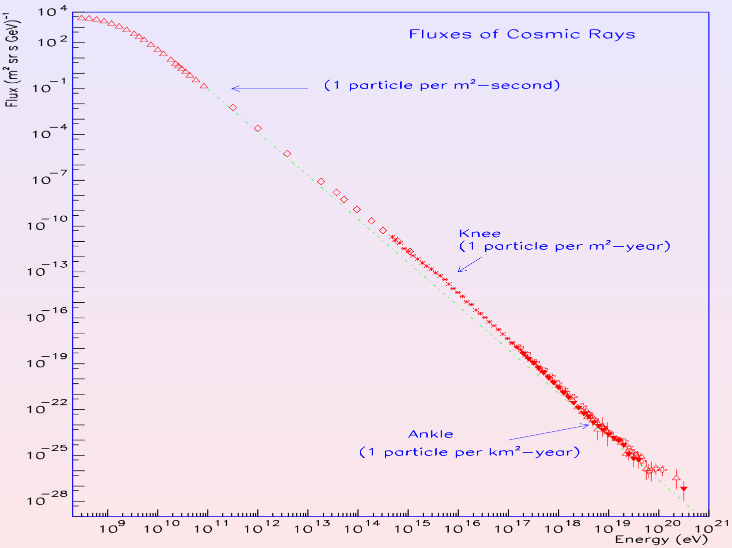
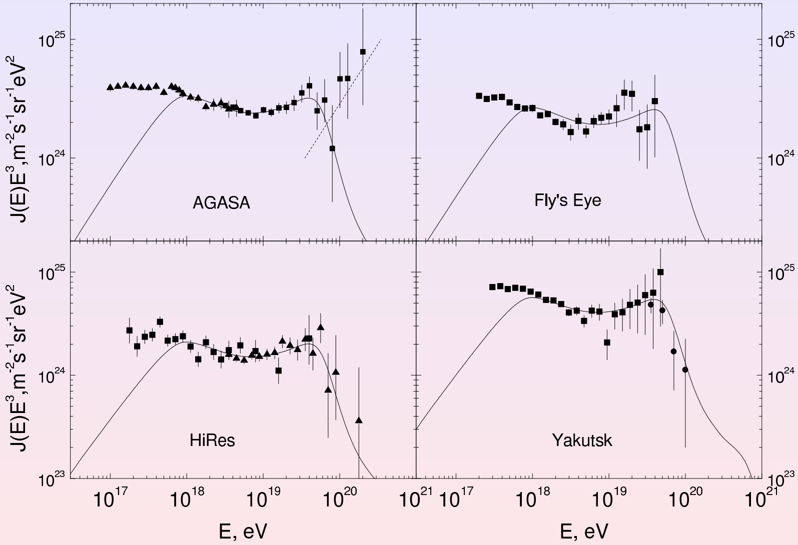
"The Future of UHECR Physics"

- Energy spectrum: confirmation of GZK effect?
- Identification of UHECR sources?
  - primaries: proton vs. nuclei
  - magnetic fields
  - small-scale clustering
  - correlations
- More than astrophysics?
  - top-down models
  - Z burst model
  - strongly interacting neutrinos
  - tests of Lorentz invariance, QCD, ...
- Summary

