Acceleration and propagation of ultra-high energy cosmic rays

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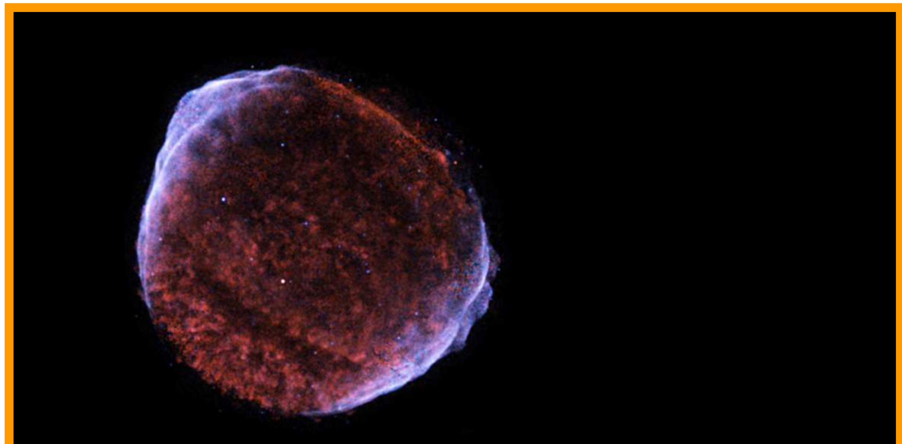
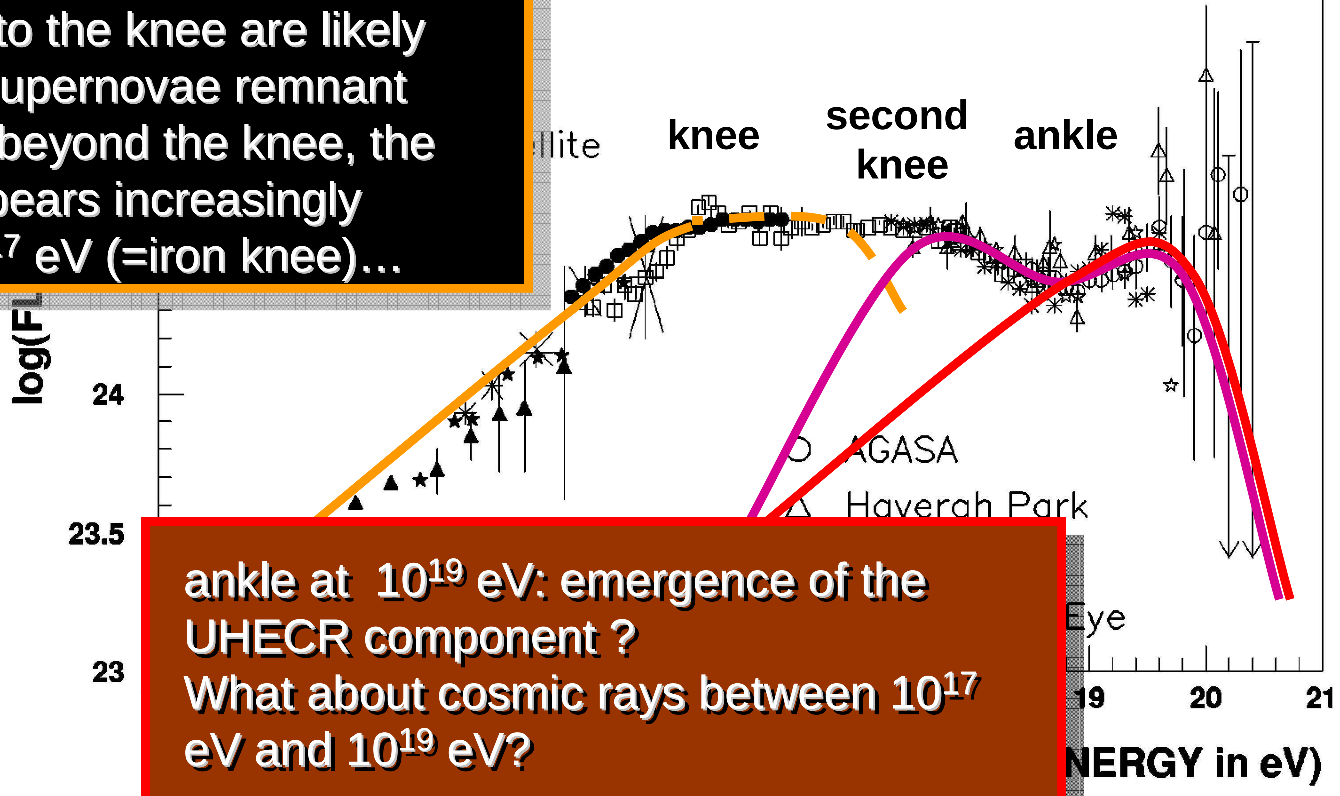
A modern view of the cosmic ray spectrum



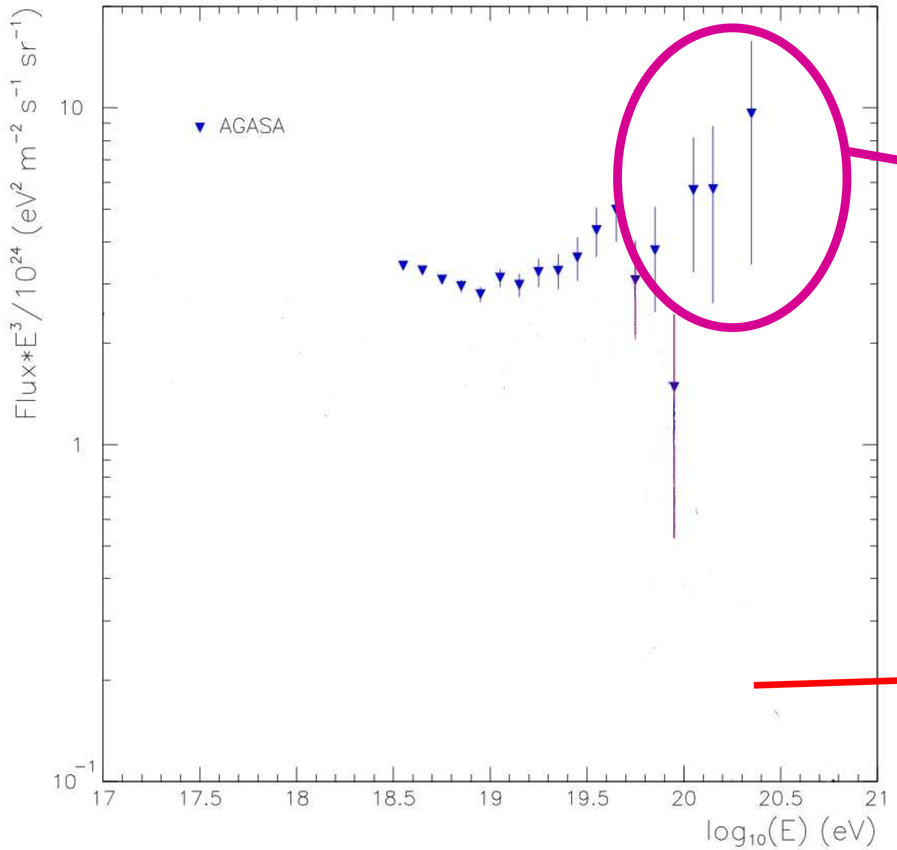
cosmic rays up to the knee are likely accelerated at supernovae remnant shock waves… beyond the knee, the composition appears increasingly heavier until 10^{17} eV (=iron knee)…

second knee at 10^{18} eV:
a controversial feature.
Does it represent the emergence of the UHECR component?
(Berezinsky et al.)



ankle at 10^{19} eV: emergence of the UHECR component ?
What about cosmic rays between 10^{17} eV and 10^{19} eV?

Zooming on ultrahigh energies



events beyond 10^{20} eV:
the mystery of 'trans-GZK' events…

GZK cut-off: Universe becomes opaque to particles with E > 6.10^{19}eV due to pion production on CMB photons

The GZK cut-off has been detected by the HiRes experiment in 2004…

- Fundamental questions:
  - **How to explain the existence of trans-GZK events ($\rightarrow$ new physics)?**
  - **Why is the source not seen in the arrival direction of the highest E event?**
  - **How to explain the acceleration of particles up to 10^{20} eV? In what source?**

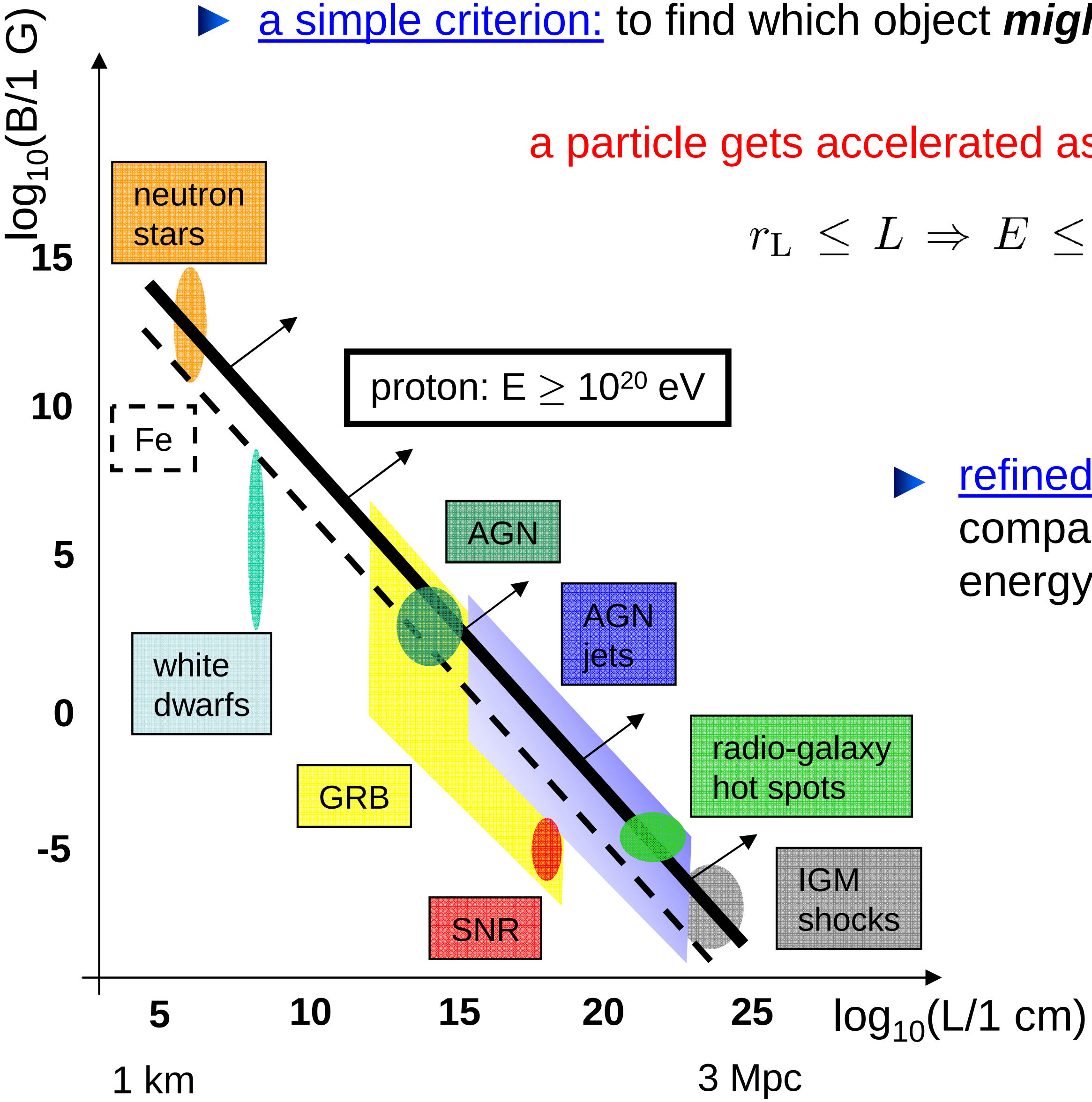
Acceleration – Hillas criterion

Hillas 84

▶ 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:

$$r_{\mathrm{L}} \leq L \Rightarrow E \leq 10^{20}\,\mathrm{eV}\, Z B_{\mu\mathrm{G}} L_{100\,\mathrm{kpc}}$$



