On the low-power extragalactic γ-ray sky

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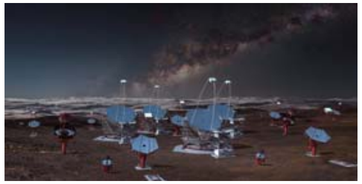
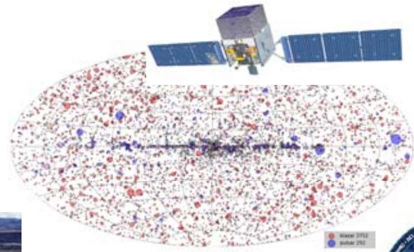
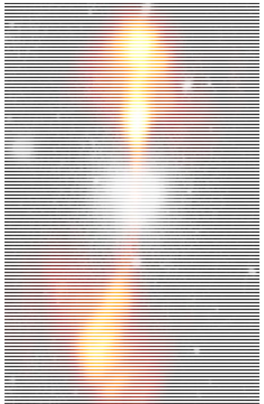
Motivation

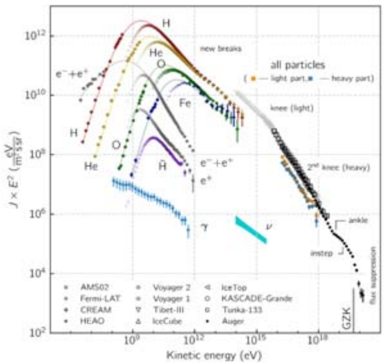




- **Improving sensitivities** of γ-ray **instruments**



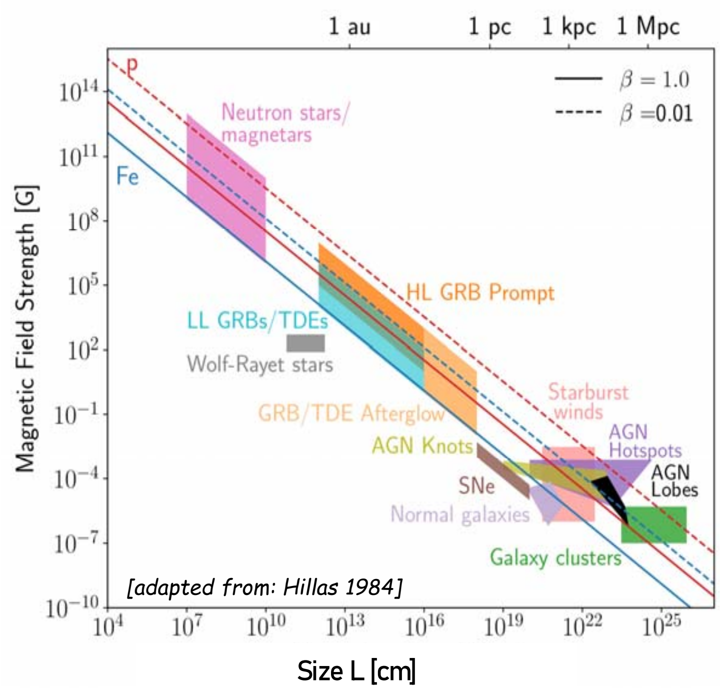
- Mis-aligned view to anisotropically emitting source populations may uncover **deeper insights into the physical workings** of the source systems



[from:: Pfrommer etal 20xx]

- **Low-luminosity sources** potentially significant **contributors to** the observed **cosmic ray (CR) flux**

Requirements on UHECR candidate source populations



- ***"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:***

  $U_{population} \sim 10^{44....45}$ erg $Mpc^{-3} yr^{-1}$ for $E_{CR} \sim 10^{18....20}$ eV

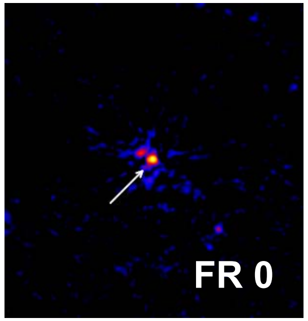
  (within UHECR horizon)

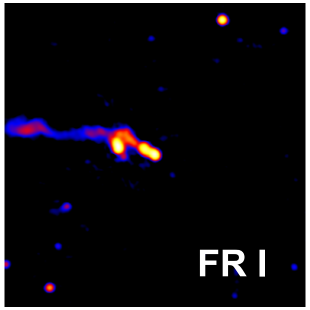
Required population density: $n_{population} \sim 10^{-5\ ...\ -4}$ Mpc^{-3} for $E_{max} \sim Z\ 10^{18}$eV

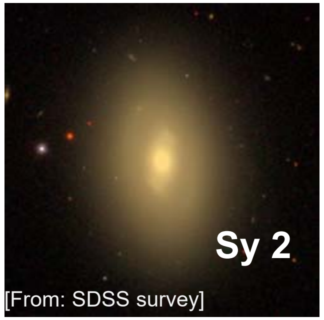
AGN in the local Universe provide the "right" number density

(e.g., blazars, GRBs, Galaxy Clusters too rare)

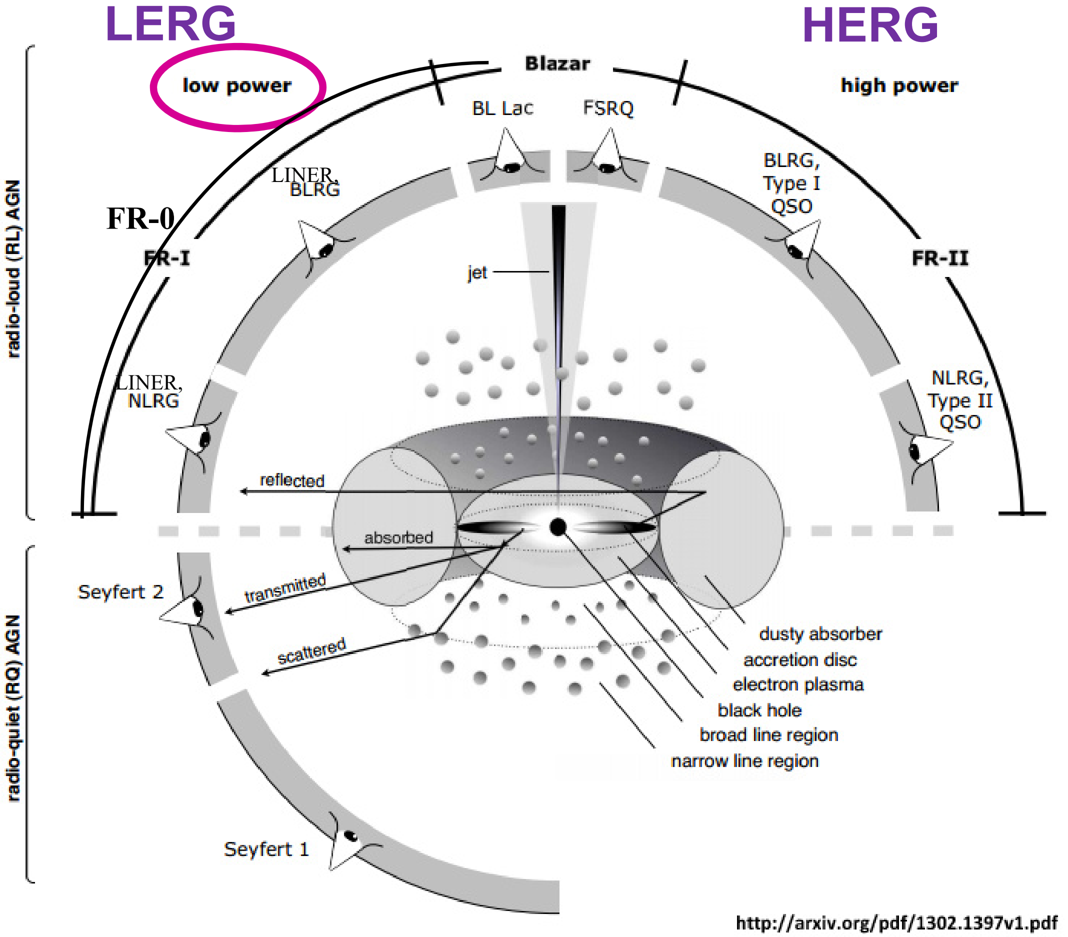
The Zoo of AGN (incomplete)

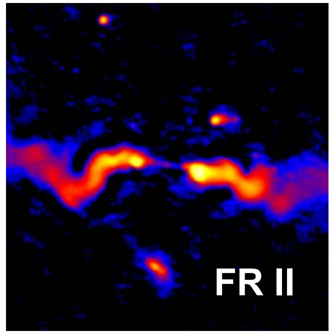






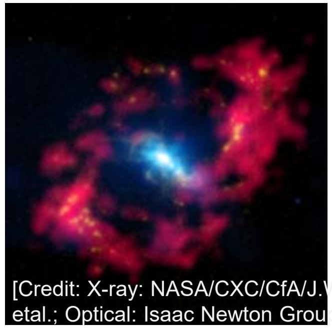
[From: SDSS survey]





Jetted AGN
(mostly Elliptical
hosts except NLSy1)

Non-jetted AGN
(mostly Spiral
hosts)

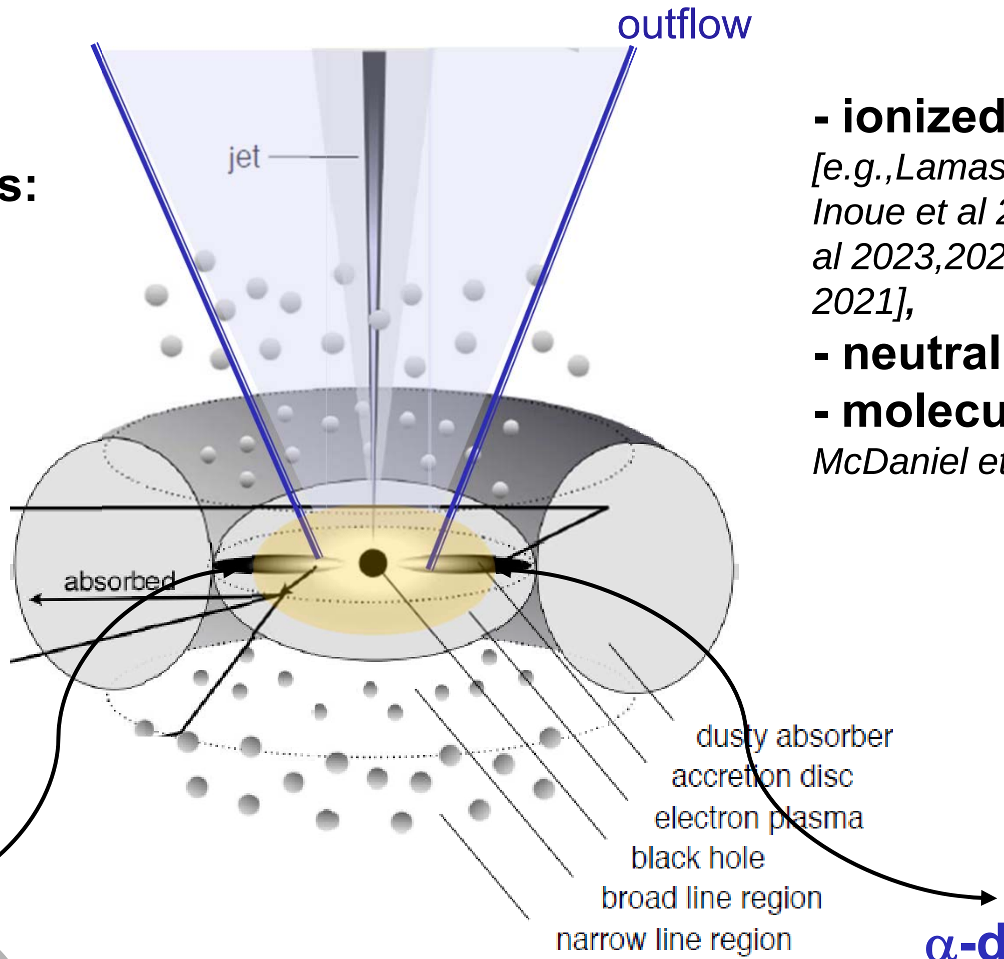


[Credit: X-ray: NASA/CXC/CfA/J.Wang etal.; Optical: Isaac Newton Group of Telescopes, La Palma/Jacobus Kapt.Tel., Radio: NSF/NRAO/VLA]

