Ultra-High Energy Cosmic Rays

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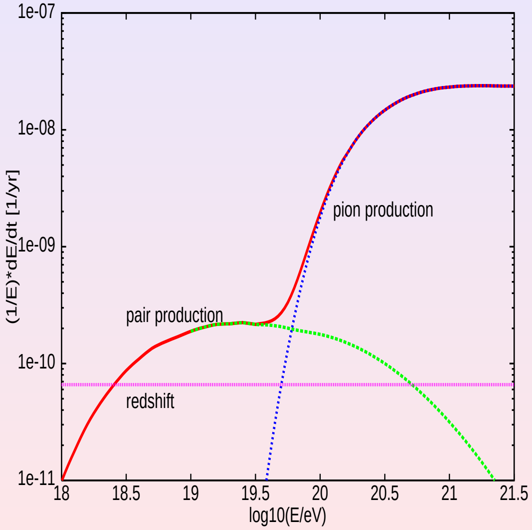
Outline of the talk:

- Data and their interpretation
  - extragalactic protons as primaries
  - magnetic fields
  - small-scale clustering
  - correlations
  - energy spectrum (above the GZK cutoff)
- Alternative models
  - Z burst model
  - strongly interacting neutrinos
  - top-down models
  - violation of Lorentz invariance
- Summary

Energy losses 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

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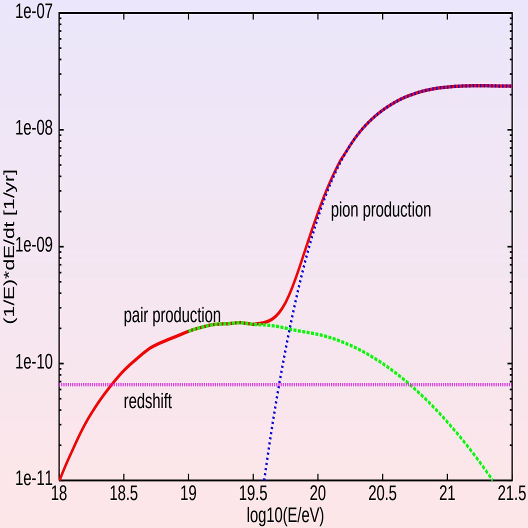
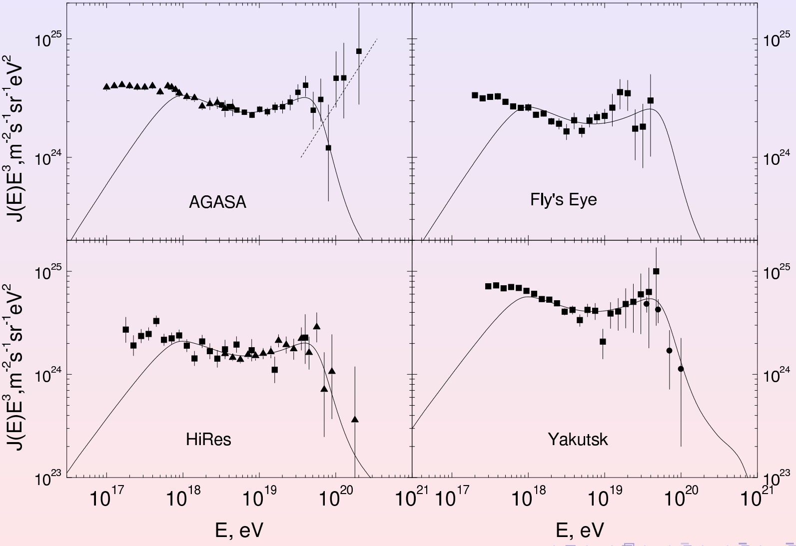


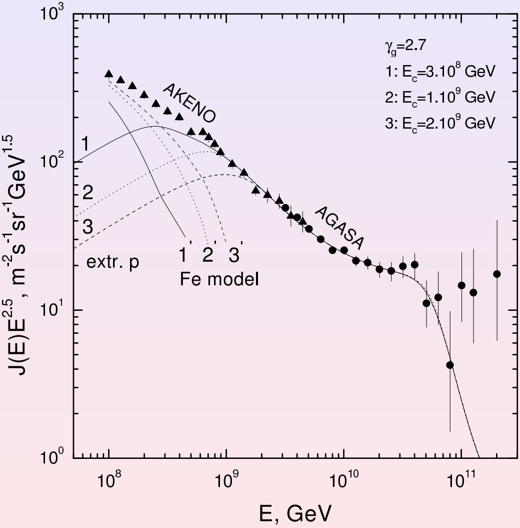
- at $E \sim 4 \times 10^{19}$ eV: $N + \gamma_{3K} \to \Delta \to N + \pi$ starts and reduces free mean path to ~ 20 Mpc
- nuclei photo-disintegrate with similar free mean path
- photons are absorbed on IR background on ~ 10 Mpc

Cosmic ray spectrum: the dip at 10^{19} eV

[Berezinsky, Grigorieva, Hnatyk '04]



Transition to extragalactic protons



[Berezinsky, Grigorieva, Hnatyk '04]

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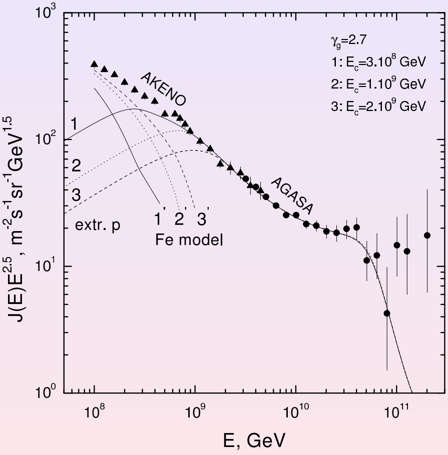
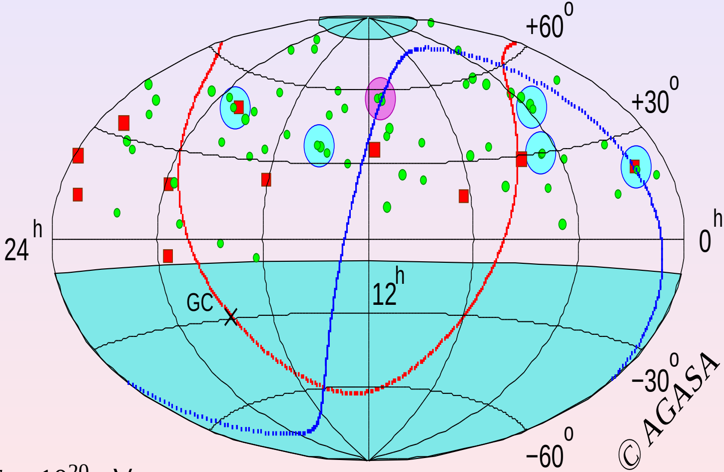


