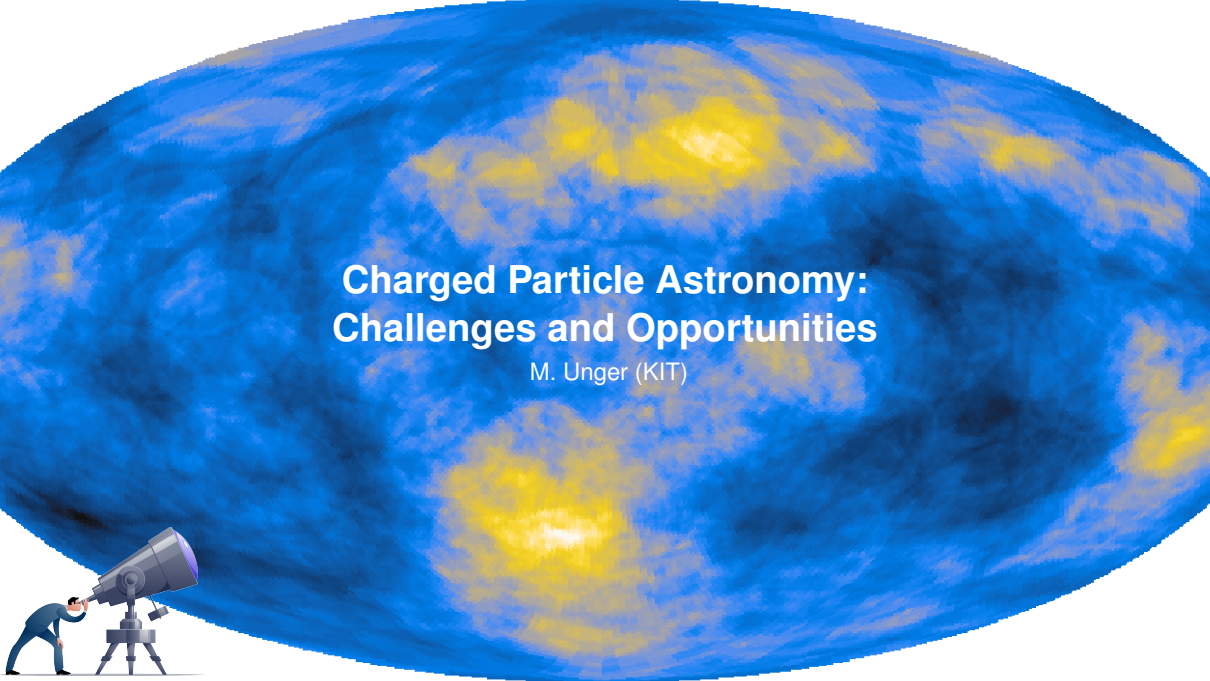


A large, oval-shaped map of the Cosmic Microwave Background (CMB) radiation. The map shows a complex pattern of blue and yellow colors, representing temperature fluctuations across the universe. The yellow areas indicate slightly warmer regions, while the blue areas indicate slightly cooler regions. The pattern is highly detailed and covers the entire background of the slide.

Charged Particle Astronomy: Challenges and Opportunities

M. Unger (KIT)



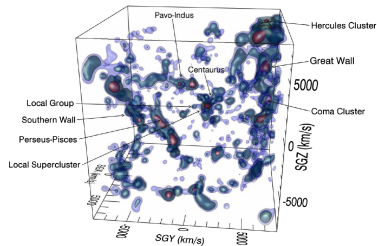


Outline

- Illustration of the challenge
- UHECR rigidity and proton fraction
- Galactic magnetic field
- Dipole and intermediate scale anisotropies
- Summary

Illustration of the Challenge

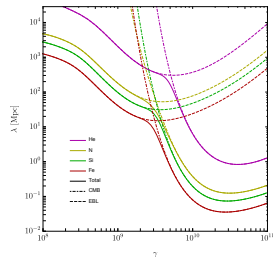
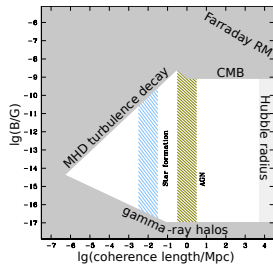
large-scale structure



CosmicFlows Hoffman+2018

here: 2M++ density field, Carrick+2015

extragalactic propagation

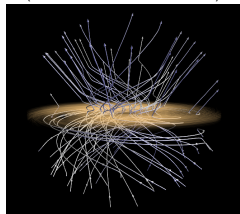


Durrer&Neronov 2013, J. Soriano (CUNY) 2018

here: neglect IGMF, attenuation via CRPropa

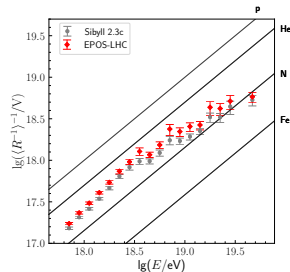
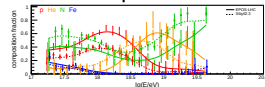
Galactic magnetic field

(coherent B and random b)



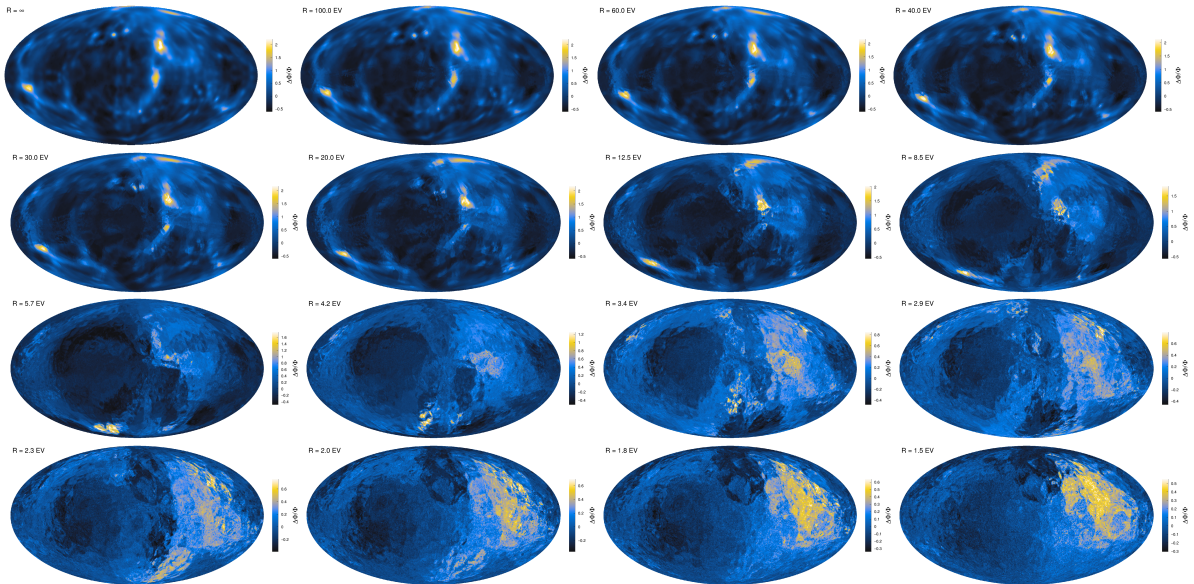
Jansson&Farrar 2012 ($l_{\text{coh}} = 50 \text{ pc}$)

