Ultra-High Energy Cosmic Rays:

Standard and Exotic Sources

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$\Delta x \Delta p_x \geq \hbar$

Theoretical Physics Division

Two outstanding questions:

- Is astronomy with UHECRs possible?
  - ◇ protons vs nuclei as primaries
  - ◇ role of magnetic fields

- Is physics beyond the SM needed to explain UHECR events?
  - ◇ energy spectrum consistent with GZK suppression?
    - suppression depends on number of sources, their minimal distances, magnetic fields, . . .
  - ◇ correlations with sources at cosmological distances?

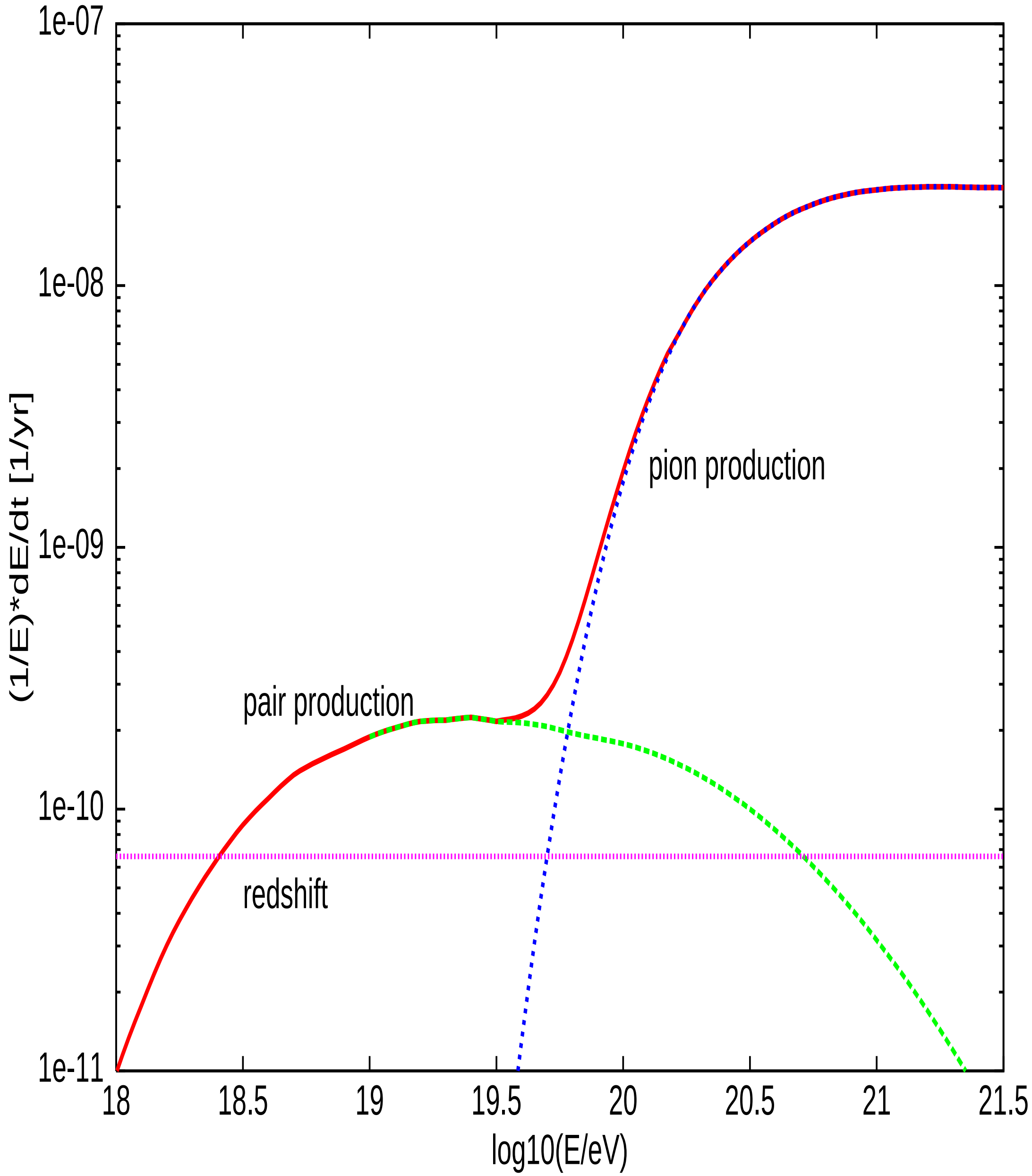
Outline of the talk:

- 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 50 Mpc

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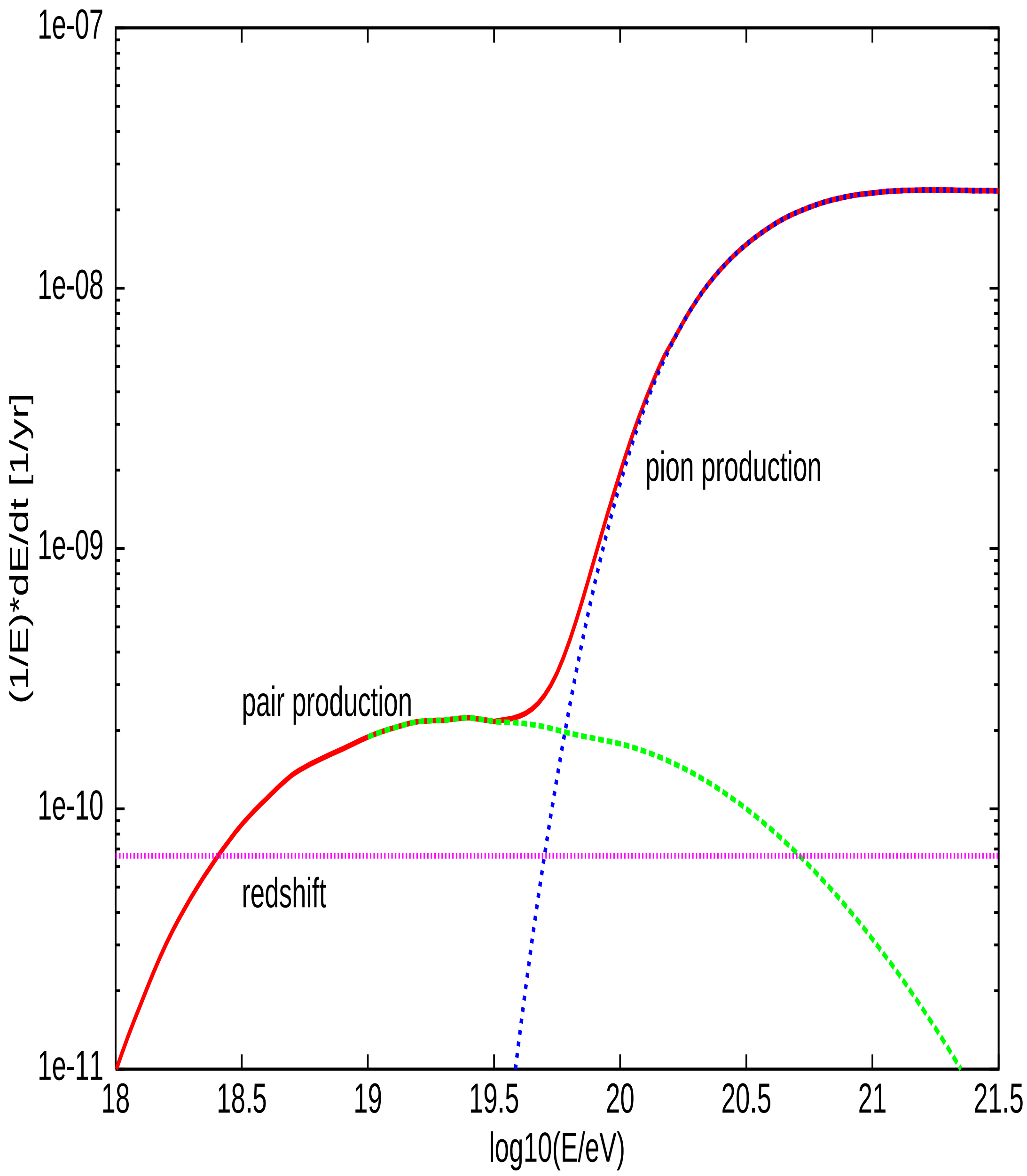
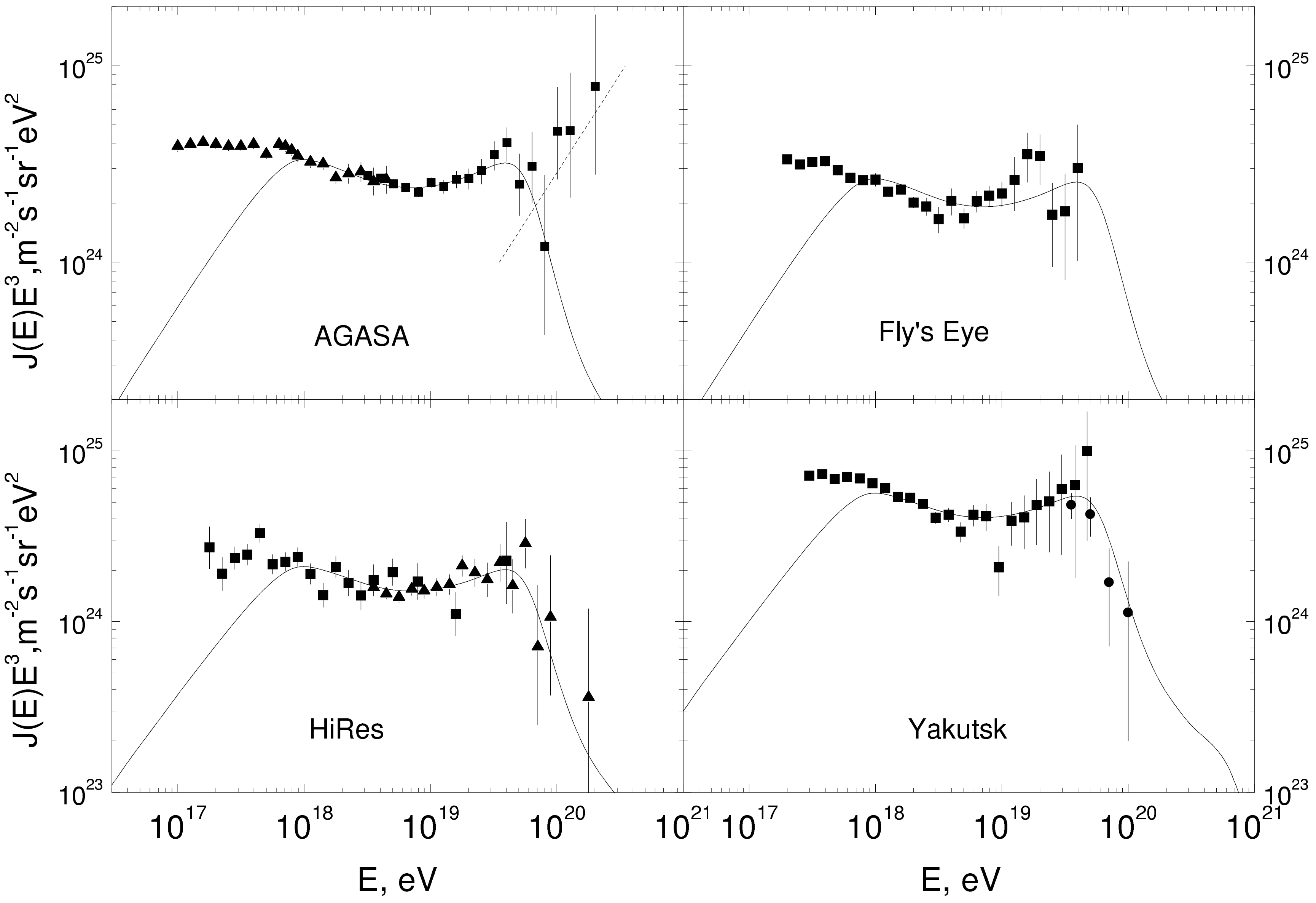


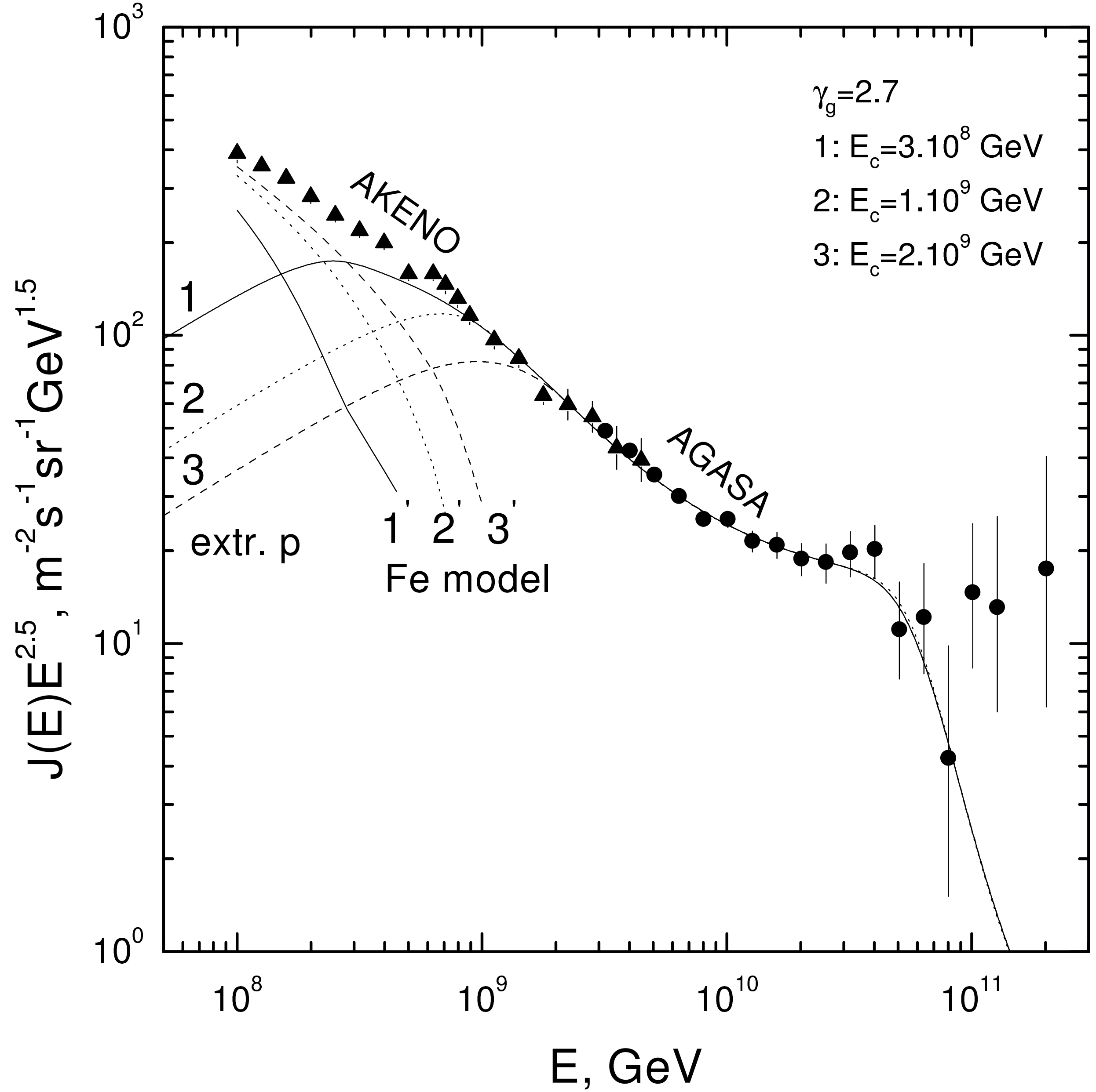
- at $E \sim 4 \times 10^{19}$ eV: $N + \gamma_{3K} \to \Delta \to N + \pi$ starts and reduces free mean path to 50 Mpc
- nuclei photo-disintegrate with similar free mean path
- photons are absorbed on IR background on ~ 10 Mpc

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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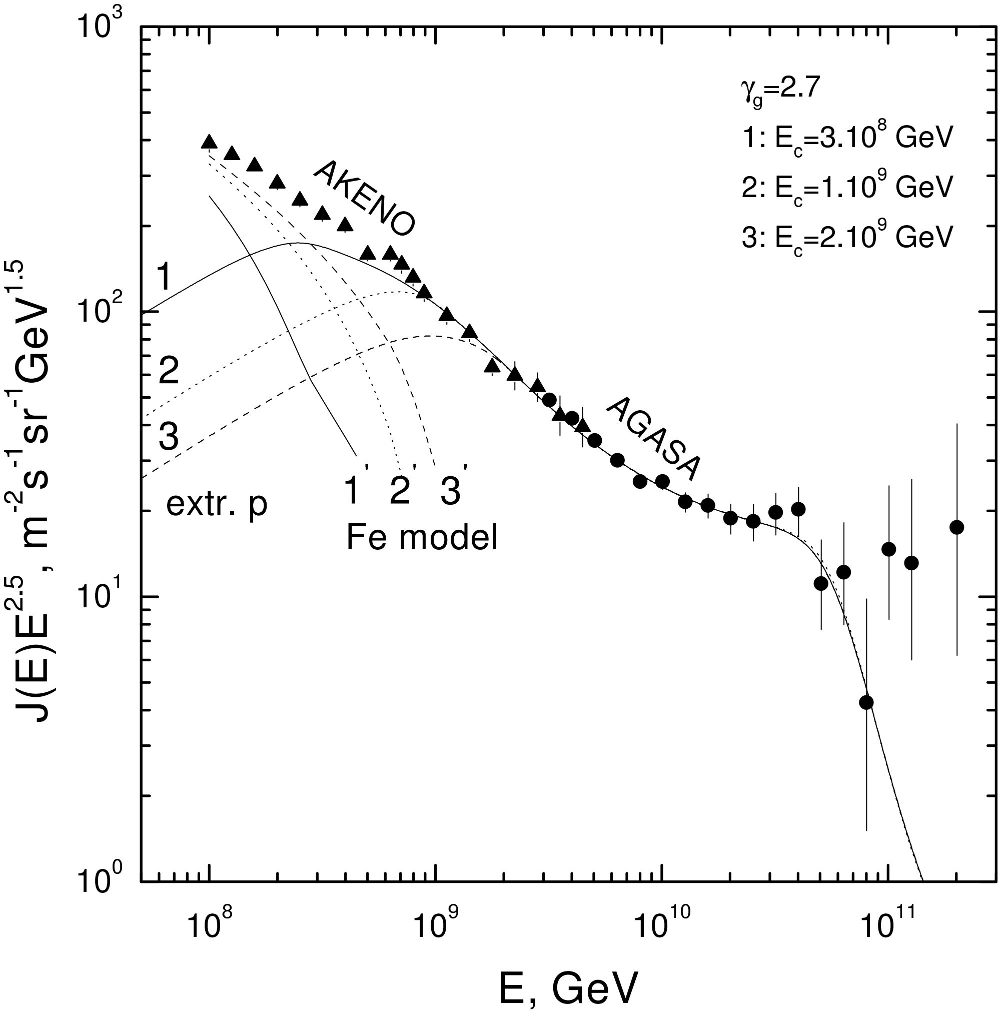

[Berezinsky, Grigorieva, Hnatyk '04]

if this interpretation of the dip is correct, then primaries above 10^{18} eV are extragalactic protons