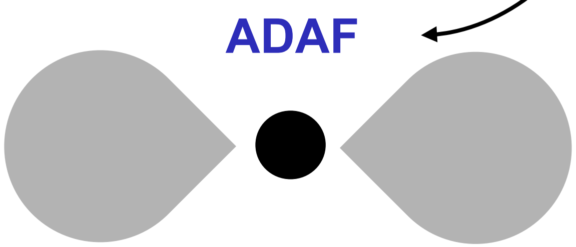
➢ **All type of AGN-systems produce γ-rays!**

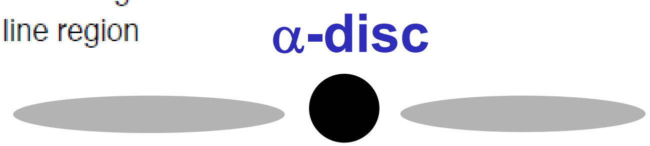
Sketch of a jetted AGN

Outflows at various phases:



- **ionized (ultra-fast)** *[e.g.,Lamastra etal 2016, Inoue et al 2022, Peretti et al 2023,2025, Ajello et al 2021]*,
- **neutral atomic,**
- **molecular** *[e.g., McDaniel et al 2023]*



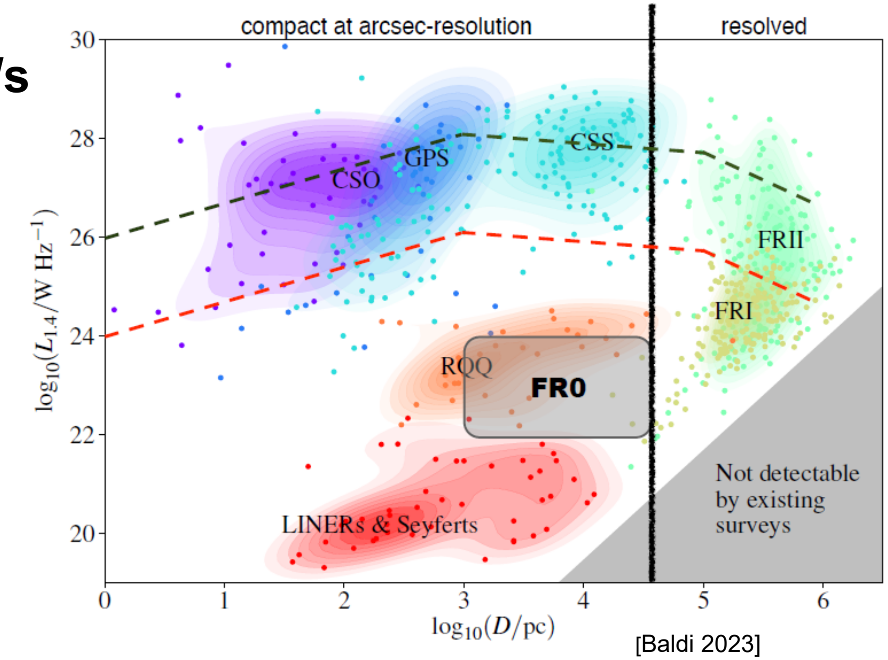


Open Questions

- **Where** (-> environment) are the γ**-rays** produced? ✖
- **How** are the γ**-rays** produced? ✖
- **Where & how** are the **radiating particles** accelerated?
- **What** is the composition of the **radiating particles**? ✖
- **How** are the γ**-rays** related to cosmic rays (and neutrinos)? ✖

Low-luminosity AGN

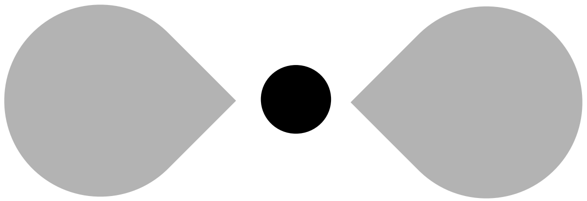
- Nuclear $L_{H\alpha}$ **< 10^{40}erg/s, L_{bol} < 10^{43} erg/s**
  [e.g., Ho 2009; Saikia et al 2018]



[Baldi 2023]

- **Low-ionisation** opt spectrum from nuclear region

- $\dot{M}_{BH}$ **< 0.01** $\dot{M}_{Edd}$,
  Advection-**d**ominated
  Accretion **F**low **(ADAF)**



geometrically thick

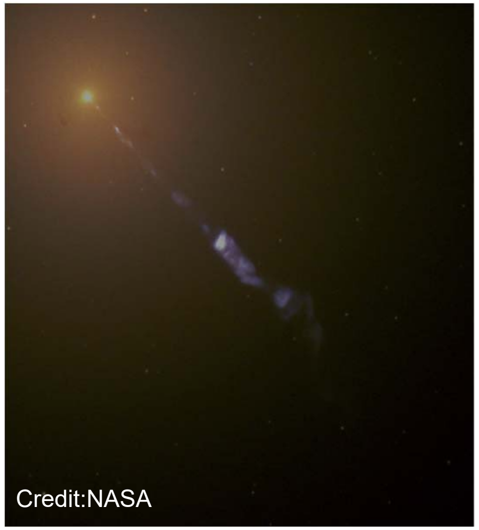
τ < 1

$\dot{M}_{BH} < \dot{M}_{crit} \sim (0.3...1)\alpha^2\dot{M}_{Edd}$

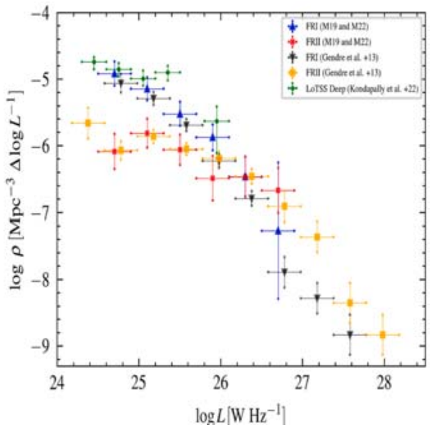
[e.g. Narayan & Yi 1995]

- **γ-ray (HE/VHE) source detections:**
  FRI (64*[Paliya etal 2024]***/7), FR0 (2/0), CS0 (6/1); low-lum. Sy?**

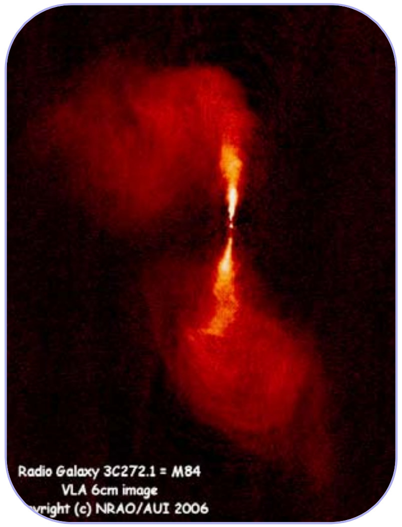
Fanaroff-Riley I (FR I) radio galaxies

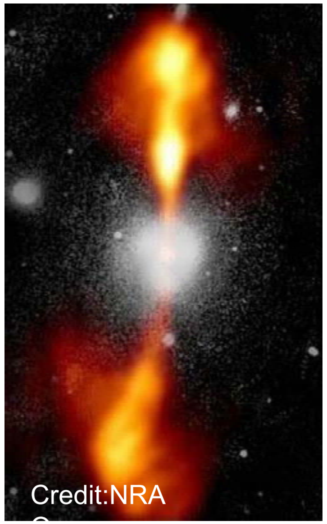


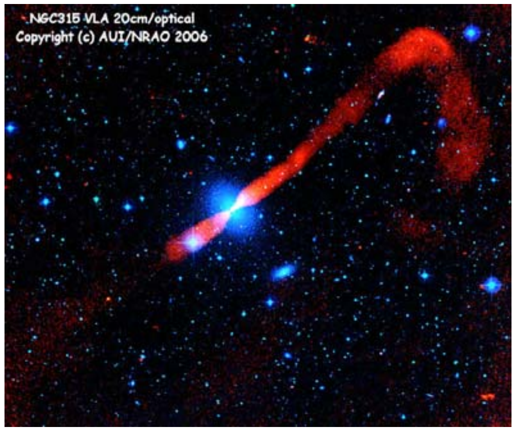
- **Core-brightened large-scale jets**
- **Mis-aligned**
- $\mathbf{L_{jet}}$ **~** a few $\mathbf{10^{42...45}}$ **erg/s** [e.g. Croston etal
- Local (z<0.3) source density **n ~ $\mathbf{10^{-5}}$ $\mathbf{Mpc^{-3}}$**
- **Potential UHECR-sources**
  [e.g., Eichmann et al 2018, 2022; de Oliveira et al 2022, …]



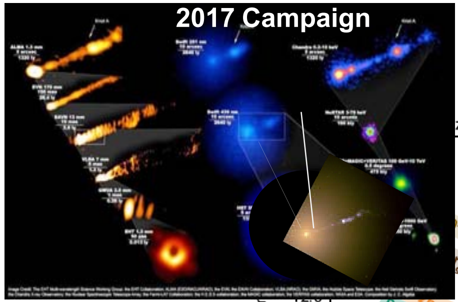
[De Jong etal 2024]



