Sensitivity of the combined fit of energy spectrum, shower depth distributions, and arrival directions at the Pierre Auger Observatory

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PIERRE AUGER OBSERVATORY

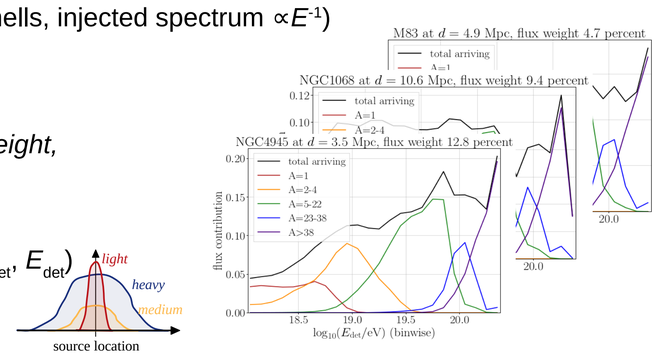
Astrophysical model & combined fit

Model:

- **sources:** homogeneously distributed background sources (SFR evolution) + contribution from catalogs of starburst galaxies (SBGs) or *γ*-ray emitting active galactic nuclei (*γ*-AGNs) [1]
- **emission**: Peter's cycle
- **propagation:** database CRPropa (1d trajectories, 5 elements, 118 distance shells, injected spectrum $\propto E^{-1}$)

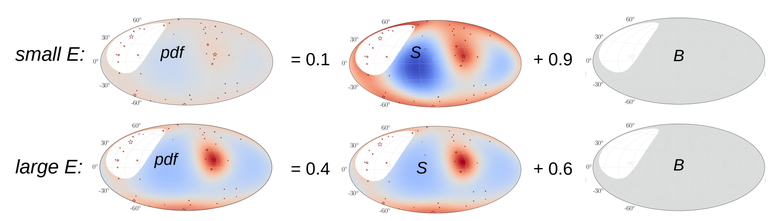
$$J_{\rm inj}(E_{\rm inj}, A_{\rm inj}) = J_0 \cdot a_A \cdot \left(\frac{E_{\rm inj}}{10^{18}\ {\rm eV}}\right)^{-\gamma} f_{\rm cut}\left(\frac{E_{\rm inj}}{Z_A R_{\rm cut}}\right)$$

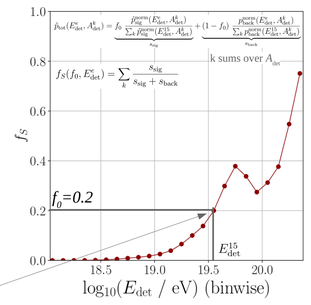
- for each **catalog source:**
  - **contribution on Earth** ↔ *distance, flux weight, position (observatory exposure), injection*
  - **arrival directions maps** $S(E^e_{\rm det}, {\rm pix}^p)$**:**
    - → add Fisher distributions for each bin ($A_{\rm det}$, $E_{\rm det}$)
    - → rigidity-dependent $\delta = \frac{\delta_0}{R/10\ {\rm EV}}$



- add up catalog contribution + background:

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





- catalog contribution f_S rises with energy (catalog sources closer)
- fit parameter: signal fraction f_0 defined at $10^{19.5}$ eV - $10^{19.6}$ eV

Likelihood function:

Poissonian [2] (one-sided for $10^{18.7}$ eV - $10^{19.0}$ eV)

Multinomial [2]

based on [1]: how well do modeled arrival maps $\mathrm{pdf}^{e,p}$ describe measured arrival directions $v^{e,p}$ in each energy bin $E^e_{\rm det}$?

$$\log\mathcal{L} = \log\mathcal{L}_E + \log\mathcal{L}_{\rm Xmax} + \log\mathcal{L}_{\rm AD} \qquad \mathcal{L}_{\rm AD} = \prod_e \prod_p \mathrm{pdf}^{e,p}(v^{e,p})$$

Inference of model parameters:

- posterior distributions from Sequential Monte Carlo sampler
- best-fit from gradient-based minimizer

