Deflections of UHECRs in Extra-Galactic Magnetic Fields

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with

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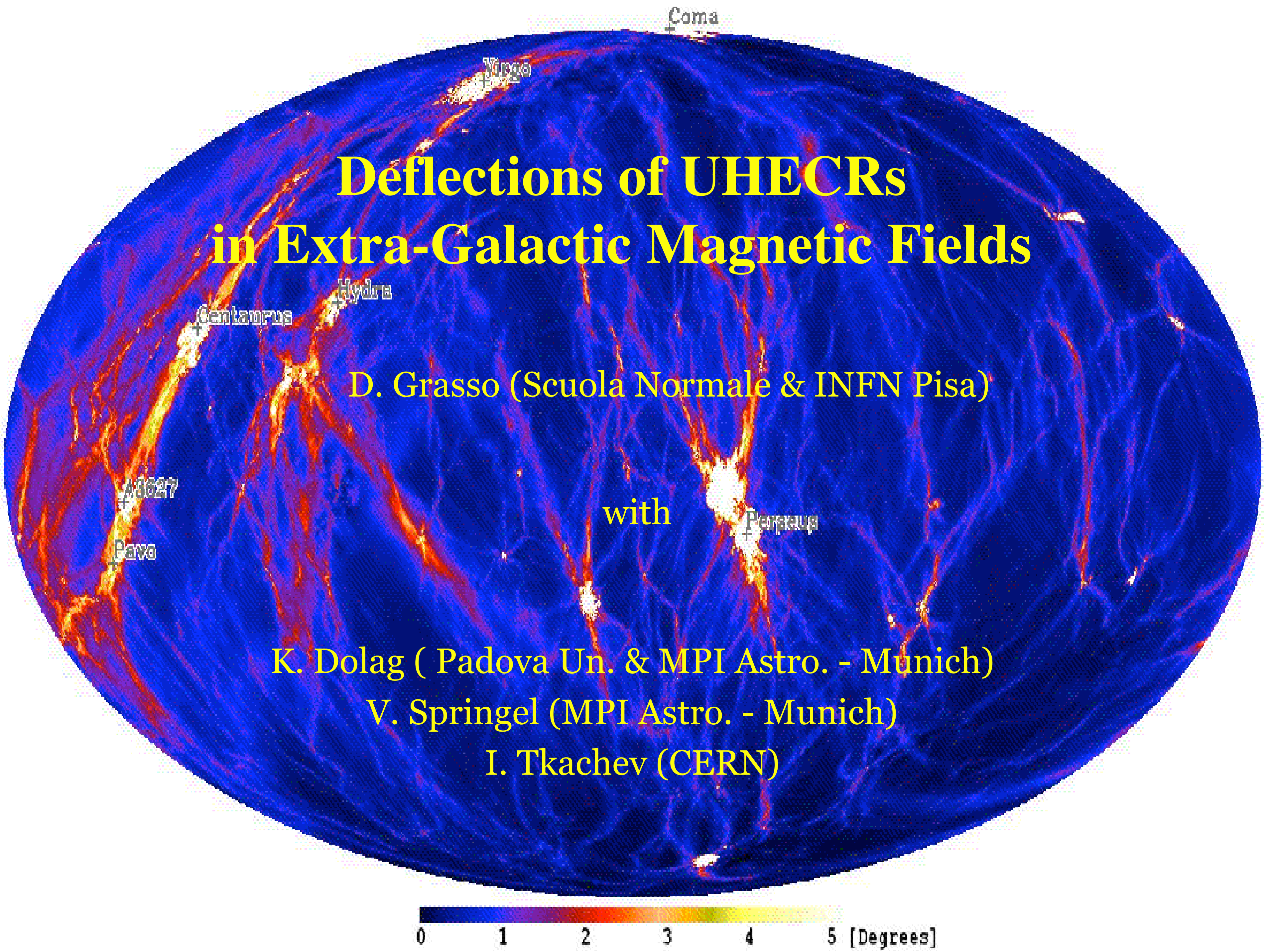


Motivations

- EAS experiments provide some angular information about the arrival direction of UHECRs (with a resolution ~ 1^{o})
- UHECRs (E > 10^{19} eV) are, most likely, protons
- At such energies protons are expected to undergo tiny deflections in the Galactic Magnetic Fields
- If Extra Galactic MFs (EGMFs) are not too big the directional information is not lost and it may allow to identify UHECRs sources

UHECR astronomy may then be possible

However

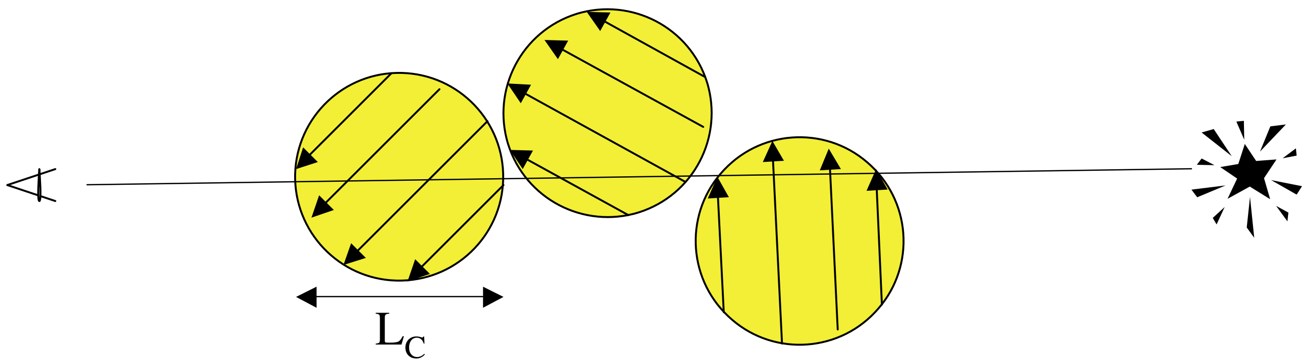
- We know very little about EGMFs from observations

We need simulations

What do we know about EGMFs from observations ?

MF in the Inter-Galactic Medium (IGMFs)

Only upper limits are available which are based on the Faraday Rotation Measurements (RMs) of Quasars' radio emission at cosmological distance ($z \sim 1$)



First limit by Kronberg'94 who, however assumed n_e = const. and $\Omega_b = 1$!!

Then Blasi, Burles and Olinto, `99 accounted for n_e inhomogen. in Ly-alpha clouds

$$\begin{cases} B_{H^{-1}} \leq 10^{-9}\ \mathrm{G} \\ B_{50\ \mathrm{Mpc}} \leq 6 \times 10^{-9}\ \mathrm{G} \\ B_{1\ \mathrm{Mpc}} \leq 10^{-8}\ \mathrm{G} \end{cases}$$

proton deflections travelling over cosmological distances may be large if these limits are saturated !

