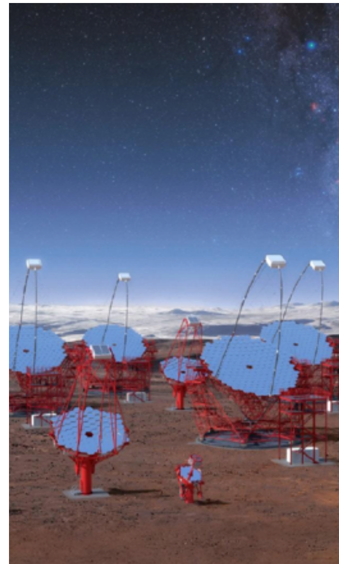
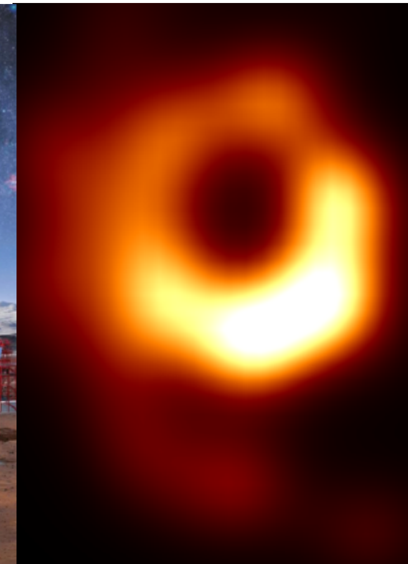
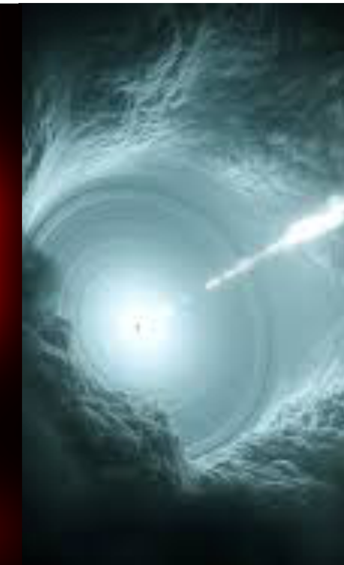




JETTED ASTROPHYSICS

Matteo Cerruti

Université Paris Cité
Astroparticule et Cosmologie (APC)

CTAO School
June 2025

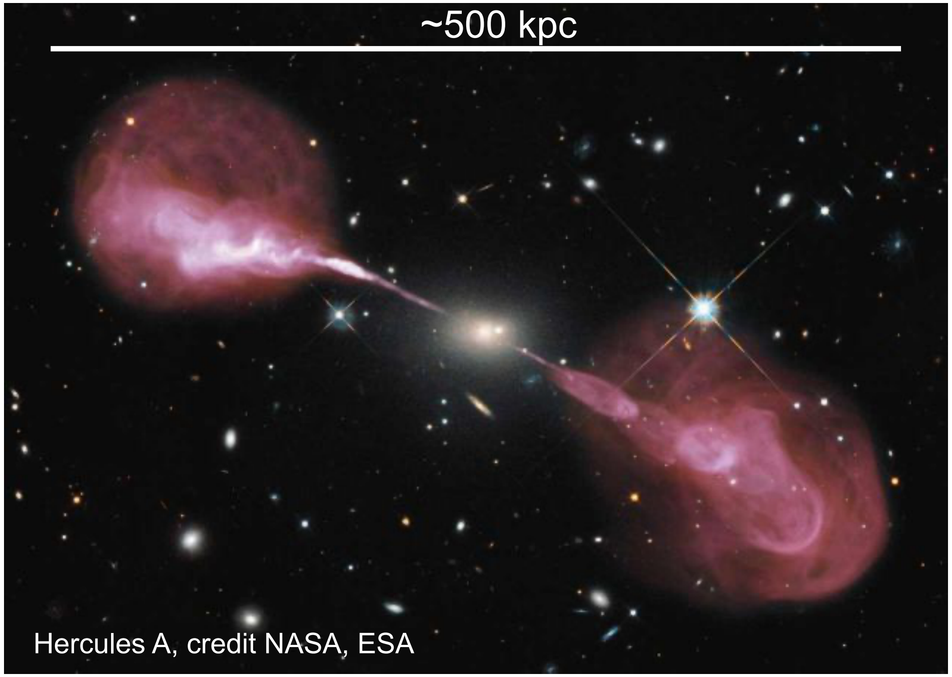
PLAN OF THE CLASSES

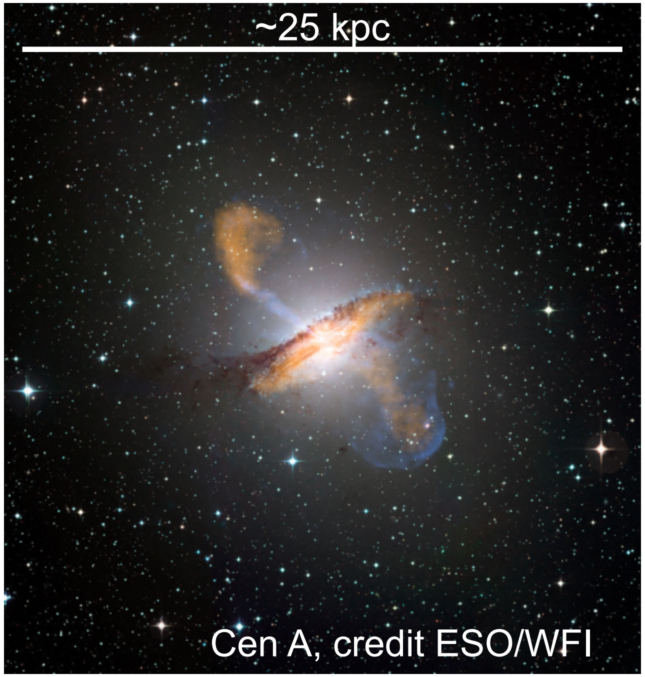
Very rough estimate, to be tuned as we go

1) What are jets?
2) Phenomenology: microquasars, AGNs and GRBs
3) Radiation mechanisms in jets
4) An application: how to model blazar emission

WHAT ARE JETS?

Collimated outflows seen in different sources and
at different scales

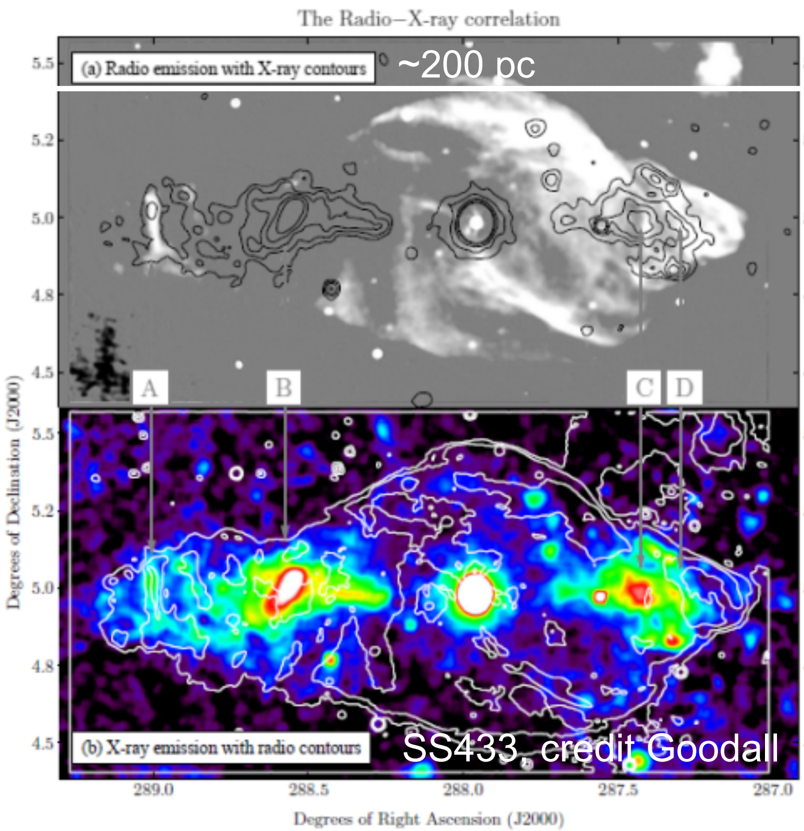


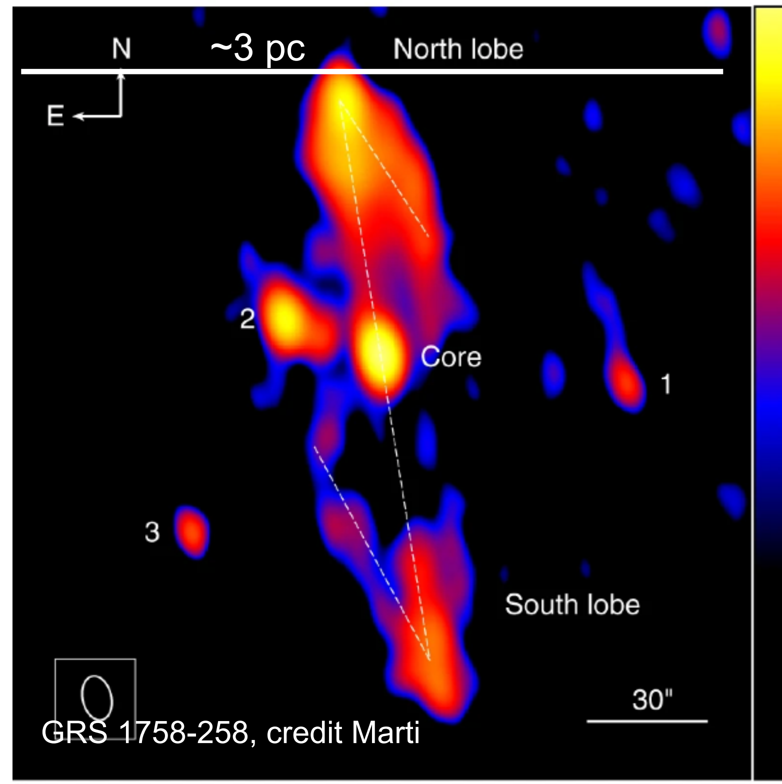


Active Galactic Nuclei

WHAT ARE JETS?

Collimated outflows seen in different sources and at different scales

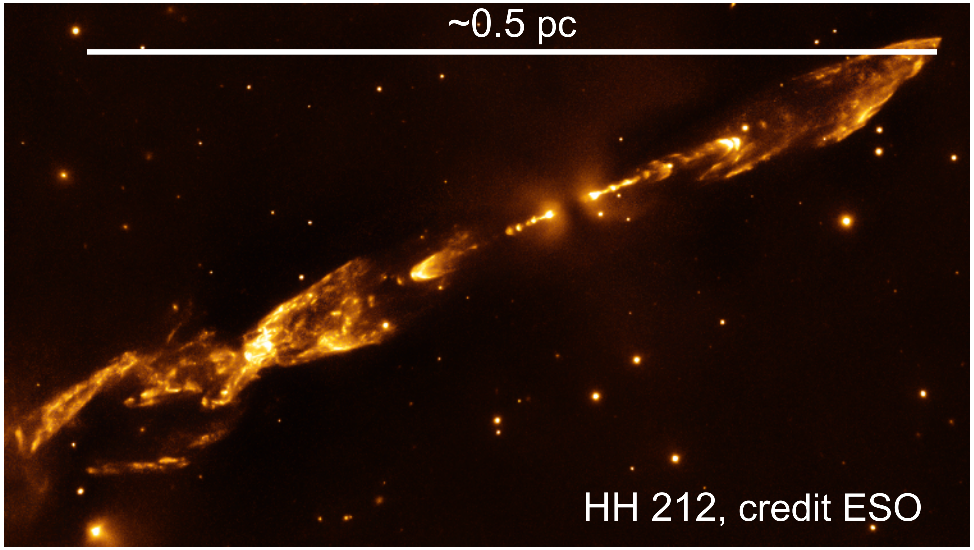


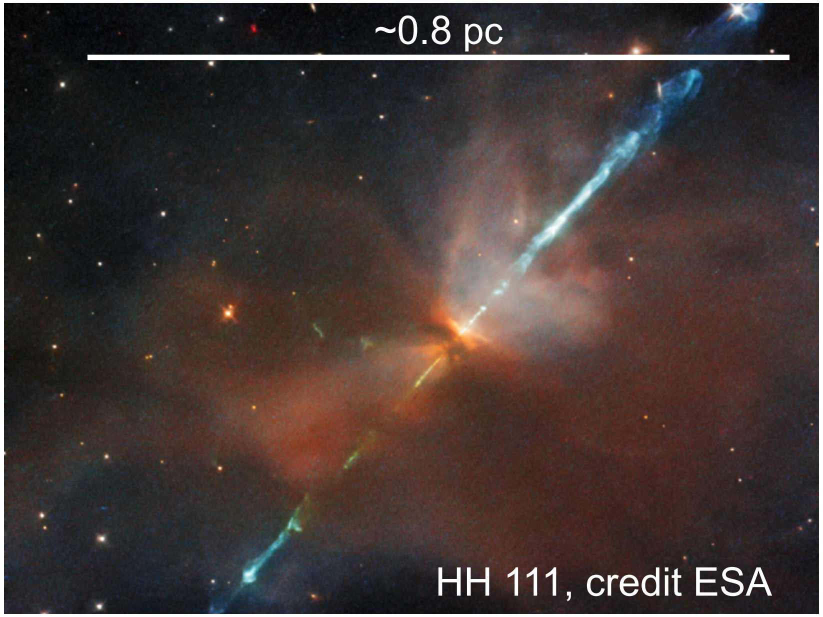


Micro quasars

WHAT ARE JETS?

Collimated outflows seen in different sources and at different scales

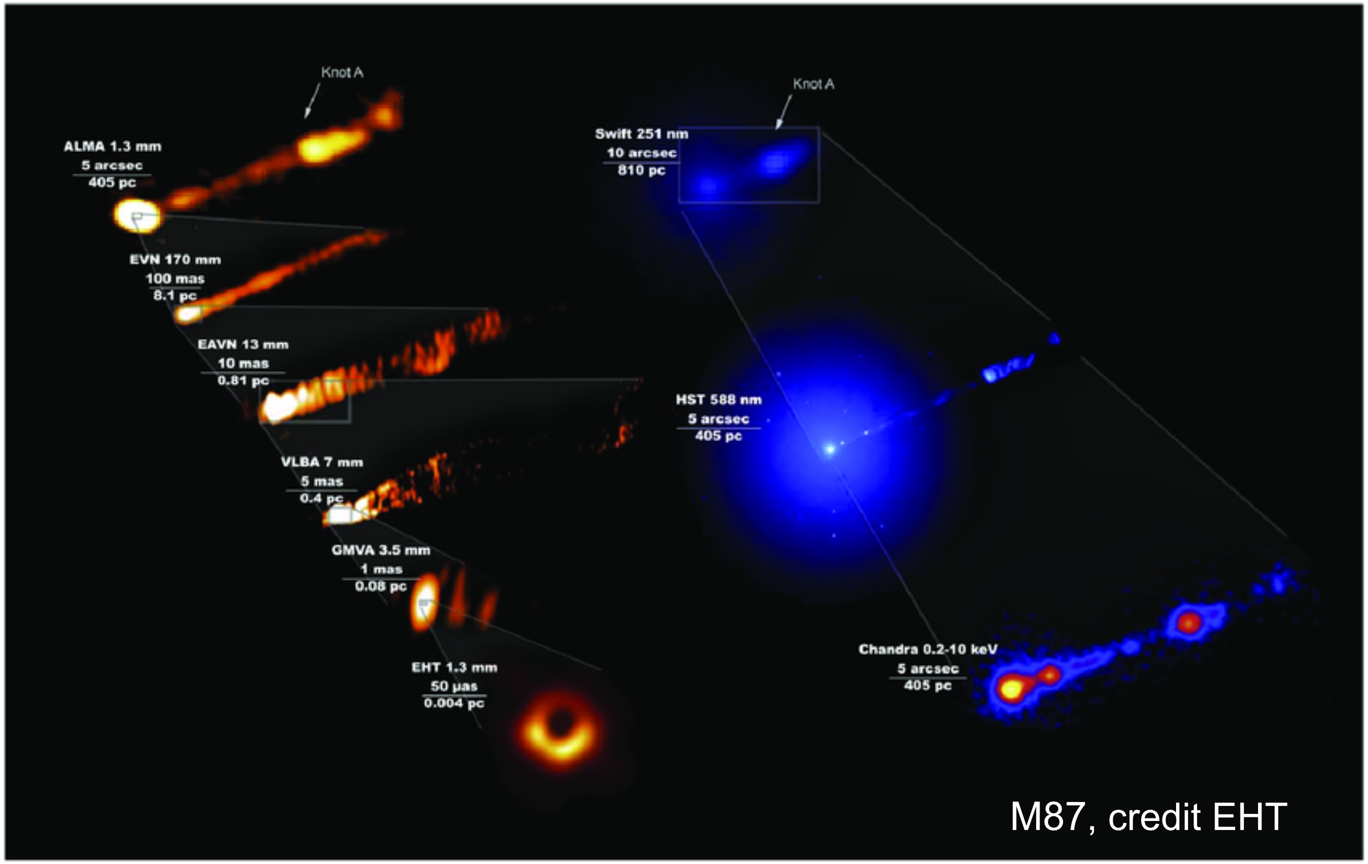




Young stellar objects

HOW DO WE STUDY JETS?

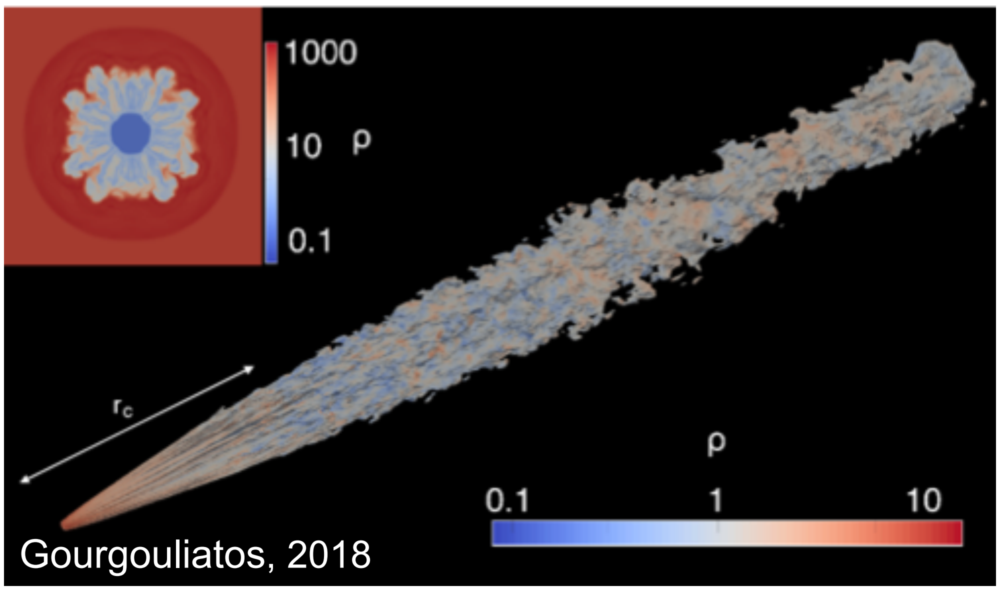
Multi-wavelength observations

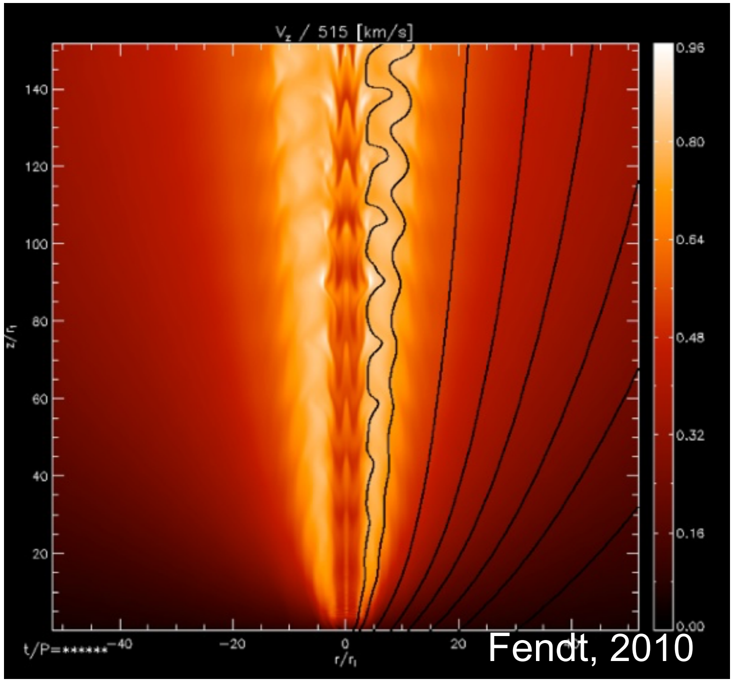


The Jet of M87 in radio, visible, X-ray

HOW DO WE STUDY JETS?

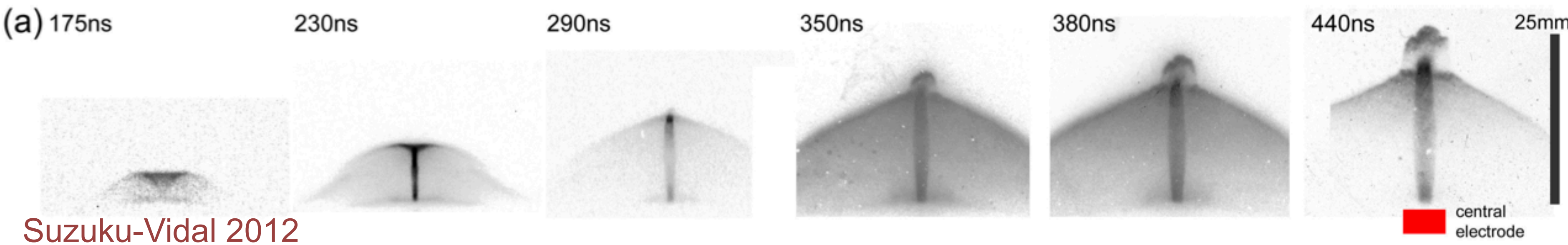
Relativistic Magneto-hydrodinamic (MHD) simulations
(+ GR if you want to study jet launching close to the black hole)



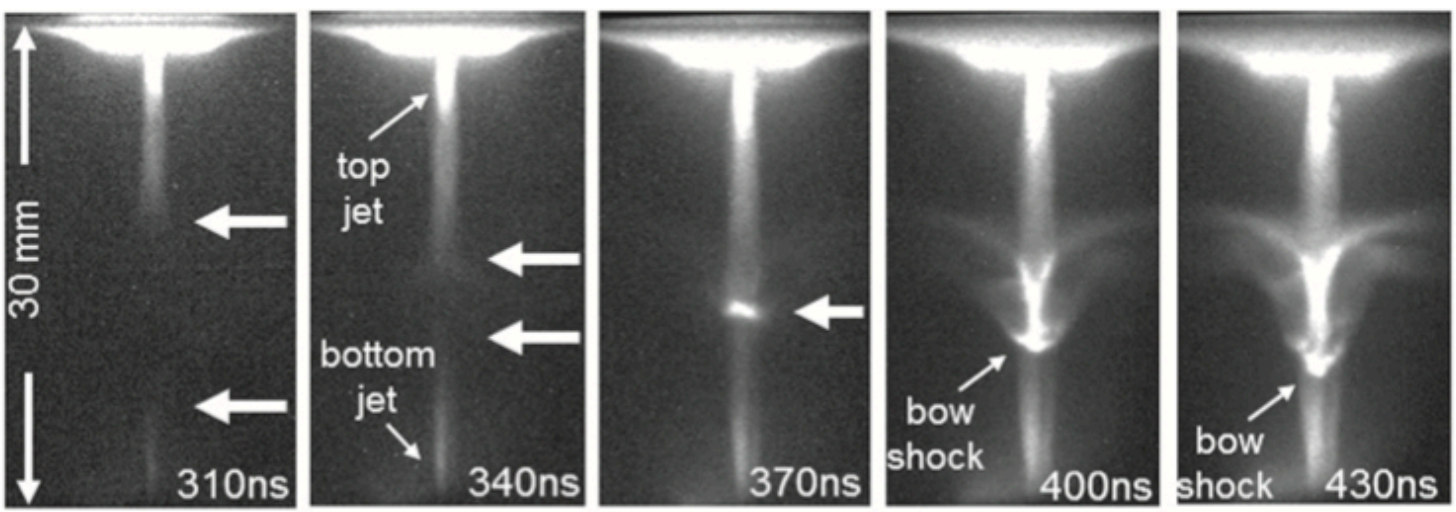


HOW DO WE STUDY JETS?

Laboratory astrophysics



Suzuku-Vidal 2012



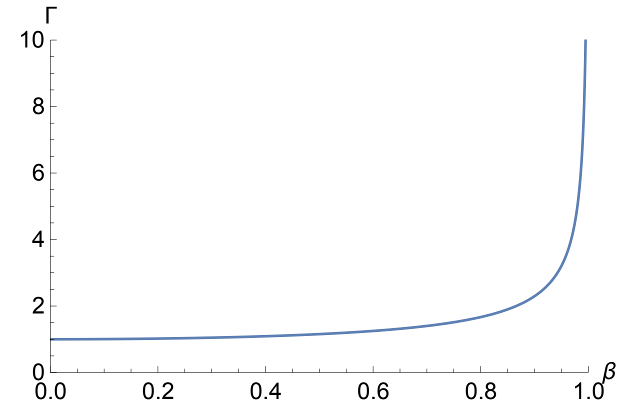
Suzuku-Vidal 2015

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:

$$t = \Gamma t'$$

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

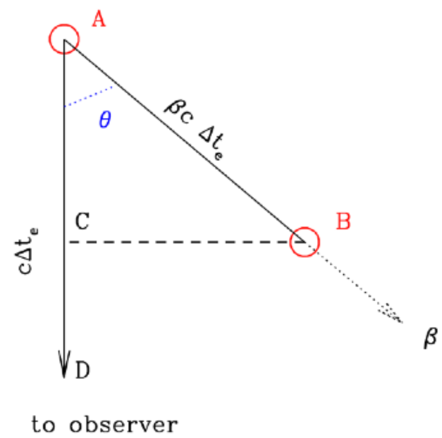
DOPPLER BOOSTING

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

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

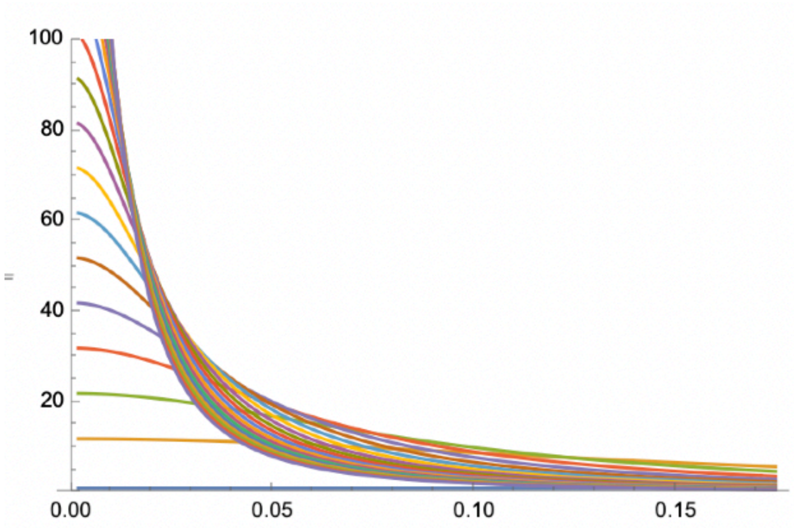
and similarly $\nu = \delta\nu'$

where δ is the Doppler factor



For the flux:

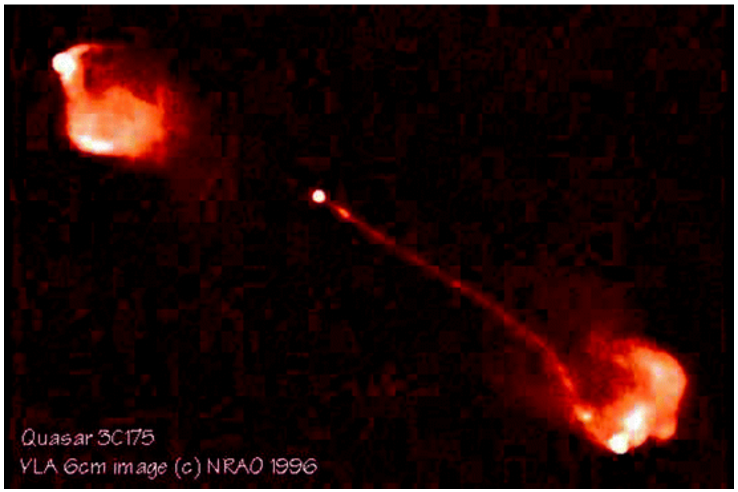
$$F_\nu = \delta^3 F'_{\nu'}$$

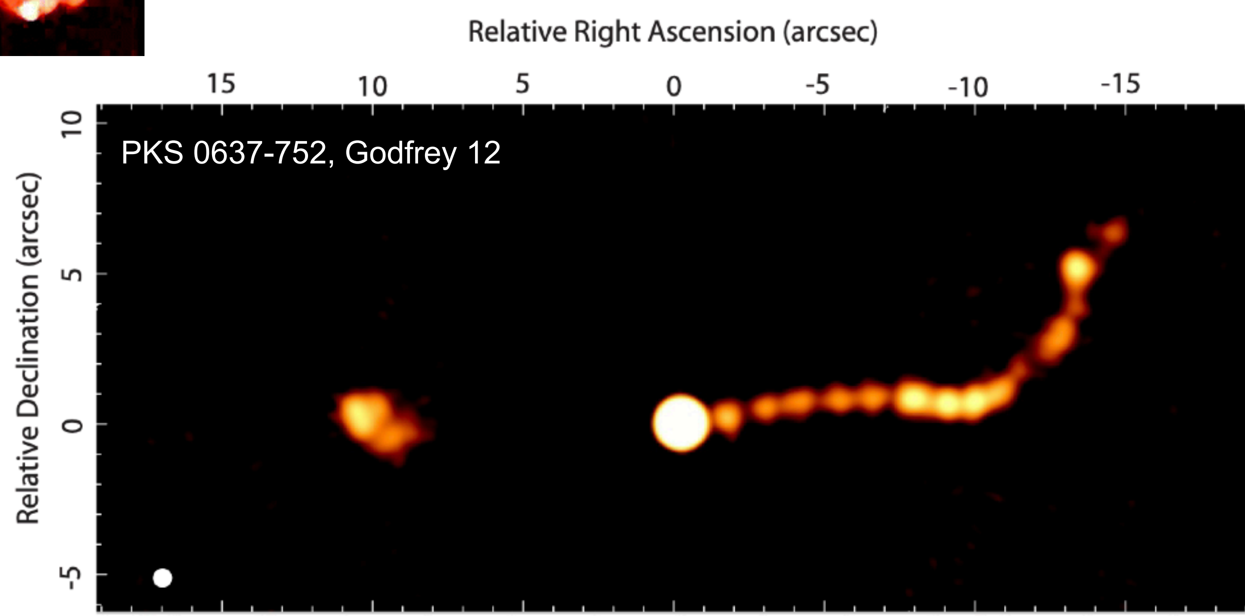


N.B.: This is for a single plasmoid;
If extended region, it goes as δ^2

JET / COUNTER-JET

Observations





JET / COUNTER-JET

For a receding jet:

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

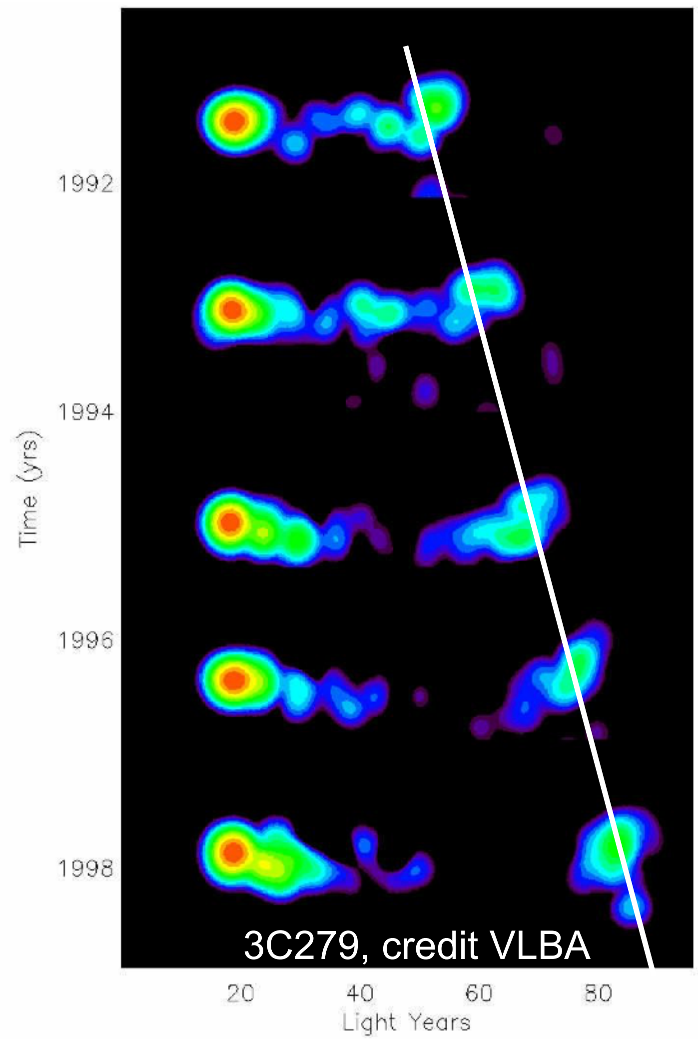
And so the flux ratio is $\frac{F_{jet}}{F_{counter-jet}} = \left(\frac{1 + \beta \cos \theta}{1 - \beta \cos \theta}\right)^3$

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!

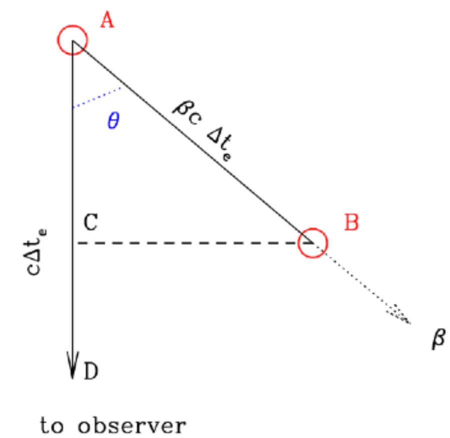
SUPERLUMINAL MOTION

In frame K:

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

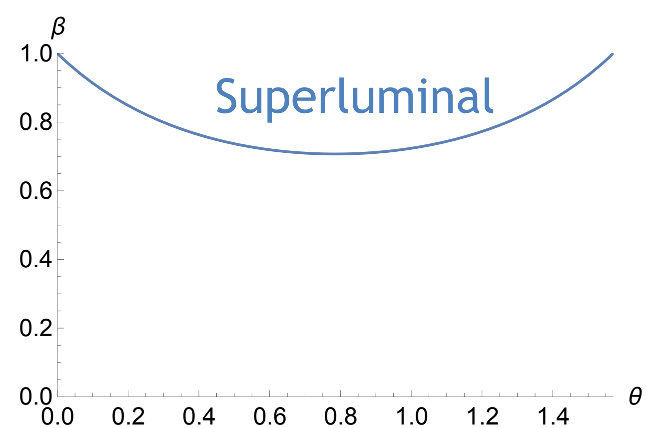
In B the knot moved towards us by
$\beta c \Delta T \cos\theta$.

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



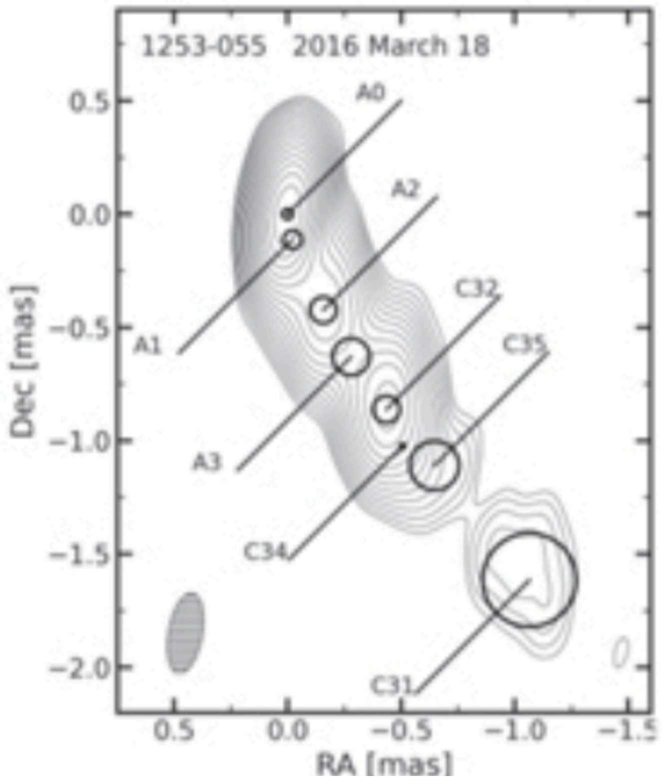
The inferred velocity of the *projected* component is $\dfrac{\beta c \Delta T \sin\theta}{\Delta T - \beta \Delta T \cos\theta}$

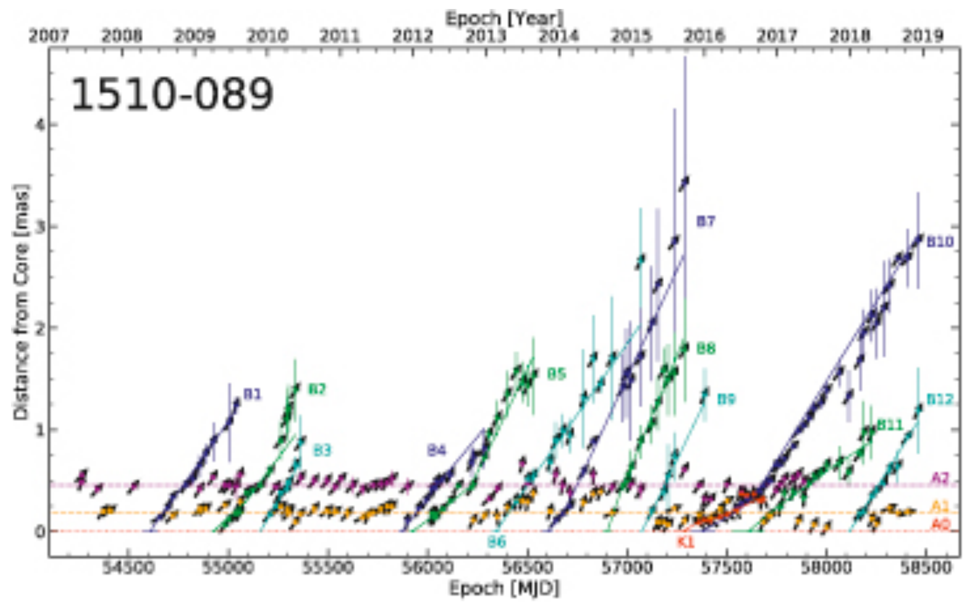
This can be > c if $\beta > \dfrac{1}{\sin\theta + cos\theta}$



KNOTS

Monitoring of features over several years
Moving vs standing knots

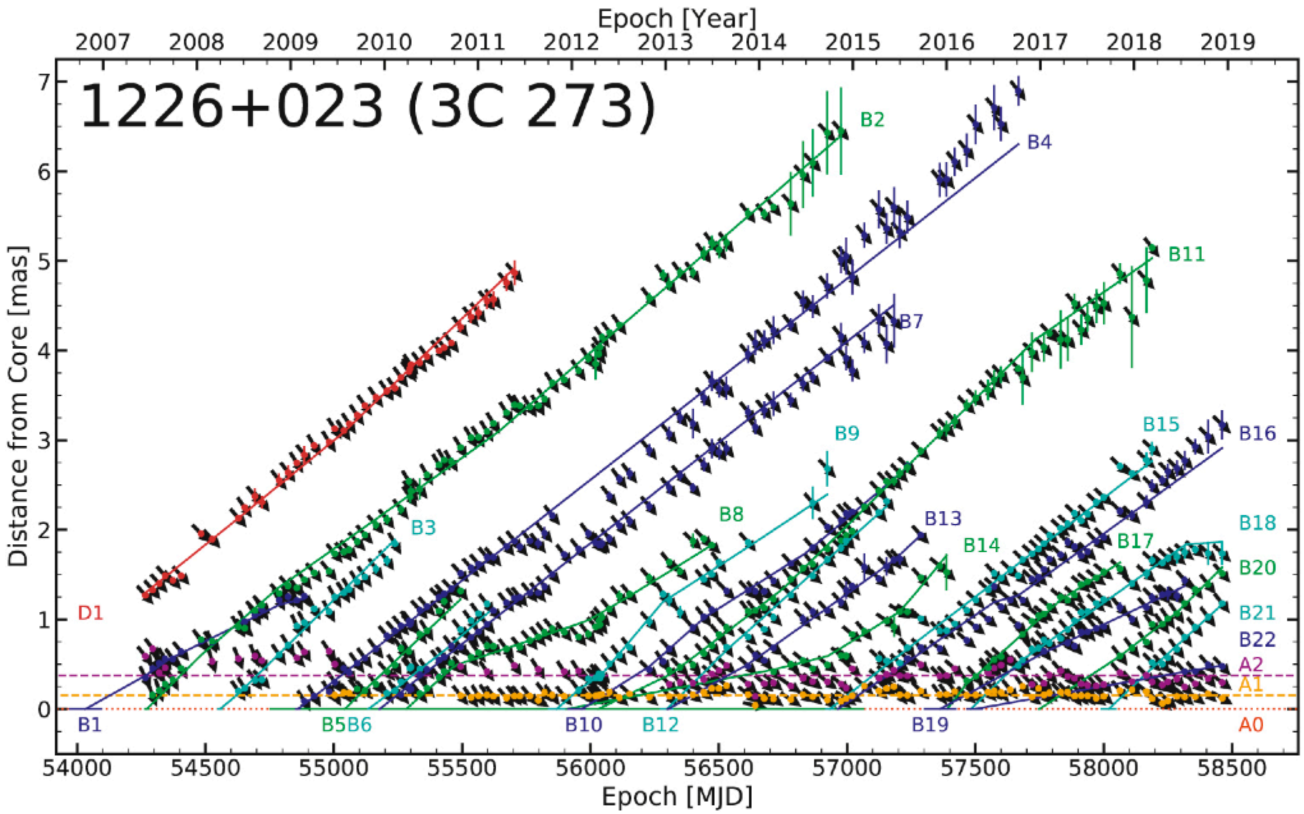




Weaver 22

KNOTS

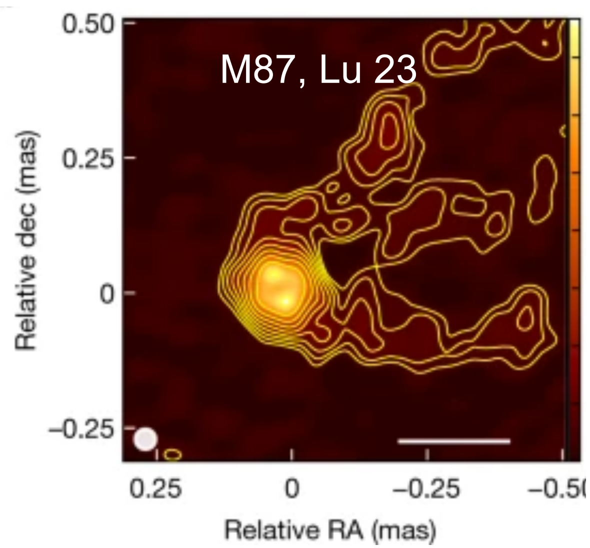
New ejections and trailing knots

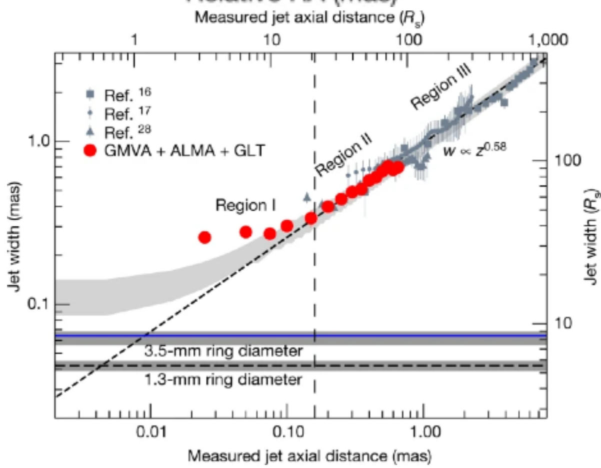


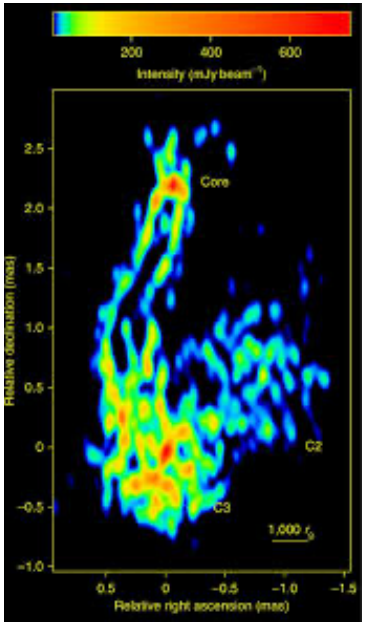
Weaver 22

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



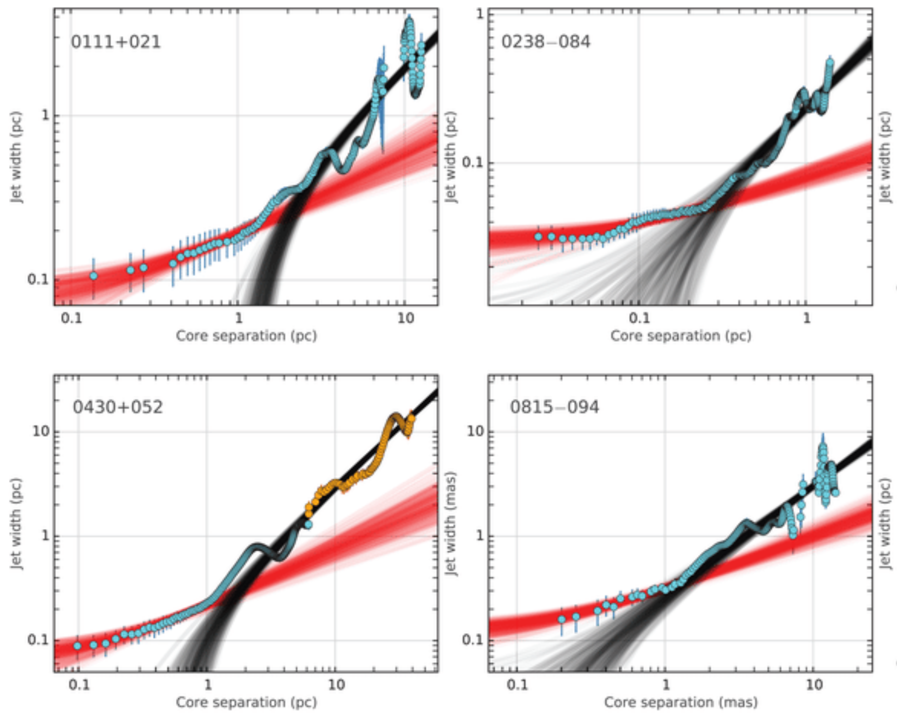




3C84, Giovannini 18

JET PROFILE AND COLLIMATION

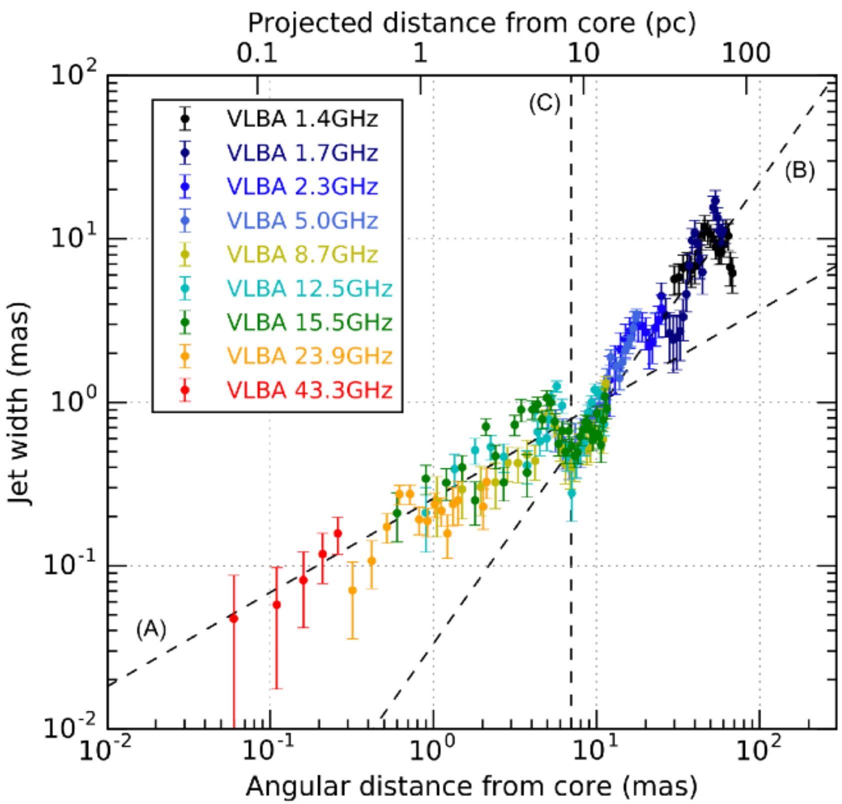
What is the jet shape? Far away it looks cylindrical
Close to the black hole we see conical and parabolic sections

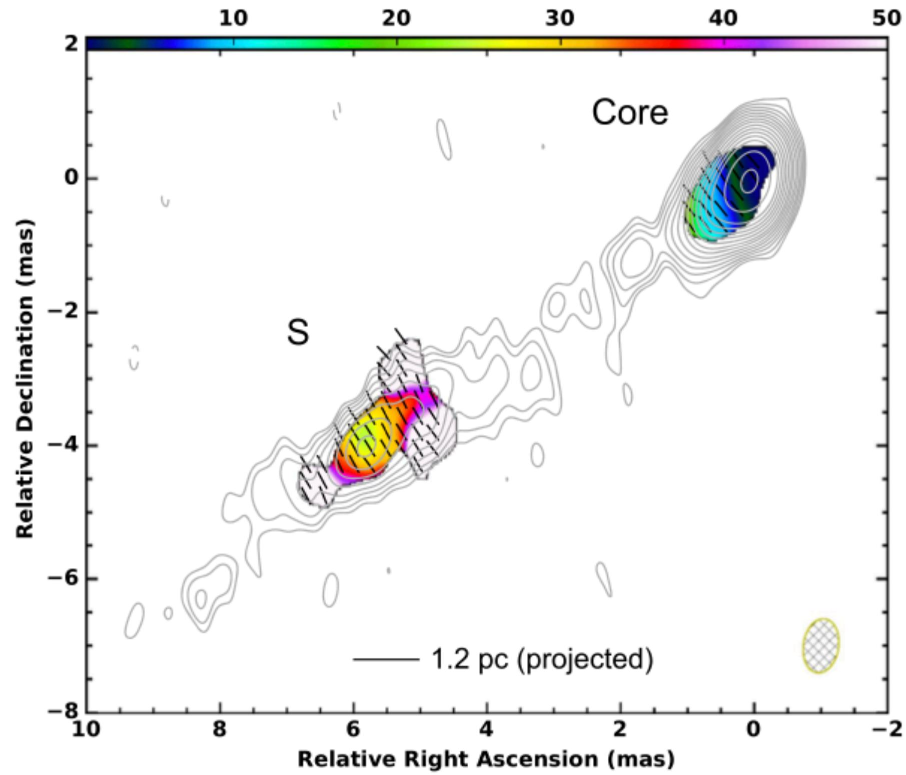


Kovalev 20

RECOLLIMATION SHOCKS

Are stationary features recollimation?