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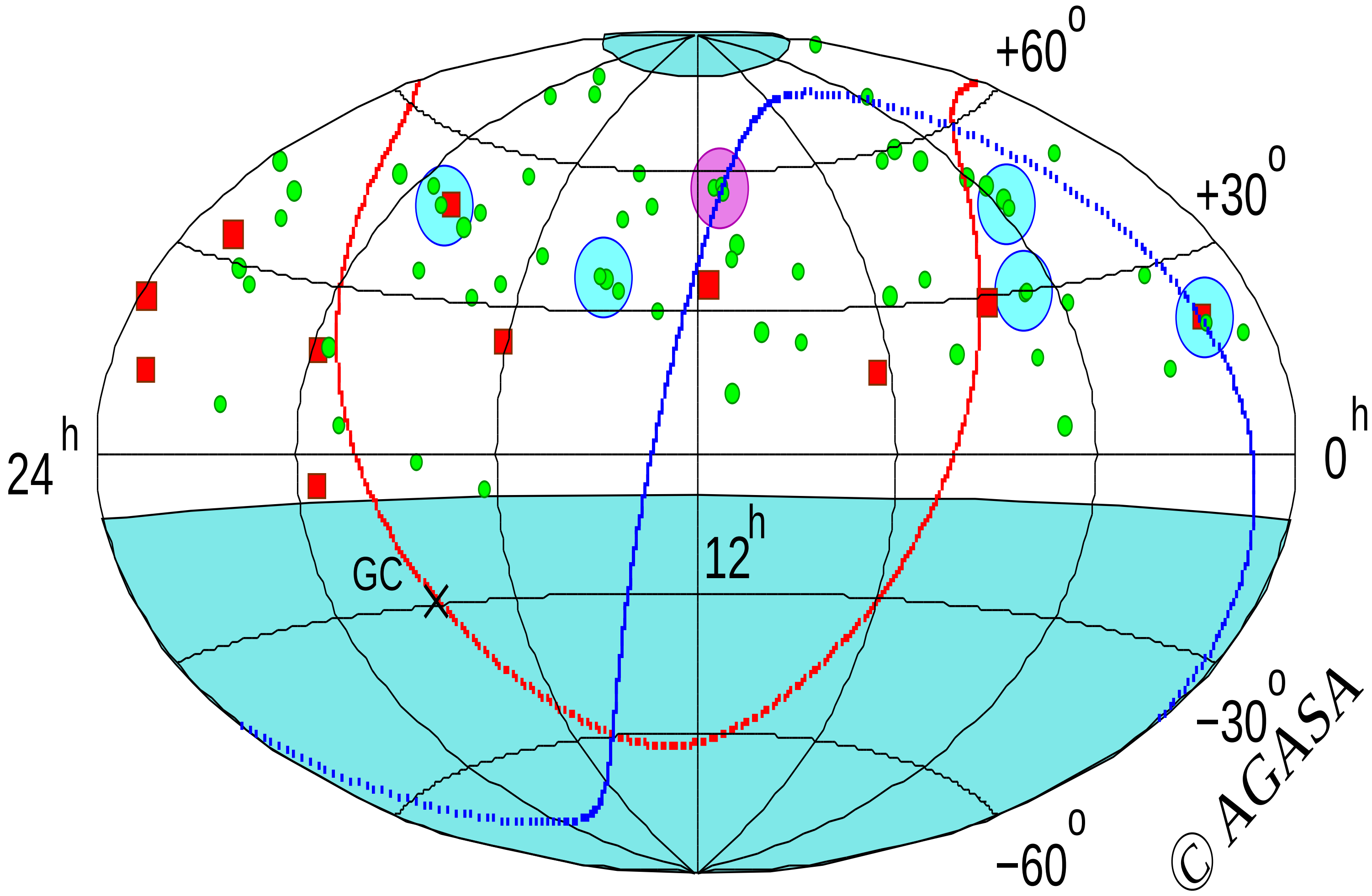
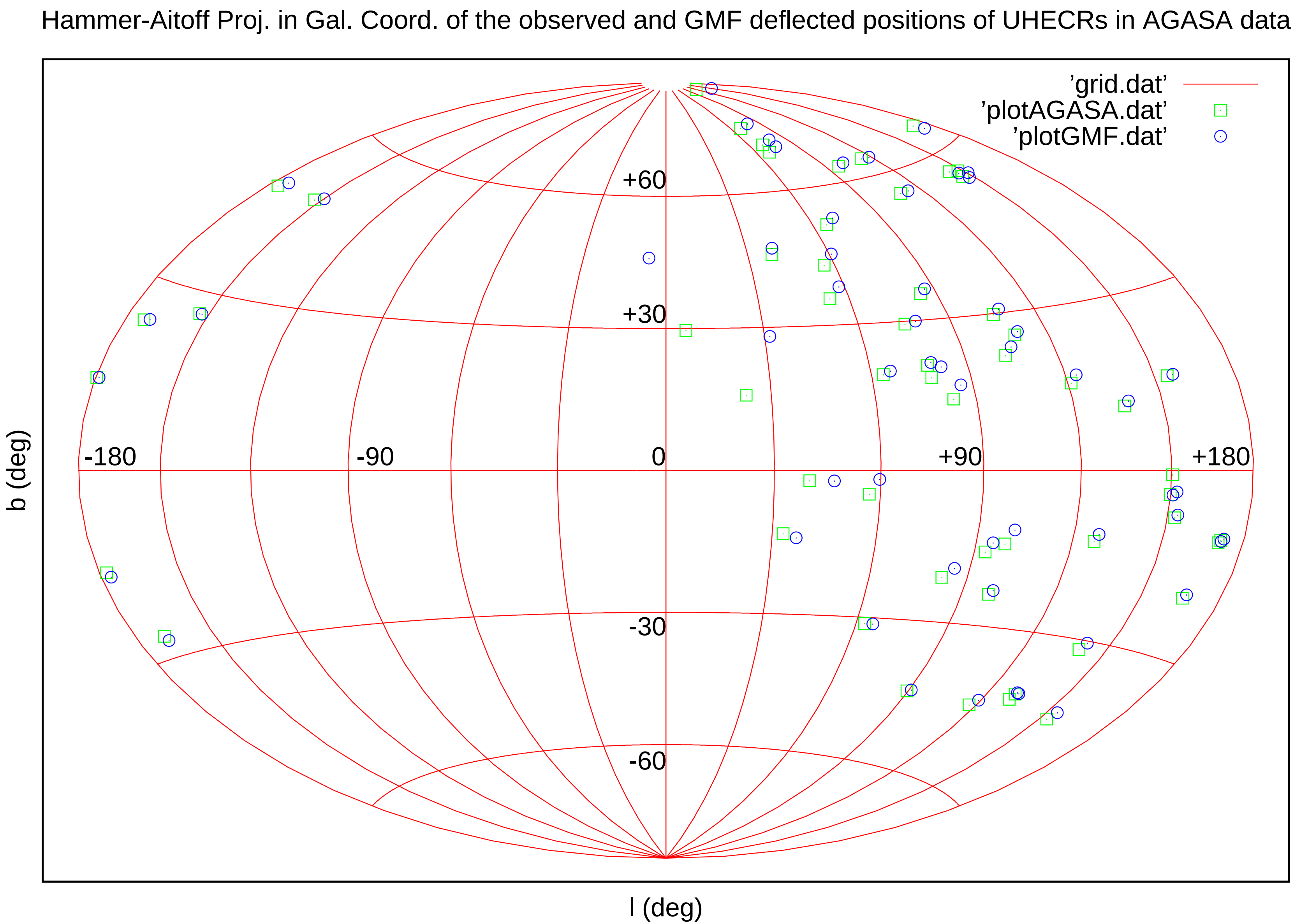
Small-scale clustering in AGASA:

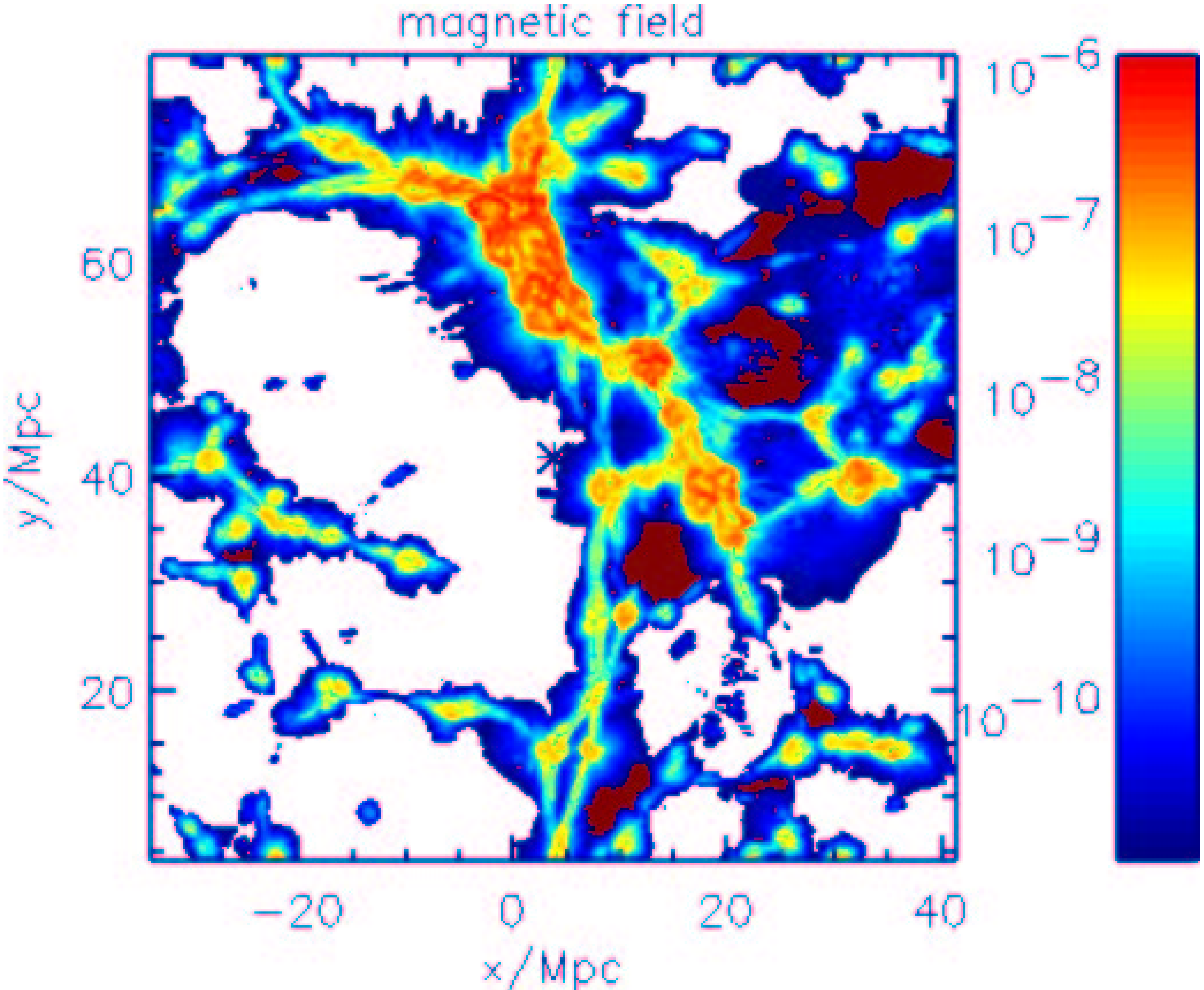


- $E > 10^{20}$ eV
- $E = 4 - 10 \times 10^{19}$ eV

Galactic magnetic field – protons:



Extragalactic magnetic field – simulation by SME:



[*Sigl, Miniato, Ensslin '03*]

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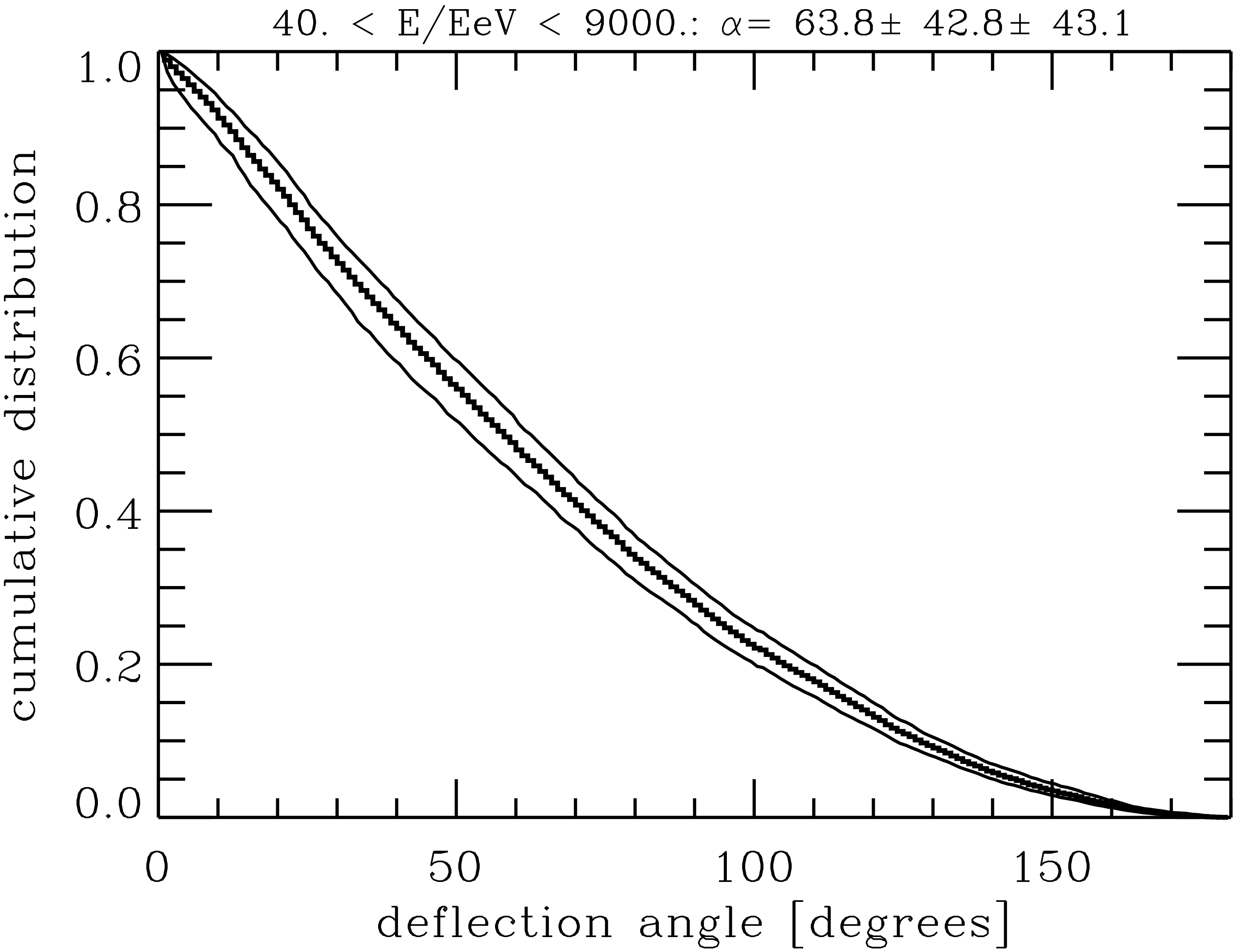

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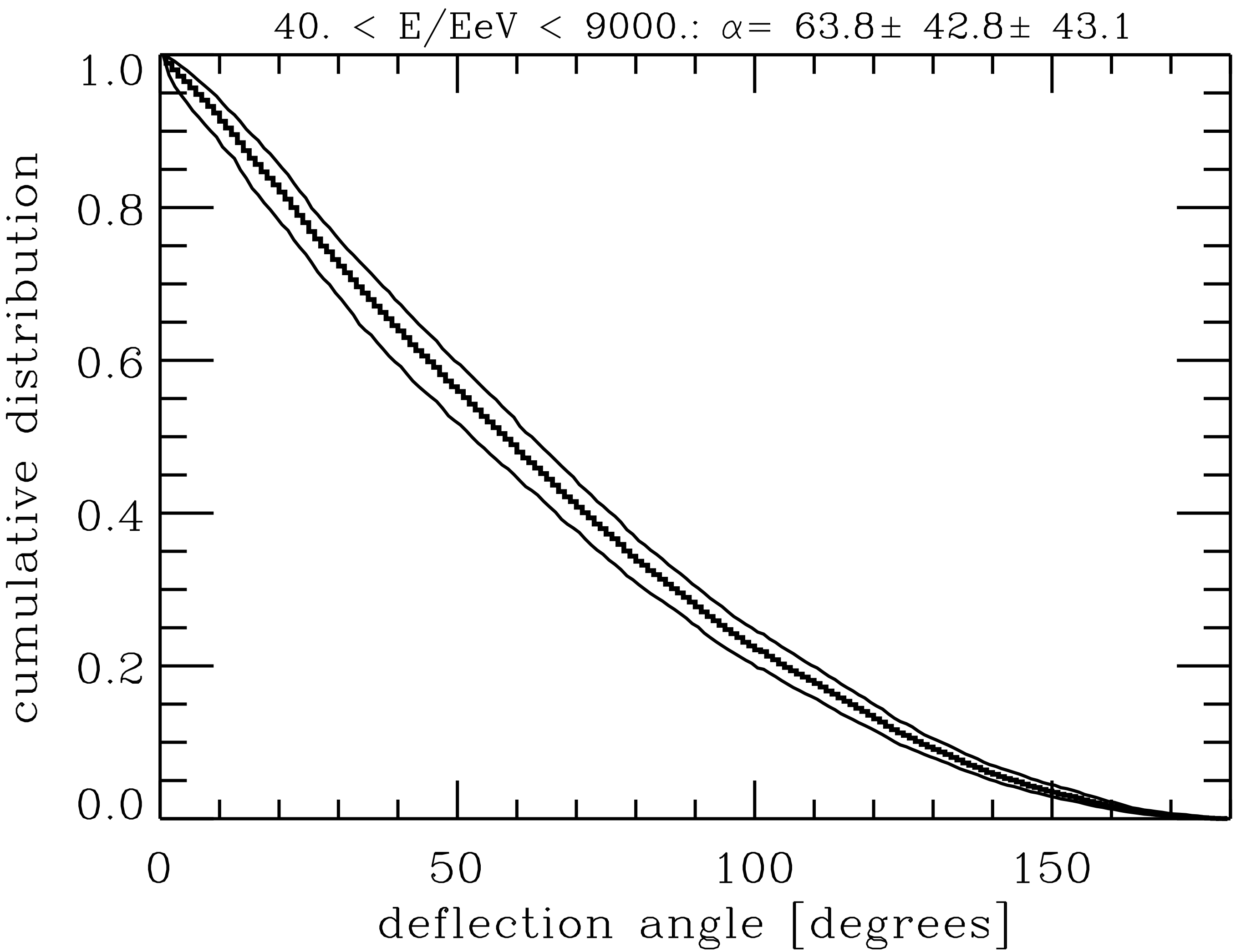
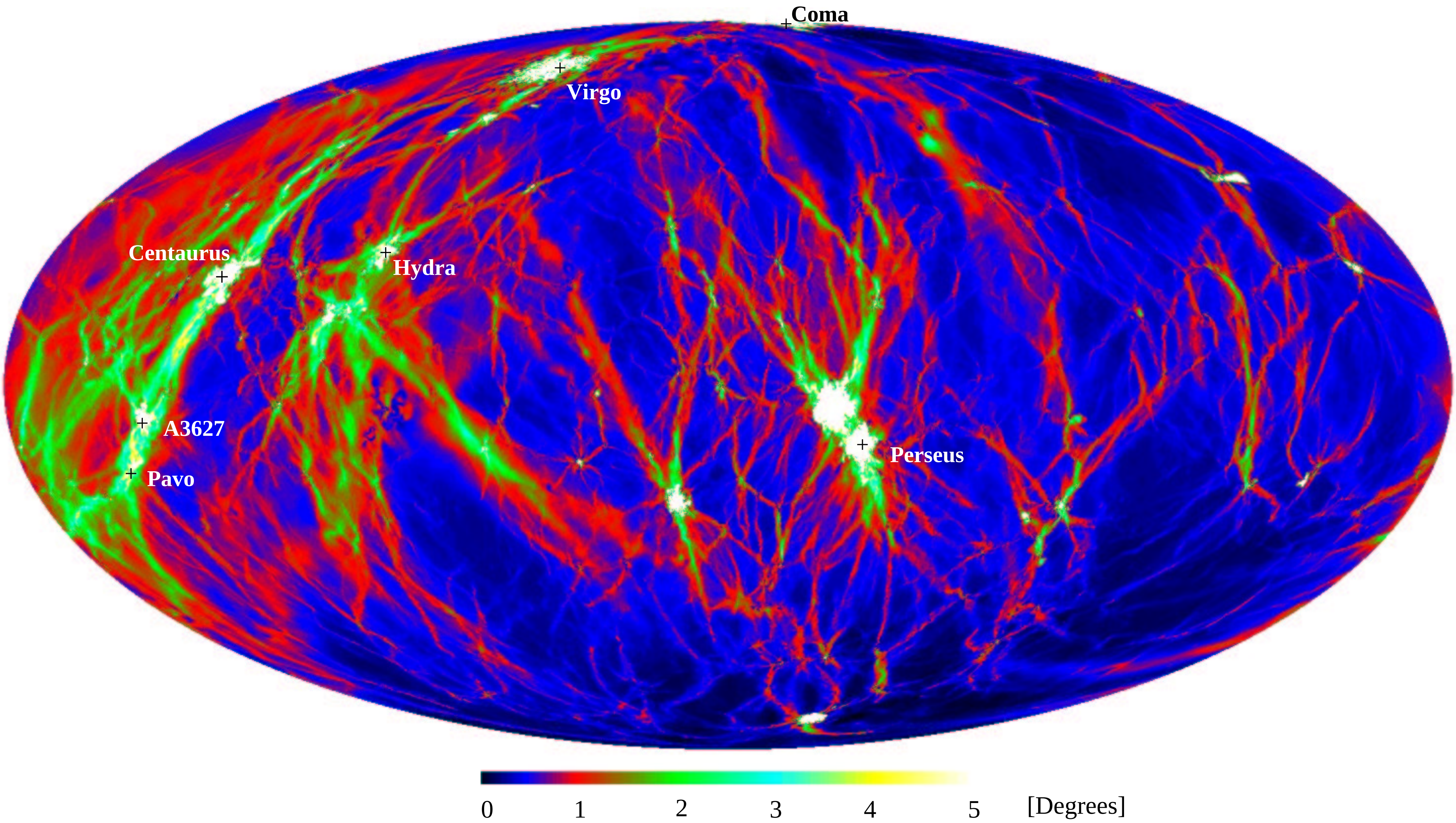


