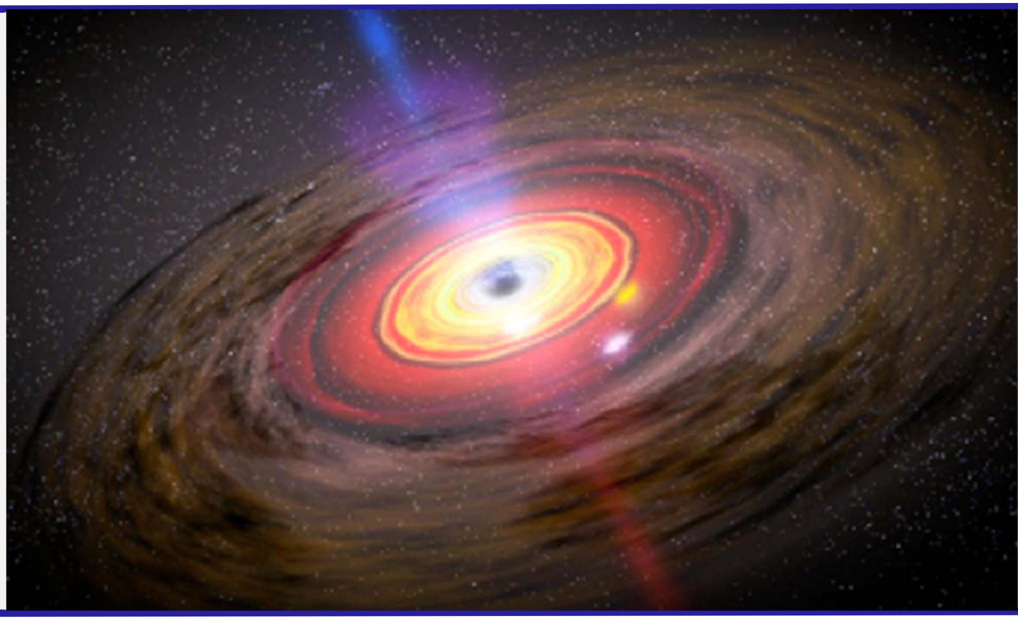
universität innsbruck

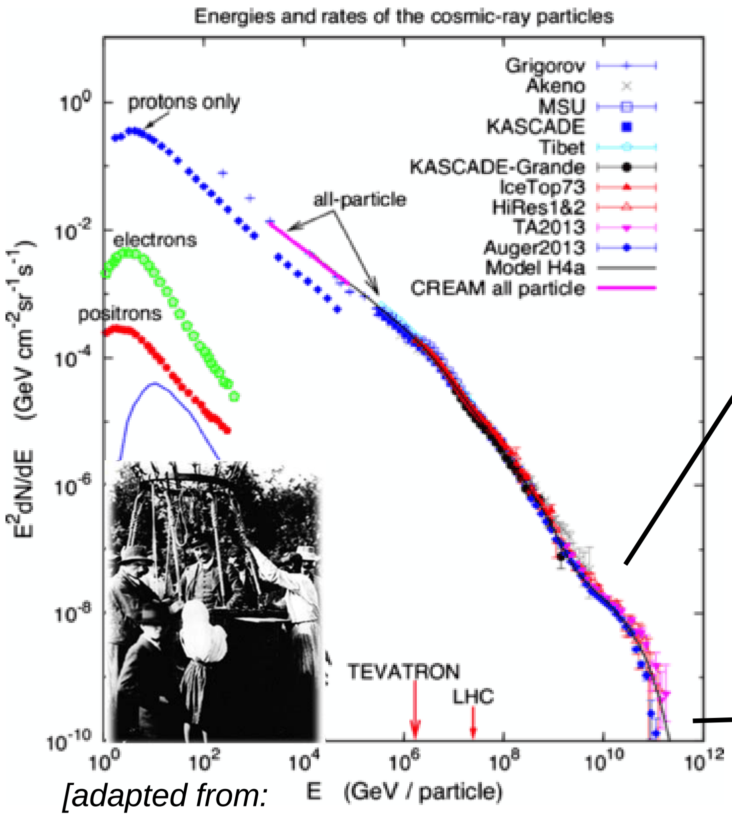


Cosmic rays in jets of Active Galactic Nuclei

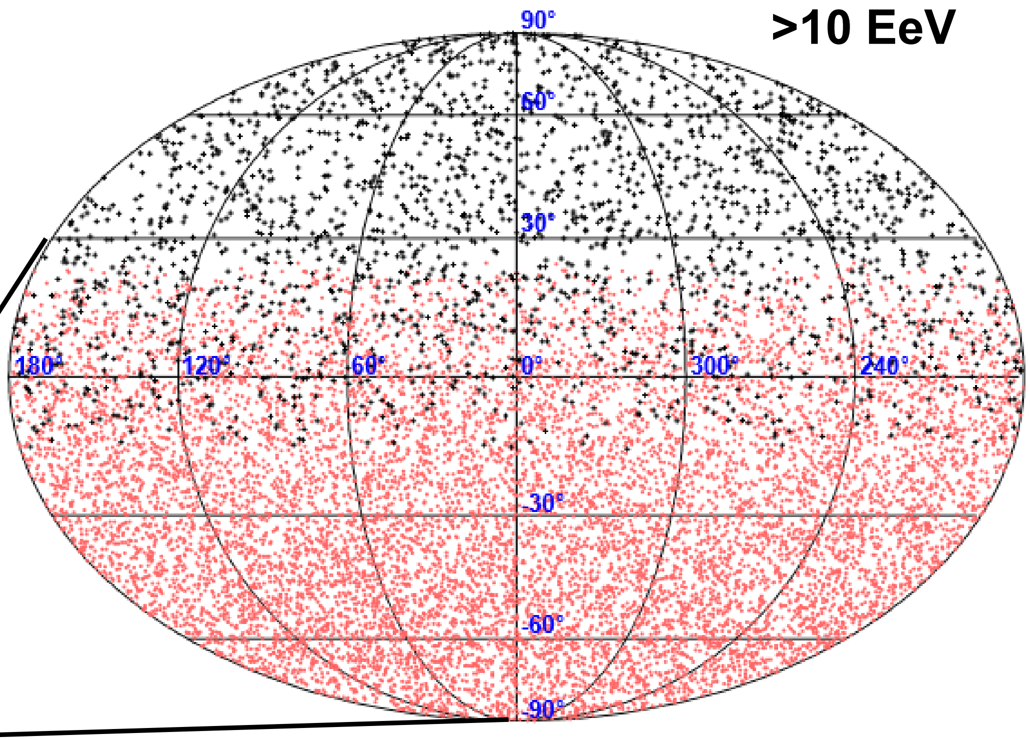
Anita Reimer

Particle Physics Seminar, University of Vienna
7 May 2024

Cosmic Rays as Messengers of the High-Energy Universe



[adapted from: Blasi 2013]



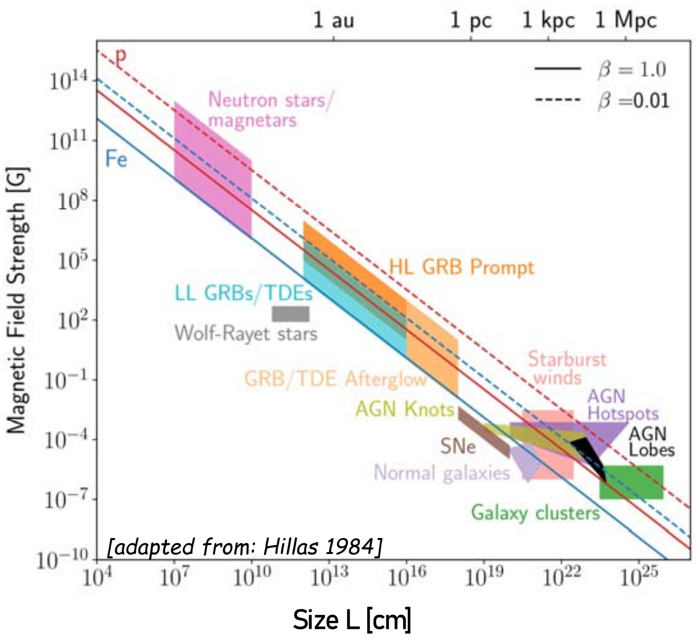
[from: Auger & TA Collab. 2014]

- **Where** do the cosmic rays originate?
- **What** are their sources?
- **How** do these cosmic particle accelerators work? (Mechanisms, environments, ...)

Outline

- Introduction
- **Jet core** of low-luminosity AGN: Site of UHECRs?
- **Extended jets** of AGN: UHECR signatures?
- Conclusions

Requirements on UHECR candidate source populations



The strongest magnetic fields ~10^{15}G

The brightest explosions ~10^{52}erg/s

The most massive black holes ~$10^{8...10}M_{\odot}$

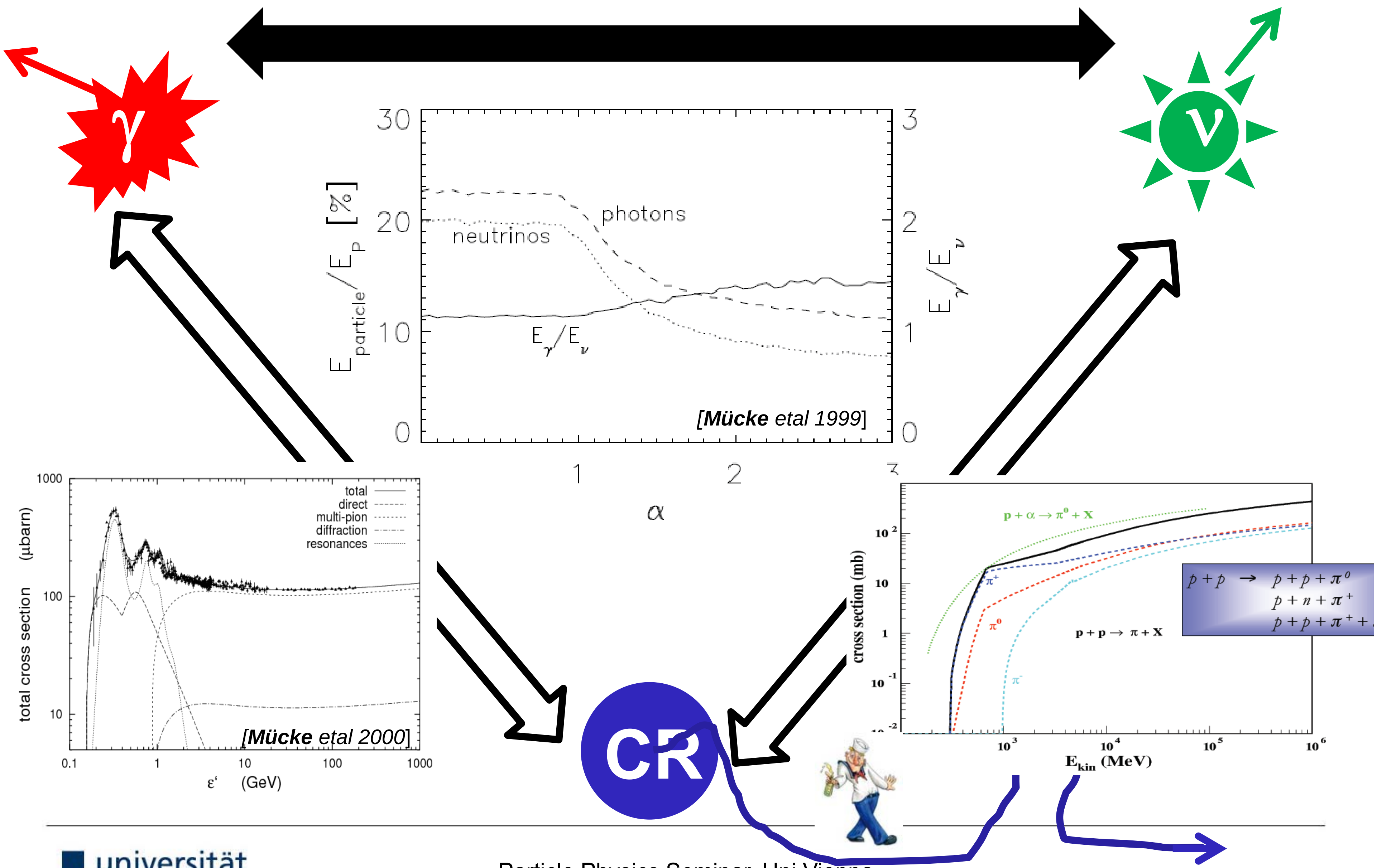
The largest gravitational objects R_{vir} ~ Mpc