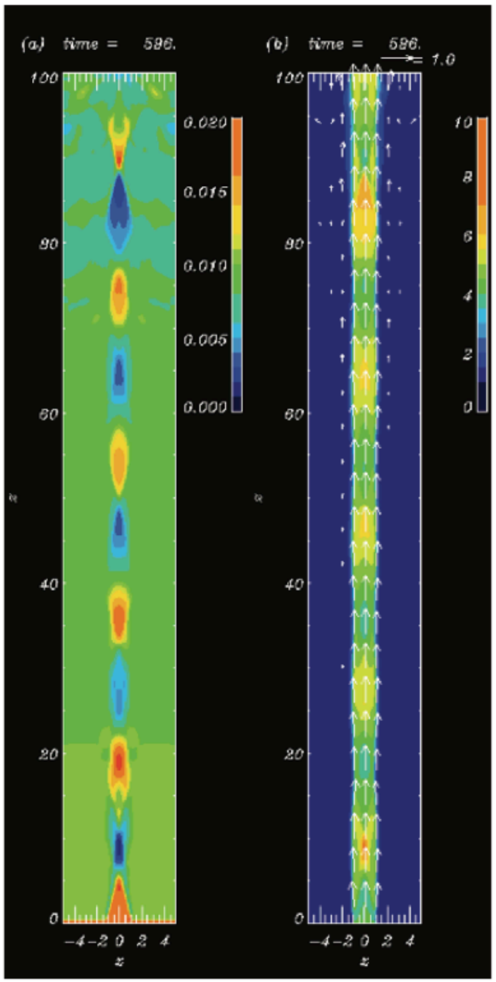


1H 0323+342, Nada 18

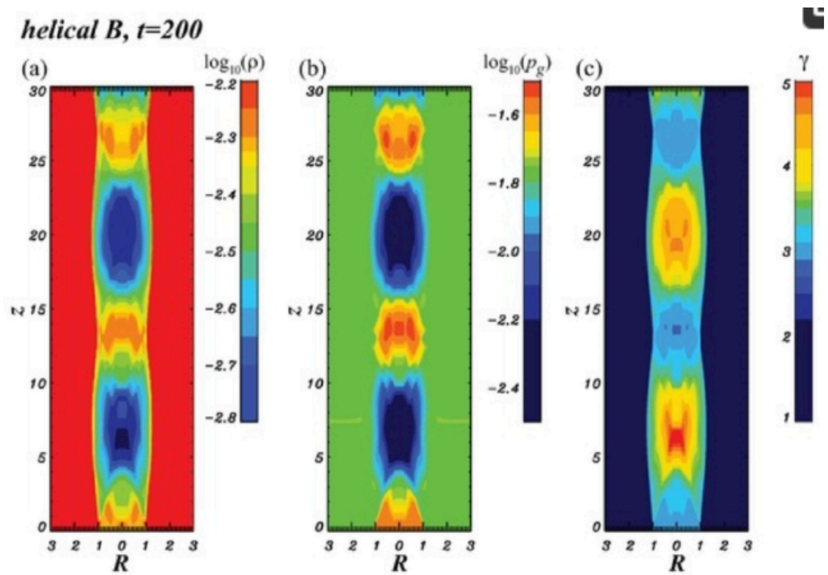
Matteo Cerruti

RECOLLIMATION SHOCKS

Simulations



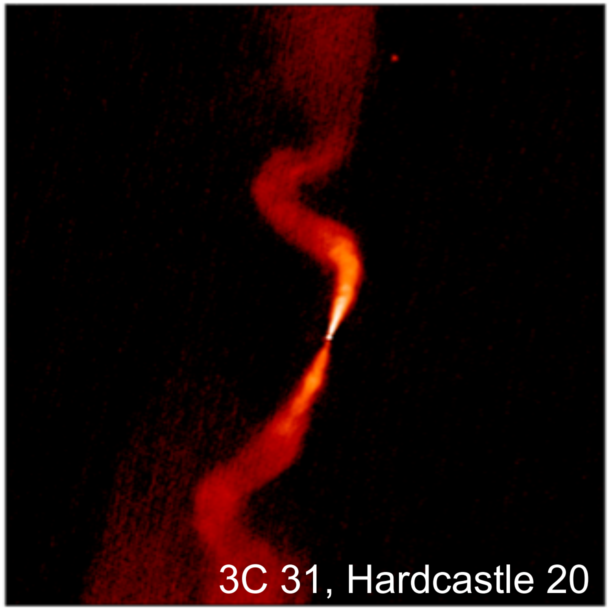
Nishikawa 13

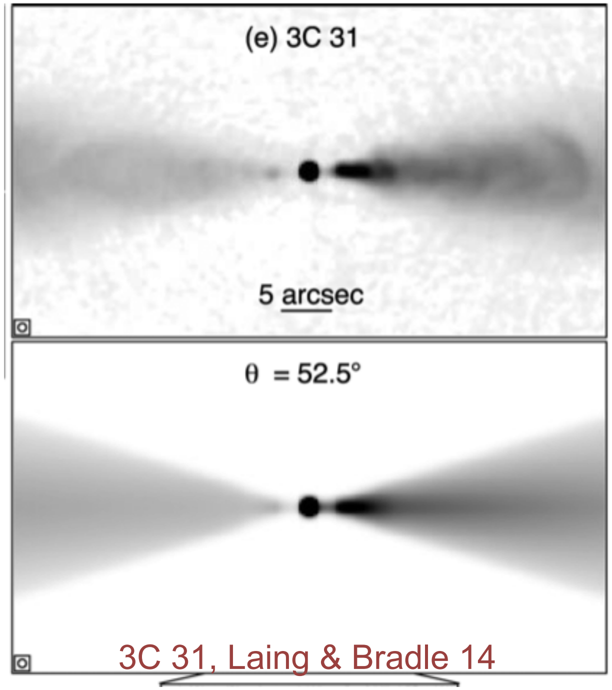


Mizuno 15

DECELERATION

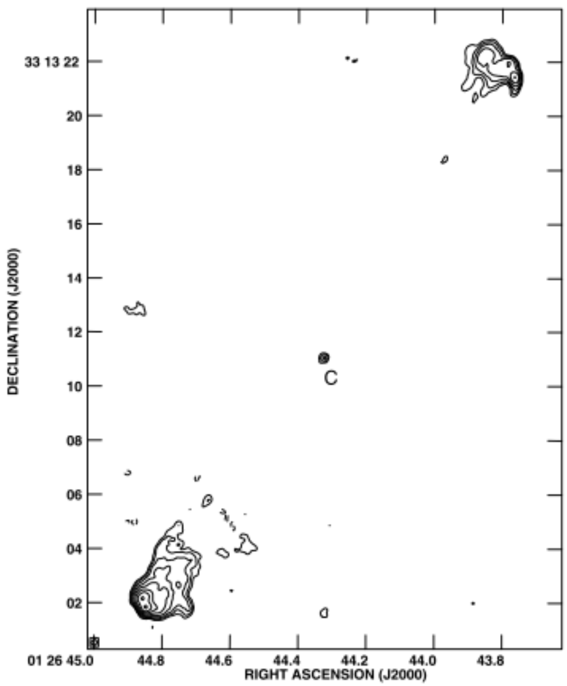
How does the jet end?
- Deceleration and disruption



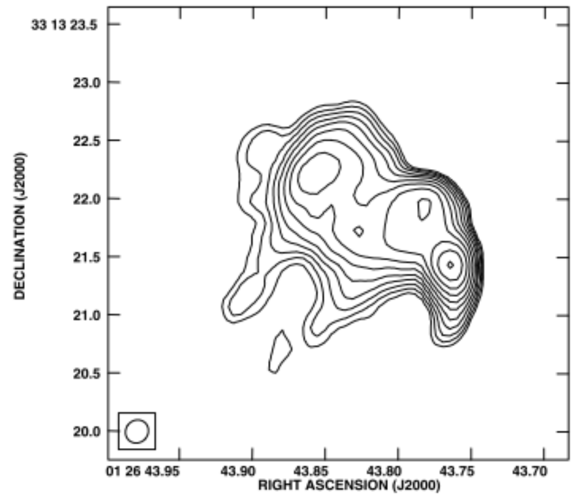


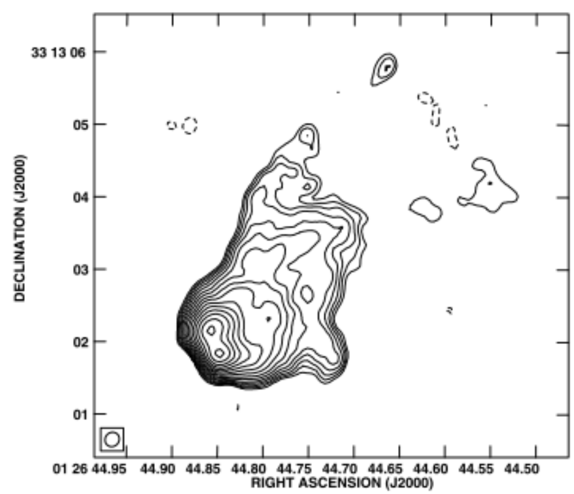
TERMINATION SHOCKS

How does the jet end?
- Termination shock



3C 41, Kharb 08





TERMINATION SHOCKS

How does the jet end?
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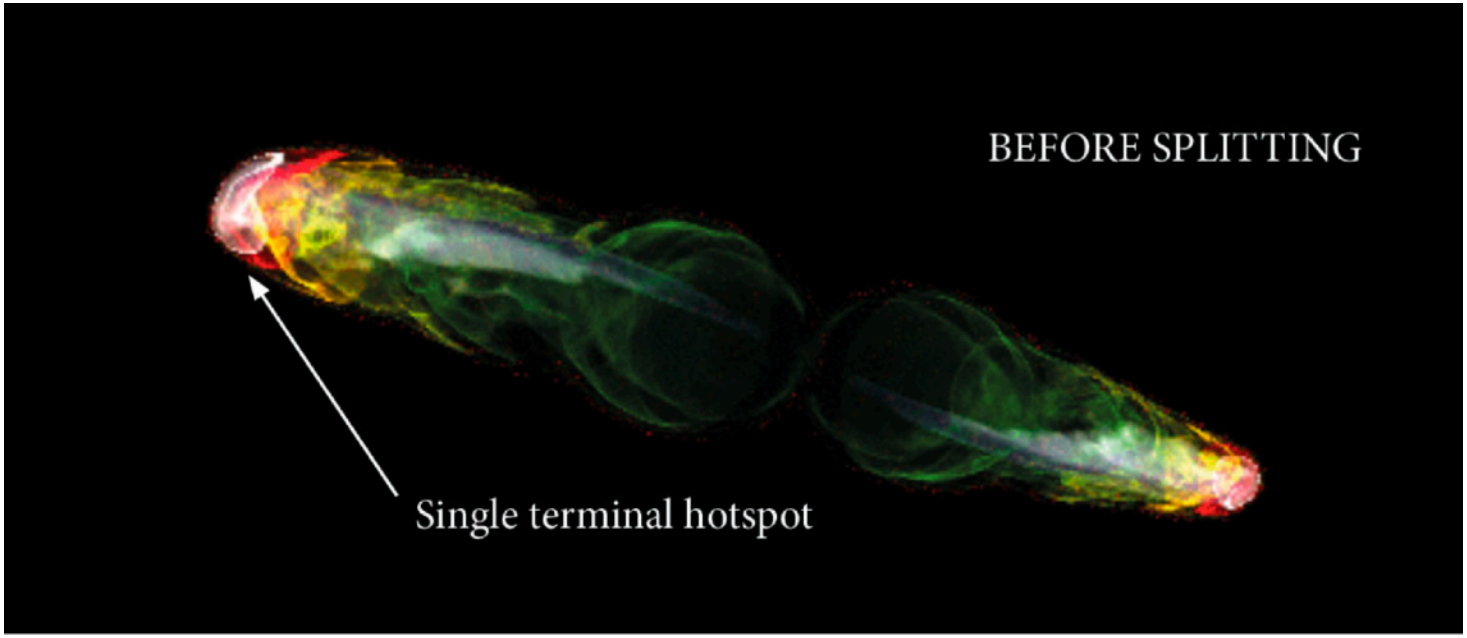
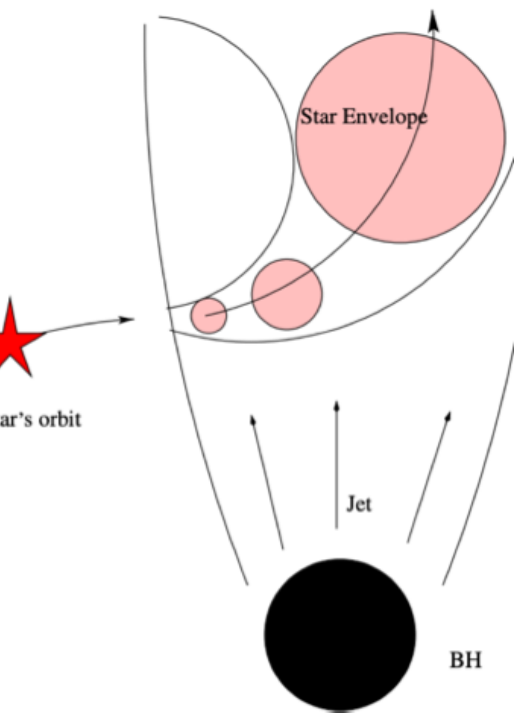


Horton 23

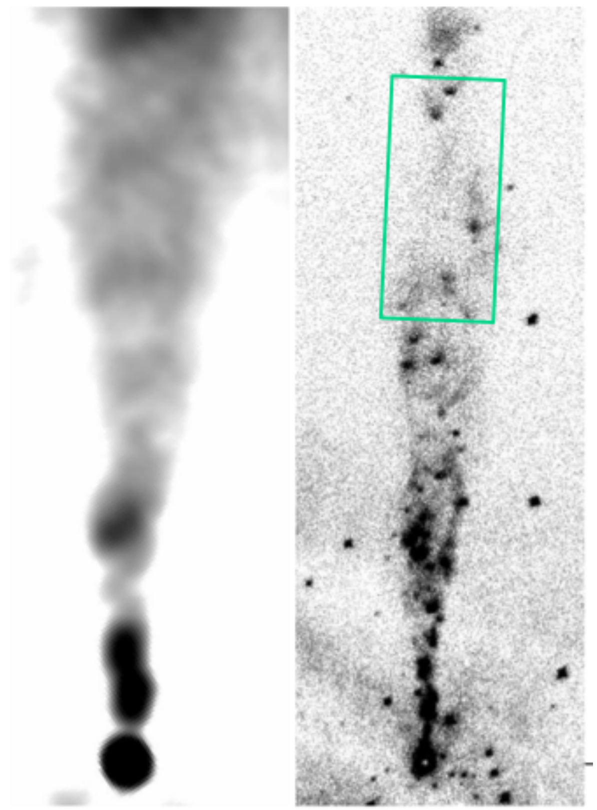
JET and OBSTACLES

The jet interacts with its environment

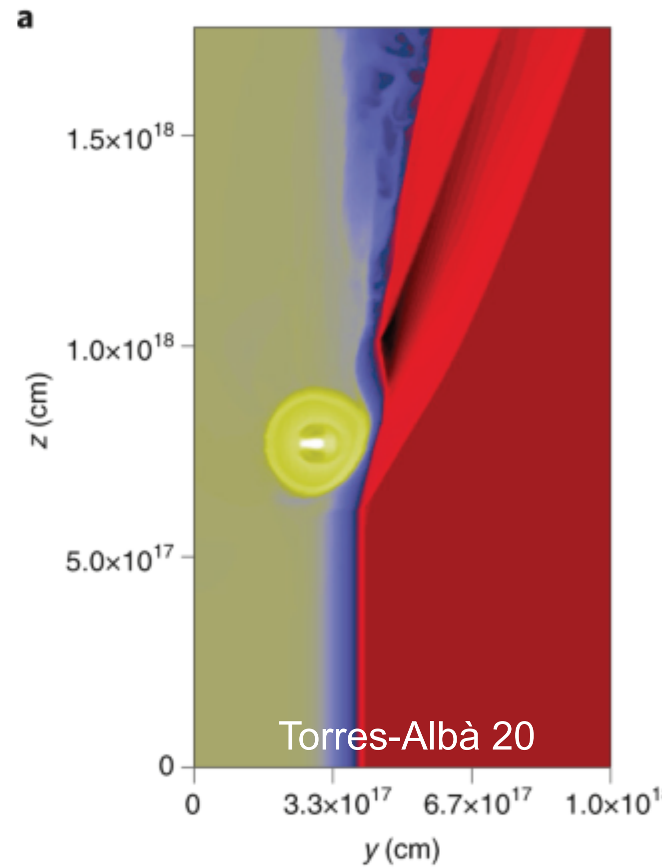
It *has to* collide with clouds and stars in the galaxy



Barkov 12

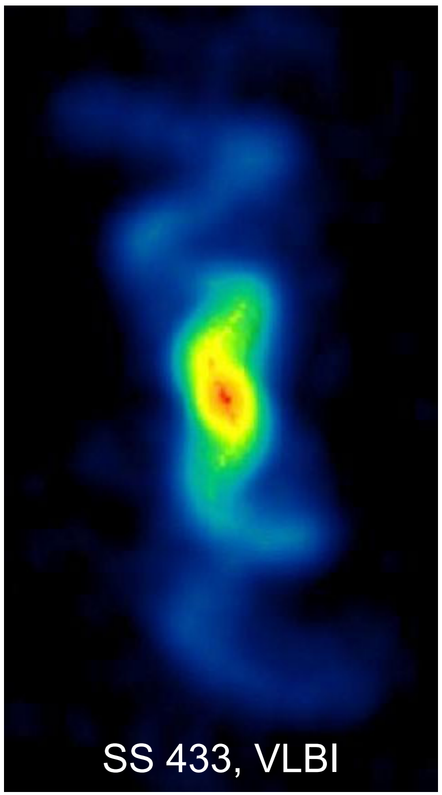


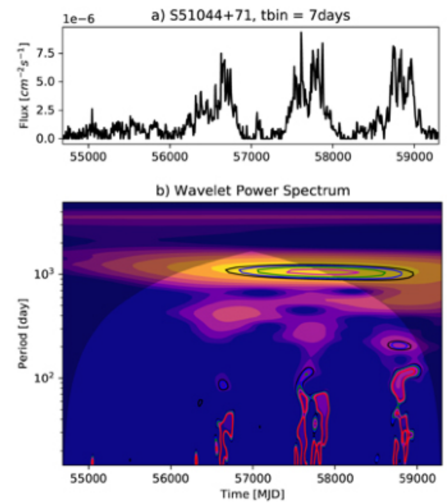
Cen A, Wykes 15



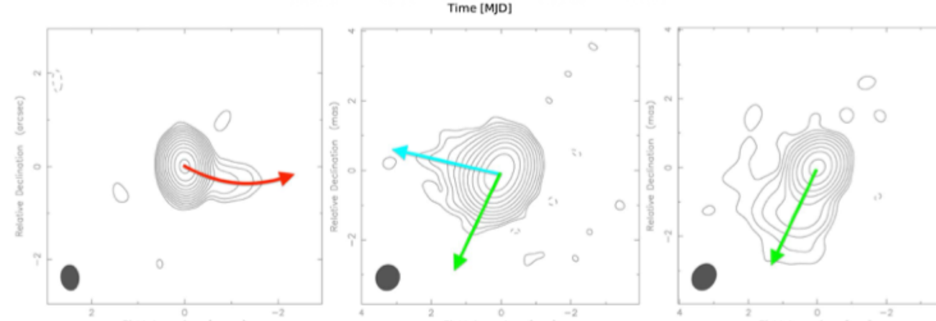
PRECESSION

Observational evidences





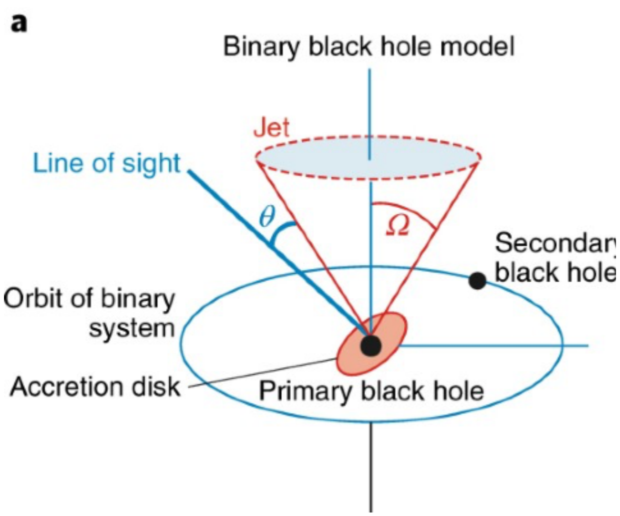
Ren 23



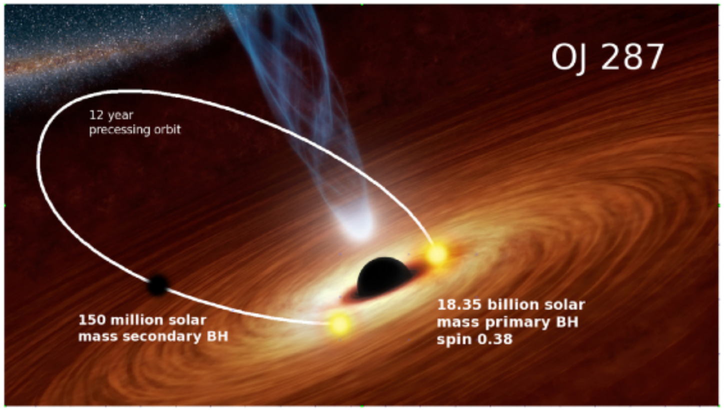
S5 1044+719, Kun 23

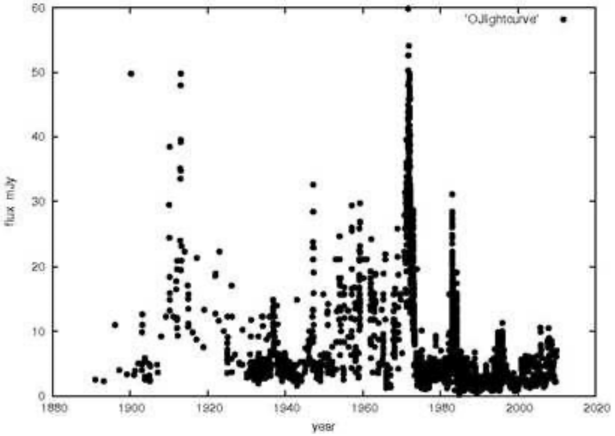
PRECESSION

OJ 287 & binaries



Abraham 18

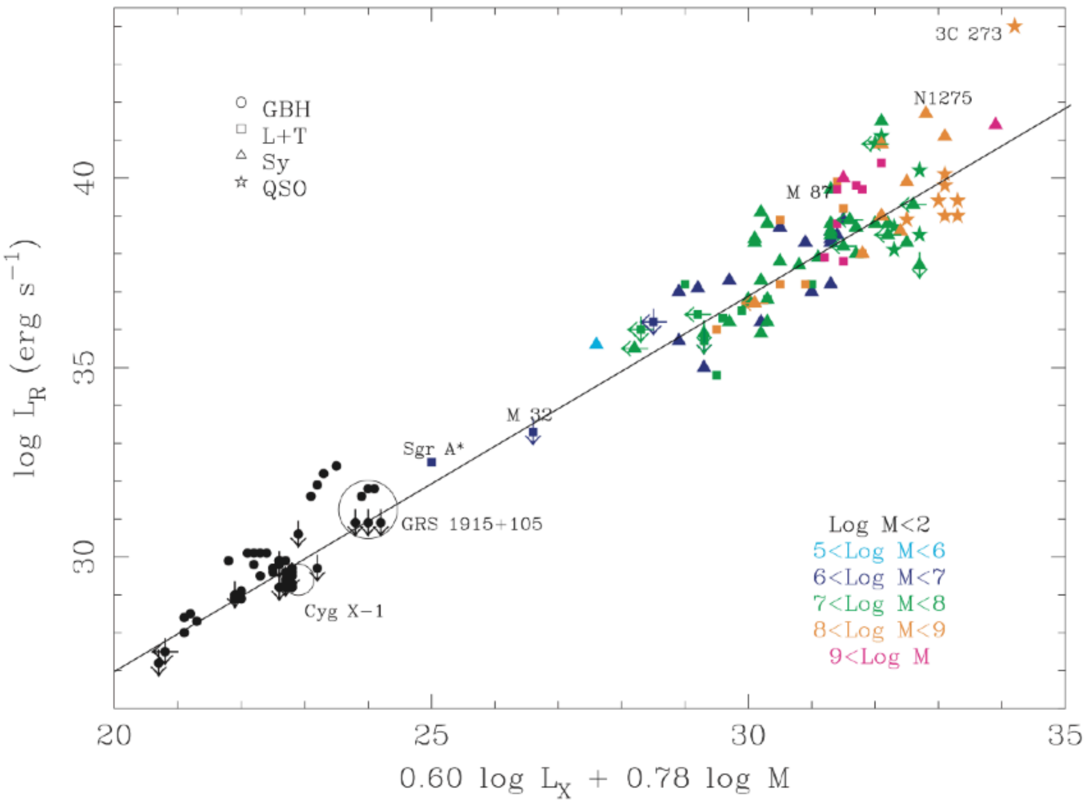




Valtonen 11

JET UNIFICATION

A fundamental plane connecting jets at various scales



Merloni 03

JET ENERGY EXTRACTION

Why? Jets require an enormous energy source.

- It has to come from somewhere

Three main mechanisms are introduced

- Penrose: Direct extraction from a rotating black hole via particle splitting in the ergosphere.

- Blandford - Znajek : Extraction of rotational energy via magnetic fields threading the black hole horizon.

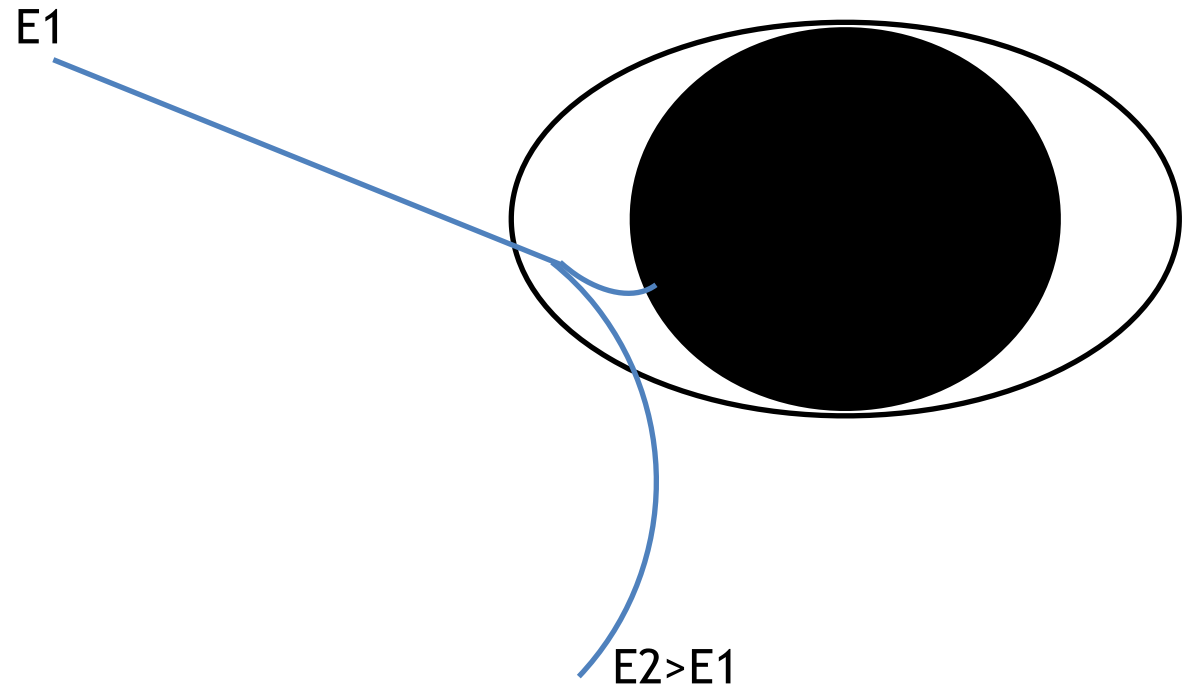
- Blandford-Payne: Disc-driven outflows launched centrifugally along open magnetic field lines

N.B. we will write down some equations but most of these things need magneto-hydrodynamic with gravitational relativity.

PENROSE PROCESS

Concept:

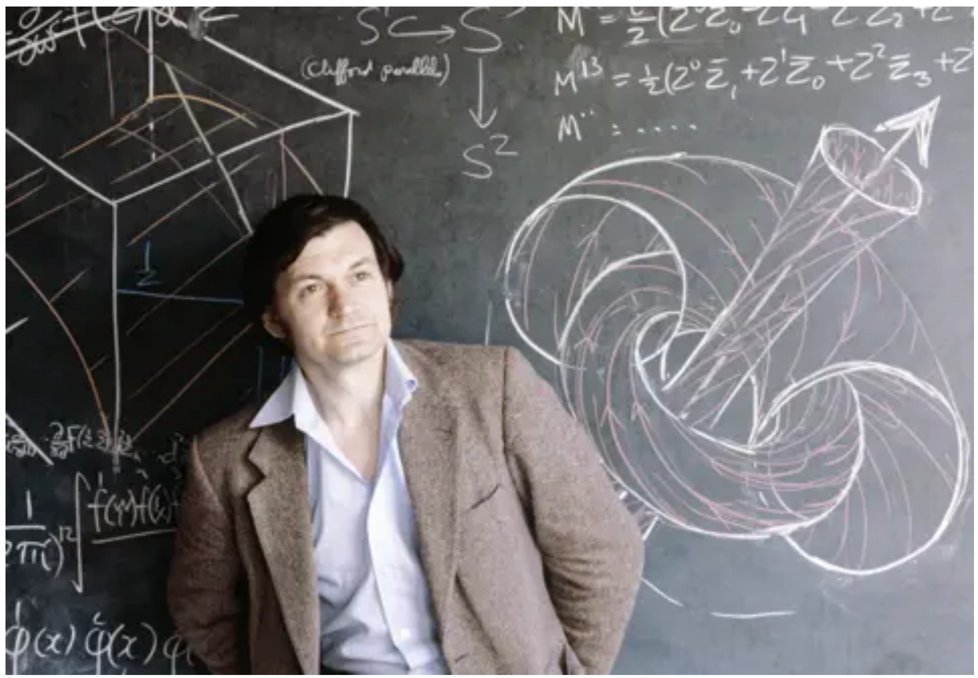
- In the ergosphere of a rotating (Kerr) black hole, particles can have negative energy (relative to infinity).
- A particle enters the ergosphere and splits into two.
- One fragment falls into the black hole with negative energy; the other escapes with energy greater than the initial one.



KNOW YOUR ASTROPHYSICIST!

Roger Penrose
(Colchester, UK; 1931)

2020



PENROSE PROCESS

Energy Extraction Efficiency:

- Maximum theoretical efficiency is roughly $\eta_{Penrose}$ ~29% for extreme Kerr black holes.
- For a particle of rest mass m, the energy gain is linked to the angular momentum and the geometry of the ergosphere.
- The efficiency is

$$\eta = 1 - \frac{M^\star}{M}, \text{ with } (M^\star)^2 = \frac{1}{2}M^2(1+\sqrt{1-a^2})$$

- the energy is extracted *from* the black hole, that in exchange loses angular momentum. As it does so, the ergosphere shrinks!

N.B. the efficiency is the maximum possible. Can this work in a systematic way? Unclear… but it shows that energy can be extracted.

ADDING MAGNETIC FIELDS

Why?

- Magnetic fields offer a more robust channel for (continuous) energy extraction
  - Blandford - Znajek taps the black hole directly via magnetic field (plus ergosphere)
  - Blandford - Payne uses the accretion disk's rotational energy

  - these are the only two mechanisms widely regarded as relevant in astrophysics

  - N.B. Black-hole electrodynamic (GR+Maxwell) / GRMHD are needed. A full demonstration is beyond this class.

Matteo Cerruti

BLANDFORD-ZNAJEK

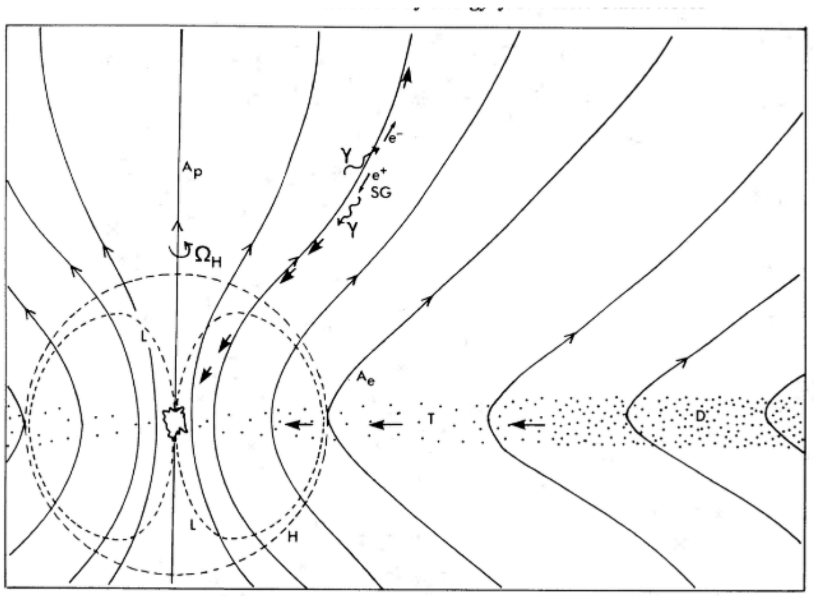
Basic Idea:

- Magnetic field lines, anchored in the surrounding accretion flow, thread the event horizon.
- Rotational energy is extracted electromagnetically via a Poynting flux.

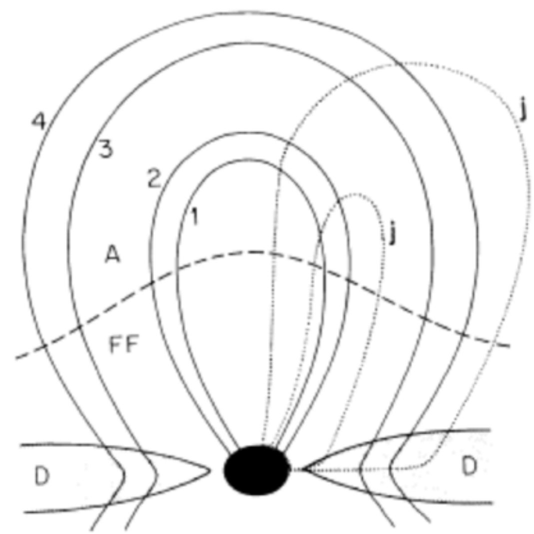
- A spinning black hole in a magnetized environment generates a twisting of field lines, which drives an outward electromagnetic energy flux.

- It needs two key ingredients: a magnetic field and a spinning black-hole

BLANDFORD-ZNAJEK



Blandford & Znajek 1977



Macdonald & Thorne 1982

$$P_{BZ} = 4 \times 10^{46} \, (\frac{B}{10^4 G})^2 (\frac{M}{10^9 M_\odot})^2 a^2 \text{ erg/s}$$

BLANDFORD-ZNAJEK

Efficiency

- The efficiency η_{BZ} (ratio of jet power to rest–mass energy accretion rate) can reach ~10%−30% for rapidly spinning black holes.

Dependency on the magnetic field

- Stronger magnetic fields (larger Φ_B) enhance the extracted power.

Dependency on the spin

- It depends on the square of a -> a higher spin has an important role

On the accretion

- The magnetic field comes from the accretion disk. No jets without accretion!

BLANDFORD-PAYNE

Overview

- Outflows launched centrifugally from an accretion disk along open magnetic field lines.

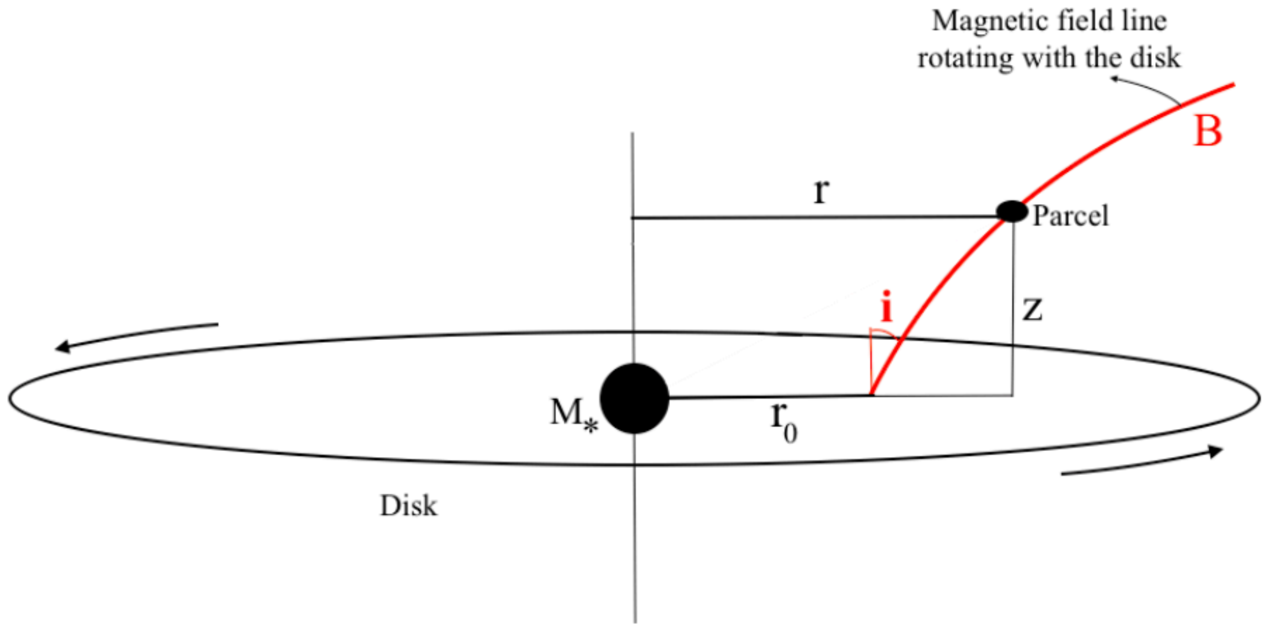
- Requires that the field lines be inclined at an angle less than 60 degrees to the disk surface for effective launching.

- Disk plasma “slides” along field lines

- Centrifugal force overcomes gravity if the angle is favorable.

N.B. Here the energy is coming from the disk, not from the black hole (although the disk is coming from accretion, so ultimately the energy reservoir is still the gravitational potential)

BLANDFORD-PAYNE



WHICH ONE?

BZ:

- Energy from the black hole;
- Needs large scale magnetic field near the horizon; and a spinning BH
- Produces highly-relativistic, Poynting-flux-dominated jets

BP:

- Energy from the accretion disk;
- Depends on the field line geometry and disk rotation
- Produces jets with lower Lorentz factors and broader opening angles

Both mechanisms can operate simultaneously

In practice, we use numerical simulations to study jet launching from compact objects

NUMERICAL SIMULATIONS

1) Talk by R. Blandford
   https://www.youtube.com/watch?v=cI2bWss4iL0

2) Simulations of jet launching by Fendt and colleagues
   https://www2.mpia-hd.mpg.de/homes/fendt/movies.html#1fendt

KNOW YOUR ASTROPHYSICIST!

Roger Blandford
(Grantham, UK; 1949)

NON–RELATIVISTIC & NON–COLLIMATED OUTFLOWS

Outflows not confined to narrow jets: broader, often quasi–spherical or wide–angle flows.

- Accretion Disk Winds: driven by radiation, thermal, or magnetic forces.
- Ultra–Fast Outflows (UFOs): high–velocity, wide–angle winds seen in AGN X–ray spectra.
- Compact Object Outflows: e.g., Pulsar Wind Nebulae (PWNe)
- Galactic–Scale winds: superbubbles from star clusters and starburst galaxies.

THERMAL WINDS

- Heat leads to thermal movement that might be sufficient to escape

- Most easily working at large radii ($v \propto r^{-1/2} \rightarrow T \propto r^{-1}$)

- Main heating is Compton scatter on electrons. We can define a Compton temperature Tc

$$r_{crit} \simeq \frac{GM\mu m_p}{k_B T_C}$$

$$r/r_g \simeq 6 \times 10^5 \frac{10^7 K}{T_C}$$

LINE-DRIVEN WINDS

- Key reference is the Castor, Abbott & Klein (CAK) paper (1975).

- Radiation carries momentum (p=E/c) that is transferred to matter when they are absorbed / scattered

1) electron scatter: transfer of momentum on free electrons

2) line absorption (line-driven winds): Many photons are absorbed in UV resonance lines of metal ions.
There is in practice a ‘force multiplier’ that depends on the number/strength of the lines, and ionization state

Line-driven winds work much better!!
It is the same process at works in winds from bright stars (OB, WR, …)

In an accretion disk, they are more efficiently present at low radii

ULTRA-FAST OUTFLOWS (UFOs)

Observational signature:

- Blue–shifted absorption lines in X–ray spectra (often Fe K lines).

Characteristics:

- Mildly relativistic , v ~ 0.1 - 0.3 c
- Wide angle (these are no jets, but speeds are relativistic!)

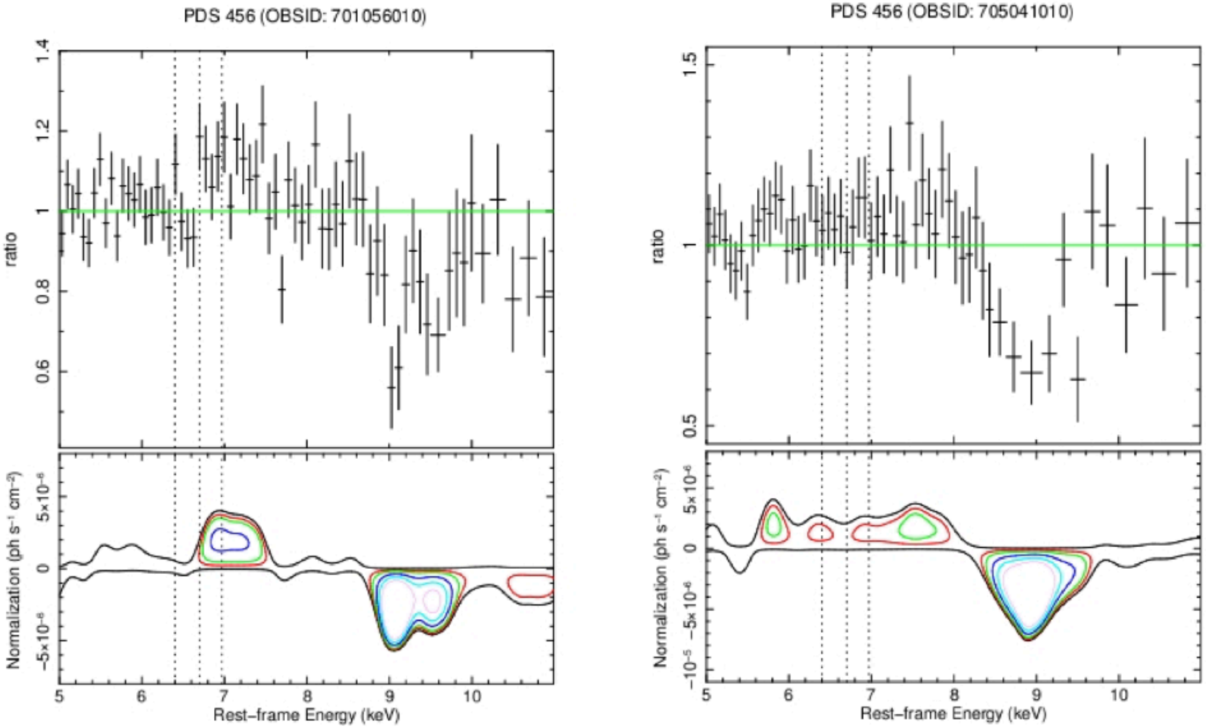
Kinetic Power:

$$\dot{E}_{UFO} = \frac{1}{2}\dot{M}_{UFO}v^2$$

UFOs can carry a substantial fraction of the accretion power and contribute to AGN feedback

ULTRA-FAST OUTFLOWS (UFOs)

PDS456 (RQ QSO, z=0.184)



SUPERBUBBLES FROM STELLAR CLUSTERS

- Bubbles inflated by the combined effects of stellar winds and supernovae from star clusters. This is a collective effect.

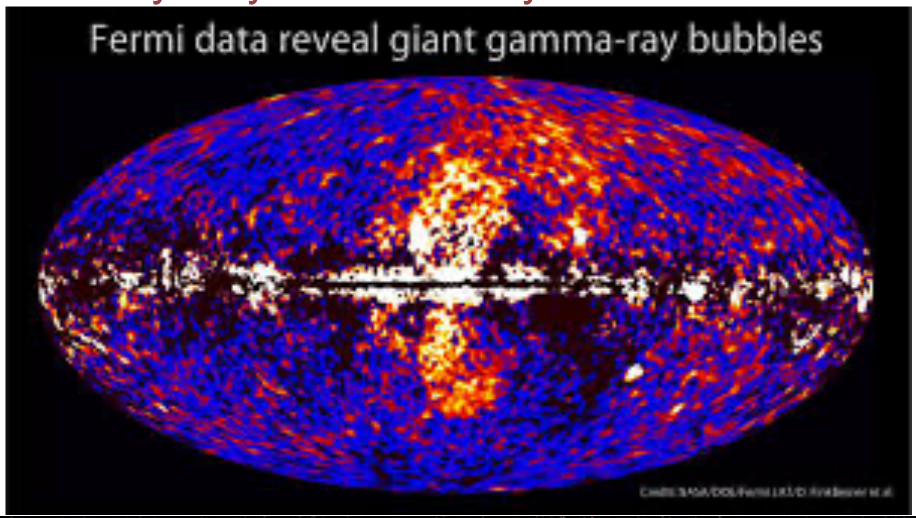
- Can be an important place for cosmic ray acceleration

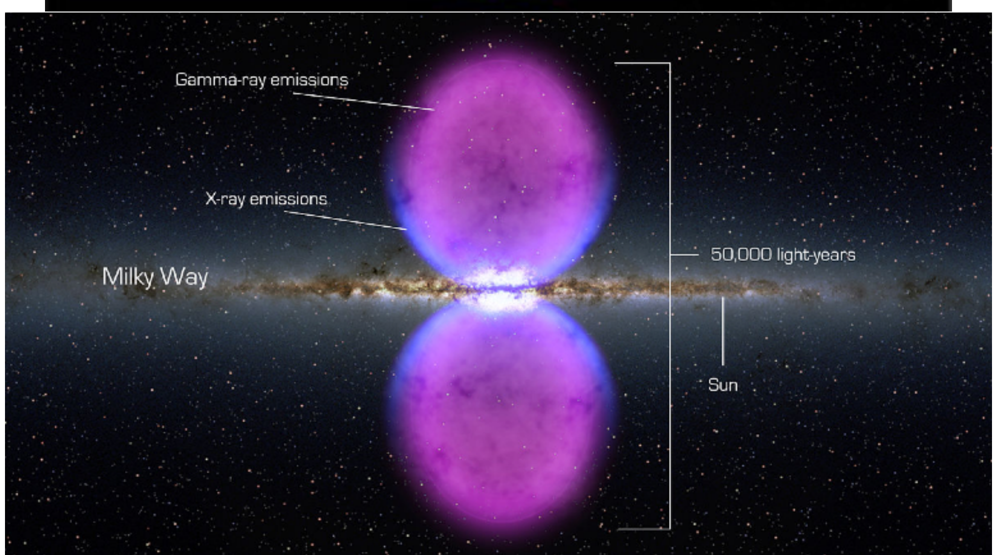
GALACTIC WINDS

- Combined energy from stellar winds and supernovae in starburst regions drives a large–scale outflow.

