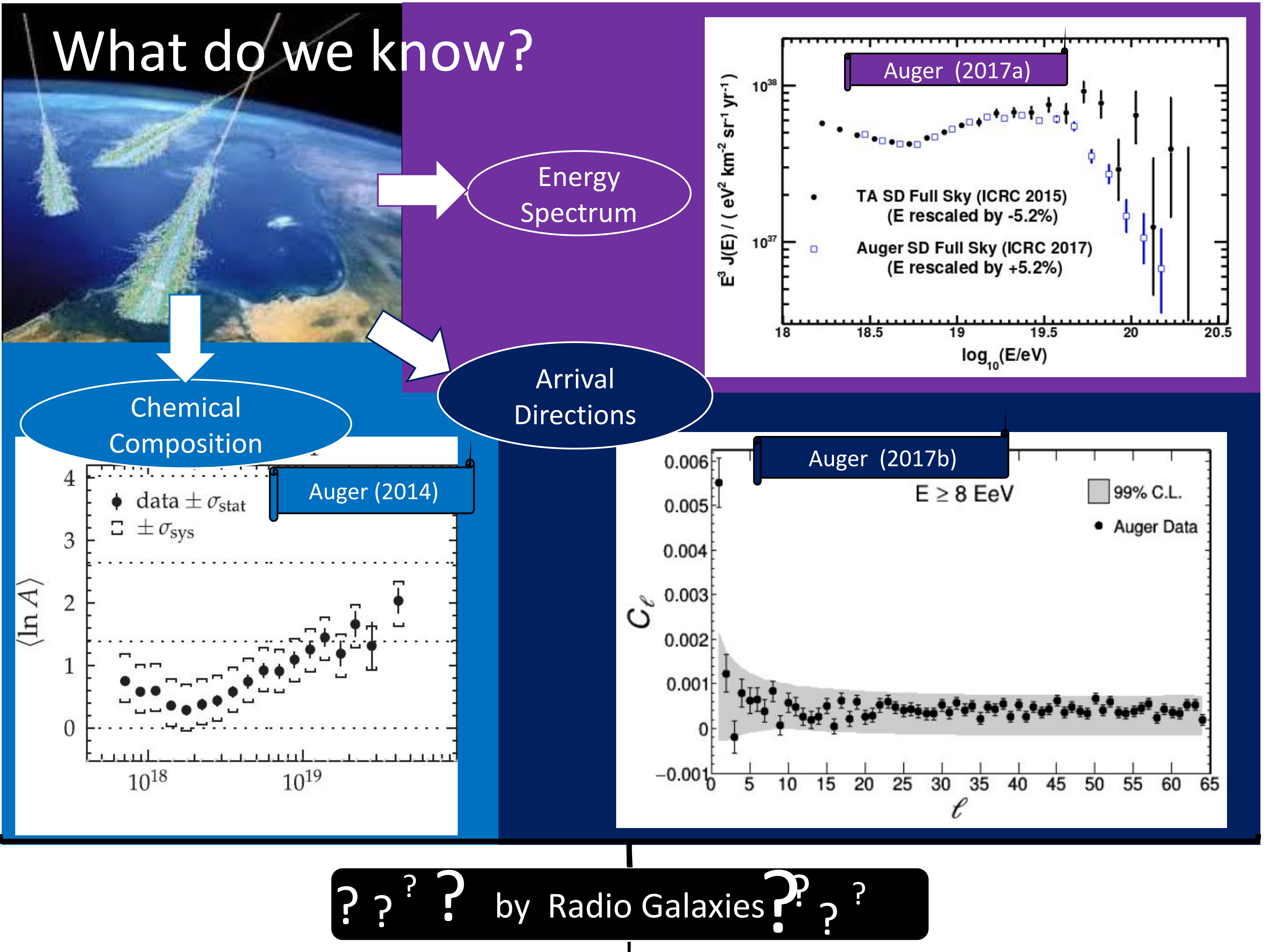
Can radio galaxies solve the UHECR puzzle?

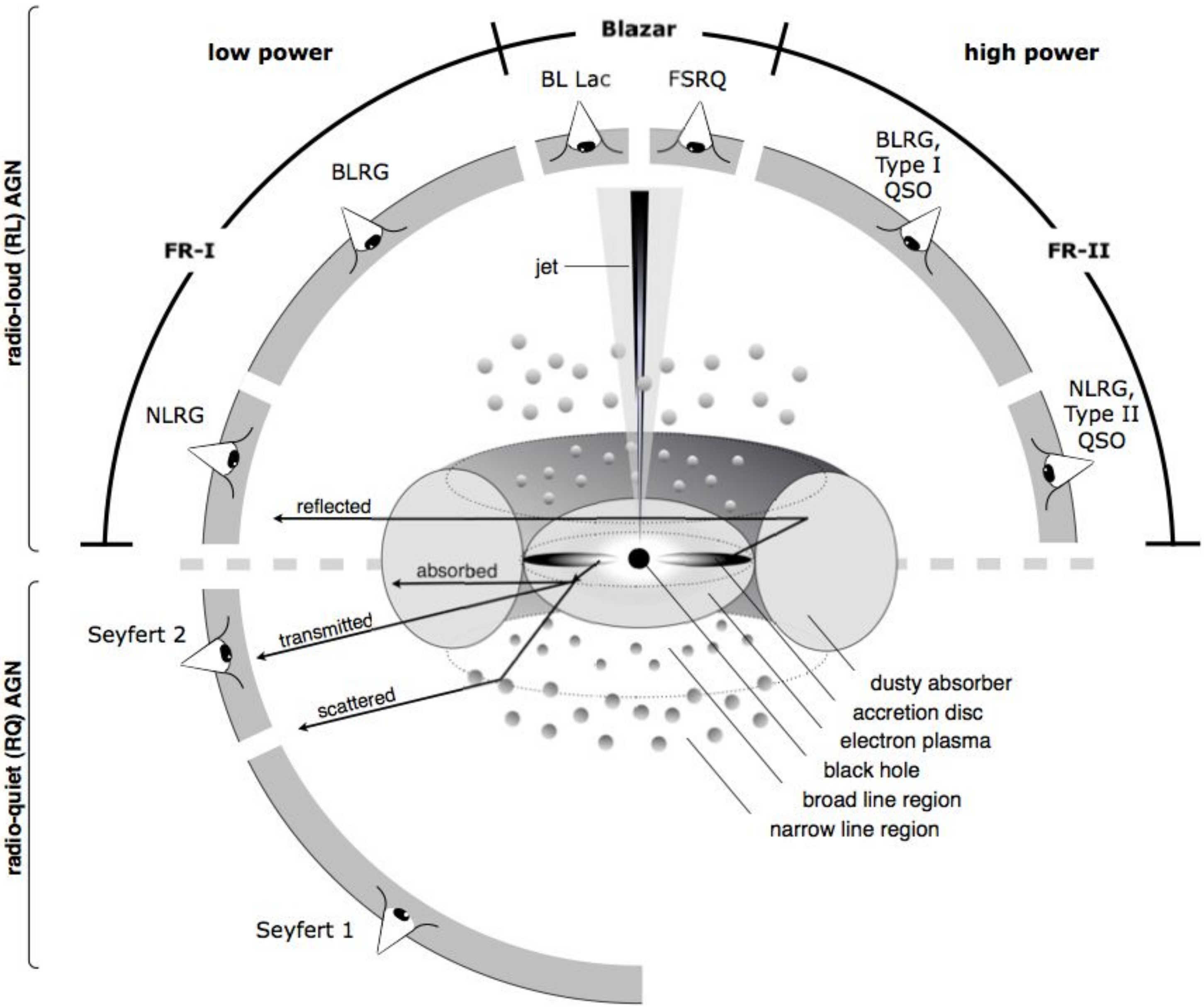
Ruhr **A**stroparticle and **P**lasma **P**hysics **Center**
Björn Eichmann, Ruhr-Universität Bochum
NTNU, 06.09.2021, Astro-seminar

RAPP
Center

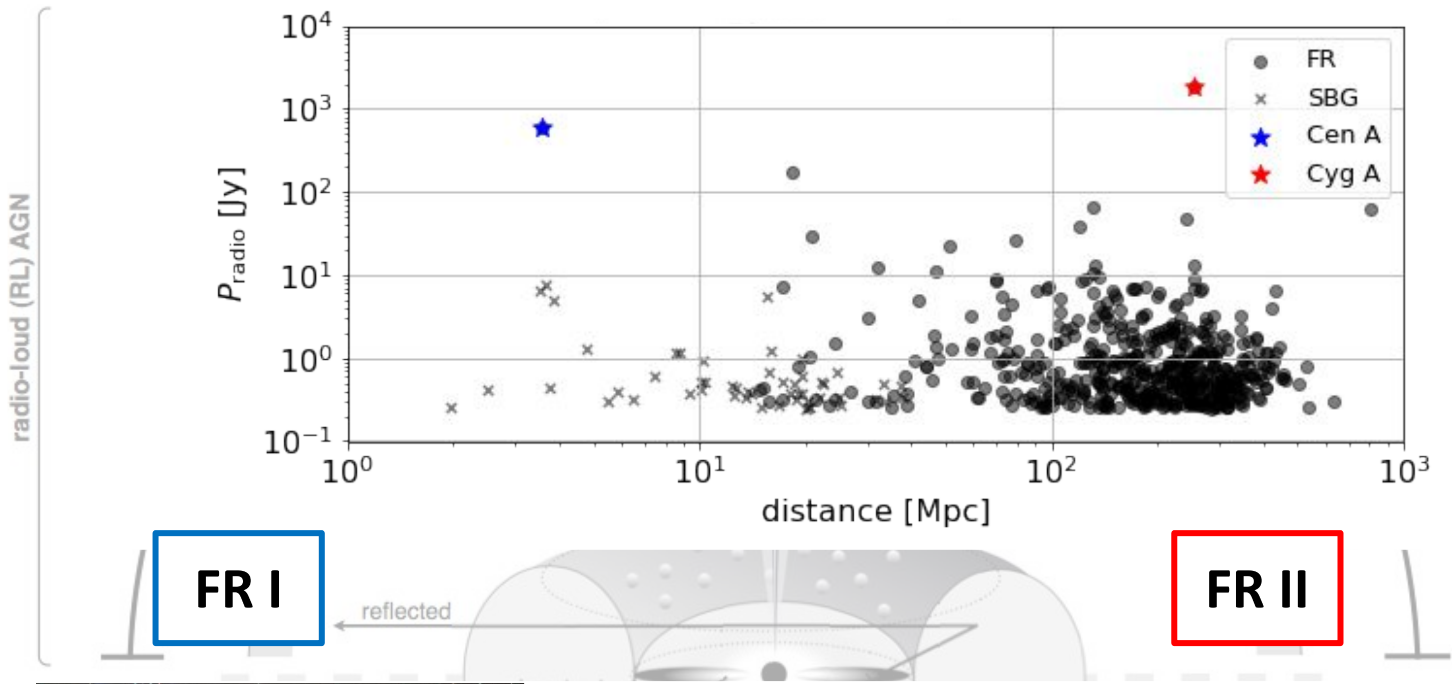


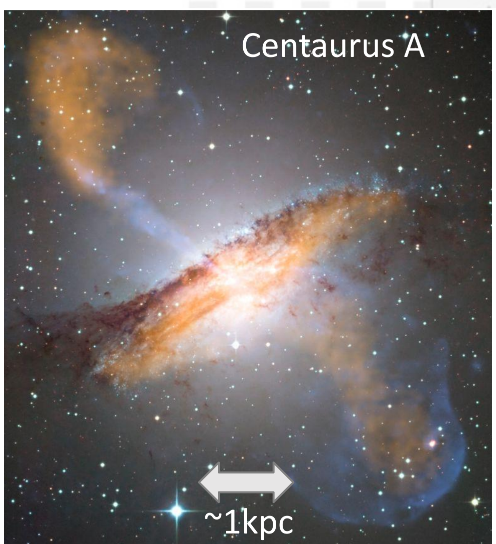
What do we know?
Energy Spectrum
Chemical Composition
Arrival Directions
Auger (2017a)
TA SD Full Sky (ICRC 2015)
(E rescaled by -5.2%)
Auger SD Full Sky (ICRC 2017)
(E rescaled by +5.2%)
E^3 J(E) / (eV^2 km^-2 sr^-1 yr^-1)
log10(E/eV)
Auger (2014)
data ± σstat
± σsys
⟨ln A⟩
Auger (2017b)
E ≥ 8 EeV
99% C.L.
Auger Data
Cℓ
ℓ
? ? ? ? by Radio Galaxies ? ? ? ?

