Ultra-high energy cosmic rays by Cygnus A or the bulk of non-local radio galaxies?

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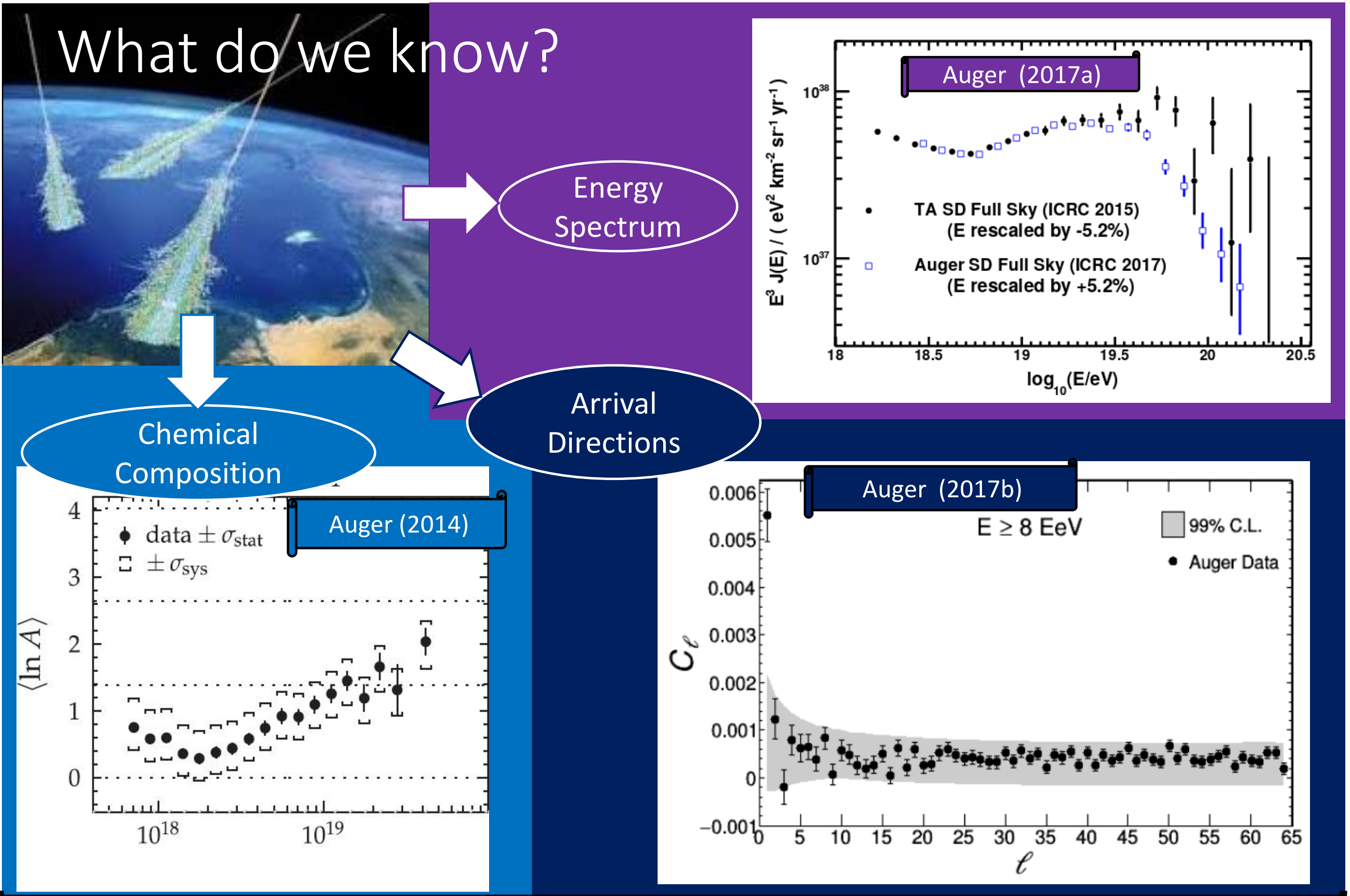
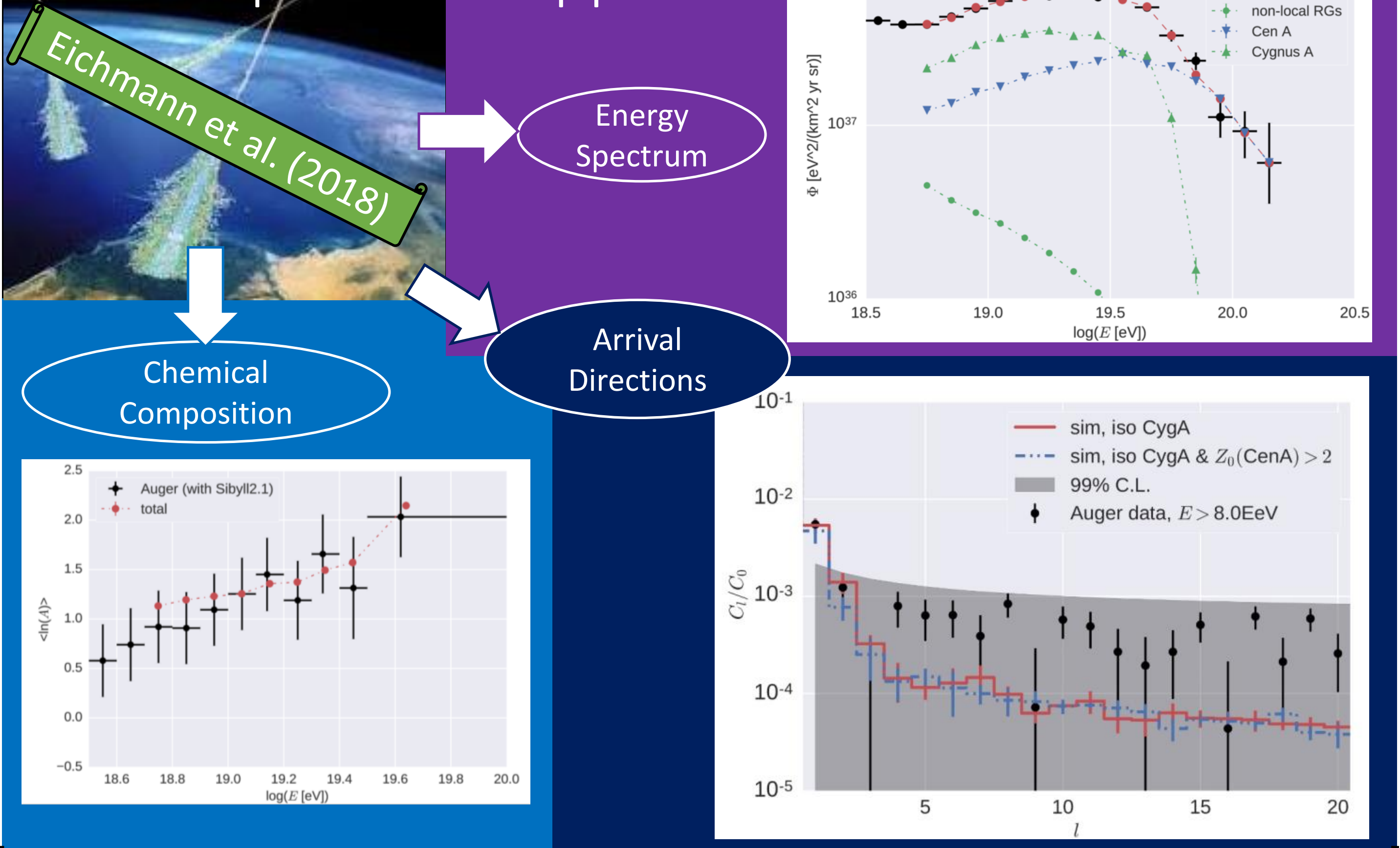