[Berezinsky, Grigorieva, Hnatyk '04]

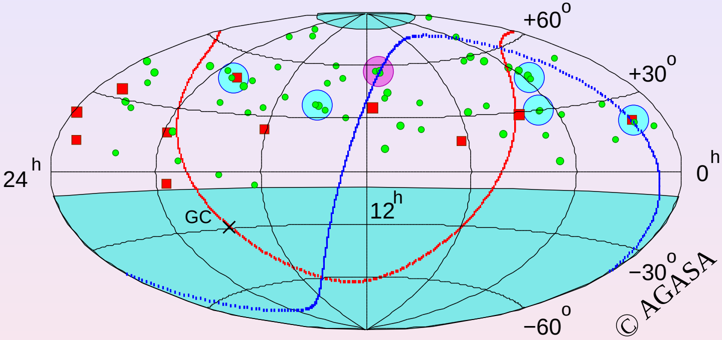
dip suggests: primaries above 10^{18} eV are extragalactic protons

Large-scale isotropy and small-scale clustering



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

Large-scale isotropy and small-scale clustering



- large-scale isotropy: extragalactic sources
  - few sources nearby, nuclei, strong EGMF?
  - many sources, protons, weak EGMF?
- small-scale clusters: chance or multiplets from same sources?

Number of sources N_s

- As N_s decreases, sources become brighter for fixed flux $\Rightarrow$ probability for clustering increases [*Waxman, Fisher, Piran '96*]

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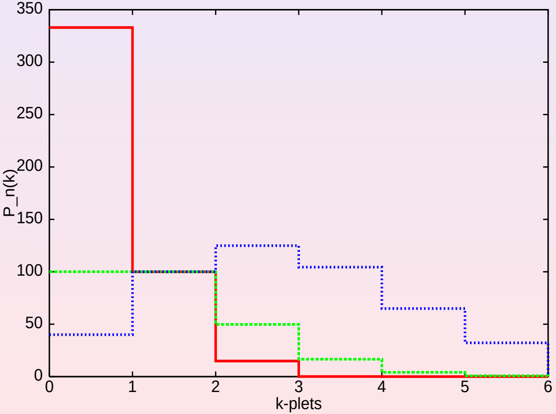

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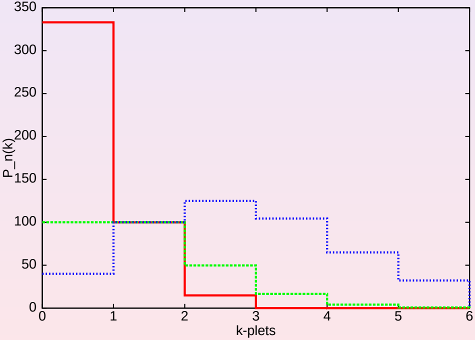

- allows to estimate N_s, but not n_s

Statistical estimator for small-scale clustering:

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

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

where ℓ_{ij} is the angular distance of CRs i,j and ℓ_1 the bin size chosen

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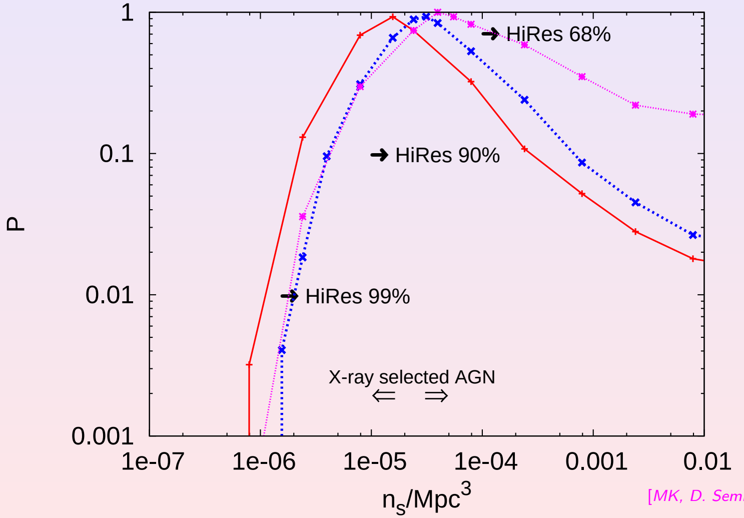
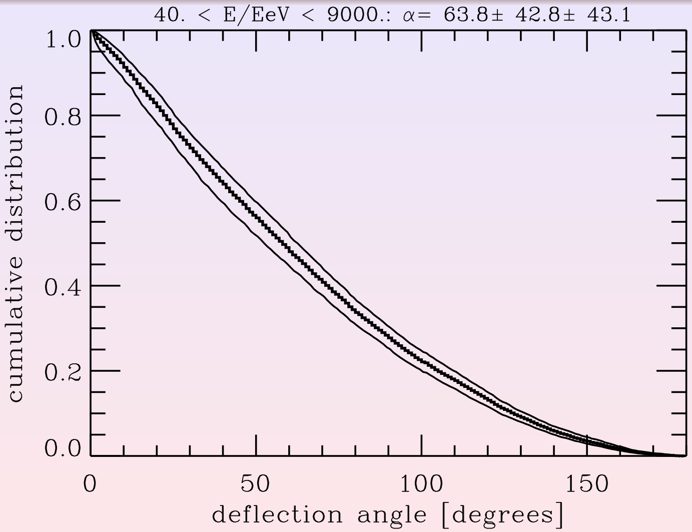
- compare to distribution $p(w_1 : \vartheta)$ from simulations:
  - choose finite number of sources according density n_s
  - generate CRs according to $dN/dE \propto E^{-\alpha}$
  - propagate them
  - calculate w_1 for fixed n_s, α, ℓ_1 ...
  - determine consistent parameters

