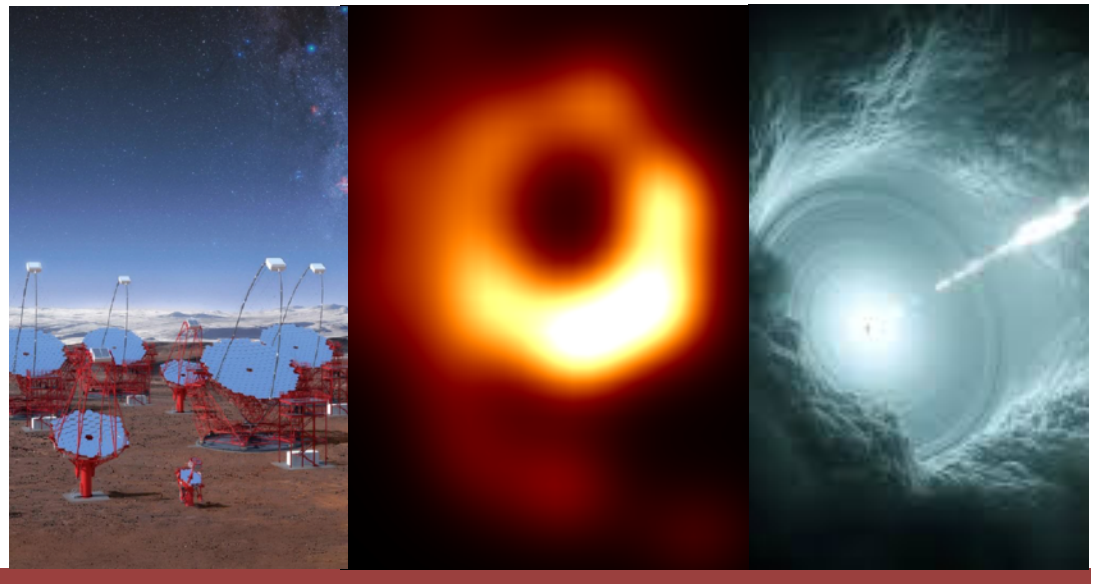


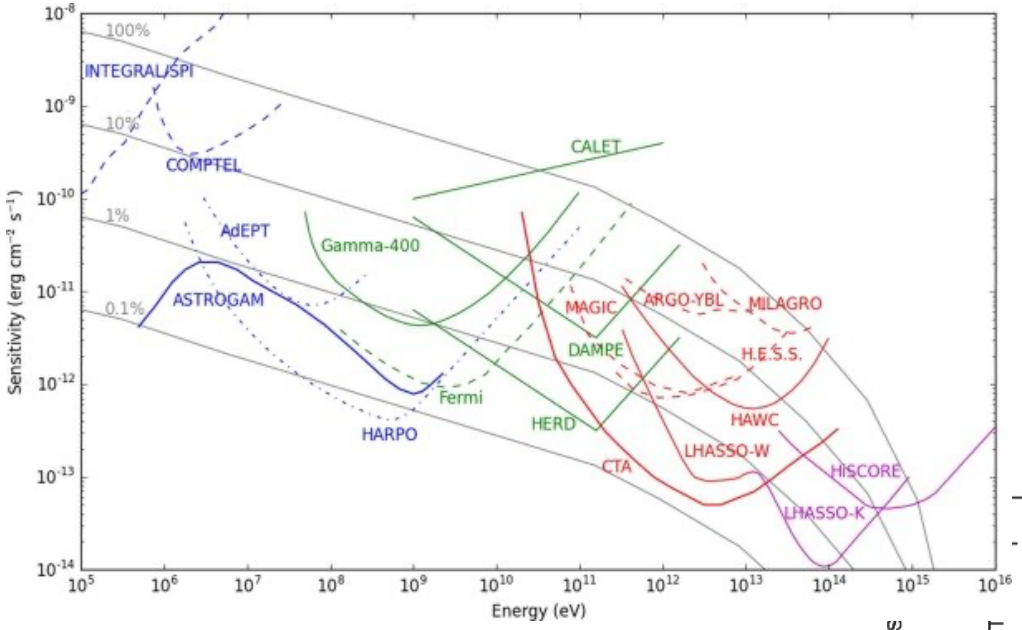
Extragalactic Gamma-ray Sources

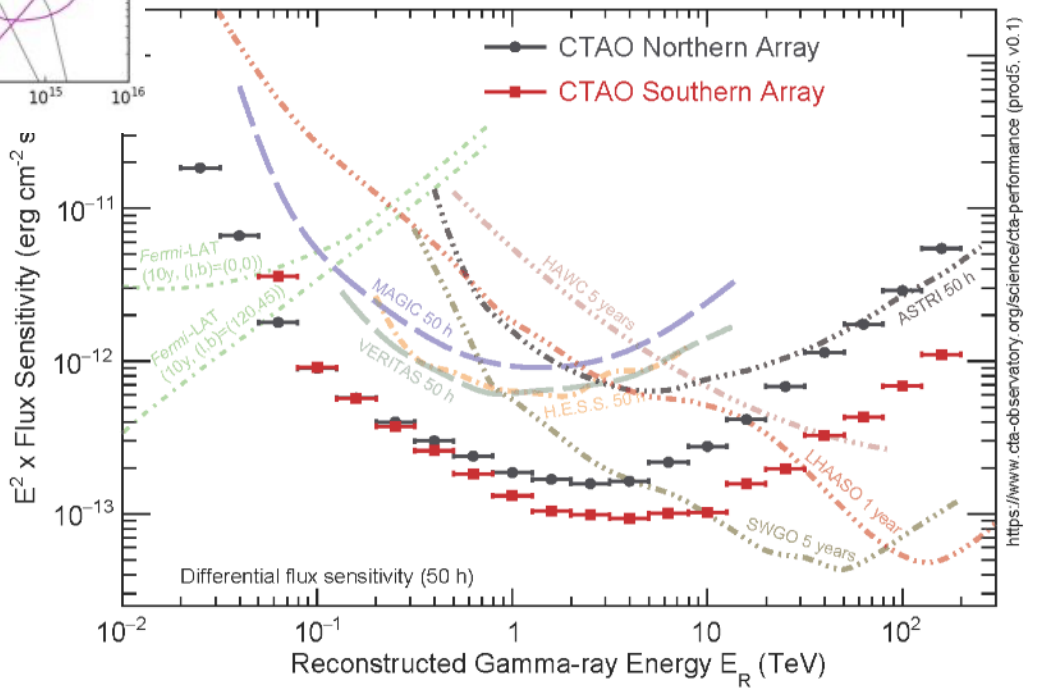
Matteo Cerruti

Université Paris Cité
Astroparticule et Cosmologie (APC)

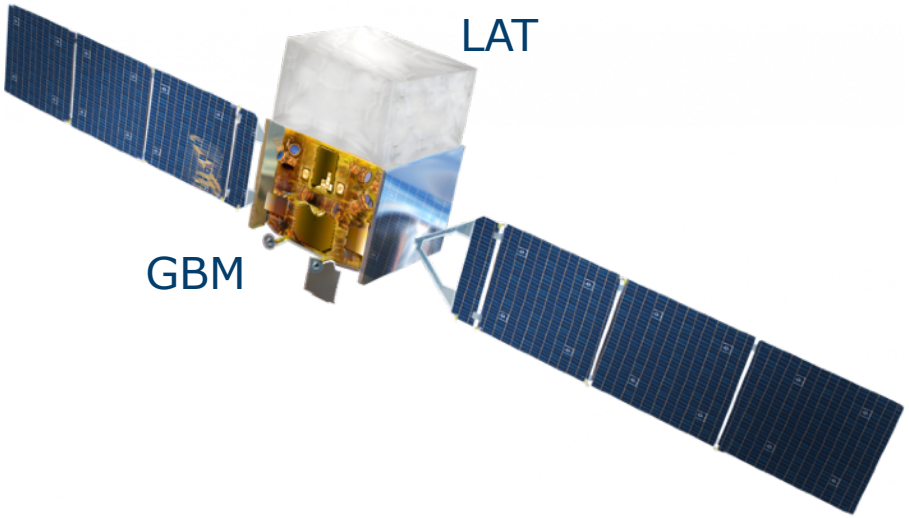
Cherenkov School
Nov 3, 2025

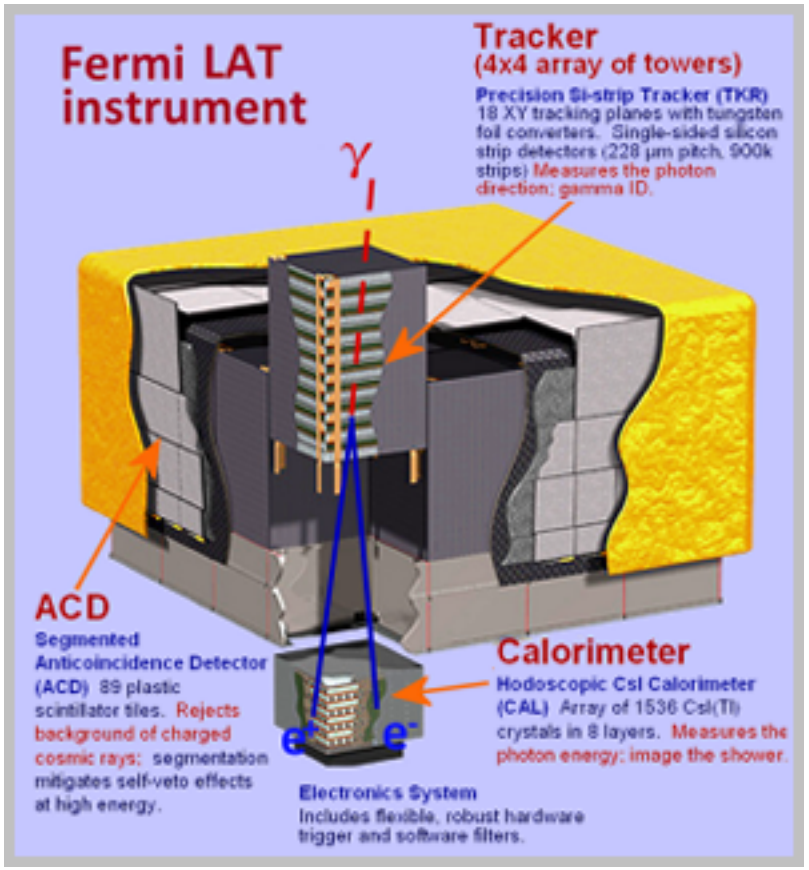
OUR GAMMA-RAY EYES

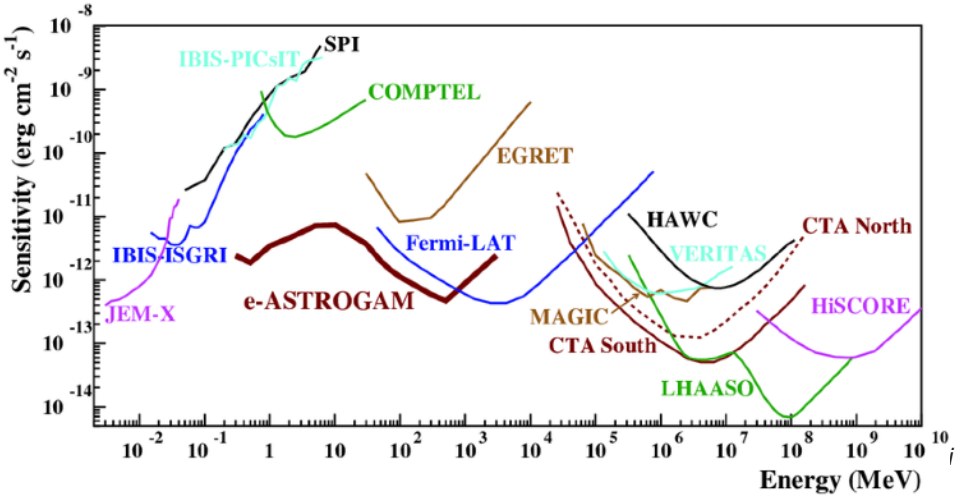




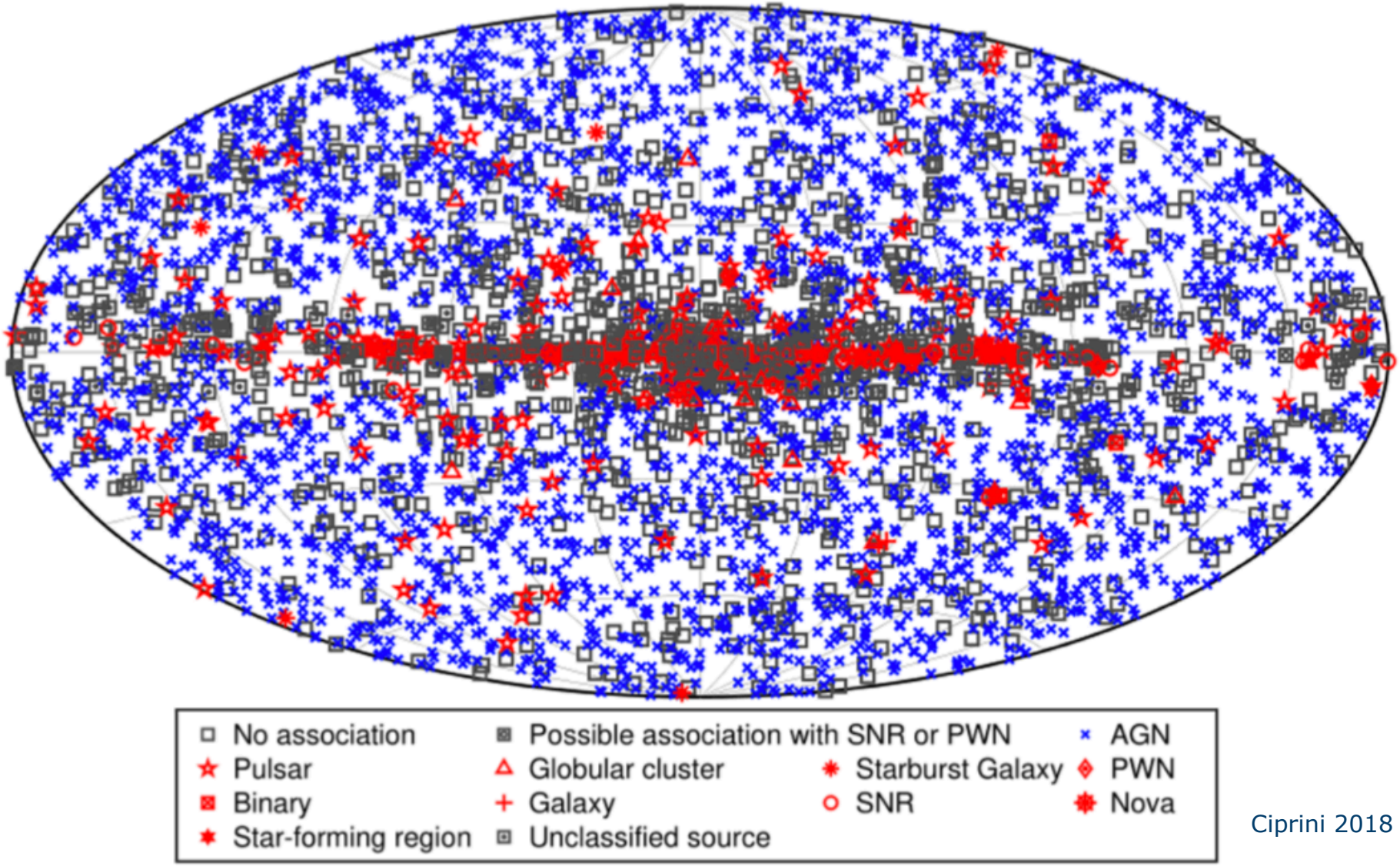
Fermi-LAT


LAT
GBM


Fermi LAT instrument
Tracker
(4x4 array of towers)
Precision Si-strip Tracker (TKR) 18 XY tracking planes with tungsten foil converters. Single-sided silicon strip detectors (228 µm pitch, 900k strips) Measures the photon direction; gamma ID.
γ
ACD
Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles. Rejects background of charged cosmic rays; segmentation mitigates self-veto effects at high energy.
e+
e-
Calorimeter
Hodoscopic CsI Calorimeter (CAL) Array of 1536 CsI(Tl) crystals in 8 layers. Measures the photon energy; image the shower.
Electronics System
Includes flexible, robust hardware trigger and software filters.

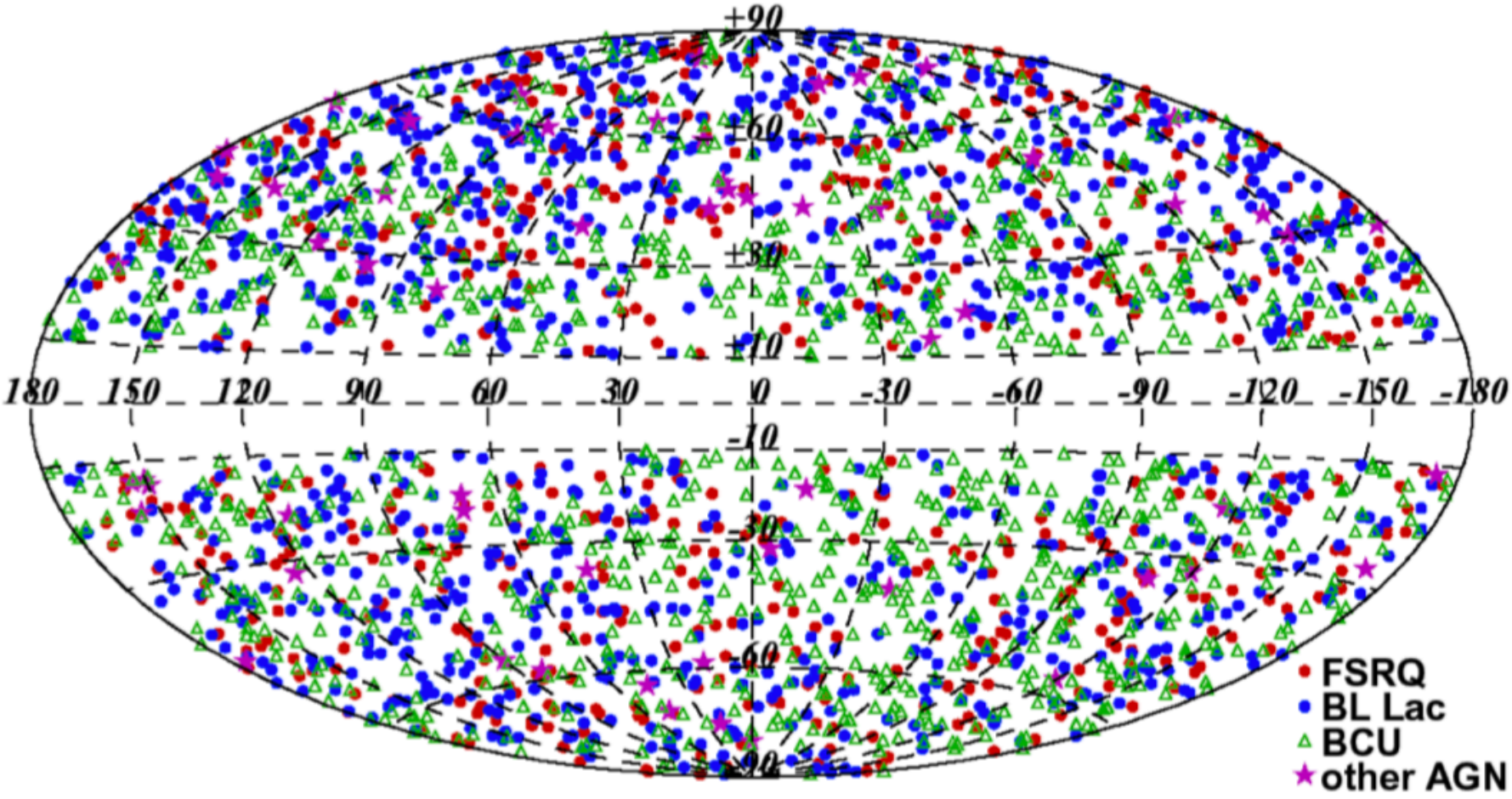

Sensitivity (erg cm^{-2} s^{-1})
Energy (MeV)
SPI
IBIS-PICsIT
COMPTEL
EGRET
IBIS-ISGRI
Fermi-LAT
HAWC
CTA North
VERITAS
JEM-X
e-ASTROGAM
MAGIC
CTA South
HiSCORE
LHAASO