⋮

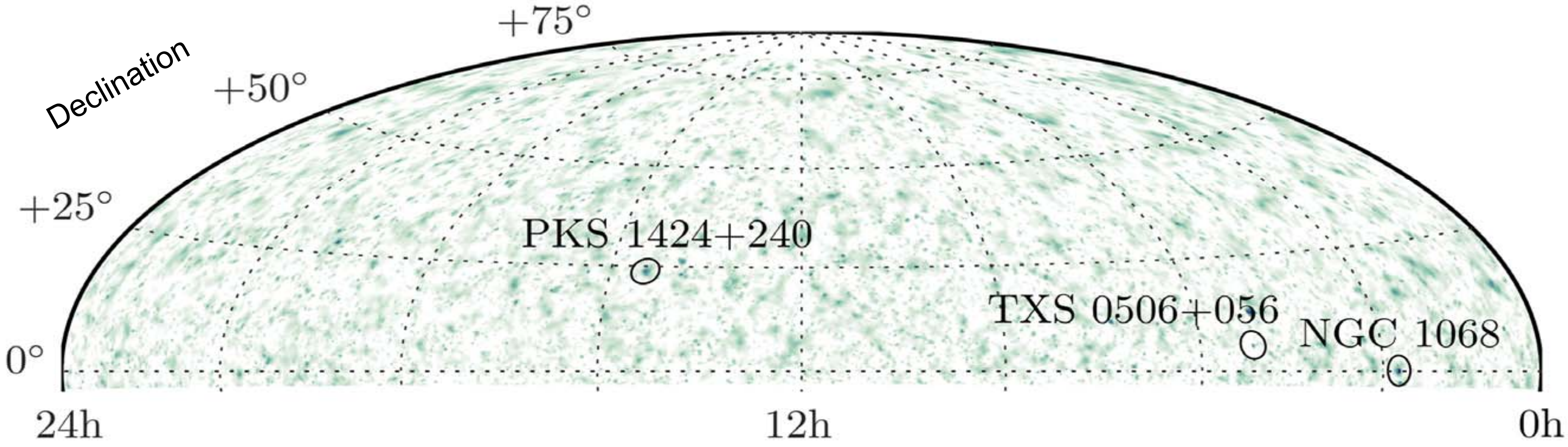
- ***"Hillas"-Criterium:*** $E_{max} \sim 10^{18}\, Z\, \beta\, (B/\mu G)\ \ (L/pc)$ eV
- ***Source power criterium:*** $P_{source} > 10^{43}\, Z^{-2}\, (E_{max}/10^{19} eV)^2$ erg/s
- ***Population power density criterium:*** $U_{population} \sim 10^{44....45}$ erg $Mpc^{-3}yr^{-1}$ for $E_{CR} \sim 10^{18....21}$ eV (within UHECR horizon)

➡ ***Required population density:*** $n_{population} \sim 10^{-8\ ...\ -4}\ Mpc^{-3}$

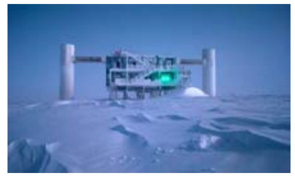
Linking cosmic rays - gamma rays - neutrinos



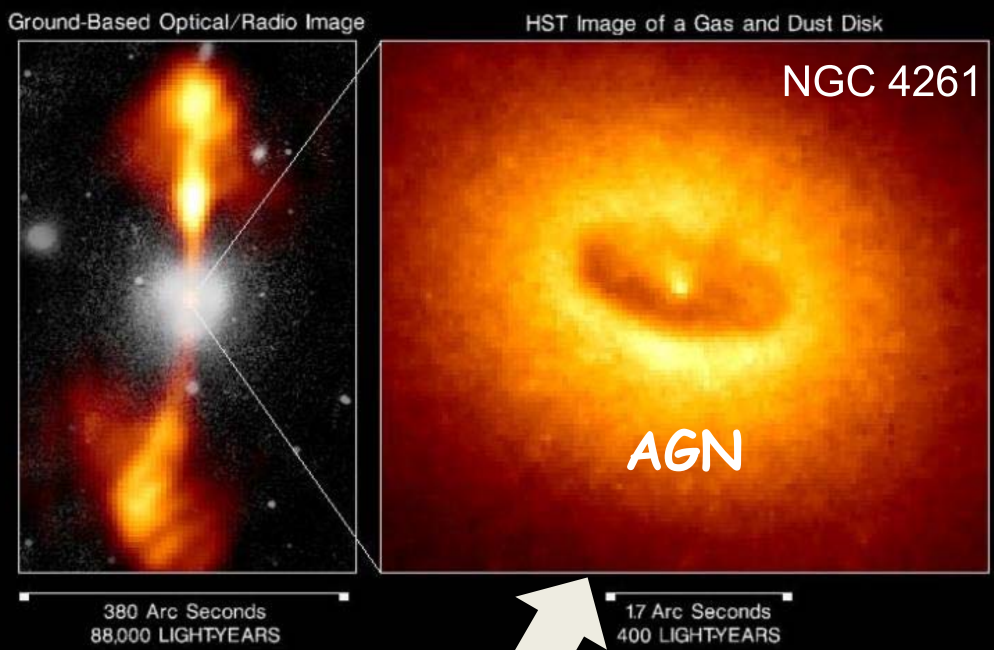
The PeV-neutrino sky

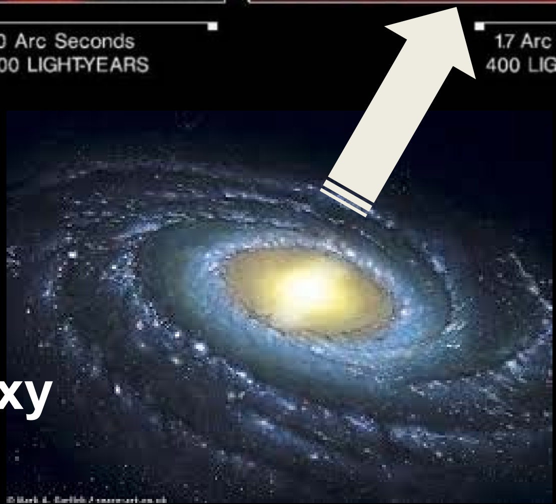


[IceCube-collab., 2022, Science]



Active Galactic Nuclei (AGN)

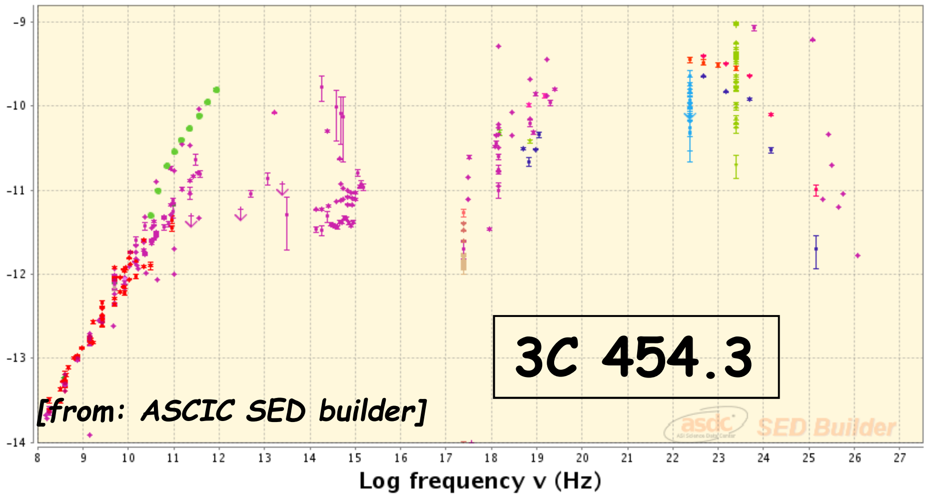


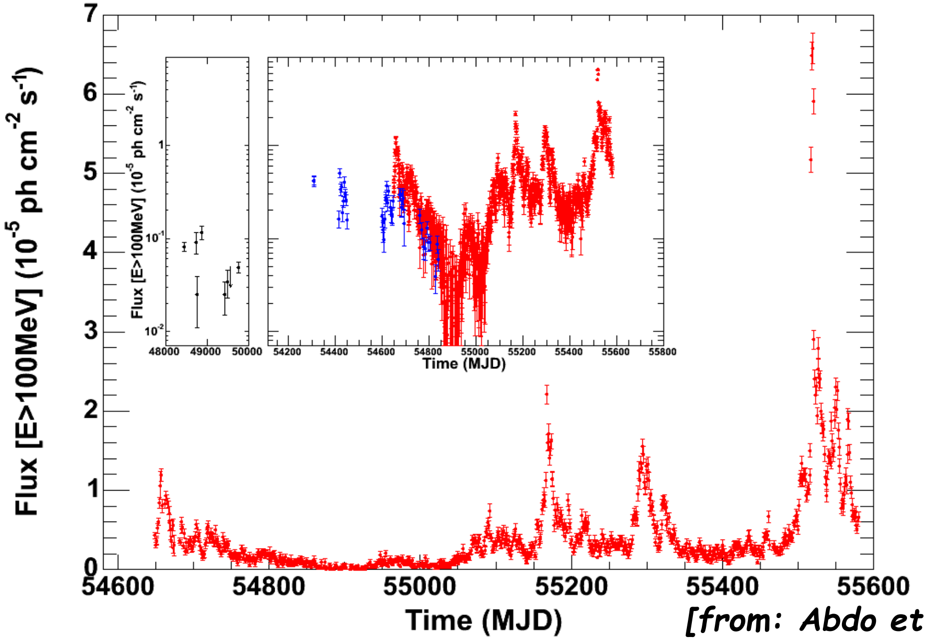


normal galaxy

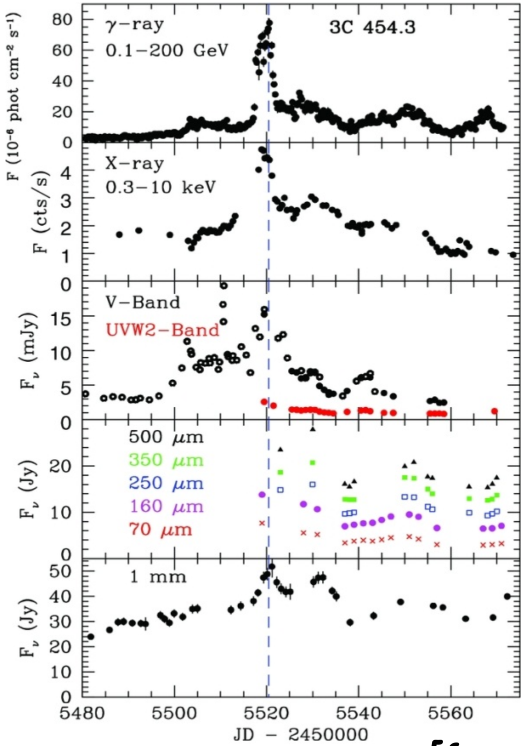
Radiative properties of the non-thermal AGN

- **Broad-band emission** (radio …. γ)
- **Highly variable at all energies** (min – months)



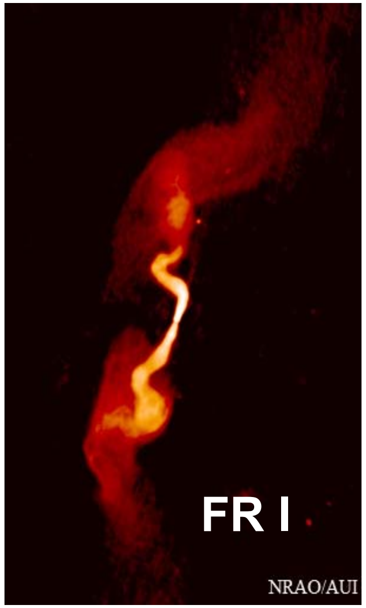


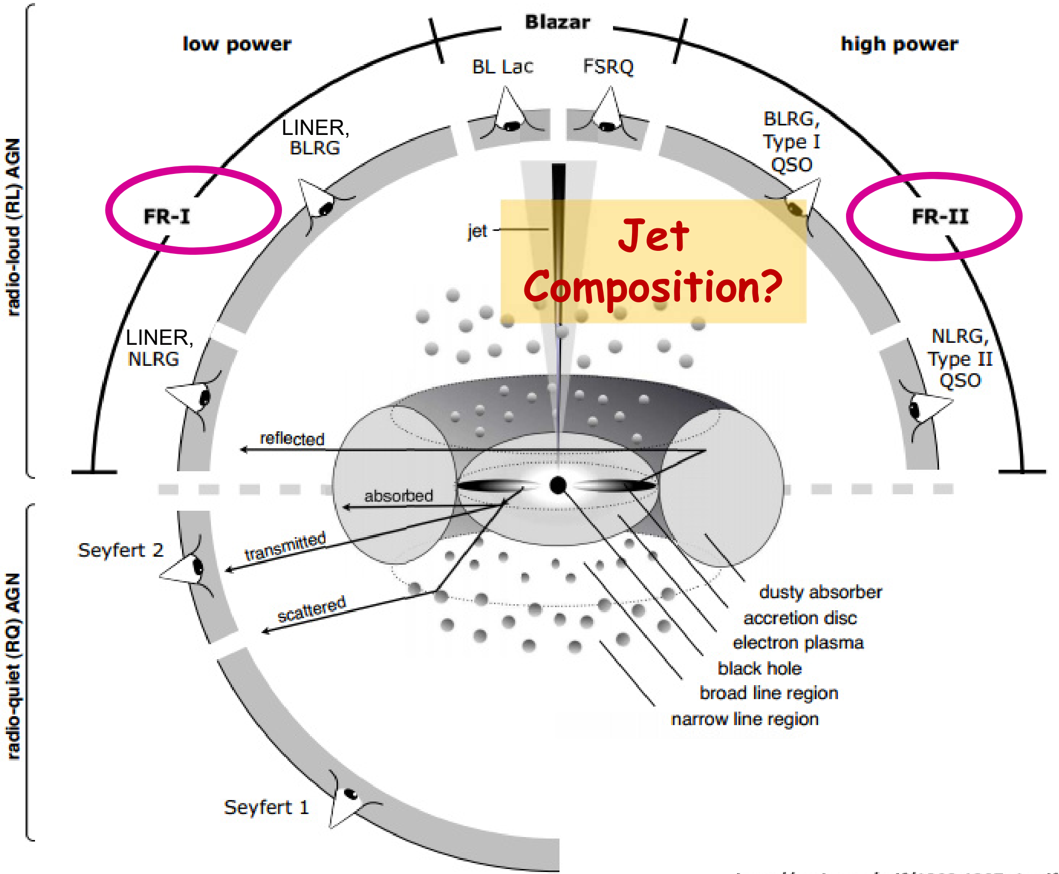
[from: Abdo et al 2011]