Small-scale clusters and density of sources:



[MK, D. Semikoz '04]

Extragalactic magnetic field – simulation by SME:



[Sigl, Miniato, Ensslin '03]

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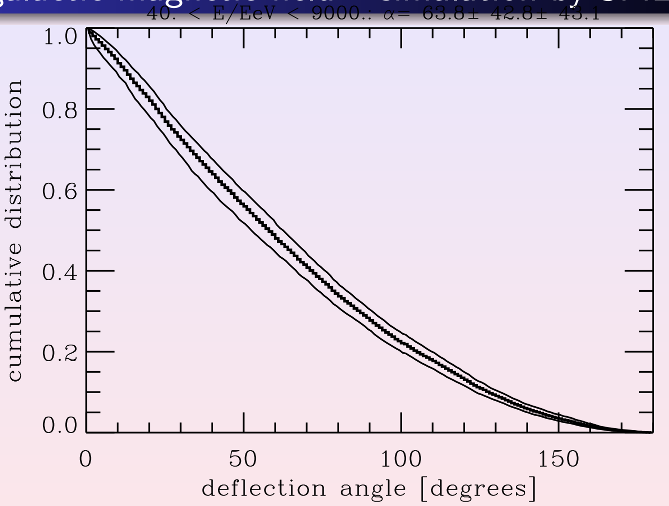
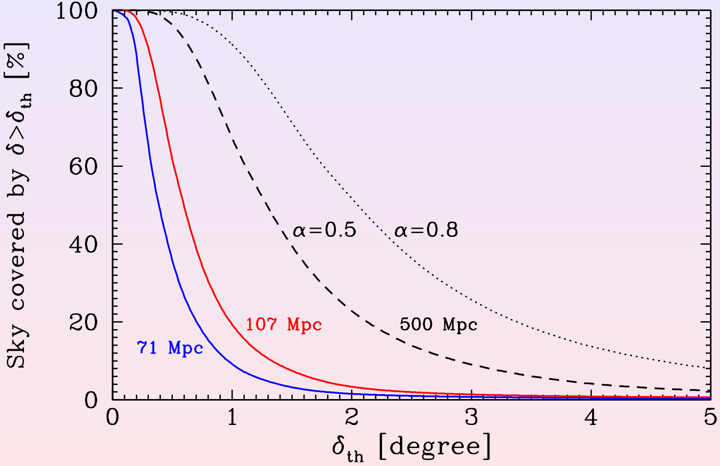


SME: astronomy with UHE protons may be impossible

Extragalactic magnetic field – simulation DGST:



[*Dolag, Grasso, Springel, Tkachev '03*]

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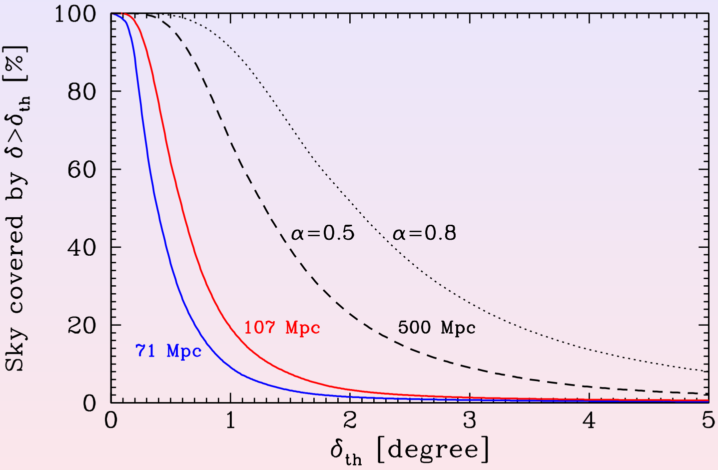
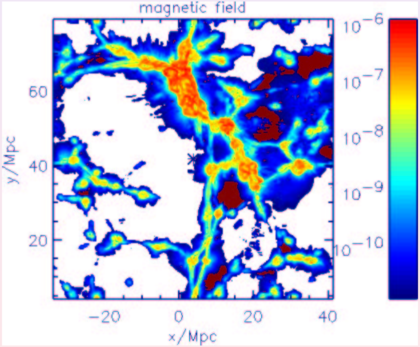


DGST: astronomy with UHE protons possible in large part of sky!

which simulation/conclusion is closer to reality?

- many technical differences between the two simulations; two major conceptional ones:
  - Sigl, Miniato, Ensslin use an unconstrained simulation, putting observer $*$ close to a cluster



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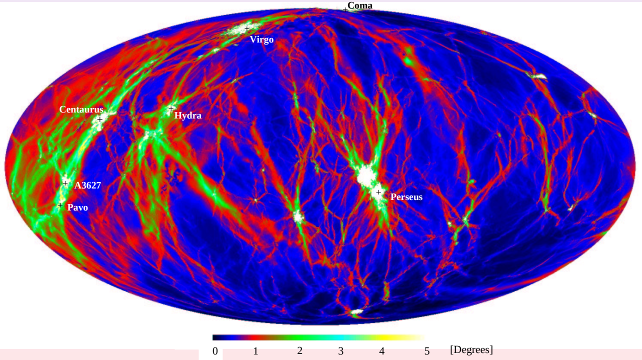