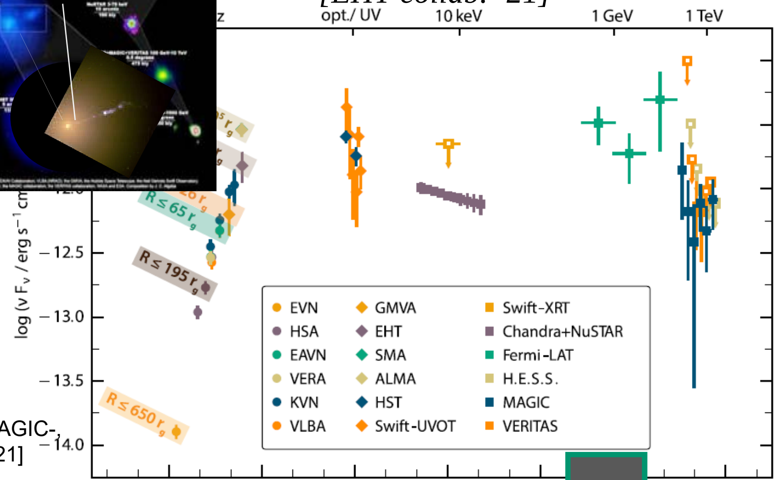




Most famous FR-I type LLAGN: M87

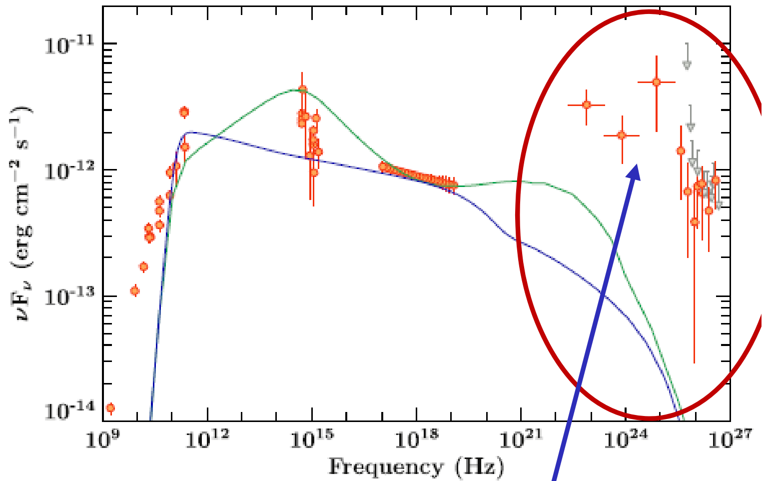


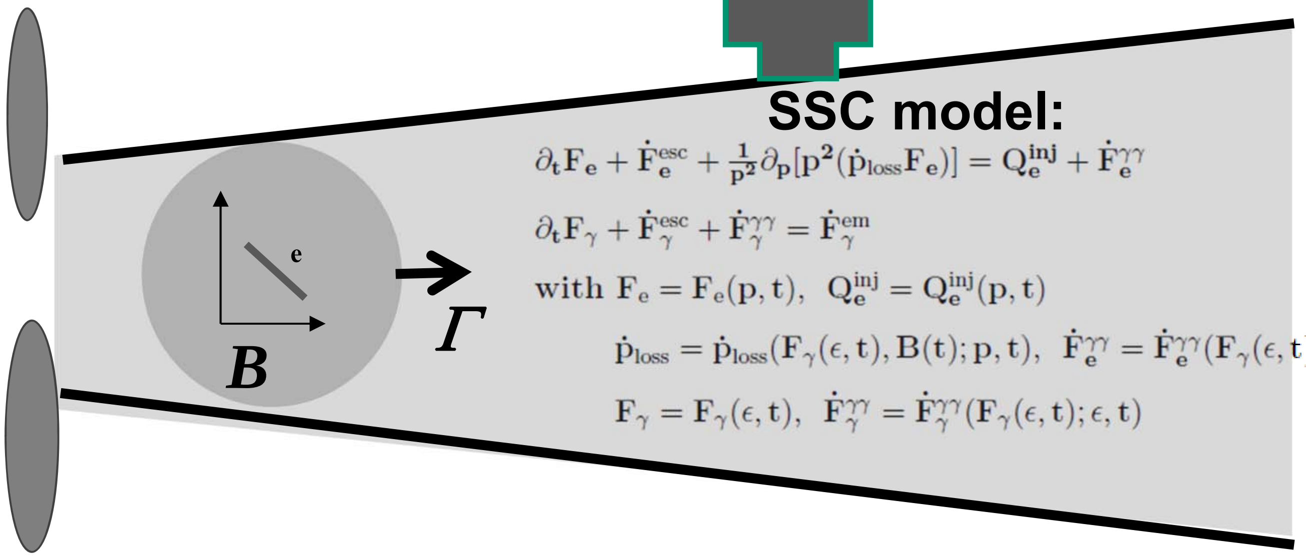
-> B_{core} ~ 5 ... 60 G
[EHT-collab. '21]



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

Viewing angle ~ 19±4° [Mertens et al 2016]





SSC model:

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

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

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

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

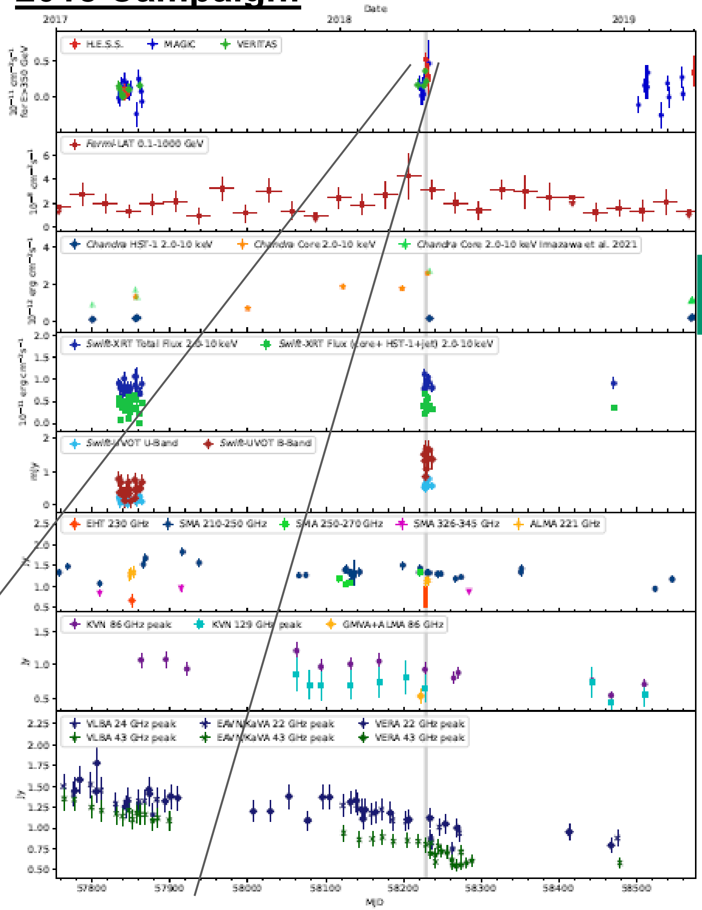
$$F_\gamma = F_\gamma(\epsilon,t),\quad \dot{F}_\gamma^{\gamma\gamma} = \dot{F}_\gamma^{\gamma\gamma}(F_\gamma(\epsilon,t); \epsilon, t)$$

γ-ray emission** in **quiet state** within **leptonic emission model <u>not</u> from jet base!

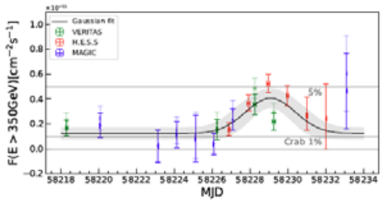
[EHT-collab., etal 2021]

Most famous FR-I type LLAGN: M87

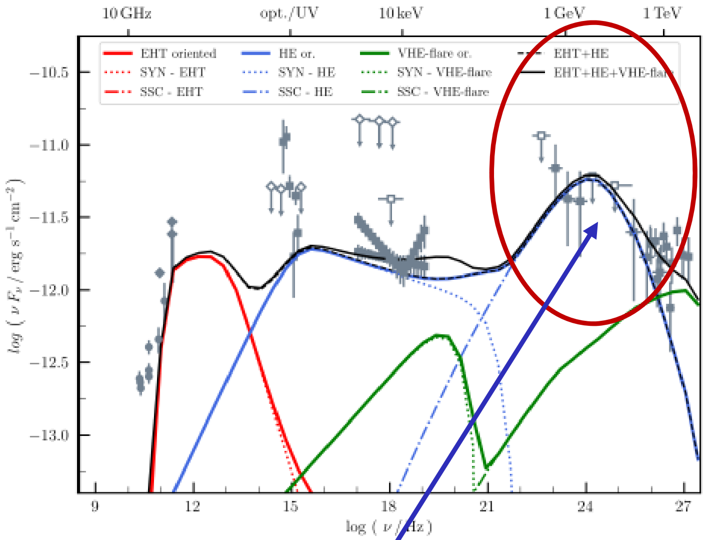
2018 Campaign:



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



Model with **25 parameters**:



γ-ray emission** in **elevated state** within **leptonic emission model** **not from jet base!

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

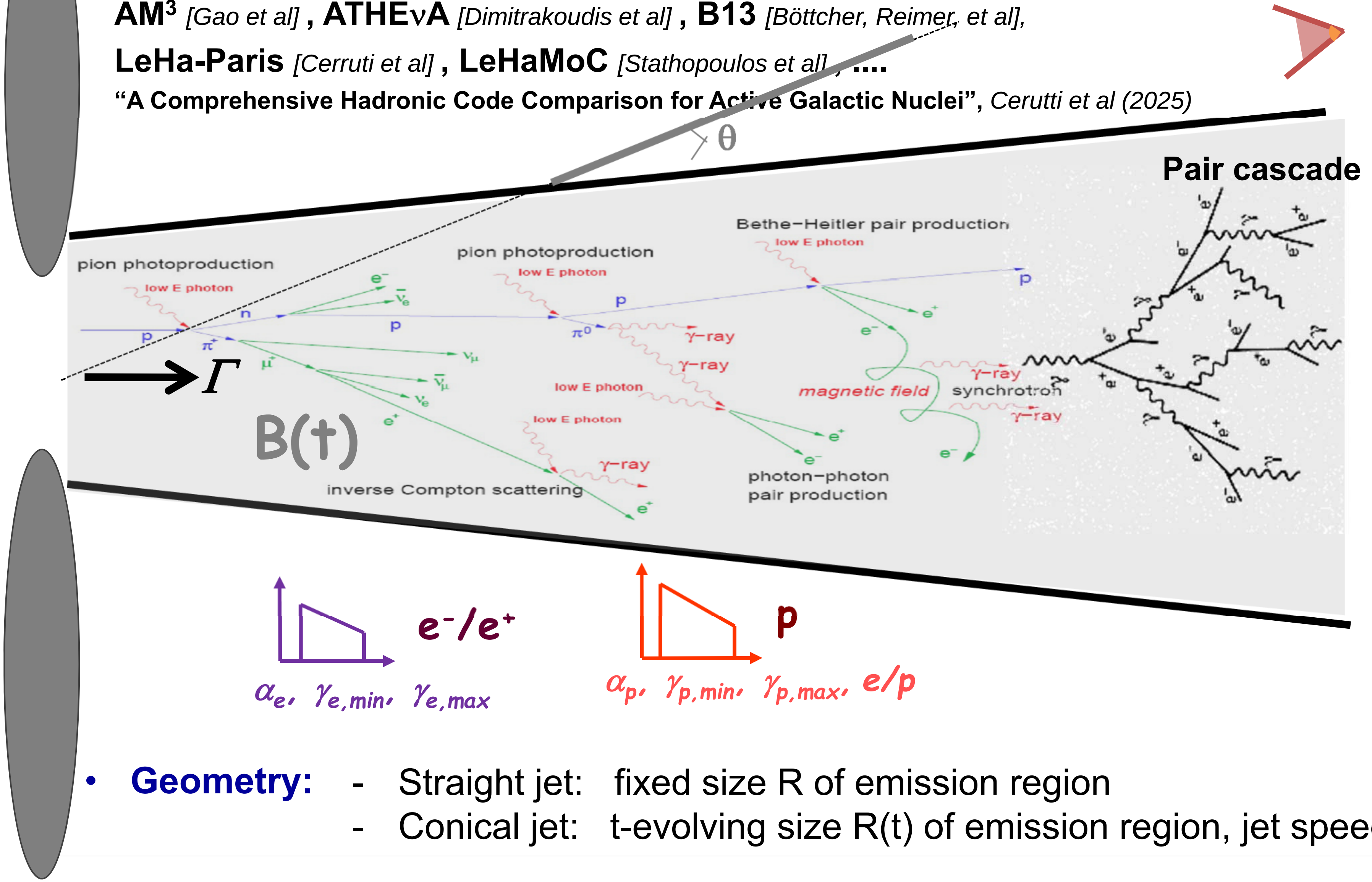
➢ **Leptonic homogenous emission models** require **multi-zone emission** regions

