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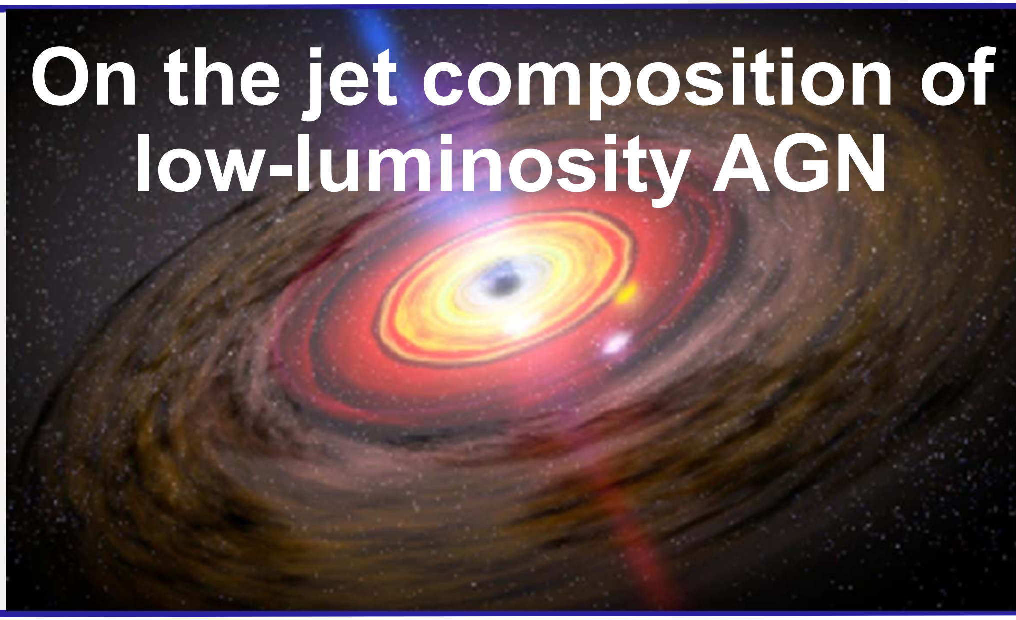
On the jet composition of low-luminosity AGN



Anita Reimer

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FWF Der Wissenschaftsfonds.

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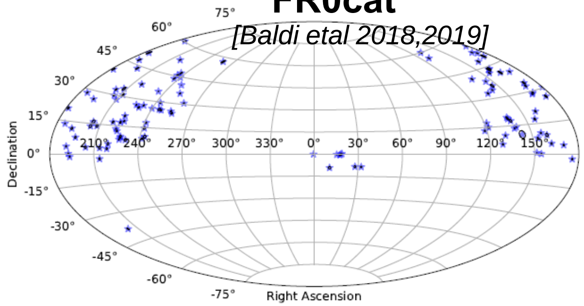
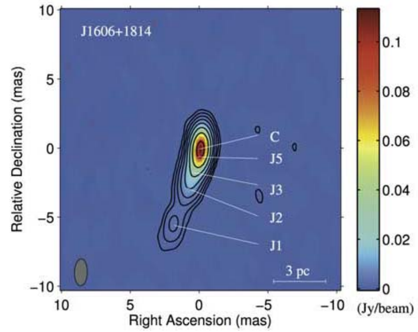
Most numerous low-luminosity AGN jet population

- Fanaroff-Riley 0 (FR0) Radio galaxies -

FR0cat
[Baldi etal 2018,2019]

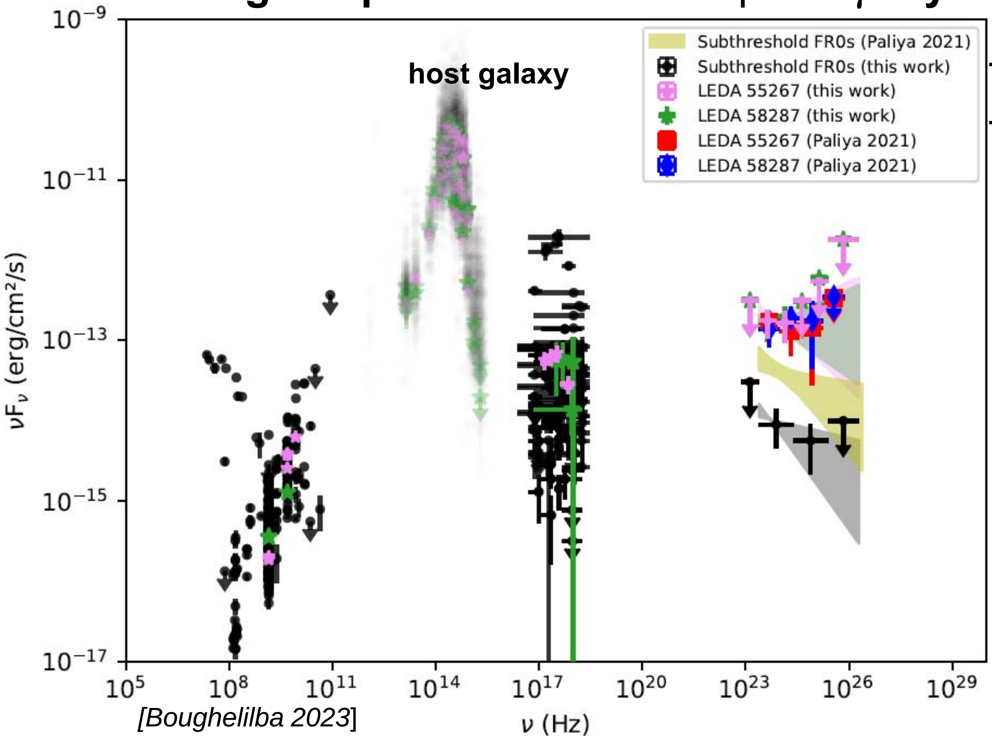


[from: Merten, Boughelilba, AR, etal 2021]



- **Core-dominated, pc ... kpc jets**
- $\mathbf{L_{jet} \approx 10^{42.5...43.5}}$ **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 2024]*
- **Auger dipole** measurem. requires **γ-ray dim, high n** source pop *[Partenheimer etal 2024]*

