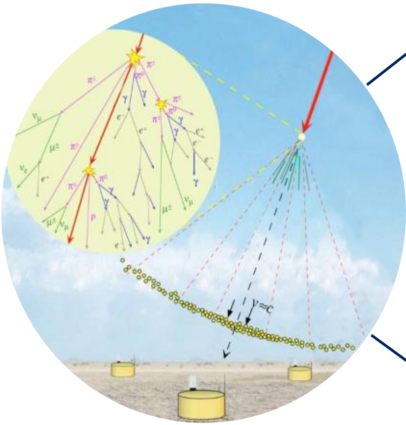
Ultra-High-Energy Cosmic Rays from Radio Galaxies (pt.1)

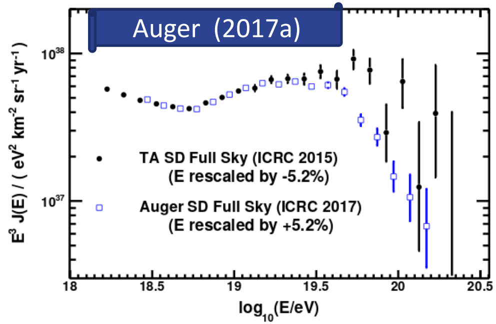
An astrophysical explanation of the UHECR data

Ruhr **A**stroparticle and **P**lasma **P**hysics **Center**
Björn Eichmann, Ruhr-Universität Bochum
in collaboration with J. Rachen, L. Merten, A. van Vliet, J. Tjus
UHECR 2018, Paris

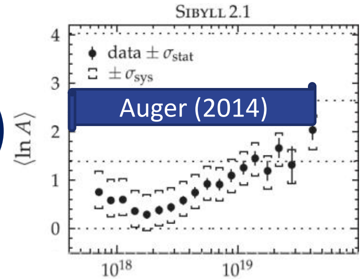
What do we know?



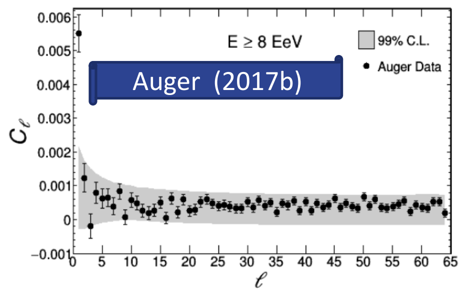
Energy Spectrum



Chemical Composition



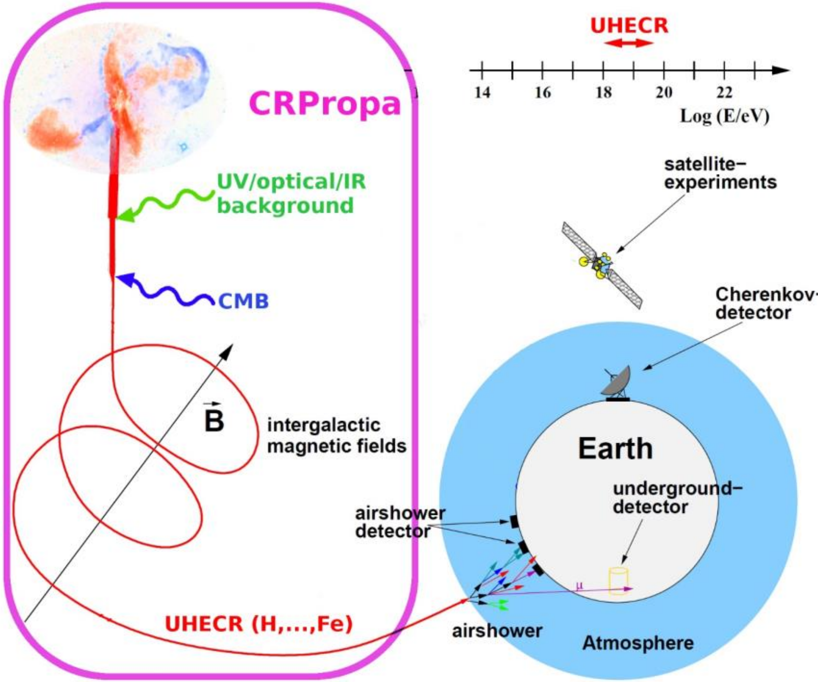
Arrival Directions



by Radio Galaxies ?

The Basic Simulation Setup

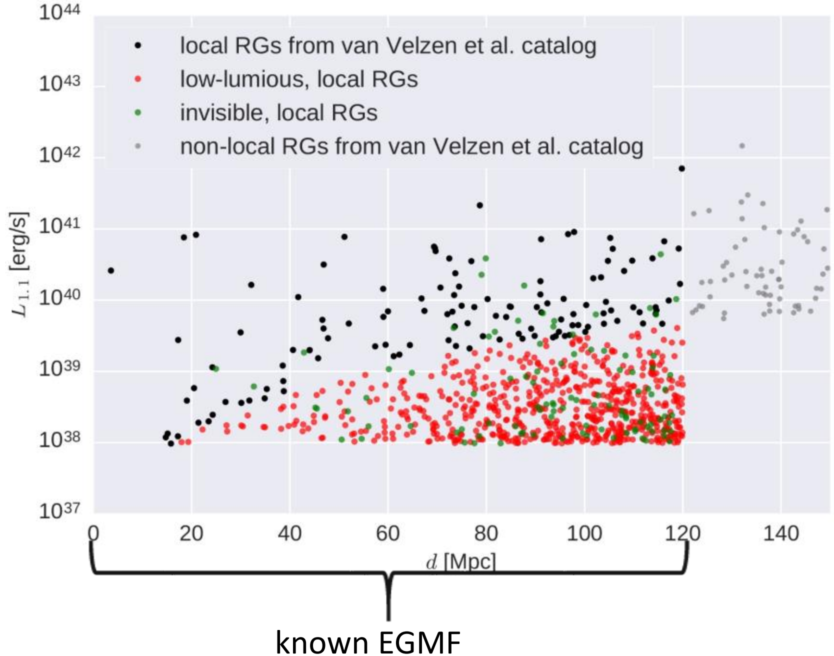
- ***SOURCES:***
  - Radio-loud AGNs/ Radio Galaxies (**RGs**)*
- ***ENVIRONMENT:***
  - Local extragalactic magnetic field (**EGMF**) up to 120Mpc distance**
  - Photon fields by CMB & IRB
- ***PROPAGATION of UHECRs:***
  - Performed with **CRPropa3*****



