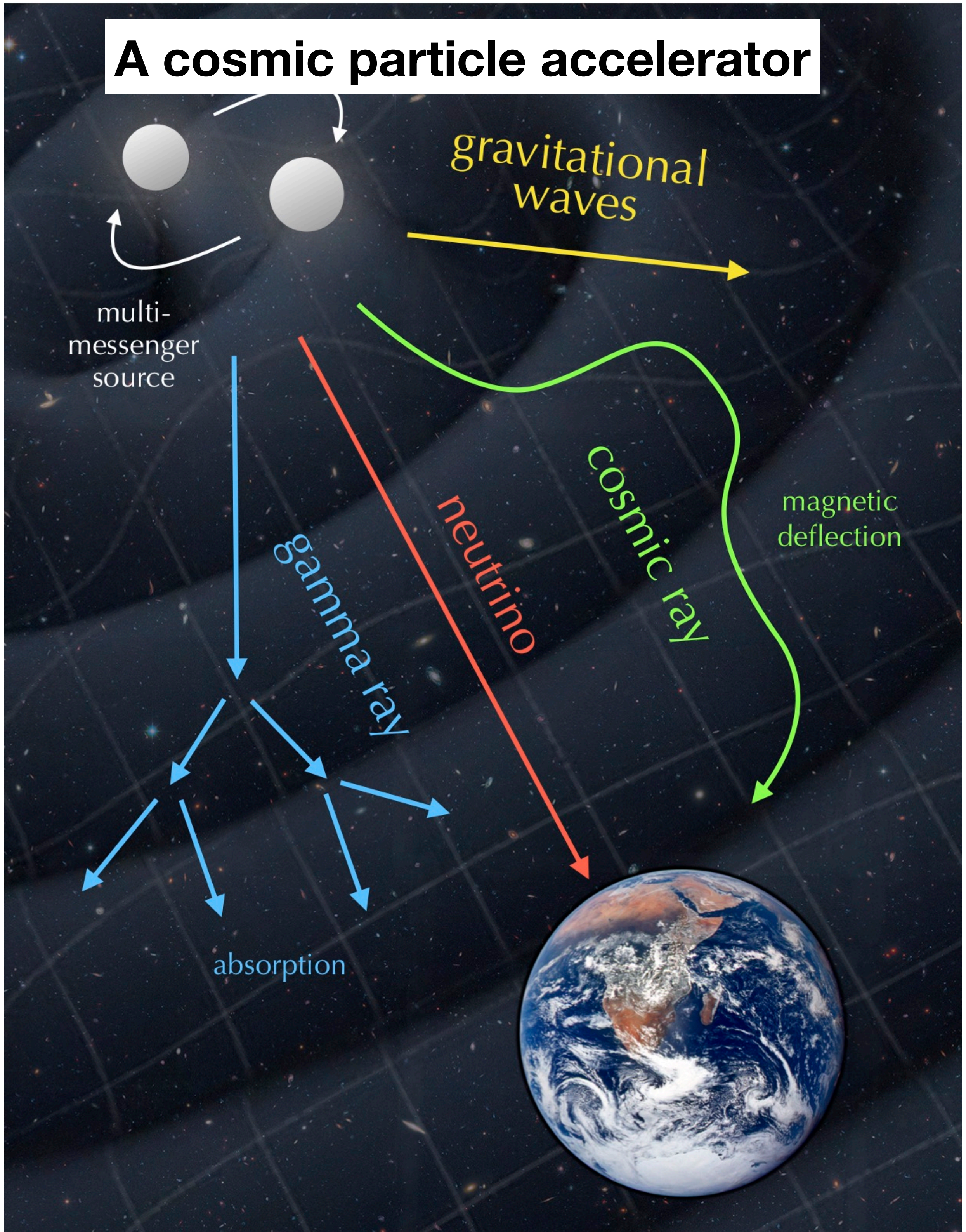
3) Transition from Galactic to extragalactic?

4) Where are their sources?

UHE CRs: 10^{18} eV < E_{UHECR} (LHC 6.5×10^{12} eV/beam)

4) Where are the (UHE)CR sources?

A century—years old puzzle



UHECRs

10^{18} eV < E_{UHECR} (LHC 6.5x10^{12} eV/beam)

Deflection by galactic and intergalactic magnetic fields

Greisen–Zatsepin–Kuzmin limit

The observed UHECR flux above ~ 5 x 10^{19} eV comes from sources within ~ 100 Mpc. It is z=0.024!

Gamma-rays make pairs with the EBL and CMB

The high-energy gamma-ray horizon at TeV energies is constrained to the universe at z < 1 and at PeV energies it is constrained to our Galaxy!

Pierre Auger Observatory (PAO):

One such event every four weeks in the 3000 km^2 area surveyed by the observatory

It is extremely difficult to find the sources of UHECRs

Multimessenger connection —Baryonic loading

Energetic hadronic beam propagating with relativistic speed interacts…

… with the ambient radiation

$$p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{0} + p \quad \text{(p=2/3)}$$
$$\rightarrow \pi^{+} + n \quad \text{(p=1/3)}$$

… with the ambient medium

$$p + p \rightarrow N_{\pi}[\pi^{0} + \pi^{+} + \pi^{-}] + X$$

(equal number of pions emerge)

The huge kinetic energy of the hadrons can exceed the rest mass of the pions

Both neutral (π^0) and charged (π^+ or π^0) secondary pions are produced

Neutral pions decays for gamma rays:

$$\pi^{0} \rightarrow \gamma + \gamma$$

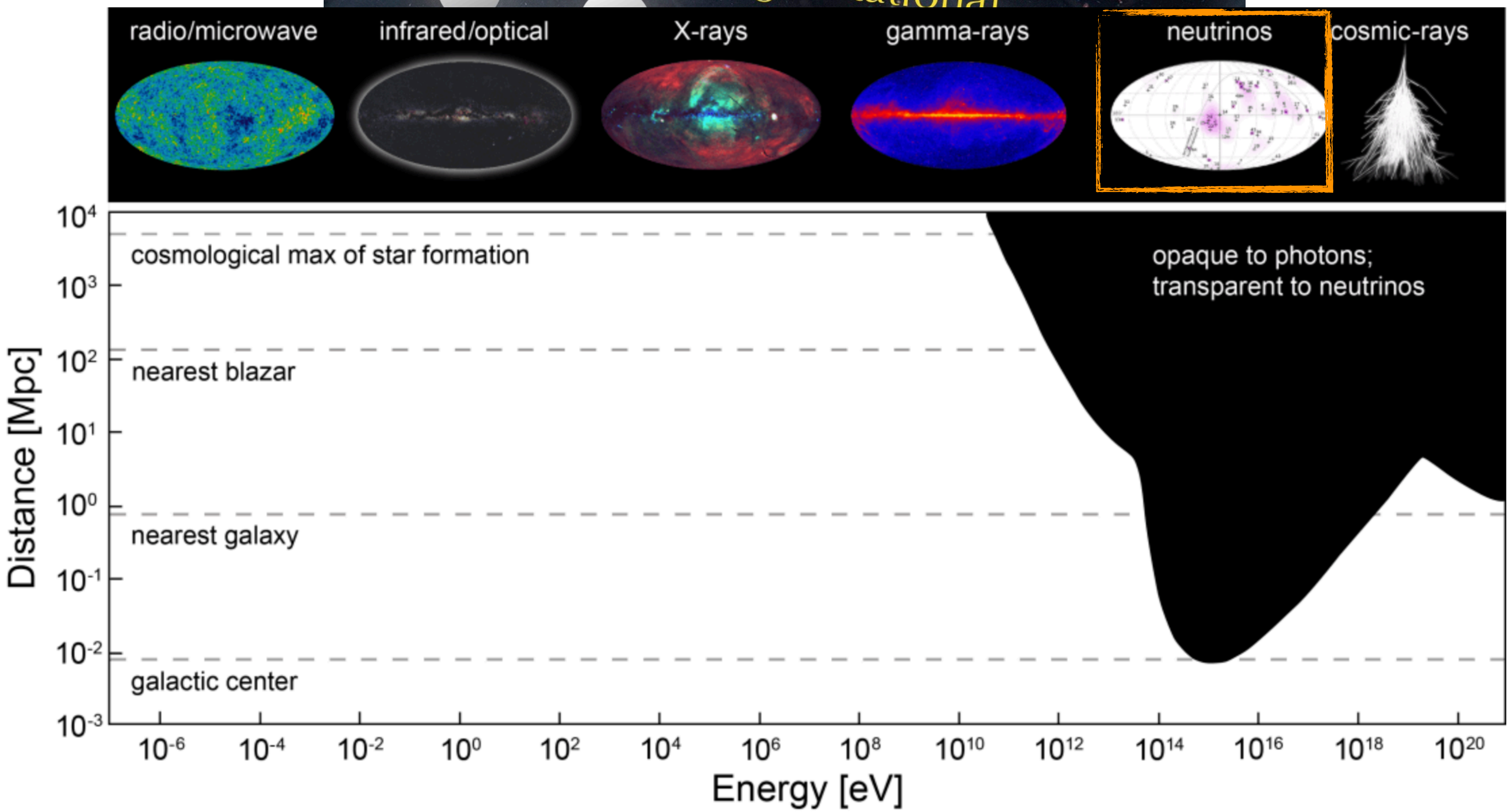
Charged pions decay via the chain:

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$
$$\mu^{+} \rightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$
$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$$
$$\mu^{-} \rightarrow e^{-} + \nu_{\mu} + \bar{\nu}_{e}$$

High-energy astrophysical neutrinos are produced: *electron* and *muon* neutrinos

Cosmic rays, gamma-photons and high-energy neutrinos are intimately related to each other

The observable Universe as function of the energy



Neutrinos are **key messengers** to reveal an **unobstructed view of the universe** where it is opaque to light, and to the high-energy cosmic rays

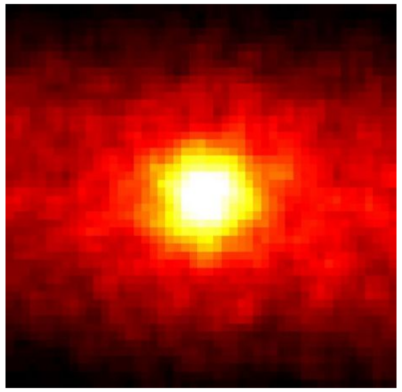
Neutrinos from the cosmos

Cosmic neutrino-background (primordial neutrinos, diffuse SN- neutrino background)

Solar (and SN) neutrinos (nuclear processes)

Energy

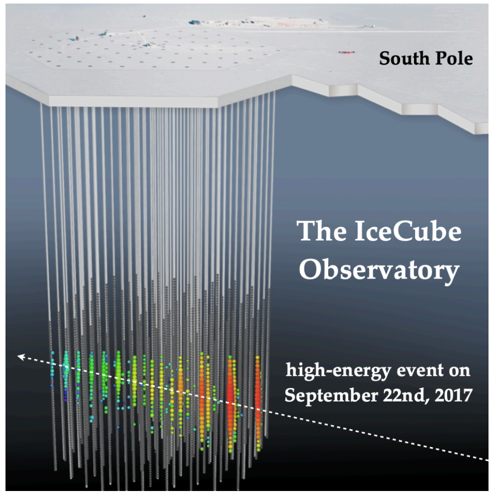
The Sun in neutrinos,
Super-Kamiokande



10^{-4} eV

>20 order of magnitudes

Cosmic neutrinos (meson decay in distant sources)



High-energy neutrino
from an active galaxy

10 PeV<

Cosmogenic neutrinos (UHECRs+CMB, GZK cutoff)

1 eV=1,6x10^{-19} J
10 PeV=1,6x10^{-3} J

The rest-mass energy of a muon neutrino is <0,17 MeV
10 PeV is 10^{11} times this

Extremely efficient acceleration

Cosmic neutrinos

Galactic

- SNII supernovae
- Binary neutron stars
- Microquasars
- Magnetars
- Anomalous X-ray pulsars
- Molecular clouds

Extragalactic

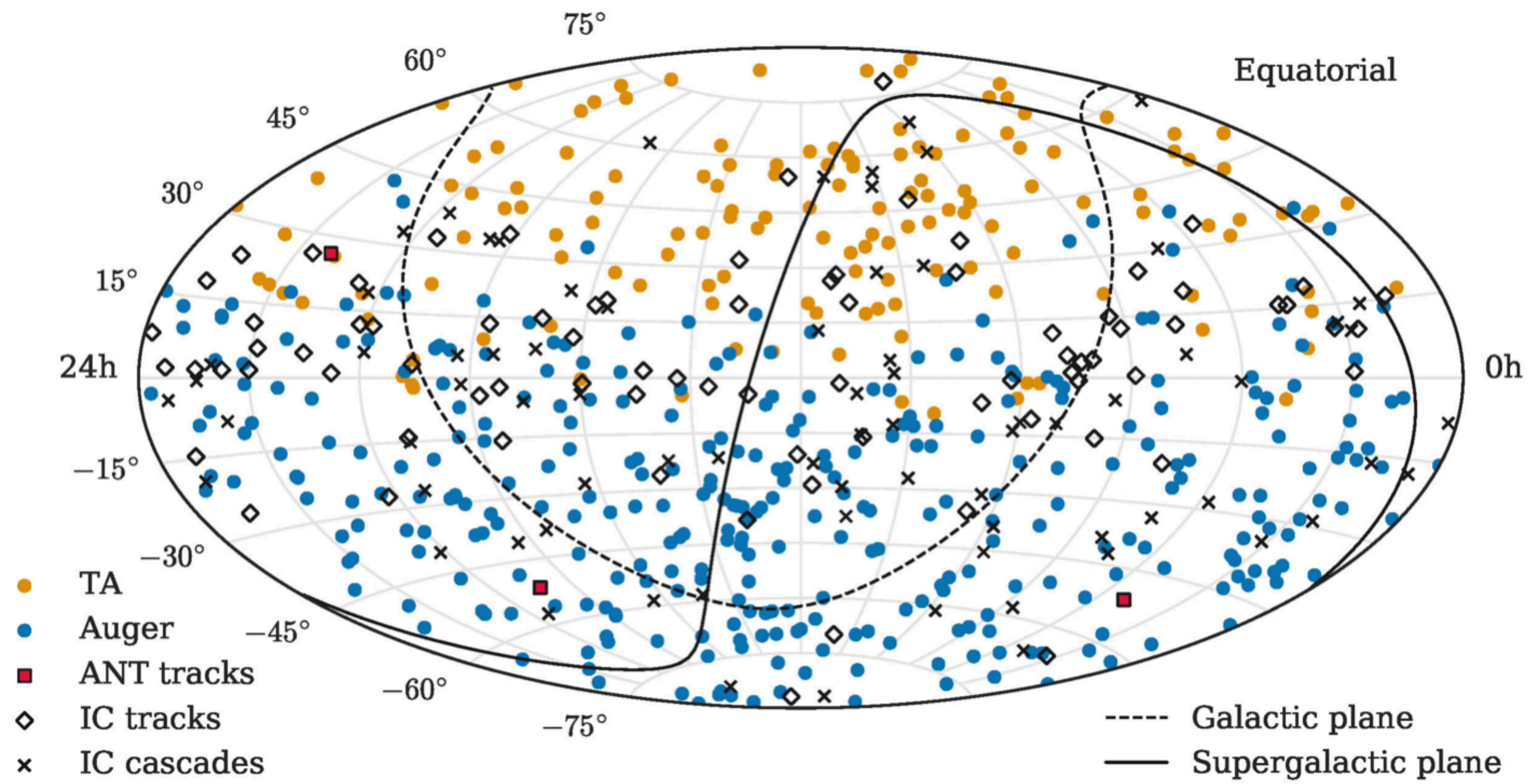
- Active galactic nuclei
- Starburst galaxies
- Tidal disruption events
- Gamma-ray bursts

What we observe might be a cumulative signal of all sources
Where are the dominant sources?

High-energy neutrinos from *extragalactic* UHECR sources?

A large part of the signal might come!

- HE neutrinos are isotropically distributed
- Their intensity is compatible with expectations
- No significant correlation between nearby UHECR sources and neutrinos



Sky map of the arrival directions of UHECR events from the Pierre Auger Observatory and the Telescope Array and high-energy neutrinos from IceCube and ANTARES. Credit: The ANTARES, IceCube, Pierre Auger and Telescope Array collaborations.

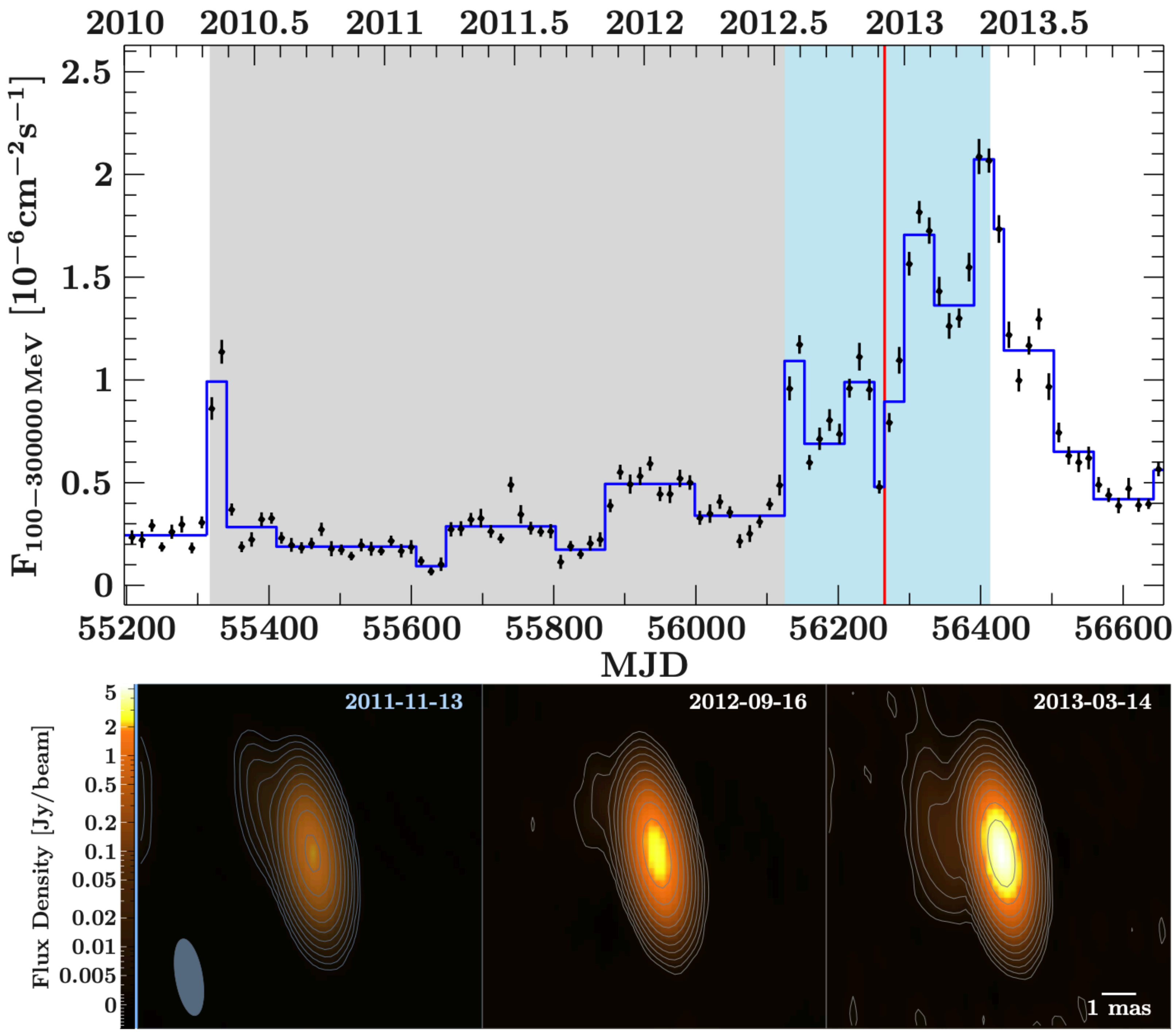
ANTARES, IceCube, Pierre Auger and Telescope Array Collaborations: M.G.Aartsen et al. Submitted to *Astrophysical Journal.* arxiv.org/abs/2201.07313

Gamma-ray observations+neutrinos

- 2nd Fermi-LAT AGN catalog (2LAC), IC-59, IC-79, IC-86 (May 2009-April 2021): max contribution of ***2LAC blazars is 27% or less*** (Aartsen et al 2017)
- ***Extended sources*** (1,2,3,4,5deg) with 7 years of IceCube data (IC-40,IC-59, IC-70, IC-86-I,II,III,IV): all maps with simulated extended sources are *consistent with* ***background only*** **models** (Pinat et al. 2017)
- 3LAC, Roma BZCAT, IC-86 (2011) tracks: ***no more than 5%-15% of the diffuse neutrino flux*** **can originate from this class of objects** (Hooper et al. 2019)
- 4LAC, IC-79(2010), IC-86(2011),IC-86(2012): ***blazars can produce no more than 15% of the IceCube's observed neutrino flux***, non-blazar sources could produce the entire flux (Smith et al. 2021)
- … and many more