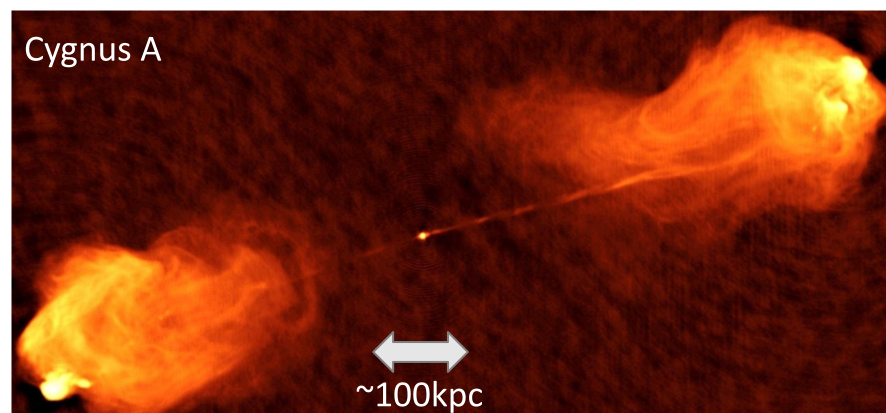
? ? ? ? Radio Galaxies ? ? ? ?



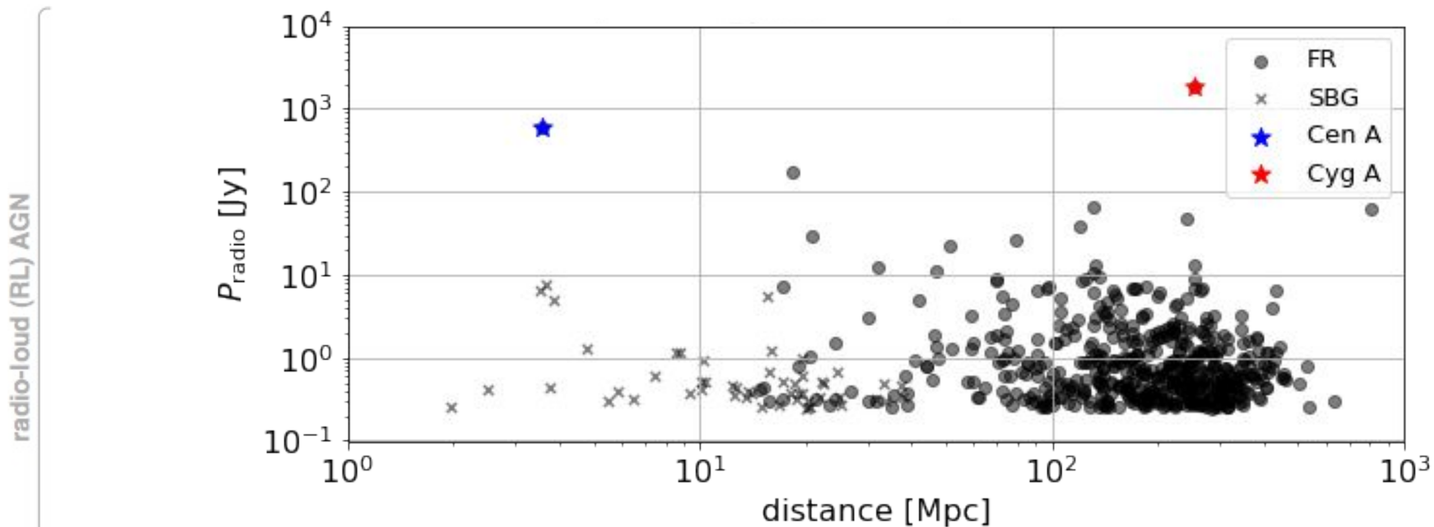
? ? ? ? Radio Galaxies ? ? ? ?

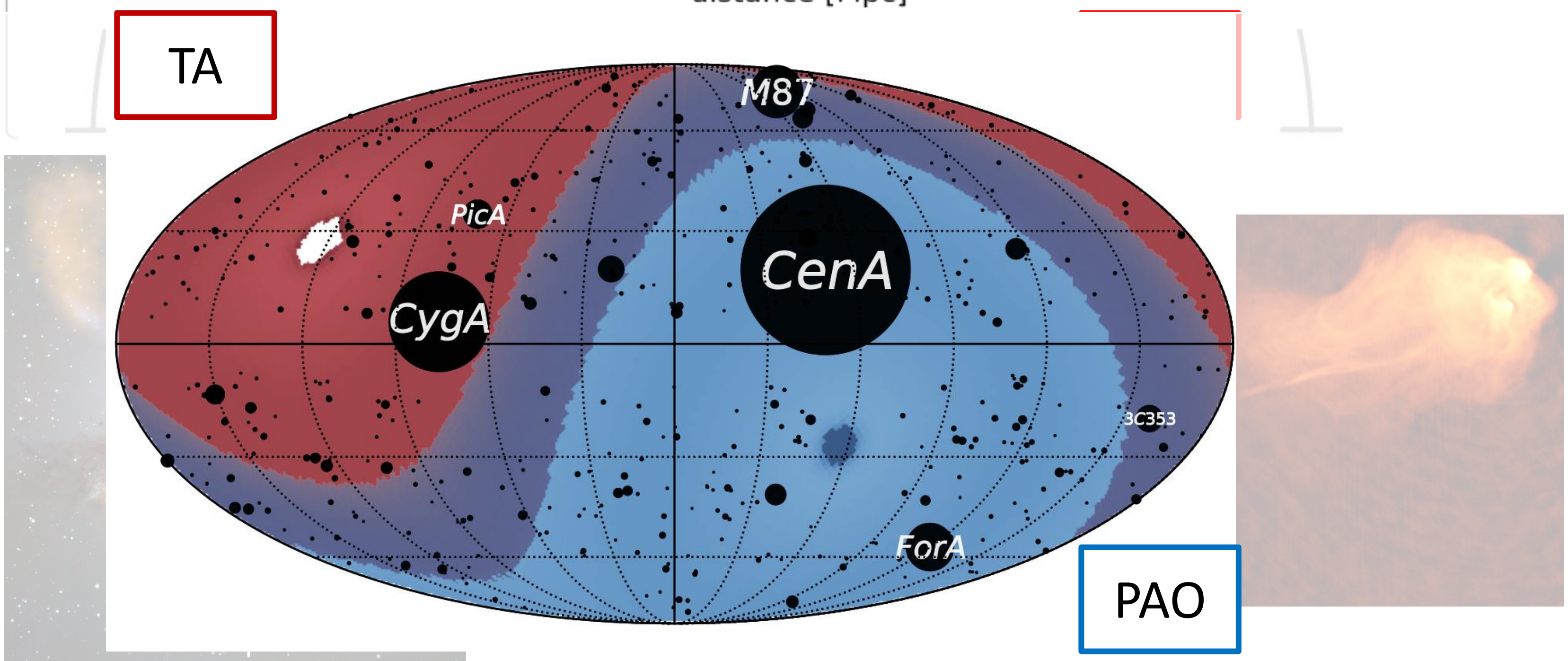






? ? ? ? Radio Galaxies ? ? ? ?

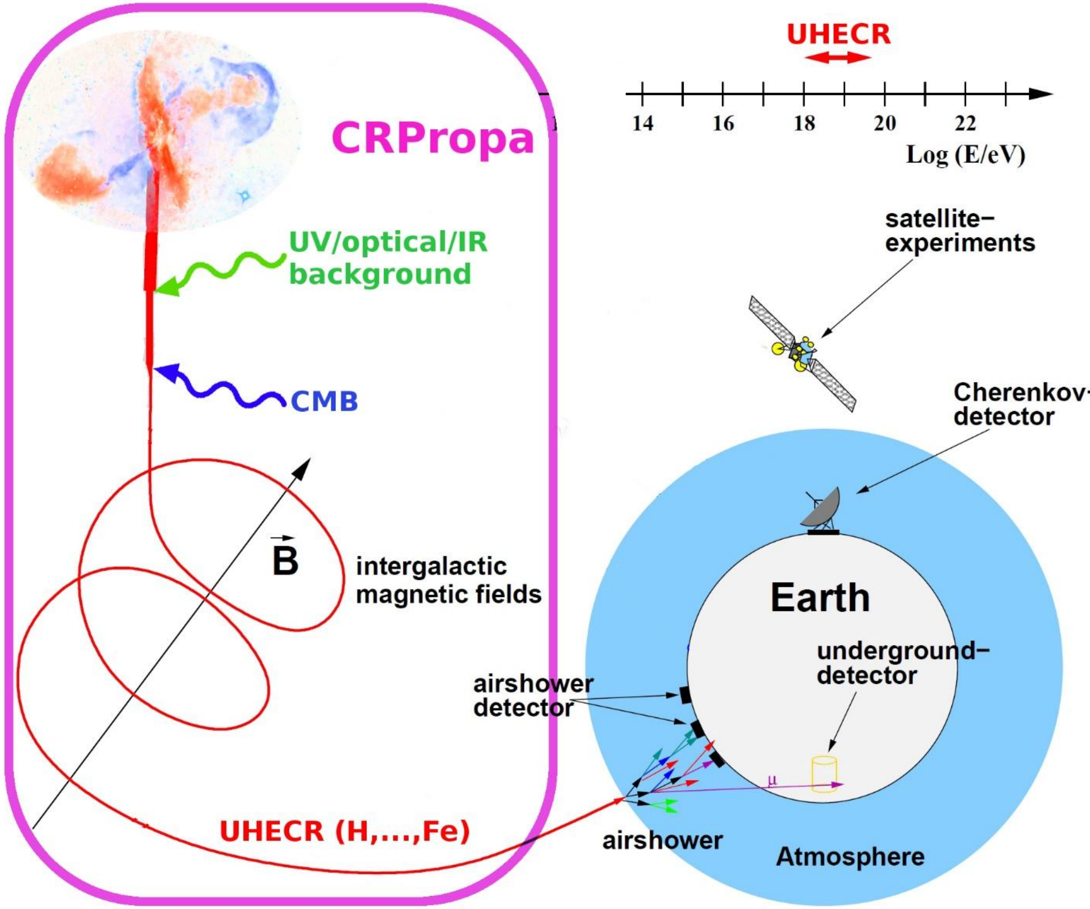




Form Radio Galaxies to Earth

The (regular) simulation setup:

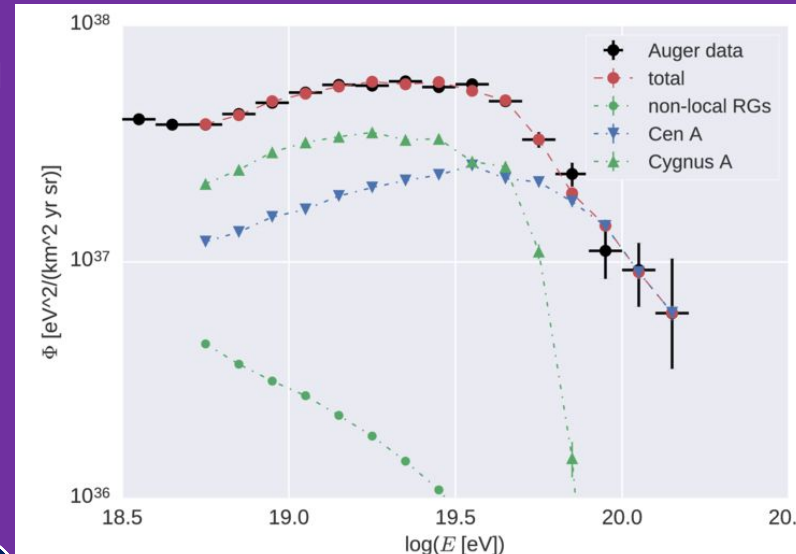
- ***SOURCES:***
  - Individual local Radio Galaxies (**RGs**)*
  - Bulk of non-local RGs
- ***ENVIRONMENT:***
  - Local extragalactic magnetic field (**EGMF**) up to 120Mpc distance**
  - Photon fields by CMB & IRB
- ***PROPAGATION of UHECRs:***
  - Performed with **CRPropa3*****



*van Velzen et al. (2012) ; **Dolag et al. (2005); ***Batista et al. (2016)

