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: are they really potential neutrino sources, i.e. do we see signs of hadronic emission?

Are blazars neutrino emitters?

TXS0506+056: Tens of SED modelling papers in arxiv
Leptonic emission dominates the second bump…

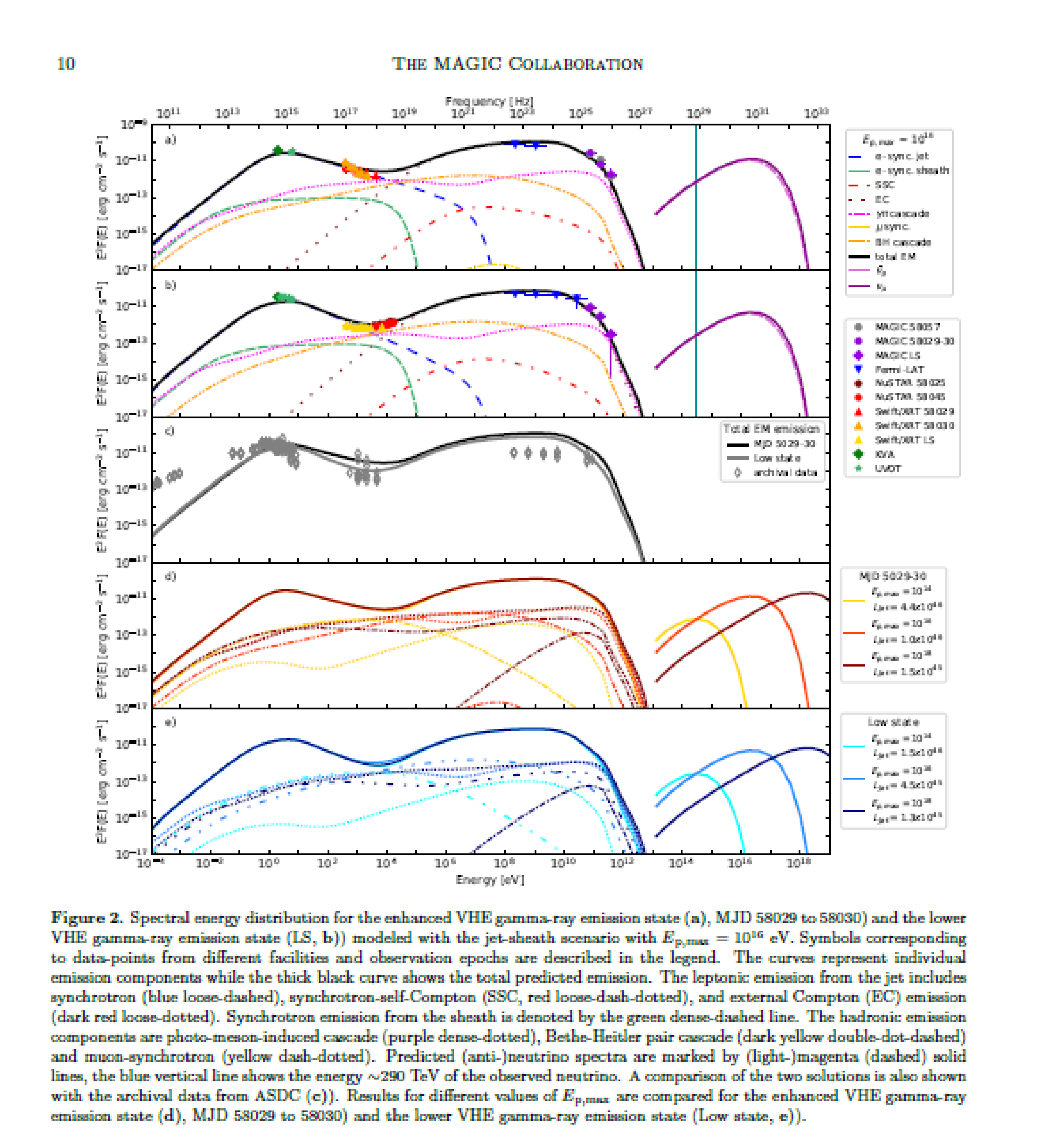
10 THE MAGIC COLLABORATION

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)).

Are blazars neutrino emitters?

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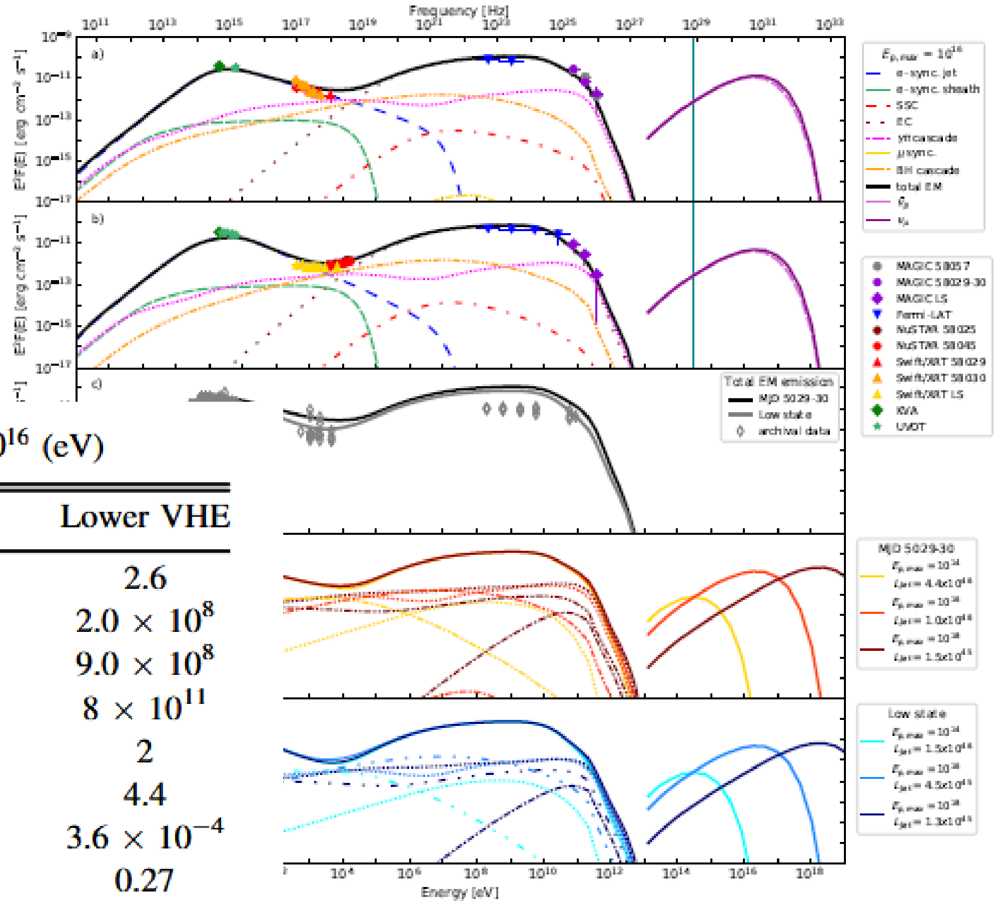
Leptonic emission dominates the second bump…

10 THE MAGIC COLLABORATION



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emission state (d), MJD 58029 to 58030) and the lower VHE gamma-ray emission state (Low state, e)).

Table 3
Parameters for the Jet-sheath Model for $E_{p,max} = 10^{16}$ (eV)

State	MJD 58029–30	Lower VHE
B (G)	2.6	2.6
E_{min} (eV)	3.2×10^8	2.0×10^8
E_{br} (eV)	7.0×10^8	9.0×10^8
E_{max} (eV)	8×10^{11}	8×10^{11}
n_1	2	2
n_2	3.9	4.4
U_e (erg cm^{-3})	4.4×10^{-4}	3.6×10^{-4}
U_B (erg cm^{-3})	0.27	0.27
U_p (erg cm^{-3})	1.8	0.7
P_e (erg s^{-1})	2×10^{42}	1.6×10^{42}
E_p (erg s^{-1})	8×10^{45}	3×10^{45}
P_B (erg s^{-1})	1.2×10^{45}	1.2×10^{45}

”Problems” of hadronic models

1. High magnetic field strengths => High jet powers… in conflict with other observational constraints
2. Cascading emission in X-rays
3. Observational evidence favors leptonic origin
4. Seed photon fields

Magnetic field strength

- Best measurements: radio band

See e.g. Pushkarev et al. 2012

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

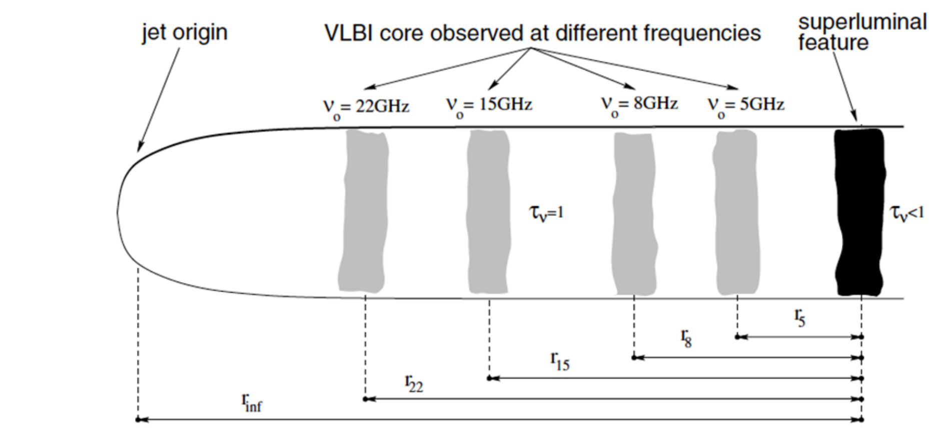

Fig. 1. A scheme illustrating the frequency-dependent position shift of the VLBI core. Adopted from Lobanov (1996).

As shown by Lobanov (1998), core shift measurements can be used for deriving a variety of physical conditions in the compact jets. In particular, assuming equipartition between the particle and magnetic field energy density ($k_r = 1$) and a jet spectral index $\alpha_{\rm jet} = -0.5$ ($S \propto \nu^{+\alpha}$), the magnetic field in Gauss at 1 pc of actual distance from the jet vertex can be calculated through the following proportionality (Hirotani 2005; O'Sullivan & Gabuzda 2009)

$$B_1 \simeq 0.025 \left(\frac{\Omega_{r\nu}^3 (1+z)^2}{\varphi\, \delta^2 \sin^2\theta} \right)^{1/4}, \qquad (2)$$

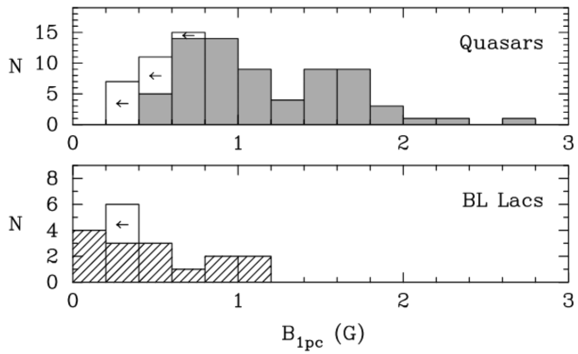

Fig. 8. Distribution of magnetic field at a distance of 1 pc from the black hole for 84 quasars (*top*), 18 BL Lacs (*bottom*). Empty bins represent upper limits.

where ϕ is the half jet opening angle, θ is the viewing angle,
δ is the Doppler factor, and Ωrv is the core shift measure

Magnetic field strengths of 10-100G seem unreasonable

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Jet power

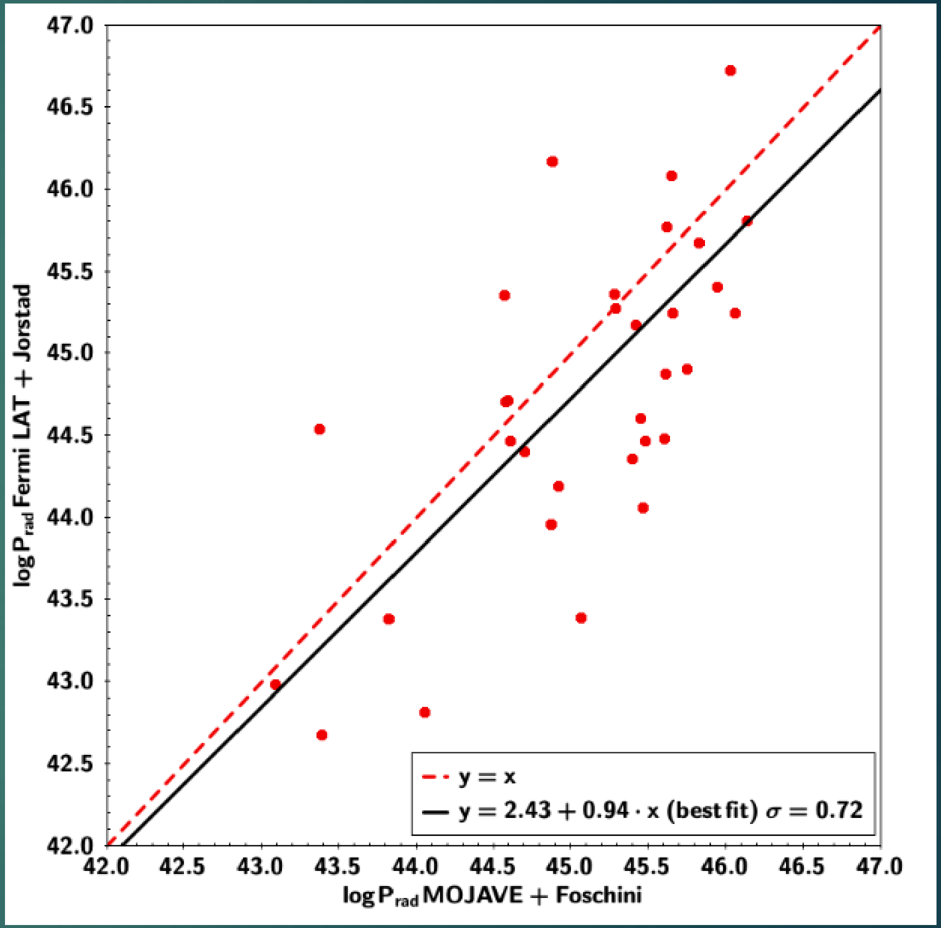
- The simplest way to estimate the radiative power is to use the luminosity measured in high-energy γ rays, the Doppler and the bulk Lorentz factors: Prad ~ $\Gamma^2(L_\gamma/\delta^4)$. (*You need to know Doppler factor*!)
- Another widely adopted method is the modeling of the spectral energy distribution (SED) by using simple one-zone leptonic models (*assumes leptonic origin*)
- Cavities excavated by the jet in the intergalactic medium. In the MHz frequency range measure the brightness of very extended jets, according to the formula: $\log P_{kin} = 0.64(\log L_{200-400MHz} - 40) + 43.54$ *(does not represent the current jet power)*
- The relationship between the jet power and the luminosity of the radio core according to the Blandford & Königl model

  $\log P_{rad} = 12 + 0.75 \log L_{15GHz}$ and $\log P_{kin} = 6 + 0.90 \log L_{15GHz}$

  (but also radio core fluxes are variable)