CR-ENTREES – Cosmic-Ray ENergy TRansport in timE-Evolving astrophysical Settings *[Reimer et al]*

AM³ *[Gao et al]* **, ATHEνA** *[Dimitrakoudis et al]* **, B13** *[Böttcher, Reimer, et al],*

LeHa-Paris *[Cerruti et al]* **, LeHaMoC** *[Stathopoulos et al]* **, ….**

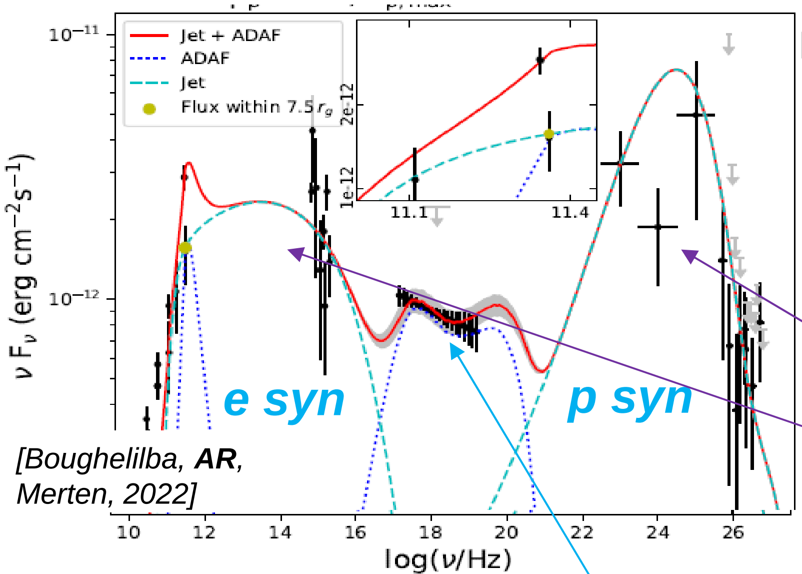
"A Comprehensive Hadronic Code Comparison for Active Galactic Nuclei", *Cerutti et al (2025)*



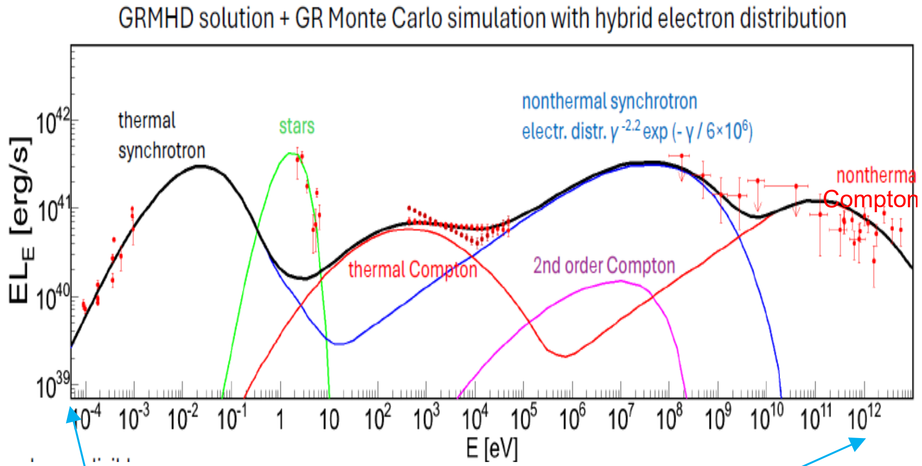
- **Geometry:** - Straight jet: fixed size R of emission region
  - Conical jet: t-evolving size R(t) of emission region, jet speed v_J

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

(Hadronic Jet) - Disc Model for M87

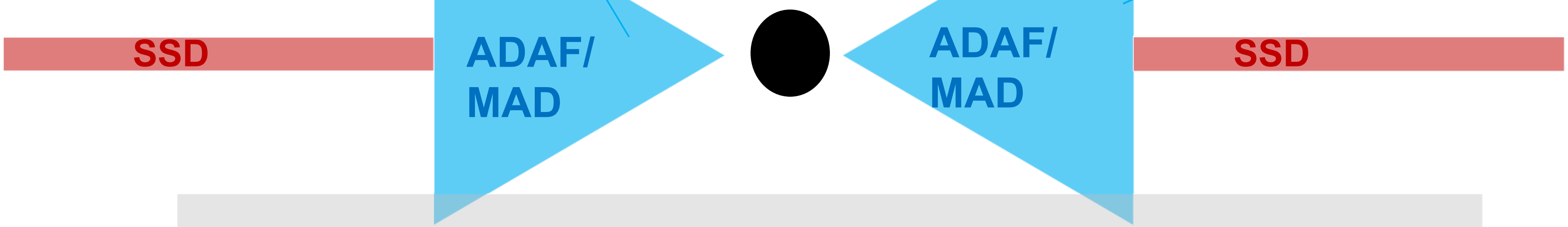


Model with **12 parameters**



- **ADAF +** strongly **magnetized** (10 ... 50G), **compact** ($5r_g$) **jet** emission region, $u_{part} \sim u_B$

- **3D-GRMHD ADAF model** *[Niedzwiecki, this conference; Niedzwiecki et al 2024]*

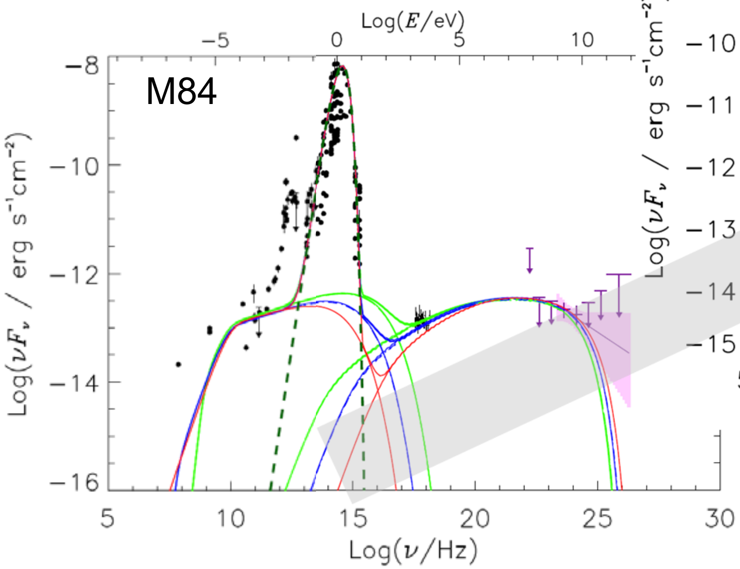


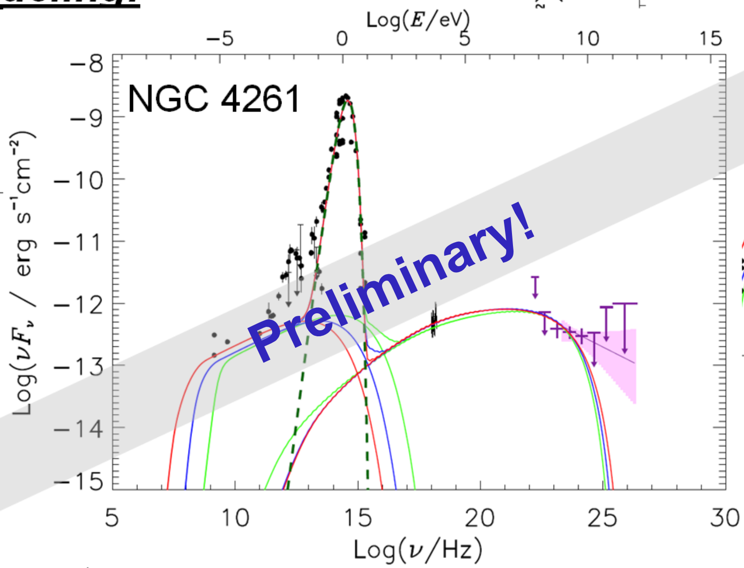
- ➢ ***Jet - ADAF*** *system*
- ➢ ***γ-rays from jet base*** *due to* ***proton synchrotron*** *radiation, or nonthermal* ***inverse Compton*** *from* ***ADAF***

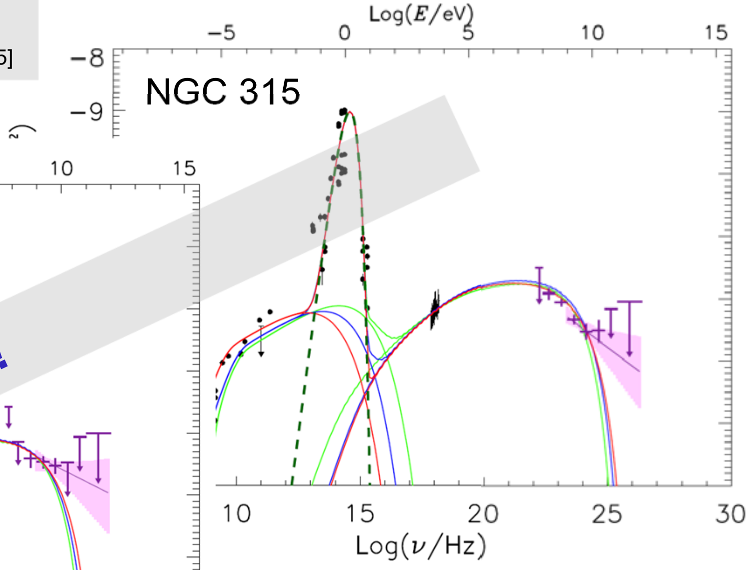
Type 2 Low-luminosity **FRI: Gamma-rays from jet core?**

Viewing angle ~ 30° - 70°
[Wang etal 2022, Yan etal 2023, Ricci et al 2022, 2025]

Examples of one-zone SSC-modeling:







[Karwin, ..., AR, etal 2025, to be subm.]

