PIERRE AUGER OBSERVATORY

Teresa Bister
for the Pierre Auger Collaboration

ICRC 2021, Berlin / Online

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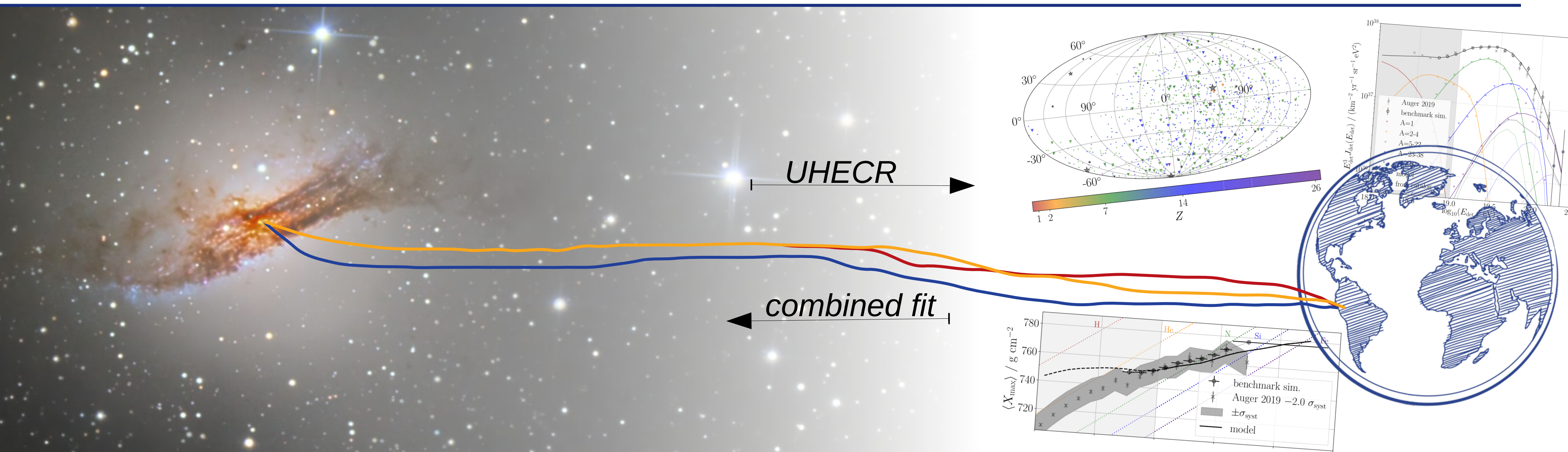
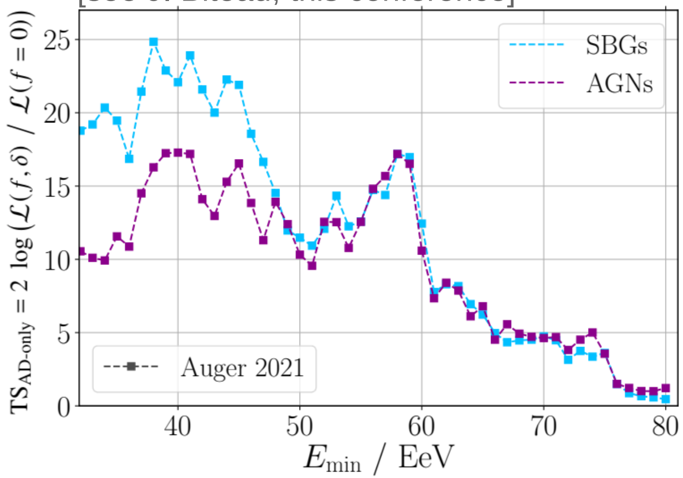
A combined fit of **energy spectrum, shower depth distributions** and **arrival directions**
to constrain models of UHECR sources



Introduction

- UHECR flux ↔ correlation with **catalogs of starburst galaxies (SBGs) / active galactic nuclei (AGNs)**
  → $\sigma_{SBG} = 4.0$, $\sigma_{AGN} = 3.1$, $E \gtrsim 38$ EeV

[see J. Biteau, this conference]



- **likelihood** analysis:

catalog model *background model (isotropy)*

$$\log \mathcal{L}_{\text{AD-only}}(f,\delta) = \sum_i \log\left(\boxed{f}\cdot \boxed{S}_{\boxed{\delta}}(\vec{v}_i) + (1-f)\boxed{B}(\vec{v}_i)\right)$$

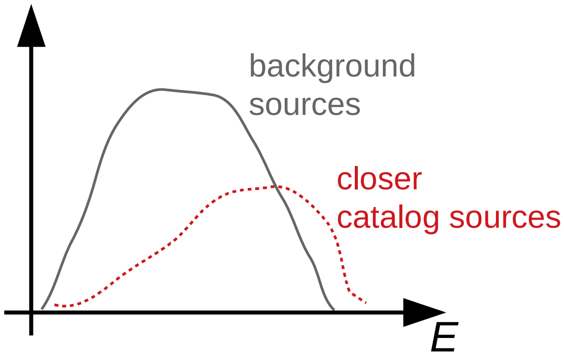
only arrival directions *signal fraction* *Fisher smearing*

but: **only with arrival directions no clear distinction possible** (similar source directions)

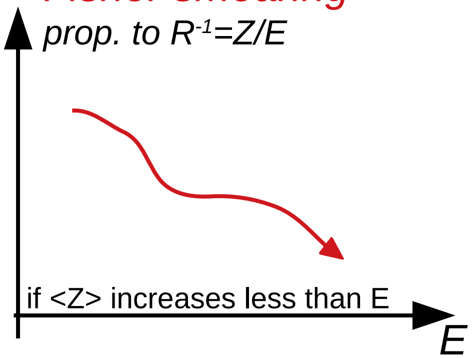
→ **combined fit of energy, shower depth Xmax & arrival directions**

- include **energy spectrum & Xmax as observables**
- describe **energy dependency** of catalog contribution & Fisher smearing

contribution

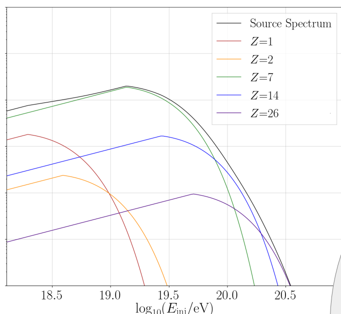


Fisher smearing



Universe model setup

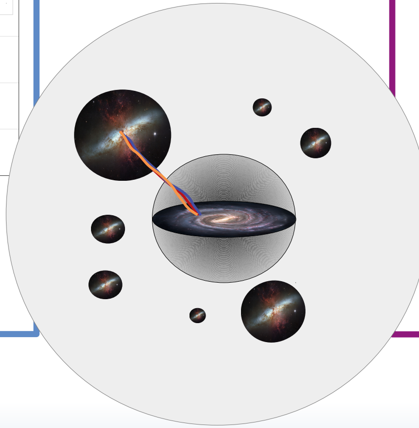
- **homogeneous background**
  - with source evolution ~$(1+z)^m$
  - isotropic arrival directions
- **catalog sources: SBGs / AGNs**
  - flux weight & distance considered
  - arrival directions
    ~ rigidity-dependent Fisher
- **injection:** power law + exp. cutoff
  - spectral index γ, rigidity cutoff R_{cut}, element fractions $a_{[H, He, N, Si, Fe]}$

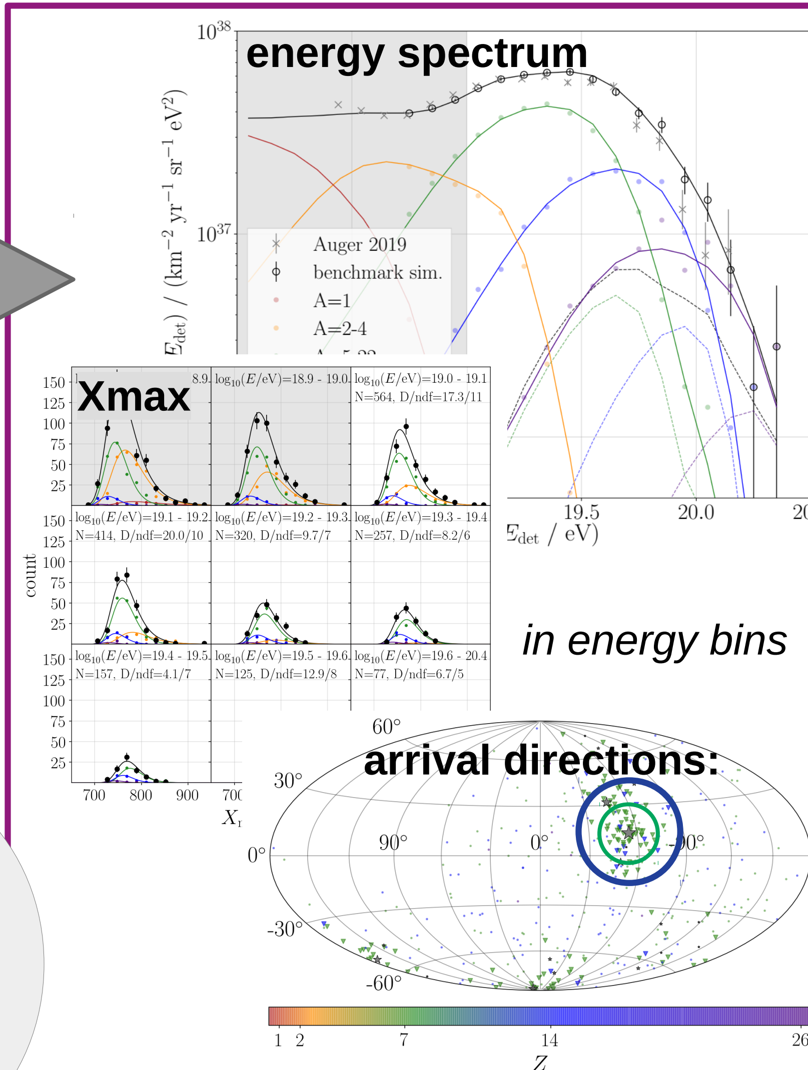


add above $10^{18.7}$ eV:
f_0 * catalog+ ($1-f_0$) * background

propagation

1d **CRPropa3** simulations
+
reweighting

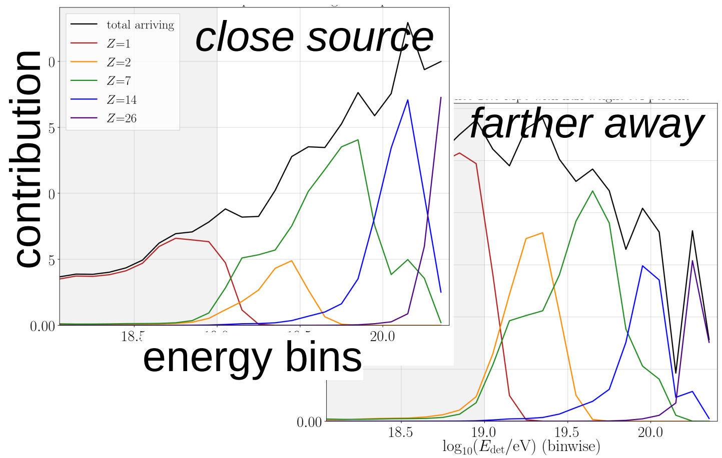




From injection to energy-dependent arrival directions

- calculate **source contribution for each energy bin e**

  depending on: flux weight, exposure, distance
  injection + propagation
  (1d CRPropa3 simulations)



- build **pdfs for arrival distributions in energy bins *e*:**

$$\mathrm{pdf}_e = \boxed{f_S(f_0, E^e_{\rm det})} \cdot \boxed{S}\left(E^e_{\rm det}, \boxed{\delta_S(E^e_{\rm det})}\right) + (1 - f_S(f_0, E^e_{\rm det})) \cdot \boxed{B}$$