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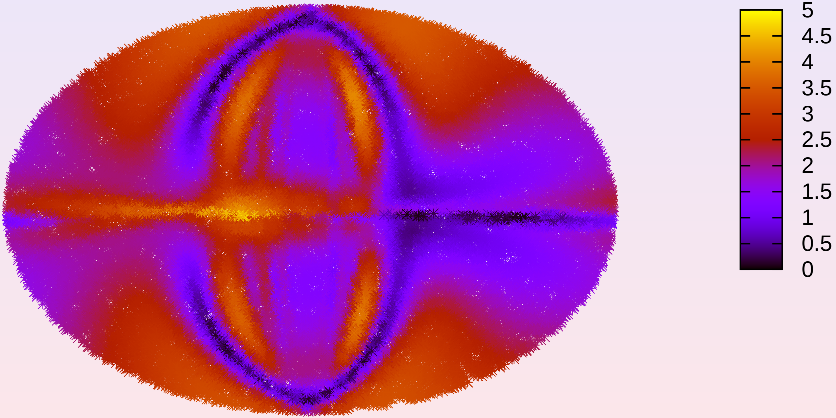
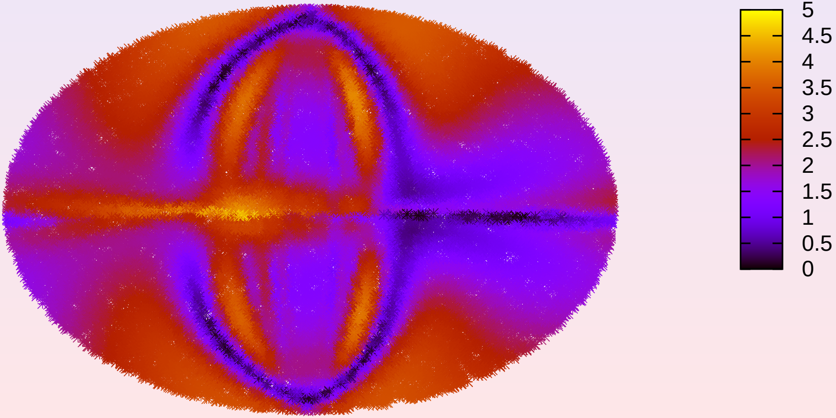
  - Dolag, Grasso, Springel, Tkachev inject protons uniformly on a sphere
  - Sigl, Miniato, Ensslin inject protons following matter distribution

Deflections for $eE/Q = 10^{20}$eV in Galactic field

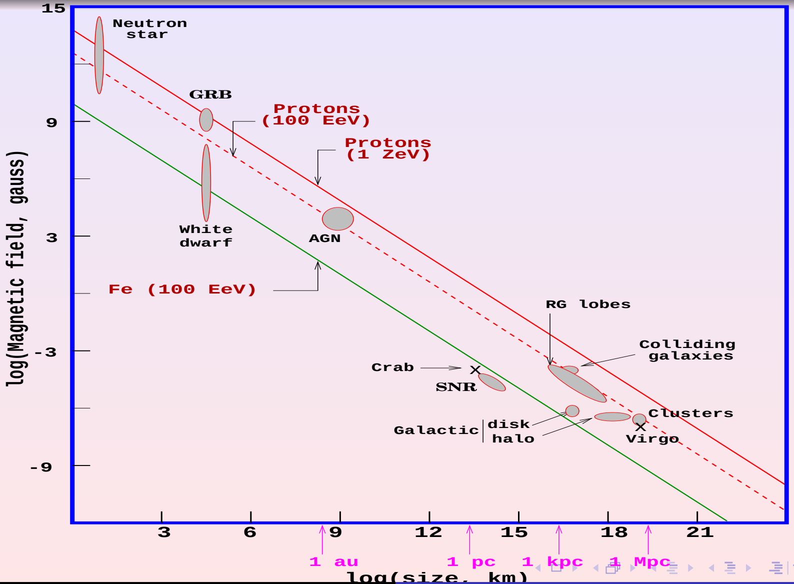


Deflections for $eE/Q = 10^{20}$eV in Galactic field

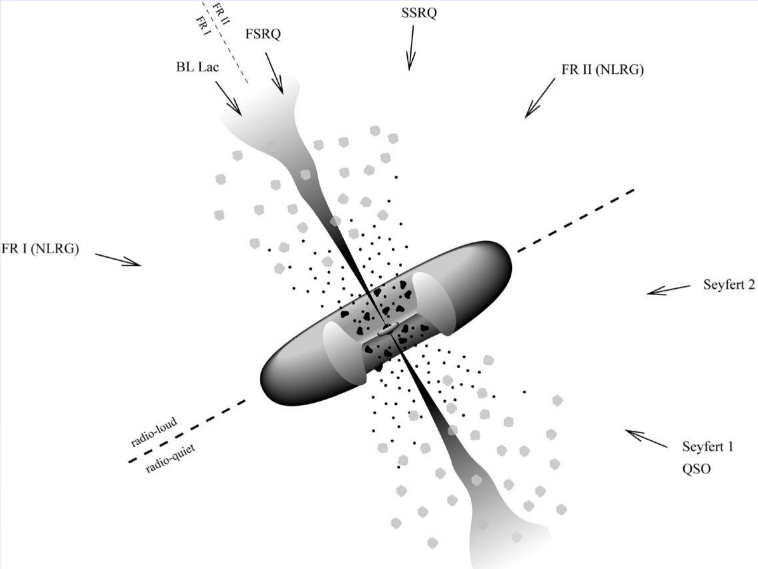
deflections $\gtrsim 2.5^\circ$ at 4×10^{19} eV in large fraction of sky



Hillas plot – potential sources for $E > 10^{20}$eV



Unified AGN picture



Correlations with astrophysical sources:

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

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

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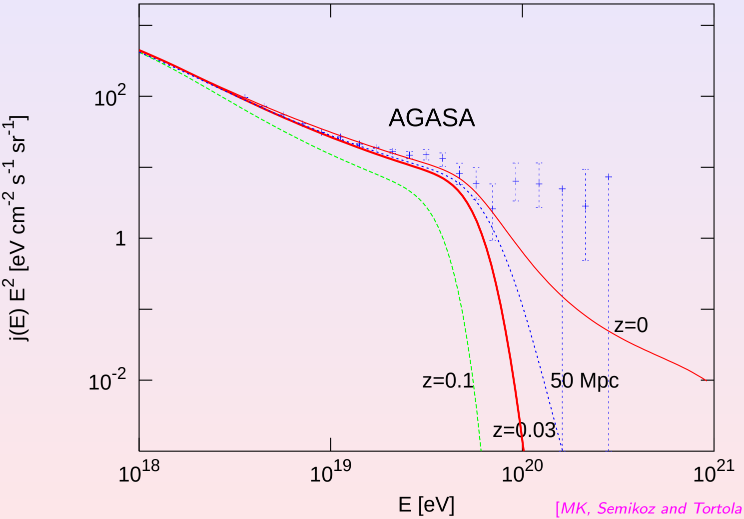
- How serious $p_{\rm ch}$ should be taken?
- Are correlations as found by Tinyakov & Tkachev possible with protons or nuclei as primaries?

