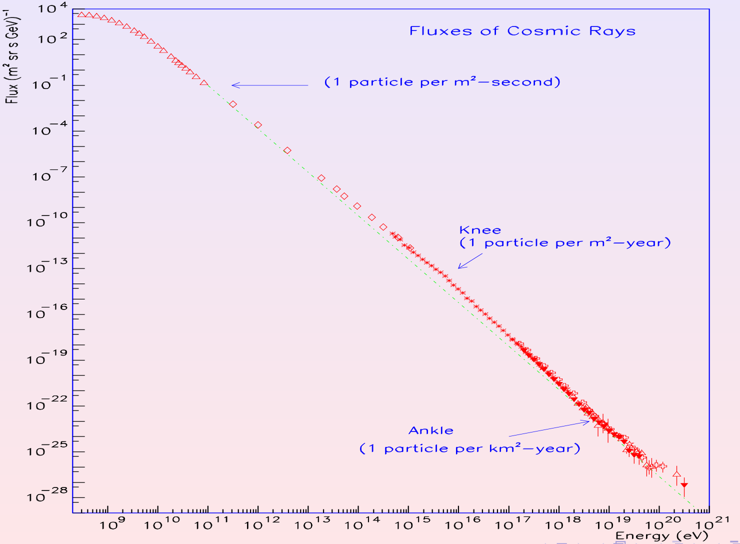
Anisotropies of High-Energy Cosmic Rays

Michael Kachelrieß

NTNU Trondheim

Introduction: CR spectrum



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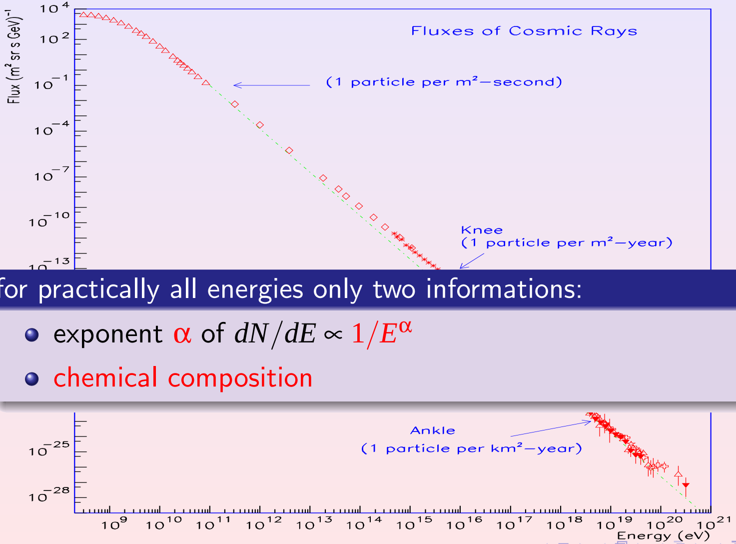
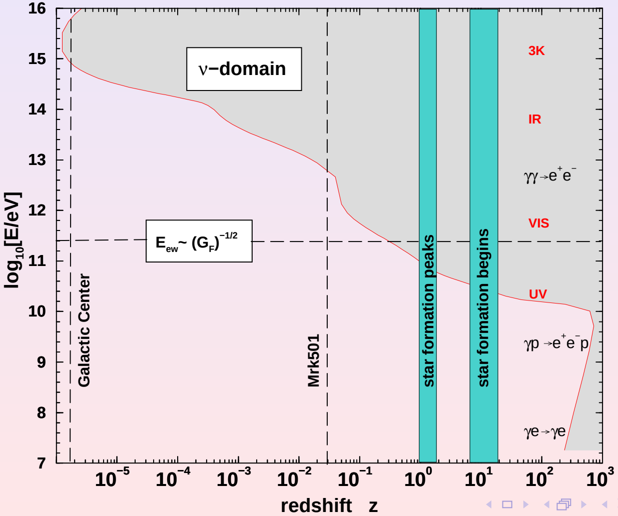


for practically all energies only two informations:

- exponent α of $dN/dE \propto 1/E^{\alpha}$
- chemical composition

Introduction: Why UHECR astronomy?