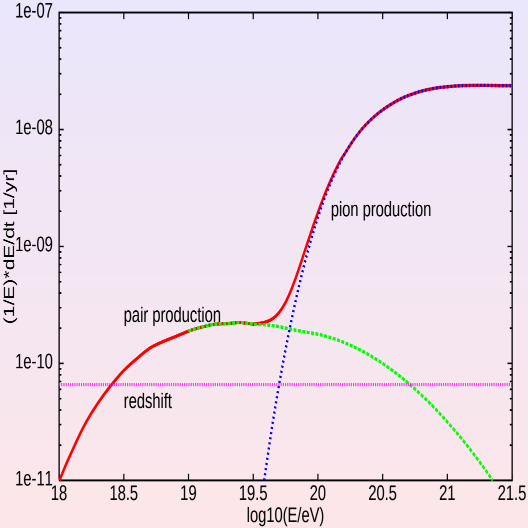
Energy spectrum and composition



Energy spectrum and composition



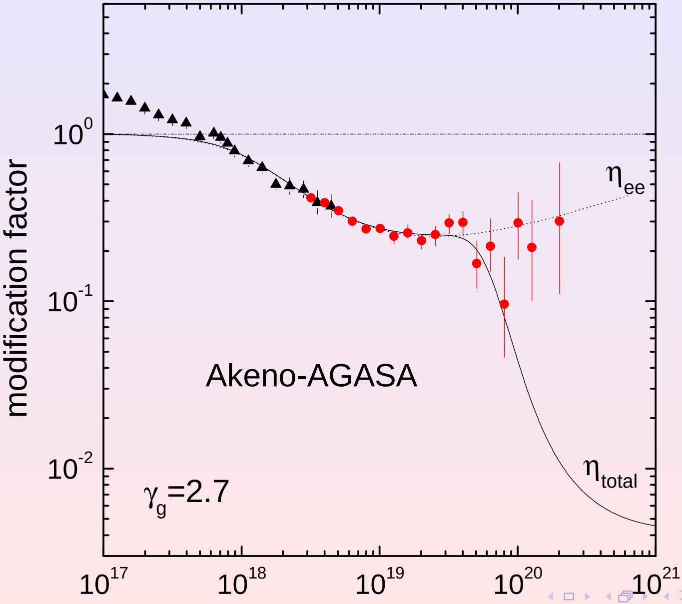
Energy losses, the dip and the GZK cutoff



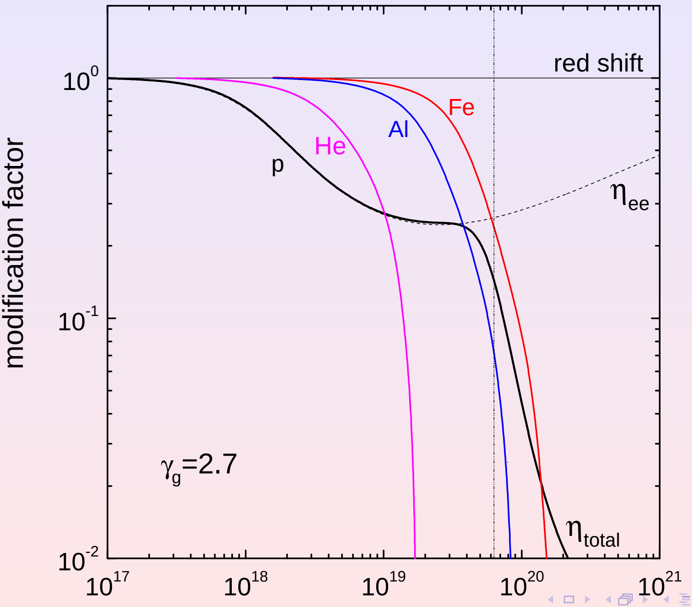
- at $E \sim 4 \times 10^{19}$ eV: $N + \gamma_{3K} \to \Delta \to N + \pi$ starts and reduces free mean path to ~ 20 Mpc
- pair production leads to a dip at $\sim 10^{19}$ eV

The (first) dip

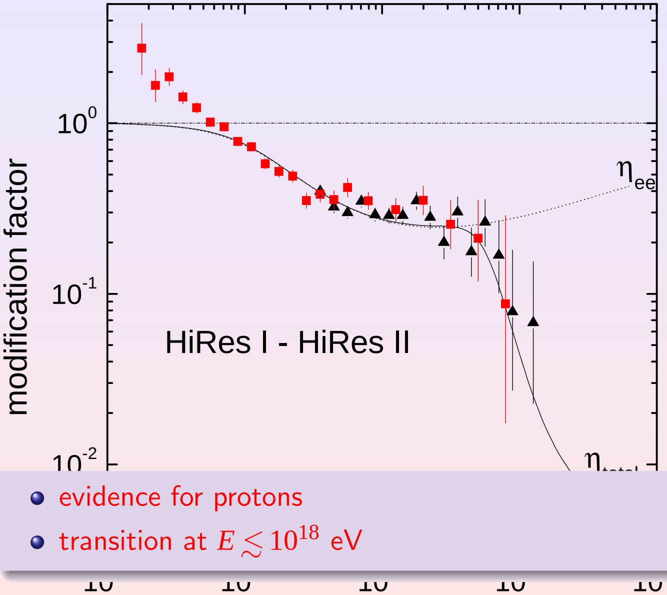
[*Berezinsky, Gazizov, Grigorieva '03*]