Successes with (gamma-ray flaring) individual sources

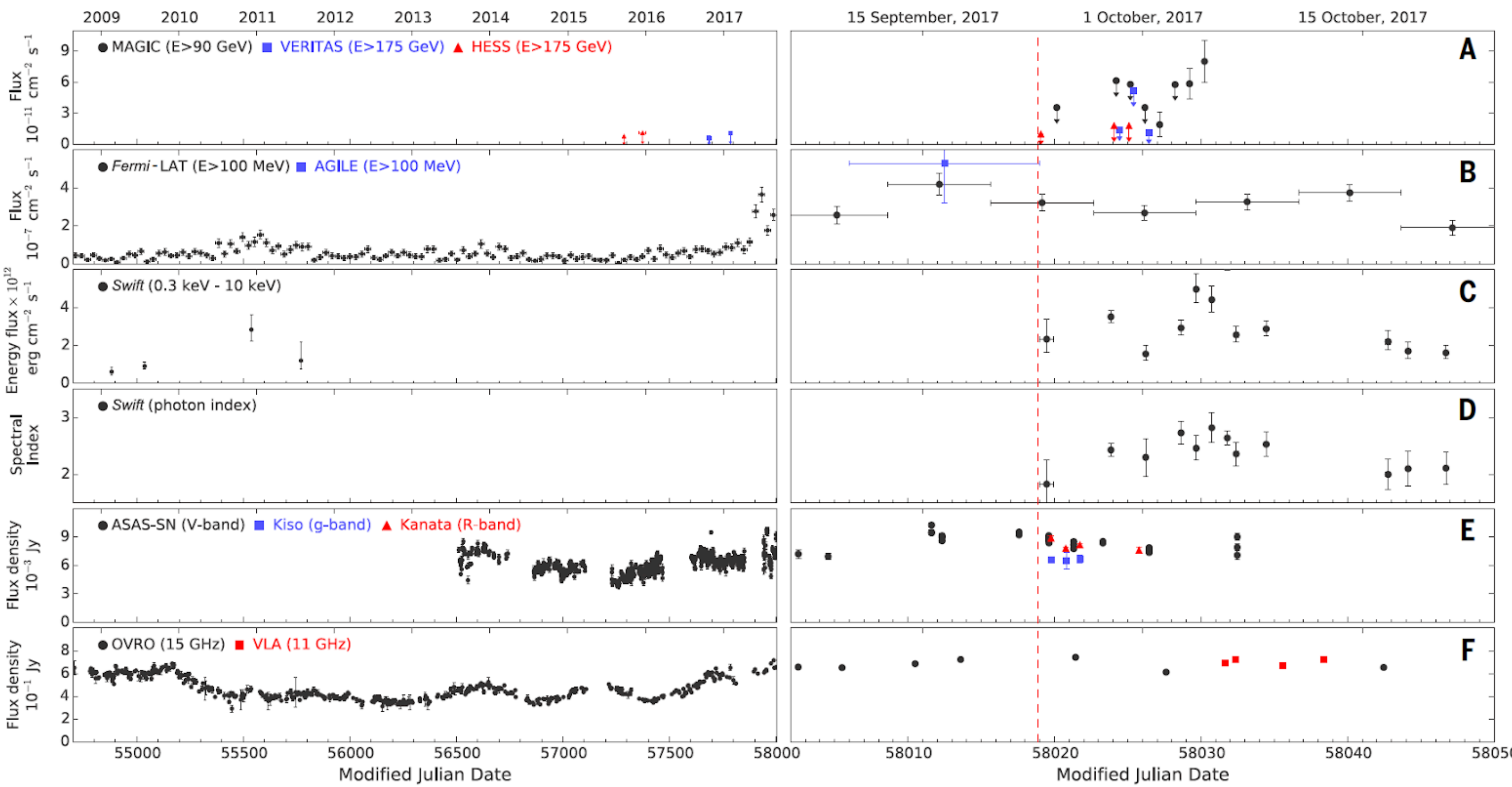
PKS B1424–418 Coincidence of a high-fluence blazar outburst with a PeV- energy neutrino event dubbed “Big Bird” **(HESE-35)**



Kadler et al., 2016, NatPhys, 12, 807

Successes with (gamma-ray flaring) individual sources

TXS 0506+056 — identified high-energy neutrino source **(3.5 σ) IceCube-170922A**

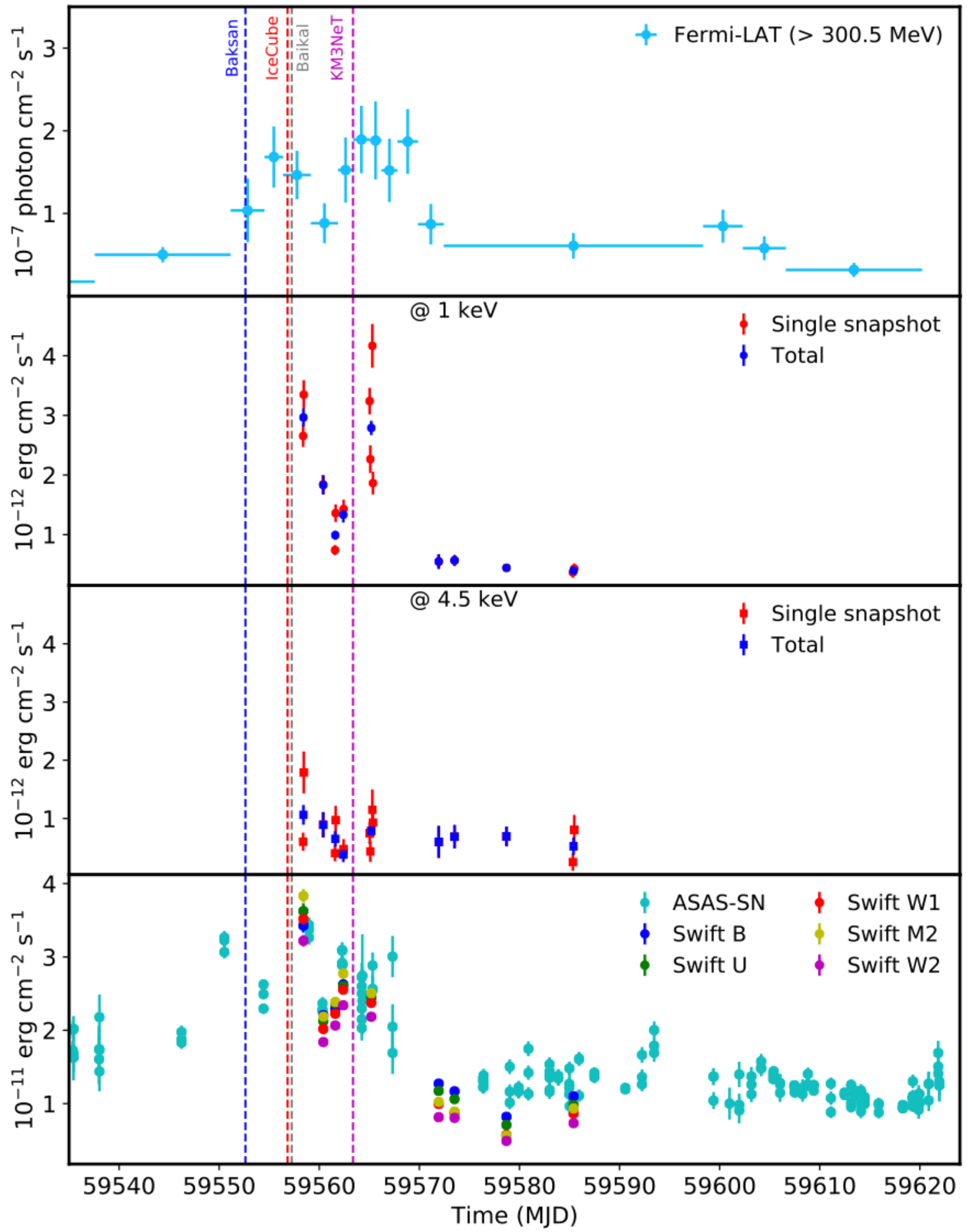


The IceCube Collaboration, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams, 2018, Science, 361, 6398

Successes with (gamma-ray flaring) individual sources

PKS 0735+178 — a new major neutrino source candidate

IceCube, Baikal, Baksan, KM3NET



Sahakyan et al., arXiv: 2204.05060

Radio observations+neutrinos

- searching correlations between astro neutrinos and individual radio sources or <u>source catalogs</u>
- 7 years of IceCube muon tracks, **8 GHz VLBI data of 3411 radio-loud AGN** (Plavin et al 2020, 2021): ***4.1 sigma connection***
- **AGN samples by** OVRO (15 GHz) and Metsahovi radio observatories (36.8 GHz), IceCube tracks (Hovatta et al. 2021): ***radio flares in blazars at the same time as the neutrino event unlikely to be random coincidence at 2 sigma level***
- method2: stacking analysis (Achterberg et al. 2006)
- **10 year of muon tracks 3,388 Radio Fundamental Catalog** (Zhou et al. 2020): ***these AGN can account for at most 30% (95 CL) of the flux of neutrino tracks***
- MOJAVE XV. Catalog (15 GHz, VLBA) 10 years of detector data (Desai et al 2021): no significant correlation

No significant findings, but there are promising results

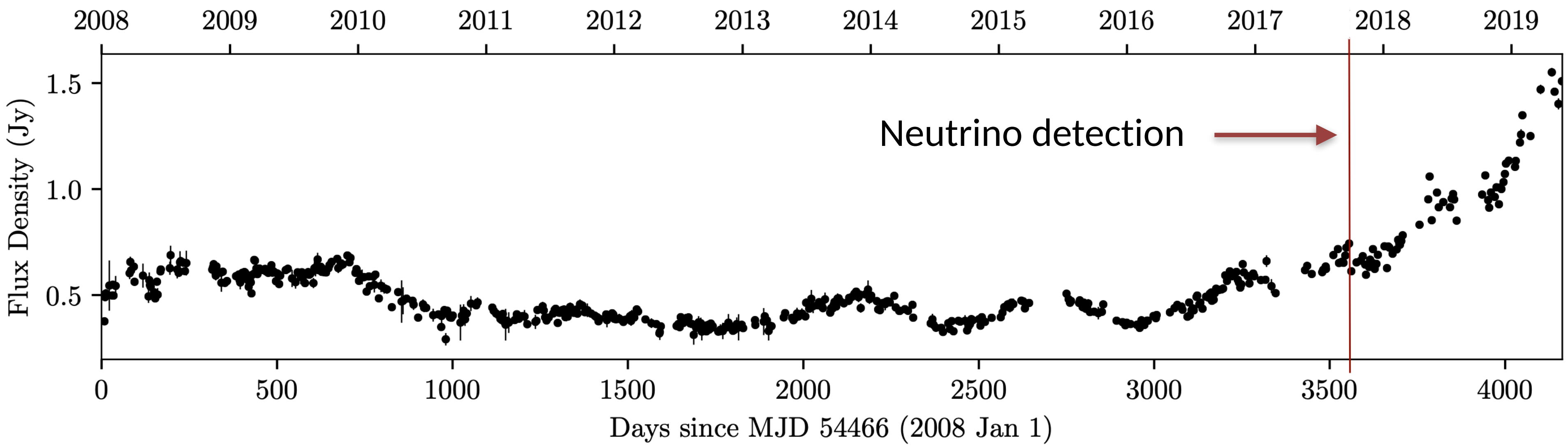
Radio observations+neutrinos

- method 1: search correlations between astro neutrinos and individual radio sources or source catalogs

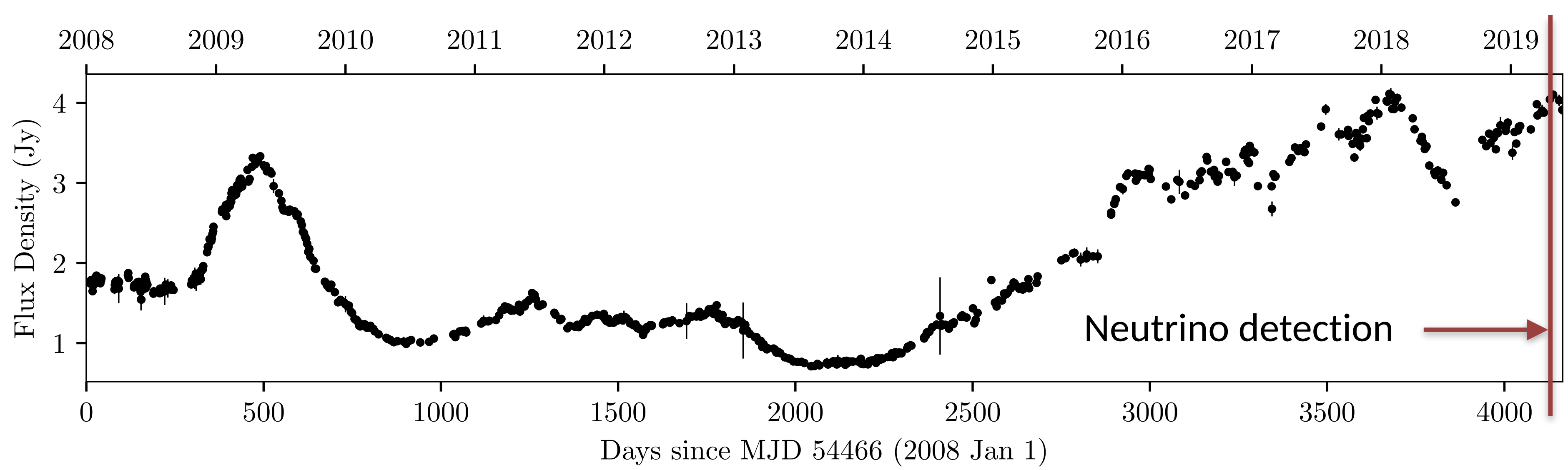
Single-dish radio observation of individual sources

Examples:

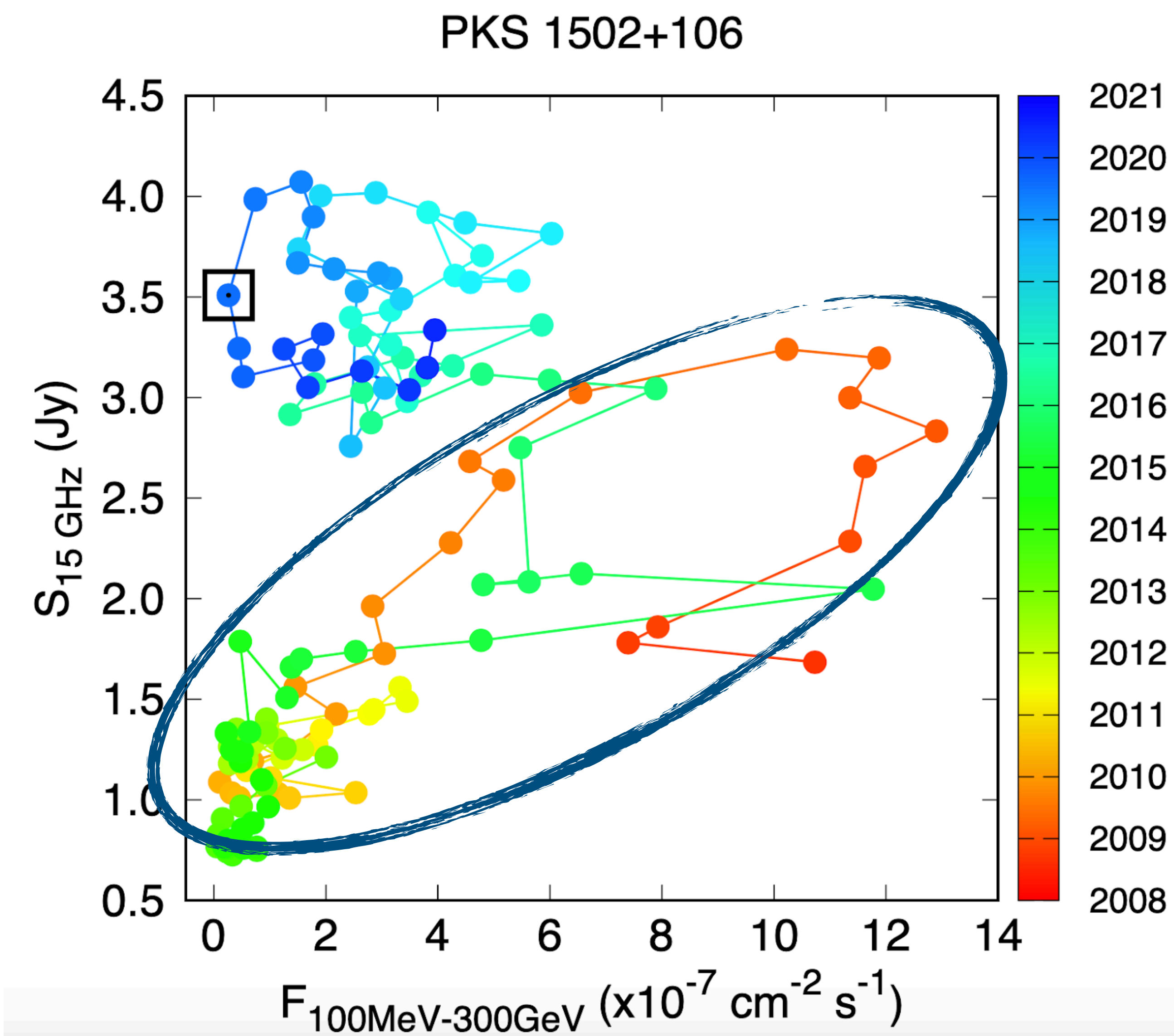
TXS 0506+056 (OVRO, 15 GHz)

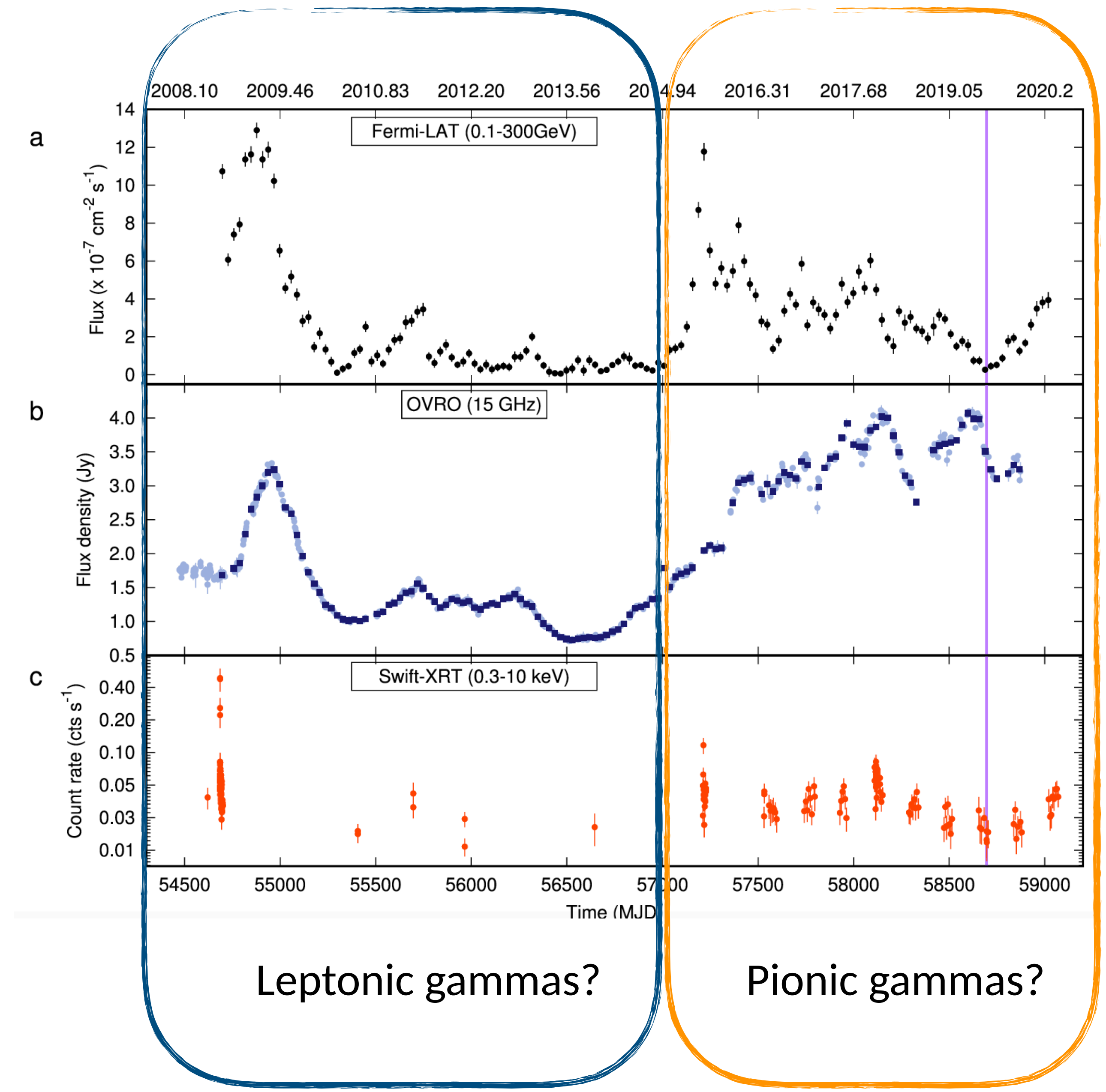


PKS 1502+106 (OVRO, 15 GHz)