? ? ? ? by radio galaxies ? ? ? ?

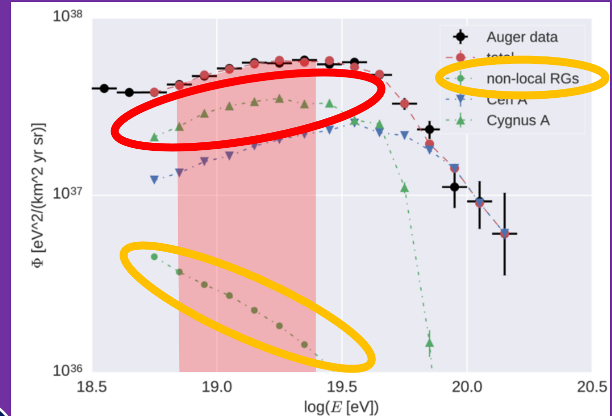
First explanation approach



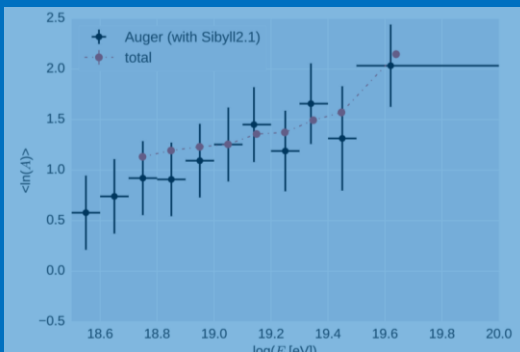
! ! ! by Cen A & Cyg A ! ! !

