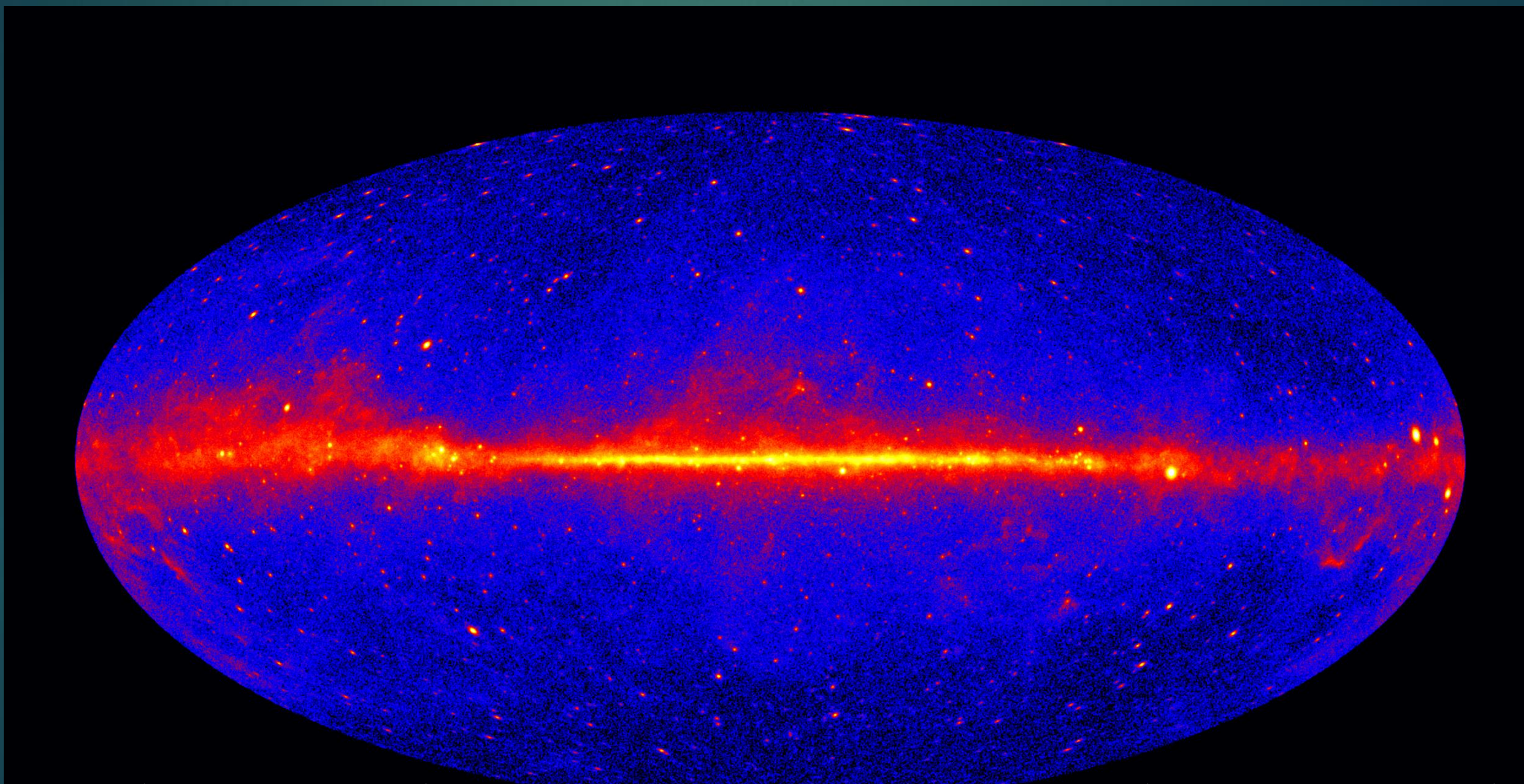
Extragalactic sources of gamma-rays, neutrinos and cosmic rays

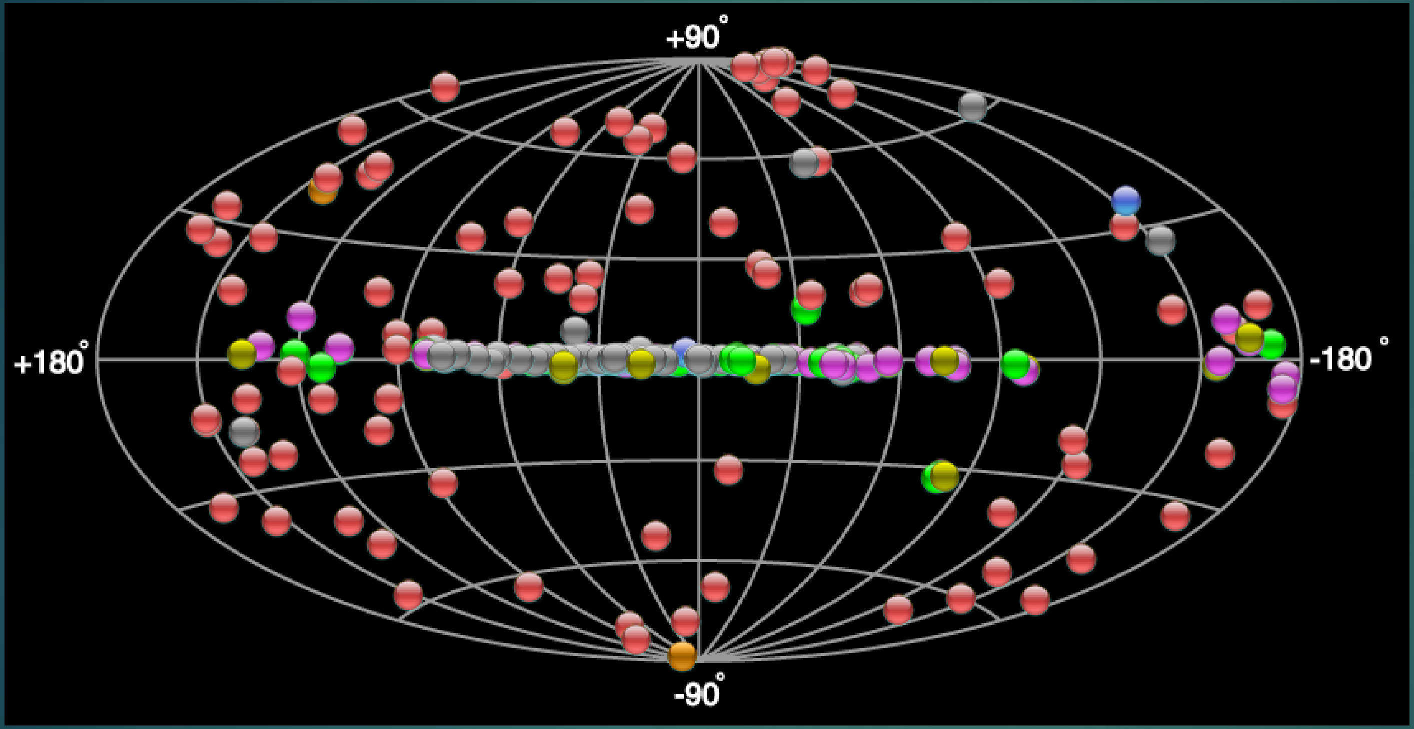
ELINA LINDFORS, UNIVERSITY OF TURKU, FINLAND

Gamma-ray sky seen by Fermi-LAT satellite (>1GeV)



The Fermi LAT 60-month image, constructed from front-converting gamma rays with energies greater than 1 GeV. Red dots=extragalactic, source count~thousands.

Very High Energy Gamma-Ray sky

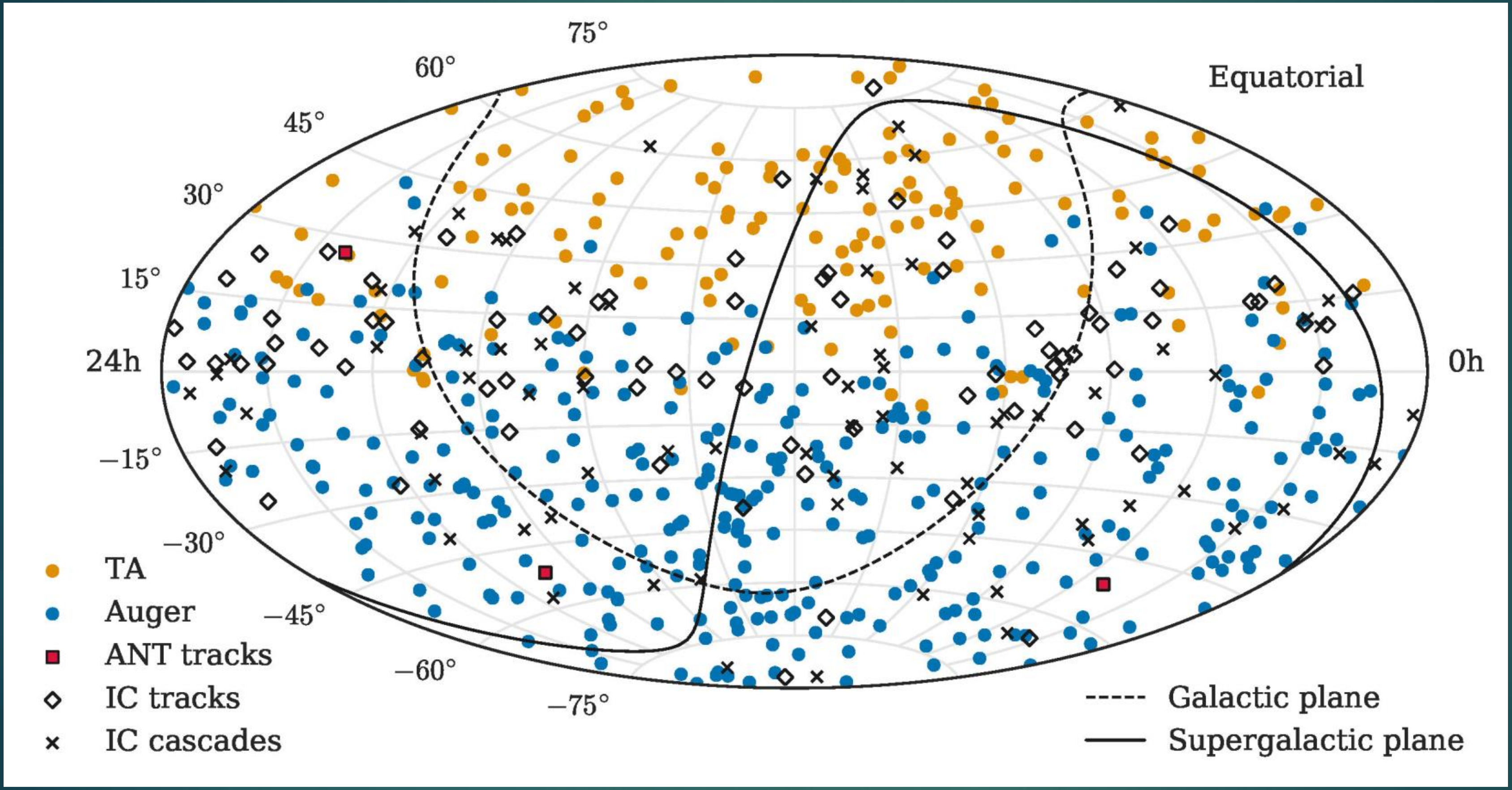


Red dots: extragalactic

Source count ~100

http://tevcat.uchicago.edu/

Skymap of Ultra High Energy Cosmic Rays and Neutrinos



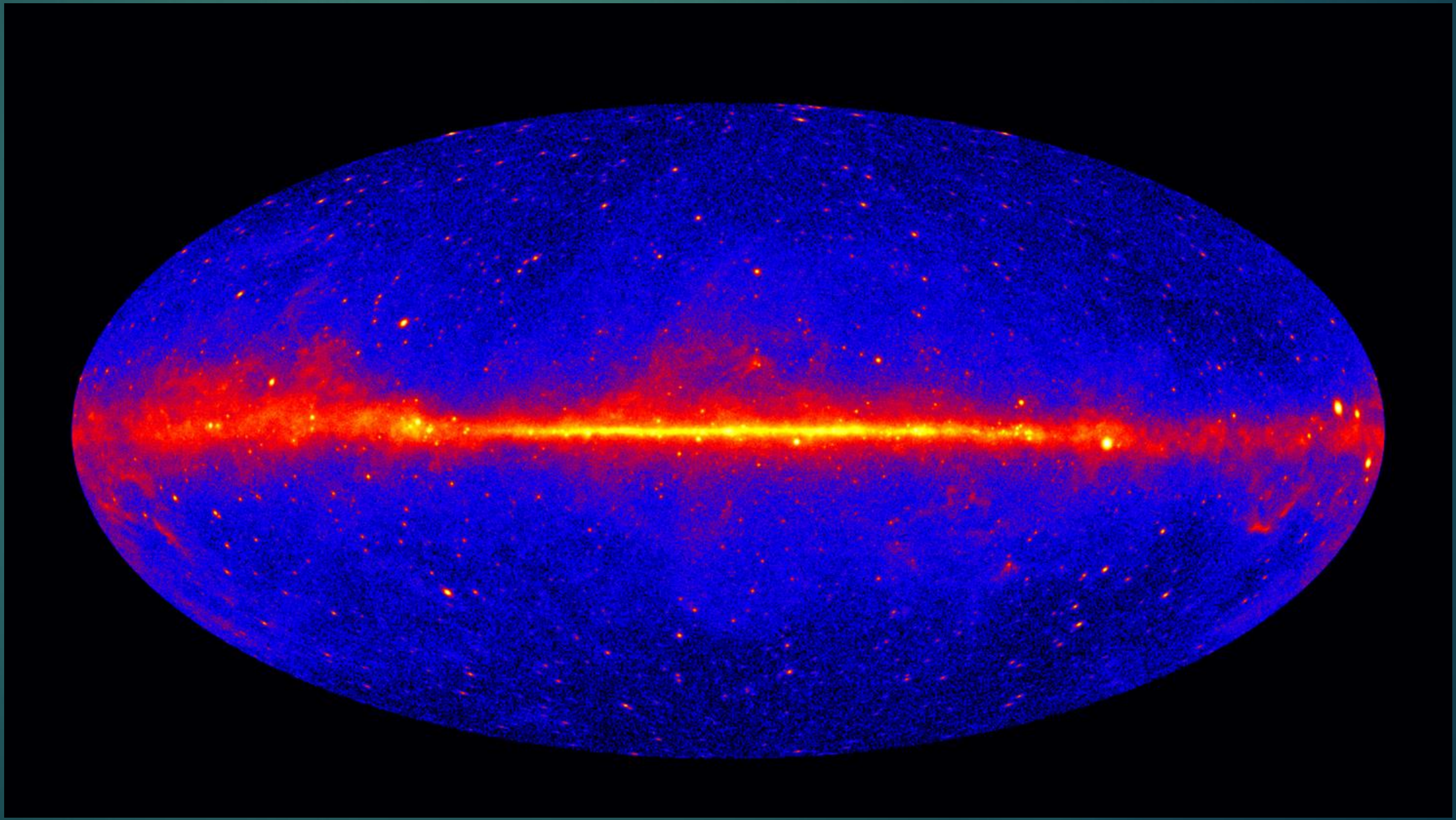
Sky map of the arrival directions of UHECR events from the Pierre Auger Observatory and the Telescope Array and high-energy neutrinos from IceCube and ANTARES. Credit: The ANTARES, IceCube, Pierre Auger and Telescope Array collaborations.

Gamma-rays, HE neutrinos and UHECRs have extragalactic origin

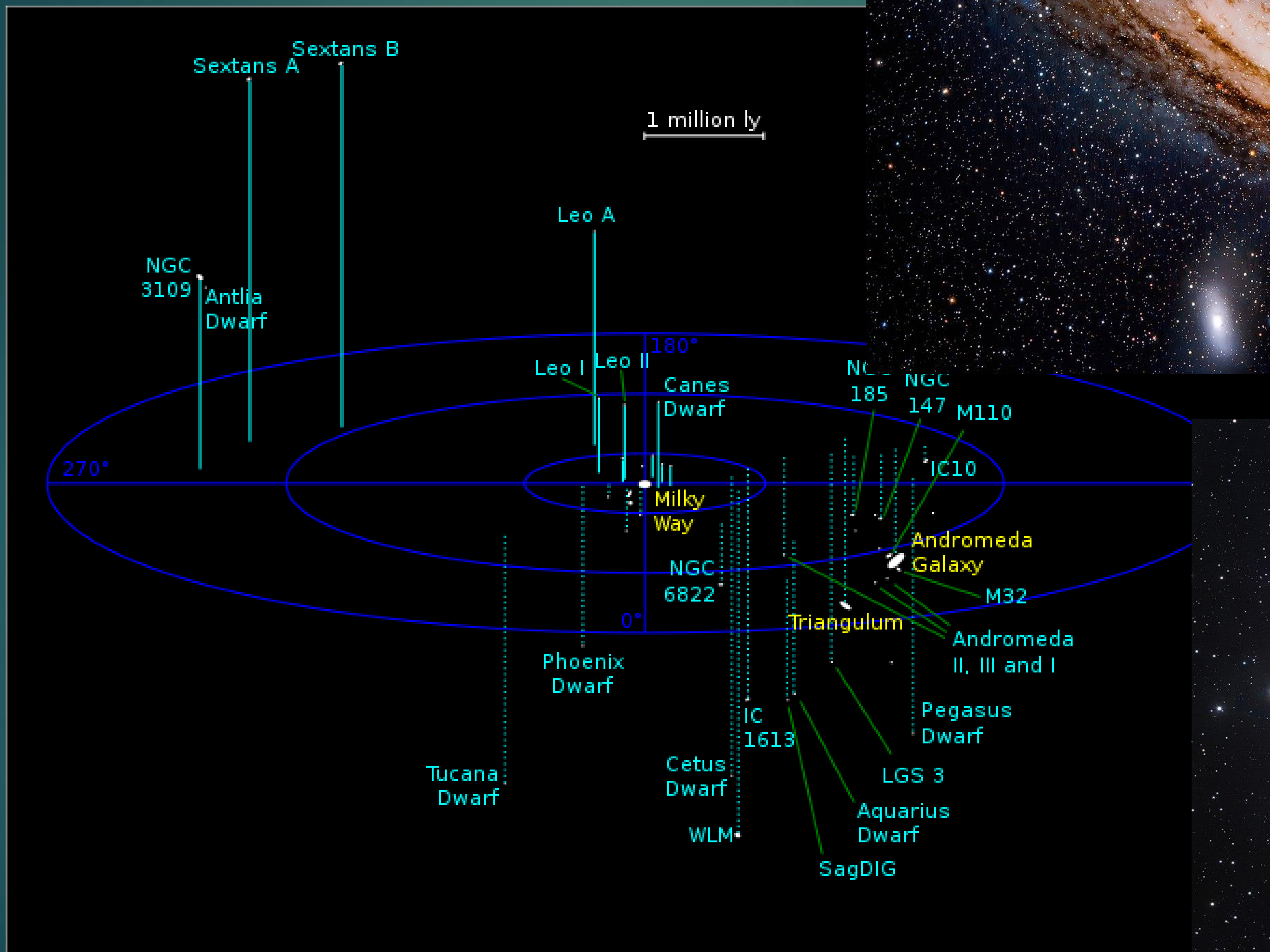
WHAT? HOW?

Normal galaxies

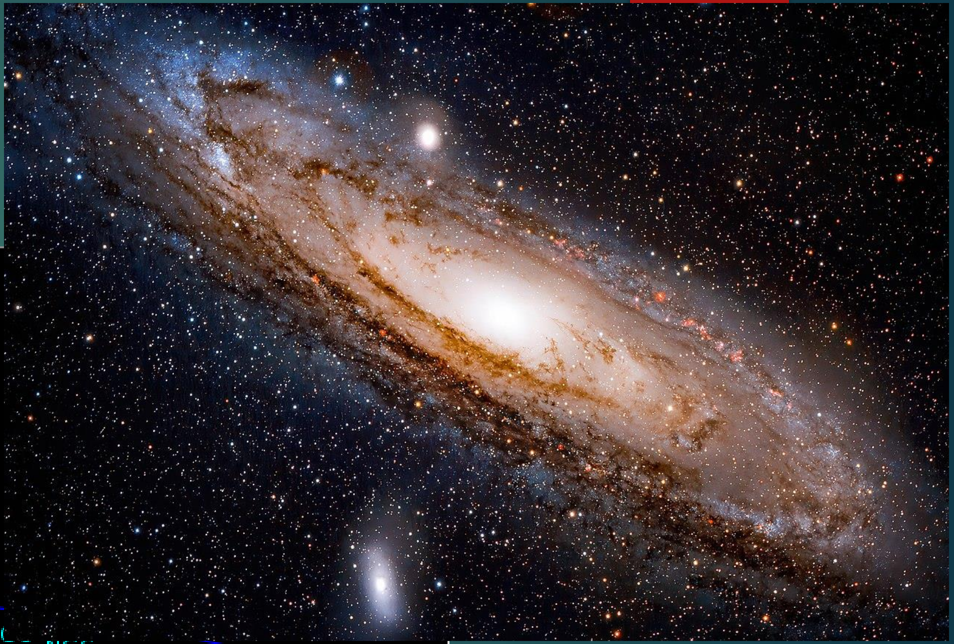
- Our galaxy is bright source of gamma-rays: cosmic rays interacting with molecular clouds.
- What about other galaxies?



Local group



Sextans B
Sextans A
1 million ly
Leo A
NGC 3109
Antlia Dwarf
180°
Leo I
Leo II
Canes Dwarf
185
NGC 147
M110
270°
IC10
Milky Way
Andromeda Galaxy
NGC 6822
M32
0°
Triangulum
Andromeda II, III and I
Phoenix Dwarf
IC 1613
Pegasus Dwarf
Tucana Dwarf
Cetus Dwarf
LGS 3
Aquarius Dwarf
WLM
SagDIG



Milky Way at distance of Andromeda

Astronomy 101: $F = \frac{L}{4\pi r^2}$

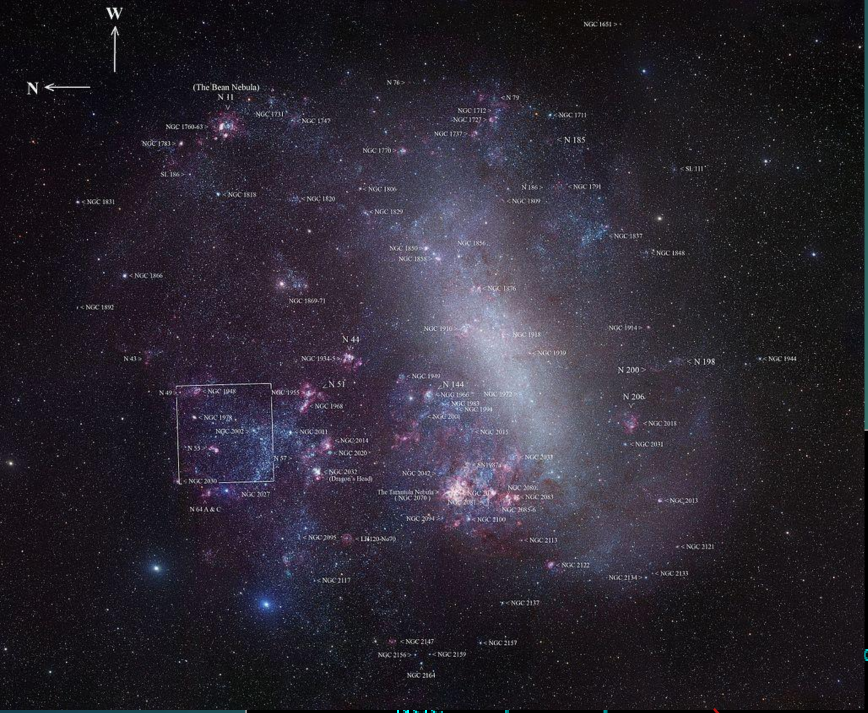
F(>100MeV)=1.17*10^{-5} photons/cm2/s/sr

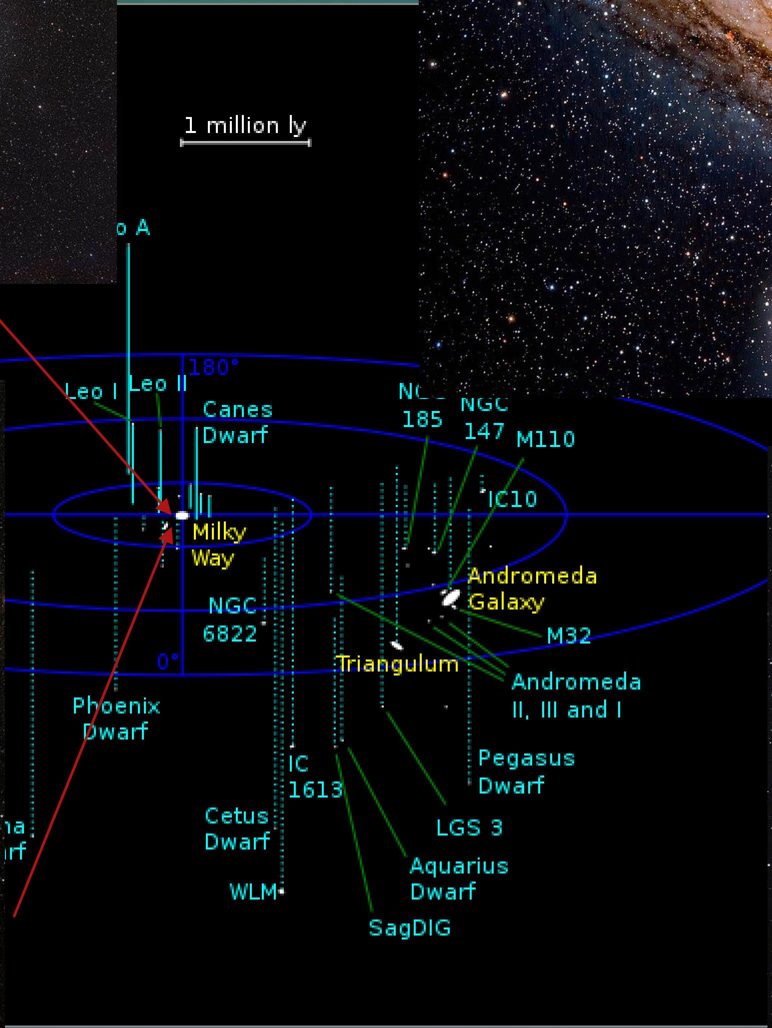
Radius of the Milky Way R=30kpc

L=1.17* 10^{-5} *8.57*10^{45} *4*pi

Distance to Andromeda r=570kpc

F=10^{41}/(3.1*10^{48})~0.3*10^{-7} photons/cm2/s




1 million ly
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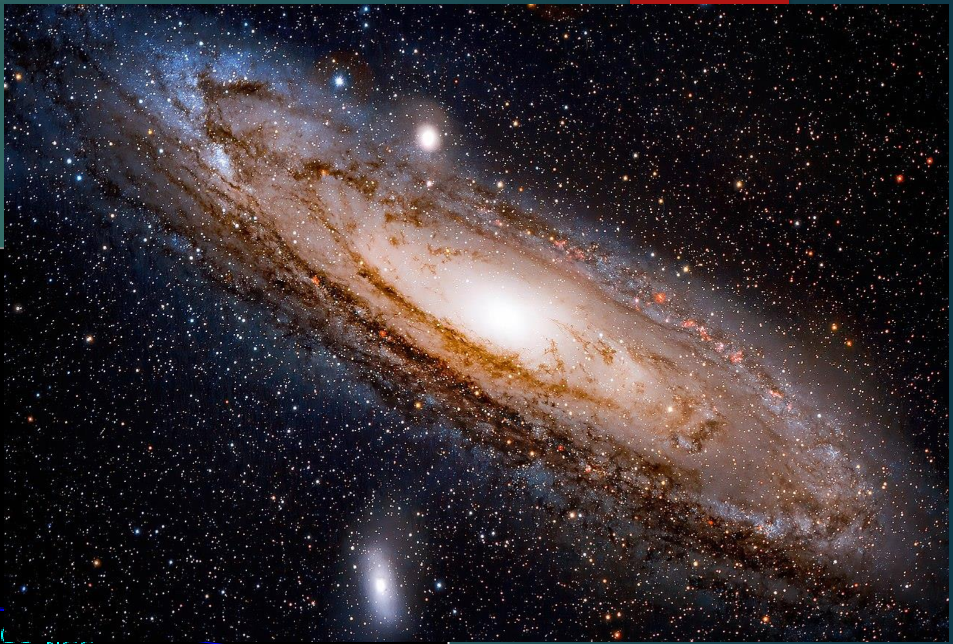
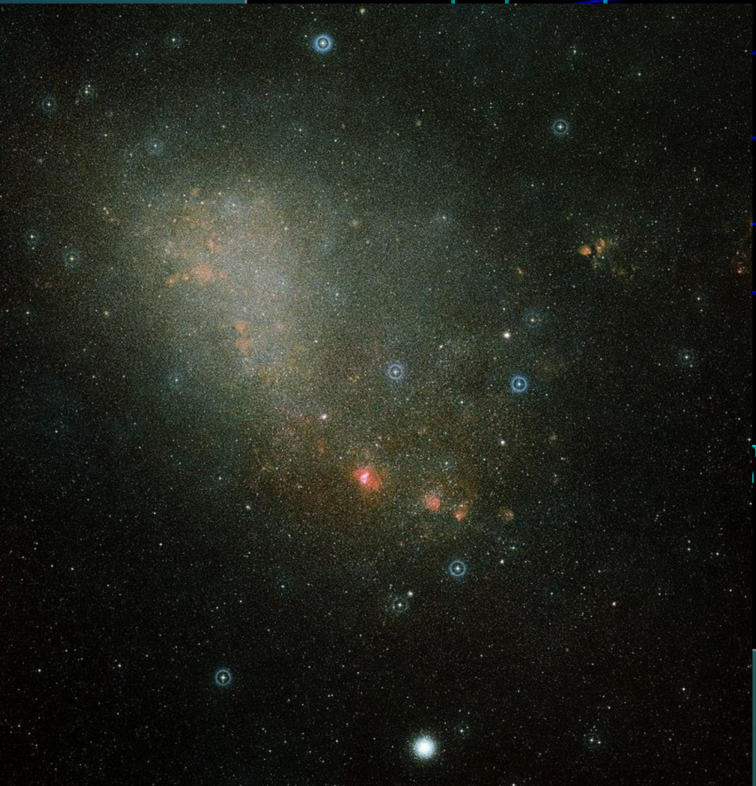




Dwarf galaxies

- Dwarf galaxies are small and faint galaxies orbiting as satellites to more massive galaxies (like MW). MW has many and they are close!
- LMC (distance 52 kpc) is source of gamma-rays: Already EGRET saw diffuse emission (1.9+-1.4)*10^{-7} /cm2/s), Fermi-LAT *extended*, but 50% of the emission is coming from 30 Doradus, also detected at VHE by HESS telescopes. SMC also detected.
- The stars show large circular velocities and velocity dispersion that compared to their modest spatial extension indicates that the dynamics are dominated by dark matter
- Dwarf spheroidal galaxies are population of very faint galaxies with high mass to luminosity ratio => high density of dark matter
- The dwarf galaxies could produce gamma-rays via WIMP annihilation (not covered on this lecture)

Starburst galaxies

- In starburst galaxies: higher density of ISM, (high star formation rate=>) more SNR=> higher density of cosmic rays and cosmic ray accelerators

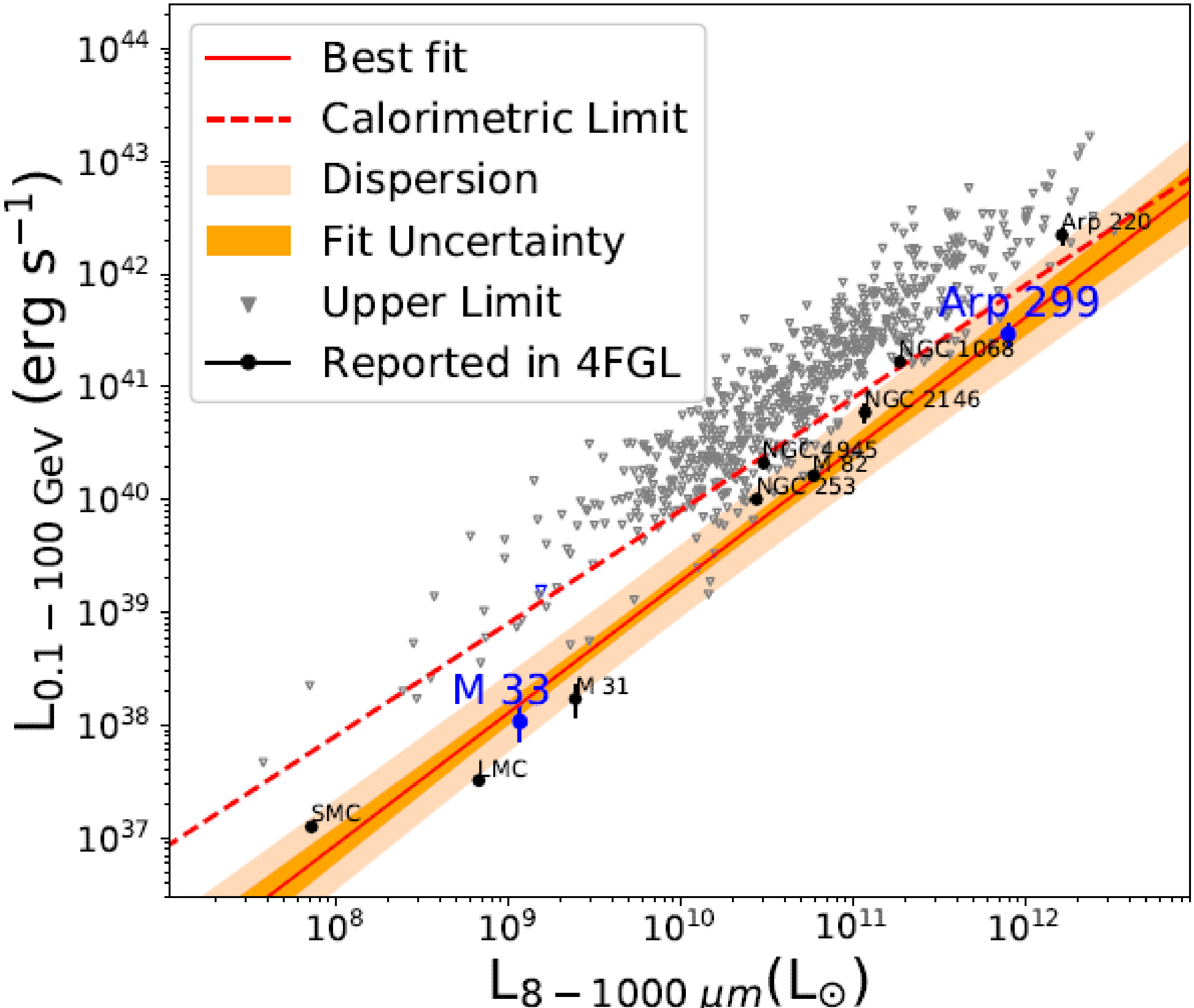
More is more:
Brighter gamma-ray sources
Can be detected from
creater distances!

Starburst galaxies - observations

- VHE gamma-rays have been observed from two starburst galaxies: M82 (d~5Mpc) by VERITAS and NGC 253 (d~5Mpc) by HESS
- Fermi-LAT sees in addition NGC4945, NGC2146, NGC1068, Arp 299

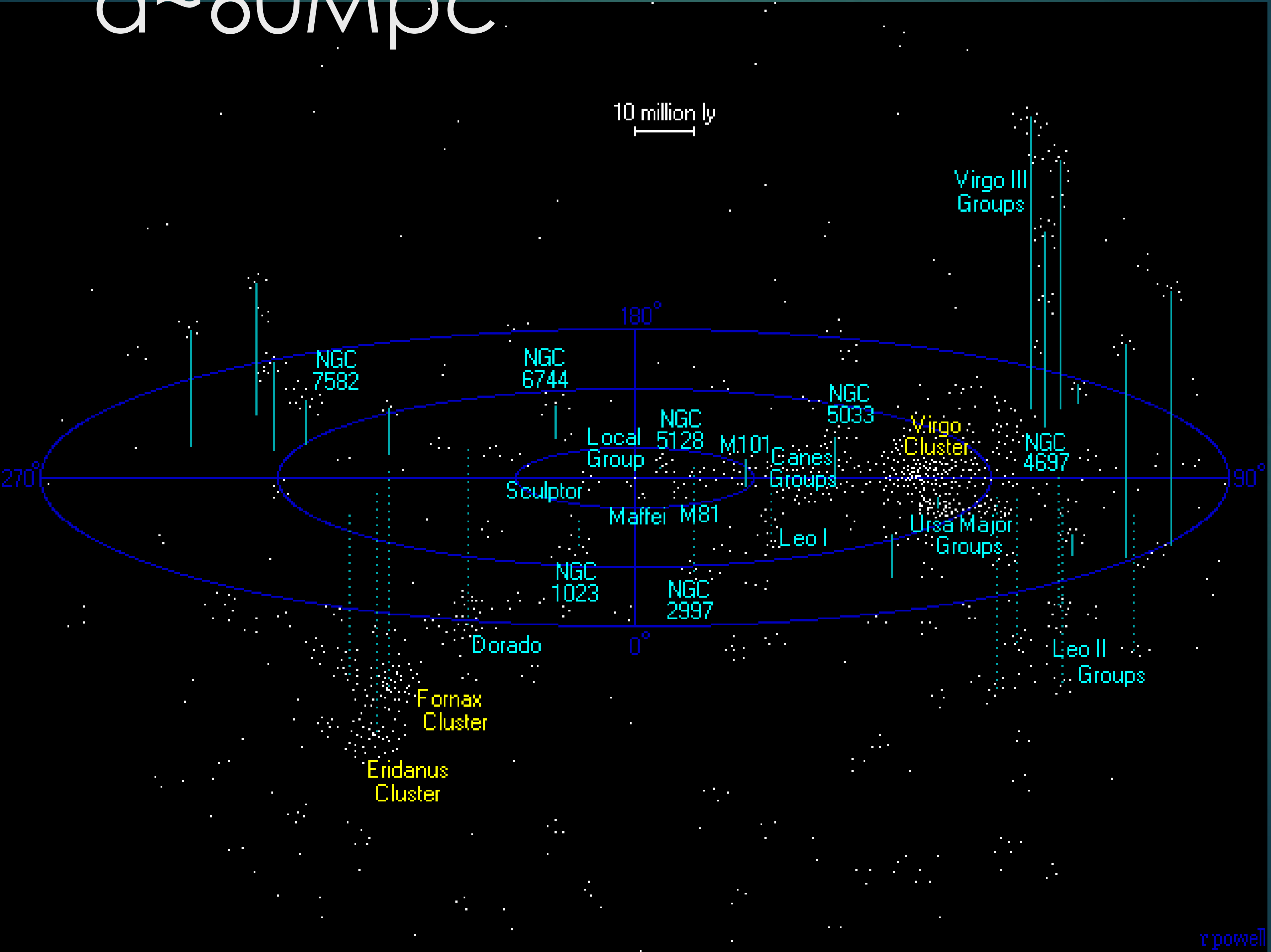
Ultraluminous infrared galaxies

- IR luminosity ~$10^{12}L_{sun}$
- Starbursting, nuclear activity, very dense environment
- Also very rare: the closest one (Arp220, d=72Mpc): no detection of VHE gamma-rays (yet).



Xi et al. 2021, ApJ, 2020, 901, 158

Virgo supercluster, d~60Mpc



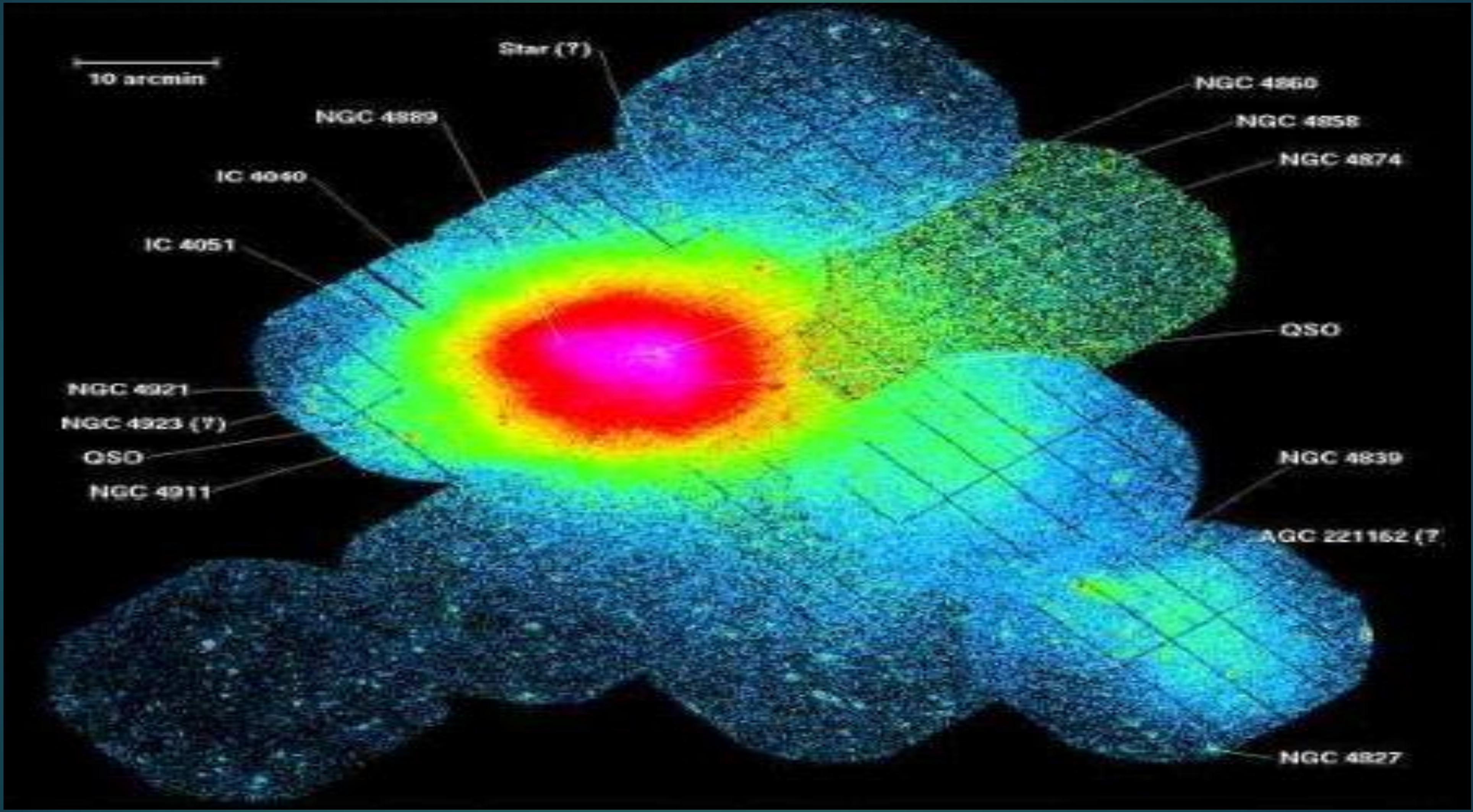
Galaxies of own supercluster ~handful of sources

WE NEED MORE, MAYBE THE CLUSTERS THEMSELVES?

