Estimation and reduction of the biases by the galactic magnetic field on the UHECR correlation studies

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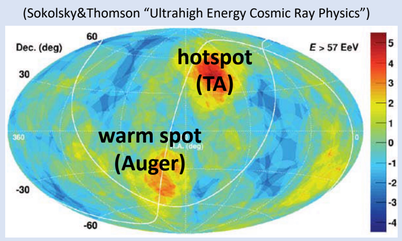
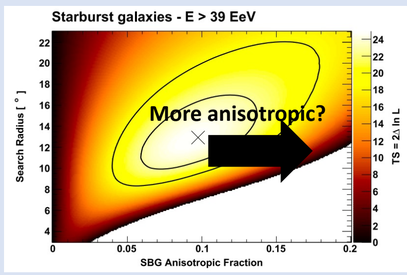
Introduction

Intermediate-scale anisotropy of UHECR arrival direction
=> correlation with the UHECR source distribution?
Possible candidates (in case of known steady source)
starburst galaxies (SBG)
active galactic nuclei (AGN), etc.
Correlation studies (Auger/TA collaborations 2018)
=>nearby SBGs contribute 10% of anisotropy？(SBG model)
The effect caused by the GMF:
rigidity (R=E/Ze) dependent coherent deflection by GMF

Questions:
How much bias in the parameter estimation w/ and w/o GMF, North & South?
Can we reduce the bias?

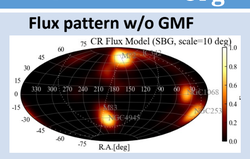
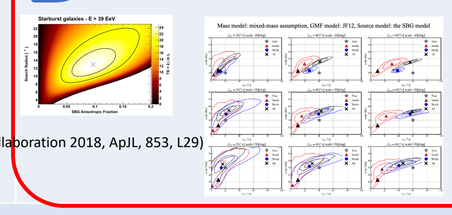
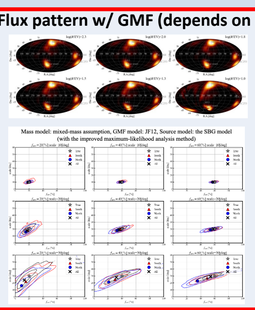
(Sokolsky&Thomson "Ultrahigh Energy Cosmic Ray Physics")



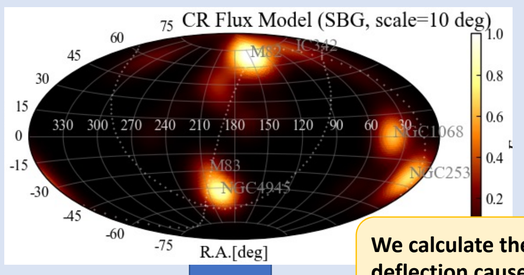


(Auger collaboration 2018, ApJL, 853, L29)

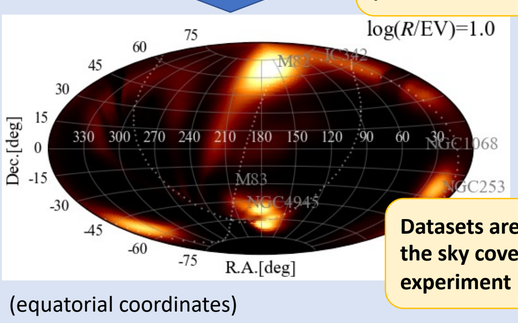
Estimation of biases with MC datasets

	Flux model w/o GMF $F_{\rm org}$	Flux model w/ GMF $F_{\rm earth}$
MC events (w/o GMF)	**A** Flux pattern w/o GMF  Ideal case (when we do not need to consider GMF effect)	We can conduct parameter estimation for MC UHECR events & flux model in 3 cases: A. events w/o GMF & flux w/o GMF; B. events w/ GMF & flux w/o GMF; C. events w/ GMF & flux w/ GMF
MC events (w/ GMF)	**B** Same case with Auger/TA Collaborations  (Auger collaboration 2018, ApJL, 853, L29)	**C** Flux pattern w/ GMF (depends on rigidity) 