composition

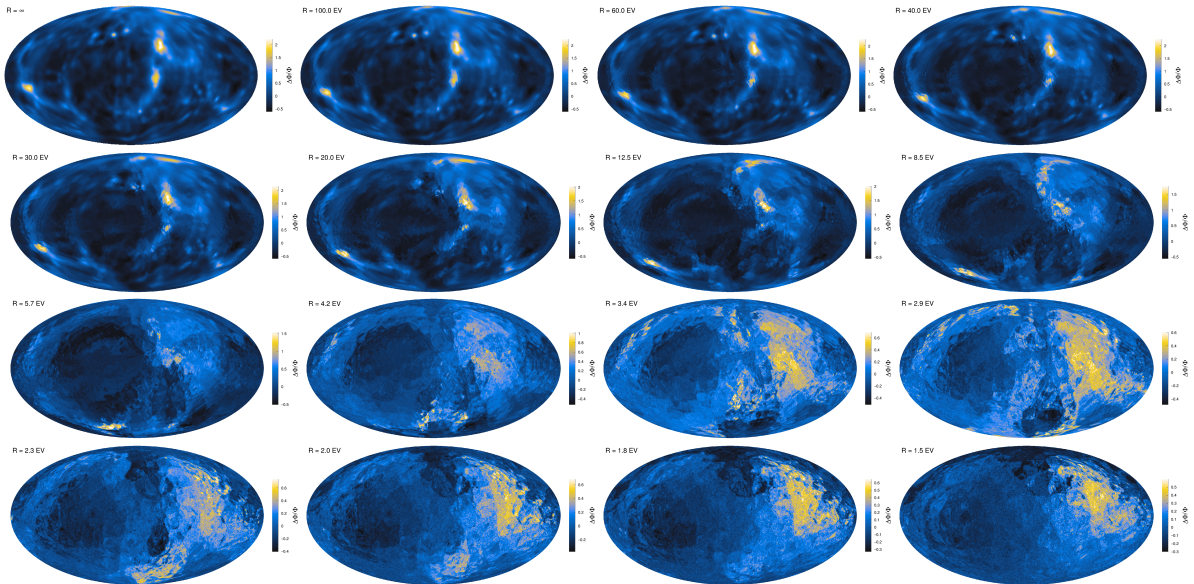


Auger 2014, O. Tkachenko (KIT)

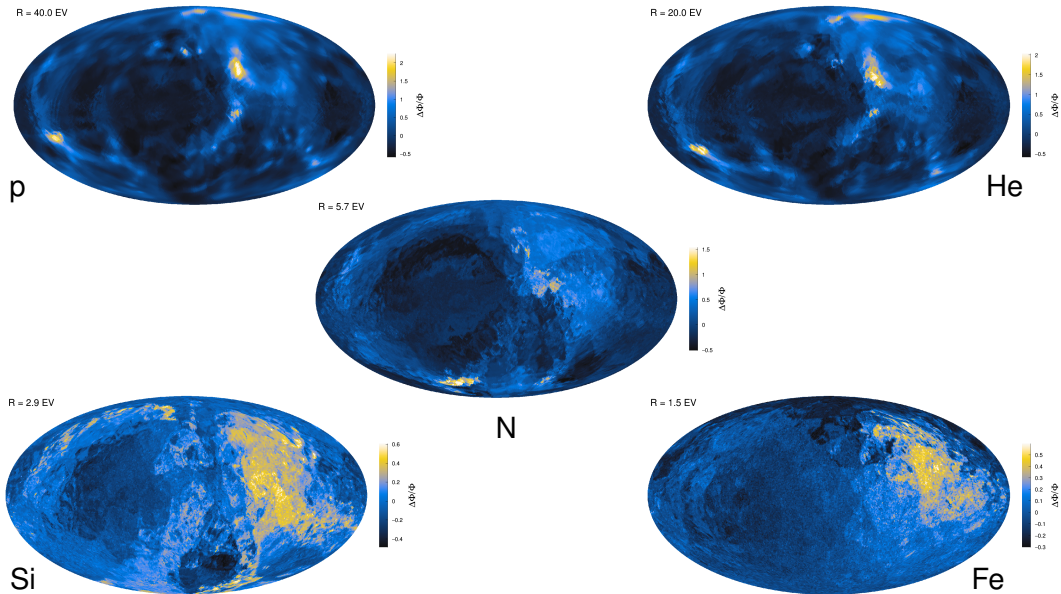
a) $B, b, D_{\text{max}}=100$ Mpc



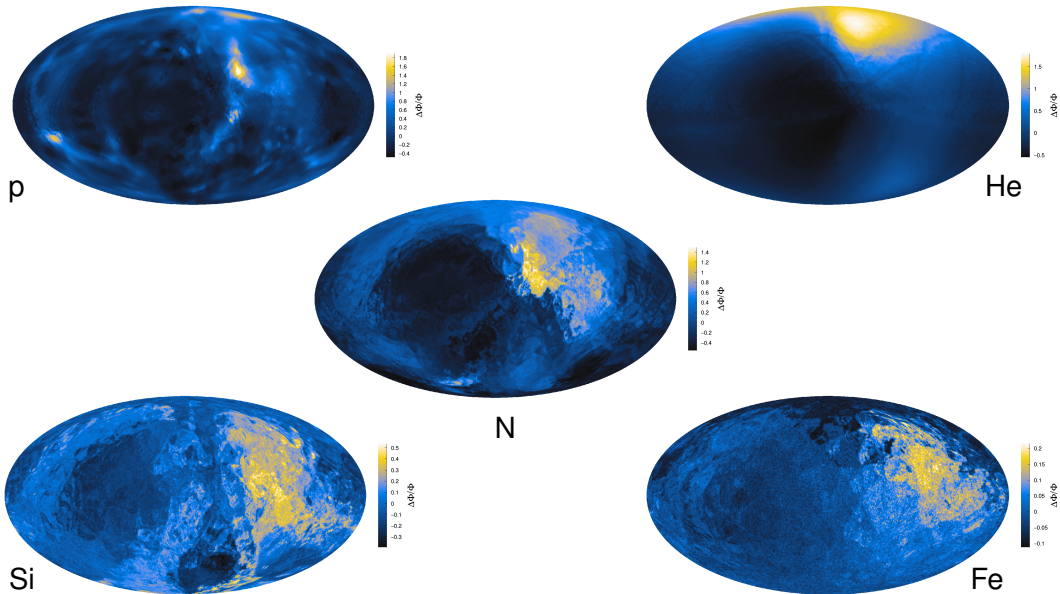
b) $B, b, D_{\text{max}}=100$ Mpc, different realization of b



