~~RELATIVISTIC~~ COLLIMATED OUTFLOWS

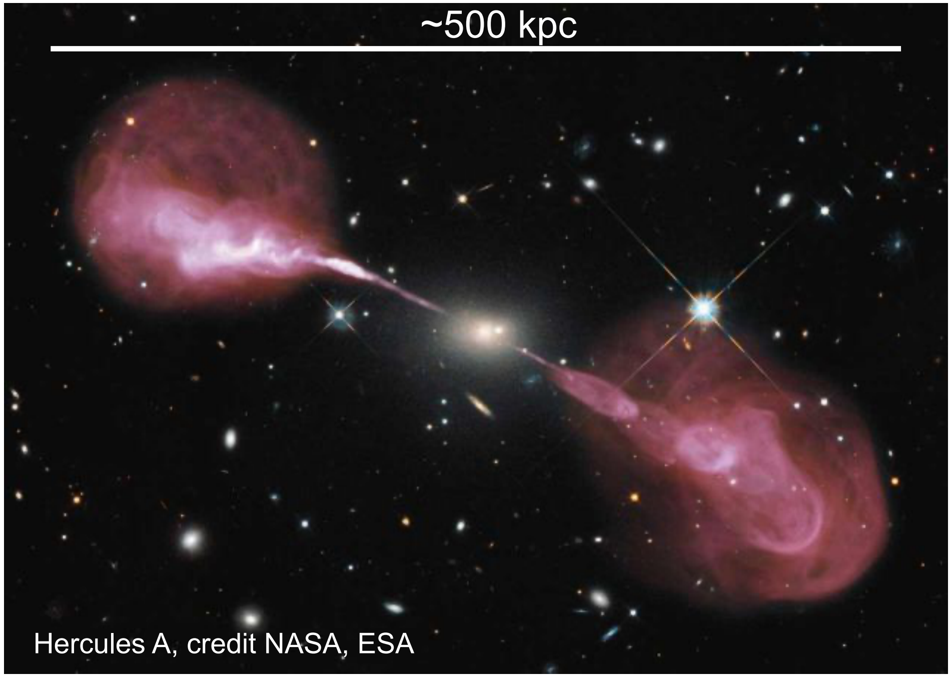
Matteo Cerruti

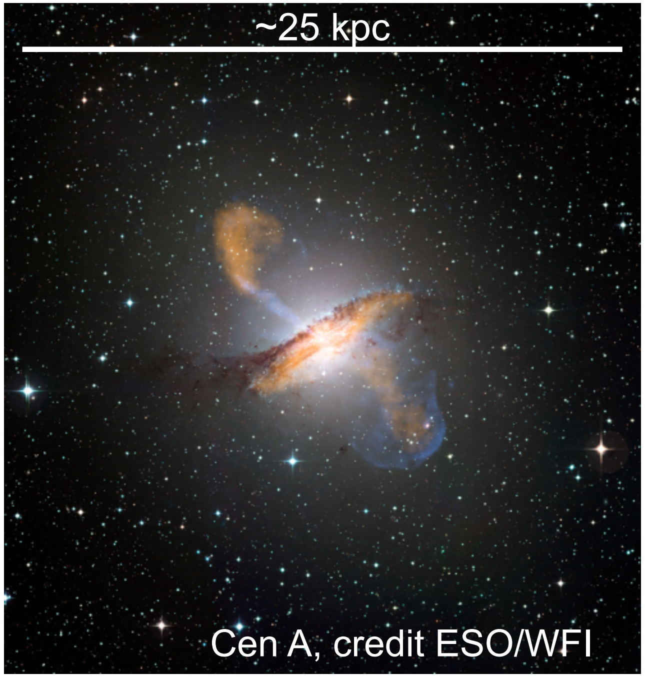
Université Paris Cité
Astroparticule et Cosmologie (APC)

CTAO School
June 18, 2024

WHAT ARE JETS?

Collimated outflows seen in different sources and
at different scales





Active Galactic Nuclei

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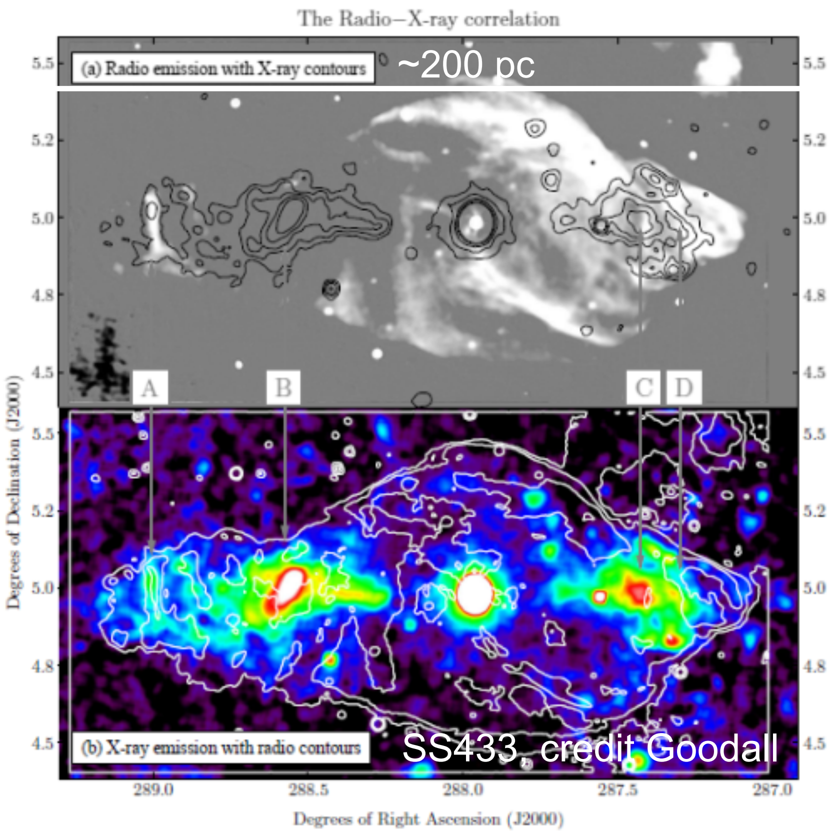

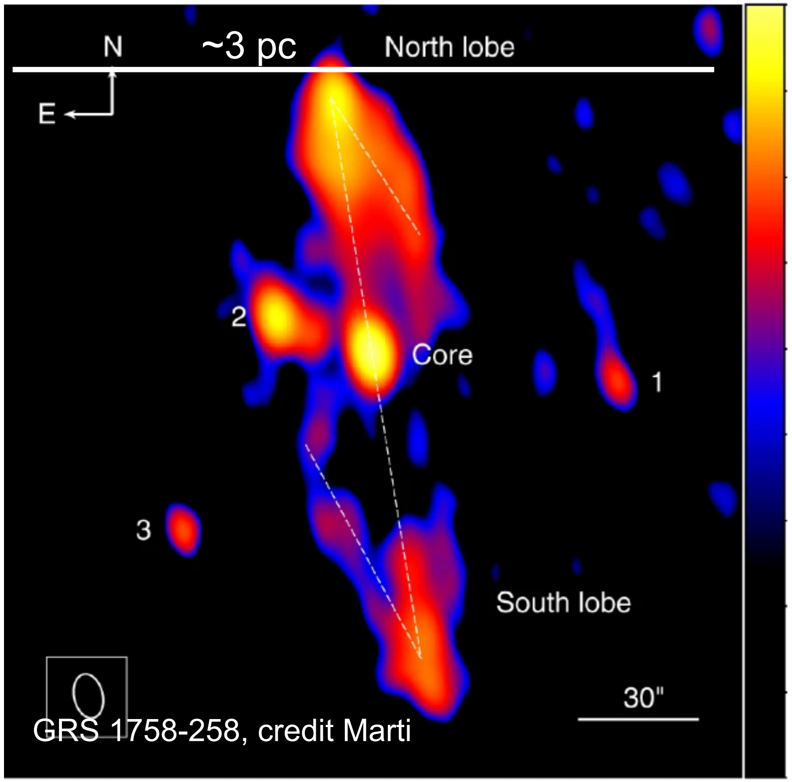

Micro quasars

WHAT ARE JETS?

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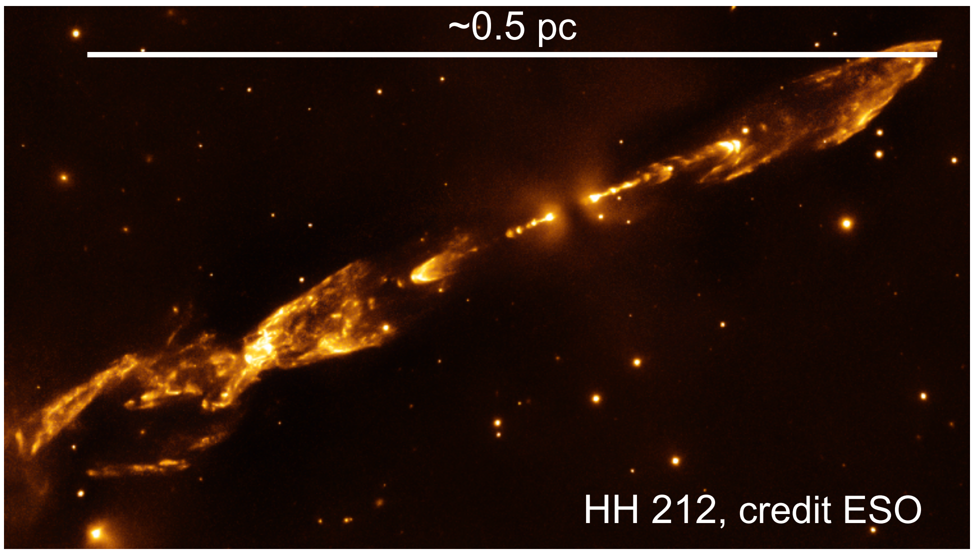
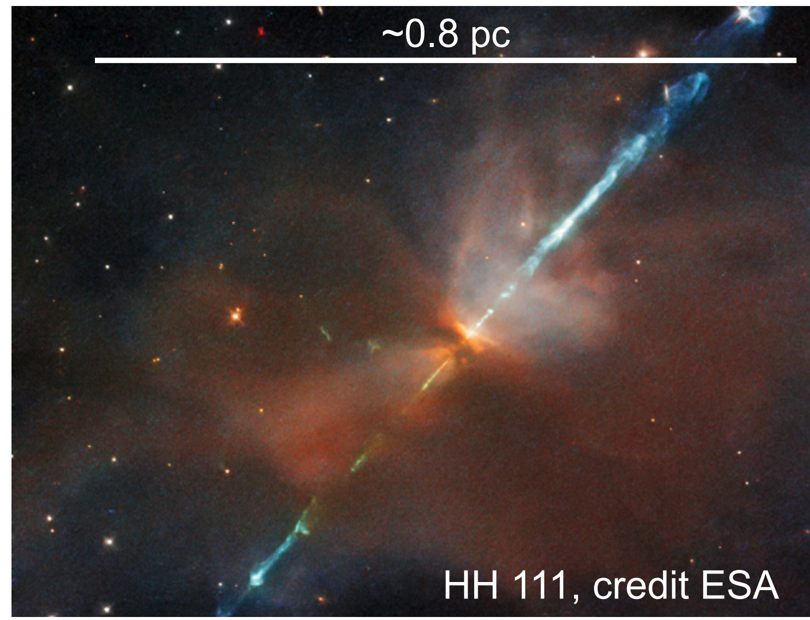
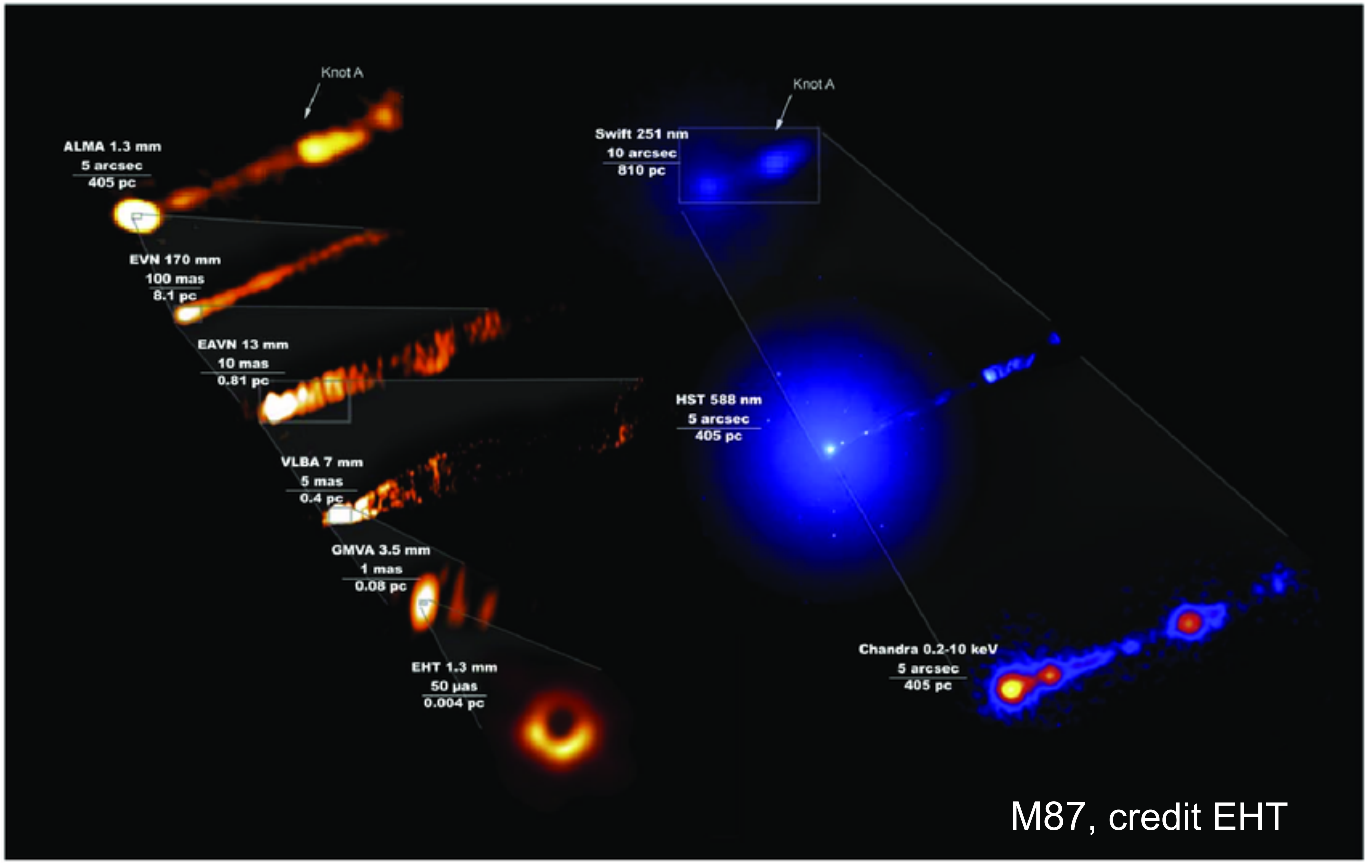




Young stellar objects

HOW DO WE STUDY JETS?

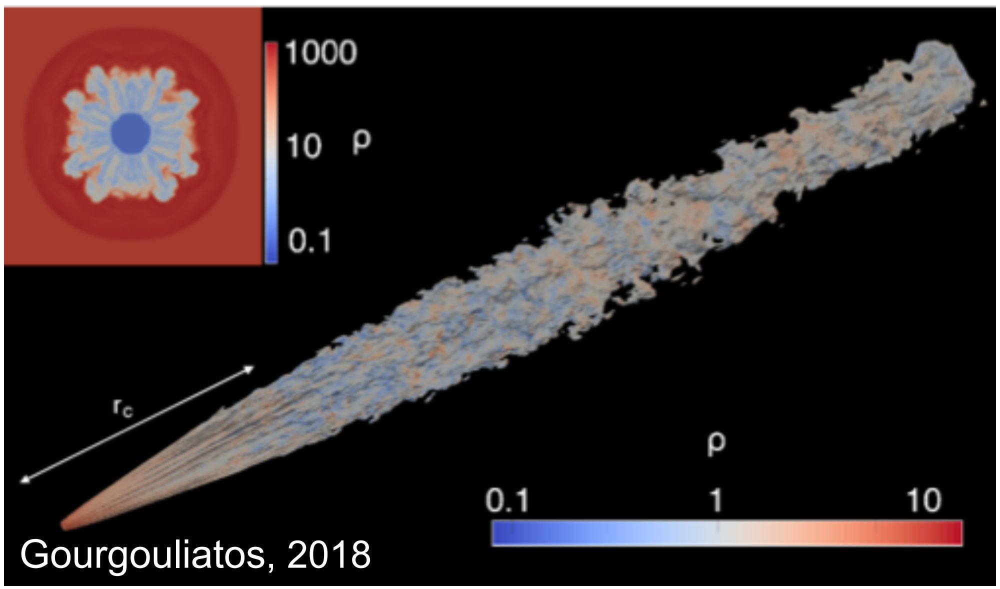
Multi-wavelength observations

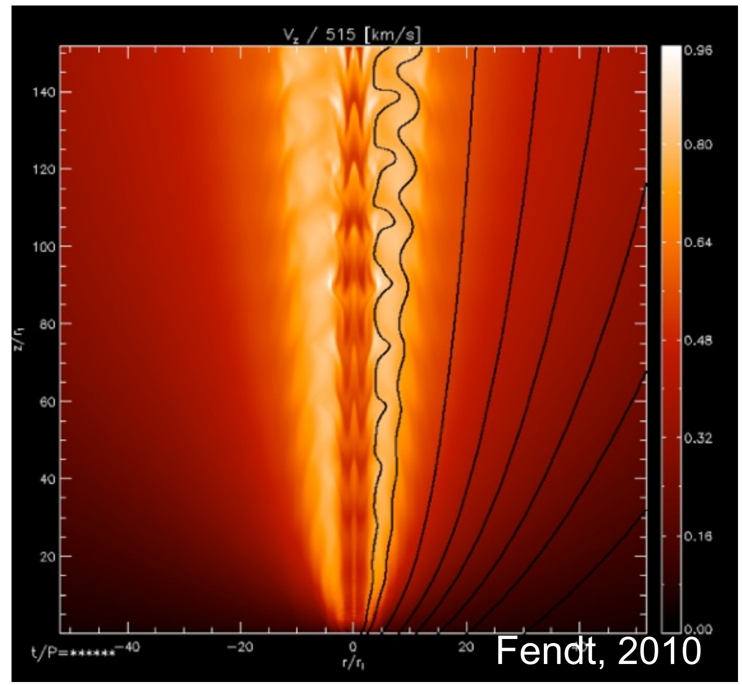


The Jet of M87 in radio, visible, X-ray

HOW DO WE STUDY JETS?

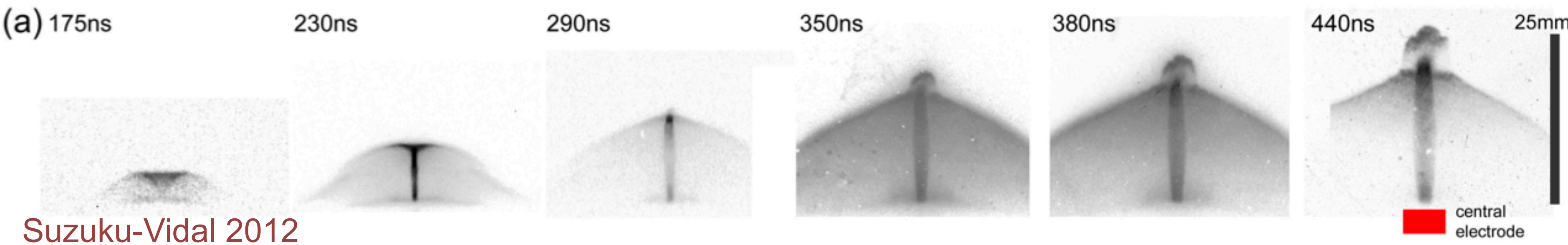
Relativistic Magneto-hydrodinamic (MHD) simulations
(+ GR if you want to study jet launching close to the black hole)



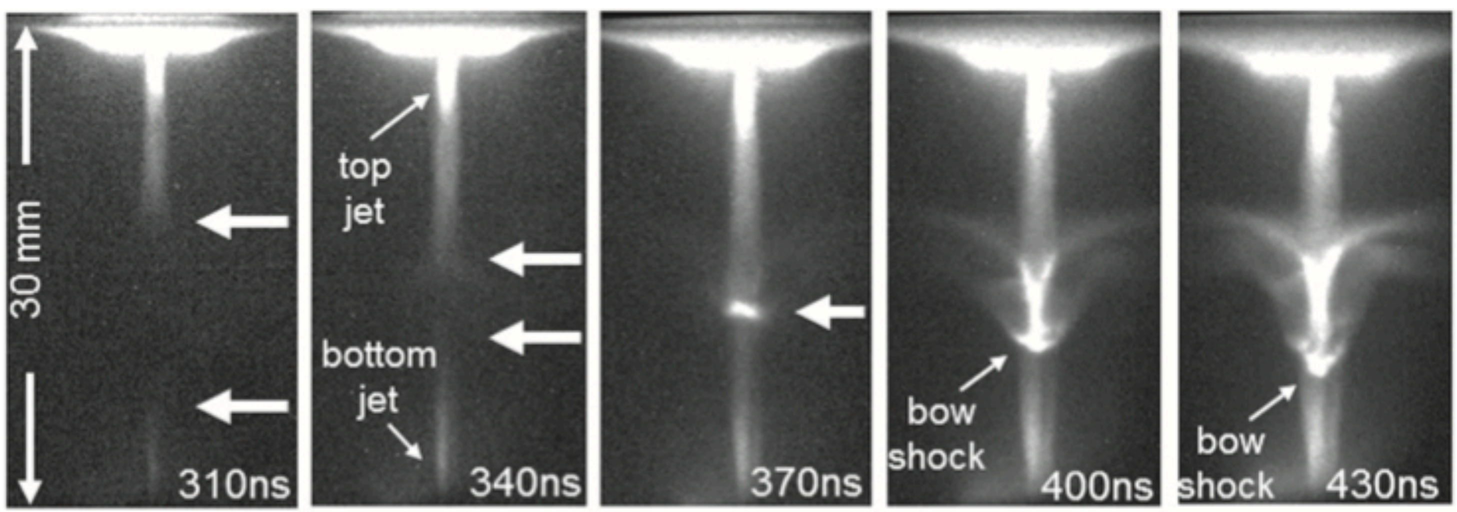


HOW DO WE STUDY JETS?

Laboratory astrophysics



Suzuku-Vidal 2012



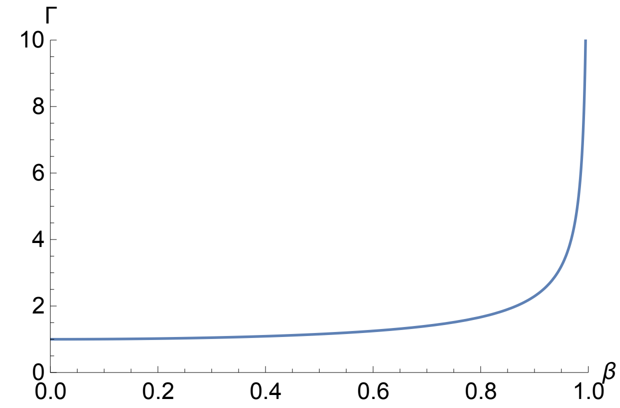
Suzuku-Vidal 2015

DOPPLER BOOSTING

Some reminders from special relativity

If $\beta = \dfrac{v}{c}$, 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:

$$t = \Gamma t'$$

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

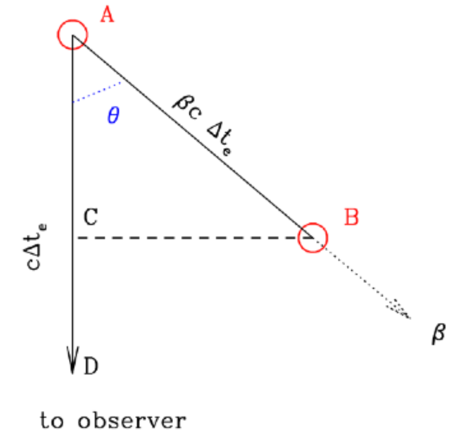
DOPPLER BOOSTING

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

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

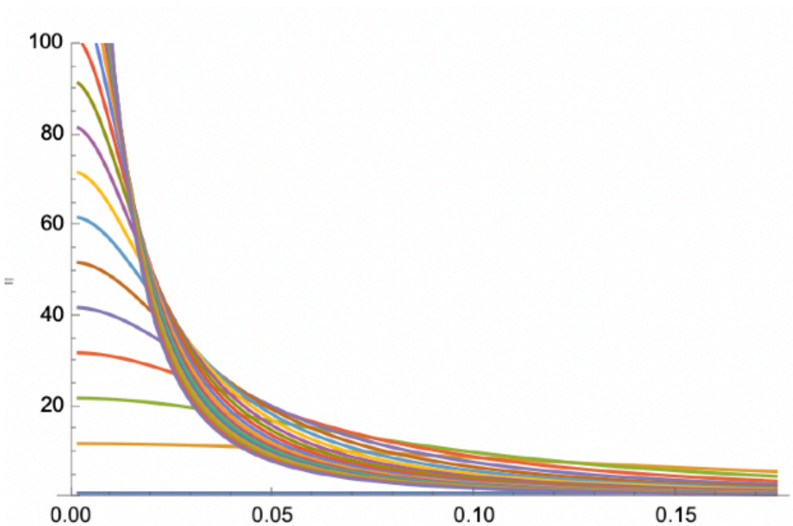
and similarly $\nu = \delta\nu'$

where δ is the Doppler factor



For the flux:

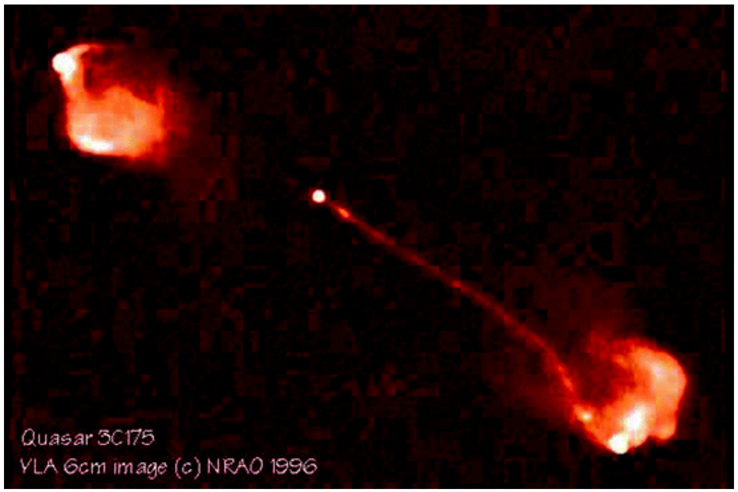
$$F_\nu = \delta^3 F'_{\nu'}$$

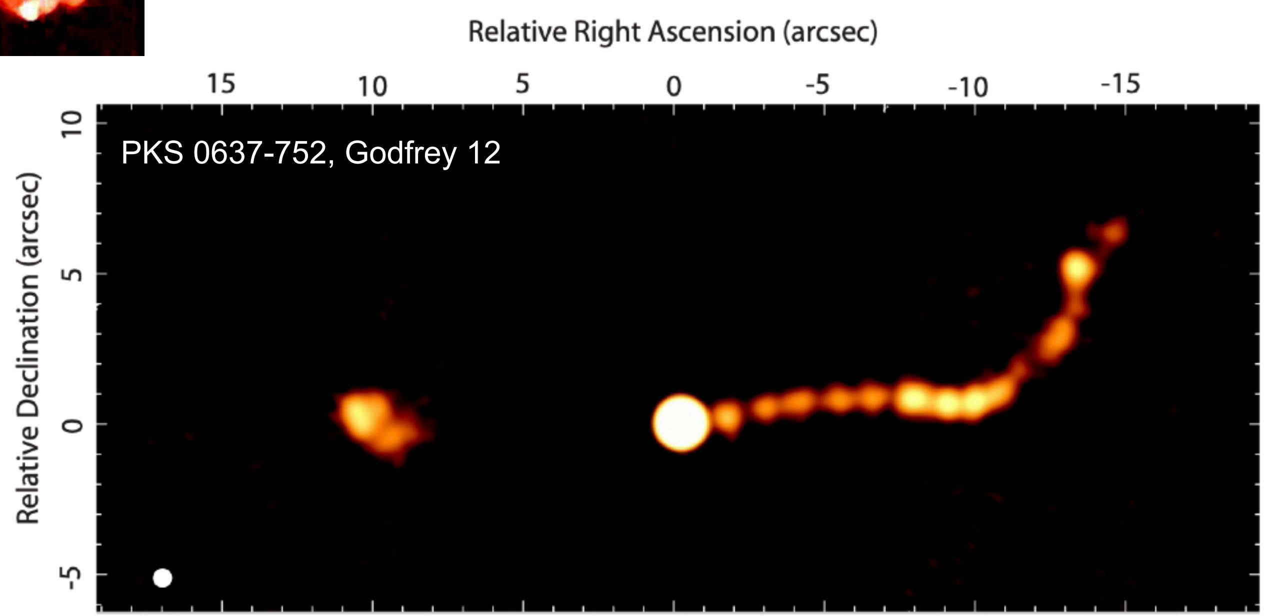


N.B.: This is for a single plasmoid;
If extended region, it goes as δ^2

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 $\dfrac{F_{jet}}{F_{counter-jet}} = \left(\dfrac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^3$

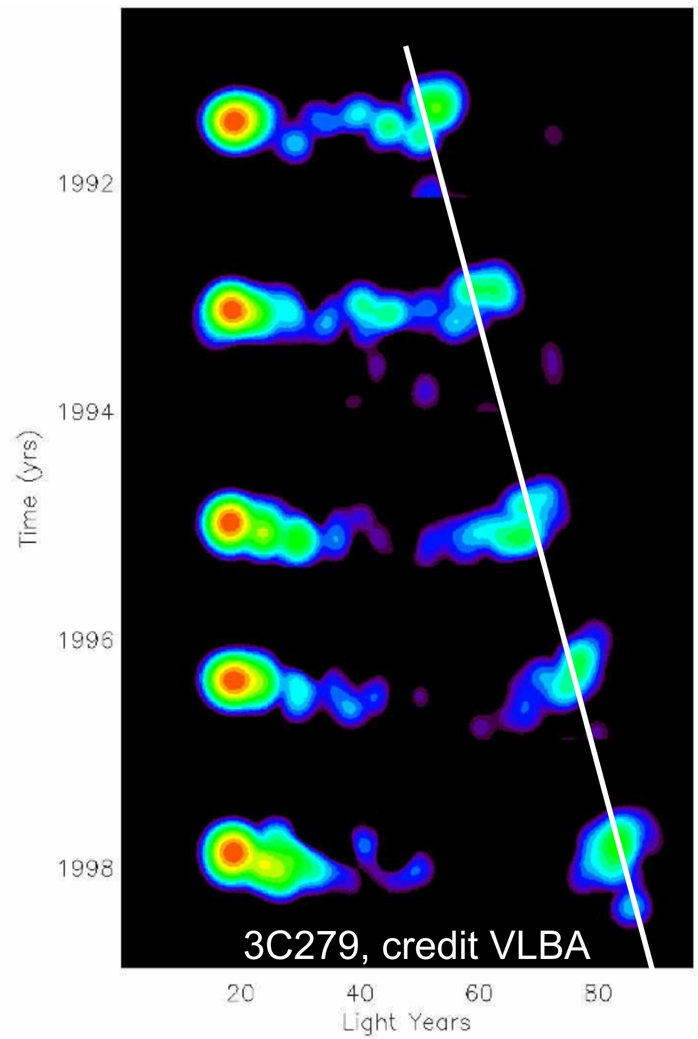
Exemple: if we measure a flux ratio of 1000,
Assuming $\Gamma = 10 \rightarrow \beta = 0.995$

We get $\theta = 35°$

Matteo Cerruti

SUPERLUMINAL MOTION

Observations



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

SUPERLUMINAL MOTION

In frame K:

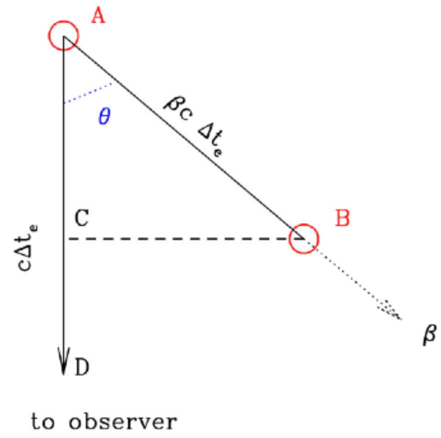
$$AB = \beta c \Delta T$$

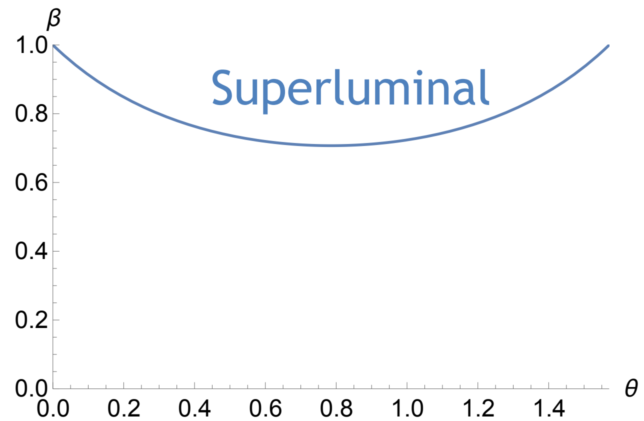
In B the knot moved towards us by
$\beta c \Delta T \cos\theta$.