Magnetic fields in galaxy clusters (ICMFs)

OBSERVATIONS

Synchrotron Radio Halos

Minimum energy condition:

$$\langle B \rangle_V = 0.1 \div 1 \; \mu G$$

Faraday Rotation Measurements (RMs)

$$RM \equiv \frac{\Delta\chi}{\Delta\lambda^2_{obs}} \propto \int_0^L n_e^T(l) \left(\frac{\lambda_l}{\lambda_{obs}}\right)^2 B(l)\cdot dl \qquad \mathrm{rad\ m^{-2}}$$

$$B_{cell} = 1 \div 10 \; \mu G$$

$$l_C = 10 \div 100 \; \mathrm{kpc}$$

Non thermal X-ray emission

if due to IC scattering ⟹

$$\frac{L_{Syn}}{L_{IC}} \propto \frac{B^2/8\pi}{\varepsilon_{CMB}} \;\Longrightarrow$$

$$\langle B \rangle_V = 0.1 \div 1 \; \mu G$$

Unknown origin, but ....

MSPH simulations in galaxy clusters

MSPH: Magnetic Smooth Particle Hydrodynamics

[Dolag, Bartelmann & Lesch, astro-ph/0109541, 0202272]

N-body simulations of DM + gas hydrodynamics (SPH) + MHD

Lagrangian simulation (adaptive resolution)

A pre-existing seed field is invoked which is amplified by

Adiabatic compression:

$$\Phi_B = \text{const} \Rightarrow B \propto R^{-2} \propto n_{gas}^{2/3}$$

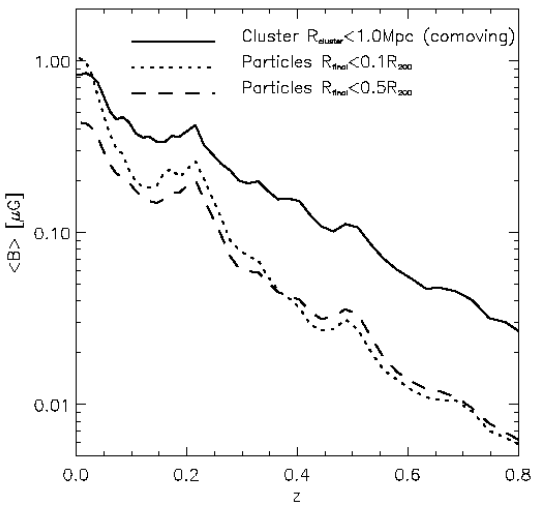
$$\text{Cosmologically this implies:} \quad B(z) \propto (1+z)^2$$

Non linear magnetic induction driven by the gas shear flows:

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right) + \vec{B}_{in}$$

Possible origin of the seed field

Primordial origin (z > 1000); turbulence at the reionization; starburst galaxies or early AGNs (z > 4) can account for the required seed



In the simulation B_{in} is switched-on at $z_{in} = 20$

ICMF evolution is highly non-linear for z < 3

□ the final field does not change significantly

if the same comoving field is switched-on

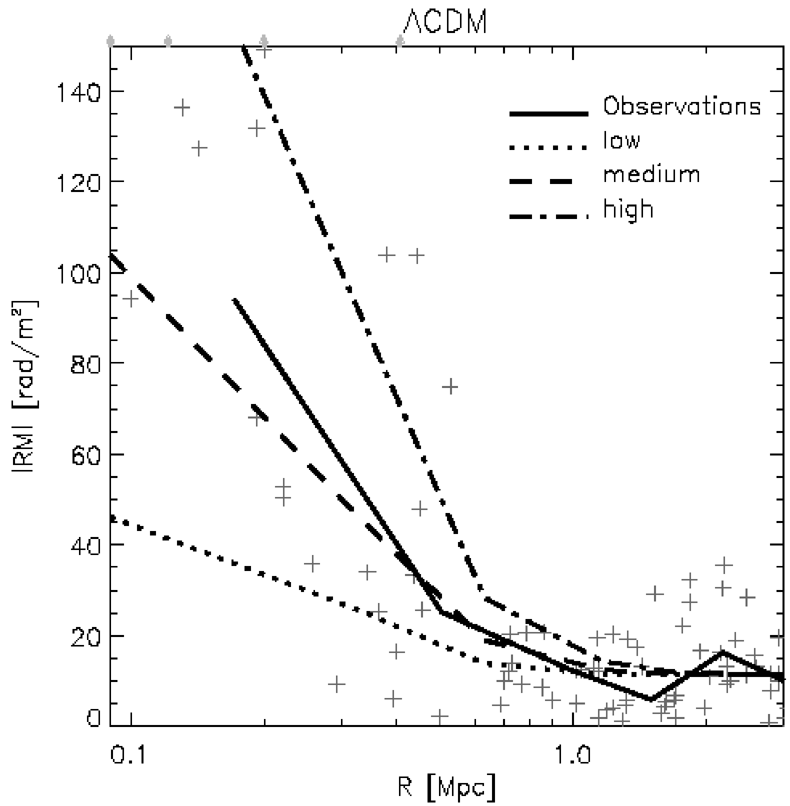
even at z ~ 3

The geometrical structure of the seed field is almost irrelevant

The memory of the seed field structure is wiped-out in the clusters

A uniform seed field can be assumed

Simulated RMs vs observations



	B_0(G)	$<B_{fin}>_{core}$
low	0.5×10^{-12}	3×10^{-7}
medium	2.5×10^{-12}	8×10^{-7}
high	1×10^{-11}	2×10^{-6}

RMs intensity and profile are reasonably reproduced for

$$5 \times 10^{-13} < B_0 < 1 \times 10^{-11}\ G$$

$$B_0 \equiv B(z_{in})\ (1 + z_{in})^{-2}$$

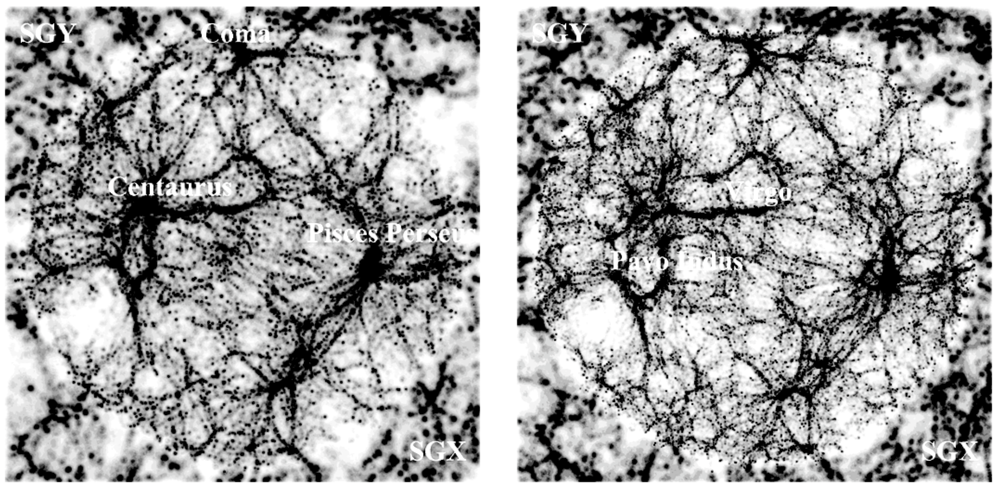
Best for $B_o \sim 2\ 10^{-12}$ G especially for A119

The strategy:

- We assume that the MF in galaxy clusters have been originated from a cosmological seed field generated at high z. This should maximize UHECR deflections (largest filling)
- We combine MSPH with a constrained N-body simulation of the DM in the local universe (R ~ 100 Mpc)
- We choose a seed field strength which best reproduce (or maximize) RMs. We assume a uniform seed field.
- We compute proton deflection along random directions and construct deflections maps of UHE protons

Constrained simulations of the local universe

Constrained Simulations: initial conditions (density fluctuations) are chosen randomly from a Gaussian field with a power spectrum compatible with ΛCMD cosmology but constrained so that the smoothed density field coincide with that observed.