c) mixed composition ($E = 40$ EeV)



d) mixed composition & attenuation ($E = 40$ EeV)

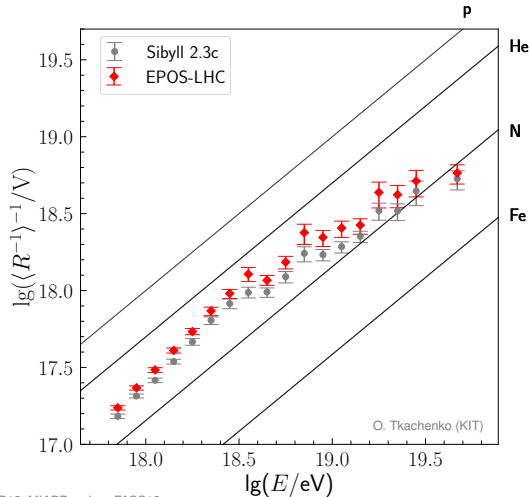
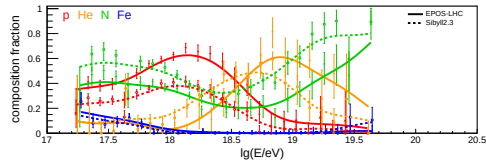
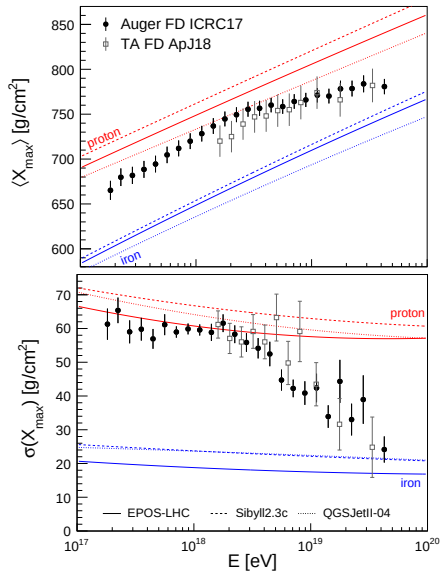




Outline

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- Galactic magnetic field
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UHECR Rigidity and Proton Fraction

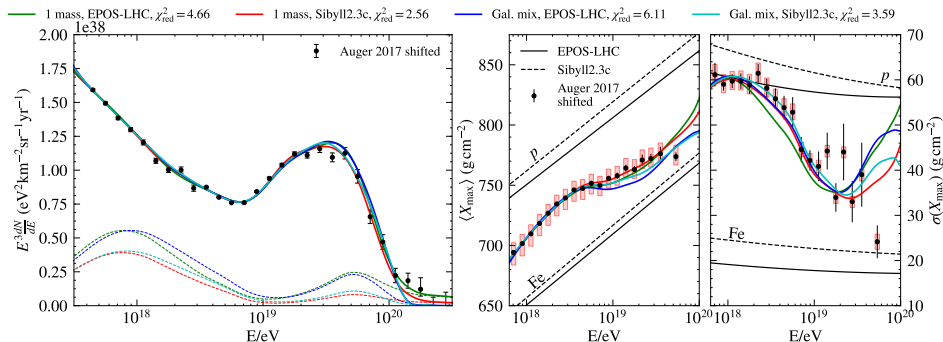
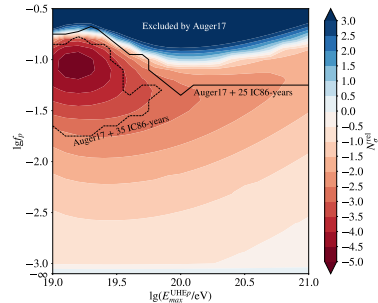


Protons at UHE?

energy fraction escaping source:

$$f_p = \frac{\int_{E_{\text{ref}}}^{\infty} E Q_p dE}{\int_{E_{\text{ref}}}^{\infty} E (Q_p + Q_{\text{mix}}) dE}$$

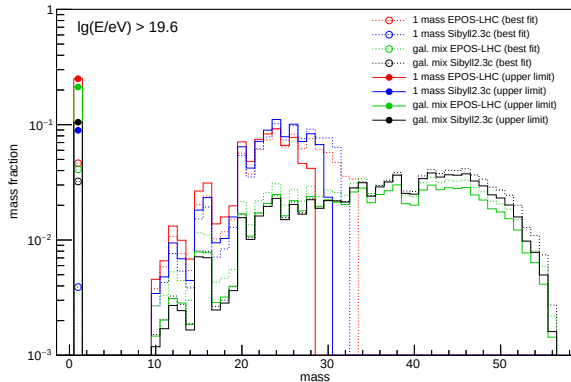
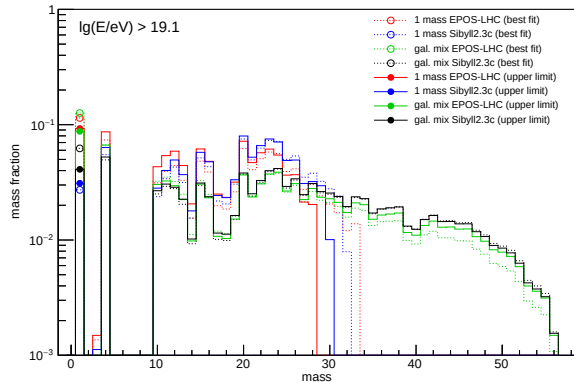
($Q_p \sim E^{\gamma_p} e^{-E/E_{\text{max}}^{\text{UHE}p}}$, $\gamma_p = -1$ and $E_{\text{ref}} = 10^{19}$ eV)



Protons at UHE?

low R_{max} , small He photo-disintegration pathlength at UHE

→ ideal window for proton-nucleus separation!