Is the GZK cutoff observed?



[MK, Semikoz and Tortola '03]

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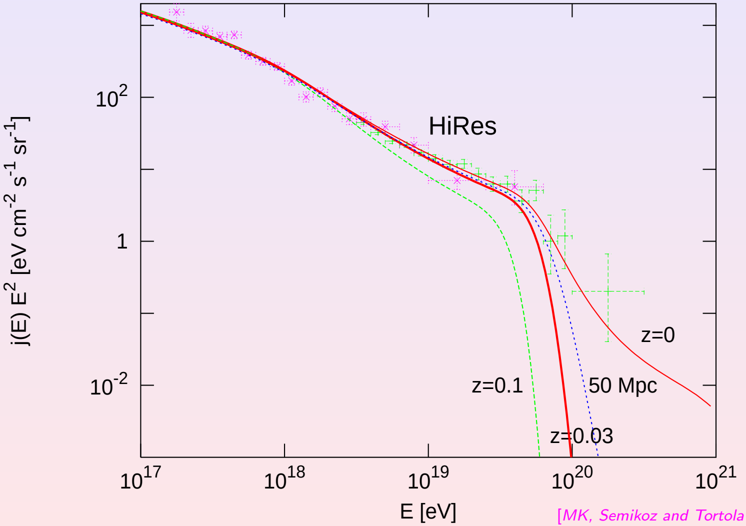
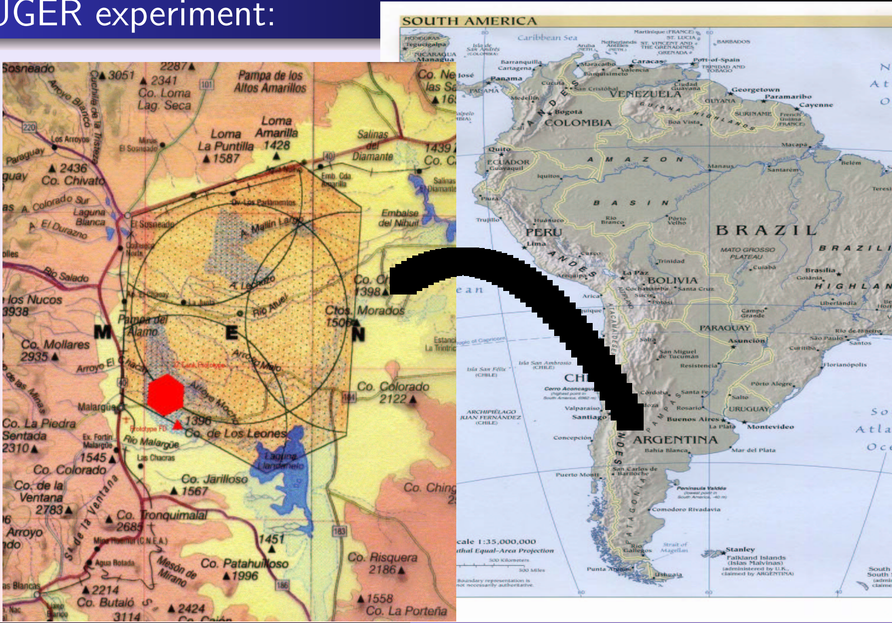


[MK, Semikoz and Tortola '03]

Three outstanding questions:

- does the UHECR spectrum shows GZK suppression or not?
  - if not: several possibilities:
    - Z burst model
    - top-down models
    - violation of Lorentz invariance
- is UHECR astronomy possible?
- do correlations with objects at cosmological distance exist?
  - if yes:
    - new primary
    - Z burst model
    - violation of Lorentz invariance

AUGER experiment:



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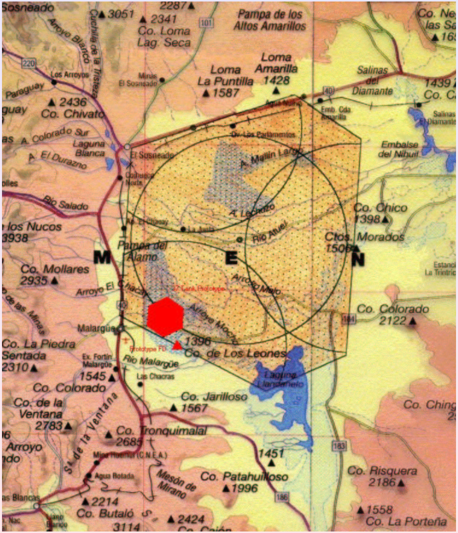
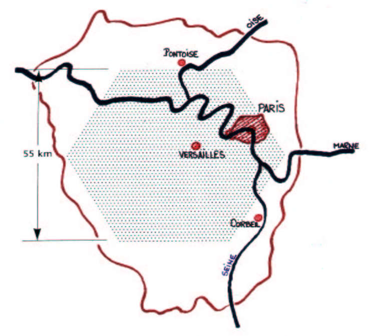
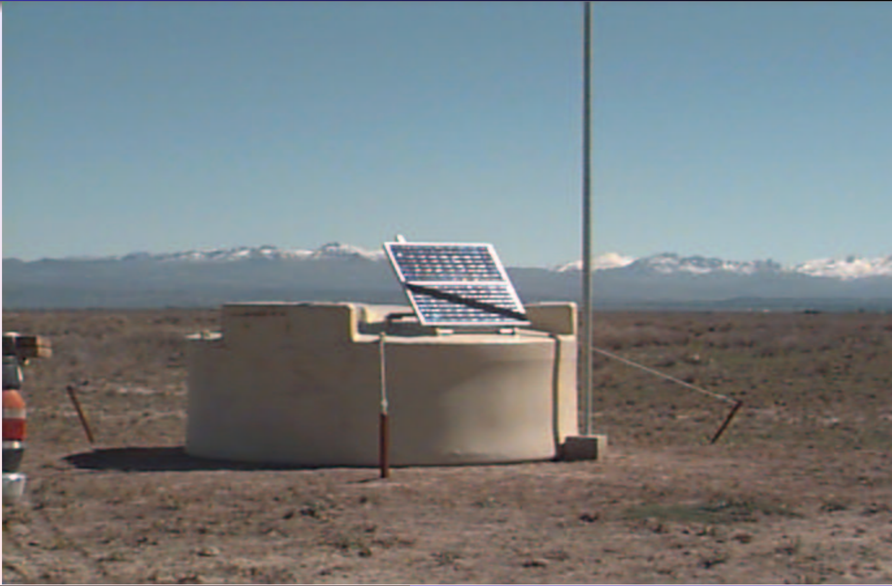




