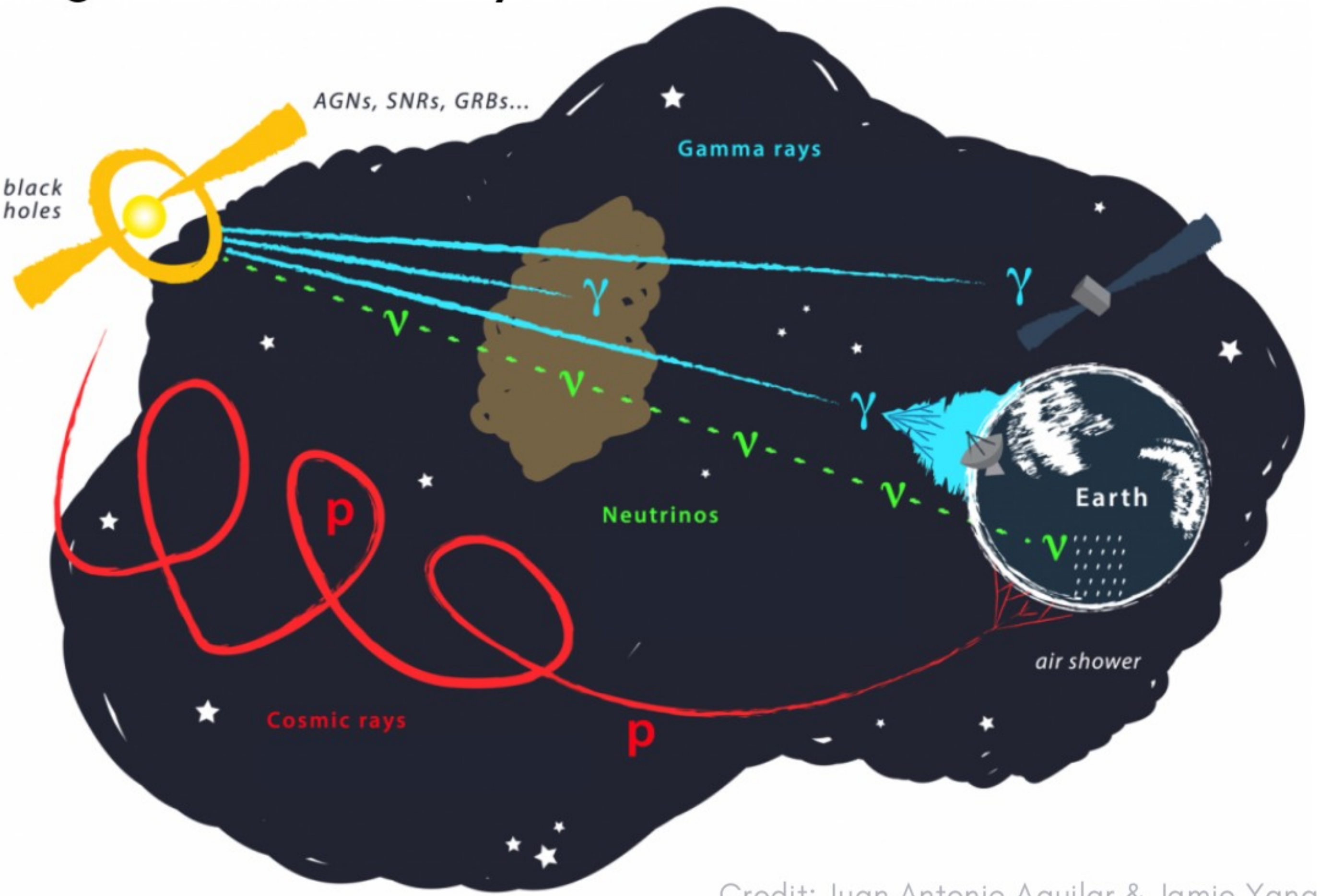
Time-Domain & Multi-messenger Astronomy

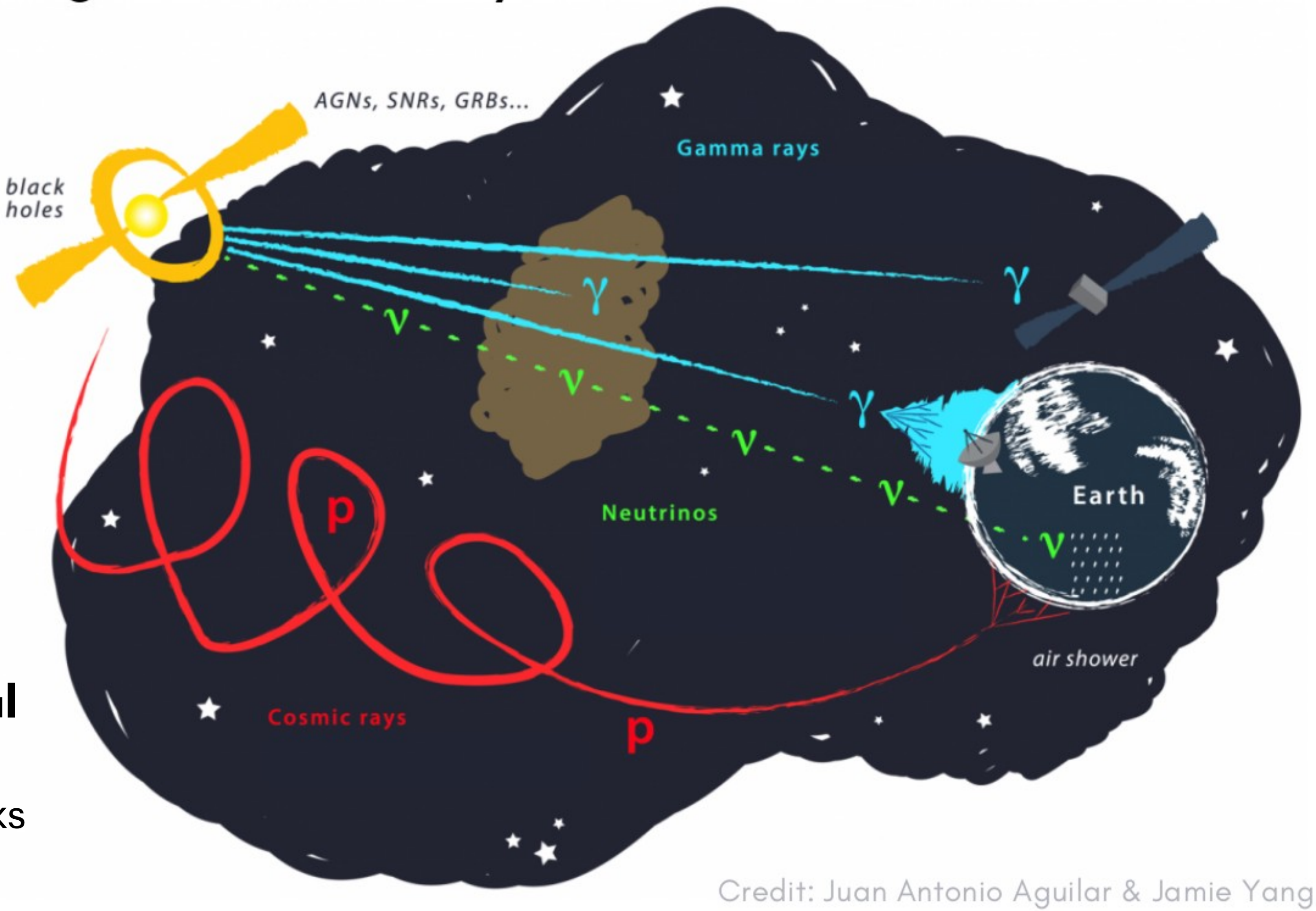
Lea Heckmann

Multi-messenger astronomy



Credit: Juan Antonio Aguilar & Jamie Yang, IceCube/WIPAC

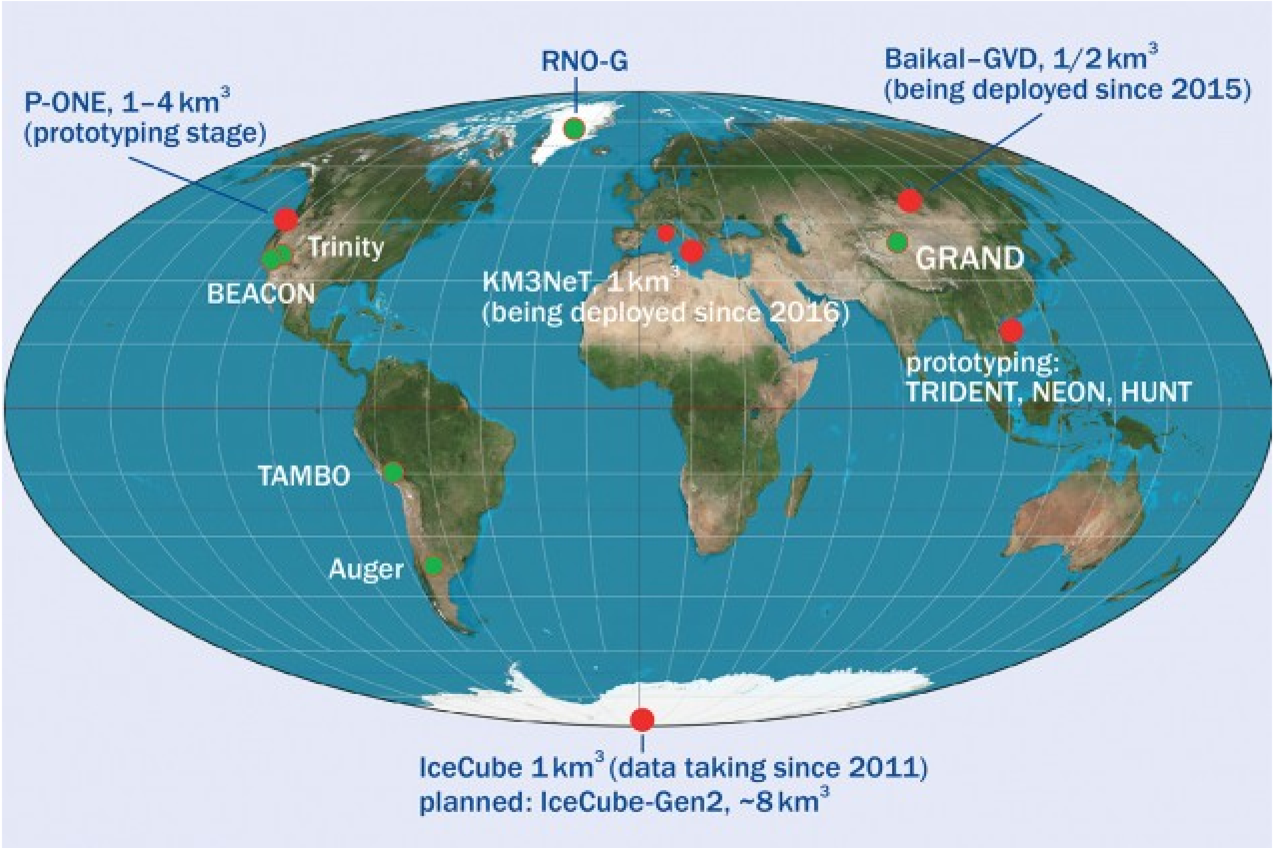
Multi-messenger astronomy



Credit: Juan Antonio Aguilar & Jamie Yang, IceCube/WIPAC

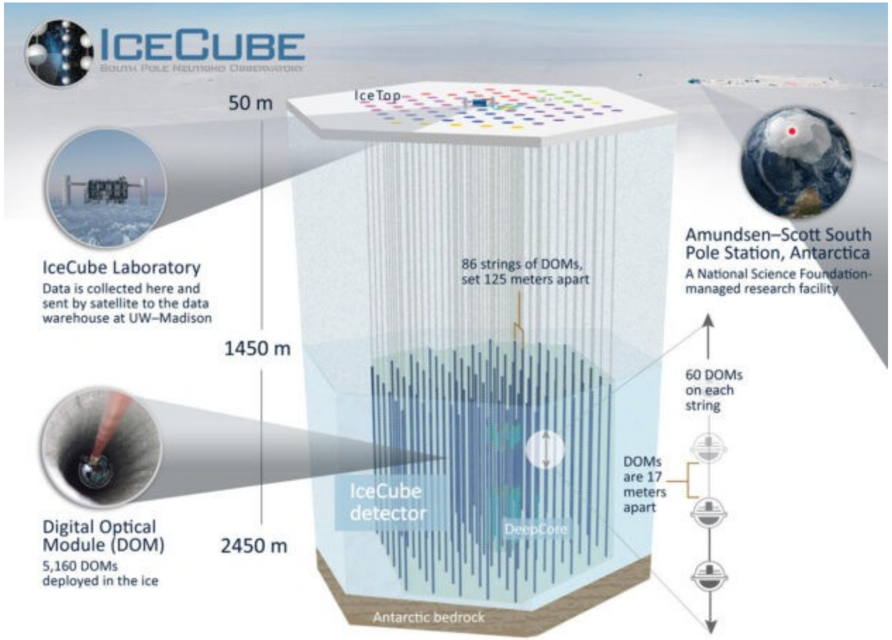
+ **Gravitational waves**
see Sylvia's talks