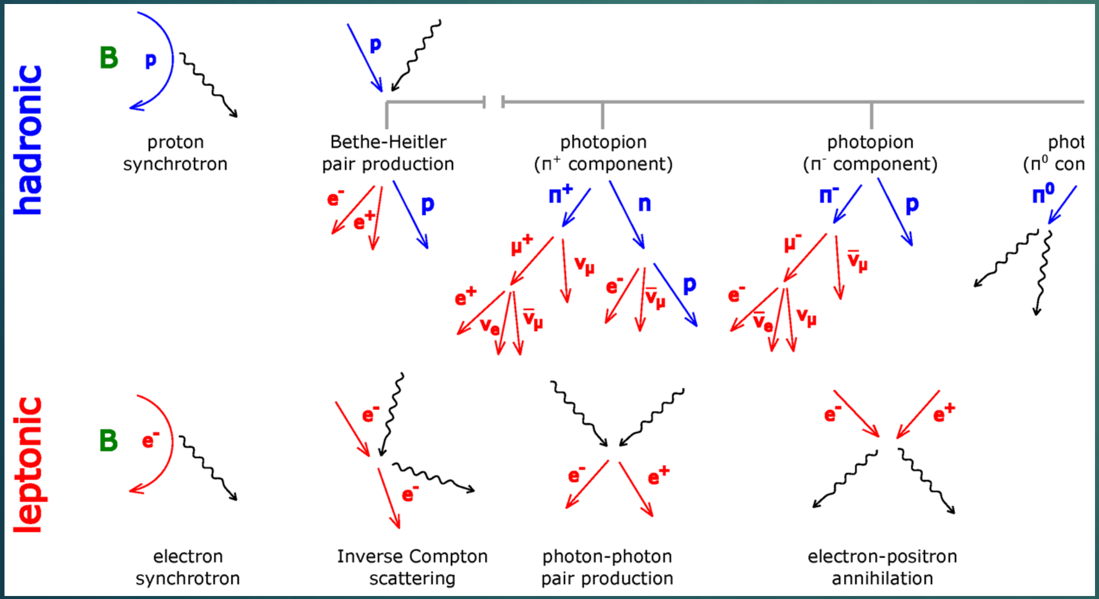
Jet power

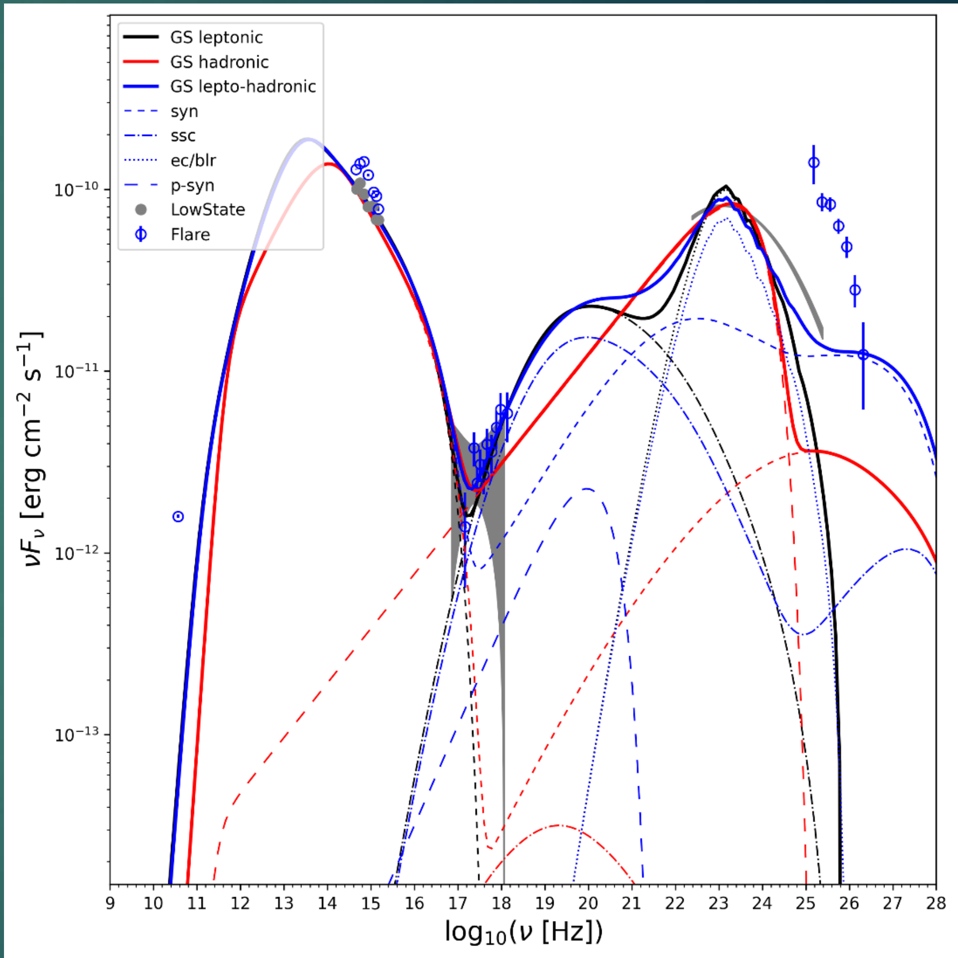
- Foschini et al. 2017: comparison of different methods
- Scatter is very significant
- But still gives you a hint of acceptable range
- Something to consider: compare luminosities you use in your model also to Eddington luminosity of 10^8 M_sun black holes, do not overly exceed that…



Cascading emission in X-rays

- Emission by the photo-pion by-products cannot be avoided
- Bright emission in X-rays, esp. If emission region is compact

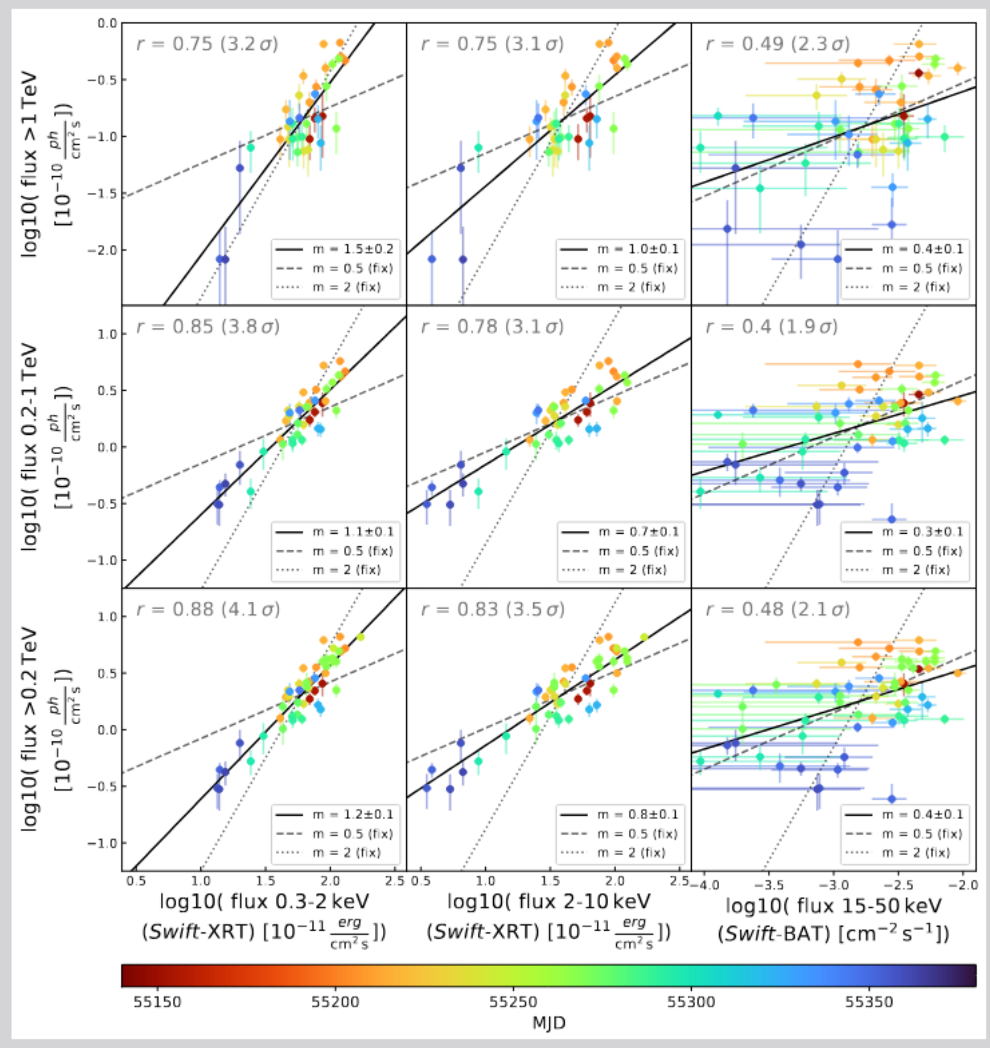




Simulation by M. Zacharias

Leptonic origin

- SSC => strong correlation between X-ray and VHE gamma-rays
- Seen during all flares in Mrk421



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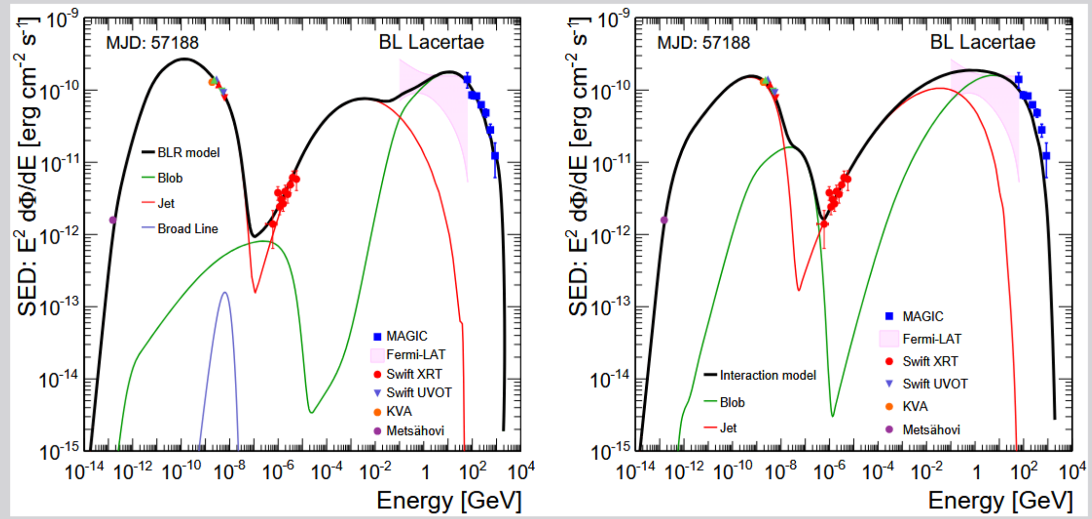
Leptonic origin

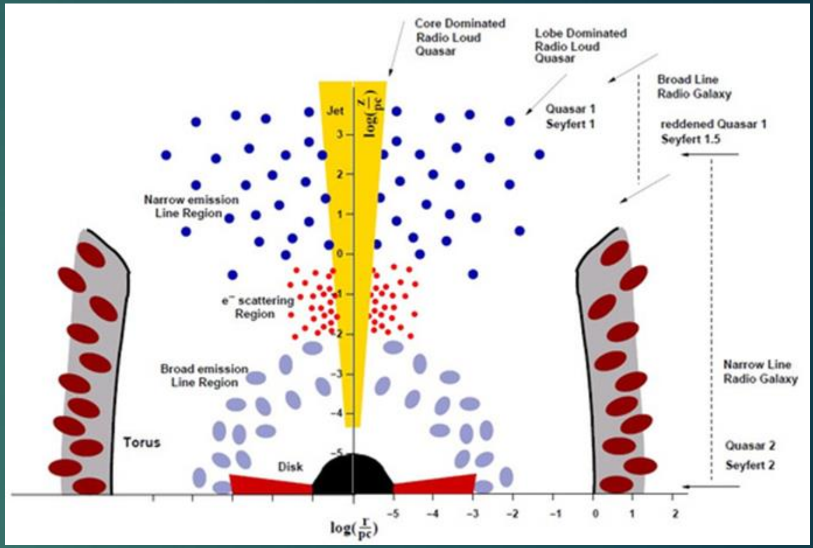
- SSC => strong correlation between X-ray and VHE gamma-rays
- Seen during all flares in Mrk421
- MWL polarization: leptonic, second bump low polarization
  hadronic, second bump at least as high polarization as first bump
- IXPE X-ray polarization => low



Kohde (pvm.)	$< \Pi_X$ (%)	Π_O (%)
BL Lacertae (6.5.–14.5.2022)	14,2	6,8
BL Lacertae (9.7.–11.7.2022)	12,6	14,2
BL Lacertae (27.11.–30.11.2022)	14,3	3–17
BL Lacertae (10.11.–18.11.2023)	7,4	$47{,}5 \pm 0{,}4$
3C 279 (13.6.–18.6.2022)	12,7	12
S4 0954+65 (25.5.–3.6.2023)	8,8	$14{,}3 \pm 4{,}1$

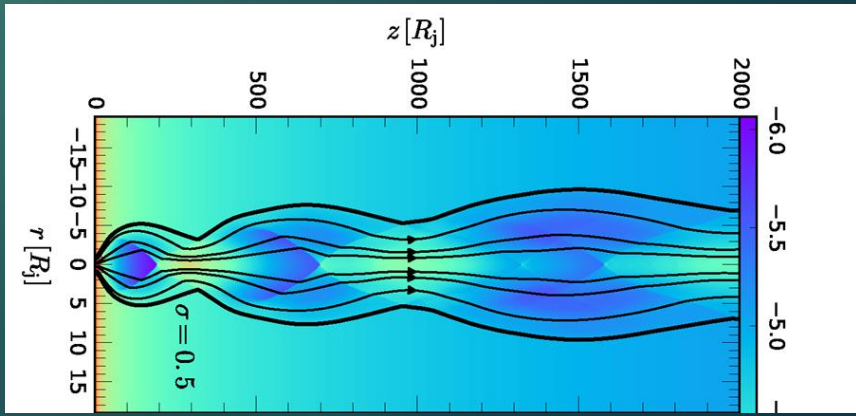
Seed photon fields

Two possible scenarios, which can be thought of as extreme, limiting cases:
(a) a target photon field that is comoving with the emission region (such as the electron–synchrotron emission), (needs typically hard X-rays)
(b) a stationary target photon field in the AGN rest frame (needs typically UV- soft X-rays)



Thermal fields not always there? Absorption

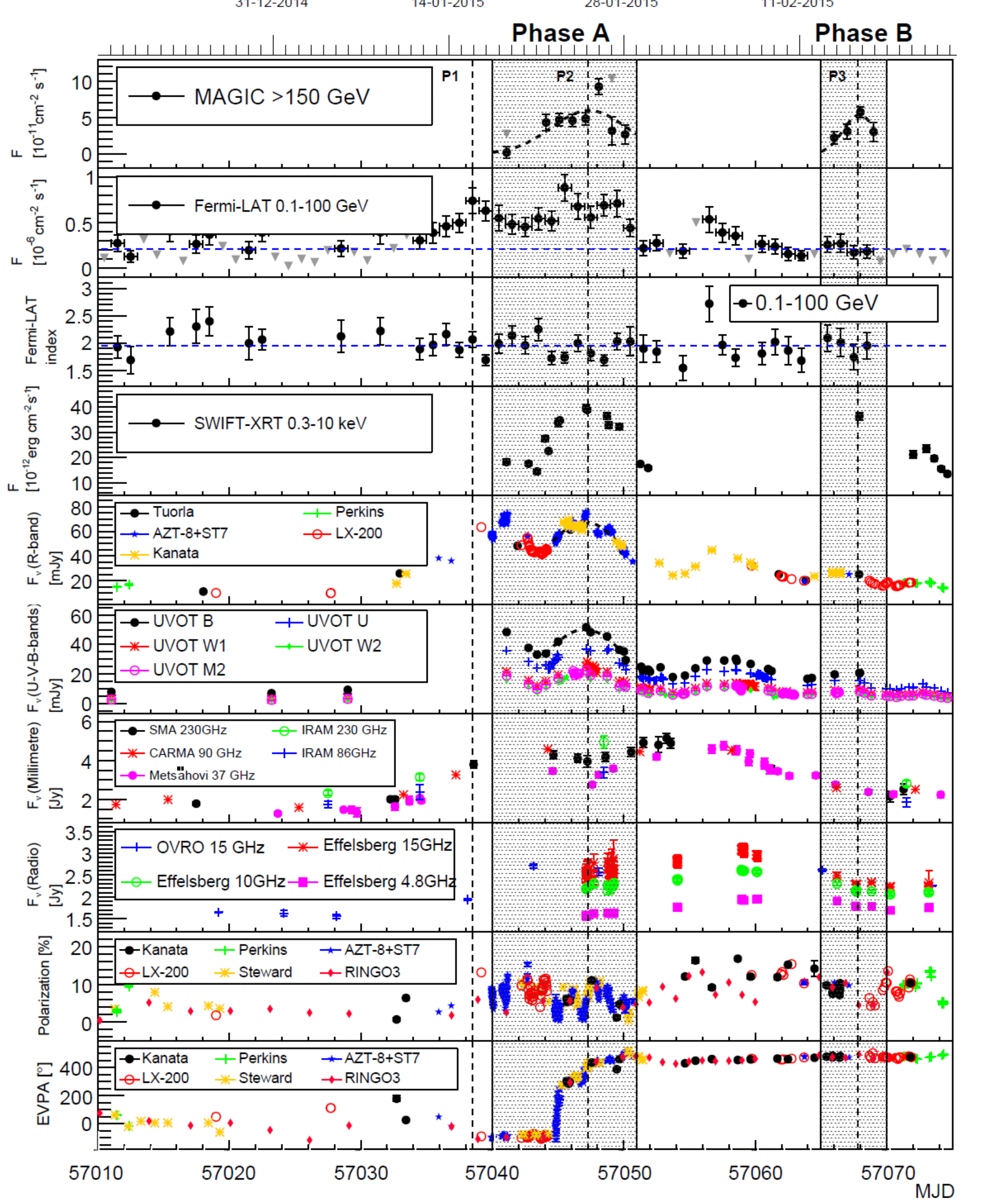
Reimer et al. 2019



Recollimation shocks, but they are pretty far downstream

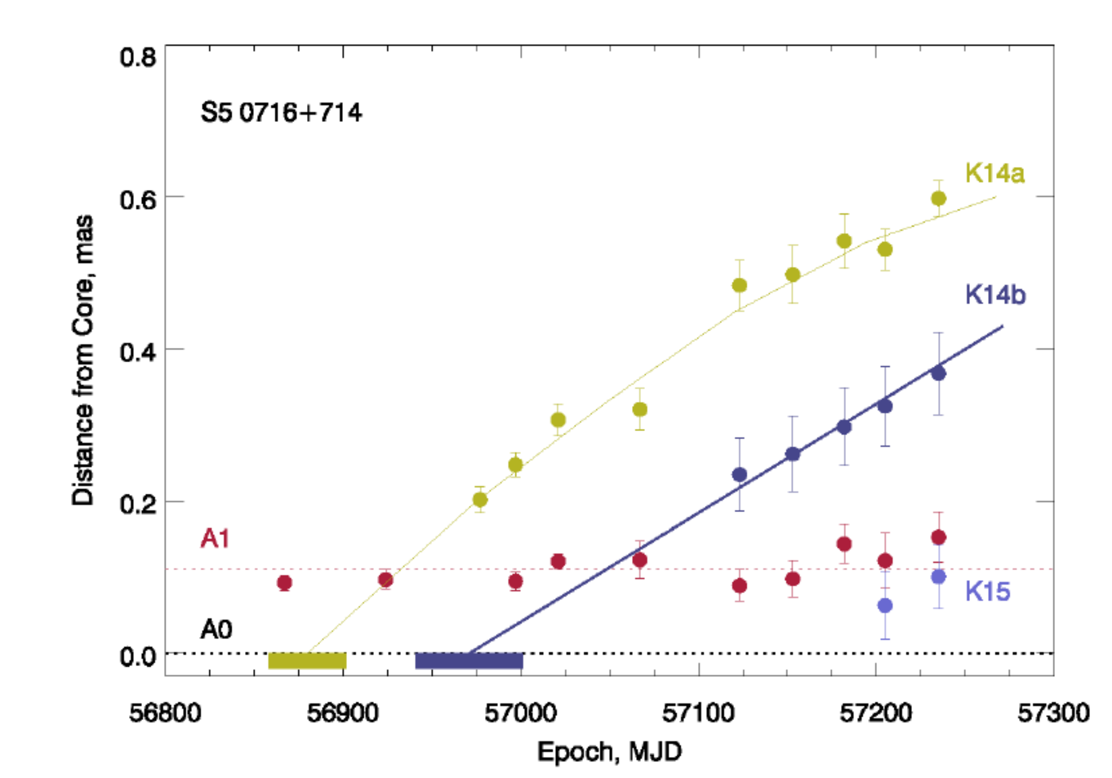
S50716+714: Unprecedented flaring state in January 2015

