The Universe

seen through

ultrahigh energy cosmic ray spectacles

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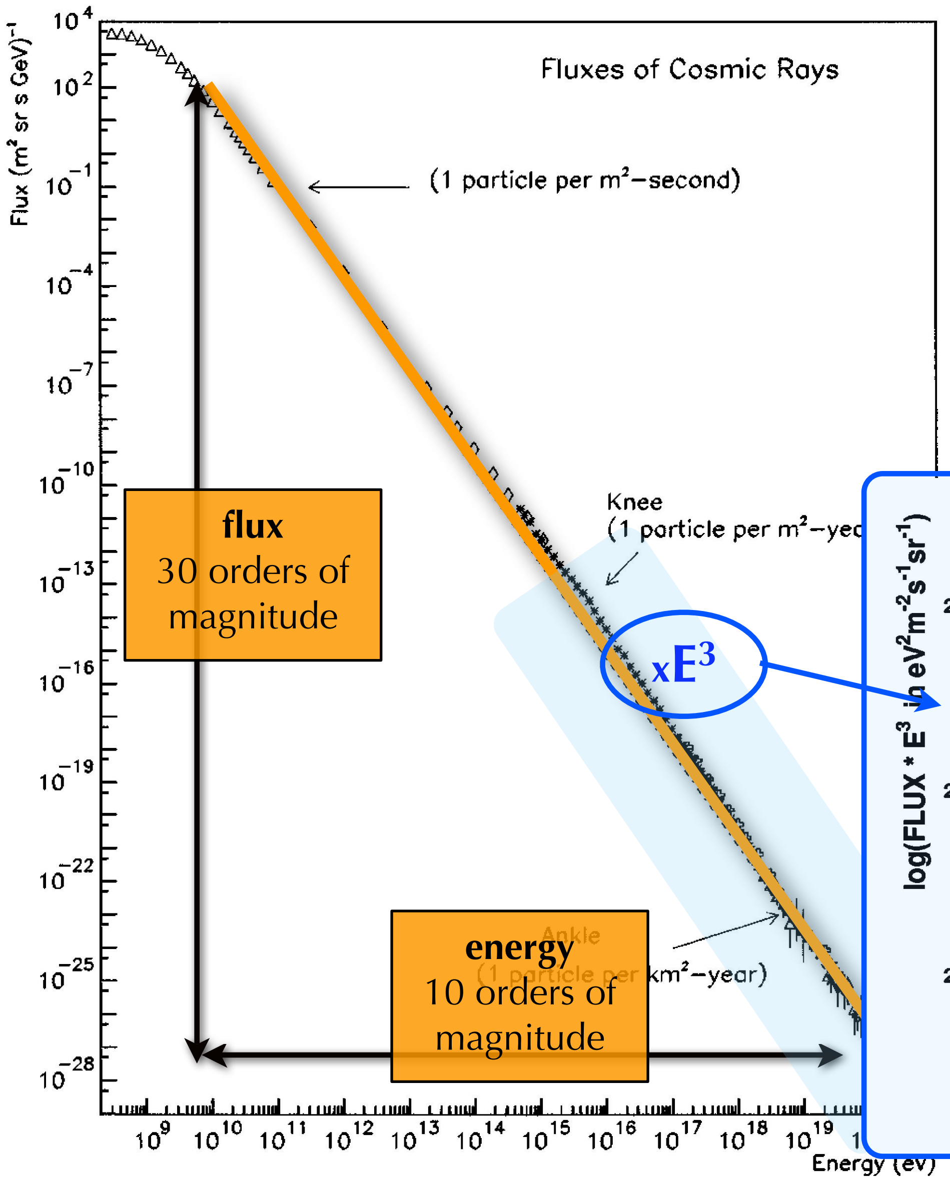
The enigma of cosmic rays sealed their spectrum

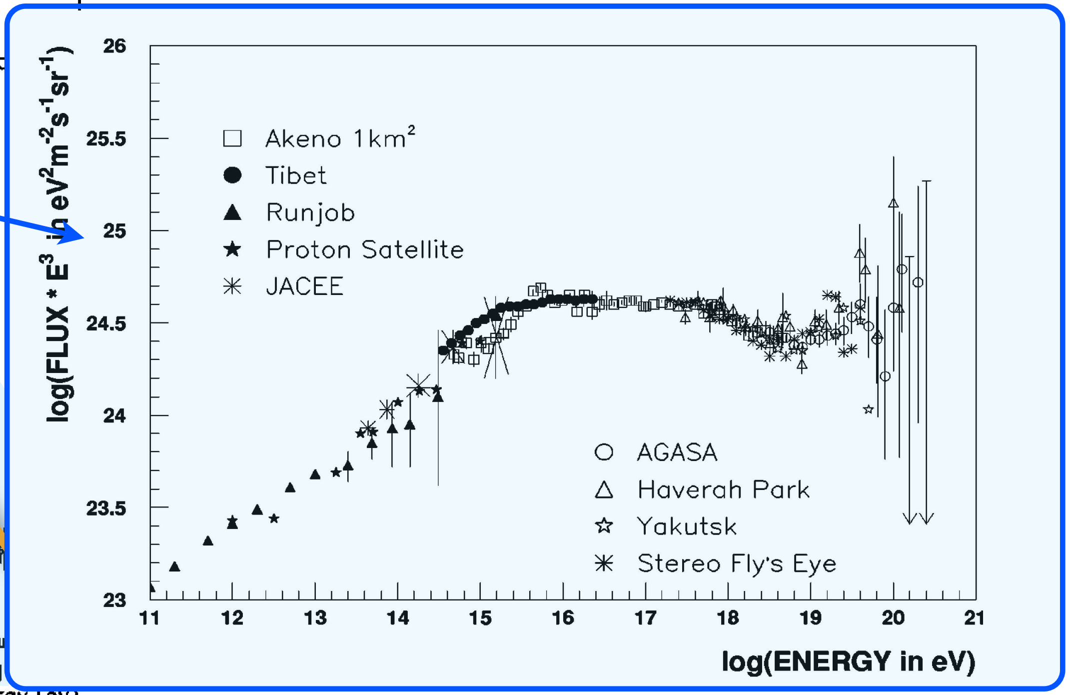


How can we accelerate particles to these energies?

In what source?

What happens between the source and us?

Nagano & Watson 00



Can the highest energy cosmic rays tell us anything?

at the highest energies:

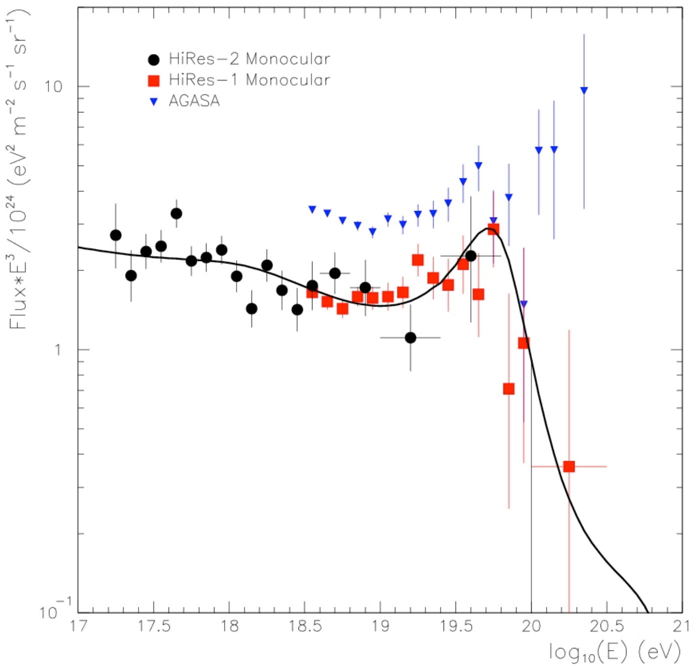
particles should travel nearly rectilinearly (very little infl fields):
we should see the sources of UHECRs in th
but we don’t... why?

PROPAGATION

particles should interact with the CMB photons
we should see a cut-off in the UHECR spectrum above 10^{20} eV (GZK cut-off)

AGASA does not see this cut-off... trans-GZK events? new Physics?

Hires saw it in 2004...

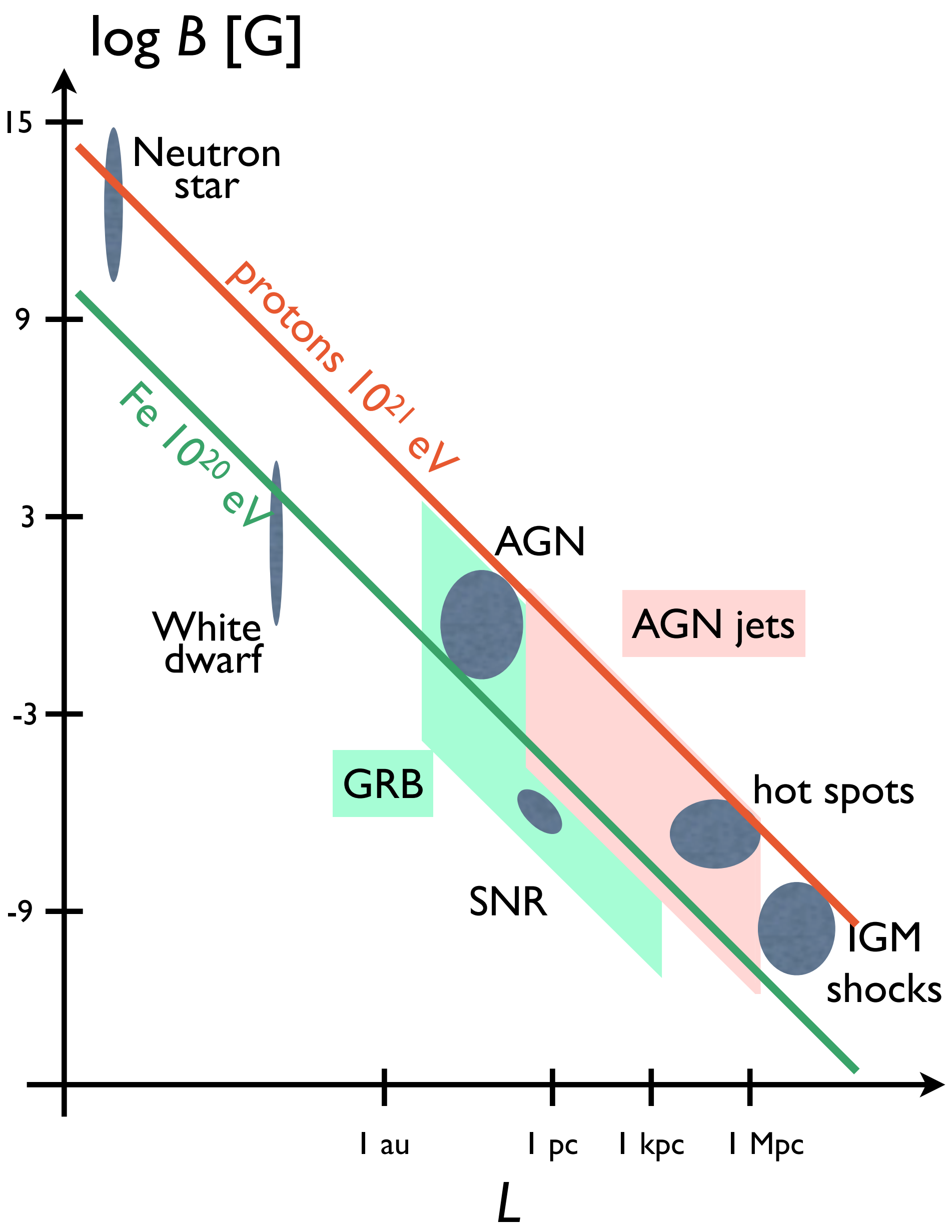


ACCELERATION

How can partic accelerated up to 10^{21} eV? In what source?