The (first) dip



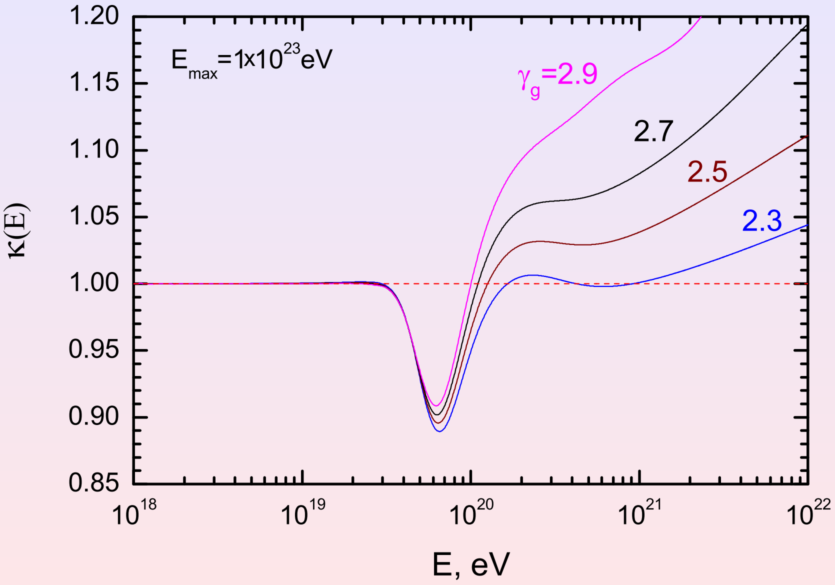
The (first) dip



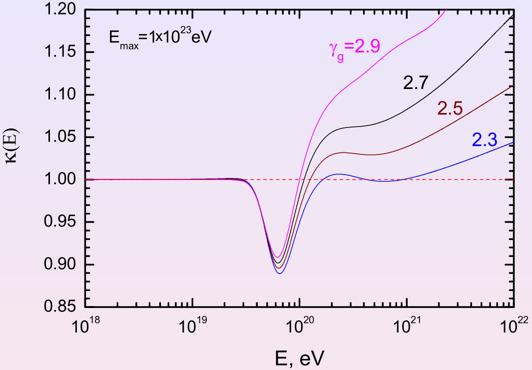
- evidence for protons
- transition at $E \lesssim 10^{18}$ eV

The second dip

[Berezinsky, Gazizov, MK '06]



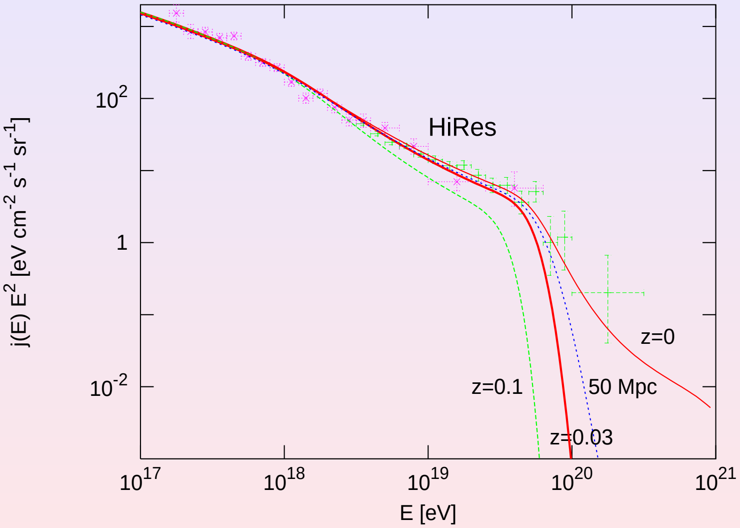
The second dip



- at E_{eq2} where $dE/dt|_{\rm pion} = dE/dt|_{\rm e^+e^-}$ $\Rightarrow$ calibration
- 2.nd dip shows up in $\kappa = J_{\rm obs}/J_{\rm CEL}$
- clean signature for CMB interactions of protons

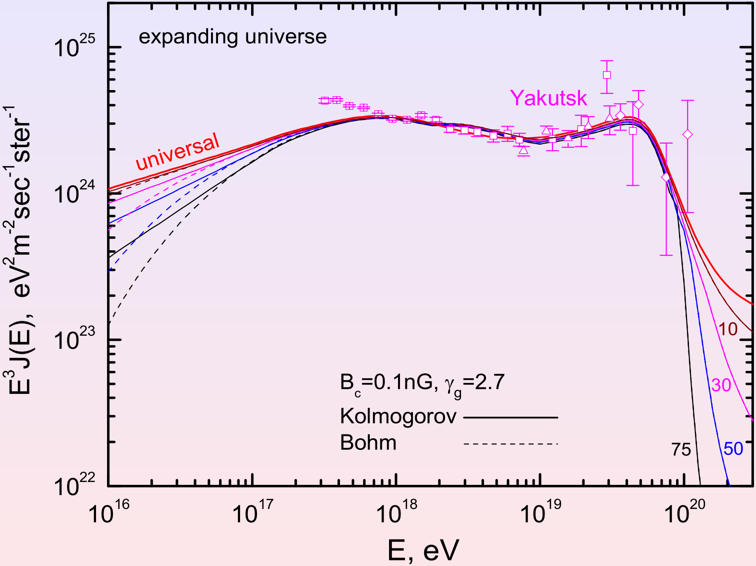
How universal is the spectrum?