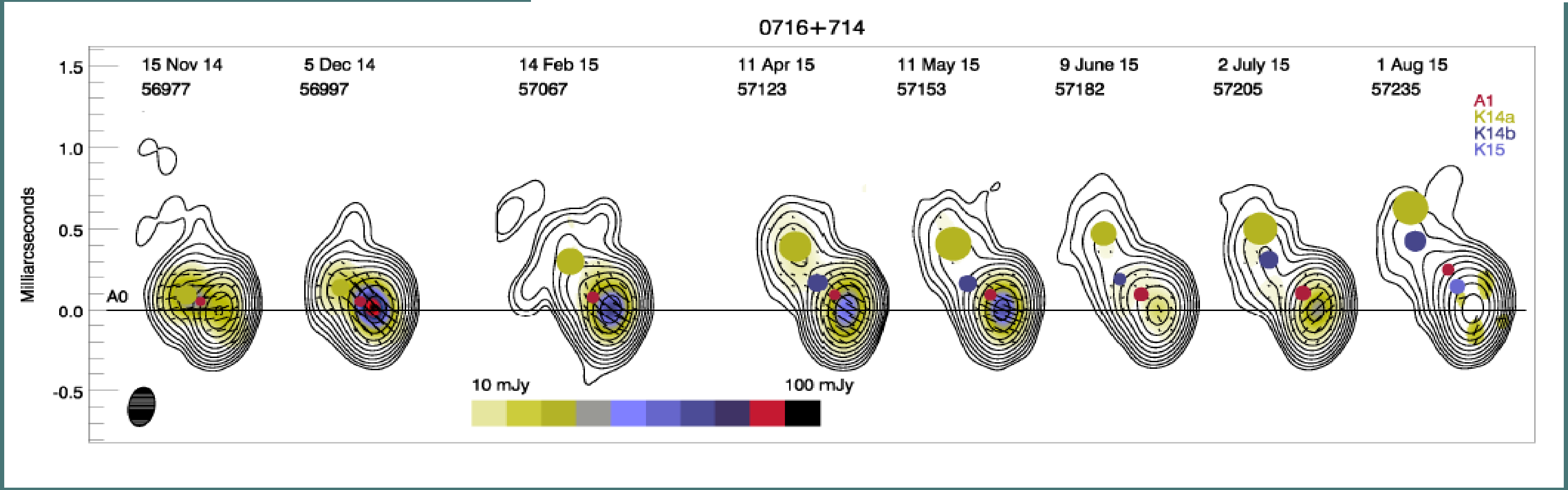
- High state (radio, optical, GeV gamma-rays) started in the beginning of January 2015
- Phase A: flare in radio, optical, X-rays, gamma-rays, VHE gamma-rays, *very fast rotation of optical EVPA*
- Phase B: flare in X-rays and VHE gamma-rays



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

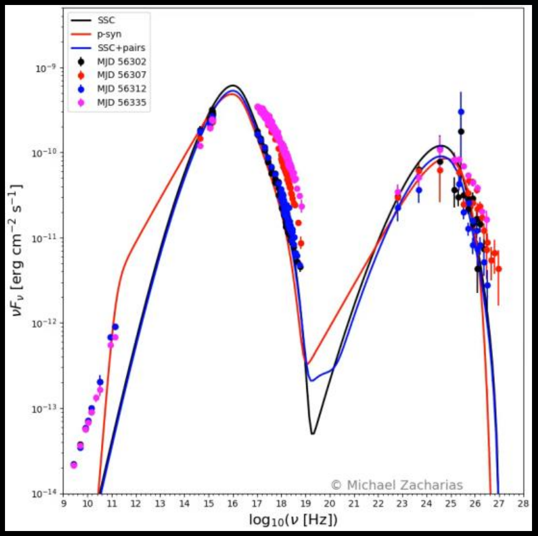
MAGIC Collaboration et al. 2018, A&A

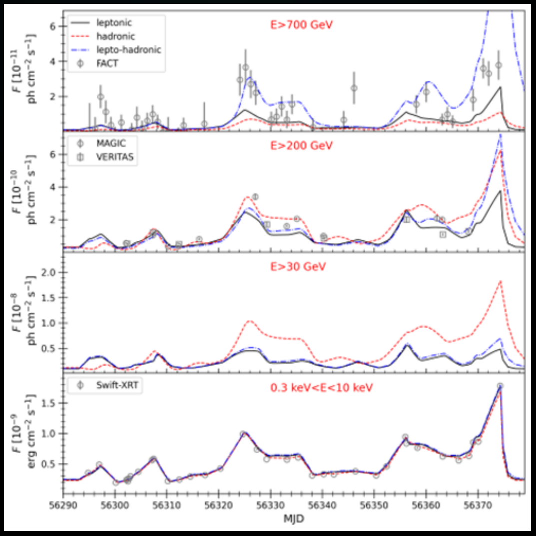
TURUN YLIOPISTO

MWL observations of variability will tell us

Mrk 421 in low/moderate state

- In low state we could maybe see the sub-dominant hadronic emission component?
- Variability patterns at VHE gamma-rays will be different: black is SSC, blue SSC+pairs, red proton synchrotron.

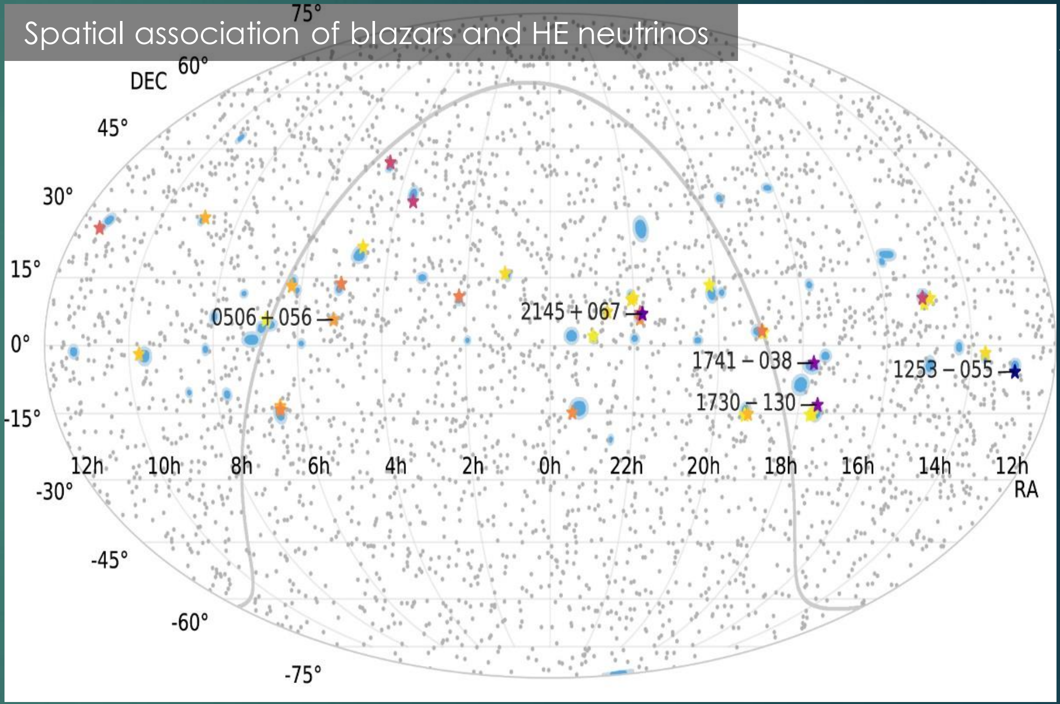




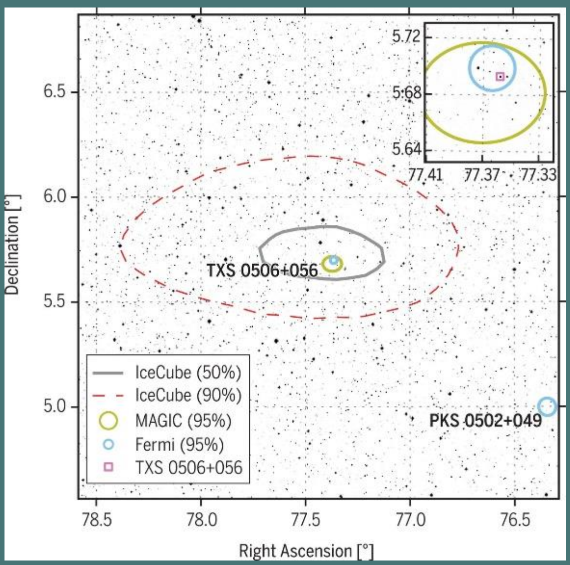
Zacharias, M.; OneHaLeZacharias, M. et al. Gamma2024

Spatial association of blazars & neutrinos

- Spatial associations are rather weak (only $\sim 2\sigma - 3\sigma$)
- But blazars are variable, maybe neutrinos only during major flaring events?



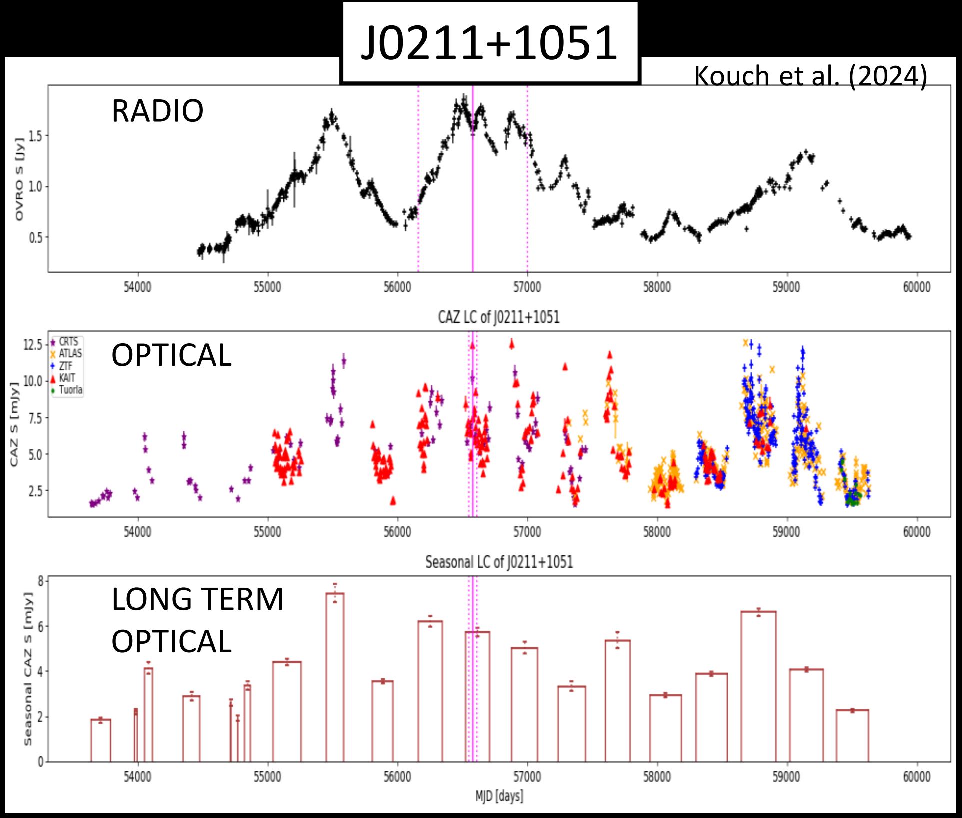
TXS 0506+056 was associated with flaring



IceCube collaboration et al. 2018, Science

Spatio-temporal assoc. of blazars & neutrinos

- Assume: EM flare ⟺ Neutrino flare
- Studies from our group:
  - Hovatta et al. (2021)
    - 56 neutrinos VS ~1200 blazars in radio
    - $\sim 2\sigma$ correlation
  - Kouch et al. (2024)
    - 283 neutrinos (IceCat-1) VS ~1200 blazars in radio and optical
    - $\sim 2.2\sigma$ correlation

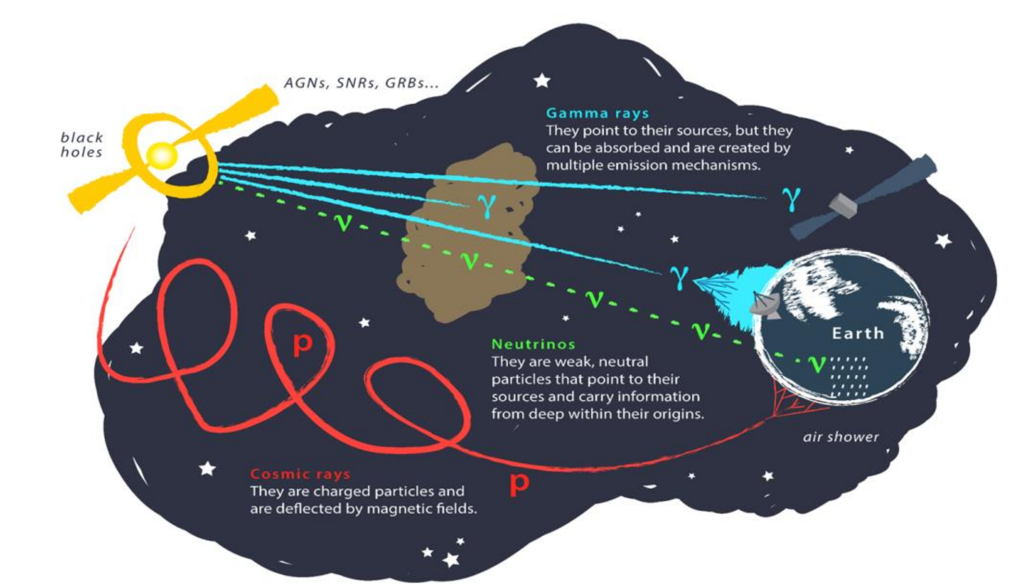


Spatio-temporal correlations are also weak...

What else?

- Gamma-ray observations of blazars
- Neutrino observations of blazars
- Radio galaxies (i.e. when jet is not pointing close to our line of sight)
- Non-jetted AGN
- GRBs
- Something else?

- Propagation effects



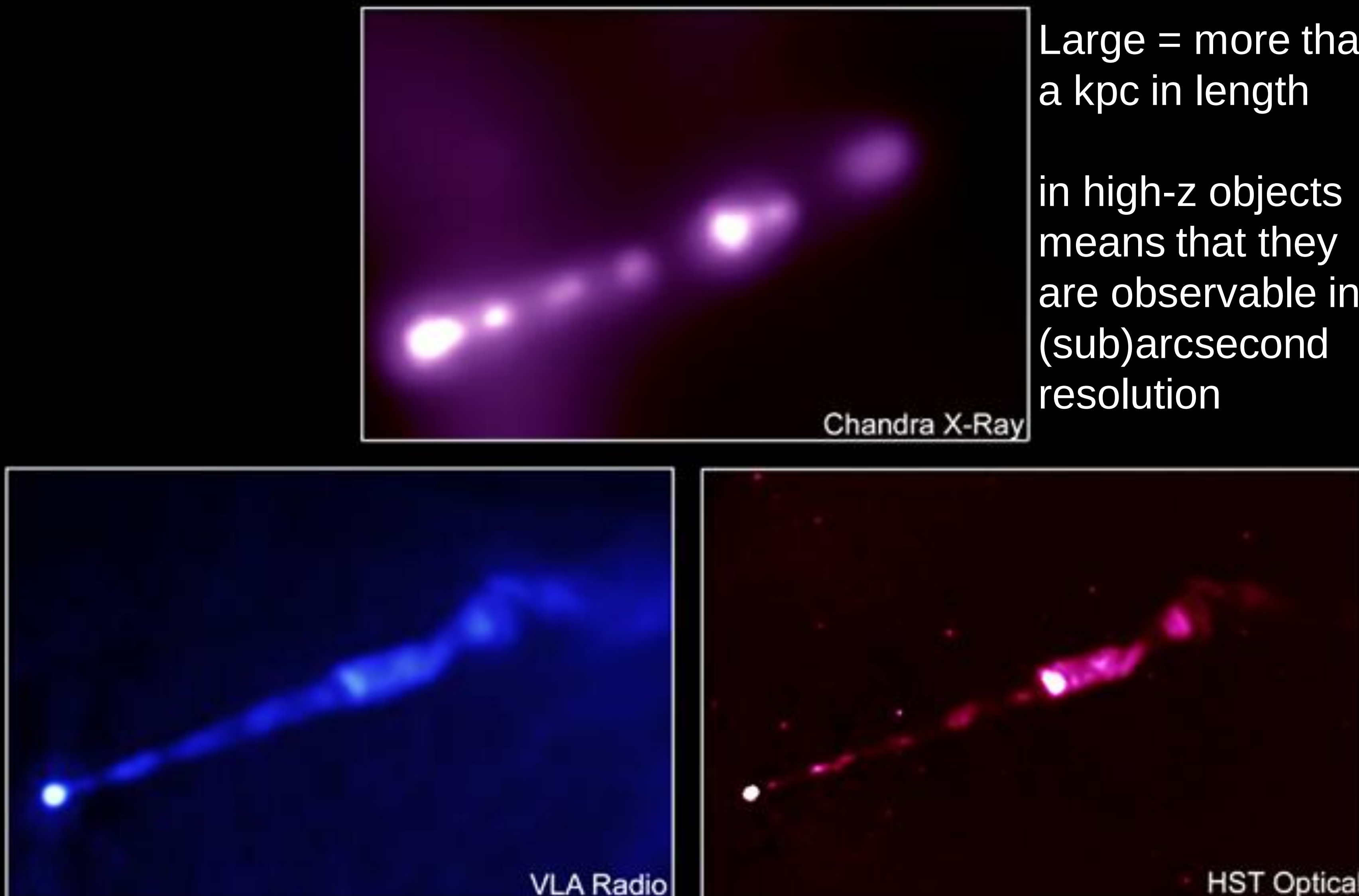
Credit: Juan Antonio Aguilar and Jamie Yang IceCube/WIPAC.