Galaxy Clusters

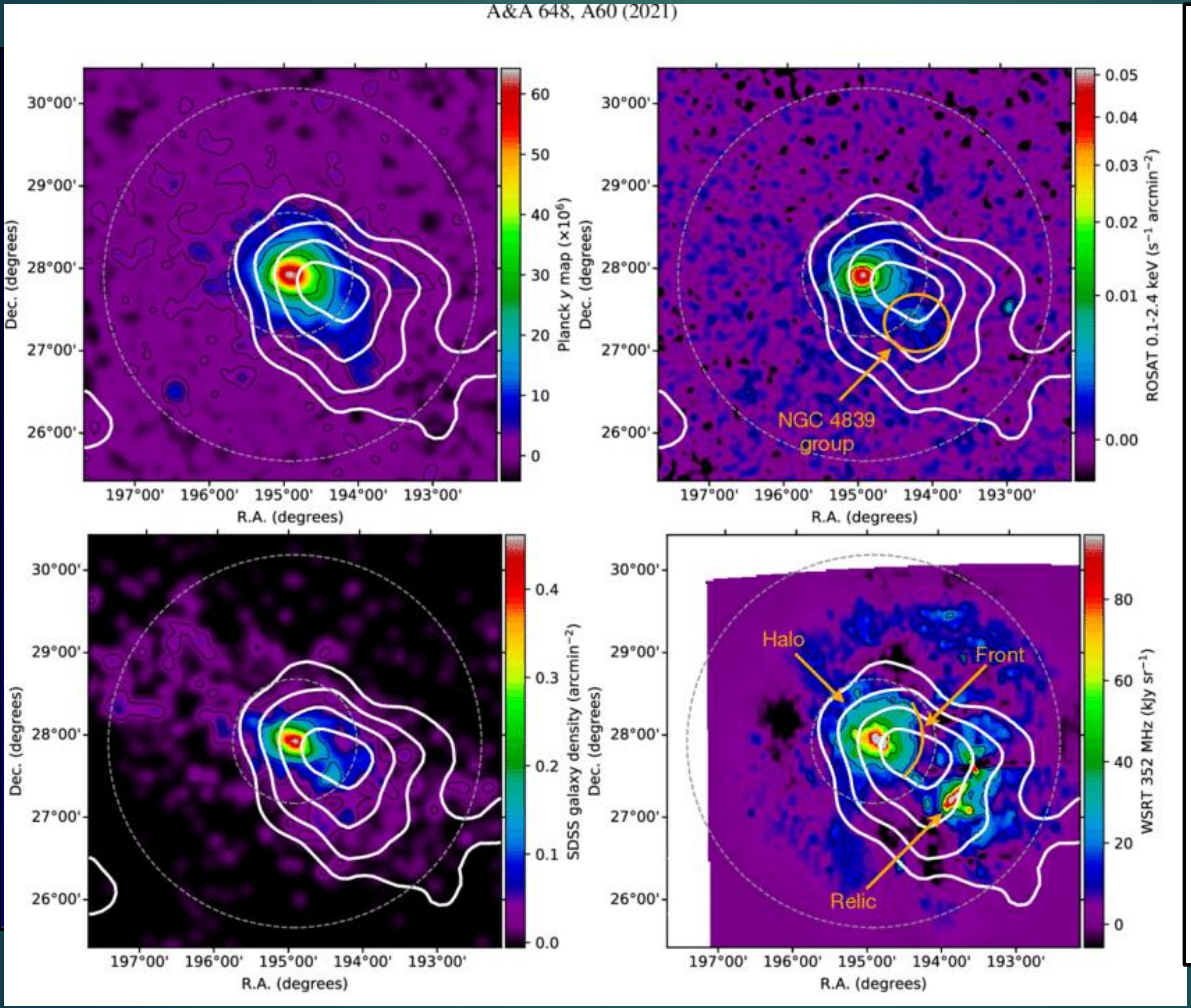
- Largest structures in the present universe in which gravitational force due to the matter overdensity overcomes the expansion of the universe
- Large collection of galaxies, gas and dark matter
- Rich clusters mass 10^{15} M_{sun}, mostly in form of dark matter, only 1% in galaxies, 5% in hot gas
- Non-thermal emission (radio, X-rays) = accelerated particles, i.e. relativistic electrons, magnetized ICM, magnetic field topologically complex

X-ray map of Coma Cluster



Hot gas + non-thermal emission

Clusters of Galaxies

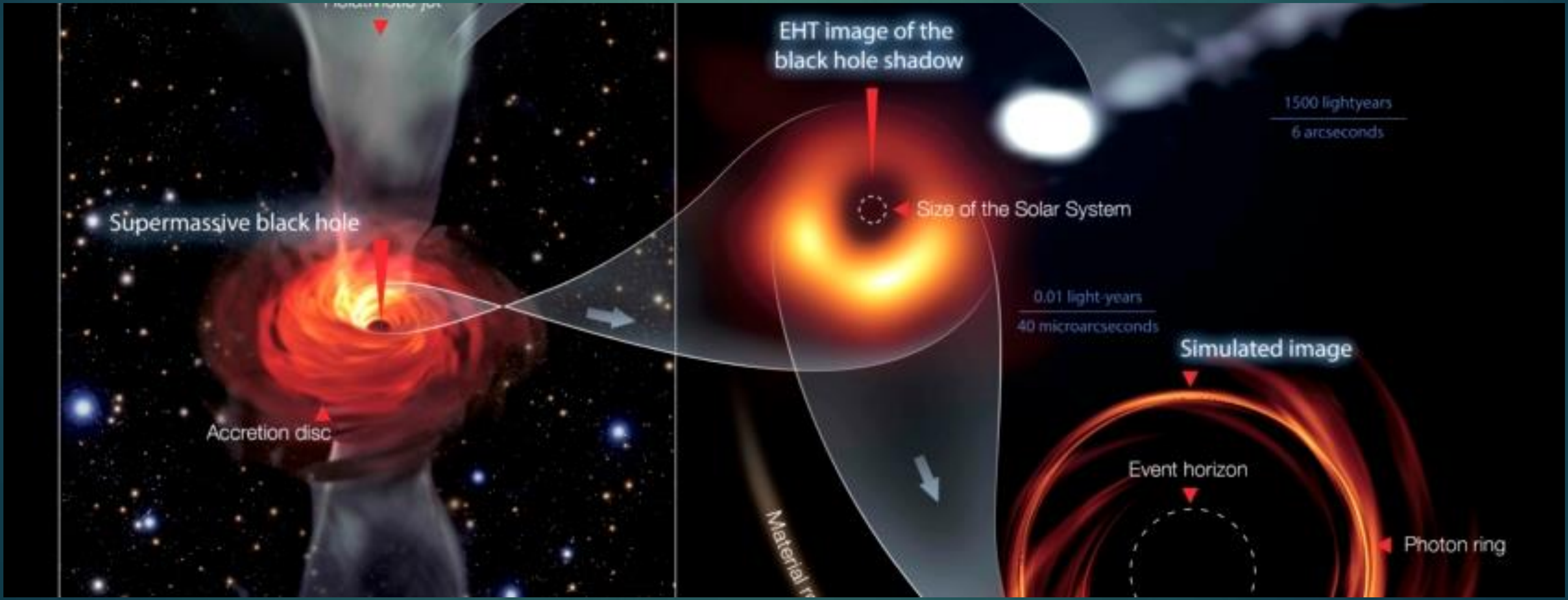


Multiwavelength morphological comparison of the Coma cluster signal to the Fermi-LAT TS map obtained in our baseline model. Top left: Planck tSZ. Top right: ROSAT X-ray. Bottom left: SDSS galaxy density. Bottom right: WSRT 352 MHz radio signal. The field of view of all images is 5 × 5 deg 2 . The white contours give the Fermi-LAT TS map (contours at 4, 9, 16, and 25) for the reference MINOT model (n CRp ∝ n 1/2 e). For all panels, the black contours correspond to the maximum of the image divided by 2 i , with i the index of the contours. The dashed gray circle provides the radius θ 500 and 3 × θ 500 . Several relevant features are also indicated in orange. For display purposes, the WSRT image has been apodized at large radii to reduce the larger noise fluctuations present on the edge of the field. As a complementary figure, Fig. 8 provides an optical image of the central region.
Ramzi et al. 2021, A&A

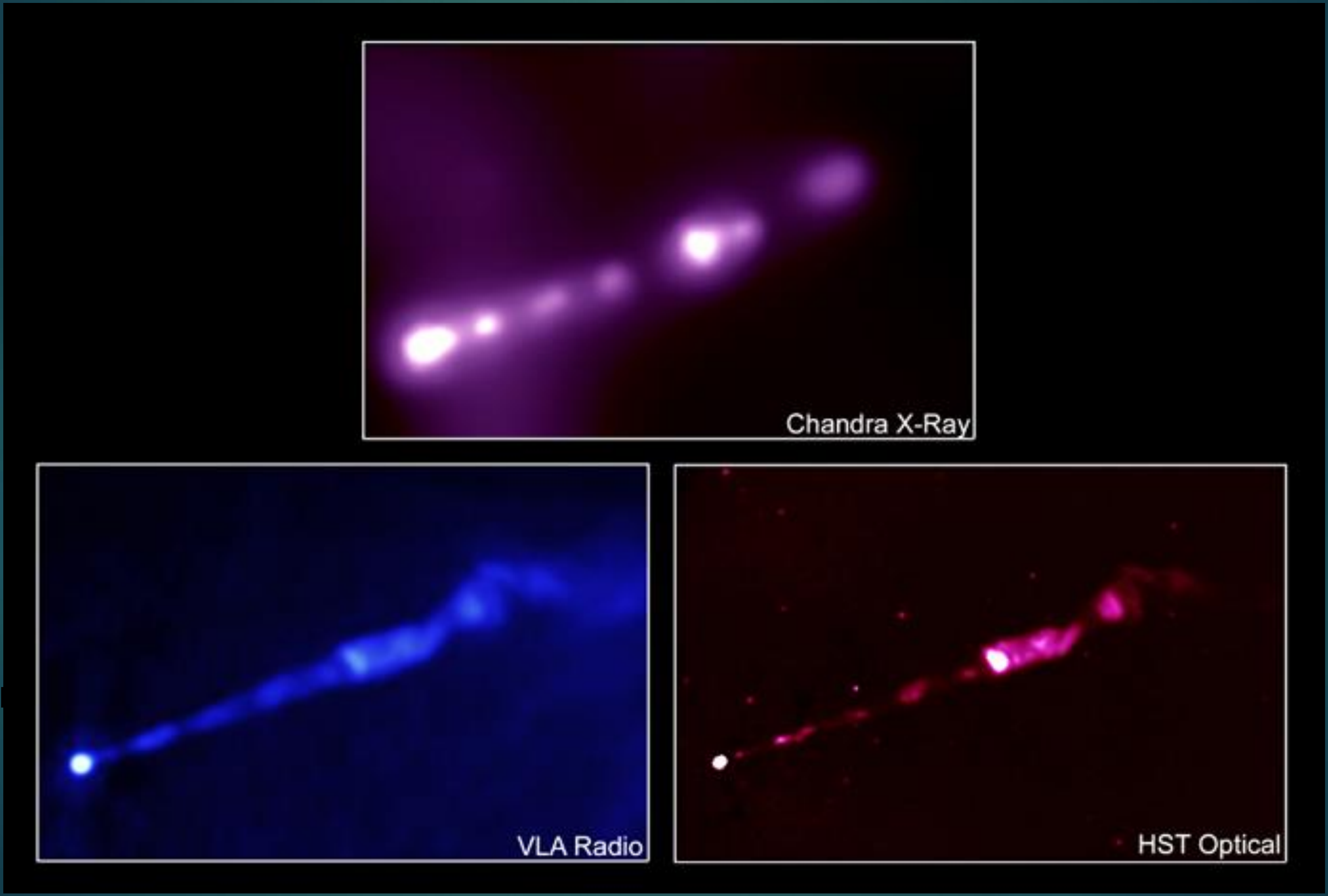
Clusters themselves: maybe few closeby…

WE NEED MORE, ANY IDEAS?

Centre of Virgo Cluster: M87, accreting supermassive black hole



M87: Relativistic jets launched by supermassive black hole



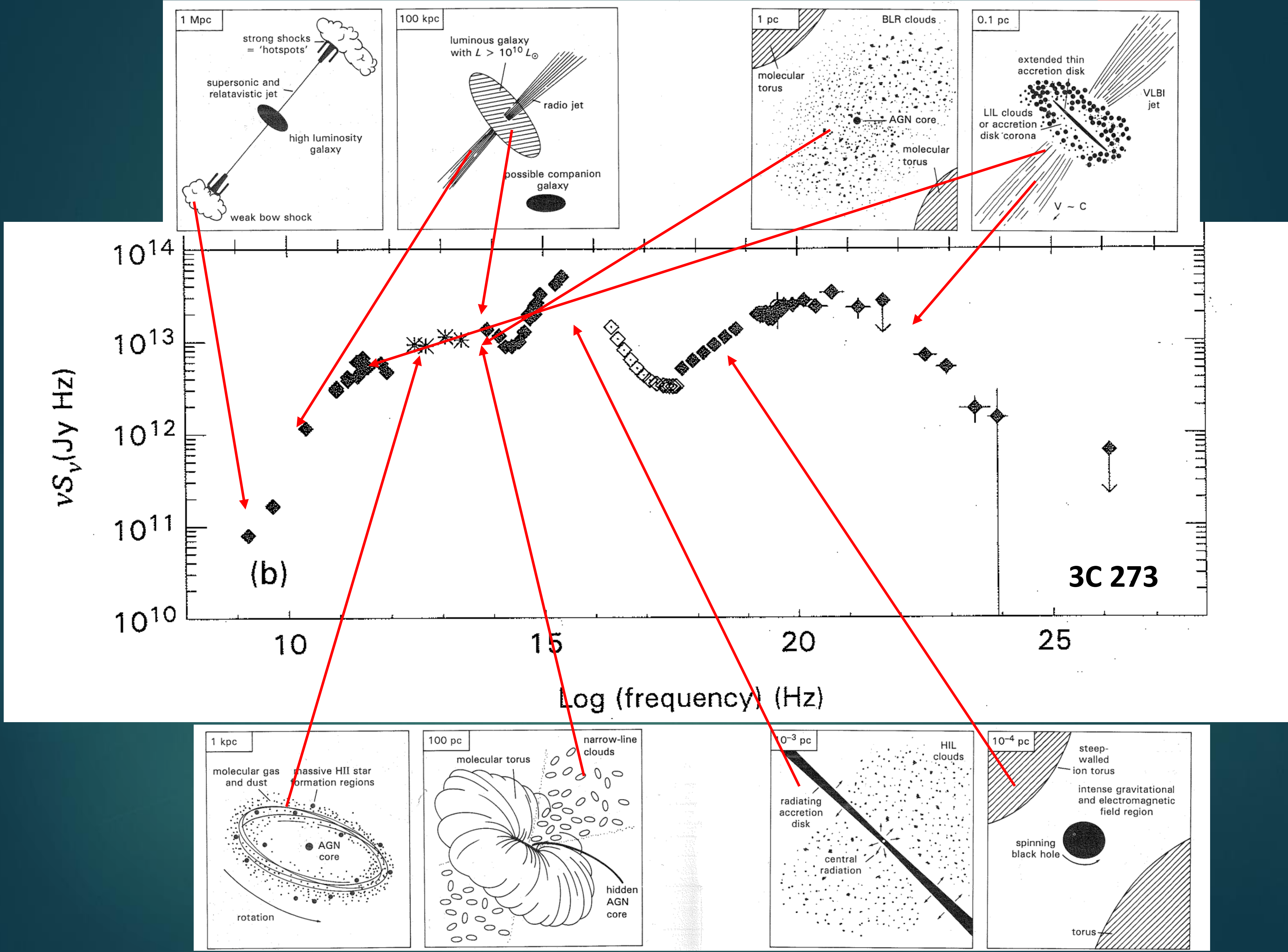
Cr

Active Galactic Nuclei

- Exceptionally bright compared to normal galaxies
- The luminosity originates from the very central region from matter accreting to supermassive black hole in the center of galaxies
- The luminosity of the nucleus outshines the thermal emission produced by the stars of the galaxy

Active Galactic Nuclei

- Central region: supermassive black hole, accretion disk, broad-line region clouds surrounded by toroidal dusty structure (dust torus)
- Note: only some ~10% supermassive black holes launch relativistic jets (10% of AGN radio loud, radio emission manifesting the existence of the jet)
- Relativistic jets: extreme particle accelerators: particle velocities close to that of speed of light


1 Mpc
strong shocks = 'hotspots'
supersonic and relatavistic jet
high luminosity galaxy
weak bow shock
100 kpc
luminous galaxy with $L > 10^{10} L_\odot$
radio jet
possible companion galaxy
1 pc
BLR clouds
molecular torus
AGN core
molecular torus
0.1 pc
extended thin accretion disk
VLBI jet
LIL clouds or accretion disk corona
V ~ C
νS_ν (Jy Hz)
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
(b)
3C 273
10
15
20
25
Log (frequency) (Hz)
1 kpc
molecular gas and dust
massive HII star formation regions
AGN core
rotation
100 pc
molecular torus
narrow-line clouds
hidden AGN core
10^{-3} pc
HIL clouds
radiating accretion disk
central radiation
10^{-4} pc
steep-walled ion torus
intense gravitational and electromagnetic field region
spinning black hole
torus

Active Galactic Nuclei

- Central region: supermassive black hole, accretion disk, broad-line region clouds surrounded by toroidal dusty structure (dust torus)
- Some ~10% supermassive black holes launch relativistic jets (10% of AGN radio loud, radio emission manifesting the existence of the jet)
- Relativistic jets with magnetic fields: extreme particle accelerators: particle velocities close to that of speed of light
- Blazars: Jets pointing very close to our line of sight: Doppler boosting

Doppler boosting

- Magnifies the apparent flux
- Doppler factor

$$S_\nu = \delta^{3-\alpha} S'_\nu ,$$

$$\delta = [\gamma(1 - \beta \cos\theta)]^{-1},$$

Spectral index

Lorentz factor

Viewing angle (small <10 degrees)

v/c, usually very close to speed of light e.g. 0.99

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

γ = Lorentz factor

v = speed of moving observer

c = speed of light

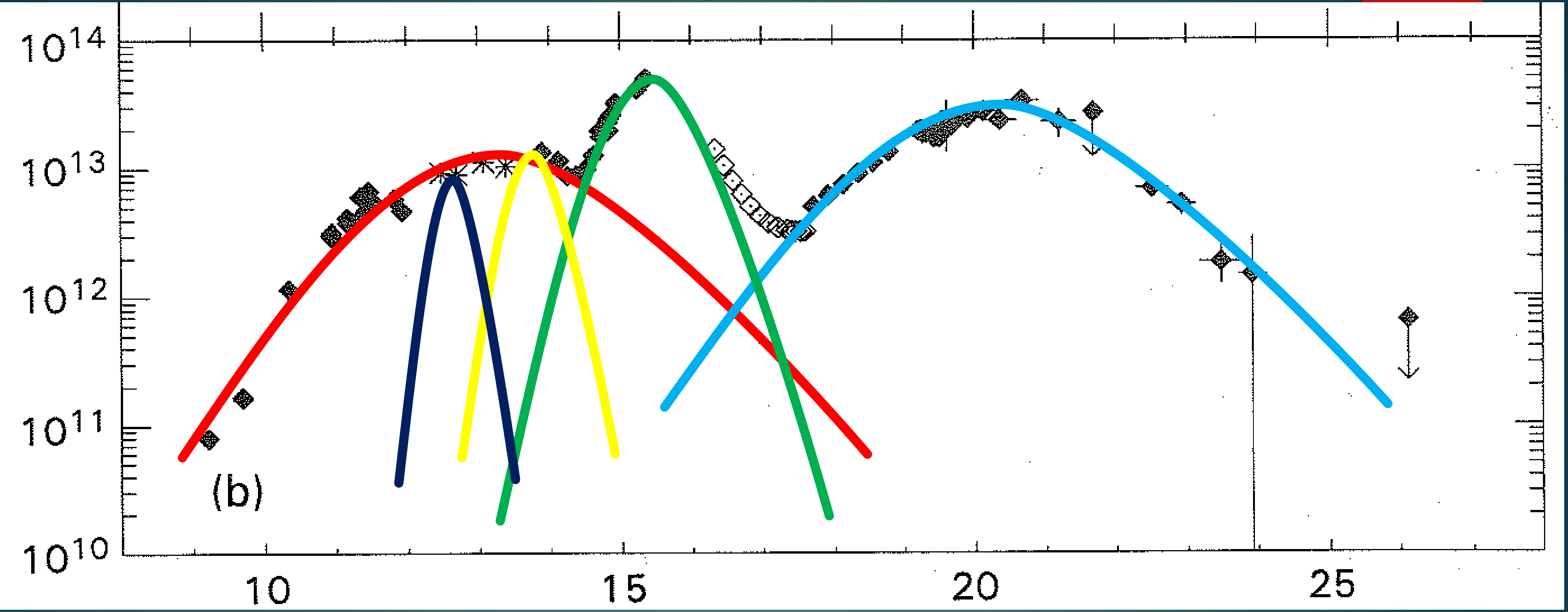
Doppler boosting

Also makes variability times shorter

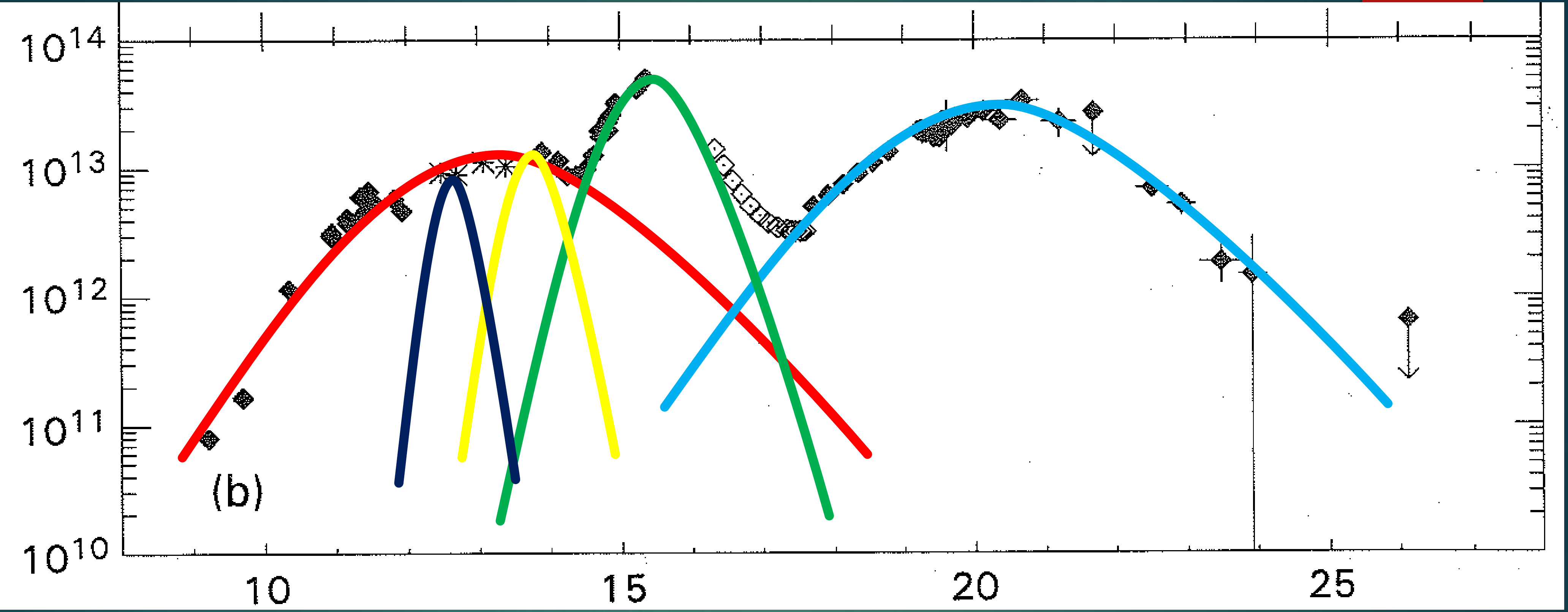
$$\Delta t_{\rm arr} = \delta^{-1} \Delta t'.$$

….Emission from the relativistic jets pointing close to our line of sight: very bright and very variable!

Radiative mechanisms in AGN in nutshell

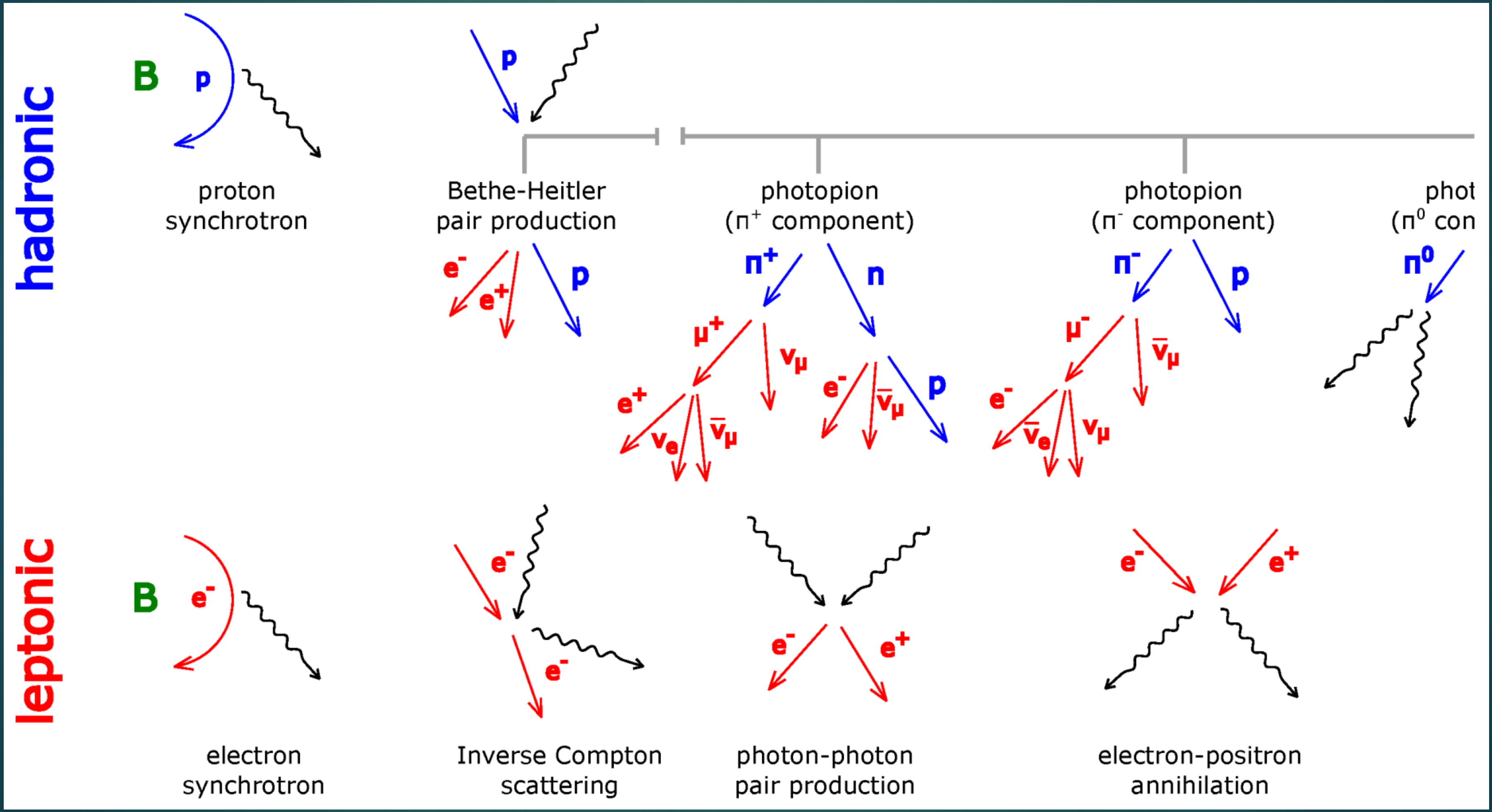


Radiative mechanisms in AGN in nutshell

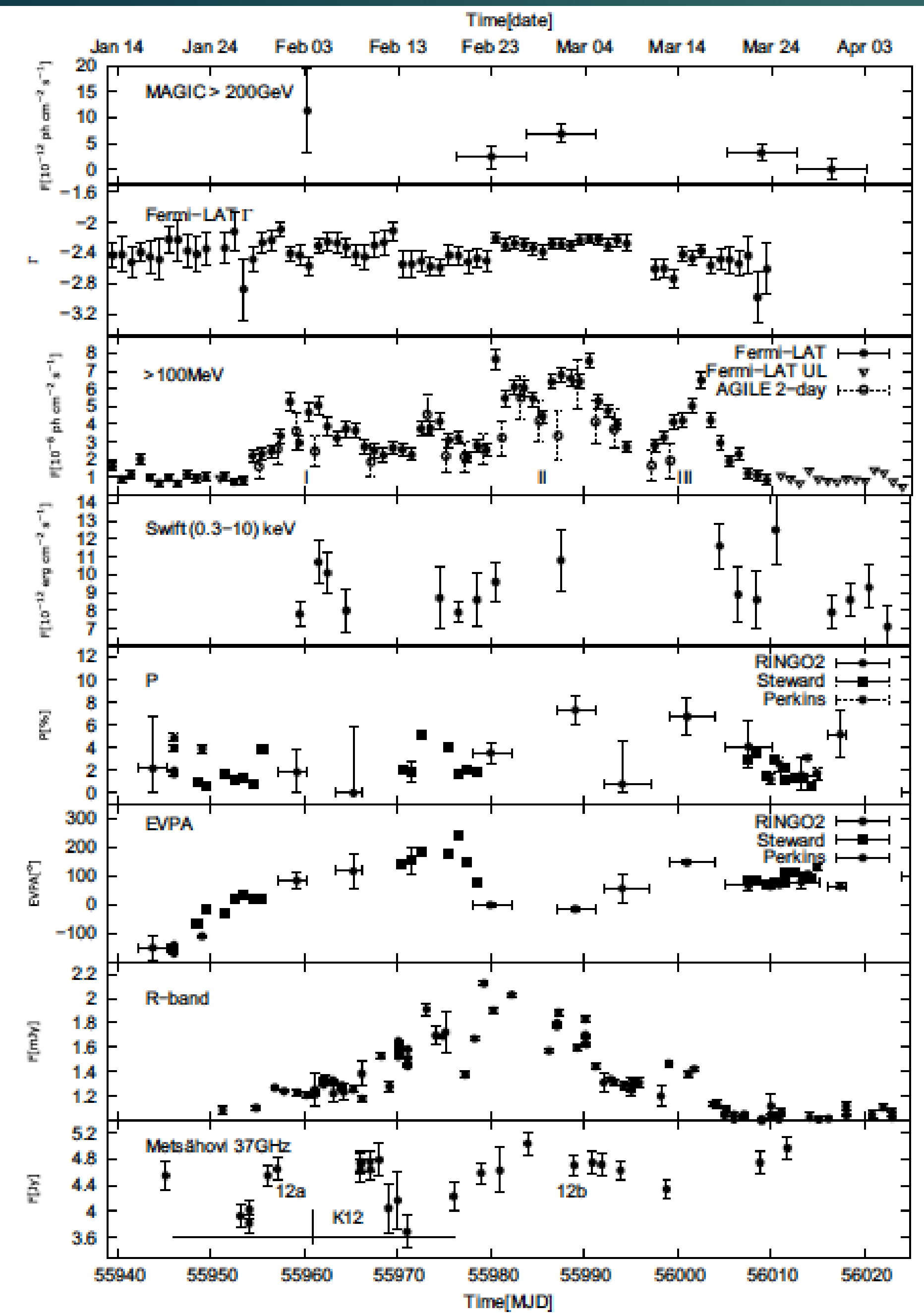


- **Synchrotron radiation** from the relativistic jet
- **Inverse Compton? radiation** from the relativistic jet
- **Blackbody (greybody) radiation** from the accretion disk
- **Blackbody (greybody) radiation** from the parent galaxy ($\Sigma 10^{11}$ stars)
- **Blackbody (greybody) radiation** from heated dust
- **[Line radiation (emission/absorption)** from gas **]**

Second SED peak; maybe also hadronic?



Variable emission

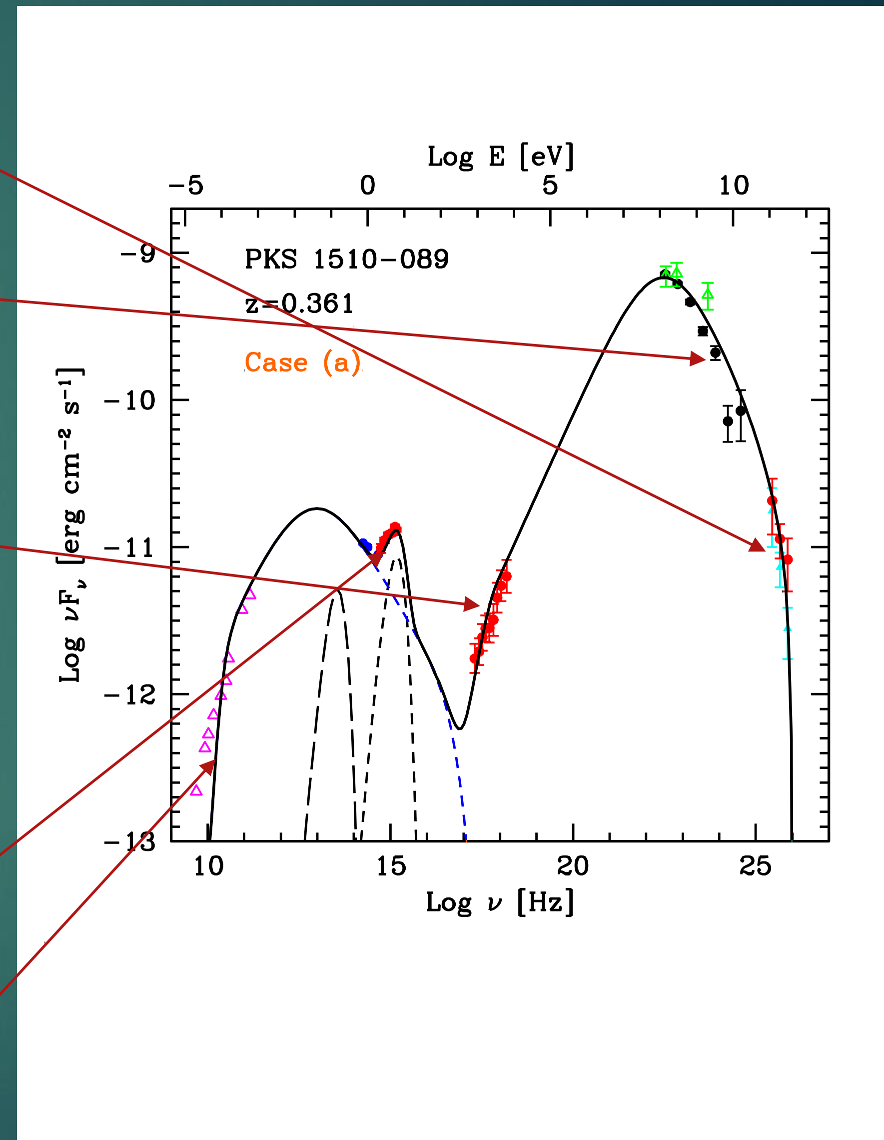


Gamma-rays

X-rays

Optical

Radio

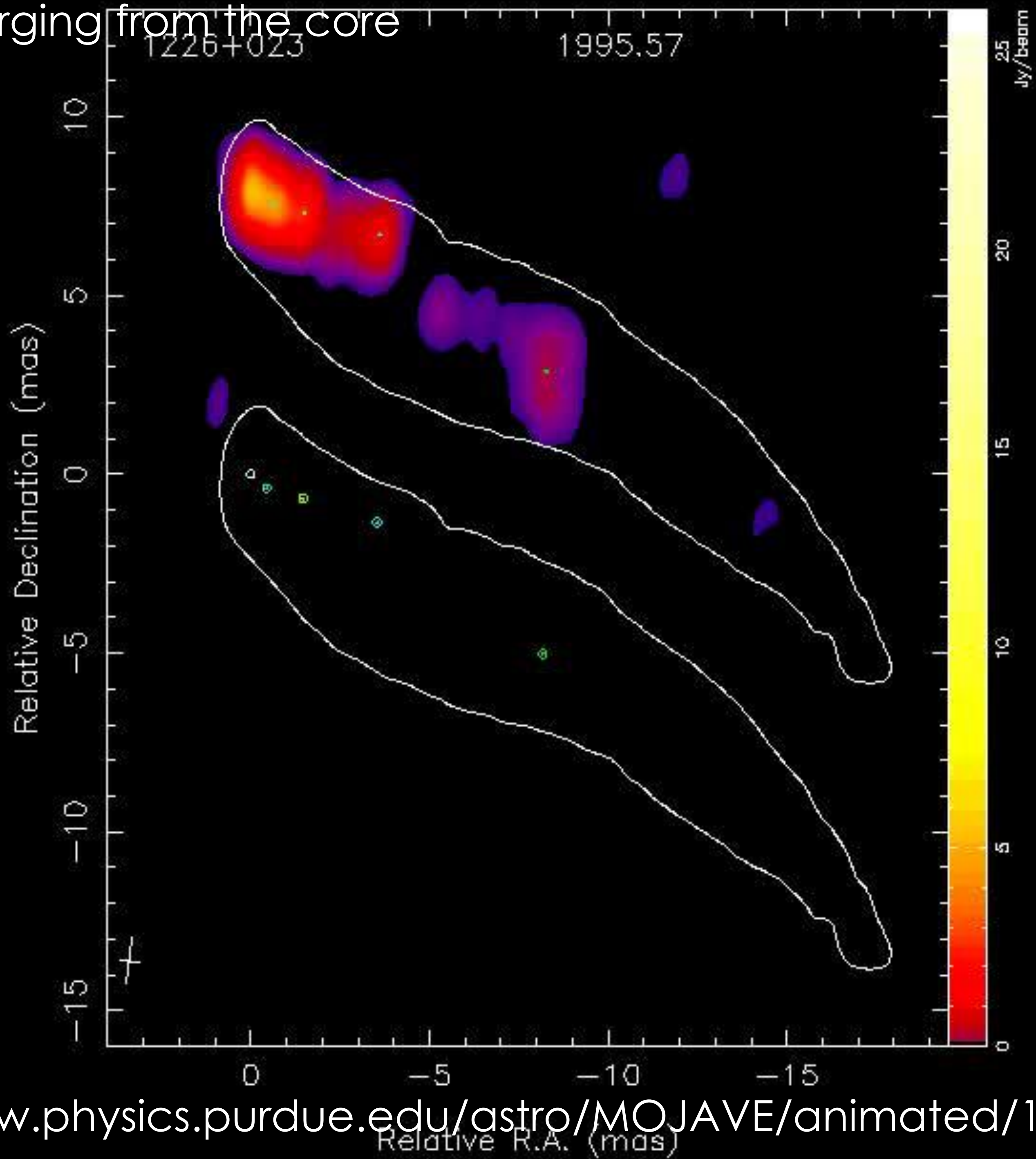


Plots from Aleksic et al. 2014

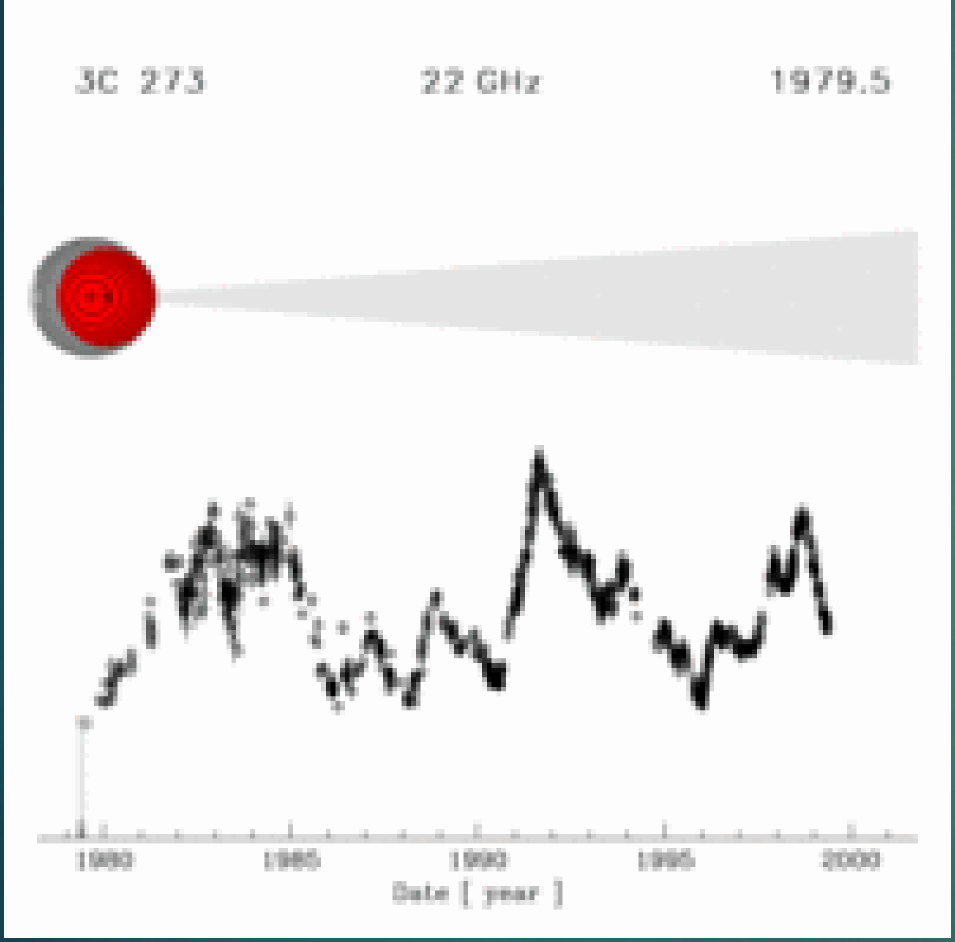
Origin of variability

OR THE BIT THAT WE THINK WE KNOW

Origin of variability in radio: Following the time evolution over several years allows one to see changes in the structure of the pc-scale jet and new “blobs” emerging from the core



http://www.physics.purdue.edu/astro/MOJAVE/animated/1226+023.i.mpg



Animation by Türler et al. 1999

It is possible to connect the blobs with variability seen on the light curves: Before a new blob emerges, the core is seen to brighten and then a blob is seen in traveling down the jet.

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THE ASTROPHYSICAL JOURNAL, 846:98 (35pp), 2017 September 10 Jorstad et al.

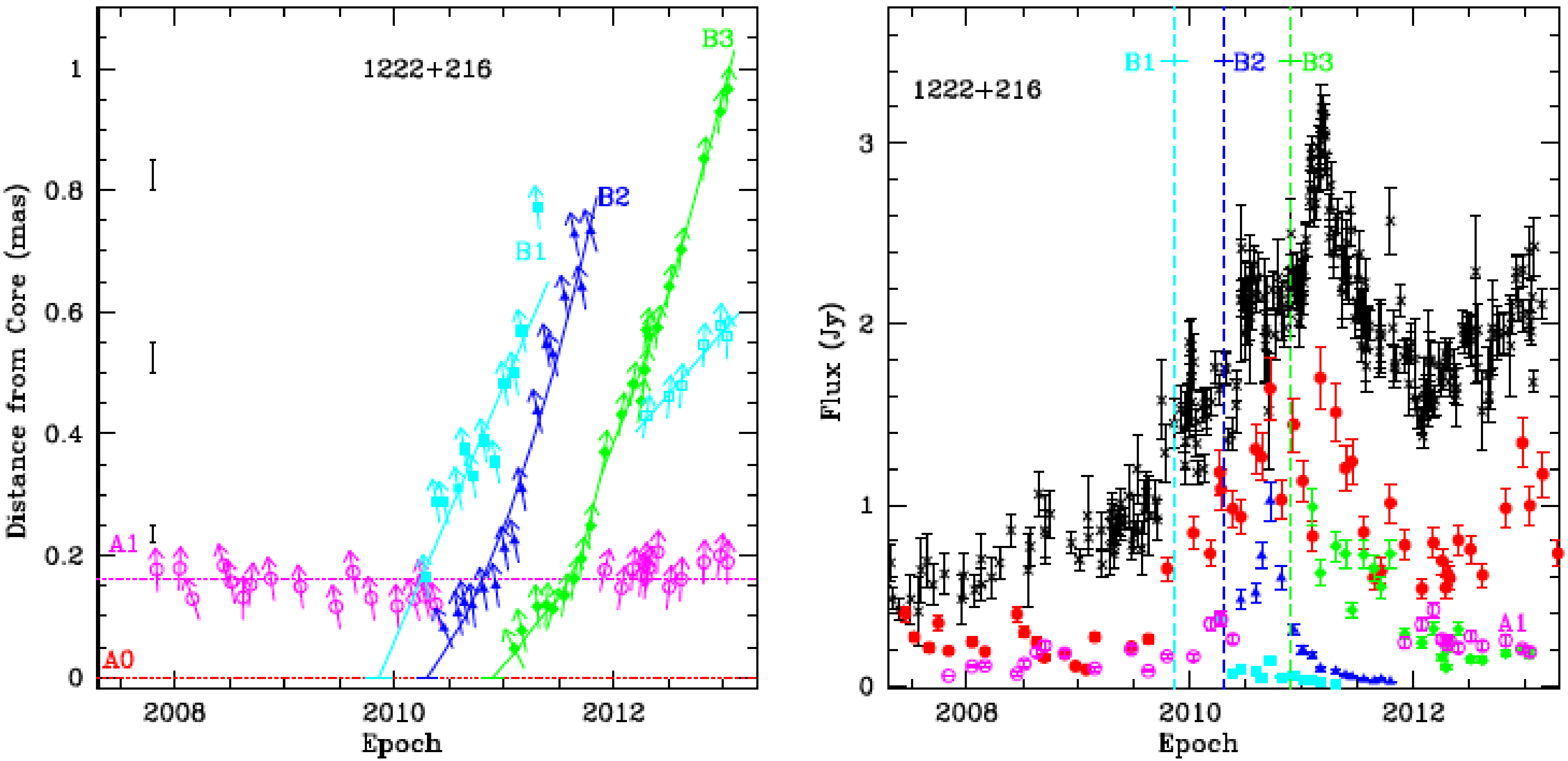
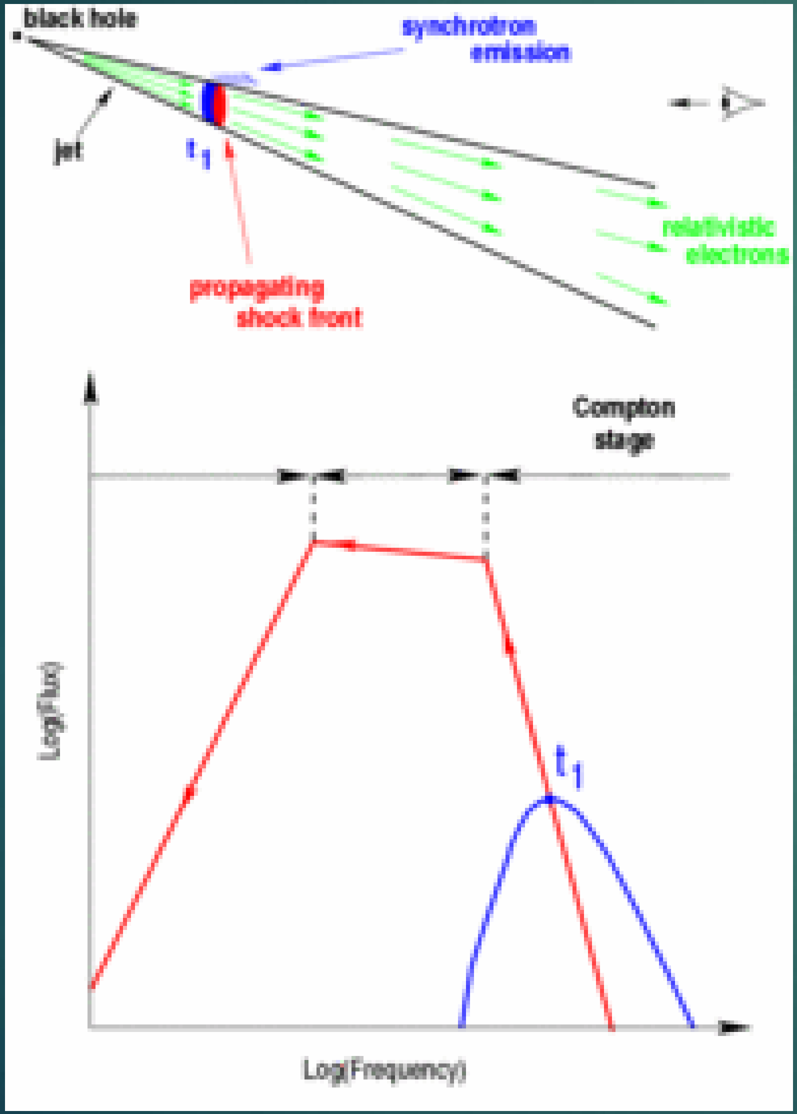


Figure 4. Separation of jet features from the core and their light curves. Left: separation vs. time of knots in the jet of the quasar 1222+216 from the VLBA-BU-BLAZAR sample. The vectors show the P.A. of each knot with respect to the core at the corresponding epoch. The solid lines or curves (depending on the parameter l in Table 5) represent polynomial fits to the motion, while the dotted red and magenta lines mark the position of the core, $A0$, and stationary feature, $A1$, respectively. The vertical black line segments show the approximate 1σ positional uncertainties based on $T_{b,obs}$. Right: the light curves of the core, $A0$ (filled circles, red), and jet components, and the light curve of the entire source at 37 GHz (black crosses); dashed lines indicate the epochs of ejection of the moving knots. Symbols and colors correspond to the same knot in the left and right plots. Plots for all sources in the sample are available in figure set.