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

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

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

… gamma-ray bursts and radiogalaxies are promising candidates…

Acceleration – Large scale shock waves

- Generic acceleration timescale: $$t_{\rm acc} = \mathcal{A}\, t_{\rm L}\,, \quad t_{\rm L} = \frac{Ec}{ZeB}$$
  - Fermi acceleration at non-relativistic shocks: $$\mathcal{A} \approx \frac{g(t_{\rm L}, l_{\rm coh})}{\beta_{\rm sh}^2} \gg 1$$

(g characterizes the diffusion coefficient, g$\gtrsim$ 1 in general, see Casse, M.L., Pelletier 02)

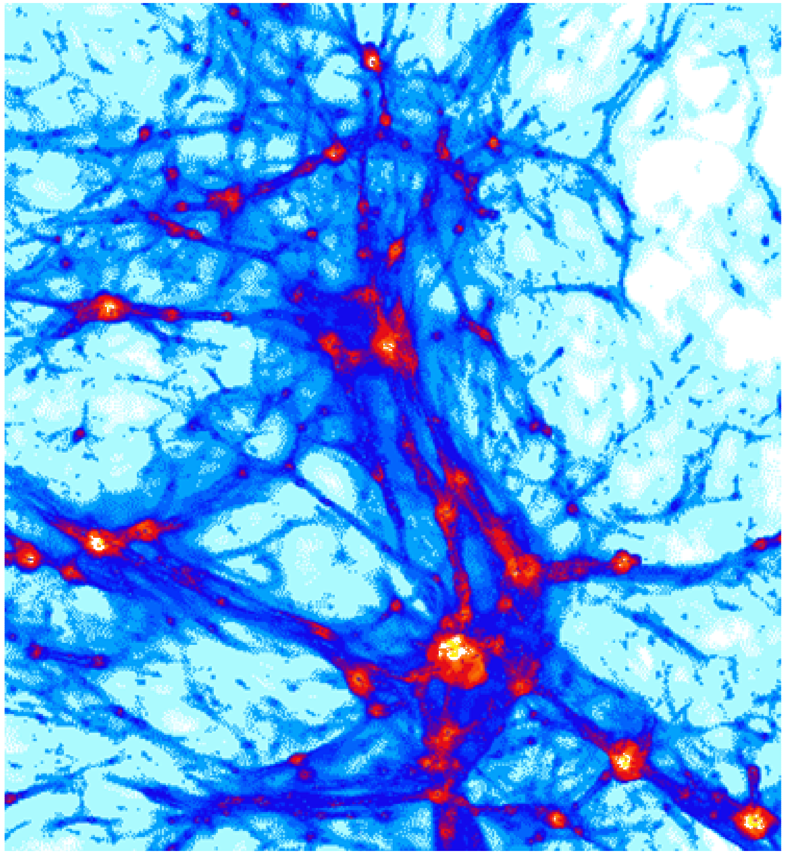
- Large scale shock waves:

$$t_{\rm acc} \approx 10^{18}\,{\rm sec}\, g\, Z^{-1} E_{20} B_{-6}^{-1} \left(\frac{v_{\rm sh}}{1000\,{\rm km/s}}\right)^{-2}$$

$$t_{\rm loss} \approx H_0^{-1} \simeq 10^{17}\,{\rm sec}...$$

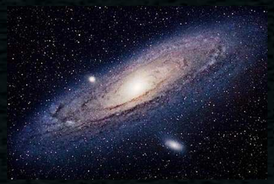
$\Rightarrow$ with optimistic assumptions, only heavy nuclei in the most powerful shocks around clusters of galaxies

$\Rightarrow$ relativistic sources are more promising (?)

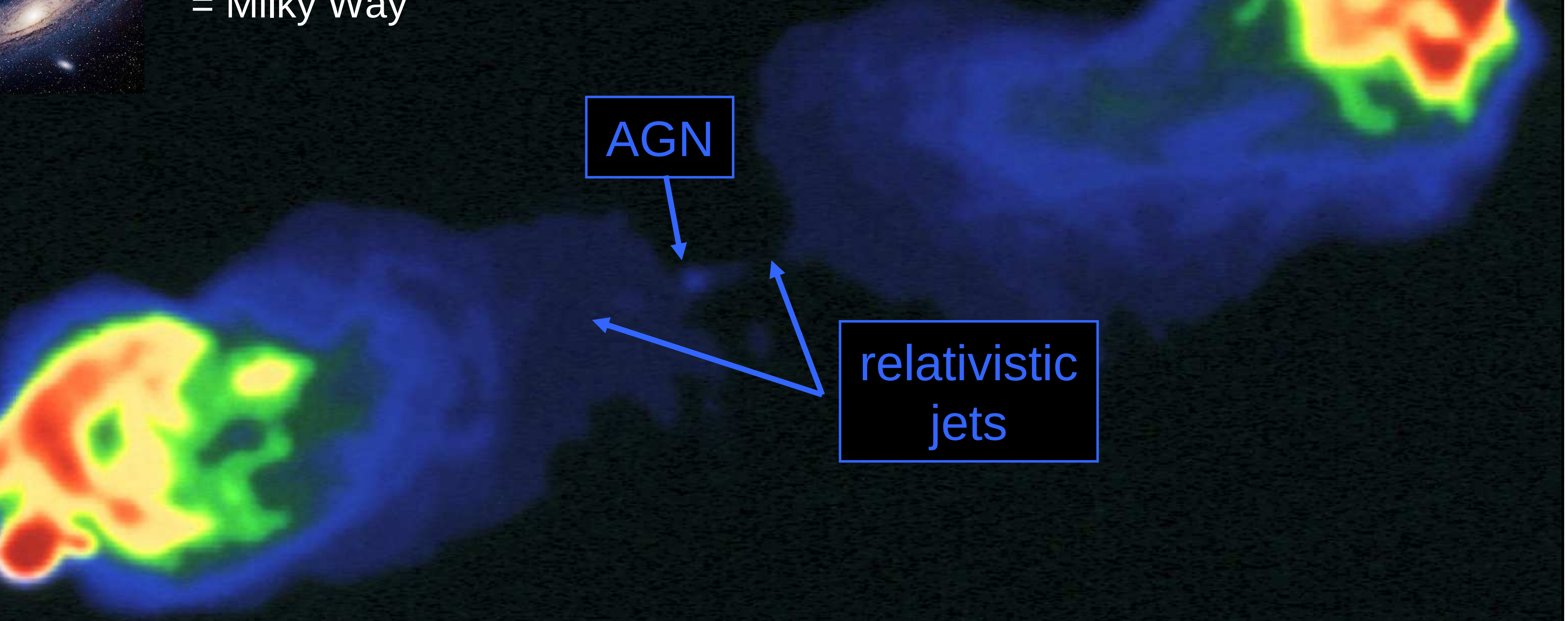


Acceleration – powerful radio-galaxies

scale:



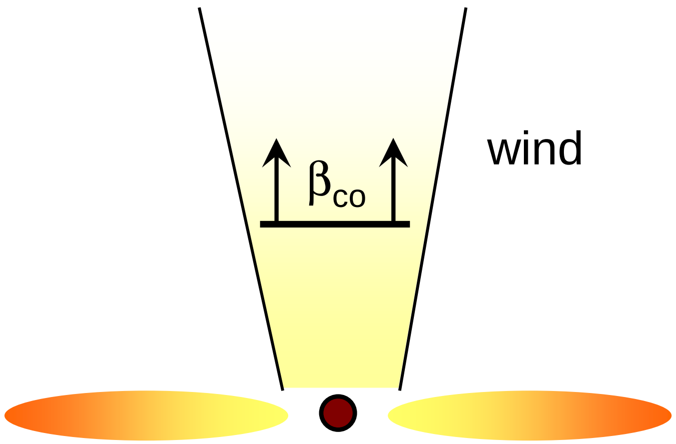
= Milky Way



Faranoff-Riley II radio-galaxy Cygnus A

Acceleration – constraints on sources

- <u>A generic case:</u>
  an acceleration region of size R (observer frame), in motion with speed β_w, with accelerating agents in motion (at most mildly relativistic)



  - time available for acceleration (comoving frame):

$$t_{\rm dyn} \approx \frac{R}{\beta_{\rm w}\Gamma_{\rm w} c}$$

  - acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm L}$

  - maximal energy: $E_{\rm obs} \leq \mathcal{A}^{-1} ZeBR/\beta_{\rm w}$

  - 'magnetic luminosity' of the source: $L_B = \Gamma_{\rm w}^2 \frac{B^2 R^2}{2}$

- <u>Constraint to reach 10^{20} eV, assuming $L_{tot} \geq L_B$:</u> $L_{\rm tot} \geq 10^{45}\,{\rm ergs/s}\ \mathcal{A}\,\beta_{\rm w}\, Z^{-1}\, E_{20}$
  Milky way: $L_{bol.} \simeq 10^{43.5}$ ergs/s
  low luminosity AGN: $L_{bol} < 10^{45}$ ergs/s
  Seyfert galaxies: $L_{bol} \sim 10^{43}$-10^{45} ergs/s
  high luminosity AGN: $L_{bol} \sim 10^{45}$-10^{47} ergs/s
  gamma-ray bursts: $L_{bol} \sim 10^{51}$ ergs/s

⇒ only most powerful AGN jets, GRBs (hot spots of radio-galaxies too)

Propagation – questions

… understand propagation effects in order to recover the source from observational data …

▶ Propagation effects:

1. Energy losses:

- objectives: $\rightarrow$ reconstruct injection spectrum
  $\rightarrow$ infer source density from GZK cut-off shape and/or cluster statistics

