Fitting an astrophysical model for the origin of ultra-high-energy cosmic rays

Model setup & Sensitivity study

CRPropa workshop, Madrid, 13.09.2022

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RWTH AACHEN UNIVERSITY

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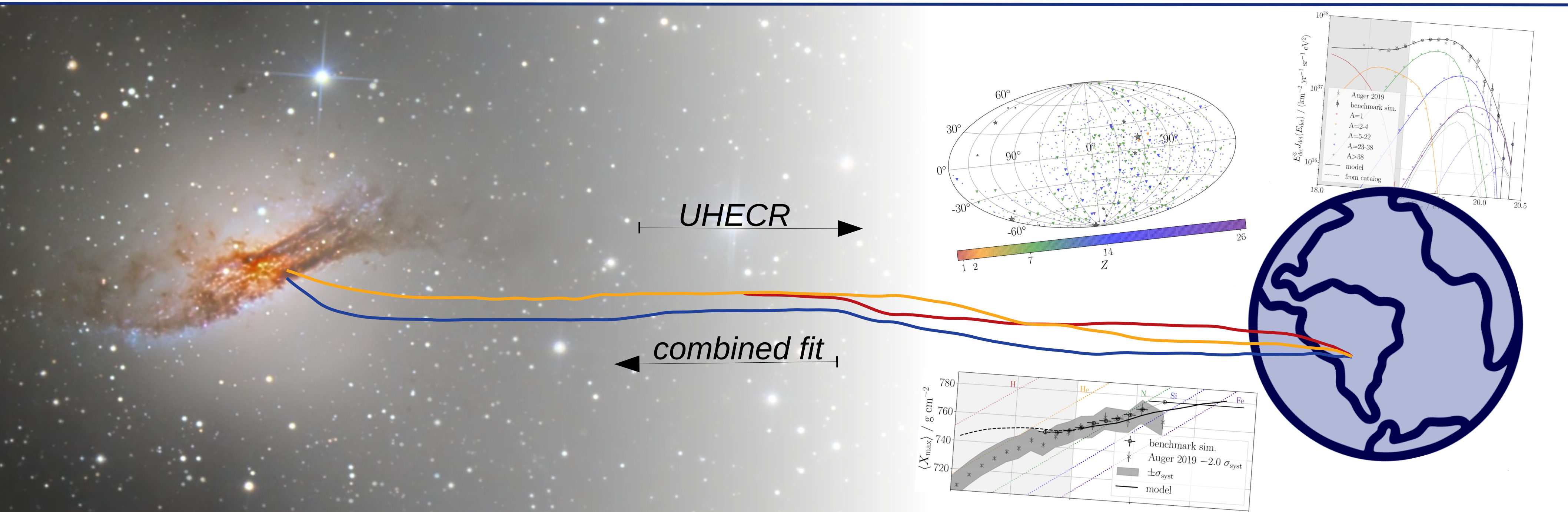
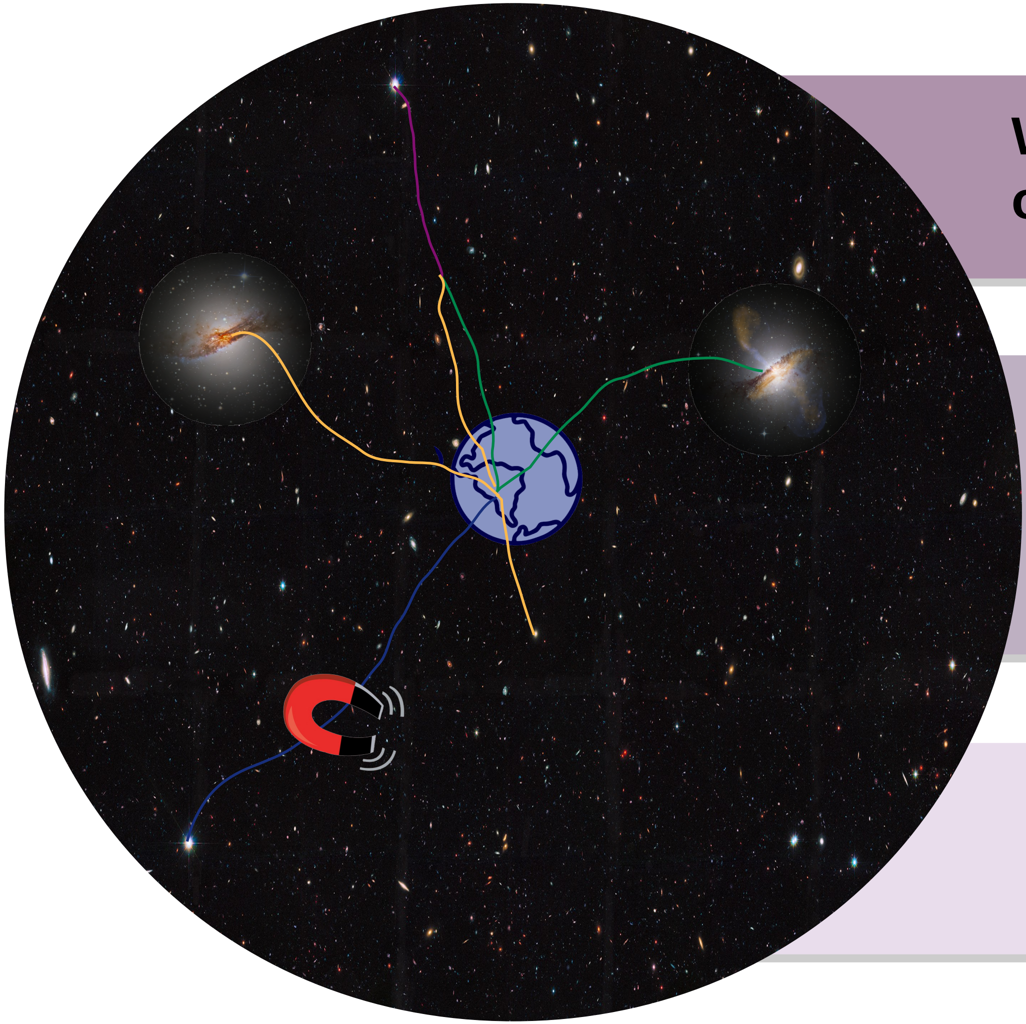
PIERRE AUGER OBSERVATORY



Motivation

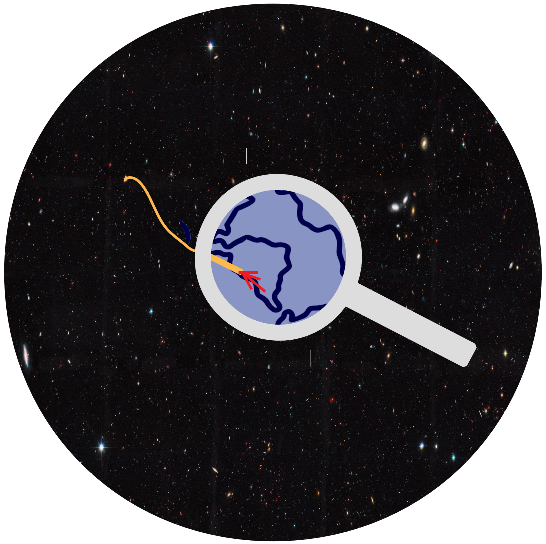


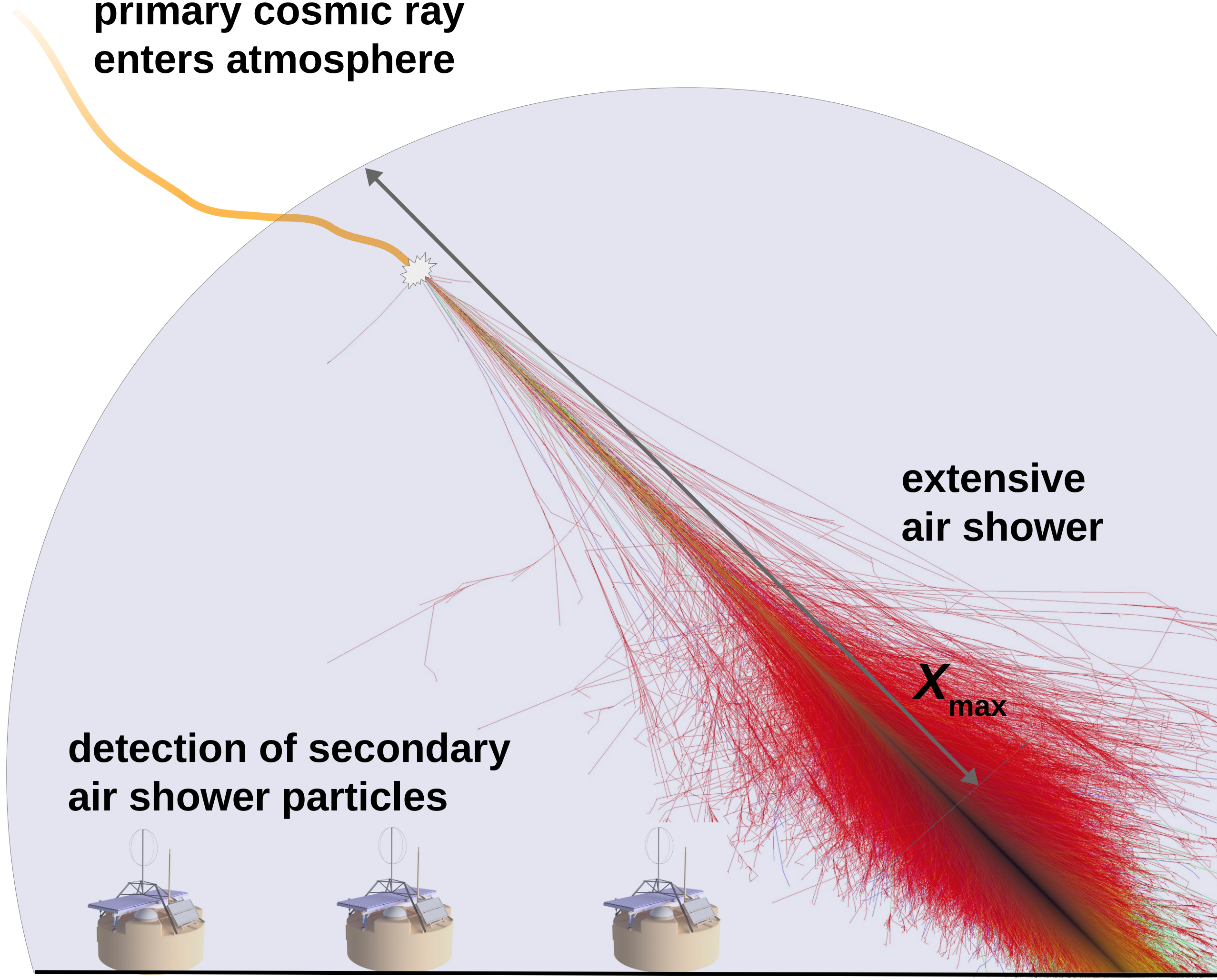
What are the sources of ultra-high-energy cosmic rays?

many open questions:
sources, acceleration,
propagation, magnetic fields,
mass composition...

➡ **find model to best describe measurements!**

Detection of UHECRs



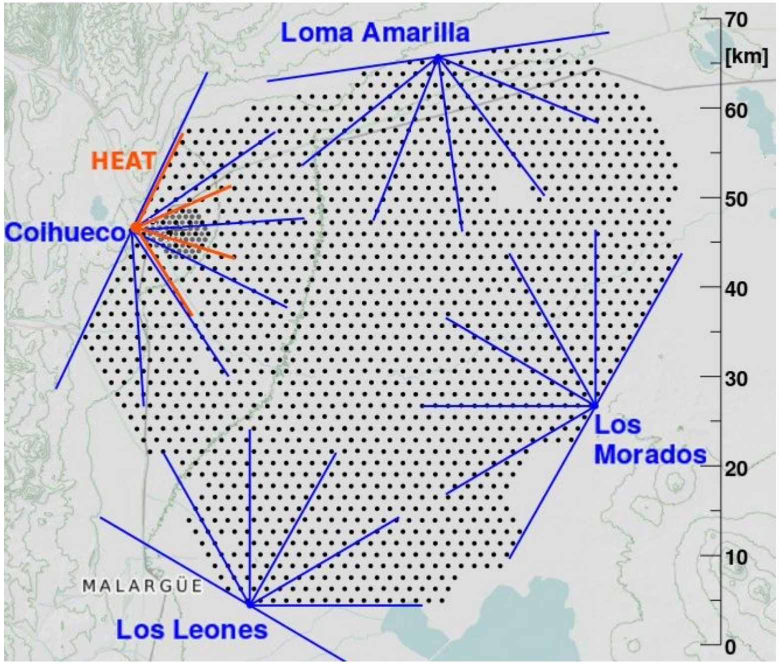


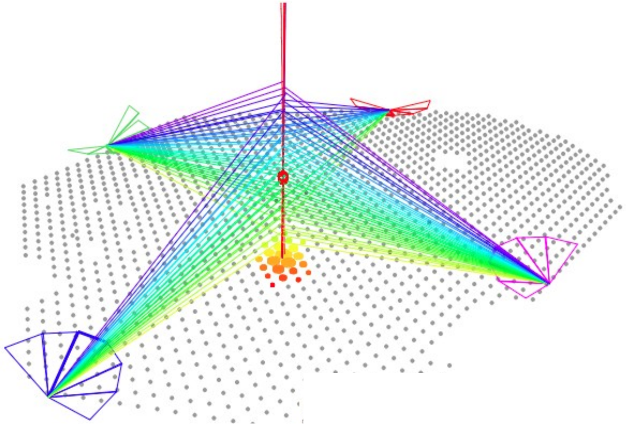
Three reconstructed properties of the primary cosmic ray:

1. arrival direction
2. energy
3. depth of the shower maximum X_{max} (→ charge)

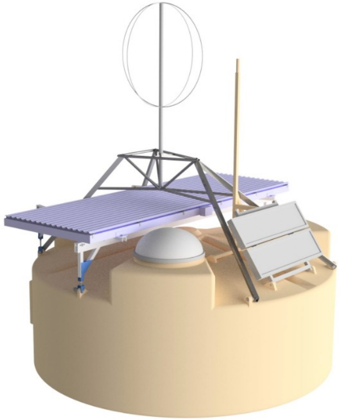
→ **use these to identify sources**

The Pierre Auger Observatory





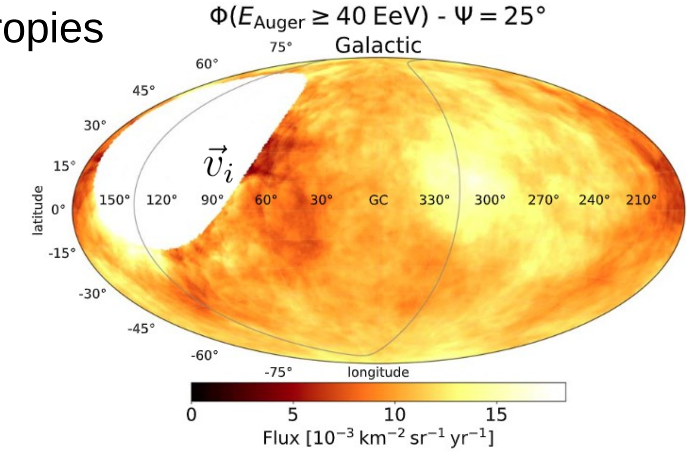
- located near Malargüe, Argentina
- **largest UHECR detector world-wide:**
  area of 3000 km²
- **hybrid detection:**
  - grid of 1600 + 60 water Cherenkov stations (SD)
    → 1500m / 750m grid, 100% duty cycle
  - 4 sites of fluorescence telescopes (FD)
    → 24 + 3 telescopes, ~15% duty cycle
- **update ongoing: AugerPrime**



Arrival directions

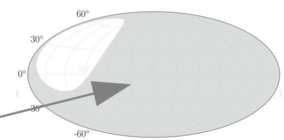
P. Abreu et al. (the Pierre Auger Collaboration) 2022 ApJ 935 170

- measured arrival directions *(ADs)*: no (significant) small-scale anisotropies
- but, when **comparing to expected fluxes from catalogs of source candidates: correlation observed!**
  - comparison of measured ADs $\vec{v}_i$ with model flux maps $\mathrm{pdf}_{\mathrm{AD-only}}$



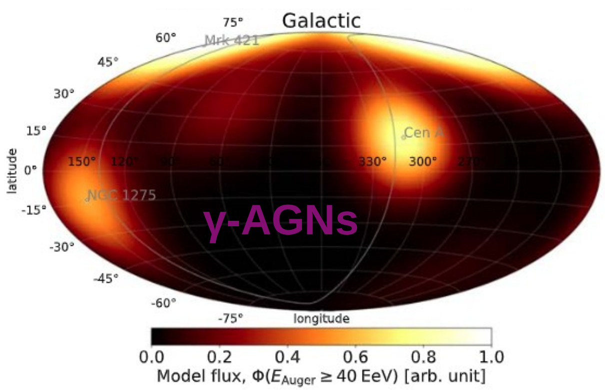
signal fraction *magnetic field blurring*

