The question of anisotropy in high-energy cosmic rays

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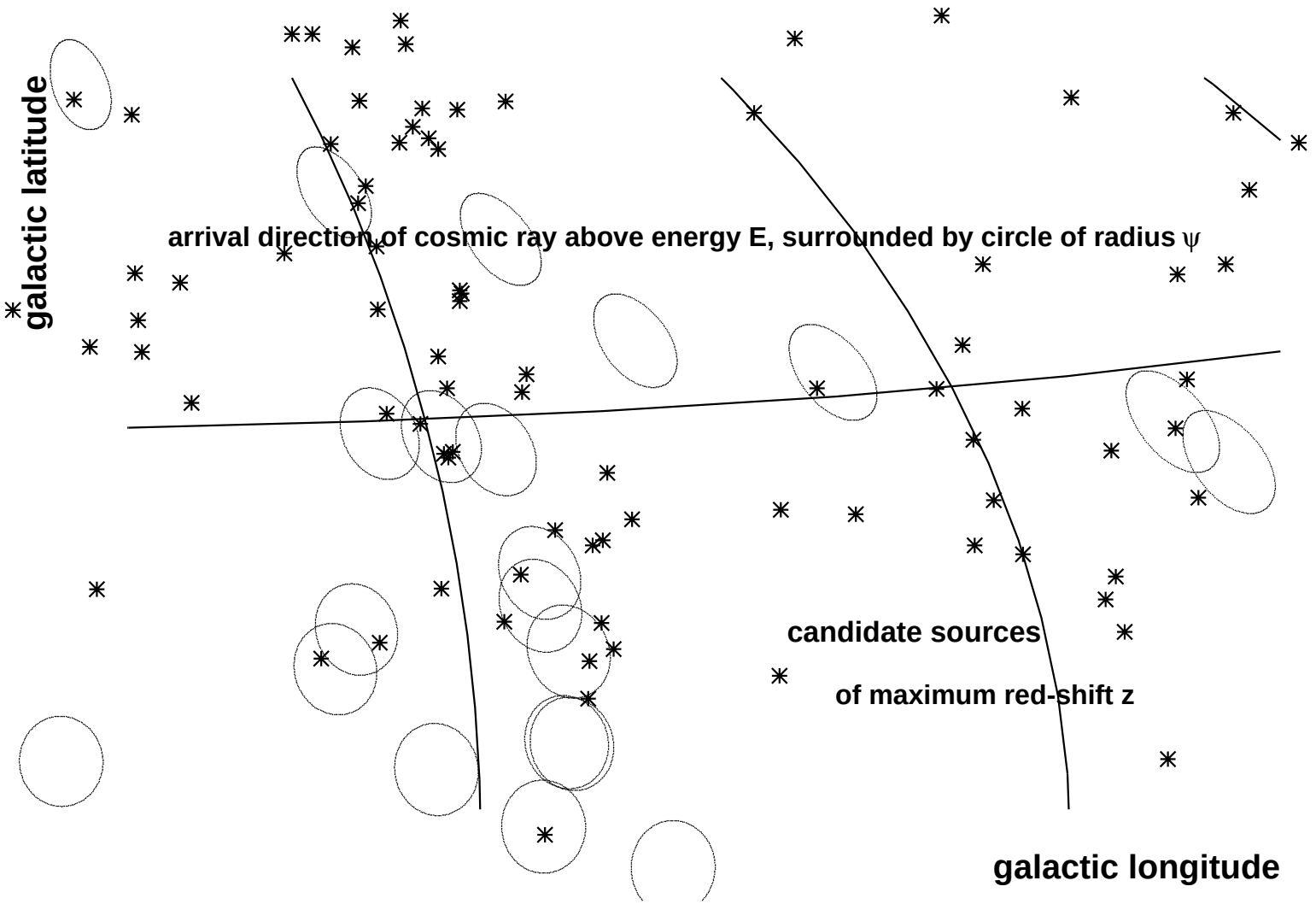
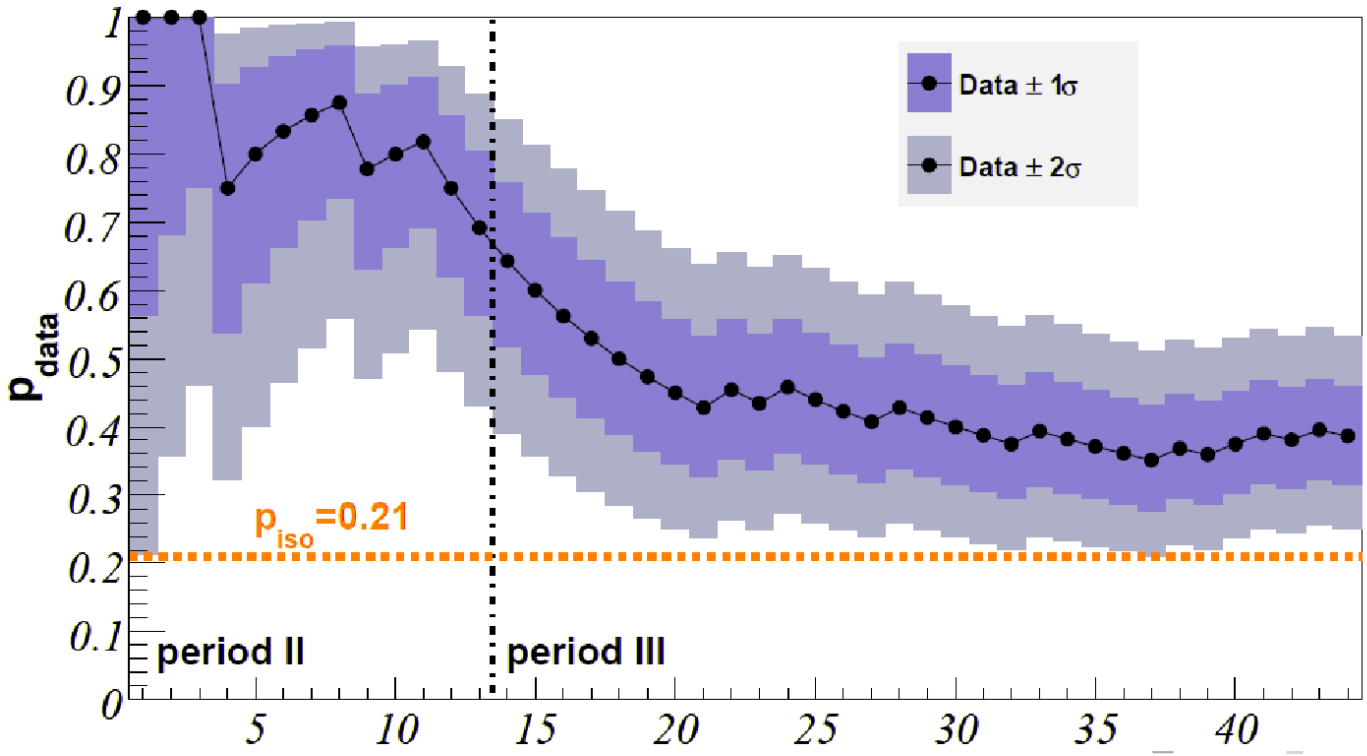
GZK effect limits the horizon of protons that can reach the earth: if there are sources, the visible ones are within a volume of about 100 Mpc radius... objects within this distance are anisotropic