Isola & Sigl 02; Yoshiguchi et al. 03; Blasi & De Marco 04; Blasi et al. 06, 07

- main parameters: source density n_s, source evolution, type of source (bursting or continuously emitting), spectral shape and spectral index (indices), chemical composition at source…

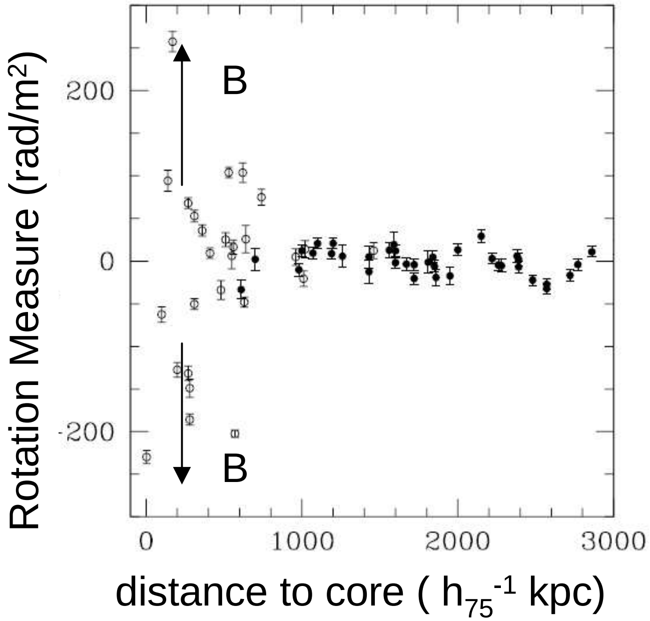
2. Influence of extragalactic magnetic fields

… a bursting point source becomes a finite image in (energy, time, angle)…

- objectives: $\rightarrow$ recover source image
  $\rightarrow$ study extragalactic magnetic fields
- main parameters: intensity, coherence length, turbulence spectrum and (inhomogeneous?) distribution of extragalactic magnetic fields…

Propagation – extra-galactic magnetic fields

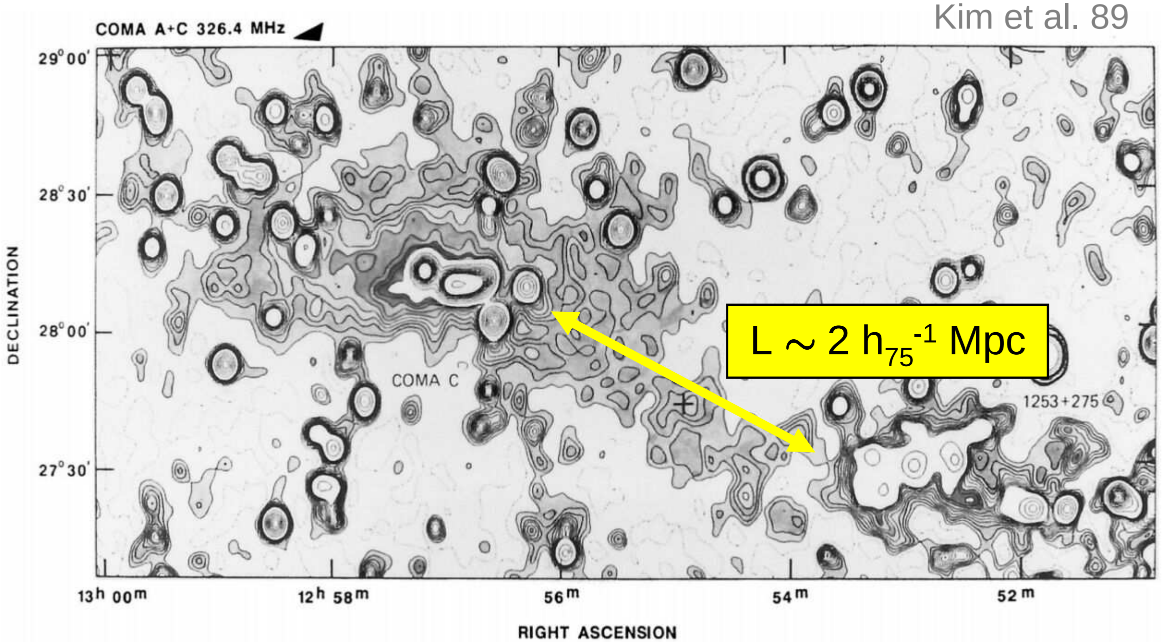
- Observational data: magnetic fields seem ubiquitous in the Universe, but their intensity, coherence length and configuration in the IGM are unknown…



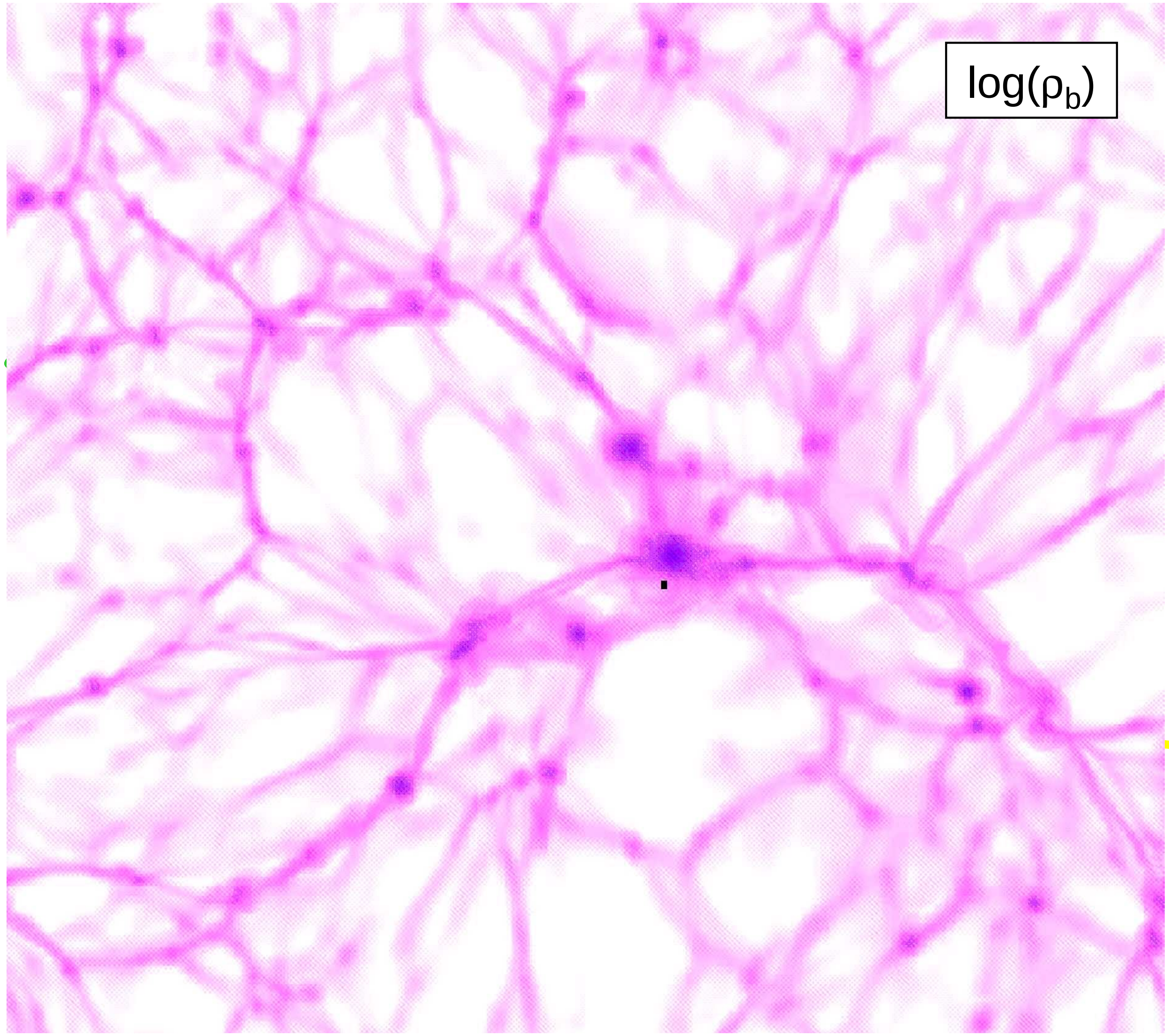
magnetic fields with strength $\sim \mu$G are seen in the cores of clusters of galaxies…

synchrotron traces of IGM magnetic fields have been detected…

Kim et al. 89



Propagation – effects of extra-galactic magnetic fields



Sigl, Miniati, Ensslin 03

Extra-galactic 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 – origin of extra-galactic magnetic fields

- Theory: generating magnetic fields is difficult, all the more so on large astrophysical scales…

  Galactic magnetic field: likely amplified through a dynamo mechanism from a pre-existing seed magnetic field of strength $B > 10^{-18}$ G…

- Extra-galactic magnetic field: two main scenarios

  1. « exotic origin » : seeded in the early Universe (reionization and beyond, >100 different models!)

  - theoretical expectations give present day strength $\ll 10^{-12}$G on galactic scales: sufficient for seeding the Galactic magnetic field, but unimportant with respect to UHECR propagation.
  - magnetic field likely all-pervading, with strength modulated by structure formation:

  $$B \propto \rho^{\alpha}, \quad \alpha \sim \frac{2}{3} \to 1$$

  (e.g., Bruni & Maartens 03, Dolag 05)

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

  - likely candidates: galactic (super)winds, radio-galaxy lobe ejection

    however: origin of magnetic field in galaxies?