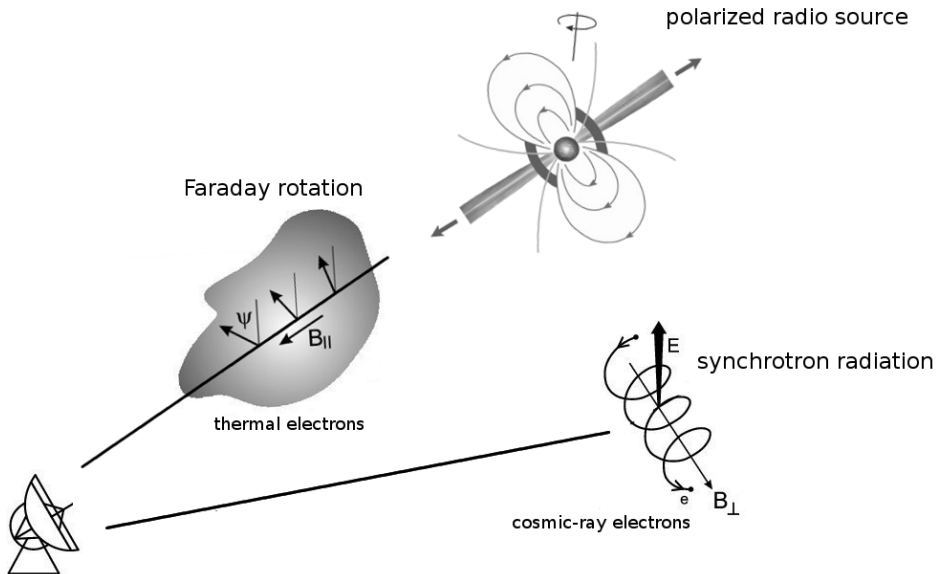
Composition fractions of Muzio+2019 models, plots from POEMMA UHECR paper, PRD2020



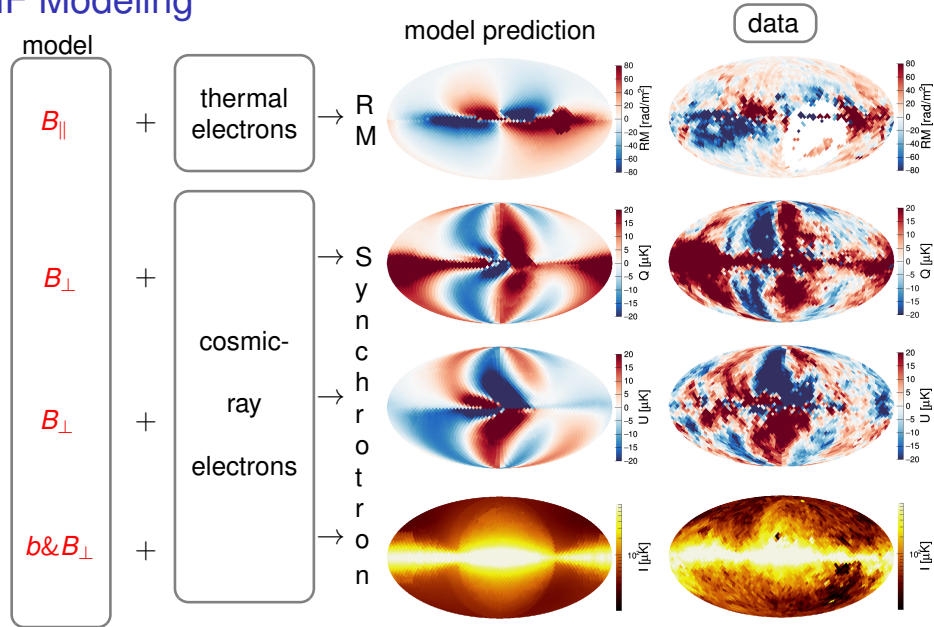
Outline

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Reminder: How to Measure the Galactic Magnetic Field

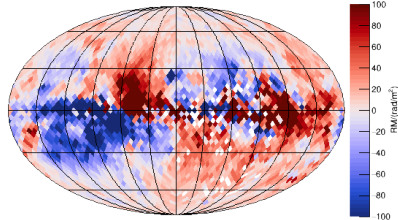
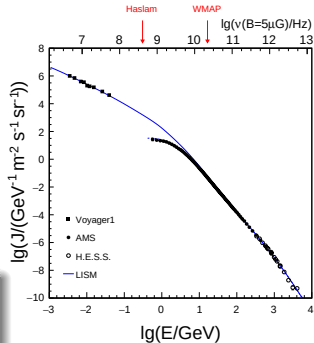


GMF Modeling



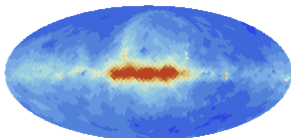
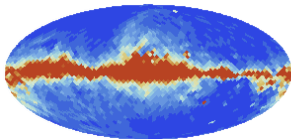
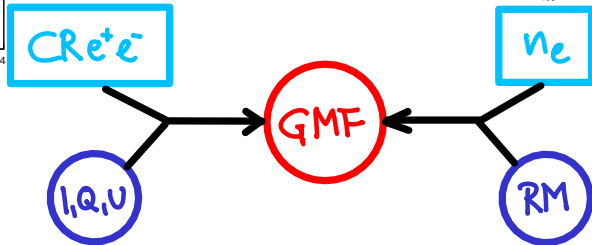
GMF Modeling

MU&Farrar in prep.