THE GeV EXTRAGALACTIC SKY



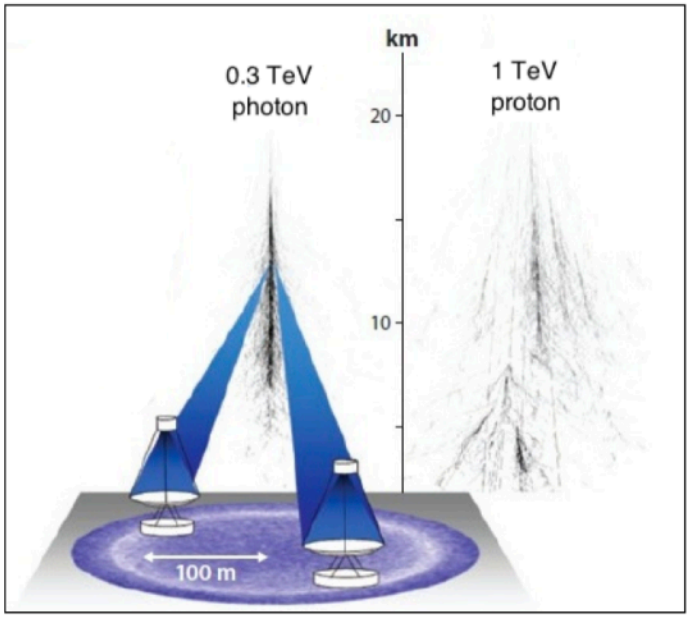
Ciprini 2018

THE GeV EXTRAGALACTIC SKY



Ciprini 2018

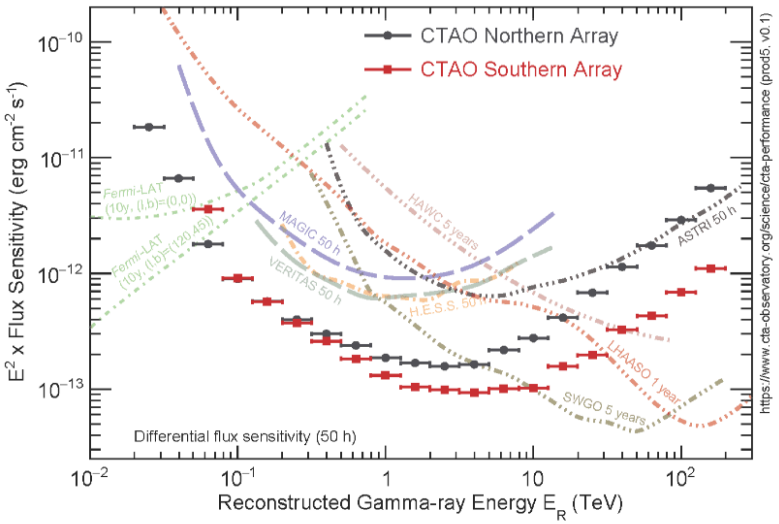
CHERENKOV TELESCOPES



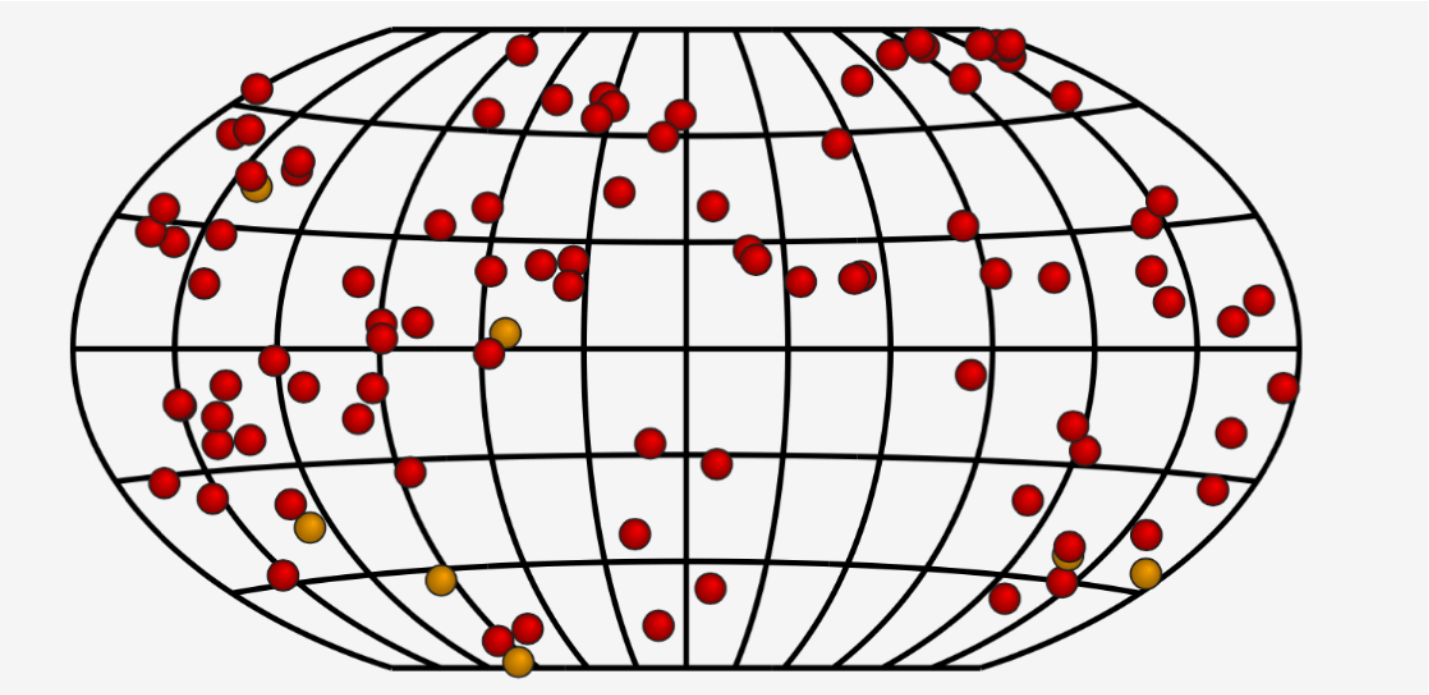








THE TeV EXTRAGALACTIC SKY



http://tevcat2.uchicago.edu

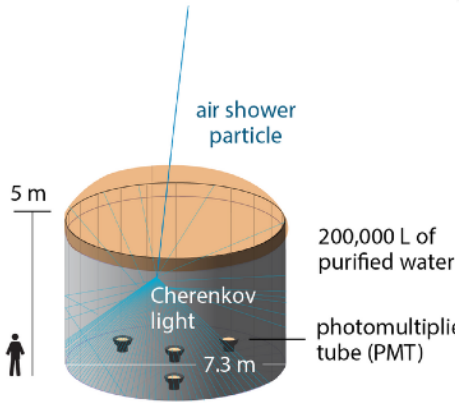
98 extragalactic sources: **4 GRB**

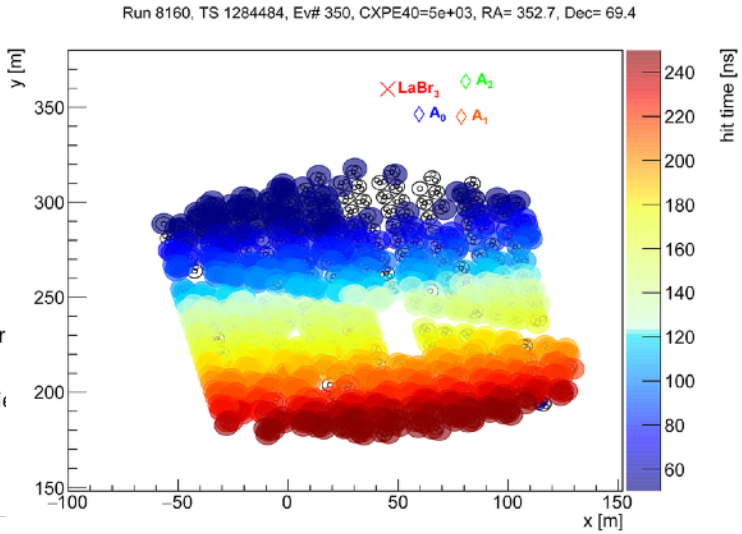
2 starburst galaxies

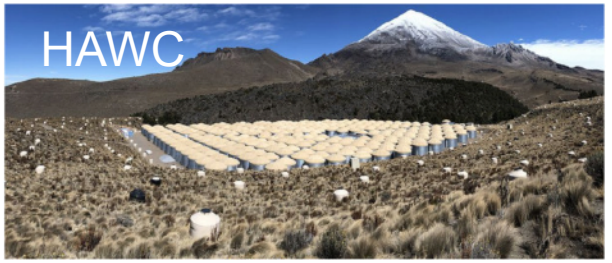
4 radio galaxies

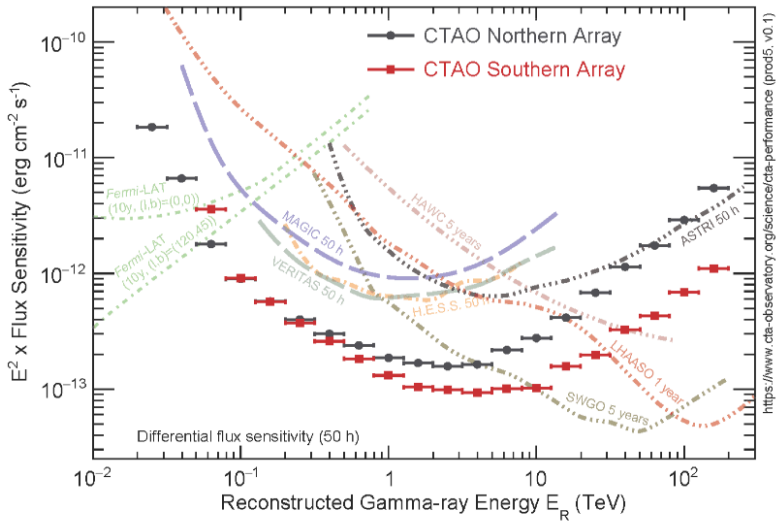
86 blazars

WATER CHERENKOV DETECTORS



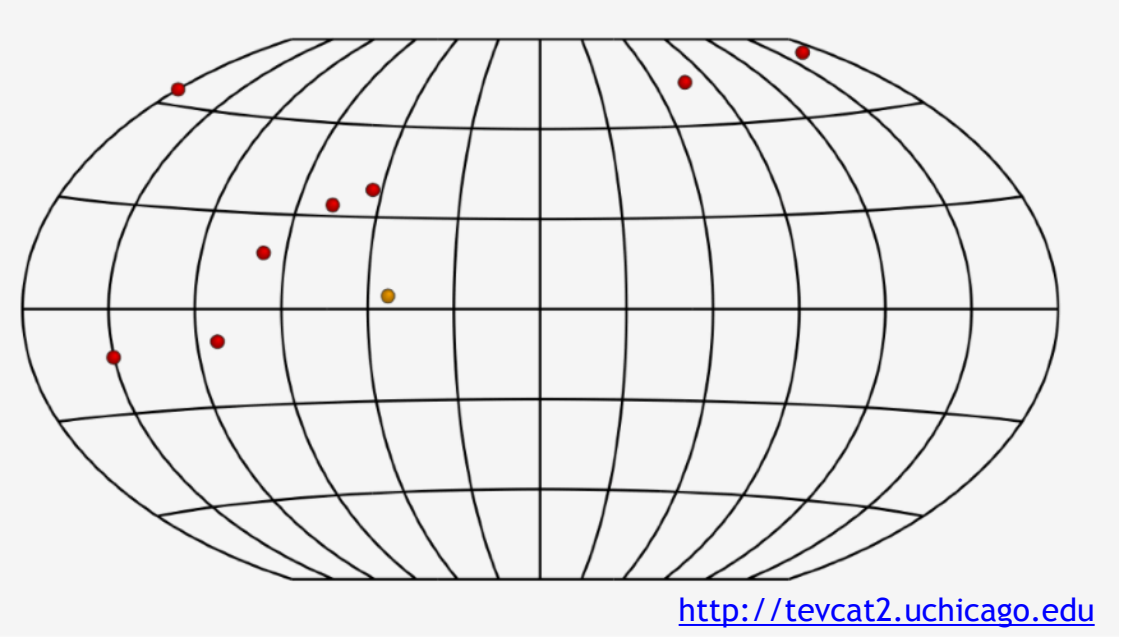








THE Multi-TeV EXTRAGALACTIC SKY



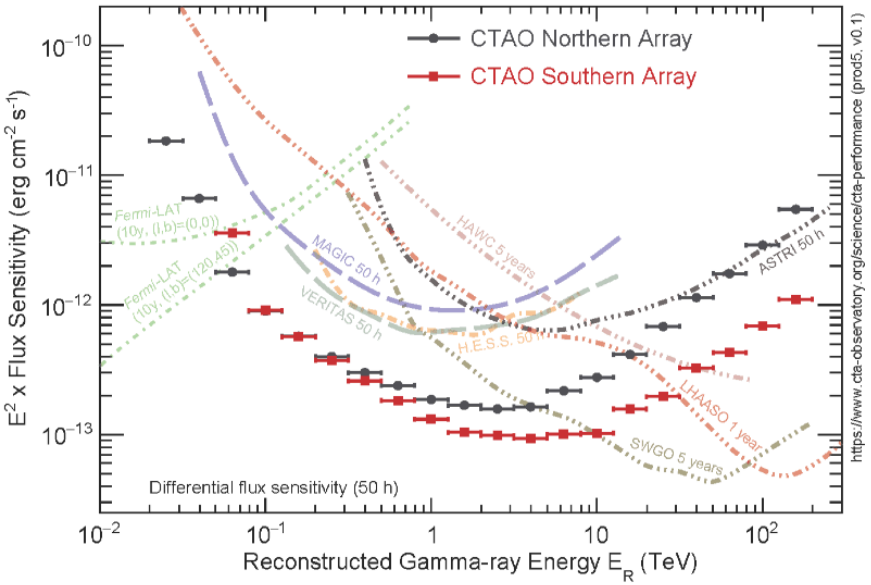
9 extragalactic sources: **1 GRB**

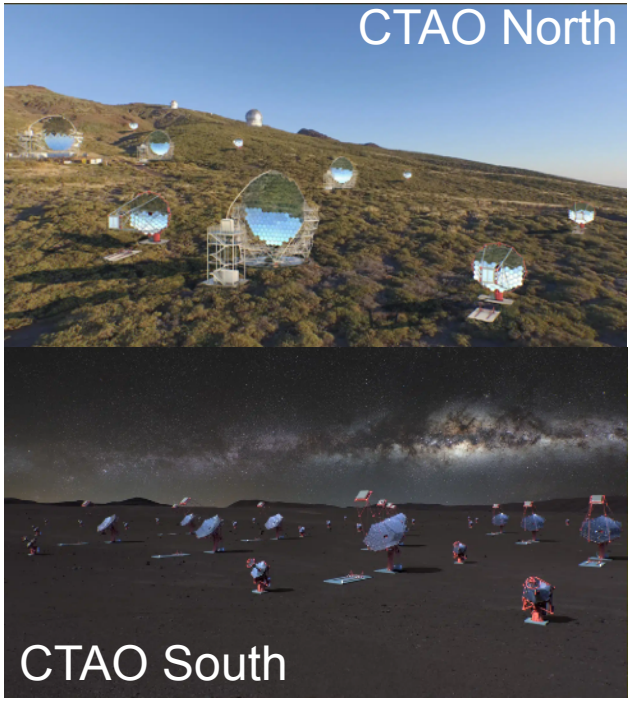
1 low-luminosity AGN

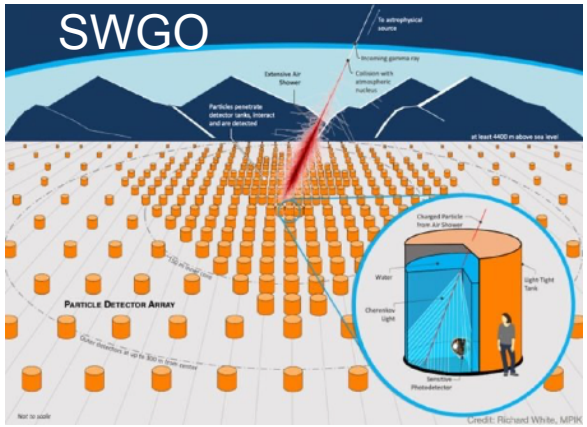
1 radio galaxies

6 blazars

WHAT IS COMING NEXT?



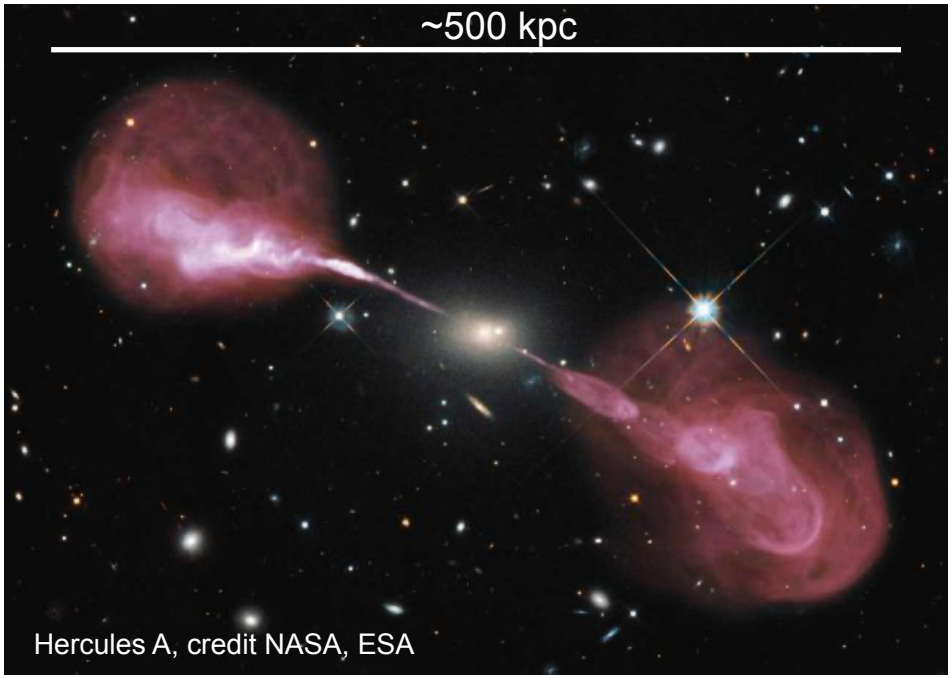


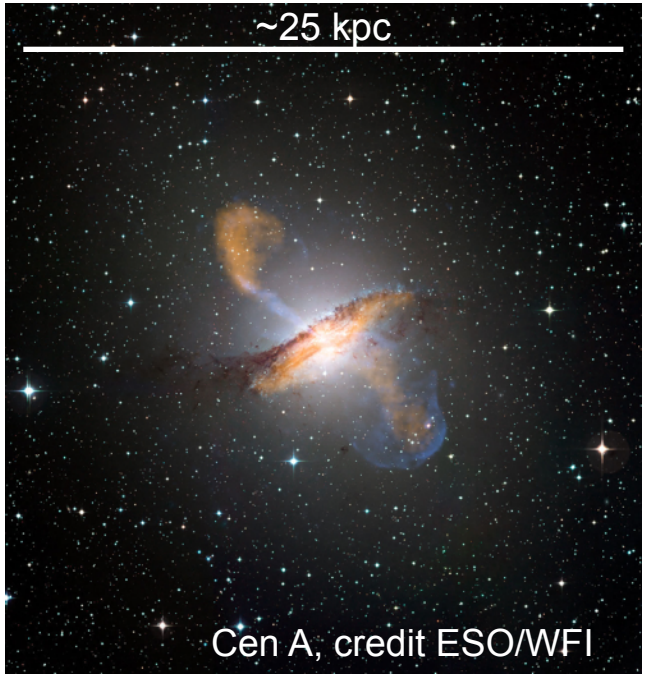


+ Hopefully one of the MeV mission, i.e. COSI (2027)

WHAT ARE JETS?

Collimated outflows seen in different sources and at different scales

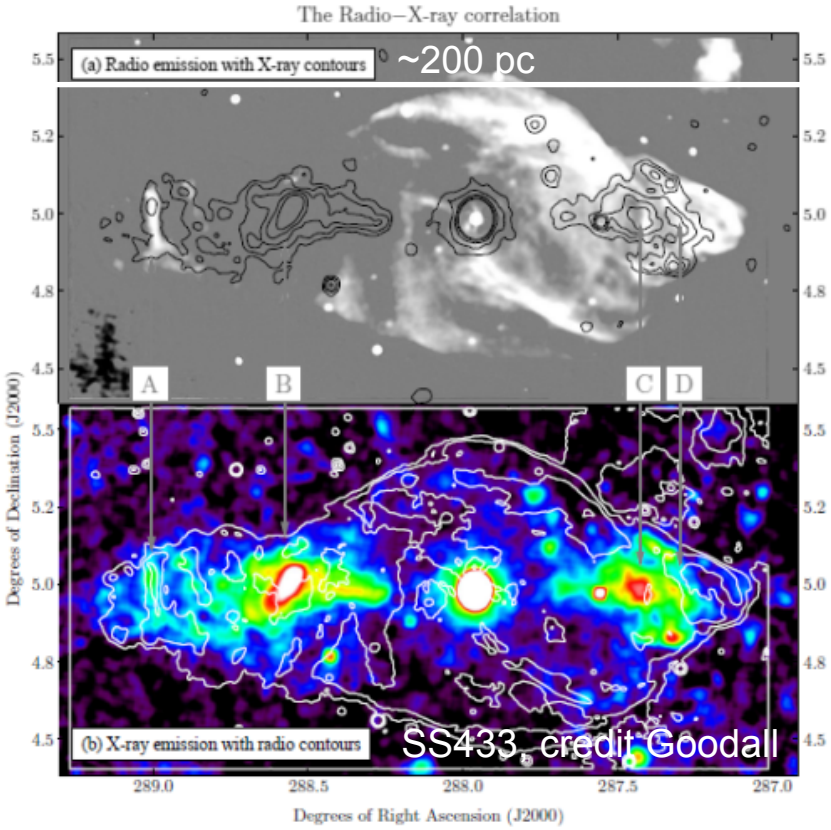


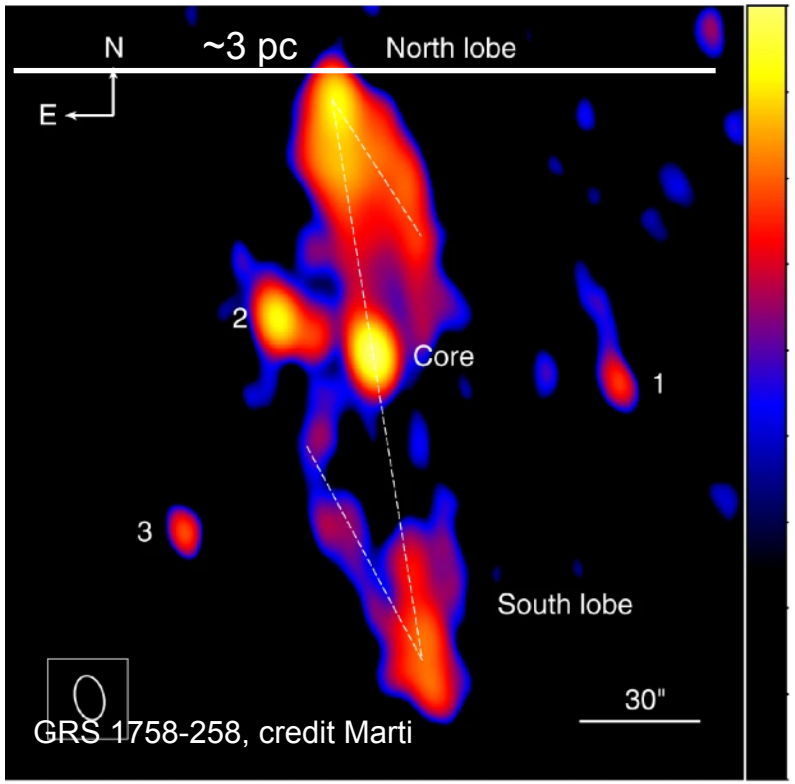


Active Galactic Nuclei

WHAT ARE JETS?

Collimated outflows seen in different sources and at different scales

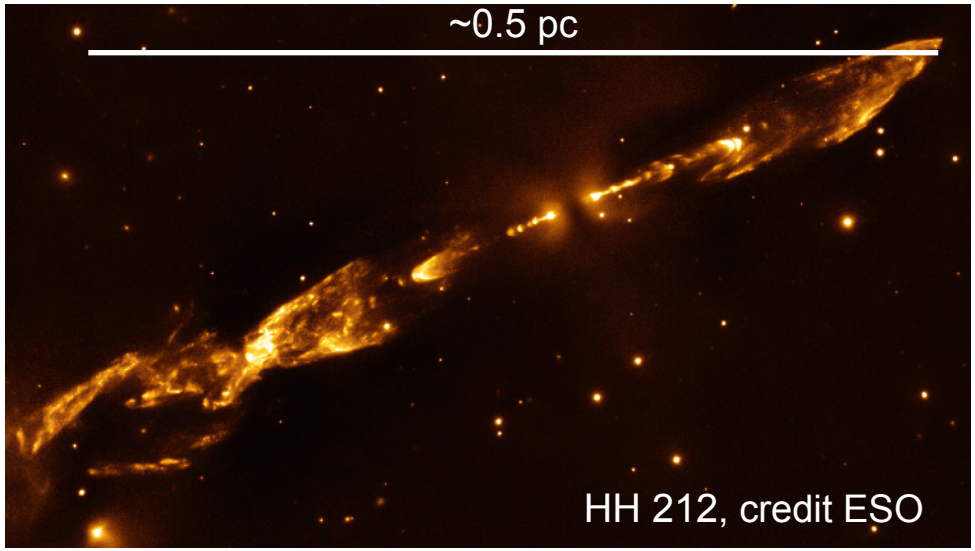


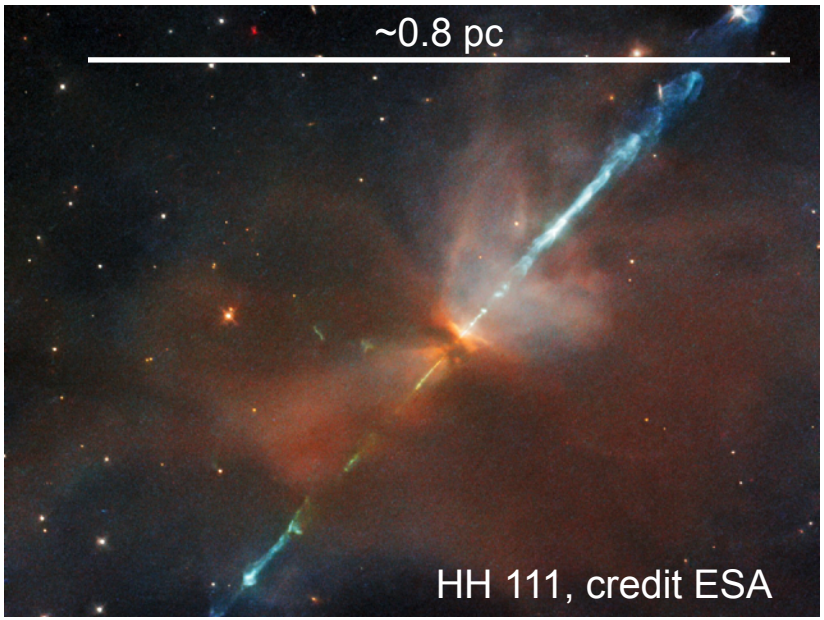


Micro quasars

WHAT ARE JETS?

Collimated outflows seen in different sources and at different scales

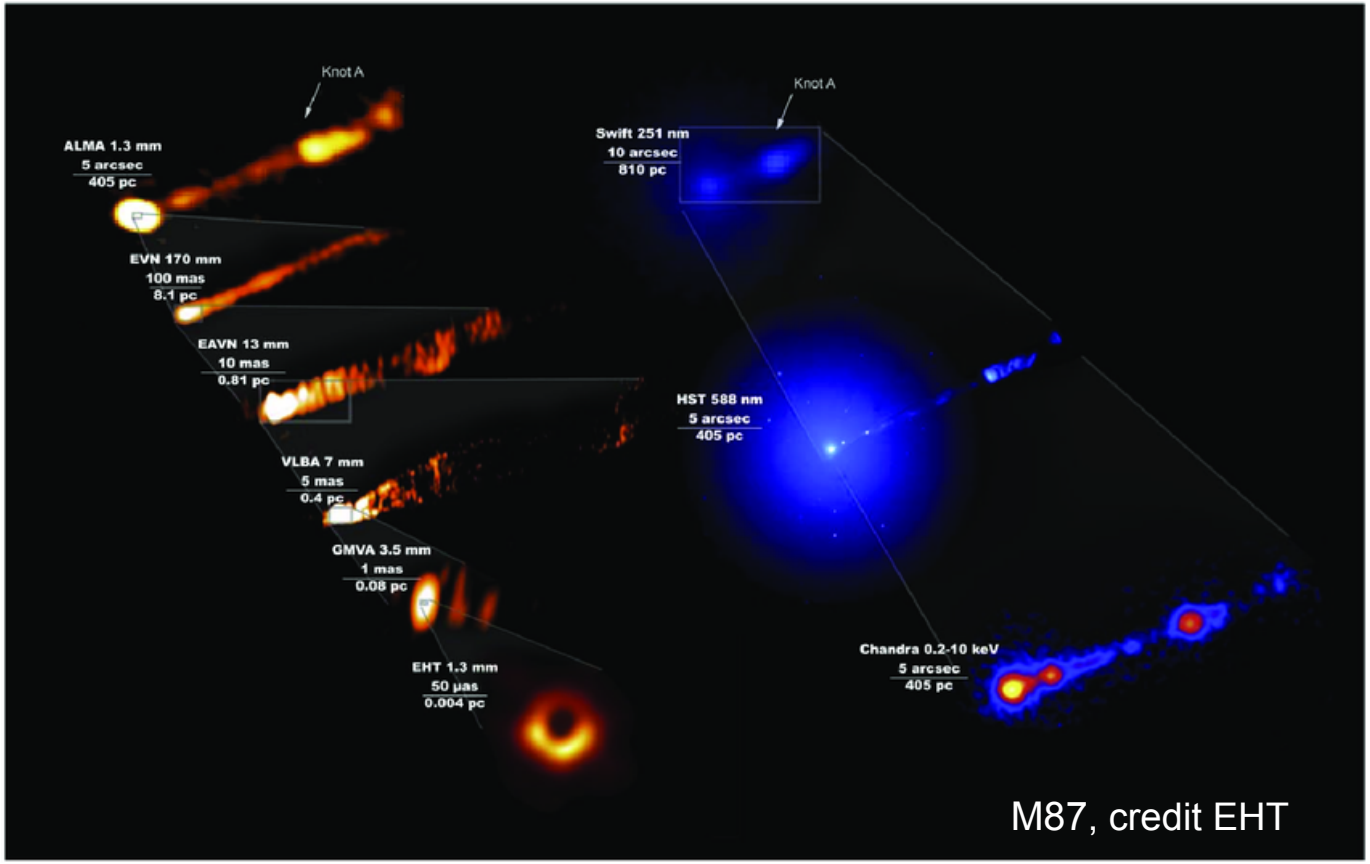




Young stellar objects

HOW DO WE STUDY JETS?

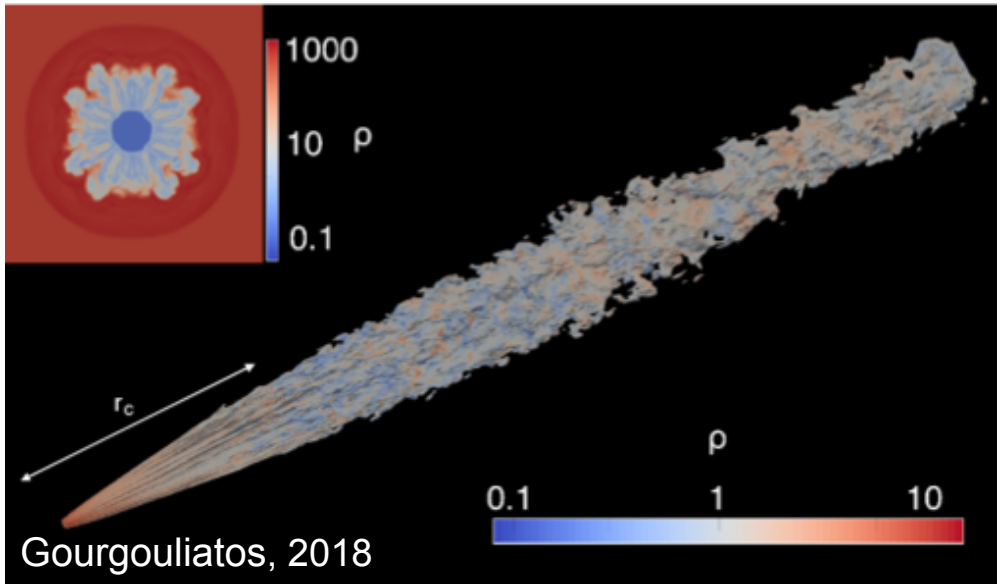
Multi-wavelength observations

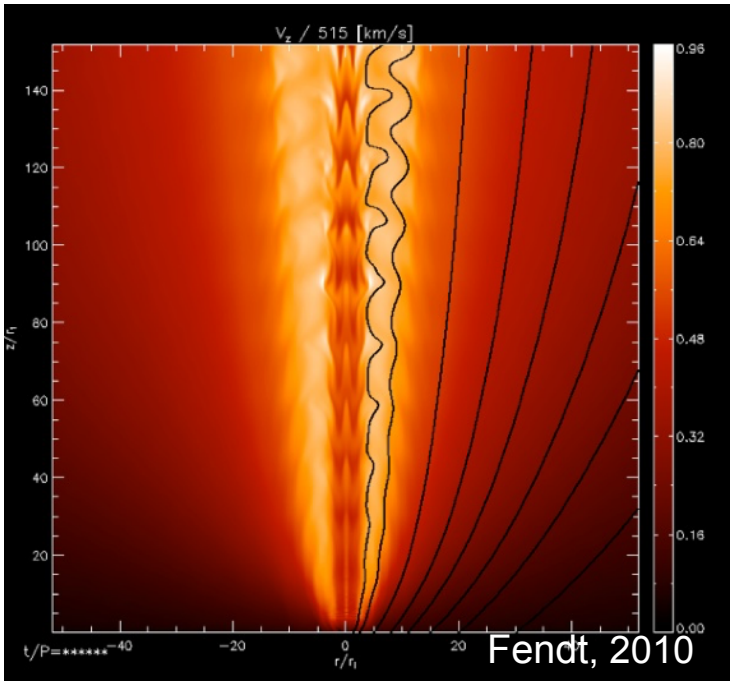


The Jet of M87 in radio, visible, X-ray

HOW DO WE STUDY JETS?