  - magnetic field strongly concentrated around large scale structure filaments and walls

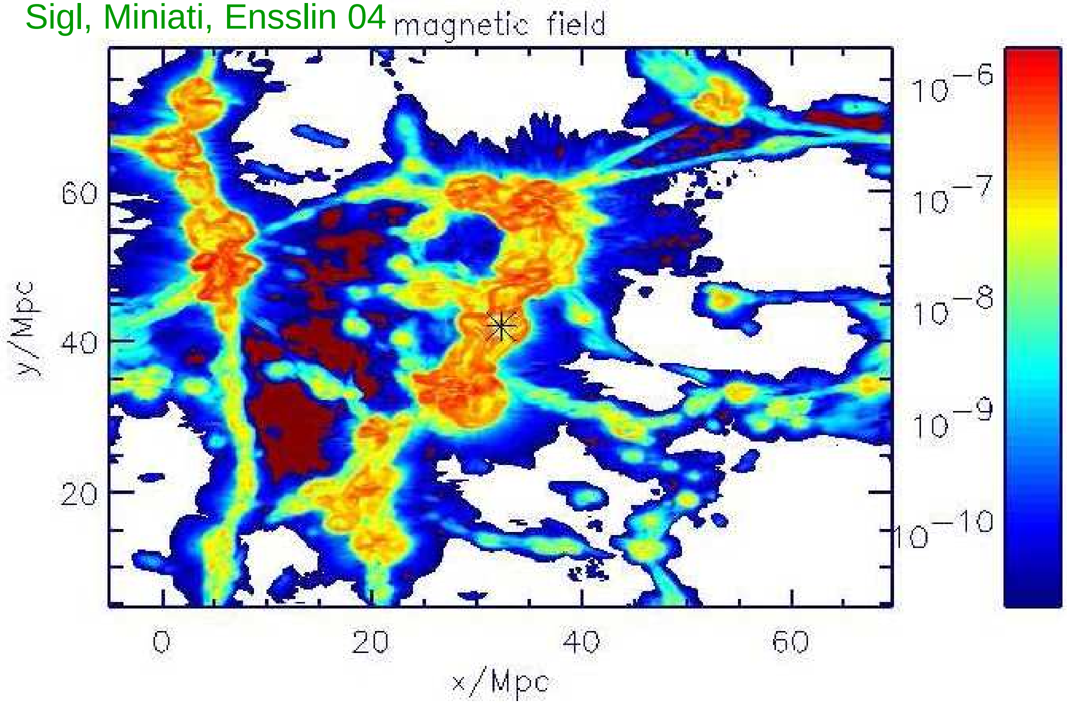
Propagation – numerical simulations of 'realistic' B

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

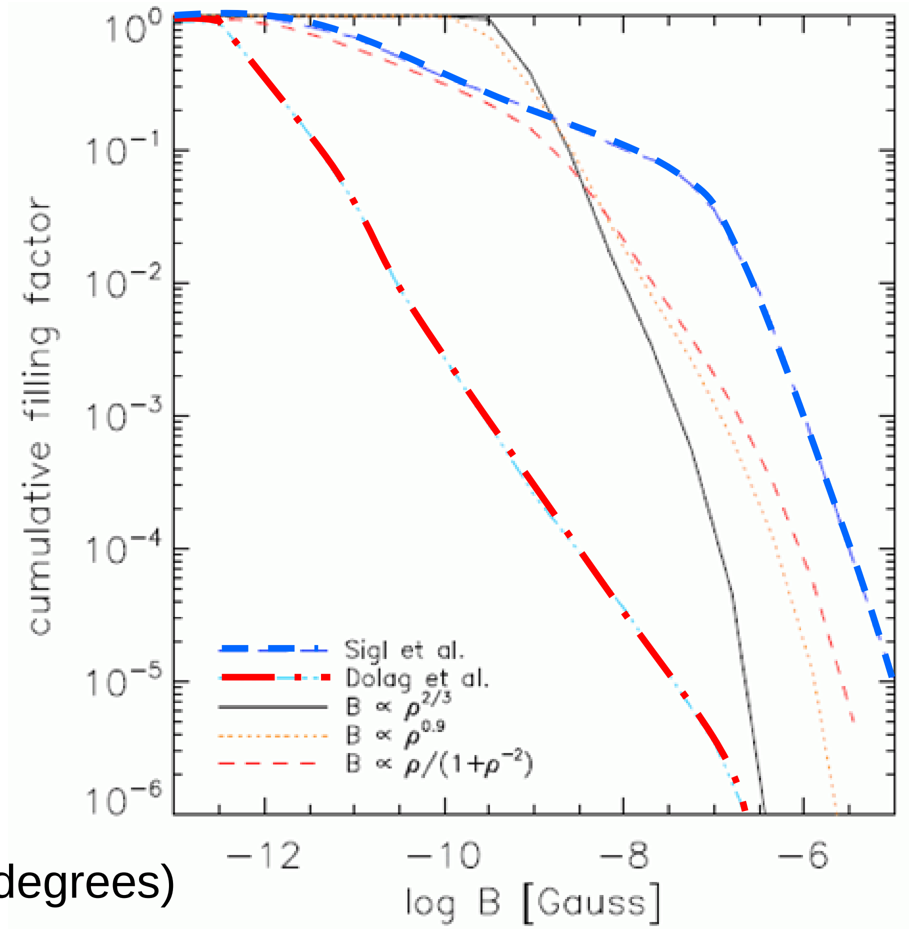
Numerical simulations: Sigl/Miniati/Ensslin 04, Dolag/Grasso/Springel/Tkachev 04 have set up initial conditions for B at high z (z=20, uniform B) and followed its evolution through structure formation, renormalizing the present-day B so as to match the observed value in clusters

⇒ very different B configurations

Sigl, Miniati, Ensslin 04



Kotera & M.L. 07



⇒ different consequences:

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

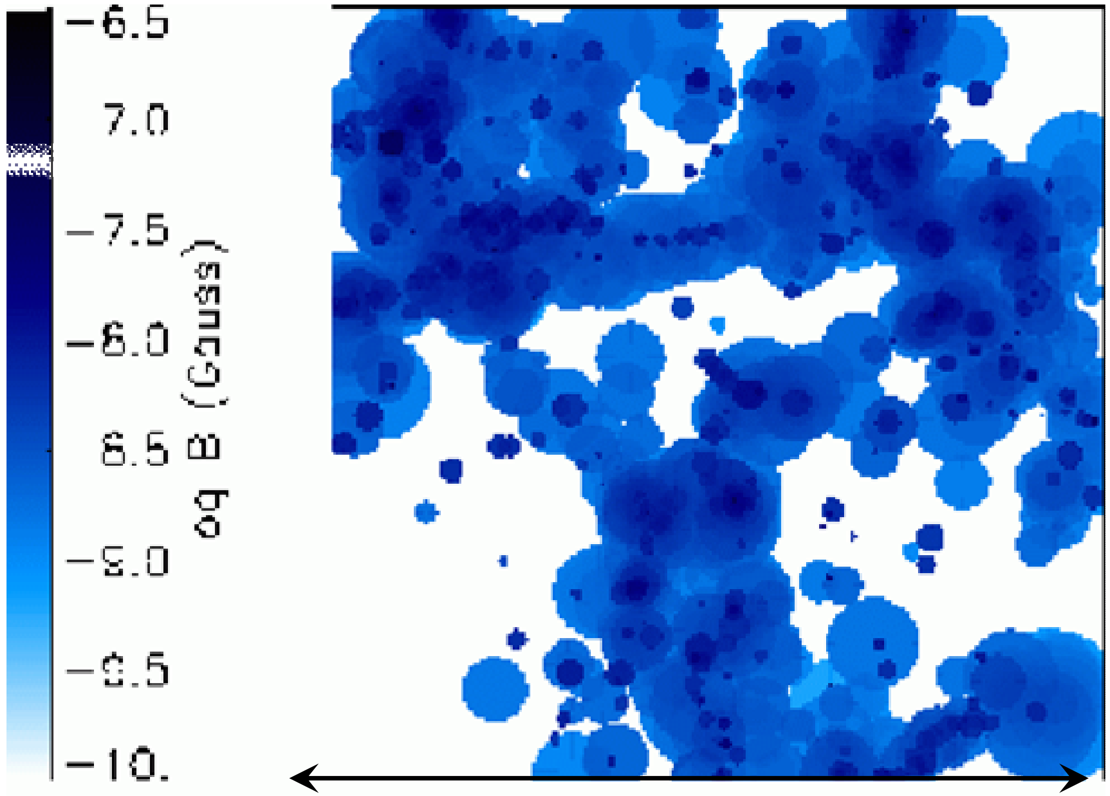
Dolag/Grasso/Tkachev: very small deflections (< few degrees)

Propagation – magnetic galactic pollution

- 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.

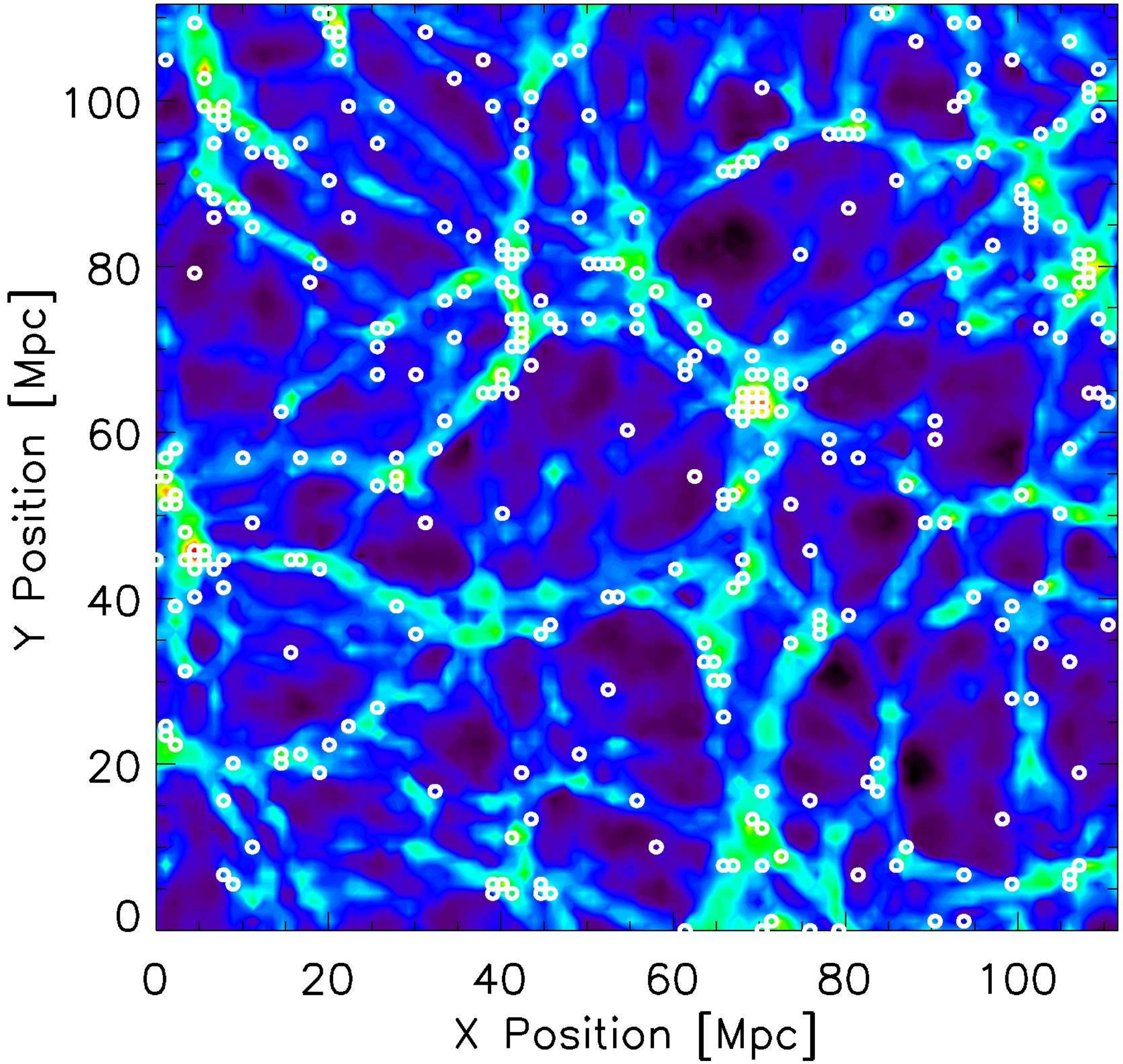
$\Rightarrow$ typical wind radius $\sim$ 1 Mpc
with B $\sim 10^{-8} - 10^{-7}$ G

