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Low-luminosity jetted AGN ….

…. as particle multi-messenger sources

Anita Reimer

on behalf of: **M. Boughelilba, L. Merten, P. Da Vela, J.P. Lundquist, S. Vorobiov**

FWF
Der Wissenschaftsfonds.

Slovenian
Research
Agency

TeVPa 2023
11 – 15 Sept 2023, Napoli

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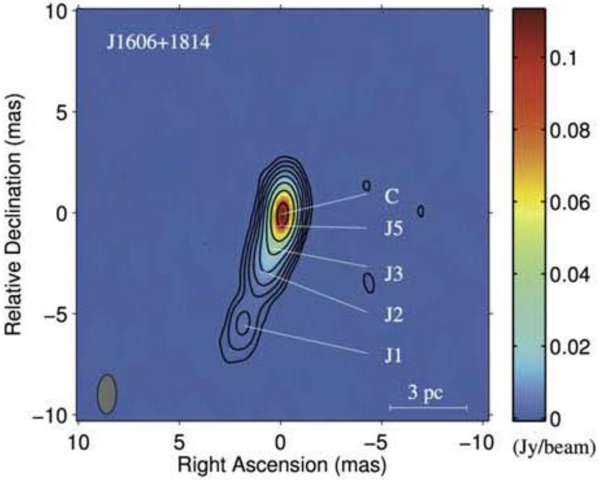
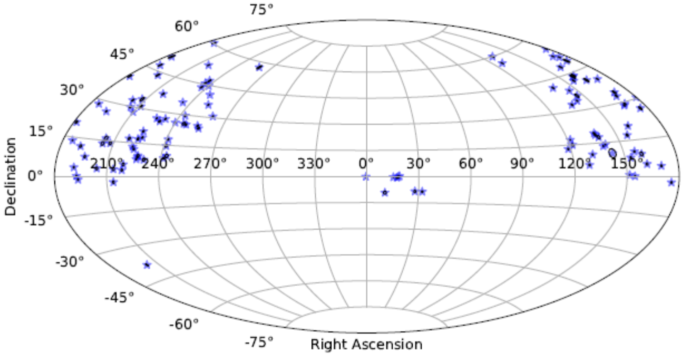
Most numerous jet population in the local Universe

- Fanaroff-Riley 0 (FR0) Radio galaxies -

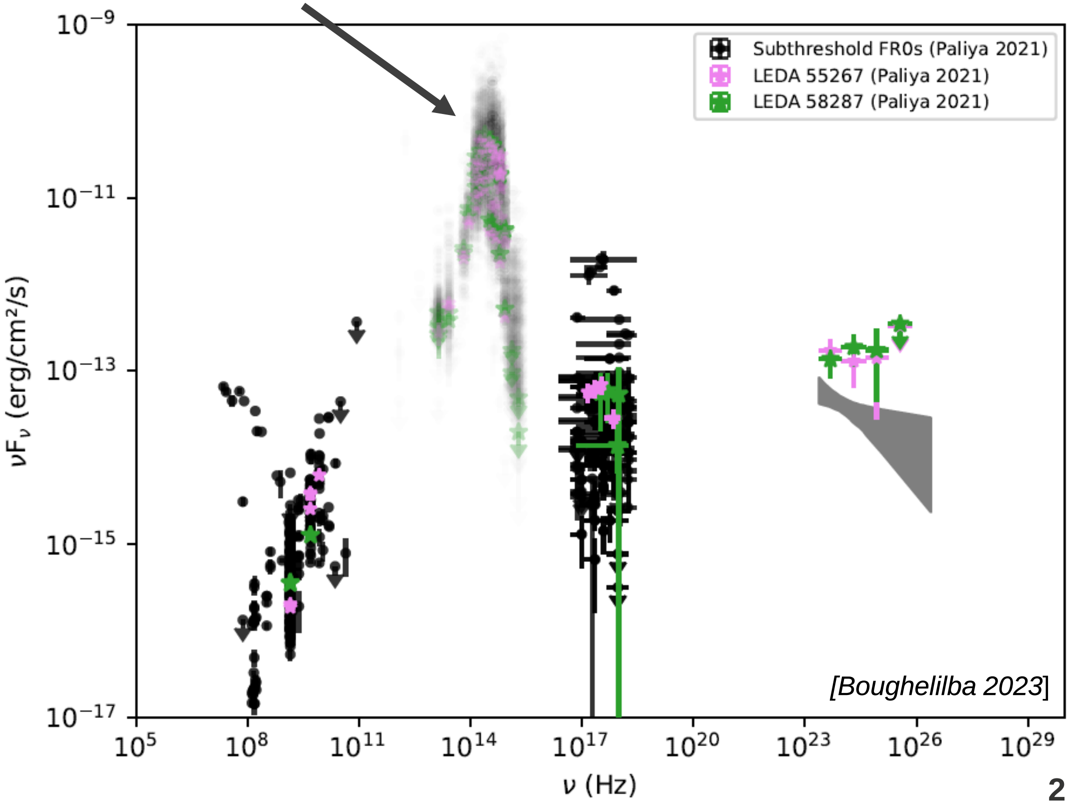
- **Core-dominated, pc ... kpc jets**
- **$L_{jet} \approx 10^{42.5...43.5}$ erg/s**
- n_{FR0} ~ a few **10^{-4} Mpc^{-3}**
- **Host galaxy: ~$10^{8...9} M_{\odot}$ Ellipticals**



[Cheng etal 2018]

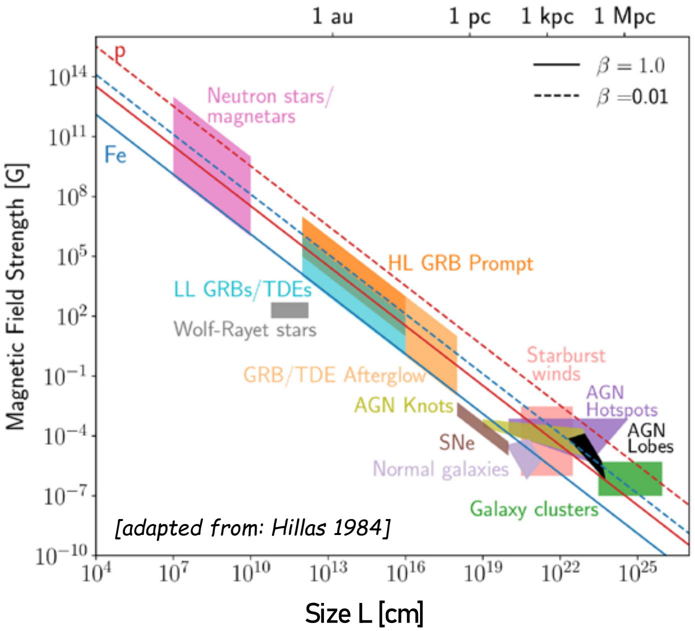


[from: Merten, Boughelilba, AR, etal 2021]



[Boughelilba 2023]

Requirements on UHECR source populations



[adapted from: Hillas 1984]

- ***“Hillas”-Criterion:*** **$E_{max} \sim 10^{18}\, Z\, \beta\, (B/\mu G)\; (L/pc)$ eV**

- ***Source power criterion:***

  $P_{source} > 10^{43}\, Z^{-2}\, (E_{max}/10^{19} eV)^{2}$ erg/s

- ***Population power density criterion:***

  $U_{population} \sim 10^{44....45}$ erg $Mpc^{-3} yr^{-1}$ for $E_{CR} \sim 10^{18....21}$ eV

  (within UHECR horizon)

