Magnetic Fields and propagation of UHECRs in the Local Universe

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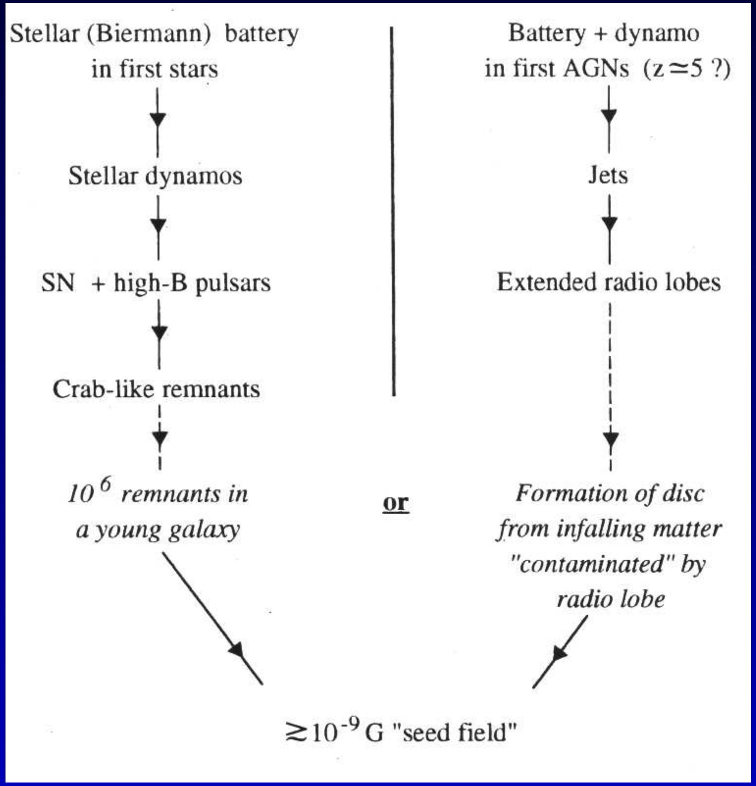
Cosmological Magnetic Fields

Origin

- Primordial
- Battery
- Dynamo (Turbulence)
- Stars
- Supernova
- Galactic Winds
- AGN, Jets
- Shocks



Rees 1994

+ further amplification by structure formation !

Cosmological Magnetic Fields

Questions

- Strength, Structure, Origin
- Evolution

$\Rightarrow$ Common Origin ?
Filament vs. Cluster, Cluster vs. cool Core, ...

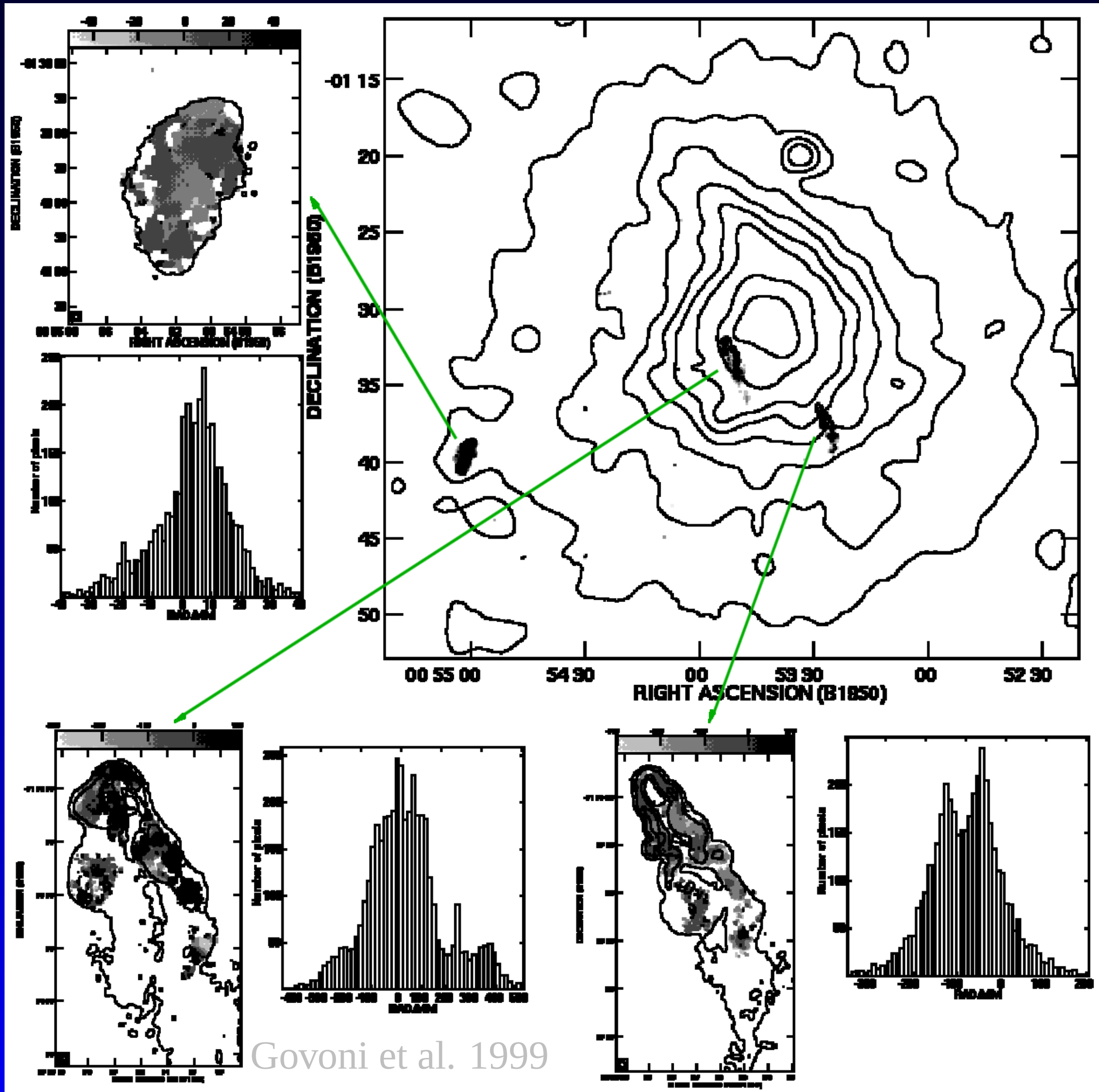
$\Rightarrow$ Relation to other LSS ”properties” ?

- scaling with density ($\propto \rho^{\alpha}$) ?
- scaling with temperature/mass ($\propto T^{\beta}$) ?
- length scales, $P_B(k)$ (Filaments, Cluster, cool Core) ?

$\Rightarrow$ Relation to dynamics ?

- Merger, Turbulence ?
- cool Core, Bubbles ?

Magnetic Fields (Observations)



A119

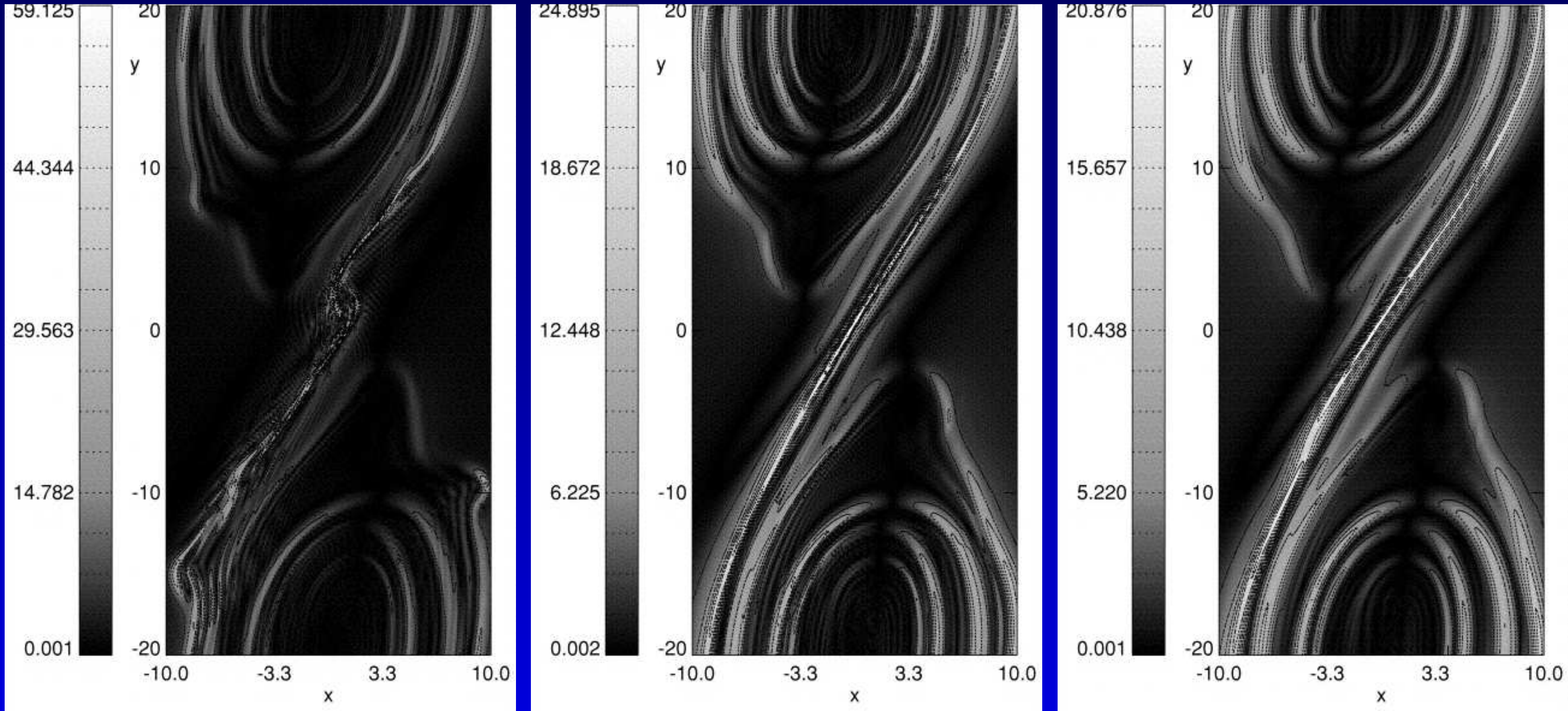
Faraday Rotation ⇒ $|B|$ of order of 10^{-6}G

KH driven amplification

Winds in galactic Halo:

$n = 1/\mathrm{cm}^3$, $B_0 \approx 10\mu G$, $v \approx 1000\mathrm{km/s}$

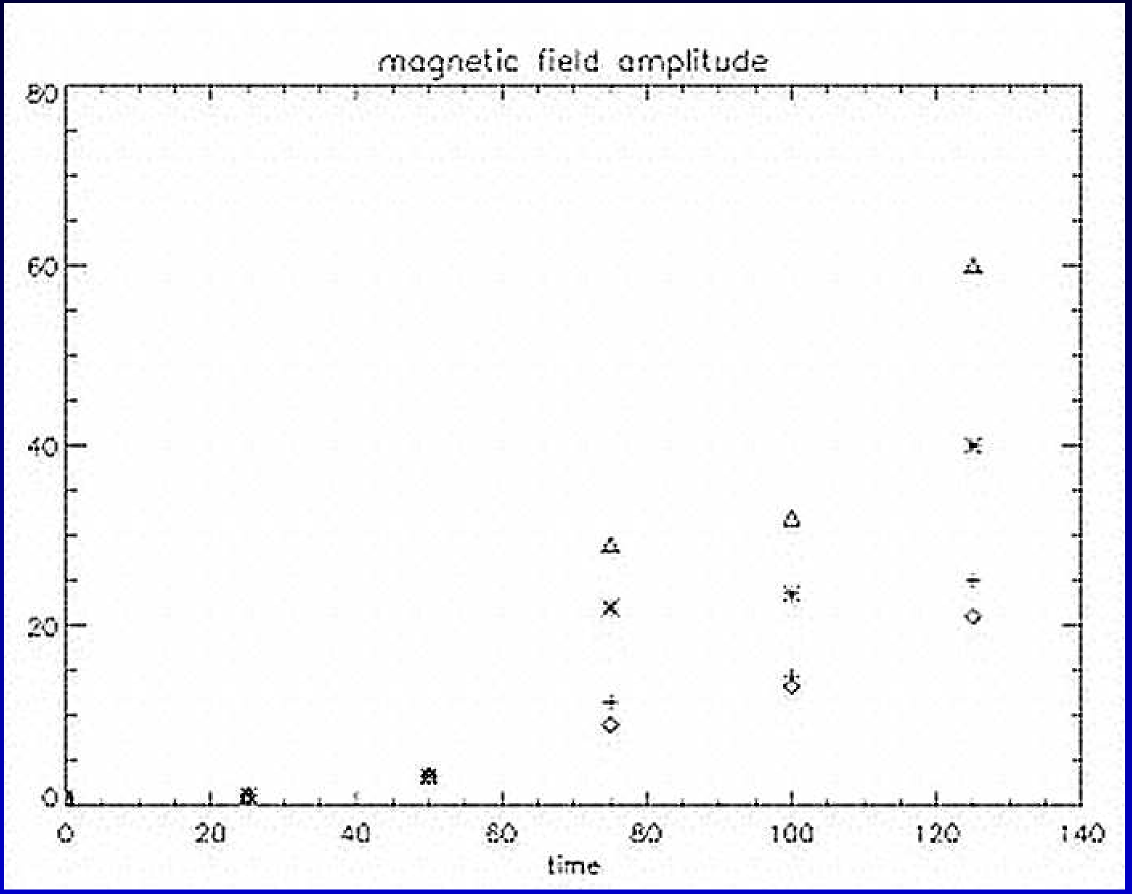
$\Rightarrow t_{\mathrm{KH}} \approx 4 \times 10^5\mathrm{Year}$



Birk et al. 1999

KH driven amplification

Large amplification of seed magnetic field !



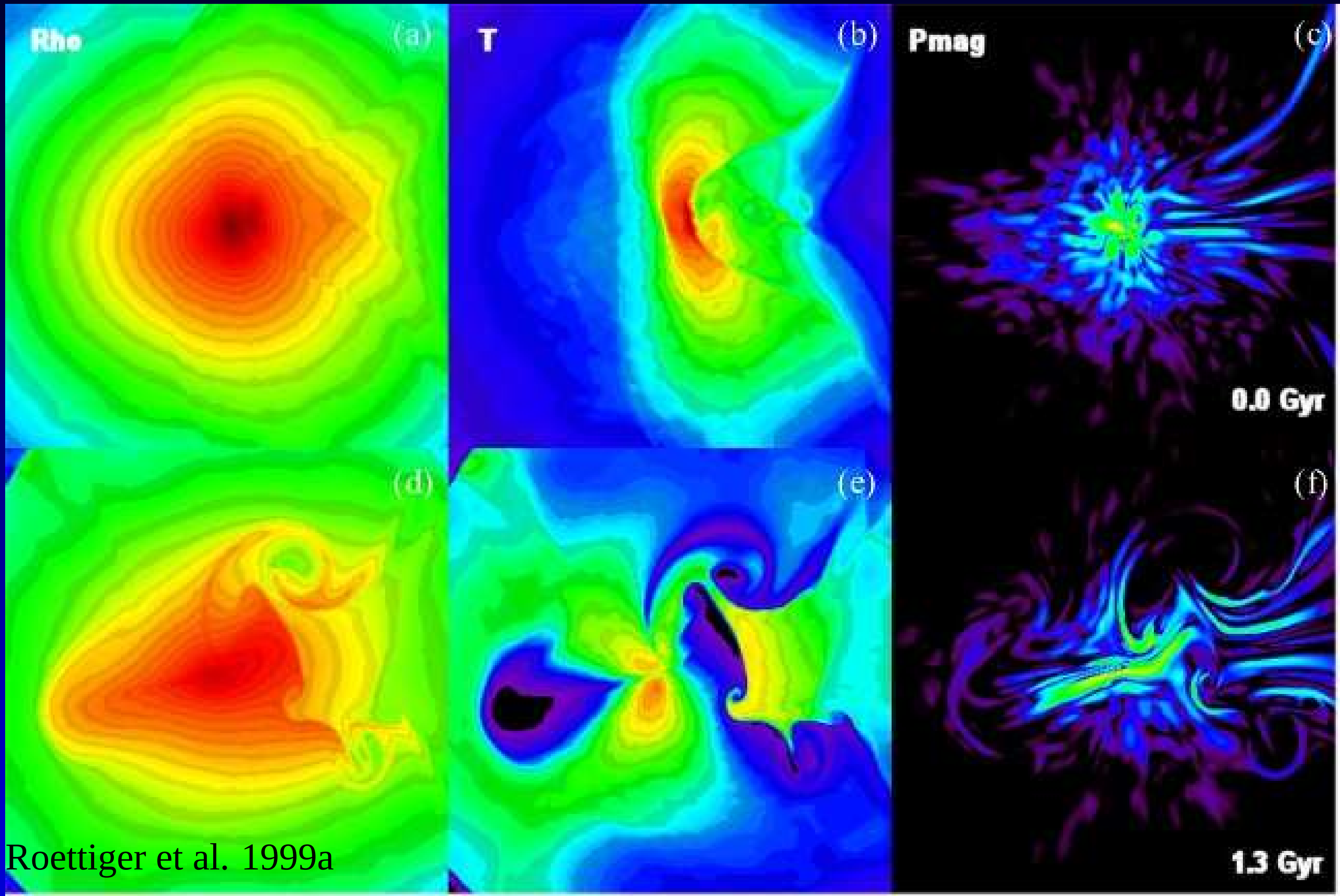
Birk et al. 1999

Should also work in galaxy cluster environment:

$n = 1 \times 10^{-3}/\mathrm{cm}^3$, $B_0 \approx 1\mu G$, $v \approx 1000\mathrm{km/s}$

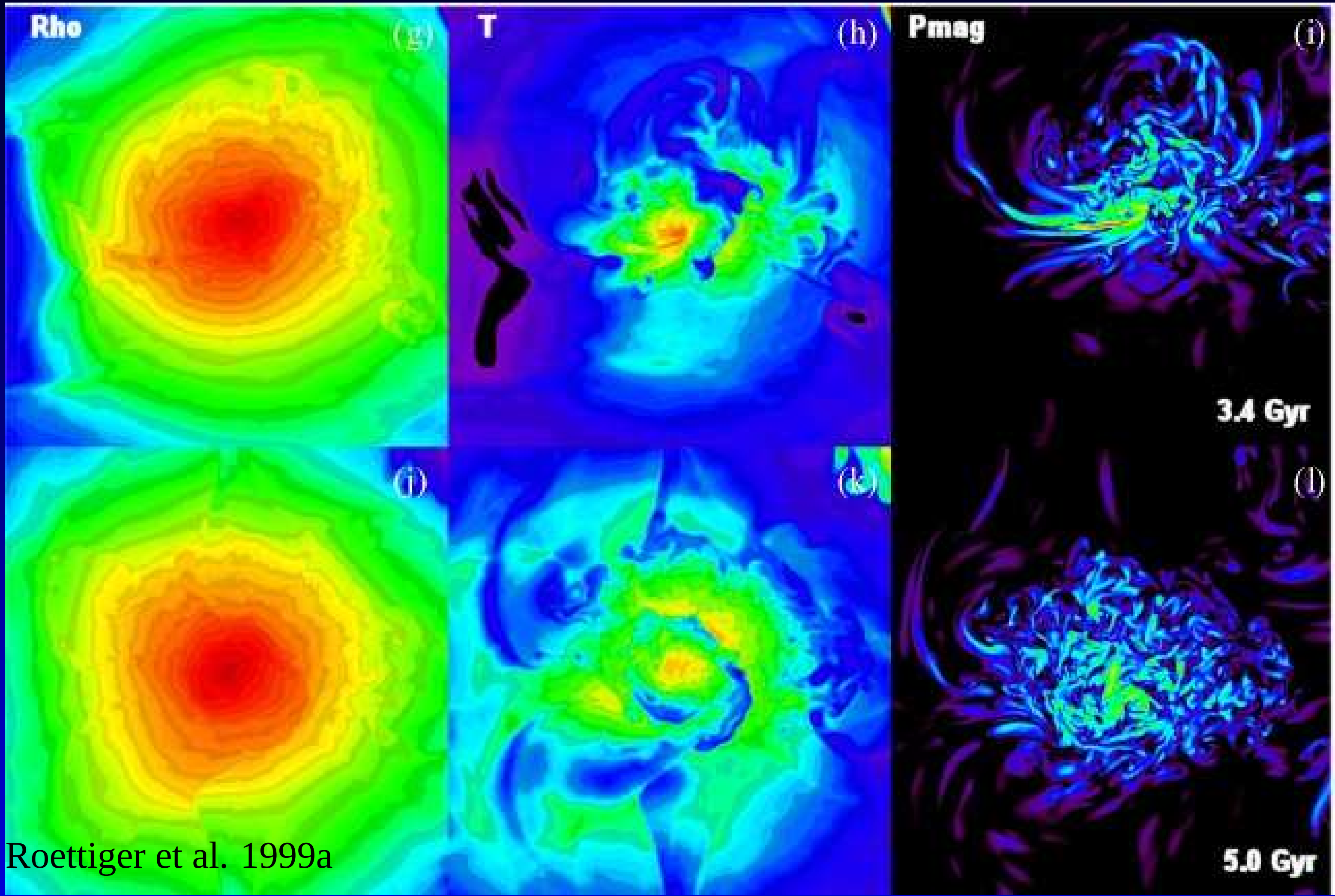
$\Rightarrow t_{\mathrm{KH}} \approx 0.1 \times 10^8 \mathrm{Year}$

Merging Clusters



- ZEUS, $3:1$ merger, $v = 2300$ km/s
- $\vec{B}$ becomes filamentary (by stretching)

Merging Clusters



- $\vec{B}$ rapidly amplified (turbulent motion)
- Locally up to a factor of 20-30 ($\vec{B}^2$!)