Neutrinos

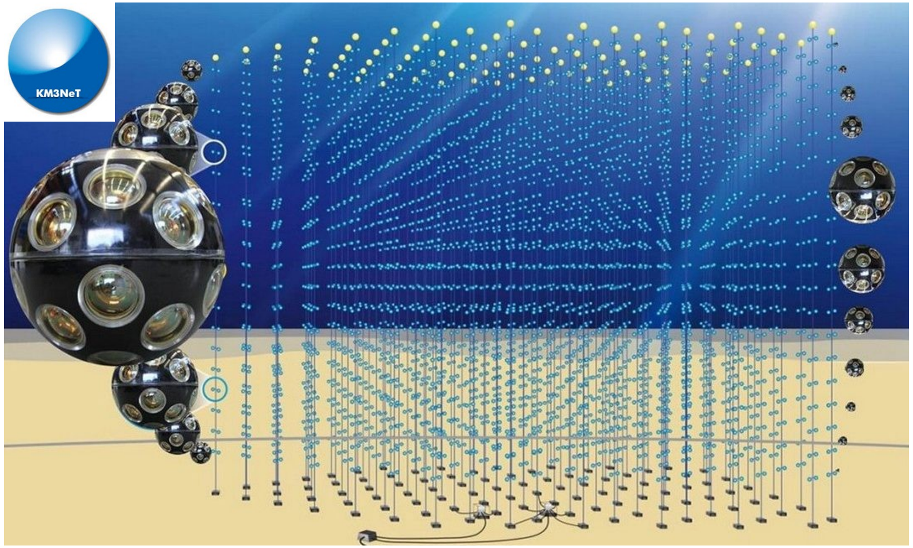


Credit: L. Lu

Neutrinos

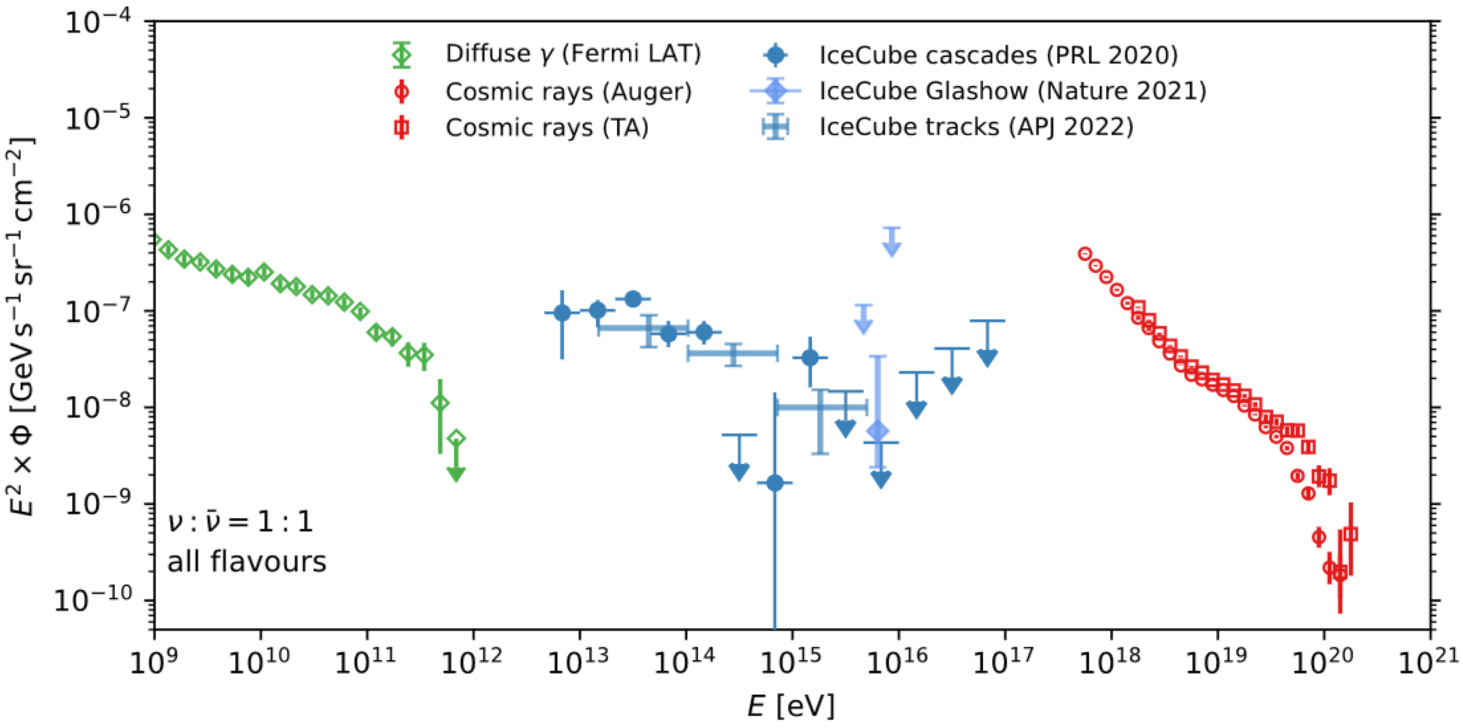


Credit: IceCube



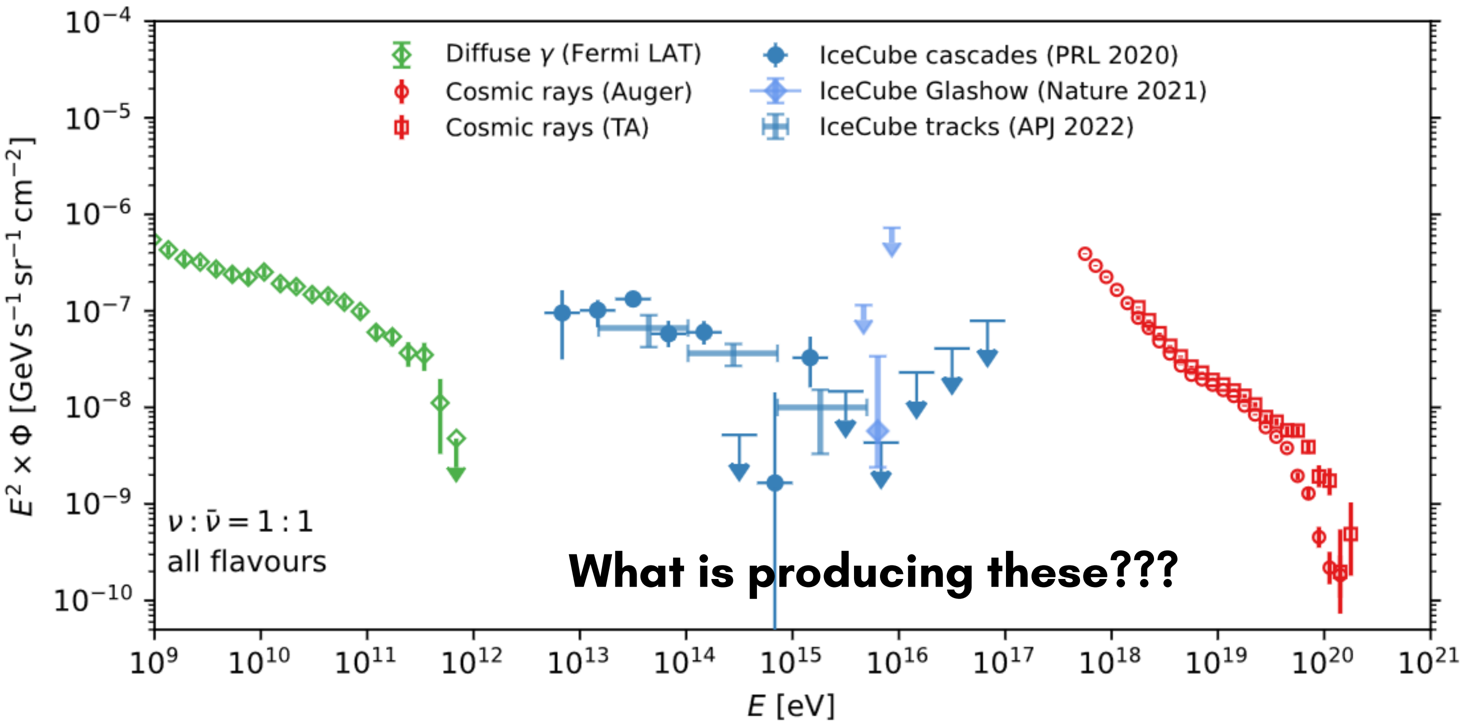
Credit: Km3Net

Neutrinos



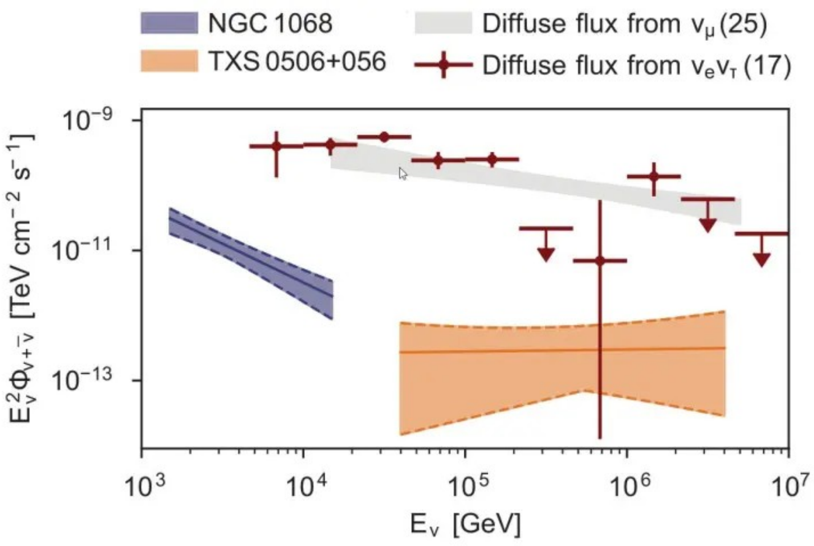
Credit: M. Ackermann 2022

Neutrinos

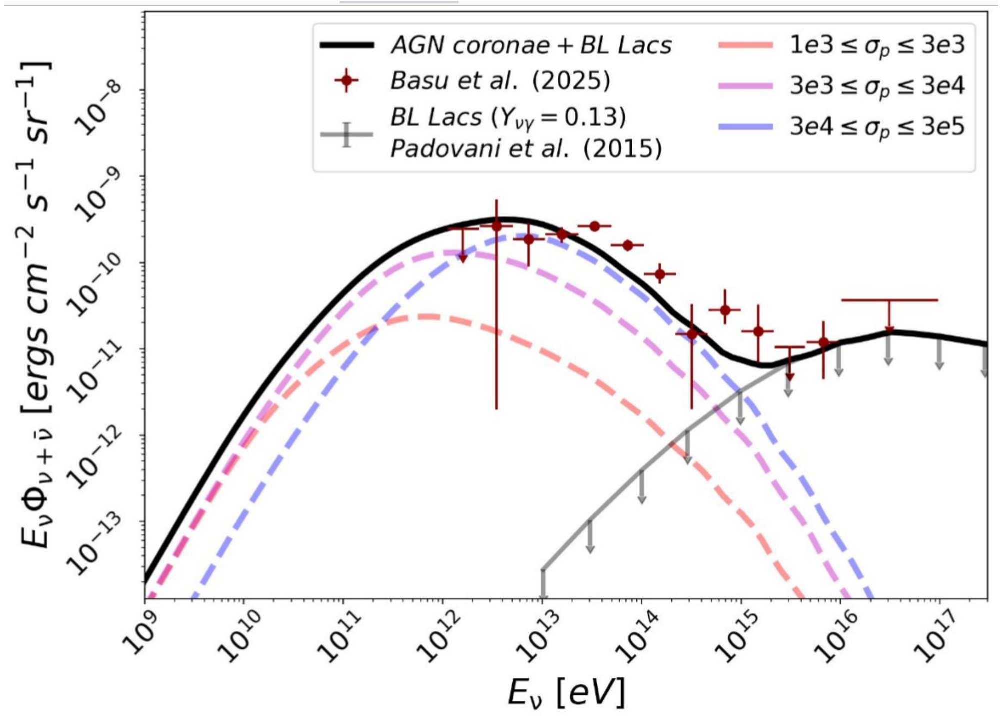


Credit: M. Ackermann 2022

AGN as multi-messenger sources

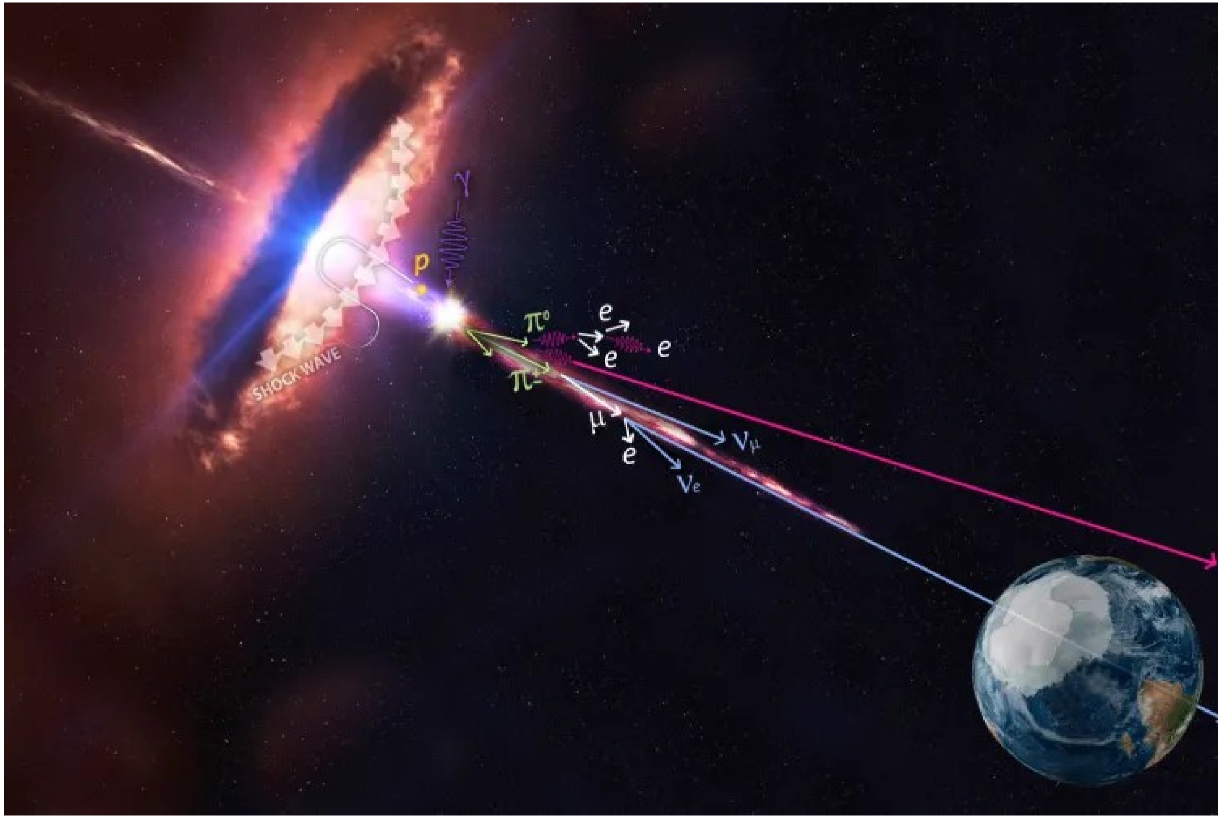


Credit: Icecube et al 2022



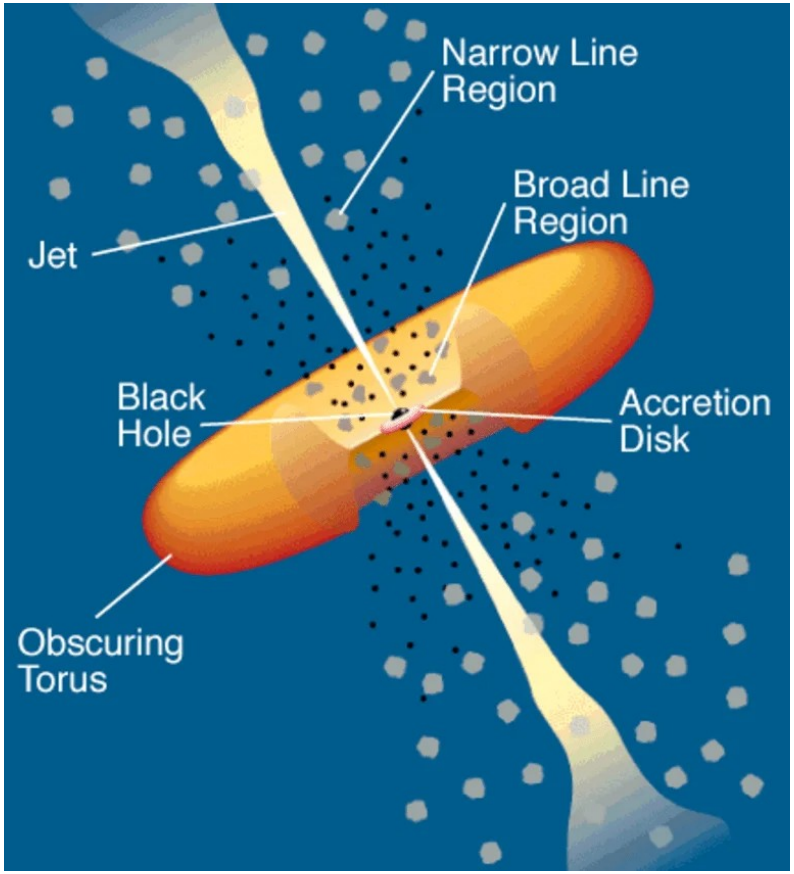
Credit: D. Karavola et al. 2026

Active Galactic Nuclei



Credit: IceCube/NASA

Active Galactic Nuclei



Credit: C.M. Urry & P. Padovani

AGN Zoo

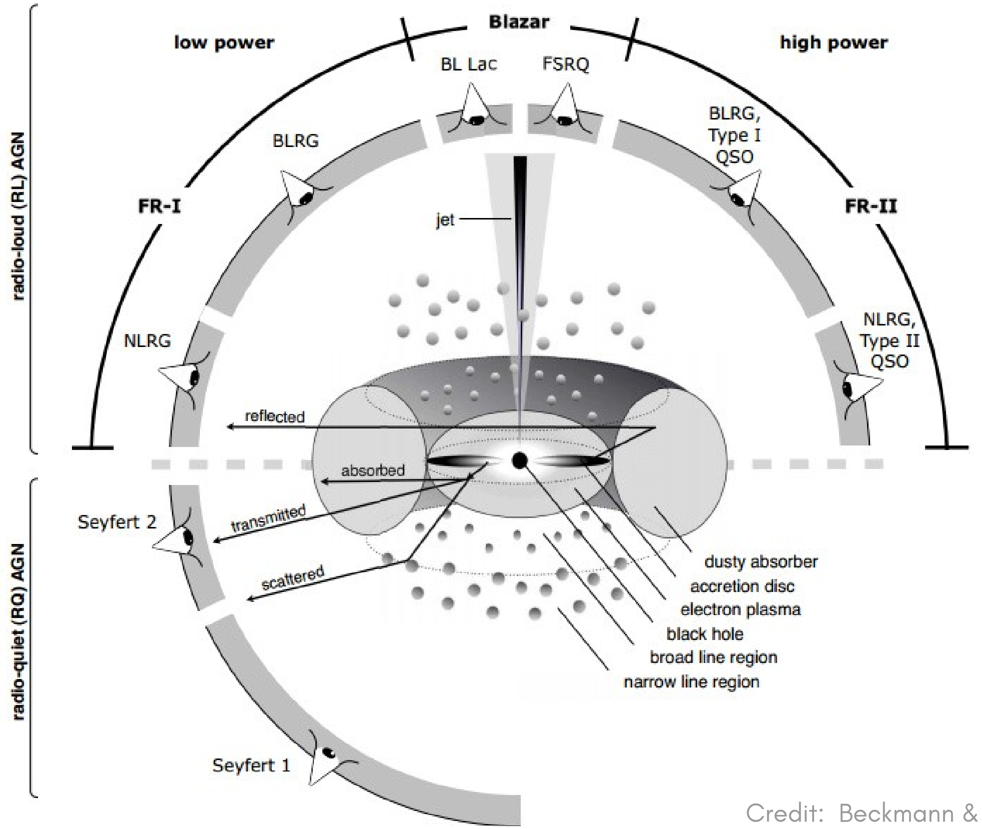
Table 1 The AGN zoo: list of AGN classes.

Class/Acronym	Meaning	Main properties/reference
Quasar	Quasi-stellar radio source (originally)	Radio detection no longer required
Sey1	Seyfert 1	FWHM $\gtrsim$ 1,000 km s^{-1}
Sey2	Seyfert 2	FWHM $\lesssim$ 1,000 km s^{-1}
QSO	Quasi-stellar object	Quasar-like, non-radio source
QSO2	Quasi-stellar object 2	High power Sey2
RQ AGN	Radio-quiet AGN	see ref. 1
RL AGN	Radio-loud AGN	see ref. 1
Jetted AGN		with strong relativistic jets; see ref. 1
Non-jetted AGN		without strong relativistic jets; see ref. 1
Type 1		Sey1 and quasars
Type 2		Sey2 and QSO2
FR I	Fanaroff-Riley class I radio source	radio core-brightened (ref. 2)
FR II	Fanaroff-Riley class II radio source	radio edge-brightened (ref. 2)
BL Lac	BL Lacertae object	see ref. 3
Blazar	BL Lac and quasar	BL Lacs and FSRQs
BAL	Broad absorption line (quasar)	ref. 4
BLO	Broad-line object	FWHM $\gtrsim$ 1,000 km s^{-1}
BLAGN	Broad-line AGN	FWHM $\gtrsim$ 1,000 km s^{-1}
BLRG	Broad-line radio galaxy	RL Sey1
CDQ	Core-dominated quasar	RL AGN, $f_{core} \geq f_{ext}$ (same as FSRQ)
CSS	Compact steep spectrum radio source	core dominated, $\alpha_r > 0.5$
CT	Compton-thick	$N_H \geq 1.5 \times 10^{24}$ cm^{-2}
FR 0	Fanaroff-Riley class 0 radio source	ref. 5
FSRQ	Flat-spectrum radio quasar	RL AGN, $\alpha_r \leq 0.5$
GPS	Gigahertz-peaked radio source	see ref. 6
HBL/HSP	High-energy cutoff BL Lac/blazar	$\nu_{synch\ peak} \geq 10^{15}$ Hz (ref. 7)
HEG	High-excitation galaxy	ref. 8
HPQ	High polarization quasar	$P_{opt} \geq 3\%$ (same as FSRQ)
Jet-mode		$L_{kin} \gg L_{rad}$ (same as LERG); see ref. 9
IBL/ISP	Intermediate-energy cutoff BL Lac/blazar	$10^{14} \leq \nu_{synch\ peak} \leq 10^{15}$ Hz (ref. 7)
LINER	Low-ionization nuclear emission-line regions	see ref. 9
LLAGN	Low-luminosity AGN	see ref. 10
LBL/LSP	Low-energy cutoff BL Lac/blazar	$\nu_{synch\ peak} < 10^{14}$ Hz (ref. 7)
LDQ	Lobe-dominated quasar	RL AGN, $f_{core} < f_{ext}$
LEG	Low-excitation galaxy	ref. 8
LPQ	Low polarization quasar	$P_{opt} < 3\%$
NLAGN	Narrow-line AGN	FWHM $\lesssim$ 1,000 km s^{-1}
NLRG	Narrow-line radio galaxy	RL Sey2
NLS1	Narrow-line Seyfert 1	ref. 11
OVV	Optically violently variable (quasar)	(same as FSRQ)
Population A		ref. 12
Population B		ref. 12
Radiative-mode		Seyferts and quasars; see ref. 9
RBL	Radio-selected BL Lac	BL Lac selected in the radio band
Sey1.5	Seyfert 1.5	ref. 13
Sey1.8	Seyfert 1.8	ref. 13
Sey1.9	Seyfert 1.9	ref. 13
SSRQ	Steep-spectrum radio quasar	RL AGN, $\alpha_r > 0.5$
USS	Ultra-steep spectrum source	RL AGN, $\alpha_r > 1.0$
XBL	X-ray-selected BL Lac	BL Lac selected in the X-ray band
XBONG	X-ray bright optically normal galaxy	AGN only in the X-ray band/weak lined AGN

The top part of the table relates to major/classical classes. The last column describes the main properties. When these are too complex, it gives a reference to the first paper, which defined the relevant class or, when preceded by "see", a recent paper, which gives up-to-date details on it. Reference key: 1. Padovani (2016); 2. Fanaroff & Riley (1974); 3. Giommi et al. (2012); 4. Weymann, Carswell, & Smith (1981); 5. Ghisellini (2010); 6. O'Dea, Baum, & Stanghellini (1991); 7. Padovani & Giommi (1995); 8. Laing et al. (1994); 9. Heckman & Best (2014); 10. Ho (2008); 11. Osterbrock & Pogge (1985); 12. Sulentic et al. (2002); 13. Osterbrock (1981)

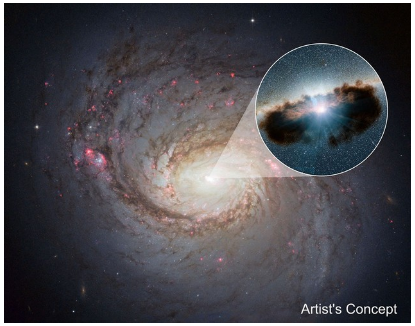
Credit: P. Padovani et al. 2012

AGN Unification

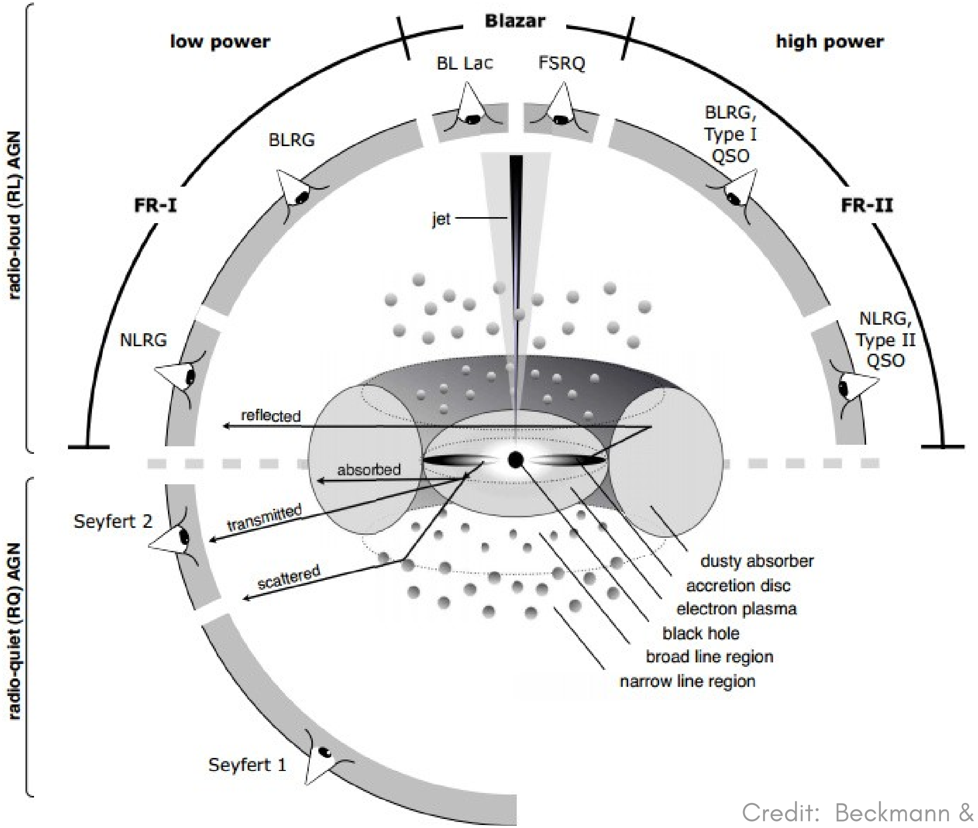


Credit: Beckmann & Shrader 2012

AGN Unification

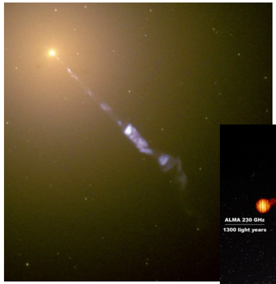


Credit: NASA

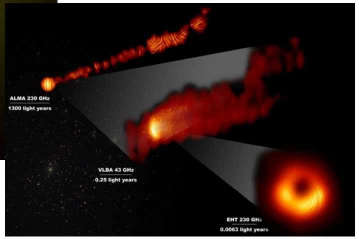


Credit: Beckmann & Shrader 2012

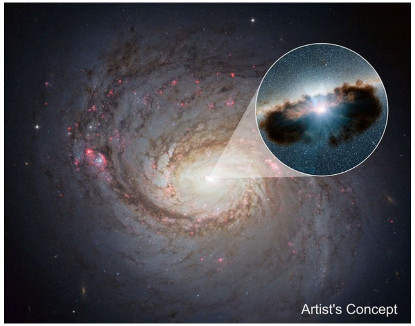
AGN Unification



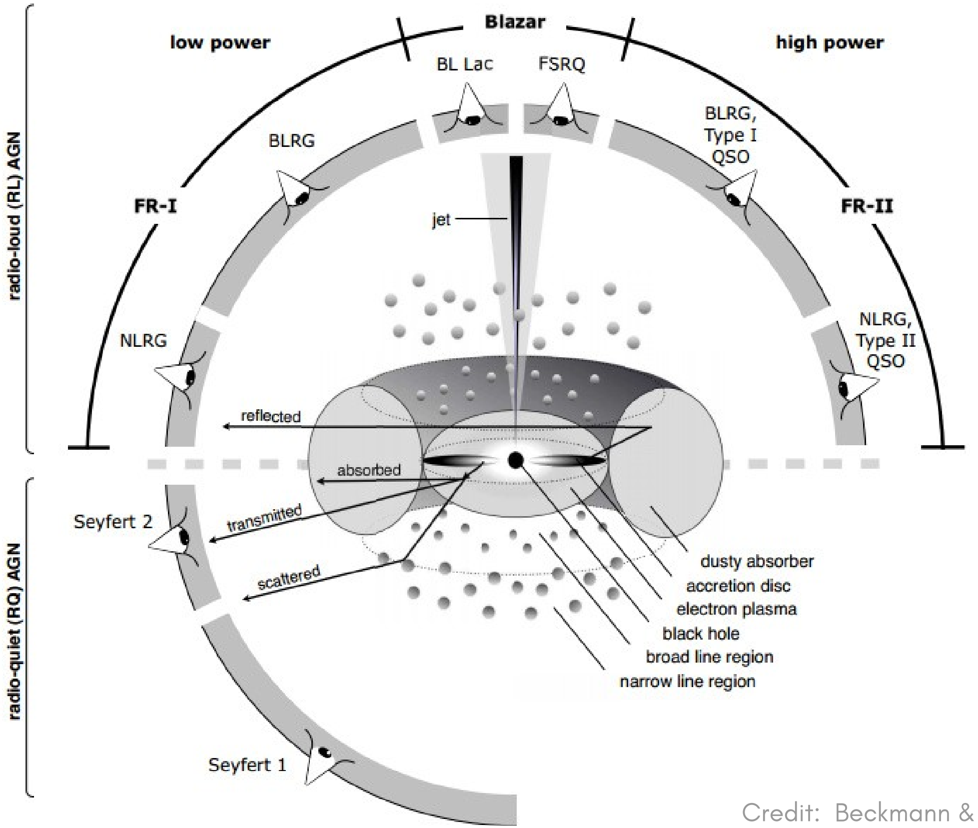
Credit: NASA



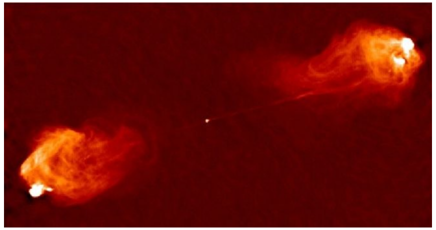
Credit: ESO



Credit: NASA

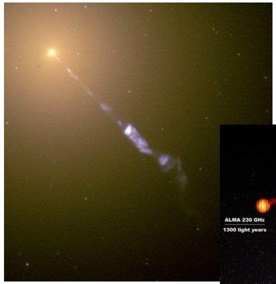


Credit: Beckmann & Shrader 2012



Credit: NRAO/VLA

AGN Unification



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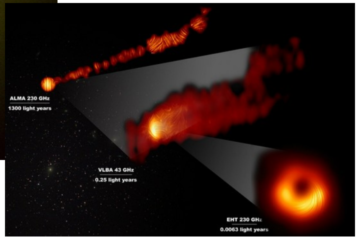

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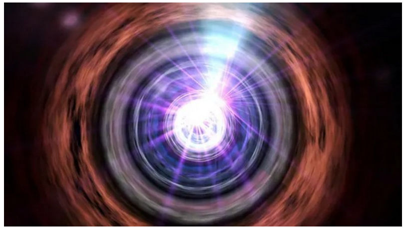
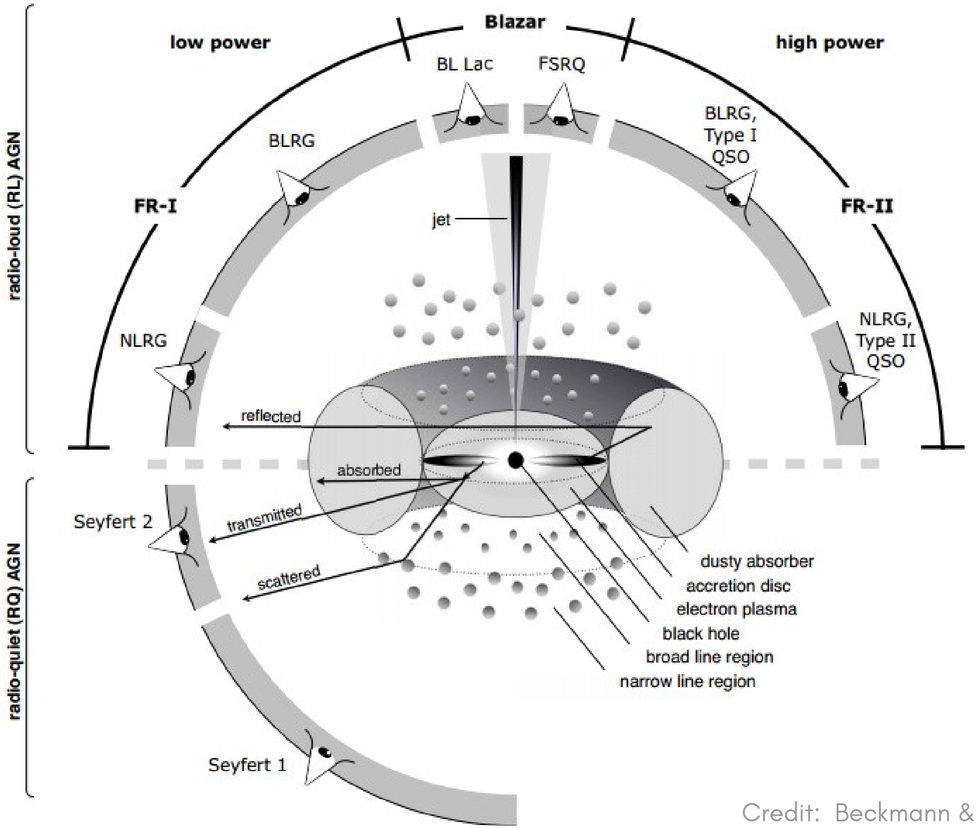


Credit: NASA



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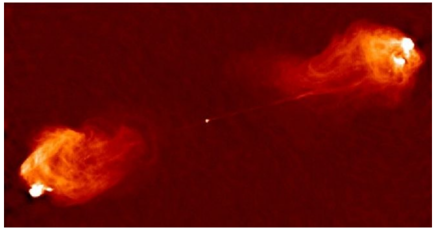

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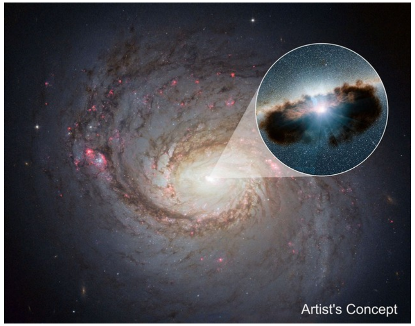
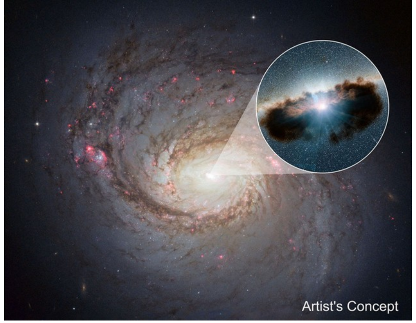