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

Propagation – structured extra-galactic magnetic fields

- A simplified model for the extra-galactic magnetic field distribution

Kotera & M.L. 08



scattering centers:

- filaments of large scale structure,
- magnetized bubbles (winds/lobes) $R \sim 1$ Mpc, $n \sim 10^{-2}$ Mpc^{-3}

in both cases:

m.f.p. to interaction $\sim$ 30 Mpc

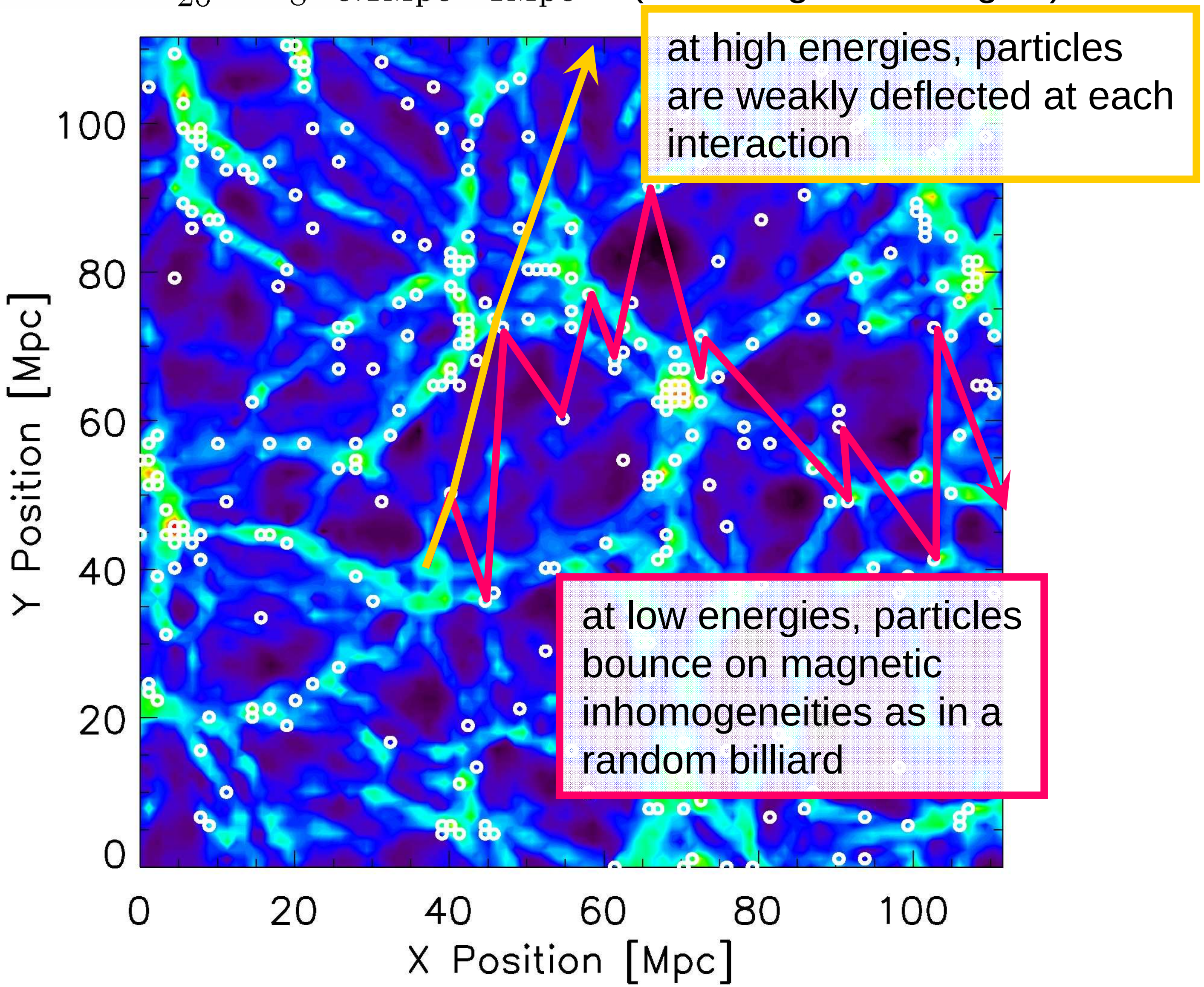
$\Rightarrow$ analytical treatment of UHECR transport in structured extra-galactic magnetic fields
(Kotera & M.L. 08, arXiv:0801.1450)

Propagation – transport in extra-galactic magnetic fields

► Transport from stochastic interactions with zones of enhanced magnetic field strength

- per interaction: $\delta\theta_i^2 \simeq 1.7^\circ E_{20}^{-2} B_{-8}^2 \lambda_{0.1\mathrm{Mpc}} R_{1\mathrm{Mpc}}$ (at the highest energies)

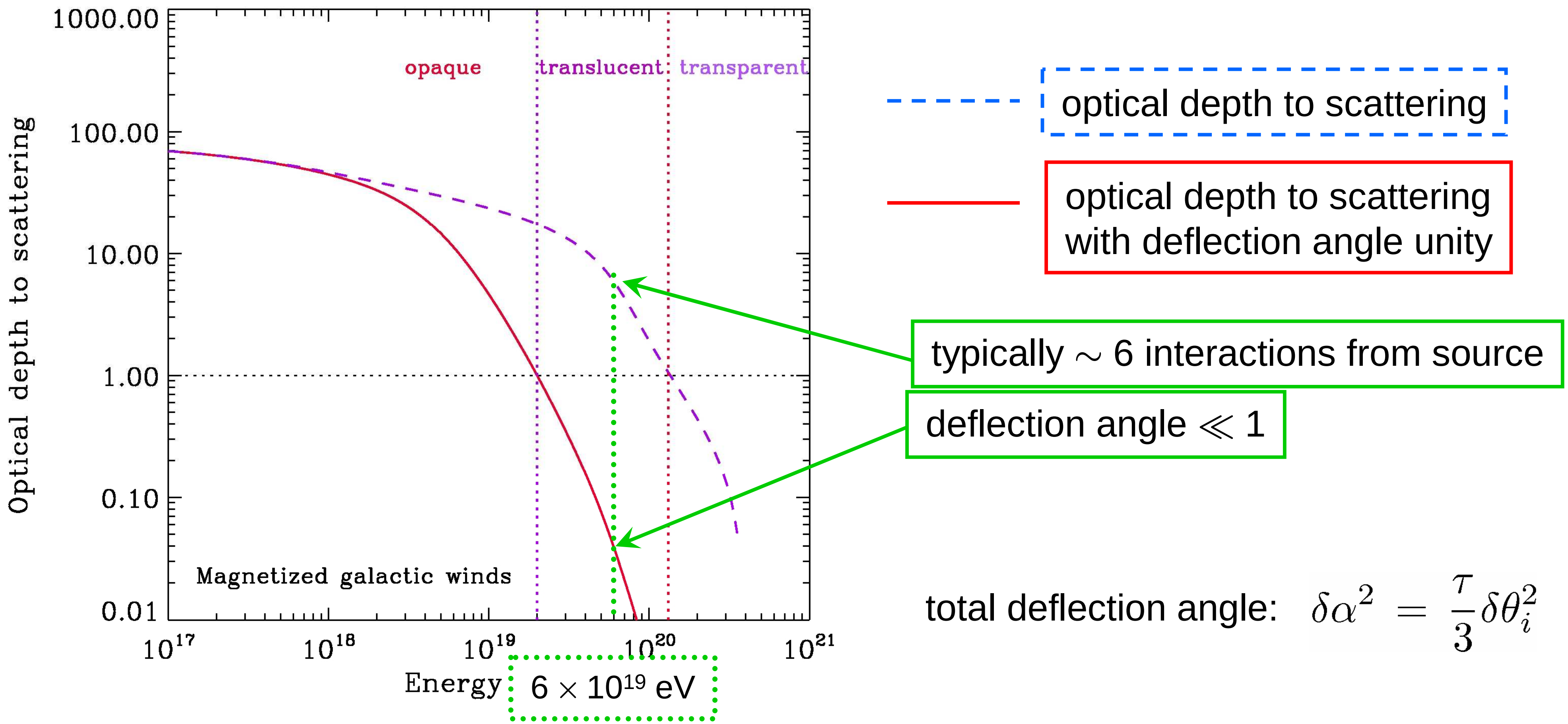
- particles of different energies experience different Universes:



Propagation – optical depth to scattering

- Propagation with stochastic interactions with zones of enhanced magnetic field strength
  - scattering centers: filaments, or bubbles (RG lobes, winds)
    with R $\sim$ 1 Mpc, n $\sim$ 10^{-2} Mpc^{-3},
    in both cases: mean free path to interaction $\sim$ 30 Mpc

per interaction: $\delta\theta_i^2 \simeq 1.7^\circ E_{20}^{-2} B_{-8}^2 \lambda_{0.1\mathrm{Mpc}} R_{1\mathrm{Mpc}}$