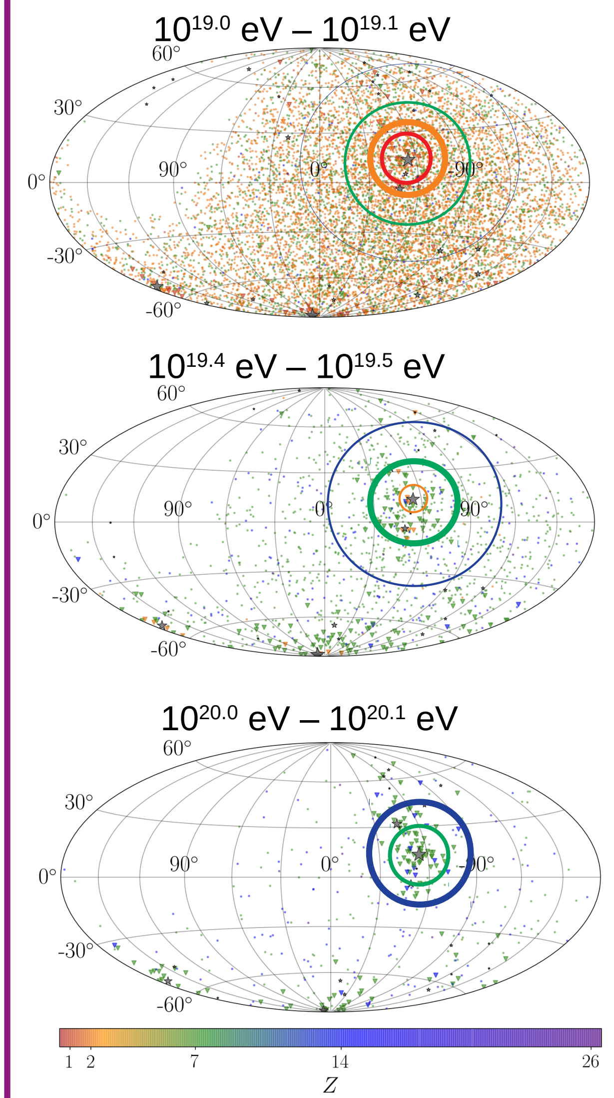
signal contribution:
depends on propagation,
source distribution

Fisher smearing for each source
& each arriving element with:

$$\delta_S = \delta_0 \, Z_{\rm det} \, \frac{10 \text{ EeV}}{E_{\rm det}}$$

- **one fully energy-dependent universe model:**
  - E, Xmax, ADs: information about source distribution
  - E-dependency of smearing & signal fraction: 2 fit parameters $\boldsymbol{\delta_0}$, $\mathbf{f_0}$

  → increased sensitivity to distinguish source models

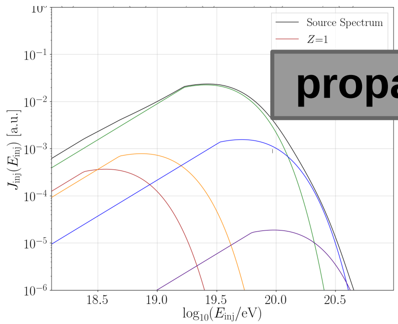


Fit method overview

Universe model setup:

injected spectrum:

γ, R_{cut}, a_i

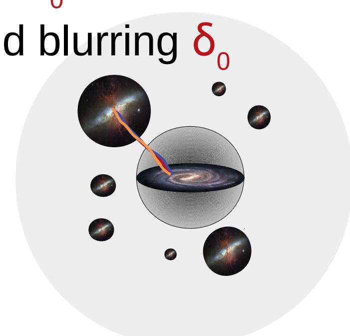


propagation

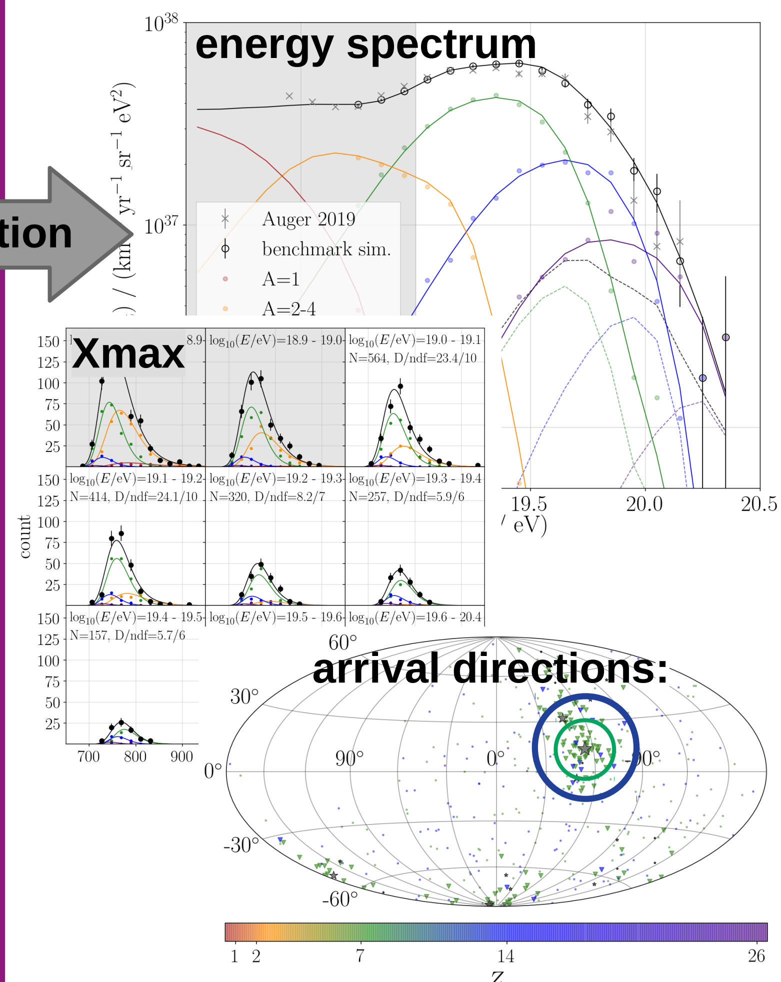
3d setup:

signal fraction f_0,

magnetic field blurring δ_0



Simulated observables:



compare to data via Likelihood:

spectrum: Poissonian

$$\mathcal{L}_E = \prod_e \frac{(p^e)^{k^e}}{k^e!} \exp(-p^e)$$

Xmax: Multinomial

$$\mathcal{L}_{\text{Xmax}} = \prod_{\tilde{e}} k^{\tilde{e}}! \prod_x \frac{(G^{\tilde{e},x})^{k^{\tilde{e},x}}}{k^{\tilde{e},x}!}$$

arrival directions: compare to modeled arrival pdf

$$\mathcal{L}_{\text{AD}} = \prod_e \prod_{i \in e} \text{pdf}_e(\vec{v}_i)$$

from:
Auger Combined Fit
Auger ADs comparison to astrophysical catalogs

adjust parameters

γ, R_{cut}, a_i, f_0, δ_0

Benchmark simulation: starburst galaxies + background

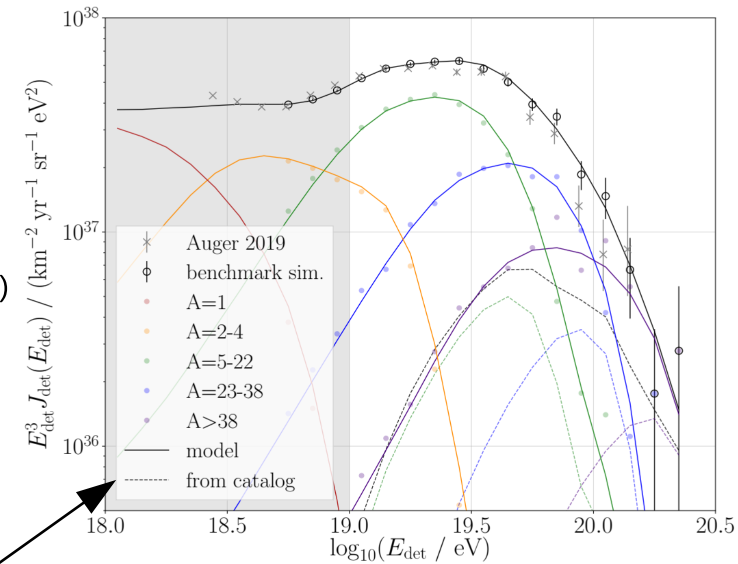
- **from fit of *E* + Xmax on Auger data** *(backup)*
  with source evolution = **star formation rate (*m=3.4*)**

γ	$\log_{10}(R_{\mathrm{cut}}/V)$	a_{H}	a_{He}	a_{N}	a_{Si}	a_{Fe}	$\nu_{X_{\max}}/\sigma$	ν_{E}/σ
−0.65	18.29	23%	2%	70%	4.0%	0.15%	−2.0	0.0

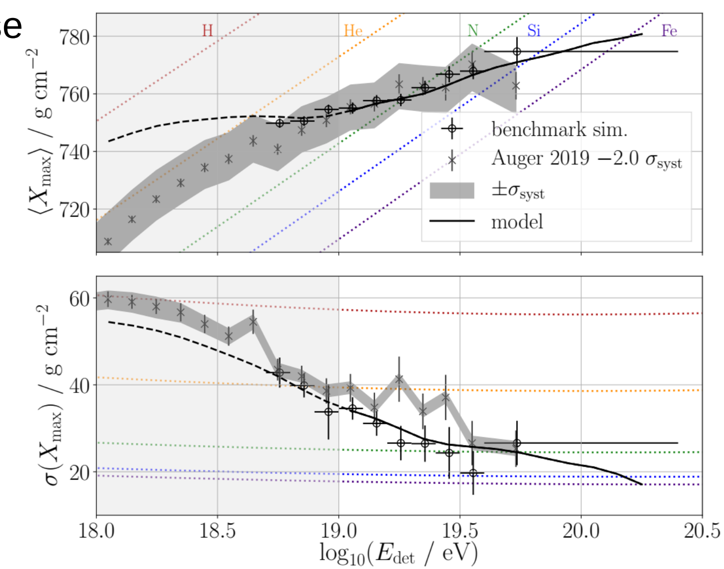
systematic scale shift

  - add f_0 = 1.2% signal fraction from **SBG catalog** (def. > $10^{18.7}$ eV = 5 EeV)
  - magnetic blurring δ_0 = 14.3° (for R = 10 EV)

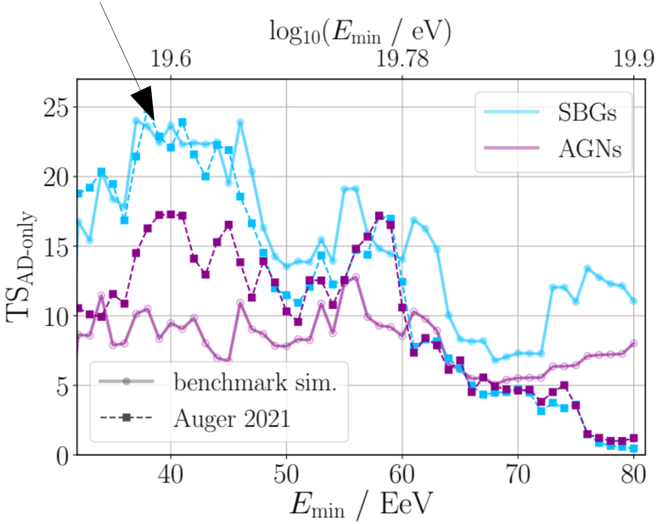
- **spectrum, composition, arrival directions, N_{CRs}**
  ≃ Auger measurements

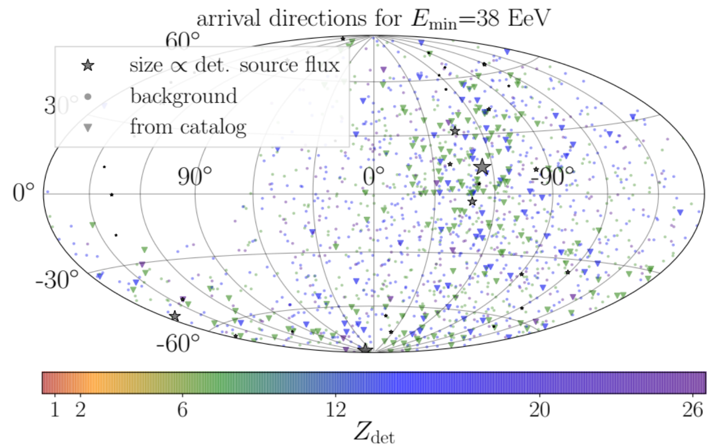


catalog contribution $f_S(f_0, E^j_{\mathrm{det}})$ grows with energy: SBGs close



simulated ADs ≃ measured ones





Fit with reference models

reminder:
benchmark sim. contains
SBG catalog as input, m=3.4

Fit different models to simulation:

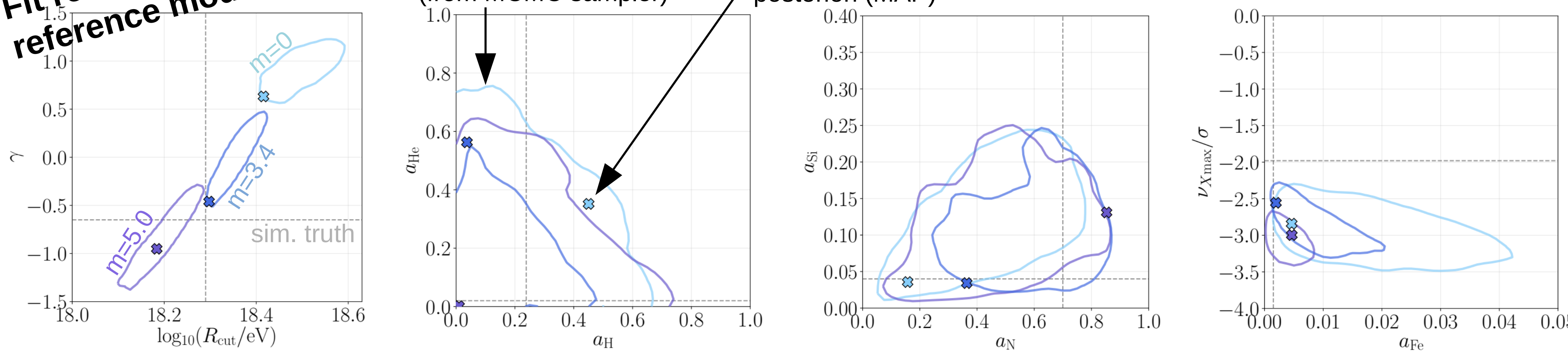
- → **SBG model**, m=3.4 *(= simulated truth)*
- → **AGN model**, m=3.4 / m=5.0
- → **reference model** (with f_0=0), m=0.0 / m=3.4 / m=5.0

⇨ **fit goal: identify best model = sim. truth**

Fit results using reference models:

90% confidence regions (from MCMC sampler)

maximum a posteriori (MAP)



source evolution-dependent correlation

light fractions below cutoff, not reconstructable

heavier fractions can be determined

Xmax scale shift correlated with composition

	D_E	$D_{X_{\max}}$	D_{total}
$m = 0$	6.0	82.1	88.1
$m = 3.4$	5.8	81.5	87.3
$m = 5.0$	12.9	84.0	96.9

→ **reference model with *true m=3.4*: lowest deviance**

→ **spectrum & Xmax well described even with only background sources**

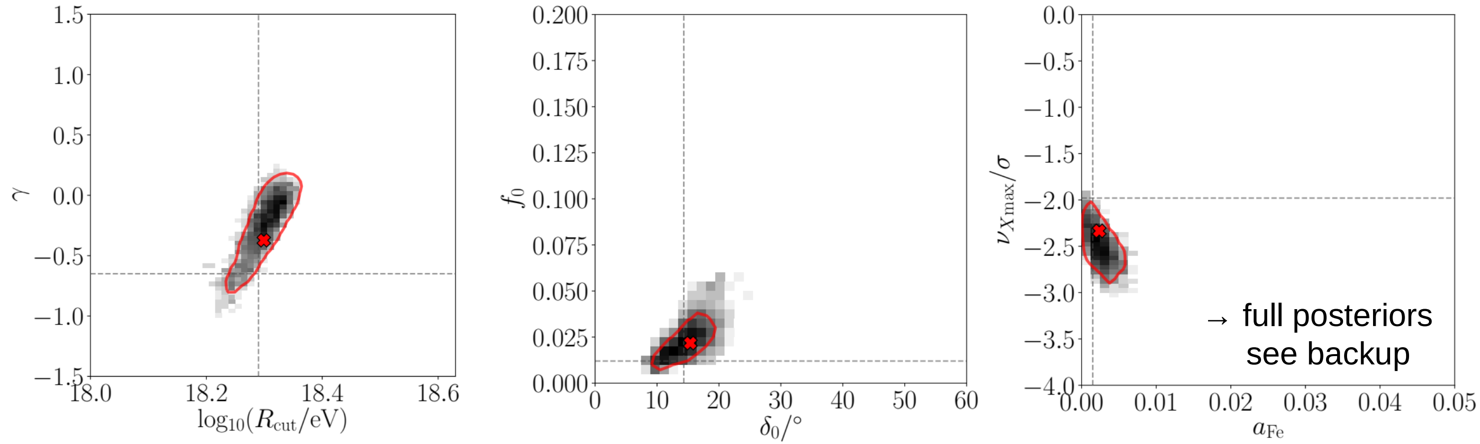
Fit with catalog models

reminder:
benchmark sim. contains
SBG catalog as input, m=3.4

SBG model (m=3.4)

= simulated truth

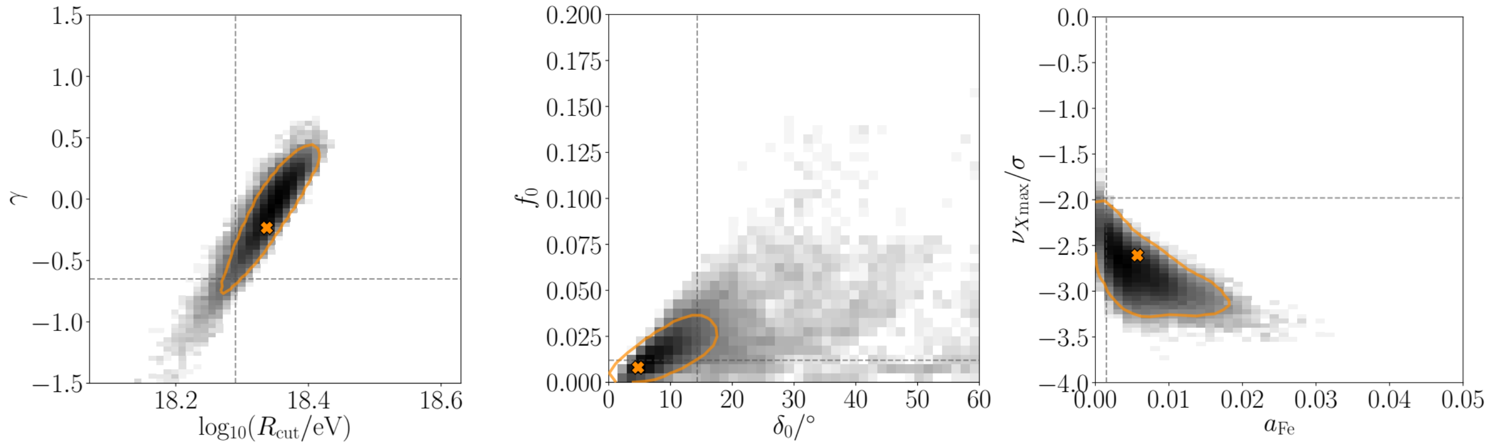
- parameters can be reconstructed well
- correlations visible ($\gamma \leftrightarrow R_{cut}$), ($f_0 \leftrightarrow \delta_0$)



as in: Auger Combined Fit, Auger ADs comparison to astrophysical catalogs

AGN model (m=3.4)

- larger uncertainties
- *true* simulated values still within uncertainties even for *false* AGN model
- best-fit (MAP) further away from truth



Fit with catalog models

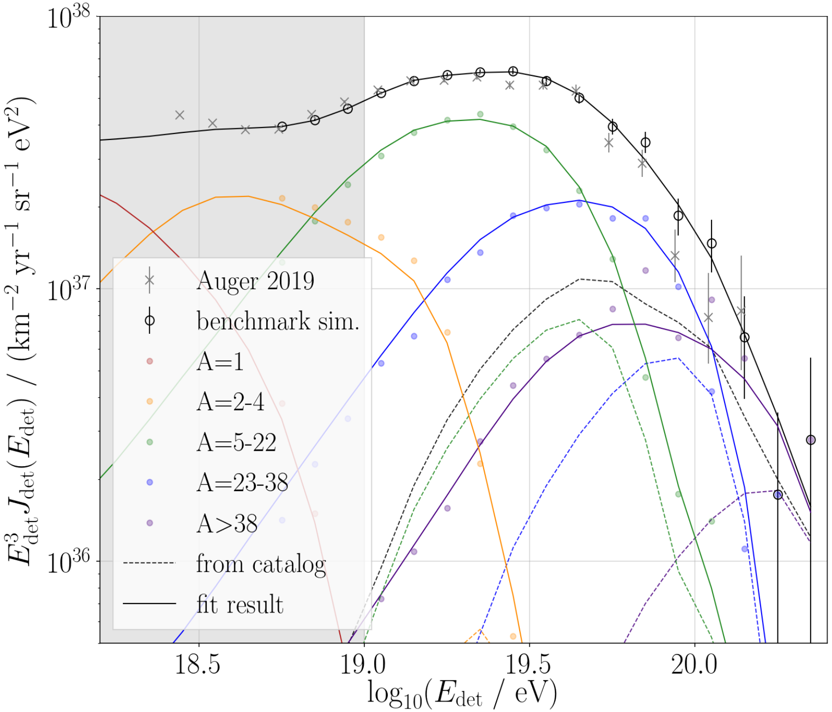
reminder:
benchmark sim. contains
SBG catalog as input, m=3.4

spectrum and composition
can be described by both models

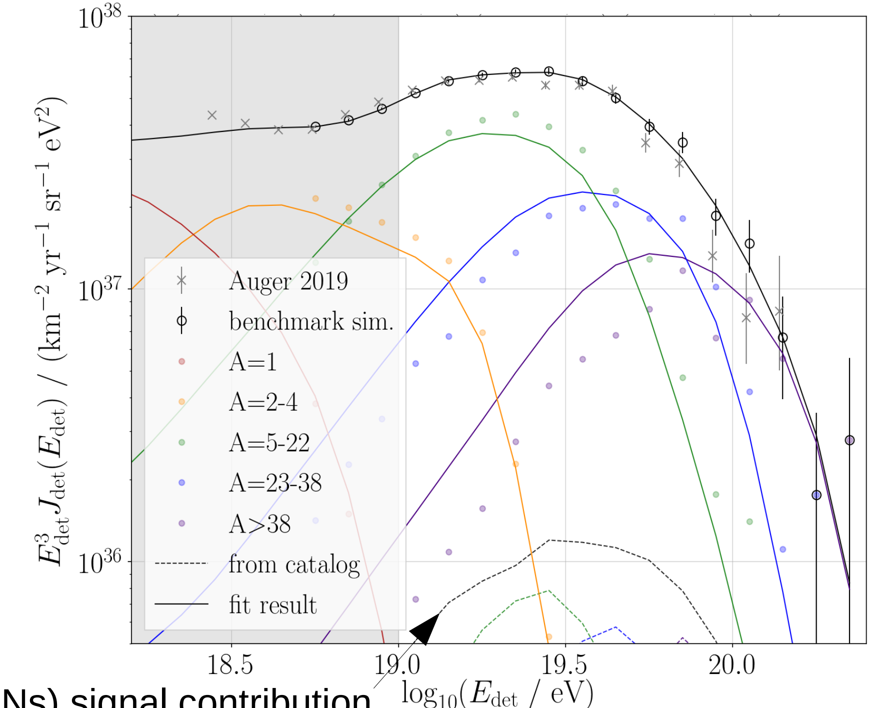
energy-dependent arrival directions not
described by *false* AGN model (directions, distances ↯)

	D_E	$D_{X_{\max}}$	D_{total}	$2\log\frac{\mathcal{L}_{\text{AD}}}{\mathcal{L}_{\text{AD}}^{\text{ref},m=3.4}}$	$2\log\frac{\mathcal{L}_{\text{sum}}}{\mathcal{L}_{\text{sum}}^{\text{ref},m=3.4}}$
SBG model ($m = 3.4$) → *sim. truth*	5.5	80.2	85.7	30.6	32.4
AGN model ($m = 3.4$)	6.0	81.8	87.8	11.2	10.8
AGN model ($m = 5.0$)	5.6	84.1	89.9	1.4	−1.0

