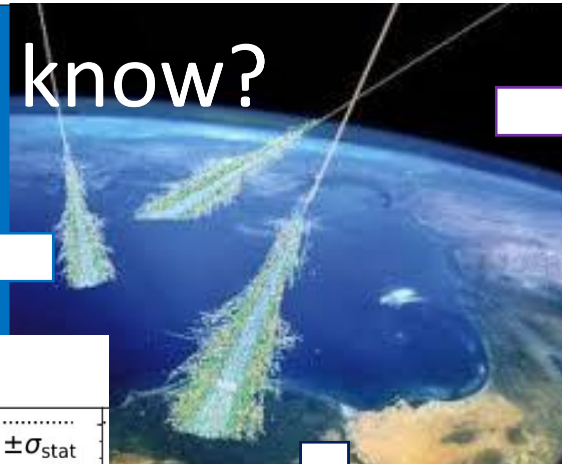
Radio galaxies as UHECR sources

Björn Eichmann

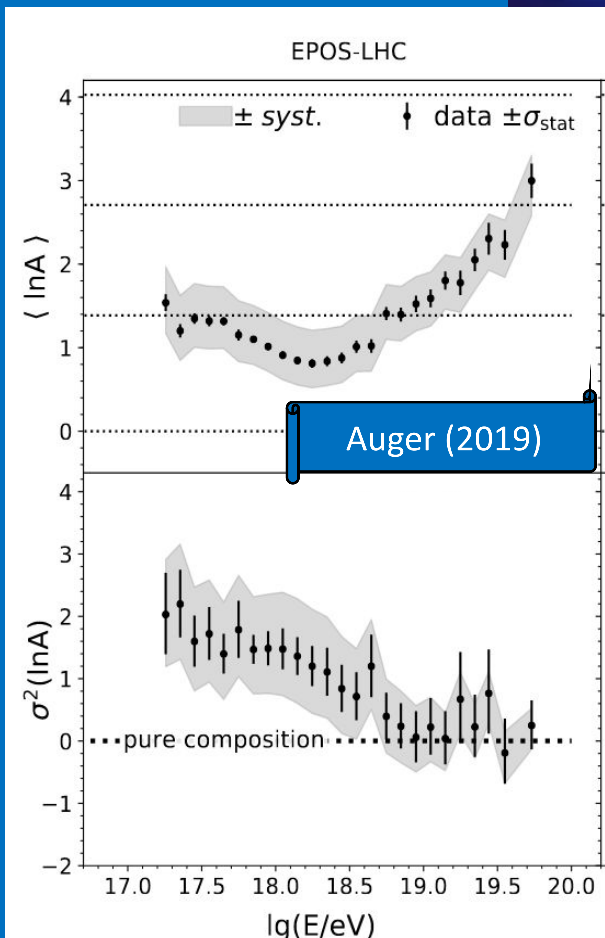
Cosmic Rays in the Multi-Messenger Era

Paris, 06.12.2022

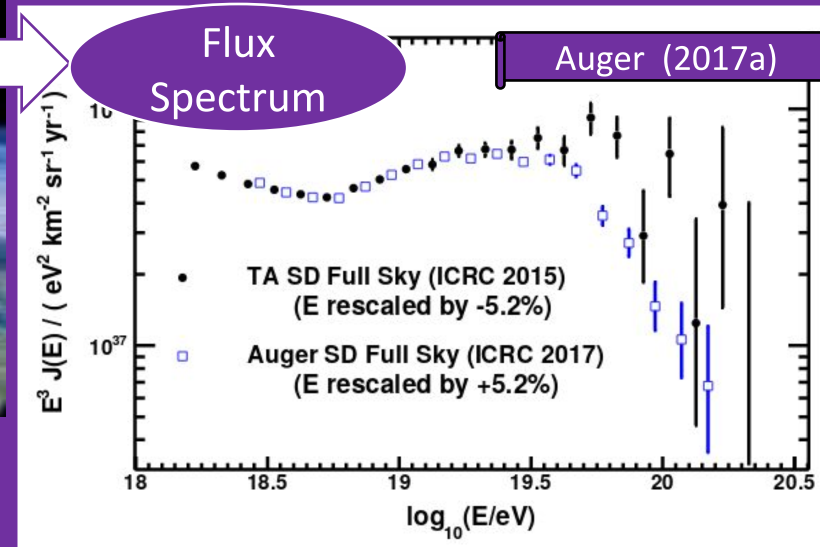
What do we know?



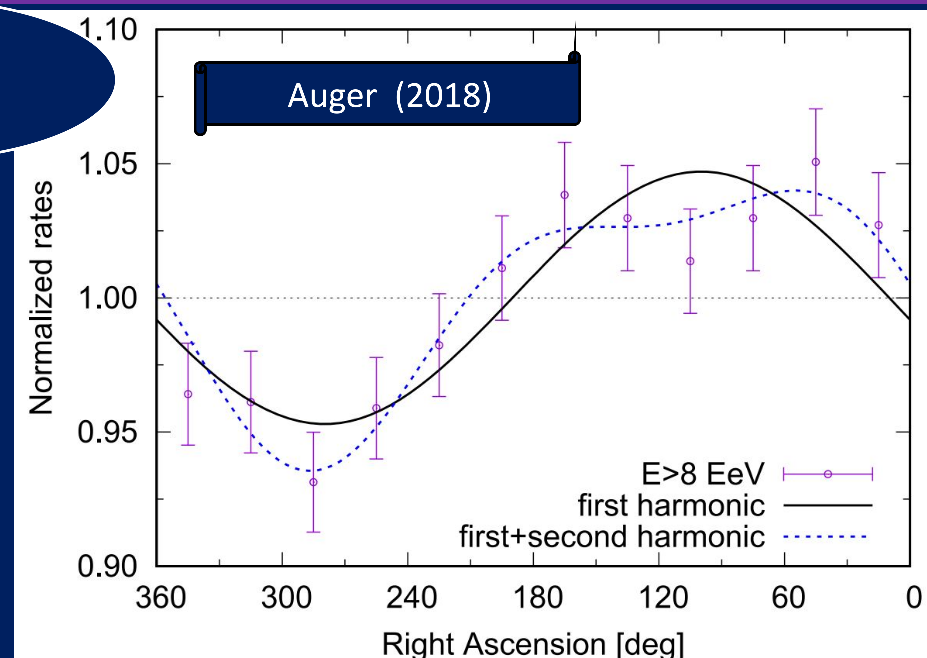
Chemical Composition



Flux Spectrum



Arrival Directions



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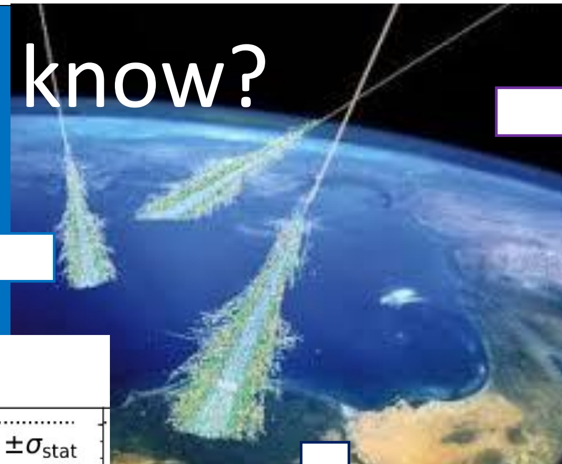

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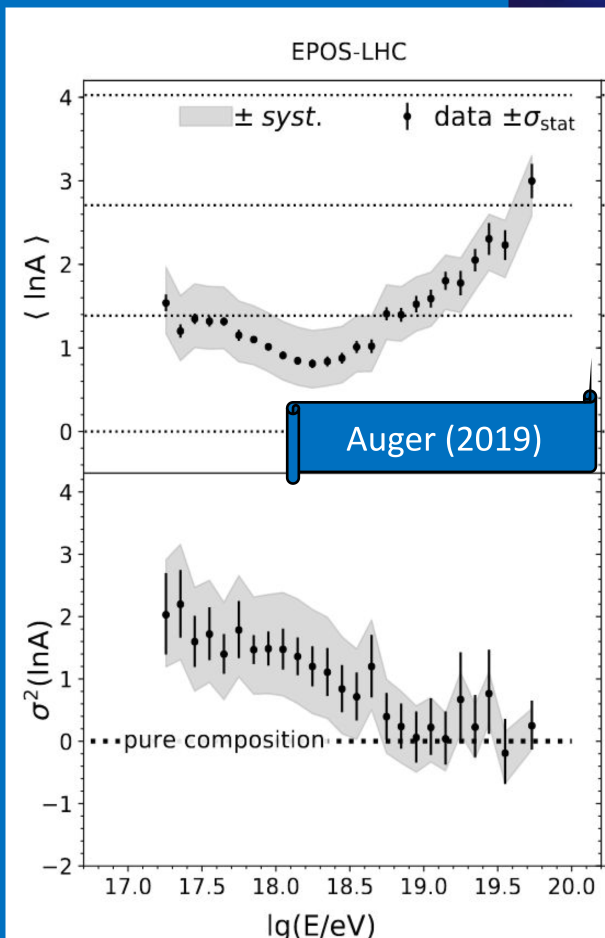
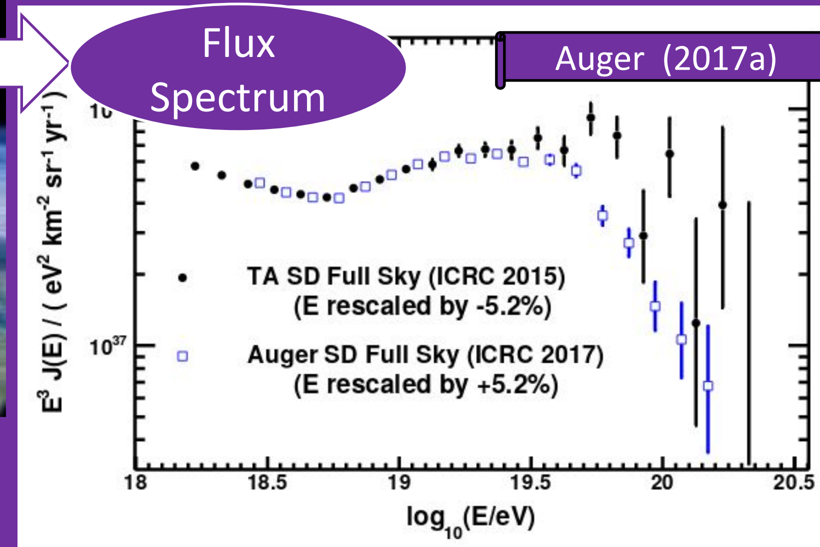


Auger (2019)

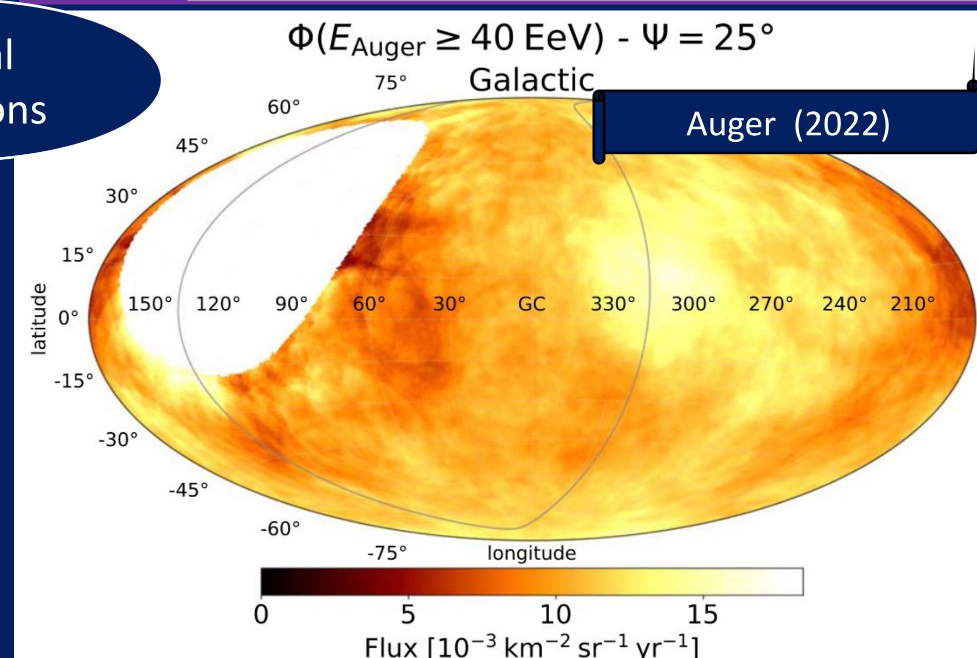
Flux Spectrum

Auger (2017a)



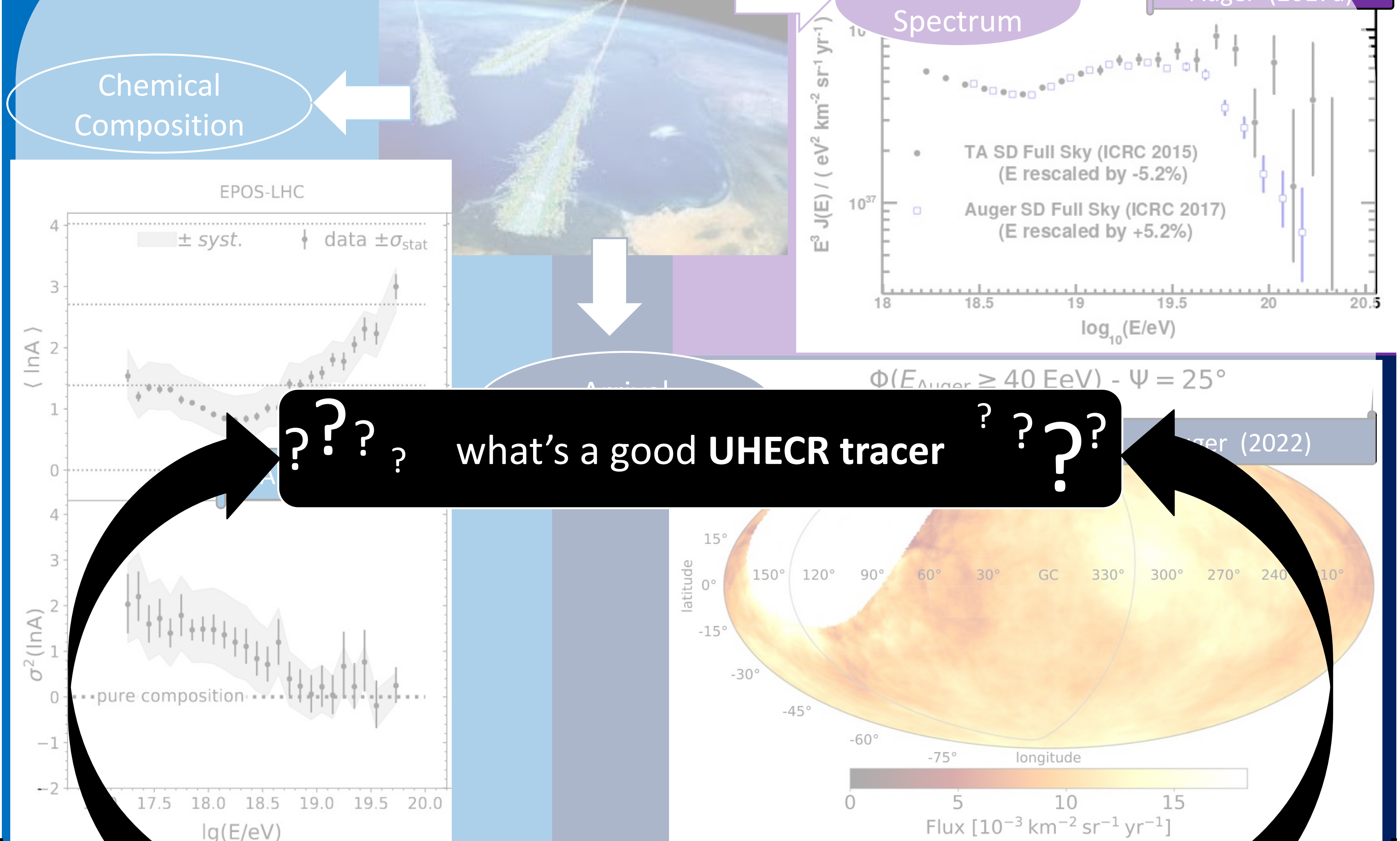
Arrival Directions

Auger (2022)



? ? ? ? what's their **origin** ? ? ? ?

What do we know?



? ? ? ? what's a good **UHECR tracer** ? ? ? ?

? ? ? ? what's their **origin** ? ? ? ?

The UHECR-radio connection

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

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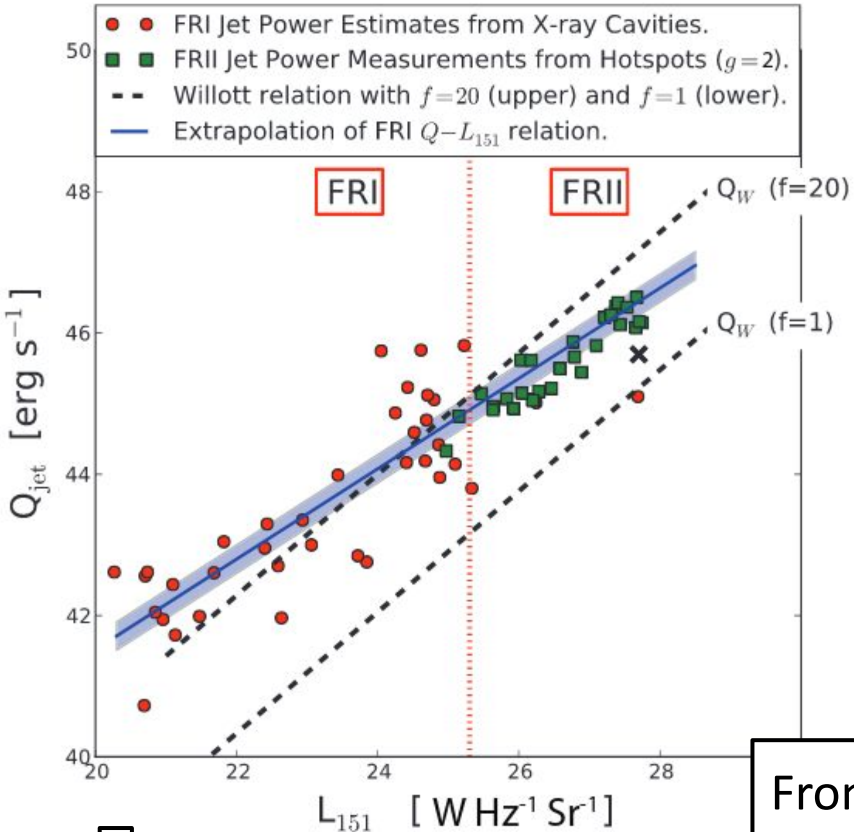
$$\hat{R} \simeq g_{acc}\sqrt{(1 - g_m)Q_{jet}/c}\,, \quad \text{with} \quad g_{acc} = \sqrt{\frac{8\beta_{sh}^2}{f_{diff}^2\beta_{jet}}}$$

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

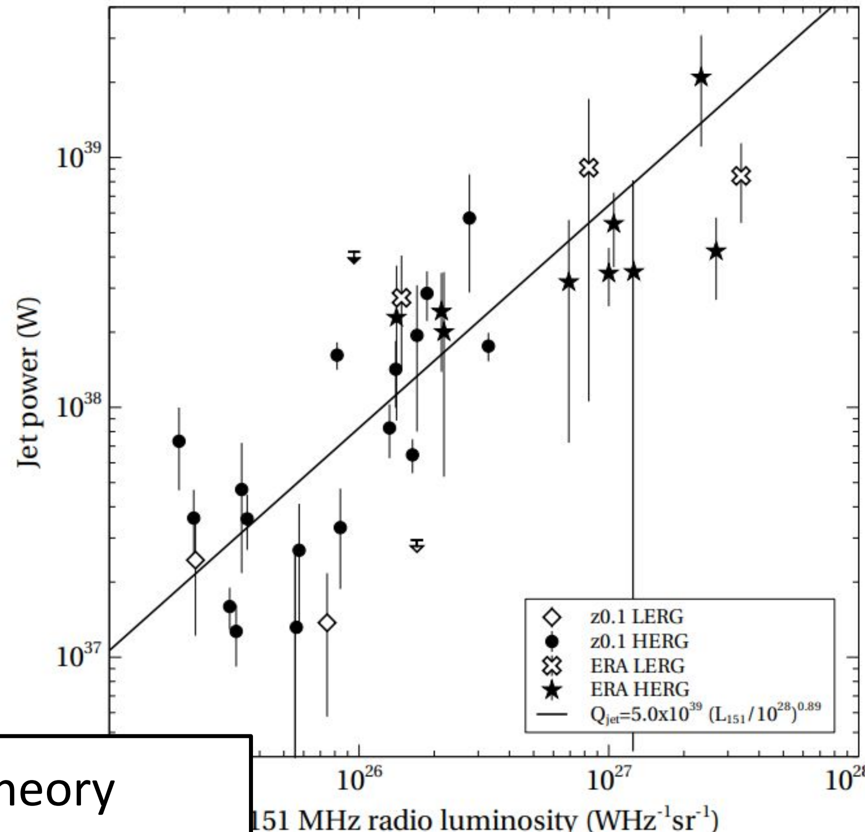
The jet power – radio connection

Godfrey+Shabala (2013):



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

Ineson+ (2017):



$$\beta_L = 0.89$$

From theory

(Godfrey+Shabala 2016):