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

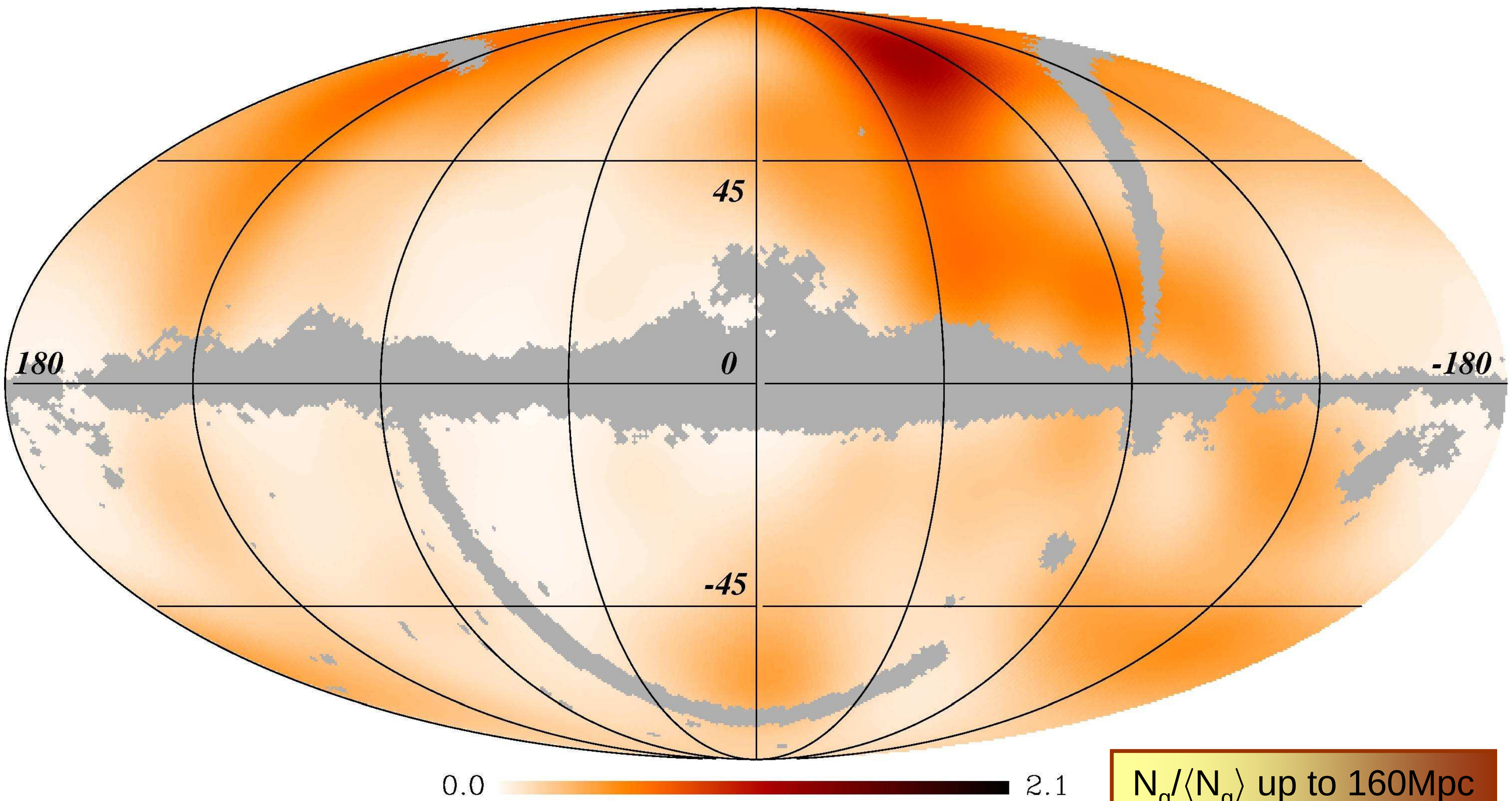
Propagation – optical depth to scattering

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

- Maps of optical depth:

D = 0 – 40 Mpc

source distance for 10^{20} eV



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

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

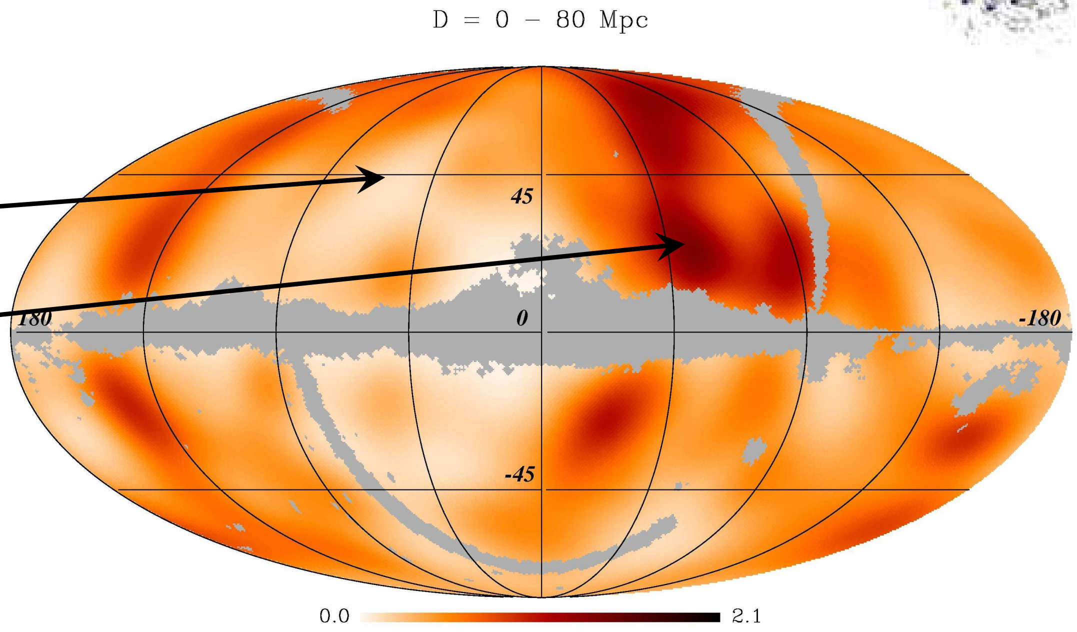
τ varies from <1 to $\gg$ 1 for typical parameters

Propagation – effects on flux and angular images

▶ Two new effects:

- if sources are gamma-ray bursts, flux from regions of $\tau < 1$ smaller by τ than flux in regions with $\tau > 1$

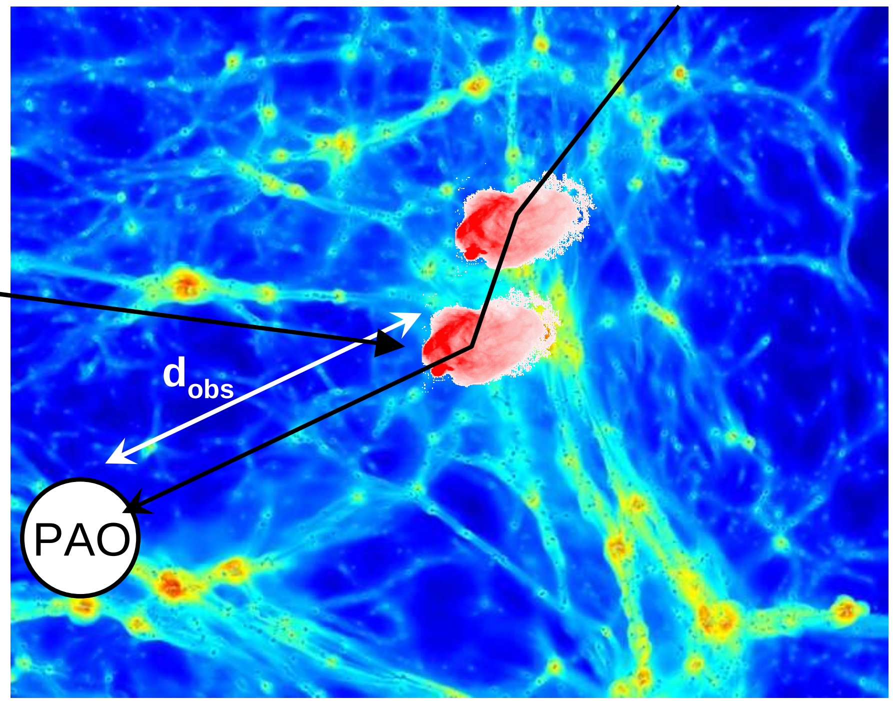
  [burst rate within 100Mpc (and 4π) : $\sim$ 1/1000 yr]

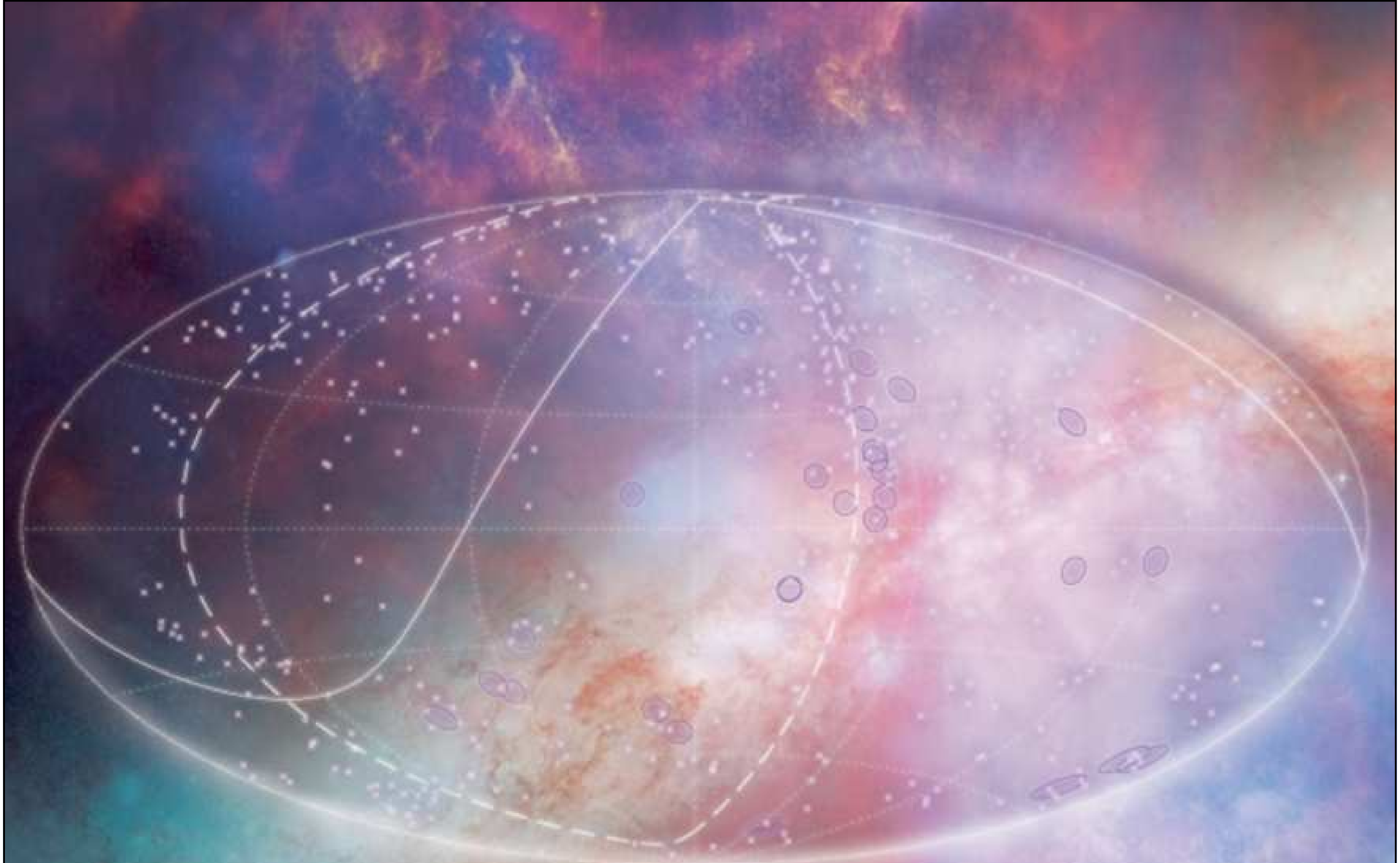


- sources of UHECRs and scattering centers share a similar property: large regions of intense magnetic field

