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Arrival directions of the highest-energy cosmic rays detected with the Pierre Auger Observatory

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Introduction

▶ We search for the presence of anisotropies at small/intermediate scale in the distribution of arrival directions of the most energetic CRs to find their sources.

▶ We analyze the angular distribution of CRs, looking for an «intrinsic» anisotropy signal without any reference to astrophysical objects.

▶ We search in the direction of potential astrophysical sources using three complementary catalogs.

The details of these analyses together with the list of arrival directions and energies of the events can be consulted in:

«Searches for anisotropies in the arrival directions of the highest energy cosmic rays detected by The Pierre Auger Observatory», The Pierre Auger Collaboration, ApJ, 804 , 15, (2015) [astro-ph/1411.6111]
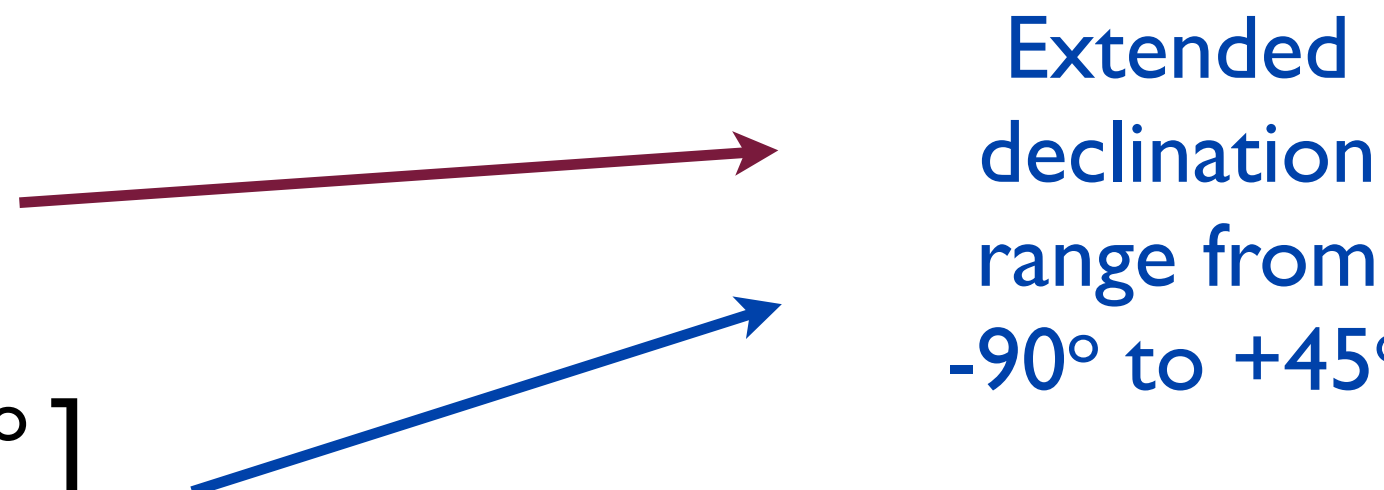
Motivation

▸ Recent limits* on the flux of UHE photons strongly disfavor top-down models: *see talk by C.Bleve, in the NU 04 session

➡ search for an astrophysical origin of CRs.

▸ Magnetic deflections are proportional to Z / E (typical value ~ 6° at 50 EeV for protons in the GMF):

➡ use the highest energy CRs

▸ Strong suppression observed in the energy spectrum* above ~ 40 EeV: *see talk by I.Valiño, in the CR17 EAS spec session

➡ GZK cut-off ? sources must be within ~ 200 Mpc.

❖ Search at high energy for correlation between CR arrival directions and the position of nearby astrophysical sources

The data set

▸ Events detected by the Surface Detector of the Pierre Auger Observatory from 1st Jan. 2004 - 31st March 2014, with ~ 66,500 km^2 sr yr exposure.

▸ 602 events with reconstructed energy E > 40 EeV.

▸ Combination of two data sets:

  - 454 «vertical» events with zenith angle $\theta \in$ [0°; 60°]

  - 148 «horizontal» events with zenith angle $\theta \in$ [60° ; 80°]

Extended declination range from -90° to +45°

▸ Angular resolution (68% containment radius) better than 0.9° for E>10 EeV.

▸ Statistical uncertainty on energy better than 12% for E>10 EeV, with 14% systematic on the absolute energy scale.
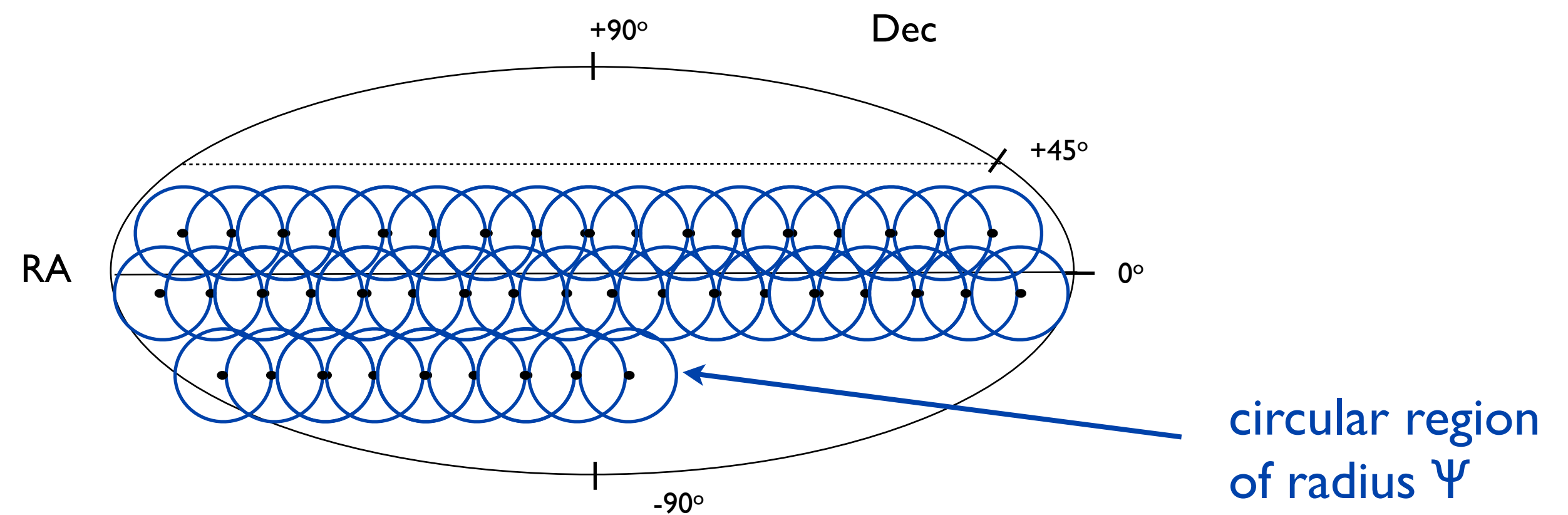
«Intrinsic» anisotropy tests

▸ Aim: characterize the distribution of CR arrival directions without any reference to astrophysical objects.

Two different methods:

Angular auto-correlation function ACF(Ψ): count the number of pairs n_{data} of CR events within angular radius Ψ.
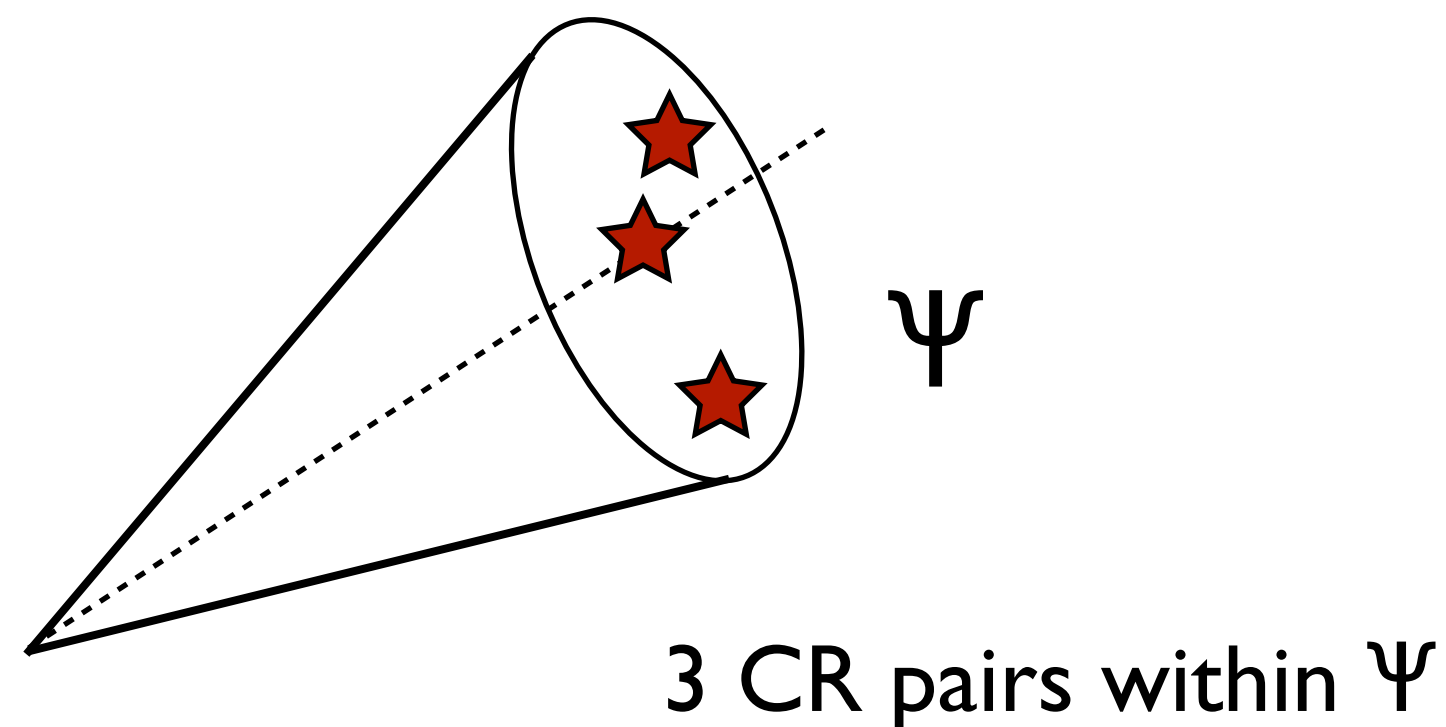
Blind search for excesses: count the number of events n_{data} inside circular regions of radius Ψ covering the whole exposed sky (1°x1° steps).

