Multiwavelength modeling of Active Galactic Nuclei

or Camels in the sky

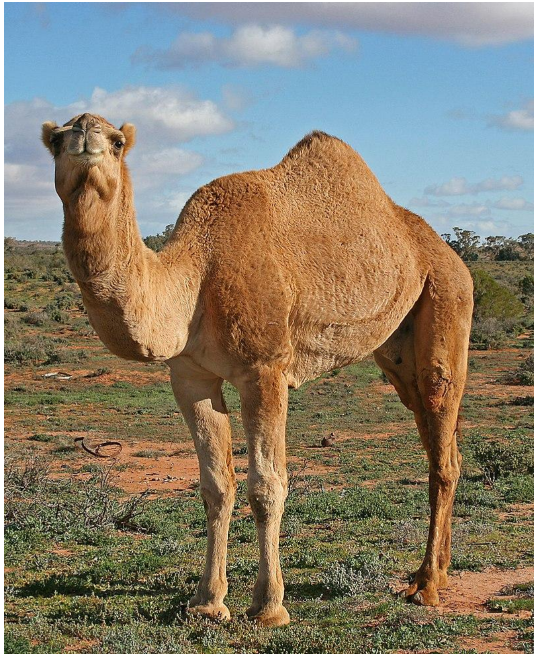
IP-2022-10-4595

Marina Manganaro

(marina.manganaro@uniri.hr)

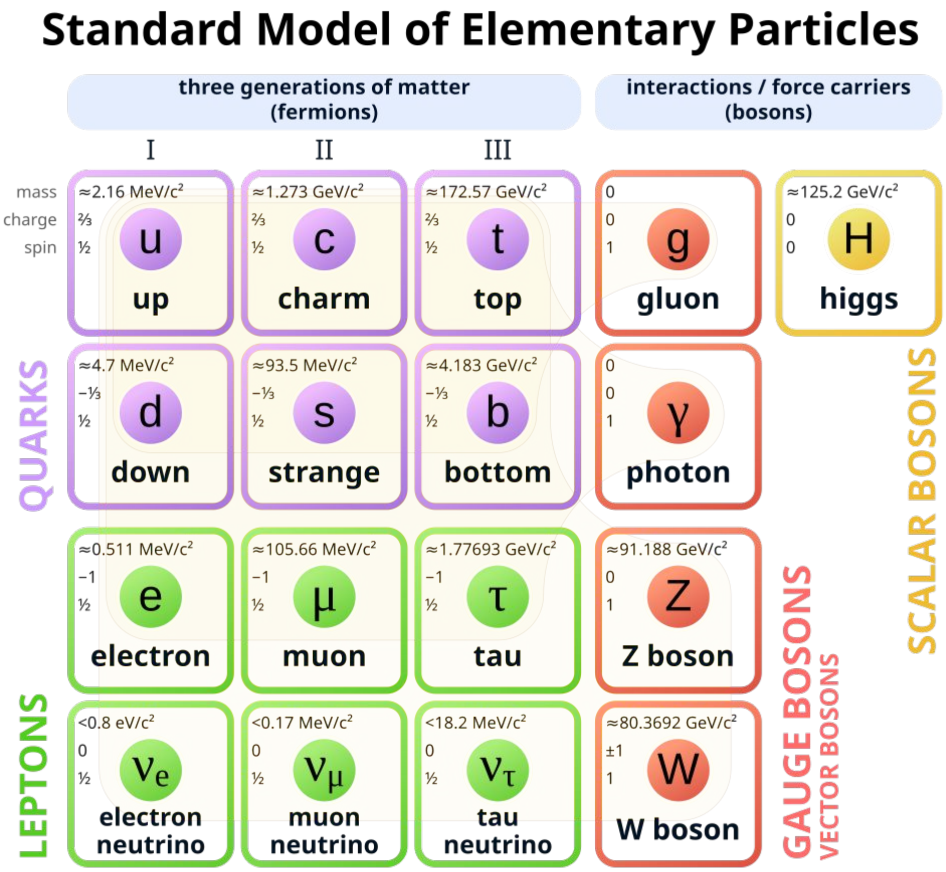
Faculty of Physics
University of Rijeka

Definitions



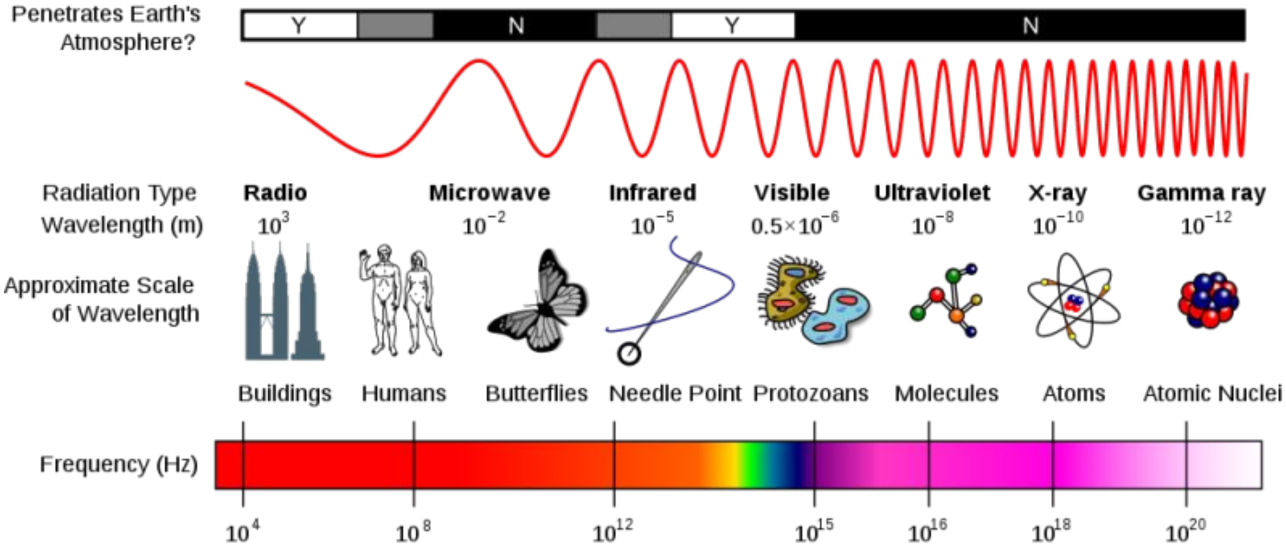
Dromedary (one hump)

Camel (two humps)


Standard Model of Elementary Particles
three generations of matter (fermions)
interactions / force carriers (bosons)
I
II
III
mass
charge
spin
≈2.16 MeV/c²
⅔
½
u
up
≈1.273 GeV/c²
⅔
½
c
charm
≈172.57 GeV/c²
⅔
½
t
top
0
0
1
g
gluon
≈125.2 GeV/c²
0
0
H
higgs
≈4.7 MeV/c²
−⅓
½
d
down
≈93.5 MeV/c²
−⅓
½
s
strange
≈4.183 GeV/c²
−⅓
½
b
bottom
0
0
1
γ
photon
≈0.511 MeV/c²
−1
½
e
electron
≈105.66 MeV/c²
−1
½
μ
muon
≈1.77693 GeV/c²
−1
½
τ
tau
≈91.188 GeV/c²
0
1
Z
Z boson
<0.8 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<18.2 MeV/c²
0
½
ντ
tau neutrino
≈80.3692 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS


PHOTON
γ
photon
Its eyes red from traveling so fast, the PHOTON is a quanta of visible light, a wave/particle that communicates the electromagnetic force, traveling at the speed of... light (!). With a mass and electric charge of zero, it also carries microwaves, radio waves and x-rays.
Acrylic felt with poly fill for minimum mass.
LIGHT
HEAVY
The PARTICLE ZOO