- ... improving on *[De Menezes et al (2020)]*
- *[Tomar et al (2021)]* for a core SSC + large scale jet (EIC) model

➢ **Slow** (β_j **<~ 0.5**), **weakly magnetized** (mG ... 0.1G), jet emission region ($10^{2....4}$ R_s),

➢ **particle** (PL exp cutoff, $\gamma_{e,max}$ ~ $10^{5...6}$) **energy density dominated** (u_B / $u_{particle}$ ~ $10^{-4 .... -1}$)

➢ strongly **constrained** by **jet power** (~$10^{43.3}$ erg/s [Allen et al 2006])

Low-luminosity FRI: Jet core velocity fields

Multi-epoch proper motion radio measurements + jet-to-counterjet flux ratios of 2-sided inner jets yield [e.g., Wang etal 2022, Ricci et al 2022, 2025, Yan et al 2023, Fariyanto etal 2025, ...] :

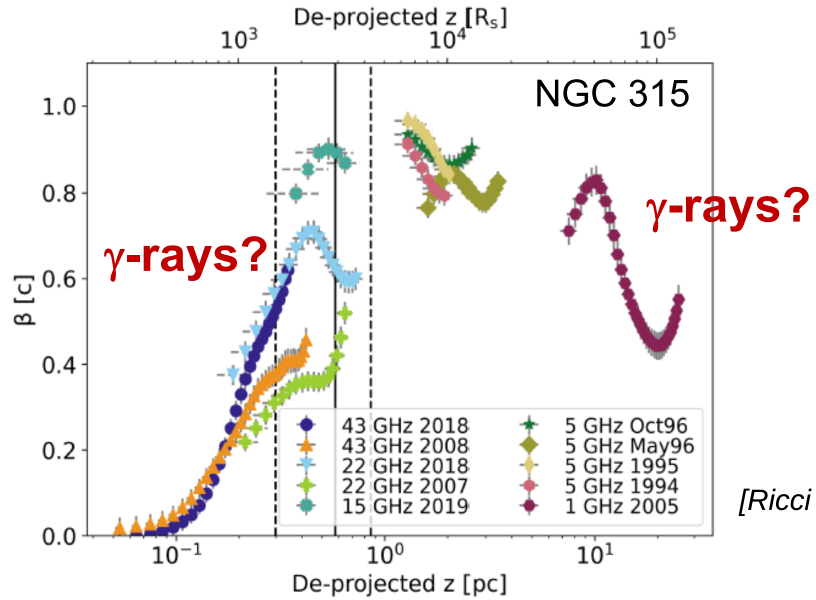
- **mildly-relativistic**
- **accelerating**
- **parabolic-shaped flow**
- **Poynting-flux dominated**

on a few 10^3 R_s scales,

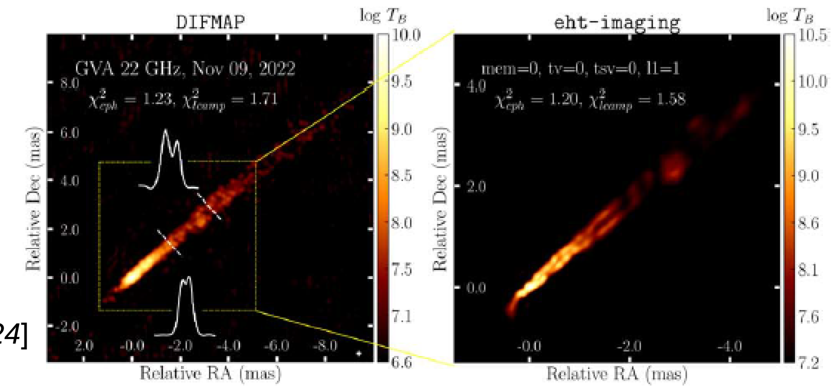
... transitions to ....

- **conical-shaped flow**

on ~10^4 R_s scales



[Ricci etal 2022]

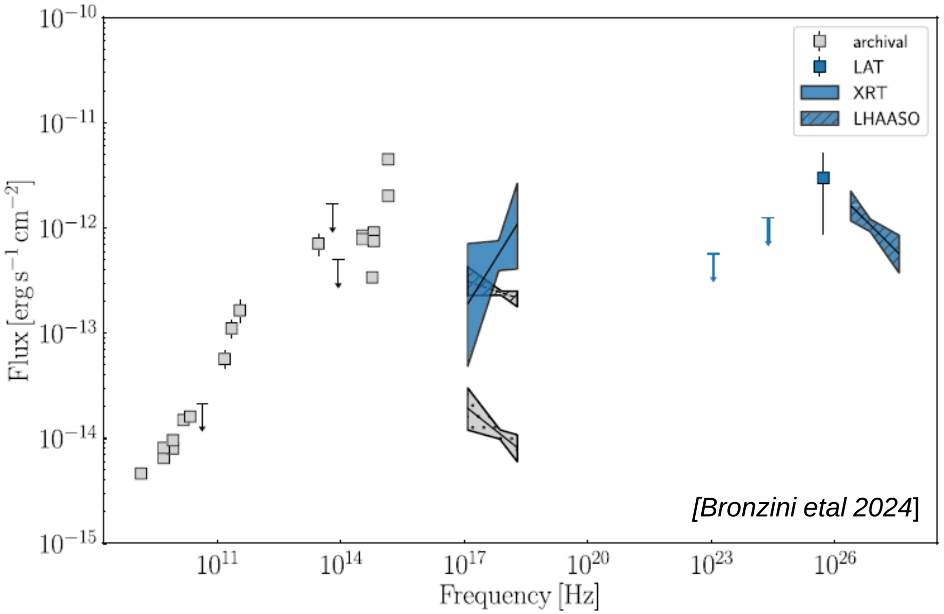


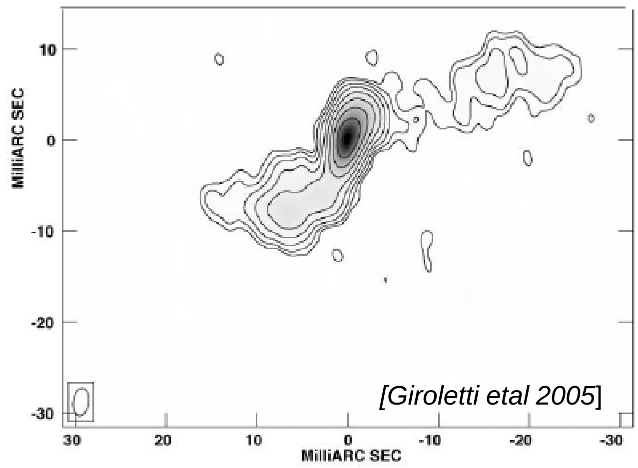
[Park etal 2024]

- **Transverse structured** jet?
- **De-beaming** effect?

➢ **Where is the location of the γ-ray emission region?**

Low-luminosity AGN: NGC 4278





- **Nearby** (d_L~16.4Mpc) **radio-faintest** (L_{jet}~10^{42} erg/s [Pellegrini etal 2012]) **LLAGN** detected to date @**VHE**
- **Under-luminous (**$L/L_{Edd} \sim 5 \cdot 10^{-6}$**) CSO** (compact (~3pc), symmetric, S-shaped radio structure [Giroletti etal 2005]) of **young** (?) **age** (<100 yrs [Giroletti etal 2005])
- **Slow jet** (β **~ 0.75** [Giroletti etal 2005]) with **viewing angle ~2-4°** **->** δ_a**~2.6,** δ_r**~0.4**

➢ **Origin of γ-rays?**

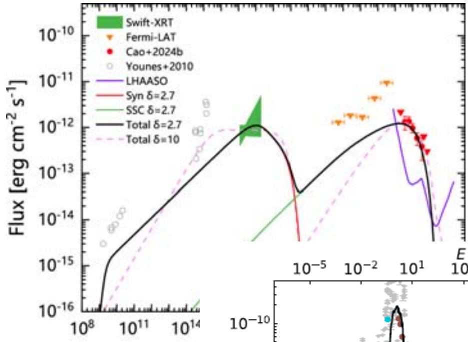
Low-luminosity AGN: NGC 4278

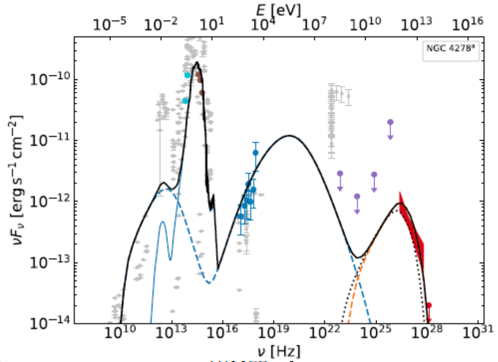
<u>From **broadband modelling:**</u>

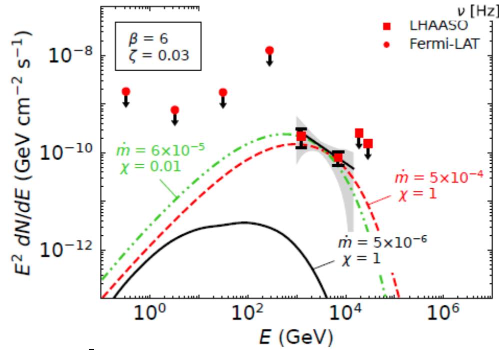
- **SSC** interpretation requires **mG fields & particle energy density dominated ($L_e \sim L_{jet} >> L_B$)** emission region *[Lian etal 2024; Dutta etal 2024]*

- **SSC + pp** interpretation requires **large jet power** (~ $10^{44\text{-}46}$erg/s), **particle energy density dominated ($L_{Edd} \sim L_{p,target} \sim L_{jet} >> L_B$)** emission region *[Wang etal 2024];*
  Chen (this conference) for a **lepto-hadronic model**

- **γ-ray** production due to **hadronuclear interaction** in **molecular cloud in the core vicinity** requires high accretion rates & small diffusion coeff. *[Shoji etal 2025]*