3 CR pairs within Ψ

circular region of radius Ψ

▸ Estimation of the significance: compare with isotropic simulations with the same number of events.

«Intrinsic» anisotropy tests

▸ Scan on parameters: compute the obs./exp number of events in each circular window for:

- $E_{th} \in [\, 40; 80\,]$ EeV in 1EeV steps

- $\Psi \in [\, 1°; 30°\,]\,)$ in 1° steps

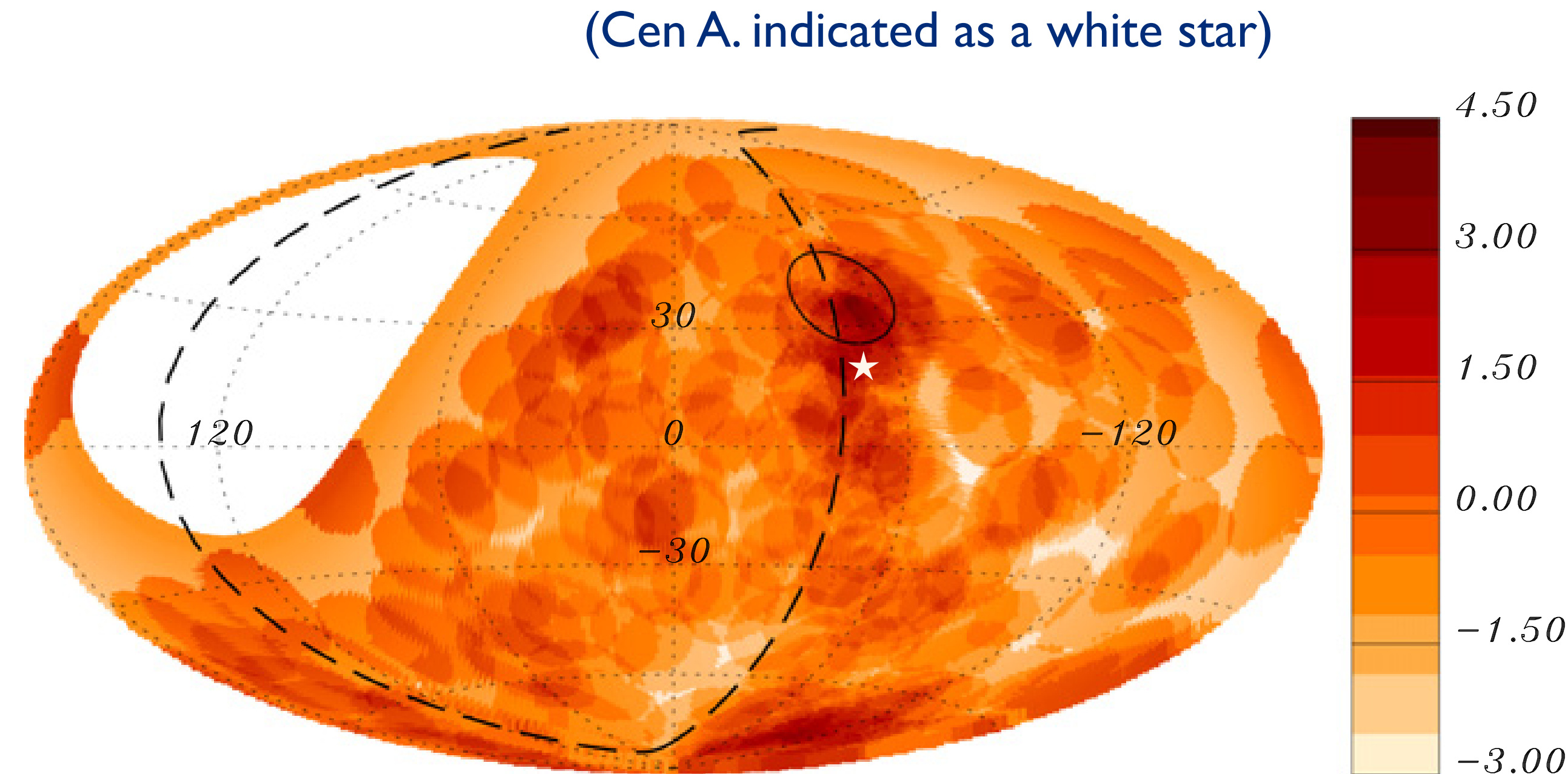▸ Most significant excess:

- Significance of 4.3σ for E_{th}=54 EeV and $\Psi = 12°$

$n_{obs} = 14$ / $n_{exp} = 3.23$

▸ Post-trial probability: $\mathcal{P}$ =69%

(fraction of isotropic simulations that have a
more significant excess under the same scan.)

(Cen A. indicated as a white star)

Li-Ma significance map (galactic coordinates)

for $\Psi = 12°$ and E>54 EeV

➡ Data compatible with isotropic expectations.

▸ Auto-correlation analysis does not find any significant excess either.

Catalogs

The 2MRS catalog:

- Almost complete (97.6%) for magnitudes brighter than K_S=11.75 (IR)

- Contains ~ 37,000 galaxies within 200 Mpc below the magnitude cut.

- Traces the location of the «regular» galaxies

The Swift-BAT X-ray catalog of AGN:

- Complete for $\Phi > 1.34\ 10^{-11}$ erg.s^{-1}.cm^{-2} in the band (14-195 keV)

- Contains ~ 300 AGN above the cut in flux within 200 Mpc.

- Majority of Seyfert I&II spiral galaxies

only ~ 5% overlap galaxies

Catalog of radio galaxies (compiled by Van Velzen et al.)

- Cut in flux $\Phi > 213$ mJy at 1.4 GHz and $\Phi > 289$ mJy at 0.843 GHz (~ flux of Cen A as seen from 200 Mpc)

- Contains ~ 200 radio galaxies with identified jets within 200 Mpc & satisfying the cut in flux

- Majority of elliptical galaxies

Cross-correlation with catalogs

▸ Select CR events with $E > E_{th}$ and galaxies with distances $d < D$ from a catalog. Count the number n_{data} of pairs of CR-galaxy within angular radius Ψ.
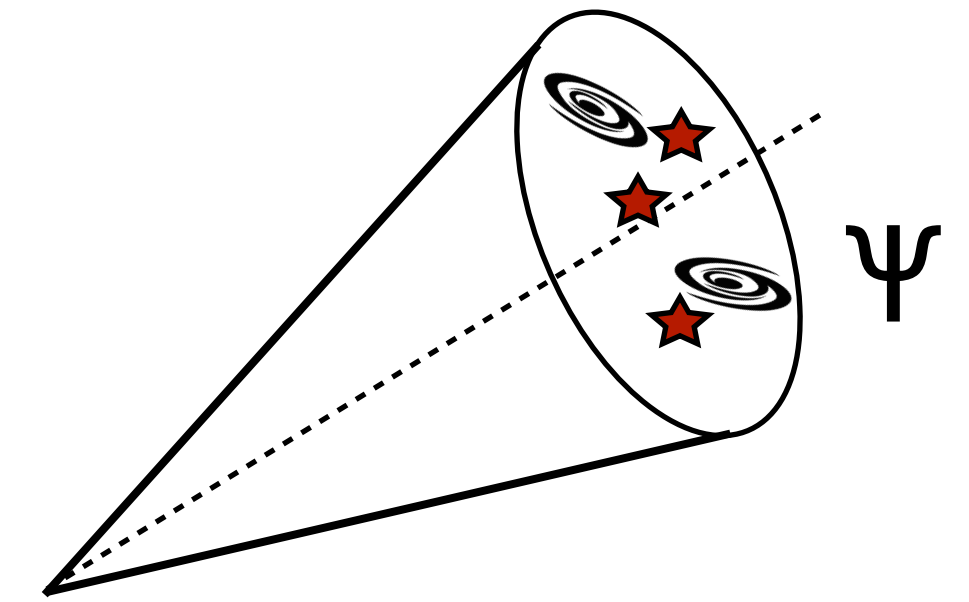
▸ Scan on parameters*: for each value of E_{th}, Ψ, compute the fraction **f** of isotropic simulations that have $n_{iso} \geq n_{data}$
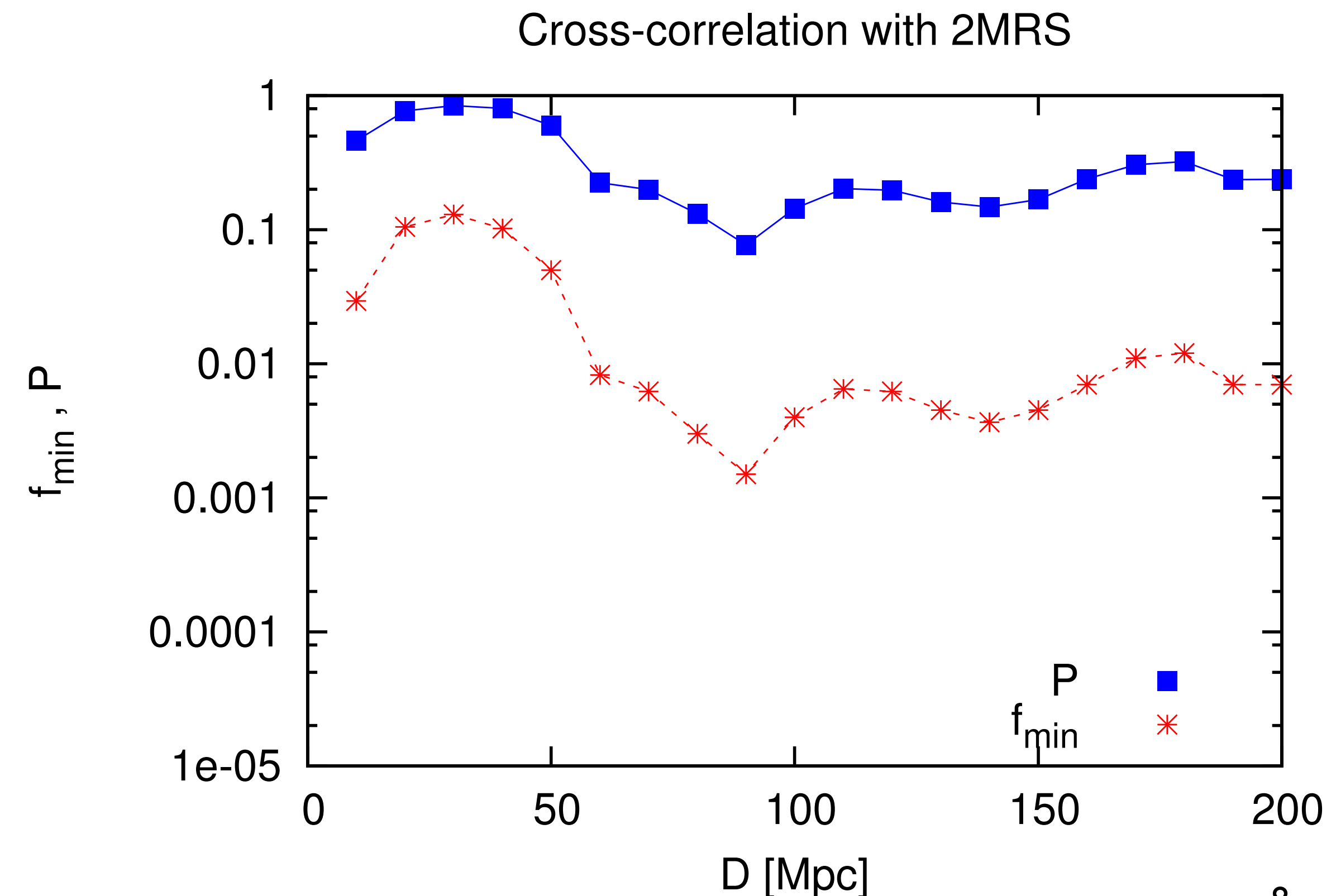
(*with $E_{th} \in [\,40; 80\,]$ EeV and $\Psi \in [\,1°; 30°\,]$)