PKS 1502+106: gamma-ray flux vs radio flux density





Mode1: gamma correlates with radio, the radio lagging behind the gamma flux (R=0.85, τ_c=59+-32 days)

Mode2: more complex connection

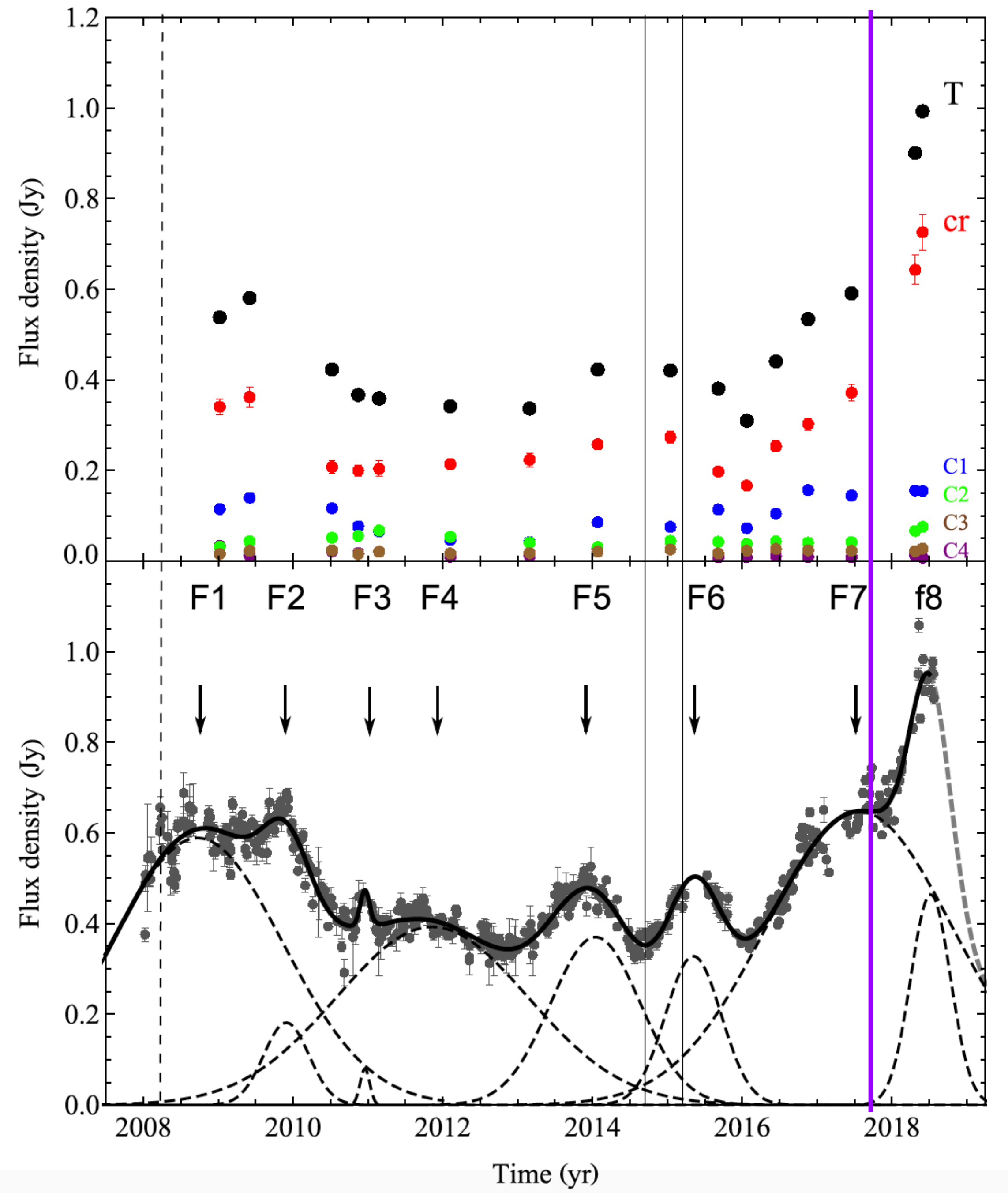
Kun, Bartos, Becker-Tjus, Biermann, Halzen, Mező, 2021, ApJL, 911, L18

What caused this switch?

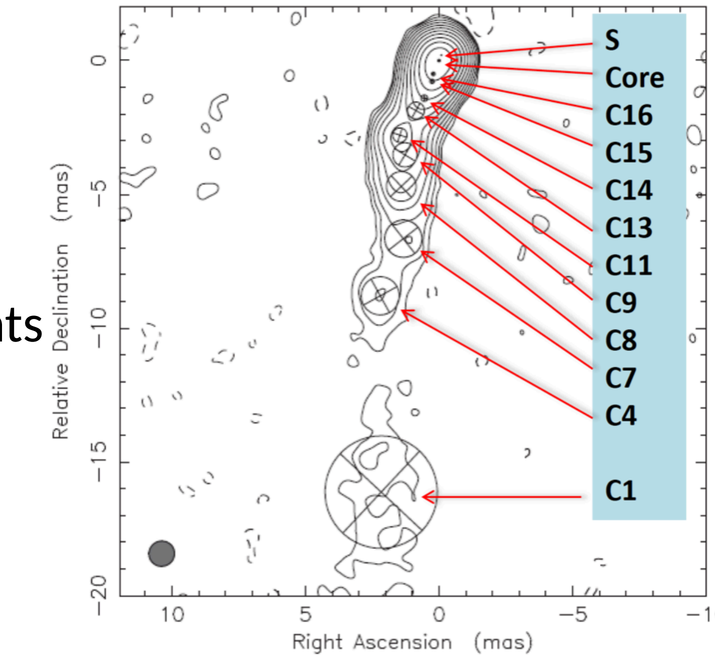
VLBI of radio-loud neutrino source candidates

Radio brightening of TXS 0506+056

Kun, Biermann, Gergely 2019, MNRAS Letters, 483, 42



VLBI of S5 1928+738 ->
VLBI core + jet components



Flux density curve of the jet components (MOJAVE/VLBA at 15 GHz)

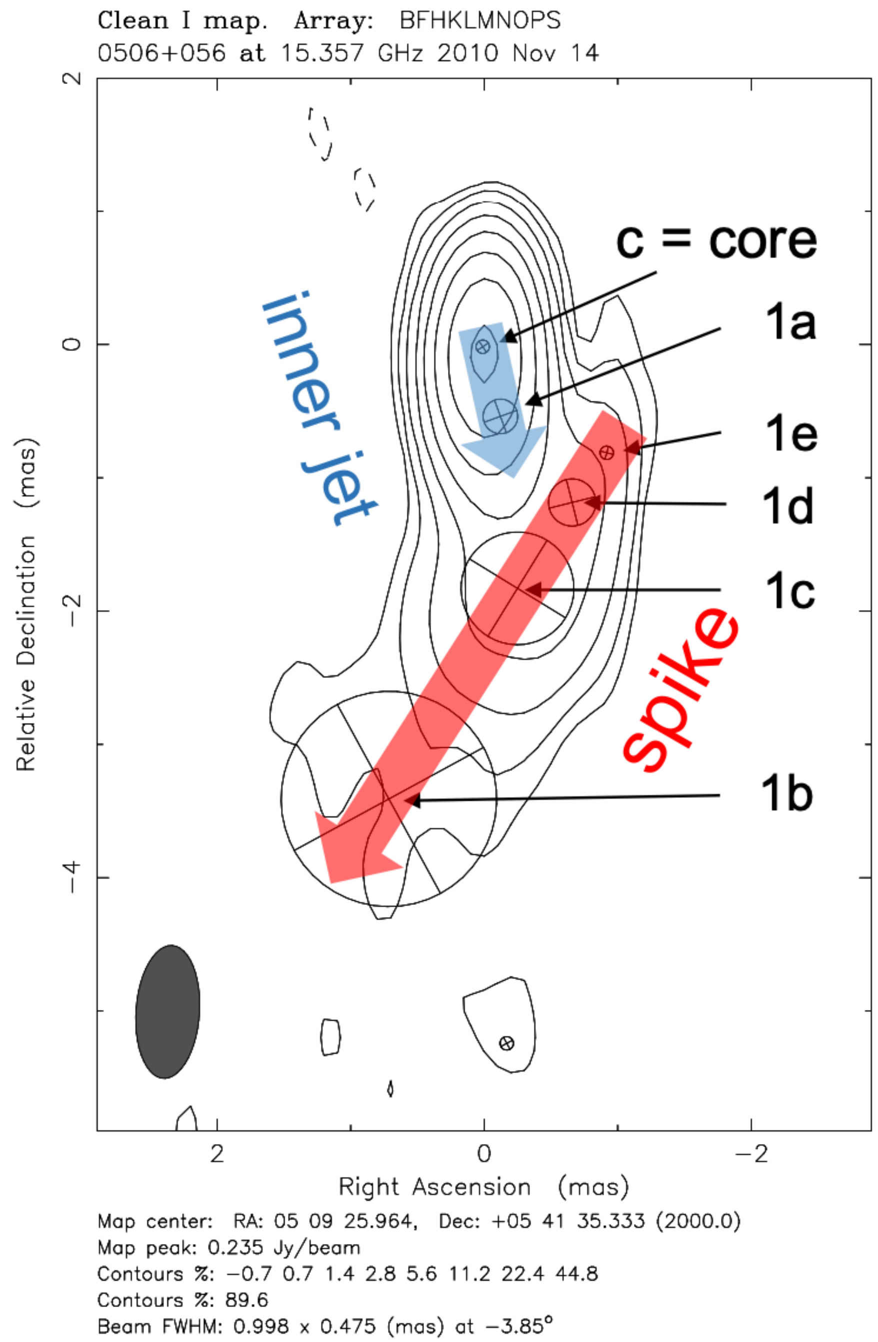
VLBI core is responsible for the brightening at 15 GHz

(same results at higher frequencies, e.g. Ros et al. 2019)

IceCube-170922A

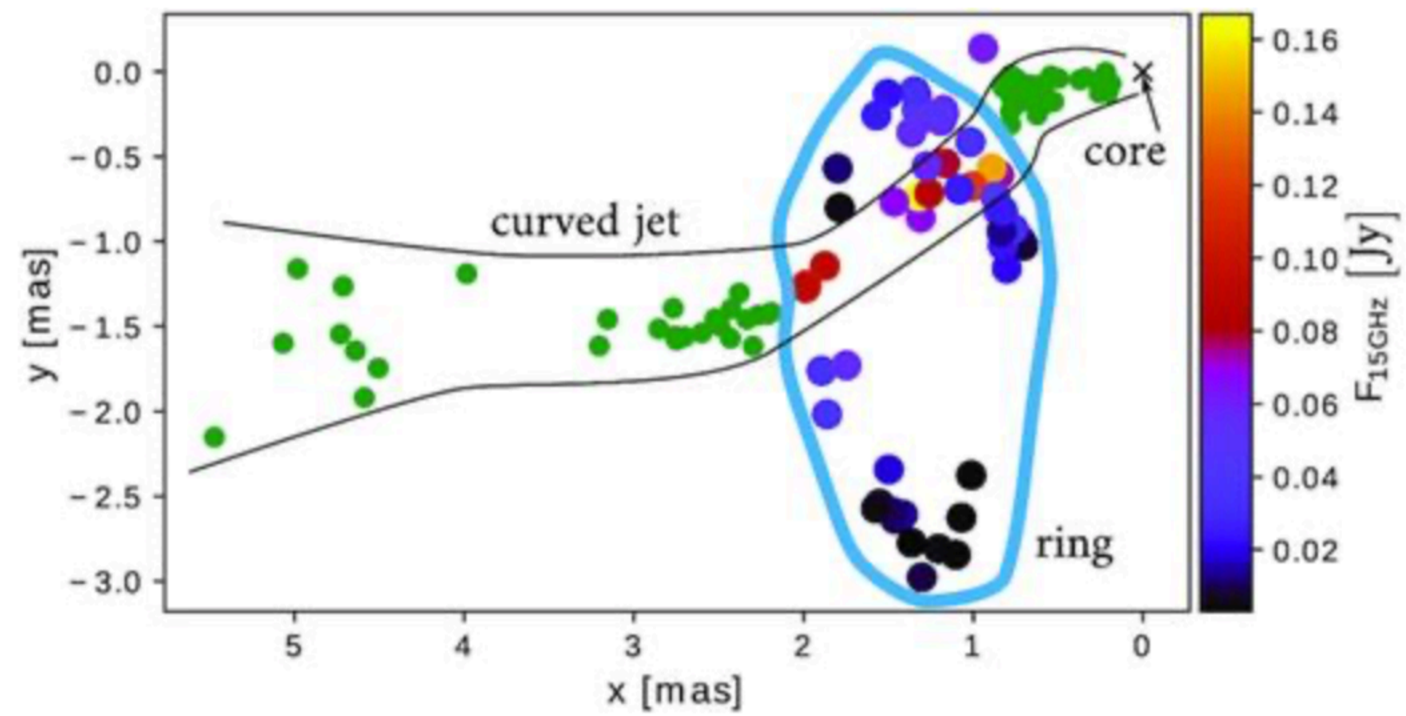
Gaussian decomposition of the single dish flux density curve at 15 GHz measured with the OVRO 40m Telescope

VLBI of individual sources



A cosmic collider: Was the IceCube neutrino generated in a precessing jet-jet interaction in **TXS 0506+056**?

Britzen et al. 2019

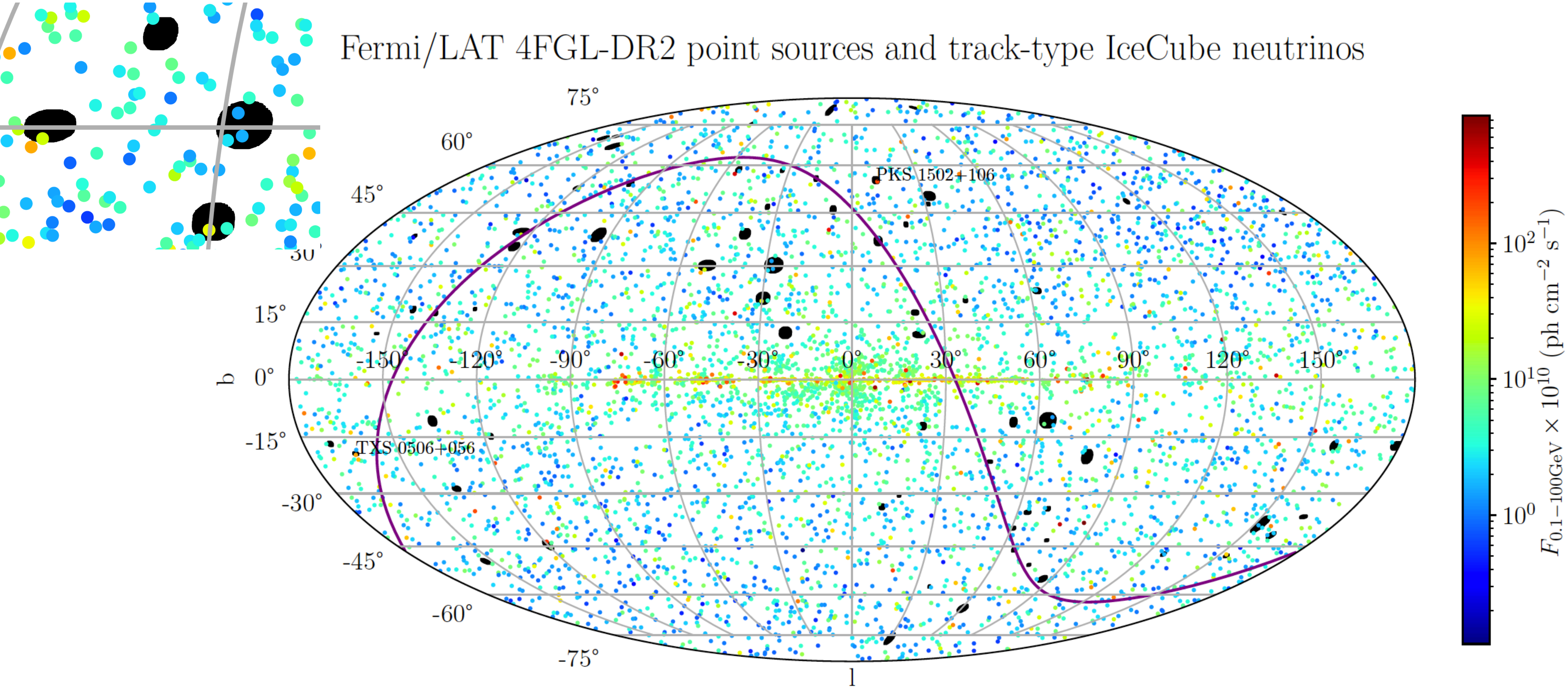


A ring accelerator? Unusual jet dynamics in the IceCube candidate **PKS 1502+106**

Britzen et al. 2021

Fermi-LAT 4FGL-DR2 + 70 IceCube muon-tracks (2009-2019)

- Matched positions of point sources in the *Fermi*-LAT 4FGL-DR2 catalog (~80% of them are blazars) with 70 track-type IceCube neutrinos (2009-2019) from Giommi et al. (2020). Number of gamma-ray sources: 5,787
- Found 29 4FGL-DR2 point sources within the 90 C.L. error ellipse of the neutrinos