THE FERMI BUBBLES

New structure of our Milky Way discovered by Fermi

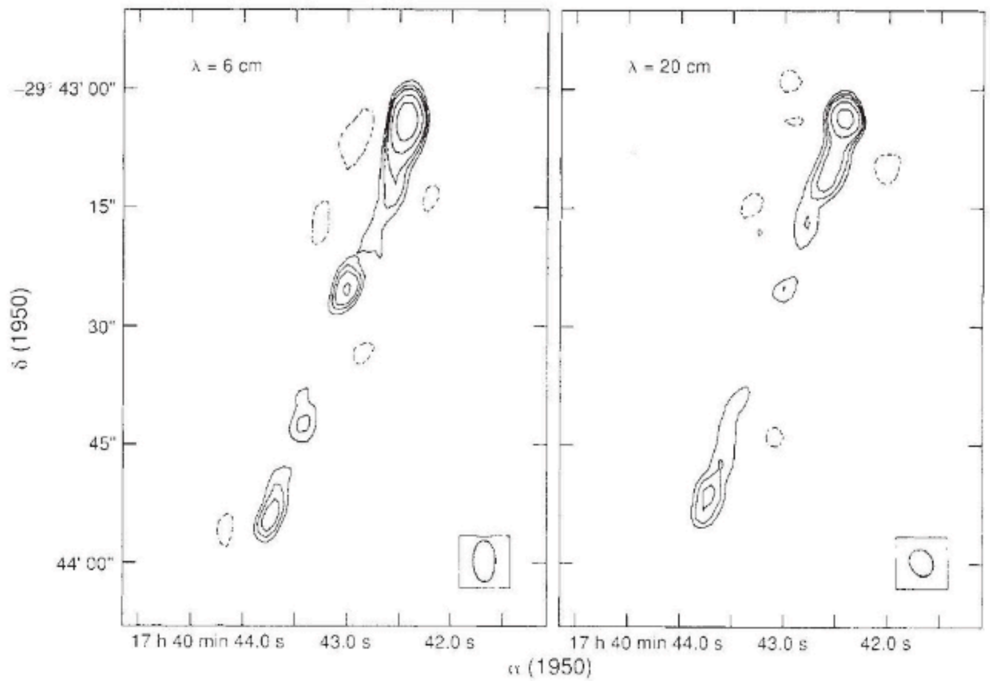




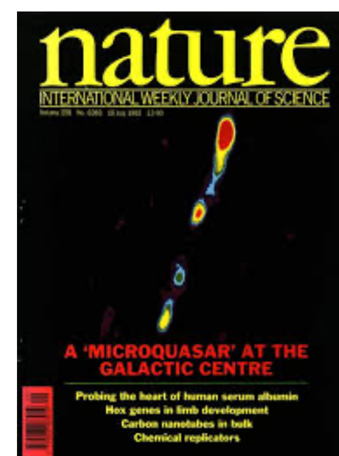
MICRO QUASARS

HISTORY

Follow up of bright X-ray sources in the Milky Way
First observations of jets that 'look like' quasars

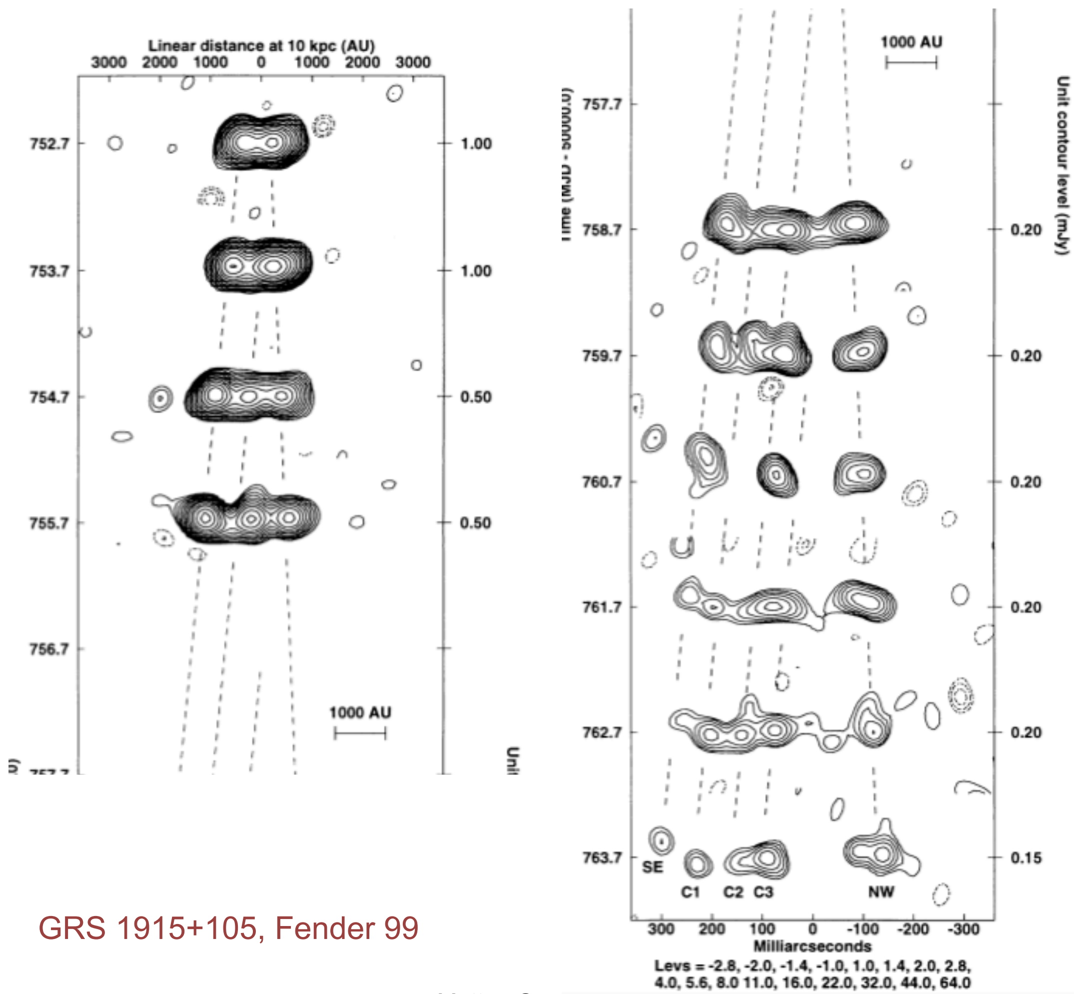


1E 1740.7-2942, Mirabel 92



HISTORY

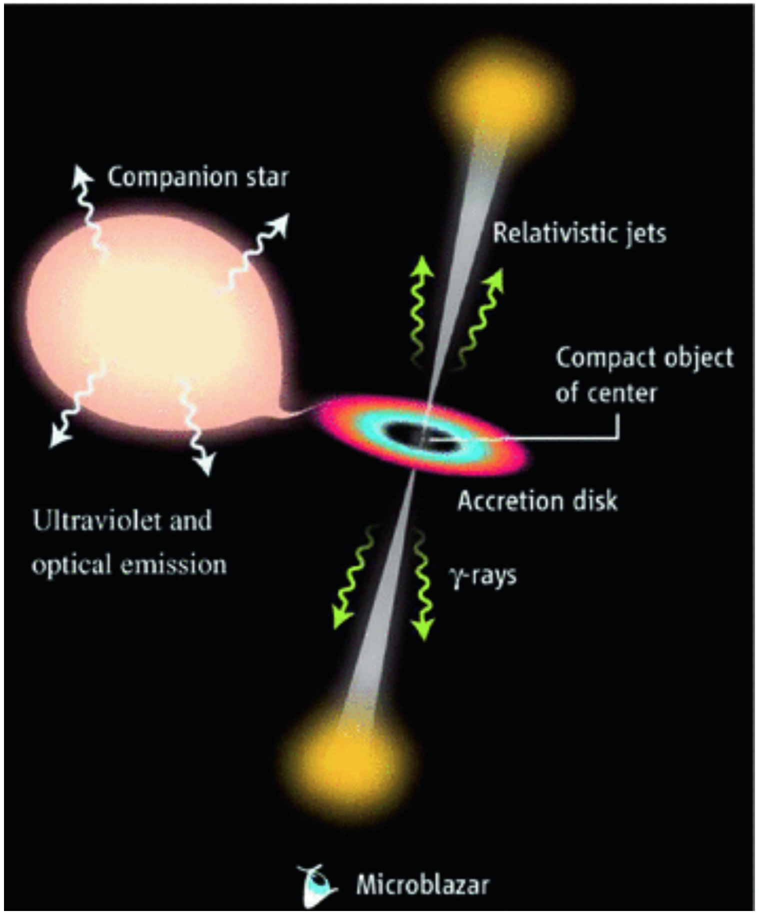
Confirmed by the discovery of superluminal motions



GRS 1915+105, Fender 99

WHAT IS A MICROQUASAR?

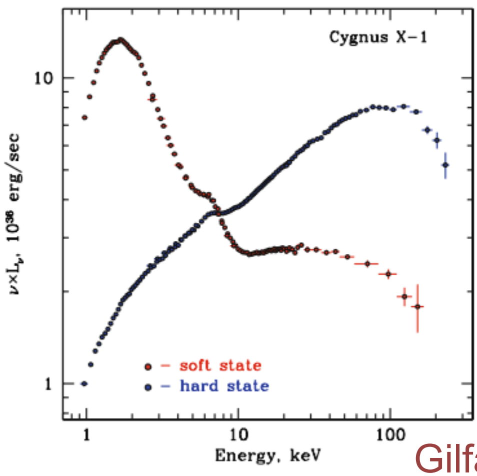
X-ray binary with radio jet

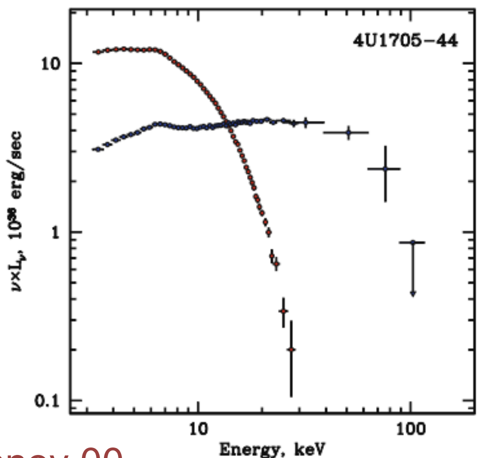


N.B. not all binaries are microquasars!

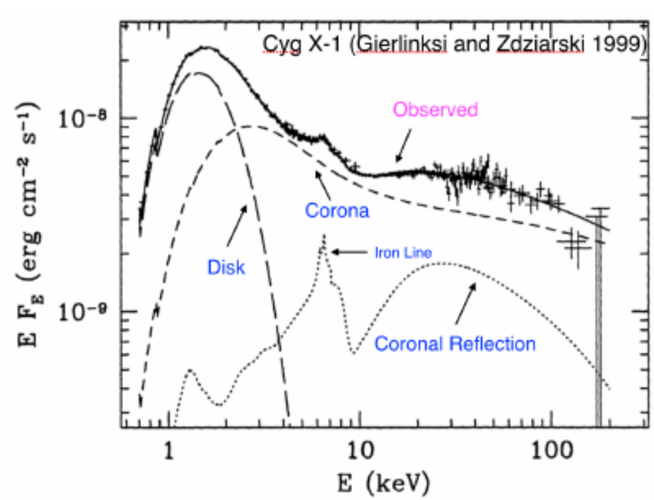
X-RAY EMISSION FROM MICROQUASARS

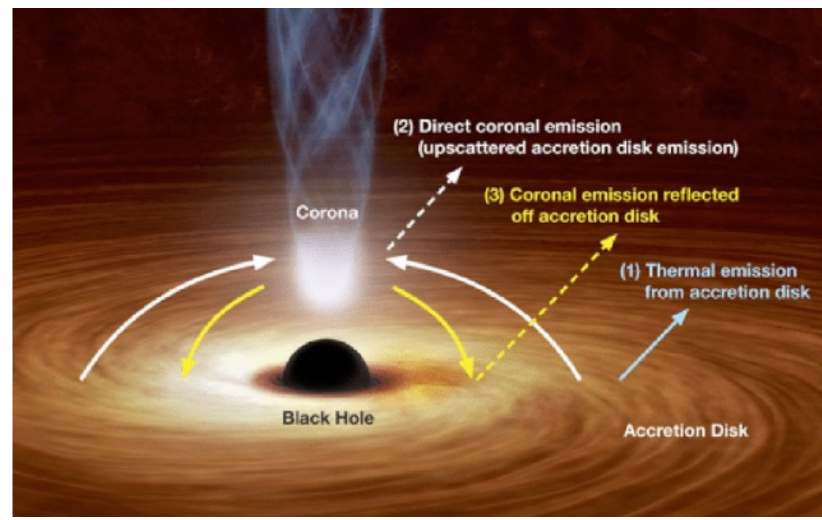
X-ray spectra from micro quasars



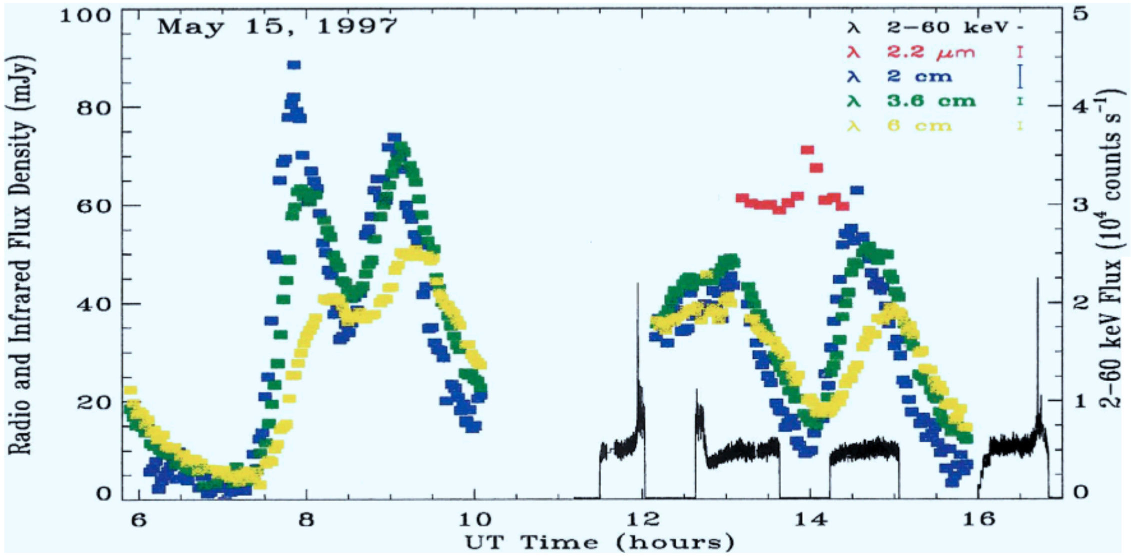


Gilfanov 00

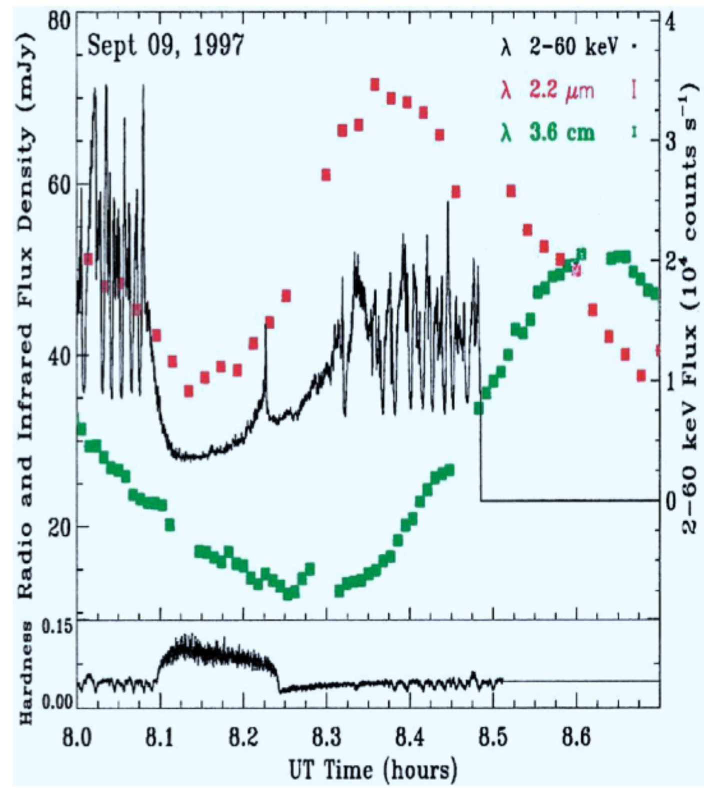




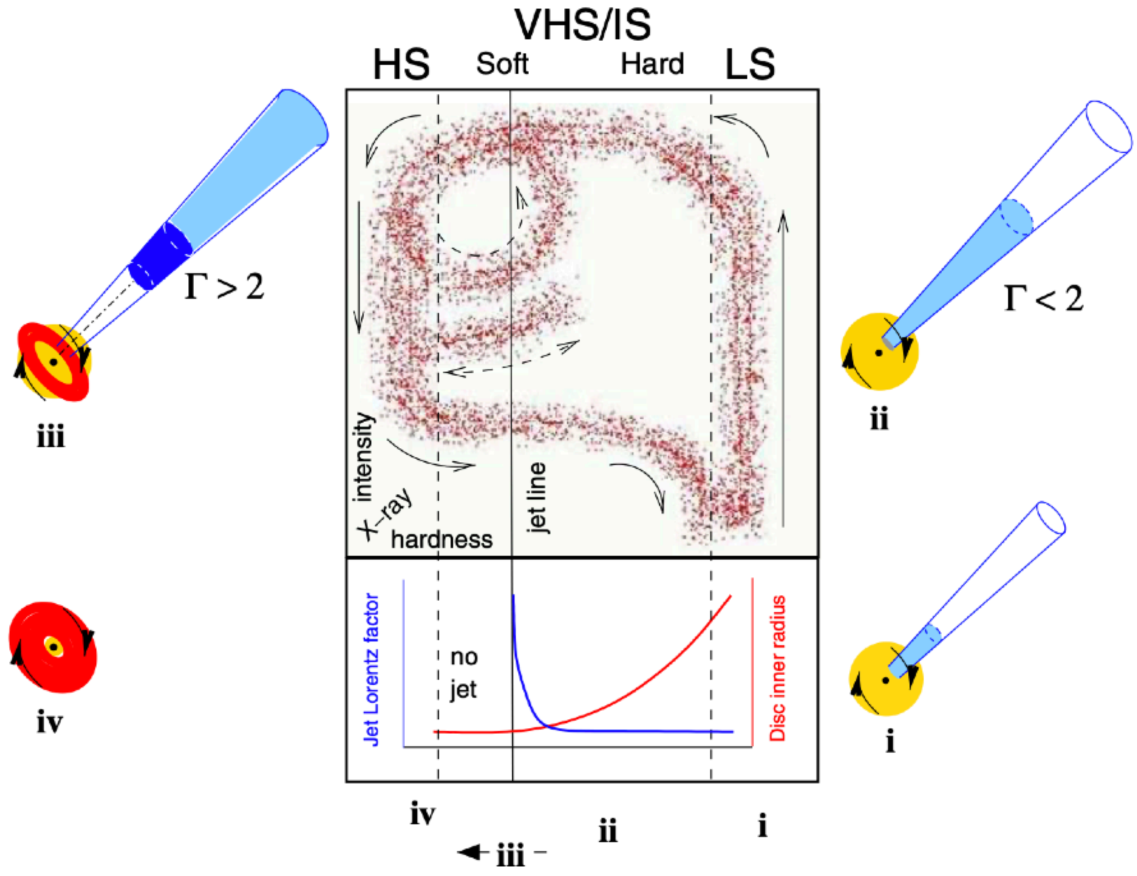
MWL EMISSION FROM MICROQUASARS



GRS 1915+105, Mirabel 97



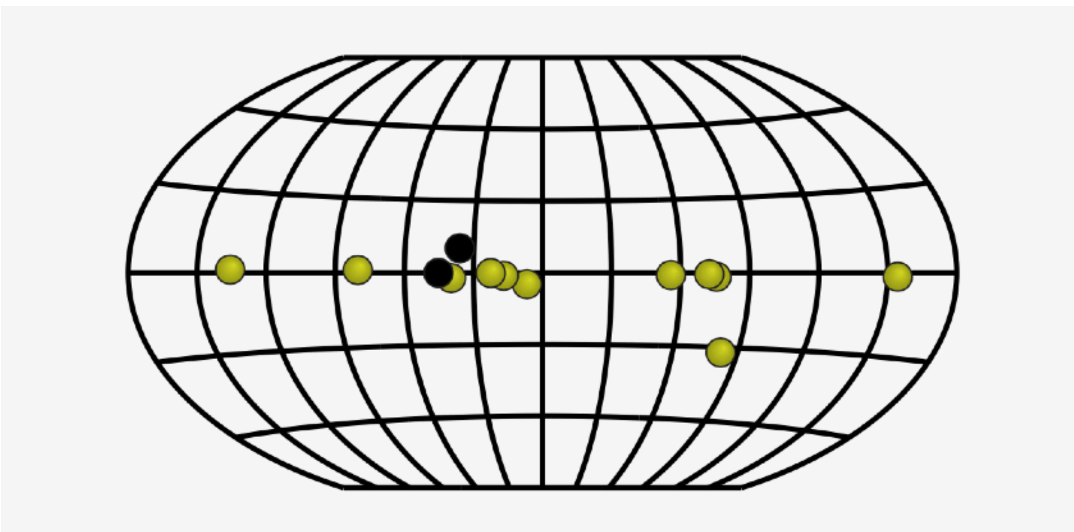
DIFFERENT STATES



Fender 04

GAMMA-RAYS FROM MICROQUASARS

13 binaries known in the TeV band,
but the emission is likely *not* associated with the jet



Name	RA	Dec	Type Tags	Distance	Catalog
LS I +61 303	02 40 34	+61 15 25	Gal,BIN	2.0 kpc	Default Catalog
LMC P3	05 36 00	-67 35 11	Gal,BIN		Default Catalog
HESS J0632+057	06 33 00.8	+05 47 39	Gal,BIN	1.4 kpc	Default Catalog
HESS J1018-589 A	10 18 58	-58 56 43	Gal,BIN		Default Catalog
Eta Carinae	10 44 35	-59 39 56.6	Gal,BIN	2.3 kpc	Default Catalog
PSR B1259-63	13 02 49.3	-63 49 53	Gal,BIN	2.7 kpc	Default Catalog
V4641 Sgr	18 19 21.63	-25 24 25.85	uQuasar,Gal,...	6.6 kpc	Default Catalog
MAXI J1820+070	18 20 48	+07 25 48	uQuasar,Gal,...	2.96 kpc	Newly Announced
LS 5039	18 26 15	-14 49 30	PeVCand,Gal...	2.5 kpc	Default Catalog
HESS J1832-093	18 32 50	-09 22 36	Gal,BIN		Default Catalog
SS 433	19 11 49.6	+04 58 57.8	Gal,BIN	4.5 kpc	Default Catalog
GRS 1915+105	19 14 31.2	+10 49 48	uQuasar,Gal,...	9.4 kpc	Newly Announced
PSR J2032+4127	20 32 10	+41 27 34	Gal,BIN	1.8 kpc	Default Catalog

2024 an important year for Microquasars, with new results from HAWC and LHAASO

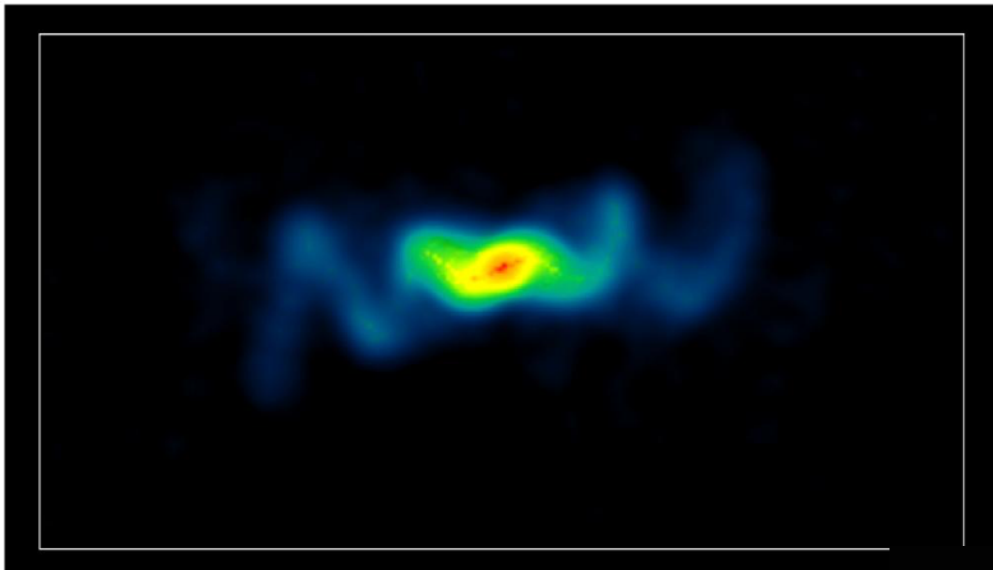
SS 433

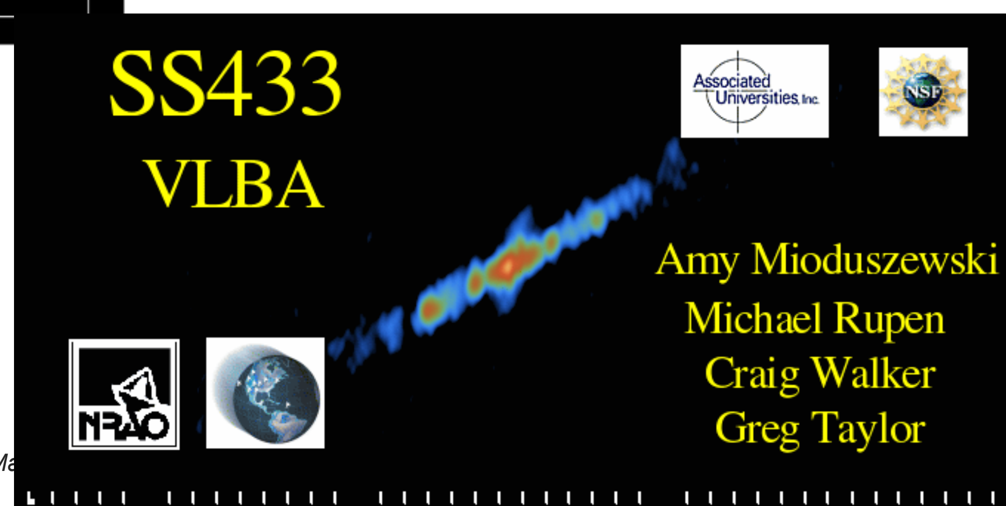
Microquasar embedded in the supernova remnant W50

Distance: ~5.5 kpc
Location: 19h11m +04d58m
Central Object: black hole with 3-30 solar masses
Companion Star: A-type
Period: 13d
Precession: 162.5 days

SS 433

Zooming in on the microquasar

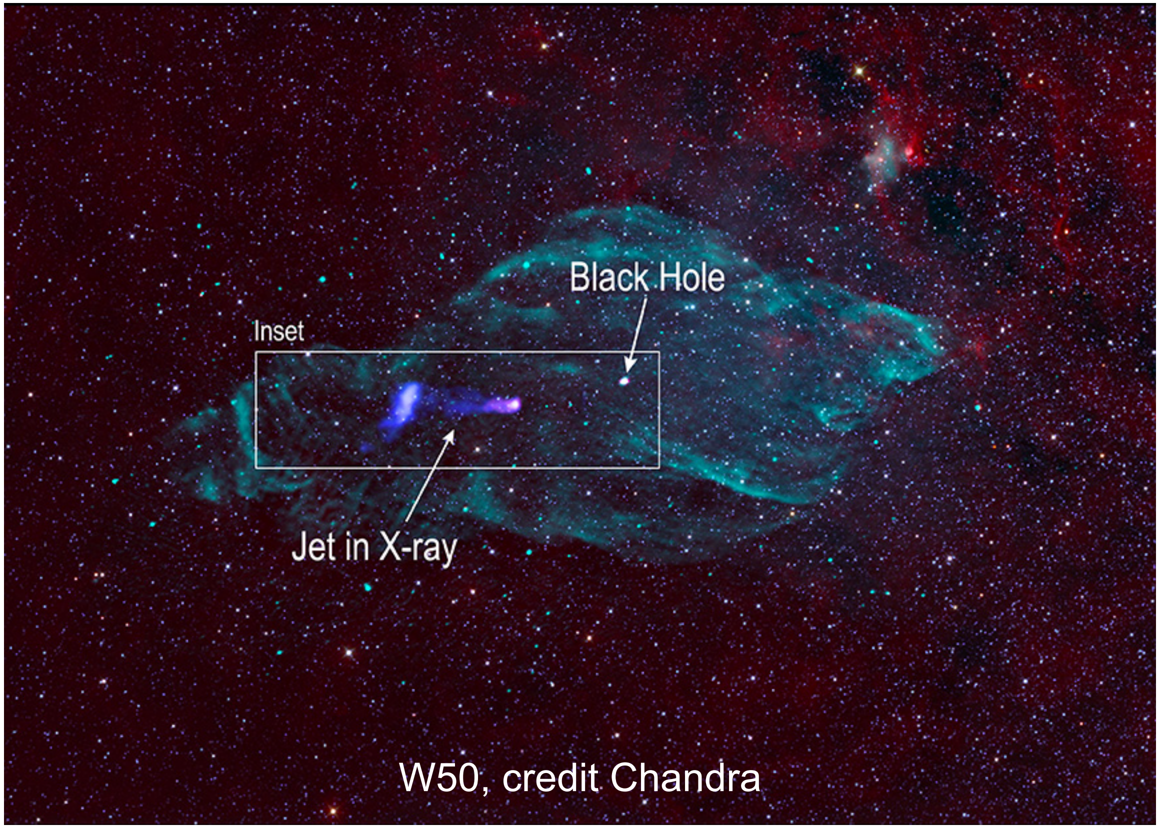




SS433, credit NRAO

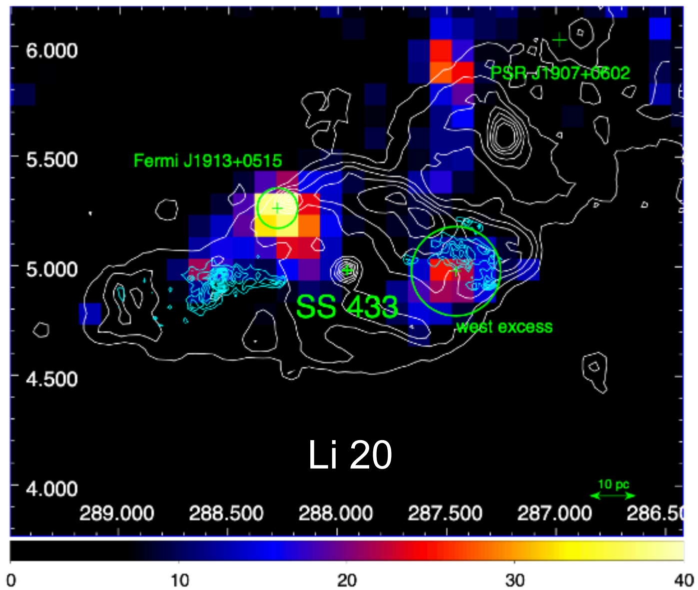
SS 433

X-ray emission

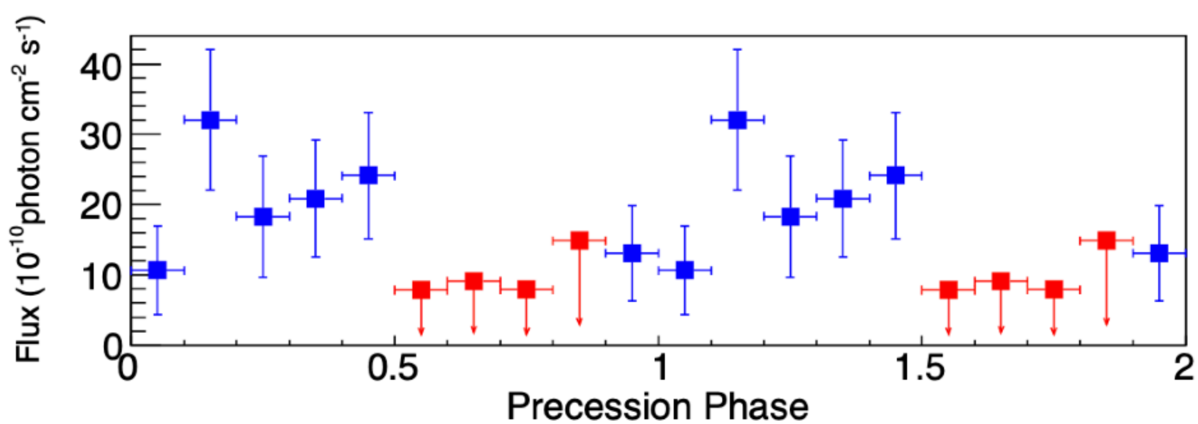


SS 433

GeV emission

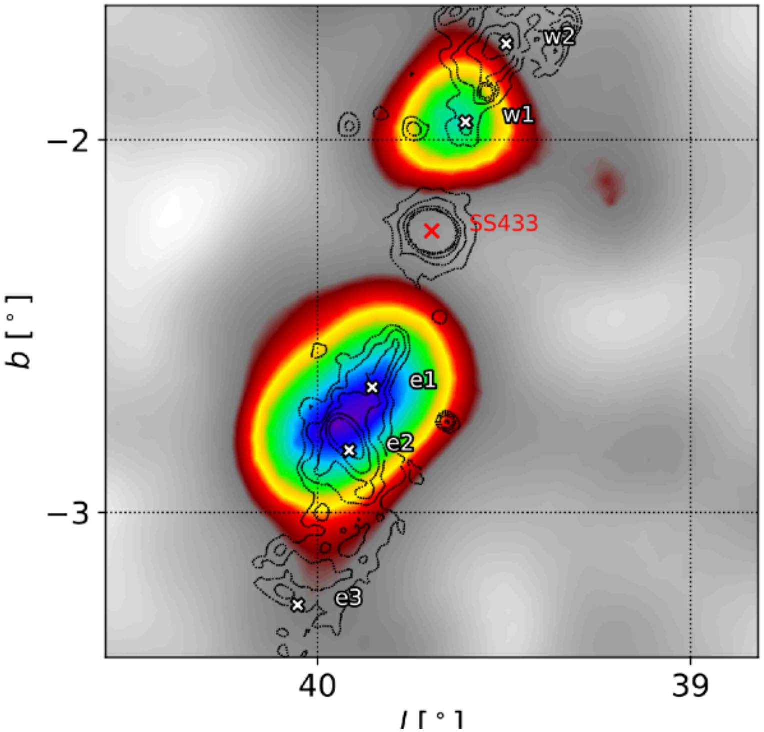


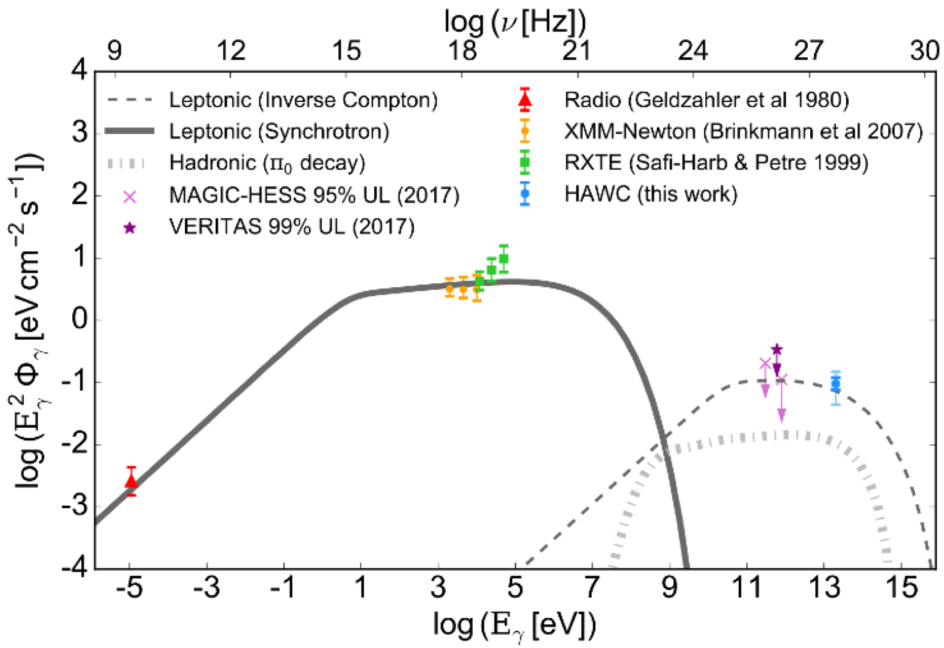
No LAT source associated with the X-ray jets. A surprising source offset from the jets, and in phase with the precession period



SS 433

Extended TeV emission detected with HAWC

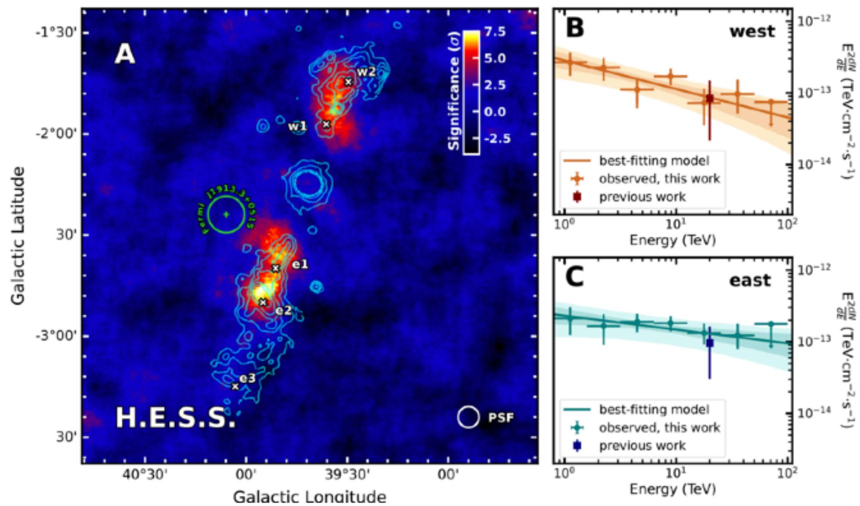


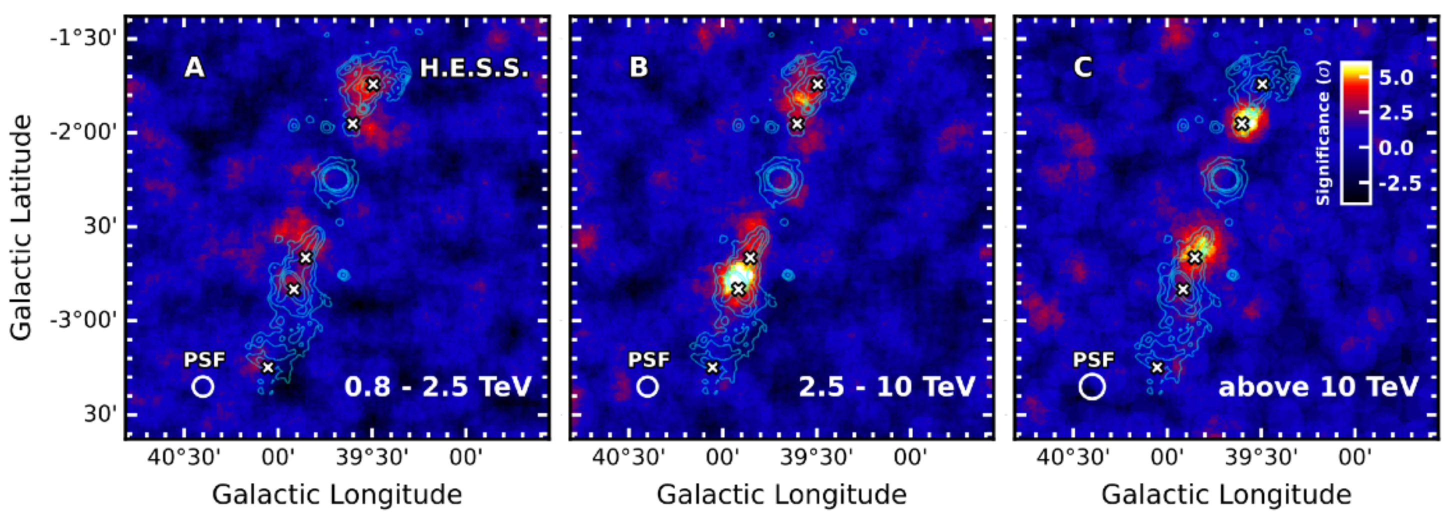


Abeysekara 18

SS 433

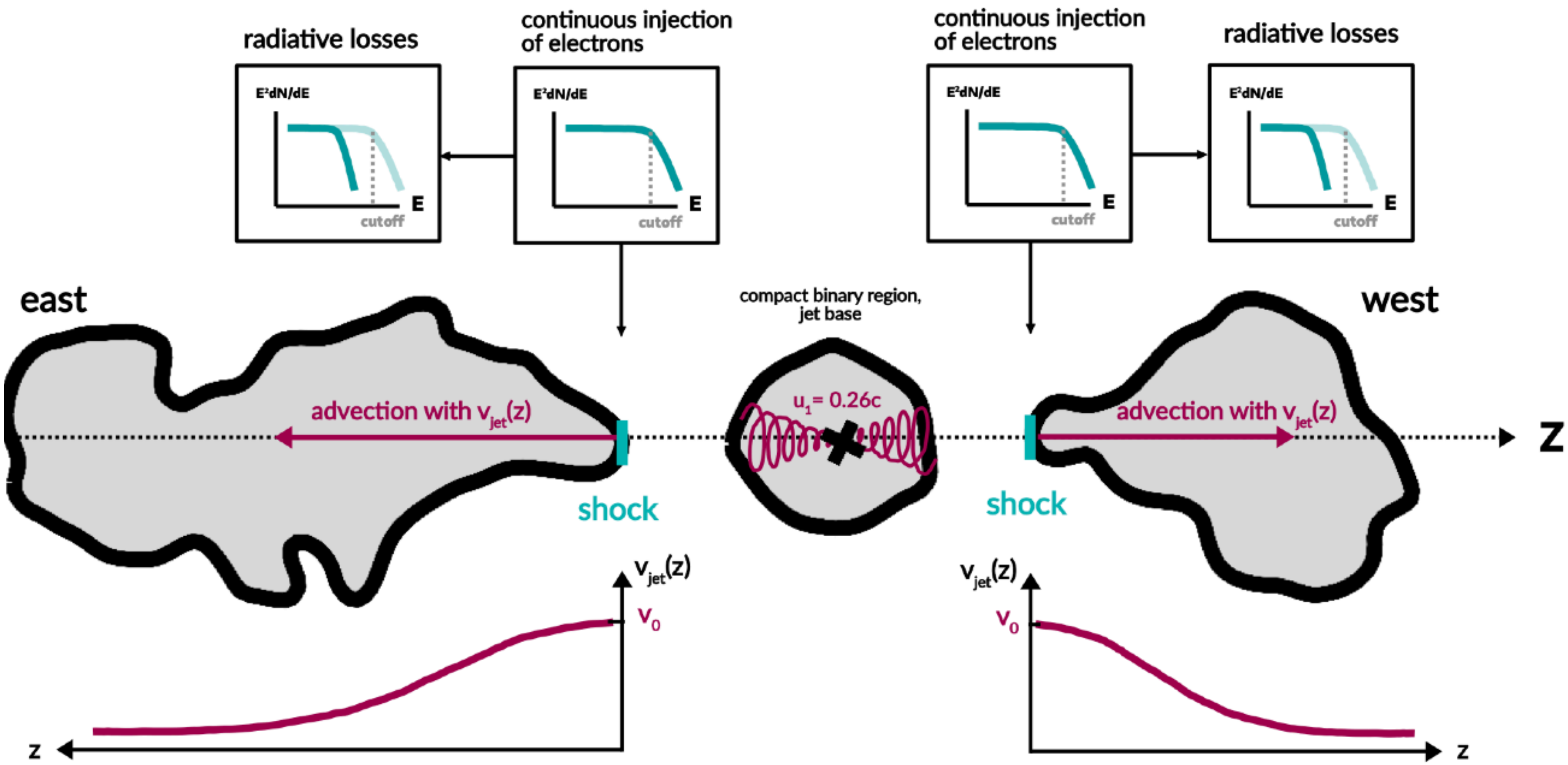
TeV emission with HESS





HESS Coll. 24

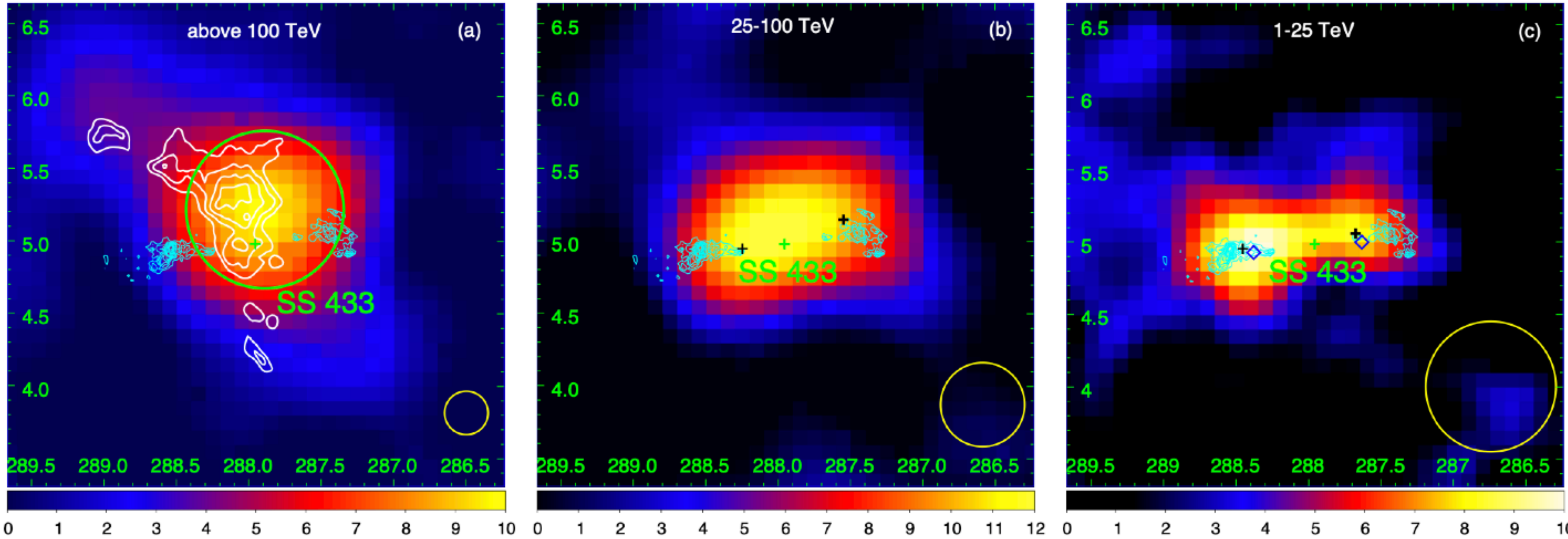
SS 433



radiative losses
continuous injection of electrons
continuous injection of electrons
radiative losses
E²dN/dE
E
cutoff
east
west
compact binary region, jet base
advection with $v_{jet}(z)$
$u_1 = 0.26c$
advection with $v_{jet}(z)$
z
shock
shock
$v_{jet}(z)$
v_0
z
$v_{jet}(z)$
v_0
z

SS 433

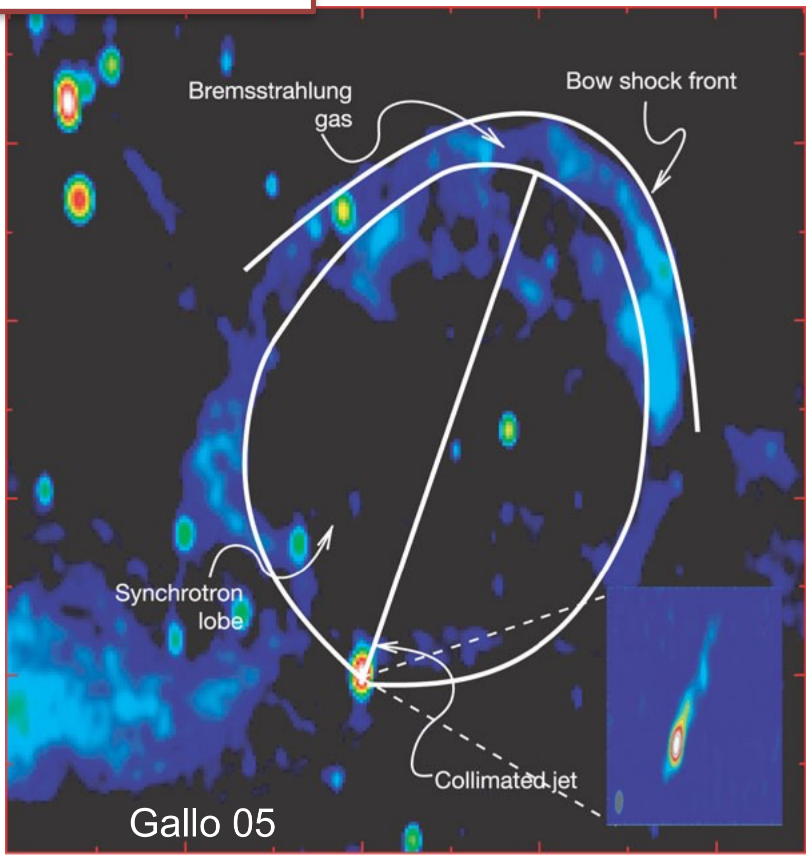
Multi TeV emission with LHAASO

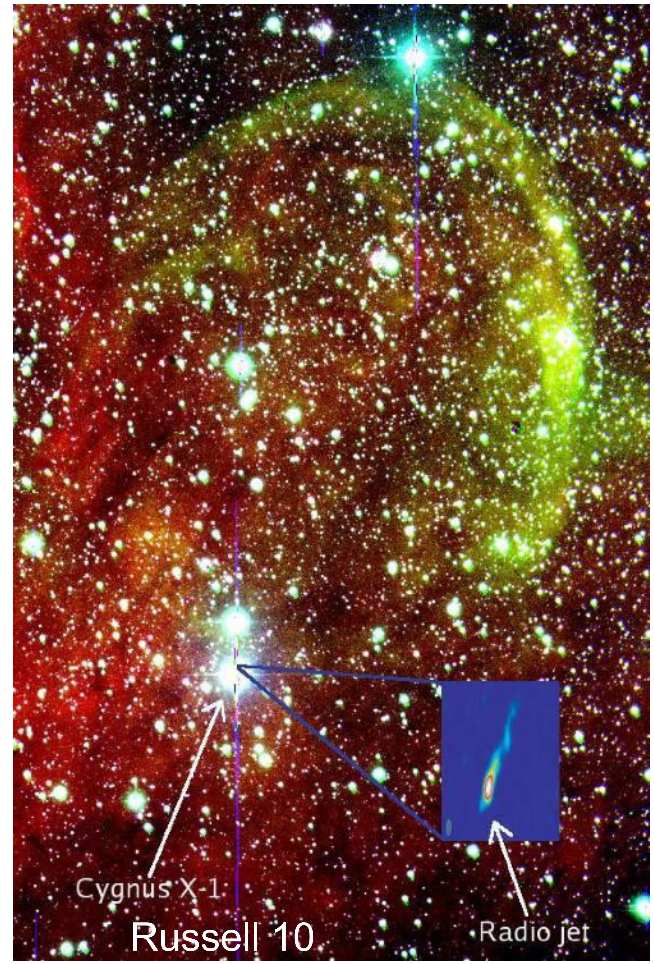


LHAASO Coll. 24

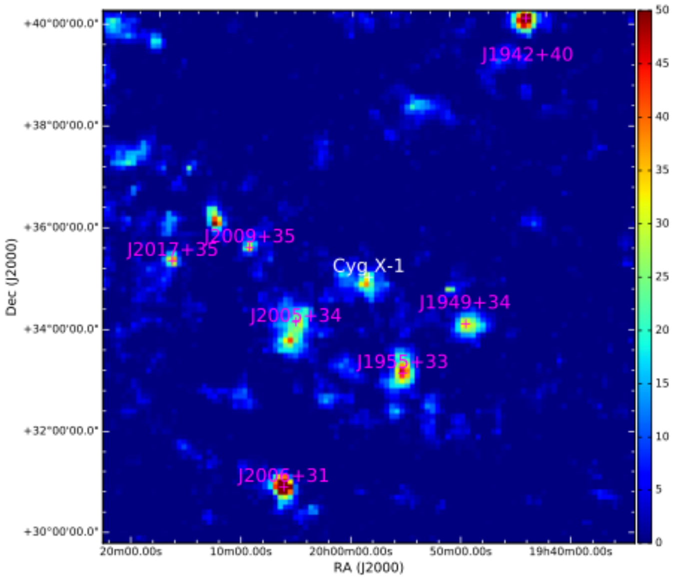
Distance: ~1.9 kpc
Location: 19h58m +35d12m
Central Object: black hole with 7-13 solar masses
Companion Star: O-type
Period: 5.6d