Credit: NASA

Seyferts

NGC 1068

- Hotspot in IceCube searches since years
- $\sim 4\sigma$



Credit: NASA

Seyferts

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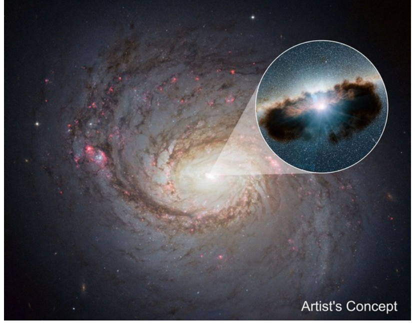
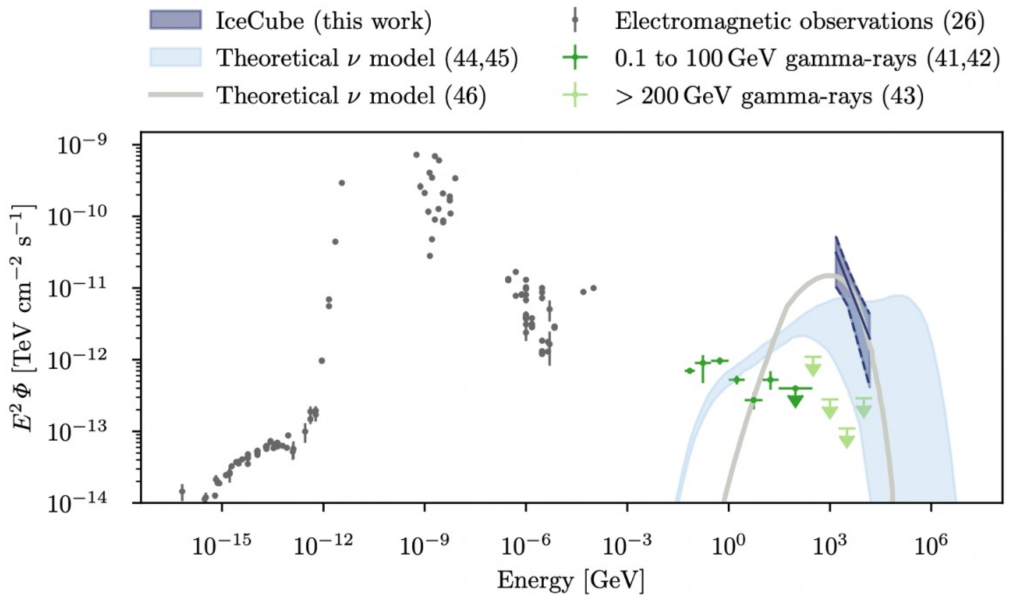


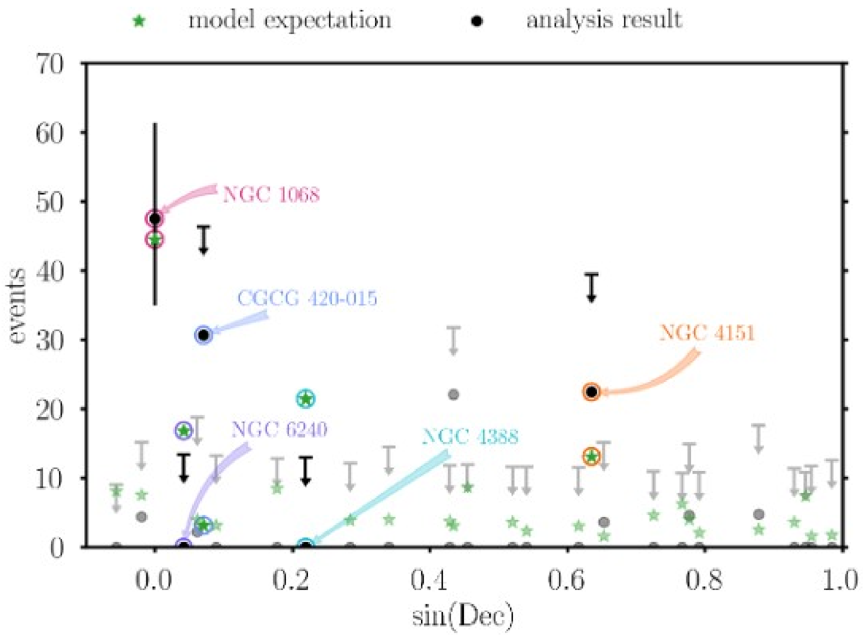
Credit: NASA



Credit: IceCube 2022

Seyferts

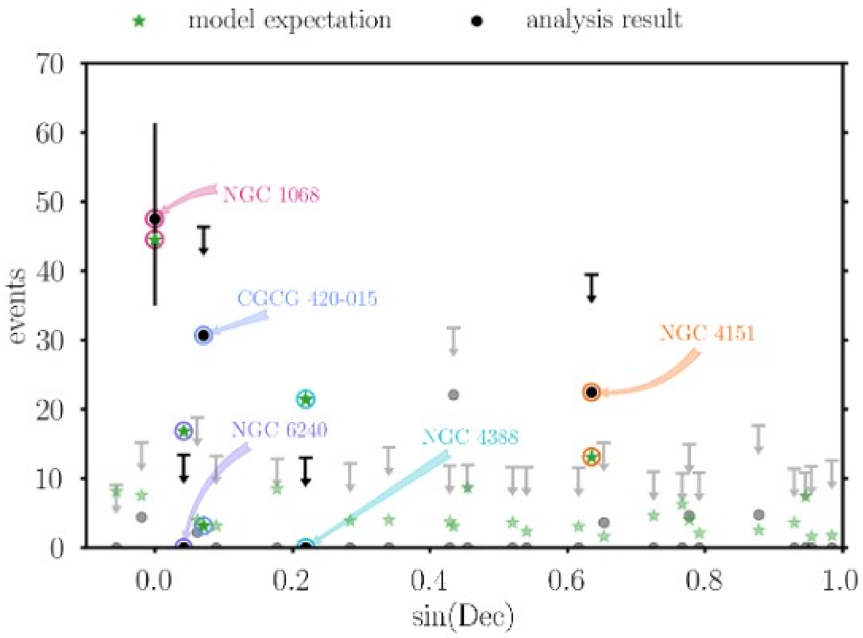
IceCube search from X-ray bright AGN → Seyferts



Credit: IceCube 2025

Seyferts

IceCube search from X-ray bright AGN → Seyferts



Credit: IceCube 2025

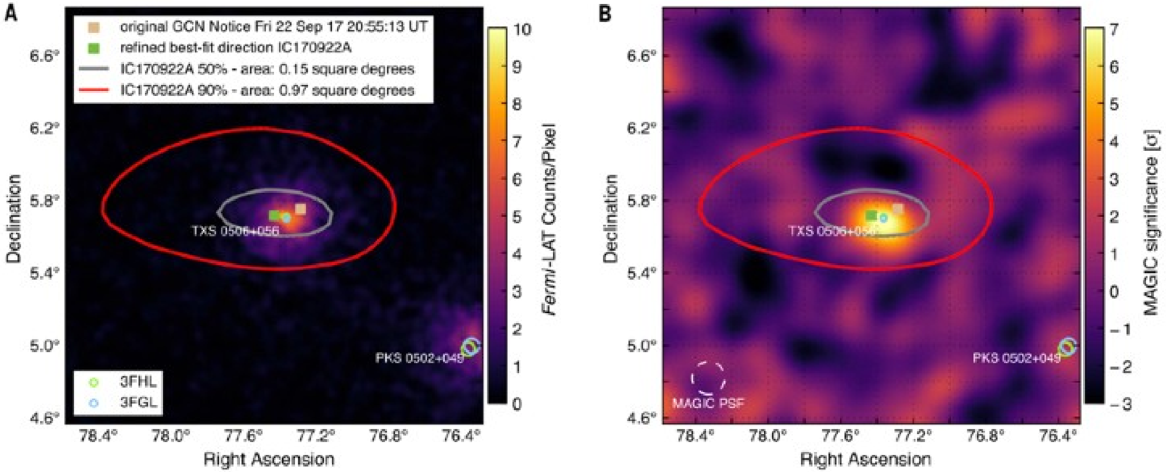
But it is a steady source
(at least in high-energies)

So we're moving to the next source class

Blazars as multi-messenger sources

IceCube-170922A / TXS 0506+056

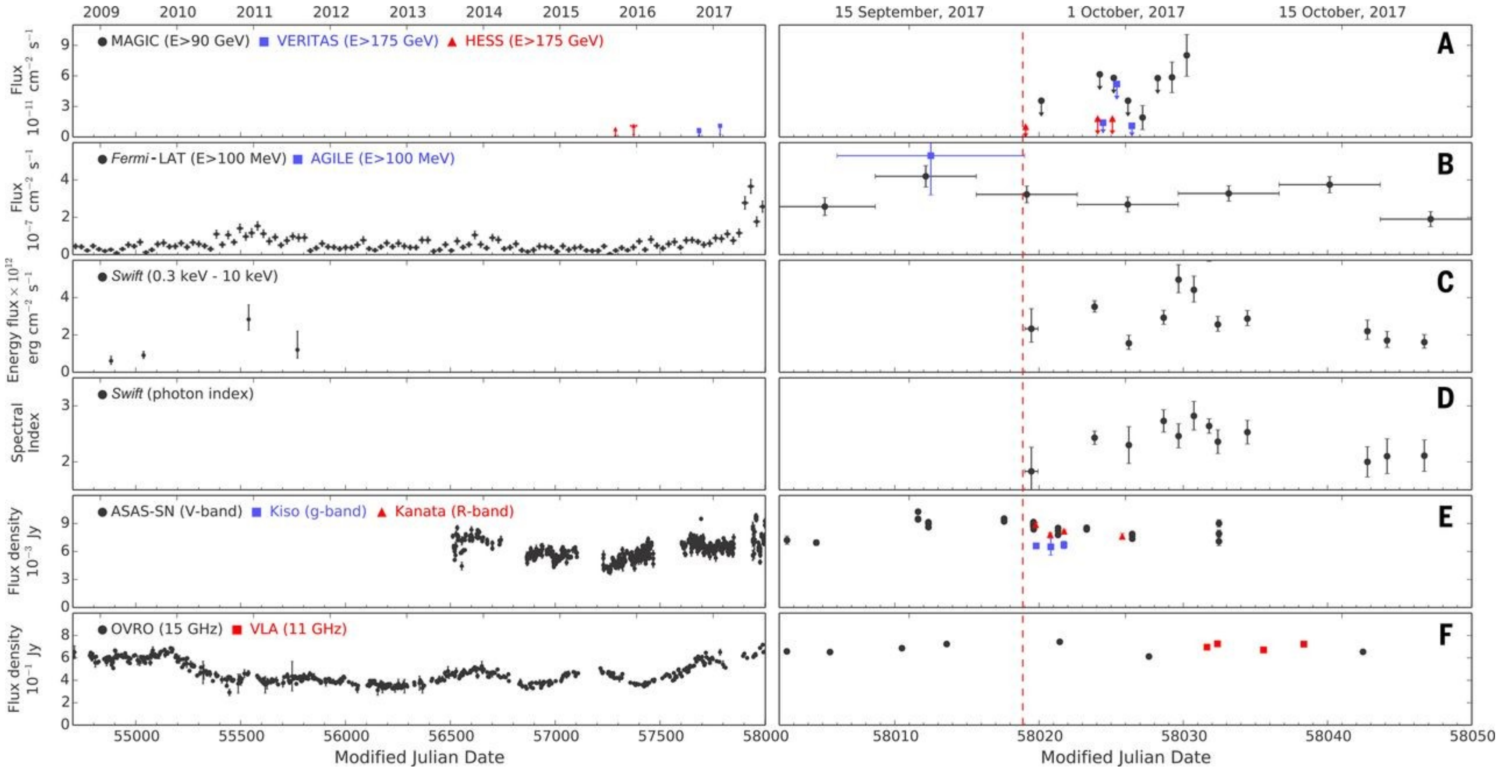
3σ - association of a high-energy (290 TeV) neutrino



Credit: IceCube, Fermi, MAGIC et al. 2018

Blazars as multi-messenger sources

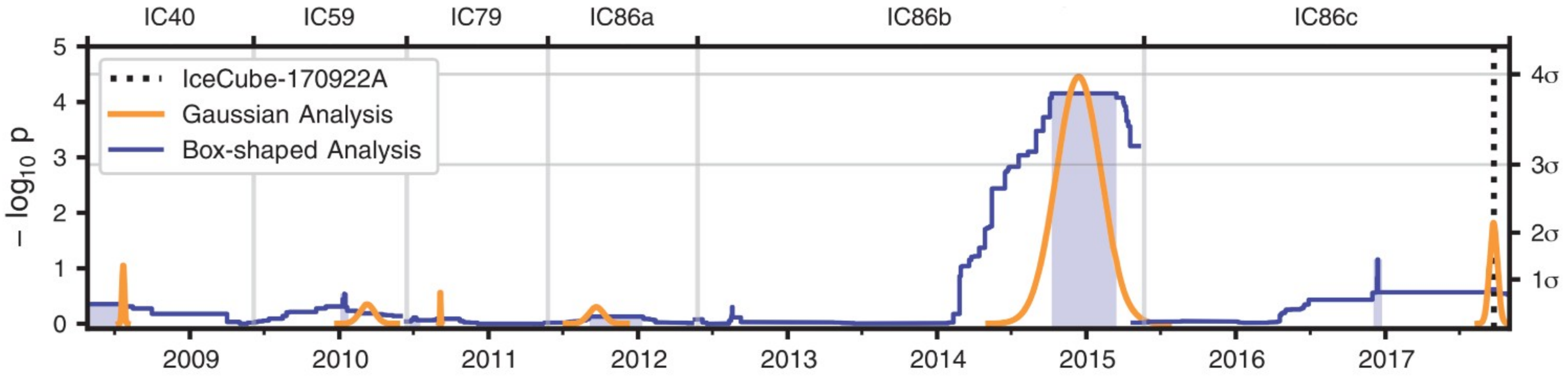
IceCube-170922A / TXS 0506+056



Credit: IceCube, Fermi, MAGIC et al. 2018

Blazars as multi-messenger sources

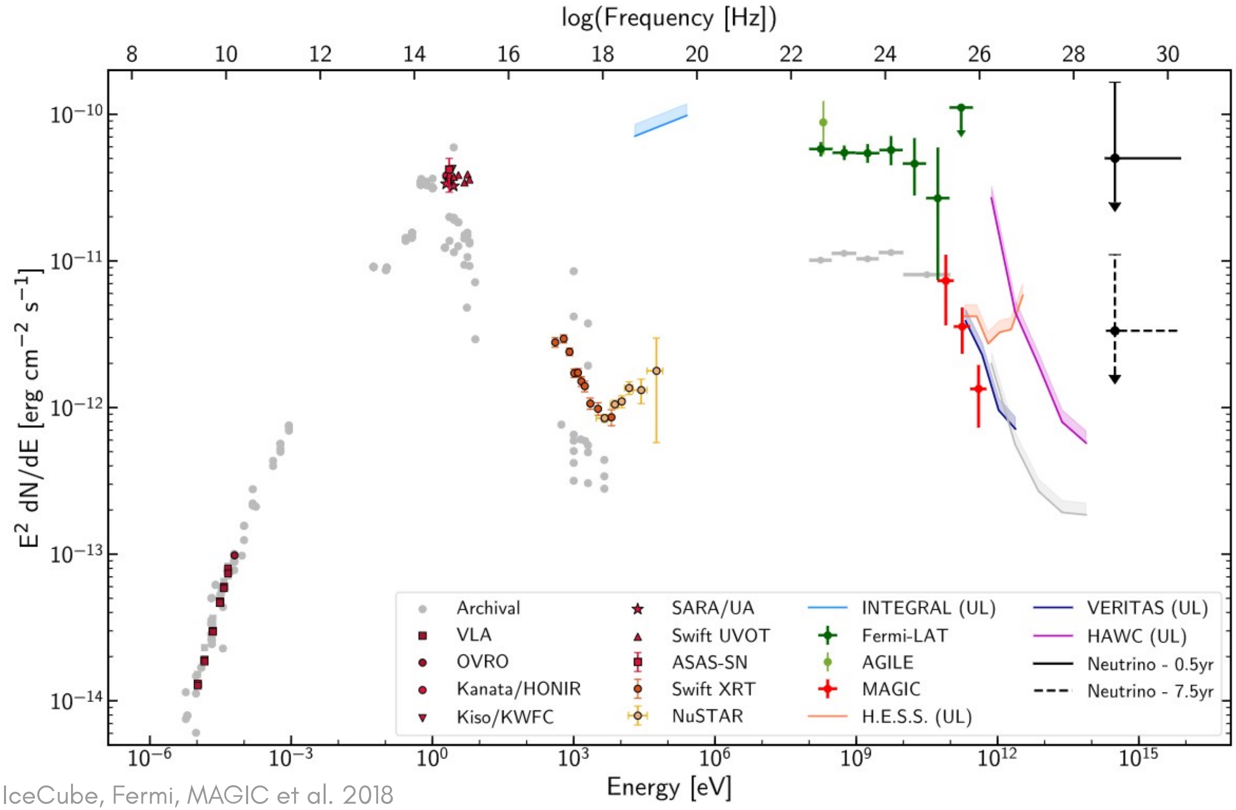
TXS 0506+056



Credit: IceCube et al. 2018b

Blazars emission models

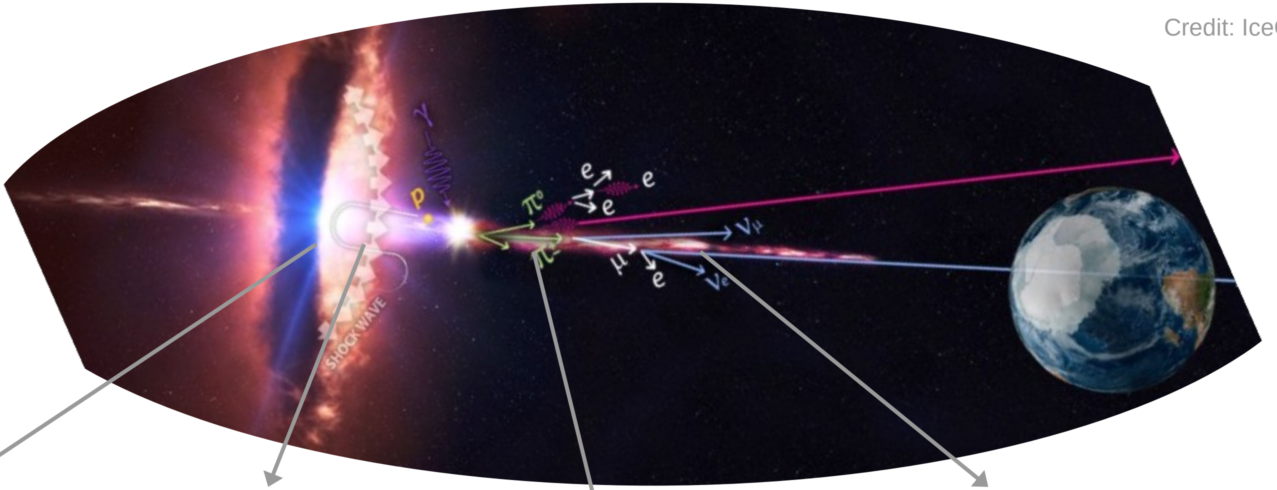
IceCube-170922A / TXS 0506+056



Credit: IceCube, Fermi, MAGIC et al. 2018

Modelling astrophysical sources

Credit: IceCube/NASA



Initial conditions:
Particle plasma,
(GR)-MHD,
PIC simulations
…

Particle acceleration & cooling

→ (relativistic) particle distributions

Radiation mechanisms

→ γ distributions

Propagation: absorption, boosting,..

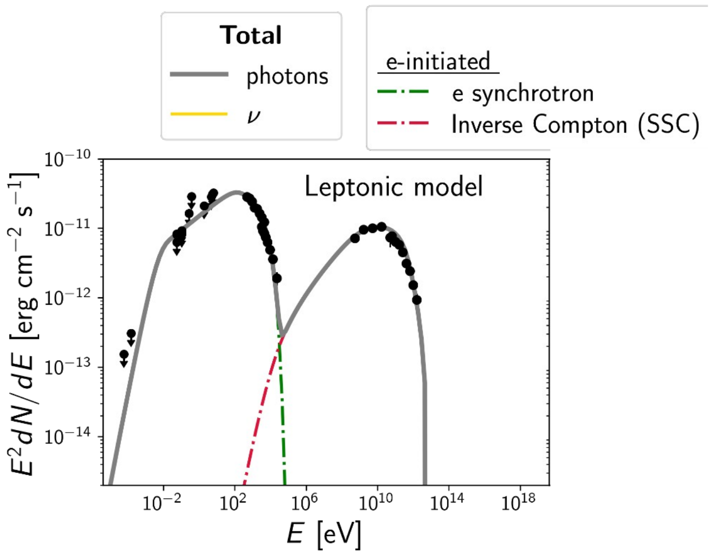
→ altered γ distributions

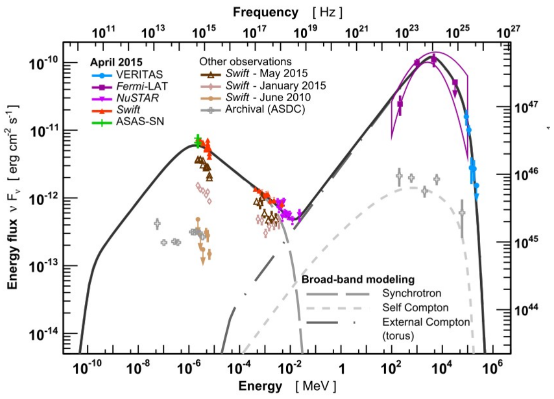
Modelled SEDs, LCs,...