[Mathis, Springel, White et al. , astro-ph/0111099]: *Lagrangian code*

IRAS 1.2 galaxy catalogue was used to constrain initial conditions
Smoothing length = 7 Mpc

Our simulations:
Constrained sim. for the DM + MSPH

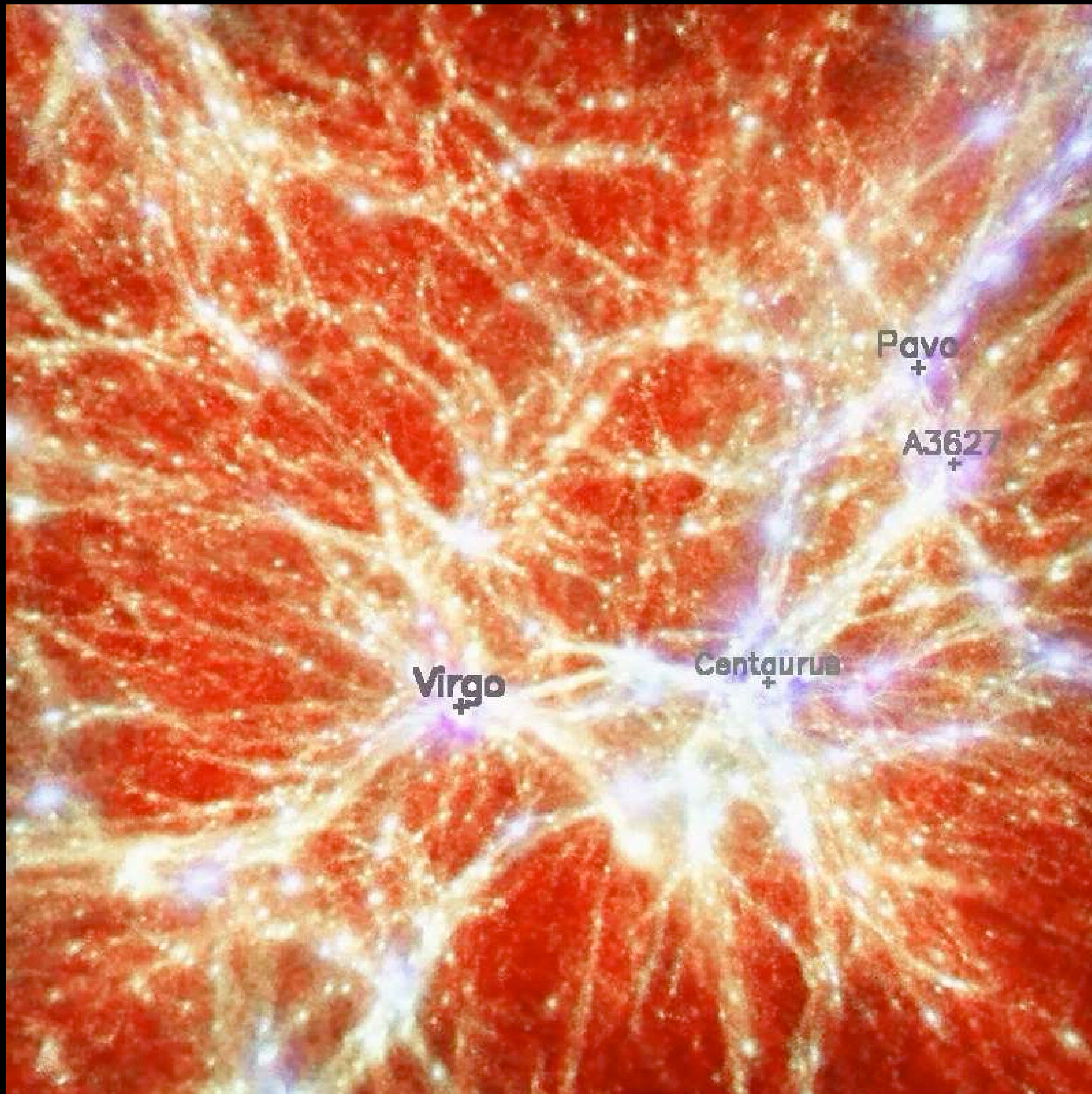
[Dolag, D.G., Springel, & Tkachev , ***astro-ph/0310902, JETP Lett. '04***
long paper submitted to JCAP '04*]*

- Simulation volume:
  high resolution sphere radius : 115 Mpc
  embedded in a low resolution box of side ~ 350 Mpc

- Resolution
  5×10^7 particles with mass: $5 \times 10^9 M_\odot$ (DM); $7 \times 10^8 M_\odot$ (gas);
  max spatial resolution (adaptative) ~ 10 kpc

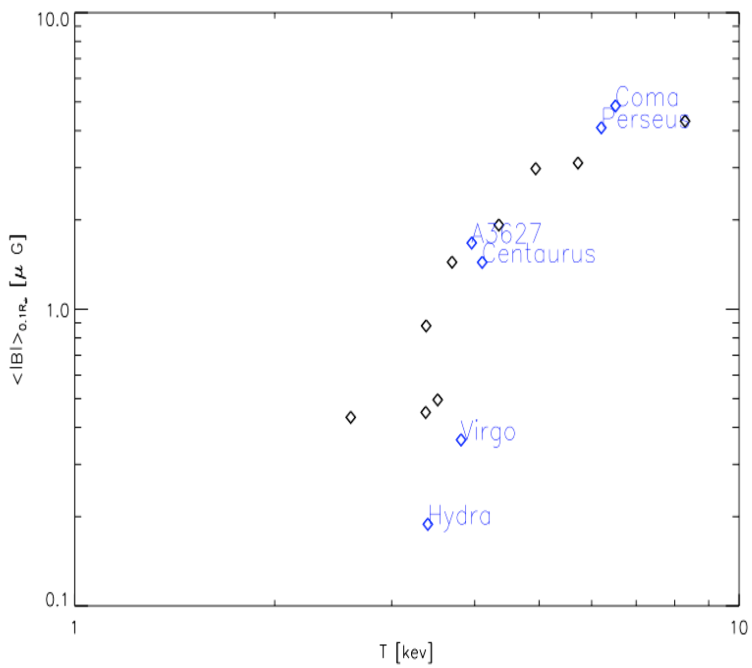
- Initial redshift: $z = 60$

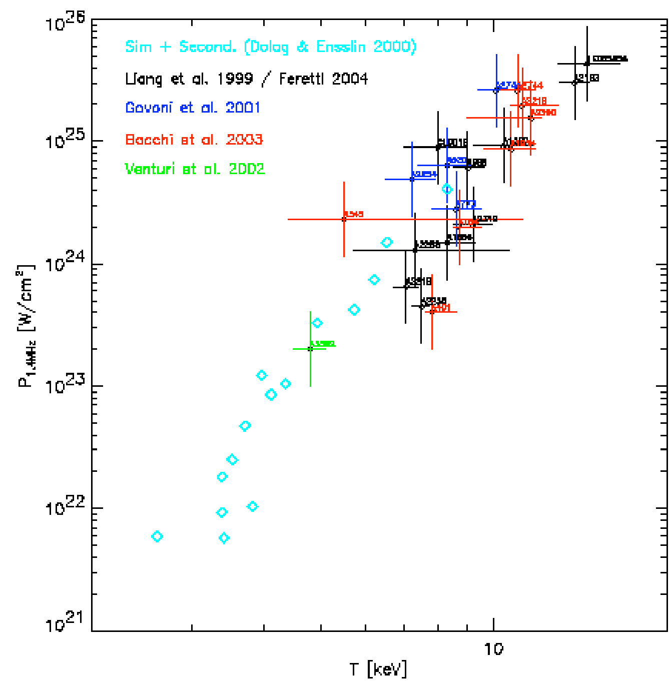
- Initial magnetic field (comoving): $B_0 = 1 \times 10^{-11}$ G (run 1: mhd_y)
  $B_0 = 2 \times 10^{-12}$ G (run 2: mhd_z)
  homogeneous in both case but with orientation