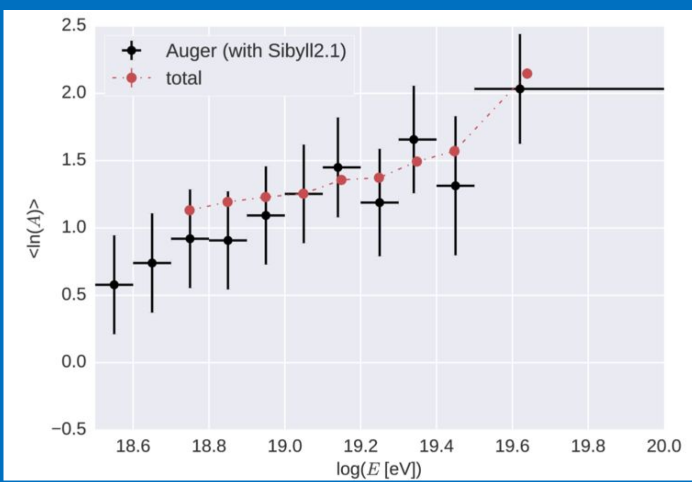
First explanation approach

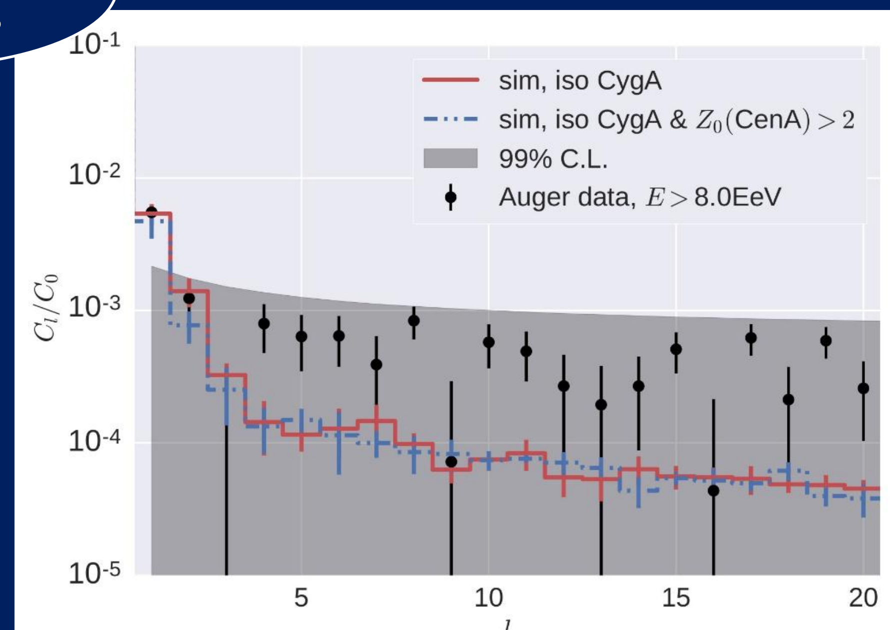
Energy Spectrum



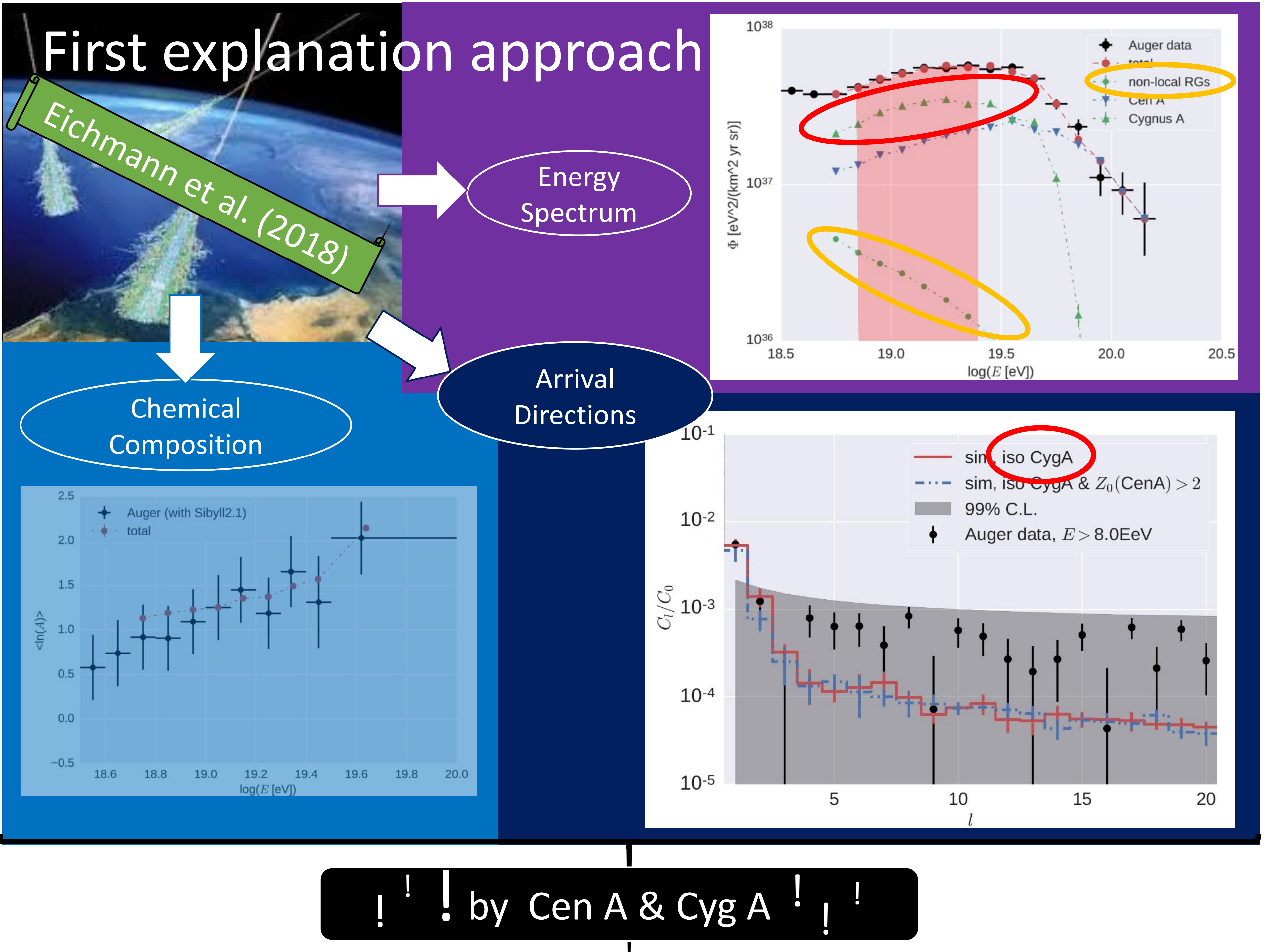
Arrival Directions

Chemical Composition





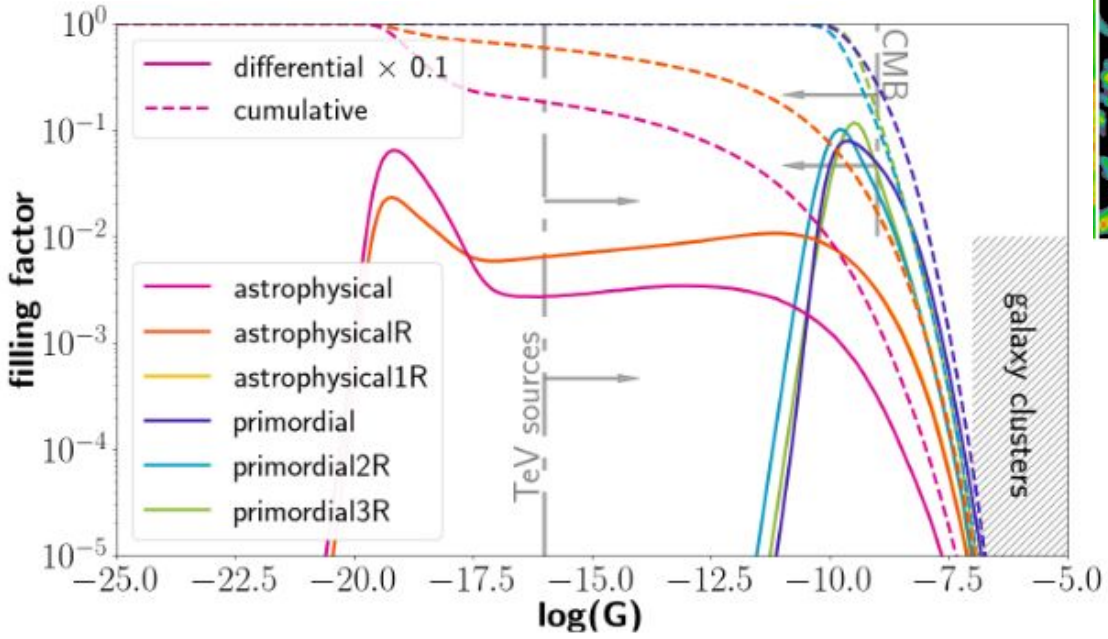
! ! ! by Cen A & Cyg A ! ! !

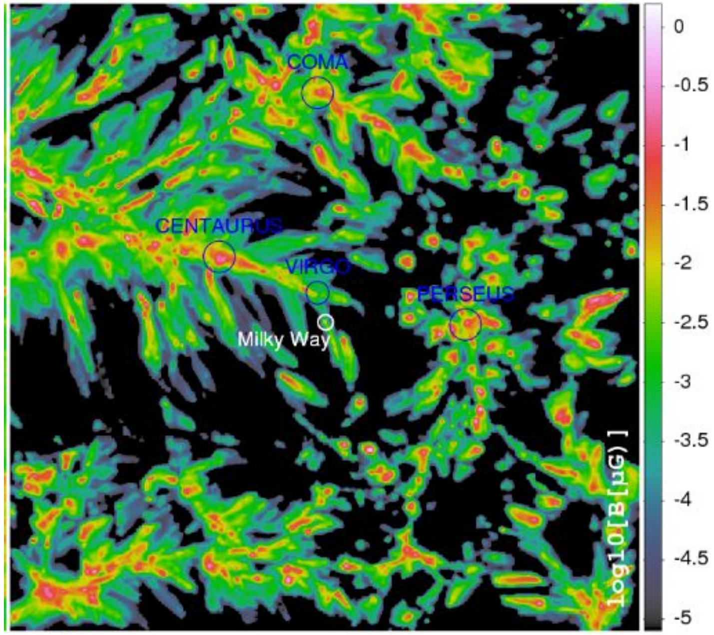

First explanation approach
Eichmann et al. (2018)
Energy Spectrum
Chemical Composition
Arrival Directions
Auger data
non-local RGs
Cen A
Cygnus A
Φ [eV^2/(km^2 yr sr)]
log(E [eV])
Auger (with Sibyll2.1)
total
<ln(A)>
sim, iso CygA
sim, iso CygA & Z0(CenA) > 2
99% C.L.
Auger data, E > 8.0EeV
Cl/C0
l
! ! ! by Cen A & Cyg A ! ! !

(I) Can UHECRs by Cyg A be isotropized?

The inverted simulation setup

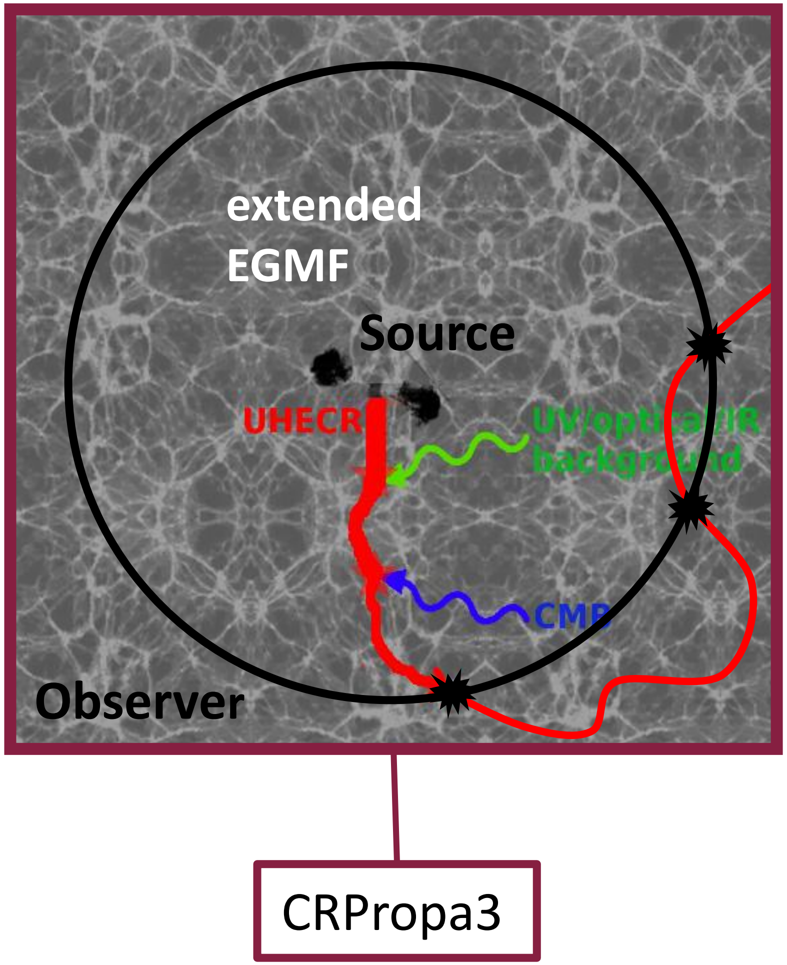
- Extended EGMF models by Hackstein et al. (2018)
  - 3 primordial models (p, p2R, p3R)
  - 3 astrophysical models (a, a1R, aR)