SPH (with Artificial viscosity)

Smoothed Particle Hydrpdynamic (SPH)

$$A(r) = \sum_{j=1}^{N} \frac{m_j}{\rho_j} A_j \, W(h_j, x_j - r) \;\; , \;\; \frac{\mathrm{d}A}{\mathrm{d}x} \Rightarrow \nabla W$$

GADGET-2 implementation of force (incl. art. viscosity)

$$\frac{\mathrm{d}v_i}{\mathrm{d}t} = \; + \; \sum_{j=1}^{N} m_j \left[f_i^{co} \frac{P_i}{\rho_i^2} \vec{\nabla}_i W_{ij}(h_i) + f_j^{co} \frac{P_j}{\rho_j^2} \vec{\nabla}_i W_{ij}(h_j) \right]$$

$$- \; \sum_{j=1}^{N} m_j \Pi_{ij} \nabla_i \bar{W}_{ij},$$

and rate of entropy change

$$\frac{\mathrm{d}A_i}{\mathrm{d}t} = \frac{1}{2} \frac{\gamma - 1}{\rho_i^{\gamma-1}} \sum_{j=1}^{N} m_j \Pi_{ij} \vec{v}_{ij} \cdot \nabla_i \bar{W}_{ij},$$

SPH (with Artificial viscosity)

Classical artificial viscosity in SPH containing

- bulk viscosity ($\propto \vec{\nabla} \cdot \vec{v}$)
- Von Neumann-Richtmyer viscosity ($\propto (\vec{\nabla} \cdot \vec{v})^2$)

$$\Pi_{ij} = \frac{-\alpha c_{ij}\mu_{ij} + 2\alpha\mu_{ij}^2}{\rho_{ij}} f_{ij}$$

if particles approach ($\vec{r}_{ij} \cdot \vec{v}_{ij} \leq 0$) (Monaghan & Gingold 1983, Balsara 1995)

$$\mu_{ij} = \frac{h_{ij}\vec{v}_{ij} \cdot \vec{r}_{ij}}{\vec{r}_{ij}^2 + \eta^2}.$$

$$f_i = \frac{\left|\left\langle \vec{\nabla} \cdot \vec{v} \right\rangle_i\right|}{\left|\left\langle \vec{\nabla} \cdot \vec{v} \right\rangle_i\right| + \left|\left\langle \vec{\nabla} \times \vec{v} \right\rangle_i\right| + \sigma_i}$$

as viscosity-limiter (Steinmetz 1996).

SPH (with Artificial viscosity)

A variant of based on analogy with Riemann solution

$$\mu_{ij} = \frac{\vec{v}_{ij} \cdot \vec{r}_{ij}}{|\vec{r}_{ij}|}$$

with signal velocity

$$v_{ij}^{\rm sig} = c_i + c_j - 3\mu_{ij}$$

leads to

$$\Pi_{ij} = \frac{-0.5\alpha v_{ij}^{sig}\mu_{ij}}{\rho_{ij}} f_{ij}$$

(Monaghan 1997).

- Now standard viscosity in GADGET-2
- Improvement in all tests done so far

SPH (with Artificial viscosity)

A time varying viscosity $\alpha(t)$:

$$\frac{\mathrm{d}\alpha_i}{\mathrm{d}t} = -\frac{\alpha_i - \alpha_{\min}}{\tau} + S_i.$$

with decay time

$$\tau = h_i \,/\, (c_i \, l),$$

and source term

$$S_i = S^* f_i \, \max(0, -| \left\langle \vec{\nabla} \cdot \vec{v} \right\rangle_i |)$$

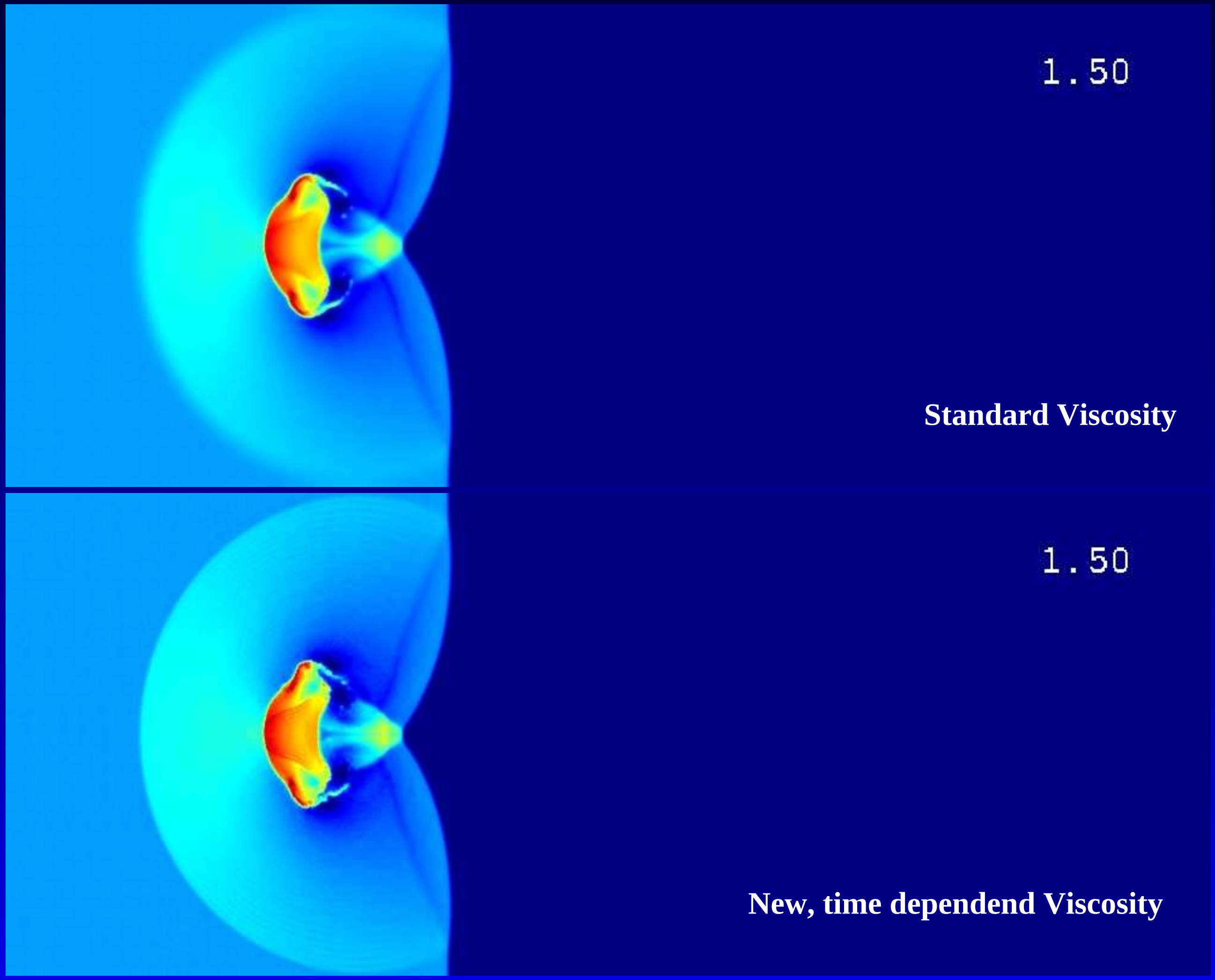
(Morris & Monaghan 1997).

Slightly changed by replacing c_i by v_{max}^{sig}.

- Fully implemented in GADGET-2 !
- Important to resolve Turbulence (Dolag et al. 2005) !

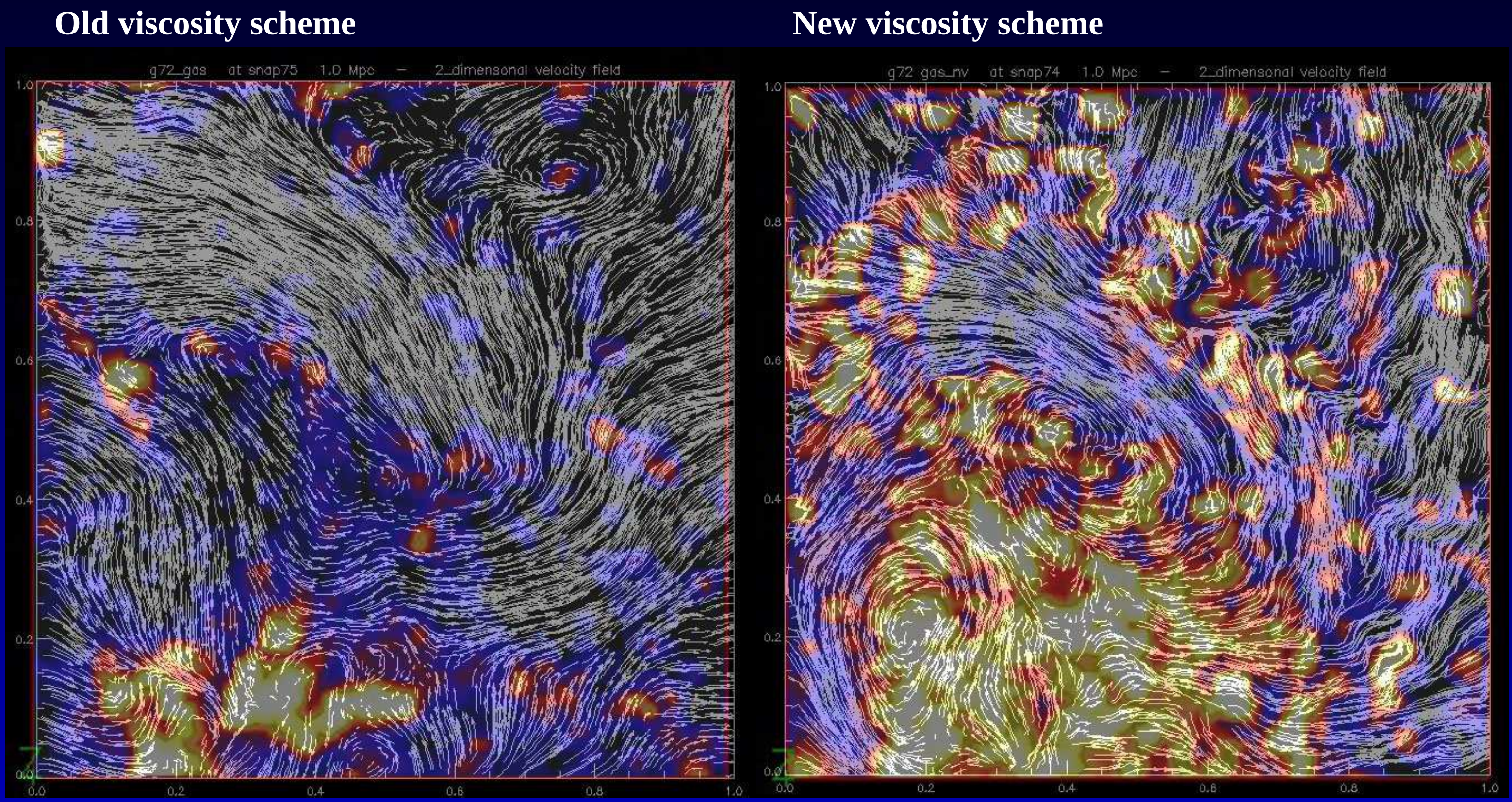
SPH (with Artificial viscosity)

Interaction of a strong shock wave with an overdense cloud:



⇒ Quest for turbulence in galaxy clusters !

Turbulence in cluster



- Instabilities less damped (e.g. Kelvin-Helmholtz).

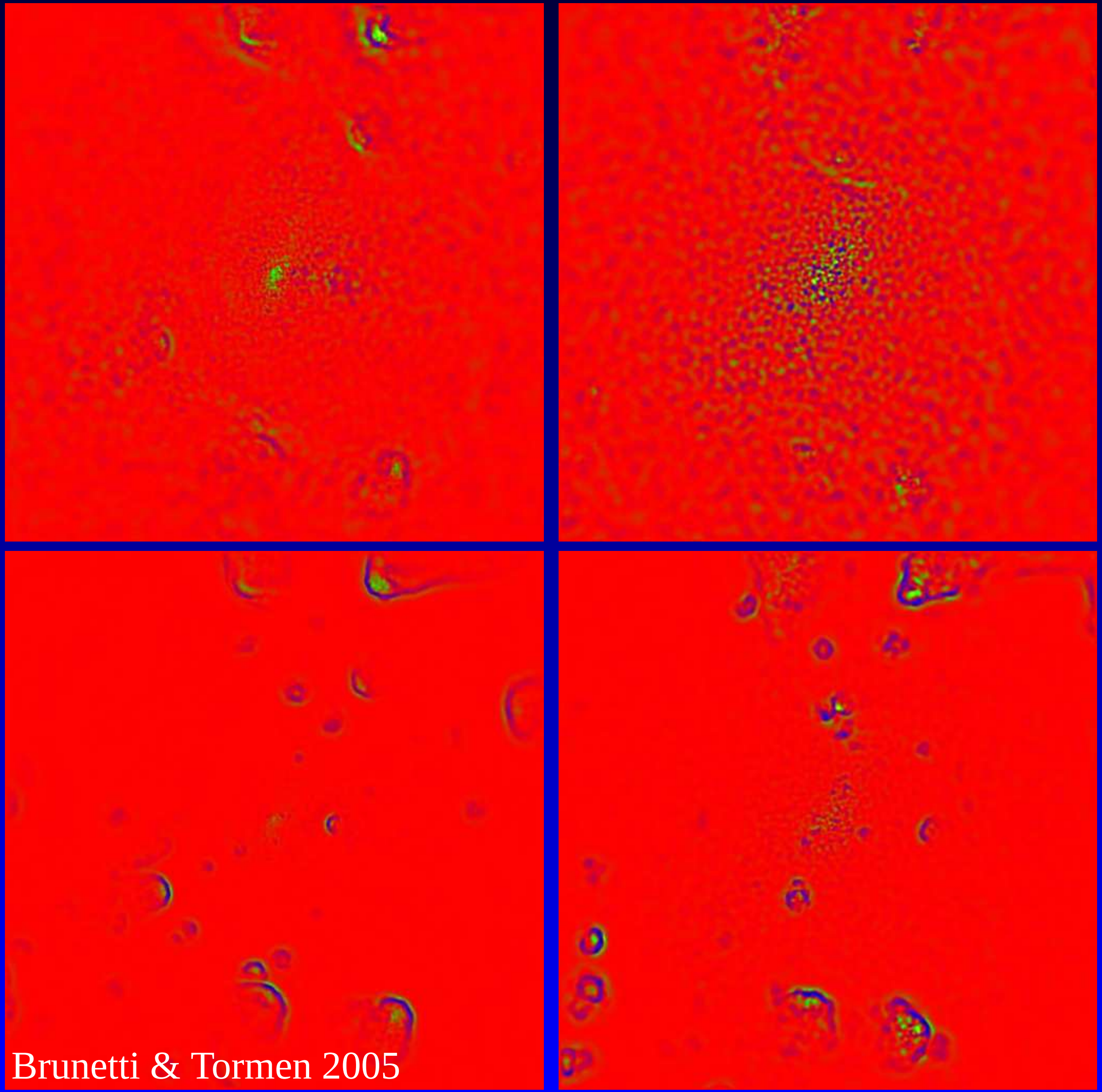
⇒ Inset of turbulence

⇒ Enlarged energy-fraction in gas velocity

Dolag, Vazza, Brunetti & Tormen 2005

Turbulence in cluster

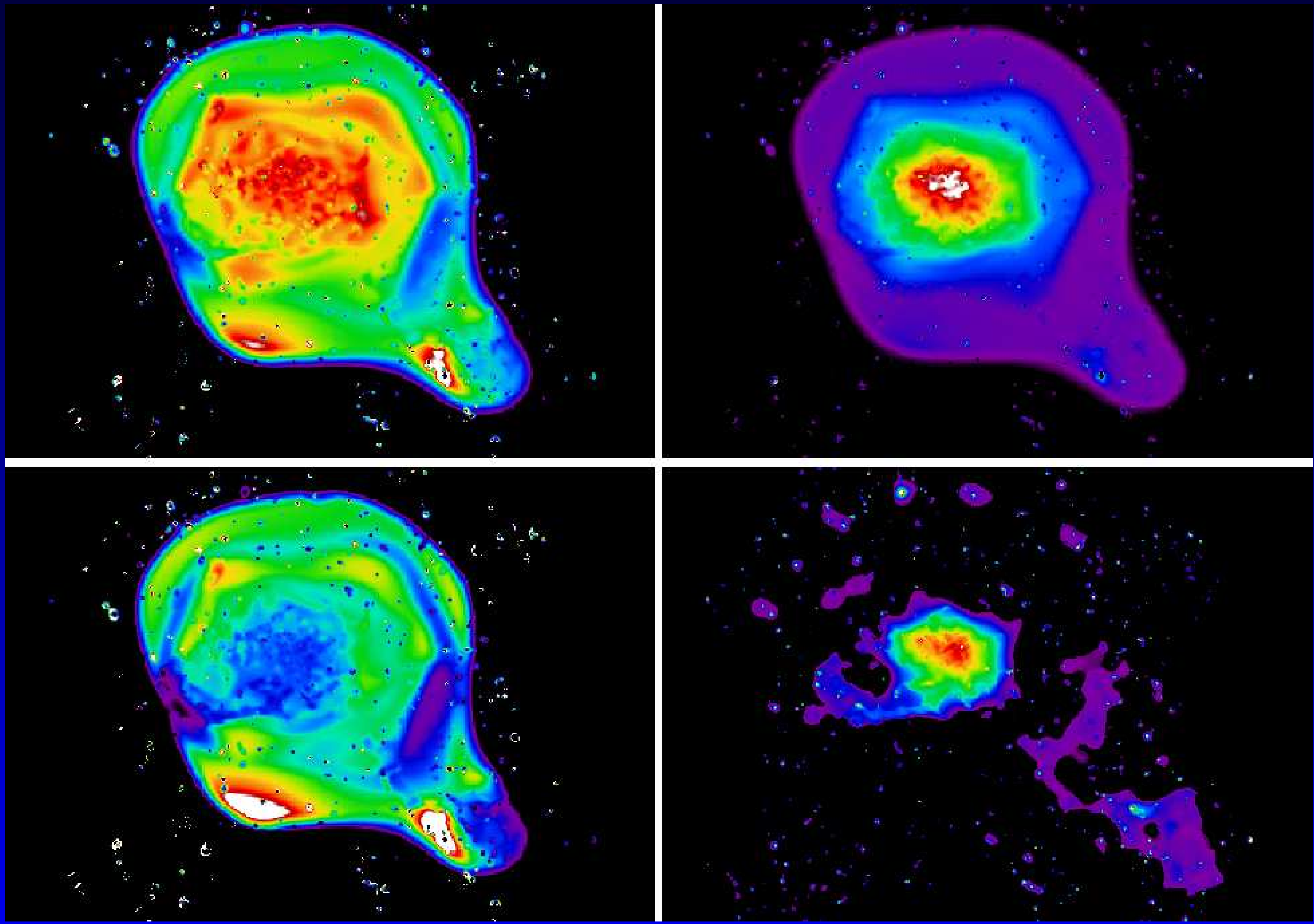
Unsharp mask images of pressure maps of one massive clusters:



Dolag, Vazza, Brunetti & Tormen 2005

Turbulence in cluster

x-Ray observation of Coma cluster:



Schuecker et al. 2004

MHD in SPH

Induction equation ($-\vec{B}(\vec{\nabla}\cdot\vec{v}) + (\vec{B}\cdot\vec{\nabla})\vec{v}$):

$$\frac{\mathrm{d}\vec{B}_i}{\mathrm{d}t} = \frac{f_i^{co}}{Ha^2\rho_i}\sum_{j=1}^{N} m_j\left[\vec{B}_i(\vec{v}_{ij}\cdot\vec{\nabla}_i\bar{W}_{ij}) - \vec{v}_{ij}(\vec{B}_i\cdot\vec{\nabla}_i\bar{W}_{ij})\right] - 2\vec{B}_i$$

($\frac{1}{Ha^2} = \frac{\mathrm{d}t}{\mathrm{d}a}$) and magnetic Lorenz force

$$\frac{\mathrm{d}\vec{v}_i}{\mathrm{d}t} = a^{3\gamma}\frac{1}{\mu_0}\sum_{j=1}^{N} m_j\left[f_i^{co}\frac{M_i}{\rho_i^2}\cdot\vec{\nabla}_i\bar{W}_i + f_j^{co}\frac{M_j}{\rho_j^2}\cdot\vec{\nabla}_j\bar{W}_j\right]$$

$$M_i^{kl} = \left(\vec{B}_i^k\vec{B}_i^l - \frac{1}{2}|\vec{B}_i|^2\delta^{kl}\right)$$

with $a^{3\gamma} = \frac{\mathrm{d}t}{\mathrm{d}\eta}$.