Kun et al. 2022, submitted

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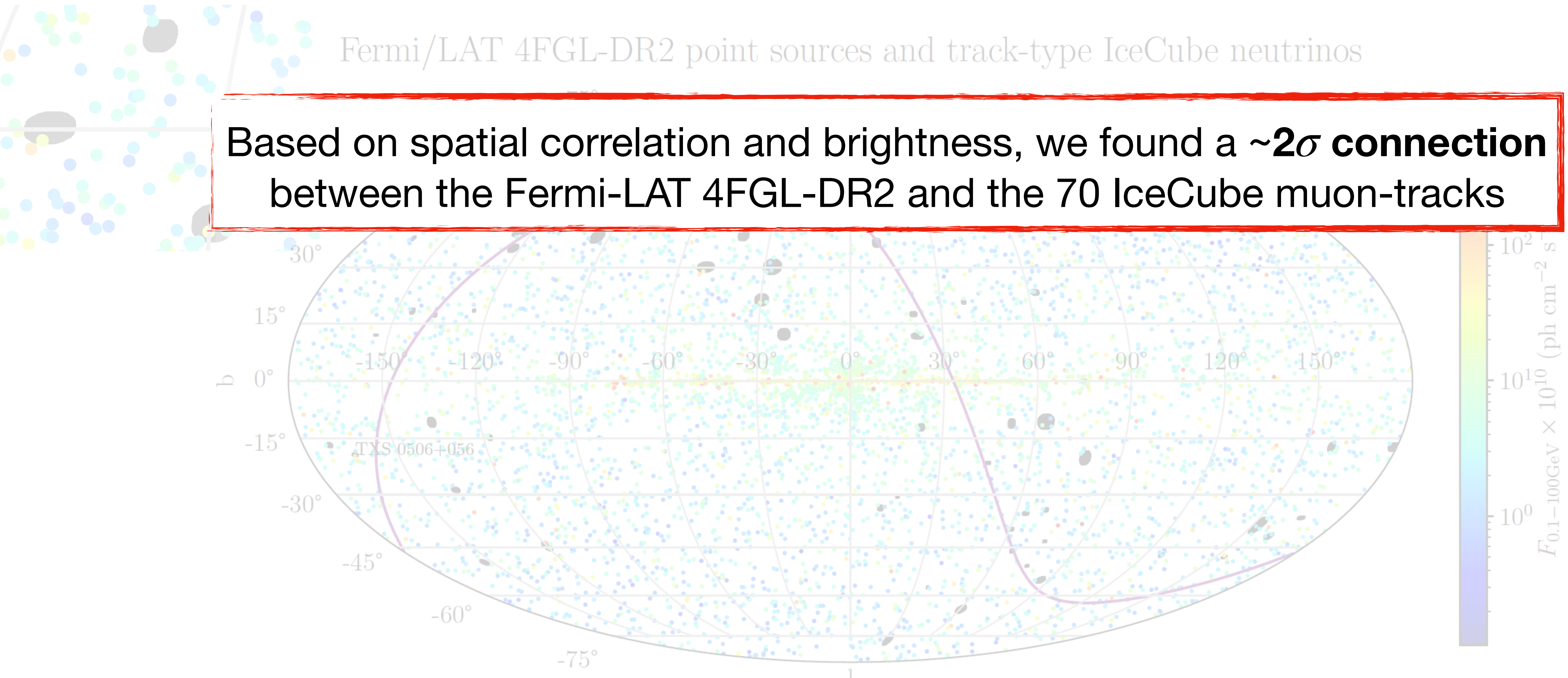
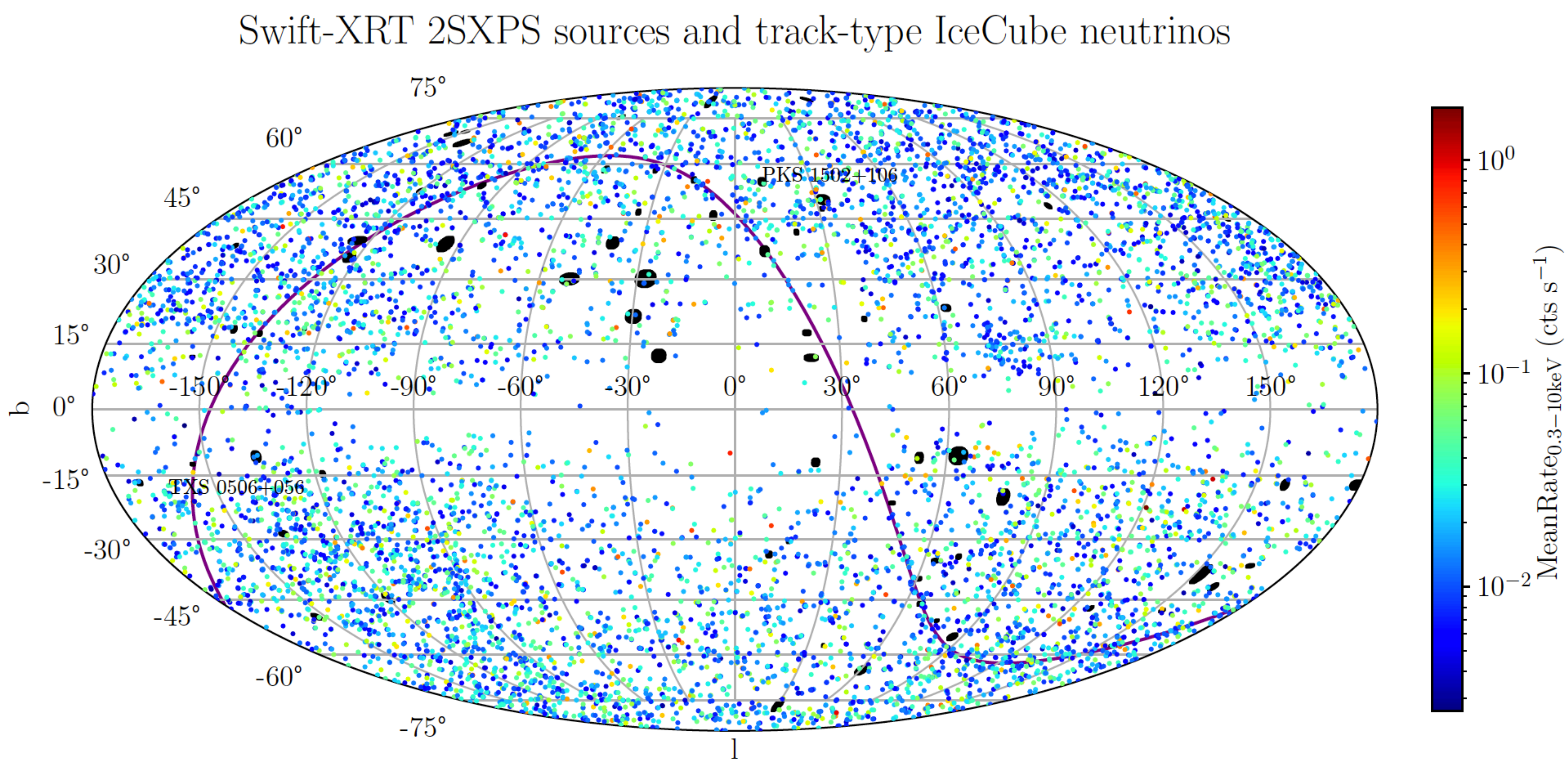


Based on spatial correlation and brightness, we found a ~2σ **connection** between the Fermi-LAT 4FGL-DR2 and the 70 IceCube muon-tracks

Kun et al. 2022, submitted

Swift-XRT 2SXPS + 70 IceCube muon-tracks (2009-2019)

- Matched positions of point sources in the Swift-XRT 2SXPS catalog with 70 track-type IceCube neutrinos (2009-2019) from Giommi et al. (2020)
- Restricted to: SNR>10, P(AGN)>99%, number of sources: 9,079
- Found 61 2SXPS point sources within the 90 C.L. error ellipse of the neutrinos



Kun et al. 2022, submitted

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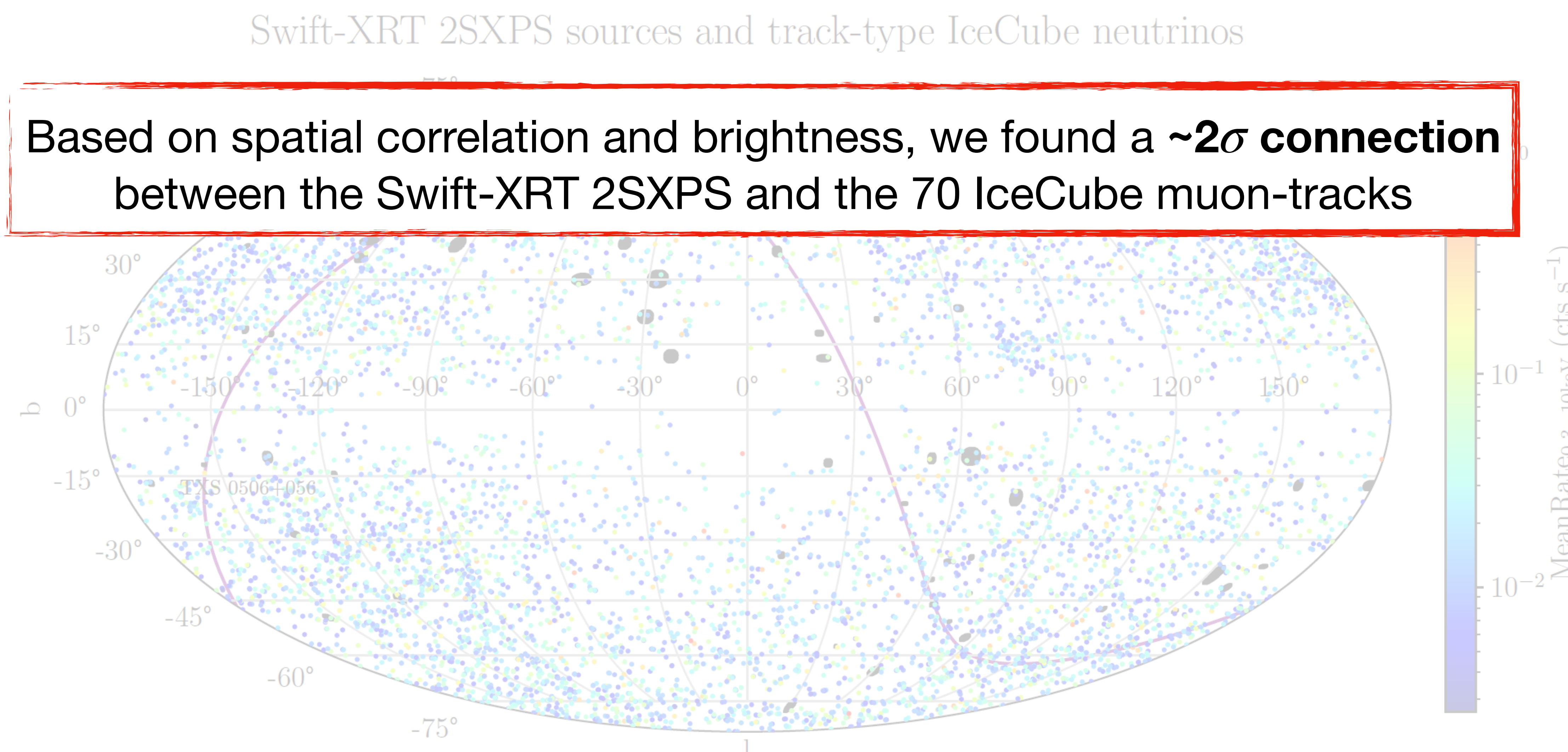

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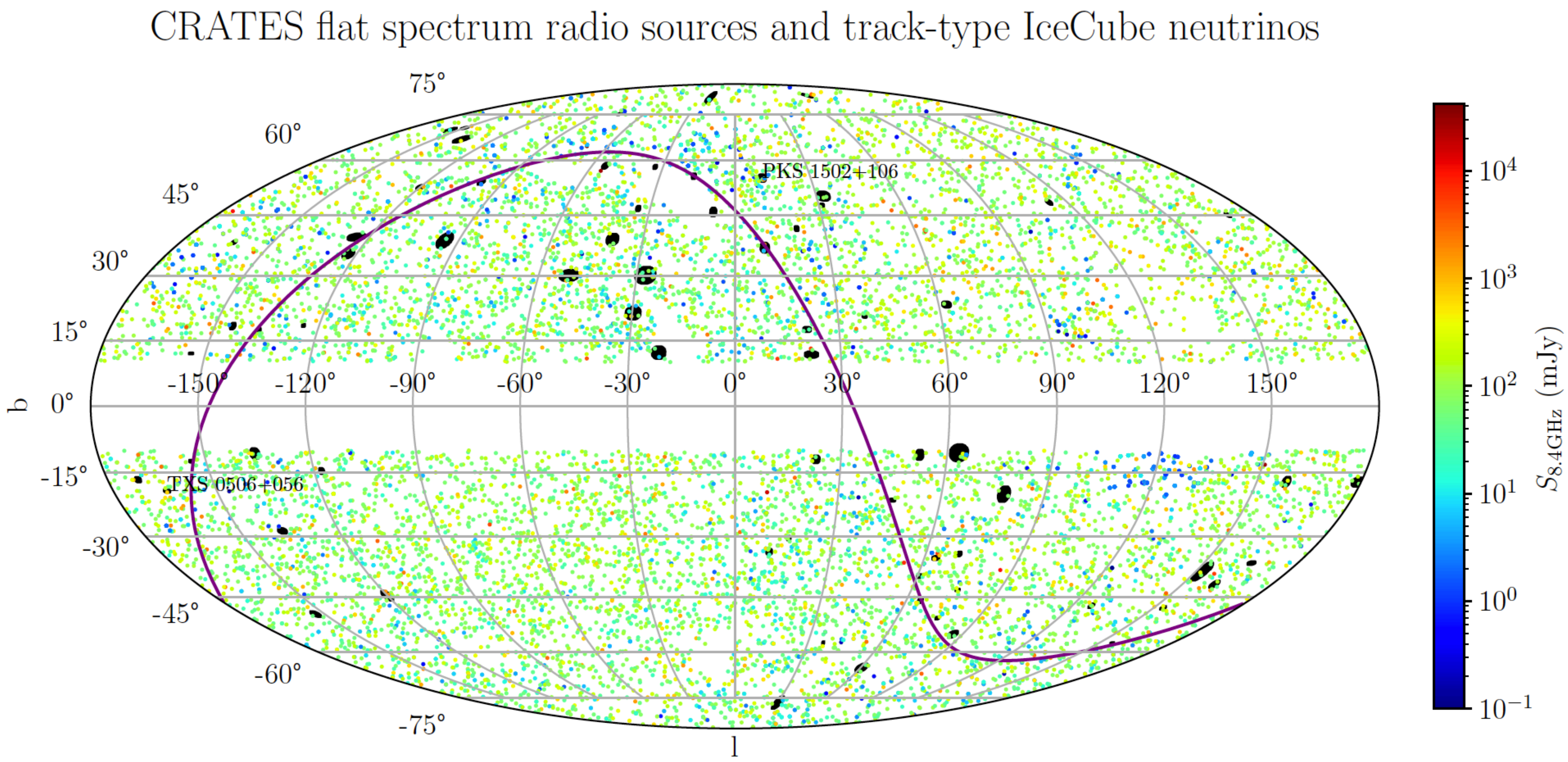
Kun et al. 2022, submitted

CRATES 4.8 GHz and 8.4 GHz + 70 IceCube muon-tracks (2009-2019)

- Matched positions of point sources in the CRATES 8.4 GHz catalog (also 4.8 GHz, mostly blazars, quasars) with 70 track-type IceCube neutrinos (2009-2019) from Giommi et al. (2020). Number of radio sources at 4.8GHz(8.4GHz): 11,131(14,467)
- Found 87 (96) CRATES sources at 4.8 GHz (8.4 GHz) within the 90 C.L. error ellipse of the neutrinos



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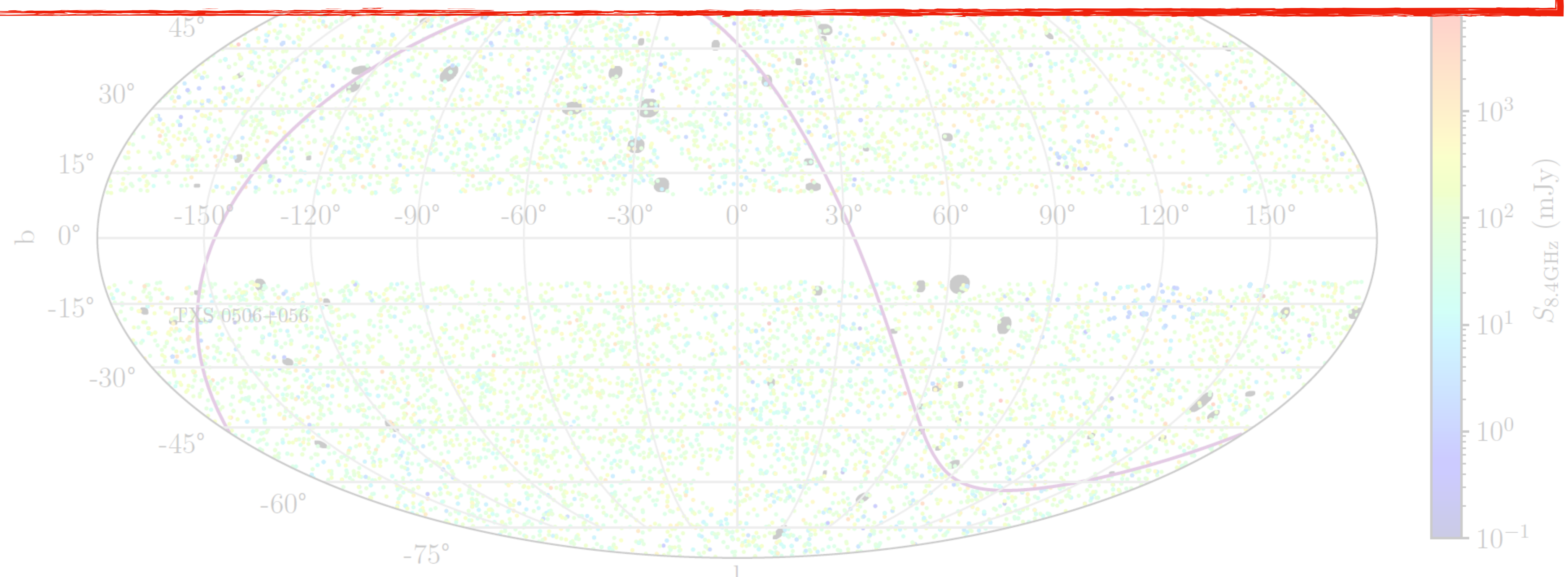
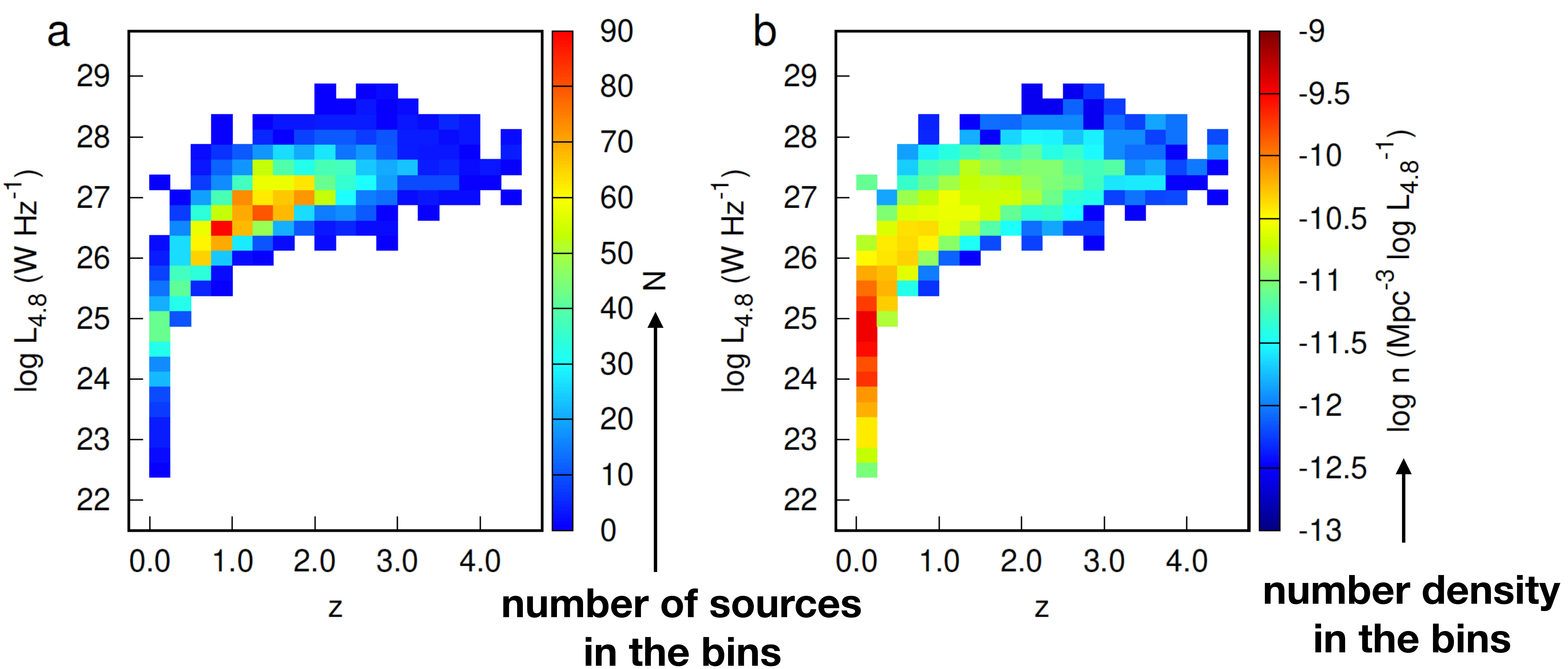
Based on spatial correlation and brightness, we found a **~2σ connection** between the CRATES catalog and the 70 IceCube muon-tracks