Datasets

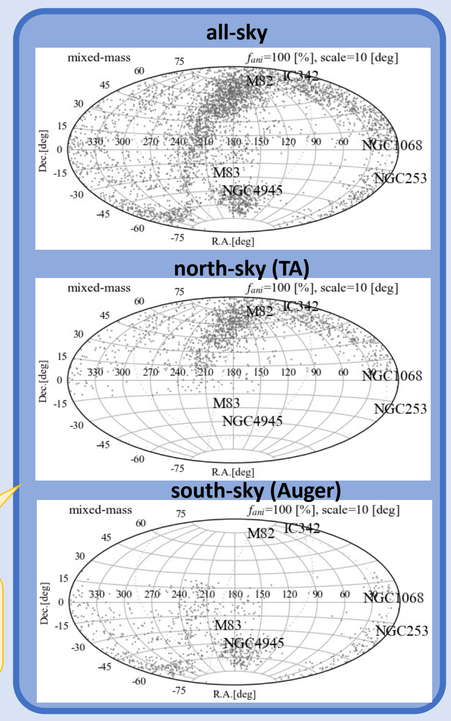


We calculate the flux model with deflection caused by the GMF (JF12model, using CRPropa 3)

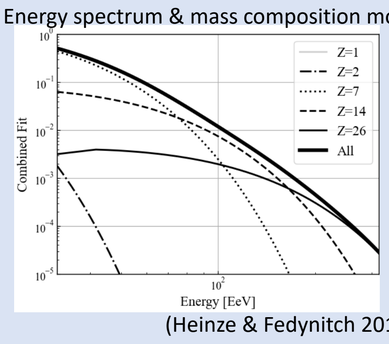


Datasets are selected based on the sky coverage of each experiment

(equatorial coordinates)



Energy spectrum & mass composition model

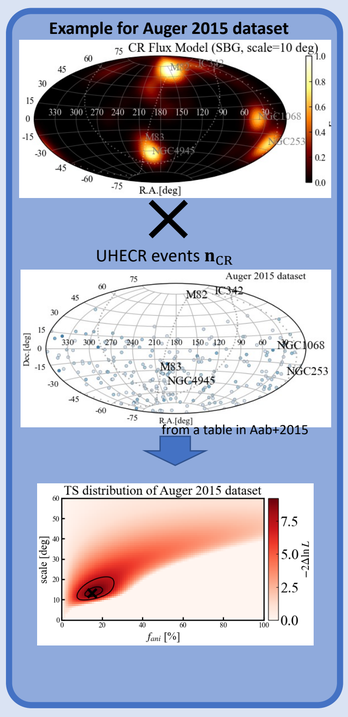


(Heinze & Fedynitch 2019)

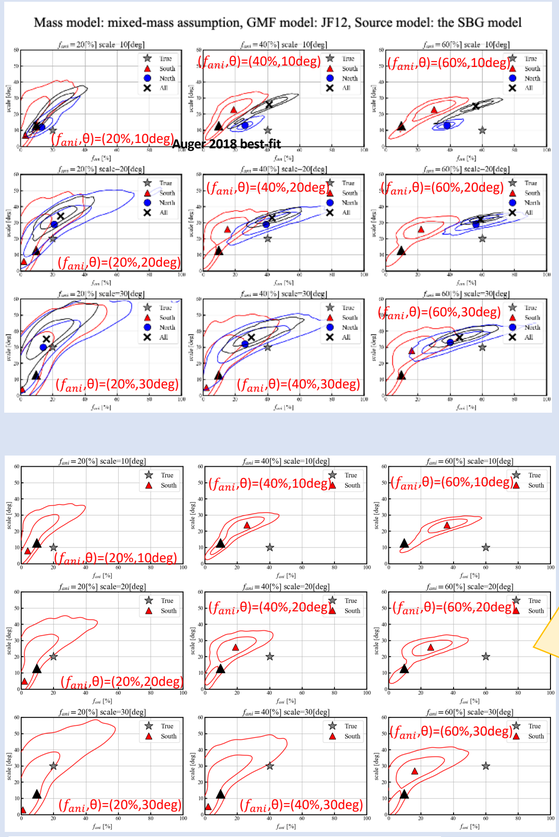
We generate MC datasets with coherent deflection caused by the GMF. 4000events from CR flux models(**all-sky**)
4000events × 1000datasets
We assume the energy spectrum & mass composition (Heinze & Fedynitch 2019)
Comparison with observation:
Selection of datasets with sky coverage of TA/Auger(**north-sky/south-sky**) (ref: Sommers 2001).
~1000events out of. $N_{\rm tot}$=4000 events for north/south-sky dataset