Acceleration: Hillas criterion

Hillas, 1984



a simple criterion: to find which object ***might*** be a source of UHE cosmic rays:

a particle gets accelerated as long as it is confined in the source:

$$r_{\rm L} \lesssim L$$

$$r_{\rm L} = 1.08\,{\rm Mpc}\left(\frac{\rm E}{10^{21}\,{\rm eV}}\right)\left(\frac{\rm B}{1\,\mu{\rm G}}\right)^{-1}$$

$$E \lesssim E_{\rm conf} = 10^{21}\,{\rm eV}\left(\frac{\rm B}{1\,\mu{\rm G}}\right)\left(\frac{\rm L}{1\,{\rm Mpc}}\right)$$

Acceleration: Hillas criterion

refined criterion:
compare acceleration timescale
with energy loss timescale and escape timescale

$$t_{\rm acc} \leq t_{\rm loss}, \quad t_{\rm esc}$$

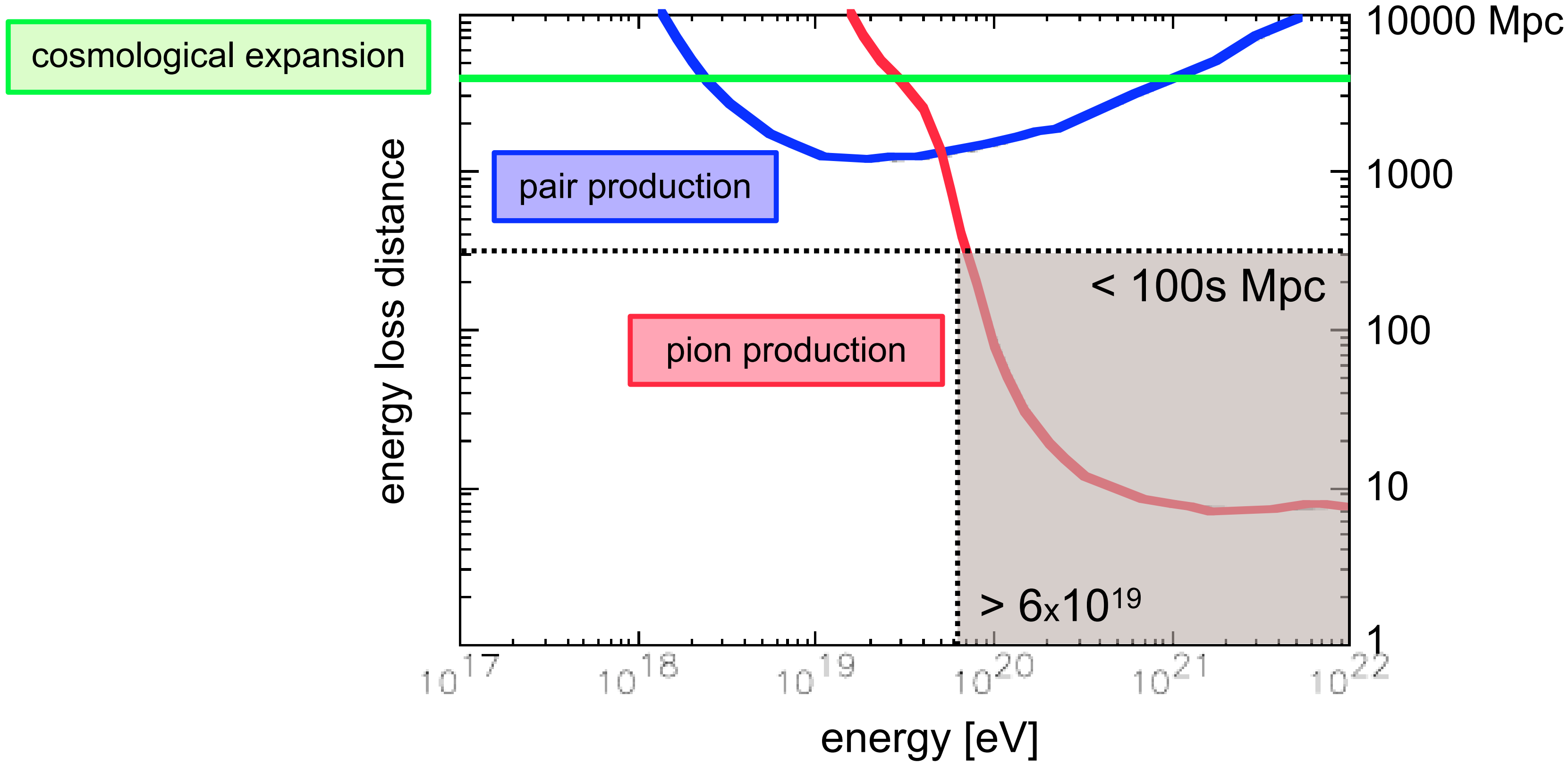
t_{acc} depends on acceleration mechanism
t_{esc} depends on magnetic field
t_{loss} depends on environment

⇒ requires an object by object study...

Norman et al. 95

... some bursting sources and radiogalaxies are promising candidates...

Propagation: energy losses



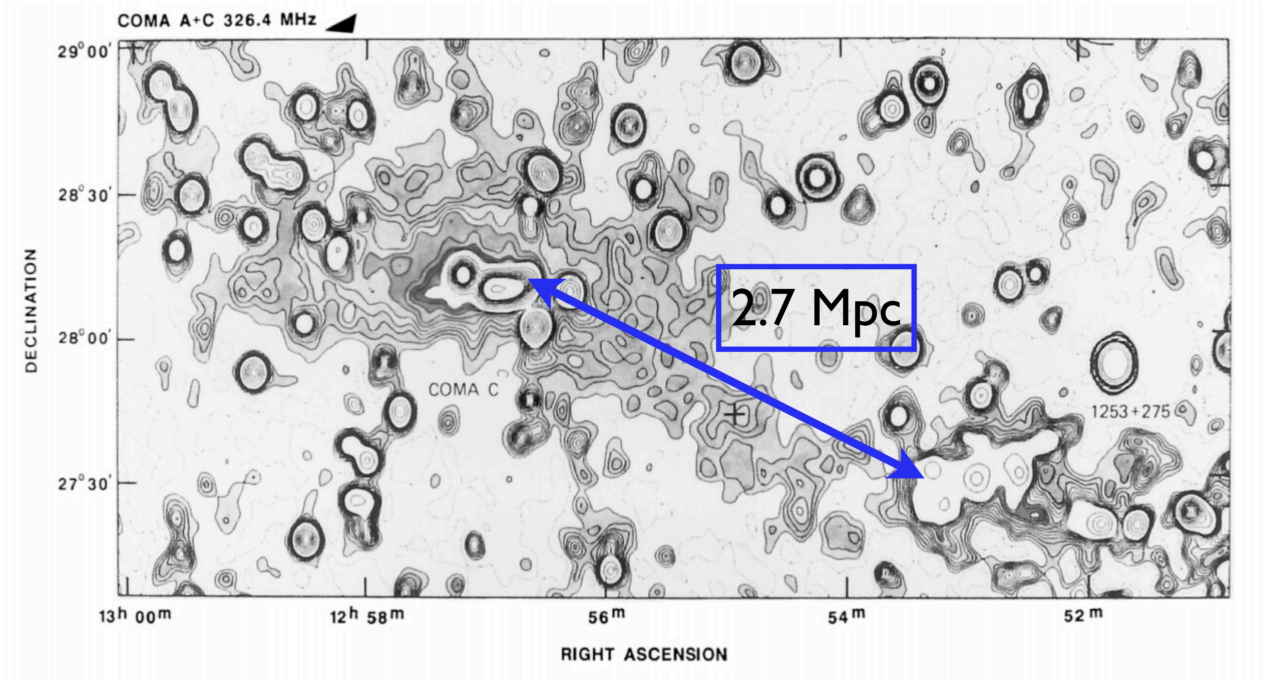
ultrahigh energy particles interact with CMB photons

particles loose energy

they cannot propagate more than some 100s Mpc before losing their energy

sources cannot be much farther than some 100s Mpc

Propagation: influence of magnetic fields

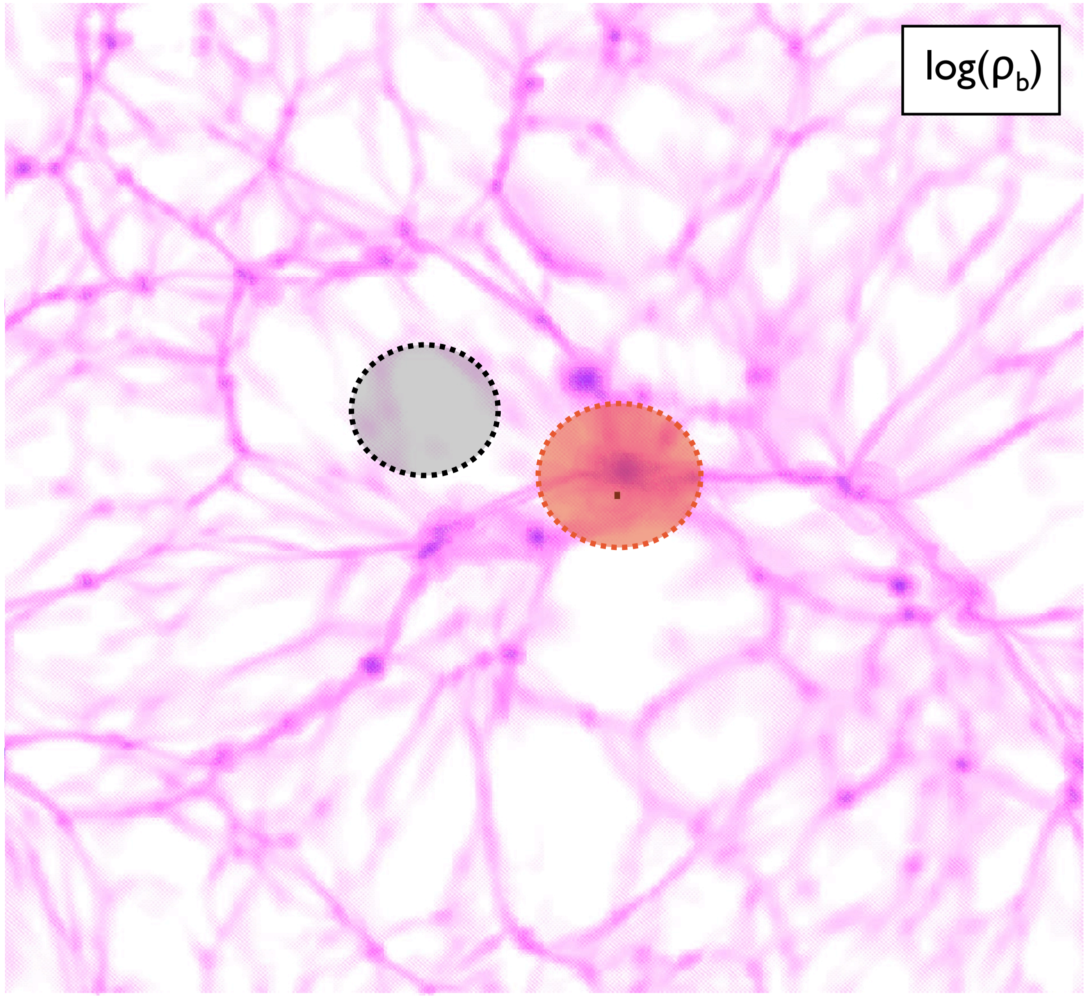


Kim et al. (1989)

possible origins

primordial origins	high redshift	low redshift
inflation, phase transition, decoupling of photons and neutrinos, reionization	same mechanisms as at low redshift, but the magnetic pollution is more largely spread	*ejection* from galactic winds and AGN jets *amplification* by compression, shear, turbulent motions, mergers