- astronomy with HE photons restricted to few Mpc:



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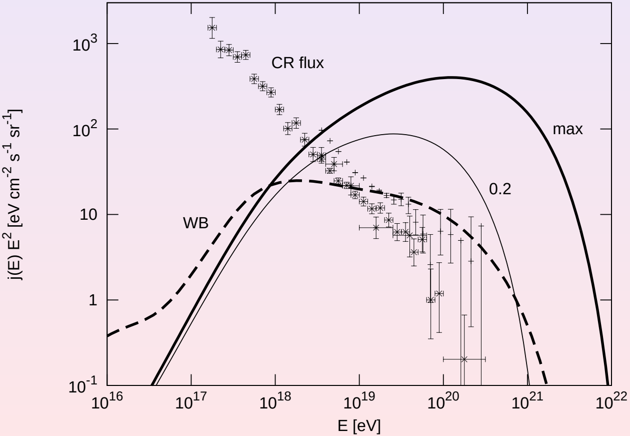

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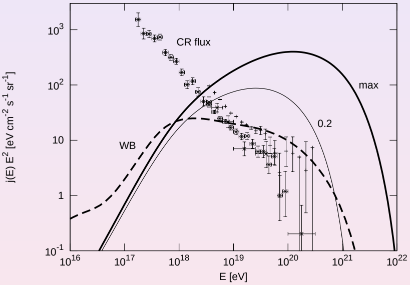

use larger statistics of UHECRs:

what can we learn from UHECRs in addition to spectrum?

Outline: Possible anisotropies of extragalactic CRs:

1. Small-scale clustering
   - Small-scale $\sim$ angular resolution of experiments

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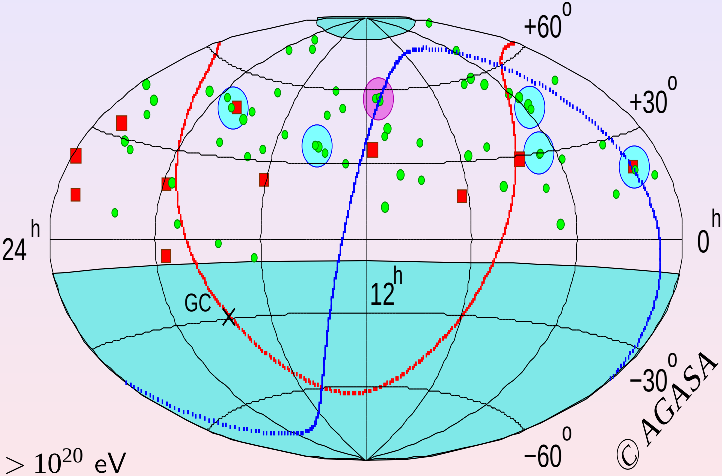
4. Dipole anisotropy and diffuse γ-ray background

Small-scale clustering and point sources:



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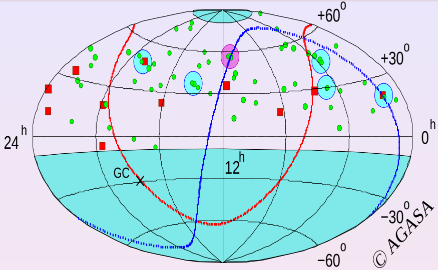

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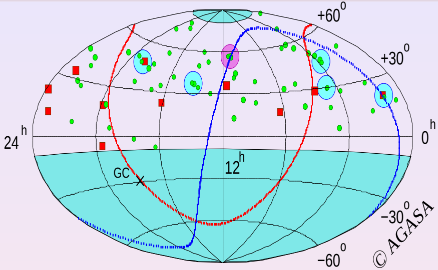

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- Second step:
  - Effect of magnetic fields
  - Chemical composition

Small-scale clustering and point sources:

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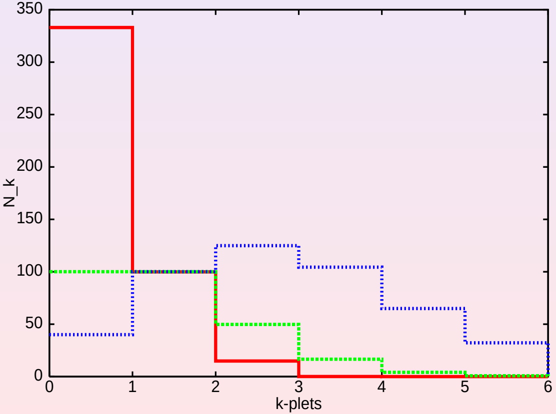