$\Rightarrow$ Instable in magnetic field dominated situations !!

MHD in SPH

Does not work proper in 3D:

- Anti clumping term (Monaghan 2000, Morris 2001):

$$M_i^{kl} = \left(\vec{B}_i^k \vec{B}_i^l - \frac{1}{2} |\vec{B}_i|^2 \delta^{kl} - R_i \vec{B}_i^k \vec{B}_i^l \right)$$

$$R_i = \frac{\epsilon}{2} \left(\frac{W_{ij}}{W_1} \right)^n$$

$$u_1 = \left(\frac{4\pi}{3} \frac{1}{N} \right)^{1/3}$$

  as artificial repulsive, very short range magnetic force.

- Particle splitting (Brove et al. 2004)

MHD in SPH

Work proper in 3D:

- Subtraction of unphysical $\vec{\nabla} \cdot \vec{B}$ component in force term

  (Brove et al. 2004)

$$\frac{\mathrm{d}\vec{v}_i}{\mathrm{d}t} = -\frac{a^{3\gamma}}{\mu_0}\vec{B}_i \sum_{j=1}^{N} m_j \left[f_i^{co} \frac{\vec{B}_i}{\rho_i^2} \cdot \vec{\nabla}_i \bar{W}_i + f_j^{co} \frac{\vec{B}_j}{\rho_j^2} \cdot \vec{\nabla}_j \bar{W}_j \right]$$

  (SPH equivalent to $\vec{B}(\vec{\nabla} \cdot \vec{B})/\rho$).

- Periodically smoothing of $\vec{B}$ (Brove et al. 2004).

MHD in SPH

Artificial magnetic dissipation:

$$\left(\frac{\mathrm{d}\vec{B}_i}{\mathrm{d}t}\right)_{\mathrm{d}} = a^{3\gamma}\frac{\rho_i\alpha_B}{2}f_i^{co}\sum_{j=1}^{N} m_j \frac{v_{ij}^{sig}}{\hat{\rho}_{ij}^2}\left(\vec{B}_i - \vec{B}_j\right)\frac{\vec{r}_{ij}}{|\vec{r}_{ij}|}\cdot\vec{\nabla}_i\bar{W}_{ij}$$

thereby induced entropy change:

$$\left(\frac{\mathrm{d}A_i}{\mathrm{d}t}\right)_{\mathrm{d}} = \frac{(1-\gamma)f_i^{co}\alpha_B}{8\rho_i^{\gamma-1}Ha^2\mu_0}\sum_{j=1}^{N} m_j \frac{v_{ij}^{sig}}{\hat{\rho}_{ij}^2}\left(\vec{B}_i - \vec{B}_j\right)^2\frac{\vec{r}_{ij}}{|\vec{r}_{ij}|}\cdot\vec{\nabla}_i\bar{W}_{ij}$$

In analogy to the viscosity $\alpha_B \rightarrow \alpha_B(t)$:

$$\frac{\mathrm{d}\alpha_B}{\mathrm{d}t} = -\frac{\alpha_B - \alpha_{\min}}{\tau} + S_B.$$

with a source term $S_B = S_B^* \frac{\left|\vec{\nabla}\cdot\vec{B}\right|}{\sqrt{\mu_0\rho}}$

(Price & Monaghan 2004/2005).

MHD in SPH

- $\vec{\nabla} \cdot \vec{B}$ cleaning

$$\frac{\mathrm{d}\vec{B}}{\mathrm{d}t} = -\vec{B}(\vec{\nabla} \cdot \vec{v}) + (\vec{B} \cdot \vec{\nabla})\vec{v} - \vec{\nabla}\psi$$

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = -c_h^2(\vec{\nabla} \cdot \vec{B}) - \frac{\psi}{\tau}$$

  propagation and diffusion of $\vec{\nabla} \cdot \vec{B}$.

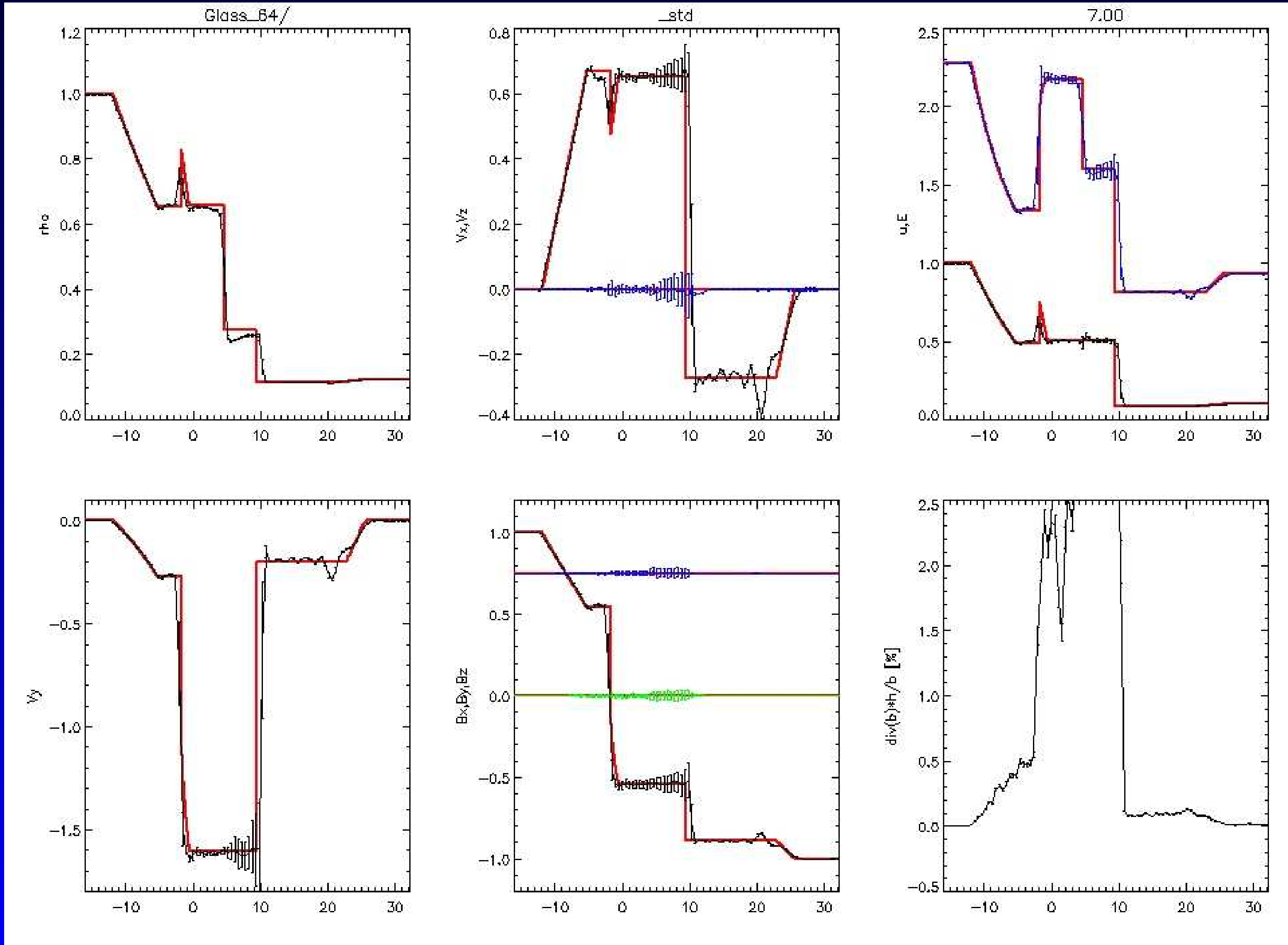
  (Dedner et al. 2002, Price & Monaghan 2004/2005)

- Projection methodes (non local !)

  (Price & Monaghan 2004/2005)

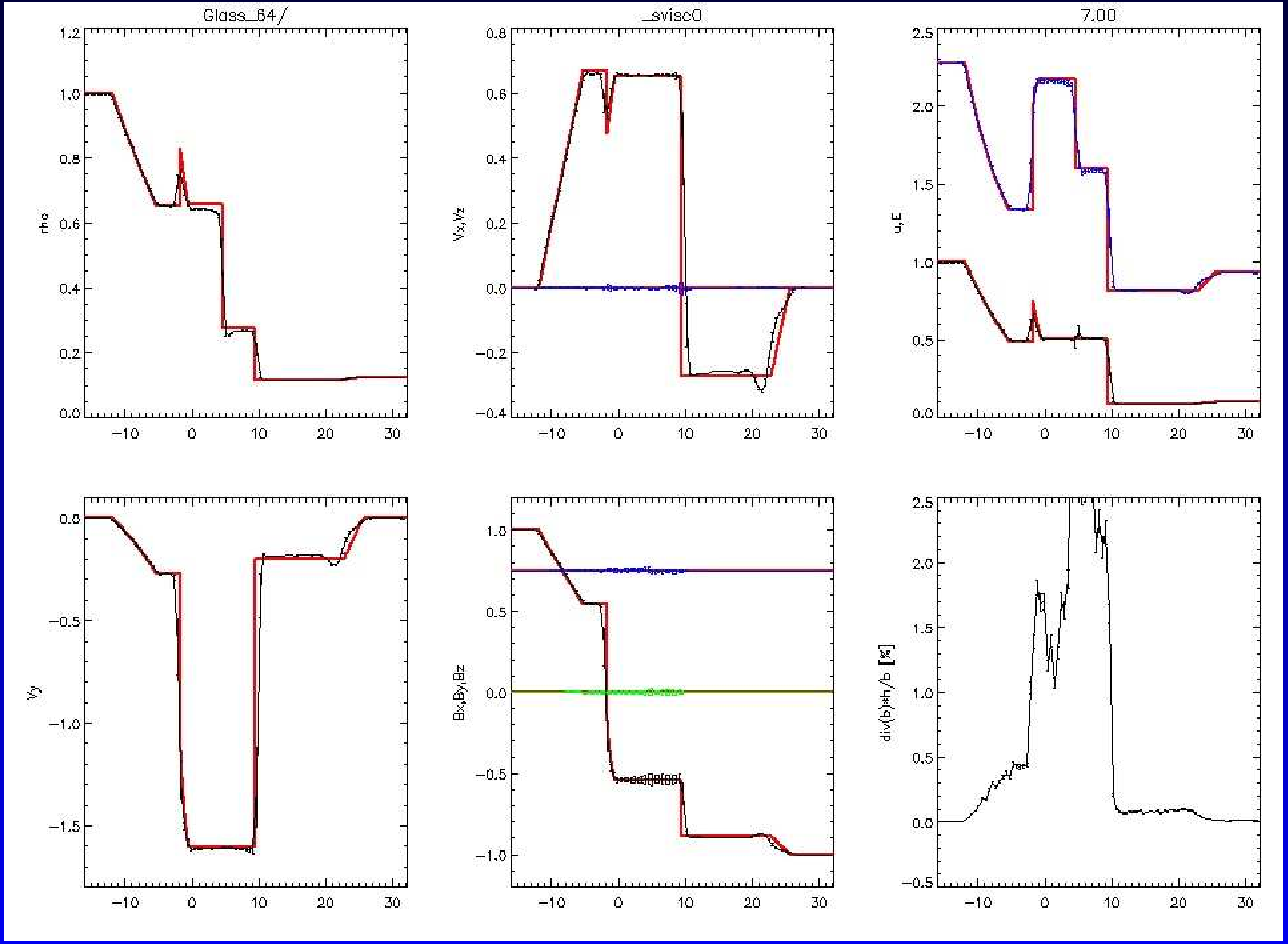
Brio & Wu shock tube

Standard SPH-MHD, no smoothing:



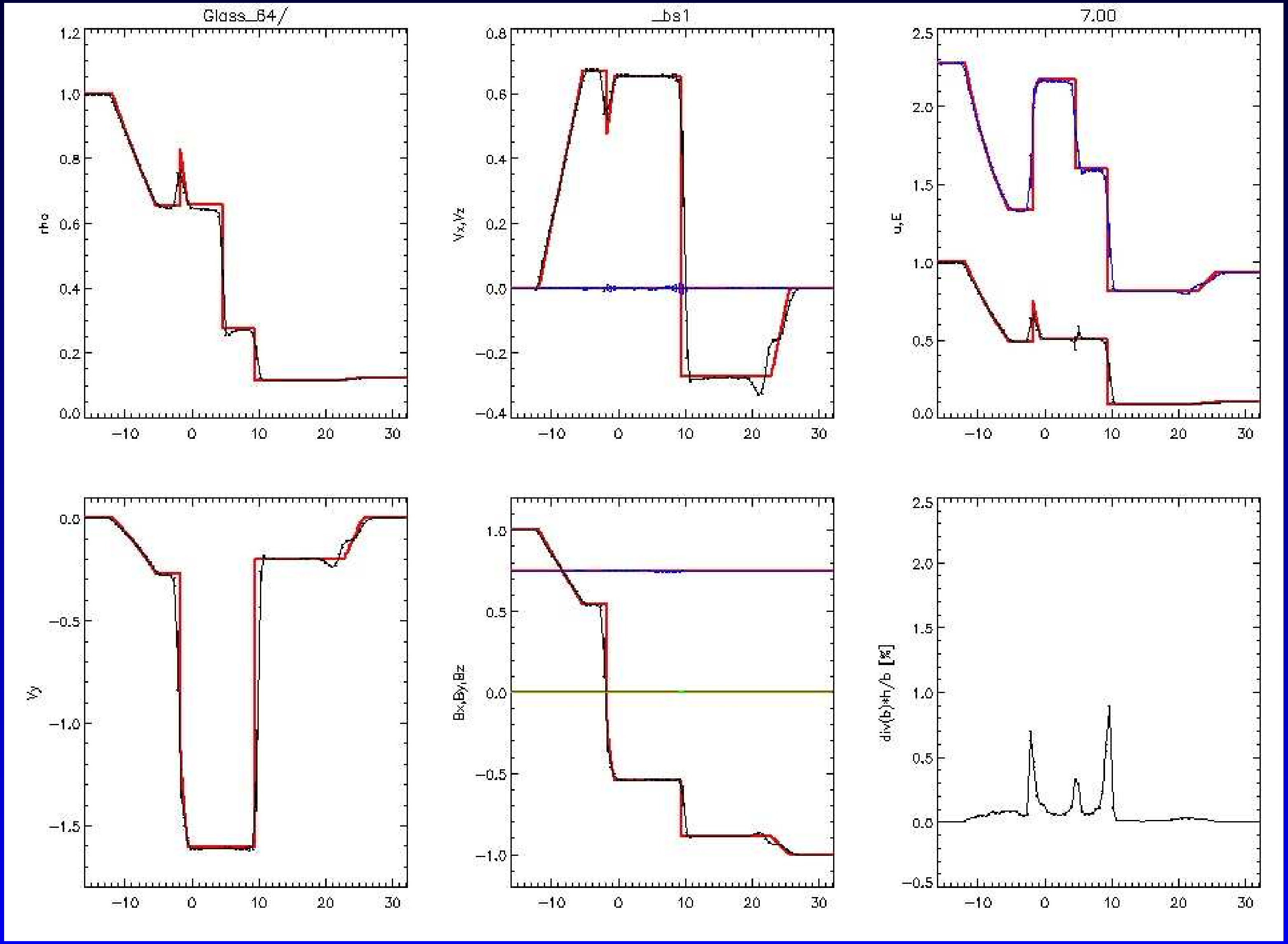
Brio & Wu shock tube

SPH-MHD, but no viscosity-limiter



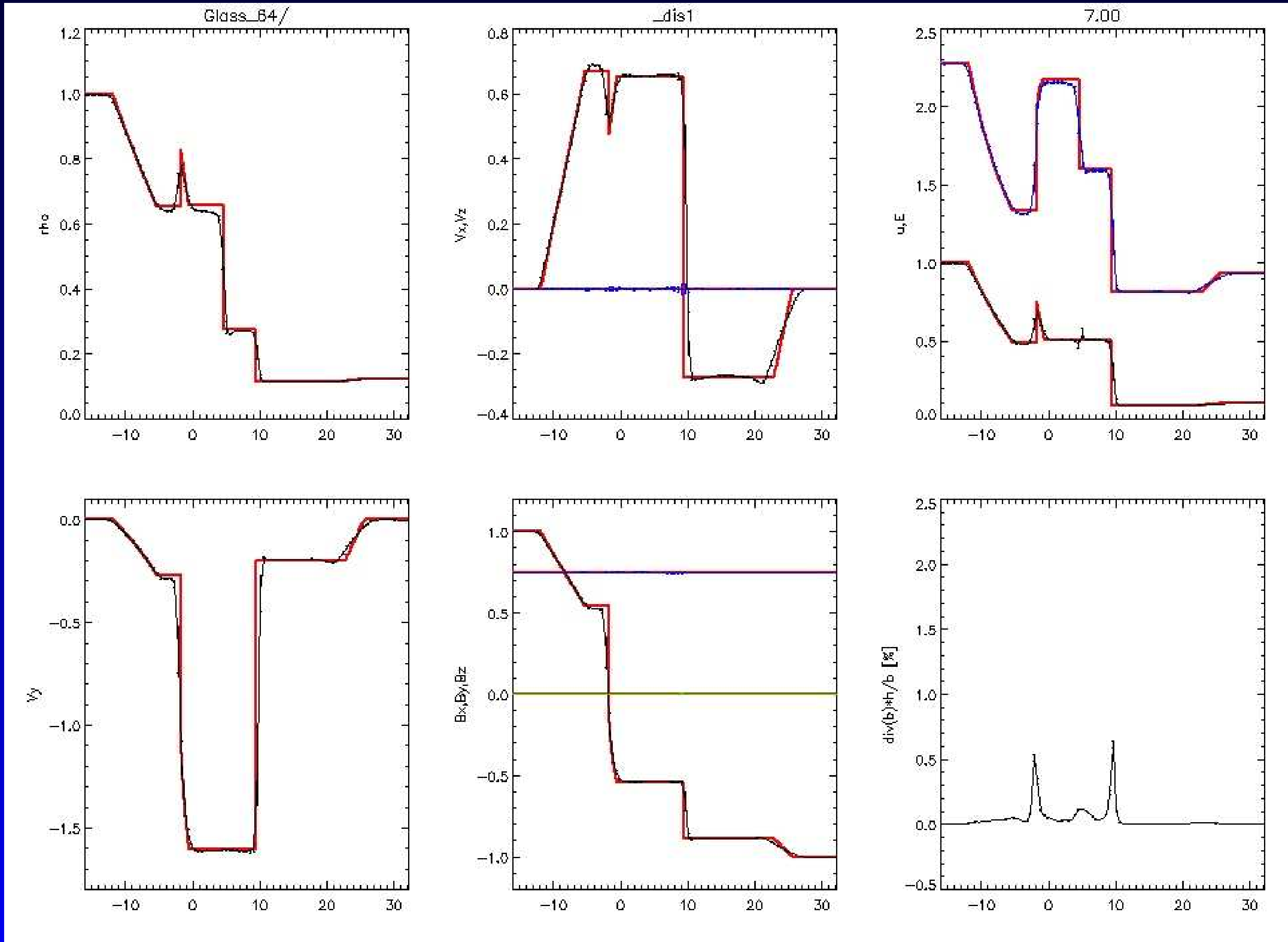
Brio & Wu shock tube

SPH-MHD plus smoothing

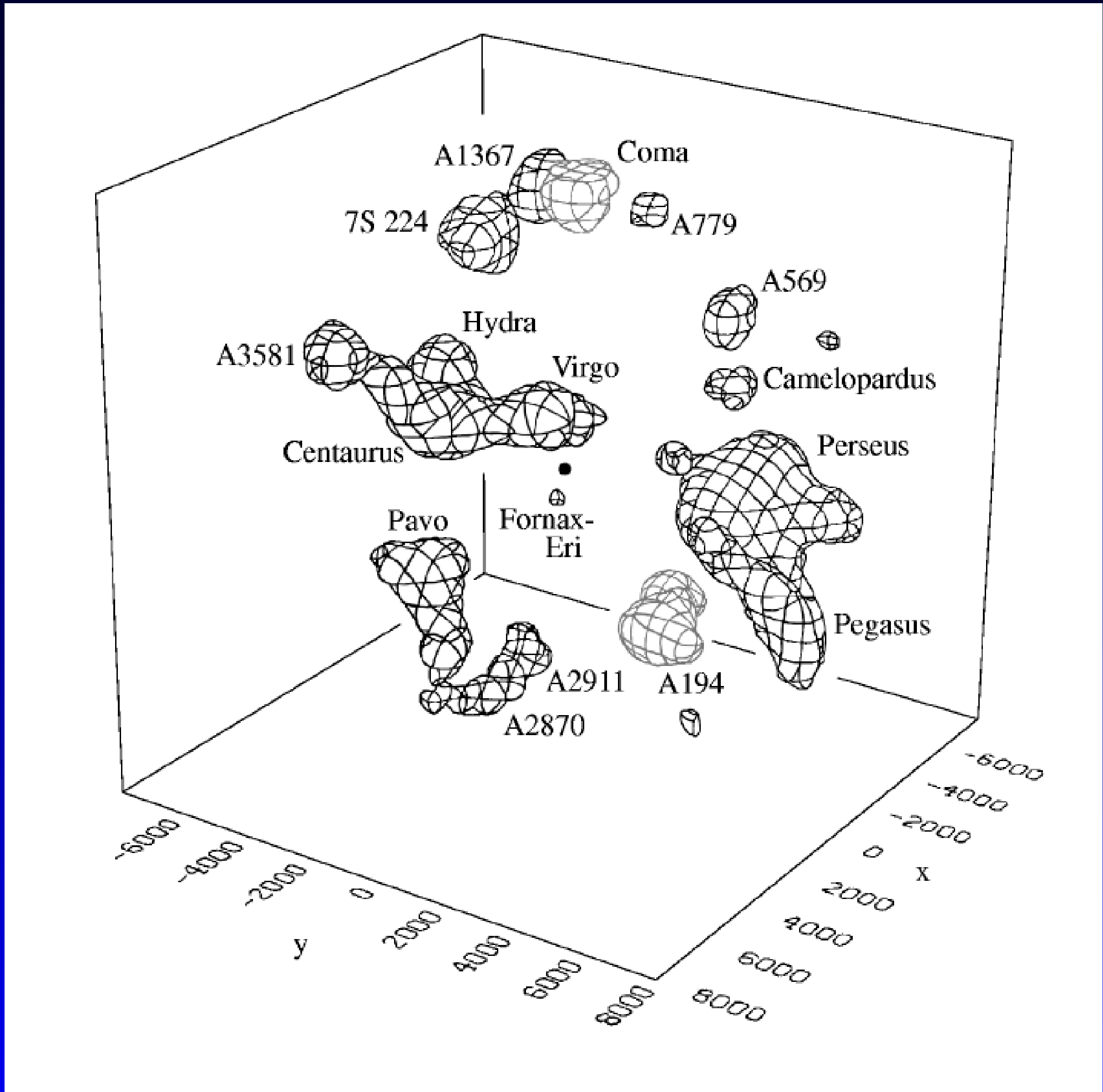


Brio & Wu shock tube

SPH-MHD plus artificial magnetic dissipation



The Local Universe

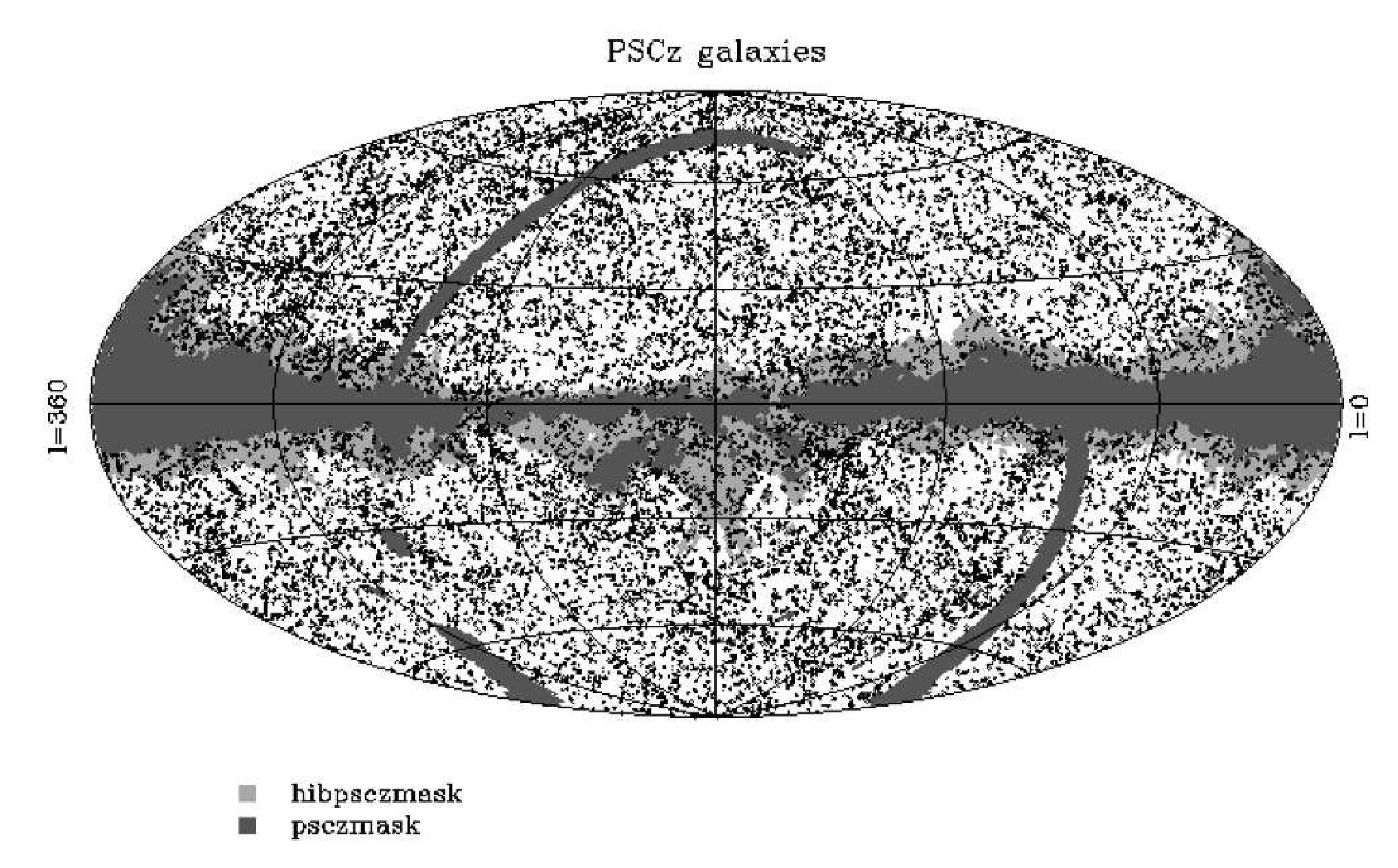


Run movie

Hudson 1993

Magnetic Field structure in Local Universe ? Charged particle astronomy possible ?

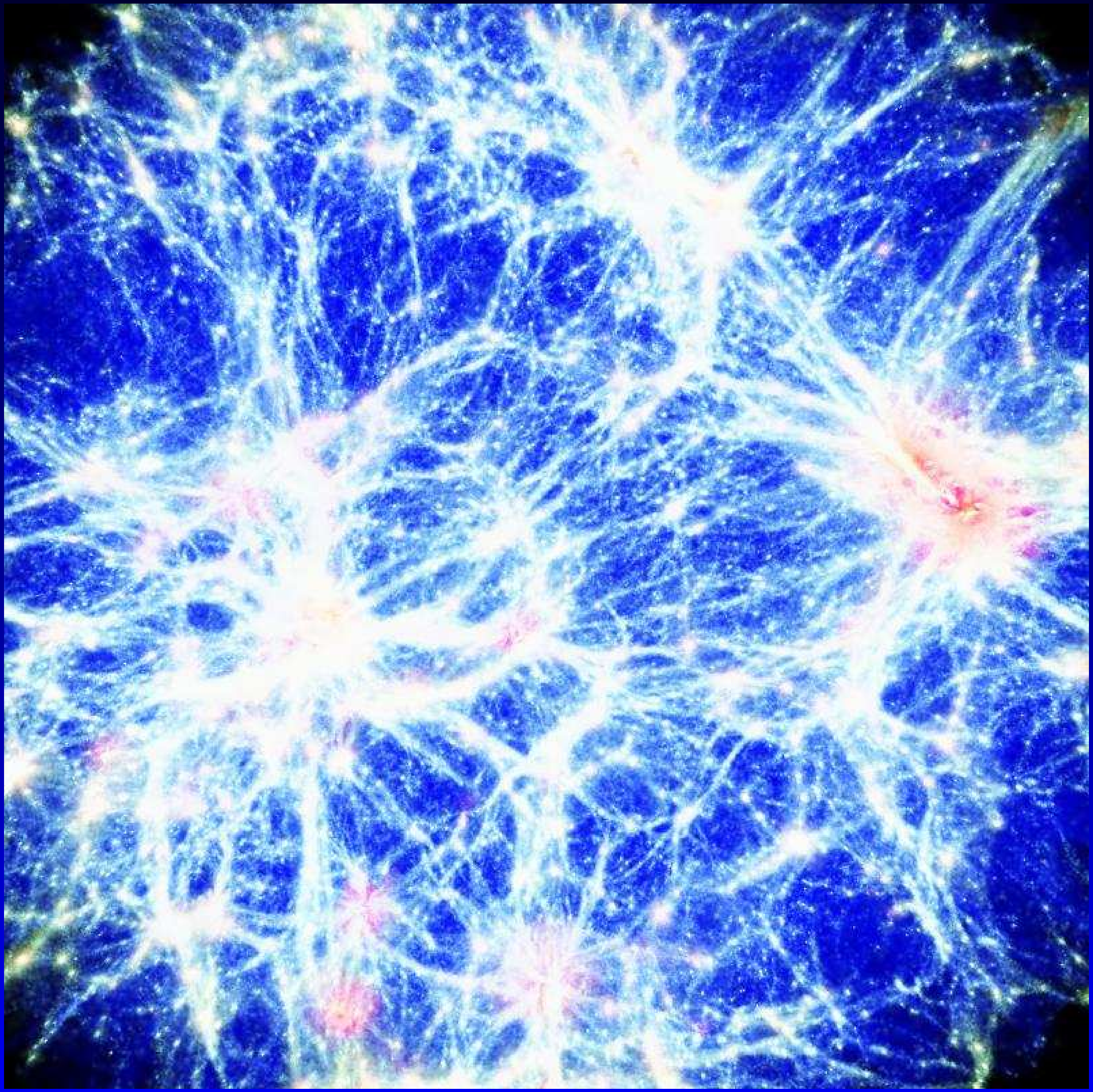
The Local Universe



Saunders et al. 2000

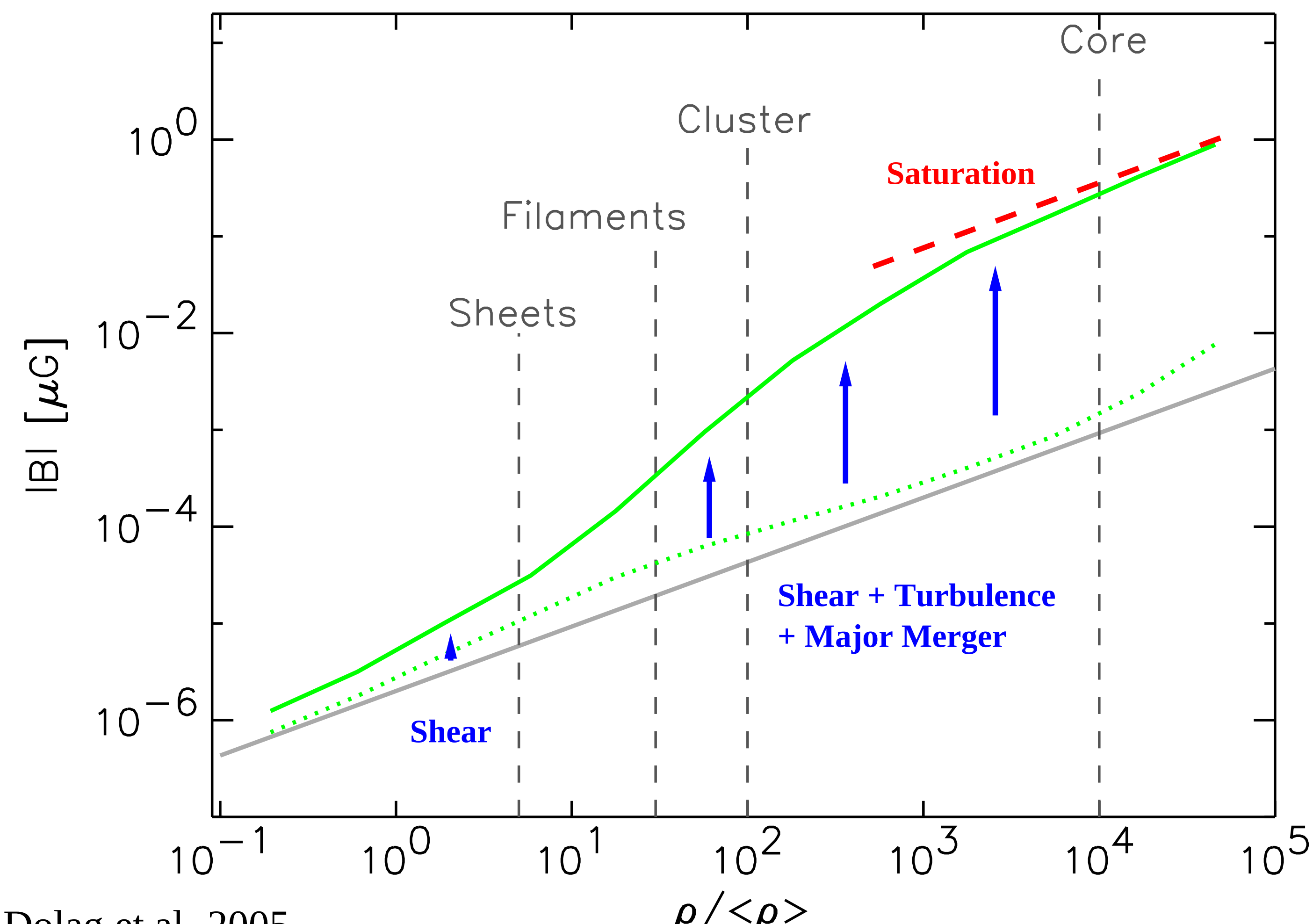
15000 IRAS Galaxies

The Local Universe

Run movie  $2 \times 50.000.000$

Mathis et al 2002 (DM-Only), Dolag et al 2004 (Gas + MHD)

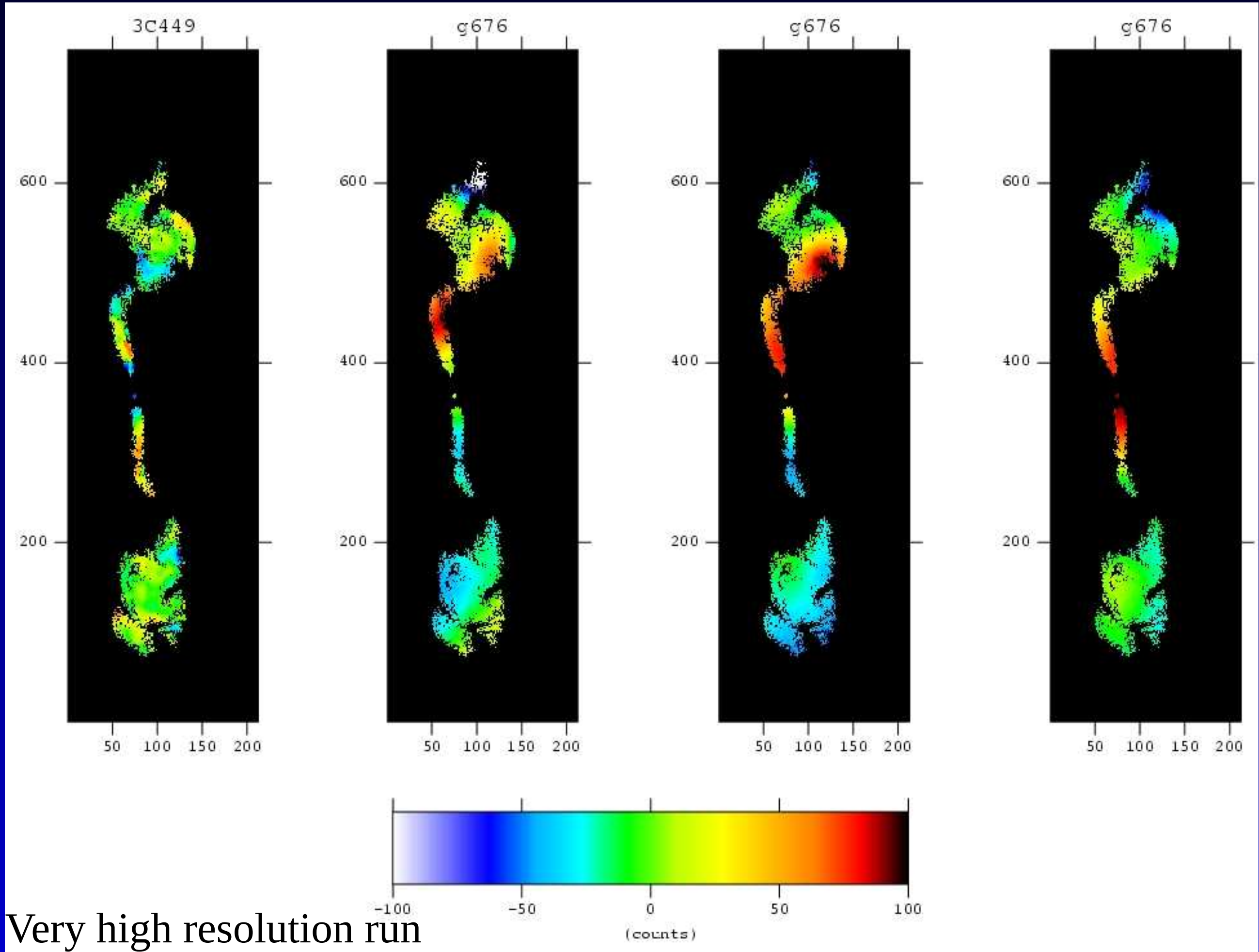
Results



Dolag et al. 2005

- Grape-MSPH / P-Gadget2-MHD (Dolag et al. 1999/2001/2005)
- $B_{ini} \approx 0.2 \times 10^{-11}(1+z)^2$ amplified to $\approx \mu$G

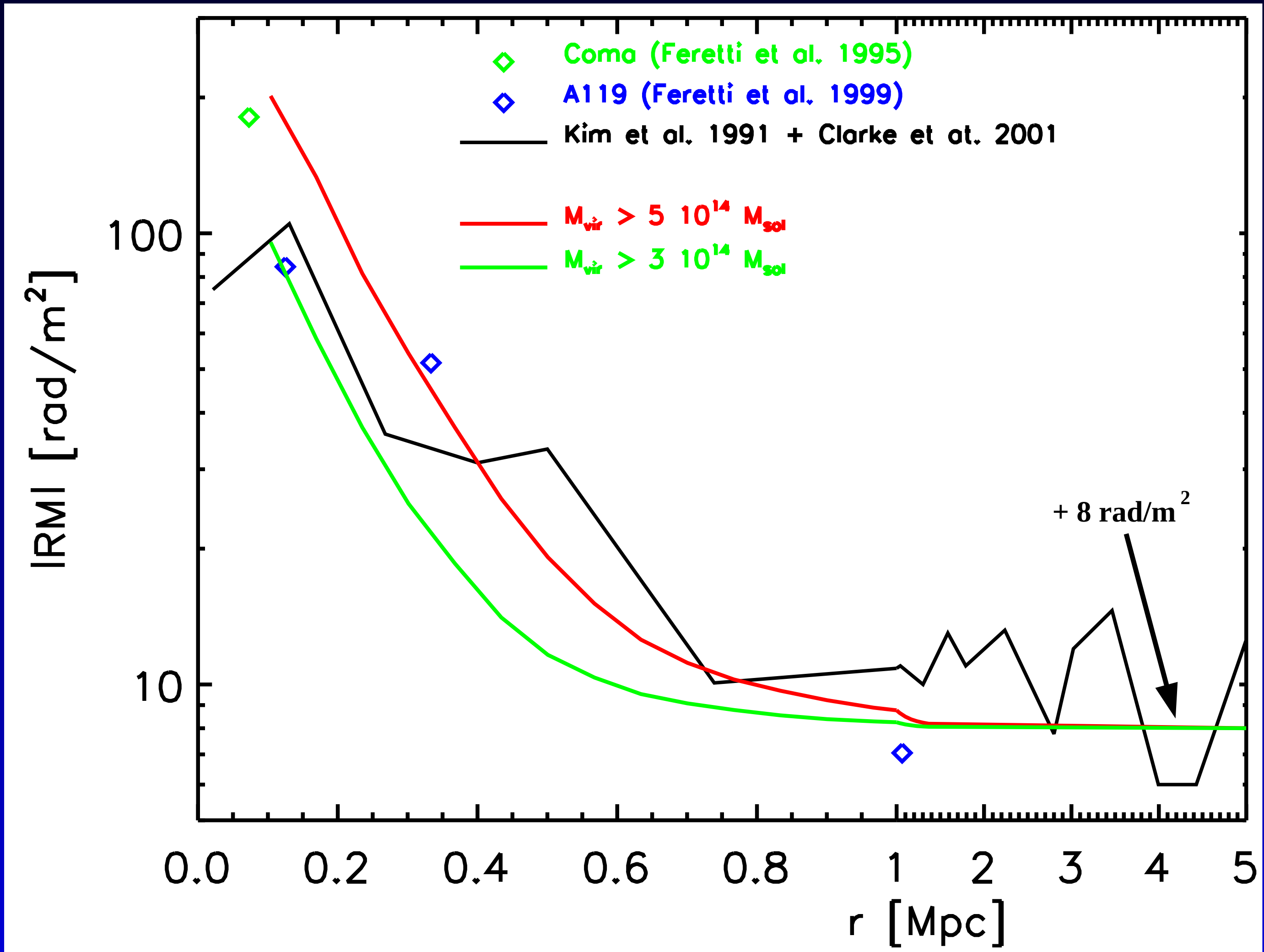
Results



Very high resolution run

- Comparison of 3C449 with simulated, 1.5kev cluster.
- Resolution 3.5kpc (Gravity) within 684Mpc box (zoomed)
- Close, but still more resolution needed !