Propagation in a magnetized universe



Sigl, Miniati, Ensslin 03

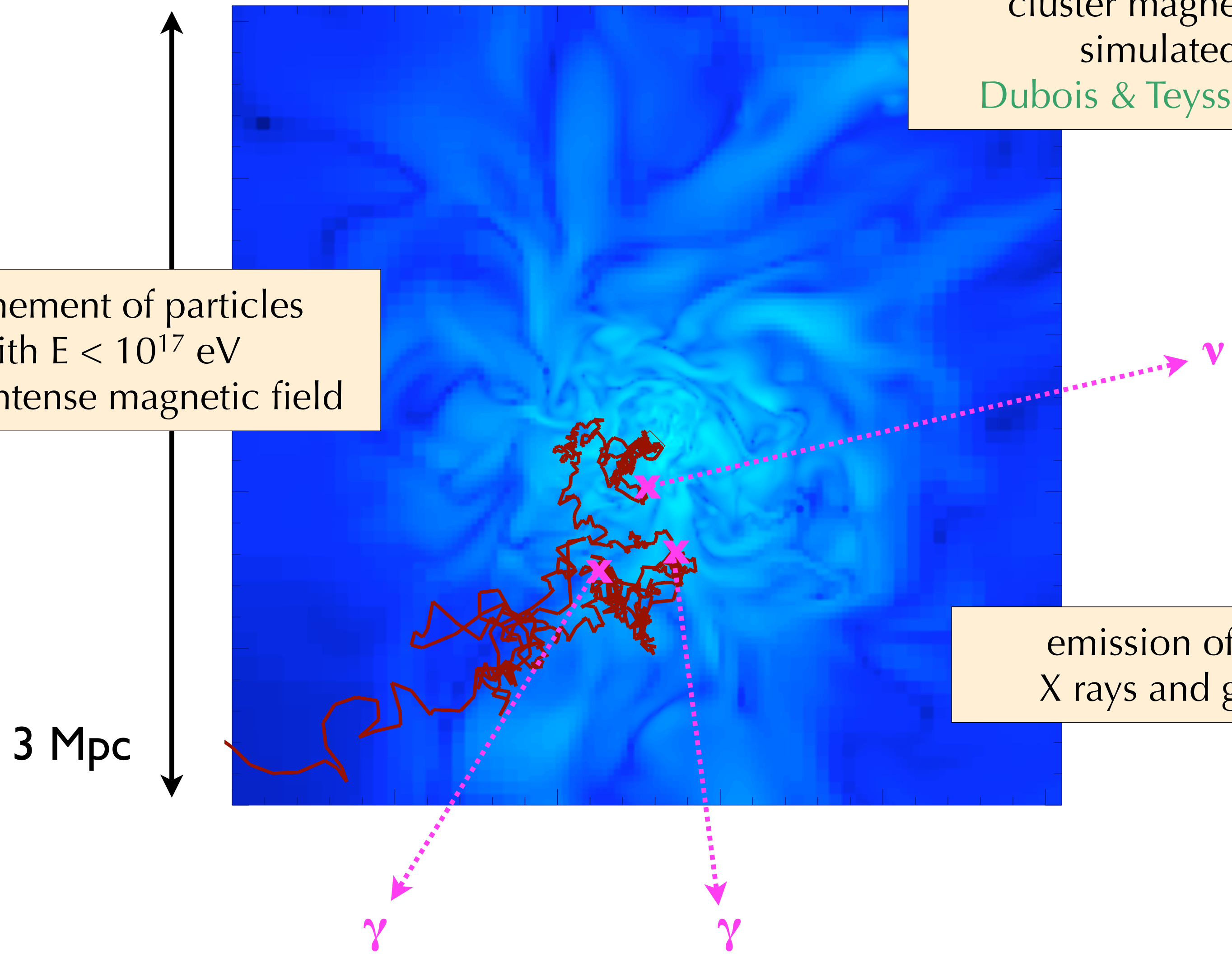
Extragalactic magnetic fields are likely distributed as the baryonic gas

Depending on energy and magnetic field strength, propagation can be **nearly rectilinear**, **diffusive**, or **'semi-diffusive'**…

Propagation in a magnetized cluster of galaxies

cluster magnetic field
simulated by
Dubois & Teyssier (2008)

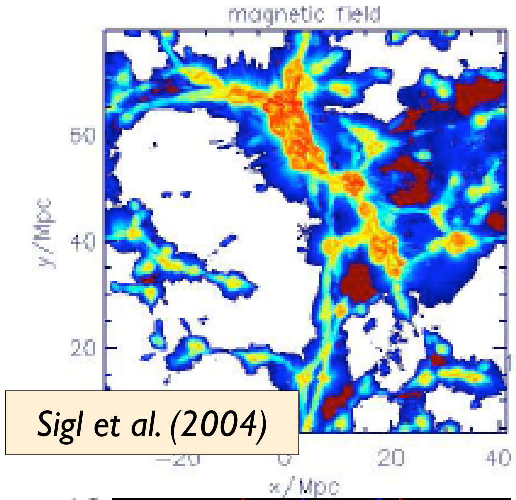
confinement of particles
with E < 10^{17} eV
due to intense magnetic field



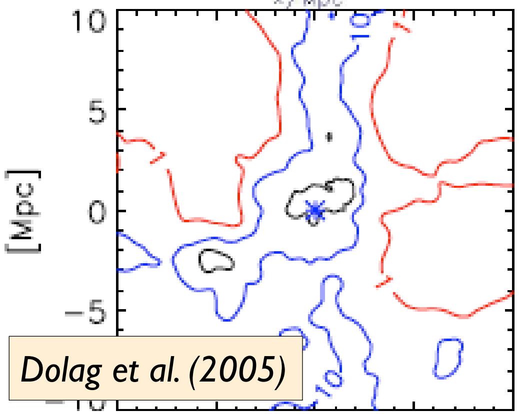
emission of neutrinos,
X rays and gamma rays

K.K., Murase, Nagataki, Allard, Aoi, in preparation

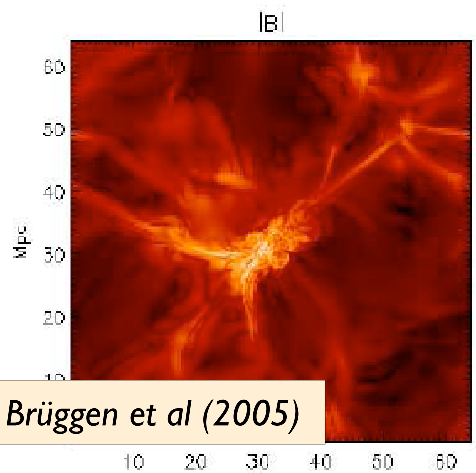
Propagation: numerical simulations of `realistic' B



Sigl et al. (2004)



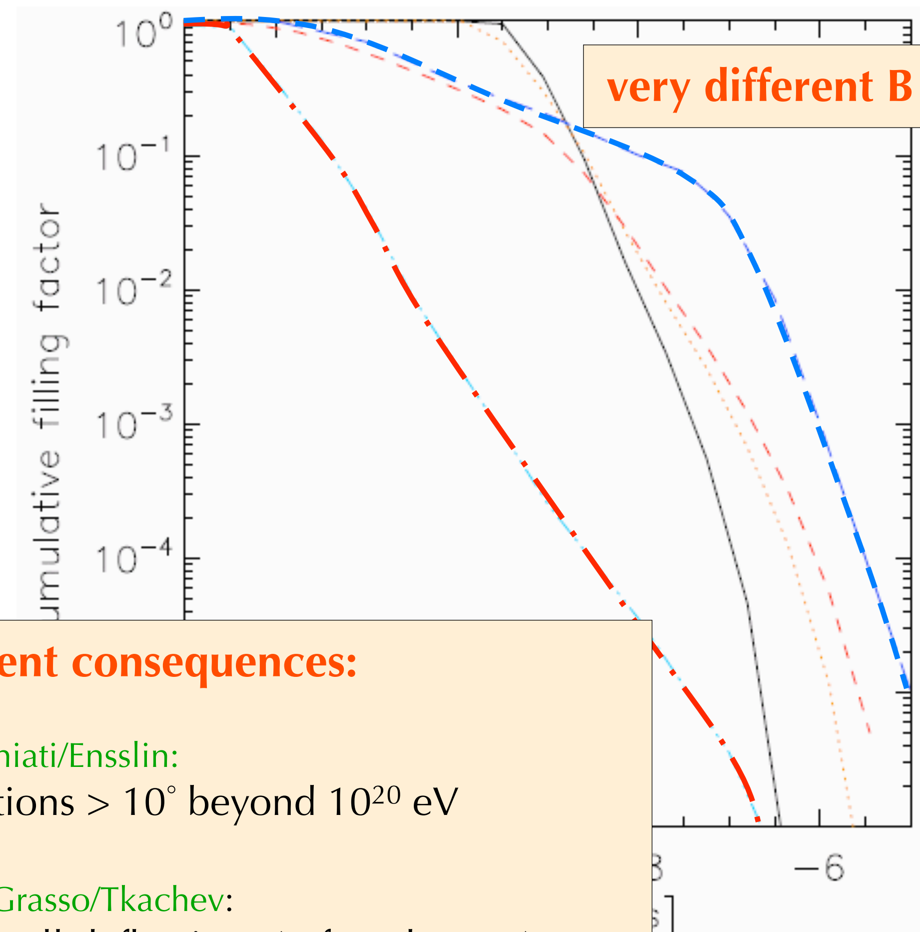
Dolag et al. (2005)



Brüggen et al (2005)

« exotic origin » : seeded in the early Universe (reionization and beyond)

Numerical simulations: Sigl/Miniati/Ensslin 04, Dolag/Grasso/Springel/Tkachev 04 have set up initial conditions for B at high z (z=20, uniform B) and followed its evolution through structure formation, renormalizing the present-day B so as to match the observed value in clusters



very different B configurations

different consequences:

Sigl/Miniati/Ensslin:
deflections > 10° beyond 10^{20} eV

Dolag/Grasso/Tkachev:
very small deflections (< few degrees)