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

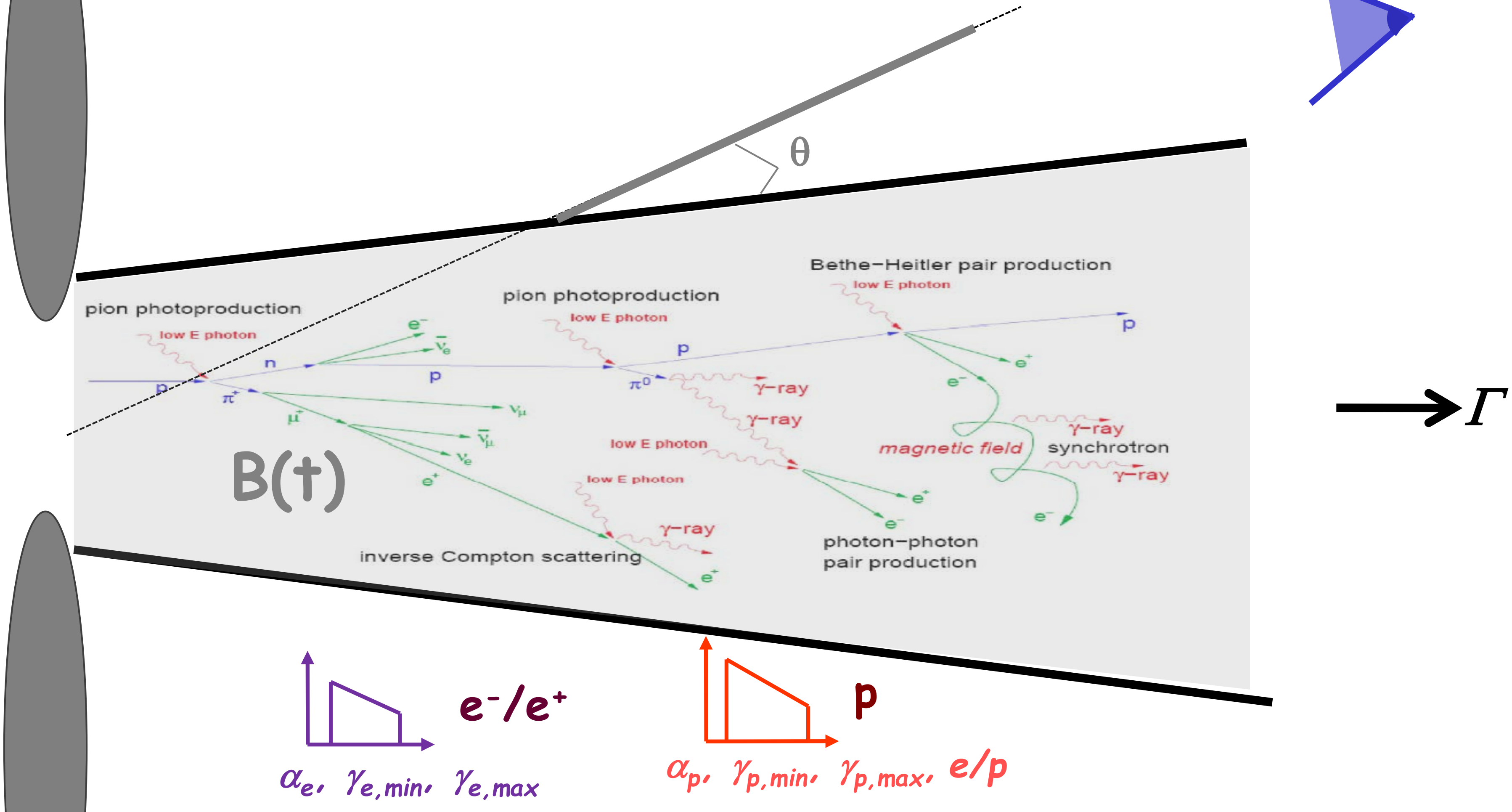
- ***Source environment suitable for particle acceleration to sufficient high energies?***

  [Merten, Boughelilba, AR, et al 2021]

- ***Photon (& ν) observations from population sources in agreement with hadronic radiation models?***

- ***Cosmic-ray (CR) observations (spectrum, composition) in agreement with CR propagation from population sources to Earth?***

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

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

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

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

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

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

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

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

- **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:**

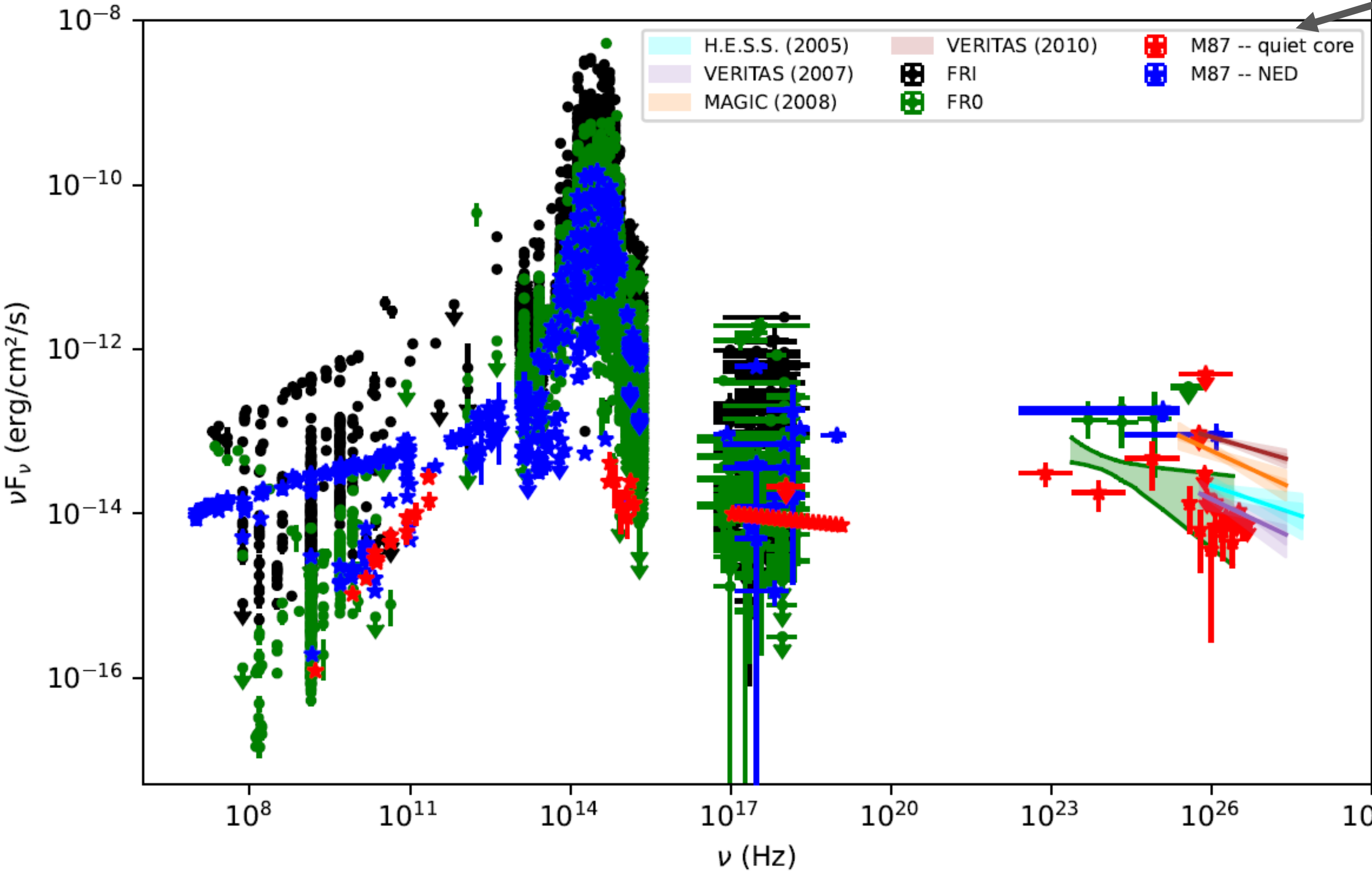
  Photomeson production, Bethe-Heitler pair production, decay of unstable particles, $\gamma\gamma$-pair production, inverse Compton scattering, synchrotron radiation, particle/photon escape, adiabatic losses.