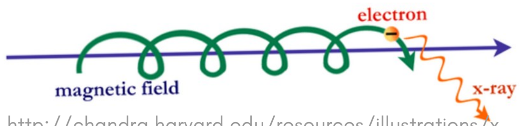
Fitting

Data

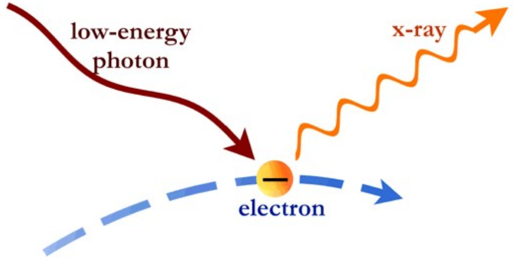
Blazars emission models







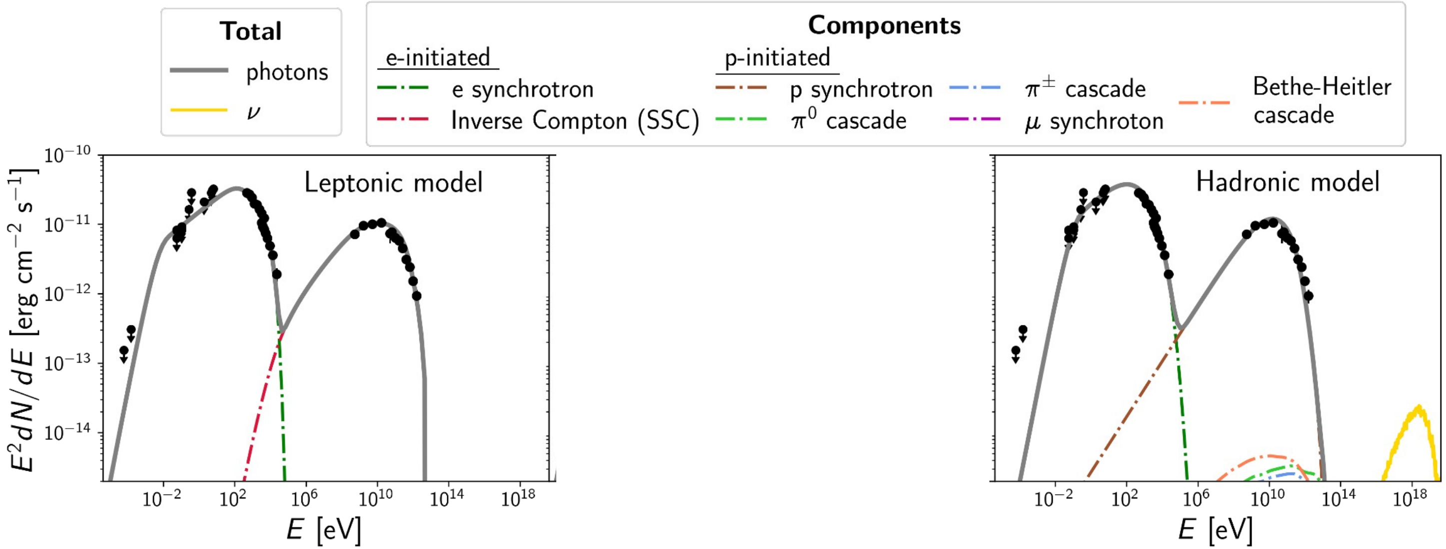
Credit: http://chandra.harvard.edu/resources/illustrations/x-raysLight.html

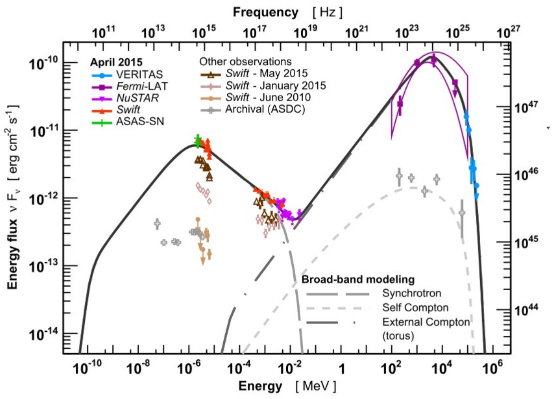


Credit: http://chandra.harvard.edu/resources/illustrations/x-raysLight.html

Credit: ApJL 815 L22 (2015)

Blazars emission models





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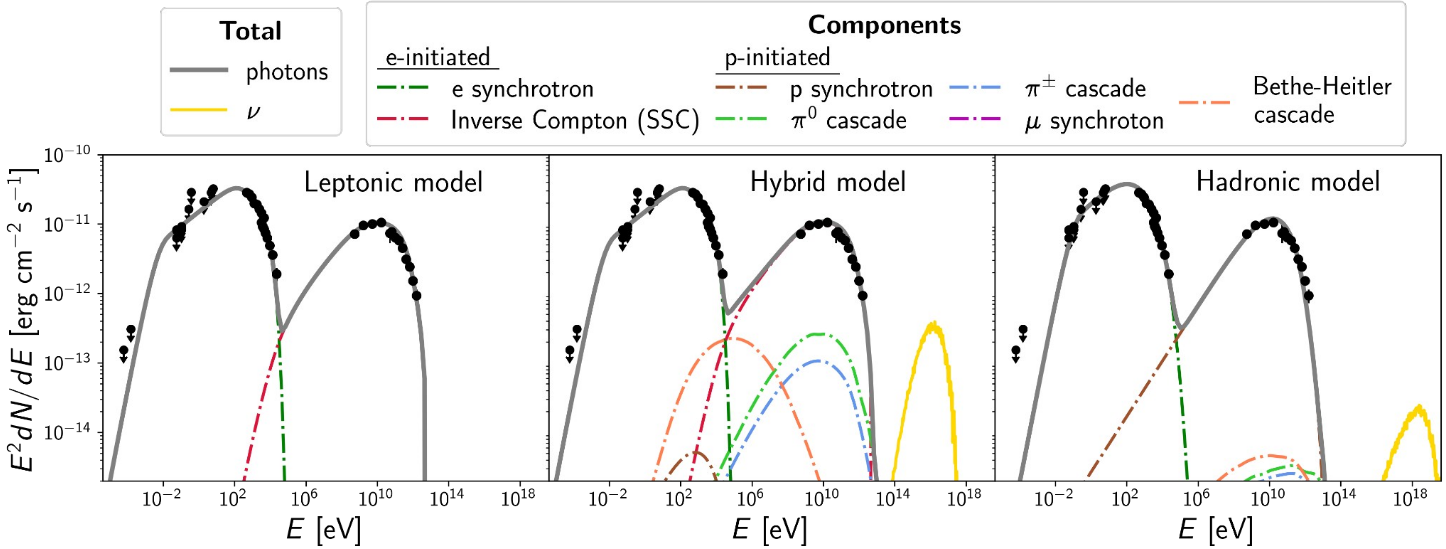
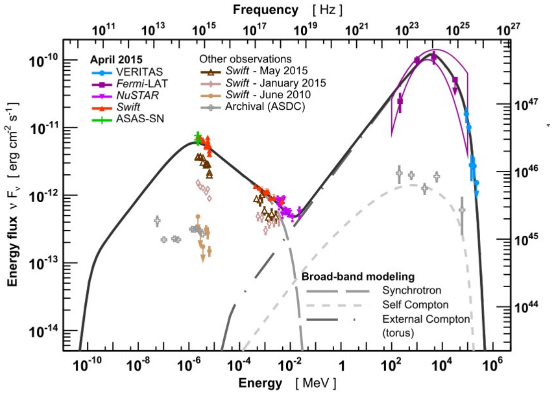
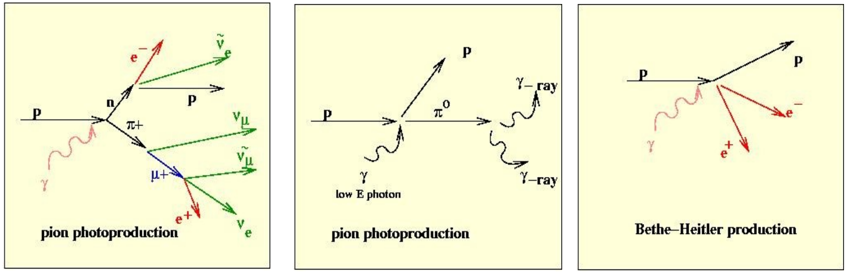
Blazars emission models





Credit: ApJL 815 L22 (2015)



Credit: http://www.physics.adelaide.edu.au/astrophysics/theory/interactions.html

Doppler boosting

- Enhances the flux when structures move relativistically towards us at an angle θ

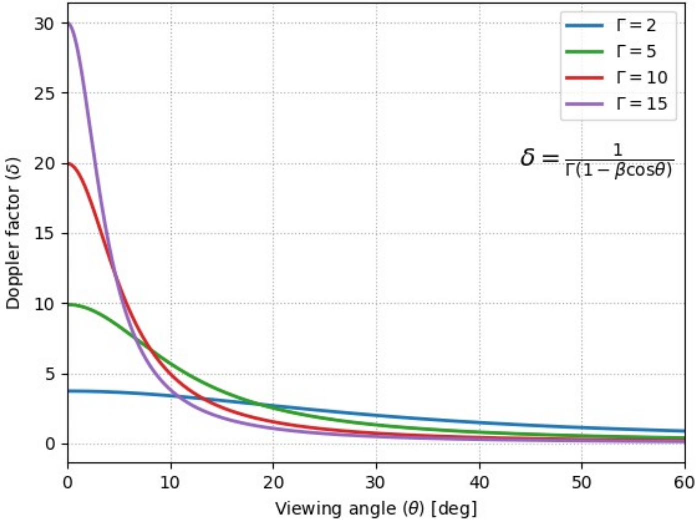
source frame vs. observer frame

$$\nu = \delta \, \nu'$$

$$dt = \delta^{-1} dt'$$

$$F_\nu(\nu) = \delta^{(3+\Gamma)} F'_\nu(\nu)$$

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



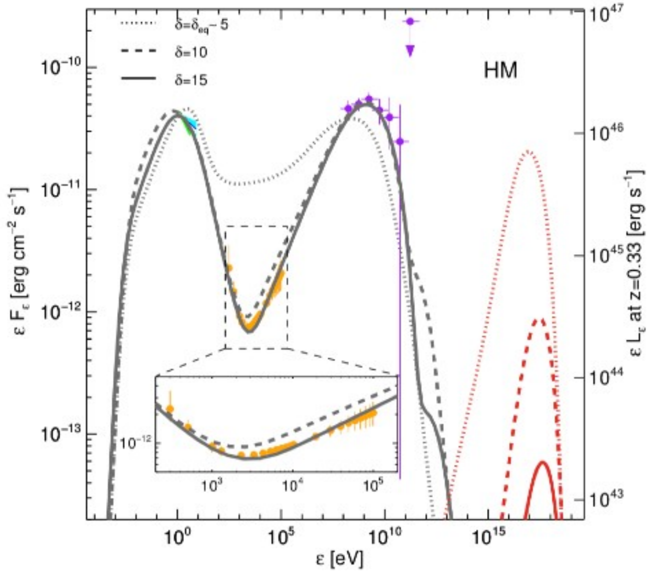
Credit: https://www.mpi-hd.mpg.de/HESS/pages/home/som/2018/04/

TXS 0506+056 flare models

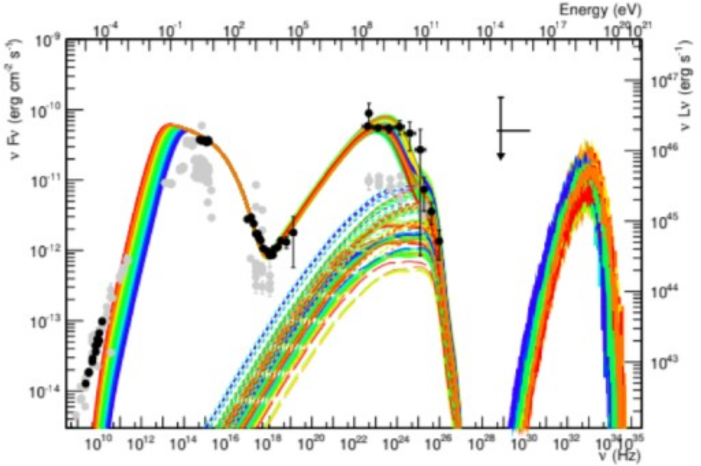
Hadronic solutions

TXS 0506+056 flare models

Hadronic solutions



Credit: Keivani et al. 2018

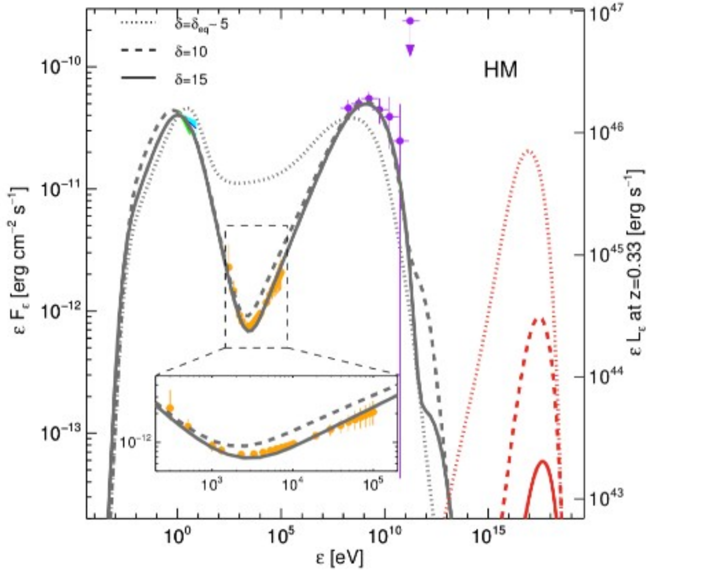


(a) Proton synchrotron modeling of TXS 0506+056

Credit: Cerruti et al. 2019

TXS 0506+056 flare models

Hadronic solutions



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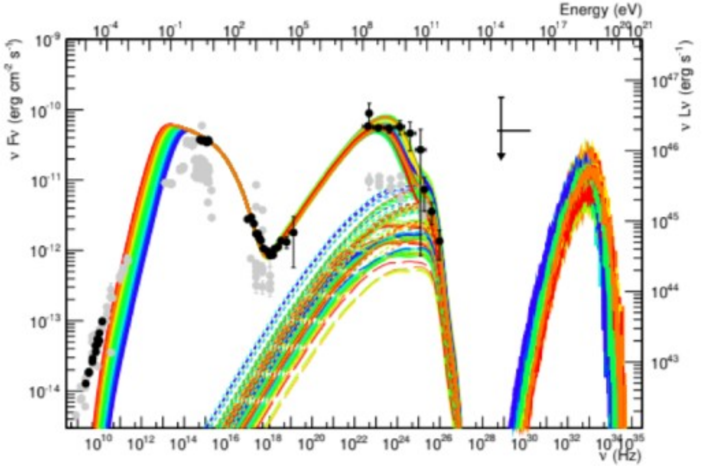


(a) Proton synchrotron modeling of TXS 0506+056

Credit: Cerruti et al. 2019

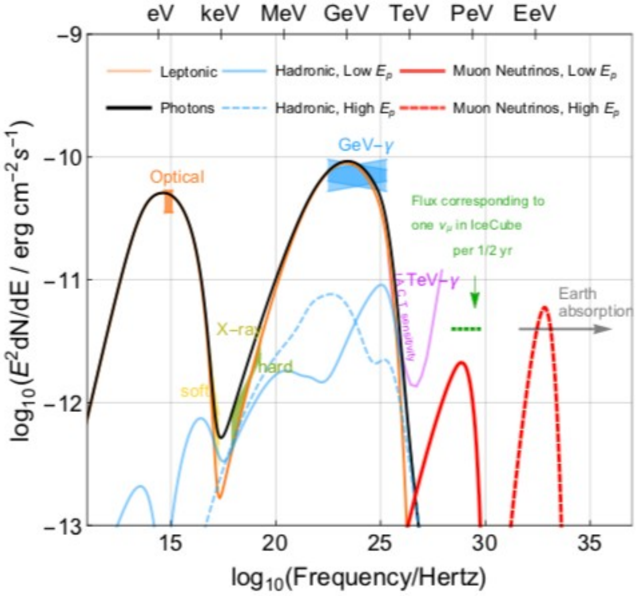
→ Low neutrino rate

TXS 0506+056 flare models

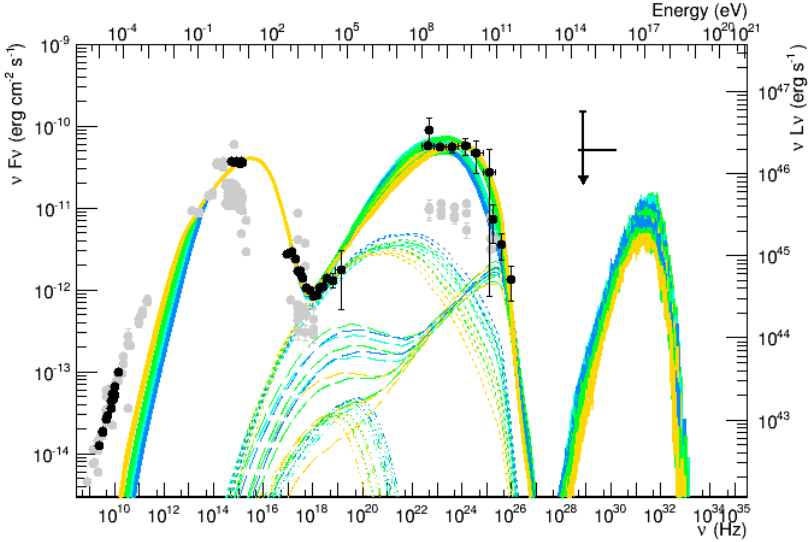
Lepto-hadronic solutions

TXS 0506+056 flare models

Lepto-hadronic solutions



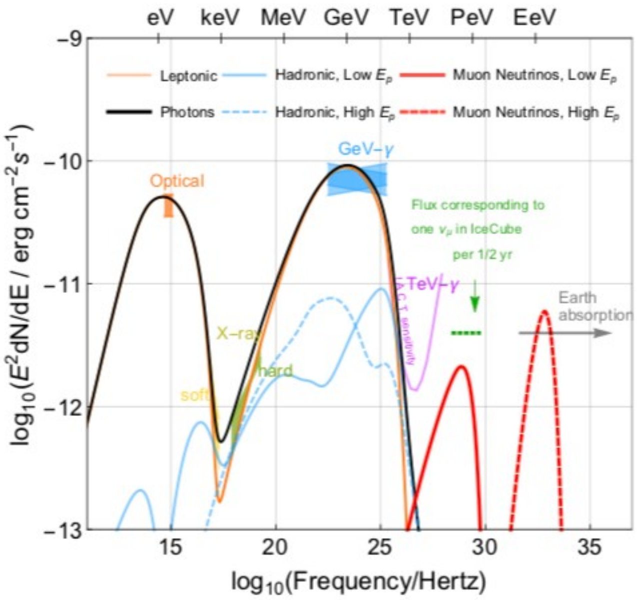
Credit: Gao et al. 2018



Credit: Cerruti et al. 2019

TXS 0506+056 flare models

Lepto-hadronic solutions



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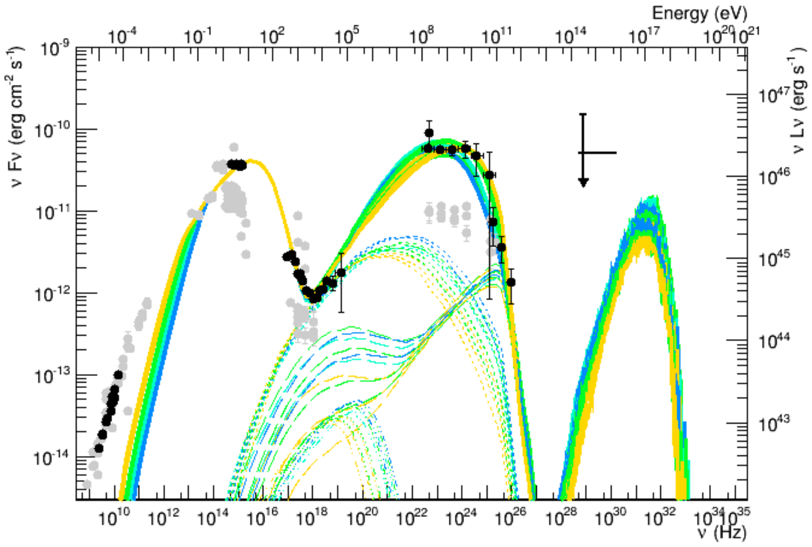
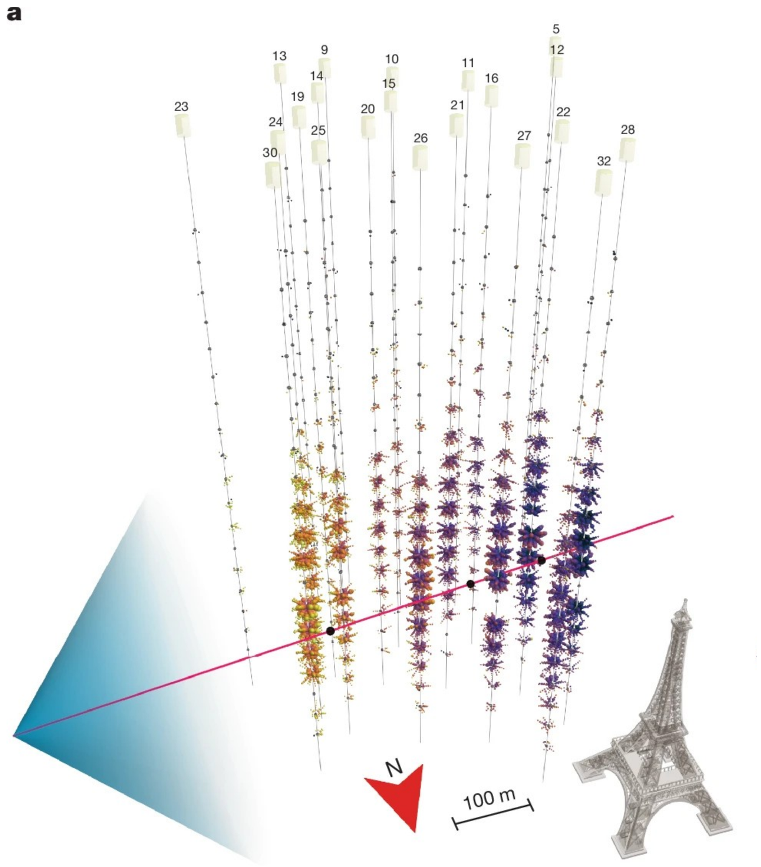


Credit: Cerruti et al. 2019

→ neutrino rates of around 0.1 / yr

BUT: $L_{jet} \gg L_{Edd}$

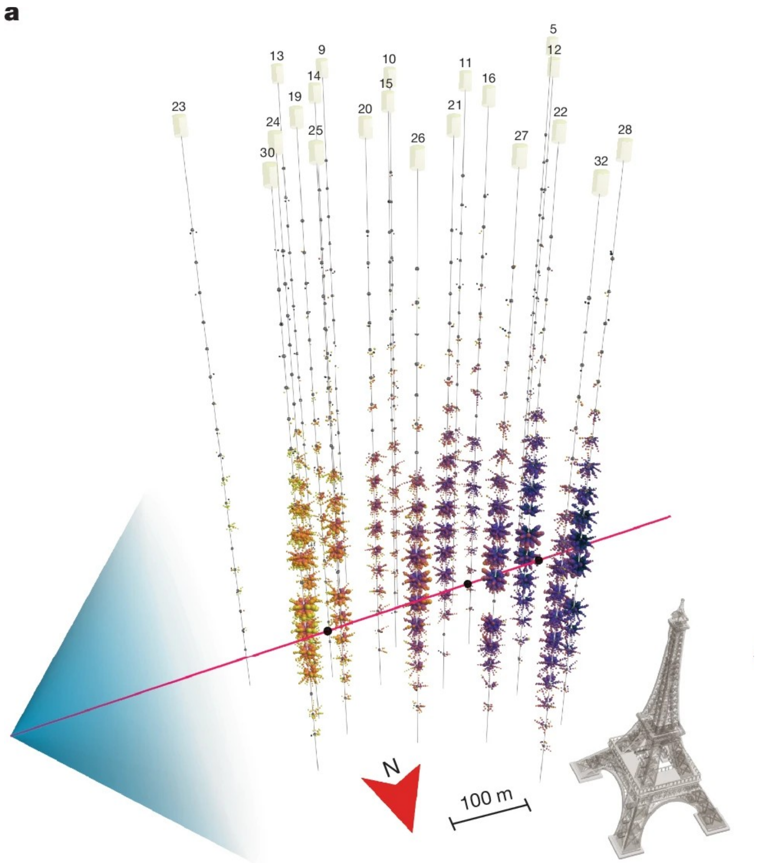
Blazars as multi-messenger sources



KM3-230213A

Credit: KM3net et al 2025

Blazars as multi-messenger sources



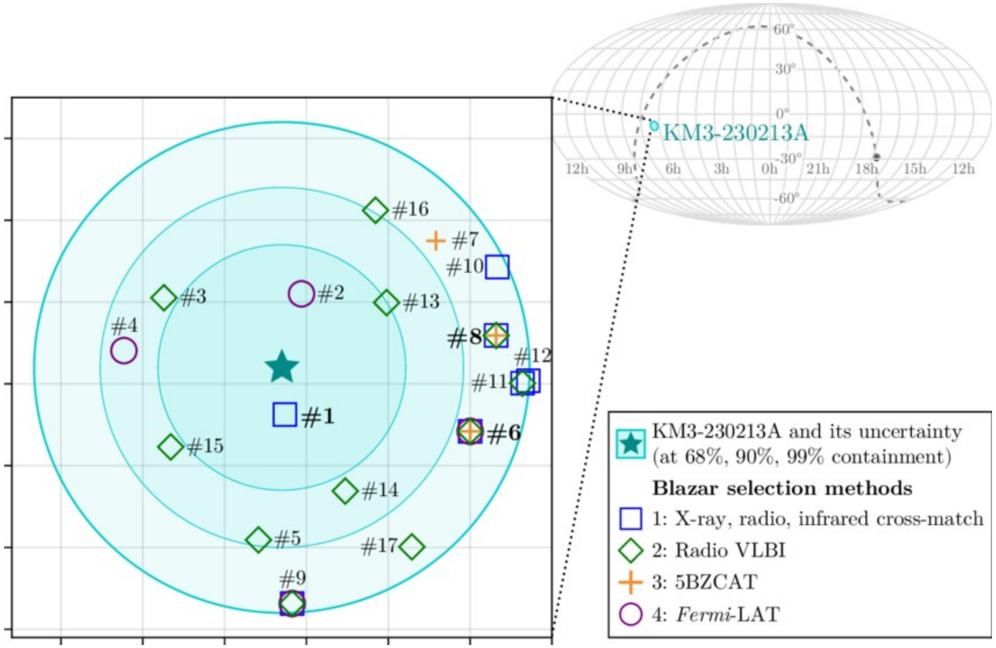
Credit: KM3net et al 2025

KM3-230213A

Highest energy neutrino so far at around 220 PeV

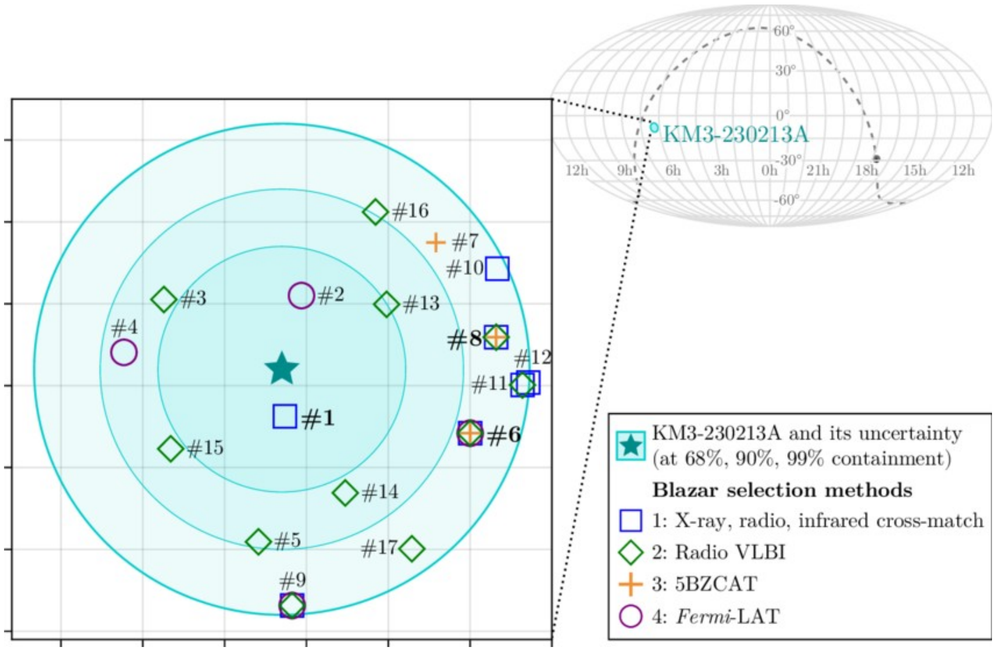
20x the highest energy neutrino detected by IceCube

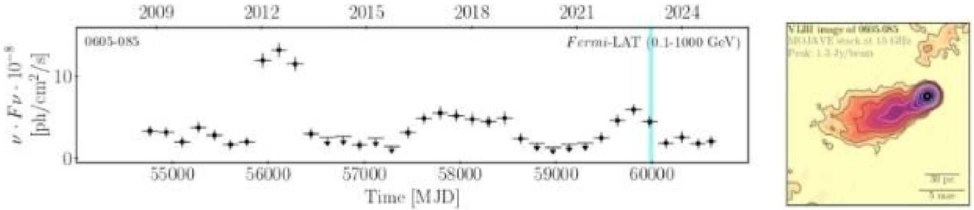
Blazars as multi-messenger sources



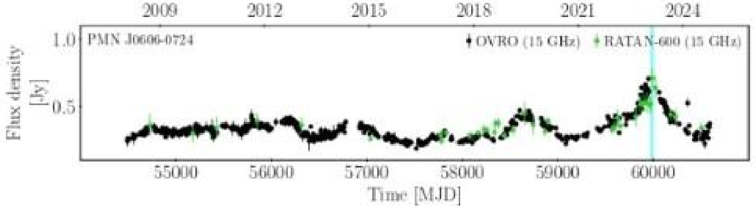
Credit: KM3net et al 2025b

Blazars as multi-messenger sources

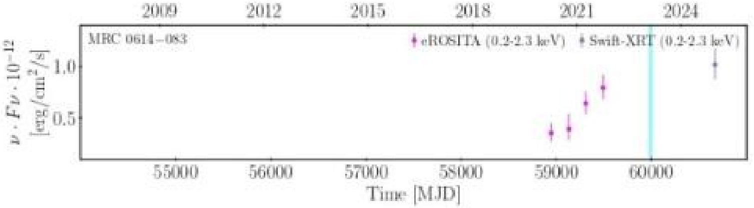




(a) The *Fermi*-LAT light curve and a VLBI image of 0605-085: the brightest radio source in the neutrino localisation region that experiences a gamma-ray flaring activity around the neutrino arrival (Section 5.1).