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 $\dfrac{\beta c \Delta T \sin\theta}{\Delta T - \beta \Delta T \cos\theta}$

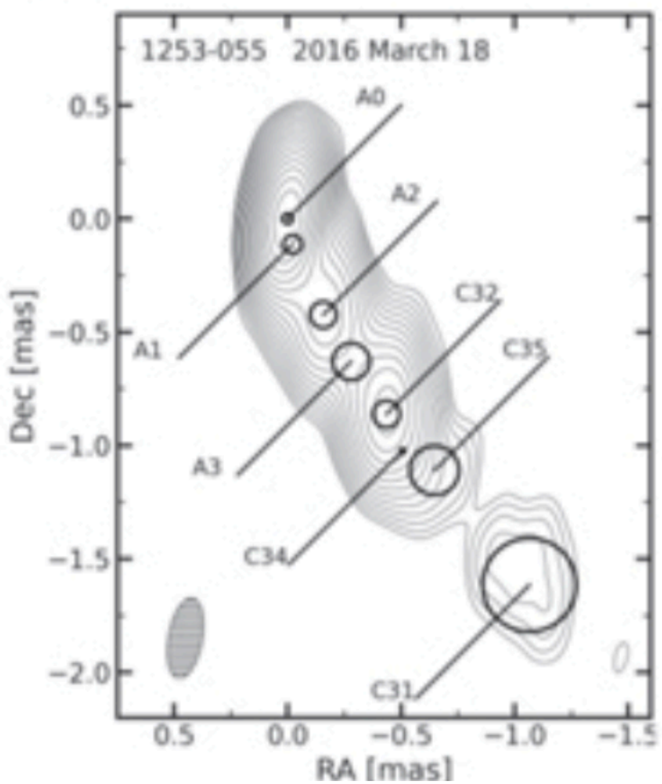
This can be > c if $\beta > \dfrac{1}{\sin\theta + cos\theta}$

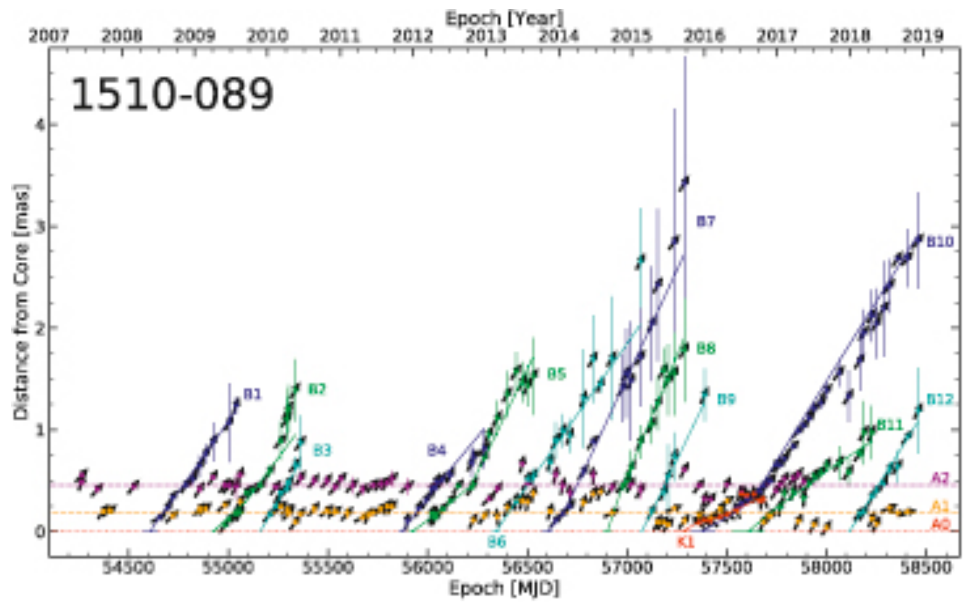




KNOTS

Monitoring of features over several years
Moving vs standing knots

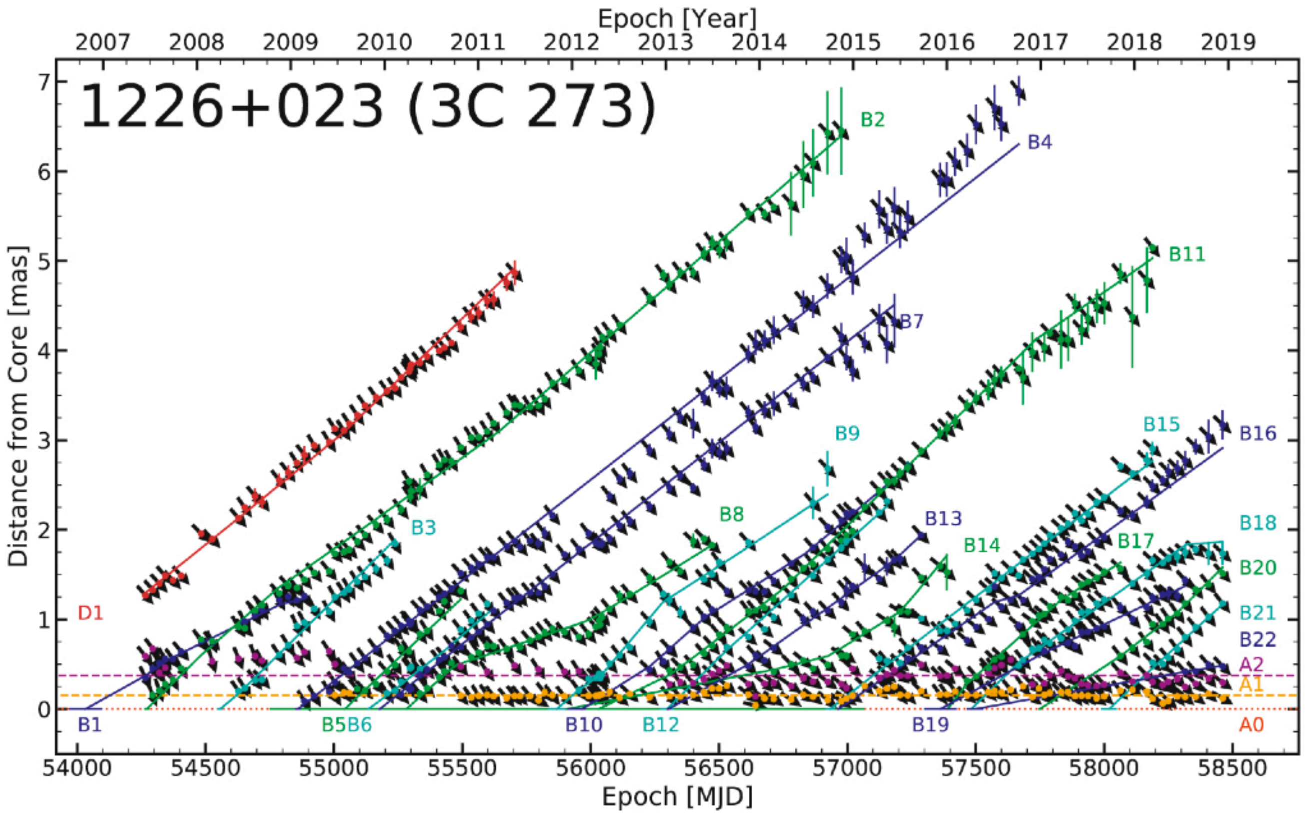




Weaver 22

KNOTS

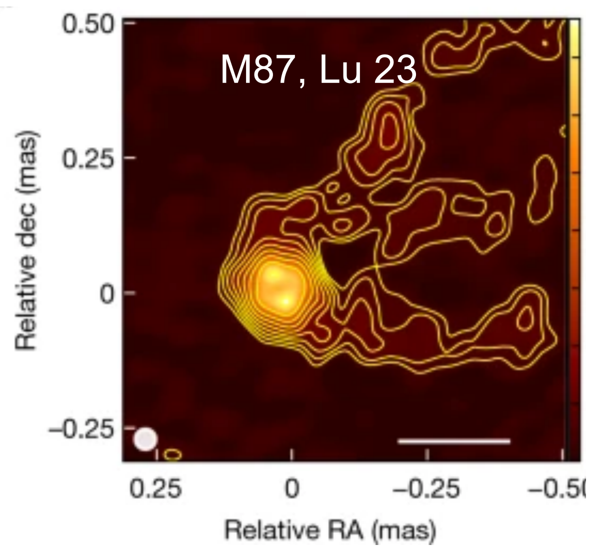
New ejections and trailing knots

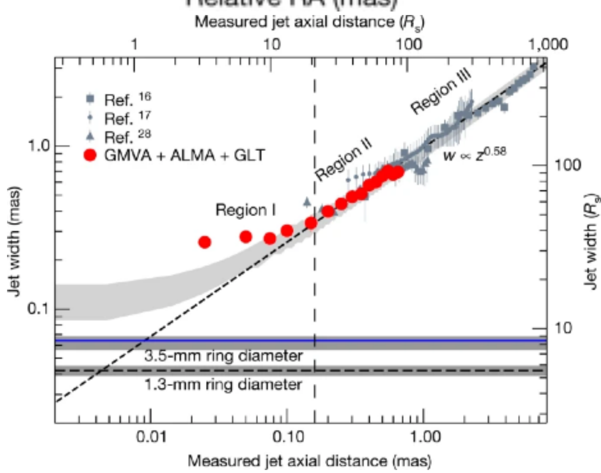


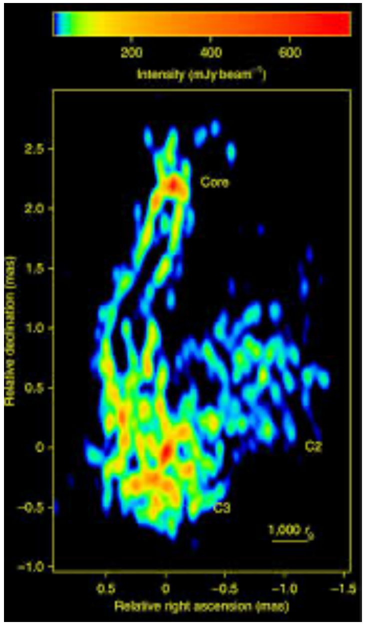
Weaver 22

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



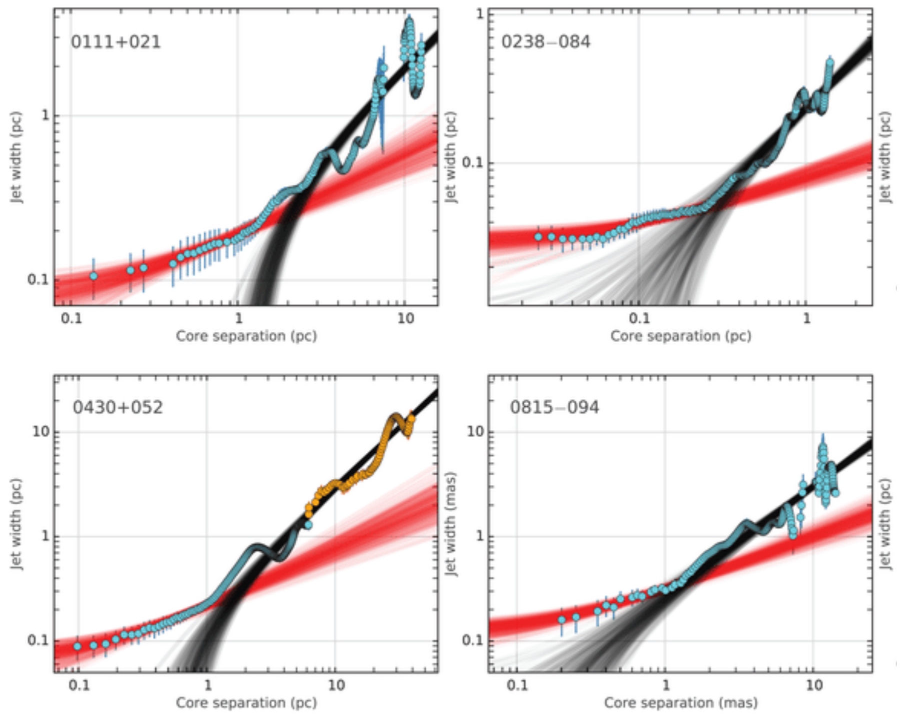




3C84, Giovannini 18

JET PROFILE AND COLLIMATION

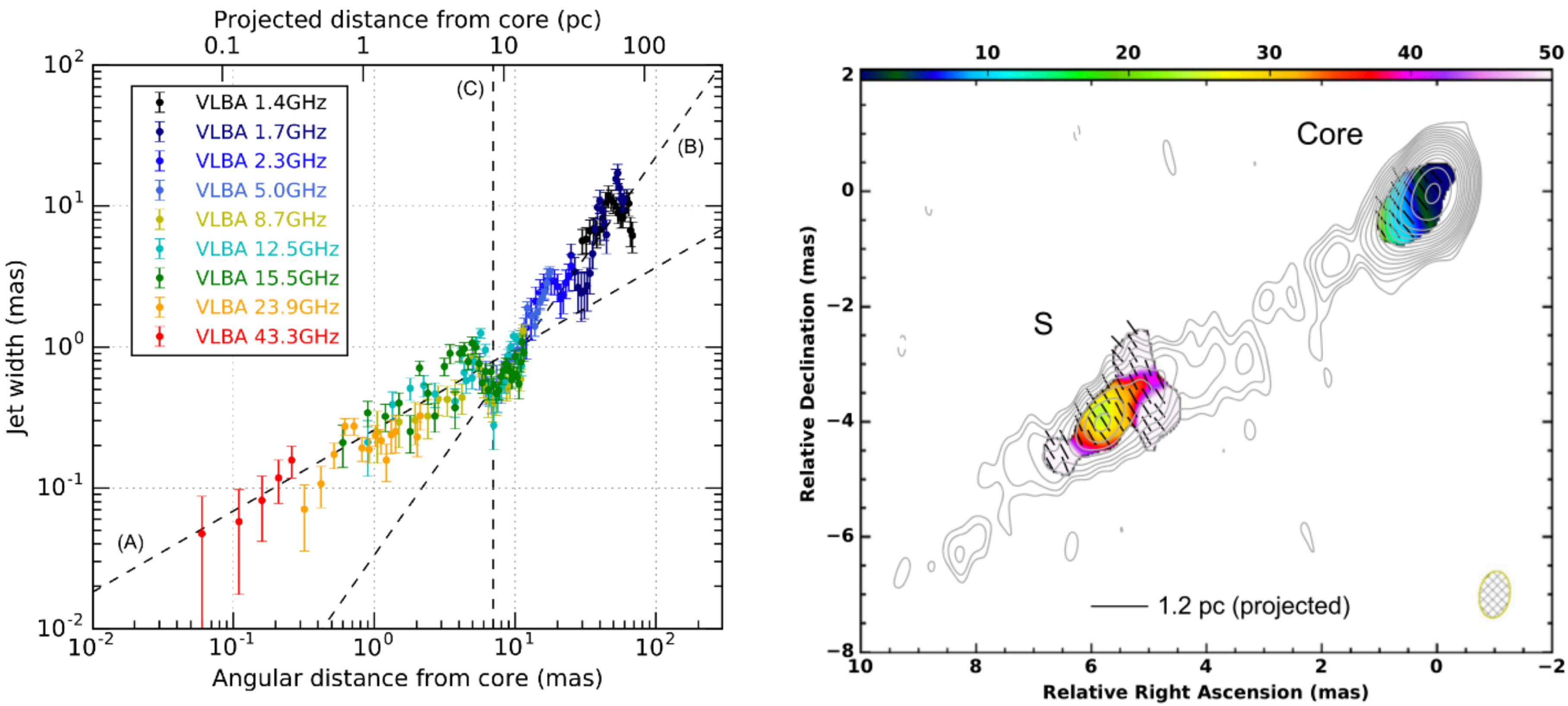
What is the jet shape? Far away it looks cylindrical
Close to the black hole we see conical and parabolic sections



Kovalev 20

RECOLLIMATION SHOCKS

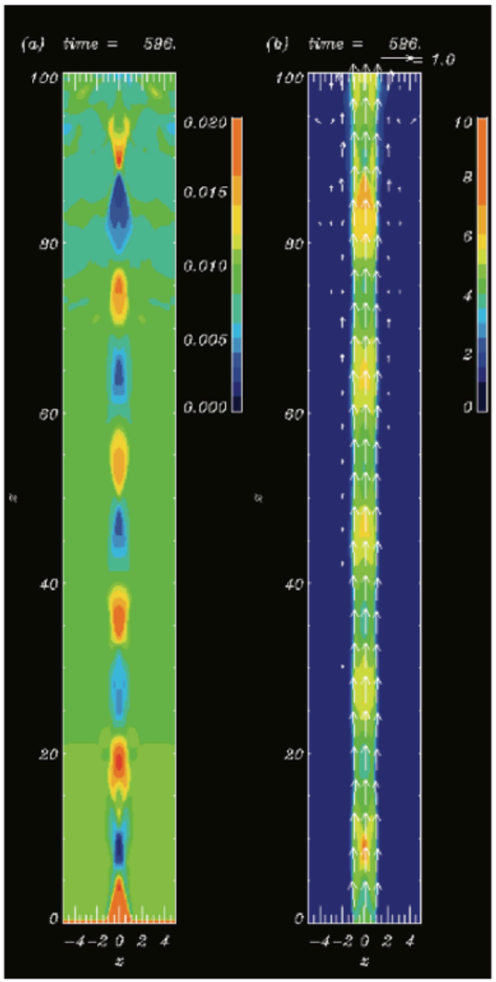
Are stationary features recollimation?



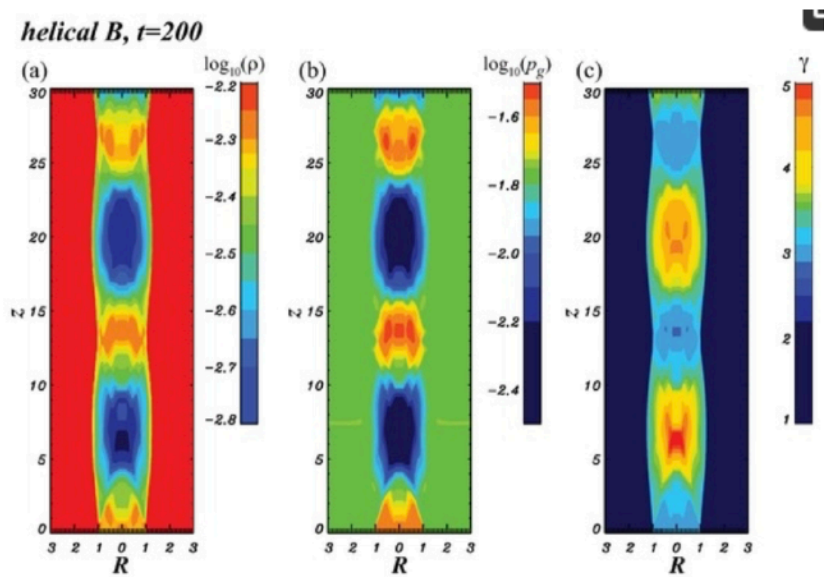
1H 0323+342, Nada 18

RECOLLIMATION SHOCKS

Simulations



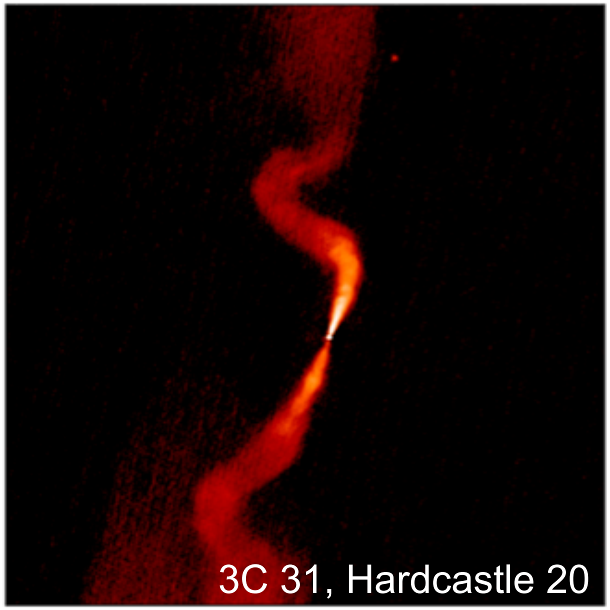
Nishikawa 13

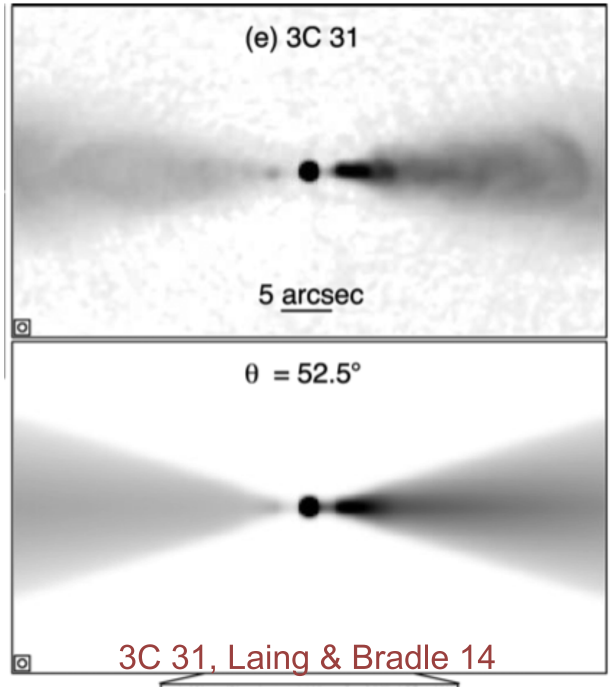


Mizuno 15

DECELERATION

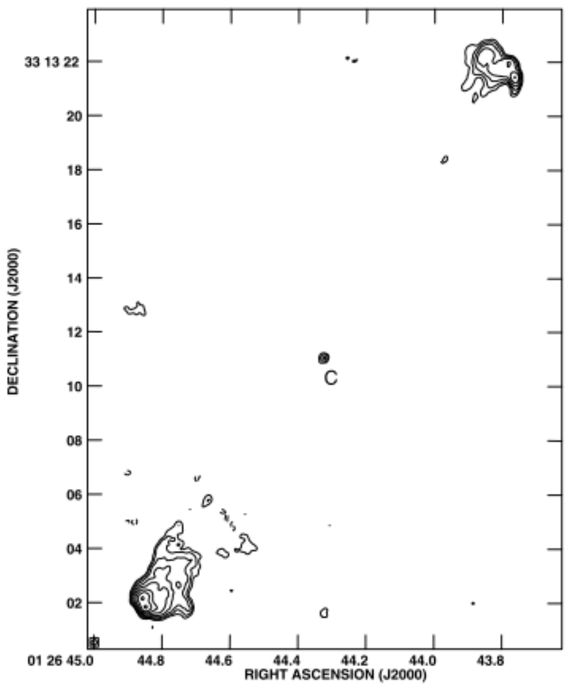
How does the jet end?
- Deceleration and disruption



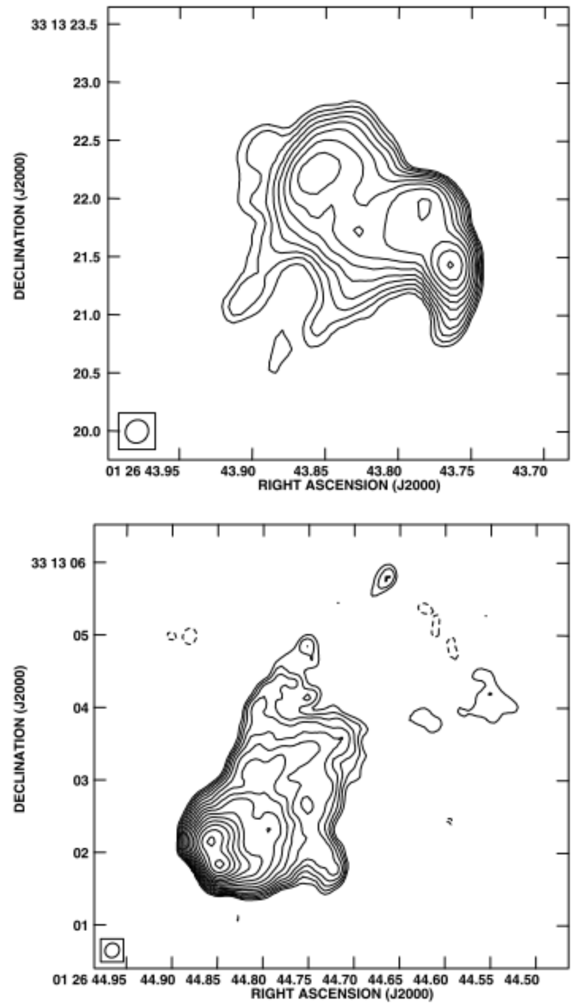


TERMINATION SHOCKS

How does the jet end?
- Termination shock



3C 41, Kharb 08



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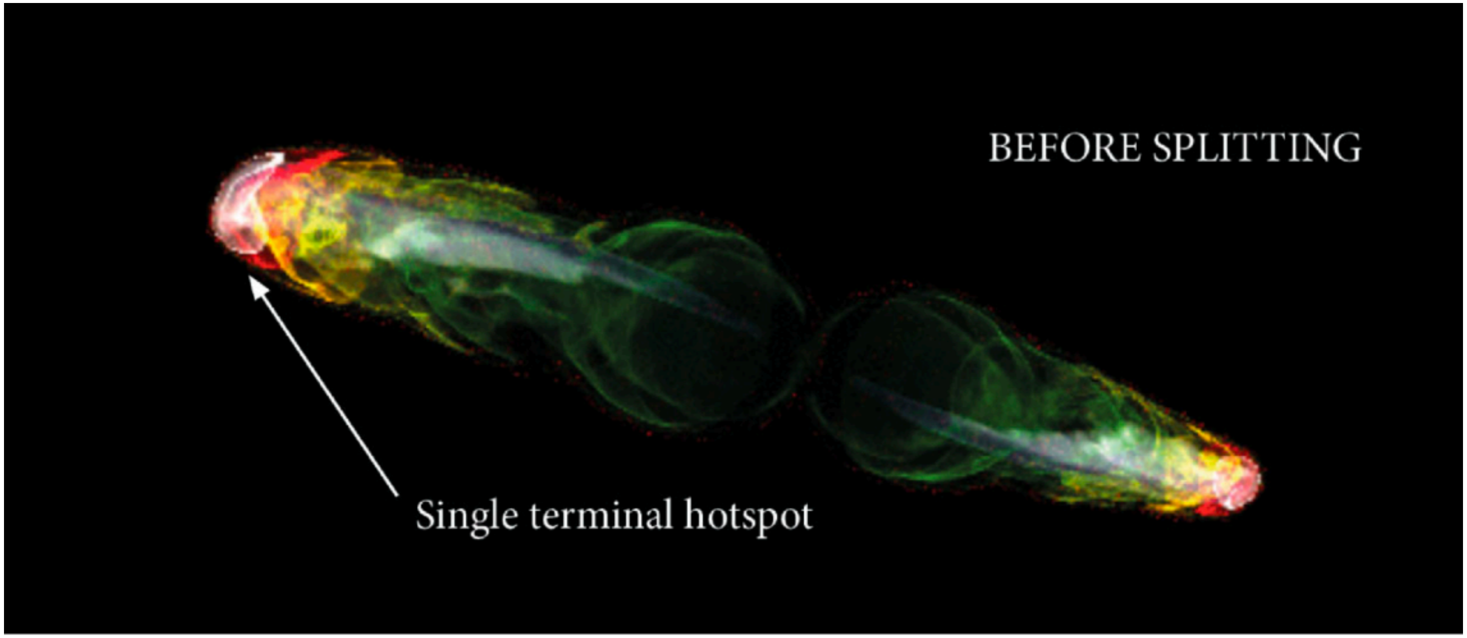
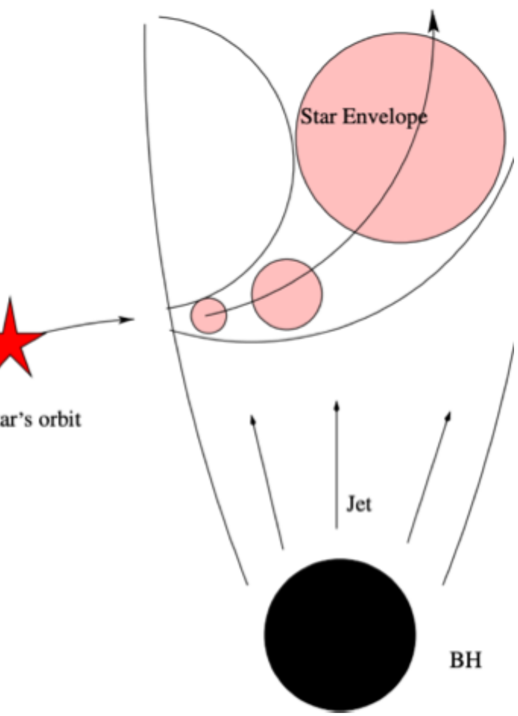


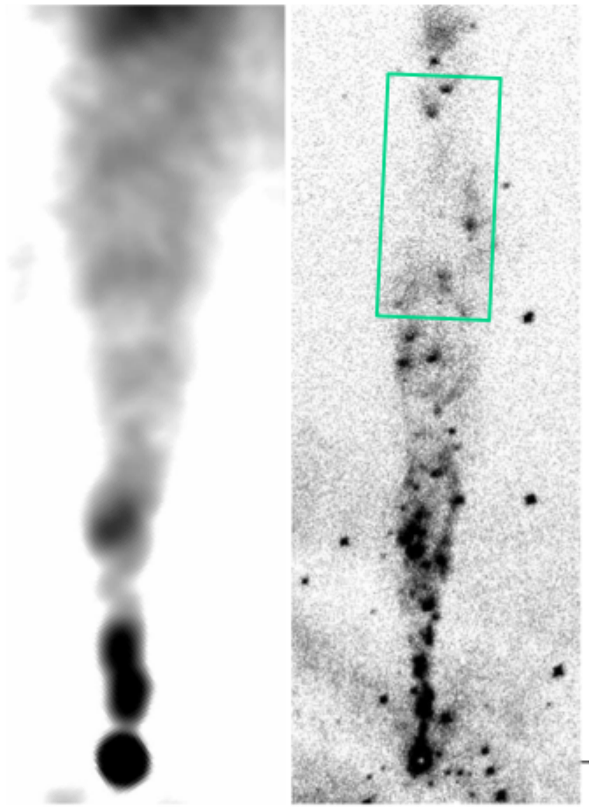
Horton 23

JET and OBSTACLES

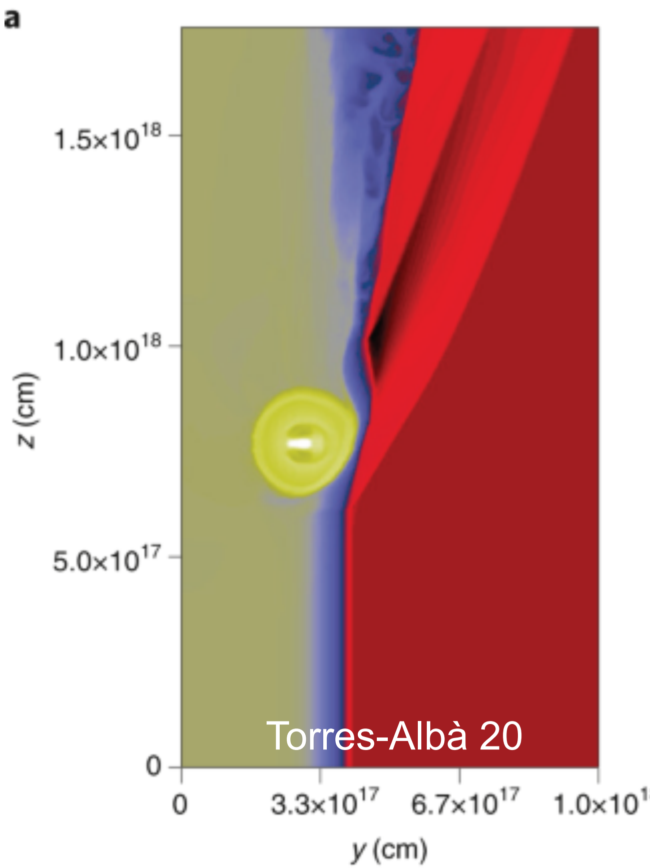
The jet interacts with its environment
It *has to* collide with clouds and stars in the galaxy



Barkov 12



Cen A, Wykes 15

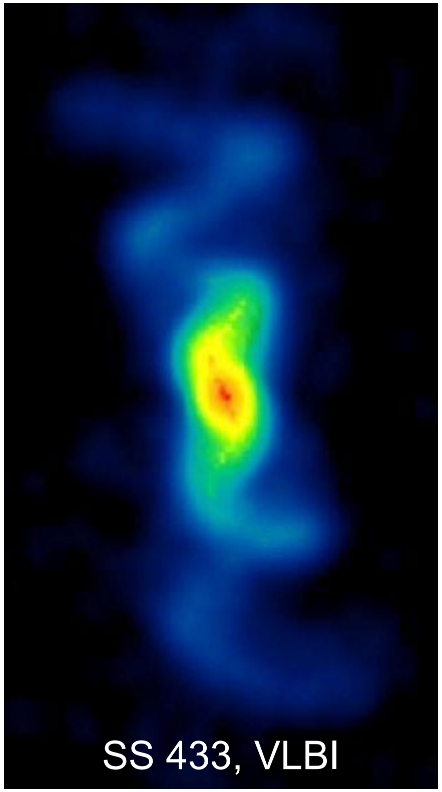


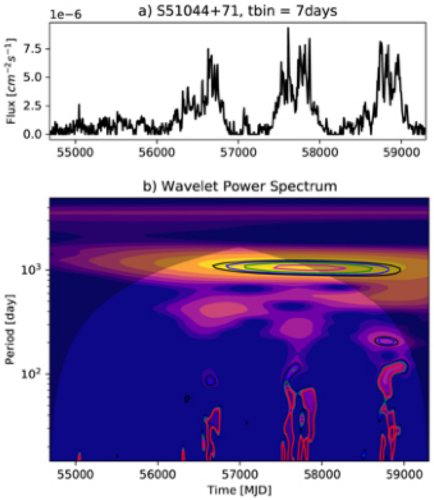
Torres-Albà 20

PRECESSION

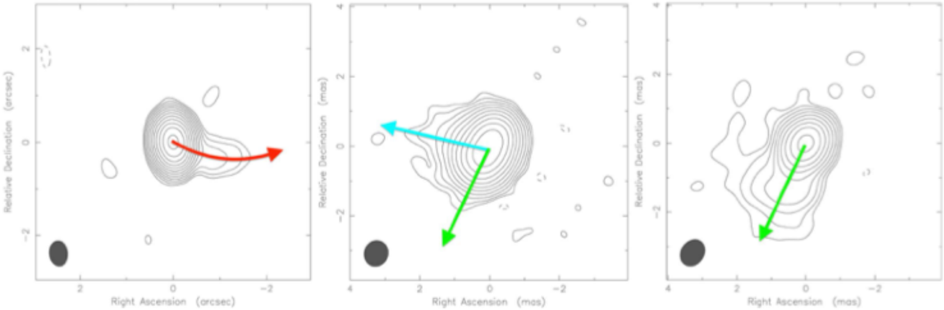
Observational evidences

Simulations





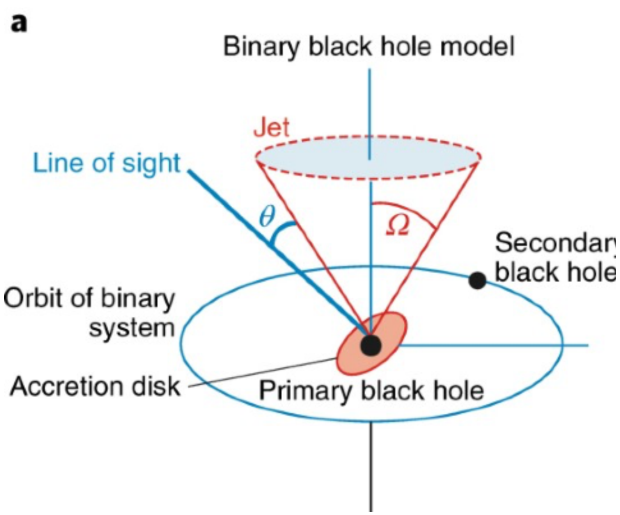
Ren 23



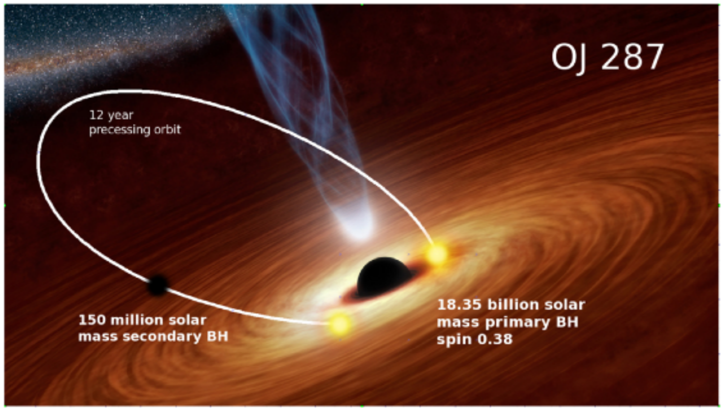
S5 1044+719, Kun 23

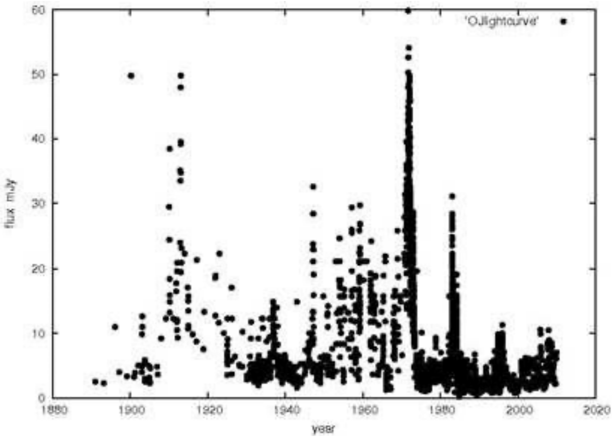
PRECESSION

OJ 287 & binaries



Abraham 18

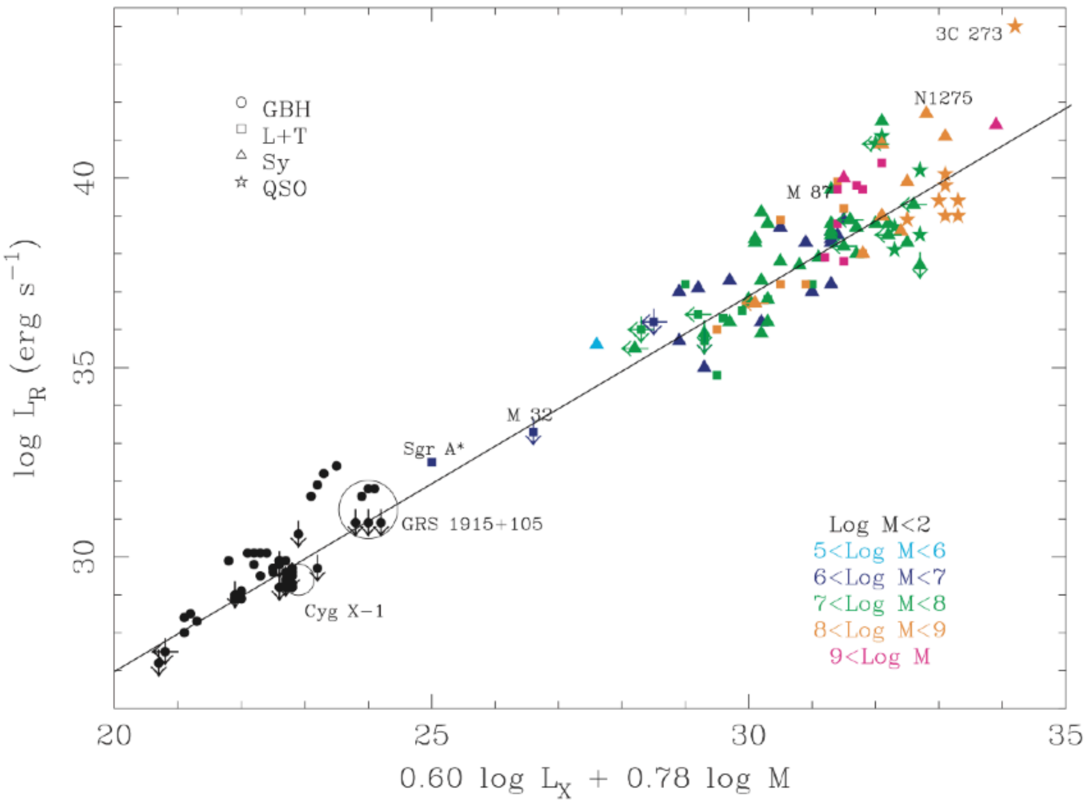




Valtonen 11

JET UNIFICATION

A fundamental plane connecting jets at various scales

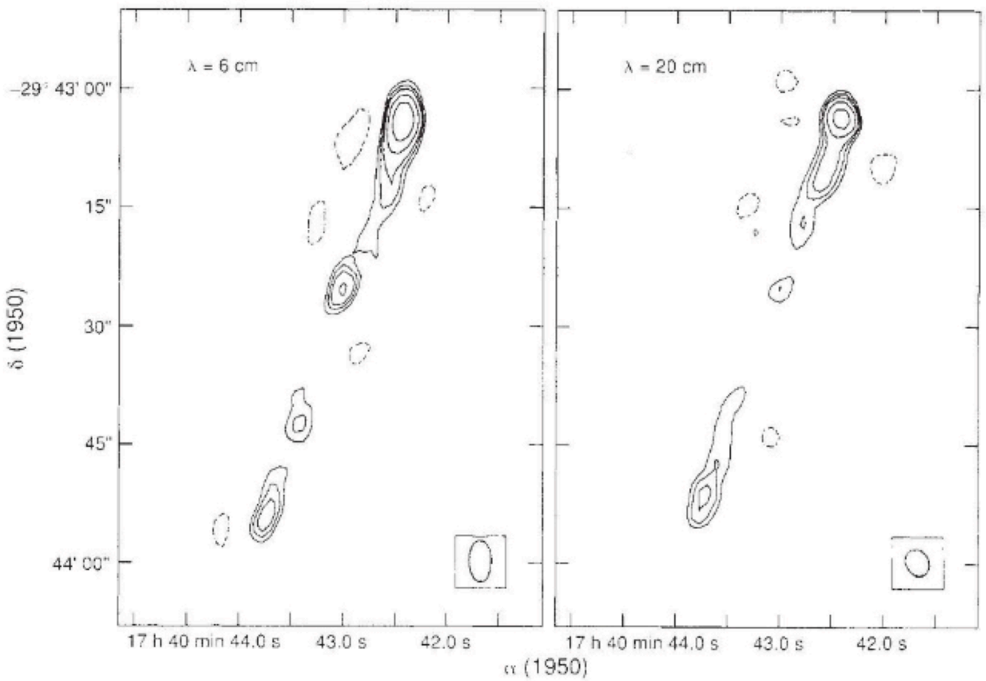


Merloni 03

MICRO QUASARS

HISTORY

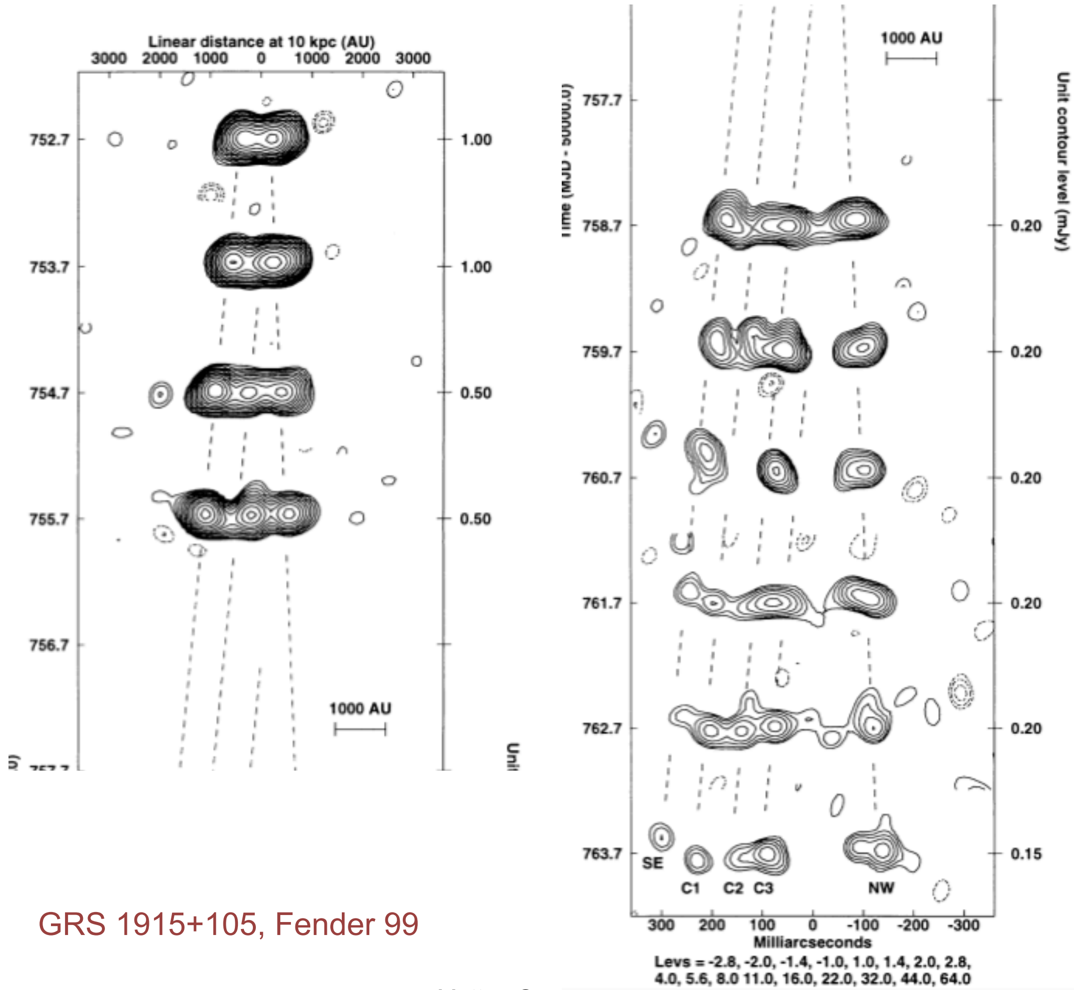
Follow up of bright X-ray sources in the Milky Way
First observations of jets that ‘look like’ quasars