galactic latitude
arrival direction of cosmic ray above energy E, surrounded by circle of radius ψ
candidate sources
of maximum red-shift z
galactic longitude

cumulative chance probability that k or more events correlate

$$P = \sum_{j=k}^{N} \binom{N}{j} p_{iso}^{j} (1 - p_{iso})^{N-j} \qquad p_{data} = \frac{k}{N} \qquad p_{iso} = \frac{1}{4\pi} \bigcup_{i=1}^{N} S_i$$



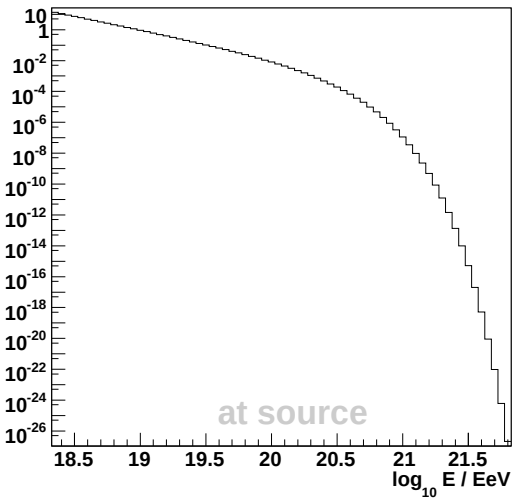
Fake maps

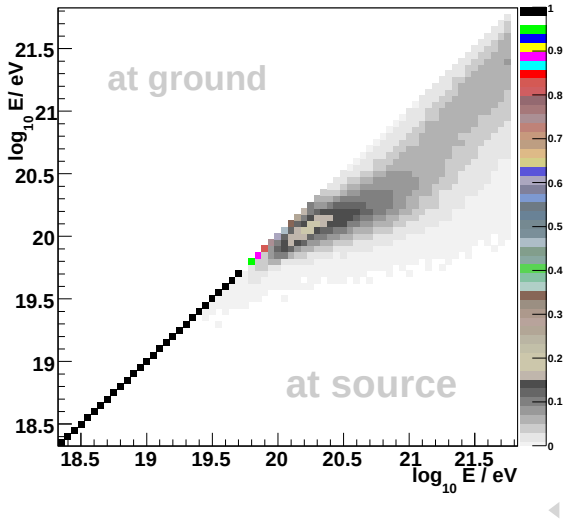
we want to question whether it is possible to obtain a map of fake Auger events from a catalogue, with a simulation of

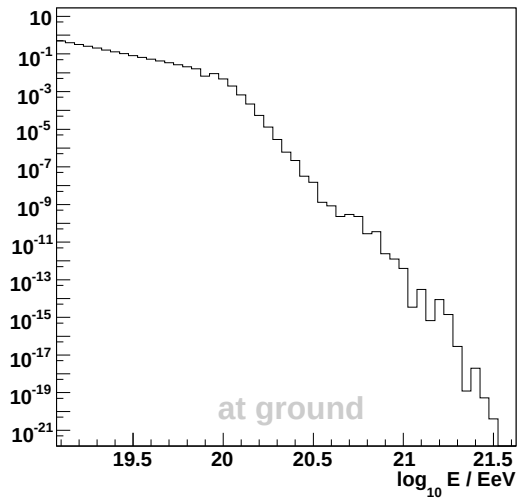
1. the initial spectral shape of each source
2. the energy loss of protons, travelling from a given distance
3. the detector properties (exposure, energy resolution)
4. the coordinate offset due to magnetic effects

perform analysis of fake data: do we see correlation? do we see the real source?