AUGER: Pampa + Detektor



Z burst model: UHE $\nu + \nu_{BR} \to Z \to$ all

[Fargion, Mele, Salis '99; Weiler '99]

advantages:

- economical: no new particle physics is needed
- for $E_\nu \sim 10^{23}$ eV, the mass of the relic neutrino should be $m_\nu = m_Z^2/(2E_\nu) \sim 0.1$ eV, compatible with oscillation data.

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problems:

- requires proton acceleration up to $E \sim 10^{23}$ eV!
- Neutrinos as HDM are not strongly clustered

$\Rightarrow$ enormous fluxes needed; luminosity of sources too high

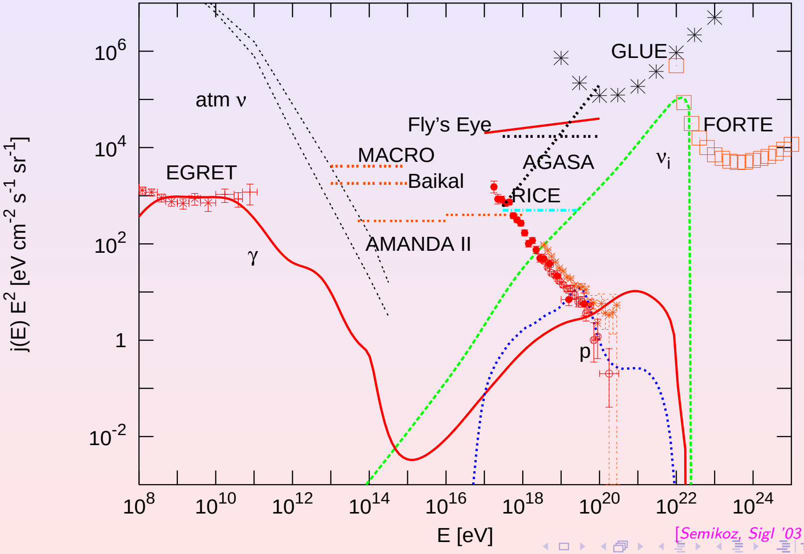
- experimental bounds on UHE neutrino fluxes constrain already Z burst model
- observed MeV–GeV-γ background implies upper bounds on UHE neutrino flux produced in (astrophysical) sources

Idea of EGRET limit

all energy in γ and $e^{\pm}$ cascades down to MeV–GeV range, bounded by observations:

$$\begin{aligned} \omega_{\rm cas} &= f_{\rm em} m_Z \int_0^{t_0} dt\,(1+z)^{-4}\,\frac{n_Z(t)}{dt} \\ &\lesssim 2\cdot 10^{-6}\,{\rm eV/cm^3} \end{aligned}$$

EGRET and neutrino limits:



[Semikoz, Sigl '03]

Neutrinos as UHE primaries

- UHE neutrinos are not absorbed, but are deeply penetrating particles in SM

$\Rightarrow$ produce mainly horizontal, not vertical EAS

- not observed up-to now

Neutrinos as UHE primaries

for primary energies $E_\nu = 10^{20} - 10^{21}$ eV:

- cms energy for collisions with background $\sim$ 100 MeV – 100 GeV $\Rightarrow$ physics well-understood
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UHE neutrinos could acquire large cross-section due to new physics:

- exchange of KK gravitons
- production of black holes
- non-perturbative effects in the SM (sphalerons)

$\Rightarrow$ talk of Huitzu Tu

Ex.: Large Extra Dimensions

t channel exchange of KK gravitons could enhance $N\nu$ cross section because of

- small mass splitting of KK gravitons, $m_{\vec{n}}^2 = \vec{n}^2/R^2$.
- fast growth, $\sigma(s) \propto s^j$ and $j = 2$.

Could neutrino be primary of observed vertical EAS above GZK-cutoff?

[*Sigl '00, Jain et. al '00*]

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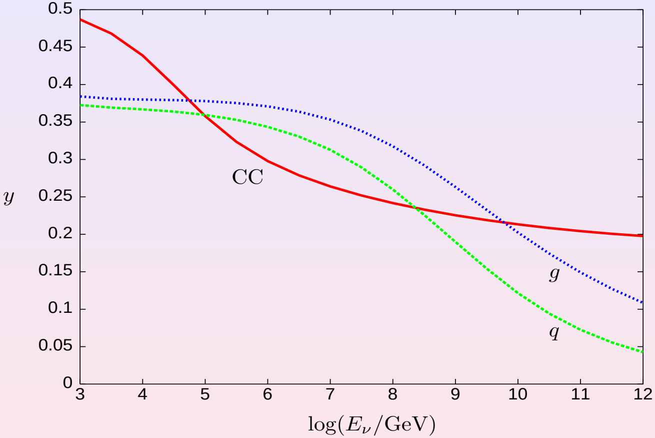
[Sigl '00, Jain et. al '00]

no, because

- unitarity slows down increase of cross section [MK, M.Plümacher '00, Giudice, Rattazzi, Wells '01]
- also large energy transfer is needed