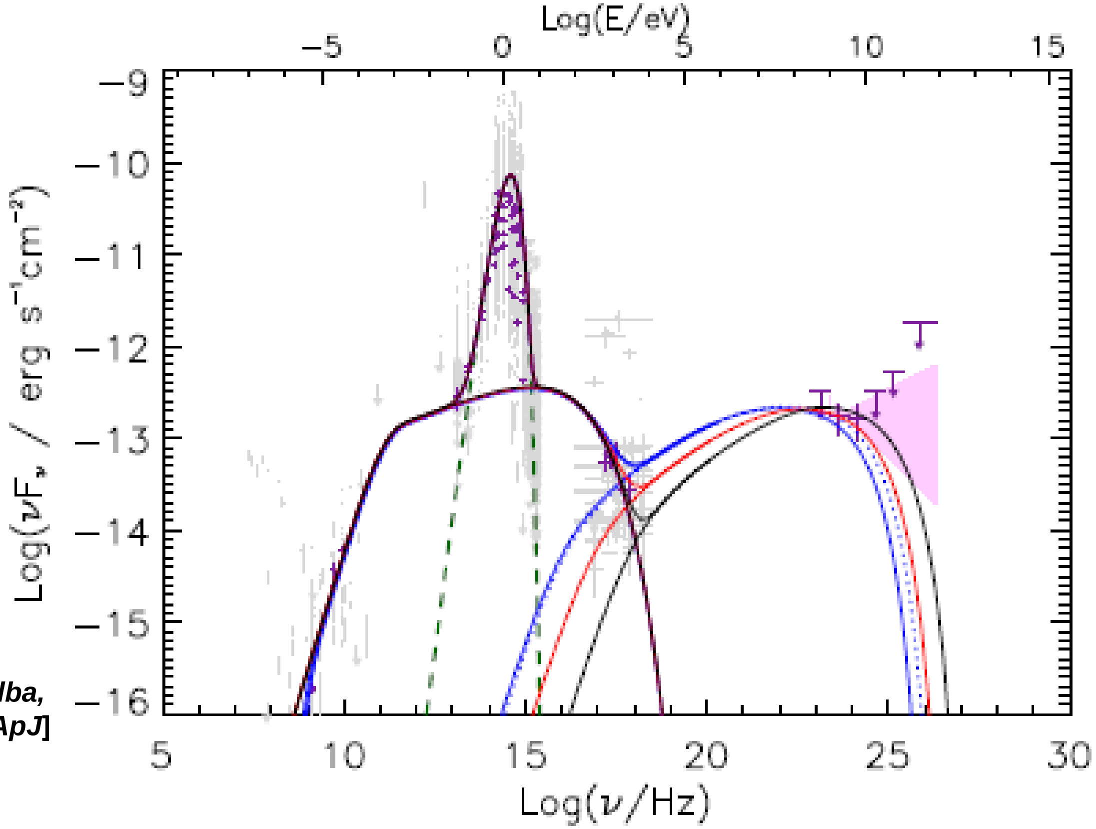
Jet composition ?



[Boughelilba 2023]

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

LEDA 55267: Leptonic Emission Model



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

Redshift z = 0.033

Black hole mass ~ $10^{8.2} M_\odot$

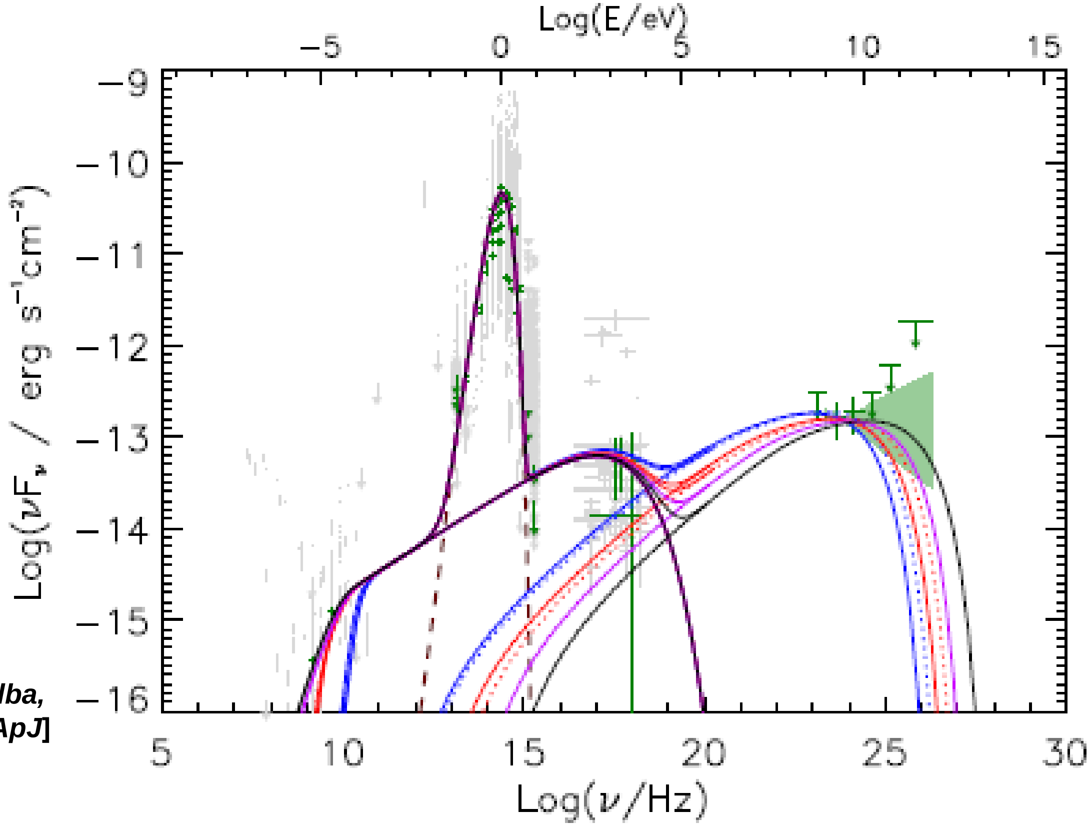
(One-zone) **SSC** models: Emission region size R' ~ $10^{16..18}$cm, bulk Lorentz factor Γ_j ~ 1.04 ... 1.34

Particle spectrum: α_e = 2.7, $\gamma_{e,max}$ ~ 7 $10^{4...5}$

Magnetic field **B' ~ 0.01 G ... 1 G** with **u_B / $u_{particle}$ ~ 0.07 ... 0.3**, L_{jet}<$10^{43.2}$ erg/s