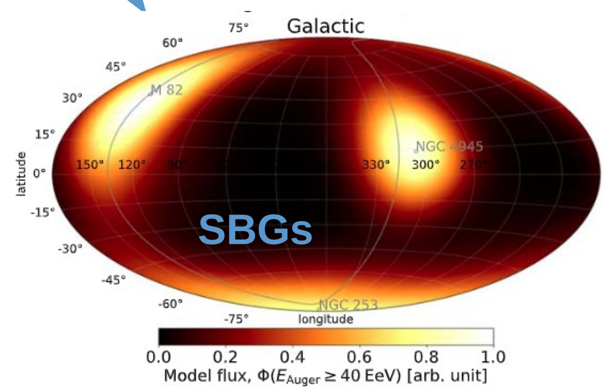
$$\mathrm{pdf}_{\mathrm{AD-only}} = f_{\mathrm{AD-only}} \cdot S_{\delta_{\mathrm{AD-only}}} + (1 - f_{\mathrm{AD-only}}) \cdot B$$



jetted active galactic nuclei ***γ-AGNs***

starburst galaxies ***SBGs***





likelihood function:

$$\mathcal{L}_{\mathrm{AD-only}}(f_{\mathrm{AD-only}}, \delta_{\mathrm{AD-only}}) = \prod_i \mathrm{pdf}_i(\vec{v}_i))$$

test statistic:

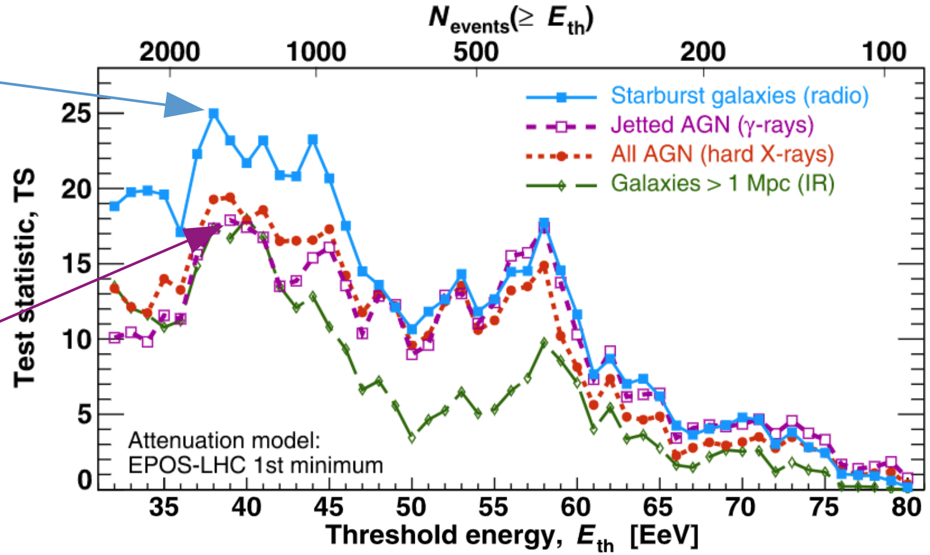
$$\mathrm{TS}_{\mathrm{AD-only}} = 2 \log \frac{\mathcal{L}_{\mathrm{AD-only}}(f_{\mathrm{AD-only}}, \delta_{\mathrm{AD-only}})}{\mathcal{L}_{\mathrm{AD-only}}(f_{\mathrm{AD-only}} = 0)}$$

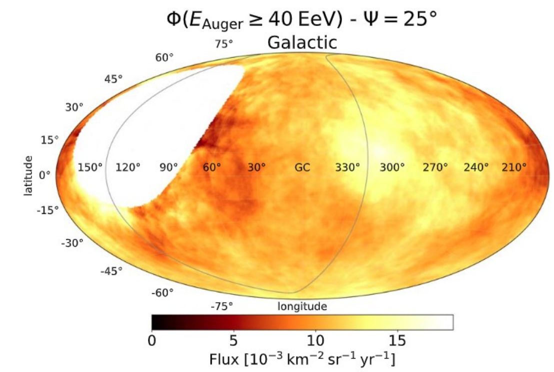
P. Abreu et al. (the Pierre Auger Collaboration) 2022 ApJ 935 170

Arrival directions

best-fit for SBGs:
TS = 25.0 (4.2σ)
for δ=15°, f=9%,
E_{th}=38 EeV

best-fit for γ-AGNs:
TS = 17.9 (3.9σ)
for δ=14°, f=96%,
E_{th}=39 EeV





Are SBGs truly favored above the other catalogs?
→ no, strongest sources into similar directions

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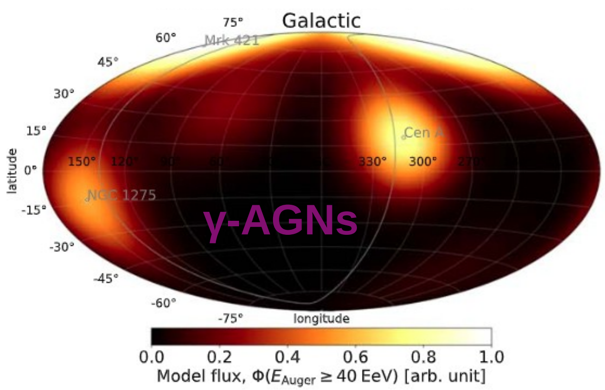

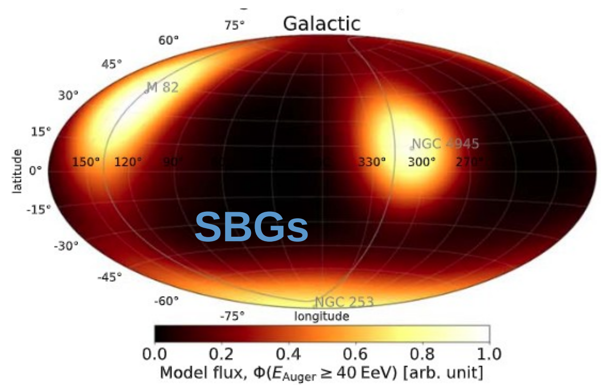

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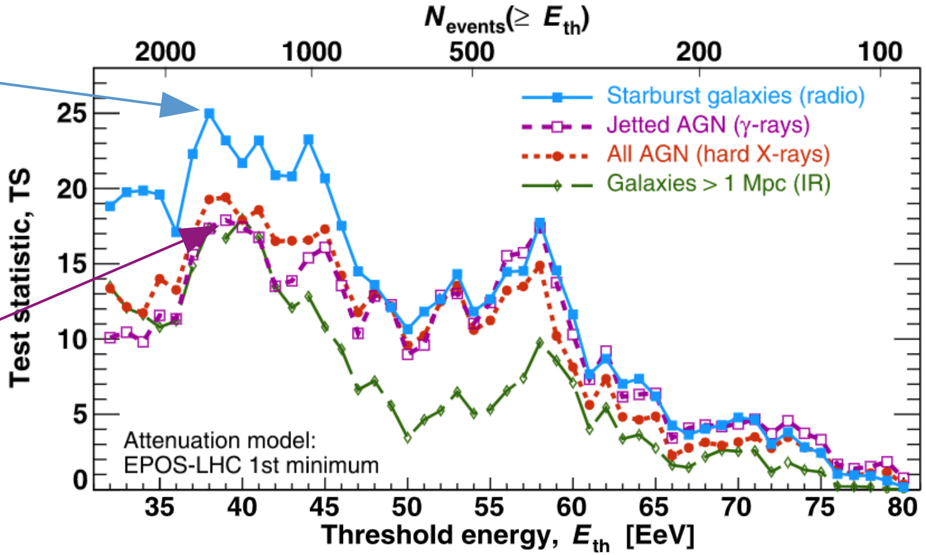

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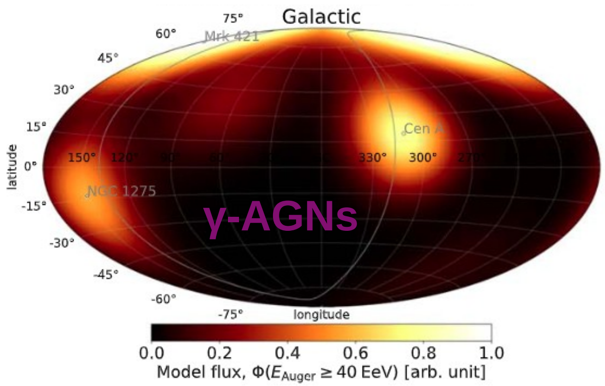
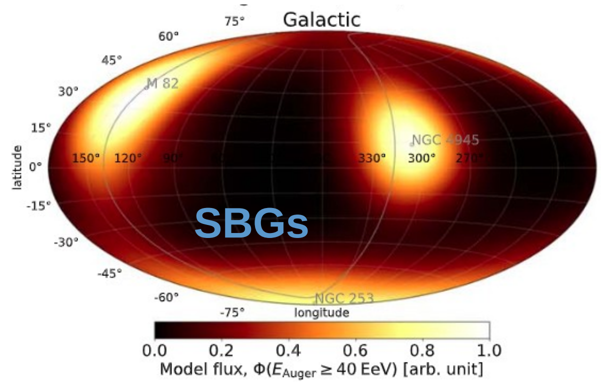
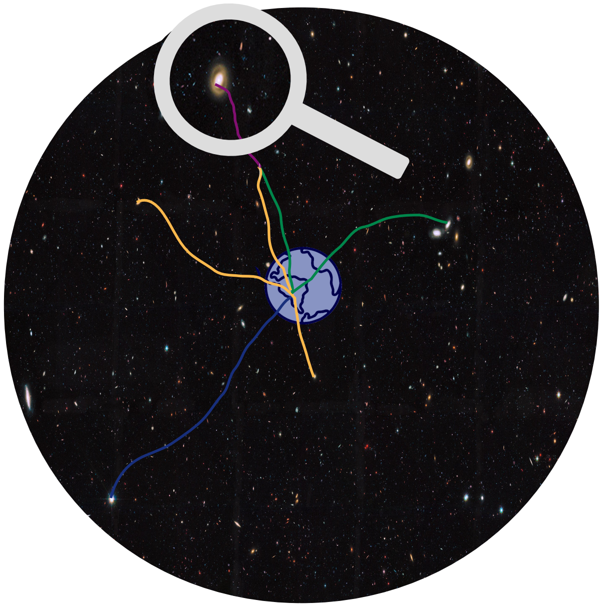




- **use combined fit of arrival directions + energy spectrum + Xmax**
  - better source catalog differentiation
  - also constrain parameters of source emission
- **for that: build more physical model**
  - include propagation, energy-dependent catalog contribution, rigidity-dependent magnetic field blurring…

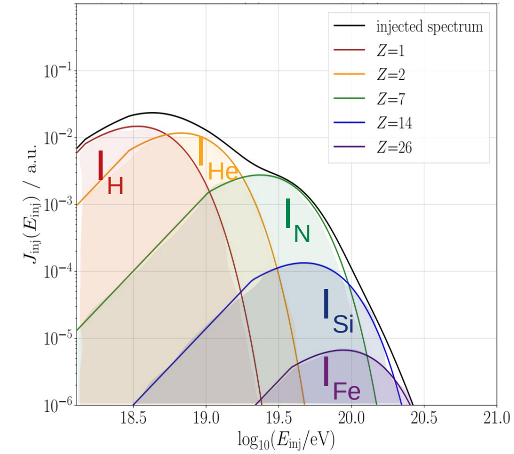
Model: reference case

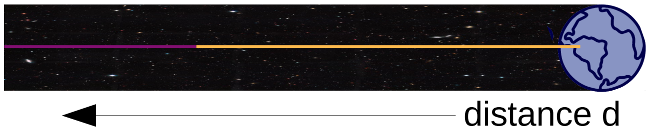


- **injection** at the sources:

$$J_{\rm inj}(E_{\rm inj}, A_{\rm inj}) = J_0 \cdot a_A \cdot \left(\frac{E_{\rm inj}}{10^{18}\ \rm eV}\right)^{-\gamma} f_{\rm cut}\left(\frac{E_{\rm inj}}{Z_A R_{\rm cut}}\right)$$

free model parameters





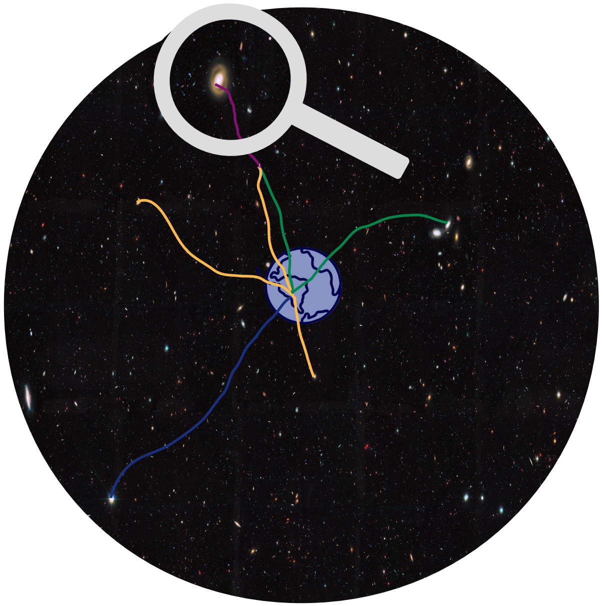
- **source distribution:**
  - only homogeneously distributed sources (in reference case)
    - isotropic arrival directions → not included as observable
    - can study propagation in 1d instead of 3d
  - expectation: flat distribution of flux per comoving distance shell

- **source evolution:**
  - simple description via: $\psi(z) \propto (1+z)^m$

redshift z=z(d)

  - for SBGs: m~3.4 (starformation rate / SFR)
    - → more sources in the past
  - for AGNs: m~5.0

Model: reference case



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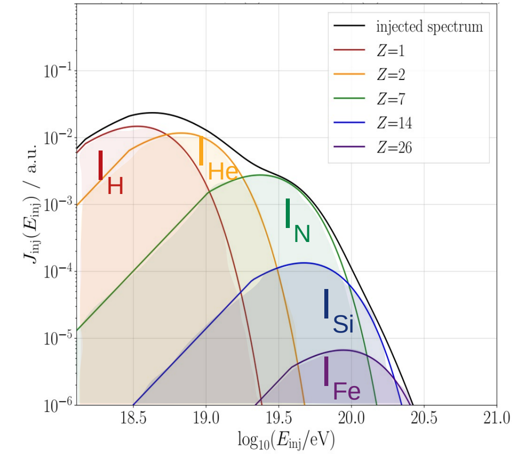

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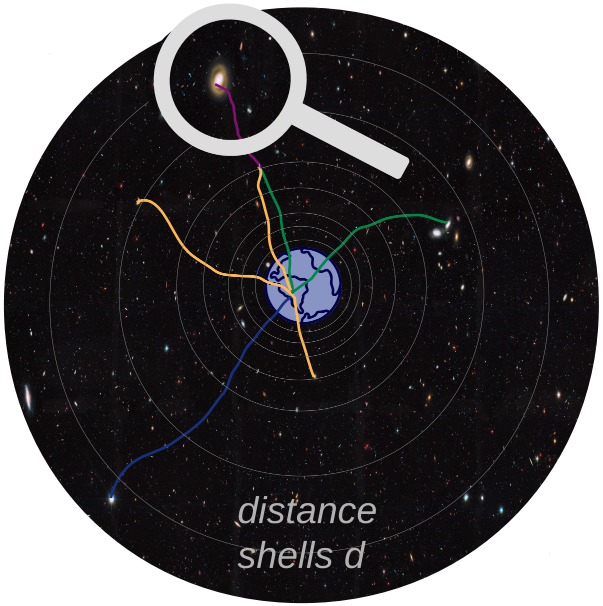