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

The jet power – radio connection

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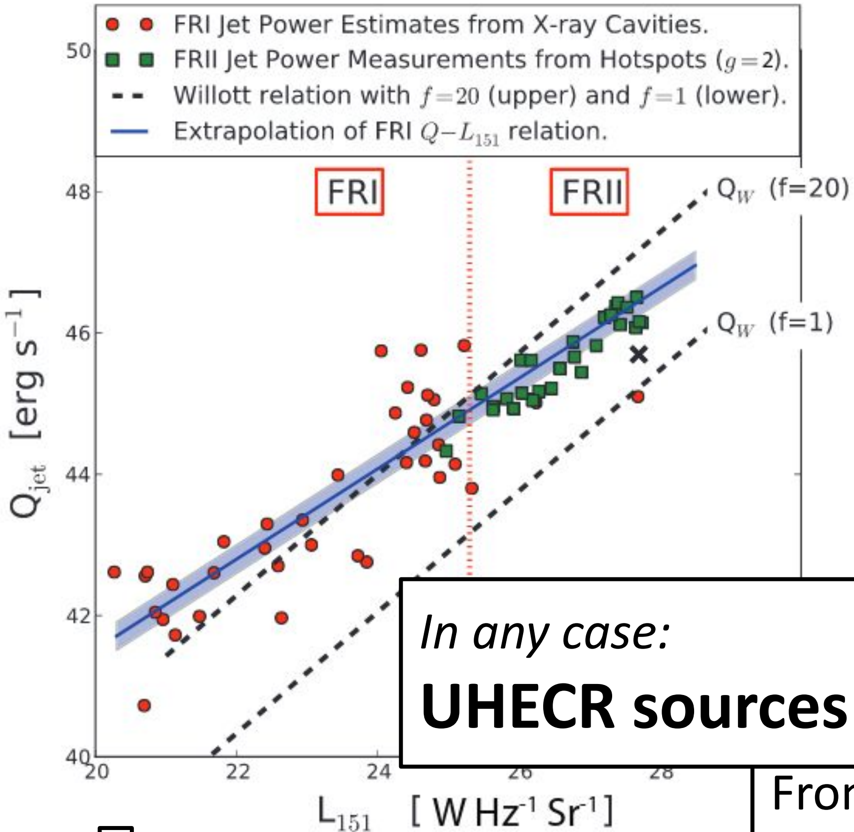

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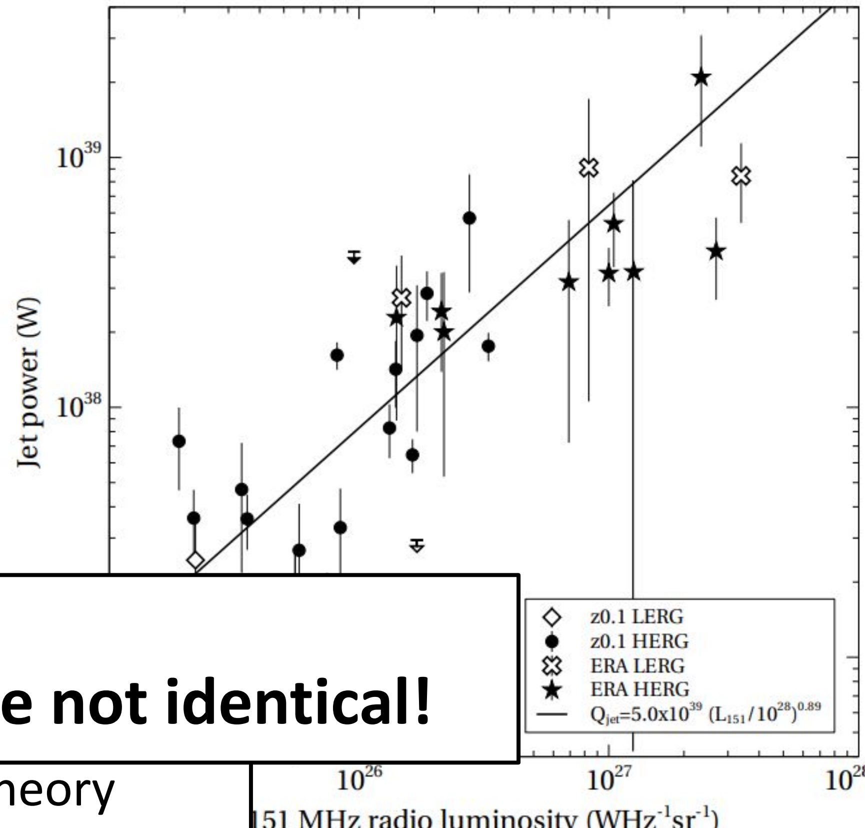


In any case:

UHECR sources are not identical!

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

From theory

(Godfrey+Shabala 2016):

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

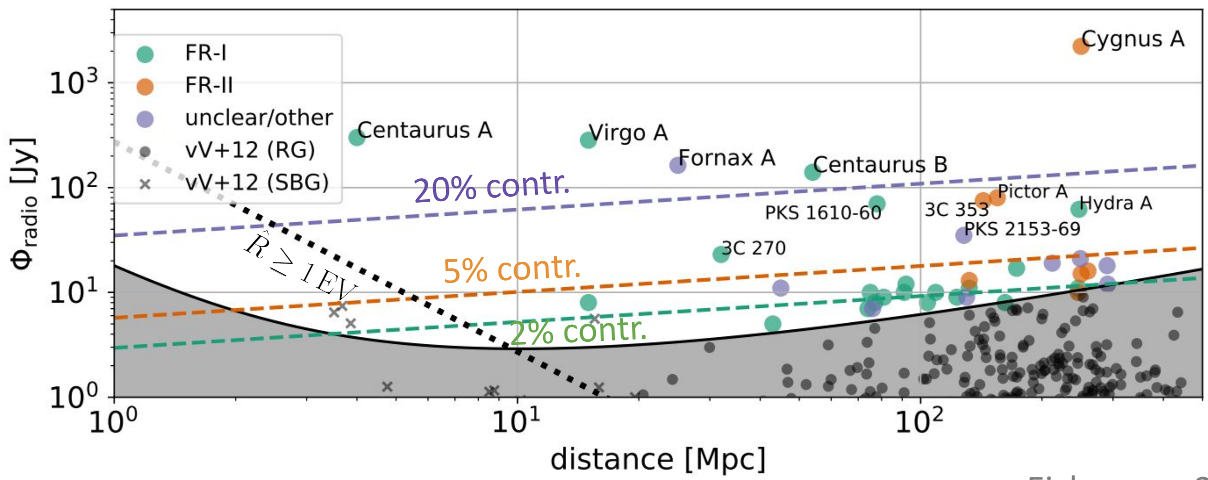
$$\beta_L = 0.89$$

The UHECR contribution *from radio galaxies*

UHECRs from local radio sources

Using the radio flux to estimate the CR contr. of the local sources:

- Only a **very limited number of sources** can compete with the brightest source (Cen A)

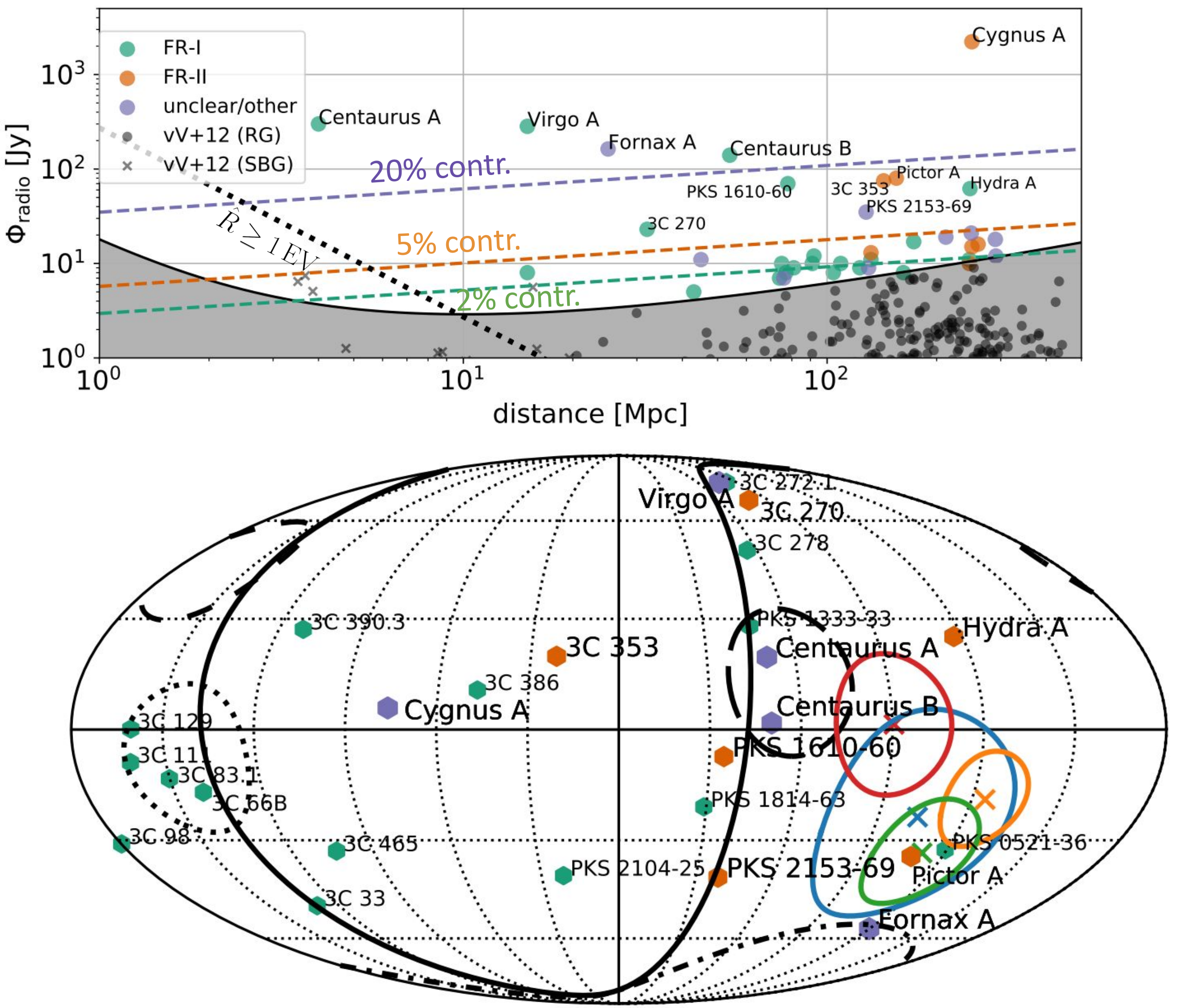


Eichmann+2022

UHECRs from local radio sources

Using the radio flux to estimate the CR contr. of the local sources:

- Only a **very limited number of sources** can compete with the brightest source (Cen A)
- **Dipole anisotropy** (colored) generally **agrees** with this source distribution
- **Most hotpots** (black dashed) show **associated sources** (except for the “TA-HS”)
- the majority of sources is **aligned with the supergalactic plane**



Eichmann+2022 [arXiv:2202.11942]

UHECRs from local radio sources

The general approach:

= source spectrum $S_i(R, \hat{R}(Q_{\rm cr}))$

= average enhancement factor due to diffusion and finite source lifetime (Harari+2021)

$$n(R,r,t_{\rm act}) = \sum_i n_i(R,r,t_{\rm act}) = n_0 \left(\frac{R}{\check{R}}\right)^{-\alpha} \exp\left(-\frac{R}{\hat{R}}\right) \bar{\xi}(R,r,t_{\rm act})\, \bar{\eta}(R,r)$$

= average spectral modification factor with $\eta_i(R,r) \equiv \frac{S_i(R,r)}{S_{0,i}(R)}$

local ind. ⇒

$$J_s(R,r_s,t_{\rm act}) \equiv \frac{\mathrm{d}N_{\rm cr}}{\mathrm{d}R\,\mathrm{d}A\,\mathrm{d}t\,\mathrm{d}\Omega} = \frac{c}{4\pi}\, n(R,r_s,t_{\rm act})$$

Using **rigidity instead of energy**

Accounting for the **angular distribution of arrival direction** based on a isotropically turbulent extragalactic magnetic field (Harari+2016) + Galactic (JF12) field

local sources

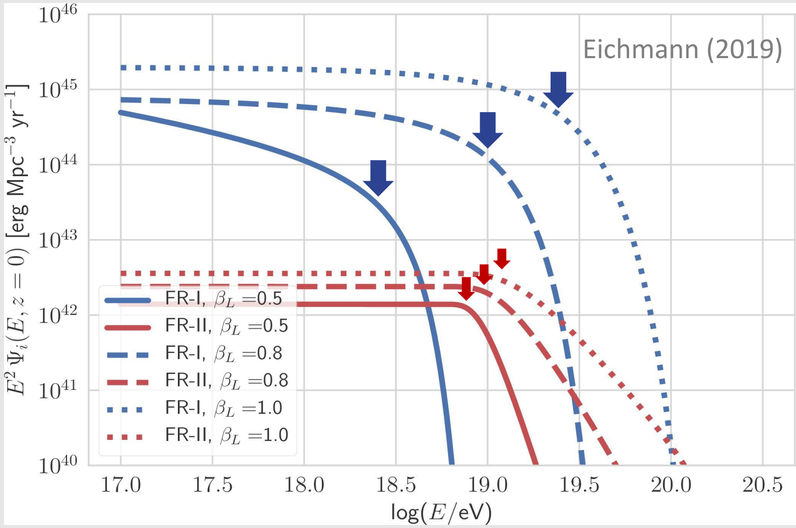
Eichmann+2022 [arXiv:2202.11942]

UHECRs from non-local radio sources

Continuous CR source function of radio galaxies based on the *radio luminosity function (RLF)* from Willott+2001

$$\Psi_i(R,\, z) \equiv \frac{\mathrm{d}N_{\rm cr}(Z_i)}{\mathrm{d}V\,\mathrm{d}R\,\mathrm{d}t} = \int_{\check{Q}_{\rm cr}}^{\hat{Q}_{\rm cr}} S_i(R, \hat{R}(Q_{\rm cr}))\,\frac{\mathrm{d}N}{\mathrm{d}V\,\mathrm{d}Q_{\rm cr}}\,\mathrm{d}Q_{\rm cr}$$

…provides an **isotropic contribution** on scales larger than the Local Supercluster



Including a diffuse contribution from the **bulk of non-local (*z>0.02*) radio galaxies**:

non-local

$$J_{\rm csf}(R, t_{\rm act}) = \frac{c}{4\pi} \int \mathrm{d}z\, \left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \sum_i \Psi_{0,i}(R,\, z)\, A_i\, \bar{\eta}_{\rm csf}(R, z)$$

non-local sources

Eichmann+2022 [arXiv:2202.11942]

UHECRs from **local+non-local** radio sources

The general approach:

$$n(R,r,t_{\rm act}) = \sum_i n_i(R,r,t_{\rm act}) = n_0 \left(\frac{R}{\check{R}}\right)^{-\alpha} \exp\left(-\frac{R}{\hat{R}}\right) \bar{\xi}(R,r,t_{\rm act})\, \bar{\eta}(R,r)$$

$\bar{\xi}$ = average enhancement factor due to diffusion and finite source lifetime (Harari+2021)

$\bar{\eta}$ = average spectral modification factor with $\eta_i(R,r) \equiv \frac{S_i(R,r)}{S_{0,i}(R)}$

local ind. ⇒ $$J_s(R,r_s,t_{\rm act}) \equiv \frac{{\rm d}N_{\rm cr}}{{\rm d}R\,{\rm d}A\,{\rm d}t\,{\rm d}\Omega} = \frac{c}{4\pi}\, n(R,r_s,t_{\rm act})$$

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Accounting for the **angular distribution of arrival direction** based on a isotropically turbulent extragalactic magnetic field (Harari+2016) + Galactic (JF12) field

local sources

Including a isotropic contribution from the **bulk of non-local (*z>0.02*) radio galaxies**:

non-local ⇒ $$J_{\rm csf}(R,t_{\rm act}) = \frac{c}{4\pi}\int {\rm d}z\, \left|\frac{{\rm d}t}{{\rm d}z}\right| \sum_i \Psi_{0,i}(R,\,z)\, A_i\, \bar{\eta}_{\rm csf}(R,z)$$

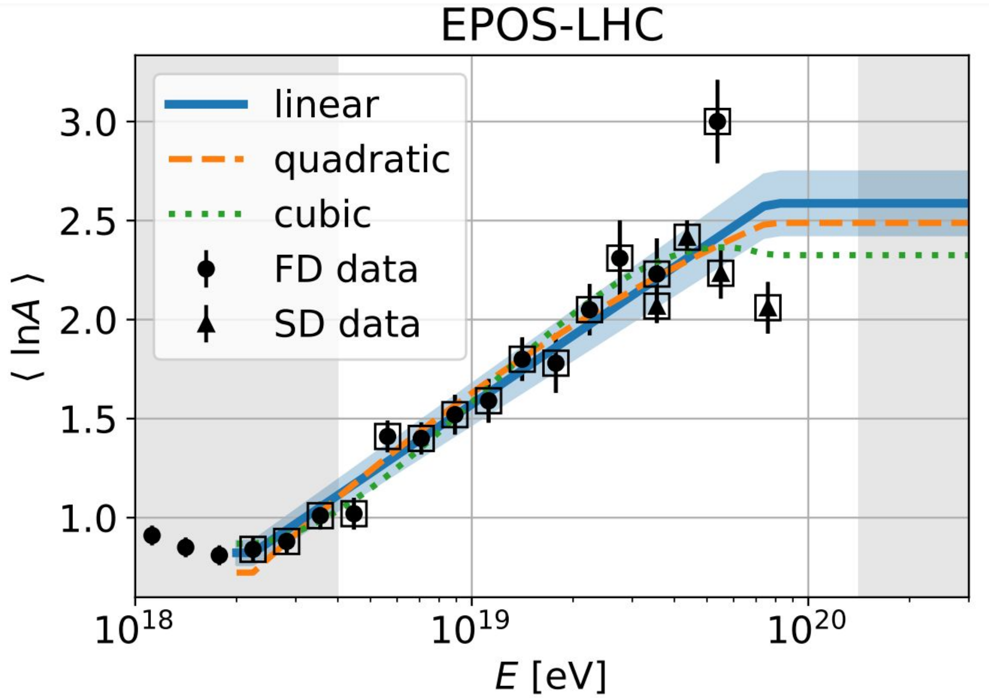
non-local sources

in total ⇒ $$J_R = J_{\rm csf} + \textstyle\sum_s J_s$$ …is (roughly) independent of the actual CR element!

Eichmann+2022 [arXiv:2202.11942]

Fitting the data

The general approach:
Using the *observed compositional data to convert rigidity into (energy, mass)*:



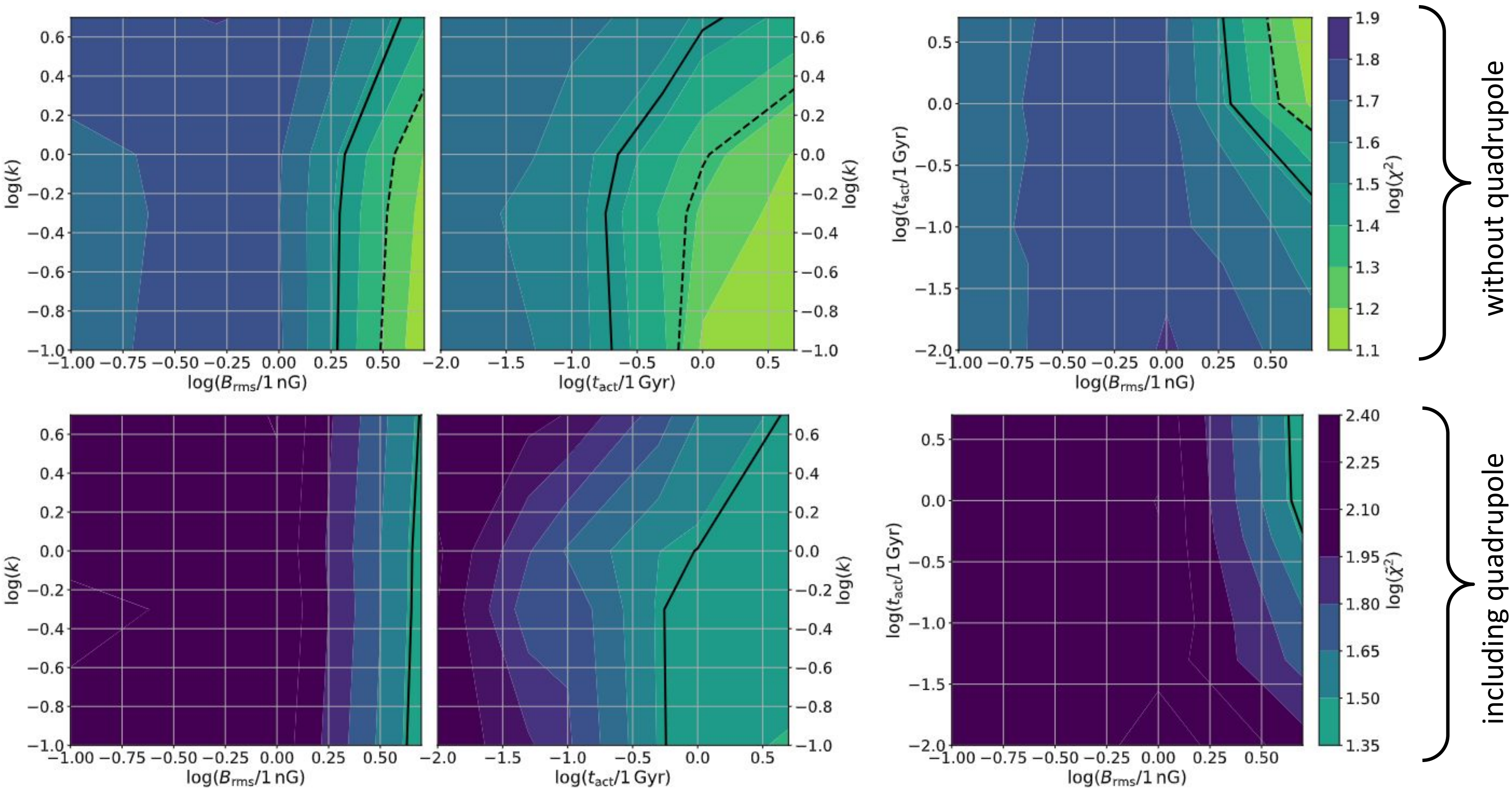
- ❖ a priori agreement with the <lnA> data but not necessarily with Var(lnA)
  - ➢ no constraint on the initial elem. abund.
- ❖ substantial decrease of the parameter space

…still the **energy spectrum and anisotropy data** (quadrupole strength is not included in the parameter optimization) needs to be fitted

Eichmann+2022
[arXiv:2202.11942]