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

The Sources

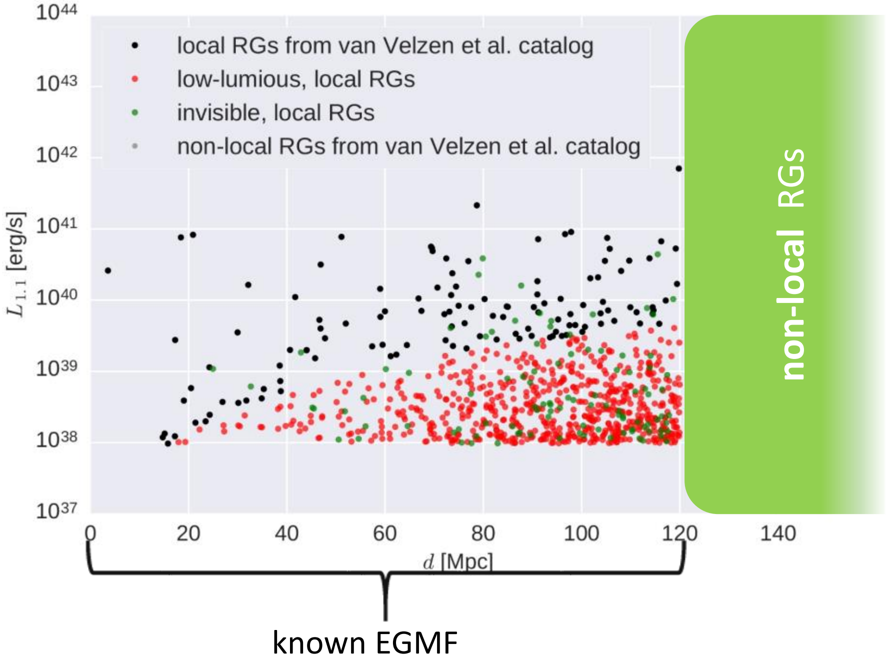
- Local RGs
  ($d \leq 120$ Mpc):
  - 121 observed*
  - 617 low luminous, 100 invisible**



*van Velzen et al. (2012);
**derived from Radio Luminosity Function by Mauch & Sadler (2007)

The Sources

- Local RGs
  $(d \leq 120\ \mathrm{Mpc})$:
  - 121 observed*
  - 617 low luminous, 100 invisible**
- Non-local RGs
  $(d > 120\ \mathrm{Mpc})$:
  - Average contribution up to $z = 2$: Continuous Source Function (**CSF**)**

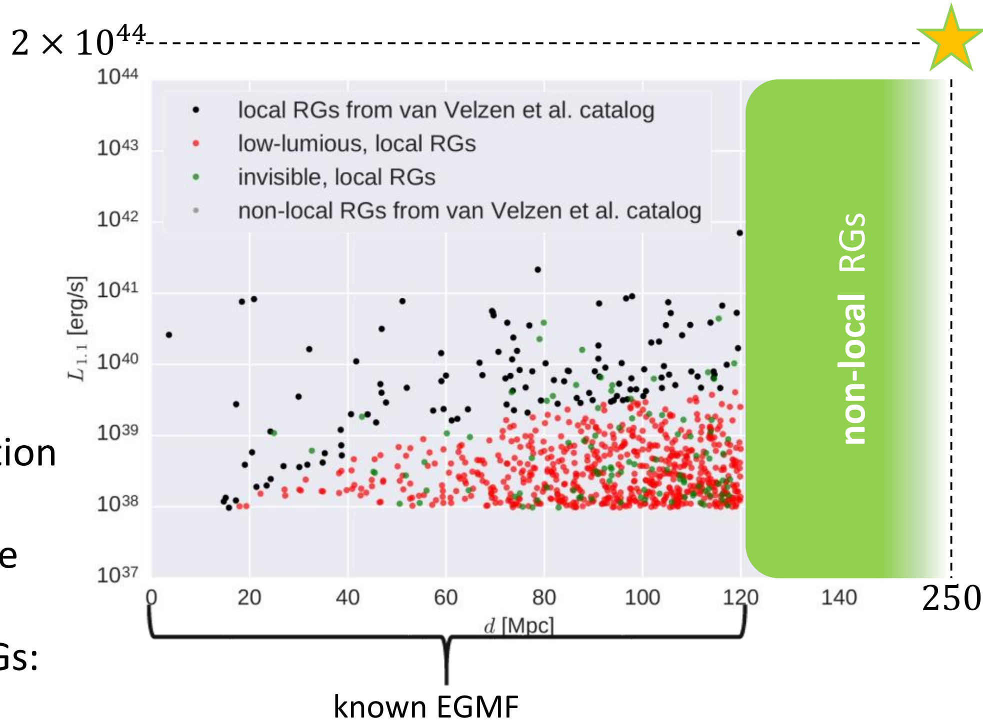


*van Velzen et al. (2012);
**derived from Radio Luminosity Function by Mauch & Sadler (2007)

The Sources

- Local RGs
  ($d \leq 120$ Mpc):
  - 121 observed*
  - 617 low luminous, 100 invisible**

- Non-local RGs
  ($d > 120$ Mpc):
  - Average contribution up to $z = 2$: Continuous Source Function (**CSF**)**
  - Ultra-luminous RGs: **Cygnus A**



*van Velzen et al. (2012);
**derived from Radio Luminosity Function by Mauch & Sadler (2007)

The Sources & their Characteristics

- **CR power** is related to the **radio luminosity** (Willott et al., 1999):

$$Q_{\rm cr} = Q_0 \, \boldsymbol{g_{cr}} \, L_{1.1\rm GHz}^{6/7} \quad \text{with} \quad 1 \le \boldsymbol{g_{cr}} \le 50$$

  - ➢ **Absolute normalization** of the CR flux

- **Maximal rigidity** is related to **CR power** (using `Hillas criterion`):

$$\hat{R} = \boldsymbol{g_{acc}} \sqrt{Q_{\rm cr}/c} \quad \text{with} \quad 0.01 \le \boldsymbol{g_{acc}} \le 1$$

  - Acceleration is constrained by CR escape.

- **Spectral index** at the sources from **shock acceleration theory**:

$$dN/dE \propto E^{-\boldsymbol{a}} \quad \text{with} \quad 1.7 \le \boldsymbol{a} \le 2.2$$

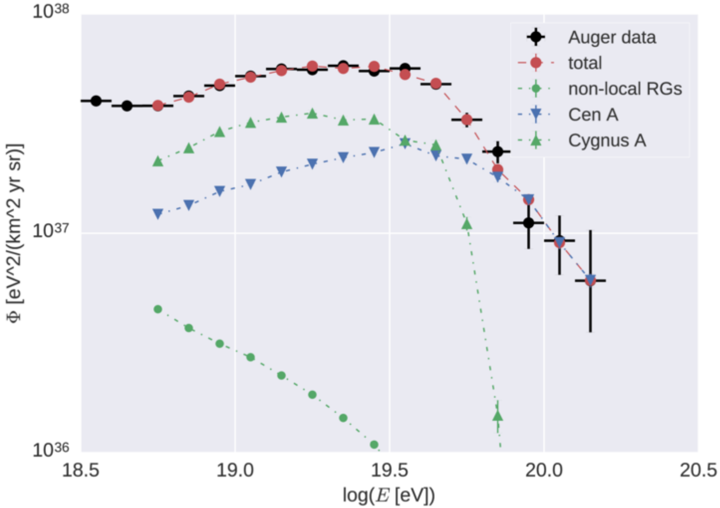
- **Abundances** at the sources mostly **solar $\boldsymbol{f}_\odot$**, but enable exceptions:

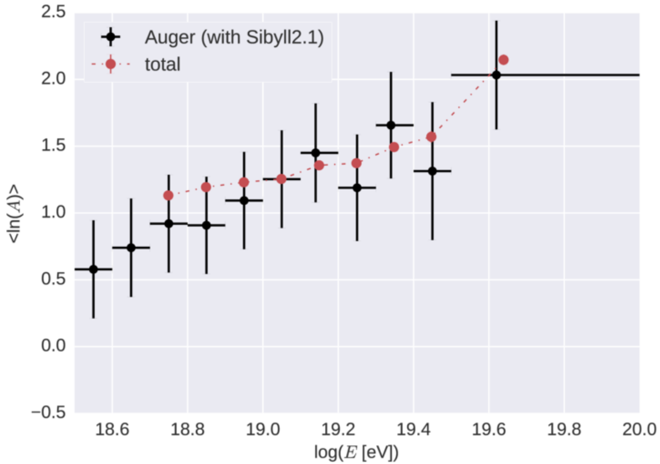
$$f = f_\odot \, Z^{\boldsymbol{q}} \quad \text{with} \quad 0 \le \boldsymbol{q} \le 2$$

- Source evolution parameter fixed to $m = 3$ (minor influence!)

Best-Fit Results (individual values for Cyg A & Cen A needed)

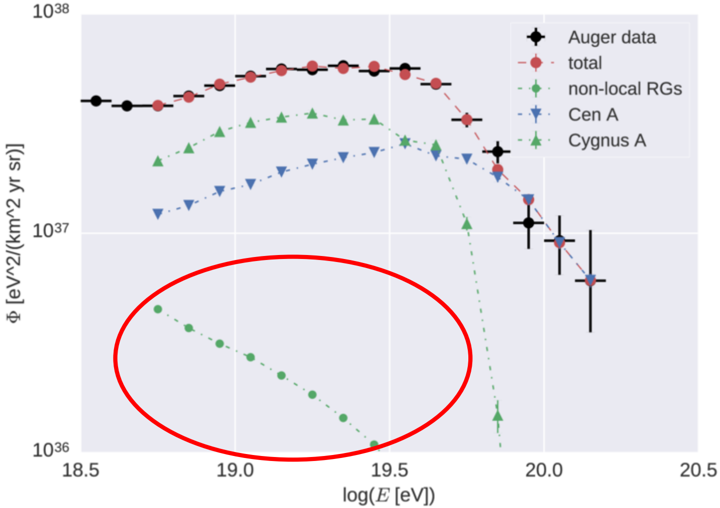
	a	$\bar{g}_{\rm cr}$	$g_{\rm cr}^{\rm CenA}$	$g_{\rm cr}^{\rm CygA}$	$g_{\rm acc}$	$g_{\rm acc}^{\rm CygA}$	$q^{\rm CenA}$	χ^2
EPOS-LHC	1.85	7.73	41.54	43.94	0.127	0.059	2	1.1
QGSJetII-04	1.82	6.31	21.20	48.84	0.220	0.056	2	1.4
Sibyll2.1	1.83	6.67	24.77	47.90	0.19	0.056	2	1.3

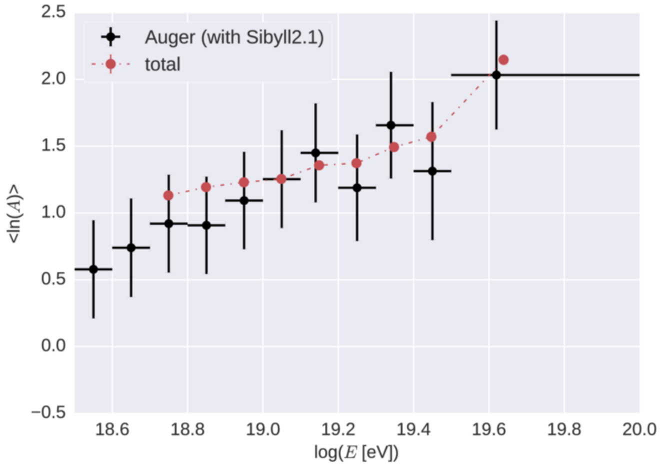




Best-Fit Results (energy spectrum & composition)

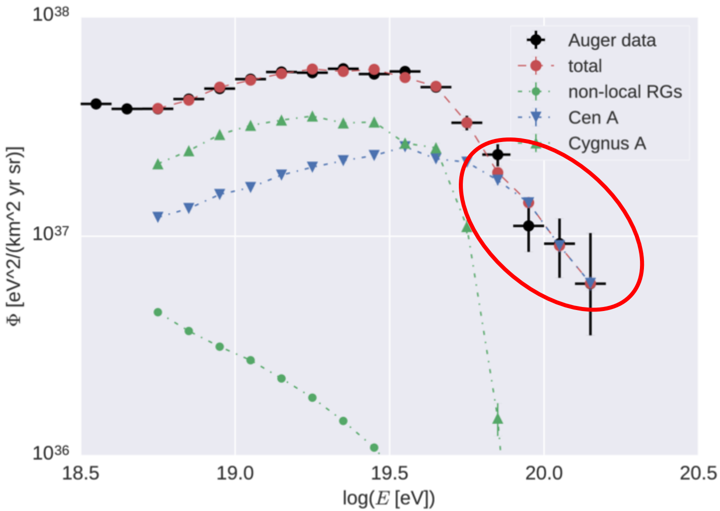
1. **CSF** is subdominant at $E \gg 5\mathrm{EeV}$

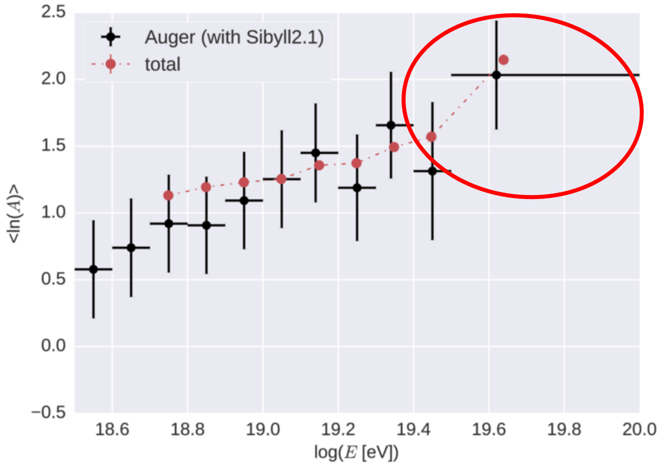




Best-Fit Results (energy spectrum & composition)