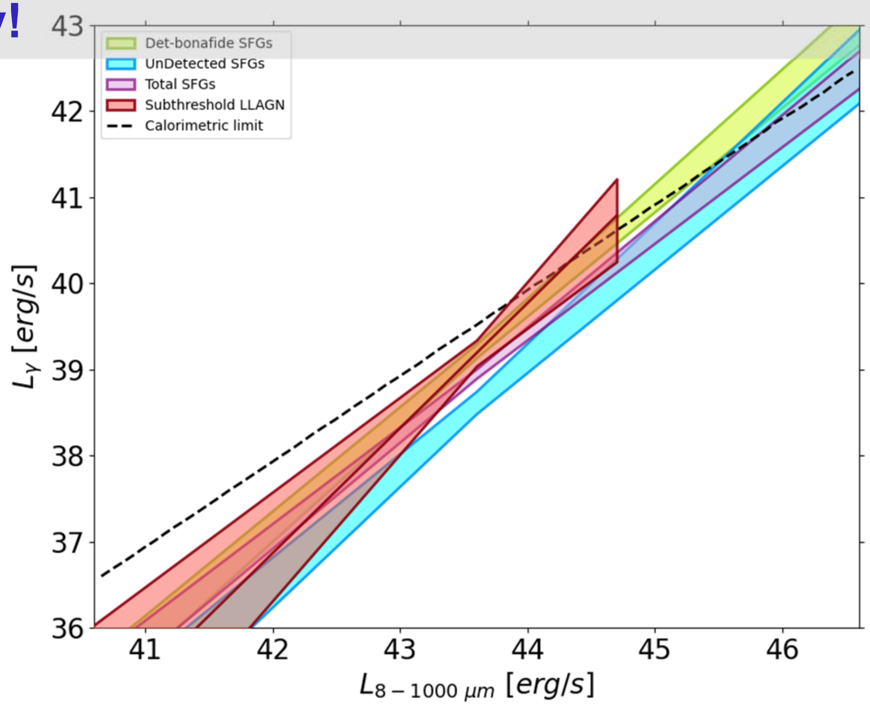
- **γ-ray** production due to **ionised gas mass outflow** ($\dot{E}_{sh}$~7 10^{37} erg/s *[Hermosa Munoz et al 2024]*) provides **not sufficient shock kinetic power** to explain observed **γ-ray flux** *[e.g., Dominguez 2025]*

> ➢ **Origin of γ-rays not settled**

LLAGN a γ-ray emitting population?

[Karwin ...., AR et al 2025, tbs; Khatiya etal 2024]

Preliminary!



- **Stacking analysis** (50MeV-1TeV) on a **sample** (186) built from **Palomar Survey** consisting of **Sy, LINERs, Transition Nuclei** revealed **5.2σ** *Fermi*-LAT **detection** with **best-fit index $2.3^{+0.2}_{-0.3}$**

- **Spiral** host galaxy (107) ***versus*** **non-spiral** host galaxy (79) **testing:**
  - ➢ **dominant signal** from **spirals!**

- **strong L_γ-$L_{8\text{-}1000\mu m}$ correlation:**

  6.4σ (all) **/ 6.3σ** (spirals)

- somewhat weaker **L_γ-L_{15GHz} correlation:**

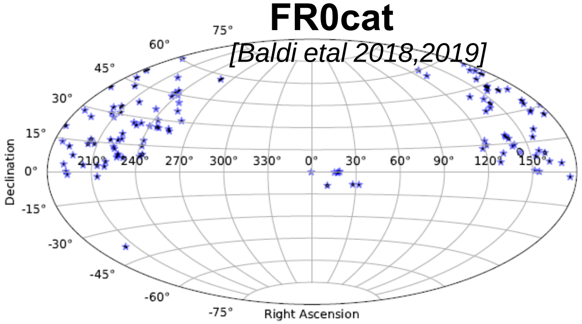
  5.8σ (all**) / 4.5σ** (spirals)

➢ **γ-rays mainly** from **star formation** with some **jet contribution**

Fanaroff-Riley 0 (FR0) radio galaxies

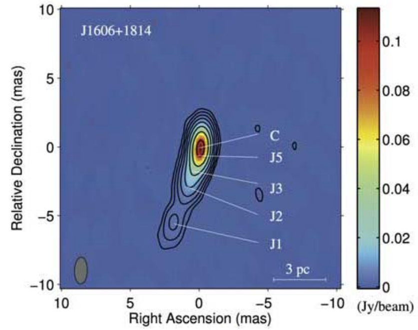
- the most numerous jet population in the near Universe -

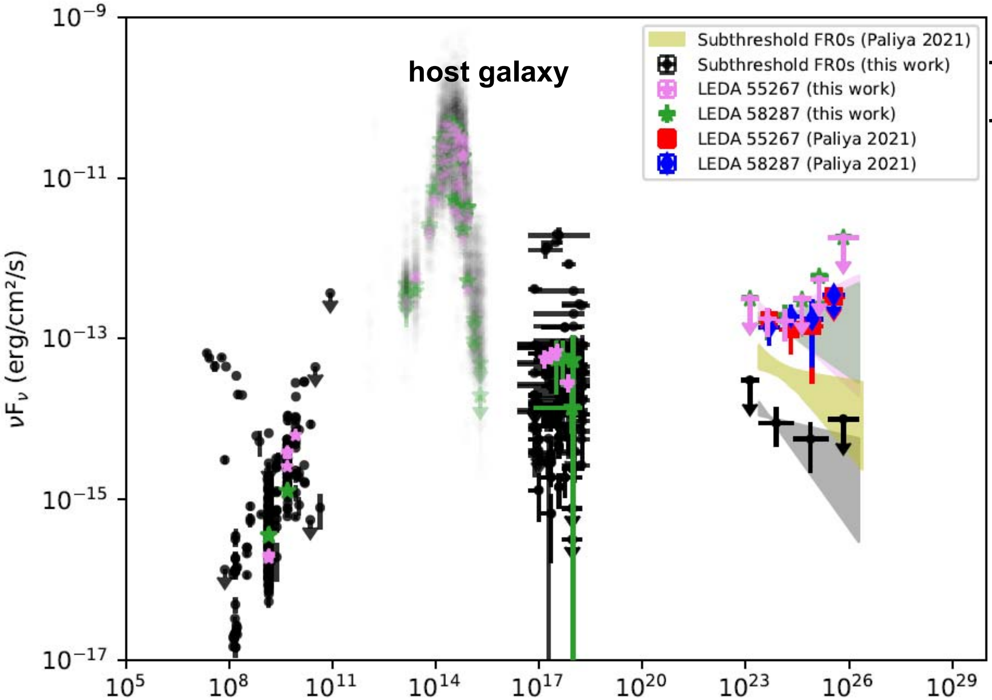
FR0cat
[Baldi etal 2018,2019]



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

- **Core-dominated (sub-)kpc jets**
- **lack extended jet emission**
- $\mathbf{L_{jet} \approx 10^{42.5...43.5}}$ **erg/s**
- **Slow** jet **speed** *[Giovannini etal 2023]*
- Local source density **n ~** a few $\mathbf{10^{-4}}$ $\mathbf{Mpc^{-3}}$
- **Potential UHECR-sources** *[Merten etal 2021, Lundquist etal 2025; [Partenheimer etal 2024]*





[Boughelilba 2023]

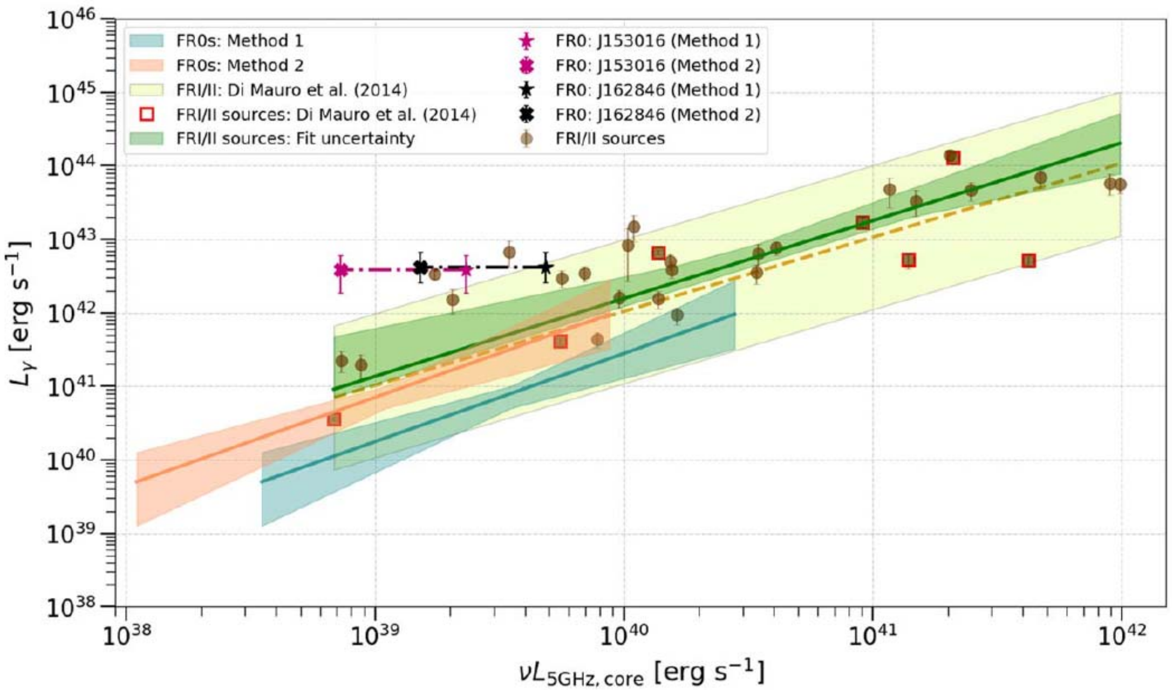
[Khatiya, Boughelilba, ... AR etal 2024, ApJ]

Jet composition ?

Fanaroff-Riley 0 (FR0) radio galaxies

- High-energy properties -

- **Stacking analysis detects FR0-population at ~4σ significance** *[Khatiya et al 2024; Paliya 2021]*
- **2 individually detected FR0**
- **No significant variability**
- **L_γ - $L_{1.4GHz,\,total}$ relation @ 3.8σ**



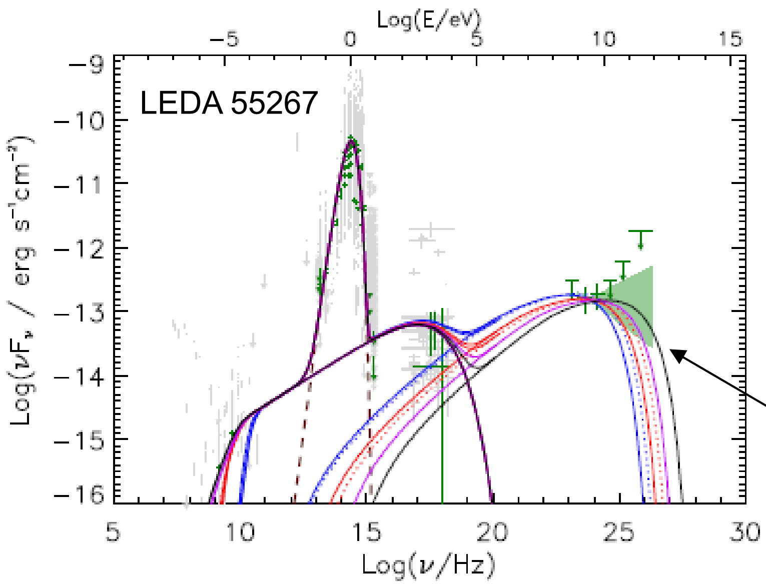
[Khatiya, Boughelilba, ... AR etal 2024]

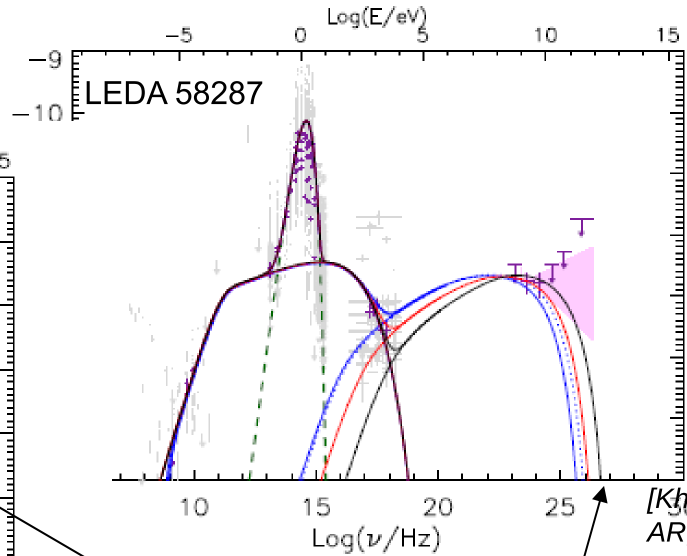
points to ....