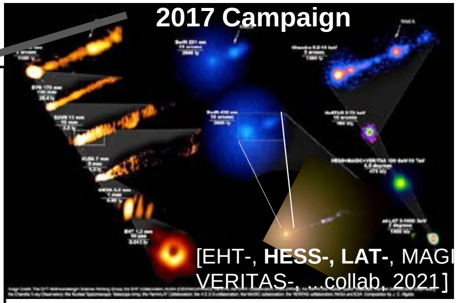
- **Target photon field:**
  - Pre-defined or custom-filled radiation field for each energy bin (-> EBL, etc)
  - Determination of internal radiation field after each time step **-> non-linearities**

- **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

Broadband SED of low-power radio galaxies





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

-> B_{core} ~ 5 ... 60 G

[EHT-collab. '21]

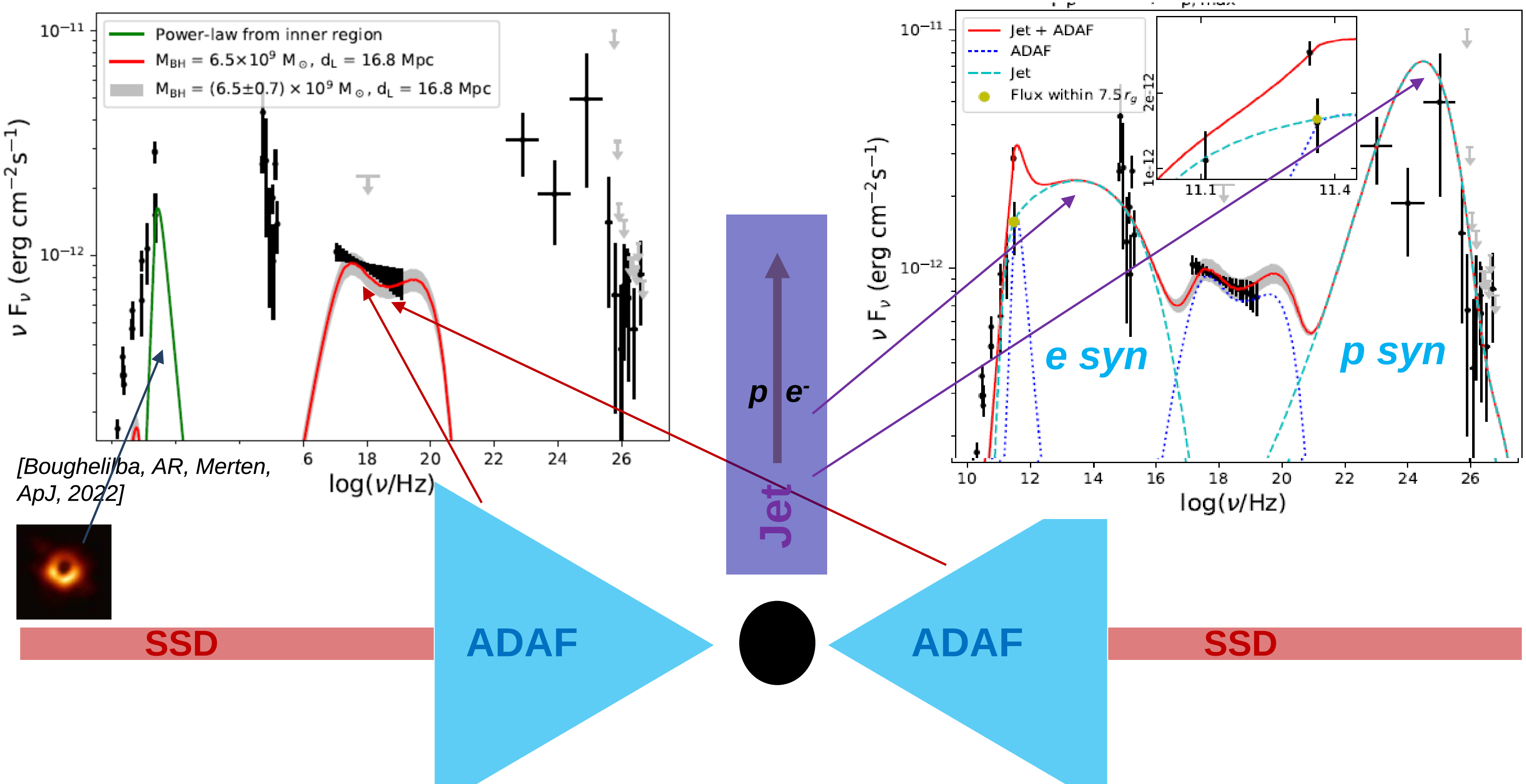
[Boughelilba & AR, 2023, ApJL, accepted]

Striking similarity of broadband photon emission between

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

Anita Reimer
TeVPa 2023, Napoli

Hadronic jet-disc model for M87



[Boughelilba, AR, Merten, ApJ, 2022]

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

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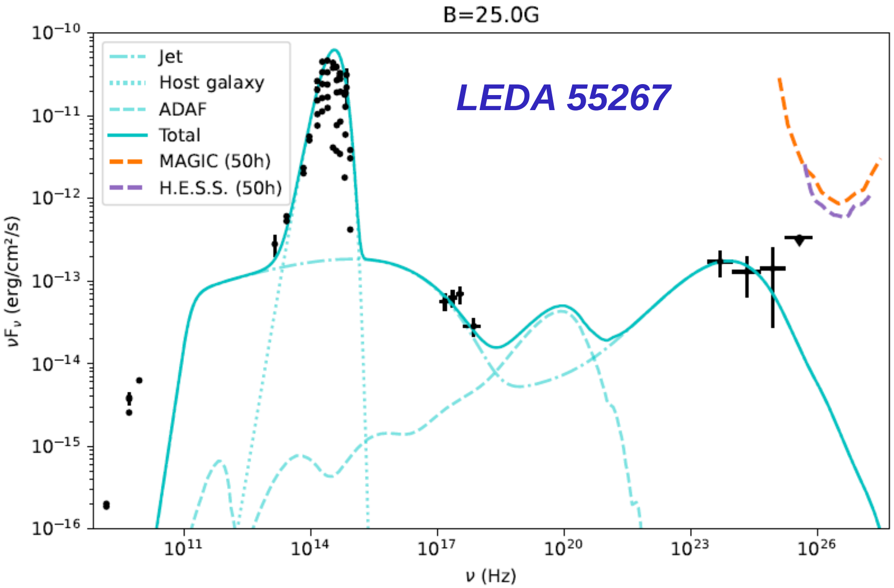
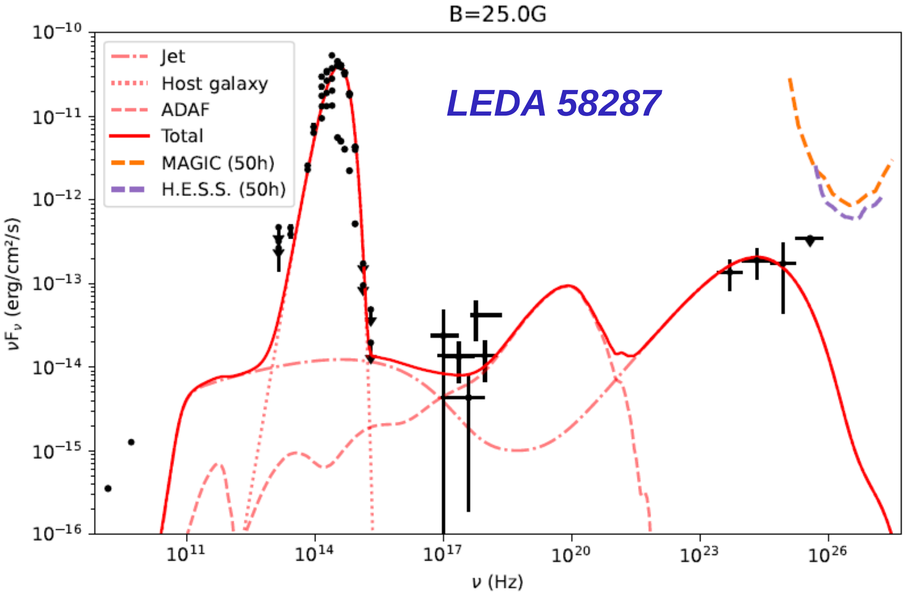
Hadronic jet-disc model for FR0s