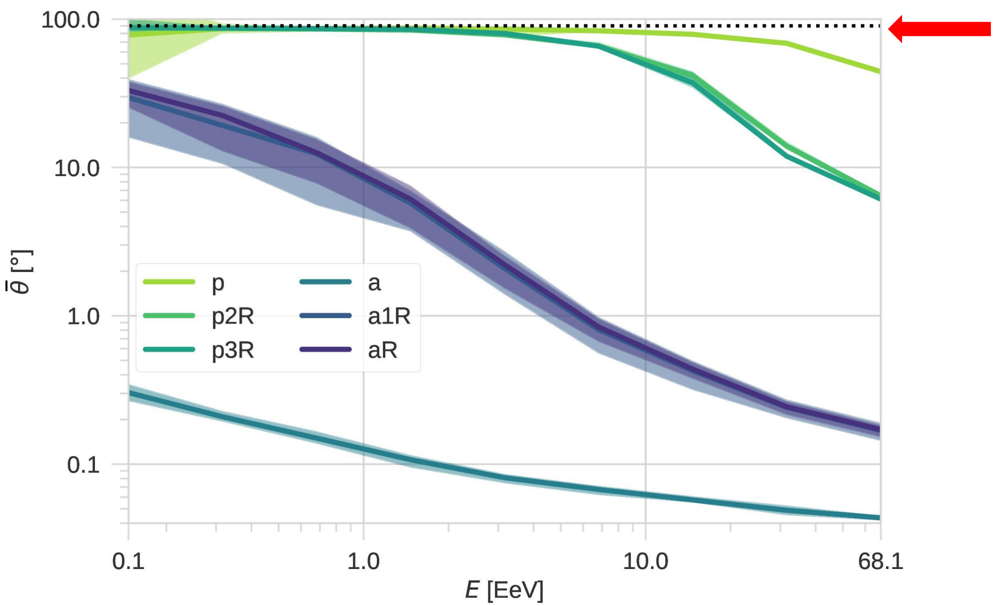


The inverted simulation setup

- 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

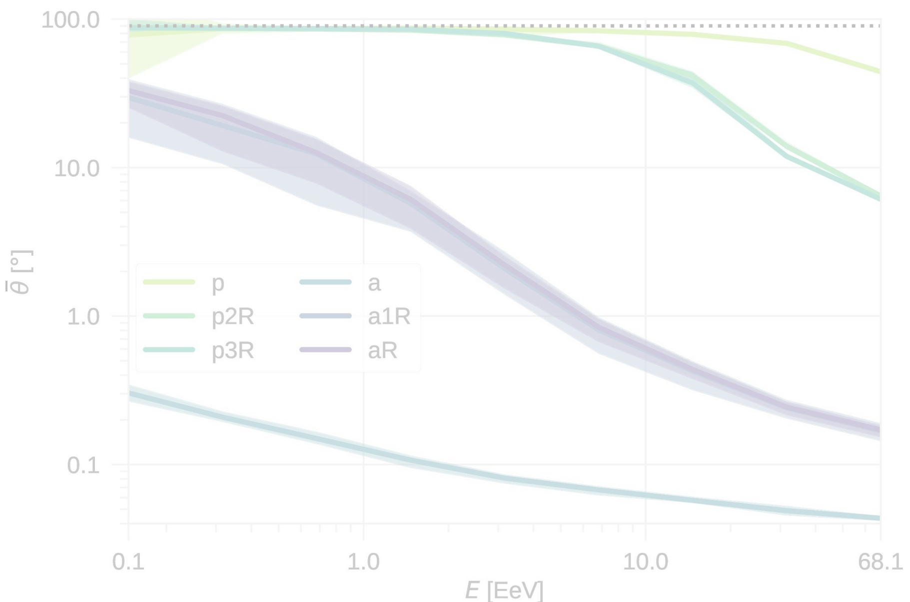


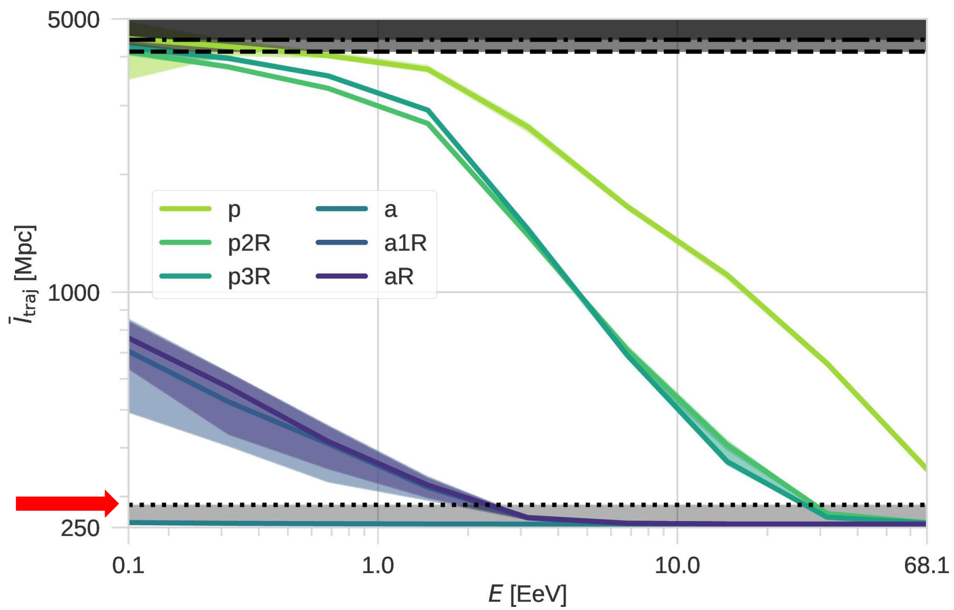
The deflection & trajectory lengths of Cyg A



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

The deflection & trajectory lengths of Cyg A

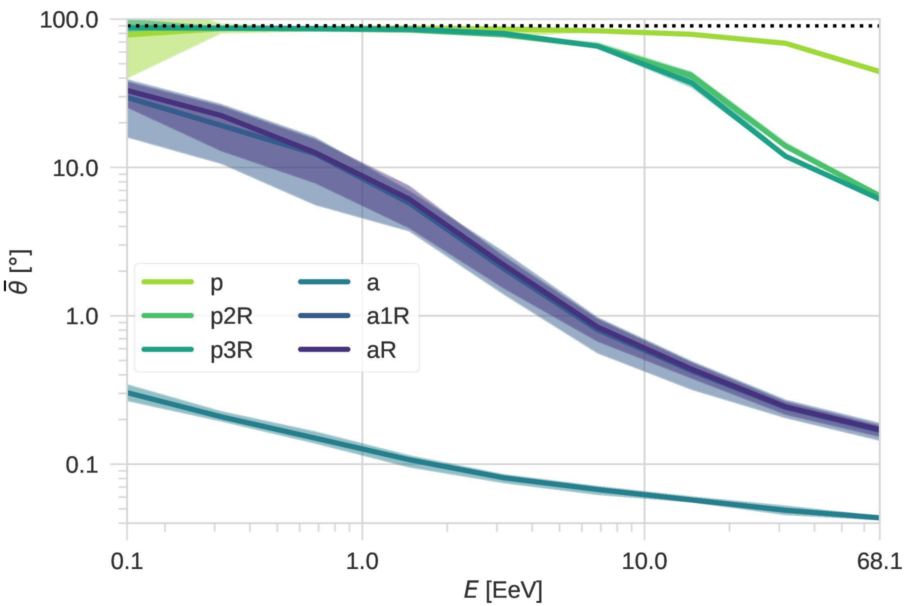


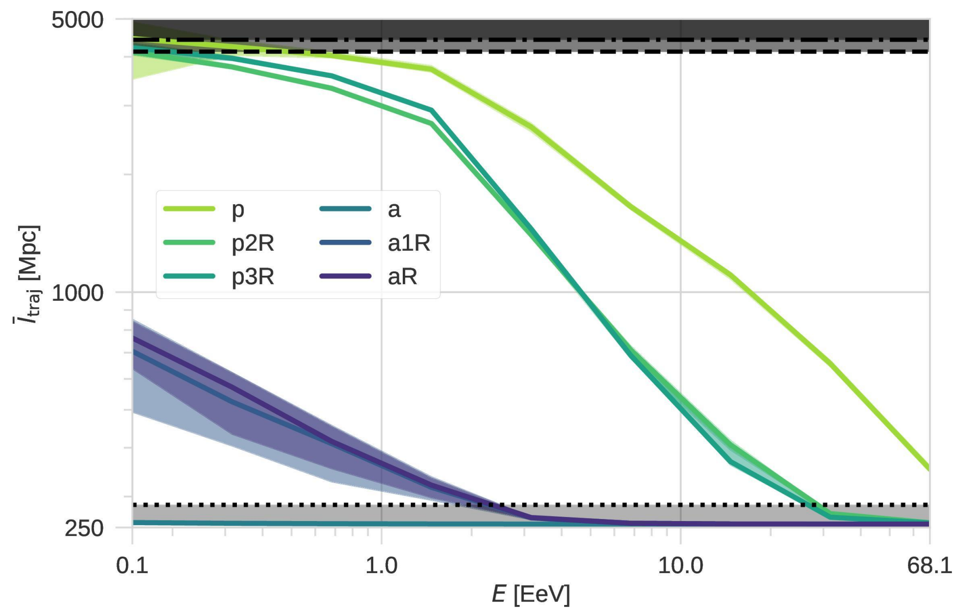


Only the primordial models (p, p2R, p3R) are able to isotropize UHECRs from Cyg A

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

Why radio instead of gamma-ray brightness?

- ***Gamma-ray flux:***
  - *depends* on the additional presence of *a sufficiently dense target* population that is not in a simple relation with the CR density;
  - can also *be produced by non-hadronic processes* like inverse Compton scattering;
  - is observed *in the GeV-TeV regime*, while UHECRs are above EeV

- ***Radio flux:***
  - more robust, as the radio luminosity is in *a simple relation to the non-thermal power of an object*, which in turn is a plausible scaling quantity for the power in CRs;
  - is *related to the magnetic field strength*, so that it sets a limit to the highest energy attainable in electromagnetic acceleration

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

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

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

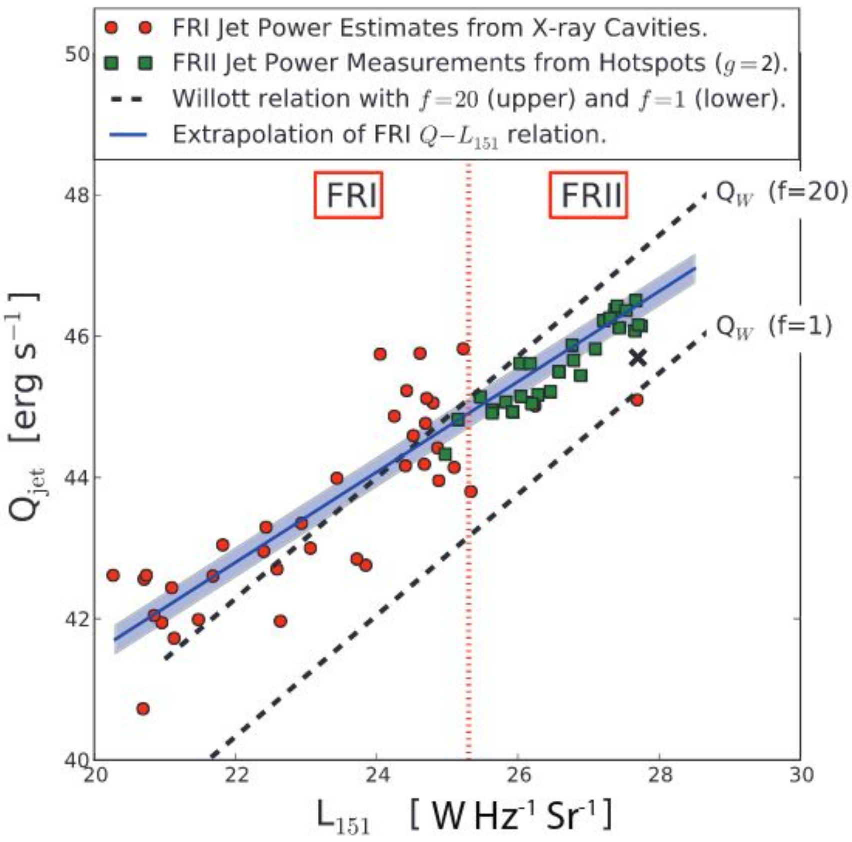
$$\hat{R} \simeq g_{acc}\sqrt{(1-g_m)Q_{jet}/c}\,, \quad \text{with} \quad g_{acc} = \sqrt{\frac{8\beta_{sh}^2}{f_{diff}^2\beta_{jet}}}$$