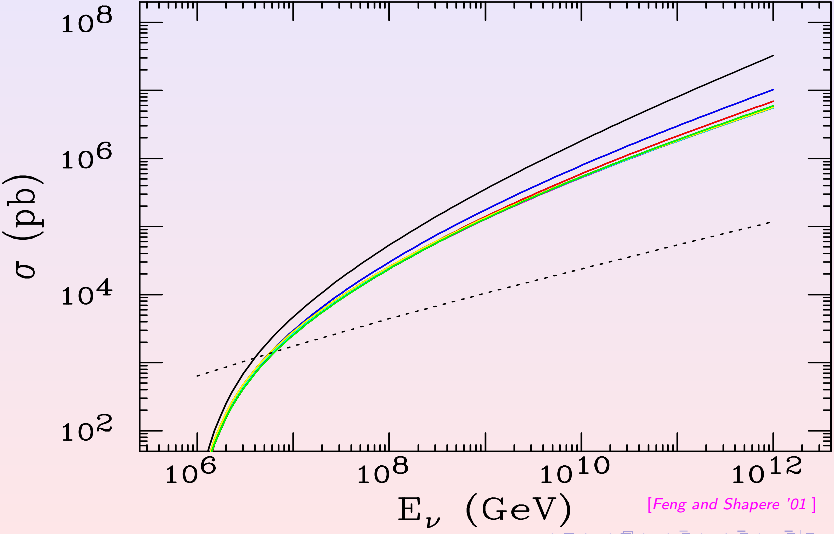
Ex.: Large Extra Dimensions



[MK, M.Plümacher '00]

⇒ neutrinos are still deeply penetrating particles

BH production and UHE ν's



[Feng and Shapere '01]

- neutrinos with non-SM interactions cannot explain observed vertical EAS
- but provide exciting experimental target for HE and UHE neutrino experiments

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

Gravitational creation of superheavy matter:

Small fluctuations of field Φ obey

$$\ddot{\varphi}_k + \left[k^2 + m_{\rm eff}^2(\tau)\right] \varphi_k = 0$$

If $m_{\rm eff}$ is time dependent, vacuum fluctuations will be transformed into real particles.
$\Rightarrow$ expansion of Universe leads to particle production

In inflationary cosmology

$$\Omega_X h^2 = \left(\frac{M_X}{10^{12}\mathrm{GeV}}\right)^2 \frac{T_{RH}}{10^9\mathrm{GeV}}$$

independent of details of particle physics, for any $M_X \lesssim H_I$

[Kuzmin, Tkachev '98; Chung, Kolb, Riotto '98]

Lifetime:

For $M_X \gtrsim 10^{10}$ GeV even gravitational interactions result in cosmological short lifetimes, $\tau_X \ll t_0$.

- global symmetry broken by wormhole effects, $\tau_X \propto \exp(S)$
- symmetry broken by instanton effects, $\tau_X \propto \exp(-4\pi^2/g^2)$
- discrete symmetries forbid operators with $d < 9$
- crypton or fractionally charged and confined particle of superstring theories

Fragmentation of heavy particles

- Consider Bremsstrahlung, $X \to \bar{f} f V$:

soft and collinear singularities generate $\ln^2(m_V^2/m_X^2)$ for $m_X^2 \gg m_V^2$
$\Rightarrow$ they can compensate the small couplings g^2,

$$g^2 \ln^2(m_X^2/m_V^2) \approx 1$$

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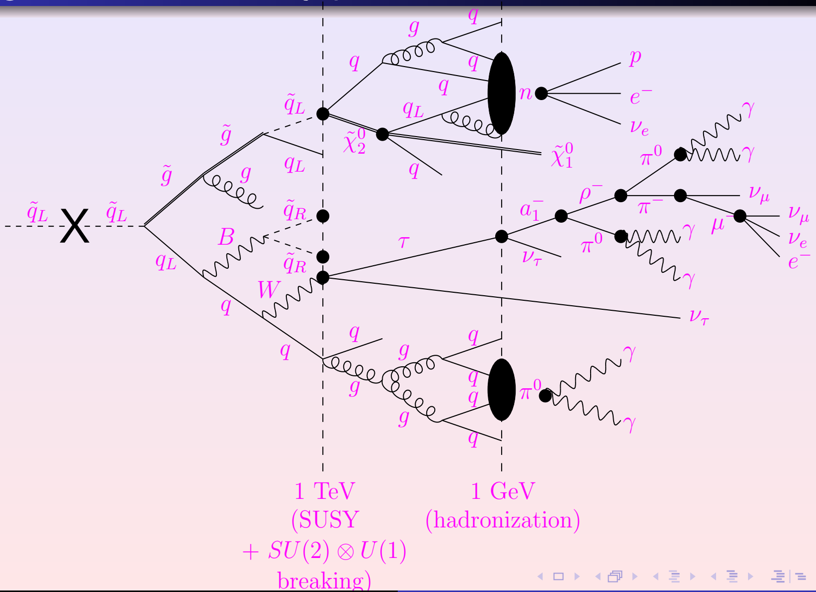
$$g^2 \ln^2(m_X^2/m_V^2) \approx 1$$

- $M_X \gtrsim 10^6$ GeV, $\Rightarrow$ naive perturbation theory breaks down:
electroweak and SUSY sector have a QCD-like behavior ("jets")

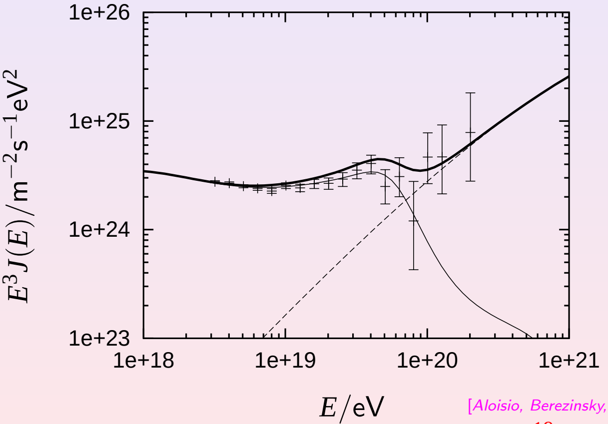
[*Berezinsky, MK '98, Berezinsky, MK, Ostapchenko '02)*]