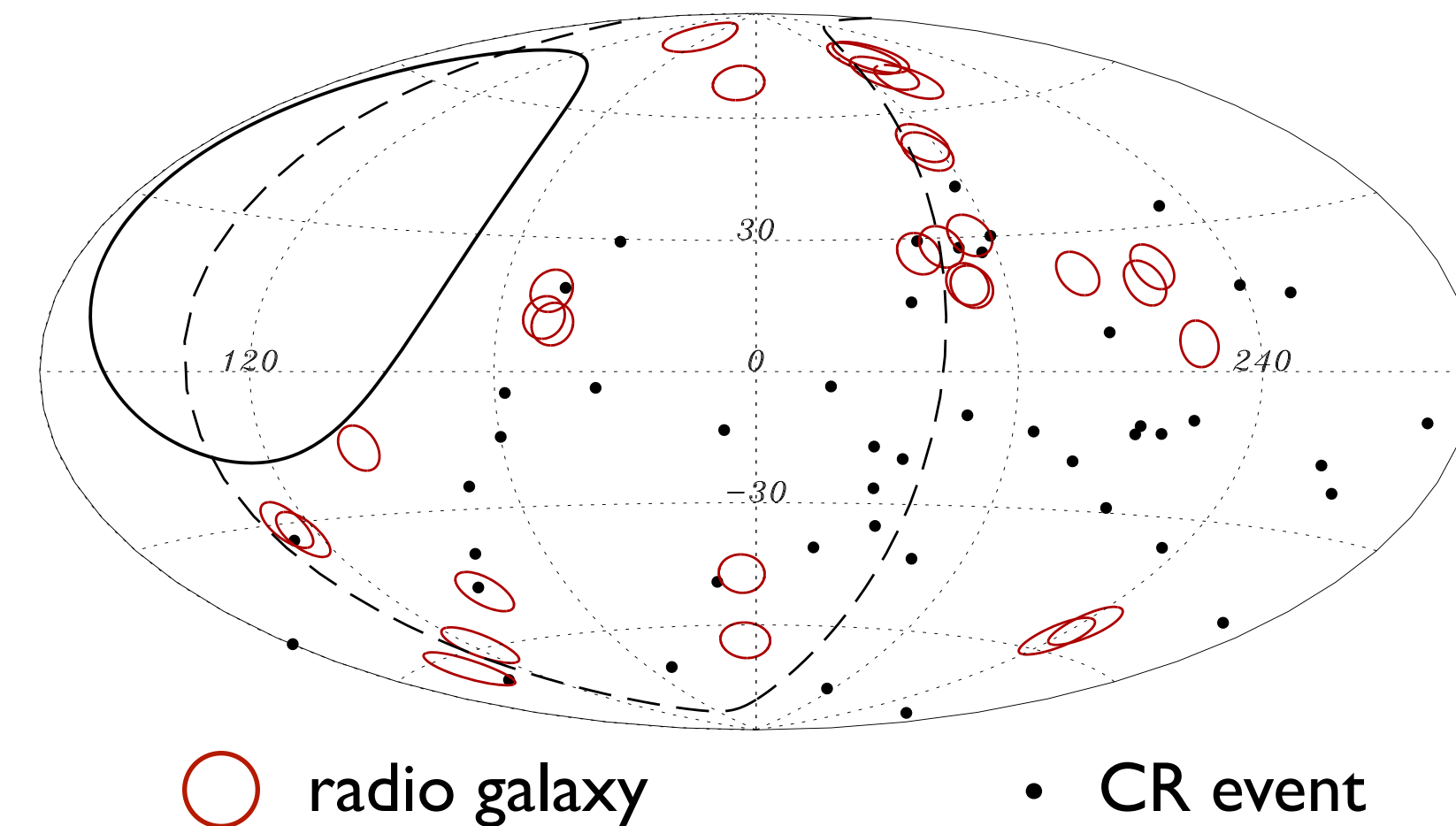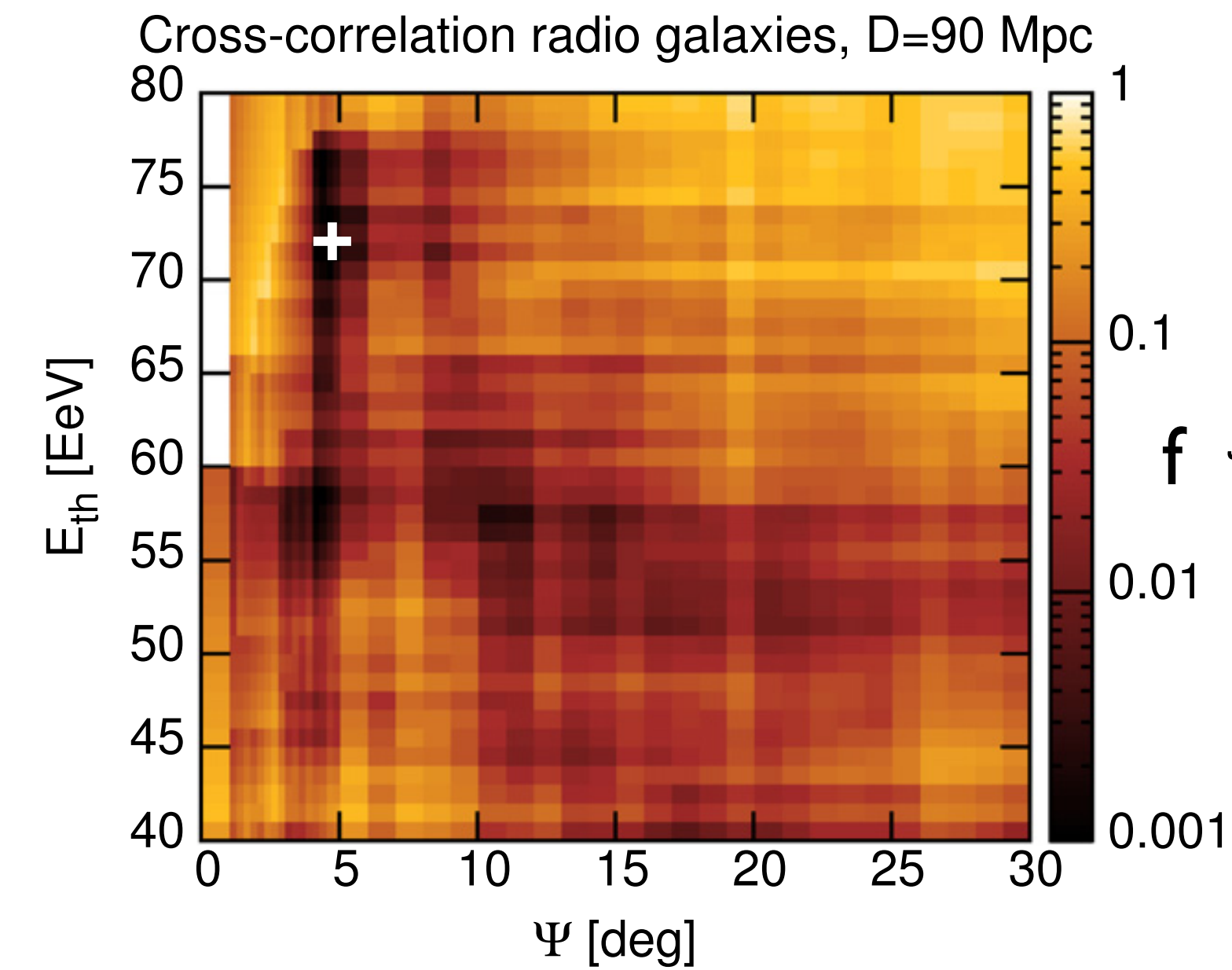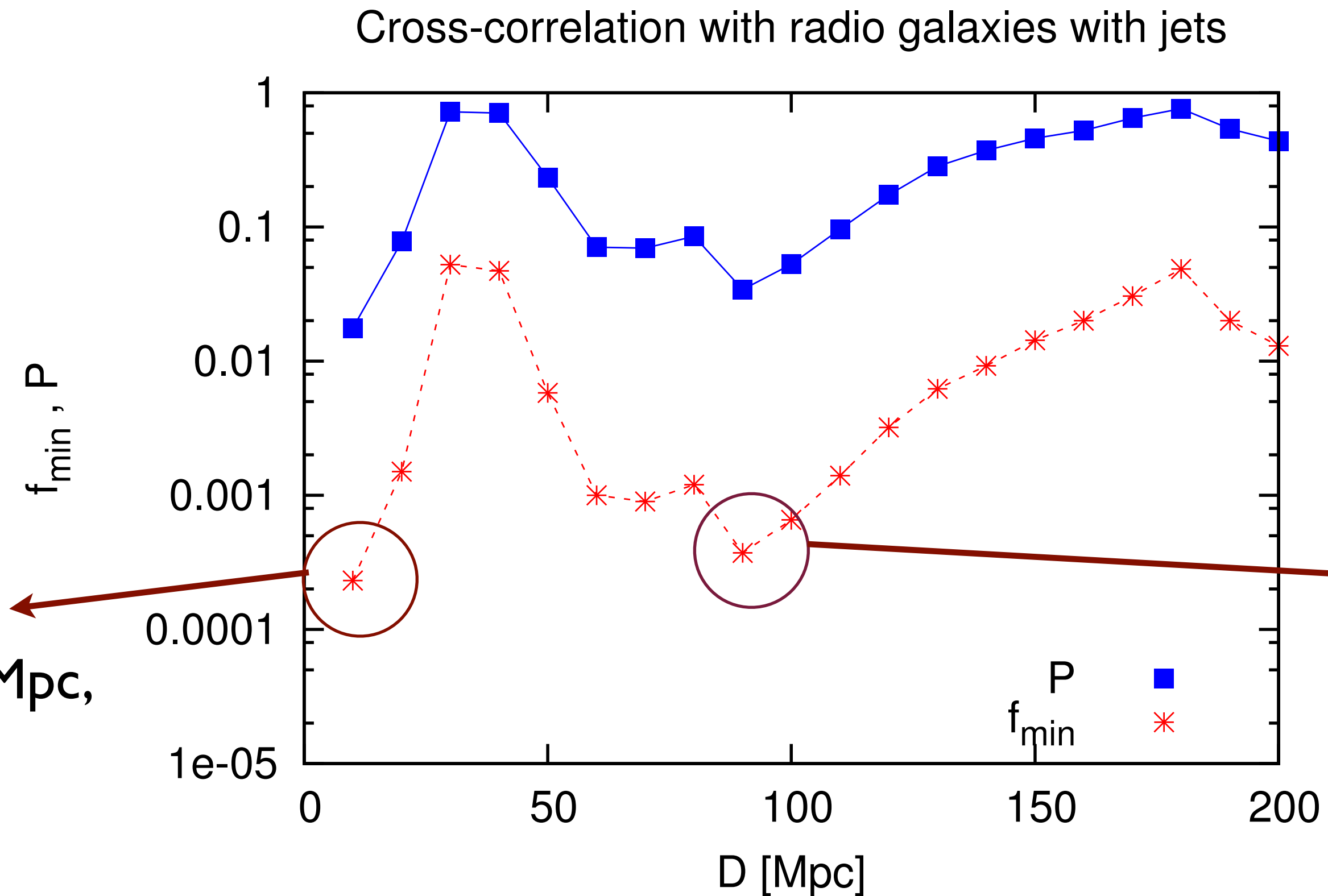▸ Compute this fraction **f** for all values of D and the penalized probability **P** :