First explanation approach

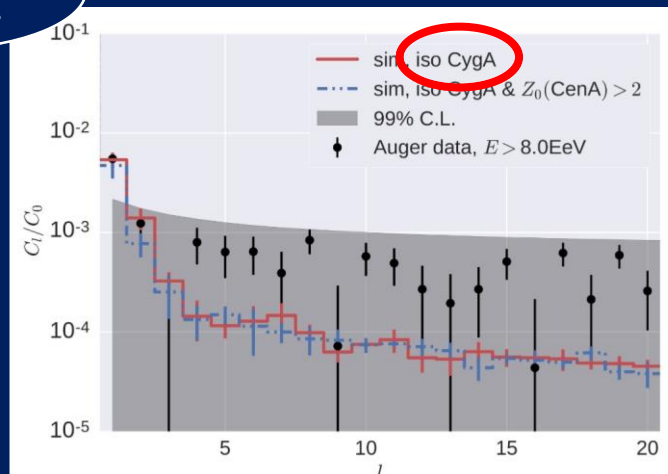
Energy Spectrum



Chemical Composition



Arrival Directions

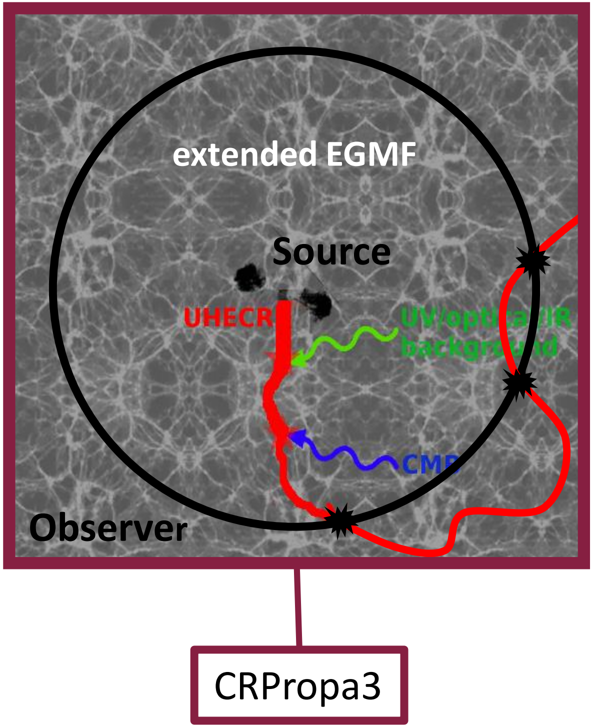


! ! ! by Cen A & Cyg A ! ! !

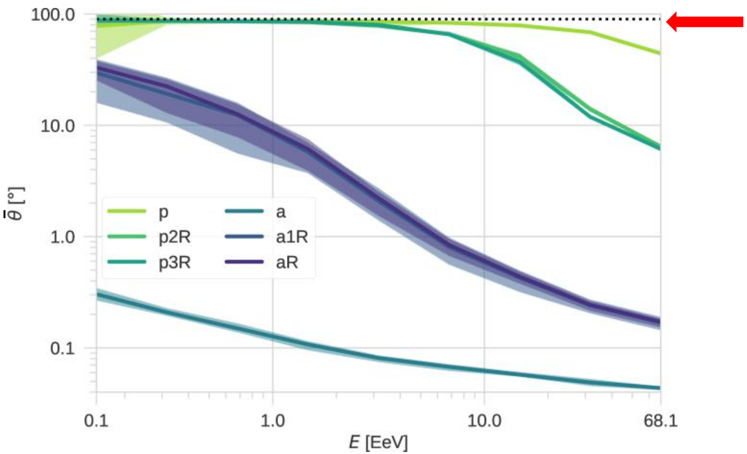
(I) Can UHECRs by Cyg A be isotropized?

The inverted simulation setup

- Extended EGMF models by Hackstein et al. (2018)
  - 3 primordial models (p, p2R, p3R)
  - 3 astrophysical models (a, a1R, aR)
- Include interactions with the EBL and CMB
- Observer sphere with radius = source distance
- Defl. angle $\theta = \sphericalangle(\vec{p}_{cr}, \vec{d}_{src})$
  - Re-weighting needed: Apply $|\cos\theta|^{-1}\,(\sin\theta)^{-1}$ to obtain a proper CR flux