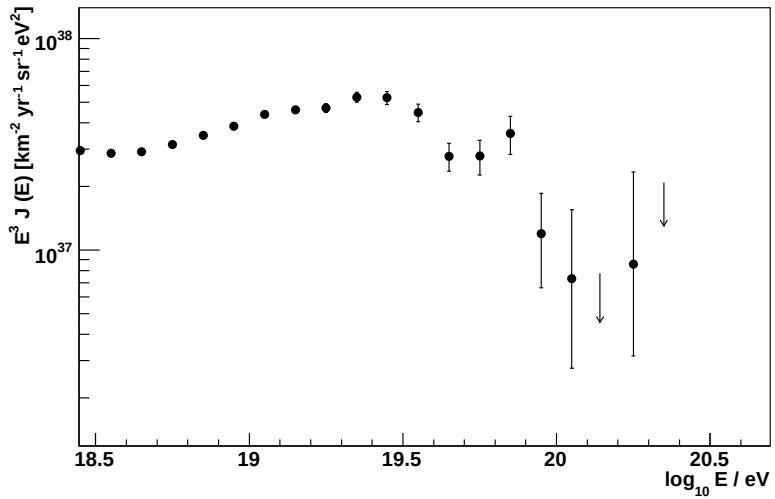
1. source: parameterised with slope, E_{max}
2. propagation: reproduced stochastically with a Montecarlo code
   - photo-pion production due GZK effect $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0$
   - pair production $p + \gamma \rightarrow p + e^+ + e^-$
   - cosmological cooling factor due to universe expansion
3. spectra at ground: obtained folding the two previous steps, as a function of the distance traveled

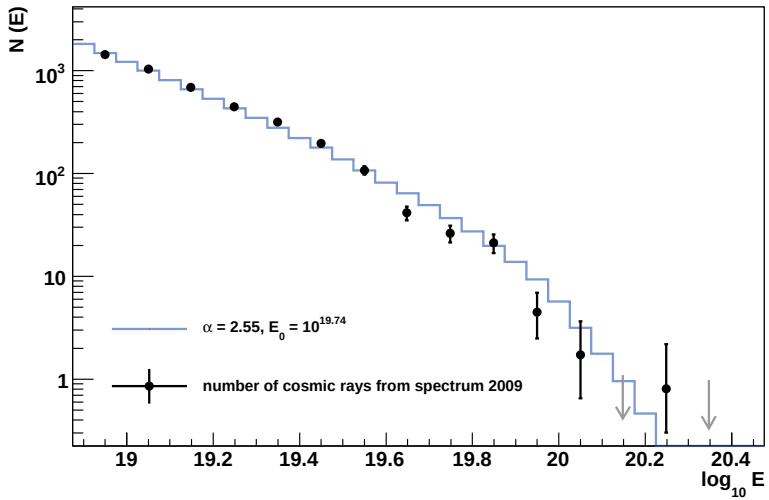






1. sum up contributions from each source in the catalogue weighting by declination and flux;
2. distributions are normalised to the CR spectrum [1002-1975] (factor n scales the number of events to the Auger exposure)