PyMC

Benchmark simulation

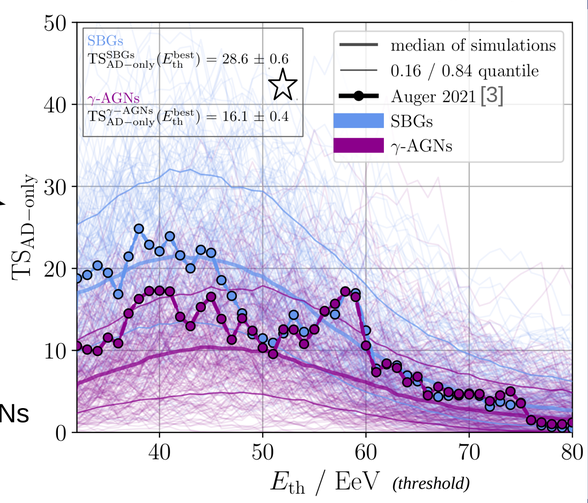
- spectral parameters **based on combined fit results** with fixed f_0=0, SFR evolution

parameter	$\gamma^{\rm truth}$	$\log_{10}(R^{\rm truth}_{\rm cut}/{\rm V})$	$I^{\rm truth}_{\rm H}$	$I^{\rm truth}_{\rm He}$	$I^{\rm truth}_{\rm N}$	$I^{\rm truth}_{\rm Si}$	$I^{\rm truth}_{\rm Fe}$	$f_0^{\rm truth}$	$\delta_0^{\rm truth}$
sim. truth	−3.22	18.09	0%	15%	77%	5.4%	2.6%	0.15	20.0°

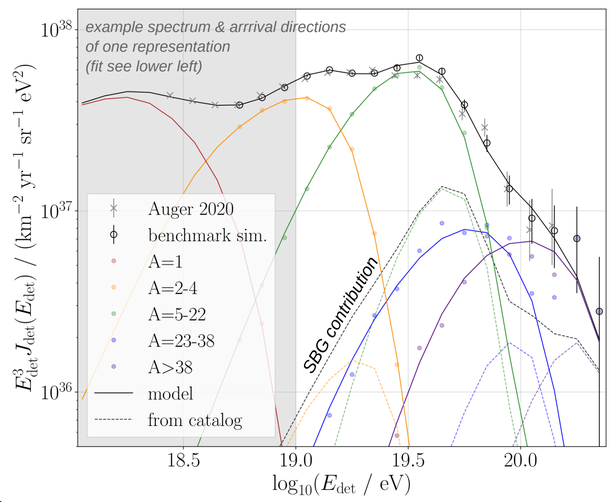
$$\mathcal{L}_{\rm AD-only}(f_{\rm AD-only}, \delta_{\rm AD-only}) = \prod_i \mathrm{pdf}_i(\vec{v}_i))$$

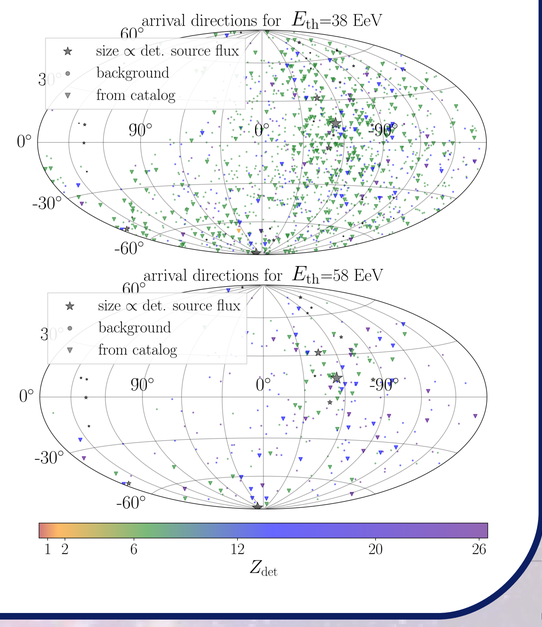
$$\mathrm{TS}_{\rm AD-only} = 2\log\frac{\mathcal{L}_{\rm AD-only}(f_{\rm AD-only}, \delta_{\rm AD-only})}{\mathcal{L}_{\rm AD-only}(f_{\rm AD-only}=0)}$$

- **contribution from SBGs:**
  - adapt signal fraction f_0 & blurring δ_0
    ↔ simulated arrival directions resemble measured ones
  - for that: apply AD-correlation analysis / stacking [1] to 200 simulation representations



- **resulting benchmark simulation:**
  - 15% signal fraction at $10^{19.5}$ eV - $10^{19.6}$ eV
  - 20° blurring for R = 10 EV, no coherent GMF
  - in median reproduces data for both SBGs & *γ*-AGNs
    - but: very large statistical fluctuations of $\mathrm{TS}_{\rm AD-only}$!
      → spikes on data most likely of statistical origin
  - also resembles spectrum & $X_{\rm max}$ measurements