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

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)

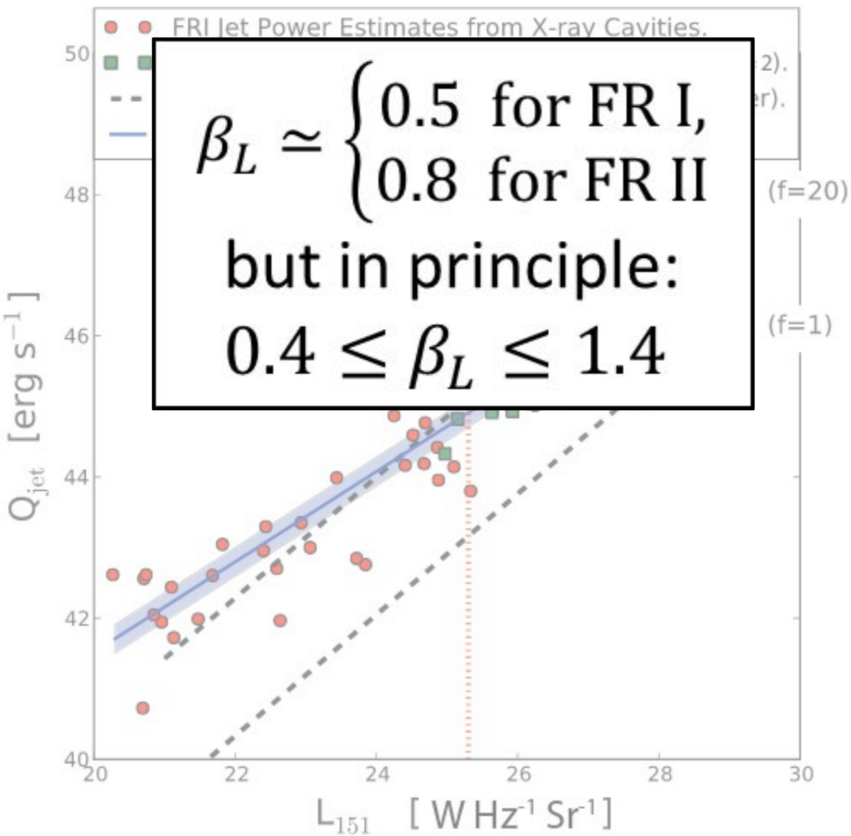
$$\text{GS2016: } \beta_L \simeq \begin{cases} 0.5 & \text{for FR I,} \\ 0.8 & \text{for FR II} \end{cases}$$

(from theor. expectations)

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:

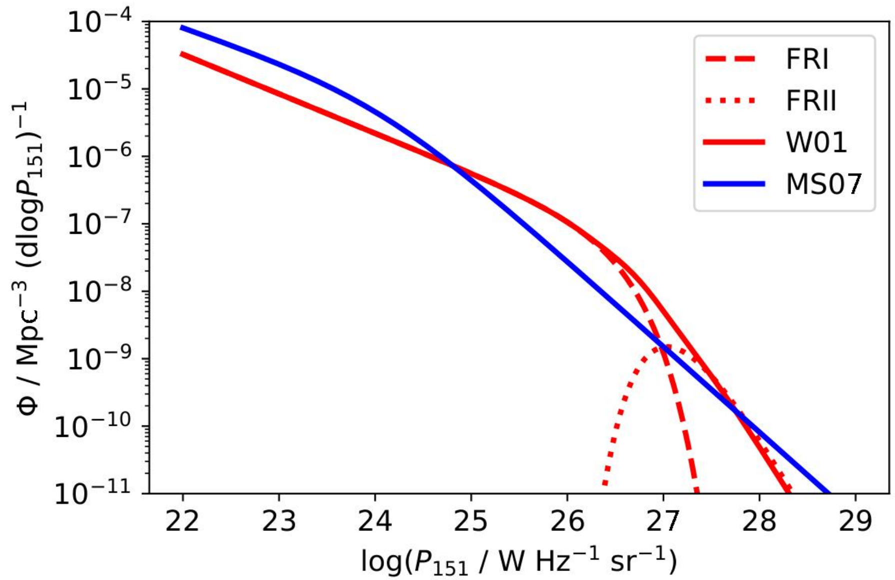


$$\beta_L \simeq \begin{cases} 0.5 & \text{for FR I,} \\ 0.8 & \text{for FR II} \end{cases}$$

but in principle:

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

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



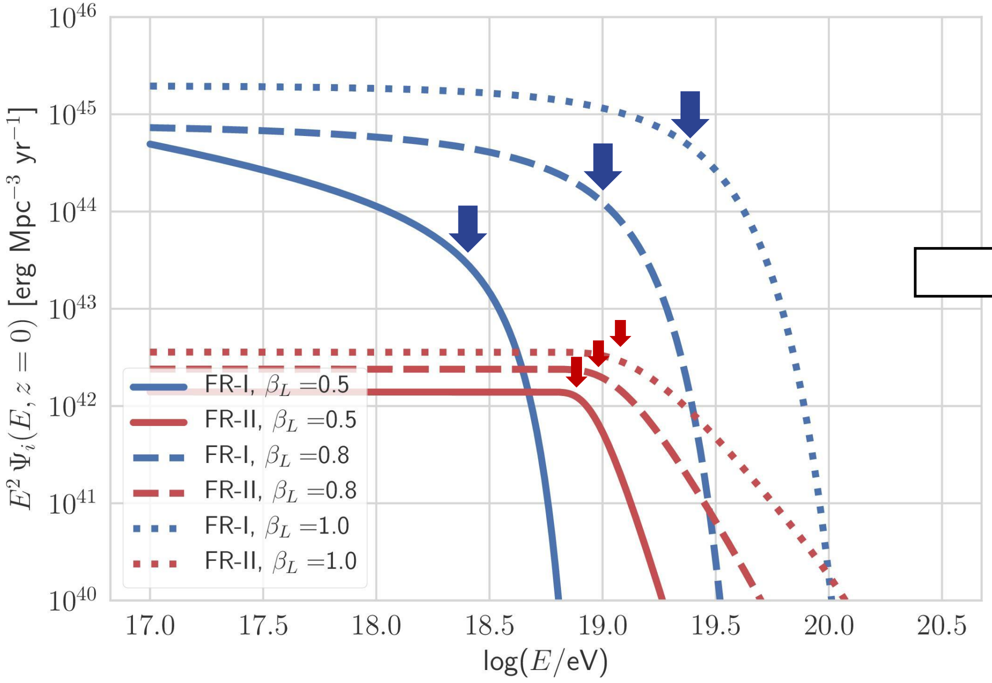
Spectral behaviour constraints

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

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

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

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



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

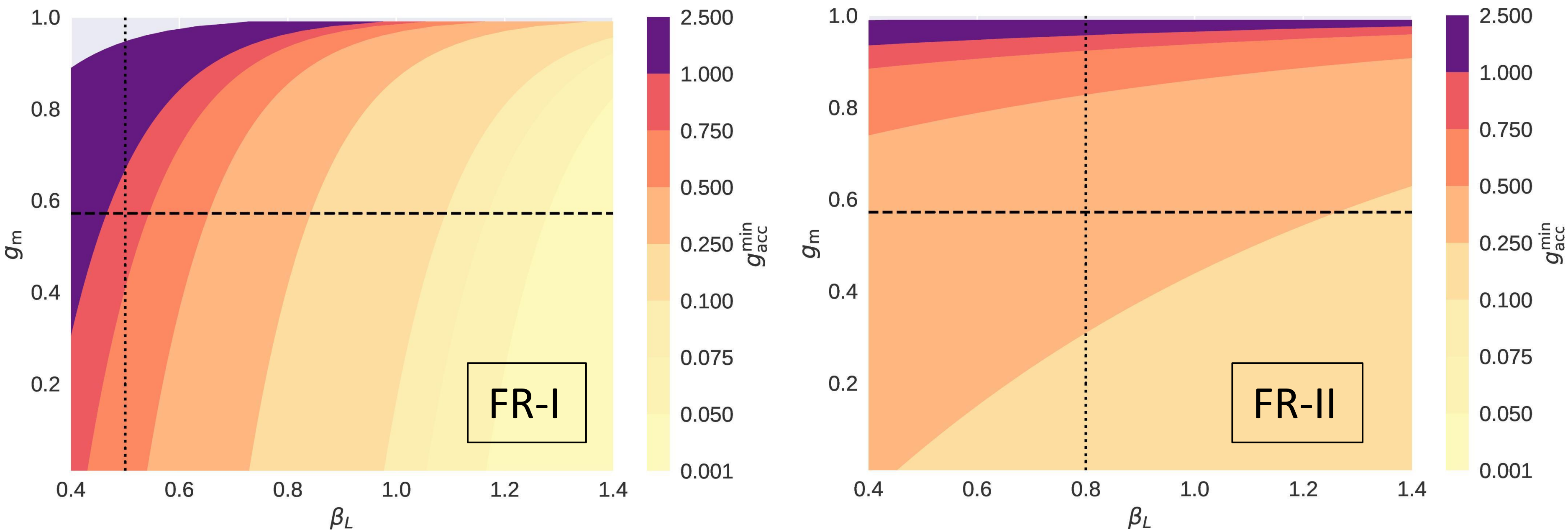
Spectral behaviour constraints

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

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

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

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



Spectral behaviour constraints

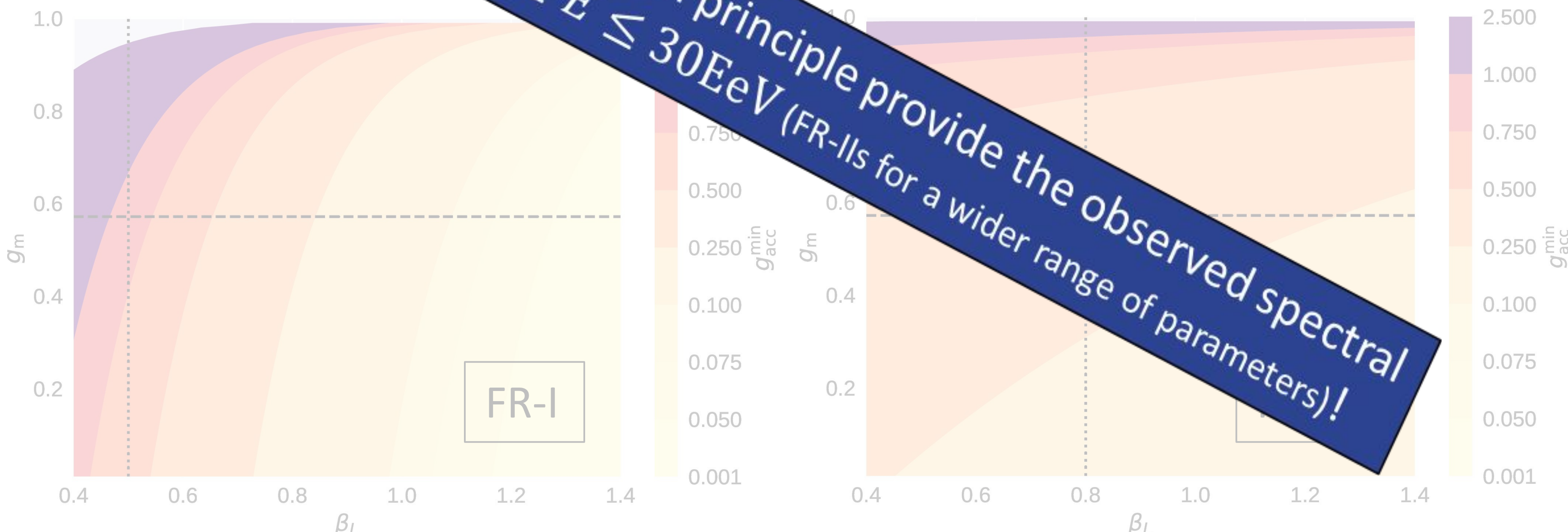
Bulk of FR-I and FR-II sources have a different critical rigidity:

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

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

$\ldots\sqrt{(1-g_m)Q_*/c}$, with $Q_* = Q_*(\beta_L)$

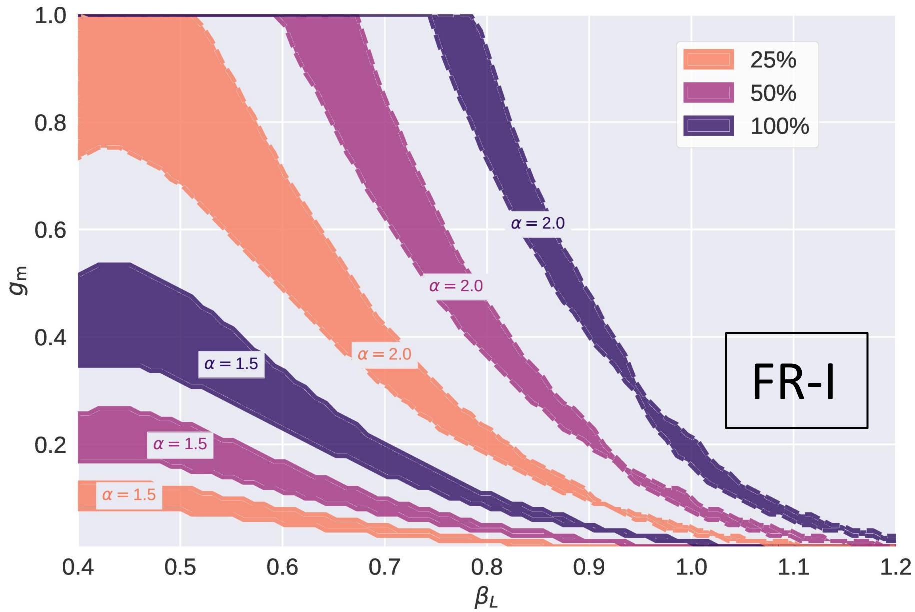
FR-I and FR-II sources can in principle provide the observed spectral behavior at $5\text{EeV} \leq E \leq 30\text{EeV}$ (FR-IIs for a wider range of parameters)!