Kun et al. 2022, submitted

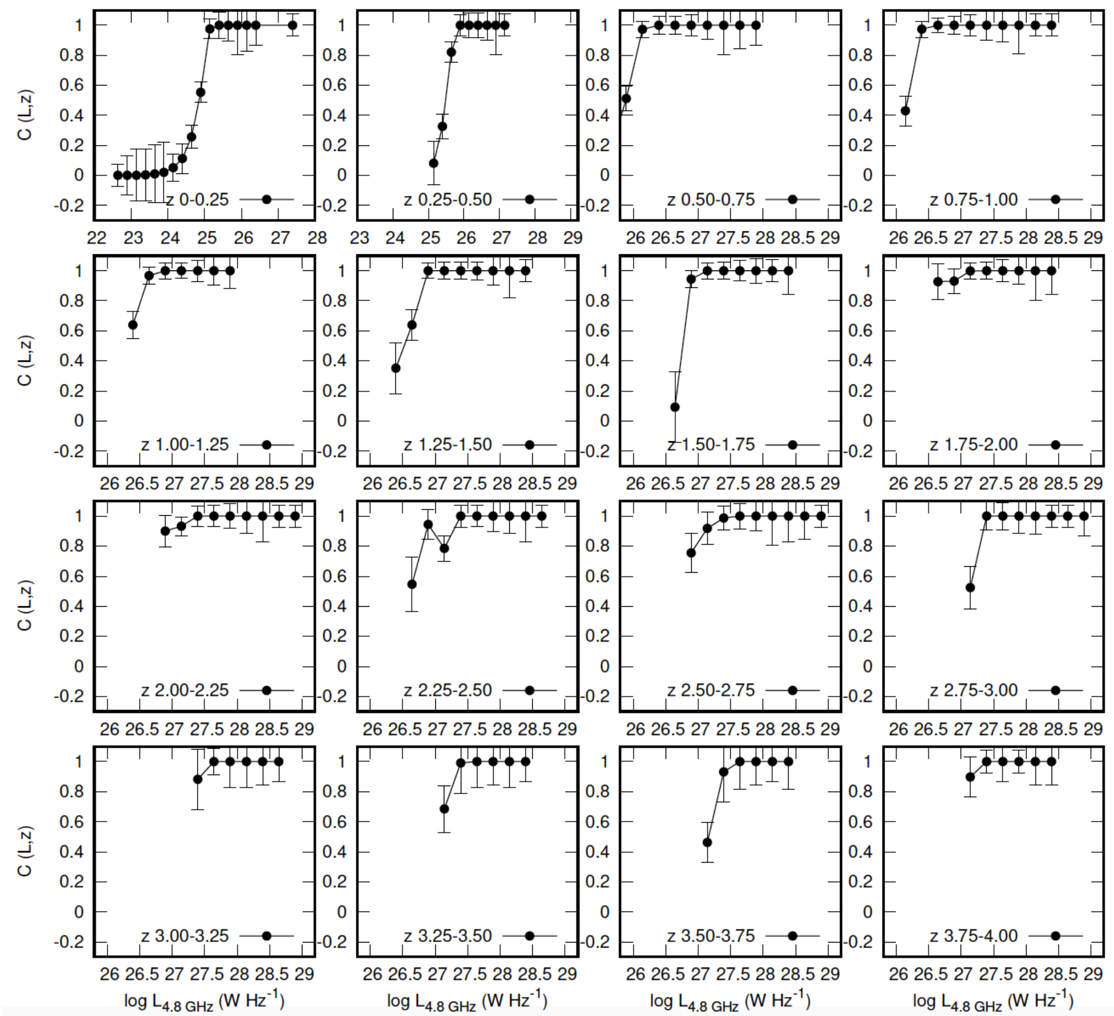
CRATES + neutrinos

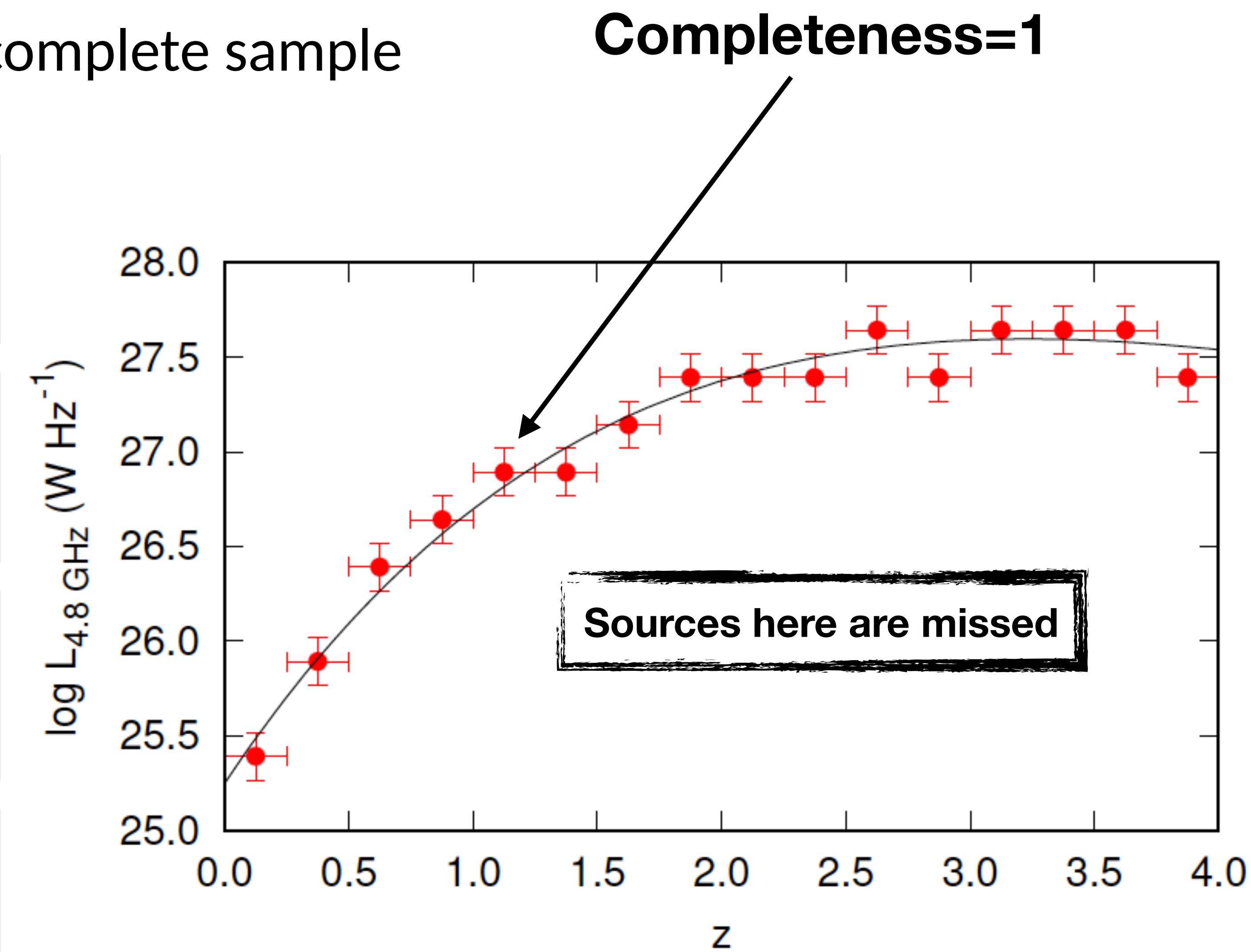
- Made a complete sample of CRATES (complete in luminosity redshift plane)
- Collection of redshifts (~1/3 of them was found), calculation of the radio luminosity, position errors
- Luminosity functions were calculated ($1/V_a$), redshift evolution was found as expected



Kun et al. 2022, submitted

- Restricted the analysis only for the complete sample



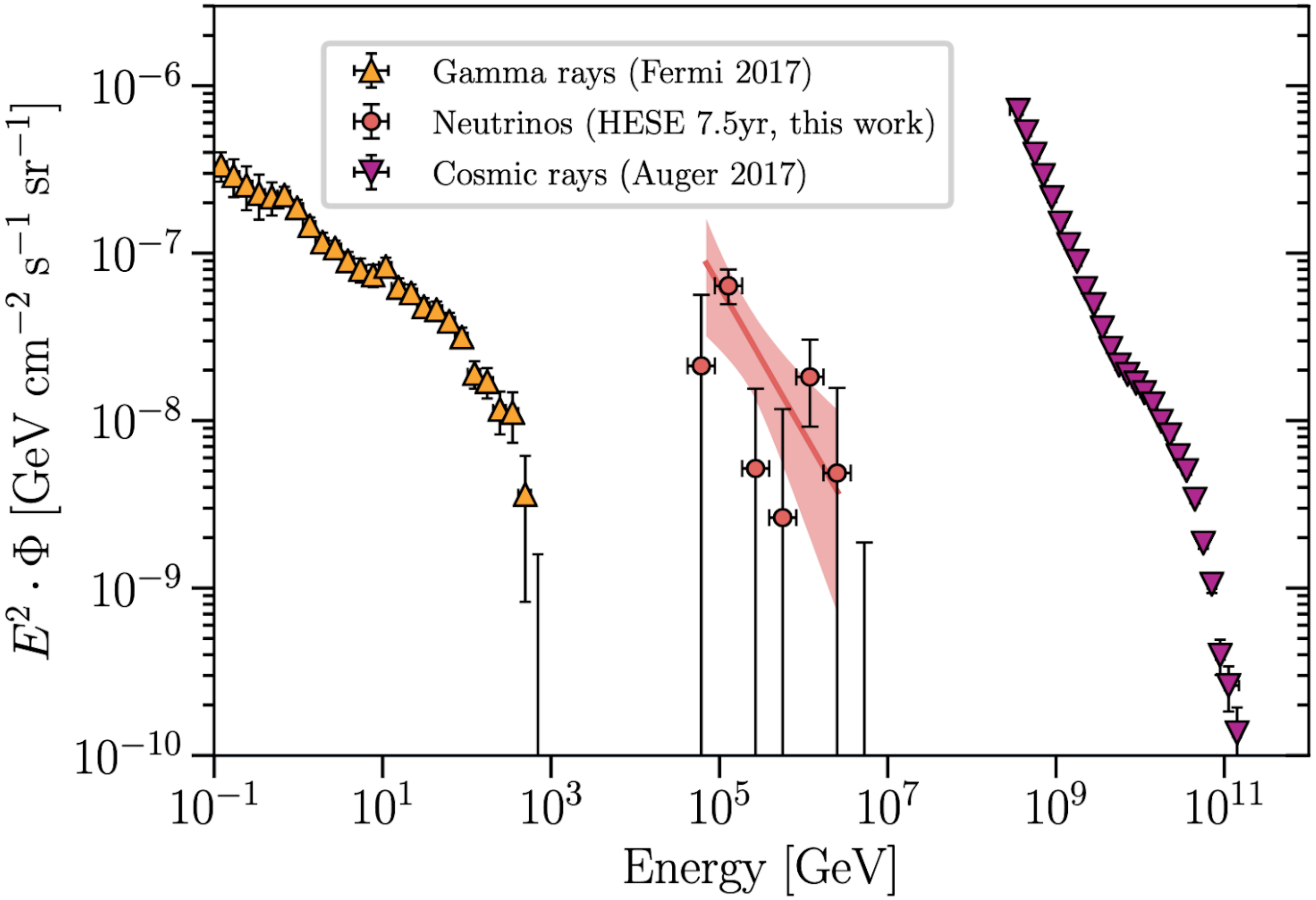


- Calculated how many neutrinos could be explained with this complete sample, if the probability to detect a neutrino is proportional to the radio luminosity
- Results: the **CRATES 4.8 GHz (8.4 GHz)** complete sub-sample **can explain between 4% and 53% (3% and 42%) of the neutrinos (90% C.L.)**.

No significant findings, but there are promising results

High-energy fluxes of gamma-rays, neutrinos, and cosmic-rays

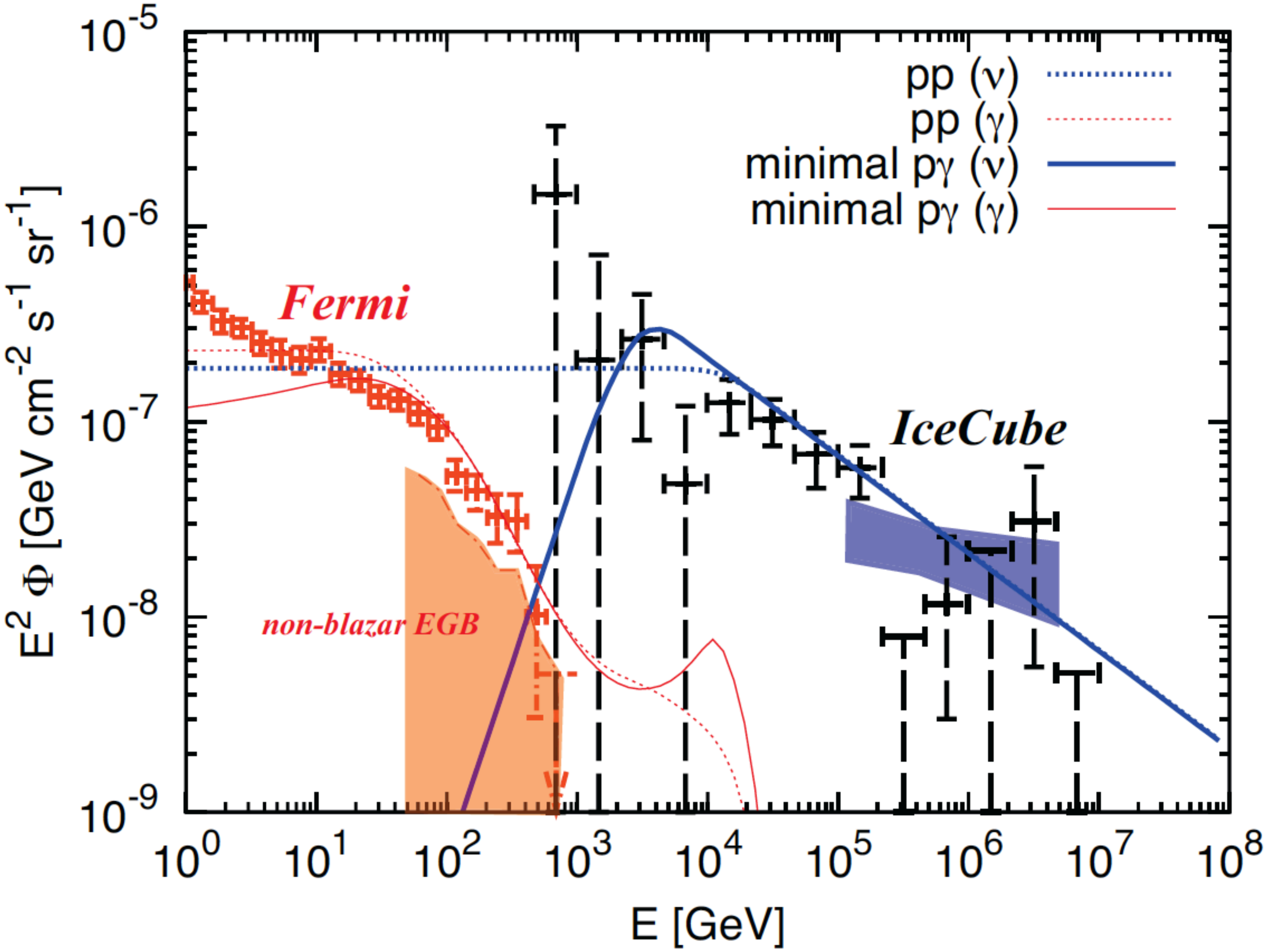
- Similar power-law energetics, Γ_ν: 2.3-2.9
- Contribution to the specific messenger:
    - Gamma-rays: blazars~80%
    - Neutrinos: blazars<30%
- More flux in neutrinos at lower energies that could be expected from gamma-rays, *if* they have the same sources.
- There could be a population of neutrino sources, that are obscured in gamma-rays



The IceCube Collaboration, Phys. Rev. D 104, 022002 (2021)

Tension between the Fermi diffuse gamma-ray sky and IceCube neutrino sky

- Calculation of the diffuse neutrino spectrum (with Γ_ν=2.0).
- Calculation of the corresponding diffuse gamma-ray spectrum, assuming sources are optically thin to two photon annihilation.
- To explain the <100 TeV IceCube neutrino observations (showers), *only* neutrino emitters should contribute to the Fermi isotropic diffuse gamma-ray background in the 3 GeV to 1 TeV range of the gamma-spectrum.
- Softer fluxes overshoot the data.



Murase, Guetta, Ahlers (2016), Murase (2019)

The flavor-averaged diffuse high-energy cosmic neutrino flux is related to cosmic-ray flux:

$$\frac{1}{3}\sum_{\alpha} E_{\nu}^{2}\frac{dN_{\nu}}{dE_{\nu}} \simeq \frac{c}{4\pi}\left(\frac{1}{2}(1 - e^{-\tau_{p\gamma}})\xi_{z} t_{H}\frac{dE}{dt}\right).$$

The IceCube all-flavor diffuse neutrino flux: ~3×10^{-11} TeV cm^{-2} s^{-1} sr^{-1}

The injection rate of cosmic rays above 10^{16} eV: dE/dt~1-2×10^{44} erg $Mpc^{-3}yr^{-1}$

Lead to optical depth for pγ interactions as: $\tau_{p\gamma}$ ~0.4

(assuming that muon neutrino emission rate follows a power law $E^{-\Gamma}$, where Γ=2.19)

$$\tau_{\gamma\gamma} \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}}\tau_{p\gamma}$$

→ $\tau_{\gamma\gamma}$ ~$\mathcal{O}(100)$

E_{ν}: 119 GeV—4.8 PeV (8 years if IC)-> E_p: 2.4 PeV—96 PeV (E_p~20 E_{ν})

Assuming the meson production is dominated by Δ—resonance,
these protons interact with X-Ray and UV target photons,
constraining the two-photon annihilation depth at E_{γ}~5-200 GeV (e.g. Murase 2018)

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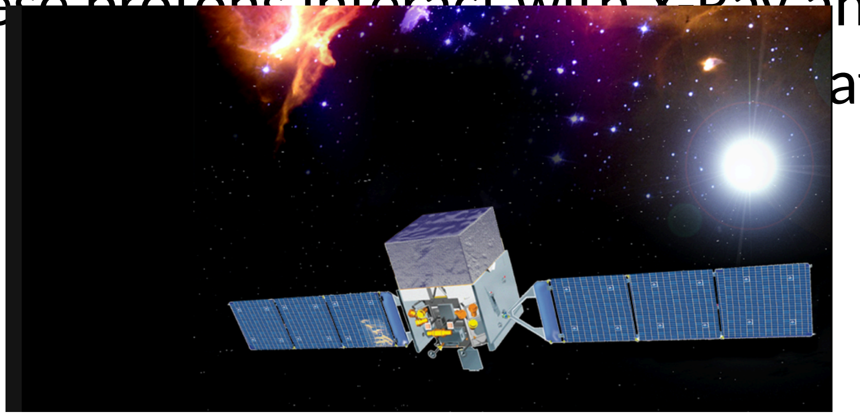

Fermi Gamma-ray Space Telescope

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In-source absorption of pionic gamma photons?

Bethe-Heitler pairs (>10^{18} eV) synchrotron radiate in the keV regime

positrons from photo-meson production* (>5×10^{19} eV) radiate in the MeV regime

Electromagnetic cascade in X-rays, soft gamma regimes

A third bump in blazar SEDs?

(e.g. Petropoulou et al. 2015; Petropoulou & Mastichiadis 2015; Murase et al. 2018; Rodrigues et al. 2019; Halzen & Kheirandish 2020, Kun et al. 2021).

*The low particle density in the jet renders the pp process subdominant (e.g., Boettcher et al. 2012).
However the jet can interact with matter (e.g. gas clouds of the BLR)

Three famous cases, when a neutrino arrived in at least a local, for PKS 1502+106 in a global gamma-minimum

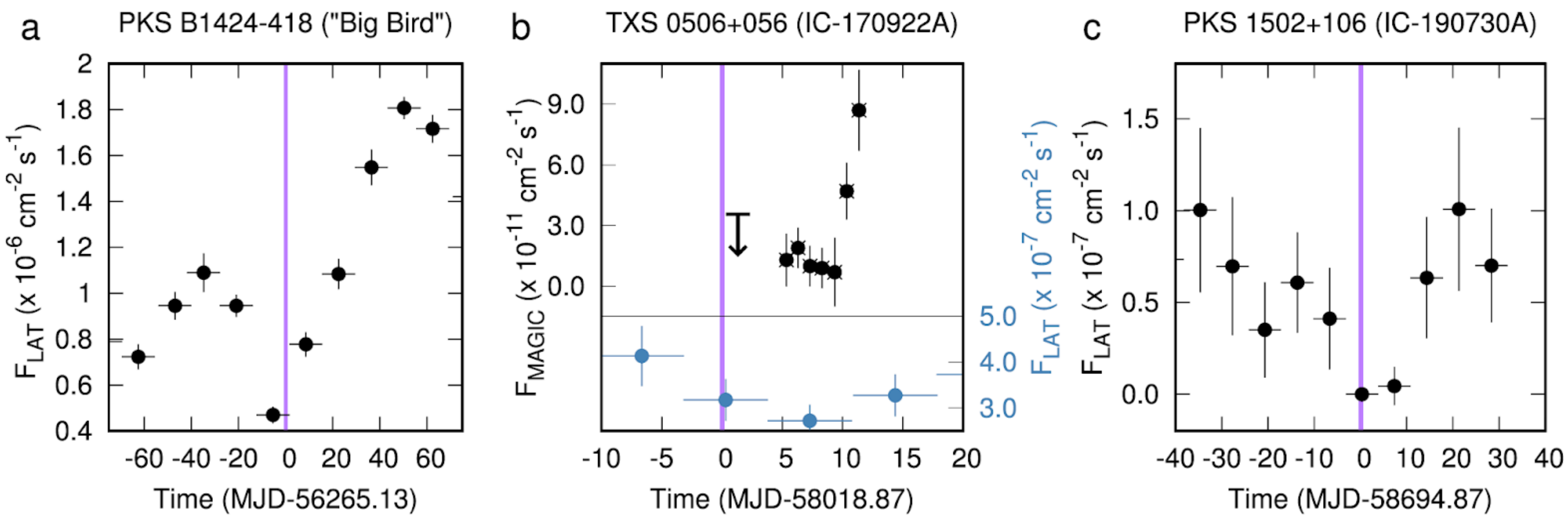

Figure 3. γ-ray light curves for three blazars with coincident high-energy neutrinos. (a) PKS B1424-418 as measured by Fermi-LAT (100 MeV–300 GeV, 14 day binning), plotted by black dots with error bars (Kadler et al. 2016). The vertical purple line marks the detection time of the neutrino event HESE 35. (b) The very-high-energy γ-ray light curve of TXS 0506+056 as measured by MAGIC ($E > 90$ GeV), plotted by black dots with error bars, and the high-energy γ-ray light curve of TXS 0506+056 as measured by Fermi ($E > 100$ MeV, 7 days binning), plotted by blue dots with error bars (IceCube Collaboration et al. 2018). The vertical purple line marks the detection time of the neutrino event IC-170922A. (c) Fermi-LAT γ-ray light curve of PKS 1502+106 (100 MeV–300 GeV, 7 days binning), plotted by black dots with error bars. The vertical purple line marks the detection time of the neutrino event IC-190730A. The arrival time of the neutrinos sets the zero value on the time axis of the plots.