-> Weakly magnetized, particle dominated jet emission region

LEDA 58287: Leptonic Emission Model



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

Redshift z = 0.04

Black hole mass ~ $10^{8.5} M_{\odot}$

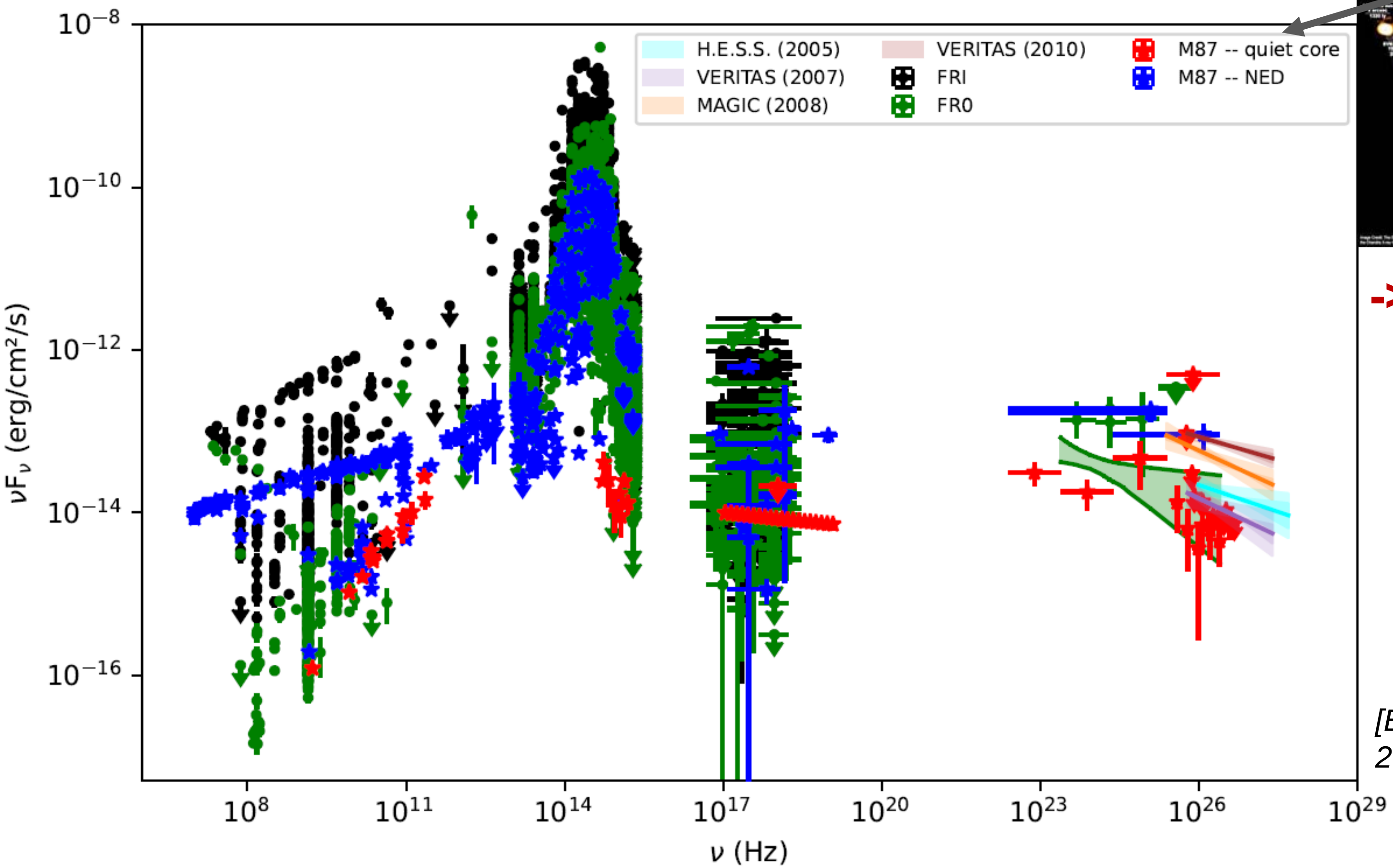
(One-zone) **SSC** models: Emission region size R' ~ $10^{14...17}$cm, bulk Lorentz factor Γ_j ~ 1.04 ... 1.34

Particle spectrum: α_e = 2.5, $\gamma_{e,max}$ ~ $10^{5...6.6}$

Magnetic field **B' ~ 0.005 G ... 5 G** with **u_B / $u_{particle}$ ~ $10^{-4 \,....\, -3}$**, L_{jet}<$10^{43.6}$ erg/s