Pavo
A3627
Virgo
Centaurus

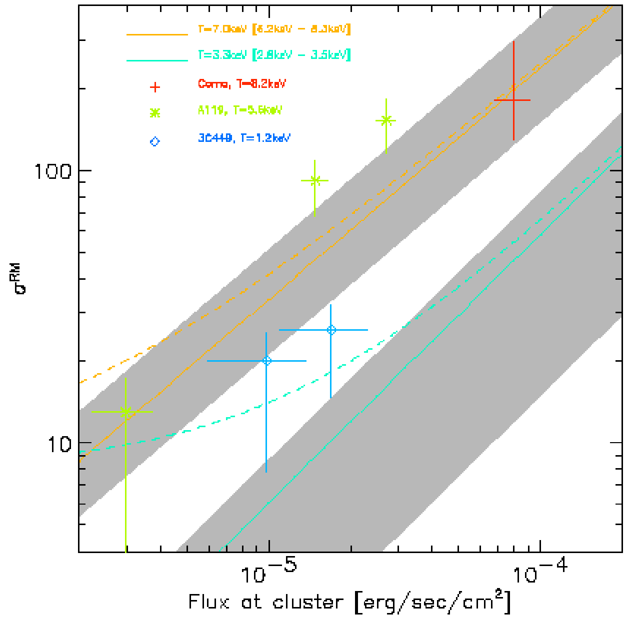
MFs in galaxy clusters





B correlates with the cluster temperature (i.e. with the mass) which agrees with the correlation observed between the cluster radio power and T_X