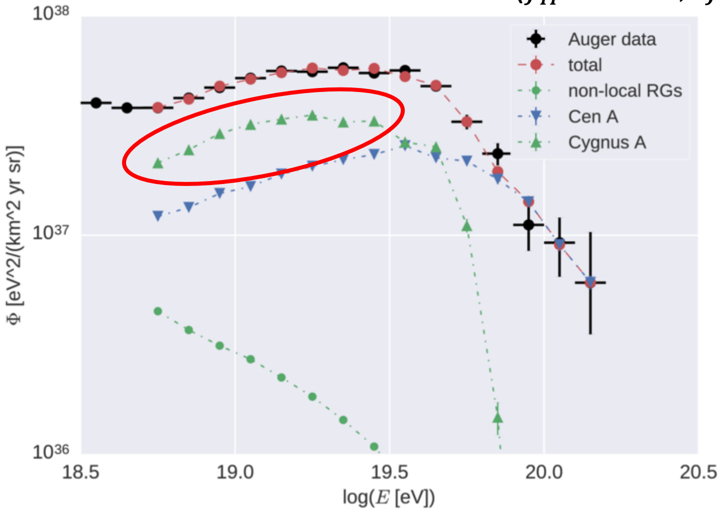
1. **CSF** is subdominant at $E \gg 5\text{EeV}$
2. **Cen A** dominates local contribution and provides heavy initial abundances $(f_H \sim 0.7,\ f_{He} \sim 0.24,\ f_{CNO} \sim 0.04,\ f_{Fe} \sim 0.02)$

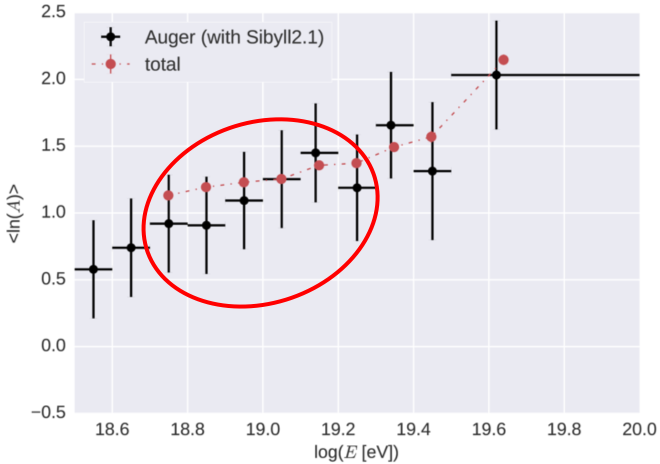




Best-Fit Results (energy spectrum & composition)

1. **CSF** is subdominant at $E \gg 5\mathrm{EeV}$
2. **Cen A** dominates local contribution and provides heavy initial abundances $(f_H \sim 0.7,\ f_{He} \sim 0.24,\ f_{CNO} \sim 0.04,\ f_{Fe} \sim 0.02)$
3. **Cygnus A** dominates non-local contribution and provides solar init. abund. $(f_H \sim 0.92,\ f_{He} \sim 0.08,\ f_{CNO} \sim 0.001,\ f_{Fe} \sim 0.00003)$





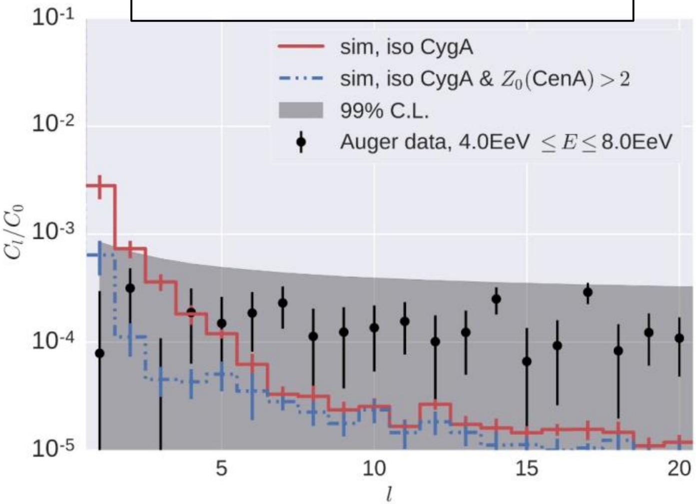
Best-Fit Results (arrival directions)

- Estimate **rms deflection of Cygnus A events** using

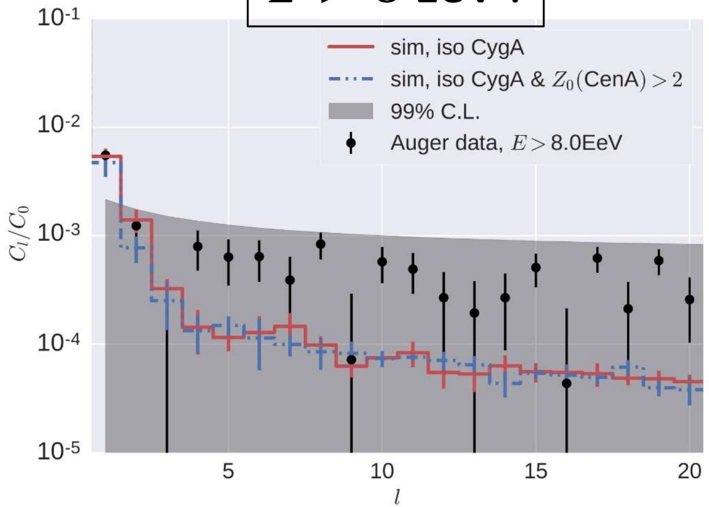
$$\theta_{rms} \simeq 0.8^\circ\, \bar{Z} \left(\frac{\bar{E}}{100\ \mathrm{EeV}}\right)^{-1} \left(\frac{d}{10\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{\lambda_c}{1\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{B_{rms}}{1\ \mathrm{nG}}\right)$$

- **Compare multipole moments** with observations (without fitting):

$4\ \mathrm{EeV} \leq E \leq 8\ \mathrm{EeV}:$



$E > 8\ \mathrm{EeV}:$



➢ Suff. deflection of Cyg A events for $\lambda_c^{1/2} B_{rms} \geq 6\ \mathrm{Mpc}^{1/2}\ \mathrm{nG}$

Conclusions

- **Thus:** Radio Galaxies are able to explain the UHECR data by using 7 physics based parameters:
  - Dominant contribution of Cen A (heavy comp.) and Cyg A (solar comp.).
  - Dipol at $E > 8$ EeV requires significant deflection of Cyg A events at $E \sim 8$ EeV.
  - Average non-local contribution needs to be subdominant at UHE.
- **But:** Contribution of M87 and Fornax A hard to constrain within this scenario!