-> Weakly magnetized, particle dominated jet emission region

Broadband SED of low-power radio galaxies



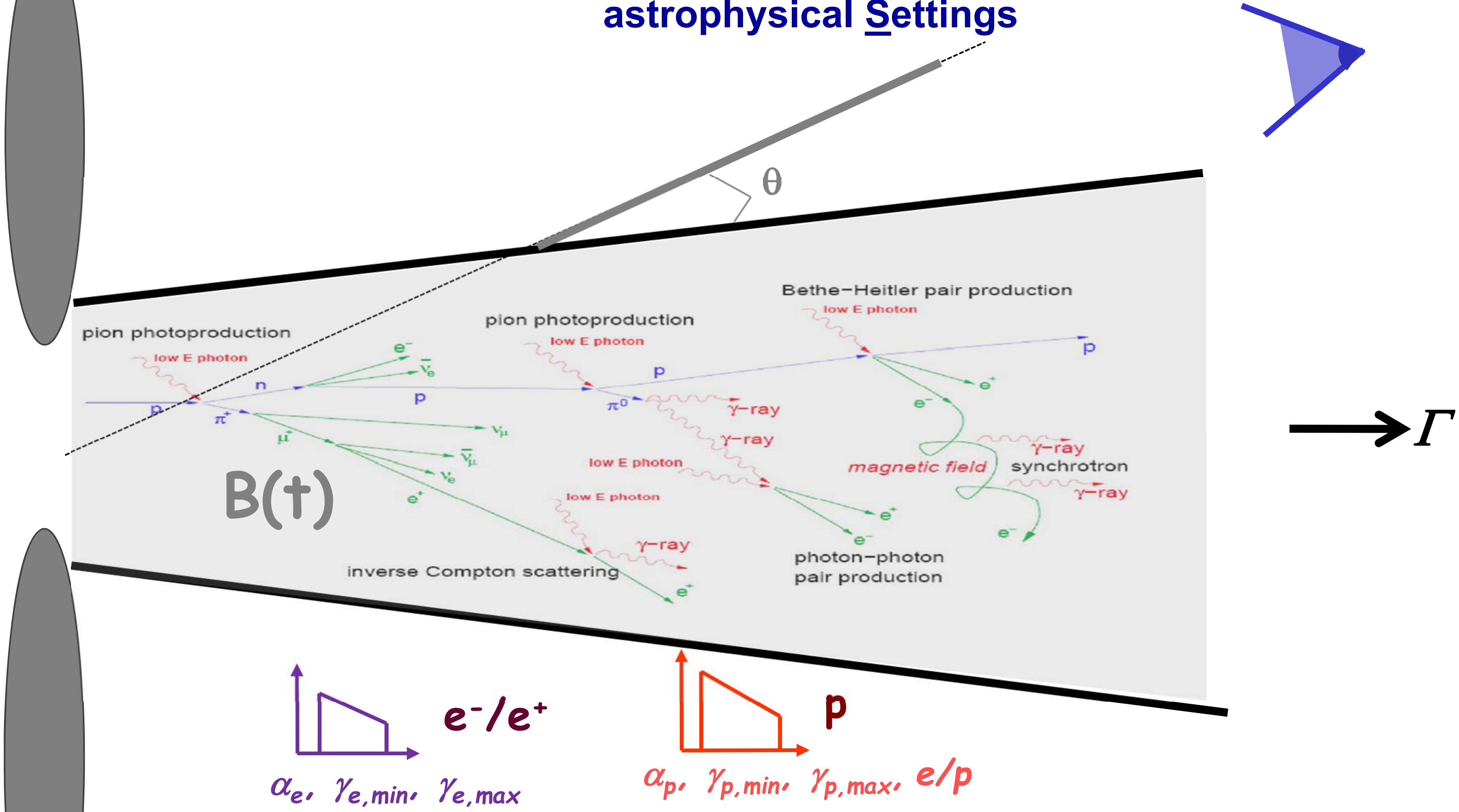
-> B_{core} ~ 5 ... 60 G
[EHT-collab. '21]

[Boughelilba & AR, 2023, ApJL]

Striking similarity of broadband photon emission between

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

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 *[Reimer etal]* & extension to CR ions *[Merten etal]*

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

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

$$\text{with } F_N = F_N(p,t),\ \ \dot{F}_N^{cat} = \dot{F}_N^{cat}(p,t),\ \ F_\gamma = F_\gamma(\epsilon,t),$$

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

$$Q_N^{inj} = Q_N^{inj}(F_\gamma(\epsilon,t), B(t), R(t); p, t)$$

- **Particle species:**
  - γ, p, n, e, π, μ, K, ν_μ, ν_e & 345 nuclei/isotopes
- **Interaction yields:**
  - Yields pre-calculated by corresponding event generators for p,e,γ-induced interactions, or calculated when required for heavy nuclei*

[branching ratio cut ~10^{-4}]*

CR-ENTREES *[Reimer etal]* & extension to CR ions *[Merten etal]*

- **Interactions & losses:**

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

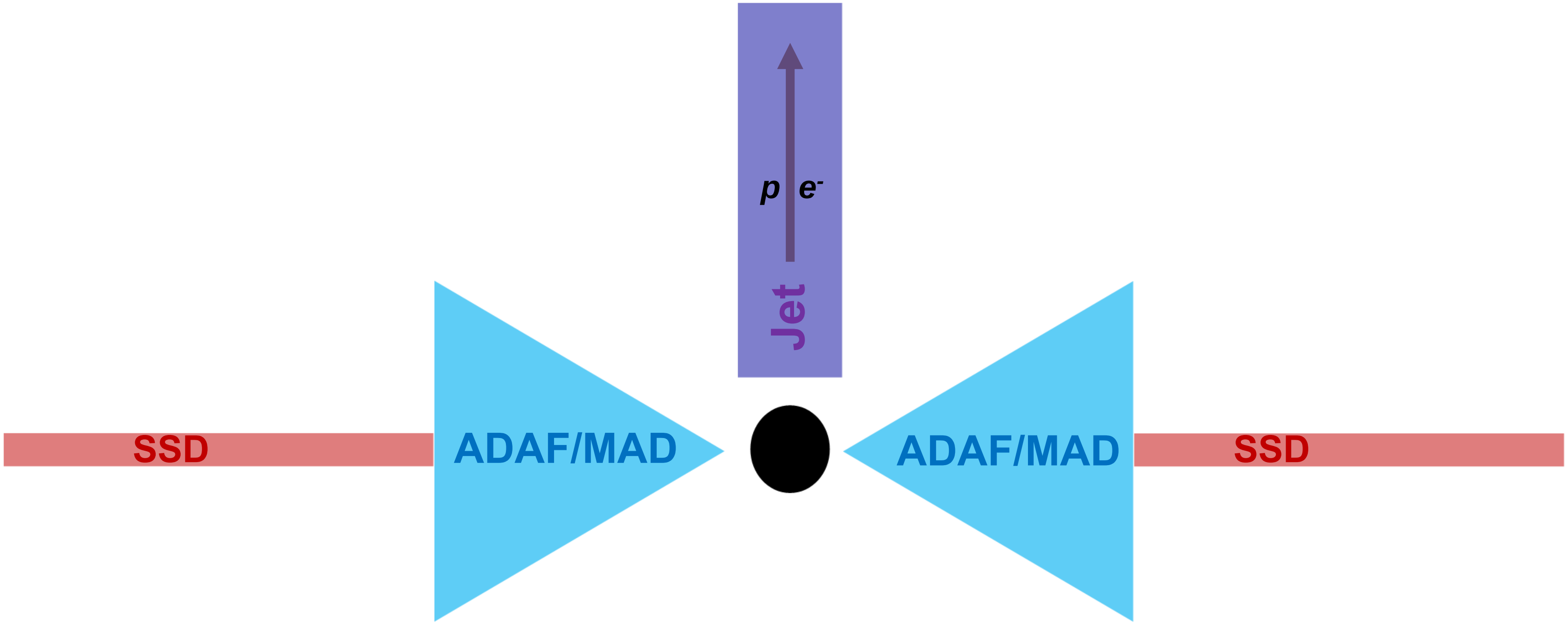
  [*immediate decay of radio-active isotopes for $\tau_{rest} < 4\ 10^{-4}$s]