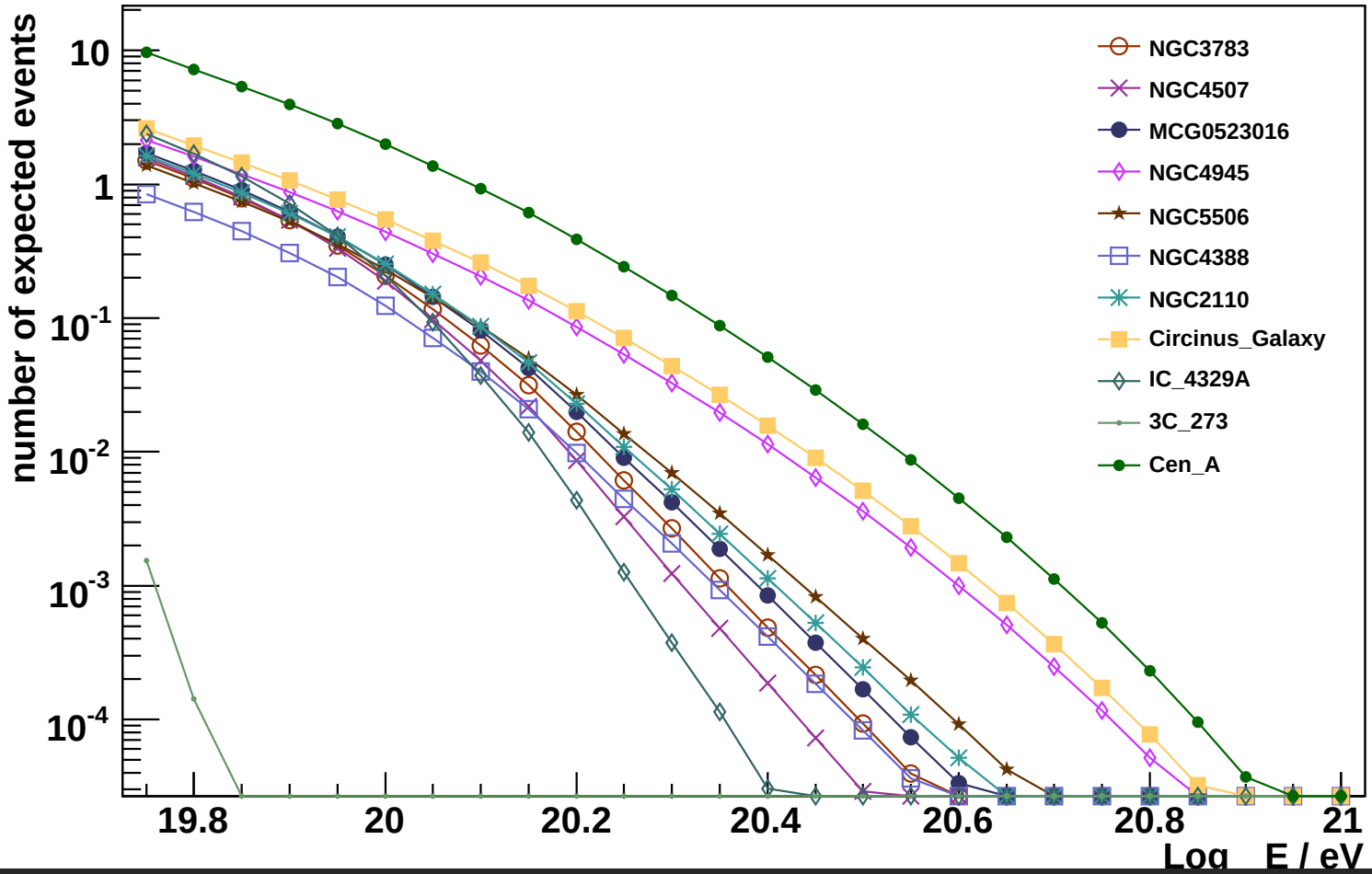


3. count number of events above a threshold E_0,

$$\lambda = \sum_{E_G = E_0}^{\infty} N(E_G) \cdot x \cdot f(\delta) \cdot n \qquad N = \mathcal{P}(\lambda)$$

Result 1 - fake data from individual sources

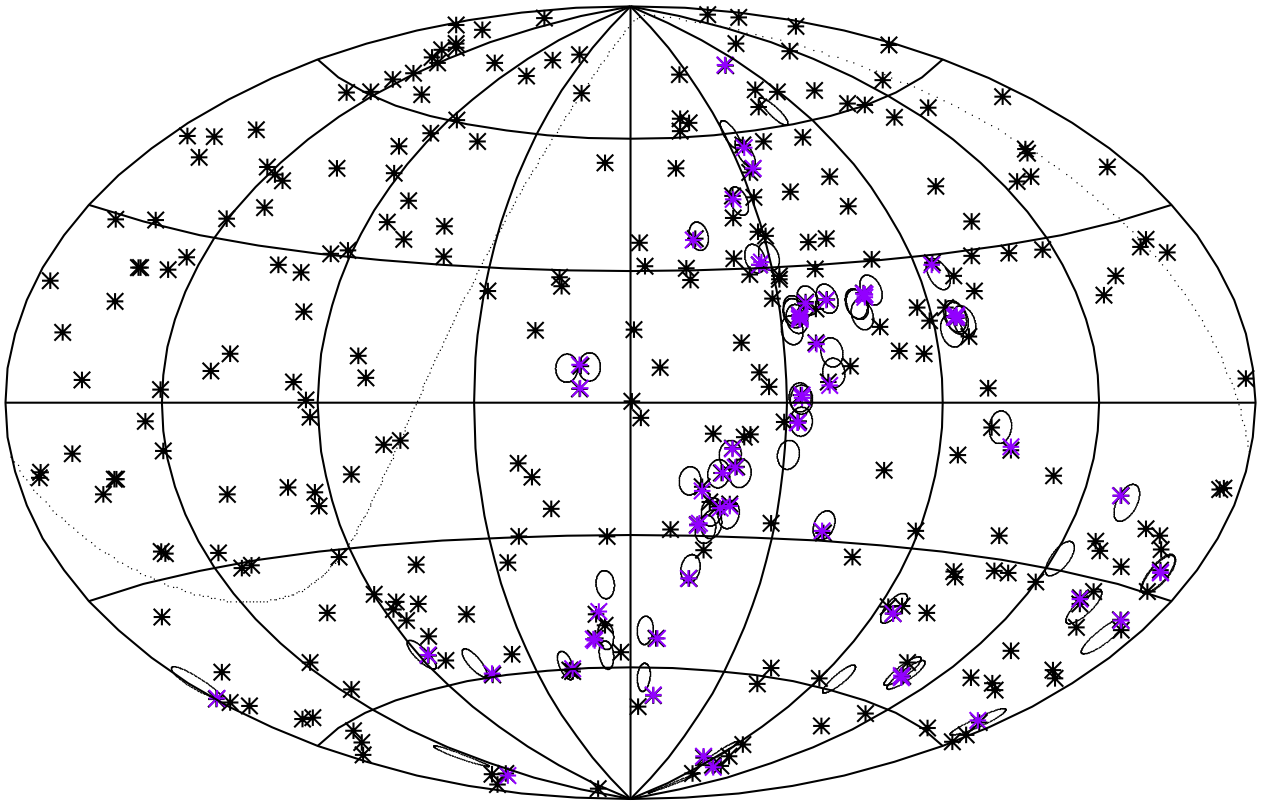
11 brightest sources in Swift-BAT catalogue of AGNs