[Boughelilba & AR, 2023, ApJL, accepted]





ADAF parameters:

$\alpha_{viscosity} \sim 0.1$

$\beta_{gas} \sim 0.99$

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

Jet parameters:

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

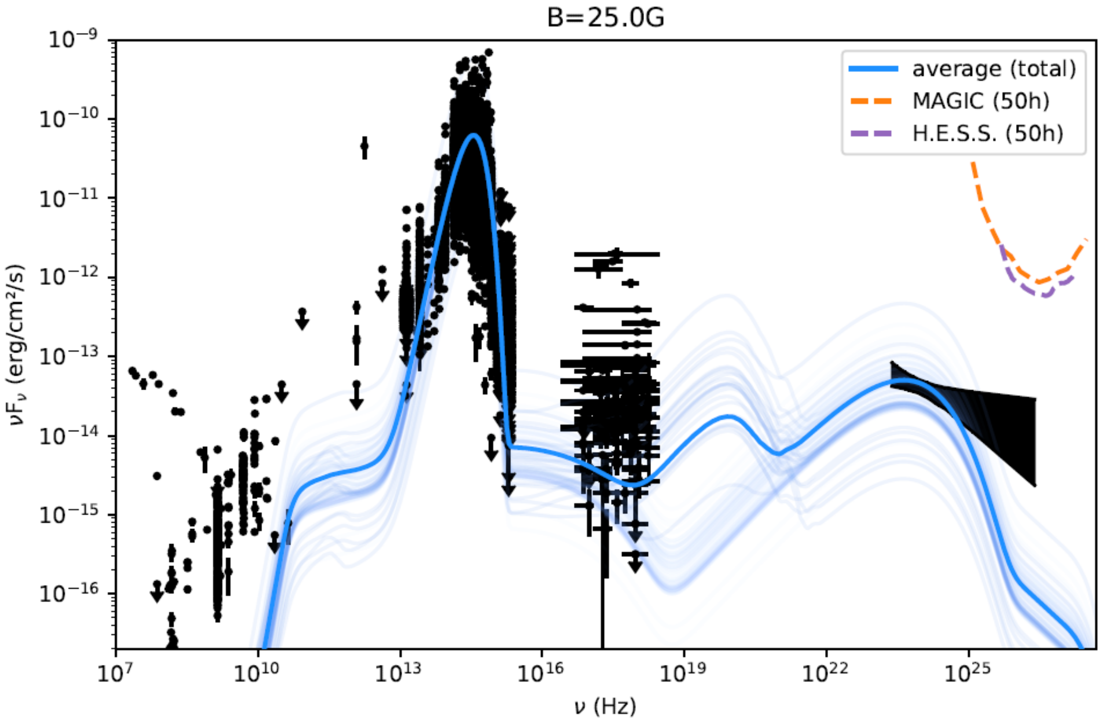
$B \sim 25 - 50$ G

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

$U_{part}/U_B \sim 0.01 \ldots 0.5$, $P_{jet} \sim (1\text{-}3)\times10^{43}$ erg/s

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

Hadronic jet-disc model for FR0 population



[Boughelilba & AR, 2023, ApJL, accepted]

- *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} ($E_{\nu,peak}$ ~ 0.1...1 EeV)*
- ***Distinct signature of ADAF emission predicted in MeV-band***

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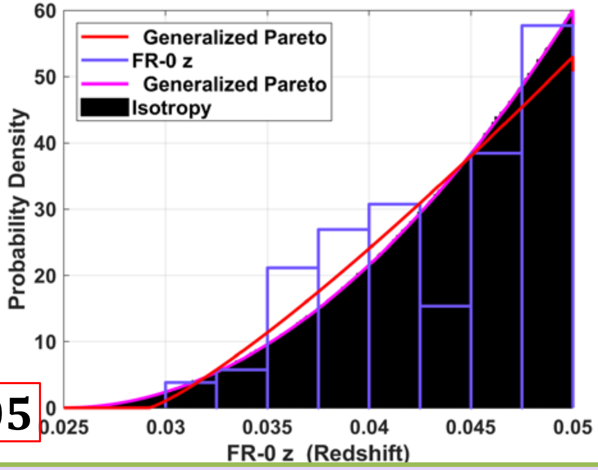
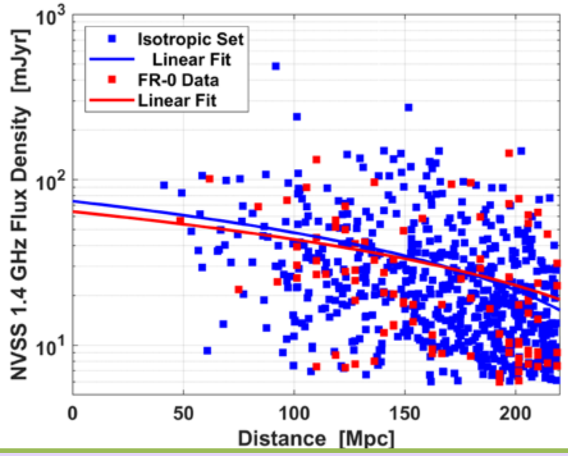
UHECR FR0 combined fit



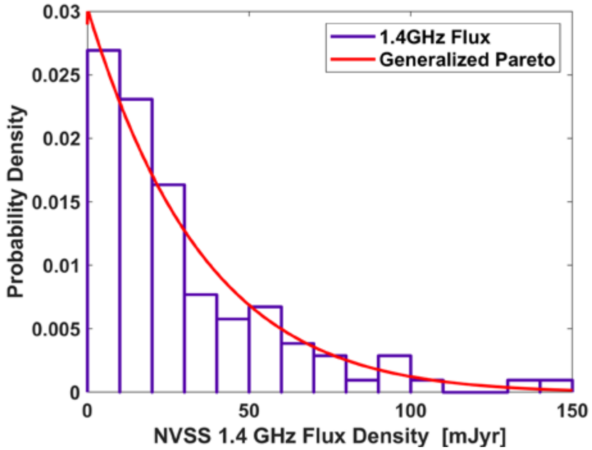
$z \leq 0.05$

CRPropa 3 intergalactic propagated five nuclei (proton, helium, nitrogen, silicon, & iron) UHECR primaries through CMB, IRB, & URB interactions [2]**.**

Simulated FR-0 redshift distribution from catalog data [1]**.**



Local source evolution modeled by correlation of radio output & redshift [1]**.**