Electromagnetic spectrum



Planck's relation

$$E = h\nu = hc/\lambda$$

Multi-wavelength observations

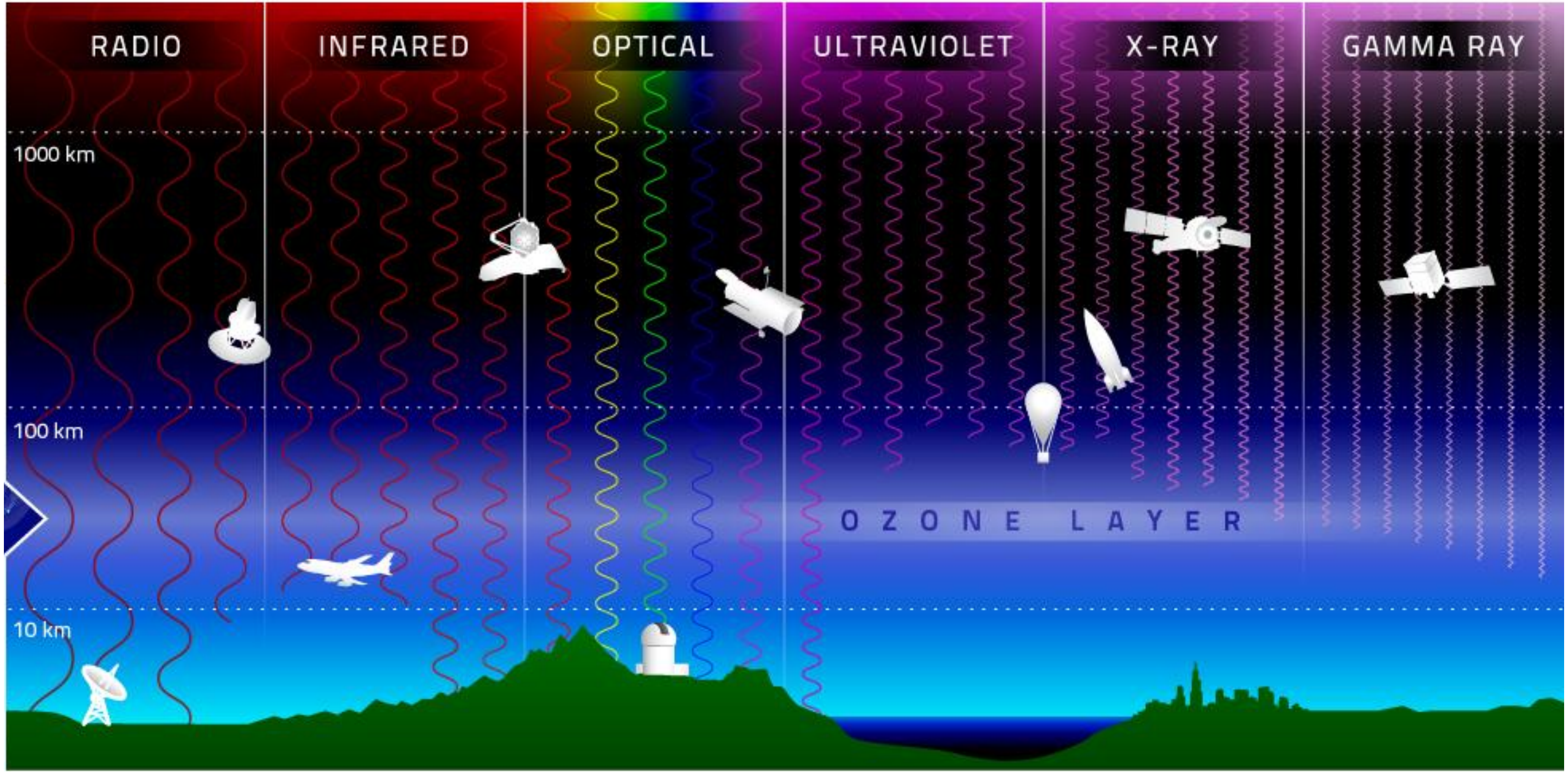
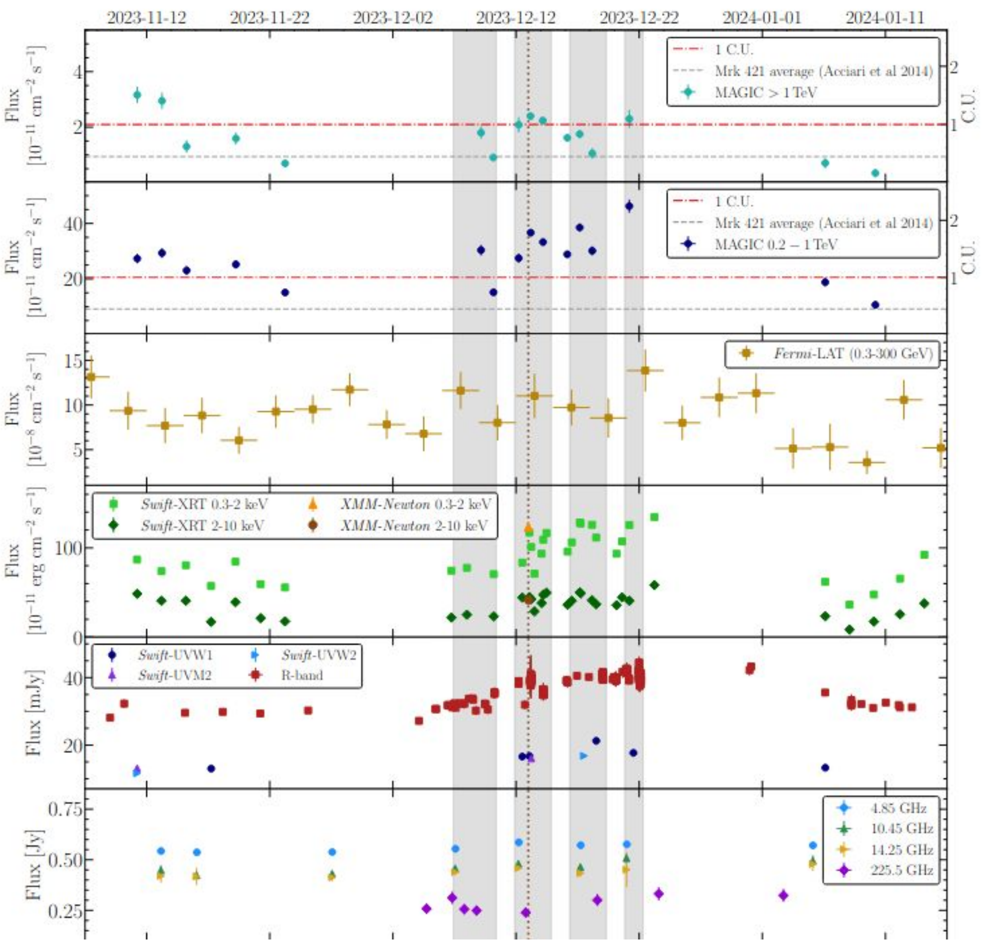


Image Credit: eCUIP Uni Chicago


Radio
Microwave
Infrared
UV
X-Ray
Gamma Ray
Radio
60,000 nm
600 K
Infrared
1200-800 nm (10-3.6 um)
4,500 K
Optical
450-750 nm
6,000 K
Ultraviolet
400-200 nm
10,000 K
X-ray
100-10 nm
10,000,000 K
Multiwavelength Whirlpool Galaxy
COLD GAS: Radio waves reveal regions of gas cool enough for CO_2 molecules to exist.
COOL STARS: Infrared shows smaller cool red stars that make up most of the galaxy.
SOLAR STARS: Optical light comes from stars around the size of the Sun.
HOT STARS: Ultraviolet shows the larger hot blue stars that are less frequent in galaxies.
HOT GAS: X-rays are emitted from the hottest regions of gas where atoms are ionized.
COOL LOW ENERGY RADIATION
VISIBLE LIGHT
HOT HIGH ENERGY RADIATION

Multi-wavelength Light Curves

- Time evolution of the signal (brightness)
- Very important to study **correlations** and **variability**
- Description (long term or short term) of the activity of the source



[Abe et al., 2025](#)

Multi-wavelength spectral energy distribution

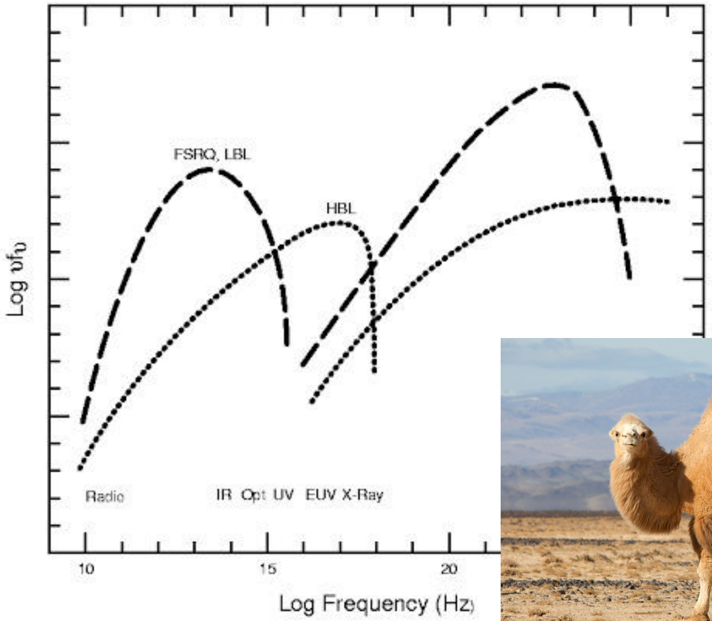
- Simultaneous or quasi-simultaneous fluxes
- Obtained from a specific time (or time-range) of the light curves, multiplying the diff. flux x unit energy by E^2

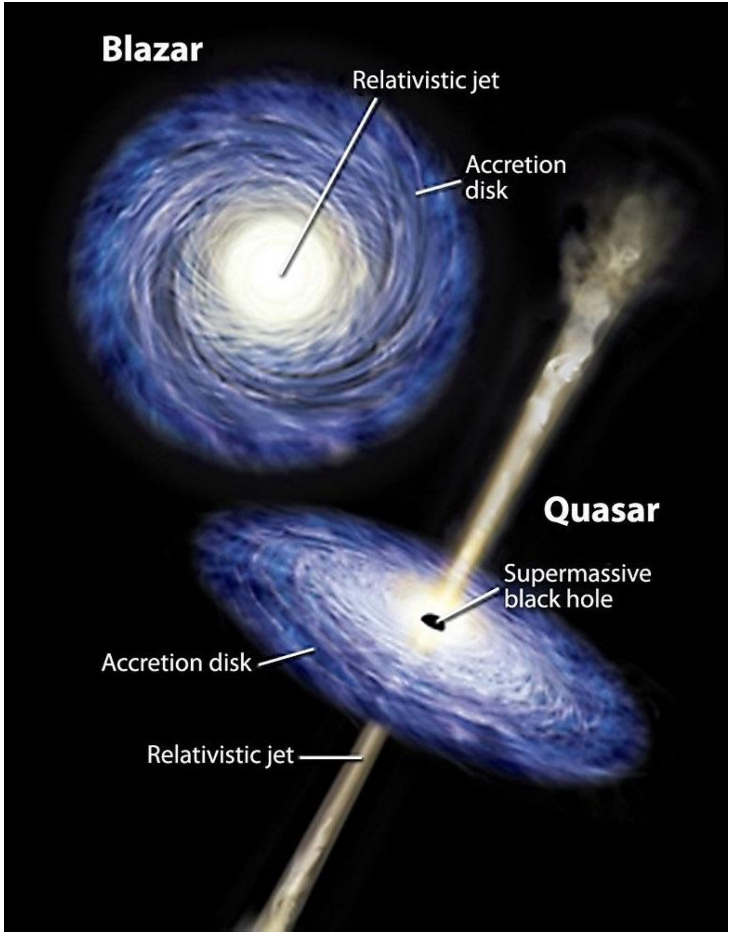
$$E^2 \frac{d\Phi}{dE}\ (\mathrm{TeV\ cm^{-2}\ s^{-1}})$$

- The broadband SED can be used to study the **emission mechanism**
- **Modeling** of the broadband SED (different models, leptonic, hadronic, hybrid…) gives the theoretical interpretation (emission scenarios)

Multi-wavelength SEDs

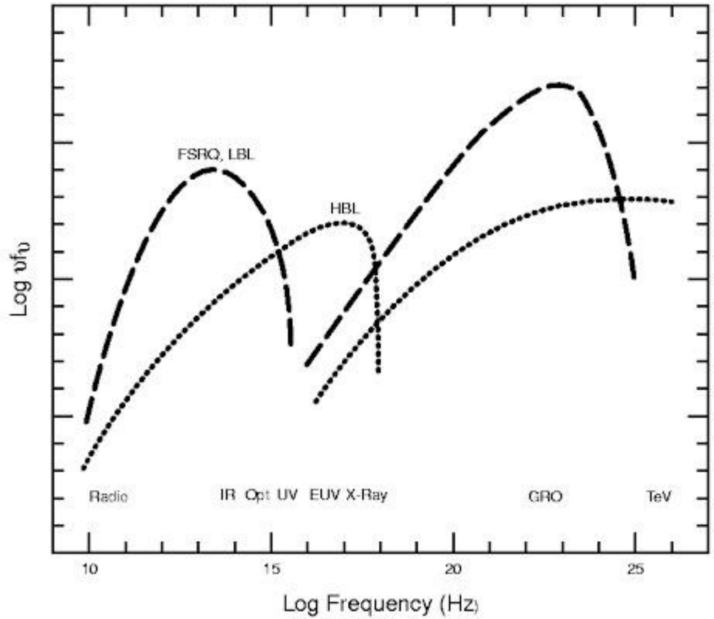
Categorization of blazars depending on their SED peaks' positions