SBG model



AGN model



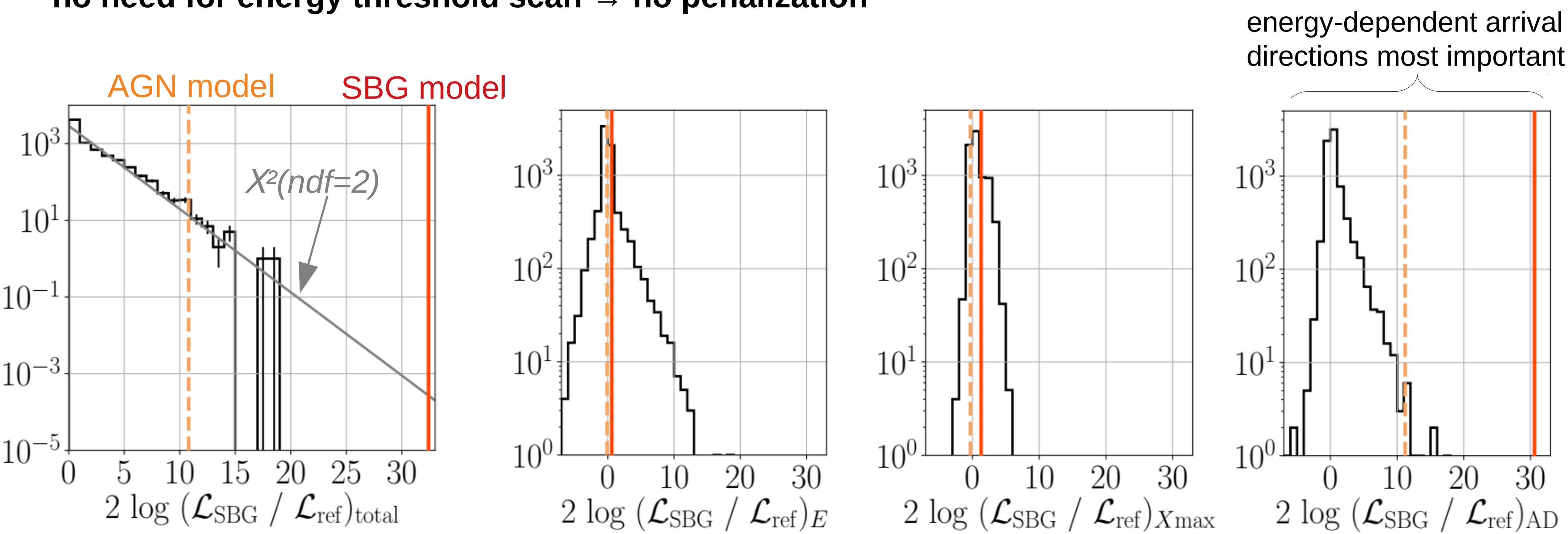
model (AGNs) signal contribution
energy dependency different from simulated input (SBGs)

Estimation of the significance

- apply analysis on **isotropic simulations** (*m=3.4*, benchmark simulation parameters)
- isotropy tail follows X^2 distribution with *ndf=2* (SBG model has 2 more fit parameters: f_0, δ_0)

→ $\boxed{p_{\mathrm{SBG}} \simeq 9 \cdot 10^{-8}}$ $\boxed{p_{\mathrm{AGN}} \simeq 5 \cdot 10^{-3}}$ → **analysis can identify true simulated SBG model**

- **more sensitive** than AD-only analysis on same simulation: $\boxed{p^{\text{AD-only, pre-trial}}_{\text{SBG}} \simeq 6.1 \cdot 10^{-6}}$ $\boxed{p^{\text{AD-only, pre-trial}}_{\text{AGN}} \simeq 1.7 \cdot 10^{-3}}$
- **no need for energy threshold scan → no penalization**



Conclusions

- presented **combined fit including energy spectrum, Xmax distributions & energy-dependent arrival directions**
- on benchmark simulation (resembles Auger data):
  - source parameters can be reconstructed including uncertainties
  - additionally determine **energy-dependent signal contribution and magnetic field smearing**
  - **enhanced sensitivity** compared to arrival directions-only analysis
  - simulated input catalog & source evolution can be identified

$p_{\mathrm{SBG}} \simeq 9 \cdot 10^{-8}$ $p_{\mathrm{AGN}} \simeq 5 \cdot 10^{-3}$

	D_E	$D_{X_{\max}}$	D_{total}	$2\log\frac{\mathcal{L}_{\mathrm{AD}}}{\mathcal{L}_{\mathrm{AD}}^{\mathrm{ref},m=3.4}}$	$2\log\frac{\mathcal{L}_{\mathrm{sum}}}{\mathcal{L}_{\mathrm{sum}}^{\mathrm{ref},m=3.4}}$
ref. model ($f_0 = 0$, $m = 0$)	6.0	82.1	88.1	0	−0.8
ref. model ($f_0 = 0$, $m = 3.4$)	5.8	81.5	87.3	0	0
ref. model ($f_0 = 0$, $m = 5.0$)	12.9	84.0	96.9	0	−9.6
SBG model ($m = 3.4$) $\longrightarrow$ *sim. truth*	5.5	80.2	85.7	30.6	32.4
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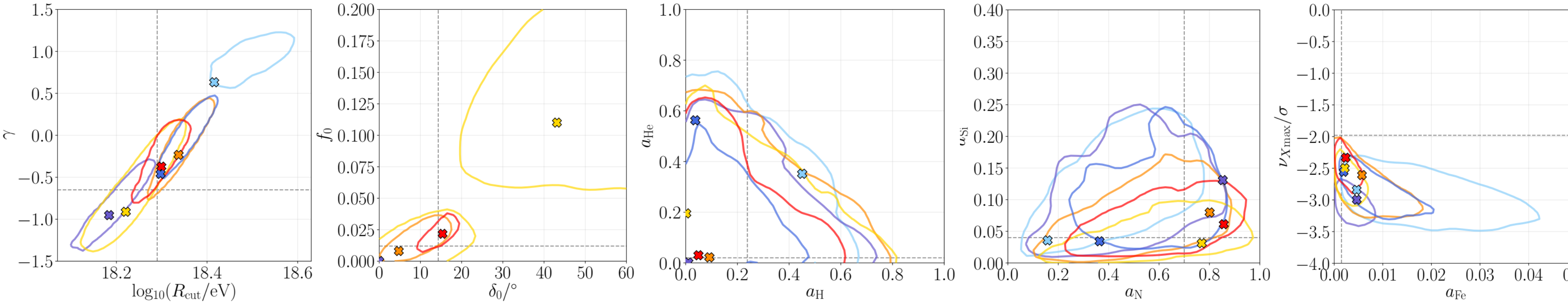


Backup

Signal contribution & smearing as a function of energy

pdfs are constructed via

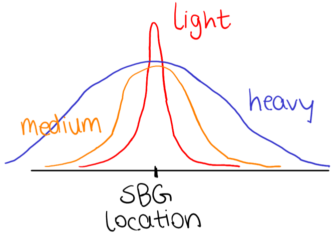
$$\mathrm{pdf}_e = \boxed{f_S(f_0, E^e_{\mathrm{det}})} \cdot S(E^e_{\mathrm{det}}, \boxed{\delta_S(E^e_{\mathrm{det}})}) + (1 - f_S(f_0, E^e_{\mathrm{det}})) \cdot B$$

signal contribution:
depends on propagation,
source distribution

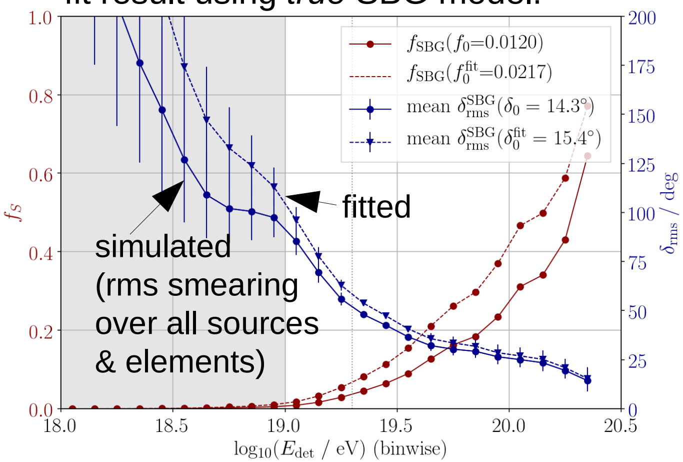
Fisher smearing for each source & each arriving element with:

$$\delta_S = \delta_0 \, Z_{\mathrm{det}} \, \frac{10\ \mathrm{EeV}}{E_{\mathrm{det}}}$$

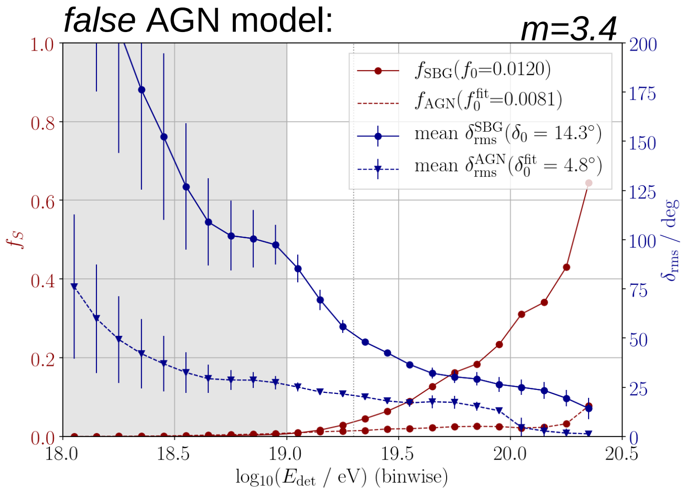
- other distances of AGNs: **different energy dependency of smearing & signal contribution**
- strong increase of signal contribution for SBGs not describable with AGN catalog
- need only 2 fit parameters:
  smearing of a R=10 EV particle & total signal fraction of complete data set E > $10^{18.7}$ eV
- even though total signal fraction f_0=1.2% is very small, at highest energies signal contribution $f_s(f_0)$ is large due to closeness of SBGs



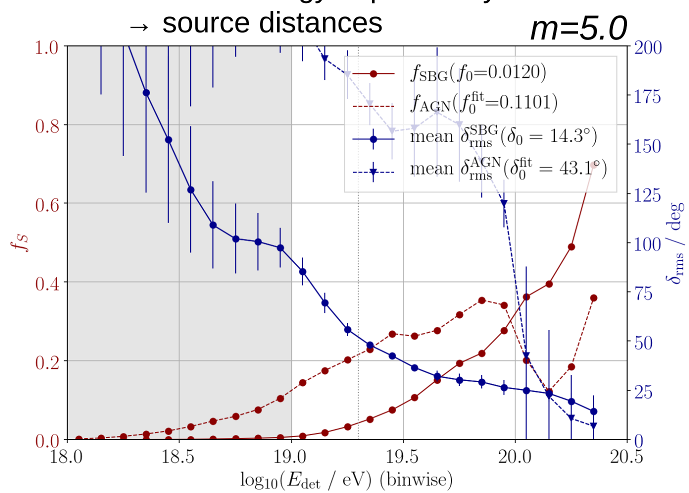
fit result using *true* SBG model:



false AGN model:

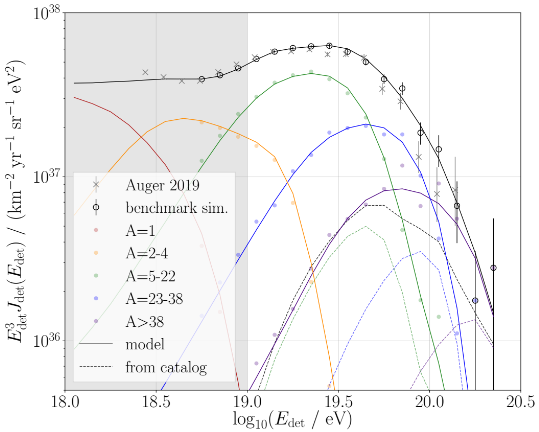


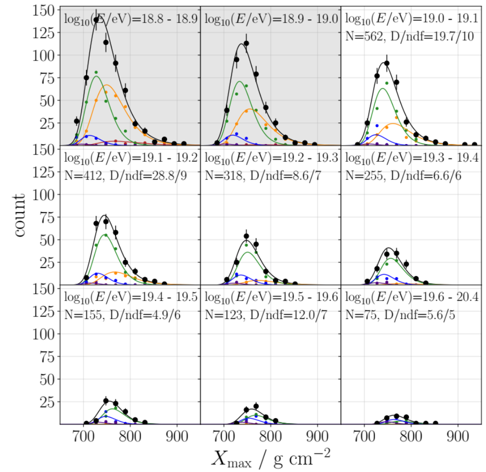
different energy dependency
→ source distances