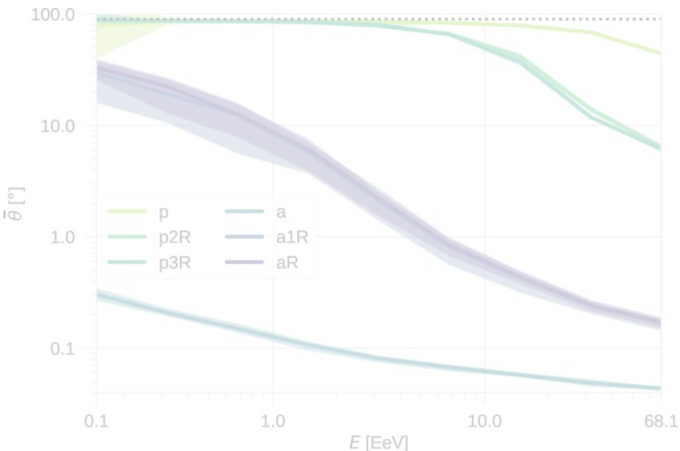


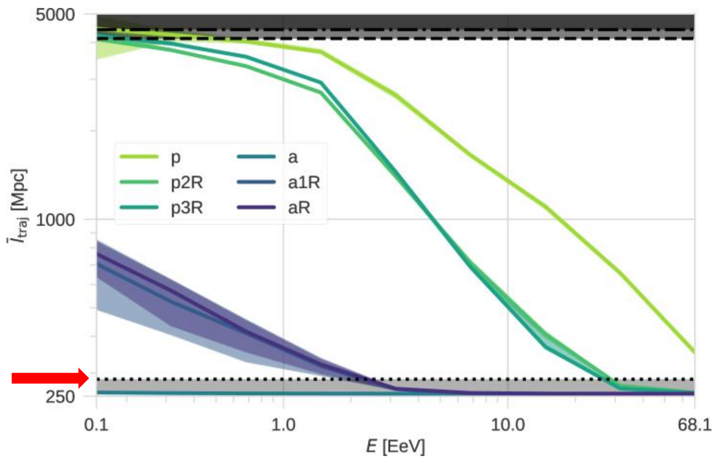
The deflection & trajectory lengths of Cyg A



Only the primordial models (p, p2R, p3R) are able to isotropize UHECRs from Cyg A

The deflection & trajectory lengths of Cyg A

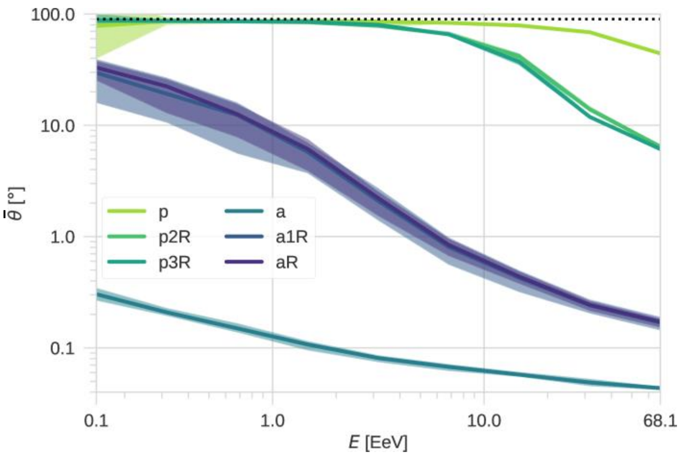


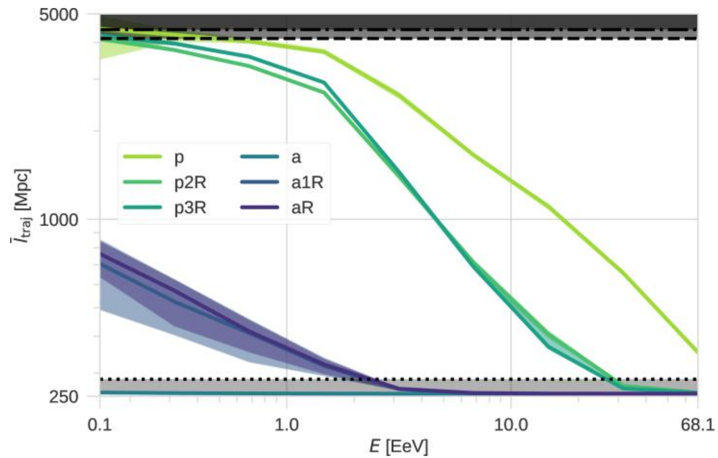


Only the primordial models (p, p2R, p3R) are able to isotropize UHECRs from Cyg A

Only the astrophys. models (a, a1R, aR) yield a delay < age of Cyg A ($< 10^8 \mathrm{yr}$)

The deflection & trajectory lengths of Cyg A





Either the arrival directions of UHECRs provide a (too) high degree of anisotropy or the delay exceeds the source age!

(II) Can the bulk of non-local radio galaxies provide the observed UHECR flux?