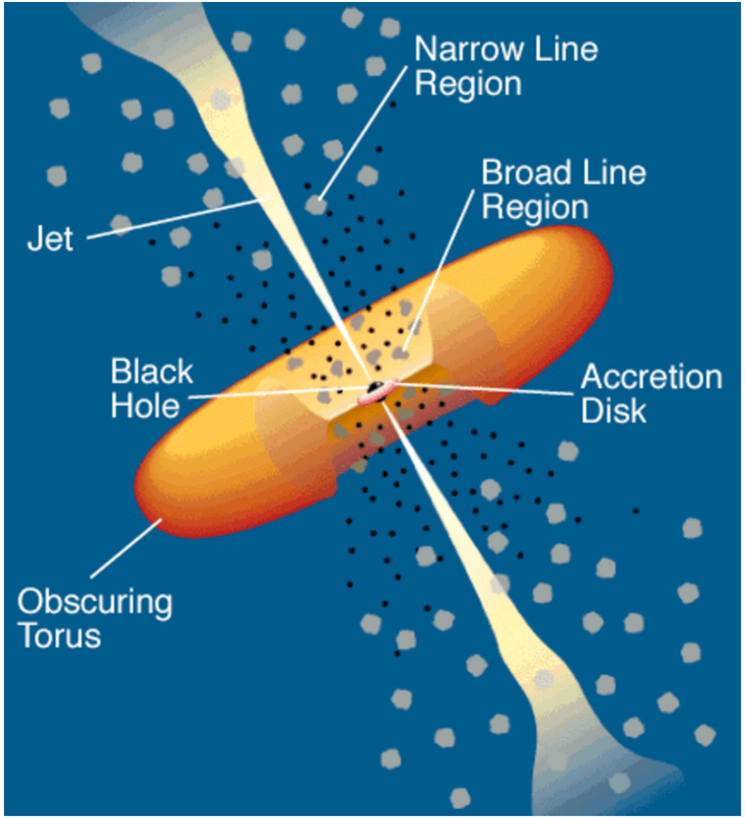




Multi-wavelength SEDs

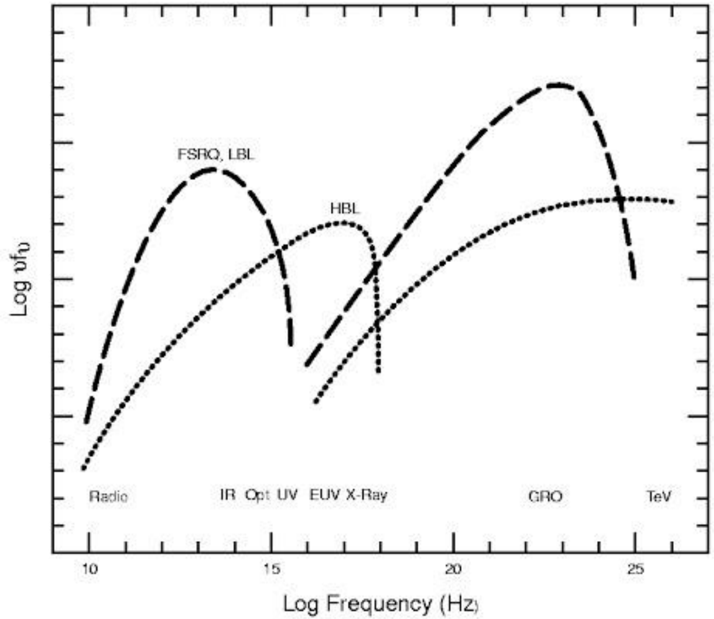
Categorization of blazars depending on their SED peaks' positions

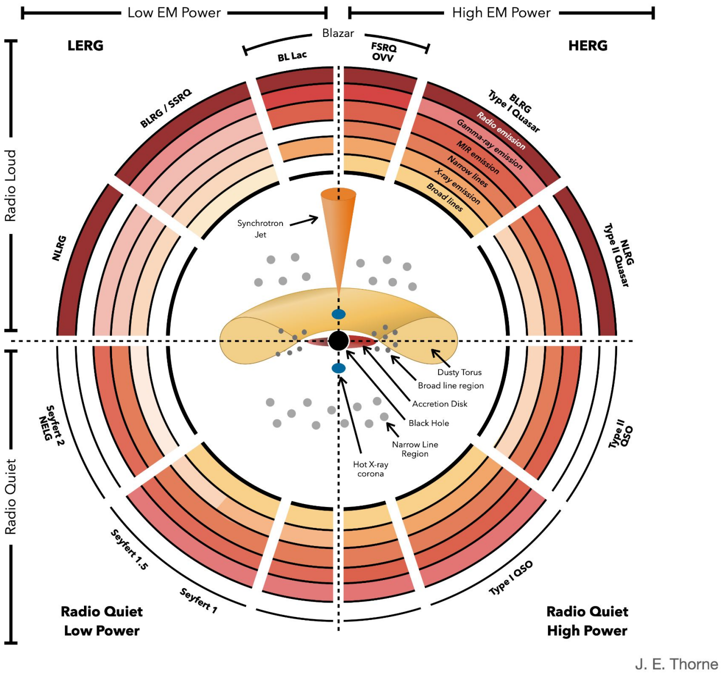




Multi-wavelength SEDs

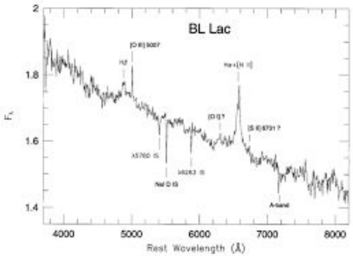
Categorization of blazars depending on their SED peaks' positions