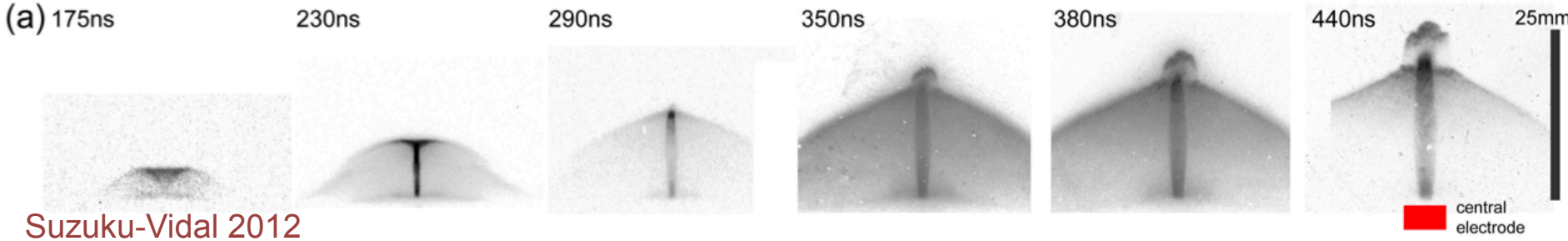
Relativistic Magneto-hydrodinamic (MHD) simulations
(+ GR if you want to study jet launching close to the black hole)



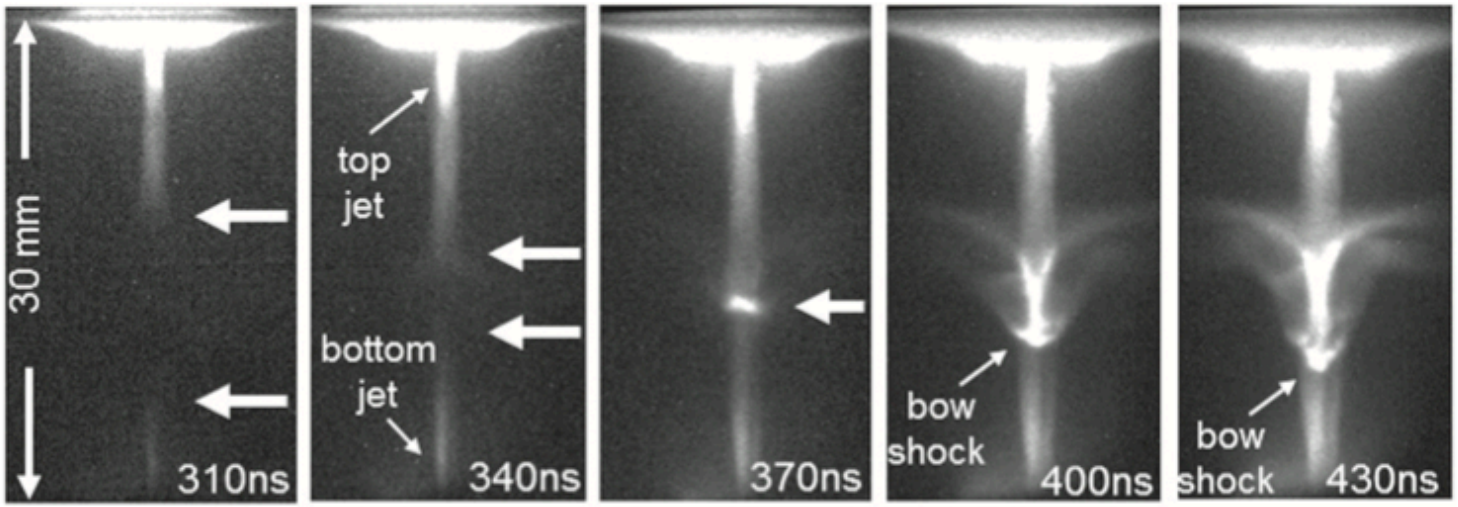


HOW DO WE STUDY JETS?

Laboratory astrophysics



Suzuku-Vidal 2012



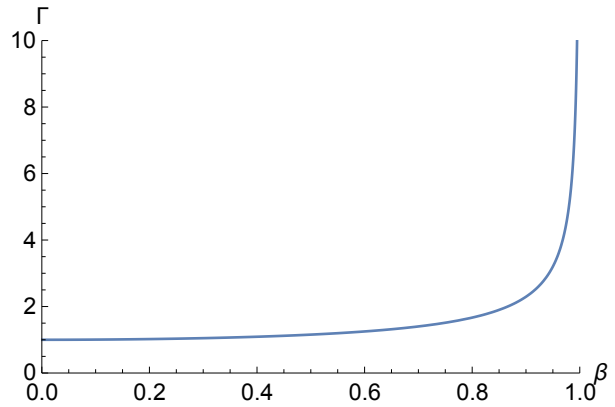
Suzuku-Vidal 2015

DOPPLER BOOSTING

Some reminders from special relativity

If $\beta = \frac{v}{c}$, we can define the Lorentz factor

$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}$$



This is the same factor that enters into the time dilation and length contraction formulae:

$$t = \Gamma t'$$

$$x = \frac{x'}{\Gamma}$$

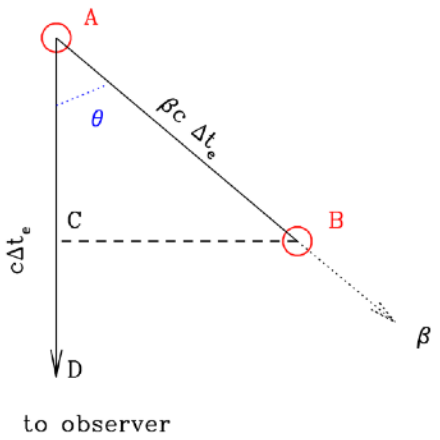
DOPPLER BOOSTING

N.B. The duration of a flare is a bit different

$$\Delta T = \Gamma(1 - \beta \cos\theta)\Delta T' \doteq \frac{\Delta T'}{\delta}$$

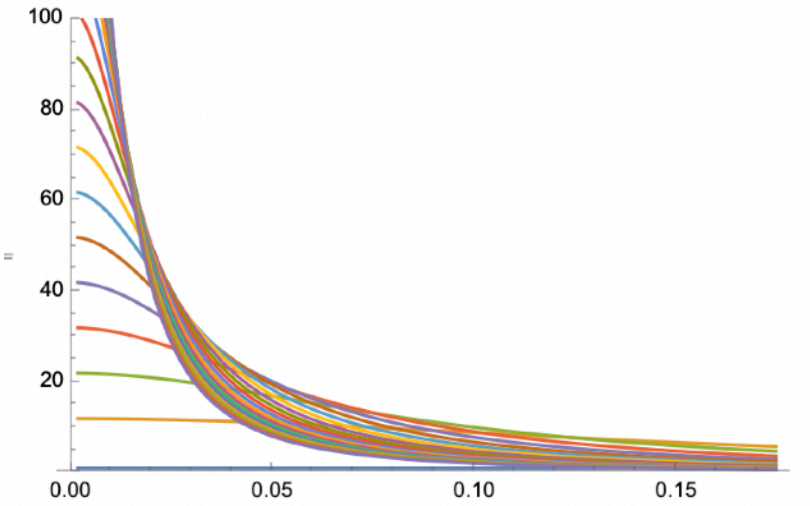
and similarly $\nu = \delta\nu'$

where δ is the Doppler factor



For the flux:

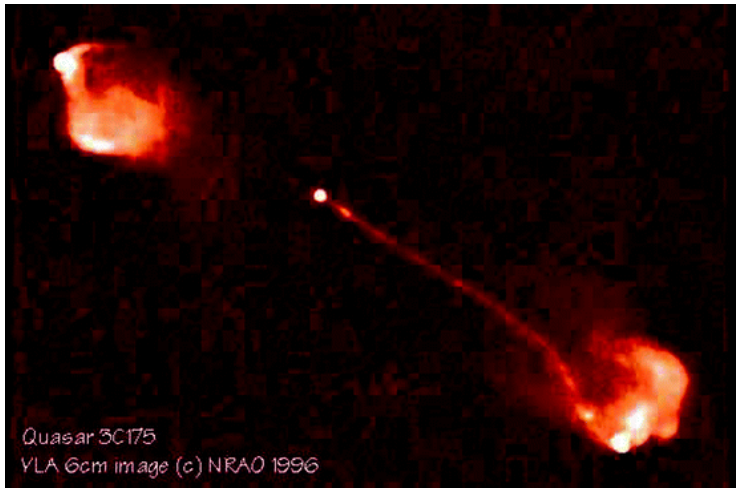
$$F_\nu = \delta^3 F'_{\nu'}$$

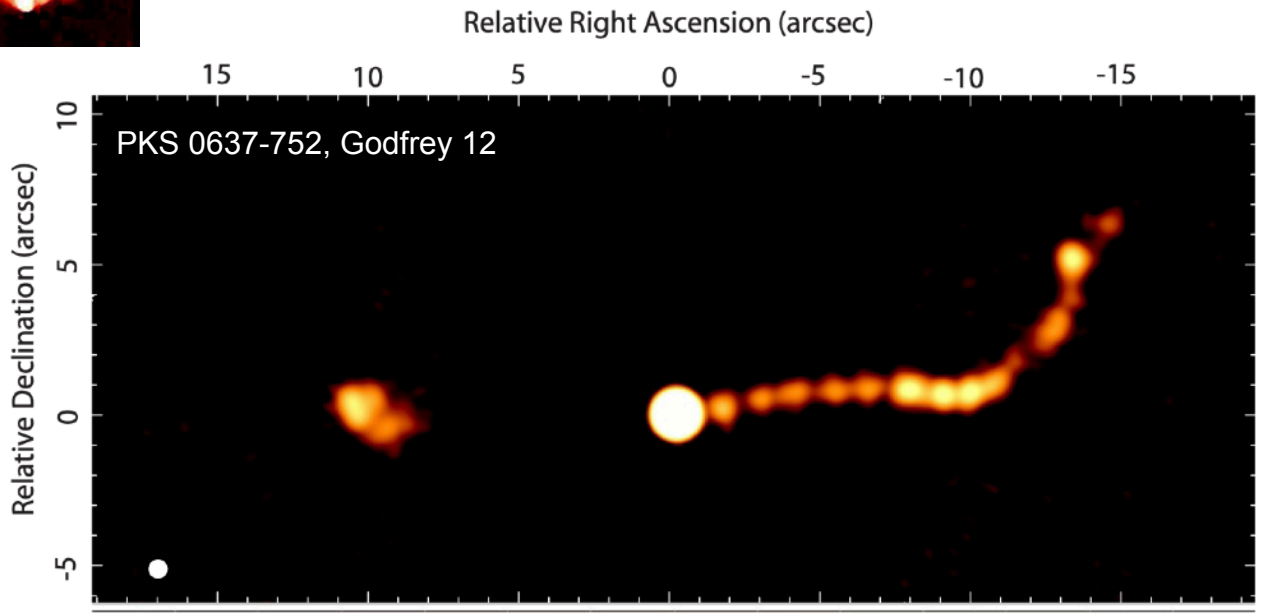


N.B.: This is for a single plasmoid;
If extended region, it goes as δ^2

JET / COUNTER-JET

Observations





JET / COUNTER-JET

For a receding jet:

$$\delta = \frac{1}{\Gamma(1 + \beta \cos\theta)}$$

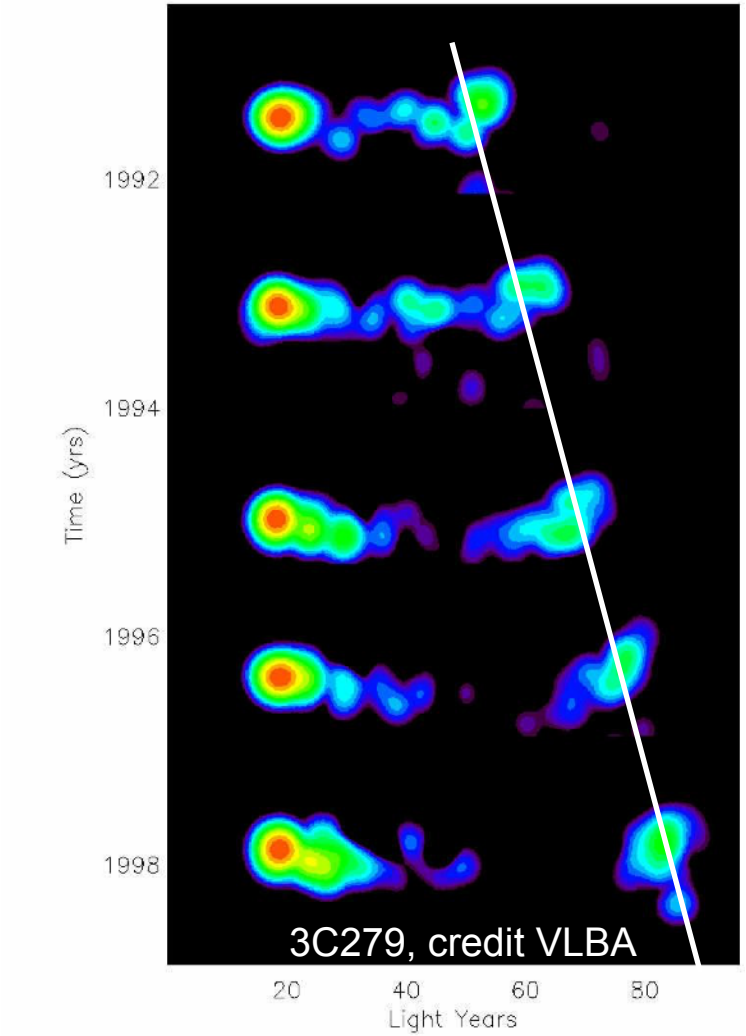
And so the flux ratio is $\frac{F_{jet}}{F_{counter-jet}} = \left(\frac{1 + \beta\cos\theta}{1 - \beta\cos\theta}\right)^3$

Exemple: if we measure a flux ratio of 1000,
Assuming $\Gamma = 10 \rightarrow \beta = 0.995$

We get $\theta = 35°$

SUPERLUMINAL MOTION

Observations



The right knot has a projected displacement of 25 light years during 1991-1998!

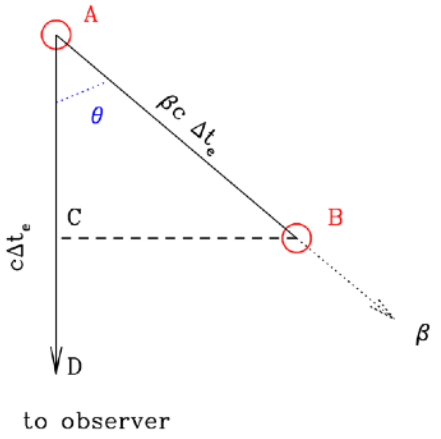
SUPERLUMINAL MOTION

In frame K:

$$AB = \beta c \Delta T$$

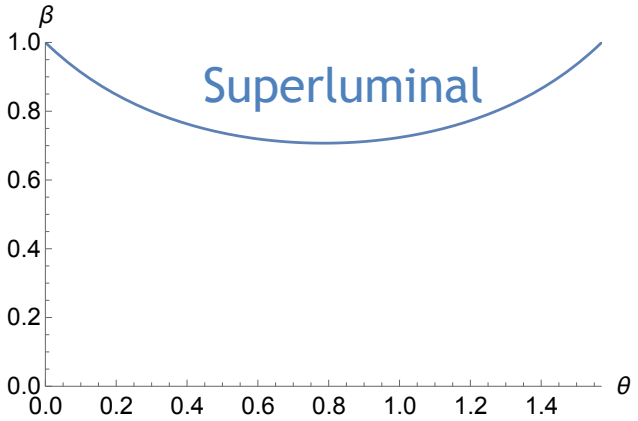
In B the knot moved towards us by $\beta c \Delta T \cos\theta$.

The time needed for the signal to reach us is $\Delta T - \beta c \Delta T \cos\theta / c = \Delta T - \beta \Delta T \cos\theta$



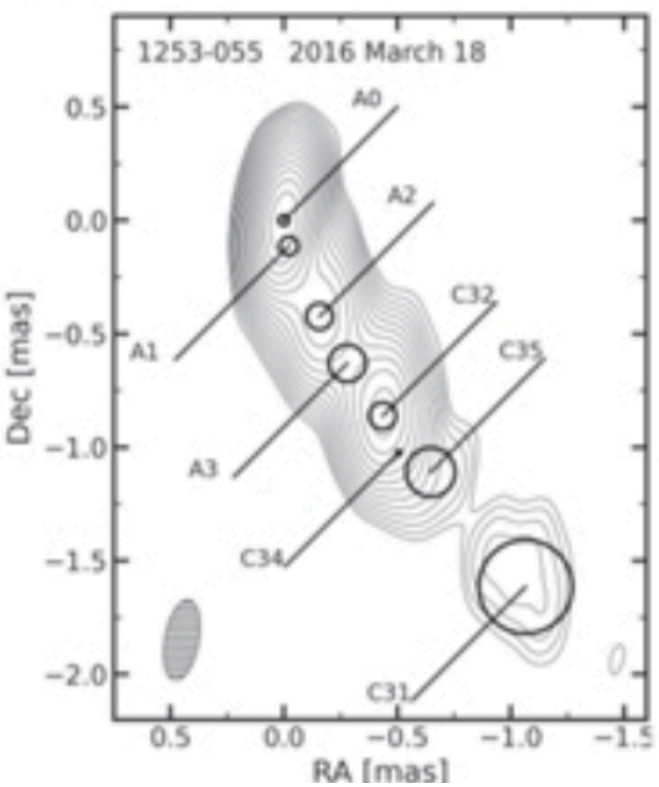
The inferred velocity of the *projected* component is $\dfrac{\beta c \Delta T \sin\theta}{\Delta T - \beta \Delta T \cos\theta}$

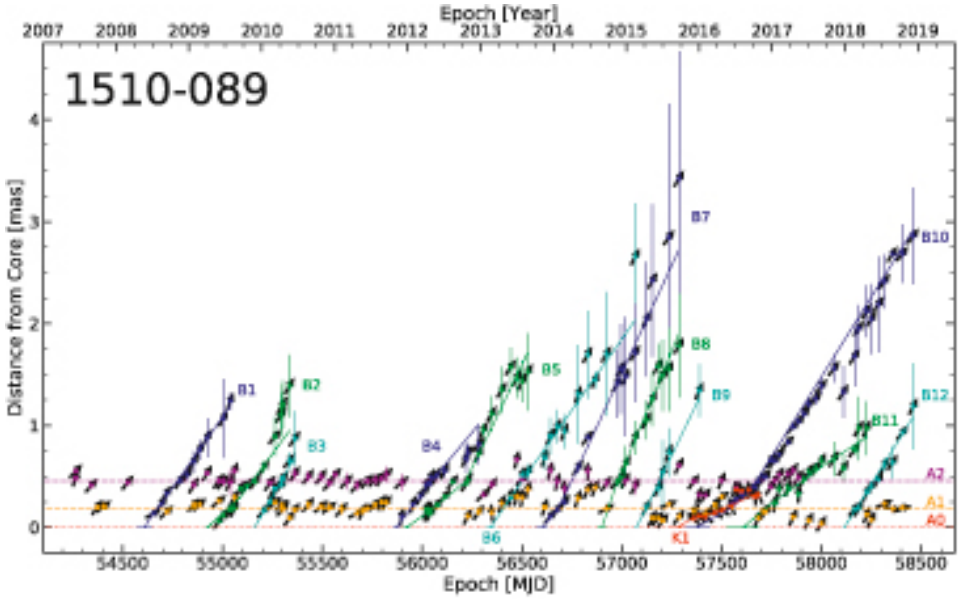
This can be > c if $\beta > \dfrac{1}{\sin\theta + cos\theta}$



KNOTS

Monitoring of features over several years
Moving vs standing knots

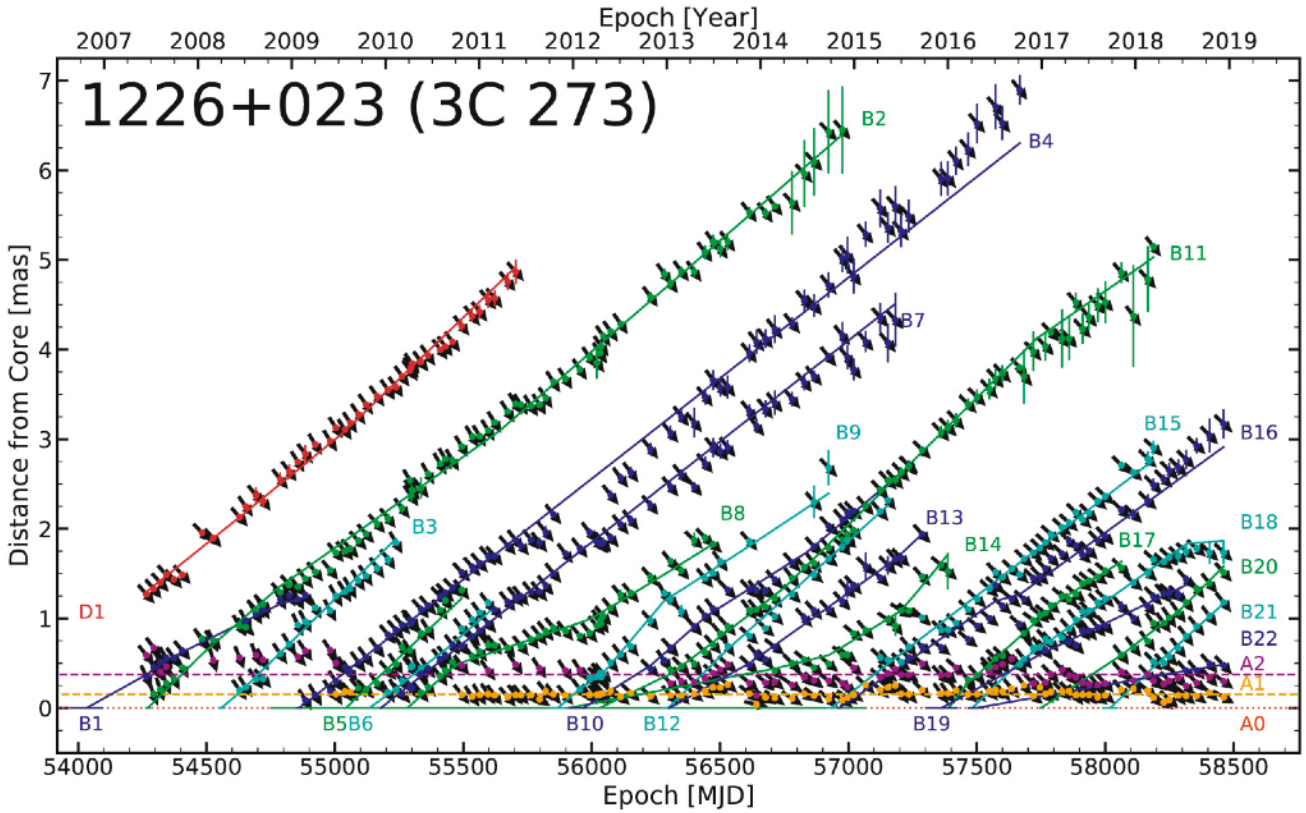




Weaver 22

KNOTS

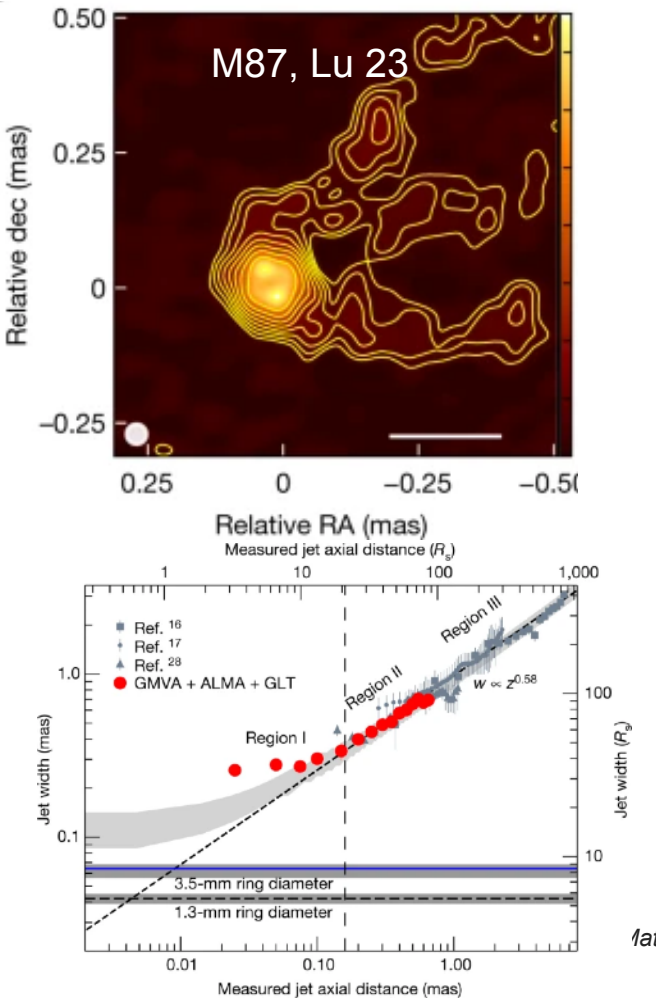
New ejections and trailing knots

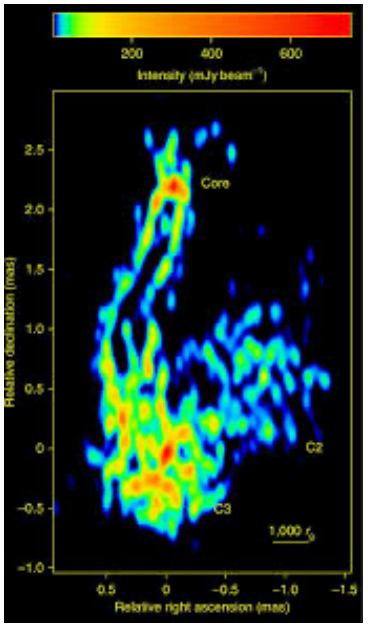


Weaver 22

JET PROFILE AND COLLIMATION

What is the jet shape? Far away it looks conical or even cylindrical
Close to the black hole we see parabolic to conical transition