1E 1740.7-2942, Mirabel 92

HISTORY

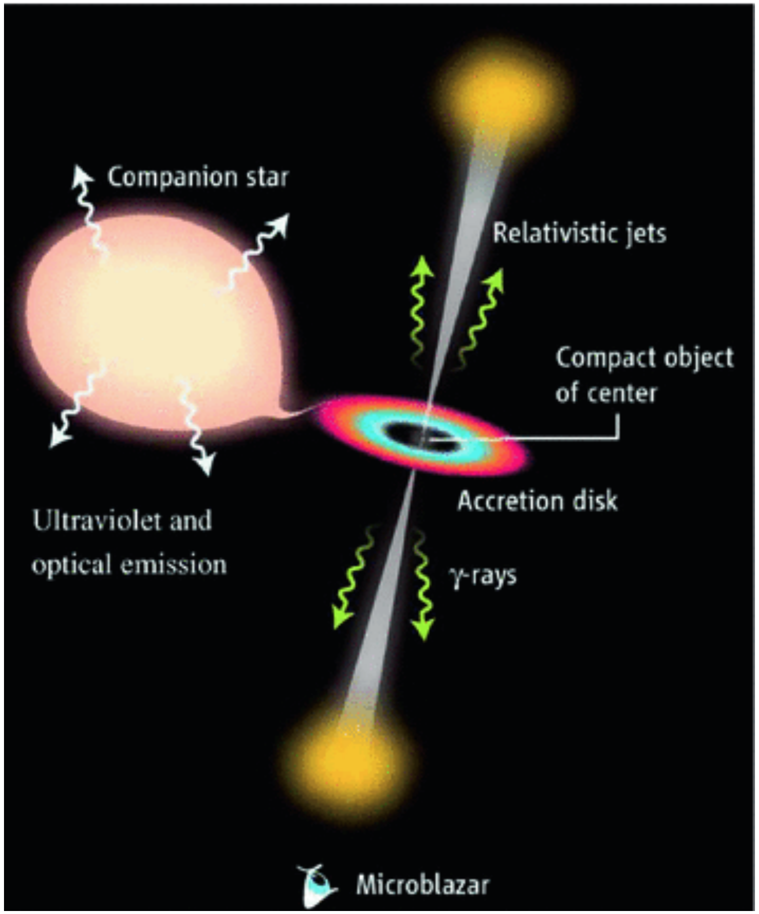
Confirmed by the discovery of superluminal motions



GRS 1915+105, Fender 99

WHAT IS A MICROQUASAR?

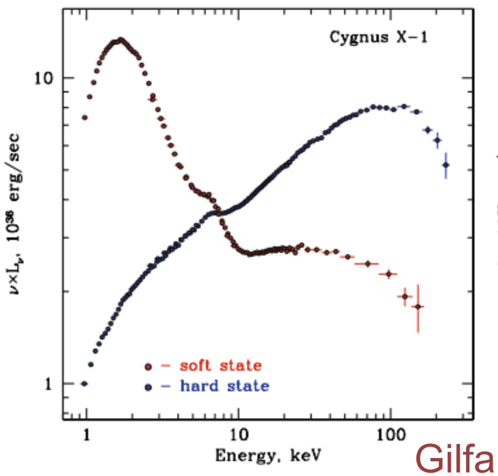
X-ray binary with radio jet

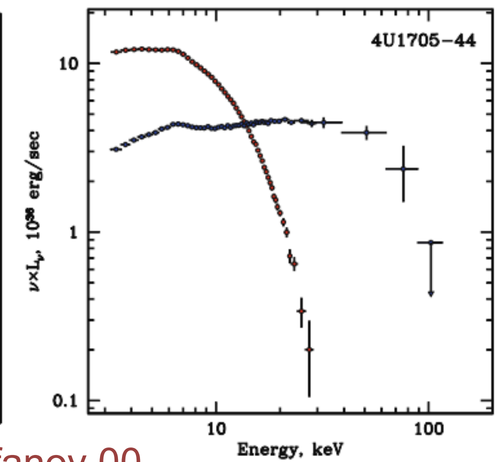


N.B. not all binaries are microquasars!

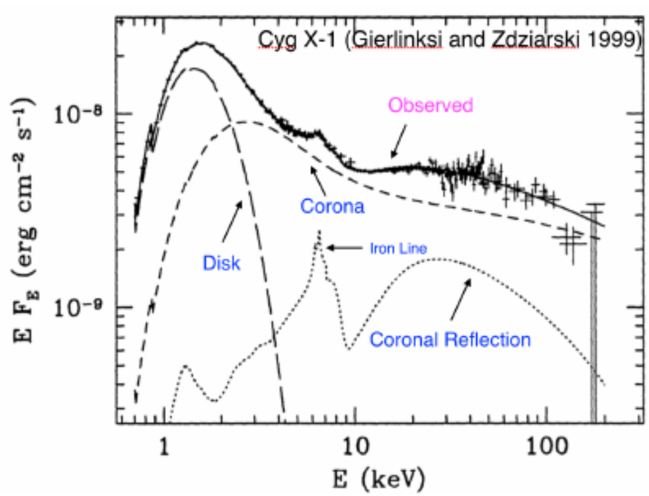
X-RAY EMISSION FROM MICROQUASARS

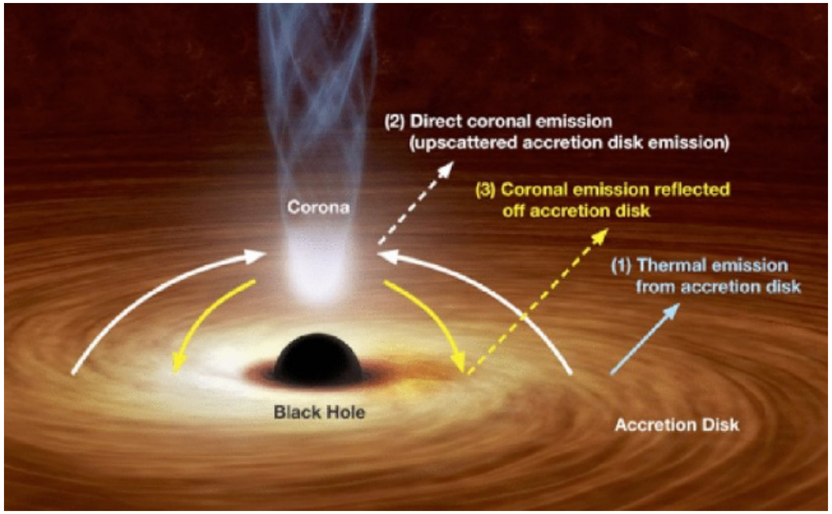
X-ray spectra from micro quasars



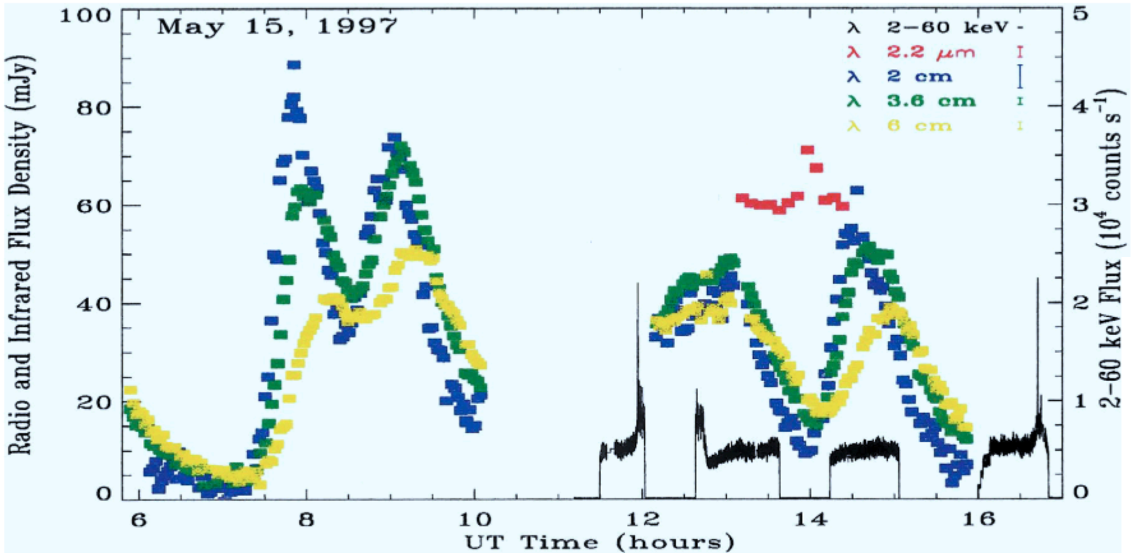


Gilfanov 00

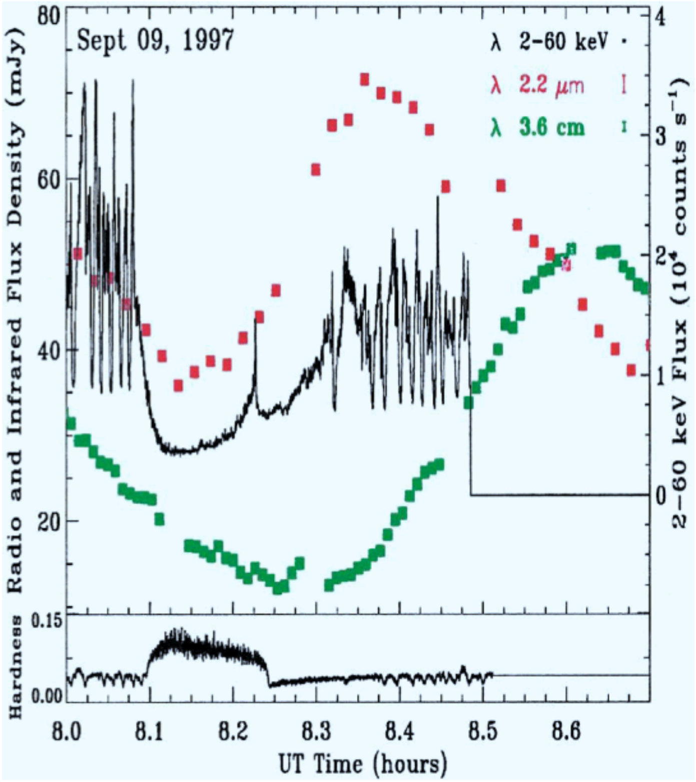




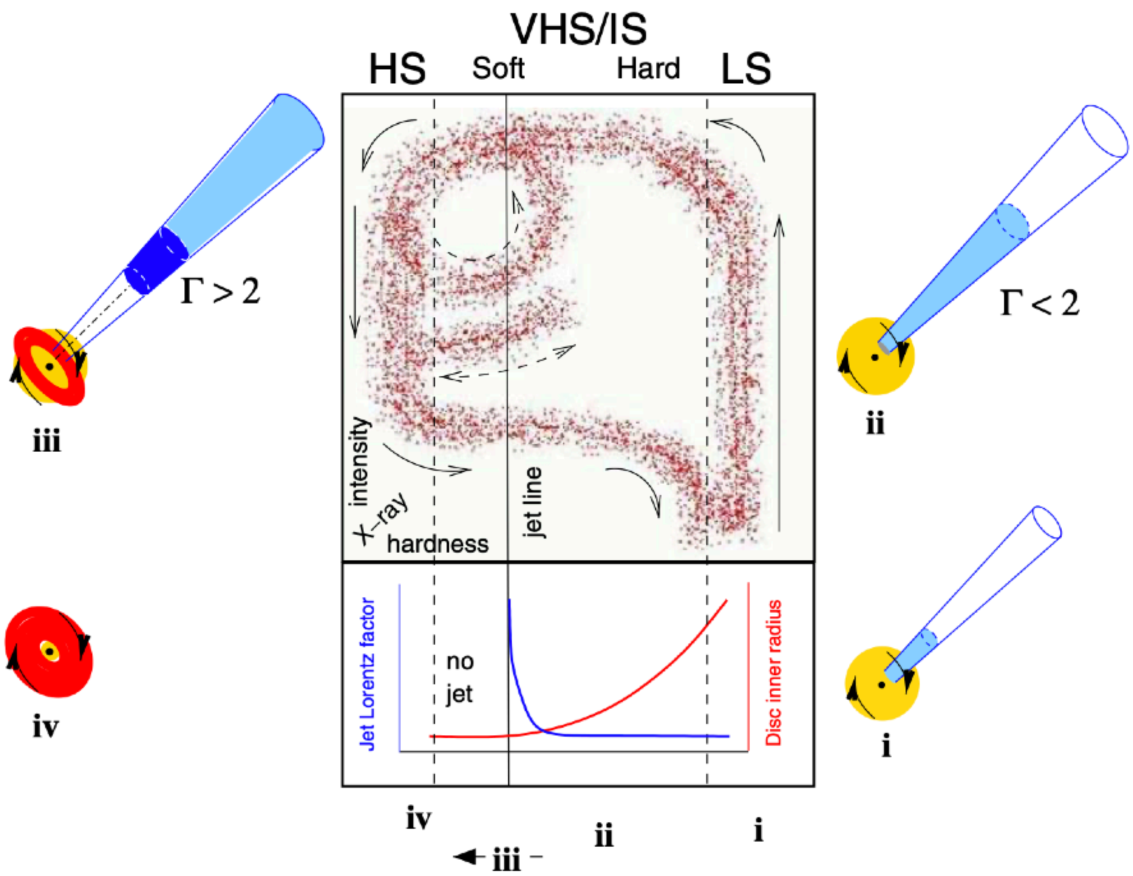
MWL EMISSION FROM MICROQUASARS



GRS 1915+105, Mirabel 97



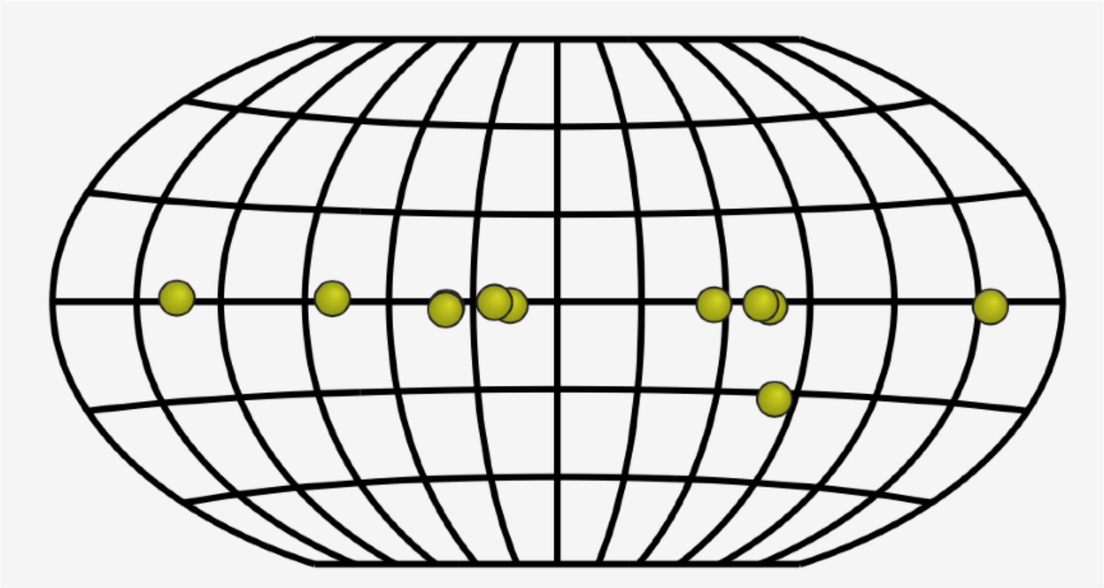
DIFFERENT STATES



Fender 04

GAMMA-RAYS FROM MICROQUASARS

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

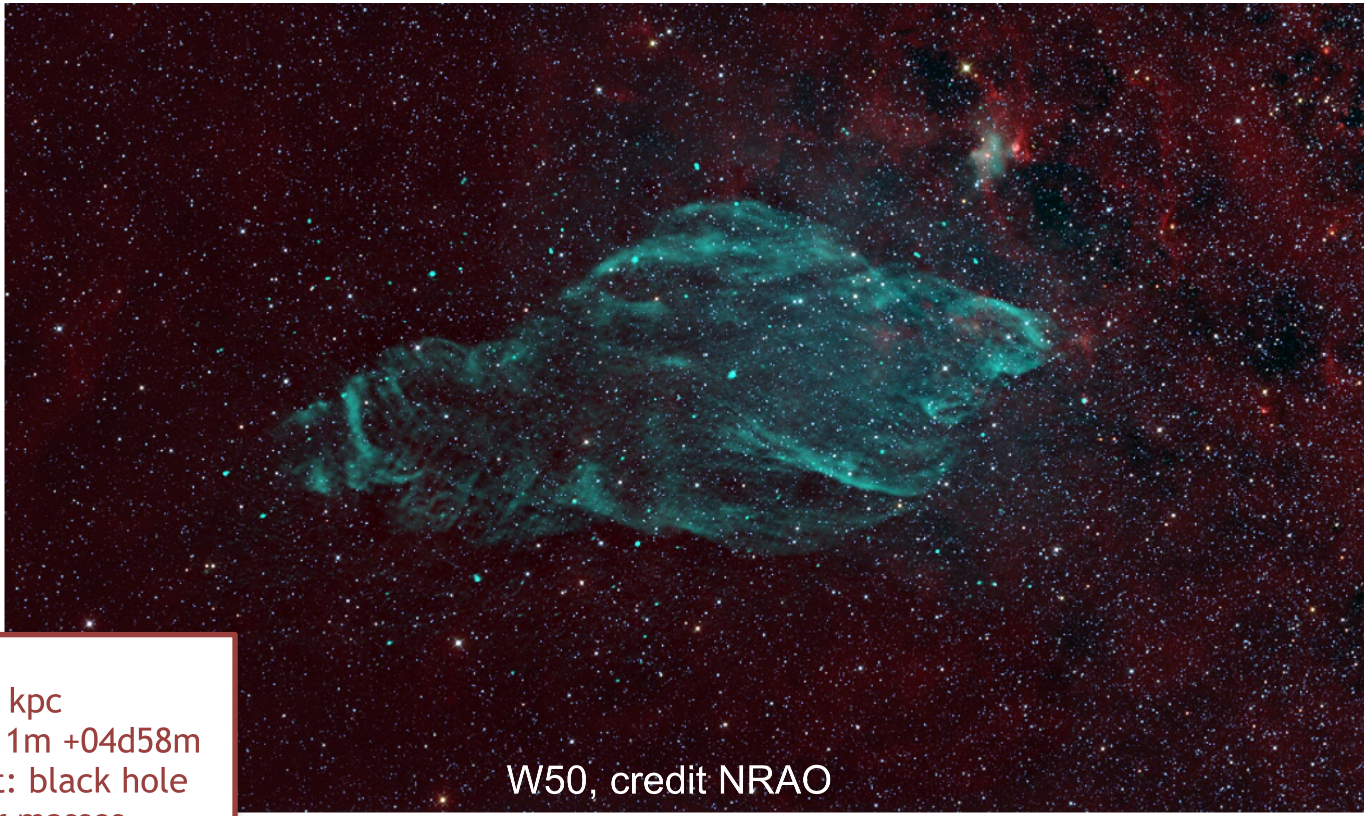


LS I +61 303	02 40 34	+61 15 25	Gal,BIN	2.0 kpc	Default Catalog
LMC P3	05 36 00	-67 35 11	Gal,BIN		Default Catalog
HESS J0632+057	06 33 00.8	+05 47 39	Gal,BIN	1.4 kpc	Default Catalog
HESS J1018-589 A	10 18 58	-58 56 43	Gal,BIN		Default Catalog
Eta Carinae	10 44 35	-59 39 56.6	Gal,BIN	2.3 kpc	Default Catalog
PSR B1259-63	13 02 49.3	-63 49 53	Gal,BIN	2.7 kpc	Default Catalog
LS 5039	18 26 15	-14 49 30	Gal,BIN	2.5 kpc	Default Catalog
HESS J1832-093	18 32 50	-09 22 36	Gal,BIN		Default Catalog
SS 433 w1	19 10 37	+05 02 13	Gal,BIN	4.5 kpc	Default Catalog
SS 433 e1	19 13 37	+04 55 48	Gal,BIN	5.5 kpc	Default Catalog
PSR J2032+4127	20 32 10	+41 27 34	Gal,BIN	1.8 kpc	Default Catalog

These sources will be covered tomorrow by P. Bordas

SS 433

Microquasar embedded in the supernova remnant W50

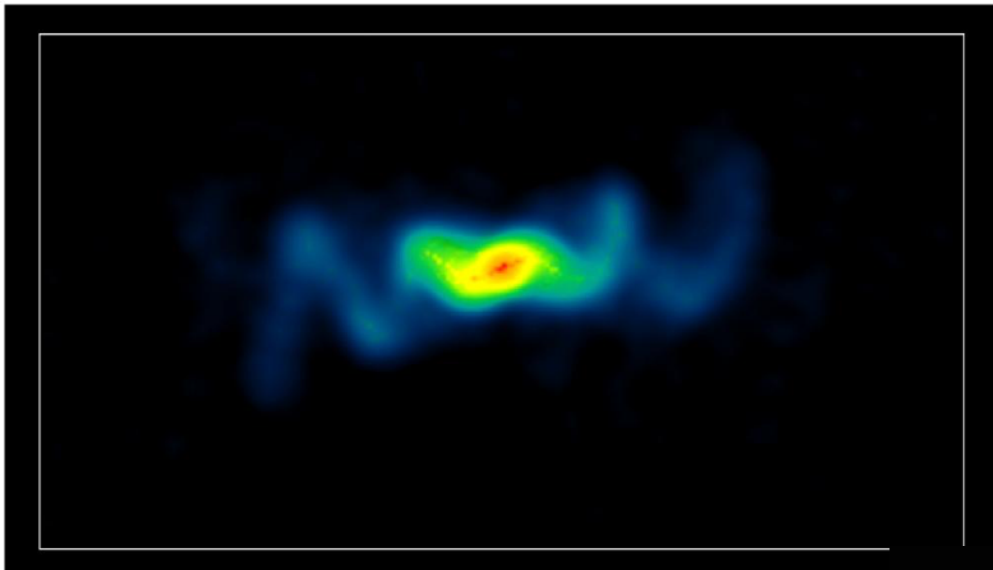


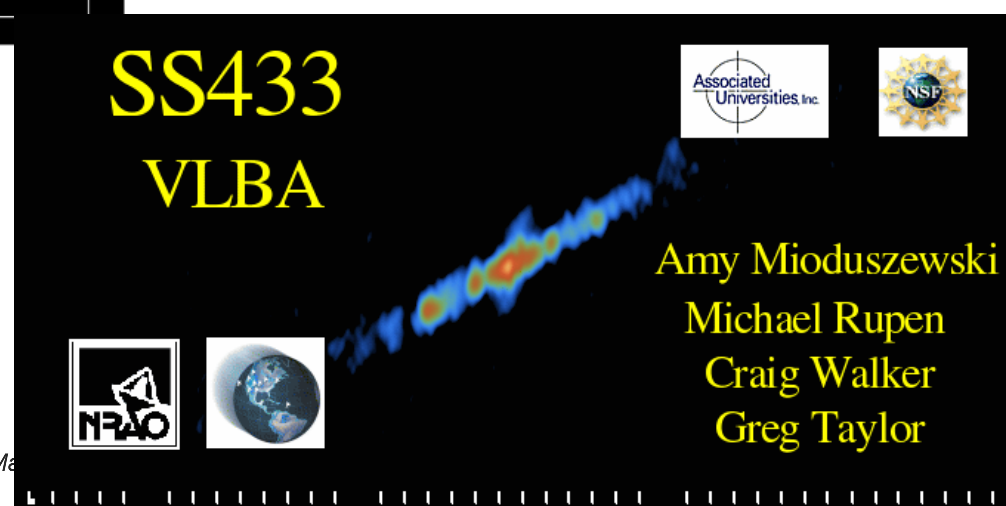
W50, credit NRAO

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

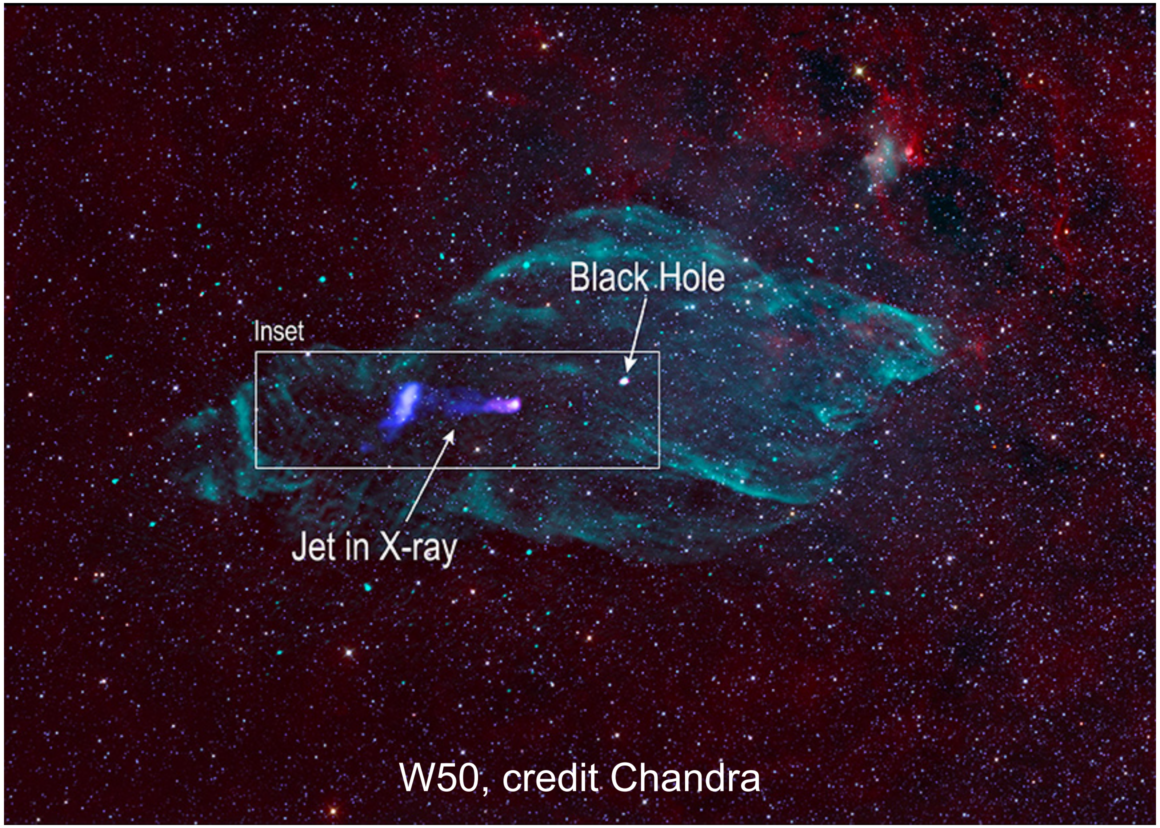




SS433, credit NRAO

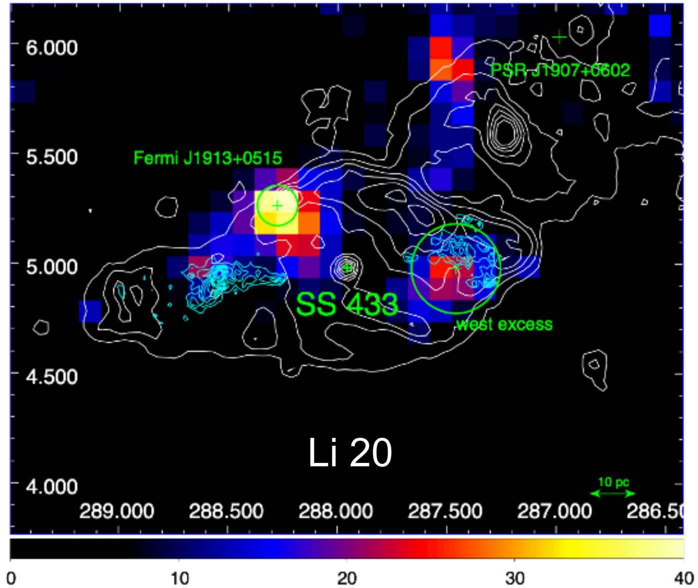
SS 433

X-ray emission

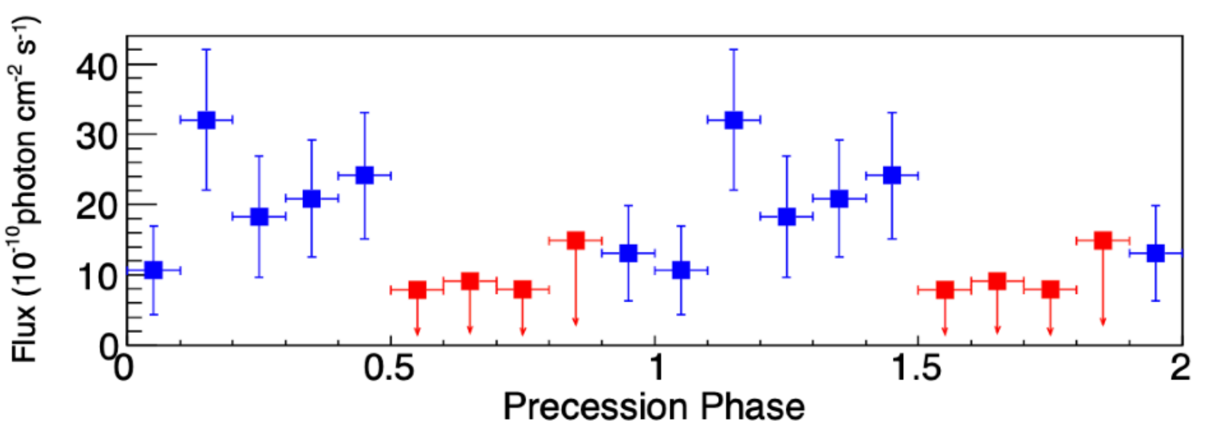


SS 433

GeV emission

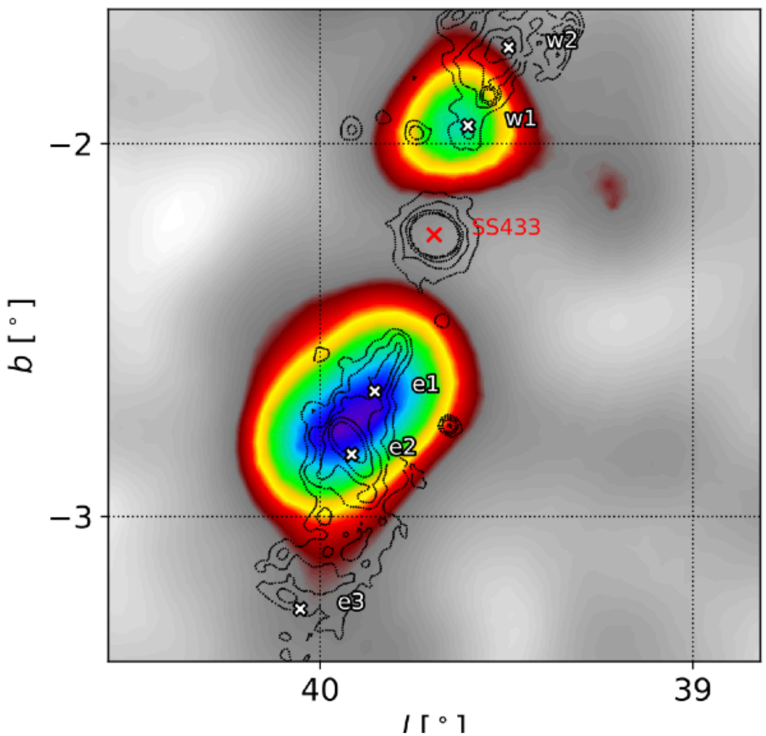


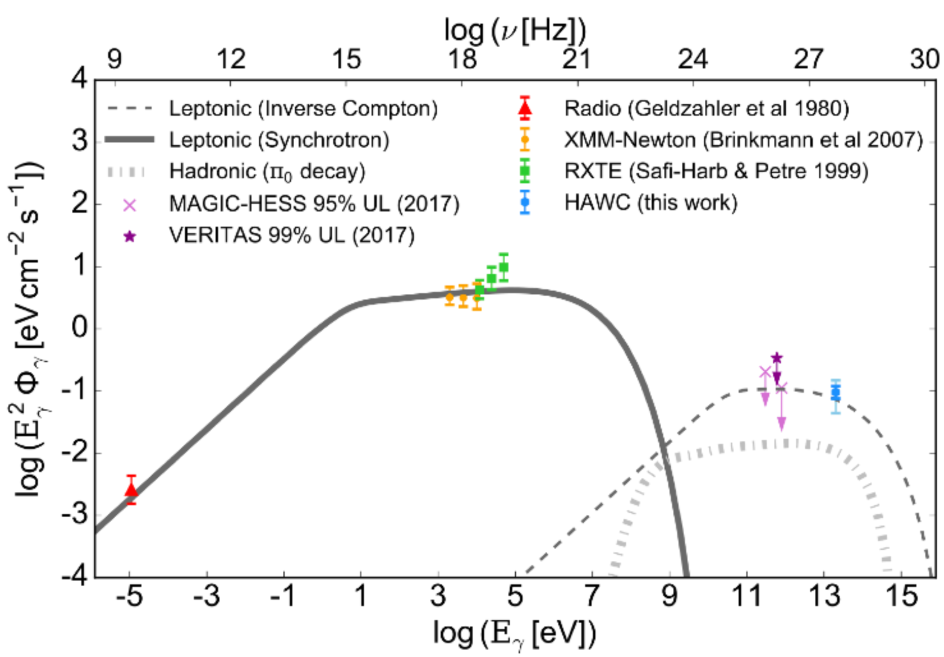
No LAT source associated with the X-ray jets.
A surprising source offset from the jets, and in phase with the precession period