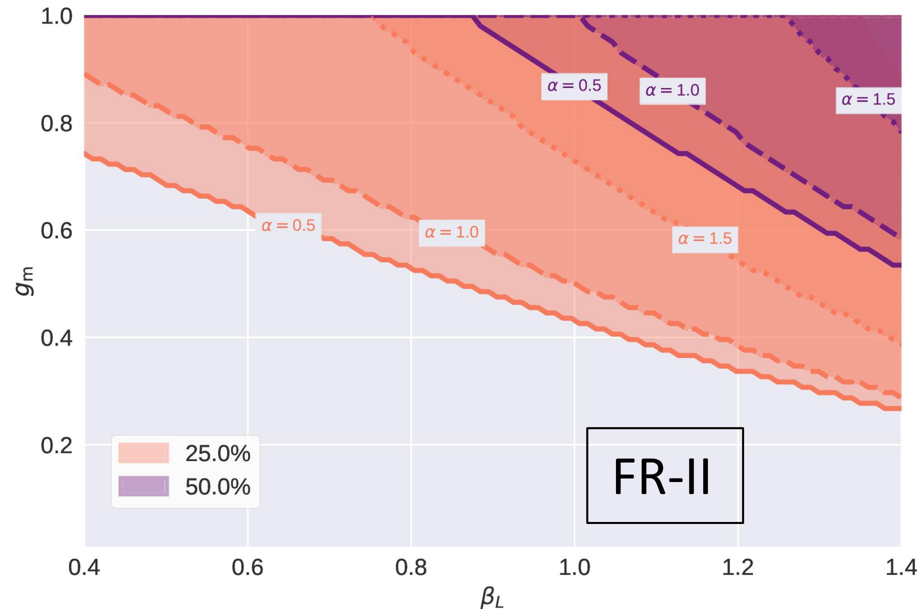


Total amount of UHECR energy constraints

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

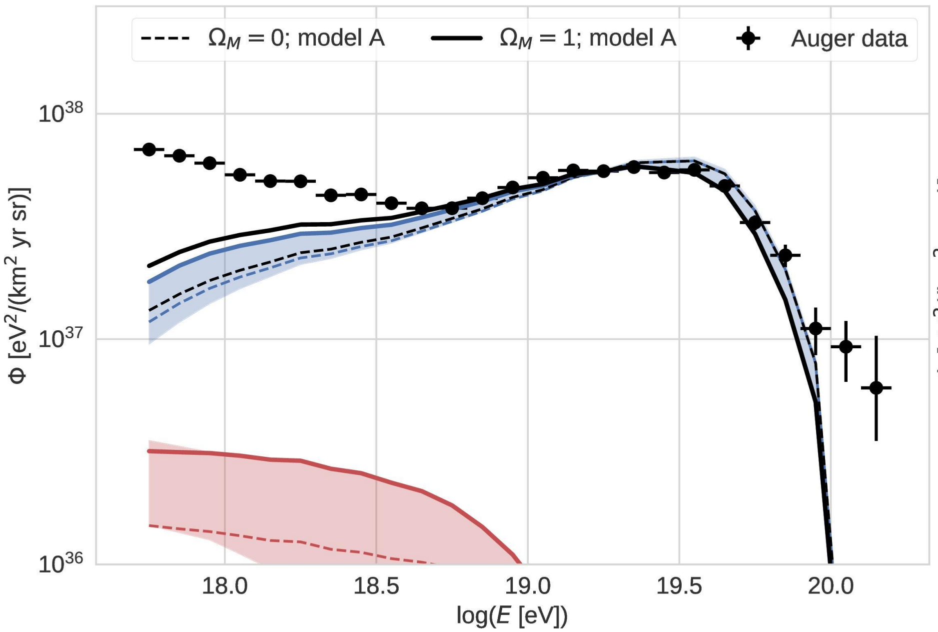
Proof of principle fit scenarios

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

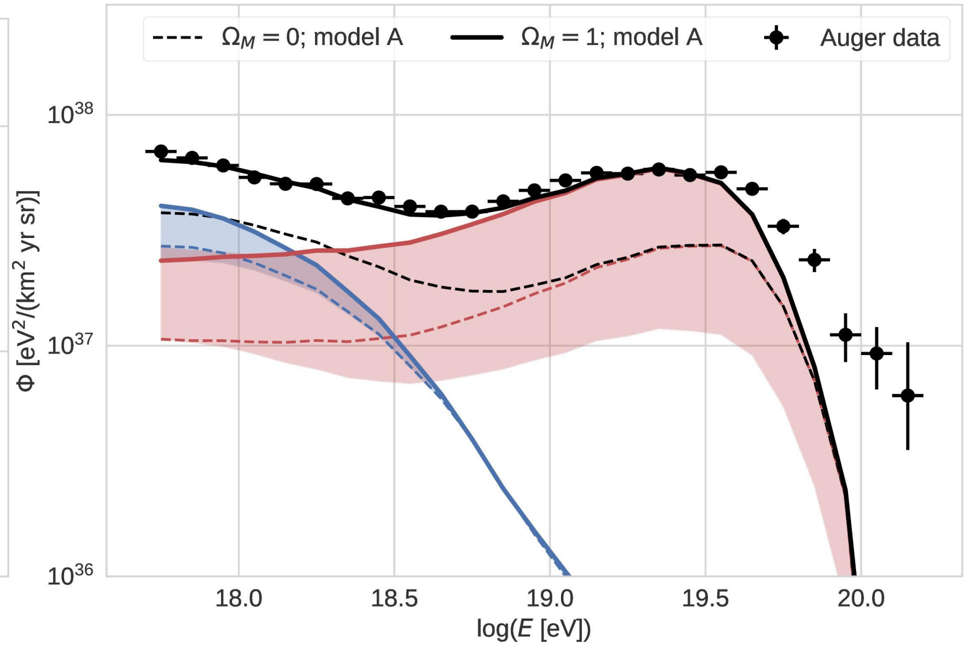


Scenario II:

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



(III) Can individual local sources contribute?

Constraints on the local source contribution

(...only a rule of thumb estimate so far.)

- At $E \gtrsim 100$EeV individual **local source(s) needed**.

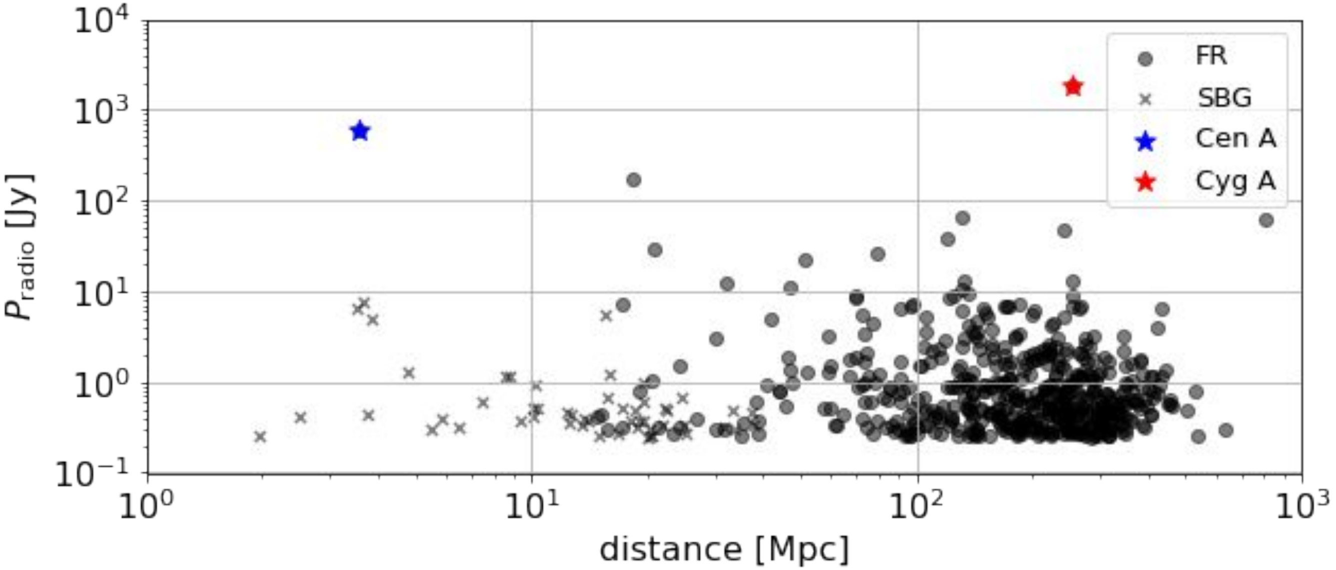
- **Three basic constraints**:
  - $P_{cr} \gtrsim P_{cr}(\mathrm{CenA})/X_p$; with $100 \gtrsim X_p \gtrsim 1$
  - $R \gtrsim R_{min}$
  - $d \lesssim d_{GZK}(R_{min}, A, Z)$

- **Two additional constraints** from the deflection by the EGMF:
  - $\tau_{delay}(\mathrm{EGMF}, R_{min}) \lesssim \tau_{age}$
  - $\theta_{defl}(\mathrm{EGMF}, R_{min}) \gtrsim \theta_{min}$

  ...using the primordial (p) and astrophysical (a) EGMF models by Hackstein et al. (2018)

Constraints on the local source contribution

The possible local source sample:

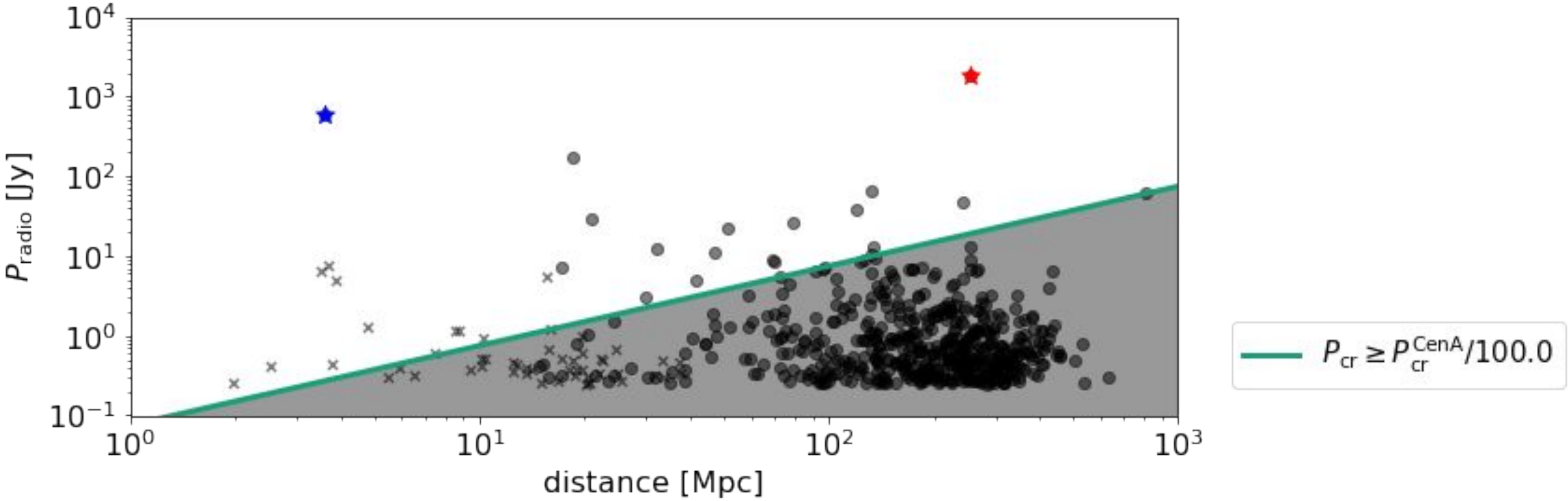


RAPP Center

Constraints on the local source contribution

The possible local source sample:

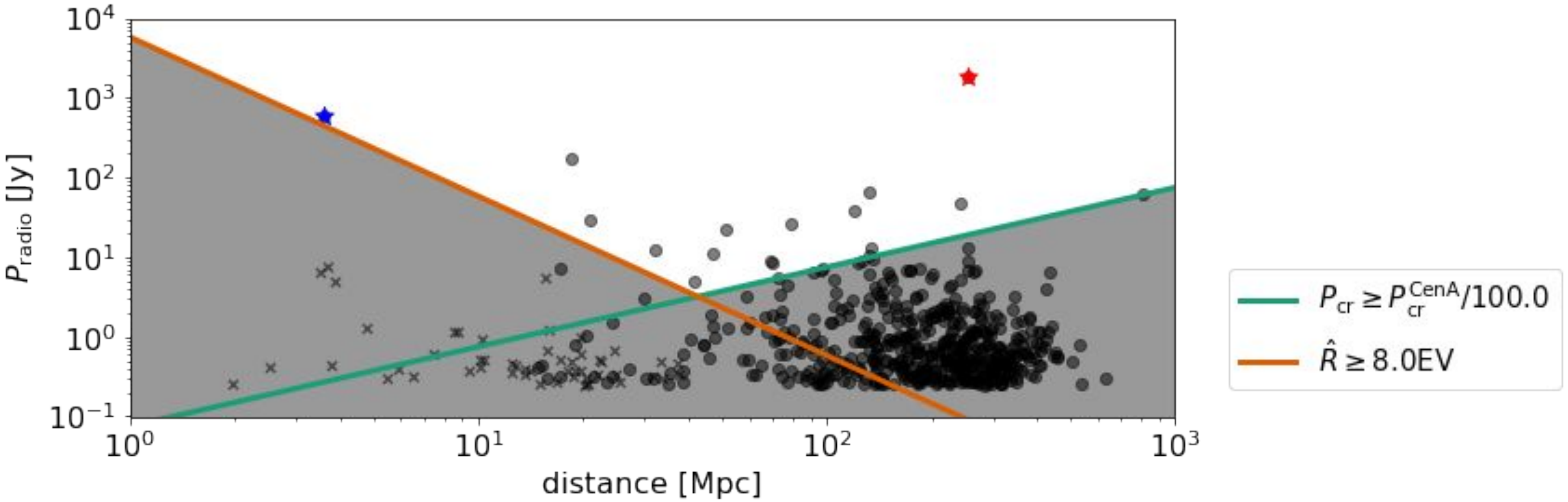
➢ distant, low-luminous sources don not provide enough CRs



Constraints on the local source contribution

The possible local source sample:

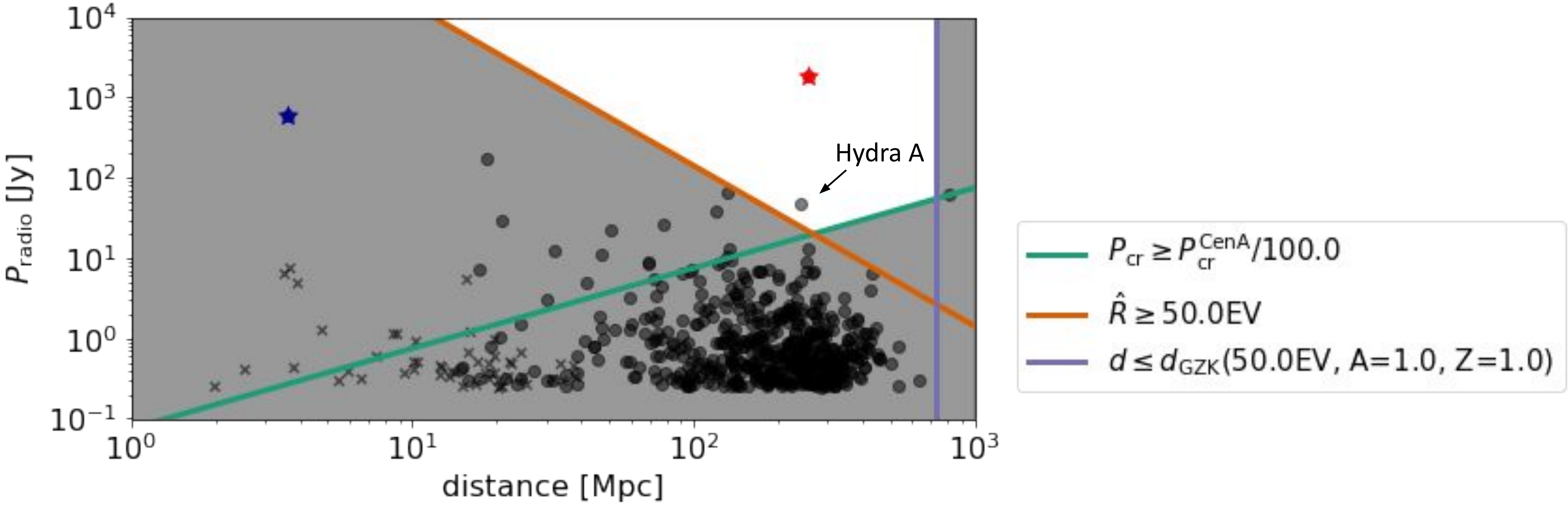
- ➢ distant, low-luminous sources don not provide enough CRs
- ➢ nearby sources (especially SBGs) hardly accelerate above 8EV



Constraints on the local source contribution

The possible local source sample:

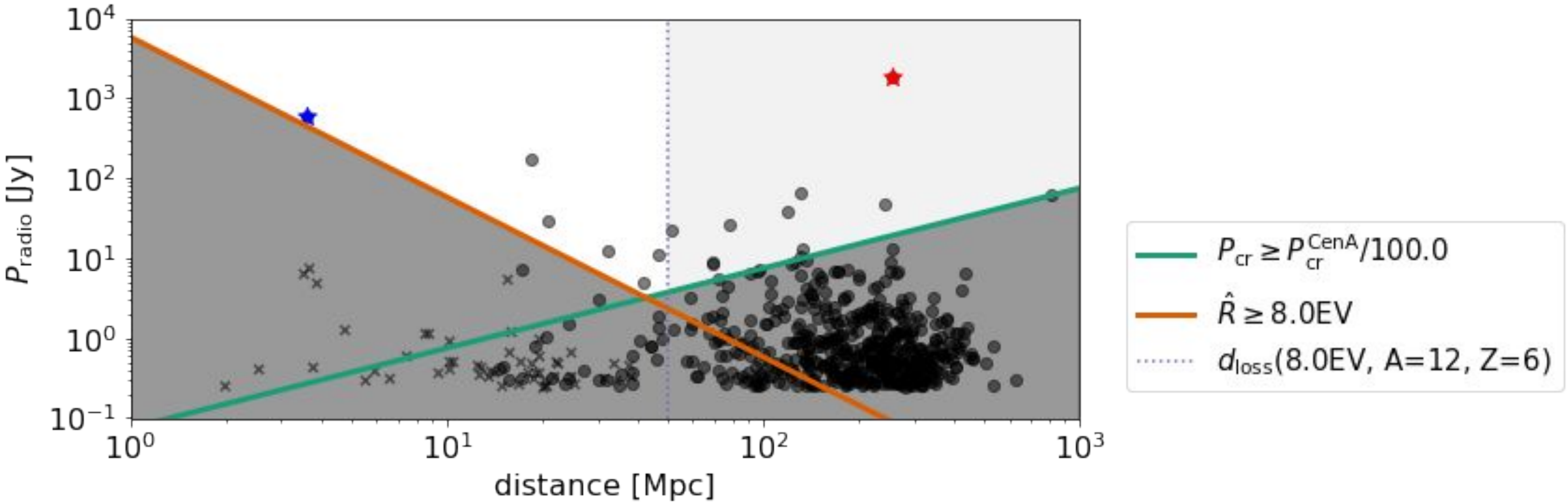
- ➢ distant, low-luminous sources don not provide enough CRs
- ➢ nearby sources (especially SBGs) hardly accelerate above 8EV
    - ○ for a light composition at 50 EeV only Cygnus A and Hydra A are possible sources



Constraints on the local source contribution

The possible local source sample:

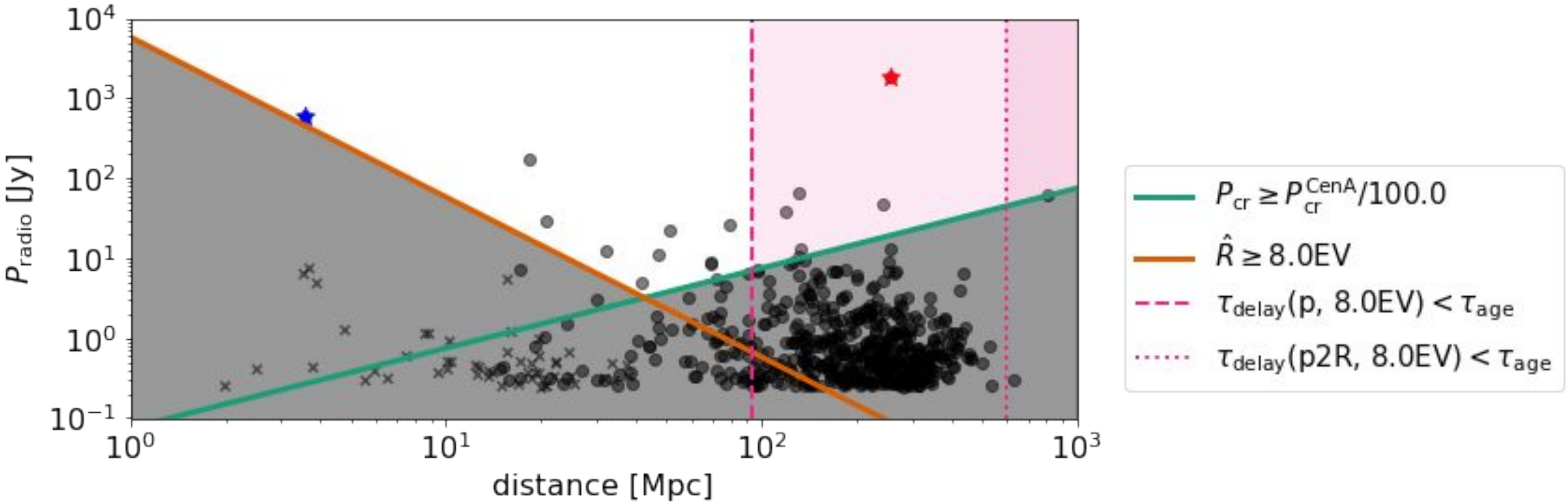
- ➢ distant, low-luminous sources don not provide enough CRs
- ➢ nearby sources (especially SBGs) hardly accelerate above 8EV
  - ○ for ~~a light composition at 50 EeV~~ → composition at 50 EeV is rather heavy (PAO)



Constraints on the local source contribution

The possible local source sample:

- ➢ distant, low-luminous sources don not provide enough CRs
- ➢ nearby sources (especially SBGs) hardly accelerate above 8EV
  - ○ for a light composition at 50 EeV → composition at 50 EeV is rather heavy (PAO)