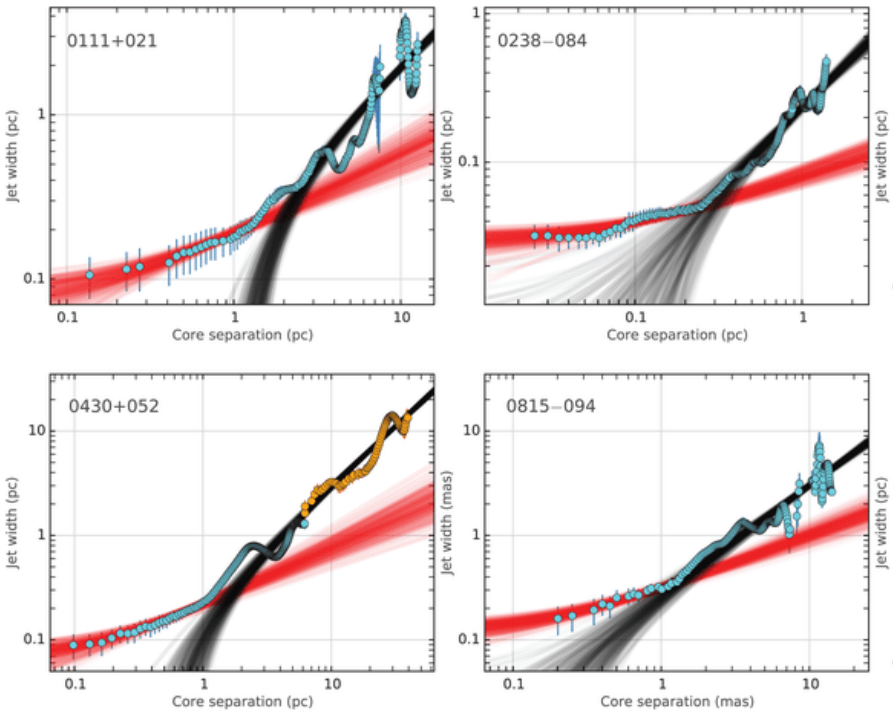




3C84, Giovannini 18

JET PROFILE AND COLLIMATION

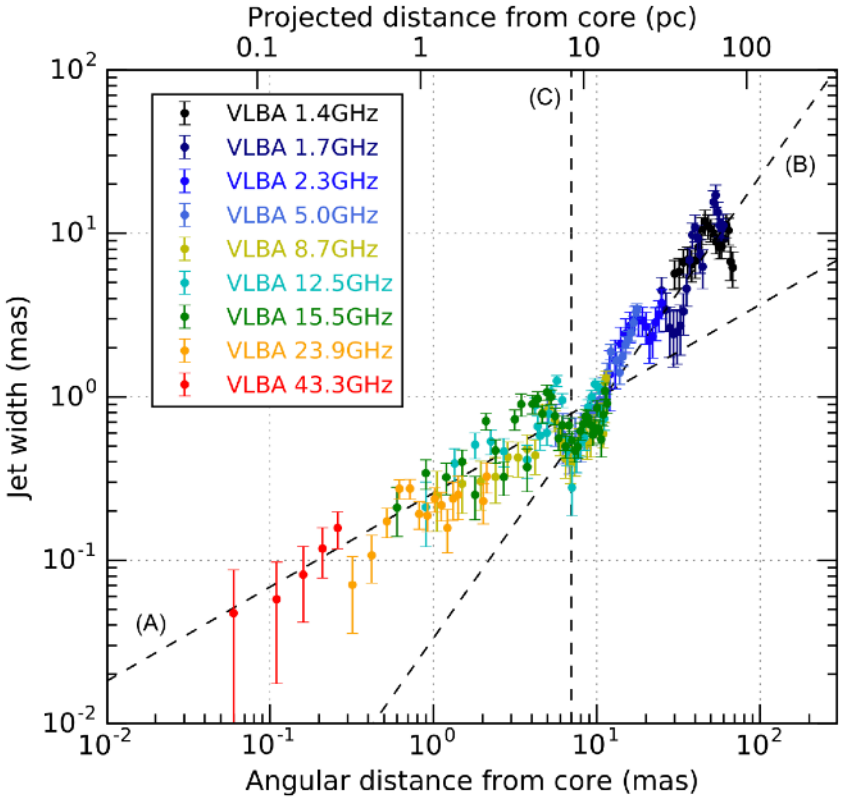
What is the jet shape? Far away it looks cylindrical
Close to the black hole we see conical and parabolic sections

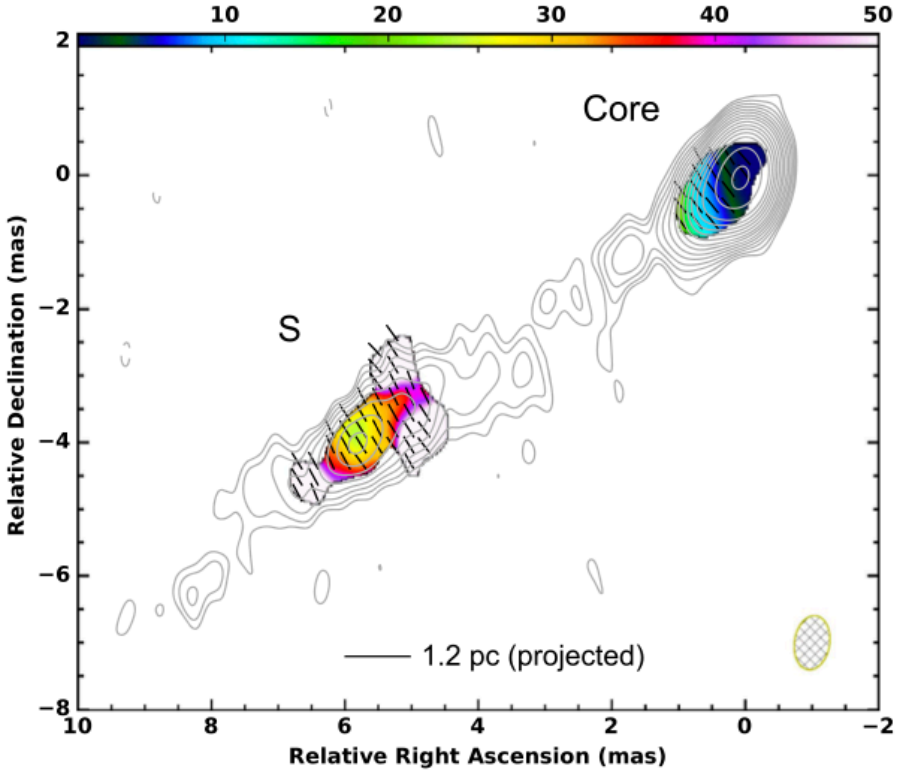


Kovalev 20

RECOLLIMATION SHOCKS

Are stationary features recollimation?

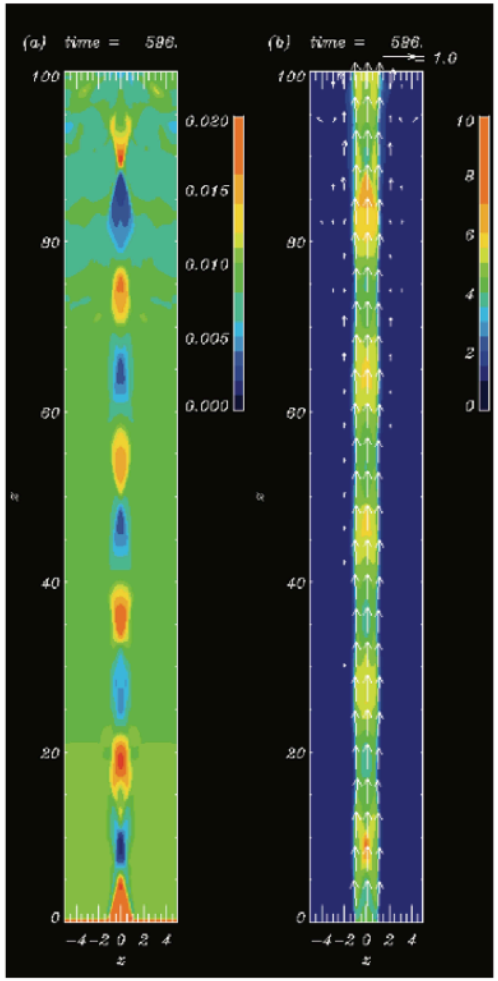




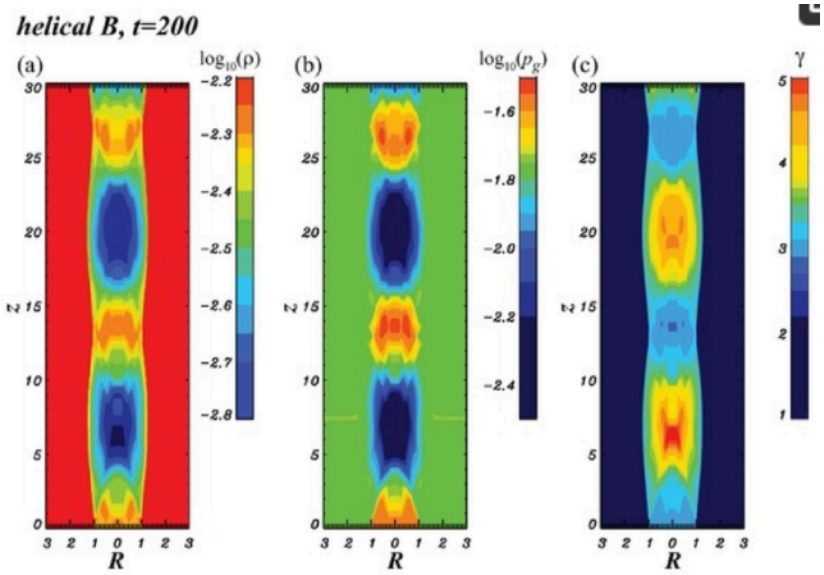
1H 0323+342, Nada 18

RECOLLIMATION SHOCKS

Simulations



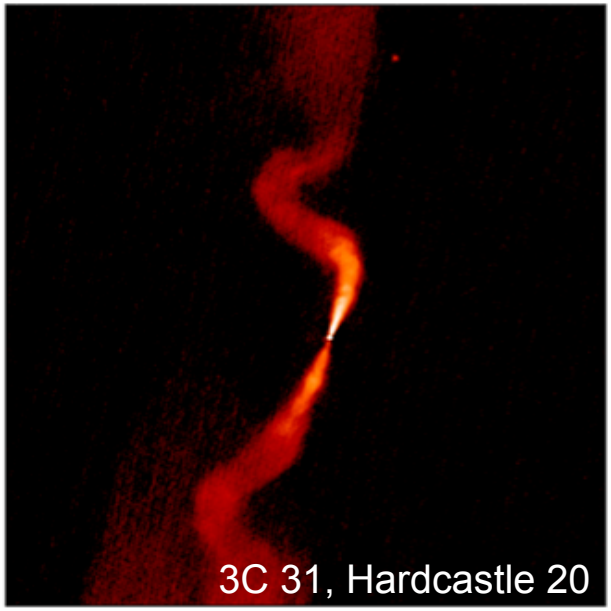
Nishikawa 13

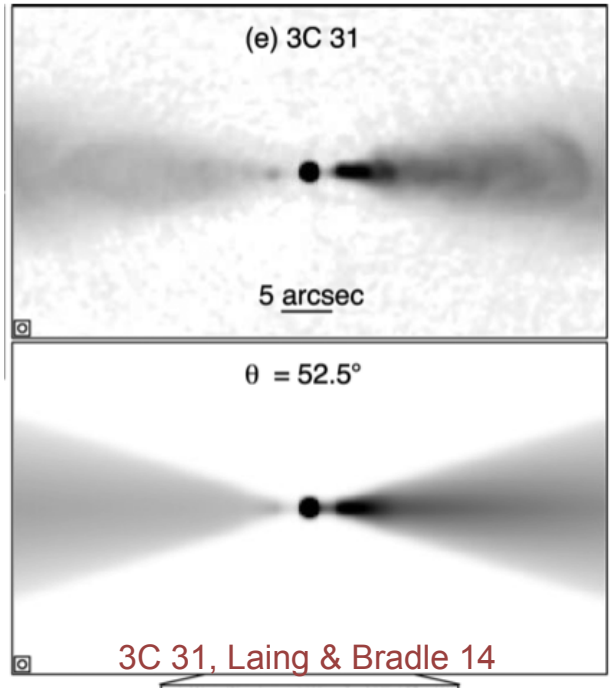


Mizuno 15

DECELERATION

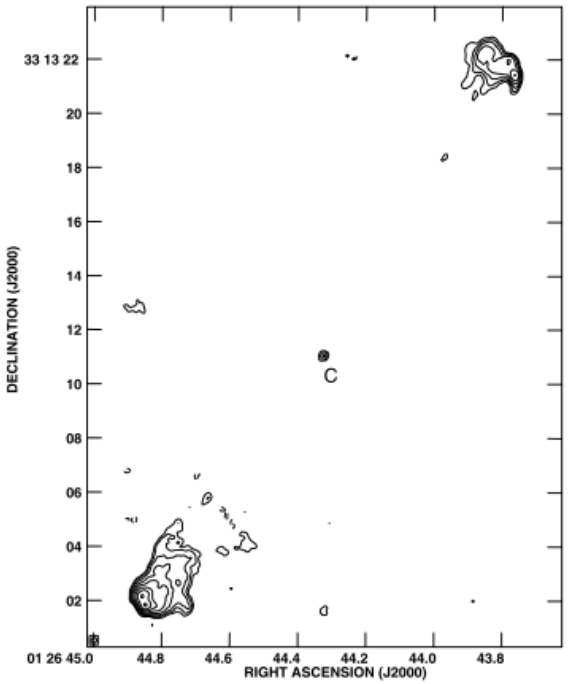
How does the jet end?
- Deceleration and disruption



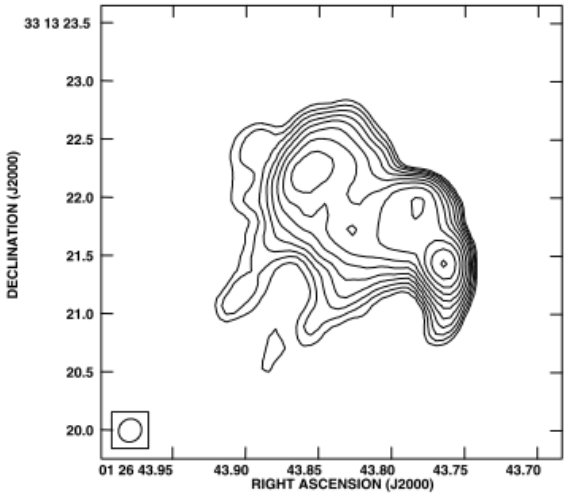


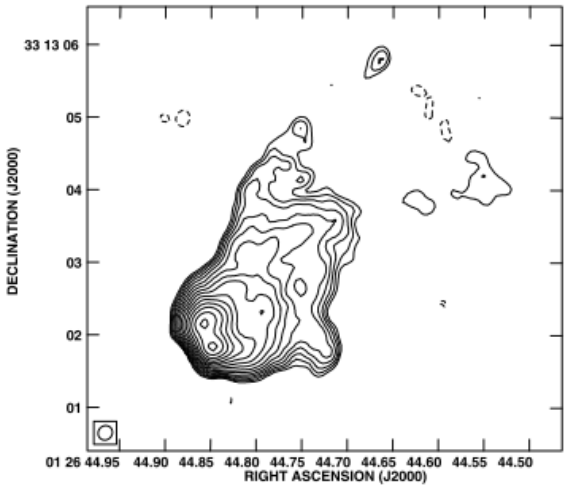
TERMINATION SHOCKS

How does the jet end?
- Termination shock



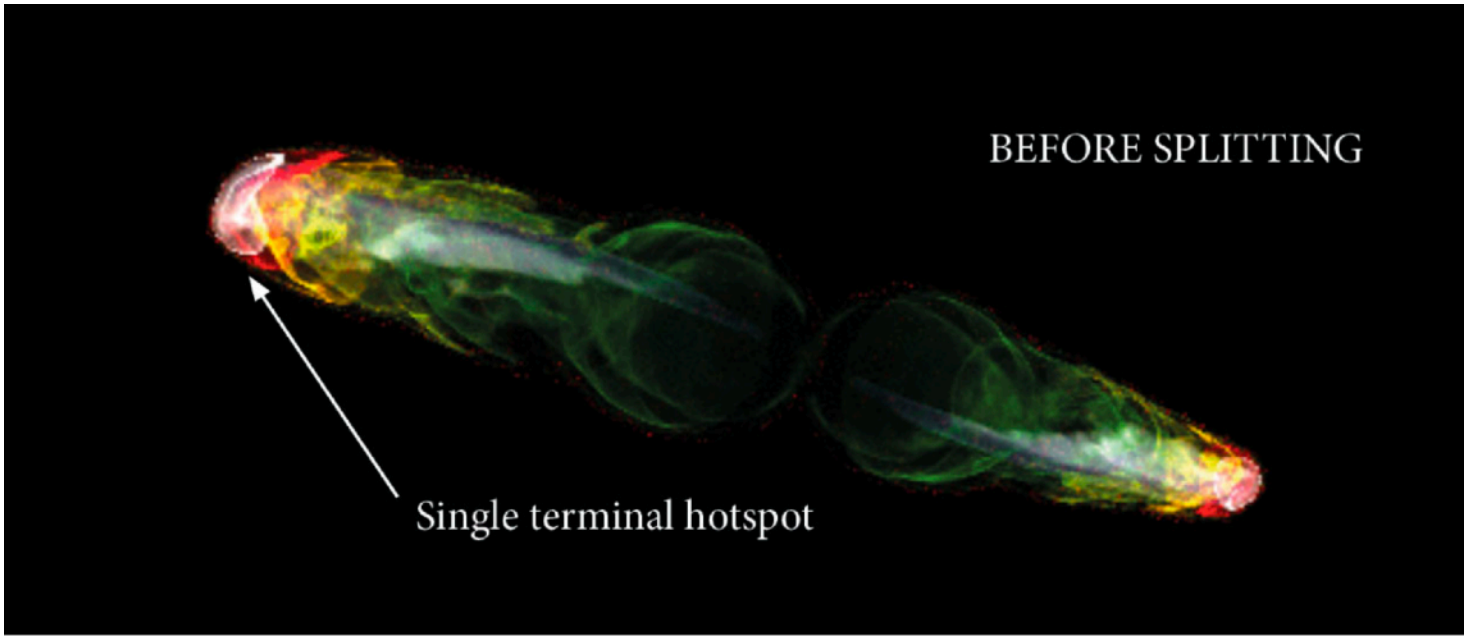
3C 41, Kharb 08





TERMINATION SHOCKS

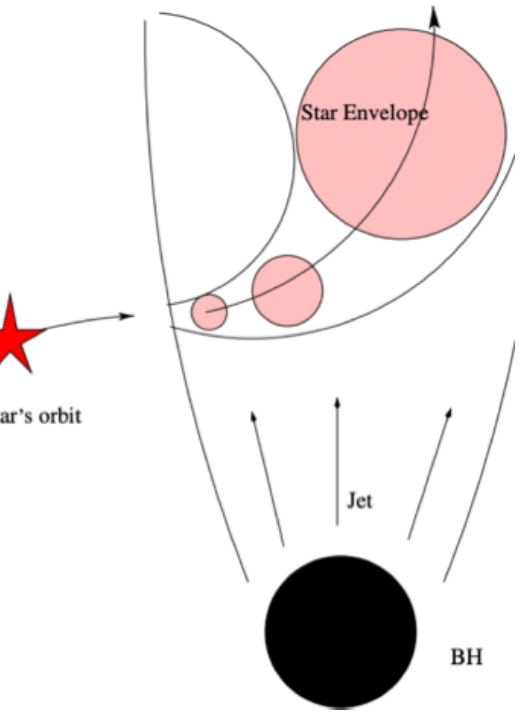
How does the jet end?
- Termination shock



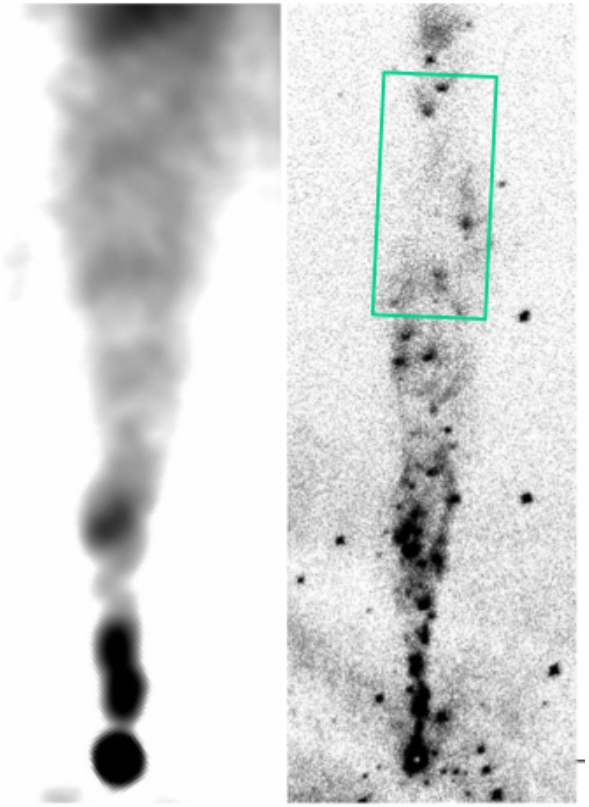
Horton 23

JET and OBSTACLES

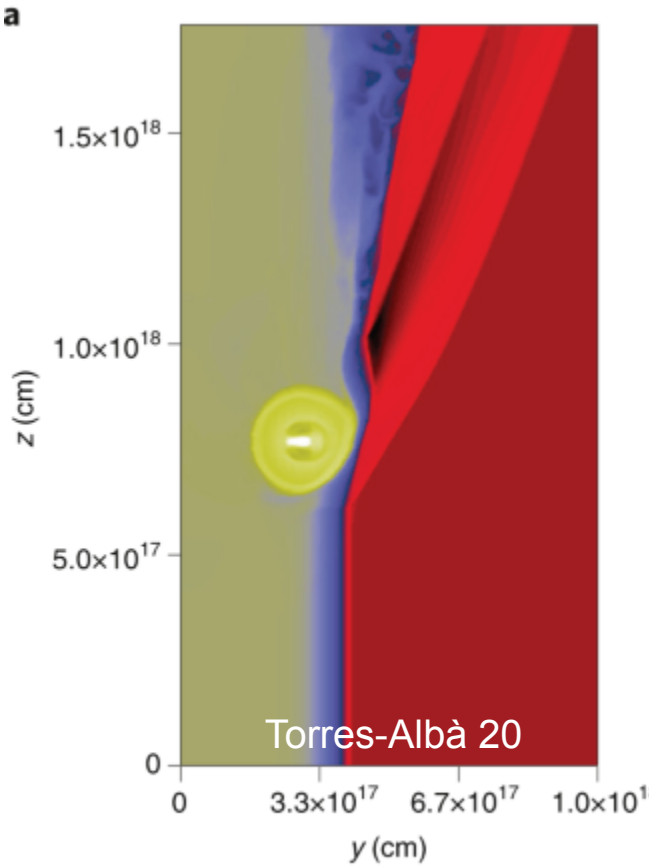
The jet interacts with its environment
It *has to* collide with clouds and stars in the galaxy