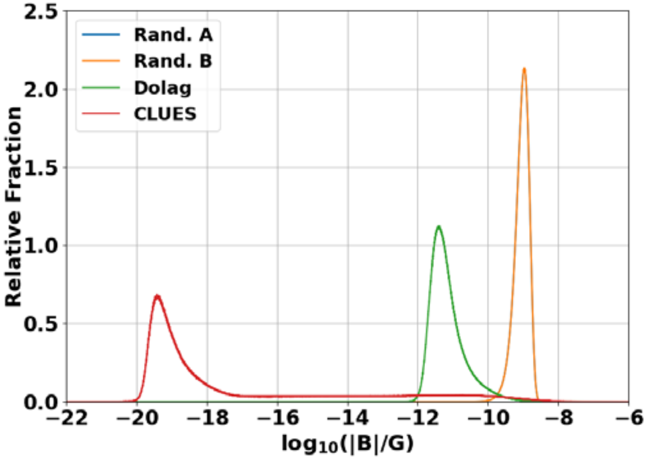
FR-0 UHECR flux ∝ radio output [1]**.**

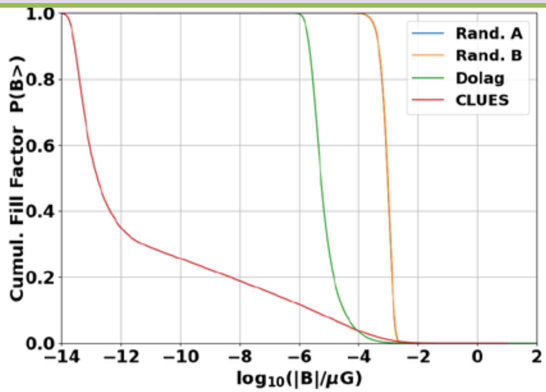
[1] Baldi, R. D. et al., A&A 609 (2018) A1.
[2] Merten, L. et al., Astropart. Phys. 128 (2021) 102564.

UHECR FR0 combined fit

MODELS:

- **Two EAS Models: EPOS-LHC & QGSJETII-04**
- **Structured Fields:**
  - **Dolag et al.** arXiv:0410419
  - **Hackenstein et al. (Astro_1B):** arXiv:1710.01353
- **1 nG Random Fields, Kolmogorov power spec:**
  - $\langle l_{\mathrm{corr}} \rangle = 234$ kpc & $\langle l_{\mathrm{corr}} \rangle = 647$ kpc
- **No magnetic Field**





Injection:

$$\frac{\mathrm{d}N_A}{\mathrm{d}E} = J_A(E) = f_A J_0 \left(\frac{E}{10^{18}\ \mathrm{eV}}\right)^{-\gamma} \times f_{\mathrm{cut}}(E, Z_A R_{\mathrm{cut}})$$

$$f_{\mathrm{cut}}(E, Z_A R_{\mathrm{cut}}) = \begin{cases} 1 & (E < Z_A R_{\mathrm{cut}}) \\ \exp\left(1 - \frac{E}{Z_A R_{\mathrm{cut}}}\right) & (E > Z_A R_{\mathrm{cut}}) \end{cases}$$

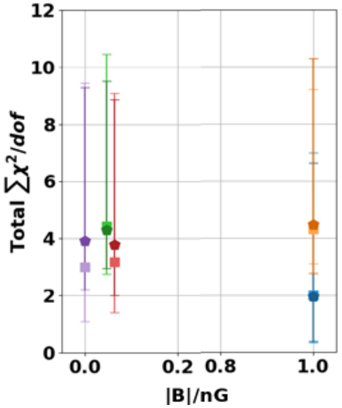
- **Constant nuclei fraction:** f_A
- **Rigidity dependent cutoff:** ZR_{cut}

Auger JCAP (2017) arXiv:1612.07155

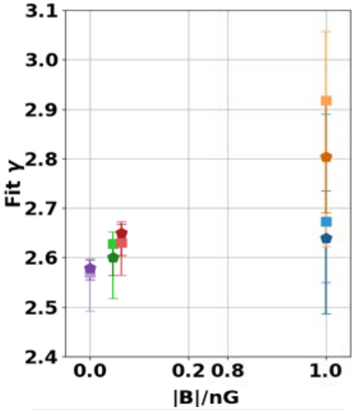
Minimize

$$\sum \chi^2_{tot}/dof = \sum \chi^2_E/dof_E + \sum \chi^2_C/dof_C$$

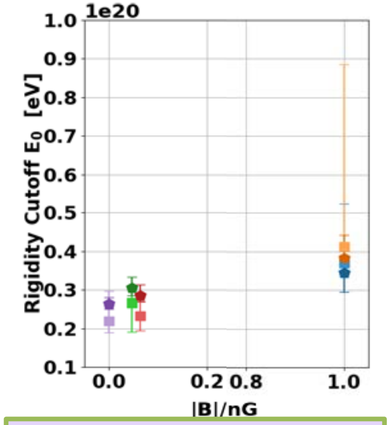
UHECR FR0 combined fit – Parameter results