RMs vs X-ray luminosity



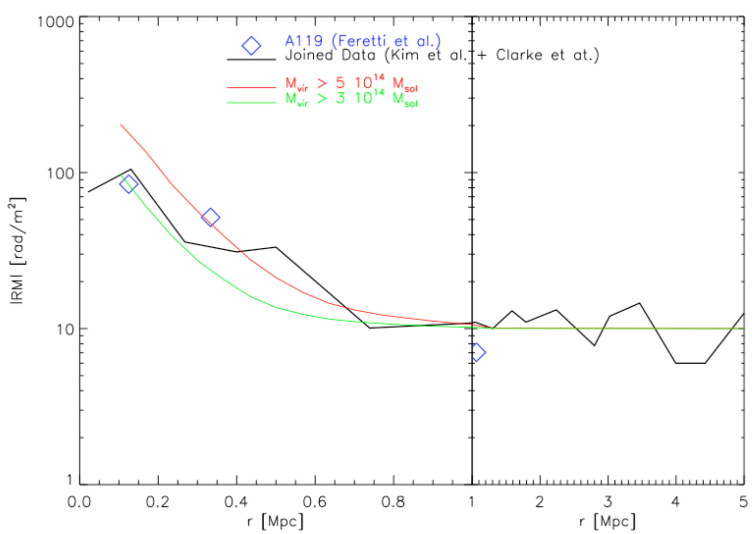
S_X □ $n_e^2 \sqrt{T}$ dx

□$_{RM}$ □ n_e $B_{\|}$ dx

Observations : □$_{RM}$ $S_X^{□}$

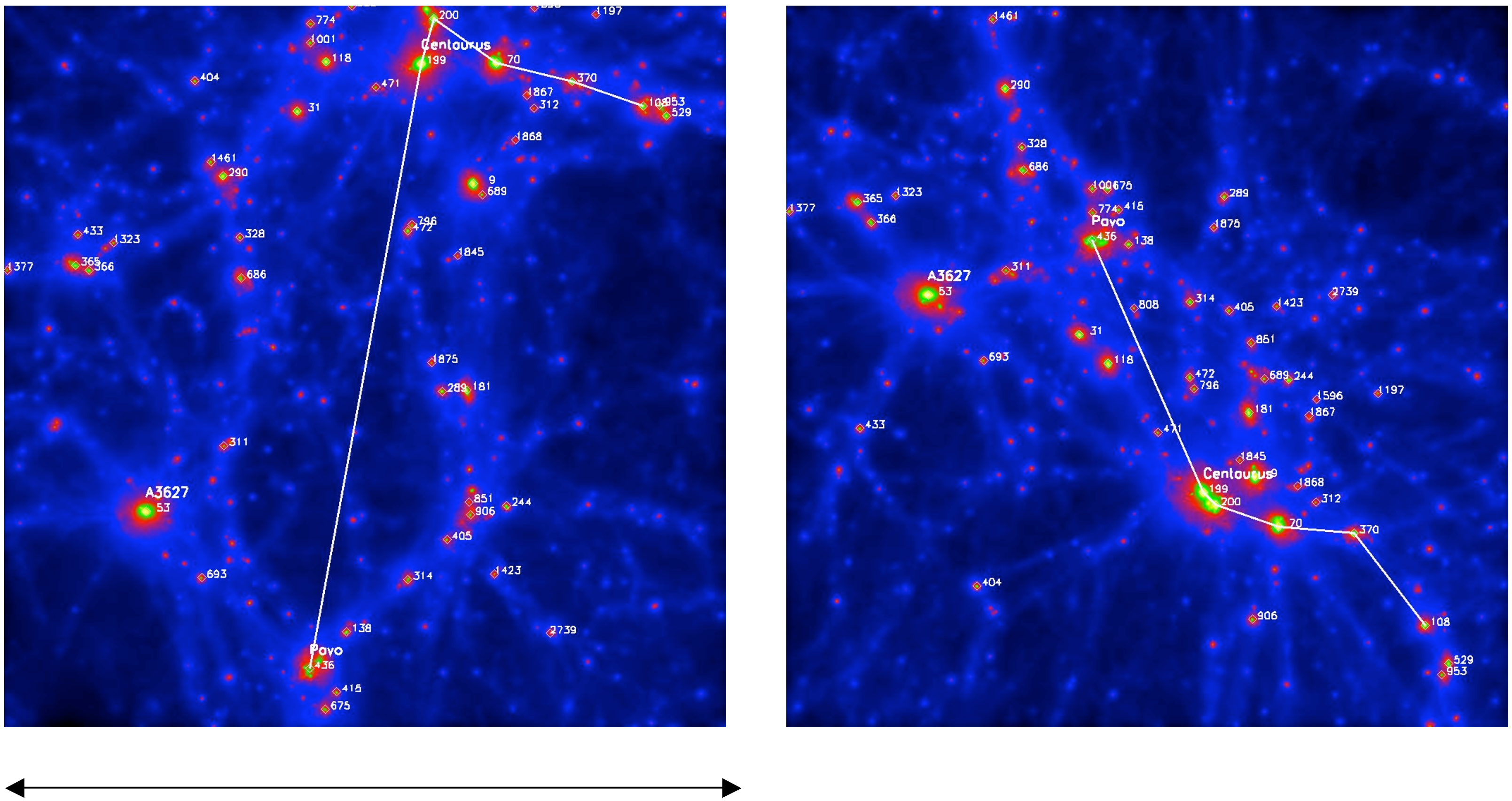
□ □1 □ B μ n_e

RMs radial profile



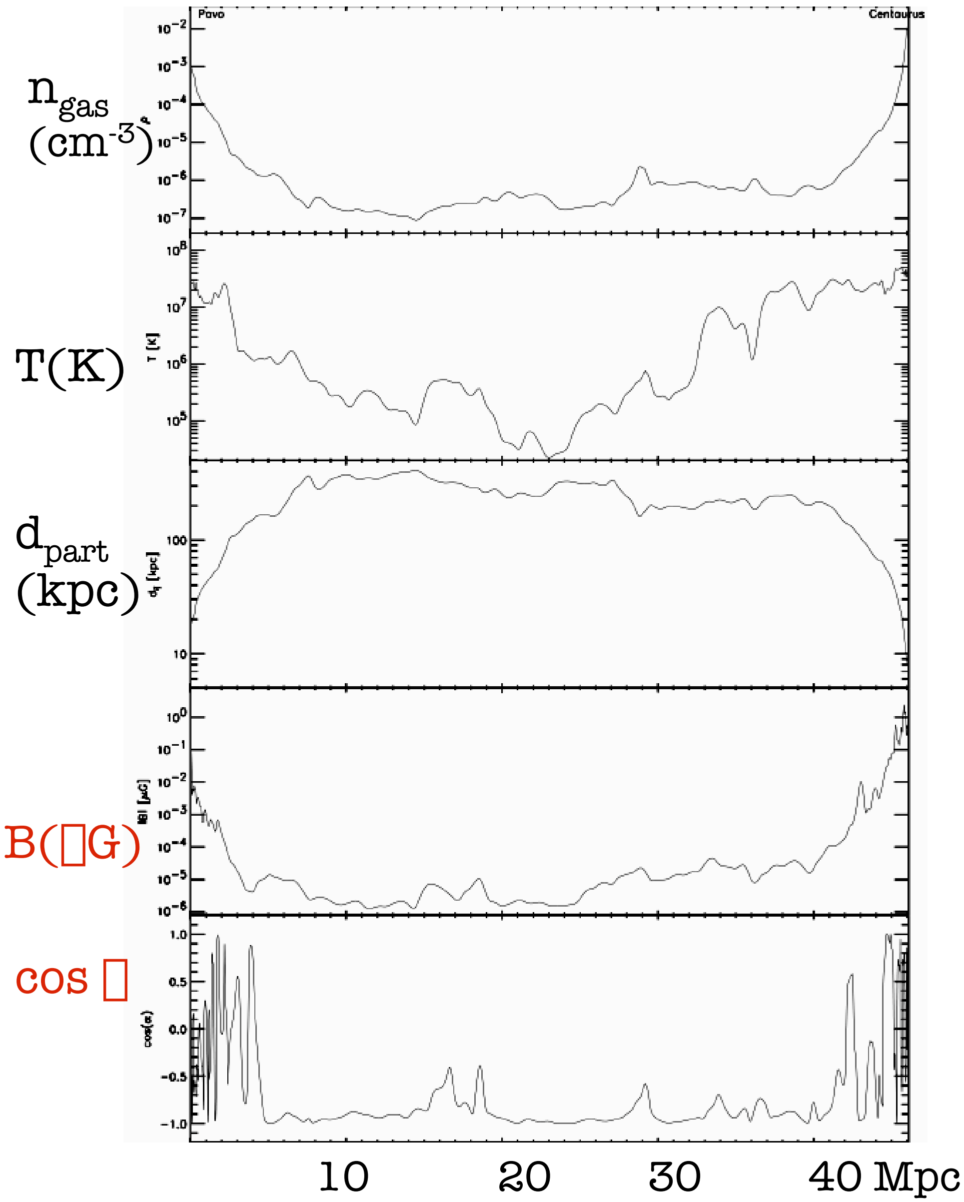
$B_0 = 2 \times 10^{-12}$ G (run 2: mhd_z)