Result 2 - fake data from catalogue

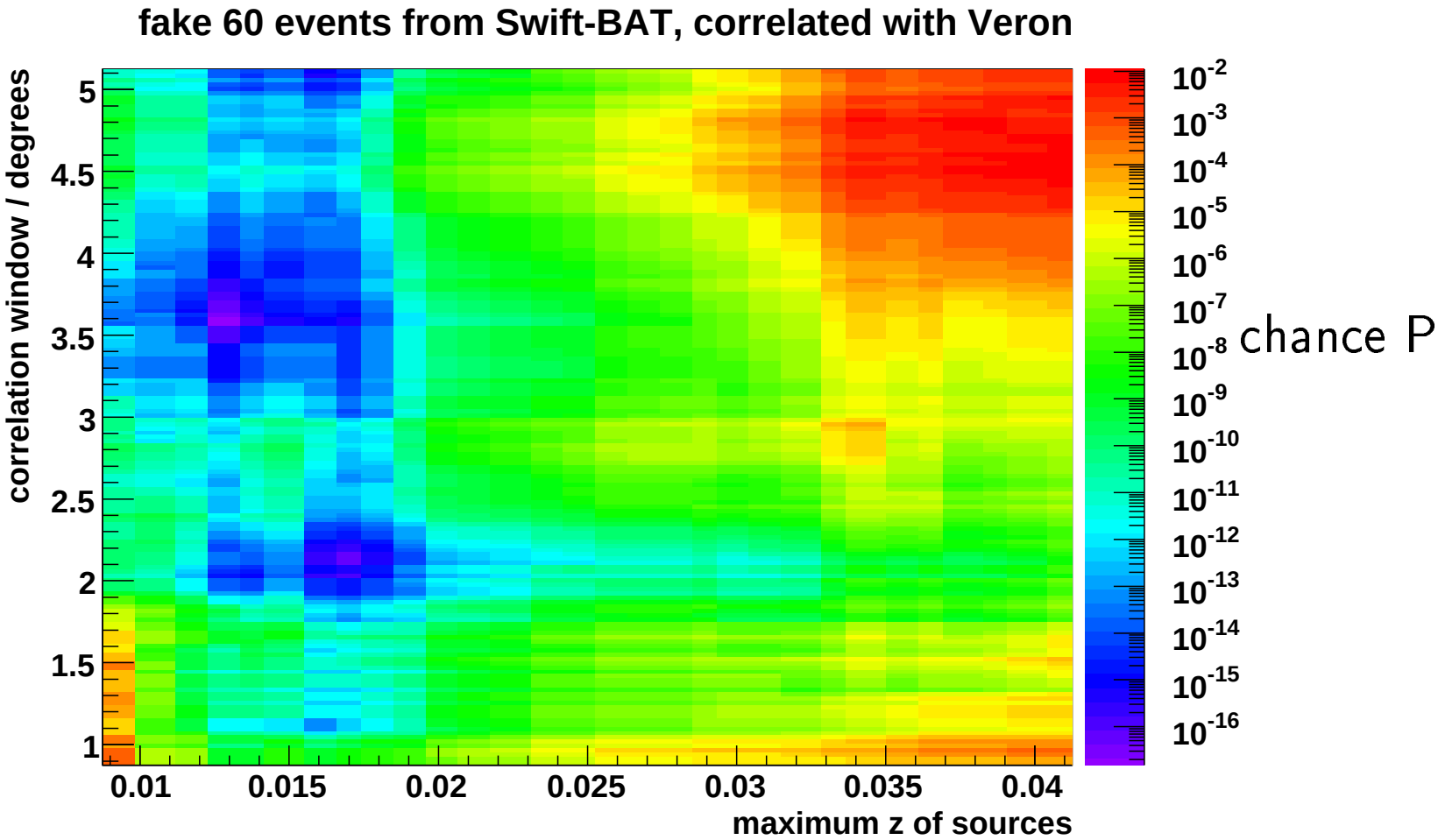
1. Choose catalogue: here (1) Swift-BAT, (2) HIPASS
2. Input source parameters: δ, x
3. Input analysis parameters: E_G, z
4. Smear energy according to resolution
5. Smear coordinates to reproduce magnetic deflections
   - galactic
   - extragalactic
   - measurement error (angular resolution)