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



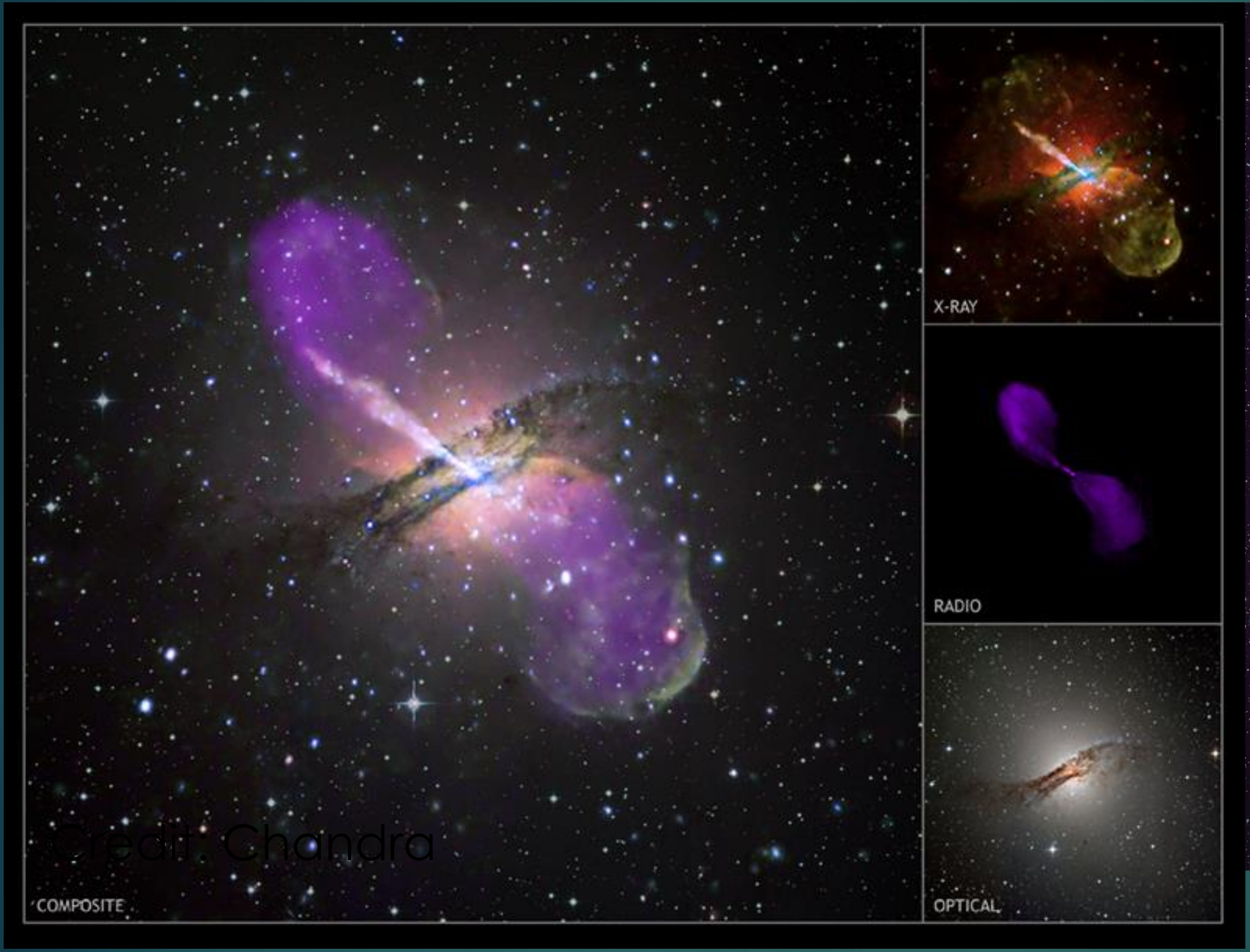
Large = more than a kpc in length

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

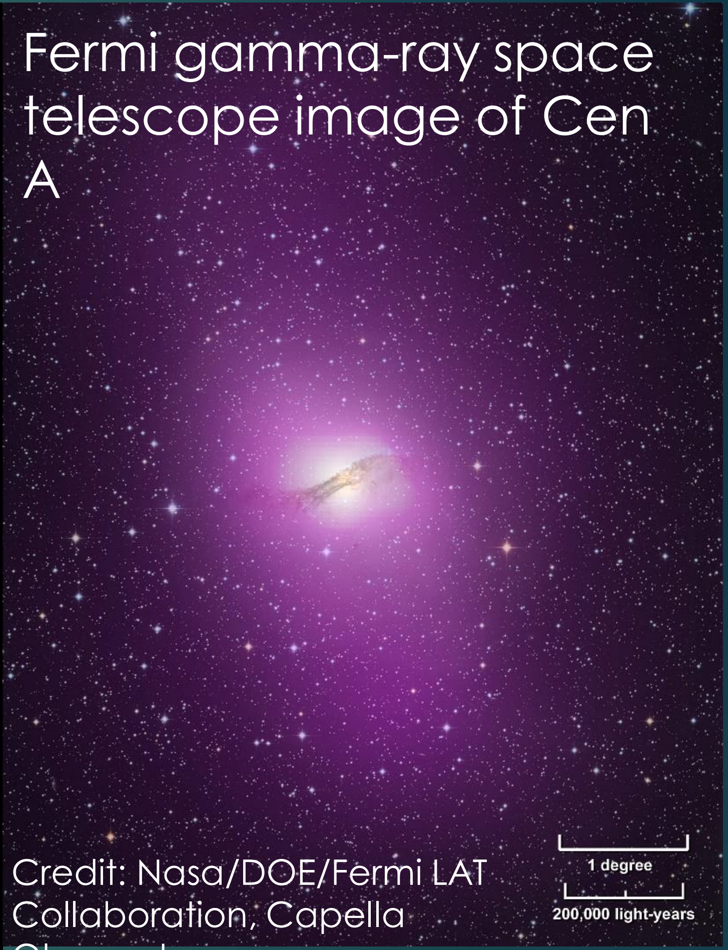
Cr

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

Centaurus A



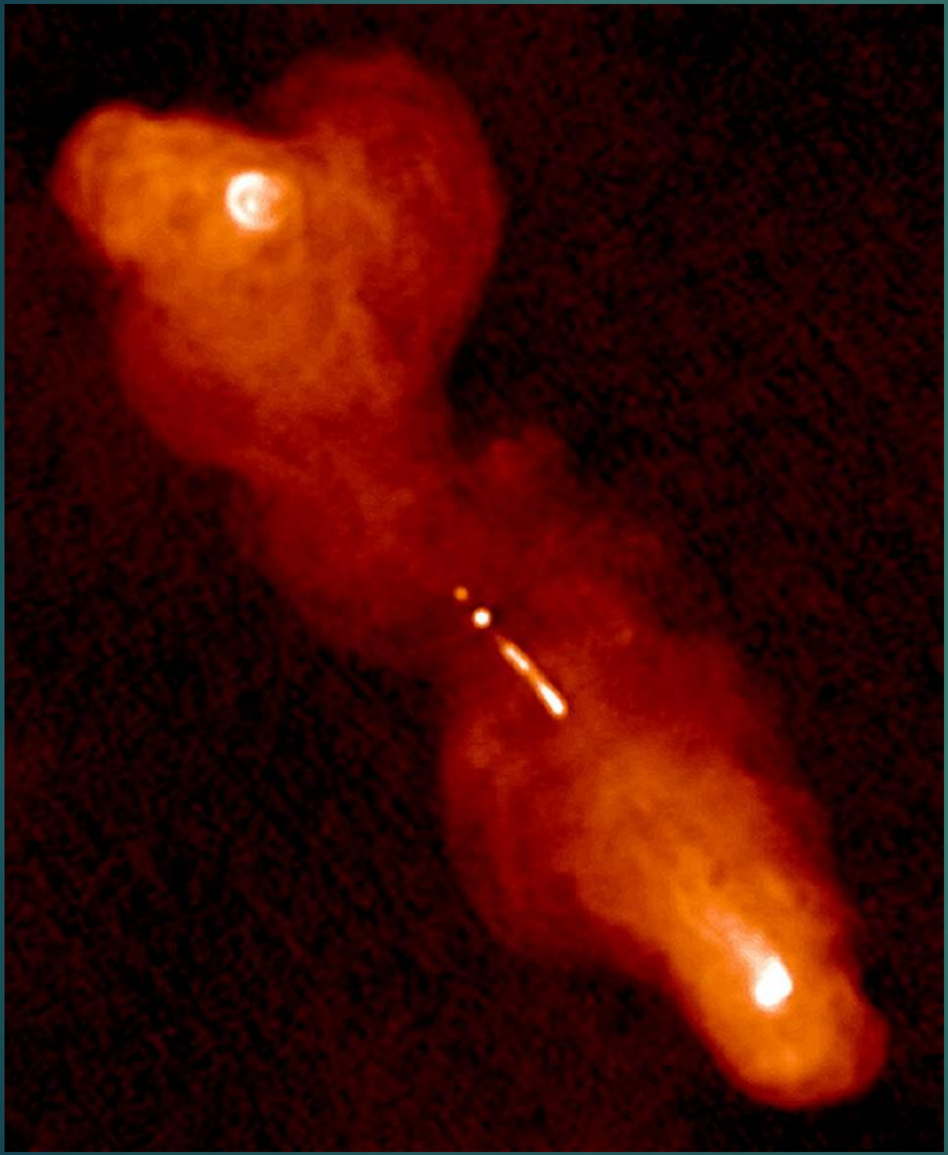
Credit: Chandra

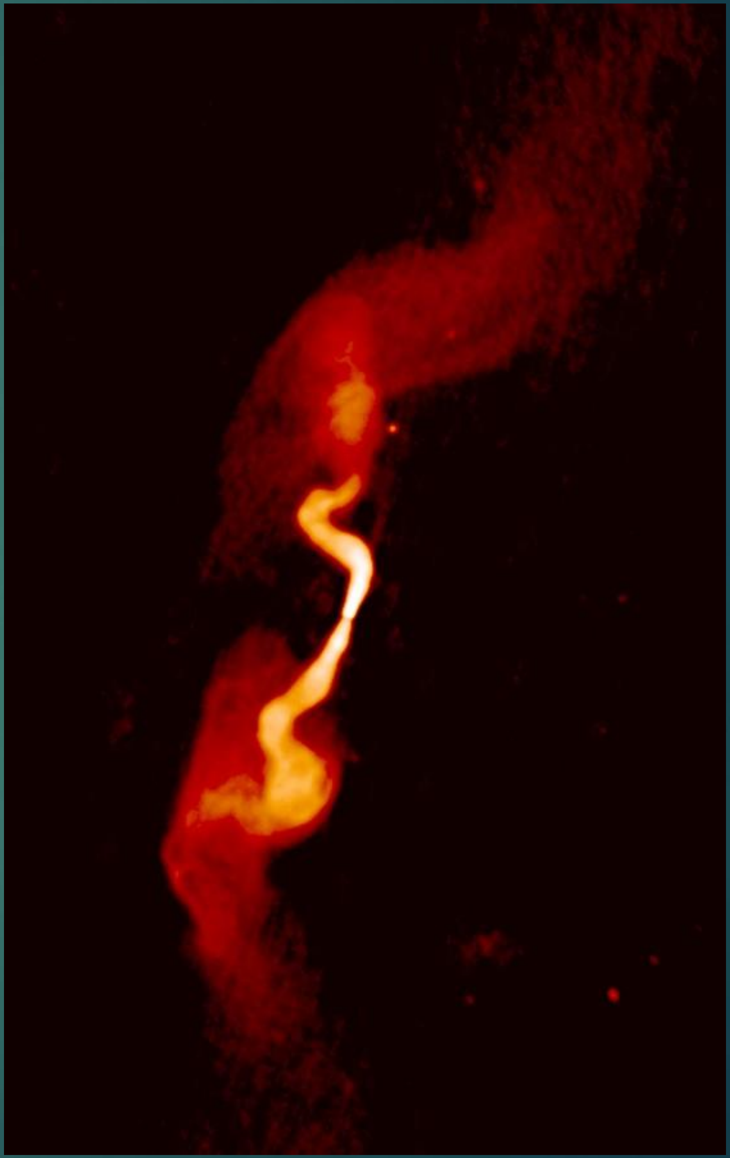


Fermi gamma-ray space telescope image of Cen A

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

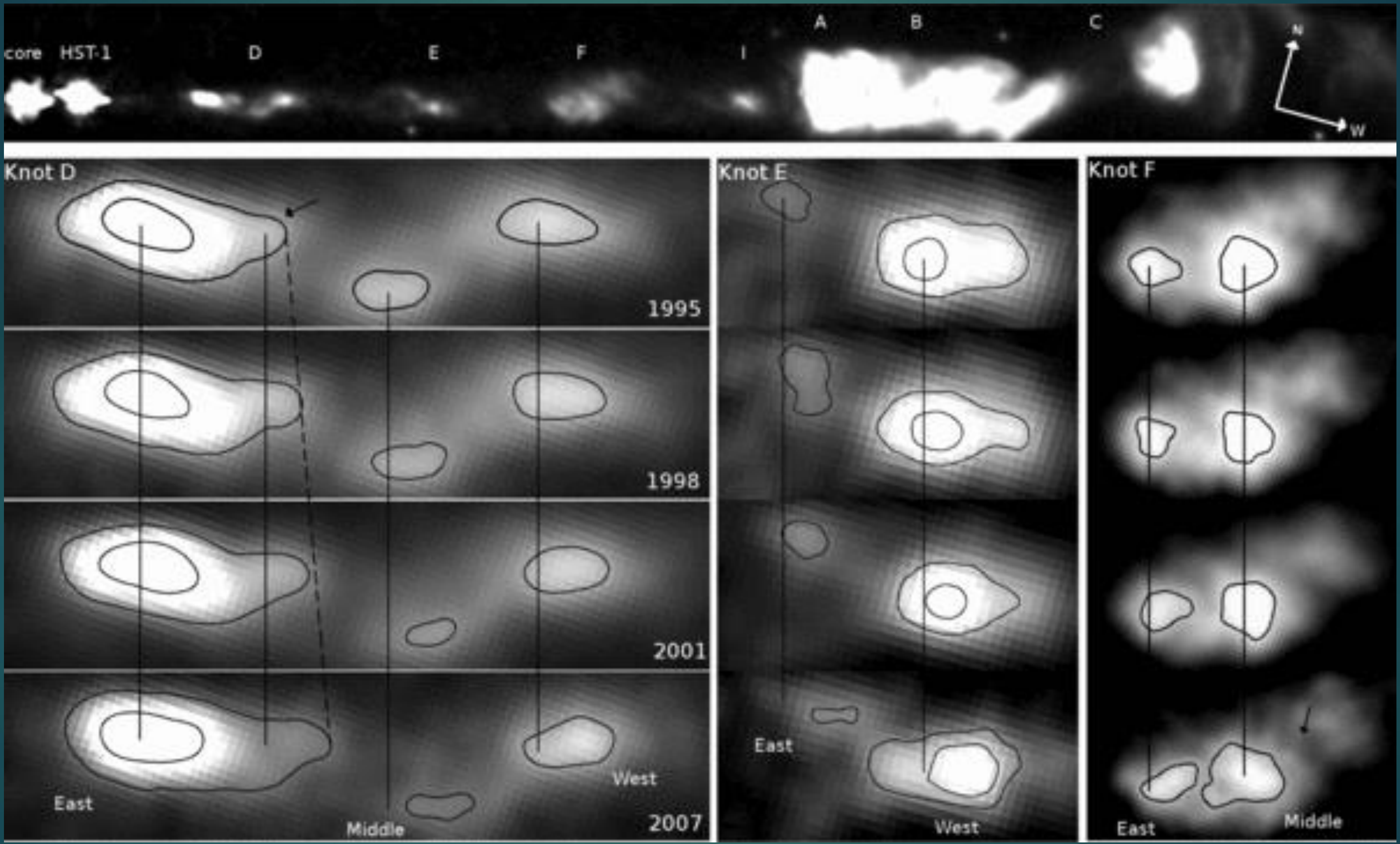
Large scale jets: the dictonomy





M87 = FRI source with jet length ~ 2kpc

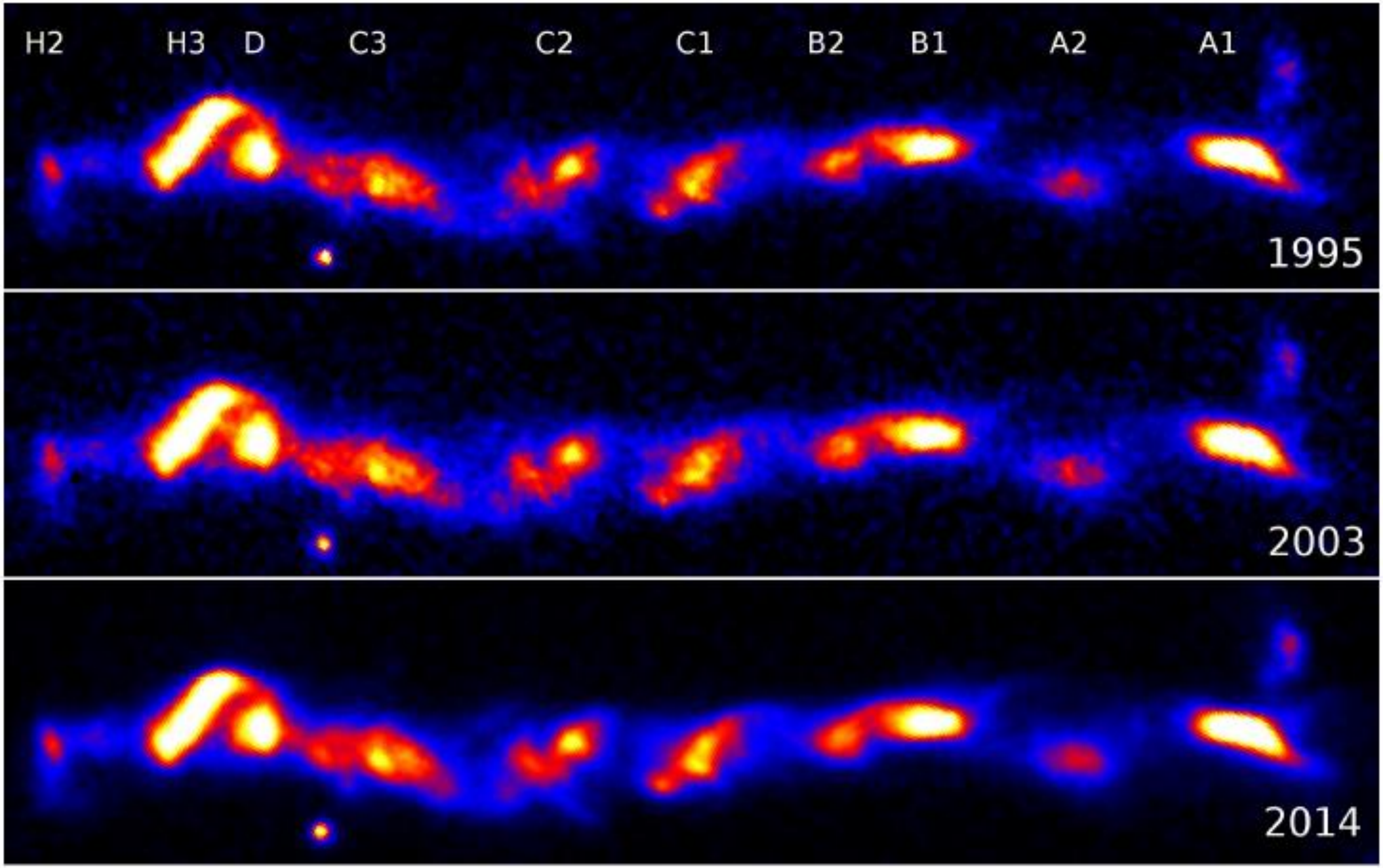
Meyer et al. 2013