SS 433

Extended TeV emission detected with HAWC

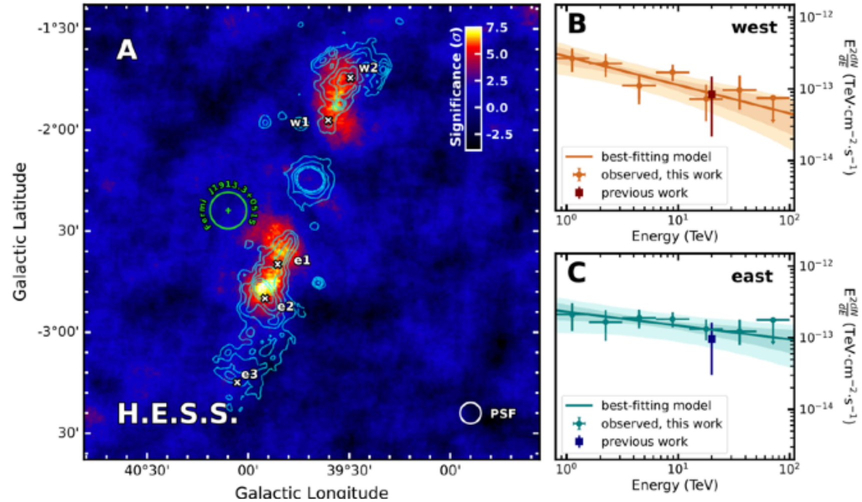


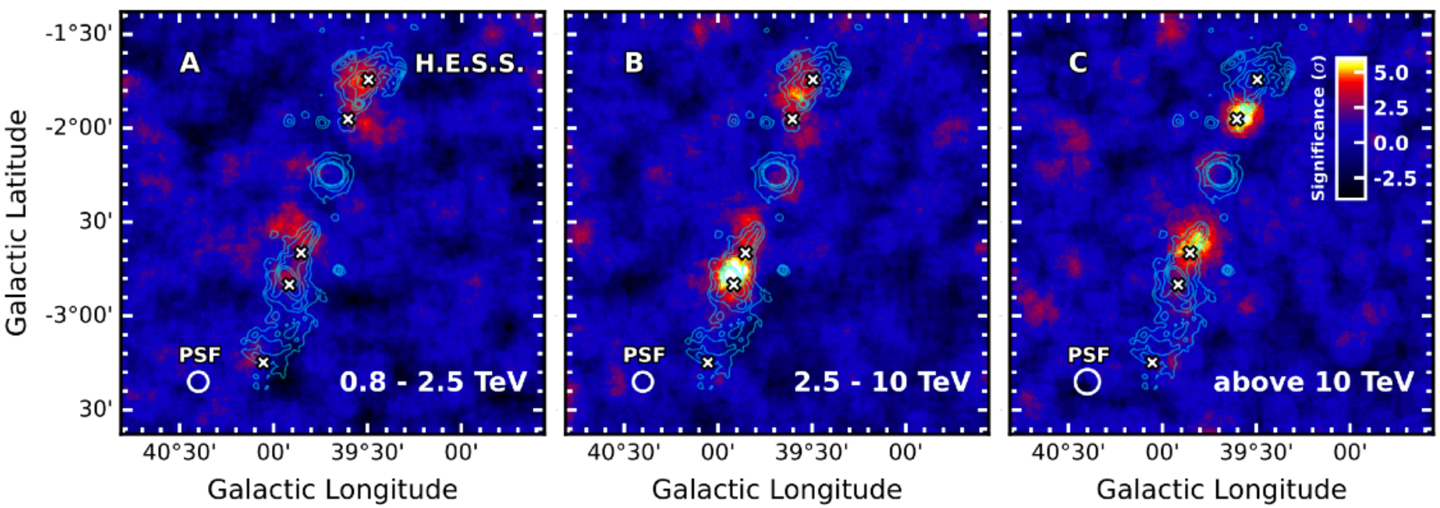


Abeysekara 18

SS 433

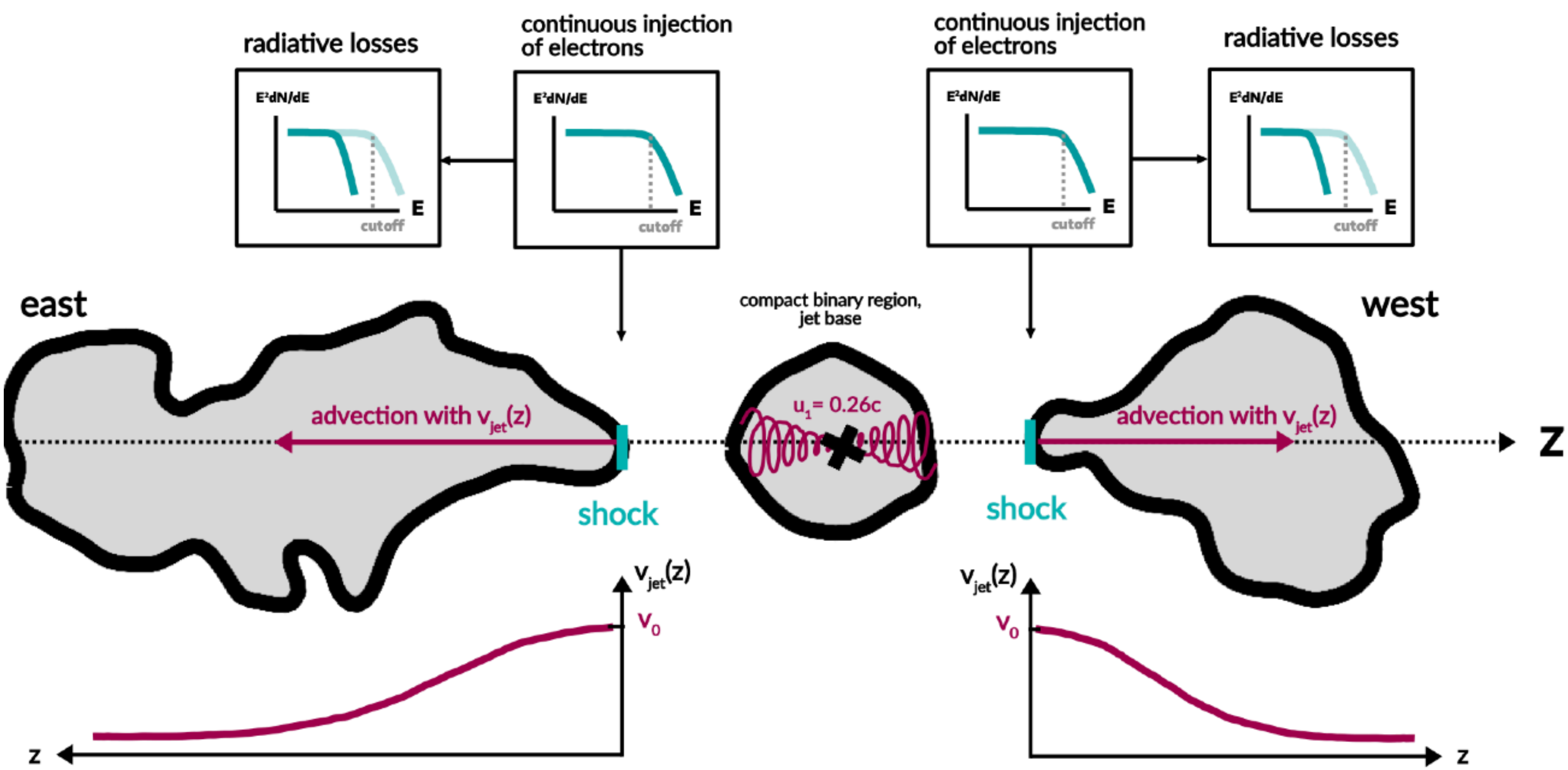
TeV emission with HESS





HESS Coll. 24

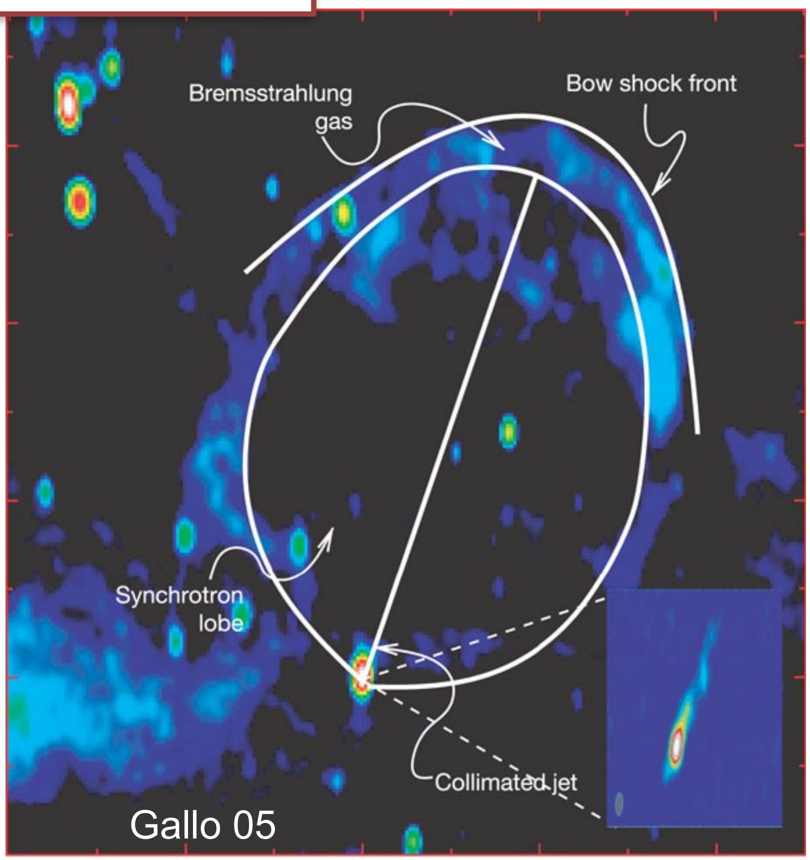
SS 433

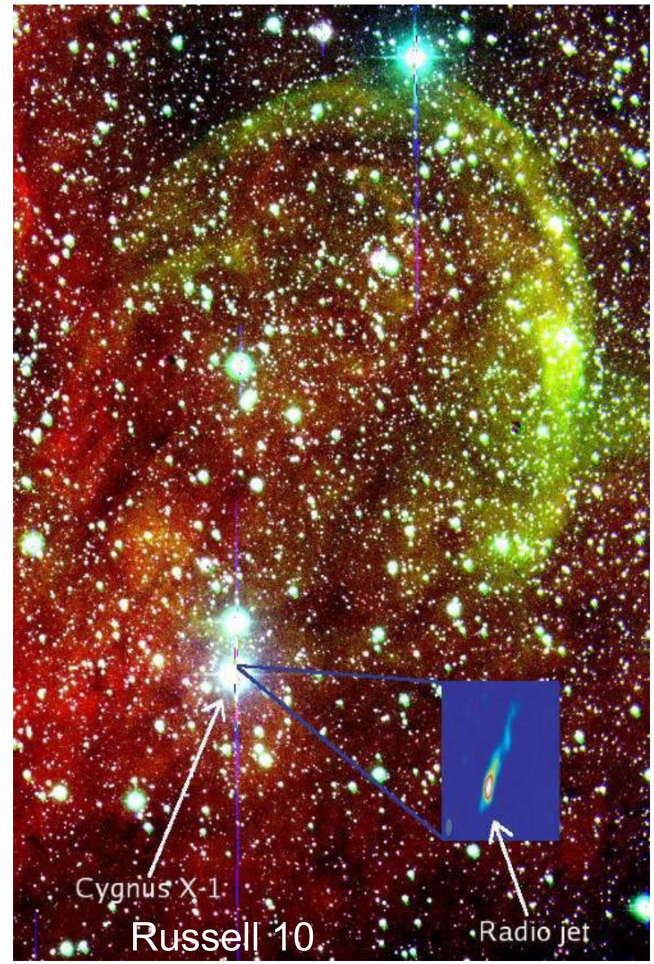


radiative losses
continuous injection
of electrons
continuous injection
of electrons
radiative losses
E²dN/dE
E
cutoff
east
west
compact binary region,
jet base
advection with $v_{jet}(z)$
$u_1 = 0.26c$
advection with $v_{jet}(z)$
z
shock
shock
$v_{jet}(z)$
v_0
$v_{jet}(z)$
v_0
z
z

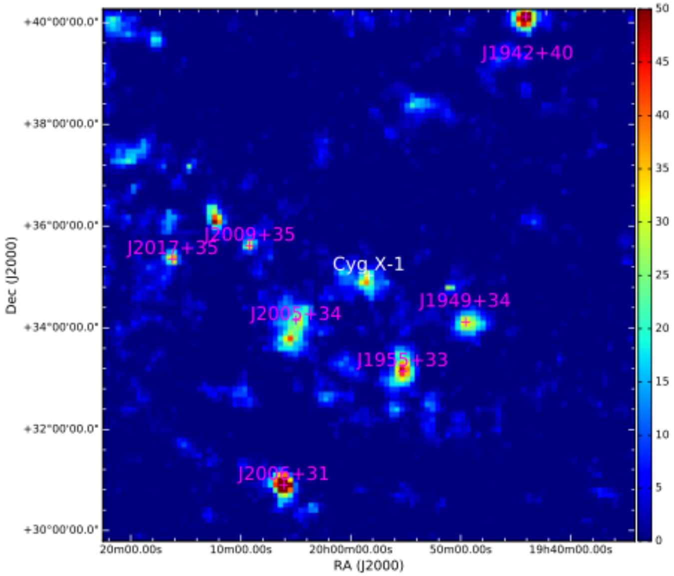
Distance: ~1.9 kpc
Location: 19h58m +35d12m
Central Object: black hole with 7-13 solar masses
Companion Star: O-type
Period: 5.6d

CYG X1



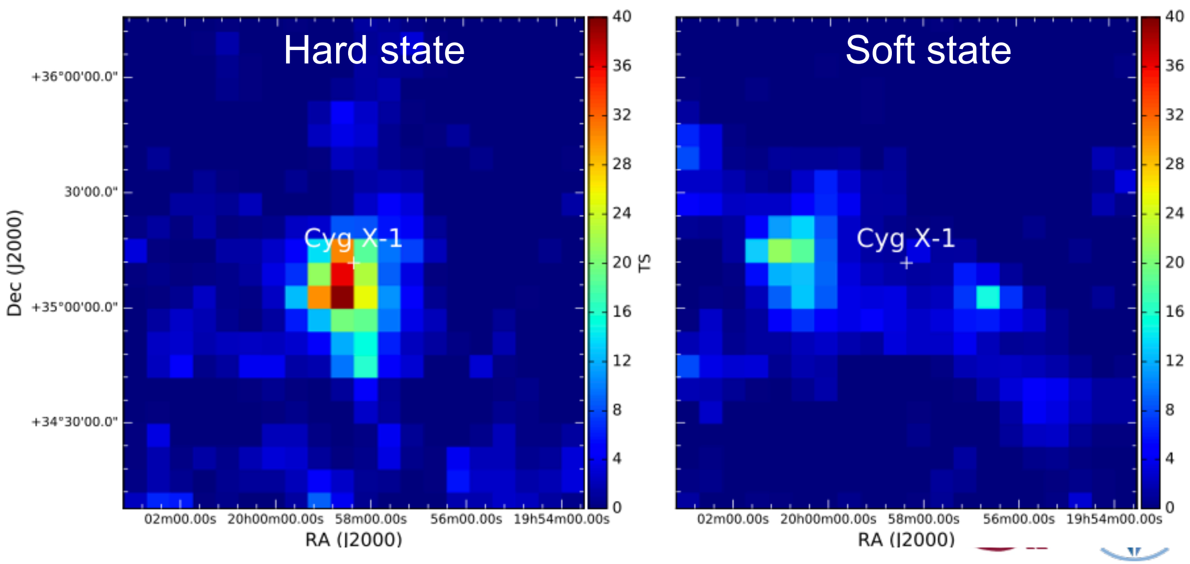


CYG X1



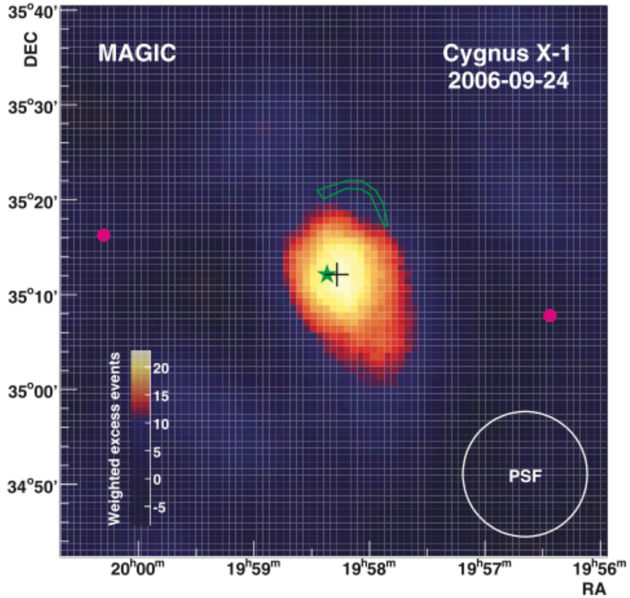
LAT emission detected during the hard state
Evidence of orbital variability implies contribution from external photons (from the companion)

Zanin 16

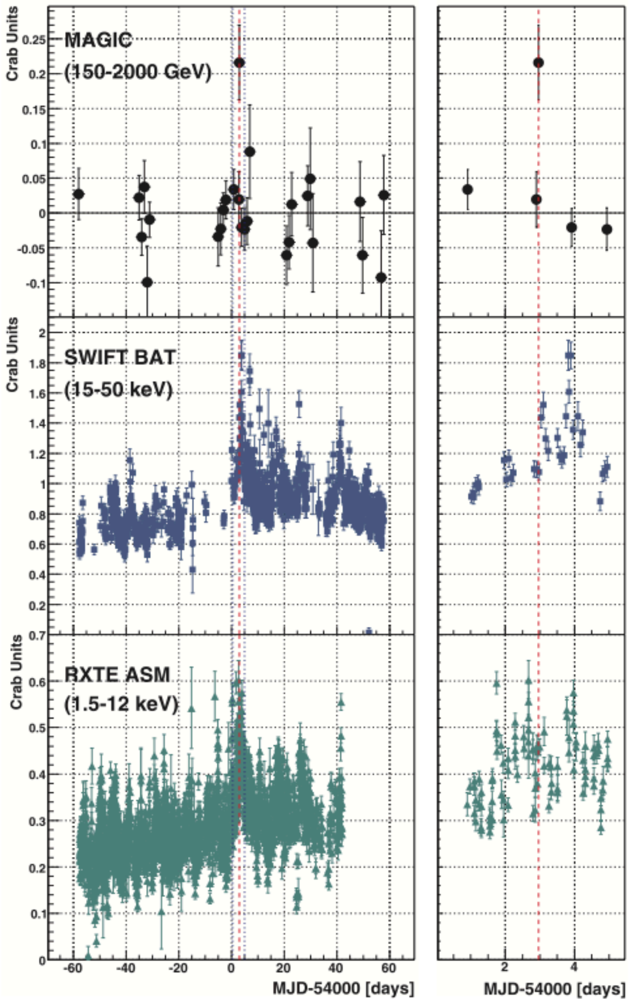


CYG X1

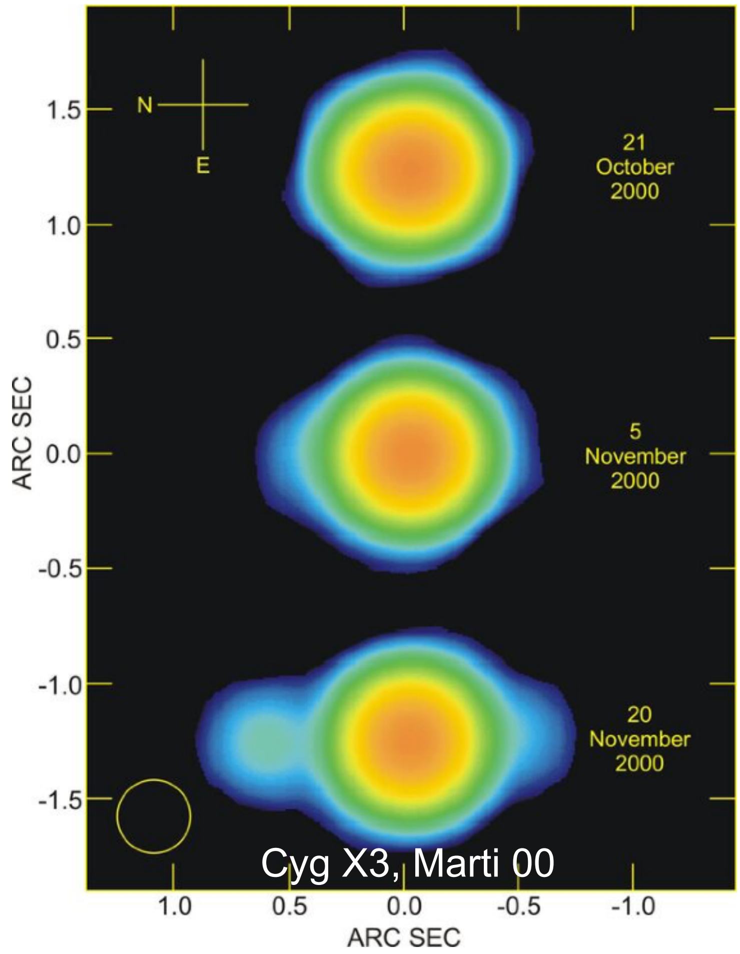
Evidence (3.2σ) for flaring activity in MAGIC data



MAGIC 06



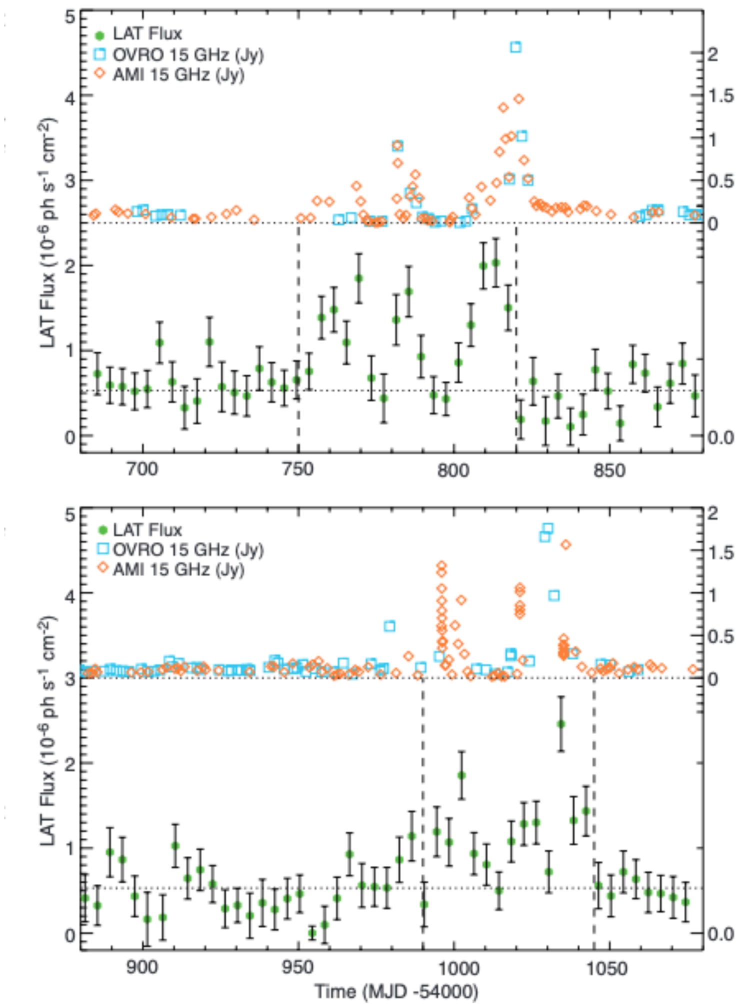
CYG X3



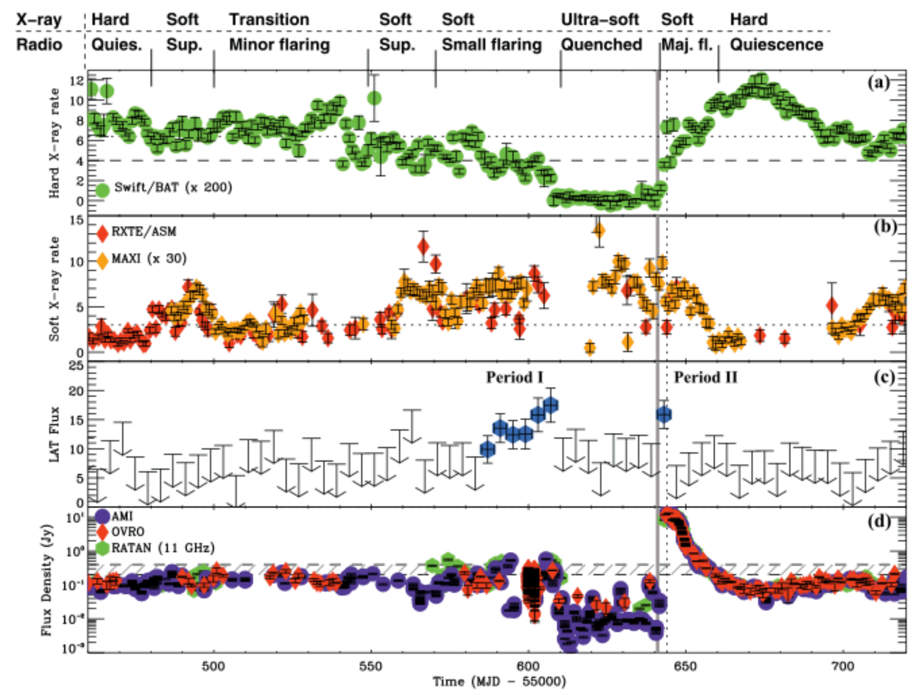
Distance: ~7.4 kpc
Location: 20h32m +40d57m
Central Object: compact object with 1.3-4.5 solar masses
Companion Star: WR-type
Period: 4.8h

CYG X3

GeV emission associated with giant radio flares



Fermi 09



Corbel 12

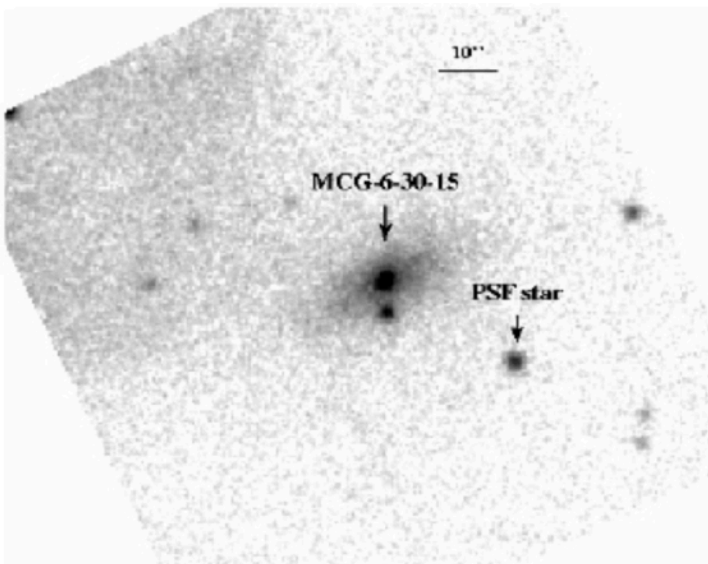
Matteo Cerruti

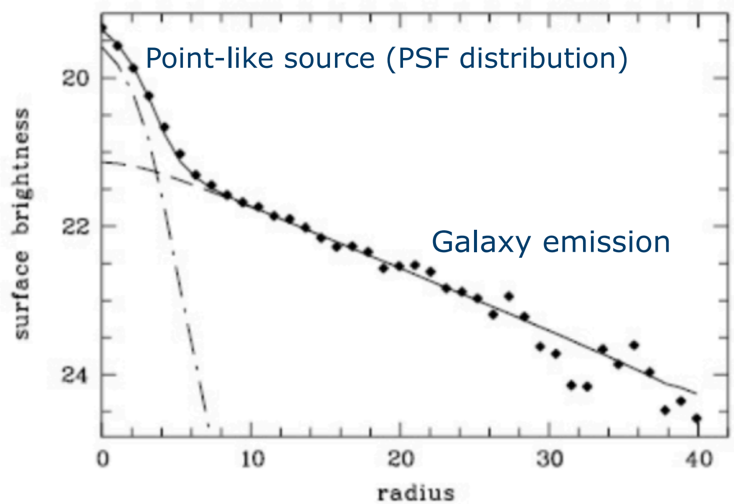
ACTIVE GALACTIC NUCLEI

ACTIVE GALACTIC NUCLEI

Point-like source of photons in galaxy center

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



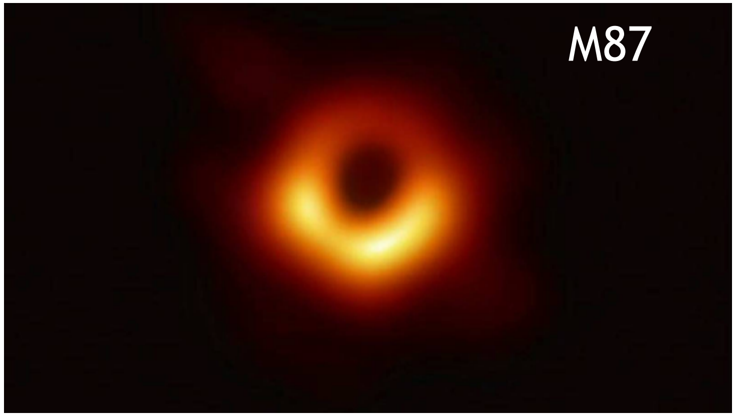


Arevalo et al. 2005

ACTIVE GALACTIC NUCLEI

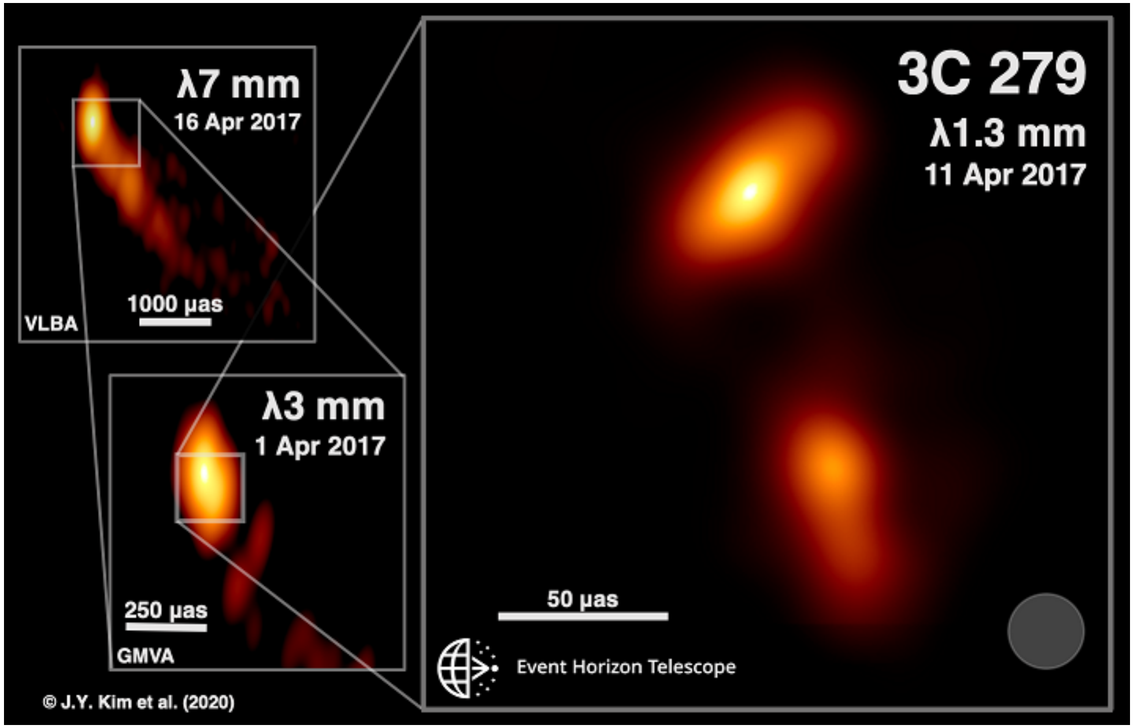
Current understanding

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



Event Horizon Telescope 2019

First image of a black-hole shadow

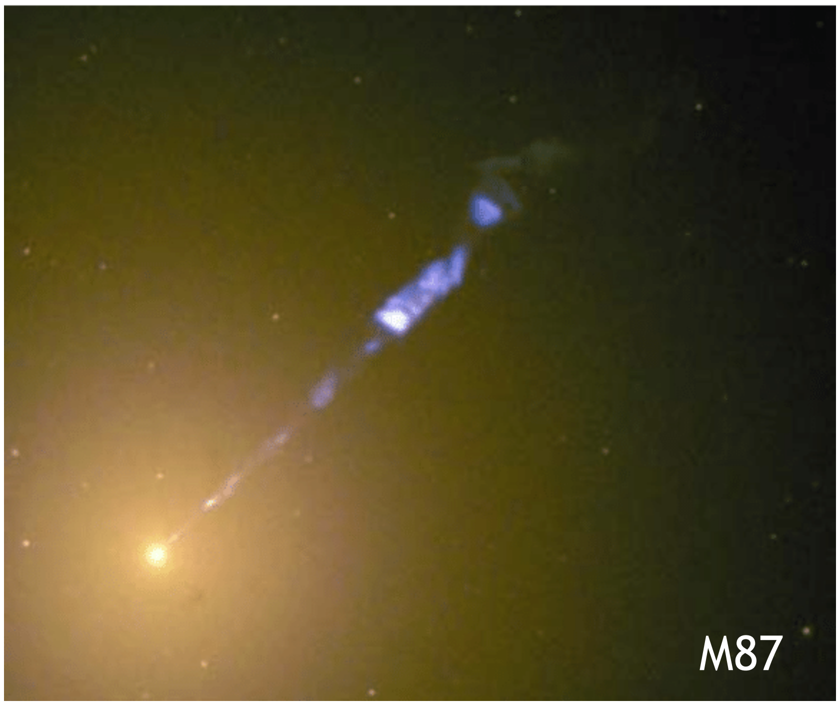


Event Horizon Telescope 2020

Jet launching

ACTIVE GALACTIC NUCLEI

Radio-loud / radio-quiet dichotomy

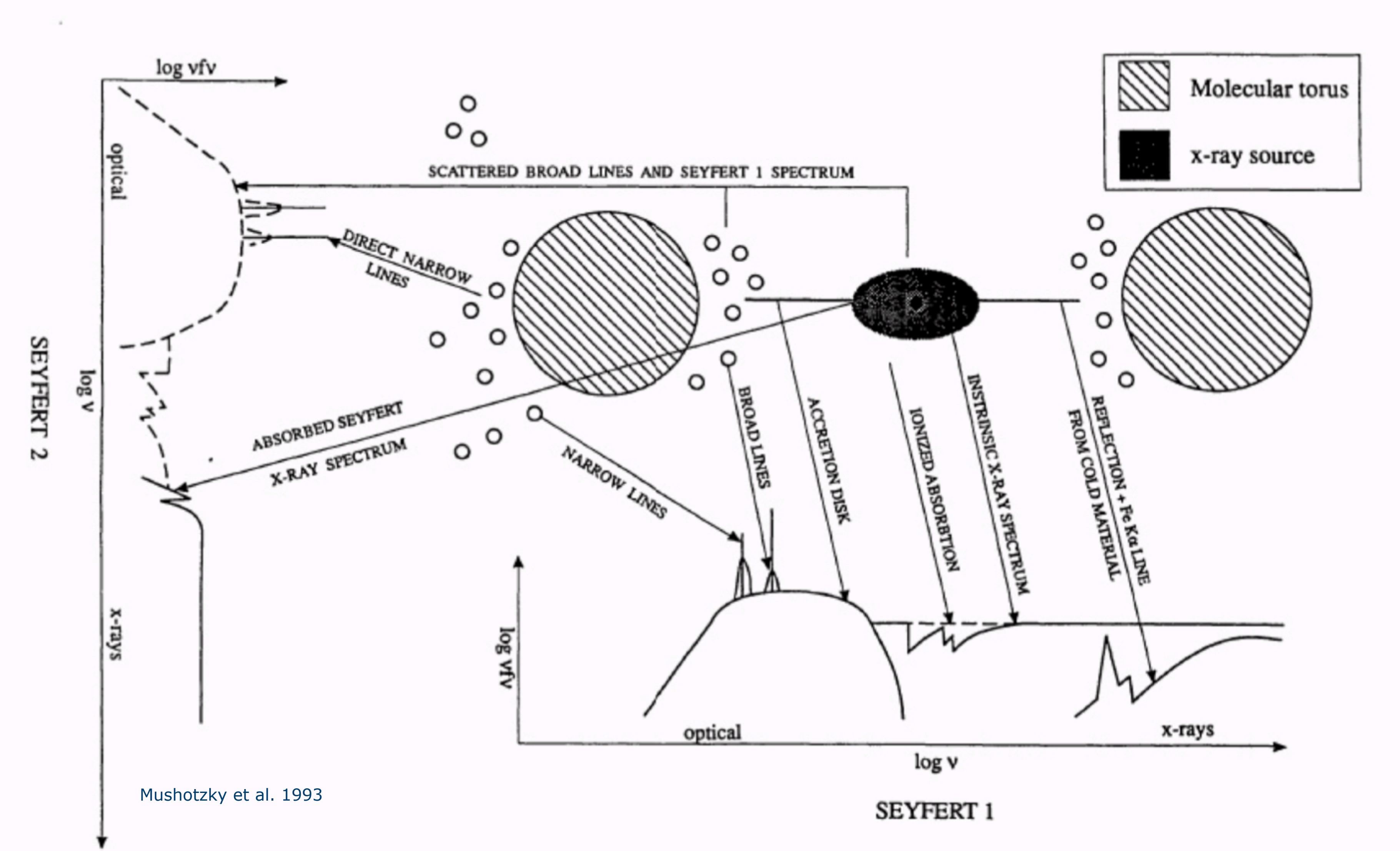


Radio-galaxy
with its relativistic jet

Seyfert galaxy

ACTIVE GALACTIC NUCLEI

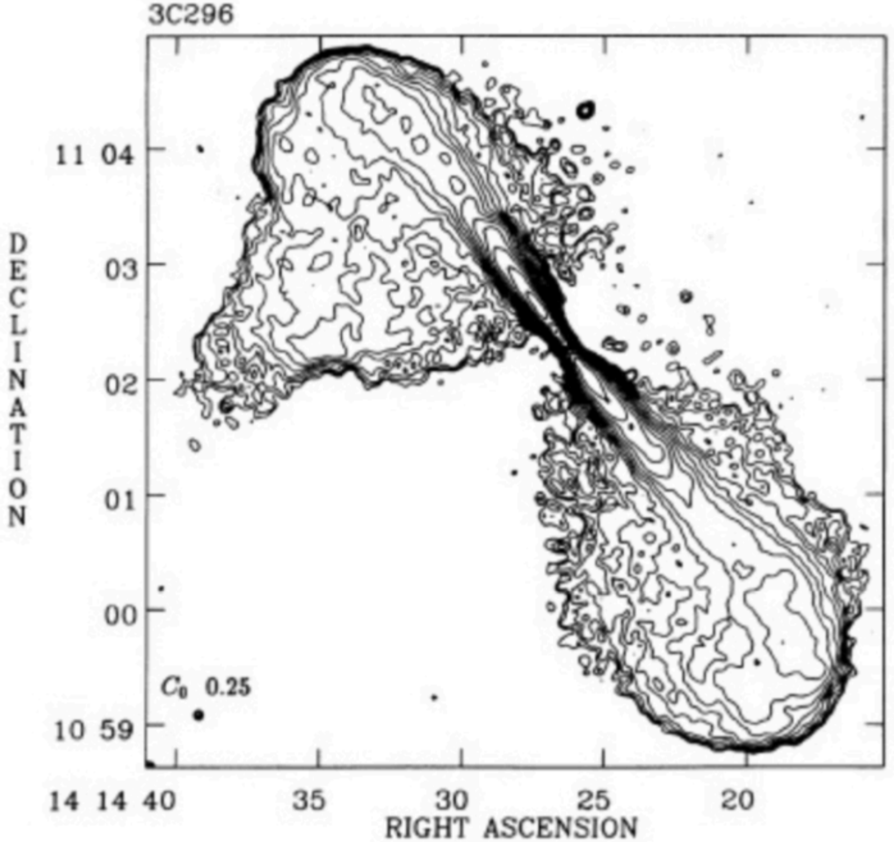
Broad-band emission from Seyfert galaxies