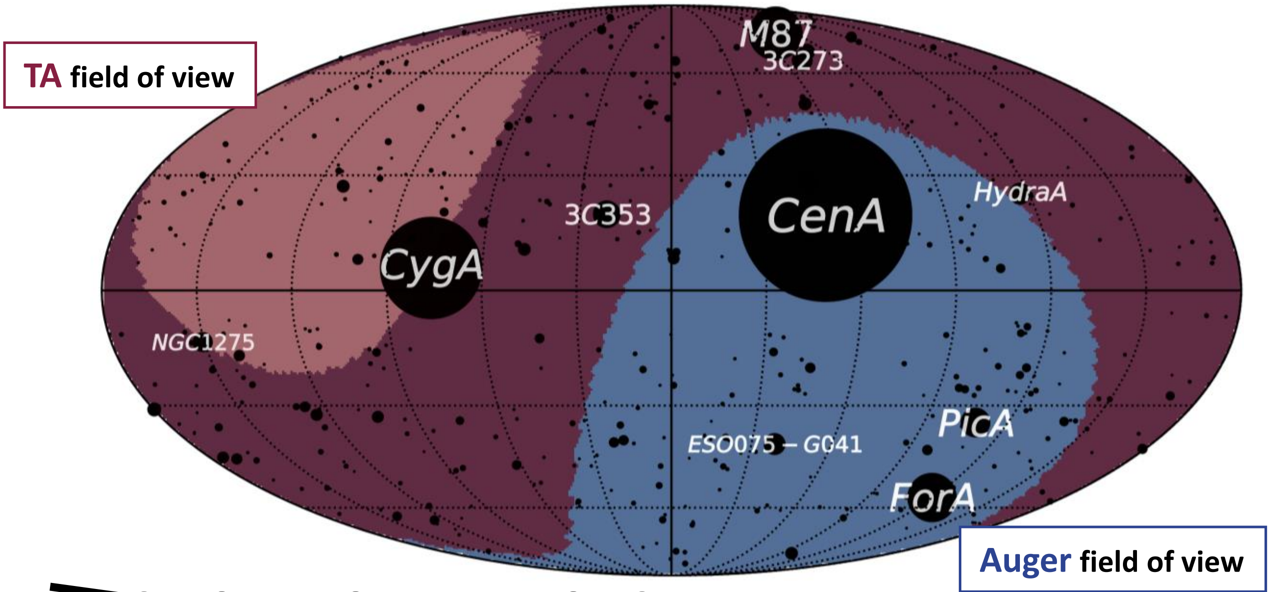
Conclusions & Outlook

- **Thus:** Radio Galaxies are able to explain the UHECR data by using 7 physics ba d parameters:
  - Dominant contribut heavy comp.) and Cyg A (solar comp.).
  - Dipol at $E > 8$ Ee flection of Cyg A events at $E \sim 8$ EeV.
  - Average non-local co inant at UHE.
- **But:** Contribution of M87 an to constrain within this scenario!

JCAP02(2018)036
(arXiv:1701.06792)

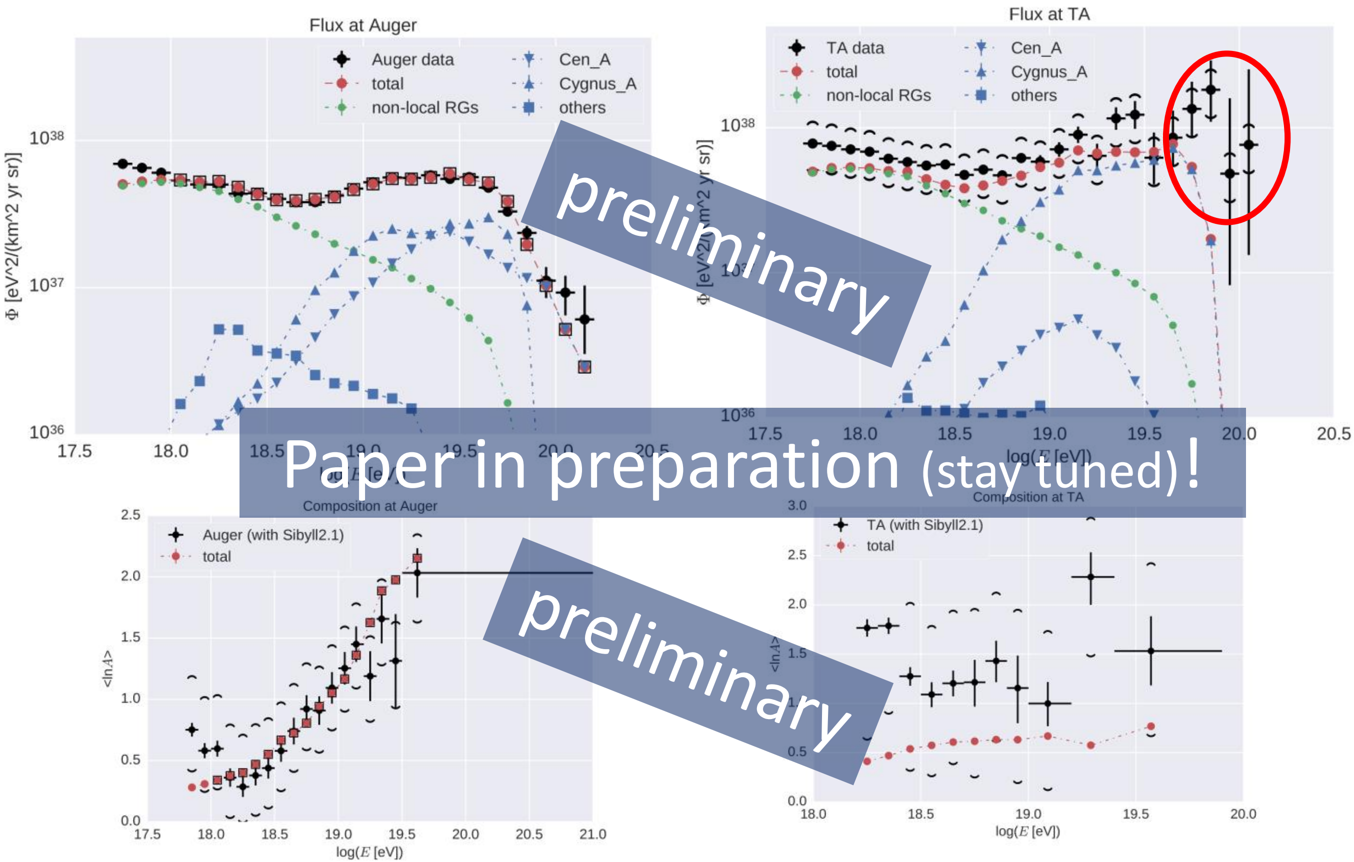
- **And what about:**
  - EGMF effects for CRs from ultra-luminous RGs beyond 120Mpc?
  - CSF contribution below the ankle?
  - Physics based difference between northern & southern UHECRs?