SME: astronomy with UHE protons may be impossible

Extragalactic magnetic field – simulation DGST:



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

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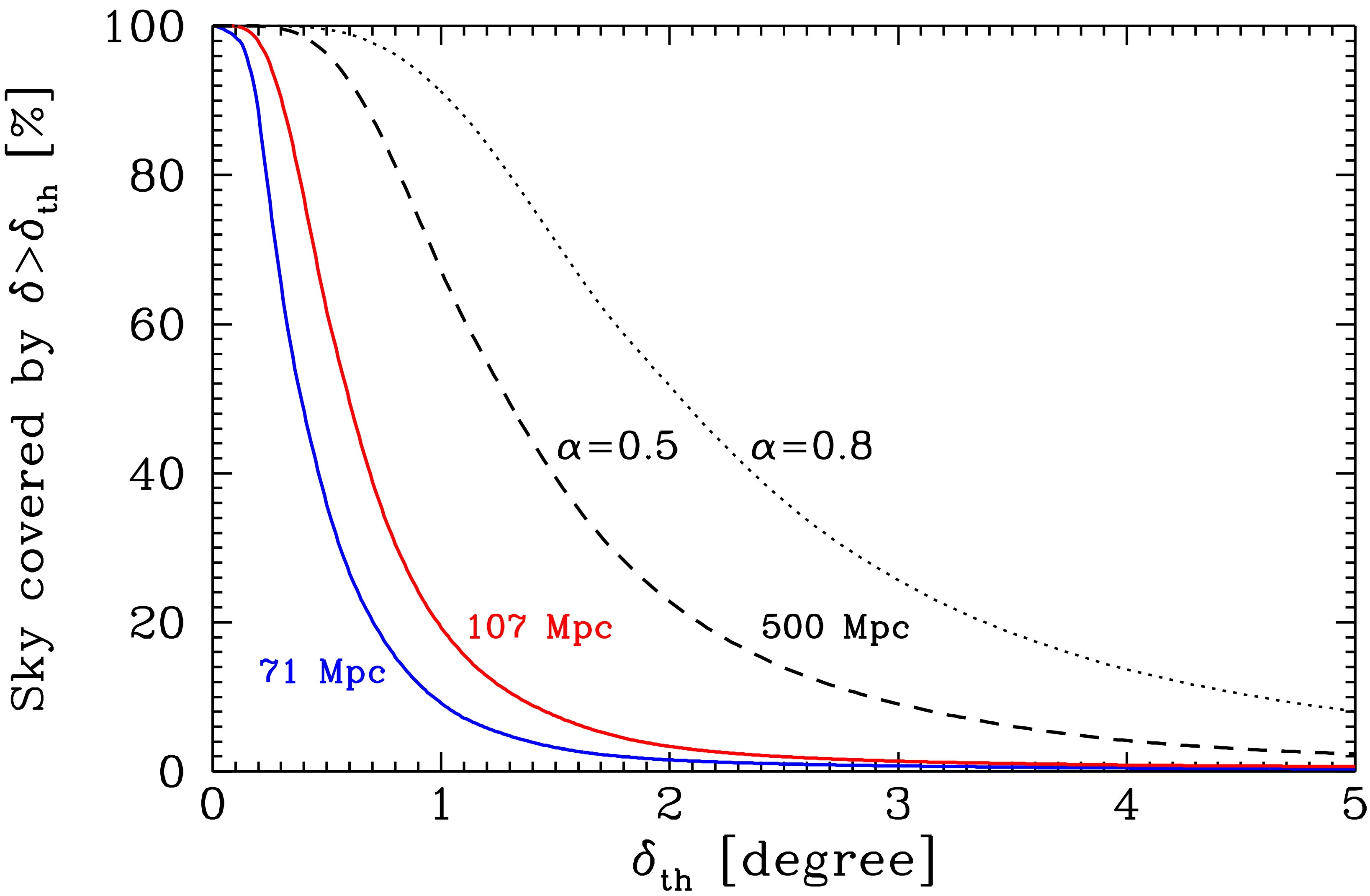

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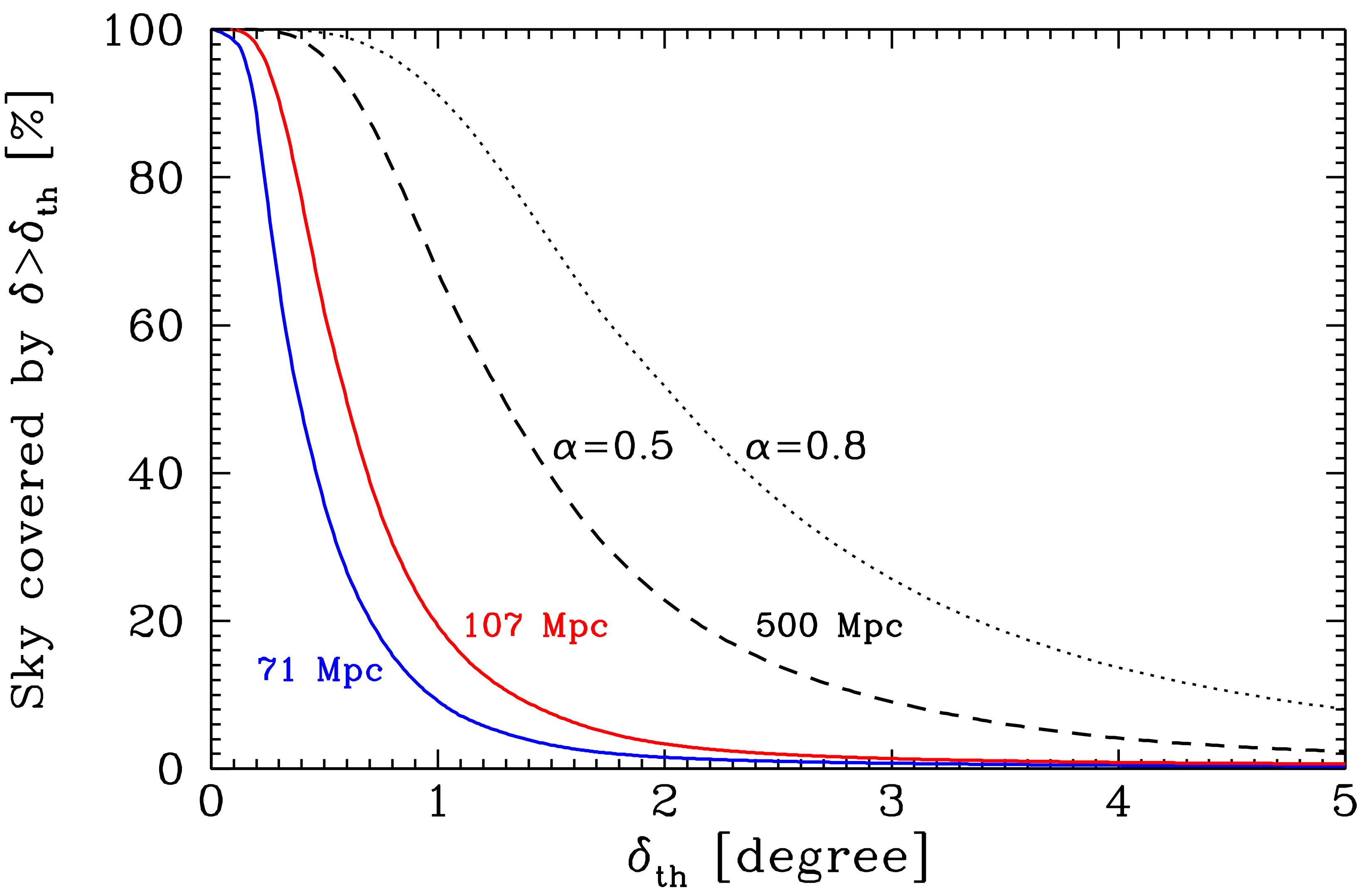
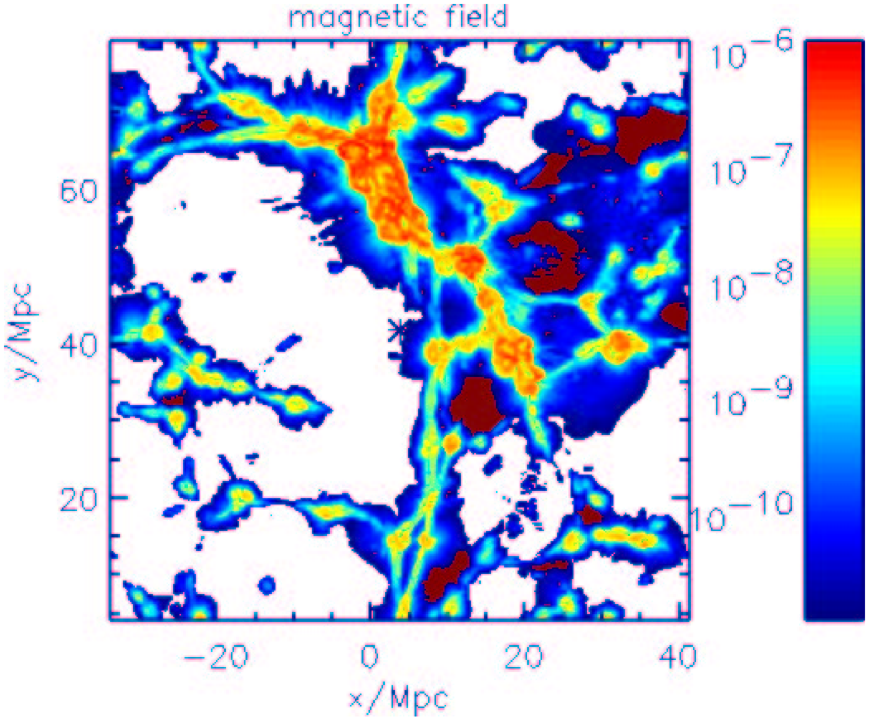


DGST: astronomy with UHE protons possible in large part of the sky!

which simulation/conclusion is closer to reality?

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



  - ◇ Dolag, Grasso, Springel, Tkachev use a constrained simulation

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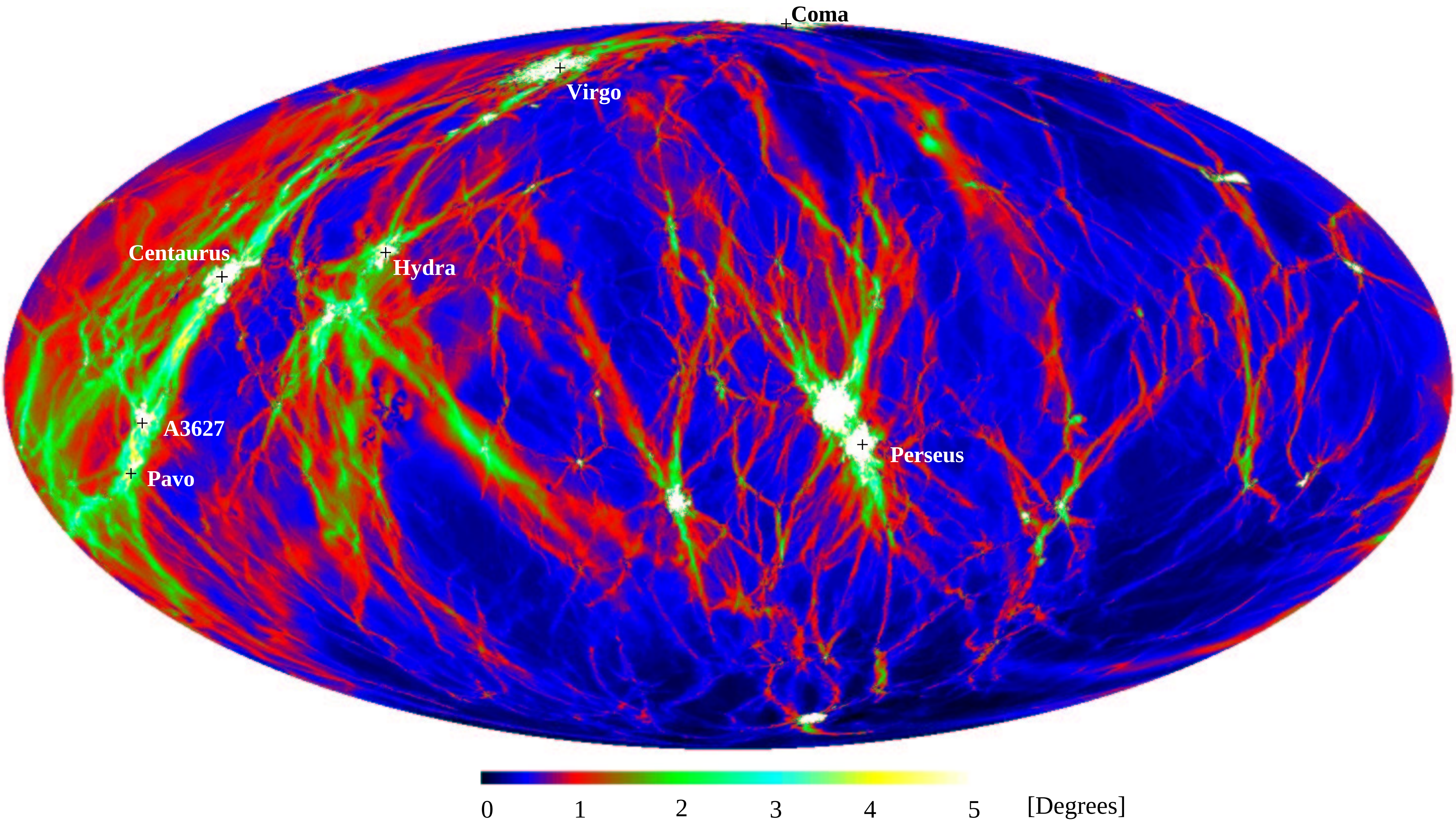

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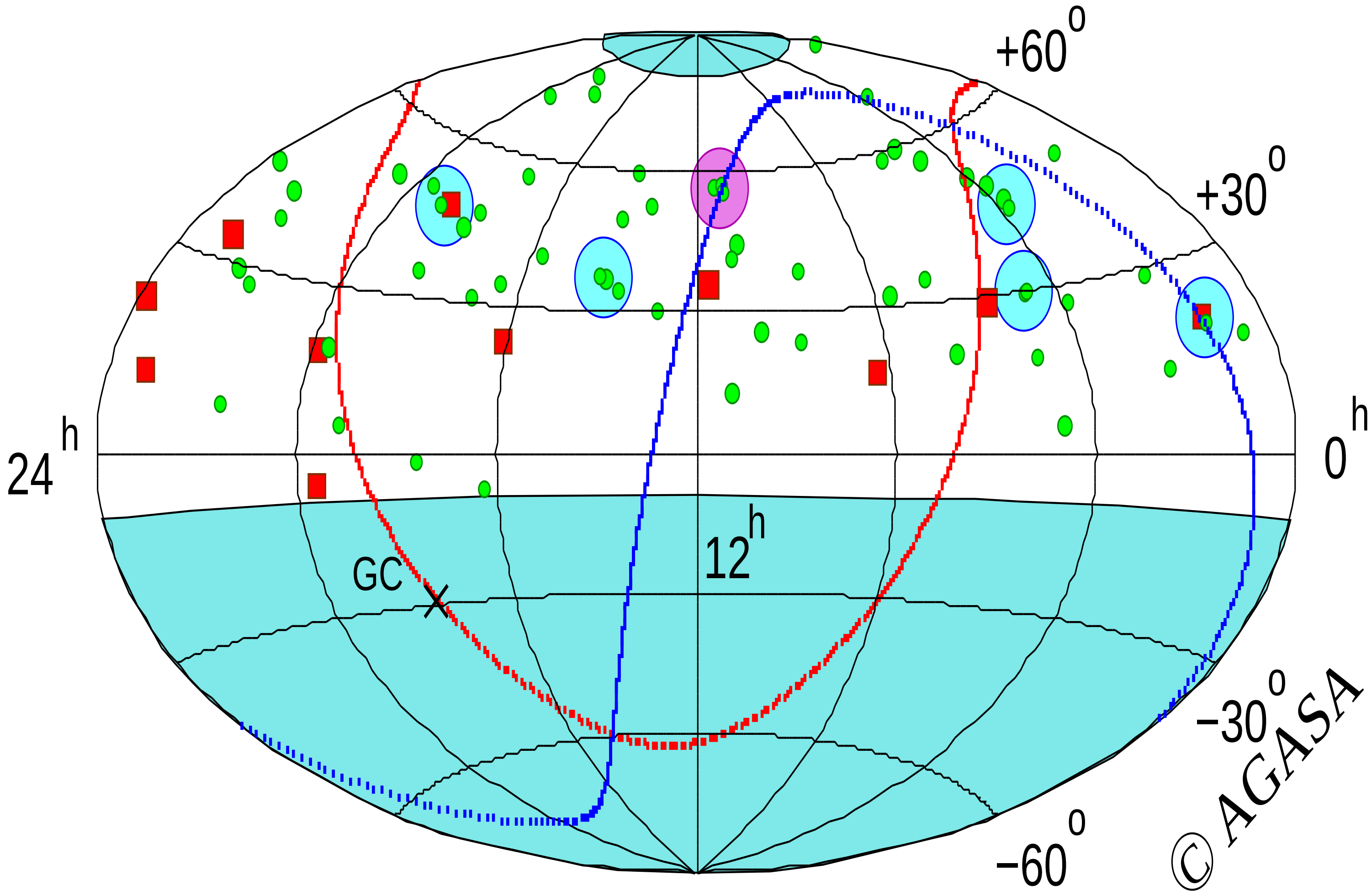