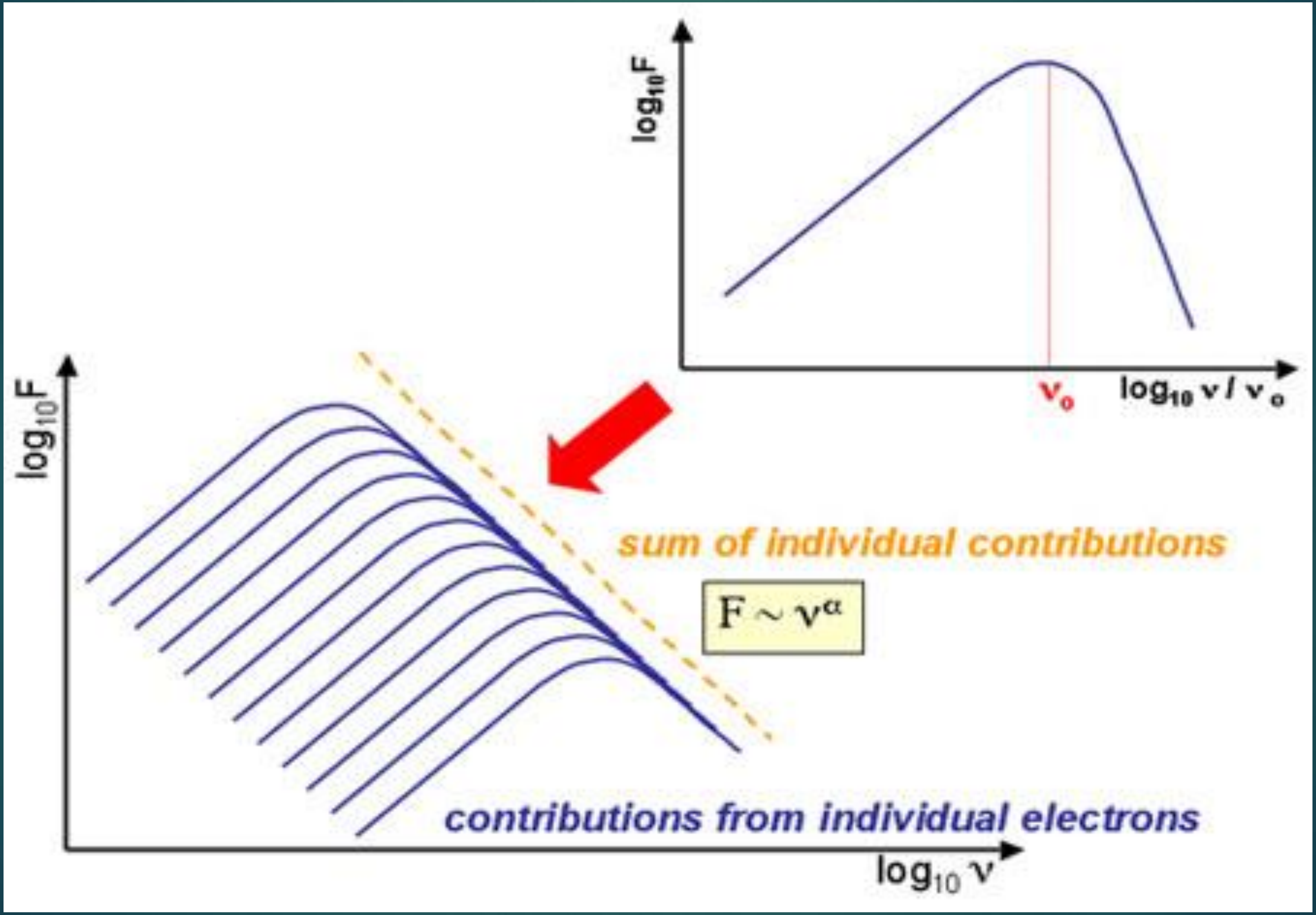
A physical explanation for this is shocks traveling down the jet. They cause the synchrotron spectrum of each individual blob to evolve in time.



Animation by Türler et al. 1999

- Before the shock model, the emission was modeled with pure adiabatic expansion – Van Der Laan model
  - Electrons simply lose energy due to expansion of the emission region
- Because the spectral shape was seen to evolve during flares, it became apparent that adiabatic expansion cannot be the cause of variability
- The first shock models were introduced in 1985 by Marscher & Gear and Hughes, Aller & Aller.
- Main difference to adiabatic model is the inclusion of inverse Compton and synchrotron radiation losses, and energy gain of the electrons in the shocks

Re-cap: What do we see in radio band? Final resulting power law spectrum is a sum of individual electron spectra



http://astronomy.swin.edu.au/cosmos/S/Synchrotron+Emission

Optically thin synchrotron spectrum between γ_1=10 and γ_2=10^4

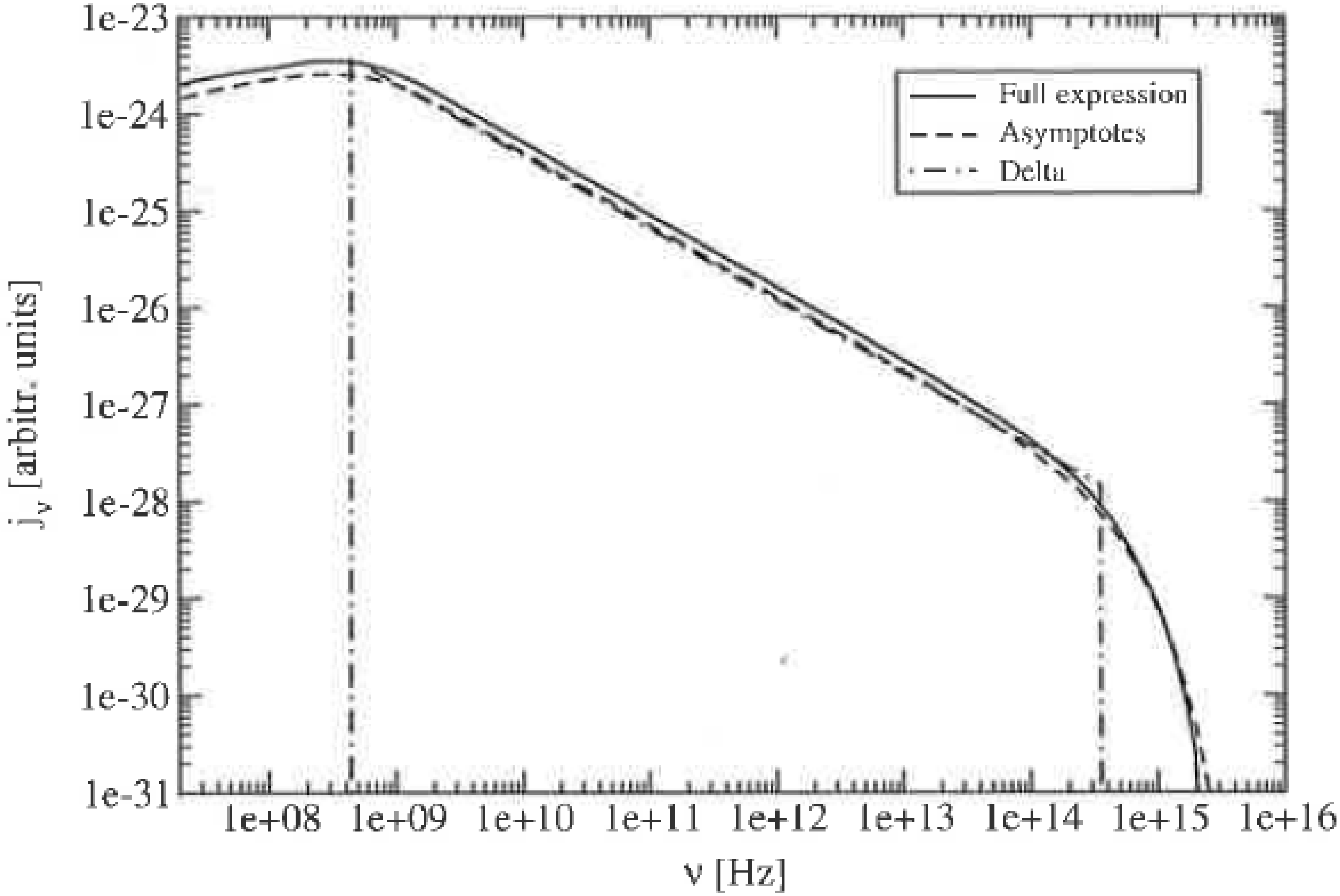


Figure 3.2 Optically thin synchrotron spectra from a power-law distribution of electrons with index $p = 2.5$ and cutoffs $\gamma_1 = 10$ and $\gamma_2 = 10^4$ for a magnetic field of $B = 1$ G. The figure compares the full expression (3.34), the $\nu^{1/3} e^{-\nu/\nu_c}$ approximation (3.38), and the δ function approximation (3.40).

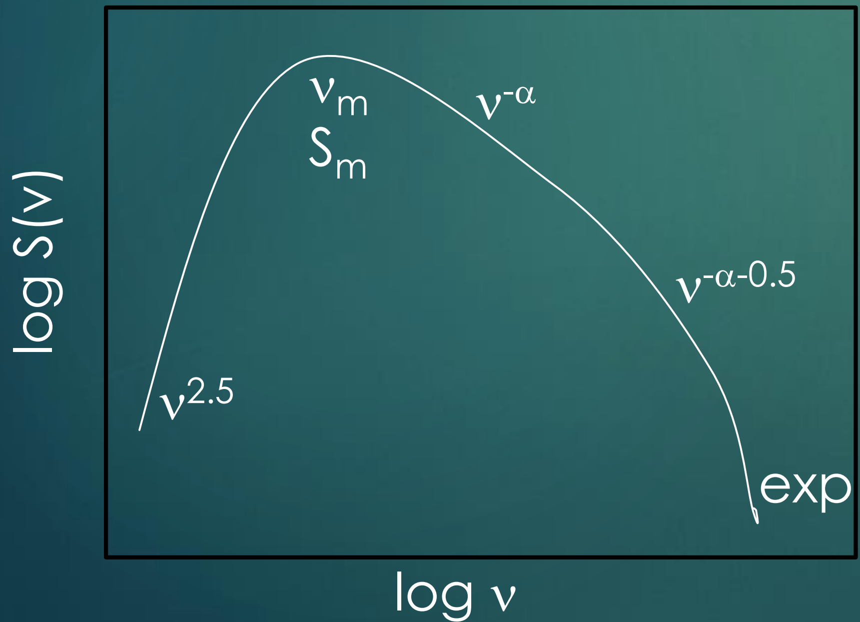
Böttcher: Relativistic Jets from AGN

Modifications

Low frequencies: *self-absorption* $\Rightarrow I(\nu) \propto \nu^{5/2}$. Also possible is a *low-energy cutoff* due to the lowest energy for accelerated electrons, E_{min}.

High frequencies: the acceleration process can only reach electron energies up to some E_{max} (Lorentz factor $\gamma_{max} = E_{max}/m_0c^2$) $\Rightarrow$ *exponential cut-off* at frequencies $\nu_h \geq 4B\,\gamma_{max}^2$

Energy losses: higher energy electrons lose energy faster $\Rightarrow$ *steepening* of the spectrum from α to α+0.5. The steepening frequency moves to lower frequencies with time.



Maximum at $\nu_m \approx 8B^{1/5}\Theta^{-4/5}S_m^{2/5}$ [GHz, G, mas, Jy]

with Θ the angular diameter of the source in milliarcseconds. In principle B can be estimated from observations, in practice rather uncertain because of the large exponents.

What is the “core” seen in the VLBA images?

At centimeter wavelengths, it is typically assumed to be the point
where the jet becomes optically thin
for the synchrotron emission at that frequency.

760 Y. Y. Kovalev et al.: Opacity in compact extragalactic radio sources

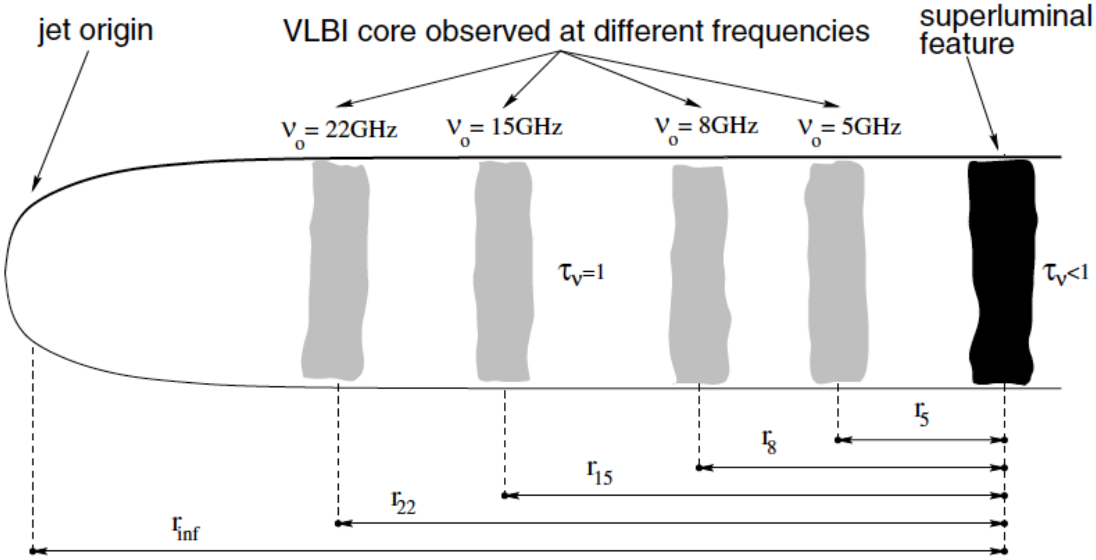


Fig. 1. A scheme illustrating the frequency-dependent position shift of the VLBI core. Adopted from Lobanov (1996).

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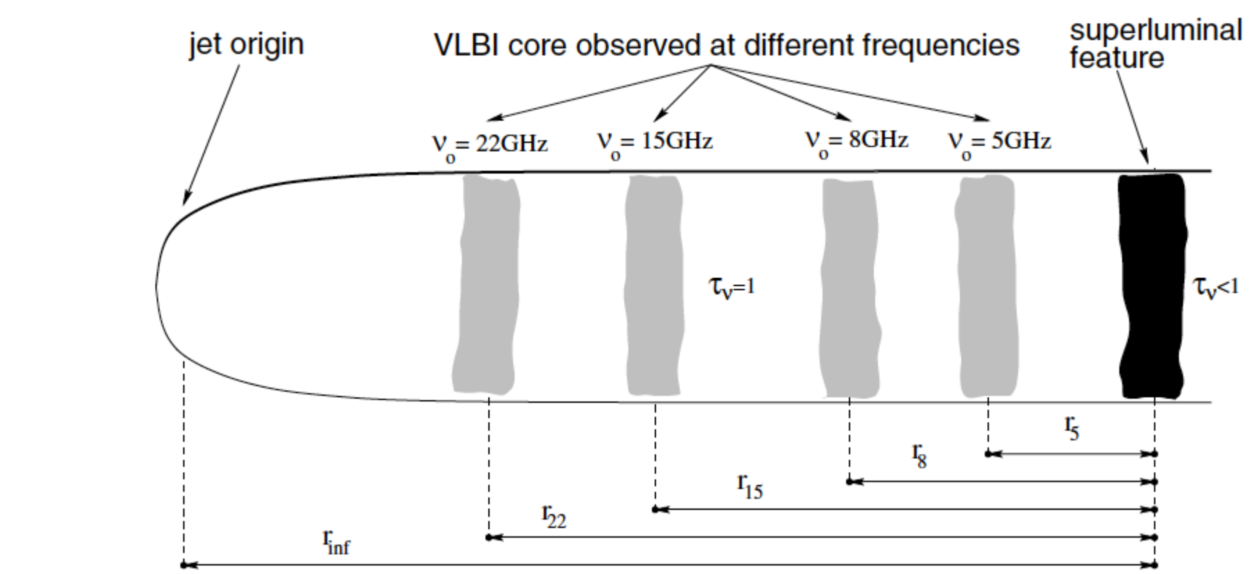
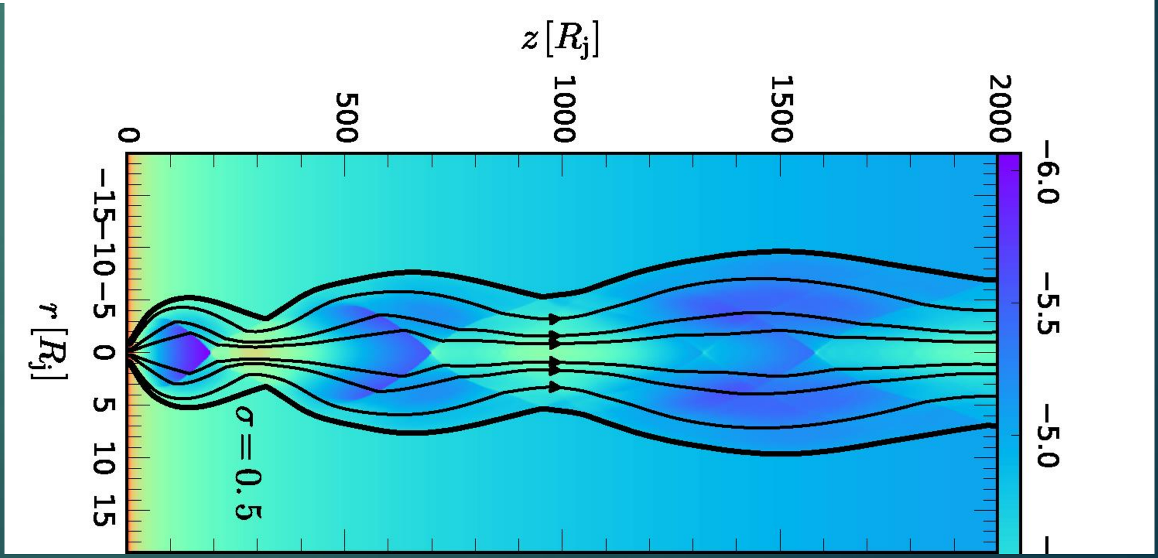


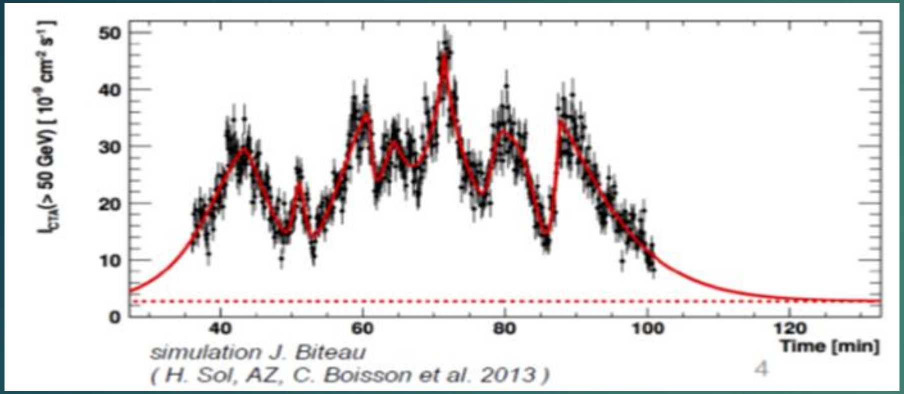
Fig. 1. A scheme illustrating the frequency-dependent position shift of the VLBI core. Adopted from Lobanov (1996).

At millimeter wavelengths, where the jet is already optically thin,
the core could be a recollimation shock

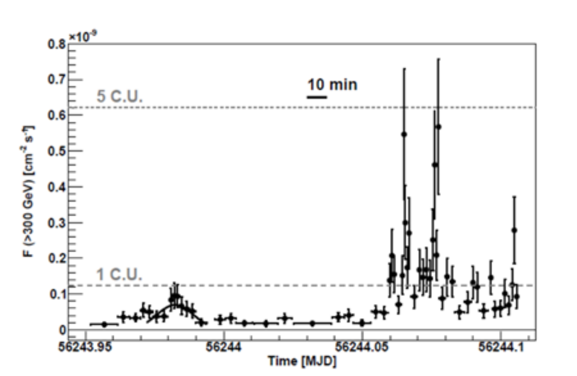


Fromm et al. 2017

What we see in radio bands is not all there is…



simulation J. Biteau
(H. Sol, AZ, C. Boisson et al. 2013)



Aleksić et al. 2014, *Science*

Variability in timescale of minutes at VHE gamma-rays cannot be explained with shock-in-jet model

Magnetic reconnection?

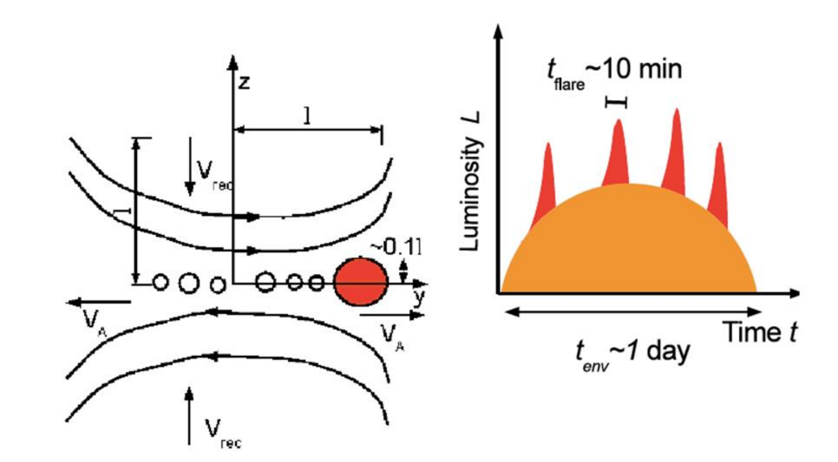


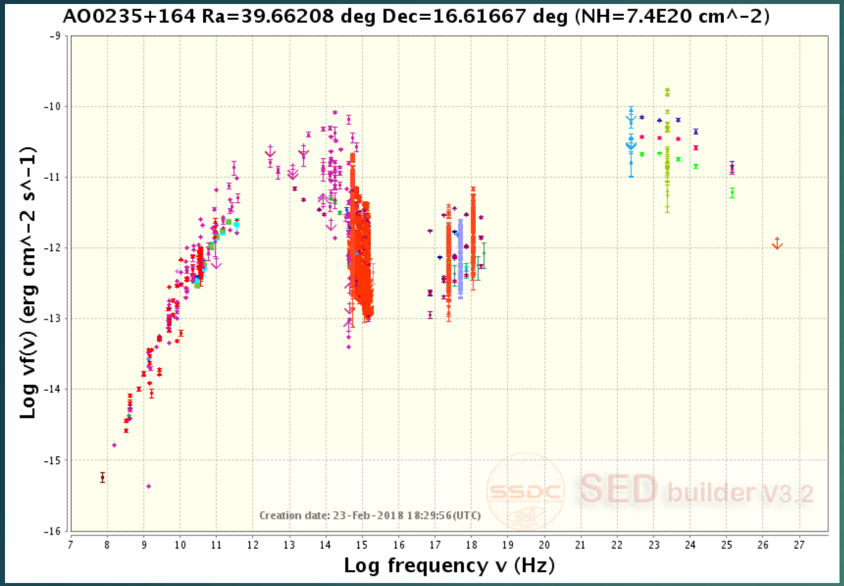
Fig. 14 *Left Panel*: Schematic representation of the geometry of reconnection process shown in a frame comoving with the jet. Magnetic field lines of opposite polarity annihilate at the $x-y$ plane with speed $v_{rec} = \beta_{in}c$. The reconnection layer fragments to a large number of plasmoids. Regularly, plasmoids undergo multiple mergers resulting in a "monster" plasmoid (shaded blob). *Right Panel*: Sketch of the emission from plasmoid-dominated reconnection. The reconnection proceeds on a global timescale $t_{rec} = l/\beta_{in}c$, powering $\sim$ 1day long flares (or envelope emission). Regularly, plasmoids grow to become "monster" plasmoids (shaded blob) giving rise to powerful, fast-evolving flares of duration $t_{flare} \sim 10$ minutes. Several fast flares are expected from a single reconnection event.

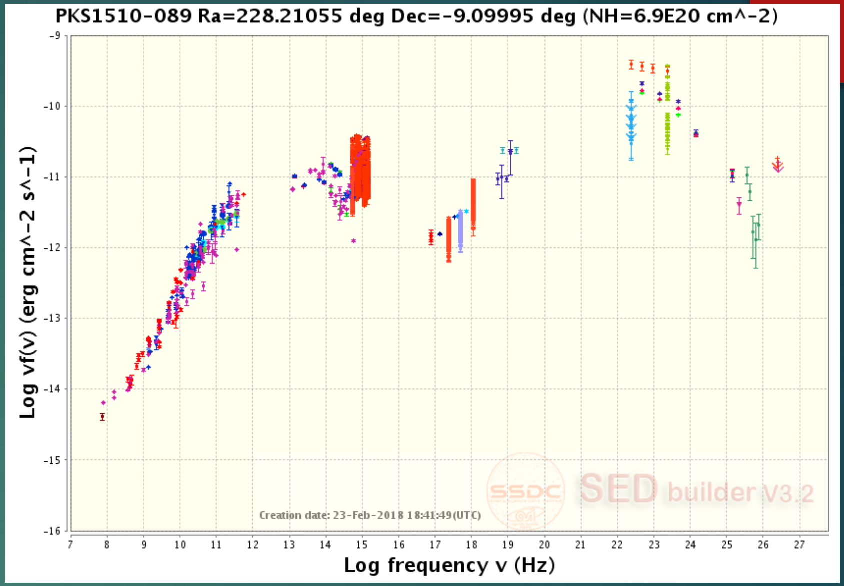
What we think we know about variability

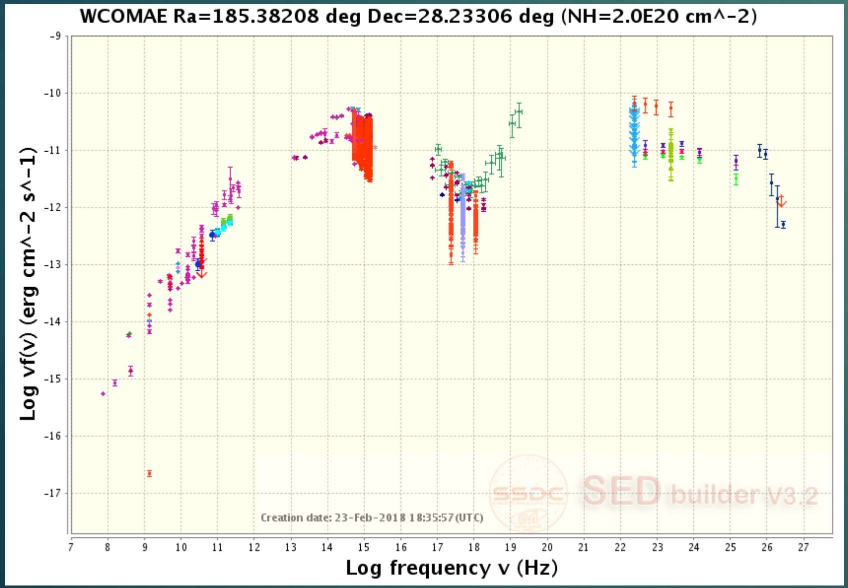
- It is there in all bands
- In radio band it probably has something to do with the emission features we see in the jet
- Emission features are likely to be shocks, but there are also standing shocks (recollimation shocks?), interacting shocks: *particle acceleration*
- Sometimes the variability is all bands have some similar patterns – common origin?
- The fastest variability in gamma-rays: extreme particle acceleration on very compact emission region (emission region much smaller than diameter of the jet)

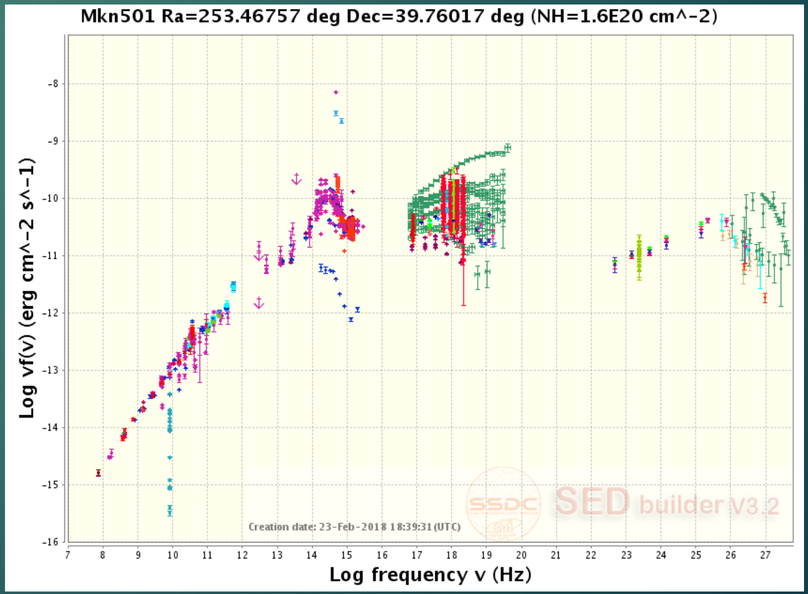
BACK TO SPECTRAL ENERGY DISTRIBUTIONS

What similarities / differences do you see in the SEDs below?

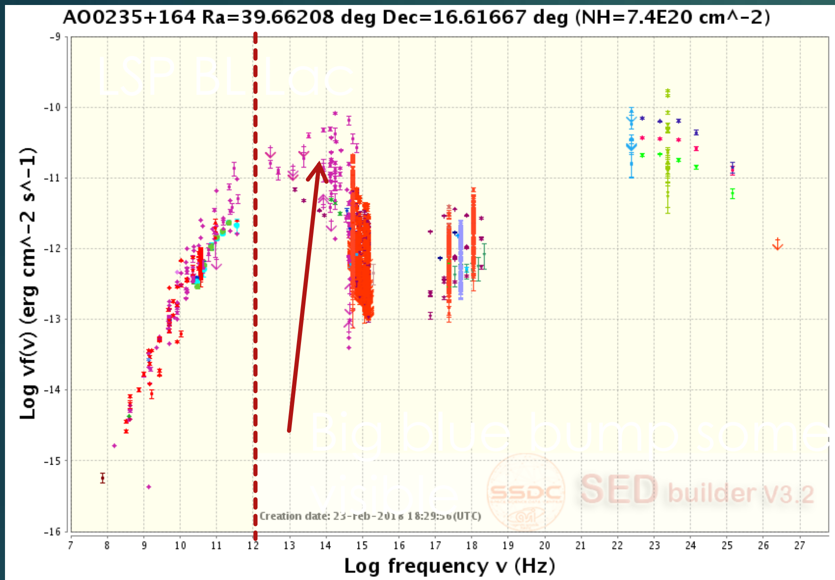


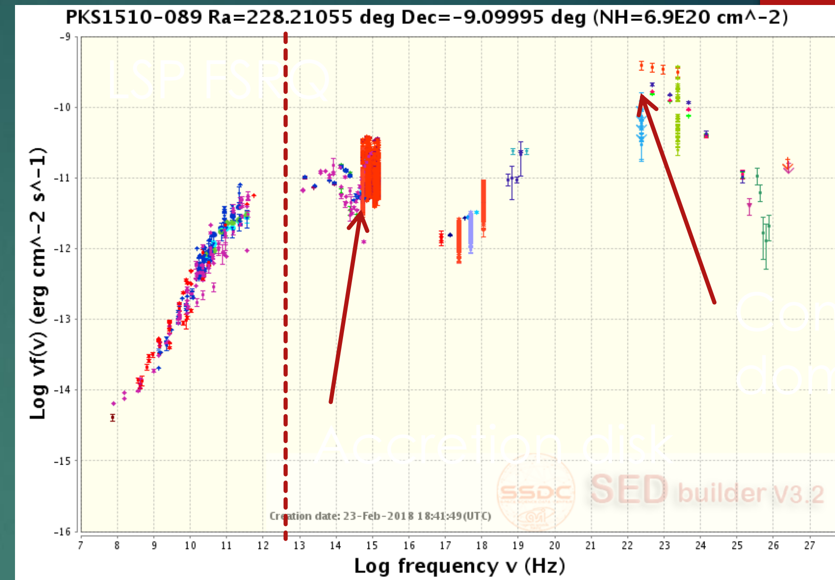






What similarities / differences do you see in the SEDs below?





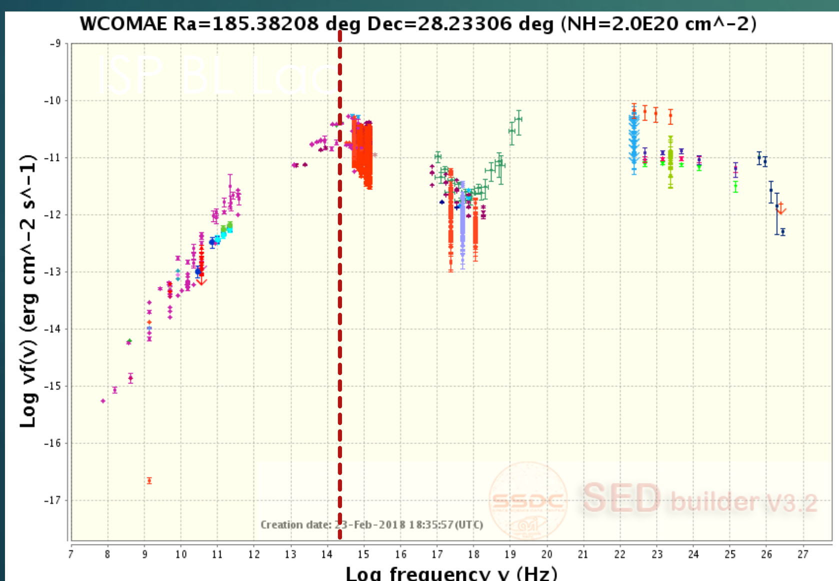
Big blue bump sometimes visible

Accretion disk

Compton dominance

Peak frequenc

of the SED



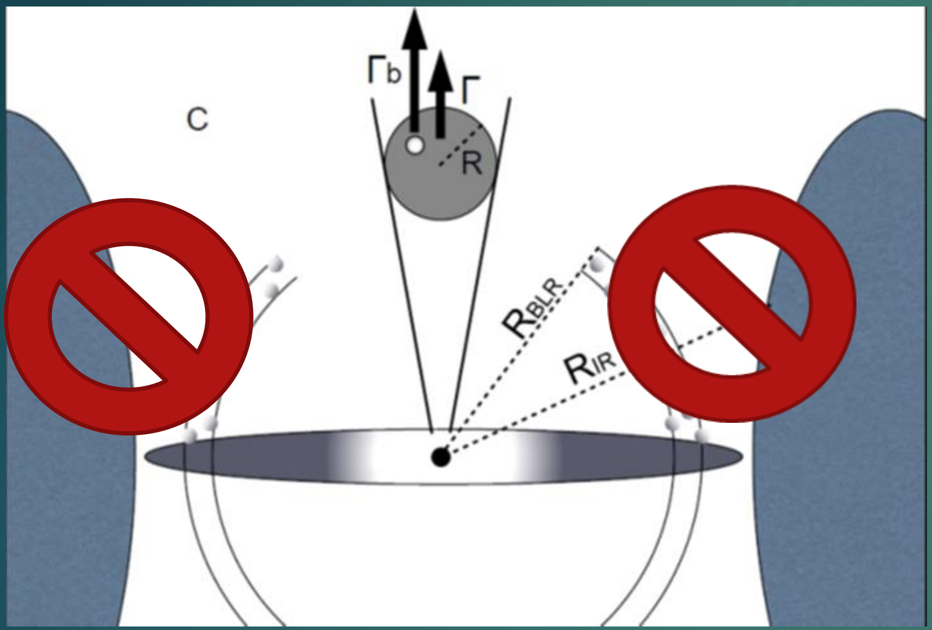
All have prominent

gamma-ray emissio

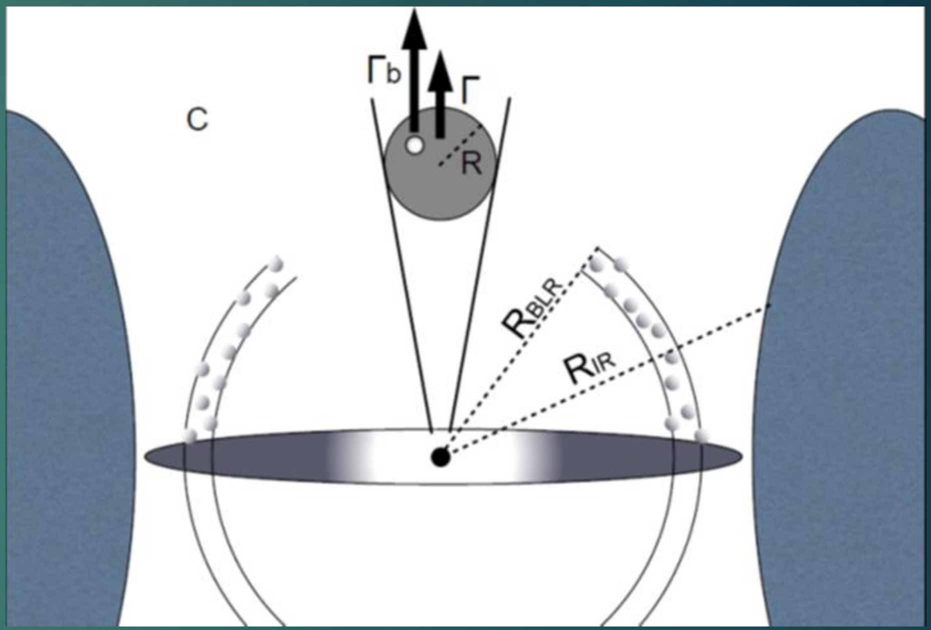
LSP = Low synchrotron peaked, ISP = intermediate synchrotron peaked, HSP = h

$\nu_{peak} < 10^{14}$Hz $10^{14} < \nu_{peak} < 10^{15}$Hz $\nu_{peak} >$

Why are they different



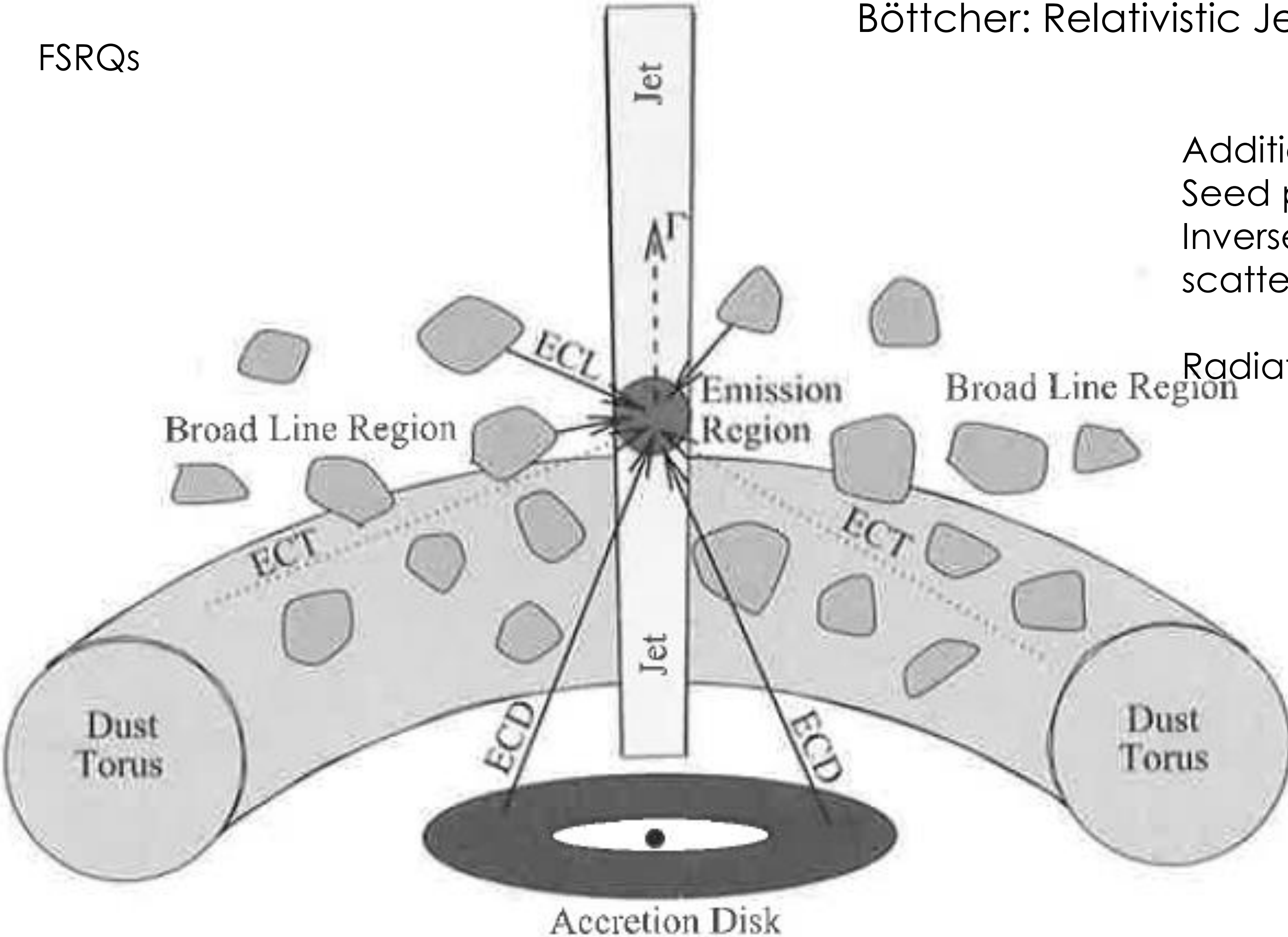
BL Lacs



FSRQs

Böttcher: Relativistic Jets from AGN

FSRQs



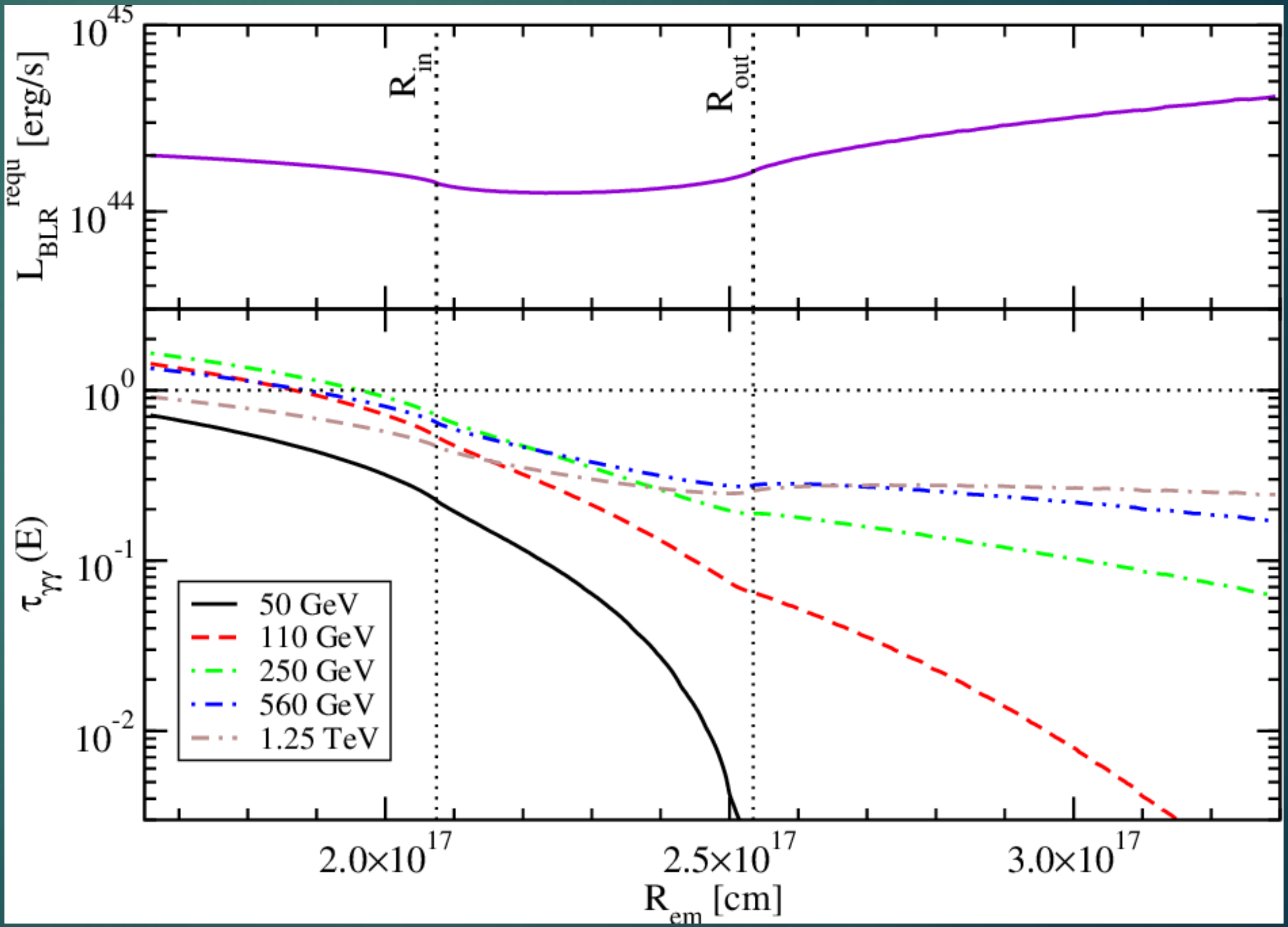
Additional source of Seed photons for Inverse Compton scattering

Radiation=Cooling

Figure 8.4 Sketch of the central region of an active galaxy, illustrating the various external radiation fields that may be Compton scattered to form the high-energy emission observed from AGNs.