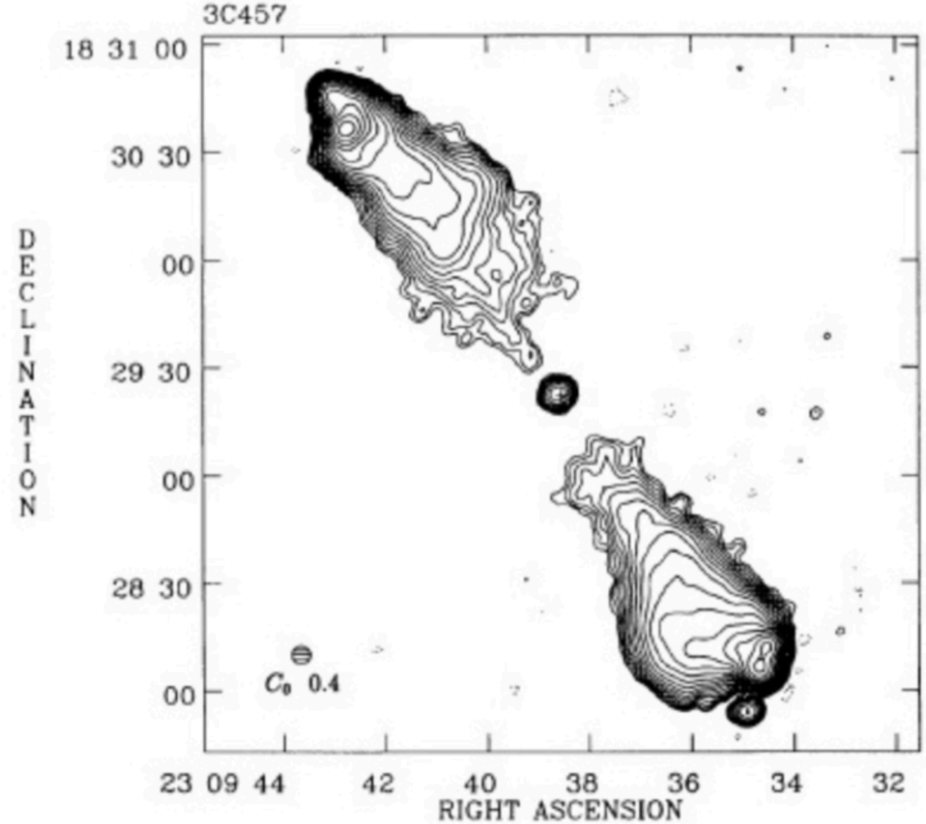


Mushotzky et al. 1993

ACTIVE GALACTIC NUCLEI

Radio-loud dichotomy: Fanaroff-Riley I and FRII

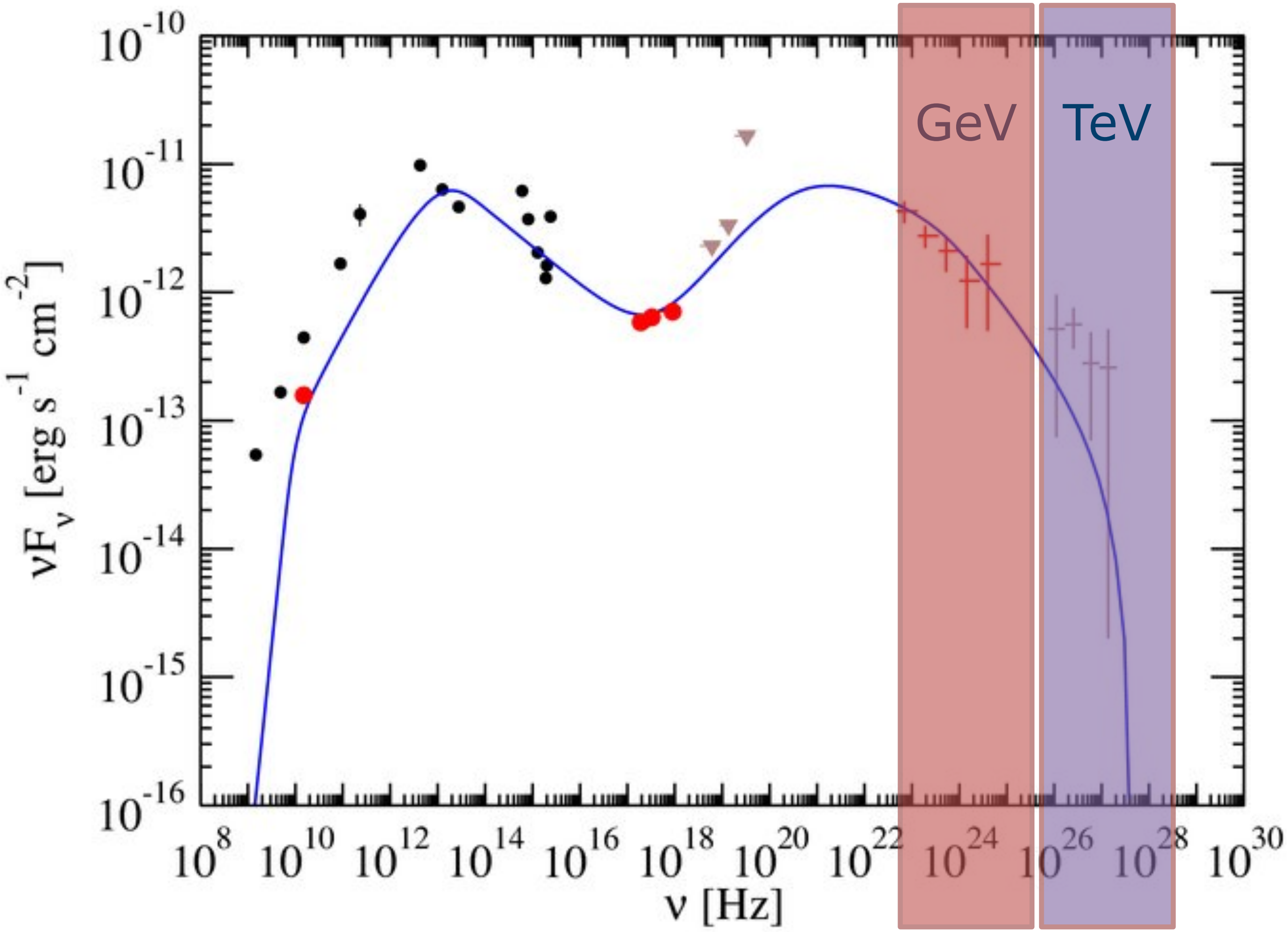




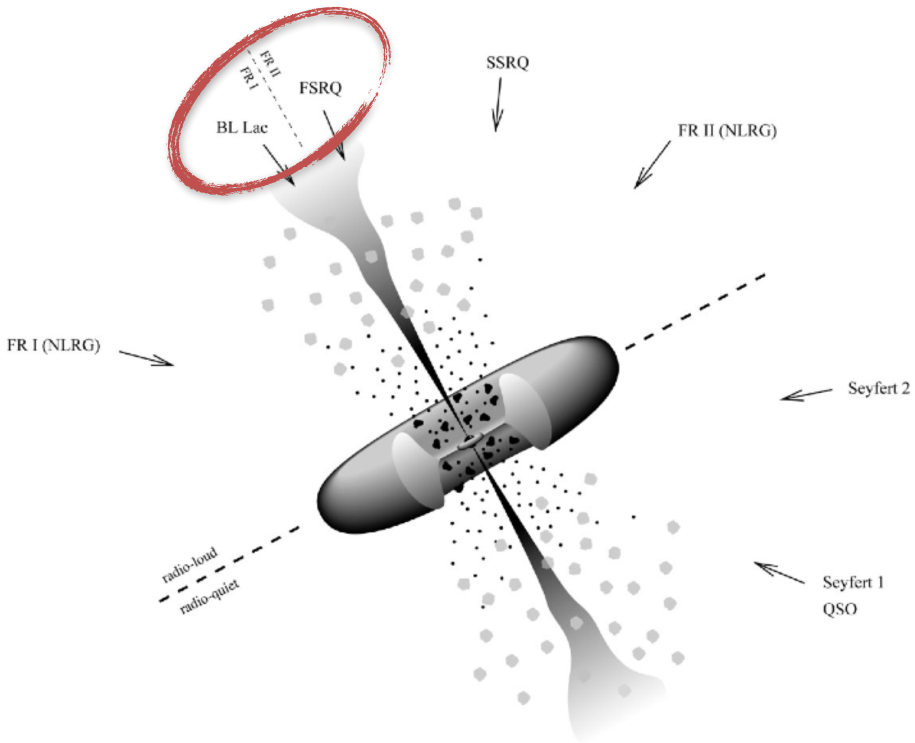
Leahy & Perley 1991

ACTIVE GALACTIC NUCLEI

Radio-galaxies SED



ACTIVE GALACTIC NUCLEI



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

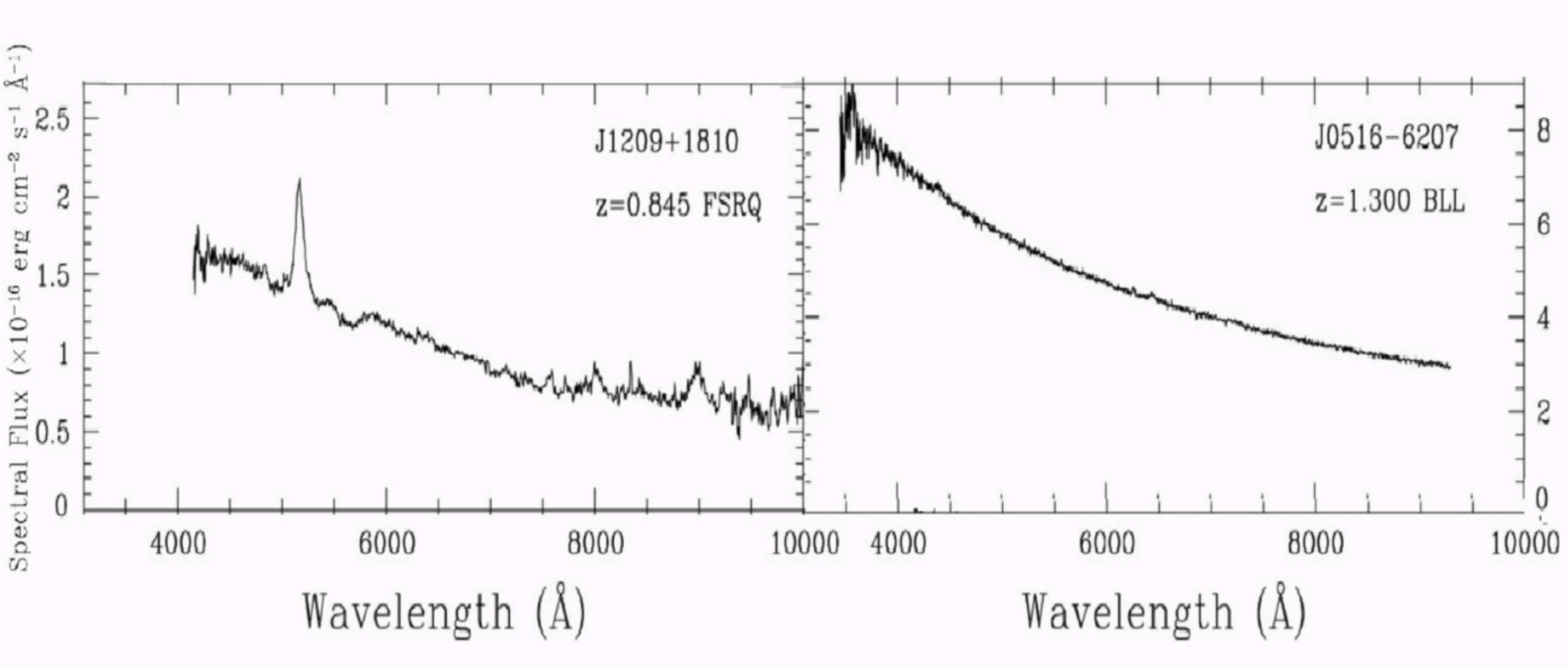
emission from the jet outshines all other AGN components (disk, BLR, X-ray corona, …)

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

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

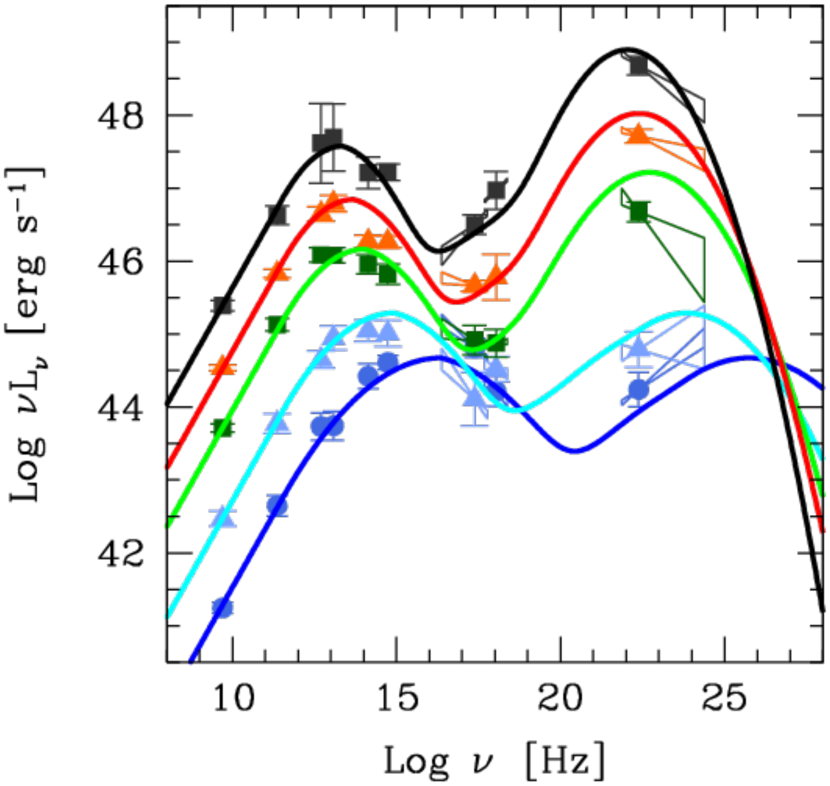
BL Lacertae objects : optical spectrum is featureless (lines $\mathrm{EW} < 5\mathring{A}$)

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

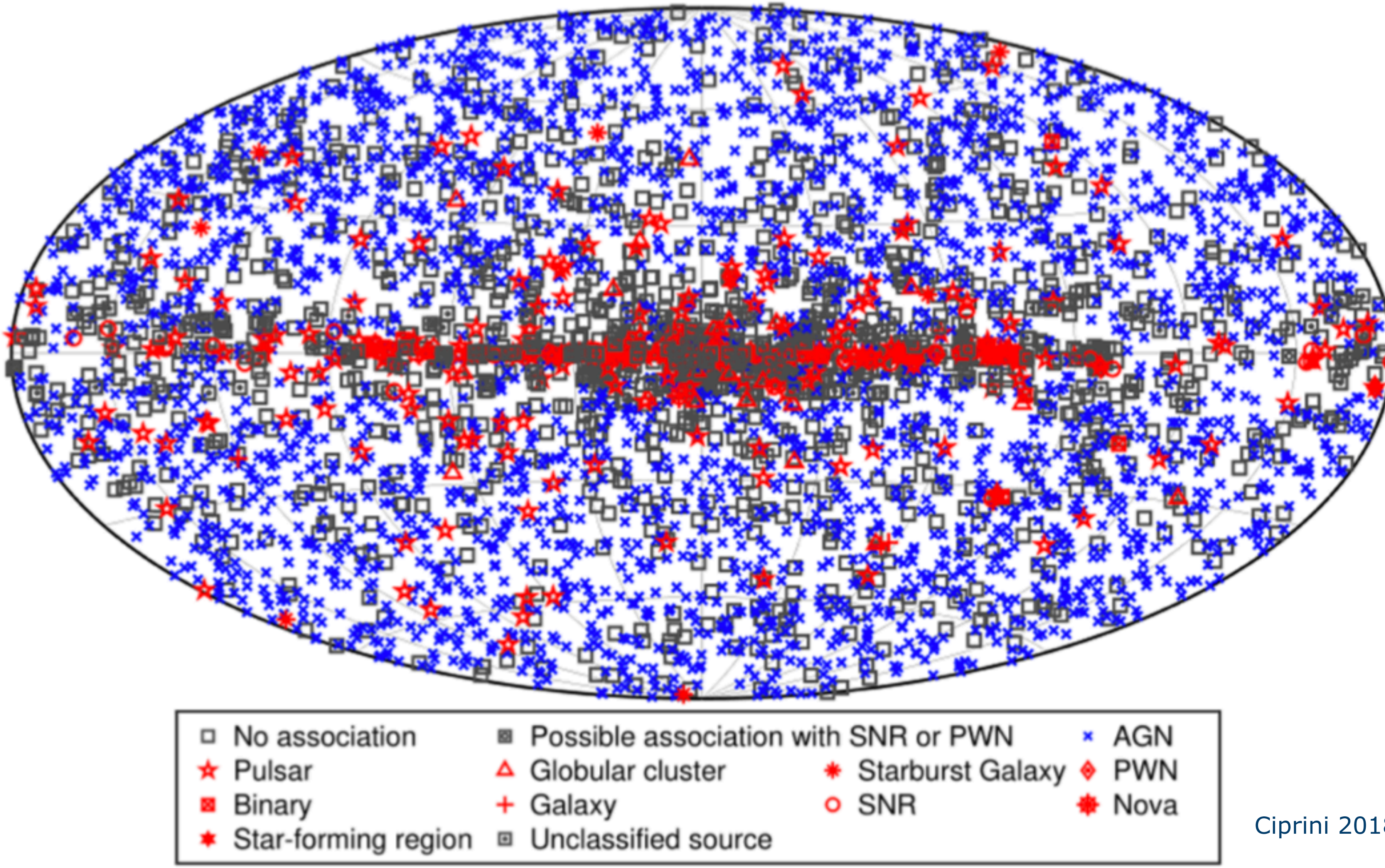
BL Lac objects are classified in:

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

- peak in optical: intermediate (IBLs)

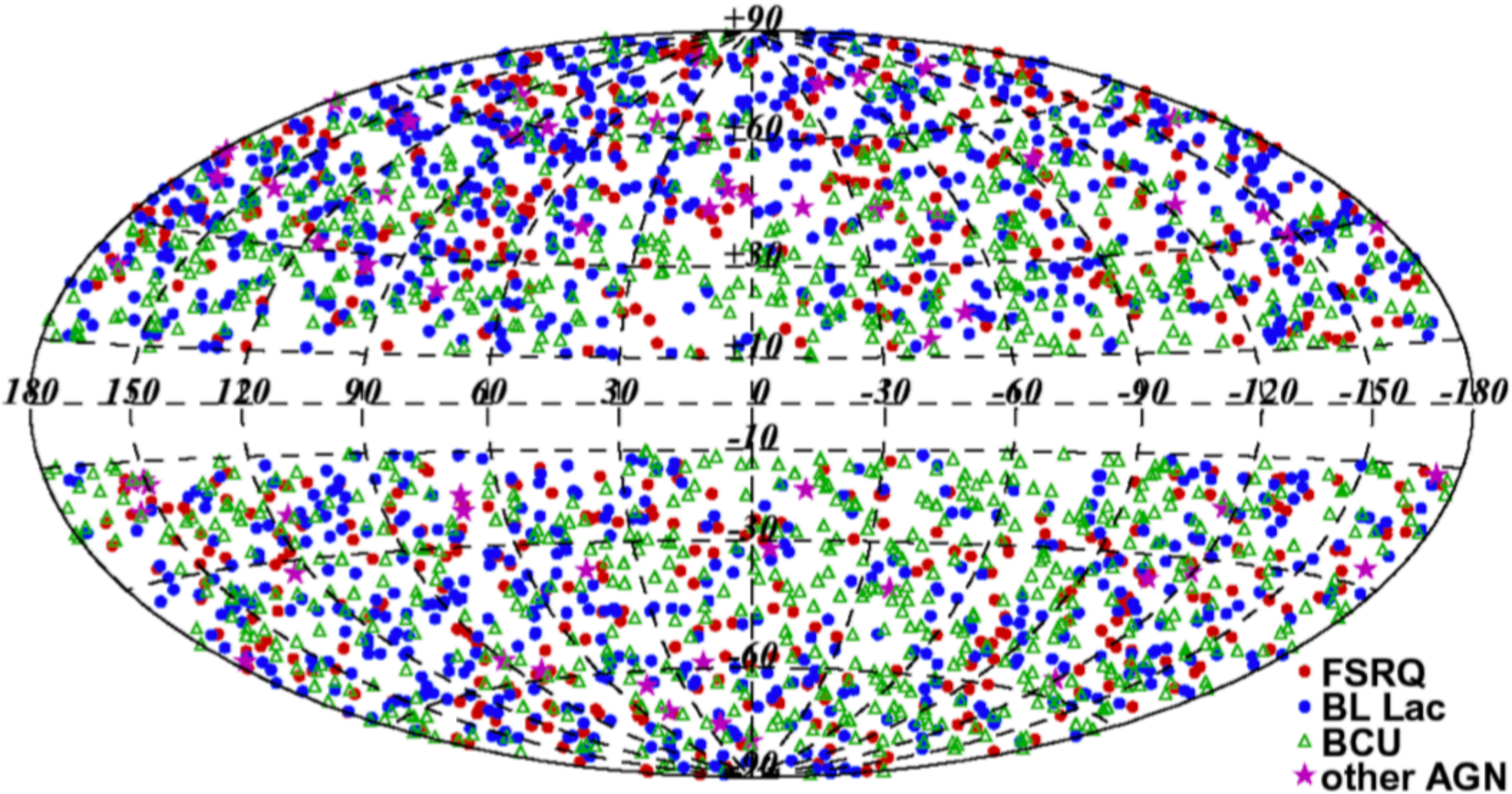
- peak in UV / X: high (HBLs)

THE GeV EXTRAGALACTIC SKY



Ciprini 2018

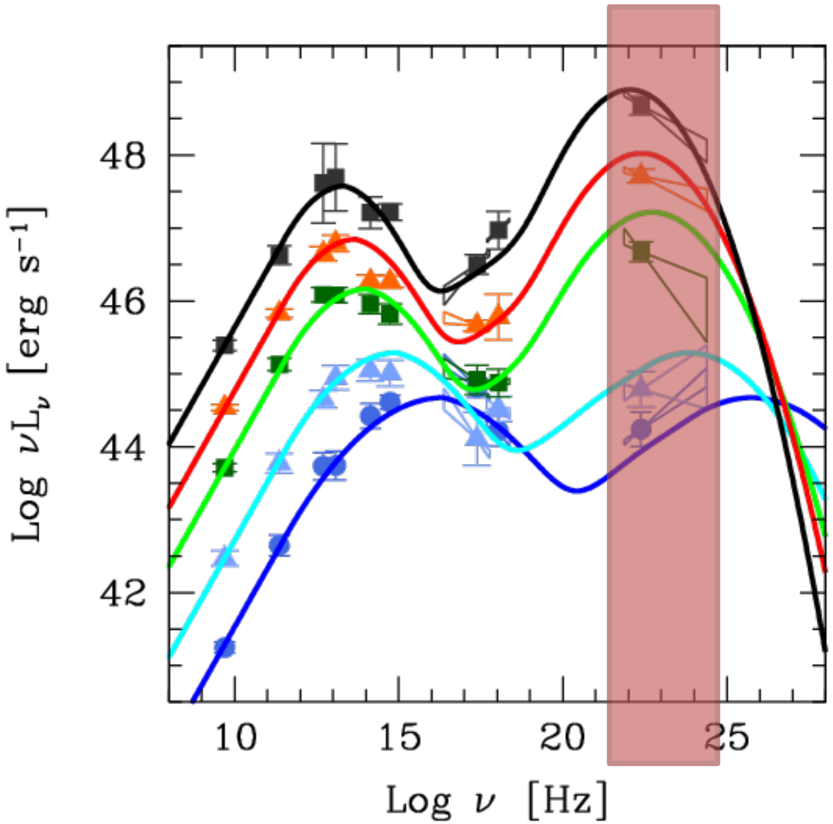
THE GeV EXTRAGALACTIC SKY



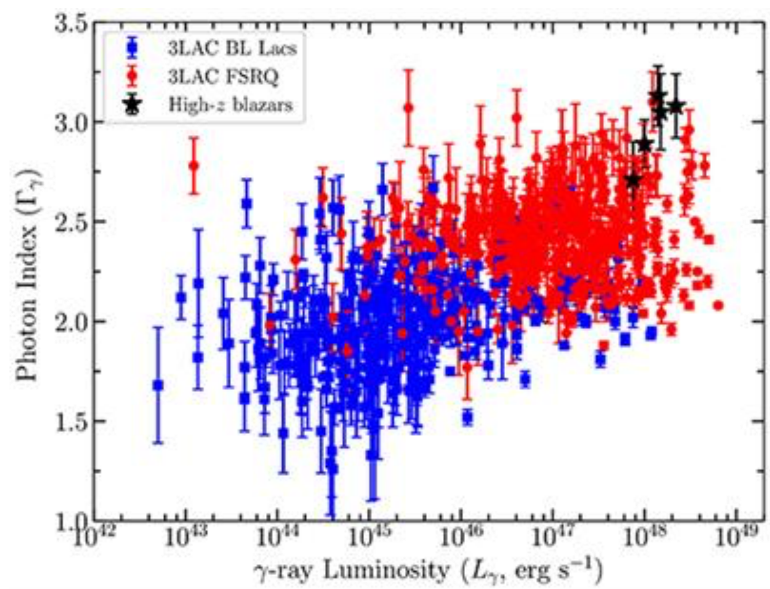
Ciprini 2018

THE GeV EXTRAGALACTIC SKY

Population of GeV AGNs

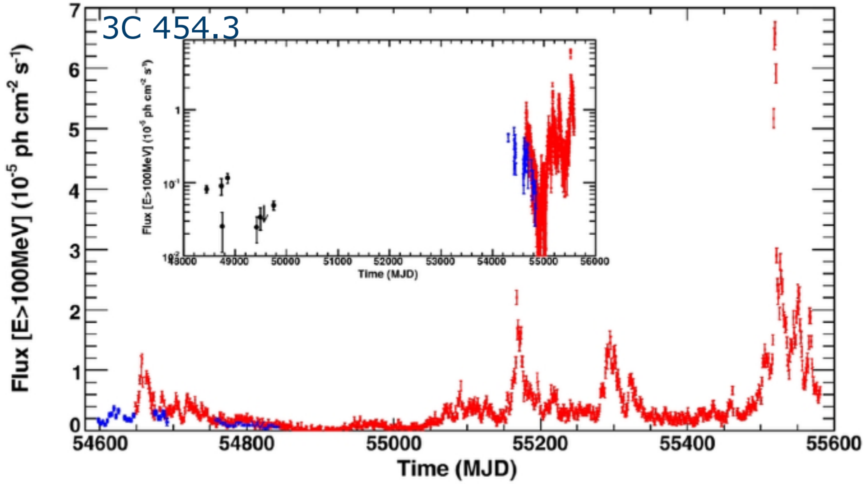


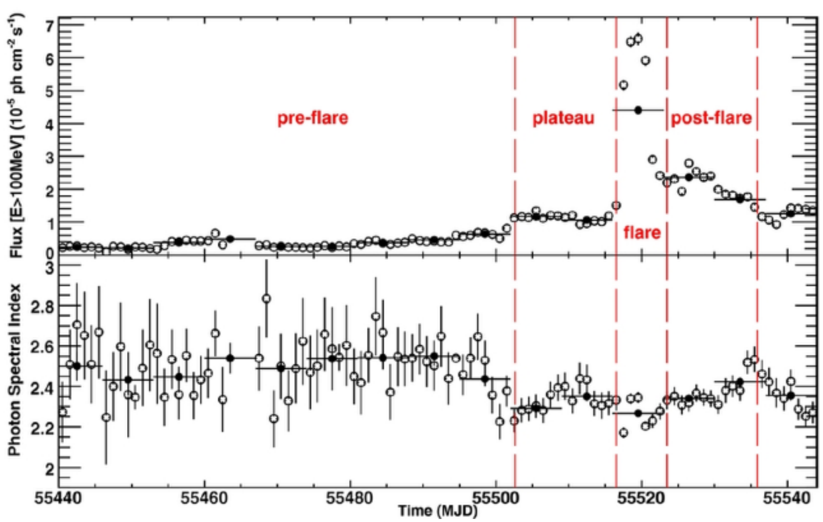
Dominated by high-luminosity FSRQs and LBLs



BLAZAR FLARES

Blazars are extremely variable

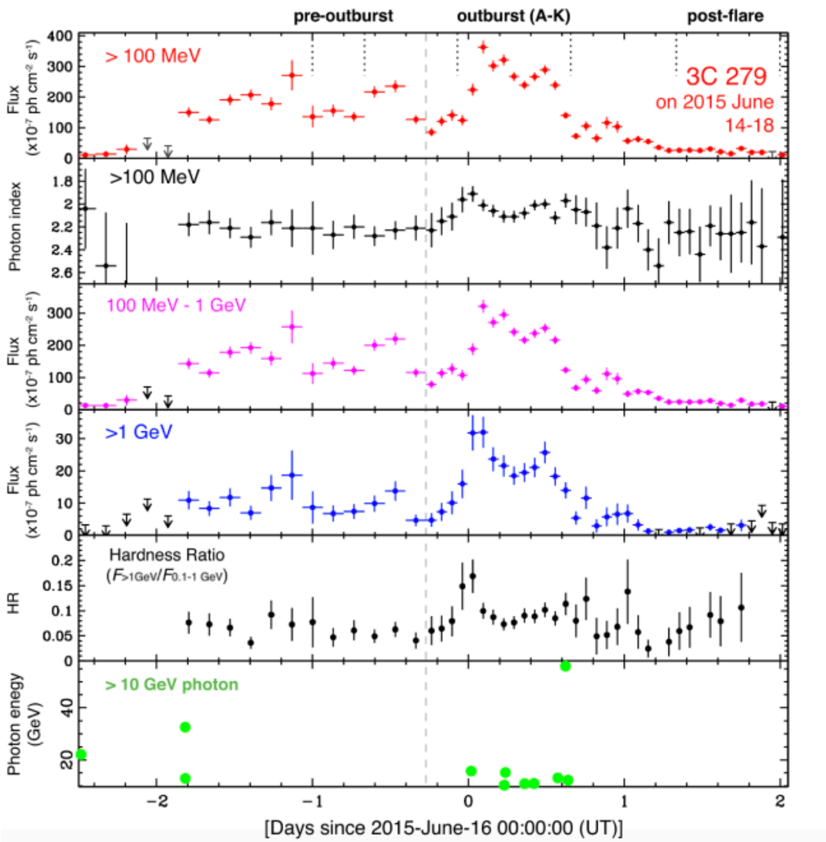


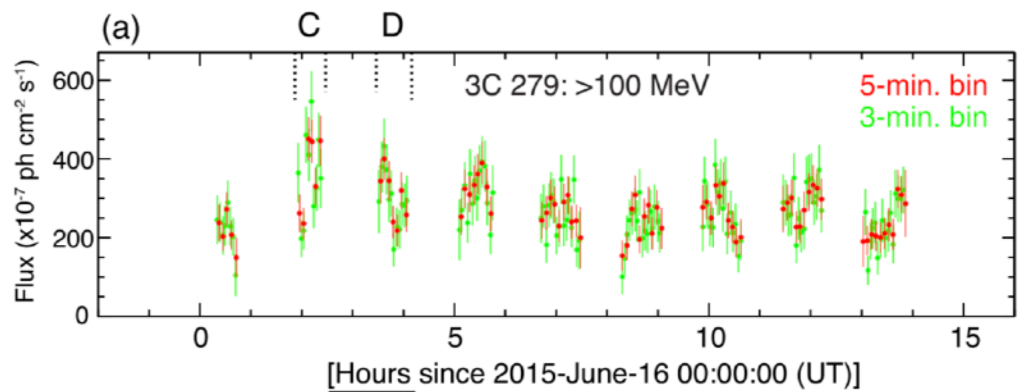


Abdo et al. 2011

BLAZAR FLARES

Rapid flares





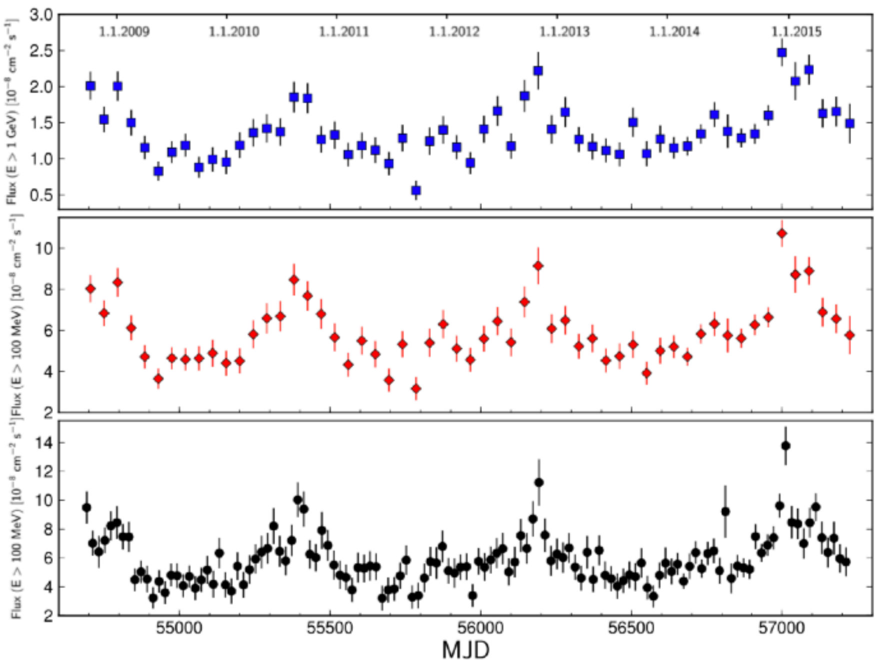
Variability can be used to constrain the size of the emitting region thanks to the causality argument