➡ **P** = fraction of isotropic simulations that lead to a **f**≤**f_data** under the same scan.

▸ Compute the final post-trial probability $\mathcal{P}$:

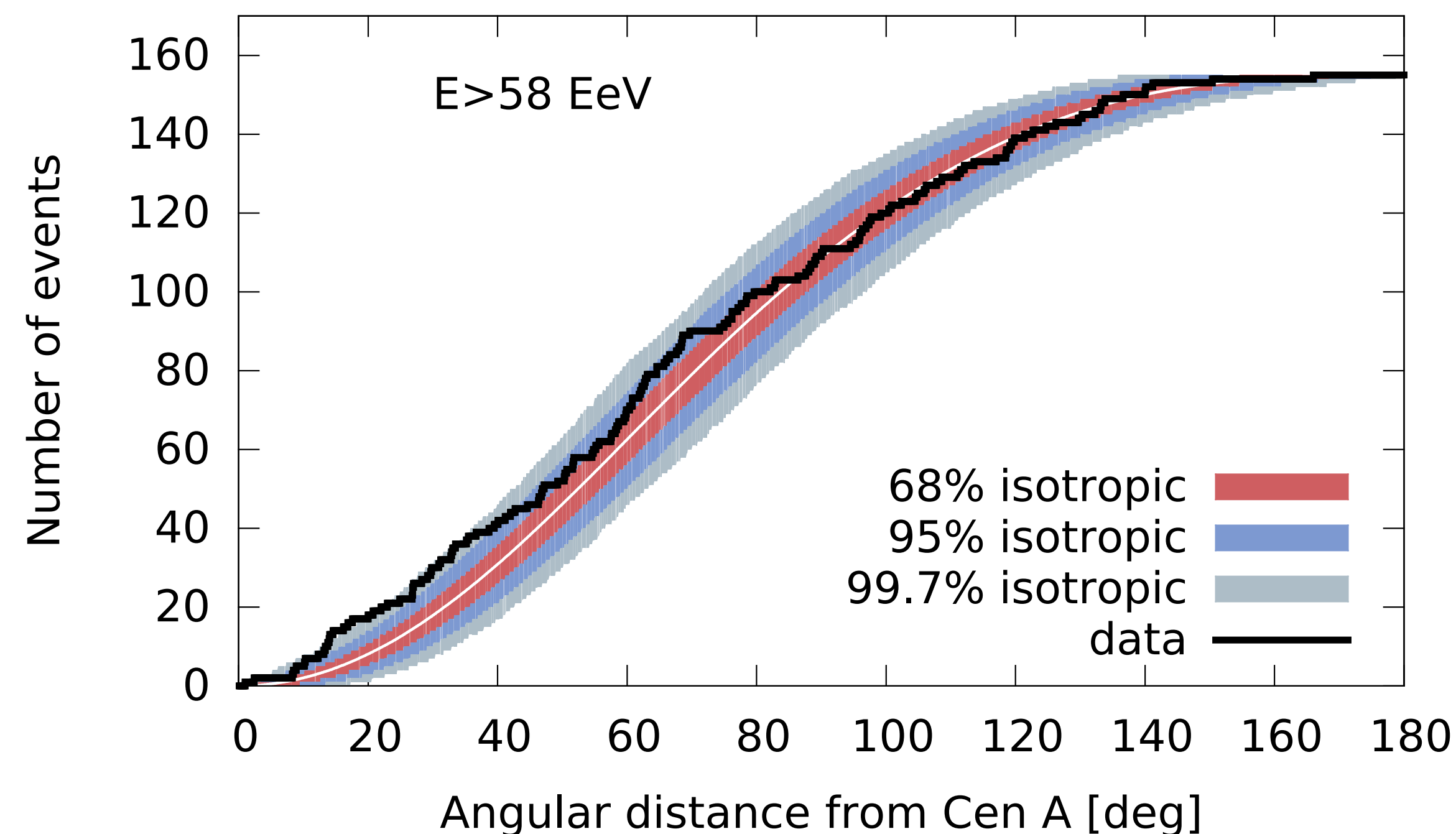➡ $\mathcal{P}$ = fraction of isotropic simulations that lead to a **P_iso** ≤**P_data** for any value of D.)

Cross-correlation with 2MRS

Results with radiogalaxies

Cross-correlation with radio galaxies with jets

Cross-correlation radio galaxies, D=90 Mpc

▶ Global minimum:

f = 2.10⁻⁴ for D=10 Mpc, corresponds to only CenA galaxy

▶ Second minimum:

f =4.10⁻⁴ for D=90 Mpc, E_{th}=72 EeV, Ψ = 4.75°

▶ Associated post-trial probability: $\mathcal{P} = 8\%$

○ radio galaxy   • CR event

The Cen A region

▸ Count the number of events n_{data} with $E > E_{th}$ that fall within Ψ of Cen A direction.
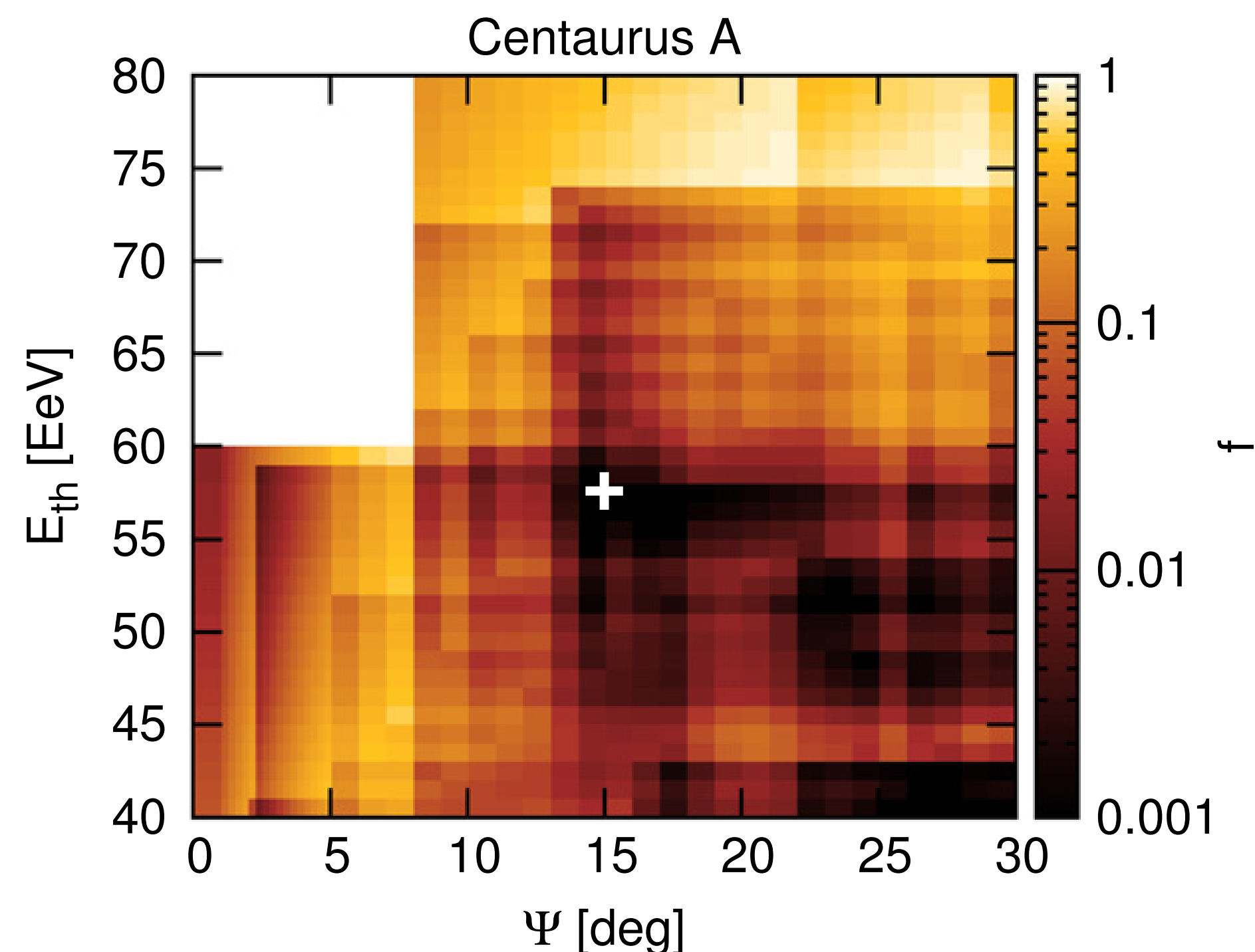
Centaurus A

E>58 EeV

68% isotropic
95% isotropic
99.7% isotropic
data

▸ Scan on parameters: for each value of E_{th}, Ψ, compute the fraction **f** of isotropic simulations that have $n_{iso} \geq n_{data}$

▸ Minimum found for:

    f $= 2 \cdot 10^{-4}$ with $E_{th} = 58$ EeV, $\Psi = 15°$

▸ Post-trial probability: P = 1.4%

    (fraction of isotropic simulations that lead to a **f** ≤ **f**$_{data}$ under the same scan.)