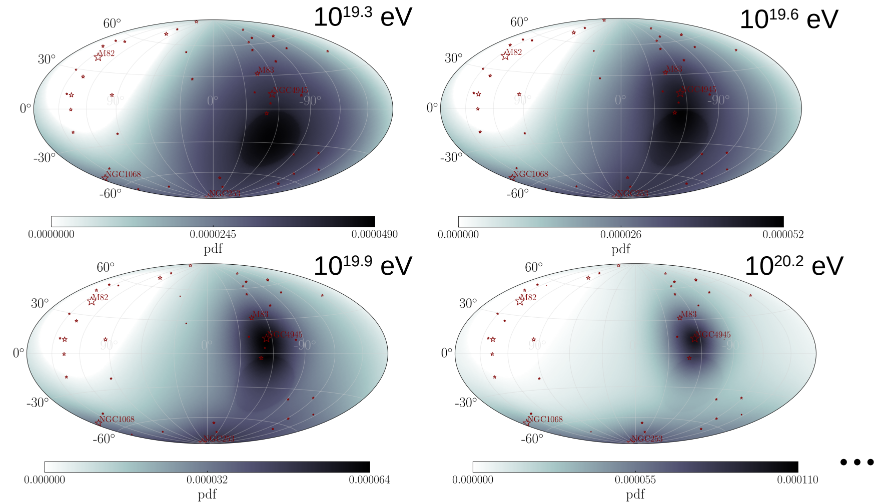


Energy thresholds used in the fit

benchmark simulation:



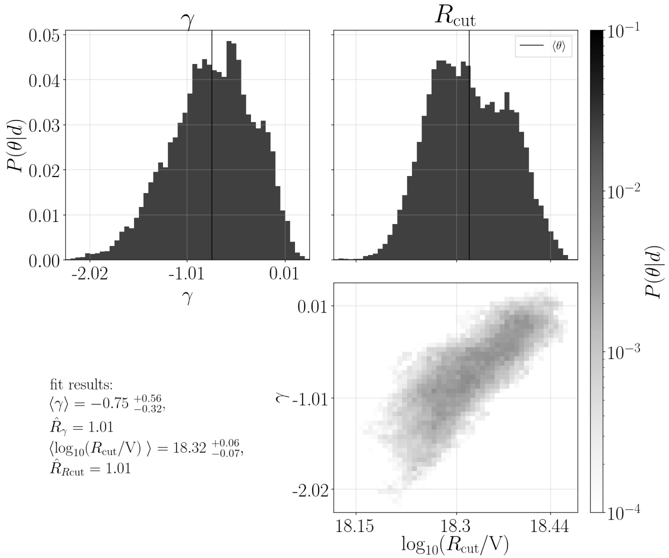




- **detected energy spectrum bins: [$10^{19.0}$, $10^{19.1}$, $10^{19.2}$… $10^{20.3}$, $10^{20.4}$] eV** *→ O(20,000 events)*
- **Xmax distribution bins: [$10^{19.0}$, $10^{19.1}$, $10^{19.2}$… $10^{19.6}$, $10^{20.4}$] eV** *→ O(2000) events*
  - similar to `Auger Paper`, but threshold moved from $10^{18.7}$ eV to $10^{19.0}$ eV because no below-ankle CRs wanted which may come from different source class
    → see E. Guido for the Pierre Auger Collaboration (this conference)
  - between $10^{18.7}$ eV and $10^{19.0}$ eV bins included in energy likelihood only if model overshoots data
- **arrival directions: [$10^{19.3}$, $10^{19.4}$, $10^{19.2}$… $10^{20.4}$] eV**
  - dipole not modeled in arrival directions, so higher energy threshold necessary
    → see R. Menezes for the Pierre Auger Collaboration (this conference)

Fit of the Auger ICRC 2019 data set > 10 EeV

→ with homogeneous reference model, m=3.4, Xmax & energy scale shift



MAP:

γ	$\log_{10}(R_{\mathrm{cut}}/V)$	a_{H}	a_{He}	a_{N}	a_{Si}	a_{Fe}	$\nu_{\mathrm{X_{max}}}/\sigma$	ν_{E}/σ
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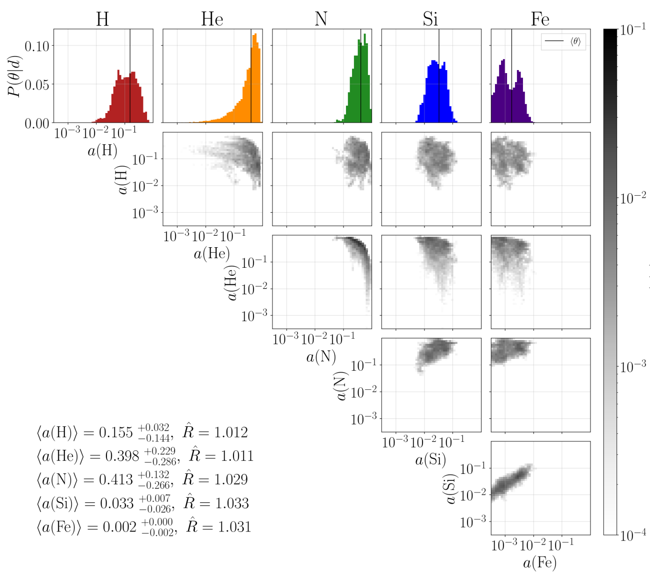
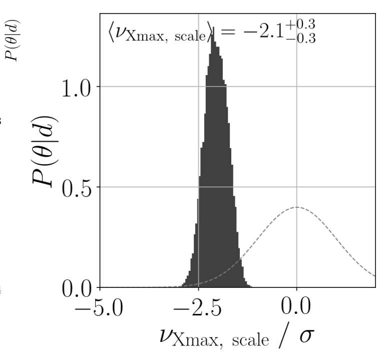
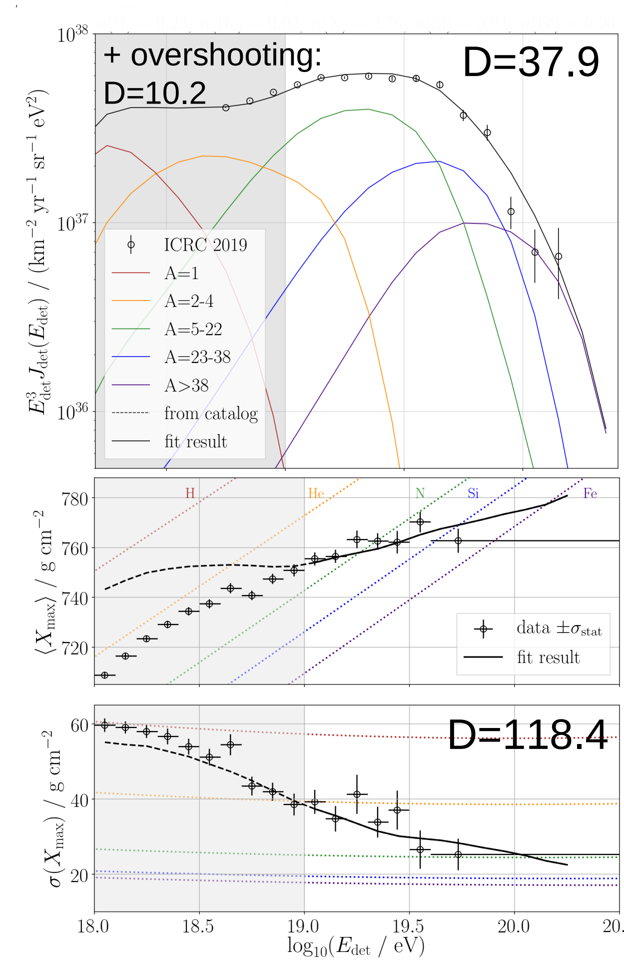
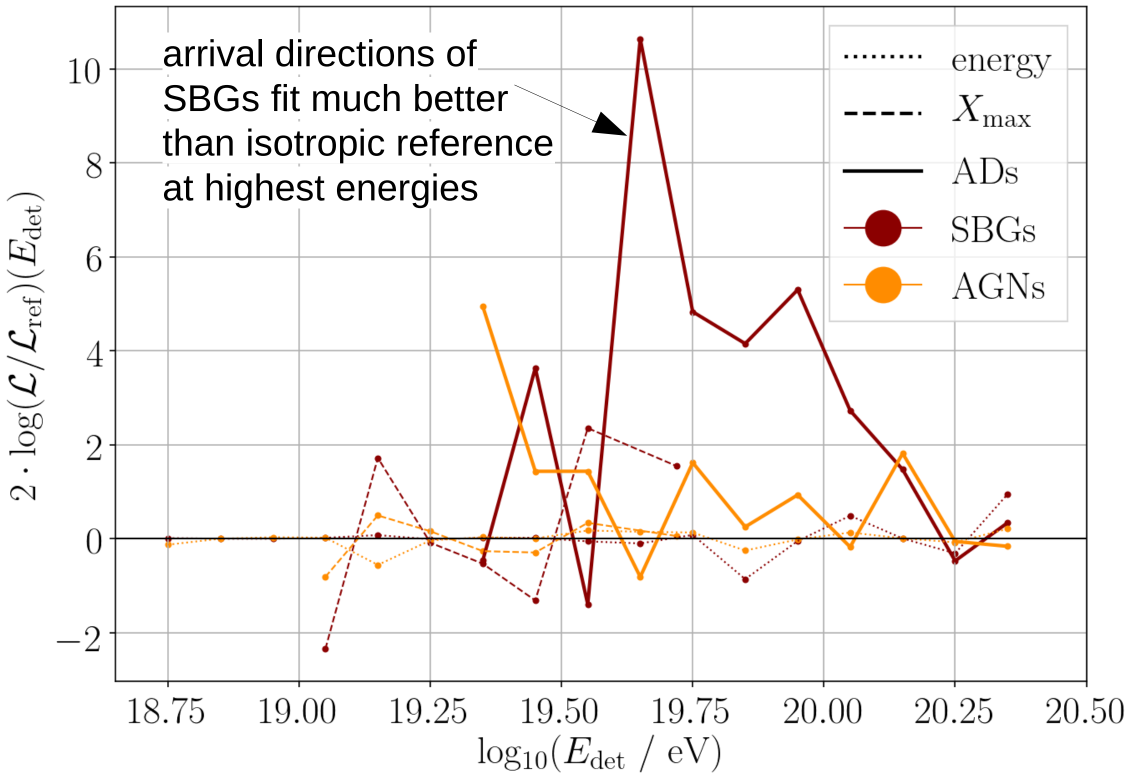






Energy dependency of the likelihood ratio



compare SBG model & AGN model with reference model (all m=3.4)