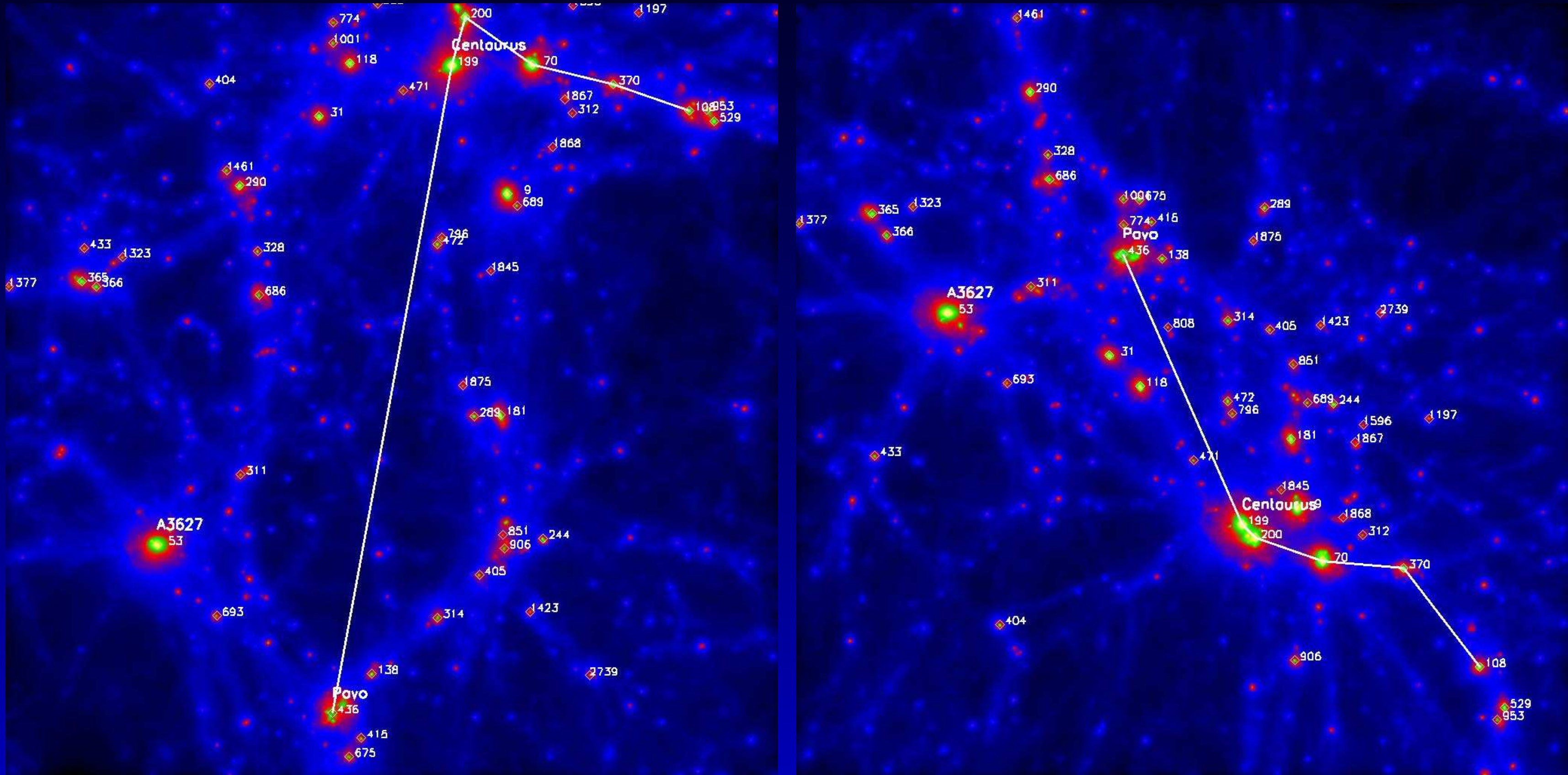
Results



Dolag et al. 2005

- Independent of initial field configuration
- $B(r) \propto \rho(r), < B > \propto T^2$

Filaments

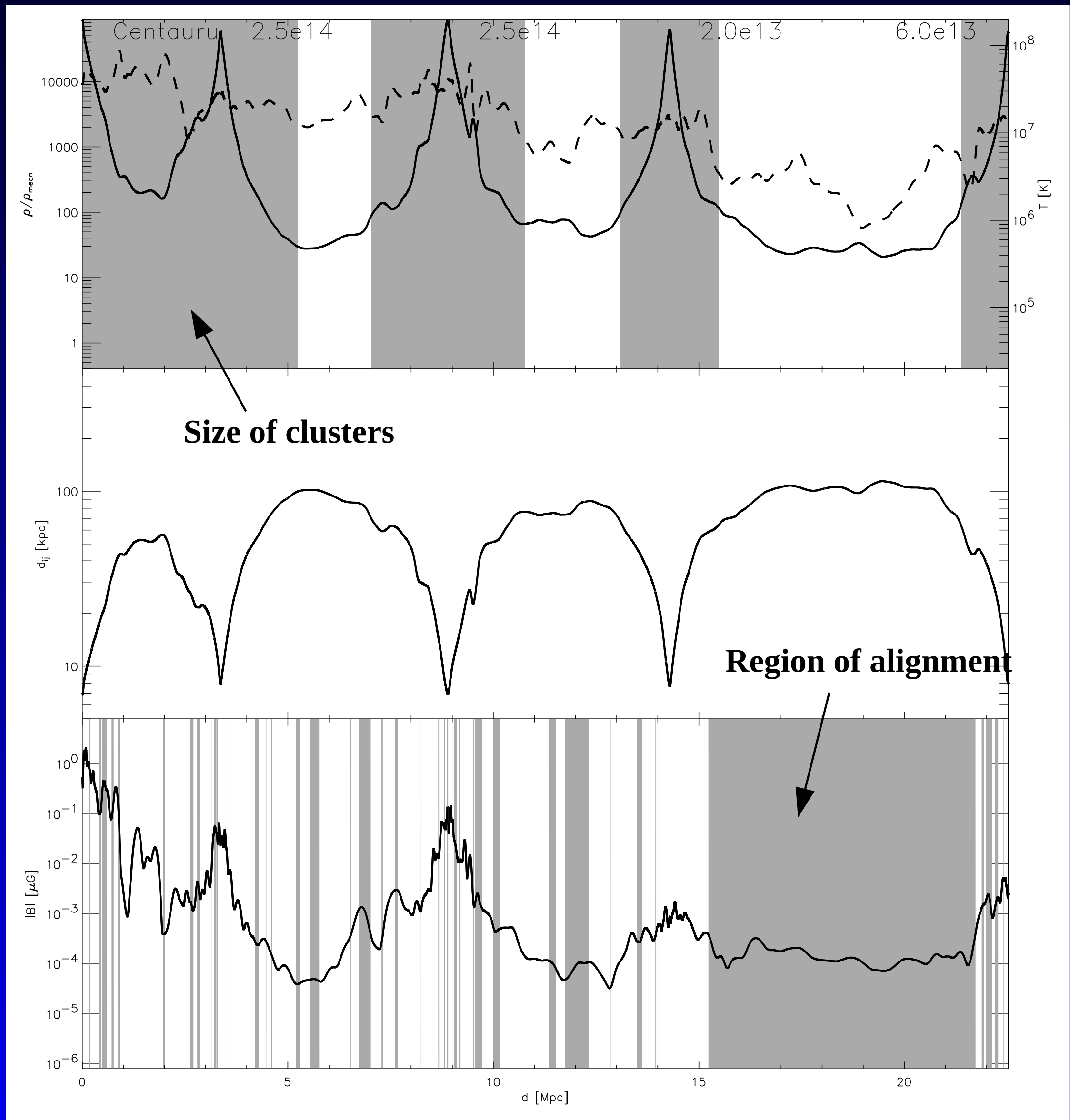


Region shown is $(50\ \mathrm{Mpc})^3$ centered between Centaurus and Pavo

Filaments and bridges between clusters, but be careful:

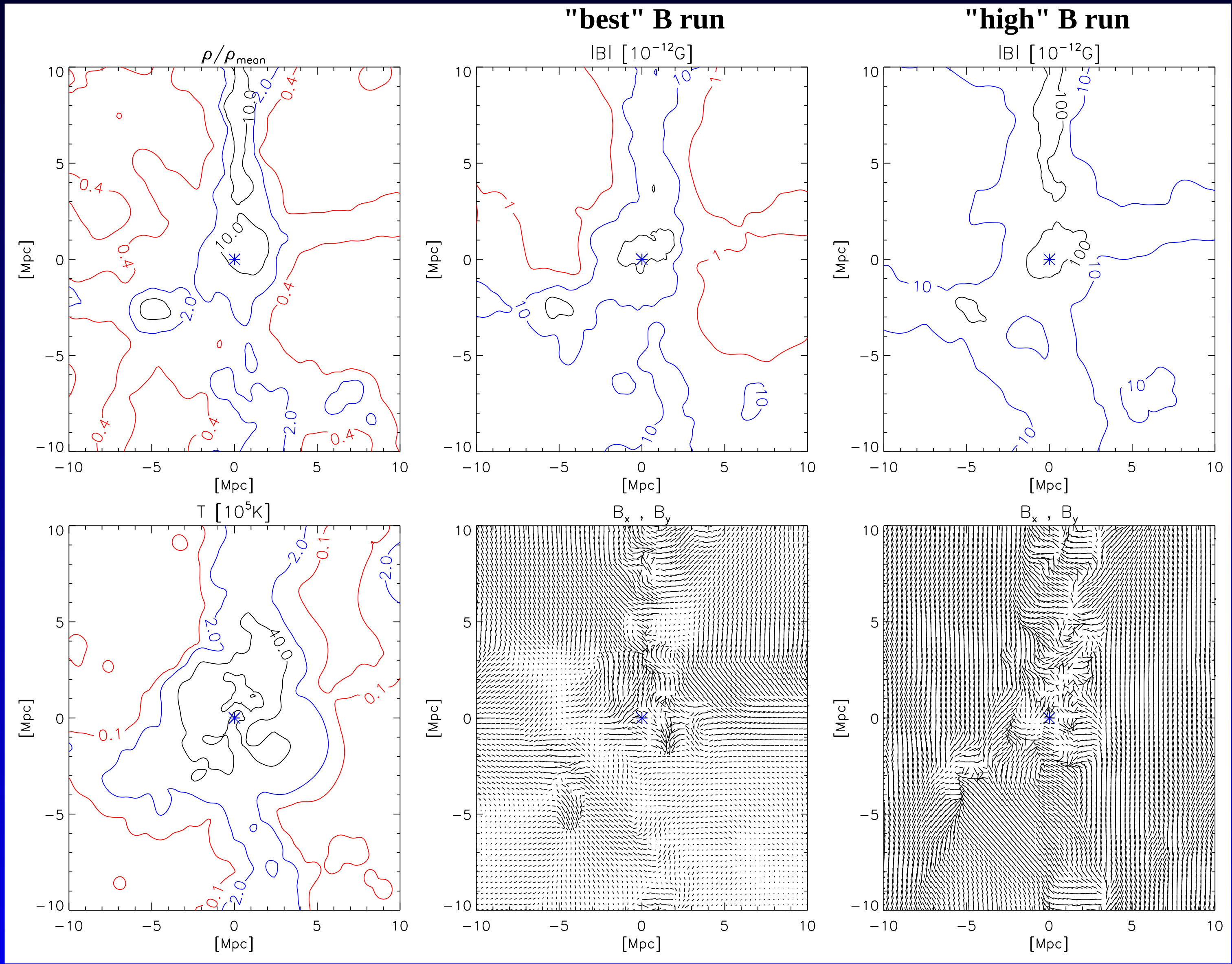
- Never straight lines !
- Always junctions of sheets !
- Sometimes projections of sheets !