CYG X1



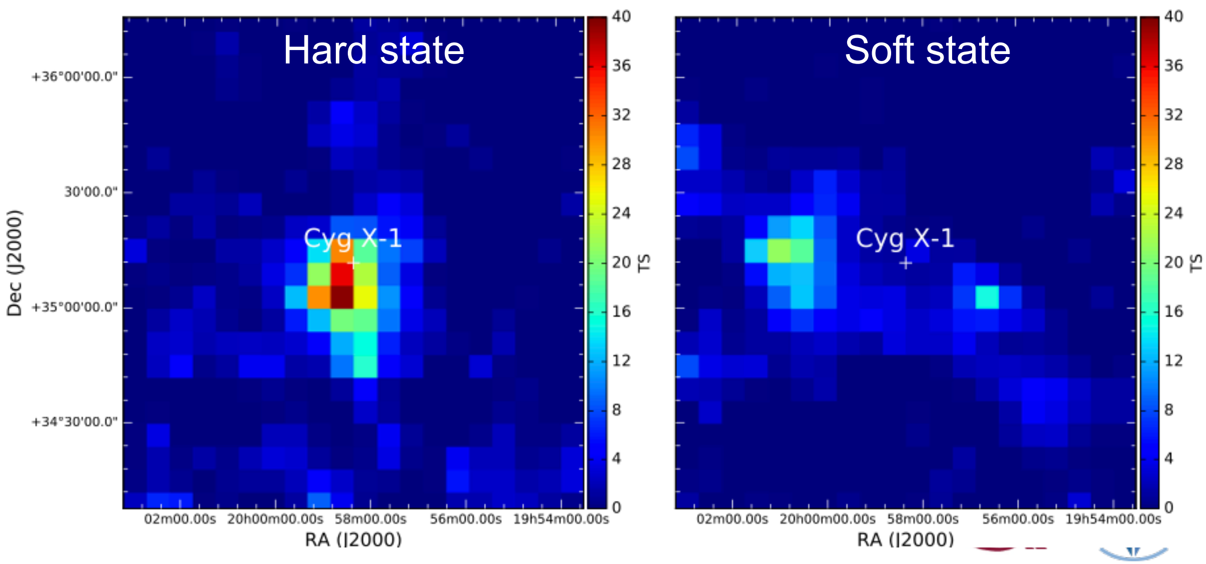


CYG X1



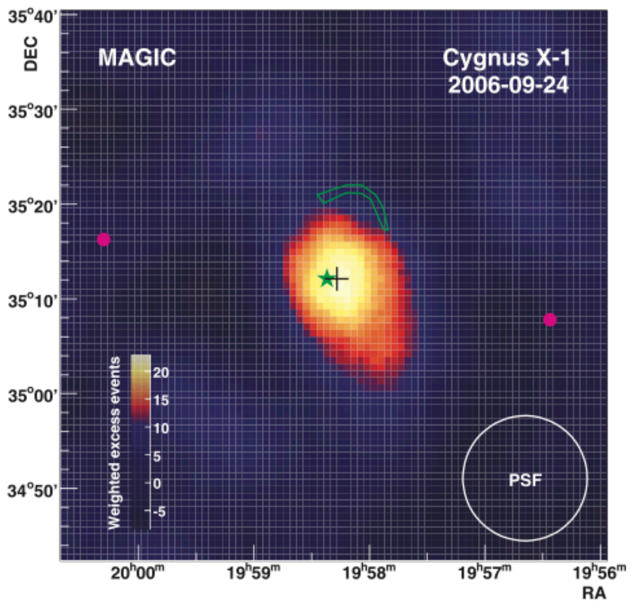
LAT emission detected during the hard state
Evidence of orbital variability implies contribution from external photons (from the companion)

Zanin 16

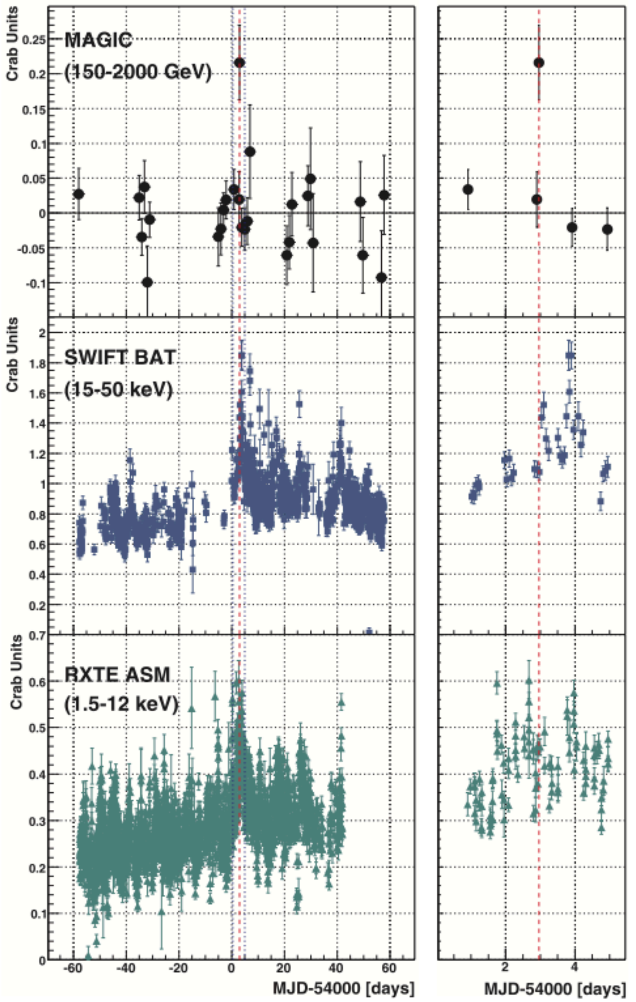


CYG X1

Evidence (3.2σ) for flaring activity in MAGIC data

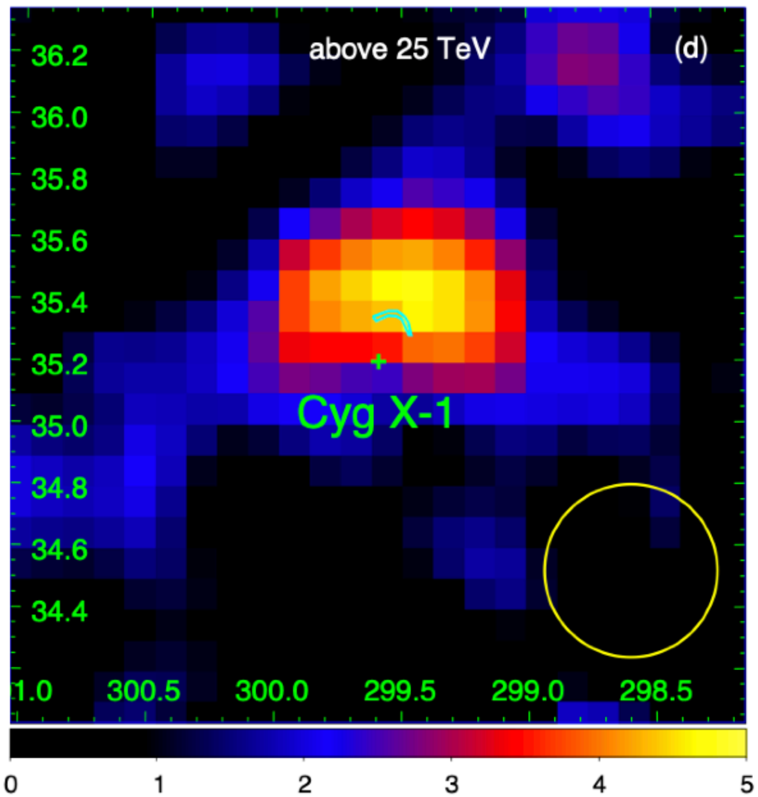


MAGIC 06



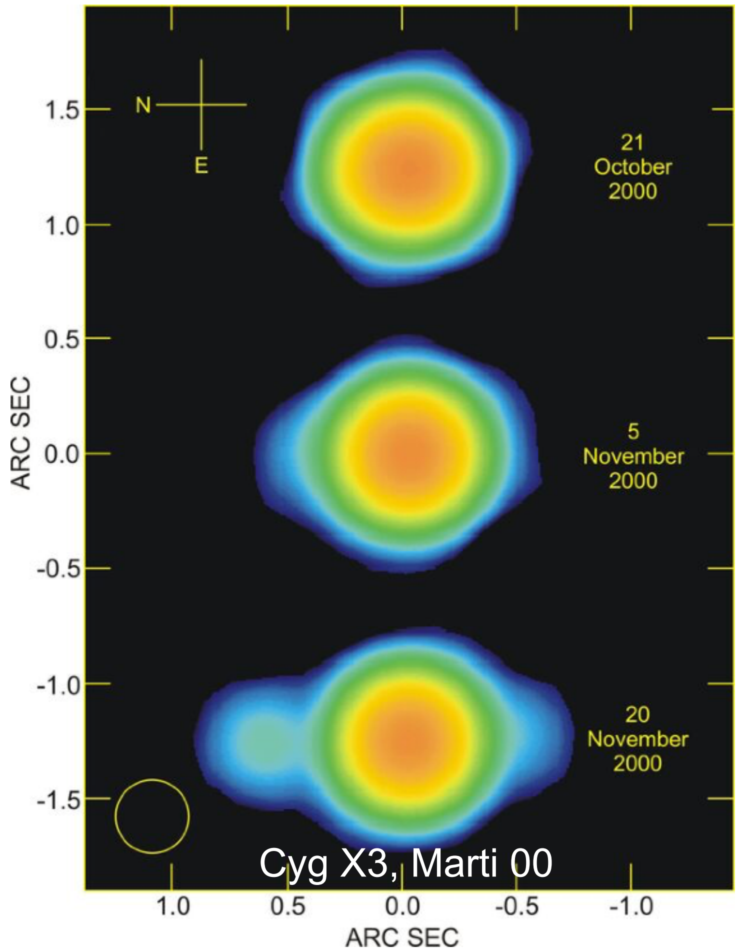
CYG X1

Evidence (4σ) for multi-TeV emission from LHAASO



LHAASO Coll. 24

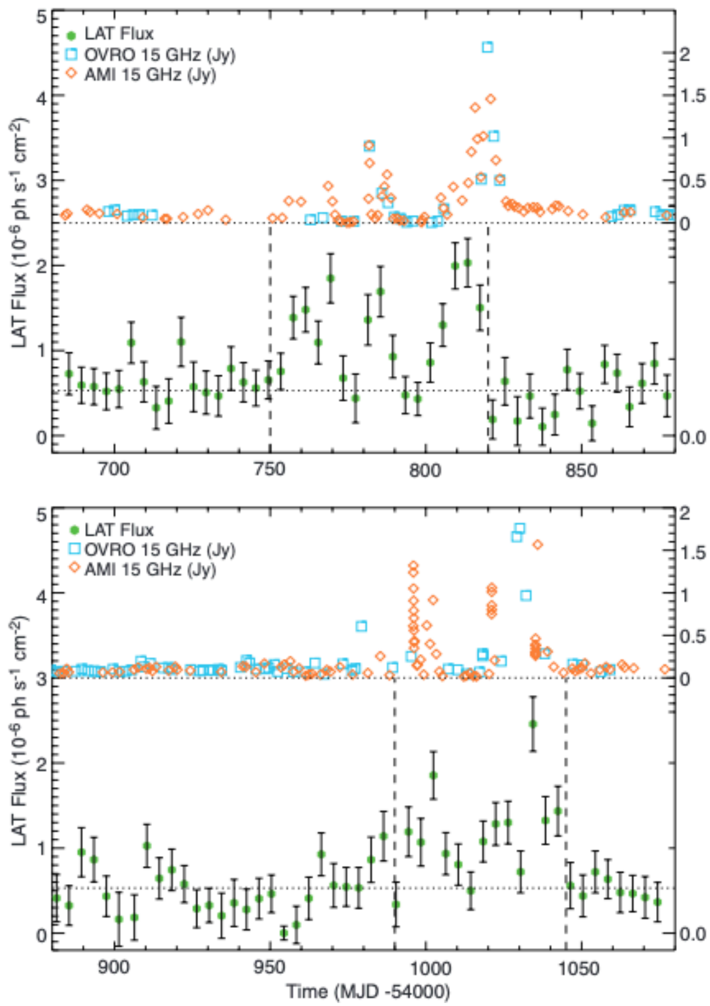
CYG X3



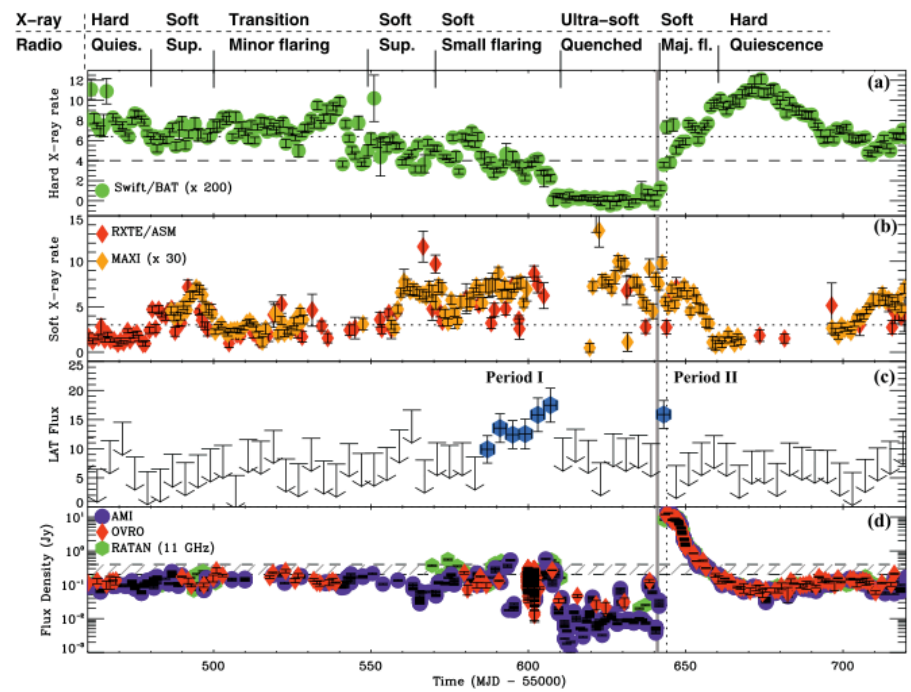
Distance: ~7.4 kpc
Location: 20h32m +40d57m
Central Object: compact object with 1.3-4.5 solar masses
Companion Star: WR-type
Period: 4.8h

CYG X3

GeV emission associated with giant radio flares



Fermi 09

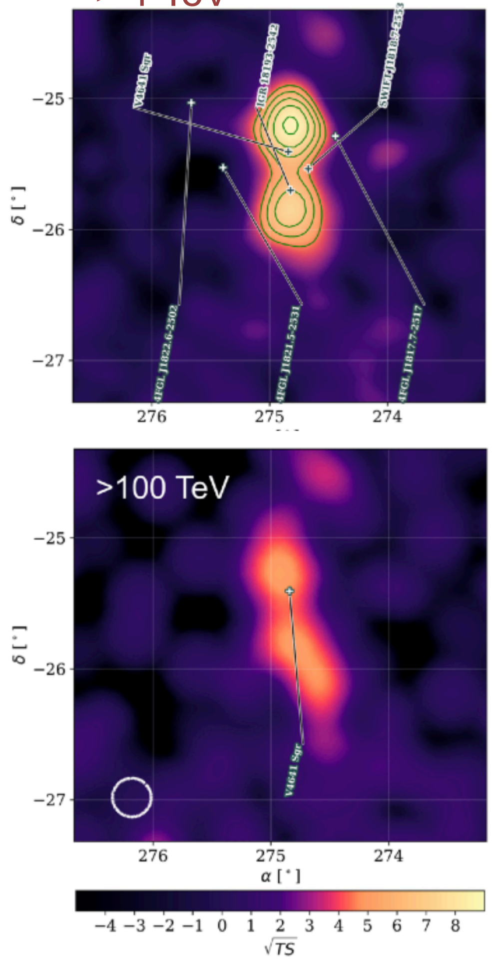


Corbel 12

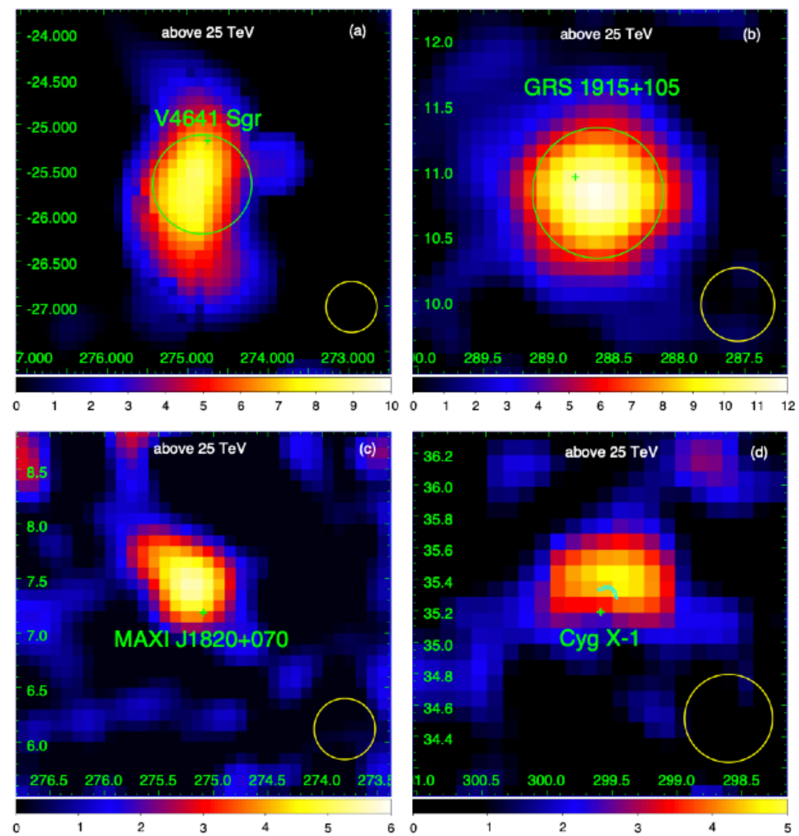
2024 DISCOVERIES WITH HAWC AND LHAASO

V4641 Sgr

> 1 TeV



HAWC Coll. 24



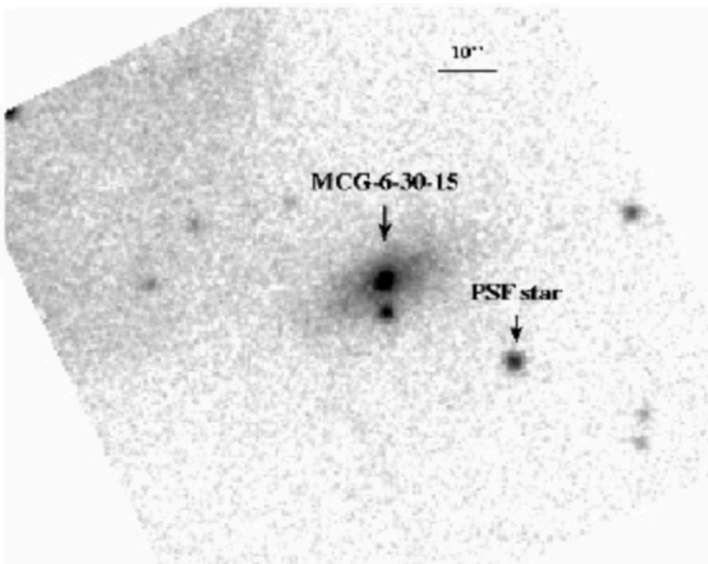
LHAASO Coll. 24

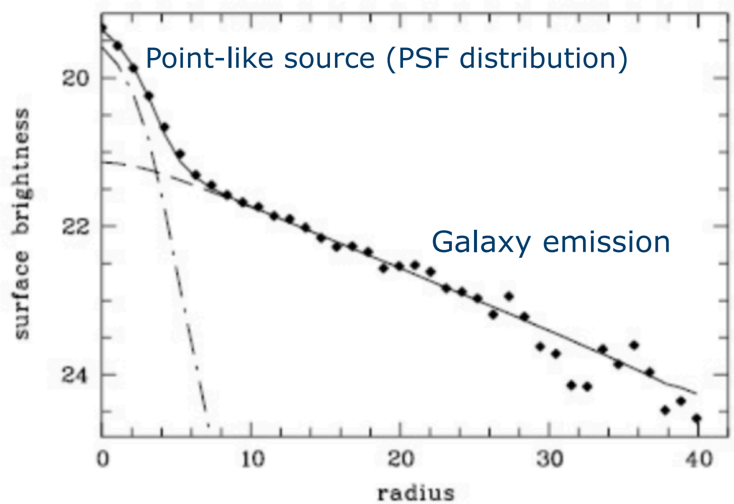
ACTIVE GALACTIC NUCLEI

ACTIVE GALACTIC NUCLEI

Point-like source of photons in galaxy center

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



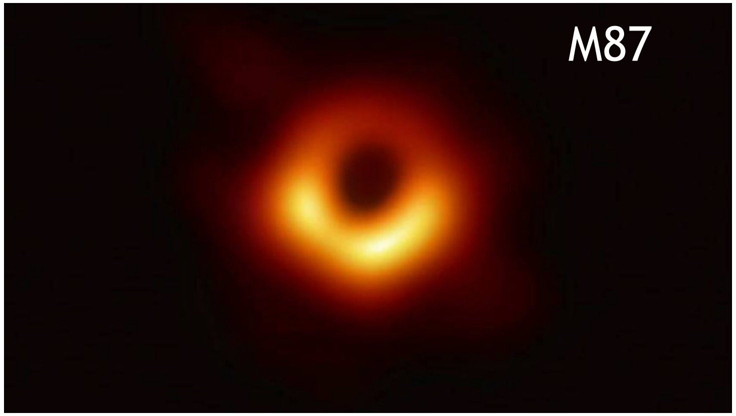


Arevalo et al. 2005

ACTIVE GALACTIC NUCLEI

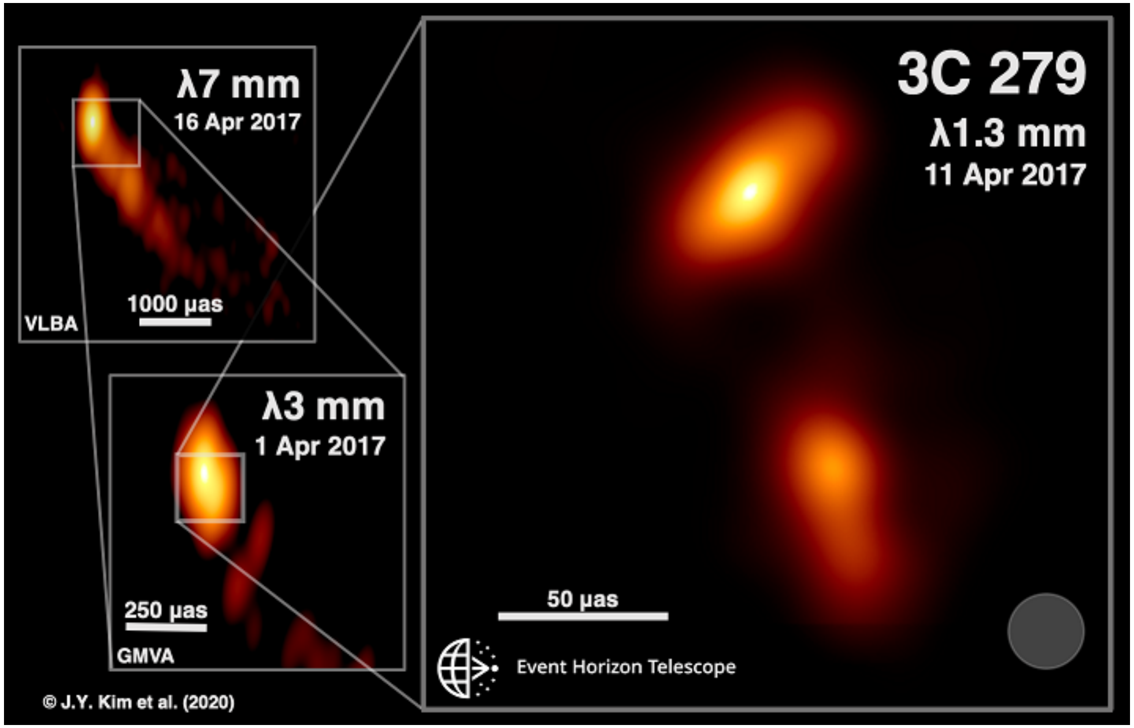
Current understanding

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



Event Horizon Telescope 2019

First image of a black-hole shadow

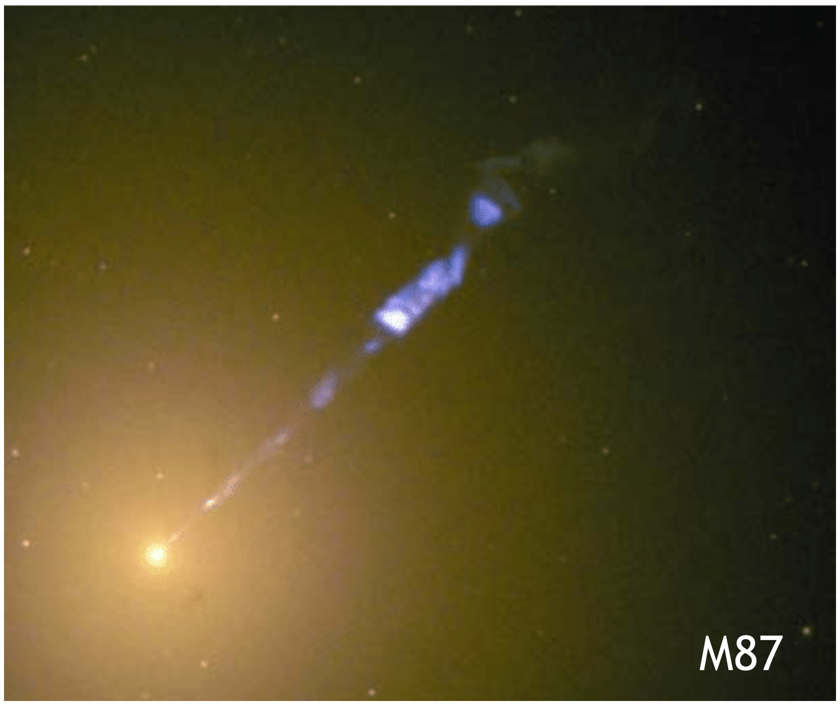


Event Horizon Telescope 2020

Jet launching

ACTIVE GALACTIC NUCLEI

Radio-loud / radio-quiet dichotomy

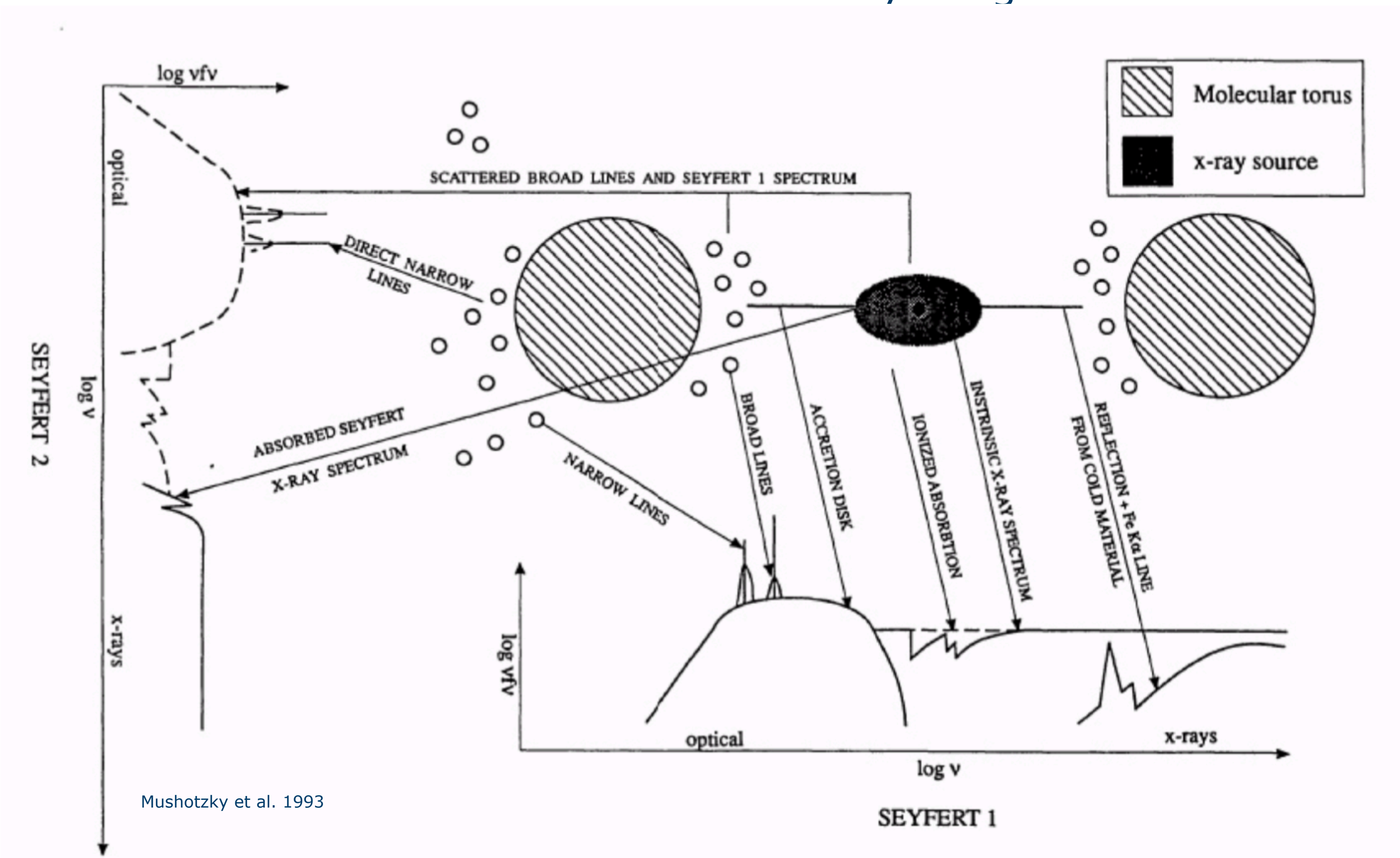


Radio-galaxy
with its relativistic jet

Seyfert galaxy

ACTIVE GALACTIC NUCLEI

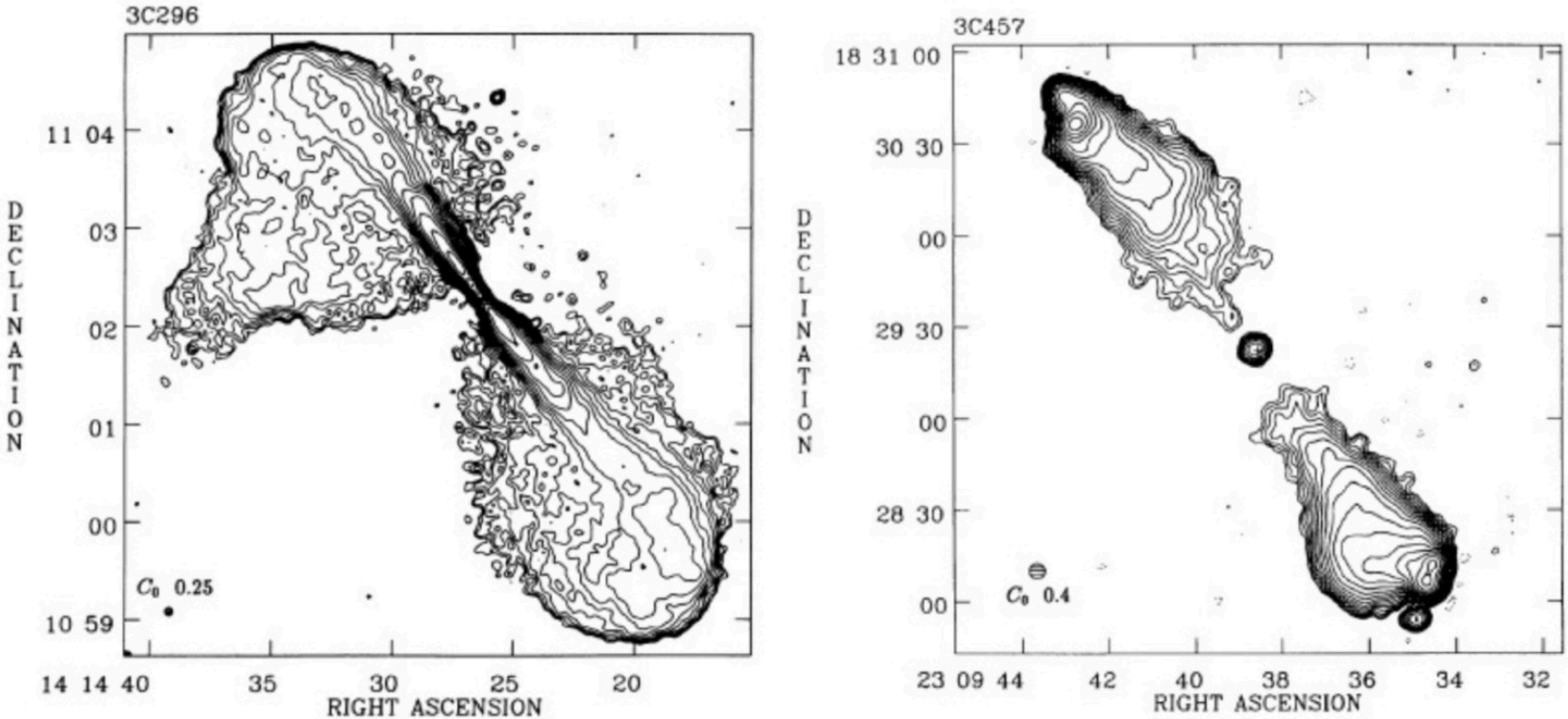
Broad-band emission from Seyfert galaxies



Mushotzky et al. 1993

ACTIVE GALACTIC NUCLEI

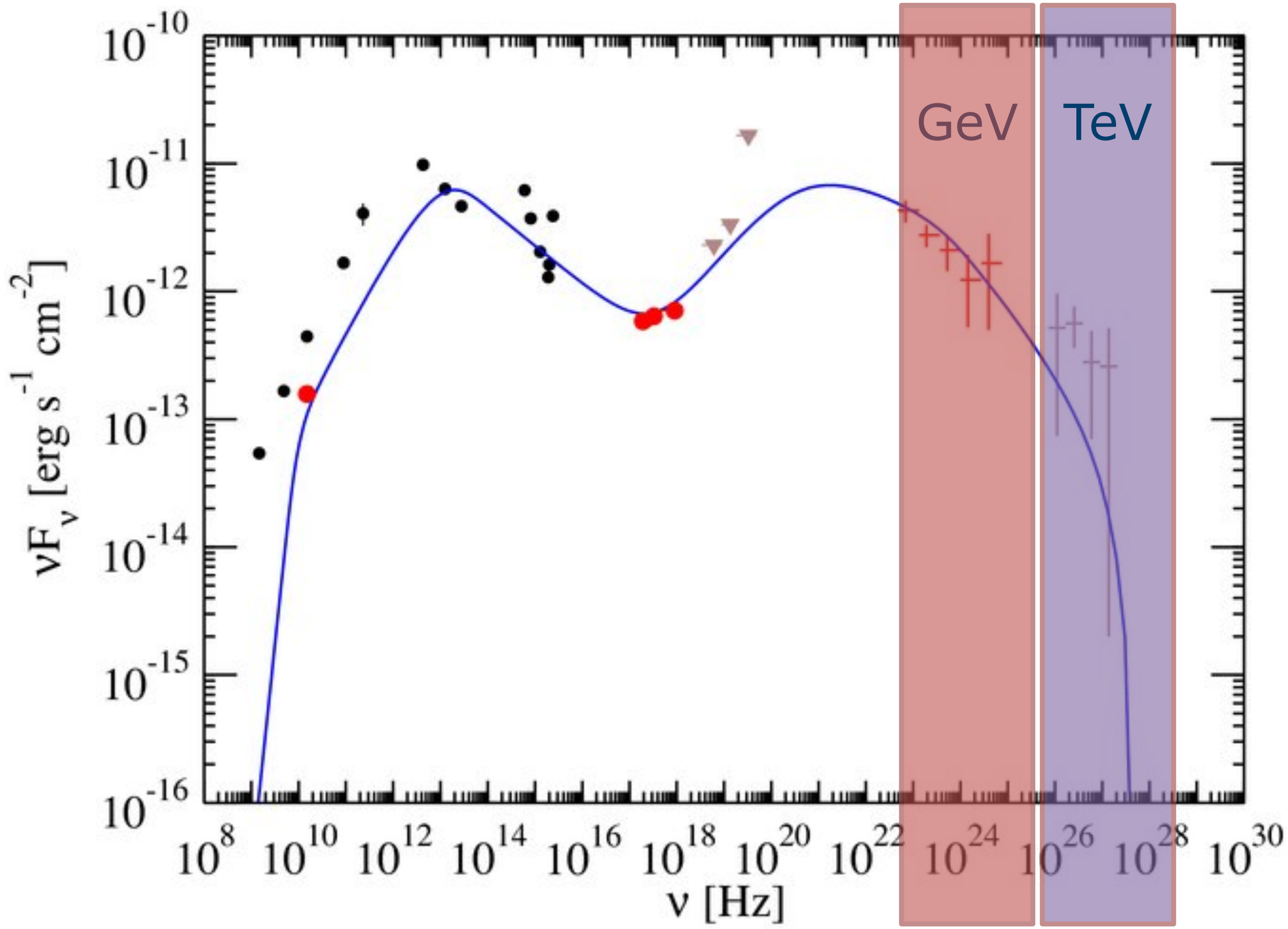
Radio-loud dichotomy: Fanaroff-Riley I and FRII



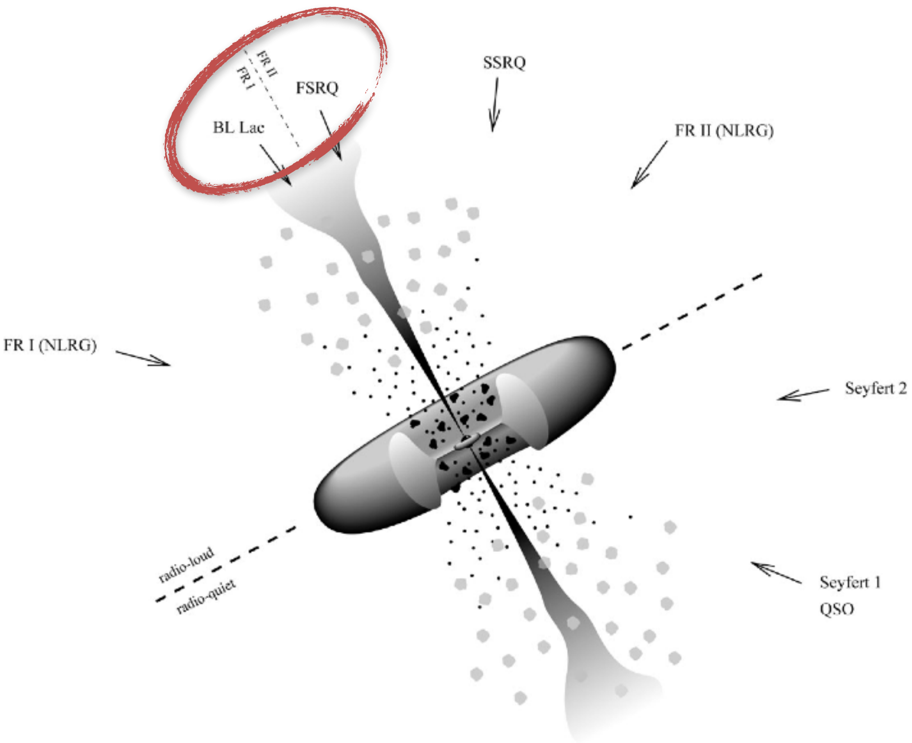
Leahy & Perley 1991

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, …)

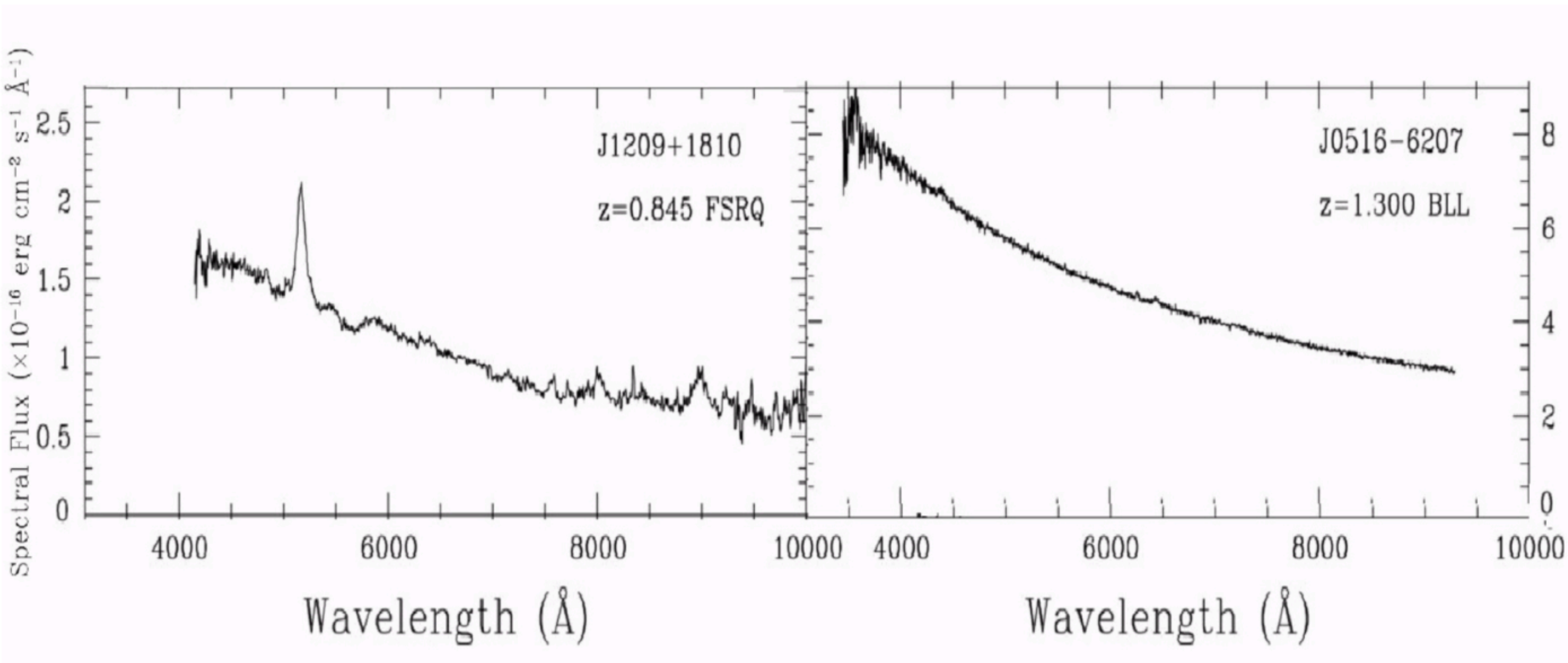
non-thermal emission from radio-to-gamma-rays, and extreme variability

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

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

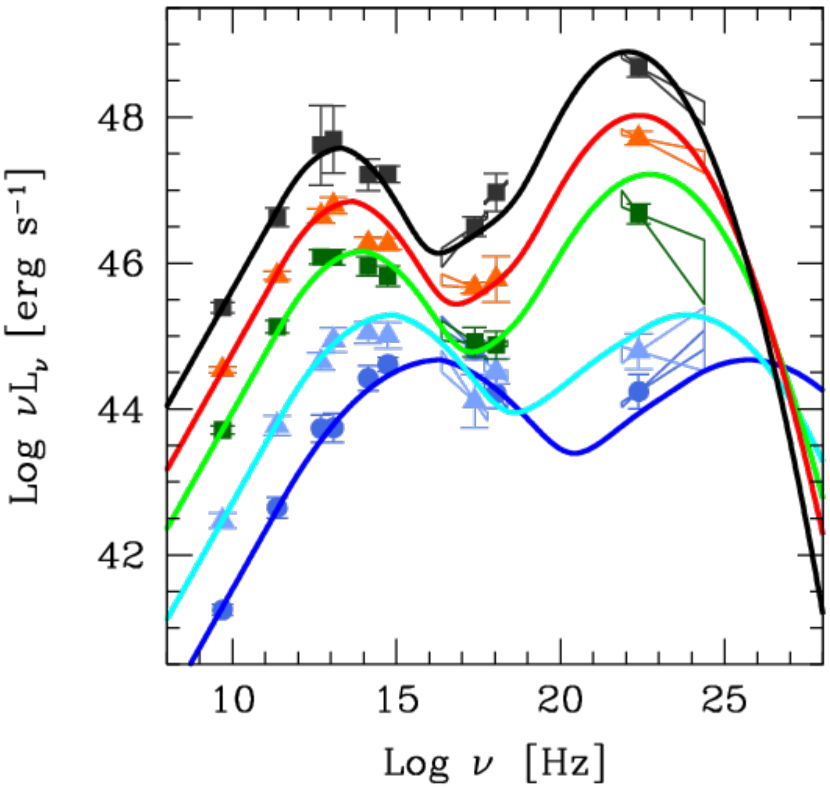
ACTIVE GALACTIC NUCLEI

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

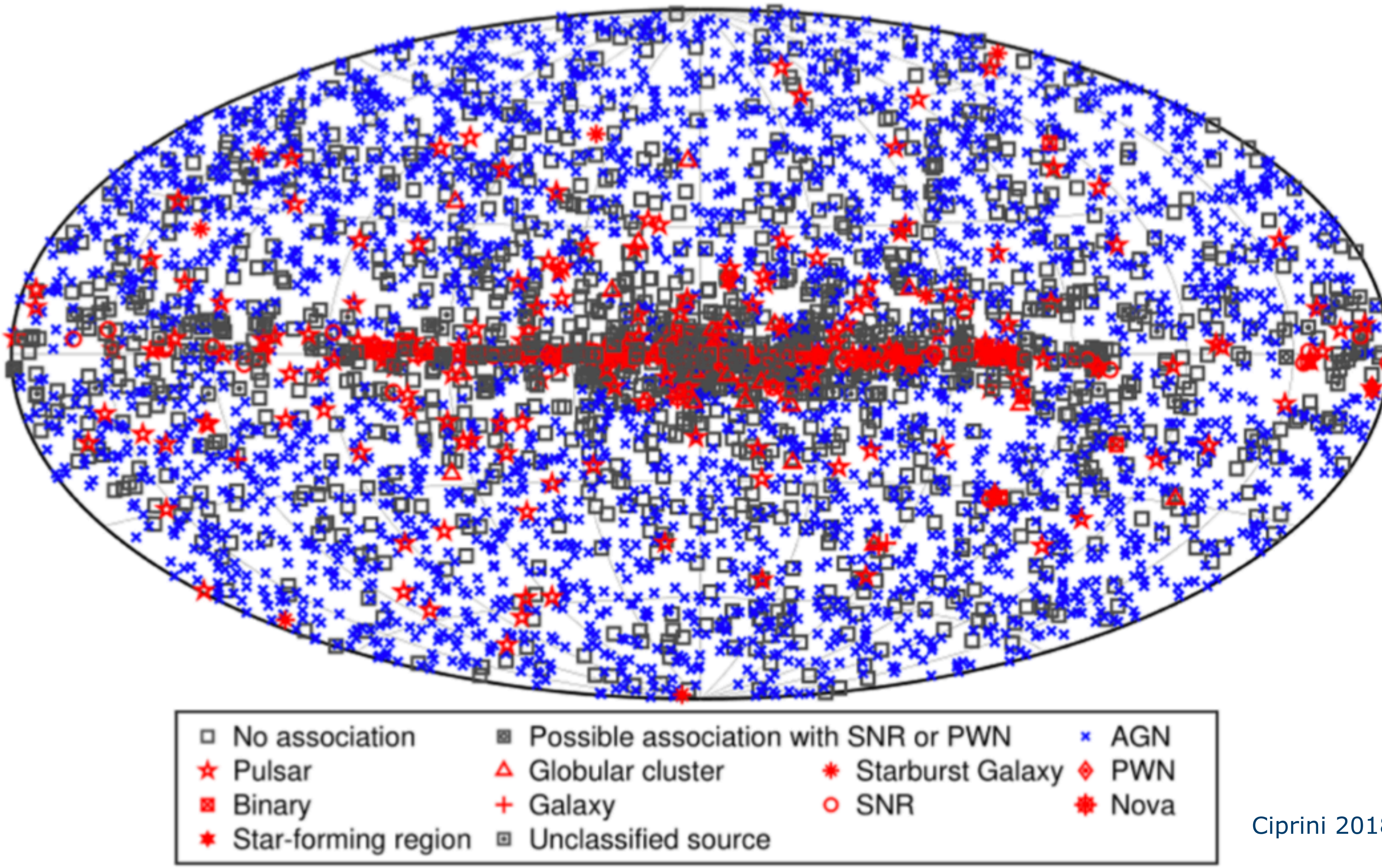
BL Lac objects are classified in:

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

- peak in optical: intermediate (IBLs)

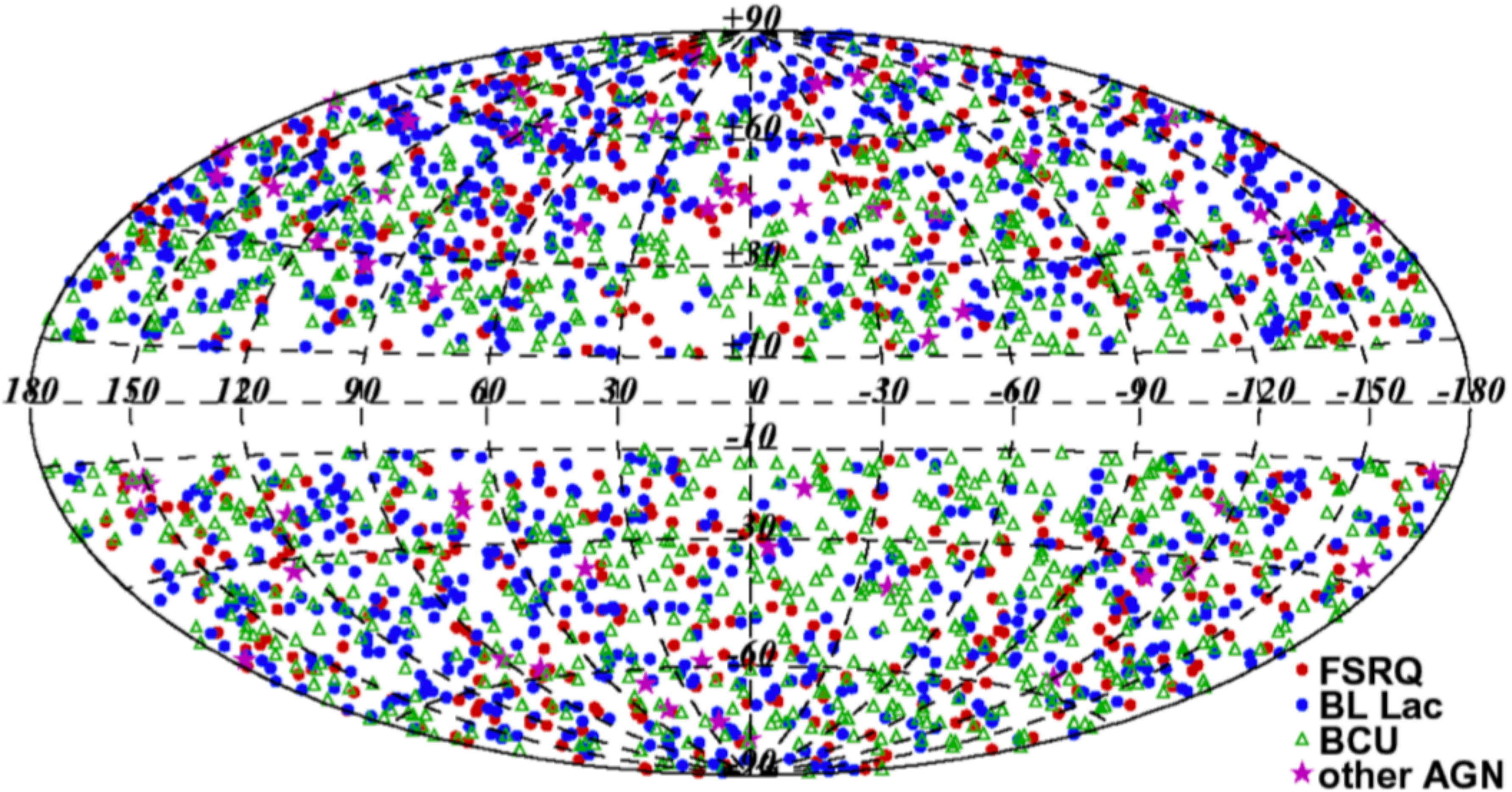
- peak in UV / X: high (HBLs)