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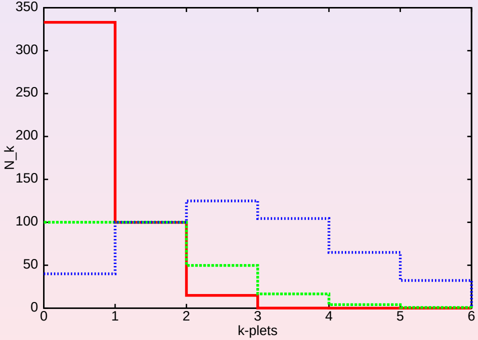

- allows to estimate n_s

Statistical estimator for small-scale clustering:

- two-point autocorrelation function of the data, i.e.

$$w_1 = \sum_{i<j} \Theta(\ell_1 - \ell_{ij}),$$

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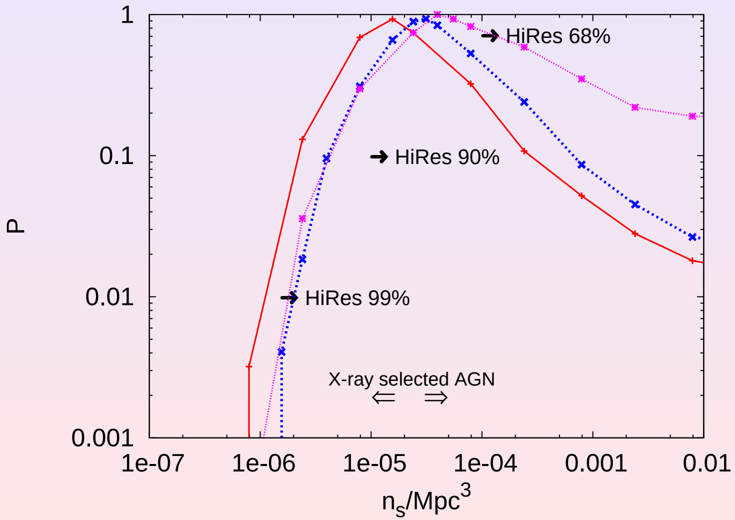
- compare to distribution $p(w_1 : \vartheta)$ from simulations:
  - choose finite number of sources according density n_s
  - generate CRs according to $dN/dE \propto E^{-\alpha}$
  - propagate them
  - calculate w_1 for fixed n_s, α, ℓ_1 ...
  - determine consistent parameters

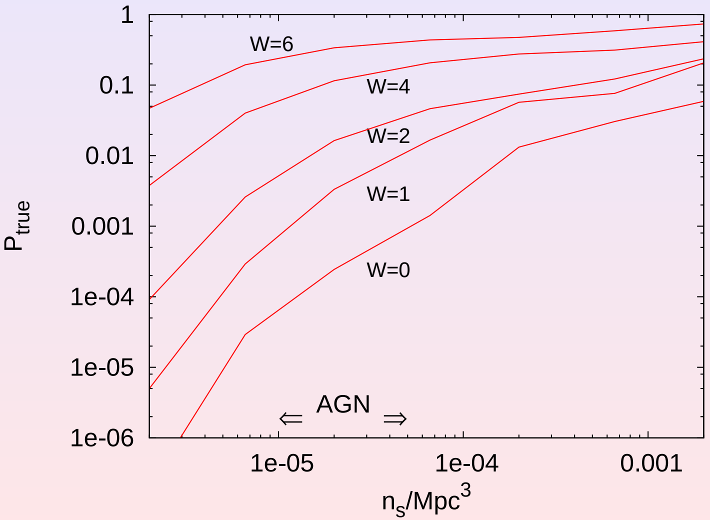
Small-scale clusters and density of sources:

[MK, D. Semikoz '04]



Small-scale clusters: how many by chance?