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

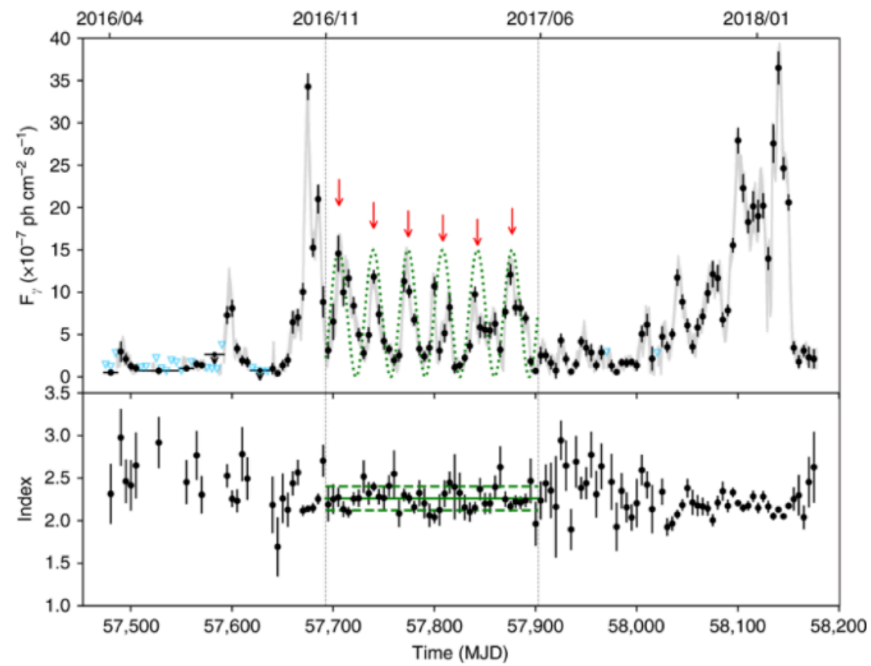
Ackermann et al. 2016

BLAZAR FLARES

Periodicity and Quasi-Periodic-Oscillations



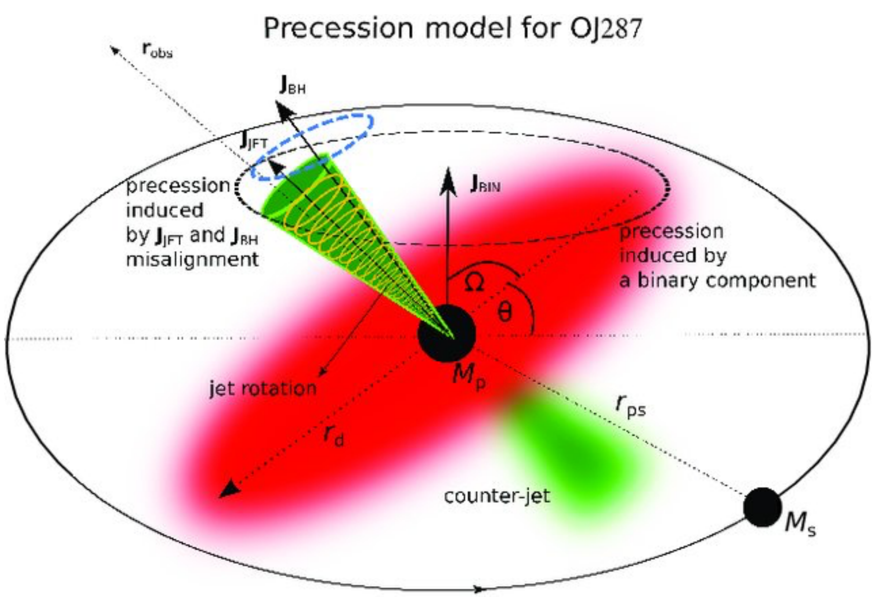
Ackermann et al. 2015



Zhou et al. 2018

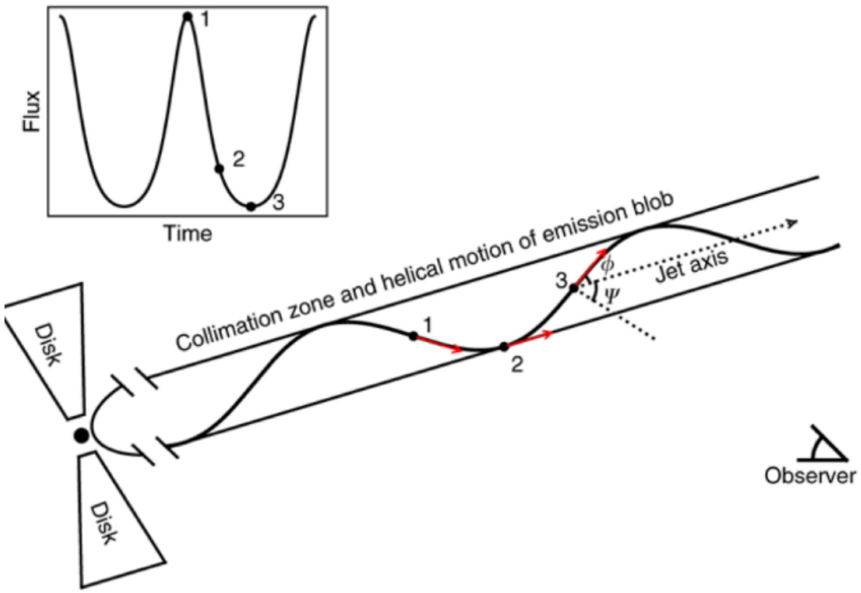
BLAZAR FLARES

Super-massive black-hole Binary



Britzen et al. 2017

Helical structure of the jet

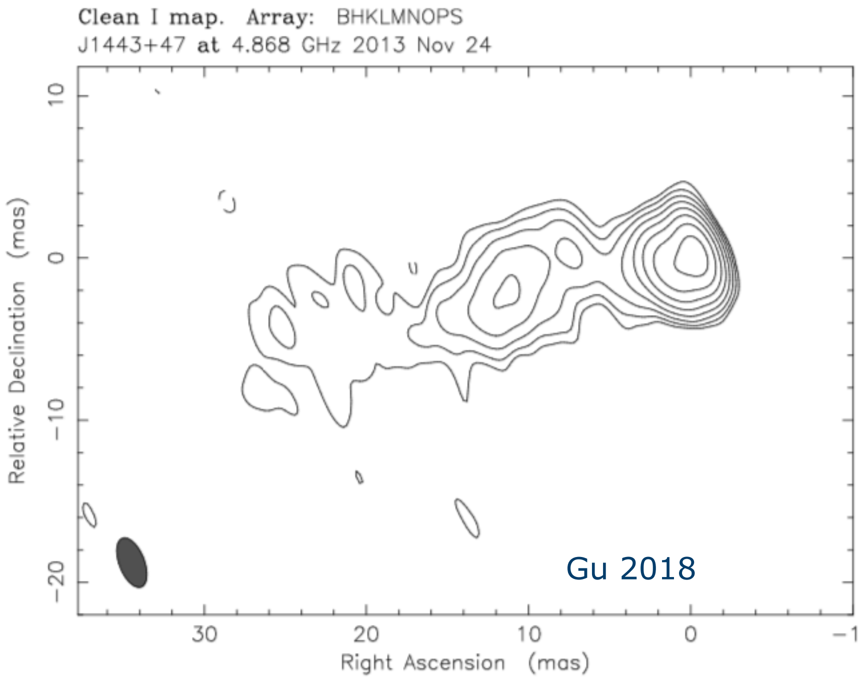


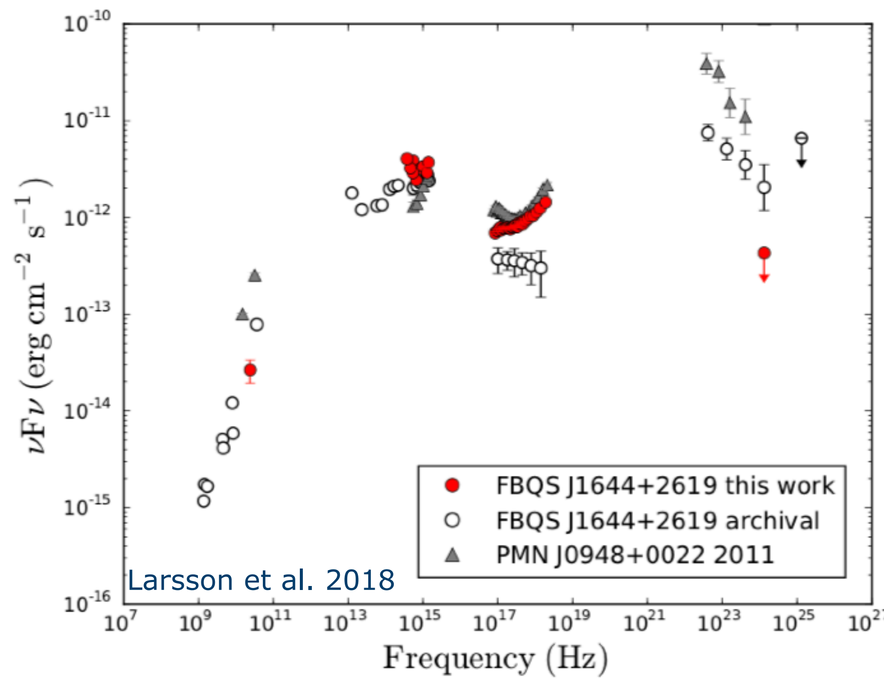
Zhou et al. 2018

NARROW LINE SEYFERT 1

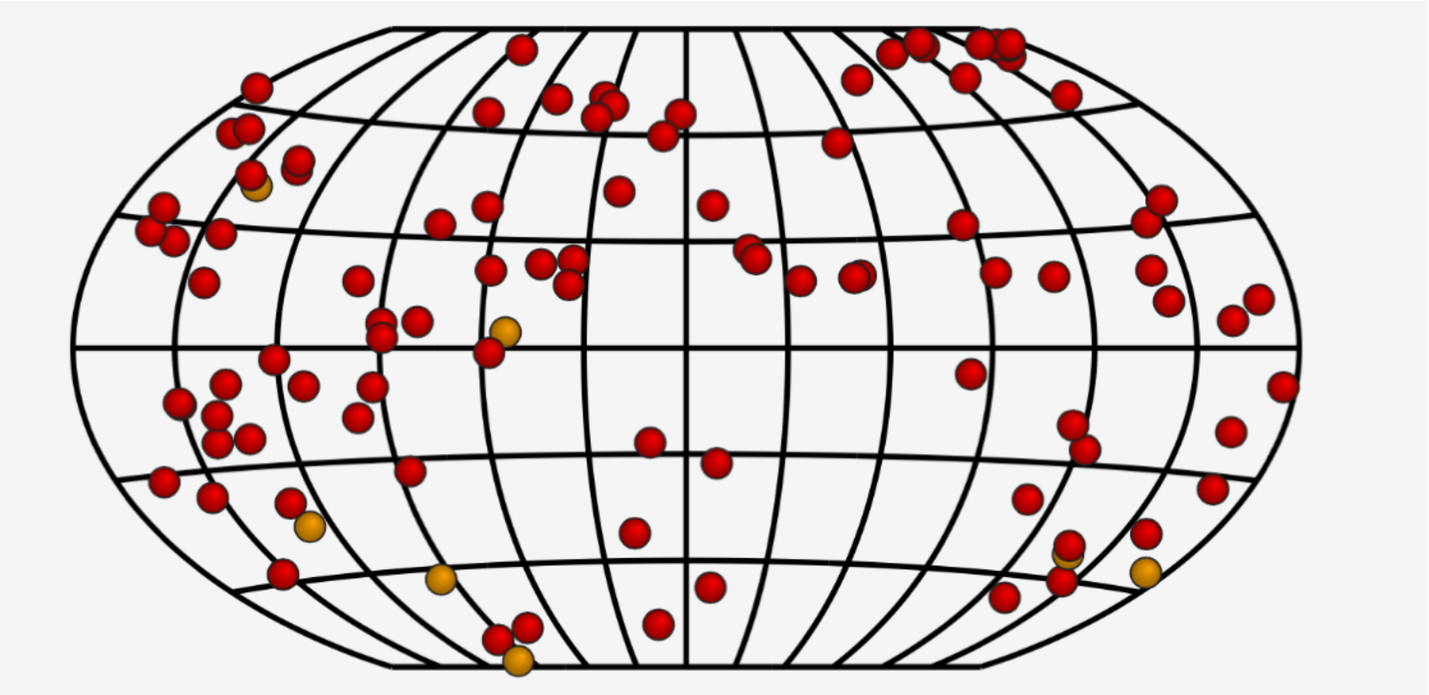
Narrow-line Seyfert 1 galaxies

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



http://tevcat2.uchicago.edu

98 extragalactic sources: **5 GRB**

2 starburst galaxies

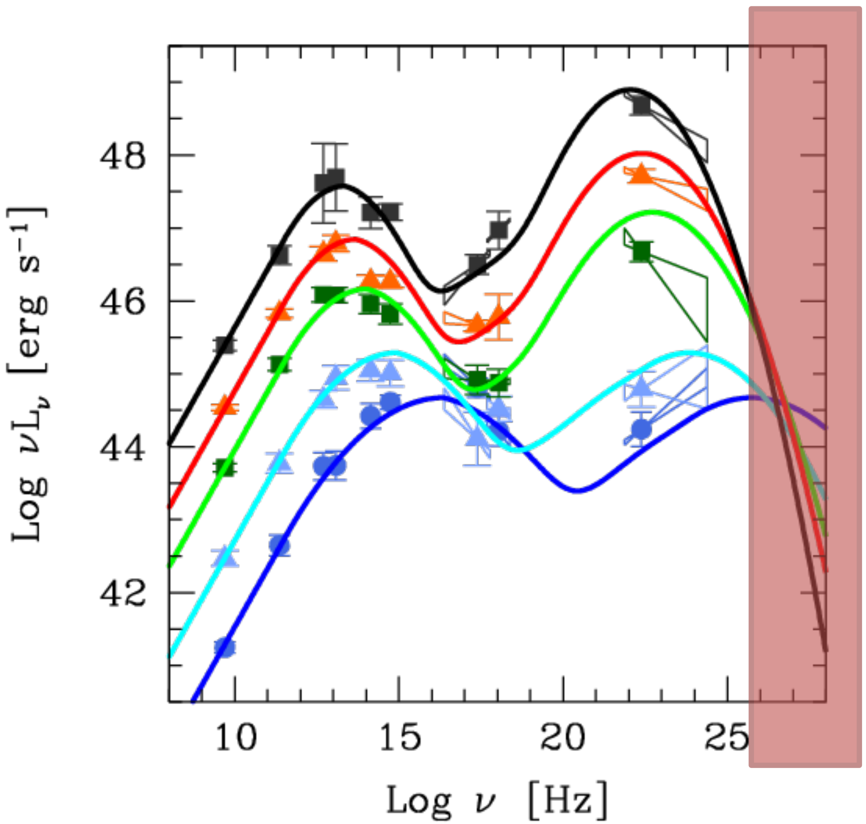
1 low-luminosity AGN

4 radio galaxies

86 blazars

THE TeV EXTRAGALACTIC SKY

Population of TeV AGNs

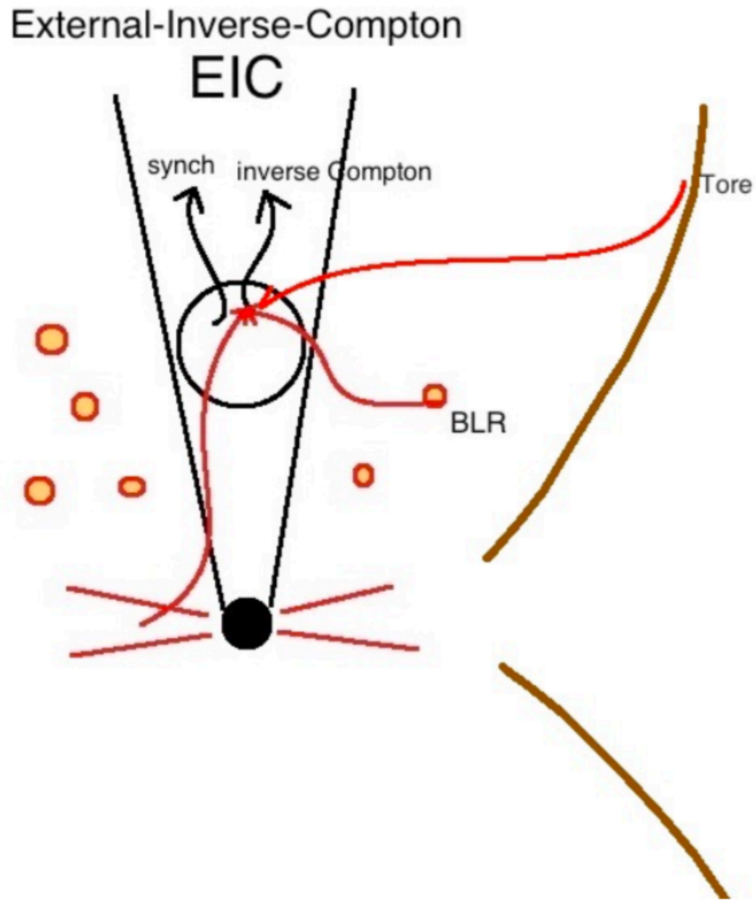


Dominated by HBLs:

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

Matteo Cerruti

FSRQs and LBLs



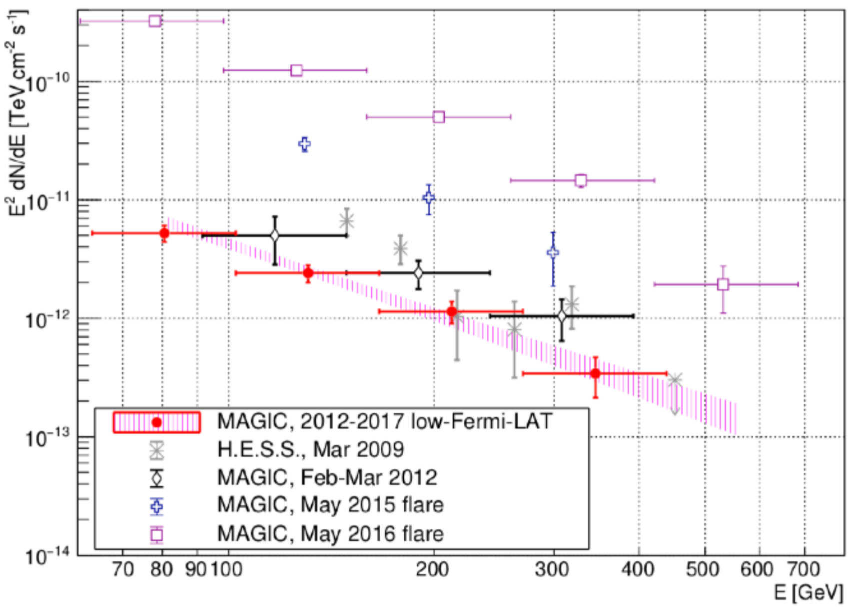
Origin of γ-ray emission:
External-Inverse-Compton

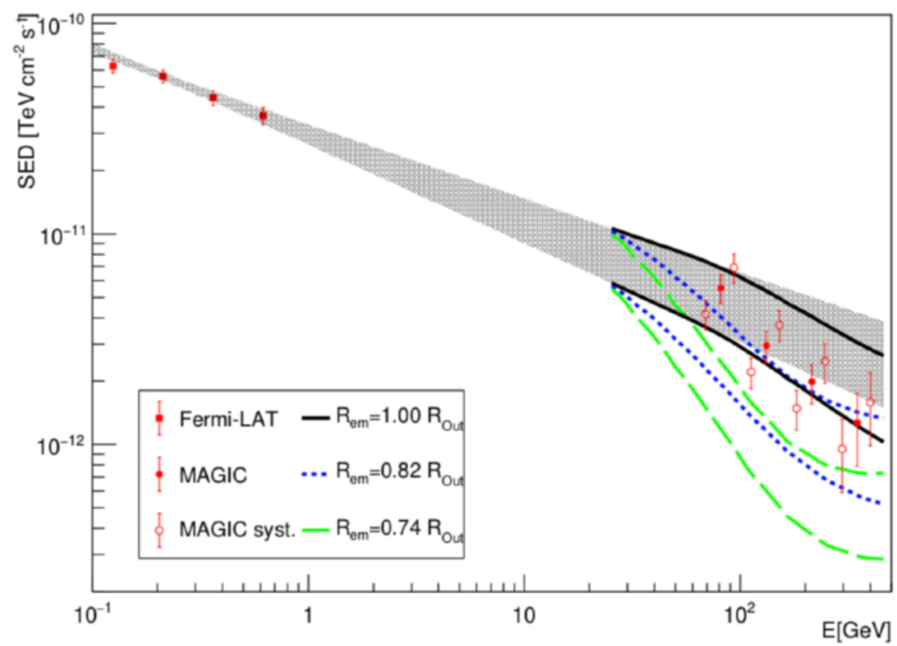
The external field also acts as an absorber via γ-γ pair-production

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!





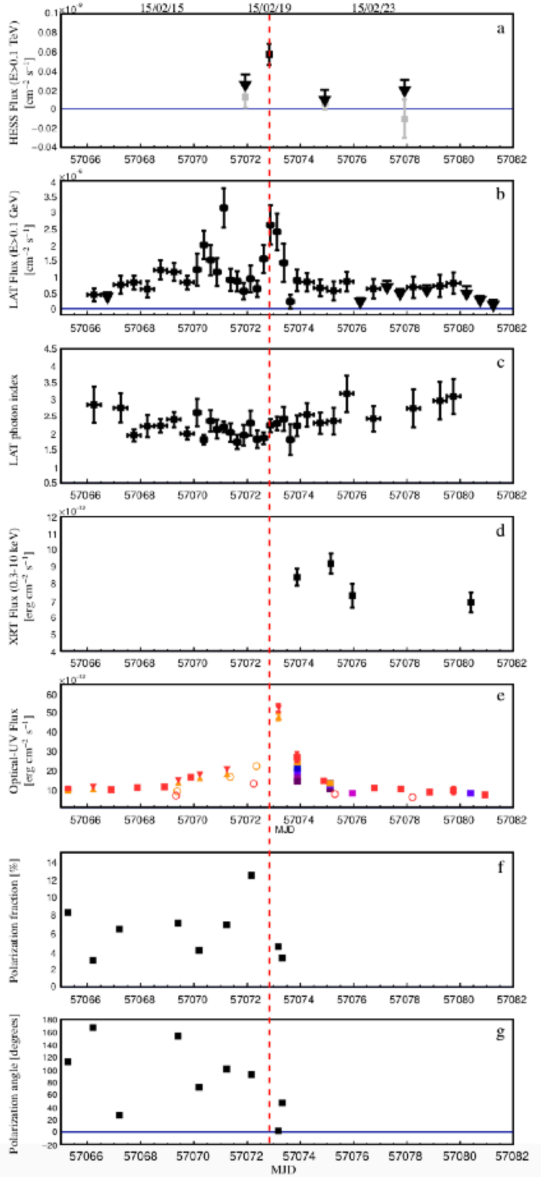
The emitting region HAS to be at
$r \geq r_{BLR}$ even during quiescence

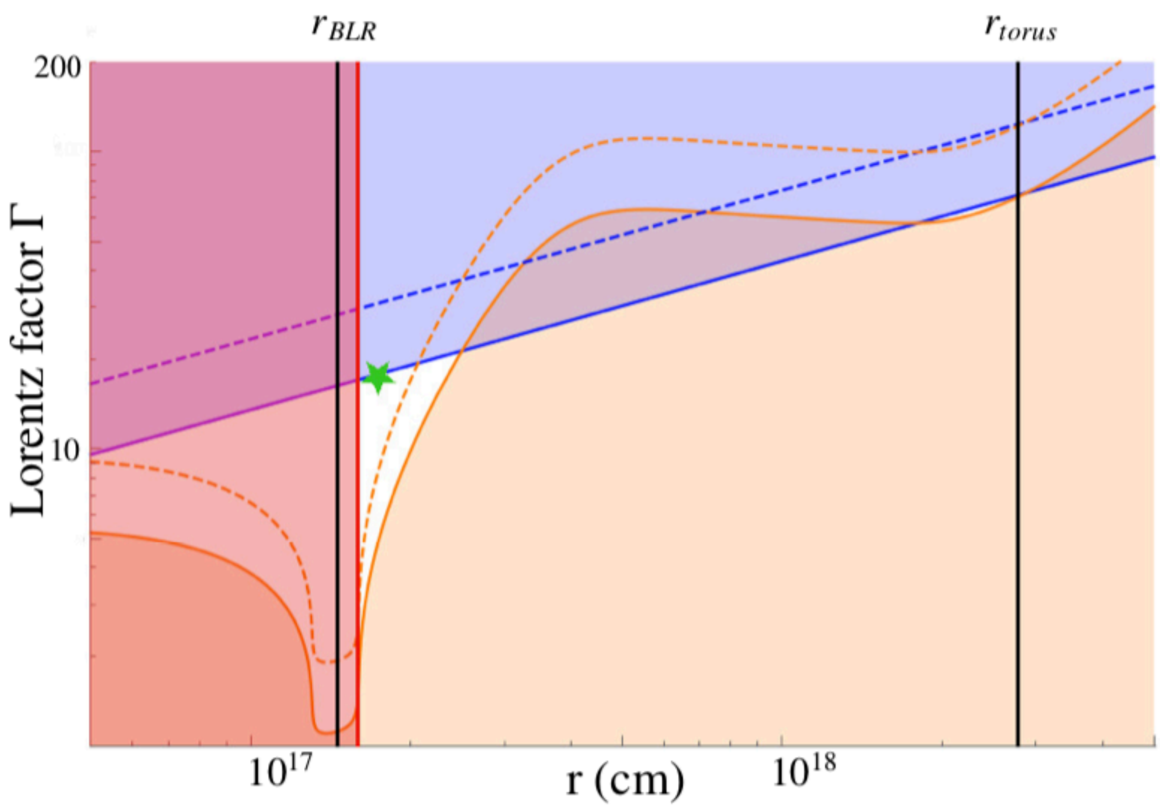
[MAGIC Collaboration et al. 2018](#)

FSRQs and LBLs

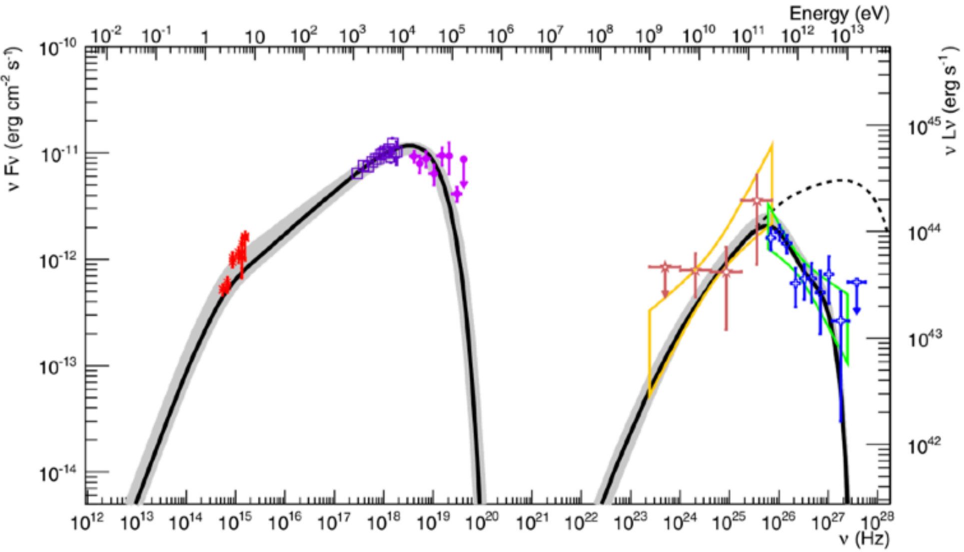
Nearest VHE FSRQ, at z=0.189

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

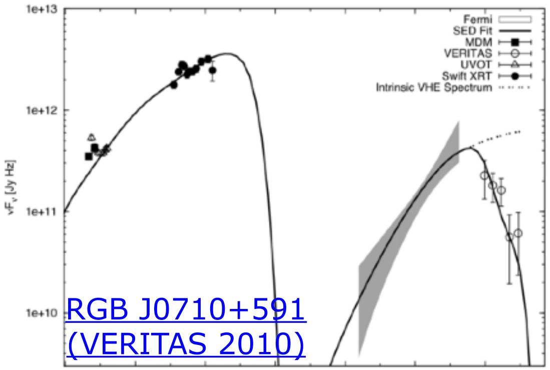
Archetypal EHBL: 1ES0229+200

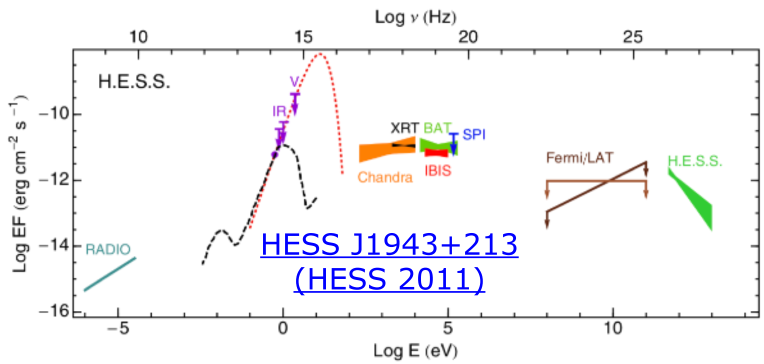
But not all EHBLs have a hard TeV spectrum! The population seems more heterogeneous

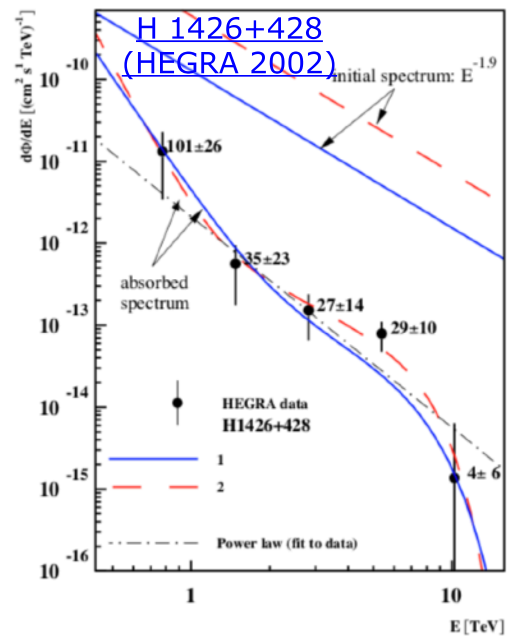
(Foffano et al. 2019

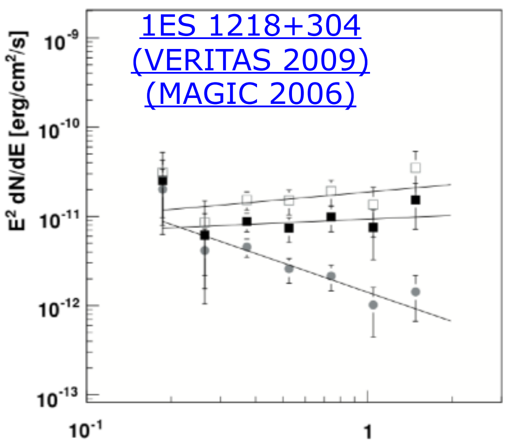
Costamante 2019)

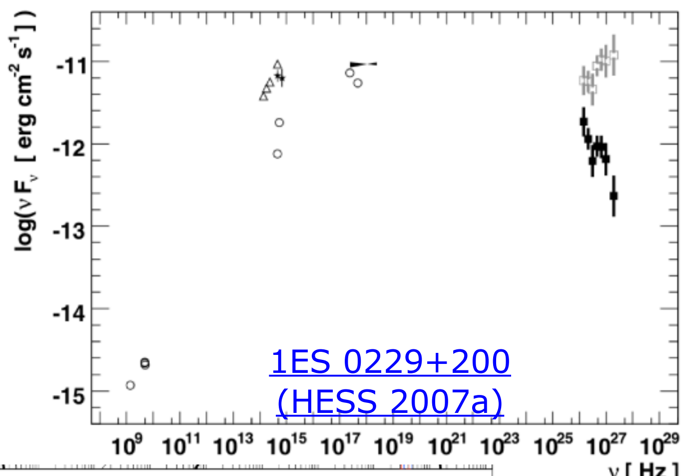
EXTREME BLAZARS

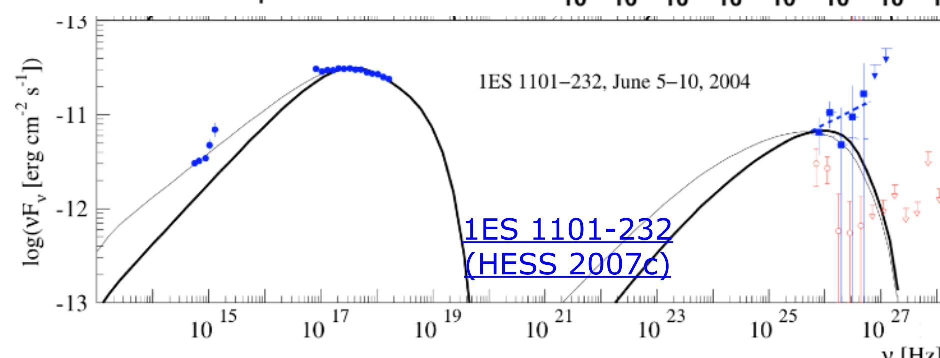


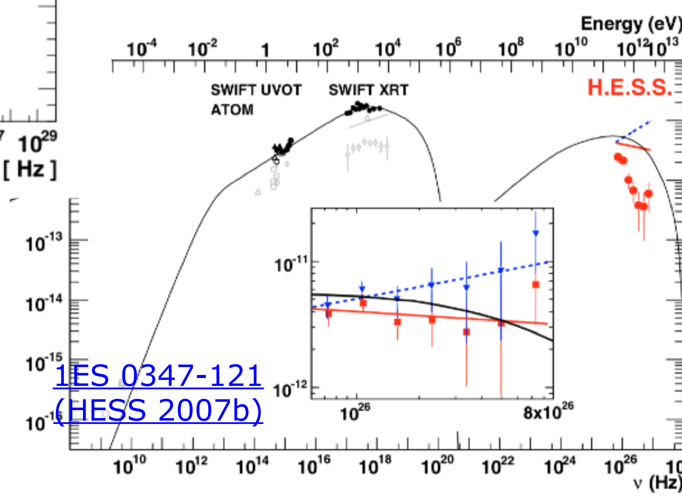






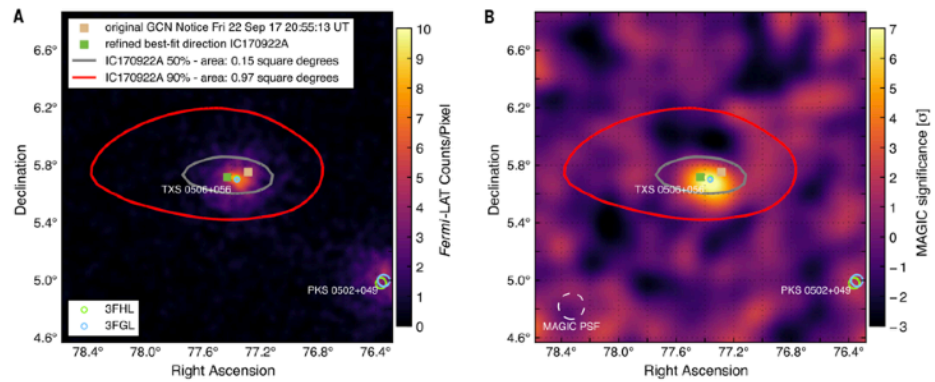


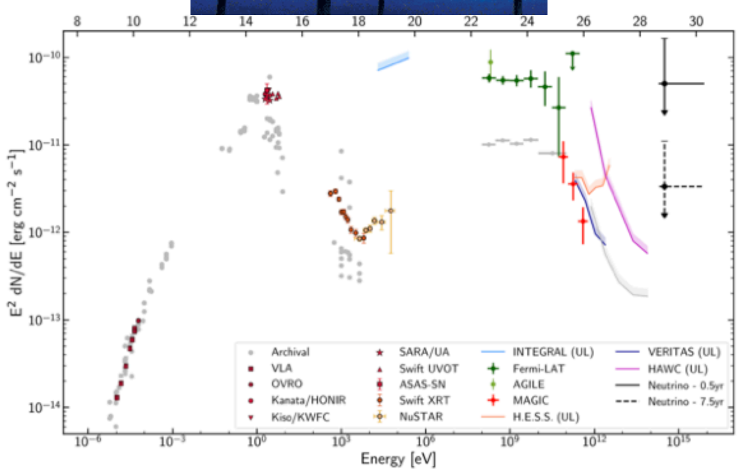


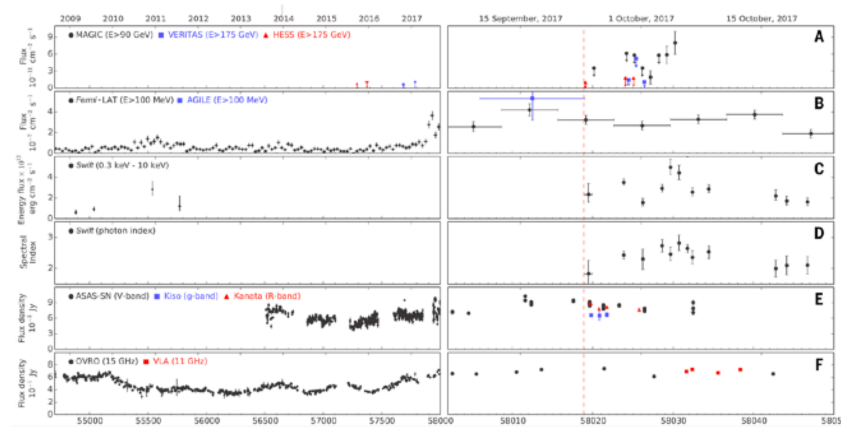


IceCube-170922A / TXS 0506+056

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

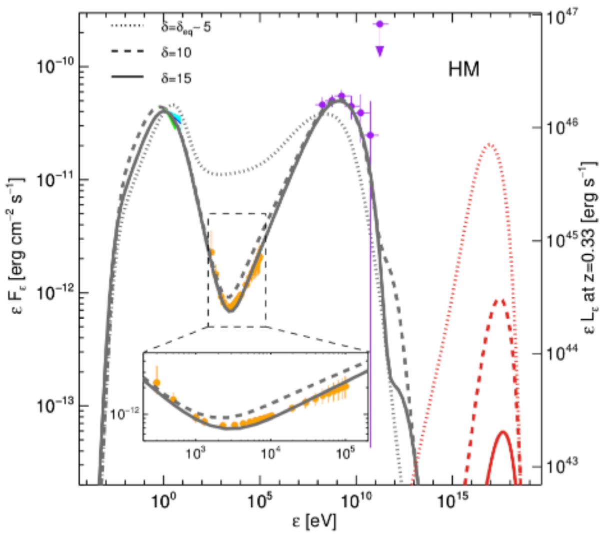


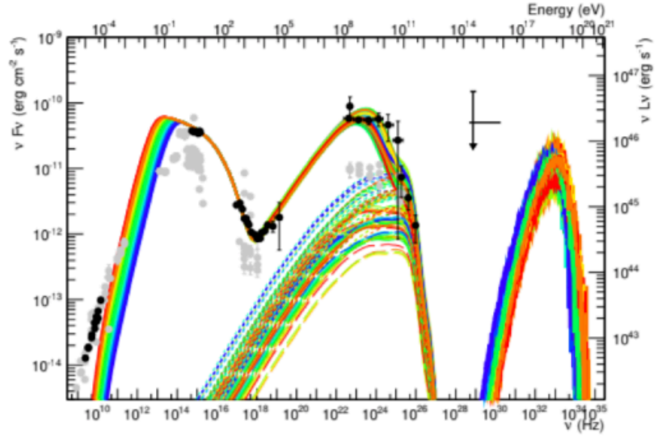




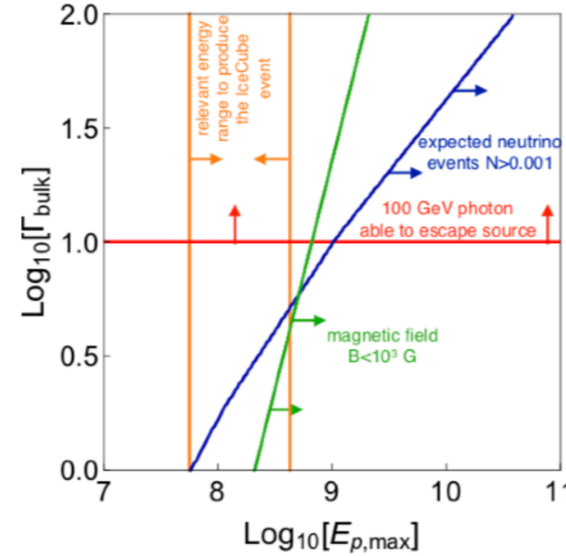
[IceCube, Fermi, MAGIC et al. 2018](#)