But it also absorbs

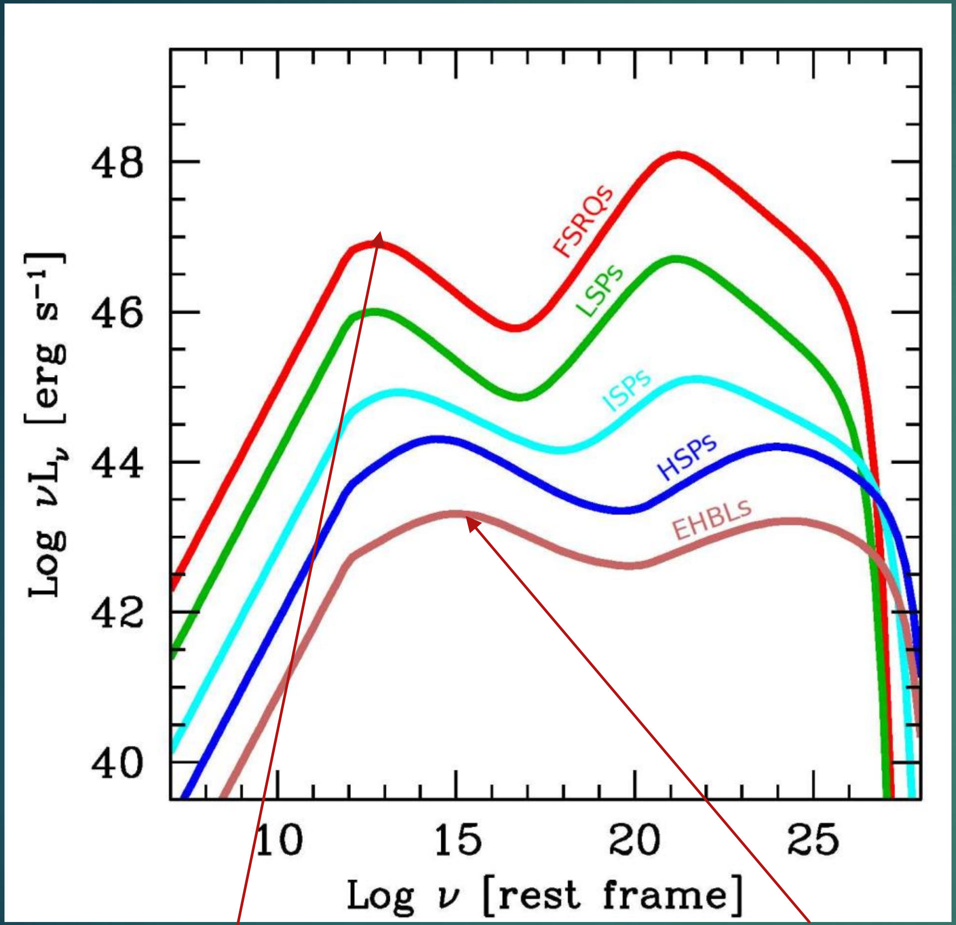
gamma+gamma -> Electron+positron

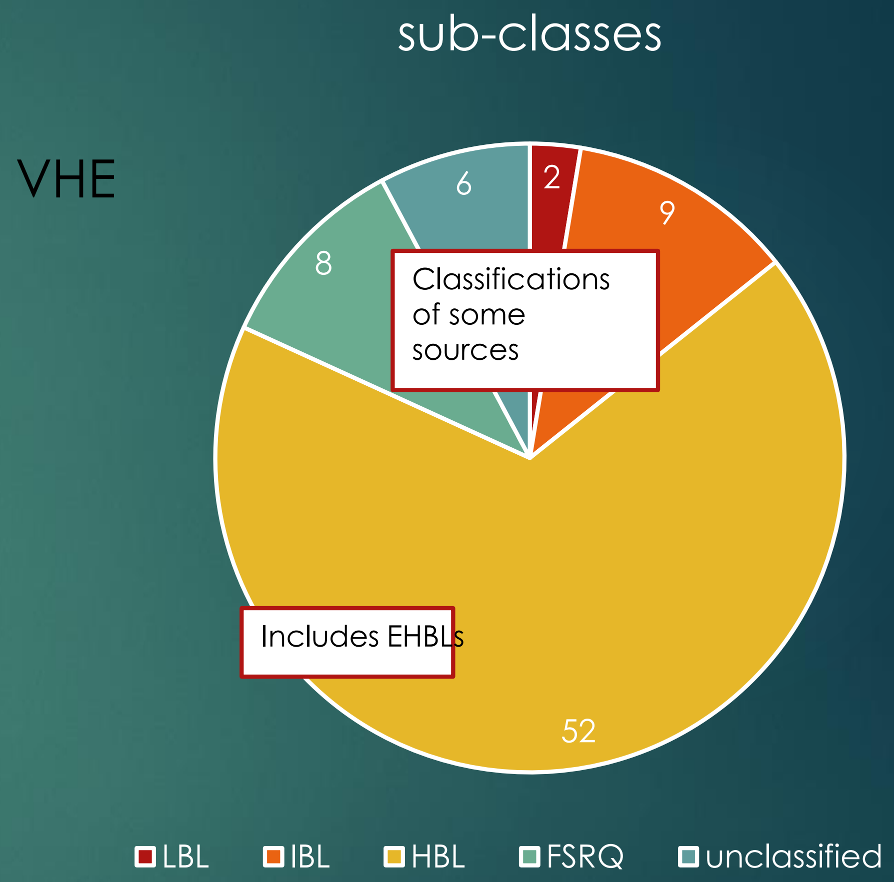


Which are more numerous sources of gamma-rays?

FSRQS OR BLLACS?

It depends…





FSRQs: most luminous

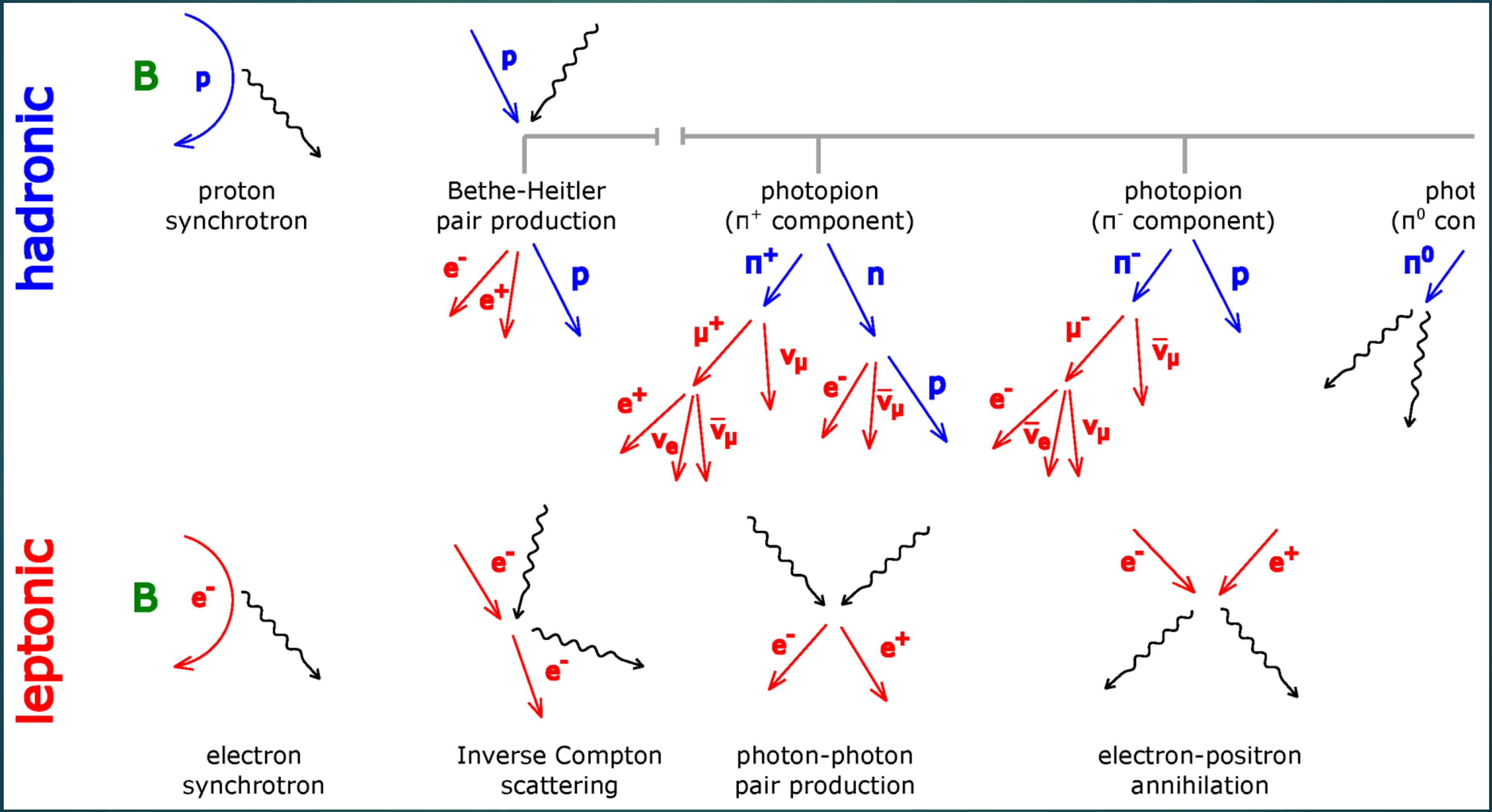
BL Lacs: higher synchrotron peak => higher IC peak

- HSPs most numerous objects
- Lower energies (Fermi) ~about equal

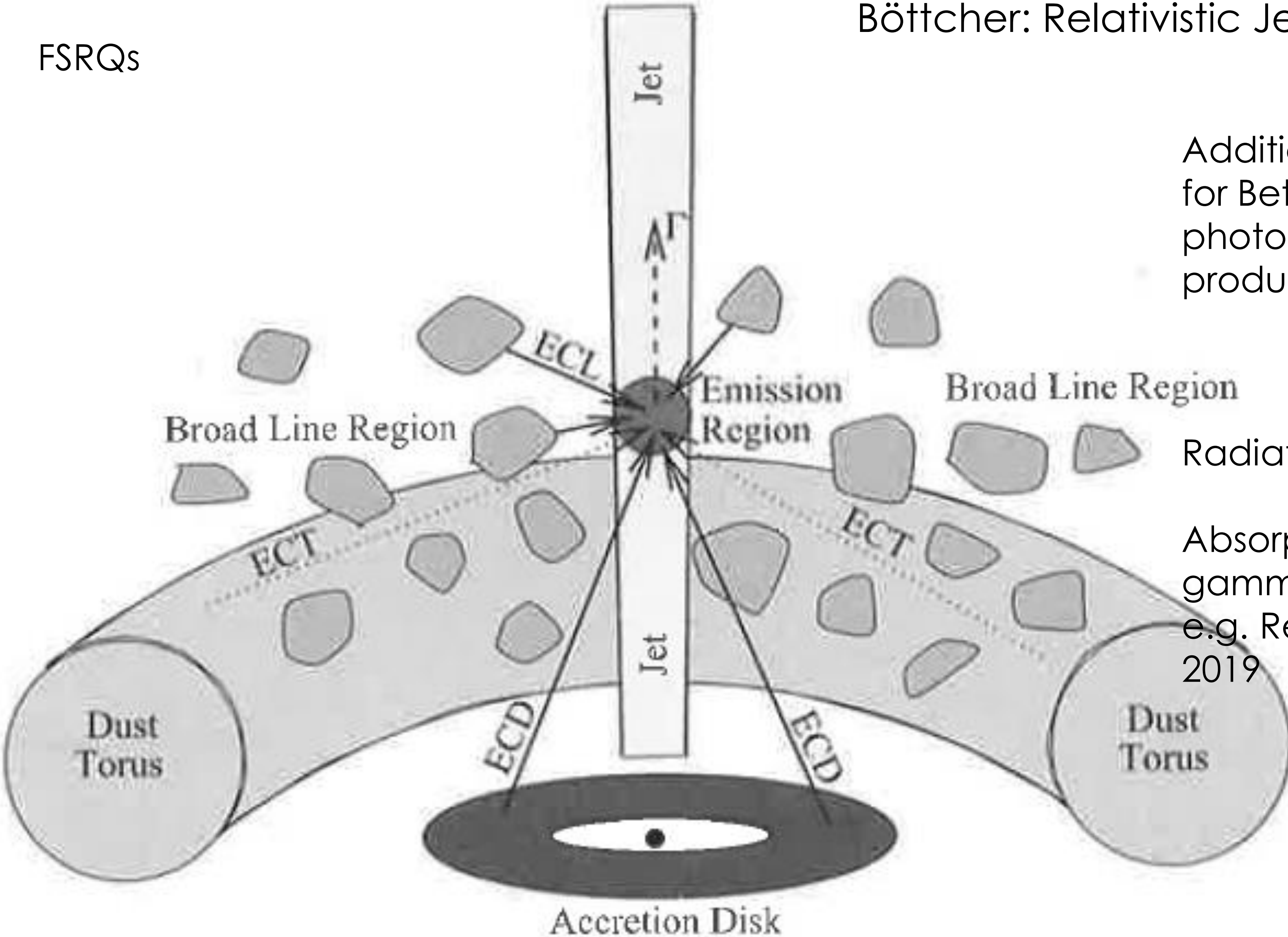
What about neutrinos? What are the best sources?

FSRQS OR BLLACS?

Reminder on what we need: protons and photons



FSRQs



Additional photons for Bethe-Heitler or photopion production

Radiation=Cooling

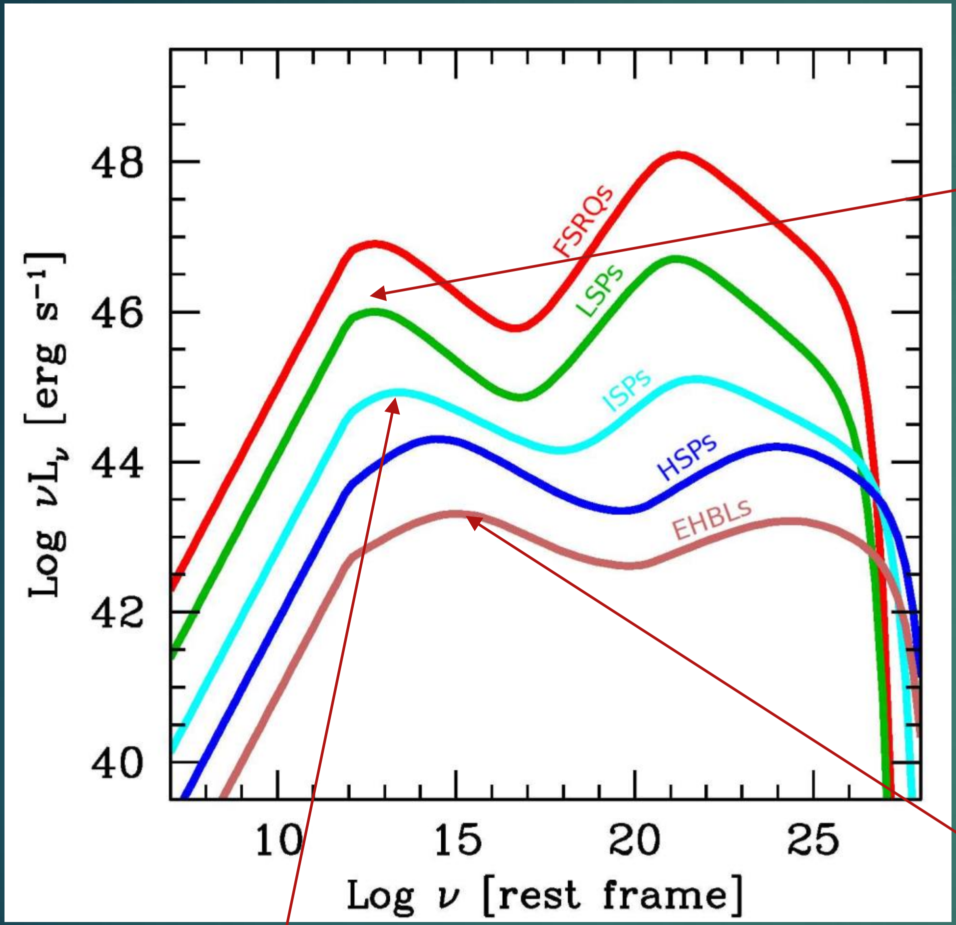
Absorption of gamma-rays (see e.g. Reimer et al. 2019

Figure 8.4 Sketch of the central region of an active galaxy, illustrating the various external radiation fields that may be Compton scattered to form the high-energy emission observed from AGNs.

What about neutrinos? What are the best sources?

FSRQS OR BLLACS?

We really have no clue…



There are also indications that radio brightness would have connection with neutrinos (Plavin et al. 2020) or that bright long-lasting radio flares would be connected to neutrinos (Plavin et al. 2020,2021, Hovatta et al. 2021), FSRQs+LSPs favored?

Statistical correlations with neutrino arrival directions: Padovani et al. Favours HSPs

TXS0506+056 is maybe ISP?

Lecture 2: Extragalactic sources of gamma-rays, neutrinos and cosmic rays

Where were we?

- Close-by sources: Normal galaxies, dwarf galaxies
- Within our supercluster: Not-so-normal galaxies (i.e. those with more ISM and CR)
- Dense clusters like Perseus and Coma

~10

- Relativistic jets launched by supermassive black holes: what do we know from electromagnetic radiation
- Blazars: relativistic jets pointing very close to our line of sight: variable emission from radio to VHE gamma-rays
- Blazars: differences in spectral energy distributions

Where were we?

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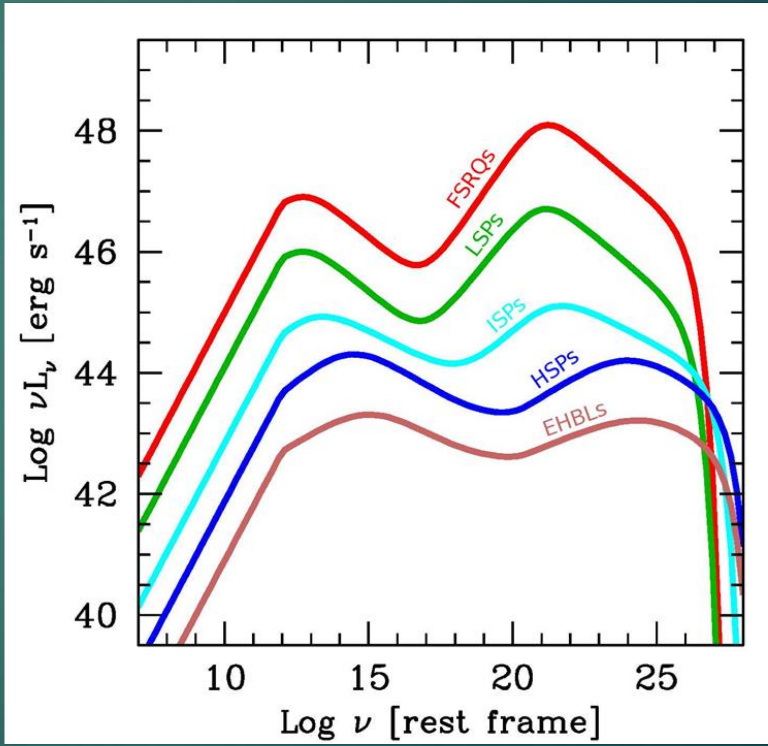
~10

- Relativistic jets launched by supermassive black holes: what do we know from electromagnetic radiation
- Blazars: relativistic jets pointing very close to our line of sight: variable emission from radio to VHE gamma-rays
- Blazars: differences in spectral energy distributions

A bit more on the SED classes

- Fossati et al. 1998: Blazar Sequence
- More luminous sources have a synchrotron component peaking at lower frequencies
- They also seem to have higher Compton dominance (external radiation field)
- This could be related to the energy losses and magnetic energy density in the sources, so that
  in low-peaking sources the radiation field dominates and high-energy electrons lose energy faster, thus radiating at lower frequencies



Blazar sequence… becomes blazar envelope

- Updated analysis including lower luminosity objects shows that instead of a simple trend, there seem to be an envelope, with two tracks
- An explanation for the change in the peak luminosity / frequency is the change in viewing angle
  - Track A, source with a constant jet speed
  - Track B, source with a velocity gradient in the jet (such as decelerating jets)

One should be careful when interpreting data of incomplete samples with biases!

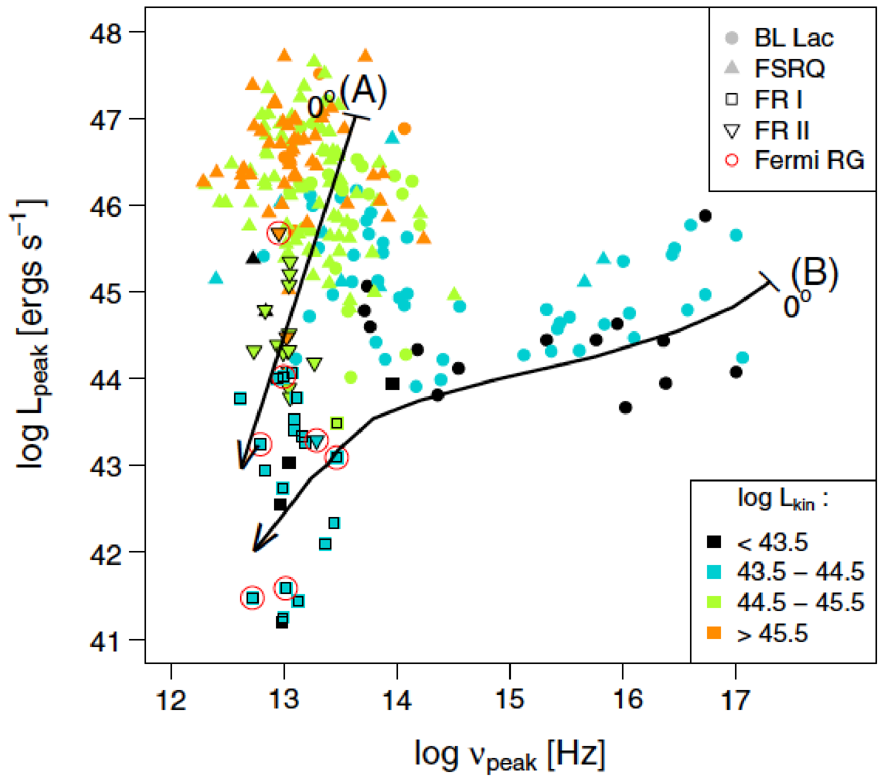


Figure 4. The blazar sequence, which originally showed an anti-correlation between synchrotron L_{peak} and ν_{peak} has been expanded into an "envelope" with the addition of new observations and radio galaxies. BL Lacs are shown as filled circles, FSRQs as filled triangles, and radio galaxies as squares (FR I) and inverted triangles (FR II). Color indicates the jet kinetic power (L_{kin} in erg s^{-1}), as estimated from extended radio flux measurements. Track (A) shows the path of a synchrotron peak for a single-component jet and (B) for a decelerating jet of the type hypothesized to exist in FR I sources. The fully aligned limit for each (0°) is shown as marked, with the arrow direction indicating the movement of the model source as it is misaligned.

Meyer et al. 2011

Compton dominance = how much higher is the luminosity in the inverse Compton component compared to the synchrotron peak => what is the dominating energy loss mechanism

- FSRQs typically have a Compton dominance > 1, which means that an External Compton component is needed to model their SED, while in BL Lacs, SSC can be sufficient.

- This is in agreement with FSRQs typically showing thermal components from the torus or accretion disk in their SED

- "Masquerading" BL Lacs are LSP sources where the non-thermal jet emission swamps the thermal components from the SED. In reality these should be classified as FSRQs (e.g. BL Lac itself!), maybe also TXS0506+056? (Padovani et al. 2018)

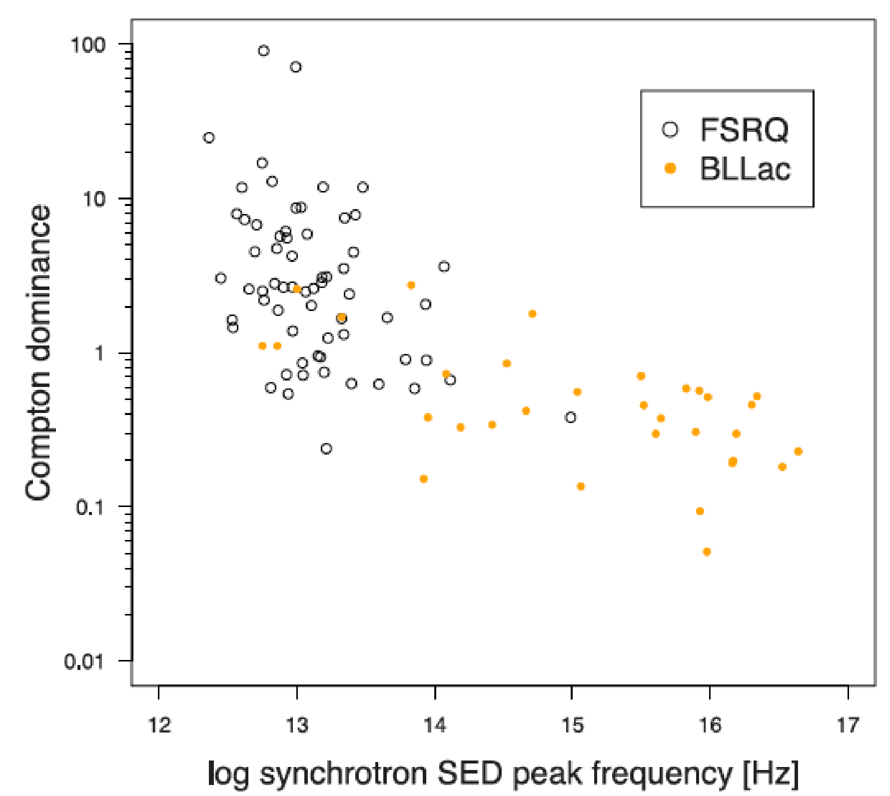


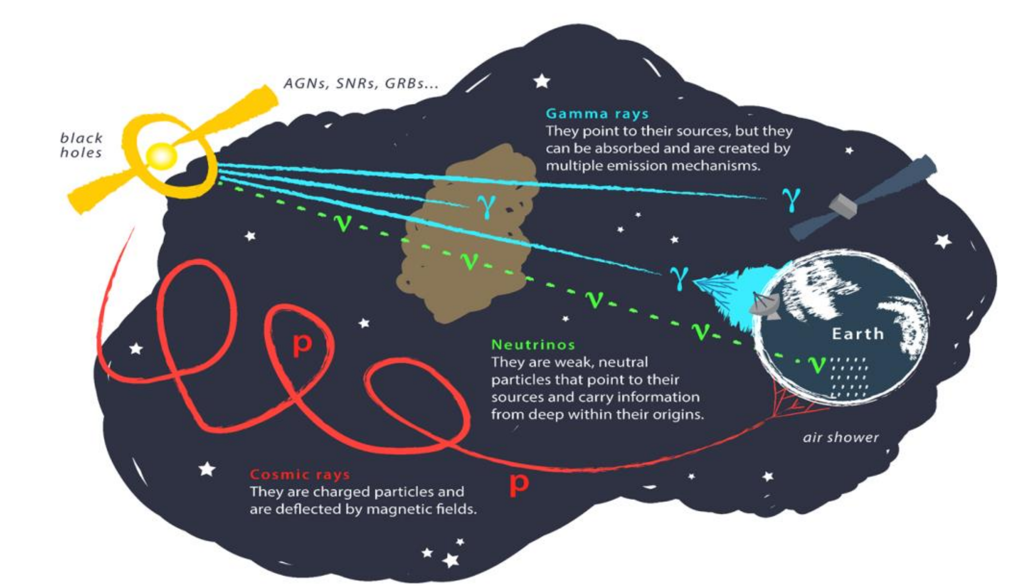
Figure 10. Compton dominance (ratio between γ-ray and PTF νF_{ν}) against the synchrotron peak frequency. Open circles are FSRQs and orange filled circles BL Lac objects.

Hovatta et al. 2014

What I will try to cover today?

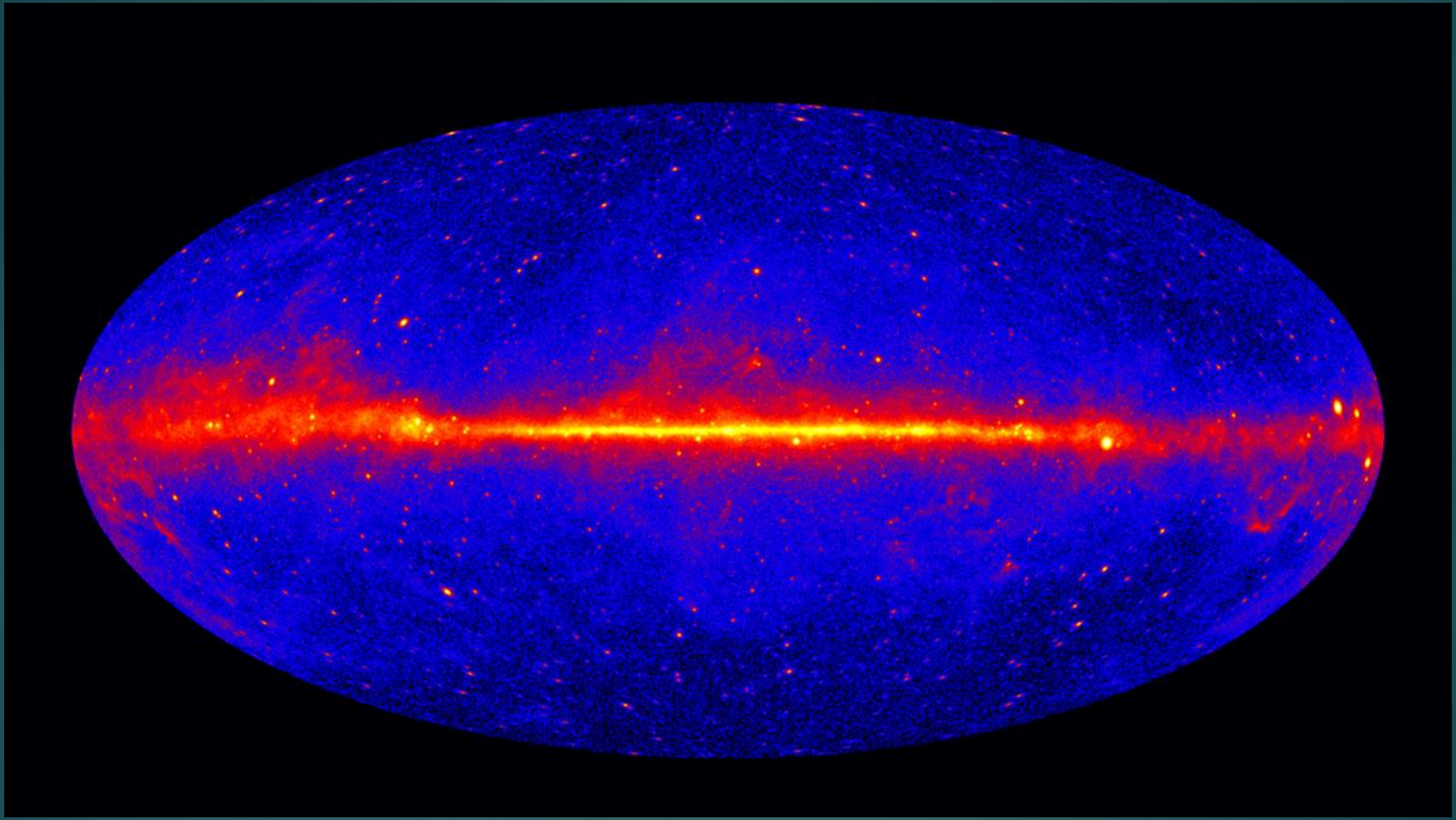
- Gamma-ray observations of blazars
- Neutrino observations of blazars
- Radio galaxies (i.e. when jet is not pointing close to our line of sight)

- Is that all?
- Propagation effects



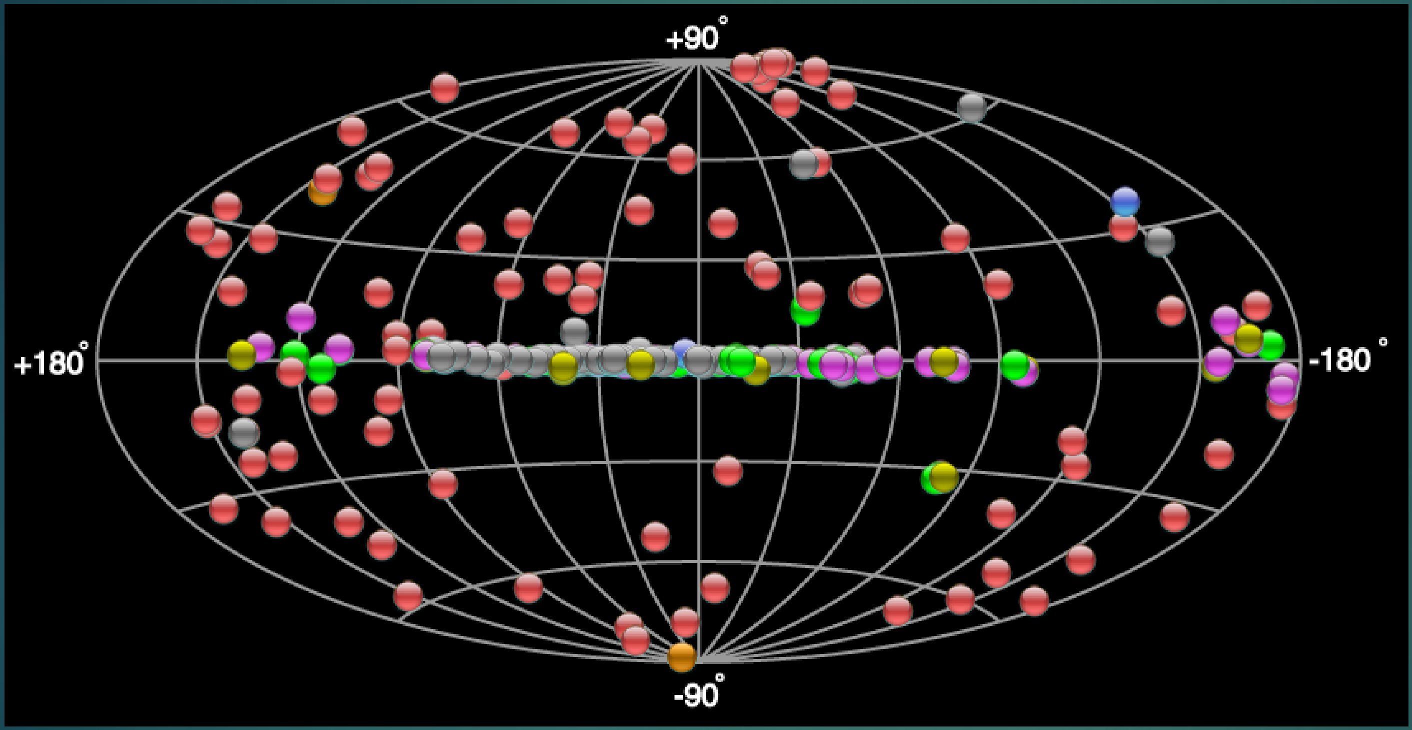
Credit: Juan Antonio Aguilar and Jamie Yang IceCube/WIPAC.

Gamma-ray observations of blazars



>90% of the thousands of extragalactic sources that Fermi sees are blazars

Very High Energy Gamma-Ray sky



Red dots: extragalactic

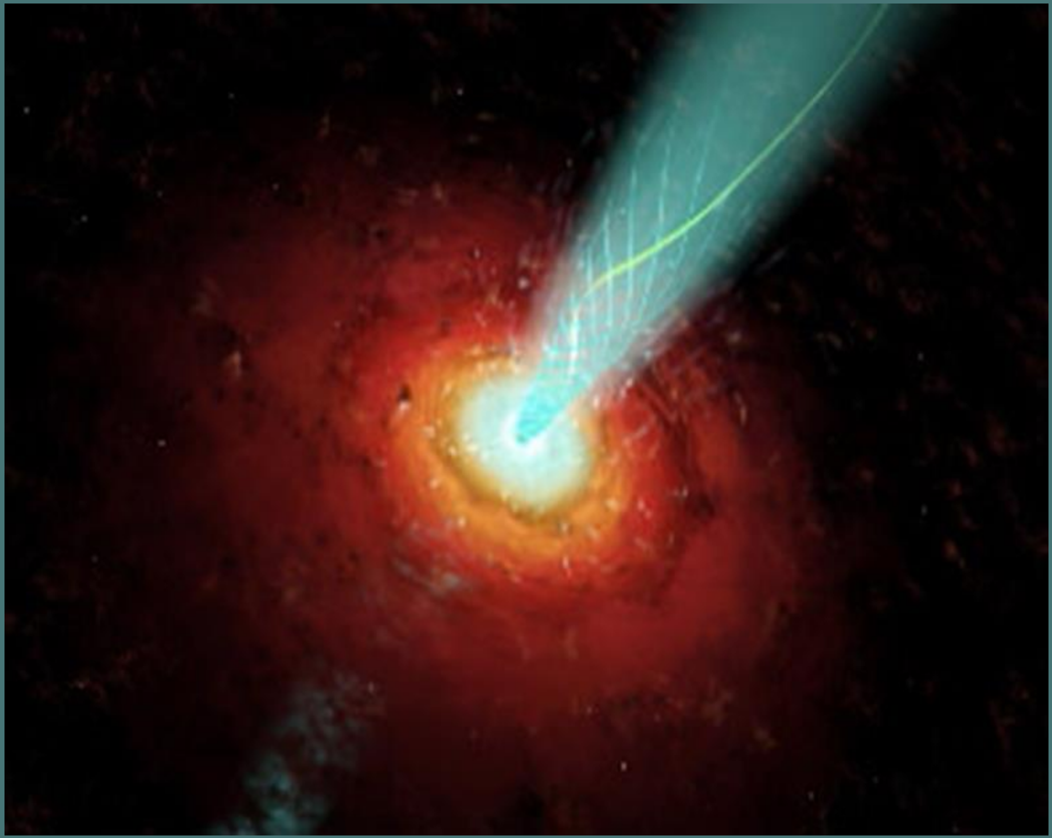
Source count ~100

~90% of them are blazars

http://tevcat.uchicago.edu/

What have we learn from these observations?

- Mechanism of the flares: the particle acceleration
- Location and physical conditions of the emission region/emission regions



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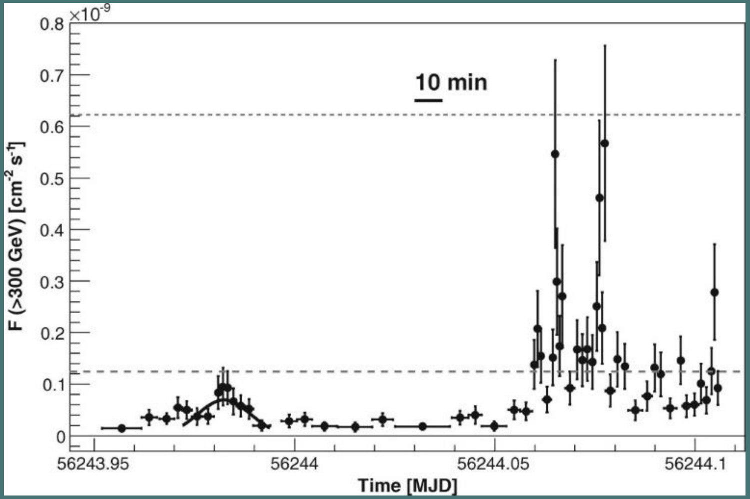
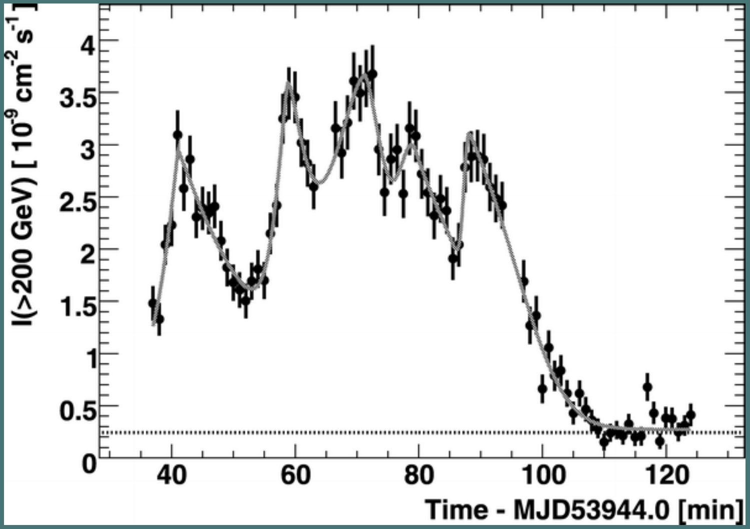
Mechanism of flares, how are particles accelerated?