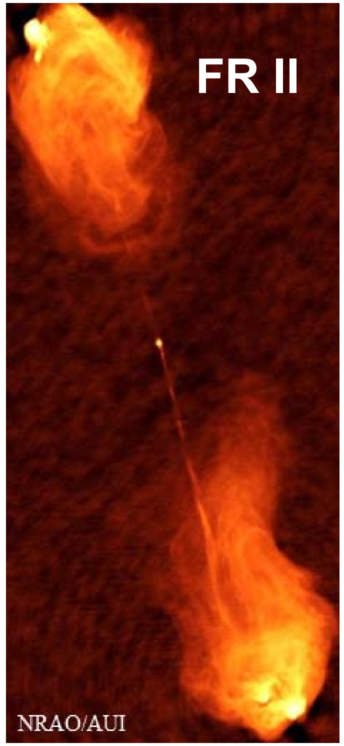
[from: Wehrle et al 2012]

The Zoo of AGN



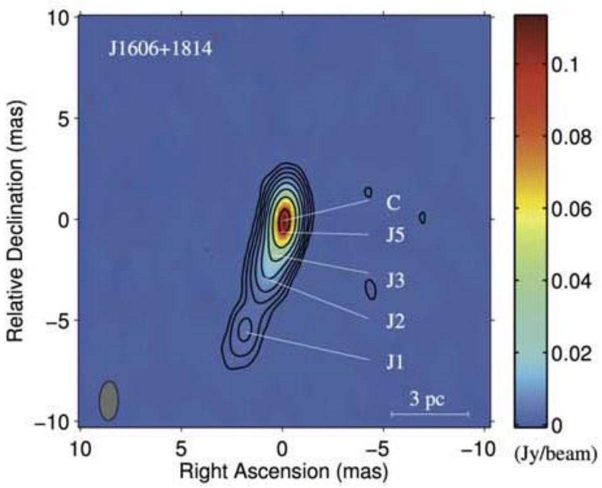


http://arxiv.org/pdf/1302.1397v1.pdf

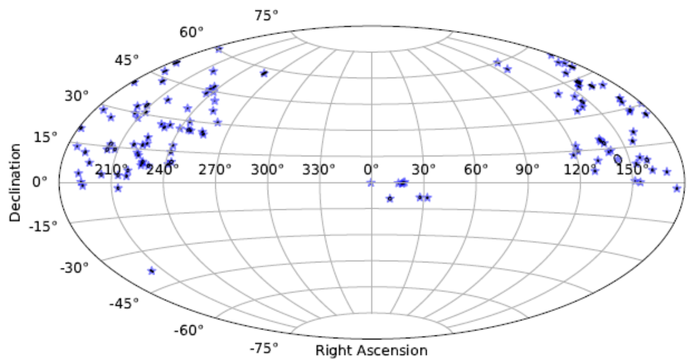


Most numerous jet population in the local Universe

- Fanaroff-Riley 0 (FR0) Radio galaxies -

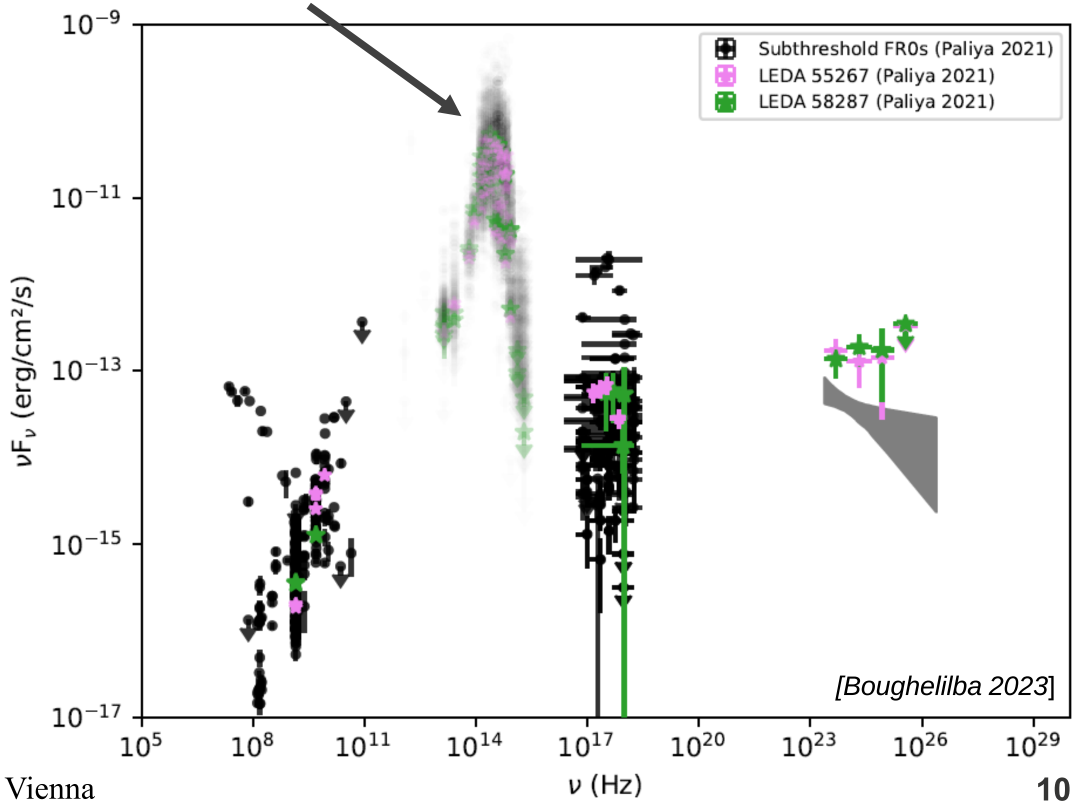


[Cheng etal 2018]



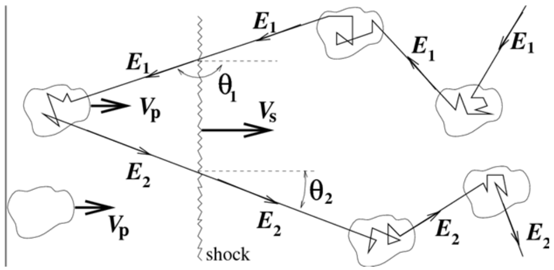
[from: Merten, Boughelilba, AR, etal 2021]

- **Core-dominated, pc ... kpc jets**
- **$L_{jet} \approx 10^{42.5...43.5}$ erg/s** ✓
- **n_{FR0} ~** a few **10^{-4} Mpc^{-3}** ✓
- **Host galaxy: ~$10^{8...9}M_{\odot}$ Ellipticals**



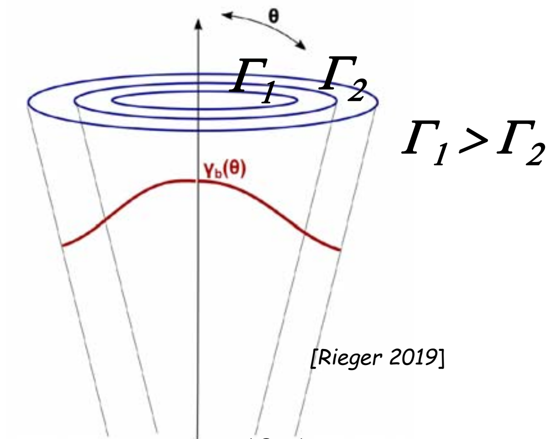
FR0 as UHECR candidate sources

- **Particle acceleration:**

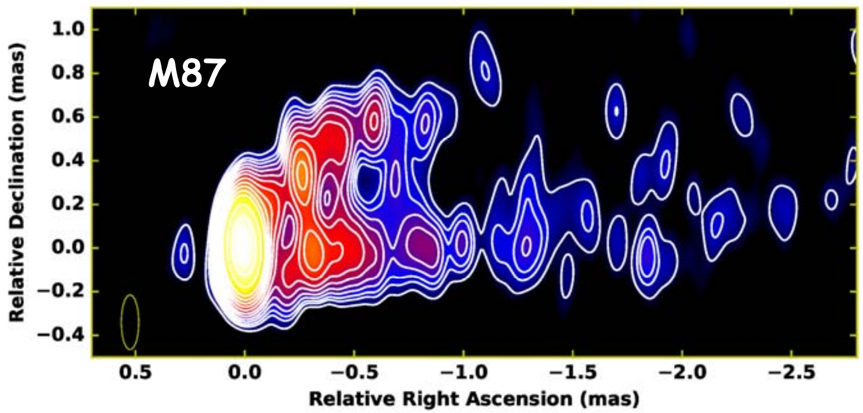


$$\mathcal{R}_{\mathrm{FermiI}}^{\mathrm{Bohm}} \sim \frac{u_s qB}{E}$$

[Merten, Boughelilba, **AR**, et al 2021]



$$\mathcal{R}_{\mathrm{shear}}^{\mathrm{Bohm}} \sim \Gamma^4 \left(\frac{\partial u}{\partial r}\right)^2 \frac{E}{Bq}$$

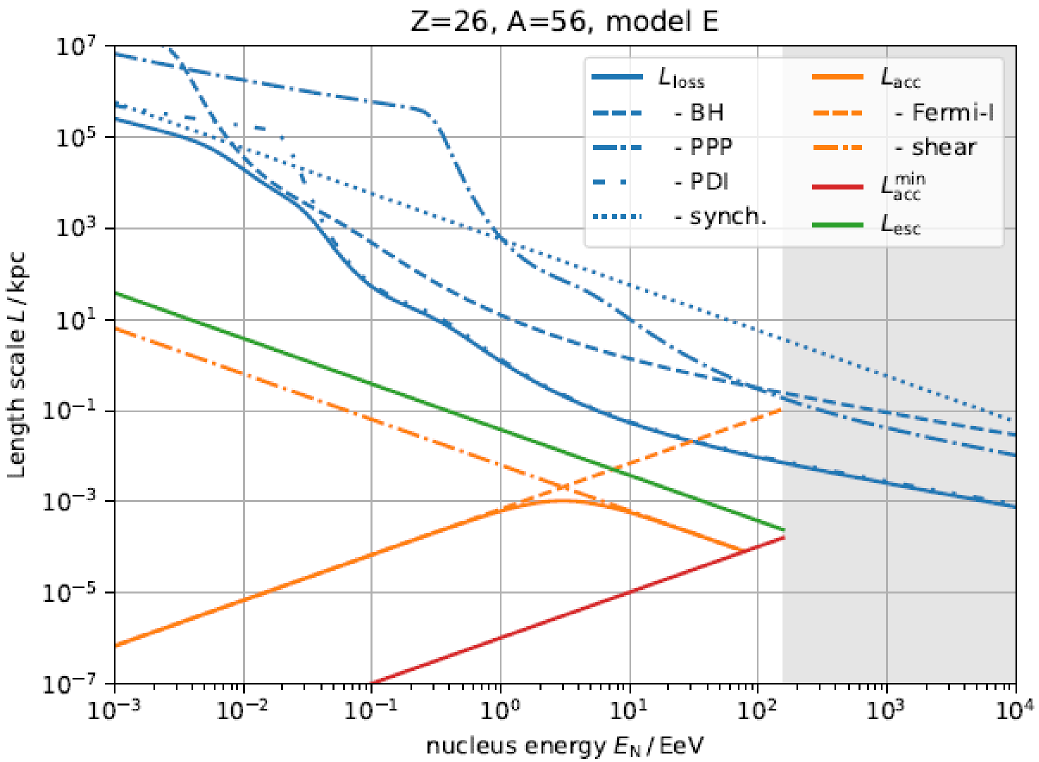


[VLBA+GBT 86 GHz image; from: Hada et al 2016]

FR0 as UHECR candidate sources

- **Particle energy losses:**

Sychrotron radiation; Photo-disintegration, photomeson production, Bethe-Heitler pair production on jet (synchrotron) radiation field



ble 3: Maximum Energy in the jet frame. Here the Bohm diffusion scenario is shown where the e Fermi-I, and the X-2 models use the hybrid approach. The shock speed was fixed at $u_s = 0.1\,c$