Fitting the data

Using the **five brightest local sources:**



Eichmann+2022
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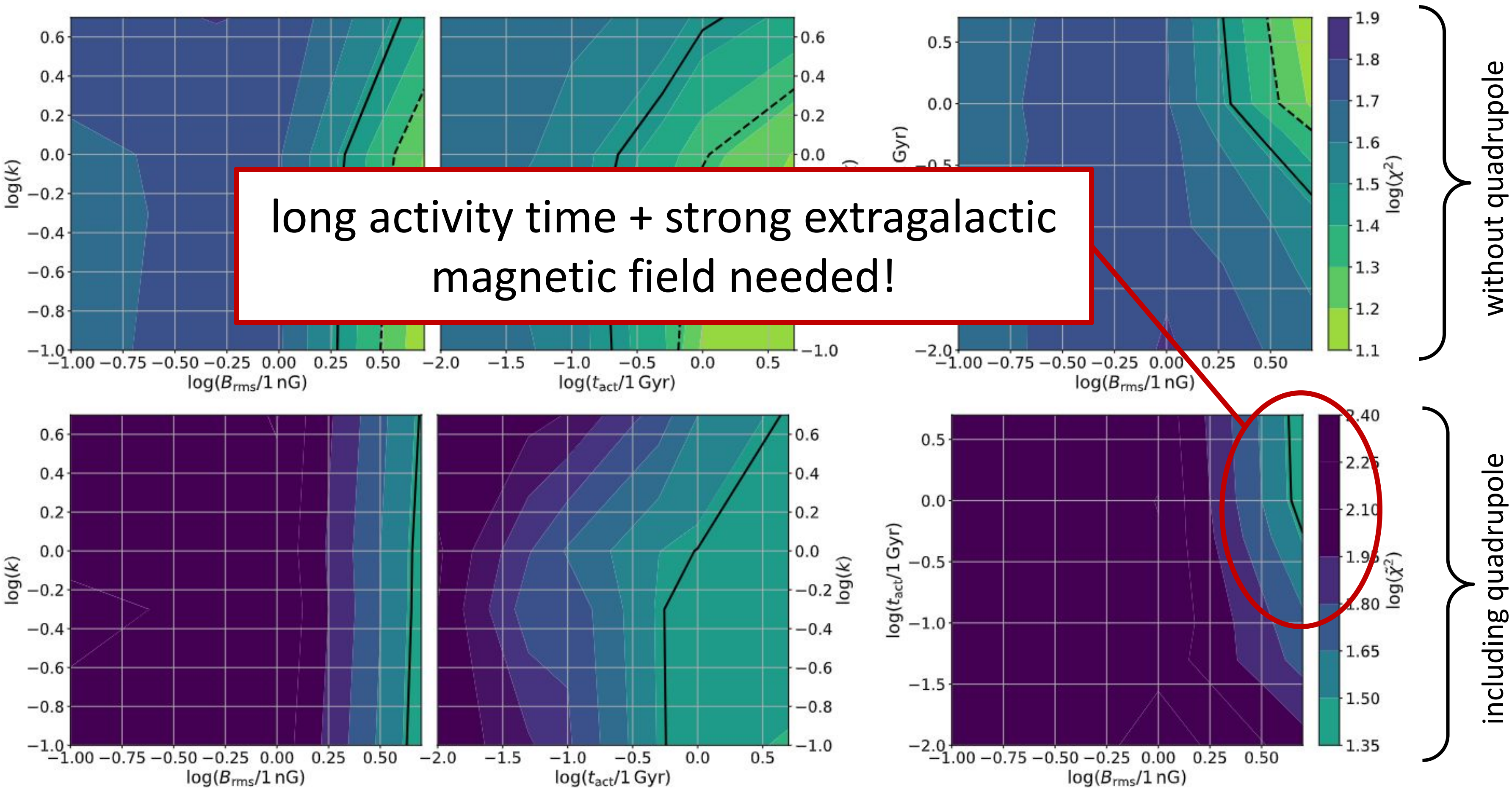
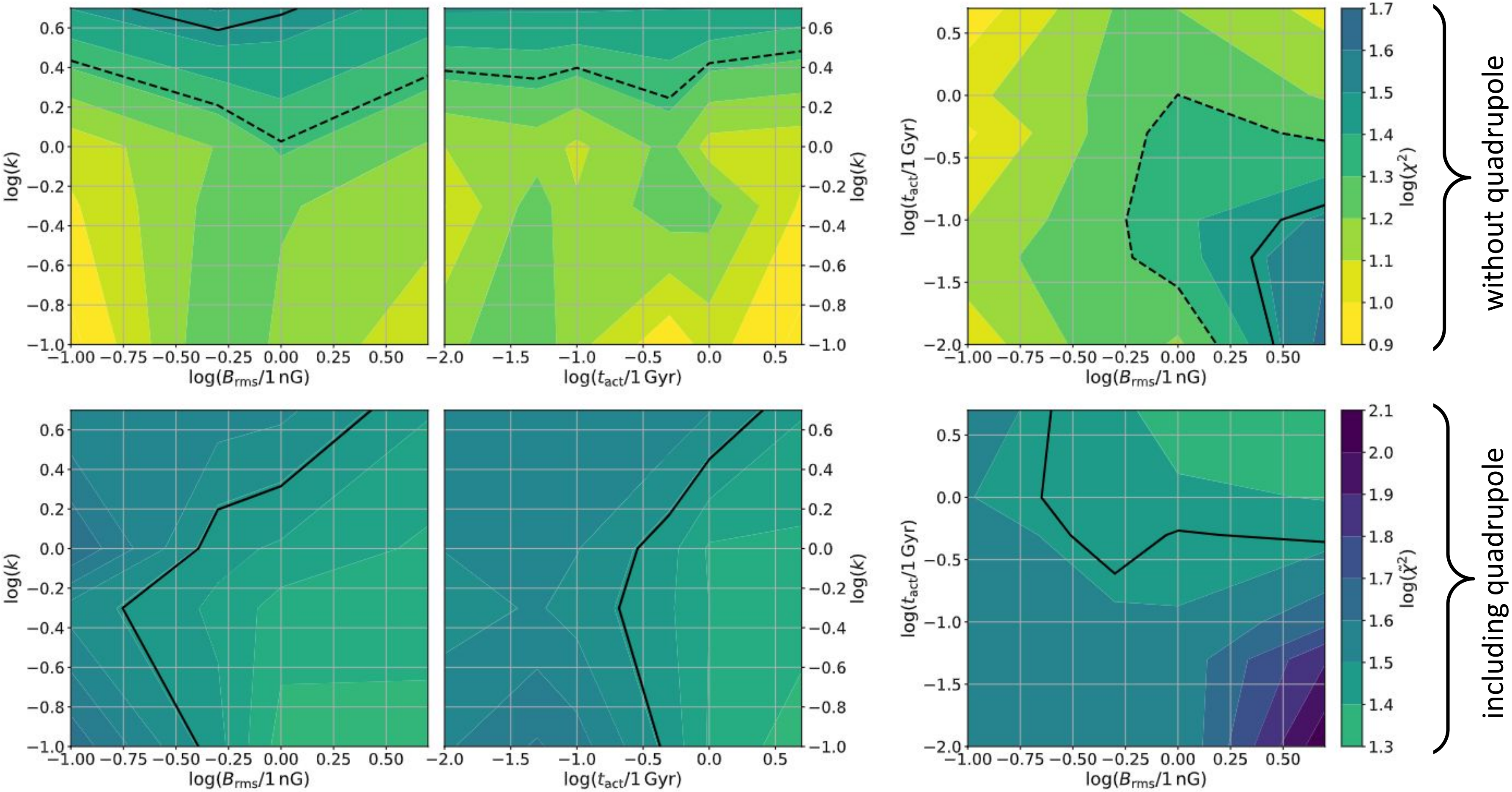


long activity time + strong extragalactic magnetic field needed!

Eichmann+2022 [arXiv:2202.11942]

Fitting the data

Using the **eleven brightest local sources:**



Eichmann+2022
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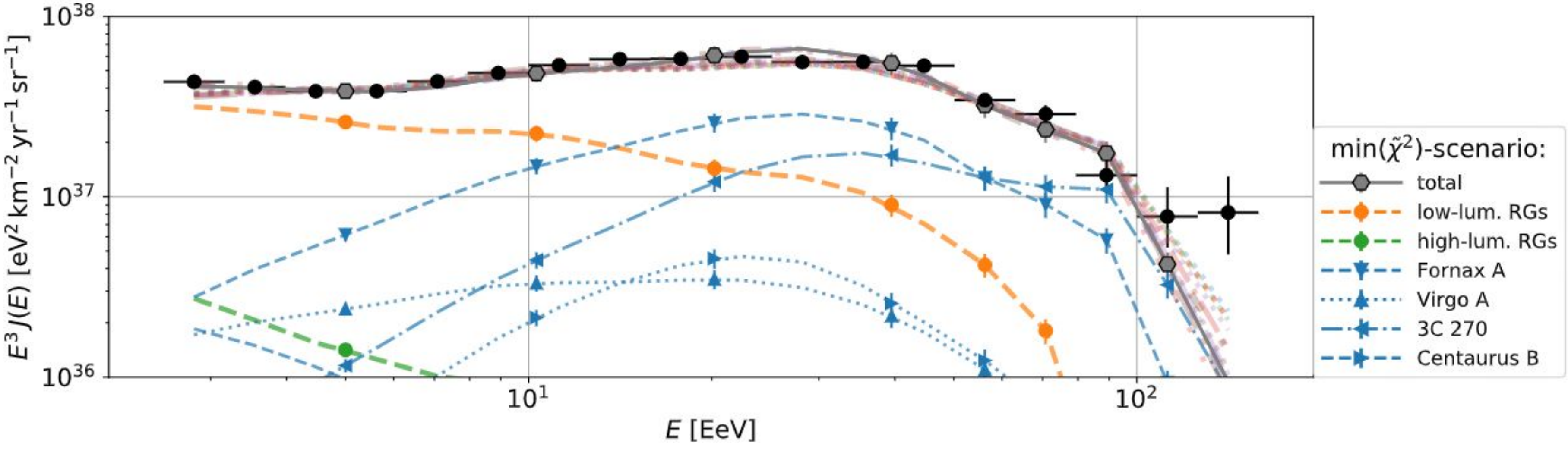
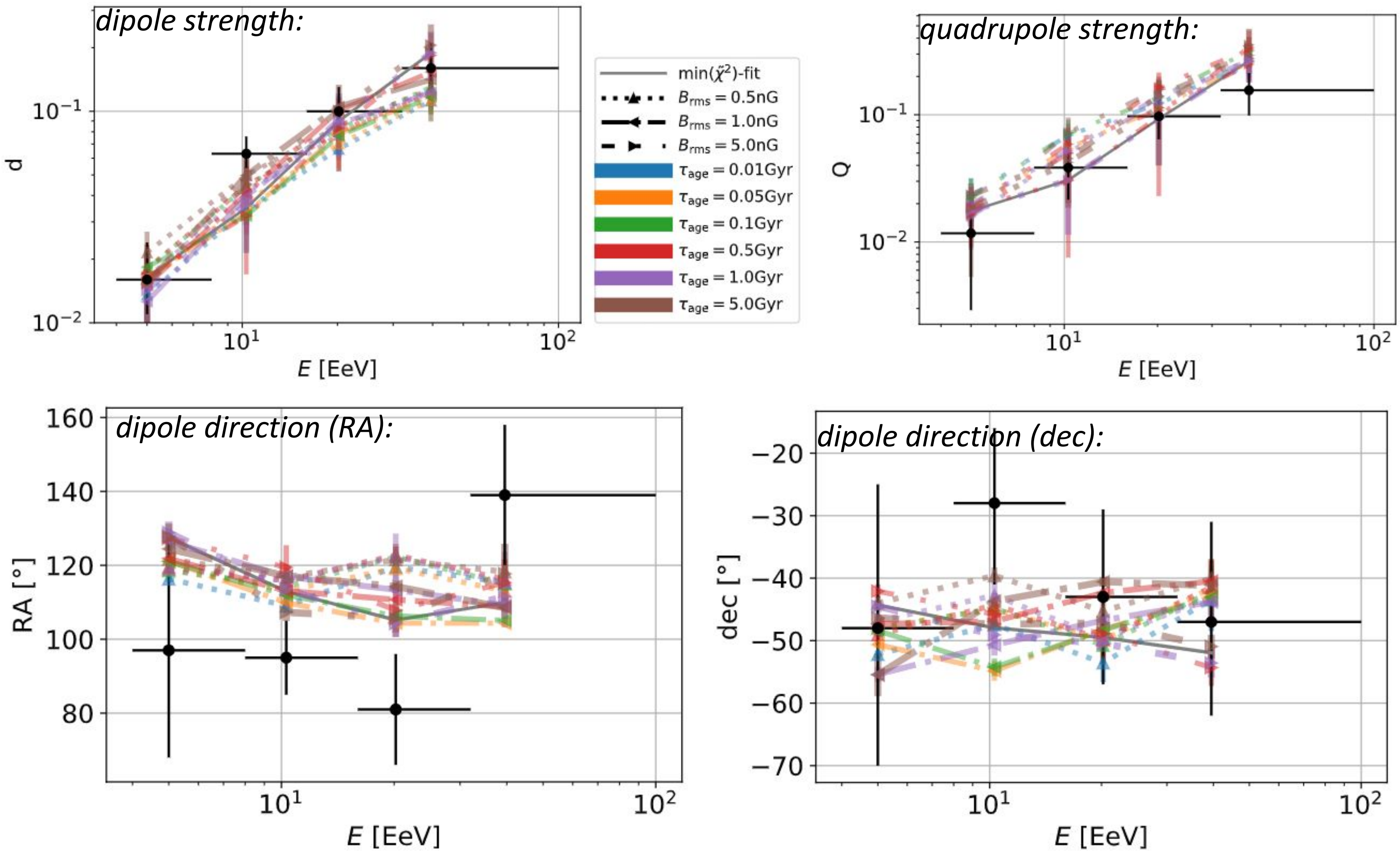


- ➢ bulk of low-luminous (FR-I) radio galaxies dominants below the ankle
- ➢ just a few local sources (such as Fornax A, Virgo A) provide a significant contribution above the ankle

Eichmann+2022
[arXiv:2202.11942]

Fitting the data

Using the **eleven brightest local sources:**

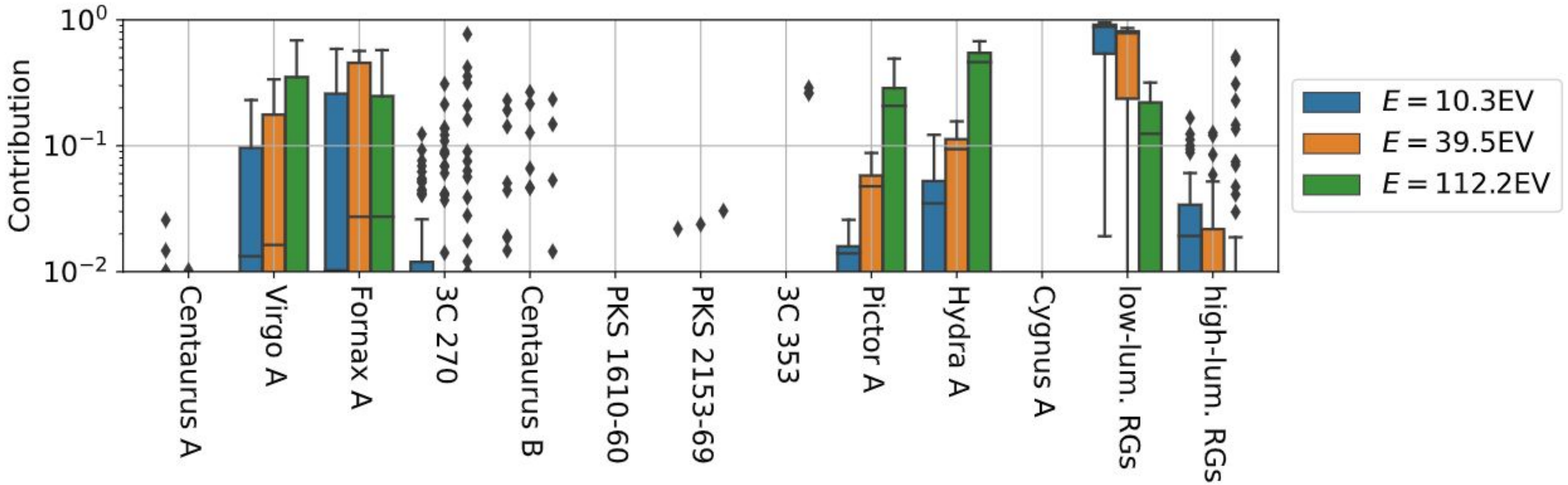


Eichmann+2022
[arXiv:2202.11942]

Fitting the data

Using the **eleven brightest local sources:**

- ➢ source contributions:



Eichmann+2022
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Fitting the data

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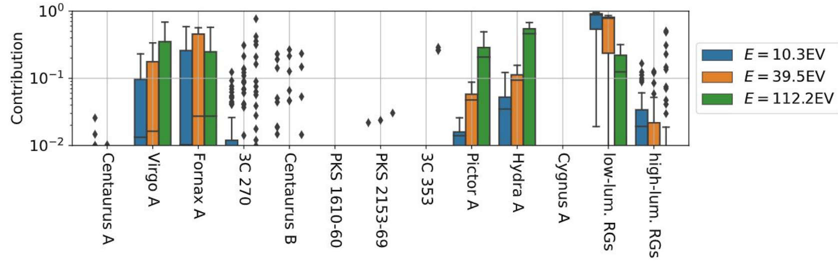
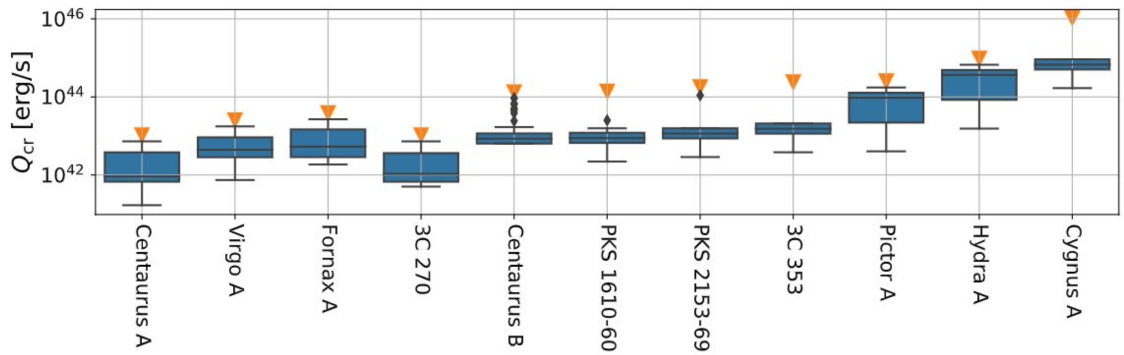
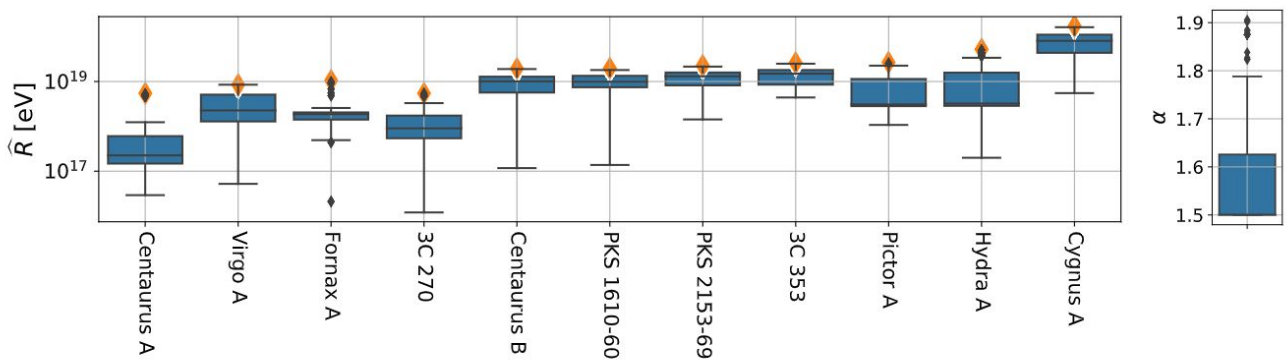


- ➢ source properties:



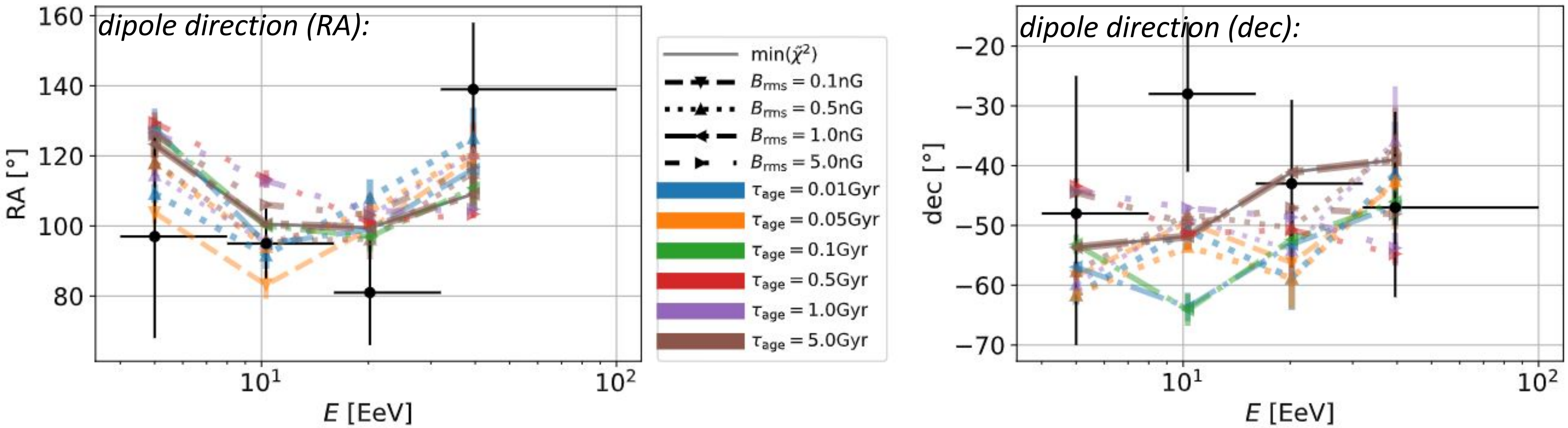


Eichmann+2022
[arXiv:2202.11942]

Fitting the data

Using the **twenty-six brightest local sources:**

➢ *only small improvements*, mostly with respect to the dipole direction:



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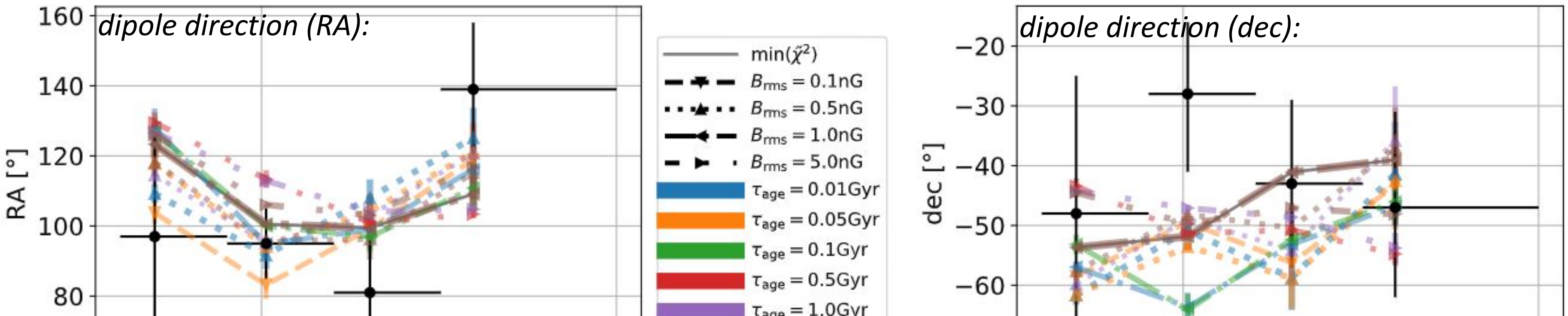


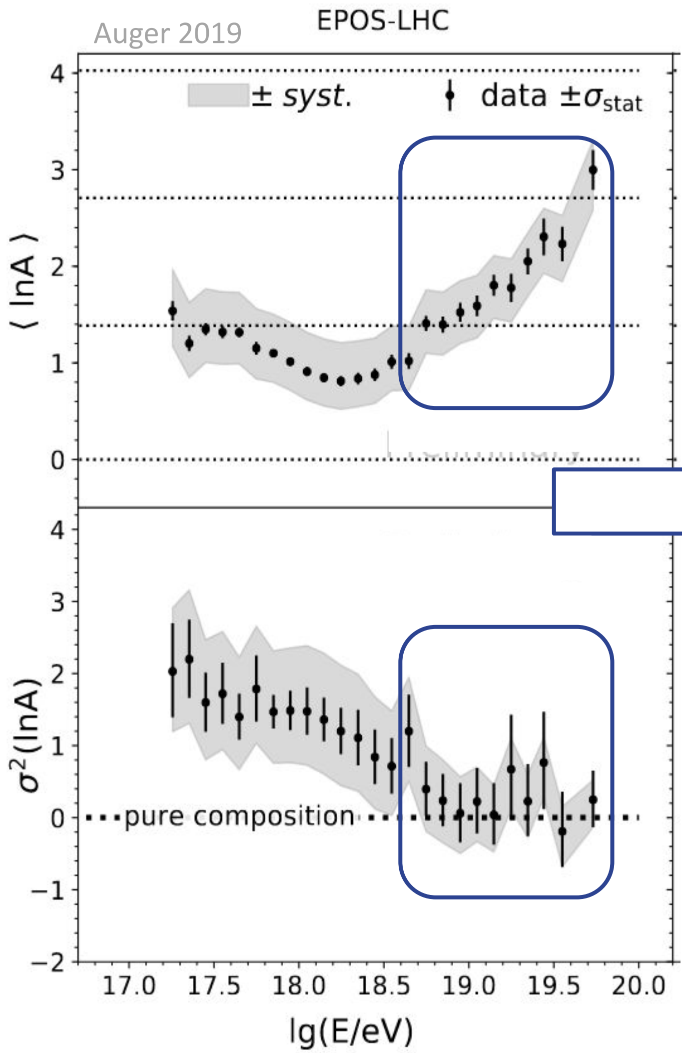
➢ UHECR data can already be explained by a small local sample of FR-I radio galaxies.

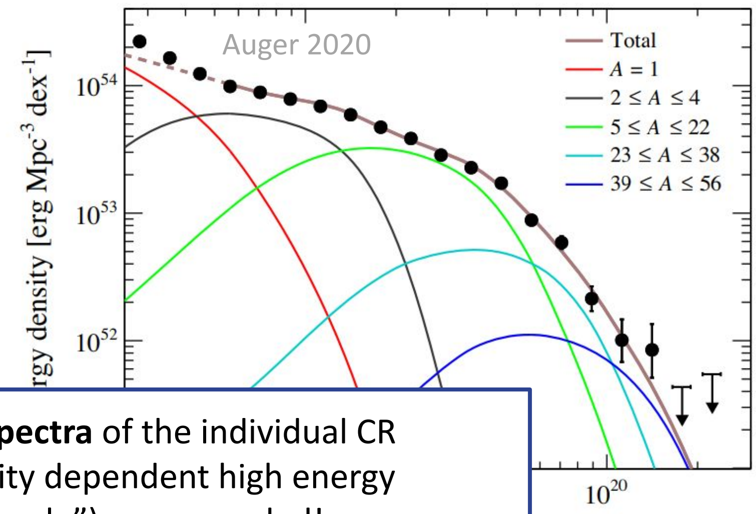
➢ But with arbitrary (different) initial element abundances

Eichmann+2022
[arXiv:2202.11942]

The hard spectra of individual UHECR nuclei

The curious case of extremely hard spectra





extremely hard spectra of the individual CR elements (& rigidity dependent high energy cut-offs - "Peters cycle") seem needed!

Spectral hardness already **at the sources**;
OR
a result from propagation effects due to a **finite source life-time?**

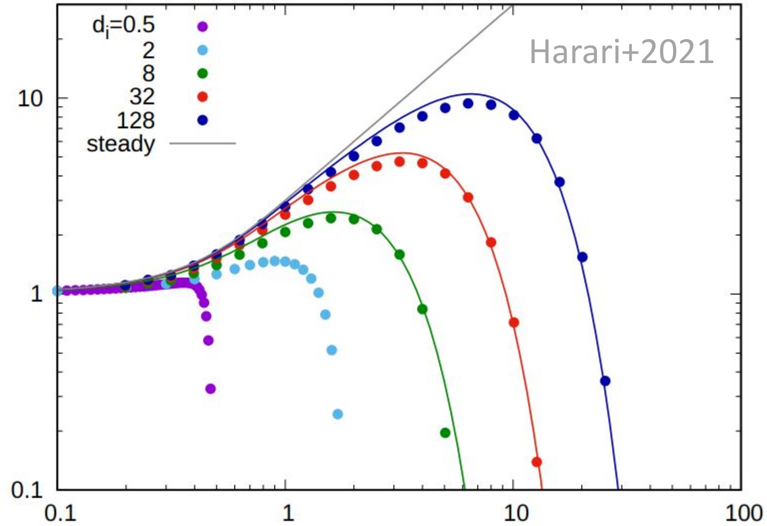
The curious case of extremely hard spectra

Using a (dimensionless) emission time measure:

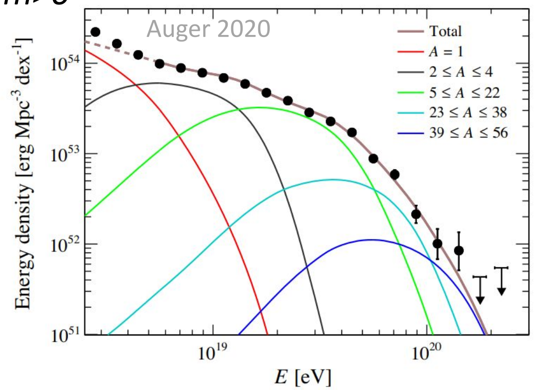
$d_i \equiv ct_i/l_D(E)$ with diff. lenght $l_D \propto (E/Z)^m$ with $m>0$

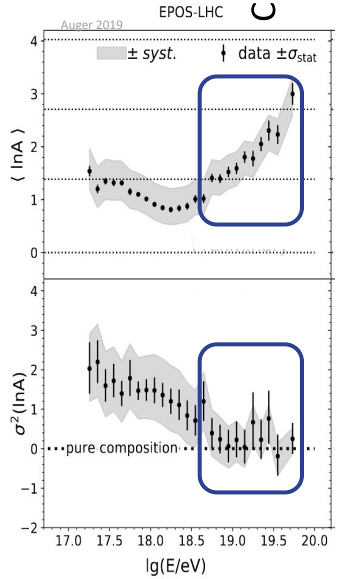
CR density with respect to the source emissivity

enhancement factor



$R \equiv r/l_D$ … the (dimensionless) source distance





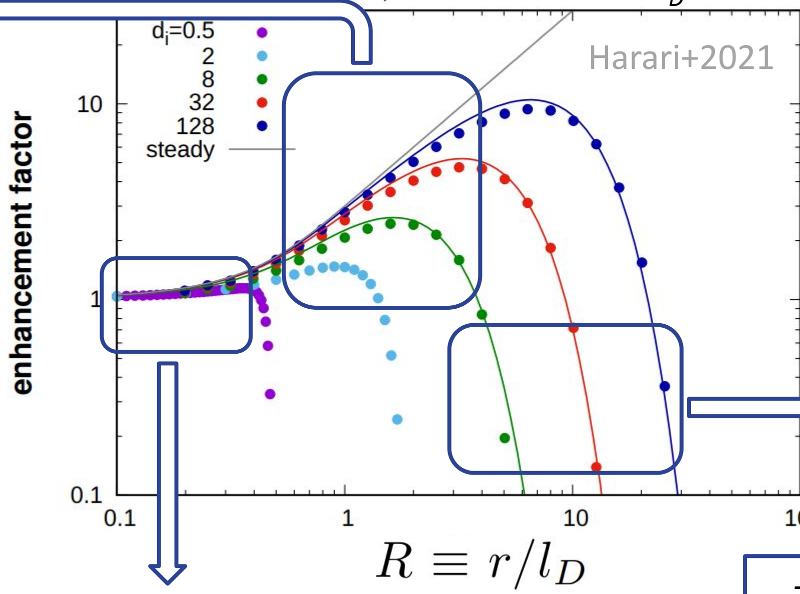
Extremely hard individual CR spectra as

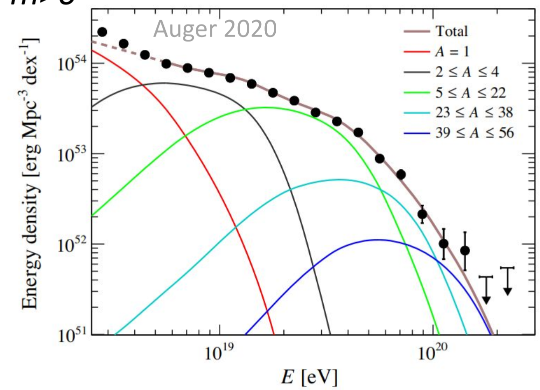
a result from propagation effects due to a **finite source life-time!**

The curious case of extremely hard spectra

$d_i \equiv ct_i/l_D(E)$ with diff. lenght $l_D \propto (E/Z)^m$ with $m>0$

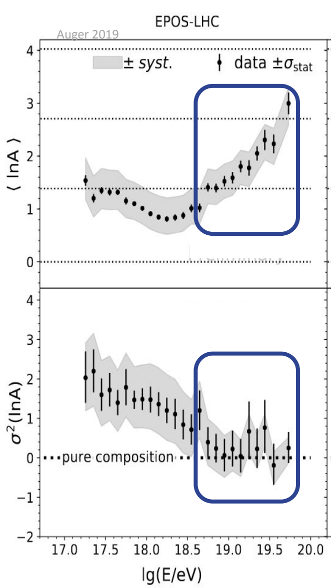
diffusion enhancement





"magnetic horizon" cutoff

Z-dependent low energy suppression leads to harder spectra



quasi-rectilinear propagation

Extremely hard individual CR spectra as

a result from propagation effects due to a **finite source life-time!**

The curious case of extremely hard spectra

diffusion enhancement

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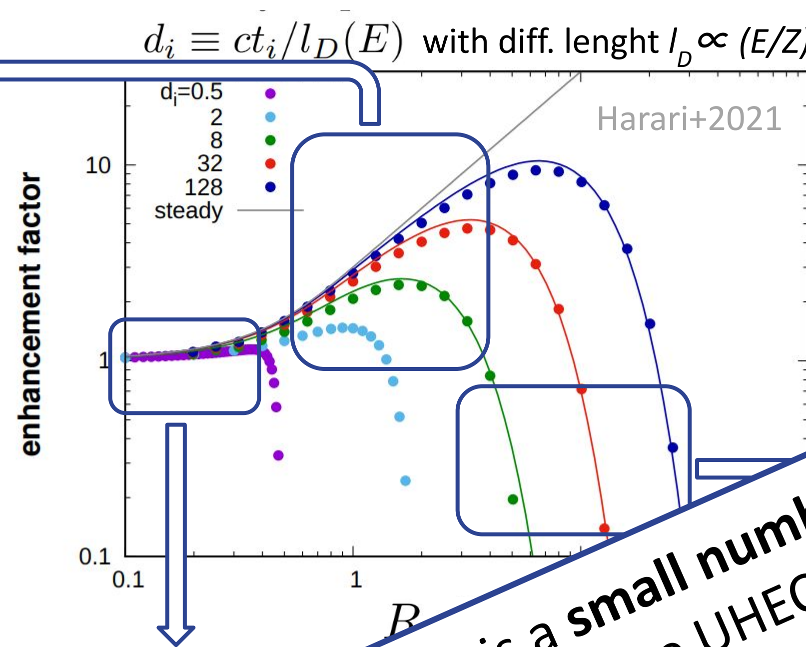
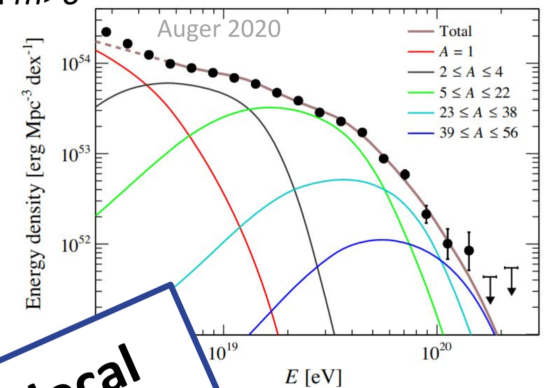
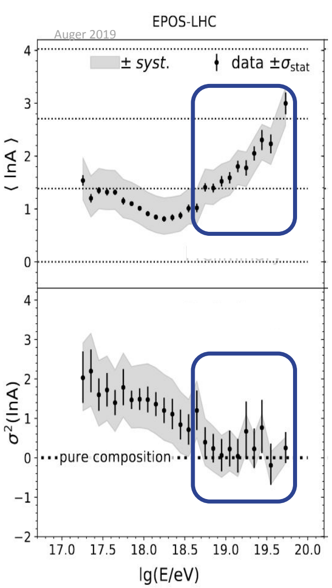






quasi-rectili… pr…

…on" cutoff

Z-dependent low energy suppression leads to harder spectra

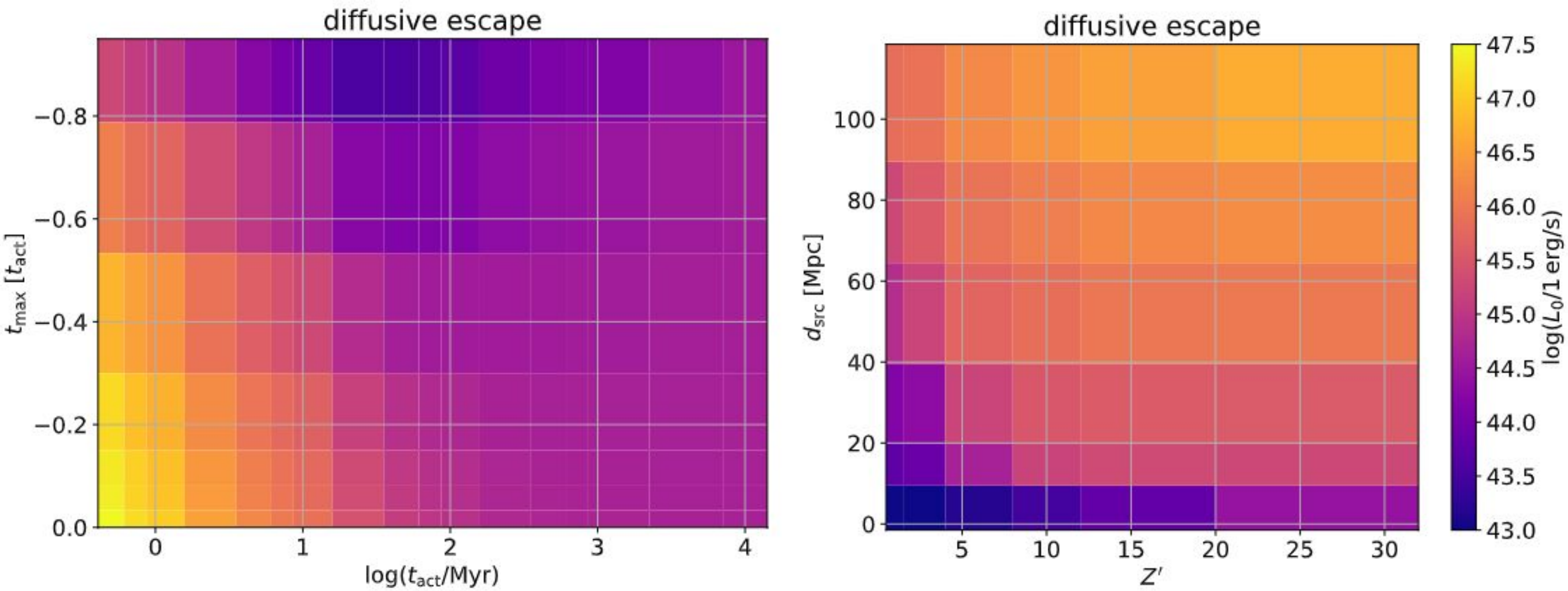
Extremely hard individual CR spectra as

a result from propagation effects due to a **finite source life-time!**

…but only if there is a **small number of local sources** that dominates the UHECR spectrum!

Dominance of local sources

The necessary CR luminosity of an **individual local source** (with a finite activity time) **to dominate**–against the large scale, steady state distribution of radio sources–the observed UHECR flux above the ankle:



Eichmann+Kachelrieß 2022
[arXiv:2210.07090]

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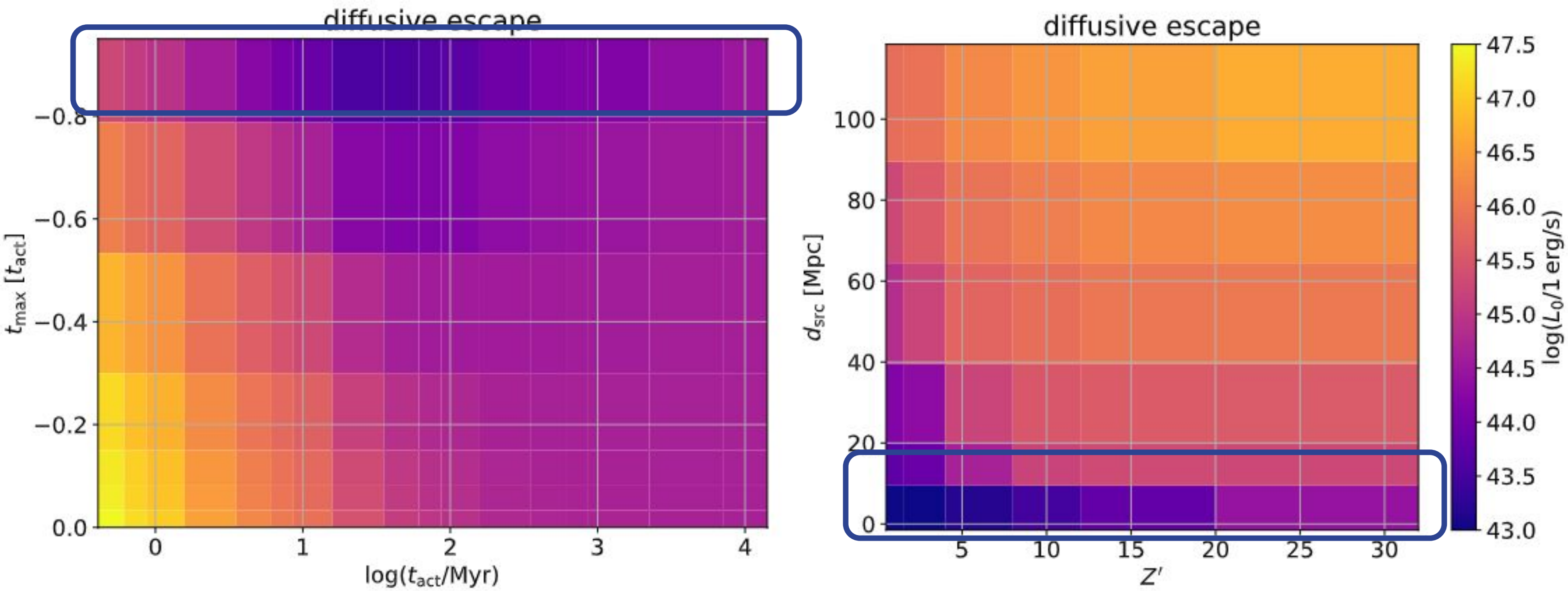


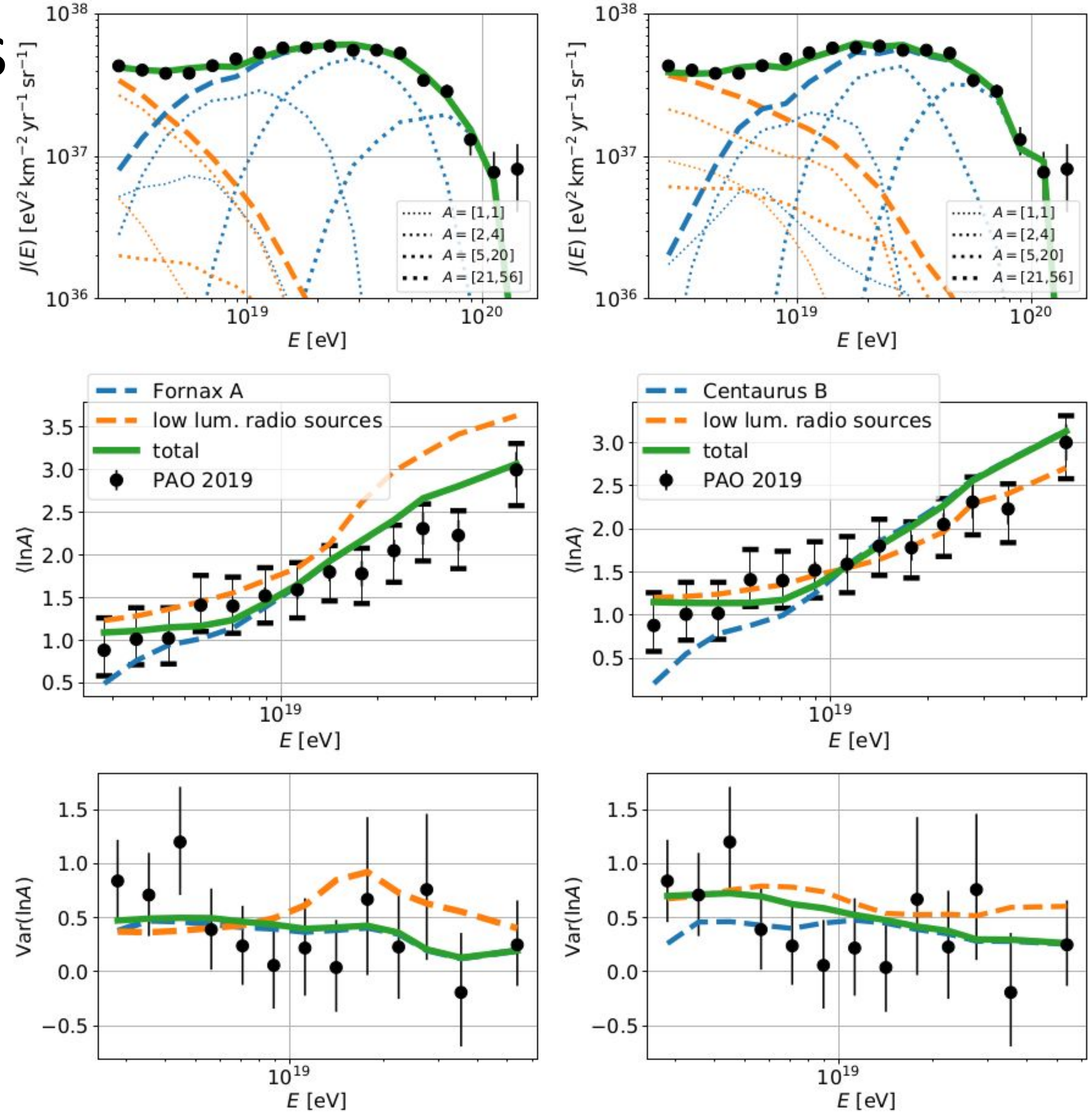
➢ **old and close-by** (at most a few x 10 Mpc for 1nG rms EGMF strength) sources are needed!