TXS 0506+056: THE 2017 FLARE





(a) Proton synchrotron modeling of TXS 0506+056



[Cerruti et al. 2019](#)

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

[Keivani et al. 2018](#)

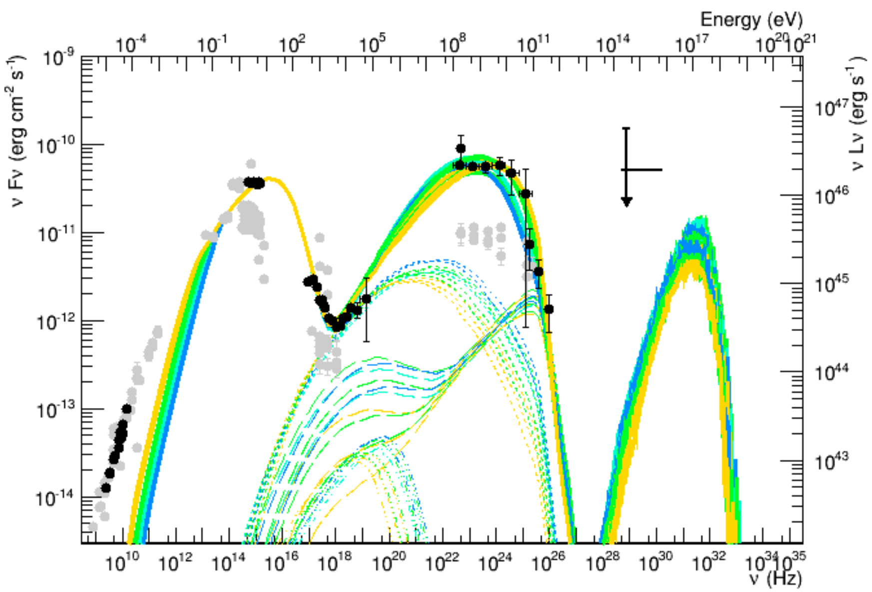
$$\nu \simeq 10^{-5}\ yr^{-1}$$

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

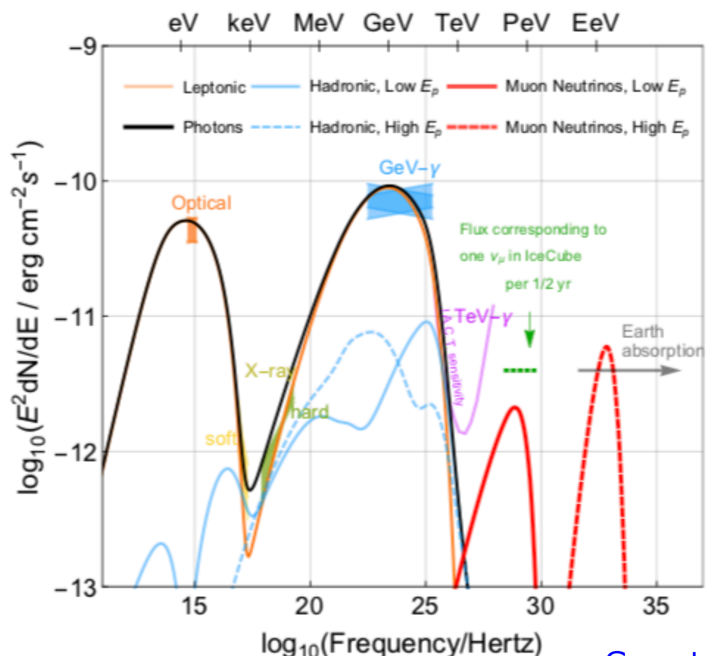
[Gao et al. 2018](#)

TXS 0506+056: THE 2017 FLARE

Lepto-hadronic solutions



[Cerruti et al. 2019]



[Gao et al. 2018]

$L_{jet} = (9 - 60) \times 10^{47} erg/s$
$\nu = 0.01 - 0.06\ yr^{-1}$

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

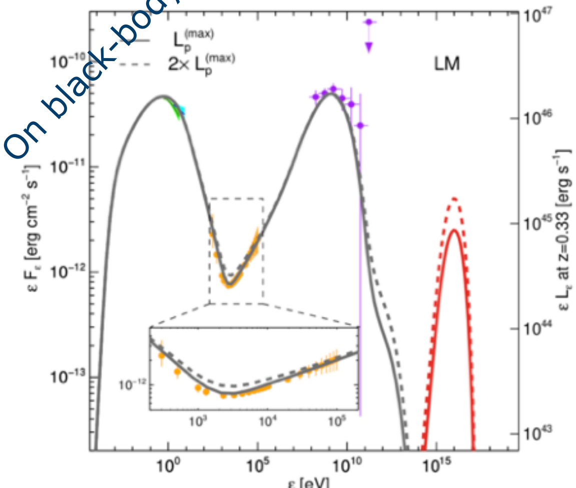
They can work: neutrino rates of the order of 0.1 / yr

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

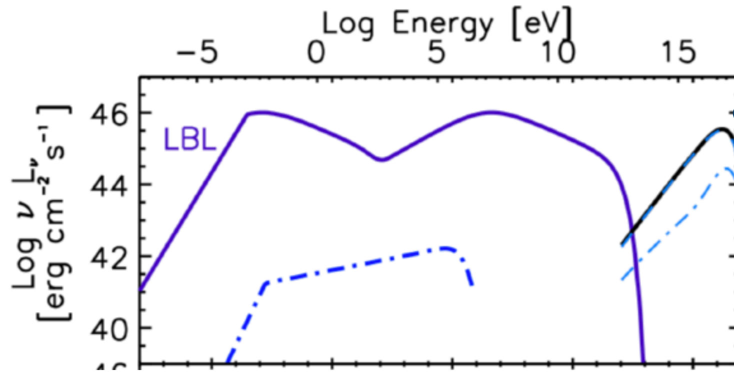
On black-body



Keivani et al. 2018

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

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



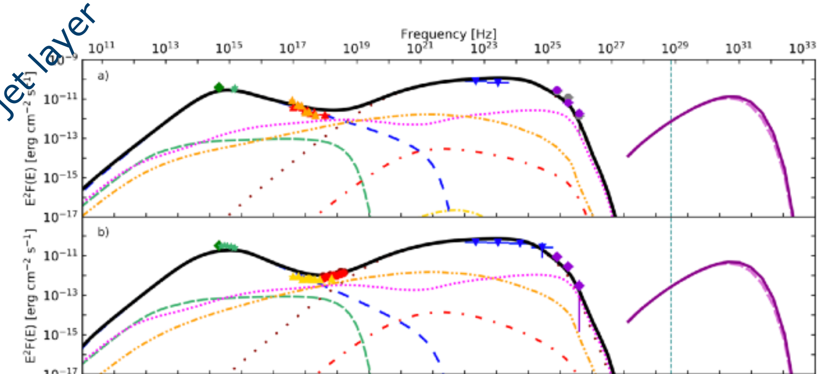
On RIAF

Righi et al. 2019

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

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

On jet layer



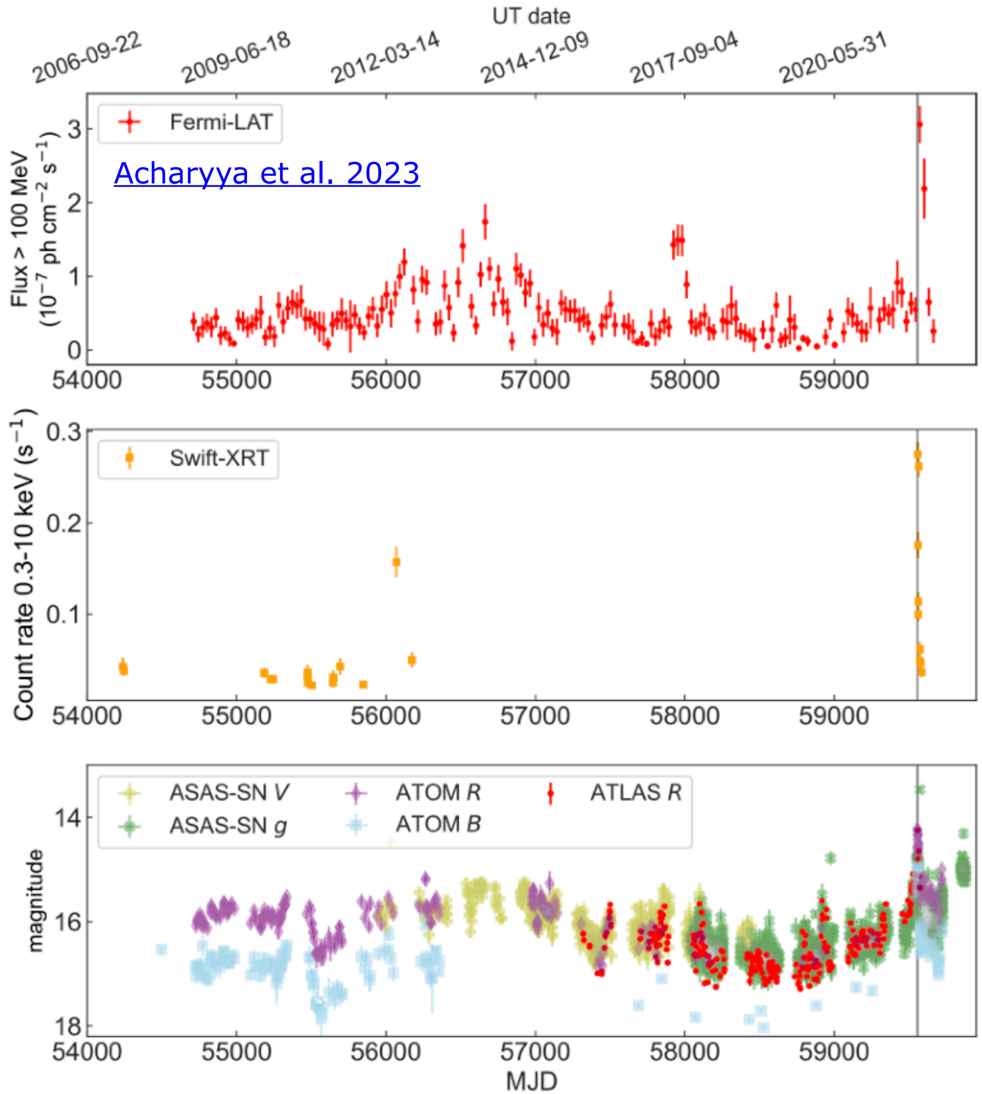
Ansoldi et al. 2018

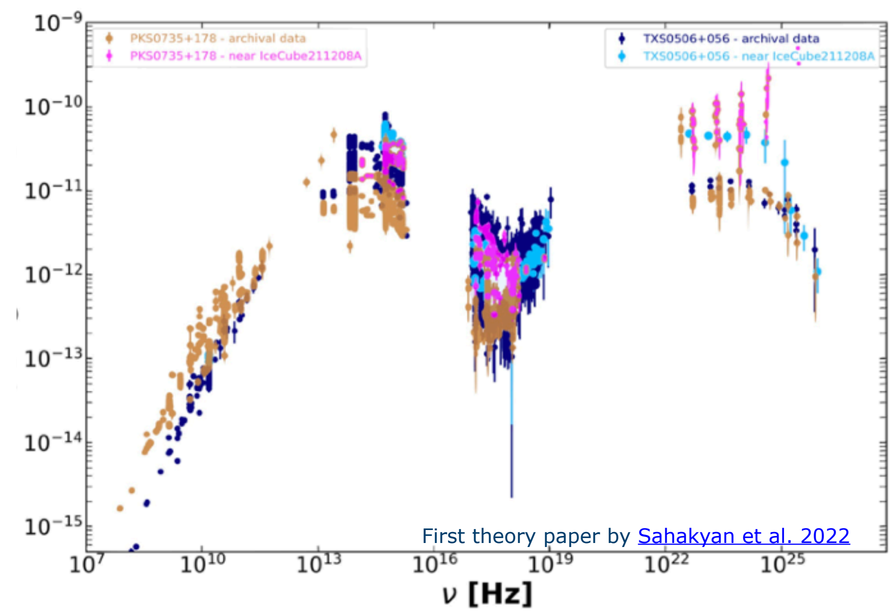
$L_{jet} = (3 - 8) \times 10^{45} erg/s$

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

WHAT HAPPENED SINCE 2017?

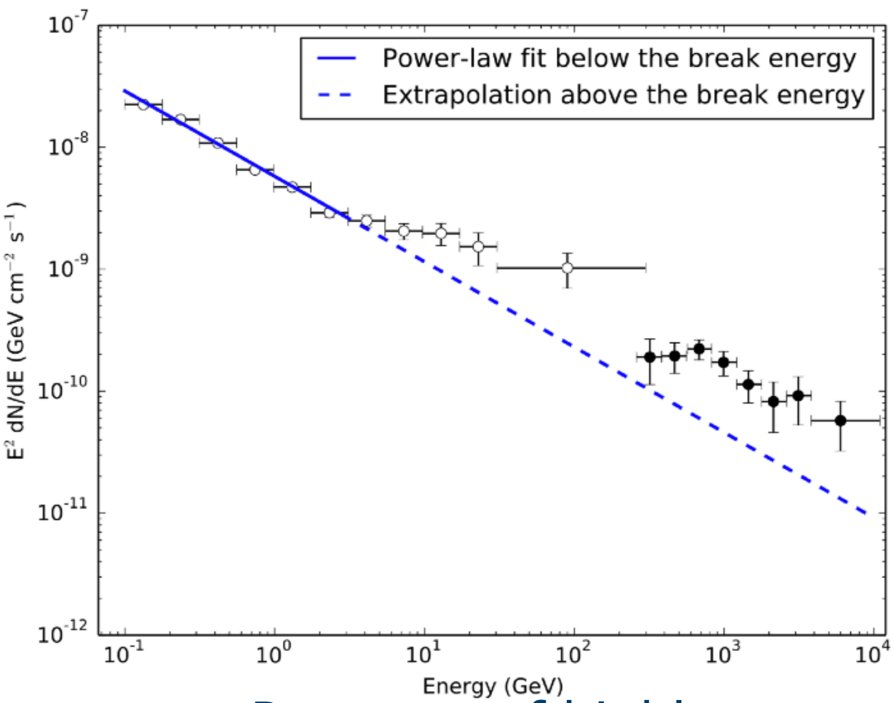
FLARE OF PKS 0735+178 / IC211208A

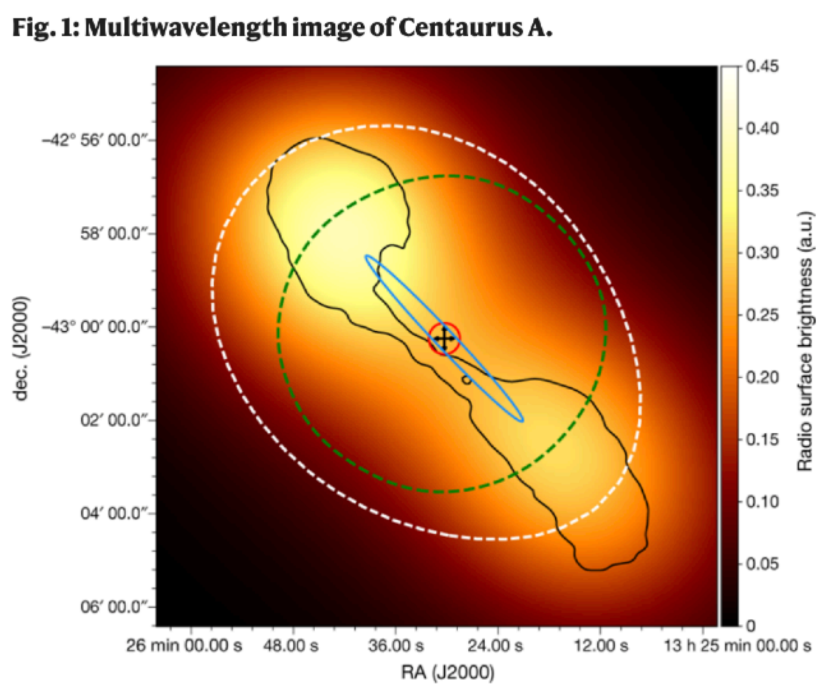




RADIO GALAXIES - Centaurus A

Not variable! Unique spectral hardening at TeV
Extended!





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

GAMMA-RAY BURSTS

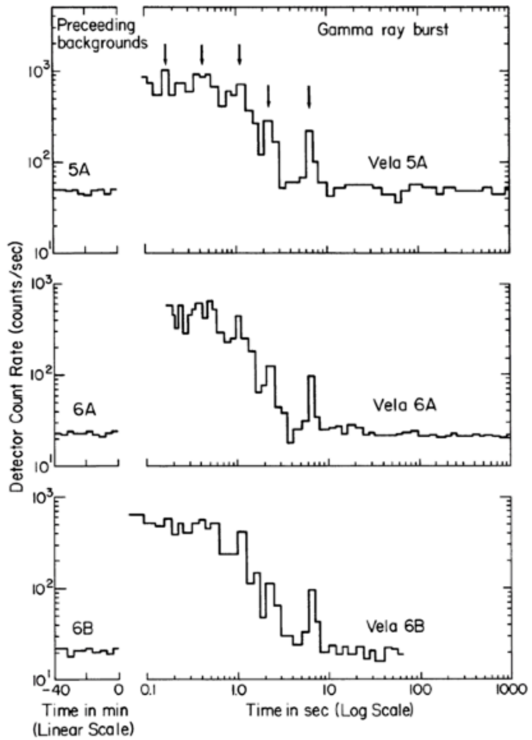
HISTORY

Discovered by militaries during cold war

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

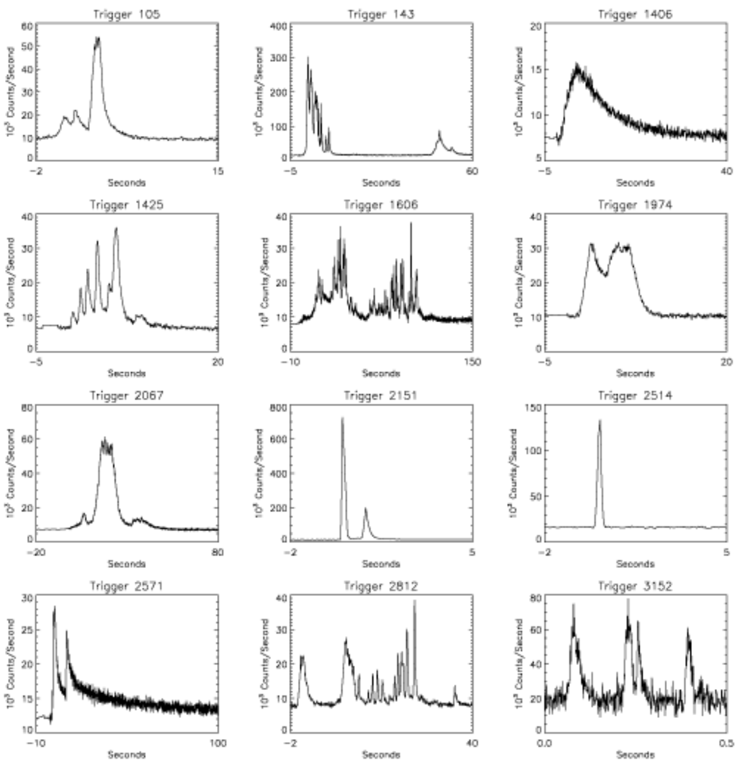
Ray W. Klebesadel, Ian B. Strong, and Roy A. Olson

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

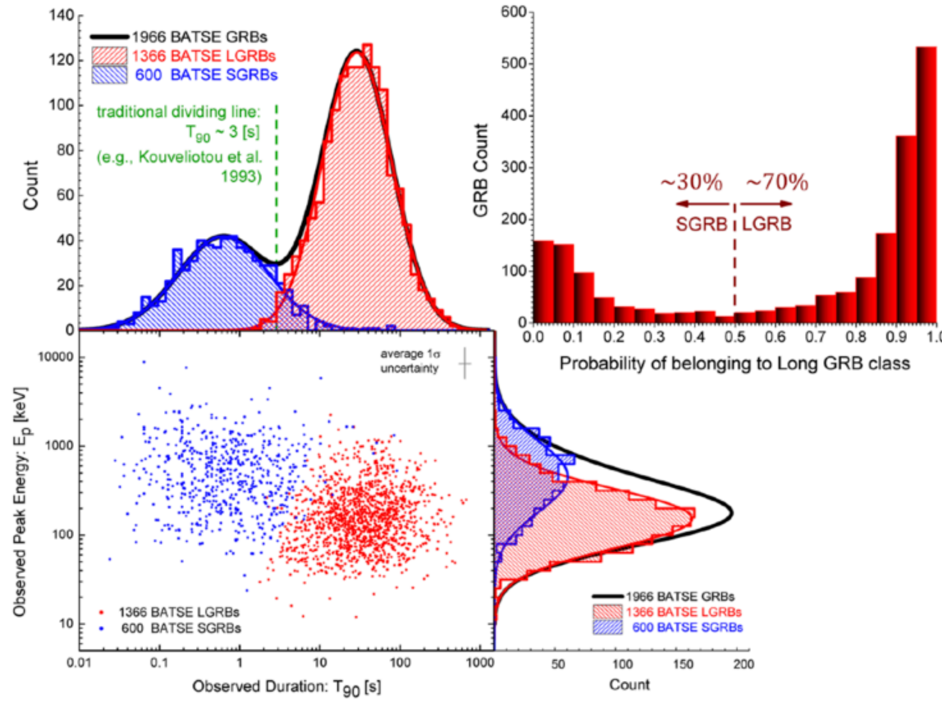


HISTORY

Classification



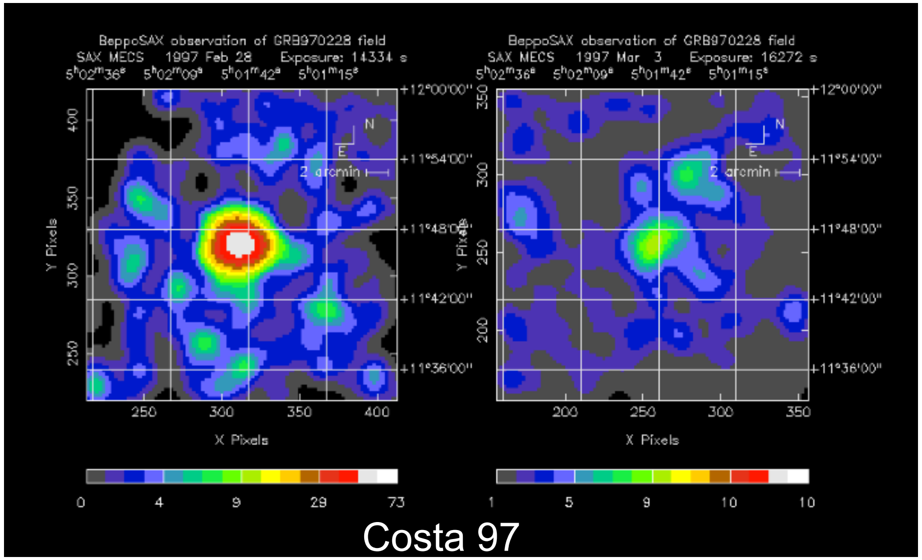
Credit NASA /GSFC

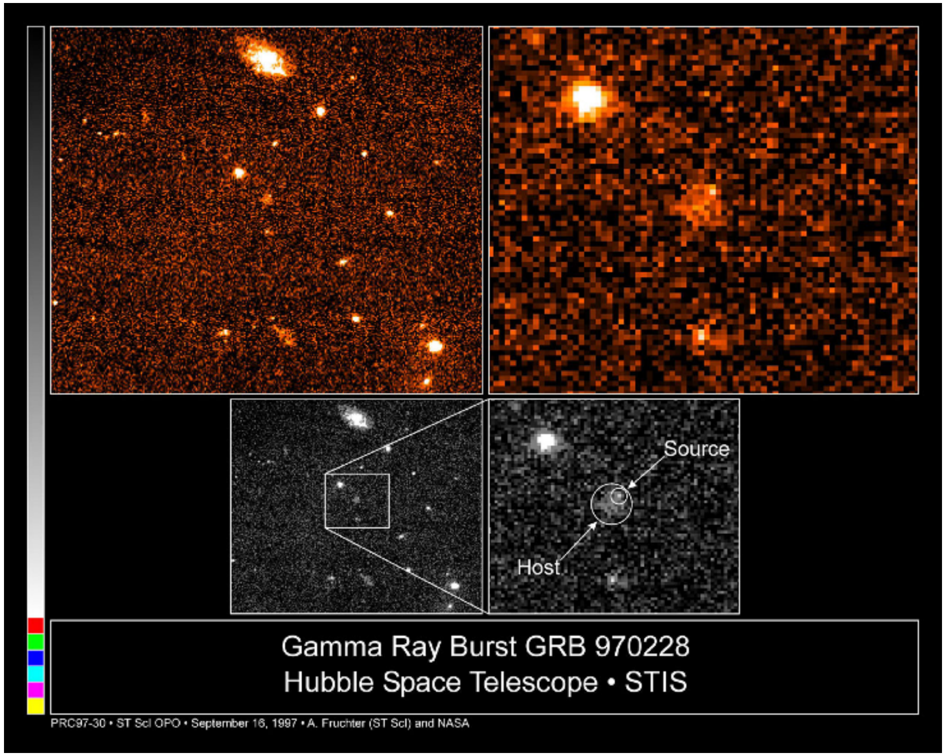


Shahmoradi 15

HISTORY

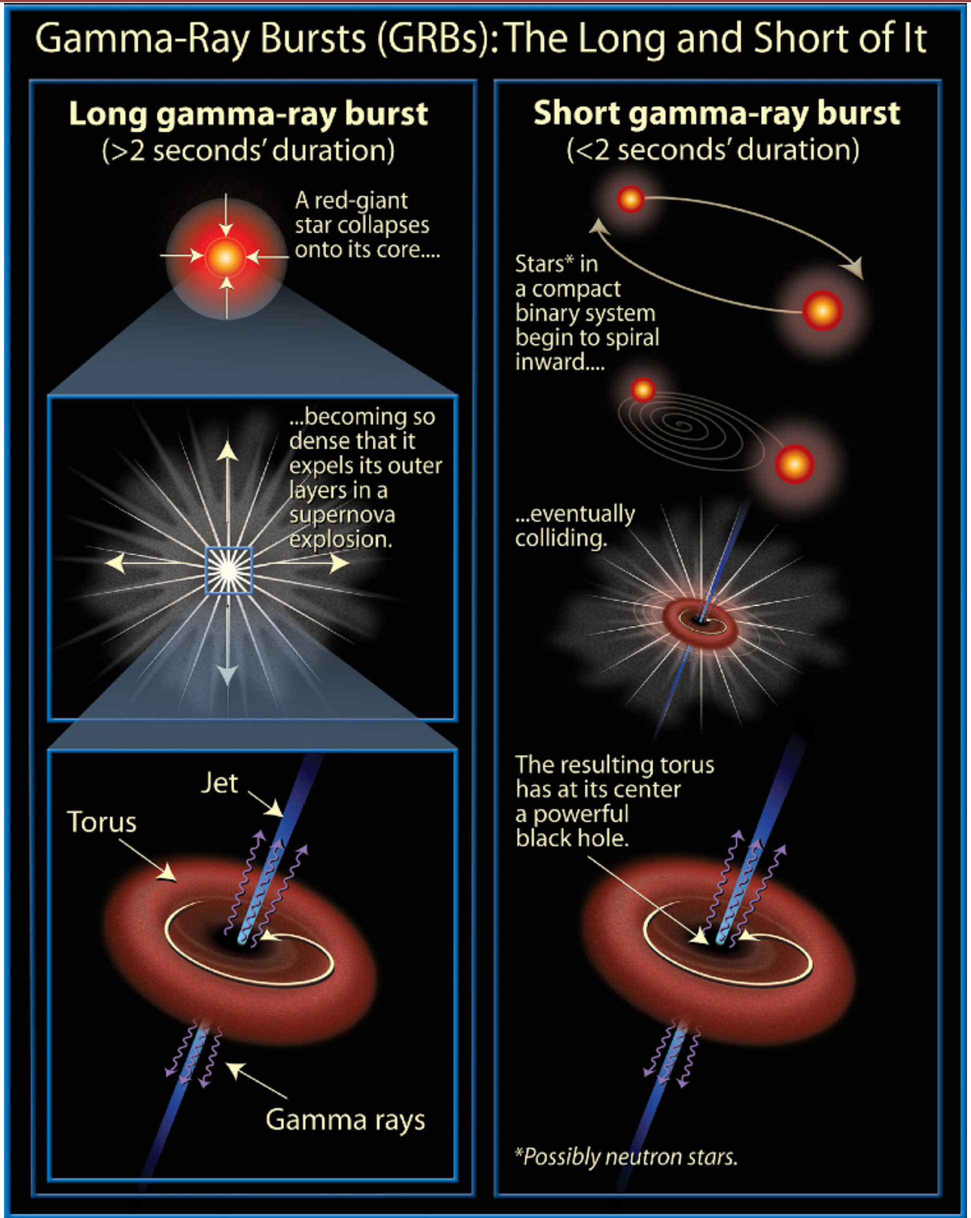
First afterglow detection: GRB 970228





WHAT ARE GRBs?

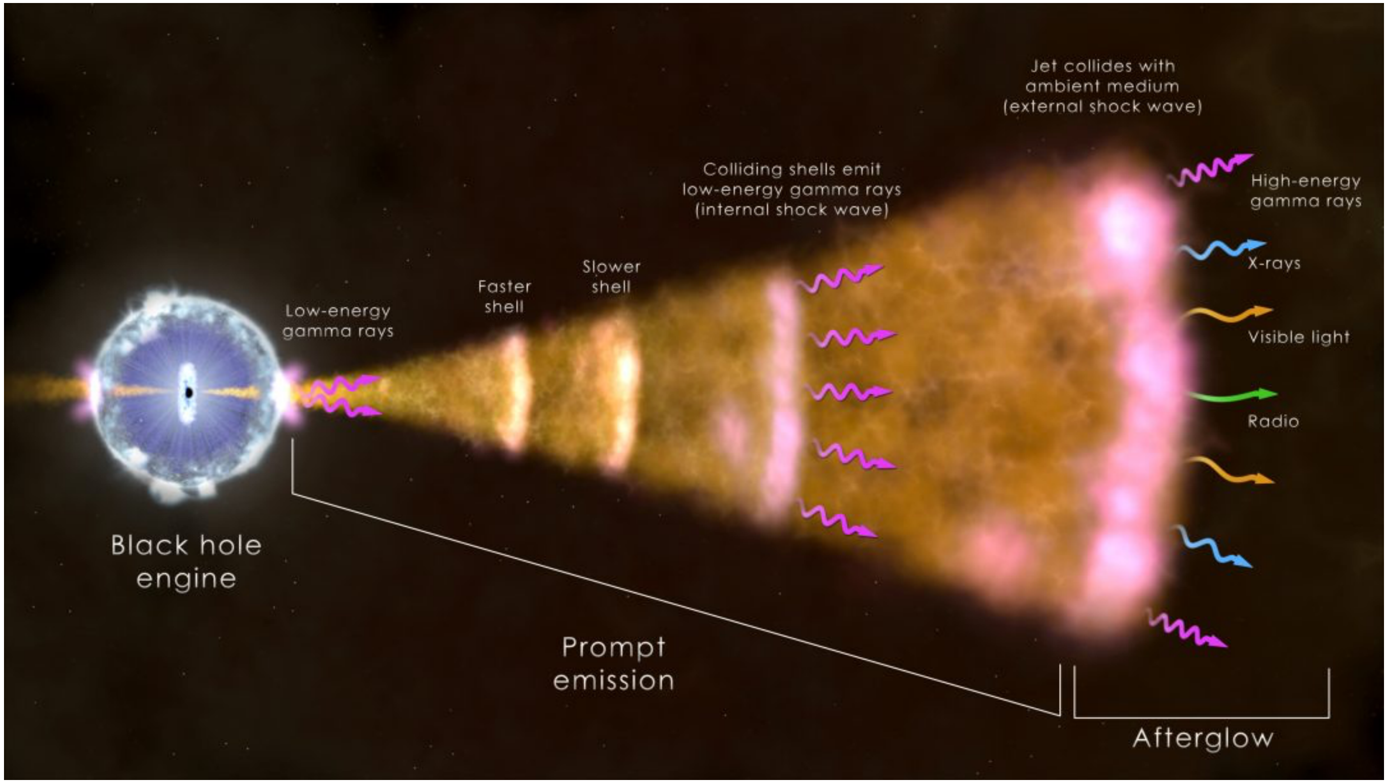
Should come with a core-collapse supernova



Should come with a kilonova, an optical transient powered by decay of elements formed through rapid neutron capture (r-process).

WHAT ARE GRBs?