[MK, D. Semikoz '04]



Small-scale clusters—personel summary

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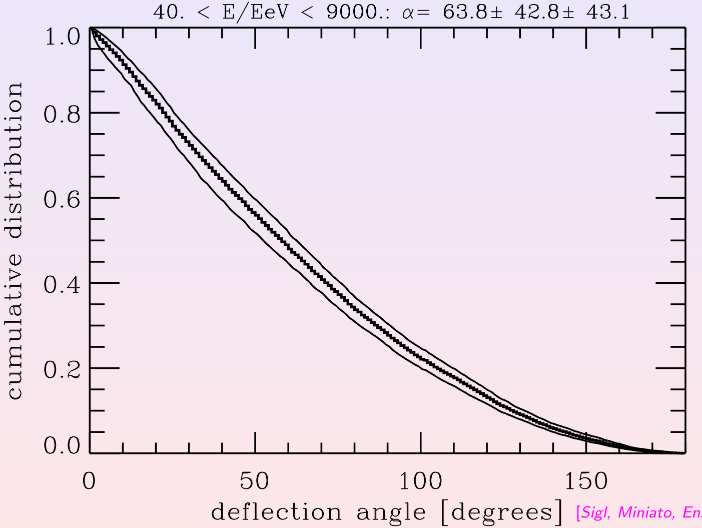
- crucial assumption: small EGMF and protons

Extragalactic magnetic field – simulation by SME:



[Sigl, Miniato, Ensslin '03]

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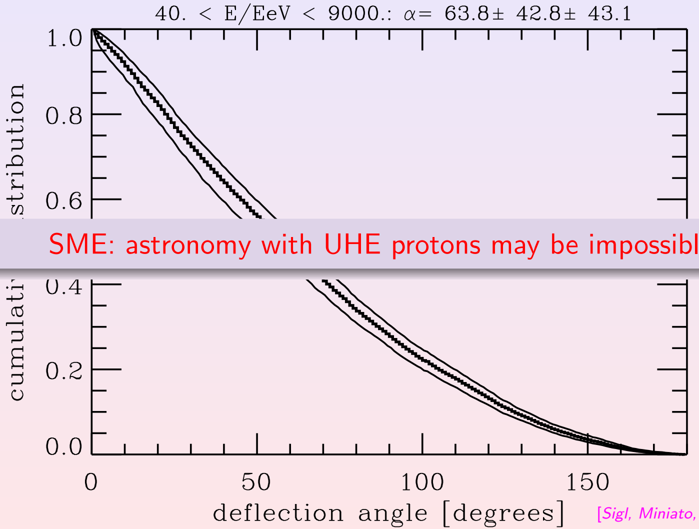
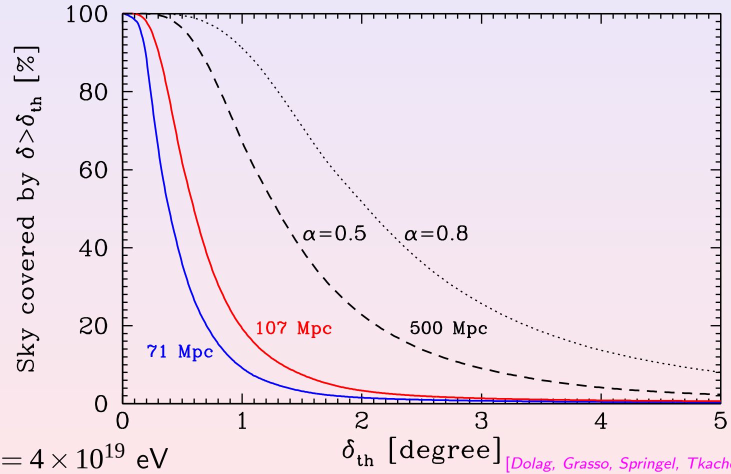


SME: astronomy with UHE protons may be impossible

[Sigl, Miniato, Ensslin '03]

Extragalactic magnetic field – simulation DGST:



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[Dolag, Grasso, Springel, Tkachev '03]