MFs in the filaments and in the voids

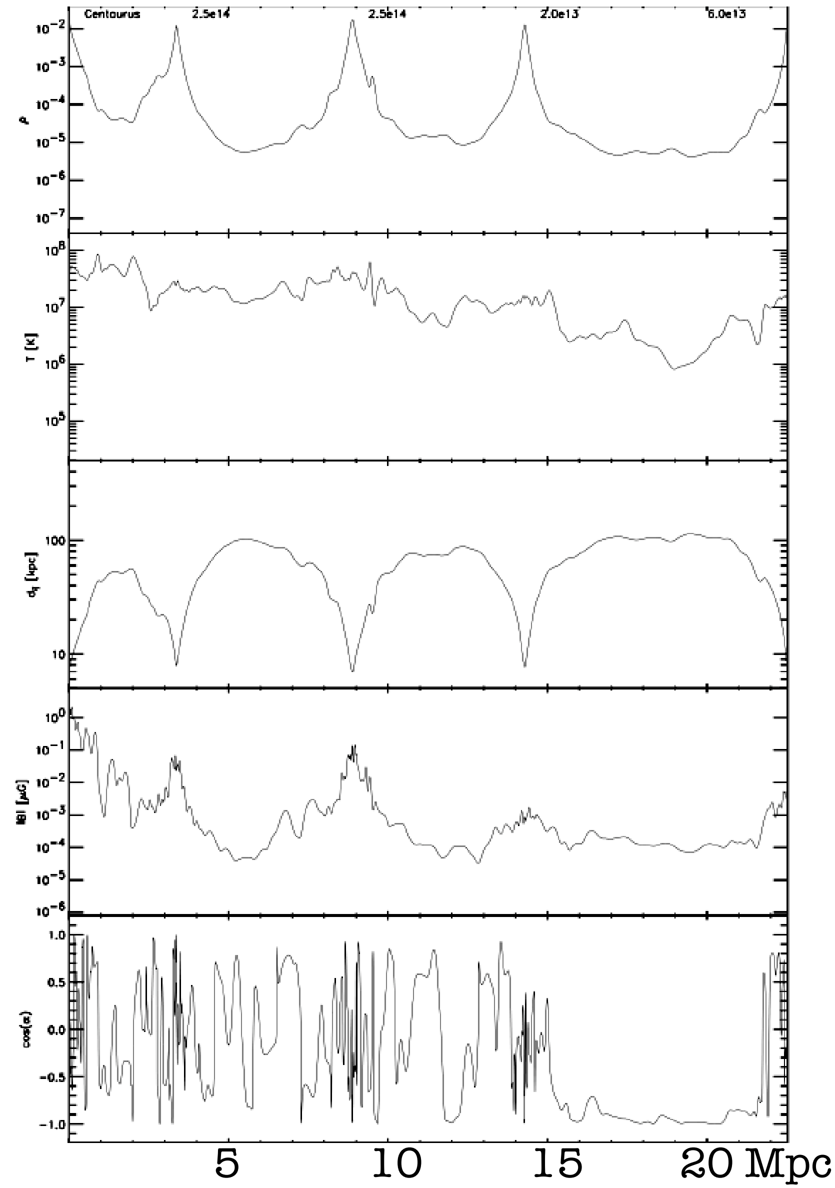


50 Mpc

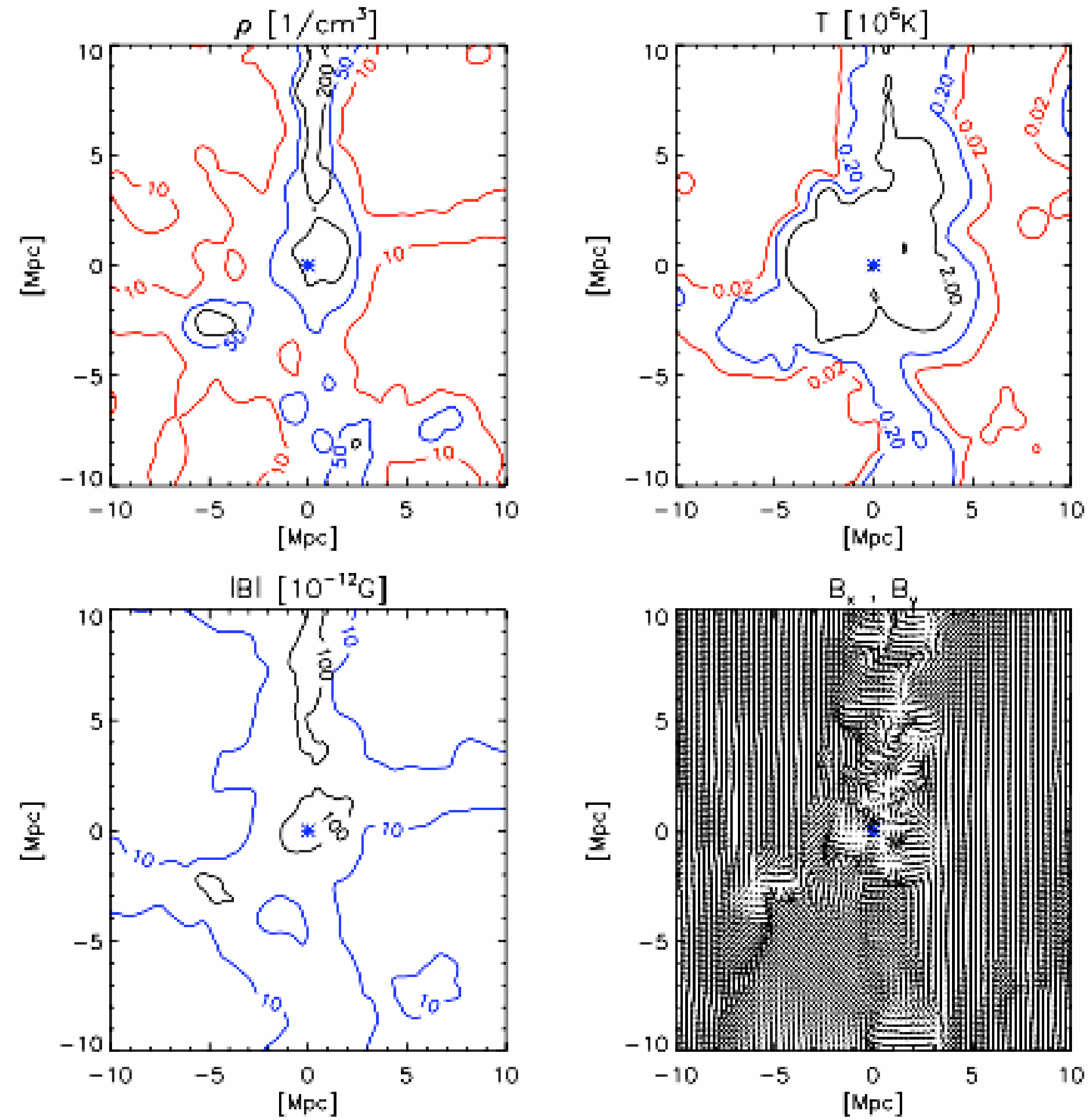
Void



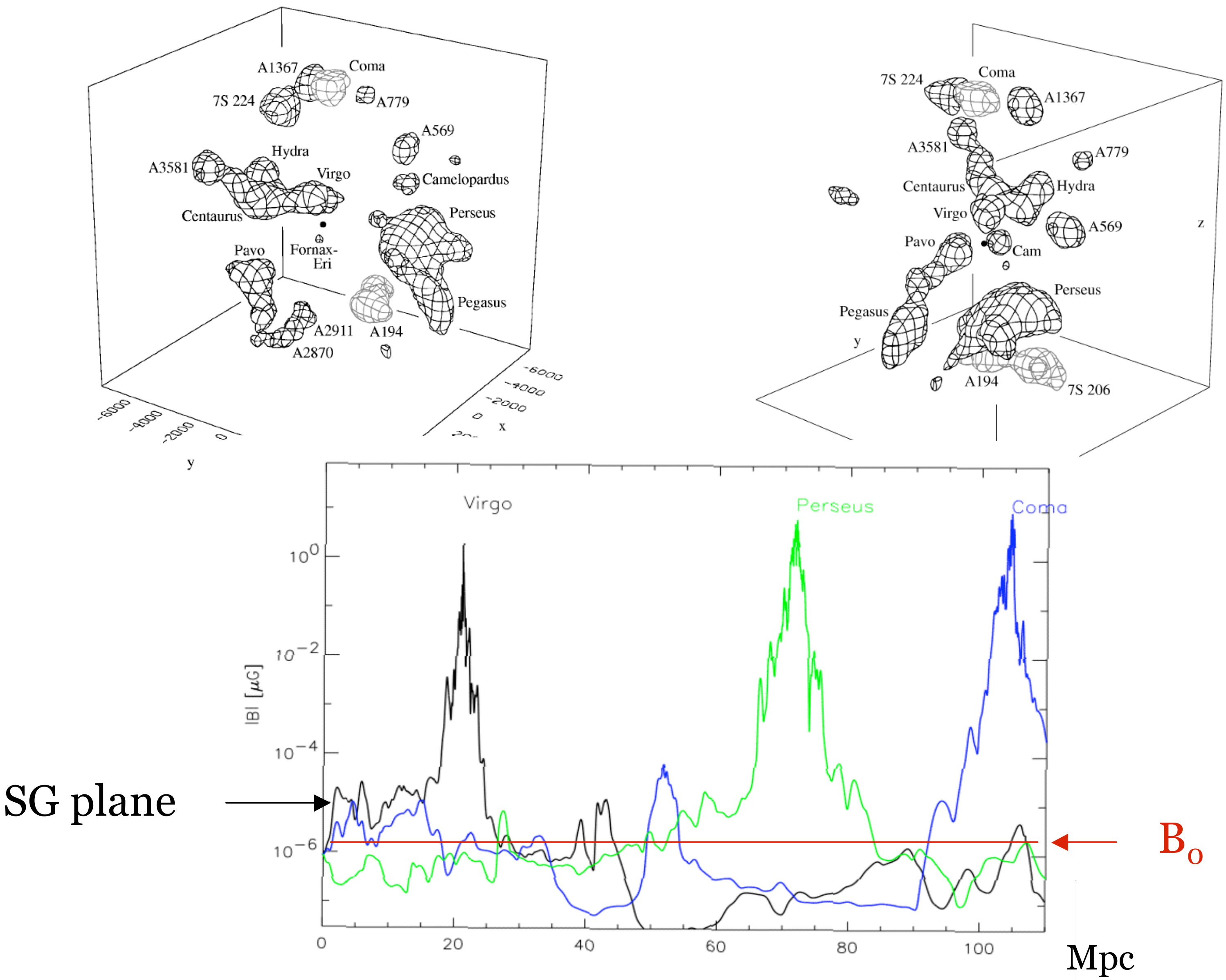
Filament



Across a filament



IGMFs in the Local Universe

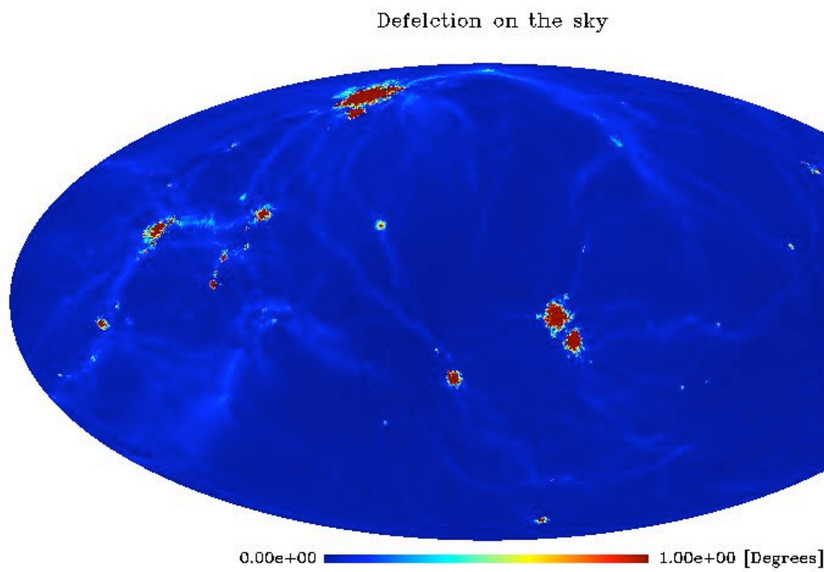


Construction of deflection maps

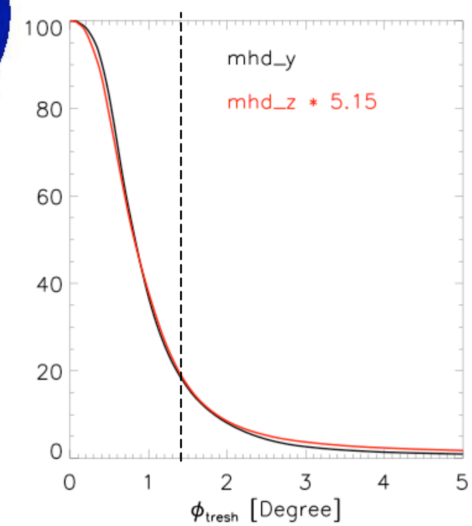
- Deflection are summed along straight lines converging from randomly distributed points at maximal distance (110 Mpc) to the observer
- Trajectories with □ > 5 ^{o} trajectories are ignored (small pitch angle only)
- We consider protons with $E = 4$ □ 10^{19} eV and $E = 10^{20}$ eV (arrival energy)
- Continuous energy losses are considered only for $E = 10^{20}$ eV