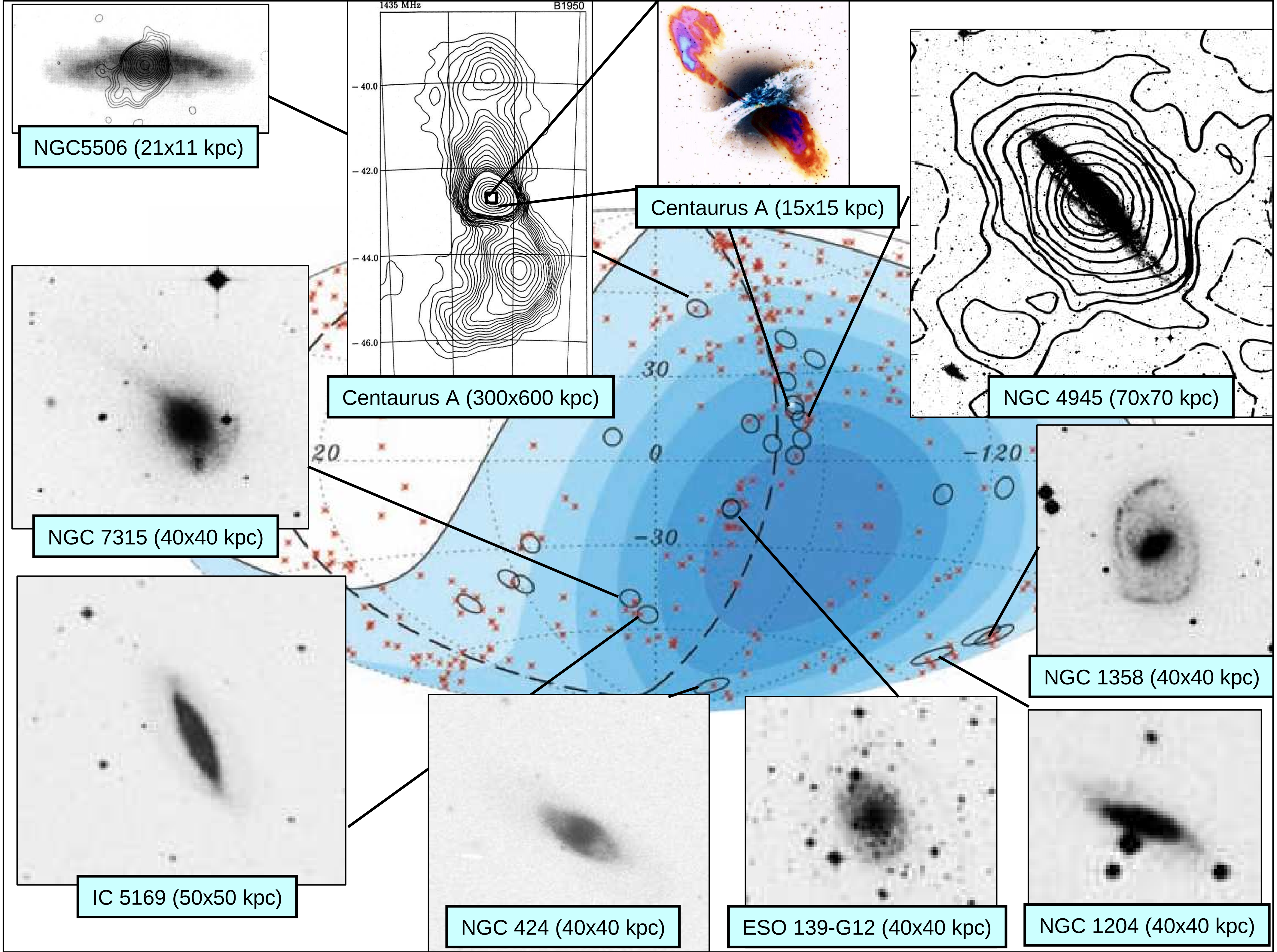
  $\Rightarrow$ do not mistake the last scattering center on the line of sight with the source!

  signature:
  inferred source distance scale d_{obs}
  smaller than expected distance scale $\sim l_{max}(E)$

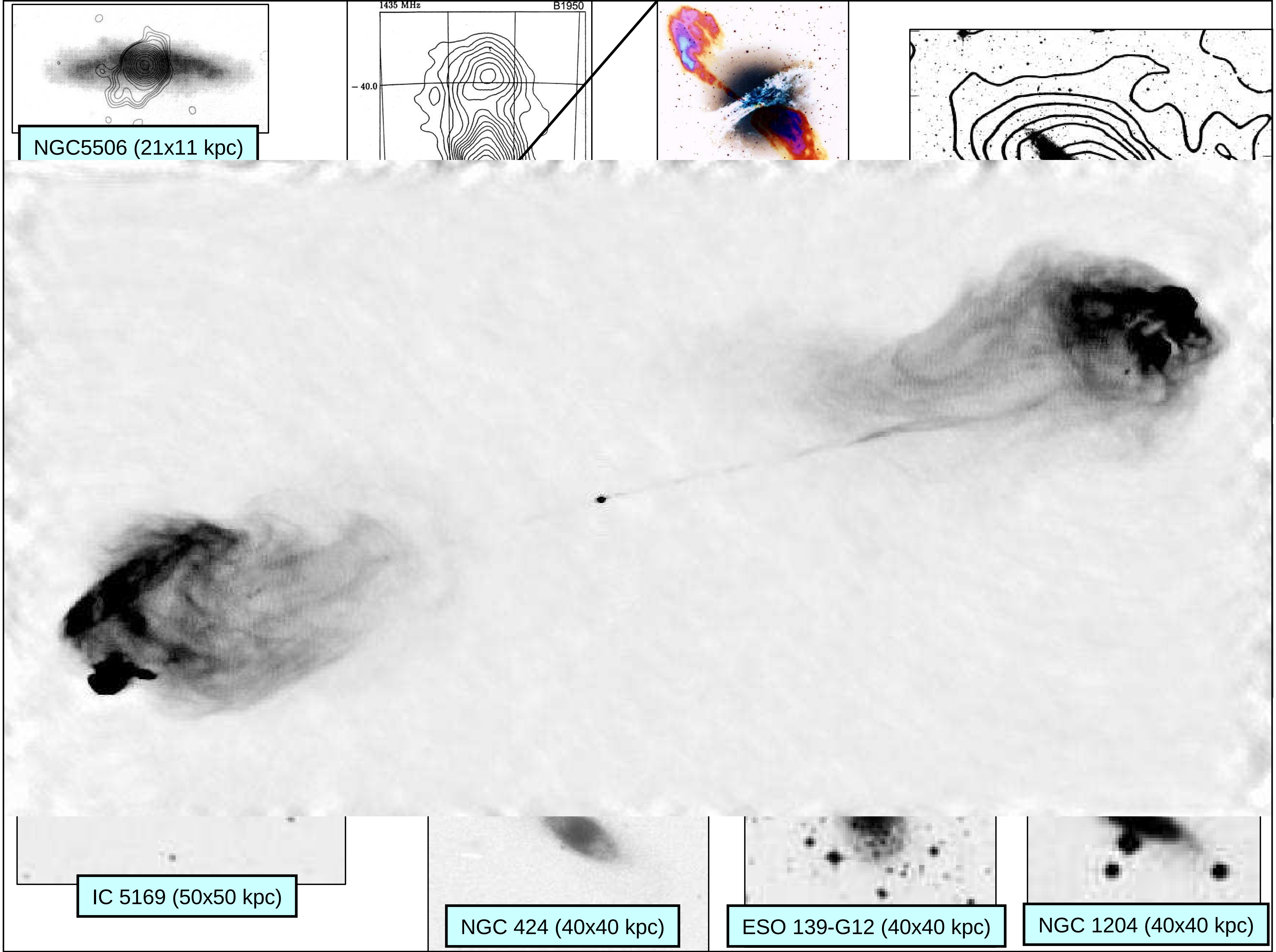




The PAO has detected a highly significant correlation of the arrival directions of cosmic rays with energy $E > 5.7\ 10^{19}$ eV with the known AGN within 75Mpc…



NGC5506 (21x11 kpc)
1435 MHz
B1950
– 40.0
– 42.0
– 44.0
– 46.0
Centaurus A (300x600 kpc)
Centaurus A (15x15 kpc)
NGC 4945 (70x70 kpc)
NGC 7315 (40x40 kpc)
30
20
0
–120
–30
NGC 1358 (40x40 kpc)
IC 5169 (50x50 kpc)
NGC 424 (40x40 kpc)
ESO 139-G12 (40x40 kpc)
NGC 1204 (40x40 kpc)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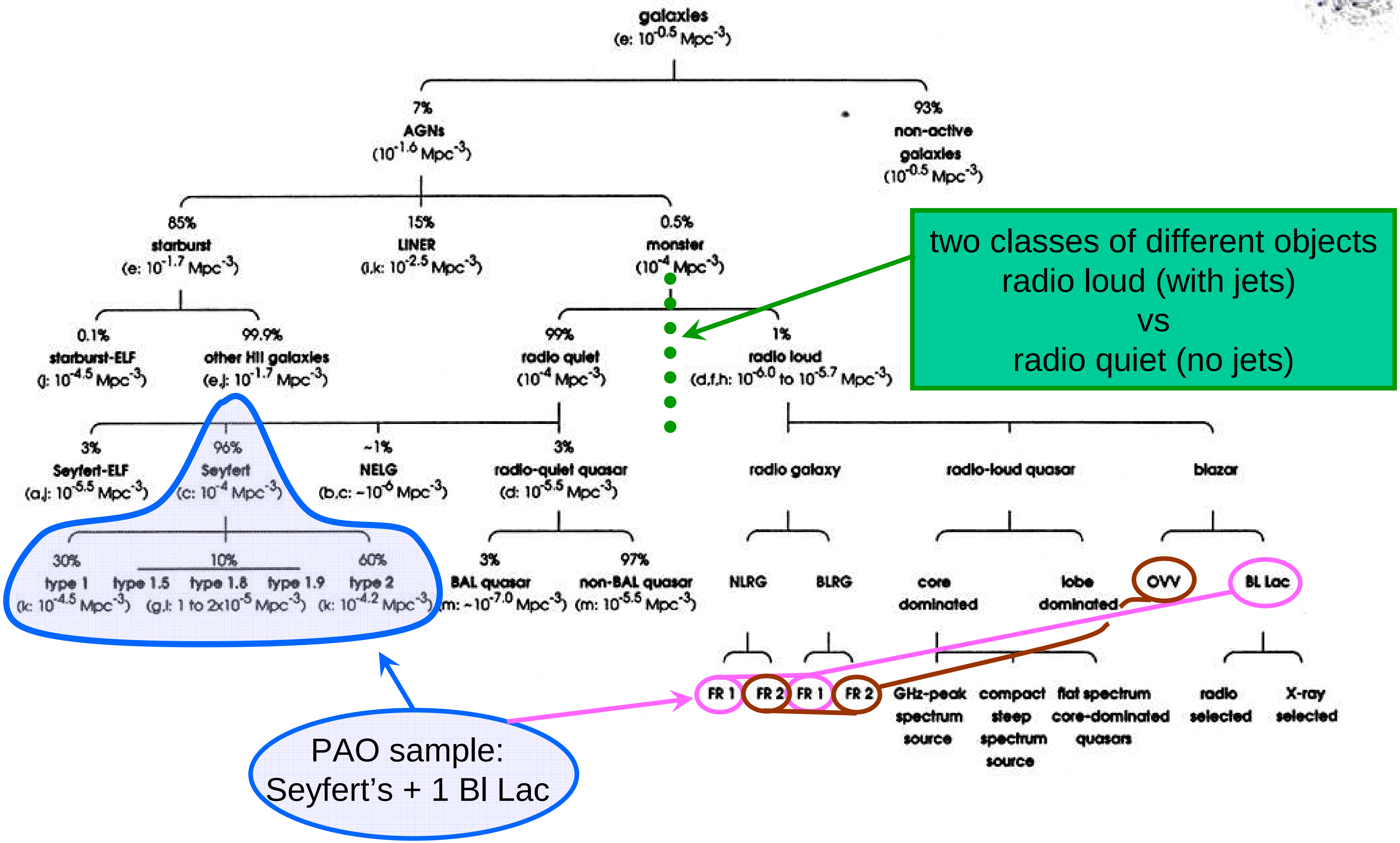
PAO results – family tree of galaxies and AGN