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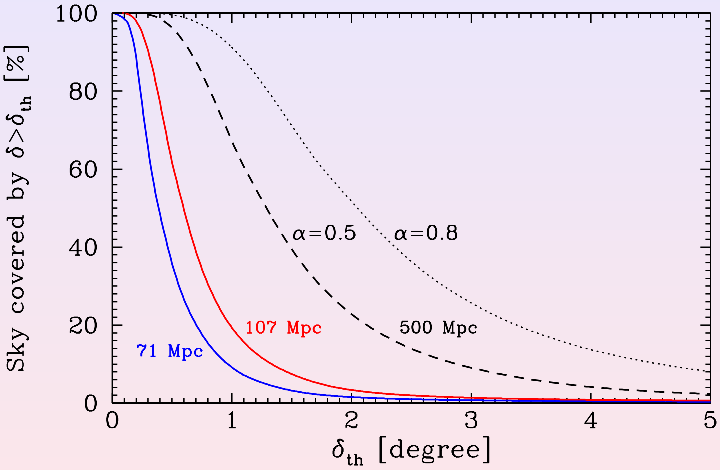

DGST: astronomy with UHE protons possible in large part of sky!

which simulation/conclusion is closer to reality?

- many technical differences between the two simulations; two major conceptional ones:
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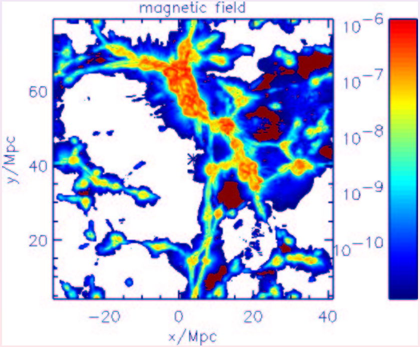

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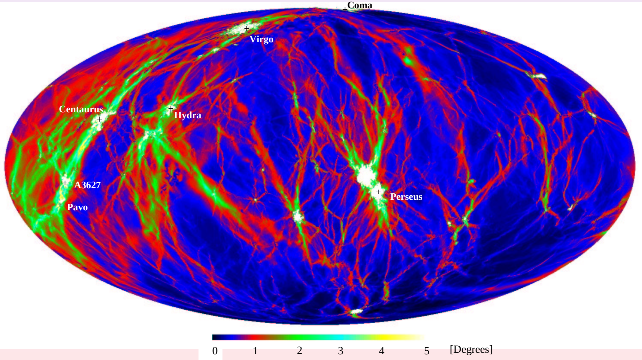

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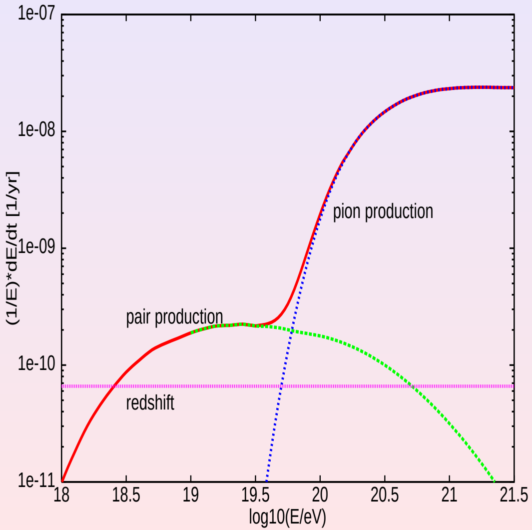
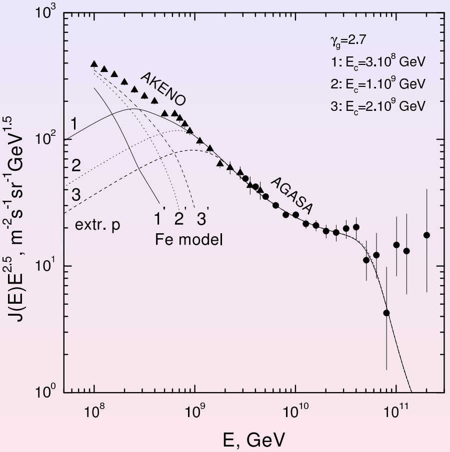
However: mechanism for generation of EGMF could be completely different!