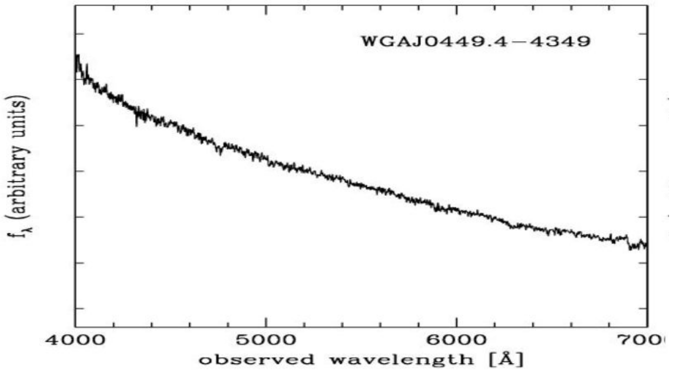


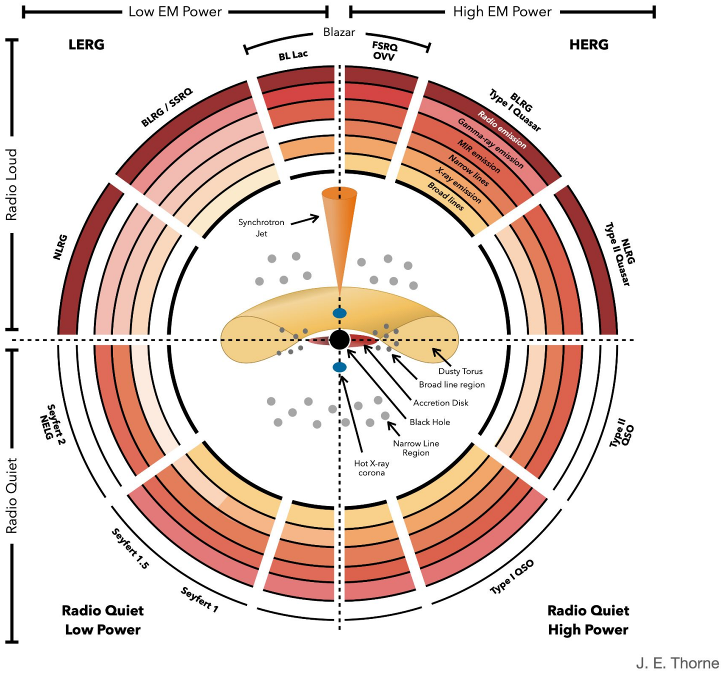


AGN unification scheme by J.E. Thorne

Blazars: BL Lacs



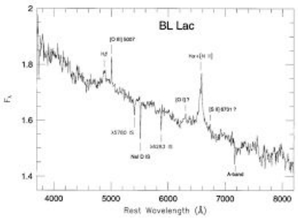


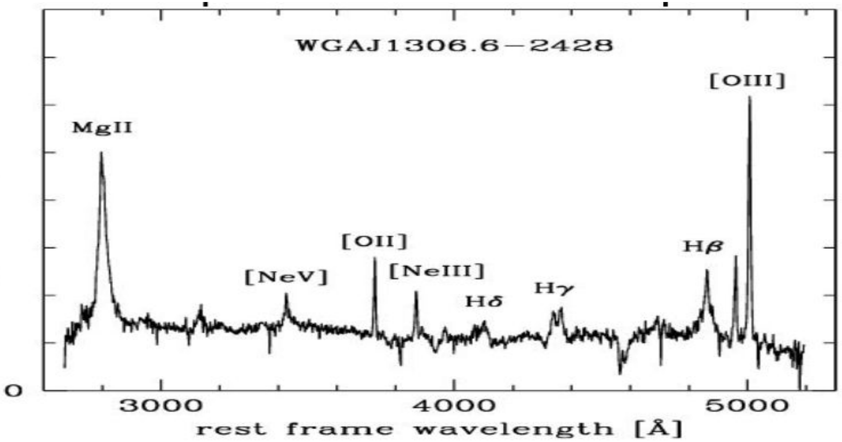


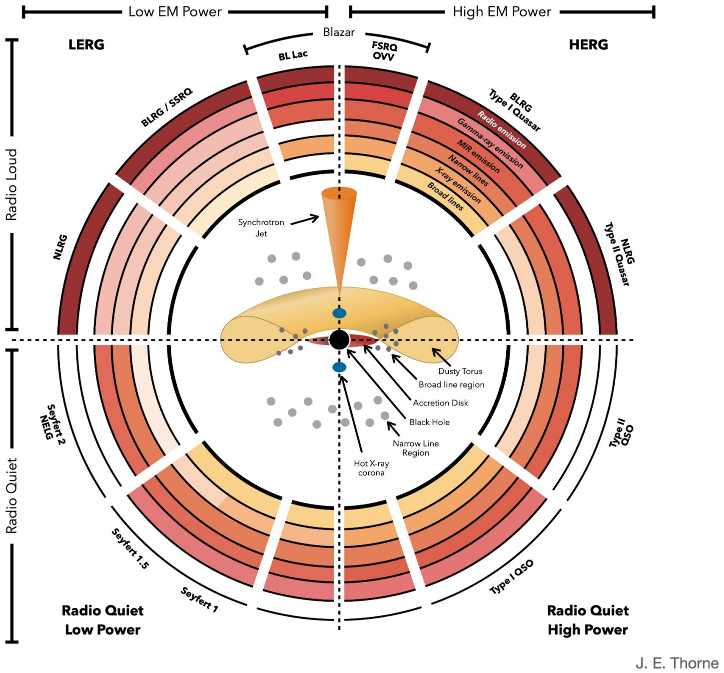
AGN unification scheme by J.E. Thorne

Blazars: Flat Spectrum Radio Quasars

FSRQs



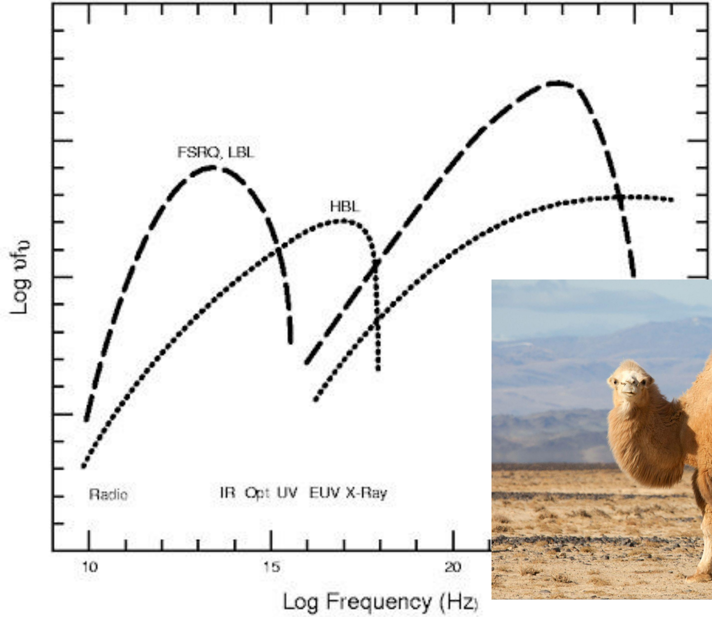


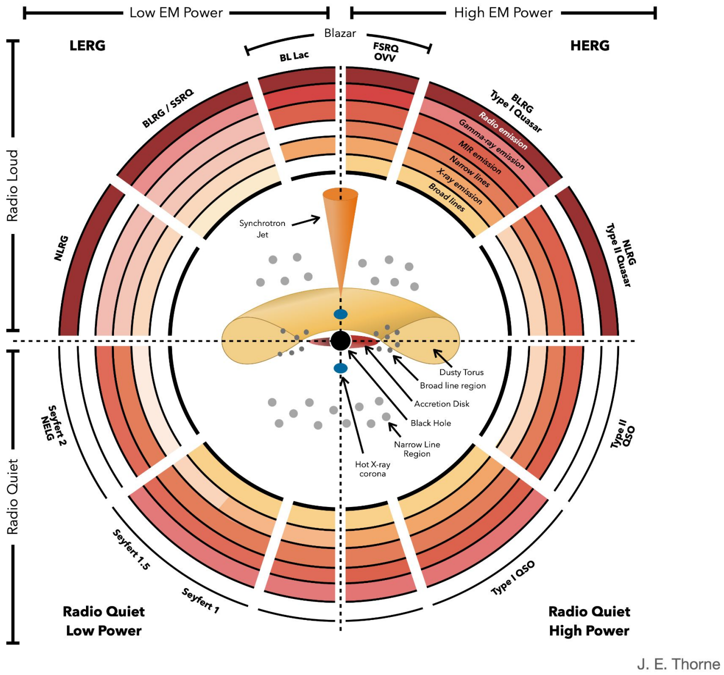


AGN unification scheme by J.E. Thorne

Multi-wavelength SEDs

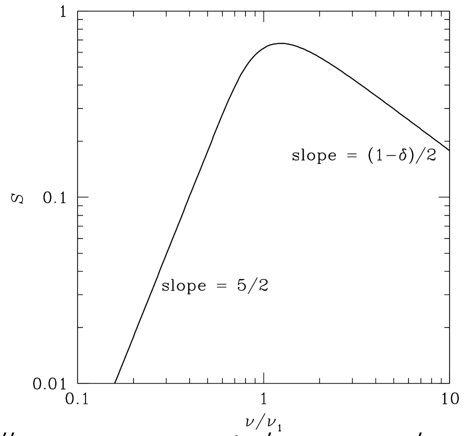
Categorization of blazars depending on their SED peaks’ positions



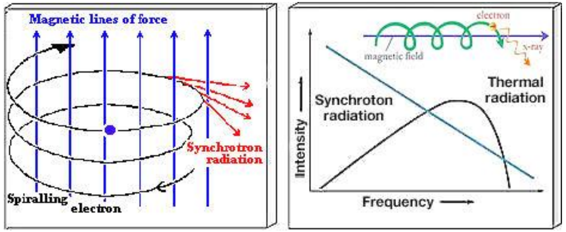


AGN unification scheme by J.E. Thorne

Multi-wavelength spectral energy distribution

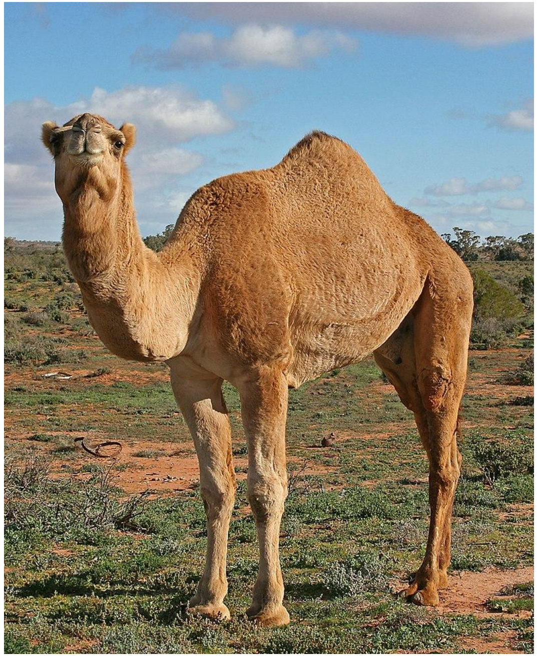


https://www.cv.nrao.edu/~sransom/web/Ch5.html

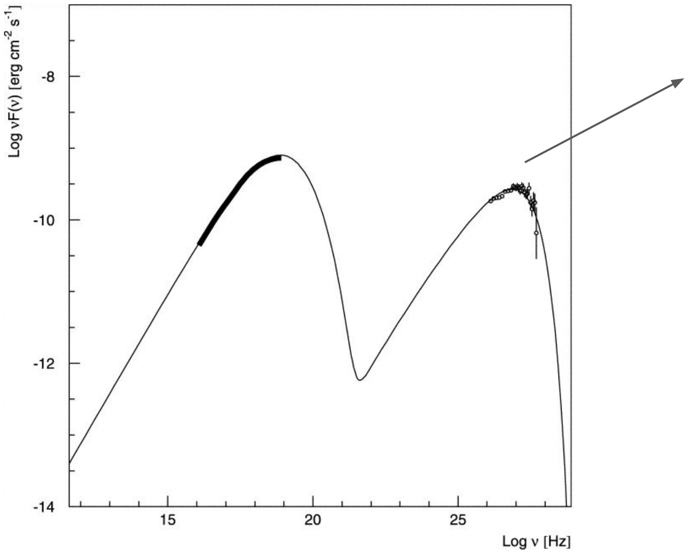


Synchrotron bump

- Generated by synchrotron emission of the charged particles moving in the magnetic field of the source



Multi-wavelength spectral energy distribution



MWL SED of Mrk501

Inverse Compton bump

- IC involves the scattering of low energy photons to high energies by ultrarelativistic electrons so that the photons gain and the electrons lose energy.
- It is called inverse because the electrons lose energy rather than the photons, the opposite of the standard Compton effect.

MWL emission models

- One zone, leptonic
  In short, we assume that the synchrotron process is due to a population of electrons. Most (but not all) luminosity is produced in a well-defined zone at some distance R from the central engine by relativistic electrons.

- One zone, hadronic
  we assume that the relativistic protons are responsible for the emission, even if not directly (except for the proton–synchrotron model). Proton–proton collisions, or more likely, photo-hadronic interactions, can produce electron positron relativistic pairs that can then radiate.

- One zone, lepto-hadronic
  Of course we can!

- Multi zone, either leptonic or hadronic or (lepto-hadronic!)
  we assume that the particles are accelerated and radiate all along the jet in a more or less continuous way. These models consider that the density of the emitting particles and the magnetic field are a (power–law) function of the distance from the black hole. In these models, the jet geometry (paraboloidal or conical) plays a crucial role.

MWL emission models

- Radiative processes:
  In all cases, the main radiation processes of the jet are the synchrotron mechanism for the low-energy part and the Inverse Compton (IC) for the high-energy part. If the seed photons for the IC scattering are the synchrotron photons produced by the same electrons producing the high-energy Compton component, the process is called Synchrotron–Self–Compton (SSC); if the main seeds are produced externally to the jet (disk radiation, BLR lines, torus, etc.), the process is called external Compton (EC).

- Spine–layer structure:
  Observational evidence and important γ–ray emission from misaligned sources led to the suggestion that the blazar jet is structured, meaning that a high-velocity spine is surrounded by a slower layer. The spine sees the layer radiation beamed, and this enhances its Compton emission. On the other hand, the layer also sees the radiation from the spine as beamed, and thus the Compton emission of the layer is also enhanced.

Thermal emission

- BL Lacs.
  In BL Lacs, we see no sign of thermal emission, leading to the suggestion that:

1. The accretion regime is not radiatively efficient;
2. This corresponds to a paucity of ionizing radiation, corresponding to the absence of broad emission lines;
3. There is no molecular torus;
4. All these properties can be understood if the accretion luminosity, in units of the Eddington one, is smaller than some critical value

- FSRQs.

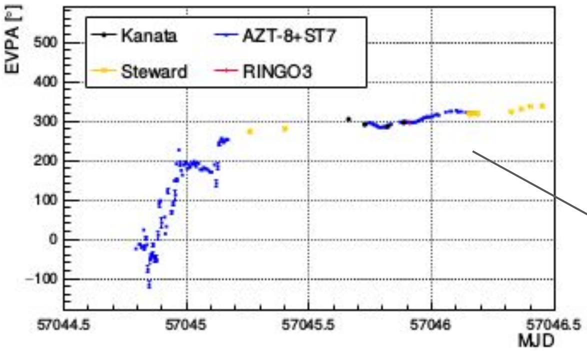
In powerful FSRQ, we do directly see the accretion disk radiation, besides the broad emission lines and the IR torus component. This therefore suggests that the high-energy emission of FSRQs is likely due to the EC process, while that of BL Lacs is due to the SSC (but possibly accounting for the spine–layer structure).