Eichmann+Kachelrieß 2022
[arXiv:2210.07090]

2 (qualitative) Examples

Using:

- *1/E²*-source spectrum;
- a single local source (For A or Cen B) that is old ($t_{max} \sim -t_{act}$);
- about 10x more heavy (i.e. A>4) nuclei ejected by the local source;
- an activity time of 4 Myr (For A) and 10 Myr (Cen A)

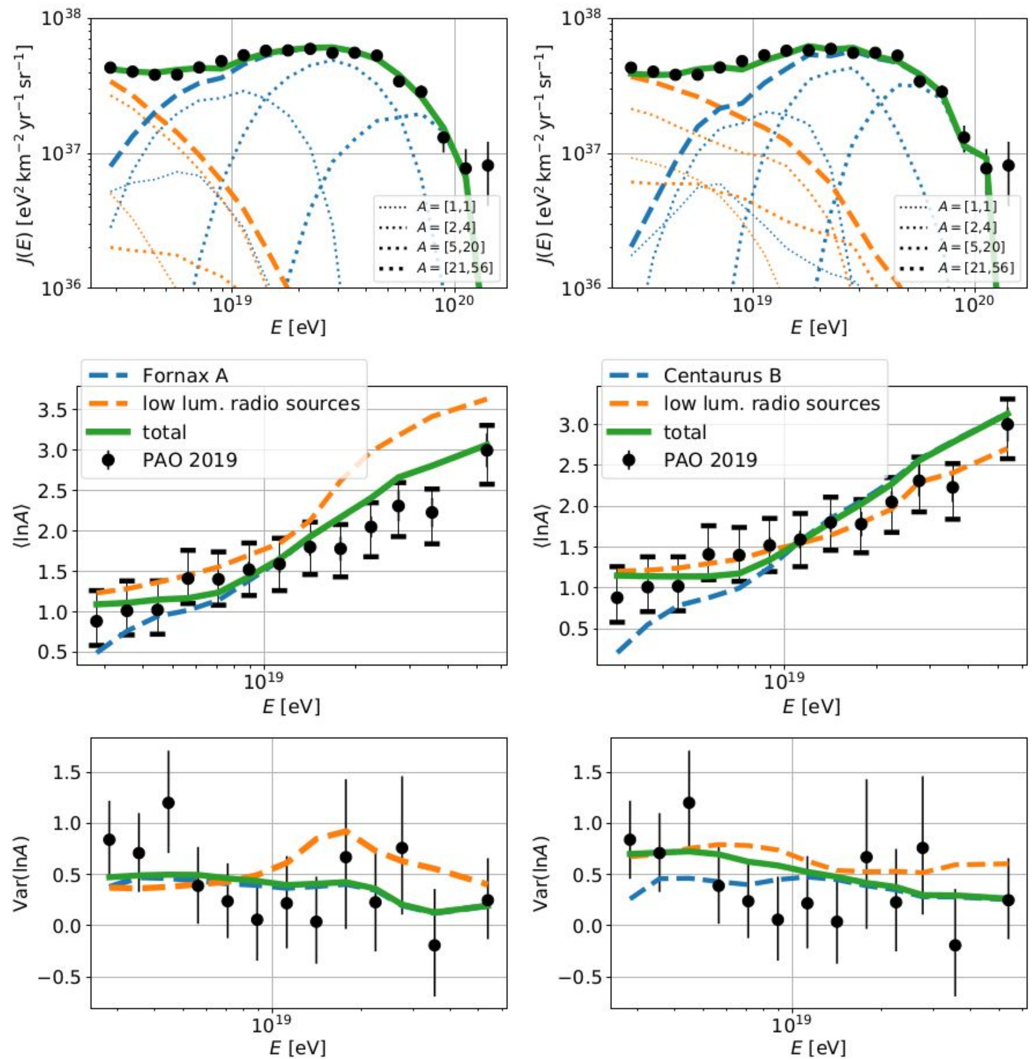


Eichmann+Kachelrieß 2022
[arXiv:2210.07090]

2 (qualitative) Examples

Using:

- *1/E*^{2}-source spectrum;
- a single local source (For A or Cen B) that is old (t_{max} ~ -t_{act});
- about 10x more heavy (i.e. A>4) nuclei ejected by the local source;
- an activity time of 4 Myr (For A) and 10 Myr (Cen A)



$$t_{\rm act} \sim \langle t_{\rm del} \rangle \simeq 1.2 \left(\frac{B}{1\,{\rm nG}}\right)^2 \left(\frac{d_{\rm src}}{10\,{\rm Mpc}}\right)^2 \left(\frac{l_{\rm coh}}{1\,{\rm Mpc}}\right) {\rm Myr}$$

…to obtain sufficient (but not too much) flux suppression at about Z EeV!

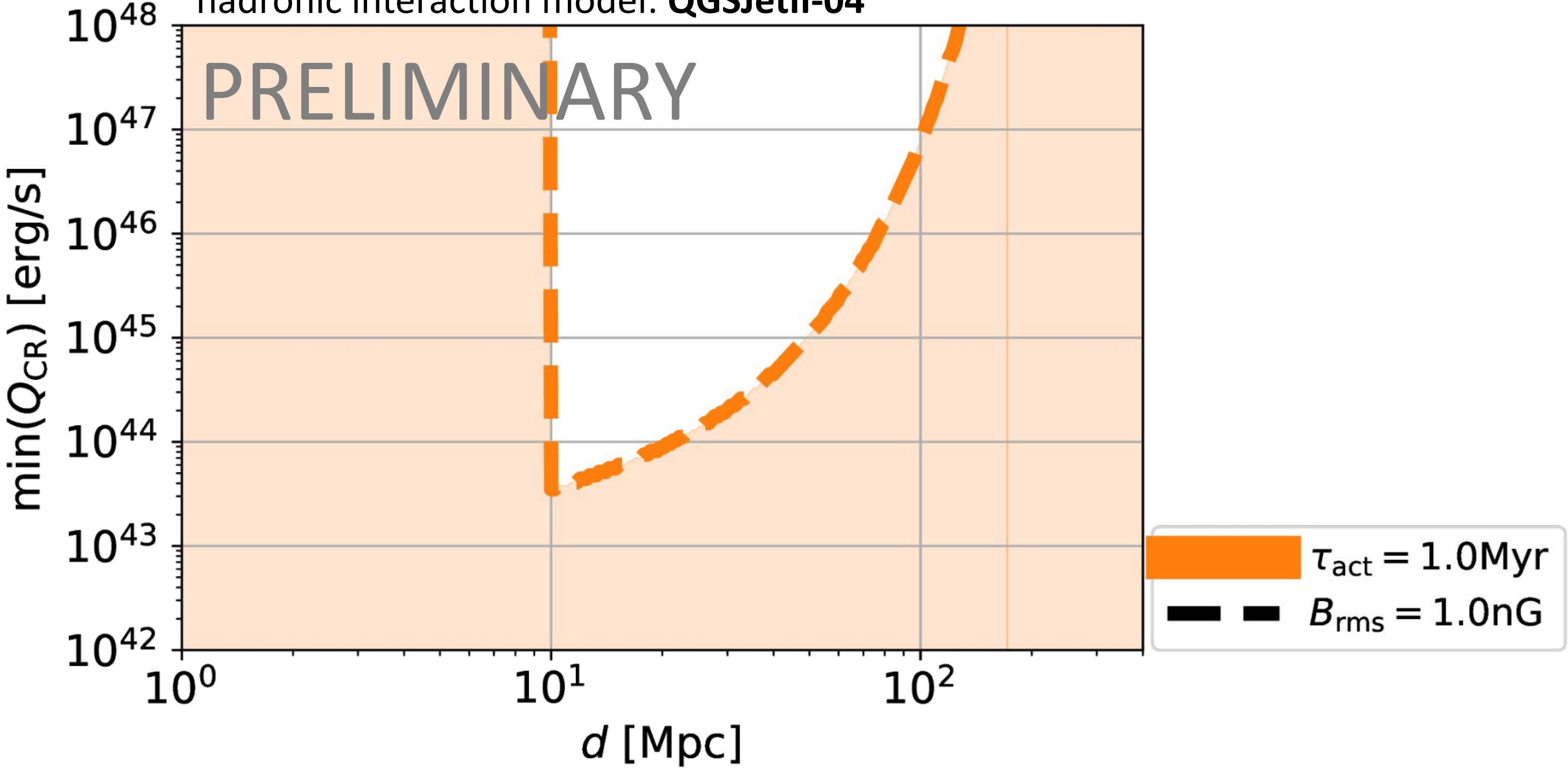
Eichmann+Kachelrieß 2022
[arXiv:2210.07090]

Constraints on UHECR sources of finite life-time

…if:

- a single source dominates at the highest energies (≳40EeV);
- magnetic horizon suppression at about the ankle (~5EeV);
- efficient UHECR production: $g_{\rm acc}\sqrt{(1/g_{\rm m}-1)(1+k)}=1$

source spectral index: **α=2**;
hadronic interaction model: **QGSJetII-04**



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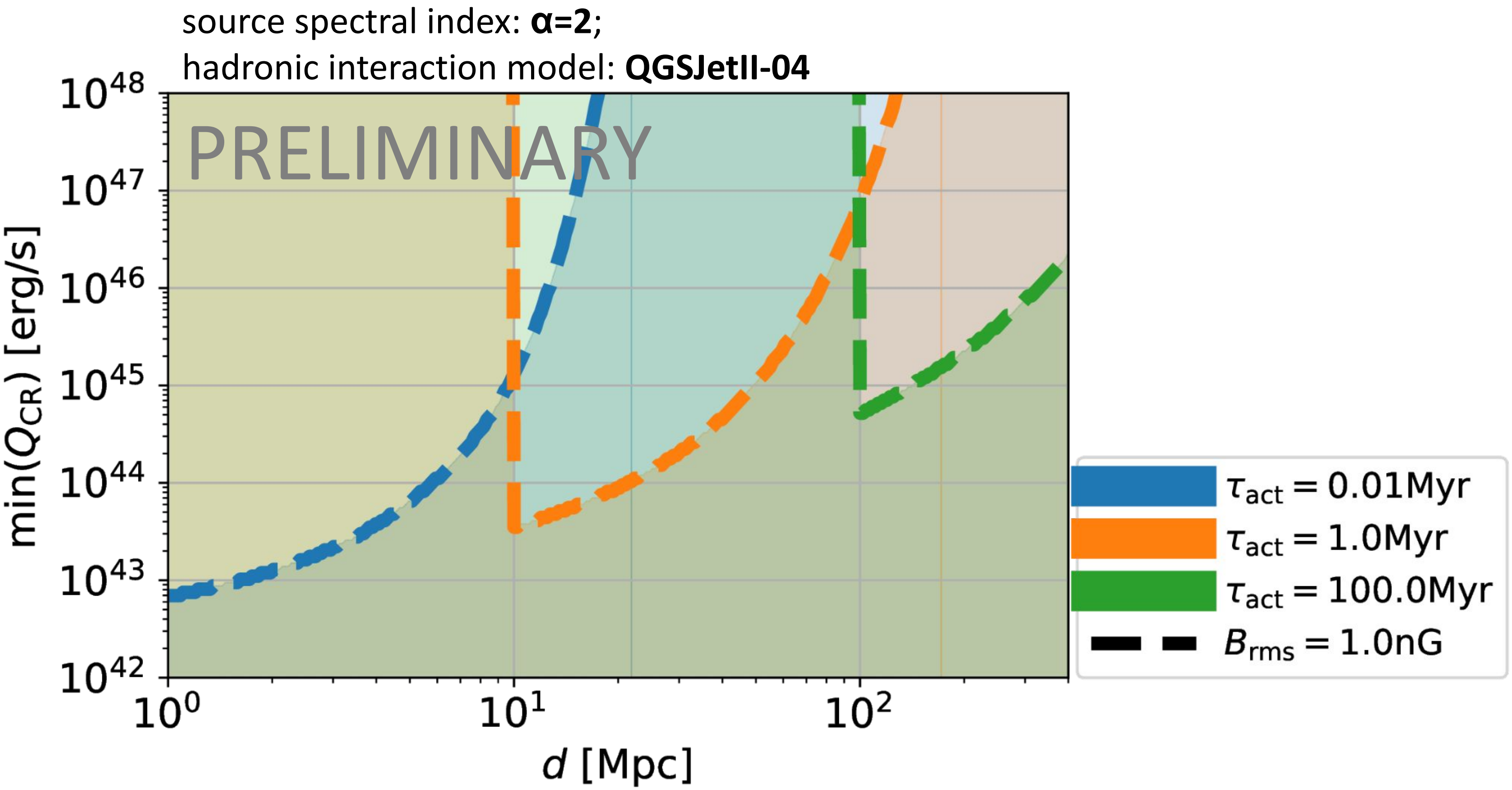

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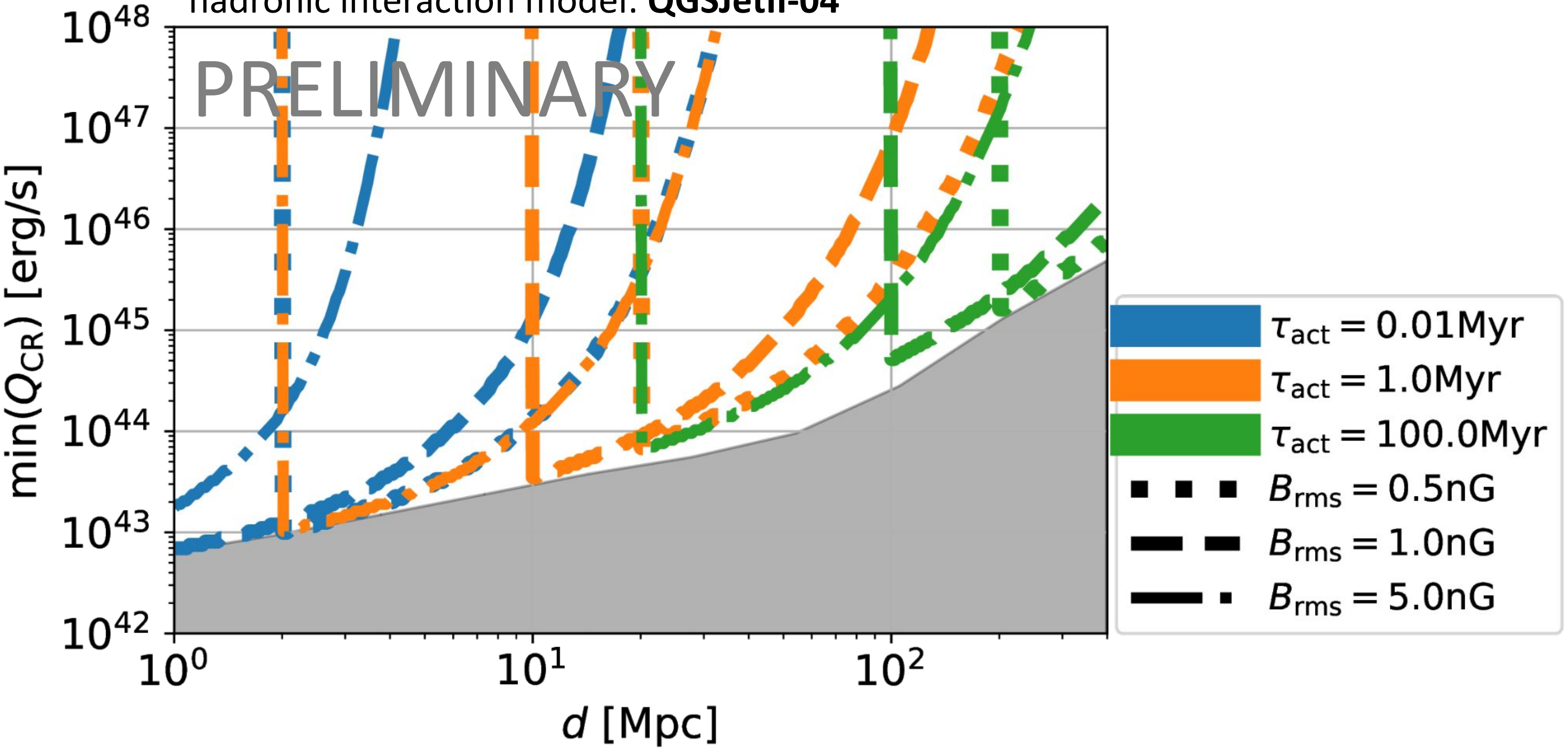

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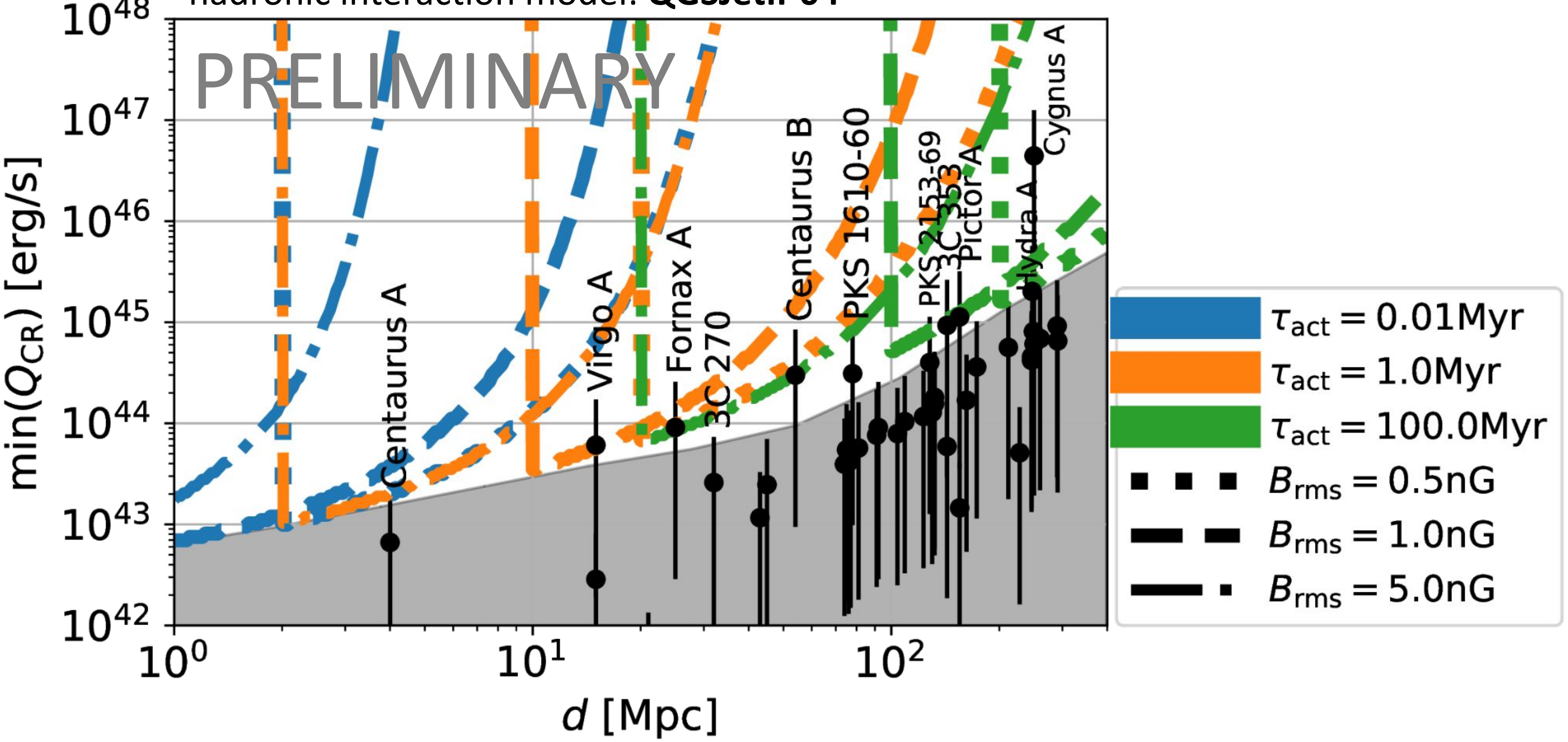