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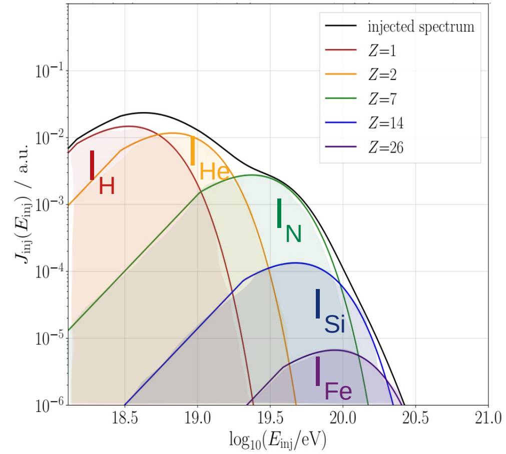


arrival probability for "background" sources (homogeneous):

universe expansion *source evolution*

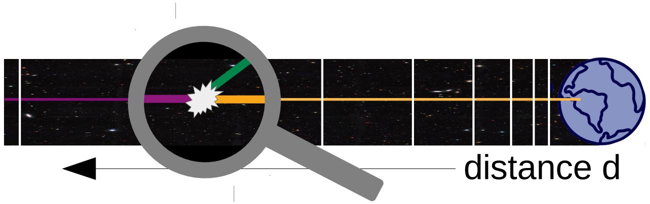
$$\boxed{p_{\mathrm{back}}(E^e_{\mathrm{det}}, A^k_{\mathrm{det}}) = \sum_l (1+z(d^l))^{-1} \cdot (1+z(d^l))^m \cdot p(E^e_{\mathrm{det}}, A^k_{\mathrm{det}}, d^l)}$$

$$\sum_h \sum_i w_{\mathrm{inj}}(E^h_{\mathrm{inj}}, A^i_{\mathrm{inj}})\ P(E^h_{\mathrm{inj}}, A^i_{\mathrm{inj}}, E^e_{\mathrm{det}}, A^k_{\mathrm{det}}, d^l)$$

injection

→ set up database of 1d simulations with CRPropa

Propagation database



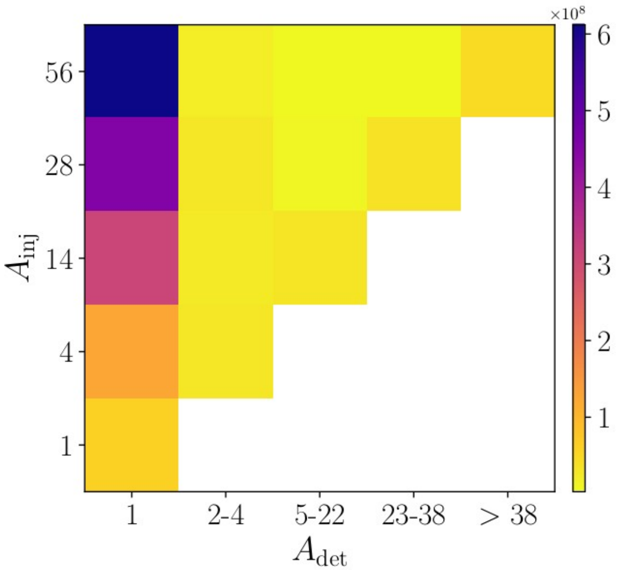
- **1d CRPropa3 simulations in the following binning:**

binning at injection

$P(E^h_{\text{inj}}, A^i_{\text{inj}}, E^e_{\text{det}}, A^k_{\text{det}}, d^l)$

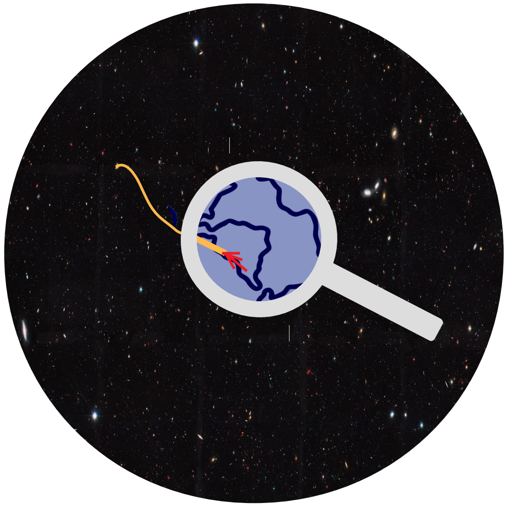
binning at detection

Parameter	bin edges	number of bins	
injected distance d	1 - 5670 Mpc z~2	118	logarithmic
injected mass A_{inj}	1, 4, 14, 28, 56	5	
injected energy E_{inj}	$10^{18.0}$ eV - 10^{21} eV	150	logarithmic
detected mass A_{det}	1, 2-4, 5-22, 23-38, > 39	5	
detected energy E_{det}	$10^{18.0}$ eV - $10^{21.0}$ eV	150	logarithmic



- in total 10^4 particles for each of the 118*5*150 = 88500 injection bins
- **interactions:** consider nuclear decay, electron pair production, photopion production, photodisintegration, adiabatic losses
  - *TALYS* model for photodisintegration
  - *Gilmore* model for extragalactic background light
- **reweight according to injection & source evolution**
  → calculate modeled observables on Earth from $p_{\text{back}}(E^e_{\text{det}}, A^k_{\text{det}})$

Simulated observables

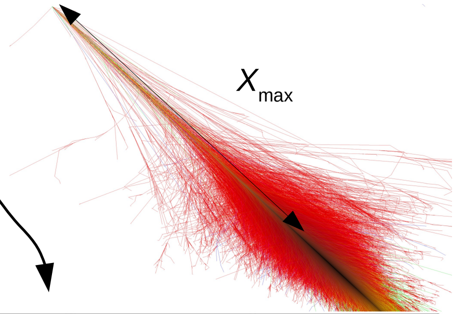


- **energy spectrum:** sum over detected particles
  - (include *forward folding* with detector resolution when fitting on real data)

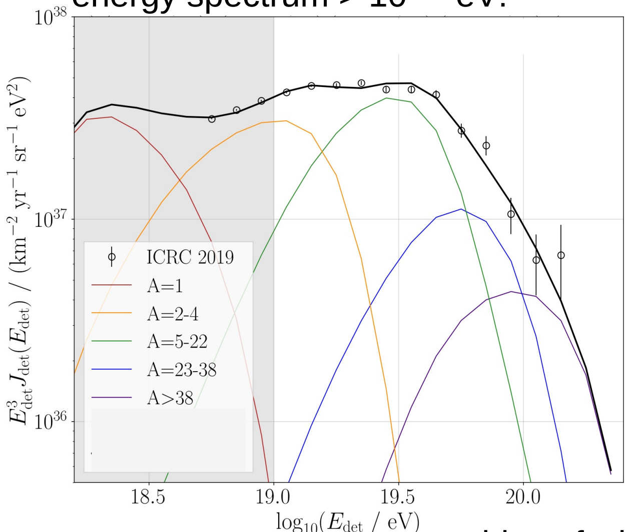
$$p(E^e_{\mathrm{det}}) = \sum_k p_{\mathrm{back}}(E^e_{\mathrm{det}}, A^k_{\mathrm{det}})$$

$$J(\tilde{E}^e_{\mathrm{det}}) = \frac{p(\tilde{E}^e_{\mathrm{det}})}{(\mathcal{E}_{\mathrm{vert}} + \mathcal{E}_{\mathrm{incl}})\ \Delta\tilde{E}^e_{\mathrm{det}}}$$

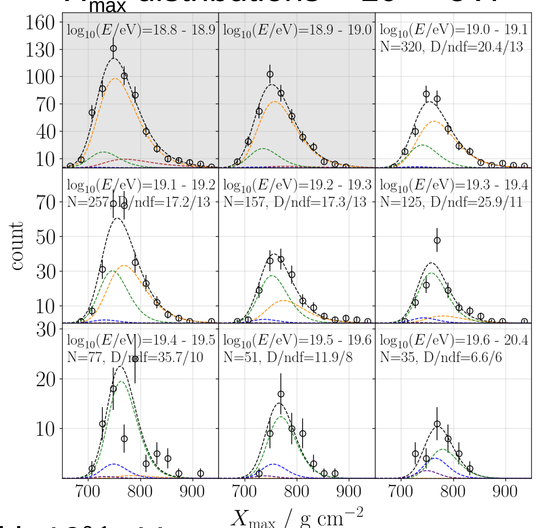
- **shower depth distributions:**
  - parameterize with Gumbel distributions
  - hadronic interaction model: EPOS-LHC
  - (fold with detector resolution & acceptance)



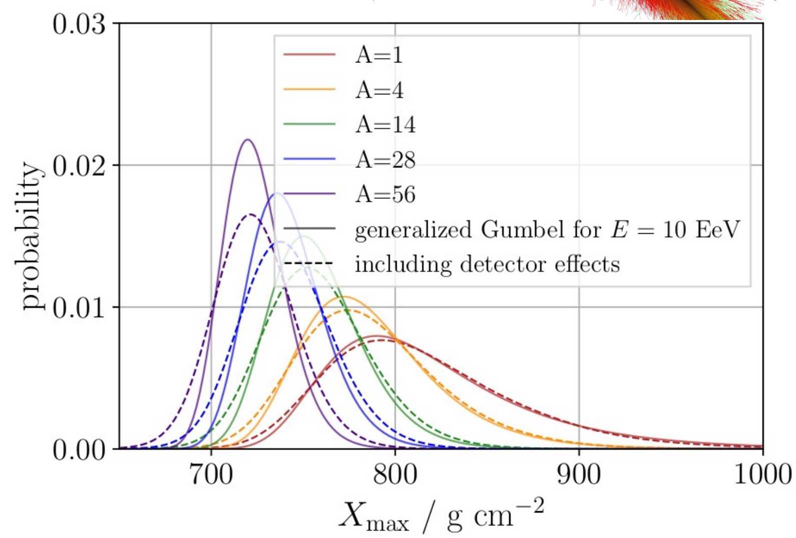
energy spectrum > $10^{19.0}$ eV:



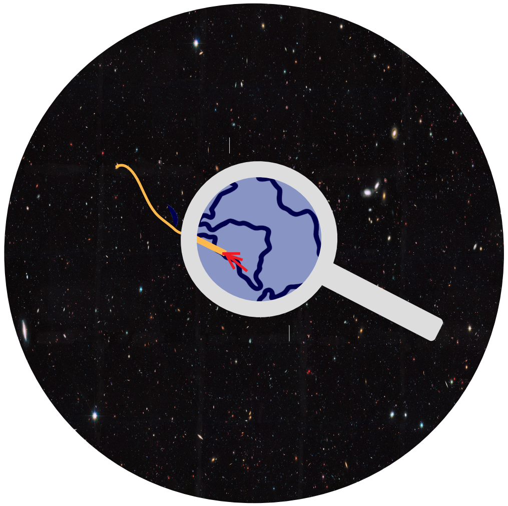
X_{max} distributions > $10^{19.0}$ eV:



bins of width $10^{0.1}$ eV



Simulated observables & Likelihood



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$$p(E^e_{\mathrm{det}}) = \sum_k \hat{p}_{\mathrm{tot}}(E^e_{\mathrm{det}}, A^k_{\mathrm{det}})$$

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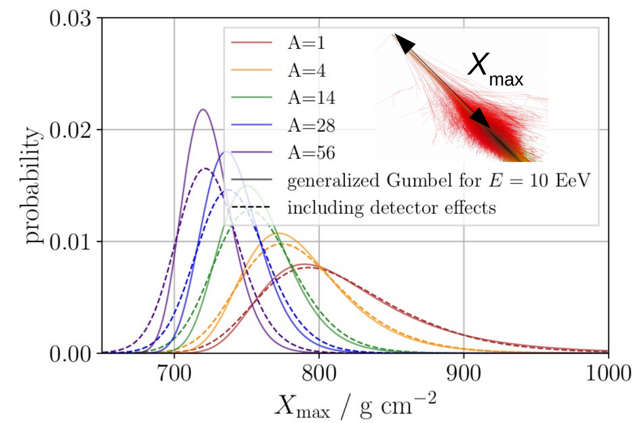

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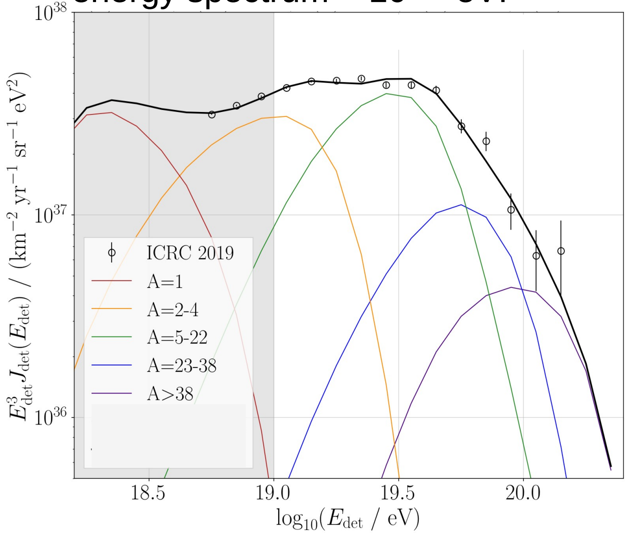

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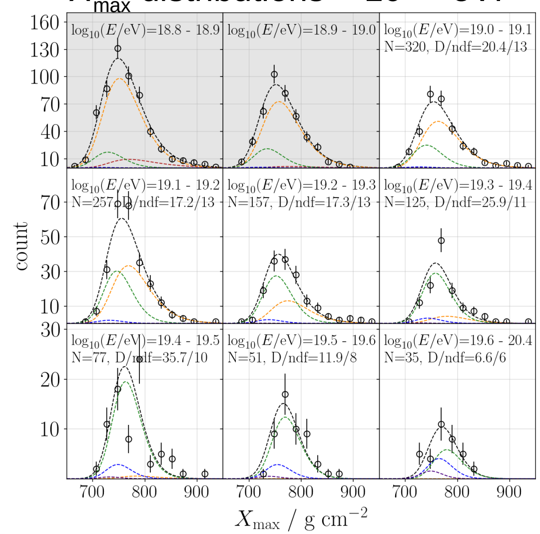


compare to data via **likelihood function:**

$$\log\mathcal{L} = \log\mathcal{L}_E + \log\mathcal{L}_{\mathrm{Xmax}}$$

Poissonian
(one-sided
$10^{18.7}$ eV – $10^{19.0}$ eV)

Multinomial

as in:

The Pierre Auger Collaboration, A. Aab et al. "Combined fit of spectrum and composition data as measured by the Pierre Auger Observatory". *Journal of Cosmology and Astroparticle Physics* 2017.04 (2017), 038–038. DOI: 10.1088/1475-7516/2017/04/038.

Inference methods

- **defined astrophysical model**
  → infer best-fit parameters according to likelihood
- **2 inference methods:**
  - gradient-based minimizer
    for the best-fit / maximum-likelihood estimate
  - Markov-Chain-Monte-Carlo sampler
    for posterior distributions
    → Sequential MC from PyMC

Bayes theorem

posterior likelihood prior

$$p(\theta|d,\mathcal{M}) = \frac{\mathcal{L}(\theta)\ p(\theta|\mathcal{M})}{p(d|\mathcal{M})}$$

parameters model evidence

parameters for the souce injection

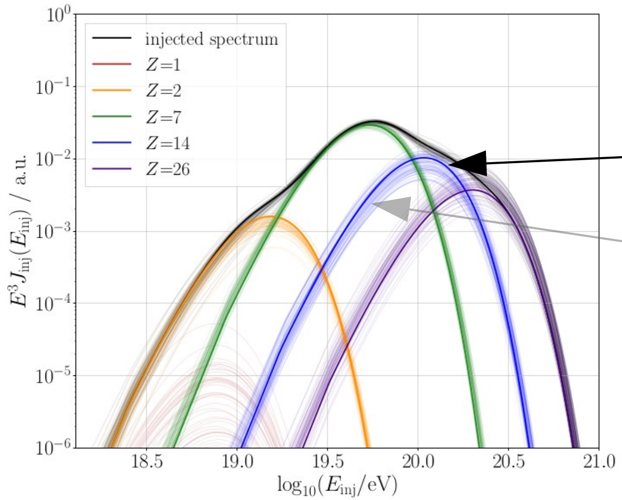
$$J_{\mathrm{inj}}(E_{\mathrm{inj}}, A_{\mathrm{inj}}) = J_0 \cdot a_A \cdot \left(\frac{E_{\mathrm{inj}}}{10^{18}\ \mathrm{eV}}\right)^{-\gamma} f_{\mathrm{cut}}\left(\frac{E_{\mathrm{inj}}}{Z_A R_{\mathrm{cut}}}\right)$$

	fit parameter	**prior**	**borders**
parameters for the souce injection (reference model)	spectral index γ	uniform	-4 to 3
	rigidity cutoff $\log_{10}(R_{\mathrm{cut}}/\mathrm{V})$	uniform	19.0 V to 20.5 V
	element fractions	unit simplex	0 to 1
	flux normalization J_0	uninformative	
for including catalog sources	signal fraction f_0	uniform	0 to 1
	magnetic field blurring δ_0	uniform	0 to 15 (0° - 86°)
for including experimental systematic uncertainties	syst. energy scale ν_E	uniform	-4 to 4
	syst. energy X_{max} $\nu_{X_{\mathrm{max}}}$	uniform	-4 to 4
for extra-galactic magnetic field	X_s	uniform	0 to 30
	E_c	uniform	0 to 30 EeV

reference model

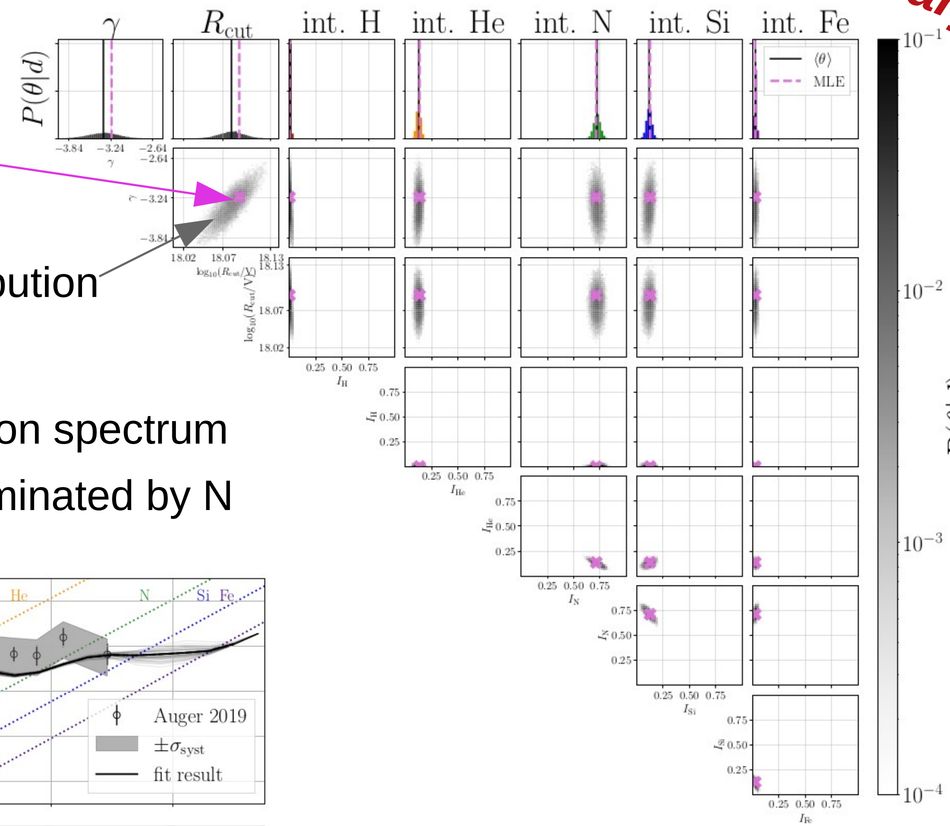
Results of reference model (SFR evolution)