The UHECR – radio connection

- **CR power** from the jet power: $Q_{cr} \simeq \frac{g_m}{1+k} Q_{jet}$
  - g_m: jet energy found in matter (hadronic *and* leptonic) → *min. jet energy cond.:* $g_m \simeq \frac{4}{7}$
  - $k = Q_e/Q_{cr}$: ratio of leptonic to hadronic energy → for a vanishing lepton fraction $k \ll 1$
- **Jet power** from extended radio emission: $Q_{jet} \propto L_{151}^{\beta_L}$
- **Maximal rigidity** from

magn. field energy $Q_B = c\beta_{jet}\pi r^2 \frac{B^2}{8\pi} = Q_{jet} - (Q_{cr} + Q_e) = Q_{jet}(1 - g_m)$

and *Hillas criterion* $\hat{R} \equiv \frac{E_{max}}{Ze} = \frac{\beta_{sh}}{f_{diff}} Br$

$$\hat{R} \simeq g_{acc}\sqrt{(1 - g_m)Q_{jet}/c}\,, \text{ with } g_{acc} = \sqrt{\frac{8\beta_{sh}^2}{f_{diff}^2 \beta_{jet}}}$$

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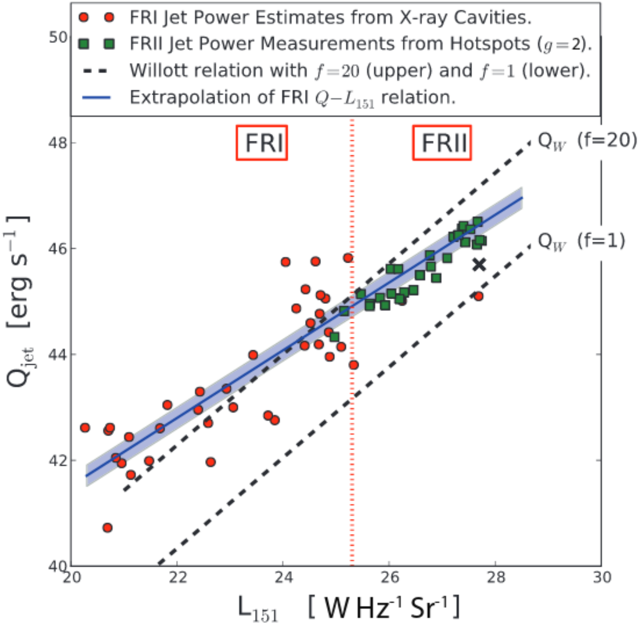
$$0.01 \leq g_{acc} \leq 1; \qquad g_m < 1 \;(g_m \sim 4/7); \qquad \beta_L = ?$$

Study of the non-local source contribution

Include fundamental differentiation between FR-I and FR-II sources:

- Use the *jet-to-radio-power correlation* from Godfrey & Shabala (GS):



$$\text{GS2013: } \beta_L = \begin{cases} 0.64 & \text{for FR I,} \\ 0.67 & \text{for FR II} \end{cases}$$

(obs. bias)

$$\text{GS2016: } \beta_L \simeq \begin{cases} 0.5 & \text{for FR I,} \\ 0.8 & \text{for FR II} \end{cases}$$

(from theor. expectations)

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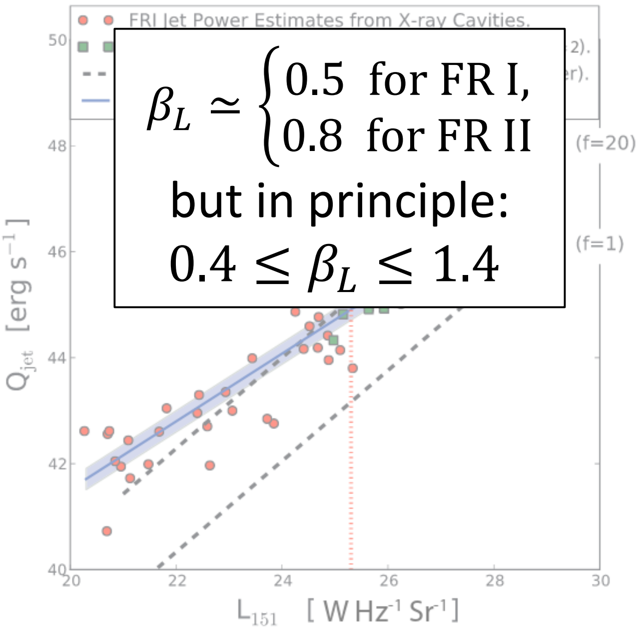
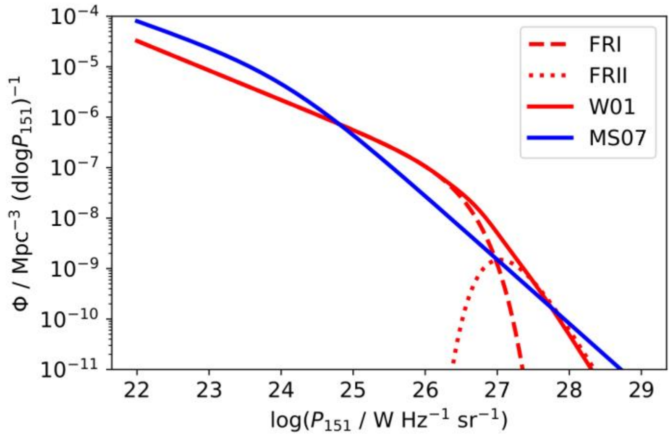