Filaments



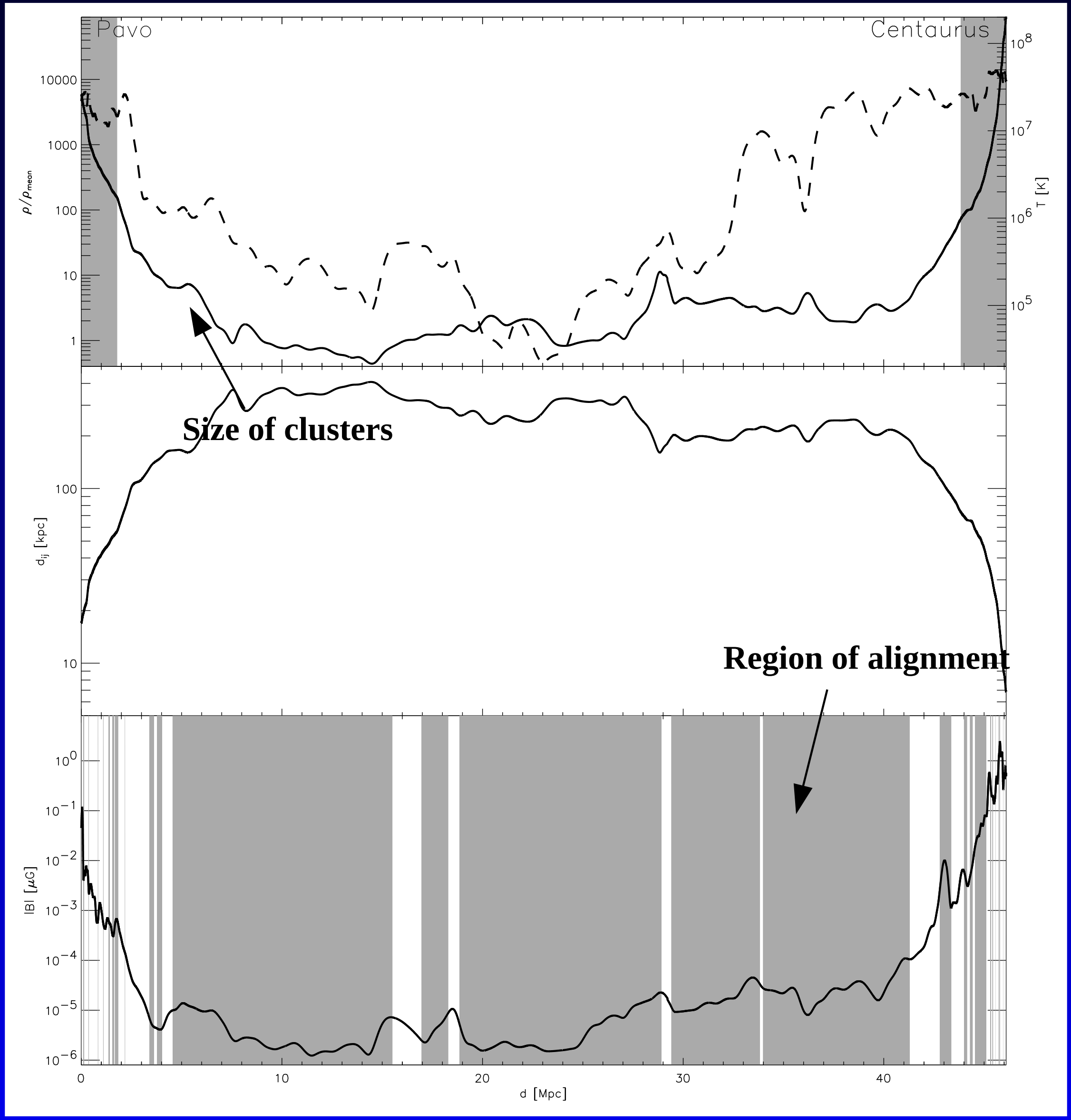
Going along a filament

Filaments

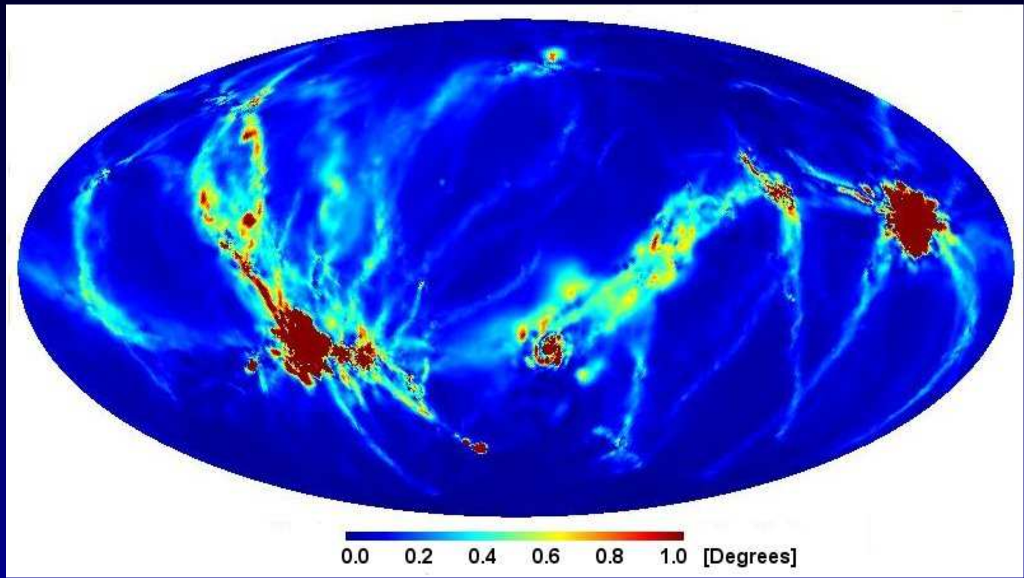


Slice perpendicular to a filament

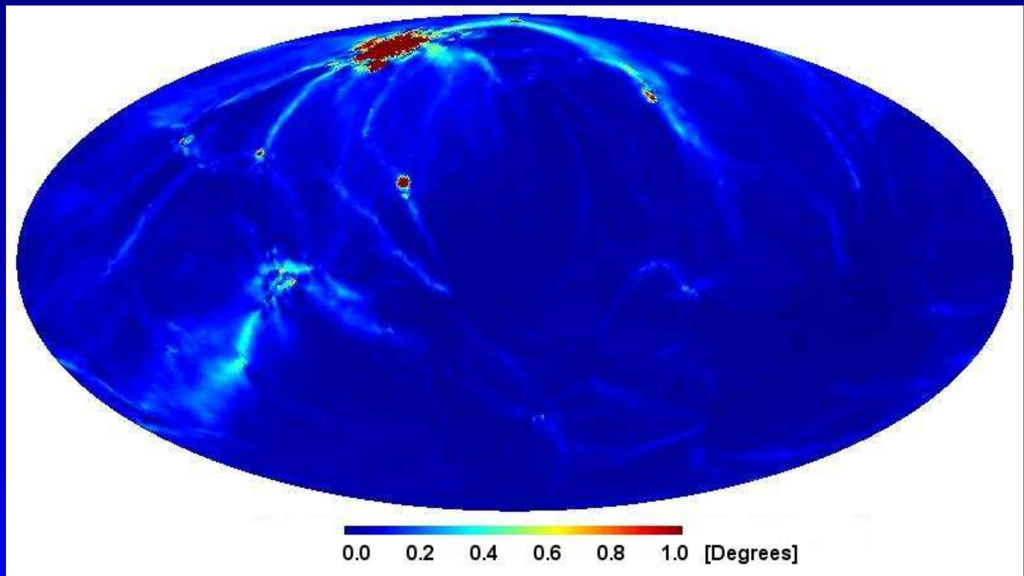
Filaments



Full Sky Deflection Map



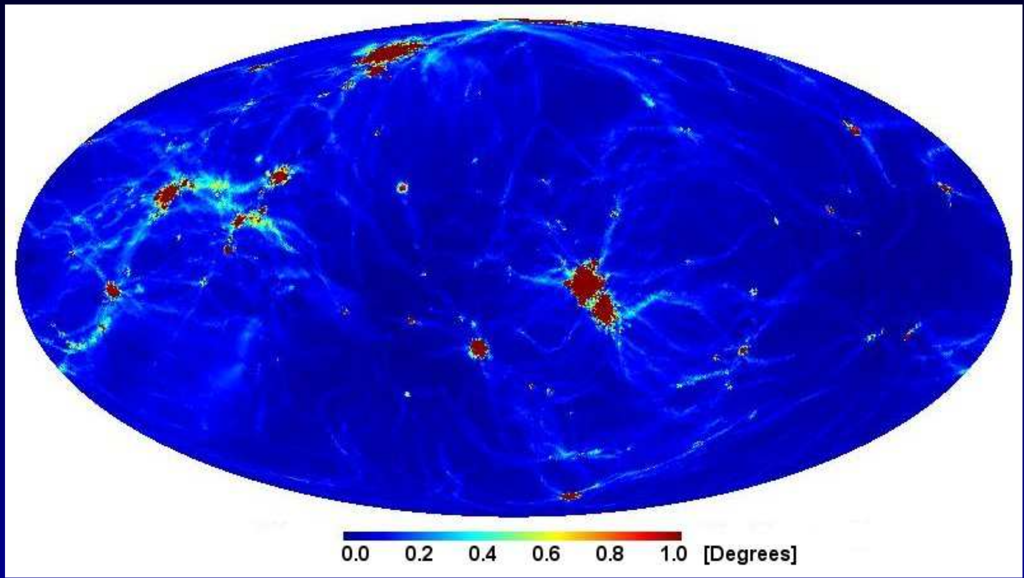
Centaurus



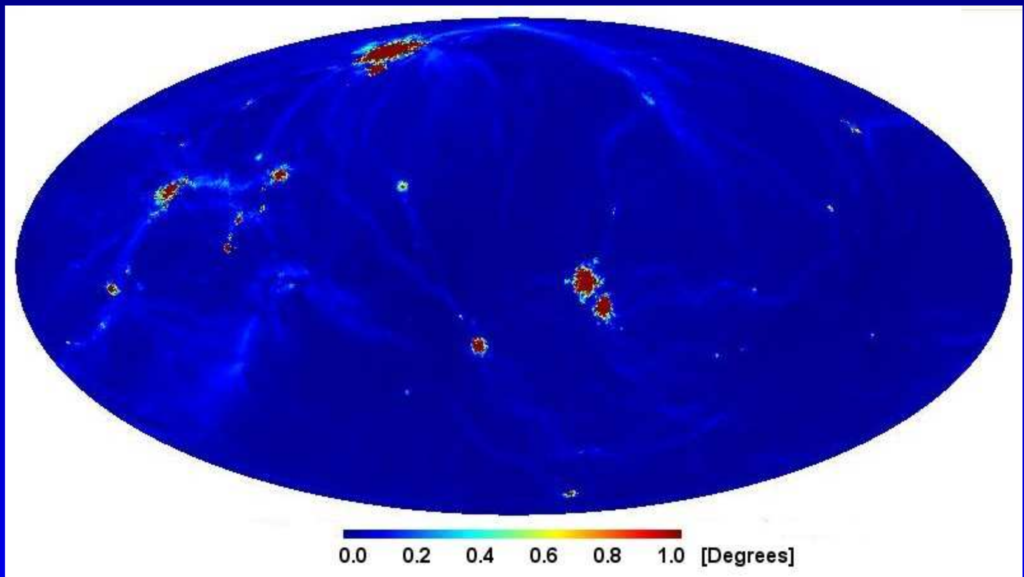
Milky Way

Full sky deflection signal for 4×10^{19}eV Cosmic Rays for two different observer position, using a sphere with radius 35Mpc.

Full Sky Deflection Map



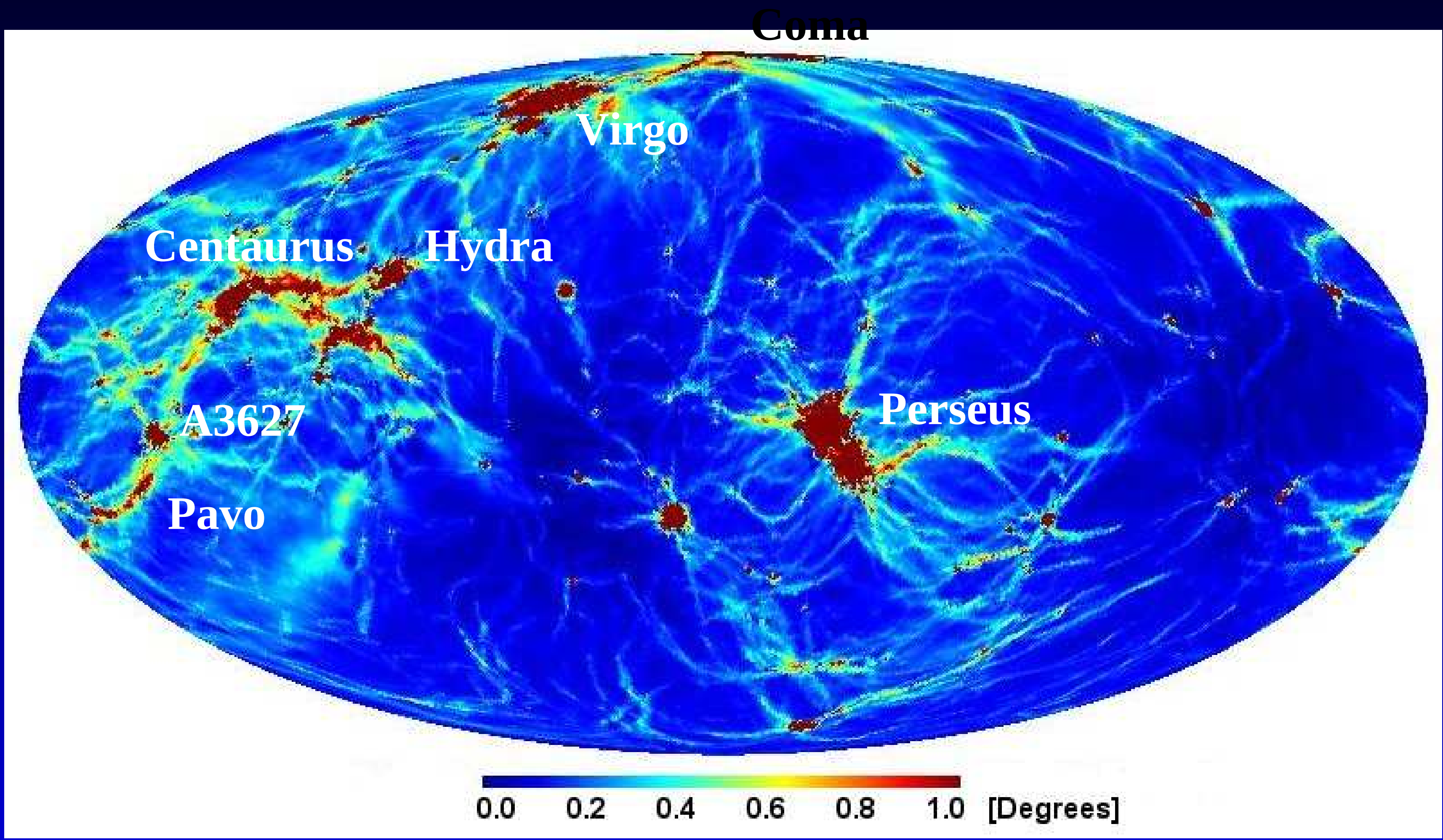
no losses



with losses

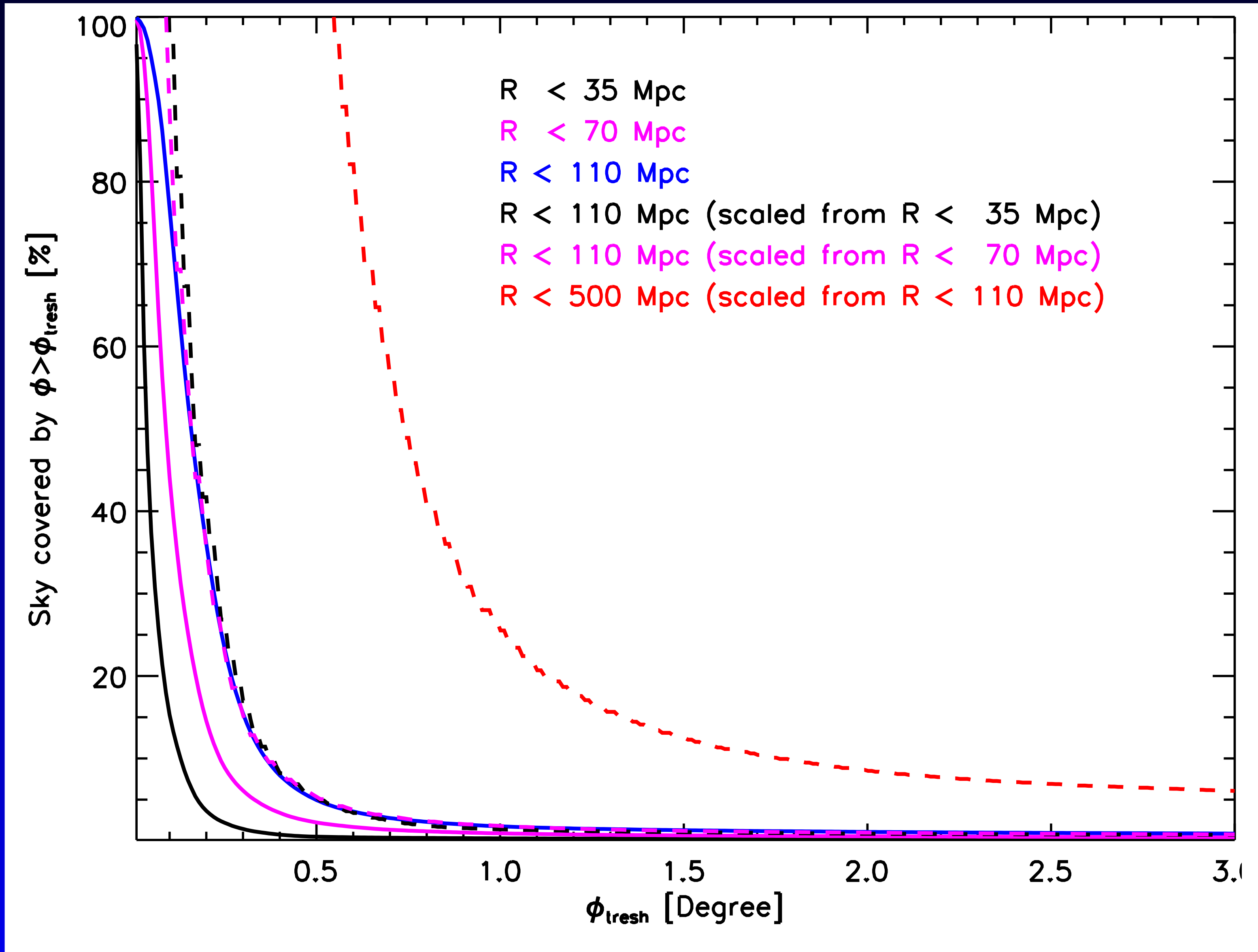
Full sky deflection signal for 1×10^{20}eV Cosmic Rays with and without losses by photo-pion production in collisions with CMB, using a sphere of 100Mpc radius.

Full Sky Deflection Map



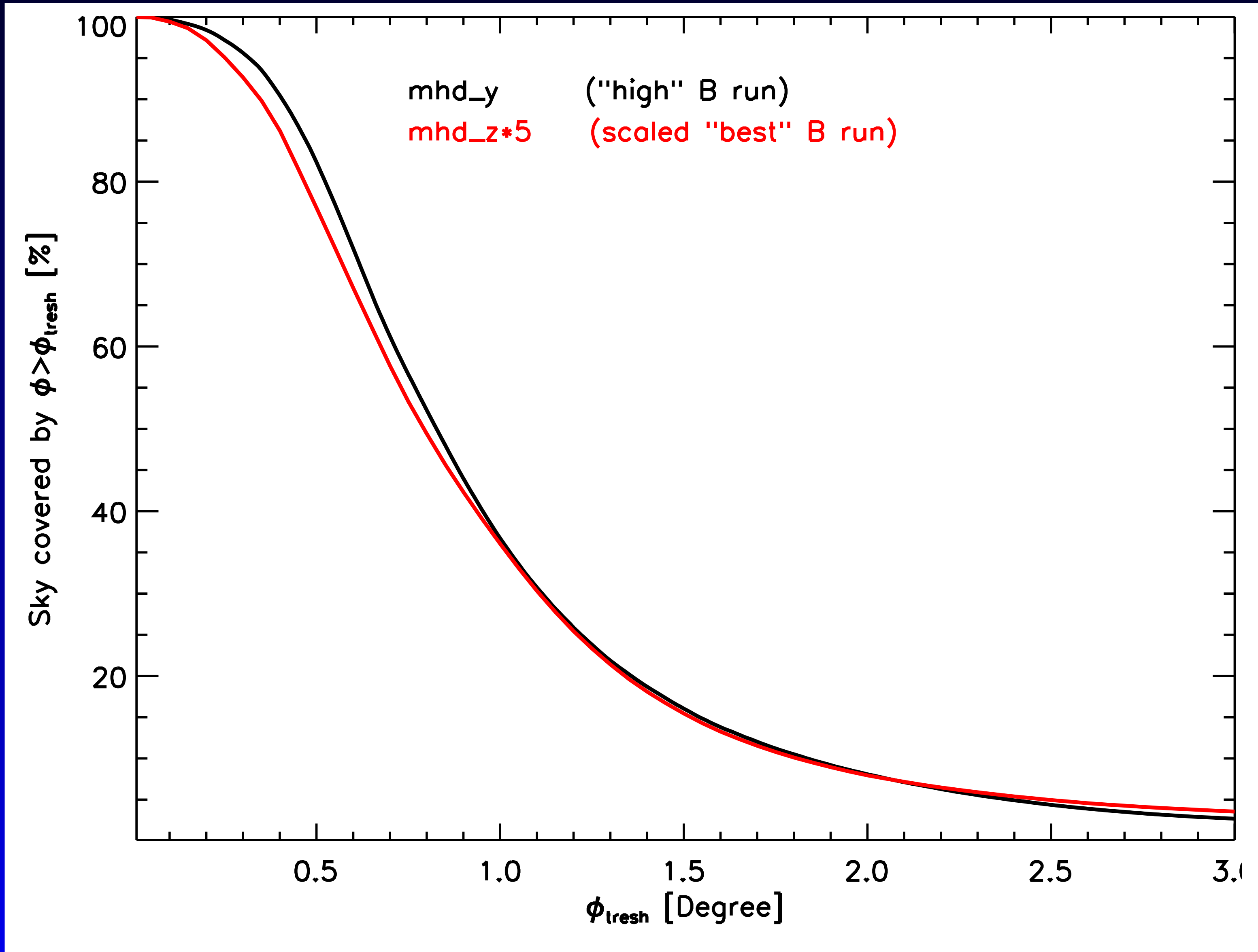
Full sky deflection signal for 4×10^{19}eV Cosmic Rays without losses, using a sphere of 110Mpc radius.

Sky coverage



Extrapolated, assuming self similarity $A(\delta_{\rm th}, d) = x^{-\beta} A_0(\delta_{\rm th} \times x^{\alpha})$,

Sky coverage



Comparing different runs using different initial field setups.

Conclusions

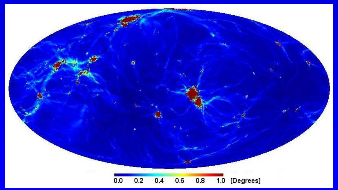
- $B_0 \approx (0.2 - 1) \times 10^{-12} \times (1+z)^2$ Gauss injected at $z > 3$ results in reasonable cluster magnetic fields.
- Simulation predicts scalings and relations which can be observational tested.

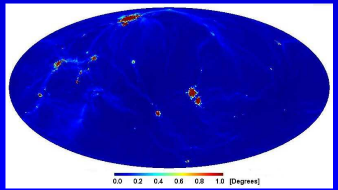
! Almost independent of details of seed creation mechanism.

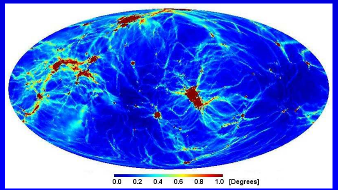
! B_0 is a robust upper limit.

! Homogenous initial seed results to upper limit in deflections by low density regions.

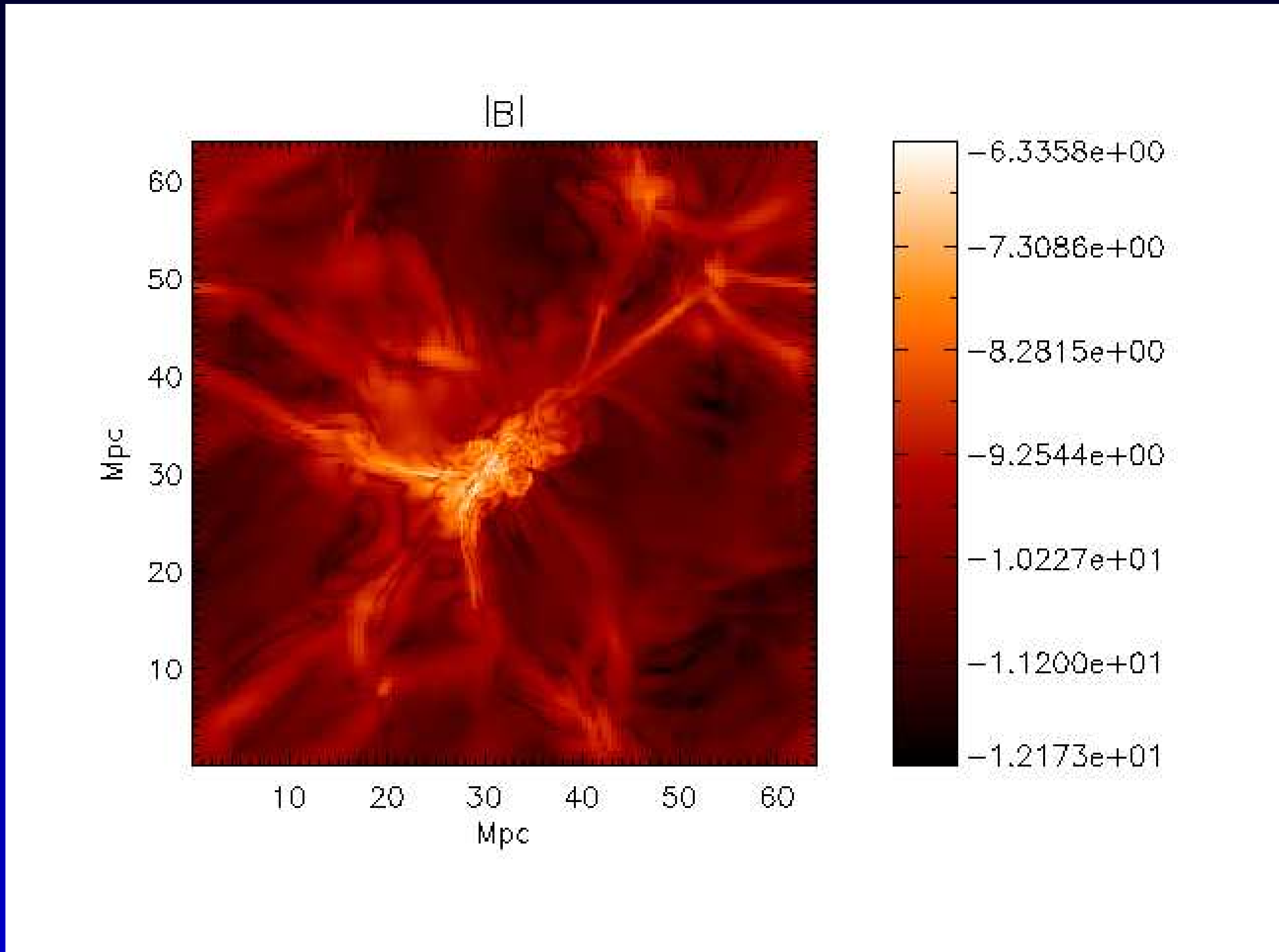
$\Rightarrow$ Deflections are small enough to allow pointing of sources of UHECRs with energies 4×10^{19}eV over most of the sky.