Apparent superluminal motion (~ 5c) detected in the large-scale jet by Biretta et al. 199
and confirmed by Meyer et al. 2013

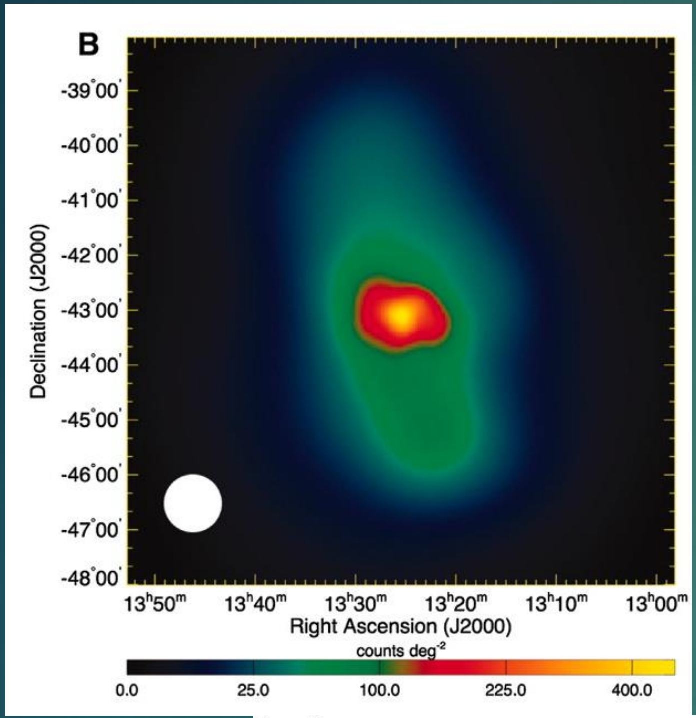
3C 273 FRII with jet length of ~ 60 kpc

Meyer et al. 2016

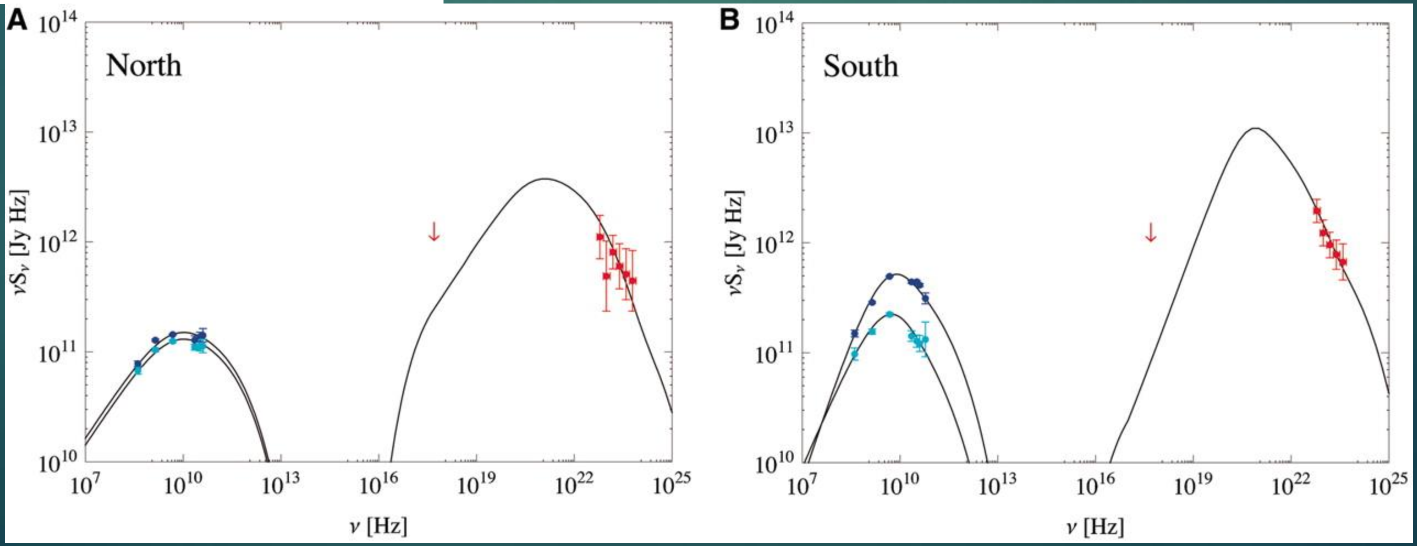


No proper motion seen on time scales of 20 years (Meyer et al. 2016)
(but much further away!)

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



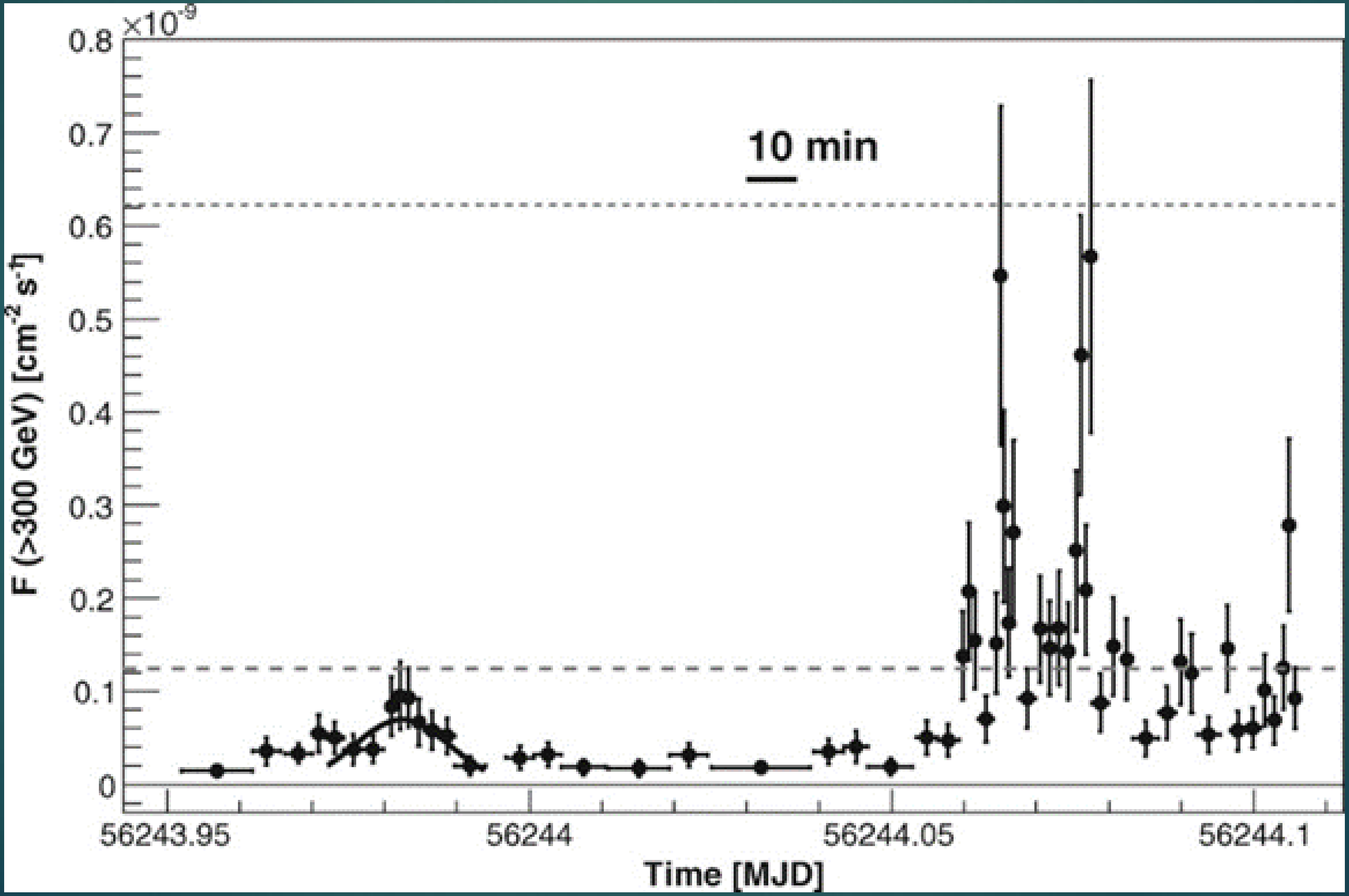
Radio galaxies

- 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…

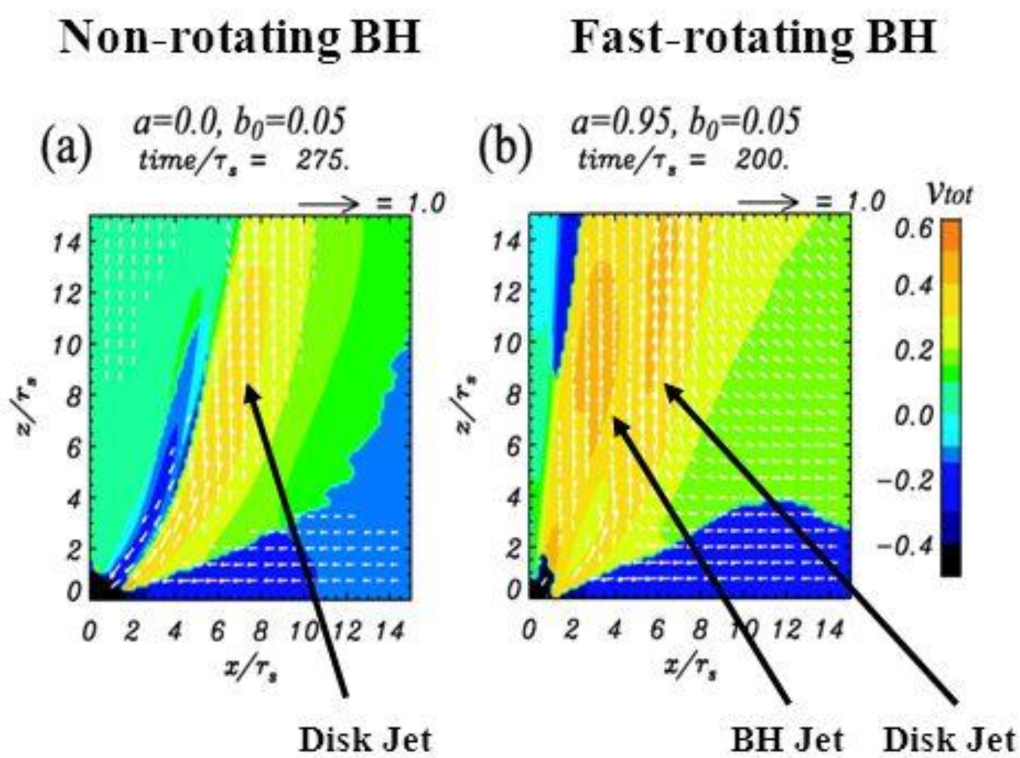
Variable emission from M87, NGC1275, IC310



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.