■ $E > 10^{20}$ eV

● $E = 4 - 10 \times 10^{19}$ eV

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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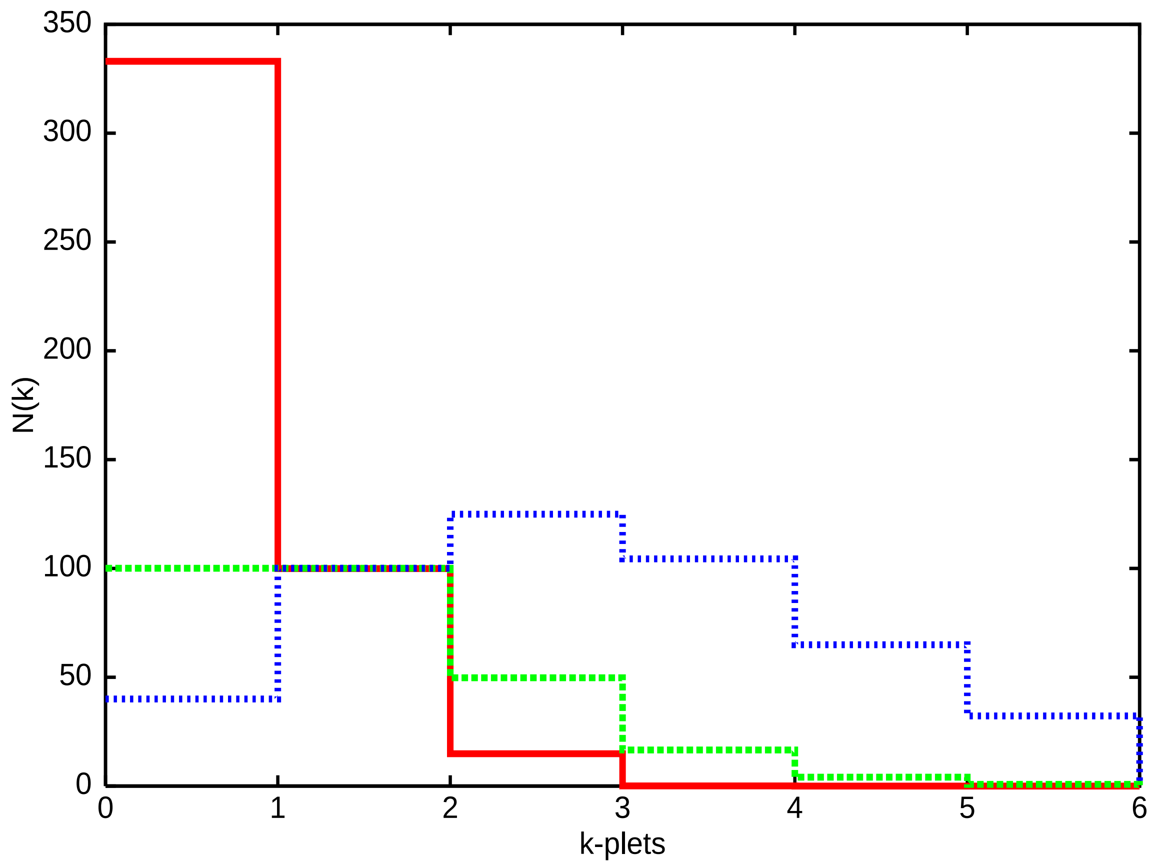
- Since $N_{\rm tot} \gg N_{\rm cl}$, most sources are not seen:



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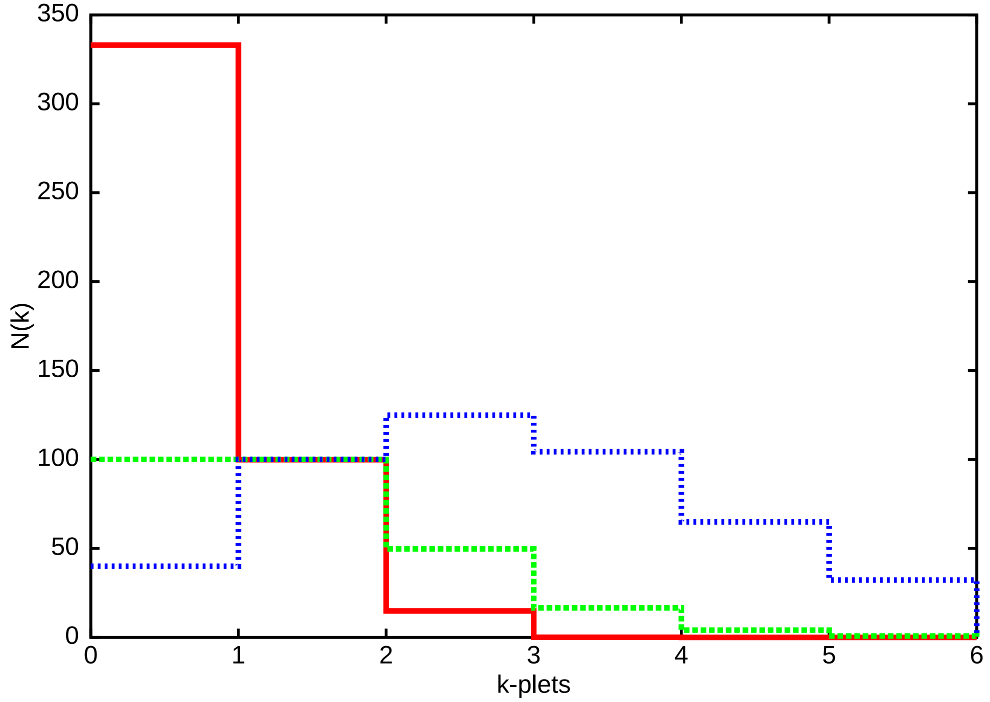


- allows to estimate n_s

Statistical estimator for small-scale clustering:

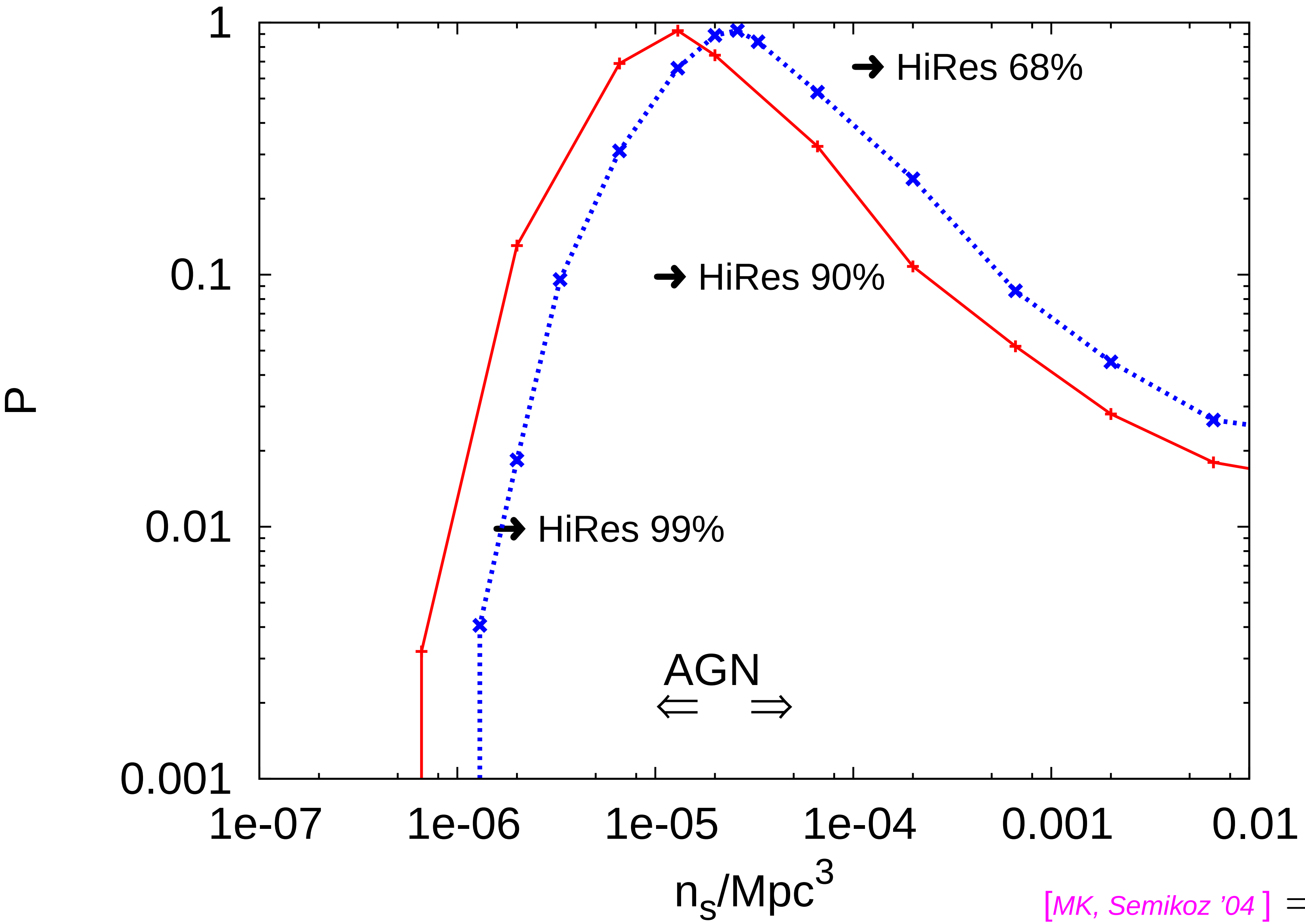
- two-point autocorrelation function of the data, i.e.

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

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

- compare to distribution $p(w_1 : \theta)$ 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, $\ell_1 \ldots$
  - ◇ determine consistent parameters

Confidence level for density n_s of uniform sources:



[*MK, Semikoz '04*] ⇒

if $n_s < \infty$:

- how many of the clusters seen are true ones?

$\Rightarrow$ if the fraction is large, search for point sources makes sense

How many of the clusters are real?

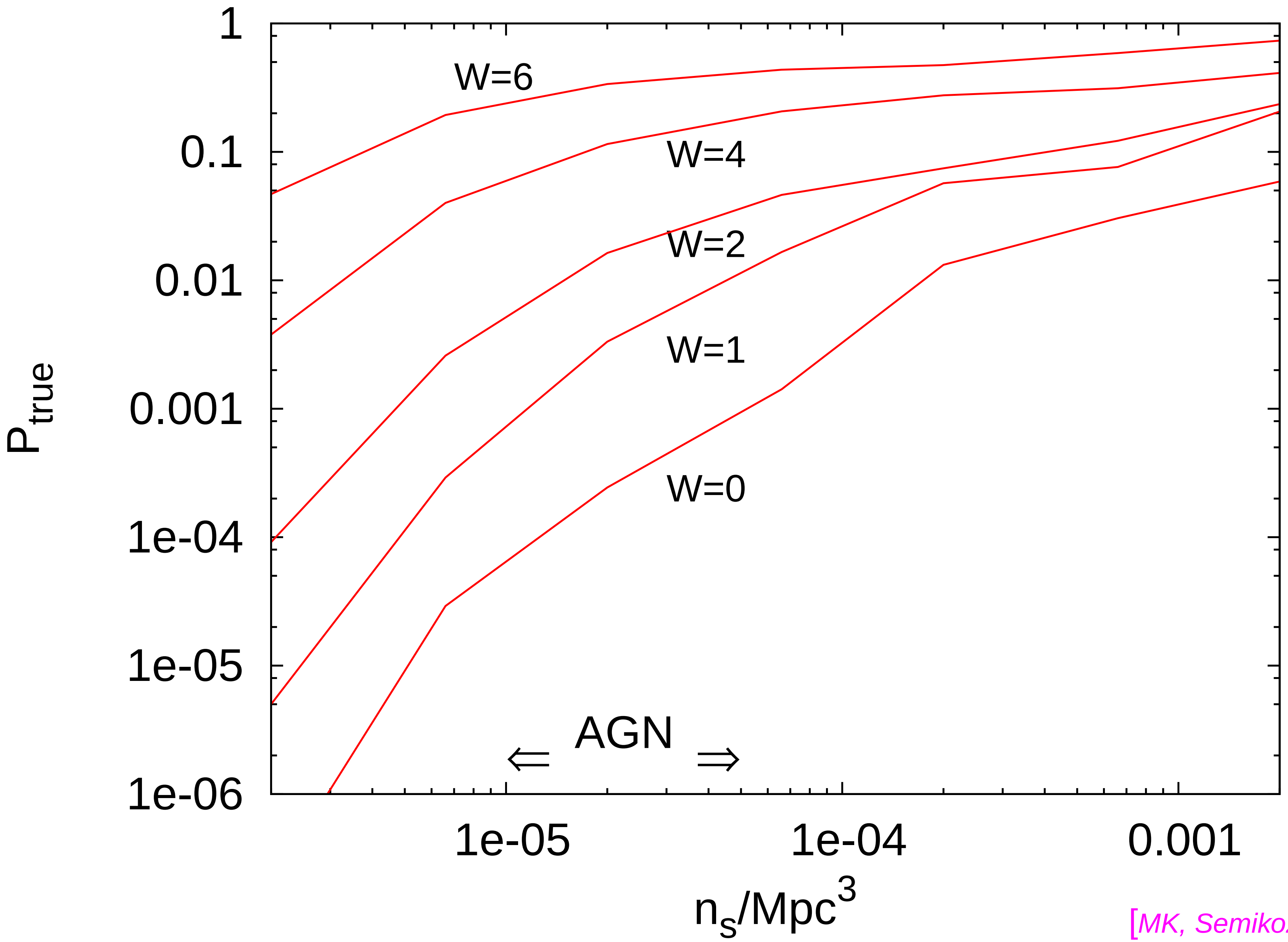
auto-correlation function w of observed event directions,

$$w = \sum_{i<j} \begin{cases} 1, & \text{for} \quad \ell_{ij} < \ell_1 \\ 0, & \text{for} \quad \ell_{ij} > \ell_1 \end{cases}$$

define additionally “true” or source auto-correlation function W,

$$W = \sum_{i<j} \begin{cases} 1, & \text{for} \quad \ell_{ij} < \ell_1 \text{ and } ij \text{ from same source} \\ 0, & \text{otherwise} \end{cases}$$

Constrained probability $P(\leq W | w_1 = 7)$:



[*MK, Semikoz '04*]

Predictions for PAO:

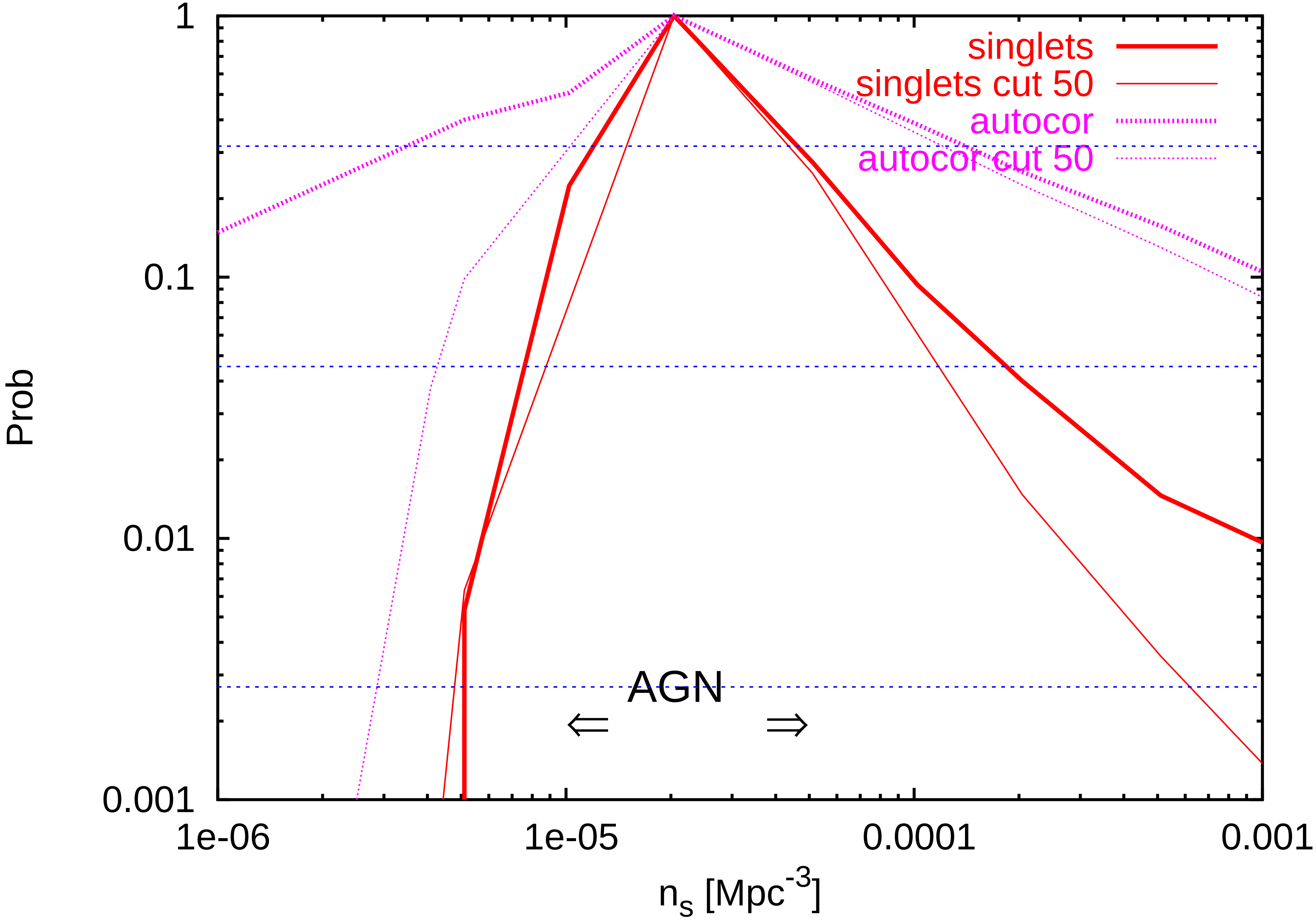
- for one year, assuming $N = 300$ events above 4×10^{19} eV
- determination of n_s
- establishing finite n_s

if not

- points towards nuclei as primaries
- or “stronger” magnetic fields

$\Rightarrow$

determination of n_s:



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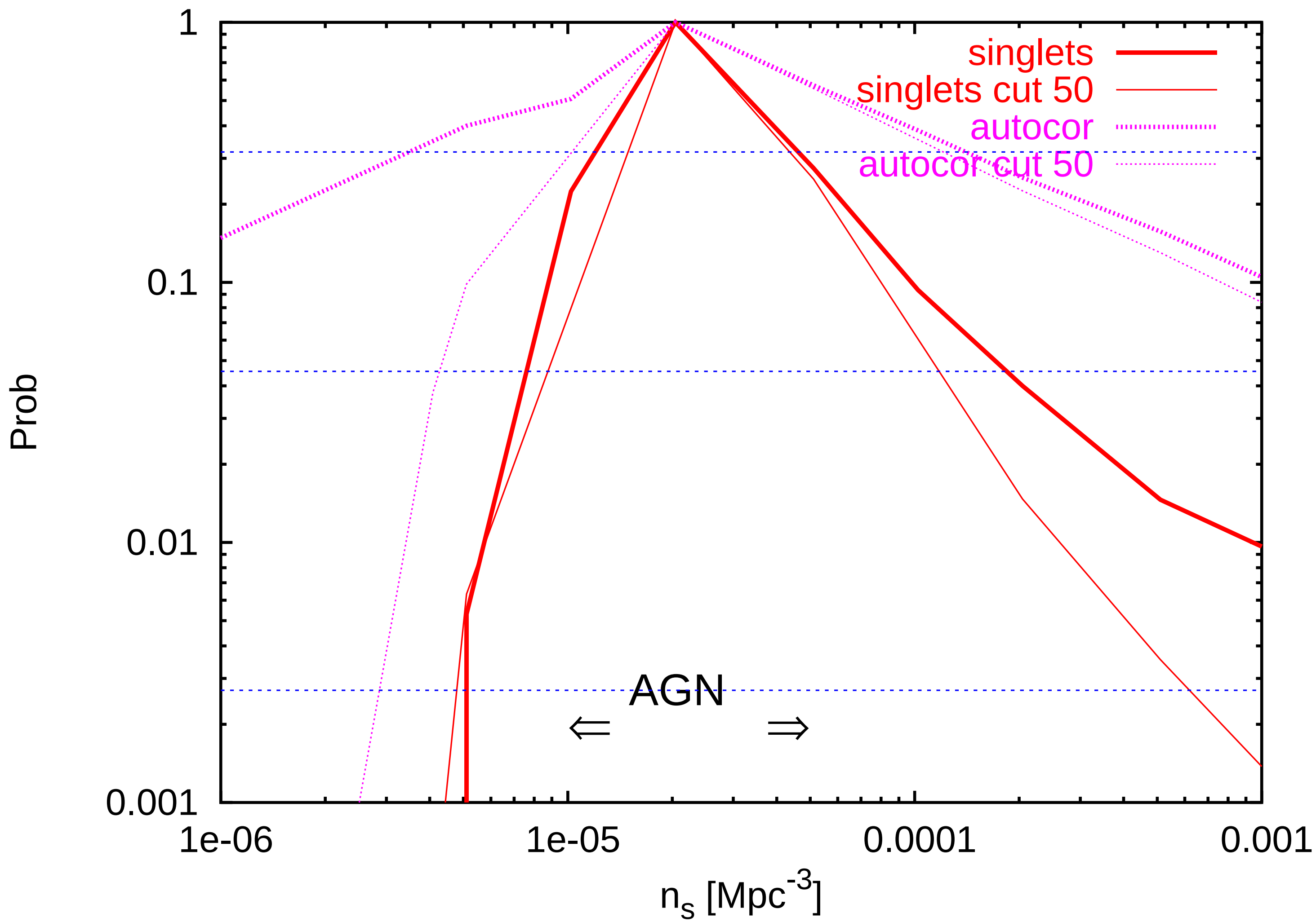
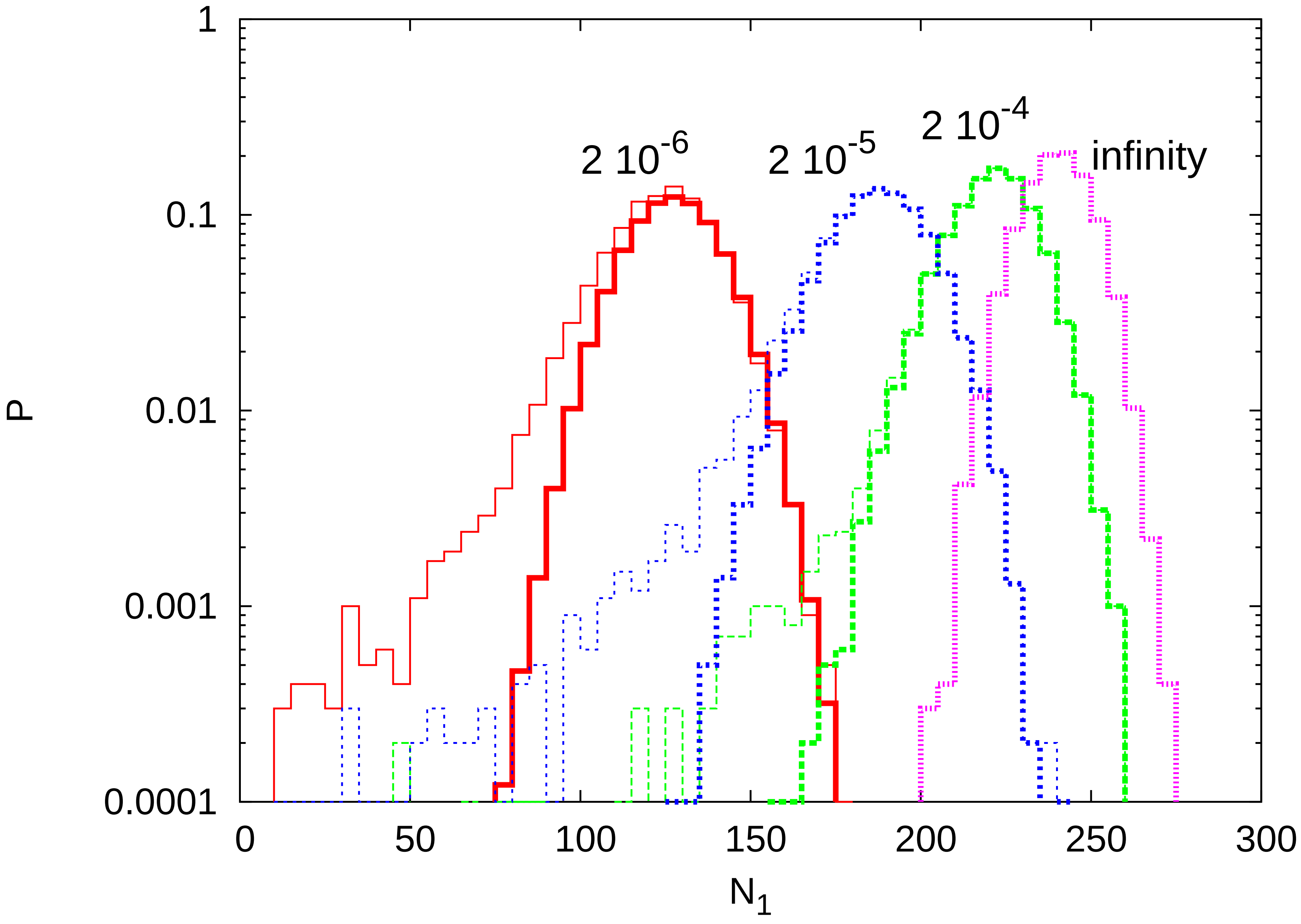
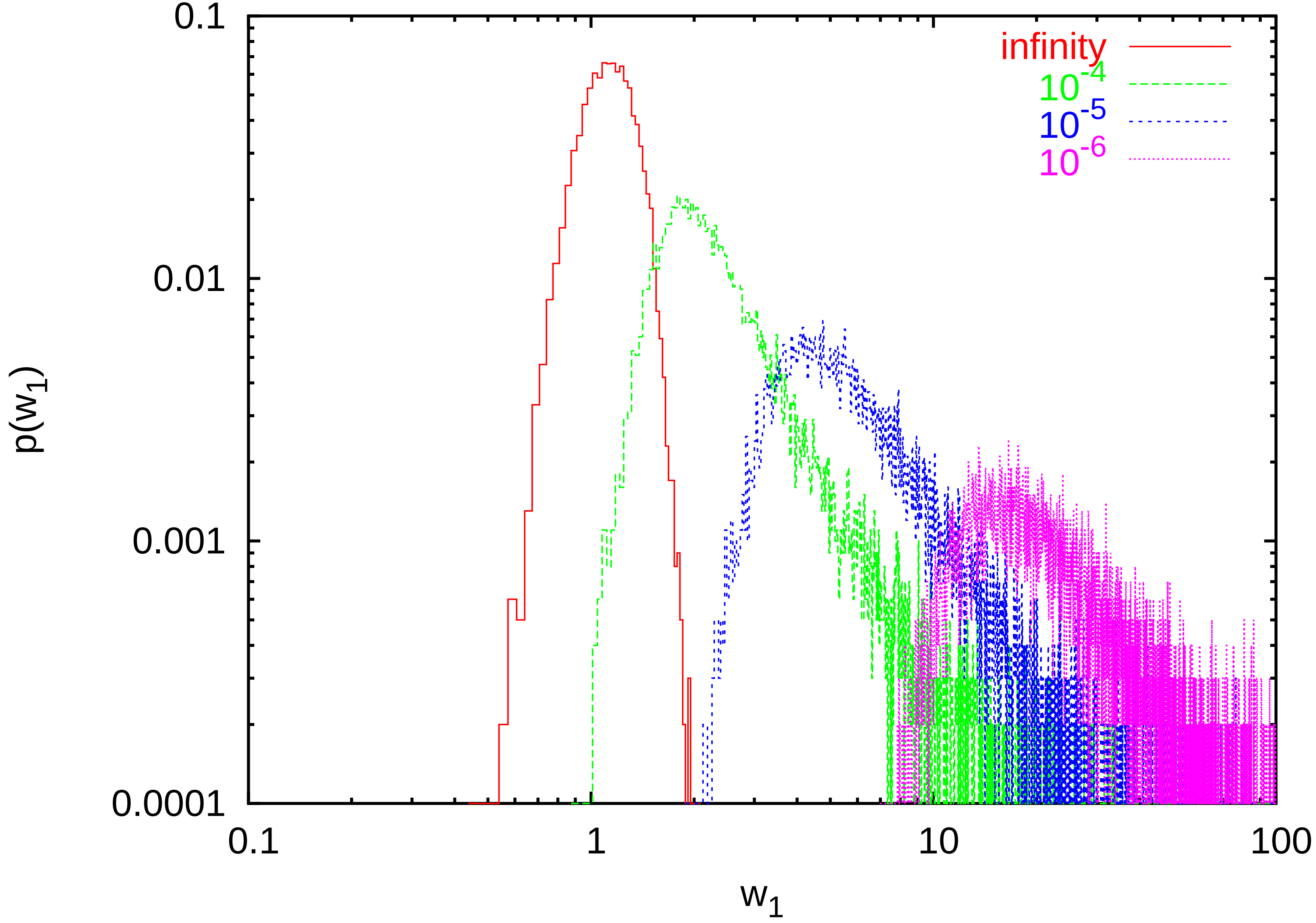


$\Rightarrow$ singlet distribution better than auto-correlation function

singlet distribution:



establishing $n_s < \infty$:



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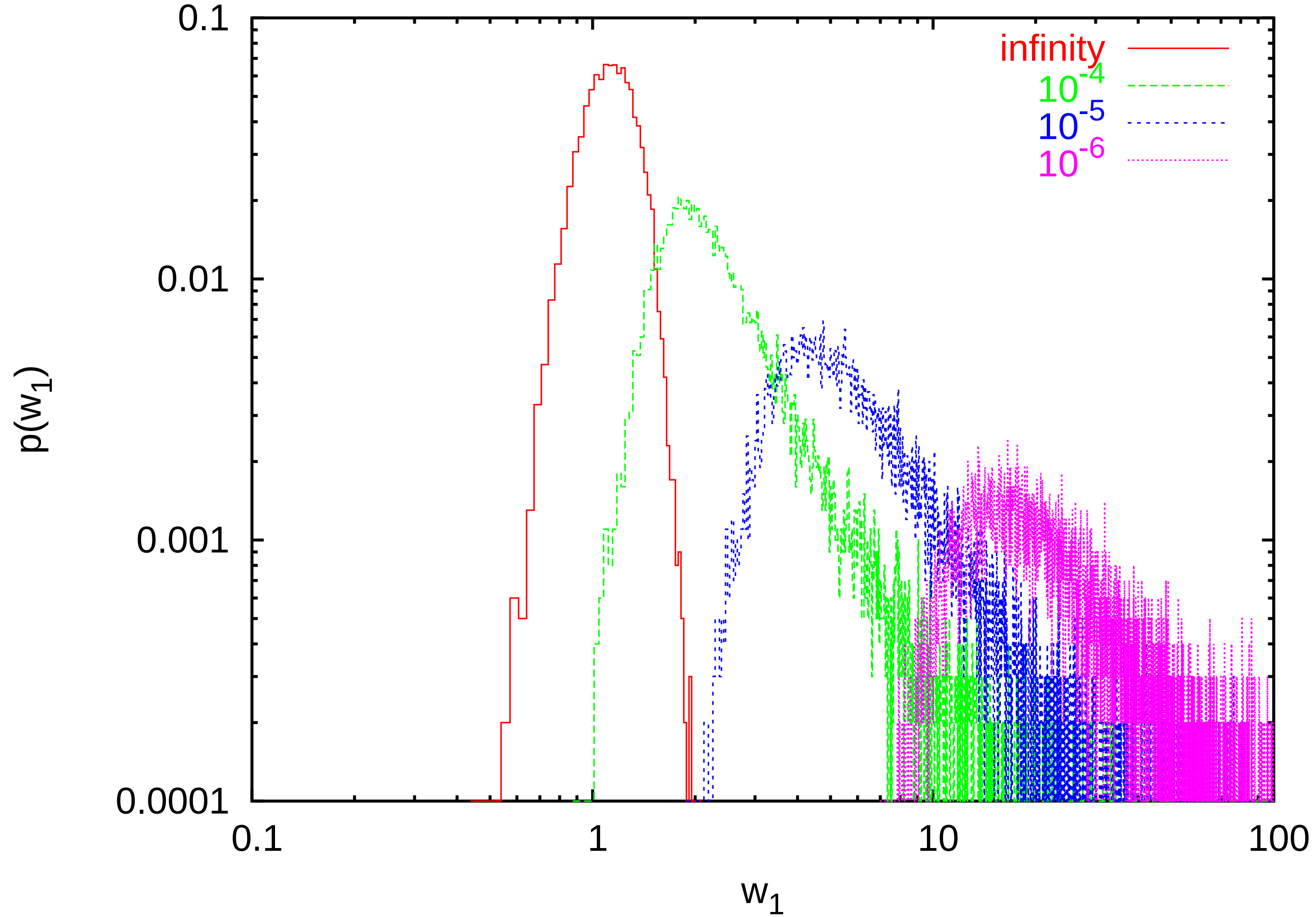

$\Rightarrow$ continuous distribution can be excluded with $< 10^{-5}$ for true densities smaller than $2 \times 10^{-5}/$ Mpc^3

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  - ◇ correlations with astrophysical objects
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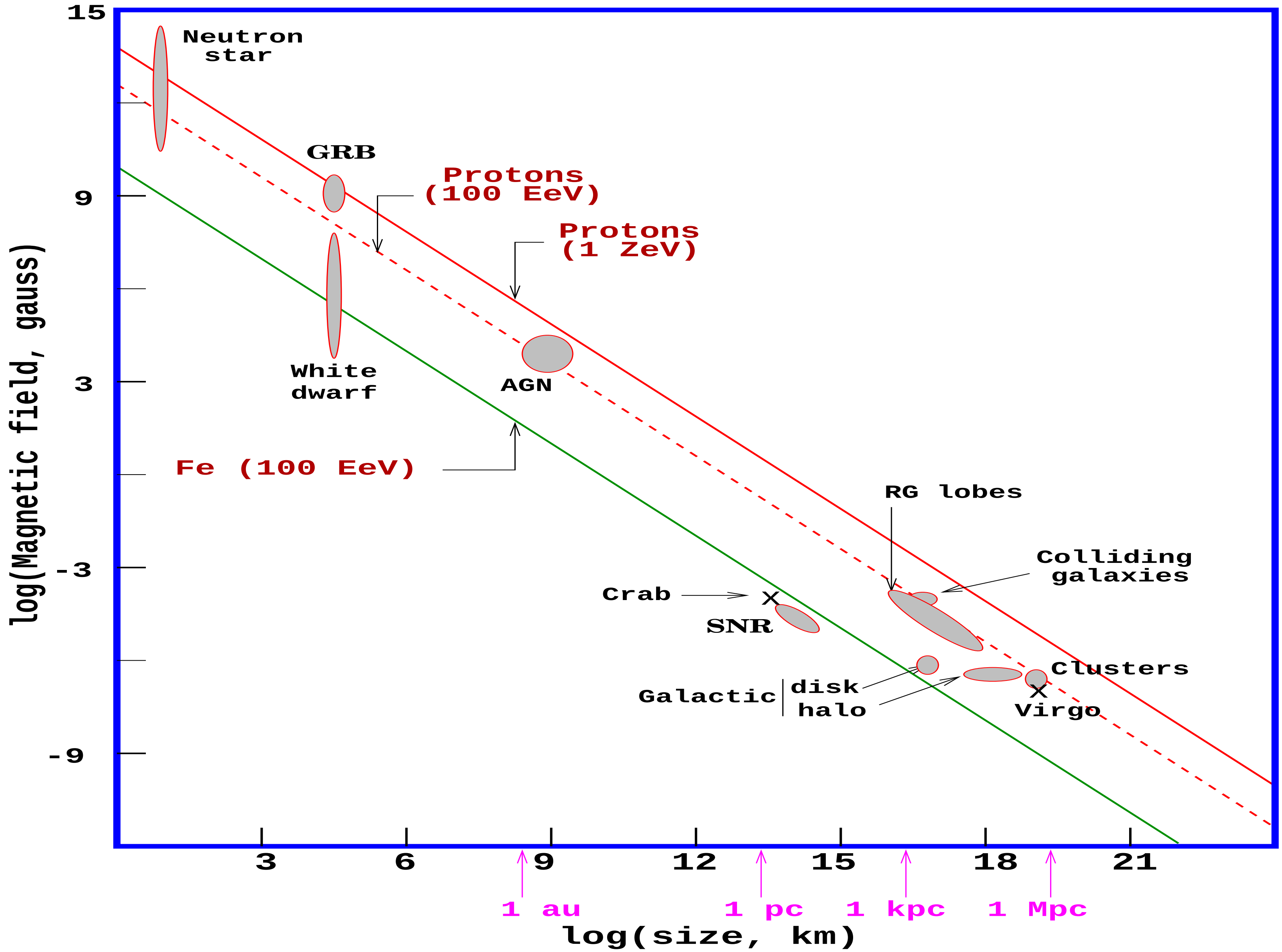
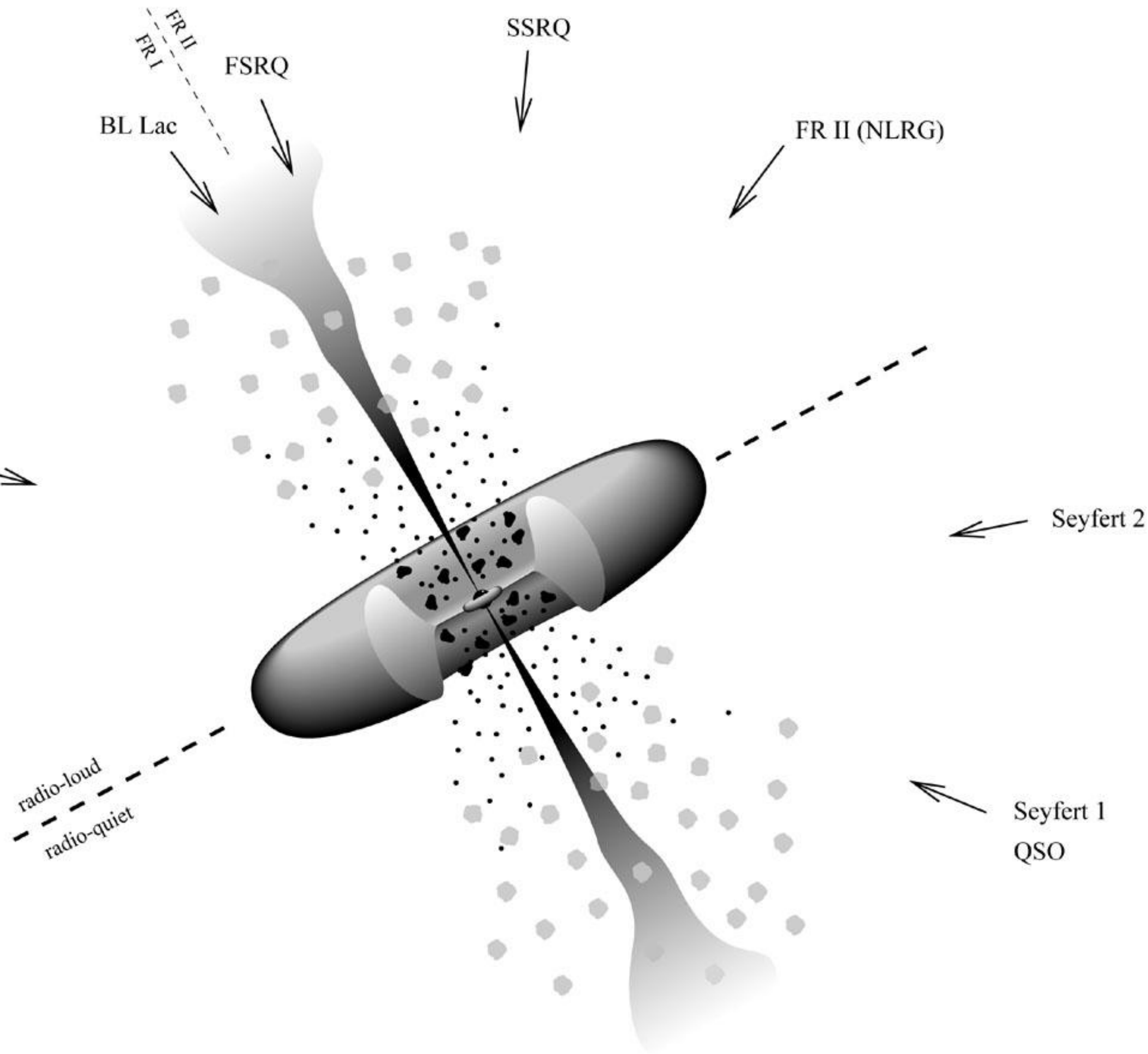
Hillas-plot
(candidate sites for E=100 EeV and E=1 ZeV)