THE GeV EXTRAGALACTIC SKY



Ciprini 2018

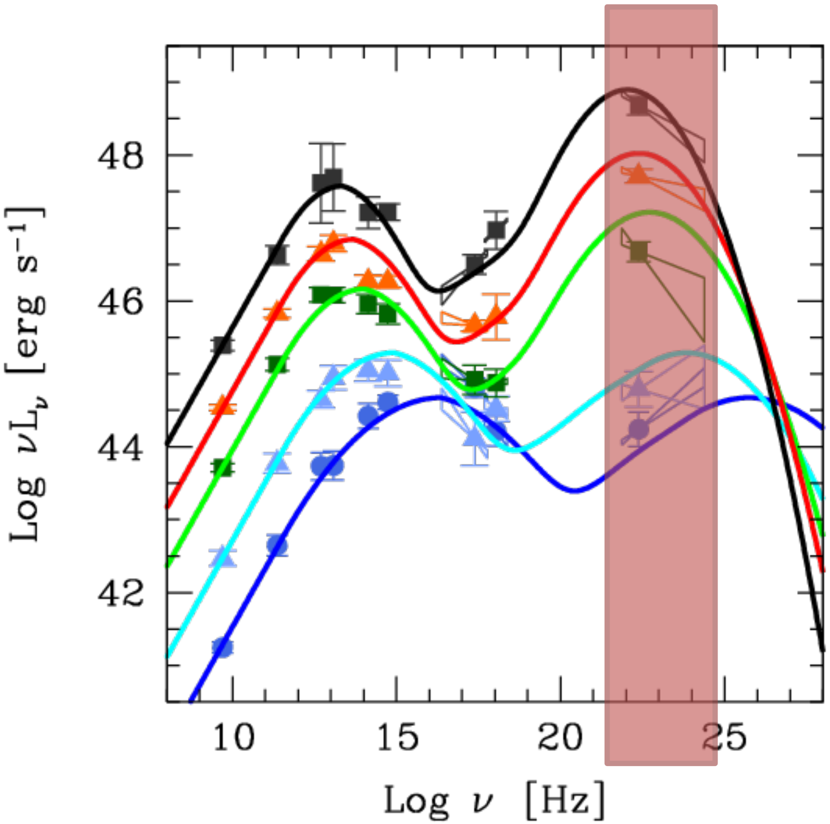
THE GeV EXTRAGALACTIC SKY



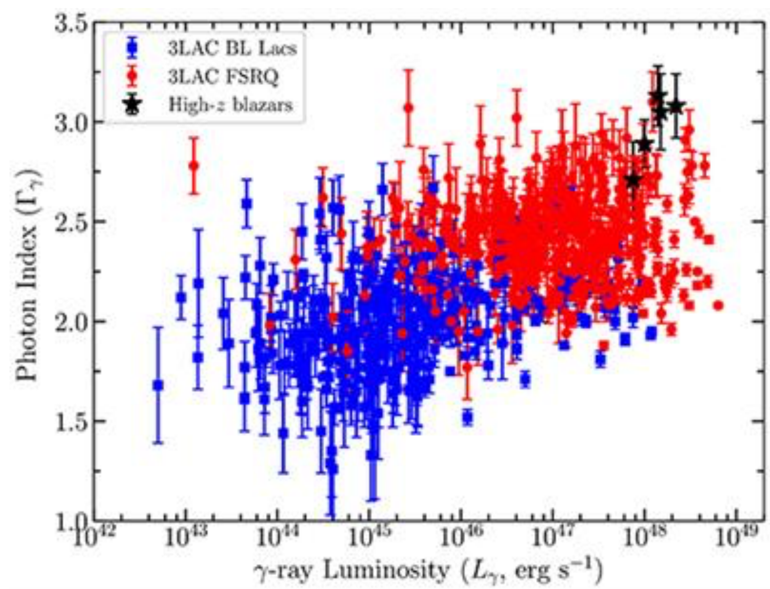
Ciprini 2018

THE GeV EXTRAGALACTIC SKY

Population of GeV AGNs

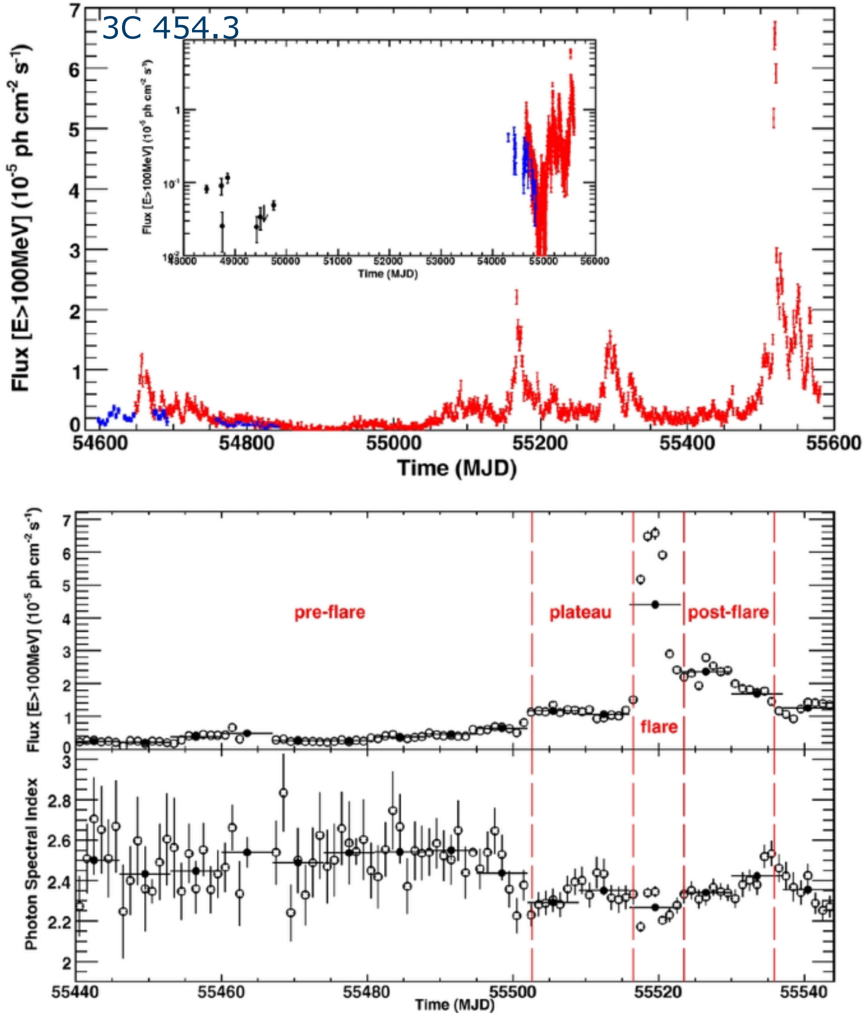


Dominated by high-luminosity FSRQs and LBLs



BLAZAR FLARES

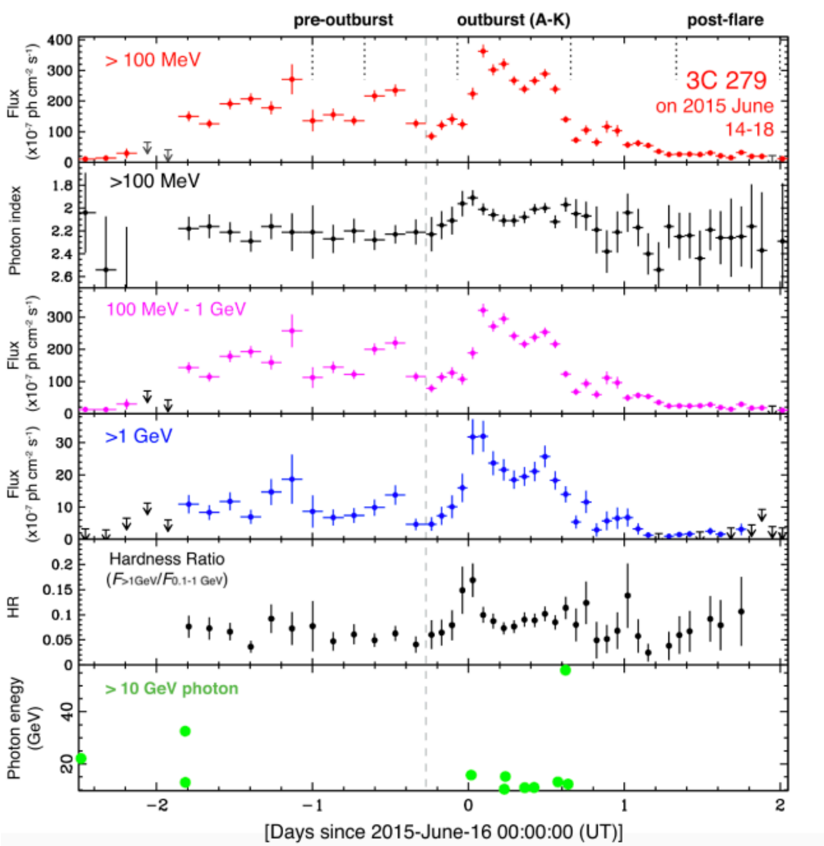
Blazars are extremely variable

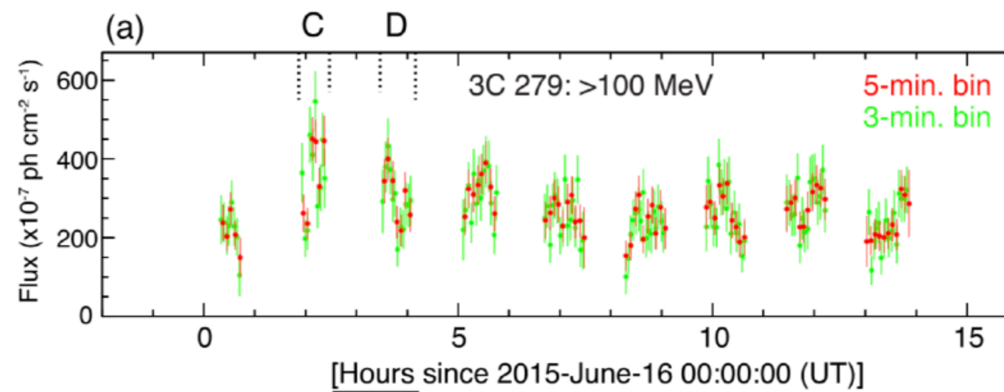


Abdo et al. 2011

BLAZAR FLARES

Rapid flares





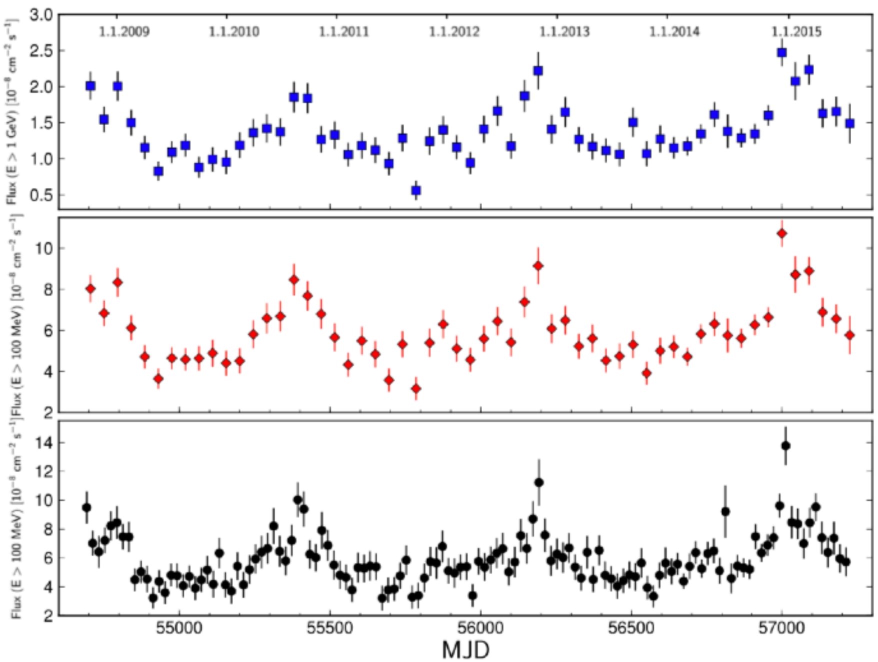
Variability can be used to constrain the size of the emitting region thanks to the causality argument

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

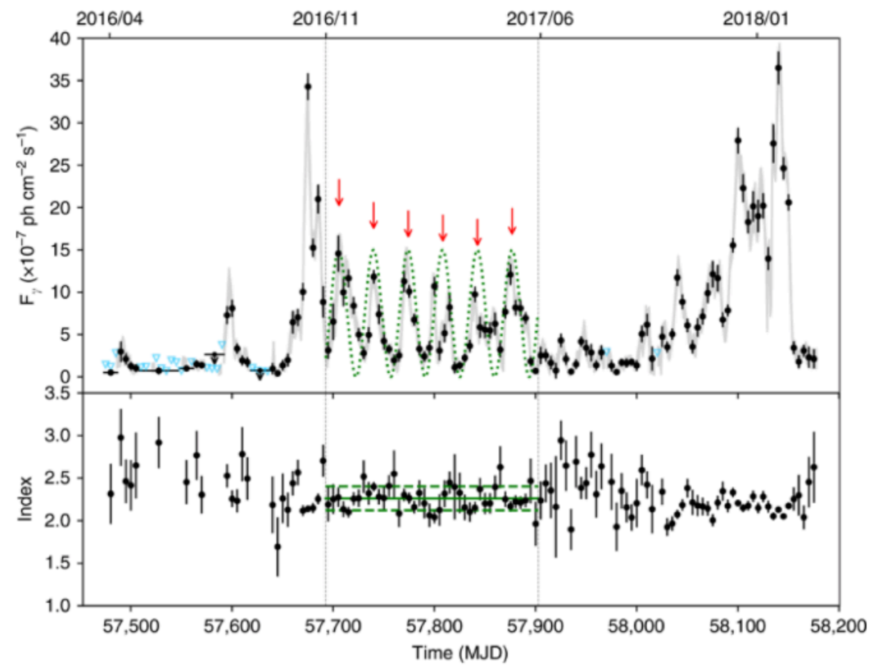
Ackermann et al. 2016

BLAZAR FLARES

Periodicity and Quasi-Periodic-Oscillations



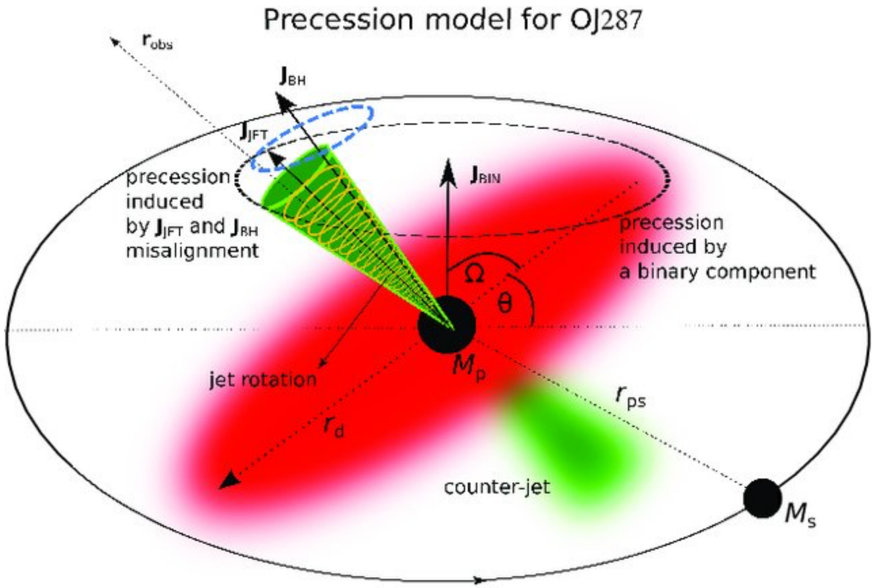
Ackermann et al. 2015



Zhou et al. 2018

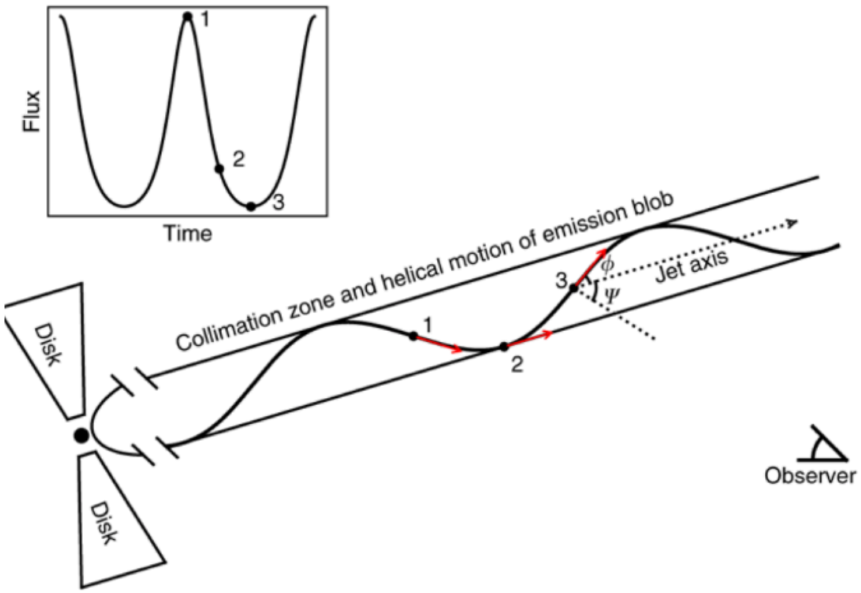
BLAZAR FLARES

Super-massive black-hole Binary



Britzen et al. 2017

Helical structure of the jet

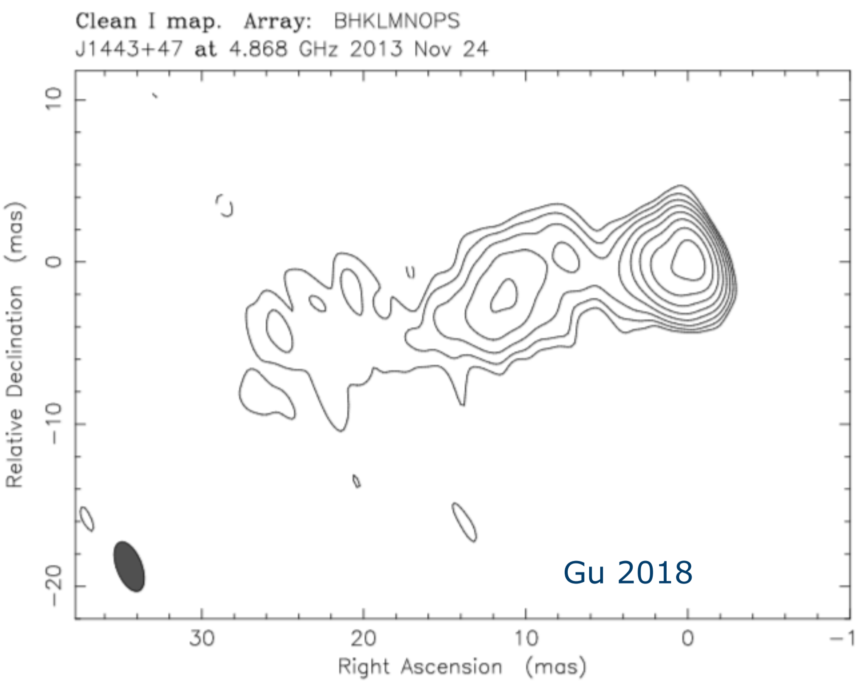


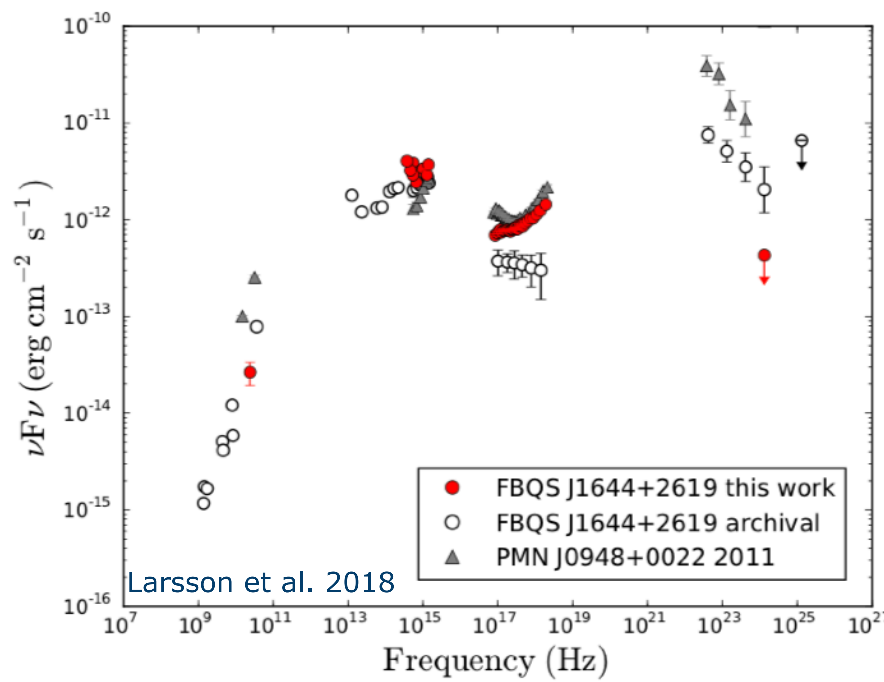
Zhou et al. 2018

NARROW LINE SEYFERT 1

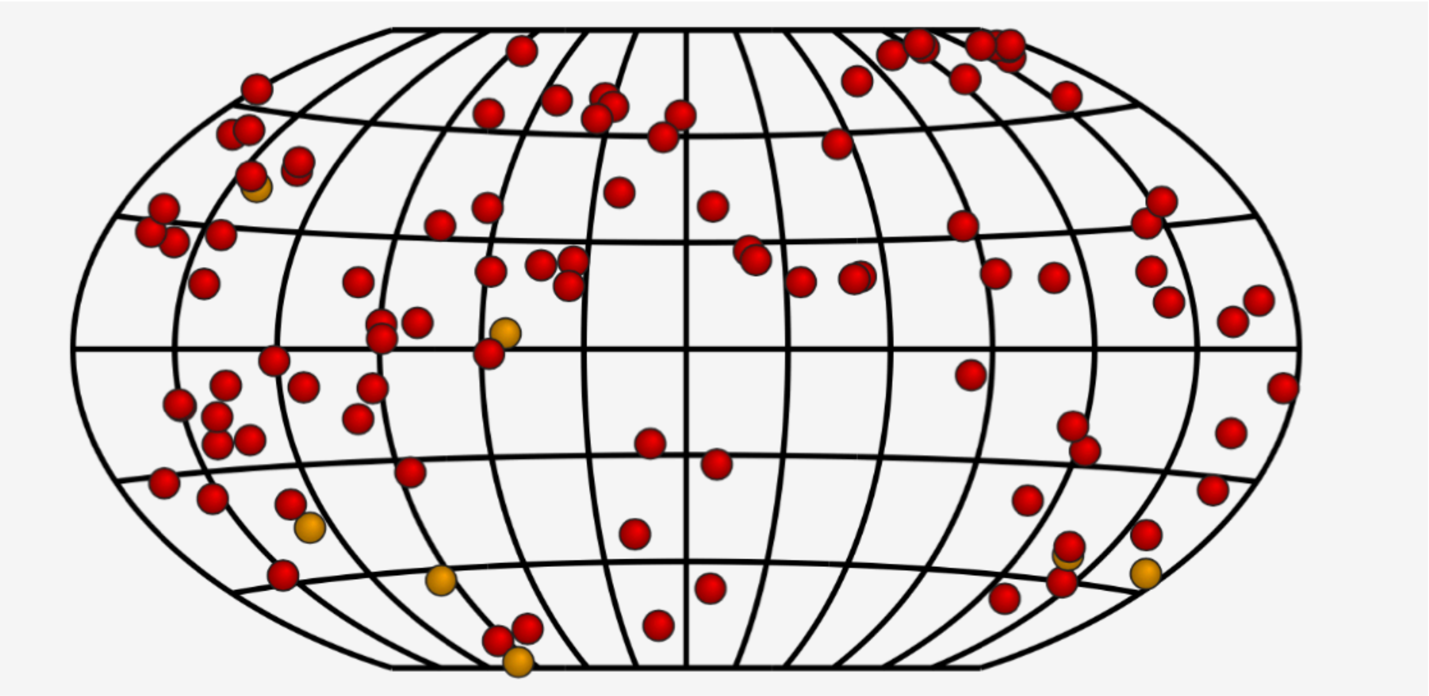
Narrow-line Seyfert 1 galaxies

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

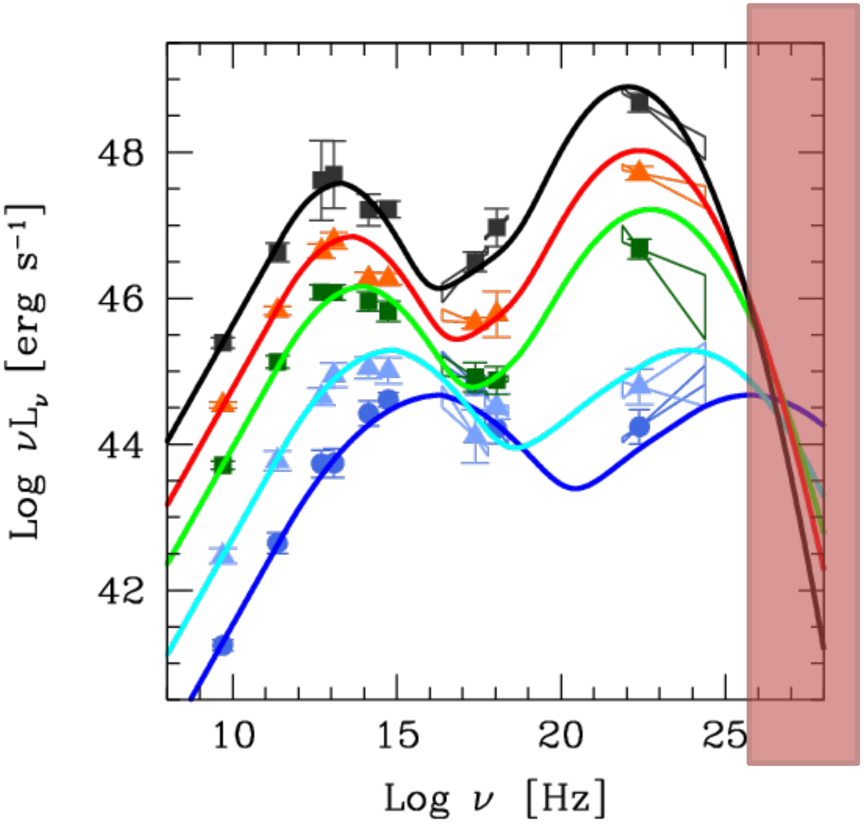


http://tevcat2.uchicago.edu

98 extragalactic sources: **5 GRB**
2 starburst galaxies
1 low-luminosity AGN
4 radio galaxies
86 blazars

THE TeV EXTRAGALACTIC SKY

Population of TeV AGNs

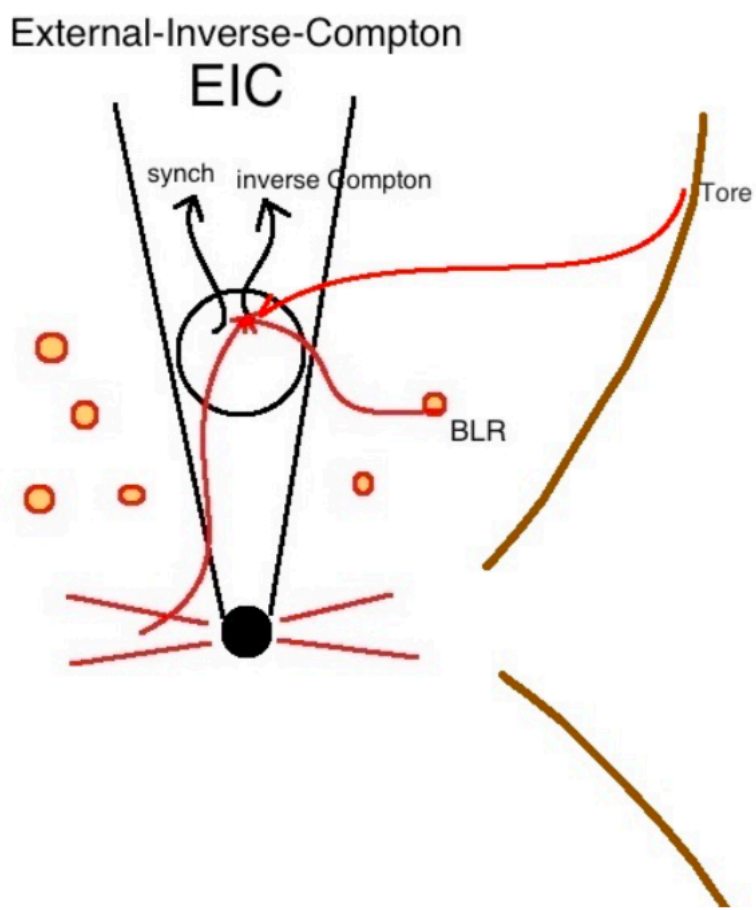


Dominated by HBLs:

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

Matteo Cerruti

FSRQs and LBLs



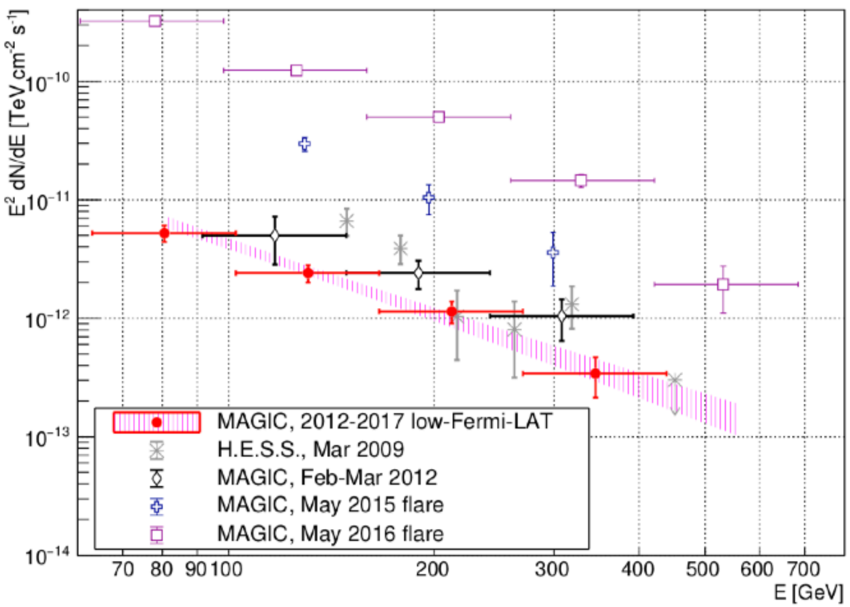
Origin of γ-ray emission:
External-Inverse-Compton

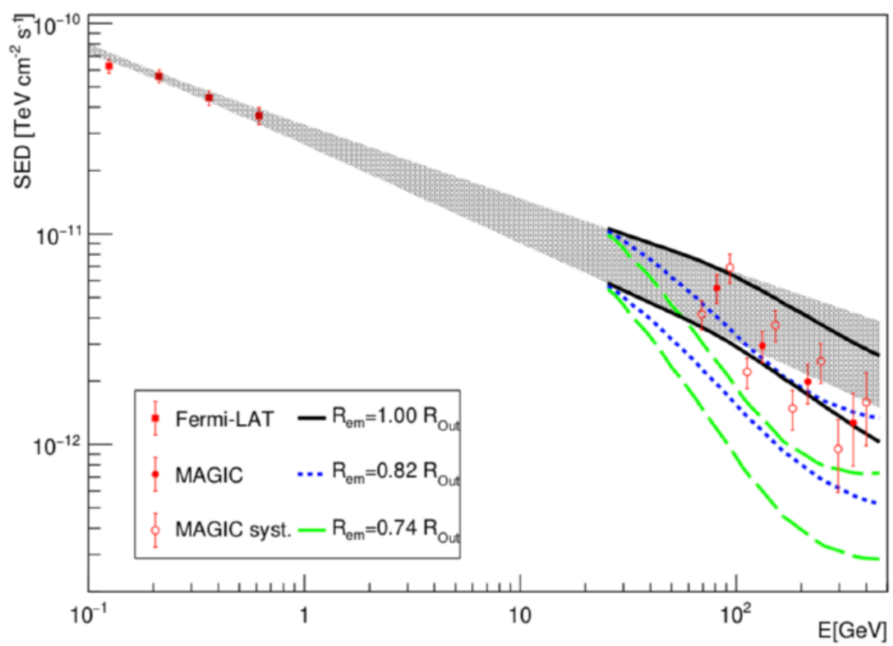
The external field also acts as an absorber via γ-γ pair-production

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!



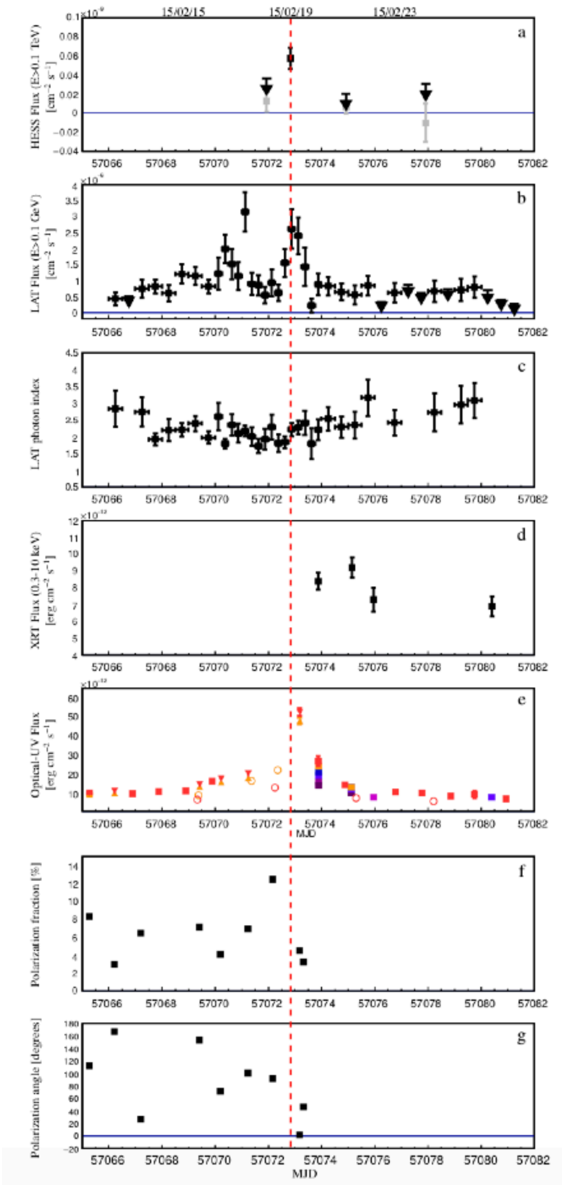


The emitting region HAS to be at $r \geq r_{BLR}$ even during quiescence

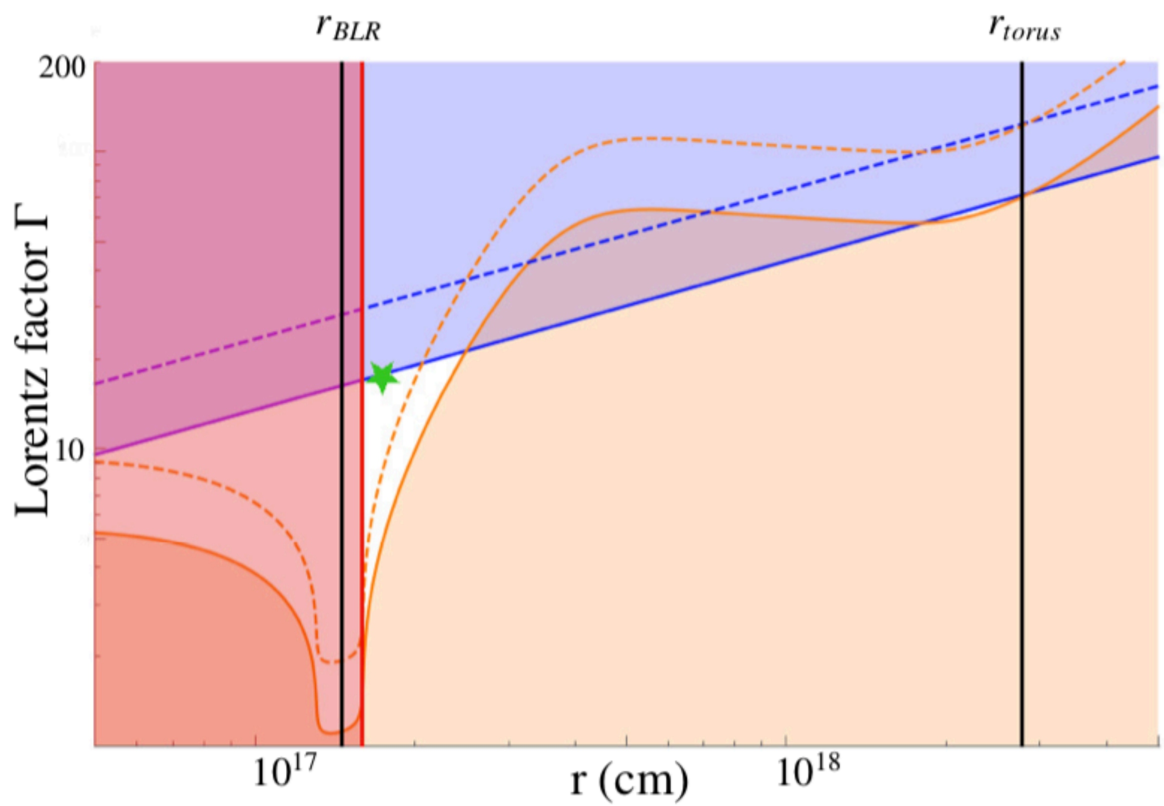
MAGIC Collaboration et al. 2018

FSRQs and LBLs

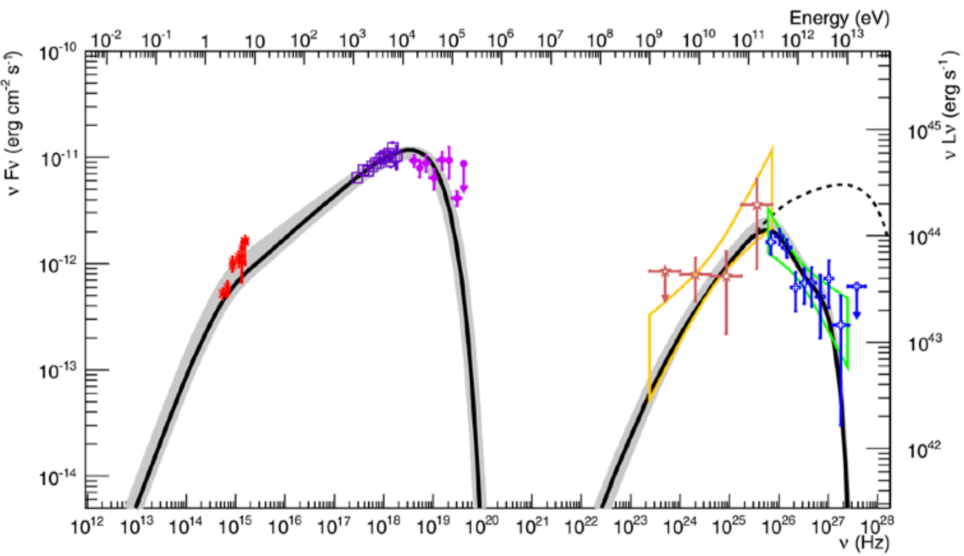
Nearest VHE FSRQ, at z=0.189



y



EXTREME BLAZARS



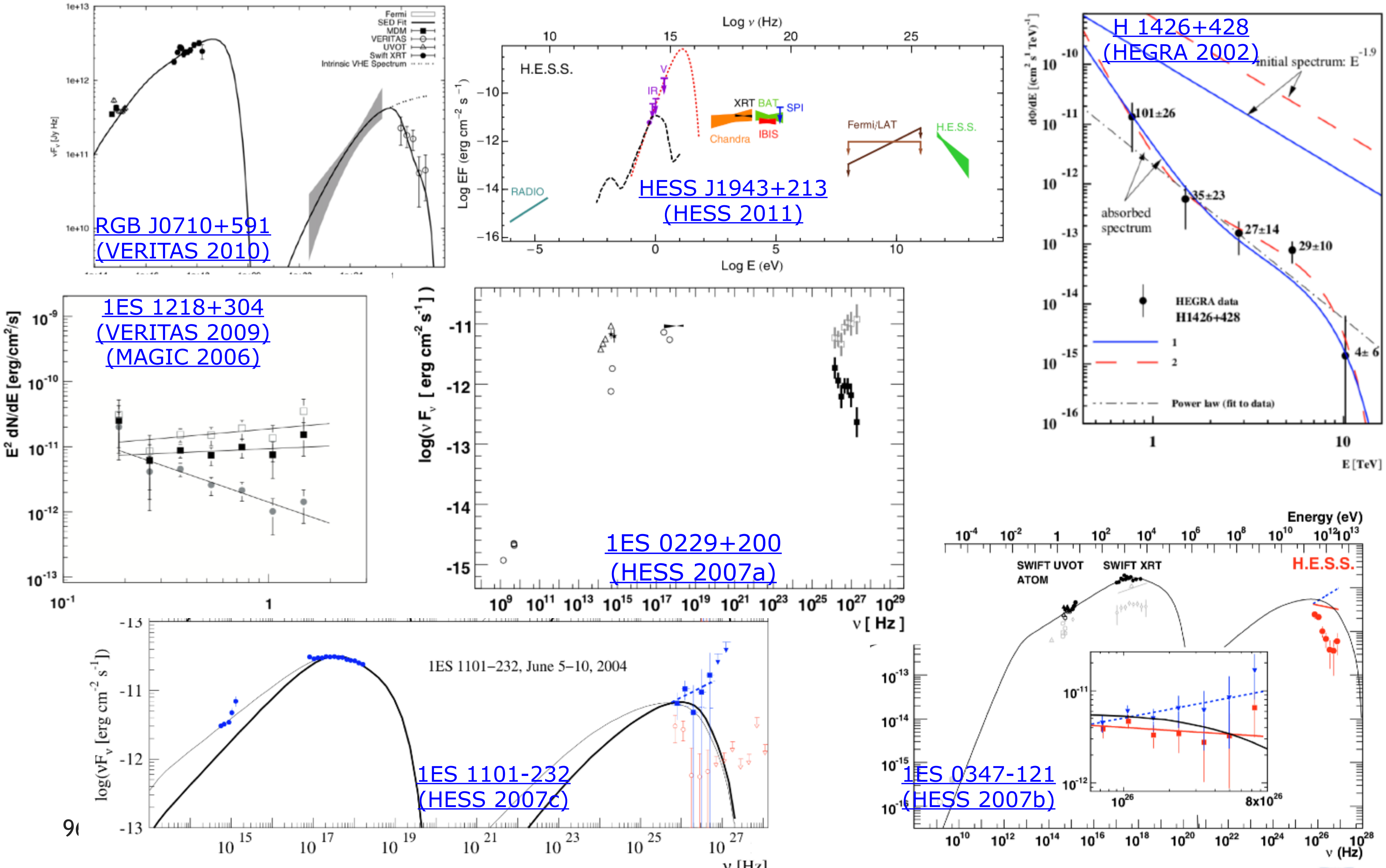
[Aliu et al. 2014]

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



RADIO GALAXIES - Centaurus A

Not variable! Unique spectral hardening at TeV
Extended!

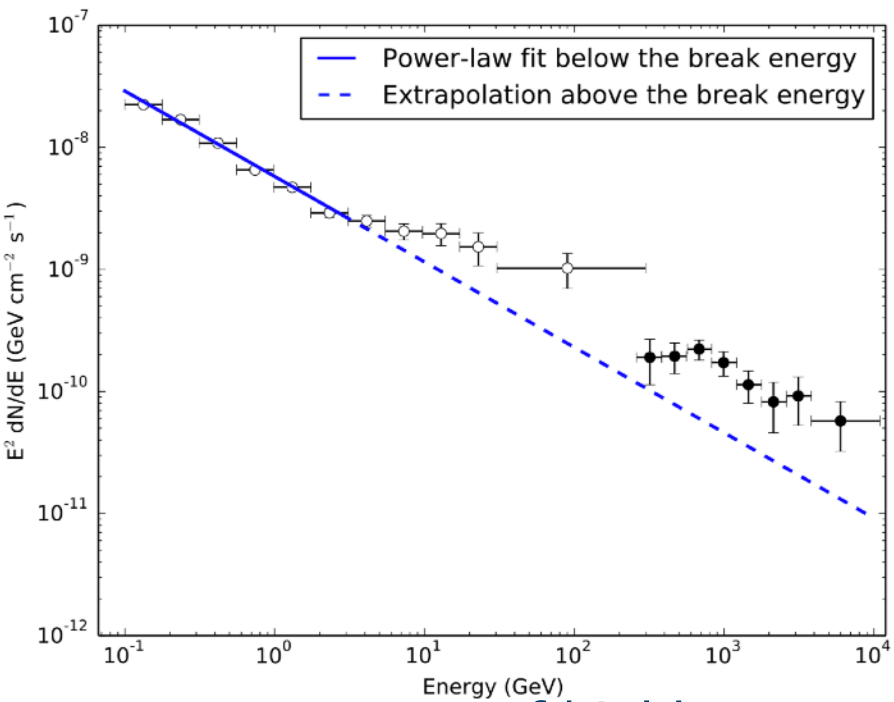
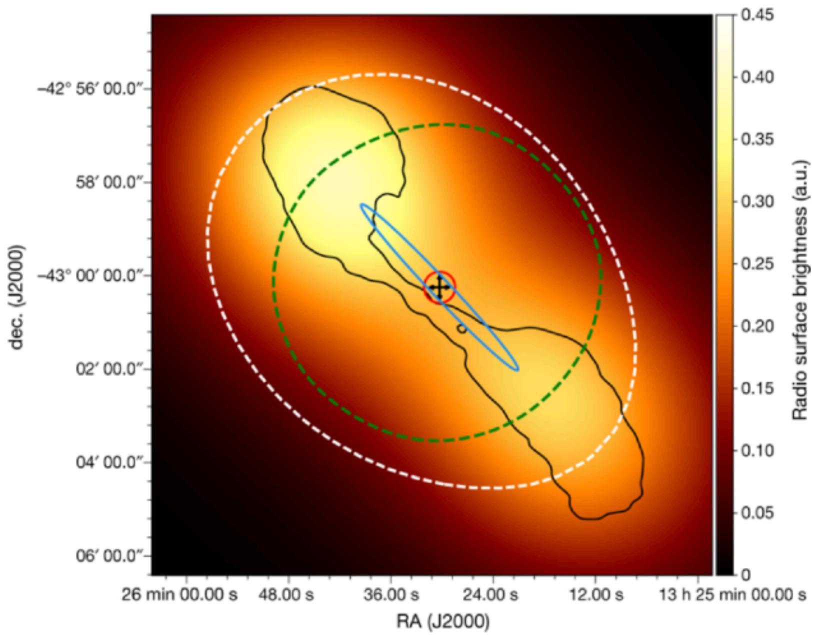


Fig. 1: Multiwavelength image of Centaurus A.

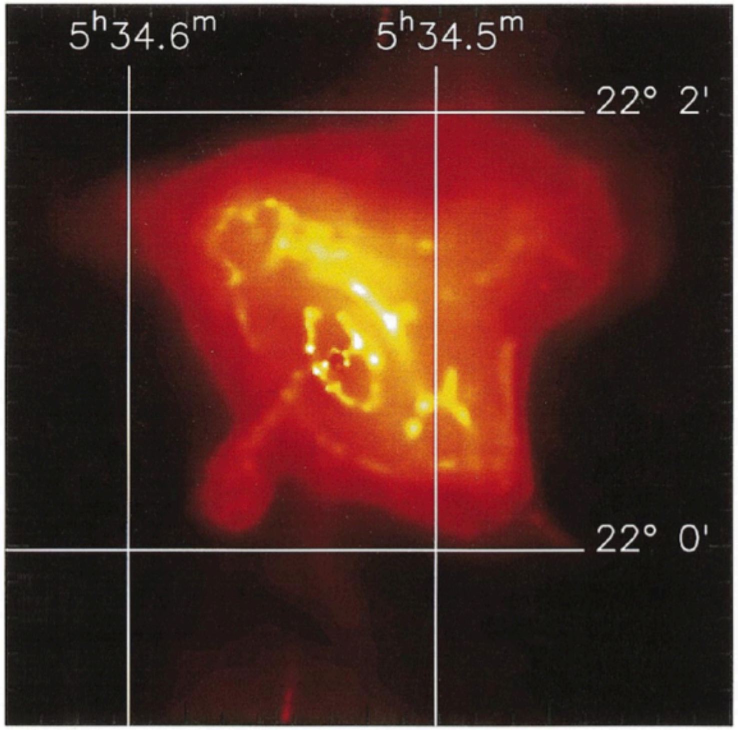


Presence of highly energetic particles over several kpc
-> continuous acceleration mechanism along the jet

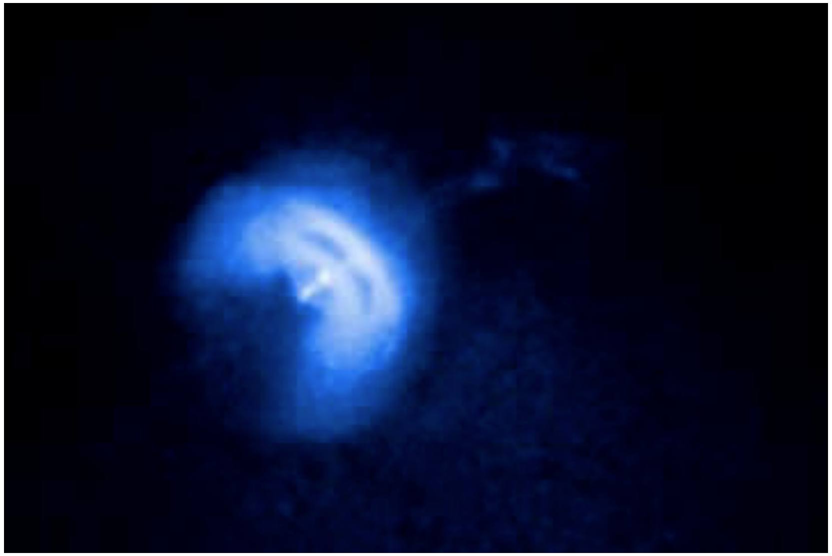
BONUS TRACK

JETS FROM NEUTRON STARS

High resolution X-ray images from Chandra clearly show jets launched from the Crab and Vela pulsars



Crab pulsar, Weisskopf 00



RADIATIVE TRANSFER

RADIATIVE TRANSFER BASICS

Luminosity: total energy emitted per unit time by a source
[erg/s] N.B. this is a power!