Models' parameters (some of them)

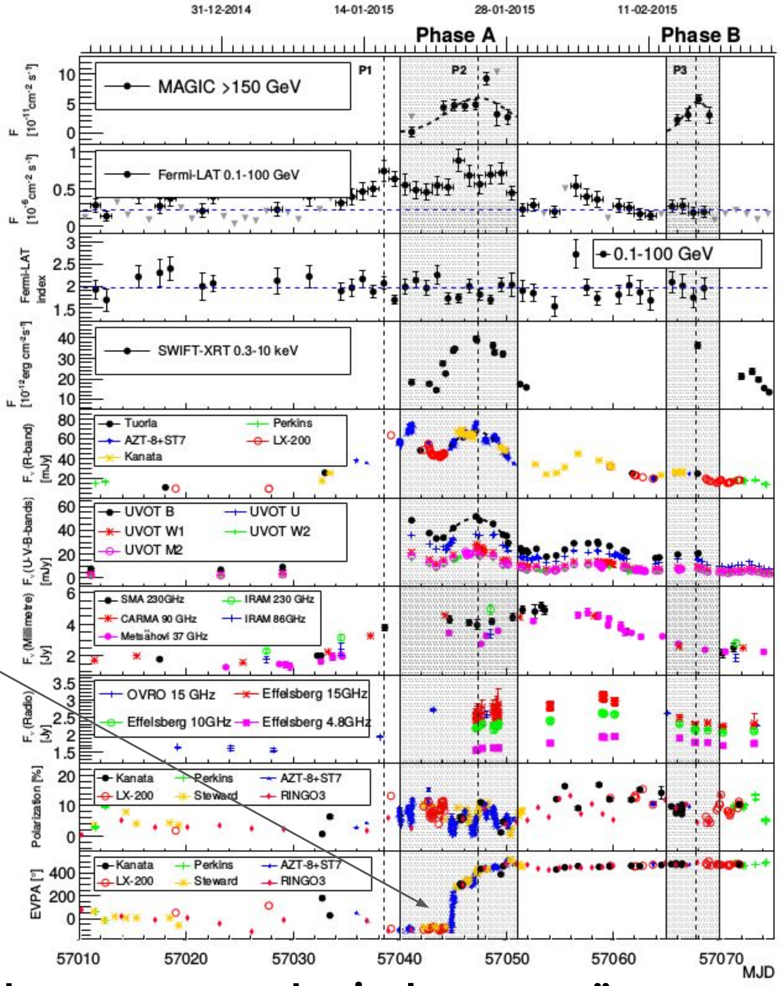
δ	Doppler Factor
R' $(\times 10^{16}$ cm)	Emission region radius
B' $(\times 10^{-2}$ G)	Magnetic Field Strength
$^{\star}U'_B$ $(\times 10^{-5}$ erg cm$^{-3})$	Energy density due to the Magnetic field
$\gamma'_{\mathrm{e,min}}$	Lorentz factor (min)
$\gamma'_{\mathrm{e,break}}$ $(\times 10^3)$	Lorentz factor (break)
$\gamma'_{\mathrm{e,max}}$ $(\times 10^5)$	Lorentz factor (max)
n'_1 n'_2	Slopes of the power law of the electron distribution
K'_{e} $(\times 10^3$ cm$^{-3})$	Normalization factor (for electrons' distribution)
$\gamma'_{\mathrm{p,min}}$	Lorentz factor (min)
$\gamma'_{\mathrm{p,max}}$ $(\times 10^7)$	Lorentz factor (max)
K'_{p}	Normalization factor (for protons' distribution)
$^{\star}U'_{\mathrm{p}}$ (erg cm$^{-3})$	Energy density of protons
$^{\star}U'_{\mathrm{p}}/U'_B$ $(\times 10^4)$	Equipartition factor
$^{\star}L$ $(\times 10^{47}$ erg s$^{-1})$	Luminosity

Examples of multi-wavelength studies

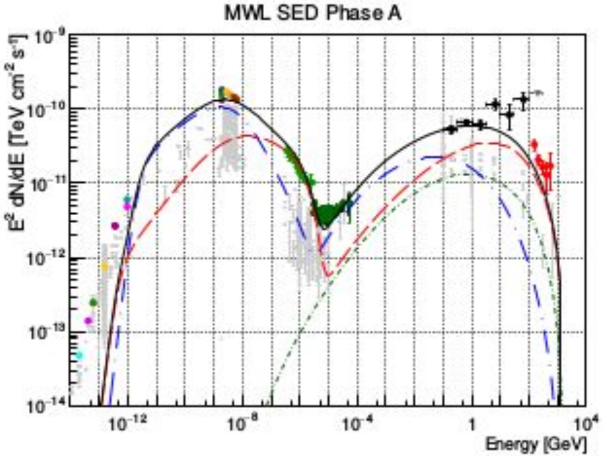
Multi-wavelength characterization of the blazar S5 0716+714 during an unprecedented outburst phase

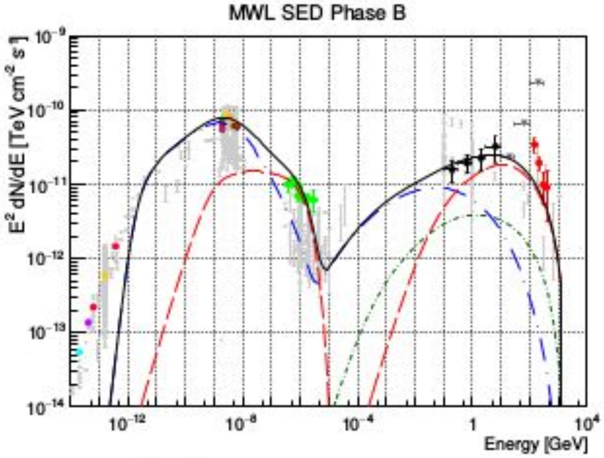


[Ahnen et al., Astronomy & Astrophysics **619**, A45 (2018)](#)

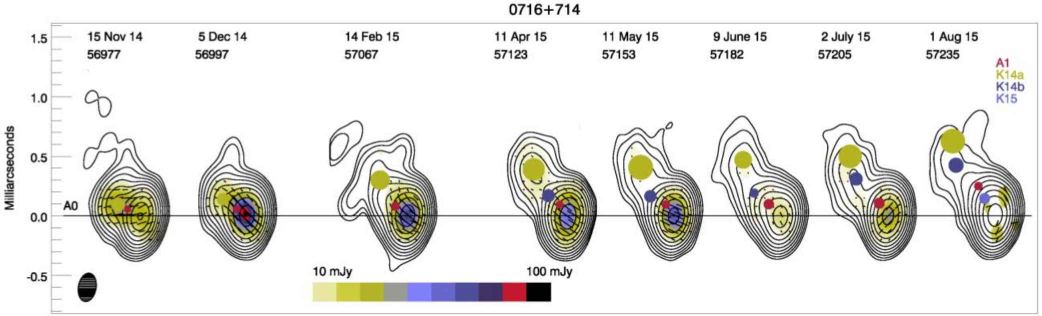


Examples of multi-wavelength studies





Two zones leptonic modeling

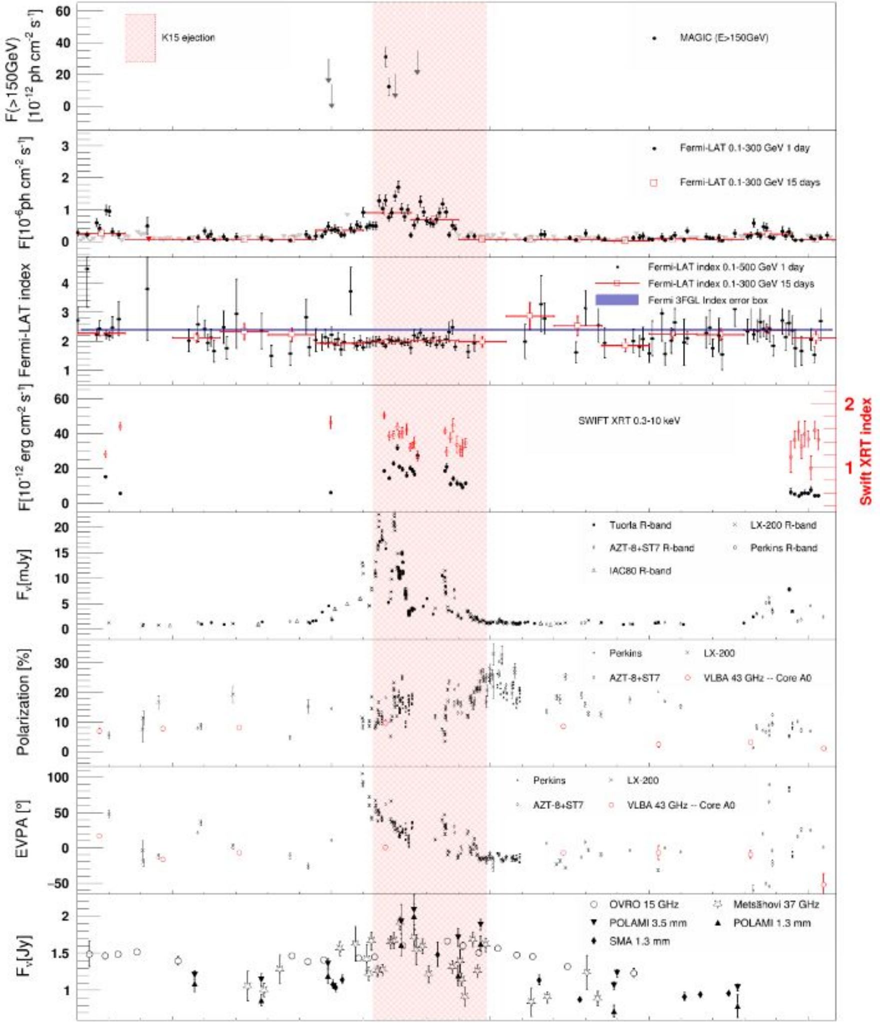


Ahnen et al., Astronomy & Astrophysics **619**, A45 (2018)

Examples of multi-wavelength studies

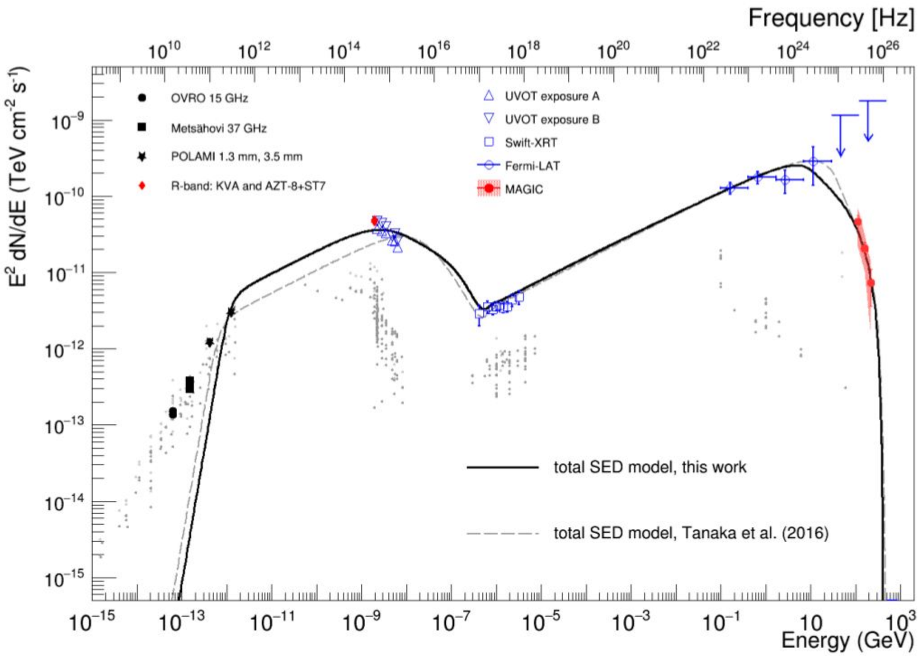
Detection of the blazar S4 0954+65 at very-high-energy with the MAGIC telescopes during an exceptionally high optical state

[Ahnen et al., Astronomy & Astrophysics, **617**, id.A30, 15 pp. (2018)]



Examples of multi-wavelength studies

Detection of the blazar S4 0954+65 at very-high-energy with the MAGIC telescopes during an exceptionally high optical state