$$\beta_L \simeq \begin{cases} 0.5 & \text{for FR I,} \\ 0.8 & \text{for FR II} \end{cases}$$

but in principle:

$$0.4 \leq \beta_L \leq 1.4$$

- Use the *radio luminosity function* from Willott et al. (2001):



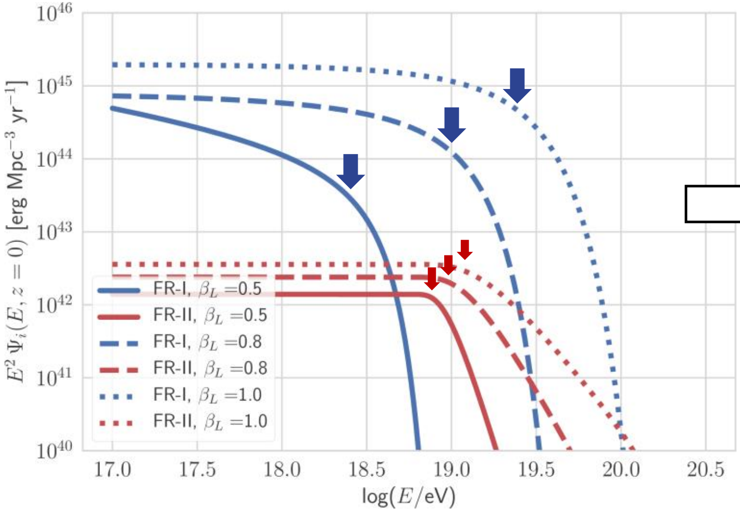
Spectral behaviour constraints

Bulk of FR-I and FR-II sources have a different **critical rigidity**:

$$R_* = g_{acc}\sqrt{(1-g_m)Q_*/c}, \quad \text{with} \quad Q_* \propto L_{I,II}^{\beta_L},$$

$$0.01 \leq g_{acc} \leq 1; \quad g_m < 1 \ (g_m \sim 4/7); \quad 0.4 \leq \beta_L \leq 1.4$$

⇨ $R_* > 30$ EV to enable an explanation of the UHECR flux $\lesssim 30$ EeV



⇨ R_* in the case of FR-I depends significantly on β_L

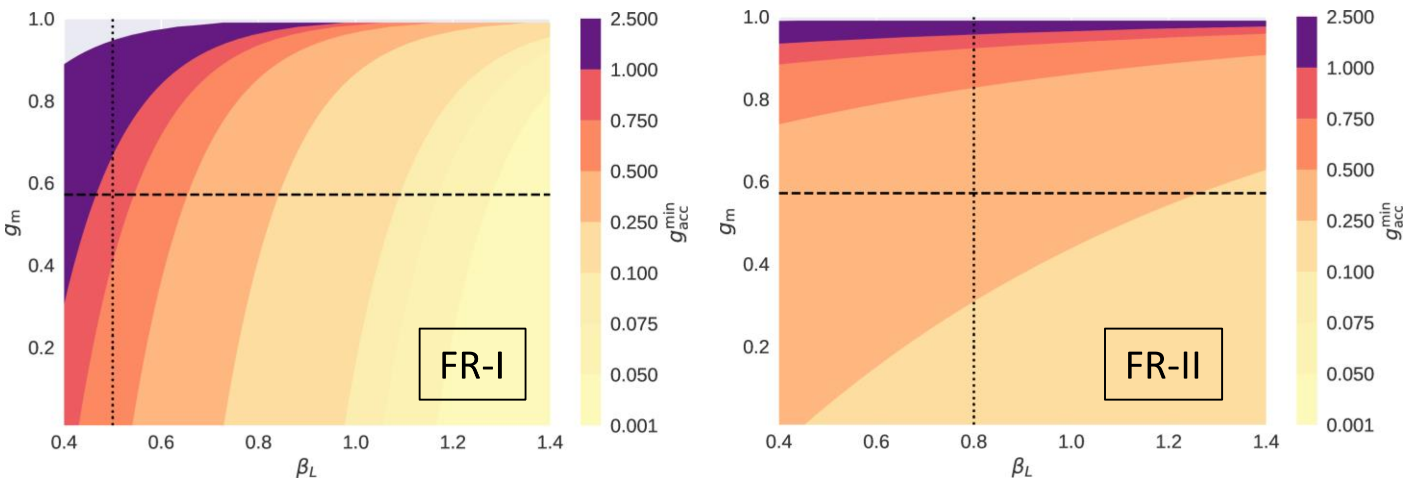
Spectral behaviour constraints

Bulk of FR-I and FR-II sources have a different **critical rigidity**:

$$R_* = g_{acc}\sqrt{(1-g_m)Q_*/c}, \quad \text{with} \quad Q_* \propto L_{I,II}^{\beta_L},$$

$$0.01 \leq g_{acc} \leq 1; \qquad g_m < 1 \ (g_m \sim 4/7); \qquad 0.4 \leq \beta_L \leq 1.4$$

$$\Rightarrow \quad g_{acc} > 30\ \mathrm{EV}/\sqrt{(1-g_m)Q_*/c}\,, \text{with } Q_* = Q_*(\beta_L)$$



Spectral behaviour constraints

B…lk of FR-I and FR-II sources have a different critical rigidity:

$$\ldots = g_{acc}\sqrt{(1-g_m)Q_*/c}, \quad \text{with} \quad Q_* \propto L_{I,II}^{\beta_L},$$

$$\ldots 1; \quad g_m < 1 \ (g_m \sim 4/7); \quad 0.4 \le \beta_L \le 1.4$$

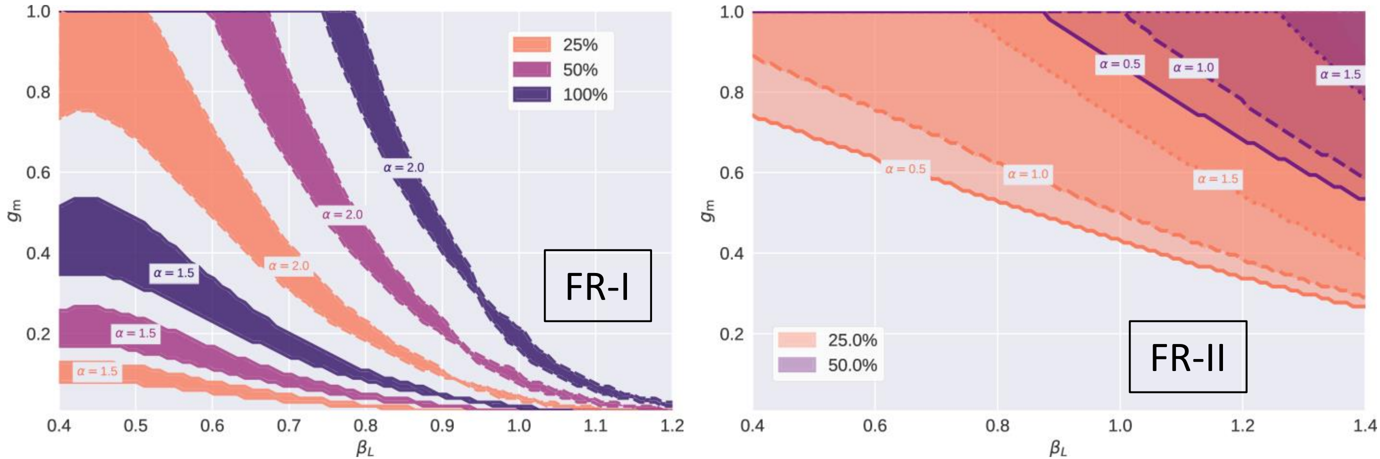
$$\Rightarrow \quad g_{acc} \ldots - g_m)Q_*/c, \text{ with } Q_* = Q_*(\beta_L)$$

FR-I and FR-II sources can in principle provide the observed spectral behavior at $5\text{EeV} \le E \le 30\text{EeV}$ (FR-IIs for a wider range of parameters)!

Total amount of UHECR energy constraints

Bulk of FR-I and FR-II sources provide a different **amount of UHECR energy** $(6\text{EeV} \leq E \leq 20\text{EeV})$ at Earth:

- dependent on the initial spectral index a, g_m, g_{acc}, β_L
- take $R_* > 30$ EV and $g_{acc} > 0.1$ into account



FR-II: hardly provide more than 25% of the obs. energy;
FR-I: provide 100% of the obs. energy for a wide range of parameters.

(I) Can UHECRs by Cyg A be isotropized?

No; or yes, but the delay exceeds the source age!