Aleksić et al. 2014



Aharonian et al. 2007

- Emission from the relativistic jets is variable in all wavebands and in timescales from years to minutes
- Several models have been invoked to explain blazar variability, typically shocks that accelerate particles
  - Shocks manage to explain the slower variability in the lower energies well
- **Very fast VHE flares** have been observed from a handful of blazars
  - Time scales of these flares are ranging from hours to minutes
  - Need a mechanism that can produce fast flares → **Magnetic reconnection**

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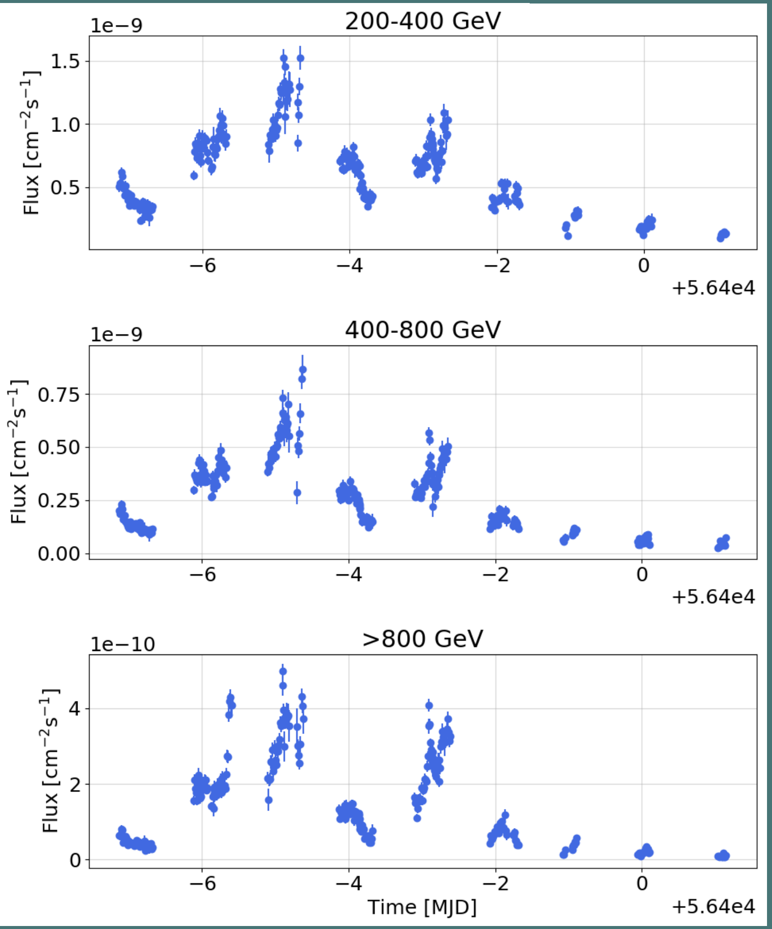
Magnetic Reconnection: Observations vs. simulations

- Actual PIC simulations of magnetic reconnection (Christie, Petropoulou et al. 2019): Produce light curves of different jet scenarios varying the viewing angle θobs, the reconnection layer angle θ', magnetic field B, and magnetization σ
- We can actually compare these to observations!
- Acciari et al. 2020 estimated the peak flux and flux-doubling time scale of plasmoids of different sizes and find a range of layer angles compatible with the observed values of one of the flares
- But the PIC simulations produce actual light curves, surely we can extend the comparison beyond amplitude and flux-doubling times

Observed data: Mrk421 in 2013
Exceptionally well-sampled lightcurve from MAGIC and VERITAS



Acciari et al. 2020

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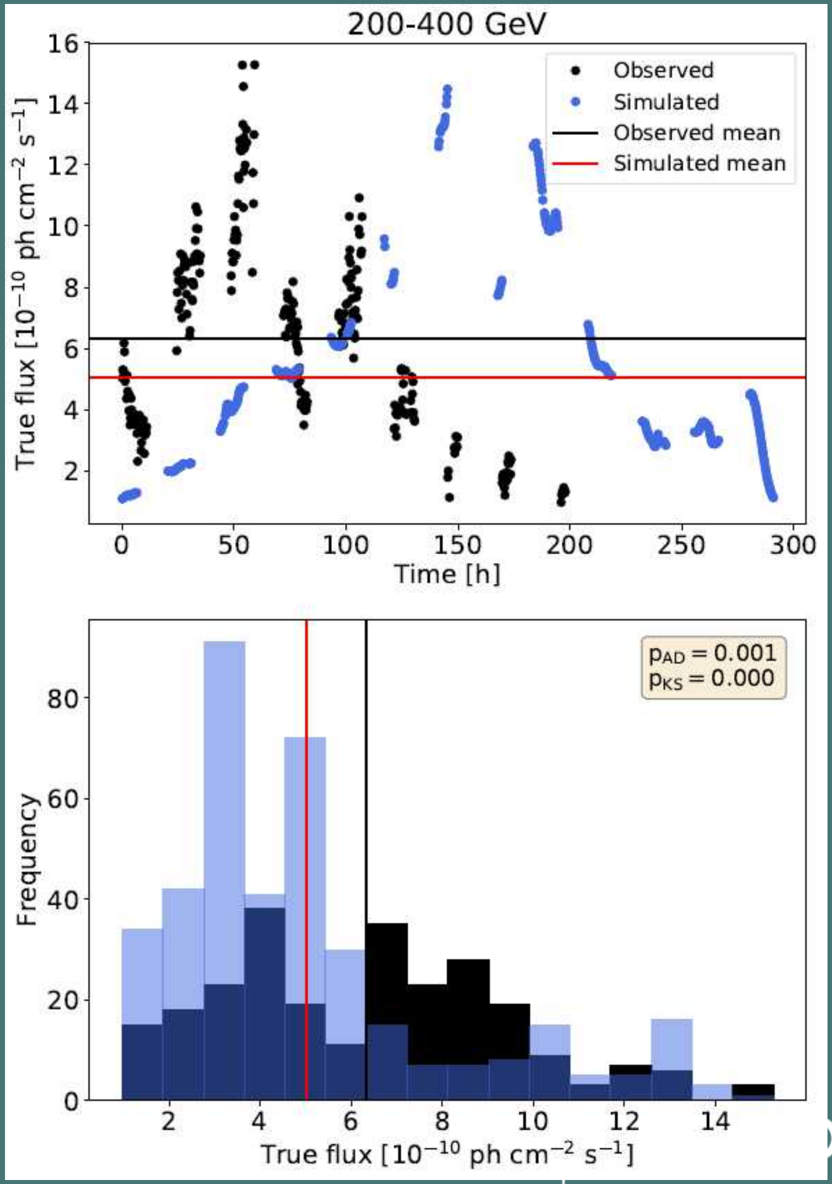
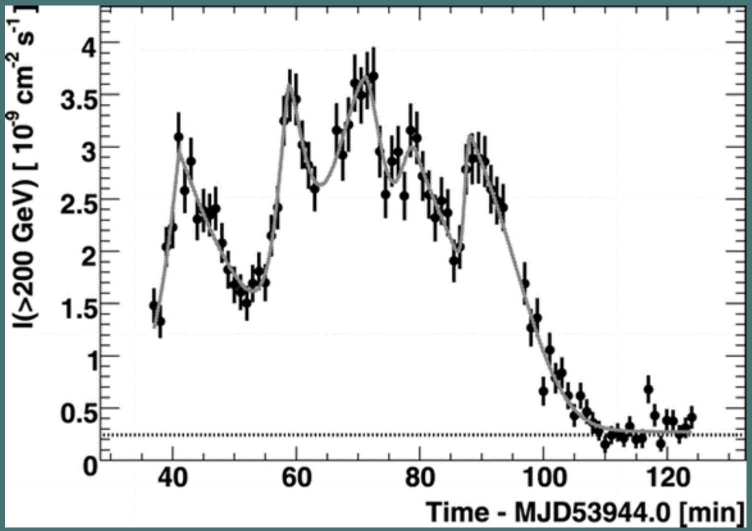
Particle acceleration
Observations vs simulations

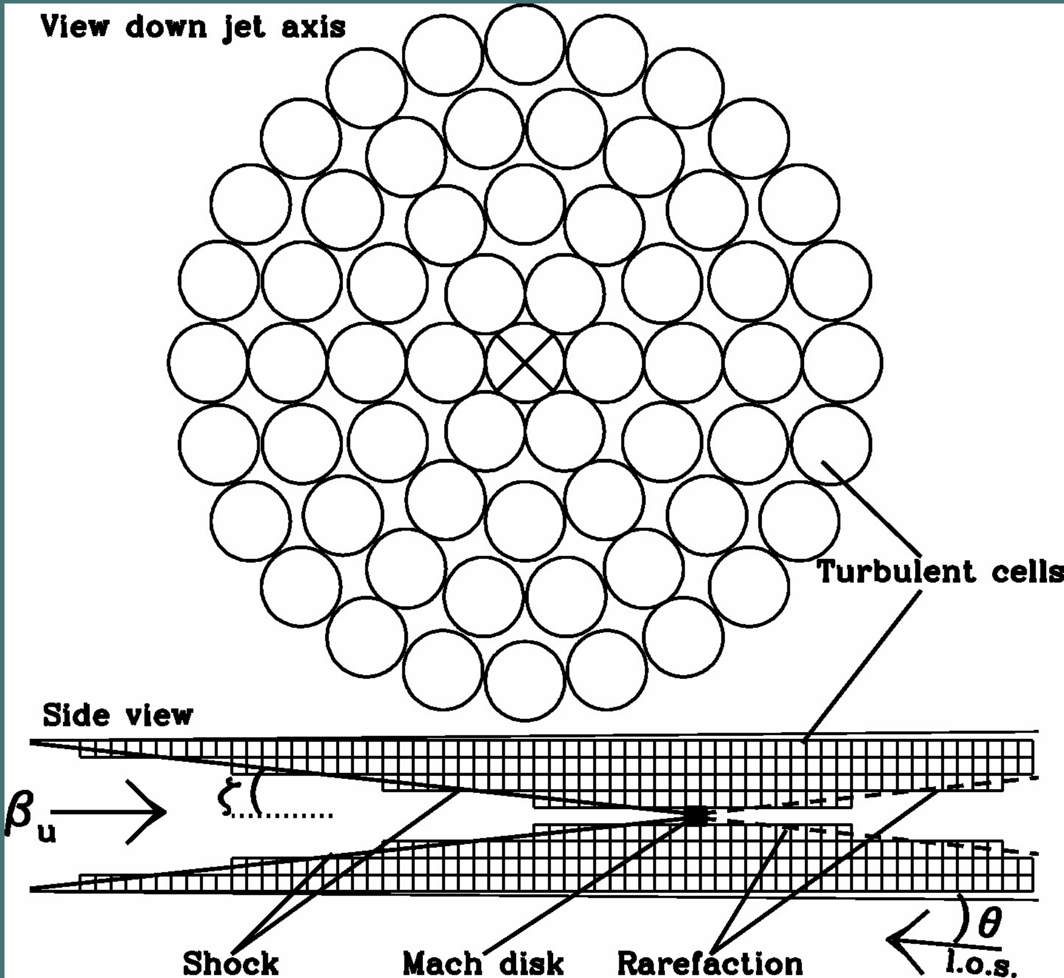
- Combine several methods in the analysis process to get a versatile view of the simulated data: flux distributions, time scales…
- Work in progress: preliminary results in Jormanainen, Hovatta, Lindfors et al. (ICRC2021)
- We do find parameters where simulations~observations
- Powerful tool to limit the parameter space: General methodology to compare to light curves from simulations



Fast flares

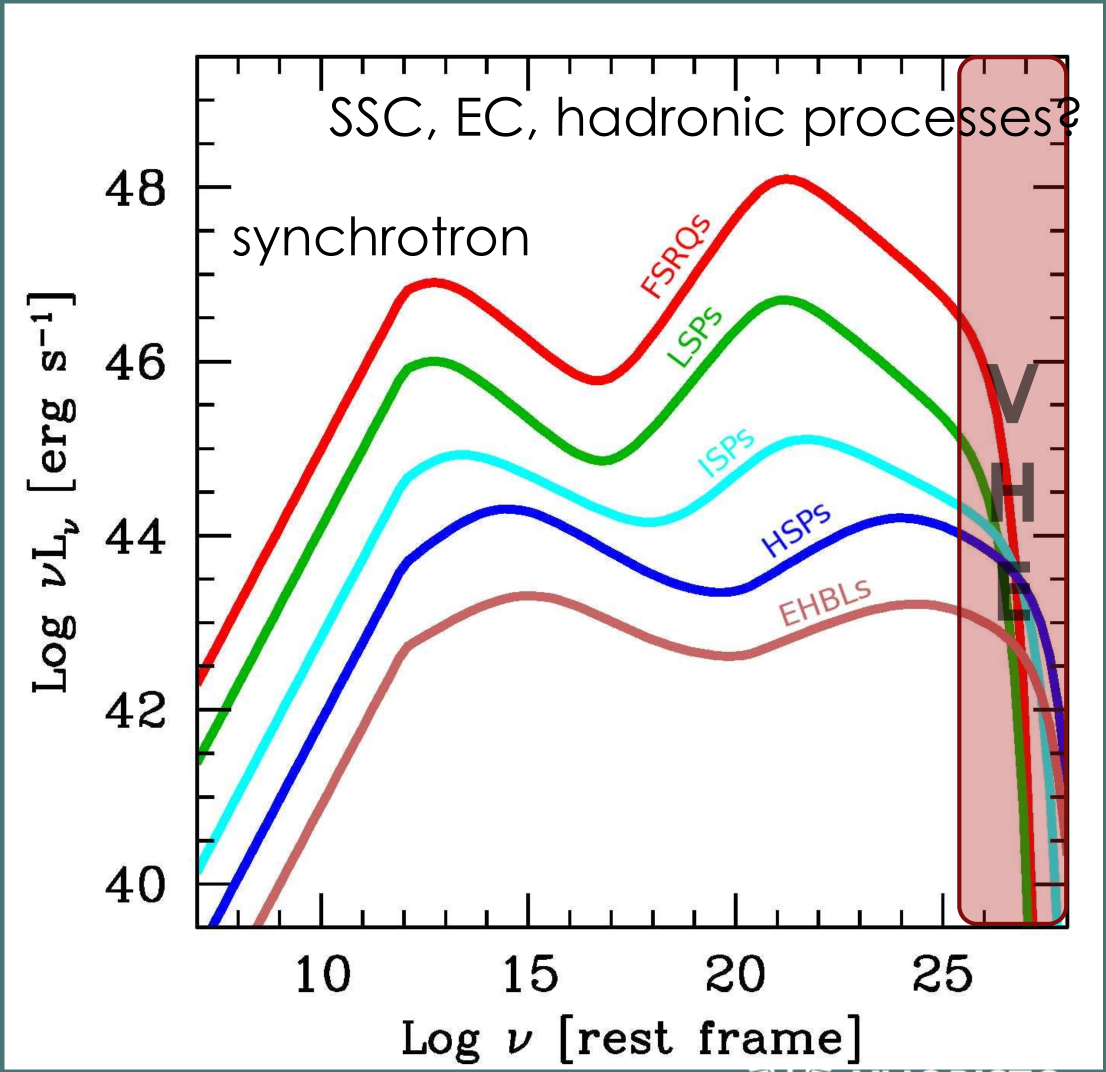
- In general: there has to be sub-structures within the jet: timescales minutes~10^15cm<0.01pc
- Jet diameter (order of at least) ~1pc
- Plasmoids from magnetic reconnection?
- Turbulent cells?





Location and physical conditions of the emission region

- Location: availability of external seed photons e.g. from broadline region and dusty torus. The availability of the seed photons is relevant to EC and hadronic processess.
- How to locate: Broadline region absorps VHE gamma-rays: if we see VHE gamma-rays



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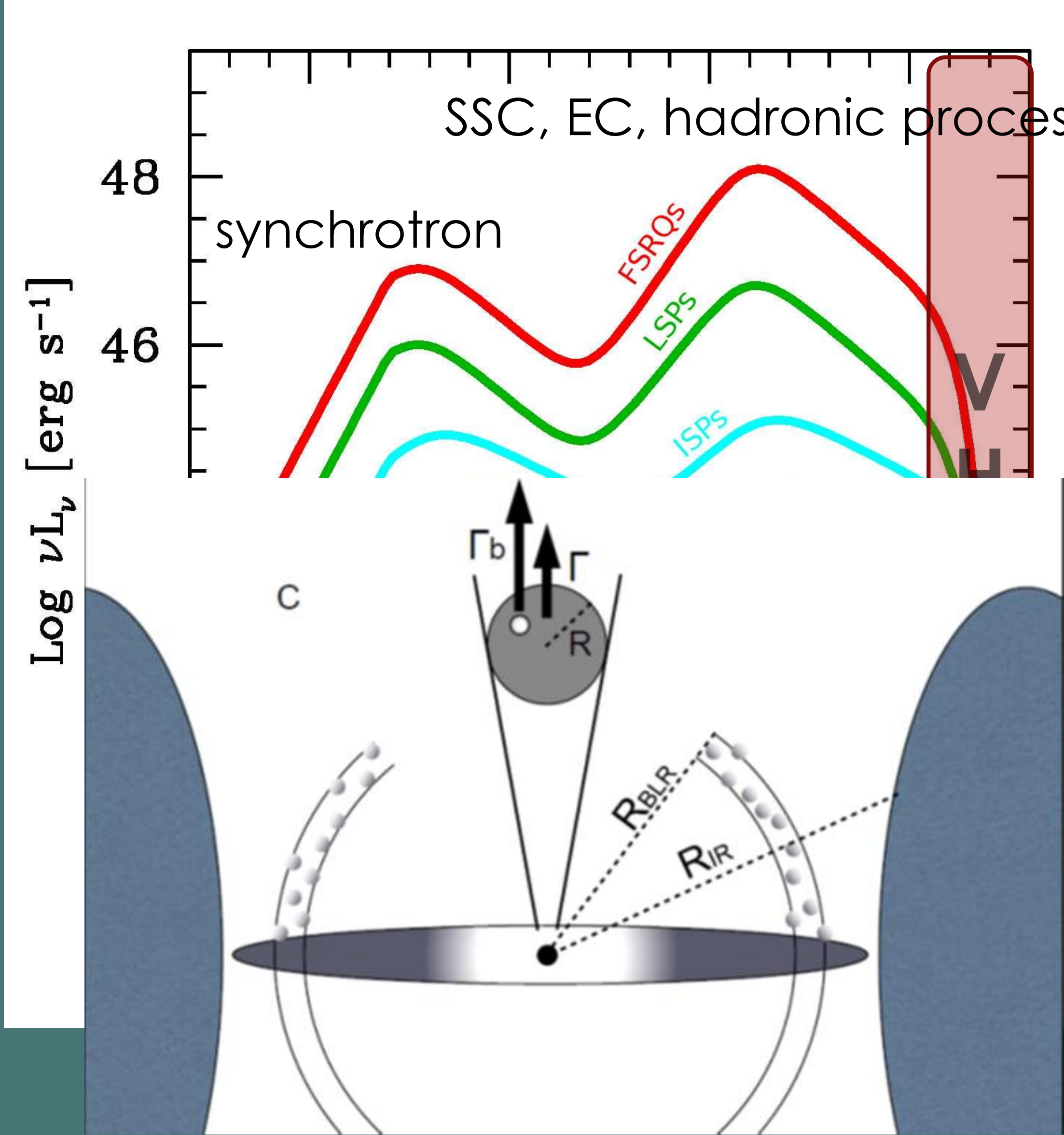
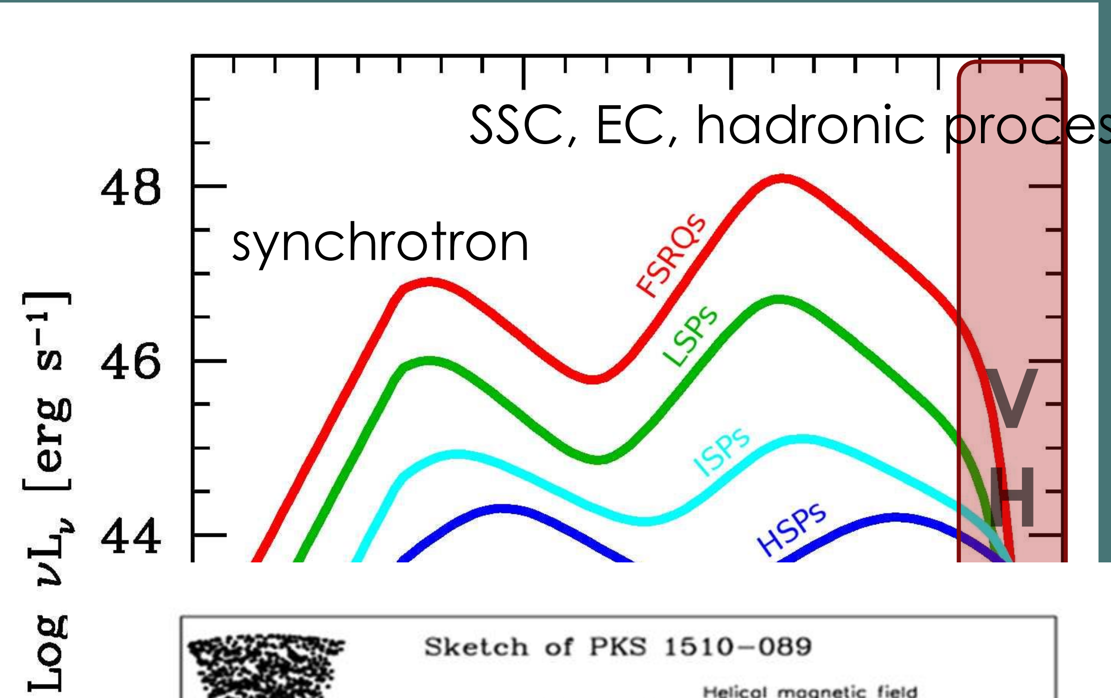
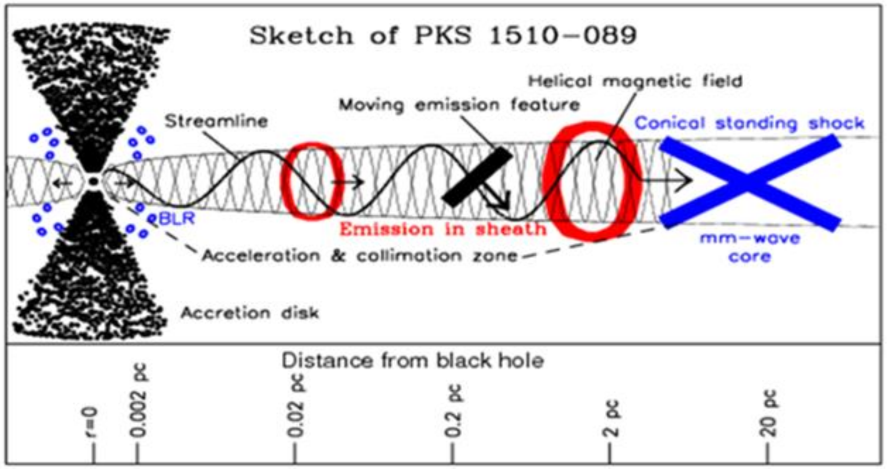


Location and physical conditions of the emission region

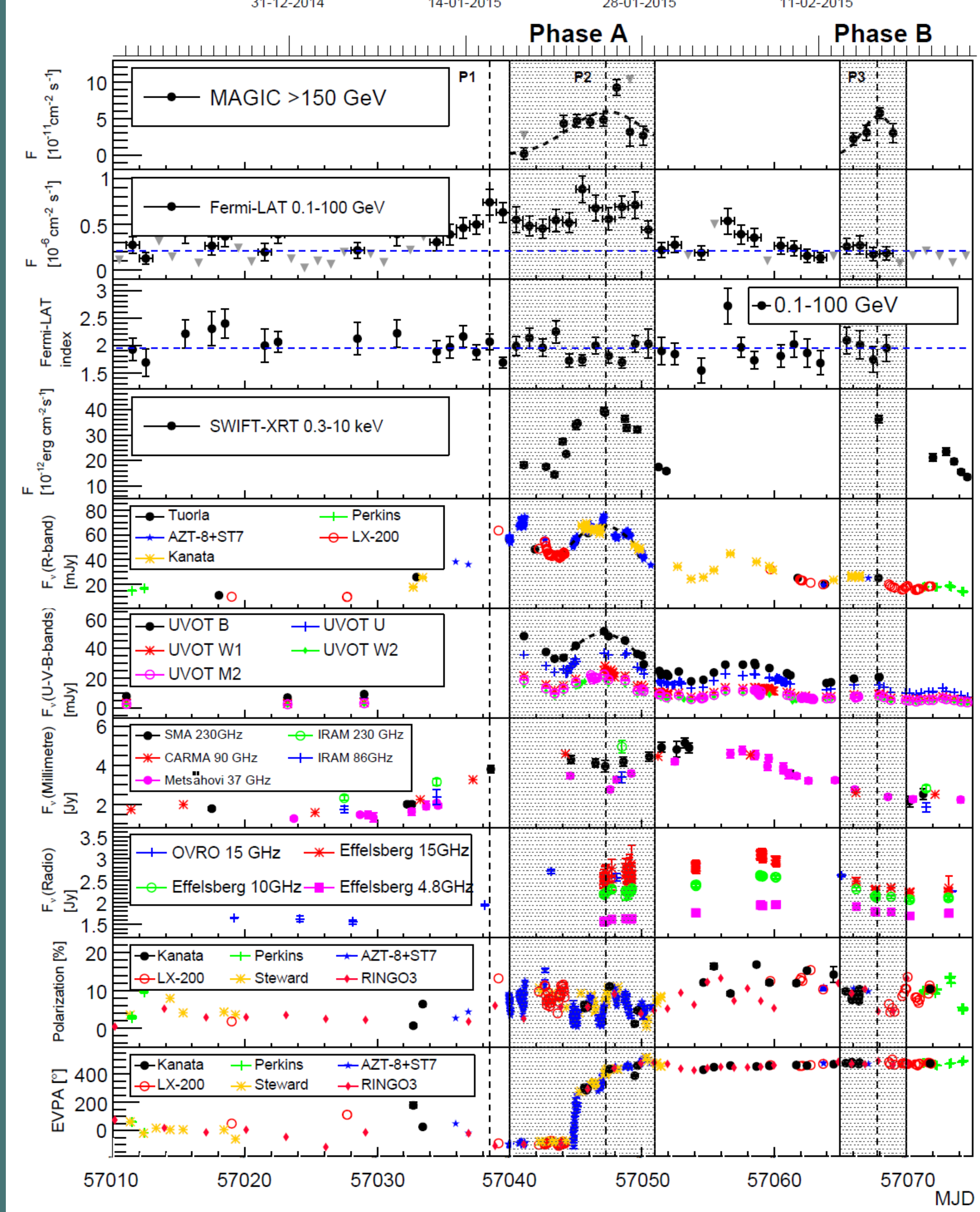
- Location: availability of external seed photons e.g. from broadline region and dusty torus. The availability of the seed photons is relevant to EC and hadronic processess.
- How to locate: Broadline region (BLR) absorps VHE gamma-rays: if we see VHE gamma-rays from FSRQ, it must originate outside BLR
- How to locate: Very Long Baseline Interferometry and MWL monitoring: timing of the events with respect to each other.





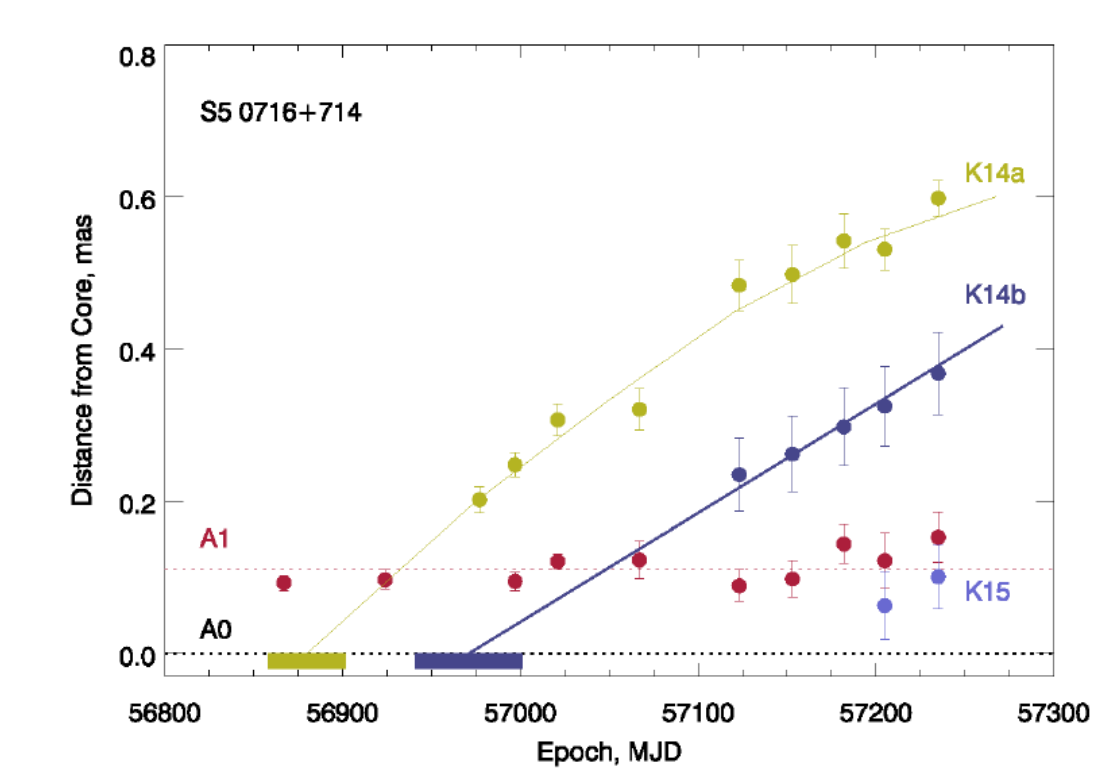
S50716+714: Unprecedented flaring state in January 2015

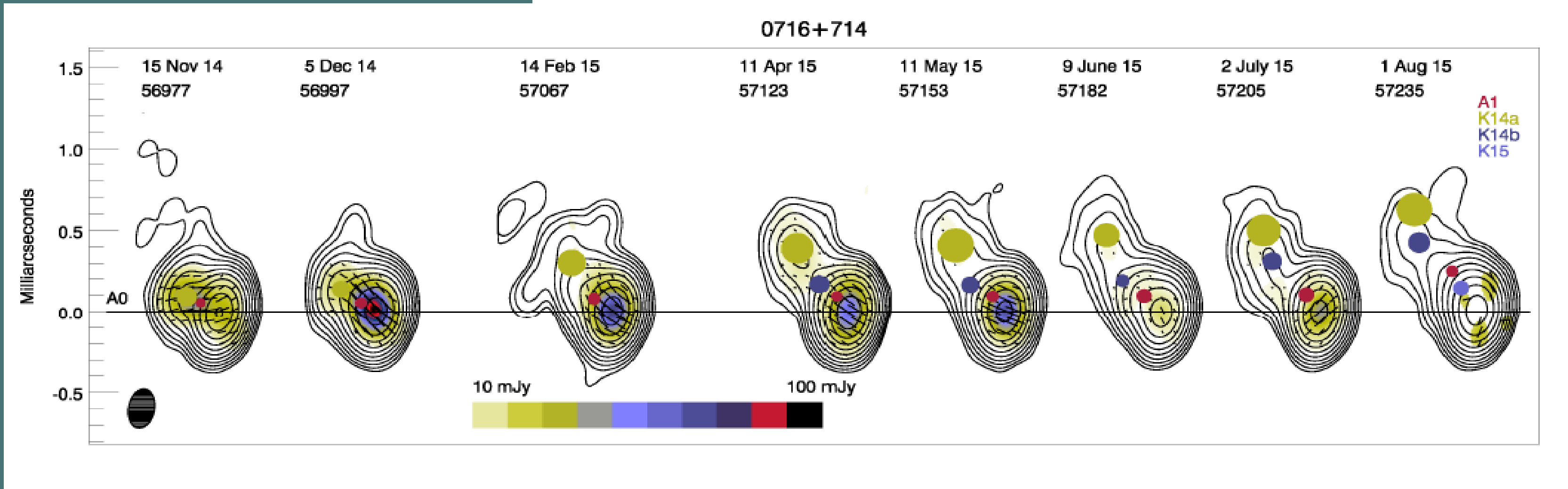
- High state (radio, optical, GeV gamma-rays) started in the beginning of January 2015
- Phase A: flare in radio, optical, X-rays, gamma-rays, VHE gamma-rays, *very fast rotation of optical EVPA*
- Phase B: flare in X-rays and VHE gamma-rays



What was happening in the jet?

- Component K14b passes through the stationary feature A1 at MJD 57050+-30 days
- Average size of A1 is (0.049+-0.020) mas, it will take K14b (35+-13) days to pass A1





VLBA data: Boston Blazar Group: https://www.bu.edu/blazars/VLBAproject.html

MAGIC Collaboration et al. 2018, A&A

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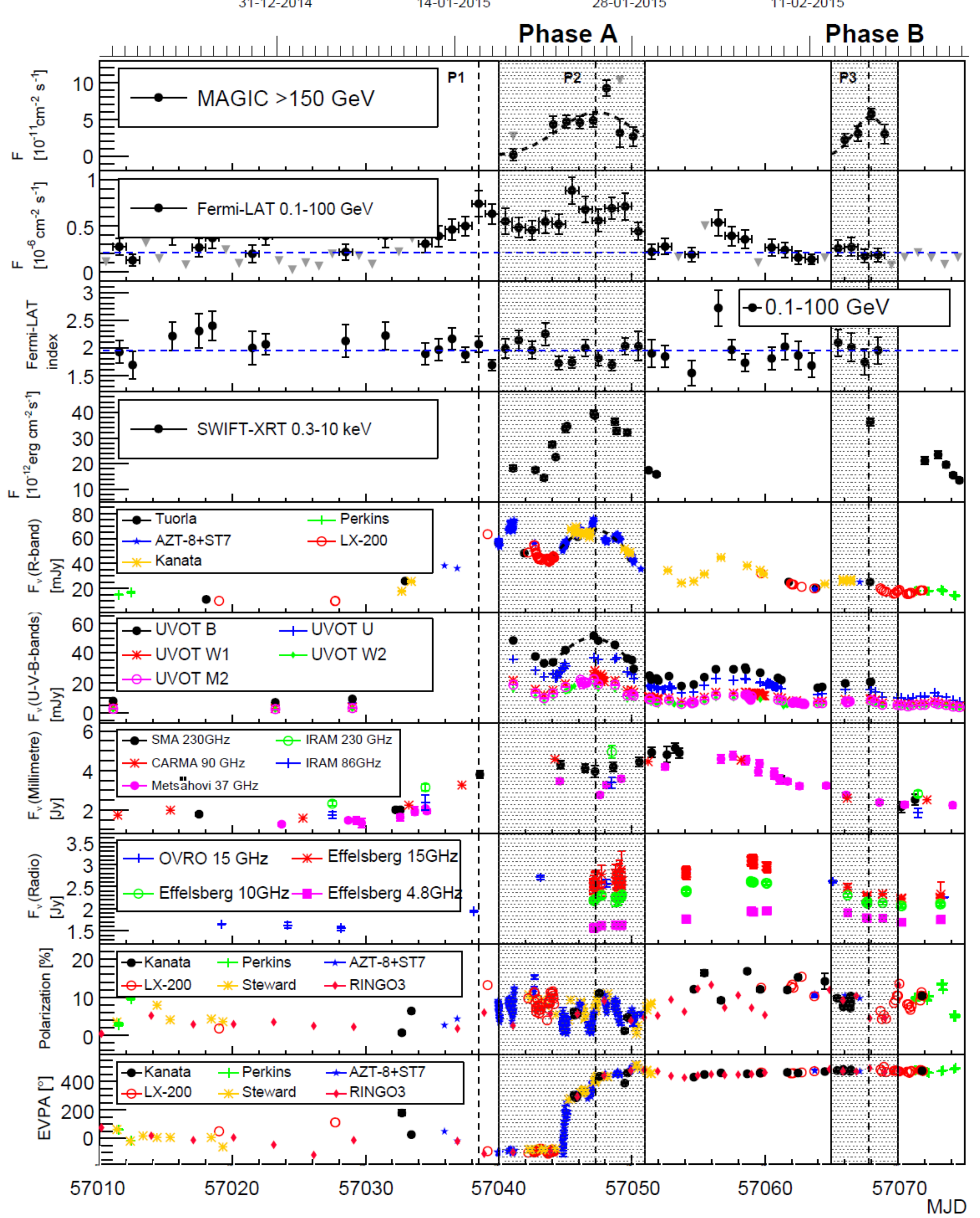
Unpredecented flaring state in January 2015

- Lightcurves+ VLBA
- The time it takes for K14b to pass A1 fits very well with the duration of 34 days of the elevated gamma-ray flux in the Fermi light curve

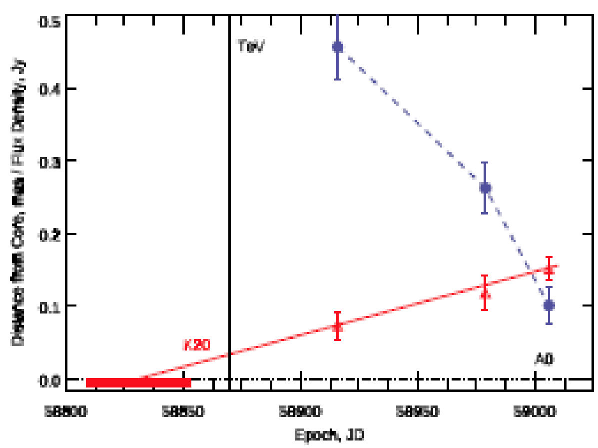
  MJD 57032 to 57066.
- In this scenario the TeV detections can be associated with the entrance and exit of the superluminal knot in and out of the recollimation shock (A1).

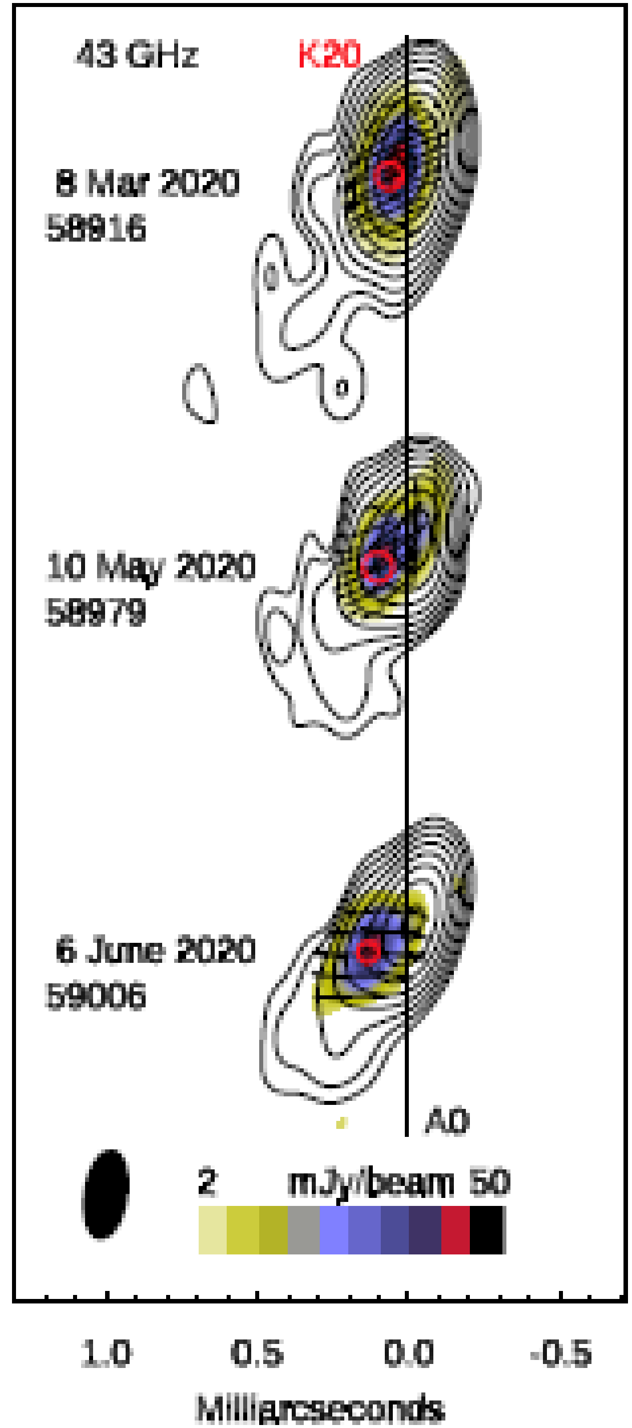


New VHE FSRQ: B1420+326

- Detected by MAGIC telescopes in VHE gamma-rays during a flaring state in January 2020
- We also see:
  - New, superluminal radio knot contemporaneously appeared in the radio image of the jet.
  - Rotation of the electric vector of position angle, low polarization degree
- Also seen with previous detections of VHE emission from other FSRQs (PKS1222+216, PKS1510-089) and BL Lac
- The core is located several parsecs away from central black hole (outside BLR, maybe even outside dusty torus), additional seed photons from shock-shock interaction?

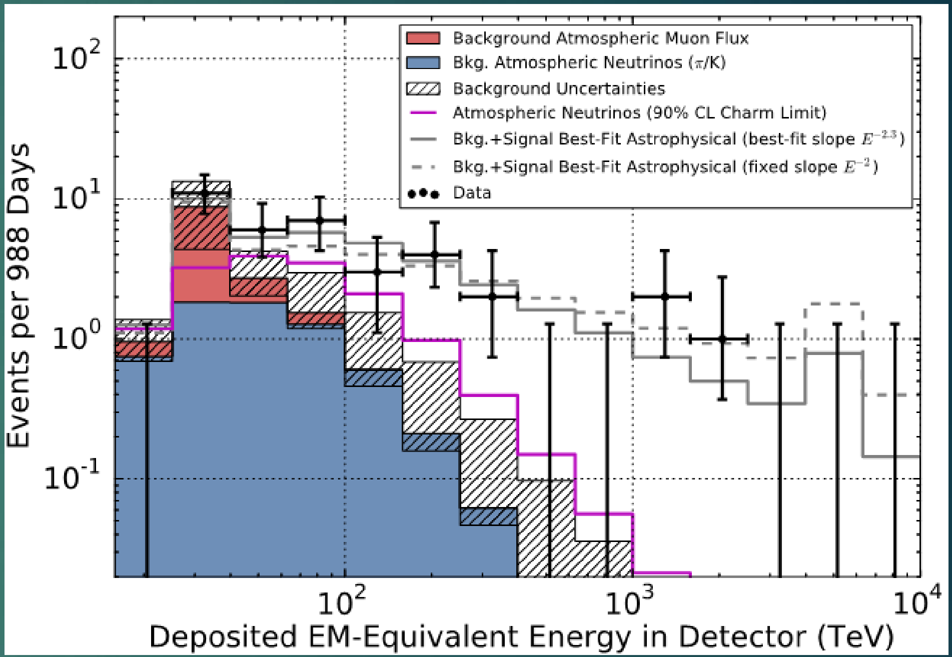
MAGIC Collaboration et al. 2021, A&A



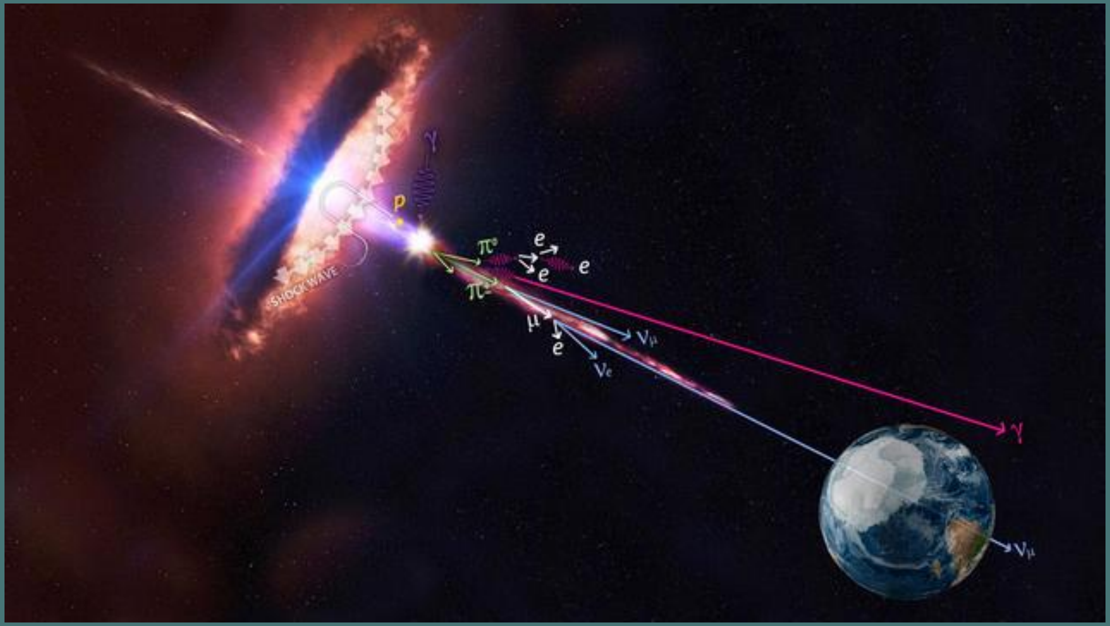


Neutrino observations of blazars

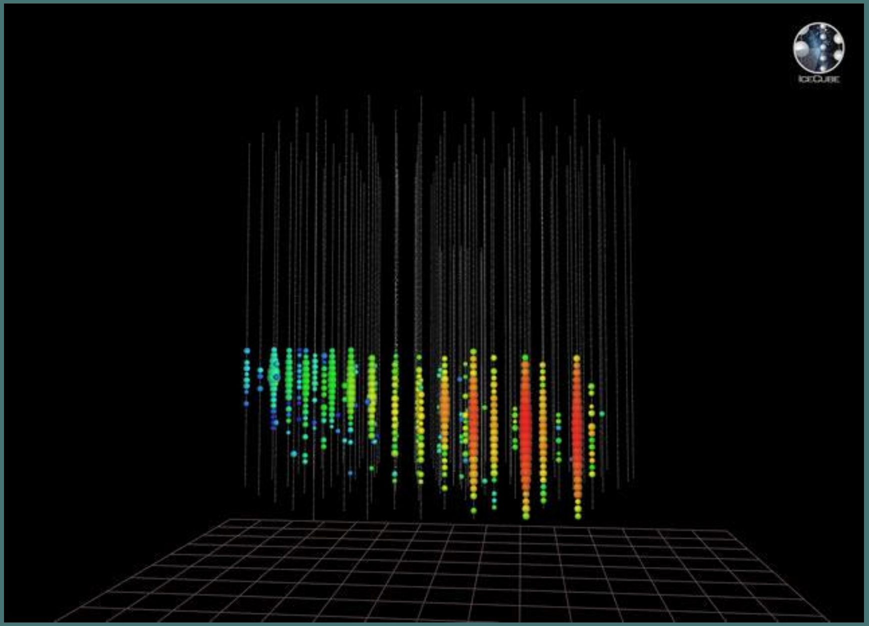
- IceCube detected an excess of astrophysical high-energy neutrinos
- There's no clear one-to-one correspondence between neutrino arrival directions and any given type of astronomical objects
- Studies cross-matching neutrino events with gamma-ray catalogues / emission have been inconclusive
- Association with blazars: Padovani et al. (2016) found the most significant connection with HSP sources. The most recent revision (with more data) suggested a connection with ISP and HSP sources (Giommi et al. 2020). On the other hand, Huber (2019) found the most significant connection(though only at 1.9sigma level) with low and intermediate synchrotron peaked BL Lac objects (LBL/IBLs) and the connection to high synchrotron peaked sources had a much lower significance (only 0.5sigma).