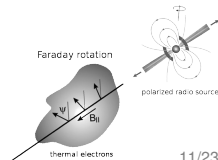
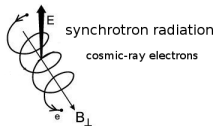


new data since JF12:

- full-sky RMs
- pulsars (RM&DM)
- precise $e^\pm$ at Earth
- final WMAP maps
- Planck maps



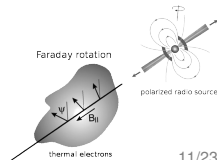
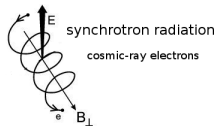
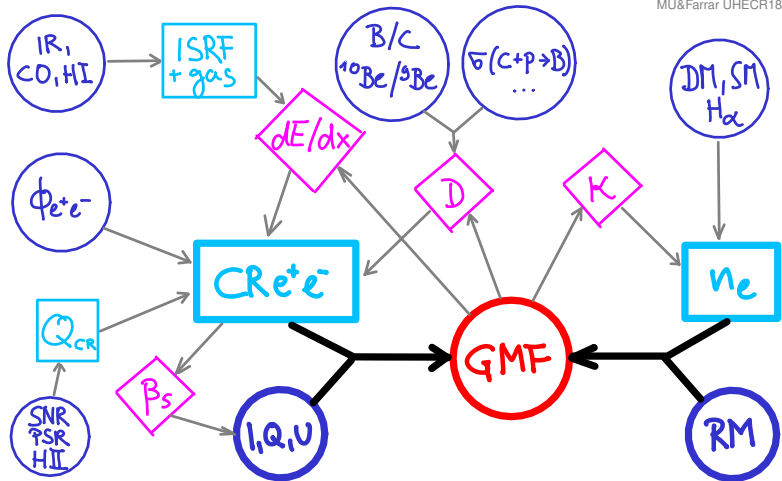
$I [\mu\text{K}]$ at 30 GHz



GMF Modeling

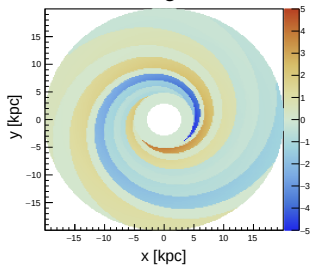
new data since JF12:

- full-sky RMs
- pulsars (RM&DM)
- precise $e^\pm$ at Earth
- final WMAP maps
- Planck maps

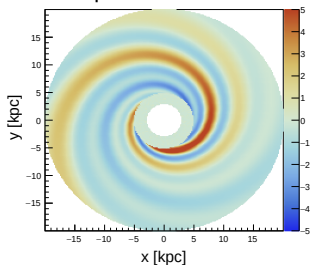


Model Developments

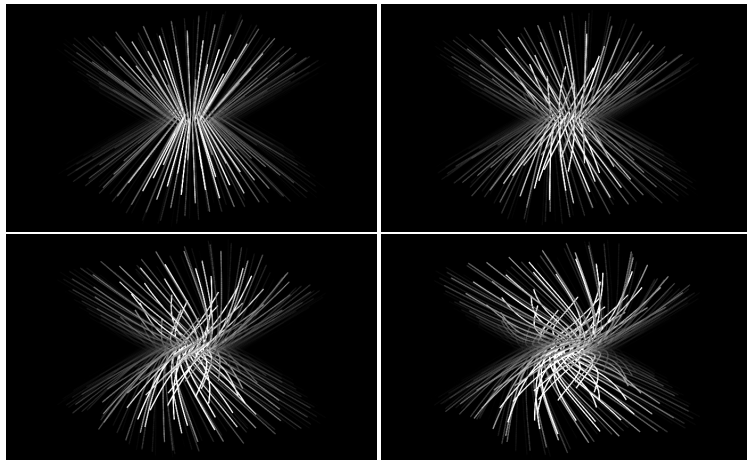
Brown+07 “wedge”-model:



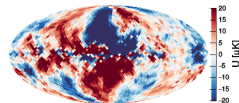
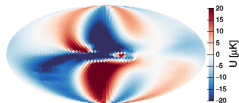
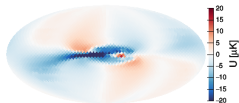
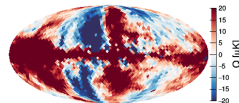
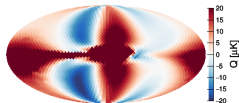
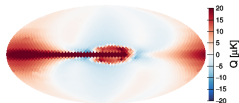
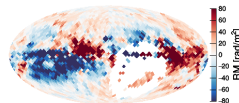
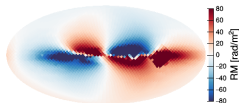
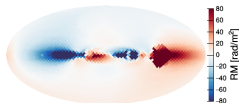
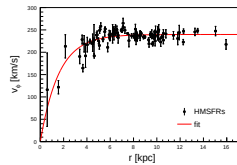
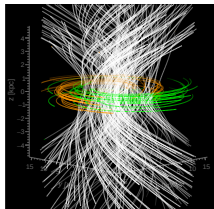
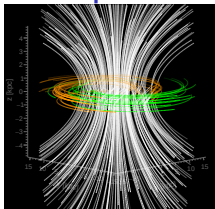
smooth spiral disk field:



- evolve poloidal field via induction equation
- radial and vertical shear of Galactic rotation generates toroidal field



Model Developments



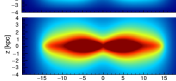
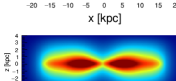
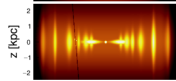
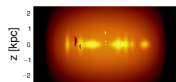
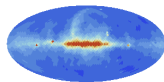
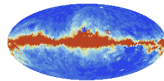
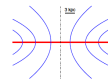
(a) $t = 0$ Myr