- **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

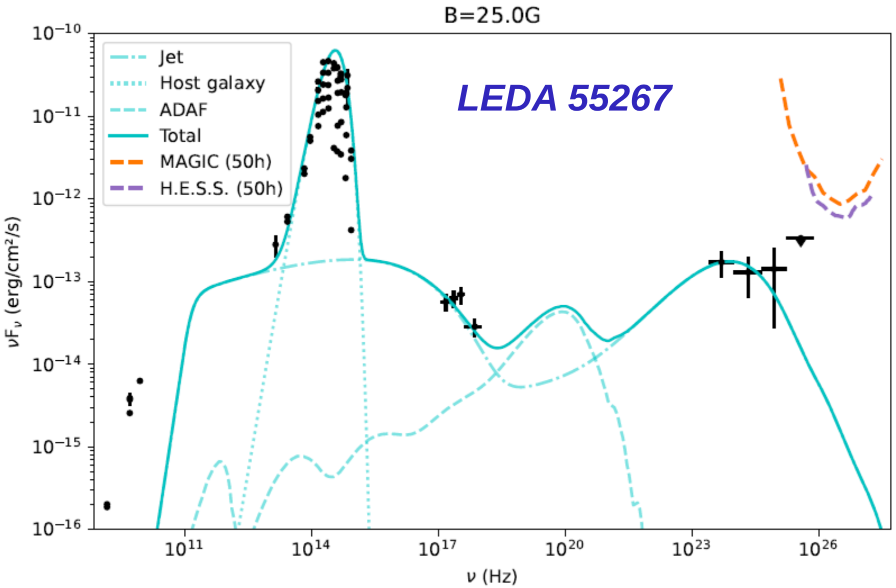
Hadronic jet - disc model

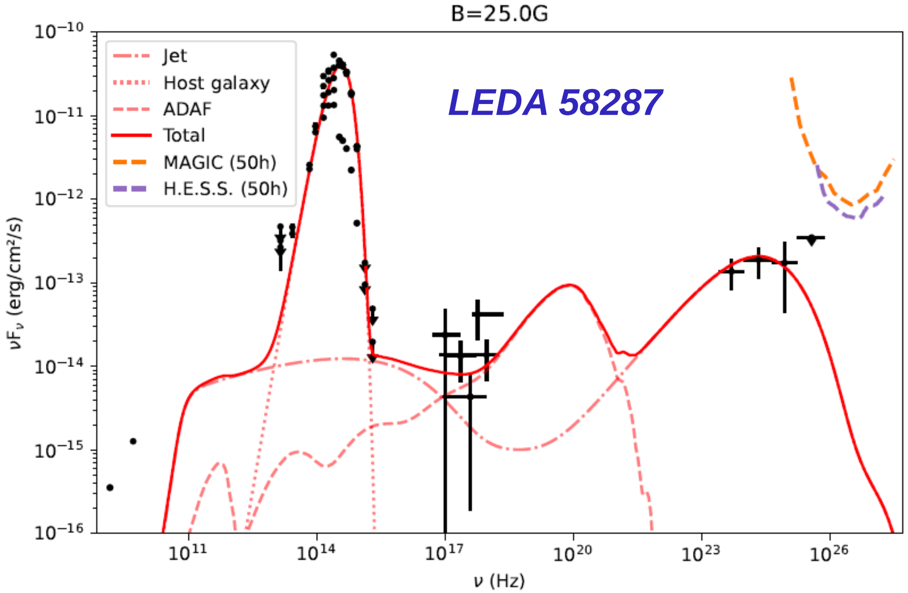


- ***M87 quiet core broadband SED*** *successfully modelled by* ***relativistic p + e jet-disc*** *(ADAF/MAD)* ***model*** ***[Boughelilba, AR, Merten, '22]***
- ***close-to-equipartition*** *parameters*
- ***Weak ν-emitter*** *in IceCube energy range*

A hadronic jet - disc model for FR0s

[Boughelilba & AR, 2023, ApJL]





ADAF/MAD 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, $\alpha_p \sim 1.7 \sim \alpha_e$

$U_{part}/U_B \sim 0.01 ... 0.5$, $P_{jet} \sim (1\text{-}3) \times 10^{43}$ erg/s

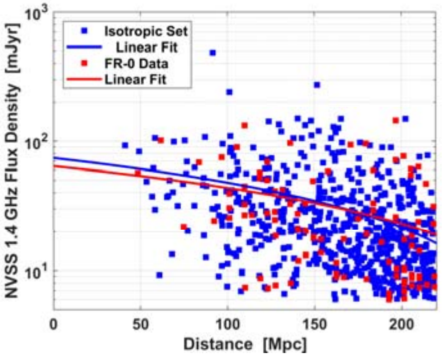
-> Slow, strongly magnetized jet containing CR-p reaching into EeV-regime

Further multi-messenger constraints ....

Simulations of **intergalactic UHECR propagation** (proton, helium, nitrogen, silicon, iron primaries) **emitted by FR0** ***[Lundquist etal 2024, arXiv:2407.06961]:***

Set-up:

- **Structured intergalactic fields:** no fields, Dolag etal (2014), Hackenstein etal (2017) ("CLUES"), 1nG random fields w Kolmog. power spec, $<l_{corr}>$= 234kpc, 647kpc
- Simulated **redshift distribution** from FR0CAT-data**:** close to **isotropy,** up-sampled to **z ≤ 0.02**
- **Source evolution** modeled by **correlation of radio output & redshift**