➢ likely **jet origin of γ-rays**

FR0: Gamma-rays from jet?

Examples of one-zone SSC-modeling:





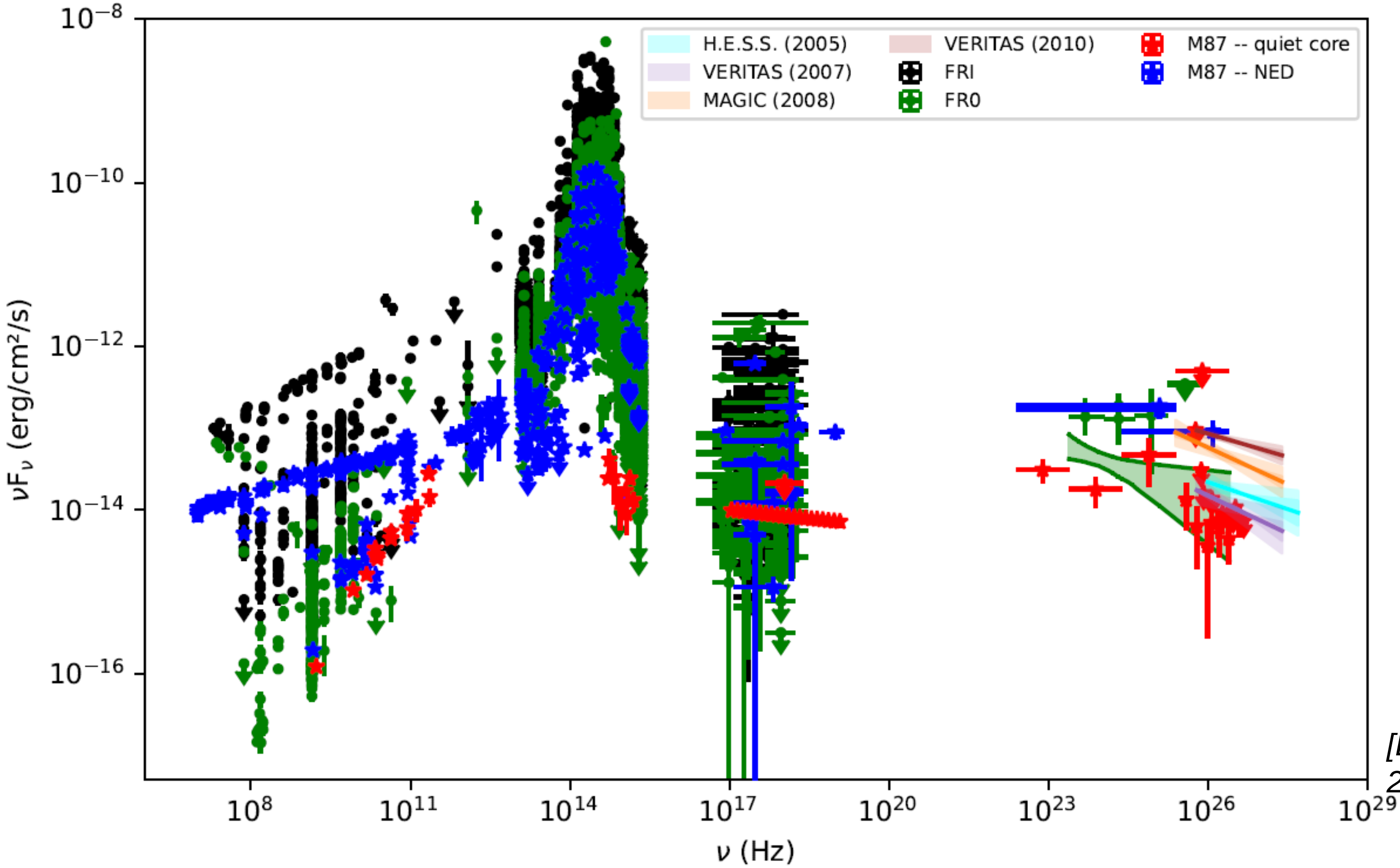
[Khatiya, Boughelilba, ..., AR, etal 2024]

No significant TeV- emission expected

- **Slow** (Γ_j **~ 1.04....1.34**), **weakly magnetized** (5mG.... G), jet emission region ($10^{2....5}$ R_s),
- **particle** (PL exp cutoff, $\gamma_{e,max}$ ~ $10^{5...6}$) **energy density dominated** (u_B / $u_{particle}$ ~ $10^{-4 .... -1}$)

...... similar to quiet LLAGN FRI !

Broadband SED of low-power radio galaxies



[Boughelilba & AR, 2023]

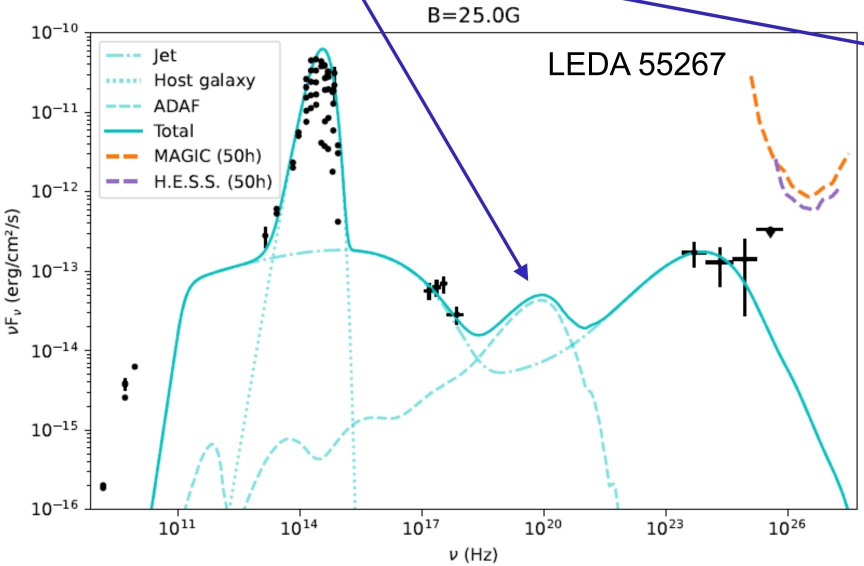
Striking **similarity of broadband photon emission** between **quiet core M87 (FR I)** & typical **FR0 core!**

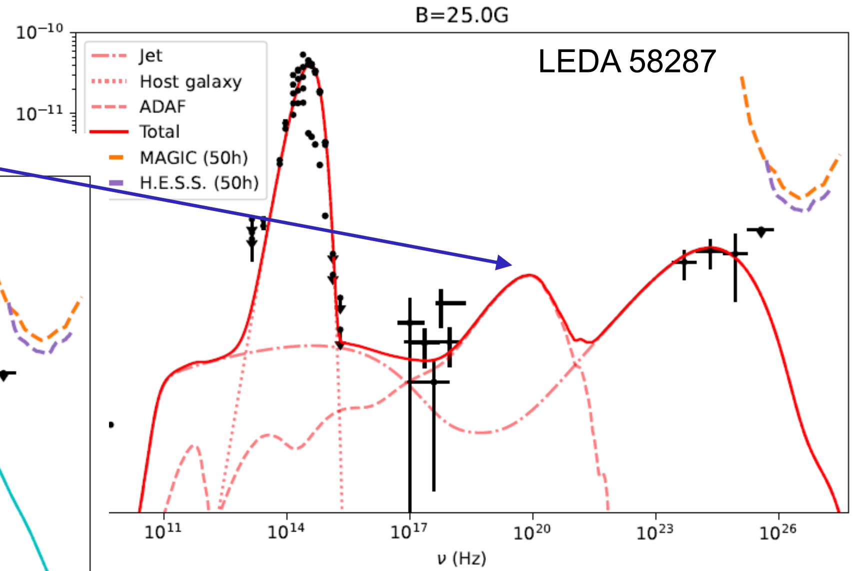
[see also Baldi 2023]

FR0s: Hadronic jet - disc modeling

ADAF: $\alpha_{viscosity} \sim 0.1,\ \beta_{gas} \sim 0.99$

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





[Boughelilba & AR, 2023]

- **Slow** **(Γ_j ~ 1.2)**, **strongly magnetized** **(25...50G)**, jet emission region (a few $10^2 R_s$),
- **particle** (PL exp cutoff, $\gamma_{e,max} \sim 10^{5...6}$) **energy density dominated** ($u_{particle} / u_B \sim 0.01...0.5$)
- **X-ray** emission due to **e-synchrotron/ADAF** radiation
- **Gamma-rays** due to **p-synchrotron** radiation

- **MeV-emission** due to **ADAF** **<u>predicted</u> in hadronic model!**

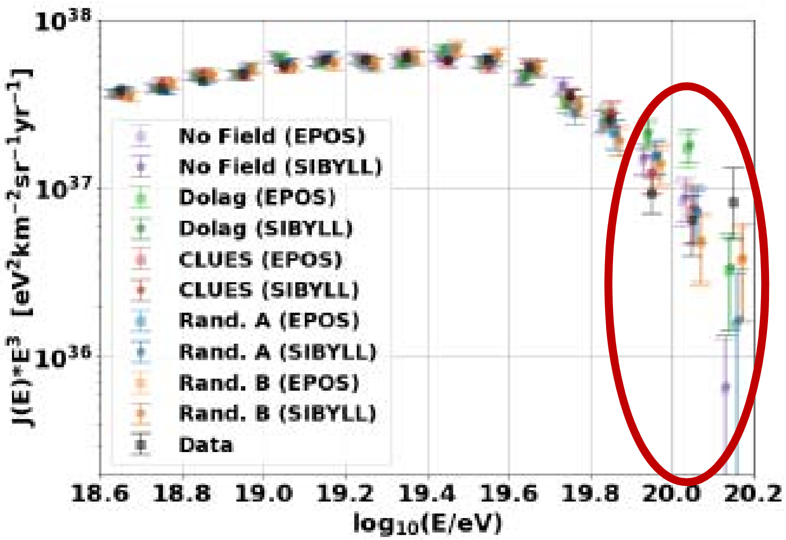
First steps towards ....