K.K. & Lemoine 2008a

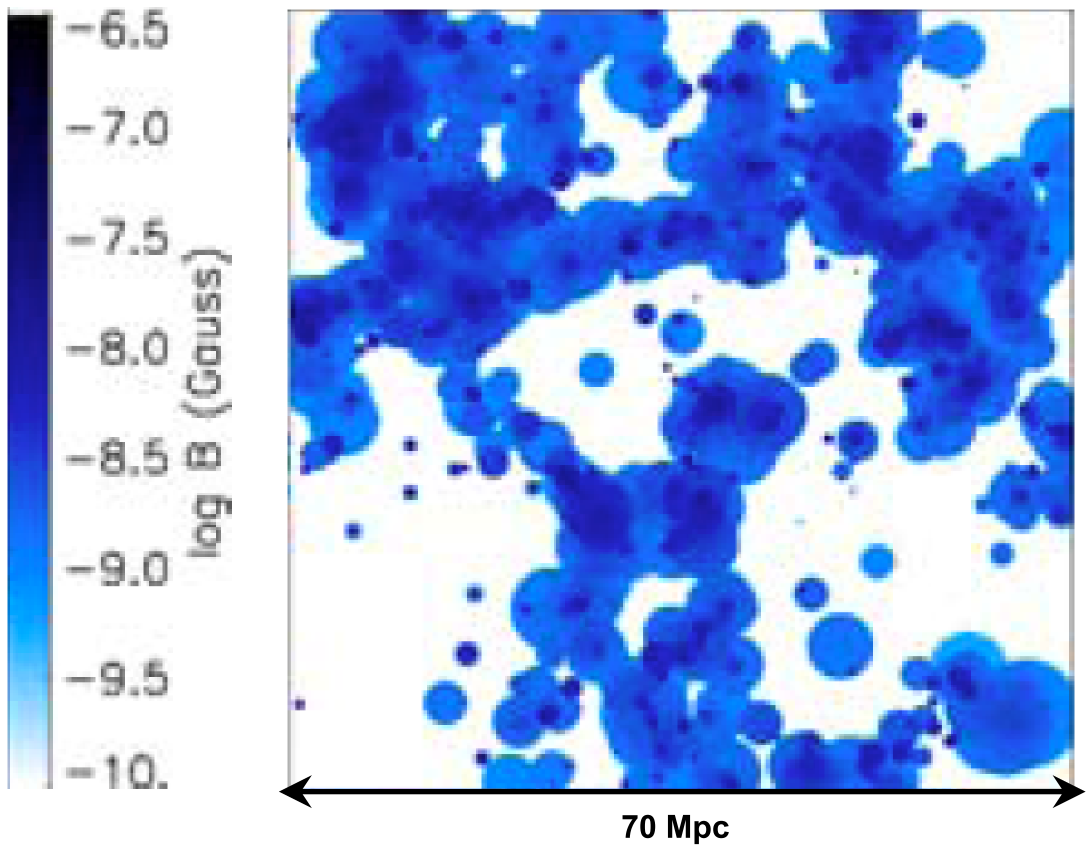
Propagation: numerical simulations of `realistic' B

more standard : extra-galactic magnetic fields produced in galaxies and ejected

… a connection with other astrophysical problems:

radio-galaxies : feedback on the intra-cluster medium?

galactic winds: enrichment of the intergalactic medium in metals?

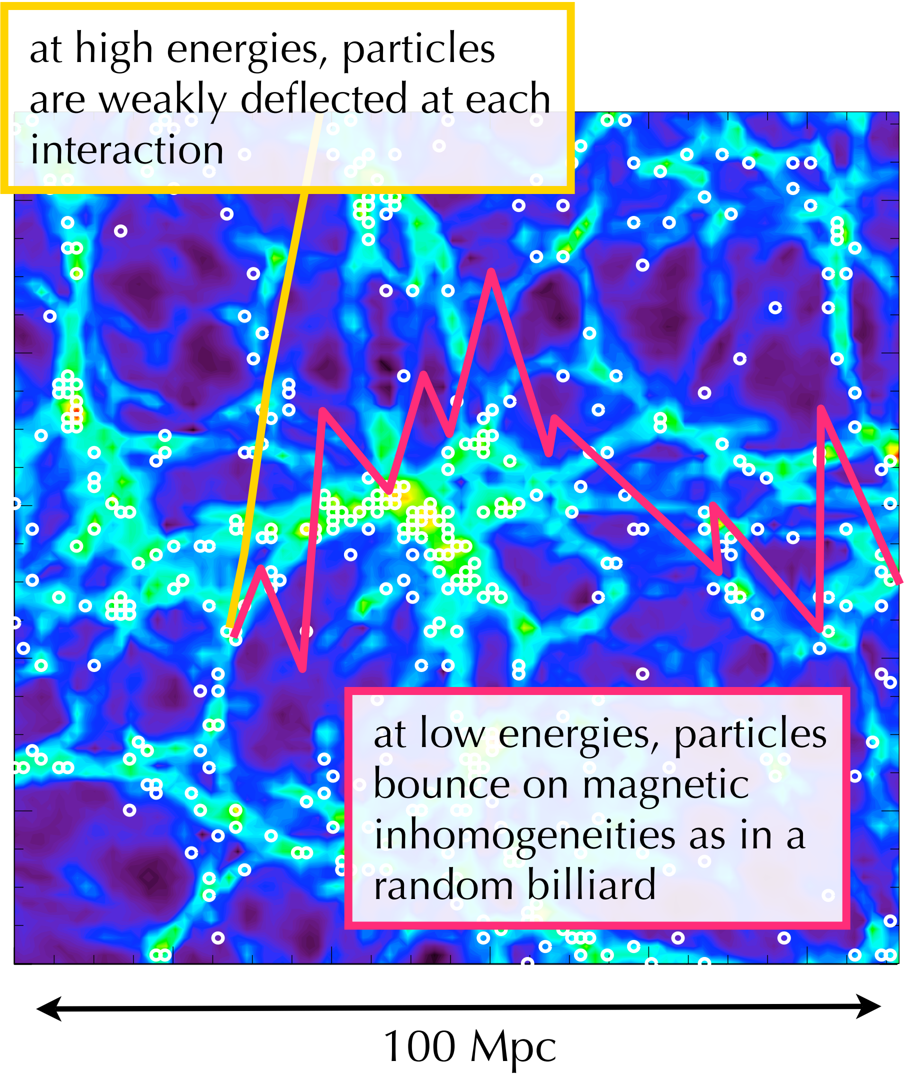


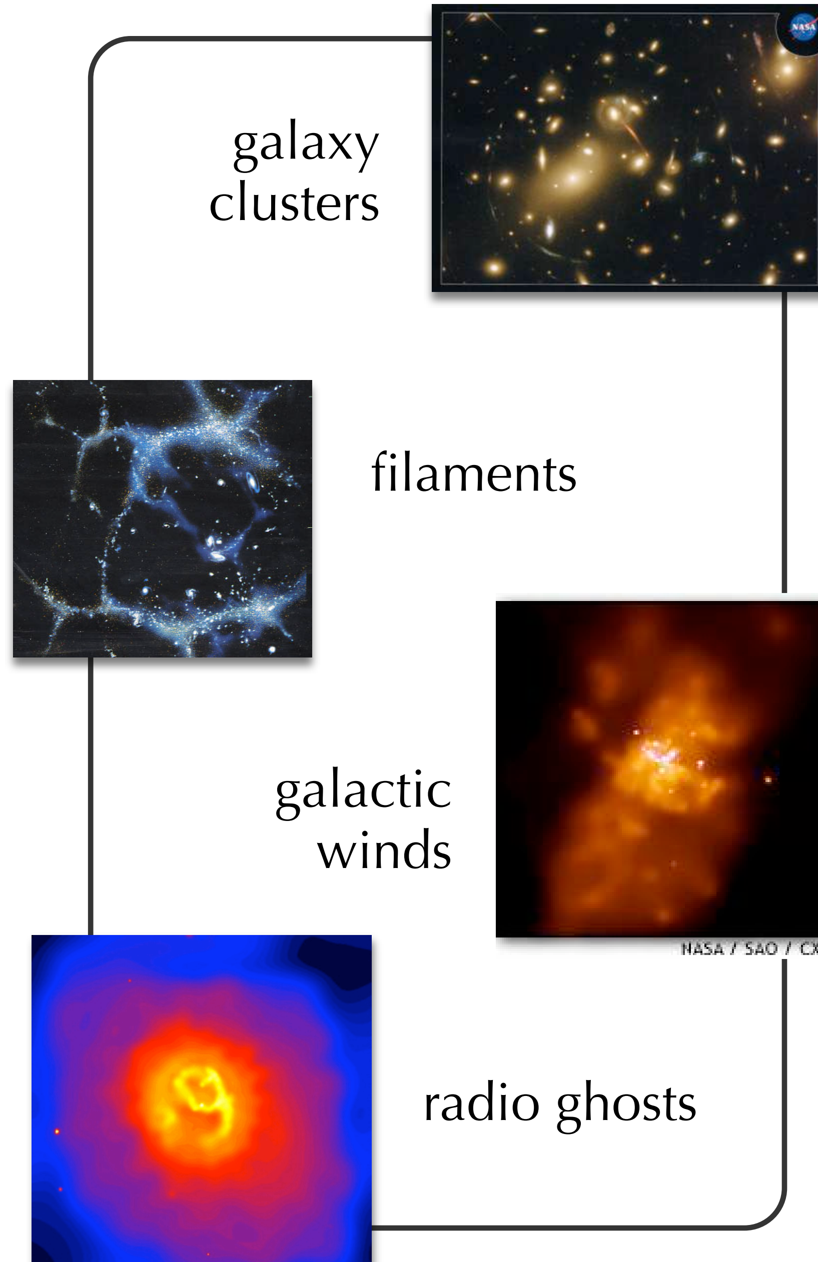
Bertone, Vogt, Ensslin 06:
pollution by magnetized galactic winds from small starburst galaxies.

typical wind radius ~ 1 Mpc
with B ~ $10^{-8} - 10^{-7}$ G

percolation picture, with most of the enrichment in filaments and walls of large scale structure

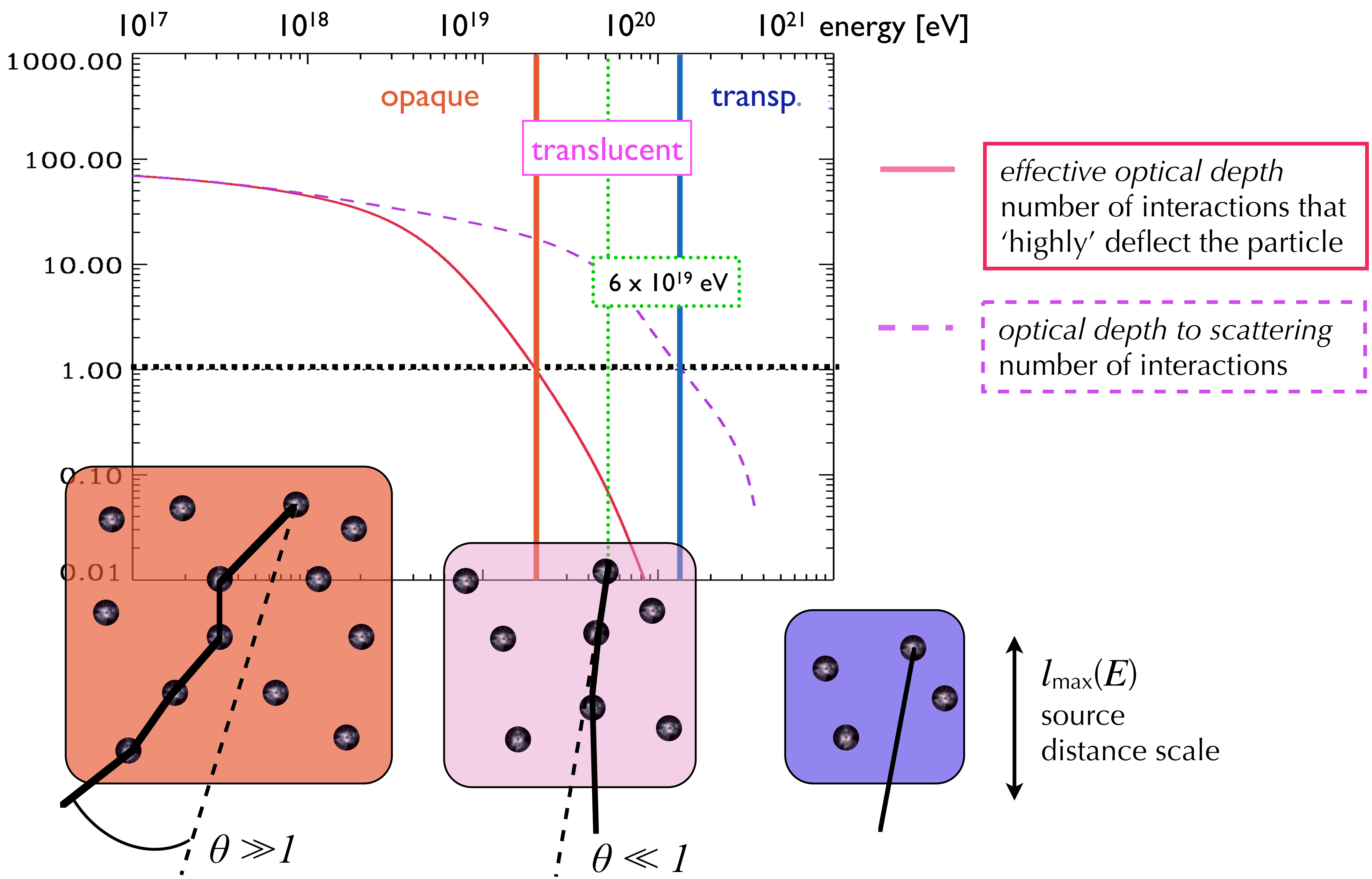
Another view of extragalactic magnetic fields for UHECR