Barkov 12

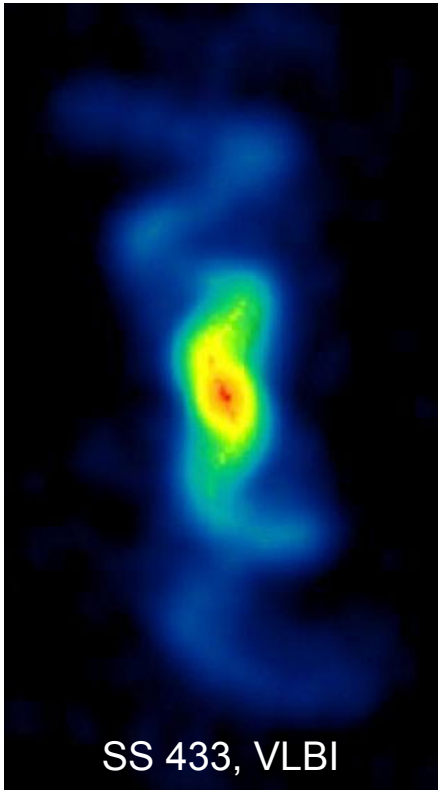


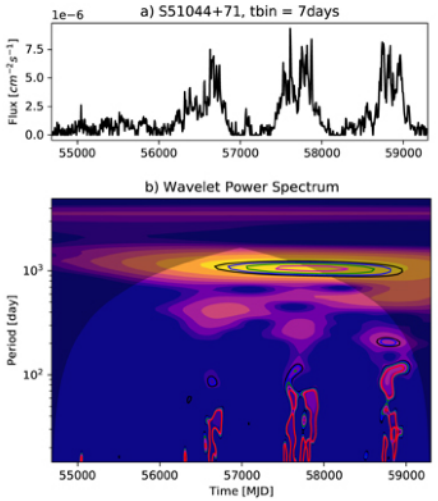
Cen A, Wykes 15



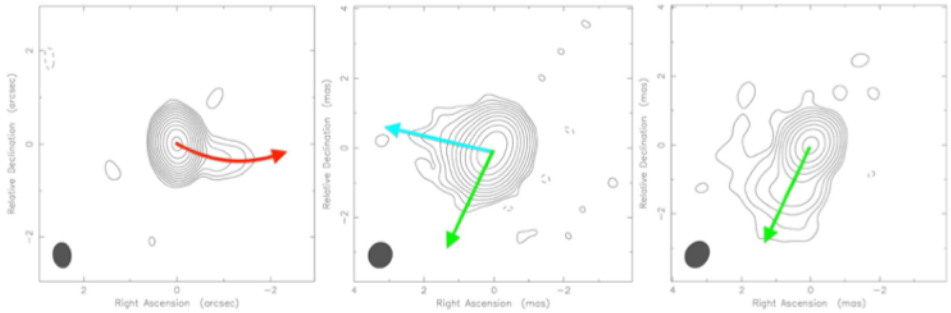
PRECESSION

Observational evidences
Simulations





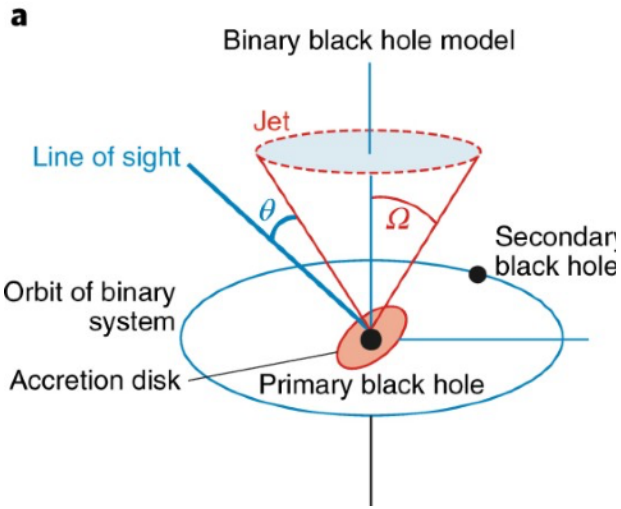
Ren 23



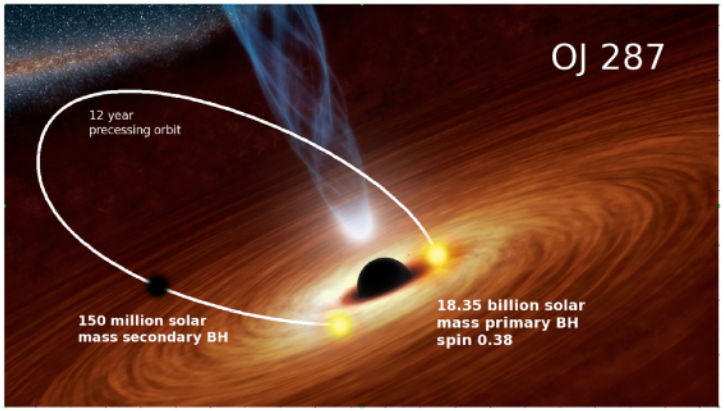
S5 1044+719, Kun 23

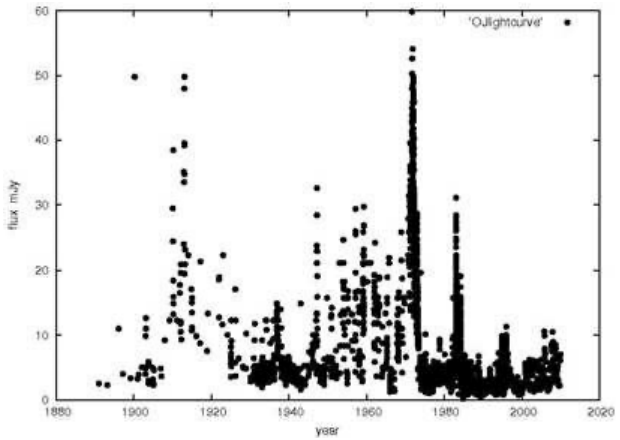
PRECESSION

OJ 287 & binaries



Abraham 18





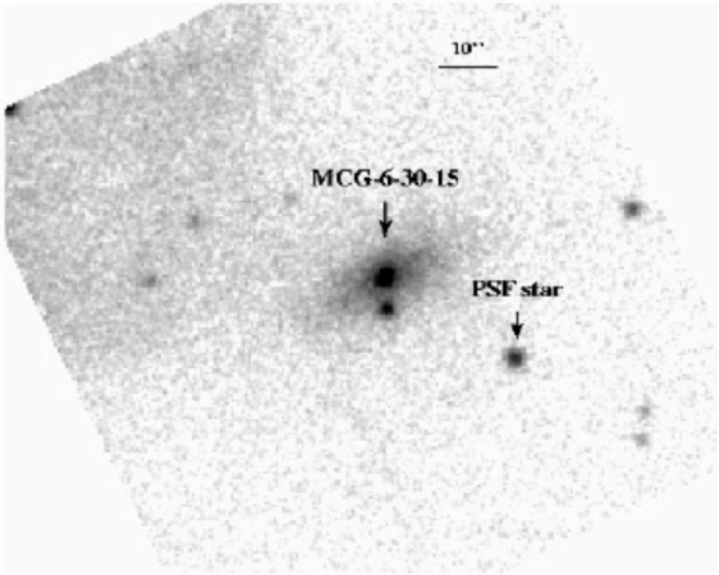
Valtonen 11

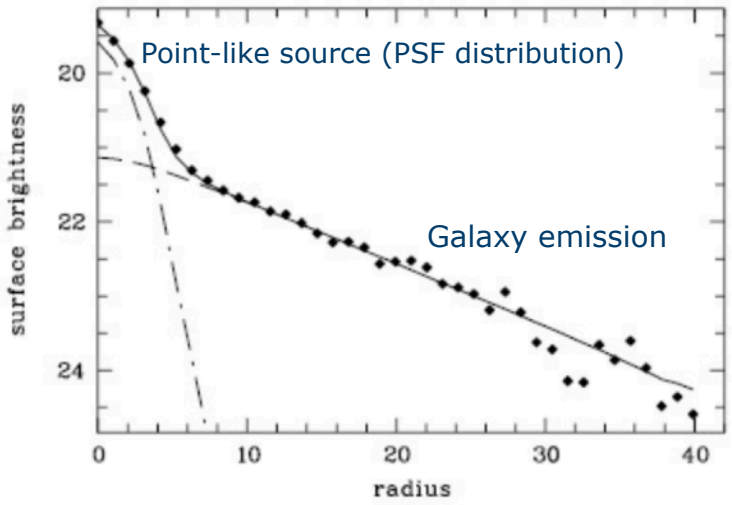
ACTIVE GALACTIC NUCLEI

ACTIVE GALACTIC NUCLEI

Point-like source of photons in galaxy center

The brightest ones can outshine the galaxy itself (=quasar)

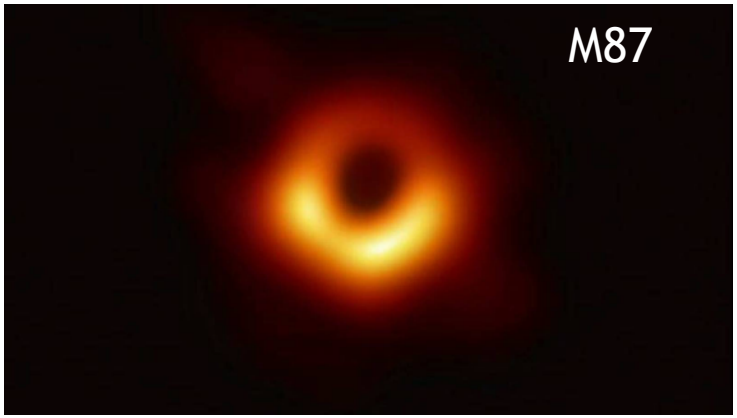




Arevalo et al. 2005

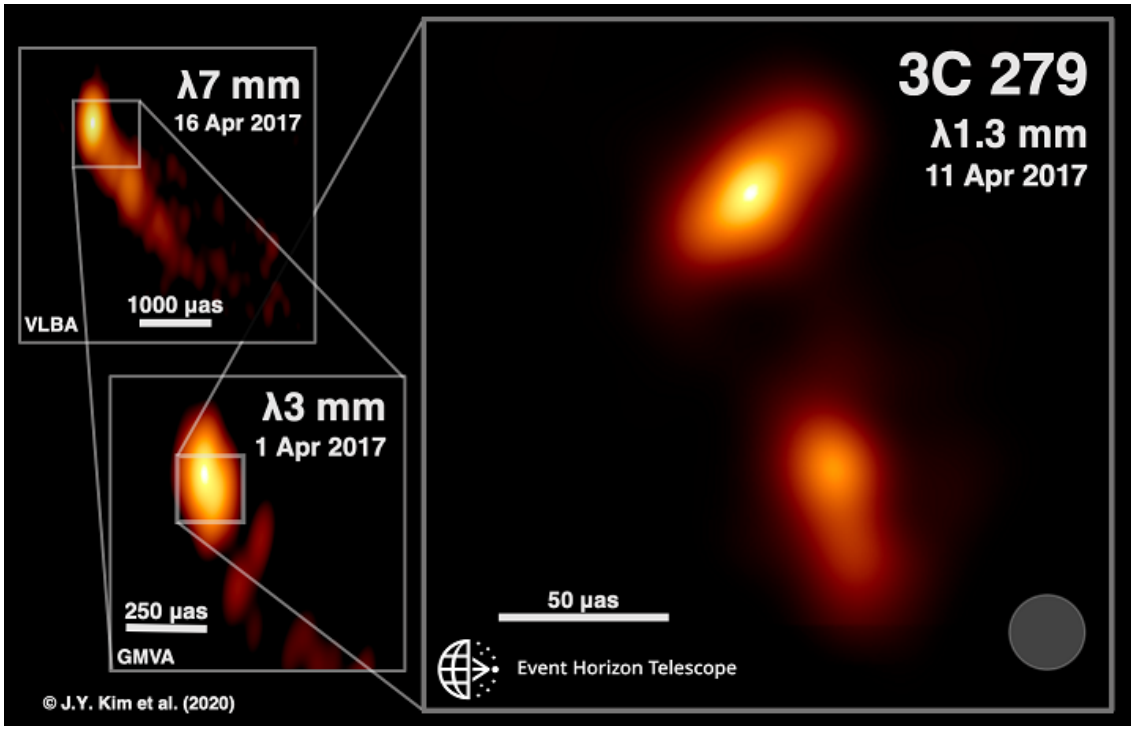
ACTIVE GALACTIC NUCLEI

Current understanding
effect of accretion of matter onto a super-massive black hole



Event Horizon Telescope 2019

First image of a black-hole shadow

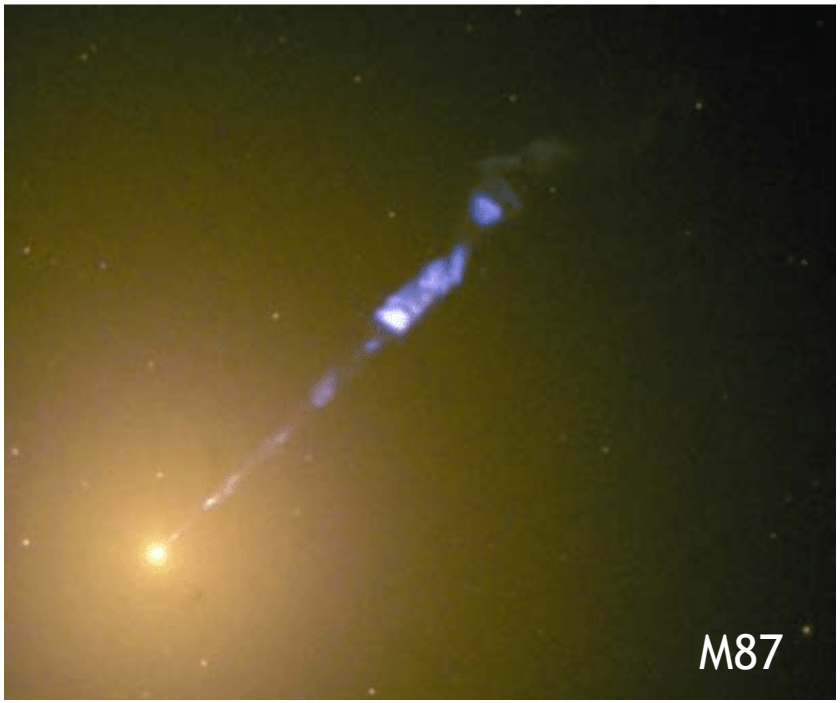


Event Horizon Telescope 2020

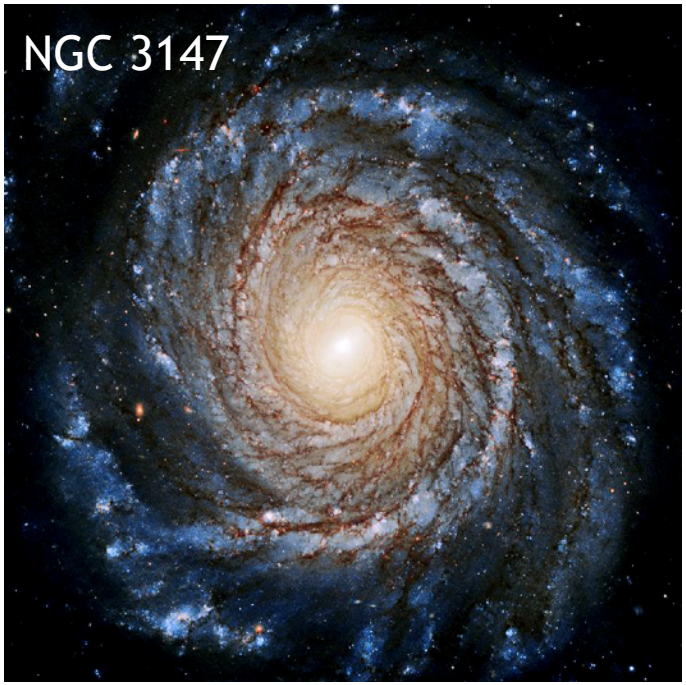
Jet launching

ACTIVE GALACTIC NUCLEI

Radio-loud / radio-quiet dichotomy



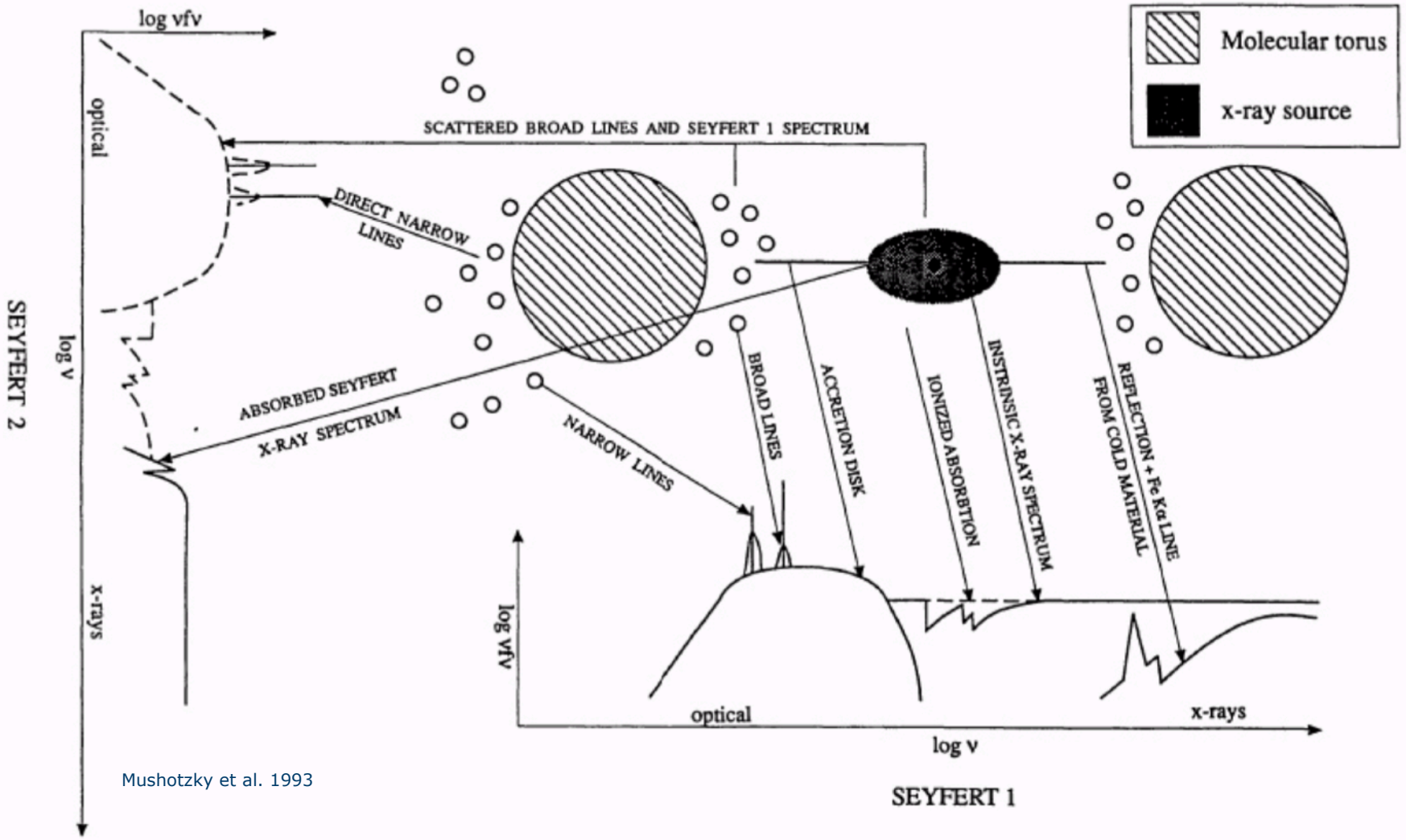
Radio-galaxy
with its relativistic jet



Seyfert galaxy

ACTIVE GALACTIC NUCLEI

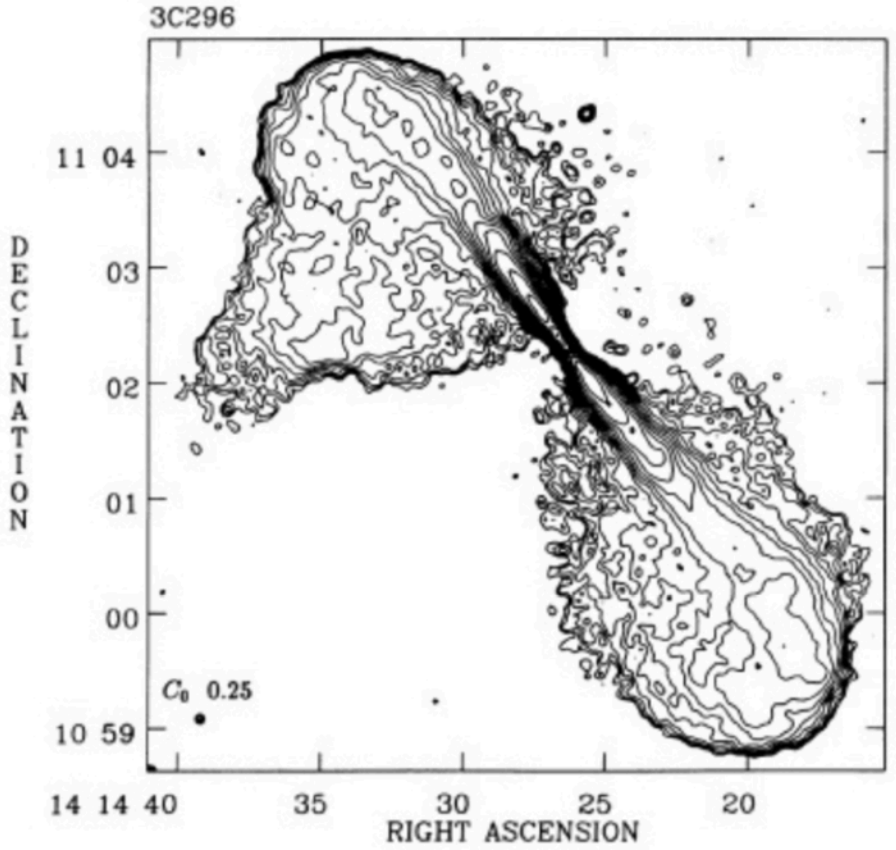
Broad-band emission from Seyfert galaxies

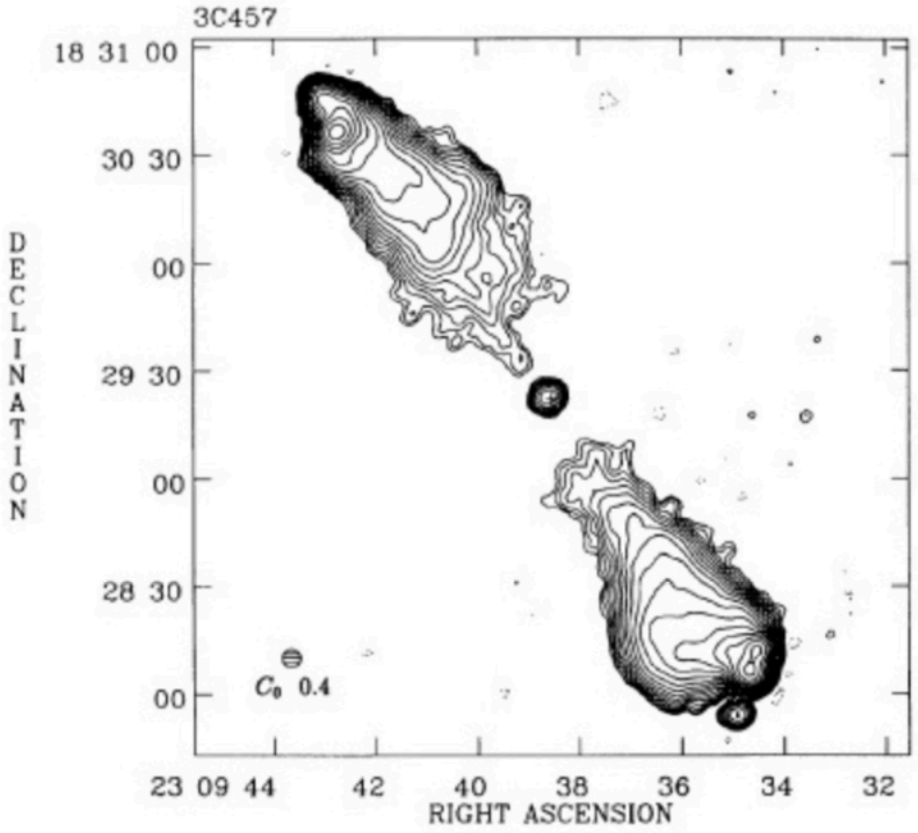


Mushotzky et al. 1993

ACTIVE GALACTIC NUCLEI

Radio-loud dichotomv: Fanaroff-Rilev I and FRII

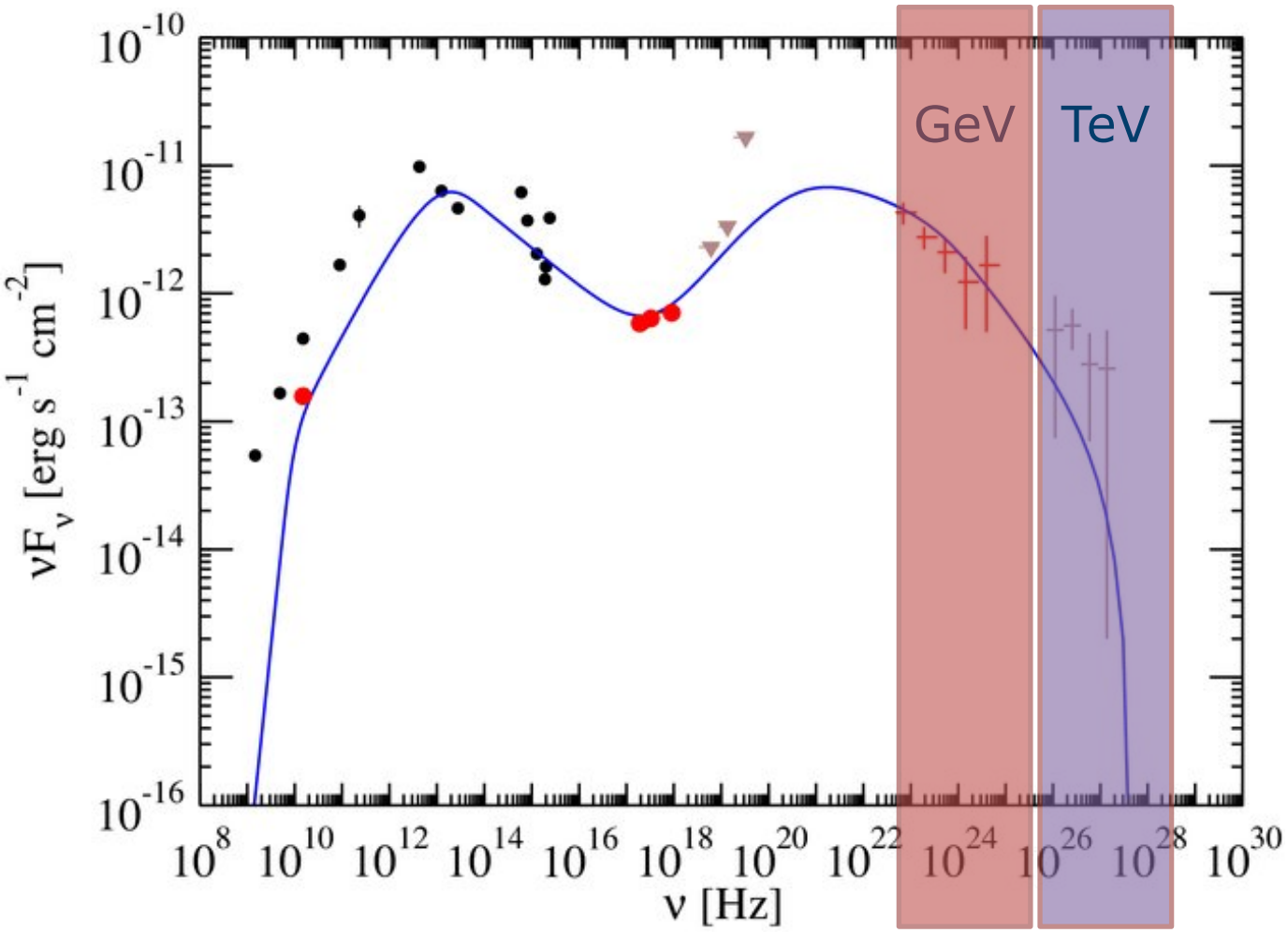




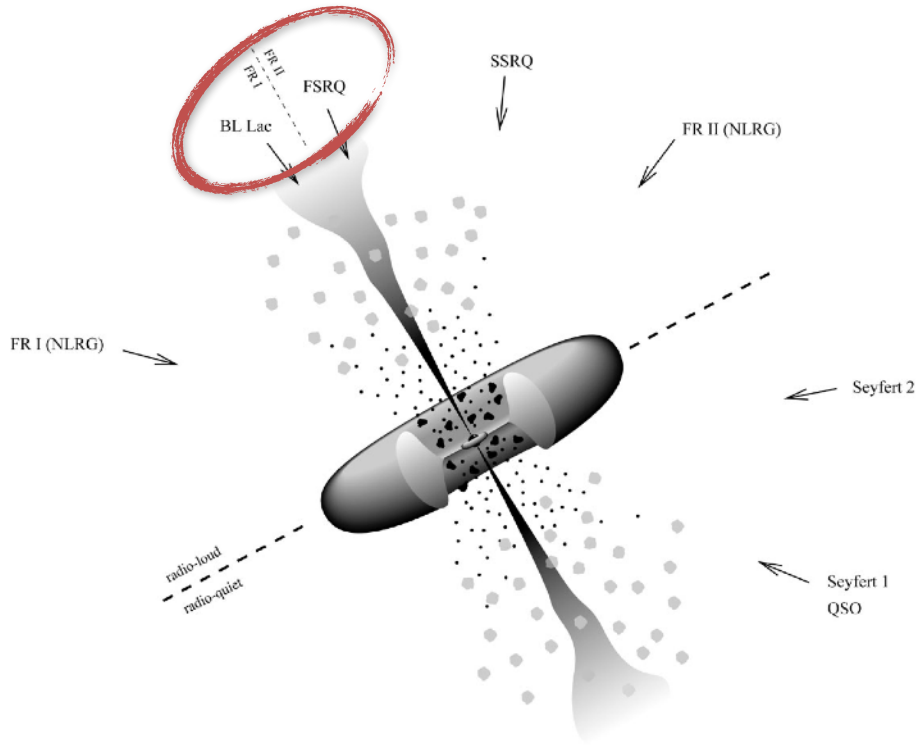
Leahy & Perley 1991

ACTIVE GALACTIC NUCLEI

Radio-galaxies SED



ACTIVE GALACTIC NUCLEI



Blazars: radio-loud Active Galactic Nucleus whose relativistic jet points towards the observer

emission from the jet outshines all other AGN components (disk, BLR, X-ray corona, …)