Energy losses, the dip and the GZK cutoff



- at $E \sim 4 \times 10^{19}$ eV: $N + \gamma_{3K} \to \Delta \to N + \pi$ starts and reduces free mean path to ~ 20 Mpc
- pair production leeds to a dip at $\sim 10^{19}$ eV

Transition to extragalactic protons



[Berezinsky, Grigorieva, Hnatyk '04]

dip suggests: primaries above 10^{18} eV are extragalactic protons

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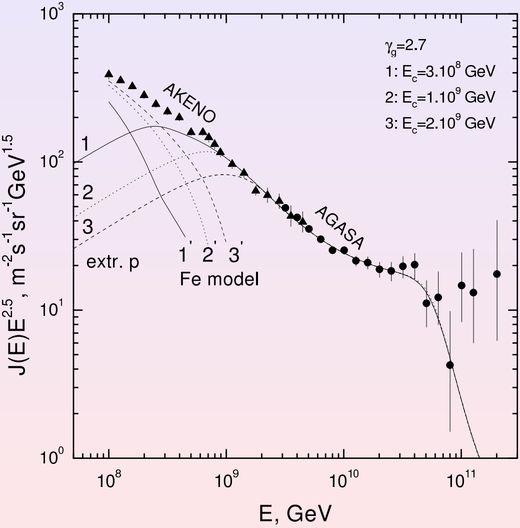

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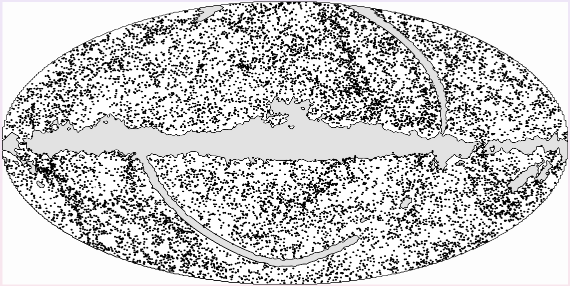

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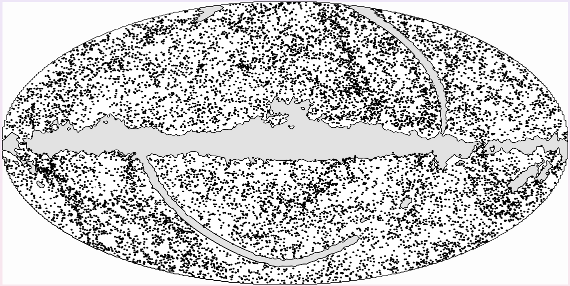

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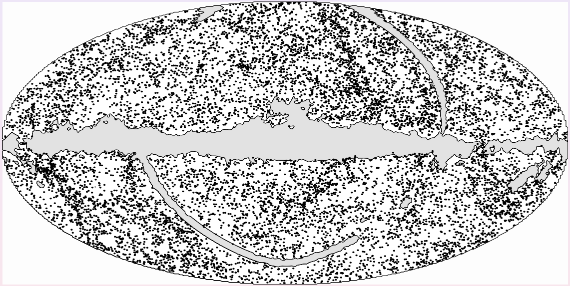

- lowering E even further, $\lambda_{\mathrm{CR}}(E) \gtrsim \lambda_{\mathrm{LSS}}$, LSS is be averaged out
- $O(100)$ events needed to detect effect, energy range around $\gtrsim 4 \times 10^{19}$ eV

[A. Cuoco et al. '05]

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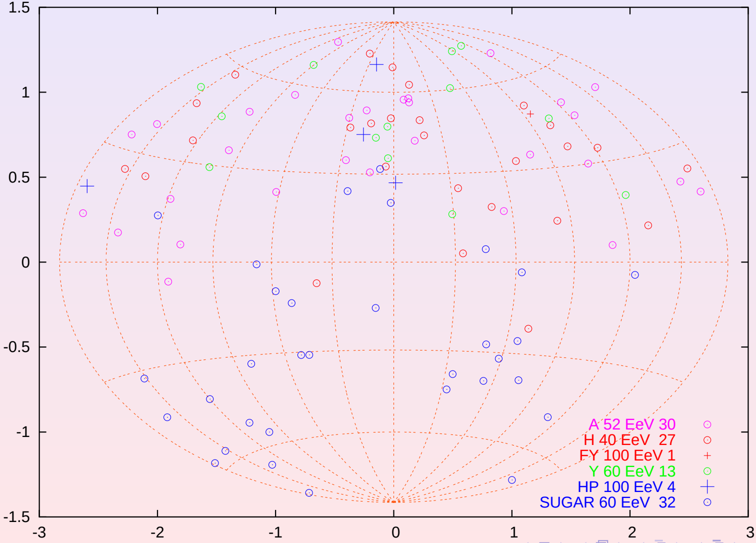