Fragmentation of heavy particles



Signatures of SHDM decays

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

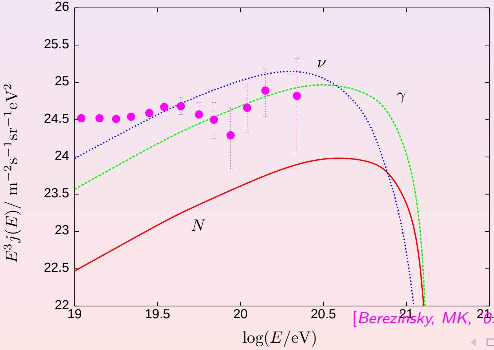


[Aloisio, Berezinsky, MK, '03]

$\Rightarrow$ 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:
  - $\gamma/p \gg 1$, no nuclei
  - large neutrino fluxes
  - LSPs, if R-Parity conserved



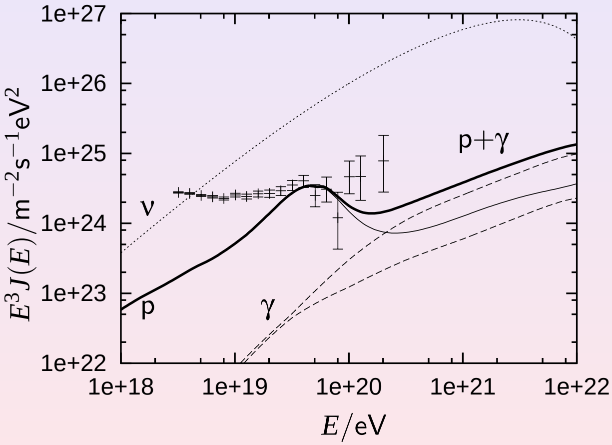
[Berezinsky, MK, '01; Aloisio, Berezinsky, MK, '03]

Signatures of SHDM decays

- flat spectra $dE/E^{1.9}$ up to $m_X/2$
- composition: [Berezinsky, MK '98]
- galactic anisotropy: [Dubovsky, Tinyakov '98]
  - SUGAR data exclude at 99.8% C.L. annihilations of superheavy DM
  - do not constrain strongly decays of superheavy DM

[MK, Semikoz '03, Kim, Tinyakov '03]

Status of topological defect models – necklaces:



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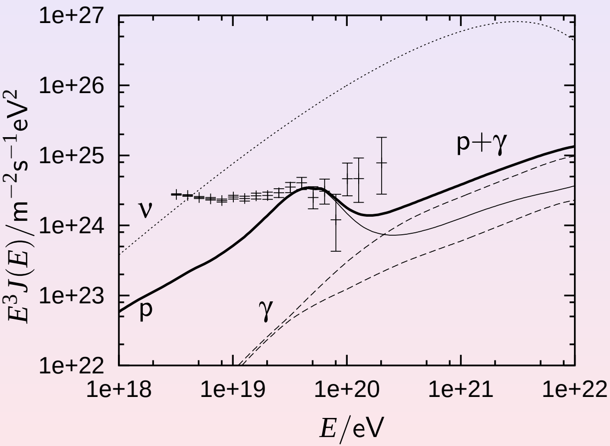

⇒ shape of spectrum allows only sub-dominant contribution

Violation of Lorentz invariance (LI)

- quantum gravity (“space-time foam”) or dim. reduction $d = n > 4 \to 4$ could induce tiny departures from LI
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then π^0 is stable above $E \sim 10^{19}$ eV and photon unstable!

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  then π^0 is stable above $E \sim 10^{19}$ eV and photon unstable!
- similar in the GZK cutoff reaction $p + \gamma_{3K} \to \Delta(1232)$
  threshold condition for head-on collision changed to

$$2\omega + \frac{m_p^2}{2E} \geq (c_\Delta - c_p)E + \frac{M_\Delta^2}{2E}$$

  if $c_\Delta - c_p \geq 2 \times 10^{-25}$, reaction forbidden

Summary I:

- UHECR data will provide soon unique information about
  - structure of galactic magnetic field
  - magnitude of extragalactic magnetic fields

if both are “small”, astronomy with UHECRs will be possible

- determination of source density n_s
- determination of source classes
- acceleration mechanism?

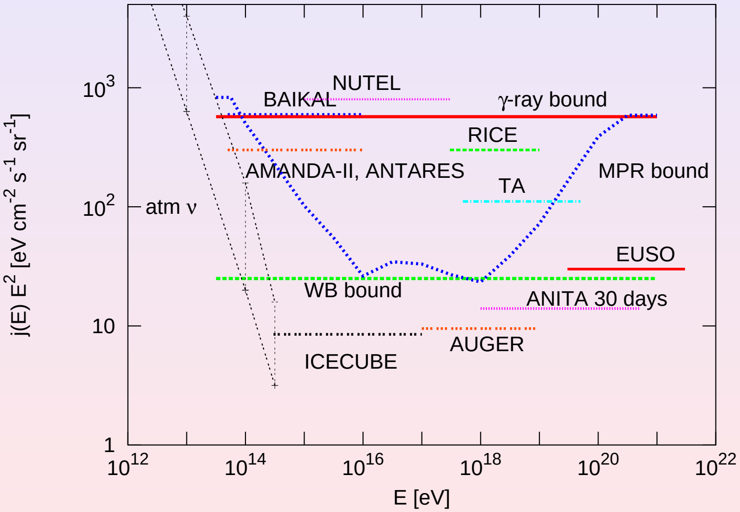
Summary II

- Z bursts and topological defects can be only subdominant sources of UHECR
- no positive evidence for superheavy dark matter from its two key signatures:
  - photons
  - galactic anisotropy

open questions for AUGER, Anita, . . . :

- clustering due to point sources?
- correlations with BL Lacs?
- existence of GZK suppression?
- photons as primaries?
- detection of UHE neutrinos?

Sensitivity of neutrino detectors



Sensitivity of neutrino detectors