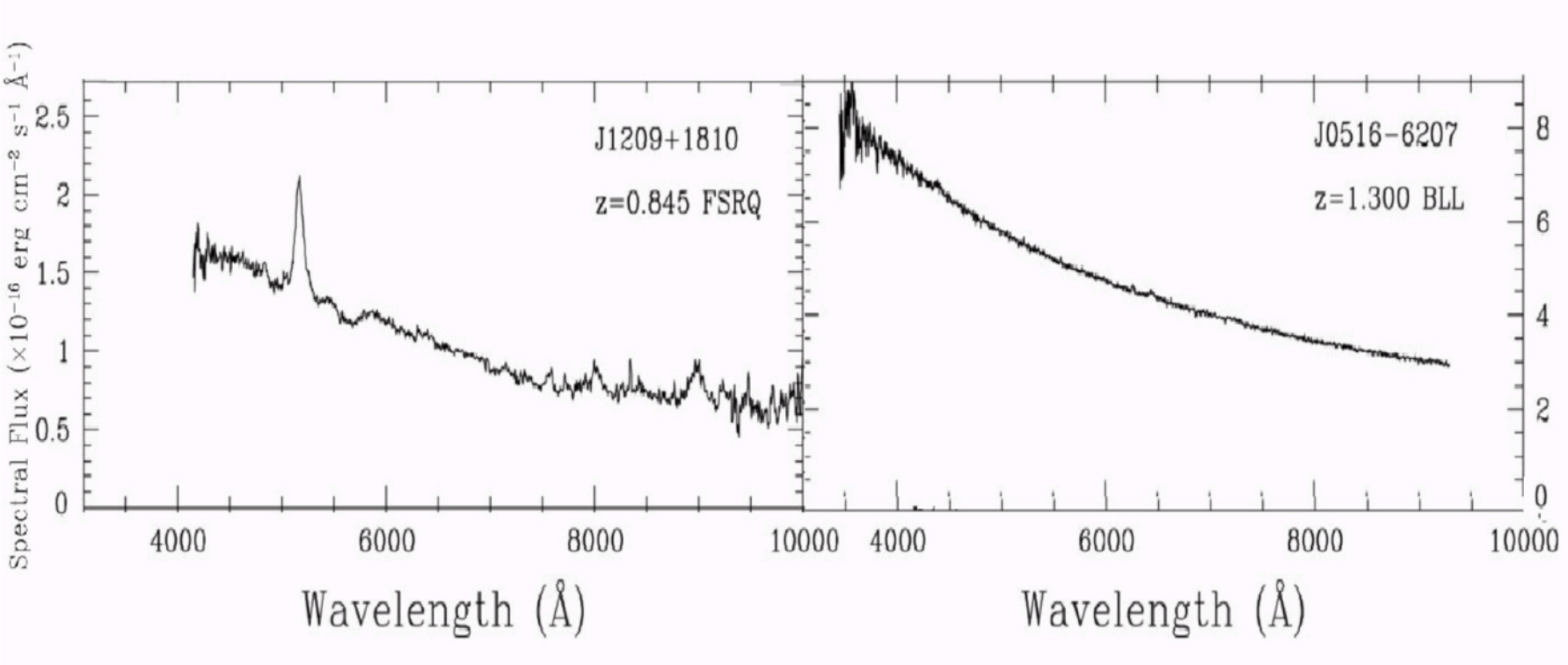
non-thermal emission from radio-to-gamma-rays, and extreme variability

Flat-spectrum-radio-quasars : optical spectrum with broad emission lines

BL Lacertae objects : optical spectrum is featureless (lines $\mathrm{EW} < 5\text{Å}$)

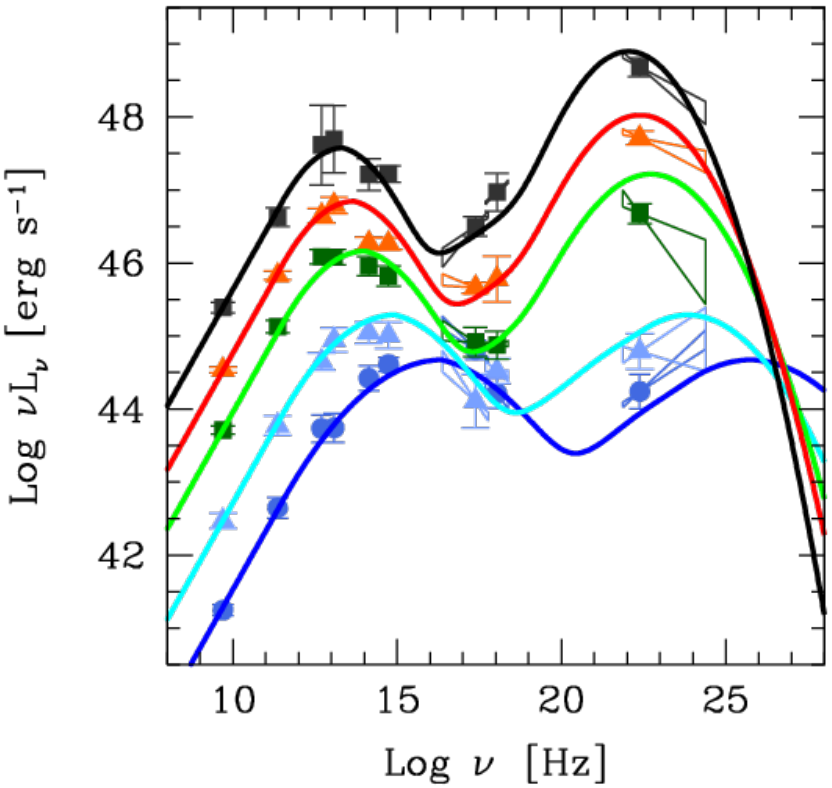
ACTIVE GALACTIC NUCLEI

FSRQs and BL Lac spectra



Shaw et al. 2012

ACTIVE GALACTIC NUCLEI



"the blazar sequence"
(Fossati et al. 1998)

Spectral energy distribution (SED): two separate components

FSRQs show a peak in IR

BL Lac objects are classified in:

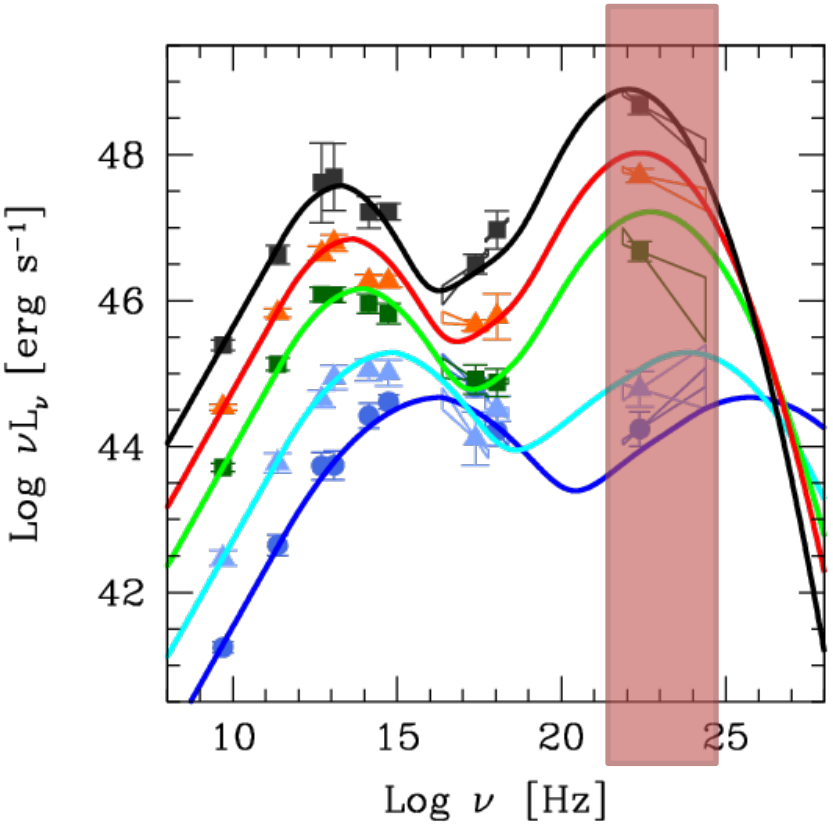
- peak in IR: low-frequency peaked (LBLs)

- peak in optical: intermediate (IBLs)

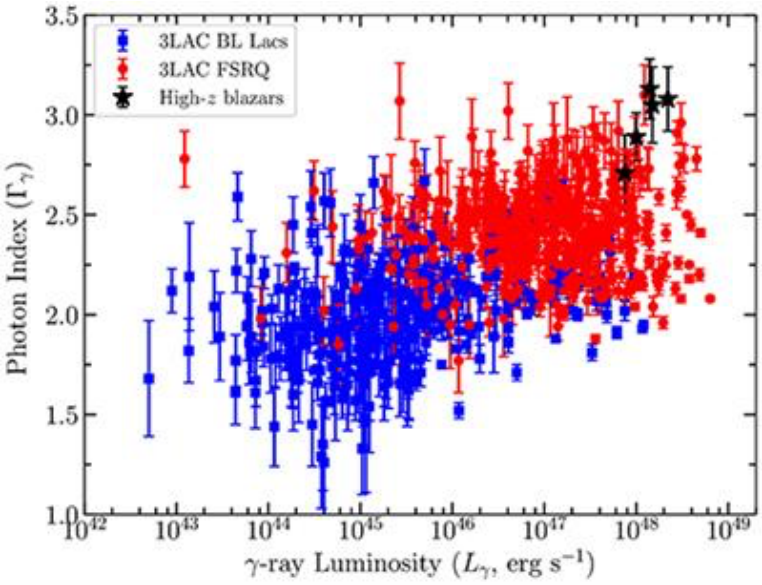
- peak in UV / X: high (HBLs)

THE GeV EXTRAGALACTIC SKY

Population of GeV AGNs

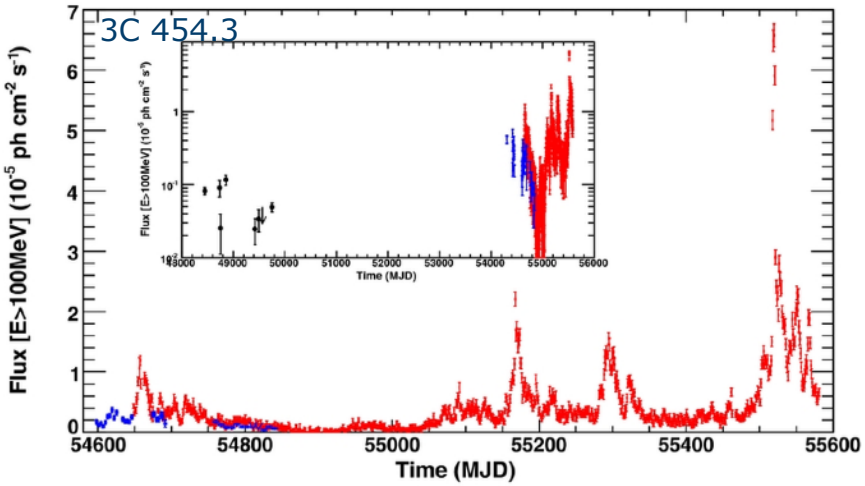


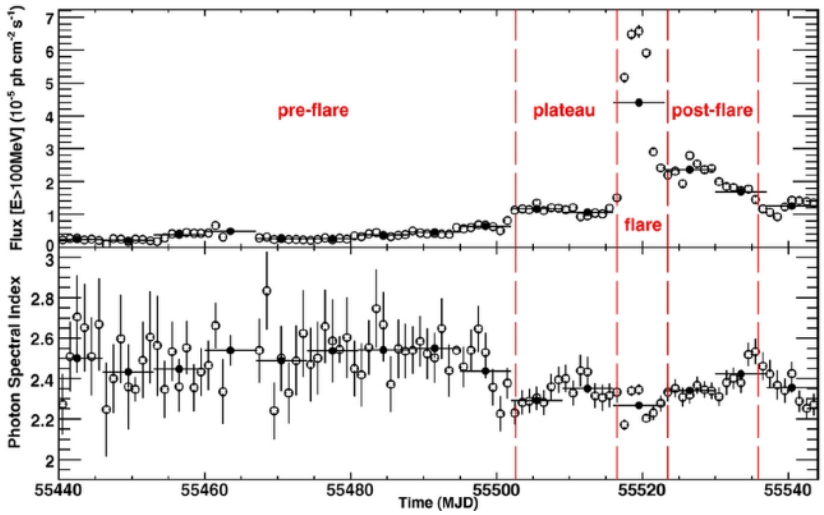
Dominated by high-luminosity FSRQs and LBLs



BLAZAR FLARES

Blazars are extremely variable

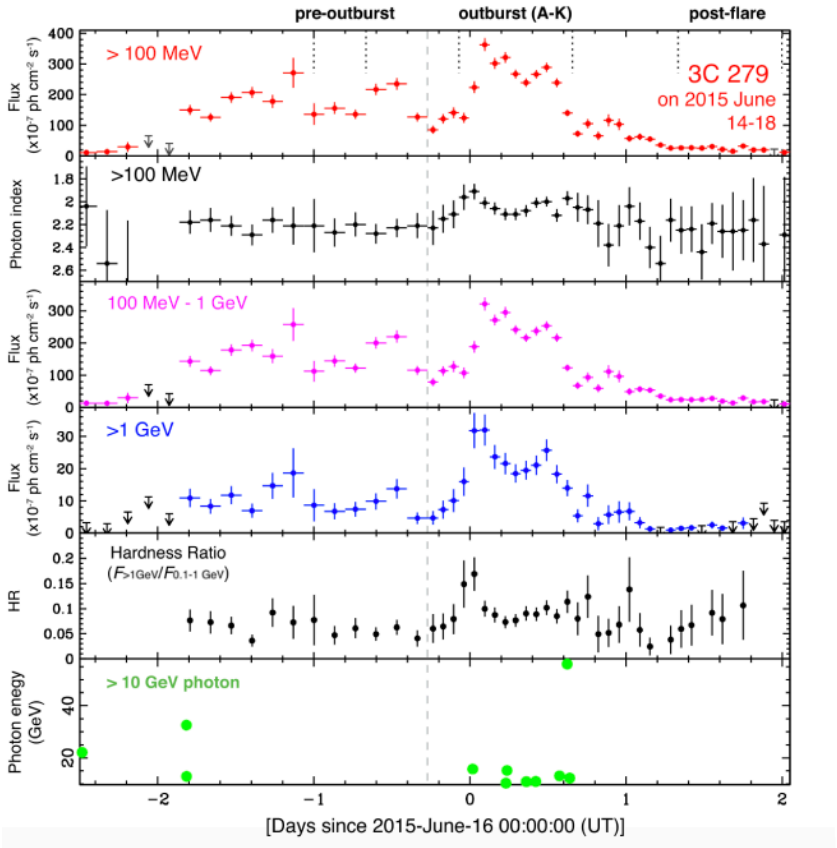


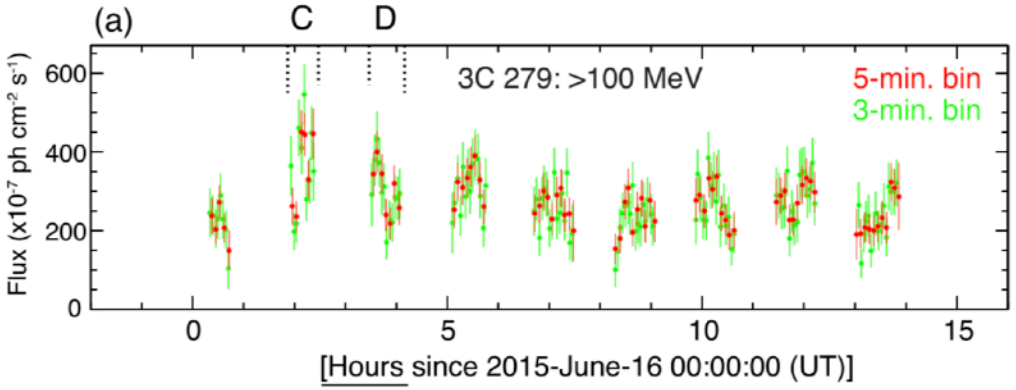


Abdo et al. 2011

BLAZAR FLARES

Rapid flares





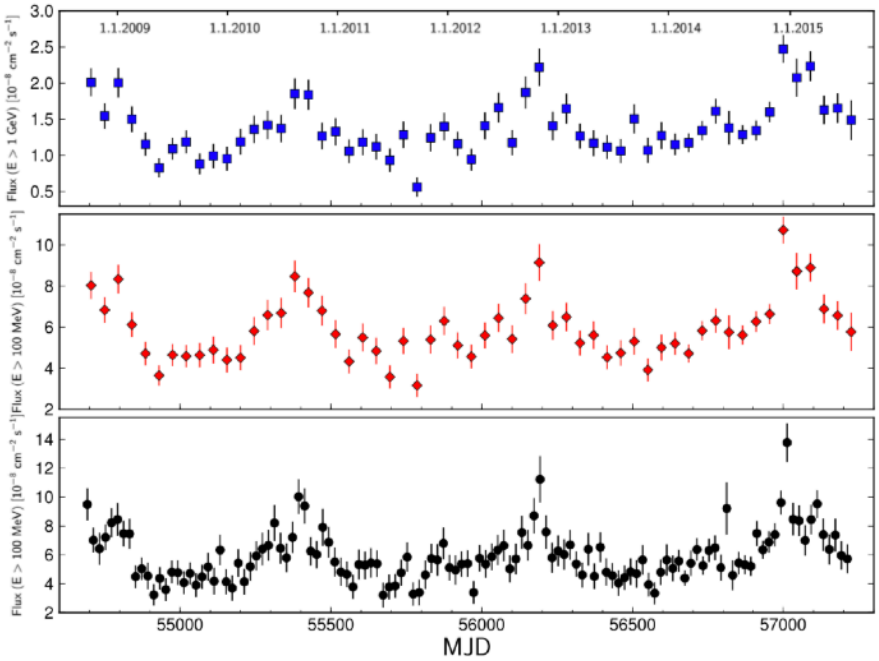
Variability can be used to constrain the size of the emitting region thanks to the causality argument

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

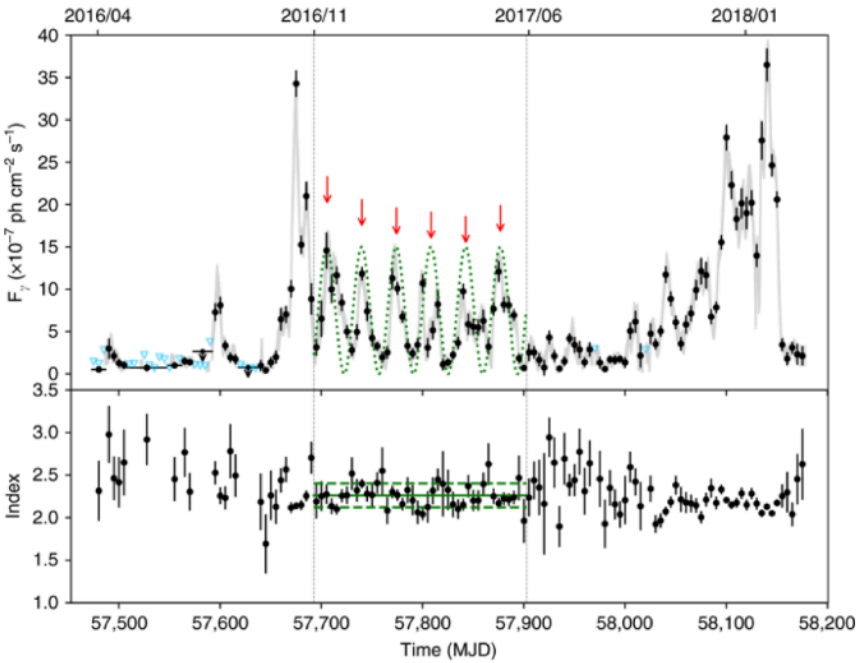
Ackermann et al. 2016

BLAZAR FLARES

Periodicity and Quasi-Periodic-Oscillations



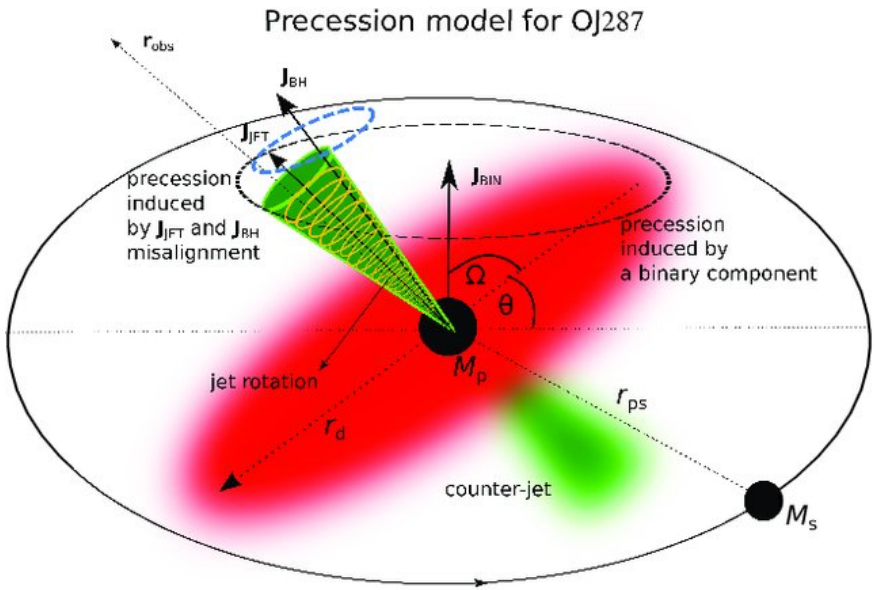
Ackermann et al. 2015



Zhou et al. 2018

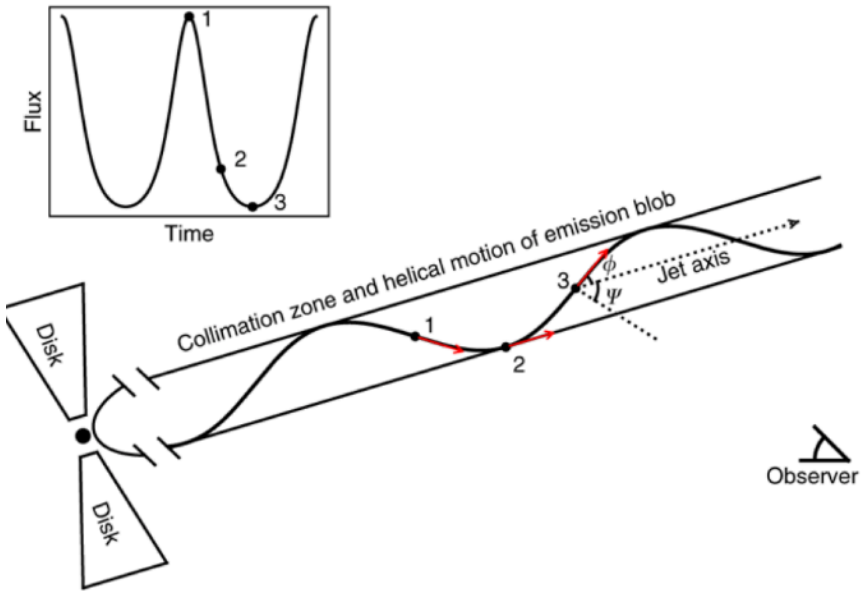
BLAZAR FLARES

Super-massive black-hole Binary



Britzen et al. 2017

Helical structure of the jet

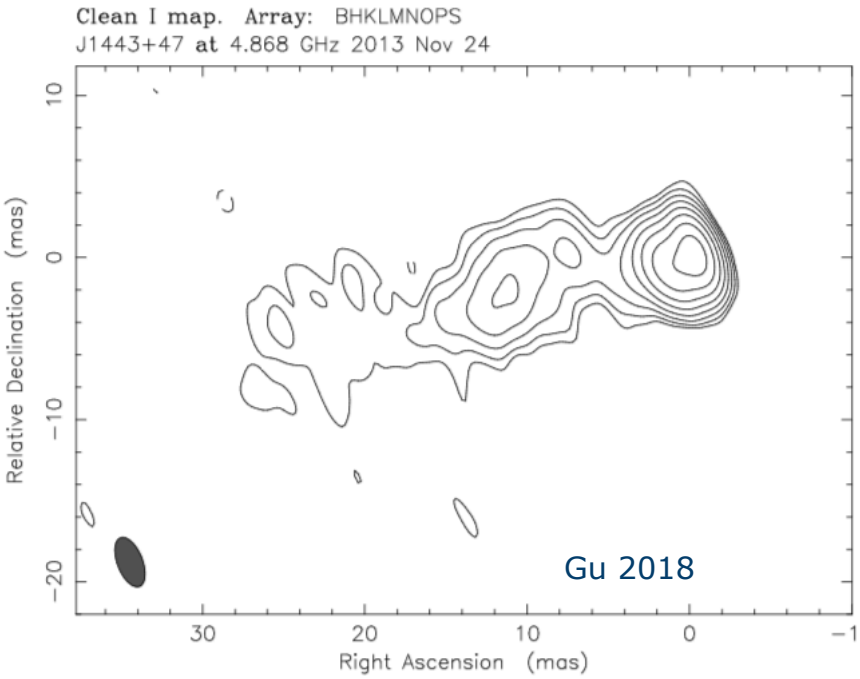


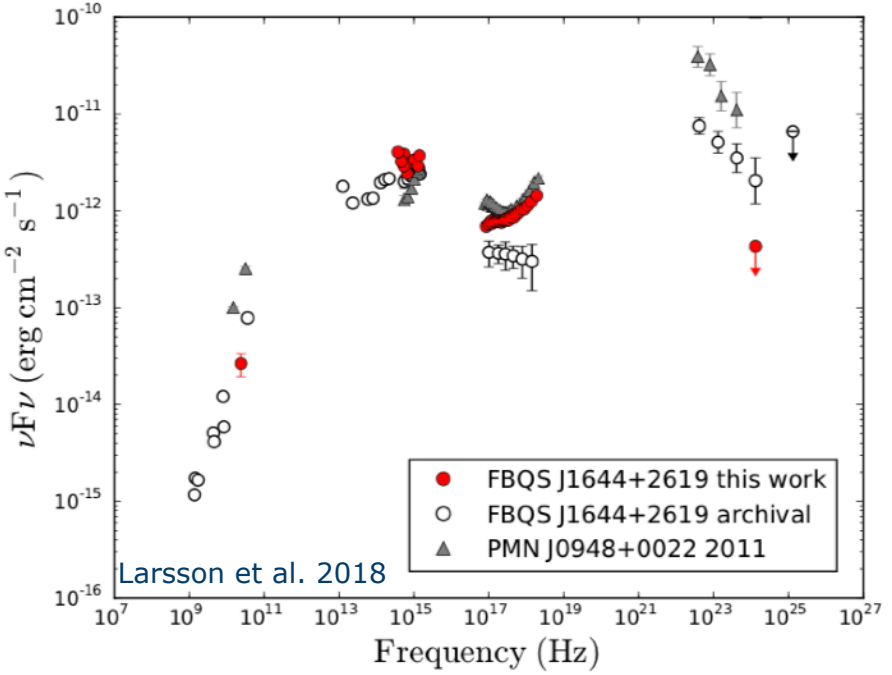
Zhou et al. 2018

NARROW LINE SEYFERT 1

Narrow-line Seyfert 1 galaxies

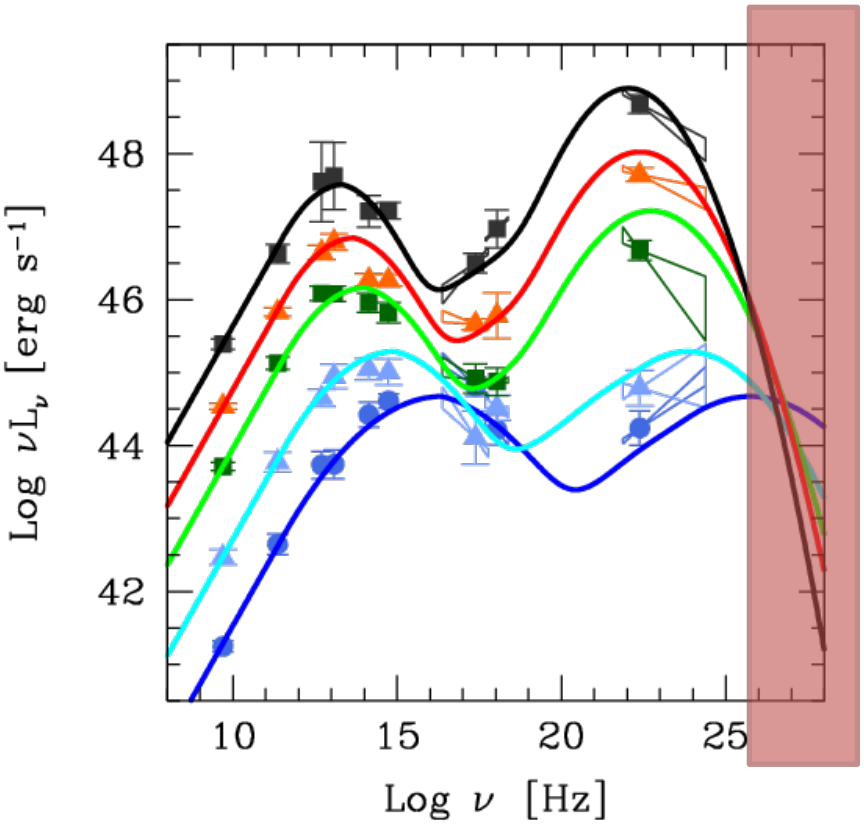
Seyfert galaxies with unusual optical spectrum
Some of them show a jet and gamma-ray emission (when flaring)
-> low-mass version of FSRQs?