(b) $t = 70$ Myr

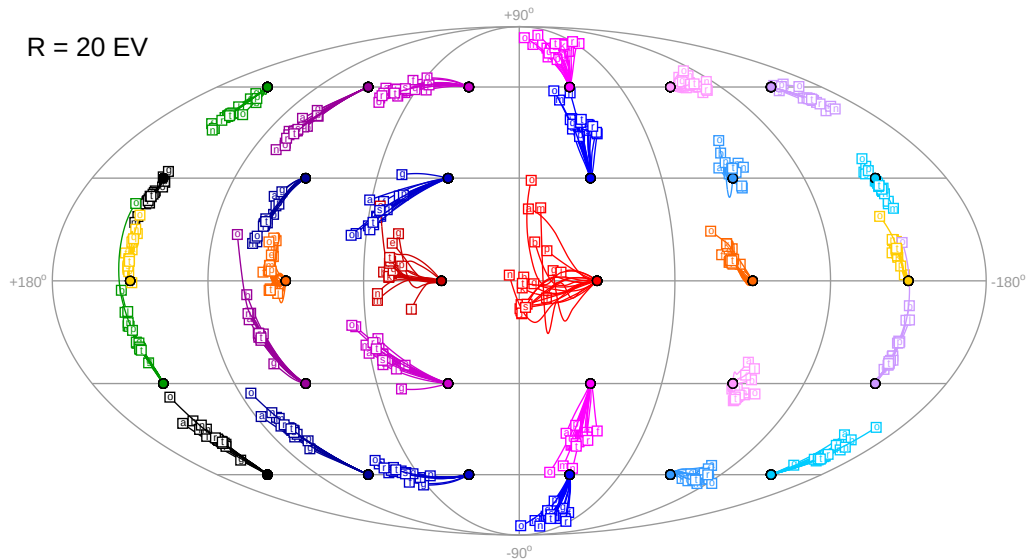
(c) data

Model Variations and Refits

id	disk	toroidal	poloidal	NE	ncre	QU	misc	χ^2/ndf
Parametric models								
a	JF	JF	JF	01	GP_JF	W7	-	1.10
b	JF	JF	FTC	01	GP_JF	W7	-	1.09
c	JF	JFsym	FTC	01	GP_JF	W7	-	1.11
d	JF	JFsym	FTC	01	GP_JF	W7	warp	1.11
e	UF	JFsym	FTC	01	GP_JF	W7	-	1.09
f	UF	UF	UFa	01	GP_JF	W7	-	1.14
g	UF	UF	UFb	01	GP_JF	W7	-	1.09
Synchrotron products								
h	JF	JFsym	FTC	01	GP_JF	W9base	-	1.22
i	JF	JFsym	FTC	01	GP_JF	W9sdc	-	1.24
j	JF	JFsym	FTC	01	GP_JF	W9fs	-	1.11
k	JF	JFsym	FTC	01	GP_JF	W9fss	-	1.22
l	JF	JFsym	FTC	01	GP_JF	P15	-	0.78
Thermal electrons								
m	JF	JFsym	FTC	16	GP_JF	W7	-	1.21
n	UF	JFsym	FTC	16	GP_JF	W7	-	1.14
o	JF	JF	FTC	01	GP_JF	W7	$\kappa = -1$	1.05
p	JF	JF	FTC	01	GP_JF	W7	$\kappa = +1$	1.05
q	JF	JFsym	FTC	01	GP_JF	W7	HIM	1.12
Cosmic-ray electrons								
r	JF	JFsym	FTC	01	O13a	W7	-	1.13
s	JF	JFsym	FTC	01	O13b	W7	-	1.12
t	JF	JFsym	FTC	01	S10	W7	-	1.13

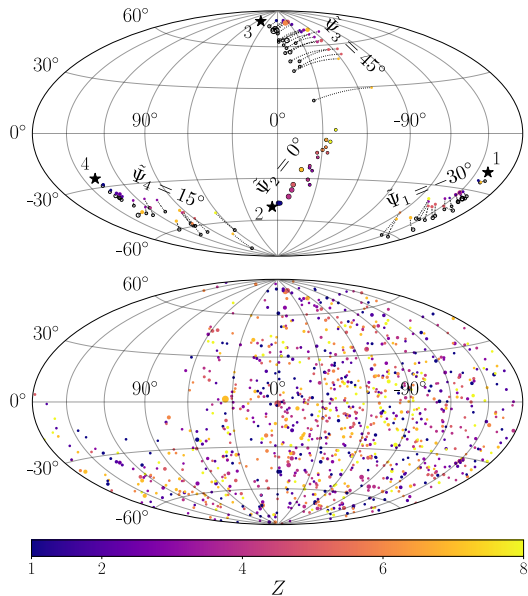


Model Variations – Effect on Backtracked Arrival Directions

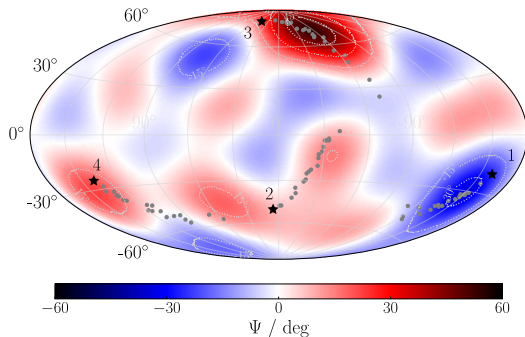


Model Perturbations?

Wirtz, Bister & Erdmann, 2101.02890



- tangent deflection vector field
- fit multipole expansion of difference to e.g. JF12 (here: rotation angle ψ)
- $\ell_{\max} = 5 \rightarrow 36$ fit parameters(!)



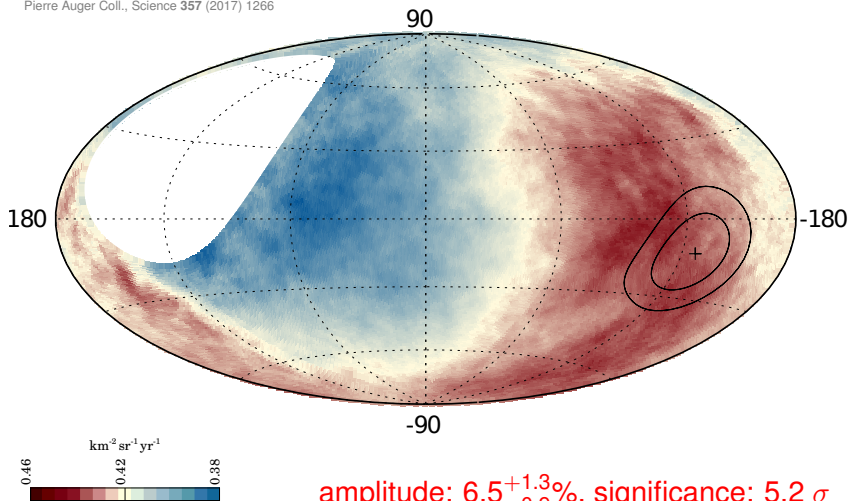


Outline

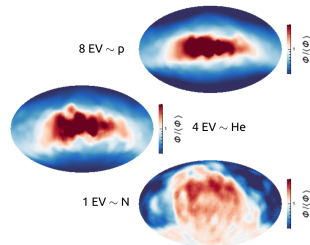
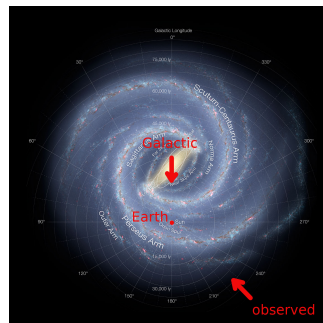
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Large-Scale Anisotropy ($E > 8$ EeV)