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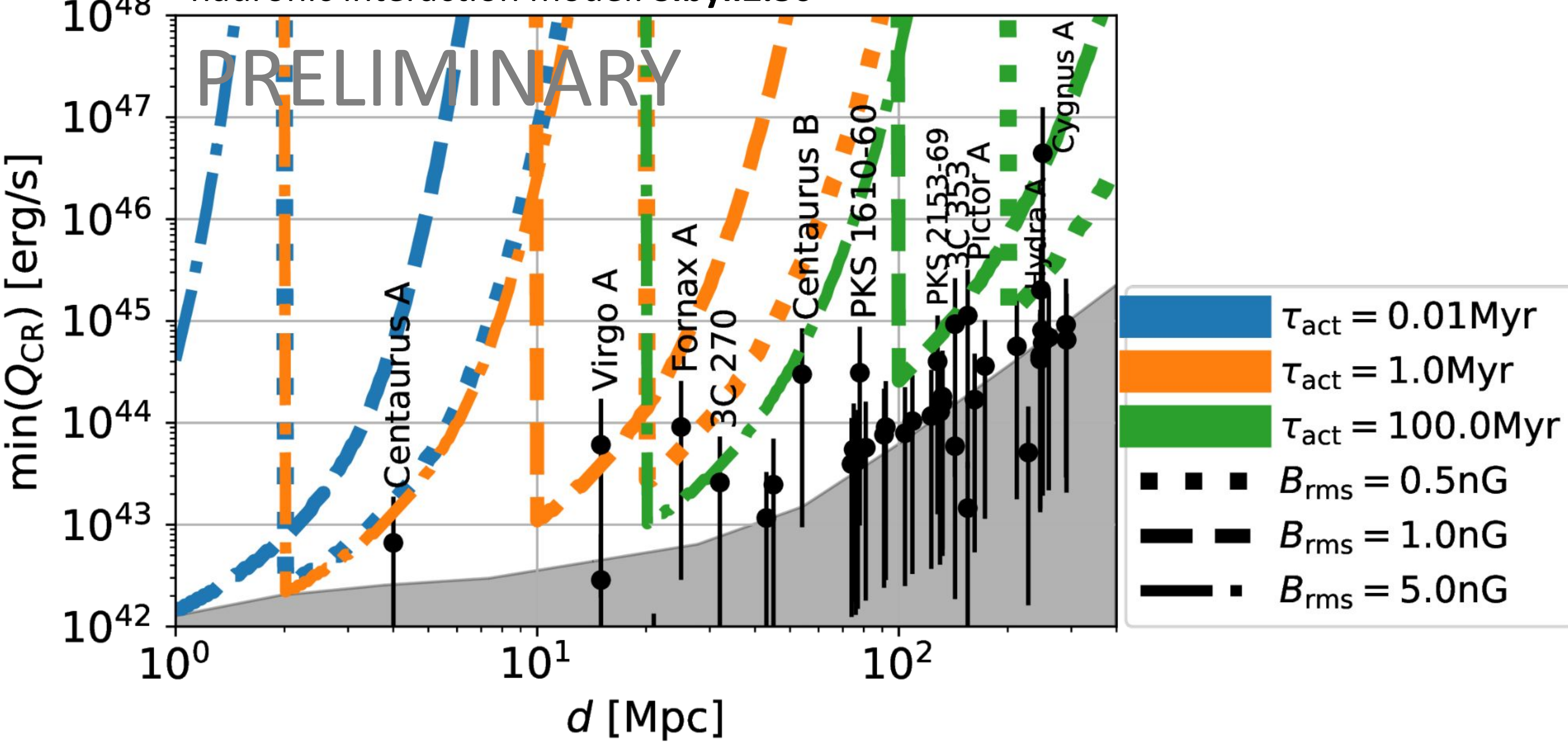
source spectral index: **α=2**;
hadronic interaction model: **Sibyll2.3c**



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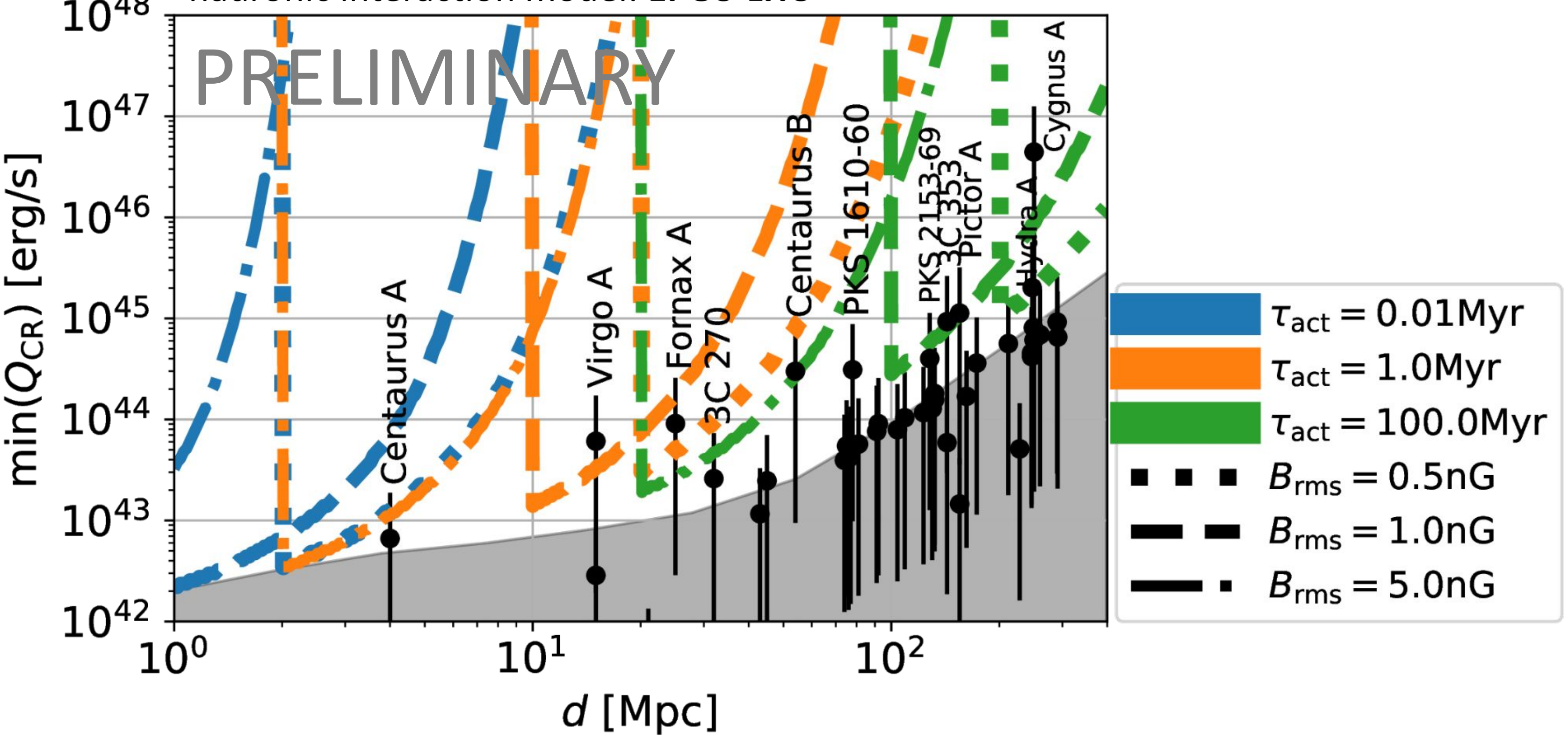
source spectral index: **α=2**;
hadronic interaction model: **EPOS-LHC**



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- magnetic horizon suppression at about the ankle (~5EeV);
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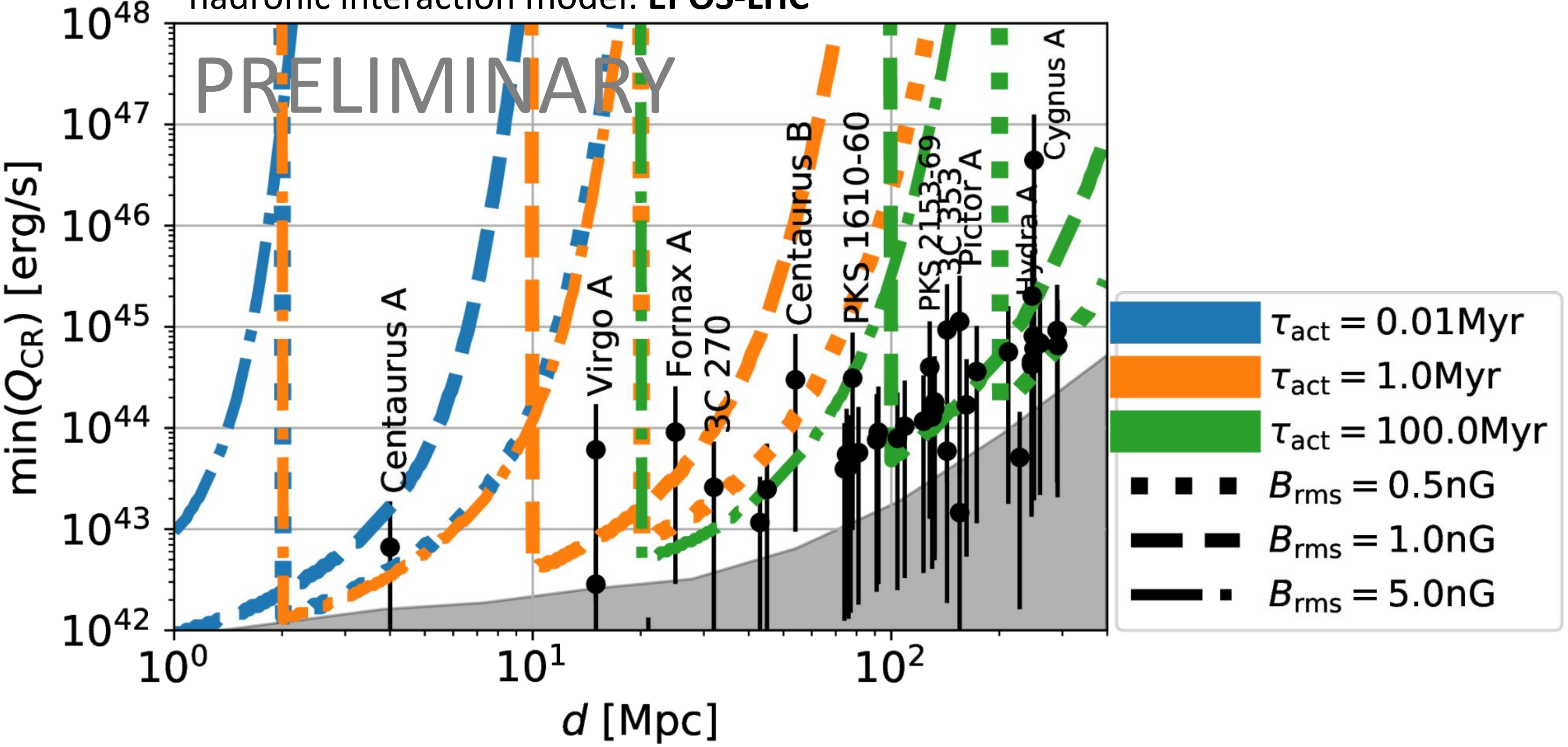
source spectral index: **α=1.5**;
hadronic interaction model: **EPOS-LHC**



Constraints on UHECR sources of finite life-time

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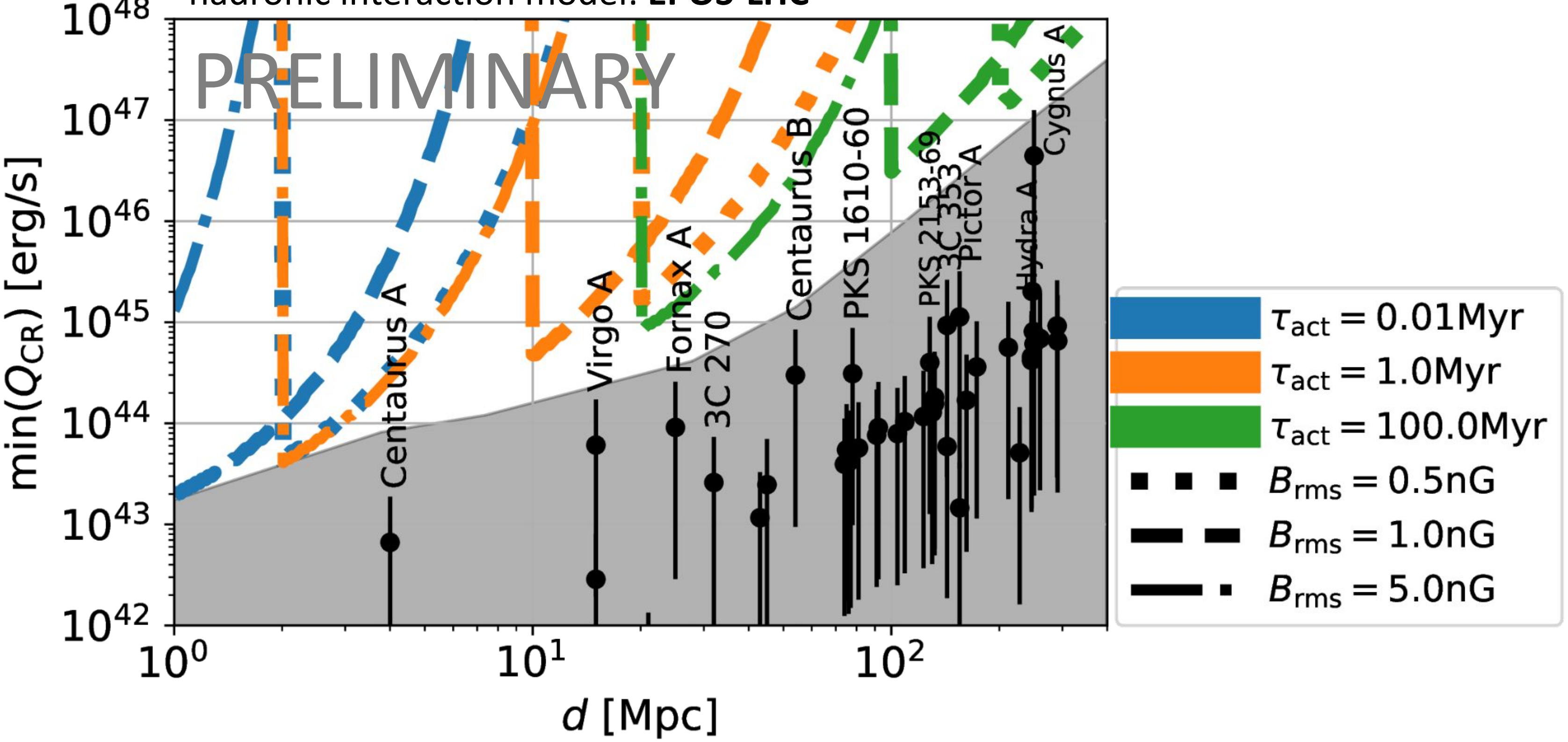
source spectral index: **α=2.3**;
hadronic interaction model: **EPOS-LHC**



Summing up

- Radio galaxies (especially of FR-I type) are the most promising sources of the UHECRs

- UHECR sources are:
  … *not standard candles*
  … *predominantly just a few that are close-by*
  … *having finite life-time (which may harden the spectra)*

- A **possible** scenario:
  - bulk of FR-Is dominates in the “shin region”;
  - a few individual local sources (e.g. Fornax A, Virgo A, …) dominate above the ankle.

Backup

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:***
  - 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

Details on the parameter space

The parameter space

Accounting for **individuality**:

- jet power - radio correlation has a huge uncertainty with respect to individual sources (using individual measurements if available)
- jet power - CR is not uniform

} individual values for g_m needed

- acceleration efficiency is not uniform

} individual values for g_{acc} needed

- individual activity time t_{act} of high-luminous (FR-II) sources, but a uniform t_{act} for the others

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- …even more in general, but with a smaller impact

Parameter	Value(s)	Per Source	Description
$g_{\rm m}$	$[0.001, \ldots, 0.9]$	yes	matter-to-jet power ratio
$g_{\rm acc}$	$[0.001, \ldots, 1]$	yes	acceleration efficiency
α	$[1.5, \ldots, 2.5]$	no	source spectral index
k	[0.1, 0.5, 1, 5]	no	leptonic-to-hadronic energy density ratio
$t_{\rm act}$ [Gyr]	[0.01, 0.05, 0.1, 0.5, 1, 5, 10]	no	low luminosity source lifetime
$B_{\rm rms}$ [nG]	[0.1, 0.5, 1, 5]	no	rms EGMF strength
$l_{\rm c}$ [Mpc]	1	no	EGMF coherence length
$\check{R}$ [GV]	1	no	minimal CR rigidity
β_L	0.89	no	radio–jet power correlation index

The parameter space …is huge

Accounting for individuality:

- jet power - radio correlation has a huge uncertainty with respect to individual sources (using individual measurements if available)
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β_L	0.89	no	radio–jet power correlation index

Individuality leads to a huge parameter space!

Details on the UHECR contribution by *individual local sources*

UHECRs from individual local sources

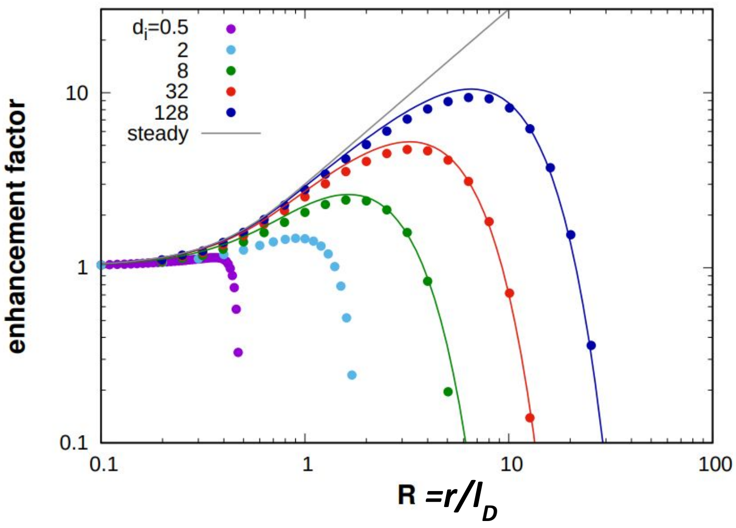
The general approach:

$$n(R, r, t_{\rm act}) = \sum_i n_i(R, r, t_{\rm act}) = n_0 \left(\frac{R}{\check{R}}\right)^{-\alpha} \exp\left(-\frac{R}{\hat{R}}\right) \bar{\xi}(R, r, t_{\rm act})\, \bar{\eta}(R, r)$$

where

$$n_0 = \frac{Q_{\rm cr}}{2\pi c\, r^2} \frac{\check{R}^{\alpha}\,(2-\alpha)}{(\hat{R}^{2-\alpha} - \check{R}^{2-\alpha})}$$

and $\bar{\xi}(R, r, t_{\rm act})$ = average enhancement factor due to diffusion and finite source lifetime (Harari+2021)



UHECRs from individual local sources

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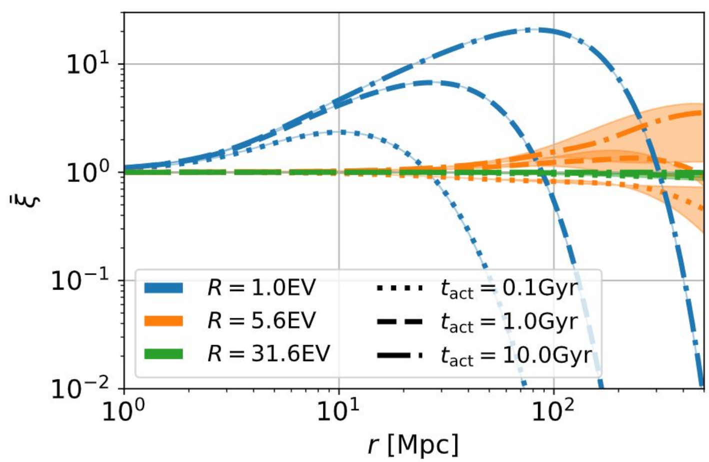
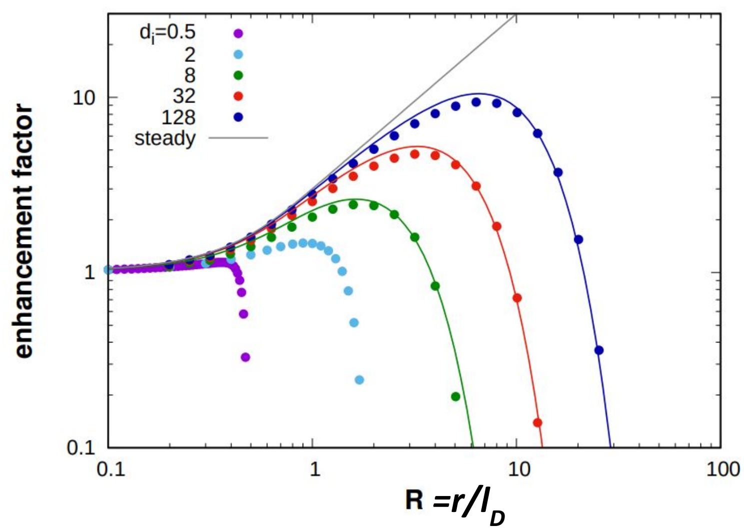


averaging



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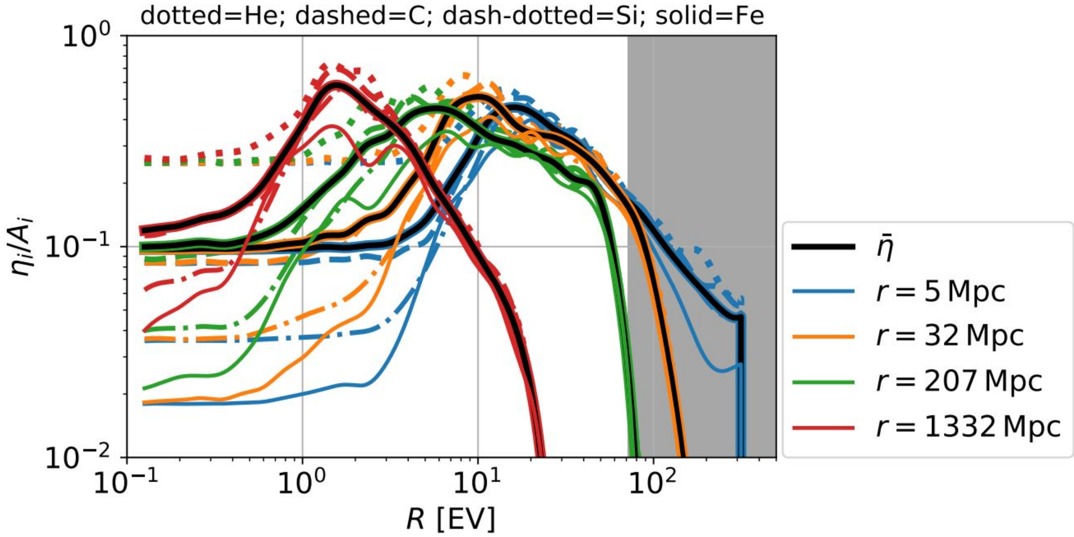
$$n_0 = \frac{Q_{\rm cr}}{2\pi c\, r^2} \frac{\check{R}^{\alpha}\,(2-\alpha)}{(\hat{R}^{2-\alpha} - \check{R}^{2-\alpha})}$$