Cross-correlation analysis summary

Results for the 3 catalogs are summarized in the following table:

Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	f_{min}	$\mathscr{P}$
2MRS Galaxies	52	9	90	1.5×10^{-3}	24%
Swift AGNs	58	1	80	6×10^{-5}	6%
Radio galaxies	72	4.75	90	2×10^{-4}	8%

➡ **No significant correlation is found**

▸ The maximum distance D is consistently ~ 80-90 Mpc

(the whole Centaurus Supercluster of galaxies gets included for D~80 Mpc.)

Summary & Outlook

▸ The distribution of arrival directions of CR with E> 40 EeV has been analyzed

▸ Data set with ~600 CRs gathered in 10 years of operation, ~ 66,500 km^2 sr yr of total exposure.

▸ «Intrinsic» anisotropy tests show no evidence of signal

▸ Cross-correlation with 3 complementary catalogs: all tests are compatible with isotropic expectations

Additional material

Update of the VCV correlation test

▸ Previous analyses:

- Correlation with AGN from the VCV catalog with d < 75 Mpc

- Count the fraction of events with E > 55 EeV that have $\Psi < 3.1°$

- Result with 69 events (2010): f = 38 ± 7 %

- Isotropic expectation f_{iso}=21%

▸ Update with the present data set: (with Eth=53 EeV with the updated energy scale)

- Correlation fraction: f = 28.1 ± 3.8 %

▸ The VCV test no longer provides a significant indication of anisotropy.
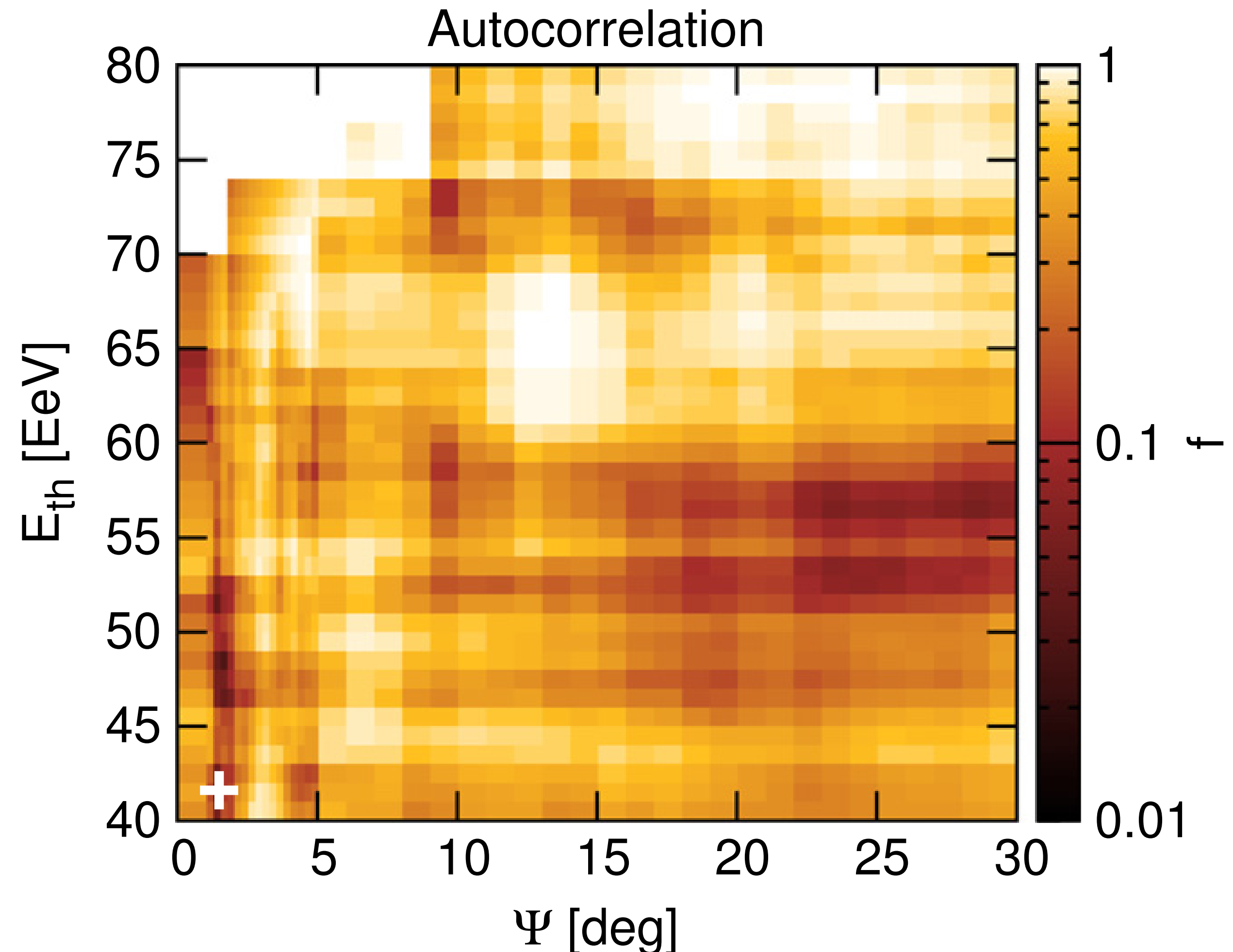
Auto-correlation analysis

▶ Scan on parameters*: for each value of E_{th}, Ψ, compute the fraction **f** of isotropic simulations that have $n_{iso} \geq n_{data}$

- $E_{th} \in [\,40; 80\,]$ EeV in 1EeV steps

- $\Psi \in [\,1°; 5°\,]$ in 0.25° steps

  $[\,5°; 30°\,]$ in 1° steps

▶ Minimum found for:

  f = 0.027 for E_{th}=42 EeV and Ψ = 1.5°

▶ Post-trial probability: $\mathcal{P}$ =70%

Autocorrelation

Correlation with bright AGNs

▶ Additional scan on the luminosity of sources:

    - select galaxies that have intrinsic luminosity $\mathscr{L} > \mathscr{L}_{min}$

        (in the X-ray band for Swift and at 1.1GHz for radiogalaxies)

    - scan on E_{th}, Ψ ,D, and $\mathscr{L}_{min}$, compute f_{min} and $\mathscr{P}$ with isotropic simulations

        (from 10^{42} - 10^{44} erg.s⁻¹ for Swift, 10^{39} - 10^{41} erg.s⁻¹ for radio galaxies)

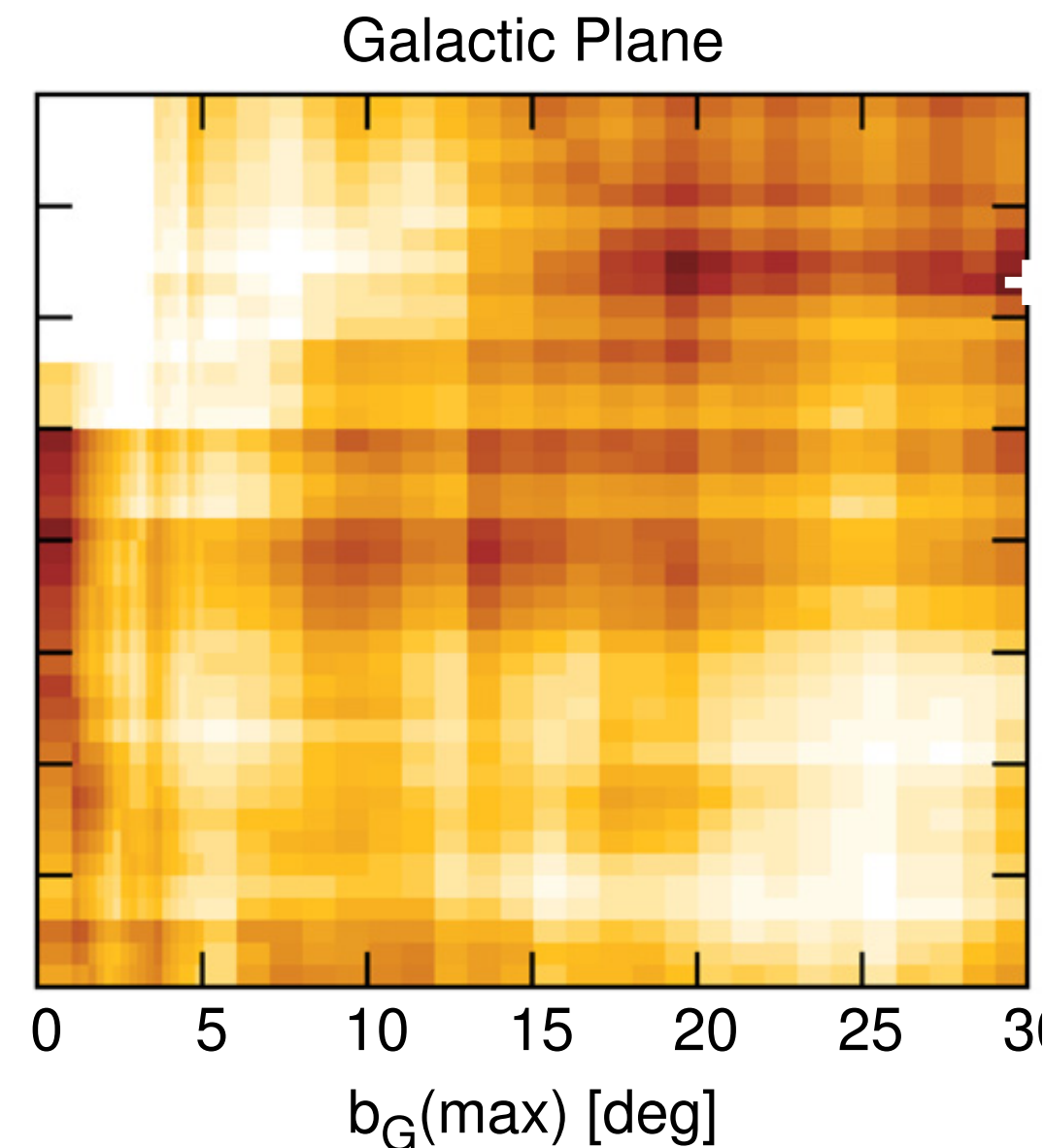| Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	$\mathscr{L}_{min}$ [erg/s]	f_{min}	$\mathscr{P}$
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	72	4.75	90	$10^{39.33}$	5.1×10^{-5}	11%