Outlook



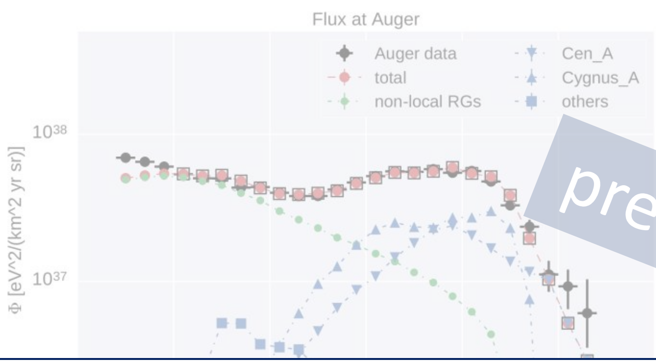
- **~~And what about~~ Include:**
  - EGMF effects for CRs from ultra-luminous RGs beyond 120Mpc
  - CSF contribution below the ankle
  - Physics based difference between northern & southern UHECRs

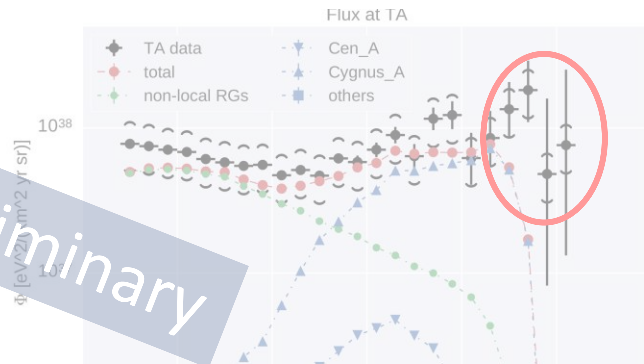
Outlook



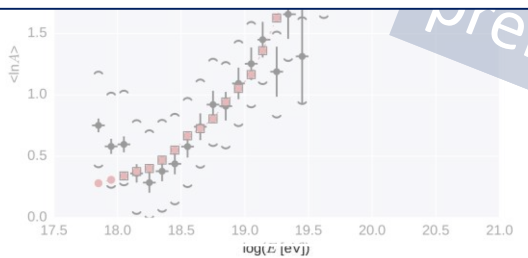
Paper in preparation (stay tuned)!

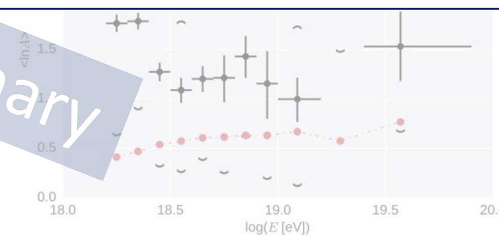
Take-home message





Radio Galaxies **(with a dominant contribution by Cen A & Cyg A) are able to explain the UHECR data using reasonable physical constraints** (`Fermi` spectrum, pred. solar abundances, normalized flux, etc.)

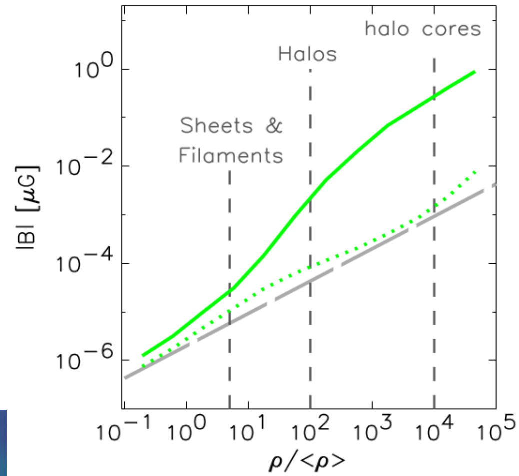




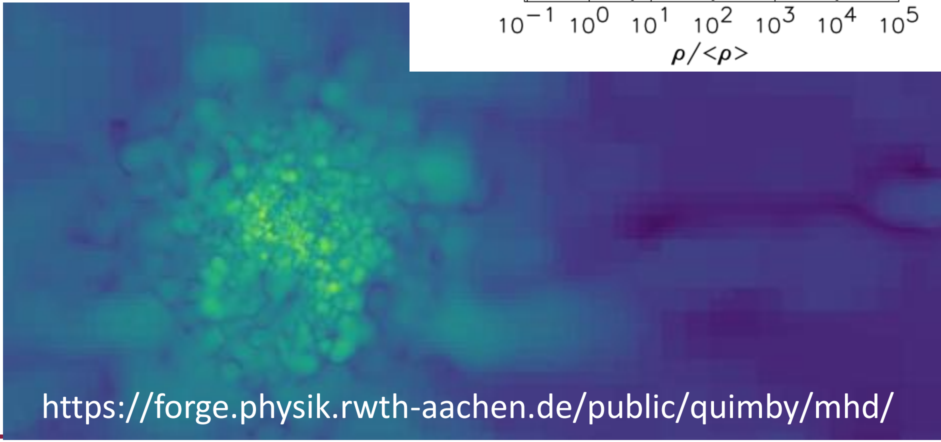
Backup

Local EGMF by Dolag et al. (2005)

- Seed field assumptions:
  - Uniform magnetic seed field $B_0 = 2 \times 10^{-12}\mathrm{G}$
  - Arbitrary initial orientation
- Cosmological MHD simulations determine the EGMF structure
  - $B_{rms} \simeq 1$ nG
  - Up to a distance of $\sim 120\mathrm{Mpc}$



- Sampled with a resolution of 14.6 kpc & stored in a multi-resolution grid using *'Quimby'* (Müller, 2016)



The Sources & Their Characteristics

- **CR power** from the jet power: $Q_{cr} \simeq \frac{4}{7} Q_{jet}$, using *minimum jet energy condition* (Pacholczyk, 1970) $Q_B \simeq \frac{3}{4}(Q_e + Q_{cr})$ & $Q_{cr} \gg Q_e$
- **Jet power** from extended radio emission (Willott et al., 1999):

$$\boxed{Q_{cr} = \frac{4}{7}\, Q_{jet} = g_{cr}\, Q_{jet,0} \quad \text{with } 1 \leq g_{cr} \leq 50}$$

$$\frac{Q_{jet,0}}{\mathrm{erg/s}} = 3 \times 10^{45} \left(\frac{P_{151}}{10^{28}\ \mathrm{WHz^{-1}sr^{-1}}}\right)^{6/7}$$

- **Maximal Rigidity** using *min. jet energy cond.* $Q_{jet} = \frac{7}{3} Q_B = \frac{7}{3} c\beta_{jet}\pi r^2 \frac{B^2}{8\pi}$ and *Hillas criterion* $\hat{R} \equiv \frac{E_{max}}{Ze} = \frac{\beta_{sh}}{f_{diff}} Br$

$$\boxed{\hat{R} \simeq g_{acc}\sqrt{g_{cr} Q_{jet,0}/c}\,, \qquad \text{with } g_{acc} = \sqrt{\frac{6\beta_{sh}^2}{f_{diff}^2 \beta_{jet}}}}$$

Average non-local source contribution

- EGMF structure limits the (3D) simulation volume

➢ Analytic construction of the ***Continuous Source Function (CSF)***:

$$\Psi_0(R) = \frac{dN_{cr}}{dR\,dt\,dV} = \frac{1}{eZ}\int_{\hat{Q}}^{\check{Q}} dQ\ \ S_{cr}(R,\hat{R})\ \ \Phi_{\mathrm{RL}}(Q),$$

with $\hat{R} = g_{acc}\sqrt{\frac{Q_{cr}}{c}}$ and radio lum. func. Φ_{RL} (Mauch & Sadler, 2007)

- Uniform 1D-distribution of sources with an individual spectrum

$$S_{cr}(R,\hat{R}) = \nu_0(a)\,Q_{cr}\,(R/\hat{R})^{-a}\Theta(\hat{R}-R)$$

with a spectral normalization correction $\nu_0(a)$.