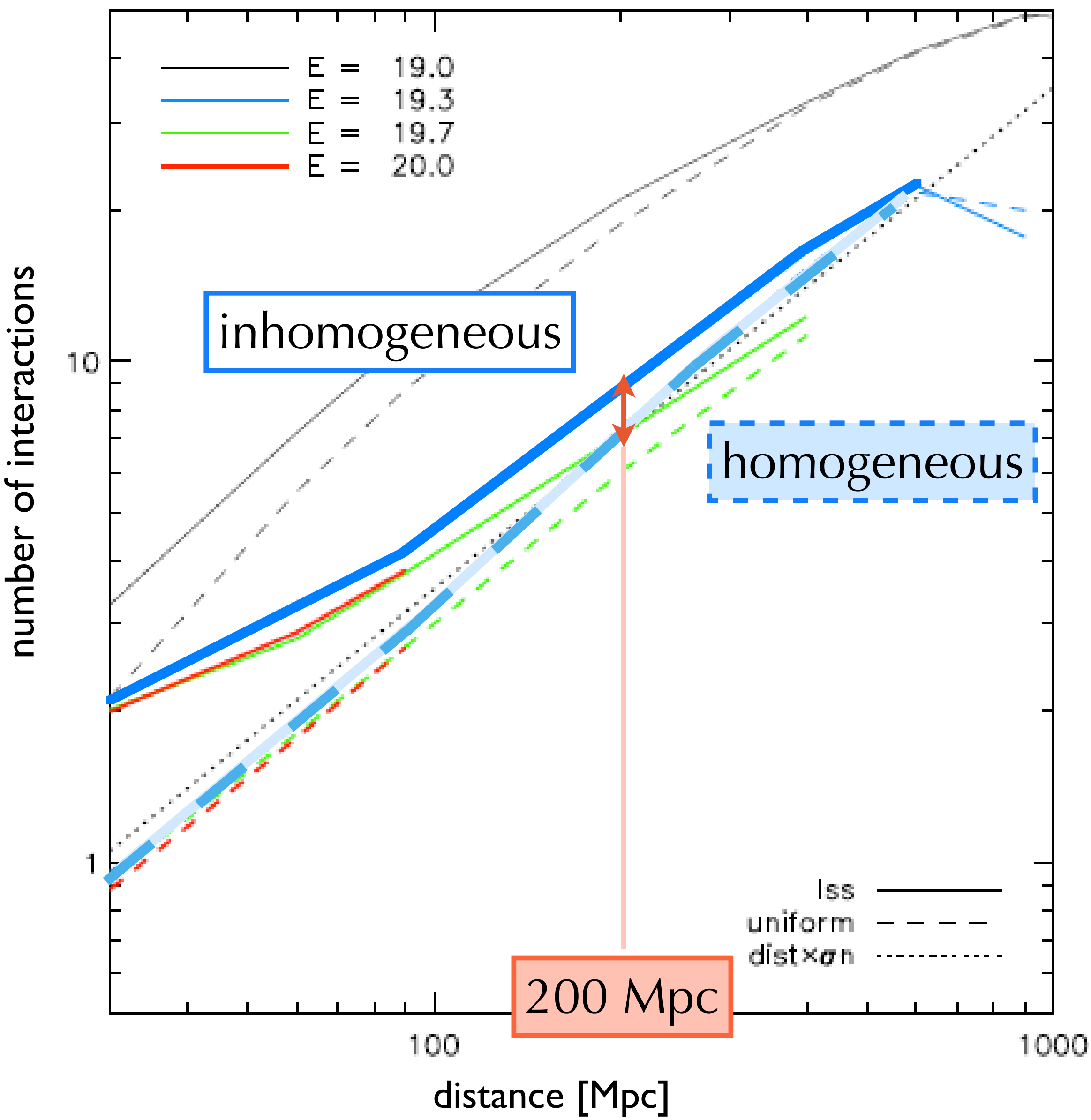


K.K. & Lemoine 2008b

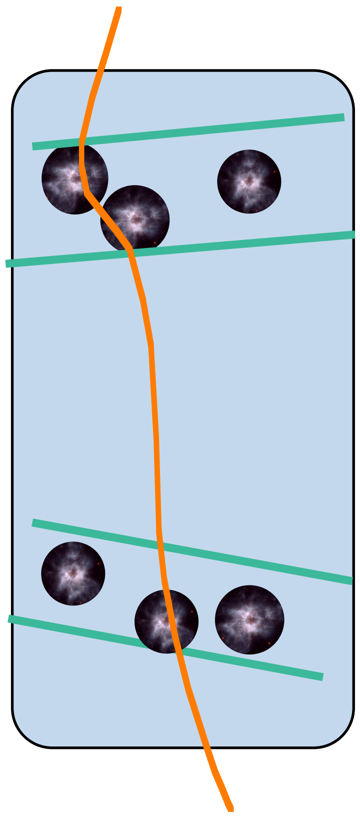
Optical depth to scattering



Inhomogeneous distribution



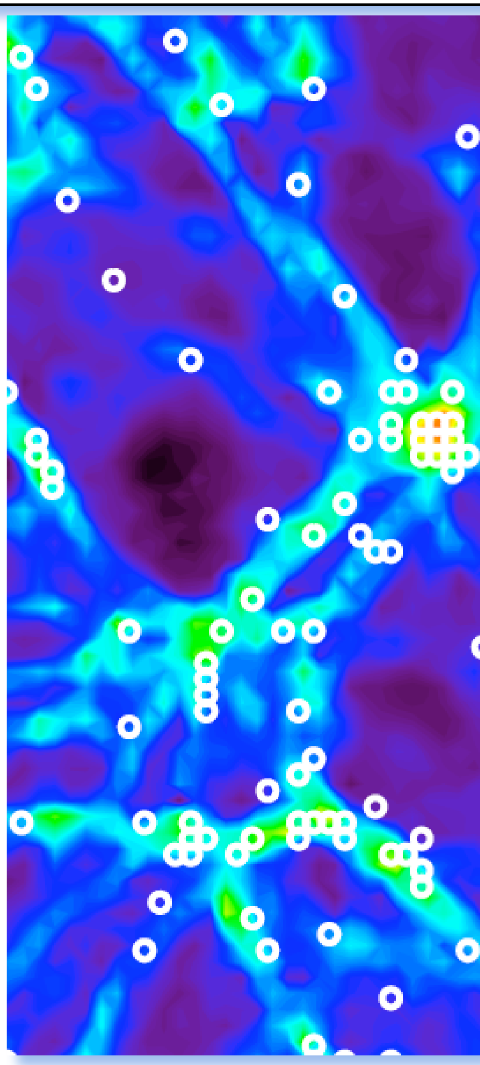
the number of interactions in filaments compensates the travelled voids

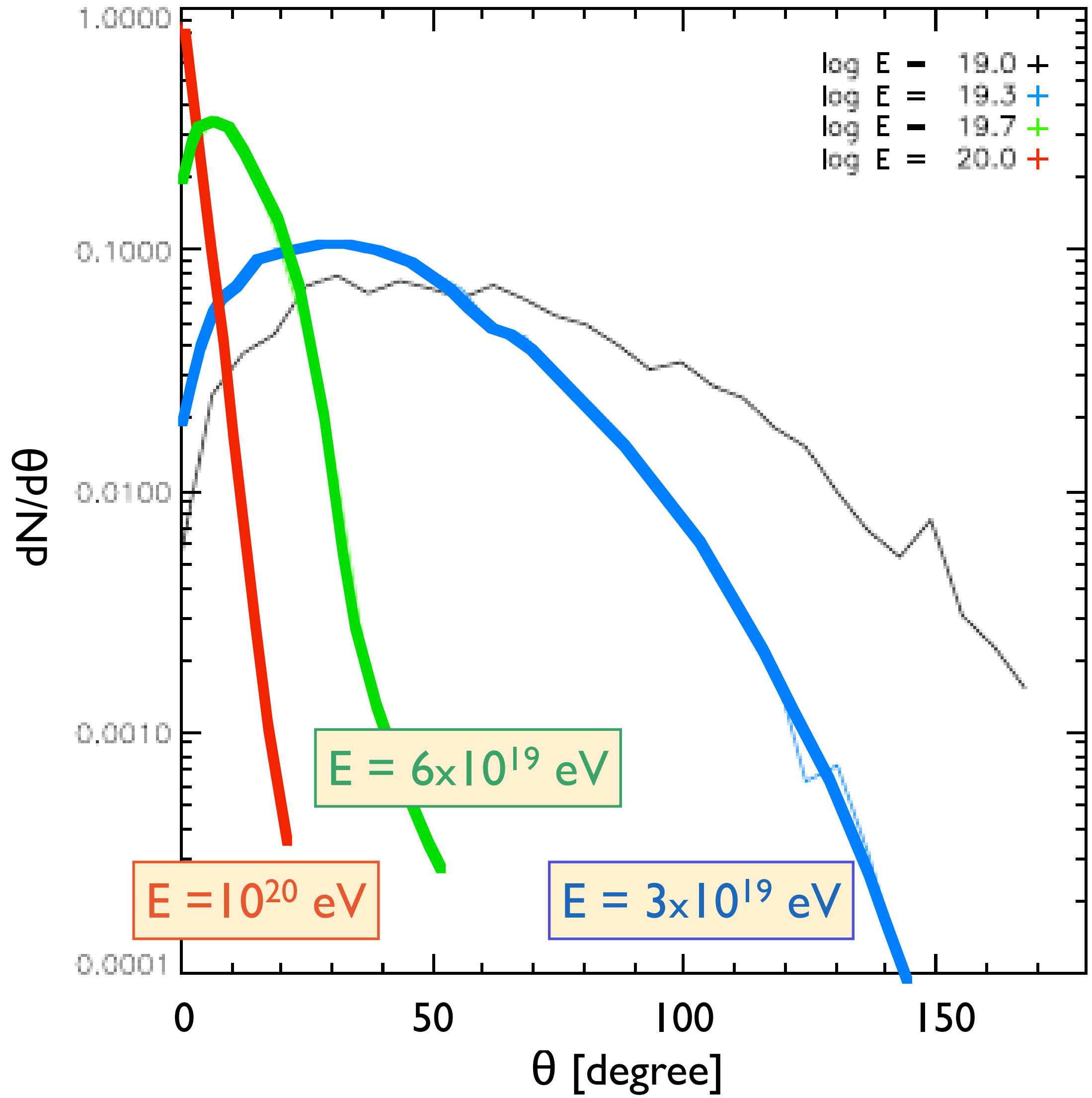


beyond some 100s of Mpcs, the propagation becomes insensitive to inhomogeneous distribution