$\bar{\eta}(R, r)$ = average spectral modification factor with

$$\eta_i(R, r) \equiv \frac{S_i(R, r)}{S_{0,i}(R)}$$



UHECRs from individual local sources

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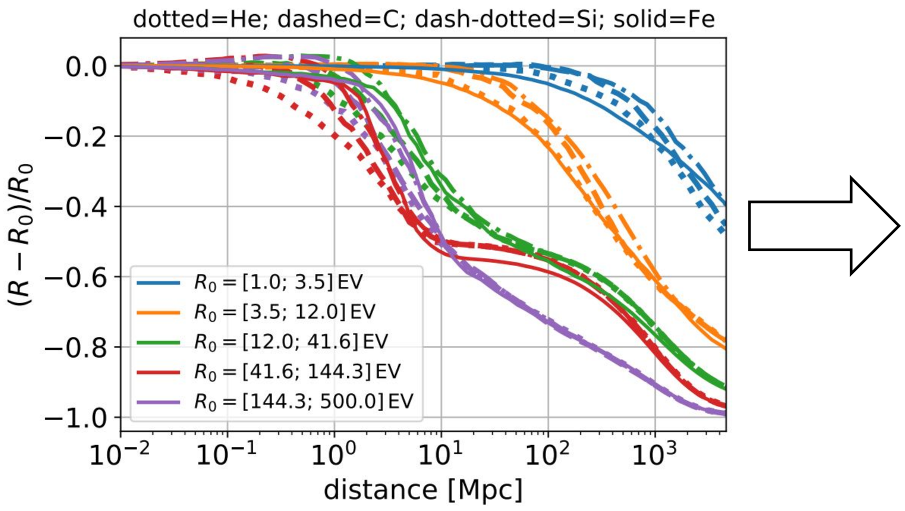
Using **rigidity instead of energy**:

- CR transport depends predominantly on the particle's rigidity



Change of the prim. particle's rigidity is roughly **independent of the nucleus type**

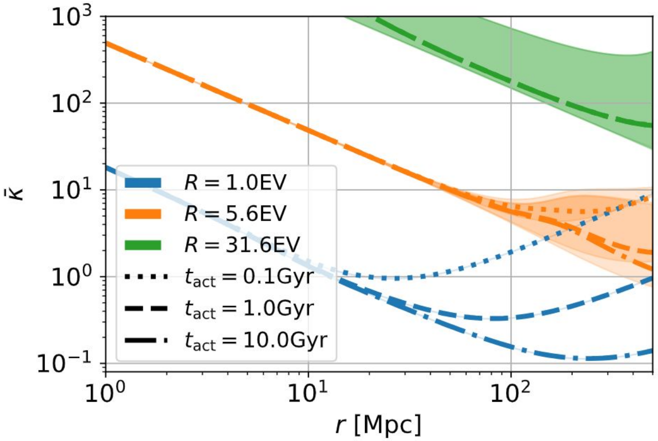
UHECRs from individual local sources

The general approach:

$$n(R, r, t_{\mathrm{act}}) = \sum_i n_i(R, r, t_{\mathrm{act}}) = \underbrace{n_0}_{= \frac{Q_{\mathrm{cr}}}{2\pi c\, r^2} \frac{\check{R}^{\alpha}\,(2-\alpha)}{(\hat{R}^{2-\alpha} - \check{R}^{2-\alpha})}} \left(\frac{R}{\check{R}}\right)^{-\alpha} \exp\left(-\frac{R}{\hat{R}}\right) \bar{\xi}(R, r, t_{\mathrm{act}})\, \bar{\eta}(R, r)$$

Using **rigidity instead of energy**

Accounting for the **angular distribution of arrival direction** based on a isotropically turbulent extragalactic magnetic field (Harari+2016) as characterized by the concentration parameter κ of the Fisher distr.:



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Using **rigidity instead of energy**

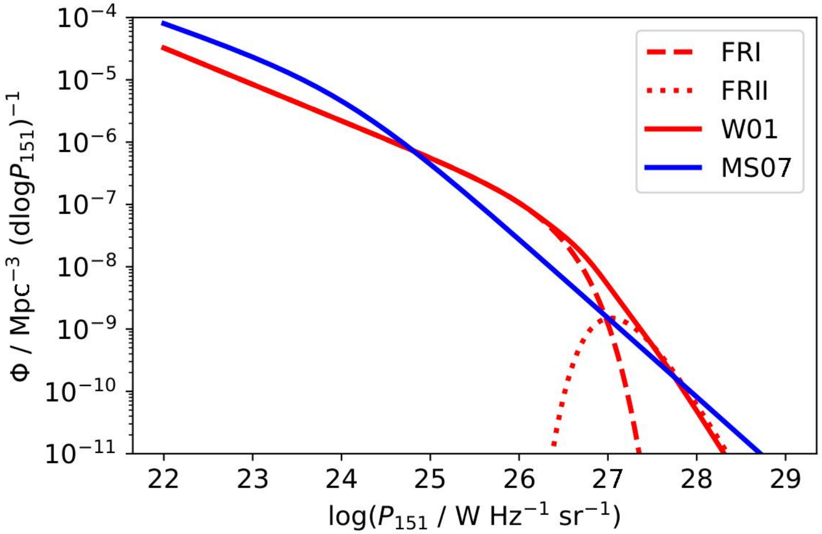
Accounting for the **angular distribution of arrival direction** based on a isotropically turbulent extragalactic magnetic field (Harari+2016) + Galactic (JF12) field

using the "lensing approach" (Bretz+2014, Eichmann+2020)

Details on
the UHECR contribution by
the large-scale population

Constraining the non-local source contribution

- Using the *radio luminosity function (RLF)* $\Phi_{\rm RG}$ from Willott+2001 to obtain
$$\frac{{\rm d}N}{{\rm d}V\,{\rm d}Q_{\rm cr}} = \frac{\Phi_{\rm RG}(L_{151},\,z)}{2.3\,\beta_L\,Q_{\rm cr}}$$



- Continuous CR source function of radio galaxies (Eichmann 2019):

$$\Psi_i(R,\,z) \equiv \frac{{\rm d}N_{\rm cr}(Z_i)}{{\rm d}V\,{\rm d}R\,{\rm d}t} = \int_{\check{Q}_{\rm cr}}^{\hat{Q}_{\rm cr}} S_i(R,\hat{R}(Q_{\rm cr}))\,\frac{{\rm d}N}{{\rm d}V\,{\rm d}Q_{\rm cr}}\,{\rm d}Q_{\rm cr}$$

$$\Psi_i(R,z) \simeq \begin{cases} \frac{\rho_{\rm lo}\,f_i\,\nu_a\,c}{2.3\,e\,\bar{Z}}\left[g_{\rm acc}^2\left(\frac{1}{g_{\rm m}}-1\right)(1+k)\right]^{-1}\left(\frac{R}{R_\star}\right)^{-a}\frac{f_I(z)}{z+1} \\ \times\left[\Gamma\left(\xi_a^I,\left(\frac{R}{R_\star}\right)^{2/\beta_L}\right)-\Gamma\left(\xi_a^I,\left(\frac{\hat{Q}_{\rm cr}(k+1)}{g_{\rm m}\,Q_\star}\right)^{1/\beta_L}\right)\right], & \text{for FR-I}, \\ \frac{\rho_{\rm ho}\,f_i\,\nu_a\,c}{2.3\,e\,\bar{Z}}\left[g_{\rm acc}^2\left(\frac{1}{g_{\rm m}}-1\right)(1+k)\right]^{-1}\left(\frac{R}{R_\star}\right)^{-a}\frac{f_{II}(z)}{z+1} \\ \times\left[\Gamma\left(\xi_a^{II},\left(\frac{g_{\rm m}\,Q_\star}{\hat{Q}_{\rm cr}(k+1)}\right)^{1/\beta_L}\right)-\Gamma\left(\xi_a^{II},\left(\frac{R_\star}{R}\right)^{2/\beta_L}\right)\right], & \text{for FR-II}, \end{cases}$$

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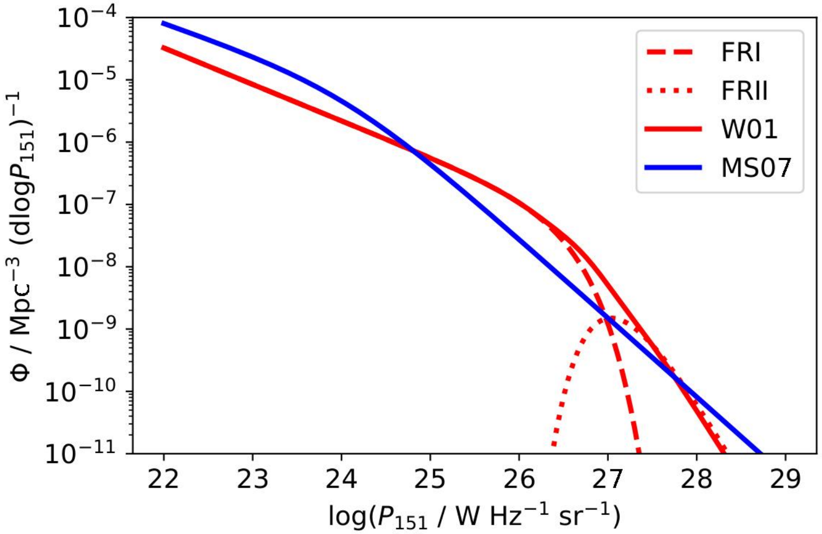


$$\Psi_i(R \ll R_\star, z) \propto \left(\frac{R}{R_\star}\right)^{-a},$$

$$\Psi_i(R \gg R_\star, z) \propto \begin{cases} \left(\frac{R}{R_\star}\right)^{-a+2\xi_a^I/\beta_L-2/\beta_L} \exp\left(-\left(\frac{R}{R_\star}\right)^{2/\beta_L}\right) & \text{for FR-I}, \\ \left(\frac{R}{R_\star}\right)^{-a-2\xi_a^{II}/\beta_L} & \text{for FR-II}, \end{cases}$$

⇒ At $R >> R_*$ the source spectrum steepens due to the RLF

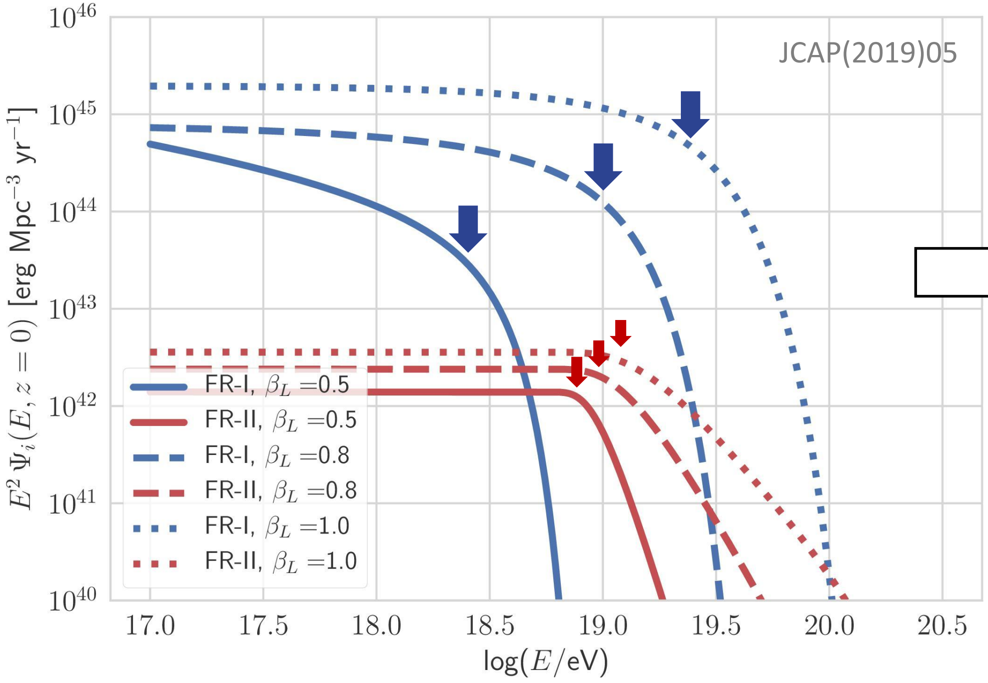
Spectral behaviour constraints

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 ≤ 30 EeV



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

Spectral behaviour constraints

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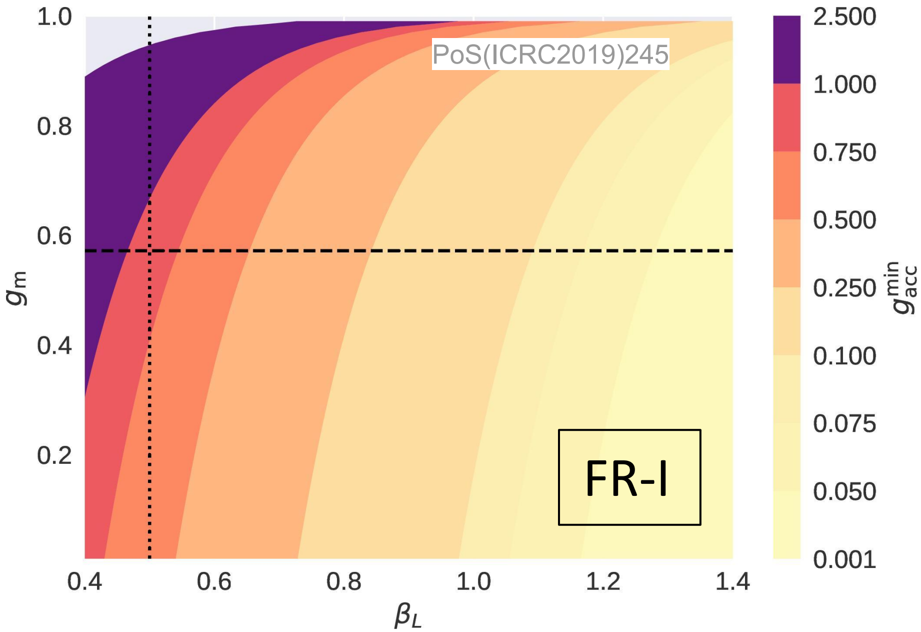
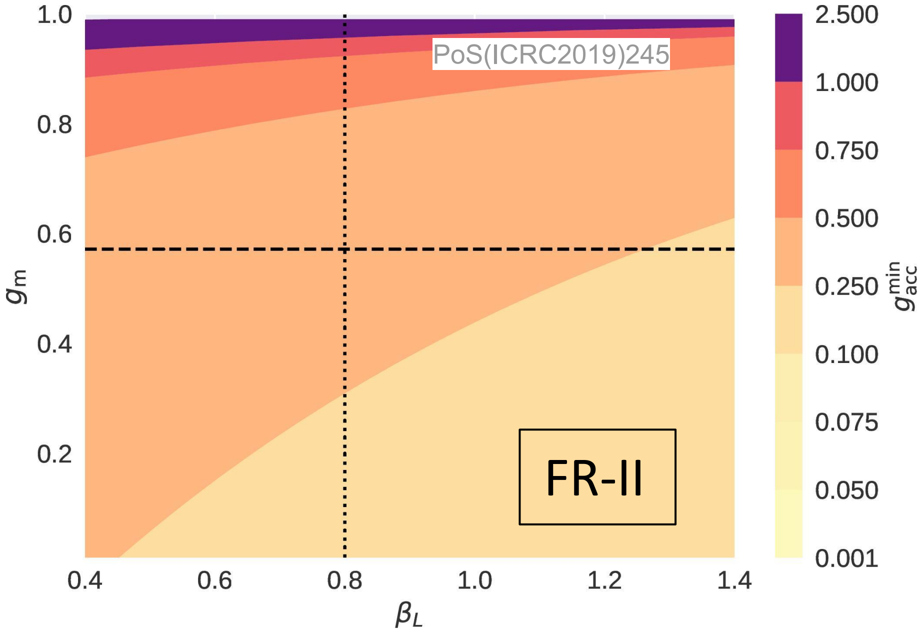
$$\Rightarrow \quad g_{acc} > 30 \text{ EV}/\sqrt{(1-g_m)Q_*/c}, \text{with } Q_* = Q_*(\beta_L)$$





Spectral behaviour constraints

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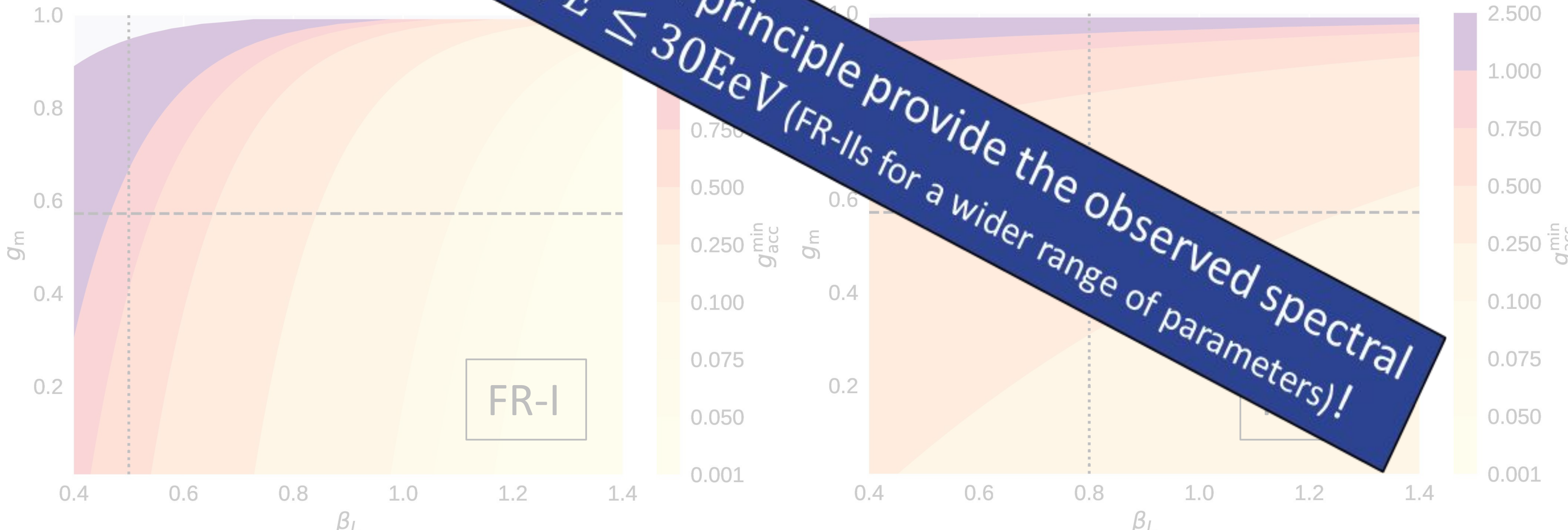
≤ 1; $g_m < 1$ $(g_m \sim 4/7)$; $0.4 \leq \beta_L \leq 1.4$

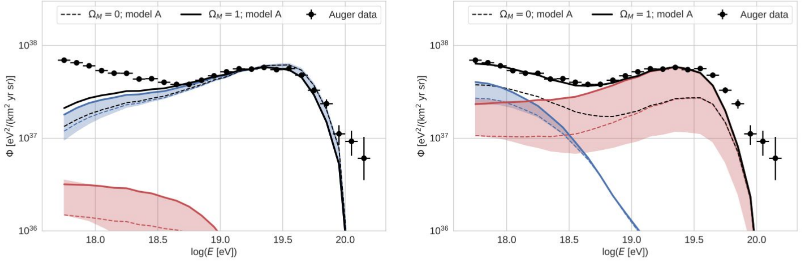
$\sqrt{(1-g_m)Q_*/c}$, with $Q_* = Q_*(\beta_L)$

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

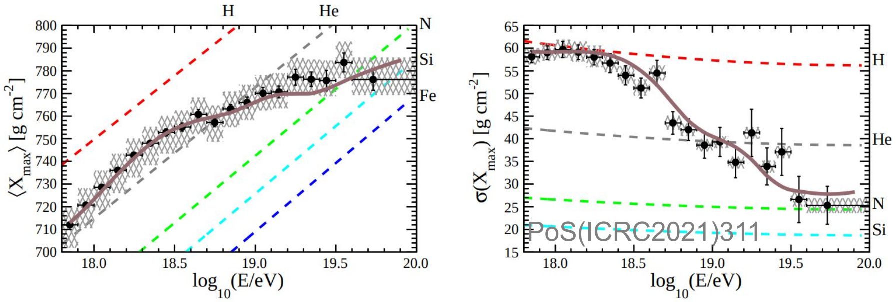


UHECRs from the large-scale population

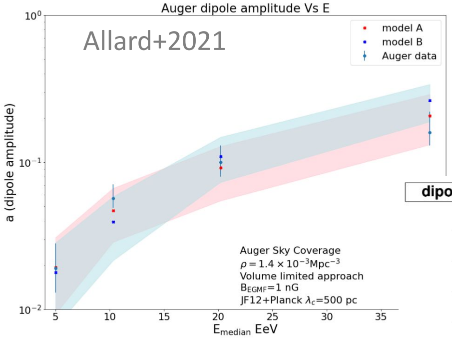
- Energy spectrum ✓ (e.g. Eichmann 2019)