Kun, Bartos, Becker-Tjus, Biermann, Halzen, Mező, 2021, ApJL, 911, L18

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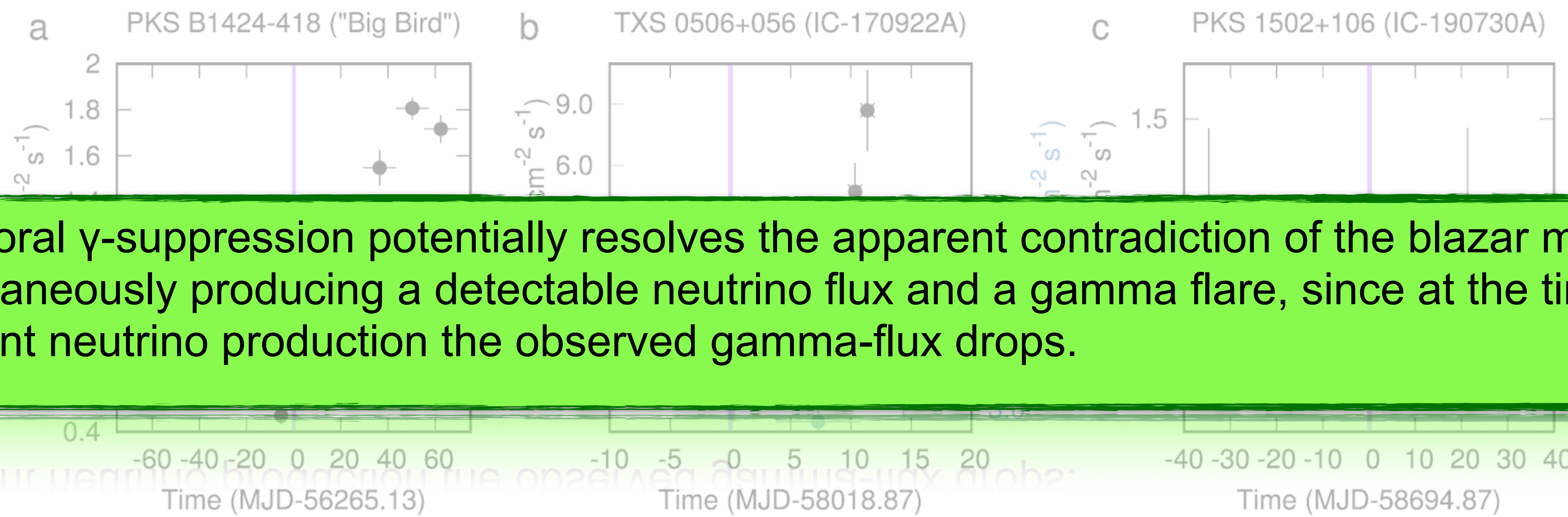

Temporal γ-suppression potentially resolves the apparent contradiction of the blazar models simultaneously producing a detectable neutrino flux and a gamma flare, since at the time of efficient neutrino production the observed gamma-flux drops.

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Likelihood analysis of 9 Fermi point sources

Motivation We found 29 *Fermi*-LAT 4FGL-DR2 neutrino source-candidates, from which in case of 9 sources the predicted number of gamma-photons in 10 years is more than 1000 (5 BLL, 3 FSRQ, 1 SEY1), so there is enough photon statistics to make light curves

Technical information:

- Dedicated project on a cluster of 16x2.2 GHz Intel Skylake vCPUs (PI: EK), ELKH Cloud (Hungary, Wigner Data Center), using Docker technology

Software packages: fermipy v1.0.1, ScienceTools v2.0.8 (FermiBottle)

- Instrument response function: P8R3_SOURCE_V2_v1
- Galactic interstellar emission model: gll_iem_v07.fits
- Isotropic diffuse emission model: iso_P8R3_SOURCE_V2_v1.txt

- Standard quality cuts (zmax=90, (DATA_QUAL > 0) &&(LAT_CONFIG==1))
- Minimum separation between two new point sources: 0.3 deg, TS_{min}=25 (~5sigma)
- Minimum separation between the source and the SUN: 5 degrees
- Adaptive binning (Lott et al. 2012, 15%)

Kun et al 2022, in prep.

Results

none of them was flaring when IceCube recorded the corresponding neutrino

-> Either no real sources
or
we need better strategies

Kun et al 2022, in prep.

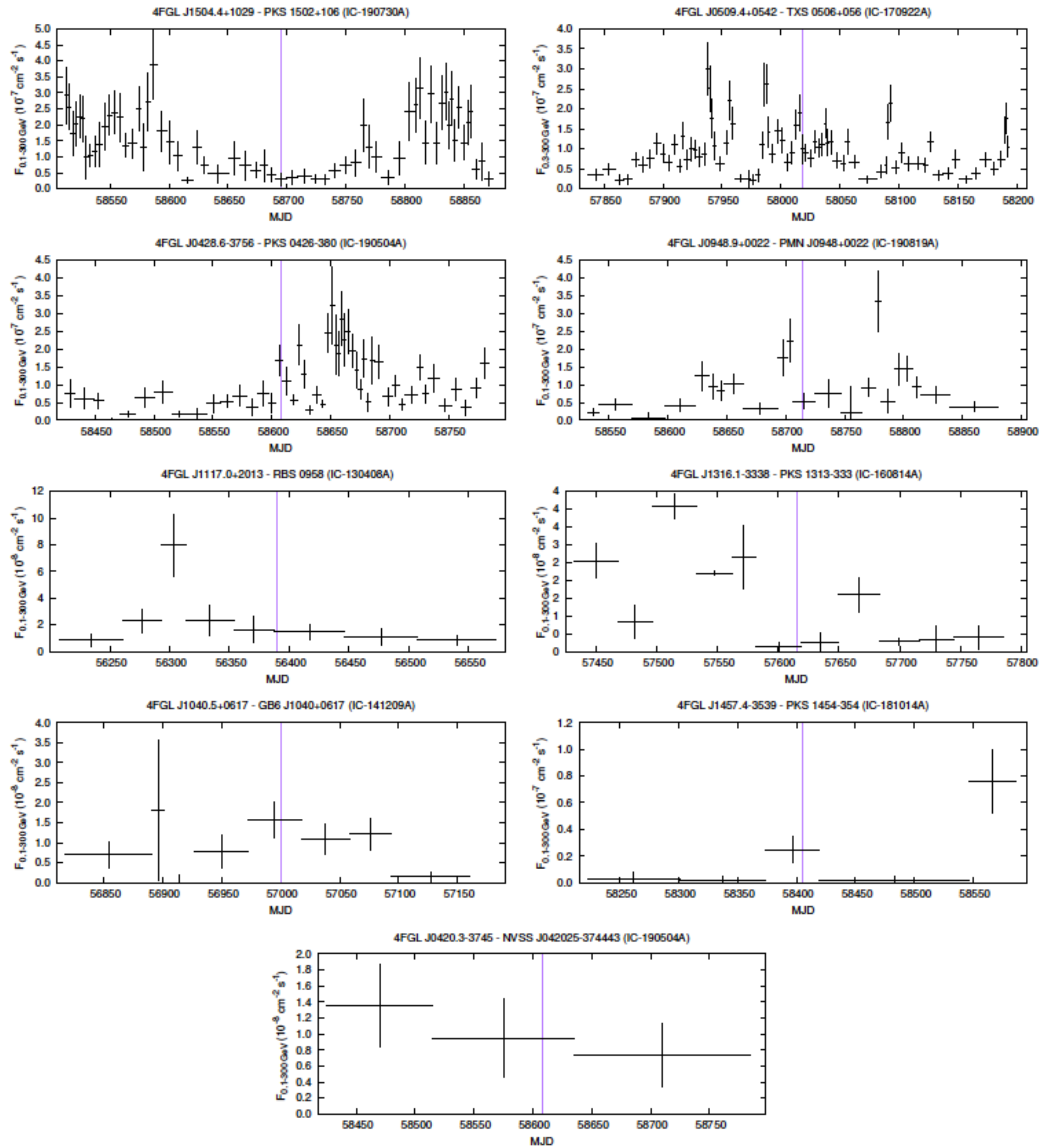
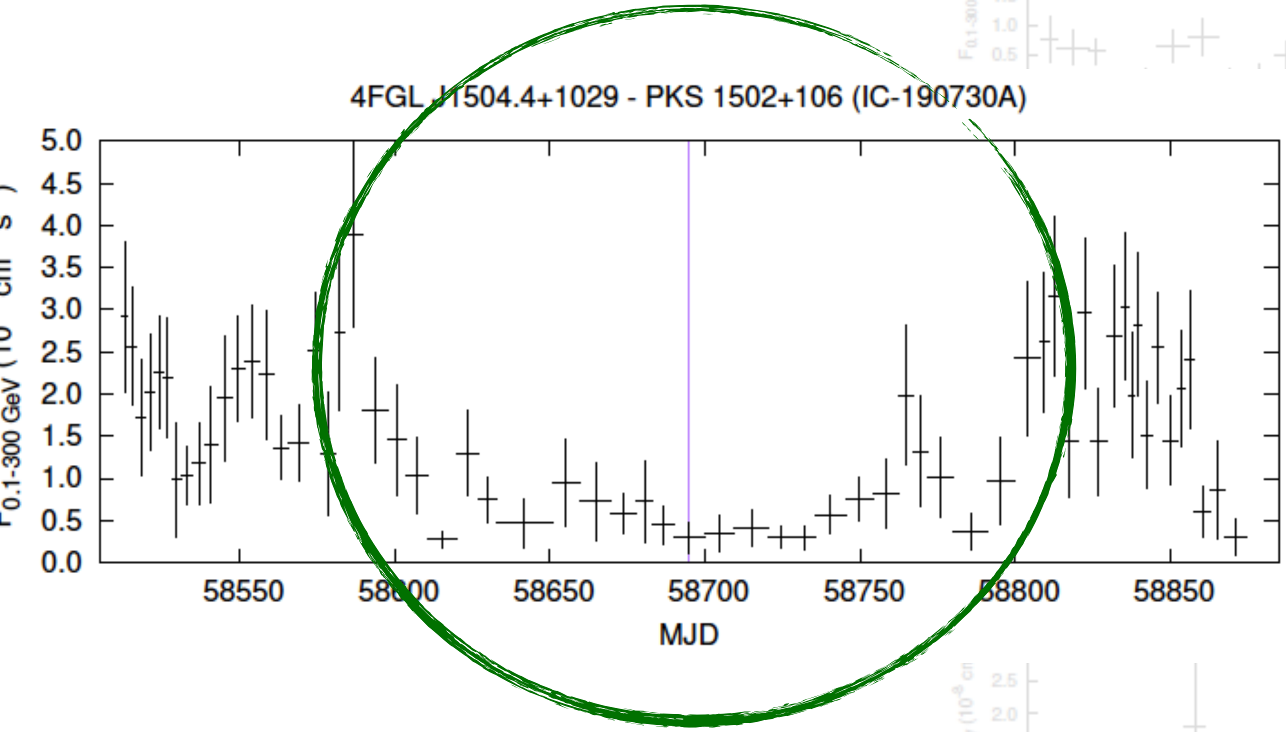


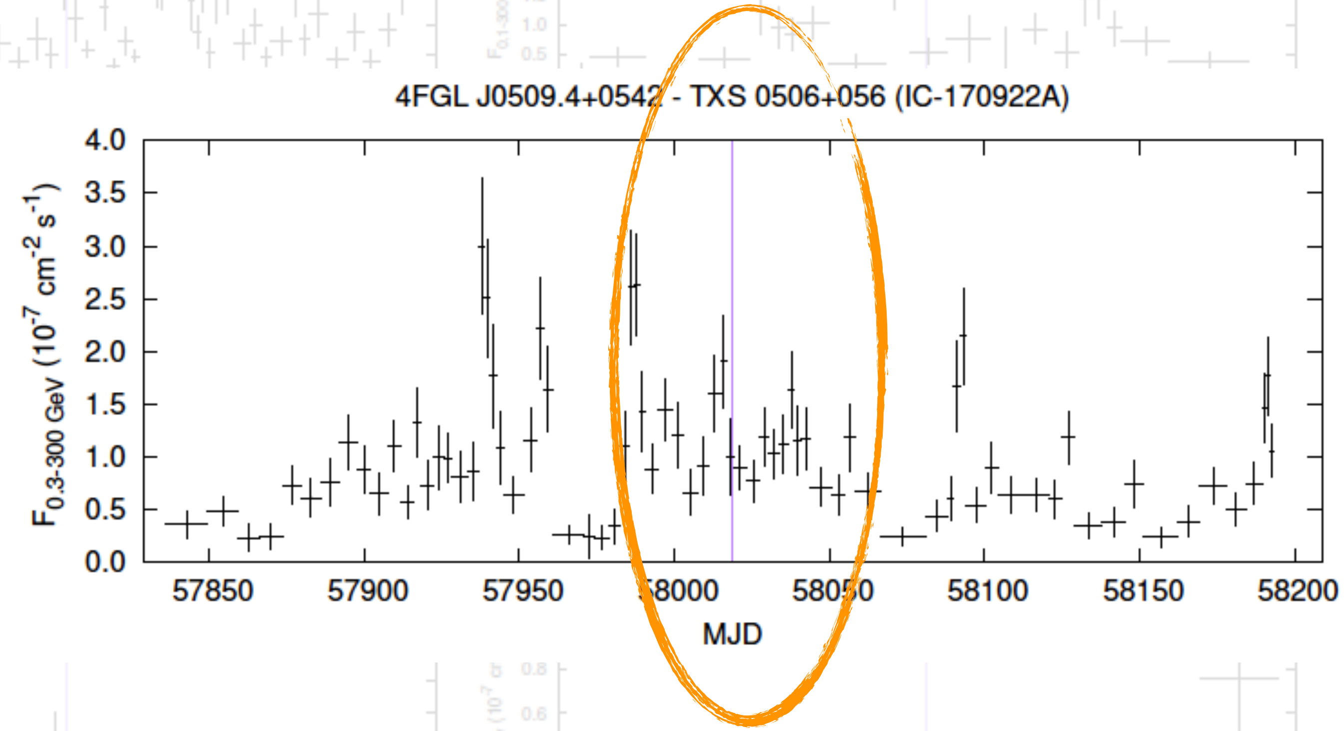
Figure 1. Likelihood light curves of the 9 Fermi/LAT neutrino source candidates, with adaptive-binning algorithm.

Results

PKS 1502+106



TXS 0506+056



More questions than answers, work in progress

Figure 1. Likelihood light curves of the 9 Fermi/LAT neutrino source candidates, with adaptive-binning algorithm.

AGN are extremely efficient particle accelerators

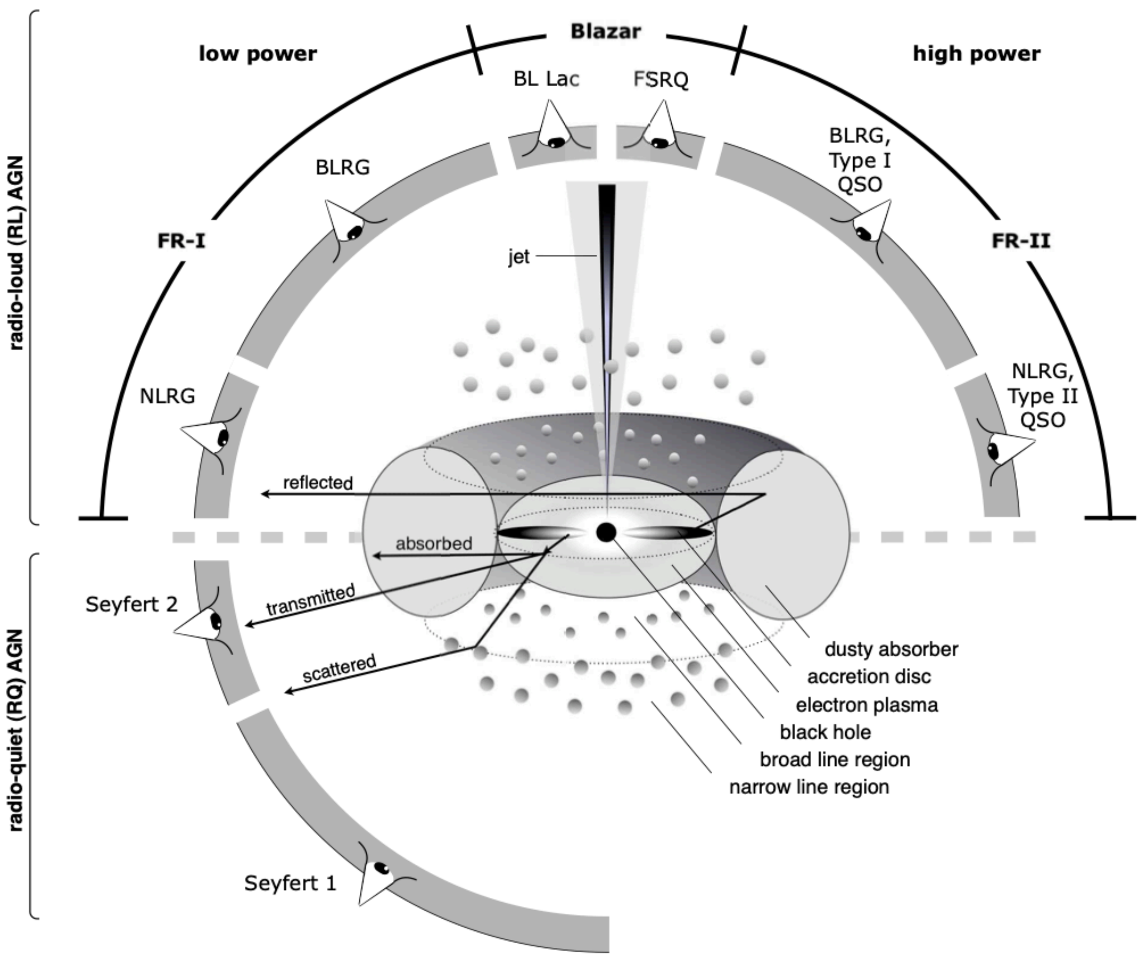
The most powerful permanent particle accelerators in the Cosmos

- The particles flow onto central supermassive black hole
- Some of the gravitational energy is released
- η measures how much of the rest mass will be converted to energy
- The efficiency η will depend on the spin (a) of the black hole:
  - for a=0 (Schwarzschild) we have η =6%
  - for a=1 (extreme Kerr) we have η =40%!

a* has a maximum at 0.89 for rotating black holes with accretions disk

for the hydrogen fusion η is about 0.7%

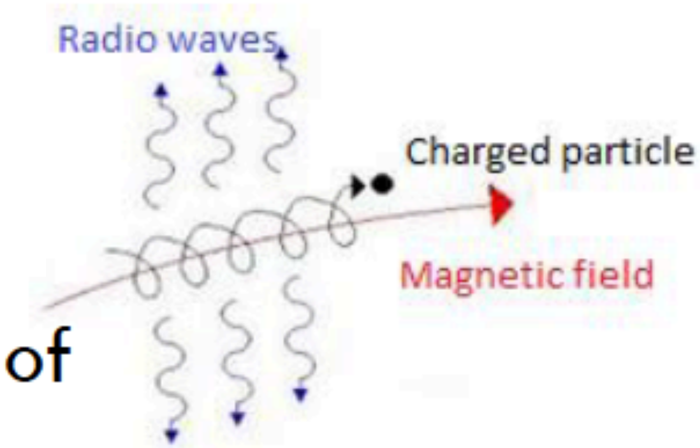
- The binding energy is transformed into the acceleration of protons or heavier nuclei