(b) The radio light curve for PMN J0606-0724 that experiences a major flare in close coincidence to the neutrino arrival (Section 5.2).



(c) The X-ray light curve for MRC 0614-083 that indicates a flaring activity around the neutrino arrival (Section 5.3).

Credit: KM3net et al 2025b

Blazars as multi-messenger sources

- A few more neutrino-associations e.g.
  - BL Lac/FSRQ (masquerading) PKS 1424-418 with a ~2 PeV Icecube neutrino
  - LBL PKS 0735+178 associated with neutrino events in 2021 & flare from optical to γ
  - FSRQ PKS 1741-038 with neutrinos in 2011 and 2022 close in time to radio outbursts
  - LBL TXS 1749+096 with neutrino in 2022
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  - Selecting different classes of blazars (e.g. masquerading BL Lacs)
  - Selecting different wavebands
  - Selecting flares in different wavebands

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  - Selecting flares in different wavebands

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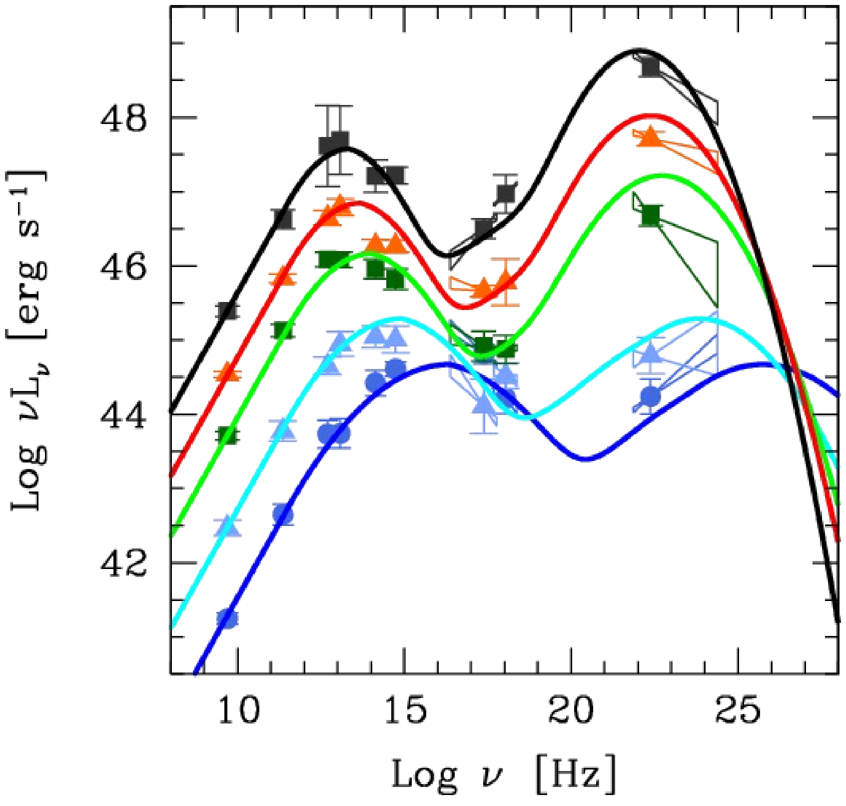
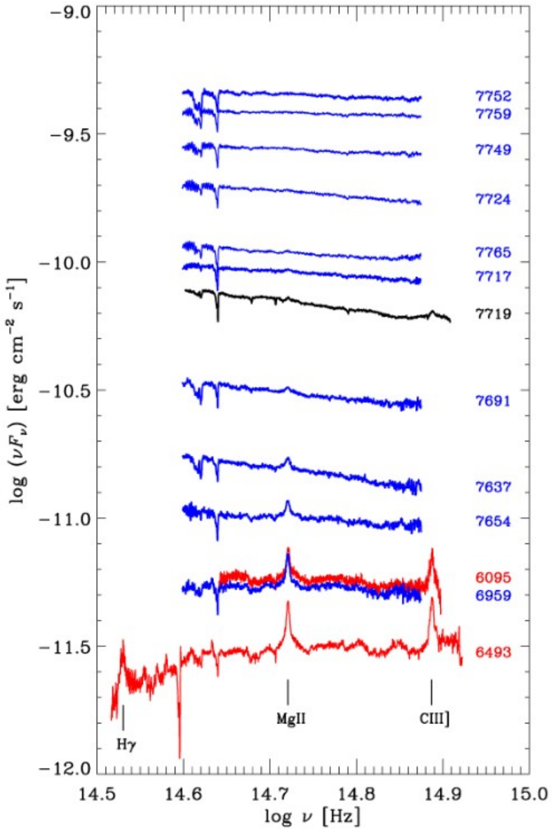
  But we can still try to understand blazar emission using multiwavelength data

MWL SEDs



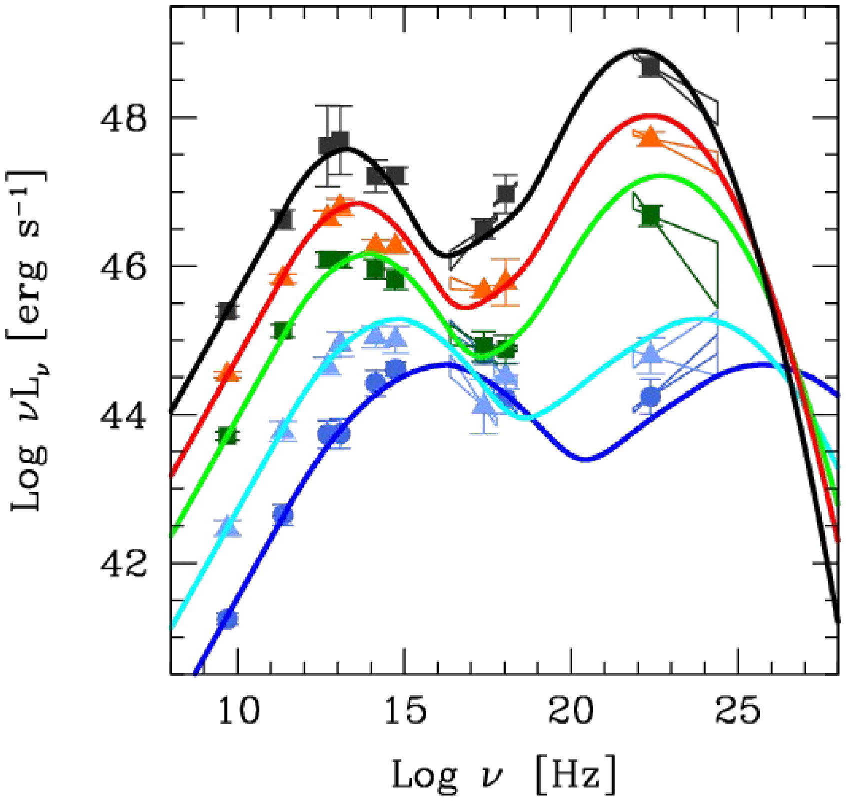
Credit: Fossati et al. 1998

FSRQs vs. BL Lacs



Credit: Raiteri et al 2017

MWL SEDs



Credit: Fossati et al. 1998

FSRQs vs. BL Lacs

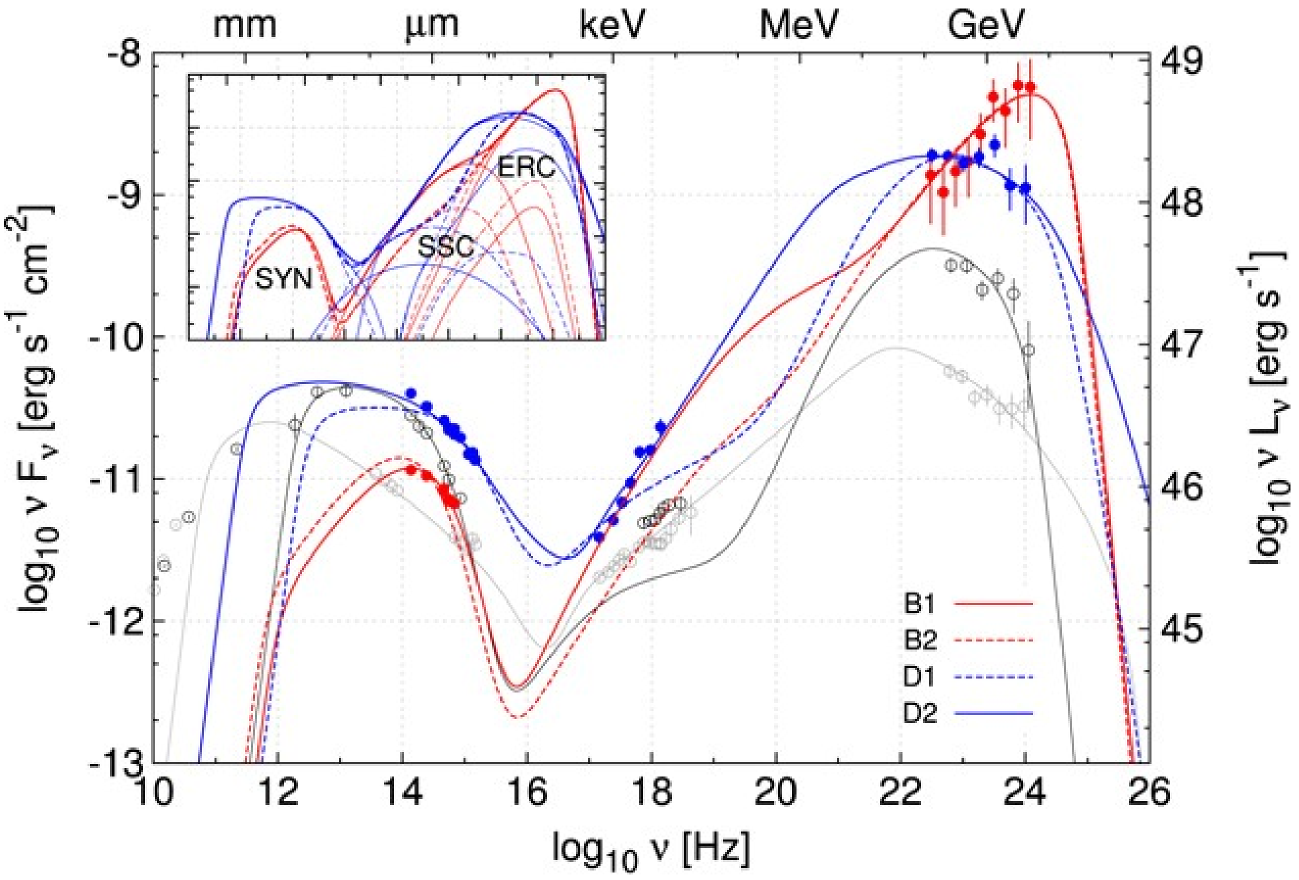
- **FSRQs** usually show a peak in IR
- BL Lac objects are classified in:
  - peak in IR: low-frequency peaked (**LBLs or LSPs**)
  - peak in optical: intermediate (**IBLs or ISPs**)
  - peak in UV / X-rays: high (**HBLs or HSPs**)
  - "Blazar sequence" – Luminosity to peak position
    - Observational bias

MWL SEDs

3C 279

MWL SEDs
of single sources
can change drastically
over time

Can also transition
between blazars
classes



Credit: M. Hayashida et al. 2015

MWL lightcurves

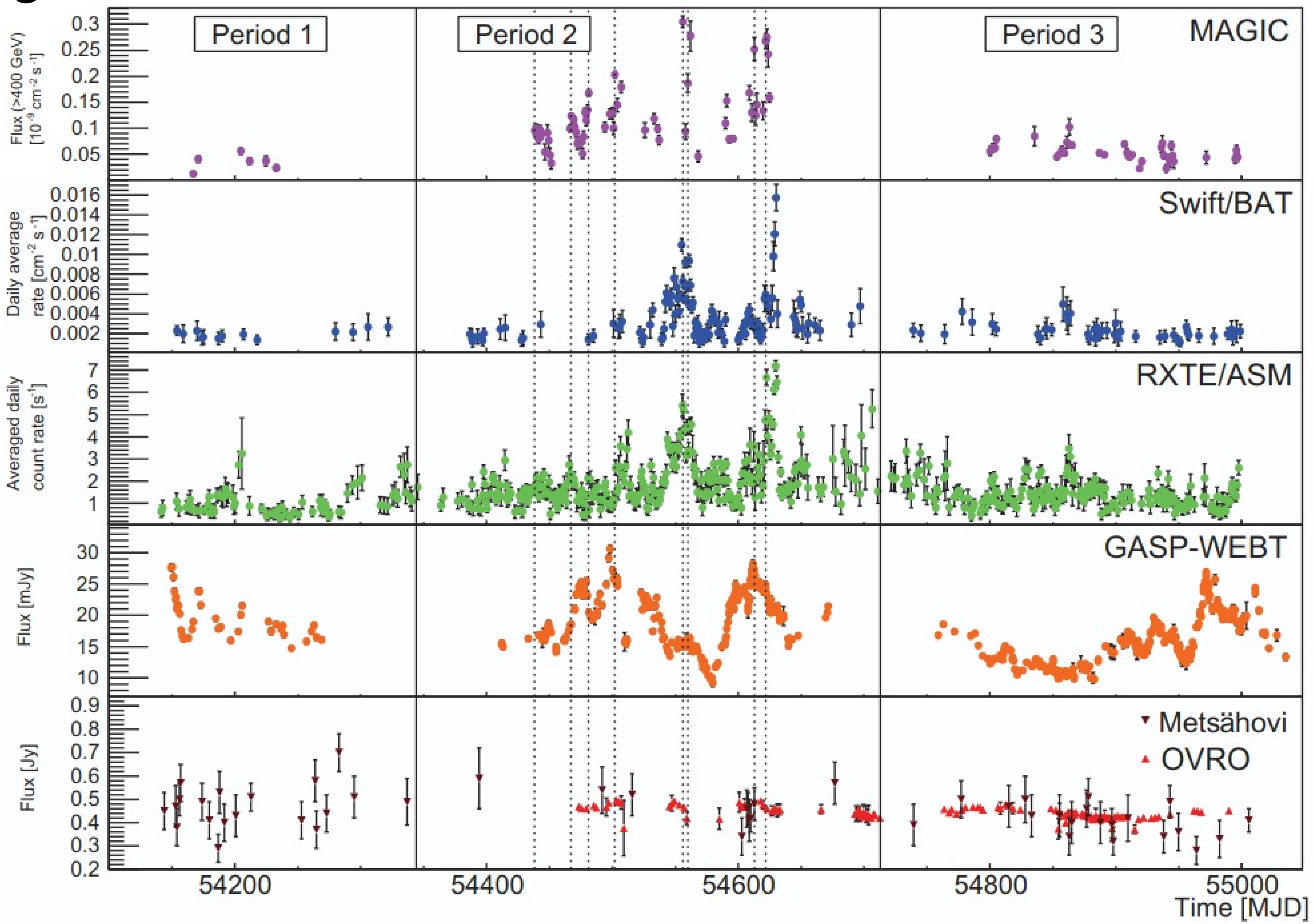
Credit: Ahnen et al 2016

Mrk 421

Blazars...

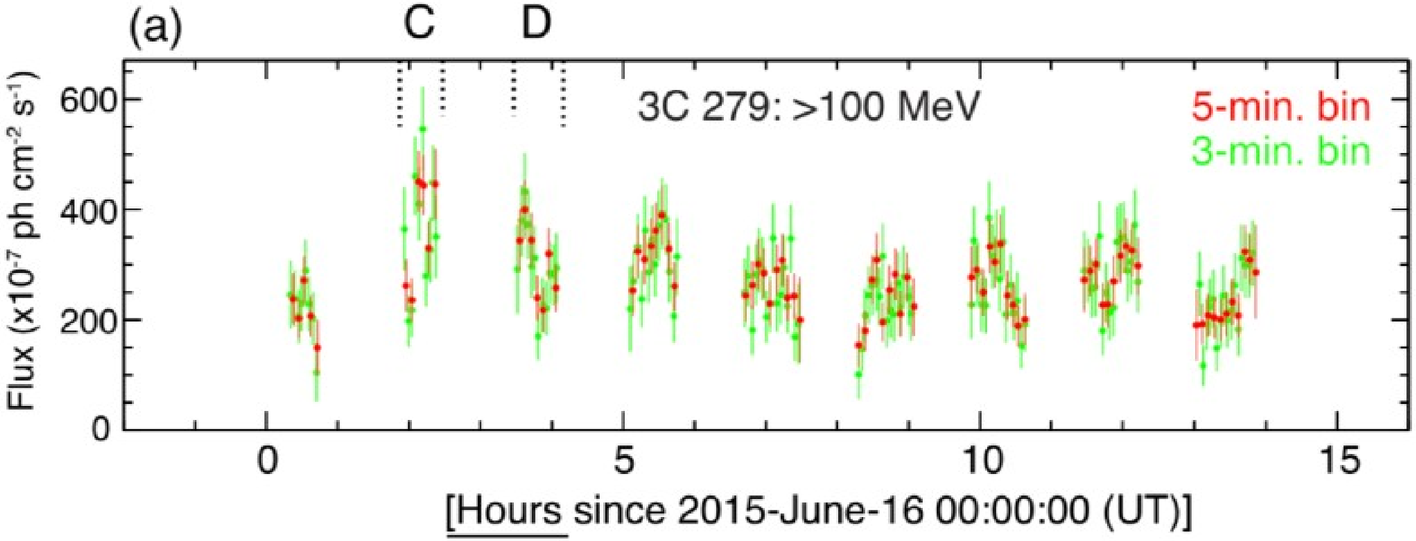
...are extremly variable

...show flares in various wavebands



MWL SEDs

...down to
min time scales



Credit: Ackermann et al 2016

MWL SEDs

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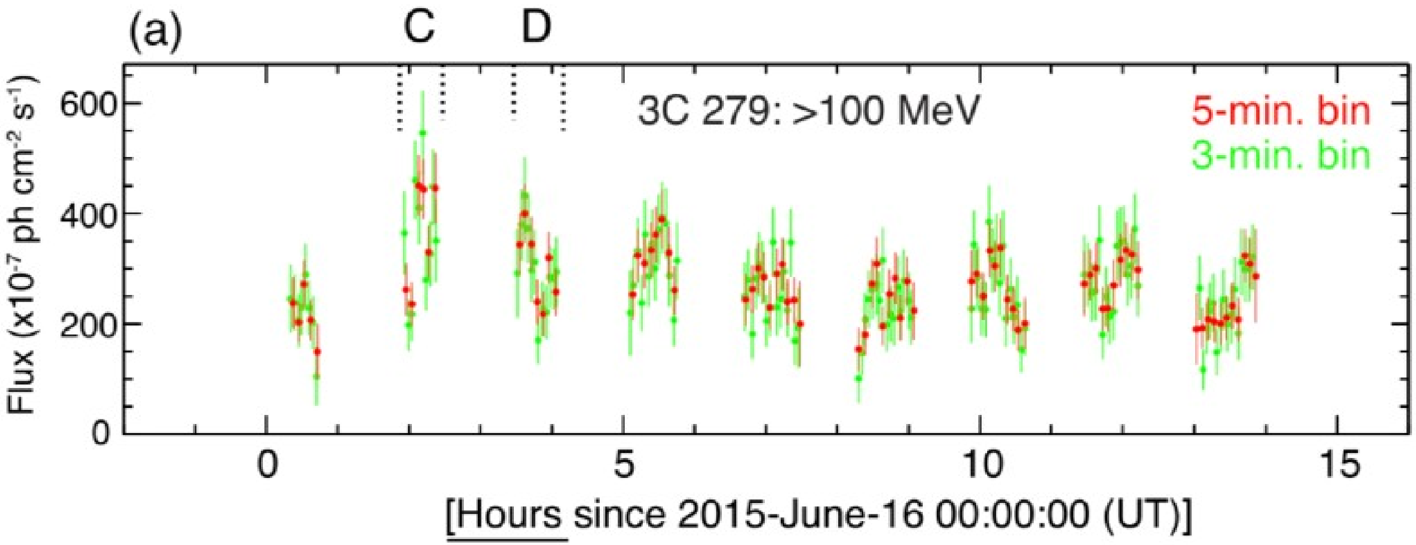


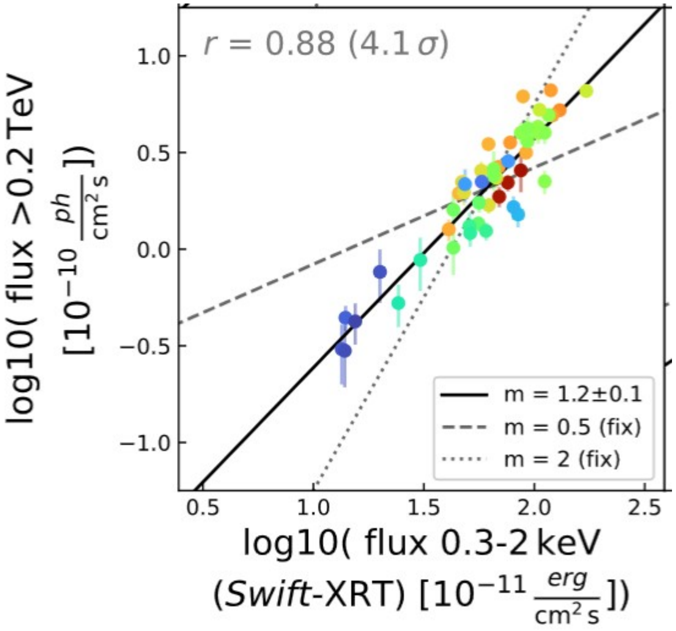
Credit: Ackermann et al 2016

→ Contraints on the emission region size

$$R \leq c\tau \frac{\delta}{1+z}$$

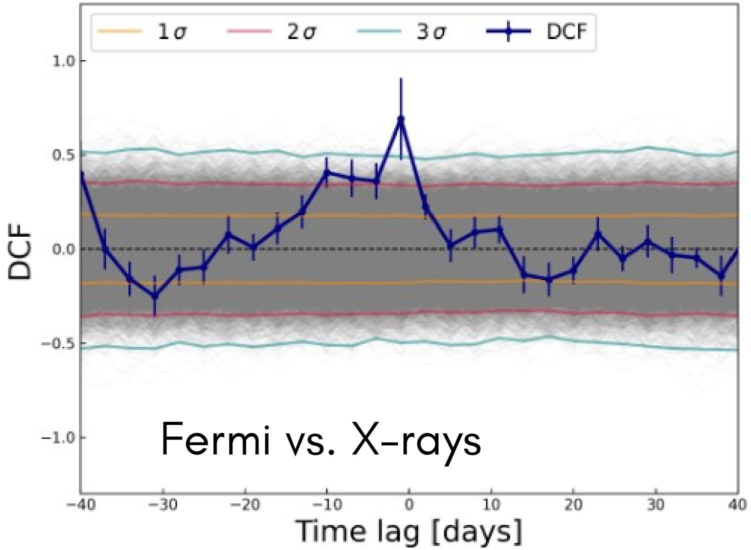
How to combine LCs and SEDs?