[MK, Semikoz, Tortola '03]



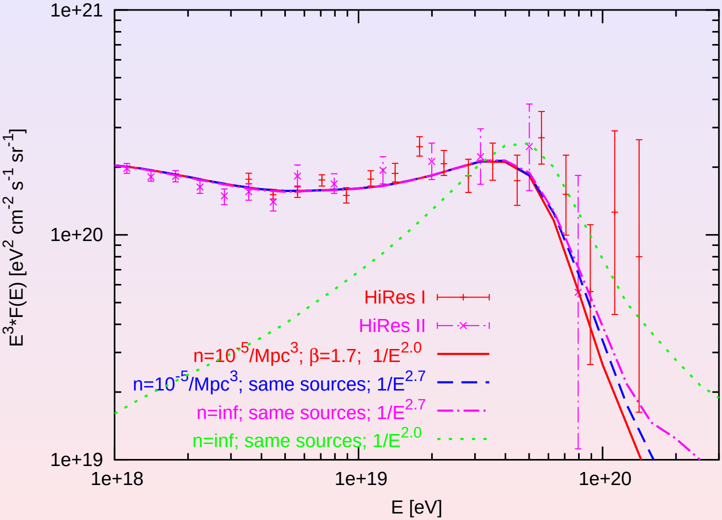
How universal is the spectrum?

[*Aloisio, Berezinsky '04*]

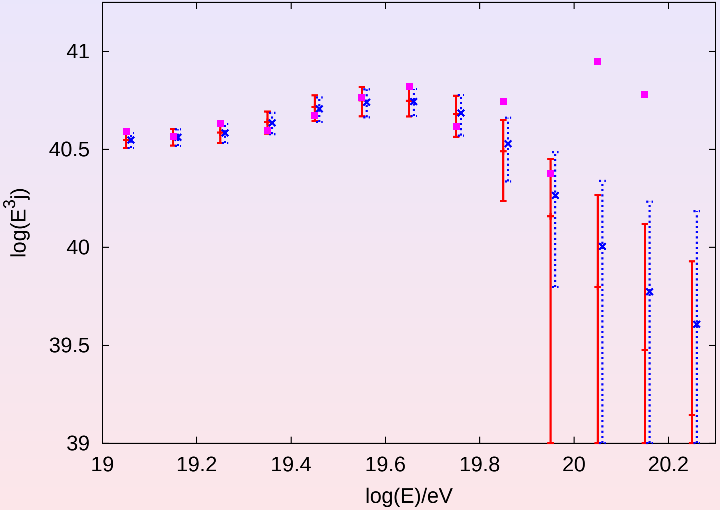


Universality and cosmic variance

[MK, Semikoz '05]



Universality and cosmic variance

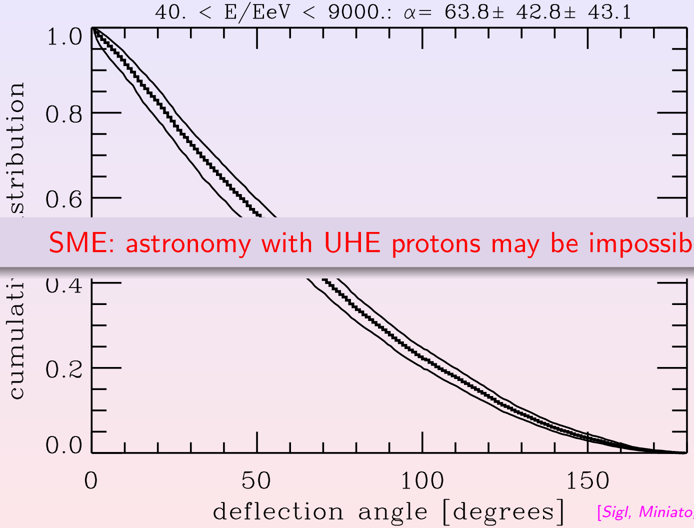


Possible anisotropies of extragalactic CRs:

1. Dipole anisotropy – cosmolog. Compton-Getting effect
   - induced by motion of Sun relative to cosmological rest frame
   - requires $\lambda_{\rm CR}(E) \gtrsim \lambda_{\rm LSS}$
2. Anisotropies on medium scales
   - $\ell \sim 20$–40 degrees
   - reflects LSS of matter, modified by B
   - requires $\lambda_{\rm CR}(E) \lesssim \text{few} \times \lambda_{\rm LSS}$
   - favoured by large n_s
3. Small-scale clustering
   - Small-scale $\sim$ angular resolution of experiments