preliminary

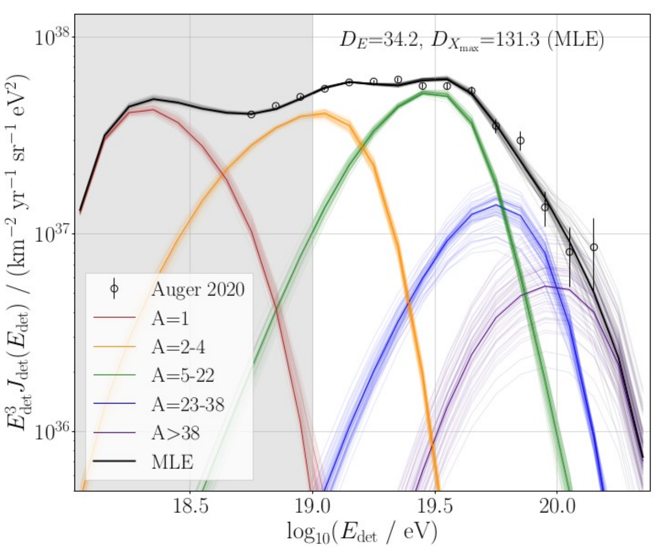


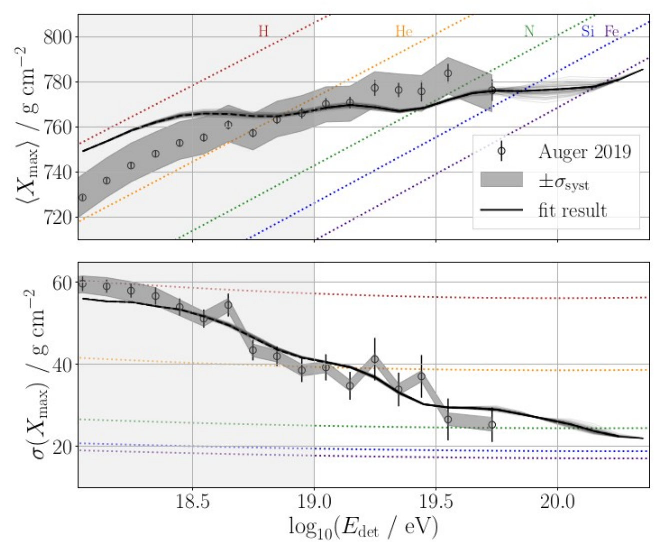
best-fit

posterior distribution

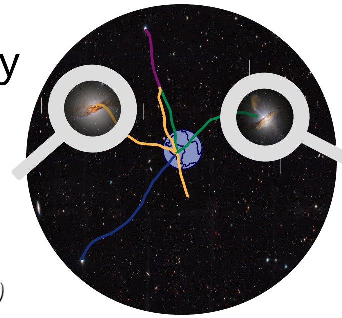


- very hard injection spectrum
- composition dominated by N



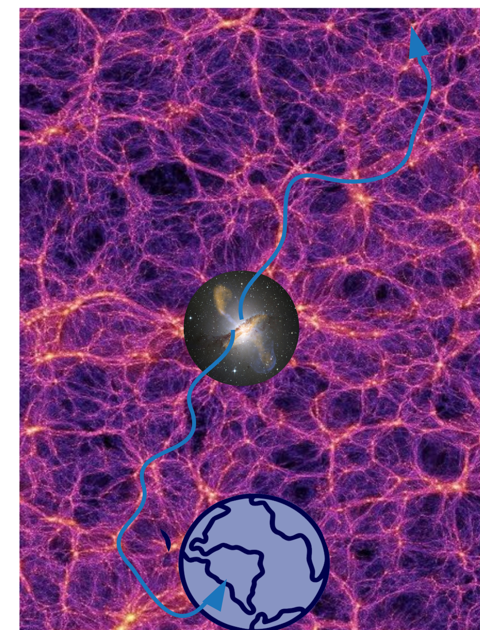


→ *keep in mind for later*



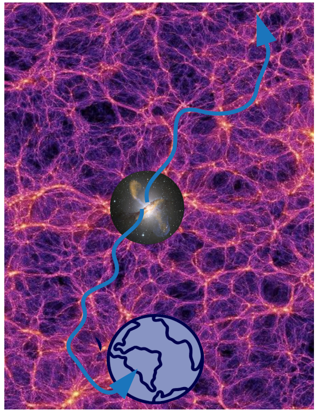
- **goal:** fit energy spectrum, shower depth distributions & arrival directions simultaneously
  - add catalog sources to model → investigate expected arrival directions

- **in CRPropa : 3d / 4d simulations?**
  - preliminary fit with EGMF & 4d simulations: D. Wittkowski for the Pierre Auger Collaboration *PoS(ICRC2017)* DOI: 10.22323/1.301.0563
  - for structured EGMF models: direction matters
    - for fit with arrival directions: would need different propagation database in every direction
    - small observer size to prevent distortions **very slow!**



- **other possibilities:**
  - **2-step approach**
    - fit only E & Xmax / take published parameters, then evaluate predicted arrival directions
    - can include structured E(GMF) models
  - **simplify propagation**
    - 1d propagation + 3d reweighting to source setup → here: simplified propagation models
    - structured GMF models

Catalog sources & arrival directions



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    - for fit with arrival directions: would need different propagation database in every direction
    - small observer size to prevent distortions **very slow!**

- <u>**other possibilities:**</u>
  - **2-step approach**
    - fit only E & Xmax / take published parameters, then evaluate predicted arrival directions
    - can include structured E(GMF) models
  - **simplify propagation** 
    - 1d propagation + 3d reweighting to source setup *(here: simplified propagation models)*
    - can include structured GMF models

B. Eichmann, J.P. Rachen, L. Merten, A. van Vliet and J. Becker Tjus, *Ultra-high-energy cosmic rays from radio galaxies*, *Journal of Cosmology and Astroparticle Physics* **2018** (2018) 036.

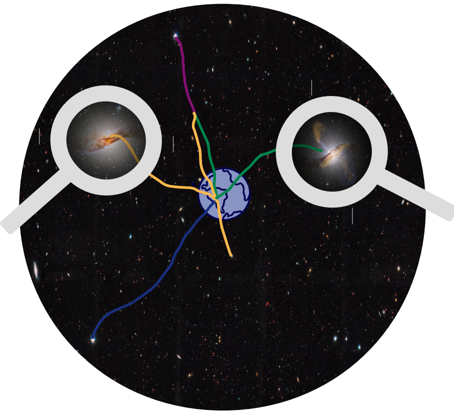
A. van Vliet, A. Palladino, W. Winter, A. Taylor and A. Franckowiak, *Extragalactic magnetic fields and directional correlations of ultra-high-energy cosmic rays with local galaxies and neutrinos*, in *Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021)*, vol. 395, p. 470, July, 2021, DOI.

D. Allard, J. Aublin, B. Baret and E. Parizot, *What can be learnt from UHECR anisotropies observations - I. Large-scale anisotropies and composition features*, *Astronomy & Astrophysics* **664** (2022) A120.

C. Ding, N. Globus and G.R. Farrar, *The Imprint of Large-scale Structure on the Ultrahigh-energy Cosmic-Ray Sky*, *The Astrophysical Journal Letters* **913** (2021) L13.

B. Eichmann, M. Kachelrieß and F. Oikonomou, *Explaining the UHECR spectrum, composition and large-scale anisotropies with radio galaxies*, *JCAP* **07** (2022) 006.

Including catalog sources in the model

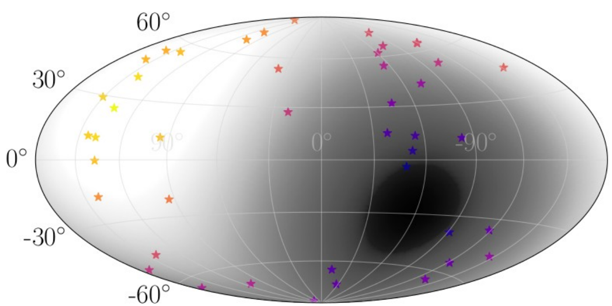


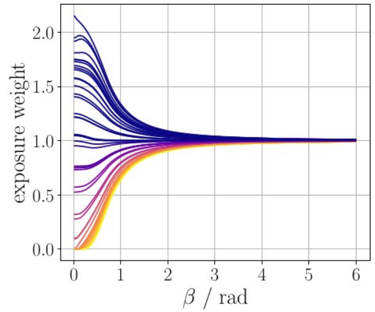
expected contribution on Earth of a source depends on:

- total flux weight
- injected spectrum
- distance
- direction (exposure)

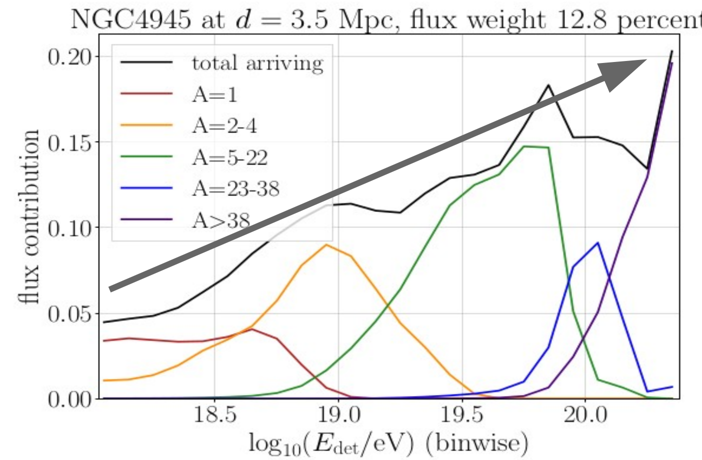
injection
+ propagation database

$$p_{\mathrm{sig}}(E^e_{\mathrm{det}}, A^k_{\mathrm{det}}, C^s) = \sum_l p(E^e_{\mathrm{det}}, A^k_{\mathrm{det}}, d^l) \cdot w_{\mathrm{interpolate}}(d^s, d^l) \cdot w_{\mathrm{flux}}(C^s) \cdot w_{\mathrm{exposure}}(E^e_{\mathrm{det}}, A^k_{\mathrm{det}}, C^s)$$

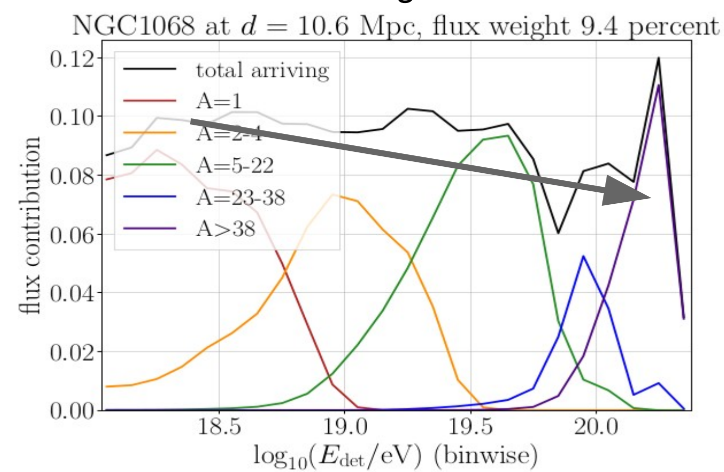




→ *depends on blurring / arrival direction modeling*
→ *see later*



source at larger distance:



Signal fraction

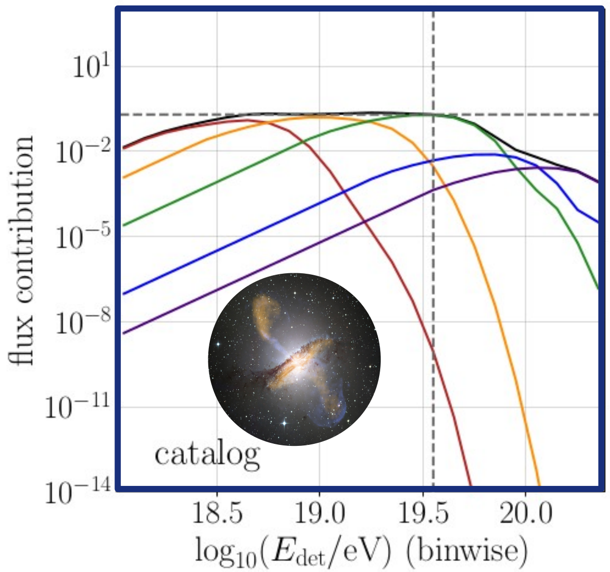
from source catalog:
summed over source candidates + normalized

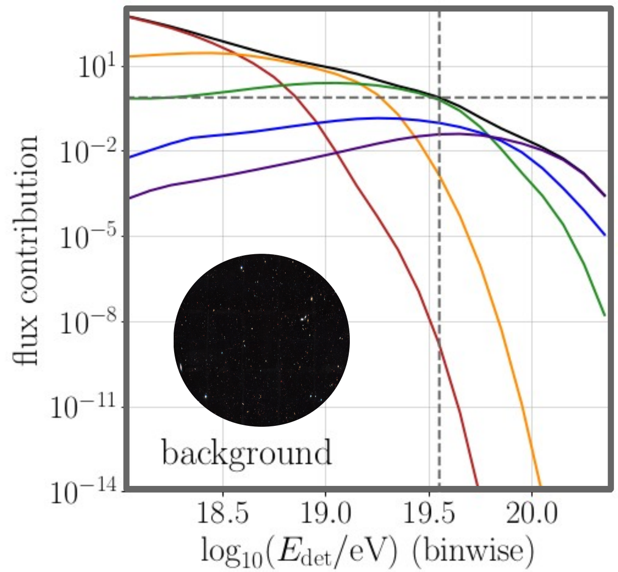
from homogeneous background

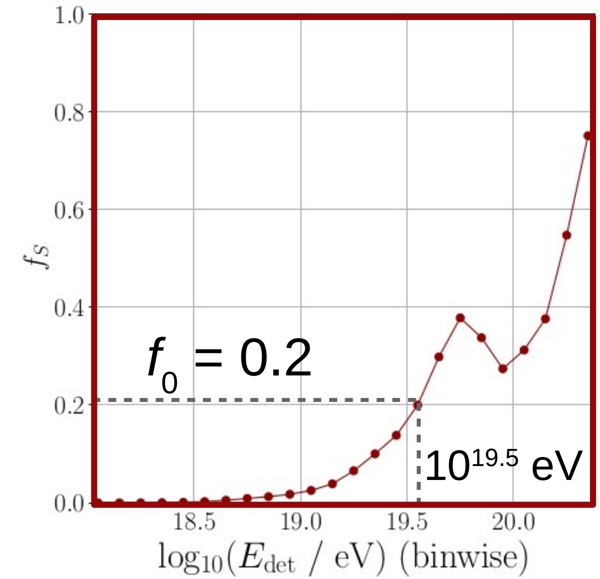
$$\hat{p}_{\mathrm{tot}}(E^e_{\mathrm{det}}, A^k_{\mathrm{det}}) = f_0 \underbrace{\frac{\hat{p}^{\mathrm{norm}}_{\mathrm{sig}}(E^e_{\mathrm{det}}, A^k_{\mathrm{det}})}{\sum_k \hat{p}^{\mathrm{norm}}_{\mathrm{sig}}(E^{15}_{\mathrm{det}}, A^k_{\mathrm{det}})}}_{s_{\mathrm{sig}}} + (1 - f_0) \underbrace{\frac{p^{\mathrm{norm}}_{\mathrm{back}}(E^e_{\mathrm{det}}, A^k_{\mathrm{det}})}{\sum_k p^{\mathrm{norm}}_{\mathrm{back}}(E^{15}_{\mathrm{det}}, A^k_{\mathrm{det}})}}_{s_{\mathrm{back}}}$$

signal fraction defined at bin $10^{19.5}$ eV to $10^{19.6}$ eV

$$f_S(f_0, E^e_{\mathrm{det}}) = \sum_k \frac{s_{\mathrm{sig}}}{s_{\mathrm{sig}} + s_{\mathrm{back}}}$$





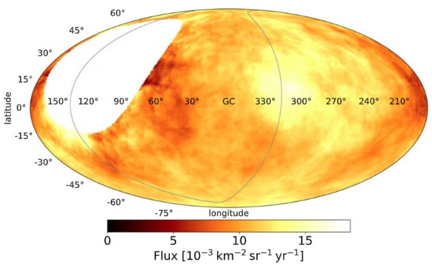


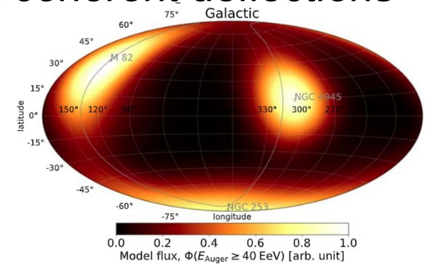
→ **catalog contribution rises with energy: catalog sources closer**

Simulated arrival directions: catalog sources

- **neglect coherent Galactic magnetic field**
  - overdensities situated around candidates
  - in halo turbulent field might be > coherent field
    (see e.g. arXiv:2202.06780)