Correlations between bands



Credit: K. Abe et al. 2025

Mrk 421 2010



How to combine LCs and SEDs?

Correlations between bands

Mrk 421 2010

VHE gamma vs. X-rays	✓
VHE gamma vs. UV	?
VHE vs. HE gamma	?
HE gamma vs. X-rays	?
HE gamma vs. UV	✓
X-rays vs. UV/optical	✗

Credit: K. Abe et al. 2025, Schmuckermaier 2024

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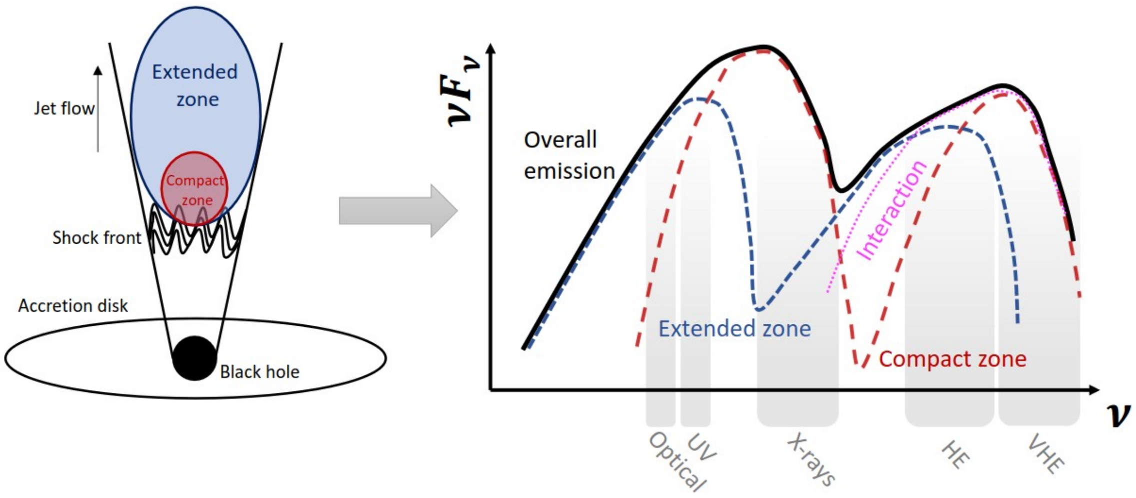
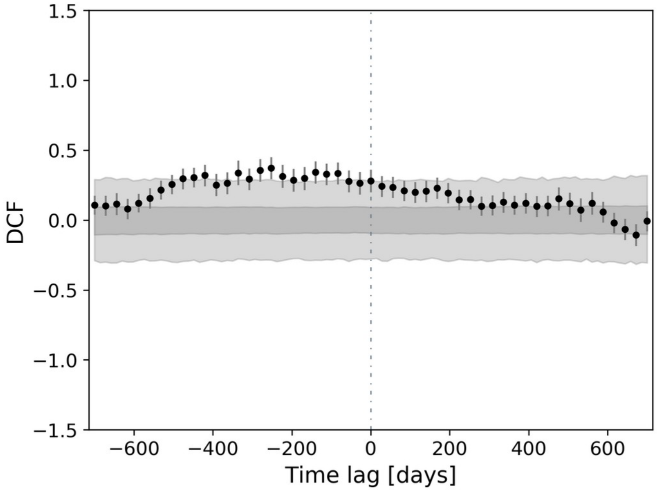


Credit: K. Abe et al. 2025, Schmuckermaier 2024

How to combine LCs and SEDs?

Correlations with a time delay – Mrk 501

Radio with high-energy γ-rays
with a time lag of 100 – 200 days



Credit: H. Abe et al. 2025,

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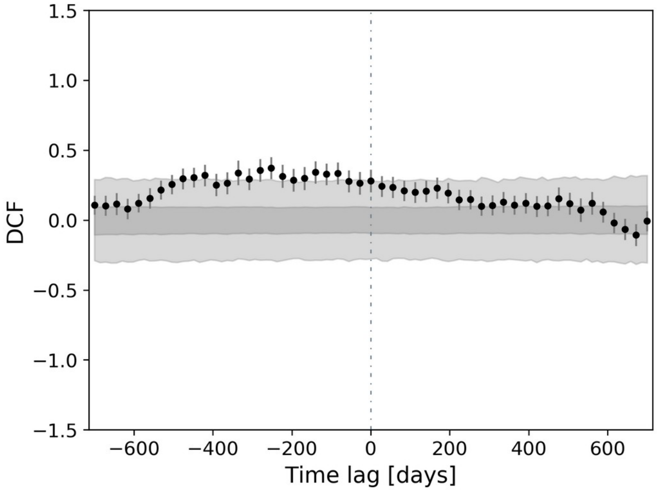
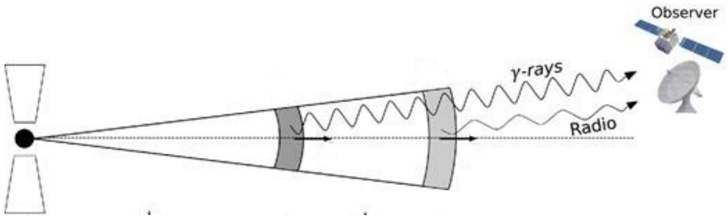


Credit: H. Abe et al. 2025,

→ location γ-ray emission upstream of radio bright regions



Credit: W Max-Moerbeck 2014

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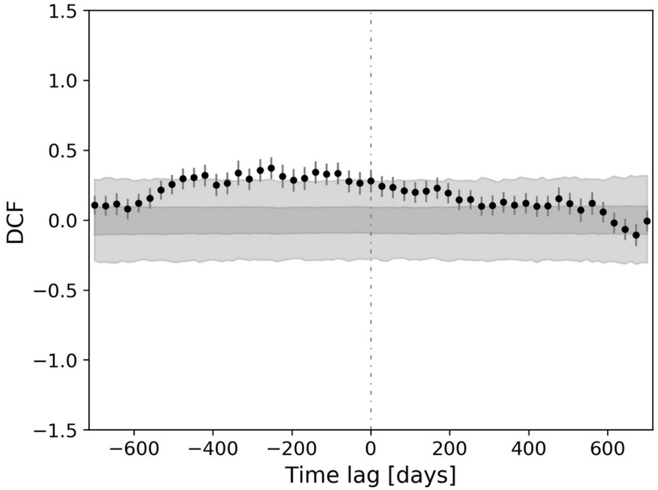

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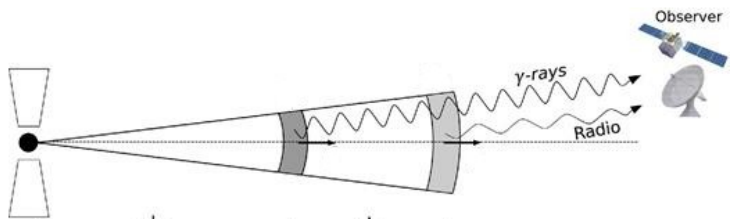
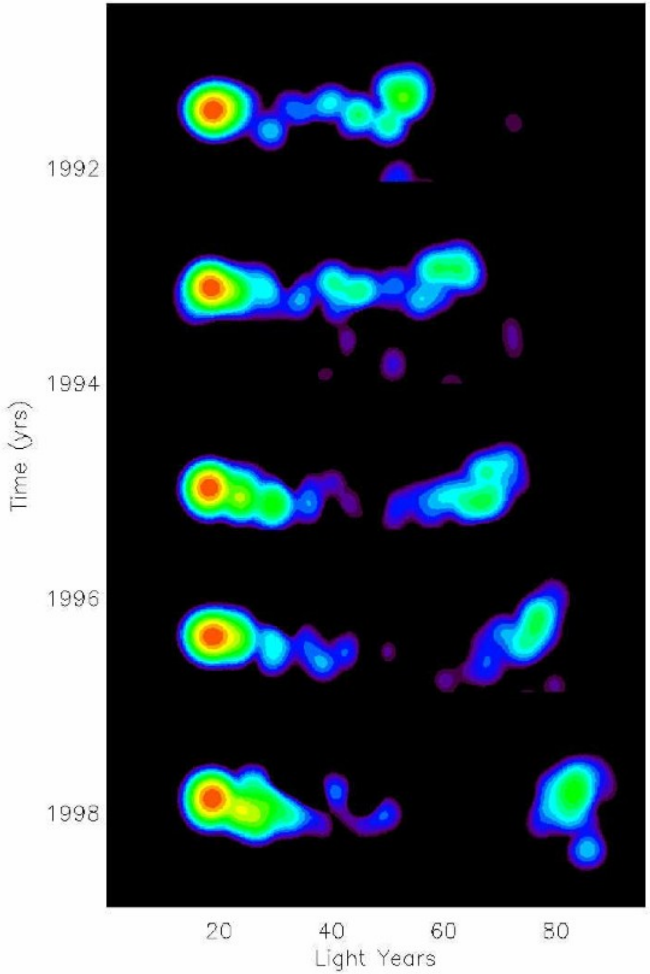


Credit: W Max-Moerbeck 2014

In general the dominant radio emission originates from more extended zone than high-energy emission

Superluminal motion

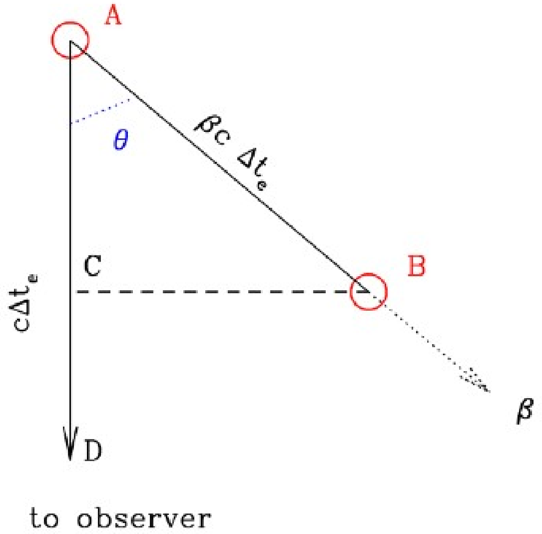
It looks like it is moving
25 light years
in 7 years



Credit: VLBA

Superluminal motion

1. Signal emitted at point A at t_1
2. Signal emitted at B at $t_2 = t_1 + \Delta t$



Superluminal motion

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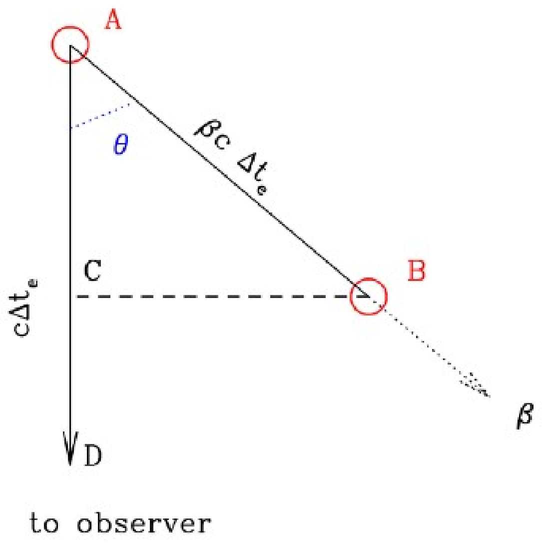
Signal from A arrives at $t_1' = t_1 + L/c$
Signal from B at $t_2' = t_2 + (L-AC)/c$

Distance travelled towards us: $AC = v\Delta t \cos\theta$



Credit: M. Cerruti

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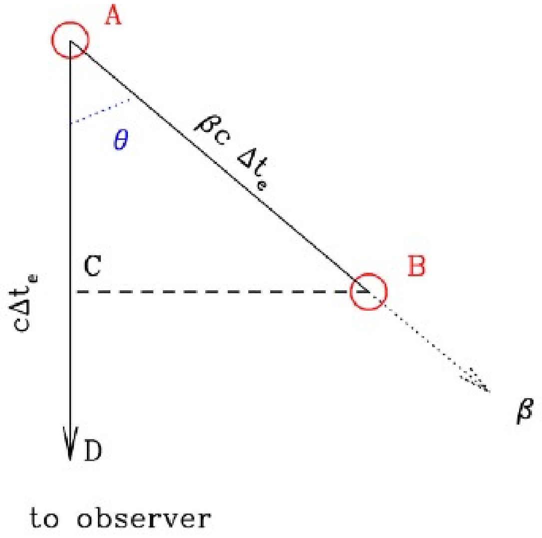
$\rightarrow \Delta t_{obs} = t_2' - t_1' = t_2 + (L - v\Delta t \cos\theta)/c - t_1 - L/c$
$= \Delta t\ (1 - v \cos\theta/c)$



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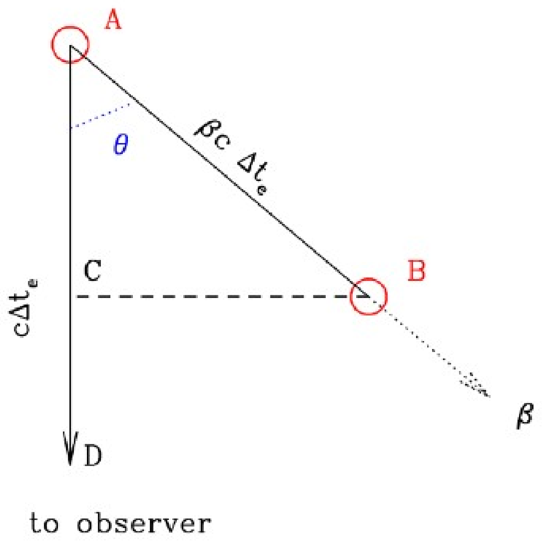
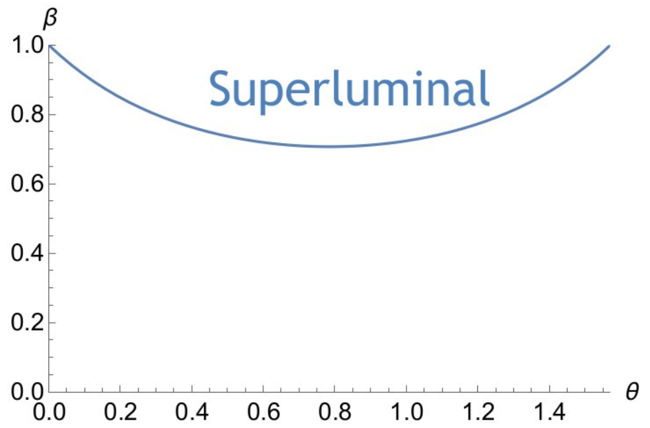
Apparent velocity of the projected component is

$v_{app} = BC/\Delta t_{obs} = v \sin\theta \,/(1 - v\cos\theta/c)$

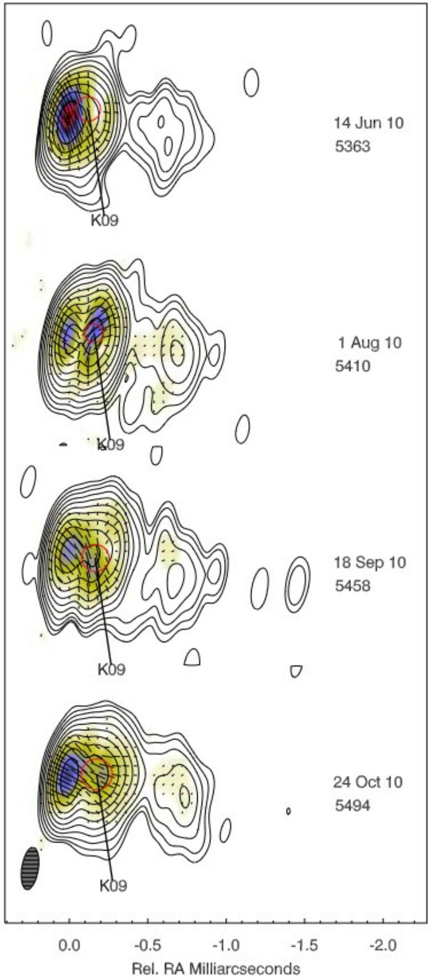




Credit: M. Cerruti

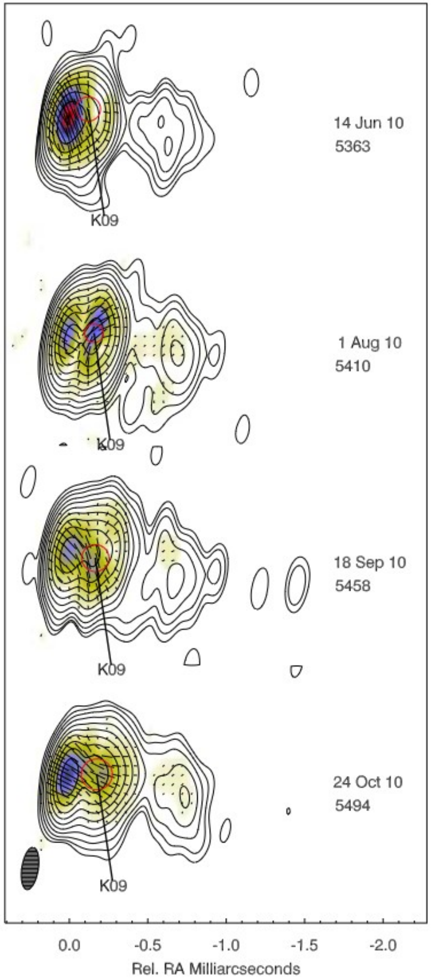
Superluminal motion

3C 454.3

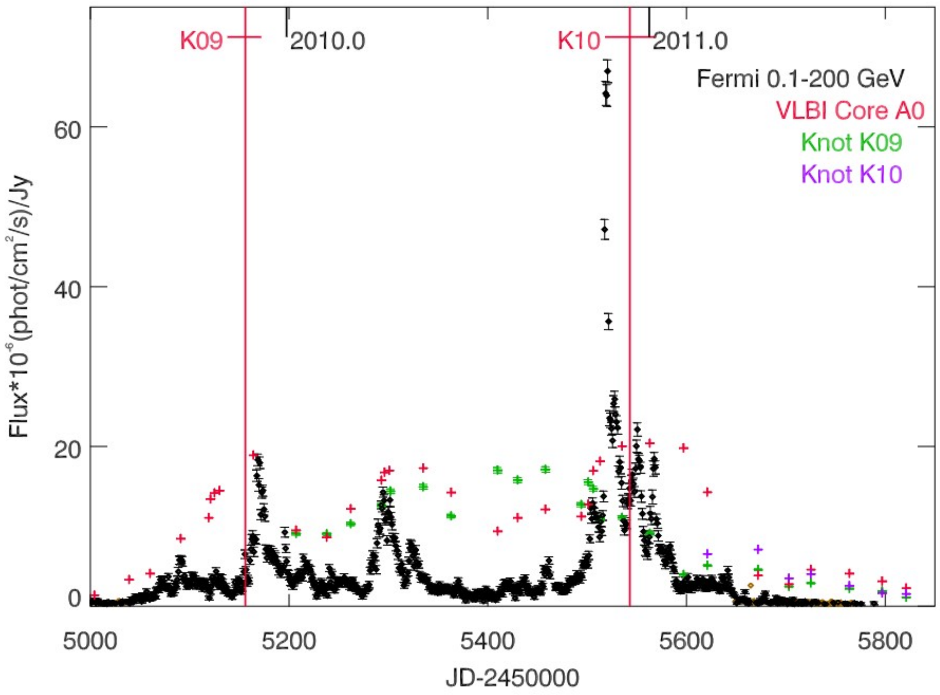


Credit: S. Jorstad et al. 2012

Superluminal motion



3C 454.3



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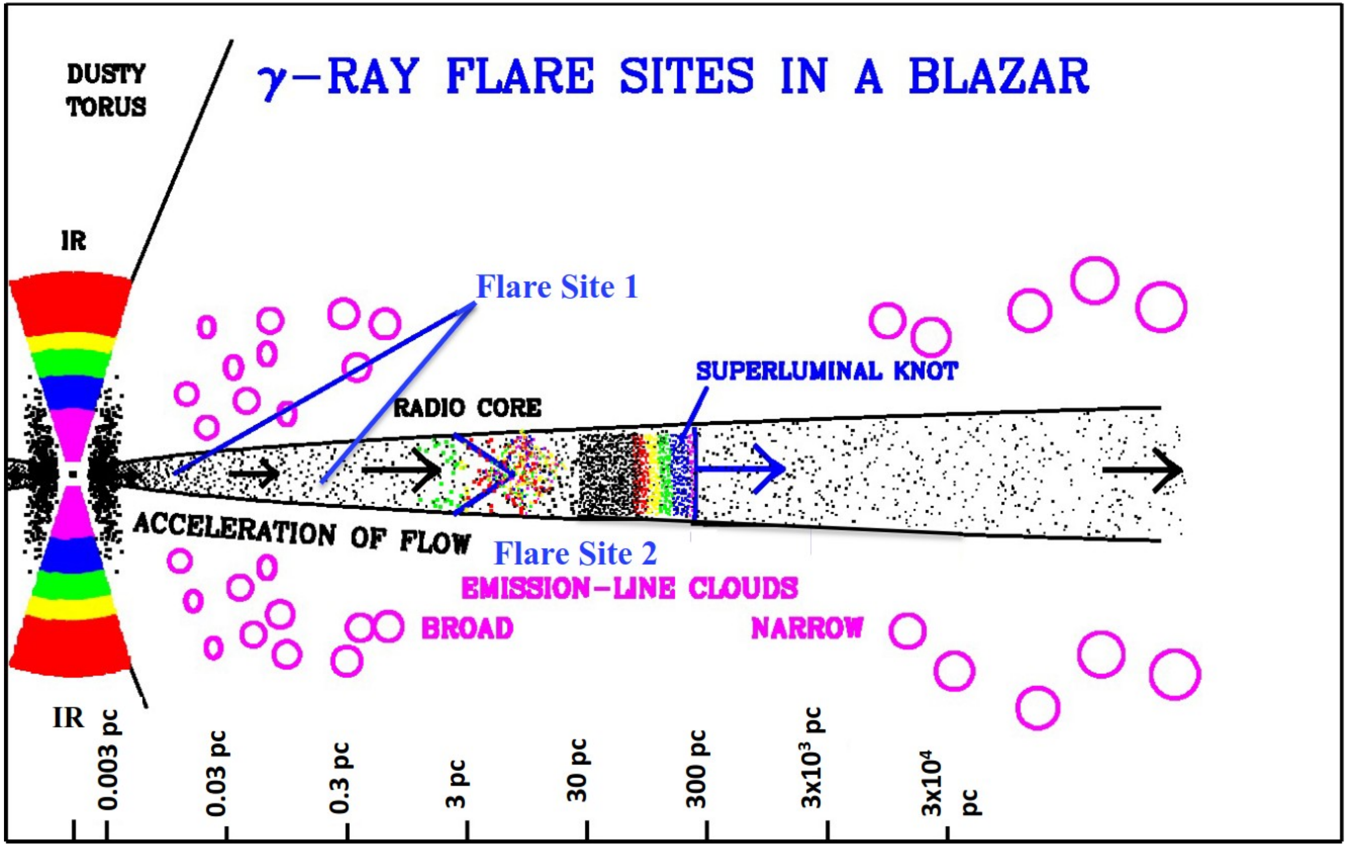
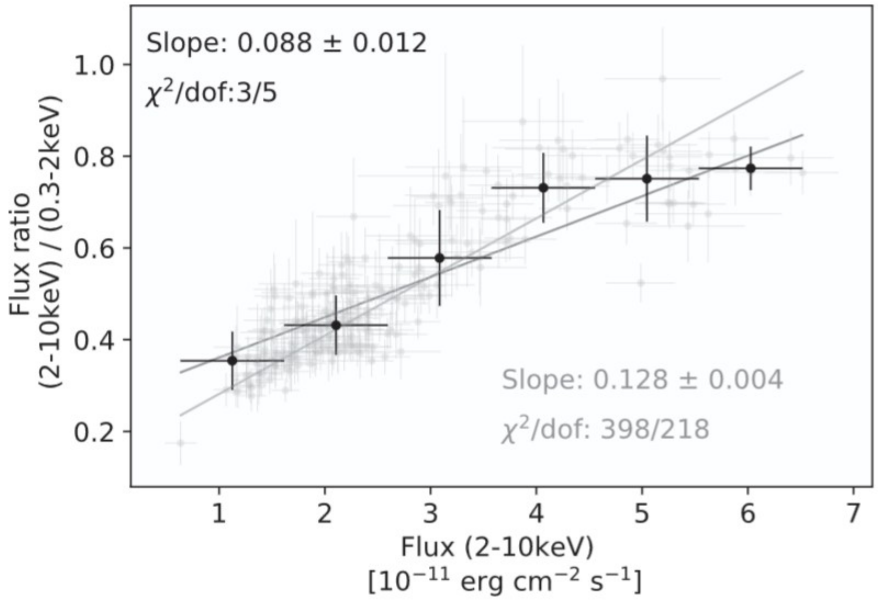