Analysis

- Parameters:
  - **anisotropic fraction $f_{\rm ani}$:** the fraction of all events due to sources
  - **smearing angle θ:** Gaussian smearing around the point sources
- Maximum-likelihood method :
  - likelihood: $L(F_{\rm norm}) = \prod_{\rm CR} \frac{F_{\rm norm}(\mathbf{n}_{\rm CR})*\omega(\mathbf{n}_{\rm CR})}{\int_{4\pi} F_{\rm norm}(\mathbf{n})*\omega(\mathbf{n})d\Omega}$
  - CR flux pattern from the source(SBG model)+isotropic flux:
    - $F_{\rm norm}(\mathbf{n}_{\rm CR}, f_{\rm ani}, \theta) = f_{\rm ani} * F'_{\rm org}(\mathbf{n}_{\rm CR}) + (1-f_{\rm ani}) * F_{\rm iso}$,
      - $F'_{\rm org} = \frac{F_{\rm org}(\mathbf{n}_{\rm CR})}{\int_{4\pi} F_{\rm org} d\Omega}$ and $F_{\rm iso} = 1/4\pi$
      - $F_{\rm org}(\mathbf{n}_{\rm CR}) = \frac{\sum_i f_i \exp(\mathbf{n}_i \cdot \mathbf{n}/\theta^2)}{\int_{4\pi} \sum_i f_i \exp(\mathbf{n}_i \cdot \mathbf{n}/\theta^2) d\Omega}$
      - $\mathbf{n}_{\rm CR}$: arrival direction of UHECR events
  - test statistics (TS): $TS = 2\ln(L(F_{\rm norm})/L(F_{\rm iso}))$
- **Auger collaboration 2018(ApJL, 853, L29)：**
  - nearby 23 SBGs × Auger UHECR events
  - >39 EeV
  - best-fit：(f_{ani},$\boldsymbol{\theta}$)=(9.7%,12.9deg)



Results



Estimation of the bias caused by the GMF

The anisotropic fraction f_{ani} is estimated lower.
In case with heavier single-mass composition, f_{ani} becomes lower.

Most-frequent values of estimated parameters in all-/north-/south-sky datasets do not agree.

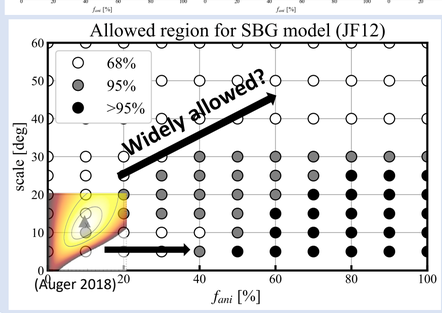
In some true parameters, estimated contour for south-sky includes the Auber best-fit (f_{ani},$\boldsymbol{\theta}$)=(9.7%,12.9deg)?

Reproduction the best-fit in Auger 2018

We only focus on the south-sky.

Generation of mock Auger 2018 datasets (894 events in south-sky × 4000 datasets)

Select the true parameters whose estimated contour includes the best-fit parameter (f_ani,θ)=(9.7%,12.9deg)