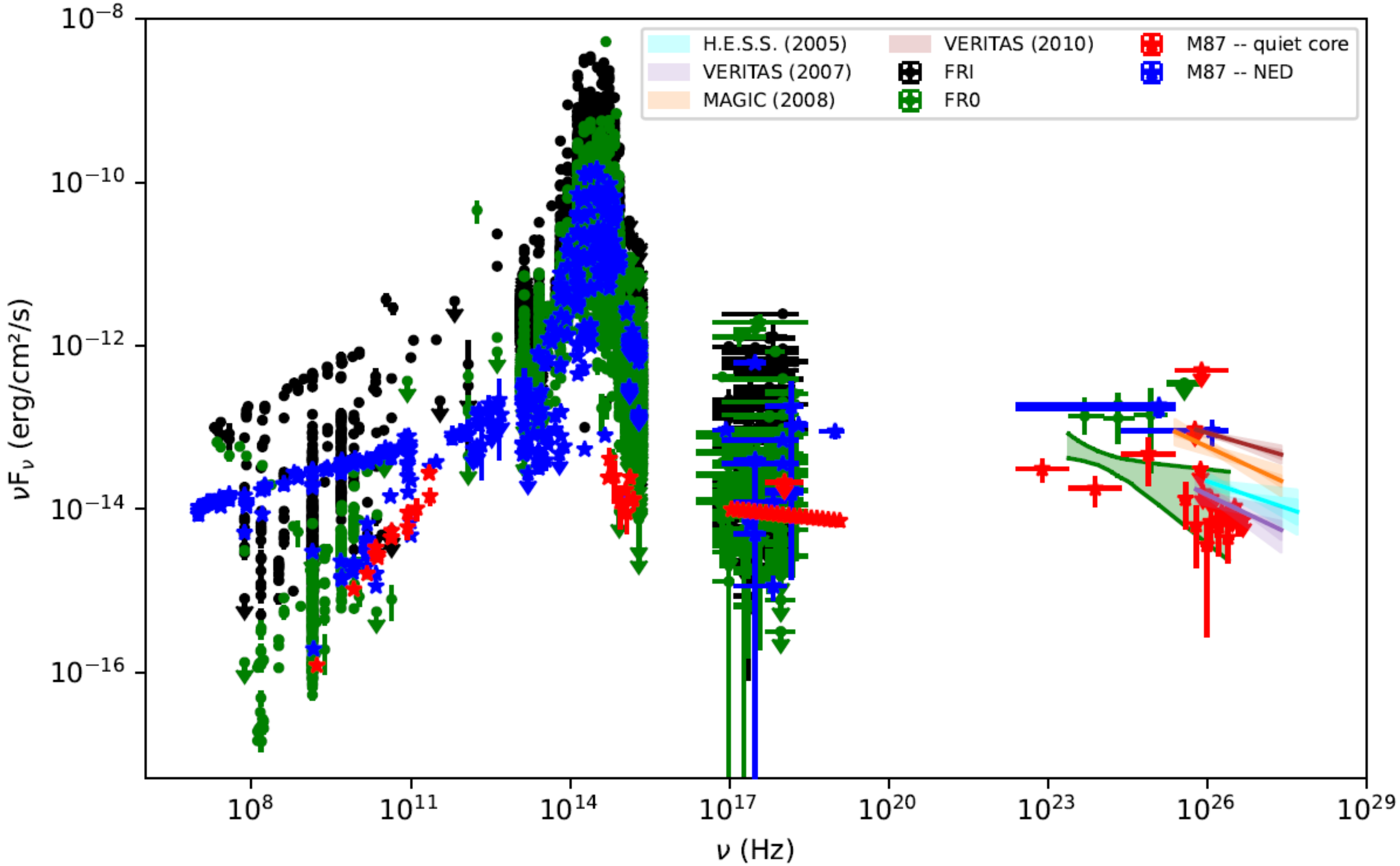
model	$\log_{10}(E'_{max}/\mathrm{eV})$					$\langle\log_{10}(\zeta'_{max}/\mathrm{V})\rangle$
	p	He	N	Si	Fe	
B-1	17.9	18.0	18.4	18.8	19.1	17.70 ± 0.11
C-1	17.1	17.3	17.6	17.9	18.3	16.90 ± 0.14
D-1	17.2	17.4	17.7	18.1	18.4	17.02 ± 0.12
E-1	17.4	17.8	18.3	18.6	18.8	17.44 ± 0.04
F-1	17.4	17.7	18.2	18.5	18.8	17.38 ± 0.02
B-2	19.2	19.5	20.0	20.3	20.6	19.18 ± 0.02
C-2	18.5	18.7	17.8	19.4	19.7	18.08 ± 0.57
D-2	17.2	17.4	17.8	18.1	18.4	17.04 ± 0.10
E-2	18.8	19.1	19.6	19.9	20.2	18.78 ± 0.02
F-2	17.6	17.9	18.3	18.7	18.9	17.54 ± 0.06

$\zeta = E/q$ is the rigidity of the particle in units of volt.

√

*[Merten, Boughelilba, **AR**, et al 2021]*

Broadband SED of low-power radio galaxies

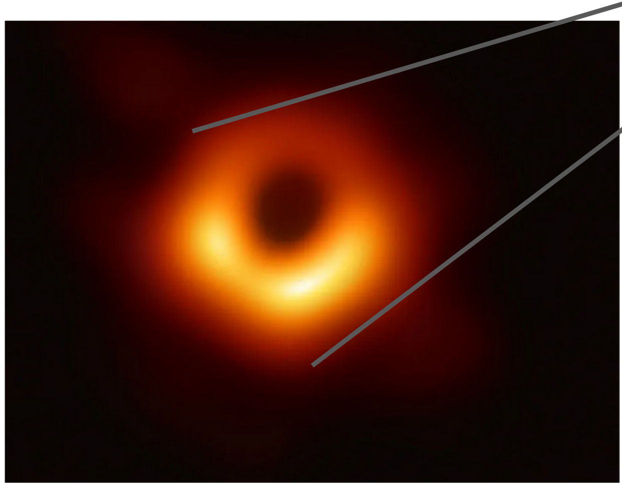


[Boughelilba & AR, 2023]

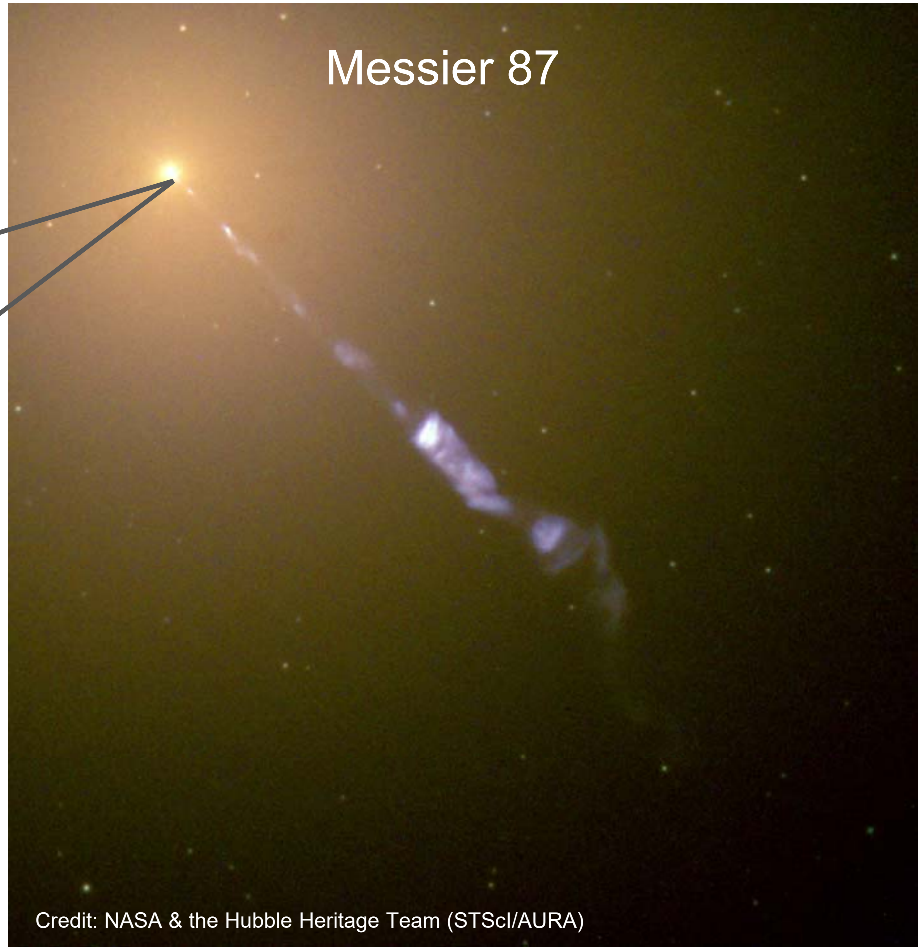
Striking similarity of broadband photon emission between

quiet core M87 (FR1) & typical **FR0 core!**

Low-luminosity AGN as UHECR-sources: FR1 core



[Credit: EHT-collab.]

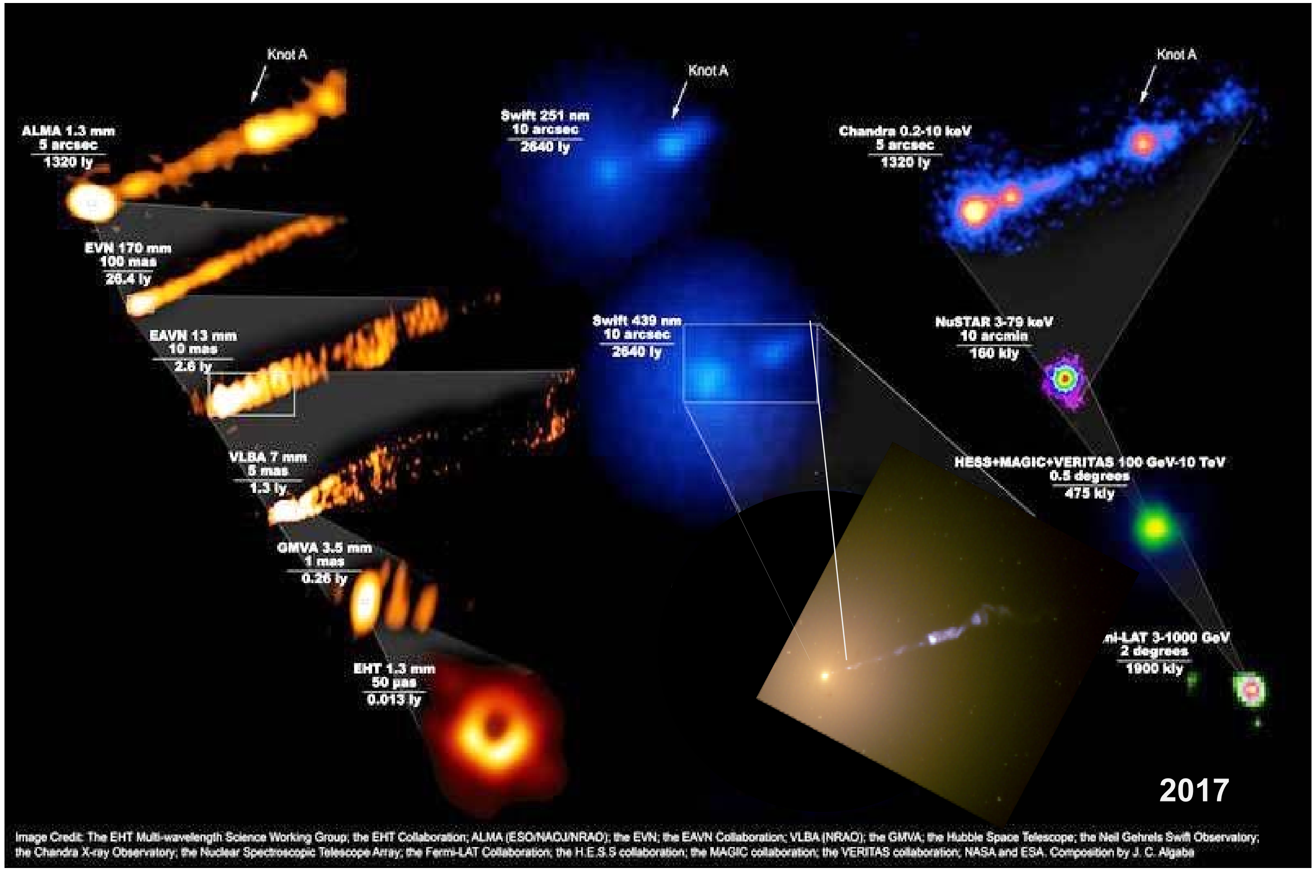


The quiescent multiwavelength view of M87

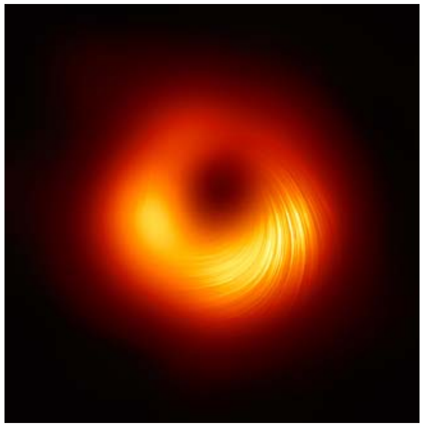
Estimate of **magnetic field strength** from SSA-turnover**:**

B ~ 5 ... 60 G

[EHT-collab. '21]



[EHT-, **HESS-, LAT-**, MAGIC-, VERITAS-, ...collab, 2021]



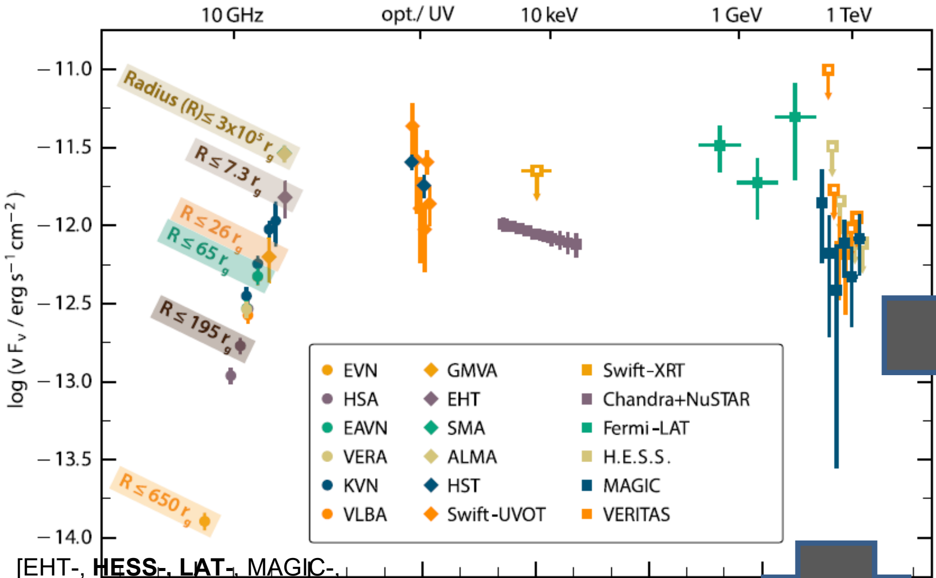
[Credit: EHT-collab.]