Flux: luminosity per unit area, measured at distance d [erg/cm^2/s]

$$F = \frac{L}{4\pi d^2}$$

L and F are typically given 'per unit frequency (or energy, or wavelength)': F_ν [erg/cm^2/s/Hz] (we also call it differential flux)

Integration gives total flux:

$$F_{0.1-1TeV} = \int_{0.1TeV}^{1TeV} dE F_E$$

But obviously $F_\nu \neq F_\lambda \neq F_E$!

RADIATIVE TRANSFER BASICS

We often use νF_ν: energy per logarithmic frequency interval:

$$\nu F_\nu = \nu \frac{dF}{d\nu} = \frac{dF}{dlog\nu}$$

Why it's useful:

Flat spectrum in $\nu F_\nu \rightarrow$ equal power per log-interval

It makes life easier for conversion: $\nu F_\nu = \lambda F_\lambda = EF_E = E^2 \frac{dN}{dE}$

Caveat for binned data:

In real data bins defined within ν_1, ν_2: $(\nu F_\nu)_i \neq \nu_i \times F_{\nu,i}$

because the flux has a spectral dependency *within* the bin

(VERY COMMON ERROR!)

RADIATIVE TRANSFER BASICS

Intensity I_ν : energy per area, time, frequency, solid angle [erg/cm^2/s/Hz/sr]

Emissivity j_ν: energy per volume, time, frequency, solid angle [erg/cm^3/s/Hz/sr]

Absorption coefficient α_ν: fractional absorption per length

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu \text{ [cm}^{-1}\text{]}$$

(In absence of emission)

It is also useful to express it as opacity: $\tau_\nu = \int \alpha_\nu ds$

RADIATIVE TRANSFER BASICS

Full equation for radiative transfer :

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

Source function: $S_\nu = \dfrac{j_\nu}{\alpha_\nu}$

$$\rightarrow \frac{dI_\nu}{ds} = -\alpha_\nu (I_\nu - S_\nu)$$

The general solution is

$$I_\nu = I_\nu(0)e^{-\tau_\nu} + S_\nu(1 - e^{-\tau_\nu})$$

We can also consider limits for optically thin ($\tau \ll 1$) or thick ($\tau \gg 1$) regimes

RADIATIVE TRANSFER BASICS

Emissivity and absorption coefficient will depend on the specific radiative process

Emissivity is computed by integrating the power of individual particles:

$$j_\nu = \int N(E) P_\nu(E) dE$$

Absorption coefficient is not independent!
(See Einstein coefficients)

For interaction processes (IC, pair production, pion production), the rate depends on the cross section:

$$R = \int \int f_1(E_1) f_2(E_2) v_{rel} \, \sigma(E_1, E_2) dE_1 dE_2$$

SYNCHROTRON EMISSION

Emission from charged particle in magnetic field.

If $\gamma = E/mc^2$, then emission at $\nu_c = \dfrac{3eB}{4\pi mc^2} \sin(\phi)\ \gamma^2$

The synchrotron power from a single particle is then

$$P_\nu = \frac{\sqrt{3}e^3 B \sin\phi}{mc^2} \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} K_{5/3}(x)dx$$

j_ν and α_ν are then calculated directly and the intensity just follows

SYNCHROTRON EMISSION

Very important property: if the particle distribution is a power law

$$N(\gamma) = K\gamma^{-n}$$

Then the differential photon flux is also a power law with

$$dN/dE \propto E^{-(n+1)/2}$$

The flux $F_\nu \propto \nu^{-(n-1)/2}$

And the SED $\nu F_\nu \propto \nu^{-(n-3)/2}$

For example, if n = 2, $\nu F_\nu \propto \nu^{1/2}$

If n= 3, νF_ν is flat

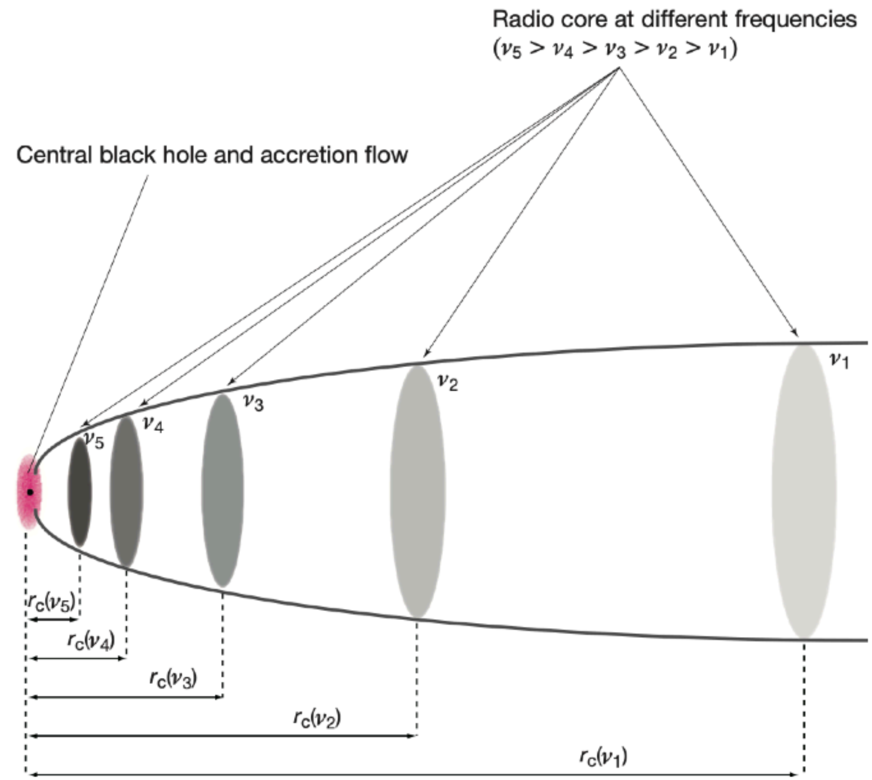
SYNCHROTRON EMISSION

At low frequencies, $\tau_\nu \geq 1$
and synchrotron self-absorption suppresses emission.

For a homogeneous source, the flux scales as $\nu^{5/2}$
So there is a critical frequency that indicates the transition from optically thick to optically thin

This self-absorption frequency ν_{SA} depends on B, R, K

Very important observational property: Core shift
In VLBI, the radio "core" is the surface where $\tau_\nu = 1$
The position of the core moves downstream at lower frequencies!



Hada 2011

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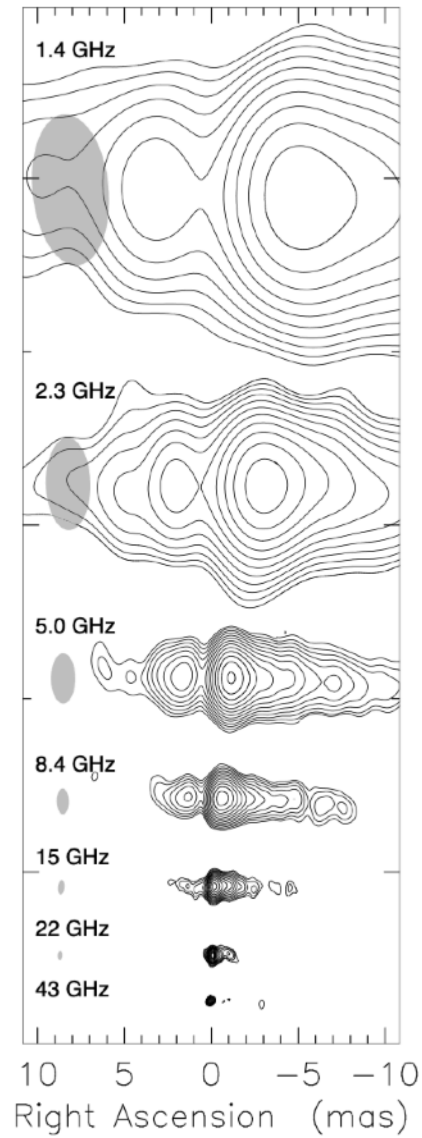
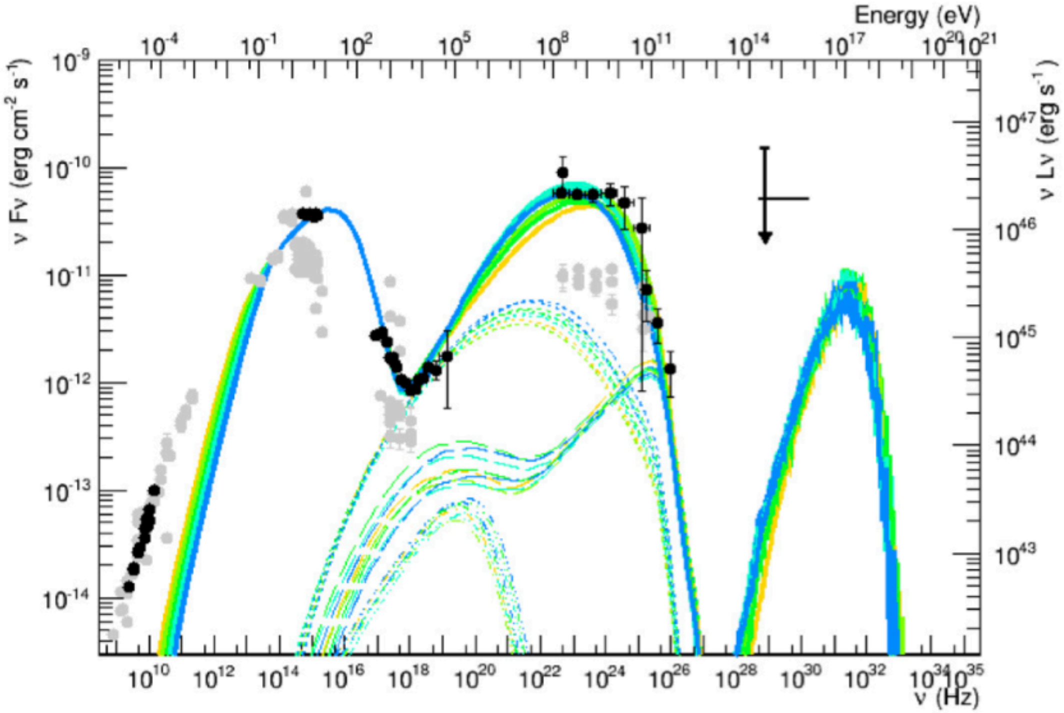


Haga 2013

SYNCHROTRON EMISSION

Second important consequence:

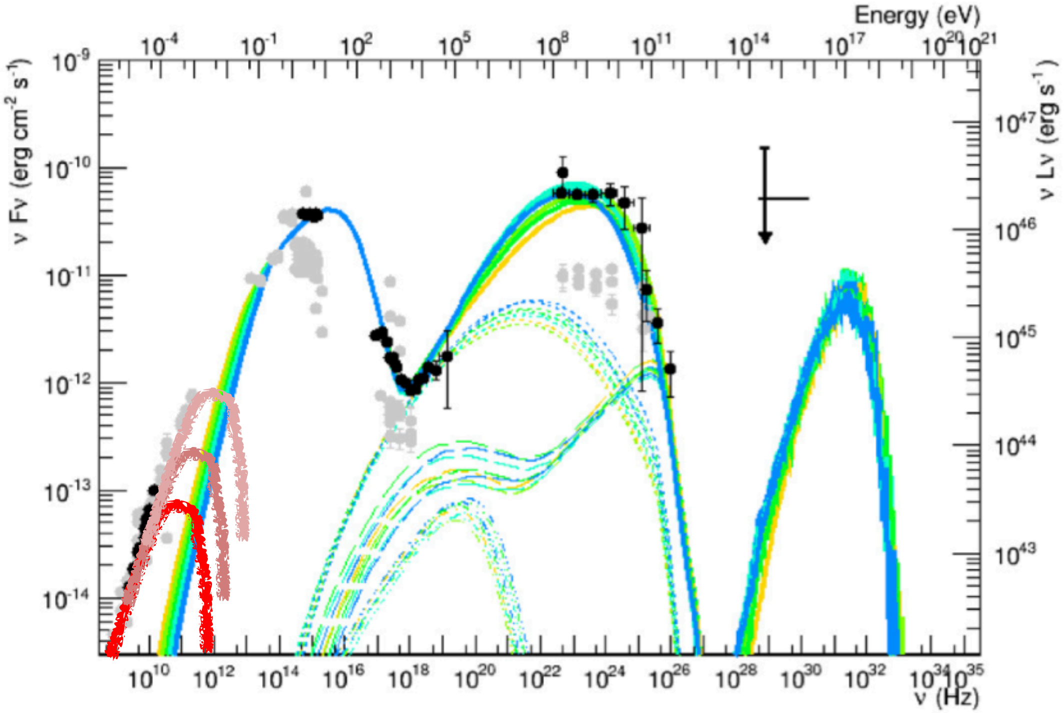
In blazar modeling, the emission that is producing the gamma cannot be the same as the one producing the radio



SYNCHROTRON EMISSION

Second important consequence:

Radio has to be the extended jet
(we see it in maps, it cannot be the single zone)



SYNCHROTRON EMISSION

Cooling and breaks: energy must be conserved!
If particles radiate a lot, they lose energy too.

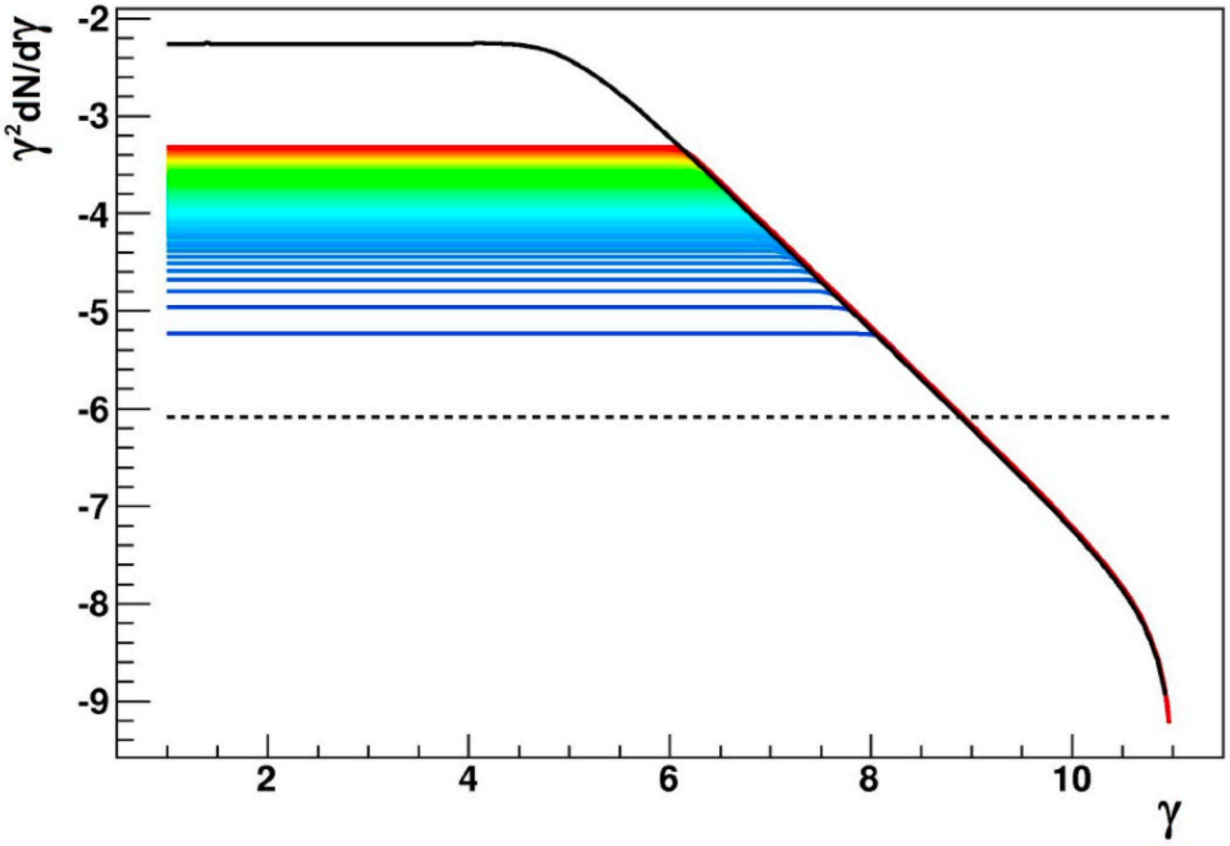
We can compute the electron distribution at equilibrium:

$$\frac{\partial}{\partial t} N'_e(\gamma'_e, t) = \frac{\partial}{\partial \gamma'_e} \left[\gamma'_e \frac{N'_e(\gamma'_e, t)}{\tau_{syn}(\gamma'_e)} \right] - \frac{N'_e(\gamma'_e, t)}{\tau_{ad}} + Q'_e(\gamma'_e)$$

with $\tau_{syn} = \frac{3mc}{4u_B\sigma_T}\frac{1}{\gamma}$ and $\tau_{ad} = R/c$

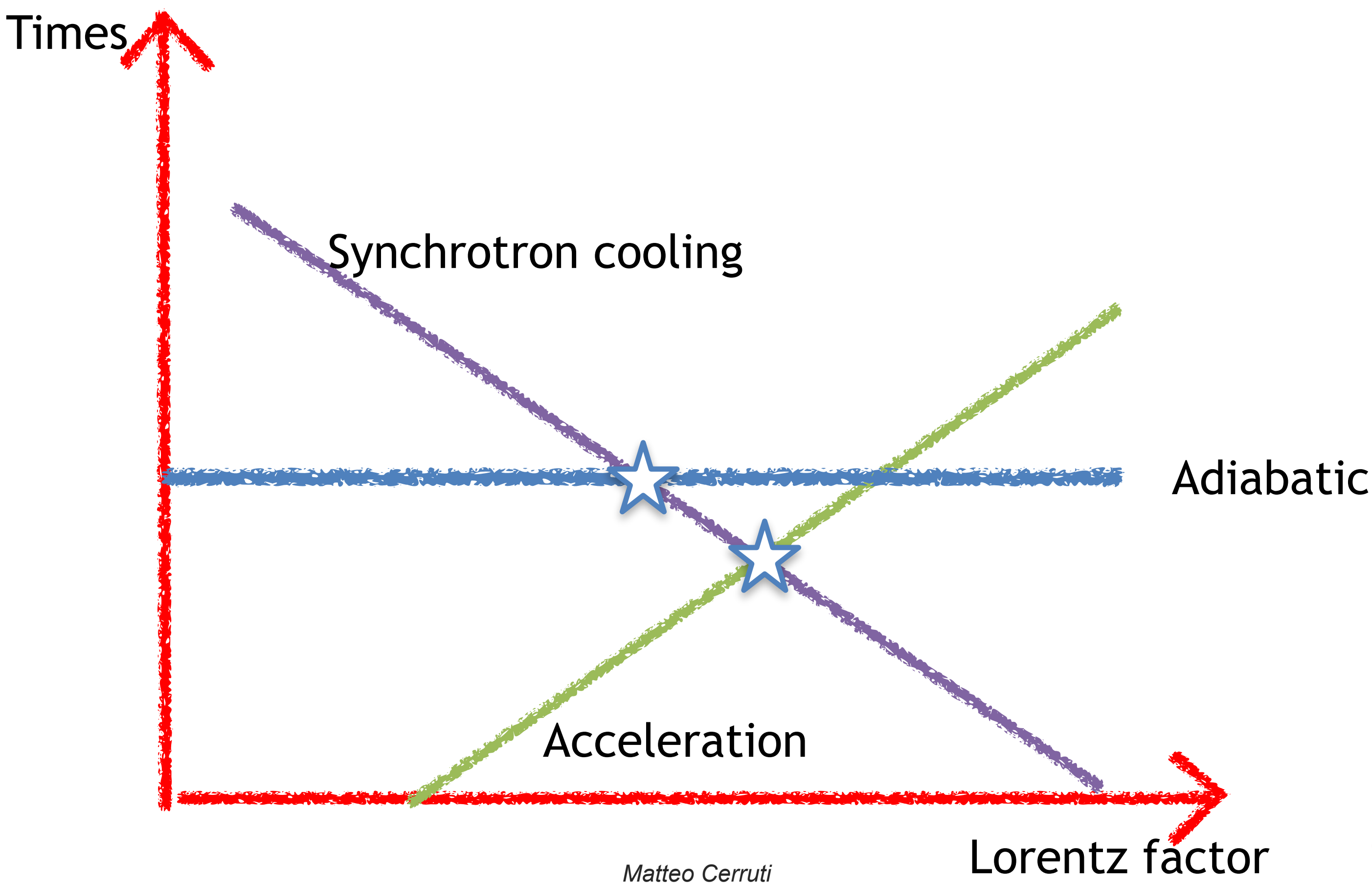
SYNCHROTRON EMISSION

By solving the differential equation we get the equilibrium



SYNCHROTRON EMISSION

You can understand equilibrium and cooling by looking at the time scale plots



INVERSE COMPTON EMISSION

A relativistic electron upscatters a soft photon:

$$e^- + \gamma \rightarrow e^- + \gamma$$

In the Thomson limit:

$$\frac{\epsilon_1}{m_e c^2} \ll 1 \;\; \Rightarrow \text{elastic scattering in electron rest frame}$$

The energy transferred to the photon can be as high as

$$\epsilon_2 = 4\gamma^2\epsilon_1$$

The total power emitted (assuming isotropic photon field) is

$$P_{IC} = \frac{3}{4}\sigma_T c \gamma^2 \beta^2 u_{ph}$$

(same form as synchrotron)

The ratio of the photon and magnetic energy densities
is thus enough to estimate if we are synchrotron or IC dominated

INVERSE COMPTON EMISSION

Transition to Klein-Nishina Regime:
Klein-Nishina becomes important when the photon energy *in the electron frame* becomes much larger

$$\epsilon_1^\star = \gamma\epsilon_1(1-\beta\cos\theta) \gg 1$$

Full cross section is the Klein-Nishina formula:

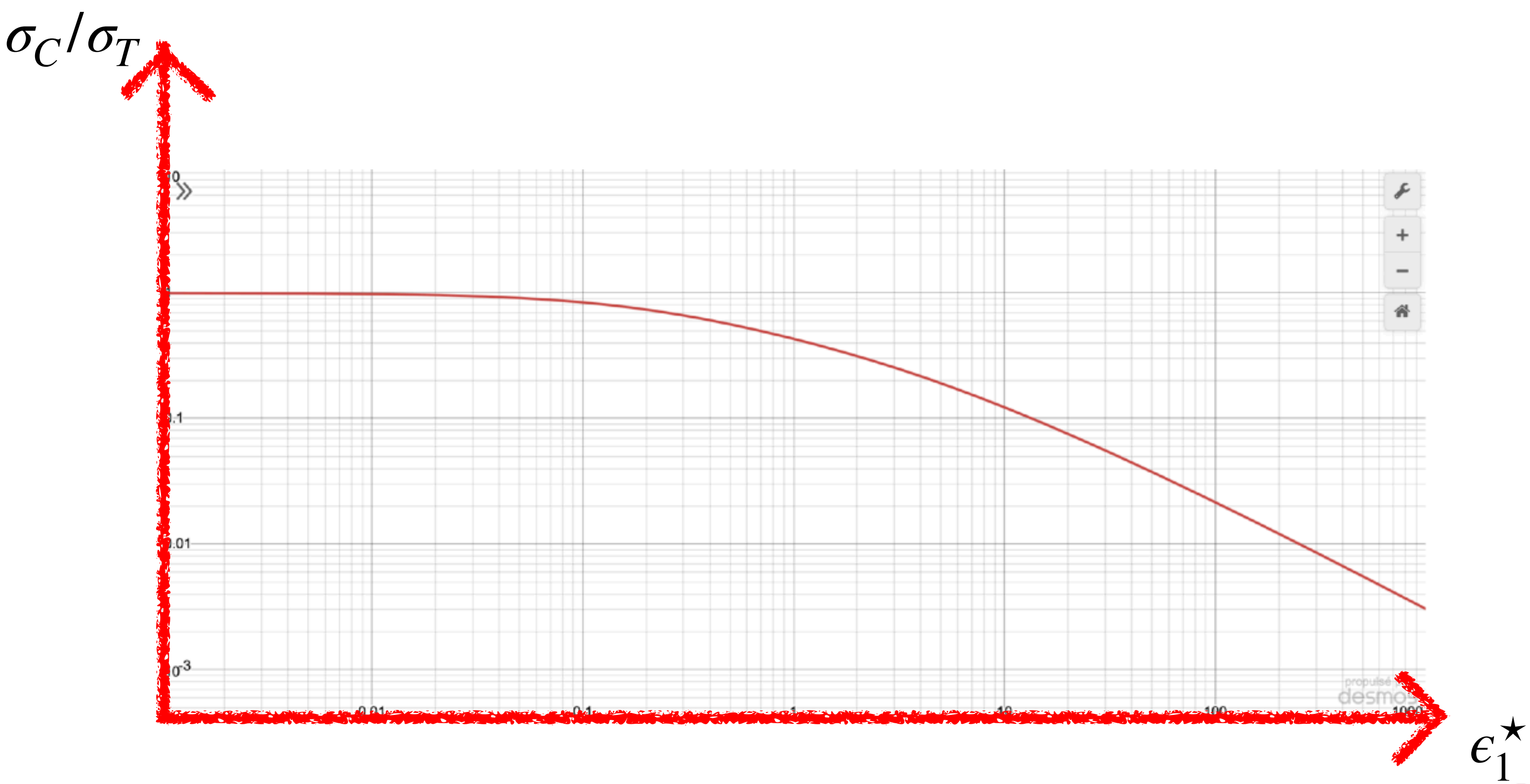
the cross section drops steadily above 1.

-> IC scattering is suppressed for high electron energies!

INVERSE COMPTON EMISSION

Klein-Nishina cross section

$$\sigma_C\left(\varepsilon_1^\star\right) = \frac{3\sigma_T}{8\varepsilon_1^{\star 2}}\left(4 + \frac{2\varepsilon_1^{\star 2}\left(1+\varepsilon_1^\star\right)}{\left(1+2\varepsilon_1^\star\right)^2} + \frac{\varepsilon_1^{\star 2} - 2\varepsilon_1^\star - 2}{\varepsilon_1^\star}\ln\left(1+2\varepsilon_1^\star\right)\right)$$



Matteo Cerruti

INVERSE COMPTON EMISSION

A population of electrons in a magnetic field, synchrotron radiate and *unavoidably* do IC scattering on their own synchrotron emission

-> synchrotron-self-Compton (SSC)

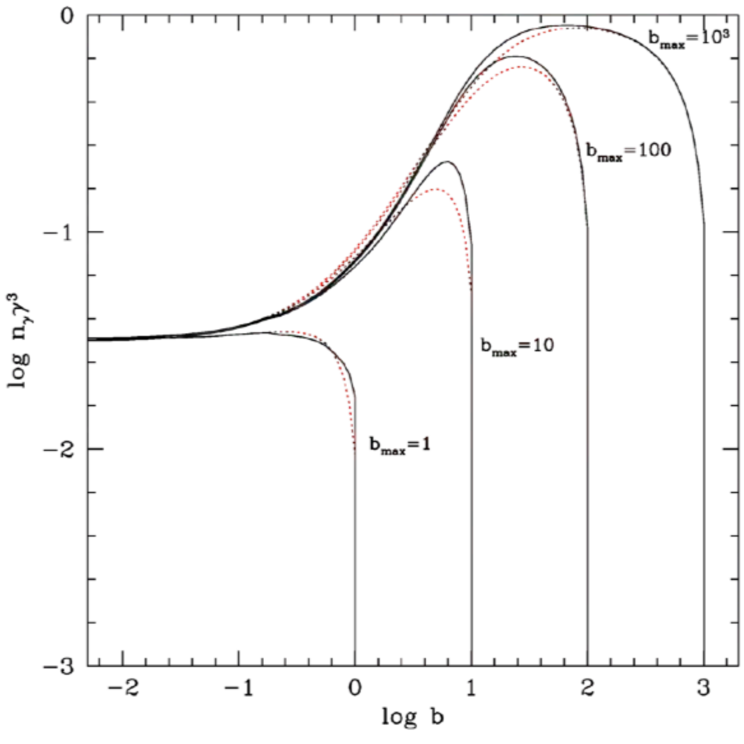
The SSC component has the same spectral shape (in the Thomson part! It gets softer once in KN)

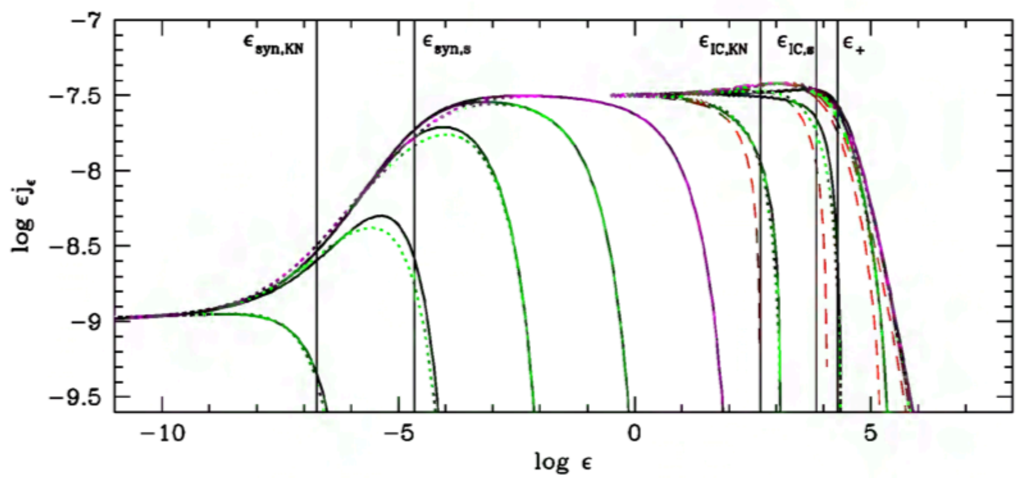
Compton dominance depends on:

$$\frac{P_{syn}}{P_{IC}} = \frac{u_B}{u_{ph}}$$

INVERSE COMPTON EMISSION

If deep in KN cooling the at equilibrium spectrum of electrons gets weird:





PAIR PRODUCTION

$$\gamma + \gamma \rightarrow e^{-} + e^{+}$$

There is a threshold: $2E_1E_2 \geq (mc^2)^2$

The cross section is

$$\sigma_{\gamma\text{-}\gamma}(s) = \frac{3\sigma_T}{16}(1-s^2)\left[2s(s^2-2) + (3-s^4)\ln\left(\frac{1+s}{1-s}\right)\right]$$

That can be better understood in the *delta approximation*

$$\sigma_{\gamma\text{-}\gamma}(\varepsilon_1, \varepsilon_2) \simeq \frac{1}{3}\sigma_T \delta\left(\varepsilon_2 - \frac{2}{\varepsilon_1}\right)\frac{1}{\varepsilon_1}$$

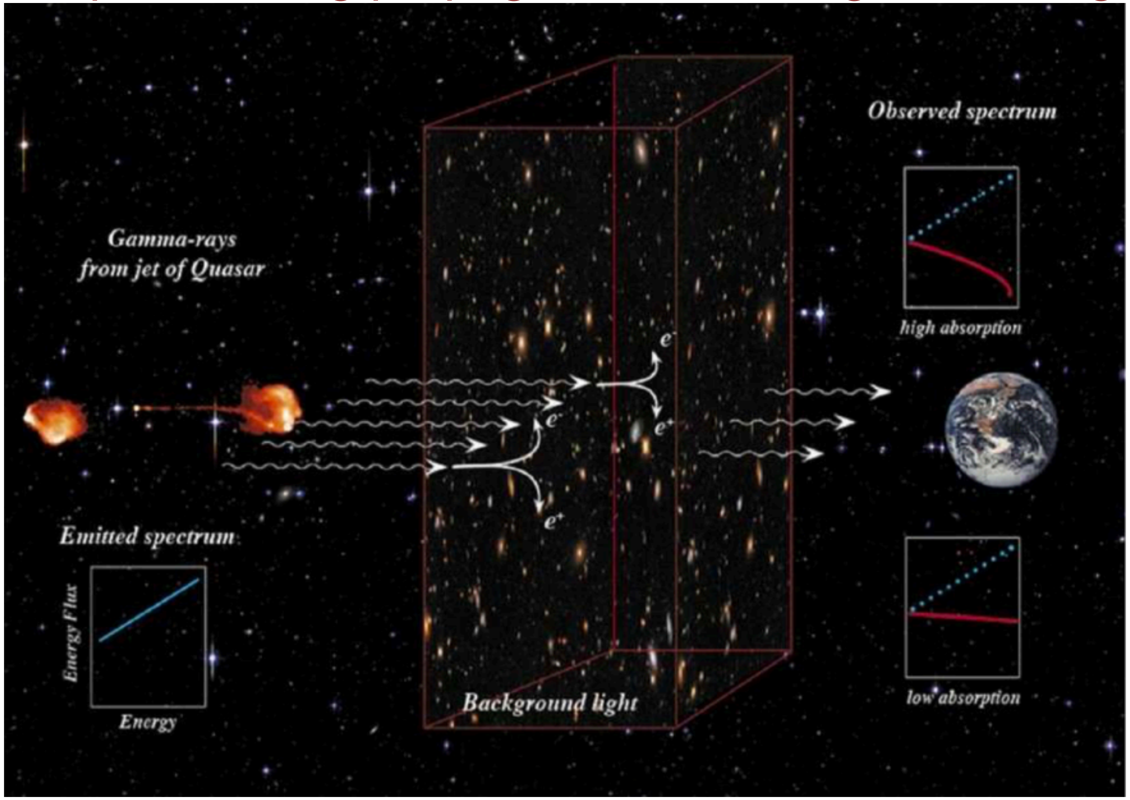
With $e_{1,2} = E_{1,2}/mc^2$

PAIR PRODUCTION

For gamma-ray photons, it is in practice an absorption

Very important topic in gamma-ray astronomy:

- Internal absorption in the source if in a dense photon field
- Absorption during propagation for extragalactic targets



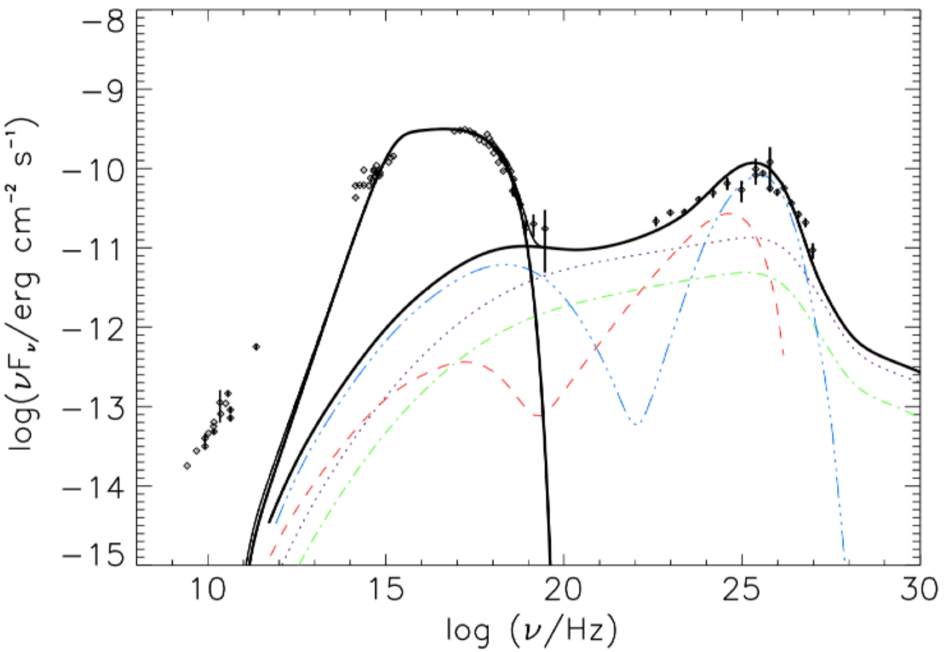
PAIR PRODUCTION

N.B. you should worry about what happens to the pairs!

In dense photon fields, pair-production can lead to cascades in the emitting region.

The secondaries radiate again (synchrotron and IC) and can pair-produce again.

If this process continues, the cascade-spectrum saturate with an index of about 2 in νF_ν



PAIR PRODUCTION

What about pair annihilation?

Not important in jets: pair need to be at rest to annihilate efficiently.

In a relativistic plasma ($\gamma \gg 1$), pair annihilation is not observed

HADRONIC INTERACTIONS

Pion production from proton-photon interactions

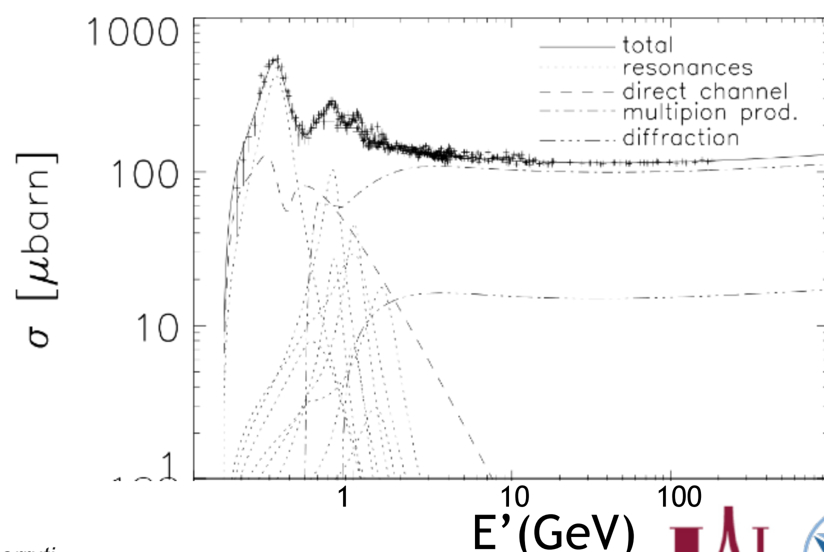
$$p + \gamma = p' + \pi^0 \rightarrow p' + 2\gamma$$
$$p + \gamma = n + \pi^+$$
$$p + \gamma = p' + \pi^+ + \pi^-$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_\mu + \bar{\nu_\mu} + \nu_e$$

The only relevant radiative processes are from leptons!

Pair cascades from neutral pion decay and charged pion decay

In some cases, muon synchrotron can be important



HADRONIC INTERACTIONS

(The same thing holds for proton-proton interactions.
In jets the p-p is not important)

HADRONIC INTERACTIONS

Bethe-Heitler pair production is the direct production of a pair in proton-photon interactions

$$p + \gamma \rightarrow p + e^- + e^+$$

It is a process that competes with photo-meson
(But without producing neutrinos!)

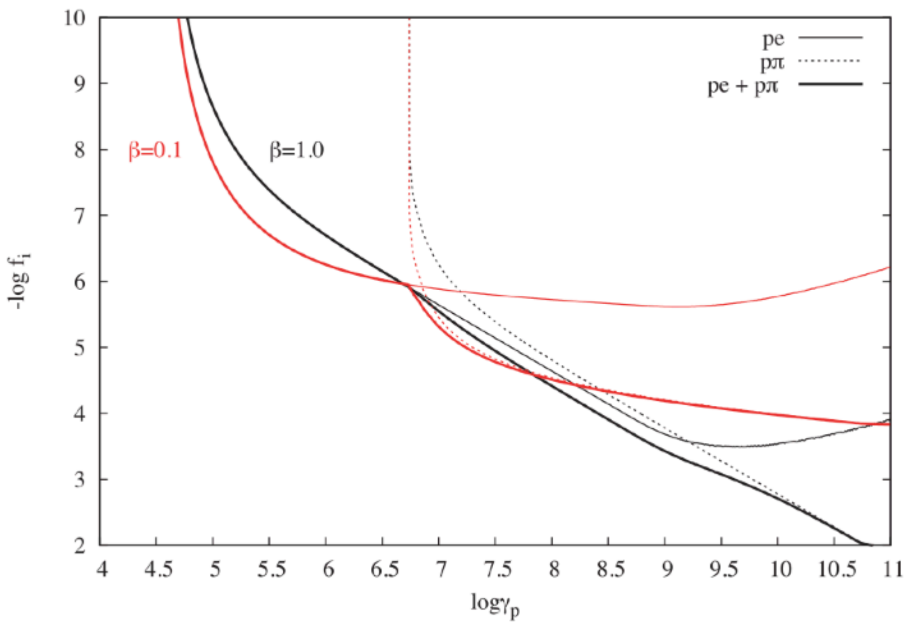
Different thresholds and different cross sections:
The ratio between photo-meson and BH depends on the spectrum of protons and photons

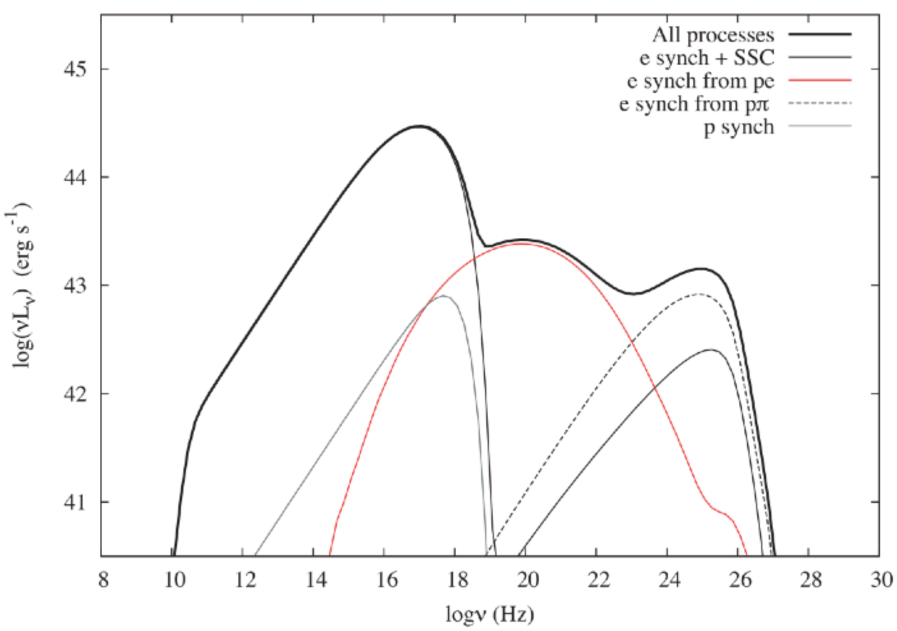
BLAZARS EMISSION MODELS

Why is Bethe-Heitler important?

Injection of pairs at lower energy (compared to photo-meson)

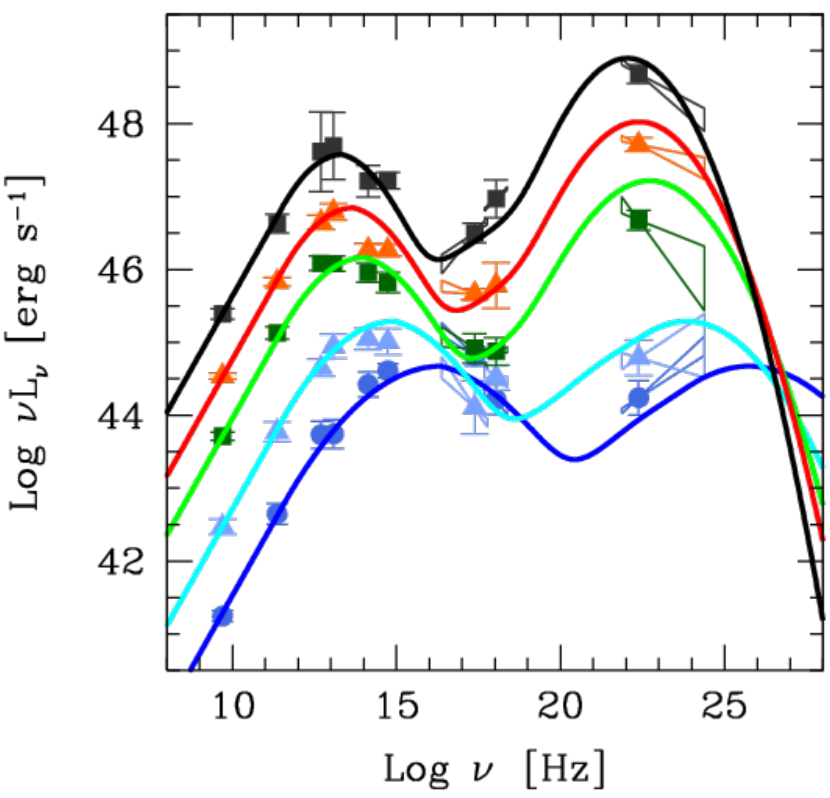
Can dominate the X-ray band and fill the SED valley





Petropoulou & Mastichiadis 2015

BLAZAR SEDs



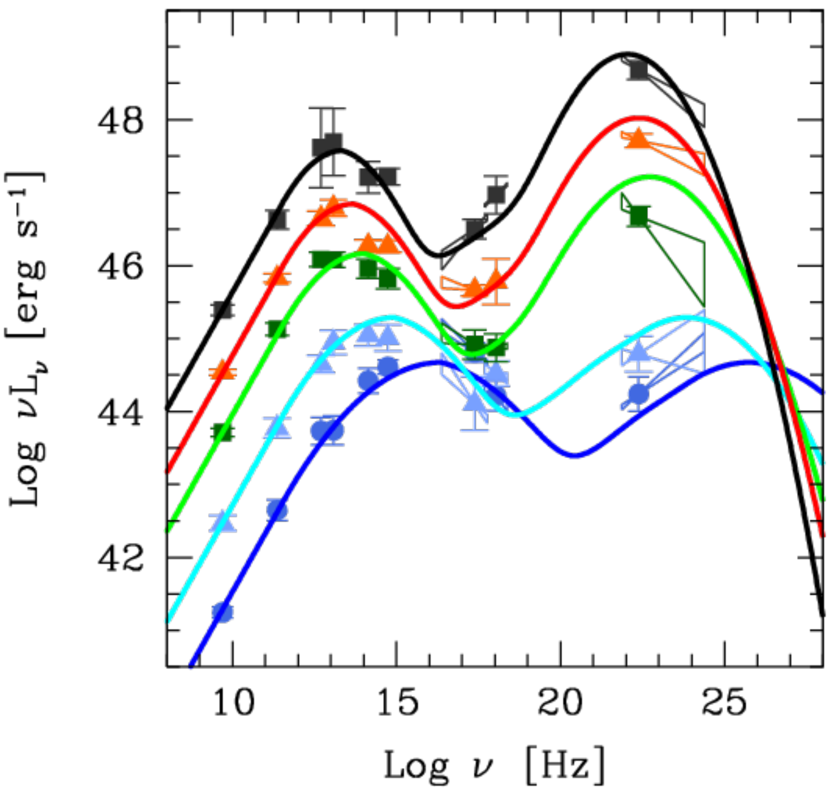
Low energy bump
(radio to X-rays)

IS

synchrotron emission by electrons/positrons

- spectral index matches
- polarization matches
- opacity from self-absorption matches

BLAZAR SEDs



High energy bump
(X-rays to gamma-rays)

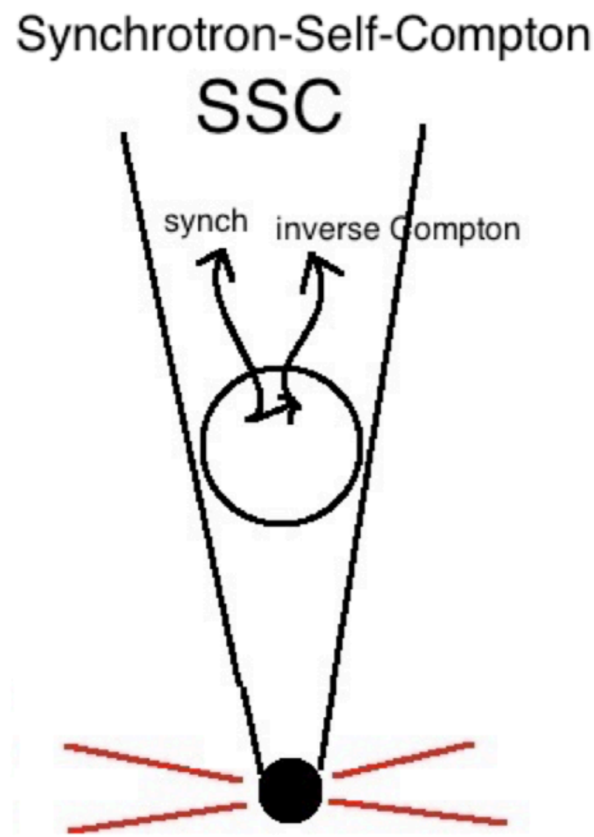
less clear

- Leptonic models: photons come from inverse Compton scattering off $e^{\pm}$
- Hadronic models: photons come from synchrotron by protons, or by secondary leptons produced in p-γ scattering

N.B. Leptonic/hadronic here means 'what type of particle are accelerated in the jet to reproduce the emission'

Synchrotron-Self-Compton

The soft photon field up-scattered by leptons is their own synchrotron radiation



- The high and low-energy bump are intimately related (we can make predictions that can be tested!)