skymap of fake events generated from Swift-BAT,

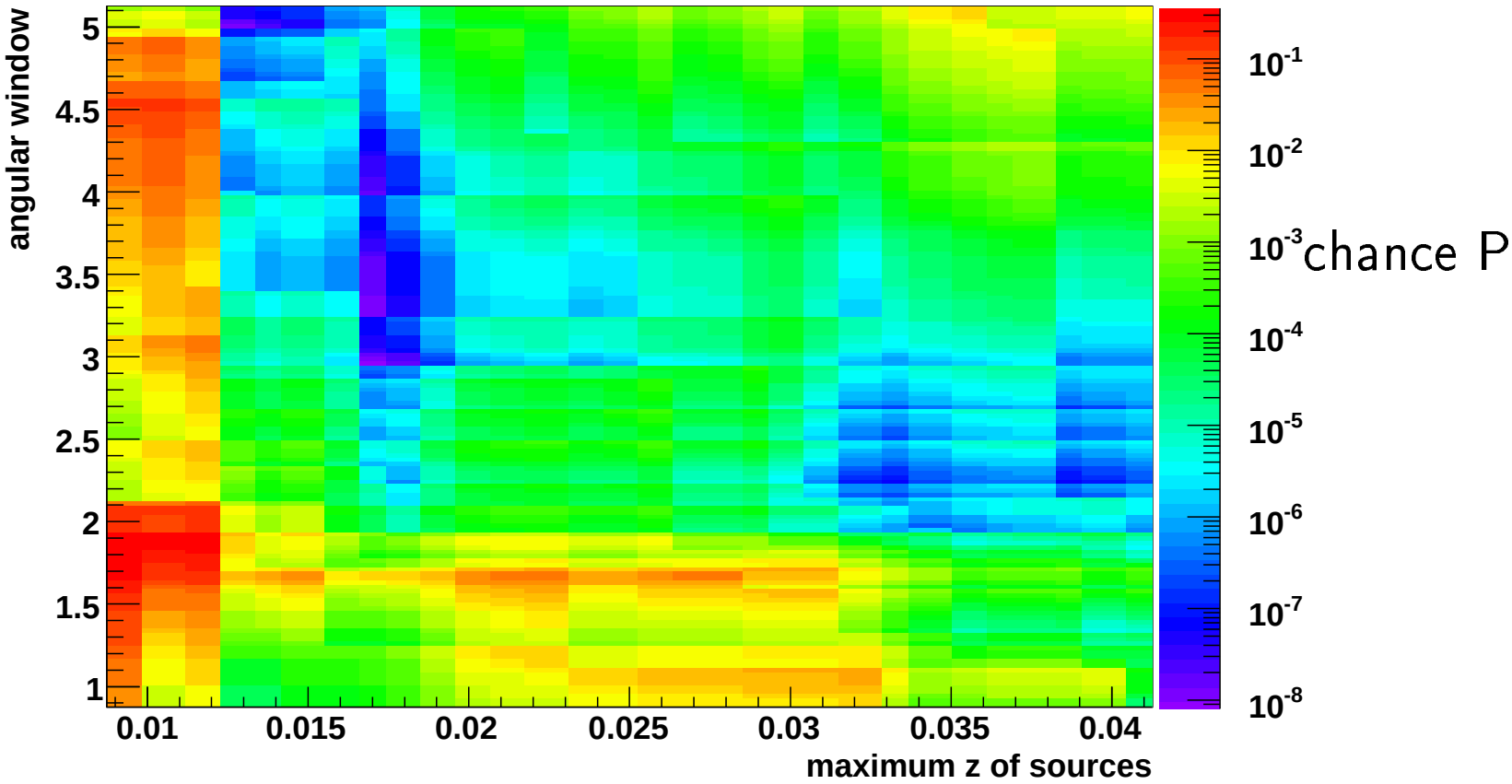


stars = Swift-BAT AGNs, blue stars = actual contributing sources,
circles = fake events

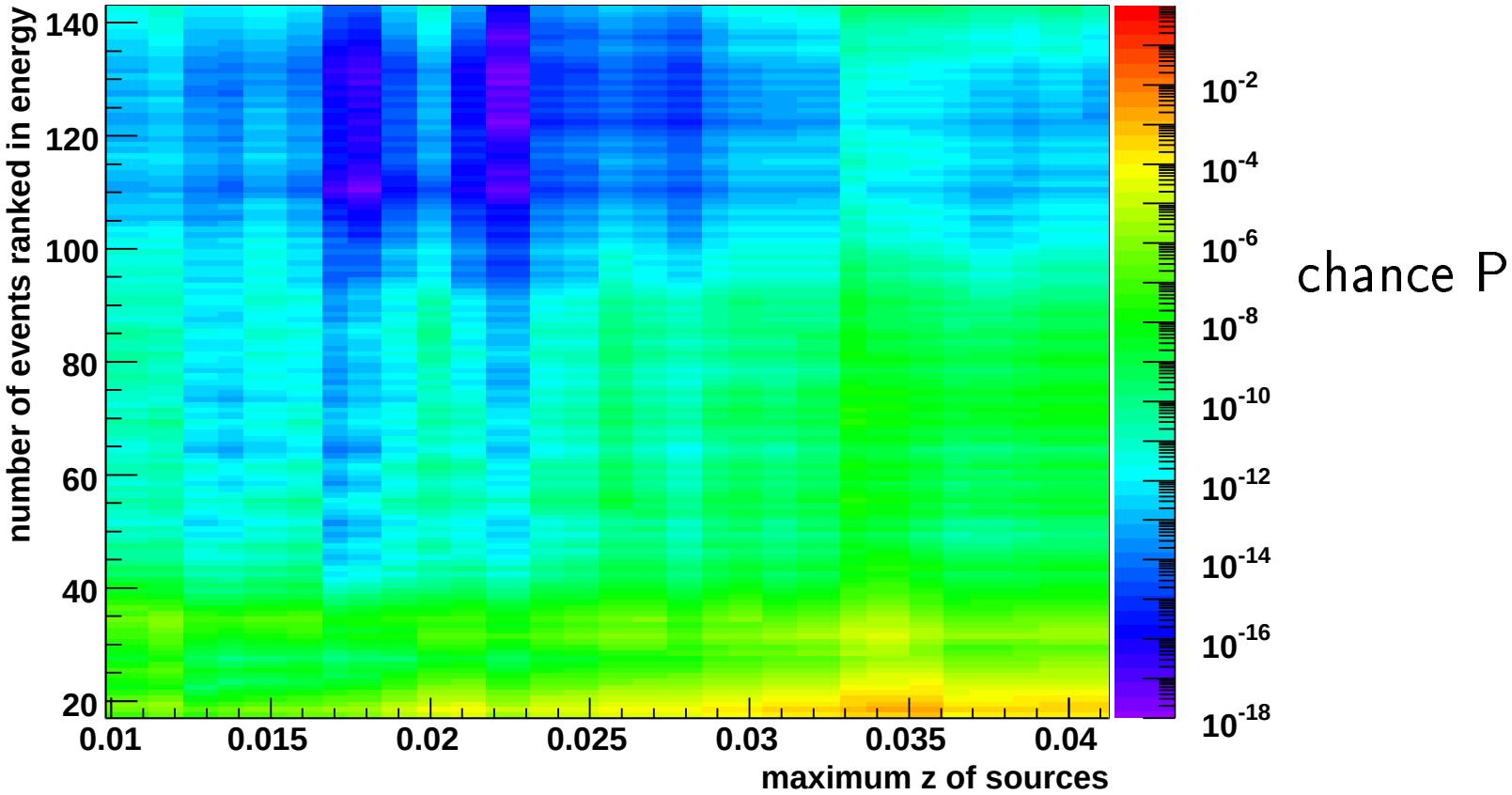
look for minimum chance $\mathcal{P}$ in the space of z, angular window