.... & polarimetric measurements**:**

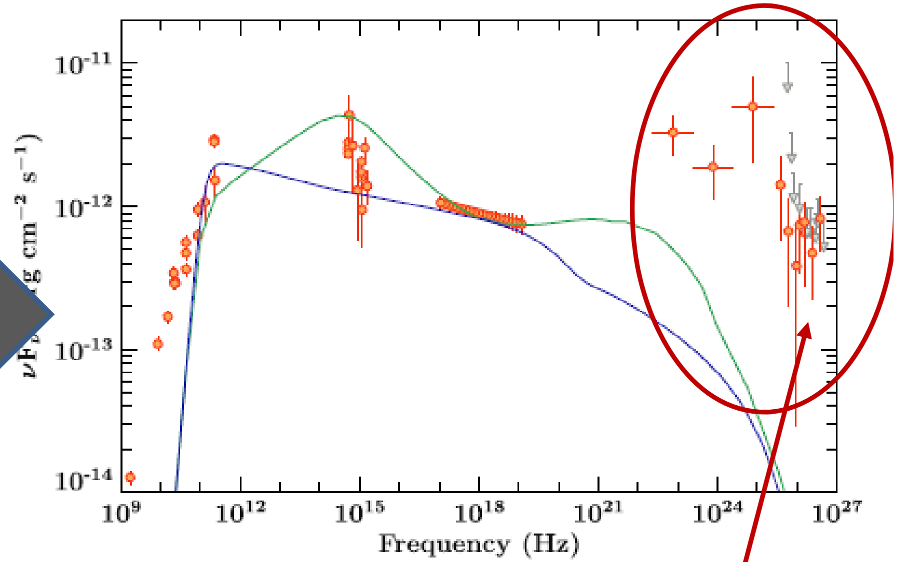
B ~ 7 ... 30 G

[EHT-collab. '23]

The quiescent core of M87

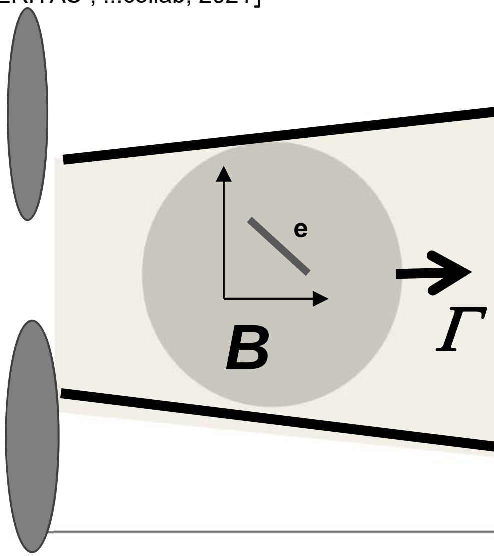


[EHT-, **HESS-, LAT-**, MAGIC-, VERITAS-, ...collab, 2021]



γ-ray emission <u>not</u> from core!

[EHT-collab., etal 2021]



$$\partial_t F_e + \dot{F}_e^{esc} + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss}F_e)] = Q_e^{inj} + \dot{F}_e^{\gamma\gamma}$$

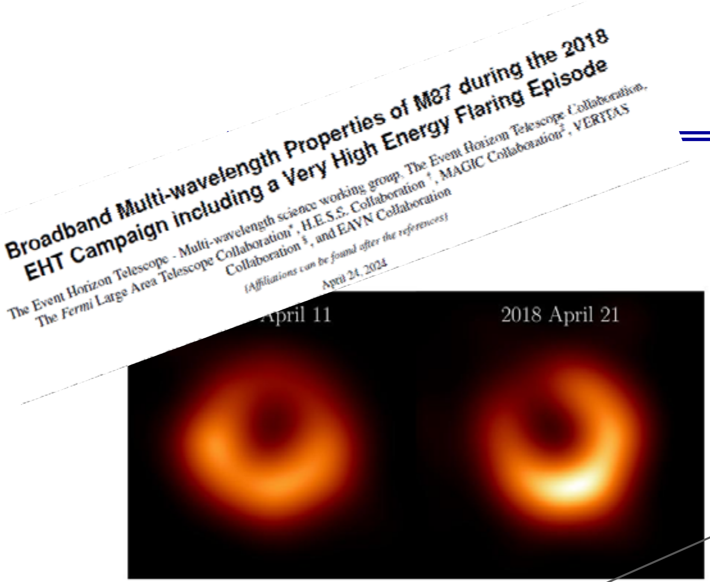
$$\partial_t F_\gamma + \dot{F}_\gamma^{esc} + \dot{F}_\gamma^{\gamma\gamma} = \dot{F}_\gamma^{em}$$

$$\text{with } F_e = F_e(p,t), \quad Q_e^{inj} = Q_e^{inj}(p,t)$$

$$\dot{p}_{loss} = \dot{p}_{loss}(F_\gamma(\epsilon,t), B(t); p, t), \quad \dot{F}_e^{\gamma\gamma} = \dot{F}_e^{\gamma\gamma}(F_\gamma(\epsilon,t); p, t)$$

$$F_\gamma = F_\gamma(\epsilon,t), \quad \dot{F}_\gamma^{\gamma\gamma} = \dot{F}_\gamma^{\gamma\gamma}(F_\gamma(\epsilon,t); \epsilon, t)$$

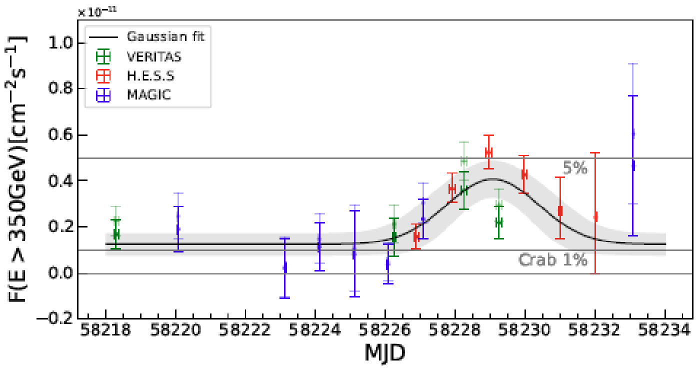
The flaring core of M87

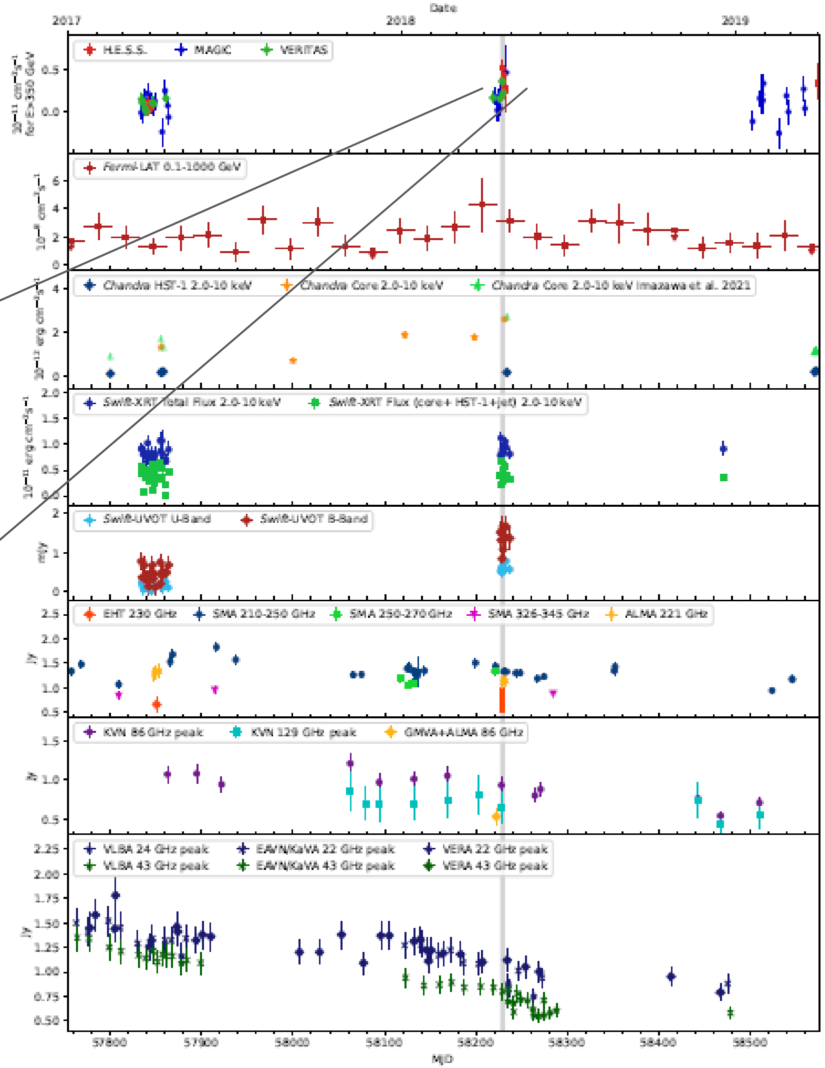

Broadband Multi-wavelength Properties of M87 during the 2018 EHT Campaign including a Very High Energy Flaring Episode

The Event Horizon Telescope - Multi-wavelength science working group, The Event Horizon Telescope Collaboration, The Fermi Large Area Telescope Collaboration, H.E.S.S. Collaboration, MAGIC Collaboration, VERITAS Collaboration, and EAVN Collaboration

(Affiliations can be found after the references)

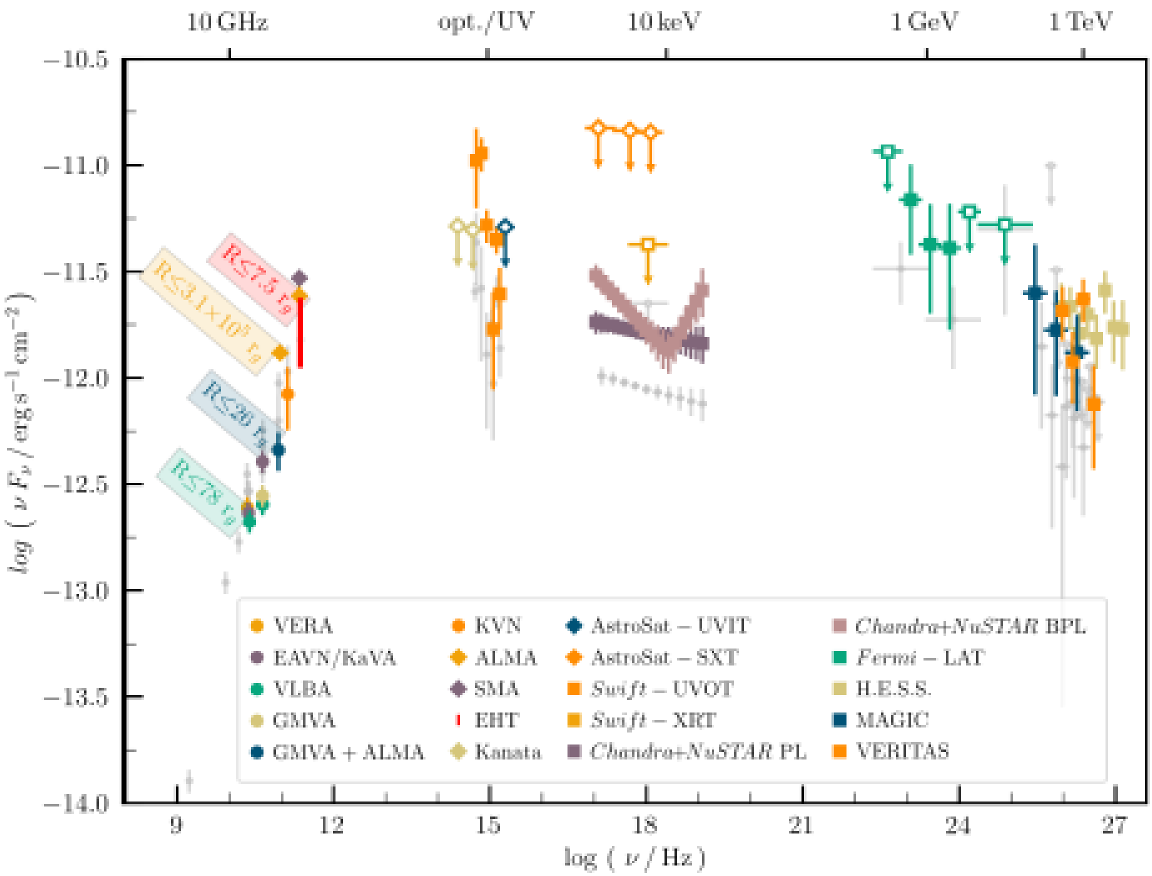
April 24, 2024





[EHT-, **HESS-, LAT-**, MAGIC-, VERITAS-, ...collab, 2024]