	D_E	$D_{X_{\max}}$	D_{total}	$2\log\frac{\mathcal{L}_{\mathrm{AD}}}{\mathcal{L}_{\mathrm{AD}}^{\mathrm{ref},m=3.4}}$	$2\log\frac{\mathcal{L}_{\mathrm{sum}}}{\mathcal{L}_{\mathrm{sum}}^{\mathrm{ref},m=3.4}}$
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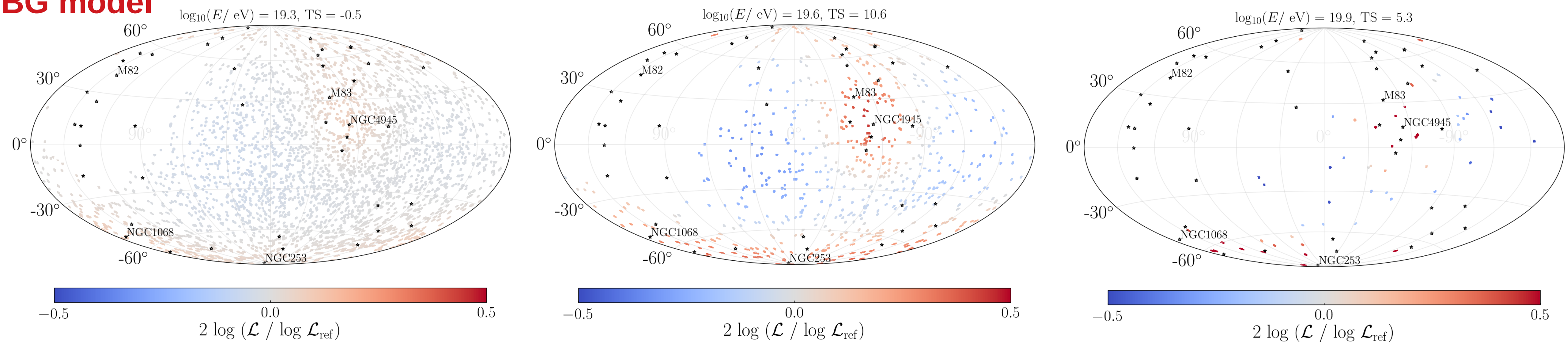
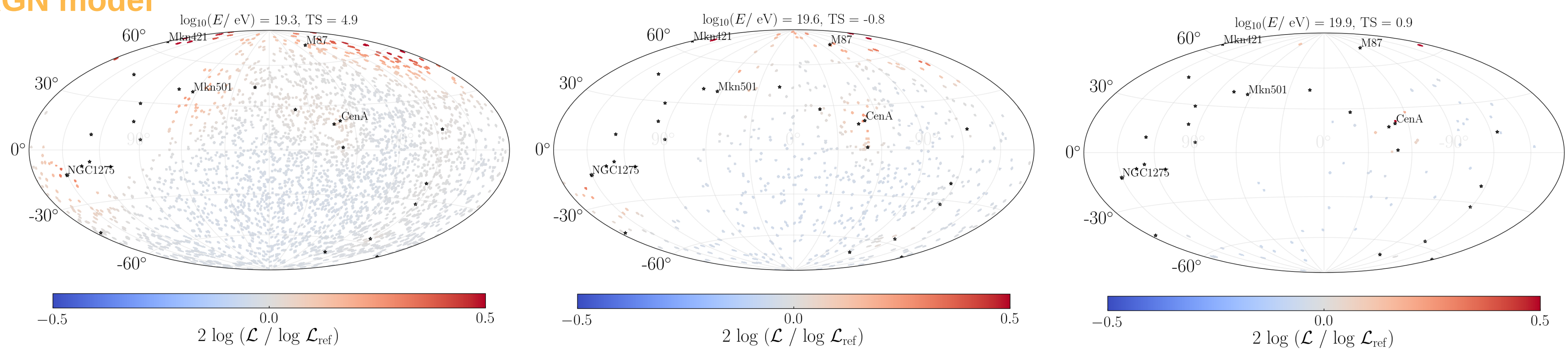
Arrival directions likelihood ratio of best-fit models

skymaps: show arrival direction pixels of benchmark simulation, colored as likelihood ratio between catalog (SBG / AGN) model and reference model (exposure).
Sum of likelihood ratio over all pixels given as TS (per energy bin), can be compared to slide 16

SBG model



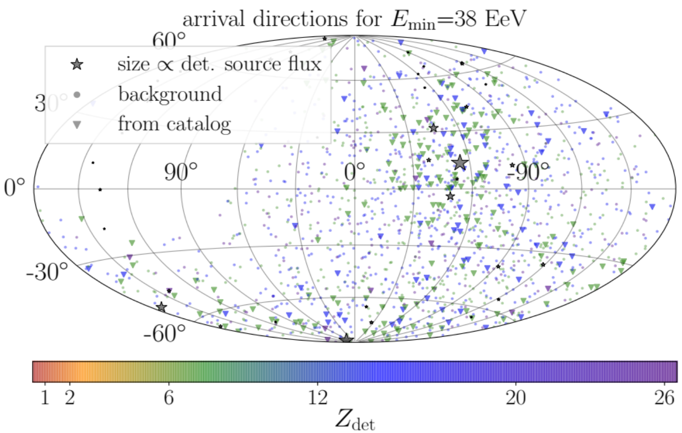
AGN model



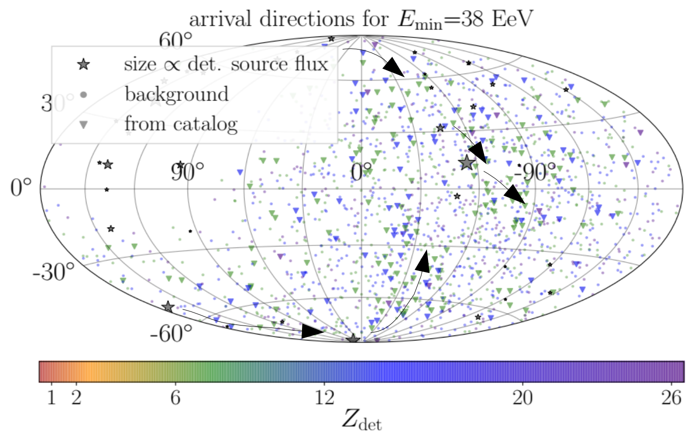
Influence of the Galactic magnetic field on the benchmark simulation

- same source parameters etc.
- test influence of deflections by JF12 magnetic field

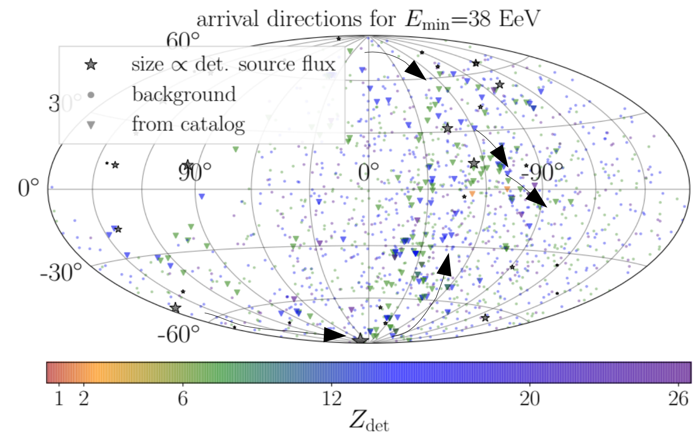
only turbulent smearing with δ_0=14.3° at R=1EV



turbulent smearing with δ_0=14.3° + JF12 regular



JF12 full (regular + turbulent + striated)

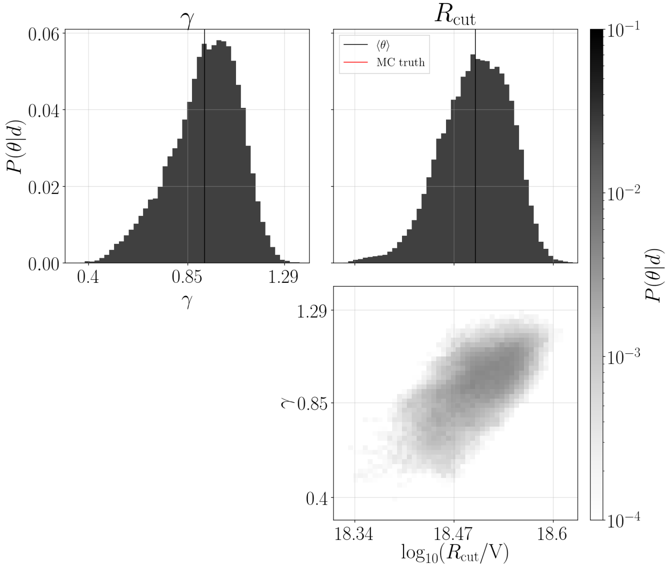


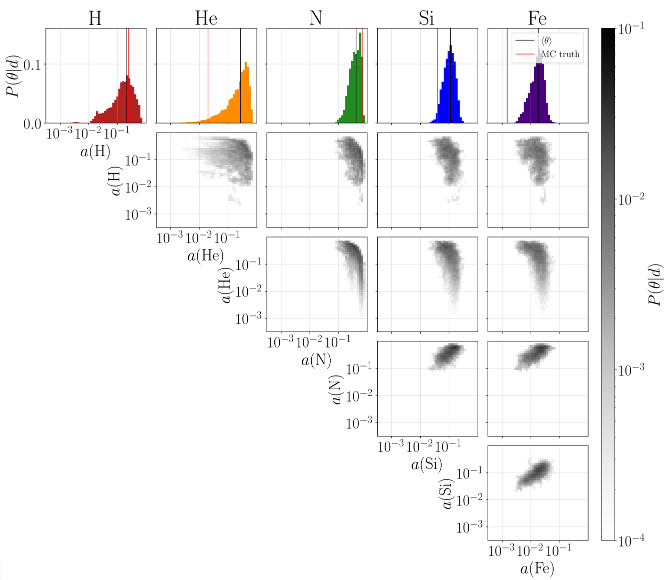
Fit results on benchmark simulation

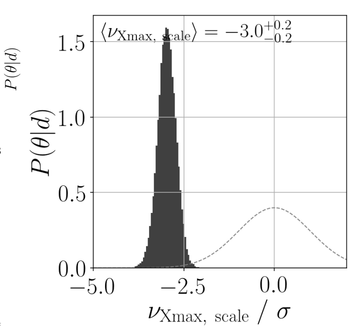
posteriors and fitted observables

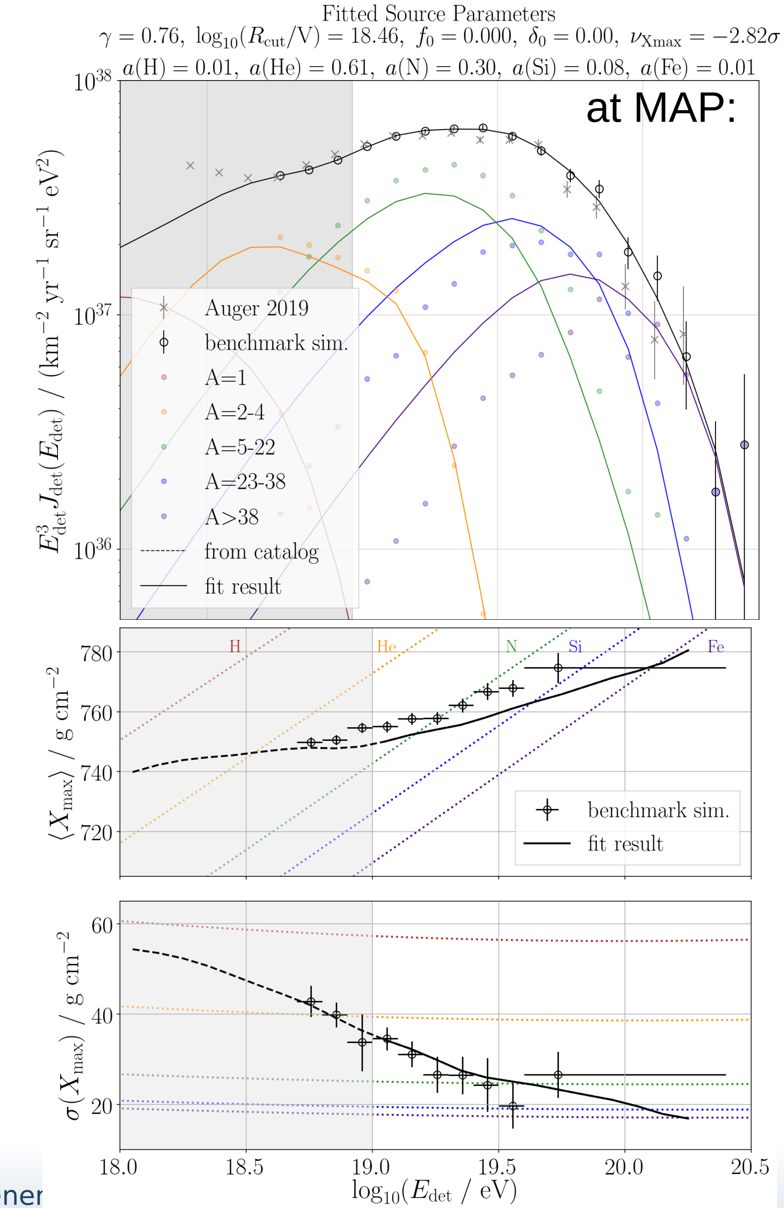
	D_E	$D_{X_{\max}}$	D_{total}	$2\log\frac{\mathcal{L}_{\text{AD}}}{\mathcal{L}_{\text{AD}}^{\text{ref},m=3.4}}$	$2\log\frac{\mathcal{L}_{\text{sum}}}{\mathcal{L}_{\text{sum}}^{\text{ref},m=3.4}}$
ref. model ($f_0 = 0, m = 0$)	6.0	82.1	88.1	0	−0.8
ref. model ($f_0 = 0, m = 3.4$)	5.8	81.5	87.3	0	0
ref. model ($f_0 = 0, m = 5.0$)	12.9	84.0	96.9	0	−9.6
SBG model ($m = 3.4$) $\rightarrow$ *sim. truth*	5.5	80.2	85.7	30.6	32.4
AGN model ($m = 3.4$)	6.0	81.8	87.8	11.2	10.8
AGN model ($m = 5.0$)	5.6	84.1	89.9	1.4	−1.0