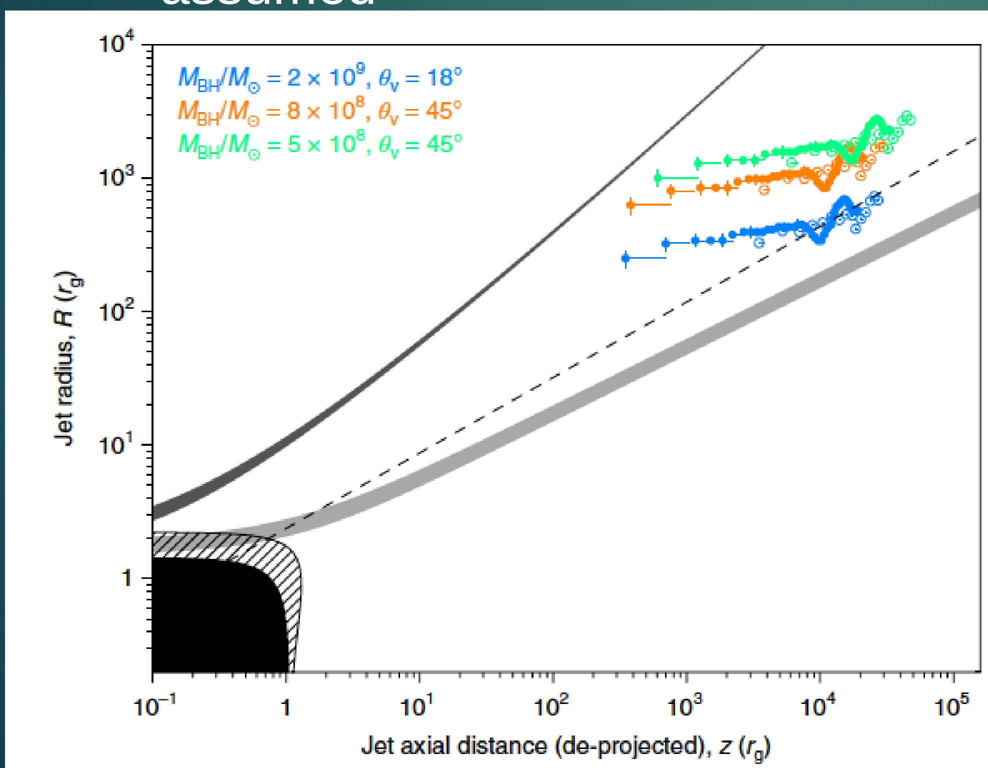


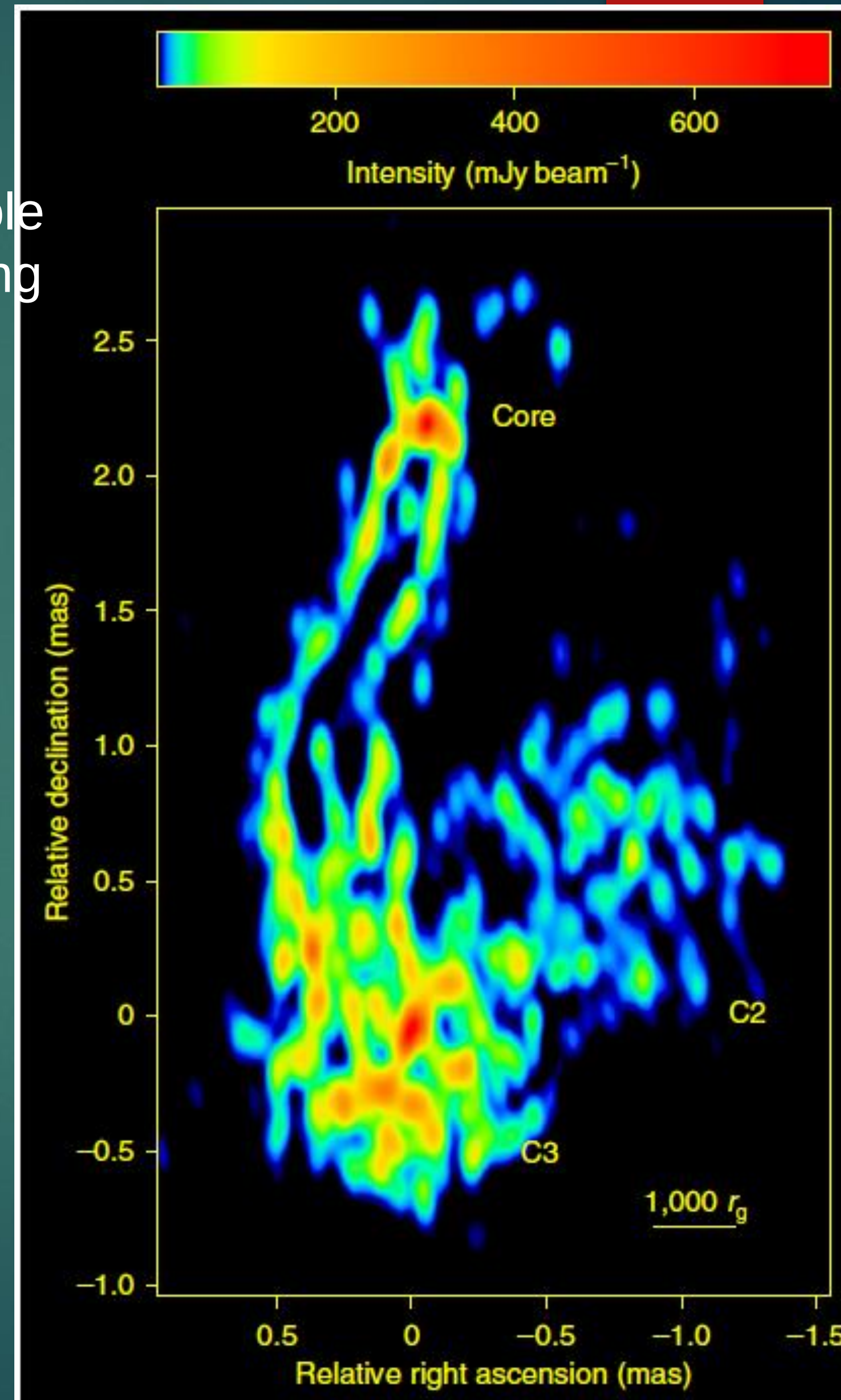
Total velocity distribution of 2D GRMHD Simulation of jet formation (Hardee, Mizuno & Nishikawa 2007)

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

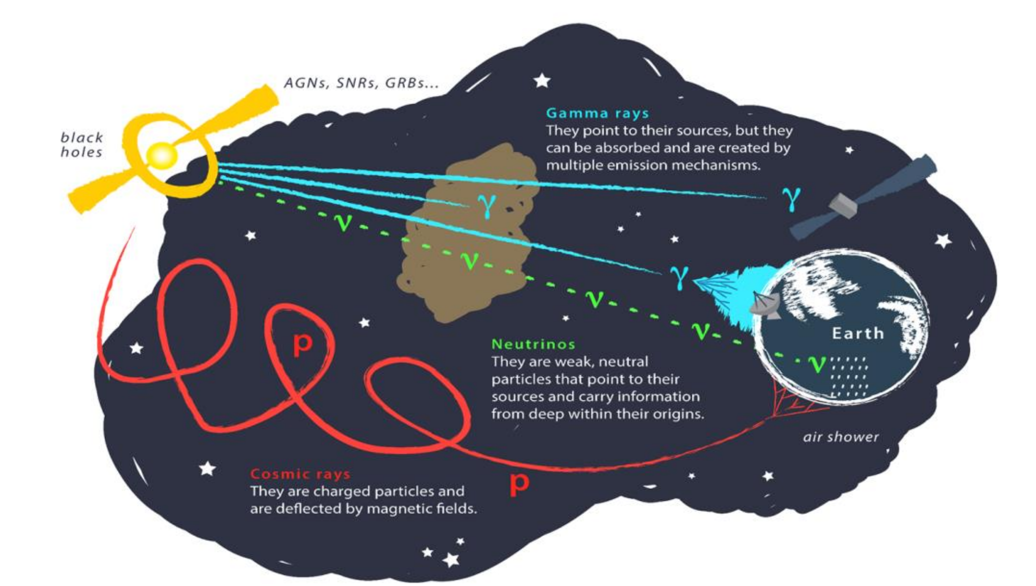
Final slide on radio galaxies

- 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
- Jet structures like the spine-sheath that we can resolve in radio galaxies should be there also in blazars, solution to ”missing seed photon fields”?

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)
- Non-jetted AGN
- GRBs

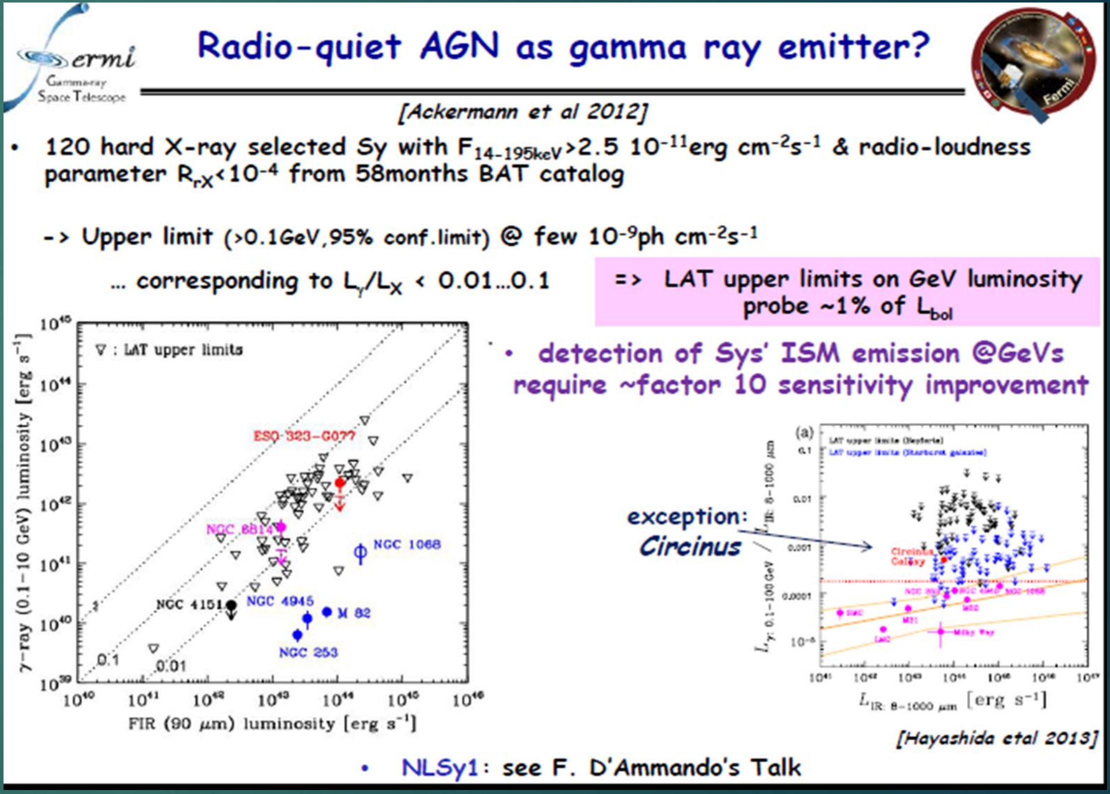
- Propagation effects



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…



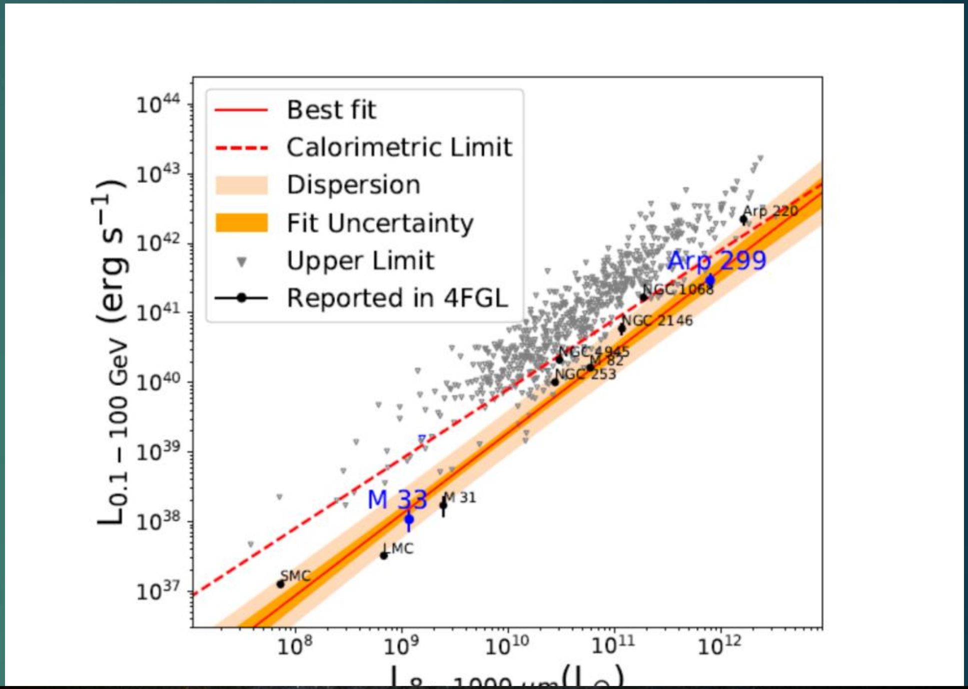
Non-jetted AGNs?

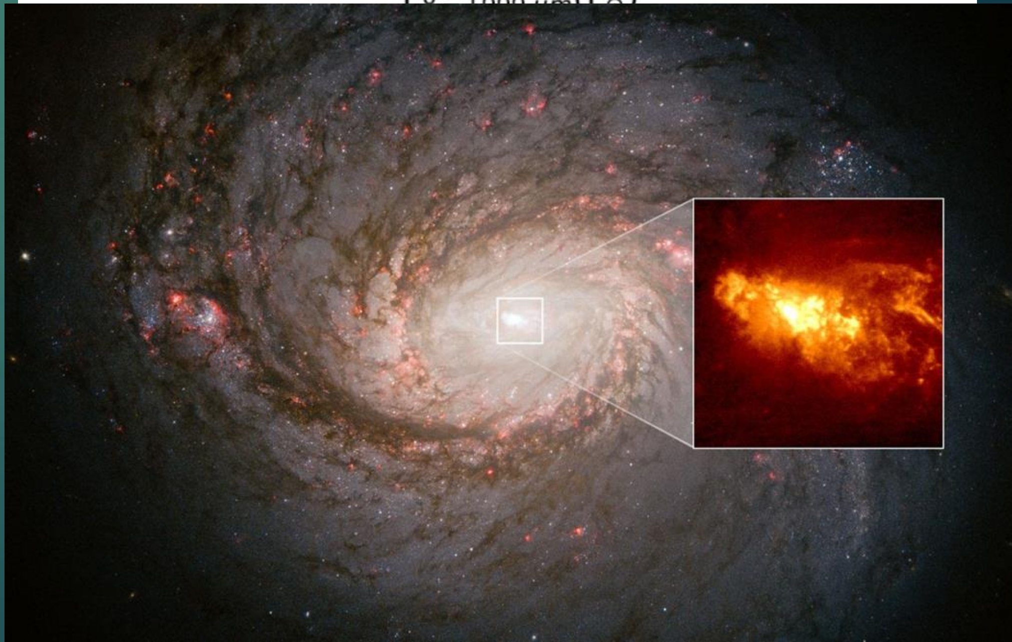
- Widespread evidence that AGN can more commonly eject moderately collimated winds of thermal plasma
- Outflow velocities from a few 100 km/s up to mildly relativistic values of ~0.3c
- Primarily observed as blue-shifted absorption features due to ionized metals at UV and X-ray energies.
- They are seen 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



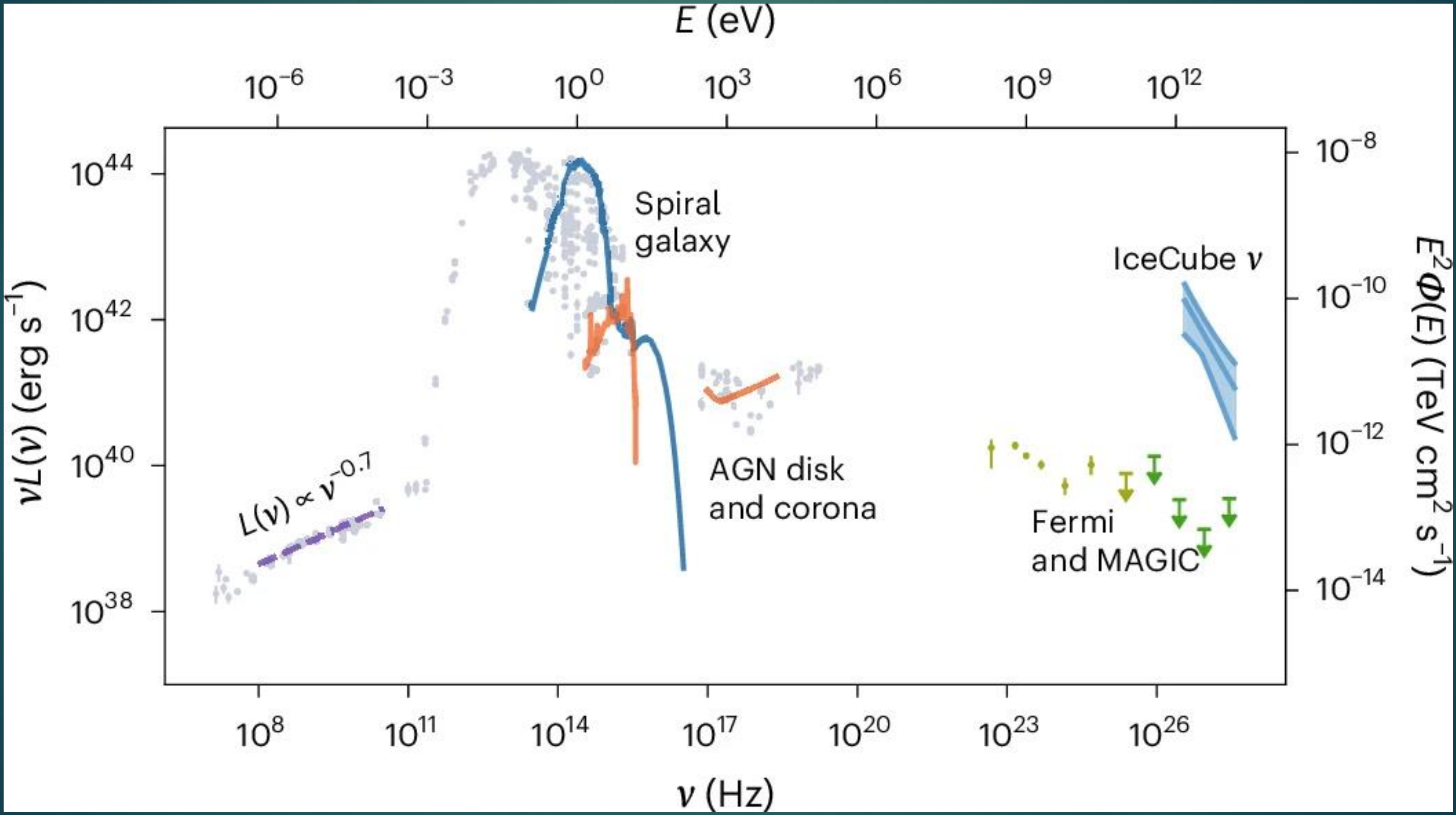


Hubble image of the outflow

Origin of neutrino emission in NGC1068?

- Padovani et al. 2024 “As it is so close, NGC 1068 can be spatially resolved into a number of components, all of which maybe be relevant to neutrino production”:
- (1) a starburst (SB) region in the spiral arms of its host galaxy
- (2) an approximately kiloparsec long jet
- (3) a sub-kiloparsec molecular outflow
- (4) the black hole vicinity (the accretion disk and perhaps the so-called corona).

Origin of neutrino emission in NGC1068



Padovani et al. 2024

Origin of neutrino emission in NGC1068?