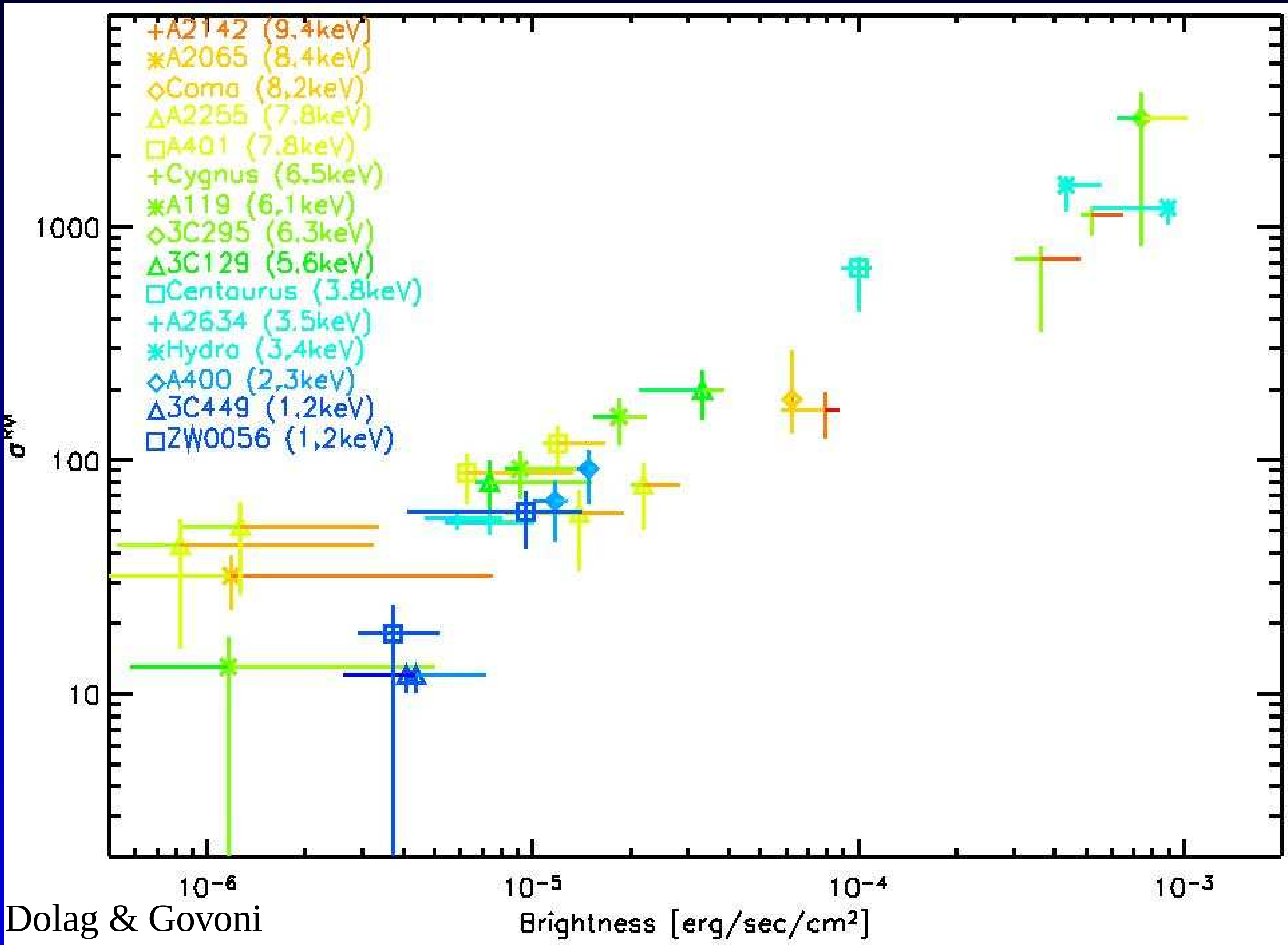
Outlook (preliminary)



Brüggen et al. 2005

- FLASH + MHD, AMR, ≈11kpc resolution
- Very similar results as before (e.g. Dolag et al. 1999/2001/2005)

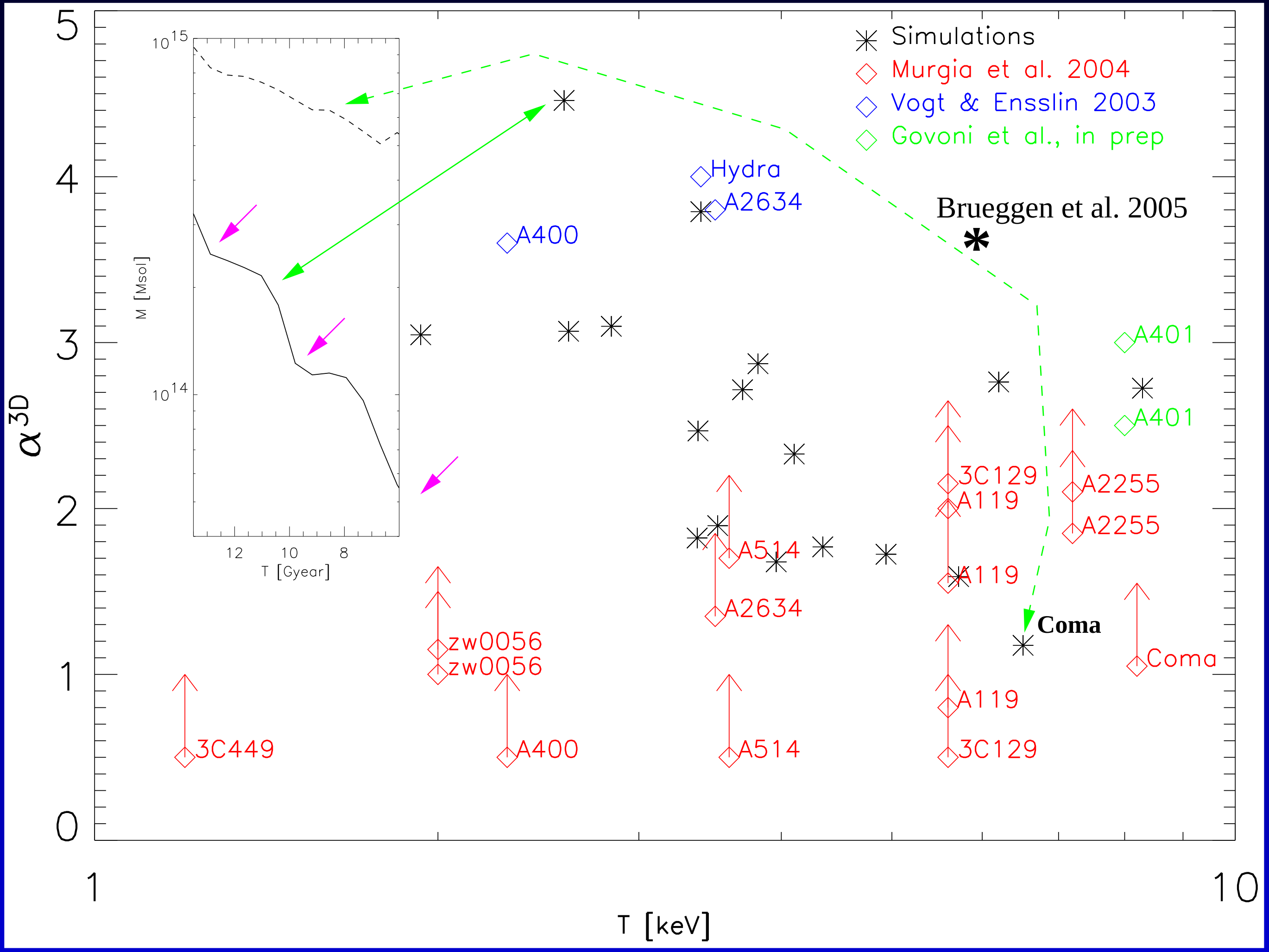
Outlook (preliminary)



Dolag & Govoni

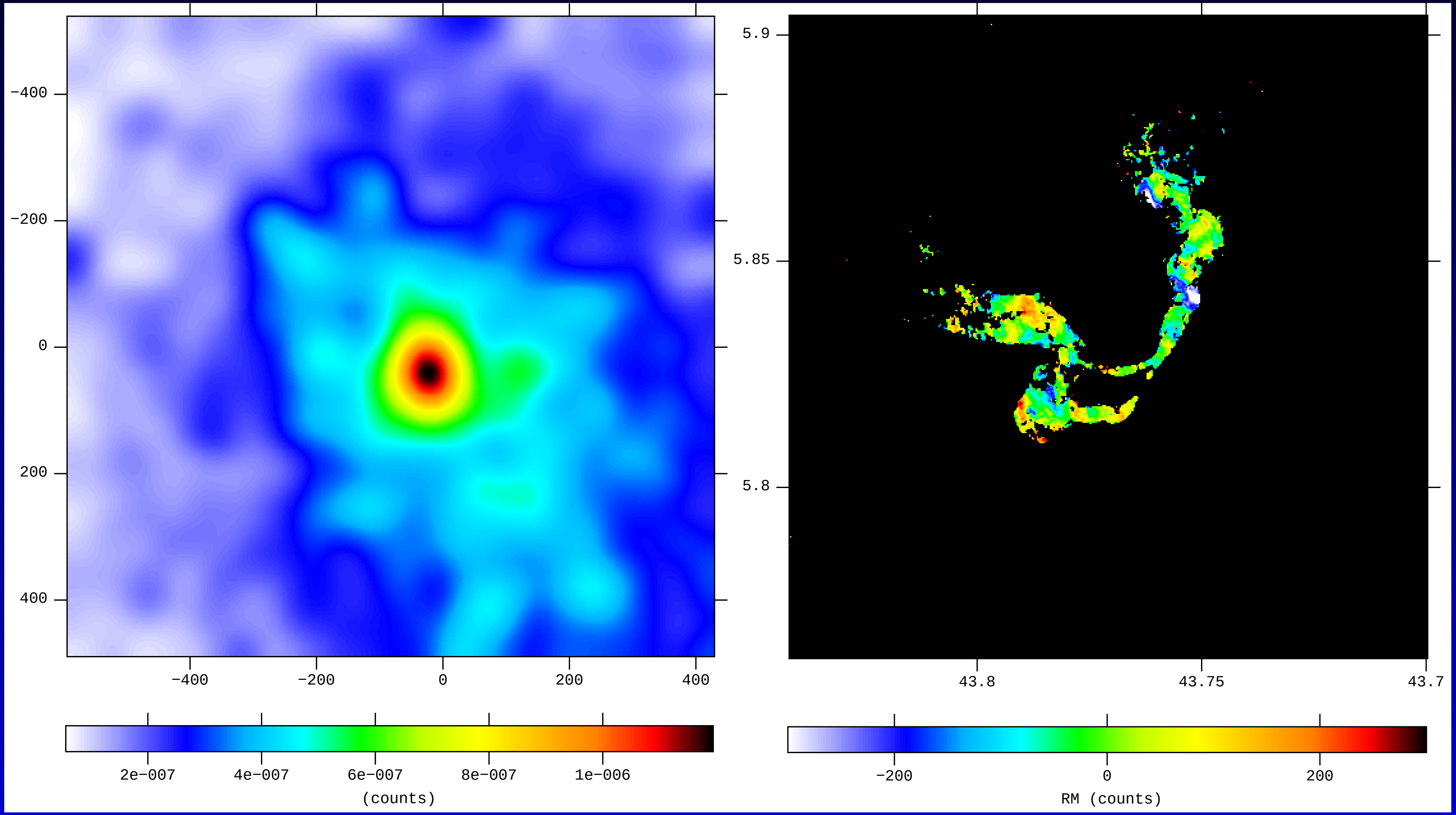
- Super adiabatic relation favored ($\alpha > 2/3$) !
- Including cooling will be crucial !

Outlook (preliminary)



- Magnetic field power spectra ($k^2 B(k)^2$) !
- Key to dynamical understanding ?

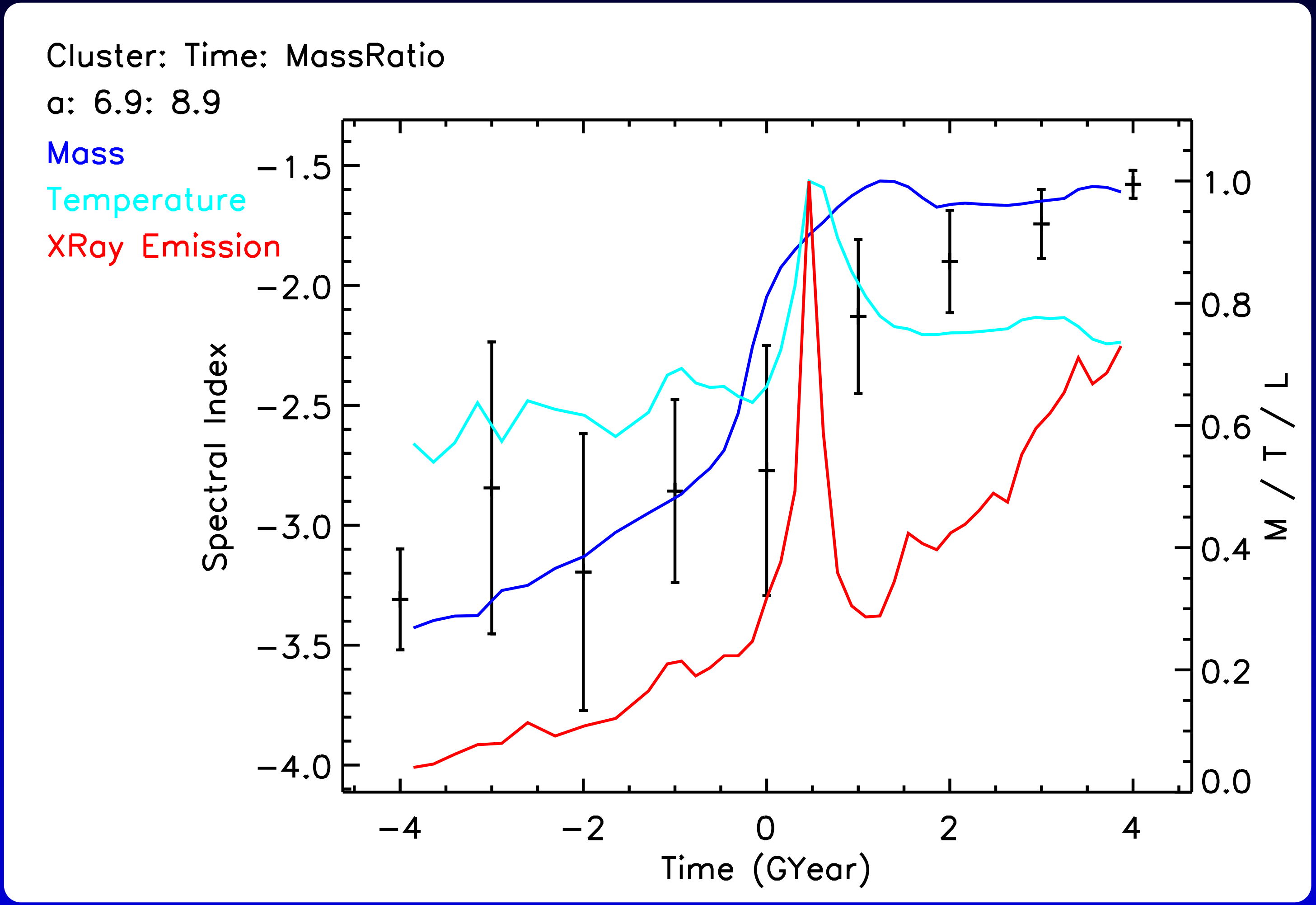
Outlook (preliminary)



Example A400, Slope observed to be high !

$\Rightarrow$ Signature of Merger or Turbulence ?

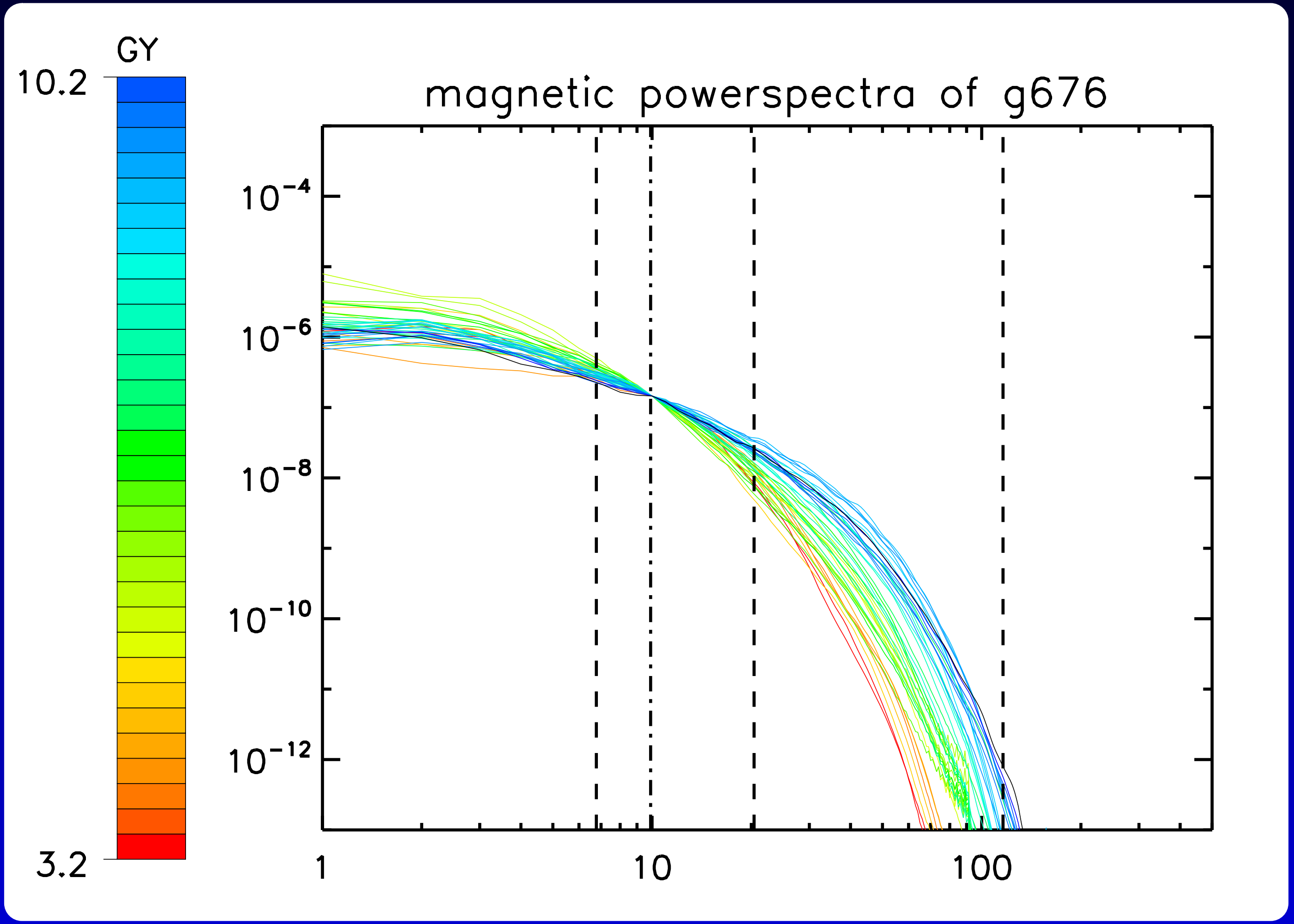
Outlook (preliminary)



Pakmor, ongoing work

Evolution of a galaxy cluster around a major merging event.

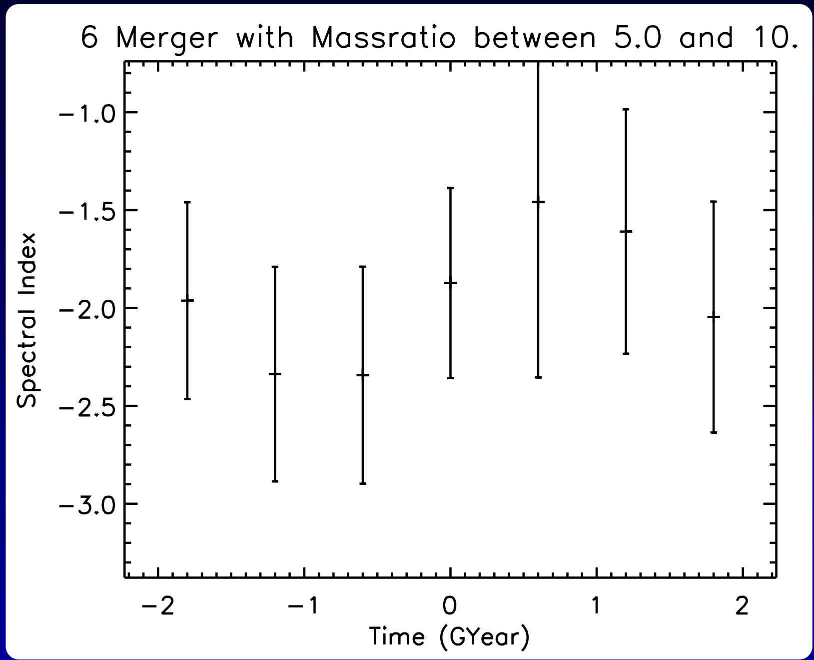
Outlook (preliminary)

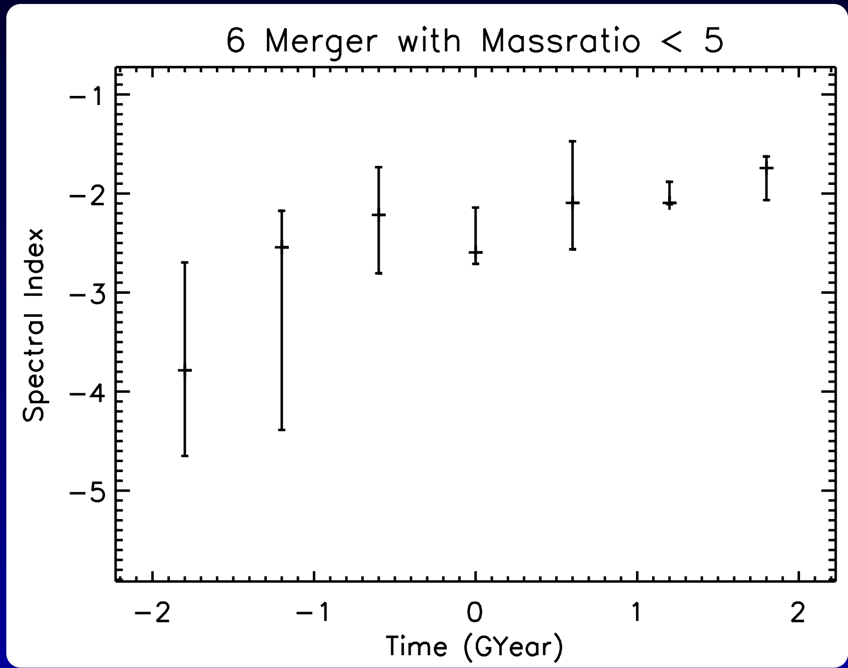


Pakmor, ongoing work

Evolution of the power spectra of the magnetic field around a major merging event.