- The number of free parameters is actually low

N.B. Single-zone: at any given moment, the jet emission is dominated by one of the plasmoids

Synchrotron-Self-Compton

Free parameters

3 for the emitting region:

Radius R (assumed spherical)

Magnetic field B (assumed homogeneous)

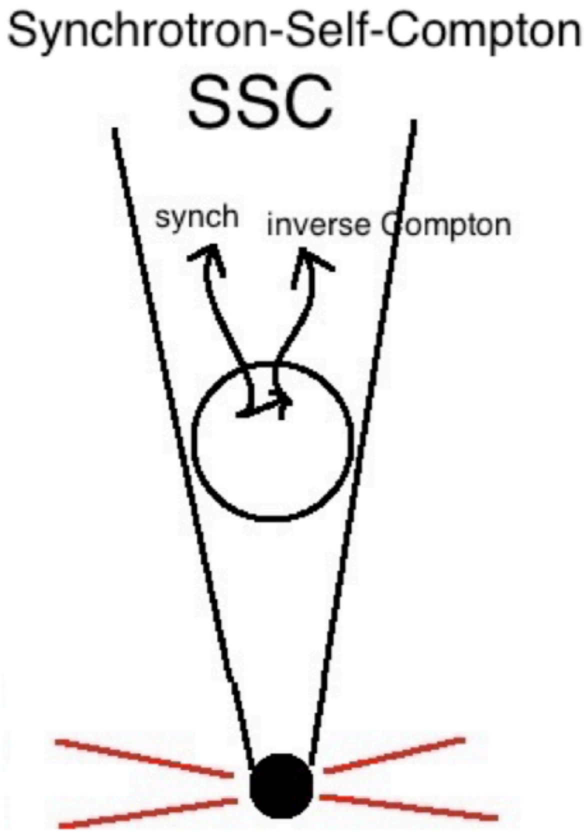
Doppler factor δ

6 (at most!) for the particles:

Normalization K

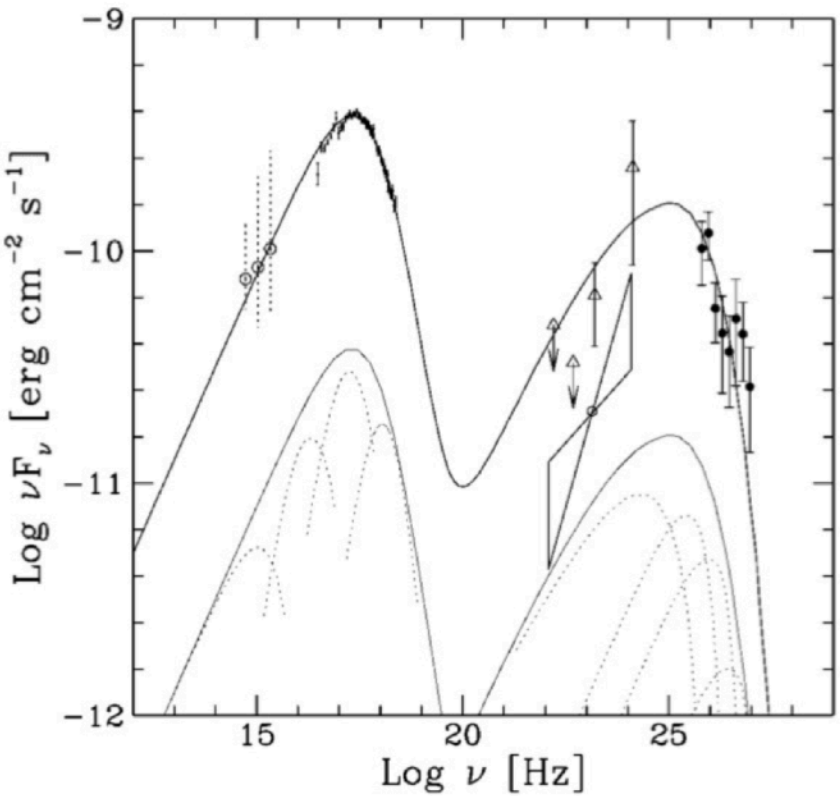
Indexes $\alpha_{1,2}$ (assumed BKNPL)

Lorentz factors $\gamma_{min,break,Max}$

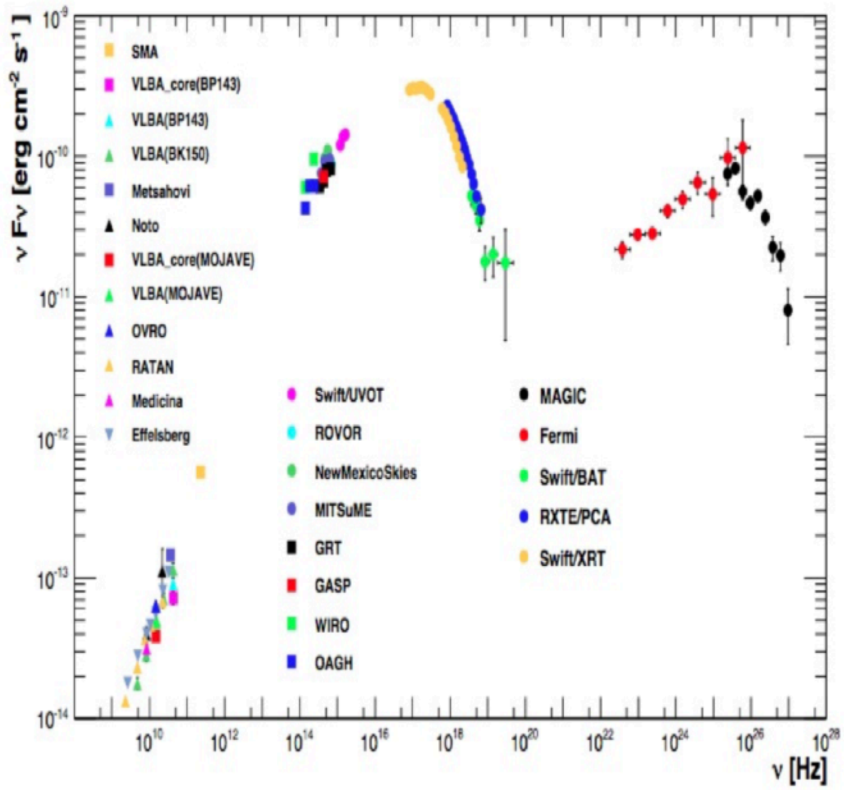


Synchrotron-Self-Compton

How did data improve in the last years



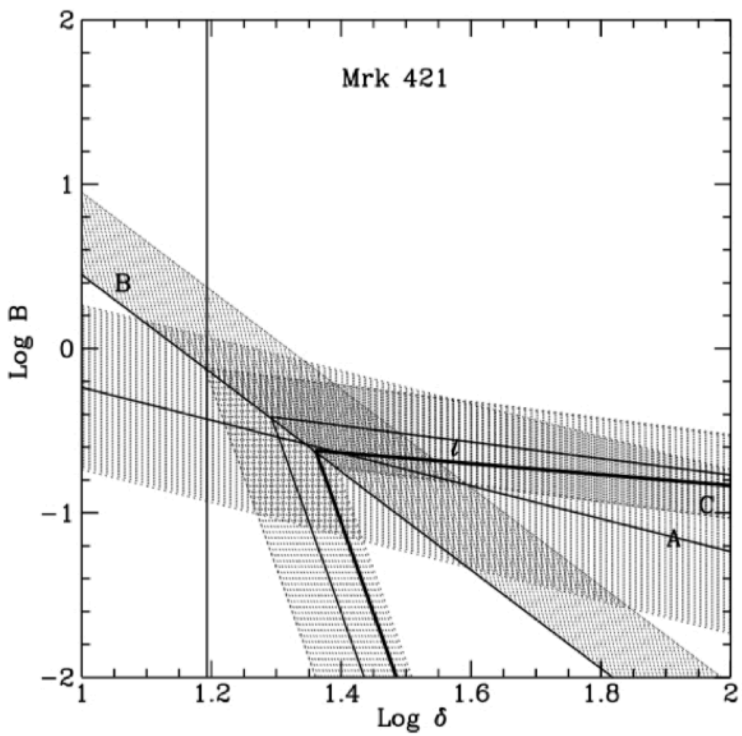
Maraschi et al. 1999



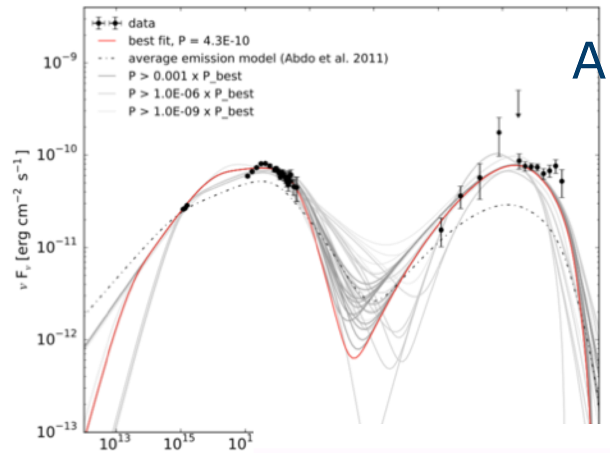
Abdo et al. 2011

Synchrotron-Self-Compton

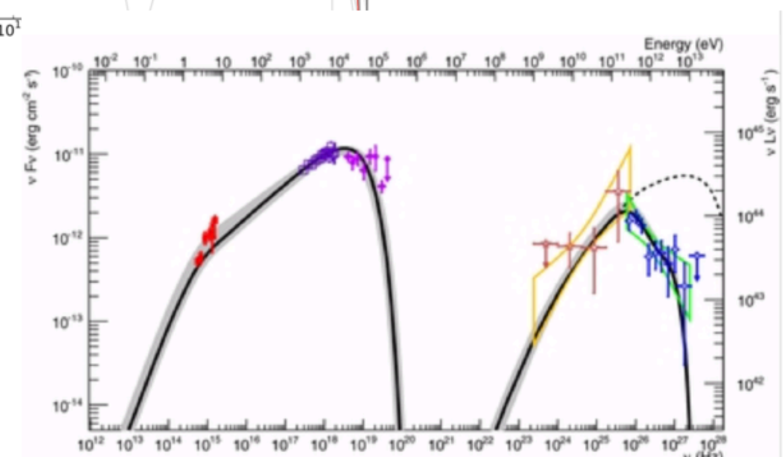
How did modeling improve



Tavecchio et al. 1998



Ahnen et al. 2017



Aliu et al. 2014

Synchrotron-Self-Compton

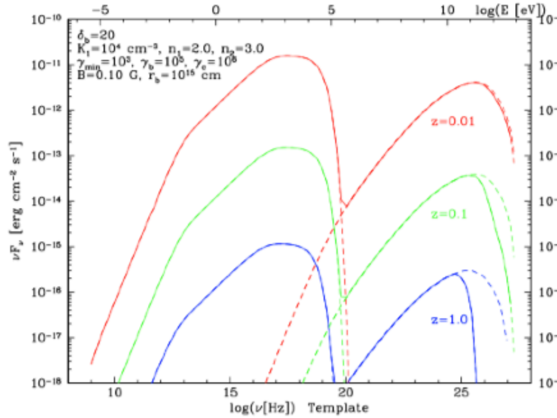
Single-zone SSC modeling works well for HBLs
and can be constrained
(if the MWL coverage is good)

but…

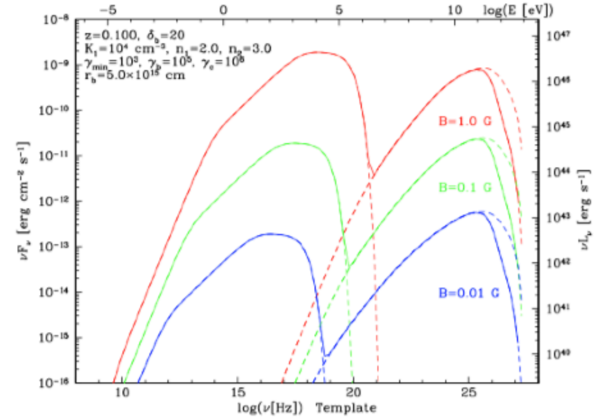
- the electron distribution is often NOT what we expect from standard acceleration and cooling

- in some cases we get strange parameter values (i.e. extreme HBLs: high value of γ_{min})

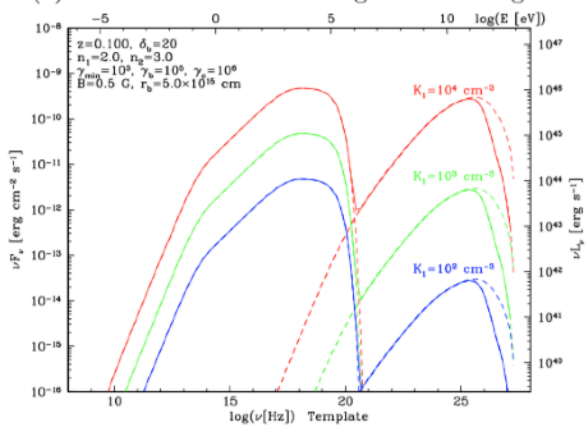
Synch



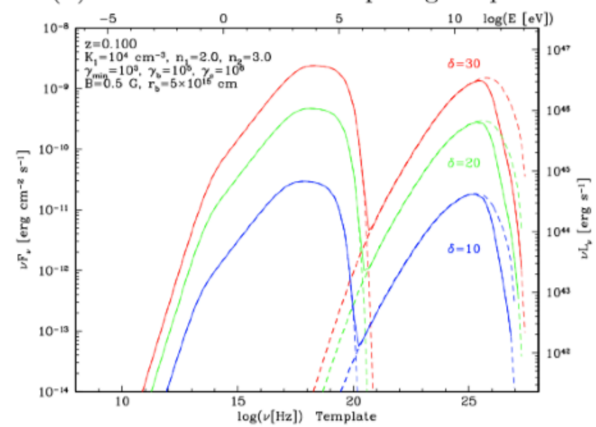
(a) Variation avec le décalage vers le rouge z.



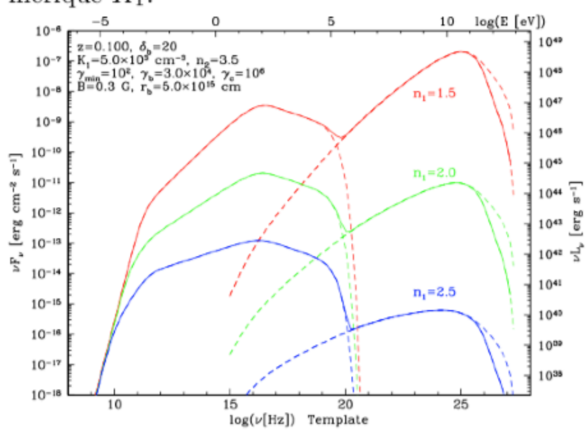
(b) Variation avec le champ magnétique B.



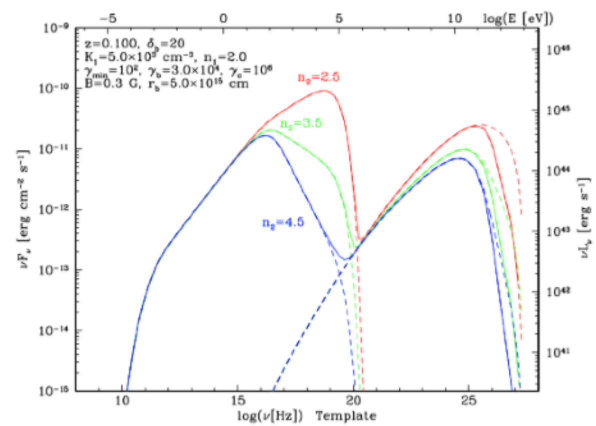
(c) Variation avec la normalisation en densité numérique K_1.



(d) Variation avec le facteur DOPPLER δ.

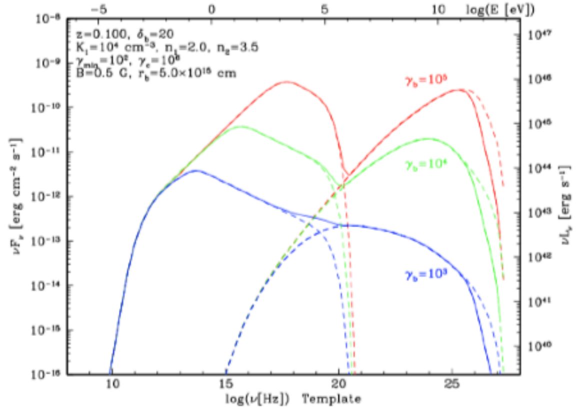


(e) Variation avec l'indice n_1.

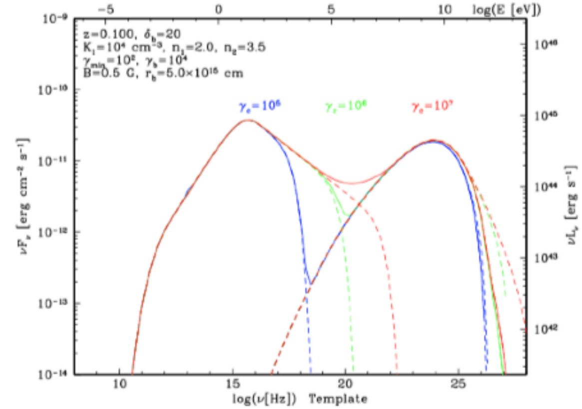


(f) Variation avec l'indice n_2.

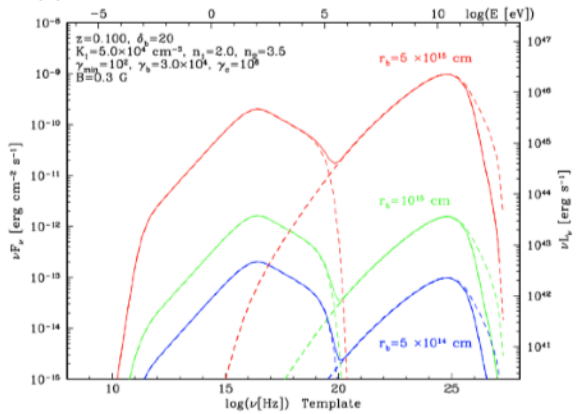
Synch



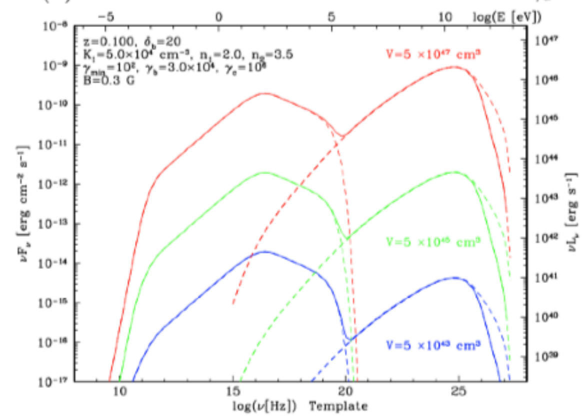
(g) Variation avec le facteur de LORENTZ γ_b.



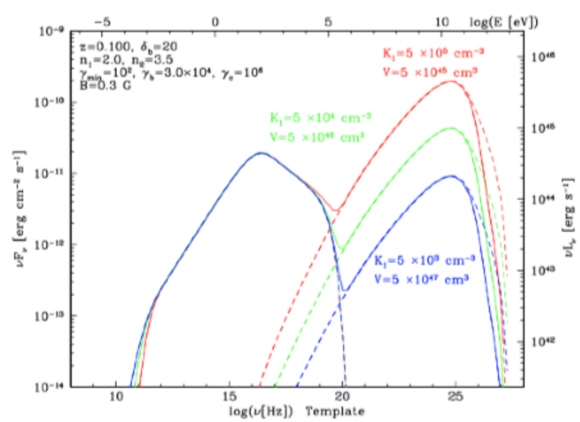
(h) Variation avec le facteur de LORENTZ γ_c.



(i) Variation avec le facteur rayon de la zone d'émission r_b.

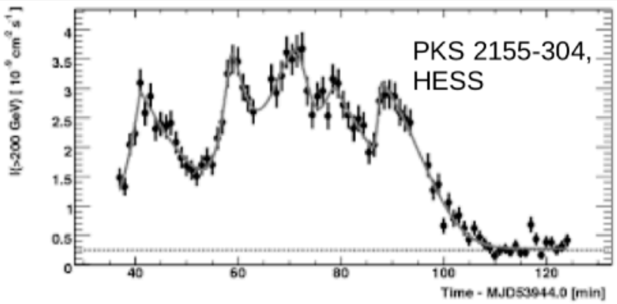


(j) Variation avec le volume de la zone d'émission.

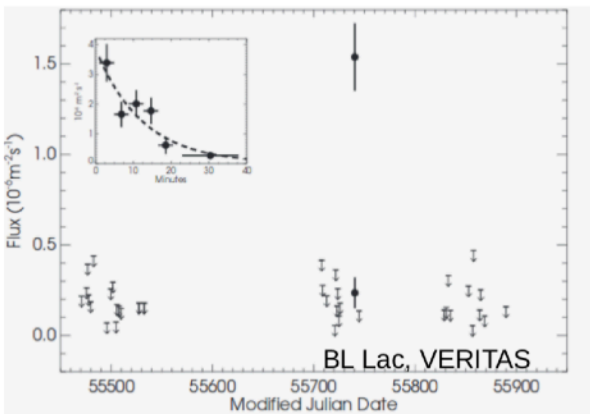


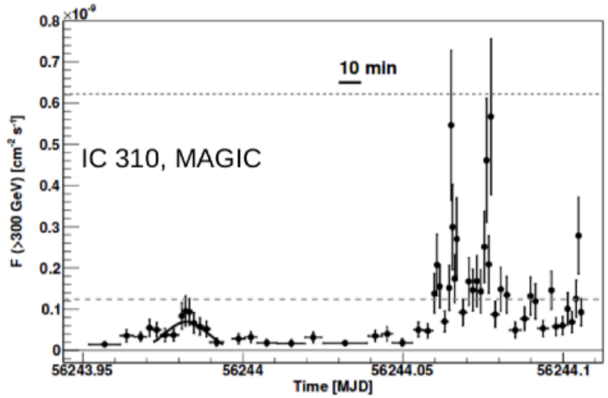
(k) Variation anti-corrélée entre K_1 et r_b, en maintenant le produit $K_1 r_b^3$ constant.

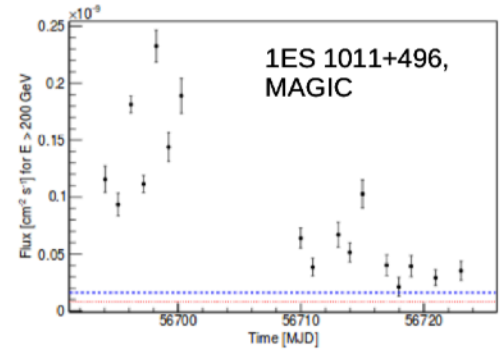
BLAZAR FLARES

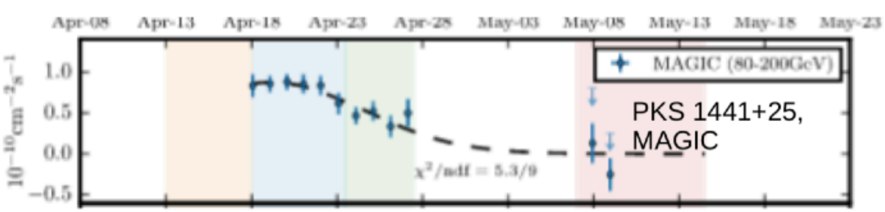


Blazars are variable, at all wavelengths and on different timescales!

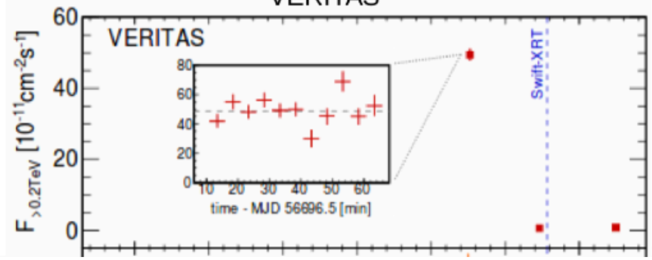








1ES 1215+303
VERITAS



Matteo Cerruti

BLAZAR FLARES

What are flares?

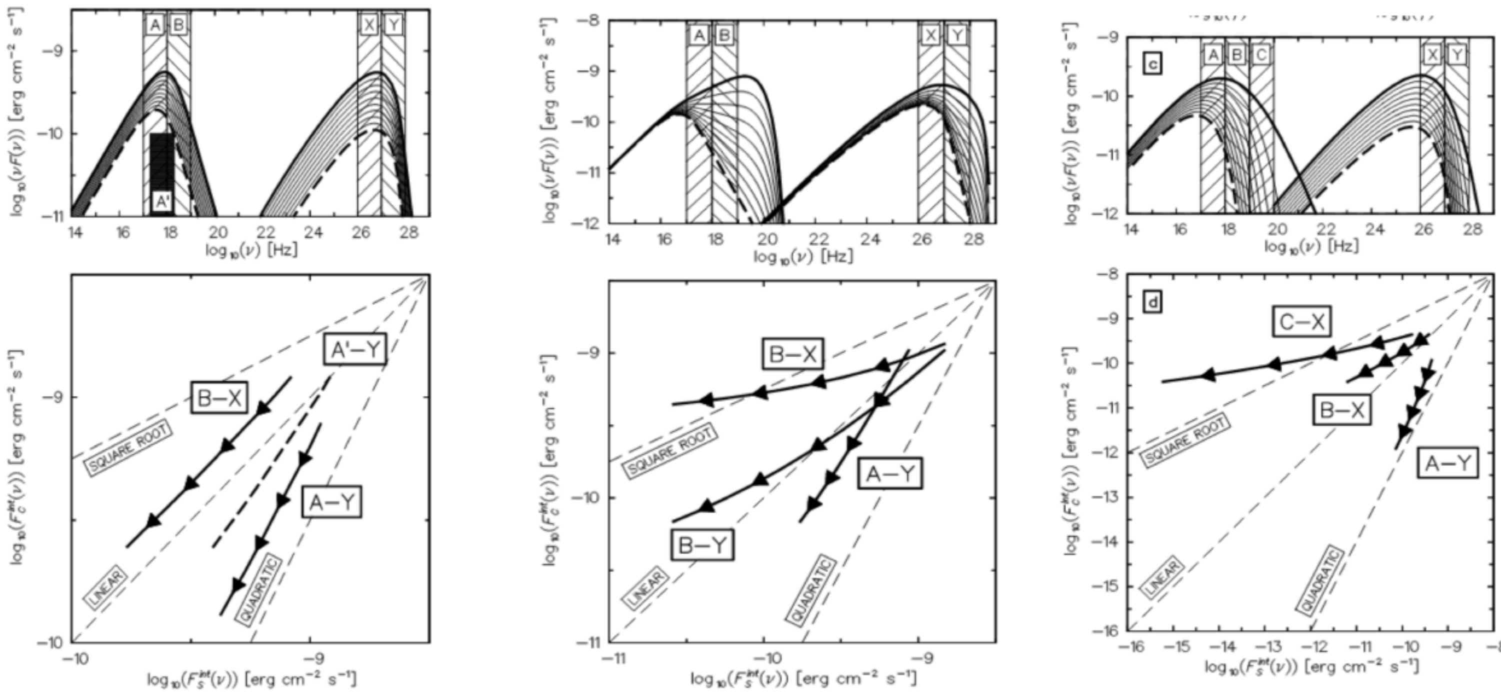
- Flares and non-flares are similar:
  same acceleration process;
  same radiative mechanism;
  same emitting region

  we can use what we learn from SED modeling as input

- Flares and non-flares are different:
  another emitting region;
  other particles;
  other radiative mechanism

TIME DEPENDENT SSC

Correlation plots



Expanding emitting region
(keeping particle density constant)

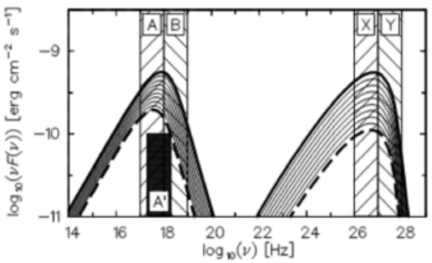
Hardening of particle distribution

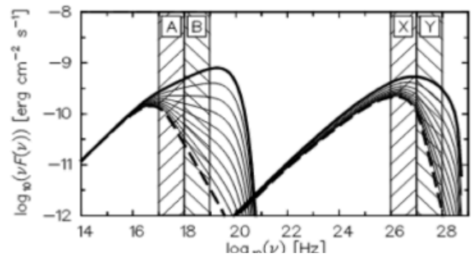
Effect of synchrotron cooling

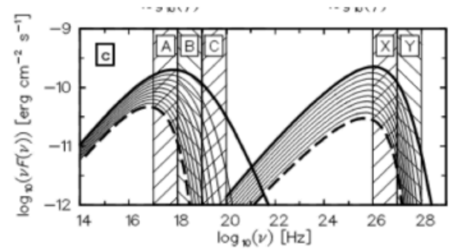
From Katarzynski et al. 06

TIME DEPENDENT SSC

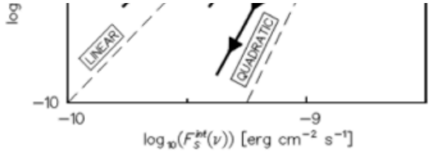
Correlation plots



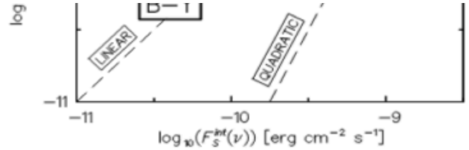




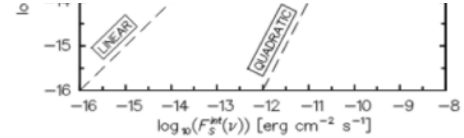
THE MWL CORRELATIONS ARE COMPLEX AND DEPEND ON THE ENERGY BAND WE ARE USING AND THE PARAMETERS THAT ARE DRIVING THE FLARE



Expanding emitting region
(keeping particle density constant)



Hardening of particle distribution



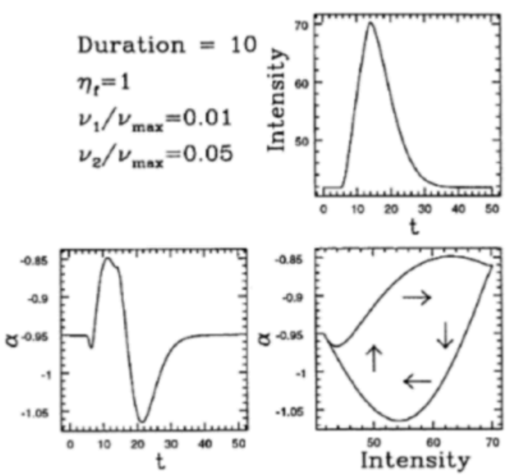
Effect of synchrotron cooling

From Katarzynski et al. 06

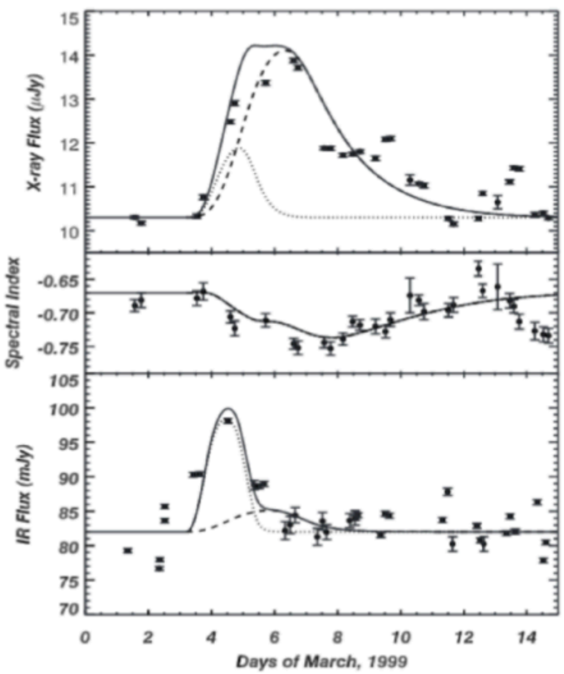
TIME DEPENDENT SSC

X-ray studies have been already done, and the literature is very rich (see Kirk et al. 98, Bottcher & Chang 02, Kataoka et al. 00, Falcone et al. 2004, Sokolov et al. 04, but MANY MORE!)

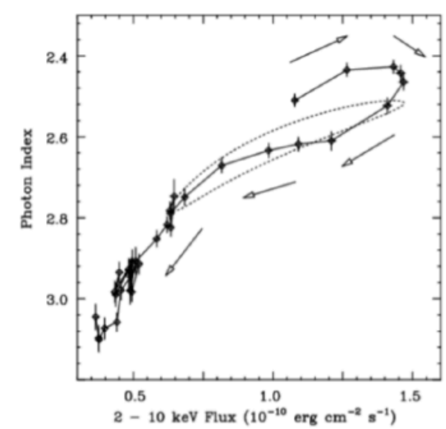
In X-rays, it is more often discussed in terms of spectral hysteresis, and not time-lag



From Kirk et al. 98



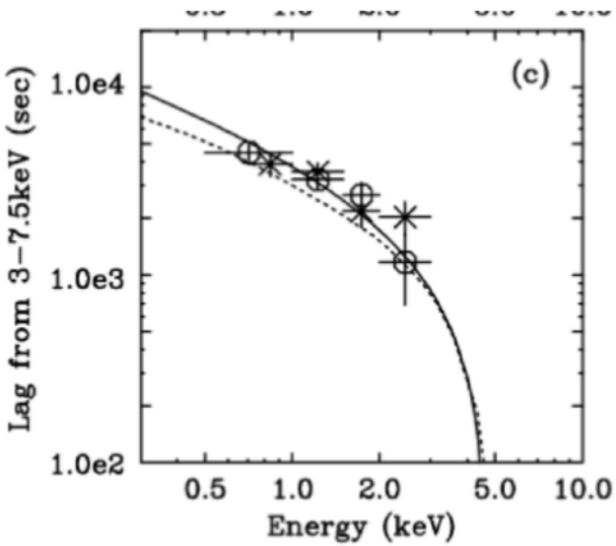
From Sokolov et al. 04



From Kataoka et al. 00

TIME DEPENDENT SSC

X-ray studies have been already done, and the literature is very rich
(see Kirk et al. 98, Bottcher & Chang 02, Kataoka et al. 00, Falcone et al. 2004, Sokolov et al. 04, but MANY MORE!)



From Kataoka et al. 00

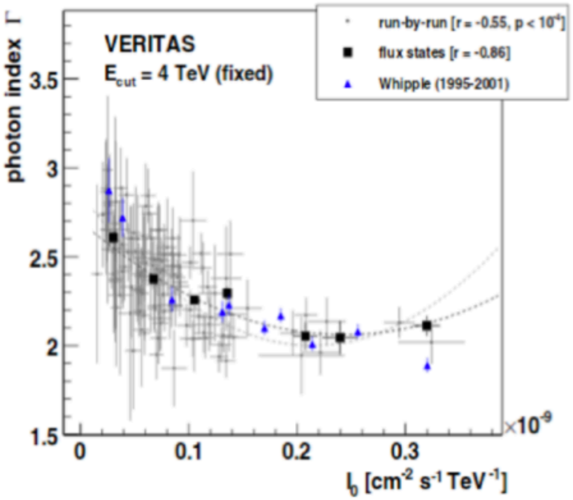
From the measurement of the time-delay we can get an independent constraint on f(B,δ) assuming that the variability is associated with synchrotron cooling

→ Together with a multi-wavelength SED, this can determine a unique solution for the one-zone SSC model

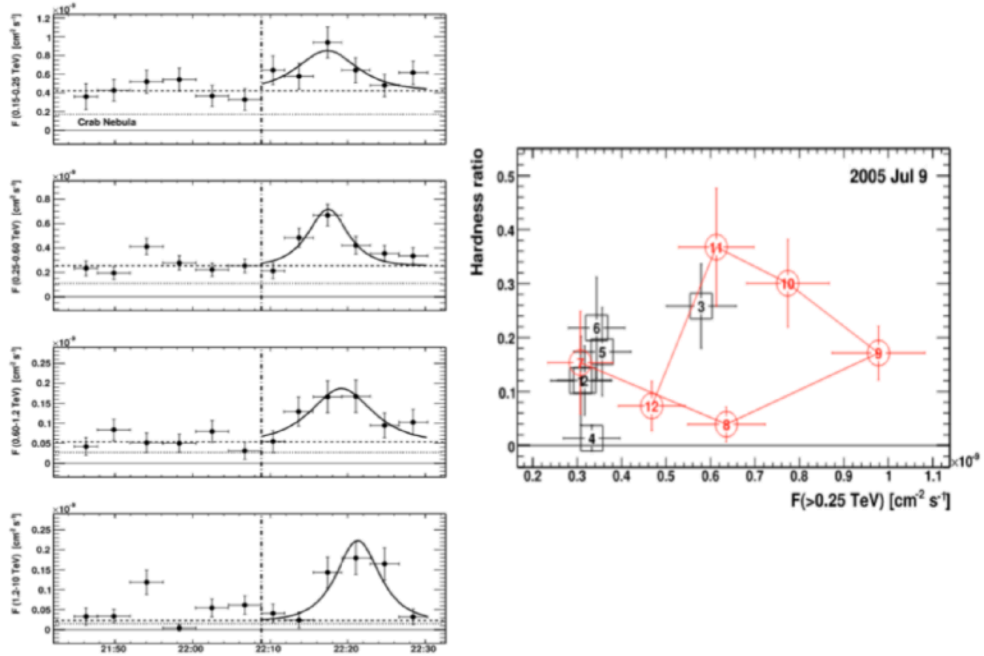
TIME DEPENDENT SSC

If there are time lags in the synchrotron component, we do expect time lags in the SSC one, although remember that the correlation may be complex!!

Some examples of spectral variability vs flux level

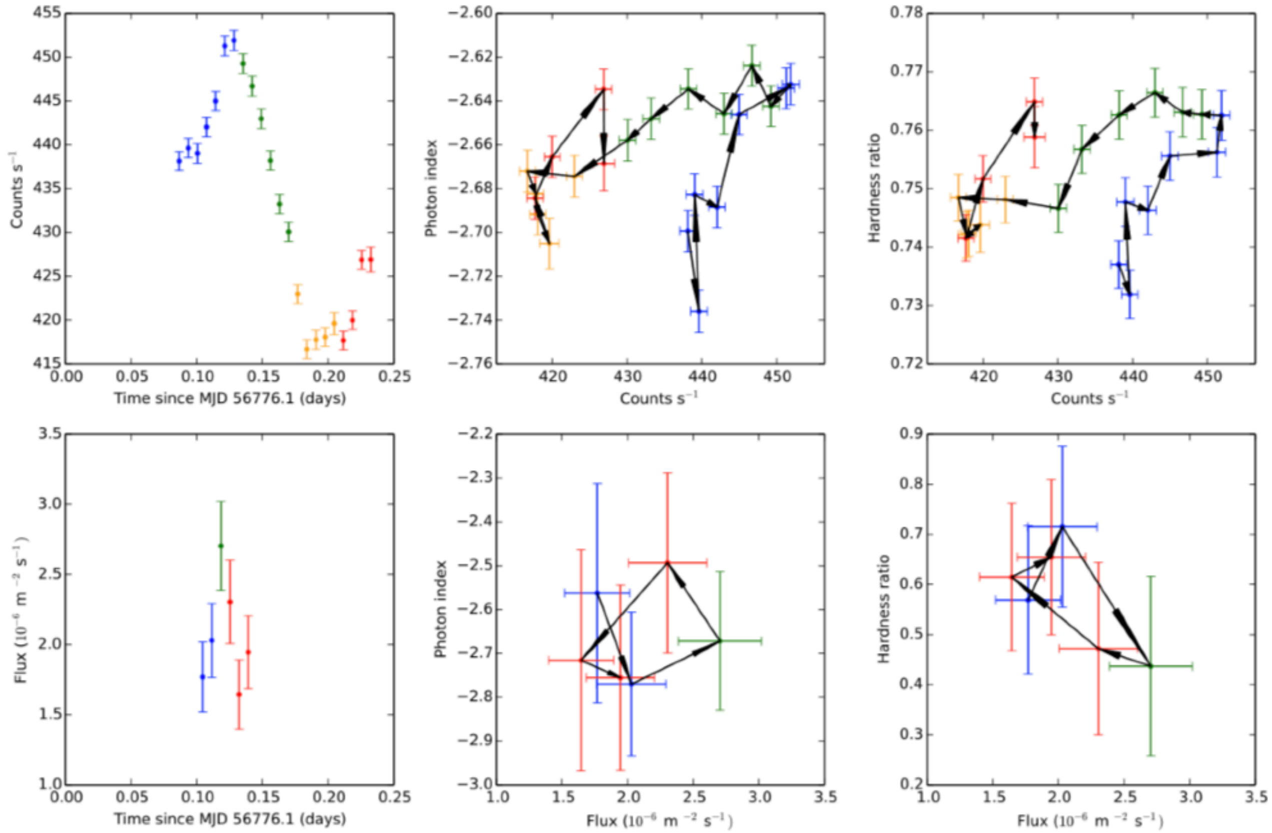


From Acciari et al. 11
(Mrk 421)



From Albert et al. 07
(Mrk 501)

TIME DEPENDENT SSC



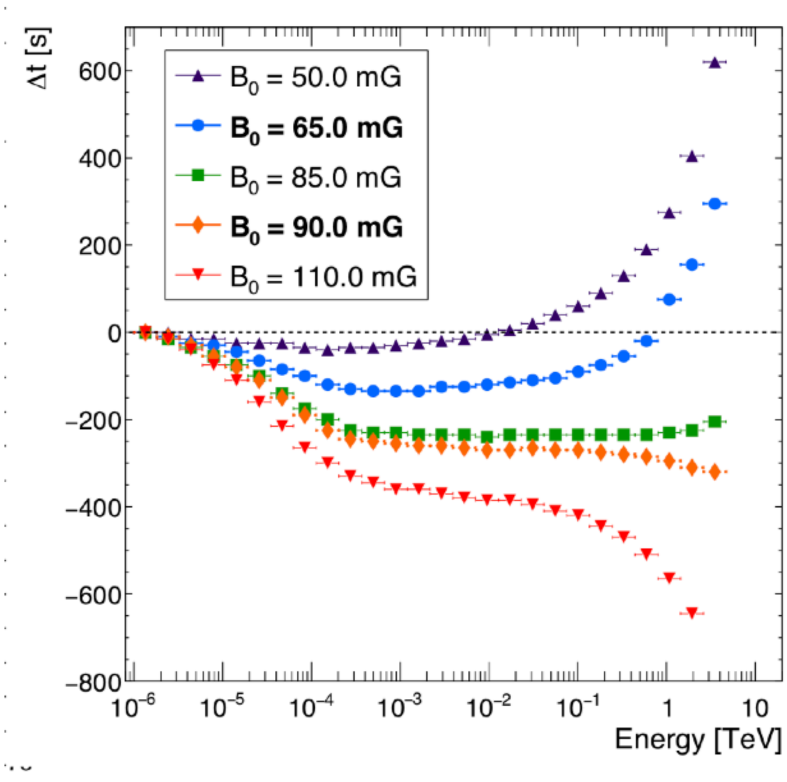
Mrk 421, Abeysekara et al. 2017

TIME DEPENDENT SSC

A detection of joint X-ray and gamma-ray spectral hysteresis / time-lags will constrain significantly the models

It will be one of the next big results on VHE blazars

TIME DEPENDENT SSC



Perennes et al. 2020

Time-lags are expected in one-zone SSC scenario

The absence of time-lags constraint significantly the parameter space, or…

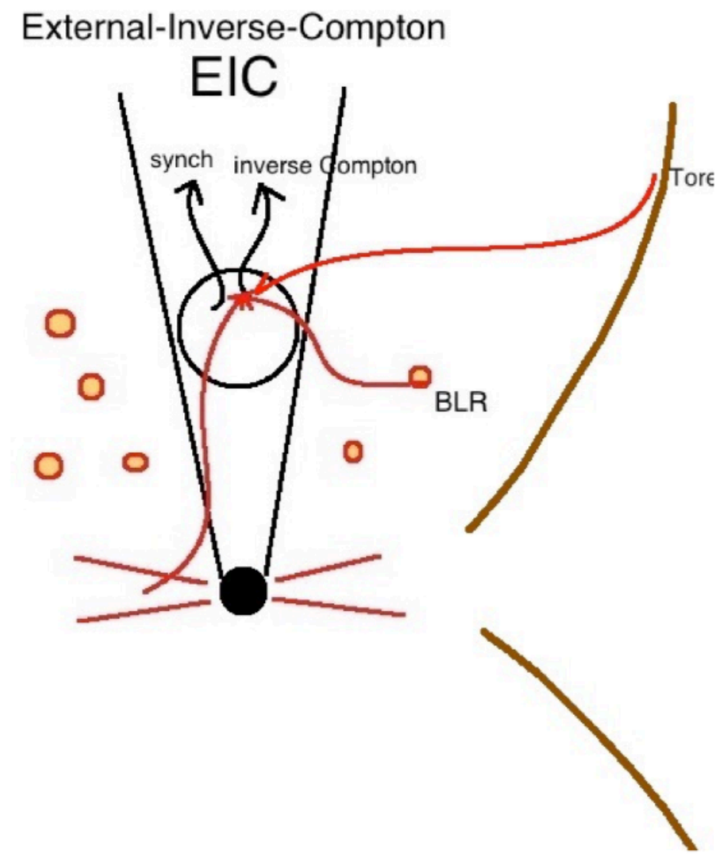
it questions this simple model

External-Inverse-Compton

The soft photon field up-scattered by leptons is external

- A third radiative component (the SSC is still there), fitting is easier

- New free parameters:
  the external fields;
  the location of the emitting region



External-Inverse-Compton

Which photon fields?

- Accretion disk (always deboosted in blob frame: it works only if very close to the black hole).
  Black body approximation is enough

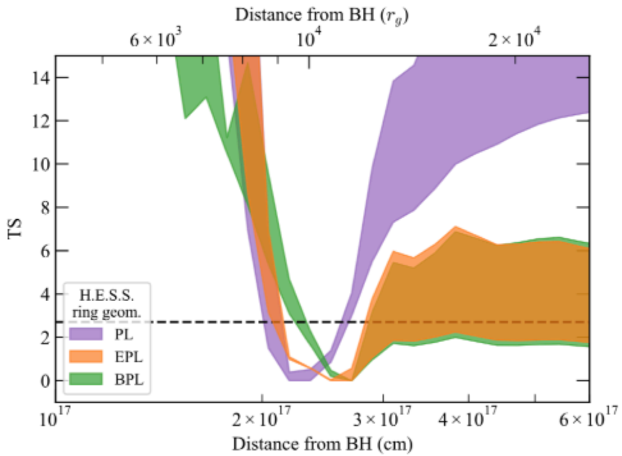
- Broad-line-region
  Monochromatic approximation is enough

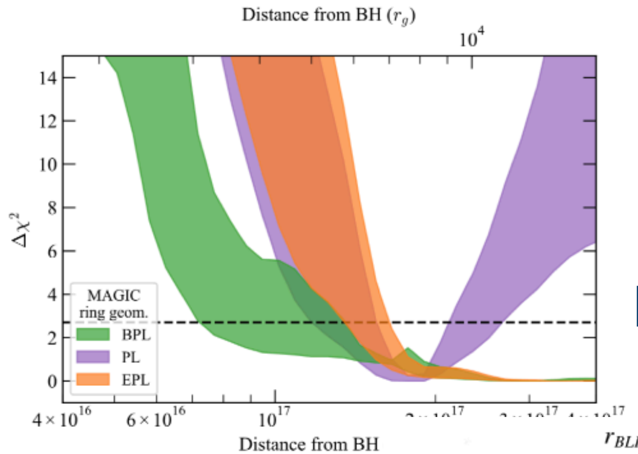
- Dusty torus
  Black body approximation is enough

- External jet
  (detailed modeling of its synchrotron emission needed)

External-Inverse-Compton

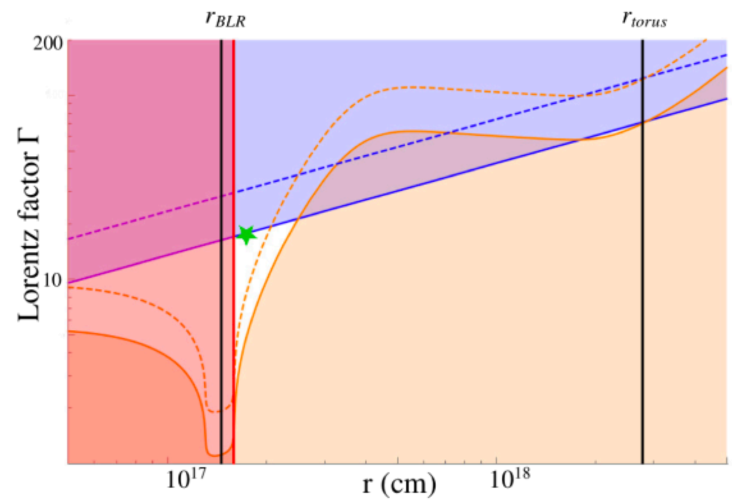
Detection of VHE photons from FSRQ is enough to put the location of the emitting region at or beyond r_{BLR}





PKS 1510-089, 2016 flare
MAGIC & HESS

PKS 0736+017
HESS



Matteo Cerruti

External-Inverse-Compton

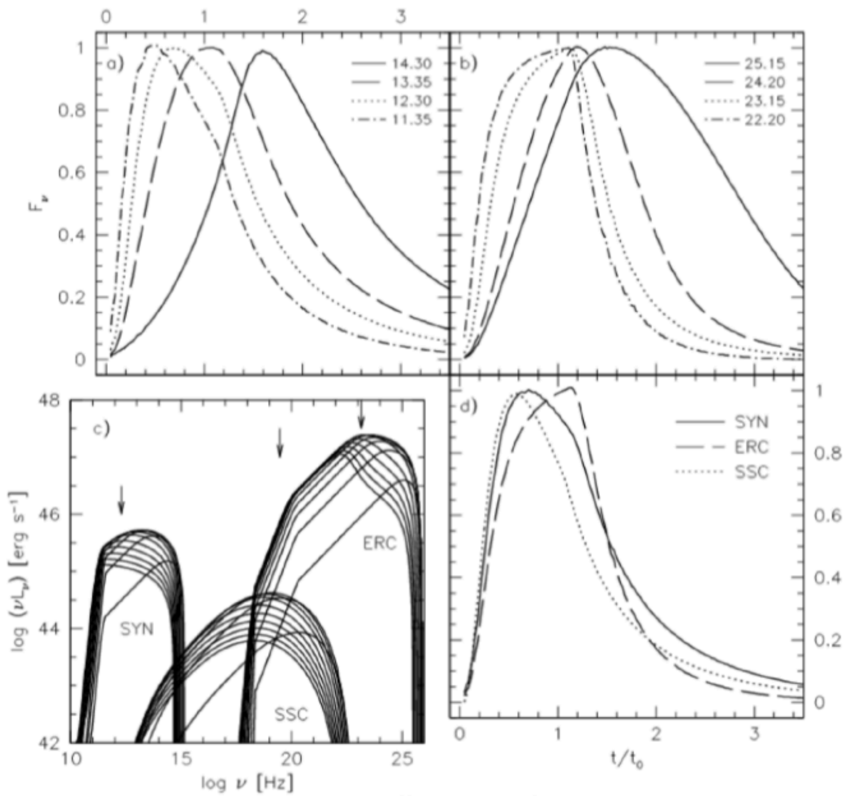
It is possible to localize the site of gamma-ray production

In an ideal scenario (super bright flare with strictly simultaneous MWL coverage) we can put constraints on the absorber itself

The dusty torus also produces an absorption cut-off but at TeV energies. It will be a big result the day we'll detect it (direct measurement of torus temperature!)

TIME DEPENDENT EIC

→ Time-dependent EIC! (not conceptually different, just add external IC cooling in the equation) (see e.g. Sikora 01, Sokolov et al. 05, Dilts & Bottcher 05)



From Sikora et al. 2001

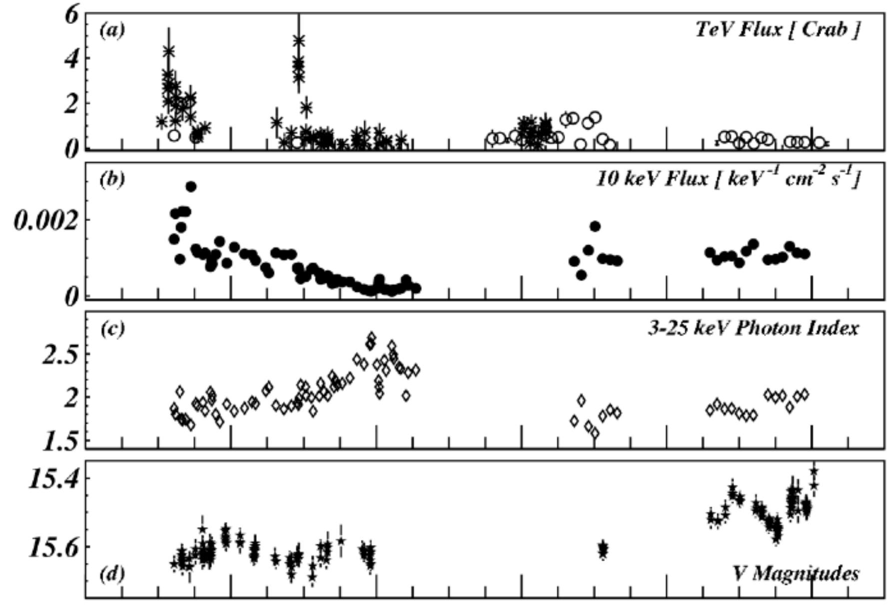
BLAZARS EMISSION MODELS

Why adding hadrons if leptons work??