~4σ correlation without coherent deflections





$R = E/Z$

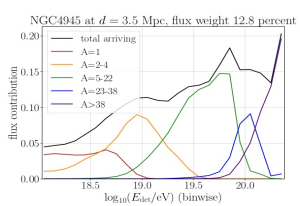
- **rigidity-dependent blurring**
  - can include also (E)GMF / distance dependency
  - model with Fisher distributions

only GMF: $\delta = \dfrac{\delta_0}{R/10\ \mathrm{EV}}$ ***or:*** ***GMF + EGMF:*** $\delta_{\mathrm{tot}} = \dfrac{\sqrt{\delta_0^2 + \beta_e^2\ d/\mathrm{Mpc}}}{R/10\ \mathrm{EV}}$

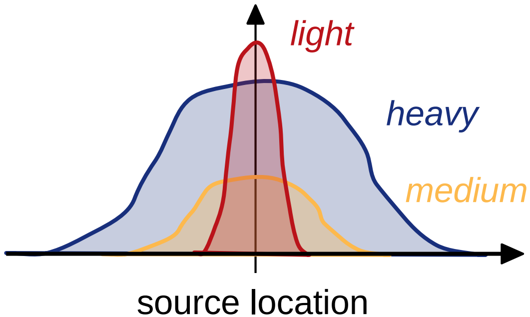
free model parameters

$$S(E^e_{\mathrm{det}}, \mathrm{pix}^p) = \sum_{k,s} \left(\hat{p}_{\mathrm{sig}}(E^e_{\mathrm{det}}, A^k_{\mathrm{det}}, C^s) \cdot F(\mathrm{pix}^p | \underbrace{E^e_{\mathrm{det}}, A^k_{\mathrm{det}}}_{\textit{rigidity}}, C^s) \cdot \mathcal{E}(\mathrm{pix}^p) \right)$$

weight *of each Fisher distribution scales with arrival probability of each mass in each energy bin*



width *of each Fisher distribution scales with rigidity / source distance*

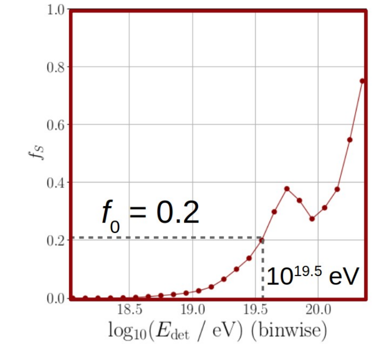


Simulated arrival directions: signal fraction

$$S(E^e_{\mathrm{det}}, \mathrm{pix}^p) = \sum_{k,s} \left(\hat{p}_{\mathrm{sig}}(E^e_{\mathrm{det}}, A^k_{\mathrm{det}}, C^s) \cdot F(\mathrm{pix}^p | E^e_{\mathrm{det}}, A^k_{\mathrm{det}}, C^s \cdot \mathcal{E}(\mathrm{pix}^p) \right)$$

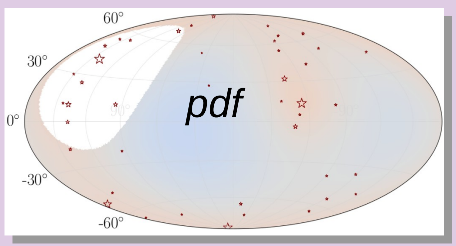
$$B(\mathrm{pix}^p) = \mathcal{E}(\mathrm{pix}^p) / \sum_p \mathcal{E}(\mathrm{pix}^p)$$

weight with signal fraction function:

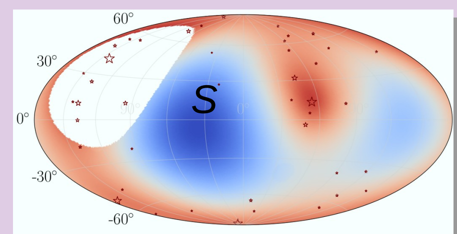


$$\mathrm{pdf}(E^e_{\mathrm{det}}, \mathrm{pix}^p) = \boxed{f_S(f_0, E^e_{\mathrm{det}})} \cdot \boxed{S(E^e_{\mathrm{det}}, \mathrm{pix}^p)} + \boxed{(1 - f_S(f_0, E^e_{\mathrm{det}}))} \cdot \boxed{B(\mathrm{pix}^p)}$$

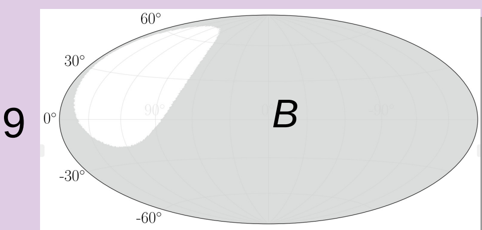
small E:



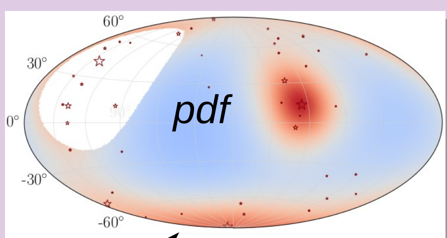
= 0.1



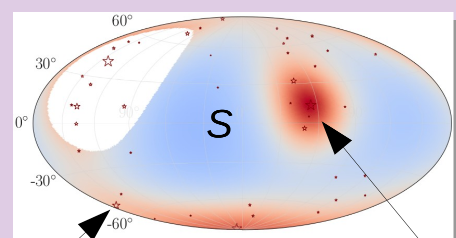
+ 0.9



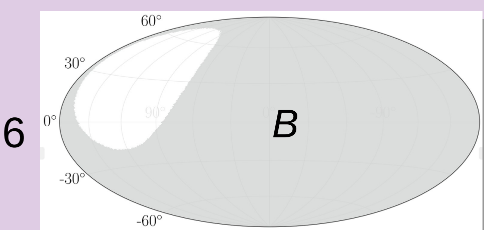
large E:



= 0.4

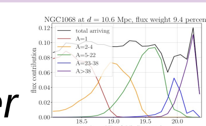


+ 0.6



catalog contribution rises with energy

influence of further away sources decreases



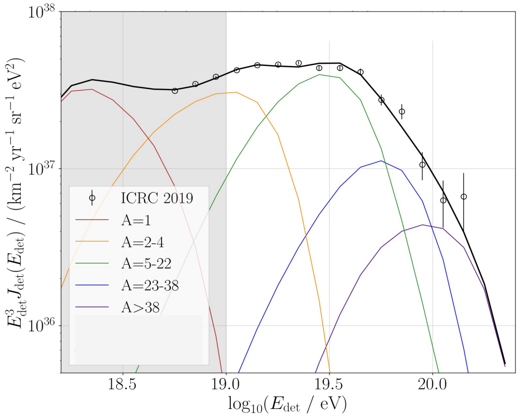
blurring decreases

$$\delta = \frac{\delta_0}{R/10\ \mathrm{EV}}$$

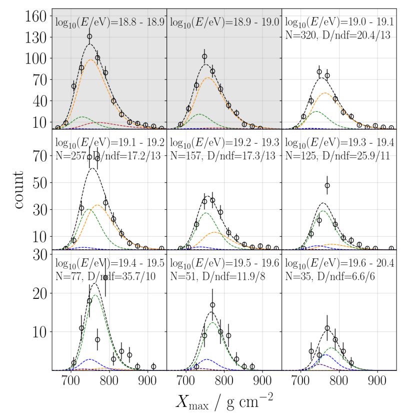
Total likelihood function

$$\log \mathcal{L} = \log \mathcal{L}_E + \log \mathcal{L}_{\mathrm{Xmax}} + \log \mathcal{L}_{\mathrm{AD}}$$

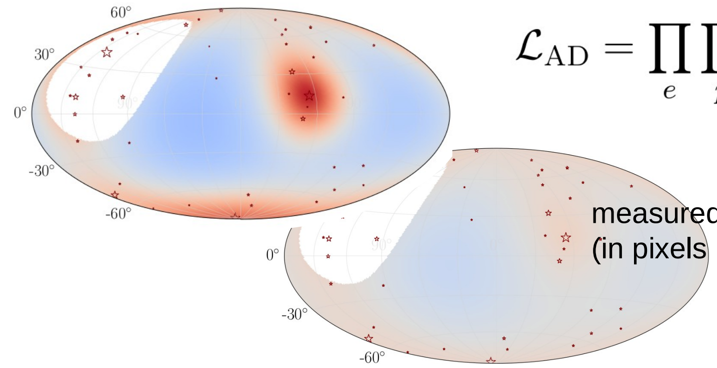
energy spectrum



X_{max} distributions

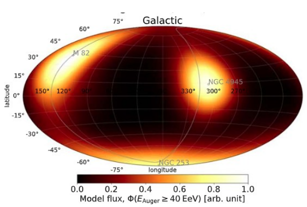


arrival directions



$$\mathcal{L}_{\mathrm{AD}} = \prod_e \prod_p \mathrm{pdf}^{e,p}(v^{e,p})$$

measured arrival directions (in pixels p & energy bins e)



comparison:
likelihood function for only AD analysis

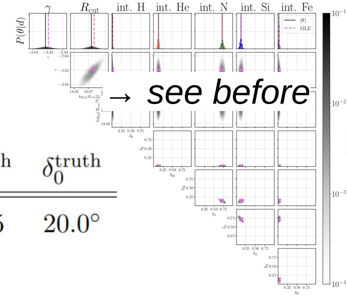
$$\mathcal{L}_{\mathrm{AD-only}}(f_{\mathrm{AD-only}}, \delta_{\mathrm{AD-only}}) = \prod_p \mathrm{pdf}^p(\vec{v}_p))$$

one value for whole data set!

advantages:

- whole energy dependency in model
  - signal contribution depends on propagation
  - rigidity-dependent blurring
  - still only 2 fit parameters (F_0, δ_0)
- no need to scan energy threshold
- more physically correct model: should fit better...

Benchmark simulation

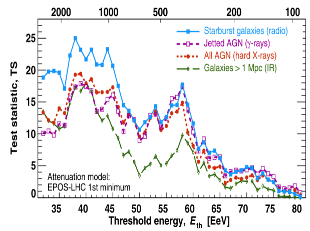


→ *see before*

- **demonstrate fit abilities on benchmark simulation**
- "simulated truth": spectral parameters based on combined fit results (reference model, SFR evolution)

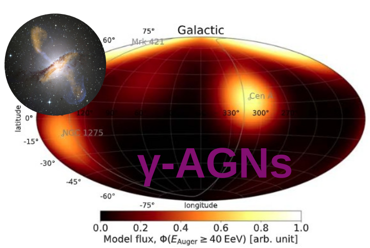
parameter	γ^{truth}	$\log_{10}(R_{\mathrm{cut}}^{\mathrm{truth}}/\mathrm{V})$	$I_{\mathrm{H}}^{\mathrm{truth}}$	$I_{\mathrm{He}}^{\mathrm{truth}}$	$I_{\mathrm{N}}^{\mathrm{truth}}$	$I_{\mathrm{Si}}^{\mathrm{truth}}$	$I_{\mathrm{Fe}}^{\mathrm{truth}}$	f_0^{truth}	$\delta_0^{\mathrm{truth}}$
sim. truth	-3.22	18.09	0%	15%	77%	5.4%	2.6%	0.15	20.0°

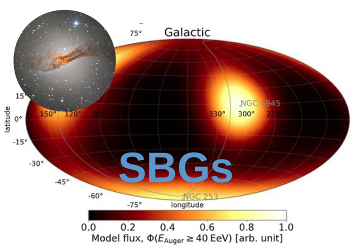
- **add contribution by starburst galaxies** 
  - adapt signal fraction f_0 & blurring δ_0 until simulated arrival directions resemble measured ones
  - apply AD-correlation analysis to 200 random representations of simulation

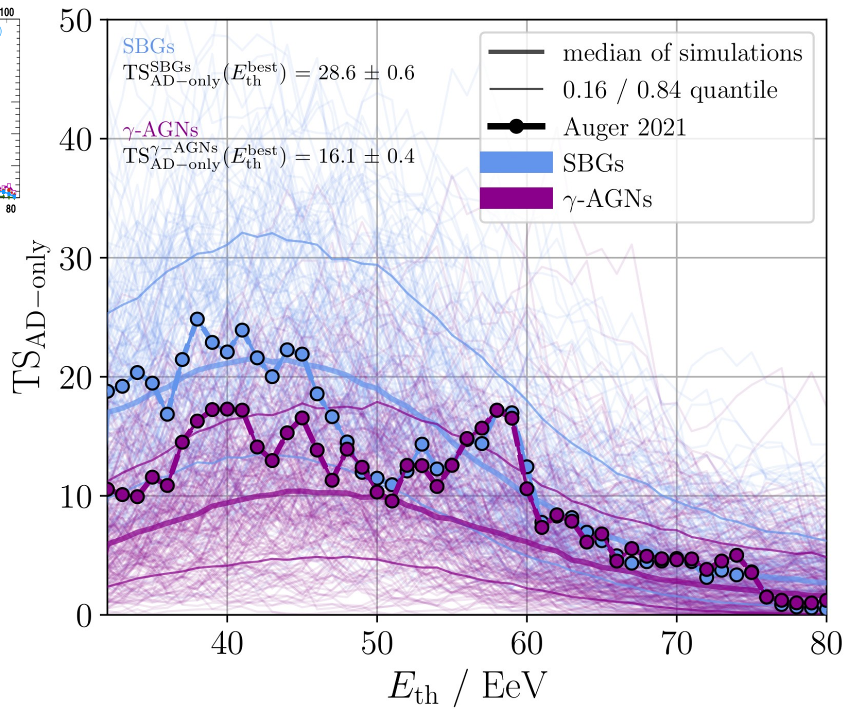


  - **best f_0=15%, δ_0=20°**

    → simulations follow data for both SBGs & γ-AGNs!