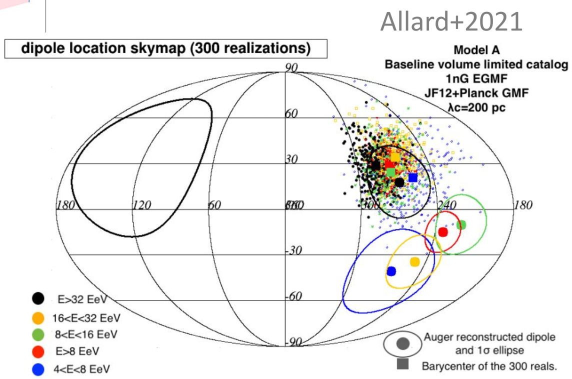


- Chemical Composition ✓ for an (extreme) hard source spectrum
(e.g. Auger 2021, Allard+2021)



- Spectral dipole amplitude ✓
(e.g. Allard+2021)





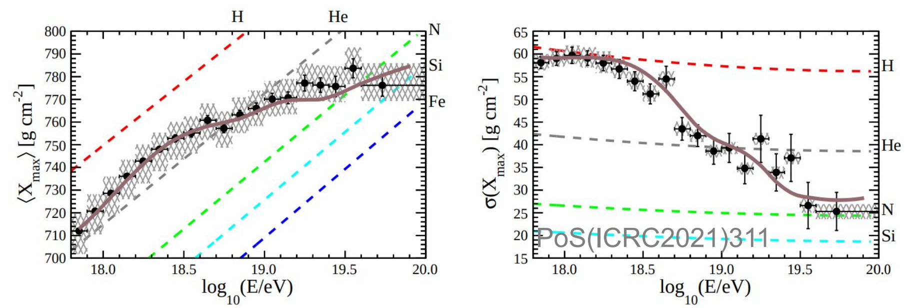
- Dipole direction & quadrupole amplitude ✗

UHECRs from the large-scale population

But using identical sources (same maximal rigidity and CR power)

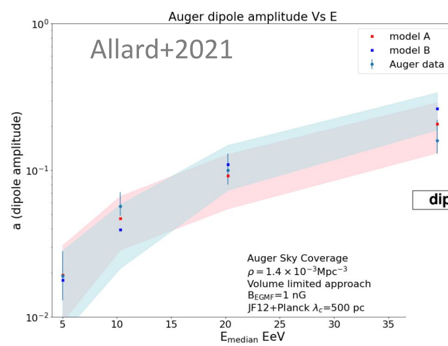
➢ which needs to be the case *if* the large-scale population dominates (see Ehlert+2022)

- Chemical Composition ✔ for a (extreme) hard source spectrum (e.g. Auger 2021, Allard+2021)

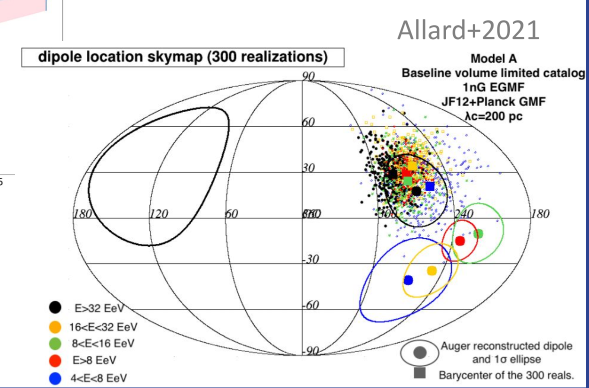


- Spectral dipole amplitude ✔

  (e.g. Allard+2021)



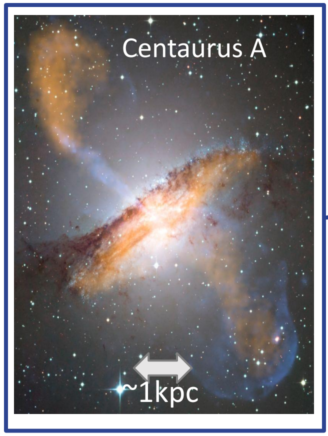
- Dipole direction & quadrupole amplitude ✘

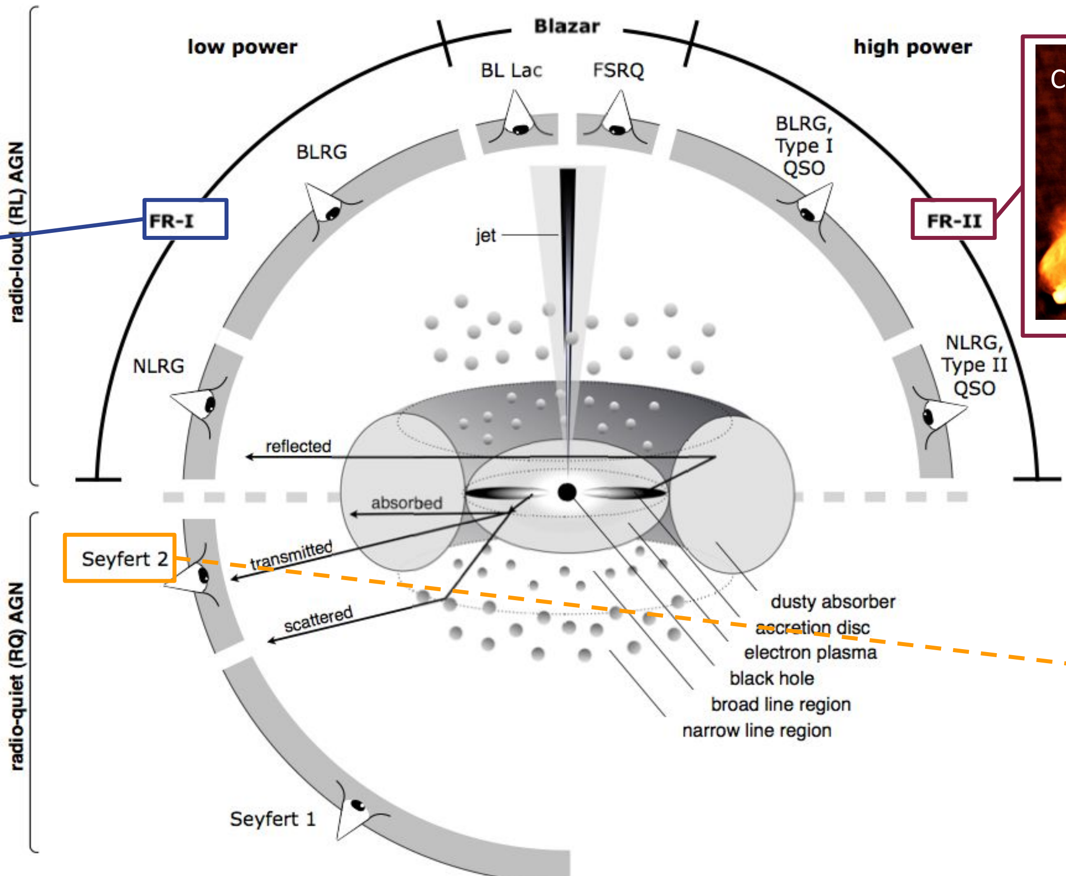


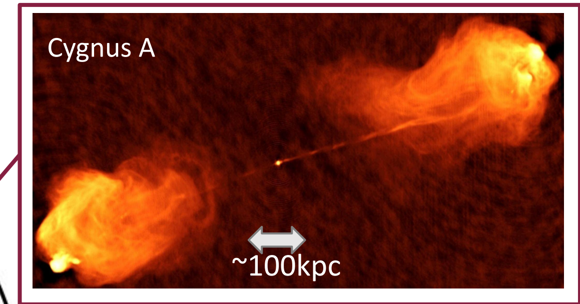
Details on possible UHECR sources

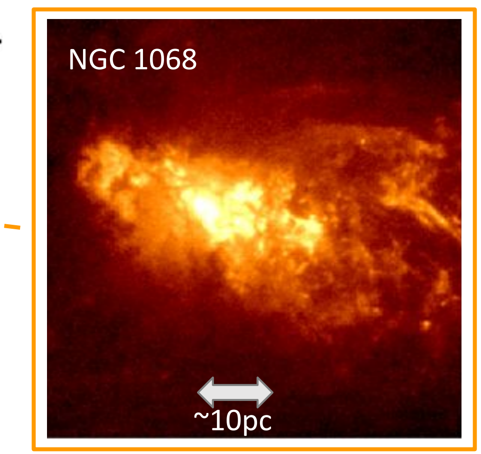
Possible UHECR sources

❖ Active Galactic Nuclei (AGNs) are the most likely (steady) sources of UHECRs









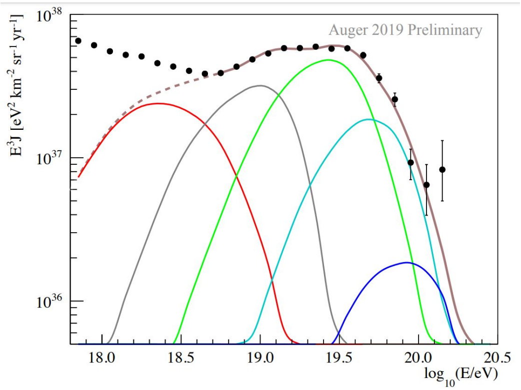
➢ …but which population?

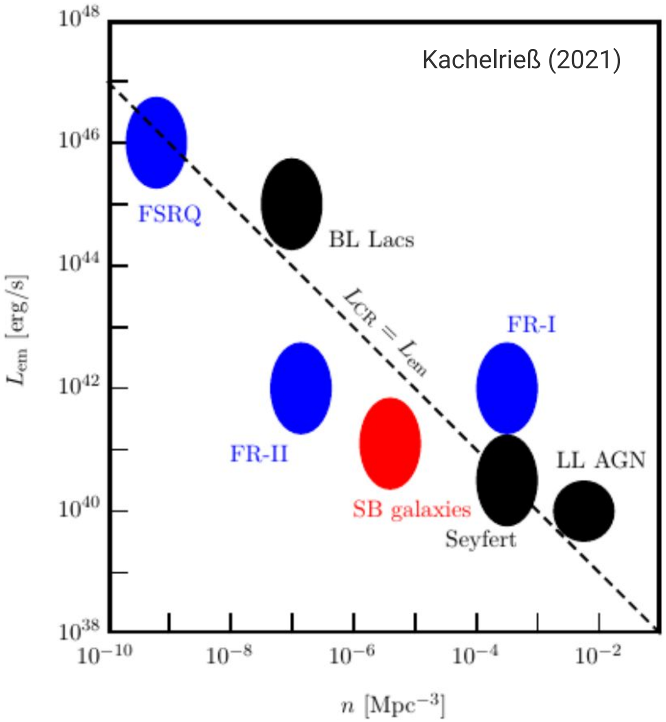
Possible UHECR sources

- **Observational constraints**:
  - Minimal CR emissivity:

    $L_{CR} n_{src} \simeq 6 \text{x} 10^{44}$ erg/(Mpc^3 yr) for E>5EeV

    $L_{CR} n_{src} \simeq 10^{46}$ erg/(Mpc^3 yr) for E>0.3EeV





Possible UHECR sources

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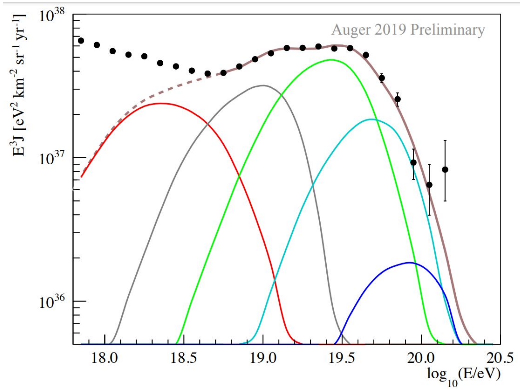
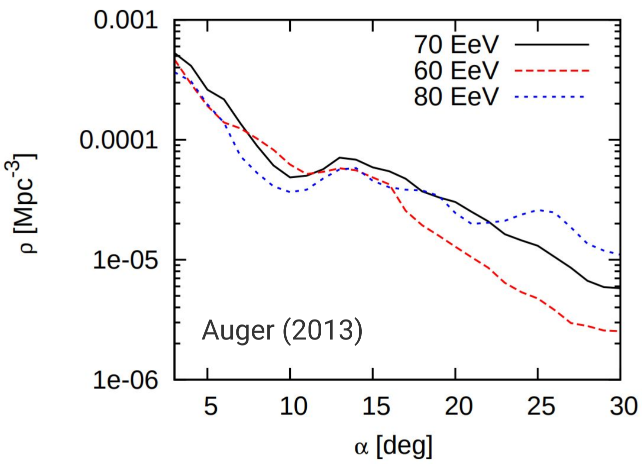
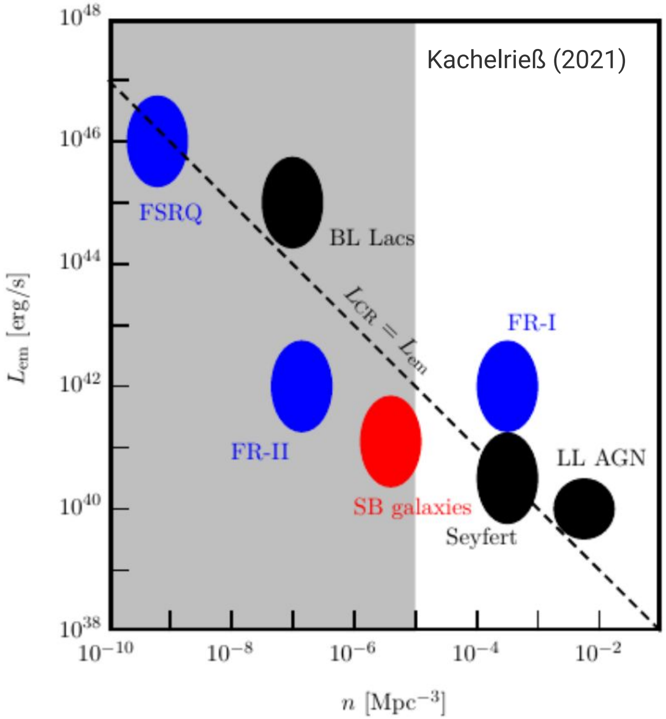


➢ Absence of small-scale clustering:

Large source density or magnetic field defl.

$n_{src} \gtrsim 10^{-5}$ Mpc^{-3}

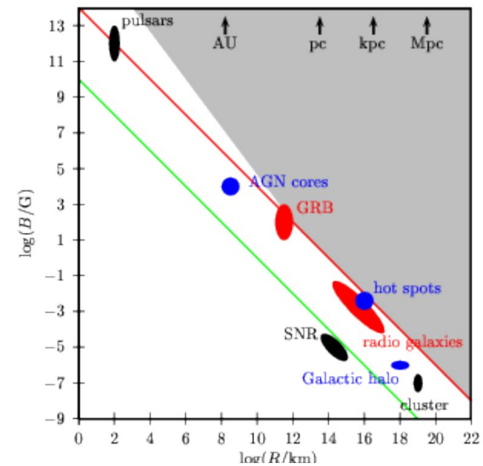


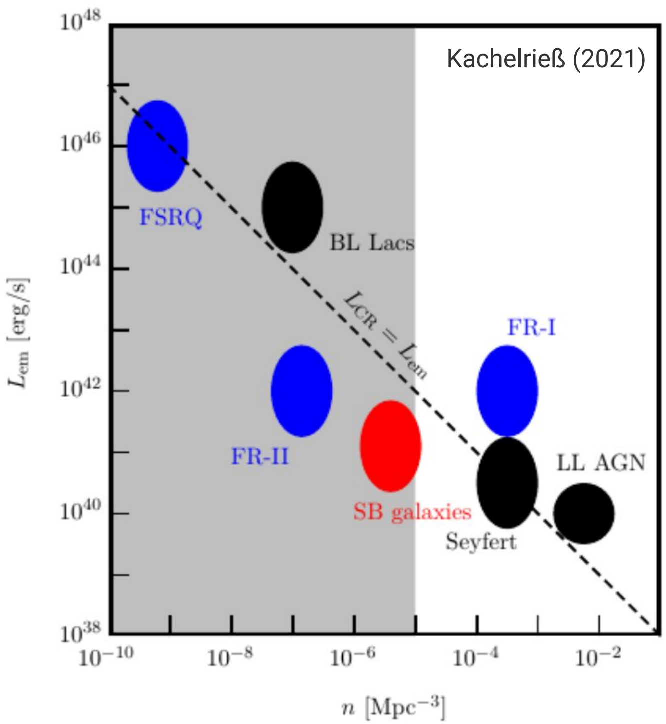


Possible UHECR sources

- **Theoretical constraints**:
  - Hillas condition:

    $r_L = E / (ZeB) \leq r_{src} \quad \longrightarrow \quad E_{max} = \Gamma ZeBr_{src}$





Possible UHECR sources

❖ **Theoretical constraints**:

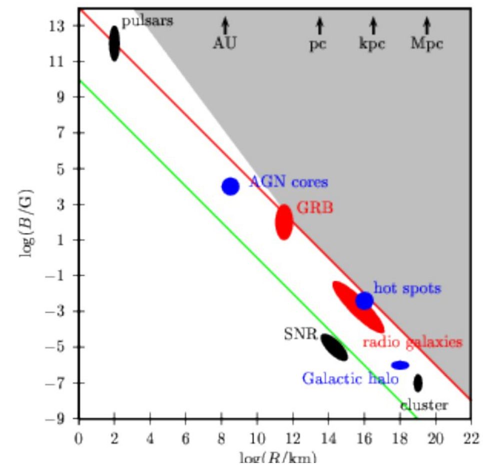
➢ Hillas condition:

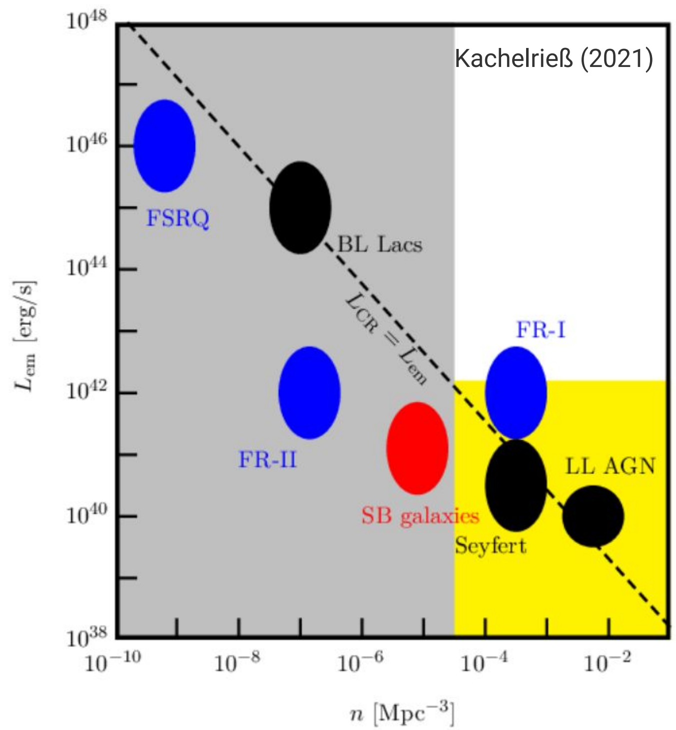
$r_L = E / (ZeB) \leq r_{src} \longrightarrow E_{max} = \Gamma ZeBr_{src}$

➢ Blandford (-Lovelace) condition:

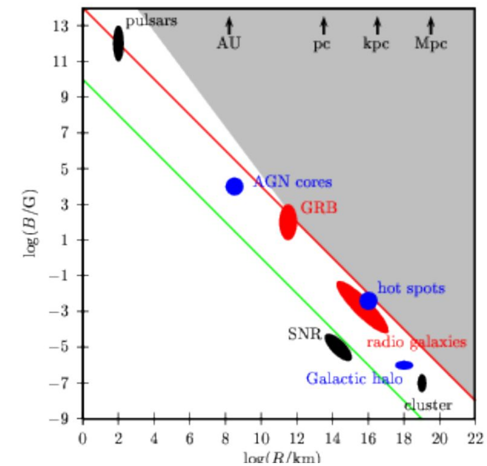
CR Power/Luminosity $L = UI = U^2/R$;
using a (vacuum) impedance $R \simeq 1000\Omega$
& including bulk motion (Γ) effects:

$$L \gtrsim 3 \times 10^{42}\,\mathrm{erg/s}\,\frac{\Gamma^2}{\beta}\left(\frac{E/Z}{5 \times 10^{18}\mathrm{eV}}\right)^2$$





Possible UHECR sources



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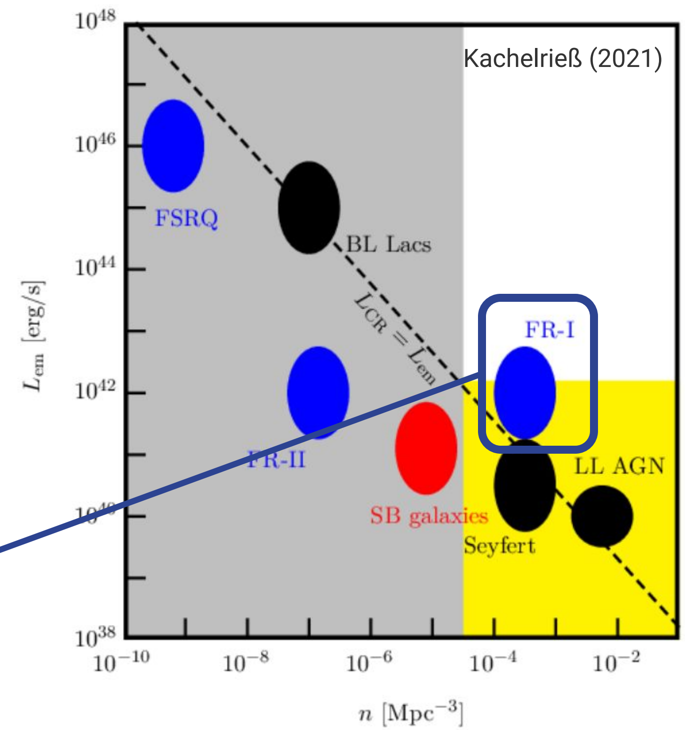

Large scale population or individual (local) sources?
Possible sub-contribution from other populations?