➢ Continuation of the local source sample (and its features!)

➢ 1D-Simulation to account for ***propagation effects*** (energy losses)

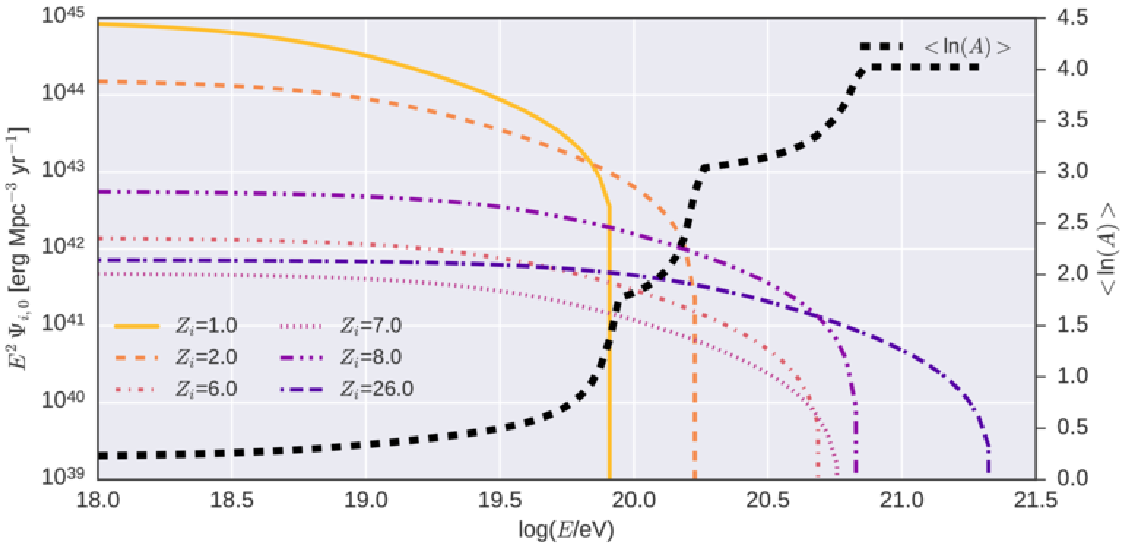
➢ Including source evolution effects: $\Psi(R,z) = \Psi_0(R)\,(1+z)^{m-1}$, $z \leq 2$

Average non-local source contribution

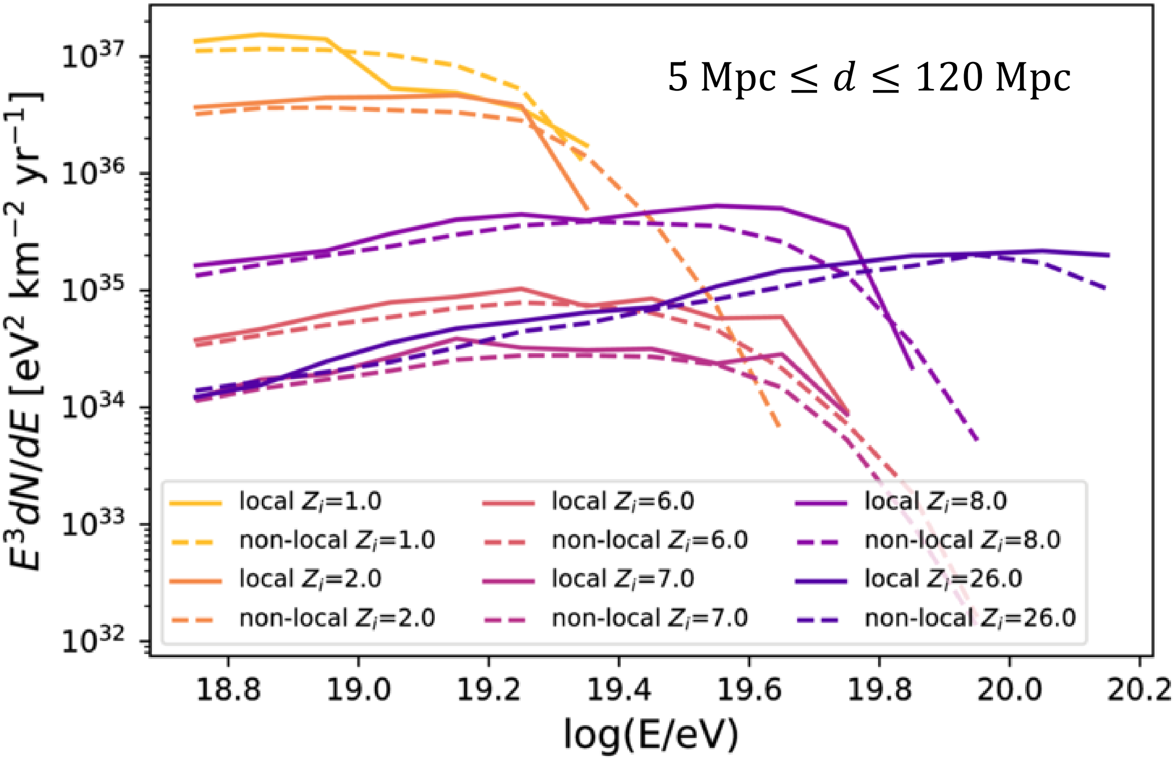
- EGMF structure limits the (3D) simulation volume

➢ Analytic construction of the ***Continuous Source Function (CSF)***:

$$\Psi_0(R) = \frac{dN_{cr}}{dR\,dt\,dV} = \frac{1}{eZ}\int_{\hat{Q}}^{\check{Q}} dQ\ \ S_{cr}\big(R,\hat{R}\big)\ \ \Phi_{\mathrm{RL}}(Q),$$

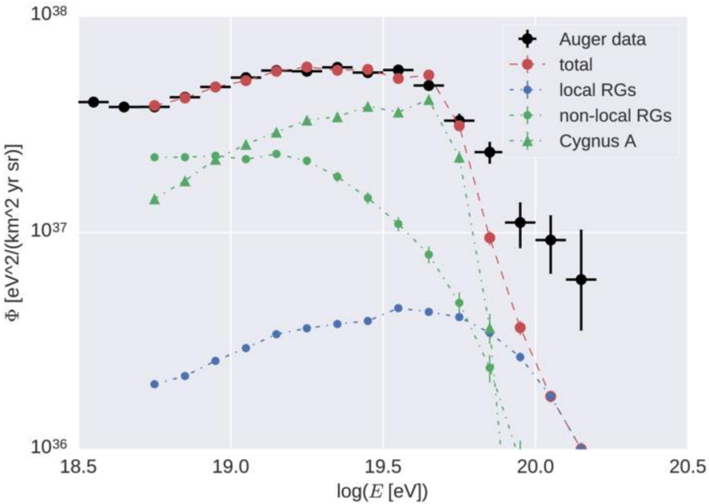


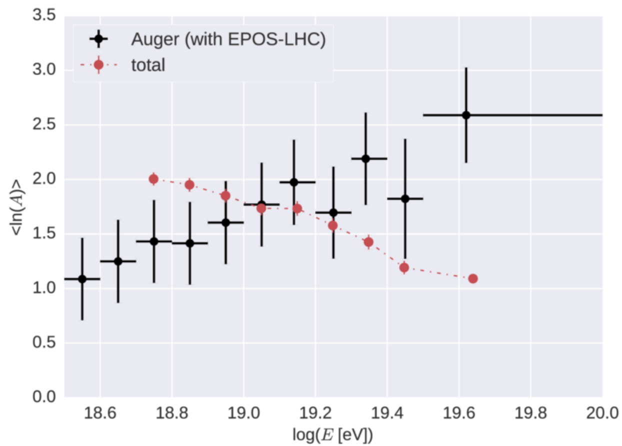
Comparison of CSF in local regime



First-Fit Approach (all the same, except Cygnus A)