Inhomogeneous distribution

numerical simulations

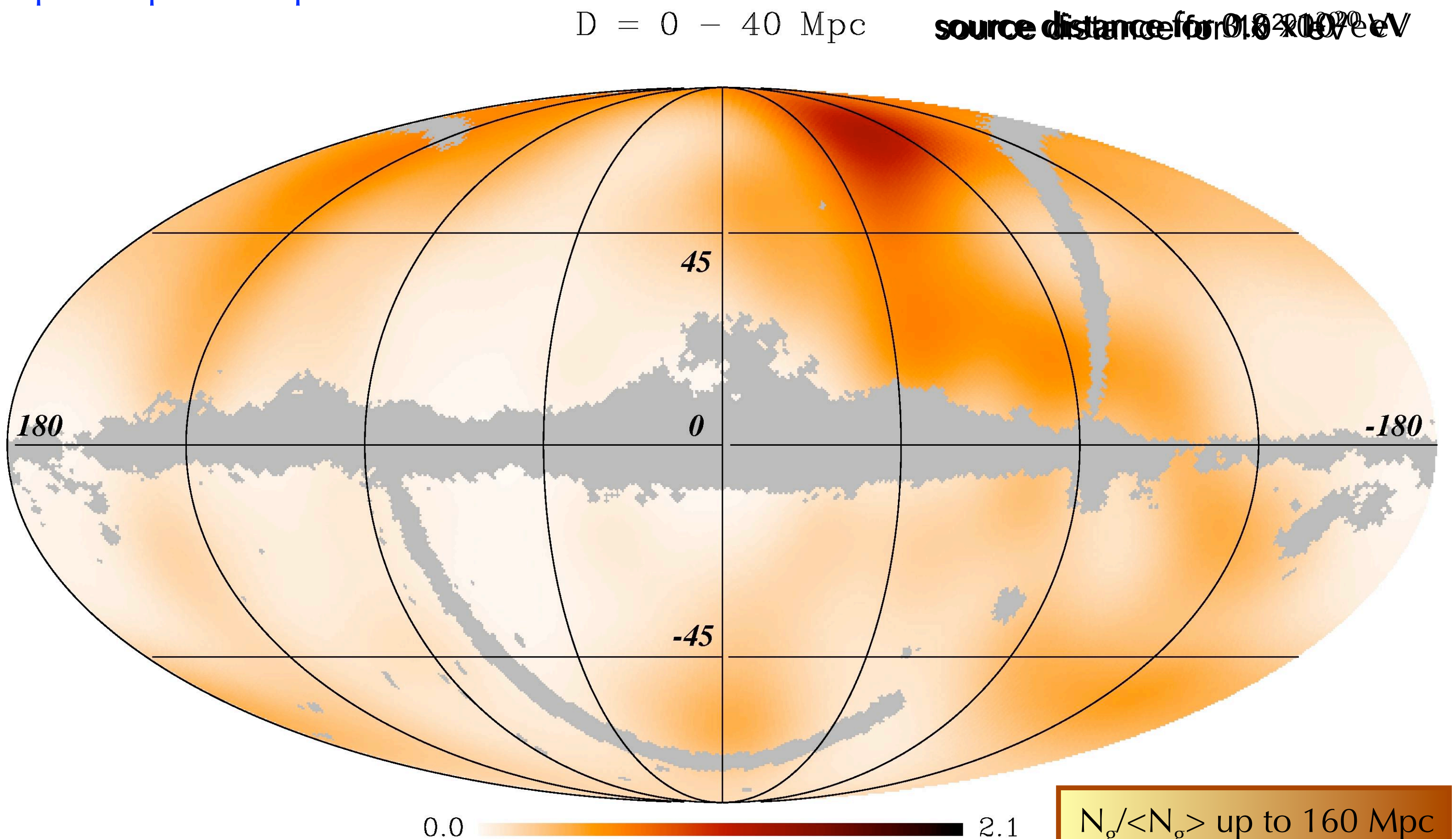




Maps of optical depth

Total deflection angle: $\delta\alpha^2 = \frac{\tau}{3}\delta\theta_i^2$

Maps of optical depth:



$N_g/\langle N_g \rangle$ up to 160 Mpc

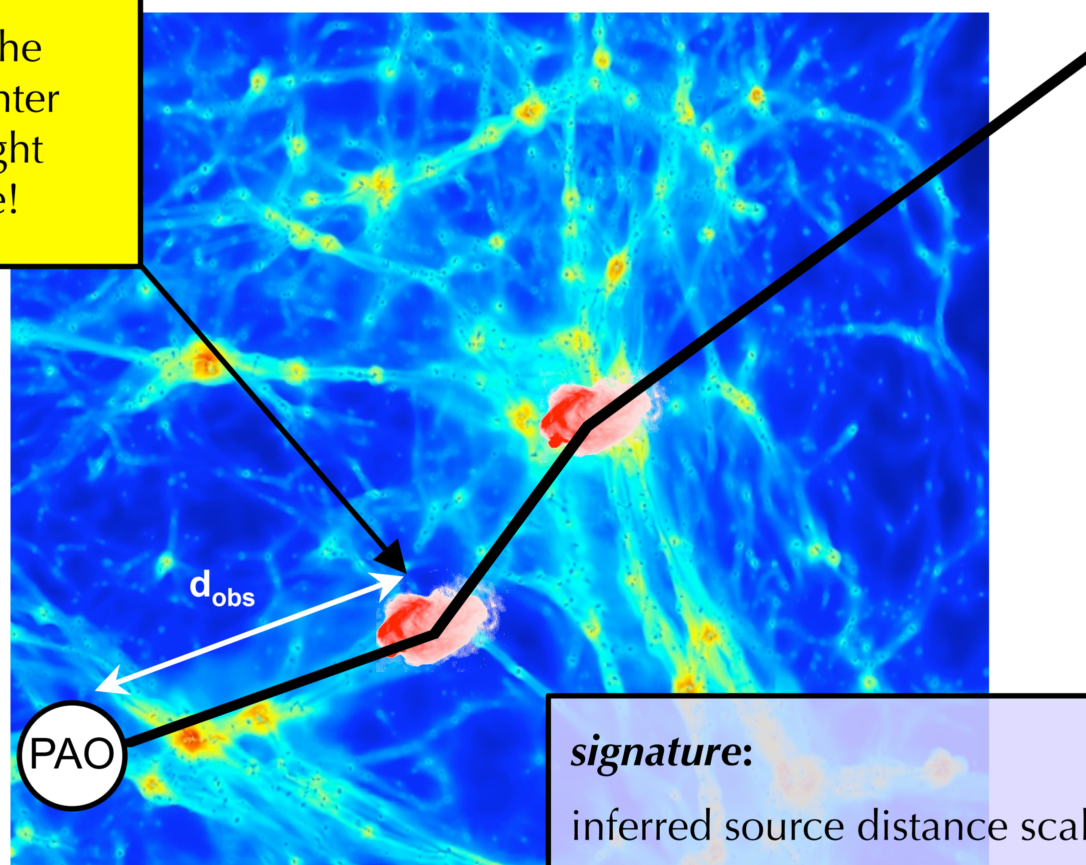
$$\tau(l_{\rm gal}, b_{\rm gal}) = \langle\tau\rangle_{160\,{\rm Mpc}} \frac{N_{\rm g}}{\langle N_{\rm g}\rangle}$$

τ varies from <1 to ~ 1 for typical parameters

Source or scattering center?

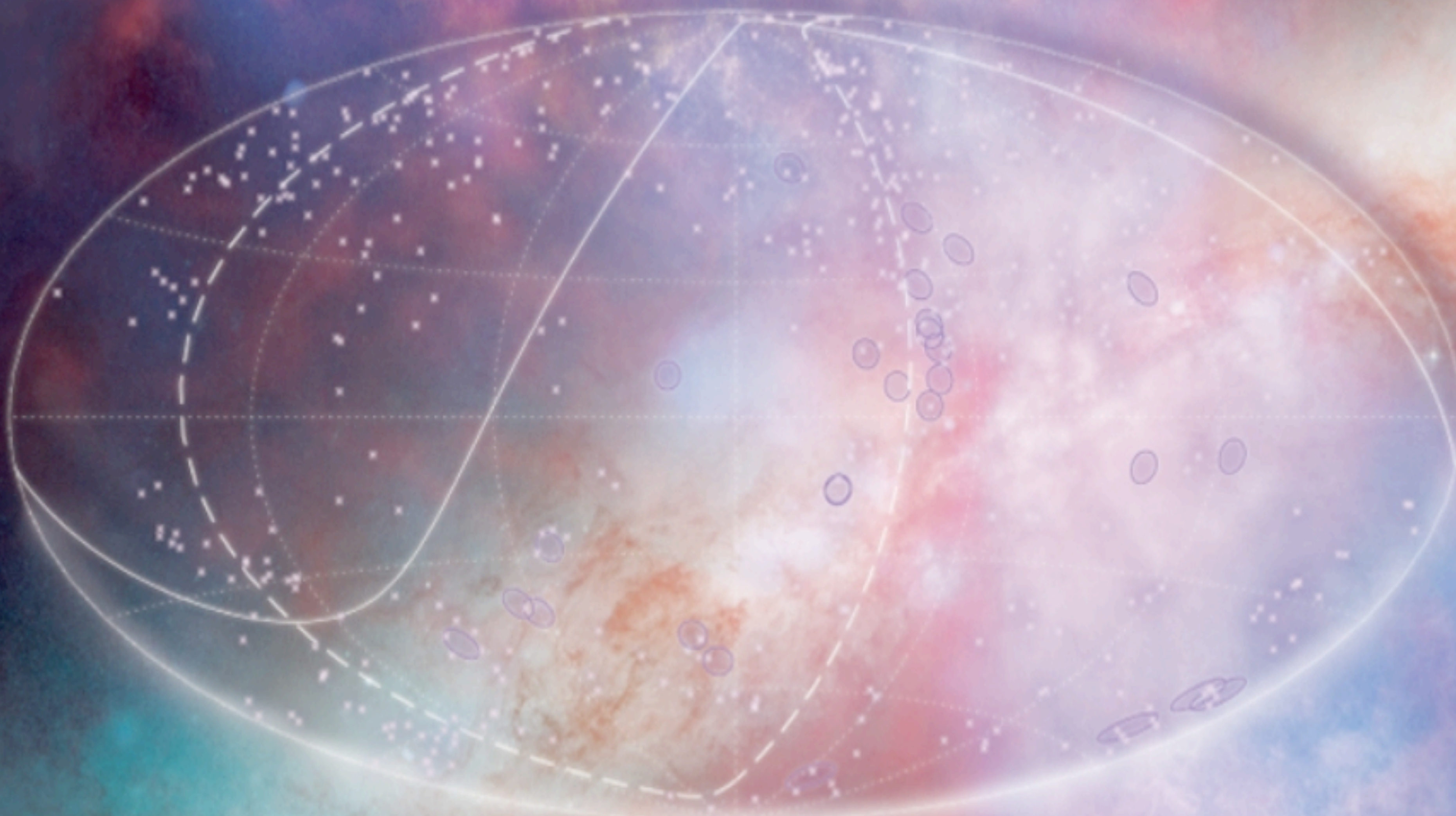
sources of UHECRs and scattering centers share a similar property:
large regions of intense magnetic field

do not mistake the last scattering center on the line of sight with the source!