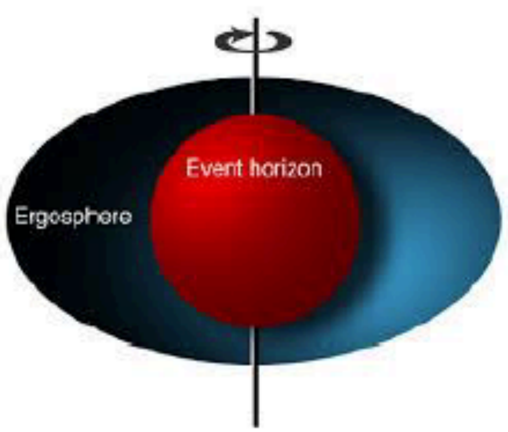
Urry&Padovani, 1995, PASP,107, 803
Beckmann & Shrader, 2012
illustration by Marie-Luise Menzel, 2012

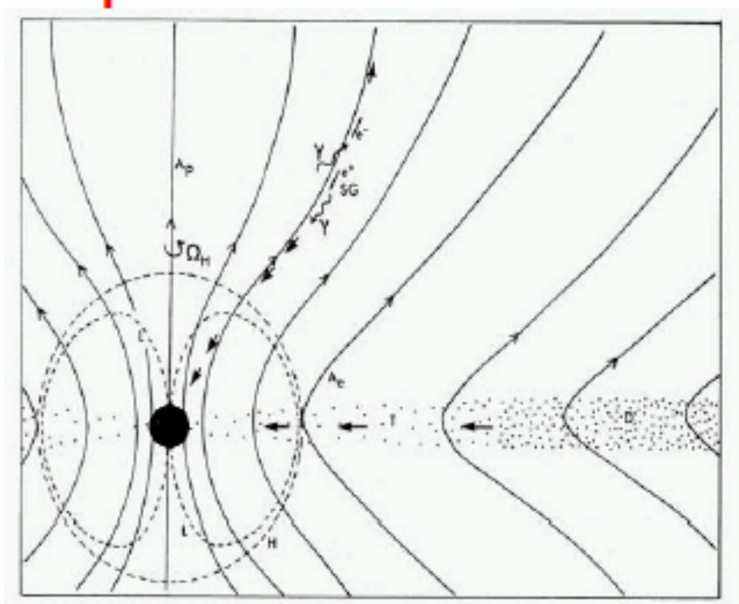
Other prime candidates: starburst galaxies, TDEs

Relativistic jets



Blandford–Znajek-effect



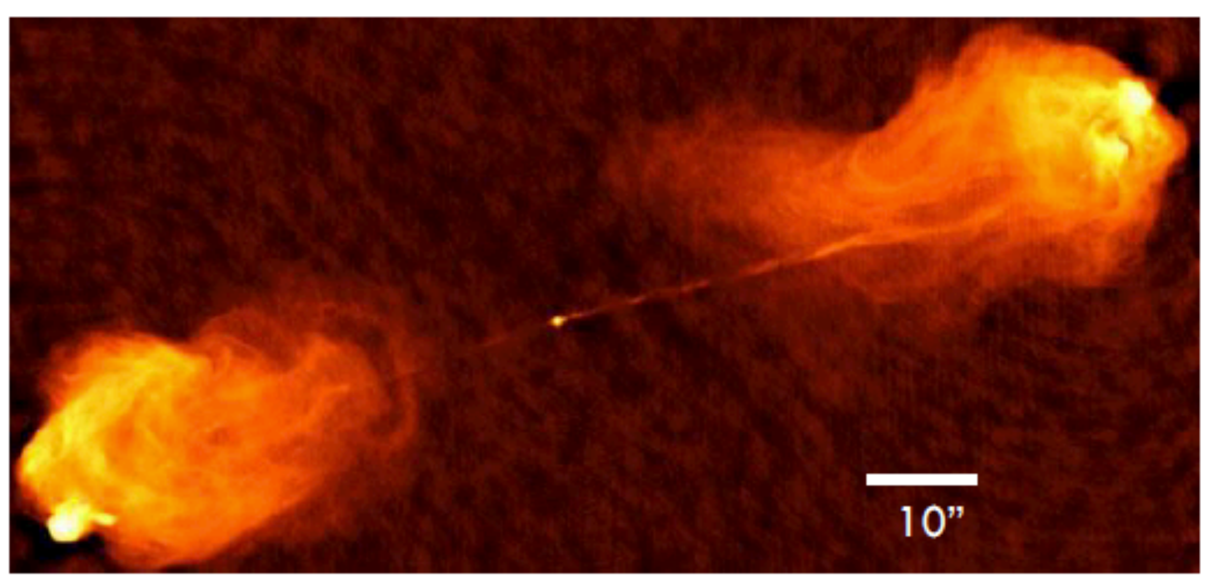


Critical frecquency of synchrotron radiation:

$$\upsilon_{c,e^-} = \frac{3}{4\pi}\frac{eB\chi}{m_{0,e^-}c}\gamma^2 = 16{,}1 \times \left(\frac{B\chi}{\mu G}\right)\left(\frac{E}{GeV}\right)^2 \text{ MHz}$$

$B_\chi = 0{,}1\,\mu G$, $E = 10\,GeV$ → $\upsilon_{c,e^-} \approx 160$ MHz

The collimated jets are observed as radio loud AGN



The Cygnus–A AGN at 5GHz (VLA)
The source-distance is 760 mega-lightyear (z=0,056, scale 1,096kpc/”)
National Radio Astronomy Observatory (NRAO)

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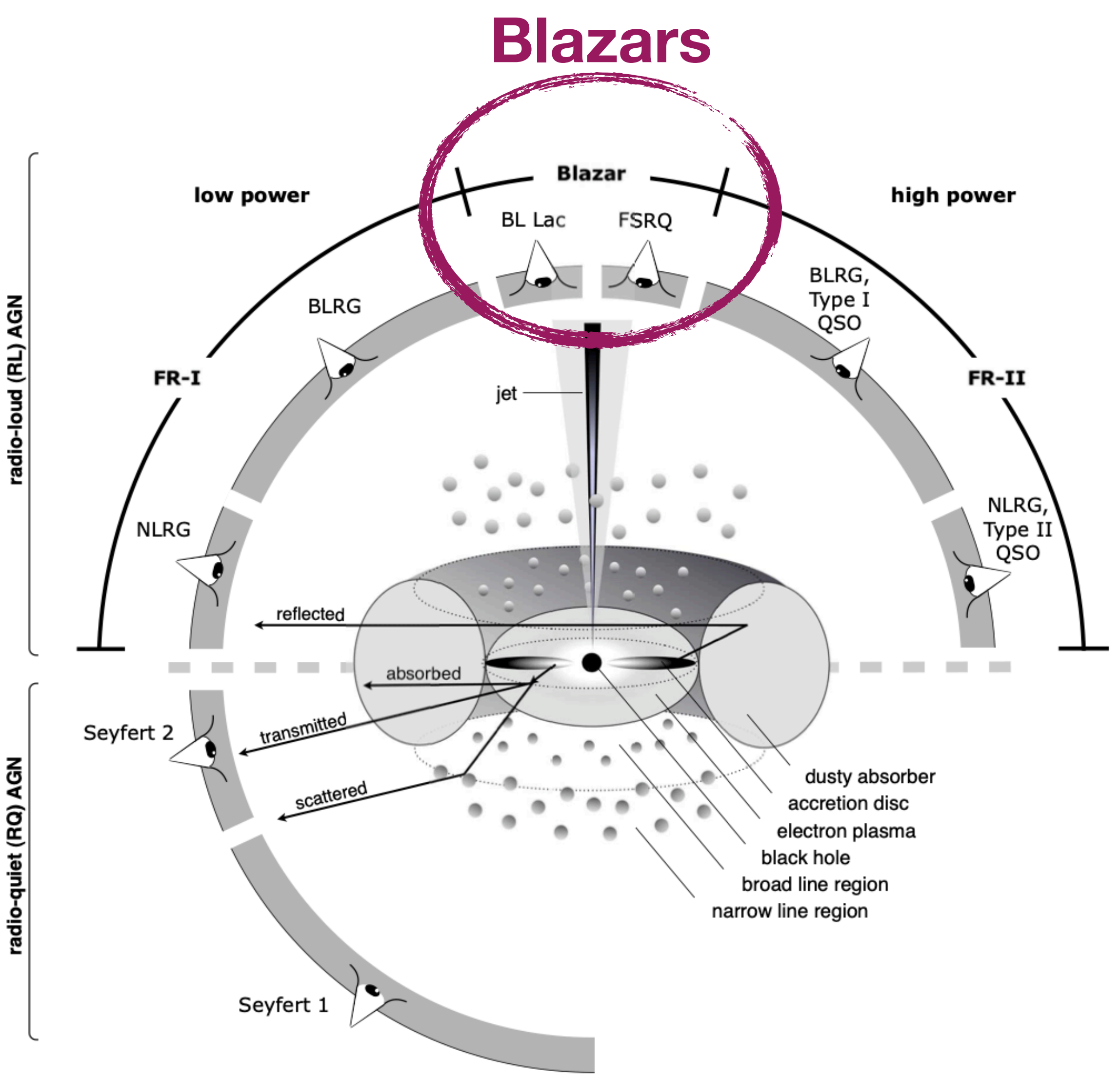

Urry&Padovani, 1995, PASP,107, 803
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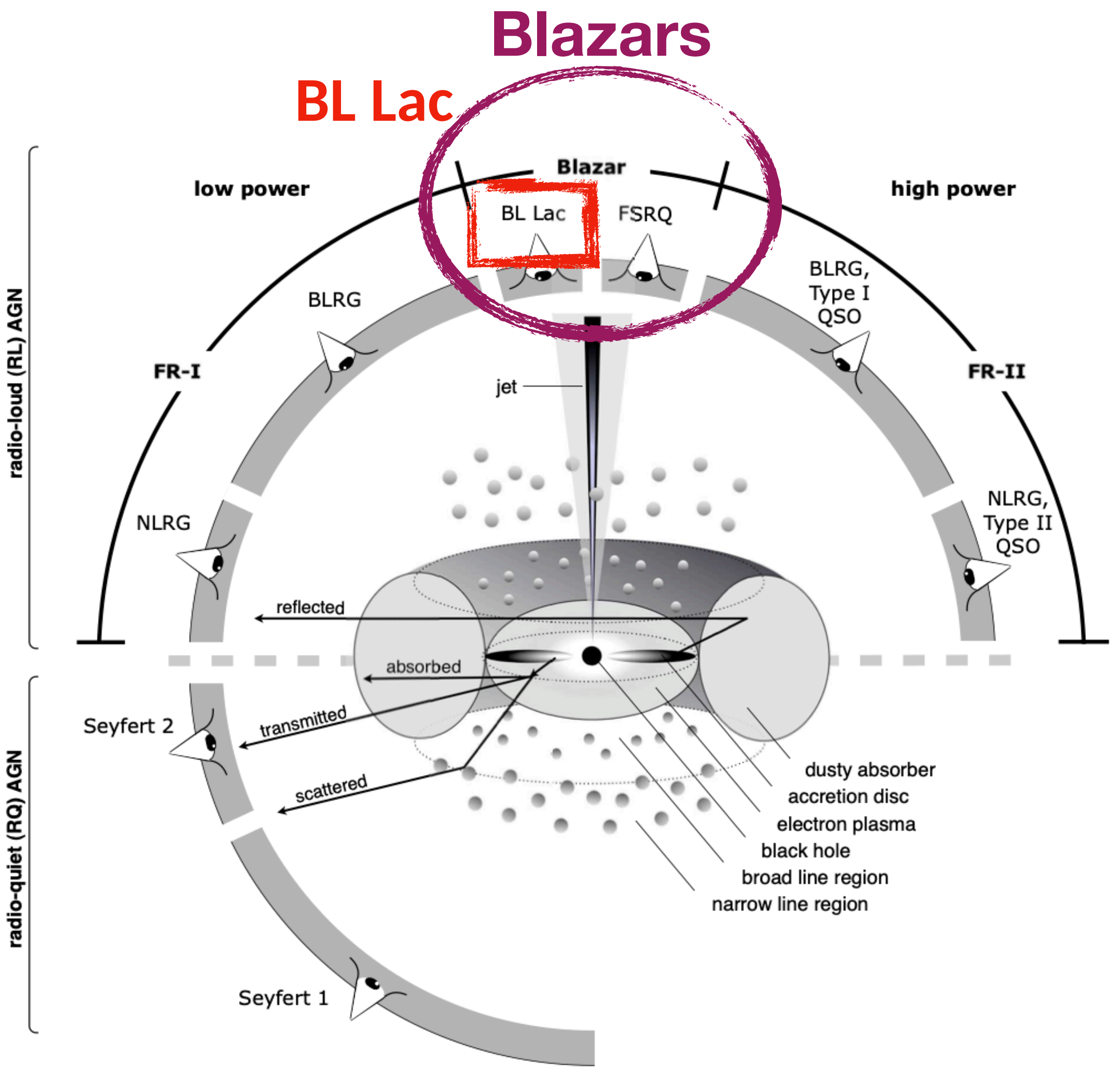

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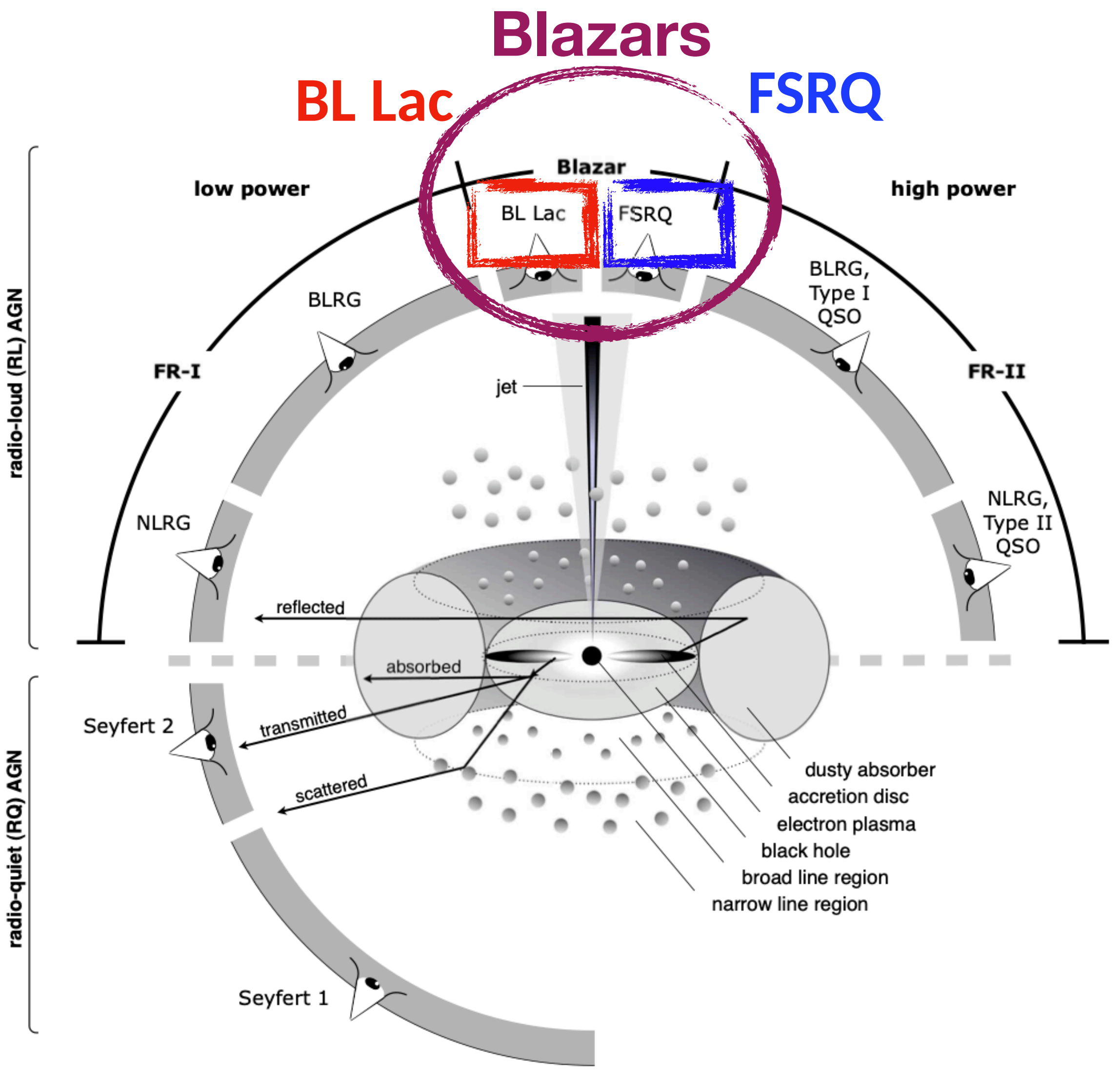

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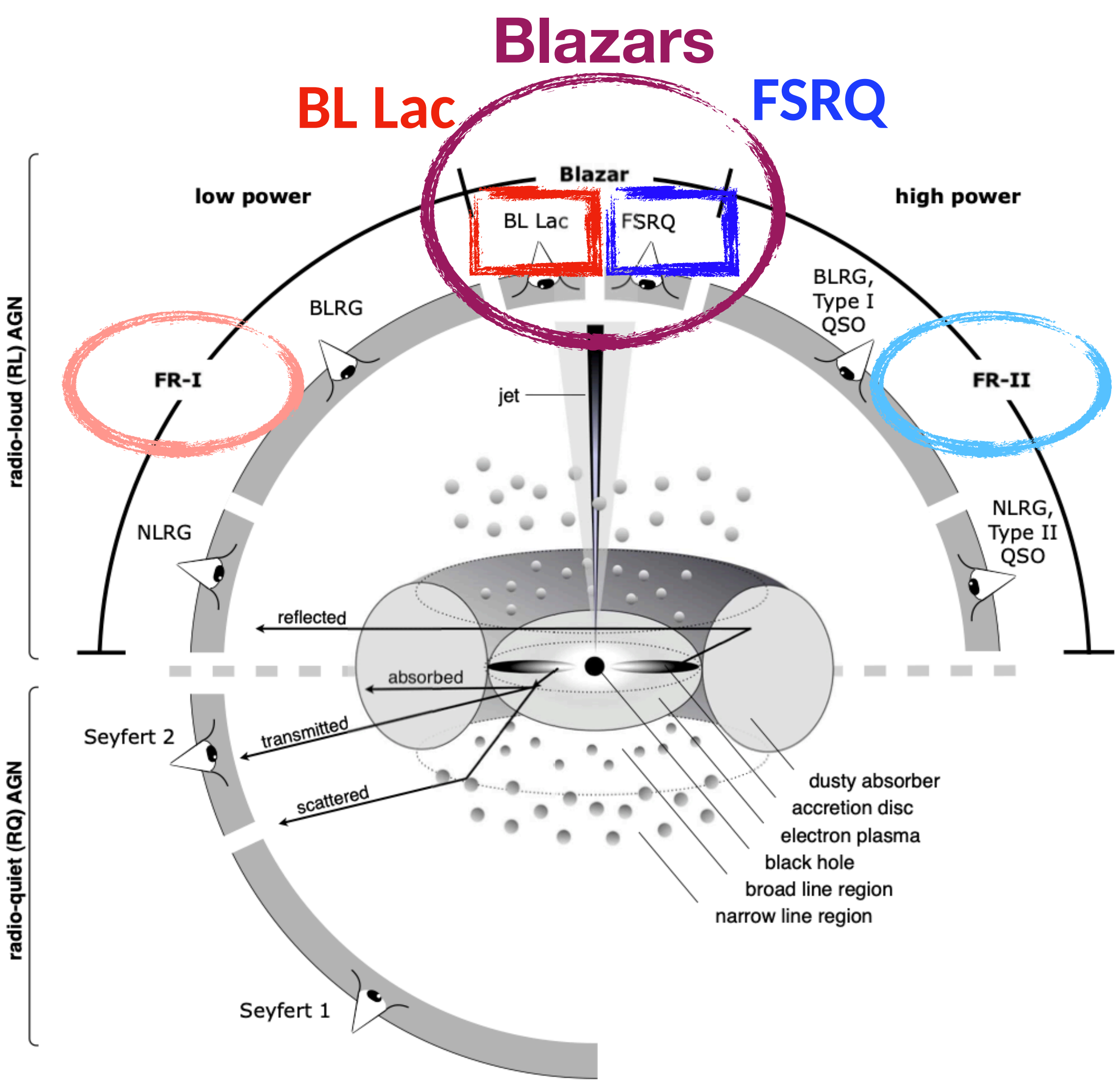