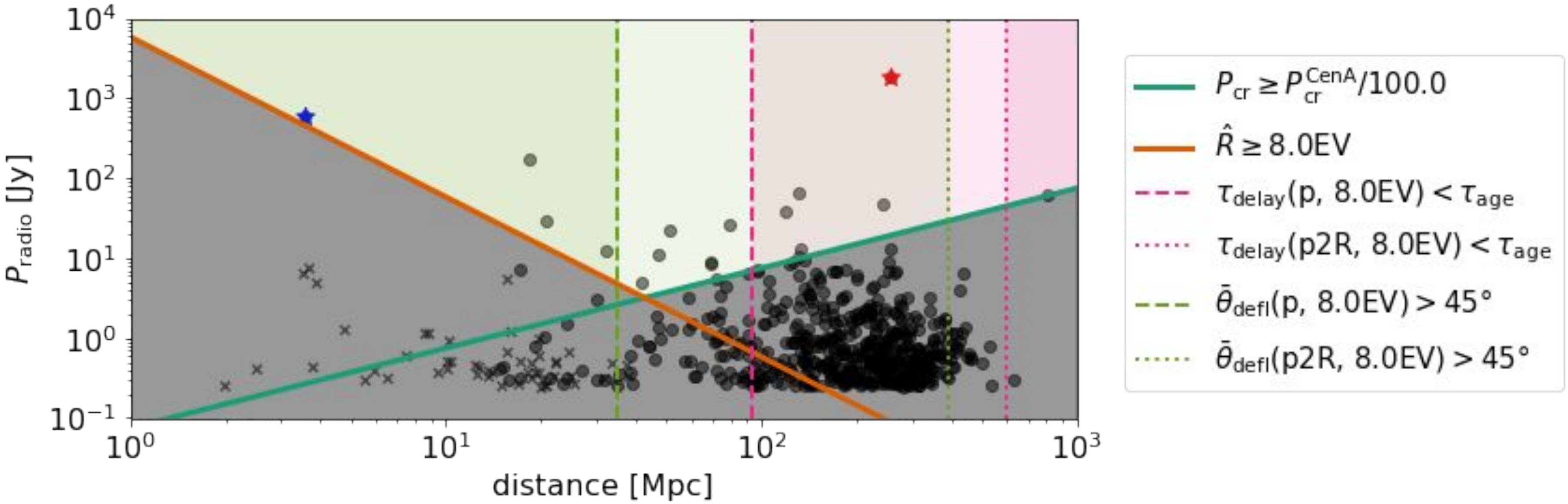


- ➢ Finite source age (τ_{age}=100Myr) constrains to a few hundreds of Mpc for strong EGMF (p,p2R)

Constraints on the local source contribution

The possible local source sample:

- ➢ distant, low-luminous sources don not provide enough CRs
- ➢ nearby sources (especially SBGs) hardly accelerate above 8EV
  - ○ for a light composition at 50 EeV $\rightarrow$ composition at 50 EeV is rather heavy (PAO)

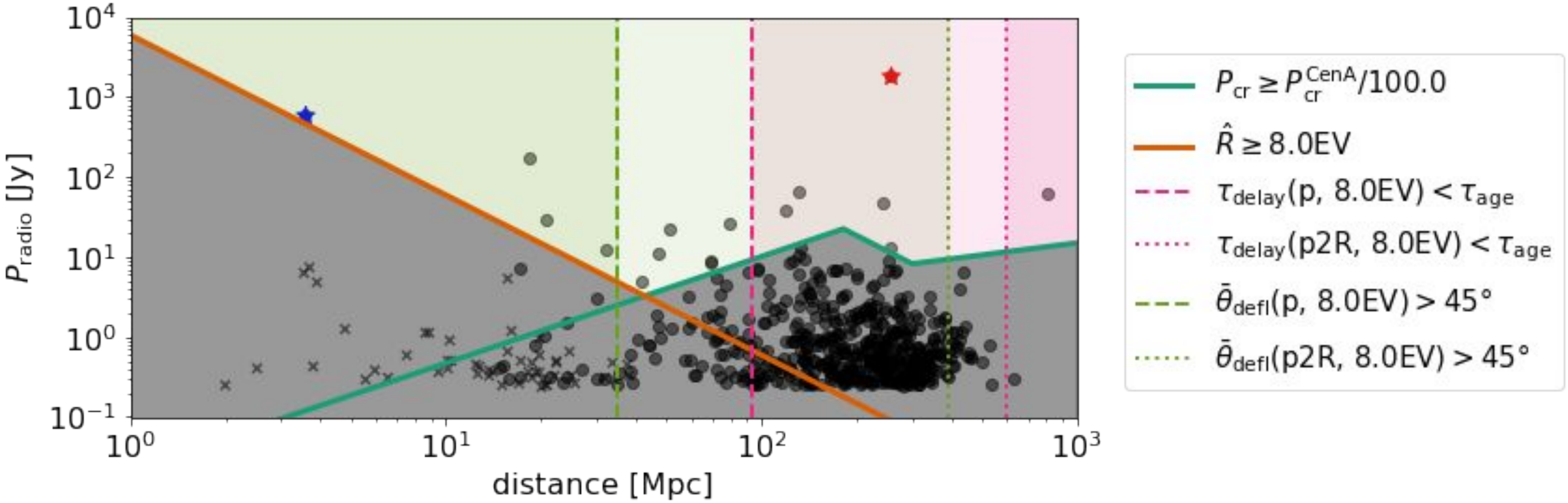


- ➢ Finite source age (τ_{age}=100Myr) constrains to a few hundreds of Mpc for strong EGMF (p,p2R)
- ➢ Minimal deflection criterion excludes sources up to few tens of Mpc for strong EGMF (p,p2R) and the whole local source sample for a weak EGMF (a).

Constraints on the local source contribution

The possible local source sample:

- ➢ distant, low-luminous sources don not provide enough CRs
- ➢ nearby sources (especially SBGs) hardly accelerate above 8EV
  - ○ for a light composition at 50 EeV $\longrightarrow$ composition at 50 EeV is rather heavy (PAO)

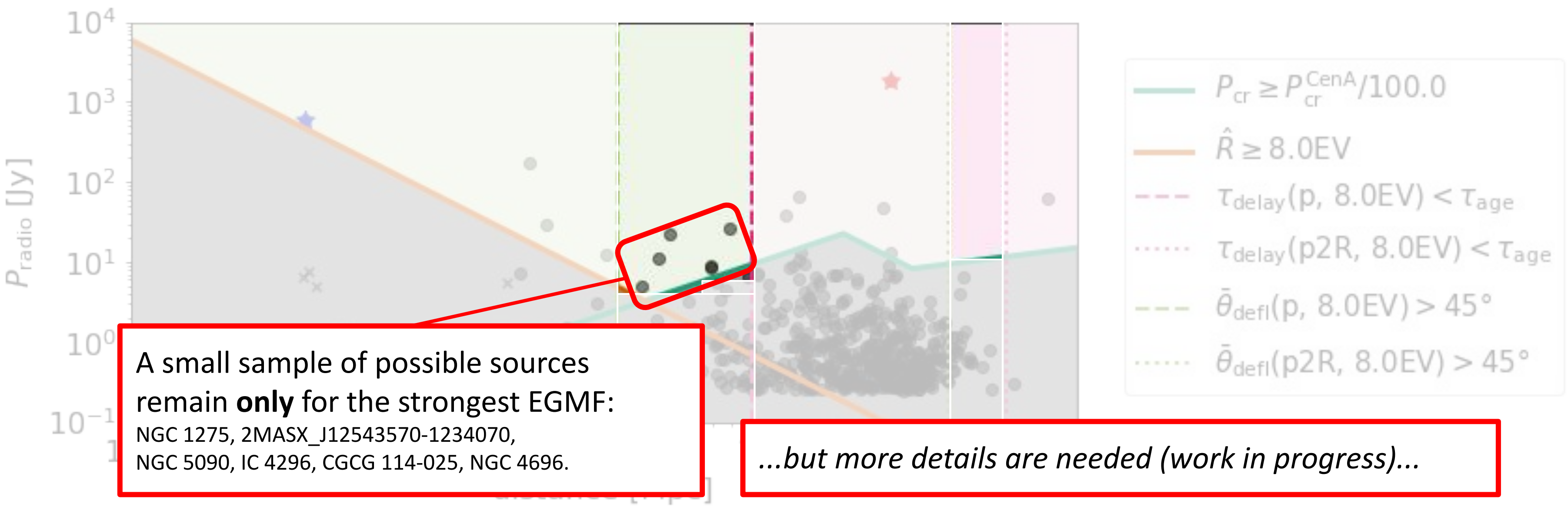


- ➢ Finite source age (τ_{age}=100Myr) constrains to a few hundreds of Mpc for strong EGMF (p,p2R)
- ➢ Minimal deflection criterion excludes sources up to few tens of Mpc for strong EGMF (p,p2R) and the whole local source sample for a weak EGMF (a).
- ➢ Different jet-to-radio-power correlations of FR-I (β_L=0.6) and FR-II (β_L=0.8) have only a minor effect

Constraints on the local source contribution

The possible local source sample:

- ➢ distant, low-luminous sources don not provide enough CRs
- ➢ nearby sources (especially SBGs) hardly accelerate above 8EV
    - ○ for a light composition at 50 EeV $\rightarrow$ composition at 50 EeV is rather heavy (PAO)



A small sample of possible sources remain **only** for the strongest EGMF:
NGC 1275, 2MASX_J12543570-1234070,
NGC 5090, IC 4296, CGCG 114-025, NGC 4696.

...but more details are needed (work in progress)...

- ➢ Finite source age (τ_{age}=100Myr) constrains to a few hundreds of Mpc for strong EGMF (p,p2R)
- ➢ Minimal deflection criterion excludes sources up to few tens of Mpc for strong EGMF (p,p2R) and the whole local source sample for a weak EGMF (a).
- ➢ Different jet-to-radio-power correlations of FR-I (β_L=0.6) and FR-II (β_L=0.8) have only a minor effect

(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!

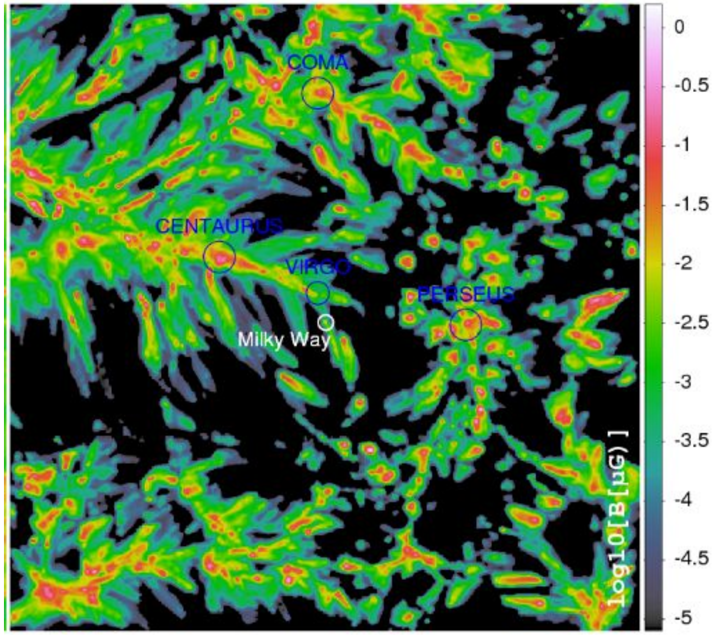
Eichmann (2019)

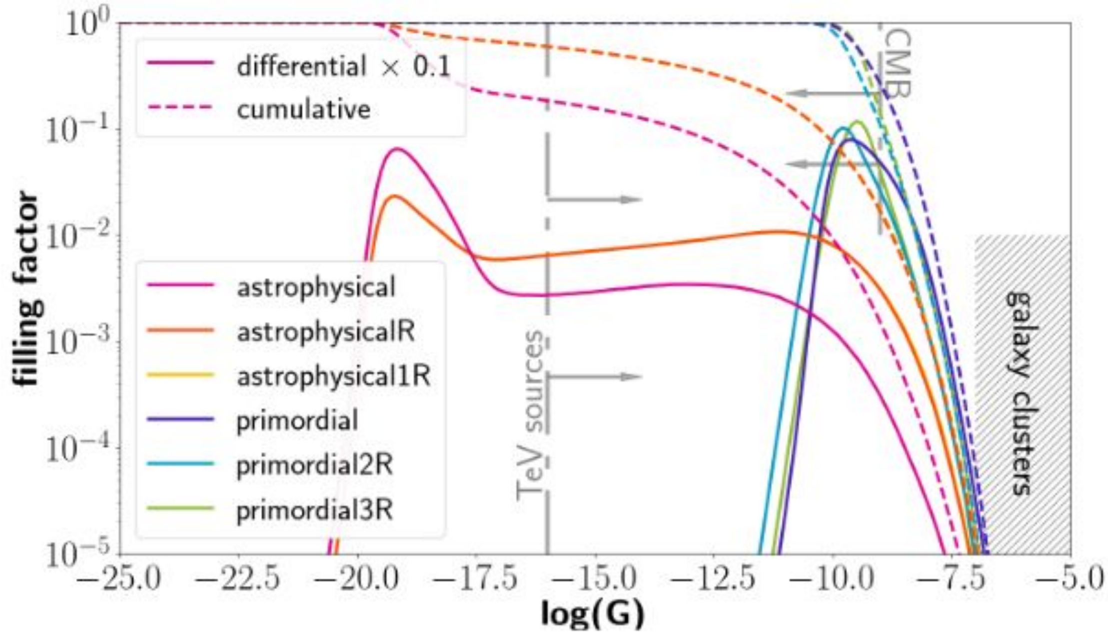
(III) Can individual local sources contribute?

They need to, but maybe these sources are even long gone...

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, $n_B = -4$	
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	

Constraints on the local source contribution

The impact of the chosen value of θ_{min}: