Galaxy Custers: Magnetized Cosmic Lighthouses

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Outline

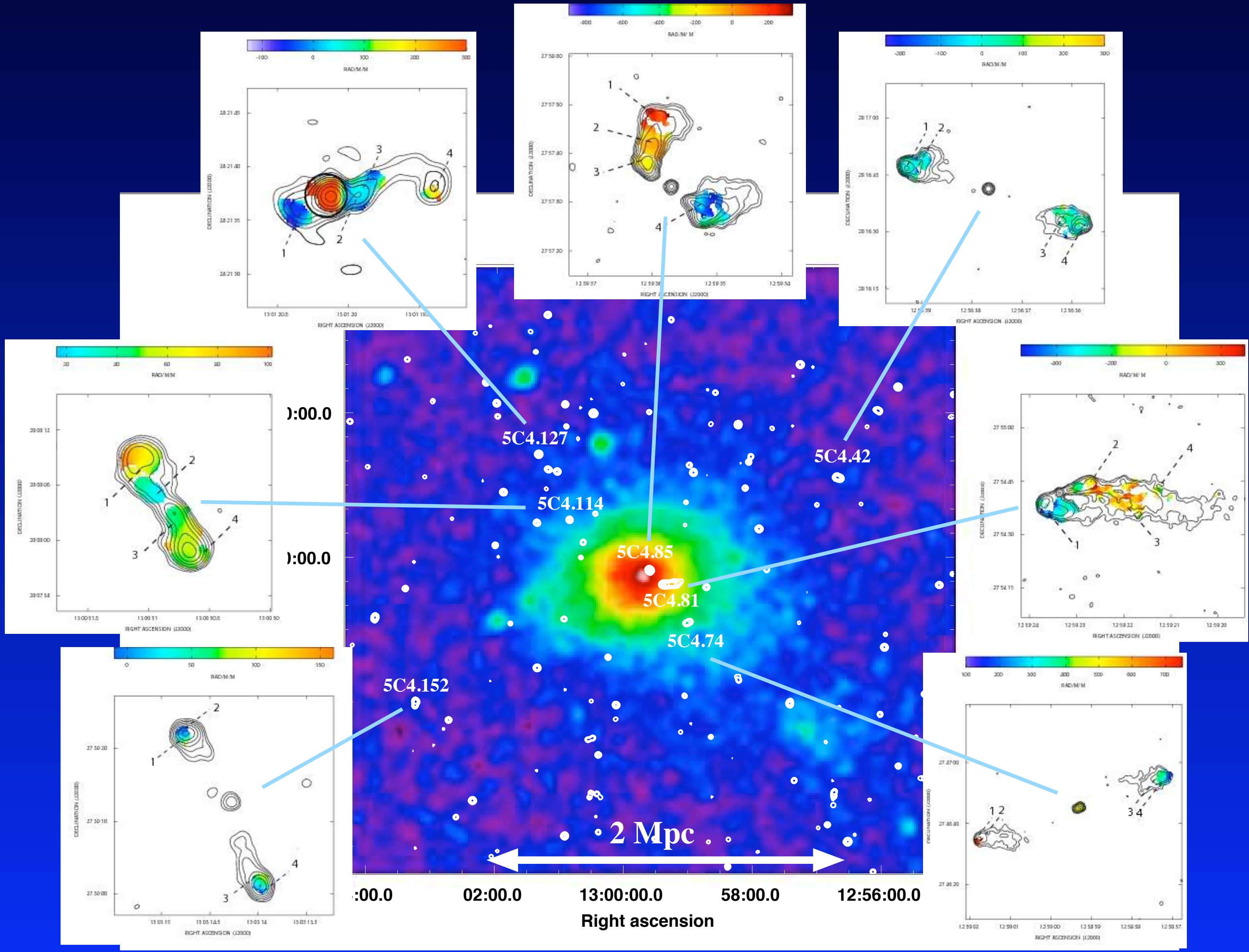
- Observed Magnetic Fields in Galaxy Clusters
  Faraday Rotation Measures
- Velocity structures within simulated Clusters
- Simulating Magnetic Fields in Galaxy Clusters
  Hierarchical Buildup of Magnetic Fields
- The Quest for Radio Halos
  Constraining Cosmic Ray Protons

On Request:

- Conduction
- Entropy beyond Rvir
- Outtakes
  Exploding Galaxies, Clusters and Voids

Observed Magnetic Fields

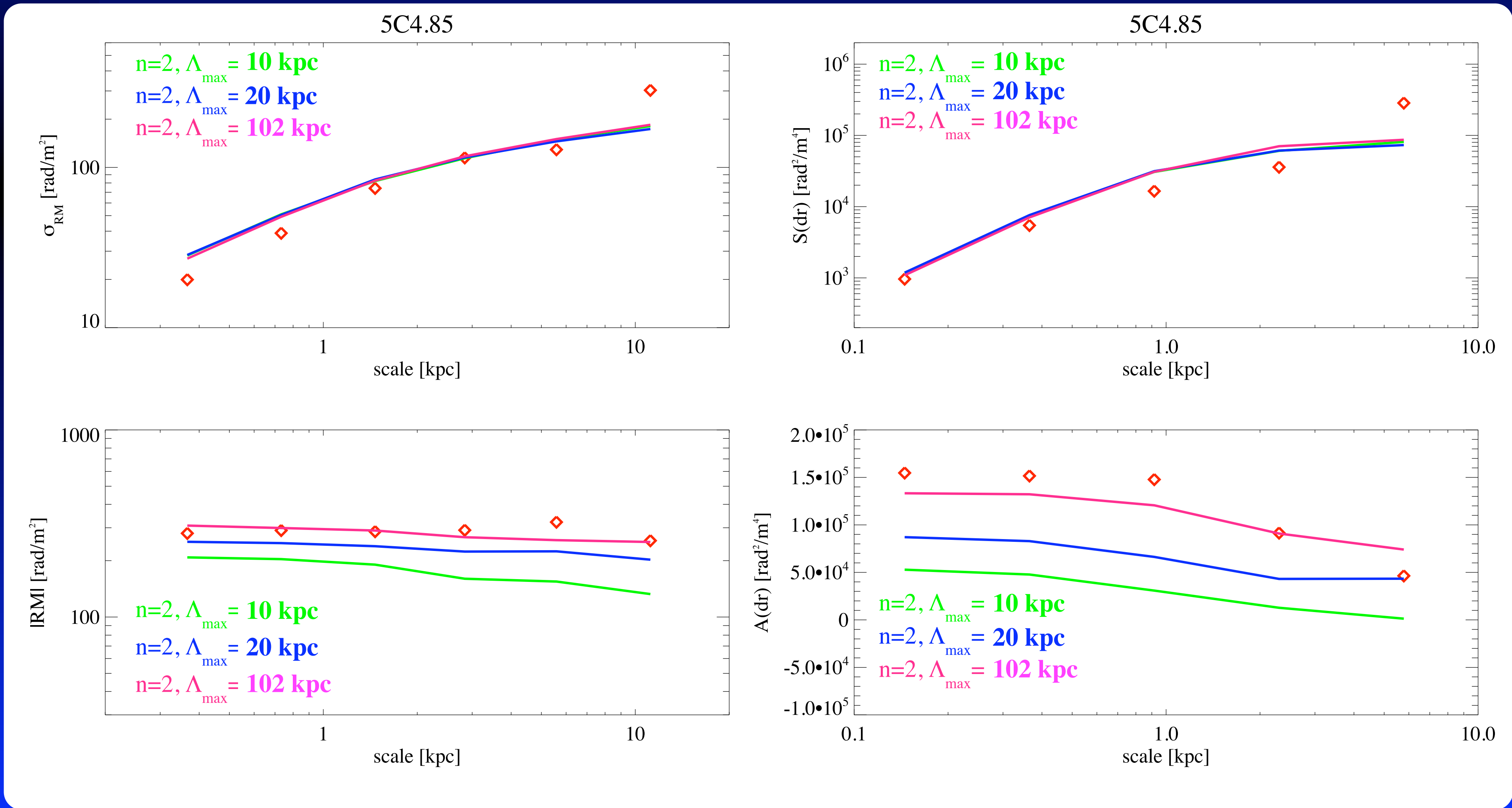
$$B(r) = B_0\left(1 + (r/r_c)^2\right)^{-1.5\mu}, \quad |B_k|^2 \propto k^{-n}, \quad (k_{\min}, k_{\max})$$



Bonafede et al. 2010

Observed Magnetic Fields

- $S(dx, dy) = \langle [RM(x, y) - RM(x + dx, y + dy)]^2 \rangle$
- $A(dx, dy) = \langle RM(x, y) \times RM(x + dx, y + dy) \rangle$
- $\langle |RM| \rangle_{\text{scale}}$, $\langle \sigma_{\text{RM}} \rangle_{\text{scale}}$, $n = 2, \Lambda_{\text{max}} = 102\text{kpc}$



Observed Magnetic Fields

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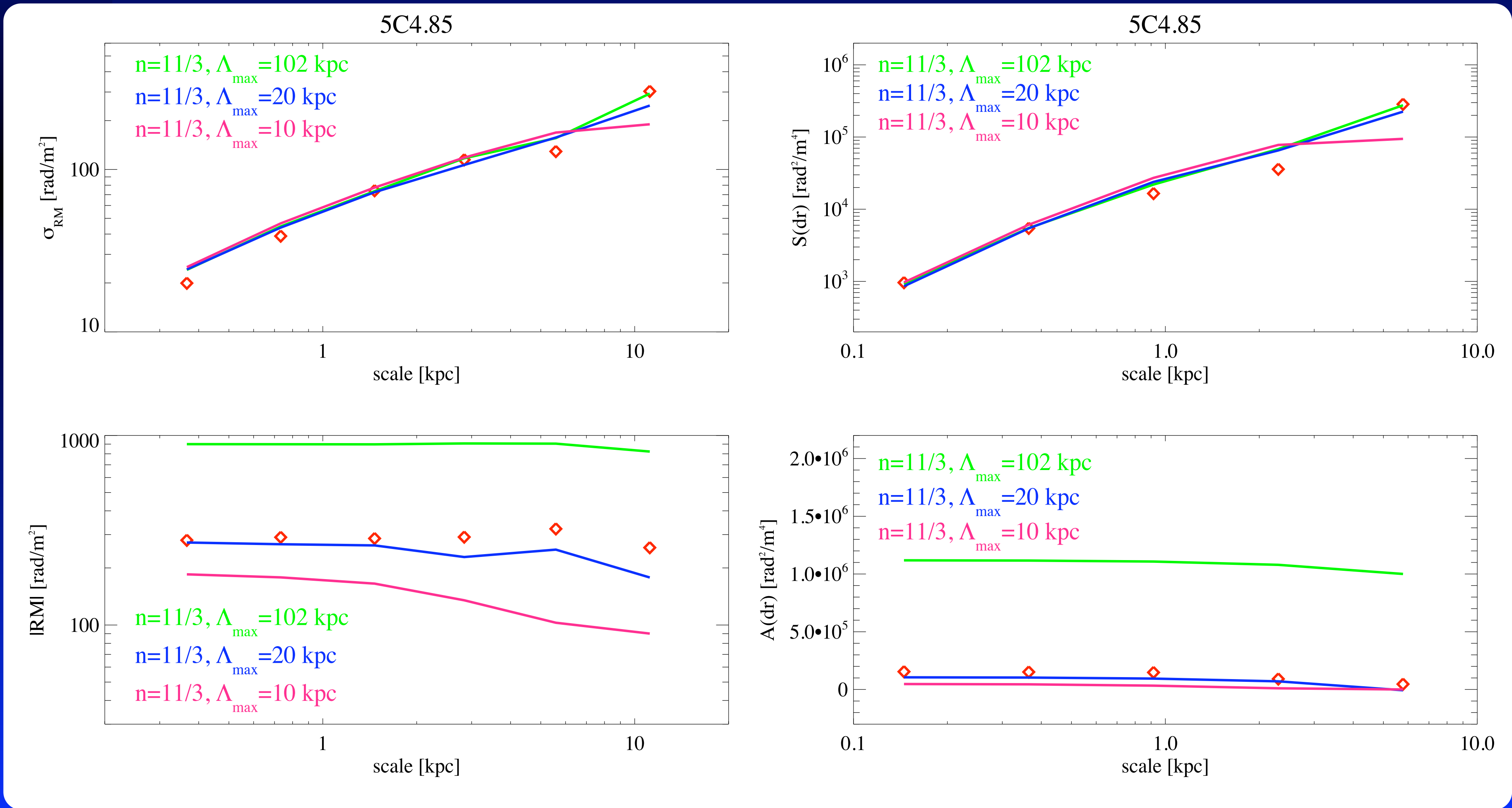
- $A(dx, dy) = \langle RM(x, y) \times RM(x + dx, y + dy) \rangle$
- $\langle |RM| \rangle_{\mathrm{scale}}$, $\langle \sigma_{\mathrm{RM}} \rangle_{\mathrm{scale}}$, $n = 11/3, \Lambda_{\max} = 24\mathrm{kpc}$



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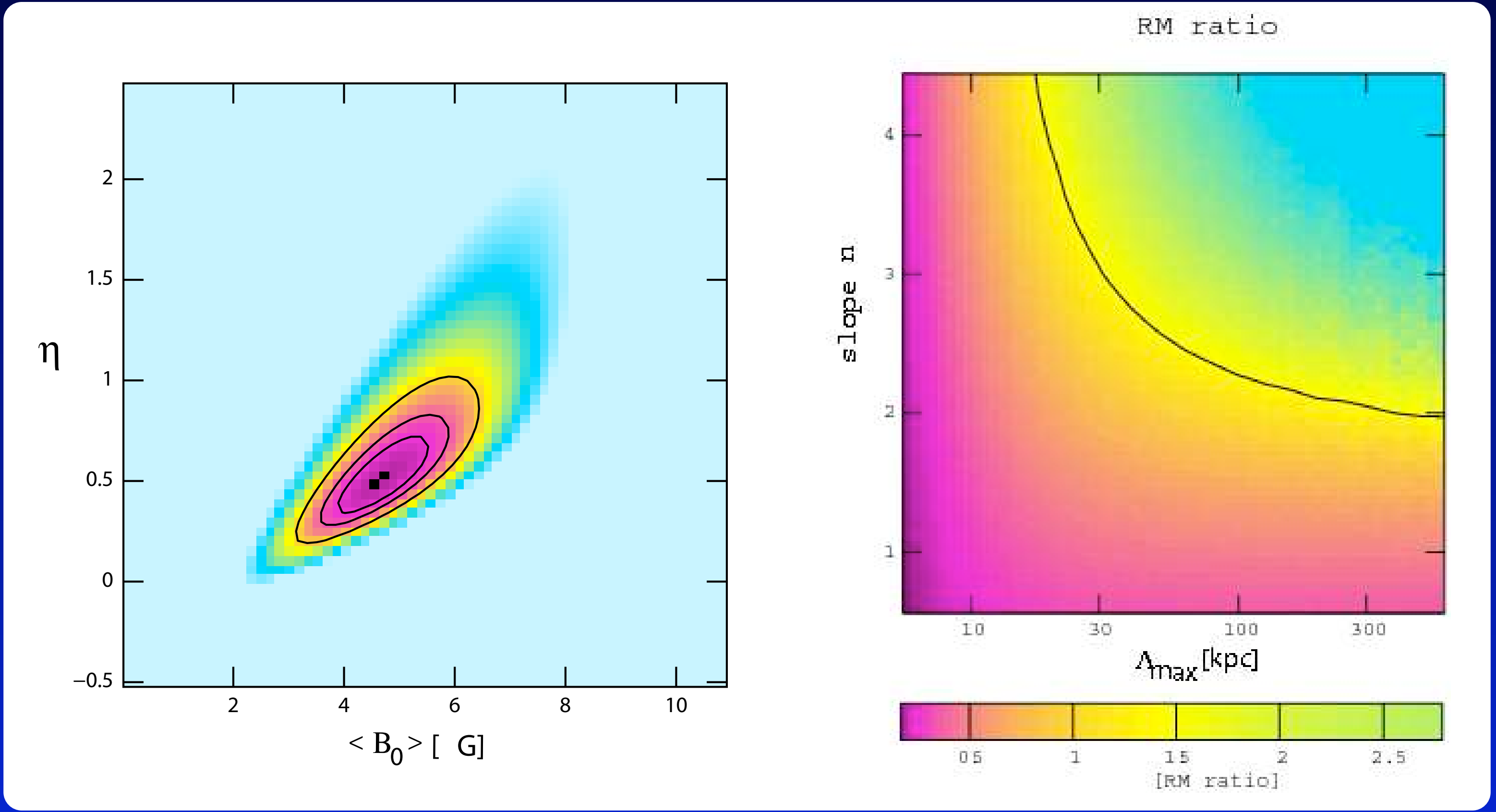
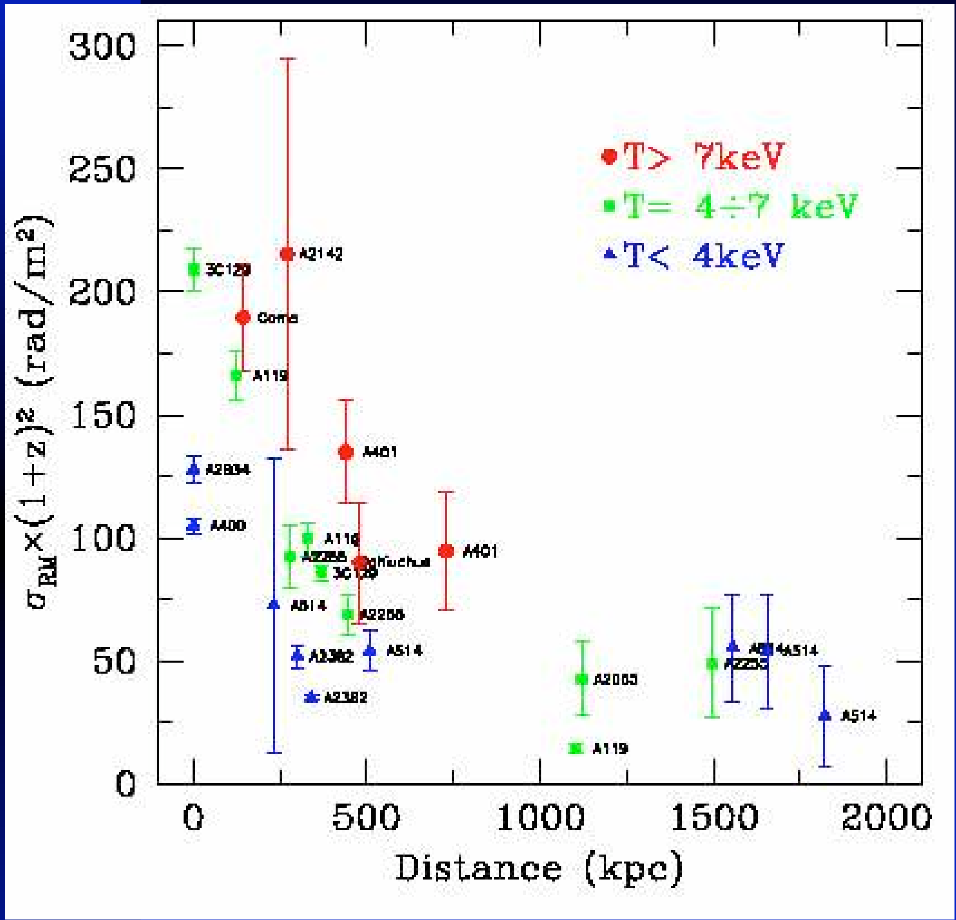
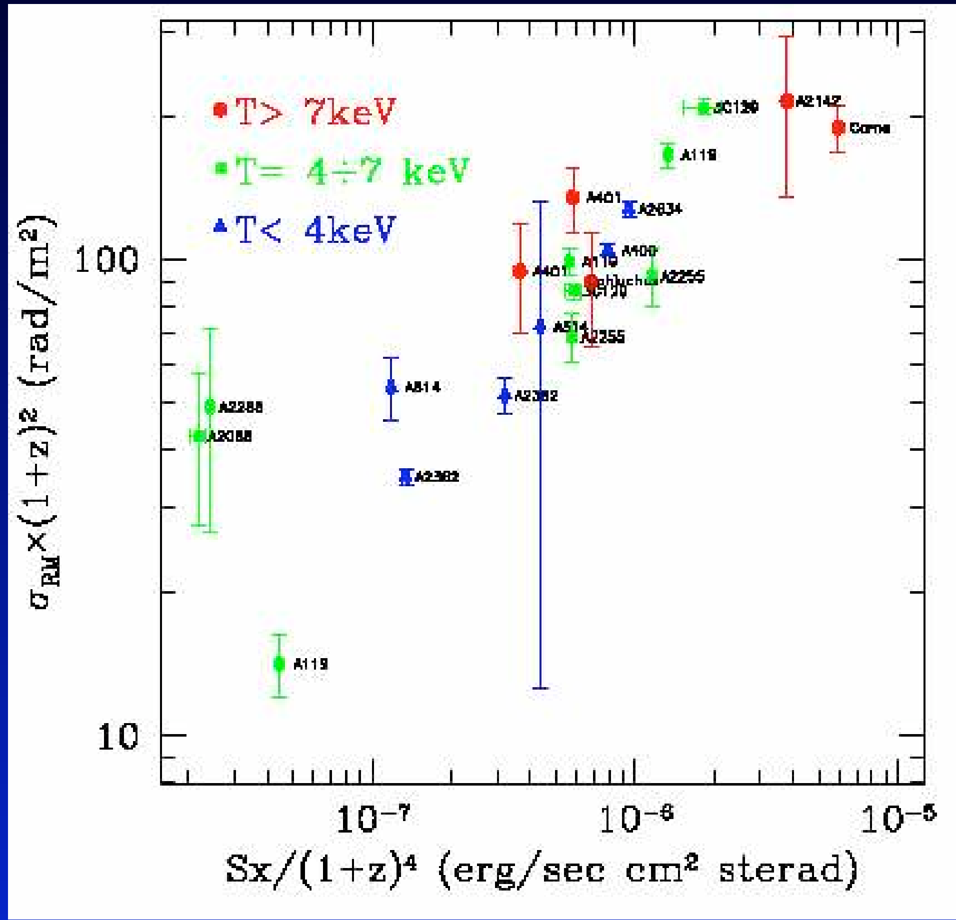


- Degeneration of injection scale $k_{\min}$ and spectral index n
- Knowing the spectrum constrains magnetic field

$\Rightarrow$ Cosmological MHD simulations

Observed Magnetic Fields



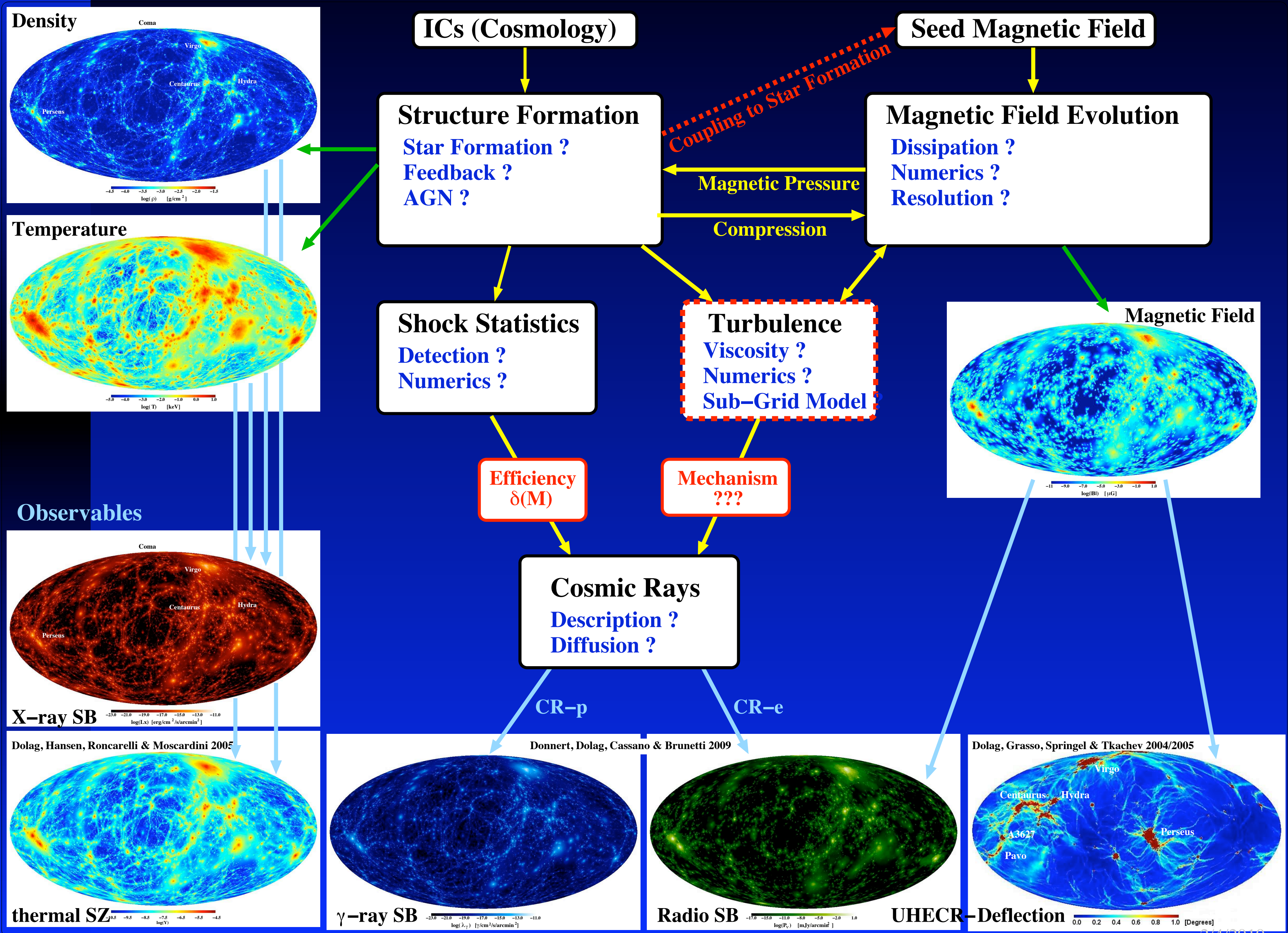


Govoni et al., submitted

- For new RM maps within massive clusters.
- How does $\vec{B}$ scale with cluster temperature ?

$\Rightarrow$ Cosmological MHD simulations

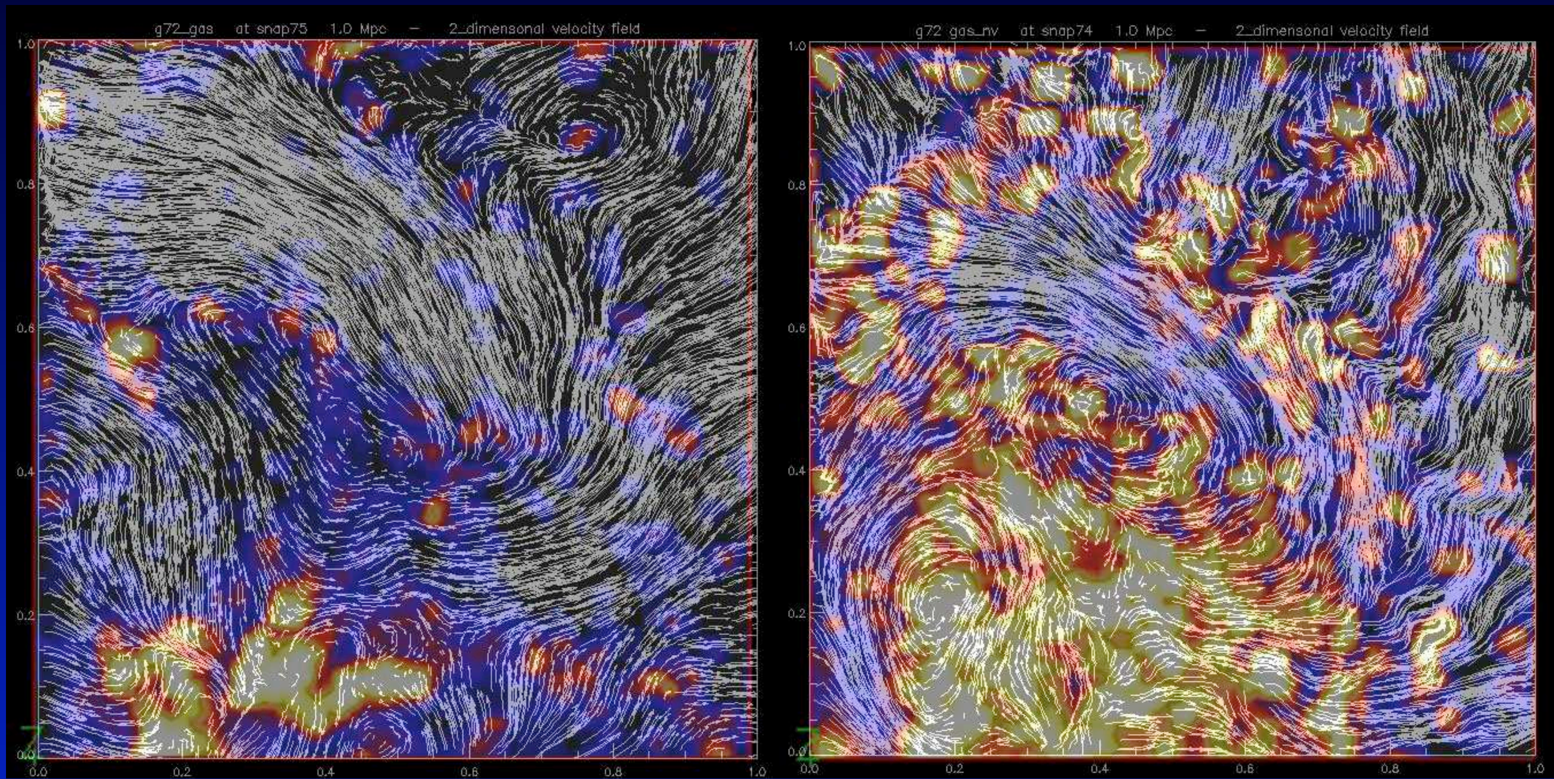
Simulation Network



Motions in the ICM

(I) Turbulence

Old viscosity scheme **New viscosity scheme**



Artificial viscosity completely switched of outside of shocks !

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

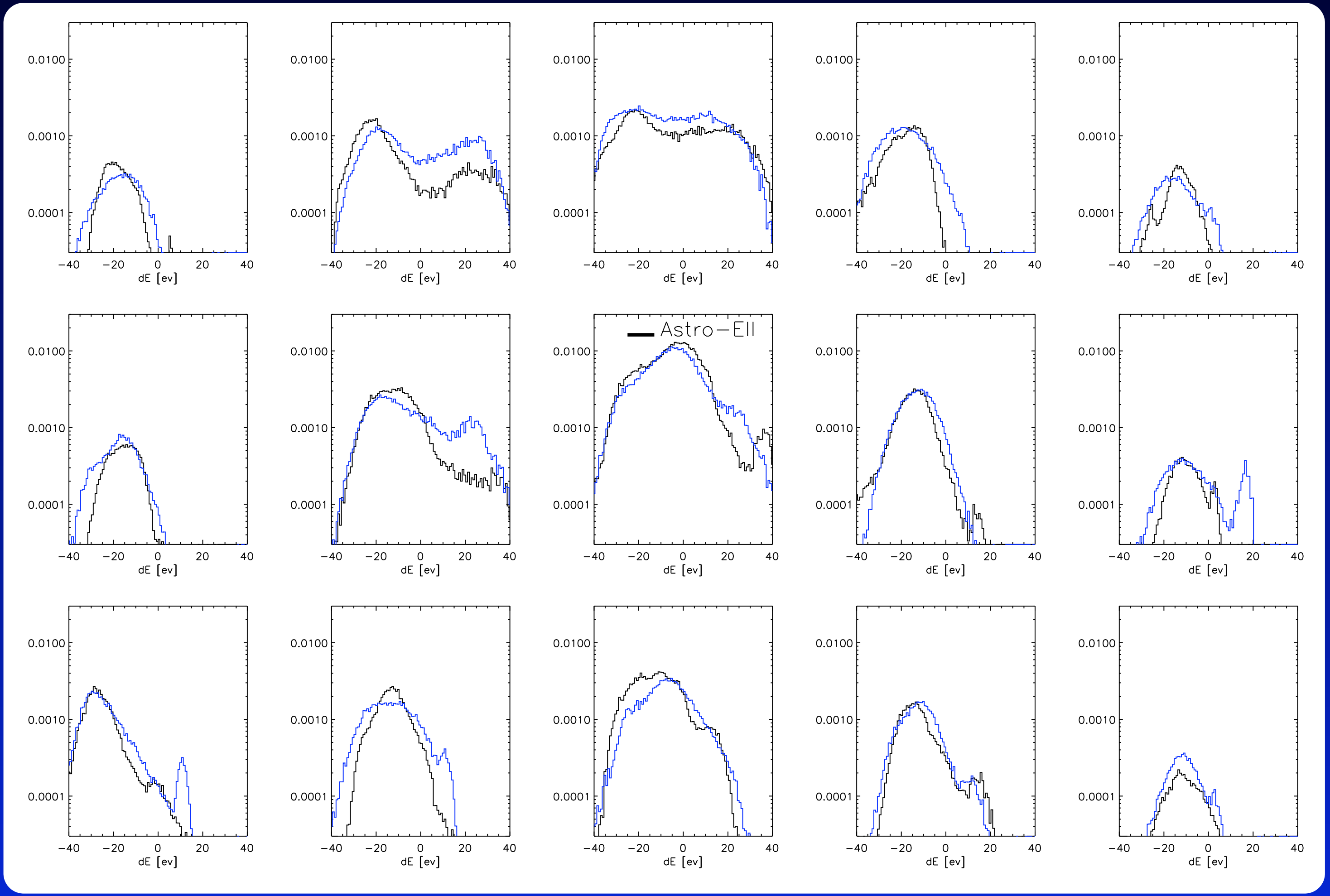
⇒ Inset of turbulence (transient phenomena)

⇒ Enlarged energy-fraction in gas velocity (10%)

Dolag et al. 2005 (see also Iappicino et al. 2008,2009, Vazza et al. 2009/2010, ...)

Motions in the ICM

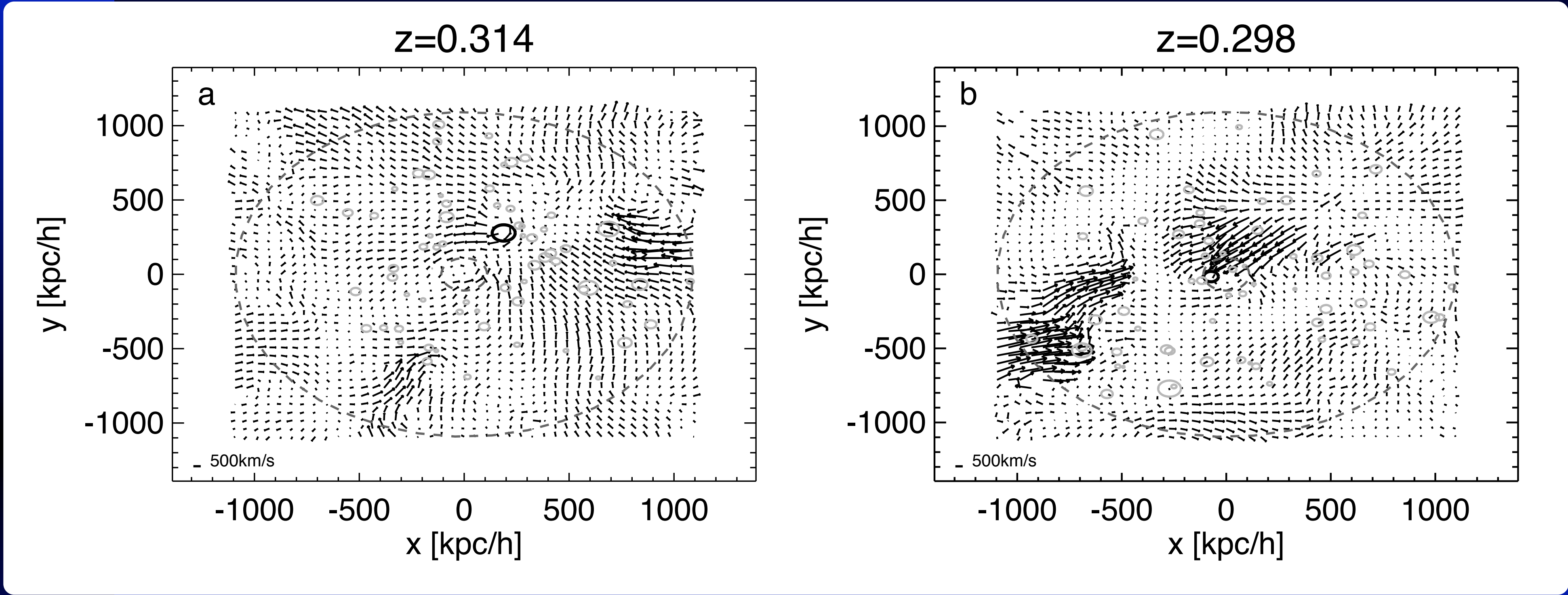
(I) Turbulence



Due to large contribution of bulk motions and beam smearing, the imprint of “true“ turbulence will be hard to detect, even resolution like Astro-E2 !

Motions in the ICM

(II) Rotation

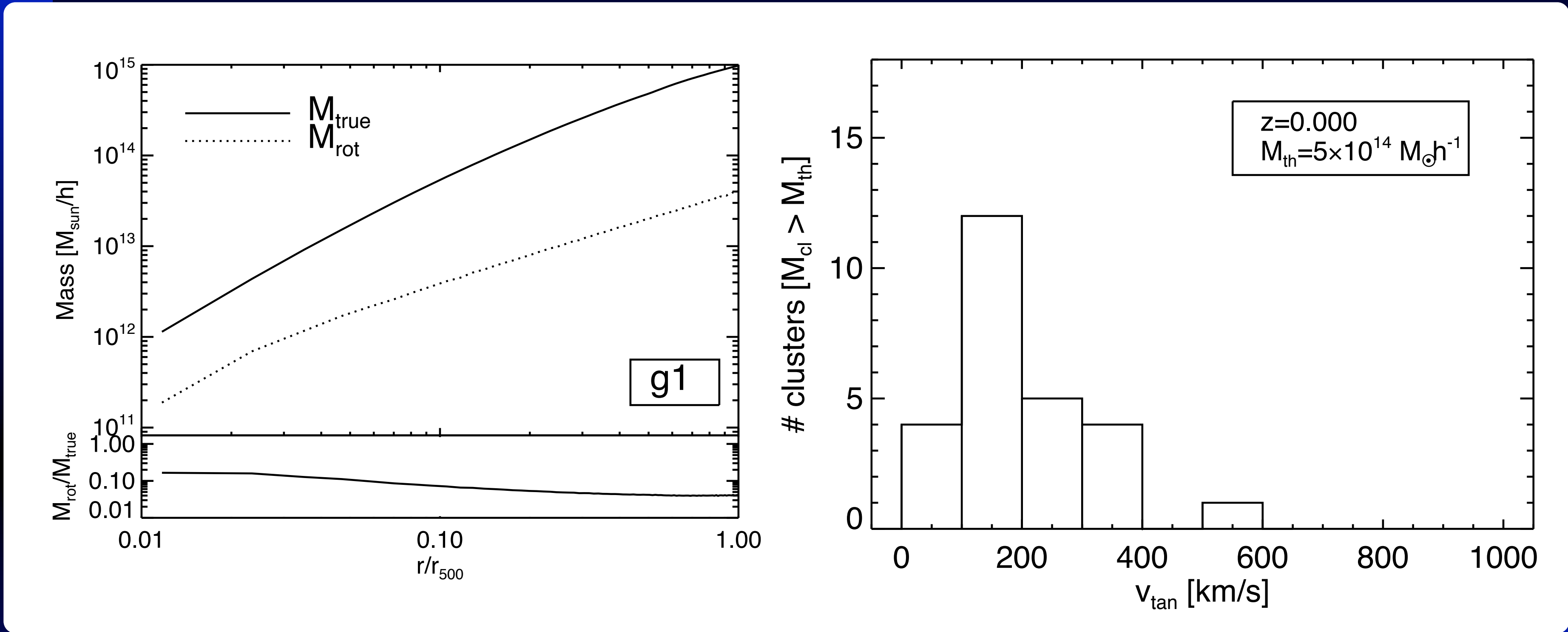


Biffi et al., in prep.

- Moderate core rotation transient phenomena
- Get destroyed by passing of a gas rich sub-structure

Motions in the ICM

(II) Rotation

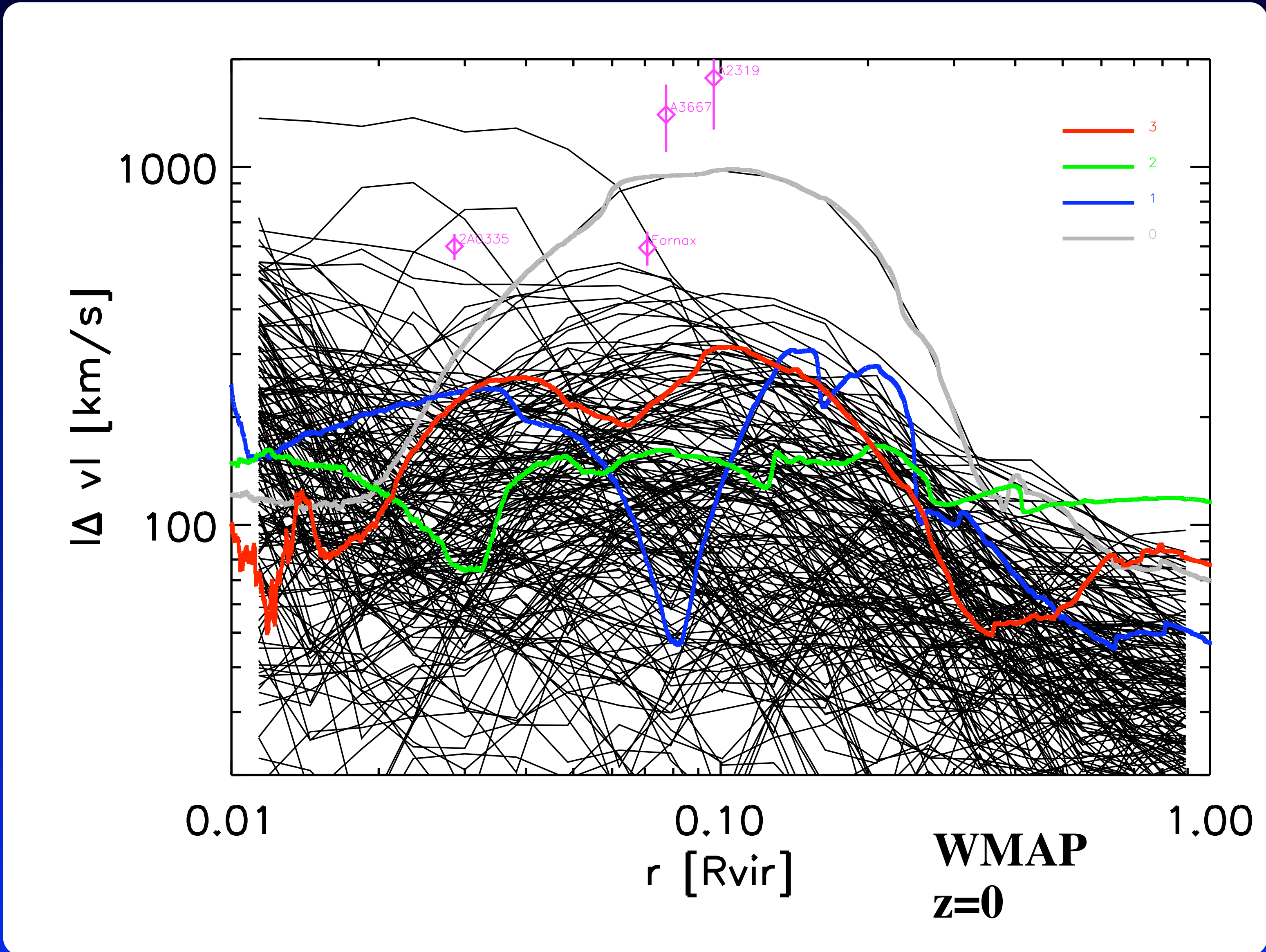


Biffi et al., in prep.

- No significant rotational support
- Typical tangential velocity component $\approx$ 200 km/s

Motions in the ICM

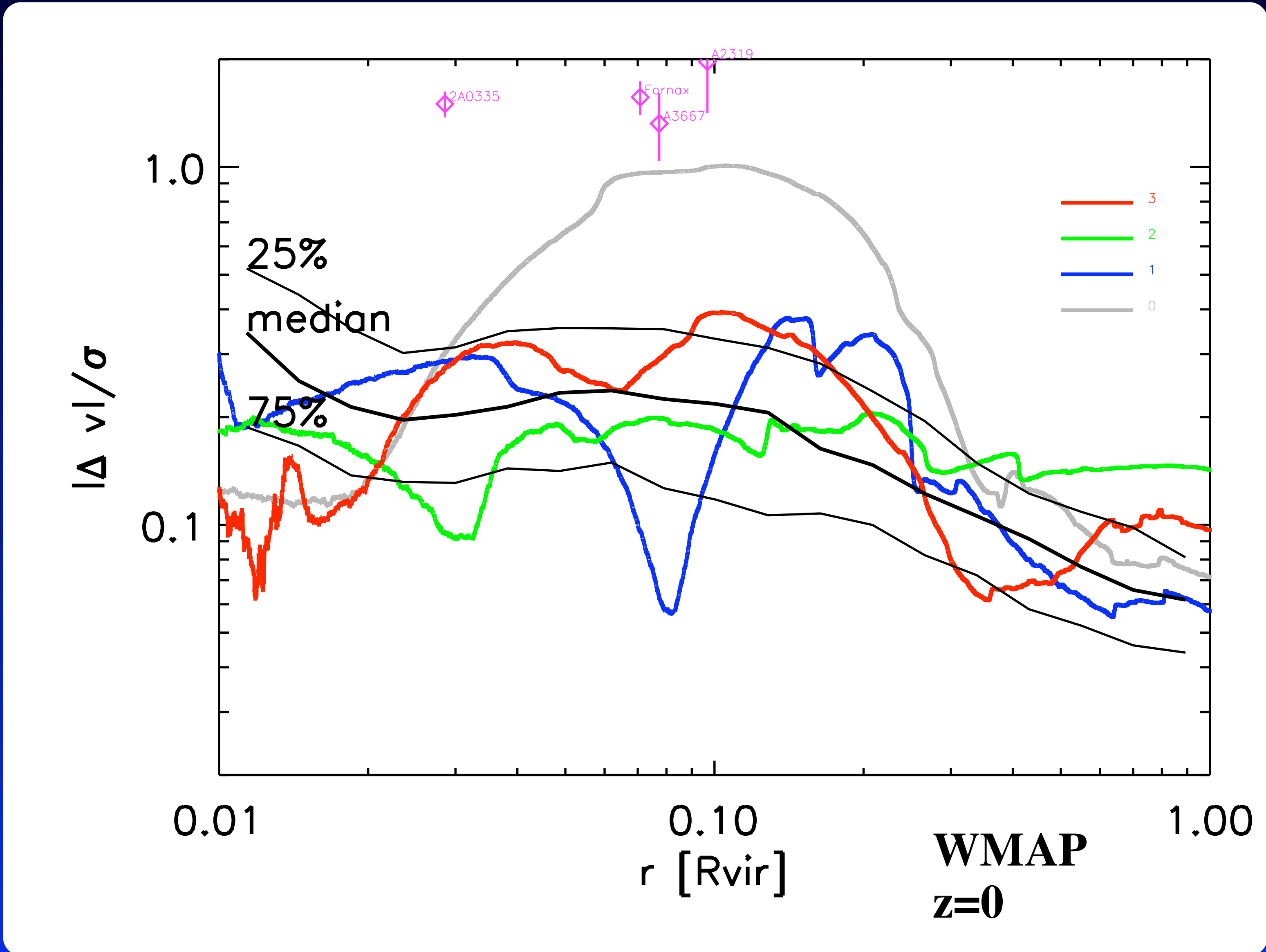
(III) Bulk Motions



Profiles of the relative motion of gas and DM compared to observations of gas sloshing.

Motions in the ICM

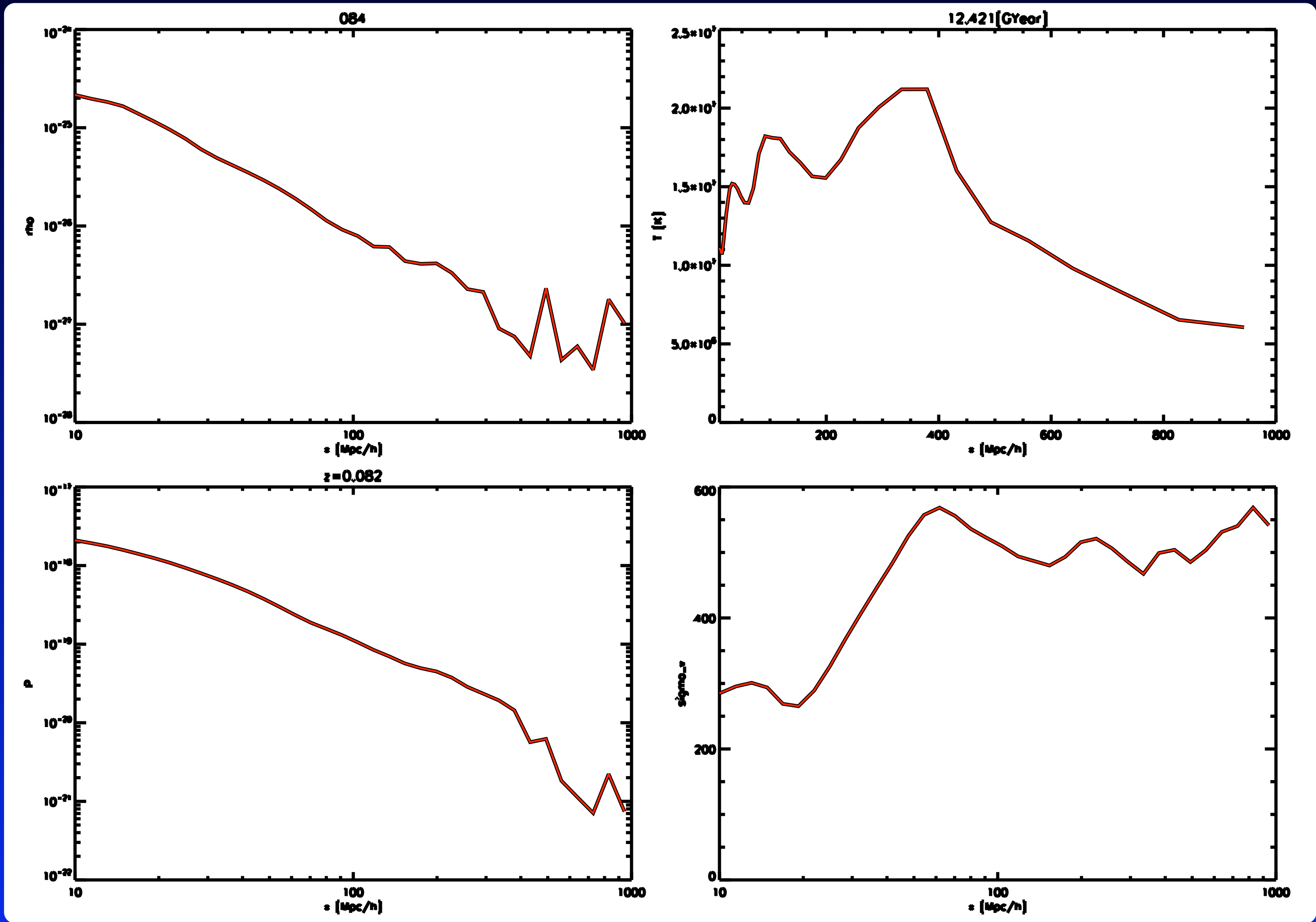
(III) Bulk Motions



Median sloshing declines from ≈200 km/s (central) to ≈50 km/s (at Rvir).

Motions in the ICM

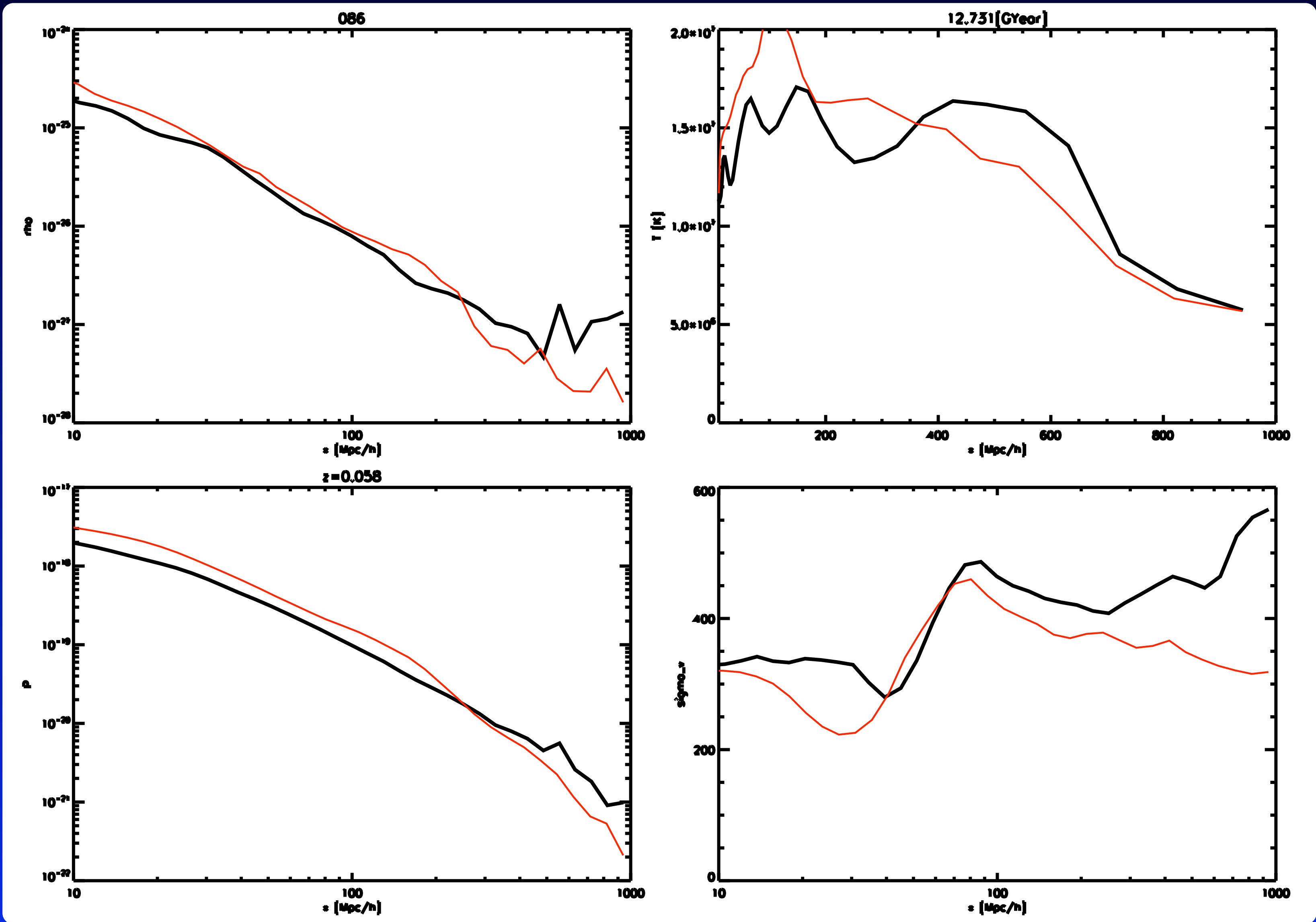
(IV) Dynamical pressure



Take cluster and set gas velocity to “zero”.

Motions in the ICM

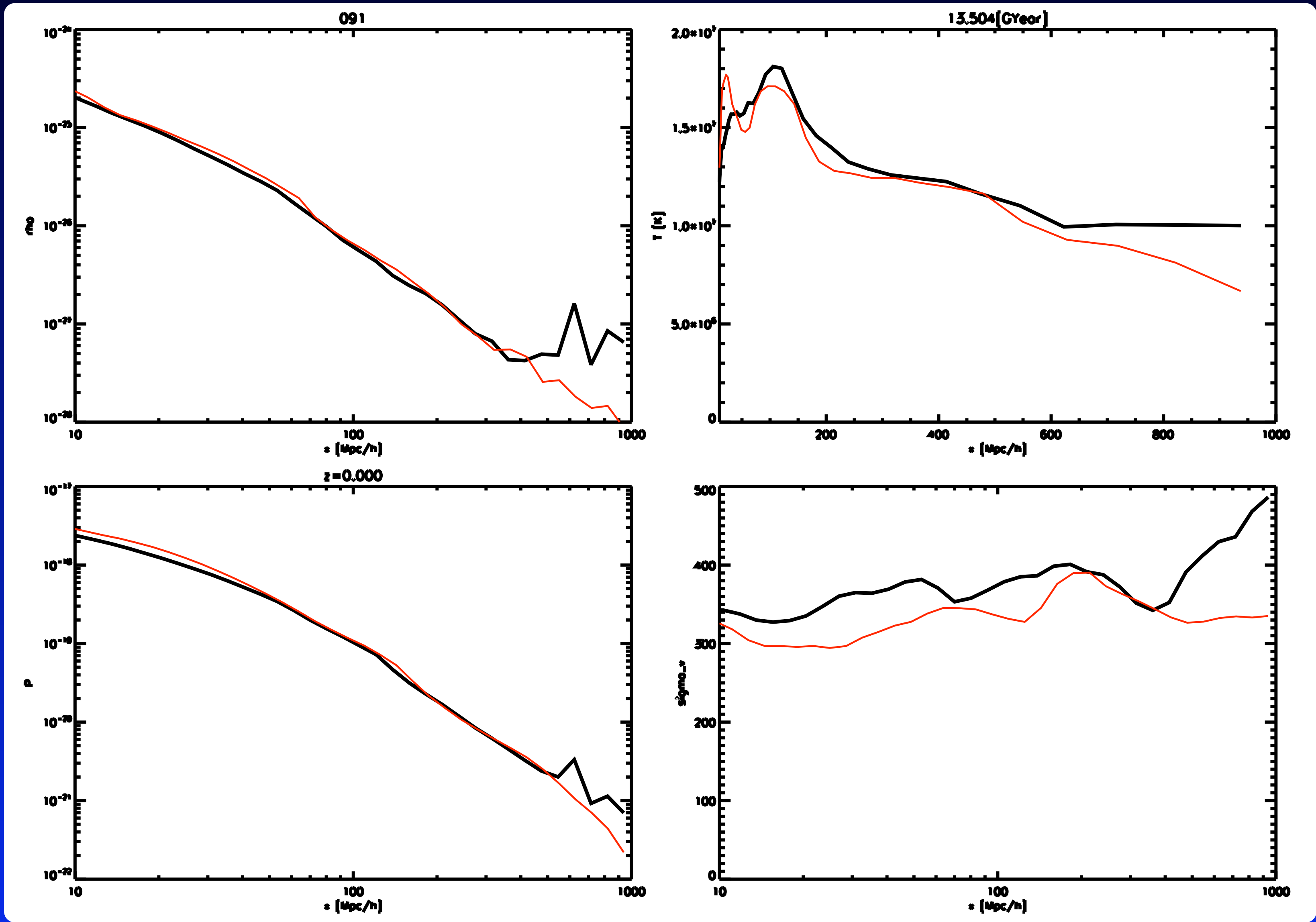
(IV) Dynamical pressure



Gas contracts to 30% higher pressure ...

Motions in the ICM

(IV) Dynamical pressure

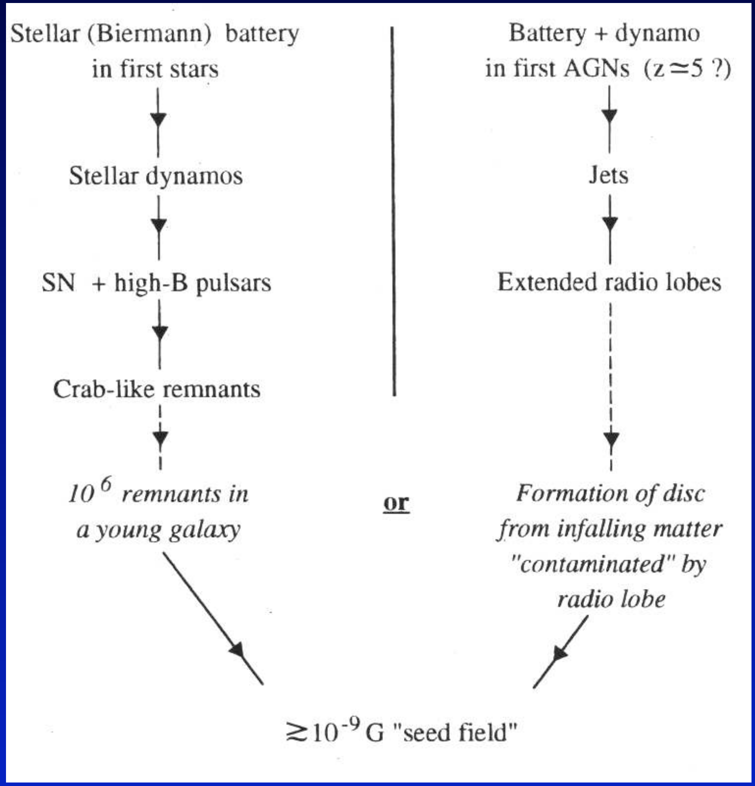


Until dynamical pressure re-establish !

Origin of Magnetic Fields

Origin

- Primordial
- Battery
- Dynamo (Turbulence)
- Stars
- Supernovae
- Galactic Winds
- AGNs, Jets
- Shocks



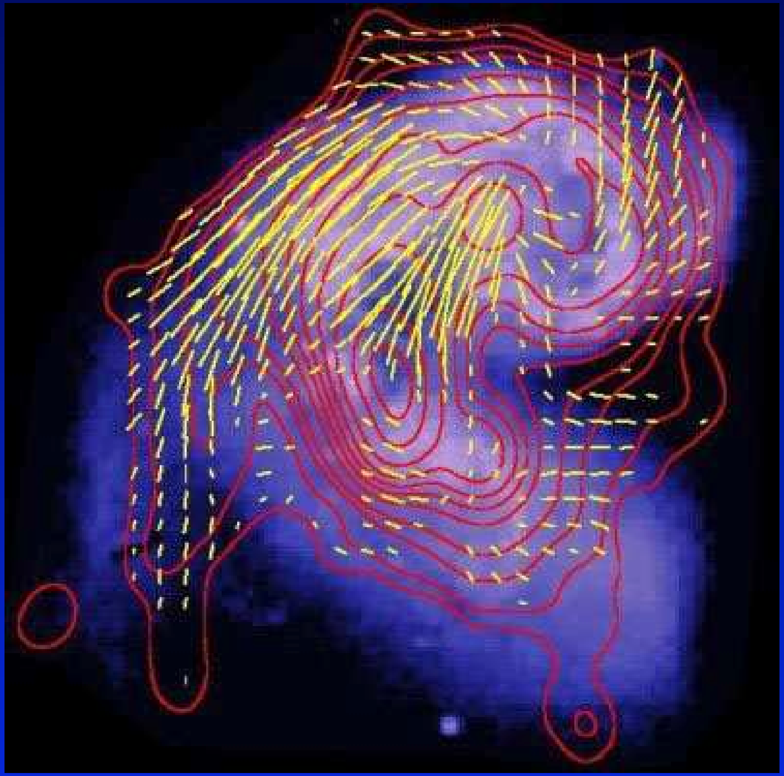
Rees 1994

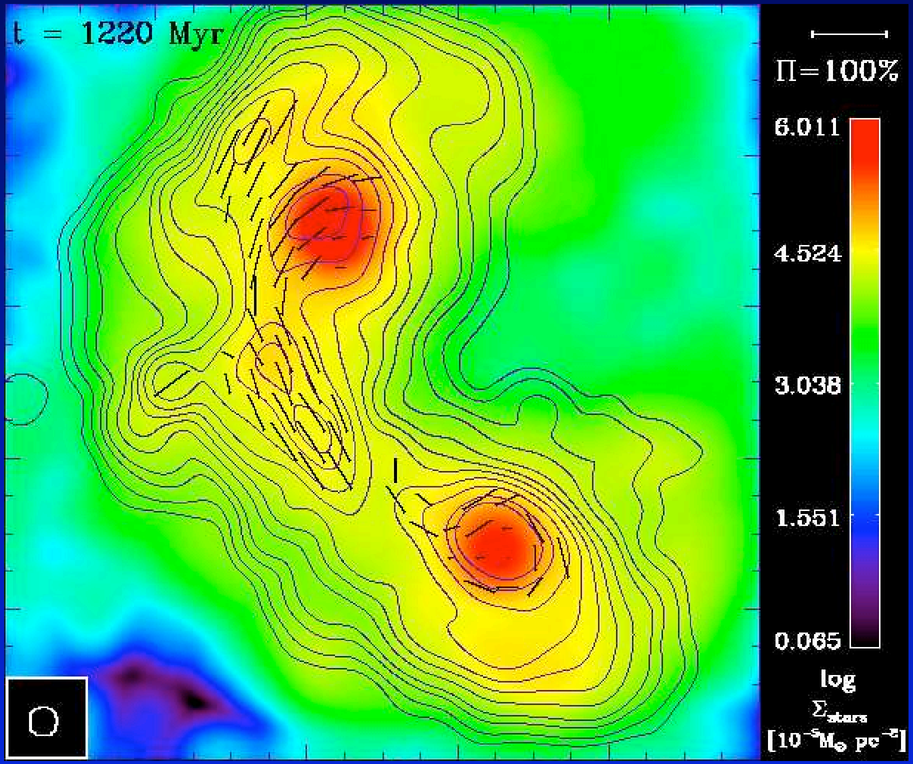
+ further amplification by **structure formation**

- dissipation ?

Origin of Magnetic Fields

Simulating the magnetic field amplification during galaxy mergers like in the Antennae system. Final magnetic field strength and field configuration in broad agreement with observations.





(Chyzy & Beck 2005 Kortarba et al. 2010)

Origin of Magnetic Fields

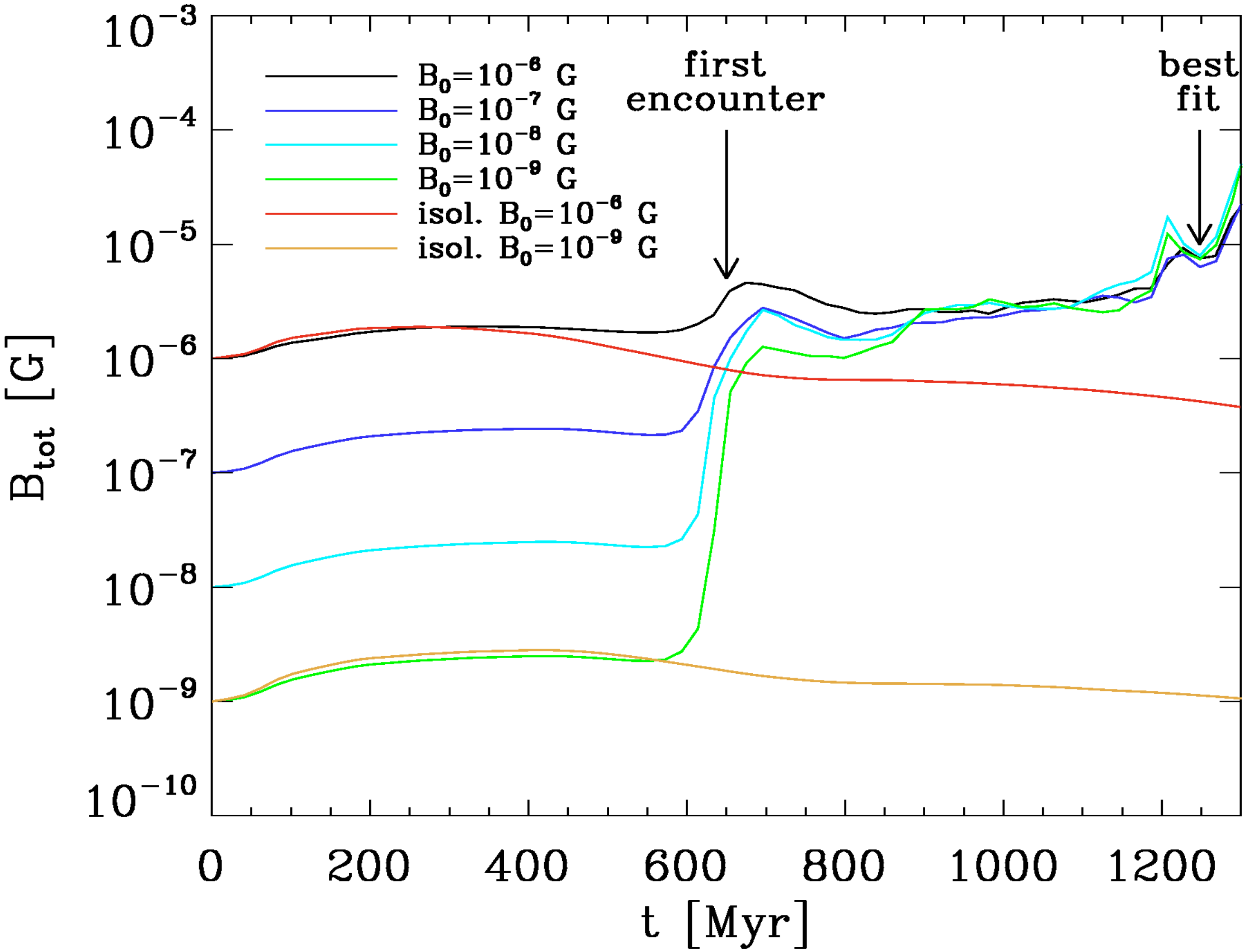
Simulating the magnetic field amplification during galaxy mergers like in the Antennae system. Final magnetic field strength and field configuration in broad agreement with observations.

(Kortarba et al. 2010)

Origin of Magnetic Fields

Final magnetic field close to equipartition with turbulent velocity component, largely independent of initial field values.

$\Rightarrow$ Hierarchical buildup of magnetic field

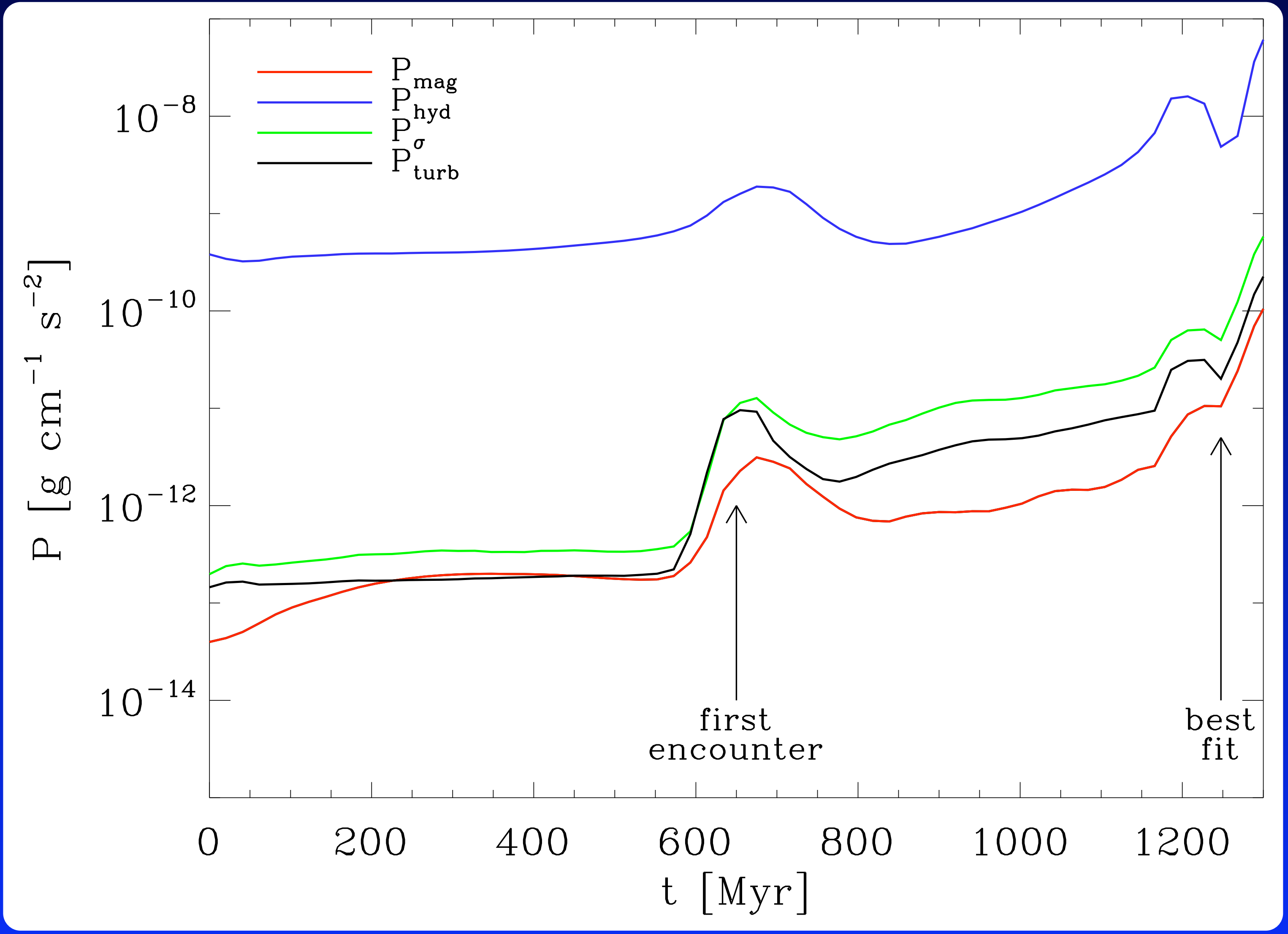


(Kortarba et al. 2010)

Origin of Magnetic Fields

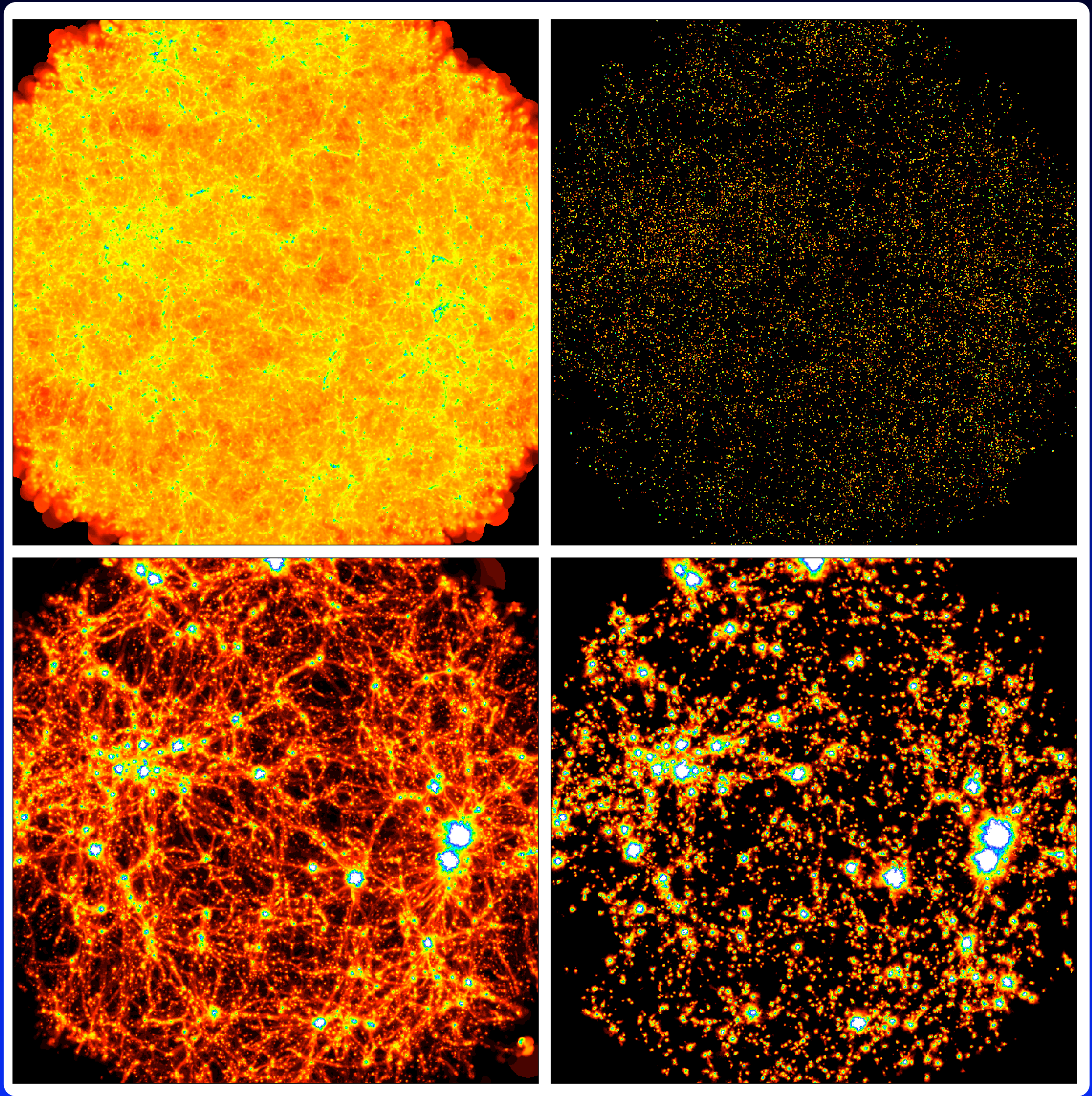
Final magnetic field close to equipartition with turbulent velocity component, quasi independent of initial field values.

$\Rightarrow$ Hierarchical buildup of magnetic field



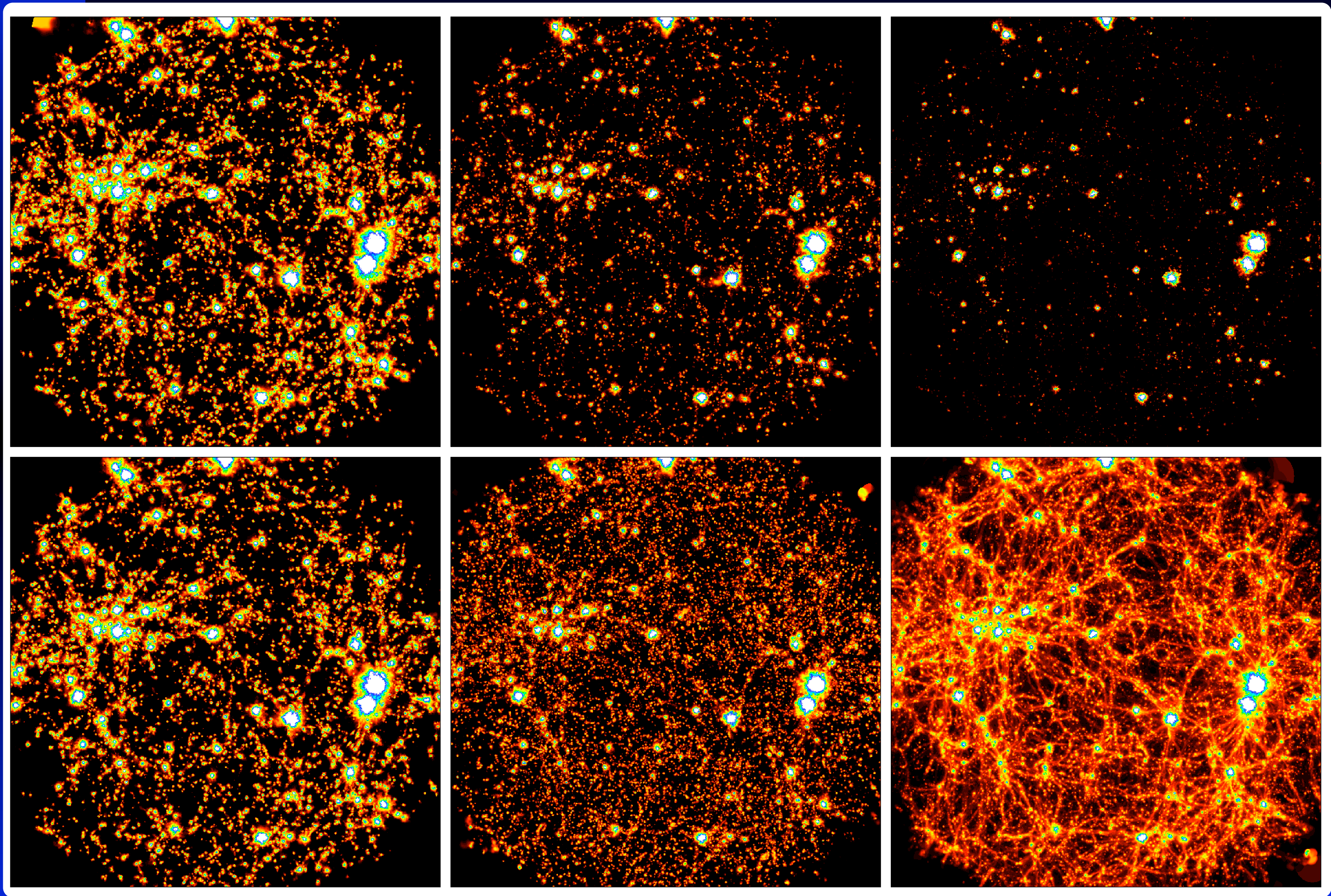
(Kortarba et al. 2010)

Origin of Magnetic Fields



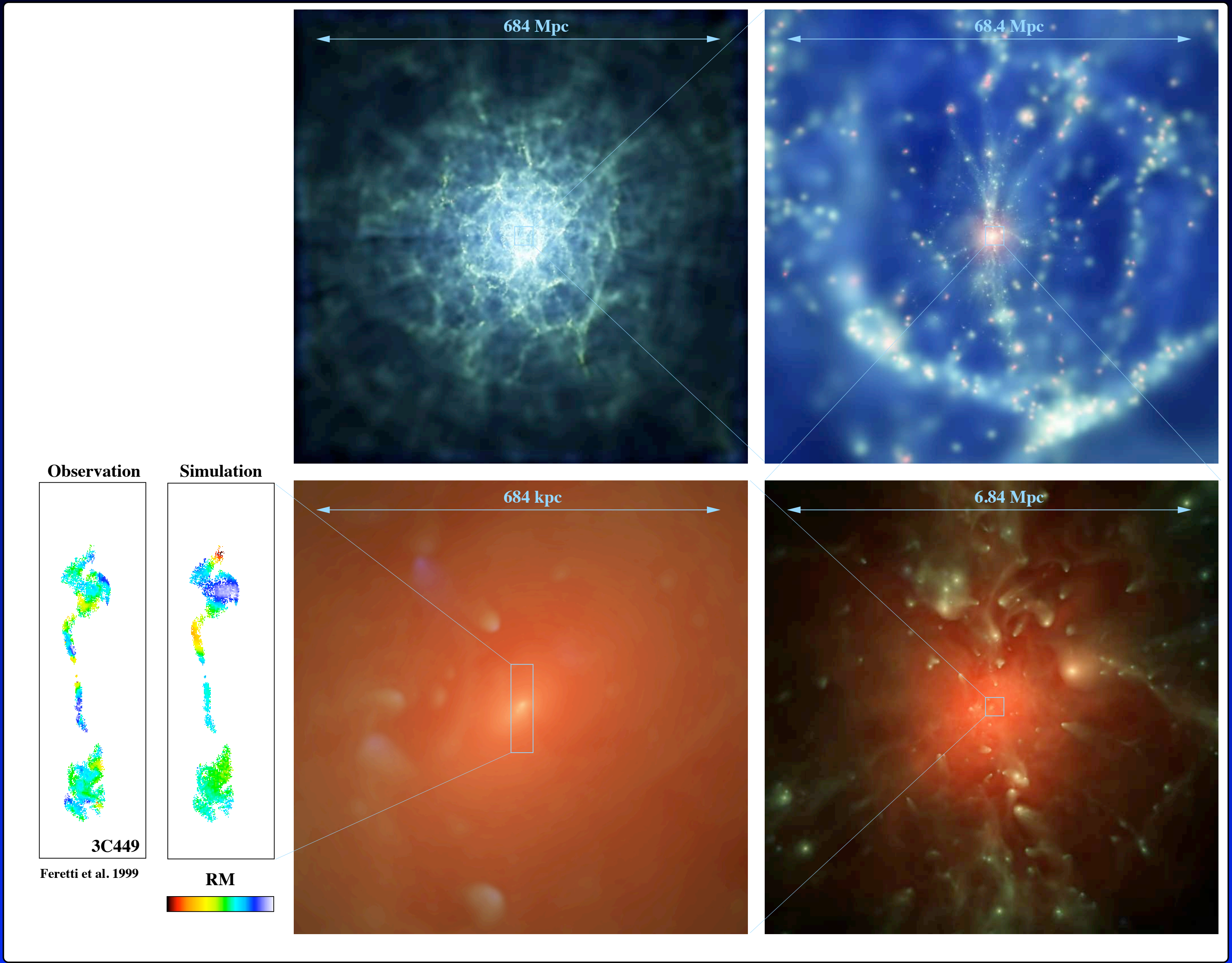
Seeding from galactic outflows (Donnert et al. 2009)

Origin of Magnetic Fields



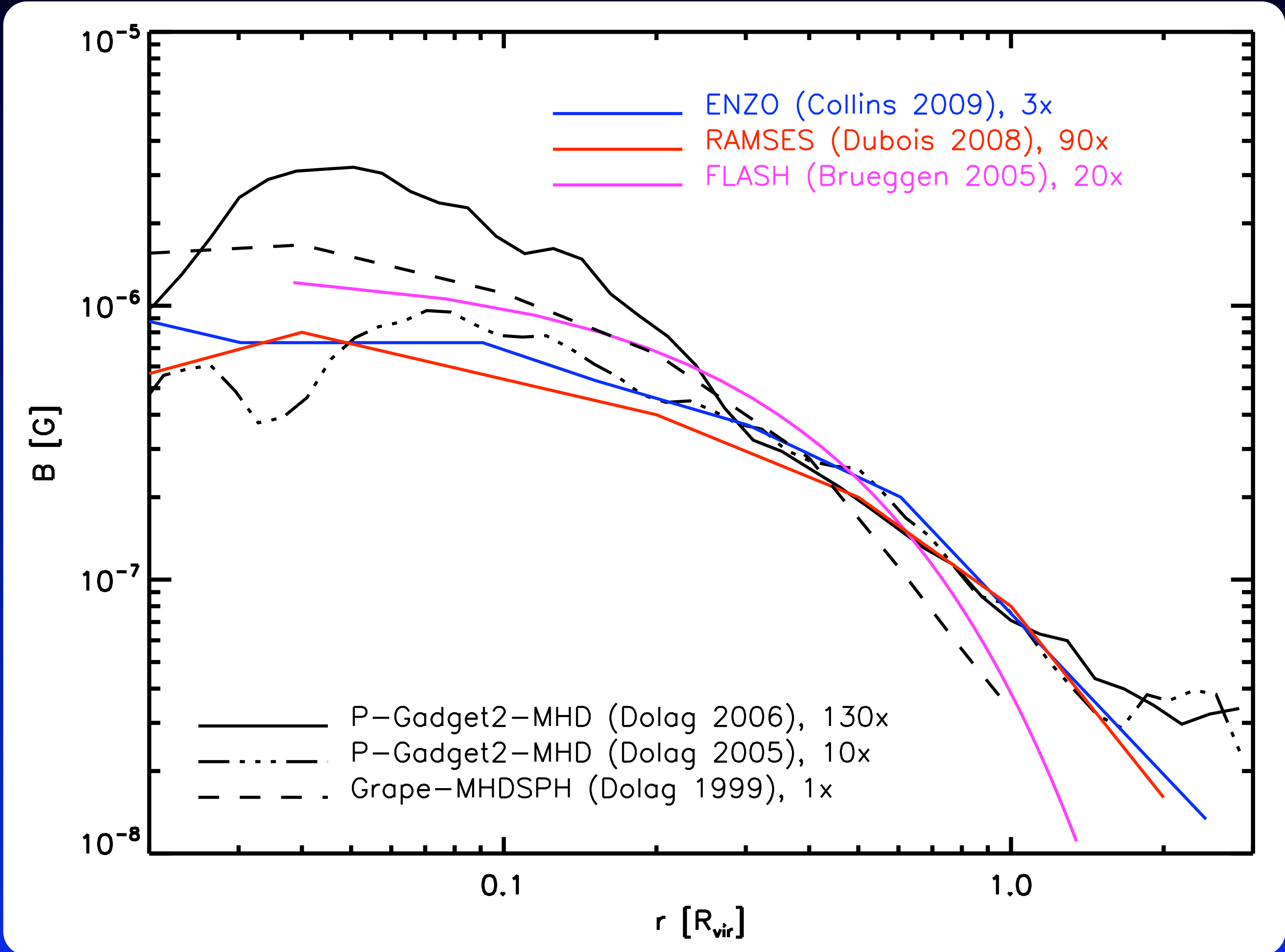
Different wind parameters (Donnert et al. 2009)

Cosmological MHD simulations



“Zoomed” cluster simulation (Dolag & Stasyszyn 2009). Movie: u,v

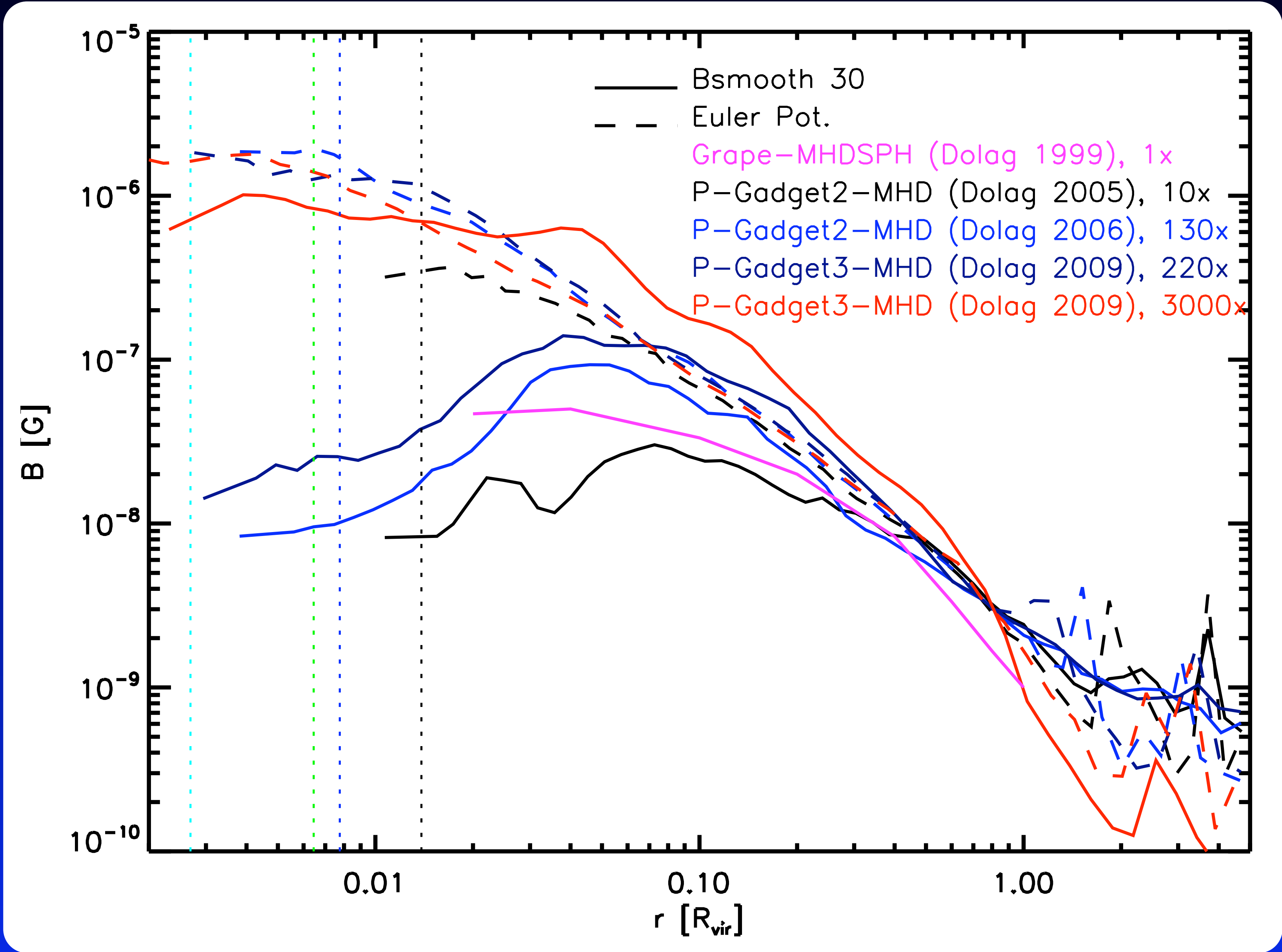
Cosmological MHD simulations



⇒ Radial shape confirmed by more recent works

⇒ Generic feature from structure formation

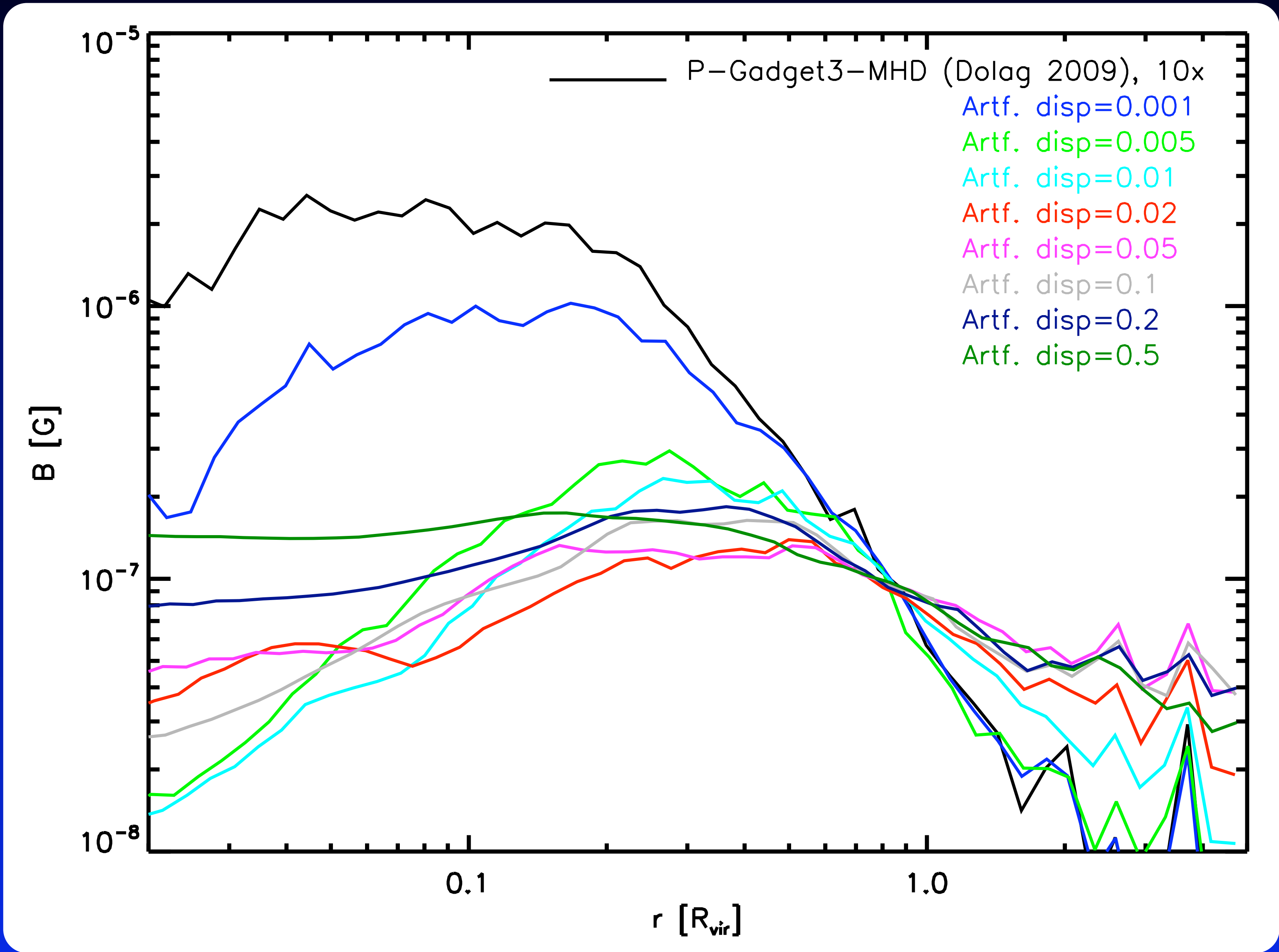
Cosmological MHD simulations



But: Central part of radial distribution steepens with resolution.

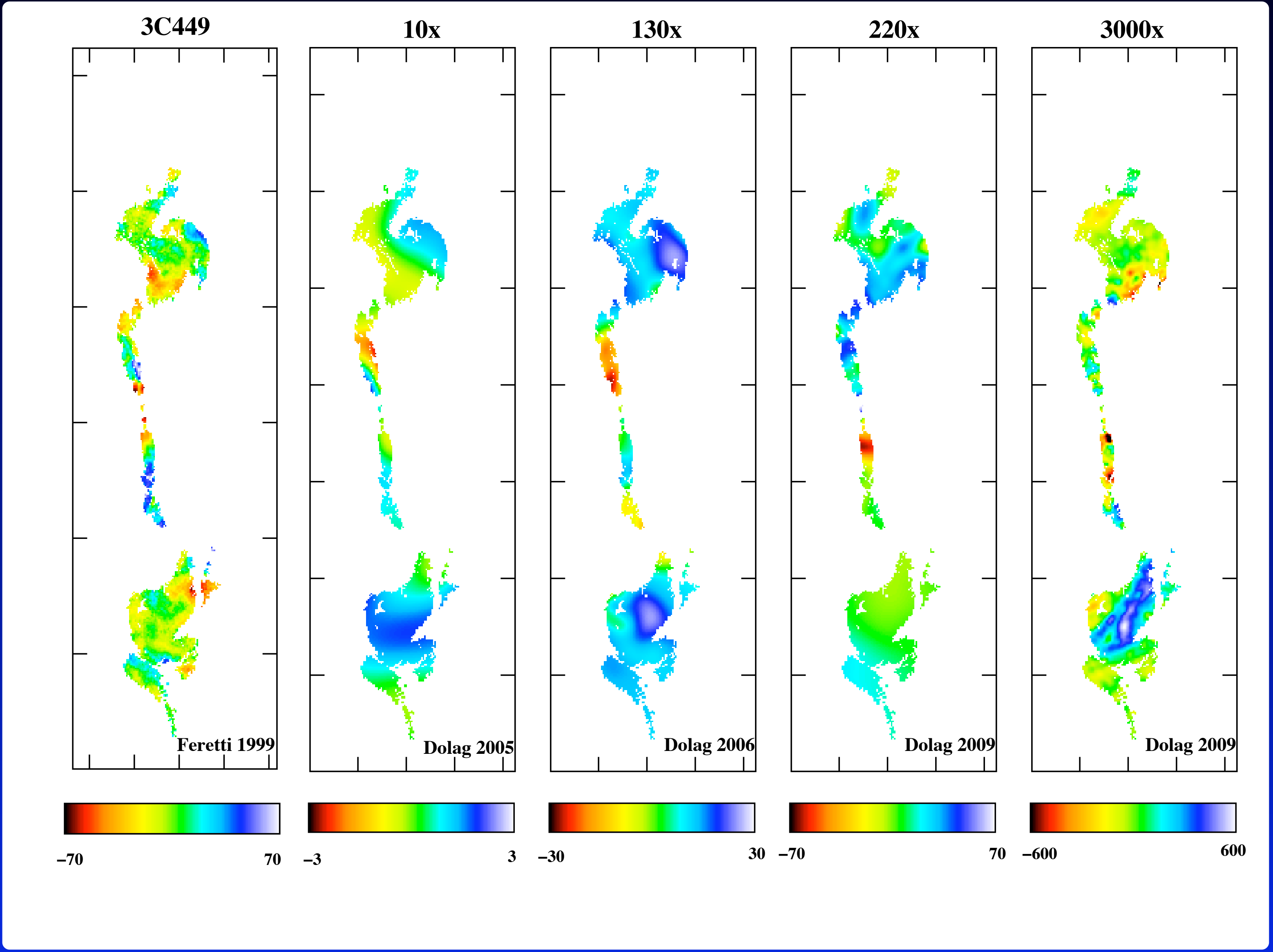
⇒ Resolution is important

Cosmological MHD simulations



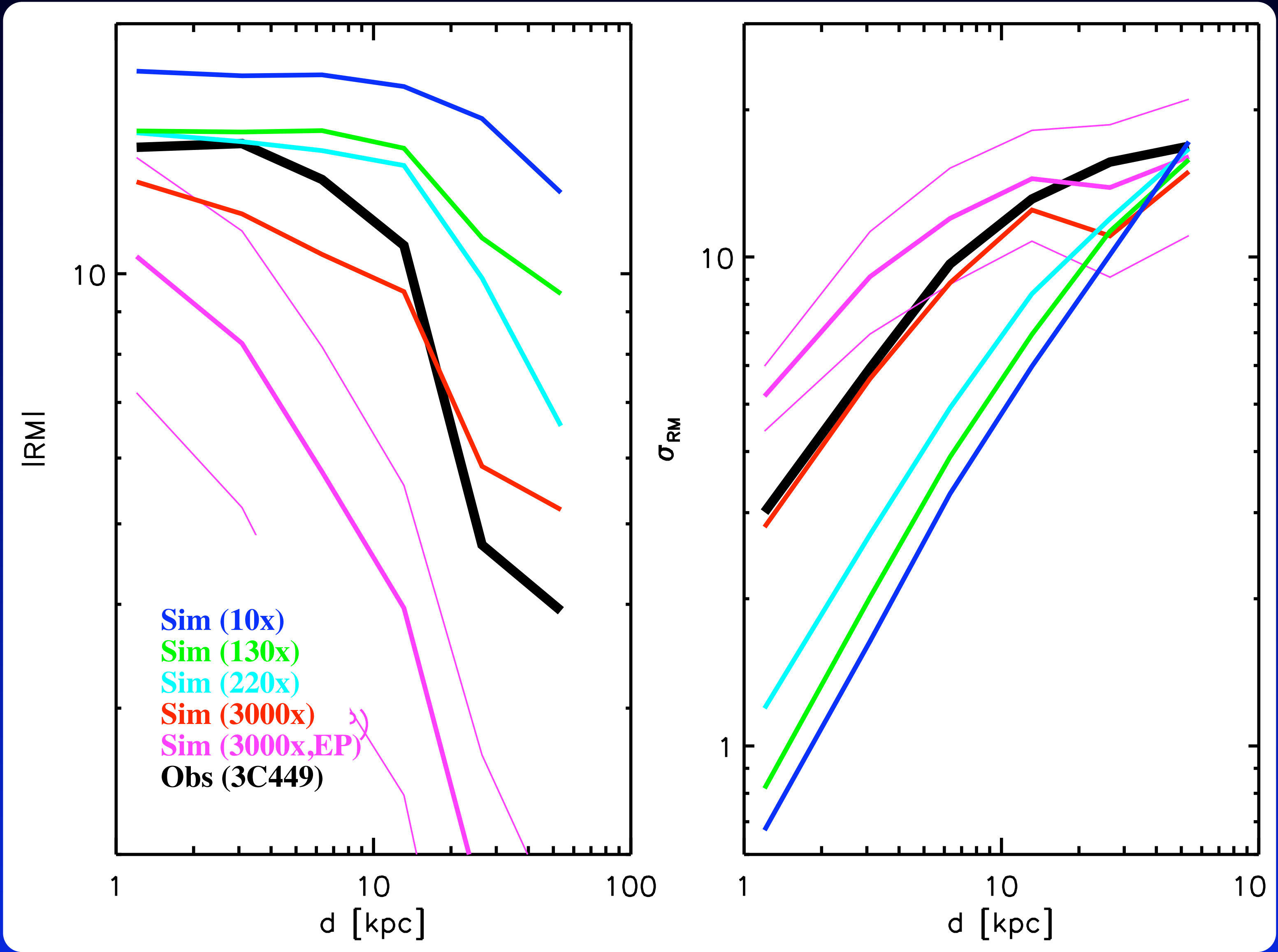
Attention: Central part flattens with higher dissipation rate
⇒ Numerical/Ohmic dissipation is important

Cosmological MHD simulations



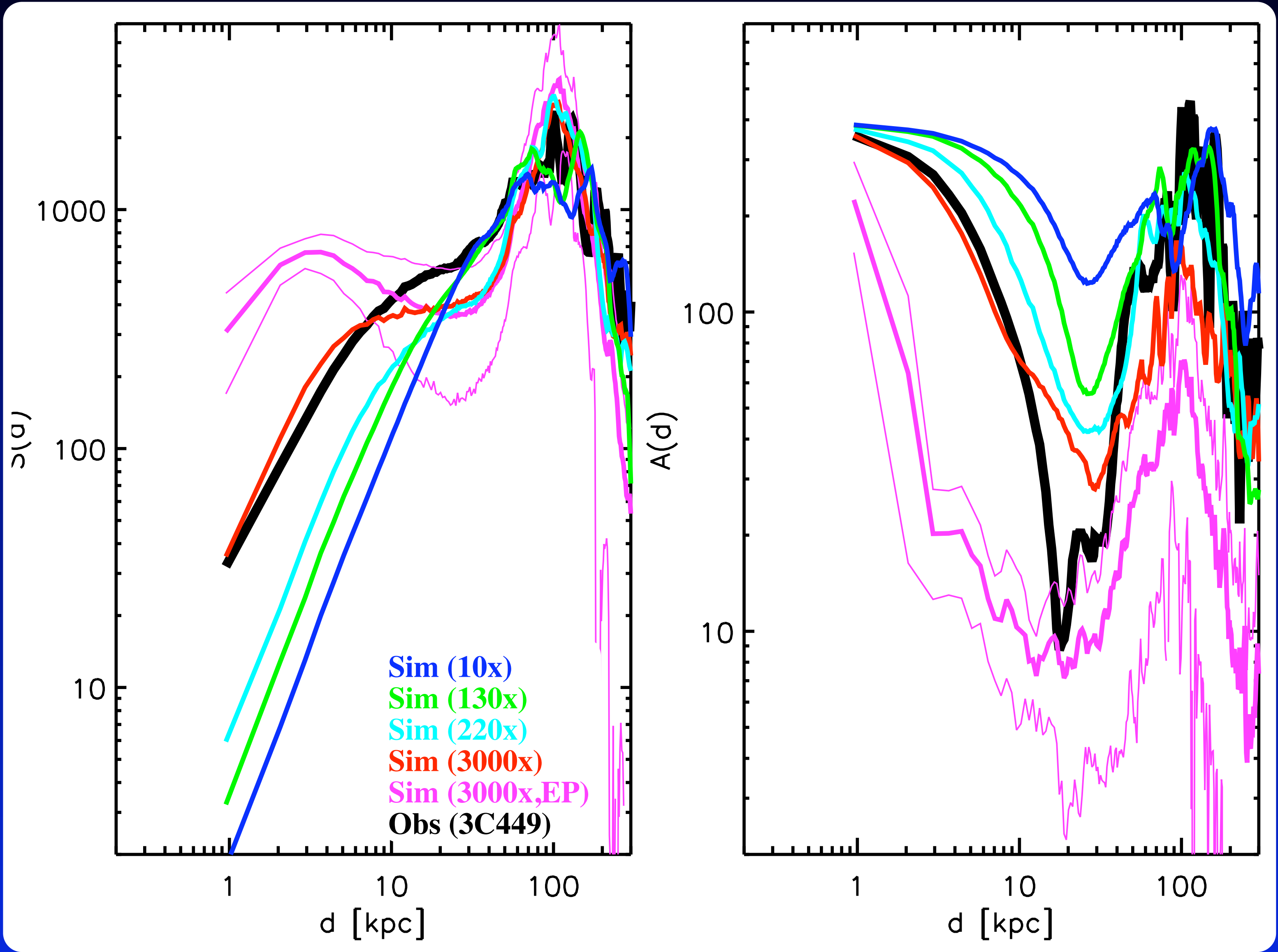
Observed and simulated RM maps up to the highest resolution simulation: 20 Million particles within R_{vir}, $m_{DM} = 10^7 M_\odot/h$, $\epsilon_{Grav} = 1$kpc/h (work in progress)

Cosmological MHD simulations



Structure functions derived from observed and simulated RM maps up to the highest resolution simulation: Indication for need of magnetic dissipation (work in progress)