Pierre Auger Coll., Science 357 (2017) 1266

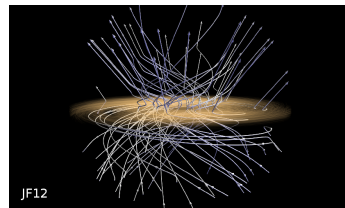
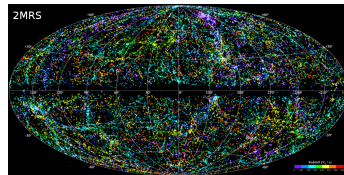
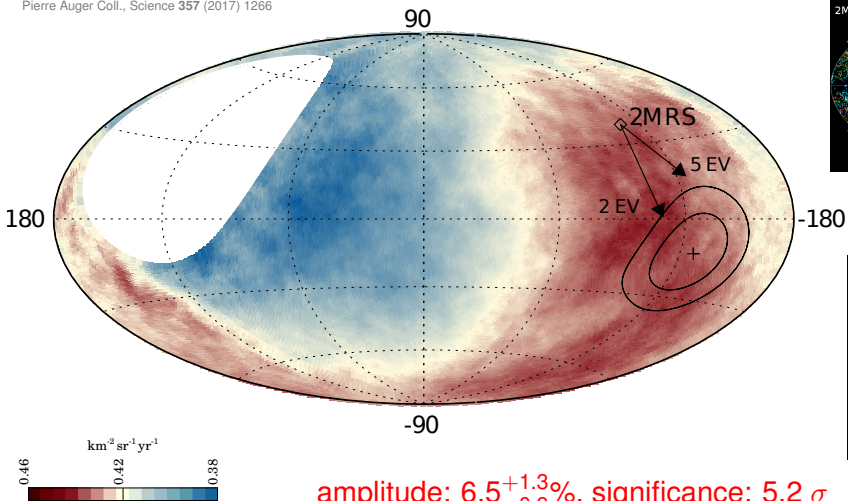


amplitude: $6.5^{+1.3}_{-0.9}\%$, significance: 5.2σ



Large-Scale Anisotropy ($E > 8$ EeV)

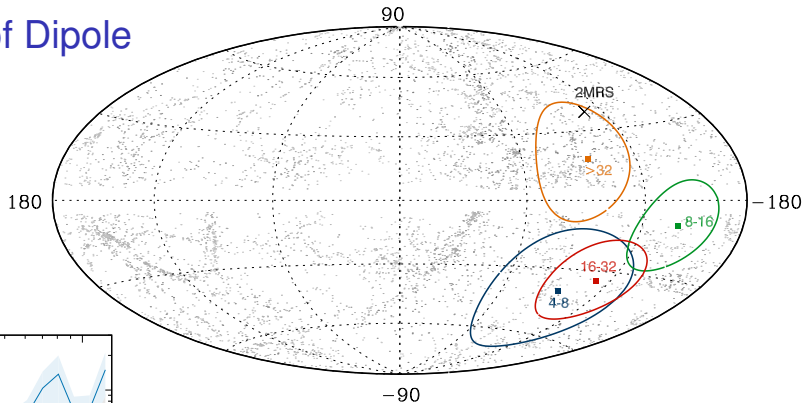
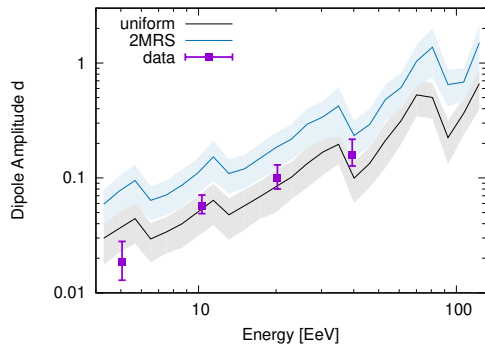
Pierre Auger Coll., Science 357 (2017) 1266



amplitude: $6.5^{+1.3}_{-0.9}\%$, significance: 5.2σ

Energy Dependence of Dipole

dipole position →

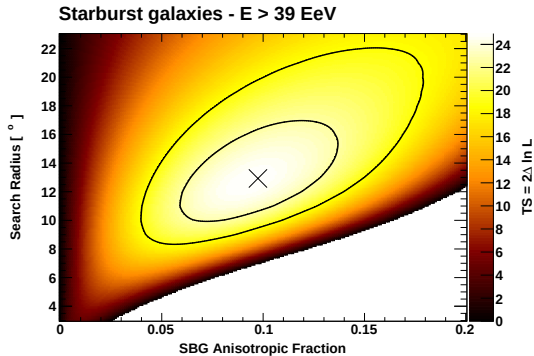


← model: mixed composition
 $R_{\text{max}} = 6 \text{ EV}, \rho = 10^{-4} \text{ Mpc}^{-3}$

Pierre Auger Coll., ApJ868 (2018) 4 and ICRC19
 (see also Globus+1808.02048, Ding+2101.04564, Allard+2110.10761)

Intermediate-Scale Anisotropy

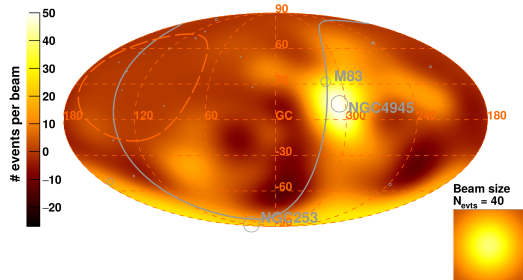
($E > 39$ EeV, $\langle E \rangle \sim 54$ EeV)



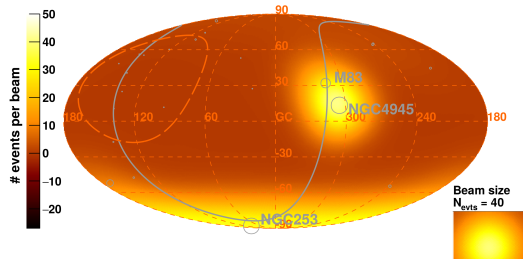
TS = 25 $\leftrightarrow$ isotropy disfavoured at 4σ