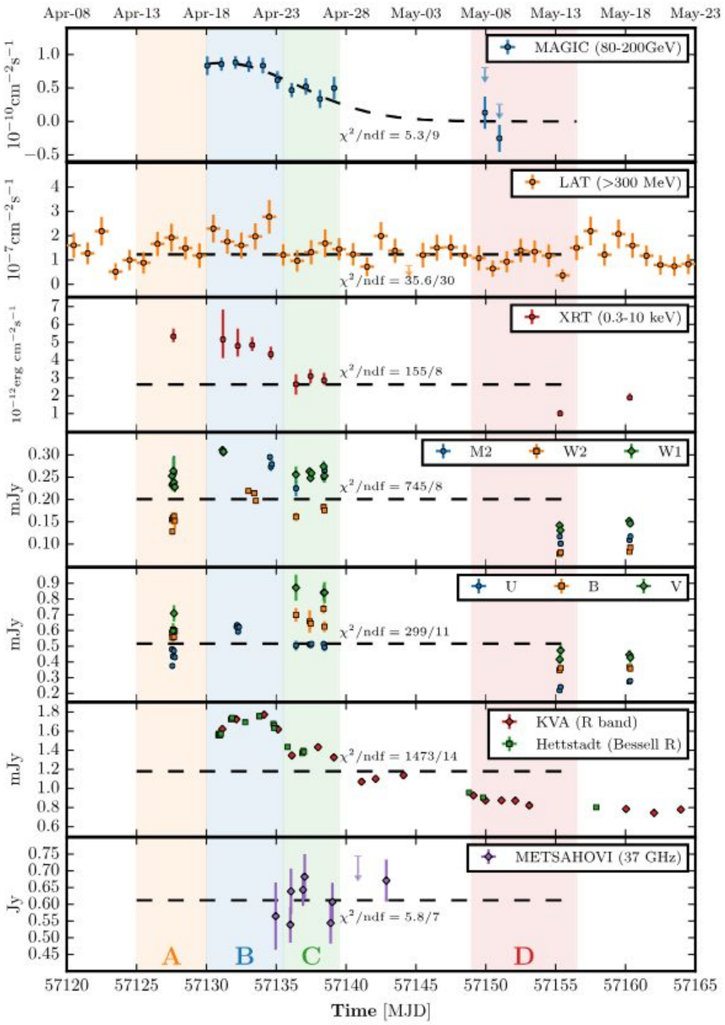
Leptonic model + External Compton contribution (Dusty torus)

Ahnen et al., Astronomy & Astrophysics, **617**, id.A30, 15 pp. (2018)

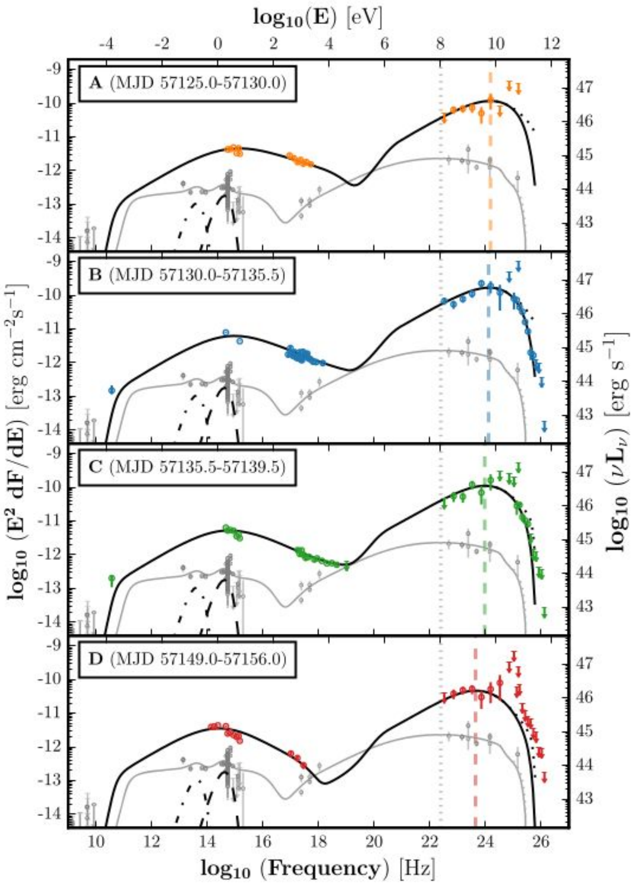
Examples of multi-wavelength studies

Very High Energy γ-Rays from the Universe's Middle Age:
Detection of the z = 0.940 Blazar PKS 1441+25 with MAGIC

Ahnen et al., The Astrophysical Journal Letters, **815**, L23 (2015)



Examples of multi-wavelength studies



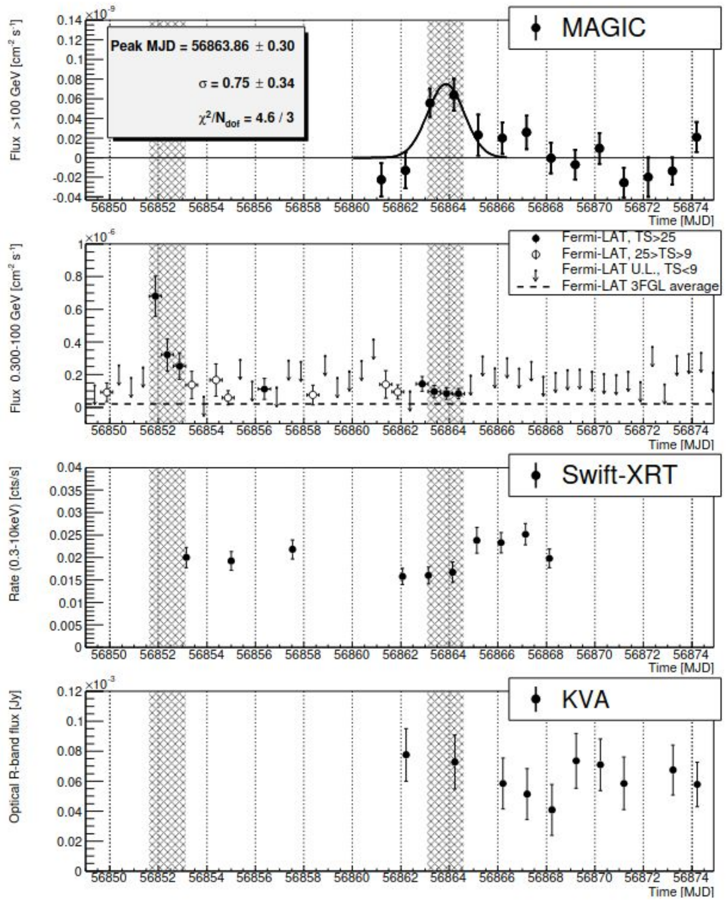
Very High Energy γ-Rays from the Universe's Middle Age: Detection of the z = 0.940 Blazar PKS 1441+25 with MAGIC

external Compton model,
emitting region originating in the jet outside the broad-line region during the period of high activity, while being partially within the BLR during the period of low (typical) activity.

[Ahnen et al., The Astrophysical Journal Letters, 815, L23 (2015)]

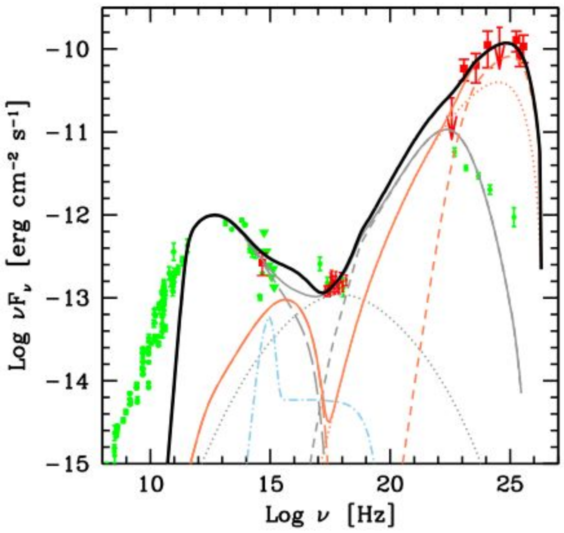
Examples of multi-wavelength studies

Detection of very high energy gamma-ray emission from the gravitationally lensed blazar QSO B0218+357 with the MAGIC telescopes



[Ahnen et al., Astronomy & Astrophysics, **595**, A98, (2016)]

Examples of multi-wavelength studies



Detection of very high energy gamma-ray emission from the gravitationally lensed blazar QSO B0218+357 with the MAGIC telescopes

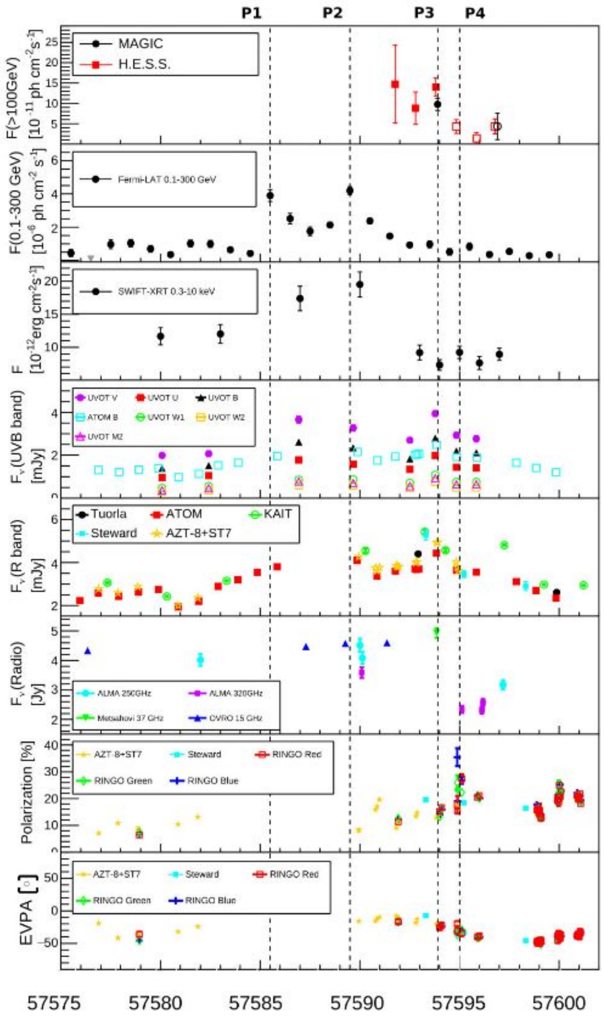
Two zone EC scenario,
GeV emission comes from an emission region in the jet, located outside the broad line region

[Ahnen et al., Astronomy & Astrophysics, **595**, A98, (2016)]