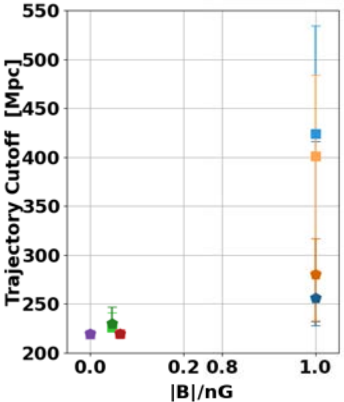
Goodness-of-Fit



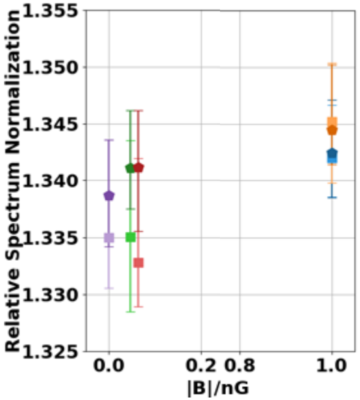
Power Law γ



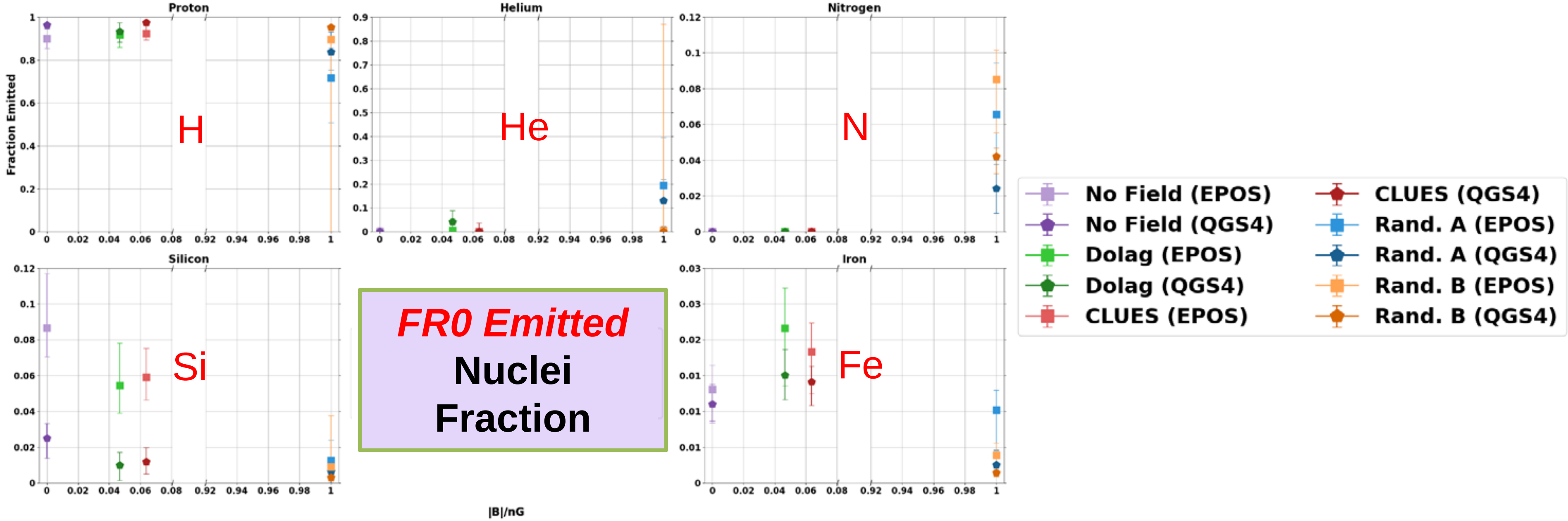
Rigidity Cut R_{cut}



Traject. Cut D_{cut}



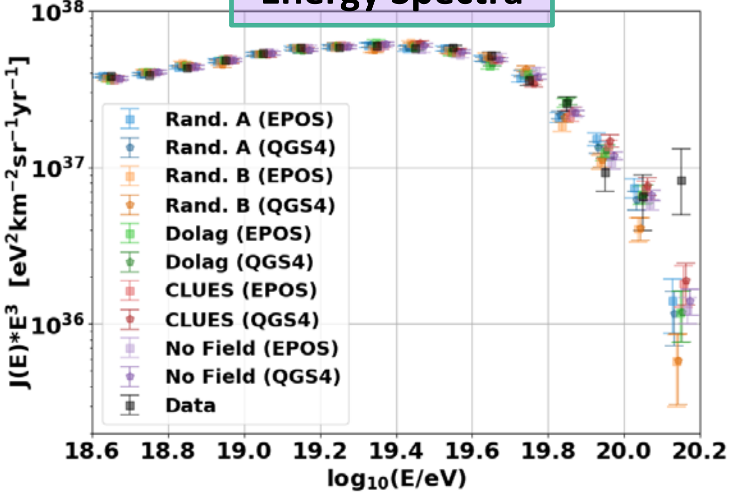
Spectrum Norm



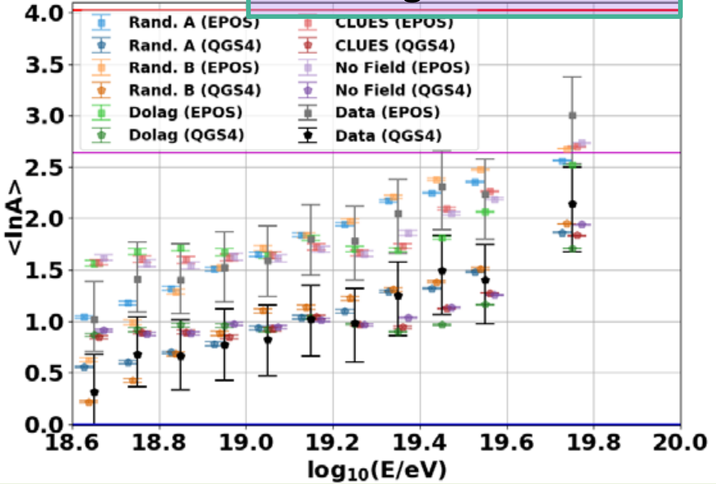
FR0 Emitted
Nuclei
Fraction

UHECR FR0 combined fit – Fitting observables

Energy Spectra



Mean log mass number

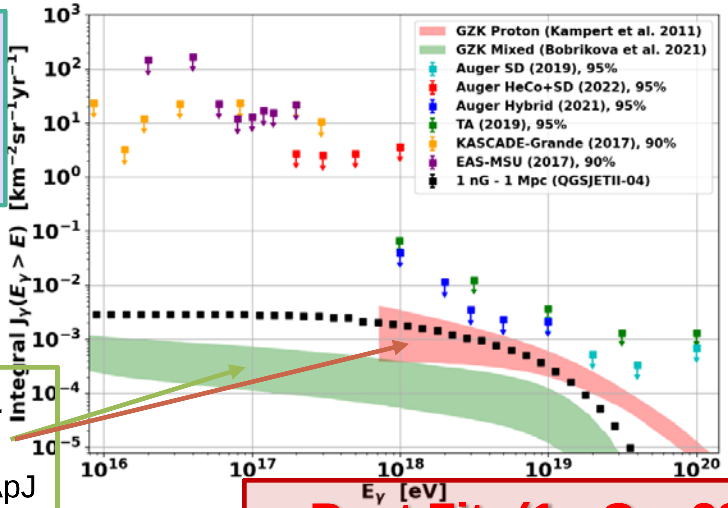


All 10 Models

FR0 not significant at highest energies.

Larger magnetic field fits lower energies.

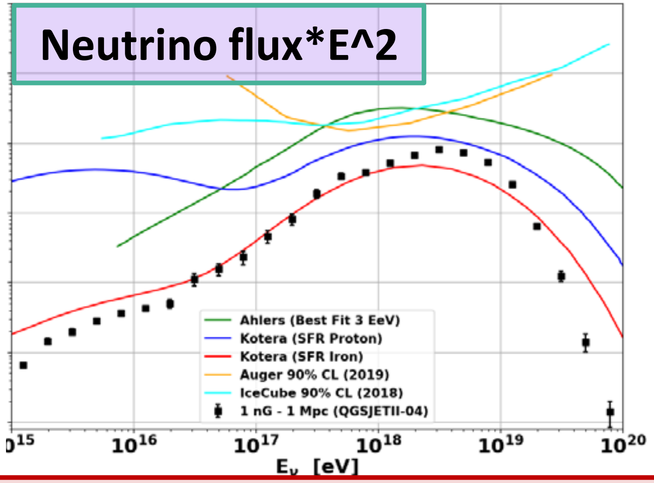
Integral photon flux



No field & GZK only

Abreu etal ApJ (2022)

Neutrino flux*E^2



Kotera et al: JCAP (2010)
arXiv:1009.1382
Ahlers et al: Astropart.Phys. (2010)
arXiv:1005.2620
IceCube: Phys.Rev.D(2018)
arXiv:1807.01820
Auger: JCAP (2019)
arXiv:1906.07422

Best Fit: (1 nG – 234 kpc, EPOS or QGSJETII-04)

Conclusions

- **FR0s** as most numerous jetted LLAGN **promising to contribute to UHECR-flux**
- **Lepto-hadronic jet-disc model** for core-emission from quiet LLAGN-jets **predicts:**
  - **close-to-equipartition conditions** in **core region, CR p-flux ≤ a few EeV (FR0)**
  - **characteristic MeV-feature** in photon SED of **FR0s from accretion flow**
  - **weak γ- & ν-emitter**
- CR-emitting **FR0** population **fits UHECR-observations** (spectrum, composition) **except @ highest energies (≥ 100 EeV)**

  Best Fit: **1 nG random field, 234 kpc corr length, QGSJETII-04 (or EPOS)**
- Source **energy spectral index γ~-2.6...-2.9, emitted composition dominated by p**
- **Cosmogenic γ-ray (ν-) flux** from z≤0.05 FR0 source sample **similar to pure p (Fe) composition**