THE TeV EXTRAGALACTIC SKY

Population of TeV AGNs



Dominated by HBLs:

57 HBLs
9 IBLs
2 LBLs
10 FSRQ
(8 unclear)

THE TeV EXTRAGALACTIC SKY

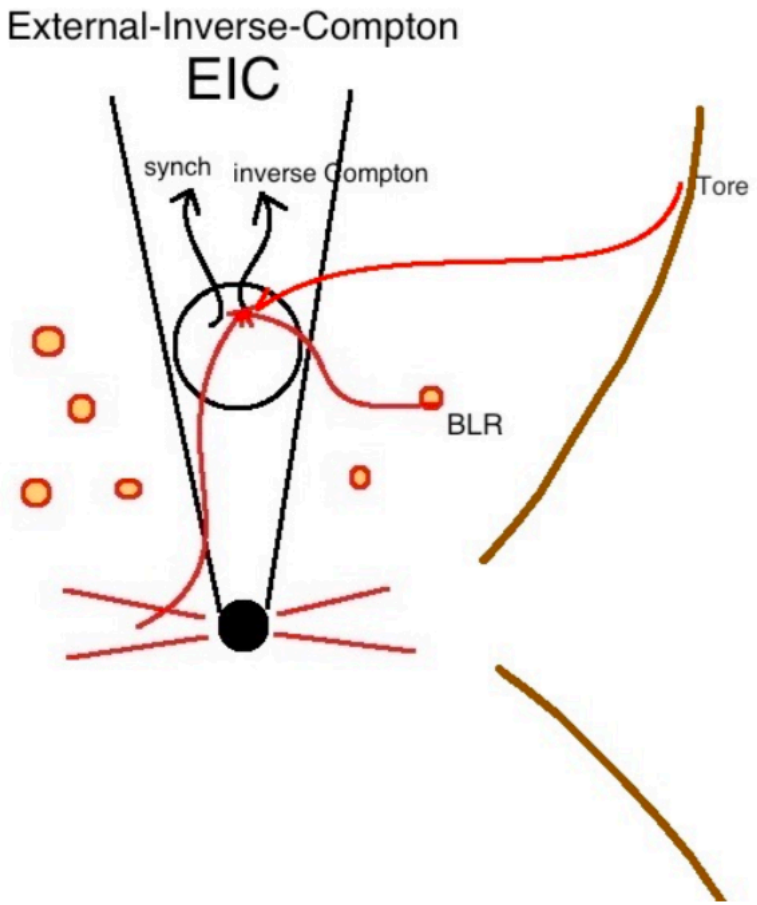
Pair production

Both in the source
(With dense photon fields: the BLR, the disk, the torus)

And during propagation
(With the Extragalactic Background Light)

THE TeV SKY HAS A HORIZON

FSRQs and LBLs



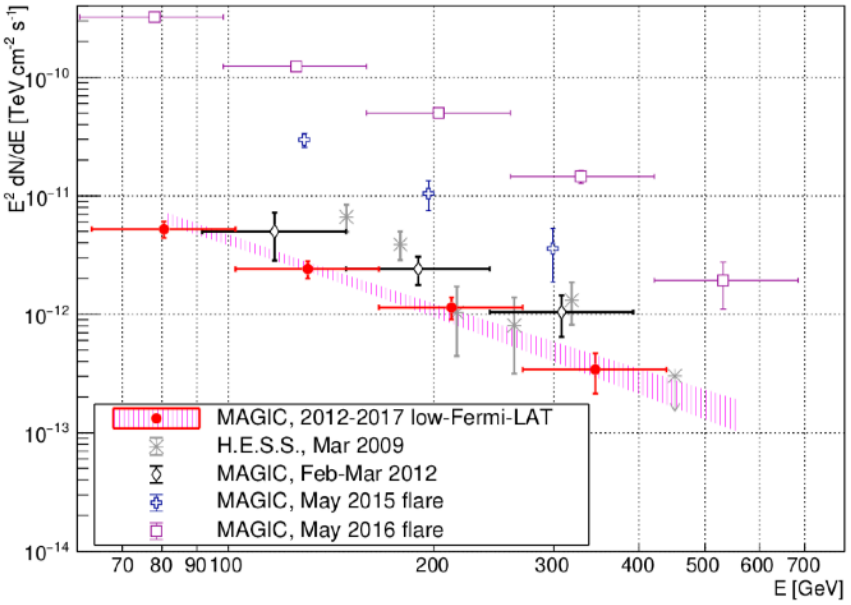
Origin of γ-ray emission:
External-Inverse-Compton

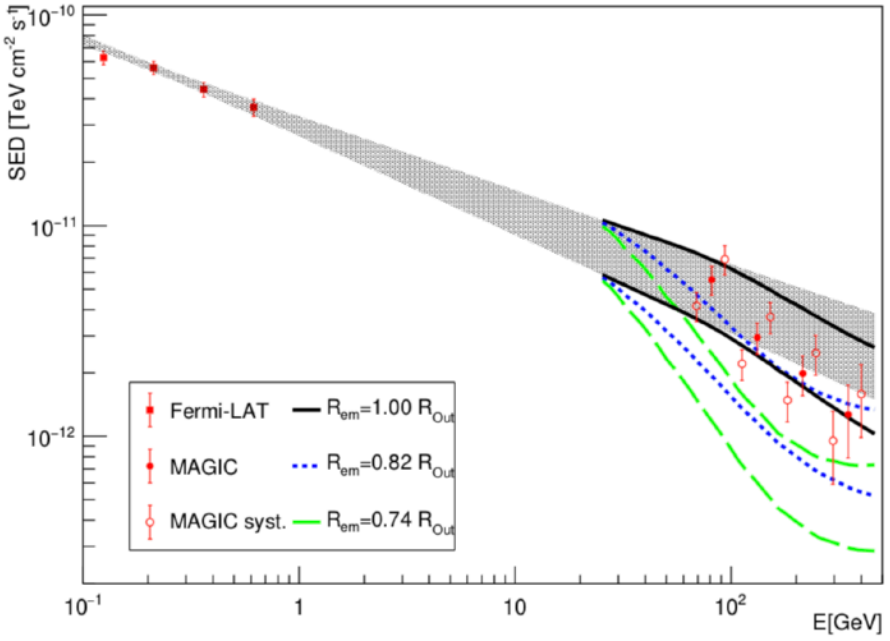
The external field also acts as an absorber via γ-γ pair-production

The detection of VHE photons can be used to constrain the location of the emitting region!

FSRQs and LBLs

First detection of a VHE FSRQ
in a non-flaring state!

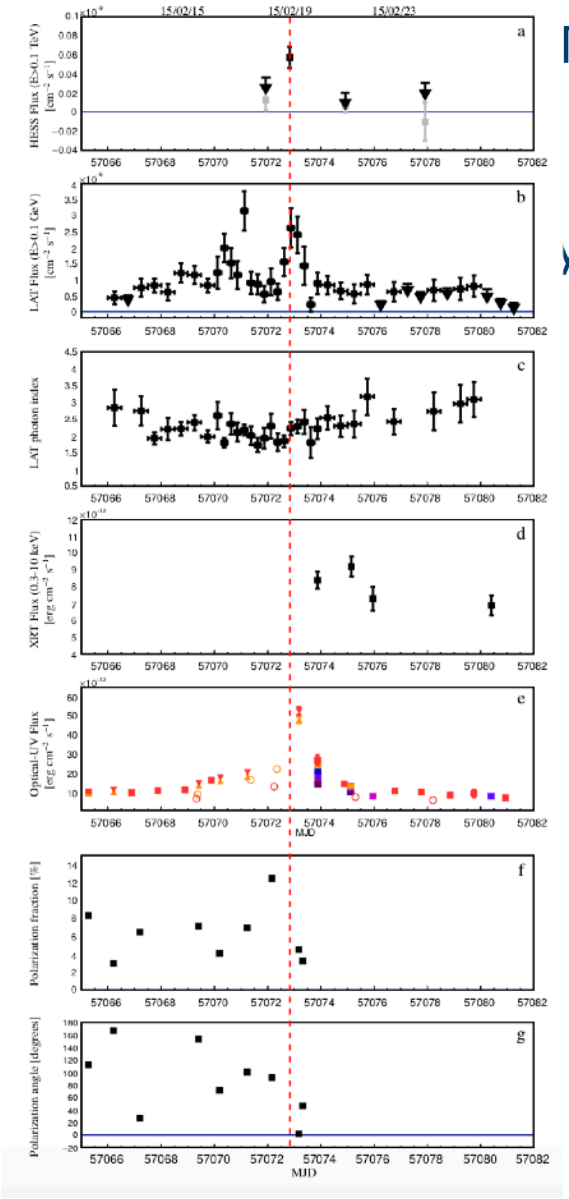




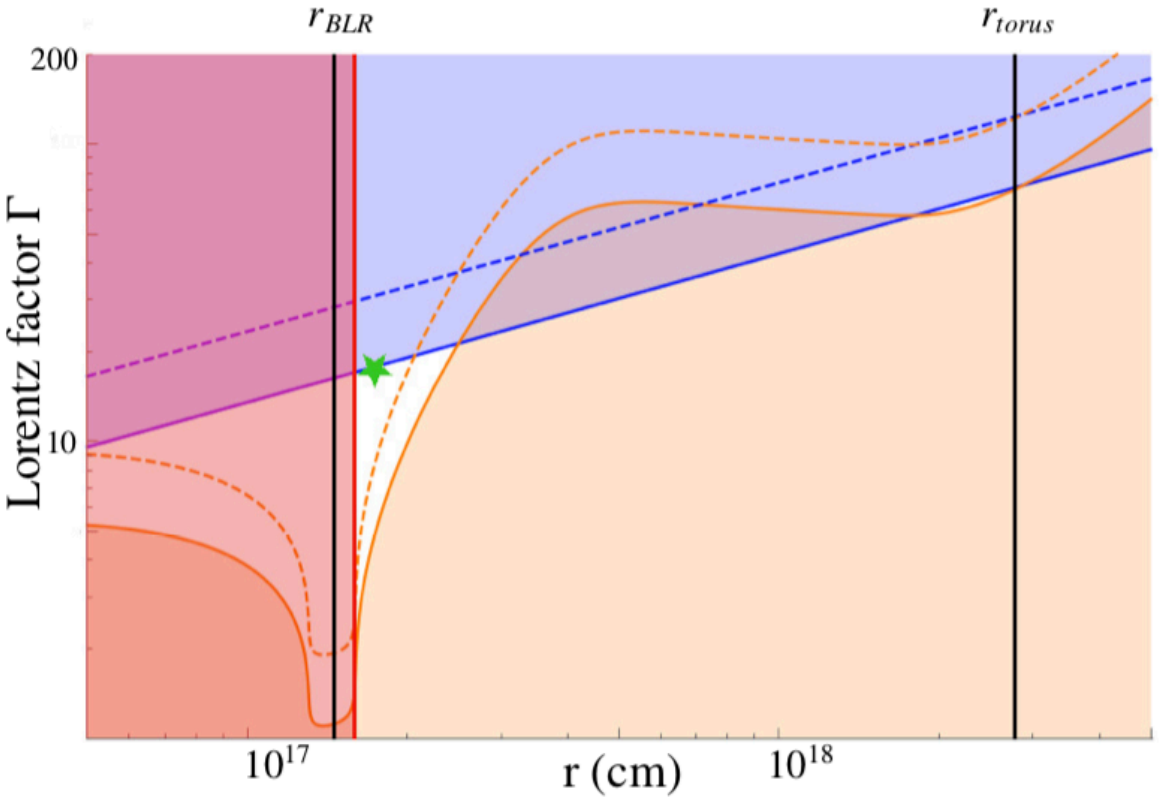
The emitting region HAS to be at
$r \geq r_{BLR}$ even during quiescence

MAGIC Collaboration et al. 2018

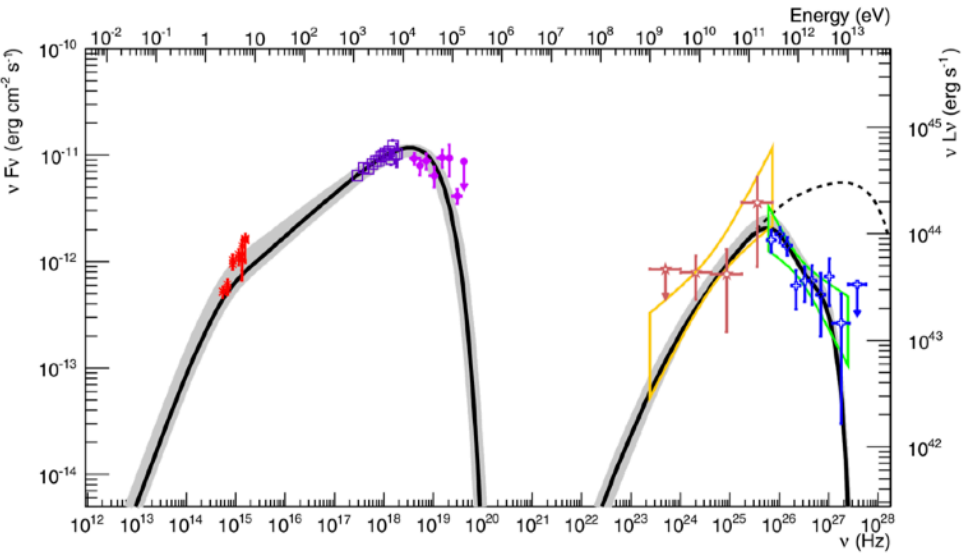
FSRQs and LBLs



Nearest VHE FSRQ, at z=0.189



EXTREME BLAZARS



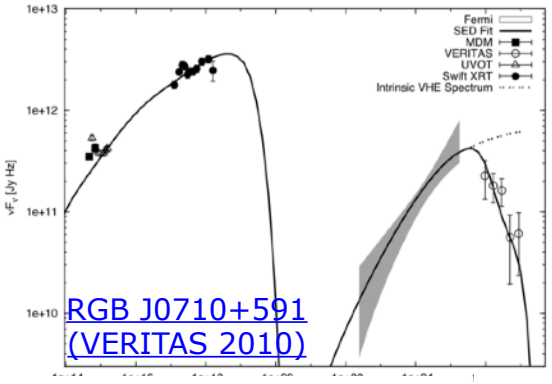
Aliu et al. 2014

If the peak is beyond soft X-rays ($\nu \geq 10^{17}$ Hz), we talk about extreme-HBLs

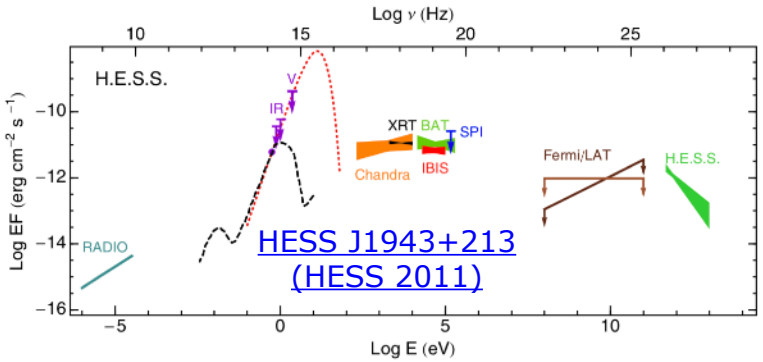
Archetypal EHBL: 1ES0229+200

But not all EHBLs have a hard TeV spectrum! The population seems more heterogeneous (Foffano et al. 2019 Costamante 2019)

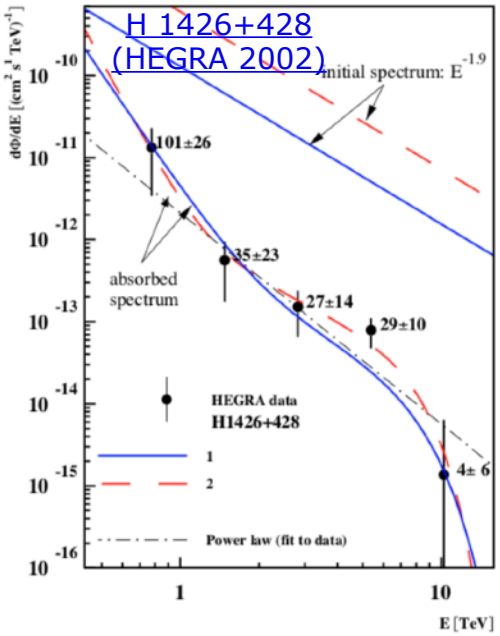
EXTREME BLAZARS



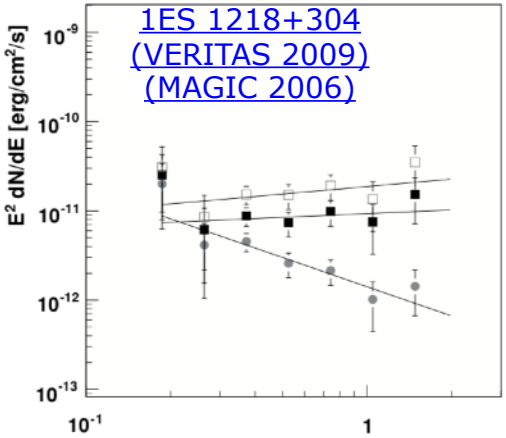
RGB J0710+591
(VERITAS 2010)



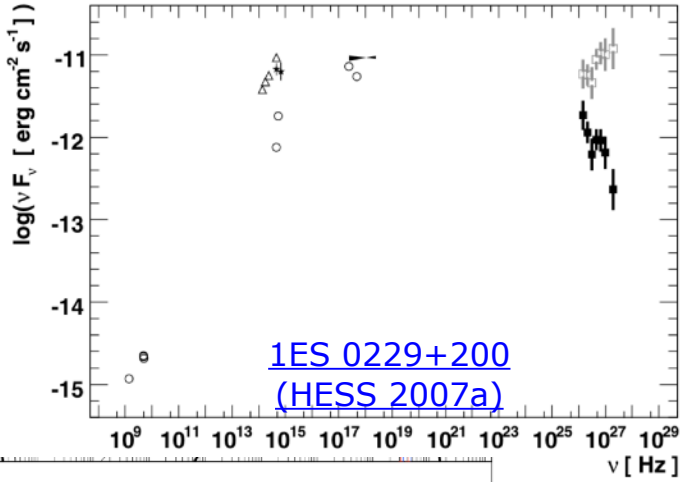
HESS J1943+213
(HESS 2011)



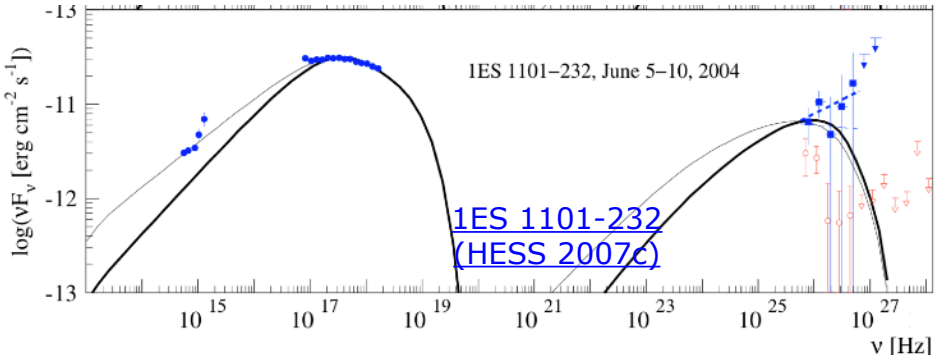
H 1426+428
(HEGRA 2002)



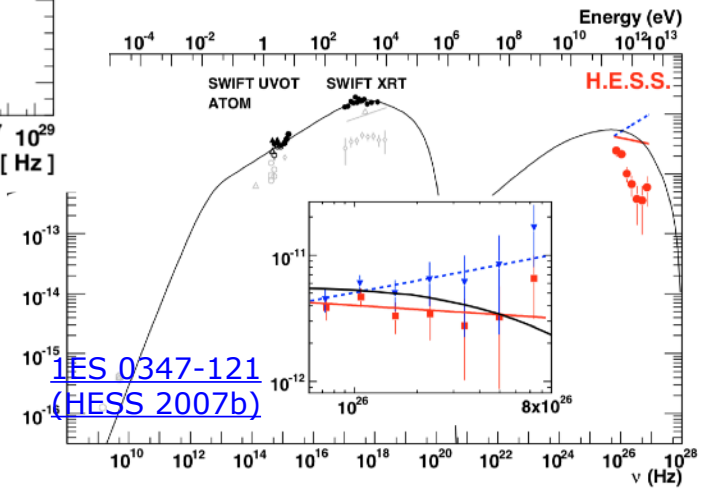
1ES 1218+304
(VERITAS 2009)
(MAGIC 2006)



1ES 0229+200
(HESS 2007a)



1ES 1101-232
(HESS 2007c)

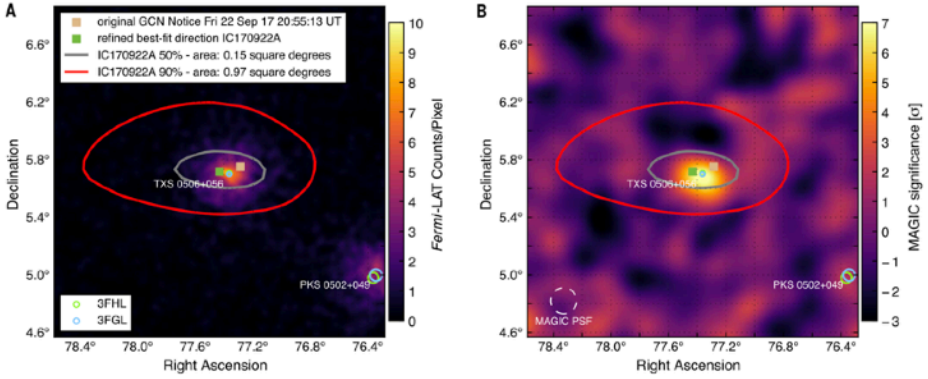


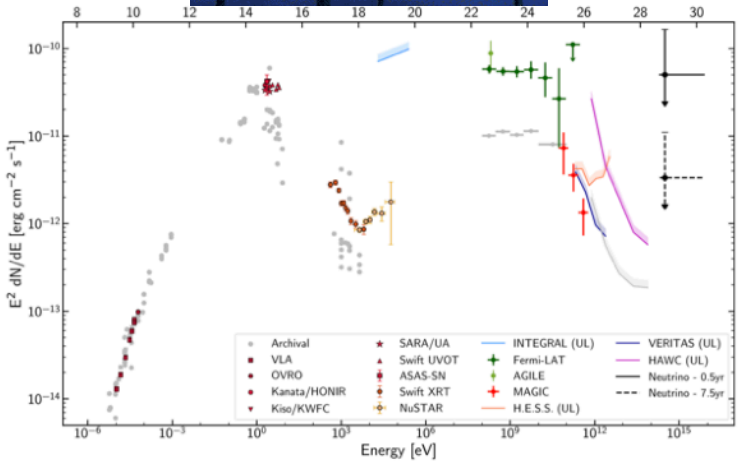
1ES 0347-121
(HESS 2007b)