$E_{max} \sim \beta ZBL$

Unified AGN picture:



Correlations with astrophysical sources:

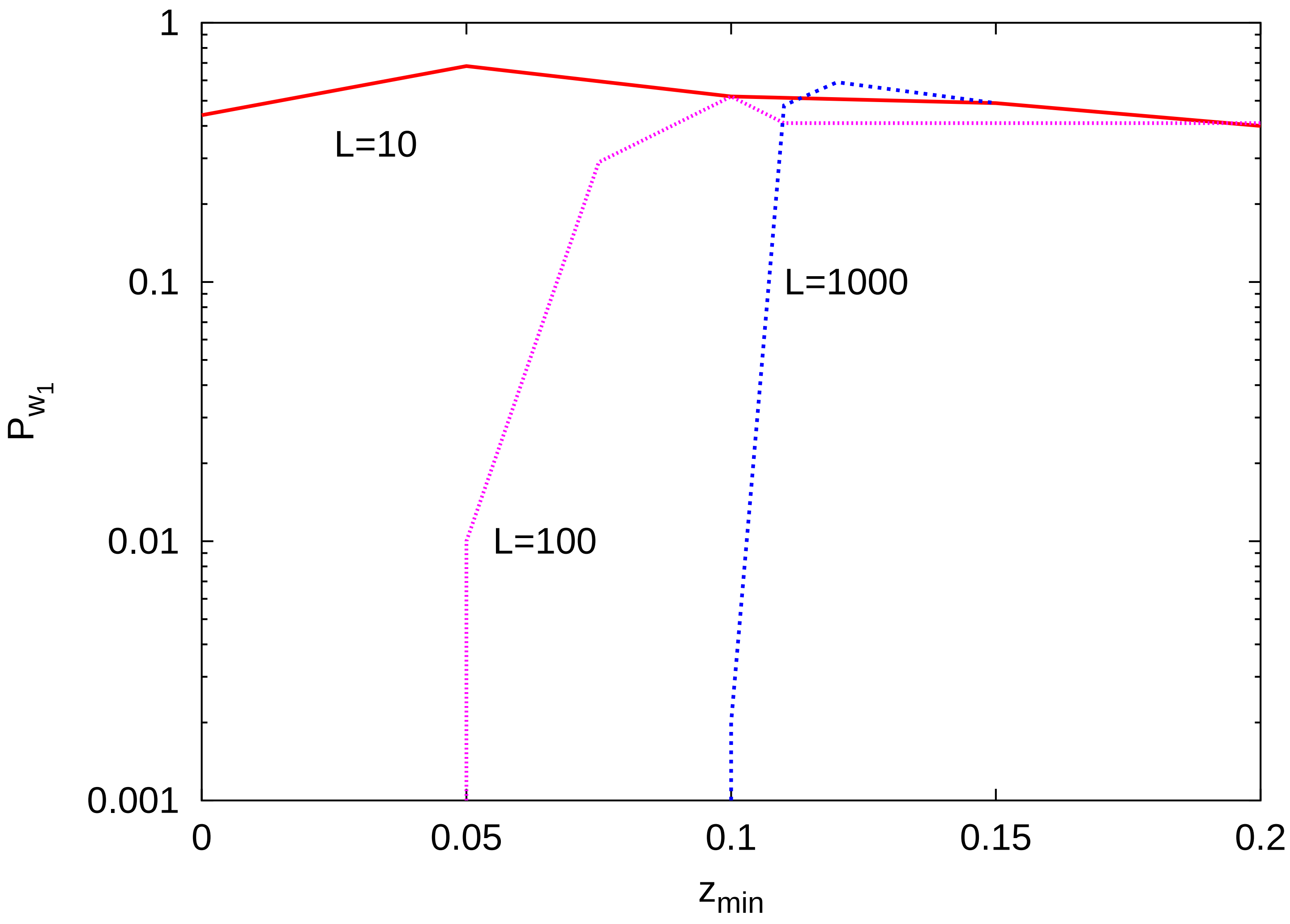
+ Farrar & Biermann '98: radio-loud QSO's, $p_{\rm ch} \sim 0.5\%$
– Sigl et al. '01: $p_{\rm ch} \sim 27\%$
+ Tinyakov & Tkachev: AY – radio-loud BL Lacs with $z > 0.1$ and $\mathrm{mag} < 18$, $p_{\rm ch} \sim 2 \times 10^{-5}$
– Torres et al.: HV no significant correlation
+ Gorbunov et al.: HiRes – all BL Lacs with $\mathrm{mag} < 18$, $p_{\rm ch} \sim 4 \times 10^{-4}$

Are correlations as found by Tinyakov & Tkachev possible with protons or nuclei as primaries?

Uniform sources and BL Lacs:

- add to uniform AGN component BL Lac distribution with larger luminosity:
- vary parameter L_{BL}/L_{AGN}, $z_{\min,BL}$, n_{AGN}:
- possible to obtain $f_{BL} = 10$–30% for reasonable parameters?

Uniform sources and BL Lacs:



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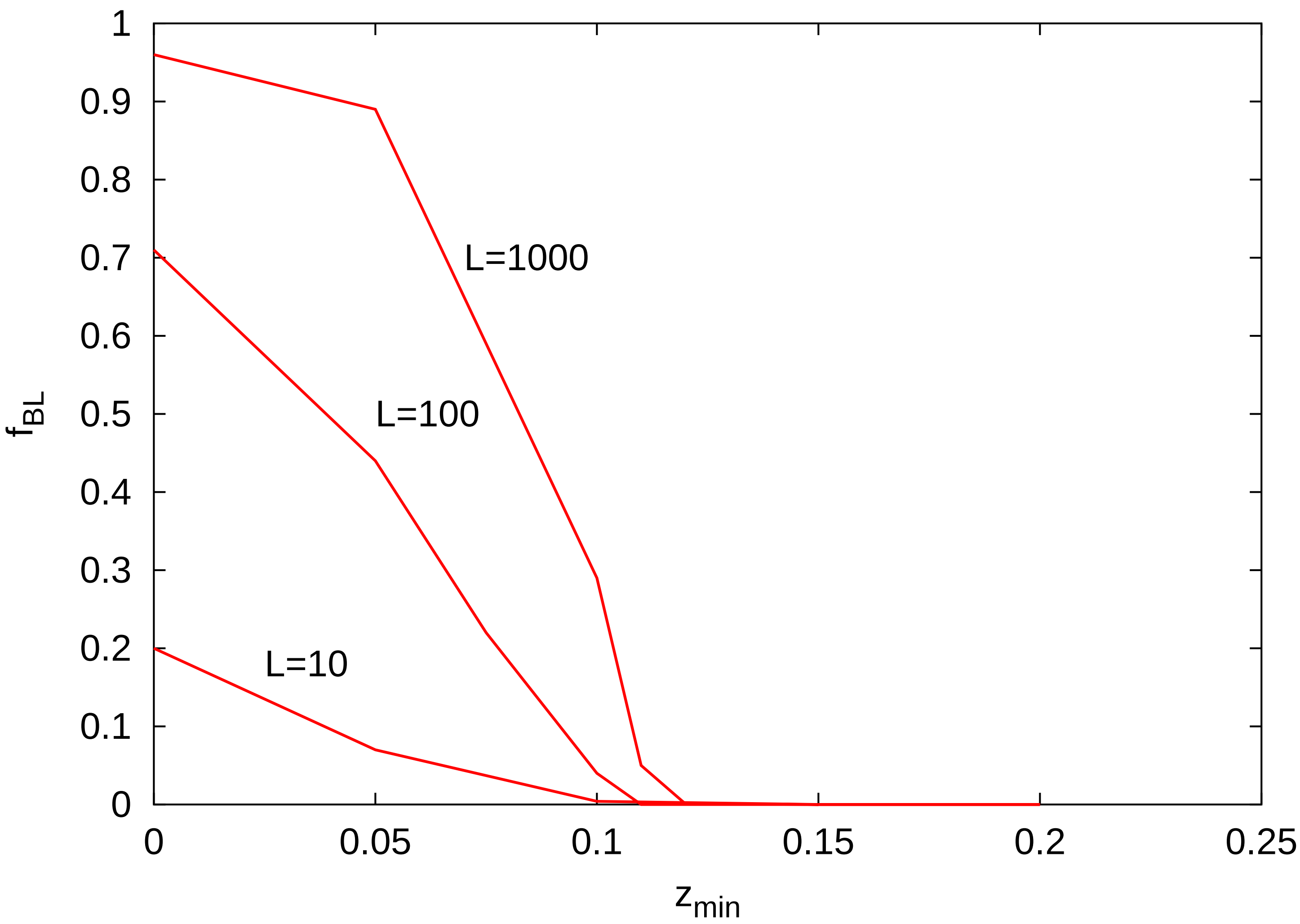

for each L small range in $z_{\rm min}$ possible with acceptable clustering and non-negligible contribution of BL Lacs

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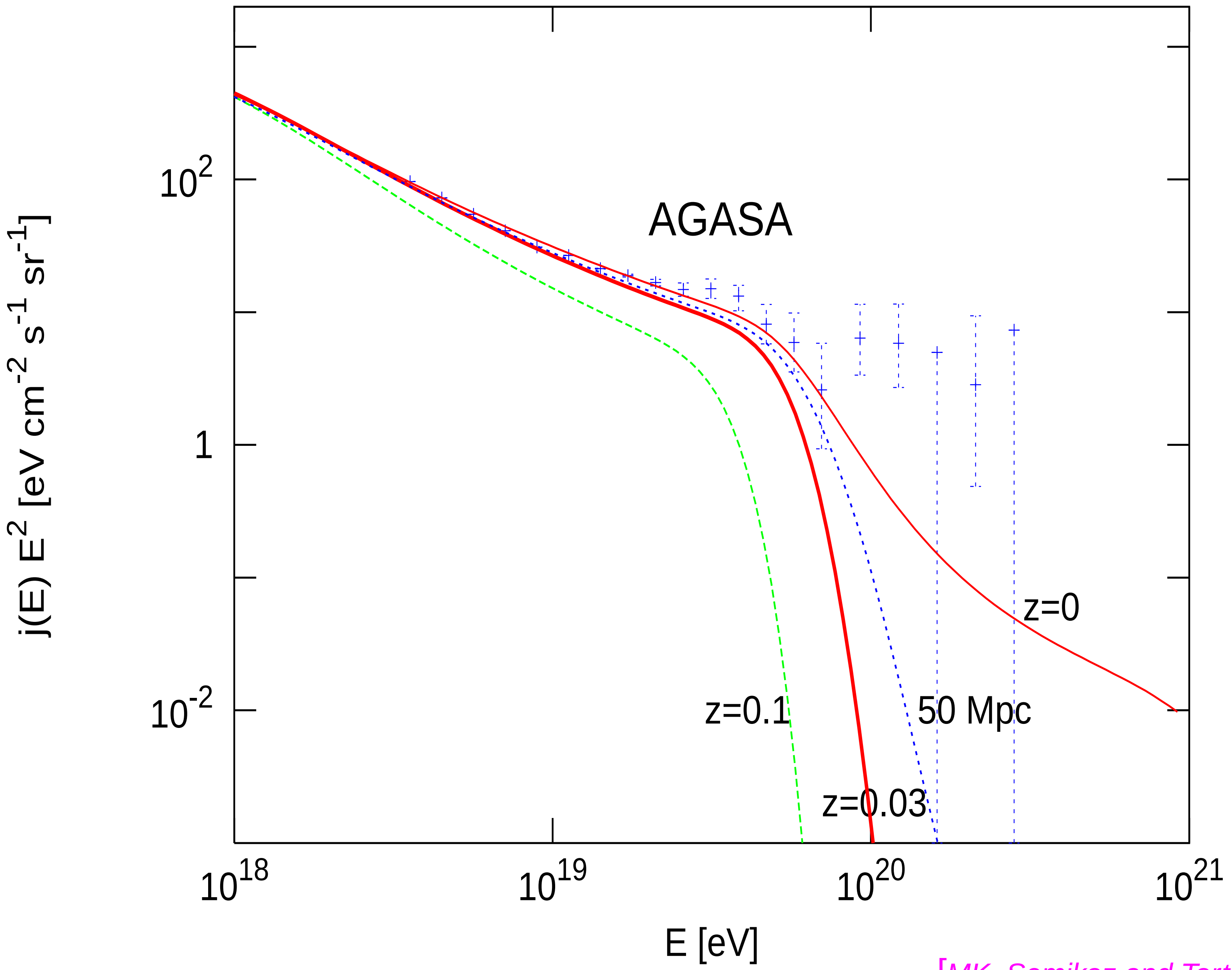
Is the GZK cutoff observed?



[*MK, Semikoz and Tortola '03*]

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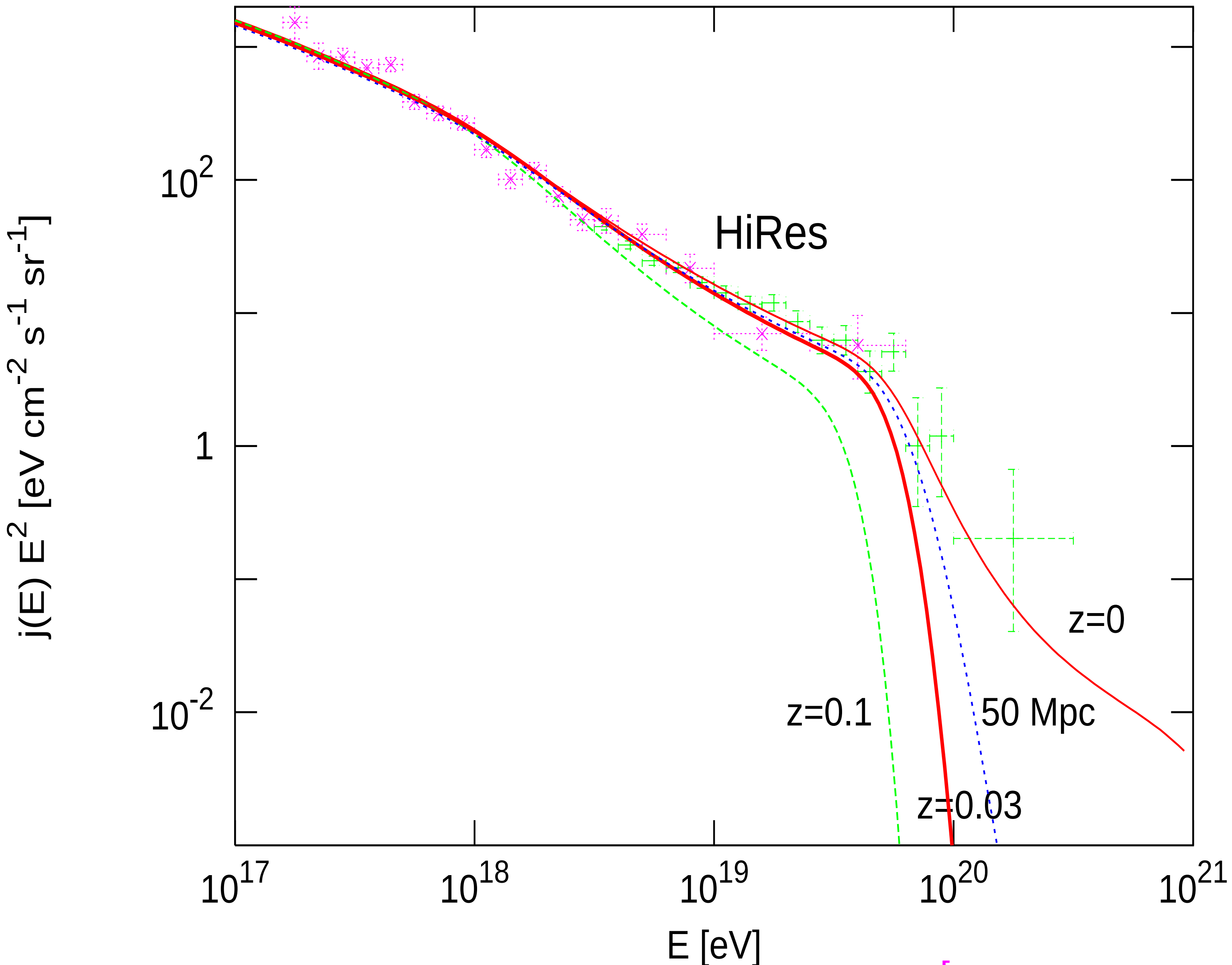

[*MK, Semikoz and Tortola '03*]

Two important questions:

- does the UHECR spectrum shows GZK suppression or not?
  - if not: several possibilities:
    - ◇ Z burst model
    - ◇ top-down models
    - ◇ violation of Lorentz invariance

- do correlations with objects at cosmological distance exist?
  - if yes:
    - ◇ new primary
    - ◇ Z burst model
    - ◇ violation of Lorentz invariance

Alternative models:

1. Neutrinos

Z **burst model:** UHE $\nu + \nu_{\rm BR} \to Z \to$ hadrons

[*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 SuperKamiokande data.