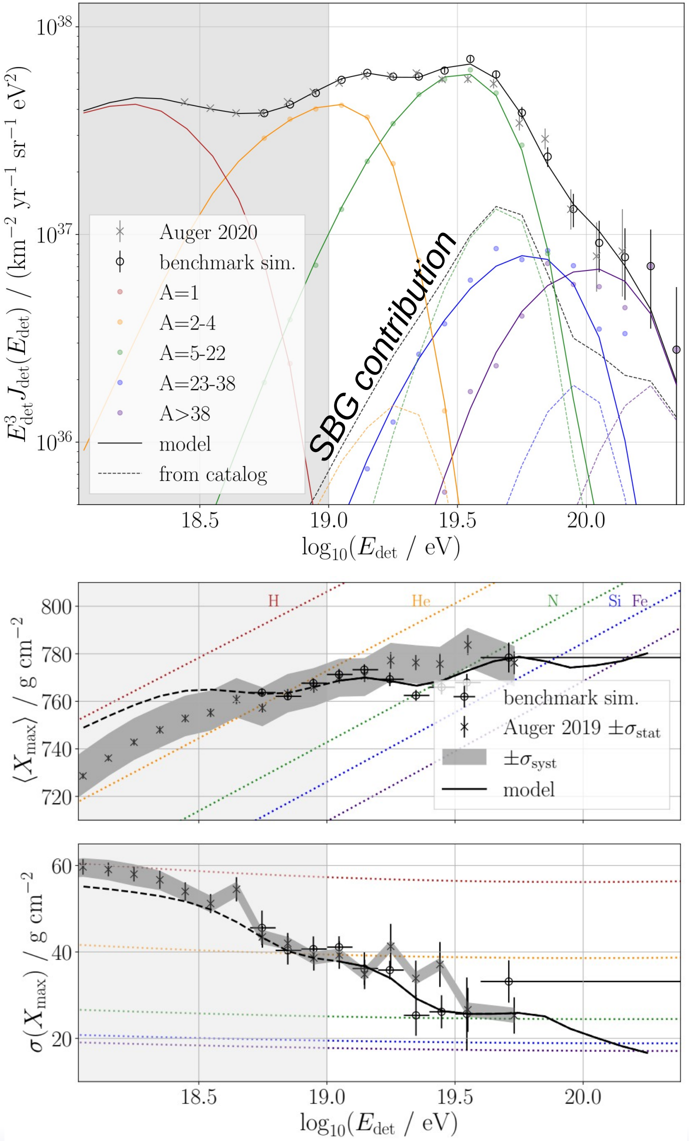


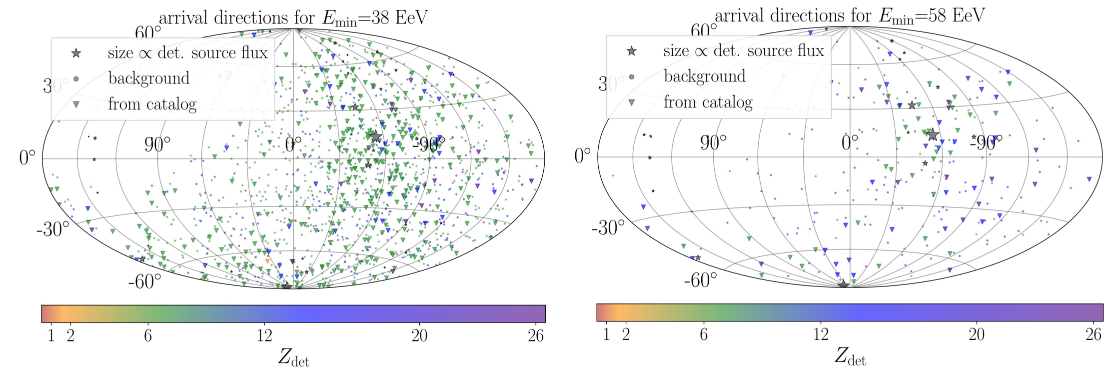


  - but, very large fluctuations of $\mathrm{TS}_{\text{AD-only}}$

    → spikes on data probably also of statistical origin

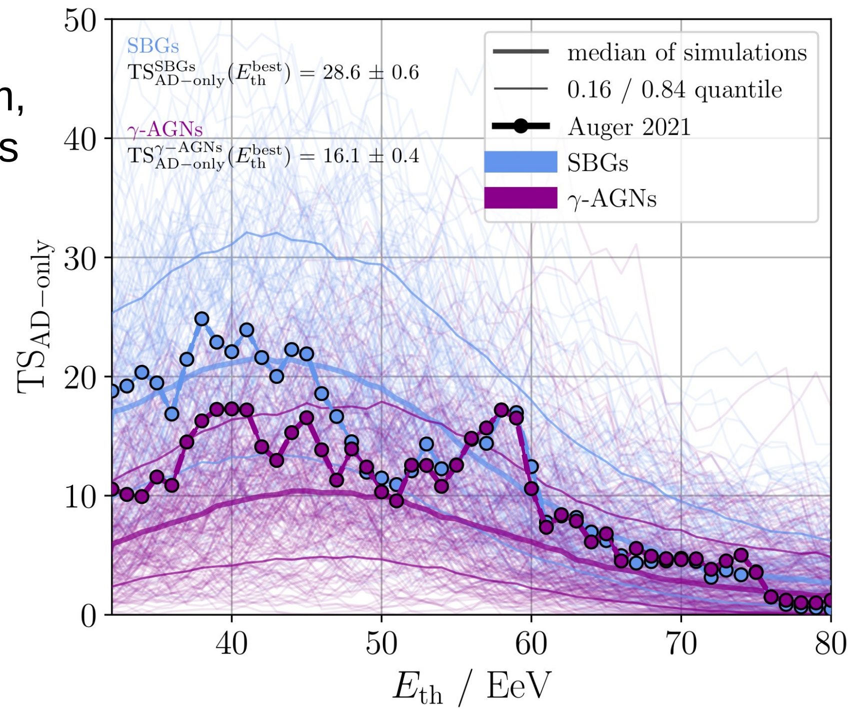
Benchmark simulation



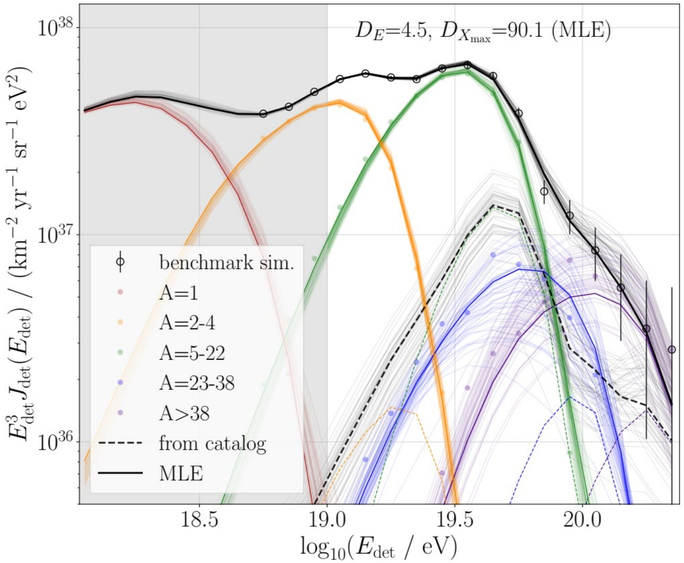


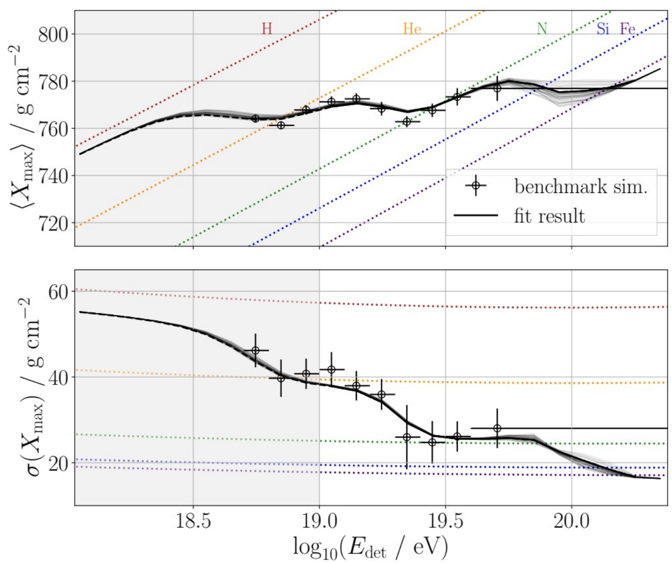
example energy spectrum, shower depth distributions & arrival directions

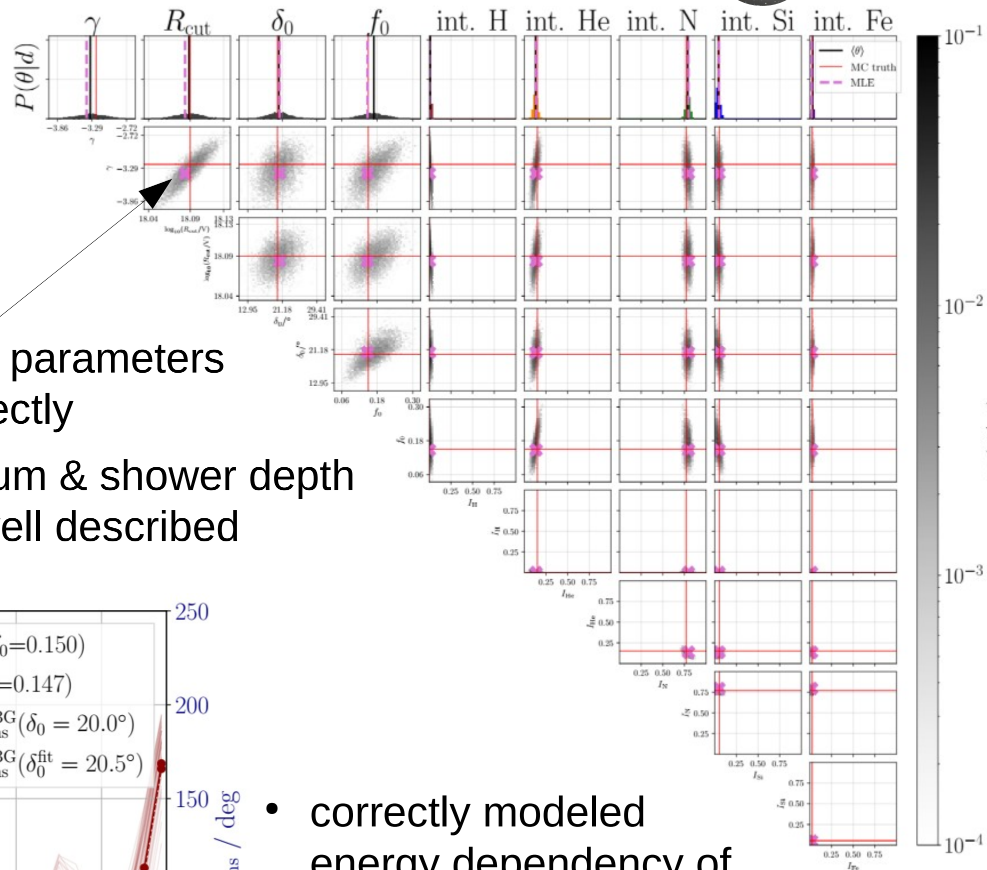
→ all resemble Auger measurements



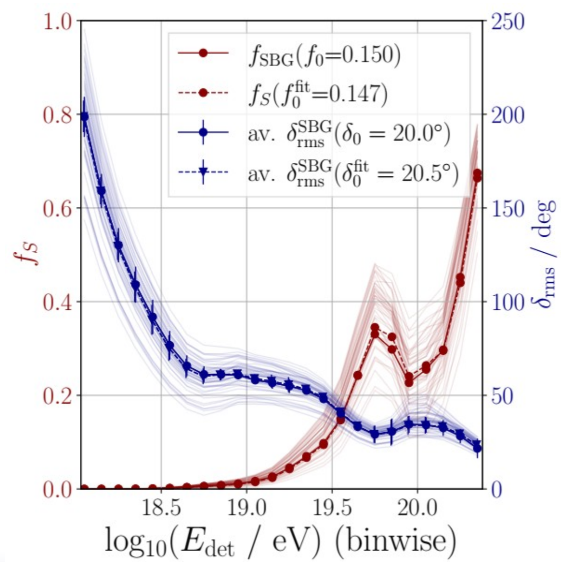
Fit of benchmark simulation: SBG model 







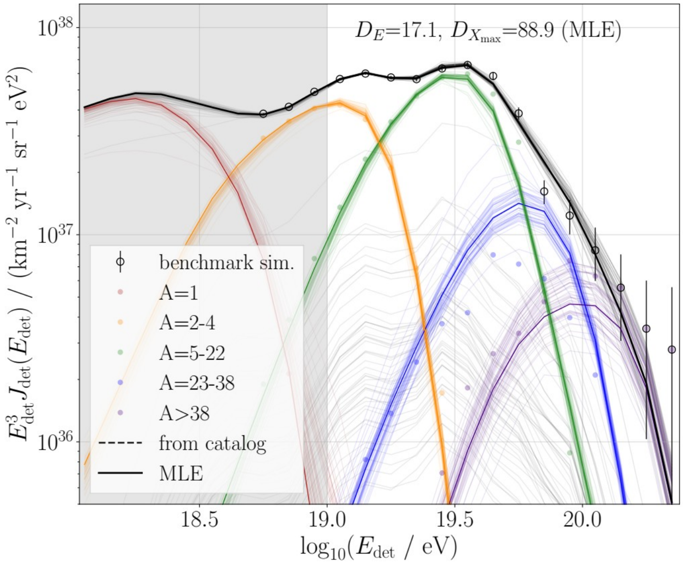
- simulated true parameters identified correctly
- energy spectrum & shower depth distributions well described

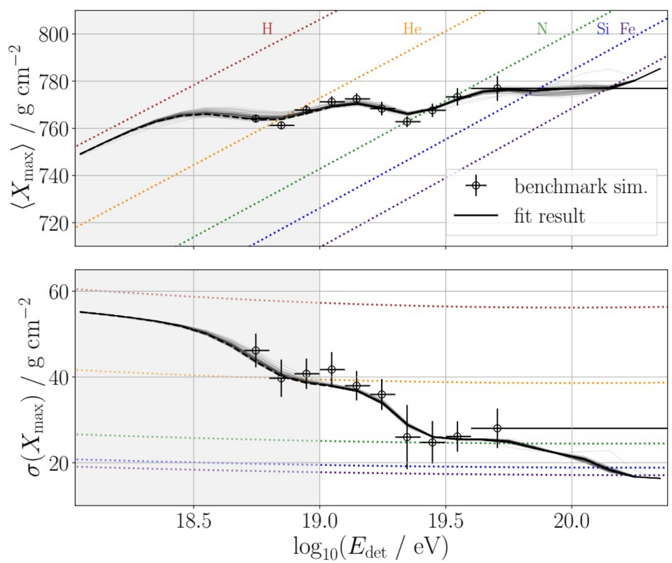


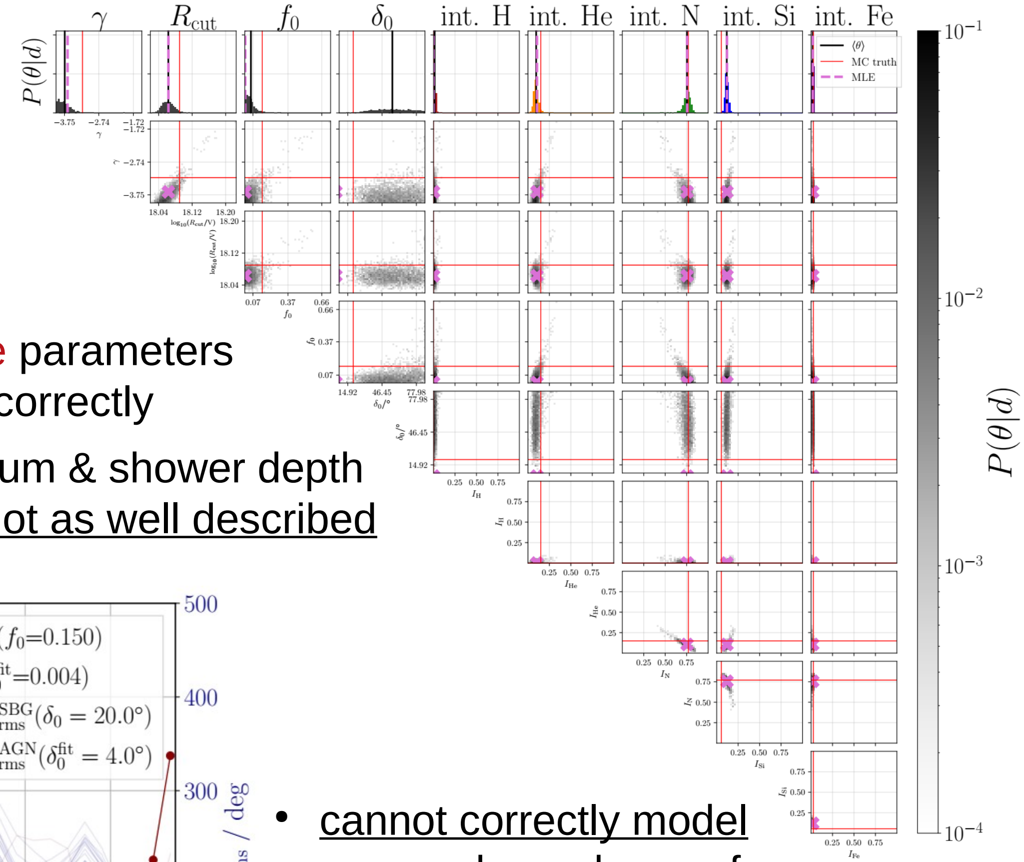
- correctly modeled energy dependency of catalog contribution & magnetic field blurring

Fit of benchmark simulation: AGN model

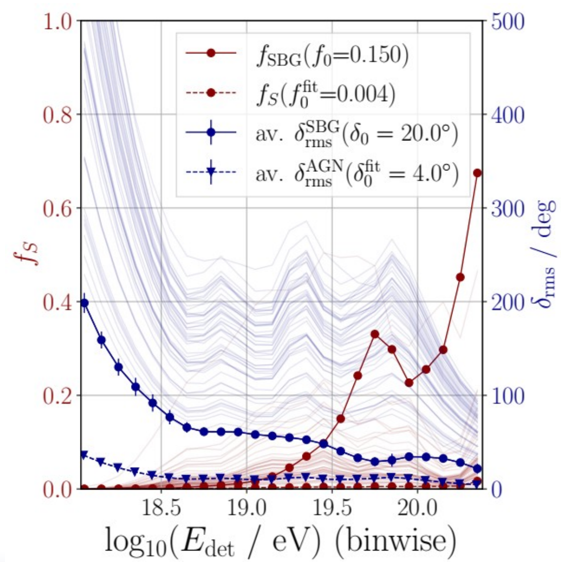
here: also SFR evolution for better comparability







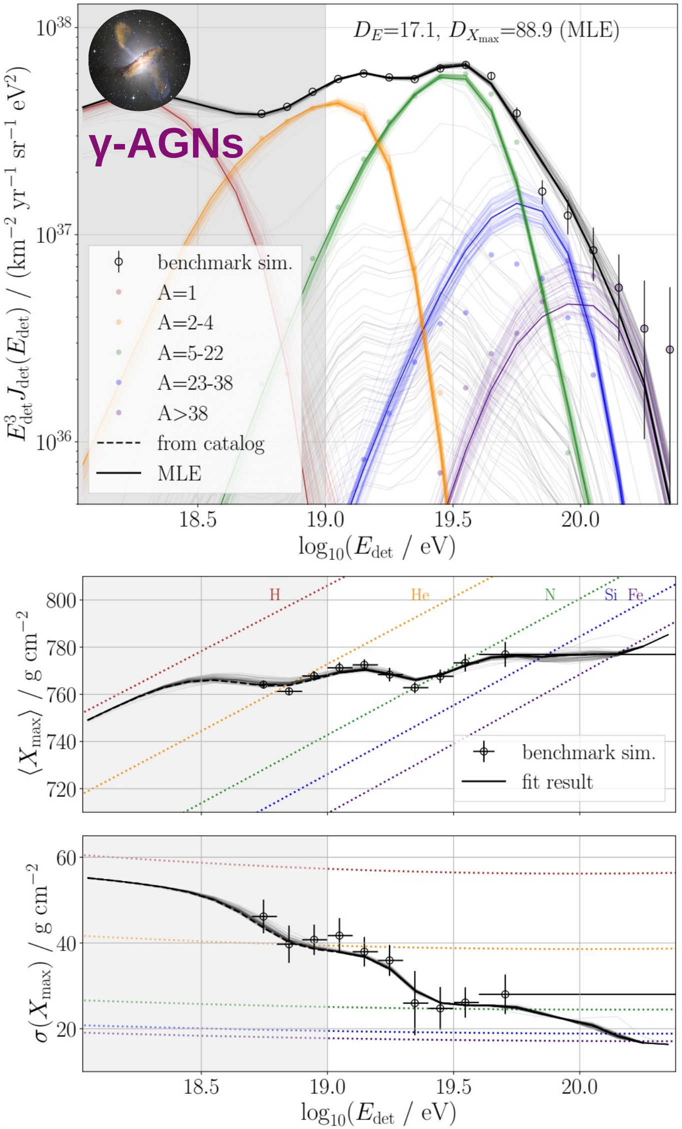
- simulated true parameters not identified correctly
- energy spectrum & shower depth distributions not as well described