Examples of multi-wavelength studies

Multiwavelength study of OT 081: broadband modelling of a transitional blazar

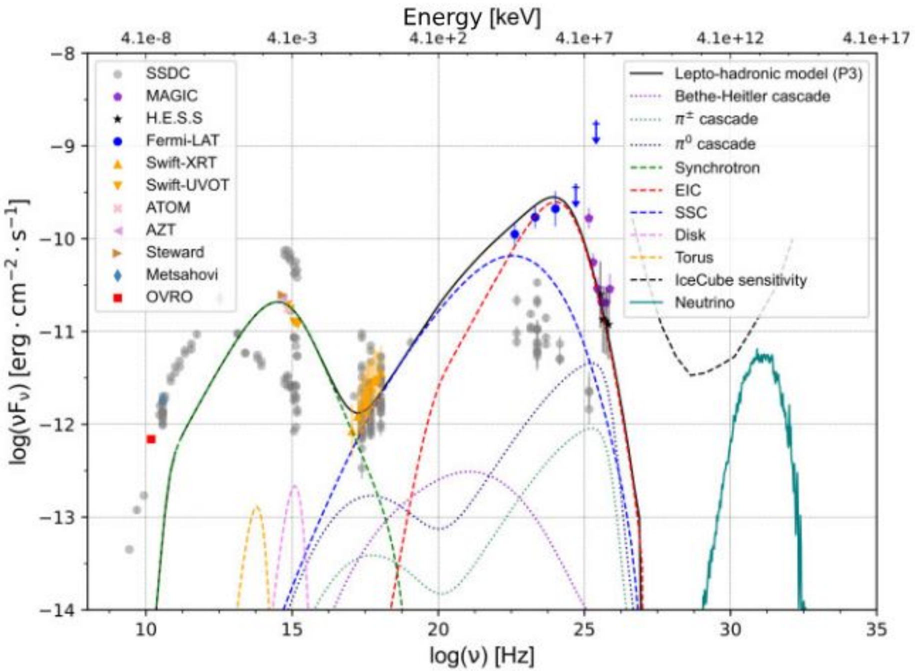
Abe et al., MNRAS 540, 364 (2025)



Examples of multi-wavelength studies

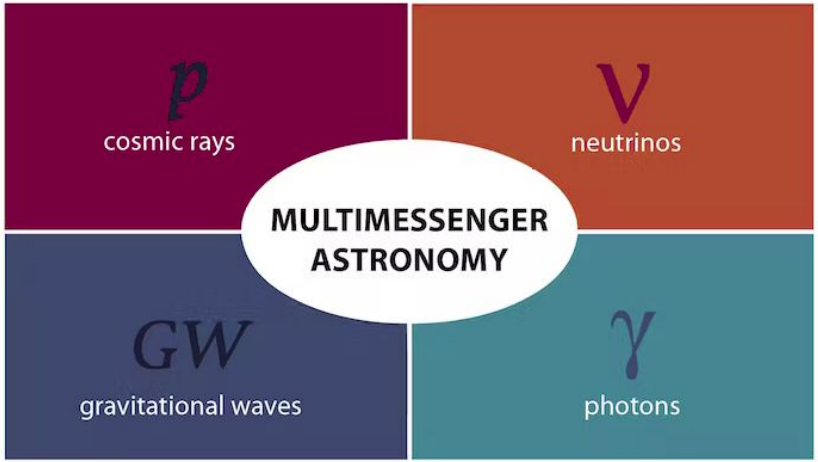
OT 081

- One-zone SSC models cannot successfully describe the dataset.
- The high energy bump of the SEDs can not be explained by Compton scattering of low-energy photons by the same electrons producing the synchrotron emission at lower frequencies …

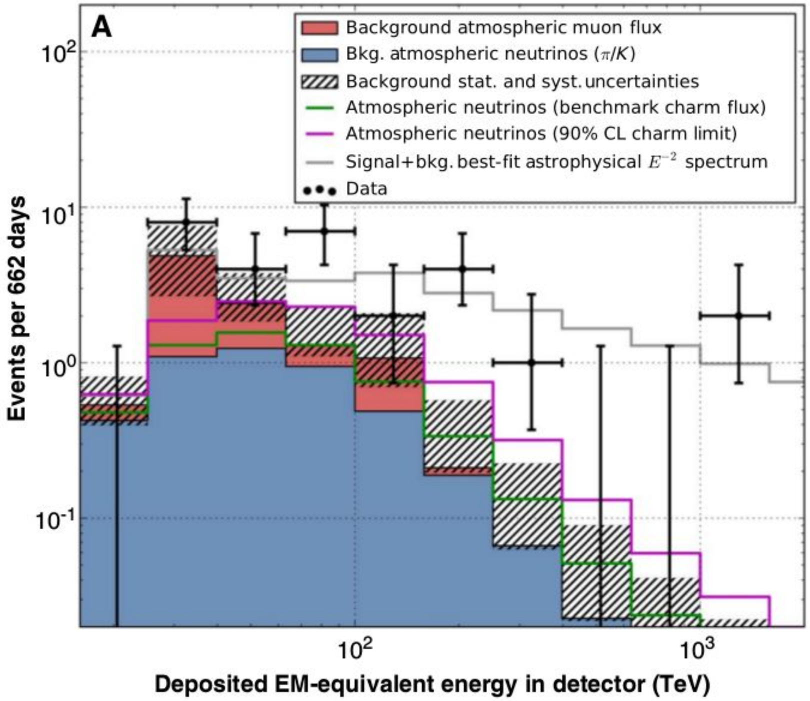


Abe et al., MNRAS 540, 364 (2025)

The future: multi-messenger astronomy

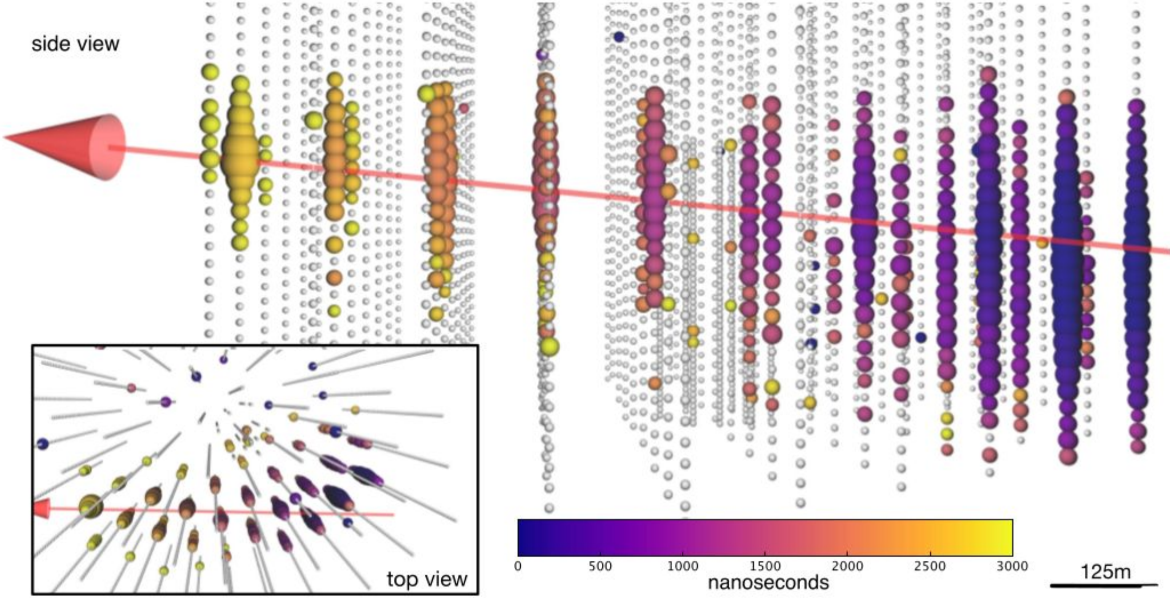


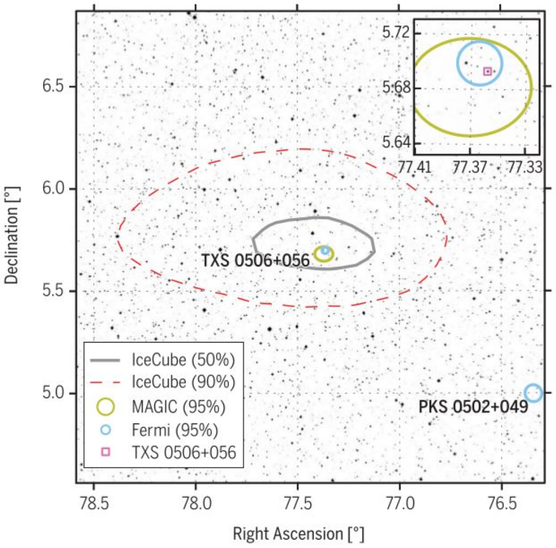
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector!



IceCube Collaboration, Science, 342, 6161, id.1242856 (2013)

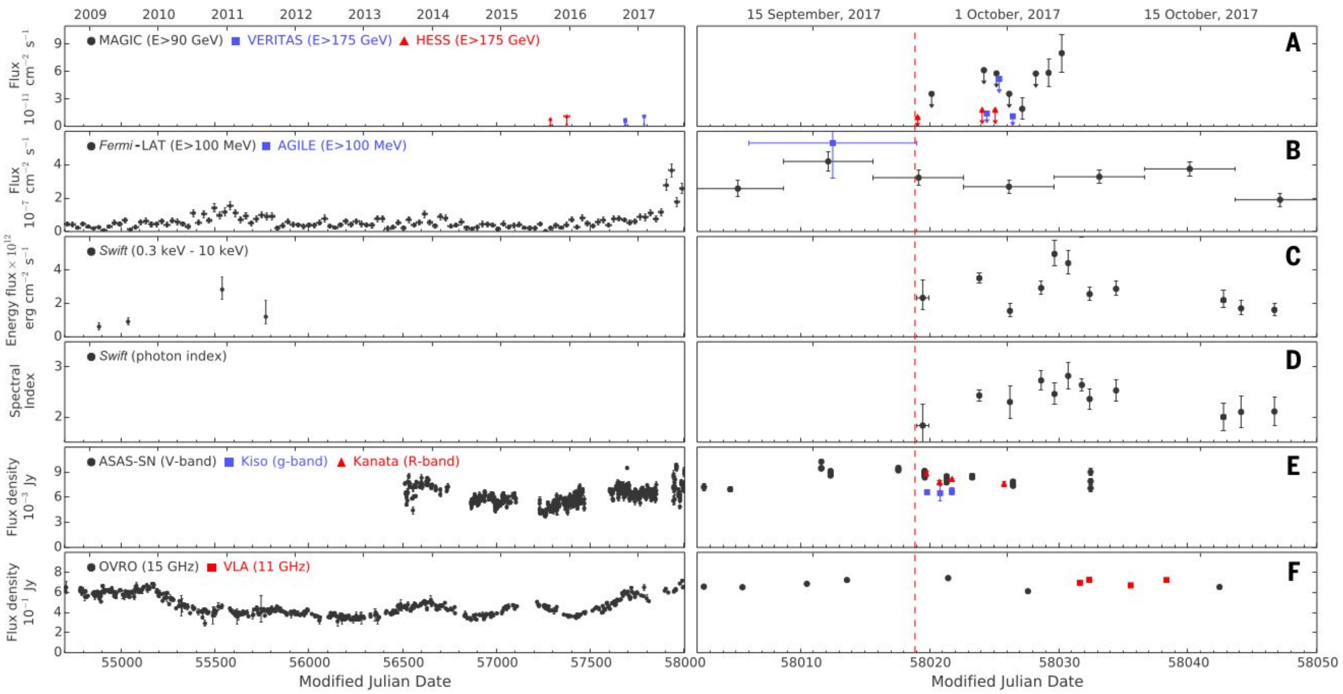
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A