Outlook (preliminary)

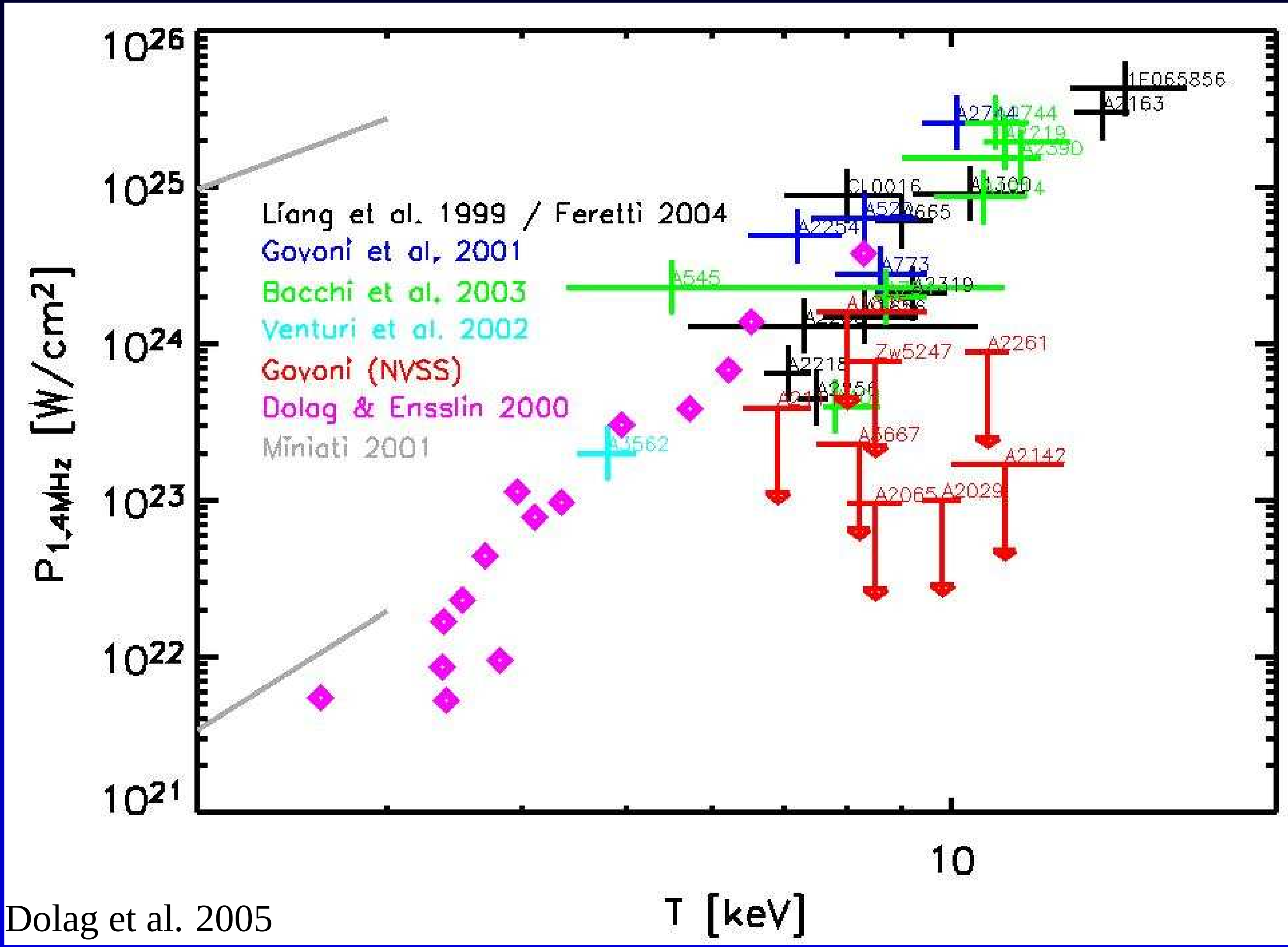




Pakmor, ongoing work

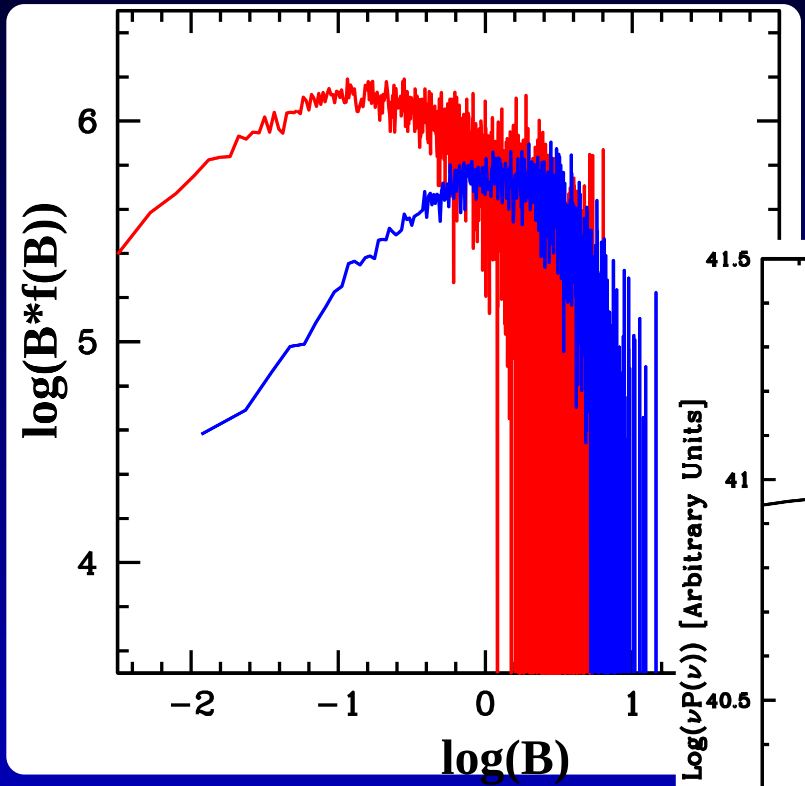
Average of 11 Clusters from a the Local Universe selected to have minor mergers (left) and major mergers (right).

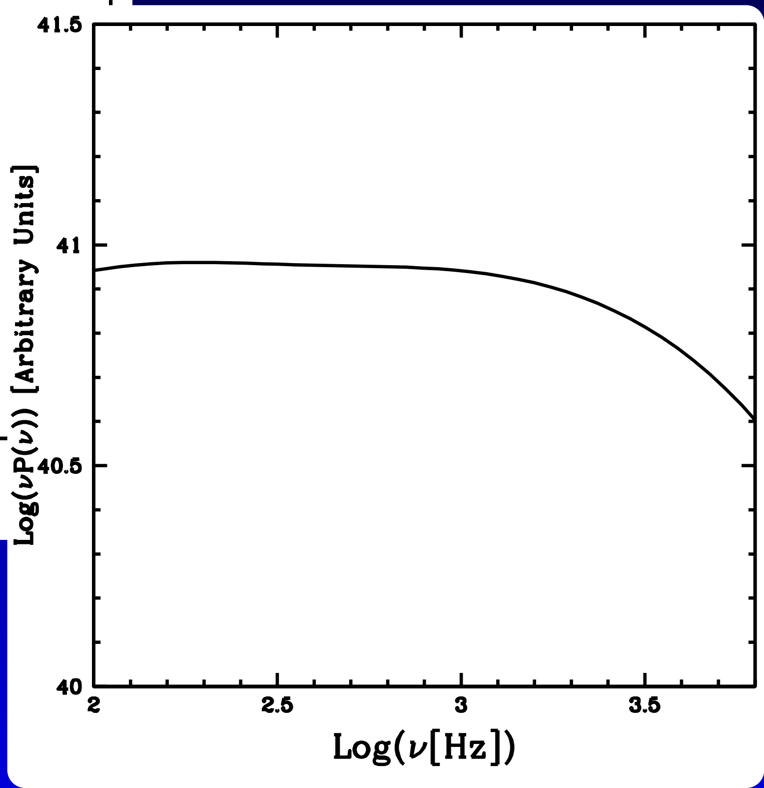
Outlook (preliminary)



- $P \propto B^{(1+\alpha)}/(B^2 + B_{cmb}^2) \Rightarrow B_0$ crucial for shape !
- Probability has to be included !

Outlook (preliminary)

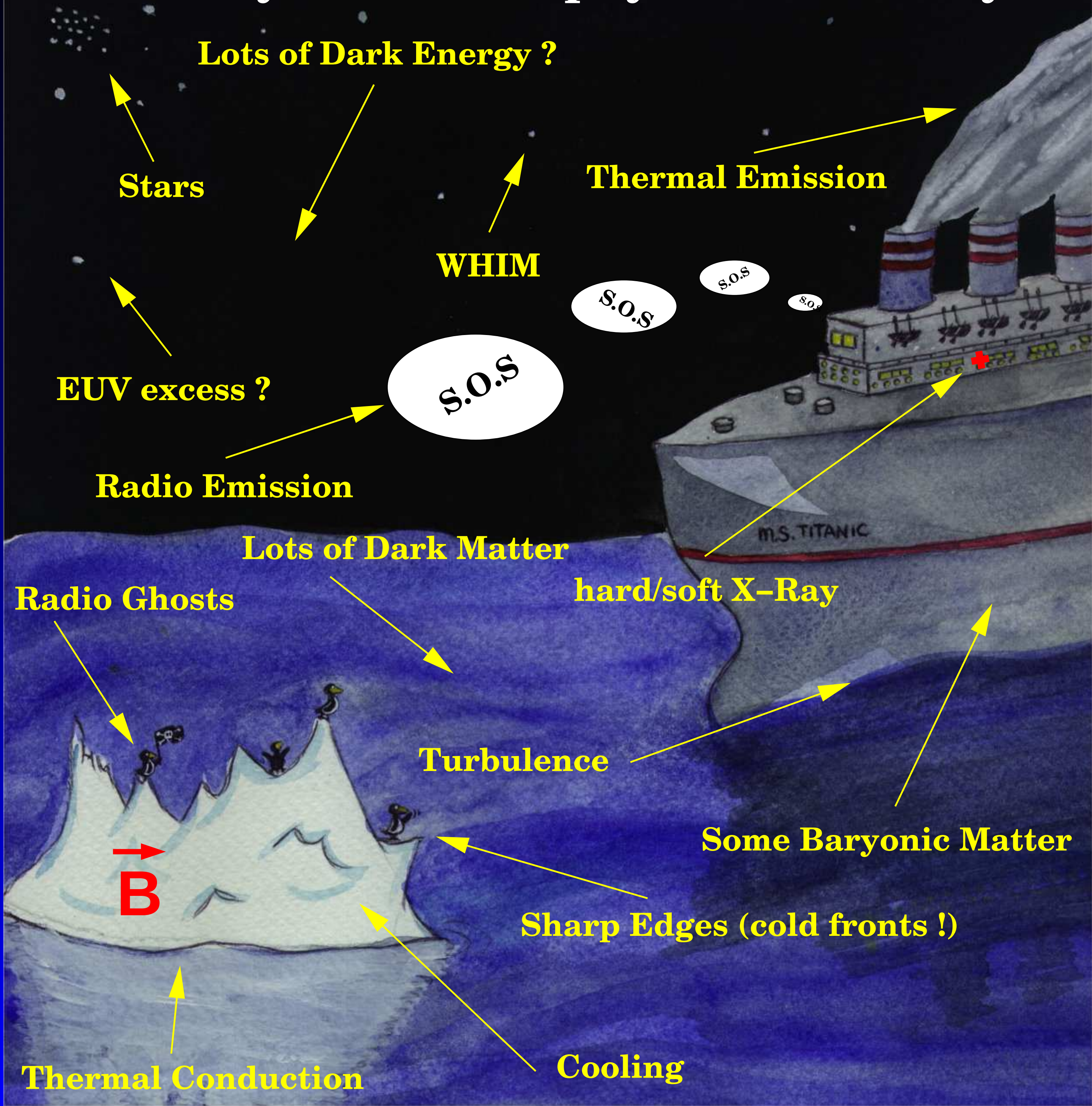




Brunetti, ongoing work

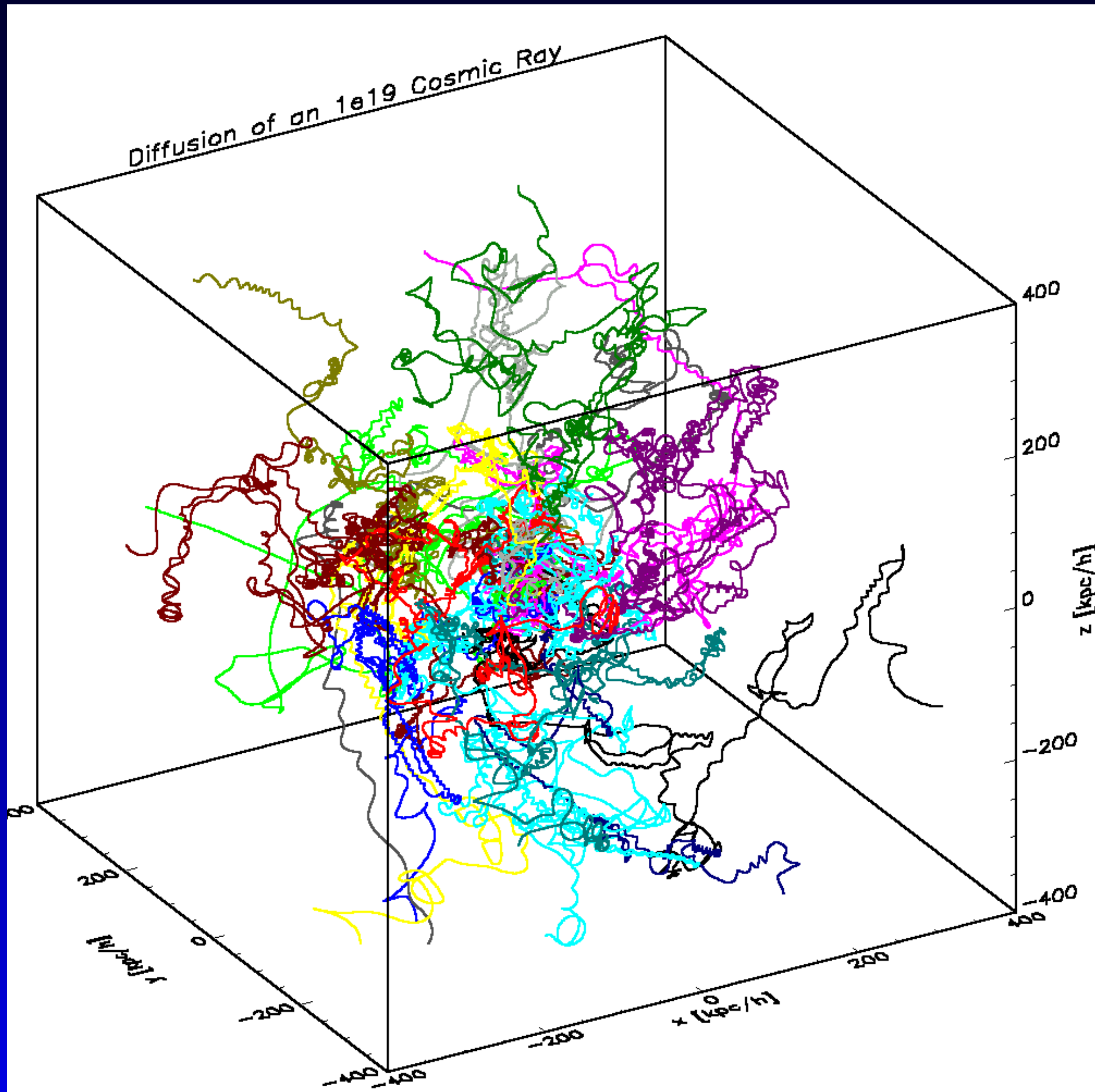
Calculation of the radio spectrum from the magnetic field distribution taken from the simulations using a particle acceleration code.

Galaxy clusters as physics laboratory:



Do we understand our "world" !?

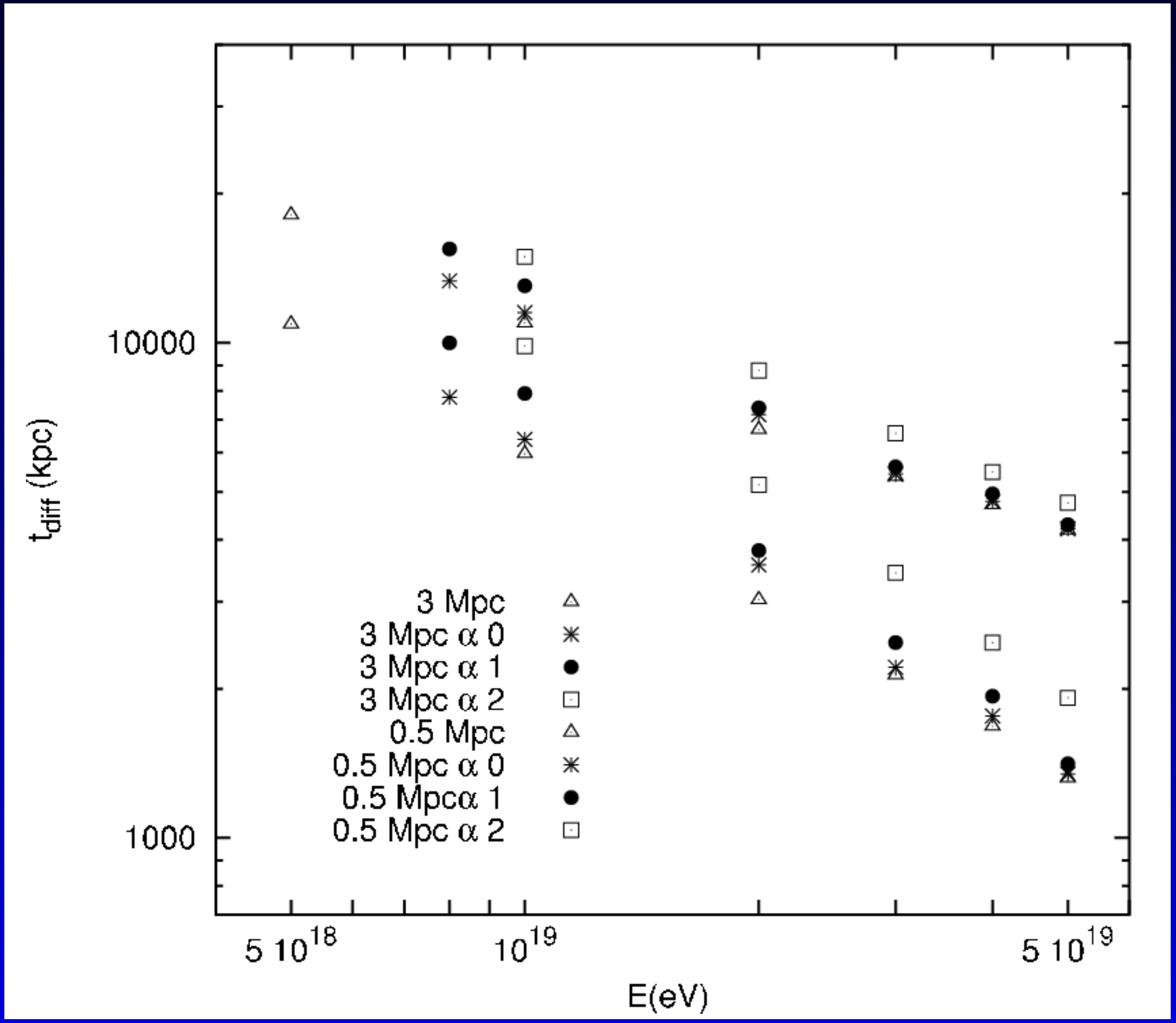
Diffusion within a Cluster



Trajectories of cosmic Rays diffusing through the cluster core.

Rordorf et al. 2004

Diffusion within a Cluster



Diffusion time for Cosmic Rays with different energies to reach a distance of 0.5 and 3 Mpc from the cluster center cluster.

Rordorf et al. 2004