- cannot correctly model energy dependency of catalog contribution & magnetic field blurring with incorrect AGN catalog

→ **best-fit f_0 approx. 0**

Fit of benchmark simulation: comparison

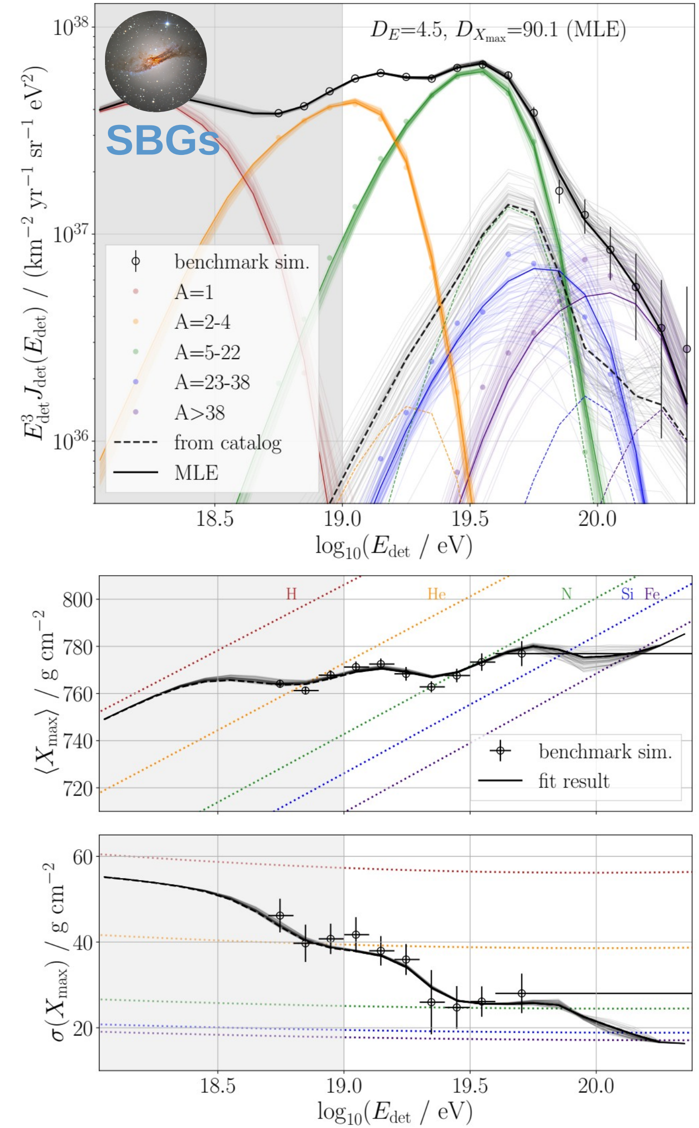


Test statistic:
2*likelihood ratio compared to reference model with f_0=0:

	γ-AGNs	SBGs
TS	**0.4**	**35.6**
TS_E	-2.8	9.8
TS_{Xmax}	0.6	-0.6
TS_{ADs}	2.6	26.4

on this example simulation:
correct model easily identified

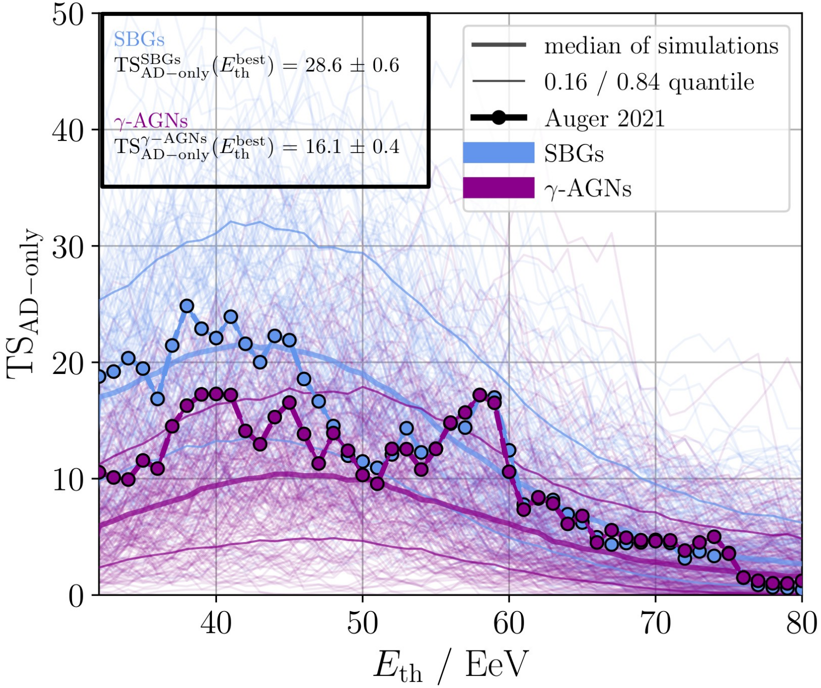
statistically significant?



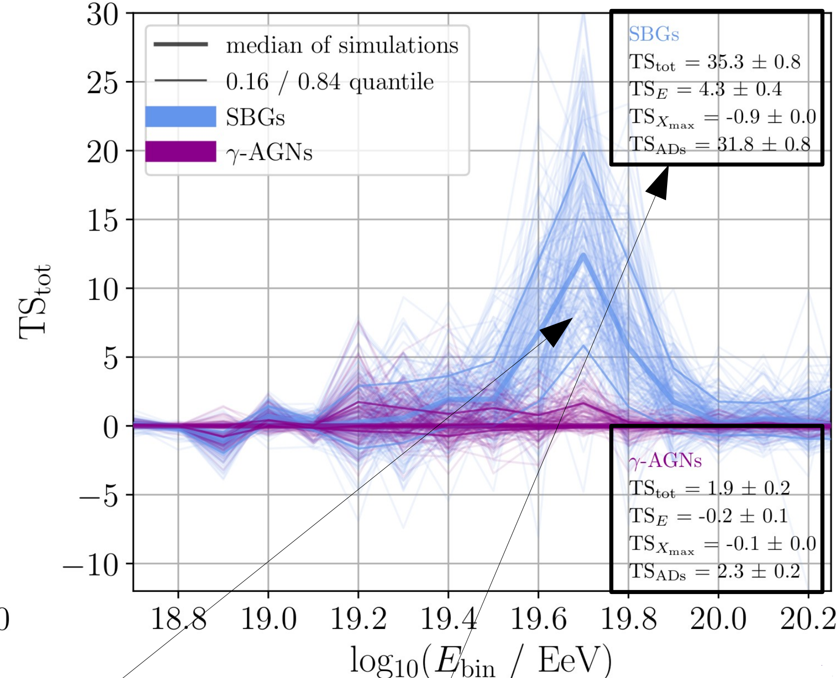
Sensitivity

calculate test statistic of all 200 random representations of benchmark simulation:

AD-only, energy scan:



combined fit with all 3 observables:



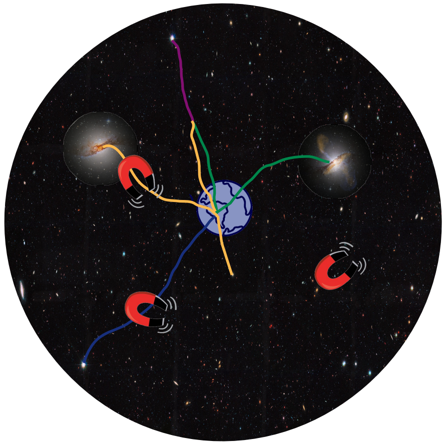
results:
SBG model:
$\mathbf{TS_{SBGs} = 35.3 \pm 0.8}$

γ-AGN model:
$\mathbf{TS_{\gamma\text{-}AGNs} = 1.9 \pm 0.2}$

sweet spot between increasing catalog contribution & decreasing statistics

most important: energy-dependent arrival directions

much greater sensitivity than only arrival directions analysis!



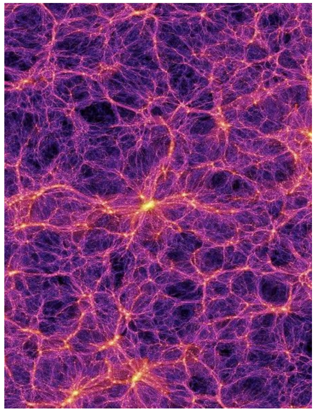
- EGMF can be described by (rms) field stregth B and coherence length l_c

- follow Mollerach & Roulet
  - critical energy:

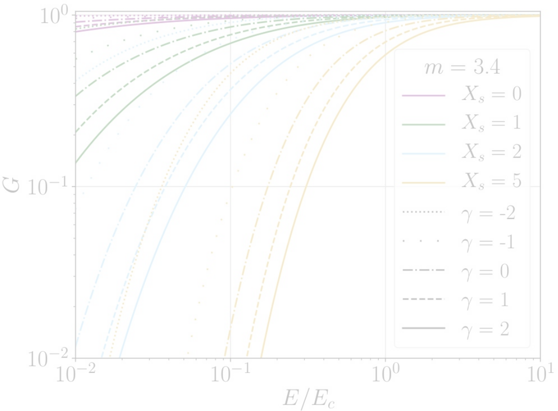
$$r_L(E_c) = l_c \quad \rightarrow \quad E_c = Z\ e\ B\ l_c \simeq 0.9\ Z\ \frac{B}{\mathrm{nG}} \frac{l_c}{\mathrm{Mpc}} \mathrm{EeV}$$

  - scale parameter: $X_s := \frac{d_s}{\sqrt{R_H l_c}} \simeq \frac{d_s}{65\ \mathrm{Mpc}} \sqrt{\frac{\mathrm{Mpc}}{l_c}}$
    relates coherence length l_c to typical source distance d_s (here SBGs: $n_s = 10^{-5}\ \mathrm{Mpc}^{-3}$)

S. Mollerach and E. Roulet. "Extragalactic cosmic rays diffusing from two populations of sources". *Physical Review D* 101.10 (2020), 103024. DOI: 10.1103/PhysRevD.101.103024.

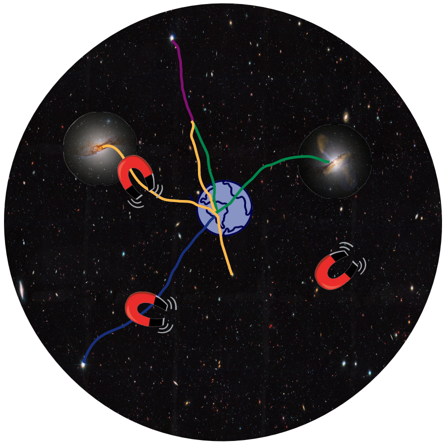


- **EGMF influence on the cosmic ray energy spectrum:**
  - suppression of further away sources due to diffusion $G(E) = \frac{J(E)}{J(E)|_{d_s \to 0}}$
  - parameterized suppression factor G as a function of X_s & E_c
  - multiply with modeled spectrum

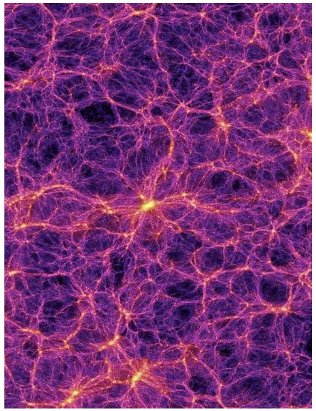


- **EGMF influence on arrival direction:**
  - calculate from X_s, E_c & rigidity for non-resonant scattering approximation
  - use in Fisher distributions $\beta_{\mathrm{EGMF}}(d, R = E/Z, l_c, B) = 25° \cdot Z \cdot \sqrt{\frac{l_c}{\mathrm{Mpc}}} \cdot \sqrt{\frac{d}{\mathrm{Mpc}}} \cdot \frac{\mathrm{EeV}}{E} \cdot \frac{B}{\mathrm{nG}}$

EGMF



- EGMF can be described by (rms) field stregth B and coherence length l_c



- follow Mollerach & Roulet

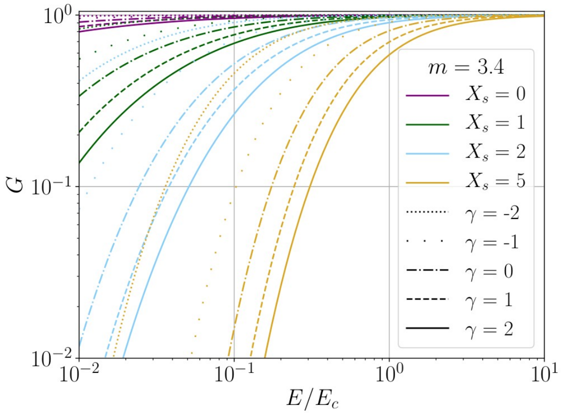
S. Mollerach and E. Roulet. "Extragalactic cosmic rays diffusing from two populations of sources". *Physical Review D* 101.10 (2020), 103024. DOI: 10.1103/PhysRevD.101.103024.

  - critical energy:

$$r_L(E_c) = l_c \quad \rightarrow \quad E_c = Z\ e\ B\ l_c \simeq 0.9\ Z\ \frac{B}{\text{nG}}\frac{l_c}{\text{Mpc}}\text{EeV}$$

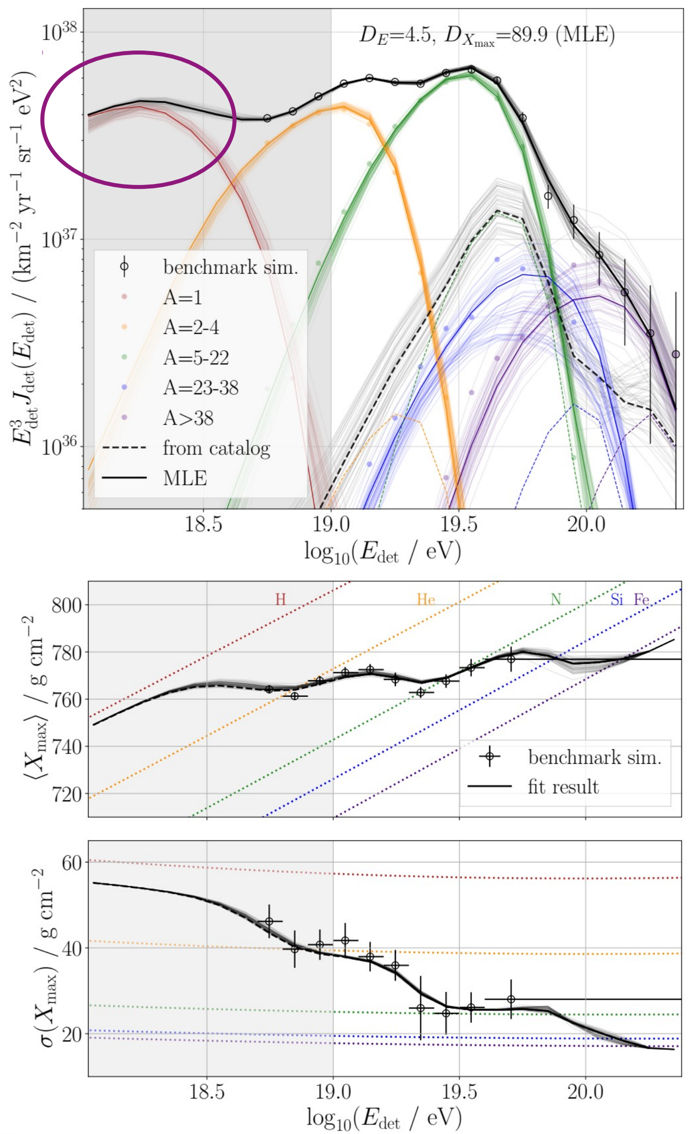
  - scale parameter: $X_s := \frac{d_s}{\sqrt{R_H l_c}} \simeq \frac{d_s}{65\ \text{Mpc}}\sqrt{\frac{\text{Mpc}}{l_c}}$
    relates coherence length l_c to typical source distance d_s (here SBGs: $n_s = 10^{-5}\ \text{Mpc}^{-3}$)