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[*Fargion, Mele, Salis ’99; Weiler ’99*]

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

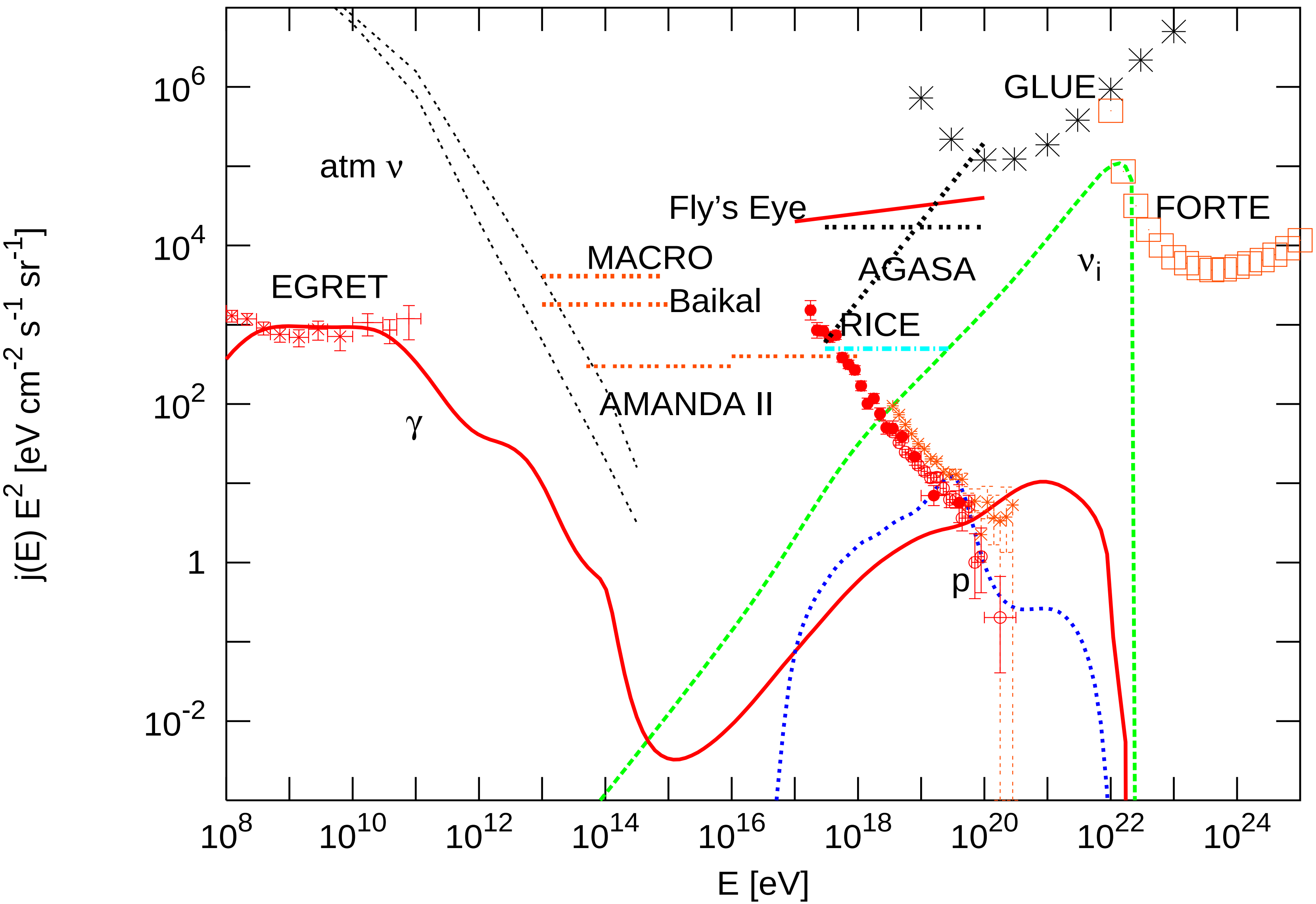
- experimental bounds on UHE neutrino fluxes constrain already Z burst model
- observed MeV–GeV-γ background implies upper bounds on UHE neutrino flux produced in (astrophysical) sources

Idea of EGRET limit:

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

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

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
- cms energy for collisions in atmosphere
  $\sim$ 100 TeV – 1 PeV $\Rightarrow$ beyond reach of accelerators

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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)

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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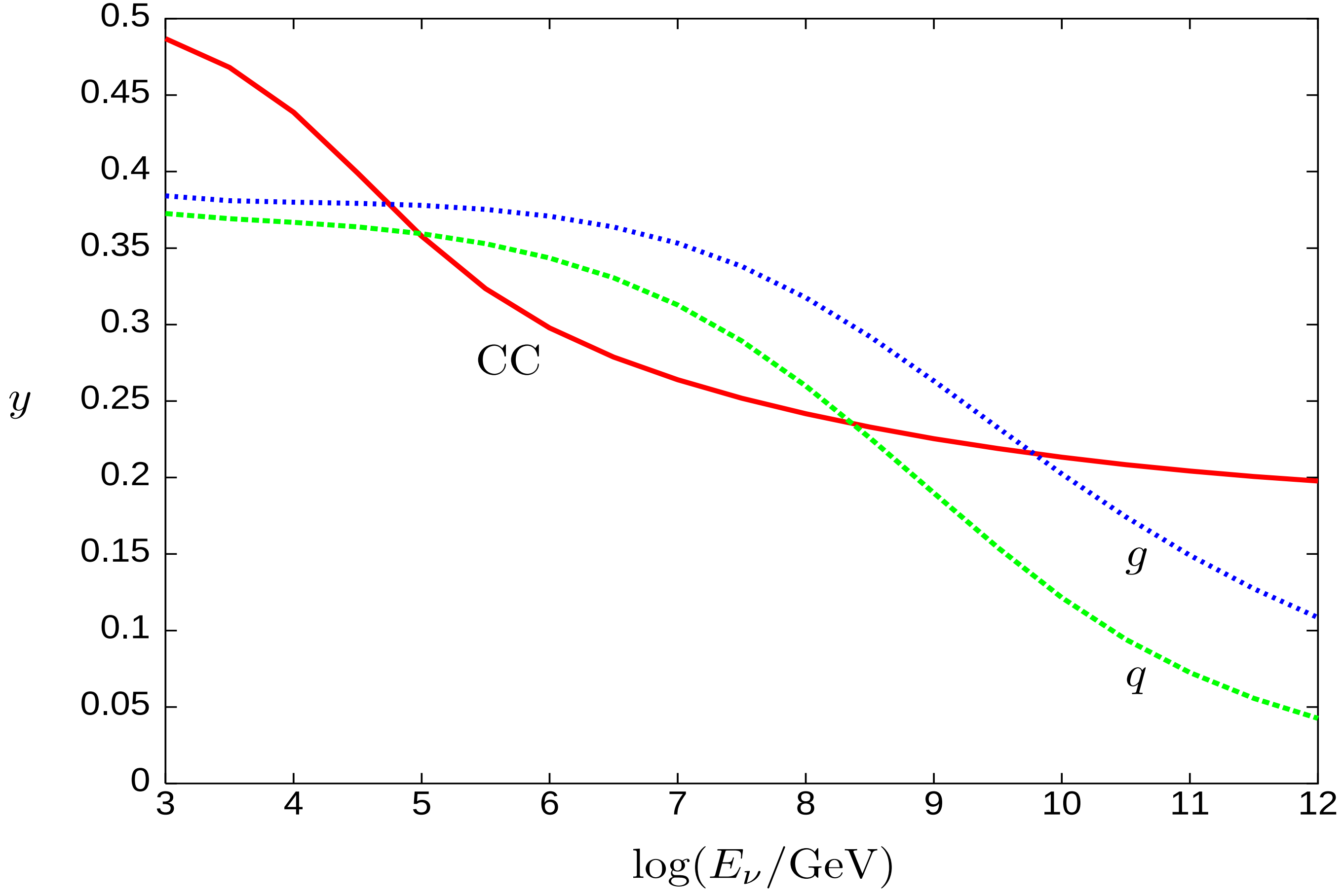
Could neutrino be primary of observed vertical EAS above GZK-cutoff? [*Sigl '00, Jain et. al '00*]

no, because

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

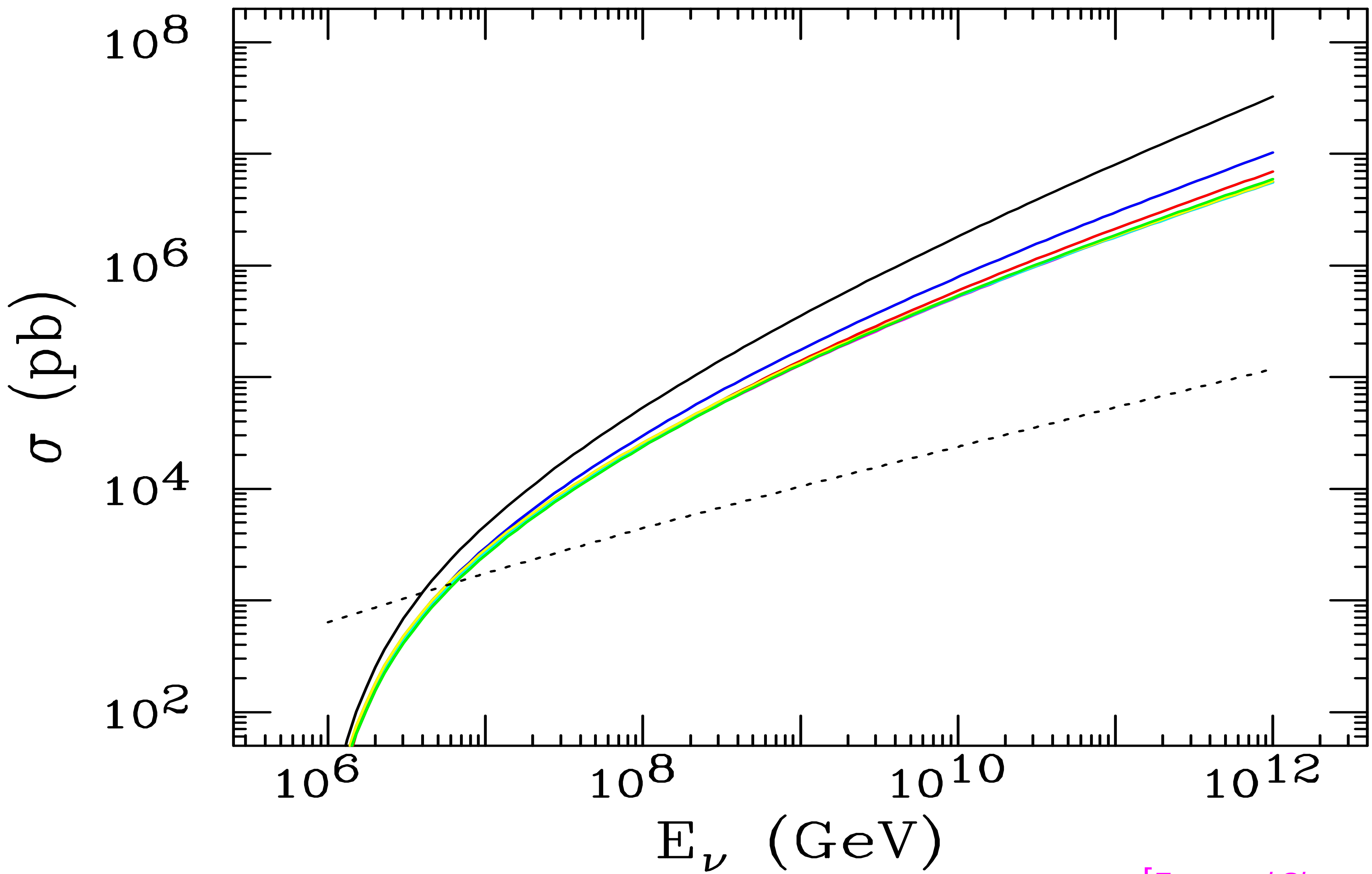
Ex.: Large Extra Dimensions



[MK, M.Plümacher '00]

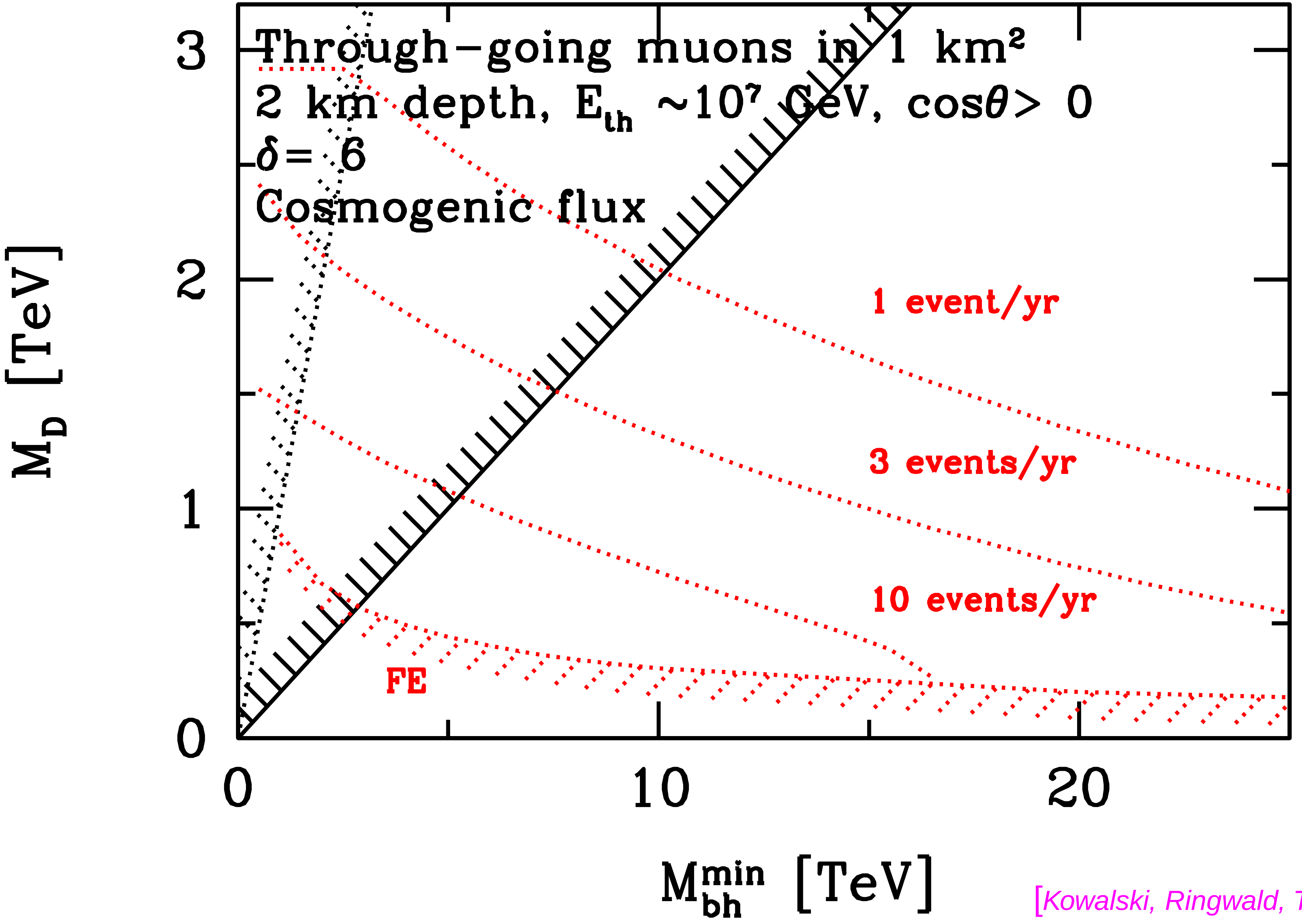
$\Rightarrow$ neutrinos are still deeply penetrating particles

BH production and UHE ν's



[*Feng and Shapere '01*]

Black Holes in ICECUBE:



[Kowalski, Ringwald, Tu '02]

- neutrinos with non-SM interactions cannot explain observed vertical EAS

- but provide exciting experimental target for HE and UHE neutrino experiments

Alternative models:

2. Top-down models

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

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

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

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

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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$\Rightarrow$ they can compensate the small couplings g^2,

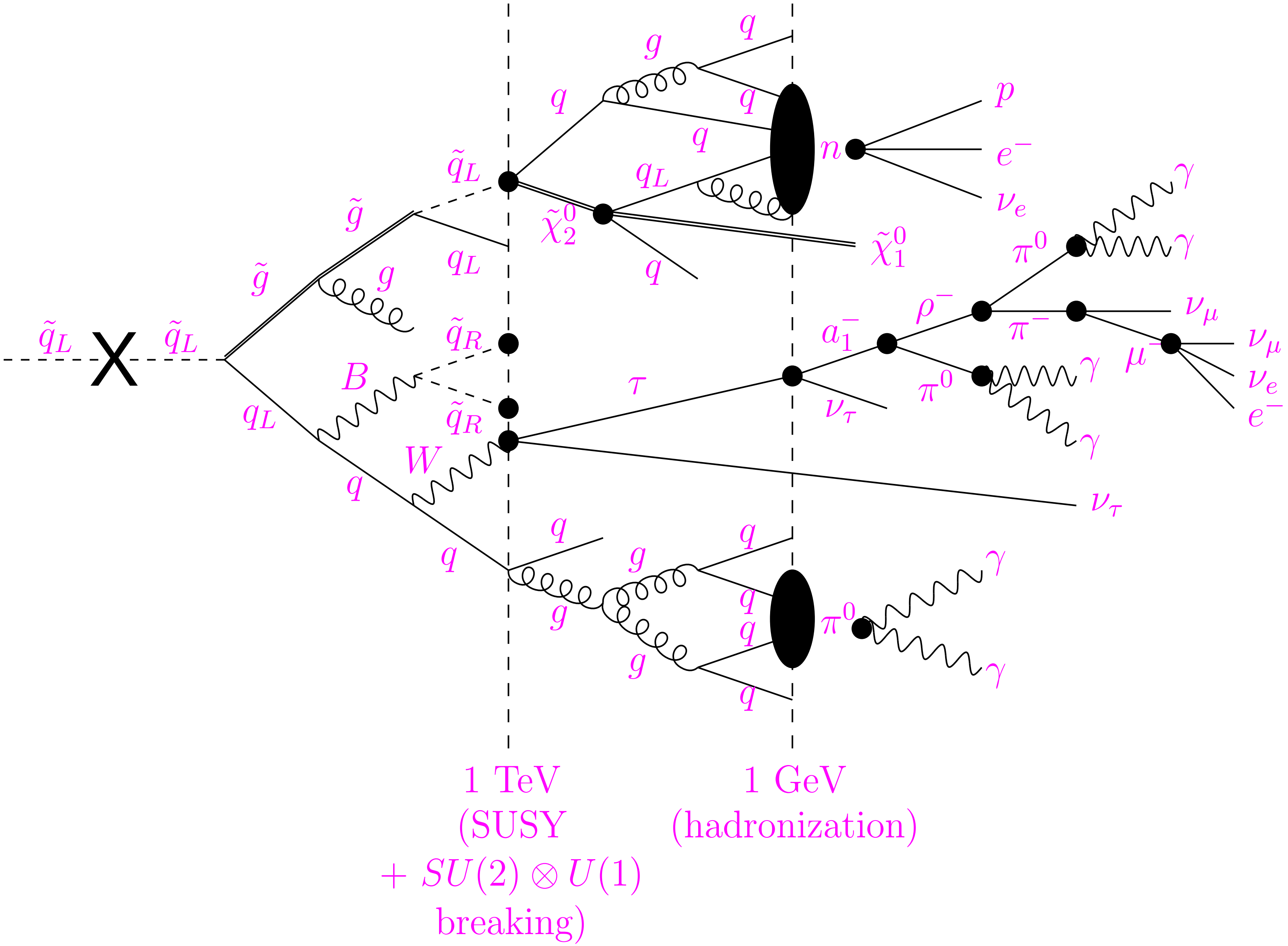
$$g^2 \ln^2(m_X^2/m_V^2) \approx 1$$

- $M_X \gtrsim 10^6$ GeV, $\Rightarrow$ naive perturbation theory breaks down:

electroweak and SUSY sector have a QCD-like behavior ("jets")

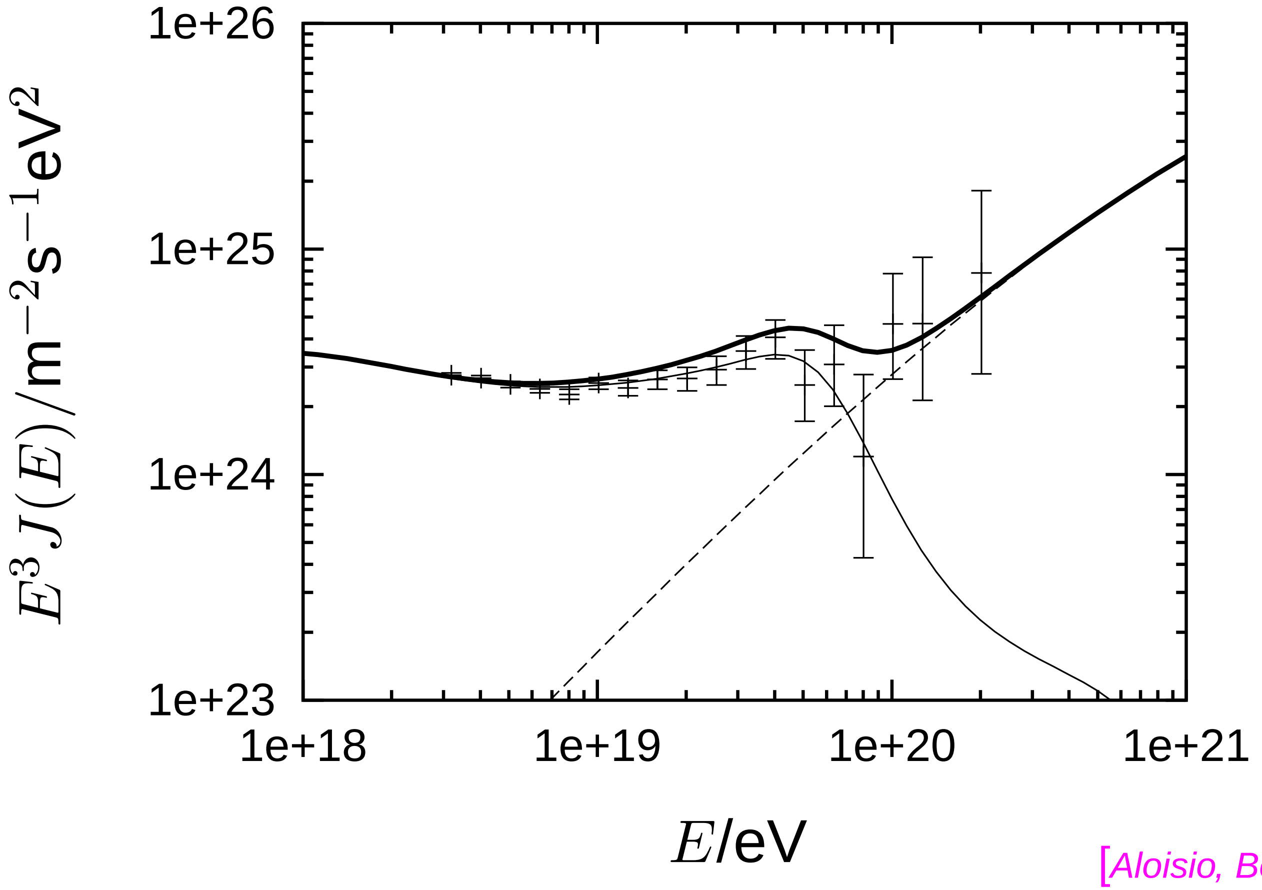
[*Berezinsky, MK '98, Berezinsky, MK, Ostapchenko '02)*]