Association of IC-170922A with the blazar TXS 0506+056



Credit: IceCube collaboration / NASA



Credit: IceCube collaboration

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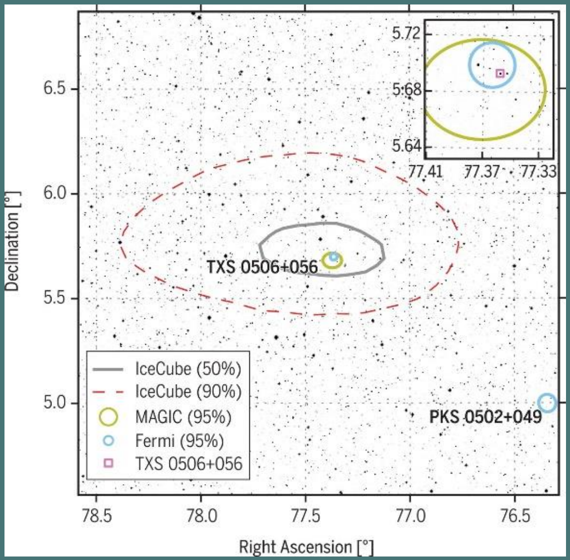
TXS 0506+056 radio association

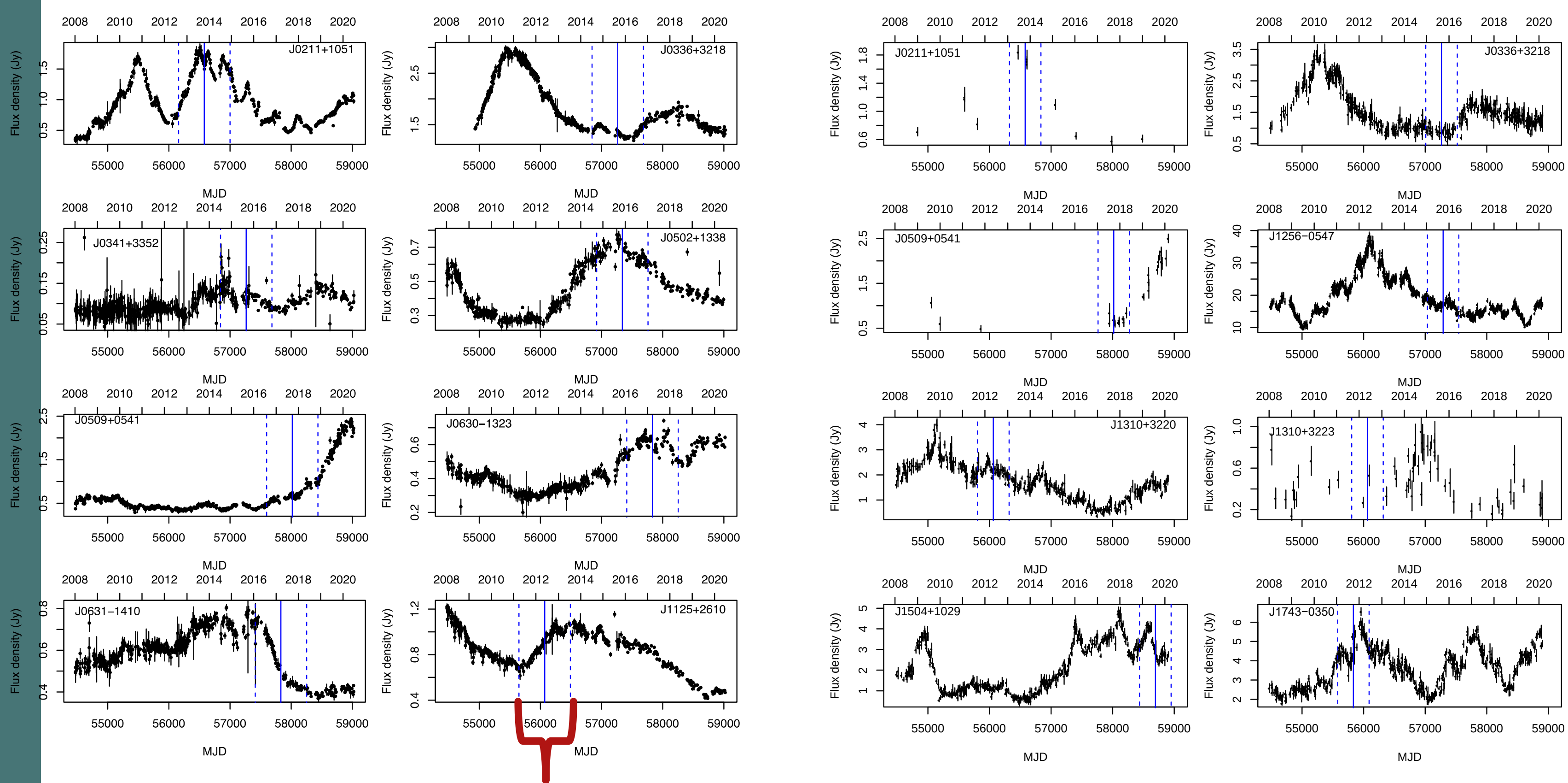


IceCube collaboration et al. 2018, Science

Radio light curves of some of the associations

OVRO 15 GHz

Metsähovi 37 GHz



Activity index = mean around the neutrino event / mean of the remaining LC

Hovatta et al. 2021

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Results

- Our number of associations is rather small: we had 56 neutrinos, ~50%, i.e. 28 of them should have astrophysical origin, but we found only 8-20 associated sources to 7-16 neutrinos (i.e.11-27%)
  - → Our radio samples are not complete (Plavin et al. 2020 found 26 associated events using the complete RFC sample)
- Not all the neutrino events coincide with a radio flare
- If there is a **large** radio flare at the same time as a neutrino event, it is unlikely to happen by random coincidence
- **Radio band is usually ignored by simulations, but it is known to be good proxy of jet activity. The missing power of multimessenger emission?**

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Implications of TXS0506+056 to SED modelling

- Tens of SED modelling papers in arxiv Leptonic emission dominates

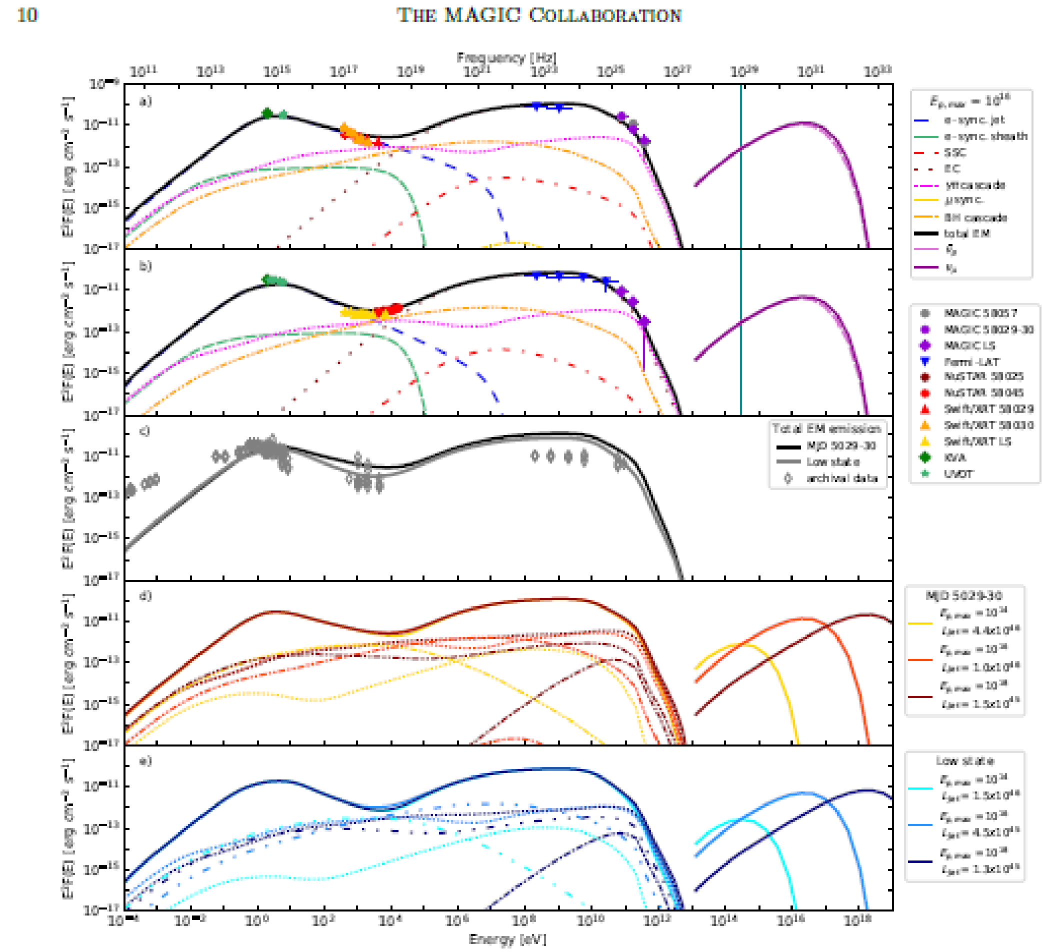


Figure 2. Spectral energy distribution for the enhanced VHE gamma-ray emission state (a), MJD 58029 to 58030) and the lower VHE gamma-ray emission state (LS, b)) modeled with the jet-sheath scenario with $E_{p,max} = 10^{16}$ eV. Symbols corresponding to data-points from different facilities and observation epochs are described in the legend. The curves represent individual emission components while the thick black curve shows the total predicted emission. The leptonic emission from the jet includes synchrotron (blue loose-dashed), synchrotron-self-Compton (SSC, red loose-dash-dotted), and external Compton (EC) emission (dark red loose-dotted). Synchrotron emission from the sheath is denoted by the green dense-dashed line. The hadronic emission components are photo-meson-induced cascade (purple dense-dotted), Bethe-Heitler pair cascade (dark yellow double-dot-dashed) and muon-synchrotron (yellow dash-dotted). Predicted (anti-)neutrino spectra are marked by (light-)magenta (dashed) solid lines, the blue vertical line shows the energy ~290 TeV of the observed neutrino. A comparison of the two solutions is also shown with the archival data from ASDC (c)). Results for different values of $E_{p,max}$ are compared for the enhanced VHE gamma-ray emission state (d), MJD 58029 to 58030) and the lower VHE gamma-ray emission state (Low state, e)).

Radio galaxies

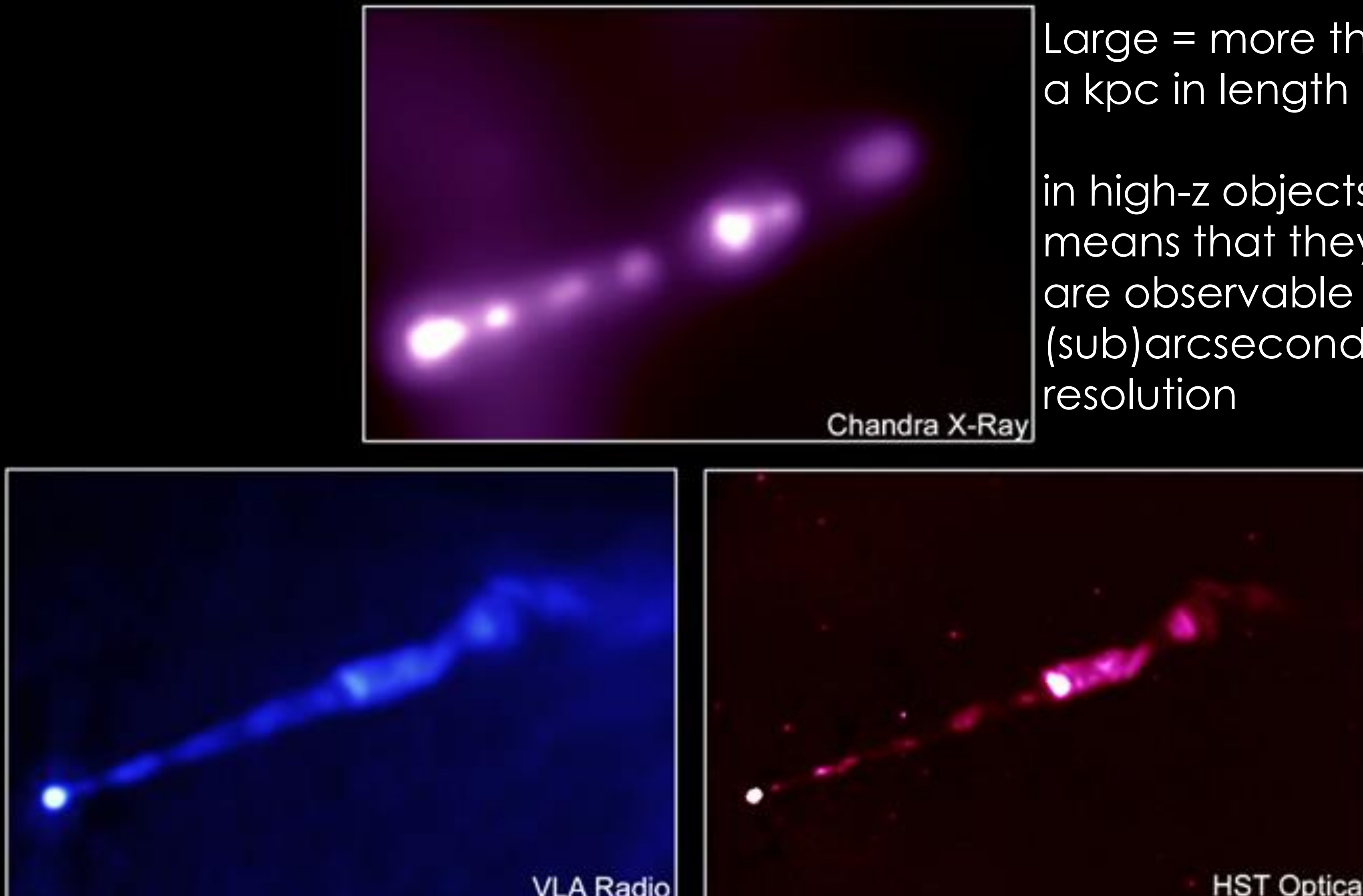
- Should be intrinsically same as blazars, but the jet oriented away from our line of sight.
- Powerful radio emission from large-scale jets, in some cases dominated by lobes far out from the host galaxy

Large-scale jets in radio galaxies are seen in radio, optical, and X-ray bands

M87

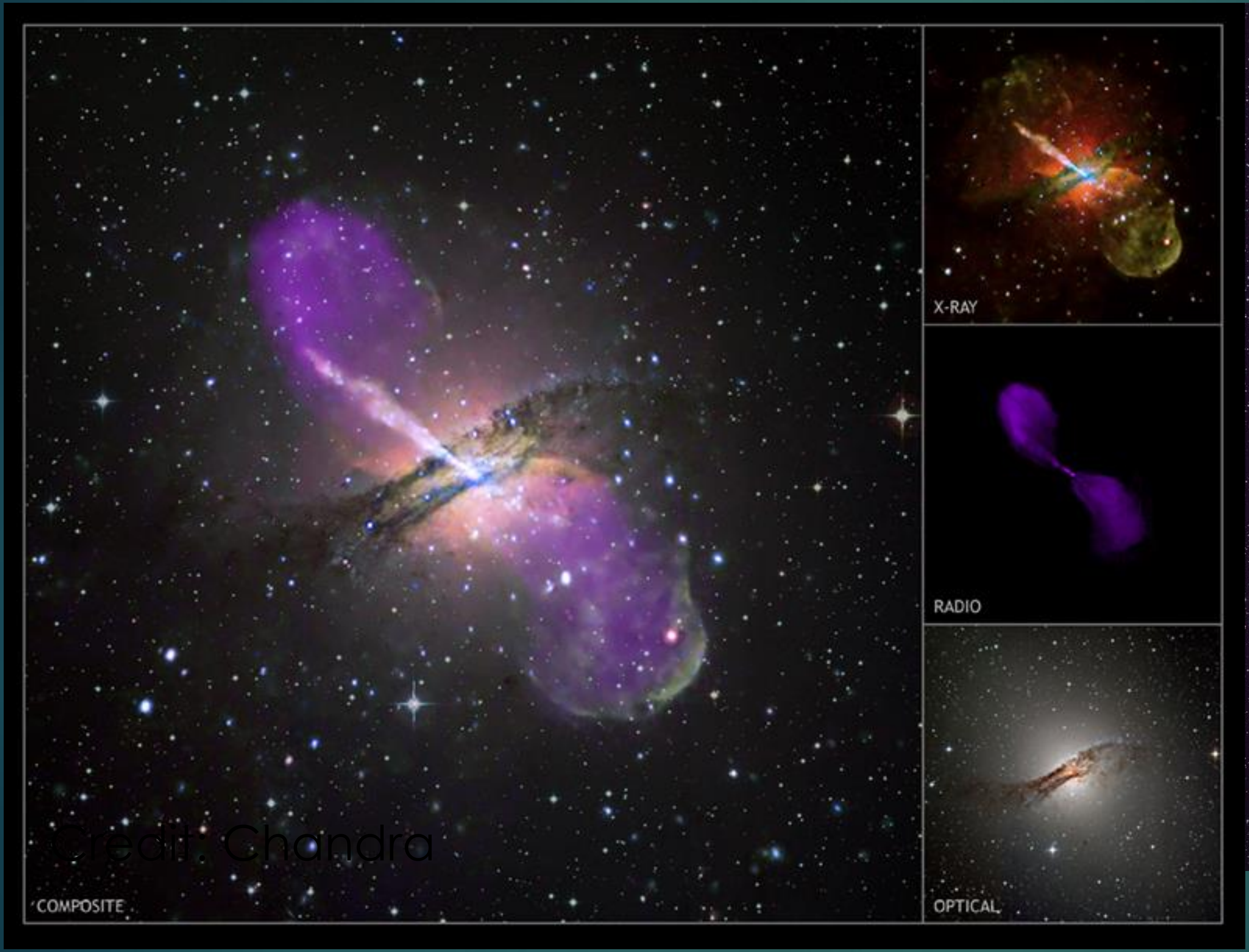
Large = more than a kpc in length

in high-z objects means that they are observable in (sub)arcsecond resolution



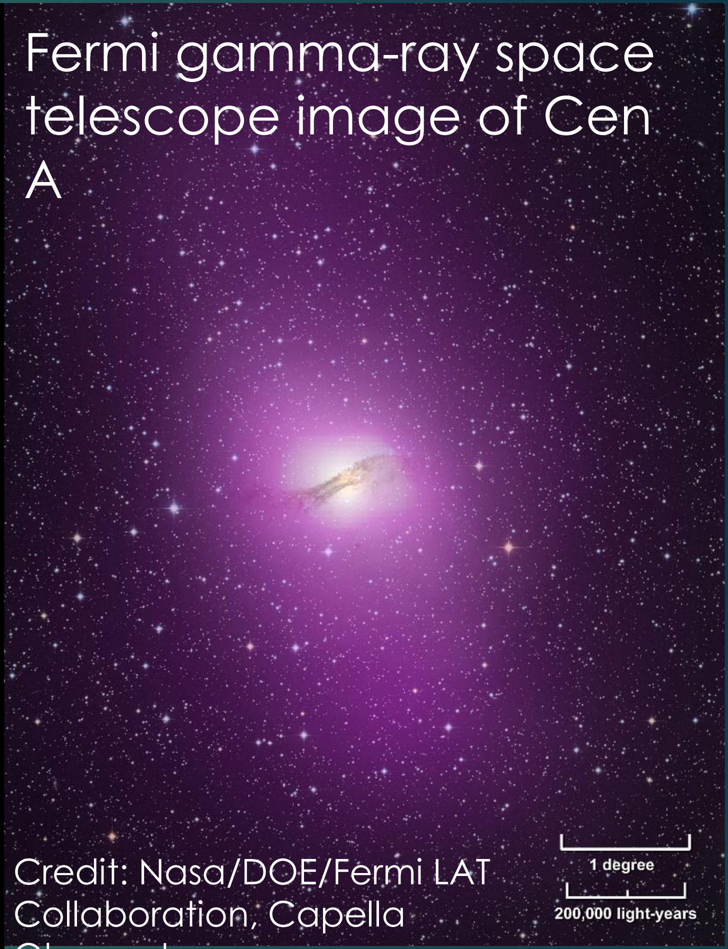
Large-scale jets in radio galaxies are seen in radio, optical, X-ray AND GAMMA-RAY bands

Centaurus A



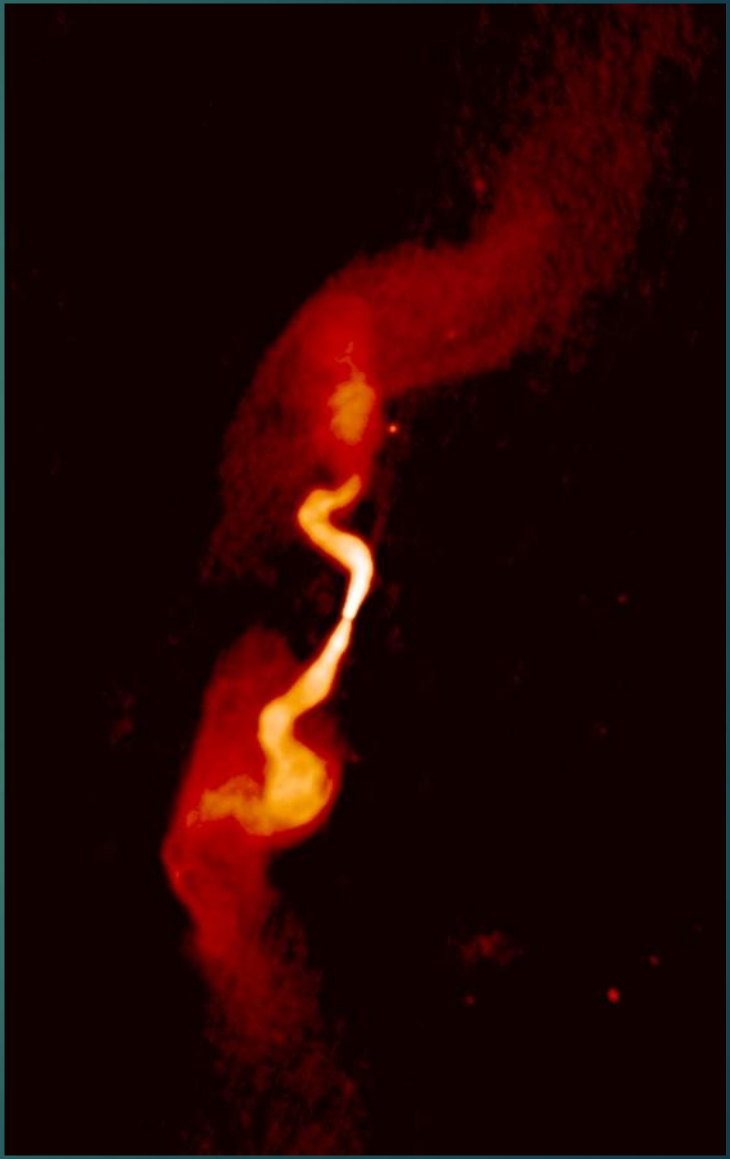
Credit: Chandra

Fermi gamma-ray space telescope image of Cen A



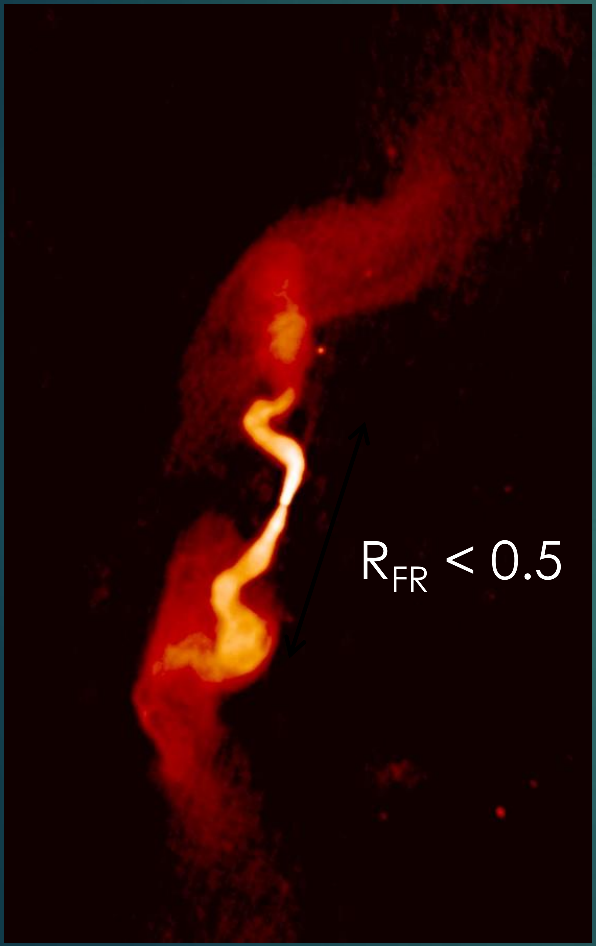
Credit: Nasa/DOE/Fermi LAT Collaboration, Capella Observatory

Large scale jets: the dictonomy



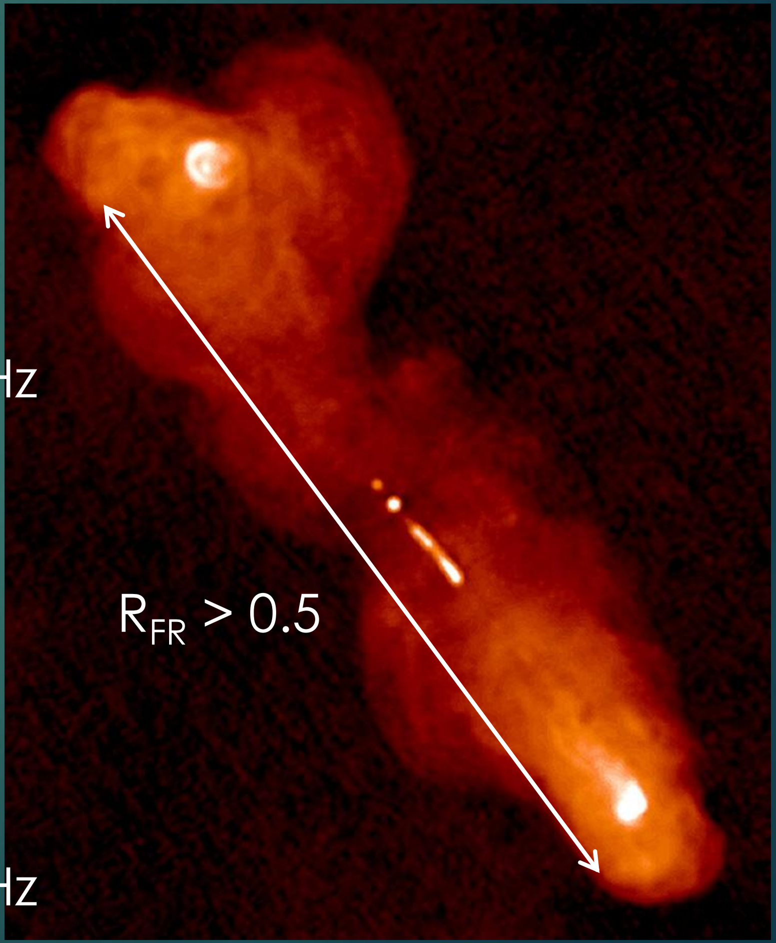
Fanaroff-Riley classification (1974)

Classification of radio galaxies based on the ratio between the high-surface-density extent and the full source extent, so that if $R_{FR} < 0.5$ the source is FR I and if $R_{FR} > 0.5$, the source is an FR II.
In their sample of 57 objects, they also noticed that FR I sources seemed to have 1.4 GHz luminosities $L_{1.4GHz} \leq 5 \times 10^{25}$W/Hz while FR II have mostly higher powers.



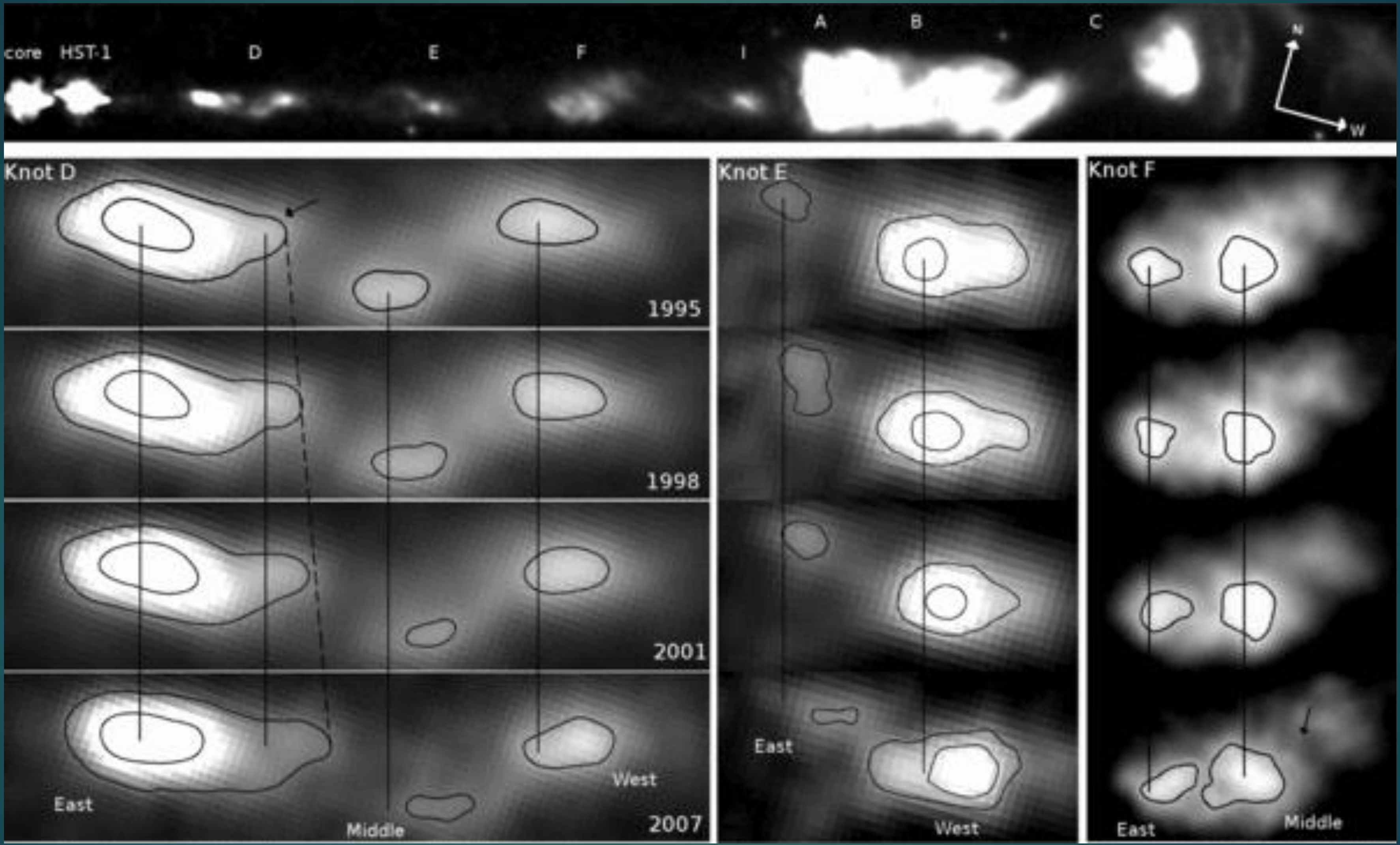
FR I:
- nucleus dominates
- broad jets ending in plumes
- two asymmetric jets
- luminosity $< 5 \times 10^{25}$W/Hz

FR II:
- lobes dominate
- weak jets ending in radio lobes with hotspots
- edge brightened jets
- luminosity $> 5 \times 10^{25}$W/Hz



M87 = FRI source with jet length ~ 2kpc

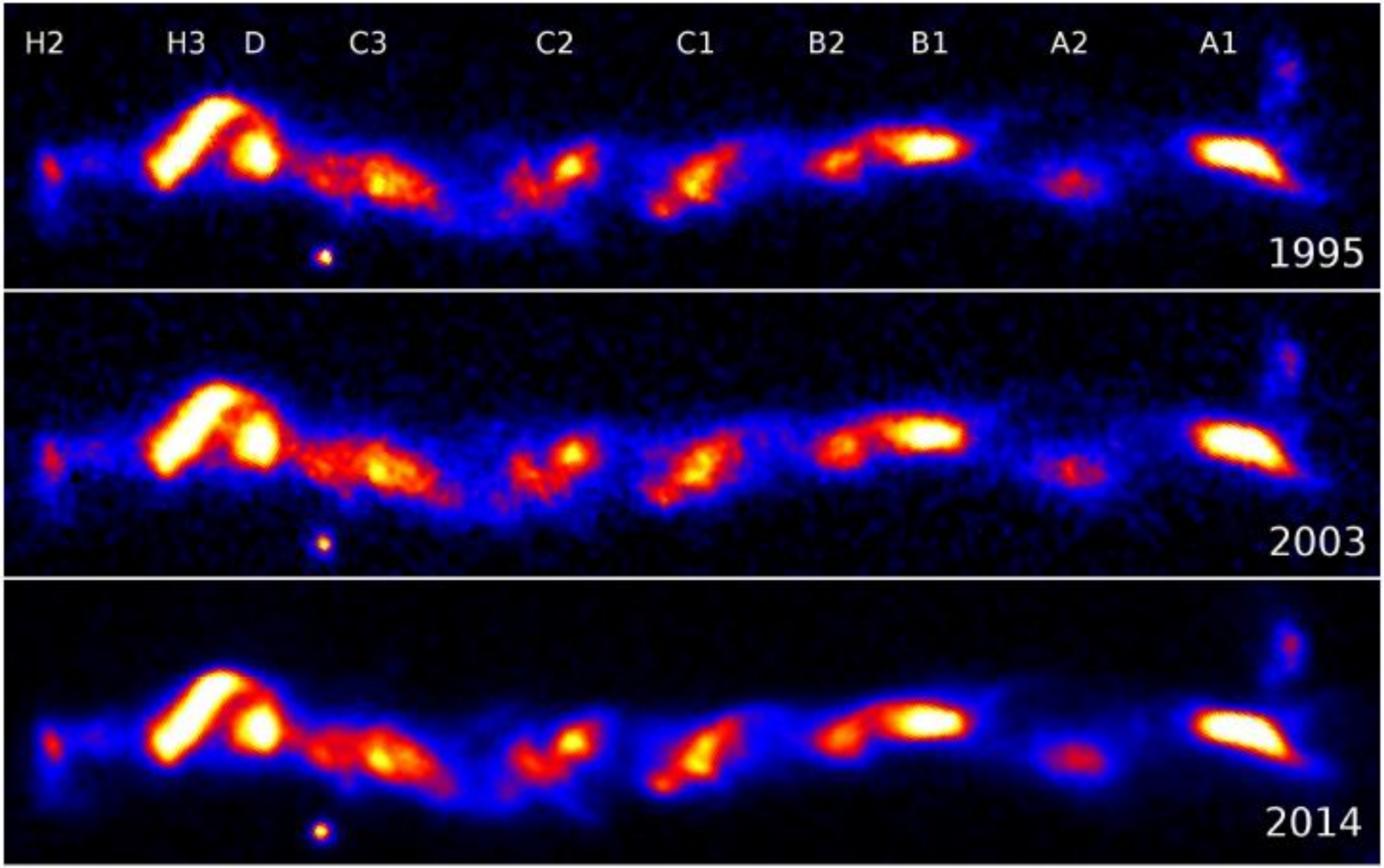
Meyer et al. 2013



Apparent superluminal motion (~ 5c) detected in the large-scale jet by Biretta e
and confirmed by Meyer et al. 2013

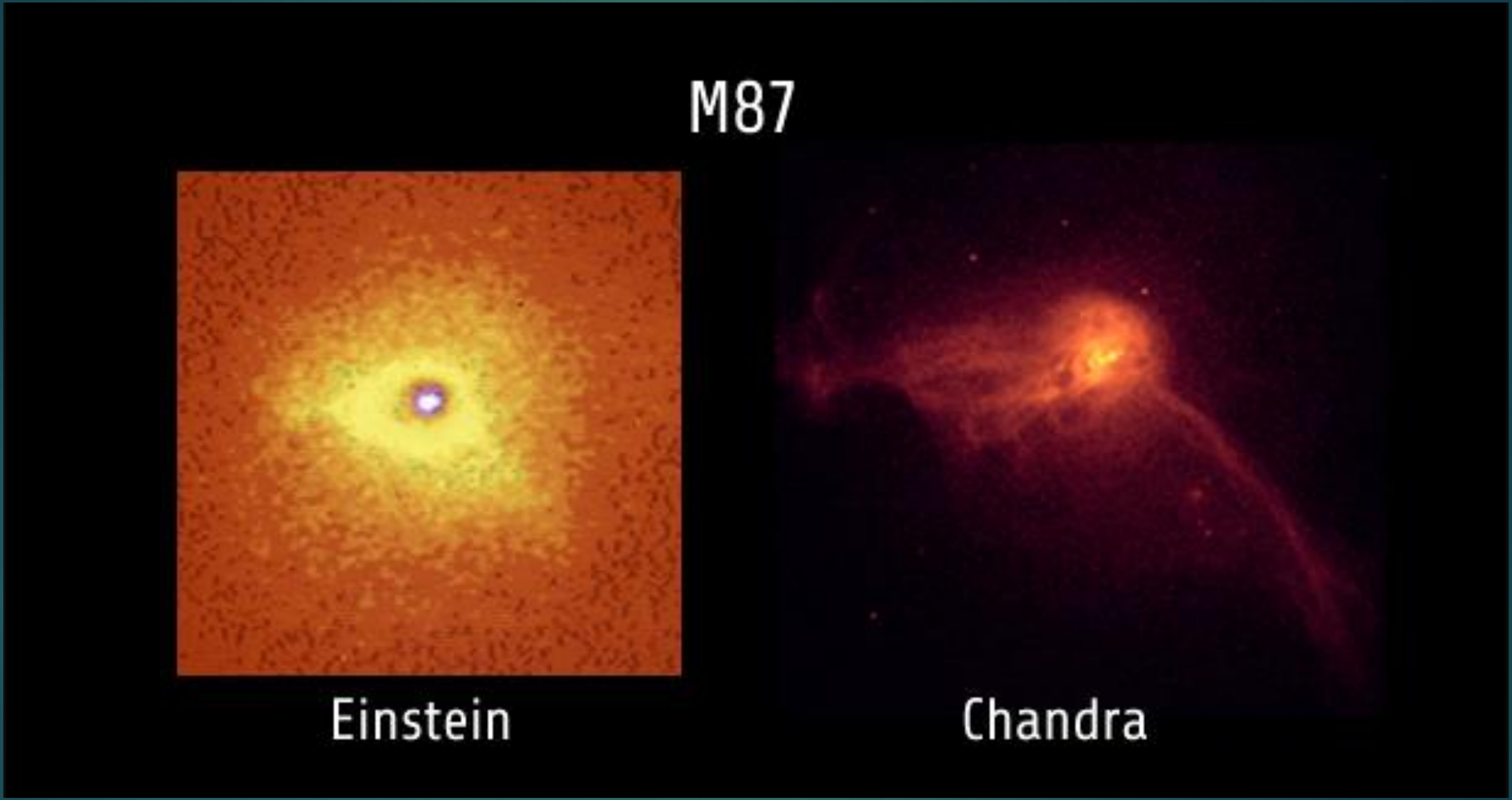
3C 273 FRII with jet length of ~ 60 kpc

Meyer et al. 2016



No proper motion seen on time scales of 20 years (Meyer et al. 2016)
(but much further away!)