- Padovani et al. 2024 “As it is so close, NGC 1068 can be spatially resolved into a number of components, all of which maybe be relevant to neutrino production”:
- (1) a starburst (SB) region in the spiral arms of its host galaxy
- (2) an approximately kiloparsec long jet (Ljet=10^42 erg/s (TXS 10^45erg/s) (radio)
- (3) a sub-kiloparsec molecular outflow
- (4) the black hole vicinity (the accretion disk and perhaps the so-called corona). Obscured behind dust so X-rays

ALMA

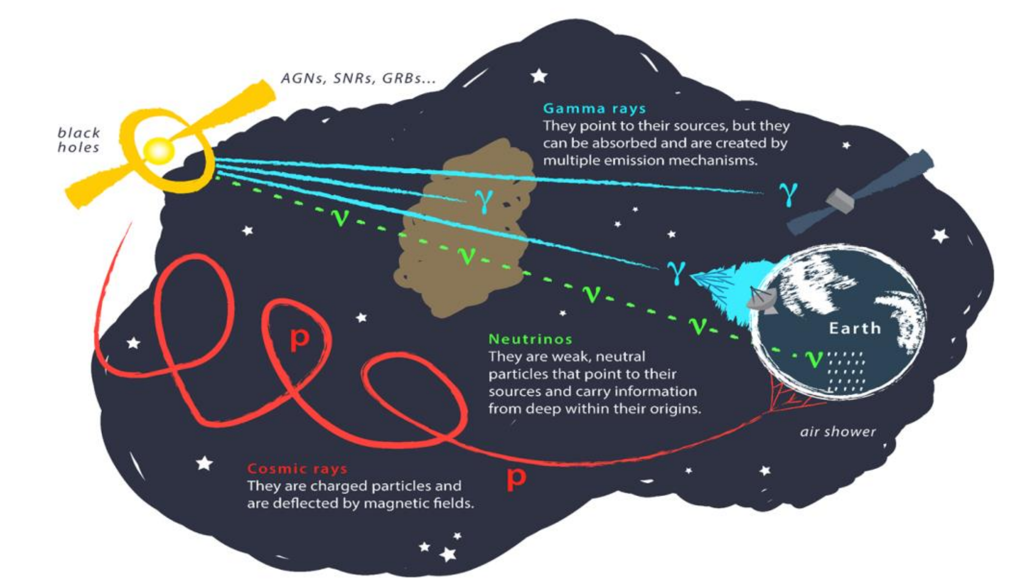
$$L_{\rm kin} = \frac{3\, M_{\rm out}\, v^3}{2\, R_{\rm out}} \frac{\tan(\alpha)}{\cos{(\alpha)}^2},$$

where Mout and Rout are the mass and radius of an outflow

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)
- Non-jetted AGN
- GRBs

- Propagation effects



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!

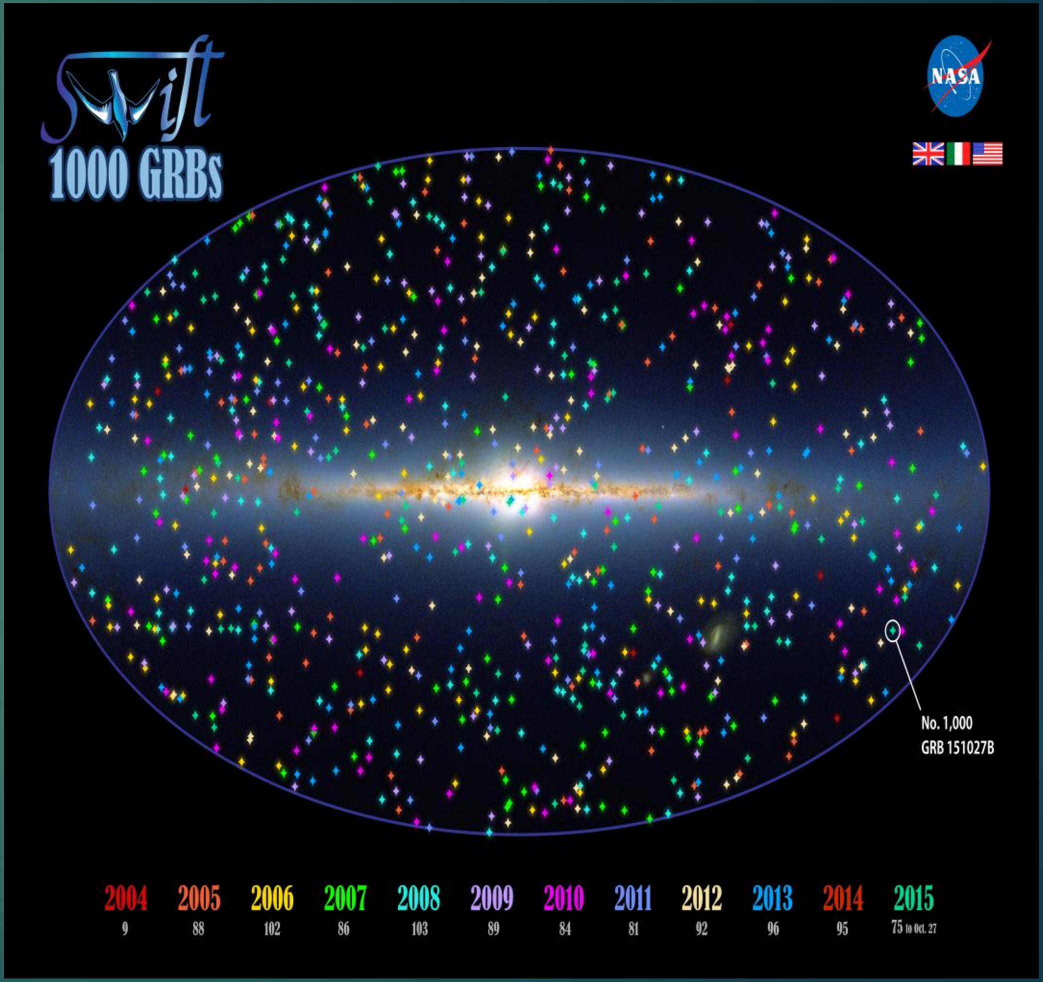
$$R_{\text{emission}} < \Gamma^2 \cdot c \cdot \delta T_{min} \approx \Gamma^2 \cdot 60\,\text{km}$$

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 expected for proton synchrotron emission (see blazars) or photo-pion production or inverse Compton scattering or reverse shock in the burst environment

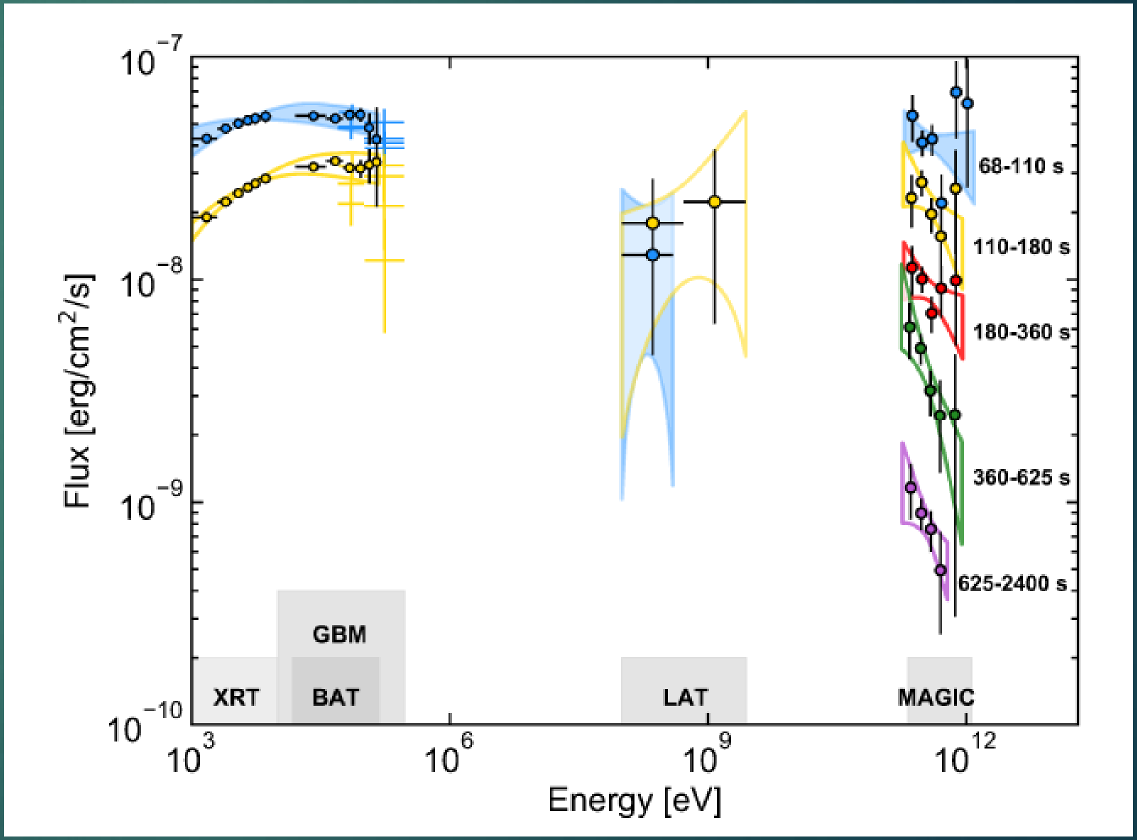
Gamma-ray bursts at VHE

- 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 CTAO we expect to detect many more

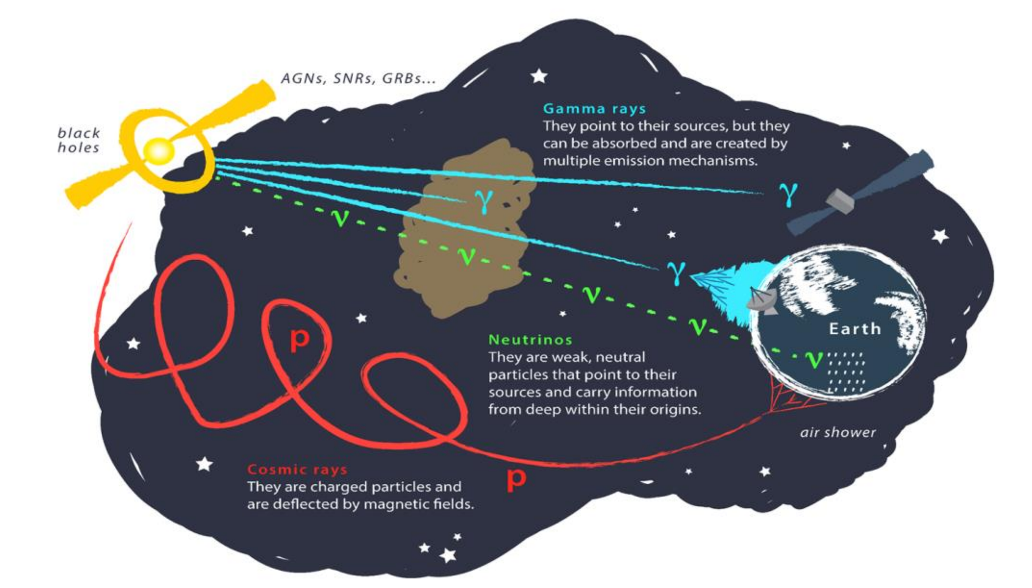


MAGIC Collaboration 2019, Nature

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.

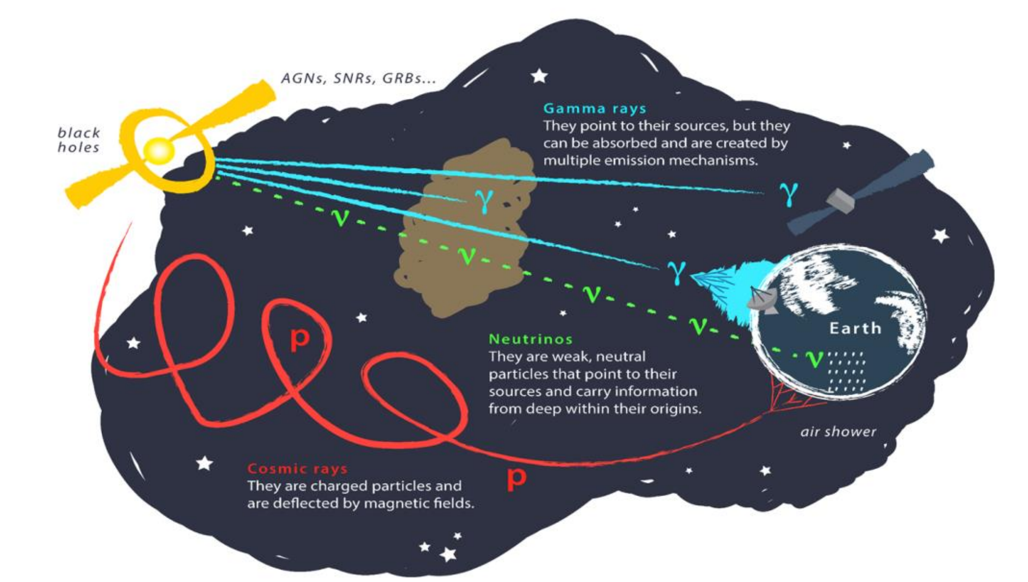
Something more: unidentified Fermi sources

- 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?

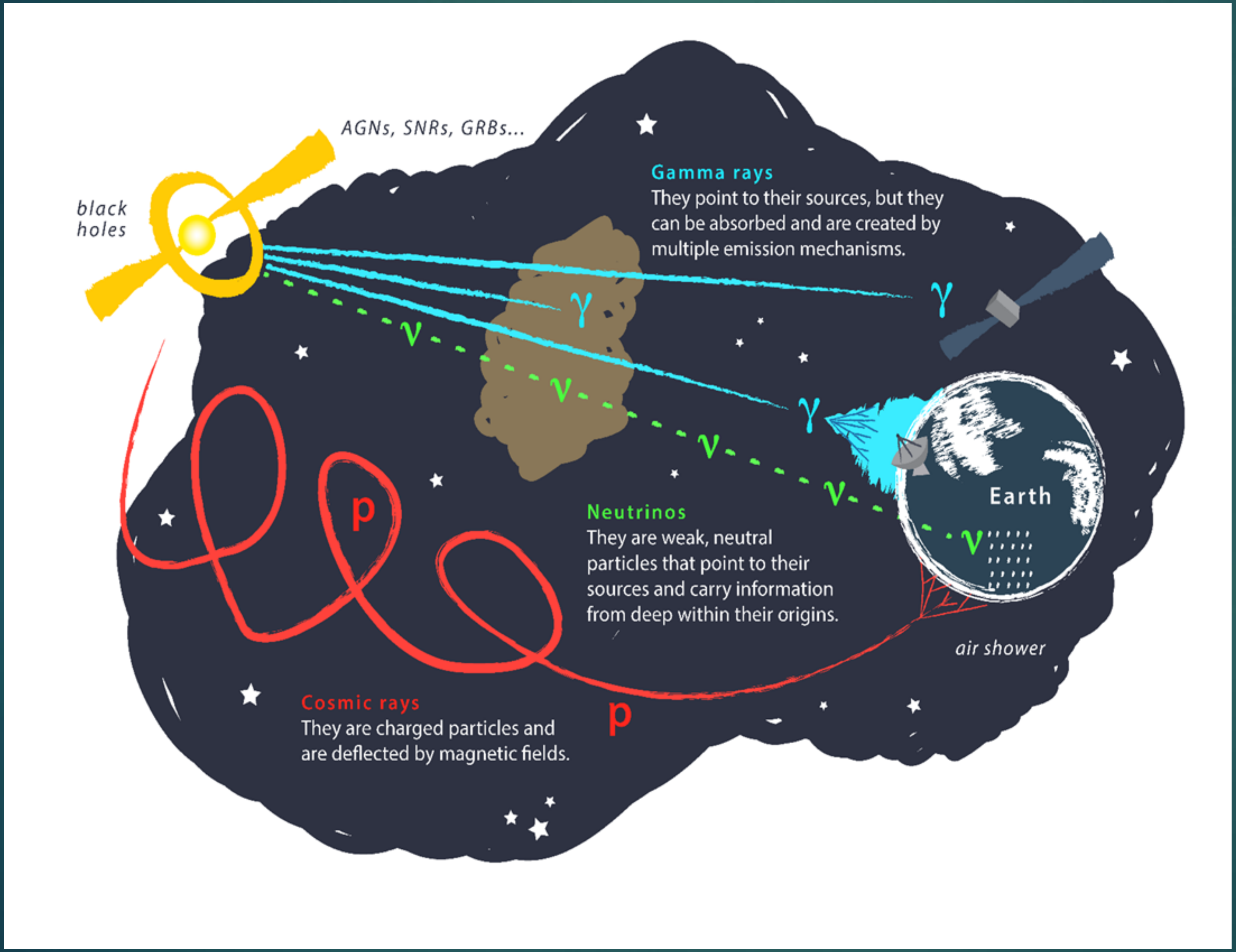
- Gamma-ray observations of blazars
- Neutrino observations of blazars
- Radio galaxies (i.e. when jet is not pointing close to our line of sight)