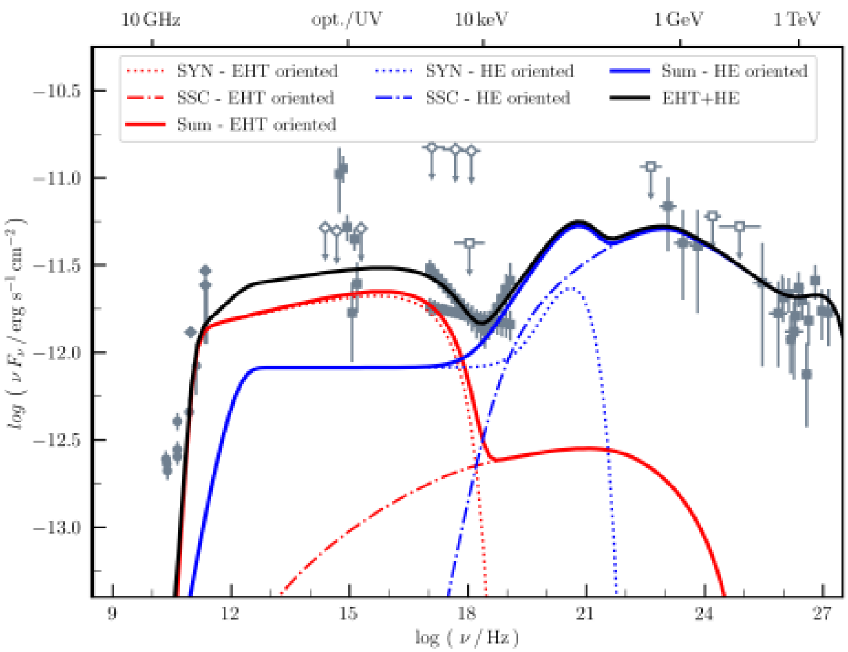
The flaring core of M87 in 2018

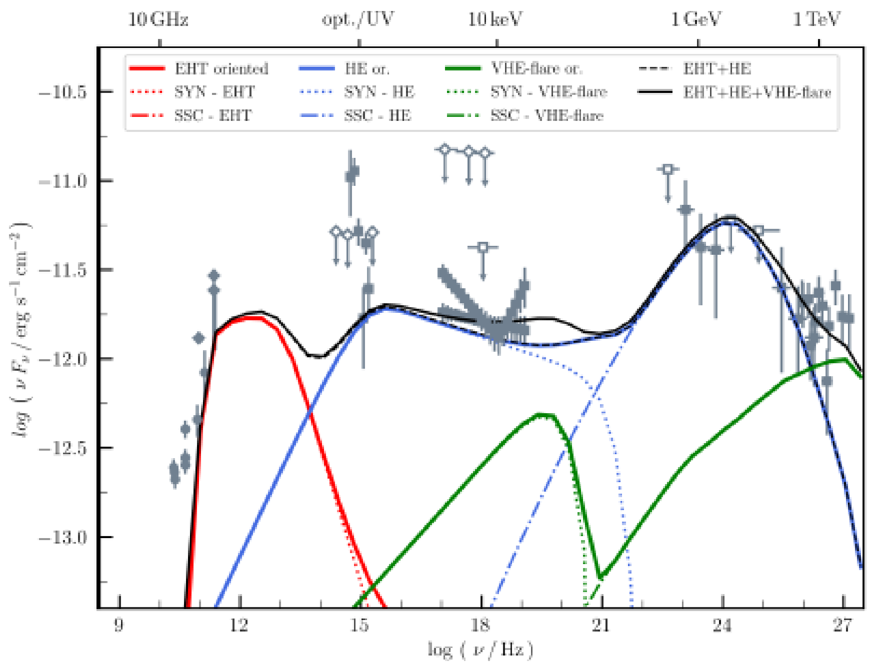


[EHT-, **HESS-, LAT-**, MAGIC-, VERITAS-, ...collab, 2024]

Similar radio-to-optical SED, increased X-ray fluxes, harder & increased GeV-VHE-emission

The flaring core of M87

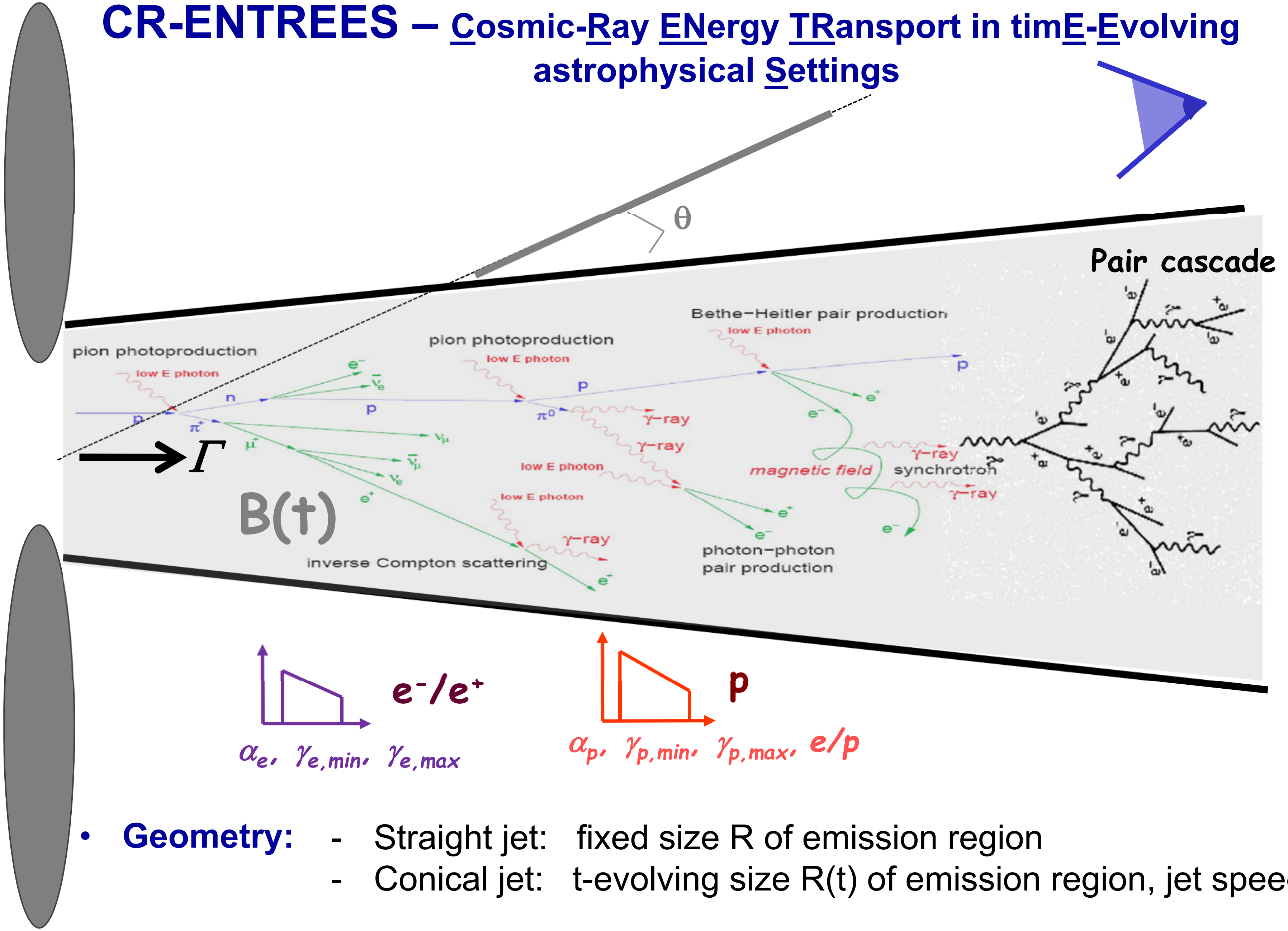




[EHT-, **HESS-, LAT-**, MAGIC-, VERITAS-, ...collab, 2024]

Emission from **2-to-3-zones required** to depict broadband SED within a **purely leptonic emission model**

CR-ENTREES – Cosmic-Ray ENergy TRansport in timE-Evolving astrophysical Settings



- **Geometry:**
  - Straight jet: fixed size R of emission region
  - Conical jet: t-evolving size R(t) of emission region, jet speed v_J

→ **Evolution of environment fully treated: R(t), B(t), u_{rad}(t), ...**

CR-ENTREES – Cosmic-Ray ENergy TRansport in timE-Evolving astrophysical Settings

$$\partial_t F_N + \dot{F}_N^{esc} + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss}F_N)] + \dot{F}_N^{dec} = Q_N^{inj,pr}$$

$$\partial_t F_{\mu,\pi} + \dot{F}_{\mu,\pi}^{esc} + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss}F_{\mu,\pi})] + \dot{F}_{\mu,\pi}^{dec} = \dot{F}_{\mu,\pi}^{p\gamma;h}$$

$$\partial_t F_e + \dot{F}_e^{esc} + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss}F_e)] = Q_e^{inj,pr} + \dot{F}_e^{\gamma\gamma} + \dot{F}_e^{p\gamma}$$

$$\partial_t F_\gamma + \dot{F}_\gamma^{esc} + \dot{F}_\gamma^{\gamma\gamma} = \dot{F}_\gamma^{em} + \dot{F}_\gamma^{p\gamma;h}$$

$$\text{with } F_{particle} = F_{particle}(p,t),\quad Q_{N,e}^{inj,pr} = Q_{N,e}^{inj,pr}(p,t),\quad \dot{p}_{loss} = \dot{p}_{loss}(F_\gamma(\epsilon,t), B(t); p, t)$$

$$\dot{F}_e^{p\gamma} = \dot{F}_e^{p\gamma}(F_\gamma(\epsilon,t); p, t),\quad \dot{F}_e^{\gamma\gamma} = \dot{F}_e^{\gamma\gamma}(F_\gamma(\epsilon,t); p, t)$$

$$F_\gamma = F_\gamma(\epsilon,t),\quad \dot{F}_\gamma^{\gamma\gamma} = \dot{F}_\gamma^{\gamma\gamma}(F_\gamma(\epsilon,t);\epsilon,t),\quad \dot{F}_\gamma^{p\gamma} = \dot{F}_\gamma^{p\gamma}(F_\gamma(\epsilon,t);\epsilon,t)$$

- **Primary particle injection & tracking: γ, p, n, e, π, μ, K, ν_μ, ν_e**
  - Impulsive or continuous; normalized via $U_B/U_{particles}$
- **Secondary particles:**
  - Yields pre-calculated by corresponding event generators

CR-ENTREES – Cosmic-Ray ENergy TRansport in timE-Evolving astrophysical Settings

- **Particle interactions & losses:**

  Photomeson production, Bethe-Heitler pair production, decay of unstable particles, $\gamma\gamma$-pair production, inverse Compton scattering, synchrotron radiation, particle/photon escape, adiabatic losses.

- **Target photon field:**

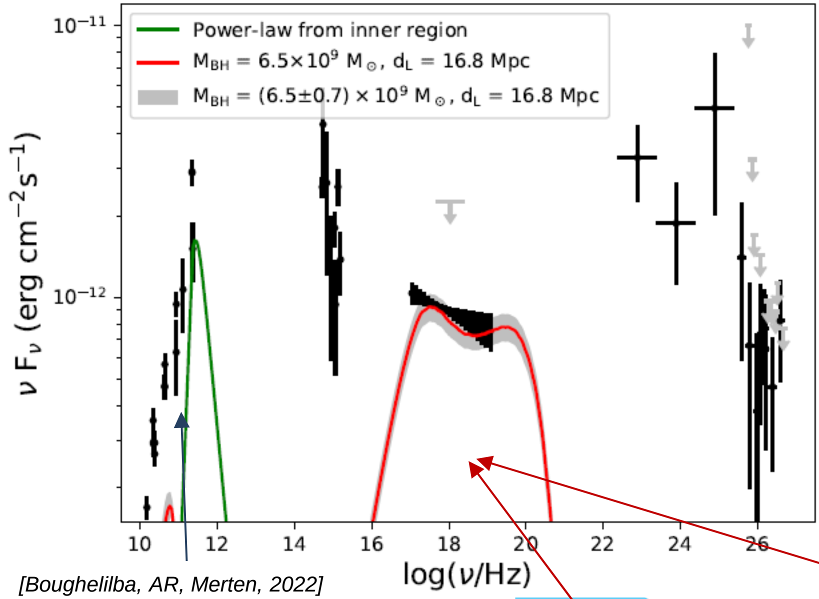
  - Pre-defined or custom-filled radiation field for each energy bin (-> EBL, etc)
  - Determination of internal radiation field after each time step **-> non-linearities**

- **Particle propagation:**

  - fixed energy grid
  - Matrix multiplication/doubling method [Protheroe '86; Protheroe & Stanev '93, Protheroe & Johnson '96] -> calculates transfer matrices
  - Energy conservation checked in each time step

→ fast, modular propagation code for radiation-dominated CR-sources

Hadronic Jet-Disc Model for M87



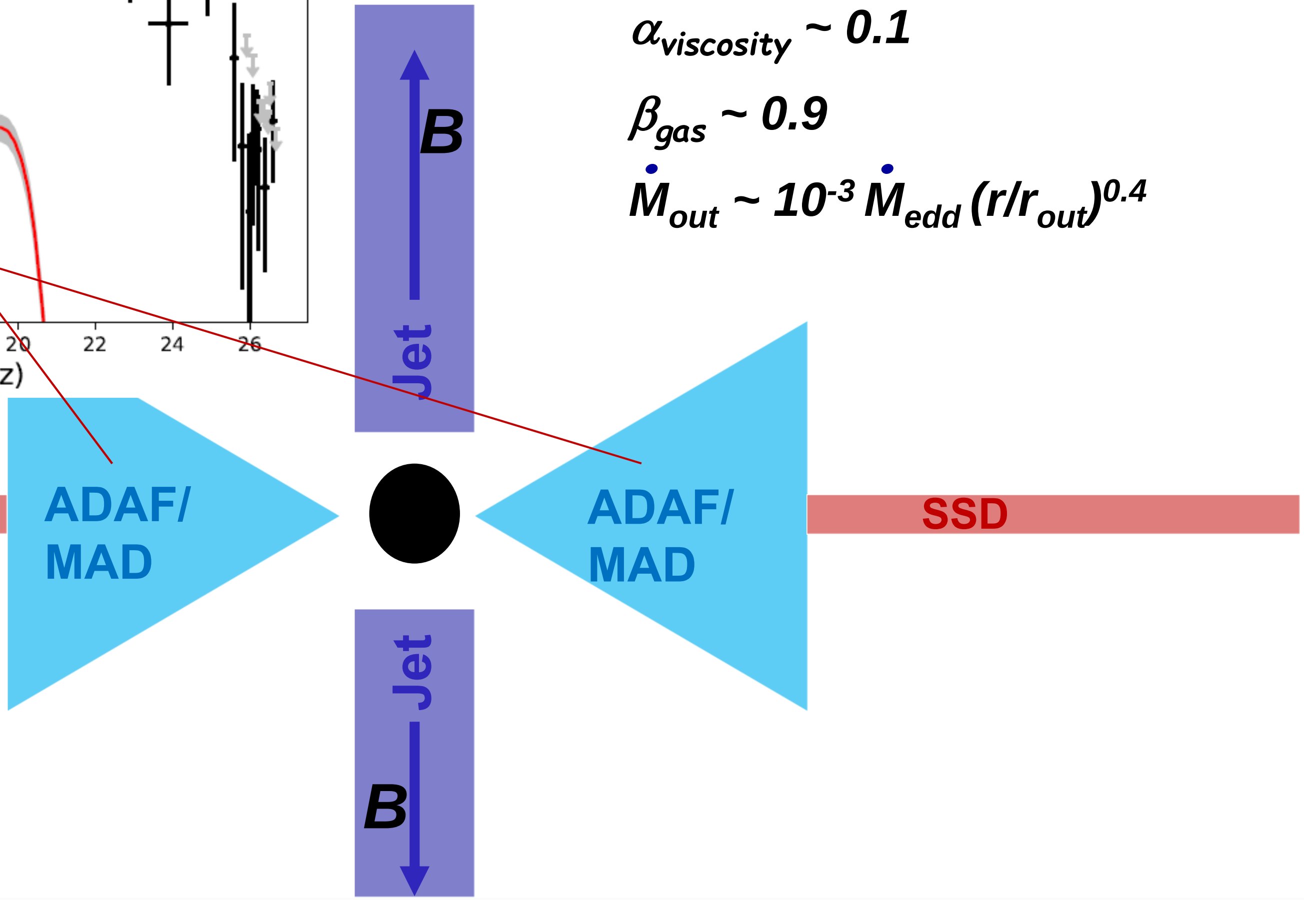
[Boughelilba, AR, Merten, 2022]