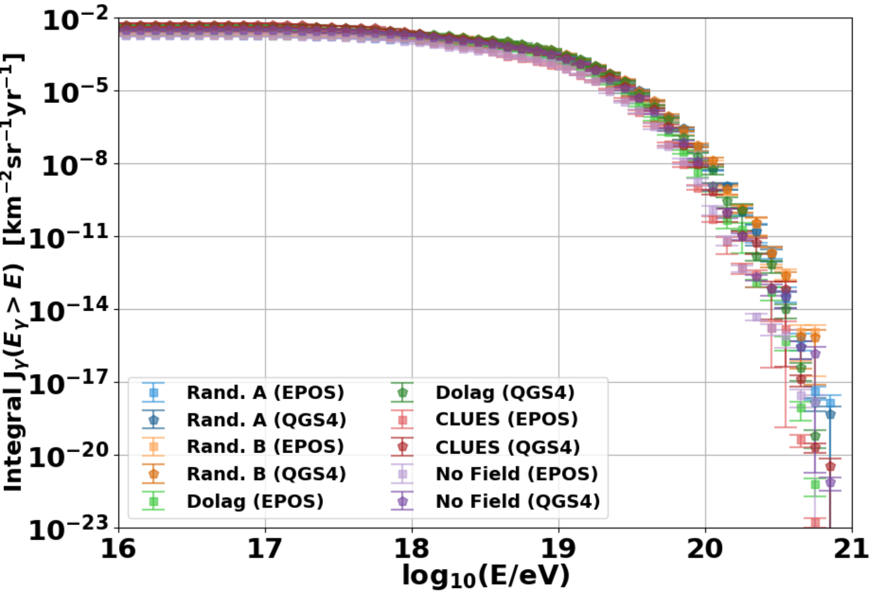
Co-funded by the European Union

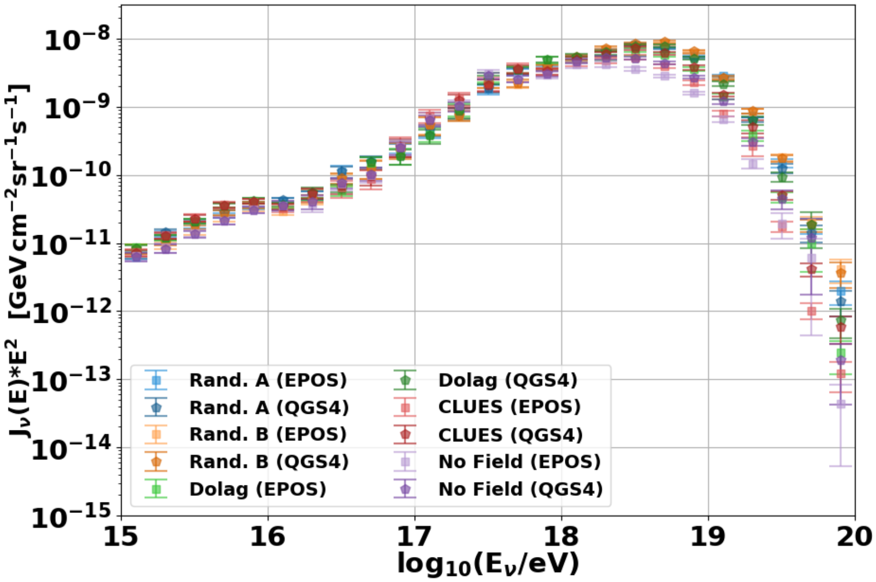
FWF Der Wissenschaftsfonds.

Slovenian Research Agency

- Back-up slides -

MODEL COMPARISONS

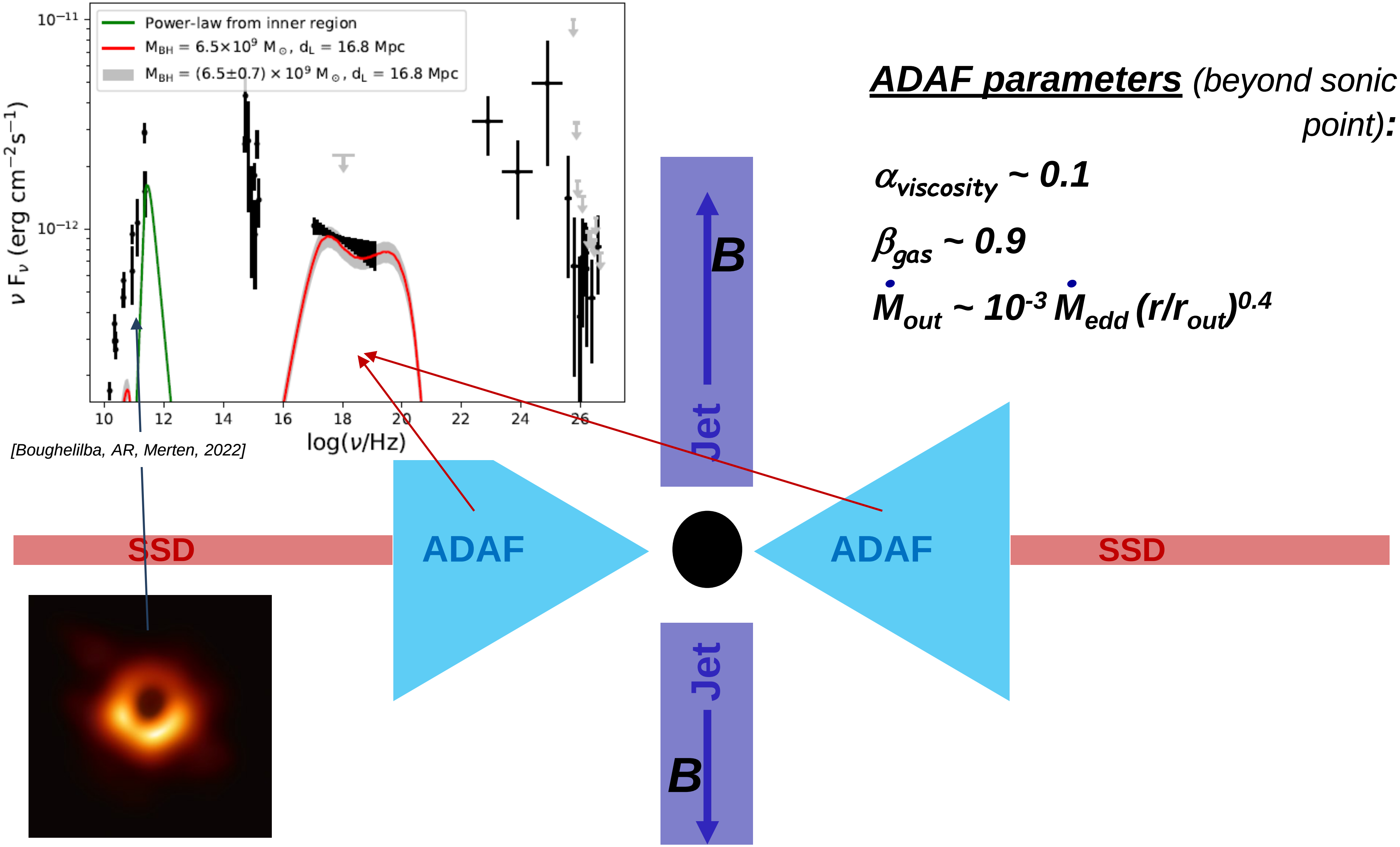




Integral photon flux for all models

Neutrino flux for all models

Hadronic Jet-Disc Model for M87



[Boughelilba, AR, Merten, 2022]

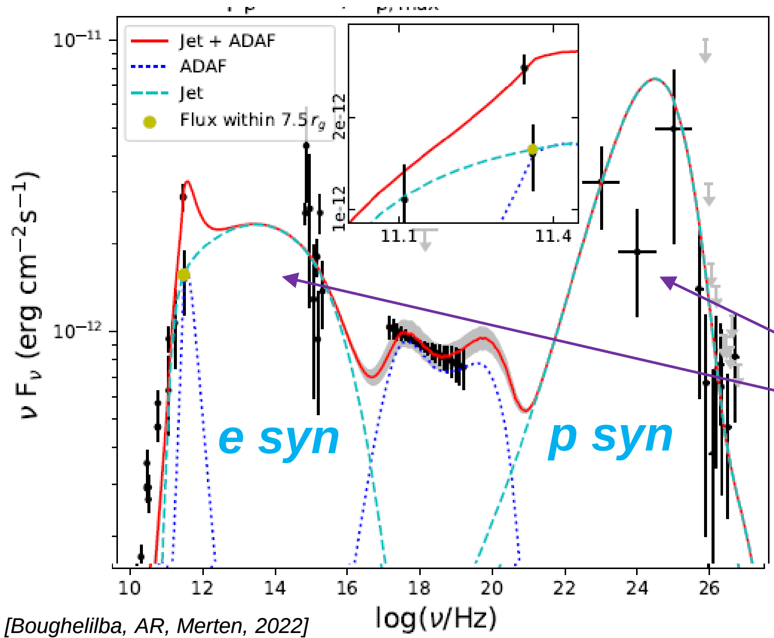
ADAF parameters *(beyond sonic point)*:

$\alpha_{viscosity} \sim 0.1$

$\beta_{gas} \sim 0.9$

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

Hadronic Jet-Disc Model for M87



[Boughelilba, AR, Merten, 2022]

Jet parameters:

R_{em} ~ 5r_g, δ_j~ 2.3

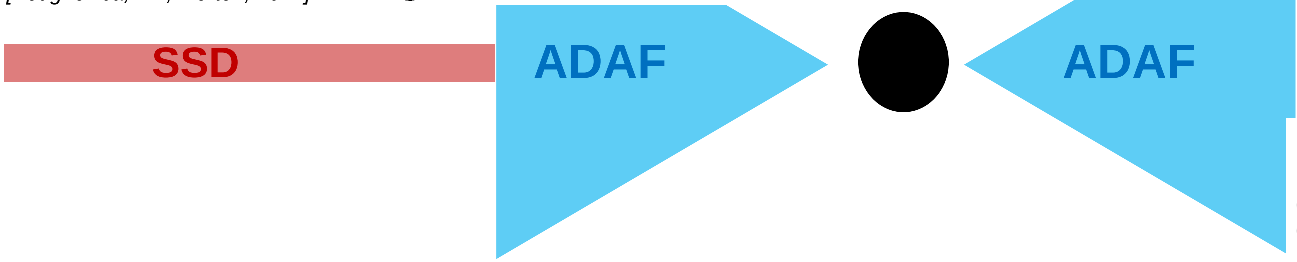
B ~ 10 (...50) **G**

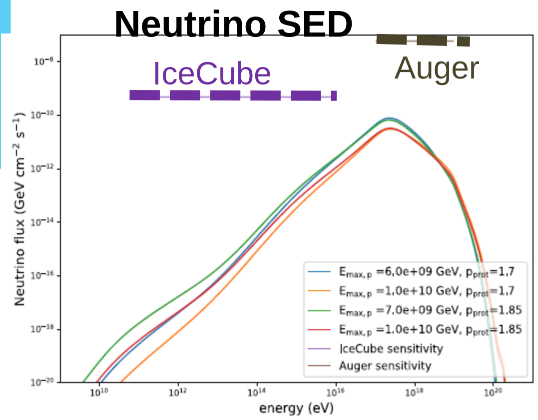
E_{pmax} ~ a few 10^{10} GeV, p_p~1.7...1.9

E_{emax} ~ 3 GeV, p_e~1.8...1.9

U_{part}/U_B ~ 0.6 ... 1.3

P_{jet} ~ 2...4 10^{43} erg/s



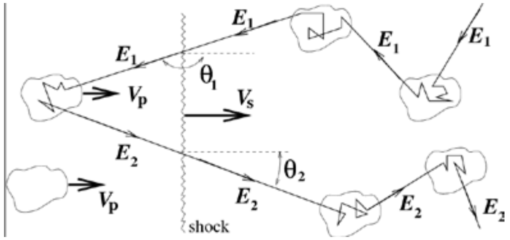


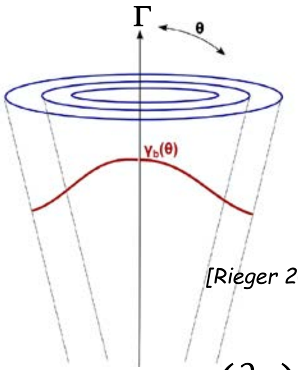
- *M87 as* ***relativistic p+e jet – ADAF system***
- ***Close-to-equipartition parameters*** *model core SED*
- ***Weak neutrino emitter*** *in IceCube energy range*

FR0 as UHECR candidate sources

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

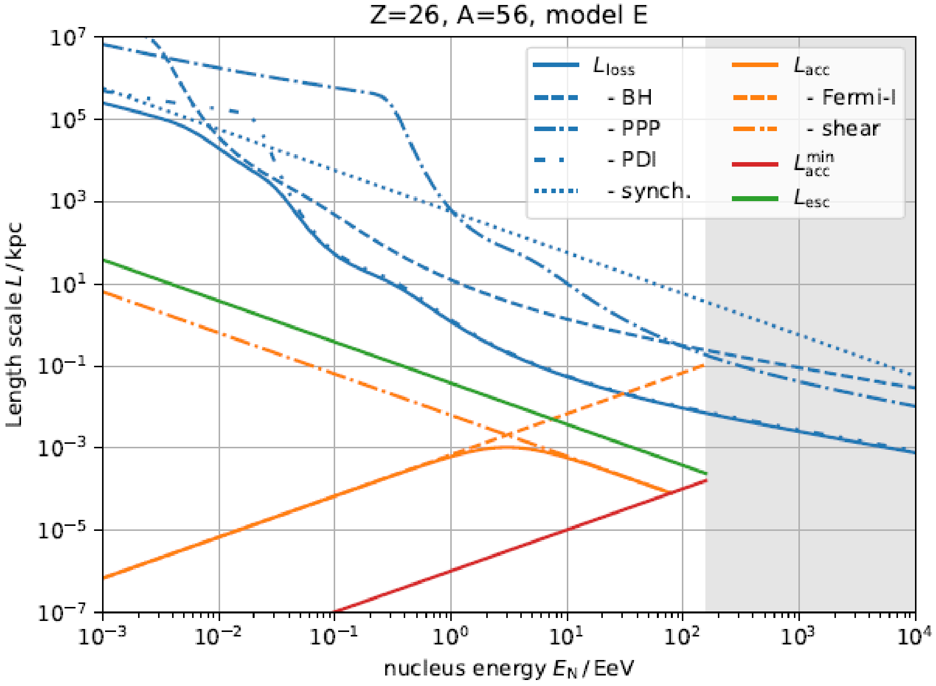
- **Particle acceleration:**





[Rieger 2019]

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



- **Particle energy losses:**

Photo-disintegration, photomeson production, Bethe-Heitler pair production, synchrotron radiation

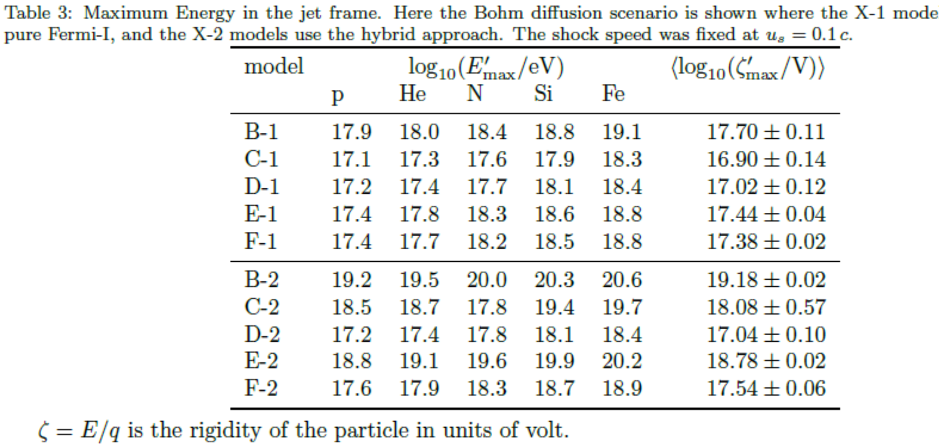


Table 3: Maximum Energy in the jet frame. Here the Bohm diffusion scenario is shown where the X-1 mode pure Fermi-I, and the X-2 models use the hybrid approach. The shock speed was fixed at $u_s = 0.1\,c$.

model	$\log_{10}(E'_{\max}/\text{eV})$					$\langle\log_{10}(\zeta'_{\max}/\text{V})\rangle$
	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.