- **UHECR Injection:**

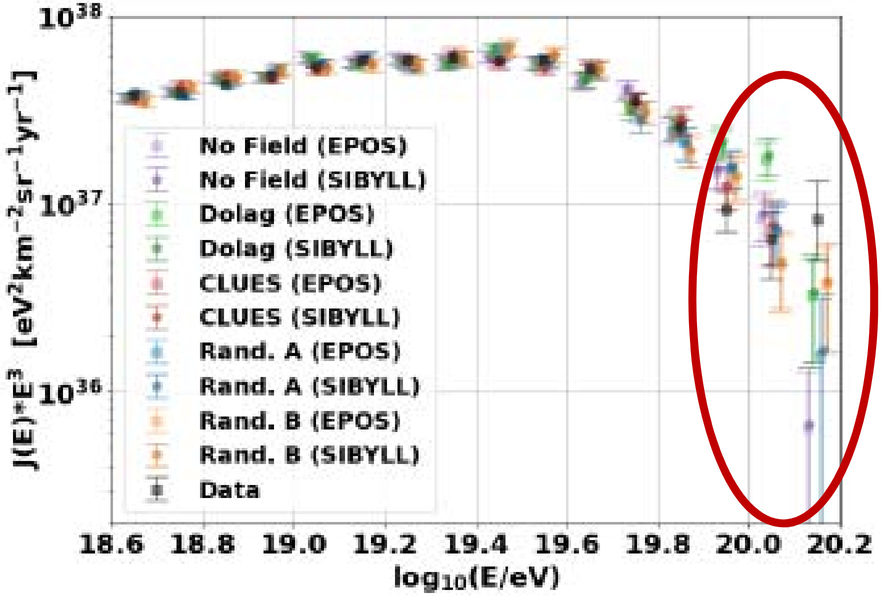
$$\frac{\mathrm{d}N_A}{\mathrm{d}E} = J_A(E) = f_A J_0 \left(\frac{E}{10^{18}\ \mathrm{eV}}\right)^{-\gamma} \times f_{\mathrm{cut}}(E, Z_A R_{\mathrm{cut}})$$

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

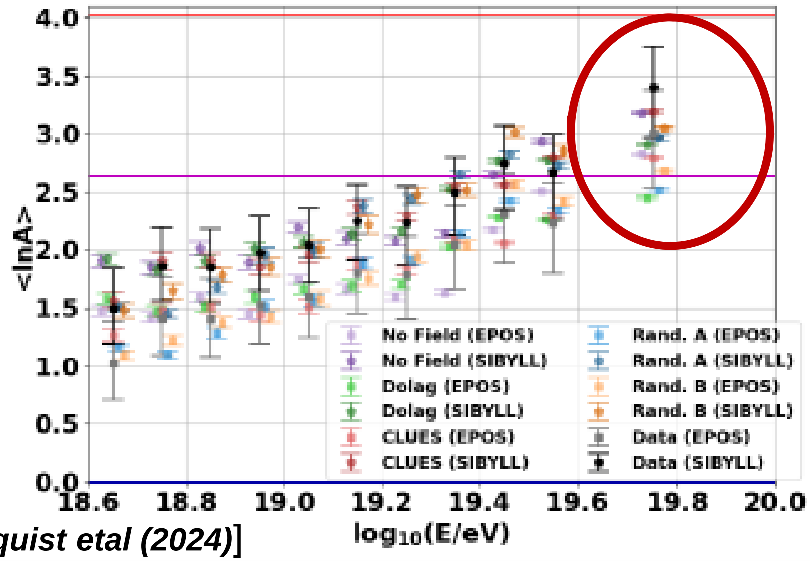
with:
- energy-independent **nuclei fraction** f_A
- rigidity-dependent **energy cutoff** ZR_{cut}

- FR-0 **UHECR flux** ∝ radio output

Further multi-messenger 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	$1.97^{+0.26}_{-0.05}$	$19.52^{+0.08}_{-0.07}$



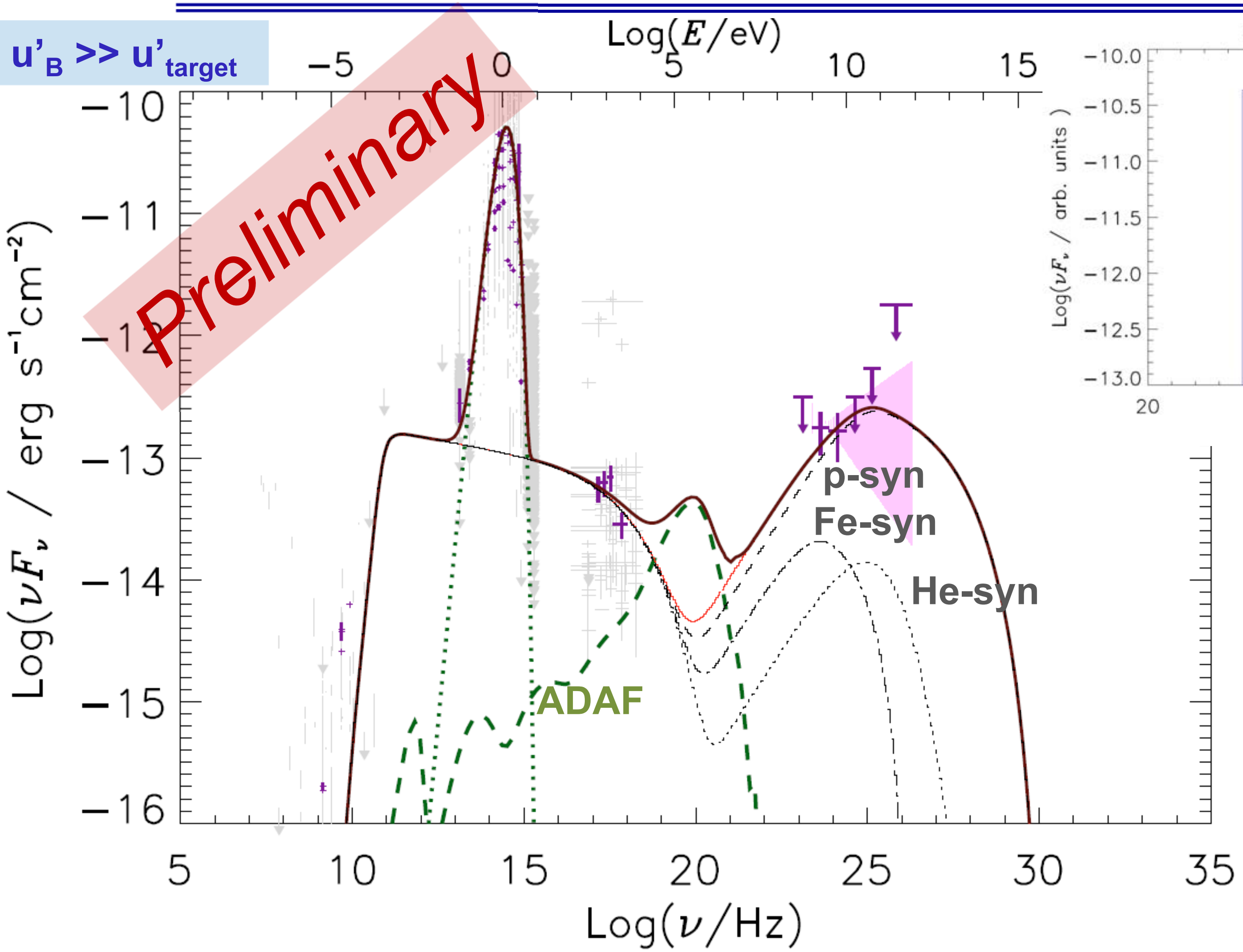
[Lundquist etal (2024)]