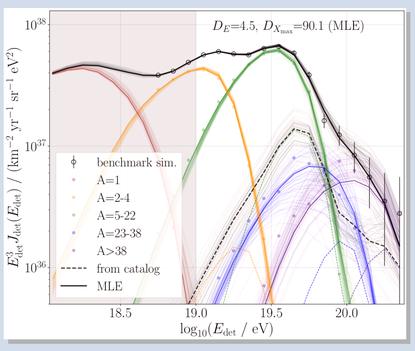


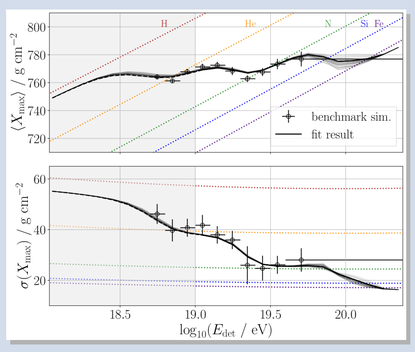
Fit result

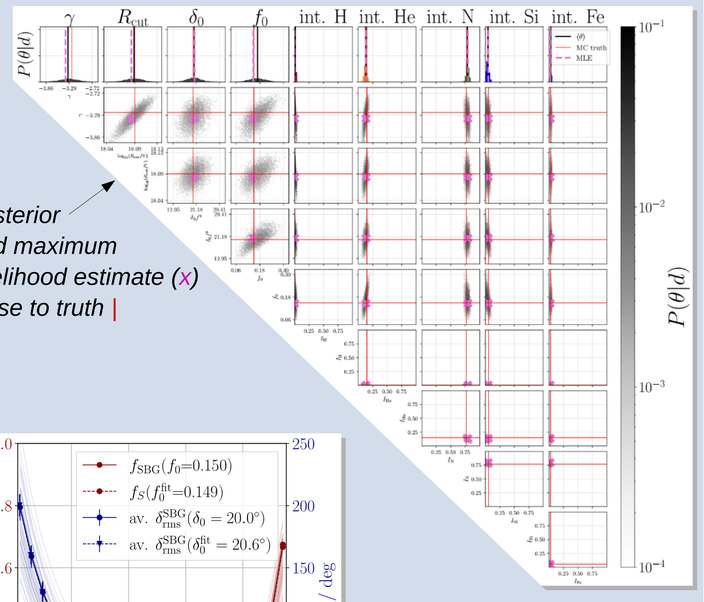
Example fit of one representation of Benchmark simulation

SBG model *(=sim. truth)*

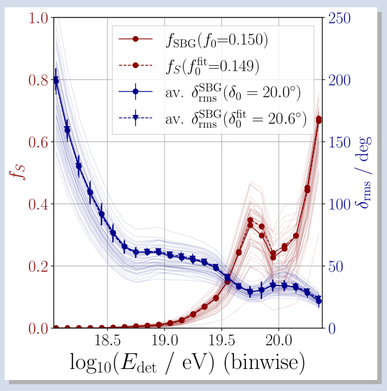
- good parameter reconstruction
- spectrum + $X_{\rm max}$ well described







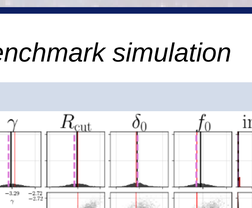
posterior and maximum likelihood estimate (x) close to truth

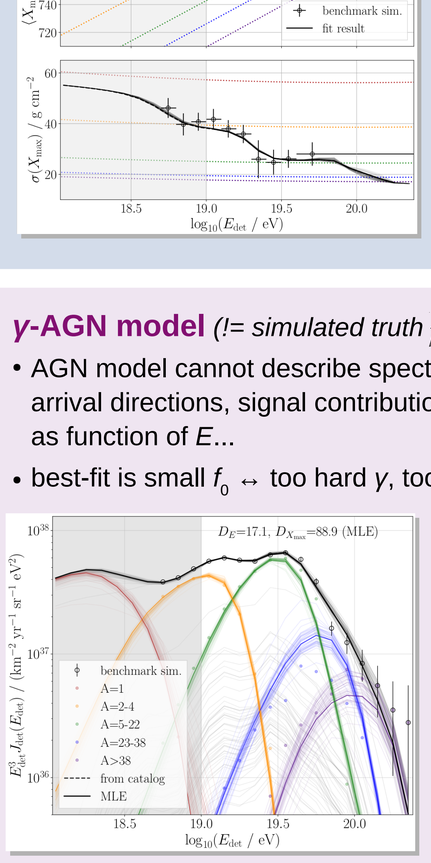


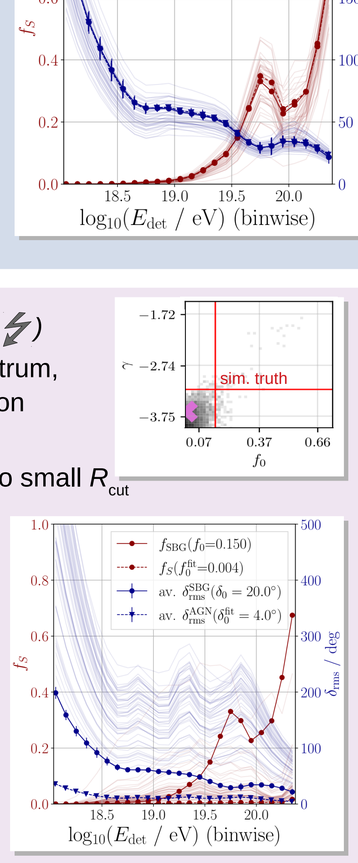
mean blurring and signal contribution modeled correctly