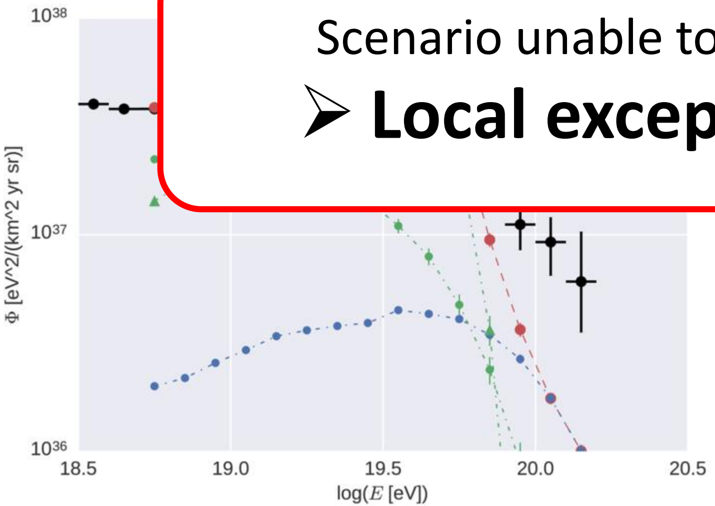
	a	$\bar{g}_{\mathrm{cr}}$	$g_{\mathrm{cr}}^{\mathrm{CygA}}$	$\bar{g}_{\mathrm{acc}}$	$g_{\mathrm{acc}}^{\mathrm{CygA}}$	$\bar{q}$	χ^2
EPOS-LHC	1.7	1.94	22.17	0.6	0.11	2	5.4
QGSJetII-04	1.76	2.23	32.60	0.6	0.090	1.84	5.6
Sibyll2.1	1.83	2.29	42.51	0.6	0.085	1.97	5.7





First-Fit Approach (all the same, except Cygnus A)

	a	$\bar{g}_{cr}$	g_{cr}^{CygA}	$\bar{g}_{acc}$	g_{acc}^{CygA}	$\bar{q}$	χ^2
EPOS-LHC	1.7	1.94	22.17	0.6	0.11	2	5.4
QGSJetII-04	1.76	2.23	32.60	0.6	0.090	1.84	5.6
Sibyll2.1	1.83	2.29	42.51	0.6	0.085	1.97	5.7



Scenario unable to explain the data!

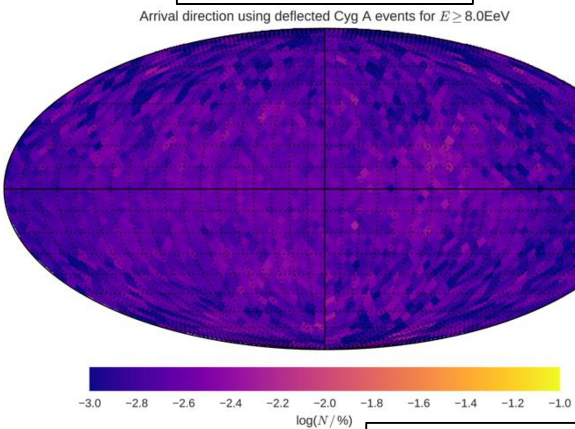
➢ **Local exception** needed!

Best-Fit Results (arrival directions)

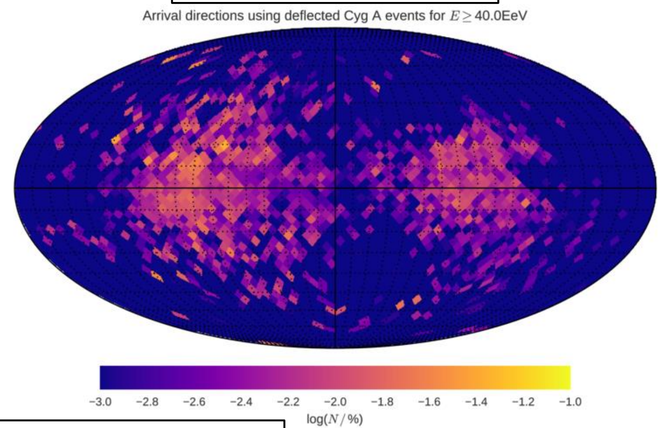
- Estimate **rms deflection of Cygnus A events** using

$$\theta_{rms} \simeq 0.8^\circ \, \bar{Z} \left(\frac{\bar{E}}{100\ \mathrm{EeV}}\right)^{-1} \left(\frac{d}{10\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{\lambda_c}{1\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{B_{rms}}{1\ \mathrm{nG}}\right)$$

$\boxed{E \geq 8\ \mathrm{EeV}:}$



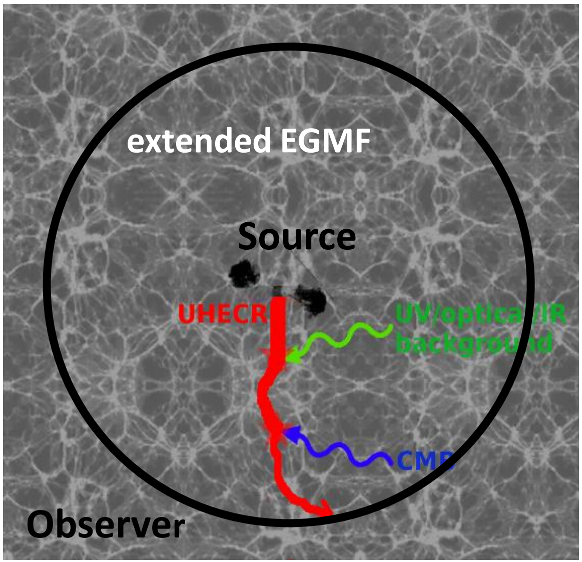
$\boxed{E \geq 40\ \mathrm{EeV}:}$



$\boxed{\text{using } \lambda_c^{1/2} B_{rms} = 6\ \mathrm{Mpc}^{1/2}\ \mathrm{nG}}$

Advanced methods

- **Include** EGMF effects for CRs from ultra-luminous RGs beyond 120Mpc by using an extended EGMF in an inverted simulation setup



- **Check** mean deflection dependence on distance and spatial position for E^{-2}-spectrum above 1EeV