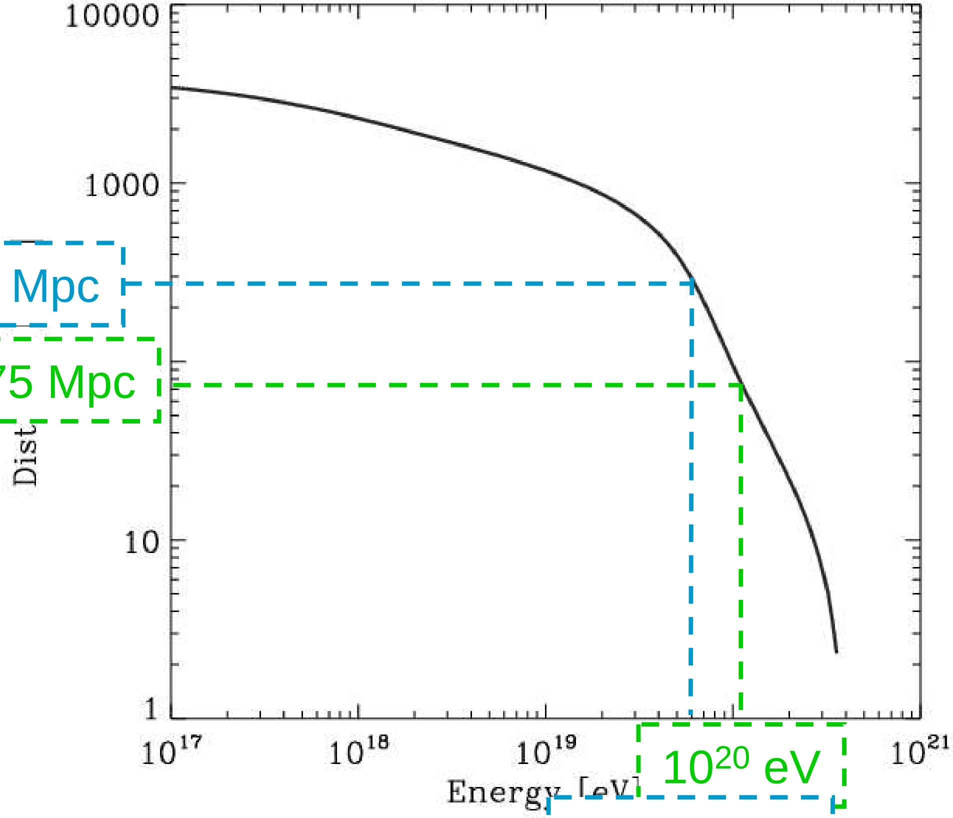
The PAO has detected a highly significant correlation of the arrival directions of cosmic rays with energy $E > 5.7\ 10^{19}$ eV with the known AGN within 75Mpc…

PAO results – distribution of counterparts seen by PAO

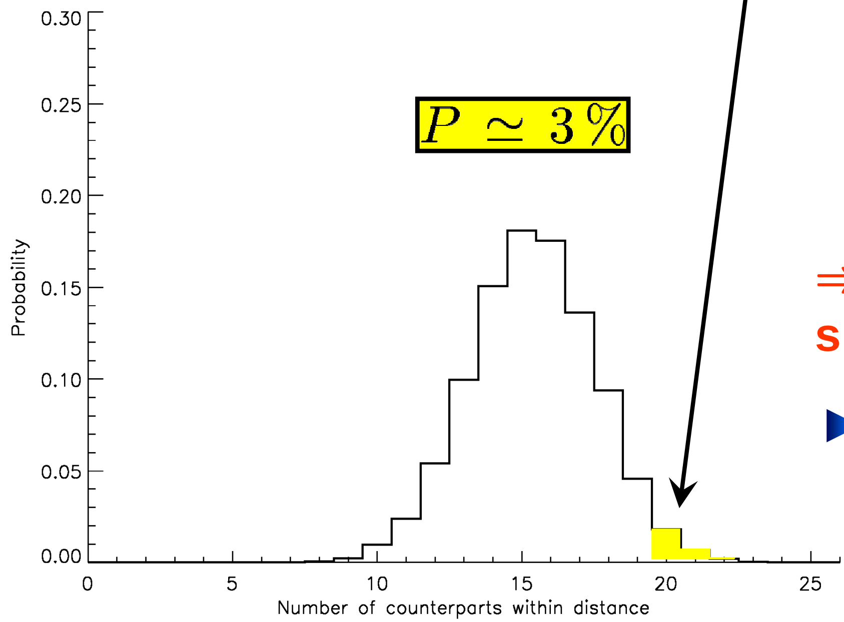
- Source distance scale:

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

⇒ distance scale ~ $l_{max}(E)$



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

- Two possibilities:

1. PAO energy scale is underestimated by ~ 30%
2. **PAO is imaging the last scattering surface…**

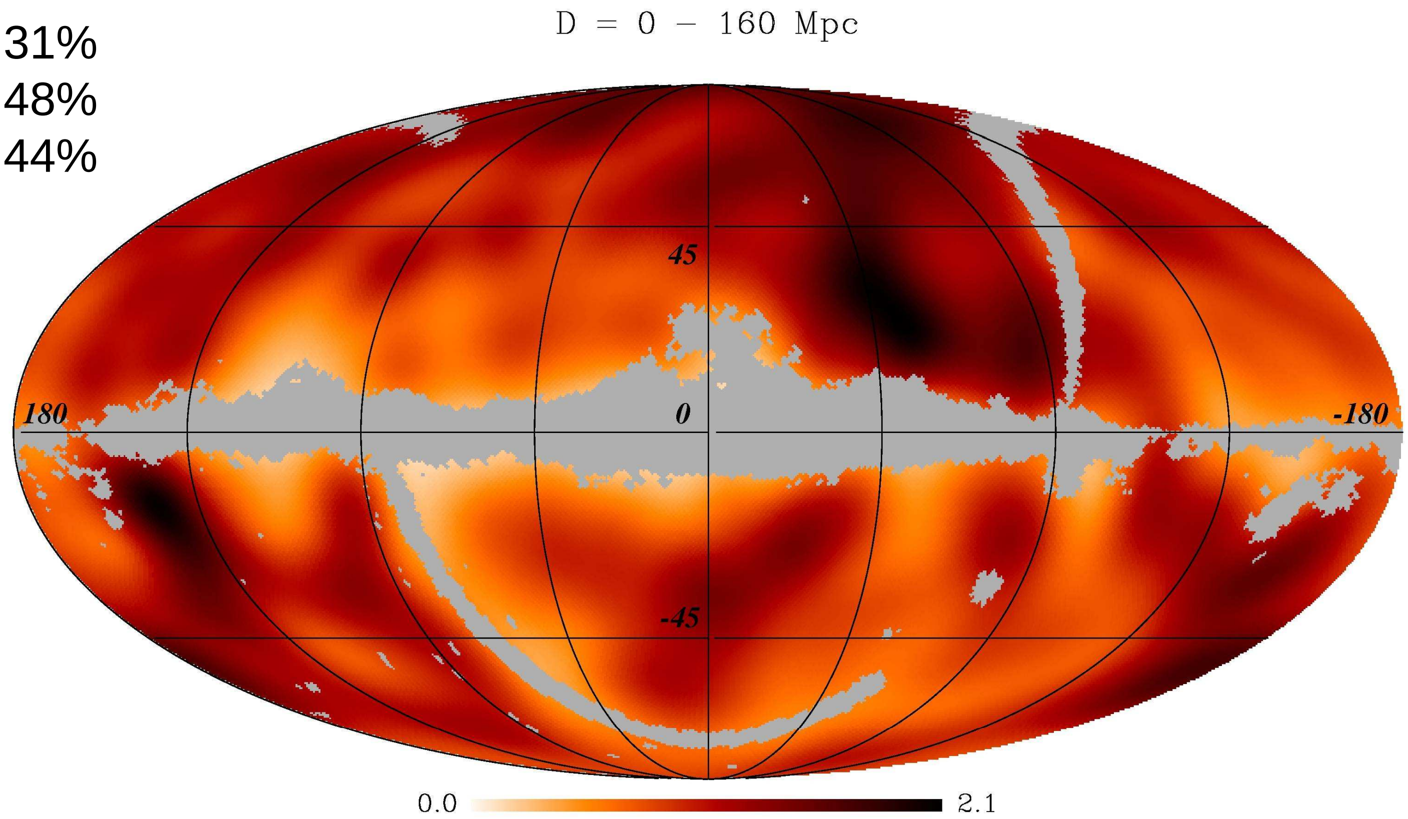
PAO results – confusion of sources

- If PAO is imaging the last scattering surface:

  - fraction of contaminated events:

    compute the probability that a direction $\delta\alpha$ away from a background galaxy (=source within 200Mpc) lies within 3° of an AGN.

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



$\Rightarrow$ correlation should not exceed 50%
(unless GRB are sources of UHECR, in which case the correlation with the foreground density is artificially enhanced due to non-detection of GRB if $\tau < 1$)

PAO results – modified energy scale

▶ PAO energy scale is underestimated by 30%

- Most conservative statement: the AGN seen by PAO trace the source distribution for events above 8×10^{19} eV (within 120Mpc) because AGN trace the large scale structure

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

- A possible guess: UHECRs are produced in gamma-ray bursts…
  [Usov 95, Vietri 95, Waxman 95]

- A consequence: no counterpart will ever be found: photons have passed by Argentina $\sim 10^4$ 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
  $\Rightarrow$ 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)

- Extra-galactic magnetic fields play a crucial role:
  - particles of energy $\leq 10^{18}$-10^{19} eV diffuse in the extra-galactic magnetic field $\Rightarrow$ 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%), 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…**