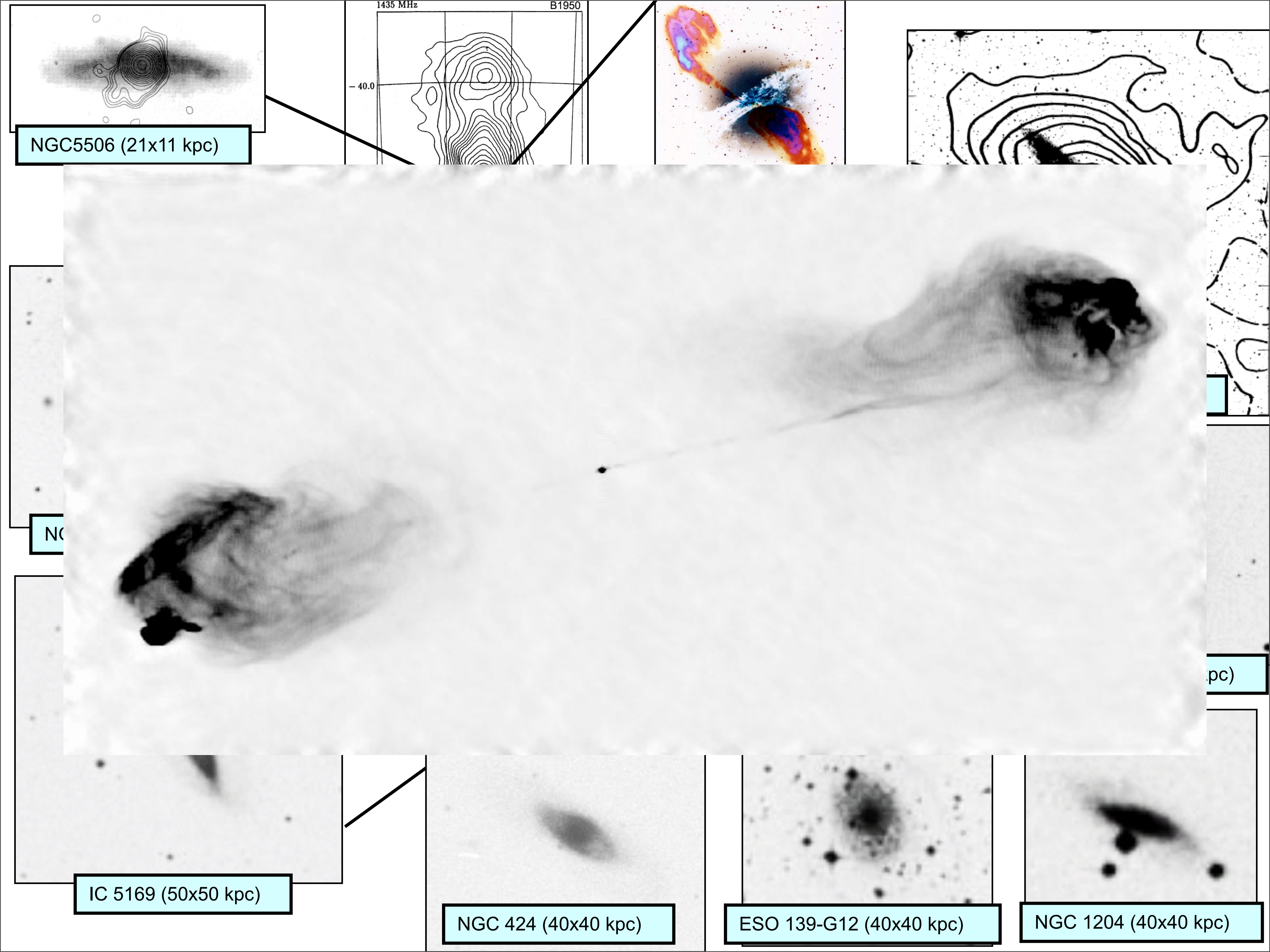


***signature*:**

inferred source distance scale d_{obs}
smaller than expected distance scale ~ $l_{max}(E)$



The PAO has detected a highly significant correlation of the arrival directions of cosmic rays with energy $E > 5.7\ 10^{19}$ eV with the known AGN within 75Mpc…


NGC5506 (21x11 kpc)
1435 MHz
B1950
− 40.0
IC 5169 (50x50 kpc)
NGC 424 (40x40 kpc)
ESO 139-G12 (40x40 kpc)
NGC 1204 (40x40 kpc)

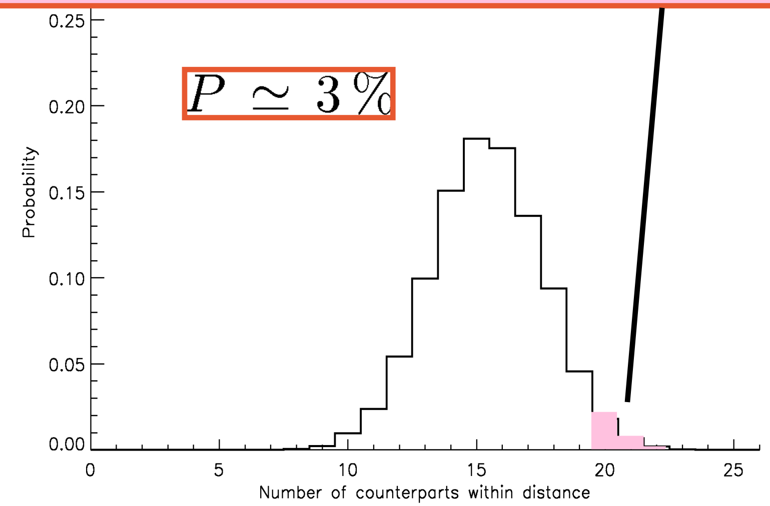
PAO: problem with the source distance scale

$$F(<l) = n_{\rm source} \dot{N}_{\rm UHECR} l$$

→ **source distance scale ~ l_{max}(E)**

~ 200 Mpc at 6×10^{19} eV

Probability of seeing 20+ events out of 27 above 6×10^{19} eV from within 75Mpc:



→ PAO: inferred source distance scale appears smaller than expected source distance scale

Three possibilities:

1. PAO energy scale is underestimated by ~ 30%
2. a bias is introduced from the PAO prescription
3. **PAO is imaging the last scattering surface…**

Source or scattering center?

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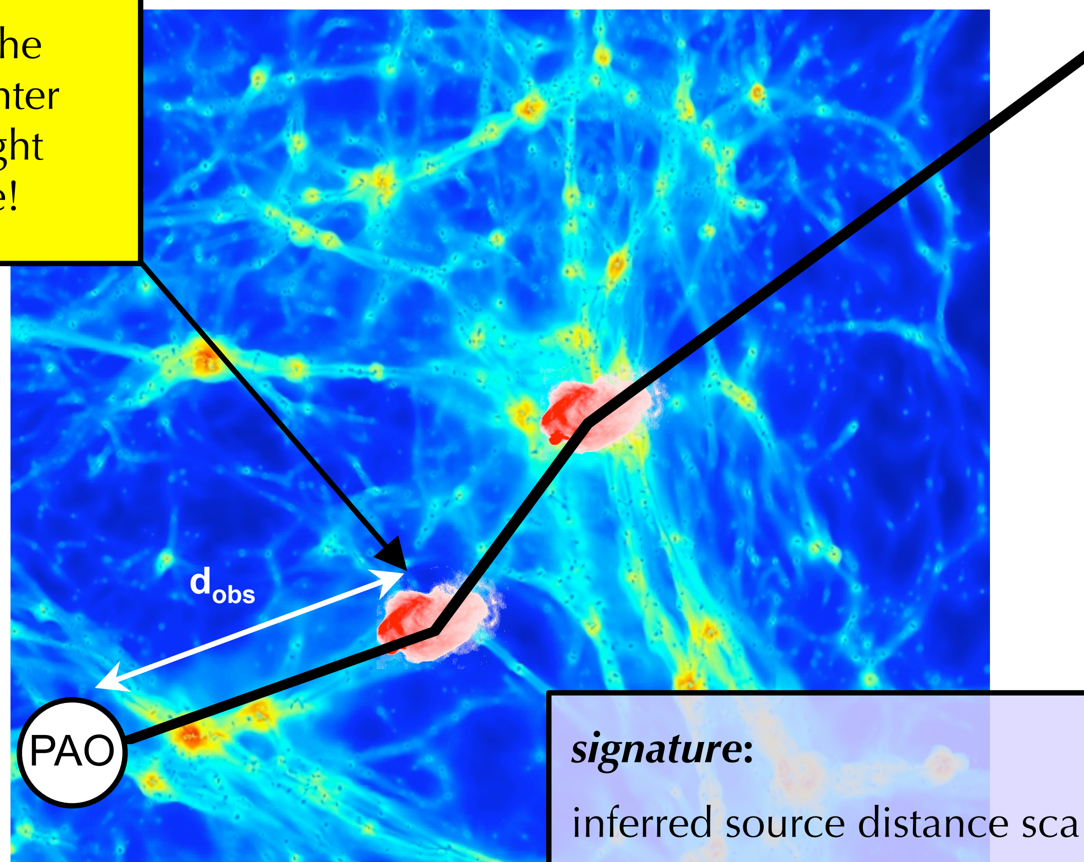


***signature*:**

inferred source distance scale d_{obs} smaller than expected distance scale ~ $l_{max}(E)$

Fraction of contaminated events

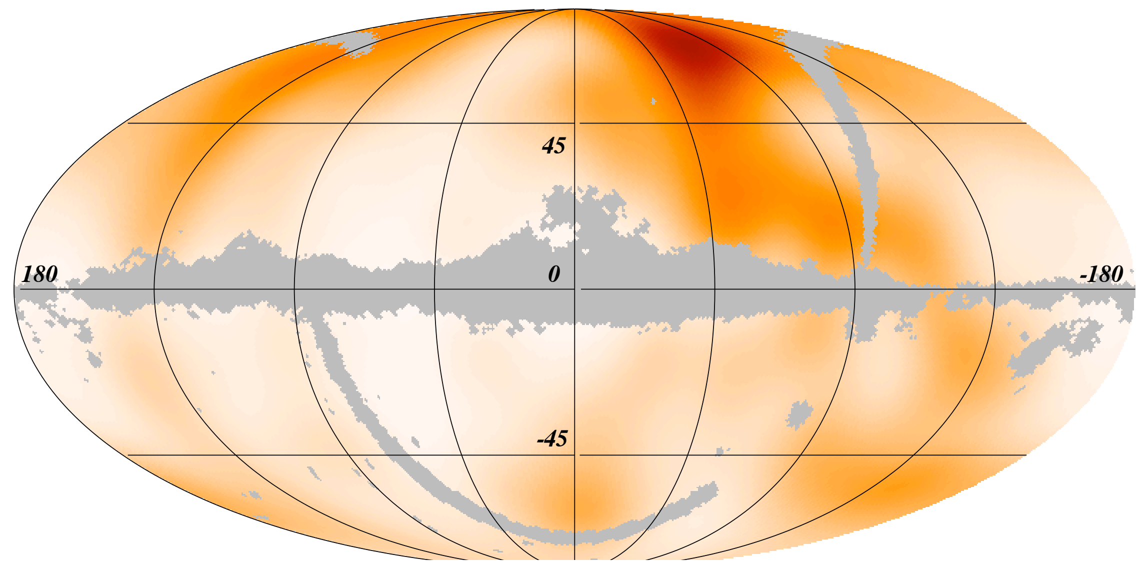
fraction of background galaxies (= source within 200 Mpc) situated at less than 3° from an AGN used by Auger:

for 27 events

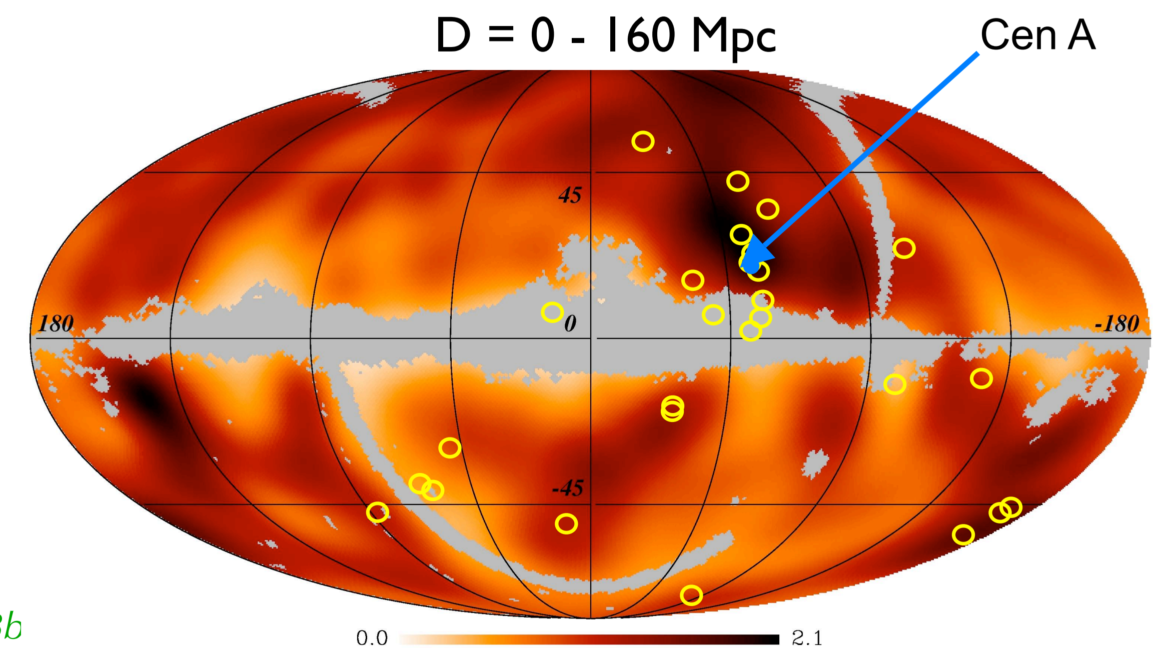
$\delta\alpha = 0$ f ~ 31%
$\delta\alpha = 3^\circ$ f ~ 48%
$\delta\alpha = 6^\circ$ f ~ 44%

correlation should not exceed 50%

D = 0 - 40 Mpc



D = 0 - 160 Mpc



K.K. & Lemoine 08b

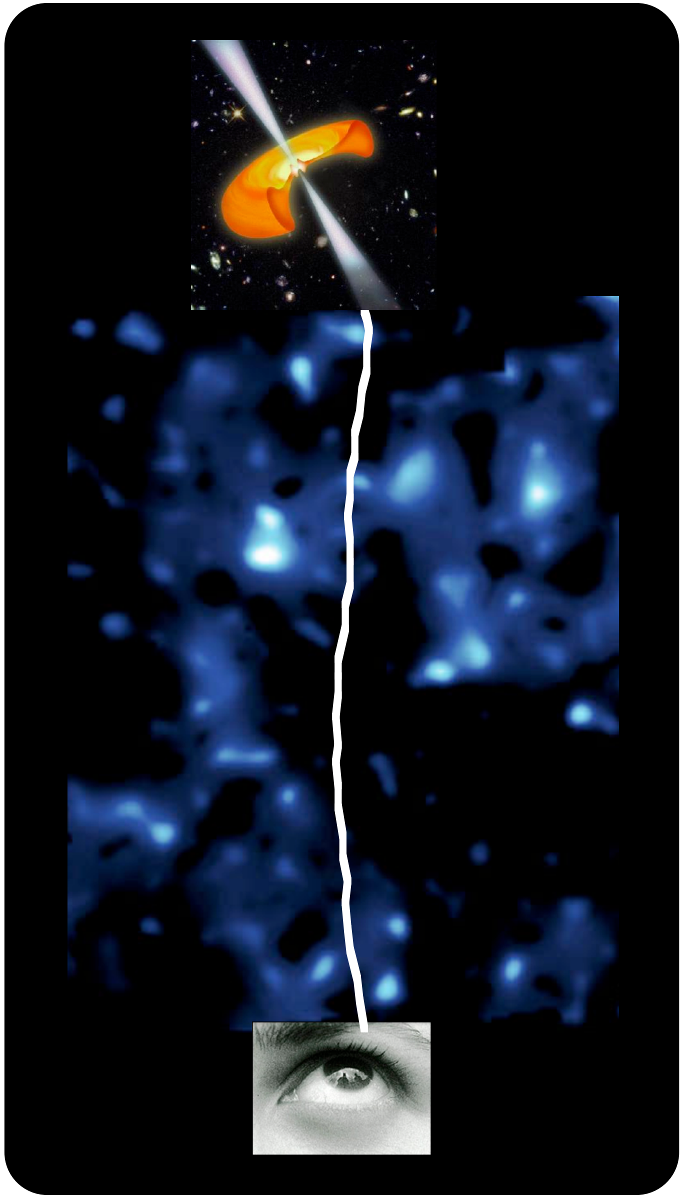
The special case of GRBs

GRBs: evanescent sources

the Universe is magnetized

time delay when charged particle propagates through it δt

source is absent in arrival direction (already extinguished)



The special case of GRBs

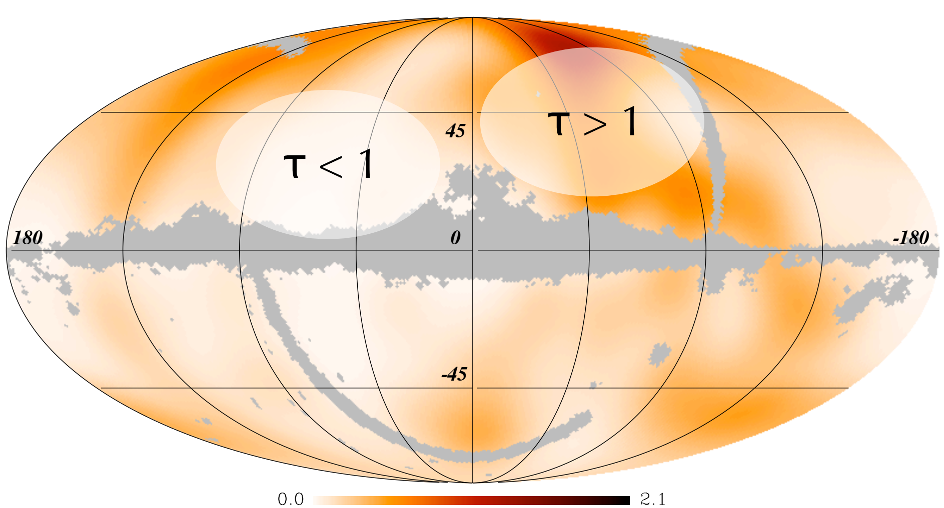
UHECR experiments: 45°of sky over 10 years

cosmic rays are `invisible'
unless
something delays randomly their arrival time

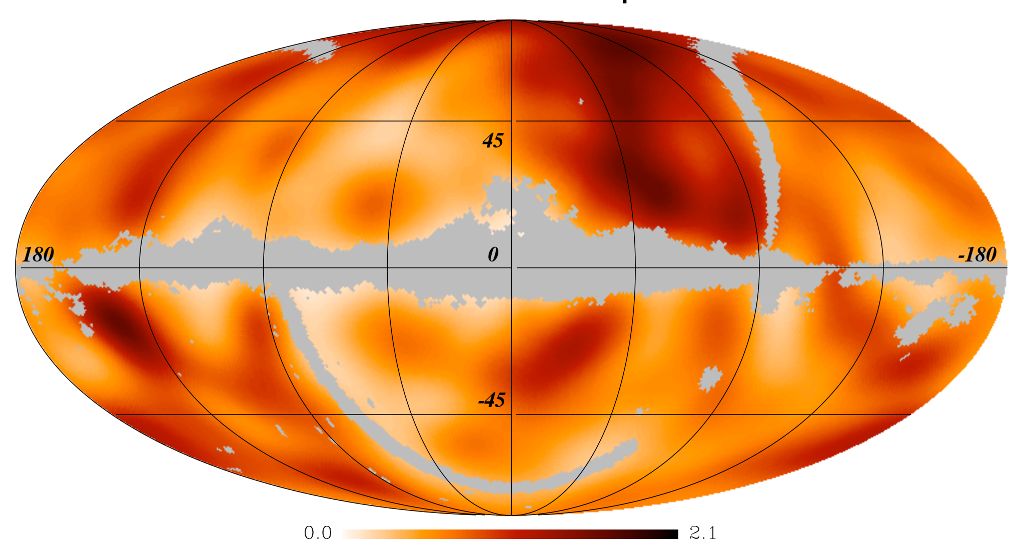
magnetic fields
random energy losses
scattering centers

if GRB are sources of UHECR:
the correlation with the foreground density is artificially enhanced due to non-detection of GRB if $\tau < 1$)

D = 0 - 40 Mpc



D = 0 - 120 Mpc



Interpretation of PAO results

The AGN seen by Auger are coincidences: sources are distributed as the large scale structures

The magnetic deflections induced by scattering centers are of a few degrees, depending on the direction.

The source is located within a few Mpc, but invisible: why?

A possible guess: UHECRs are produced in bursting sources (GRBs, magnetars…)

[Usov 95, Vietri 95, Waxman 95, Aarons 2003, Farrar & Gruzinov 2008]

A consequence: no counterpart will ever be found: photons have passed by Argentina 10^4 years ago

no high energy gamma-ray, no neutrino, no gravitational wave will be seen from these sources

A test (?): detect the departure from a power law of the flux at > 1-3 10^{20} eV due to the small number of GRBs seen at those energies

Auger North?

(Waxman & Miralda-Escude 1996)

Conclusions

The search for the origin of UHECR is intimately related to:

high energy processes in powerful astrophysical objects
(and probably the physics of relativistic collisionless shock waves)

the distribution of cosmic magnetic fields on the largest scales
(which itself is related to the origin of astrophysical magnetic fields)

Extragalactic magnetic fields play a crucial role:

particles of energy 10^{18}-10^{19} eV diffuse in the extragalactic magnetic field ⇒ signatures on the spectrum

at the highest energies, magnetized scattering centers may be mistaken with the source if one makes a blind search for counterparts

The search is not over:

the counterparts seen by the PAO are unlikely to be the source of UHECR

the PAO may be mistaking the counterparts with the last scattering centers

or, if the energy scale is underestimated (30%), or if there is a selection bias, the PAO may have located the invisible source within a few Mpc

in any case, the PAO opens up a new era of data acquisition...