Fragmentation of heavy particles



Signatures of SHDM decays:

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

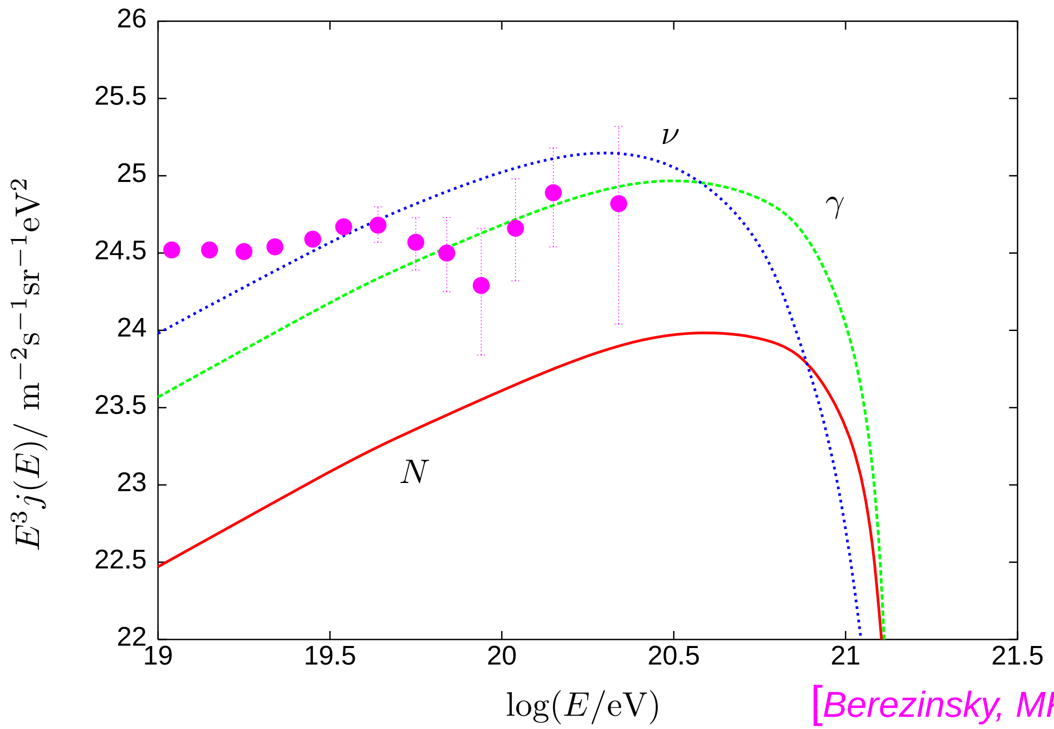


[*Aloisio, Berezinsky, MK, '03*]

$\Rightarrow$ 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: [Berezinsky, MK '98]
  - $\gamma/p \gg 1$, no nuclei
  - large neutrino fluxes
  - LSPs, if R-Parity conserved



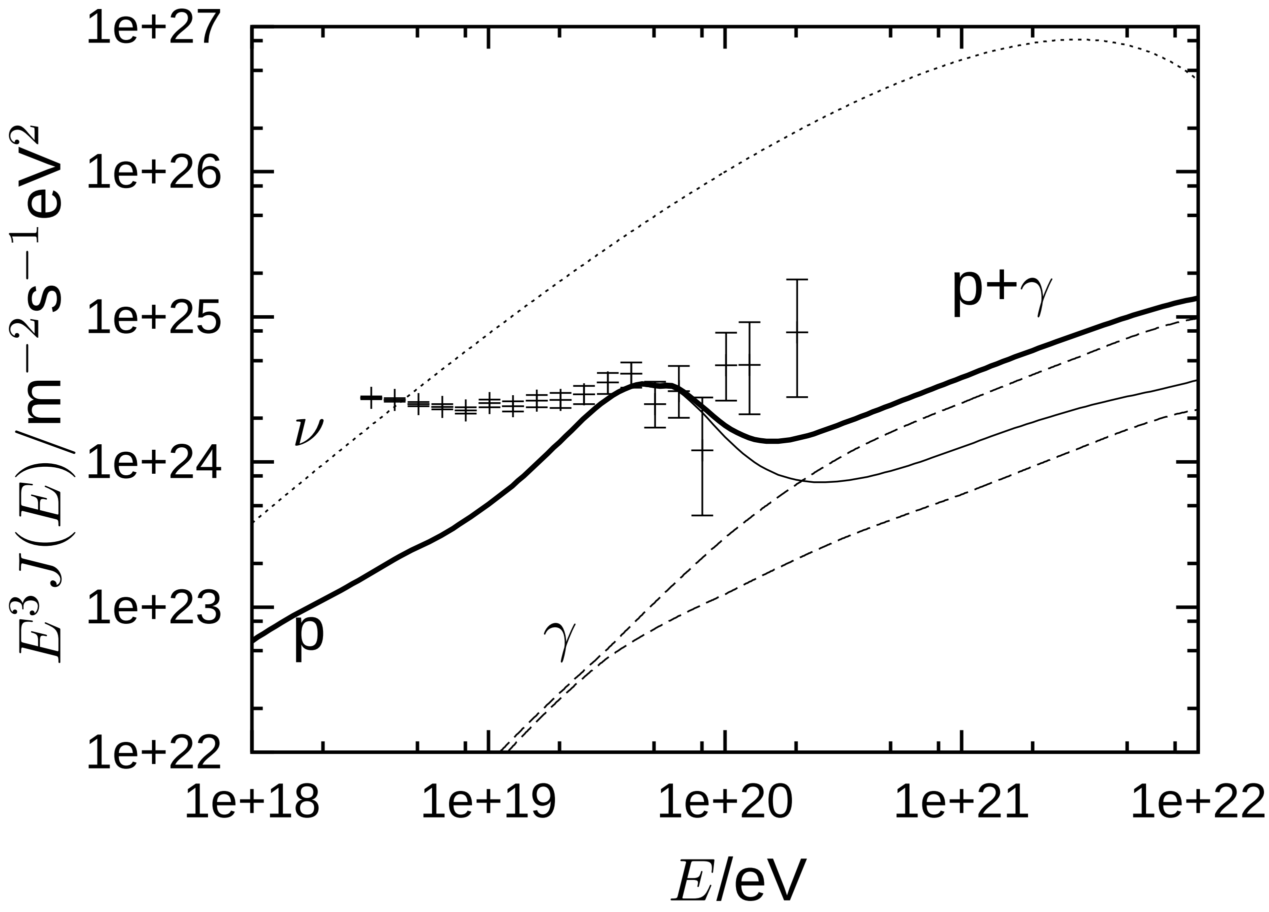
[Berezinsky, MK, '01; Aloisio, Berezinsky, MK, '03]

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:



[*Aloisio, Berezinsky, MK, '03*]

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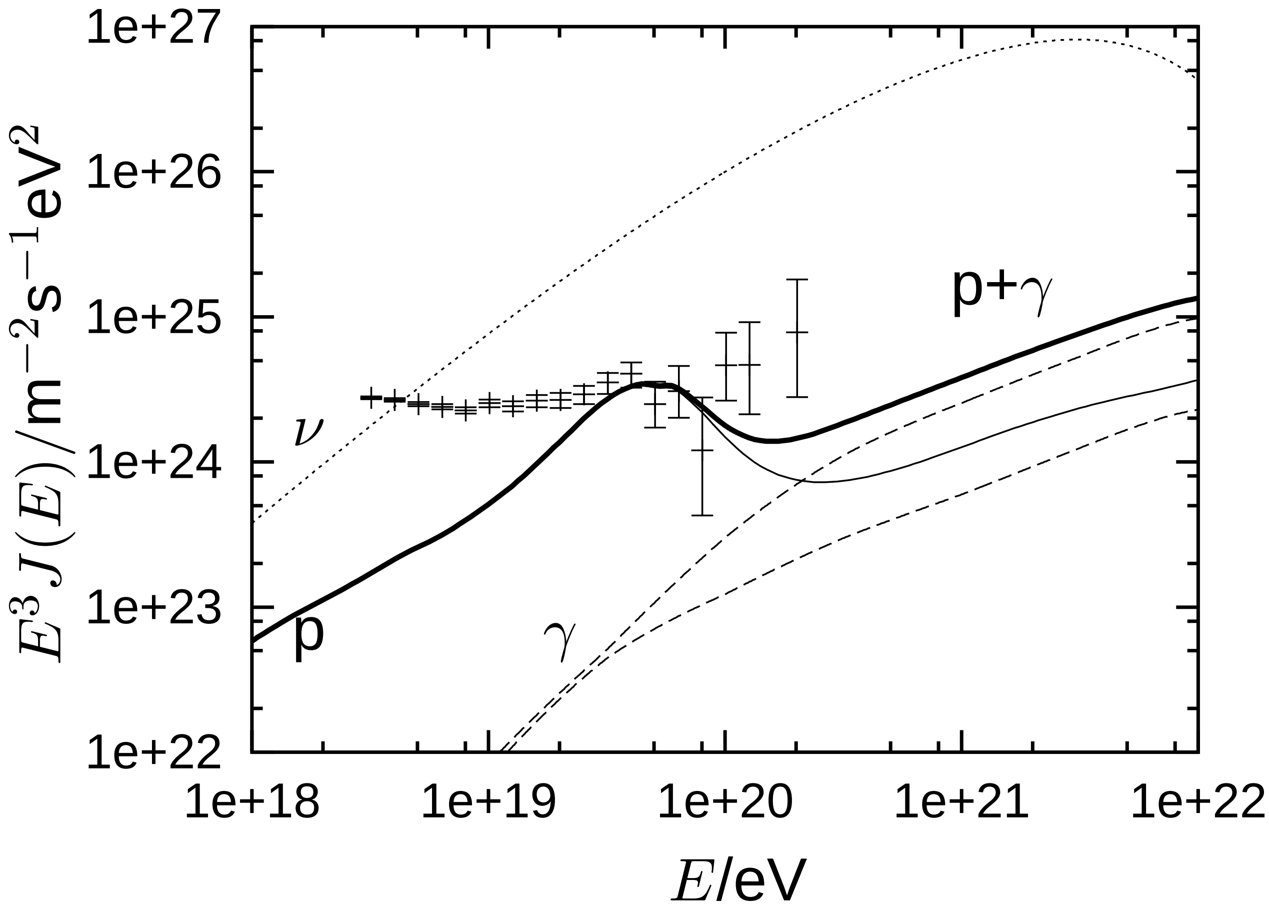

⇒ shape of spectrum allows only sub-dominant contribution

Violation of Lorentz invariance (LI)

- quantum gravity ("space-time foam") or dim. reduction $d = n > 4 \rightarrow 4$ could induce tiny departures from LI
  $\Rightarrow$ non-universal maximal velocities

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- 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

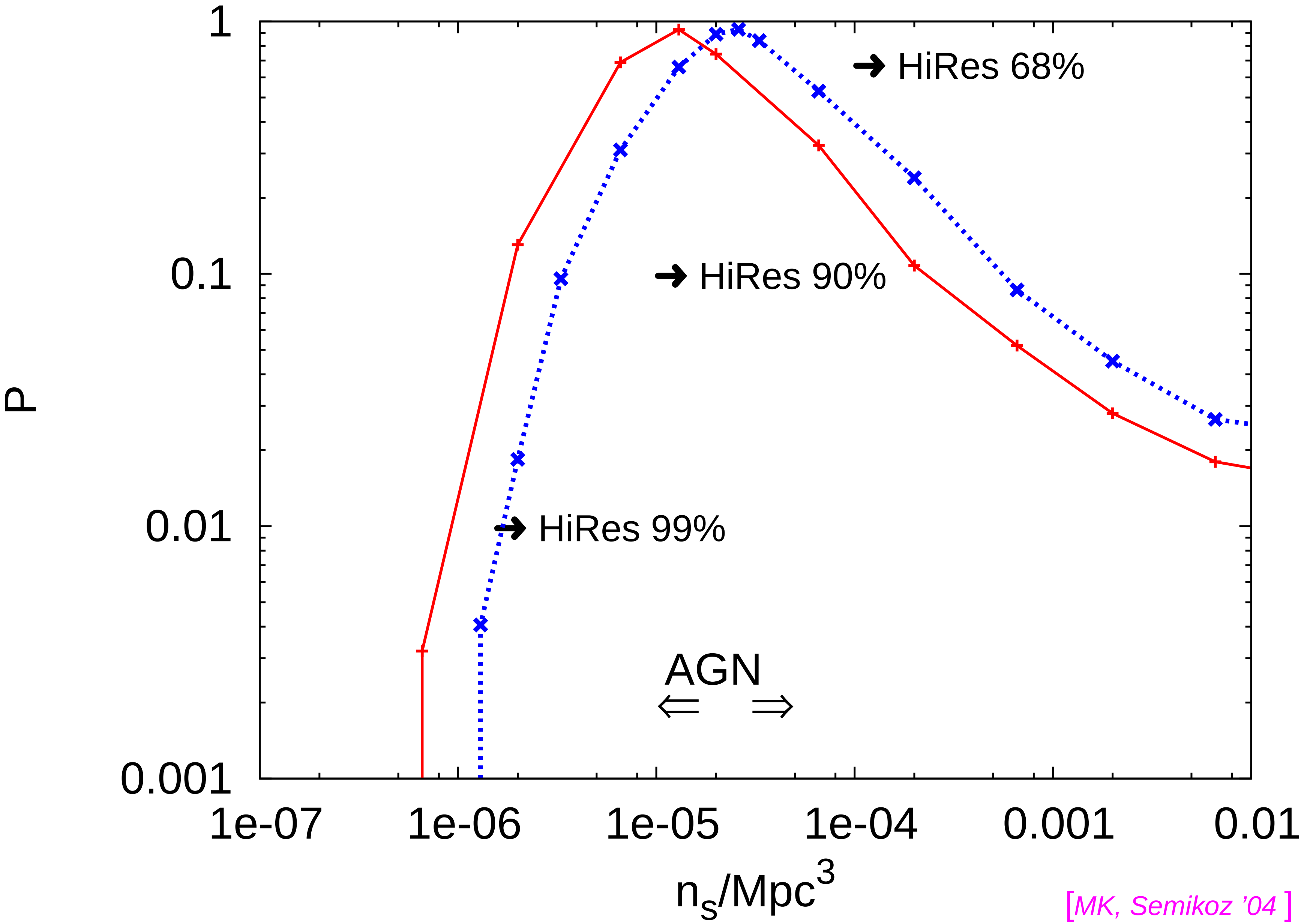
- Z bursts and topological defects can be only subdominant sources of UHECR
- no positive evidence for superheavy dark matter from its two key signatures:
  1. photons
  2. galactic anisotropy

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?

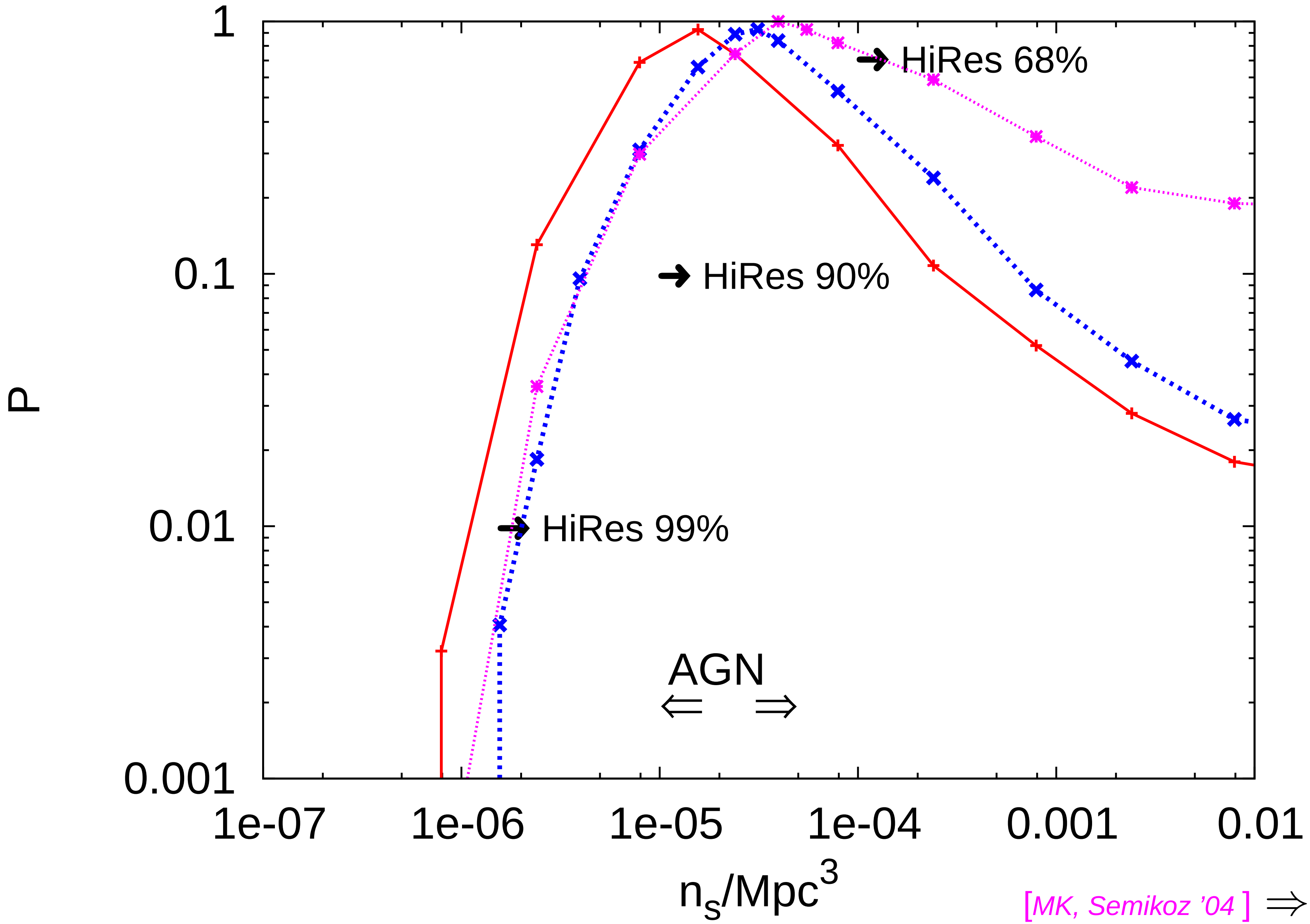
back-up slides

Density n_s of uniform sources, $\ell_1 = 2.5°$:



[MK, Semikoz '04]

Density n_s of uniform sources, $\ell_1 = 2.5,\ 5°$:



[*MK, Semikoz '04*] ⇒