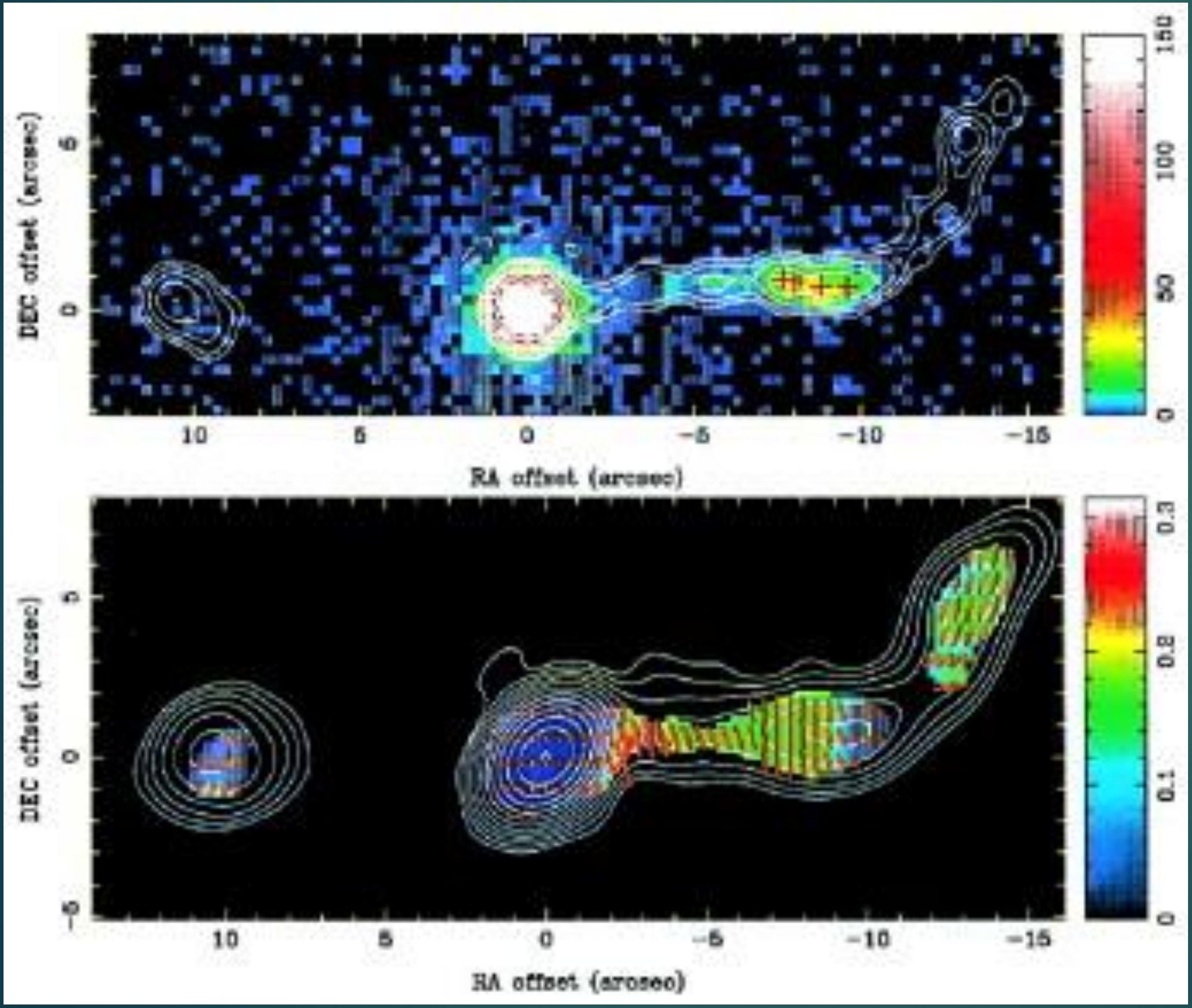
X-ray emission from jets was first detected by the Einstein Observatory … but revolution came with Chandra



Einstein was launched in 1978, Chandra in 1999 and there was ROSAT in betwee

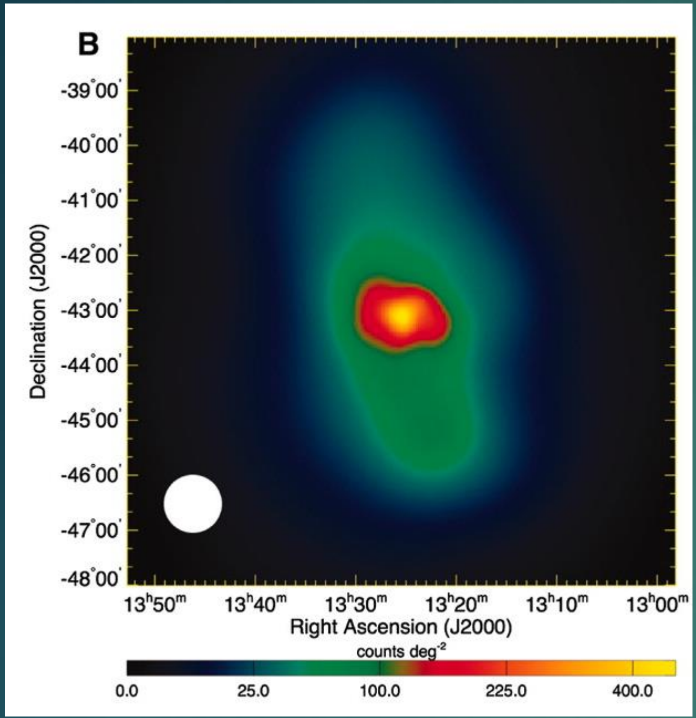
Chandra pointing calibration revealed a kpc-scale jet in PKS 0637-752

Schwartz et al. 2000

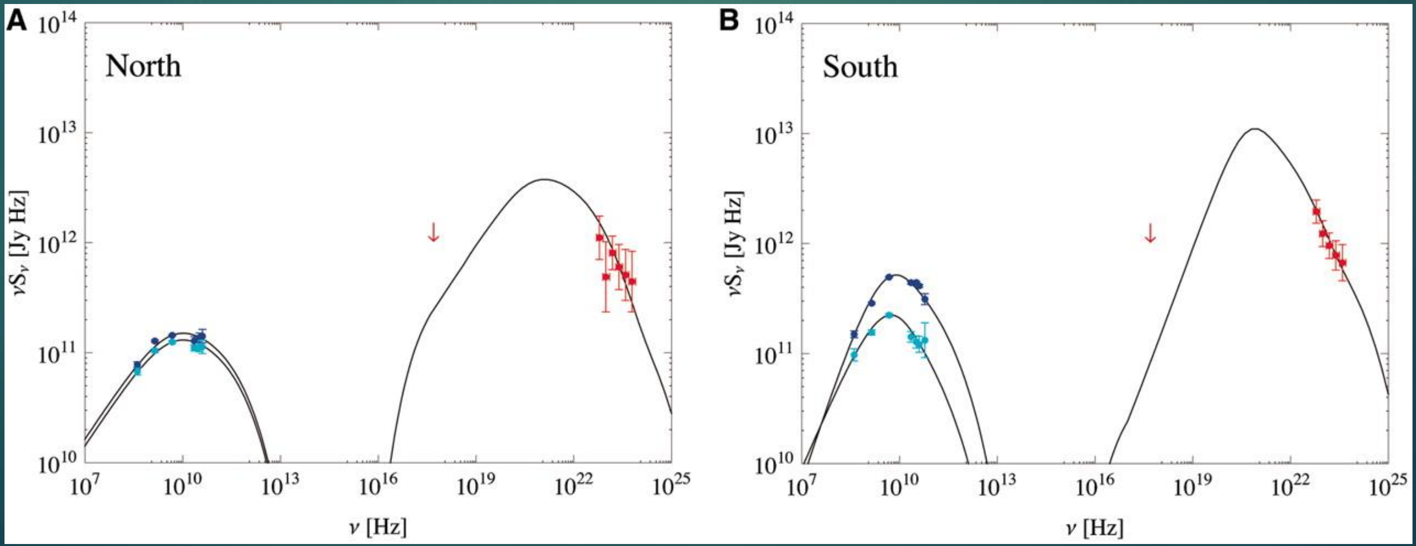


- For the first observations of Chandra they selected a "definite" point source PKS 0637-752 to verify the point-spread-function
- As often happens with new instruments, it turned out that this source actually shows a prominent kpc-scale X-ray jet!
- The jet has a very similar appearance as the radio jet
- Now more than 100 sources with detected X-ray knots http://hea-www.harvard.edu/XJET/

Gamma-ray detection of the lobes of Centaurus A by Fermi



- One of the few spatially resolved extragalactic sources on the gamma-ray sky
- Despite the radio lobes dominating the radio emission, most of the energy in the lobes is actually emitted in gamma-ray energies!
- Best model to fit the gamma-ray data is inverse Compton emission off the CMB photons

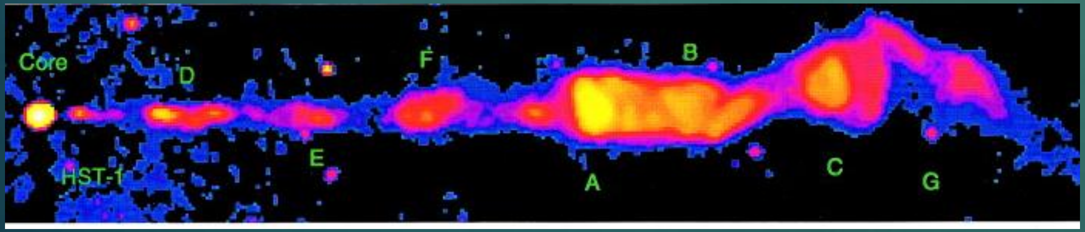


Possible emission mechanisms for the X-ray energies include synchrotron, SSC or IC / CMB question and this is an active

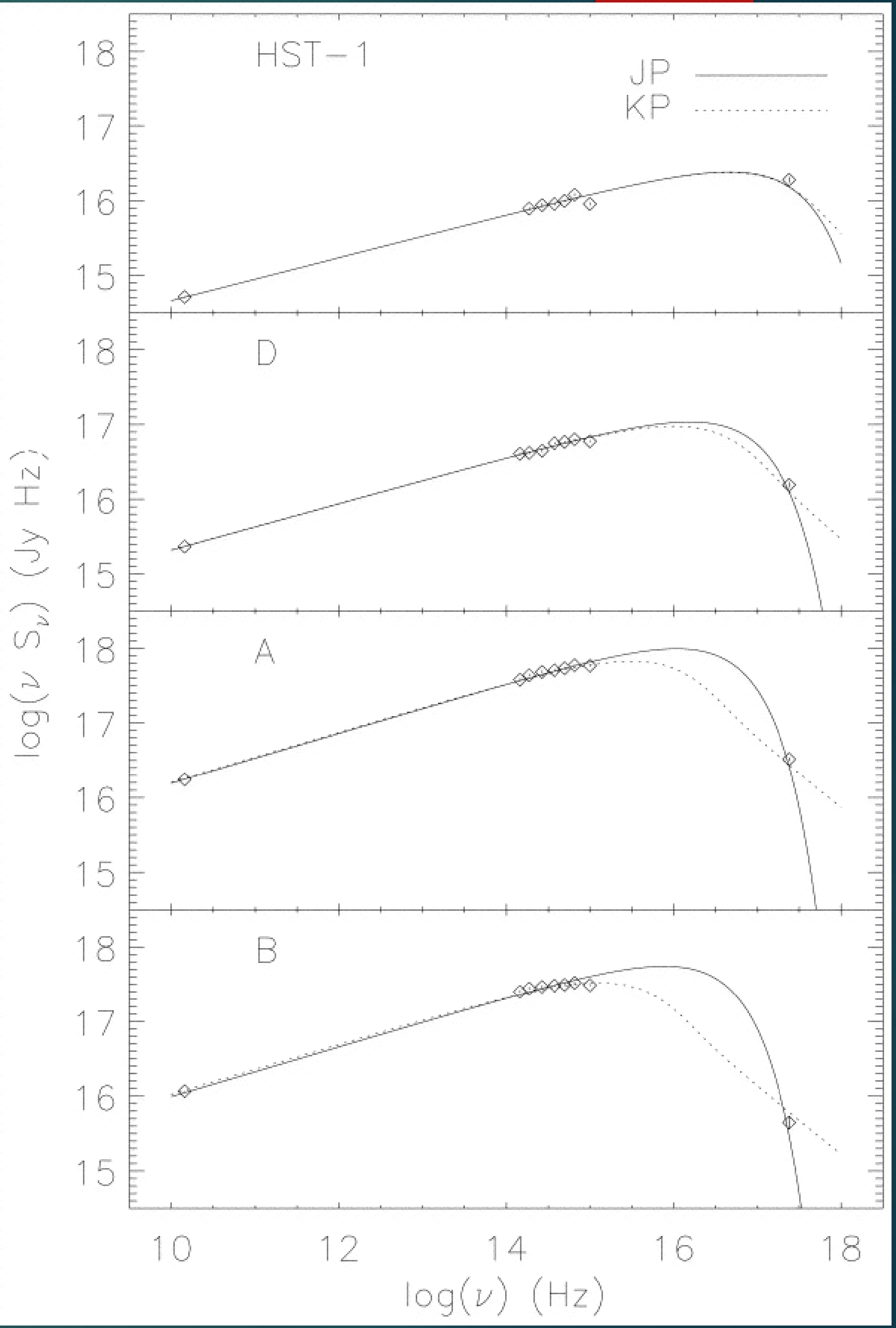
In FRI type jets, such as M87, the X-ray fluxes fall on a power-law extrapolation of the radio – optical spectrum

→ This is interpreted as a synchrotron origin one population of electrons

Implication is that FRI jets must be able to accelerate particles to very high energies!



Marshall et al. 2002

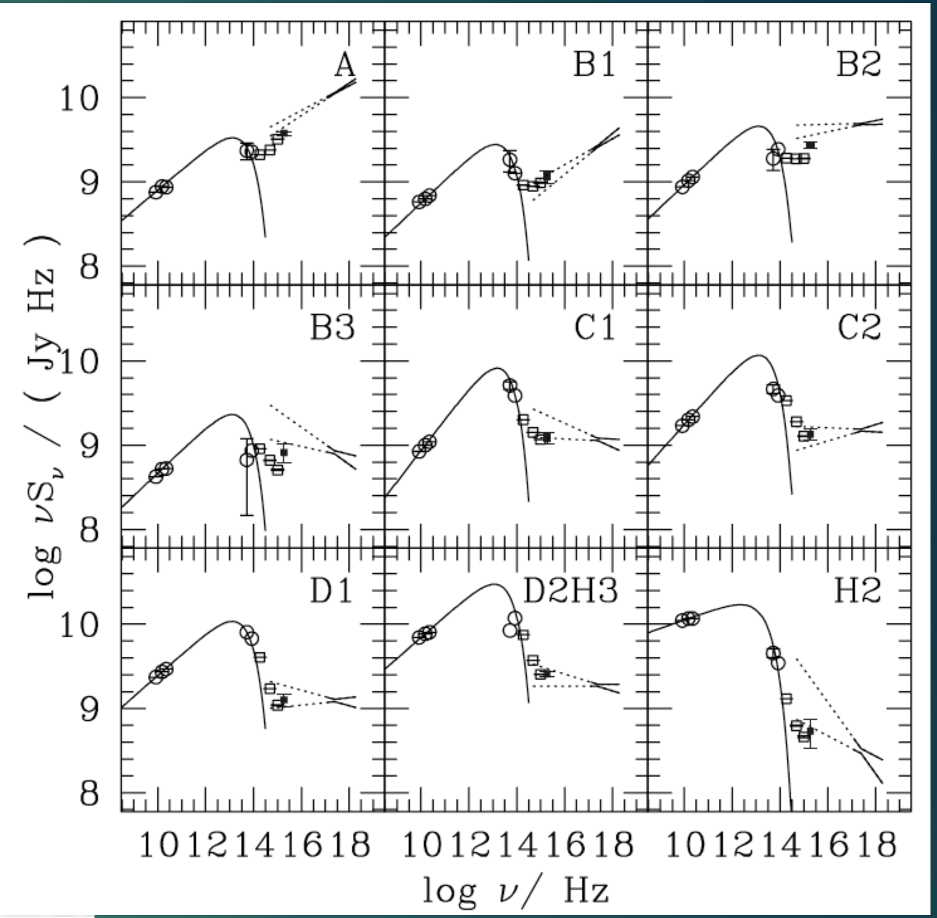


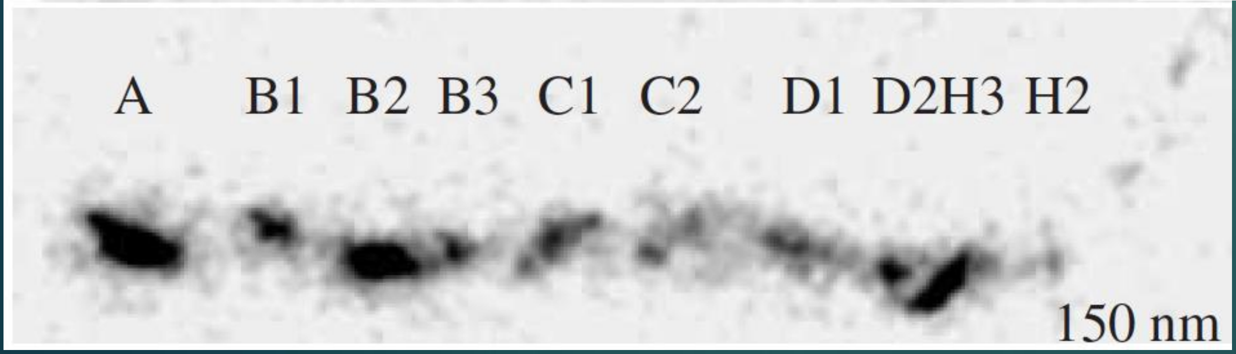
Possible emission mechanisms for the X-ray energies include synchrotron, SSC or IC / CMB question and this is an active field of research

In FRII type jets, such as 3C273, the situation is much less clear because the synchrotron does not seem to fall on the same power-law spectrum.

→ In these sources the X-ray emission could be also due to inverse Compton mechanism, but this is highly debated!

If the X-ray emission would be IC off CMB photons, it would mean that there must be a large population of low-energy electrons (to scatter the photons), and the jet power must be very large.





Jester et al. 2007

FR II jets can often be modeled with both synchrotron and IC/CMB models, but the implications for the jet characteristics in the two models are very different

IC/CMB jet: $\Gamma = 40$, $\delta = 20 \rightarrow \theta = 2.48^{\circ}$
$\gamma_{min}=1.6$, $\gamma_b=160$, $\gamma_{max}=3\times10^5$

→ Jet kinetic power 34 x Eddington luminosity of a 10^9 M_{BH} black hole, projected length of the jet 1.63 Mpc (would be one of the largest ever known)

2 synchrotron components: $\Gamma=\delta=2$, $\theta=30^{\circ}$
Radio-optical SED: $\gamma_{min}=100$, $\gamma_{max}=7\times10^5$

optical – X-ray SED: $\gamma_{min}=3\times10^6$, $\gamma_{max}=2\times10^8$

→ Jet kinetic power ~7% of Eddington luminosity, projected length of the jet 140 kpc

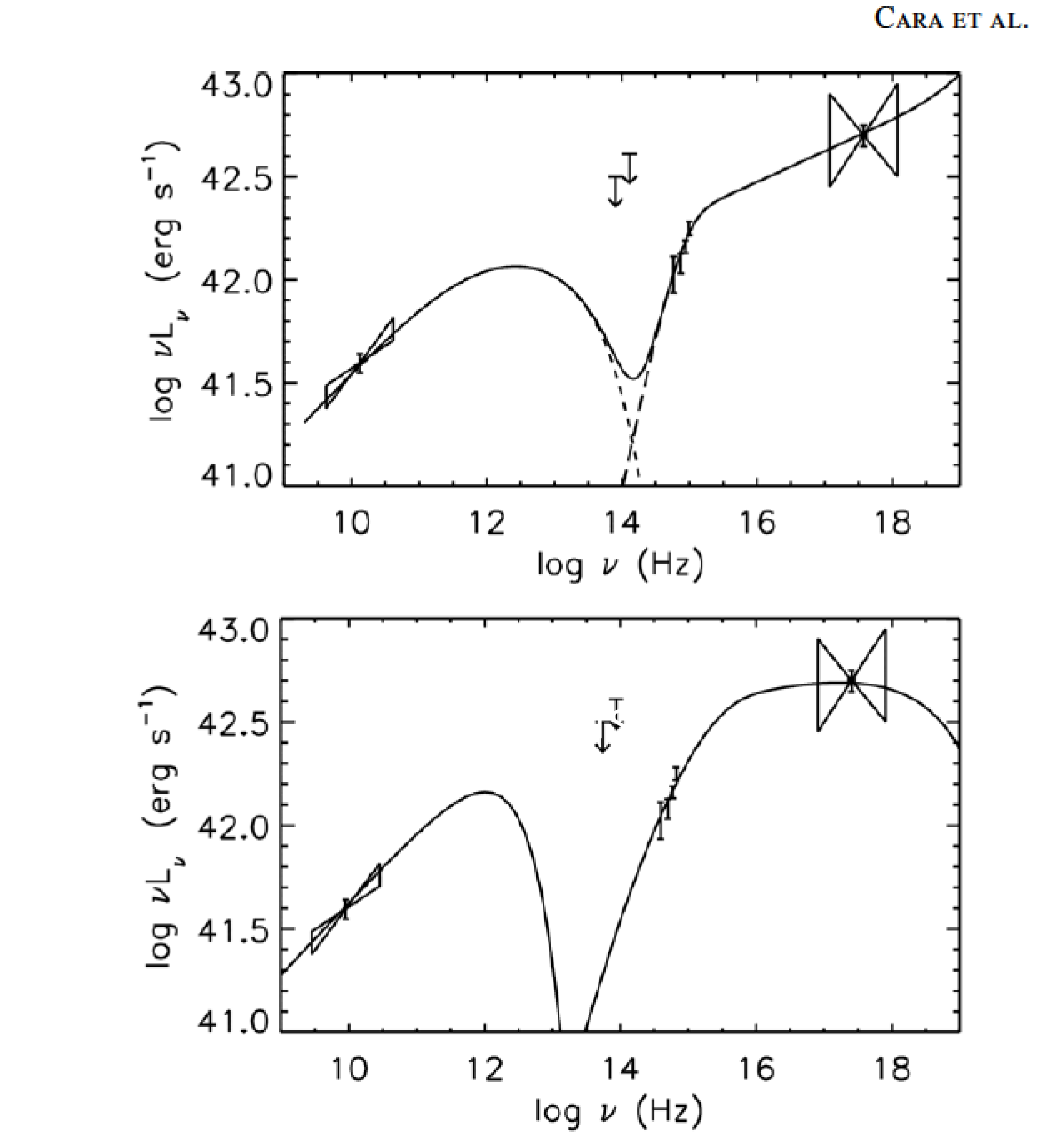


Figure 6. Fits of the knot A data of PKS 1136−135 with the IC/CMB (top) and two-synchrotron component (bottom) models. Both fits are reasonably good. They correspond, however, to extremely different jets (see text).

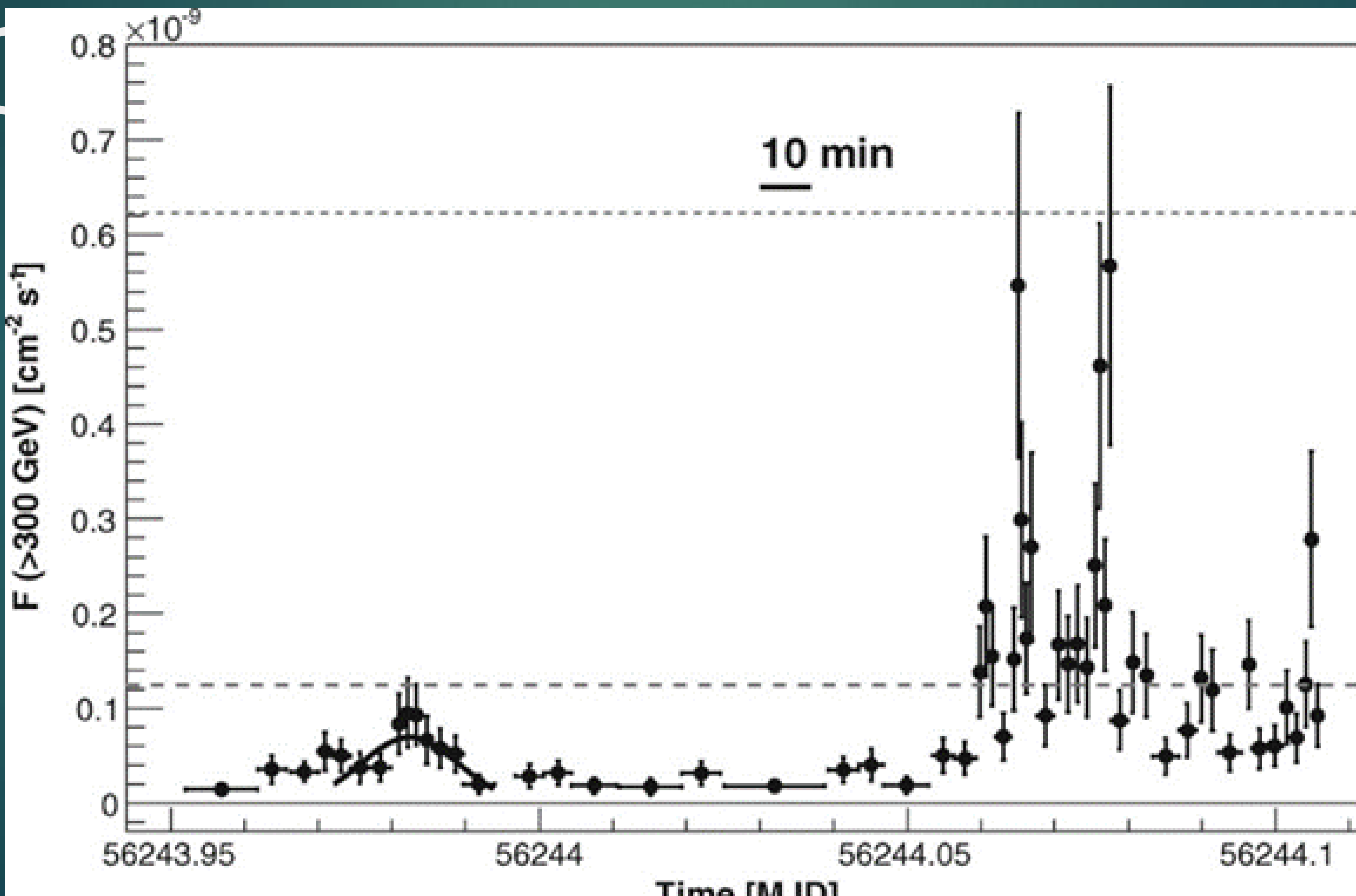
Cara et al. 2013, source PKS 1135-135

Radio galaxies

- Should be intrinsically same as blazars, but the jet oriented away from our line of sight.
- Powerful radio emission dominated by lobes far out from the host galaxy
- Jet not pointing towards us: Problem for gamma-ray emission: Doppler boosting needed...but if theta is not small, these are very difficult to achieve...
- Structured jets? The large scale jet has different direction than the jet close to black hole?

And we do detect them in gamma-rays

In addition to Cen A…
Variable emission from M87,
NC



Some ideas to overcome this

Structured jet models were suggested (e.g. Ghisellini et al. 2005):
-spine would dominate emission in blazars
-layer would dominate in radio galaxies

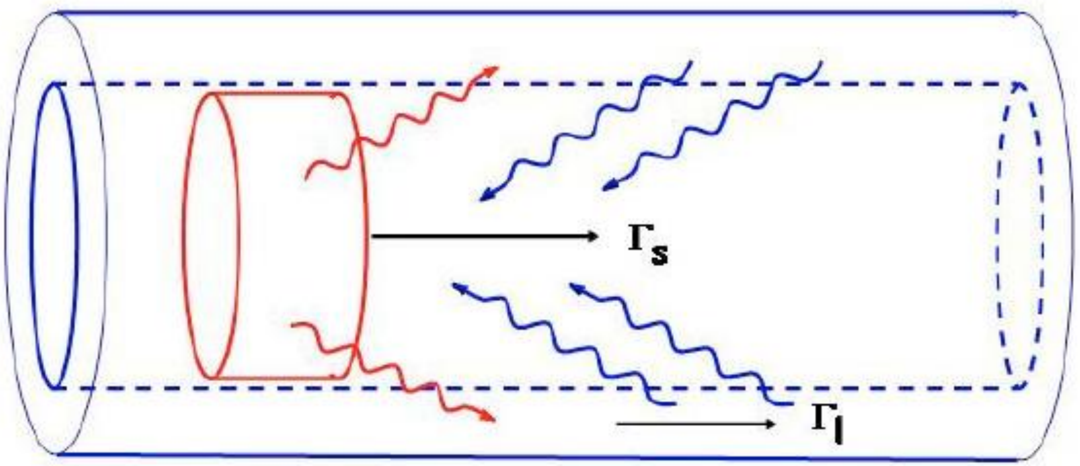
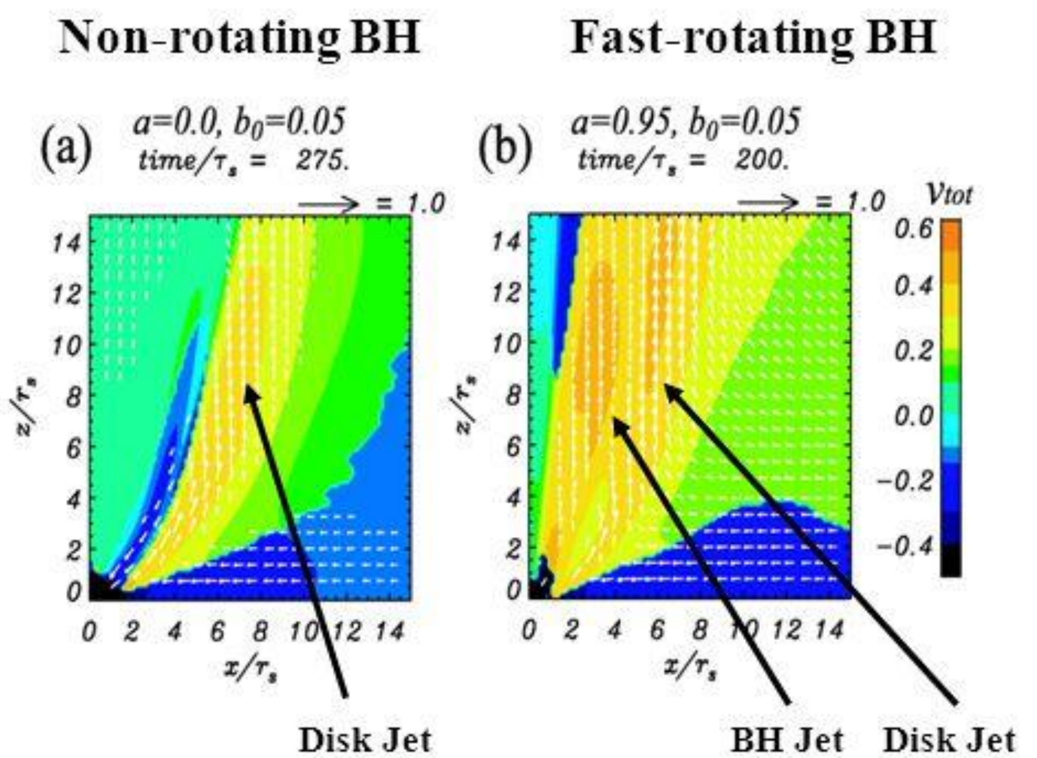


Fig. 1. Cartoon illustrating the layer+spine system.

Center spine may be deboosted due to Doppler effects (fast enough speed with large enough viewing angle causes de-boosting)
Sheath may be naturally bright because of mass-loading from the ISM and particle acceleration along the jet edge

Spine-Sheath Relativistic Jets (GRMHD Simulations)

- In recent general relativistic MHD simulation of jet formation (e.g., Hawley & Krolik 2006, McKinney 2006, Hardee et al. 2007), simulation results suggest that
  - a jet spine driven by the magnetic fields threading the ergosphere
  - may be surrounded by a broad sheath wind driven by the magnetic fields anchored in the accretion disk
- This configuration might additionally be surrounded by a less highly collimated accretion disk wind from the hot corona.

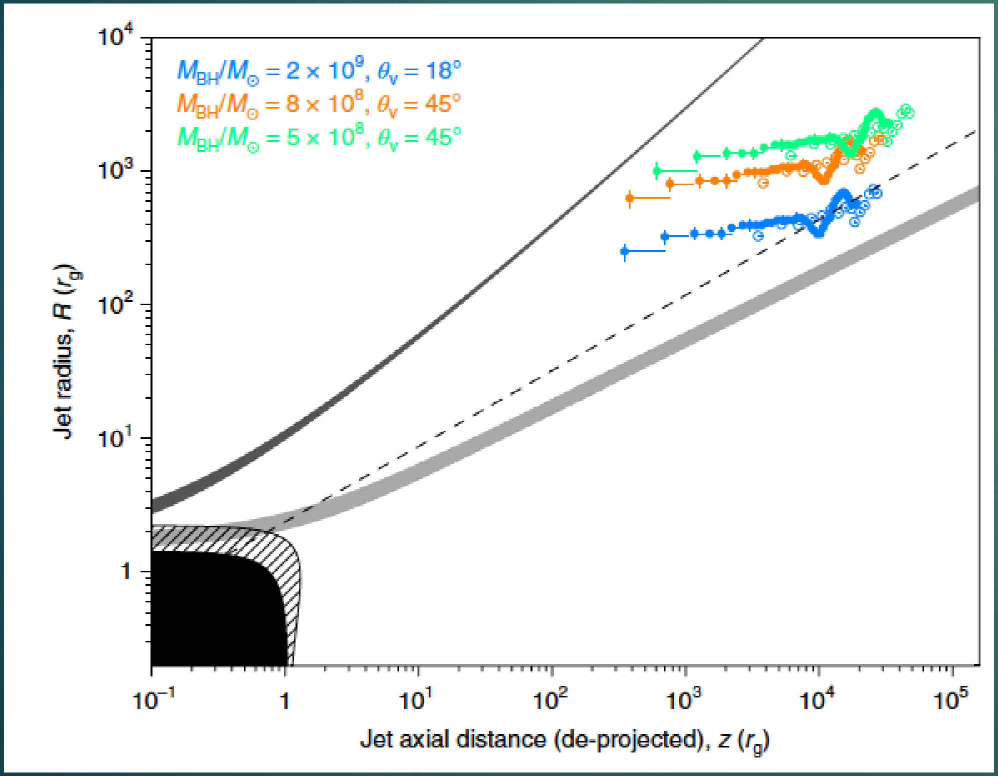


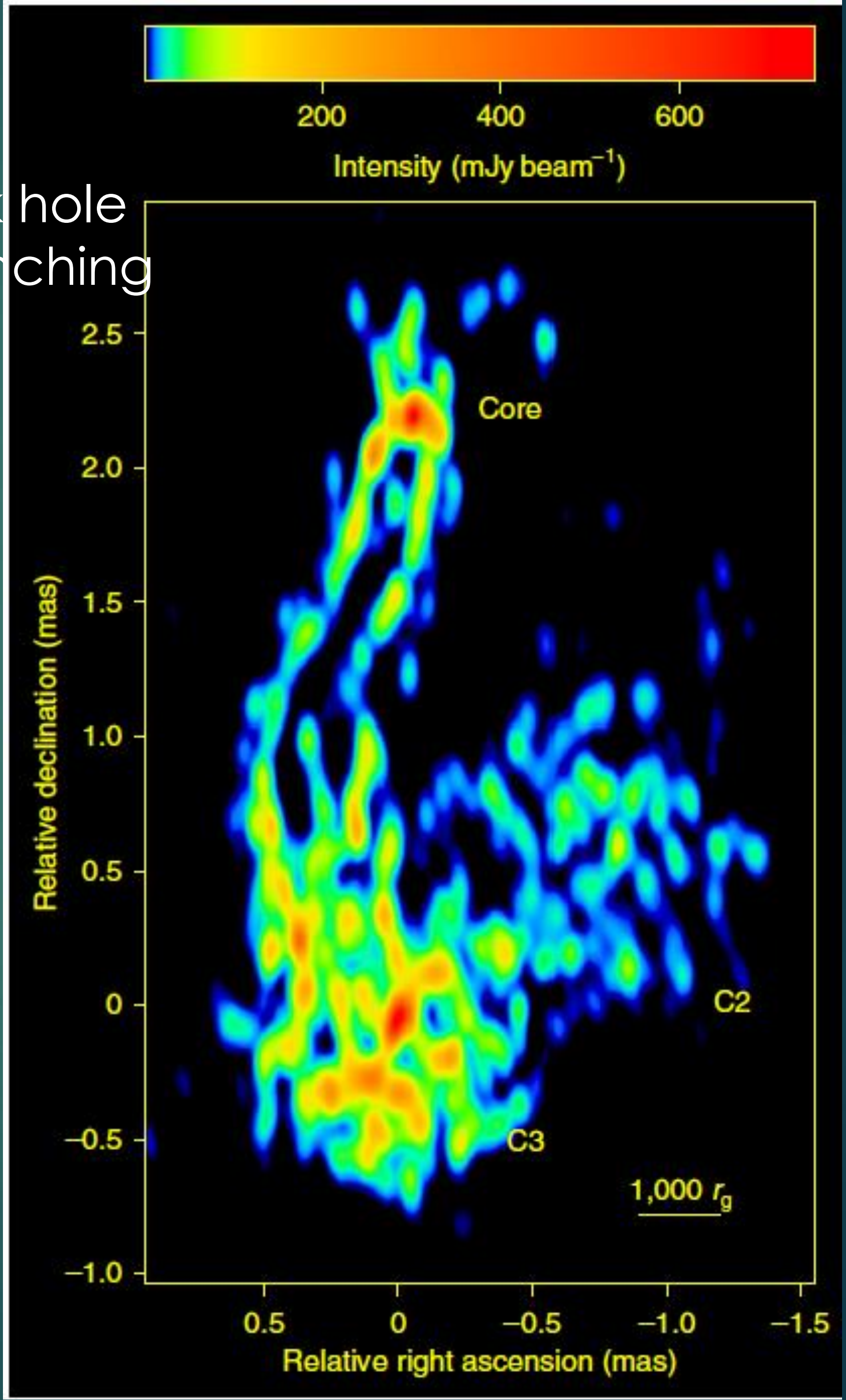
Total velocity distribution of 2D GRMHD Simulation of jet formation (Hardee, Mizuno & Nishikawa 2007)

Slide taken from a presentation by Mizuno

RadioAstron image of the nearby radio galaxy 3C84 reveal a spine-sheath structure of the jet

- Angular resolution is **27μas**
- Jet is seen down to ~$10^2 r_g$ from the black hole
- Jet is much wider than expected for launching from the black hole ergosphere!
  - launched from the accretion disk, or external pressure much weaker than assumed

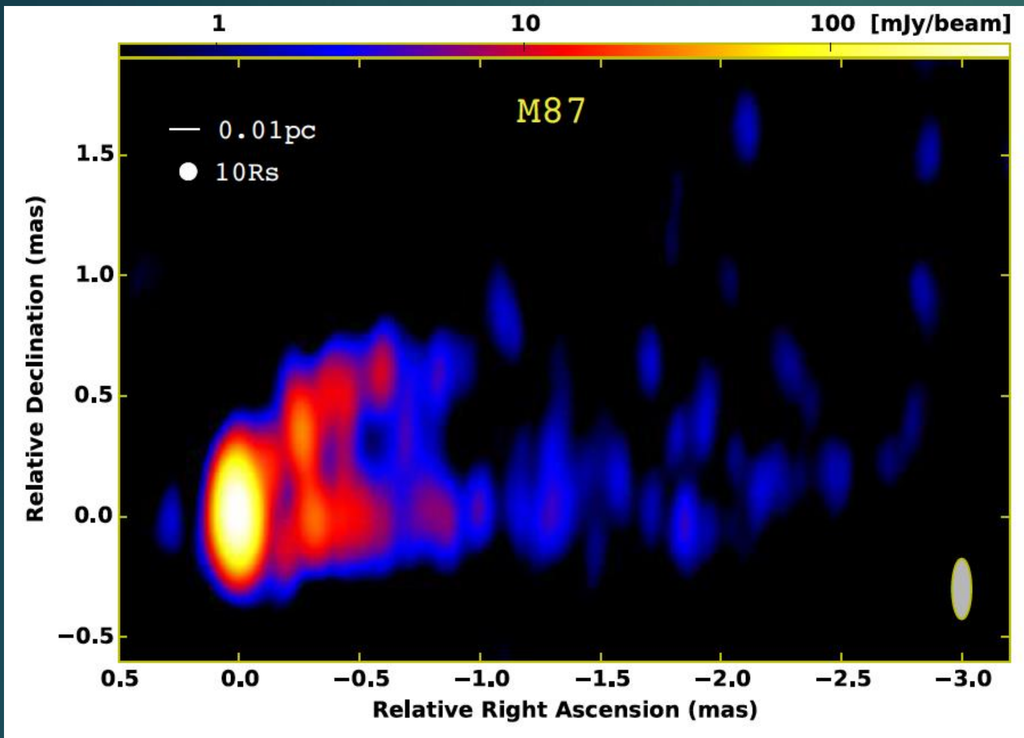


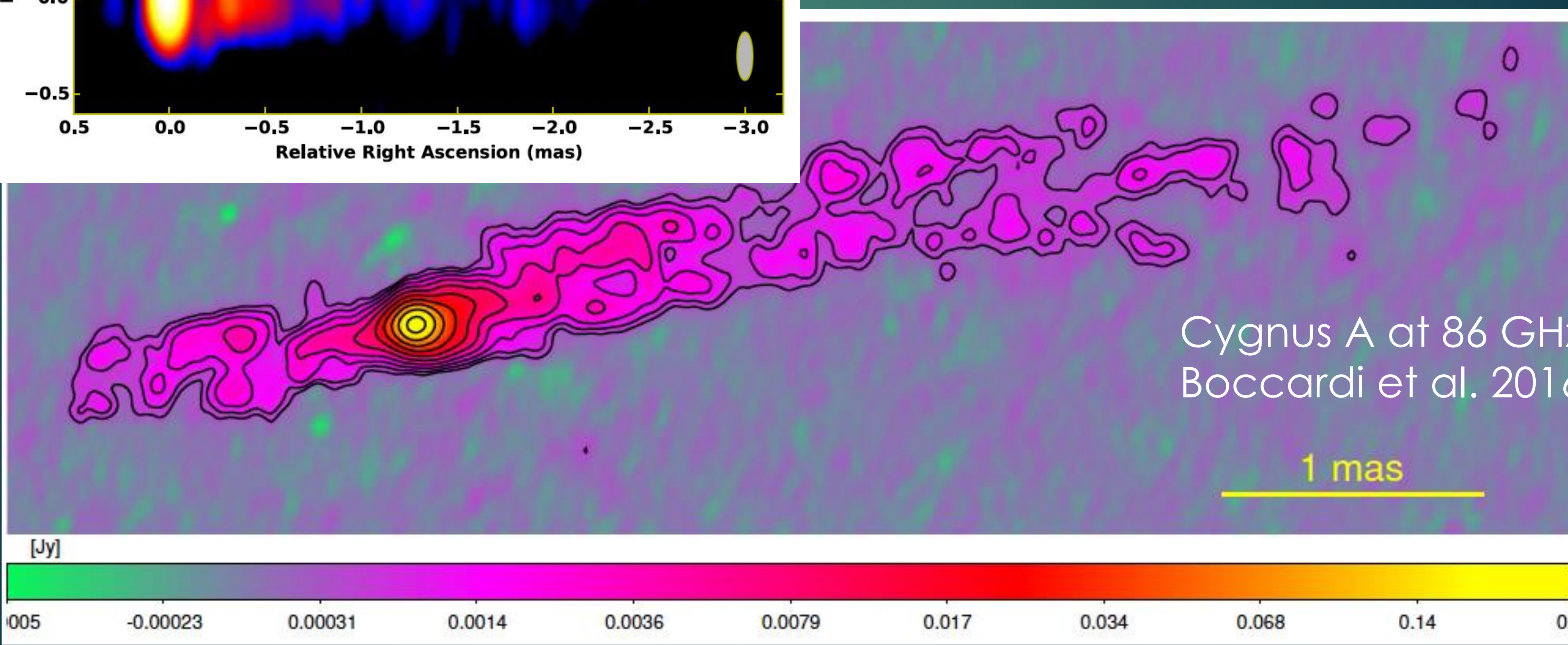


Giovannini, Savolainen et al. 2018

Direct indications of spine-sheath structures are seen in other nearby radio galaxies as well

- Center spine may be deboosted due to Doppler effects (fast enough speed with large enough viewing angle causes de-boosting)
- Sheath may be naturally bright because of mass-loading from the ISM and particle acceleration along the jet edge





Cygnus A at 86 GHz
Boccardi et al. 2016

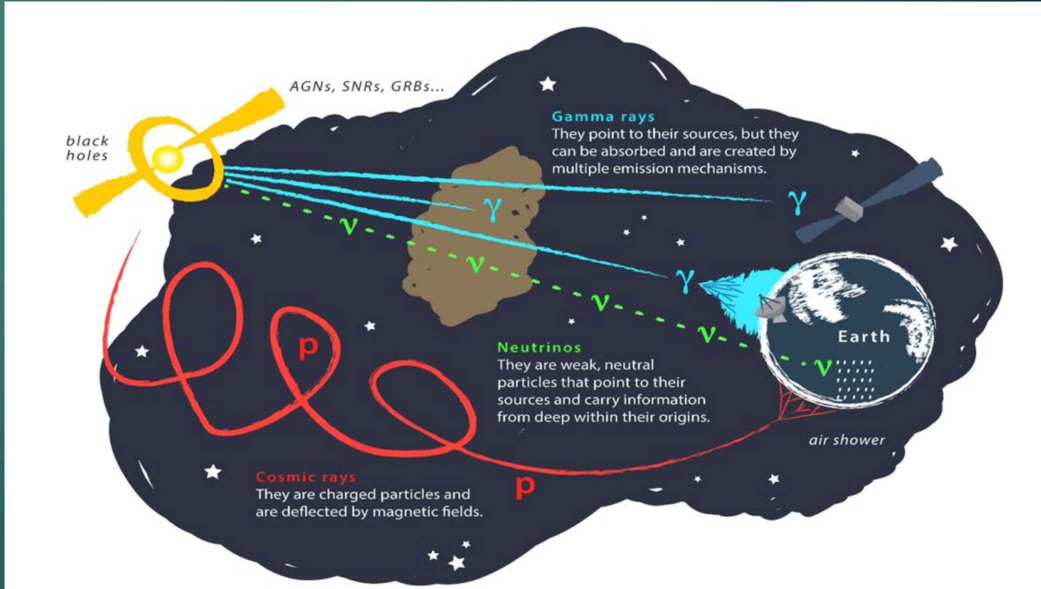
Final slide on radio galaxies

- Many open questions at observational and simulations side which makes is difficult to access the jet speed, magnetic fields and kinetic power that are all very relevant for UHECRs acceleration

What I will try to cover today?

- Gamma-ray observations of blazars
- Neutrino observations of blazars
- Radio galaxies (i.e. when jet is not pointing close to our line of sight)

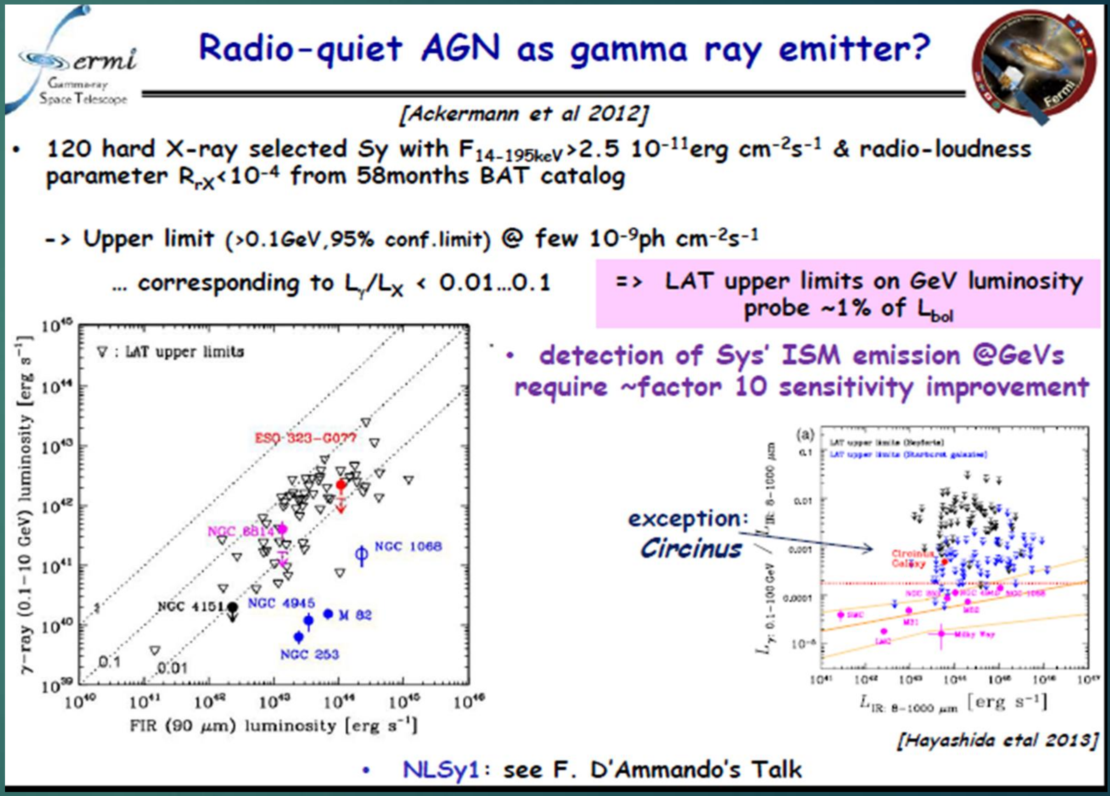
- Is that all?
- Propagation effects



Credit: Juan Antonio Aguilar and Jamie Yang IceCube/WIPAC.

Non-jetted AGNs?

- Reminder: these are ~90% of the sources
- All same ingredients close to central engine, just NO JET
- Outflows/winds from the accretion disk
- Seemed uninteresting for astroparticle physics…



Non-jetted AGNs?

- Widespread evidence that AGN can more commonly eject moderately collimated winds of thermal plasma
- Outflow velocities from a few 100 km/s up to mildly relativistic values of ~0.3c
- Primarily observed as blue-shifted absorption features due to ionized metals at UV and X-ray energies.
- They are seen in at least ~40% of all nearby AGN, of both radio-loud and radio-quiet types (i.e. with or without strong jets).
- The winds are inferred to be generated on sub-pc scales, and their estimated kinetic power can reach a fair fraction of the AGN bolometric luminosity.

But the real game-changer:

NGC1068

- NGC 1068, a nearby (distance ~14 Mpc), type-2 Seyfert galaxy
- Known to possess a conspicuous AGN-driven wind
- The GeV gamma rays detected from the object was initially suggested to be of starburst origin
- But could also be photopion production of gamma rays induced by protons accelerated in the AGN wind external shock
- NGC 1068 has been shown to be a tentative source of neutrinos by IceCube, the most significant point in the northern hemisphere in a full-sky scan. A 2.9sigma excess over background.
- Not detected at VHE (yet?): Upper limits in gamma rays at energies above 0.2 TeV by MAGIC: important constraints on the origin of such neutrinos.