γ-AGN model *(!= simulated truth ⚡)*

- AGN model cannot describe spectrum, arrival directions, signal contribution as function of *E*...
- best-fit is small f_0 ↔ too hard *γ*, too small $R_{\rm cut}$







simulated truth identified easily

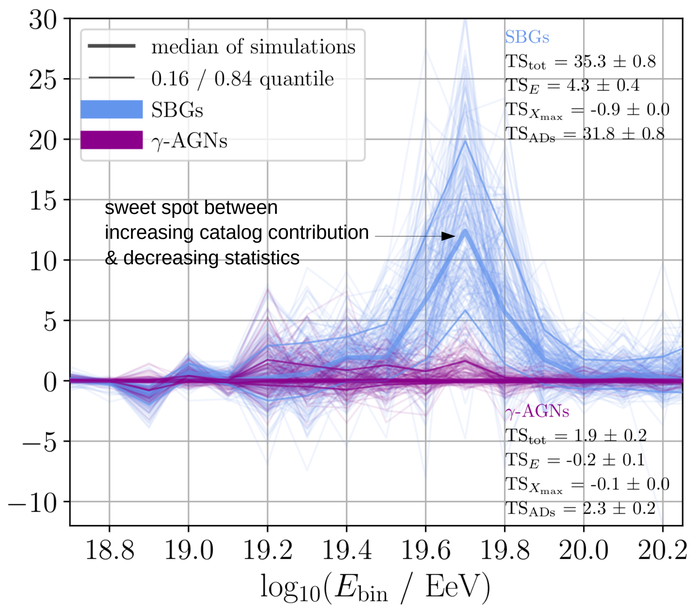
Fit quality
likelihood ratio compared to model with f_0=0:

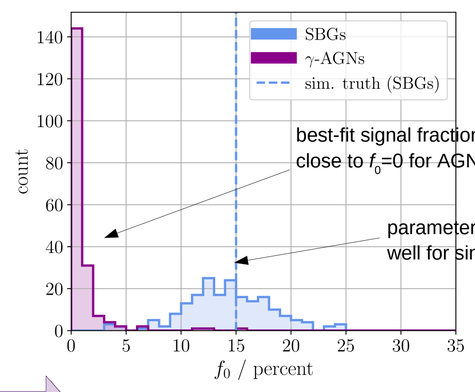
	SBGs	γ-AGNs
TS	**35.6**	**0.4**
$\mathrm{TS}_{\rm E}$	9.8	-2.8
$\mathrm{TS}_{\rm Xmax}$	-0.6	0.6
$\mathrm{TS}_{\rm ADs}$	26.4	2.6

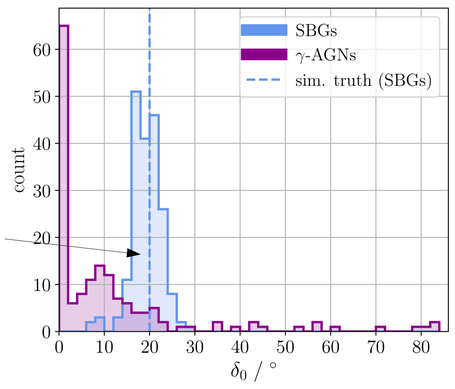
Sensitivity estimation

- on example simulation *(see left)* true model (here SBGs) easily identified
- investigate statistical significance → apply to benchmark simulation representations *(above)*

- **results:**
  - SBG model test statistic: **$\mathrm{TS}_{\rm SBGs}$ = 35.3 ± 0.8**
  - ≫ than only ADs *(compare ☆)*
  - *γ*-AGN model test statistic: **$\mathrm{TS}_{\gamma\text{-AGNs}}$ = 1.9 ± 0.2**
  - ≪ than only ADs *(compare ☆)*
  - energy-dependent arrival directions most important for source identification
  - $X_{\rm max}$ currently not as important (small statistics at high *E*)







- **benchmark simulation application: largely improved sensitivity to source catalog** compared to only arrival direction analysis [1] *(see above)*
- TS to significance: X^2-distribution with ndf=2 (f_0, δ_0) [4]
- **no energy scan threshold necessary**
  → **capture whole energy dependency in model**

stay tuned for data application!

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References

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