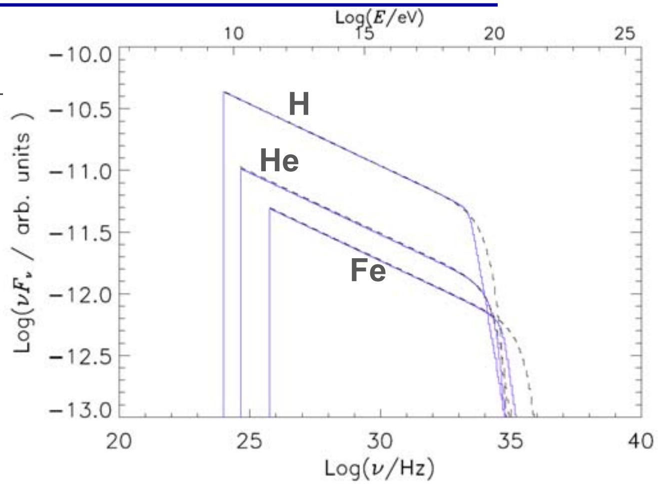
Best "Fit":

- emitted spectrum @source with γ**~2.4-2.5**
  -> **harder in-source particle spectrum**
- Composition @ source:
  f_{H+He} :f_N:f_{Si}: f_{Fe} ~
  0.804...0.948 :0:0: 0.057...0.117
- *Caveat:* Too low flux & too light composition @ highest E (>**50 EeV**)

LEDA 55267 jet containing UHECR nuclei

$u'_B >> u'_{target}$





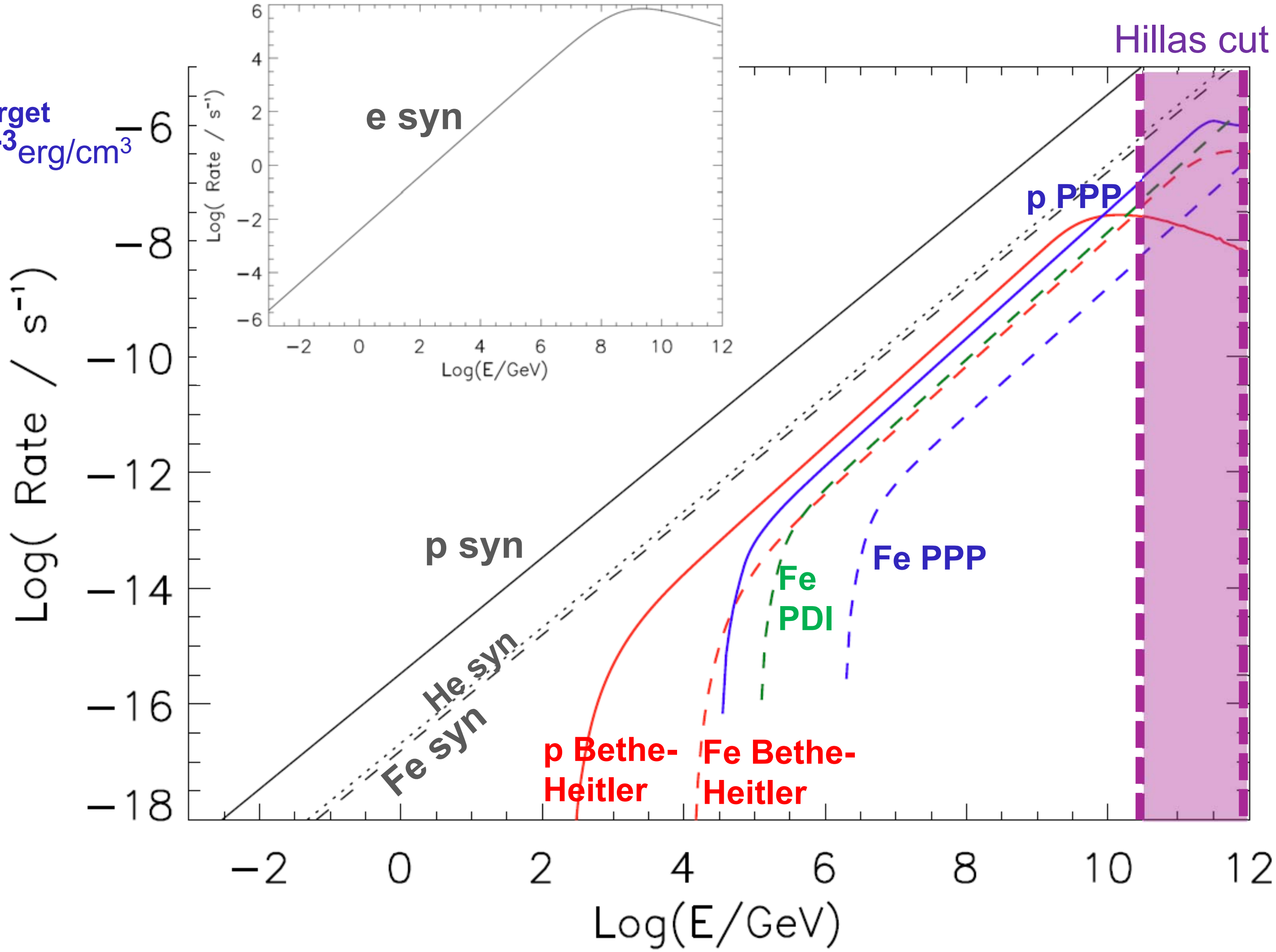
Jet parameters:

R'=4 10^15cm, Γ_j=1.2,
B'=25G, u'_{CR,inj} ~ 0.5 u'_B,
H:He:Fe = .745 : .173 : .082
(CLUES+SYBILL best-fit),
$u'_{e,inj}$~0.04$u'_{CR,inj}$,
$E_{emax,ss}$~10GeV
$\alpha_{CR} = \alpha_e = 2.1$,
$E_{CR,max,ss}$~ Z $10^{19.5}$eV,
L_{jet} ~ $10^{43.5}$ erg/s