   $\Rightarrow$ CR from the same point sources
   - requires small qB/E and small n_s

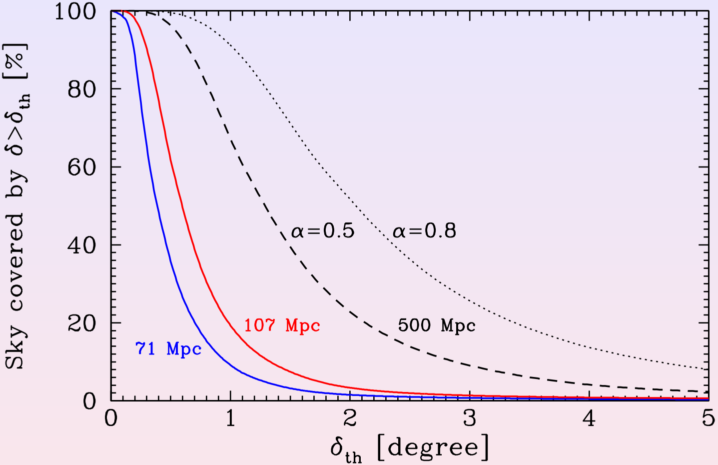
Extragalactic magnetic field – simulation by SME:



SME: astronomy with UHE protons may be impossible

[*Sigl, Miniato, Ensslin '03*]

Extragalactic magnetic field – simulation DGST:



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

which simulation/conclusion is closer to reality?

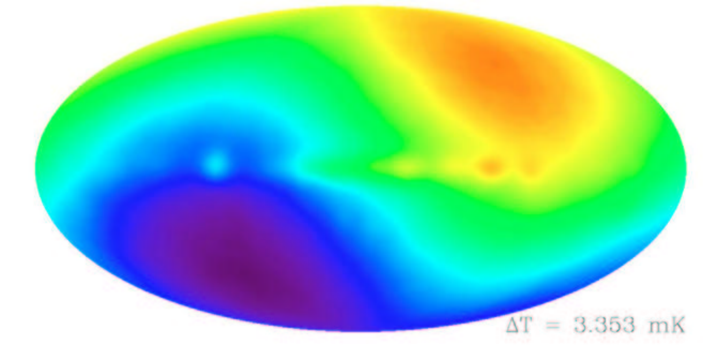
- many technical differences between the two simulations; two major conceptional ones:
  - Sigl, Miniato, Ensslin use an unconstrained simulation, putting observer $*$ close to a cluster
  - Dolag, Grasso, Springel, Tkachev use a constrained simulation
  - Dolag, Grasso, Springel, Tkachev inject protons uniformly on a sphere
  - Sigl, Miniato, Ensslin inject protons following matter distribution
  - presentation of results maximizes differences

Seed fields and amplification mechanism of EGMF could be completely different!

Cosmological Compton-Getting effect:

[*MK, Serpico '06*]

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



Cosmological Compton-Getting effect:

[MK, Serpico '06]

- Solar System is moving with $v \approx 368$ km/s relative to CMB
- UHECR sources are on average at rest

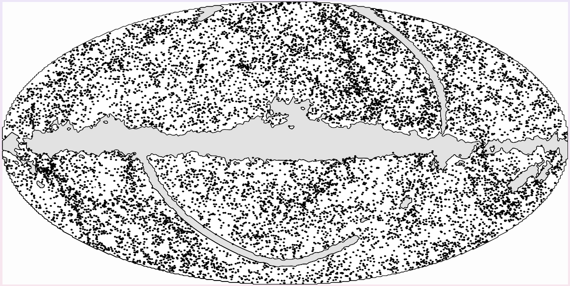
$\Rightarrow$ dipole anisotropy also visible in UHECR flux $I(E) = E^2 f(p)$,

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

- amplitude independent of primary charge and energy
- GMF shifts dipole vector by $\delta \sim 20^\circ \times 10^{19}{\rm eV}(Q/E)$
- comparison of δ at 2 energies gives (average) primary charge
- upper energ range depends on loss horizon $\lambda_{\rm CR}$
- lower on transition energy $E_{\rm tr}$ to galactic CRs

Medium-scale anisotropies in UHECRs:

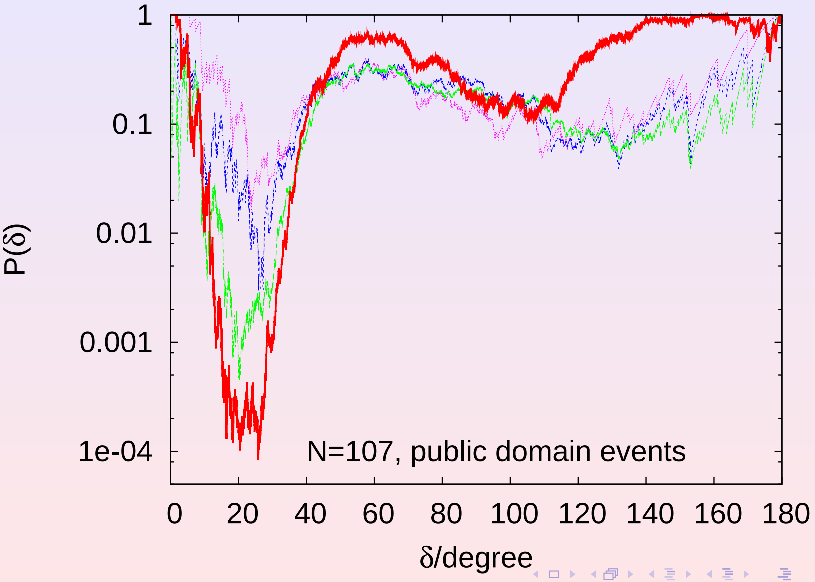
- increasing E/qB or decreasing n_s, LSS of sources becomes visible



- $O(100)$ events needed to detect effect, energy range around $\gtrsim 4 \times 10^{19}$ eV [A. Cuoco et al. '05, '06]
- increasing E even further, single sources become visible

Medium-scale anisotropies in UHECRs:

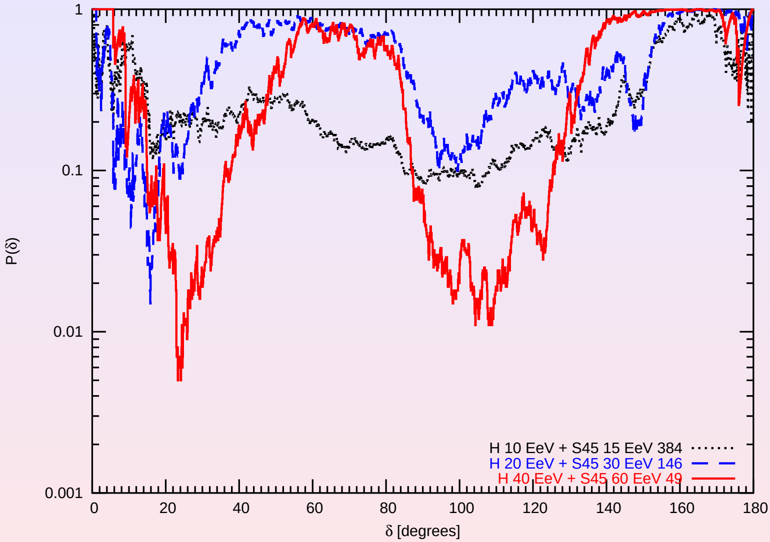
[MK, D. Semikoz '05]



True effect?

- independent of energy, if artefact due to incorrect combination of experiments

True effect?



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
H 20 EeV + S45 30 EeV 146
H 40 EeV + S45 60 EeV 49

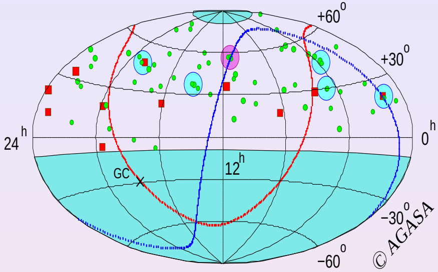
True effect?

- independent of energy, if artefact due to incorrect combination of experiments

$\Rightarrow$ signal disappears due to $\lambda_{\rm CR}(E) \nearrow$ and $\delta_B \nearrow$

- penalty factor for scan over angles: ~ 6–30

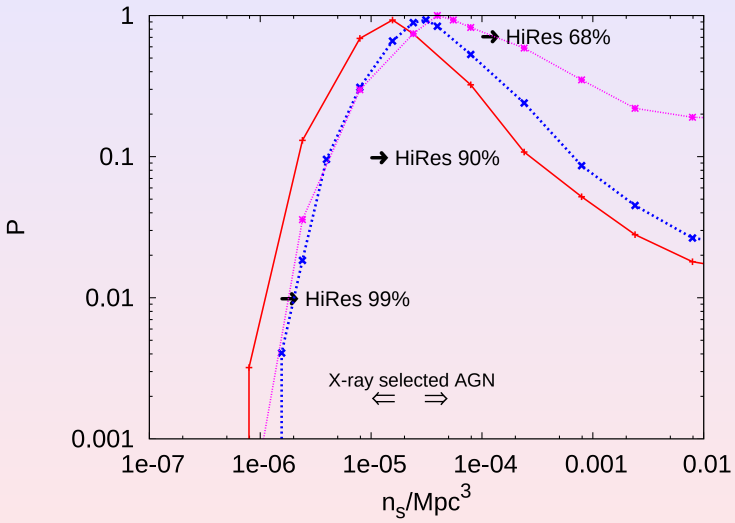
Small-scale clustering and point sources:



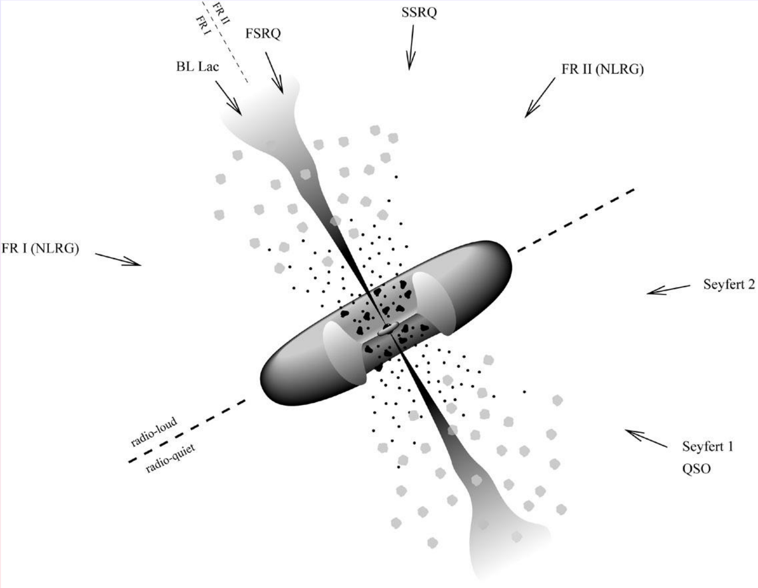
- $E > 10^{20}$ eV
- $E = 4 - 10 \times 10^{19}$ eV

- no contradiction between AGASA and HiRes
- significant cross-correlation between HiRes and AGASA, if energies are rescaled
- depends strongly on triplet
- PAO: only search for local excess; different GMF

Small-scale clusters and density of sources: [MK, D. Semikoz '04]



Unified AGN picture



Correlations with astrophysical sources:

+ Farrar & Biermann '98: radio-loud QSO's, $p_{\mathrm{ch}} \sim 0.5\%$
− Sigl et al. '01: $p_{\mathrm{ch}} \sim 27\%$

+ Tinyakov & Tkachev: AY – radio-loud BL Lacs with $z > 0.1$ and $\mathrm{mag} < 18$, $p_{\mathrm{ch}} \sim 2 \times 10^{-5}$
− Torres et al.: HV no significant correlation

+ Gorbunov et al.: HiRes – all BL Lacs with $\mathrm{mag} < 18$, $p_{\mathrm{ch}} \sim 4 \times 10^{-4}$

- How serious p_{ch} should be taken?
- PAO should see correlations with AGNs with 1-2 years

Top-Down Models

UHECR primaries are produced by decays of supermassive particle X with $M_X \gtrsim 10^{12}$ GeV.

- topological defects: monopoles, strings, ...

  [*Hill '83; Ostriker, Thompson, Witten '86*]

- superheavy metastable particles

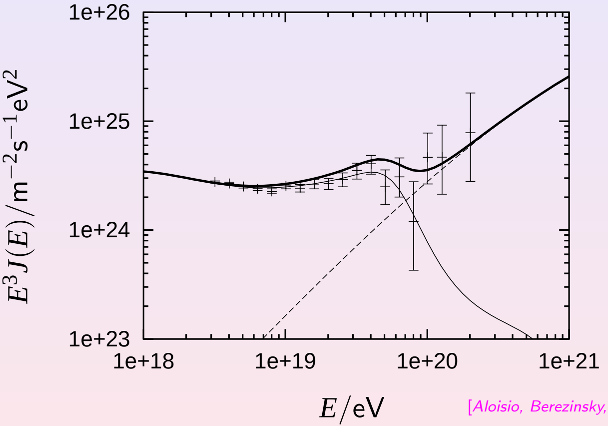
  [*Berezinsky, MK, Vilenkin '97; Kuzmin, Rubakov '97*]

Advantages:

- no acceleration problem
- no visible sources
- if $X \in$ CDM, no GZK-cutoff
- theoretically motivated; testable predictions