Urry&Padovani, 1995, PASP,107, 803
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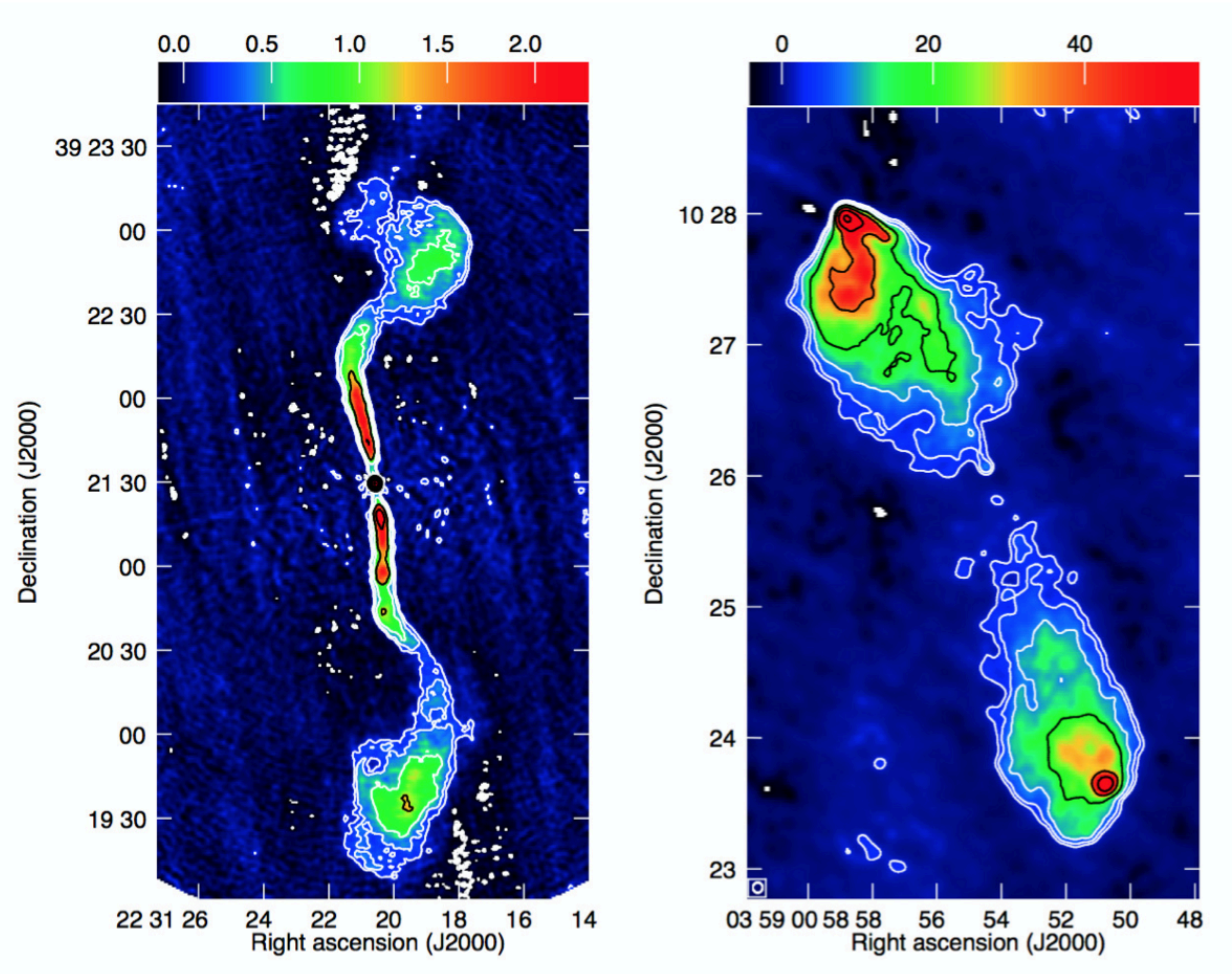
Fanaroff-Riley classification of radio galaxies

FRI (lower power) FRII (higher power)



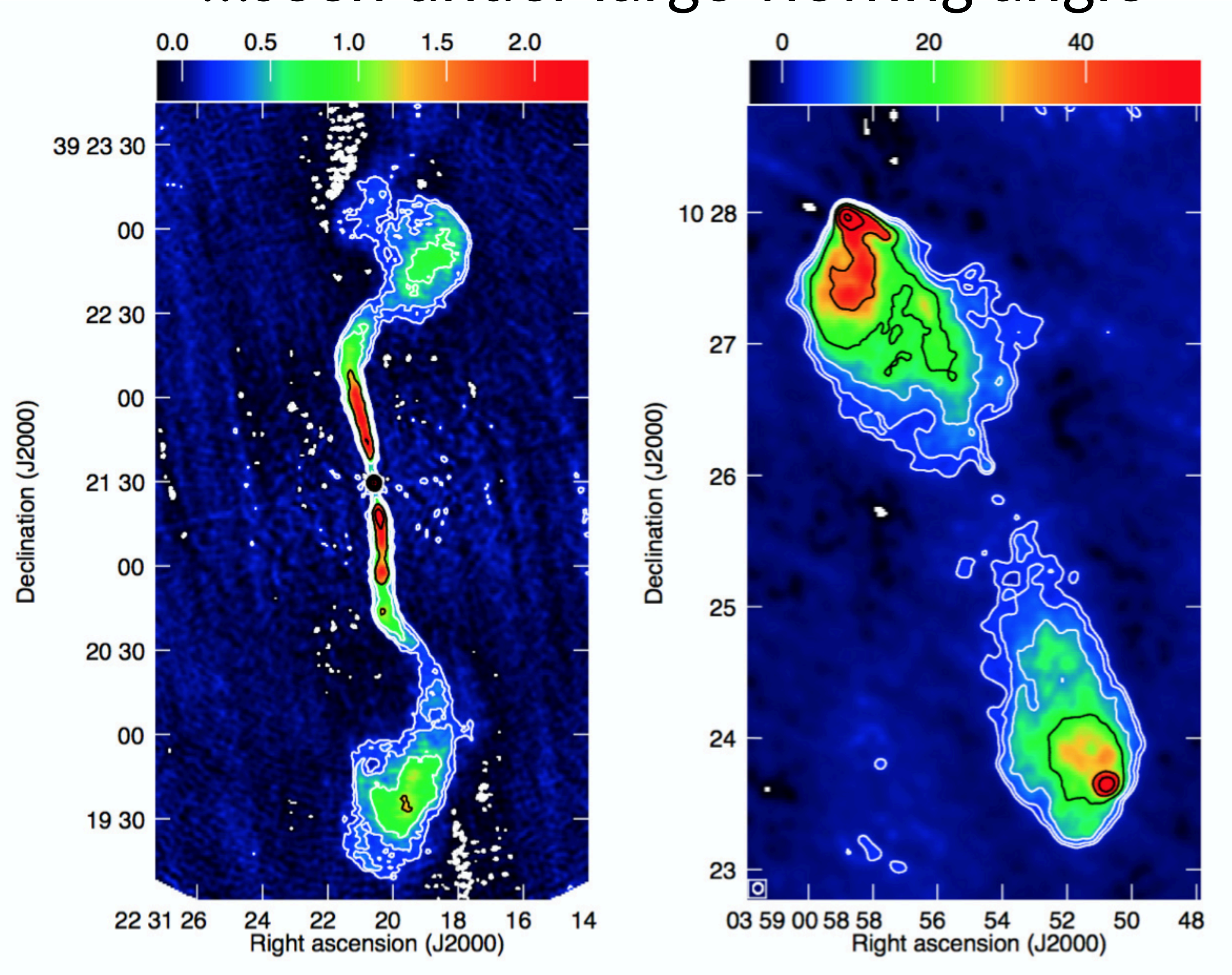
3C 449 3C 98

P. Kharb, E. Stanley, M. Lister, H. Marshall, C. O'Dea, and S. Baum (2015)

Fanaroff-Riley classification of radio galaxies

BL Lac FSRQ...

...seen under large viewing angle



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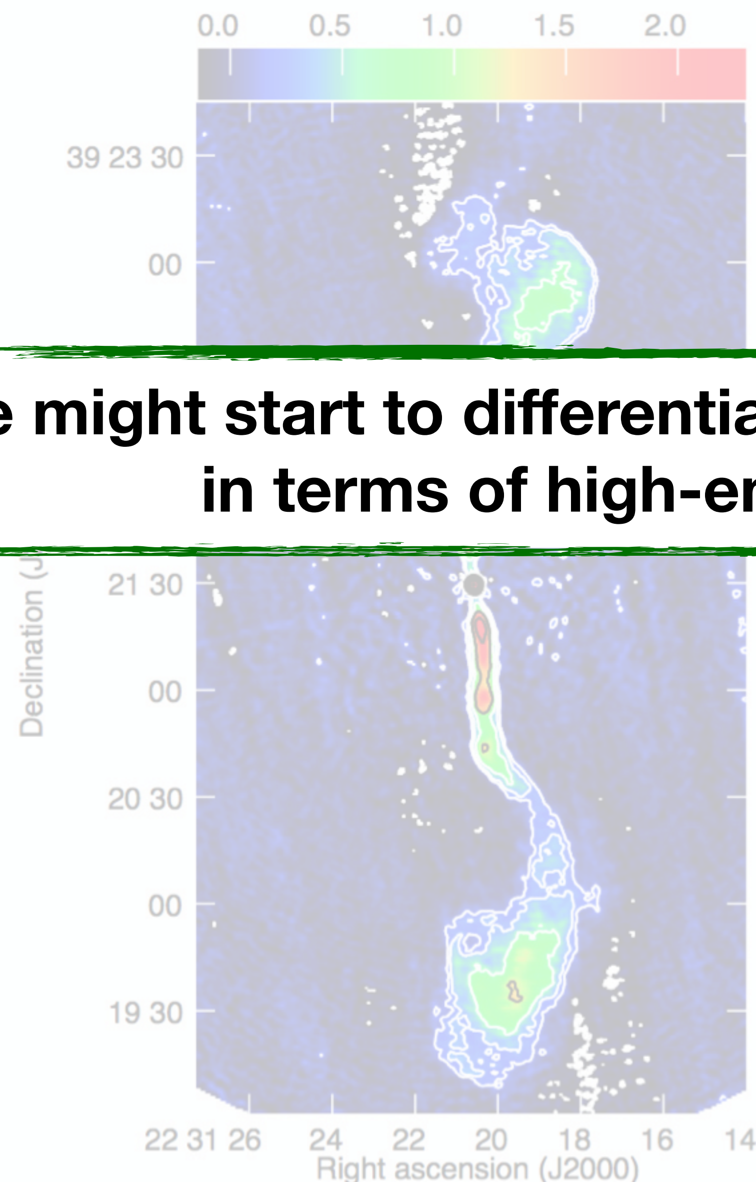
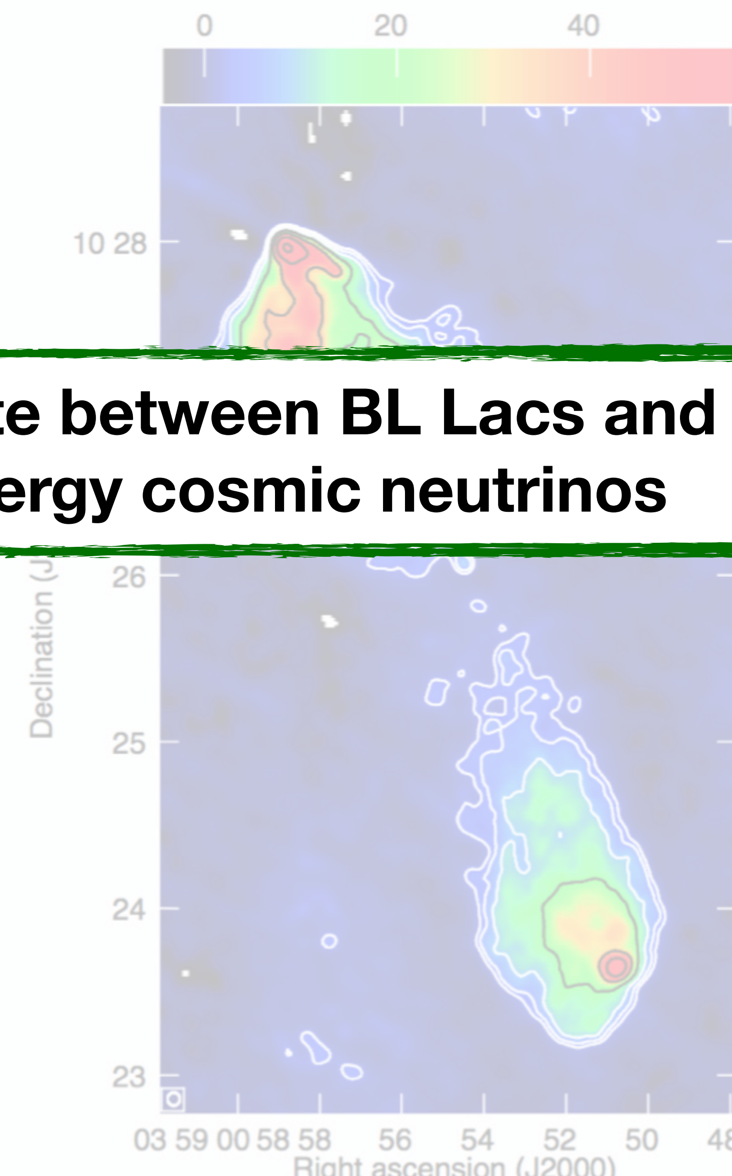


3C 449



3C 98

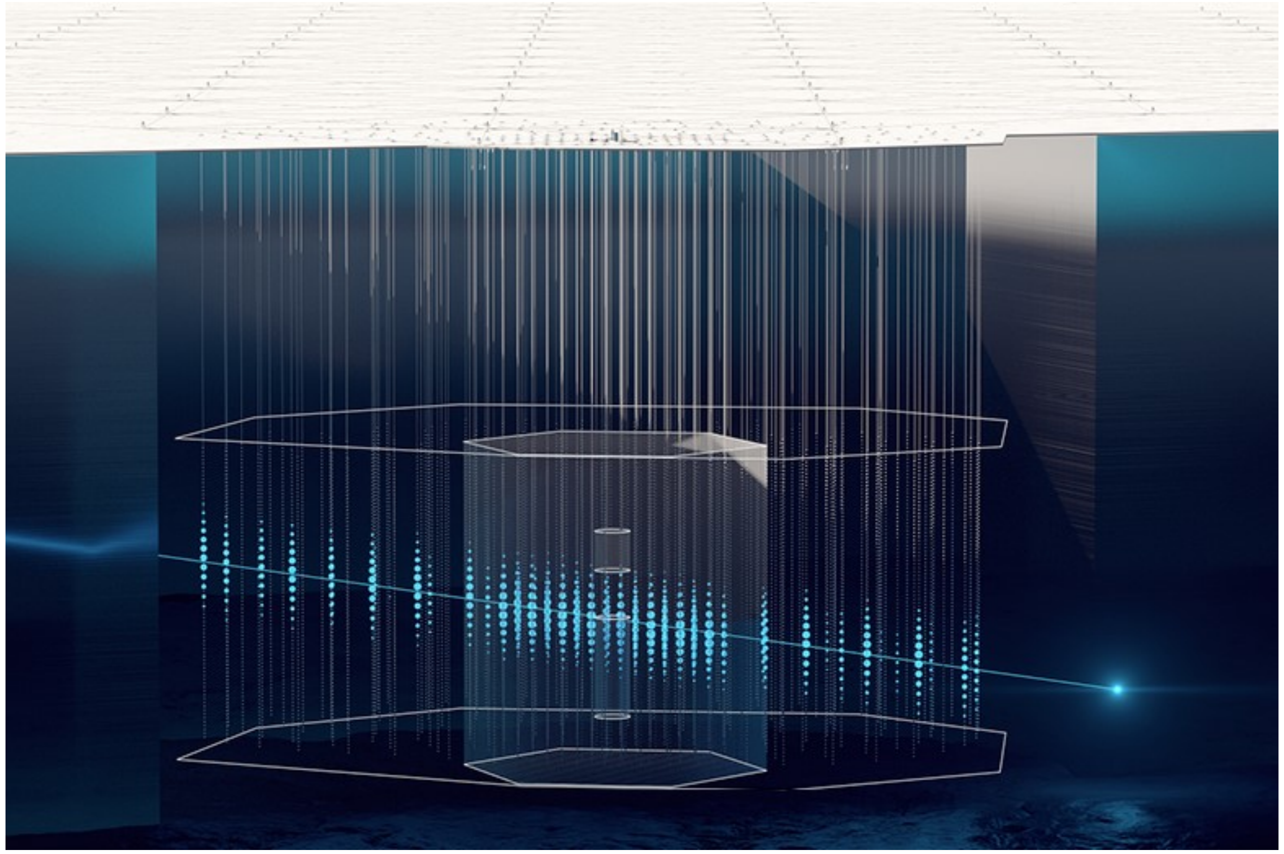
We might start to differentiate between BL Lacs and FSRQs in terms of high-energy cosmic neutrinos

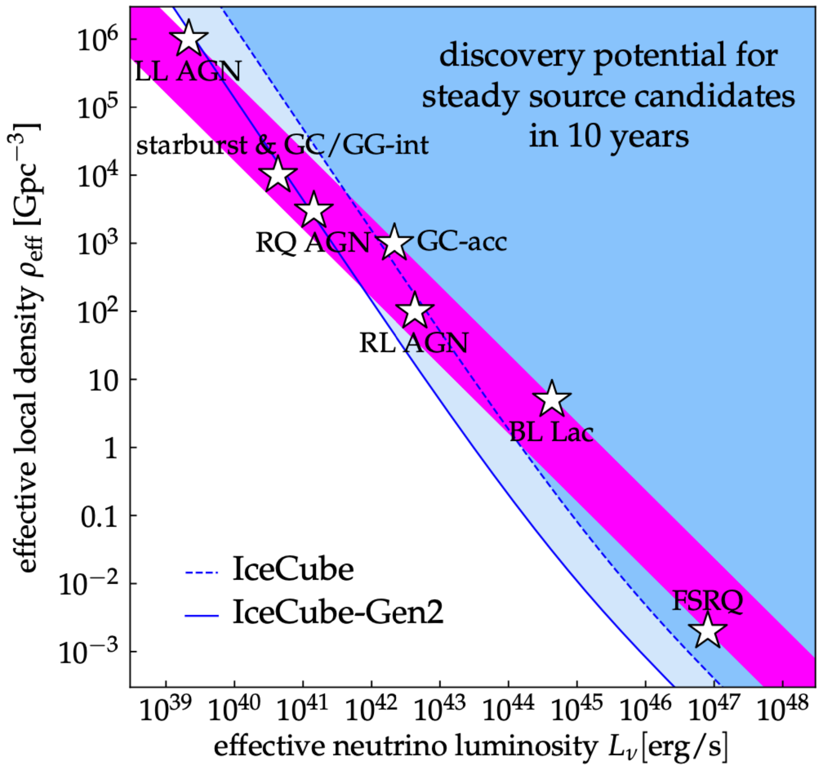
P. Kharb, E. Stanley, M. Lister, H. Marshall, C. O'Dea, and S. Baum (2015)

Conclusion — we need more neutrino observations, detectors

we do not know yet where are the cosmic particle accelerators

- UHECR and high-energy neutrino detections are rare and difficult to observe
- Chasing the 5σ: we need better models, more advanced data analysis and in general much more data (see IceCube-Gen2 below), proton/nuclei mass composition of UHECRs (AugerPrime), propagation codes, improve the simulation of galactic magnetic fields, new detectors (eg KM3NET, GVD, ICGEN2) etc..





Aartsen et al, 2019

IceCube-Gen2 ten cubic kilometer detector

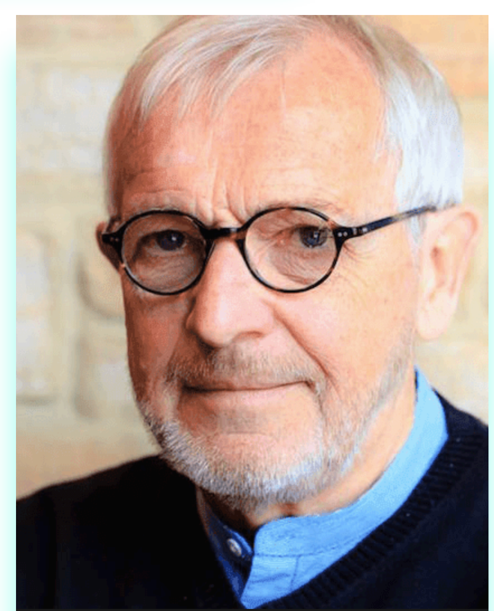
100s of neutrinos between PeV-EeV energies, spectral studies of individual sources











…and more and more
Many thanks CIM!

Thank you for your attention!