Fit results: reference model (m=0.0)

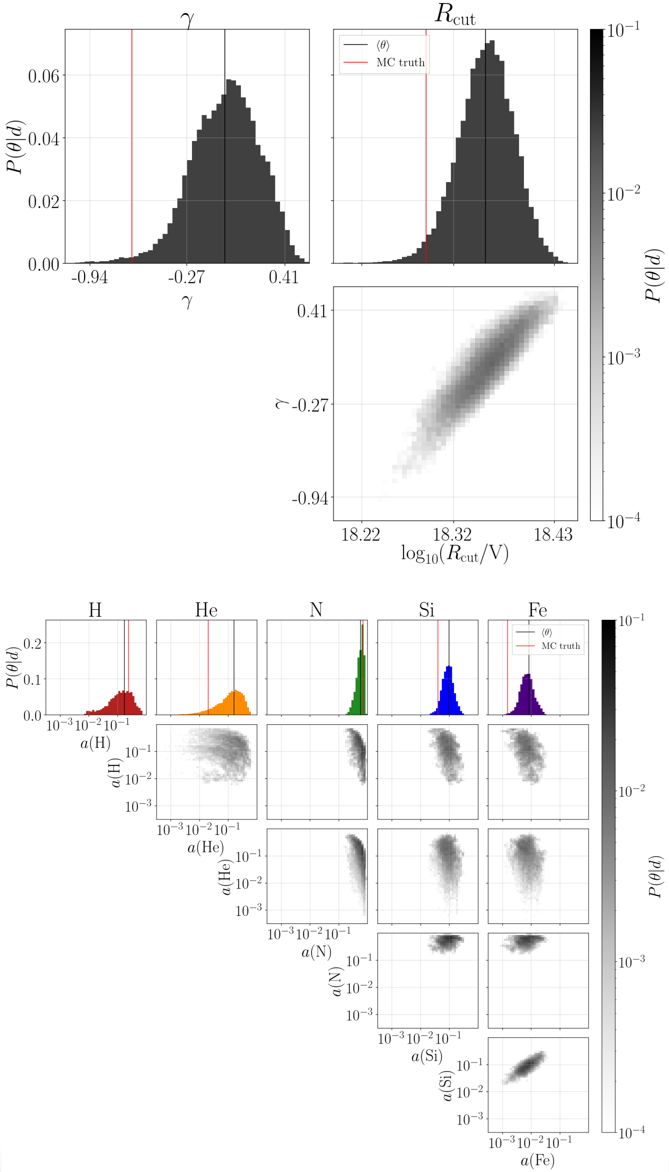


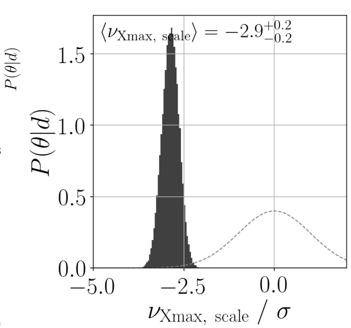


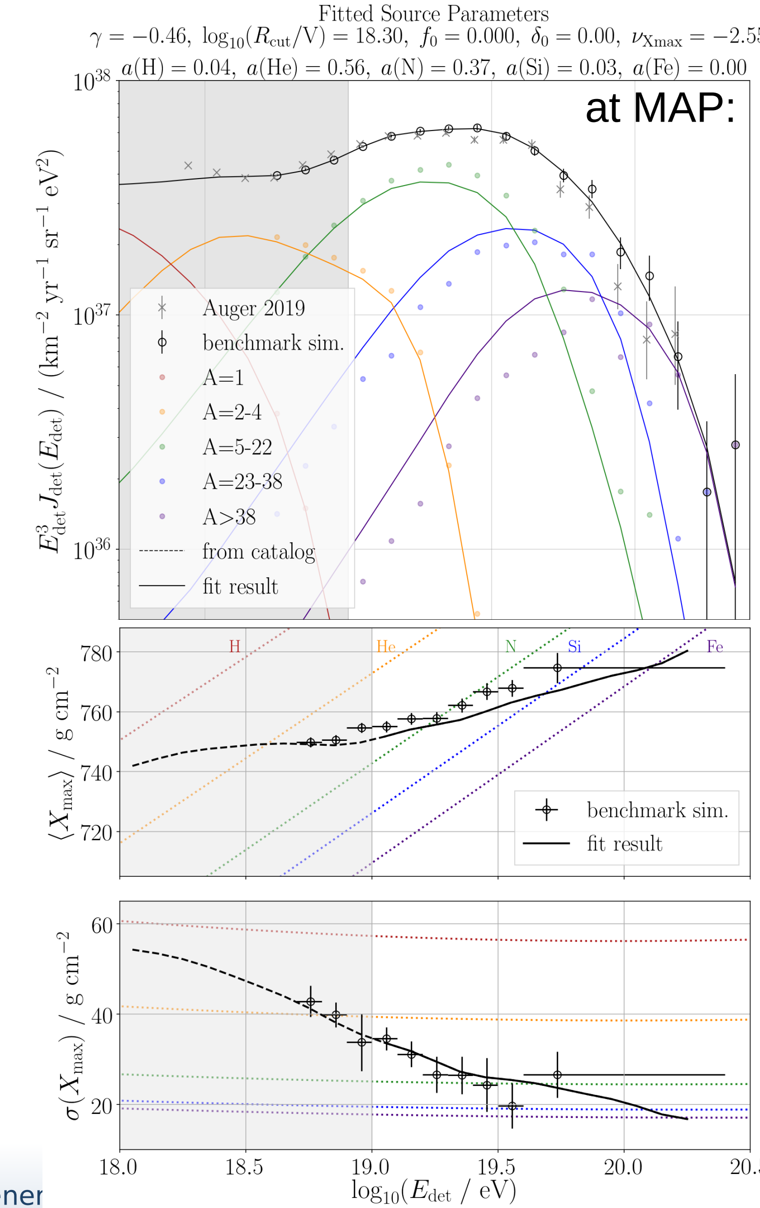




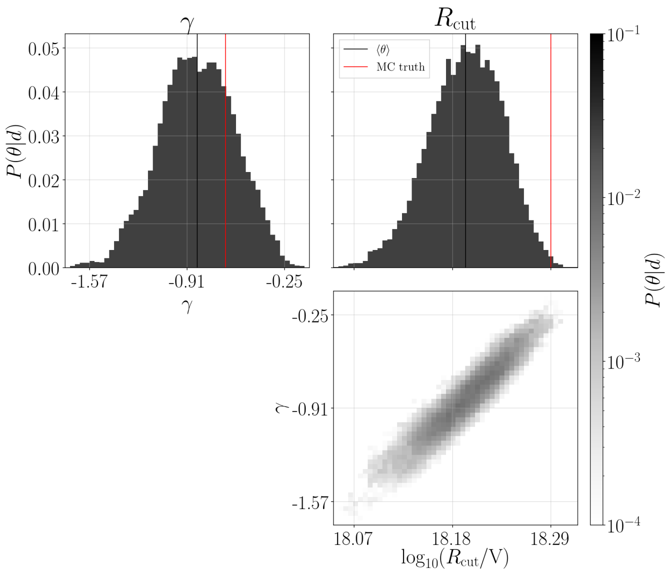
Fit results: reference model (m=3.4)

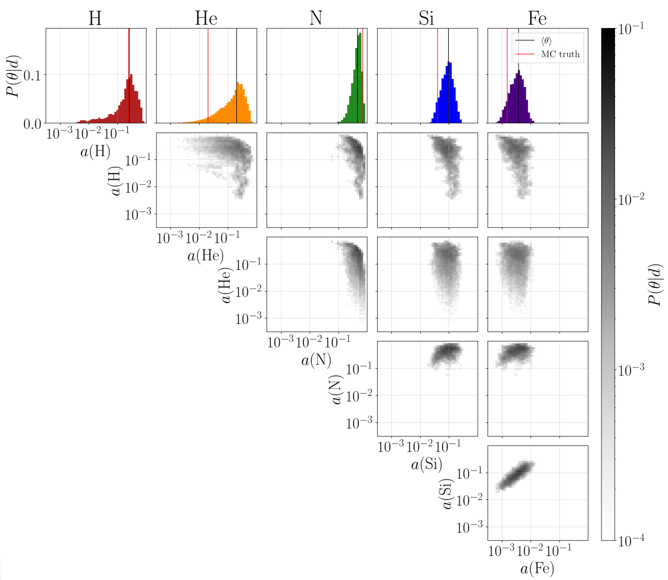


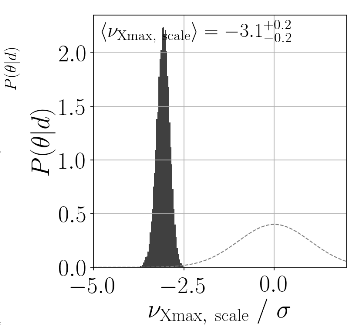


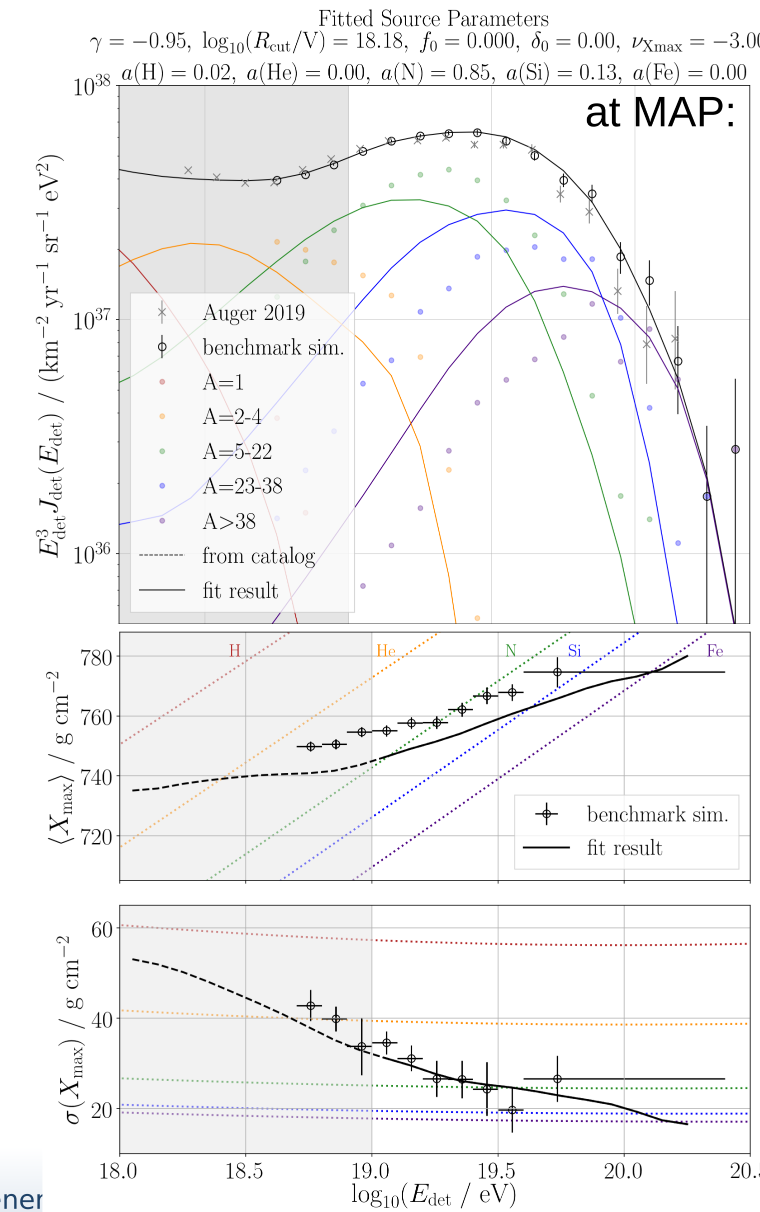


Fit results: reference model (m=5.0)