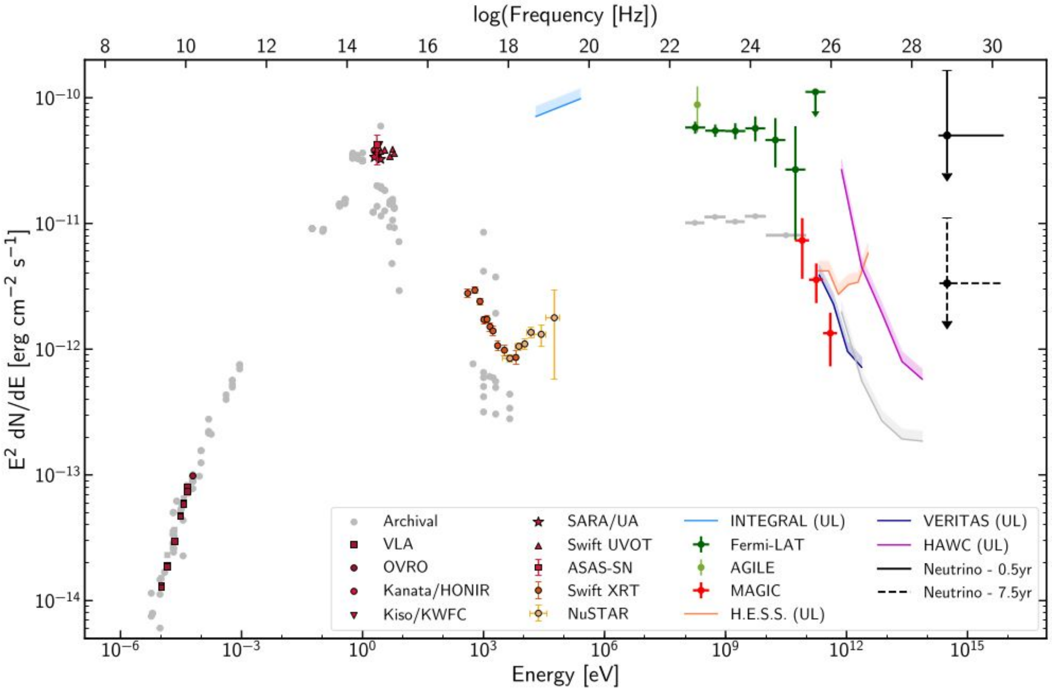


IceCube Collaboration et al., Science **361**, eaat1378 (2018)

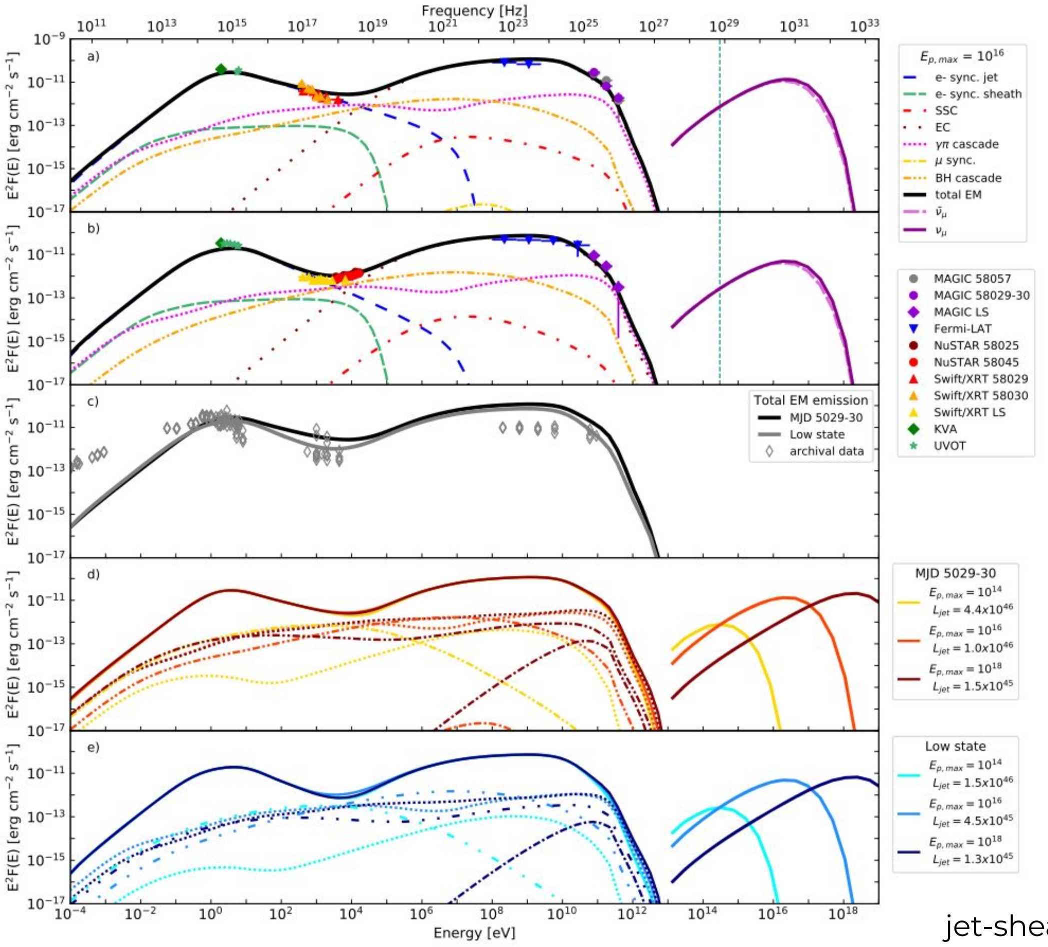
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A



Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

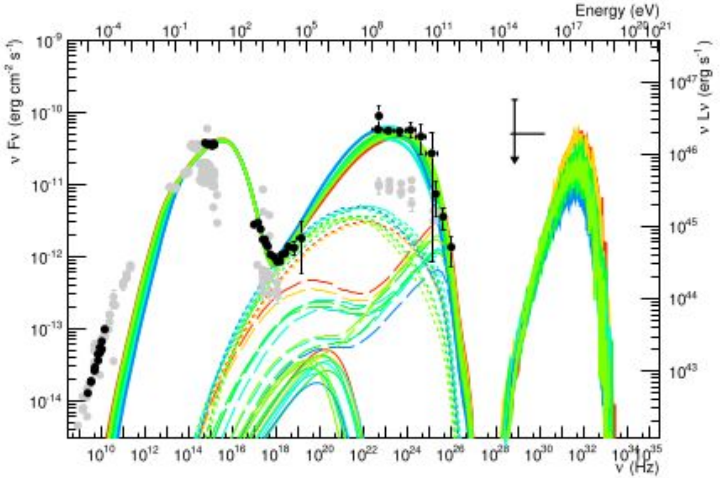


[IceCube Collaboration et al., Science **361**, eaat1378 (2018)]()



jet-sheath scenario

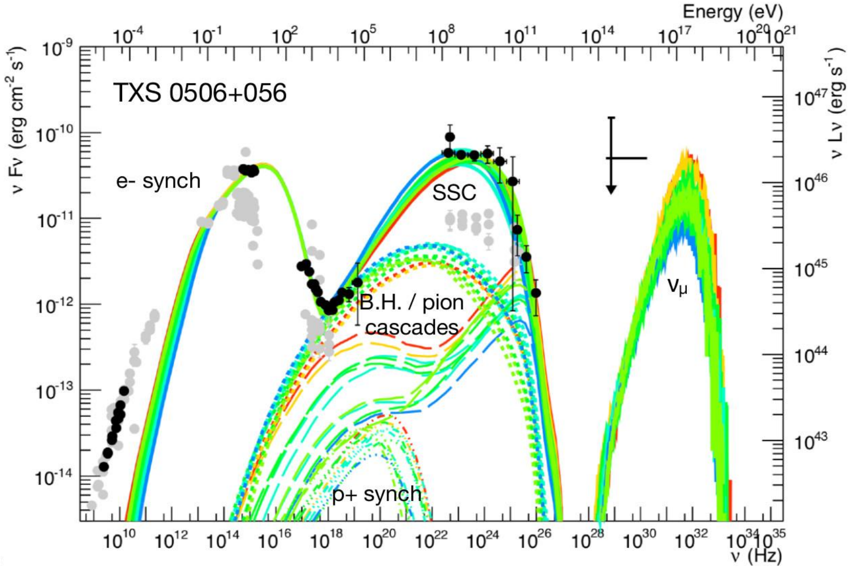
The Blazar TXS 0506+056 Associated with a High-energy Neutrino: Insights into Extragalactic Jets and Cosmic-Ray Acceleration

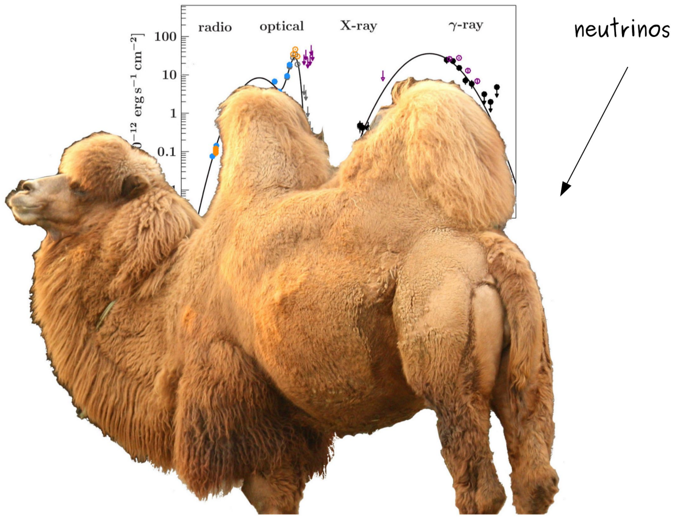


[Cerruti et al., Monthly Notices of the Royal Astronomical Society: Letters, Volume 483, Issue 1, p.L12-L16 (2019)]

lepto-hadronic

[Ansoldi et al., The Astrophysical Journal Letters, **863** (2018) L10]





Credit: Krauss et al. 2014, A&A 566, L7 & Wikipedia

Message

- Multiwavelength studies are fundamental in understanding blazars' nature
- Theoretical models are difficult to constrain in many cases
- We need simultaneous data and to keep going with MWL campaigns...
- Multimessenger astrophysics is a reality!!!
- Nevertheless we have only a few multi-messenger observations
- Last photon+neutrino observation was in 2017
- Gravitational wave+Gamma-ray Burst as well in 2017
- New data are coming...we need to get ready to a global interpretation and to develop new observational strategies

But most importantly...

We need to move towards a more global picture (long term studies, try to put together the pieces of the puzzle...)

MAGIC

Major Atmospheric Gamma Imaging Cerenkov Telescopes

Thanks for your attention!

And a special thank you to Giovanni P. for borrowing me his laptop and allowing me to complete this presentation!

@MAGICtelescopes