Auger Coll. ApJ 2018 and ICRC21

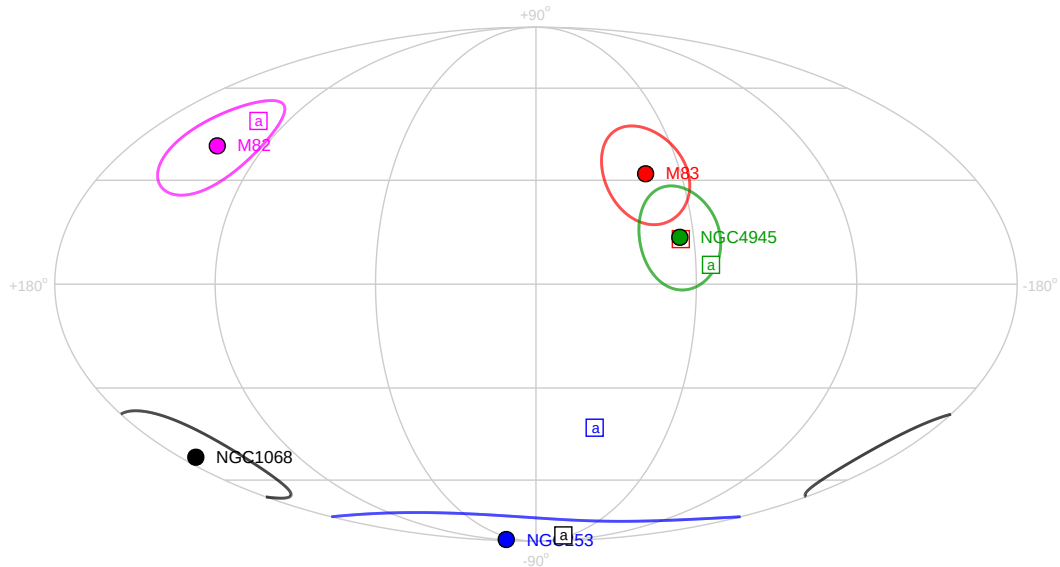
Observed Excess Map - $E > 39$ EeV



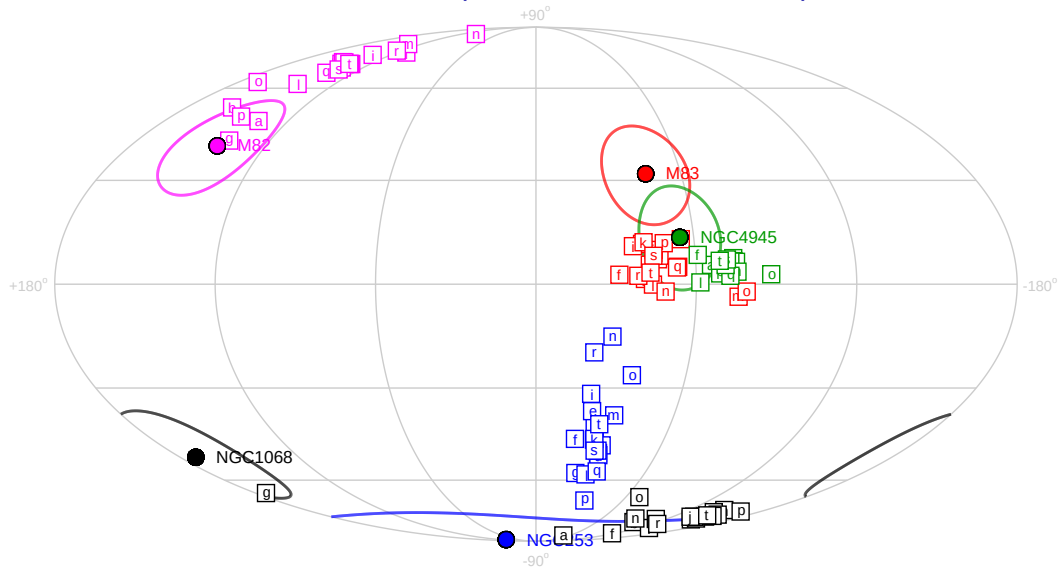
Model Excess Map - Starburst galaxies - $E > 39$ EeV



Coherent Deflections at 8 EV (JF12)

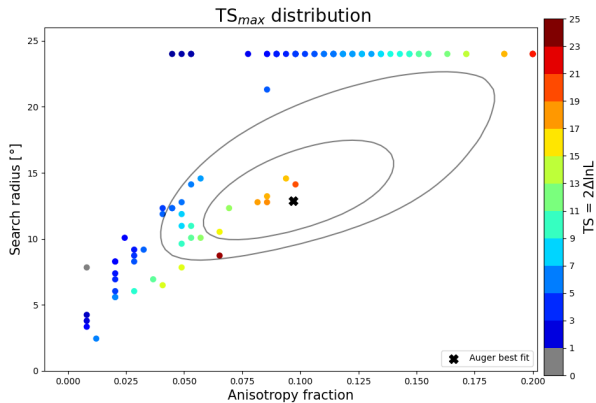


Coherent Deflections at 8 EV (all model variations)



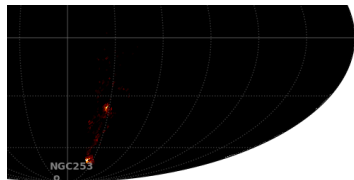
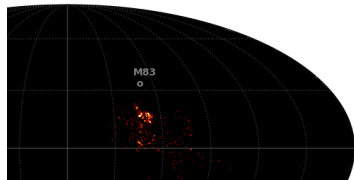
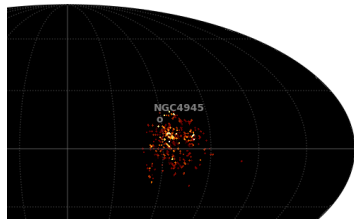
Simulated “SBG Sky” (650 events, N, Auger flux weights & JF12)

100 realizations using an anisotropic fraction of 0.2:



L. Deval (KIT)

see also K. Kawata et al. [TA Coll.] ICRC21





Summary – Charged Particle Astronomy

Challenges:

- $\langle R \rangle \leq 10^{19}$ eV for $E < 10^{20}$ eV
- need to isolate lightest air showers
- complicated interplay of R (deflection) and E (attenuation)
- uncertainties from
 - hadronic interactions (mass $\rightarrow$ charge)
 - GMF modeling (B and b)

Opportunities:

- near-future improvements of systematics via
 - p+O runs at LHC
 - new GMF-related data and analyses
(starlight pol., RM syn., pulsars...) (updated JF12, IMAGINE, ...)
- UHECR spectrometry and tomography
 $\theta_{\text{defl}} \propto Z/E$ $D_{\text{max}} \propto E/A$
- study GMF and EGMF
- “How isotropic can the UHECR flux be?”

di Matteo&Tinyakov 2017