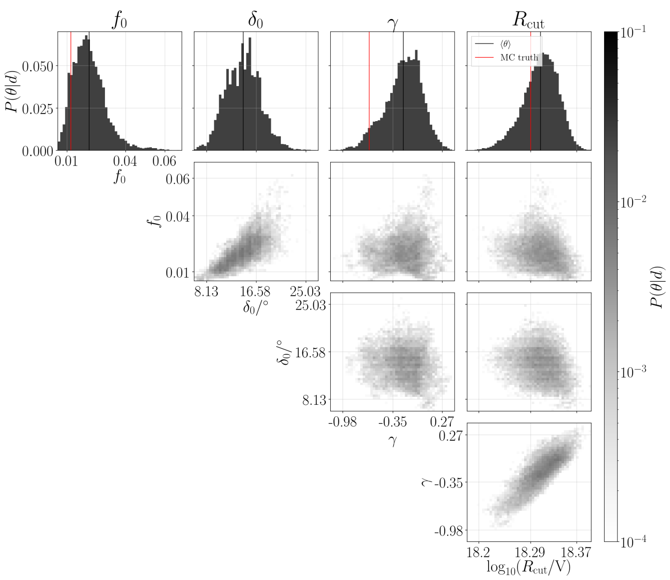


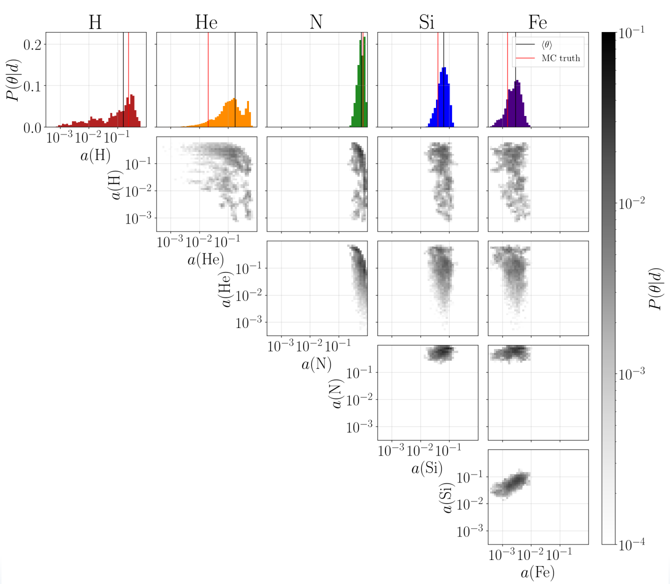


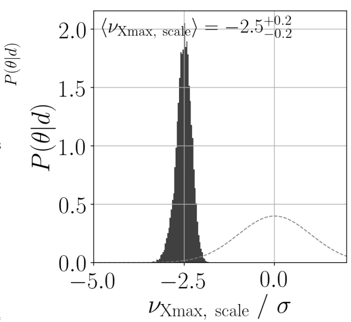


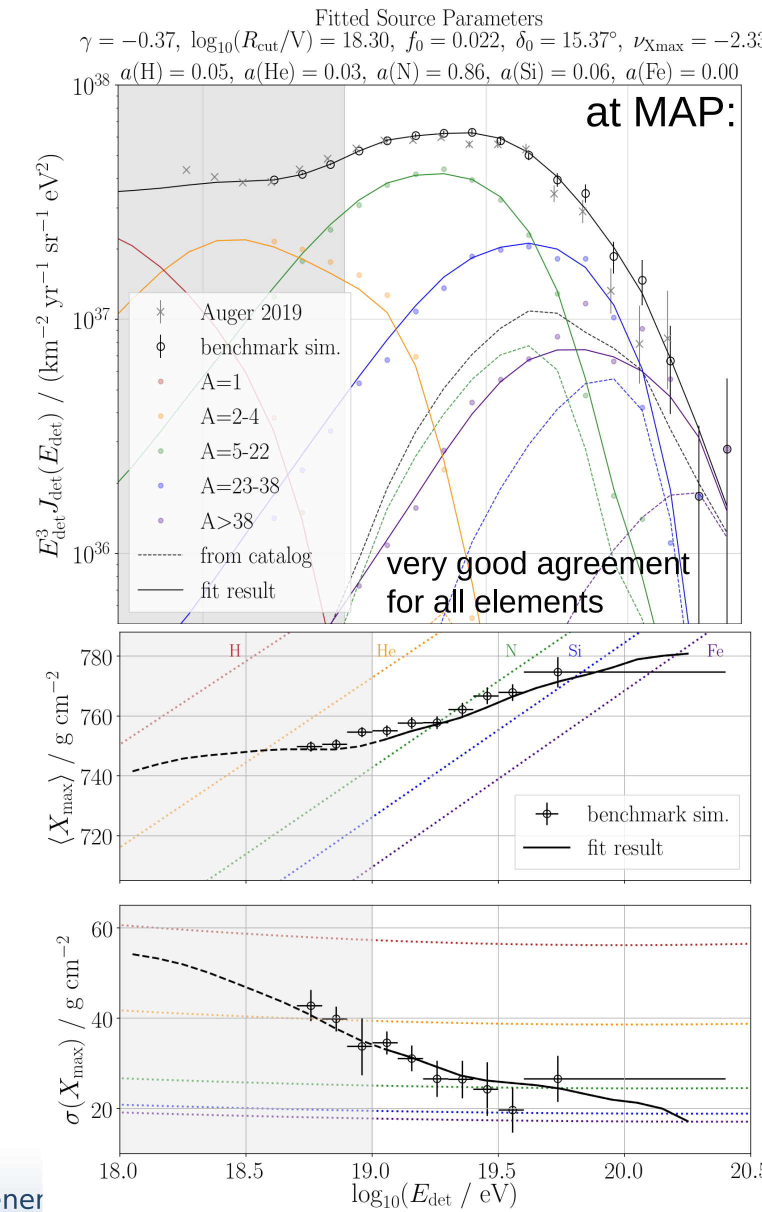


Fit results: SBG model (m=3.4)

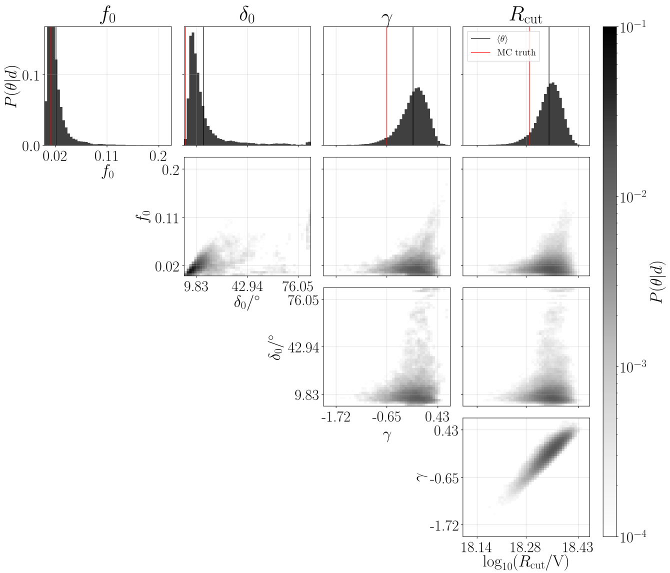


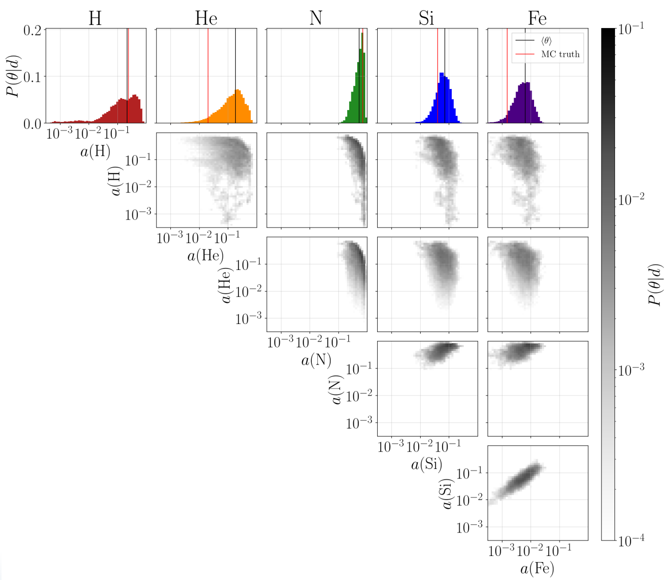


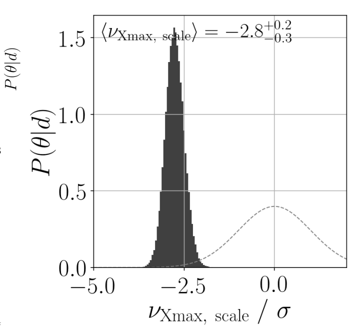


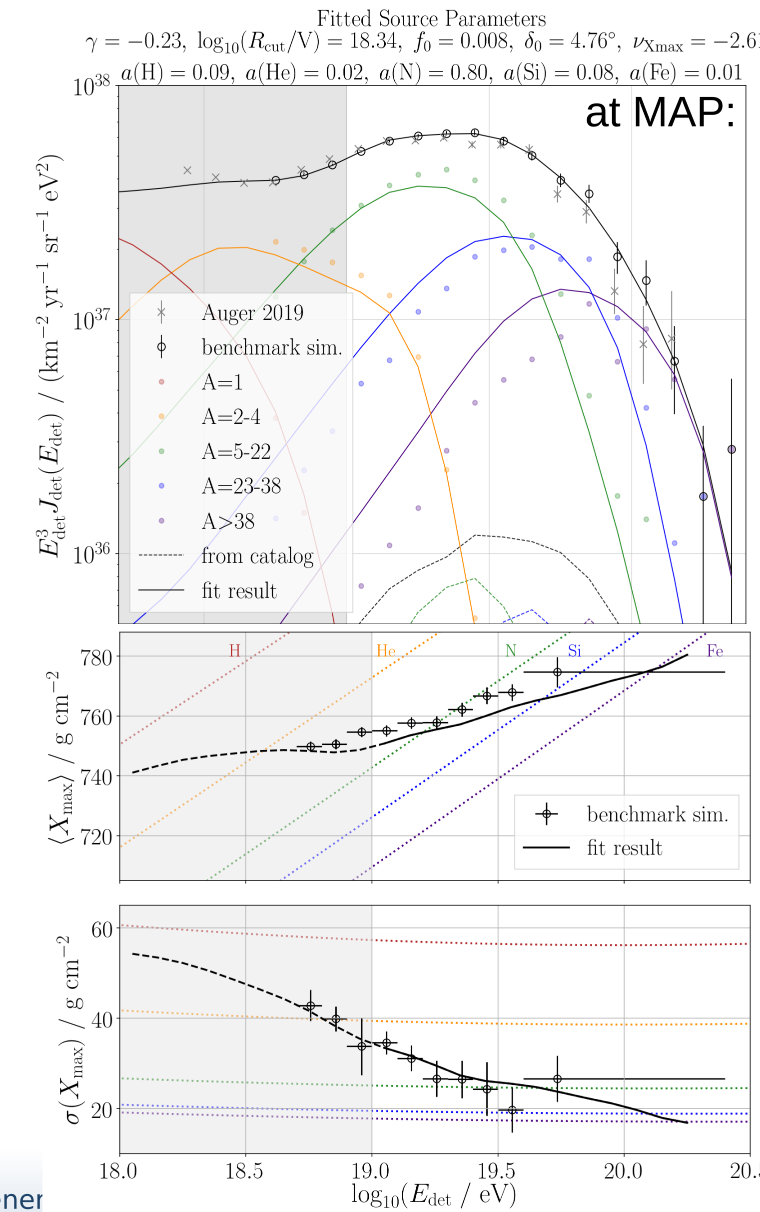


Fit results: AGN model (m=3.4)









Fit results: AGN model (m=5.0)