Combined source - intergalactic CR propagation modeling

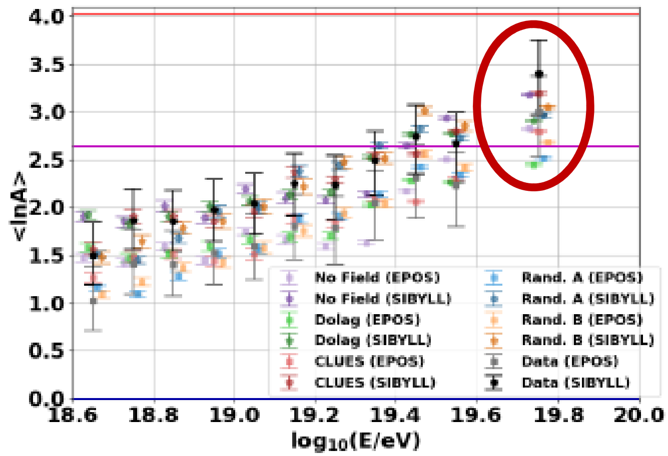
<u>Example:</u> Probing **FR0 population** as contributor to the UHECR flux:

-> Simulations of **intergalactic UHECR propagation** (p, He, N, Si, Fe) ***[Lundquist etal 2025]:***

- **Structured intergalactic fields (5)**
- Simulated **redshift distribution** from FR0CAT-data**,** close to **isotropy**
- **Source evolution** modeled by **correlation of radio output & redshift**
- **UHECR injection**: PL exp cutoff with: energy-independent **nuclei fraction,** rigidity-dep **energy cutoff** ZR_{cut}, FR-0 **UHECR flux** $\propto$ radio output



Good fit up to ~30 EeV, too low flux & too light composition @ highest E (>**30 EeV**)



Cosmic ray constraints

Field	Model	$\Sigma\chi^2$/dof	γ	$\log_{10}(R_{cut}/V)$
No Field	SIBYLL	3.21	$2.51^{+0.02}_{-0.67}$	$19.36^{+0.23}_{-0.31}$
	EPOS	3.15	$2.50^{+0.02}_{-0.16}$	$19.40^{+0.13}_{-0.06}$
	QGS4	3.47	$2.47^{+0.03}_{-0.08}$	$19.43^{+0.10}_{-0.03}$
Dolag	SIBYLL	4.41	$2.29^{+0.06}_{-0.79}$	$19.74^{+0.00}_{-0.40}$
	EPOS	4.74	$2.23^{+0.11}_{-0.06}$	$19.75^{+0.03}_{-0.29}$
	QGS4	6.28	$2.23^{+0.08}$ [illegible]	$19.64^{+0.10}_{-0.12}$
CLUES	SIBYLL	1.76	$2.54^{+0.00}_{-0.19}$	$19.45^{+0.50}_{-0.12}$
	EPOS	1.87	$2.43^{+0.06}_{-0.13}$	$19.51^{+0.36}$ [illegible]
	QGS4	3.10	2.32 [illegible] $_{-0.05}$	$19.56^{+0.08}_{-0.07}$
Rand.A	SIBYLL	2.84	$2.40^{+0.07}_{-0.11}$	$19.86^{+0.12}_{-0.18}$
	EPOS	2.15	$2.34^{+0.08}_{-0.09}$	$19.69^{+0.19}_{-0.08}$
	QGS4	2.51	$2.23^{+0.07}_{-0.07}$	$19.58^{+0.07}_{-0.08}$
Rand.B	SIBYLL	2.57	$2.47^{+0.04}_{-0.16}$	$19.71^{+1.40}_{-0.08}$
	EPOS	2.29	$2.33^{+0.09}_{-0.15}$	$19.60^{+0.23}_{-0.09}$
	QGS4	2.60	$1.97^{+0.26}_{-0.05}$	$19.52^{+0.08}_{-0.07}$

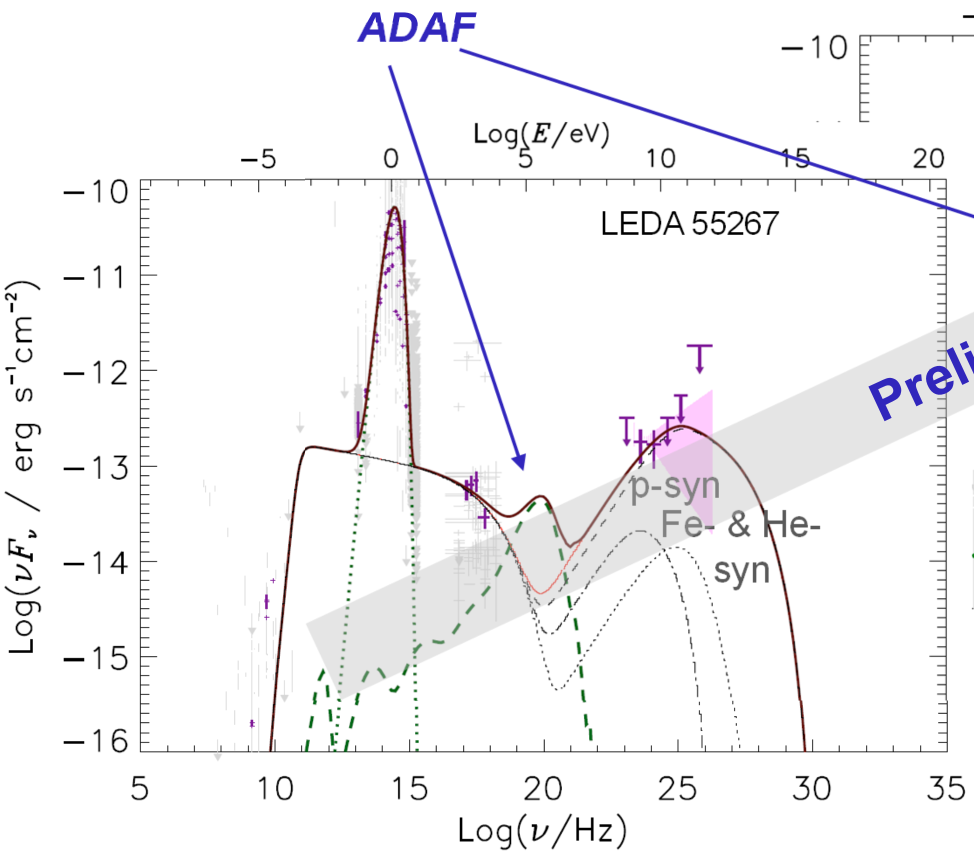
[*Lundquist etal (2025)*]

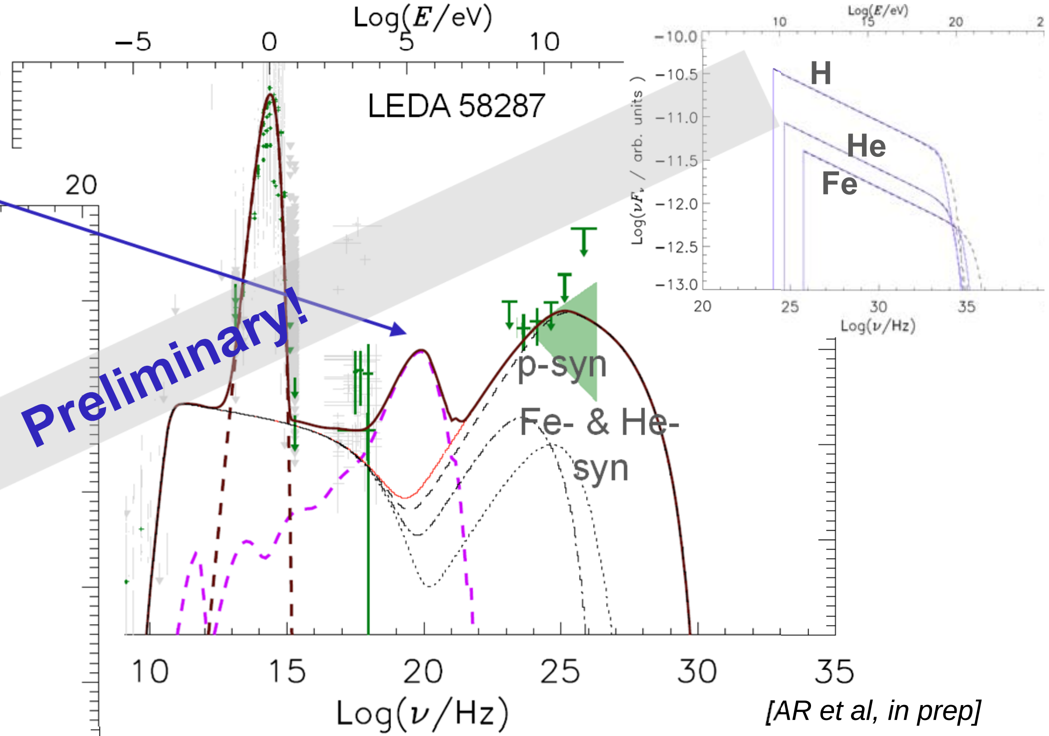
Best "Fit":

- emitted spectrum @source with γ**~2.4-2.5**
  -> expect **harder in-source particle spectrum**
- Composition @ source:
  $\mathbf{f_{H+He} : f_N : f_{Si} : f_{Fe}} \sim$
  0.804...0.948 :0:0: 0.057...0.117
- ***Caveat:*** Too low flux & too light composition @ highest E (>**30 EeV**)

The open question on CR escape from source ..

FR0s: Electron+ion jet - disc modeling





[AR et al, in prep]

Jet characterized by

***α_{CR} = α_e = 2.1**, **$E_{CR,max,ss}$~ Z $10^{19.5}$eV**, **B'=25G**,*
$u'_{CR,inj}$~0.5...0.75u'_B**, **H:He:Fe = .745 : .173 : .082
(CLUES+SYBILL best-fit), L_{jet} ~ $10^{43.5...43.6}$ erg/s

➢ **Broadband SED in line** with **slow jet** (containing **CR ions) + ADAF model**

➢ **FR0s** promising **contributor** to **extragalactic CR flux < 30 EeV**

Summary

- **All types of AGN systems emit gamma rays.**

- Exploring the **faint extragalactic γ-ray populations** promises .....
  - to learn on the **diversity of γ-ray production (& sites)** in AGN systems (jet, outflow, accretion disc/flow, host/starforming regions, ...),
  - to learn on the **composition** of the emission region,
  - to learn on the **origin of the extragalactic CR-flux.**

- Aim for **comprehensive, self-consistent modelling combining in-source physics** and **intergalactic propagation physics**

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