Credit: A. Marscher

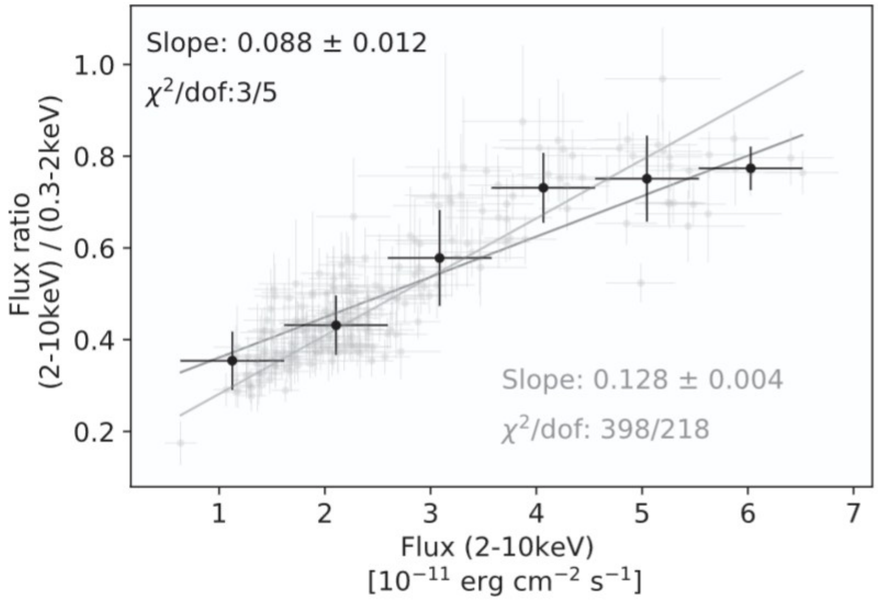
Spectral changes vs. flux



Credit: H. Abe et al. 2023

"Harder-when-brighter" behavior

Spectral changes vs. flux



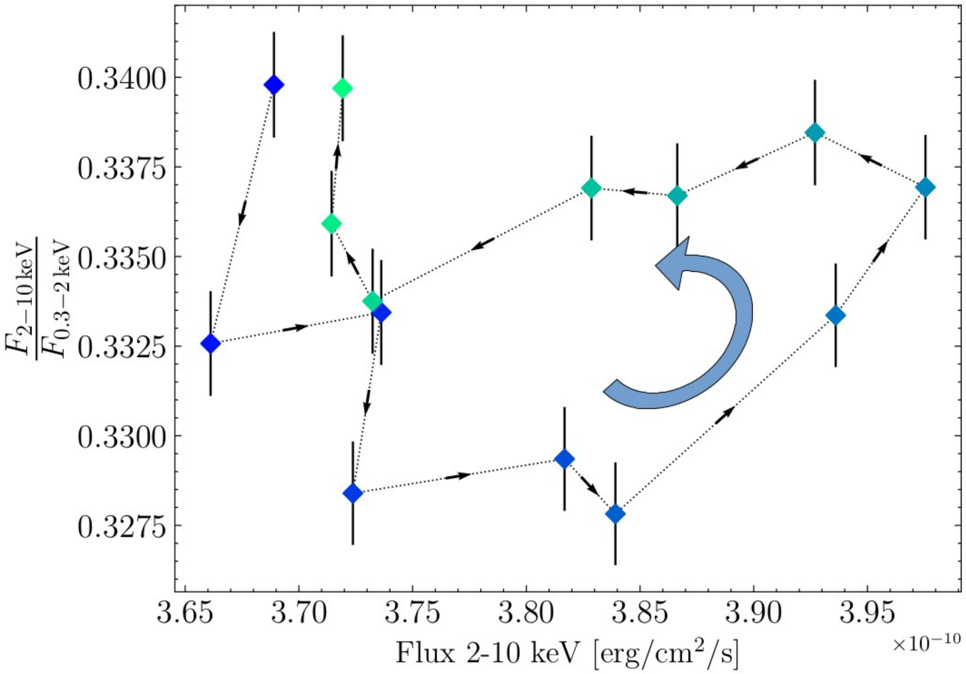
Credit: H. Abe et al. 2023

"Harder-when-brighter" behavior

Flares = flux increases
Explain by enhanced particle acceleration
→ injection of new particles
→ more high-energy electrons
→ harder spectrum.

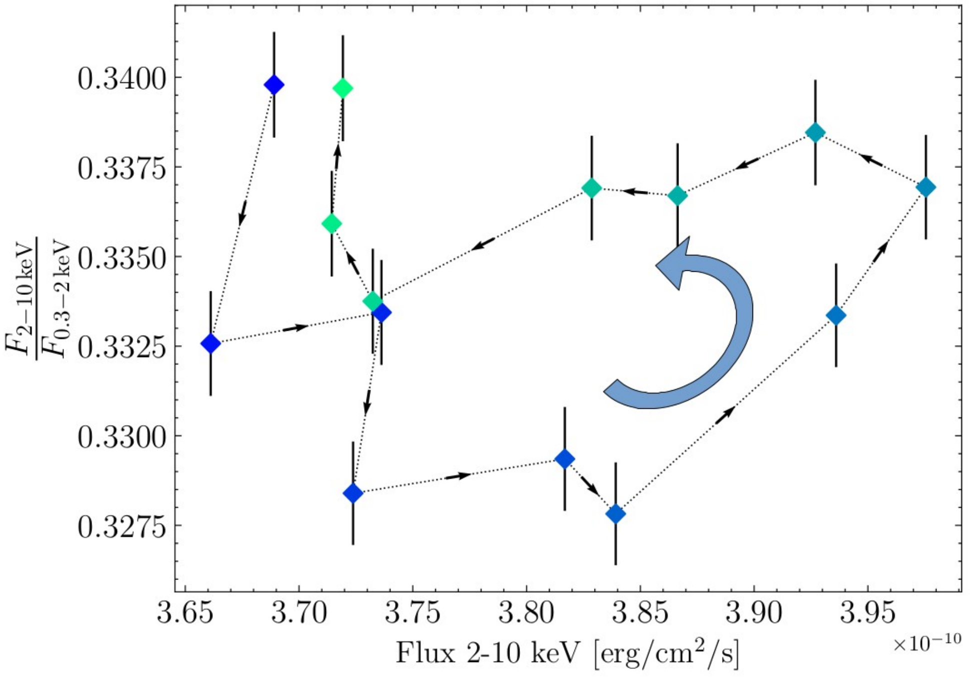
Spectral changes vs. flux

Hysteresis loops



Credit: MAGIC Collaboration et al. 2025

Spectral changes vs. flux



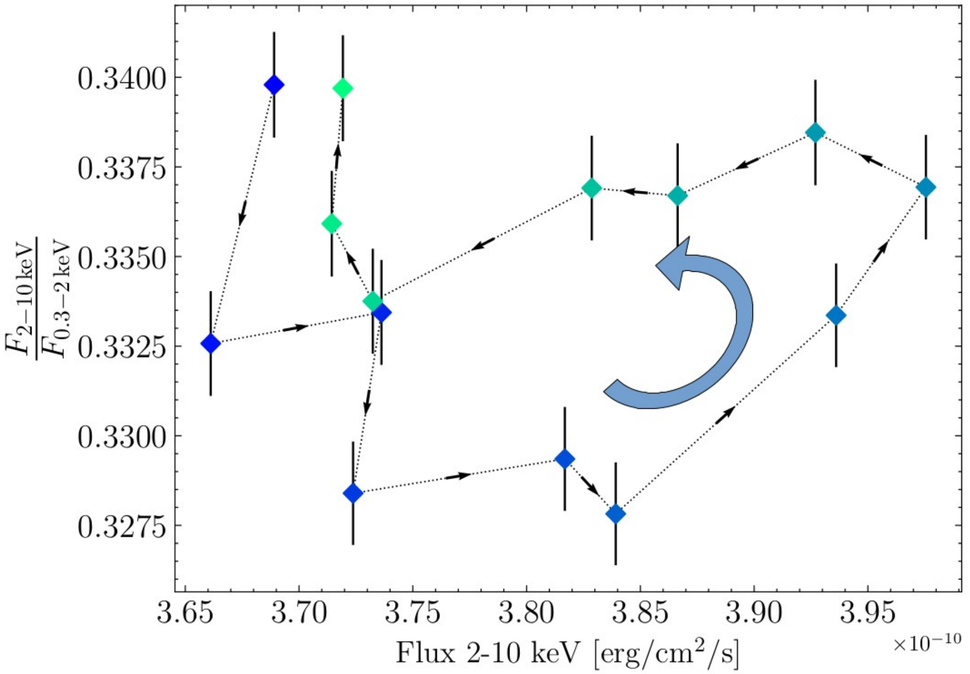
Credit: MAGIC Collaboration et al. 2025

Hysteresis loops

Clock-wise (soft lag = LE lags behind HE)

- Rapid particle injections → delay in Synchrotron cooling
  - High-energy electrons cool very rapidly
  - Low-energy slower
- $t_{acc} >> t_{cool}$

Spectral changes vs. flux



Credit: MAGIC Collaboration et al. 2025

Hysteresis loops

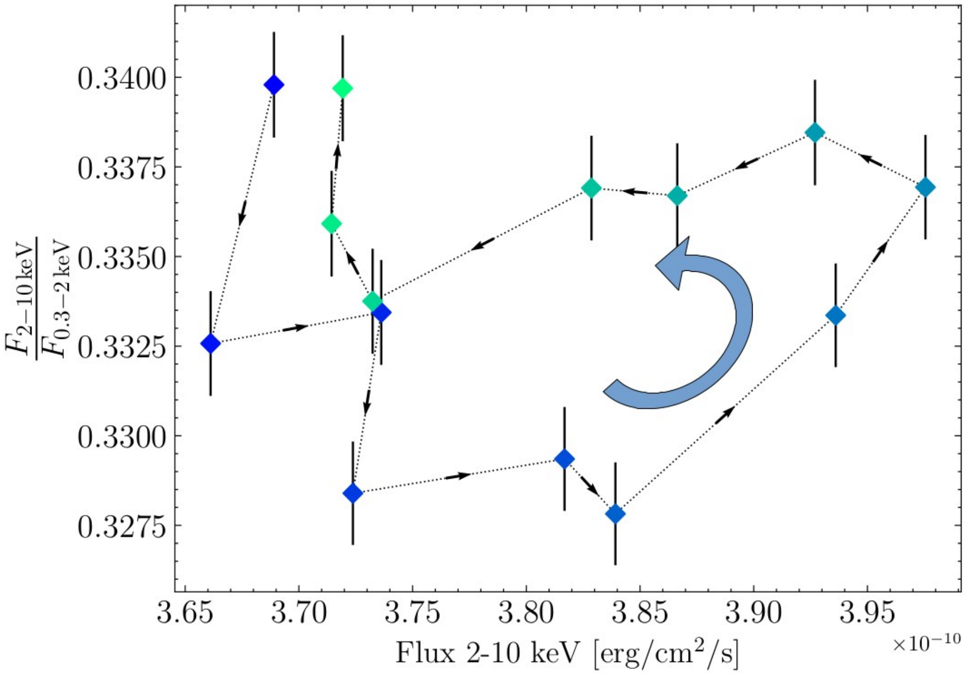
Clock-wise (soft lag = LE lags behind HE)

- Rapid particle injections → delay in Synchrotron cooling
  - High-energy electrons cool very rapidly
  - Low-energy slower
- $t_{acc} >> t_{cool}$

Counter clock-wise (hard lag = HE behind LE)

- Gradual particle injections
  - Low-energy electrons produce soft photons first
  - High-energy emission later → Spectrum becomes harder
  - $t_{acc} \sim t_{cool}$

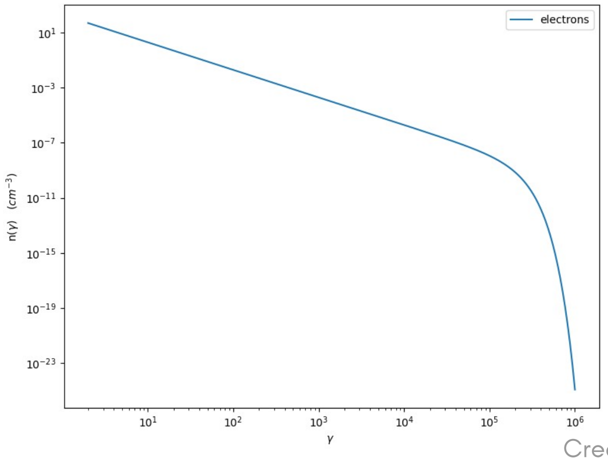
Spectral changes vs. flux



Credit: MAGIC Collaboration et al. 2025

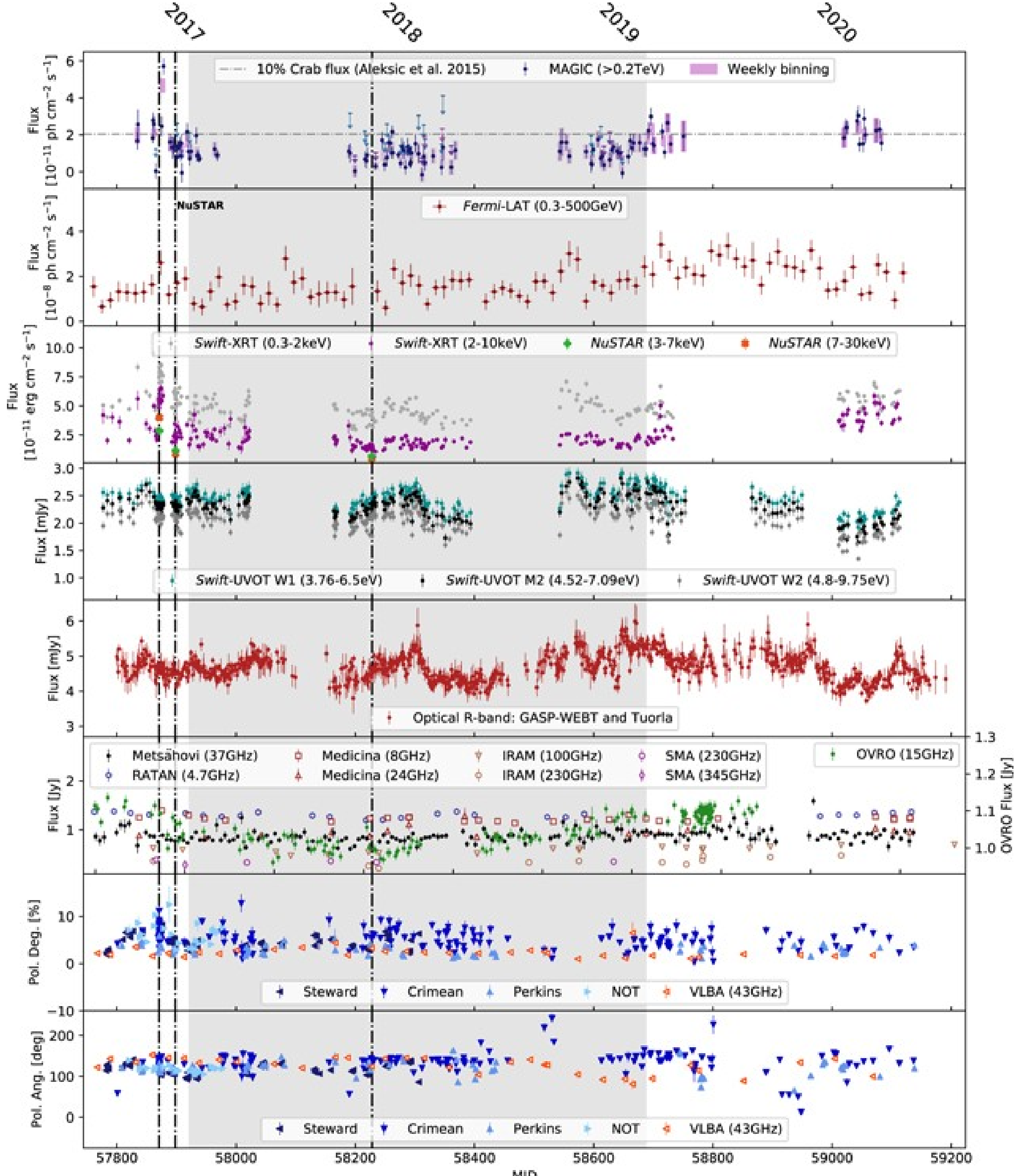
→ Probing the emission of the highest electrons in this energy range

→ constraints on E_{max} in our model



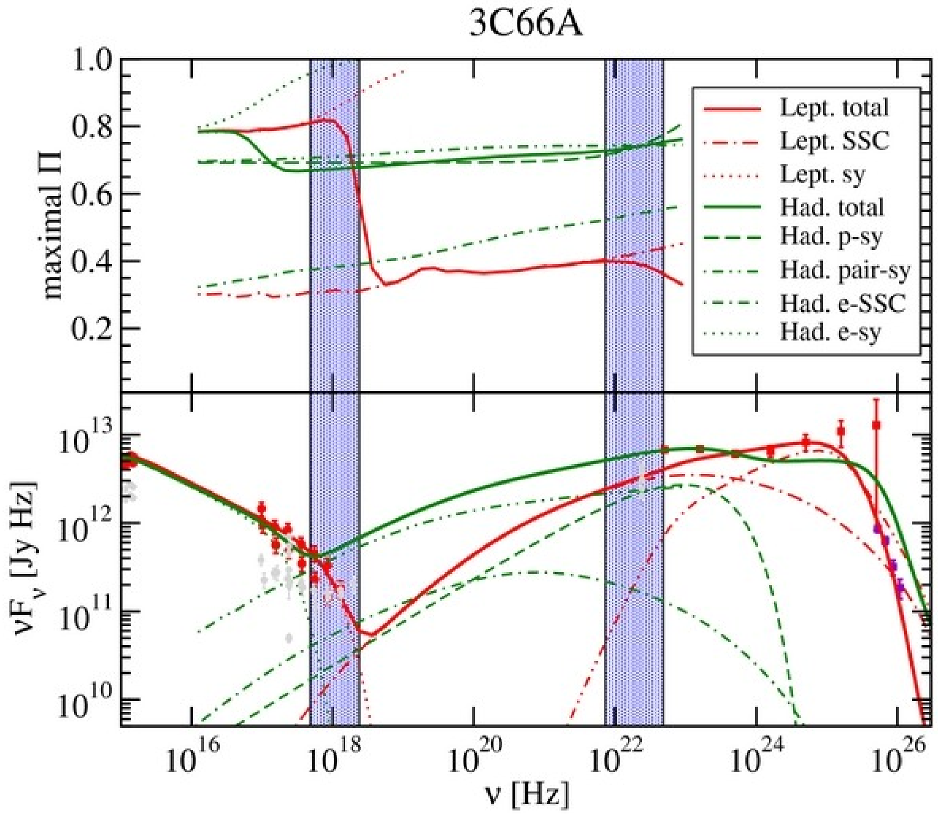
Credit: Jetset

MWL polarization



Credit: H. Abe et al 2023

MWL polarization



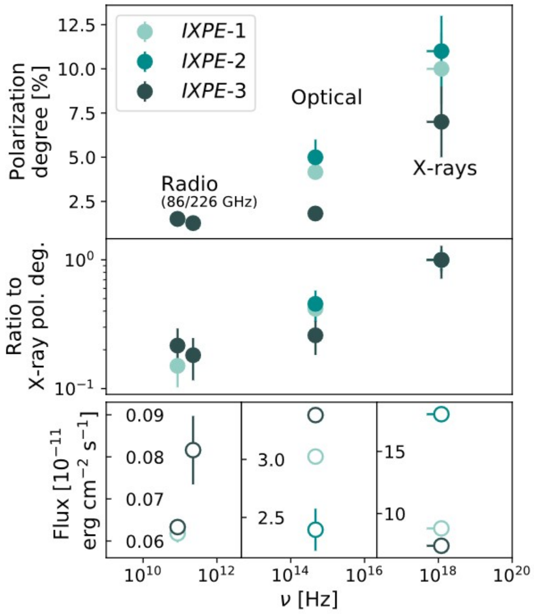
Credit: H. Zhang et al. 2013

X-ray polarization as a new window

- Imaging X-ray Polarimetry Explorer (IXPE)
  → probe acceleration mechanisms
  → probe the order of the magnetic fields in emission regions

- First X-ray measurements of blazars find:
  - Polarization degree higher than optical & radio

Credit: http://ixpe.iaps.inaf.it/



Credit: MAGIC et al. 2024

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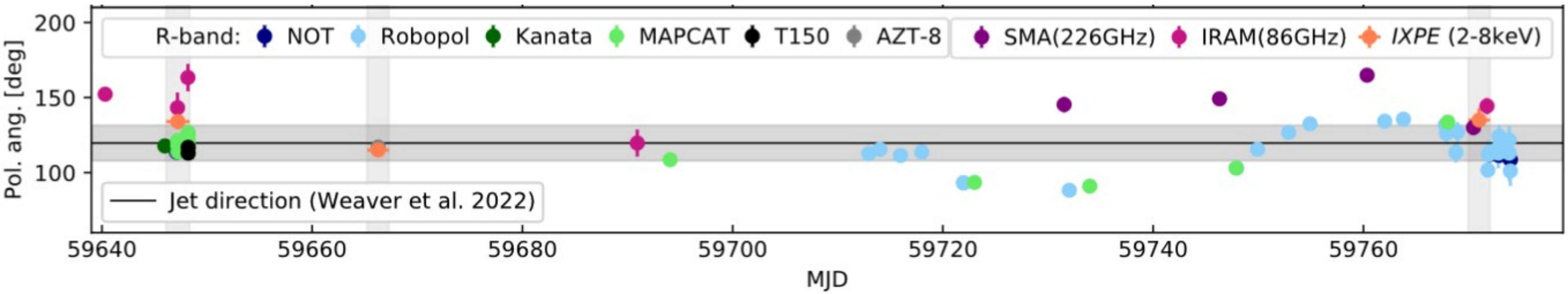

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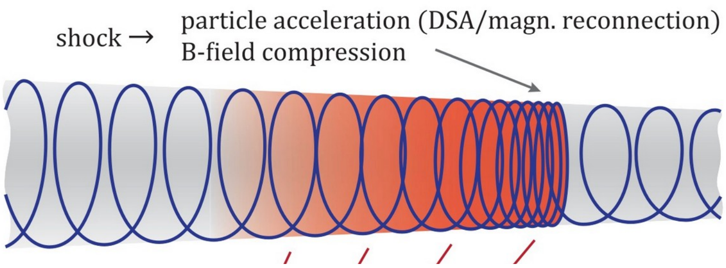
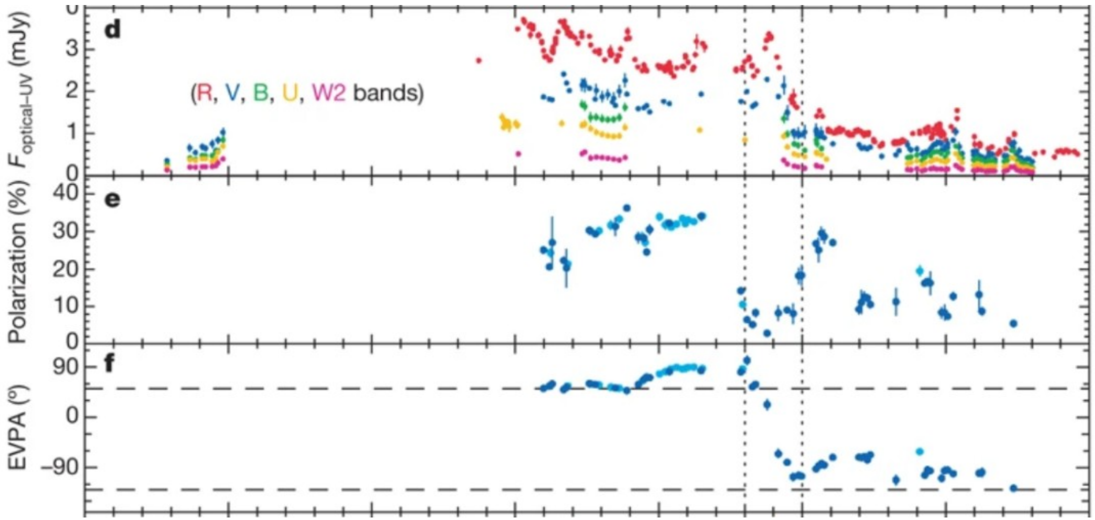
  → Shock acceleration in an energy stratified jet