NGC1068

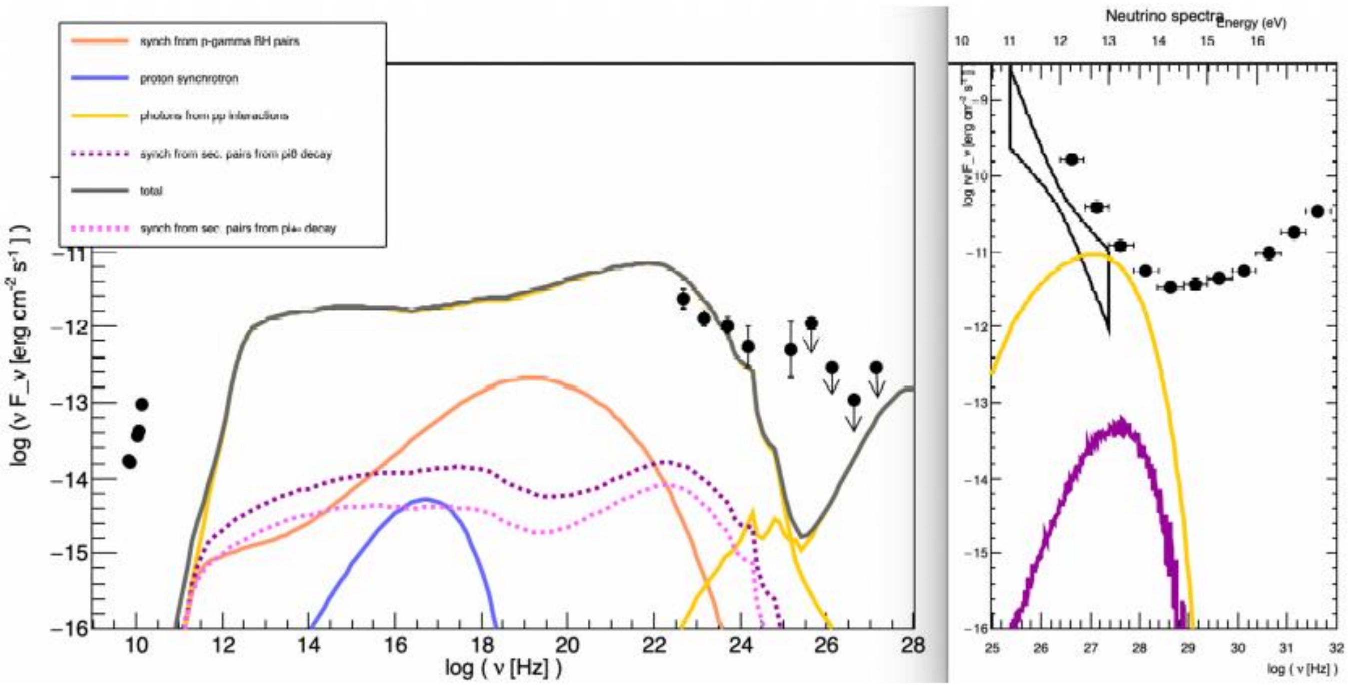


Figure 2: Multi-messenger spectral energy distribution for the model parameters discussed in the text, compared with observational data for NGC 1068. Left panel: Photon model curves for π^0 decay gamma rays and cascade emission due to pp interactions (yellow solid), cascade emission due to $p\gamma$ Bethe-Heitler interactions (orange solid), cascade emission due to $p\gamma$ π^0 and $\pi^\pm$ decay (purple and magenta dashed, respectively), protron synchrotron emission (blue solid). Data from Fermi-LAT [11] MAGIC [15] and ALMA [17]. Right panel: Neutrino model curves for pp (yellow solid) and $p\gamma$ (purple solid). Data for NGC 1068 [14] and the 10-yr point-source sensitivity of IceCube.

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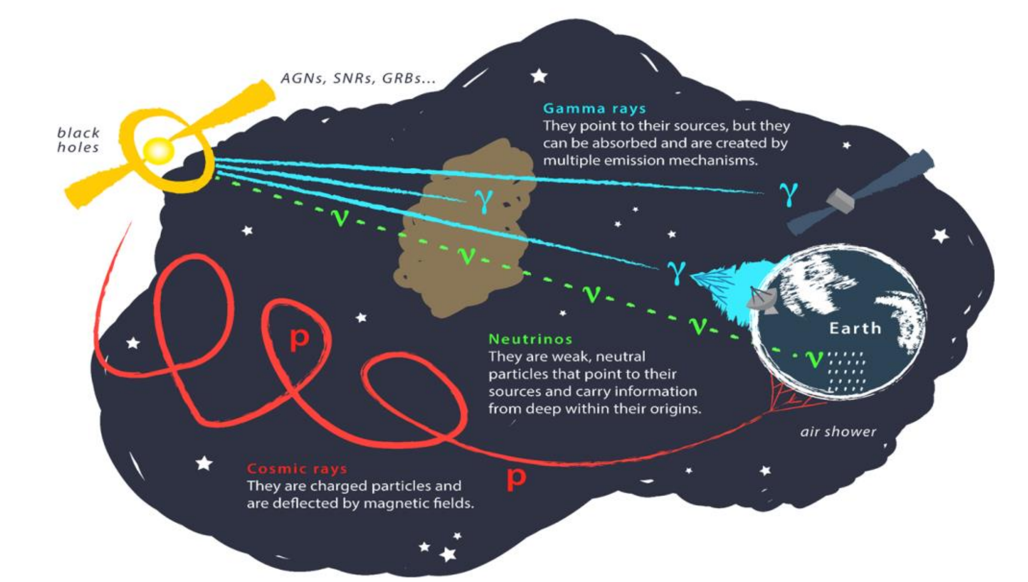


Credit: Juan Antonio Aguilar and Jamie Yang IceCube/WIPAC.

Gamma-ray bursts

- Short, very bright bursts of gamma-rays, first discovered by Vela satellites
- BATSE (onboard CGRO) observed 2700 GRBs (about one a day): isotropic distribution => extragalactic origin
- Long and short duration bursts: diviation at 2s
- Very short “variability time scale” ~<1ms =>emission region very compact!

$$R_{\mathrm{emission}} < \Gamma^2 \cdot c \cdot \delta T_{min} \approx \Gamma^2 \cdot 60\,\mathrm{km}$$

Gamma-ray bursts

- Progenitors of the long duration bursts are supermassive stars; GRB occurs when the core collapses directly to black hole, for short bursts merger models (neutron star-neutron star, neutron star- black hole) have been suggested
- The emission can be described with the “fireball model”: where the central object produces highly variable, ultrarelativistic (Gamma>>100) outflow of optically thick plasma shell (“the fireball”) containing mostly electrons, positrons and gamma-rays

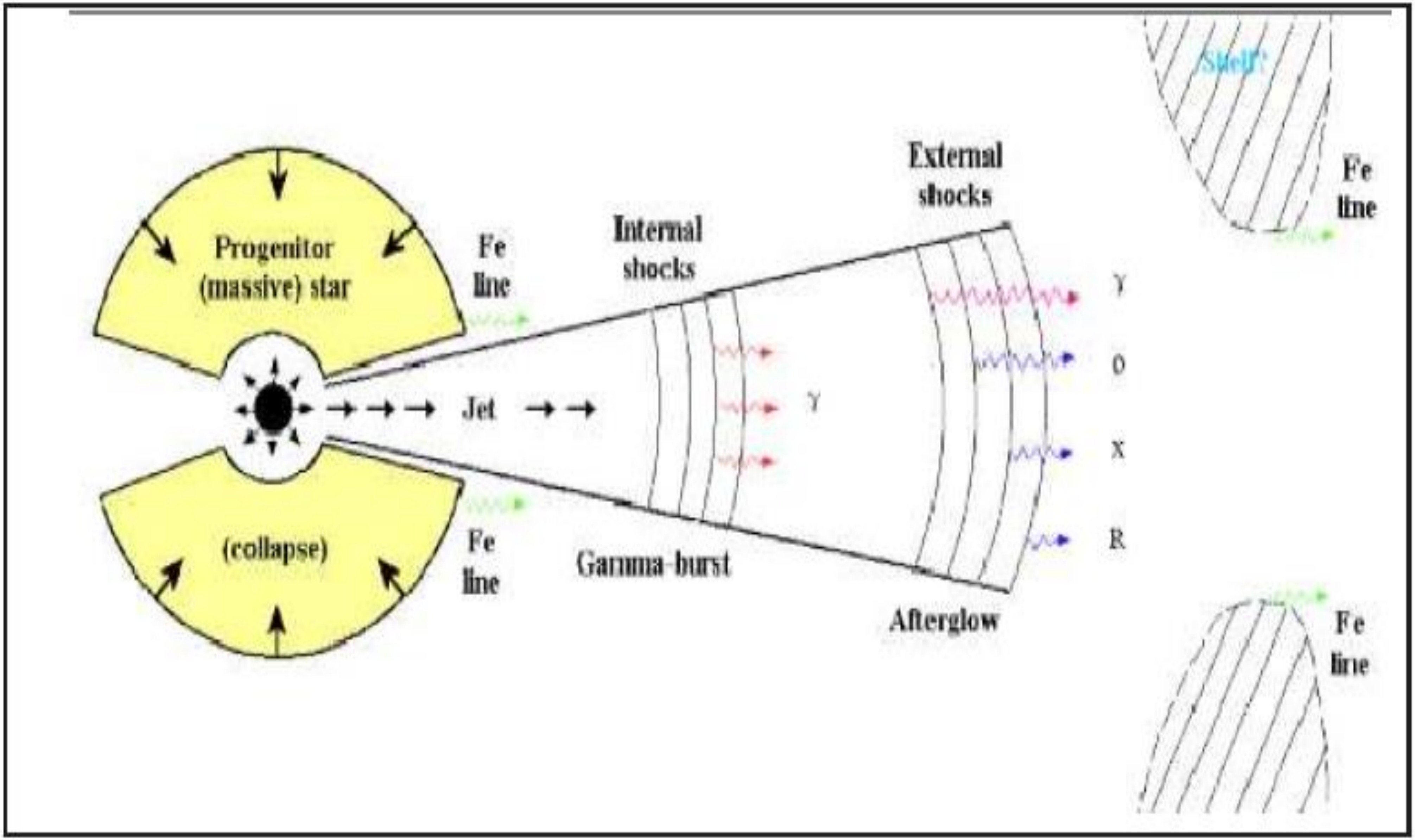


Figure 18: A sketch of the ***fireball*** model.

Gamma-ray Bursts

- The energy is transported via bulk motion to 10^{13}-10^{15} cm before the plasma becomes optically thin and radiates the GRB
- The kinetic energy is reconverted to radiation, relativistic shocks (Gamma>100) accelerate electrons and positron at very short time scales, large scale turbulences distribute the energy dissipated in the shock over the shocked gas.
- Various such outflows can collide with each other – producing relativistic *internal shocks* at 10^{14}-10^{16} cm from triggering event AND emit the prompt gamma-rays

Gamma-ray bursts

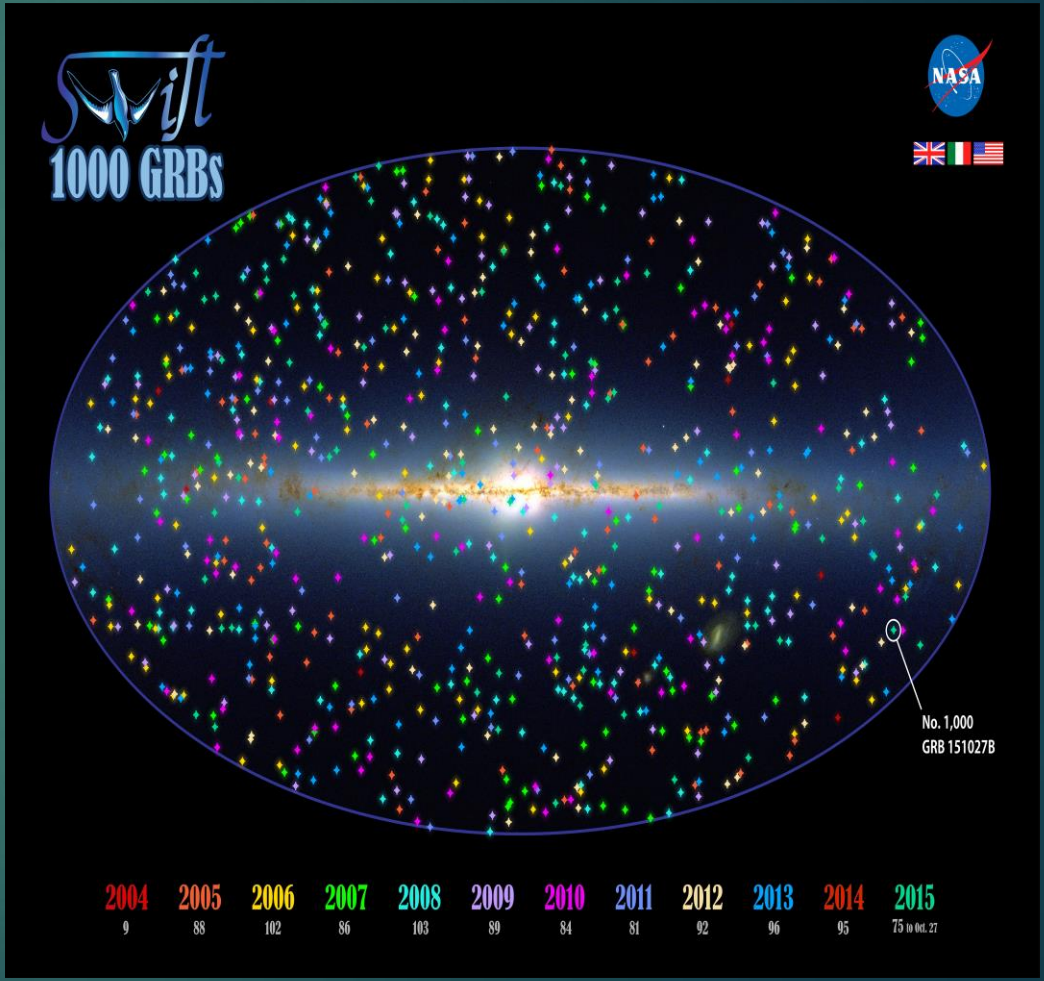
- At the later stage the shell interacts with interstellar medium and relativistic *external shock* is produced, electrons accelerated (1st order Fermi); the external shock radiates the *afterglow* (synchrotron radiation from the electrons)
- Because of the *relativistic beaming* only a small fraction of the expanding shock is visible at the beginning and thus the time profile of the arriving gamma-rays is not smoothed by the simultaneous emission from different points in the expanding shell
- As the Lorentz-factor of the fireball decreases, the beaming angle opens up and the expansion is seen as if it was isotropic.

Gamma-ray bursts

- The gamma-rays emitted are usually at keV -MeV range (hard X-rays, soft gamma-rays)
- Several attempts have been made to observe GeV emission: both EGRET and LAT observations indicate that the GeV emission would be delayed with ~1 hour from the onset of the burst
- From theoretical point of view: the delayed GeV-TeV was be expected for proton synchrotron emission (see blazars) or photo-pion production or inverse Compton scattering or reverse shock in the burst environment

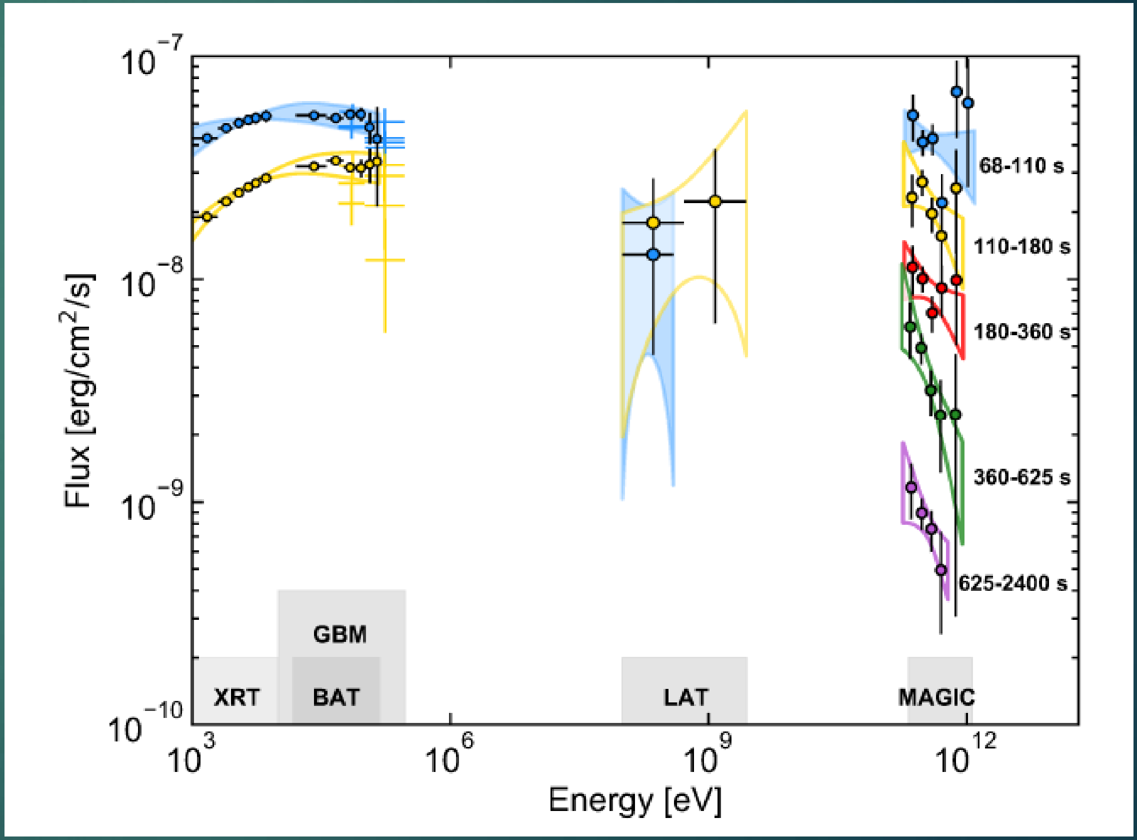
Gamma-ray bursts at VHE

- Observed at Very High Energy gamma-rays with IACTs 4 (GRB 180720B, GRB 190829A by H.E.S.S., GRB190114C, GRB 201216C by MAGIC)



What does the VHE observation tell us?

- GRB190114C: Very High Energy gamma-rays from inverse Compton scattering: New emission component
- Still debated
- GRBs also valuable for EBL studies (distant and bright!)
- With CTA we expect to detect many more



MAGIC Collaboration 2019, Nature

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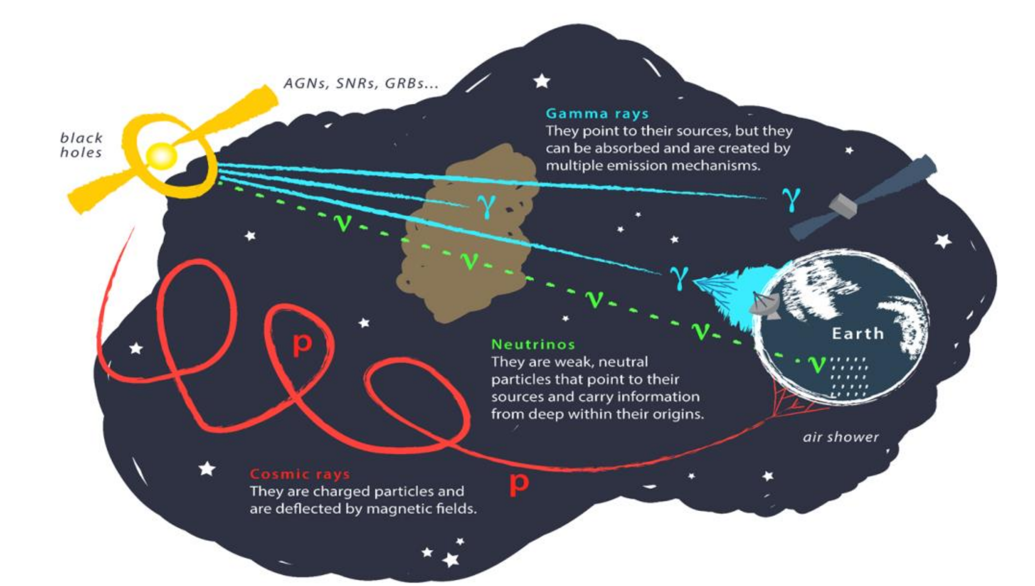

Credit: Juan Antonio Aguilar and Jamie Yang IceCube/WIPAC.

Something more: unidentified Fermi sources

- Sample of unidentified or unassociated γ-ray sources (UGSs) constitute about one-third of all gamma-ray sources detected to date.
- At high galactic latitudes, likely to have extragalactic origin
- (Sidenote: to great surprise Fermi-LAT also identified large population of MSP that explained many EGRET unidentified sources)
- Efforts to identify counterparts e.g. in X-rays (e.g. Marchesini et al. 2020), good for finding blazars of BL Lac type (almost all Fermi detected BL Lacs have X-ray counterpart), confirmation of classification with optical spectroscopy
- Is there a source type that I did not cover during this lecture hiding there? No clue…

What I will try to cover today?

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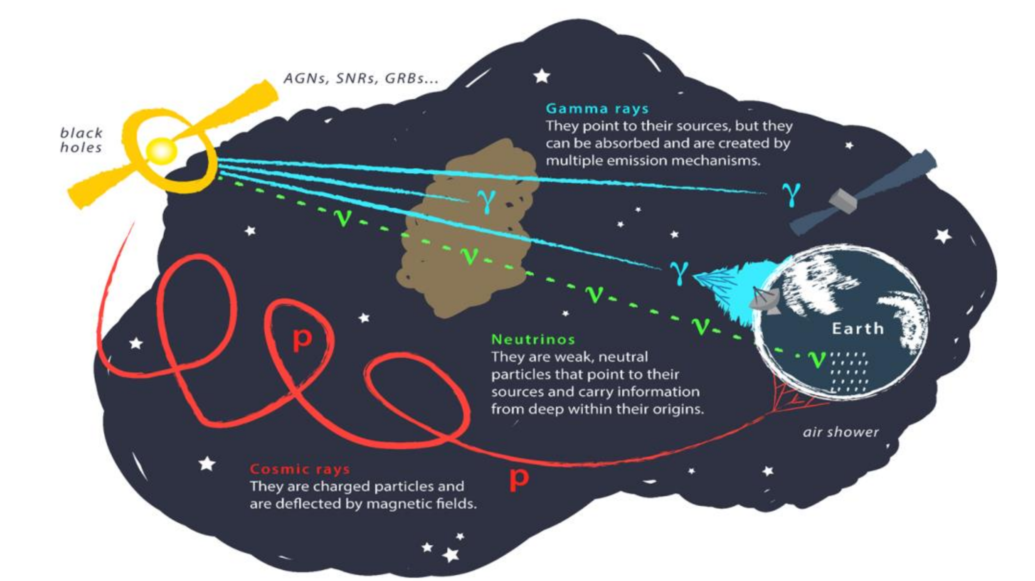
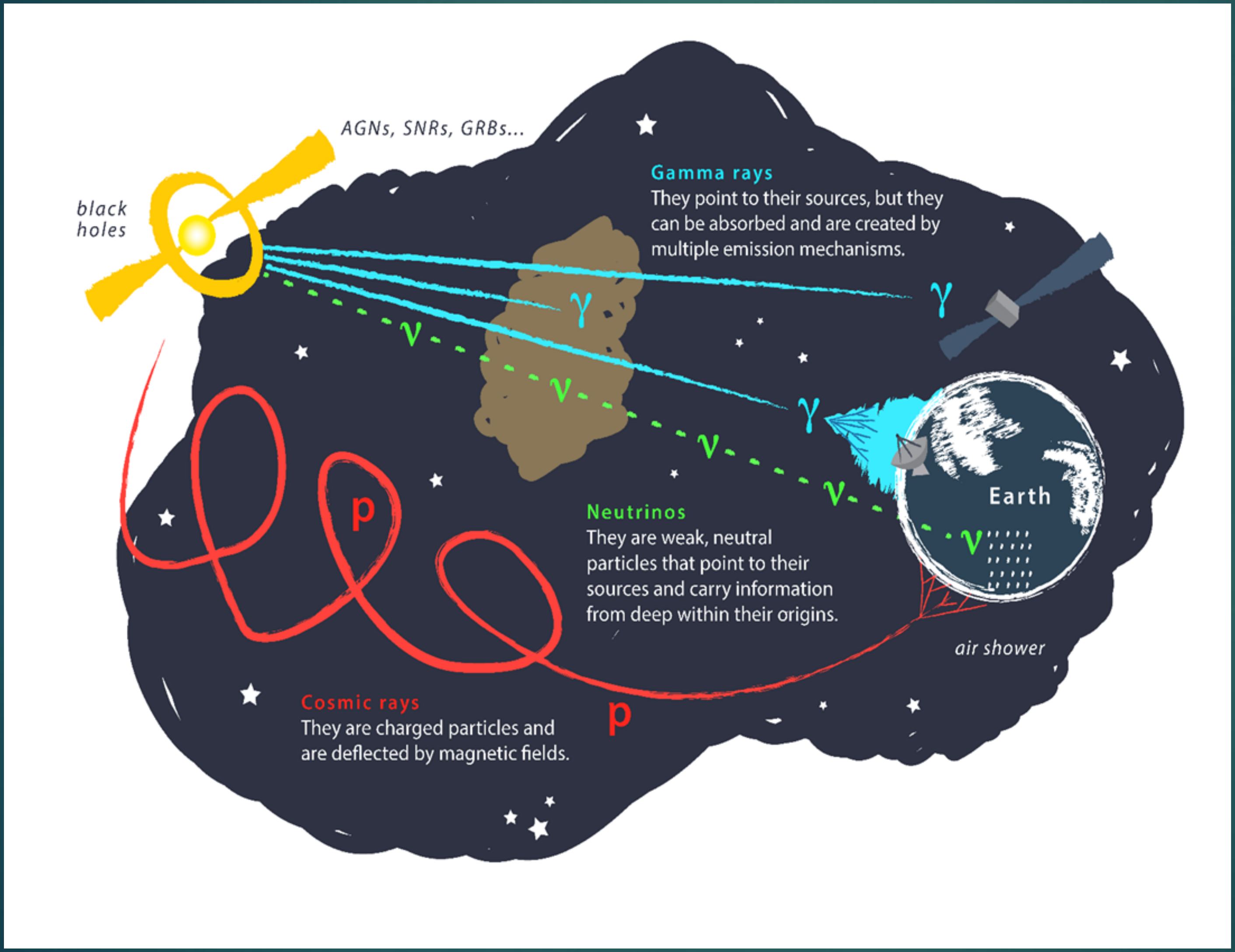
- Neutrino observations of blazars
- Radio galaxies (i.e. when jet is not pointing close to our line of sight)

- Is that all?
- Propagation effects

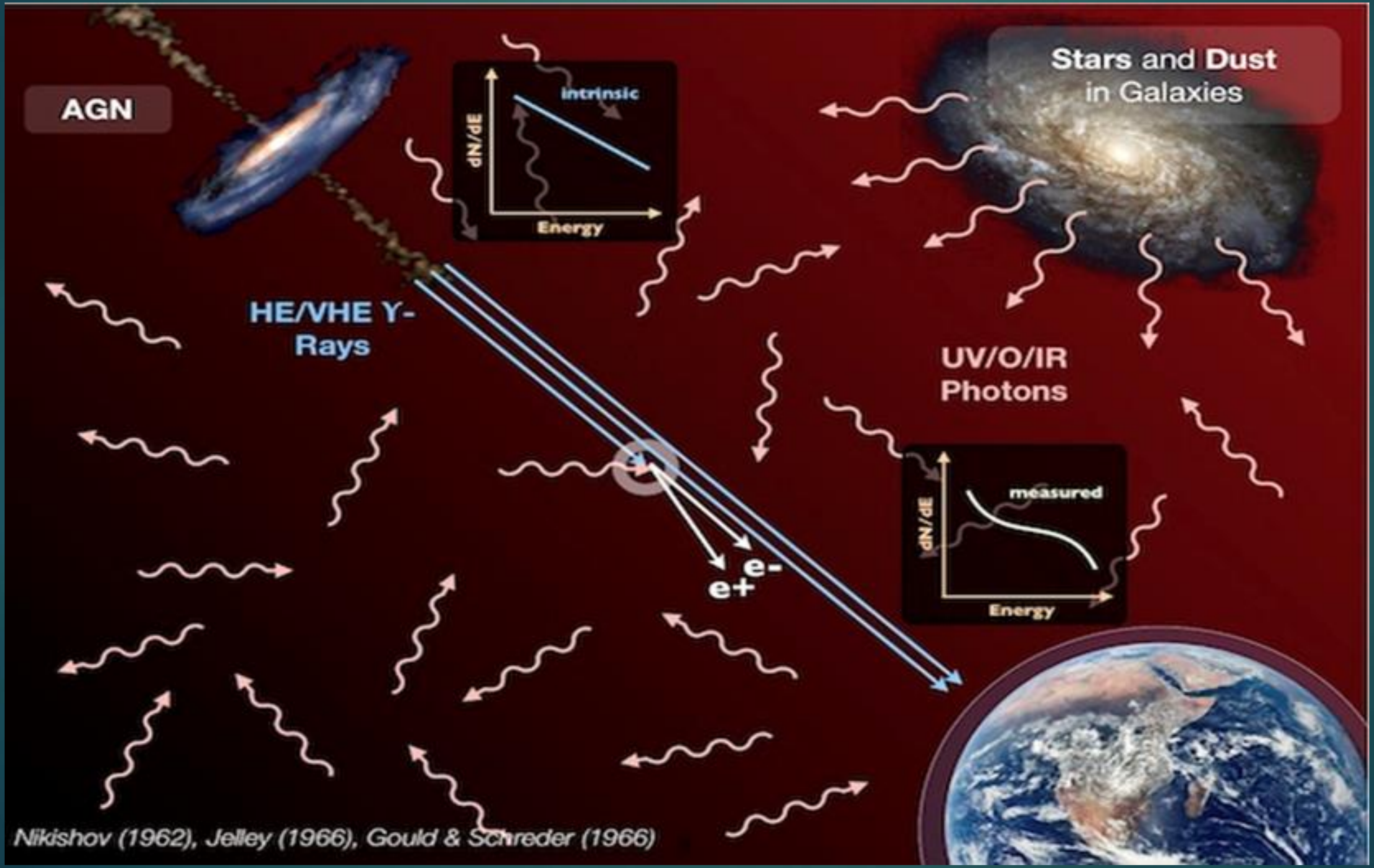


Credit: Juan Antonio Aguilar and Jamie Yang IceCube/WIPAC.

Propagation of Astroparticles



Propagation of VHE gamma-rays



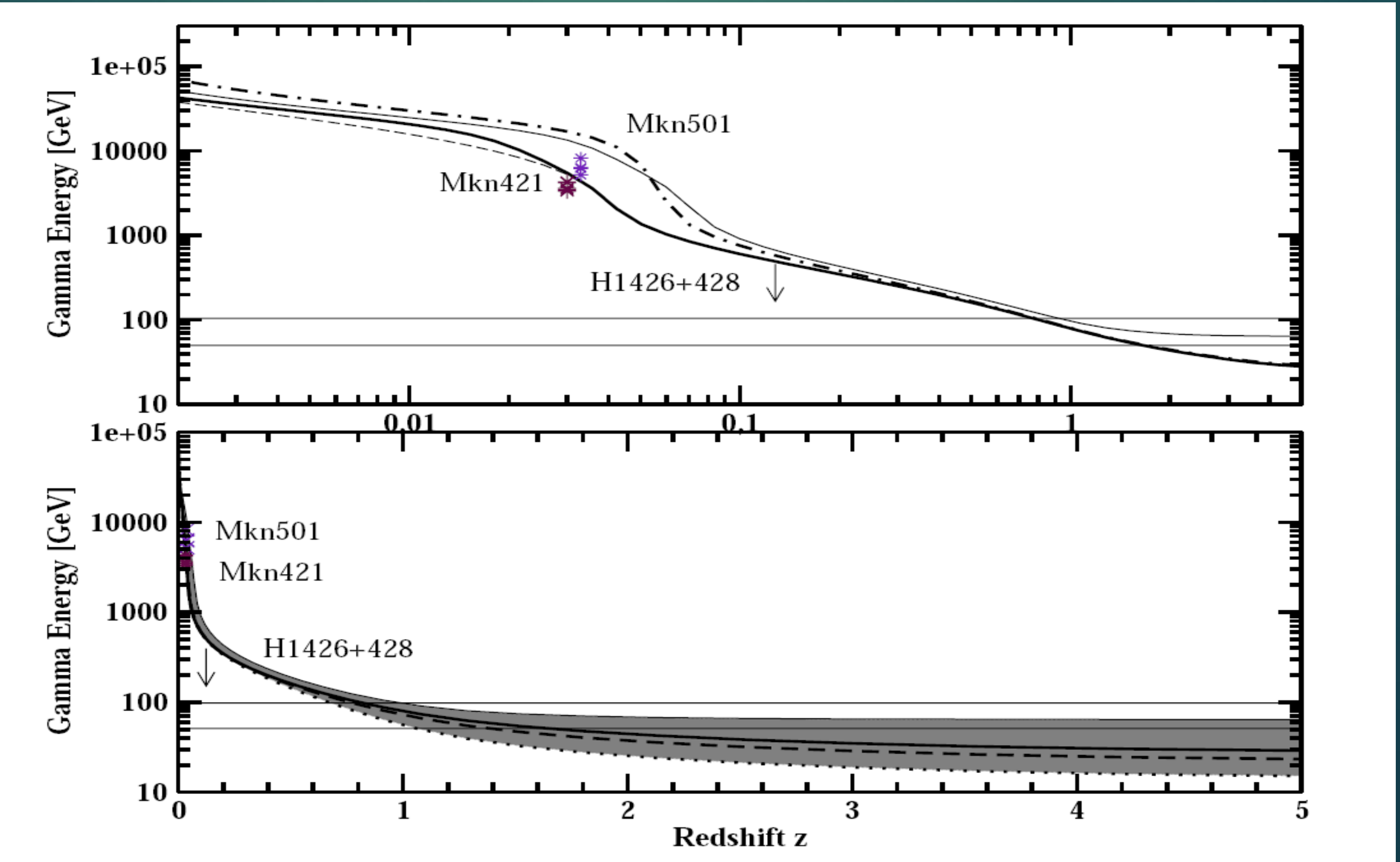
Gamma-ray Horizon

- Because of the pair production with the low energy (IR, optical) diffuse and isotropic extragalactic background light (EBL) photons the visible universe to high energy gamma-rays is limited
- Threshold energy for pair production: E*gamma(1-cosθ)>$2m_e^2c^4$ where E is the gamma-ray energy, gamma is the photon energy, theta is the scattering angle
- Given the certain model about the EBL, the attenuation of a hypothetical monoenergetic flux from a source can be parameterized by the *optical depth* tau:

$$\phi(E,z) = \phi(E,0) \cdot \exp\left[-\tau(E,z)\right]$$

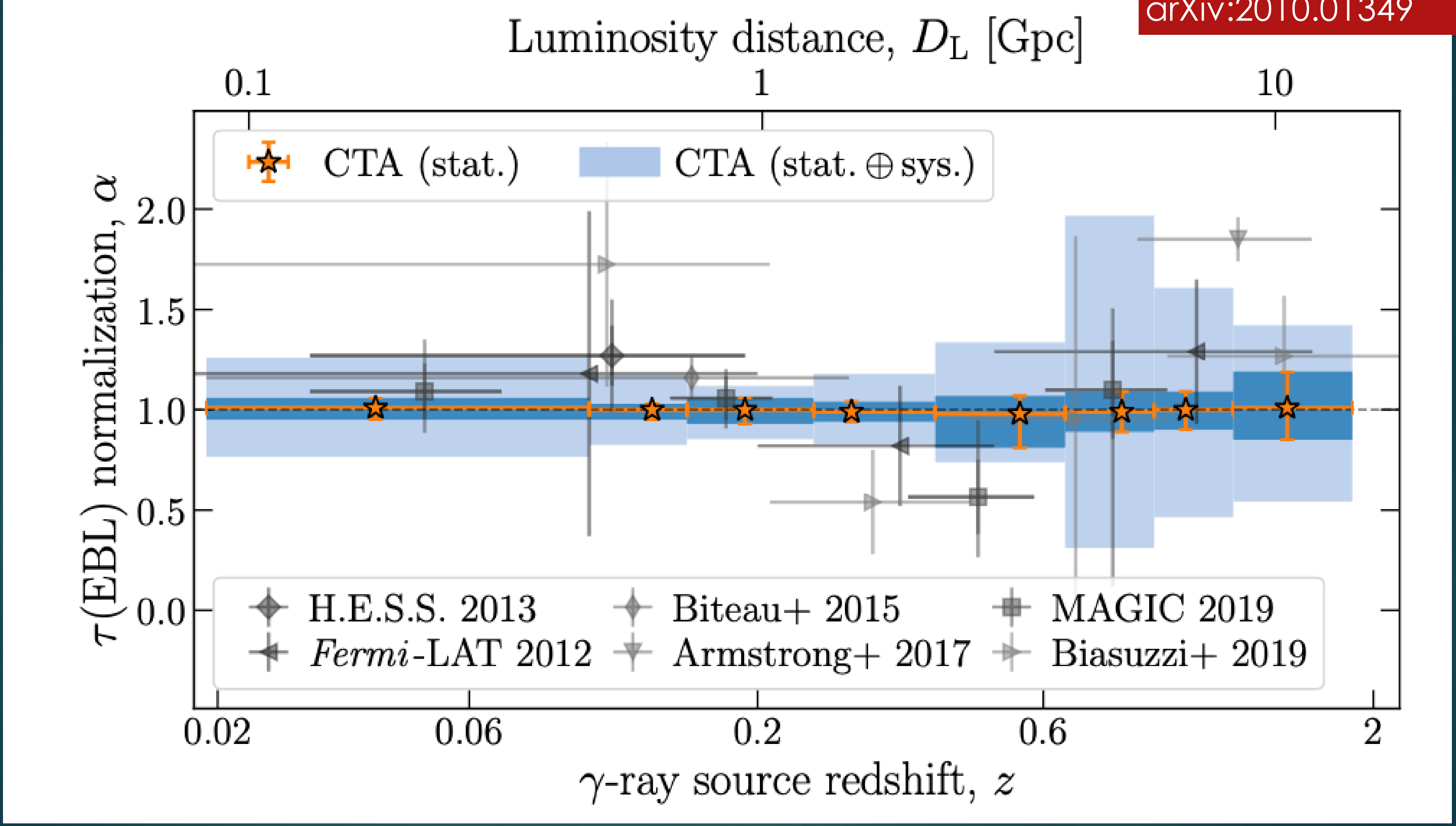
Gamma-ray Horizon

- The condition Tau(E,z)=1 defines the Gamma-ray Horizon also known as Fazio-Stecker relation: 1/*e* of the flux Tau(E) is lost traveling from the distance *z* from the source



How far do we see and what do we expect from CTA?

CTA consortium, 2021
arXiv:2010.01349



Cosmic ray horizon

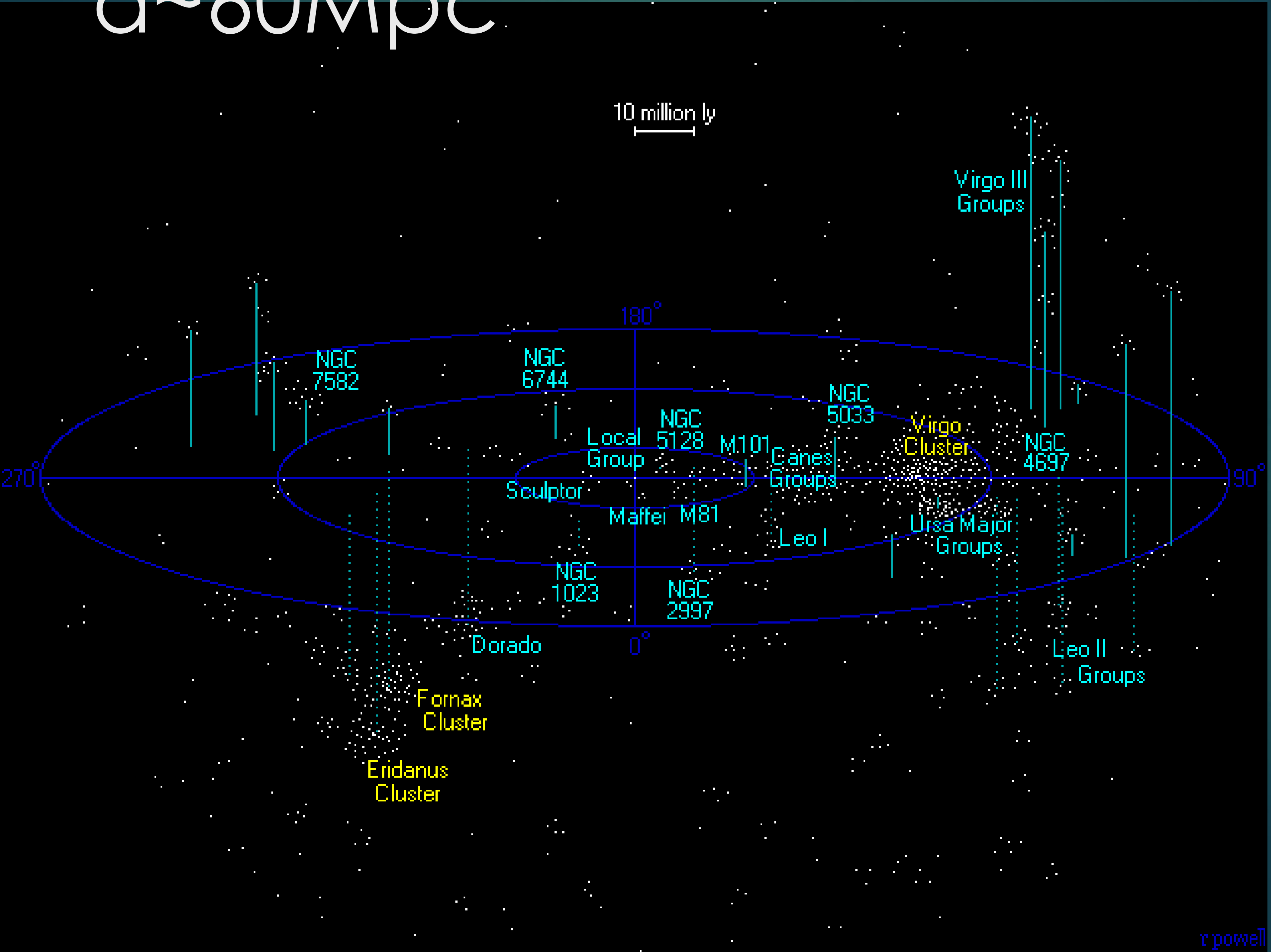
- Hadrons loose their energy fast in intergalactic medium via photoproduction of pion off blackbody photons
- Mean free path for protons:

$$\lambda_{\gamma p} = \frac{1}{N\,\sigma}\,, \tag{7.23}$$

where N is the number density of blackbody photons and $\sigma(\gamma p \rightarrow \pi^0 p) \approx 100\,\mu\text{b}$ the cross section at threshold. This leads to

$$\lambda_{\gamma p} \approx 10\,\text{Mpc}\,. \tag{7.24}$$

Virgo supercluster, d~60Mpc



Cosmic ray horizon

- Therefore, e.g. Mrk 421 and Mrk 501 are out; from the distance of 100 Mpc, the arrival probability for protons with energy 10^{20} eV is only $\approx e^{-x/\lambda} \approx 4 \times 10^{-5}$
- If the local GZK sphere is defined to be ~30 Mpc (i.e. several mean free paths), there is hardly any blazars within the sphere, closeby GRBs dont happen often (in average z~2 for GRBs), but

Cosmic Ray Horizon

There are quite some radiogalaxies like Cen A, M87 and NGC 315 and starburst galaxies like M82 and NGC 253

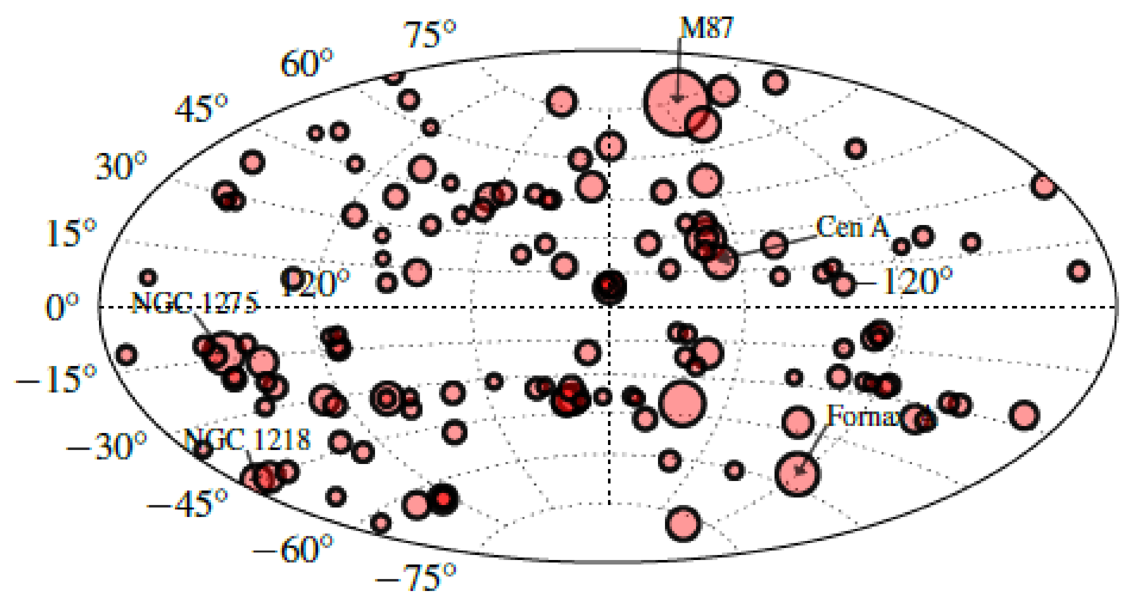


Figure 6. Map in Galactic coordinates with the radio galaxies of the volume-limited sample ($z < 0.03$). The area of the circles is proportional to the radio flux of the source. The location of some famous sources is indicated (M87 and NGC 1275 are the brightest members of the Virgo and Perseus cluster, respectively).

Thank you for your attention