Broadband SED in line with slow jet (containing **CR p, He, Fe) + ADAF model**

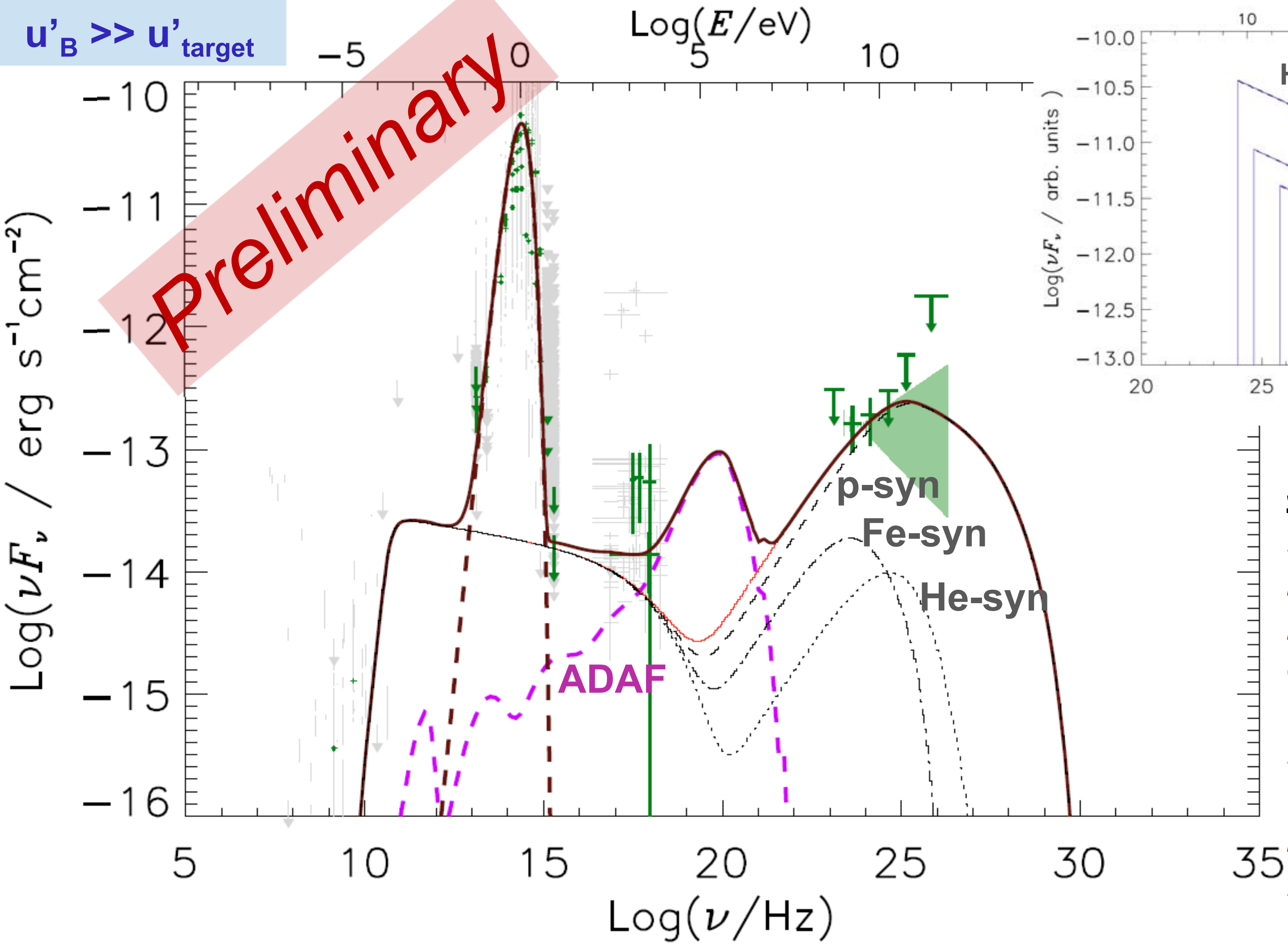
Interactions

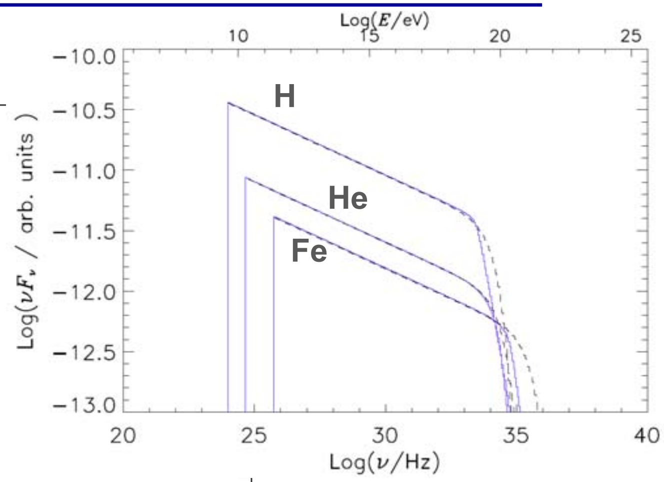
B = 25G,
$u'_B \gg u'_{target}$ $\sim 10^{-3}$erg/cm^3



LEDA 58287 jet containing UHECR nuclei

u'$_B$ >> u'$_{target}$





Jet parameters:

R'=4 10^{15}cm, Γ_j=1.2,
B'=25G, u'$_{CR,inj}$ ~ 0.75 u'$_B$,
H:He:Fe = .745 : .173 : .082
(CLUES+SYBILL best-fit),
u'$_{e,inj}$ ~ 0.007u'$_{CR,inj}$,
$E_{e,max,ss}$~ 10GeV,
α_{CR} = α_e = 2.1,
$E_{CR,max,ss}$ ~ Z $10^{19.5}$eV,
L_{jet} ~ $10^{43.6}$ erg/s

Broadband SED in line with slow jet (containing **CR p, He, Fe) + ADAF model**

Conclusions

- Bulk of **UHECR sources γ-ray dim, ν-weak** & sufficient **numerous:**

  -> FR0s as most numerous jetted LLAGN promising

- **Broadband modelling** to investigate **FR0 jet composition:**

  - **Relativistic $e^{\pm}$ -jets:**

    low magnetized, particle-dominated emission region

  - **Relativistic e^{-}-ion jets:**

    high magnetized, close-to-equipartition conditions in emission region

    in line with all particle multi-messenger constraints

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