1) Leptonic models do not always work. See for example

- extreme blazars (pretty high Doppler factor and/or minimum electron energy)

- orphan flares (leptonic model predicts perfect)



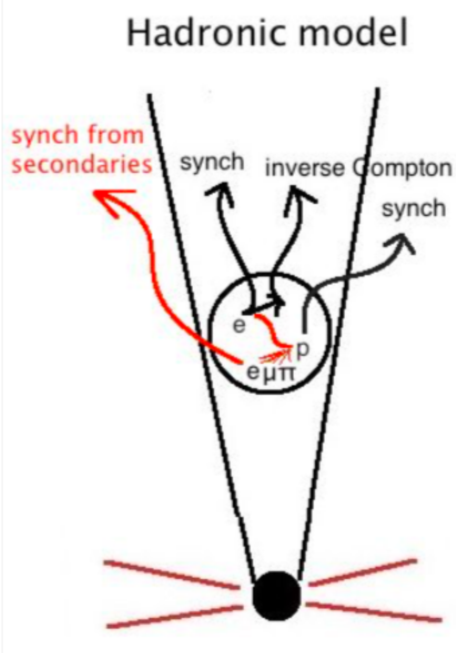
Krawczynski et al. 2004

2) Natural link with cosmic-rays and neutrinos

BLAZARS EMISSION MODELS

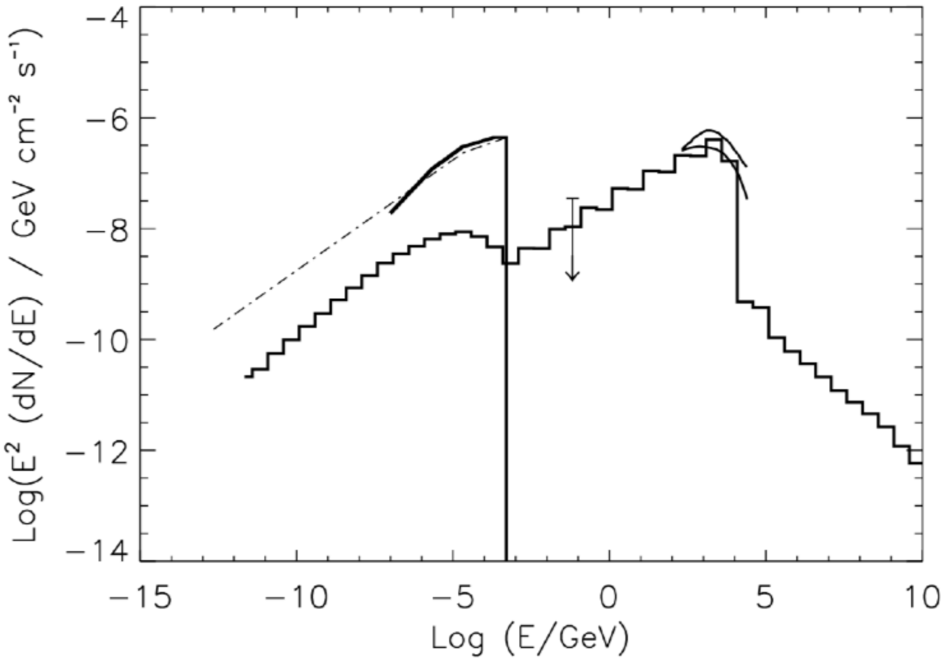
Hadronic models

Simplest hadronic model:



The high-energy component is proton synchrotron radiation

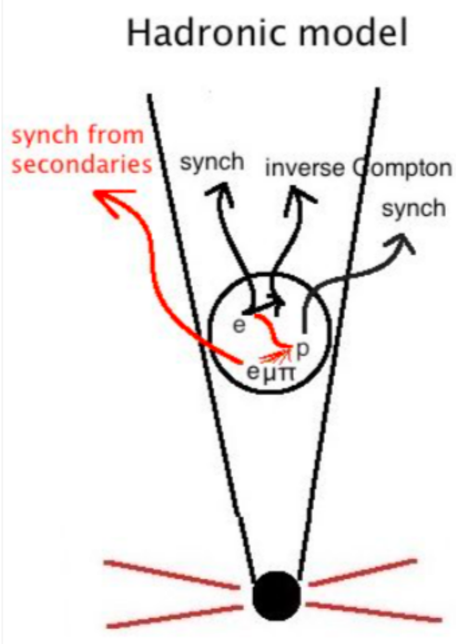
(Mannheim 1993, Aharonian 2000, Mucke & Protheroe 2001)



Mucke & Protheroe 2001

Matteo Cerruti

BLAZARS EMISSION MODELS



Proton-photon interactions complicate the modeling

Photo-meson

$$p + \gamma = p' + \pi^0 \rightarrow p' + 2\gamma$$
$$p + \gamma = n + \pi^+$$
$$p + \gamma = p' + \pi^+ + \pi^-$$

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

Bethe-Heitler pair production

$$p + \gamma = p' + e^+ + e^-$$

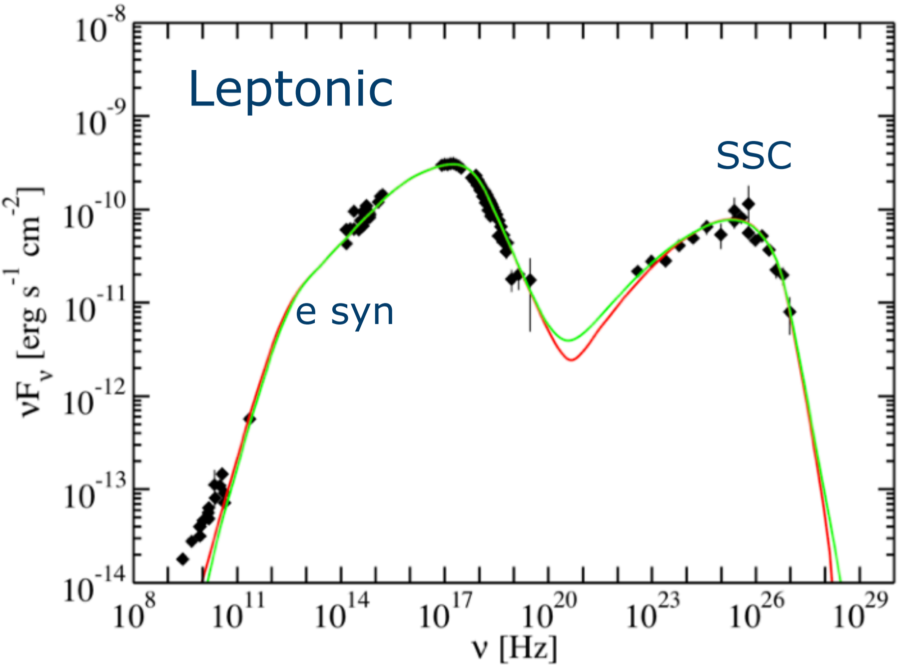
Injection of secondary leptons in the emitting region, triggering synchrotron supported pair-cascades

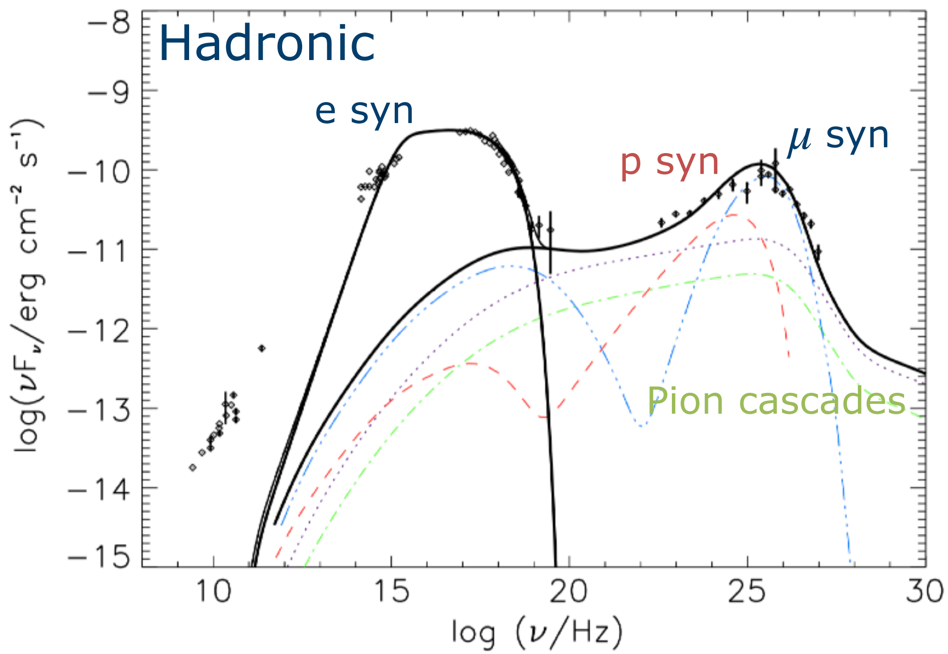
Synchrotron emission by muons can be important

BLAZARS EMISSION MODELS

Leptonic and hadronic models can both work!

Example for Mrk 421 in 2011

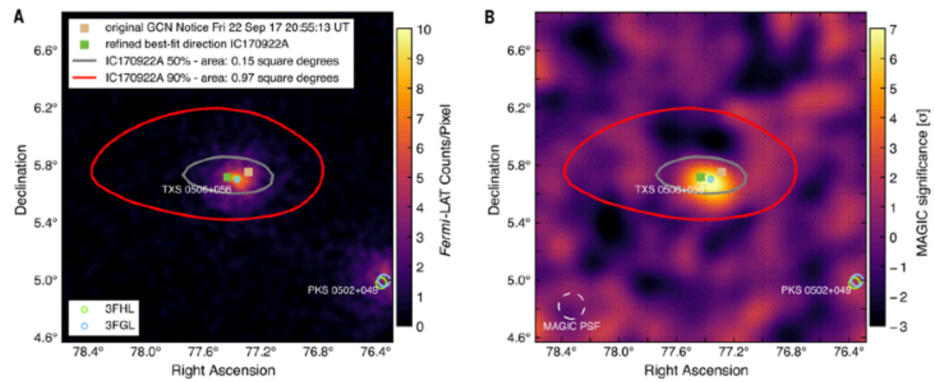


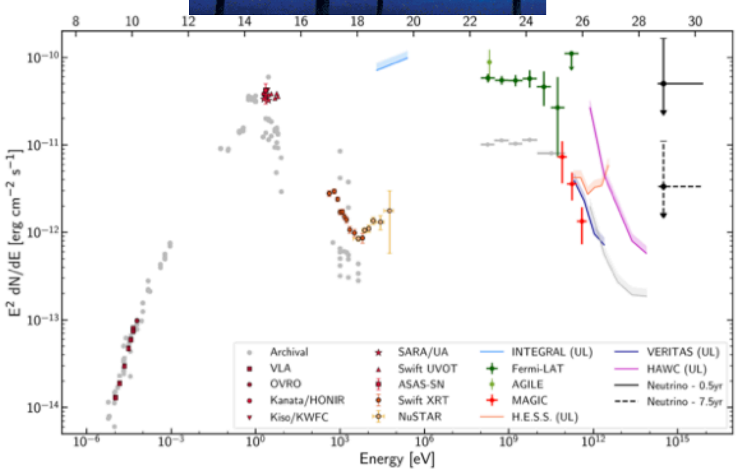


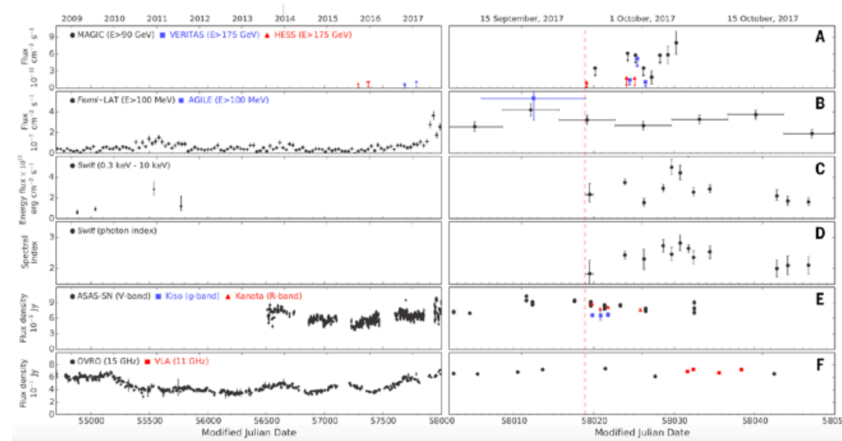
[Abdo et al. 2011]

IceCube-170922A / TXS 0506+056

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

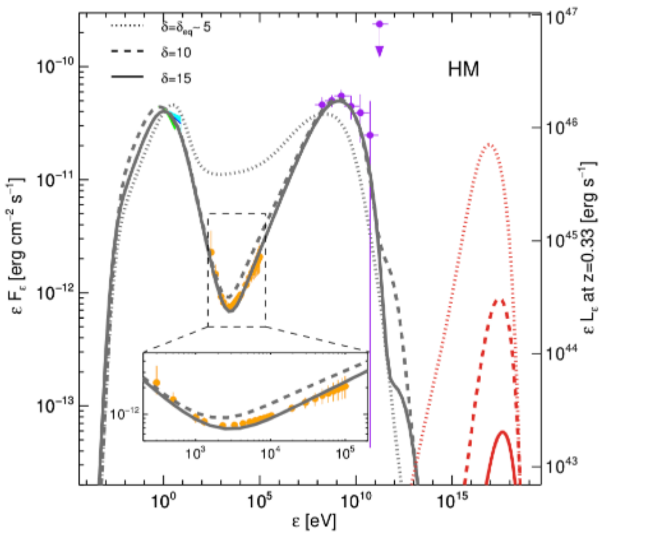


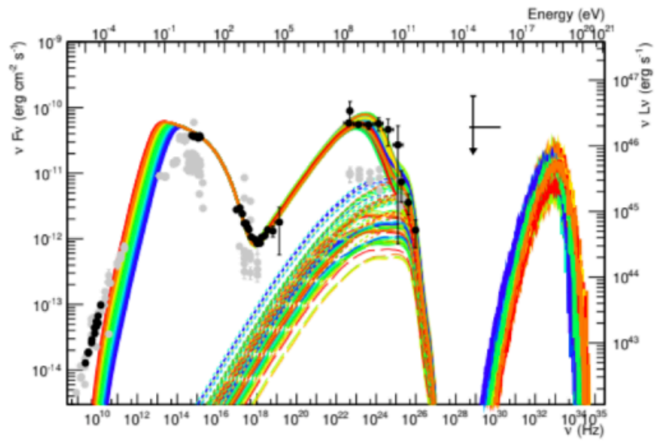




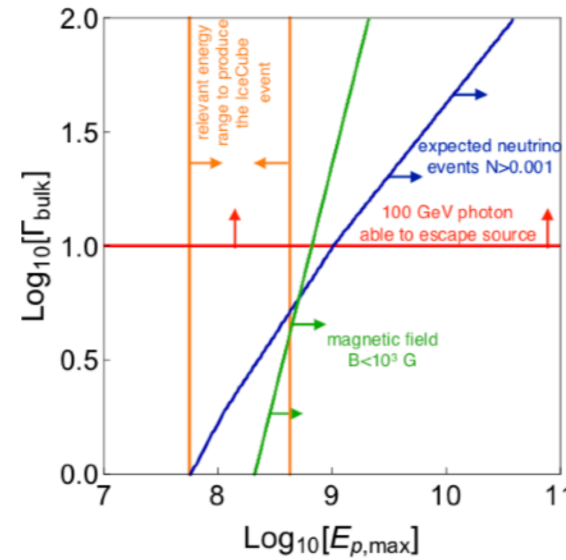
[IceCube, Fermi, MAGIC et al. 2018]

TXS 0506+056: THE 2017 FLARE





(a) Proton synchrotron modeling of TXS 0506+056



Keivani et al. 2018

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

Cerruti et al. 2019

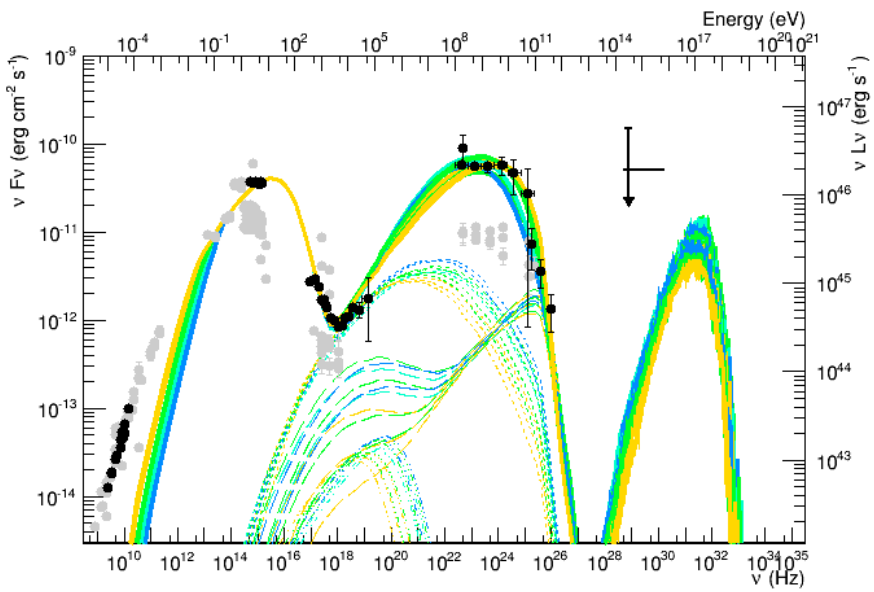
$\nu = 10^{-5} - 10^{-3}\ yr^{-1}$

Gao et al. 2018

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

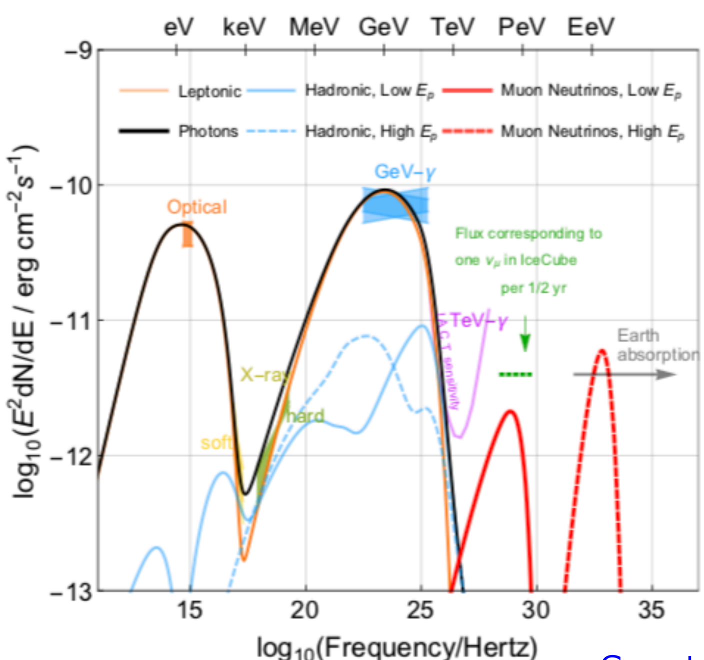
TXS 0506+056: THE 2017 FLARE

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

$L_{jet} \simeq \times 10^{50} erg/s$
$\nu = 0.3\ yr^{-1}$

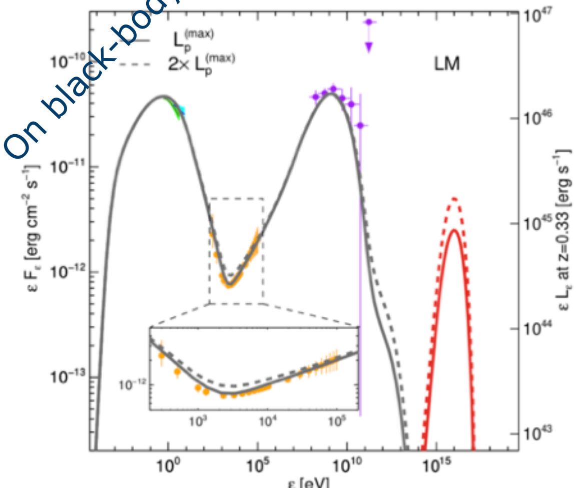
They can work: neutrino rates of the order of 0.1 / yr

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

TXS 0506+056: THE 2017 FLARE

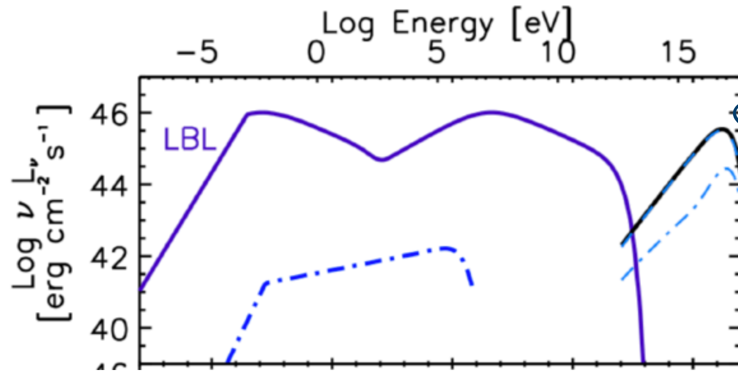
Proton-photon interaction on external photon fields

On black-body



Keivani et al. 2018

$$L_{jet} = (4 - 150) \times 10^{45} erg/s$$
$$\nu_{max} = 0.02\ yr^{-1}$$

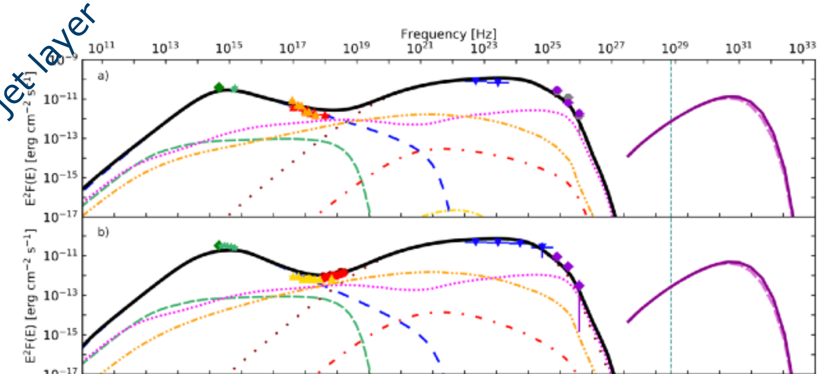


On RIAF

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

$$L_{jet} = (3 - 8) \times 10^{45} erg/s$$
$$\nu = 0.12 - 0.34\ yr^{-1}$$

TXS 0506+056: the 2017 flare

What did we learn on blazars?

- Pure hadronic solutions are excluded!

- The favored scenario is a leptonic electromagnetic emission, with subdominant hadronic component

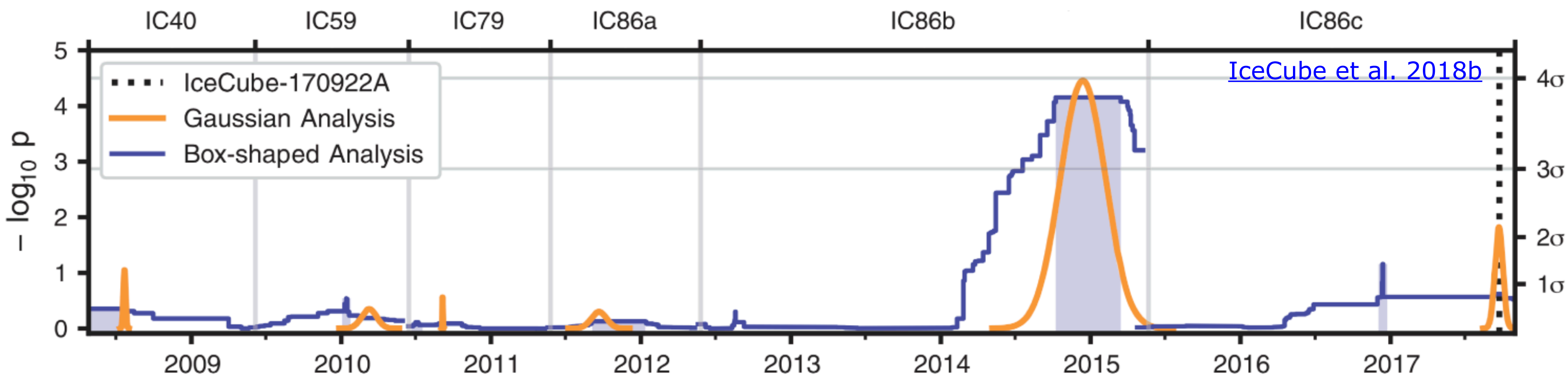
- Simple one-zone models can be enough, at the expenses of a high proton luminosity, and only if the acceleration efficiency is low

- External fields as photon target can help on this aspect

- Maximum proton energy is a free parameter: no UHECR (from this source)

TXS 0506+056: the 2014/15 flare

Detection of a second neutrino flare in 2014-2015
(without a gamma-ray counterpart)

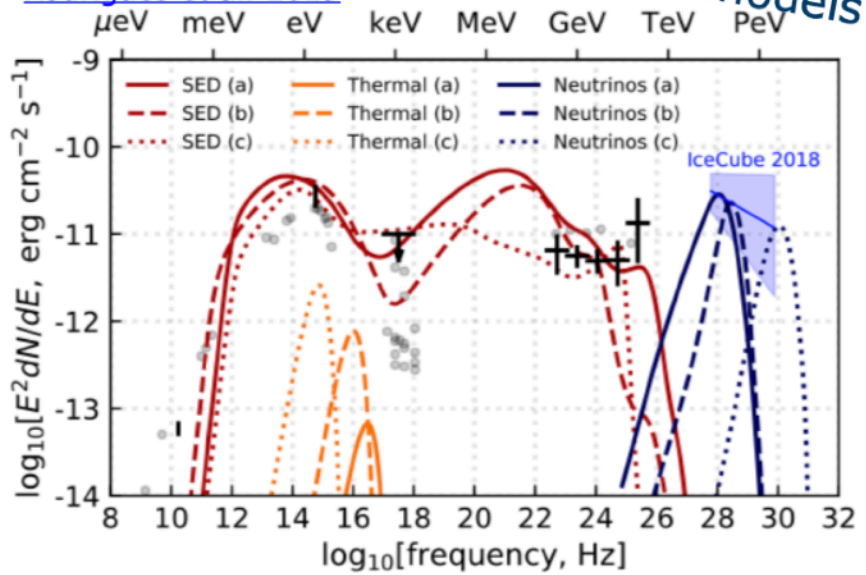


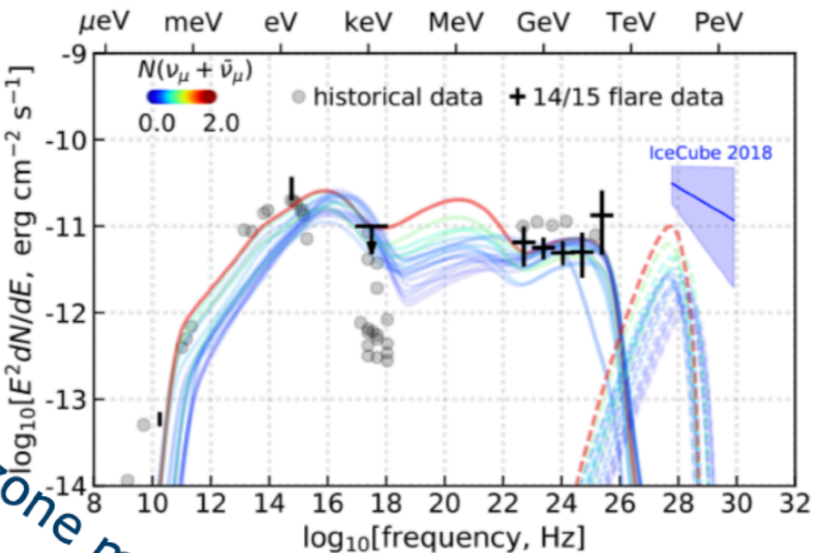
3.5σ evidence for neutrino emission in 2014-2015 independent from the 2017 event

TXS 0506+056: the 2014/15 flare

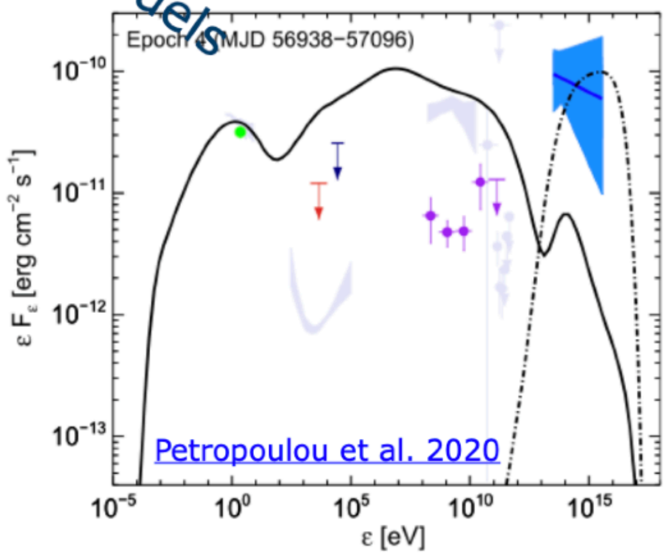
External field models

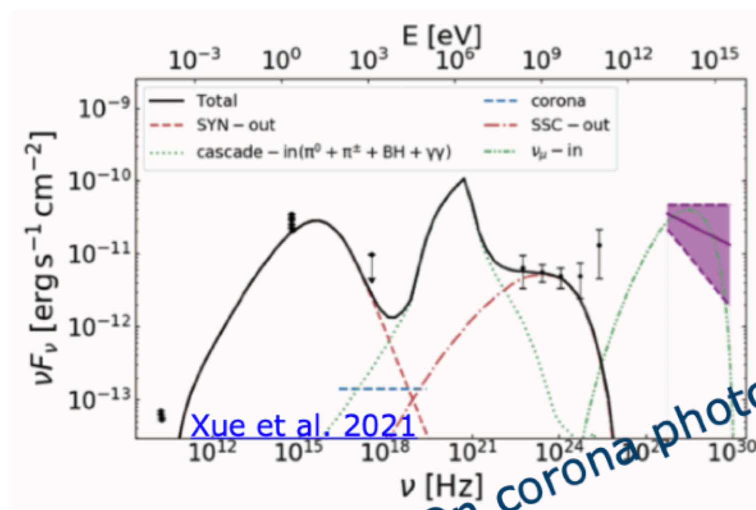
Rodrigues et al. 2019





1-zone models





On corona photons

TXS 0506+056: the 2014/15 flare

What did we learn?

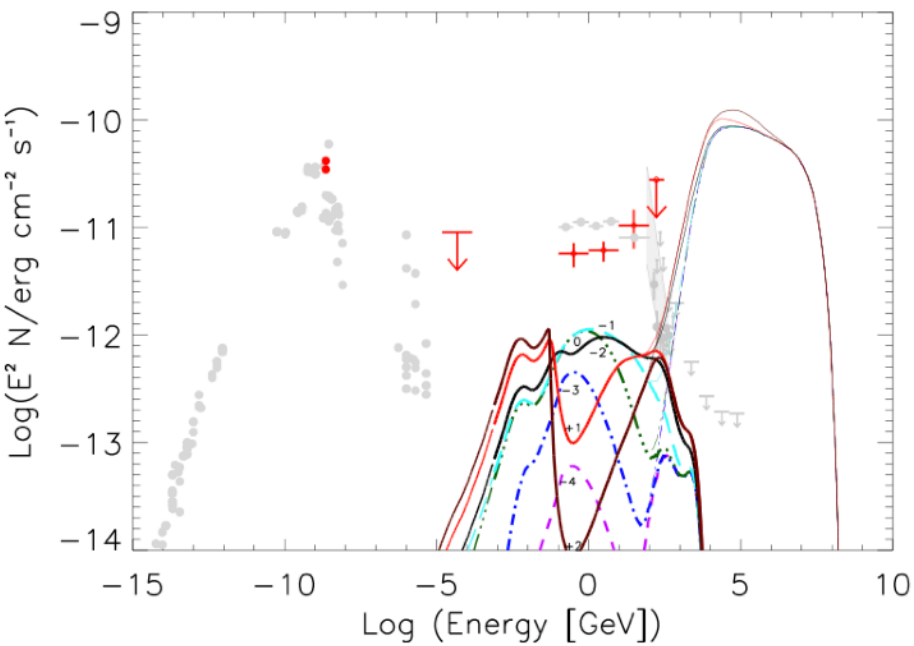
- Single zone models are disfavored : very difficult to get no photons with the neutrino flare
(although there may be some room in the MeV band)

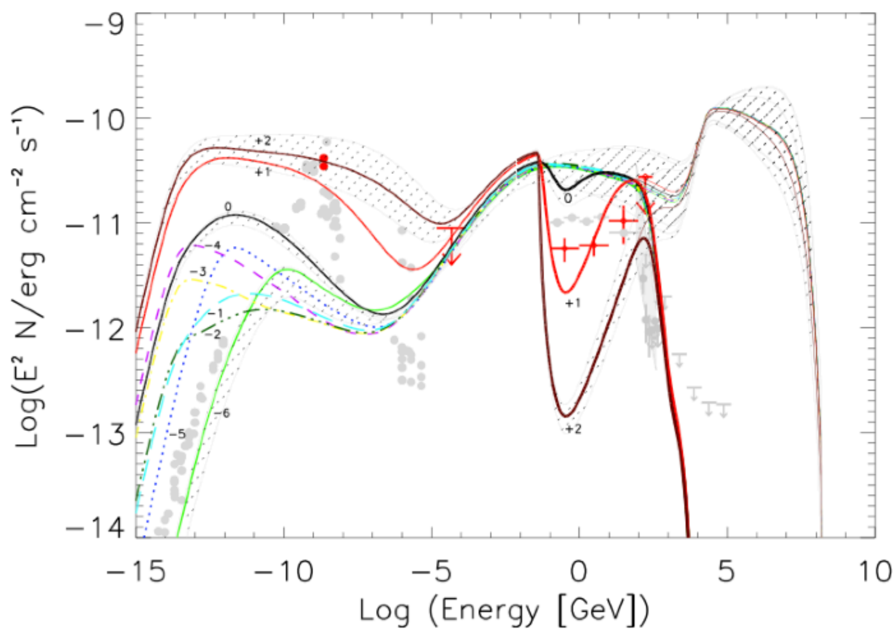
- A possible solution could be a two-zone models:
  the ν and the γ-ray emitting region are not the same

TXS 0506+056: the 2014/15 flare

The exact cascade spectrum varies a lot in the parameter space

inverse-Compton cascade vs synchrotron cascade





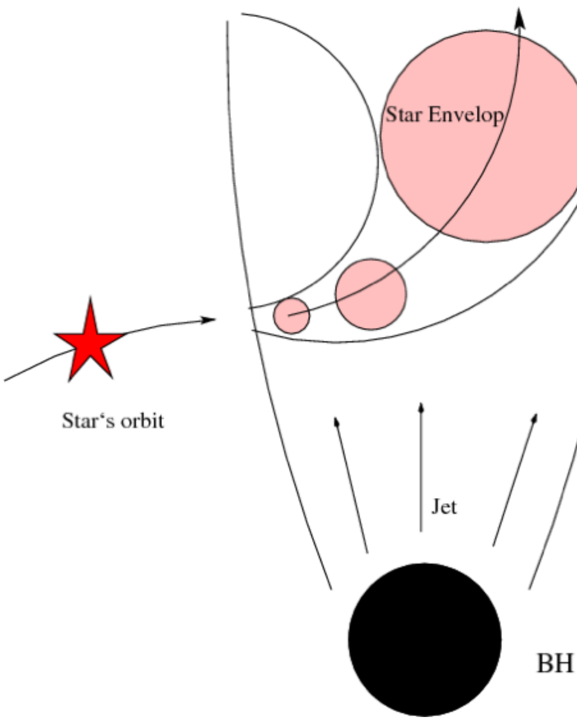
Reimer et al. 2020

ON p-p INTERACTIONS

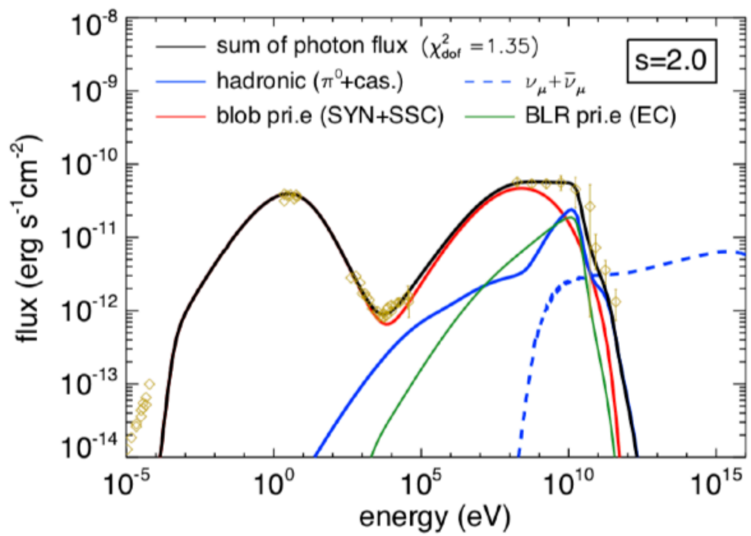
Can p-p interactions be important?

Usually neglected in single zone models

Can become the dominant channel in jets-obstacles models



Barkov et al. 2012



$$L_{jet} = (0.8 - 5) \times 10^{46} erg/s$$

$$\nu = 0.26\ yr^{-1}$$

Liu et al. 2019

HADRONIC CODE COMPARISON

Comparison of five numerical hadronic codes in the literature:
AM3 (Gao et al. 2017), Athena (Dimitrakoudis et al. 2012),
B13 (Böttcher et al. 2013), LeHa-Paris (Cerruti et al. 2015), LeHaMoc (Stathopoulos et al. 2024)

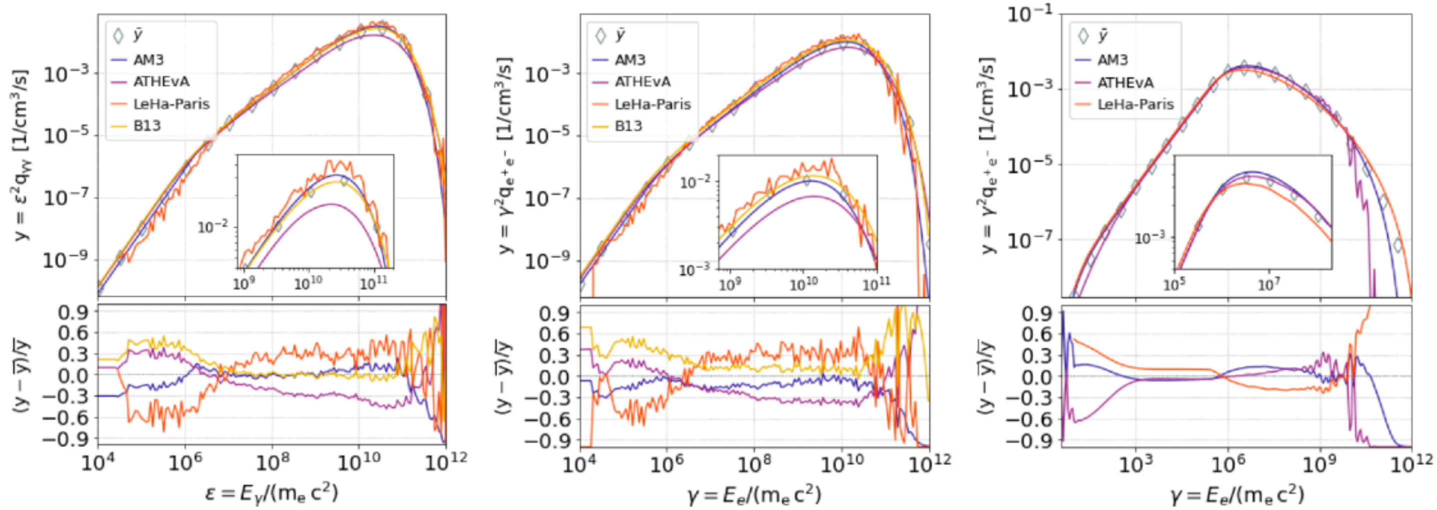
- run tests from simple 'artificial' cases
(Mono-energetic protons on black-body)
to 'realistic' ones
(proton-synchrotron or lepto-hadronic)

- Compute systematic uncertainties from theoretical simulations
- Release all files as benchmark for future developments

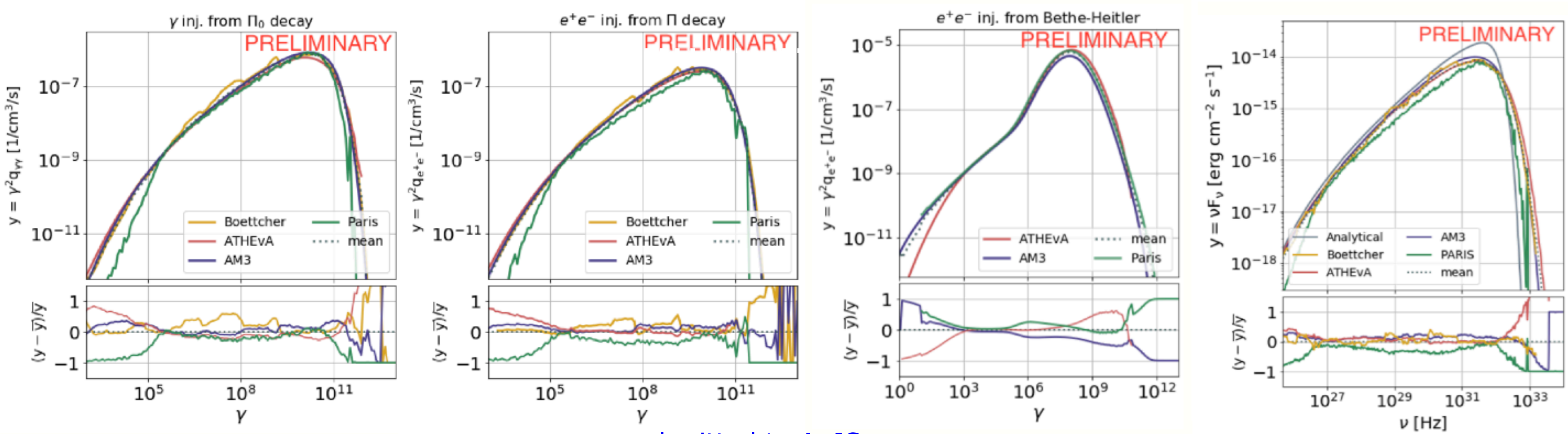
Take home message: spectral shapes are ok; 40% spread in normalization

HADRONIC CODE COMPARISON

Power-law protons on power-law photons



Proton-synchrotron scenario



submitted to ApJS

PKS 0735+178

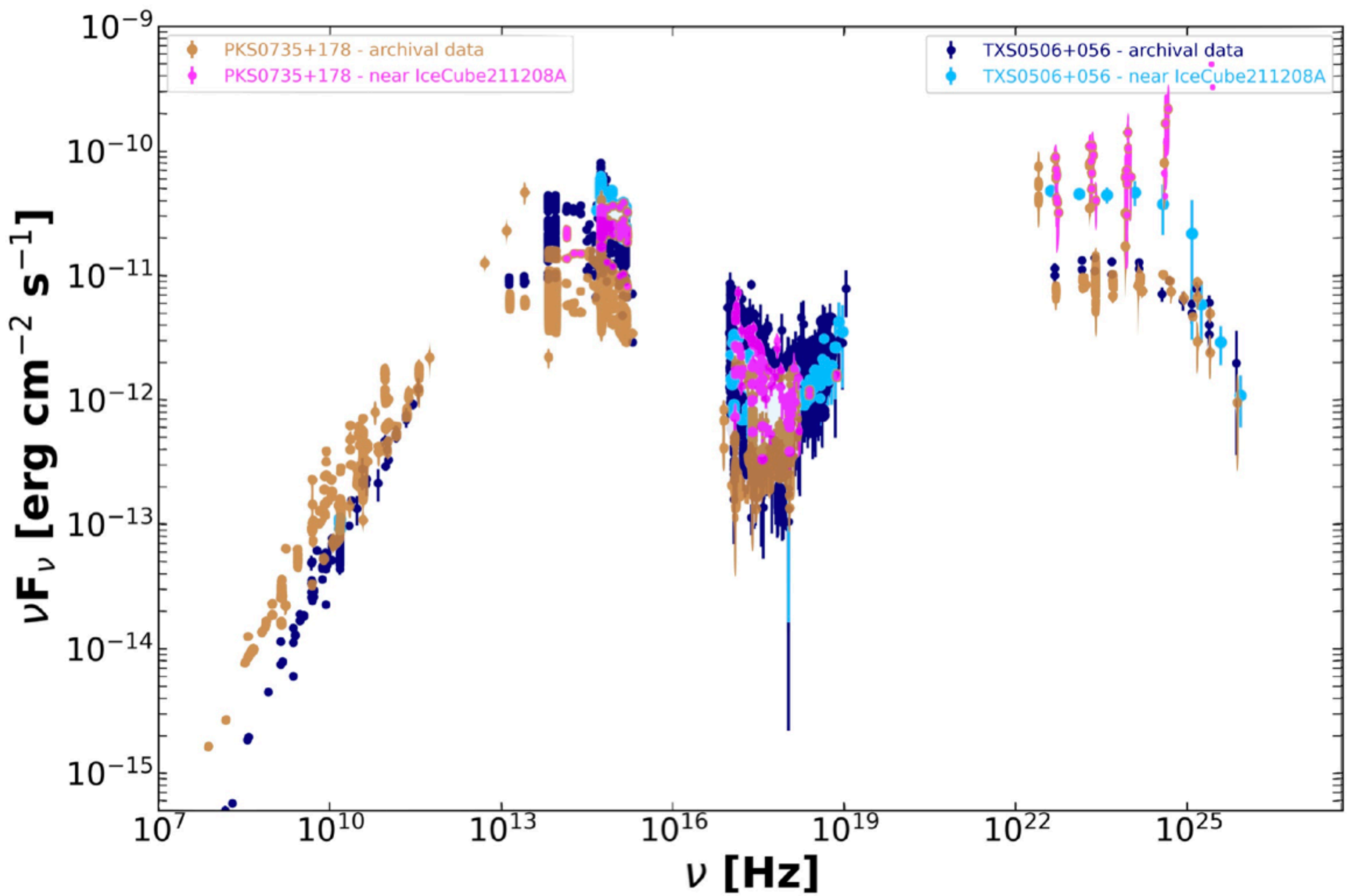
IBL@z=0.65? (>0.42) and IC211208A:

- Neutrino in IC with false alarm rate of 1.2 /yr (GCN)
- LAT source 2.2deg away (slightly beyond the 90% contour)

- Neutrino in Baikal (4h later). Chance coincidence prob. 2.85σ (ATel)
- Neutrino in KM3Net on Dec.15, p-value of 14% (ATel)
- Neutrino in Baksan on Dec.4, p-value of 0.2% (ATel)
- Flaring in Fermi-LAT, optical, X-rays

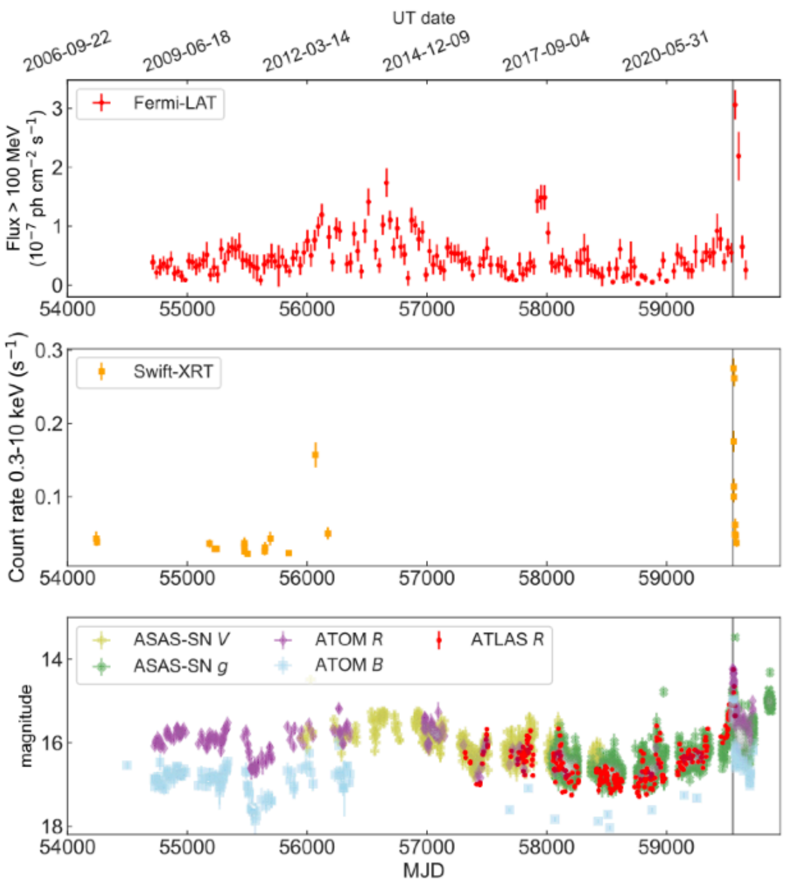
PKS 0735+178

First theory paper by [Sahakyan et al. 2022]

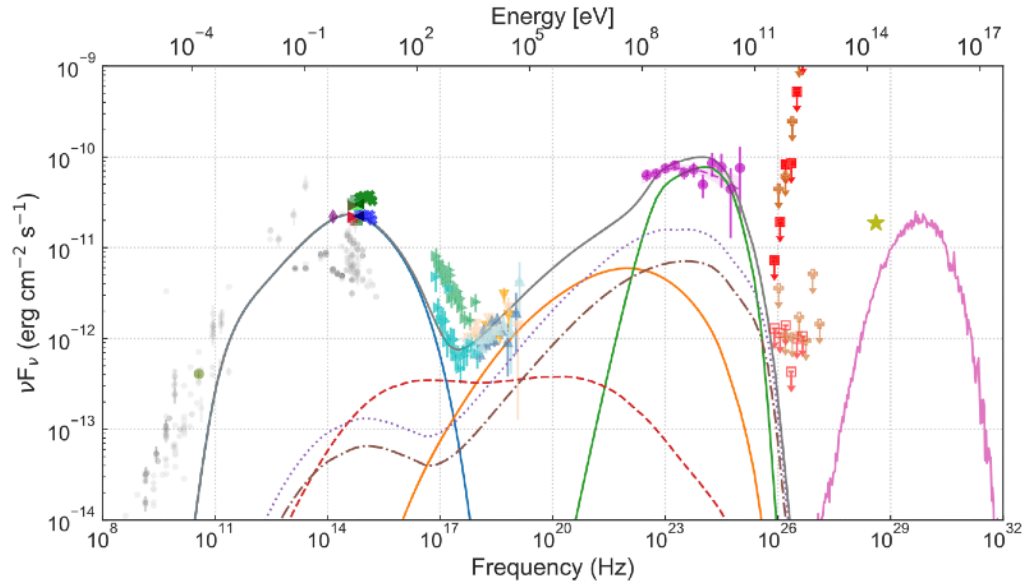


PKS 0735+178

[Acharyya et al. 2023](#)



(a)



WHICH CODES?

Leptonic only:

Jetset
Agnpy

Lepto-hadronic:
AM3
LehaMoc

IF YOU LIKE RADIATIVE CODES…

New series of technical workshops focused on numerical multi-messenger modeling:

Three-days meetings in February, with co-working time

- Bochum 2023
- Paris 2024
- Berlin 2025
- **Athens 2026!**