same for the real Auger data at the time of publication

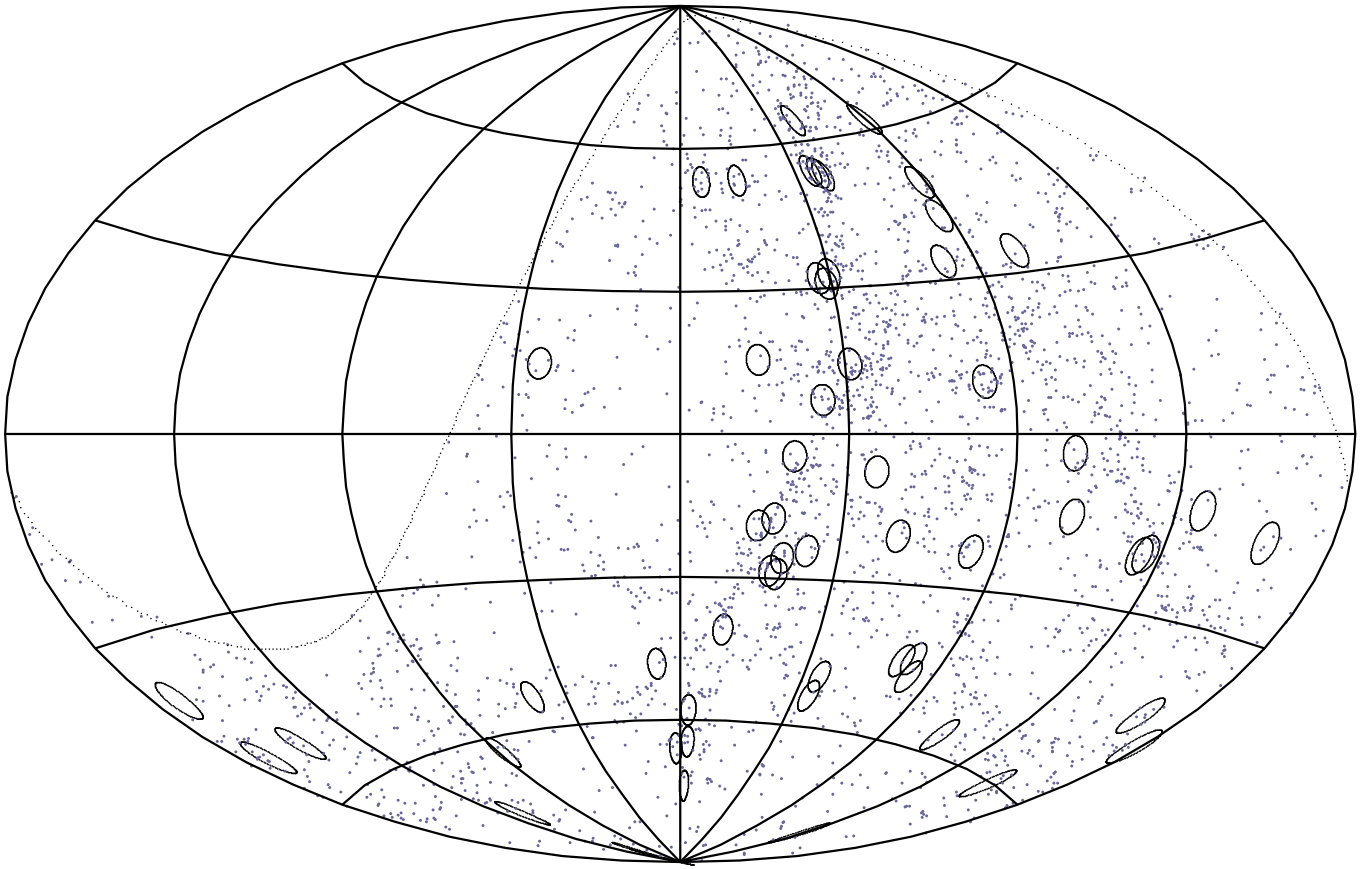


look for minimum chance $\mathcal{P}$ in the space of z, energy

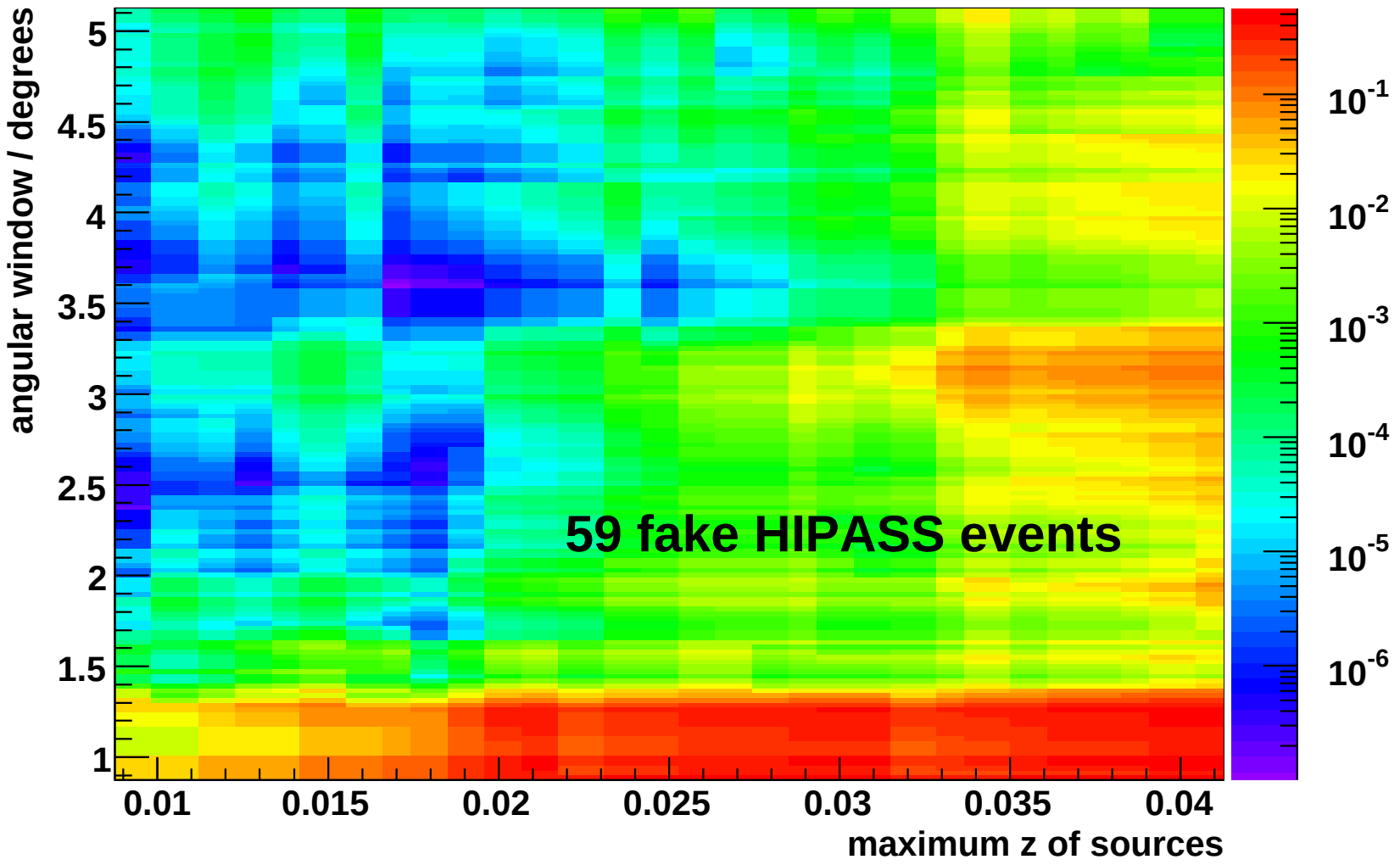


alternative catalogues - HIPASS

HI galaxies, weighted by amount of hydrogen ($\propto$ star formation rate)



look for minimum chance $\mathcal{P}$ in the space of z, angular window



Swift-BAT

- quite strong clustering strength (supergalactic plane)
- possibly well-motivated, no deficit of sources on the galactic plane

HIPASS

- higher multiplicity, sparse sources
- other candidate sources (GRBs)

some values of binomial probabilities when correlated with another catalogue (Véron-Cetty)

k/N	p	P	
17/44	0.21	$4.7 \cdot 10^{-3}$	data
19/39	0.21	$8.4 \cdot 10^{-5}$	fake Swift
34/60	0.21	$1 \cdot 10^{-9}$	fake Swift
29/59	0.21	$9.7 \cdot 10^{-7}$	fake HIPASS

summary of the simulation chain

- 'good guess' for starting spectral shape
- stochastic proton propagation
- detector resolution
- RA, DEC smearing
- intensity of each source
- declination of each source

what we do not account for

- chemical composition: all protons
- differences between sources: our spectra are universal
- does it make sense to weight on intensity of each source? i.e. is the cosmic ray flux proportional to the X-ray flux?

Conclusions

about the search for possible sources of cosmic rays

1. cosmic rays at the highest energies are expected to be anisotropic if there is a GZK horizon
2. disappointingly, the significance of the correlation of the Auger data with the Véron-Cetty catalogue decreases with time
3. we are optimising a simulation chain to produce fake maps; results are promising, we can tune analyses on mock data
4. some future work is needed to implement photo-disintegration, propagation, deflections of heavy elements, improve description of magnetic fields, ...