Signatures of SHDM decays

- flat spectra $dE/E^{1.9}$ up to $m_X/2$

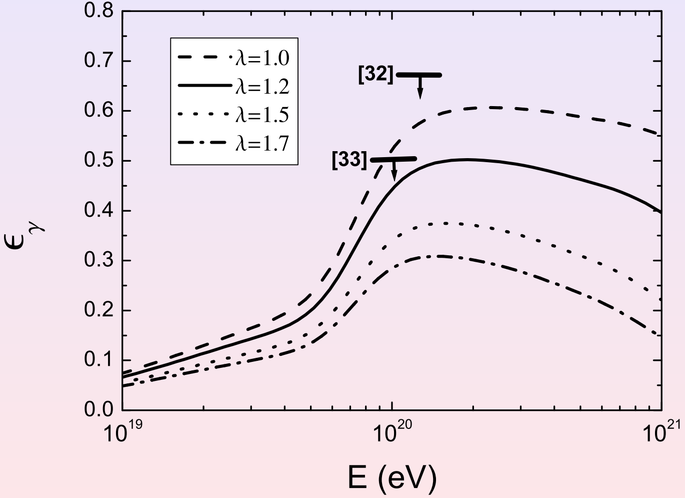


[Aloisio, Berezinsky, MK, '03]

$\Rightarrow$ SHDM dominates UHECR flux only above $\sim 8 \times 10^{19}$ eV

Signatures of SHDM decays

- flat spectra $dE/E^{1.9}$ up to $m_X/2$
- composition: photon dominance



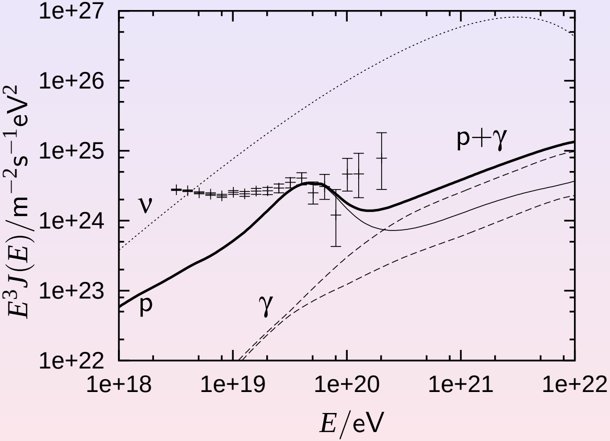
[Alosio, Berezinsky, MK '06]

Signatures of SHDM decays

- flat spectra $dE/E^{1.9}$ up to $m_X/2$
- composition: photon dominance
- galactic anisotropy

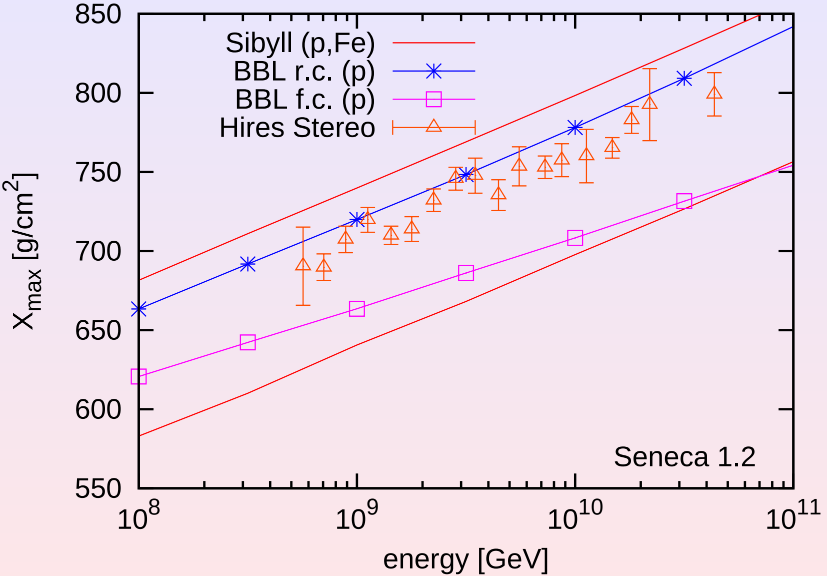
[Dubovsky, Tinyakov '98]

Status of topological defect models – necklaces:



⇒ shape of spectrum allows only sub-dominant contribution

Restricting QCD: Color Glass Condensates, . . .



[Drescher, Dumitru, Strikman '04]

Summary

Current main uncertainties:

- chemical composition: proton vs. nuclei
- extragalactic magnetic fields: deflections
- type of sources: density

Autocorrelation on medium scales

- physically well motivated
- to be falsified within 1–2 (?) years by PAO

Correlations with sources, favoured:

- EGMF in voids ~ 0 plus protons
- correlation with (subclass) of AGNs
- various claims to be falsified within 1–2 (?) years

Particle physics:

- no need for new physics (?)
- top-down models attractive
- test for QCD, new physics, ...