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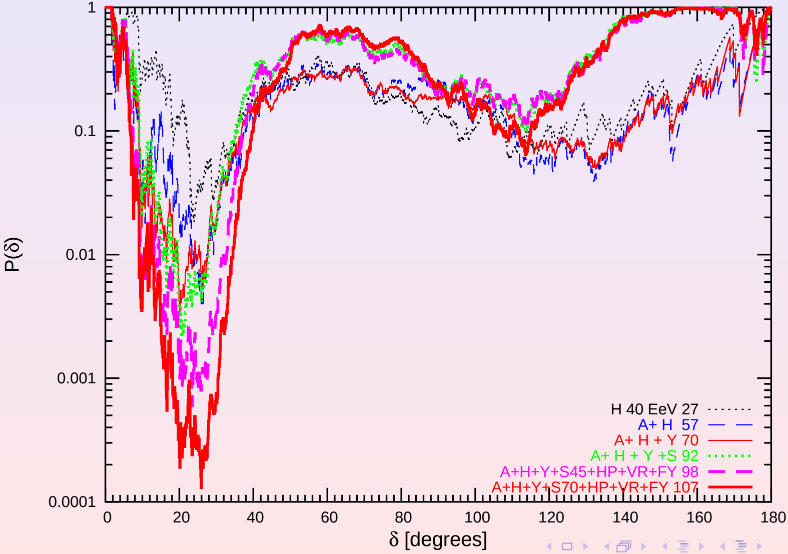

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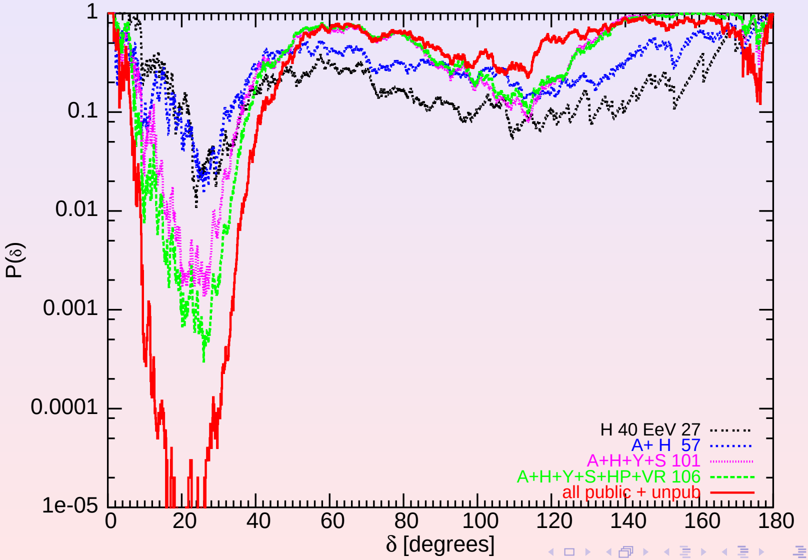

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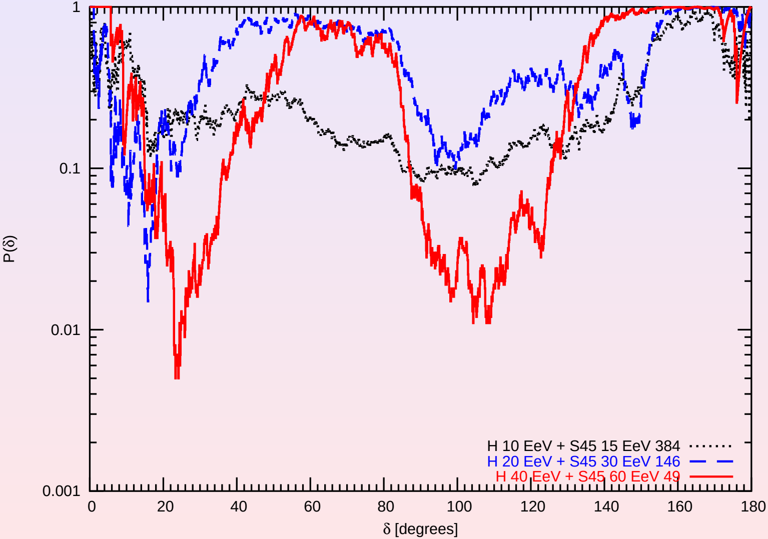
1
0.1
0.01
0.001
P(δ)
0
20
40
60
80
100
120
140
160
180
δ [degrees]
H 10 EeV + S45 15 EeV 384
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- penalty factor for scan over angles: $\sim$ 6–30