Prompt and afterglow

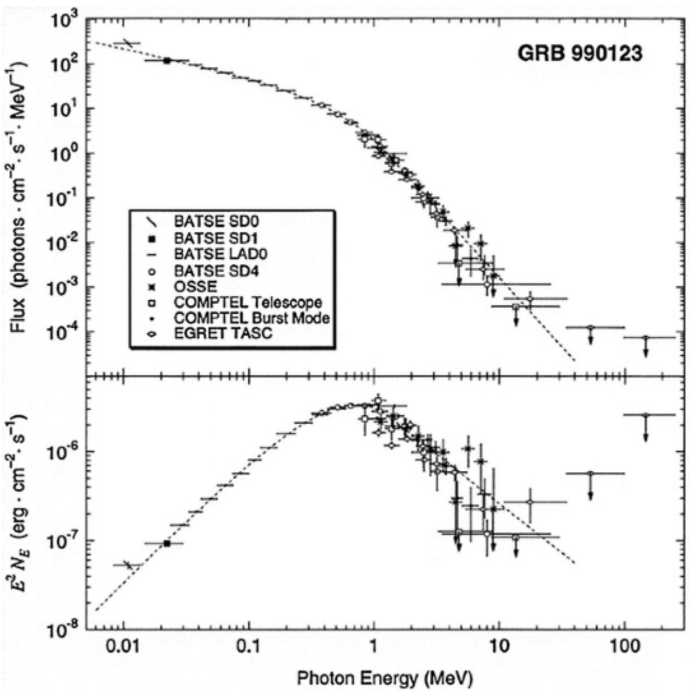


PROMPT PHASE SPECTRA

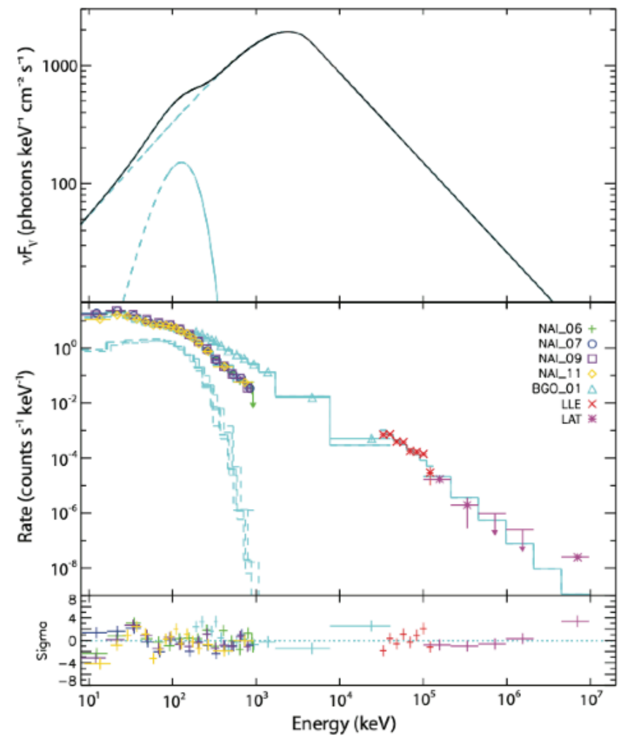
Prompt spectra are well fitted by a smoothly broken power law (Band function, see Band 93)

$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right), \quad (\alpha-\beta)E_0 \geq E\,,$$

$$= A\left[\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta} \exp(\beta-\alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta}, \quad (\alpha-\beta)E_0 \leq E\,,$$



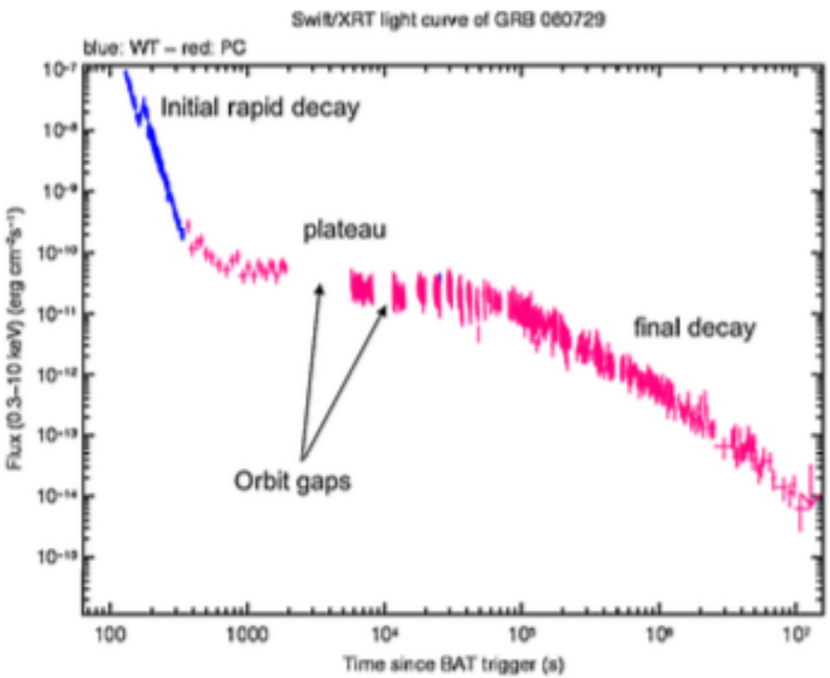
Briggs 99



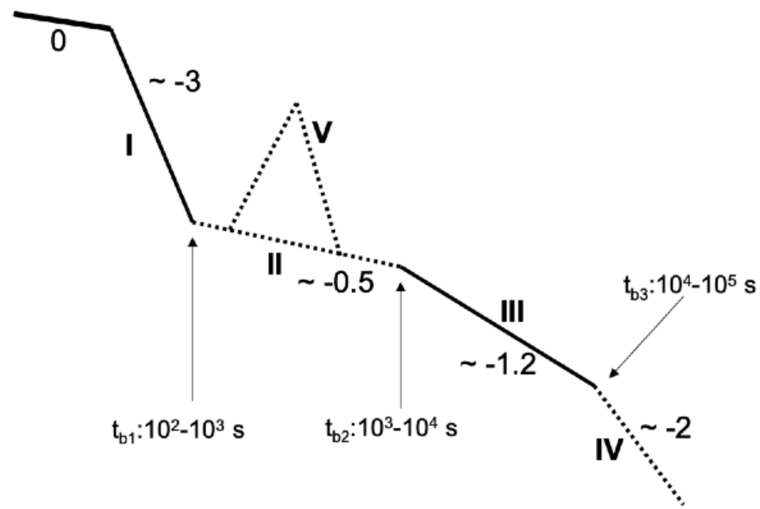
Axelsson 12

AFTERGLOW EVOLUTION

X-ray light-curves of afterglow



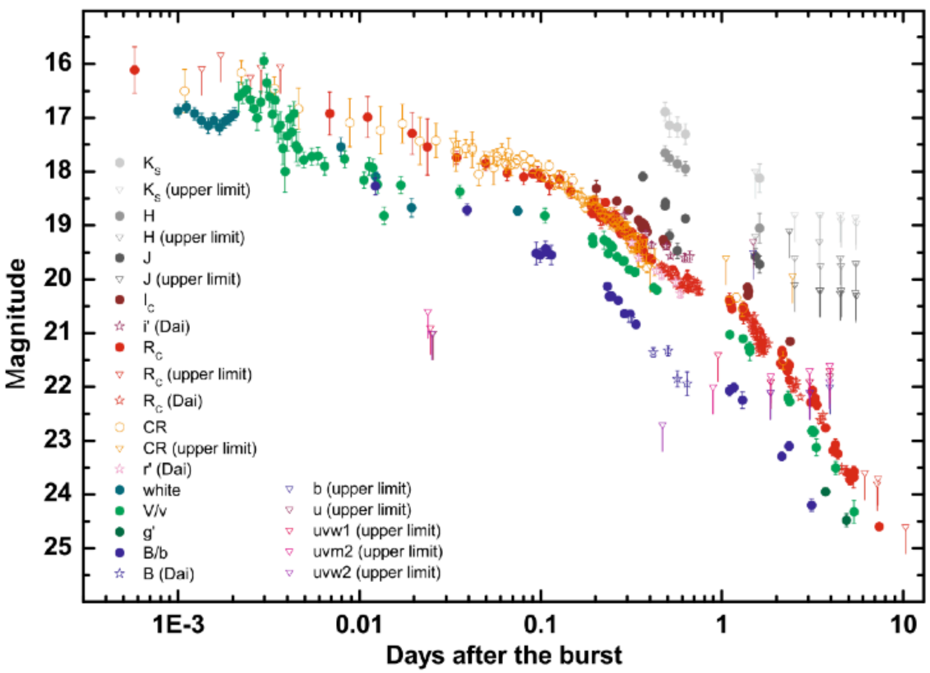
Willingale 16



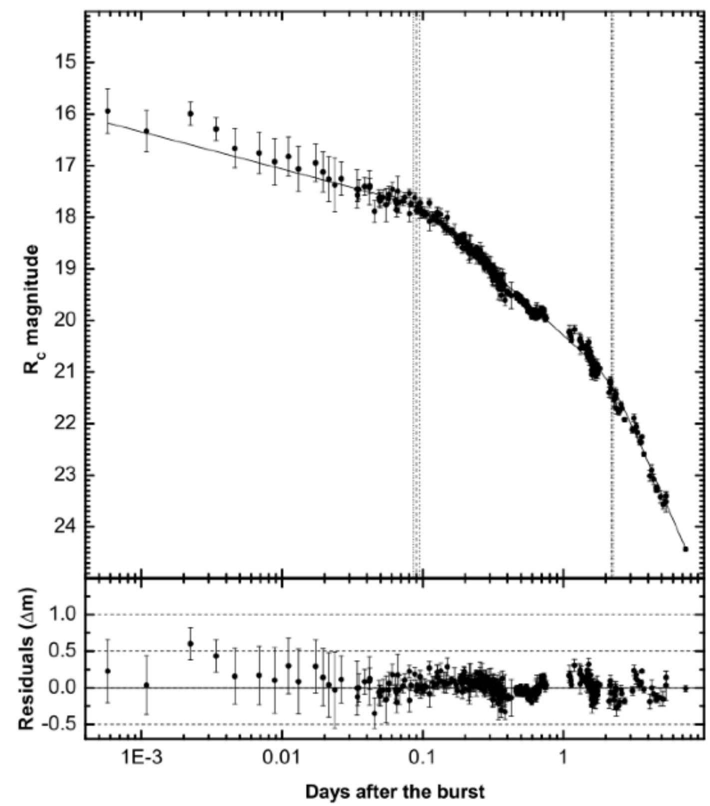
Zhang 06

AFTERGLOW EVOLUTION

Optical light-curves of afterglow



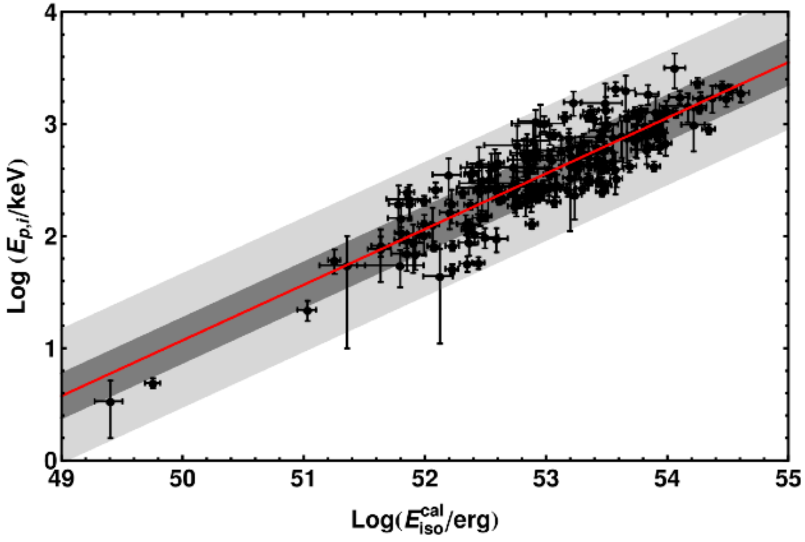
GRB 060526, Thöne 08



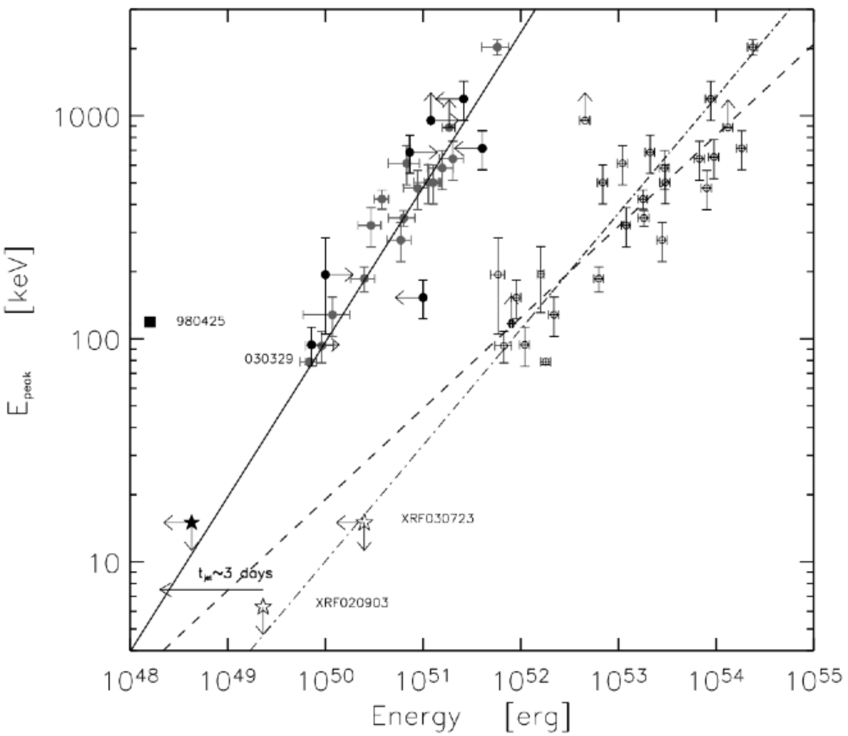
Matteo Cerruti

HISTORY

Important relationships

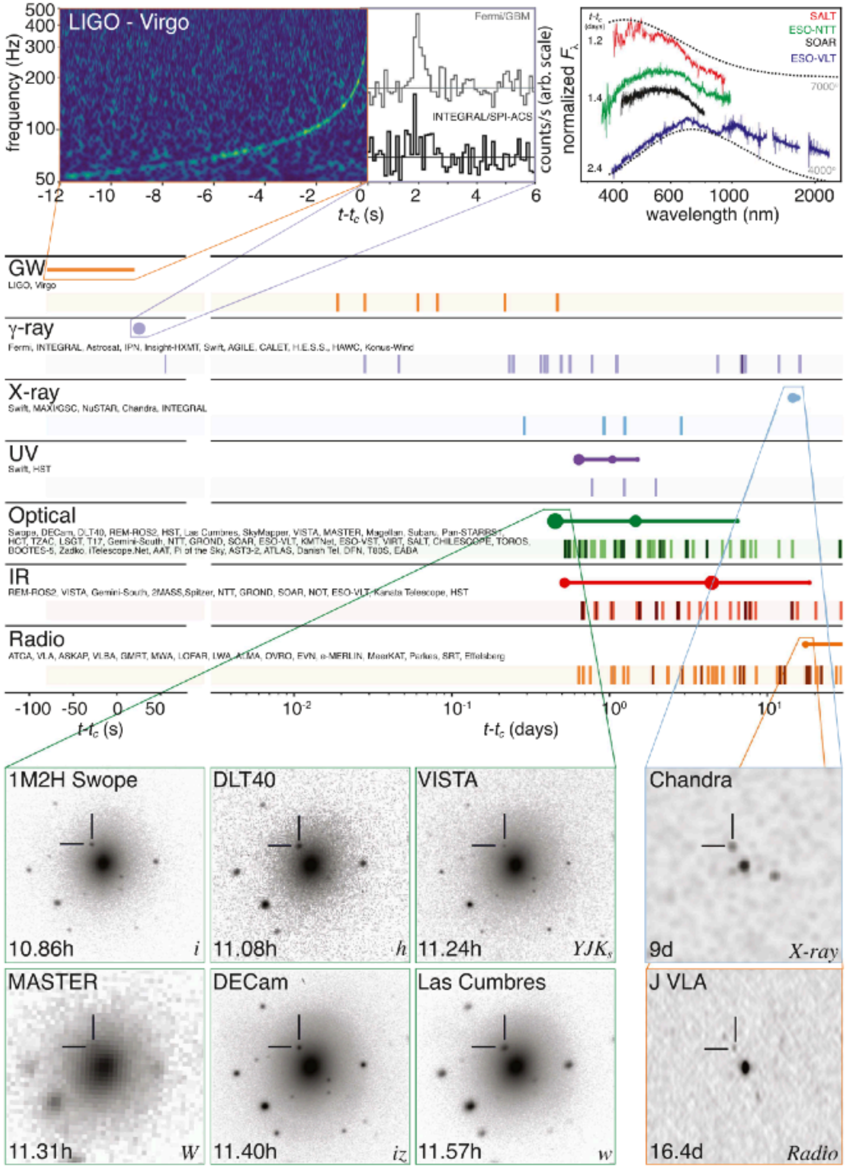


Amati 19



Ghirlanda 04

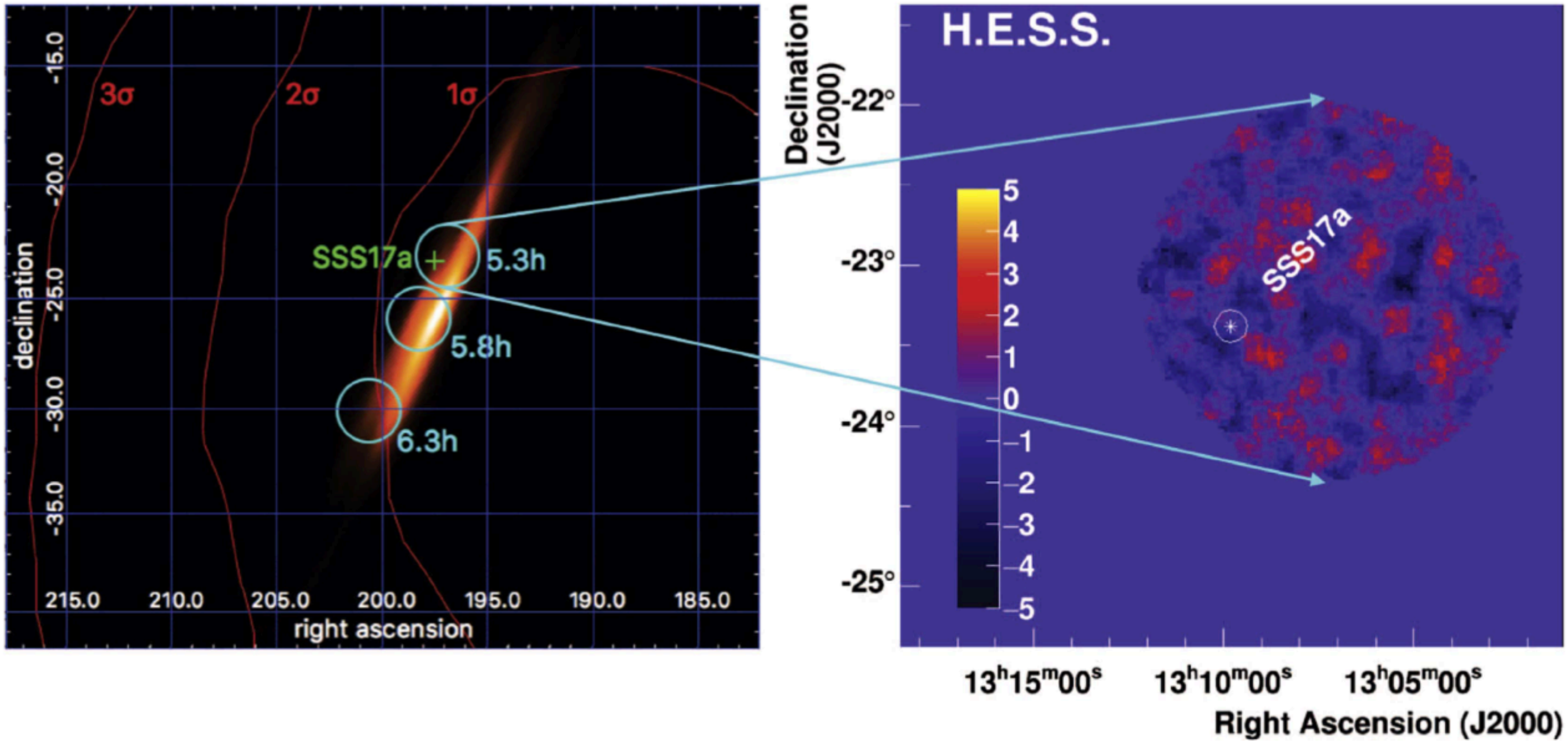
GW 170817



Neutron star binary merging together with a short GRB and a kilonova

GW 170817

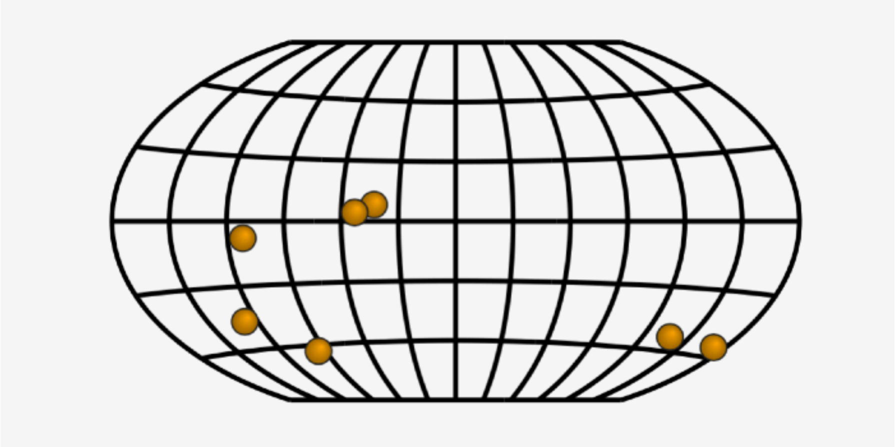
Follow up observations in the TeV band



H.E.S.S. Collaboration 17

THE TeV EMISSION

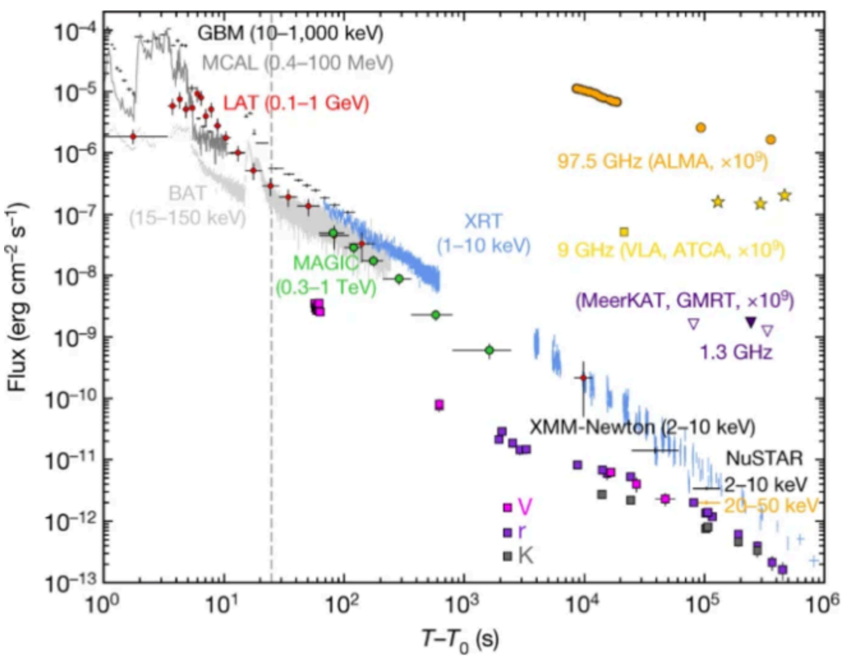
Since July 2018 we had 5 TeV GRBs (and 2 candidates)

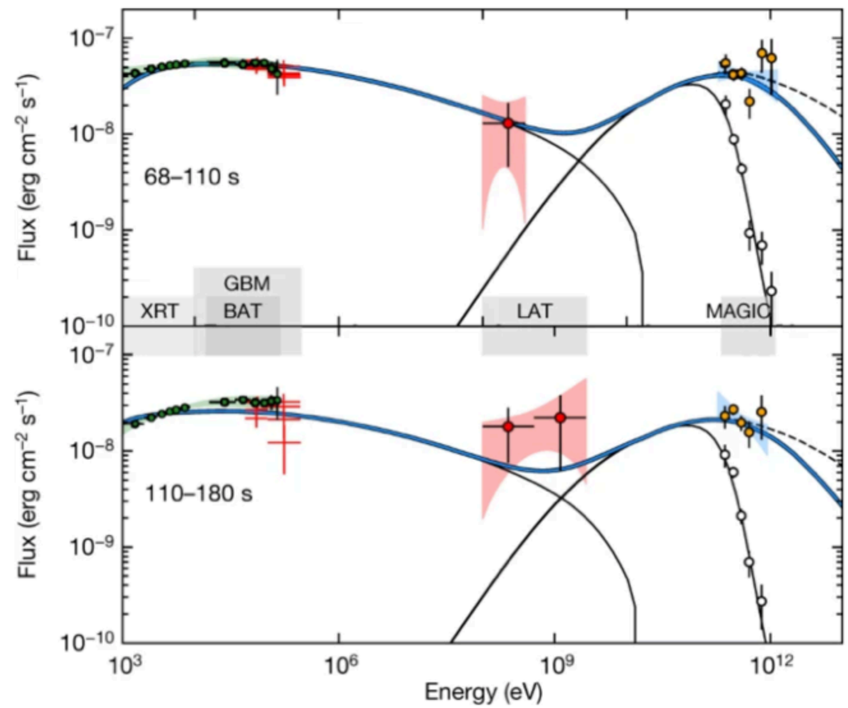


GRB 180720B	00 02 06.87	-02 55 05.2	XGal,GRB,I...	z=0.654	Default Catalog
GRB 201216C	01 05 28.88	+16 30 58.0	XGal,GRB,I...	z=1.1	Newly Announced
GRB 190829A	02 58 10.51	-08 57 28.1	XGal,GRB,I...	z=0.0785	Default Catalog
GRB 190114C	03 38 01.17	-26 56 46.73	XGal,GRB	z=0.4245	Default Catalog
GRB 160821B	18 39 54.71	+12 34 56....	XGal,GRB,s...	z=0.16	Source Candidates
GRB 221009A	19 13 03	+19 48 09	XGal,GRB,I...	z=0.151	Default Catalog
GRB 201015A	23 37 16.42	+53 24 55.8	XGal,GRB,I...	z=0.43	Source Candidates

THE TeV EMISSION

GRB 190114C, seen with MAGIC

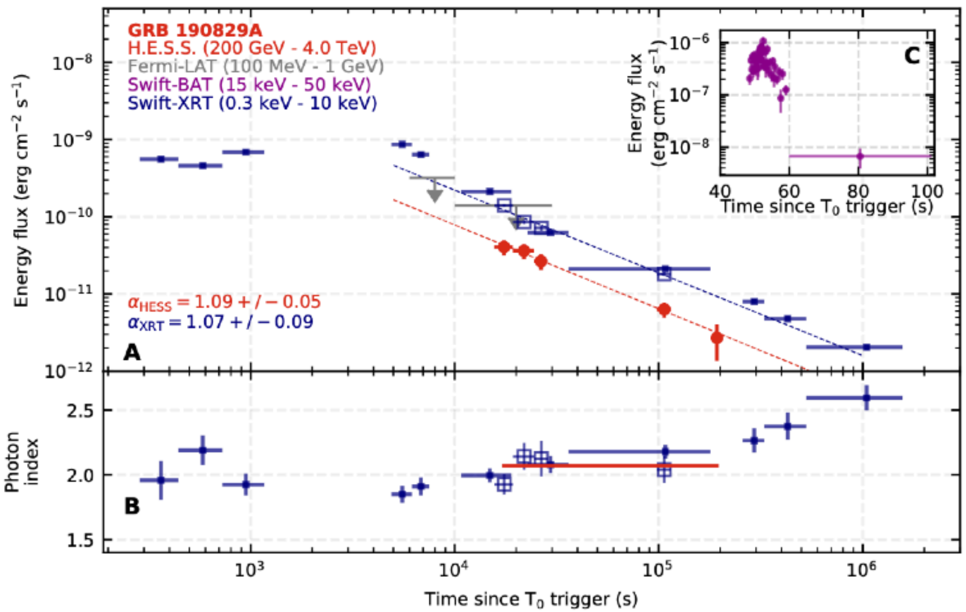


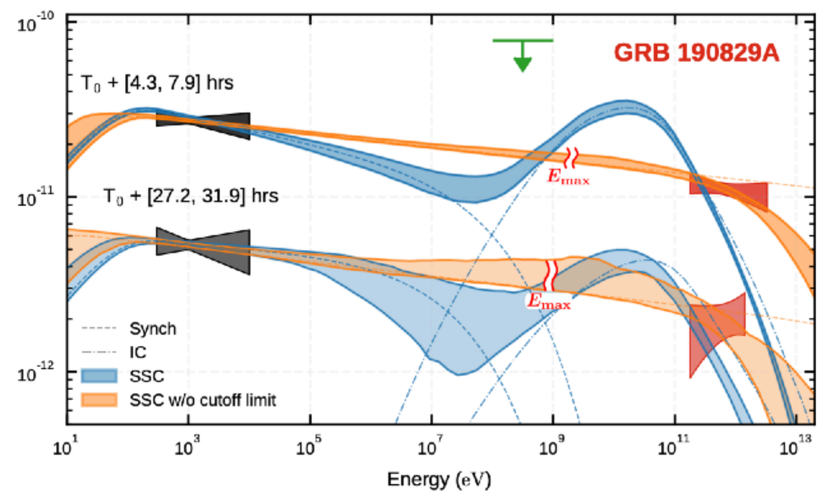


MAGIC Collaboration 19

THE TeV EMISSION

GRB 190829A, seen with HESS

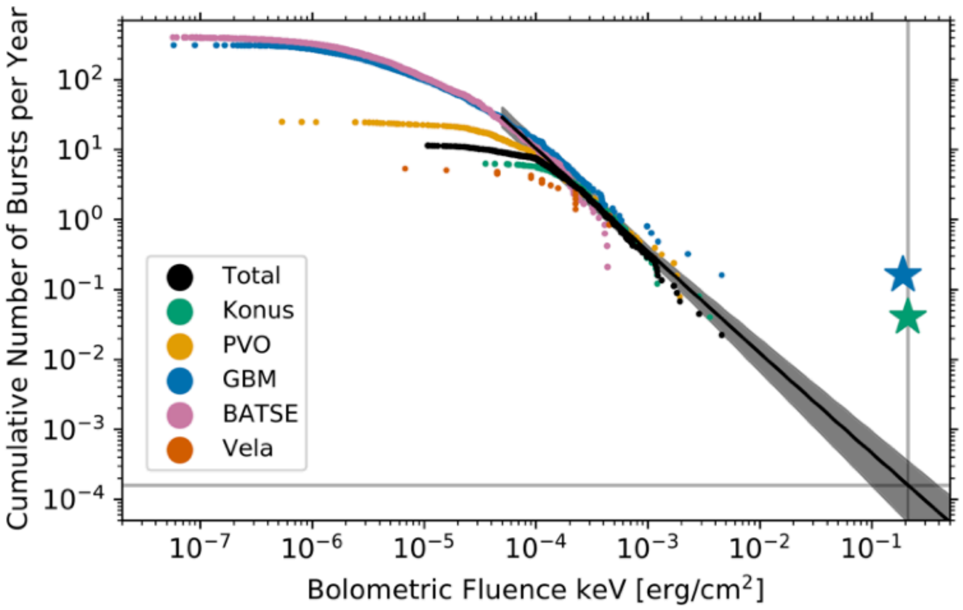




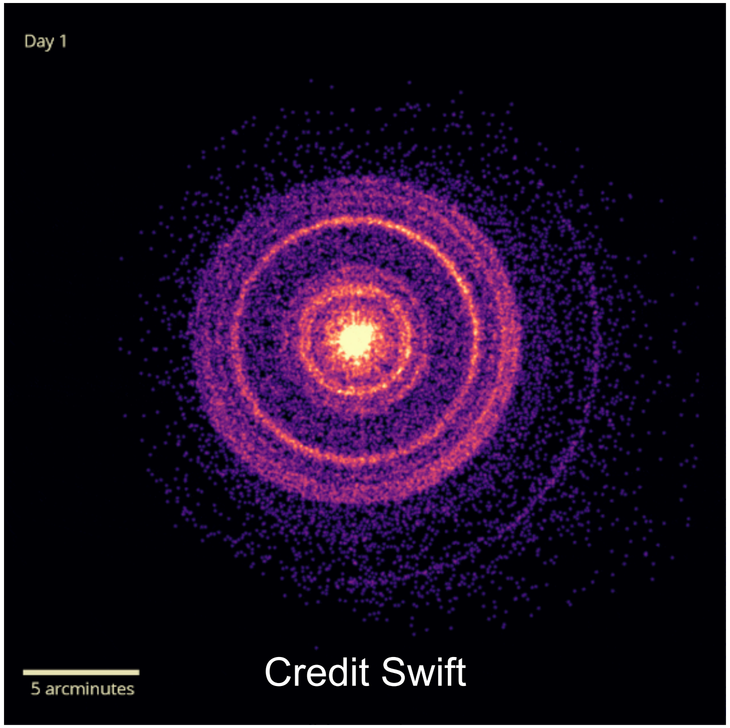
HESS Collaboration 21

THE BOAT

GRB 221009A, the brightest of all times

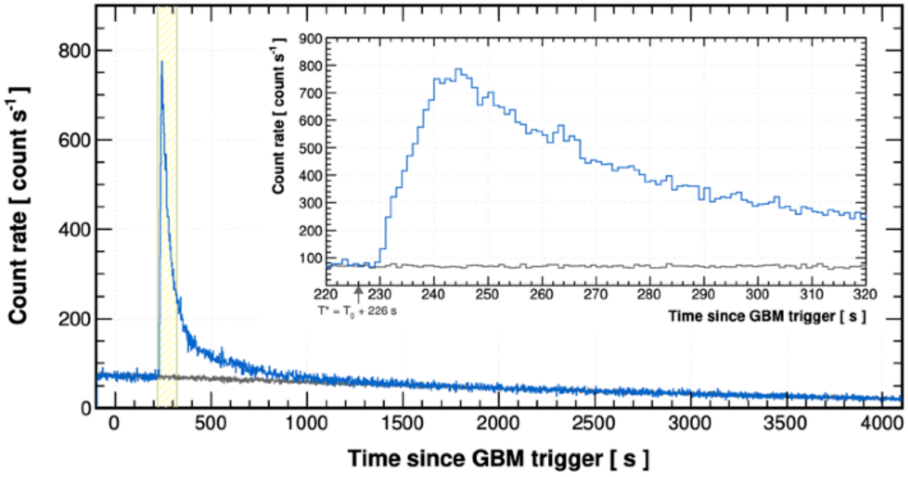


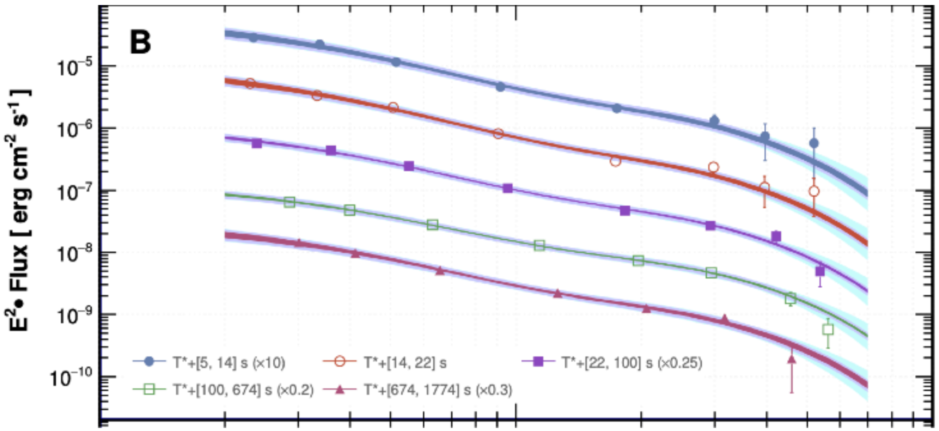
Burns 23



THE BOAT

Seen by LHAASO-WCDA

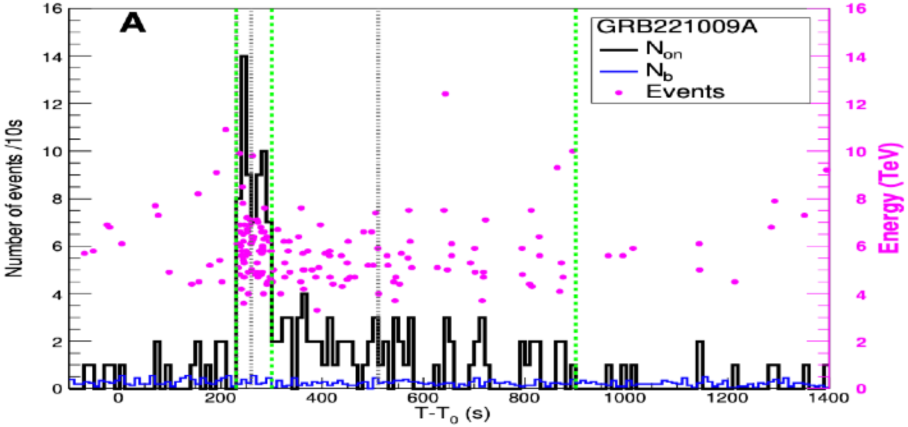


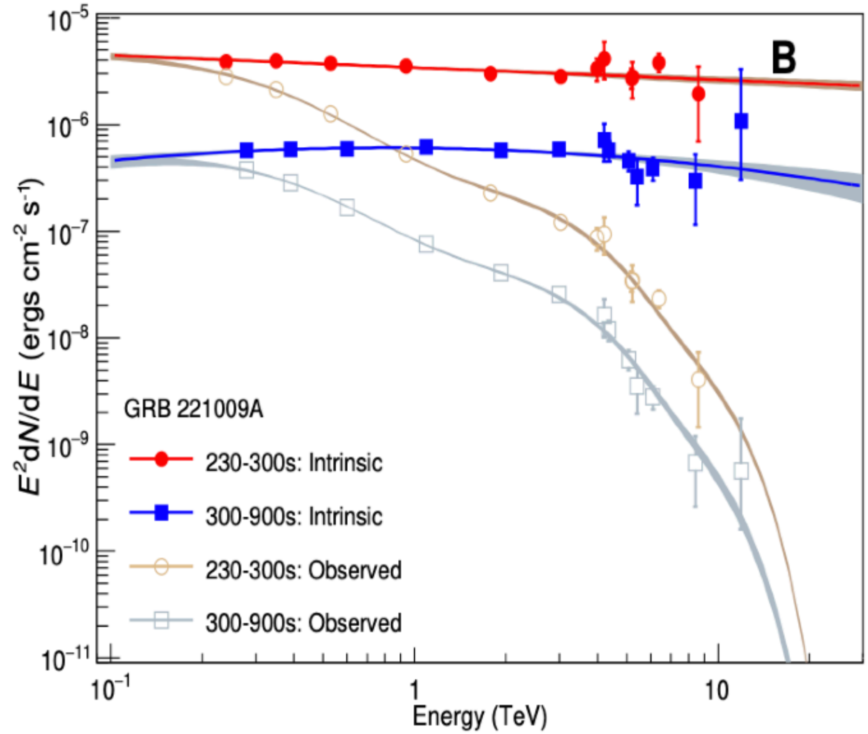


LHAASO Collaboration 23

THE BOAT

And also by LHAASO-KM2A



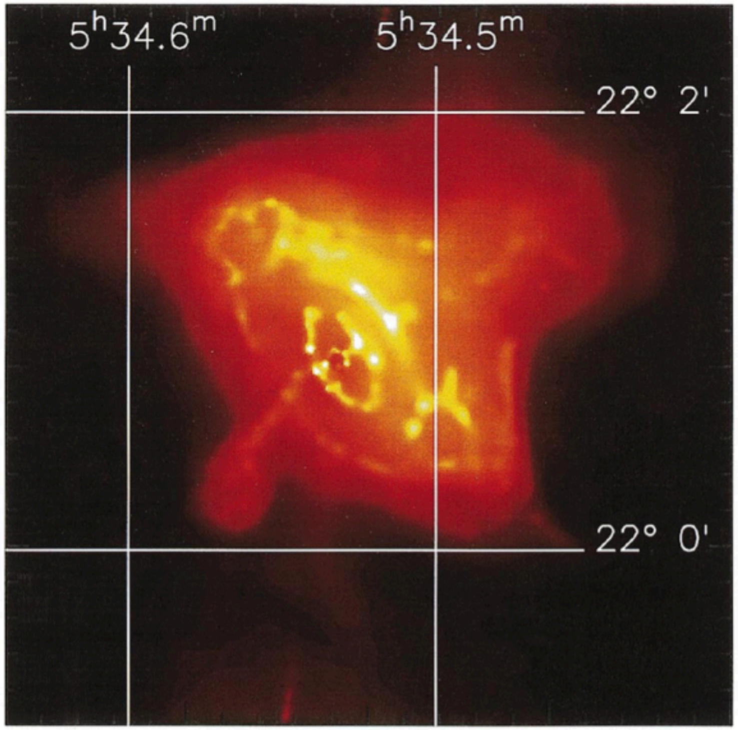


Highest significant bin is at 10 TeV.
Initial claims of 18 TeV energies were not confirmed
(Also claim by CARPET of a 250 TeV photon, also not confirmed)

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