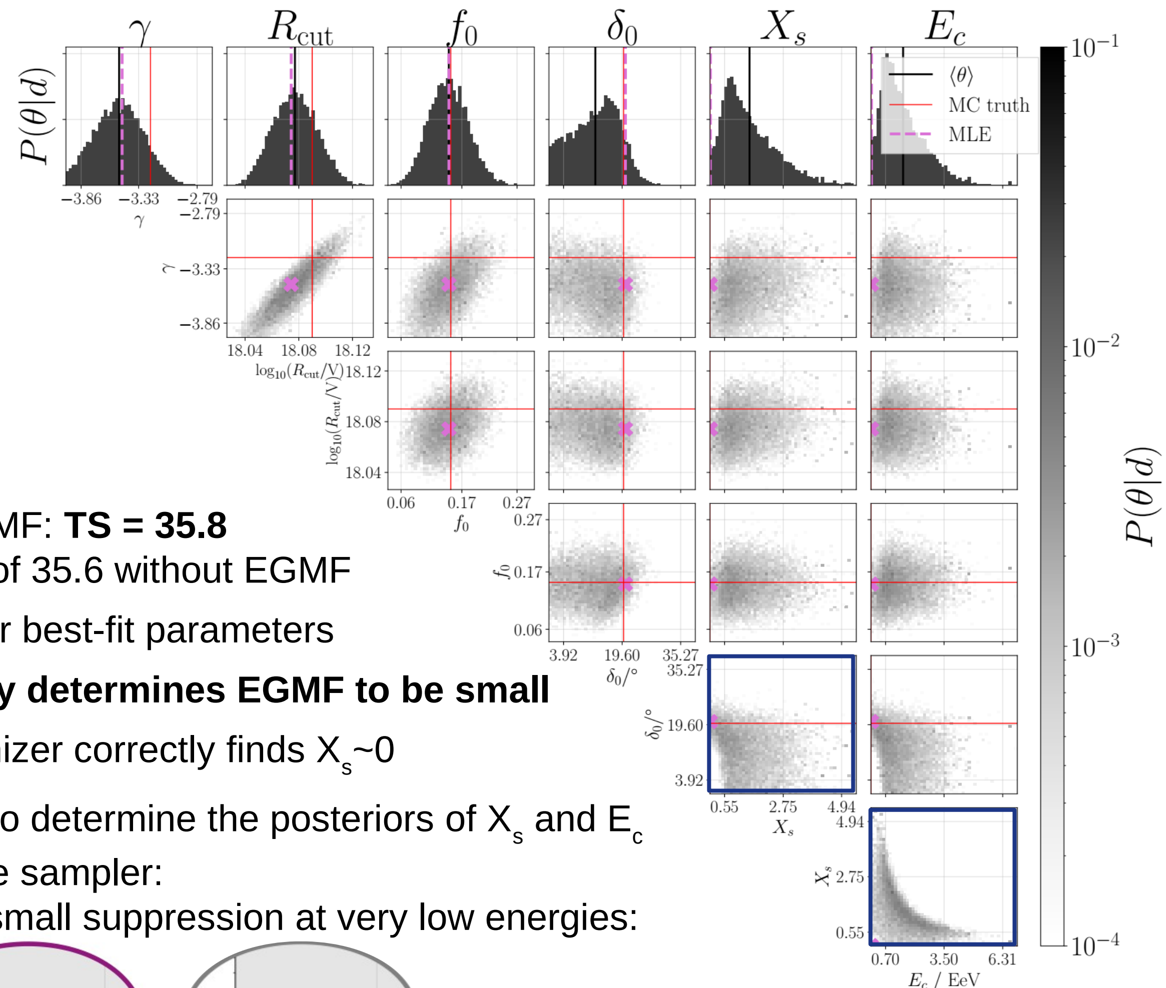
- **EGMF influence on the cosmic ray energy spectrum:**
  - suppression of further away sources due to diffusion $G(E) = \frac{J(E)}{J(E)|_{d_s \to 0}}$
  - parameterized suppression factor G as a function of X_s & E_c
  - multiply with modeled spectrum



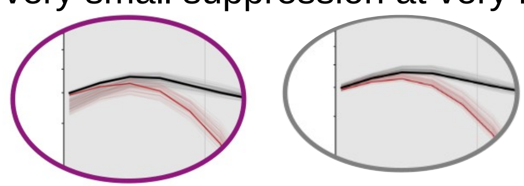
- **EGMF influence on arrival direction:**
  - calculate from X_s, E_c & rigidity for non-resonant scattering approximation
  - use in Fisher distributions $\beta_{\text{EGMF}}(d, R = E/Z, l_c, B) = 25° \cdot Z \cdot \sqrt{\frac{l_c}{\text{Mpc}}} \cdot \sqrt{\frac{d}{\text{Mpc}}} \cdot \frac{\text{EeV}}{E} \cdot \frac{B}{\text{nG}}$

Fit with EGMF: SBG model





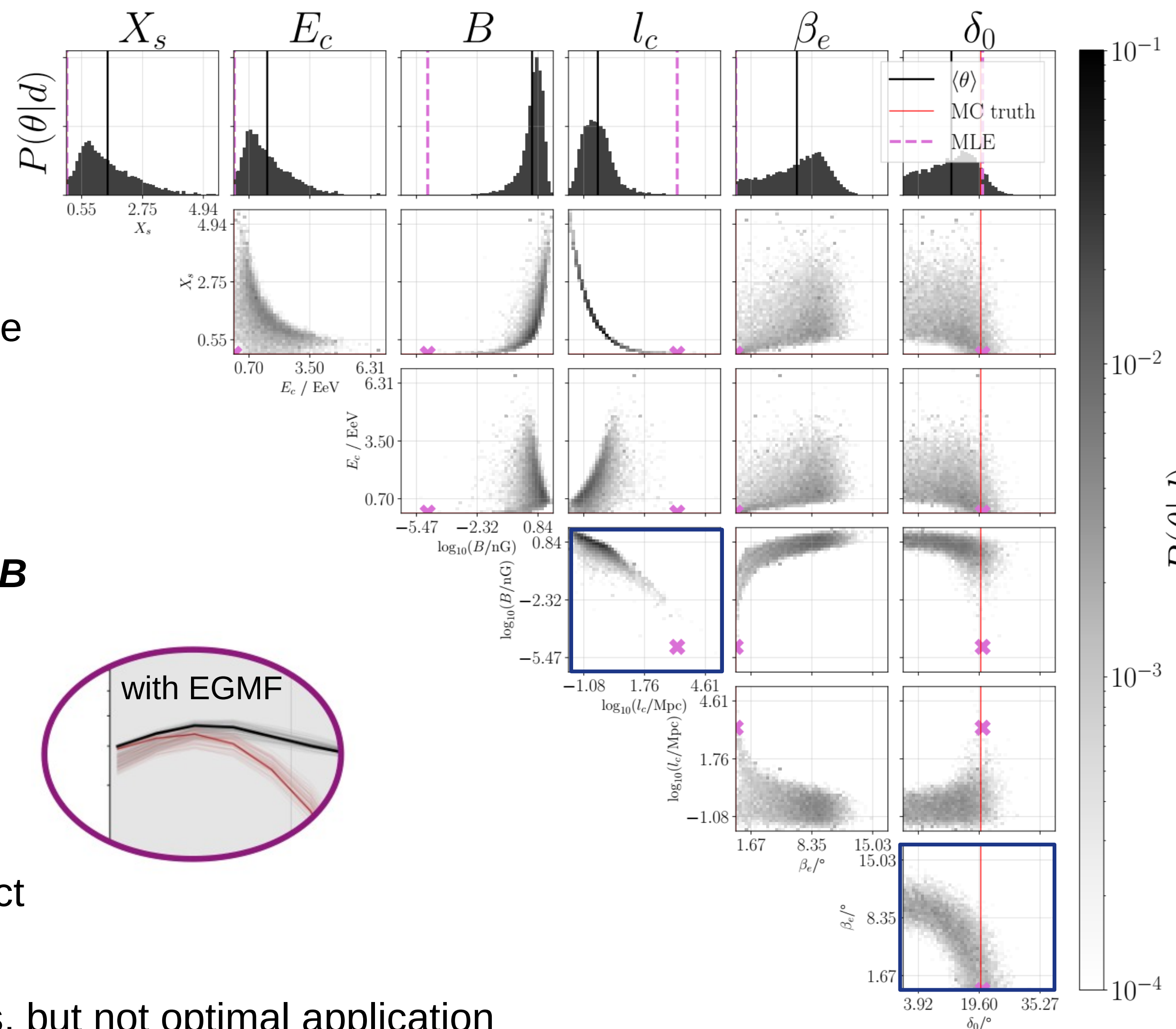
- with EGMF: **TS = 35.8** instead of 35.6 without EGMF
  - similar best-fit parameters
- **correctly determines EGMF to be small**
  - minimizer correctly finds X_s~0
  - hard to determine the posteriors of X_s and E_c for the sampler: very small suppression at very low energies:



with EGMF　　without EGMF

Fit with EGMF: EGMF parameters

- can calculate **EGMF parameter posteriors** from E_c and X_s posteriors
- e.g. EGMF blurring β_e: expected anticorrelation with local blurring visible
- calculate posteriors for B and l_c
  → could set limits
- **overestimates EGMF field strength *B***
  - would work better for stronger field strengths with larger suppressions up to higher energies
  - or: decrease energy threshold and model also lower energies where suppression has larger impact



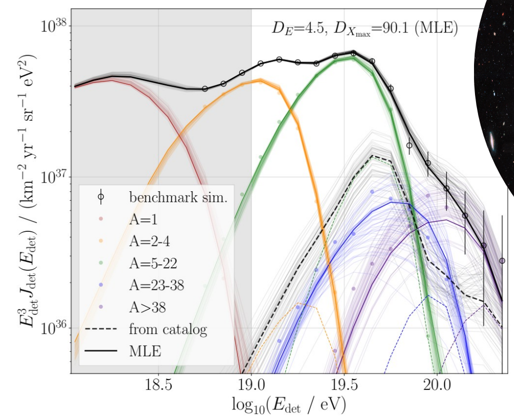
demonstration that principle works, but not optimal application

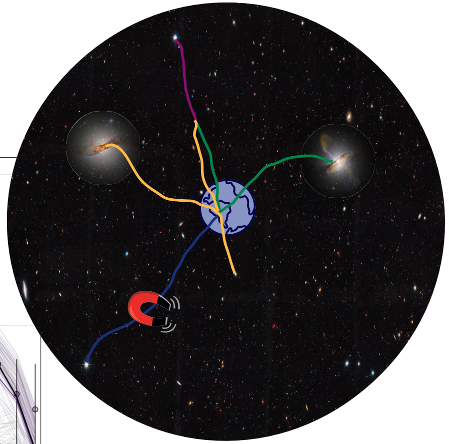
- demonstrated simultaneous **combined fit of energy spectrum, shower depth distributions, and arrival directions**

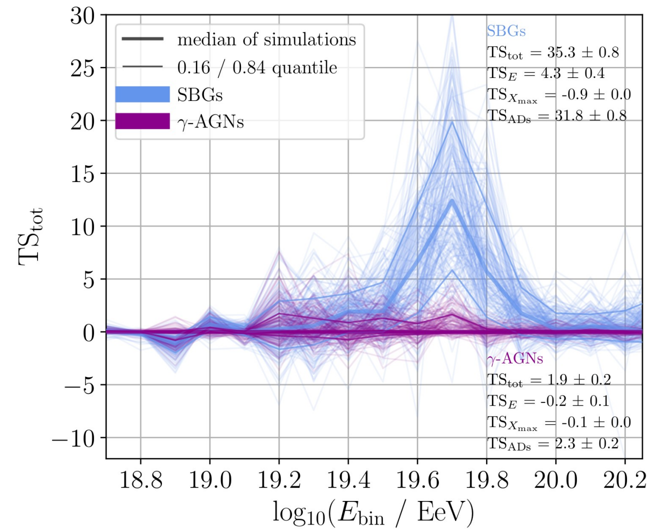
- astrophysical model is assembled from **1d CRPropa3** simulations:
  → fast, easily adaptable to include e.g. (E)GMF

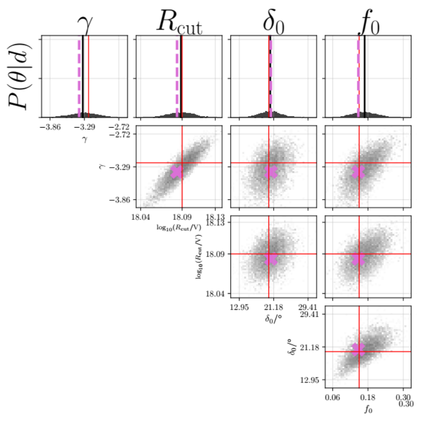
- **benchmark simulation with SBGs as sources can reproduce all 3 observables**

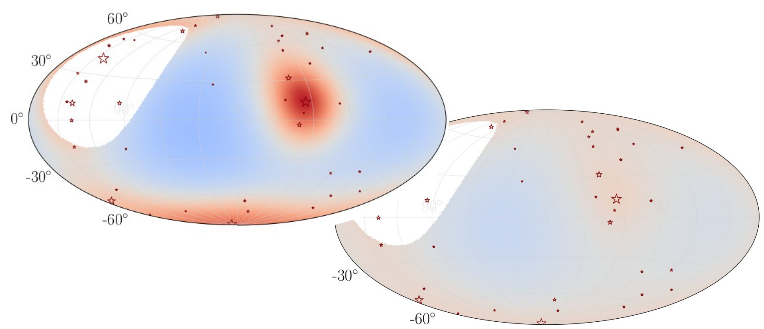
- significantly **larger sensitivity** to distinguish catalogs












thanks for listening!
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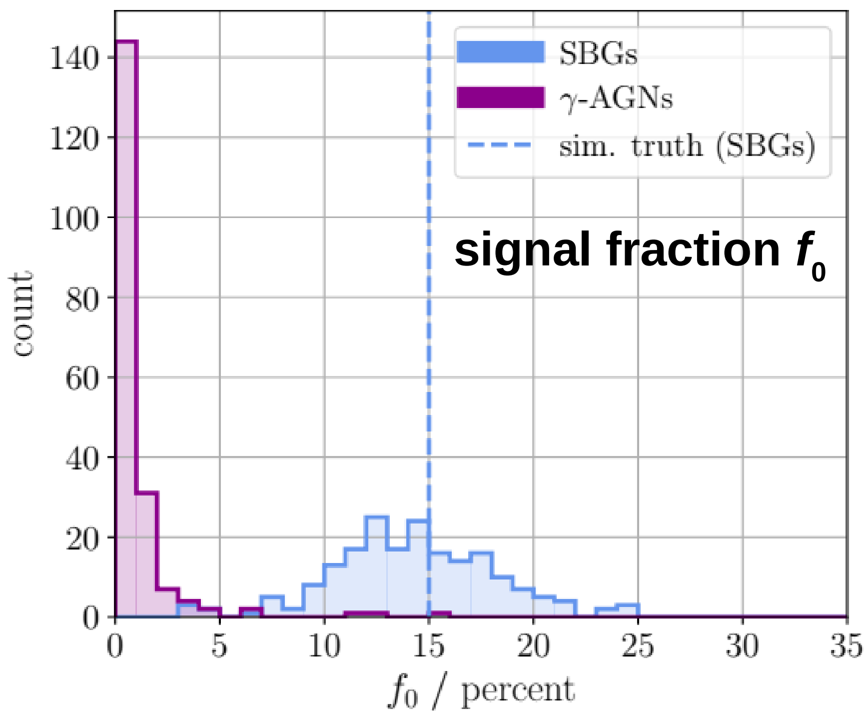
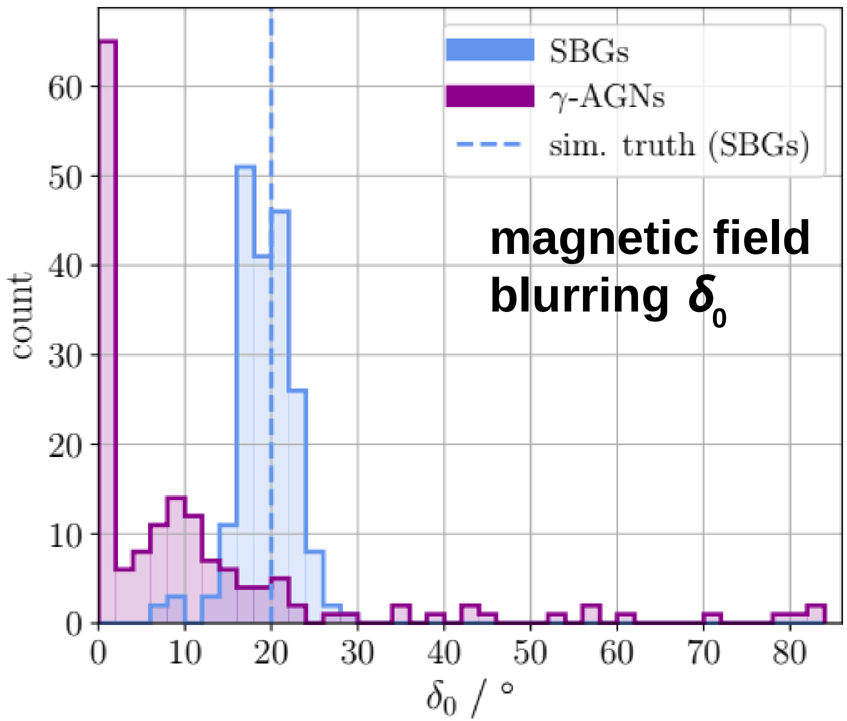
Sensitivity to best-fit parameters

for incorrect model:
often reconstructs signal fraction f_0=0 because observables cannot be described with wrong catalog

for correct model:
reliable reconstruction of simulated truth





Conversion of TS to significance

T. Bister for the Pierre Auger Collaboration, *A combined fit of energy spectrum, shower depth distribution and arrival directions to constrain astrophysical models of UHECR sources*, in *Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021)*, vol. 395, p. 368, 2021, DOI.

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

  → $\boxed{p_{SBG} \simeq 9 \cdot 10^{-8}}$ $\boxed{p_{AGN} \simeq 5 \cdot 10^{-3}}$ → **analysis can identify true simulated SBG model**
- **more sensitive** than AD-only analysis on same simulation: $\boxed{p_{SBG}^{\text{AD-only, pre-trial}} \simeq 6.1 \cdot 10^{-6}}$ $\boxed{p_{AGN}^{\text{AD-only, pre-trial}} \simeq 1.7 \cdot 10^{-3}}$
- **no need for energy threshold scan → no penalization**