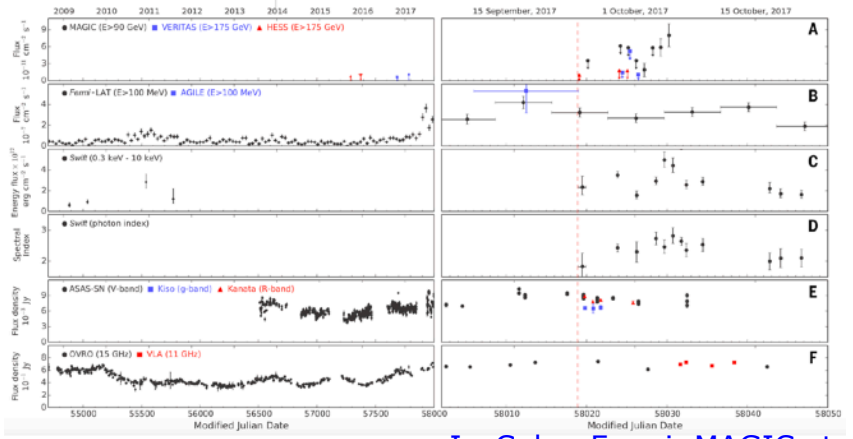
IceCube-170922A / TXS 0506+056

Most significant association (3σ)
of a high-energy (290 TeV) neutrino with an astrophysical source



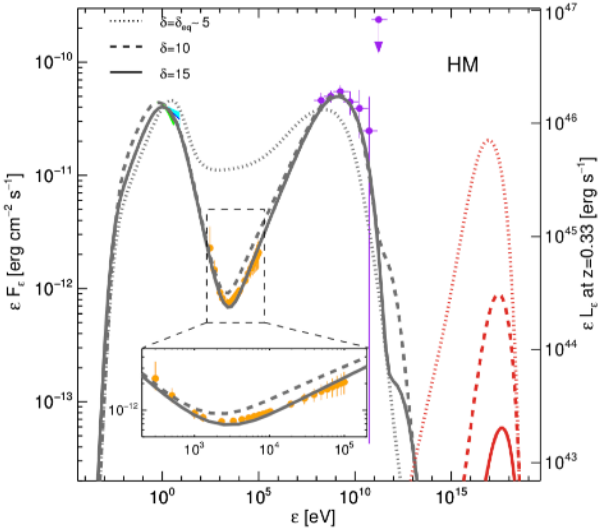






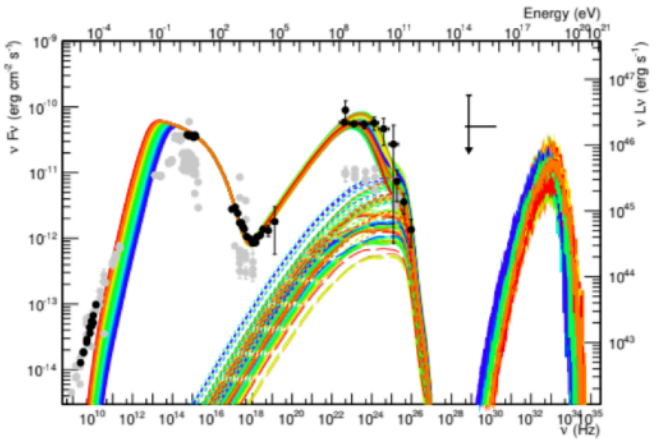
IceCube, Fermi, MAGIC et al. 2018

TXS 0506+056: THE 2017 FLARE



Keivani et al. 2018

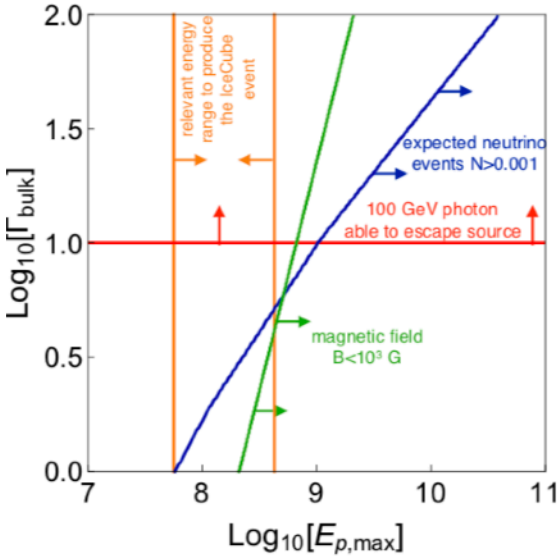
$\nu \simeq 10^{-5}\ yr^{-1}$



(a) Proton synchrotron modeling of TXS 0506+056

Cerruti et al. 2019

$\nu = 10^{-5} - 10^{-3}\ yr^{-1}$

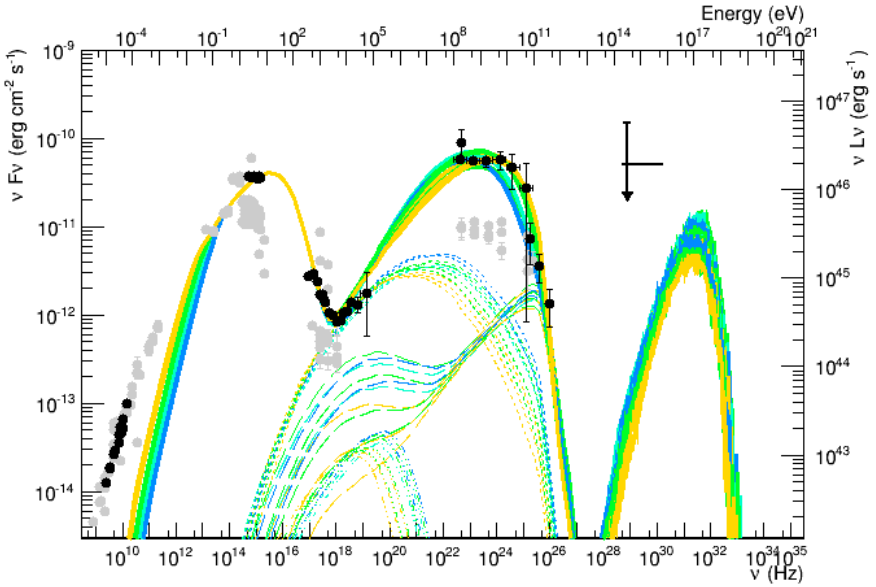


Gao et al. 2018

Proton synchrotron solutions exist,
but the expected neutrino rate is very low

TXS 0506+056: THE 2017 FLARE

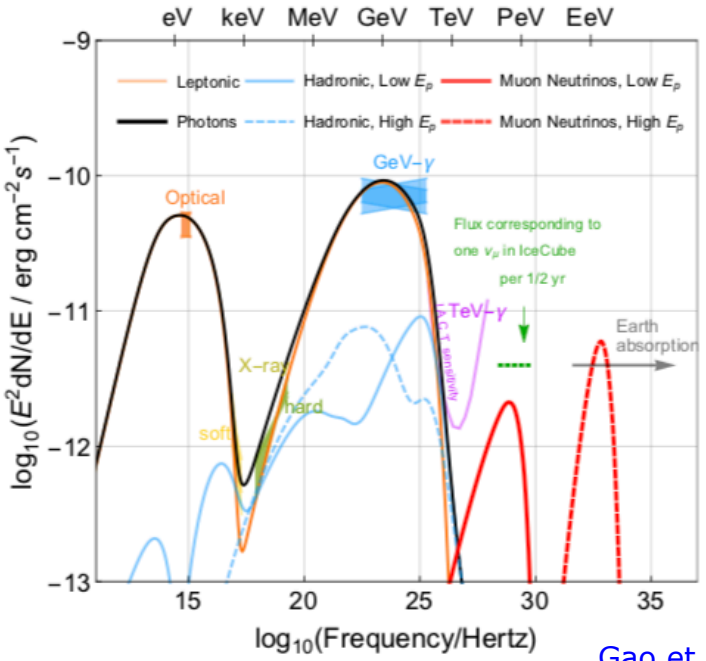
Lepto-hadronic solutions



Cerruti et al. 2019

$L_{jet} = (9 - 60) \times 10^{47} erg/s$

$\nu = 0.01 - 0.06\ yr^{-1}$



Gao et al. 2018

$L_{jet} \simeq \times 10^{50} erg/s$

$\nu = 0.3\ yr^{-1}$

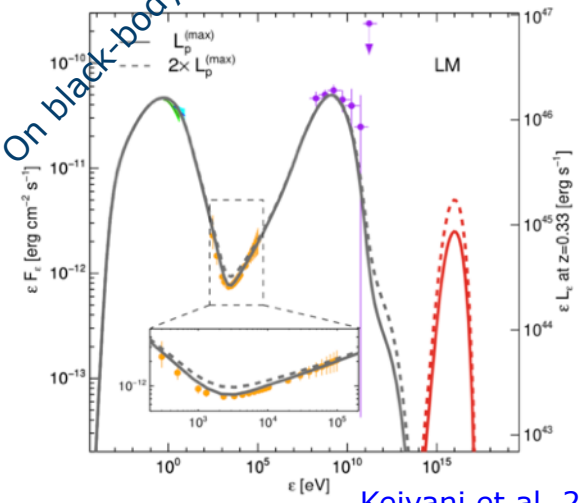
They can work: neutrino rates of the order of 0.1 / yr

But rather high energetic requirement : $L_{jet} \gg L_{Edd} \simeq \times 10^{46-47}\ erg/s$

TXS 0506+056: THE 2017 FLARE

Proton-photon interaction on external photon fields

On black-body

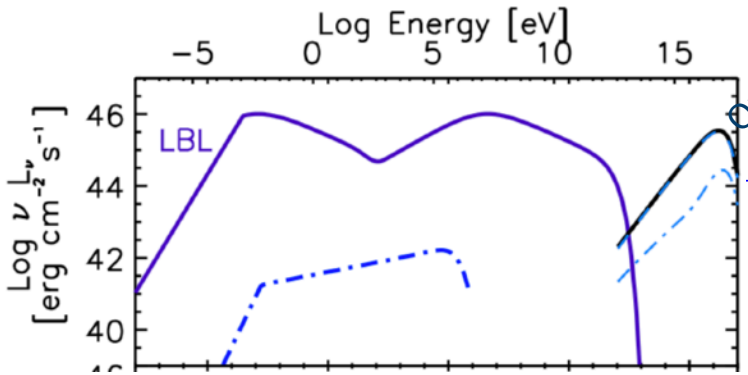


Keivani et al. 2018

$L_{jet} = (4 - 150) \times 10^{45} erg/s$

$\nu_{max} = 0.02\ yr^{-1}$

On RIAF

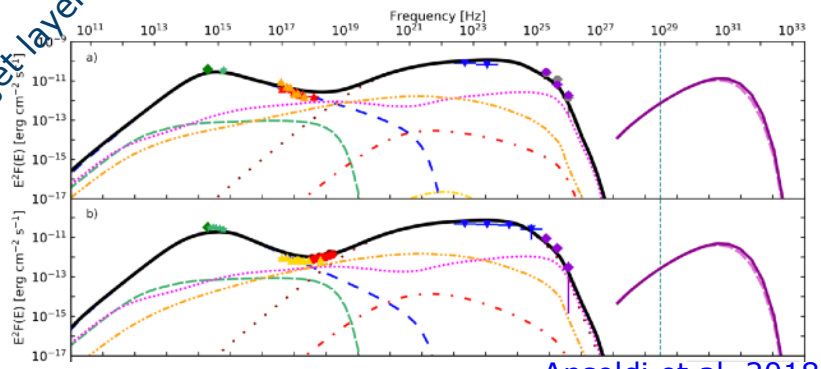


Righi et al. 2019

$L_{jet} = 6.3 \times 10^{45} erg/s$

$\nu = 0.14\ yr^{-1}$

On jet layer



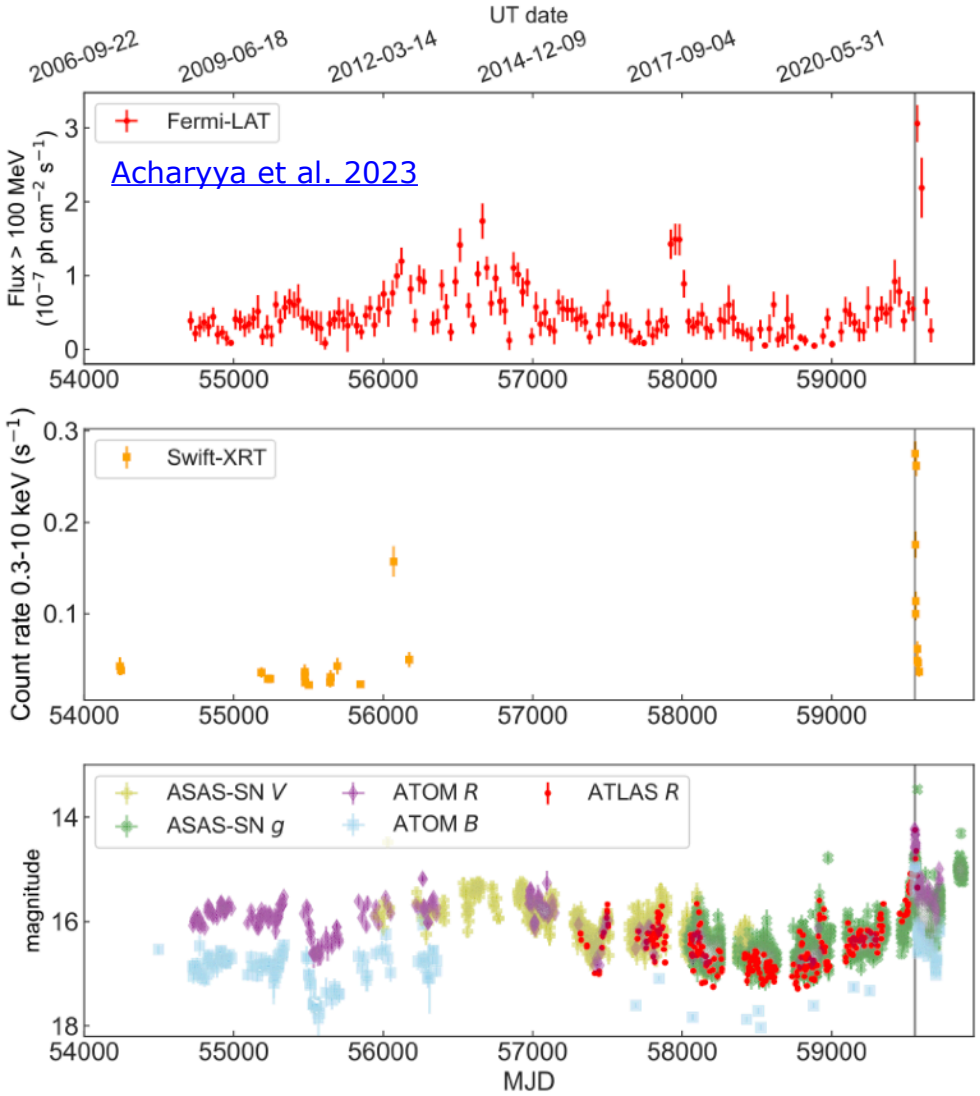
Ansoldi et al. 2018

$L_{jet} = (3 - 8) \times 10^{45} erg/s$

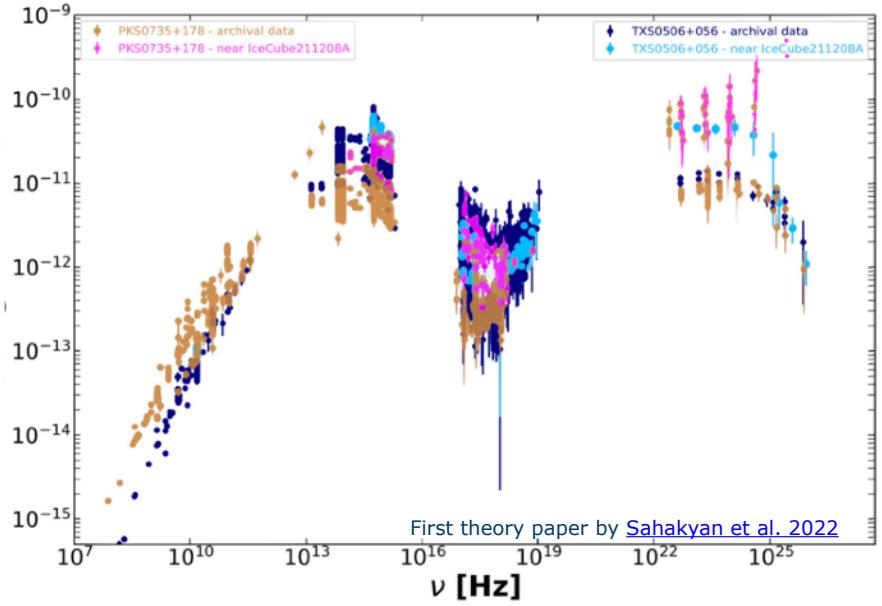
$\nu = 0.12 - 0.34\ yr^{-1}$

WHAT HAPPENED SINCE 2017?

FLARE OF PKS 0735+178 / IC211208A



Acharyya et al. 2023

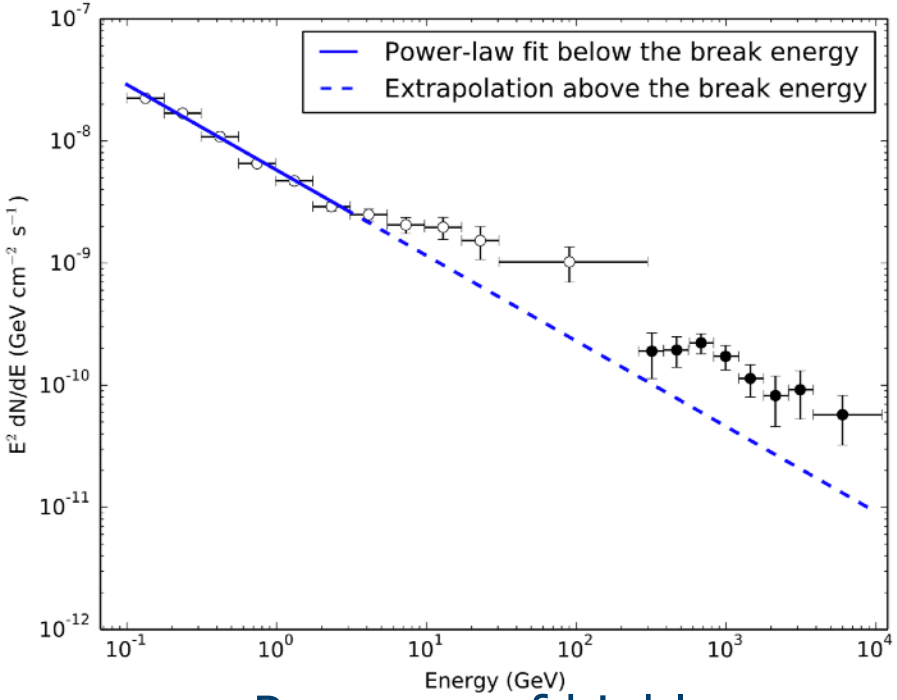


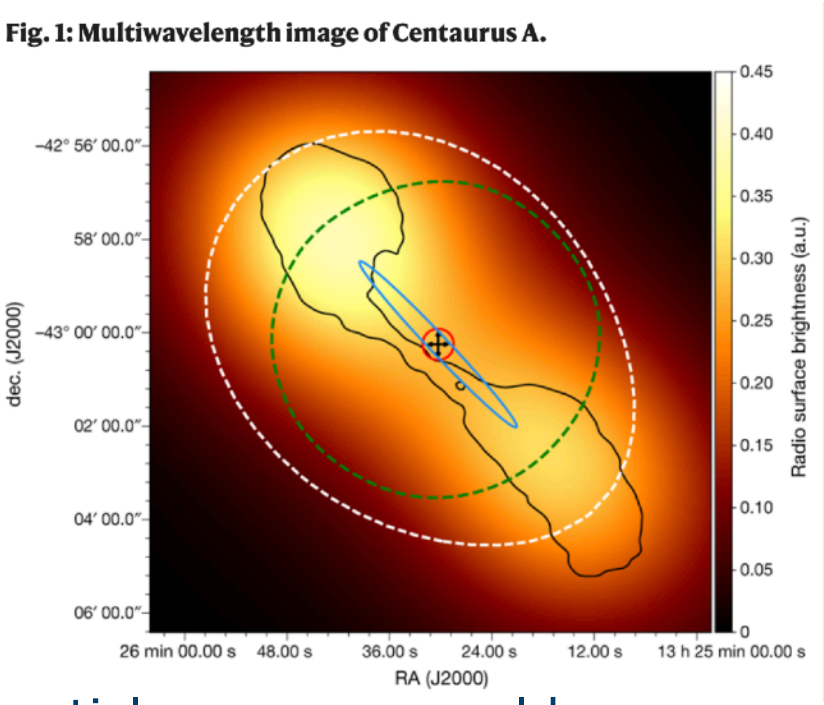
First theory paper by Sahakyan et al. 2022

RADIO GALAXIES - Centaurus A

Not variable! Unique spectral hardening at TeV

Extended!



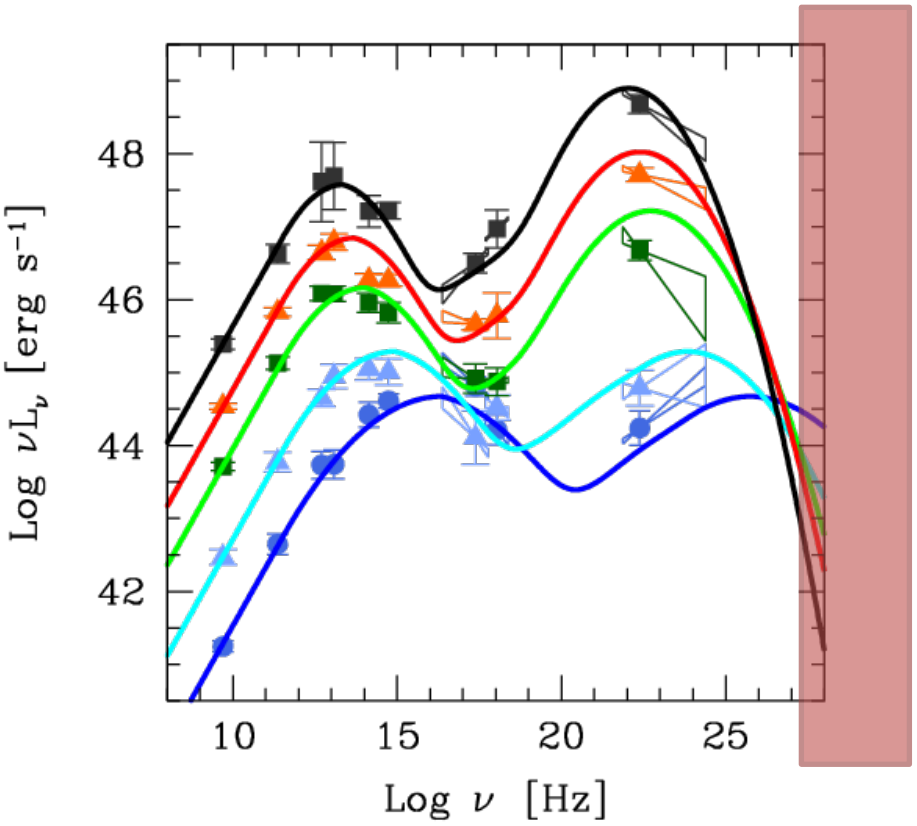


Presence of highly energetic particles over several kpc

-> continuous acceleration mechanism along the jet

THE Multi-TeV EXTRAGALACTIC SKY

Population of TeV AGNs



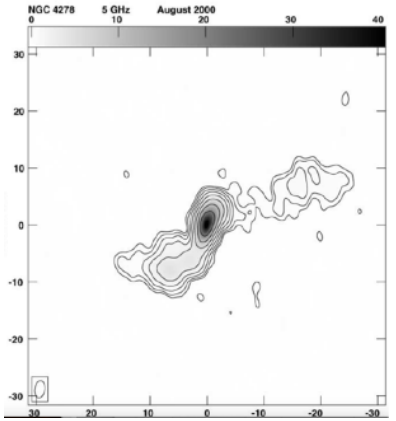
Dominated by HBLs:

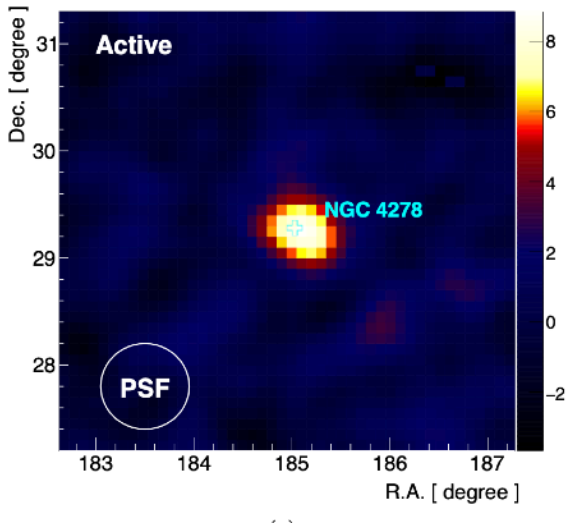
6 HBLs
1 RG (M87)
1 Low-lum. AGN (NGC 4278)

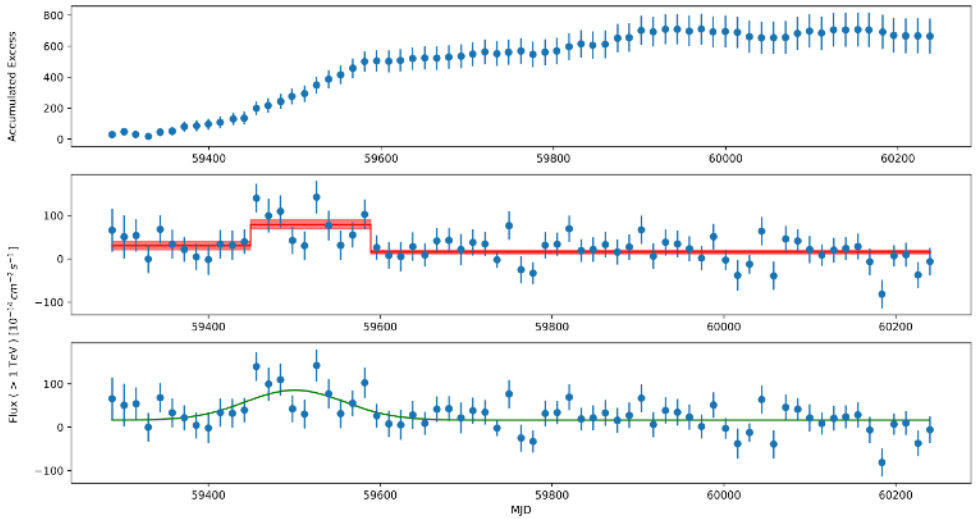
NGC 4278

- Source in the first LHAASO catalog: 1LHAASO J1219+2915
- Now claimed at 8.8 sigma in about 900 days exposure

- Very close (16.4 Mpc, z = 0.002) low-luminosity AGN
- LINER core
- $M_{bh} = 3 \cdot 10^8$ solar masses, and $L/L_{Edd} = 10^{-6}$
- Radio VLBI shows compact radio symmetric morphology







NGC 4278

Spectrum and comparison with other TeV sources