$E_{obs} = 10^{20}$ eV with energy losses

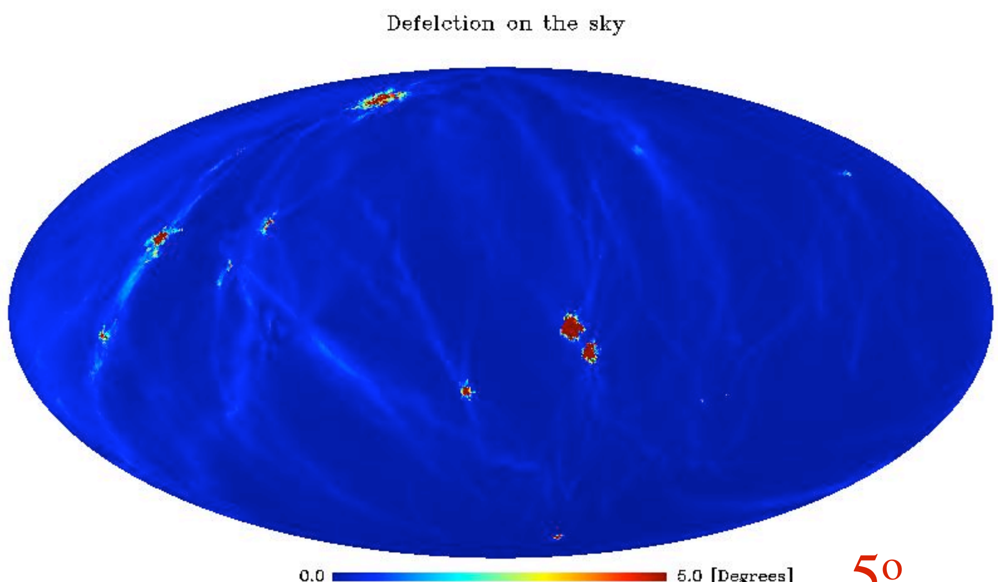
$B_0 = 2e10^{-12}$ G
mhd_z



1°

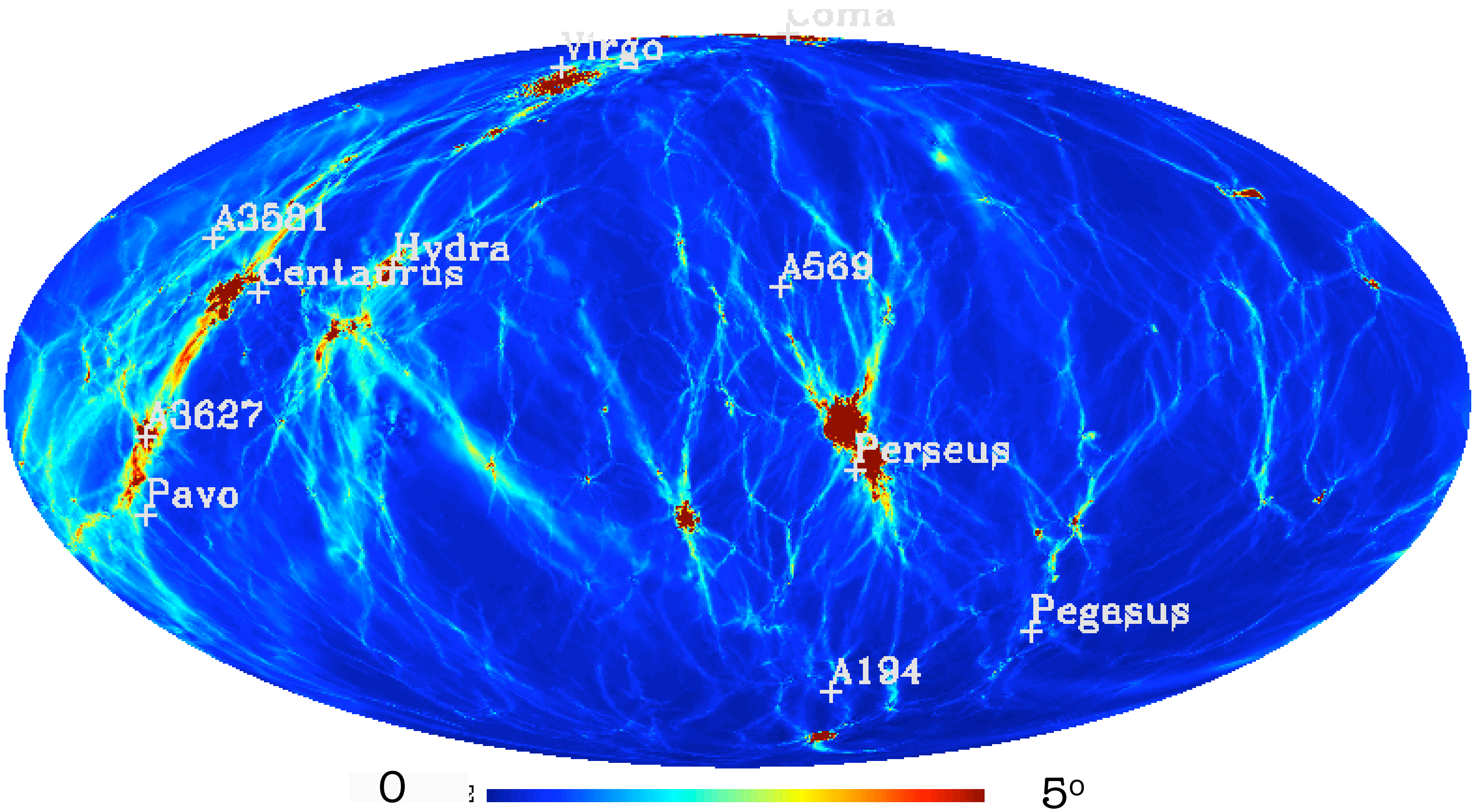


$B_0 = 10^{-11}$ G
mhd_y



5°

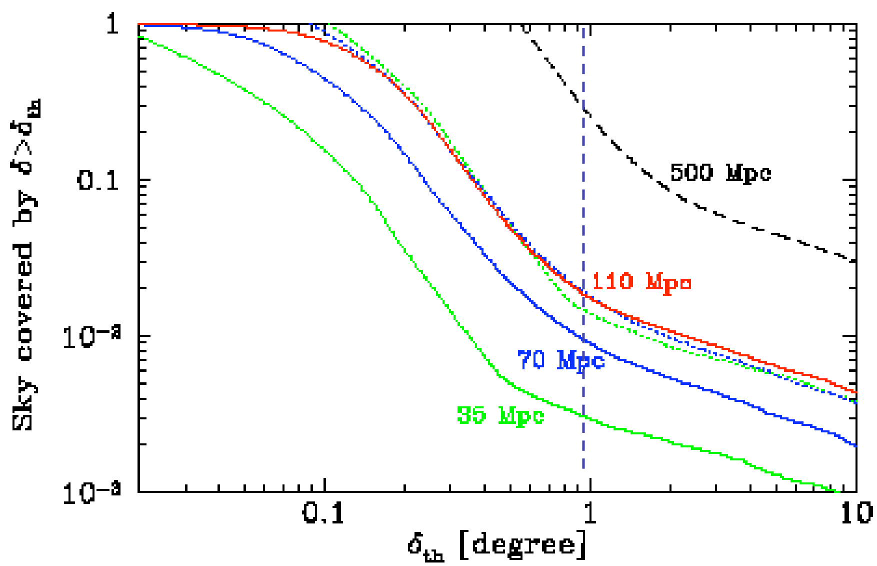
$E = 4 \times 10^{19}$ eV $B_0 = 10^{-11}$ G ("maximal") $d_s = 110$ Mpc



Sky fraction covered by observable deflections extrapolation at large distances

E = 4□10^{19} eV

B_0 = 2e10^{-12} G (mhd_z)



$$A(\delta_{\mathrm{th}}, d) = x^{-\beta} A_0(\delta_{\mathrm{th}} \times x^{\alpha})$$

$x = d_0/d$

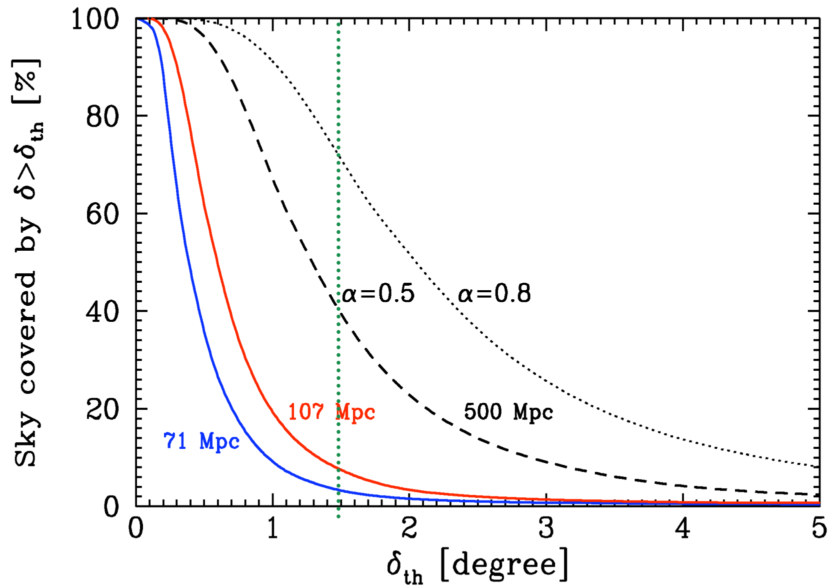
□ = 1 □ = 1/2 (random walk)

This behaviour is consistent with a uniform density of deflectors (filaments)

There is a considerable fraction of the sky where correlation with sources is preserved !!

Sky fraction covered by observable deflections extrapolation at large distances

$E = 4 \square 10^{19}$ eV $\quad B_0 = 10^{-11}$ G ("maximal")



Conclusions

- We constructed the first simulated maps of UHE proton deflection produced by MF in the LSS of the local universe
- These maps have to be intended as maps of <u>maximal deflections</u> produced under the hypothesis that the seed field was originated before major cluster accretion mergers
  (deflections are smaller if ICMFs are produced locally)
- Pointing of UHECR sources should not be prevented over almost the entire sky at 10^{20} eV independently on the structure of the seed field
- At smaller energies ~ 4×10^{19} eV deflections are mainly produced in filaments and sheets. Observable deflections may be produced over a significant fraction of the sky the exact amount depending on the structure of the seed field.
- The study of correlation with sources (e.g. BL Lacs) may allow to learn something on this structure, hence on the origin of EGMFs.