Credit: Angelakis et al. 2016

MWL polarization

Polarization angle swings

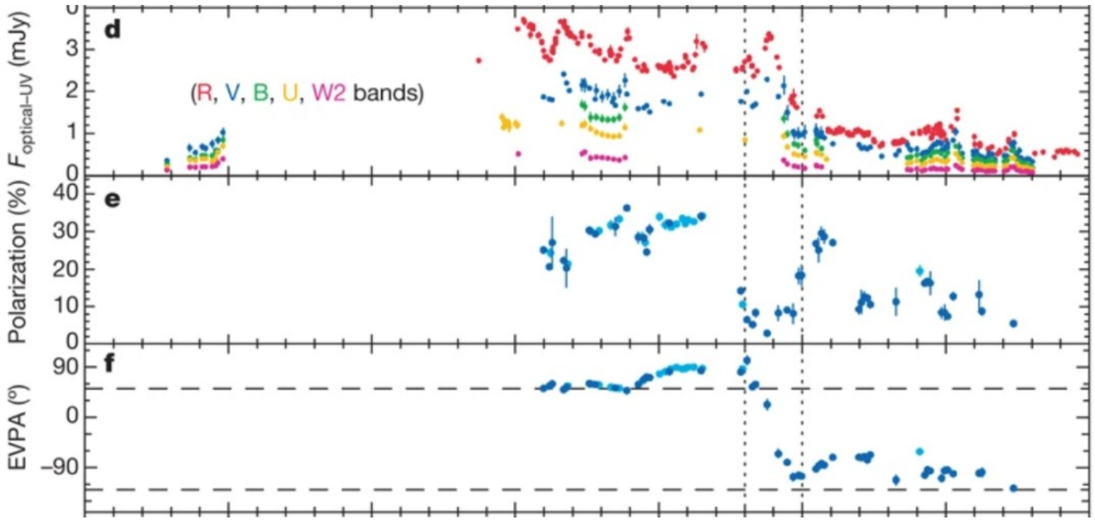


Credit: Abdo et al 2010

MWL polarization

Polarization angle swings

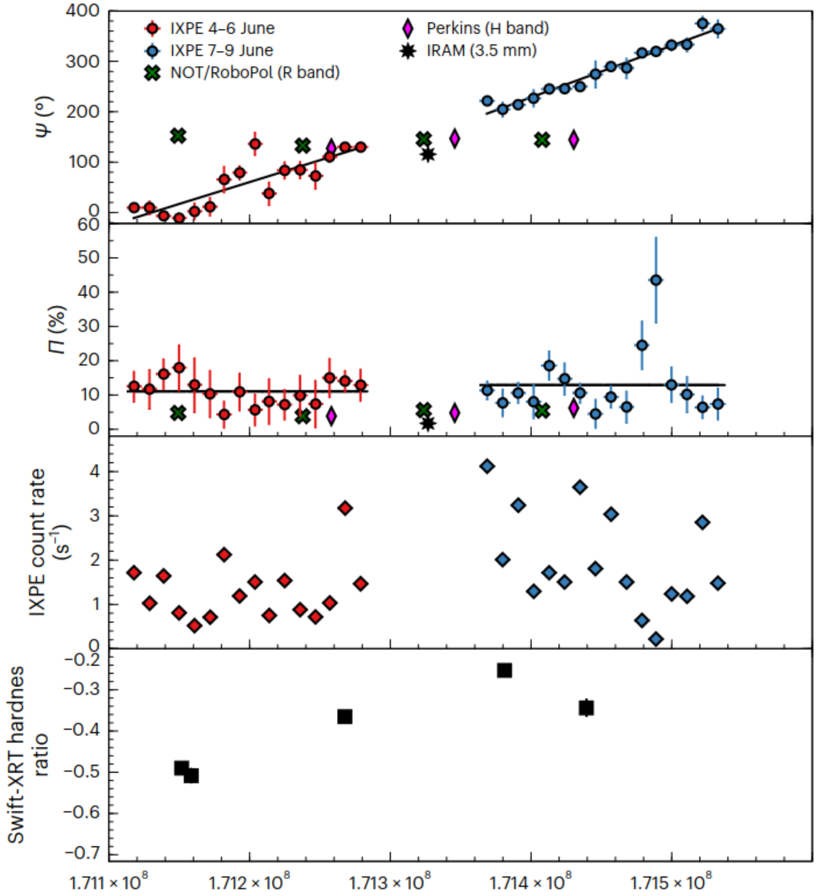
- Helical magnetic field + moving emission region
- Curved jet / bent trajectory
- Magnetic reconnection
- ....

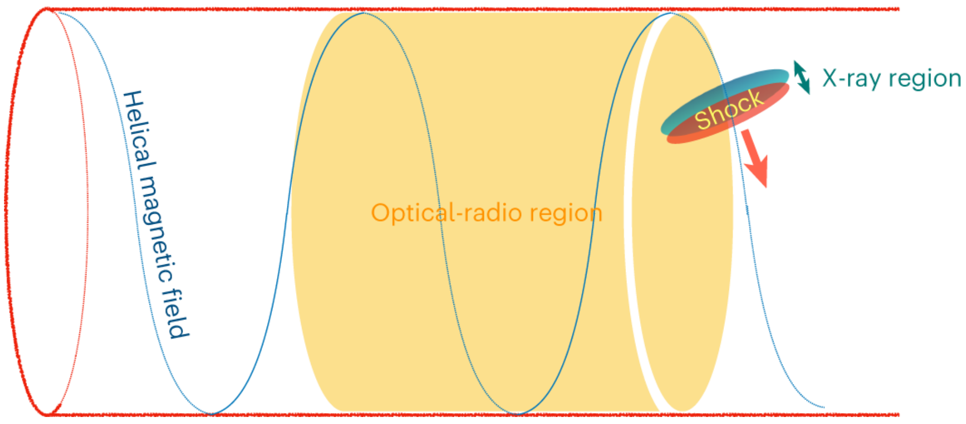


Credit: Abdo et al 2010

MWL polarization

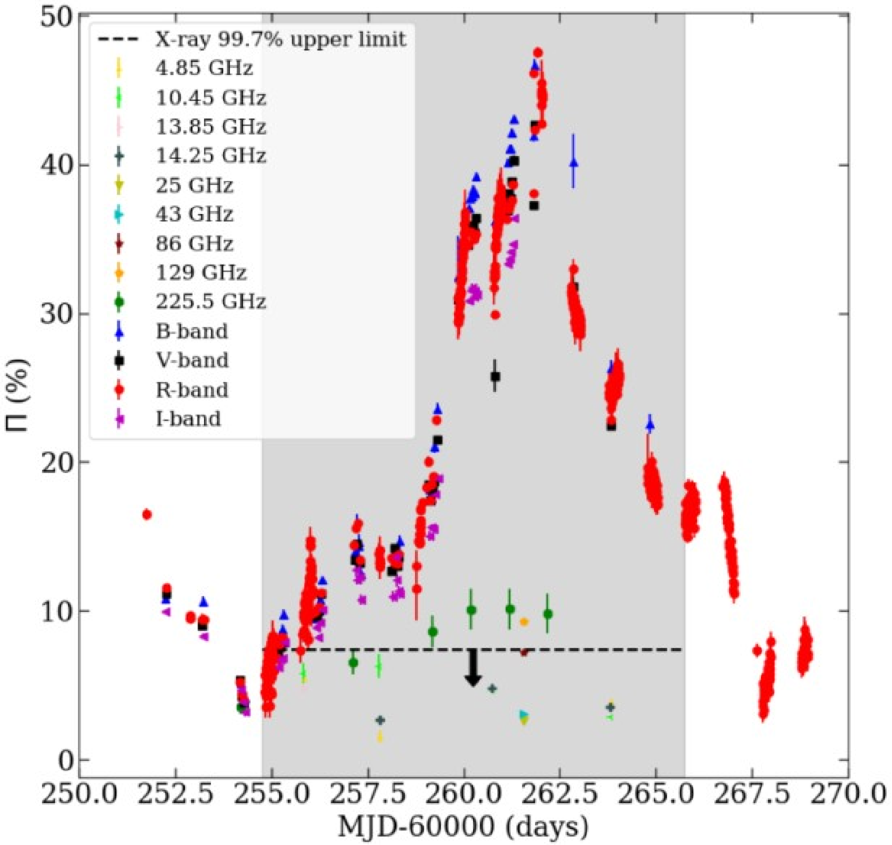
Mrk 421





Credit: Di Gesu et al 2023

MWL polarization



Credit: Agudo et al. 2025

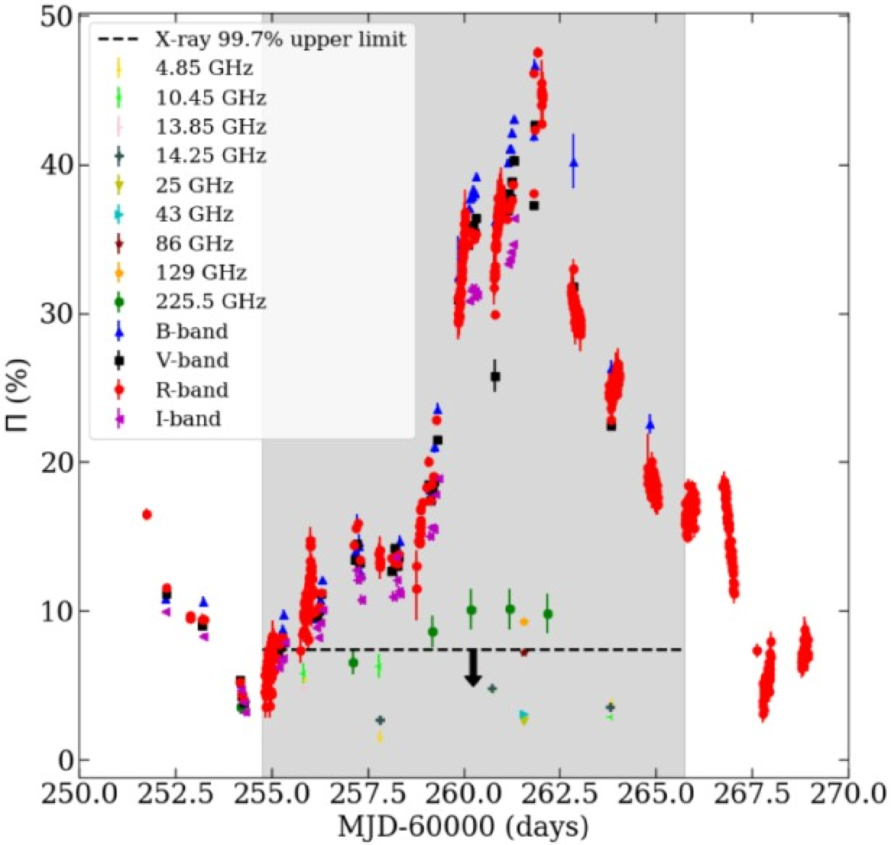
BL Lac:

X-rays cover the high-energy peak

High polarization degree and variability in optical

X-rays < 10% polarized

MWL polarization



Credit: Agudo et al. 2025

BL Lac:

X-rays cover the high-energy peak

High polarization degree and variability in optical

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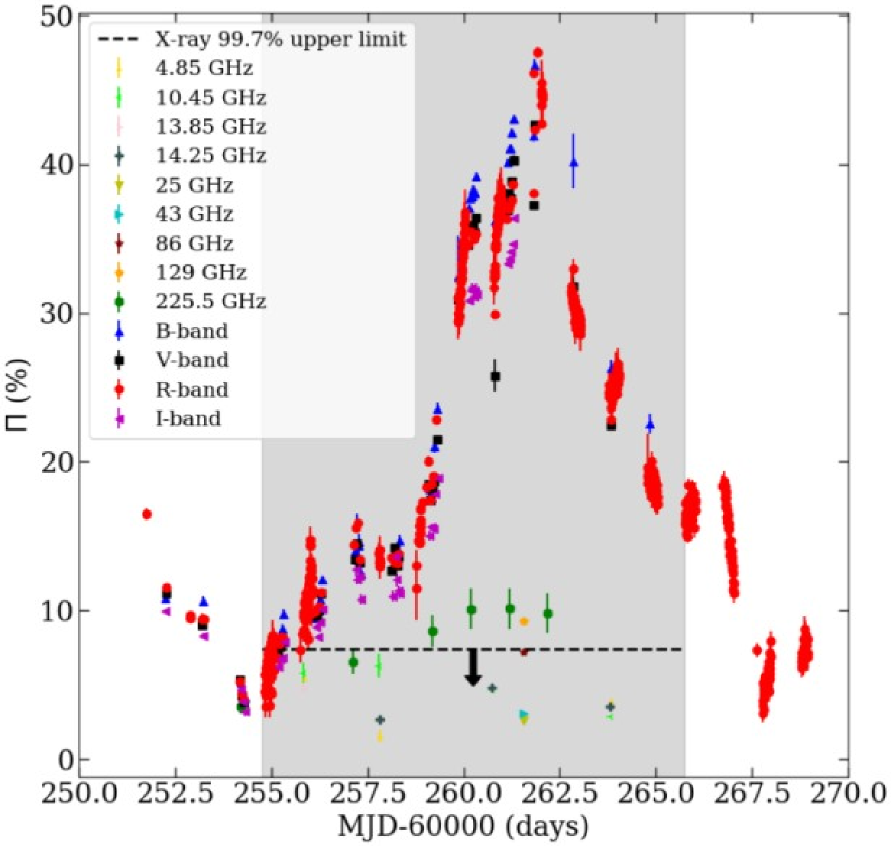
→ What do you think it tells us?

MWL polarization



Credit: Agudo et al. 2025

BL Lac:

X-rays cover the high-energy peak

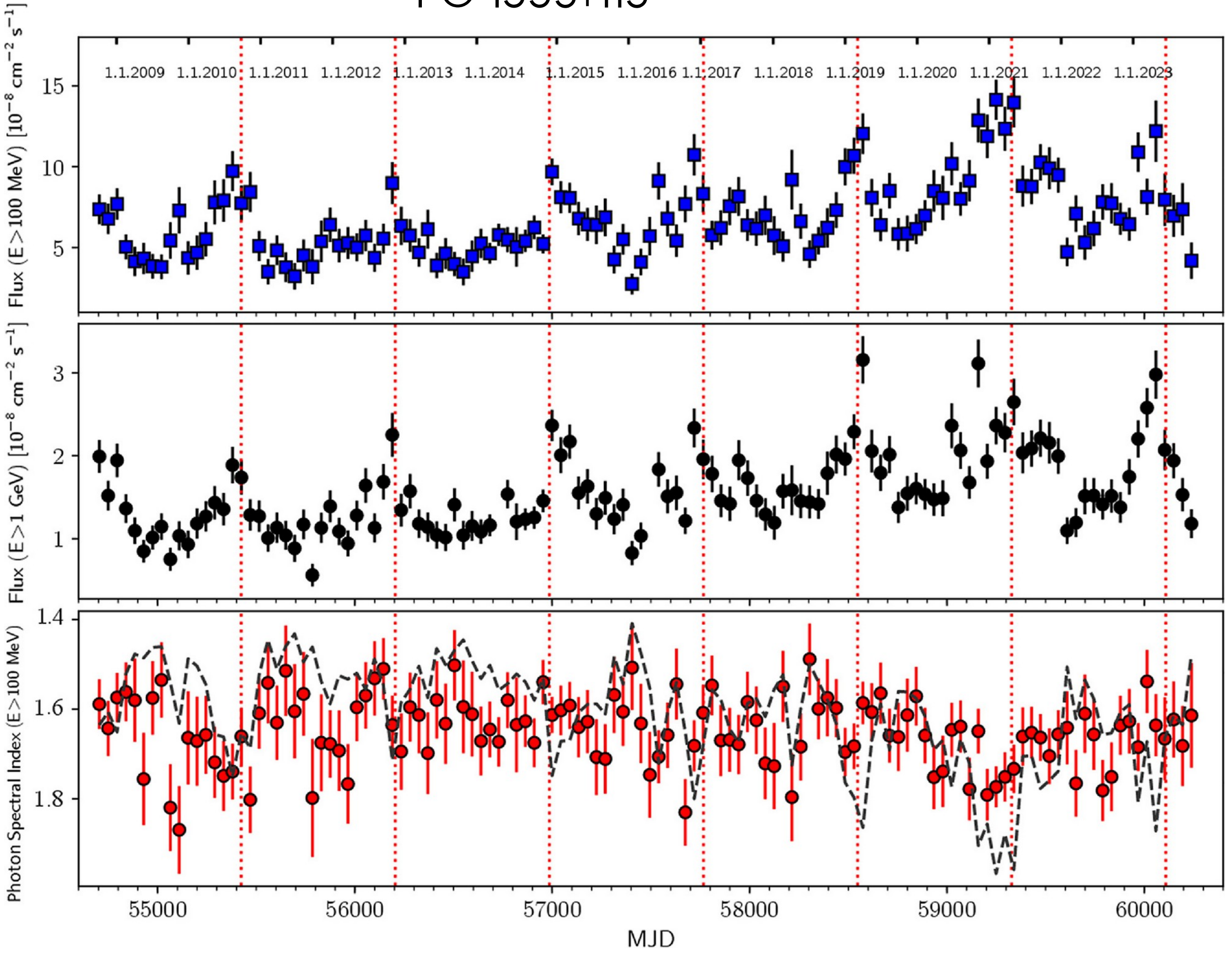
High polarization degree and variability in optical

X-rays < 10% polarized

→ Leptonic Inverse Compton scenario favored

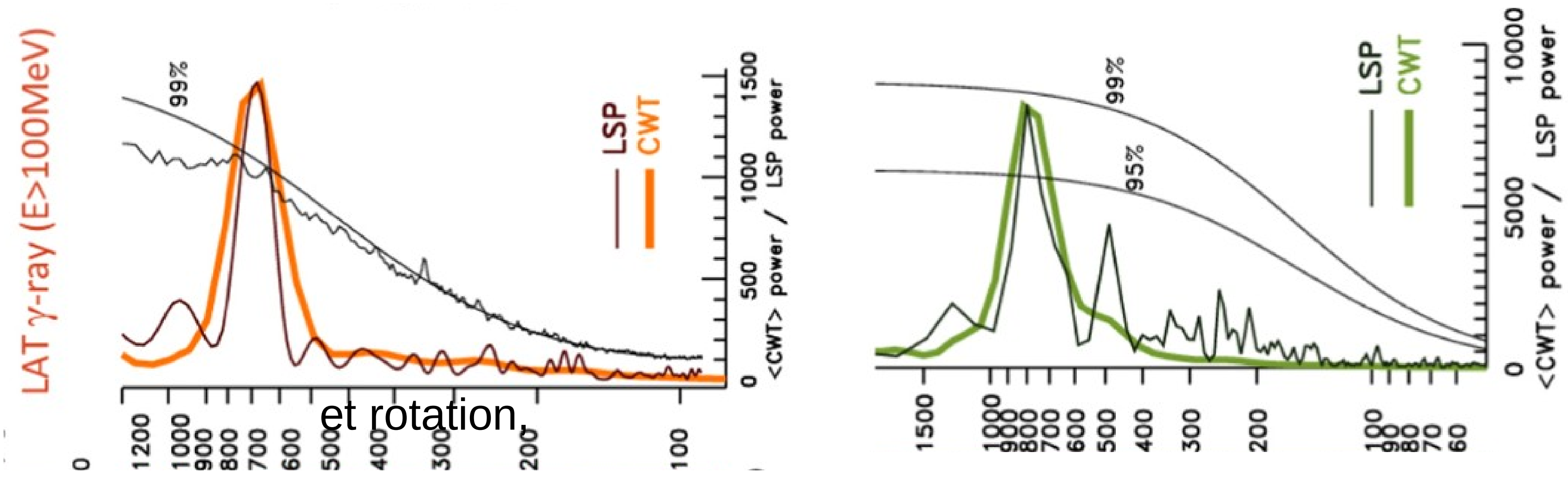
Periodicity

PG 1553+113



Periodicity

PG 1553+113



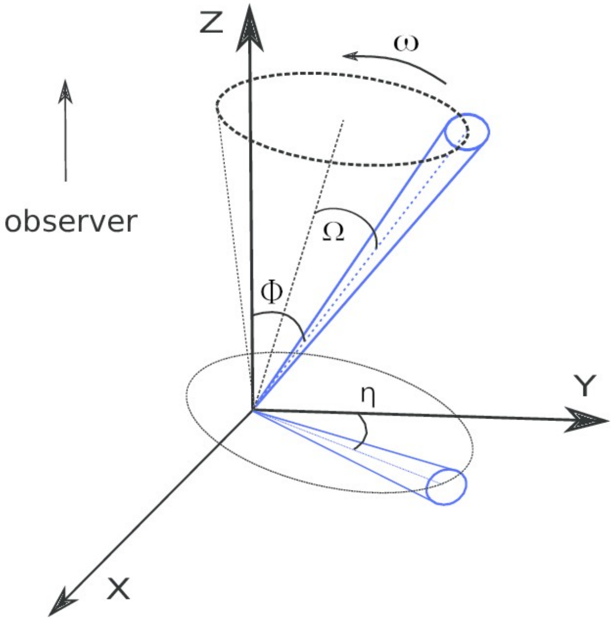
Credit: S. Abdollahi et al. 2024

2.1 years of periodicity in gamma-rays (Fermi-LAT)

Periodicity

Potential scenarios to explain (quasi-)periodic behavior:

- Intensity modulation by Doppler factor
- Jet precession

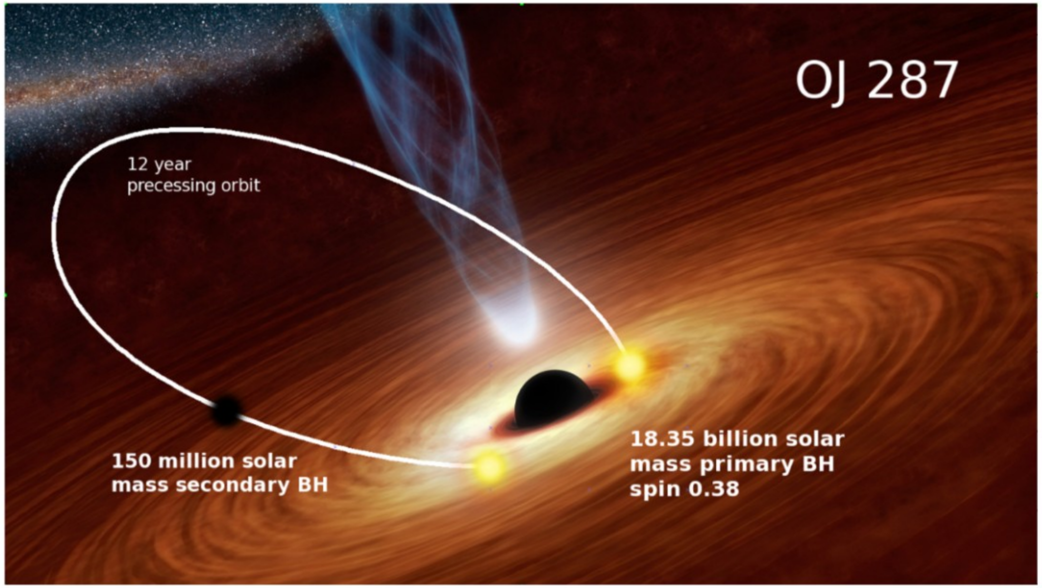


Credit: Rozgonyi et al.

Periodicity

Potential scenarios to explain (quasi-)periodic behavior:

- Intensity modulation by Doppler factor
- Jet precession
- Orbital motion in a BBHS
- ...



Credit: Dey et al 2018

Conclusions

To understand the origin of neutrinos, cosmic rays, gamma-rays,… we need to exploit all dimentions that we have

- Time-domain
- Multi-messenger

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- very diverse “animals” in the AGN zoo
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Coordinate MWL observations are key!! Also on the longterm.

Thank you for your attention!