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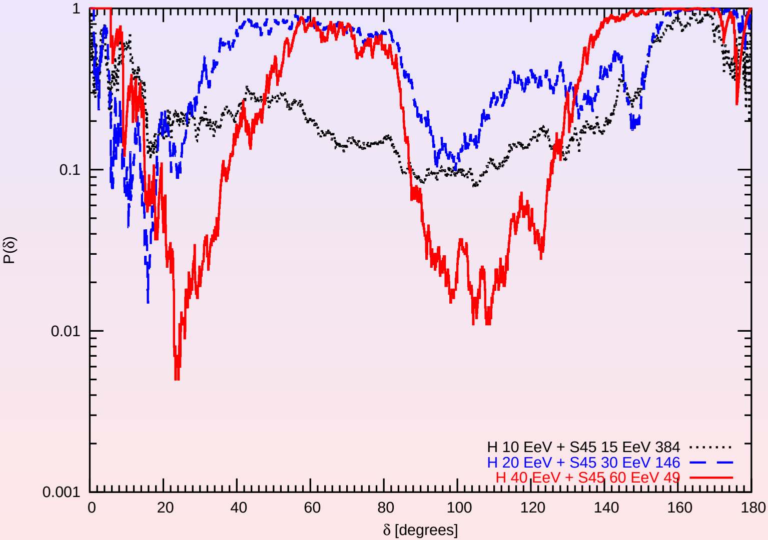

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$\Rightarrow$ analysis to be done. . .

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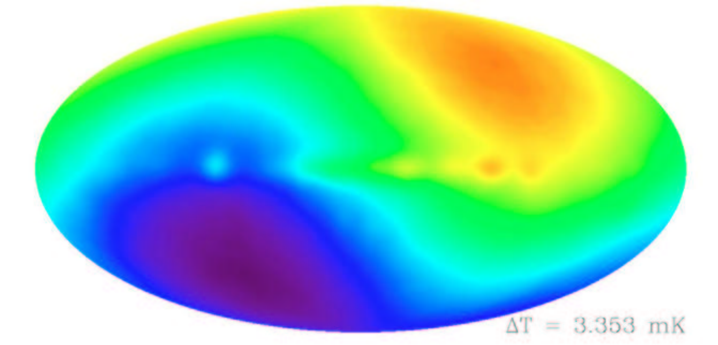
[MK, Serpico '06]

- Solar System is moving with $v \approx 368$ km/s relative to CMB



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$\Rightarrow$ dipole anisotropy also visible in UHECR flux $I(E) = E^2 f(p)$,

$$A_{\rm CCG} \equiv \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \left(2 - \frac{d\ln I}{d\ln E}\right) v \approx 0.6\% .$$

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- error of amplitude $A(l=1)$ for N events,

$$\sigma_A = \sqrt{\frac{3}{N}}\left[1 + 0.6\sin^3(\delta)\right],$$

[*Mollerach, Roulet '05*]

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- if extragal., 3σ detection within one year

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  - $\lambda_{CR}(E) \lesssim \lambda_{LSS}$: imprint of LSS as anisotropies on medium scales
  - for small enough qE/B and n_s (or large L), point sources detectable

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- $E \gtrsim E_{\rm tr}$: extragalactic cosmic rays:
  - $\lambda_{CR}(E) \gtrsim \lambda_{LSS}$: cosmological CG effect leads to 0.6% dipole anisotropy
  - $\lambda_{CR}(E) \lesssim \lambda_{LSS}$: imprint of LSS as anisotropies on medium scales
  - for small enough qE/B and n_s (or large L), point sources detectable
- CG effect allows GLAST to determine diffuse extragal. γ-ray background