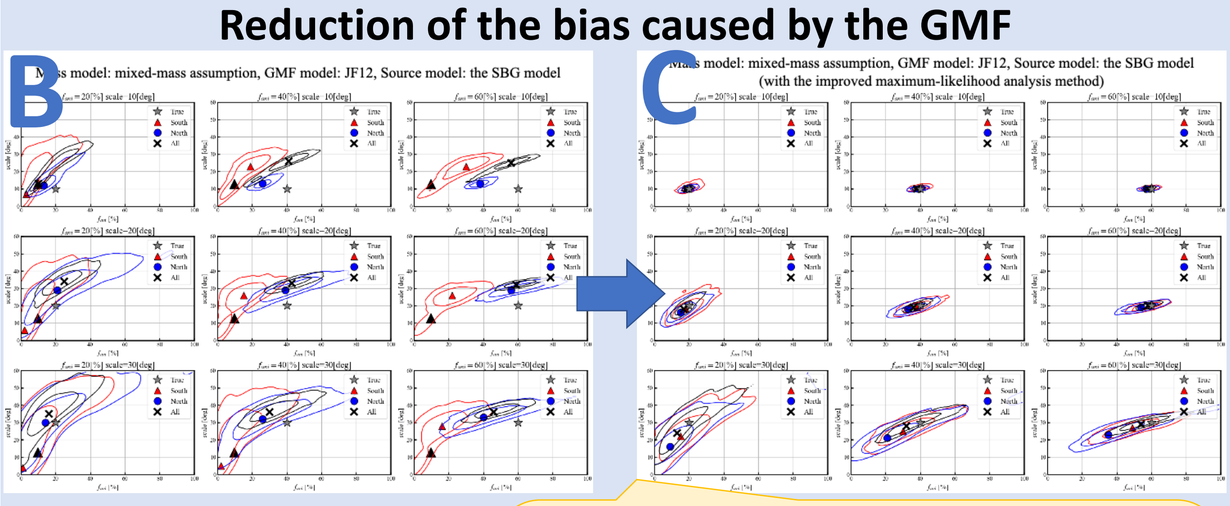


Allowed parameter to reproduce the best-fit parameter in Auger 2018.

Except for a narrow region with an extremely large f_{ani} and small scale $\boldsymbol{\theta}$, the SBG model is allowed in a wide region with 95% C. L

Discussion

Reduction of the bias caused by the GMF



We change the CR flux model (from w/o GMF to w/ GMF) in the estimation.

Most frequent parameters are well estimated.

Process:

$$F'_{\rm org}(\mathbf{n}_{\rm CR}) \Rightarrow F'_{\rm earth}(\mathbf{n}_{\rm earth}, R) = \frac{F_{\rm earth}(\mathbf{n}_{\rm CR})}{\int_{4\pi} F_{\rm earth} d\Omega}$$

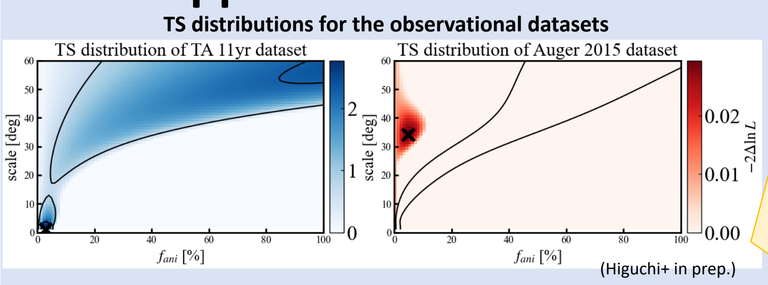
$$F_{\rm earth}(\mathbf{n}_{\rm earth}, R) = F_{\rm org}(A_{\rm BT}(\mathbf{n}_{\rm earth}, R))$$

$$\mathbf{n}_{\rm org} = A_{\rm BT}(\mathbf{n}_{\rm earth}, R)$$

$A_{\rm BT}$: **backtracking calculation**

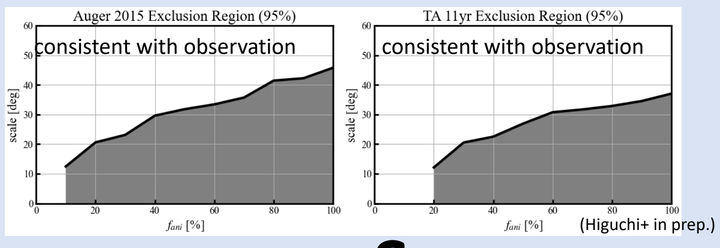
Application to the observational datasets

TS distributions for the observational datasets



(Higuchi+ in prep.)

Allowed region on the SBG model



(Higuchi+ in prep.)

We don't know event by event mass
=>With assumption of mass composition model, we weight TS calculation

Low TS to separate to SBG model/isotropic model
=> search for consistent parameter space with observation

Summary

Take home message:

GMF does affect the correlation study of UHECR anisotropy!

higher-mass composition => more isotropic

limitation of sky coverage for each experiment also affects

To do next:

The necessity to conduct a correlation study with all-sky observational datasets & GMF models =>TA/Auger-combined dataset

GMF model dependence (PT11 etc.) & mass model dependence

Suggestion for **the new source model** (which fits both TA & Auger datasets better)