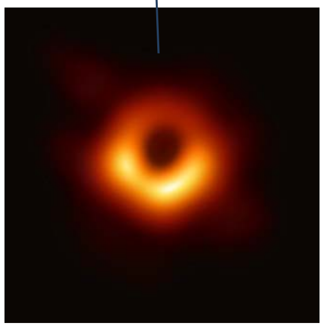
ADAF parameters *(beyond sonic point)*:

$\alpha_{viscosity} \sim 0.1$

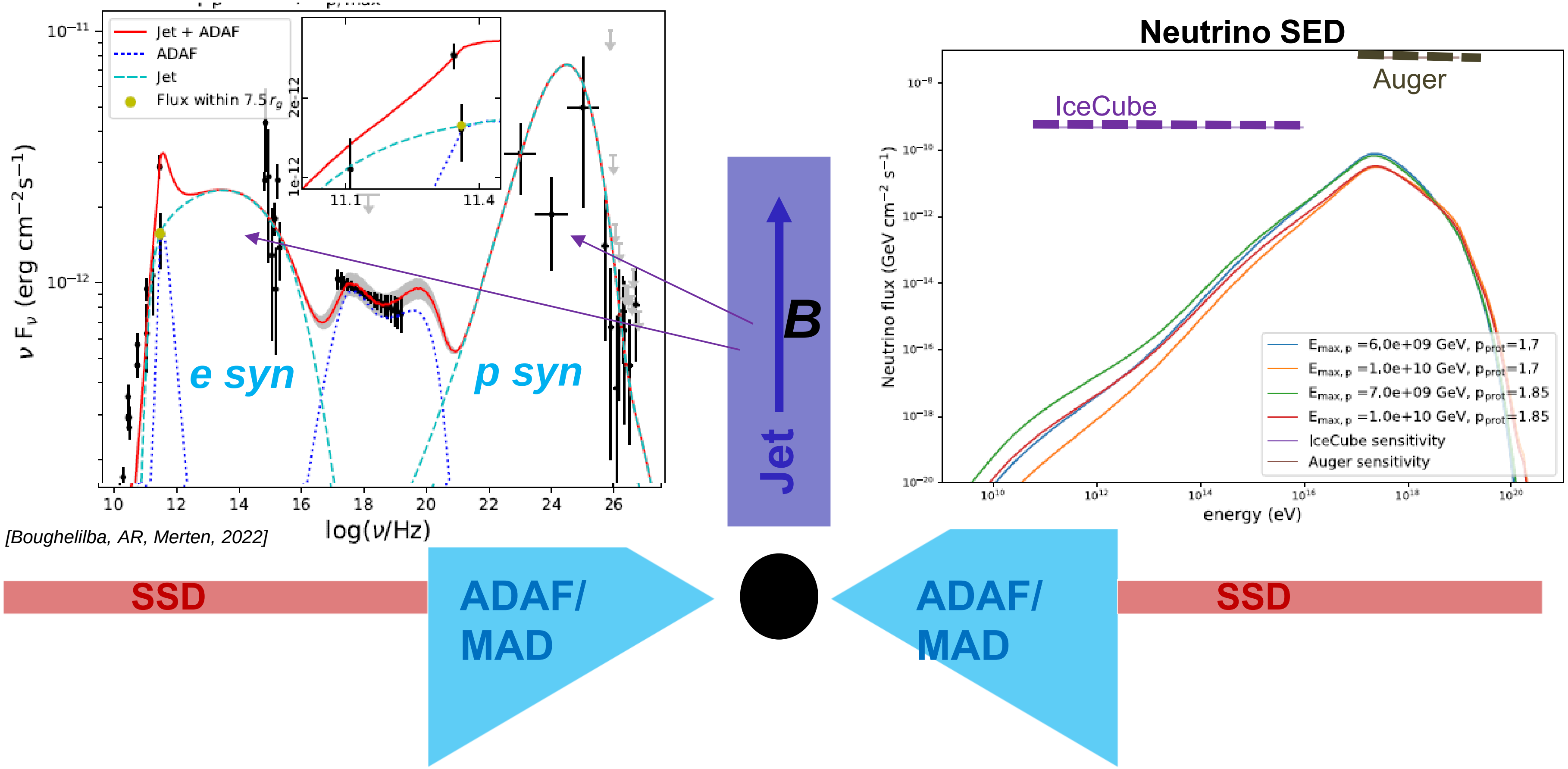
$\beta_{gas} \sim 0.9$

$\dot{M}_{out} \sim 10^{-3}\,\dot{M}_{edd}\,(r/r_{out})^{0.4}$



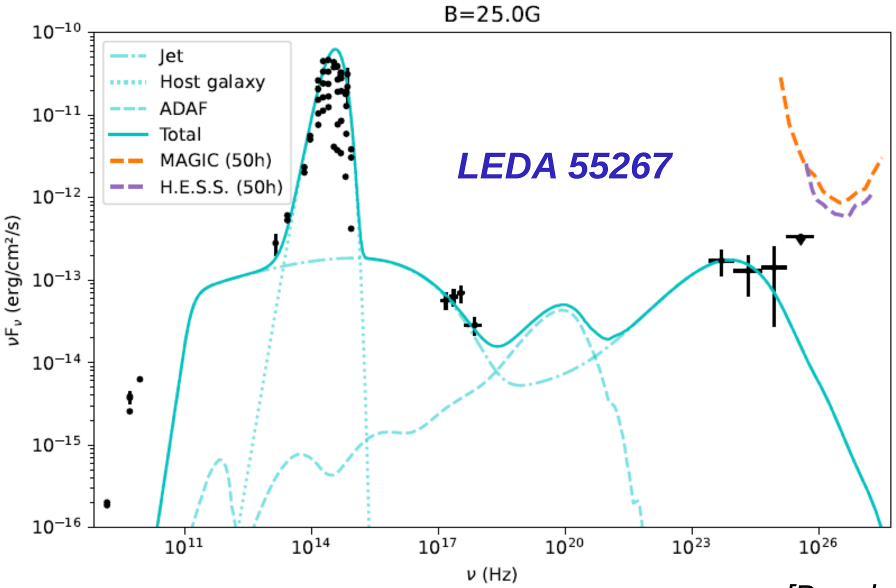


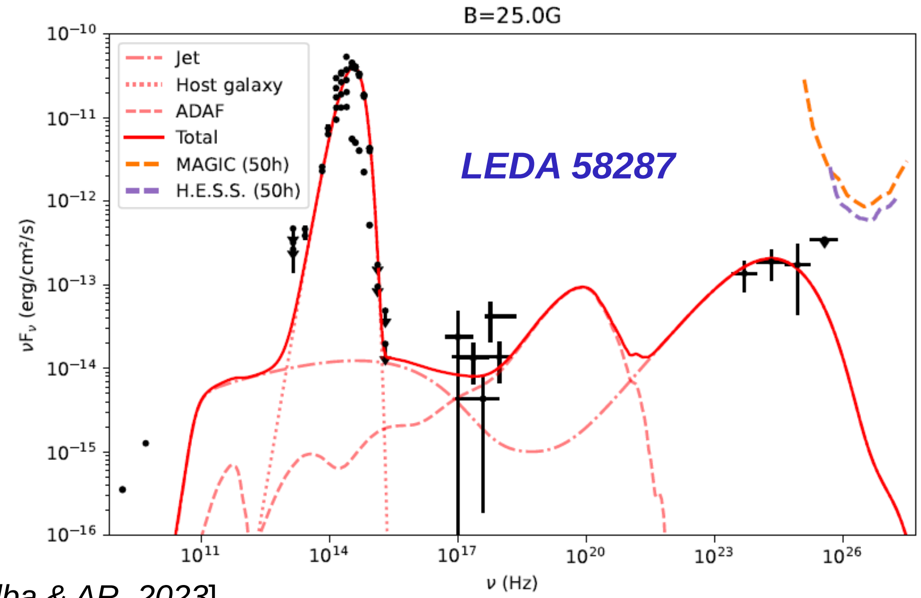
Hadronic Jet-Disc Model for M87



- M87 as ***relativistic proton+electron jet – disc system***
- ***Close-to-equipartition parameters*** *model core SED of M87*
- ***Weak neutrino emitter*** *in IceCube energy range*

Hadronic Jet-Disc model for FR0s





[Boughelilba & AR, 2023]

ADAF parameters:

$\alpha_{viscosity} \sim 0.1$

$\beta_{gas} \sim 0.99$

$\dot{M}_{out} \sim 10^{-3...-4}\, \dot{M}_{edd}\, (r/r_{out})^{0.1}$

Jet parameters:

$R_{em} \sim$ a few 10^{15}cm, $\Gamma_j \sim 1.2$

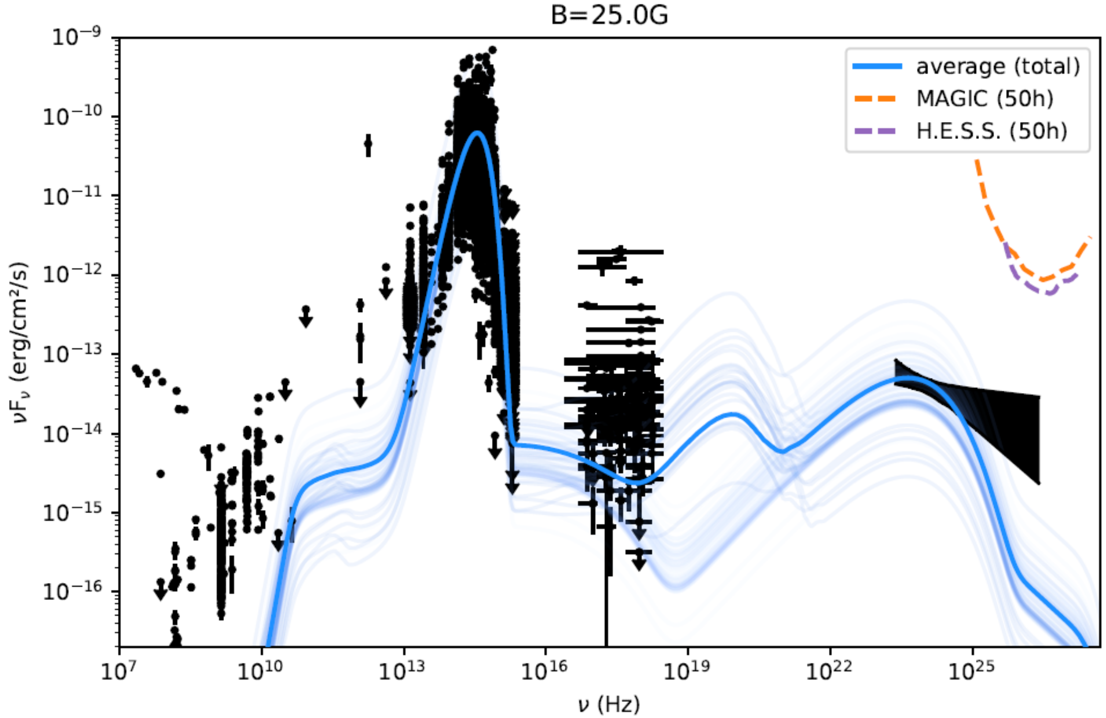
$B \sim 25 - 50$ G

$E_{p,max} \sim$ a few 10^{18} eV, $p_p \sim 1.7 \sim p_e$

$U_{part}/U_B \sim 0.04 ... 0.5$, $P_{jet} < 2\ 10^{43}$ erg/s

-> Slow, strongly magnetized jet containing CR-p reaching a few EeV

Hadronic Jet-Disc model for FR0 population

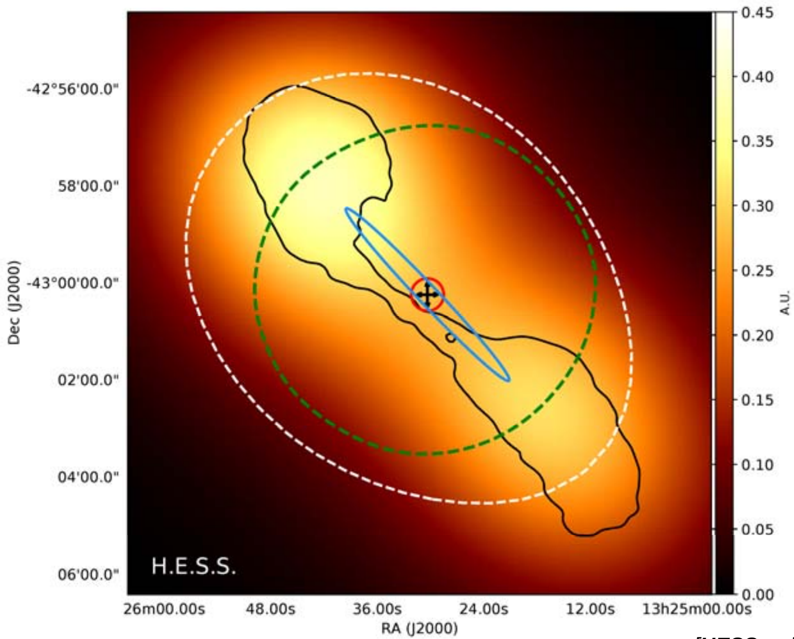


[Boughelilba & AR, 2023]