▶ Penalized probability reach the 1% level for Swift
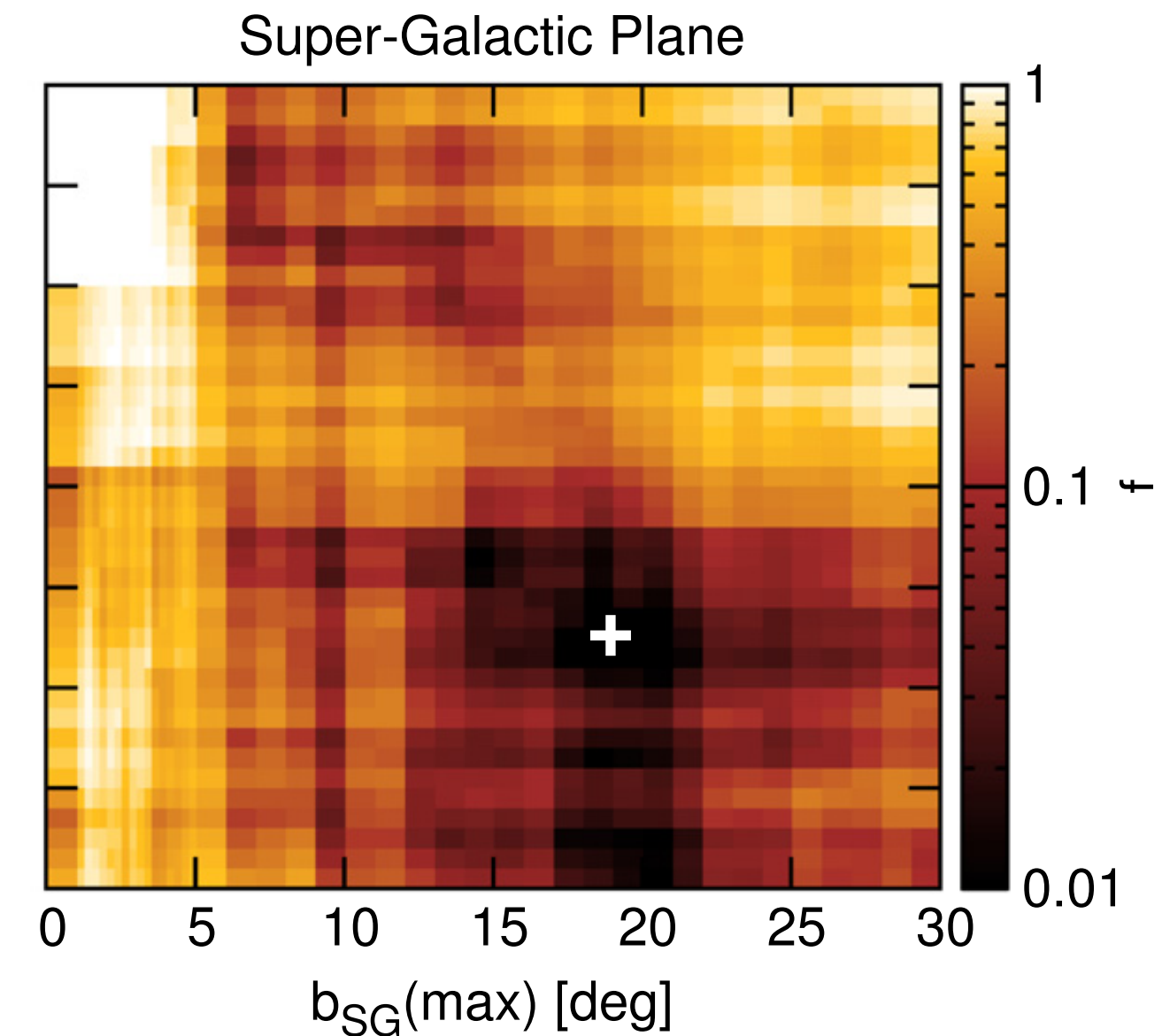
Correlation with astrophysical structures

▸ Search for excesses in the GC region, and in latitude bands around the Galactic Plane & Super-Galactic Plane.
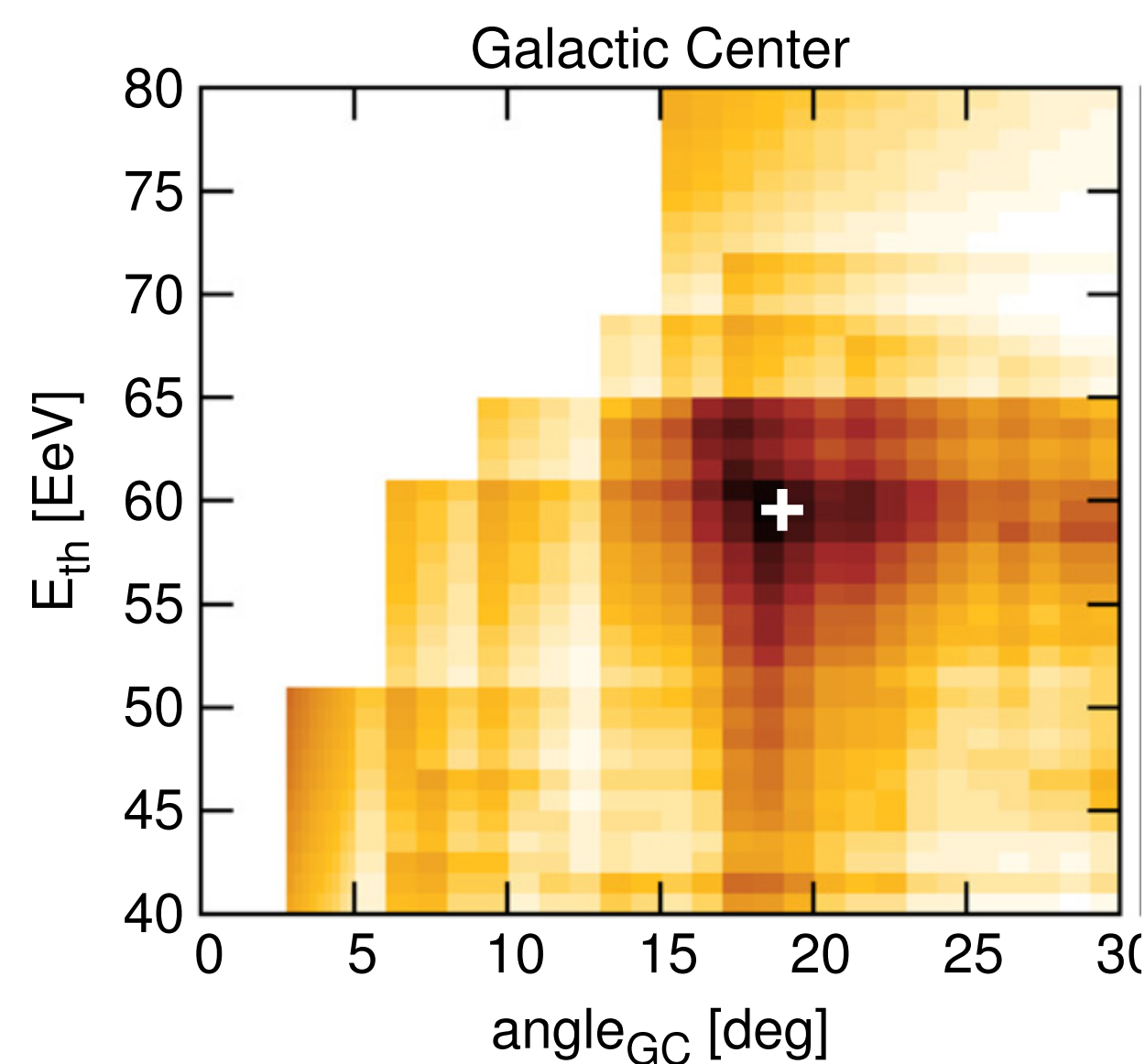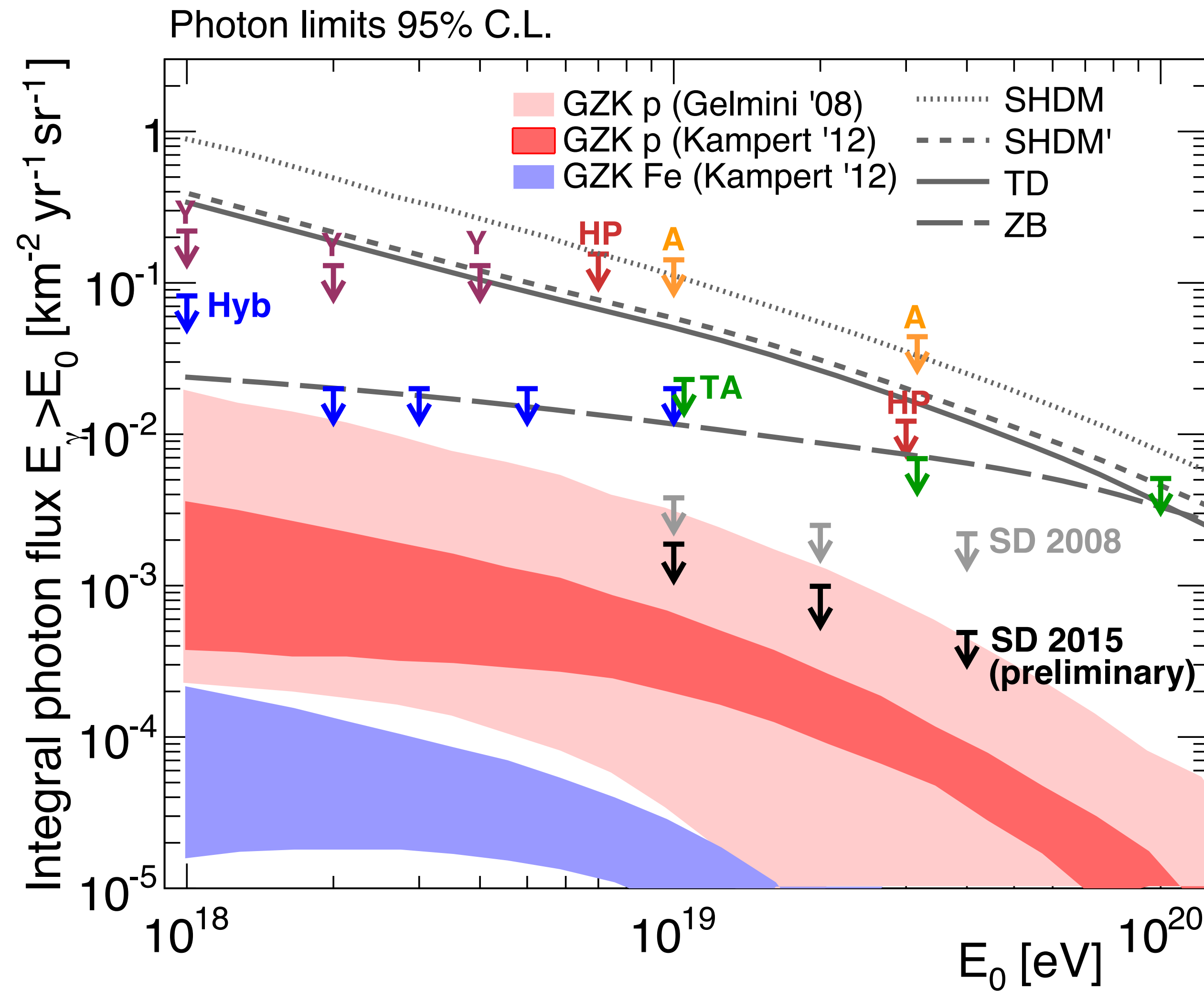