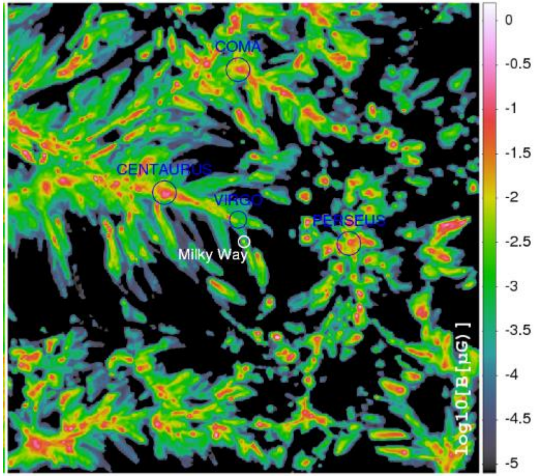
(II) Can the bulk of non-local radio galaxies provide the observed UHECR flux?

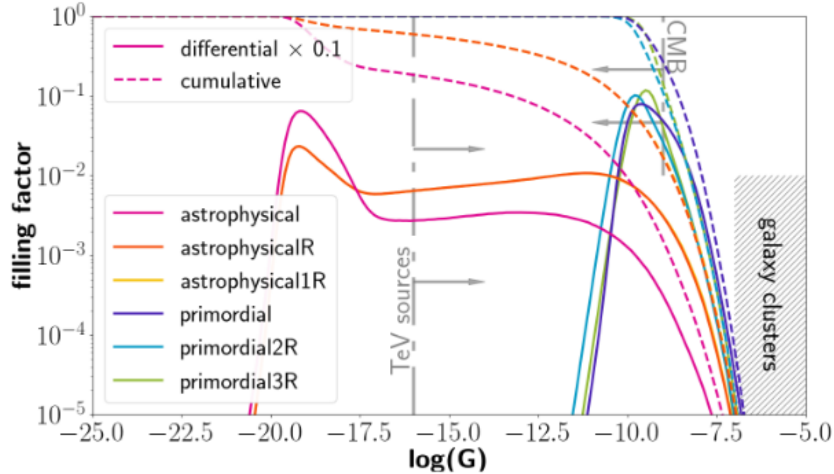
Yes, but predominantly FR-I radio galaxies!

Eichmann (2019)

Backup

Hackstein et al. (2018) EGMF models





mnemonic	gas physics	magnetic field	
B=0	non-radiative	$B_0 = 0$	
primordial	non-radiative	$B_0 = 0.1$ nG	very strong
primordial2R	non-radiative	$(\langle B^2 \rangle)^{0.5} = 1$ nG, $n_B = -3$	strong
primordial3R	non-radiative	$(\langle B^2 \rangle)^{0.5} = 1$ nG, $n_B = -4$	strong
astrophysical	cooling and AGN feedback	$5 \cdot 10^{58}$ erg, $z < 4$; $B_0 = 10^{-11}$ nG	very weak
astrophysicalR	cooling and AGN feedback	10^{60} erg, $z < 4$; $B_0 = 10^{-11}$ nG	weak
astrophysical1R	cooling and AGN feedback	10^{60} erg to $5 \cdot 10^{58}$ erg, $z < 1$; $B_0 = 10^{-11}$ nG	weak

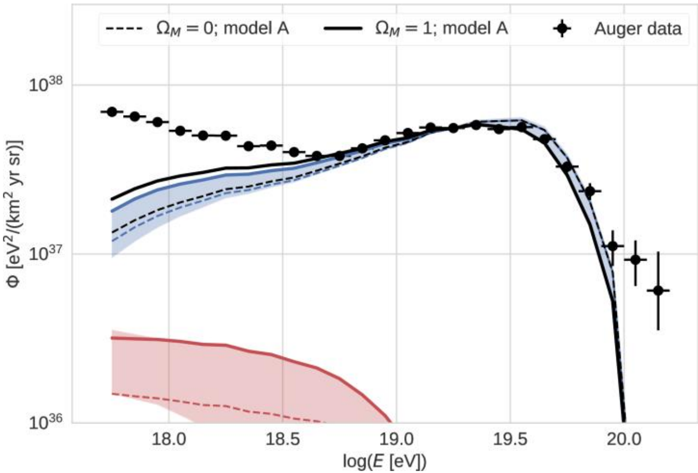
Proof of principle fit scenarios

Scenario I:

Both FR types: $a = 1.8,\ g_m = \frac{4}{7},$

FR-I: $\beta_L = 0.9,\ k = 12,\ g_{acc} = 0.8$

FR-II: $\beta_L = 0.8,\ k = 0,\ g_{acc} = 0.1$



Scenario II:

Both FR types: $k = 0,\ g_m = \frac{4}{7},\ g_{acc} = 0.2$

FR-I: $\beta_L = 0.5,\ a = 1.9$

FR-II: $\beta_L = 0.8,\ a = 1.8,\ 10 \times Q_{jet}$