- *FR0s as **relativistic proton+electron jet – ADAF system***
- ***Close-to-equipartition parameters** model core SED of FR0s*
- *Can potentially contribute significantly to **UHECR-flux** up to **a few 10^{18}eV***
- ***Weak neutrino emitter** $\leq 10^{-13}$ GeV cm^{-2} s^{-1} ($E_{\nu,peak} \sim 0.1...1$ EeV)*
- ***Distinct signature of ADAF emission predicted in MeV-band***

Cosmic rays in extended jets of AGN

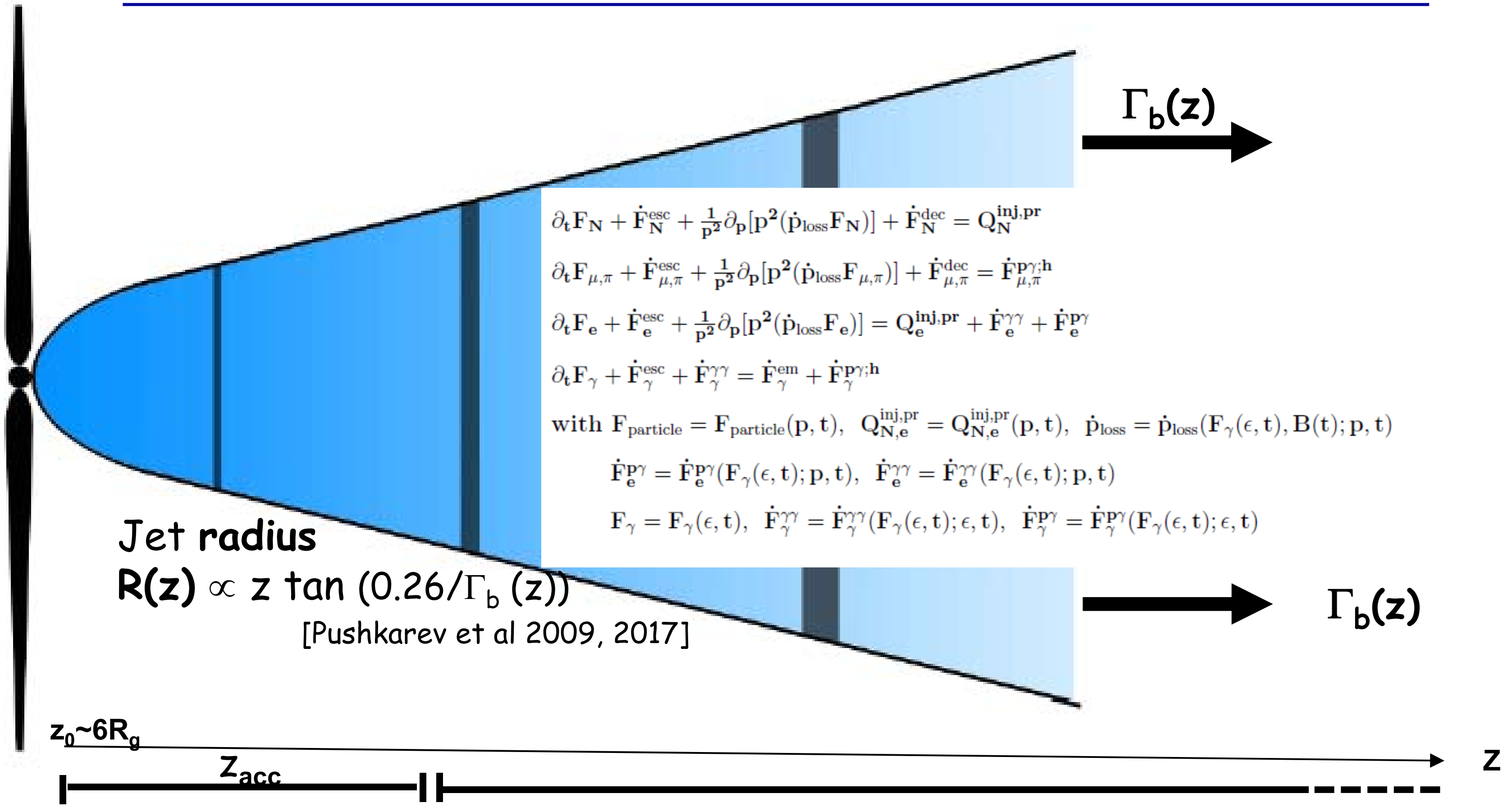
kpc-jet of Centaurus A



*[**HESS-collab.**, 2020, Science]*

Gamma rays up to TeVs from extended jets!

Extended hadronic jet emission model



$$\partial_t F_N + \dot{F}_N^{esc} + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss}F_N)] + \dot{F}_N^{dec} = Q_N^{inj,pr}$$

$$\partial_t F_{\mu,\pi} + \dot{F}_{\mu,\pi}^{esc} + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss}F_{\mu,\pi})] + \dot{F}_{\mu,\pi}^{dec} = \dot{F}_{\mu,\pi}^{p\gamma;h}$$

$$\partial_t F_e + \dot{F}_e^{esc} + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss}F_e)] = Q_e^{inj,pr} + \dot{F}_e^{\gamma\gamma} + \dot{F}_e^{p\gamma}$$

$$\partial_t F_\gamma + \dot{F}_\gamma^{esc} + \dot{F}_\gamma^{\gamma\gamma} = \dot{F}_\gamma^{em} + \dot{F}_\gamma^{p\gamma;h}$$

$$\text{with } F_{particle} = F_{particle}(p,t),\ \ Q_{N,e}^{inj,pr} = Q_{N,e}^{inj,pr}(p,t),\ \ \dot{p}_{loss} = \dot{p}_{loss}(F_\gamma(\epsilon,t), B(t); p, t)$$

$$\dot{F}_e^{p\gamma} = \dot{F}_e^{p\gamma}(F_\gamma(\epsilon,t); p, t),\ \ \dot{F}_e^{\gamma\gamma} = \dot{F}_e^{\gamma\gamma}(F_\gamma(\epsilon,t); p, t)$$

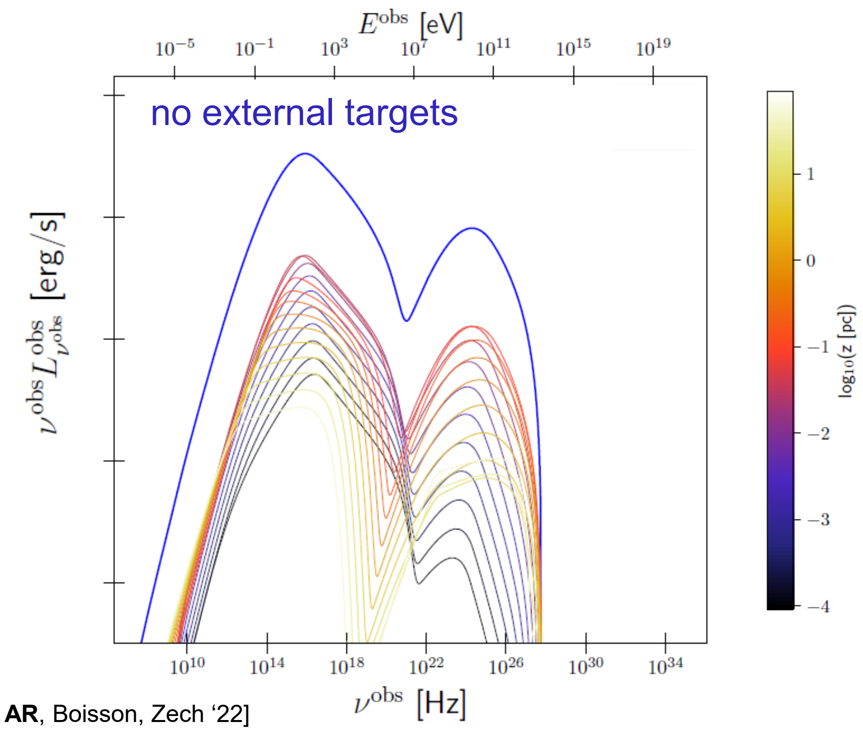
$$F_\gamma = F_\gamma(\epsilon,t),\ \ \dot{F}_\gamma^{\gamma\gamma} = \dot{F}_\gamma^{\gamma\gamma}(F_\gamma(\epsilon,t); \epsilon, t),\ \ \dot{F}_\gamma^{p\gamma} = \dot{F}_\gamma^{p\gamma}(F_\gamma(\epsilon,t); \epsilon, t)$$

[Zacharias, **AR**, Boisson, Zech, 2022]

Poynting flux dominated parabolic bulk **acceleration zone**: $\Gamma_b(z) \sim \sqrt{z}$

Conical **coasting zone**: $\Gamma_b \sim$ const

Extended hadronic jet emission model



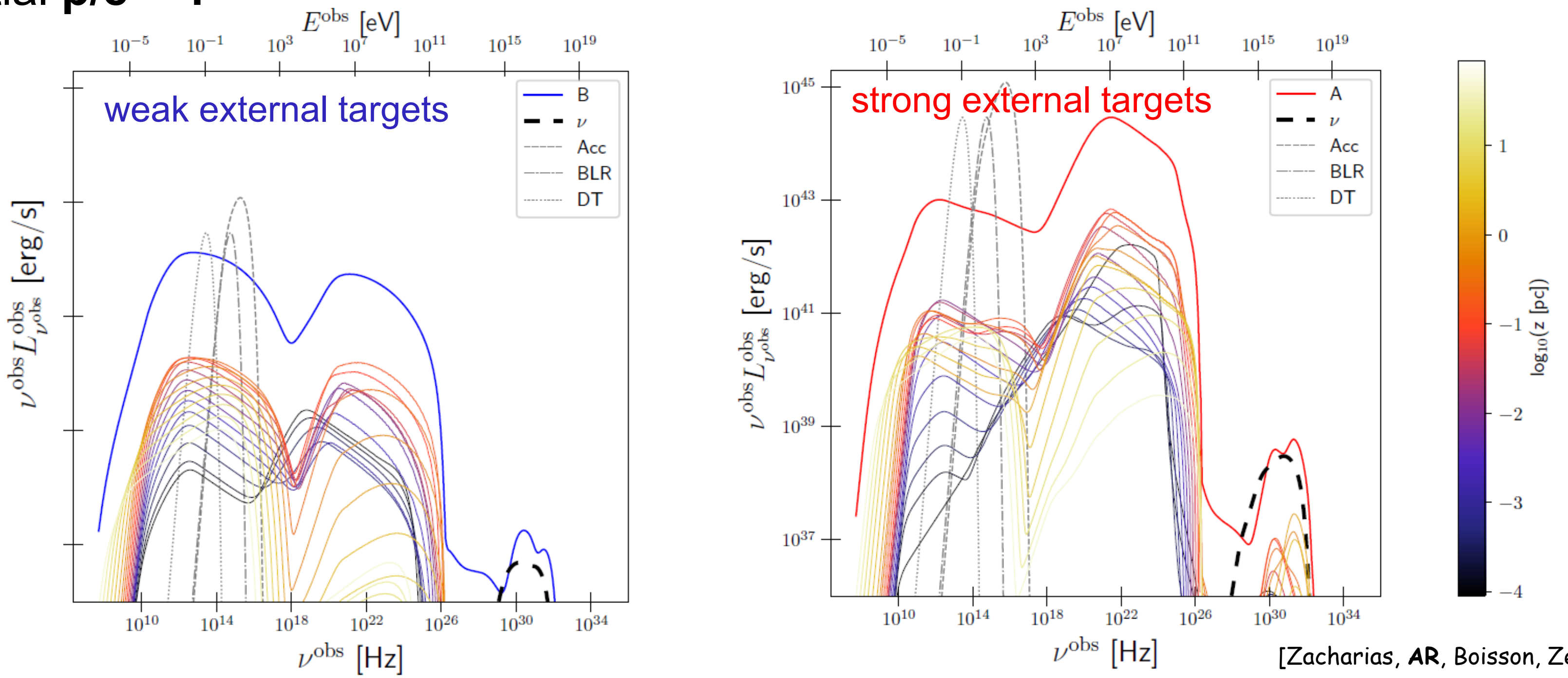
[Zacharias, **AR**, Boisson, Zech '22]

- Initial proton-to-electron (**p/e**) ratio = $\mathbf{10^{-10}}$

- Photon spectra dominated by **radiation from pairs** (**synchr., SSC**)
- γ-ray emission drops faster than radio-to-X-ray emission along the jet

Extended hadronic jet emission model

- Initial **p/e = 1**



[Zacharias, **AR**, Boisson, Zech '22]

- Notable γ-ray production (dominated by radiation from pairs) all **along the jet**
- **Relativistic protons** responsible for appreciable **pair injection along the jet**

Concluding Remarks

- **AGN jets** as **particle multi-messenger** (γ, ν, CR) sources

- Sources of the hadronic UHECRs likely require different environment as compared to bright γ-/ν-source

-> Low-luminosity jetted AGN (FR0, FR1) suitable UHECR sources

(prediction of **close-to-equipartition conditions in core region & MeV-feature in SED of FR0s)**

- Hadronic UHECRs excellent energy carrier along extended jets

-> HE-brightness distribution of extended jets may hold signatures of protonic UHECRs in jets

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