P ≈29%   P ≈70%   P ≈22%

▸ Result: no significant excess is found.

▸ If deflections are small, CR are unlikely of galactic origin above E > 40 EeV, and do not seem to come from the Super-Galactic Plane.

Top down models

Photon limits 95% C.L.

Legend (left, partially cut off):
- ν models
- Fermi-LAT best-fit (Ahlers '10)
- Fermi-LAT 99% CL band (Ahlers '10)
- FRII & SFR (Kampert '12)
- , FRII & SFR (Kampert '12)
- or mixed, SFR & GRB (Kotera '10)
- axman-Bahcall '01

Legend (right plot):
- GZK p (Gelmini '08)
- GZK p (Kampert '12)
- GZK Fe (Kampert '12)
- SHDM
- SHDM'
- TD
- ZB

Axis labels: Integral photon flux $E_\gamma > E_0$ [km^{-2} yr^{-1} sr^{-1}], E_0 [eV]

Data labels: Y, HP, A, Hyb, TA, SD 2008, SD 2015 (preliminary)

*see talk by C.Bleve, in the NU 04 session for details.

▸ Limits on photon flux from Auger excludes several SHDM, TD & Z-burst models
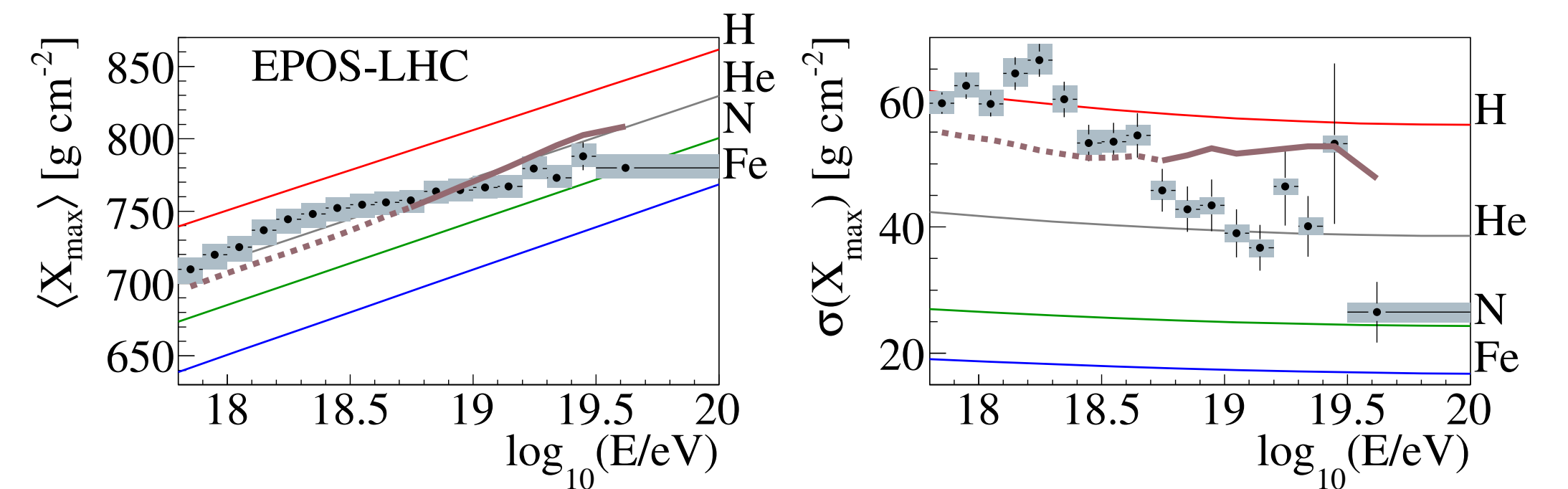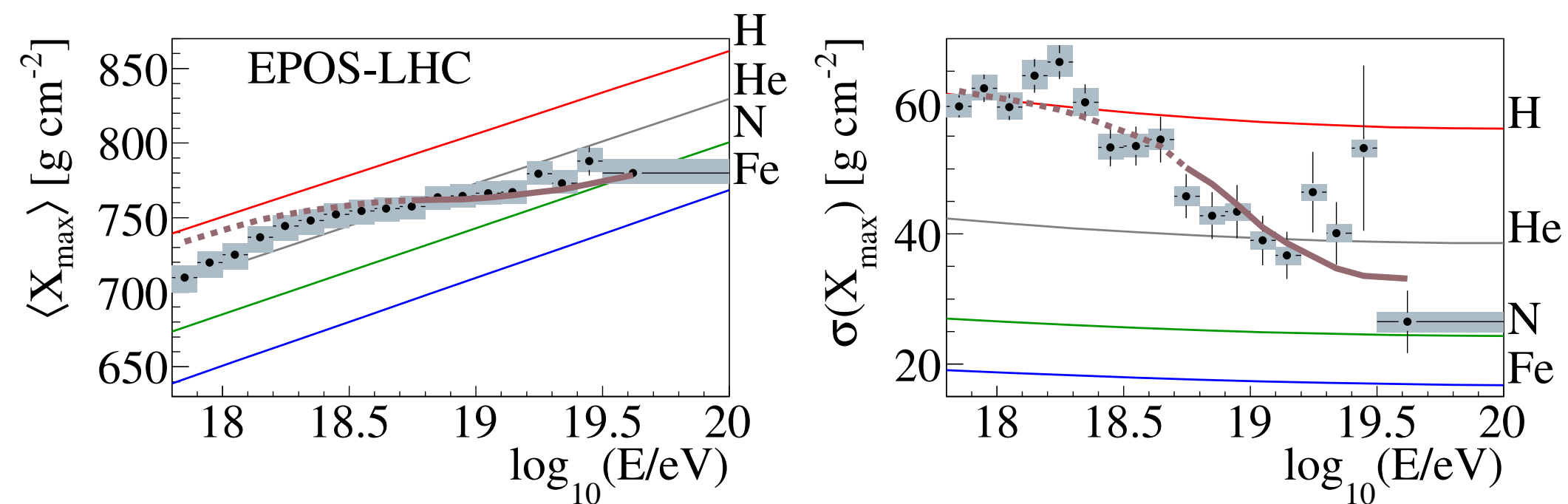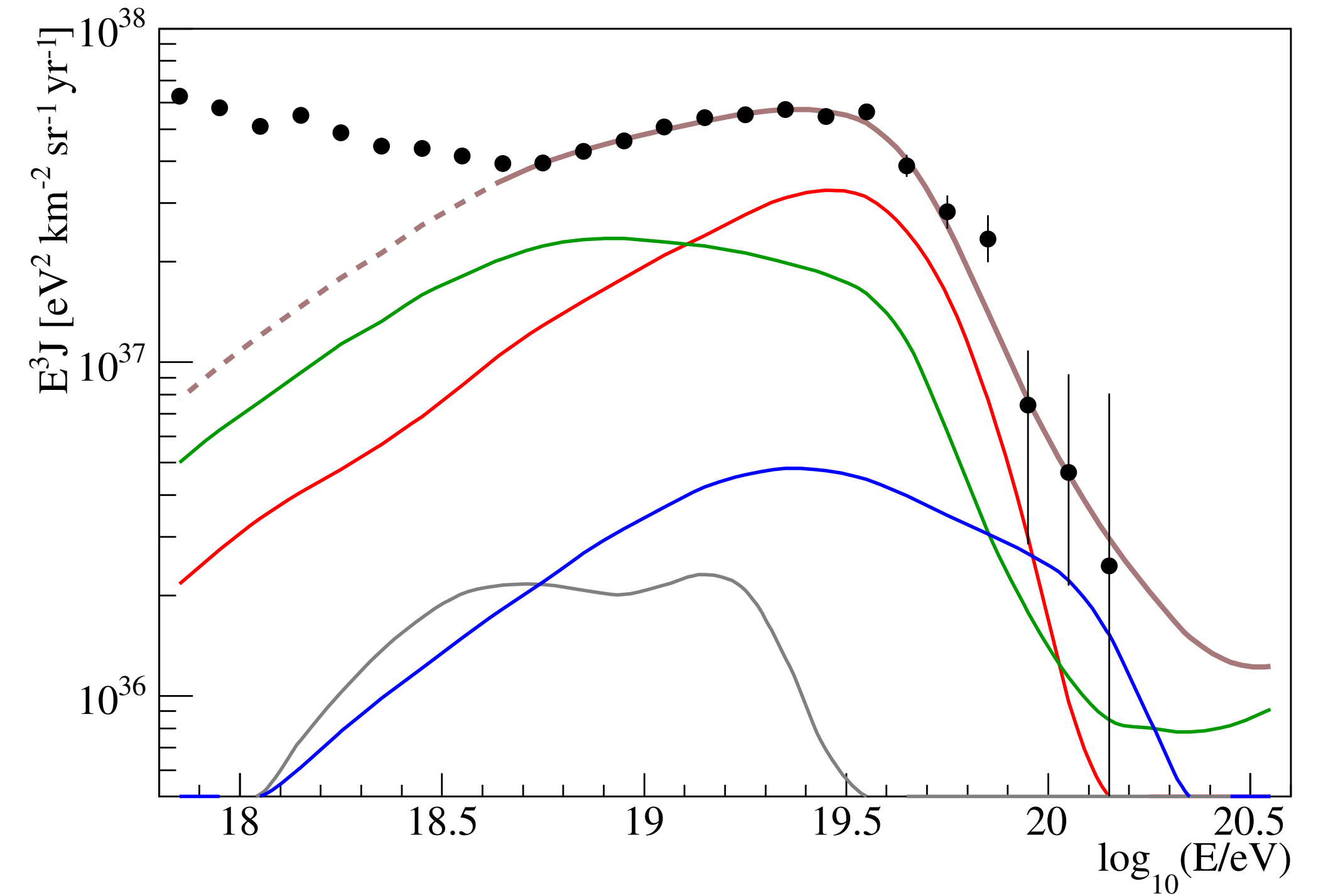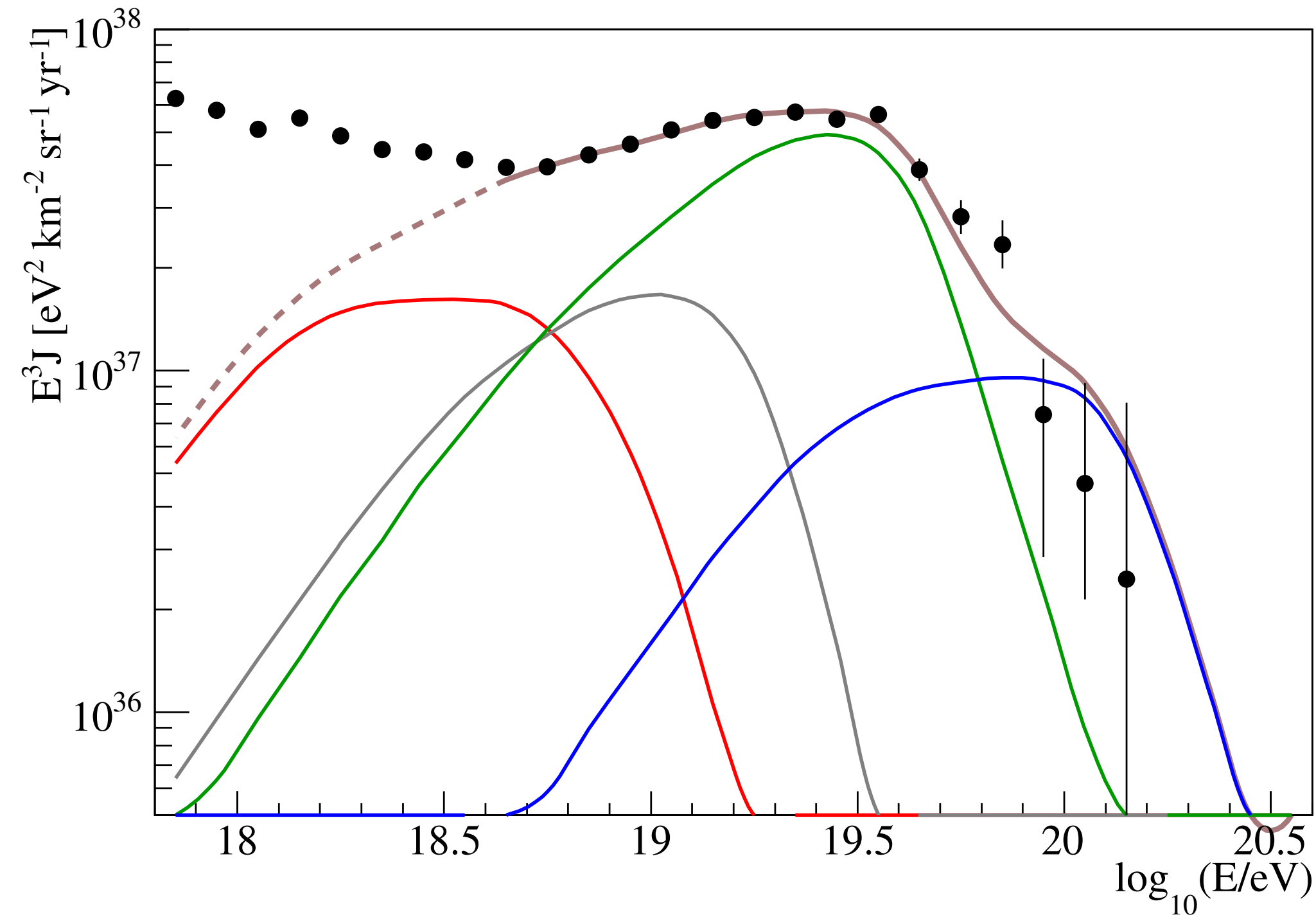
CR composition
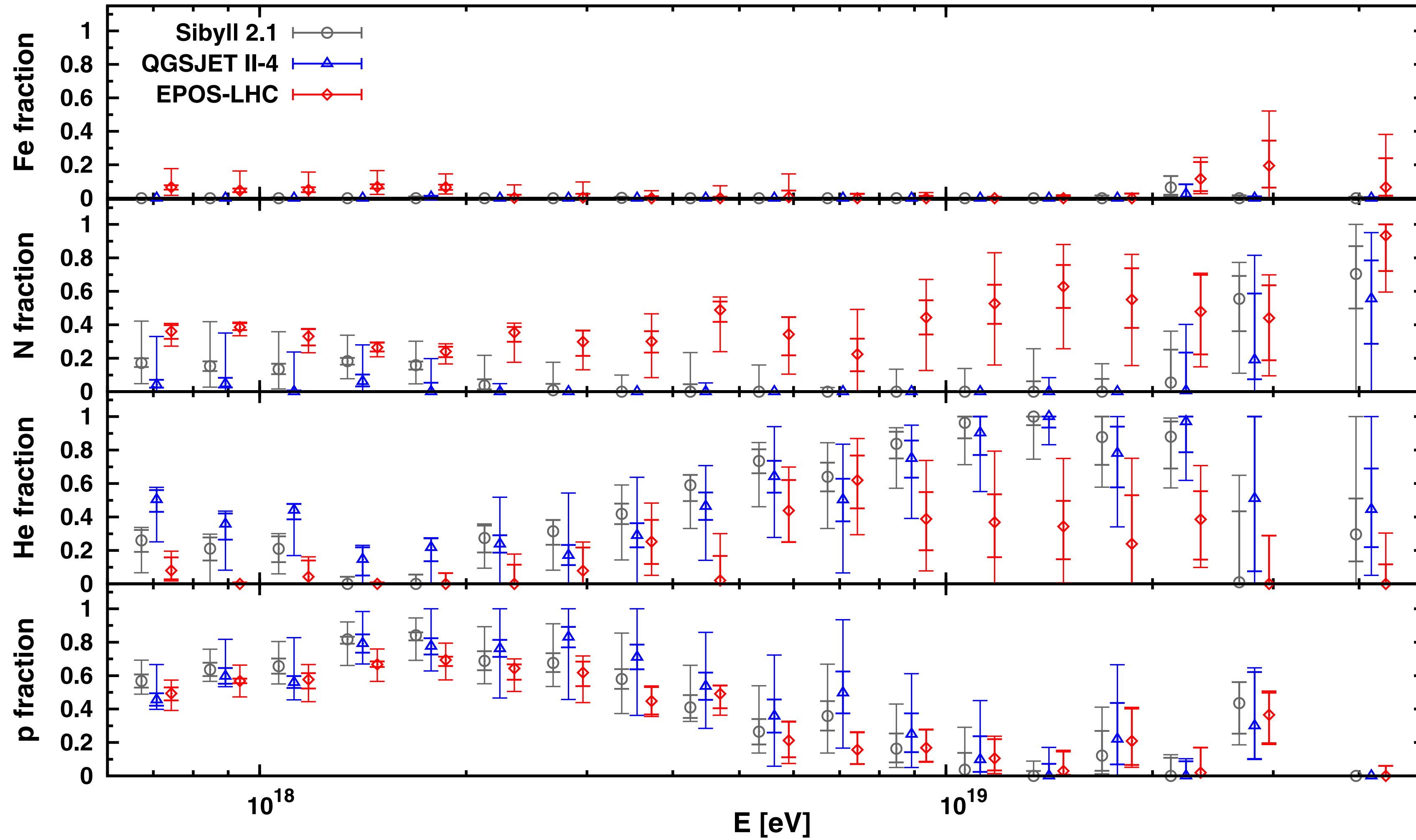
Depth of maximum of air-shower profiles at the Pierre Auger Observatory.
II. Composition implications

Energy spectrum & composition fit

(see talk by A. di Matteo, in the CR13 EX EAS session)

Energy spectrum

E[eV]

10^{18} 10^{19} 10^{20}

$\log_{10}(E^3 \, J/(m^{-2} \, s^{-1} \, sr^{-1} \, eV^2))$

22217 13210 7774 4611 2639 3450 2629 2006 1344 60423 34861 26325 16317 10991 7585 5221 3491 2238 1405 888 569 267 130 54 10 4 1

$$E_{\text{ankle}} = 4.8 \times 10^{18} \text{ eV}$$

● —— Auger (ICRC 2015 preliminary)

$\log_{10}(E/eV)$