- Is that all?
- Propagation effects

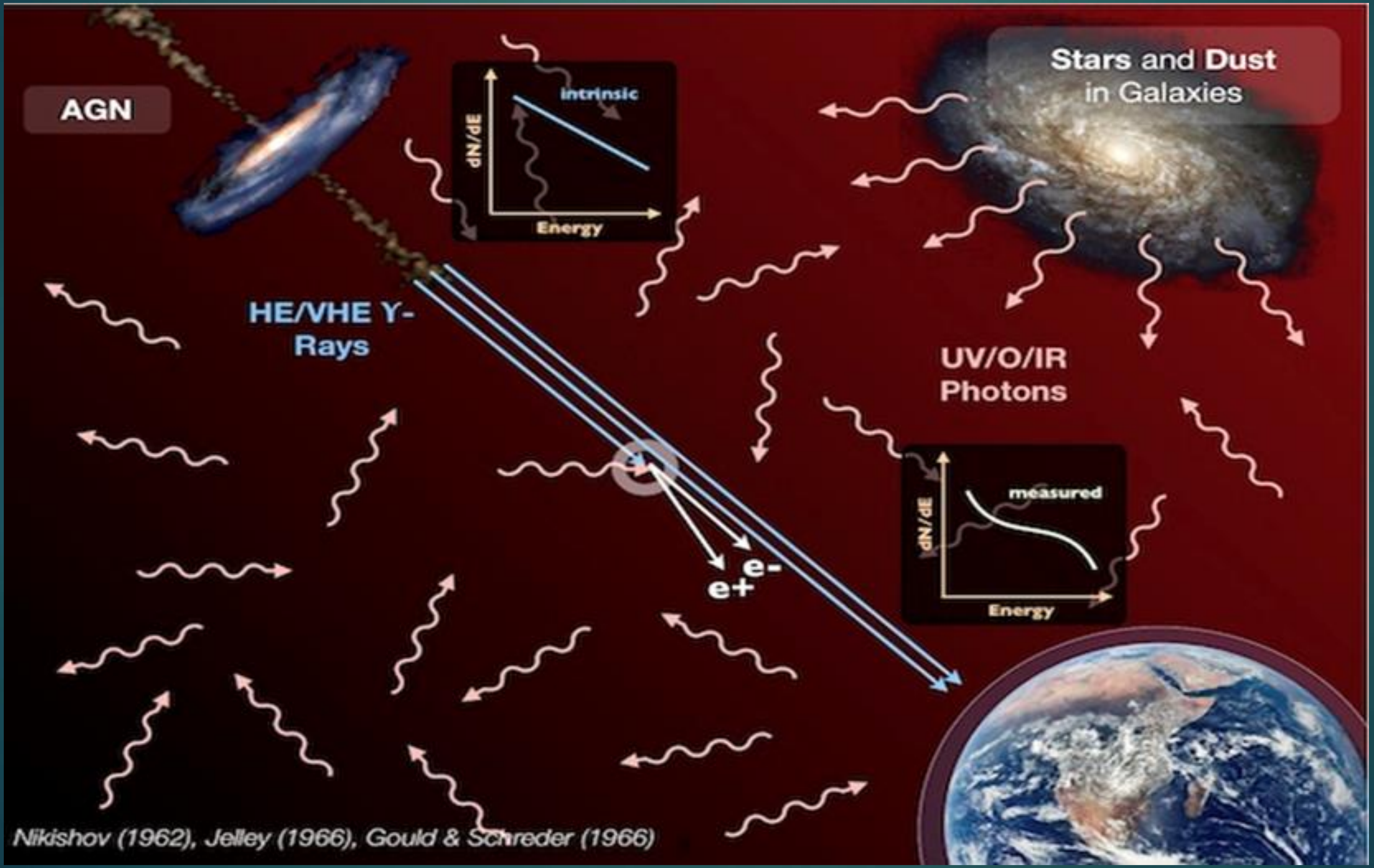


Credit: Juan Antonio Aguilar and Jamie Yang IceCube/WIPAC.

Propagation of Astroparticles



Propagation of VHE gamma-rays



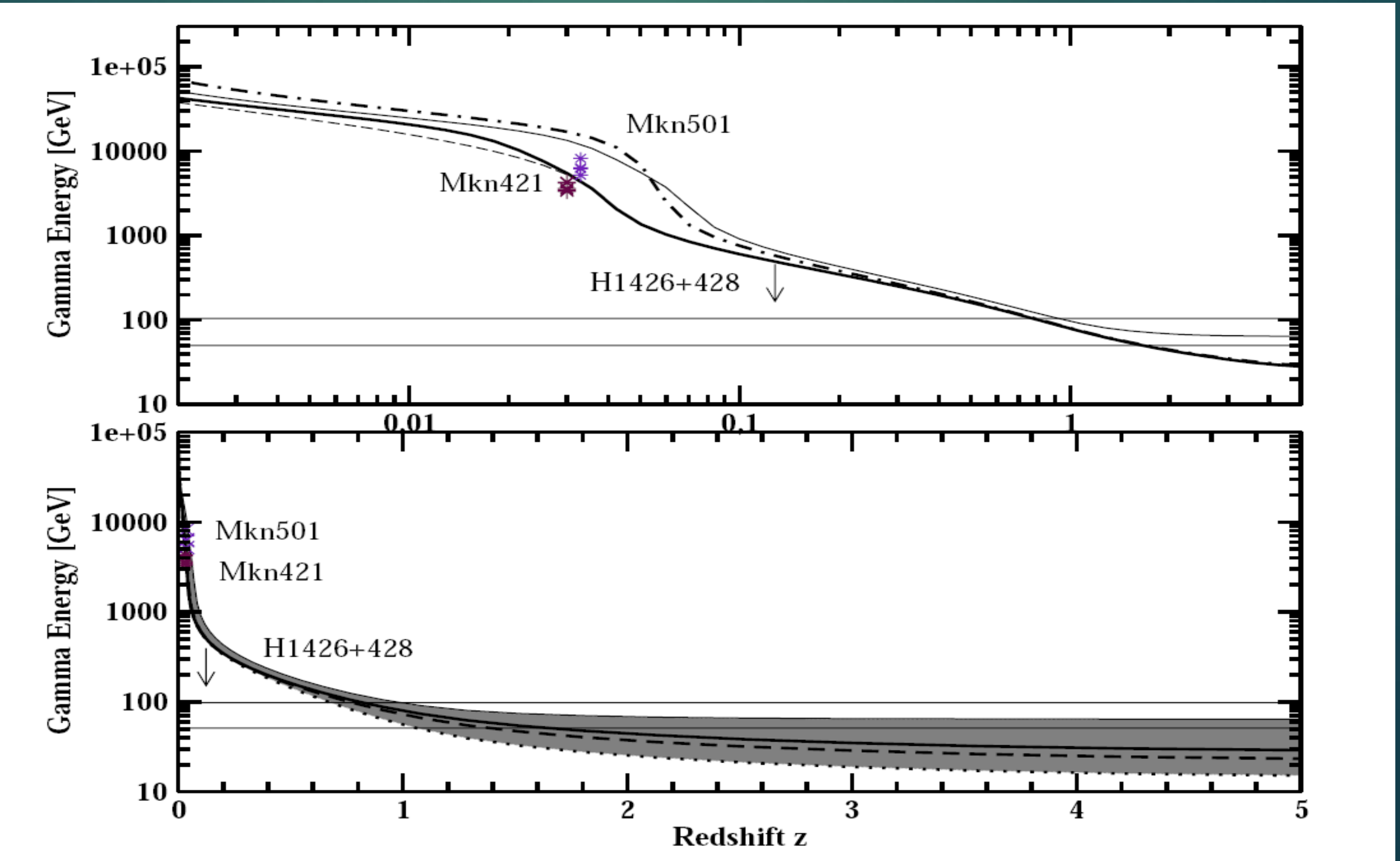
Gamma-ray Horizon

- 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)>2$m_e^2 c^4$ 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:

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

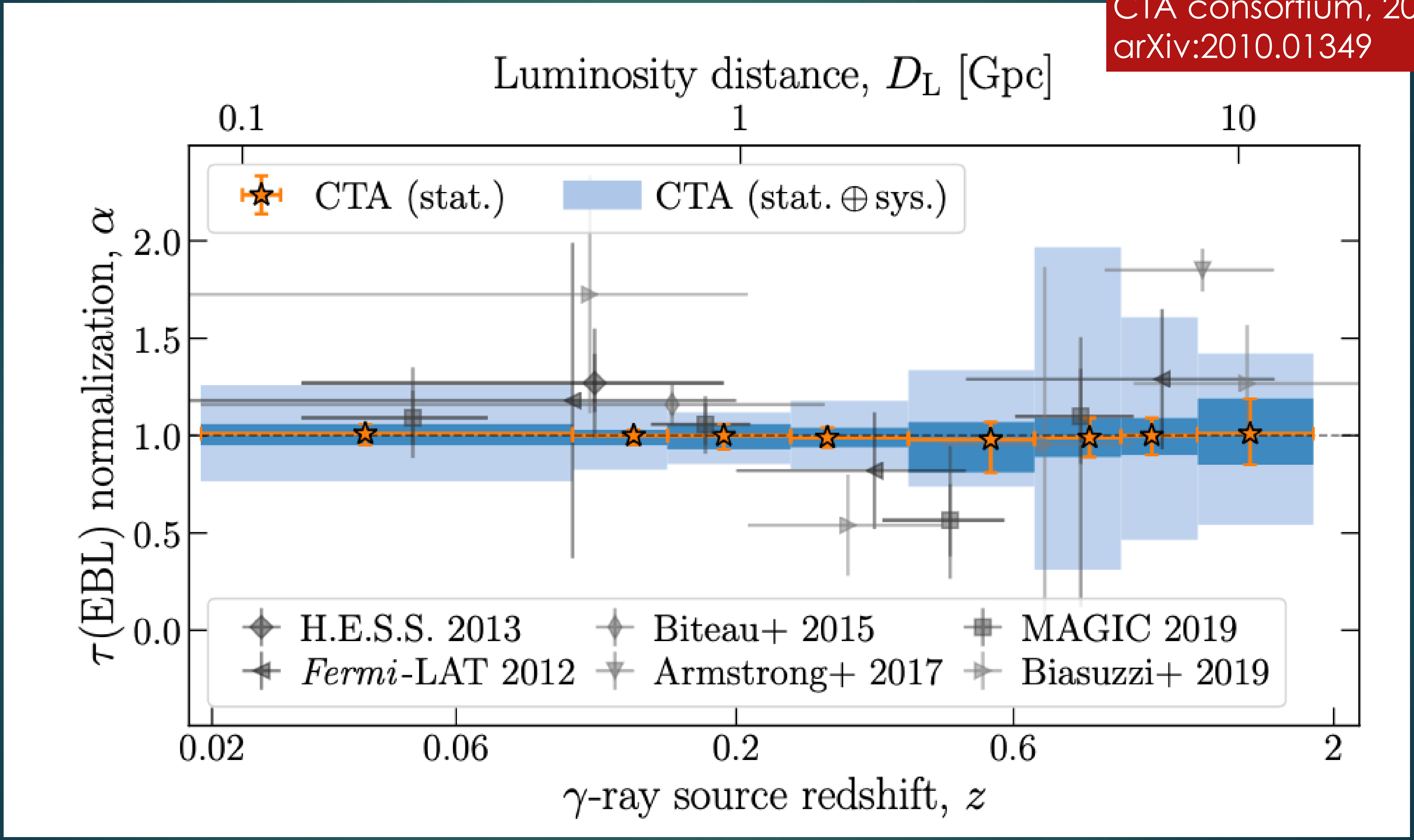
Gamma-ray Horizon

- 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

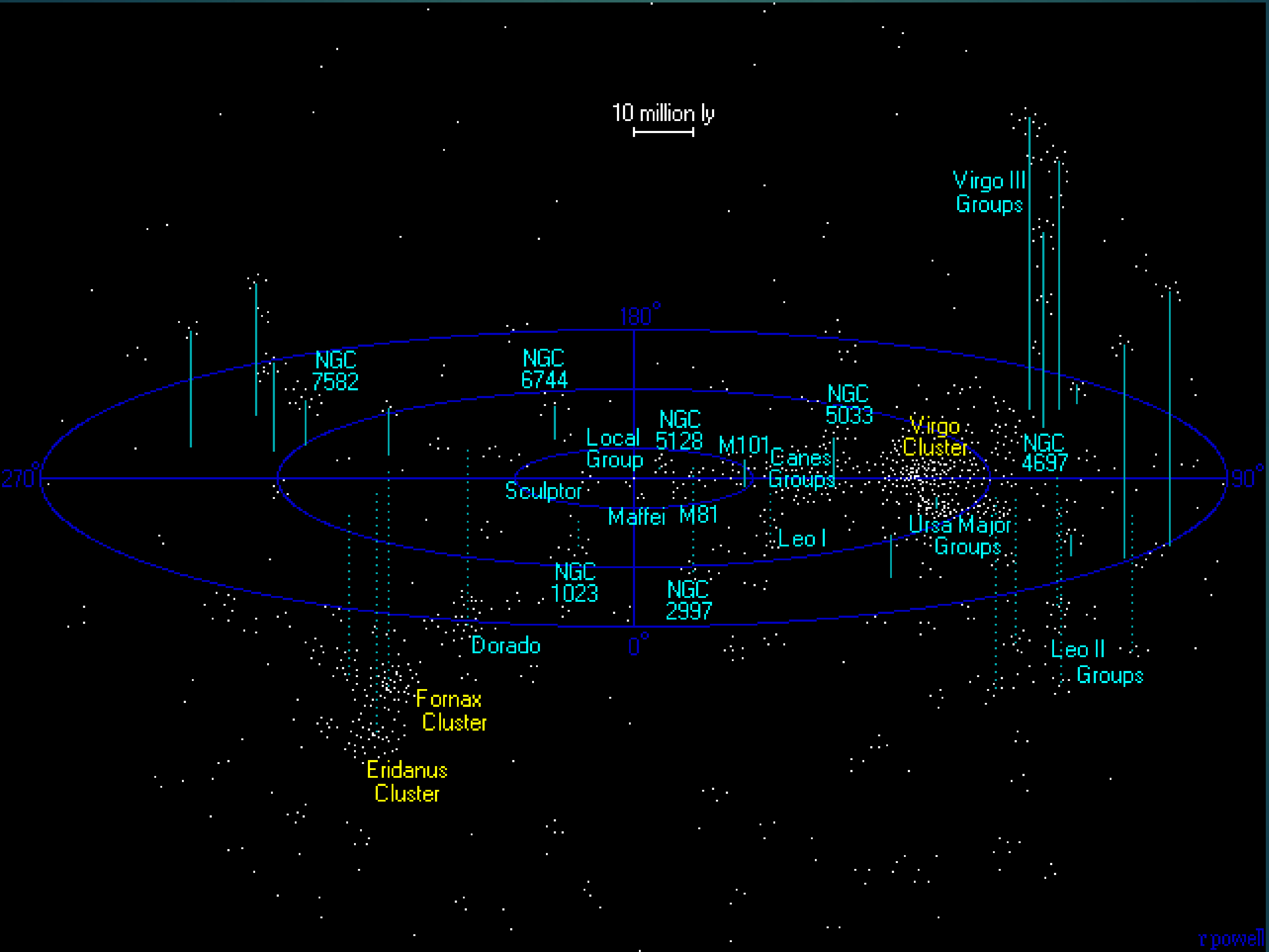
- Hadrons loose their energy fast in intergalactic medium via photoproduction of pion off blackbody photons
- Mean free path for protons:

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

where N is the number density of blackbody photons and $\sigma(\gamma p \to \pi^0 p) \approx 100\,\mu\text{b}$ 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, the now very famous NGC1068 (11Mpc) and few other Seyferts and and starburst galaxies like M82 and NGC 253

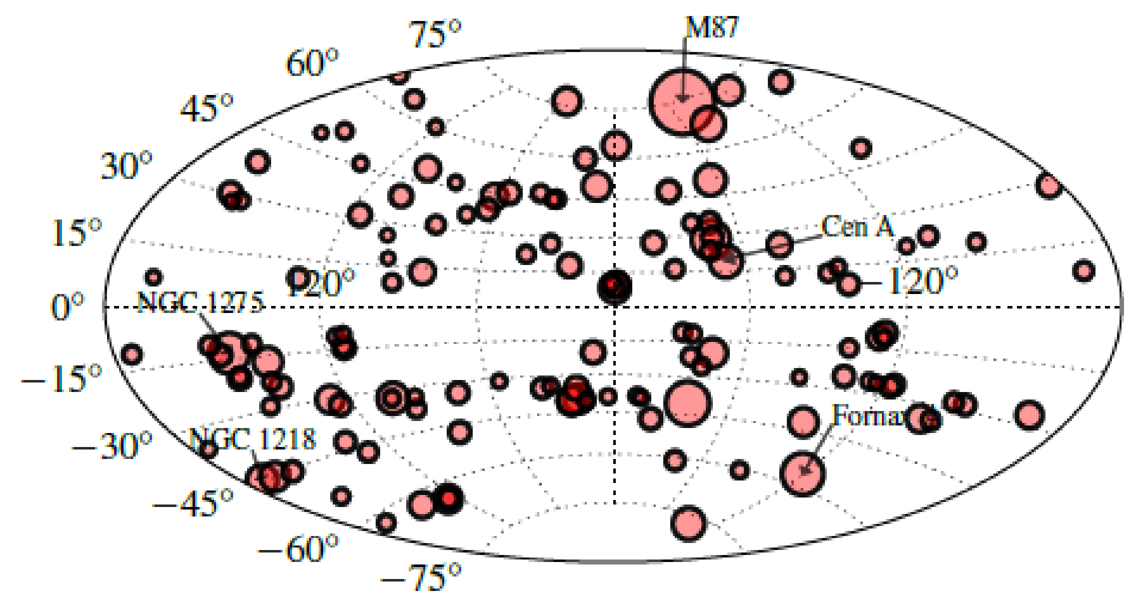


Figure 6. Map in Galactic coordinates with the radio galaxies of the volume-limited sample ($z < 0.03$). The area of the circles is proportional to the radio flux of the source. The location of some famous sources is indicated (M87 and NGC 1275 are the brightest members of the Virgo and Perseus cluster,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

Thank you for your attention