Cosmological MHD simulations



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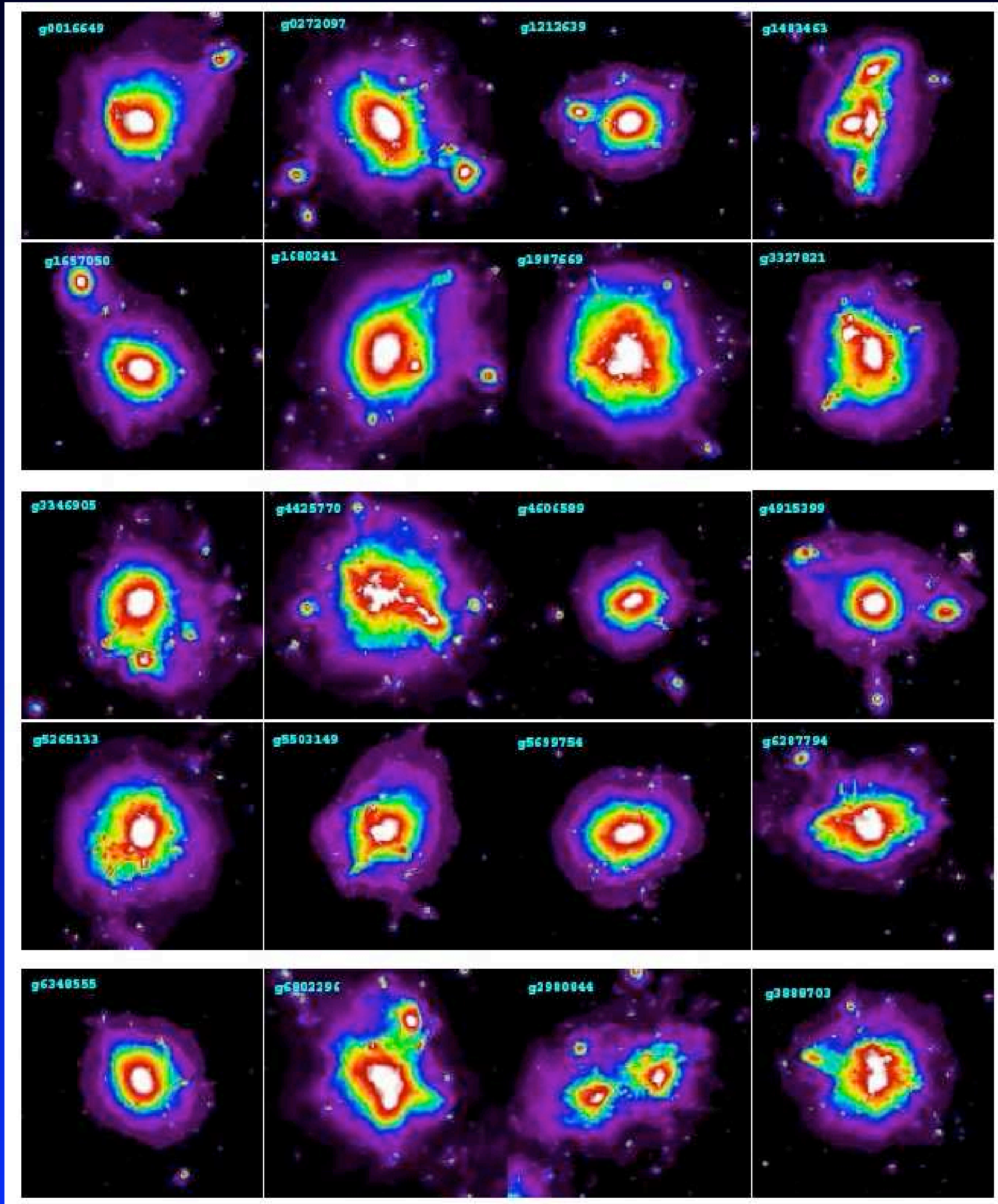
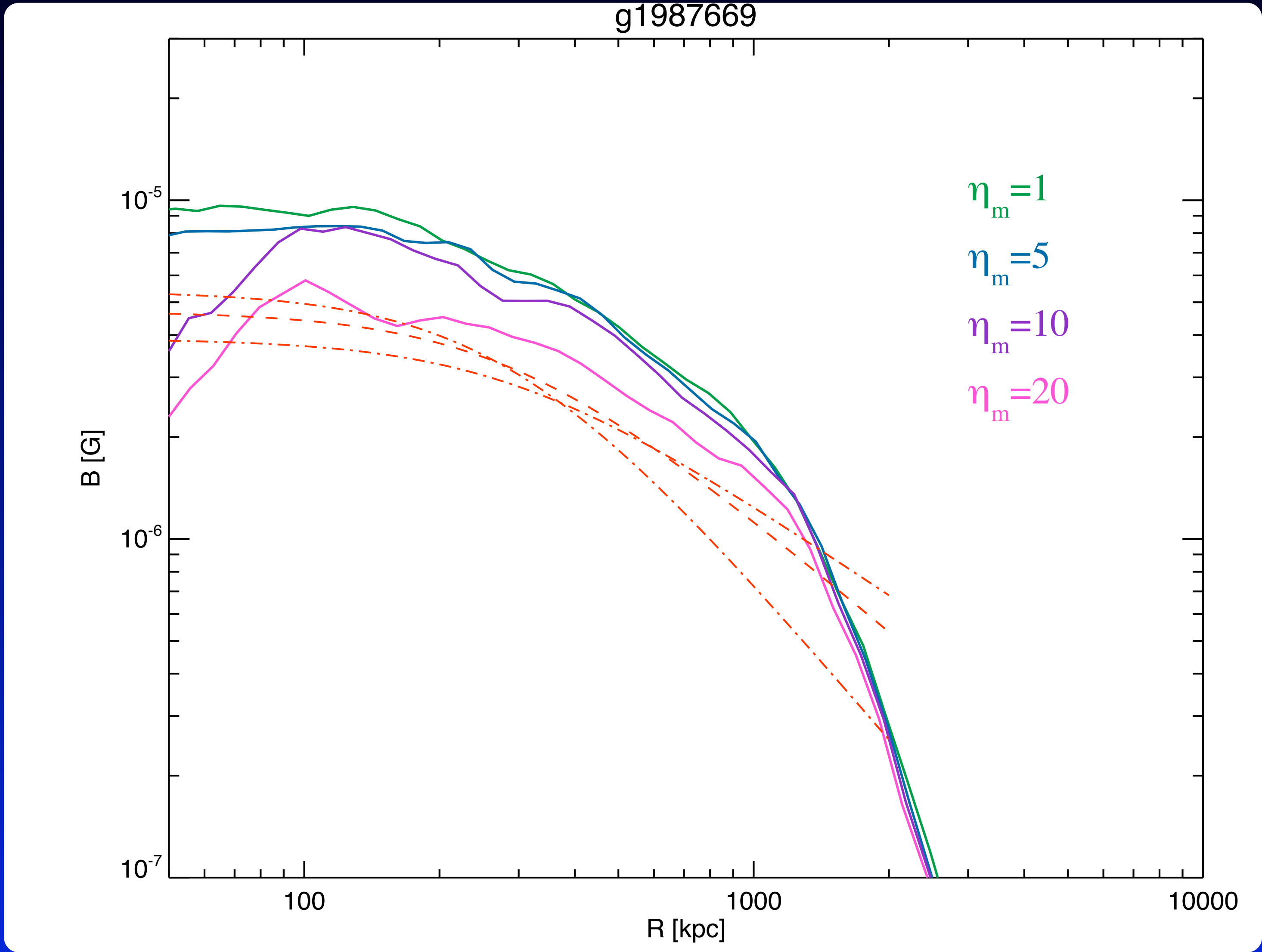
Cosmological MHD simulations



A. Bonafede

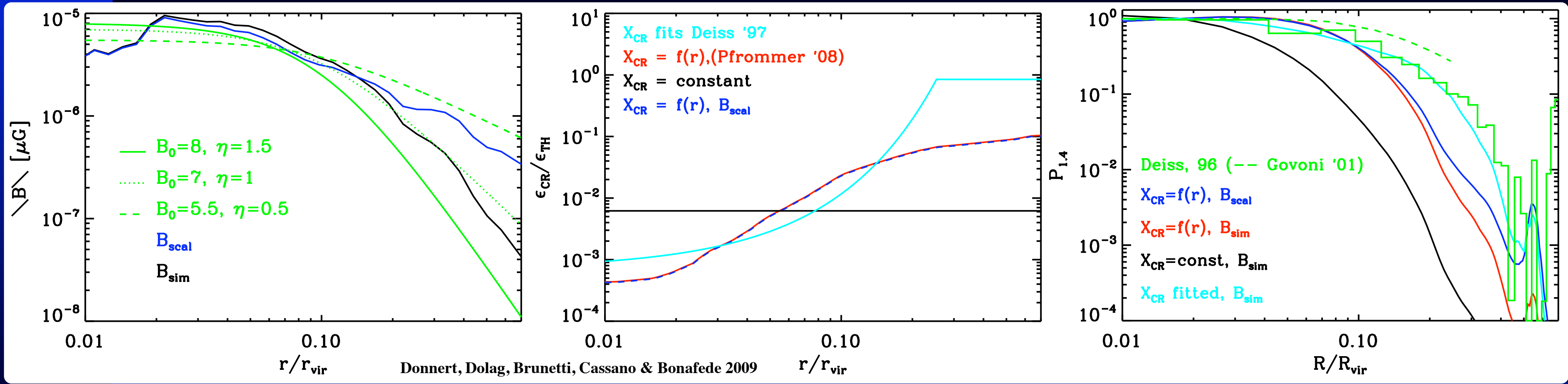
Cosmological MHD simulations



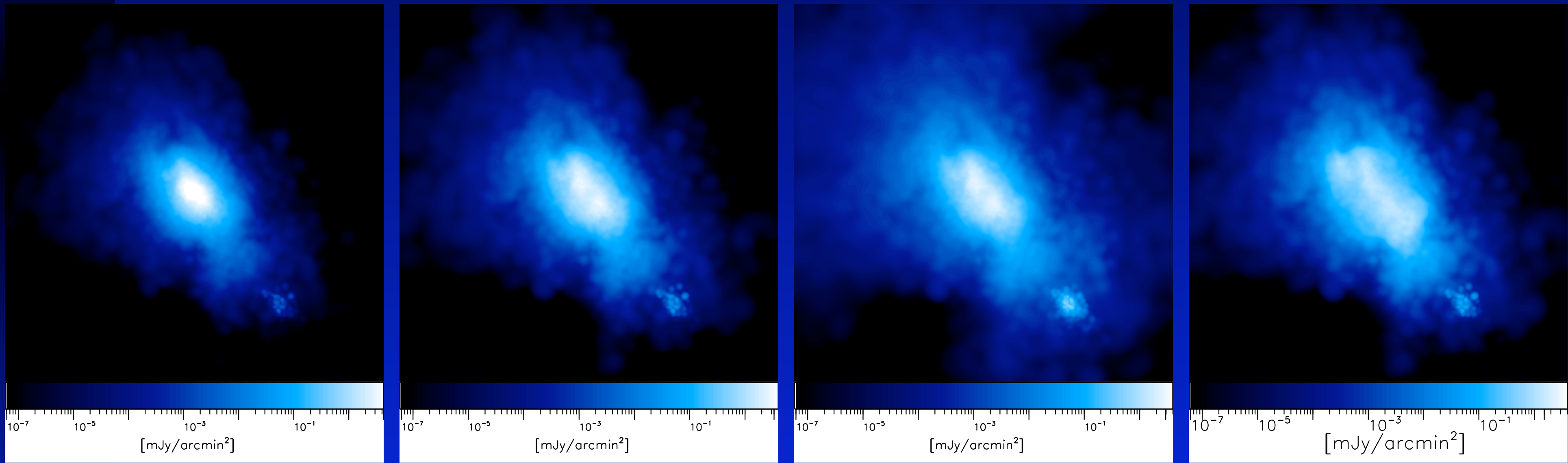
A. Bonafede

$$\frac{\mathrm{d}\vec{B}}{\mathrm{d}t} = (\vec{B}\cdot\vec{\nabla})\vec{v} - \vec{B}(\vec{\nabla}\cdot\vec{v}) + \eta\vec{\nabla}^2\vec{B}$$

CRs and non-thermal Emission



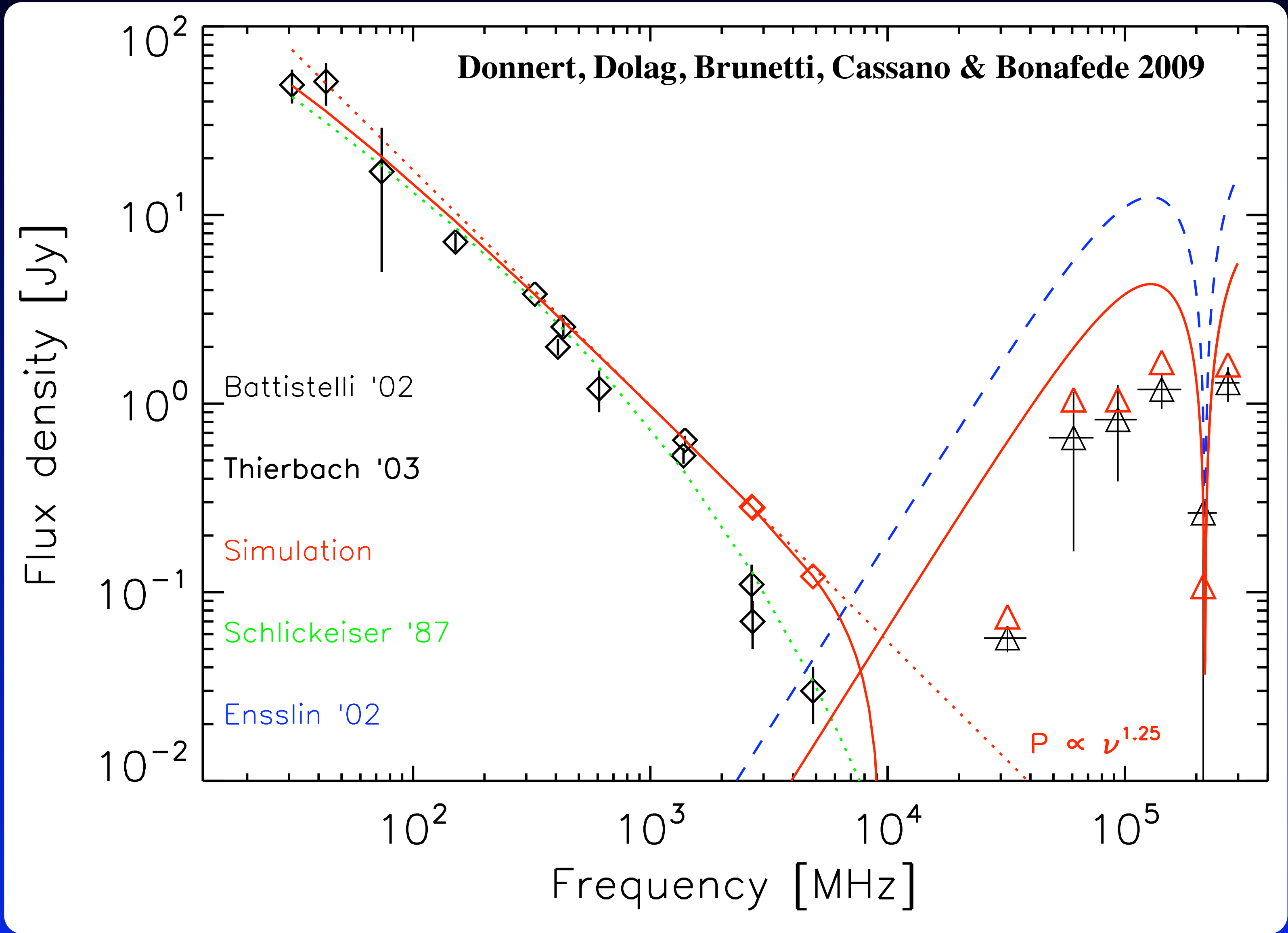
Donnert, Dolag, Brunetti, Cassano & Bonafede 2009



Hadronic interactions of CR-p^+ (>GeV) with ICM-p^+ will produce pions. The charged pions decay into secondary electrons producing synchrotron emission.

$\Rightarrow$ Radial energy distribution / emission disfavors model !

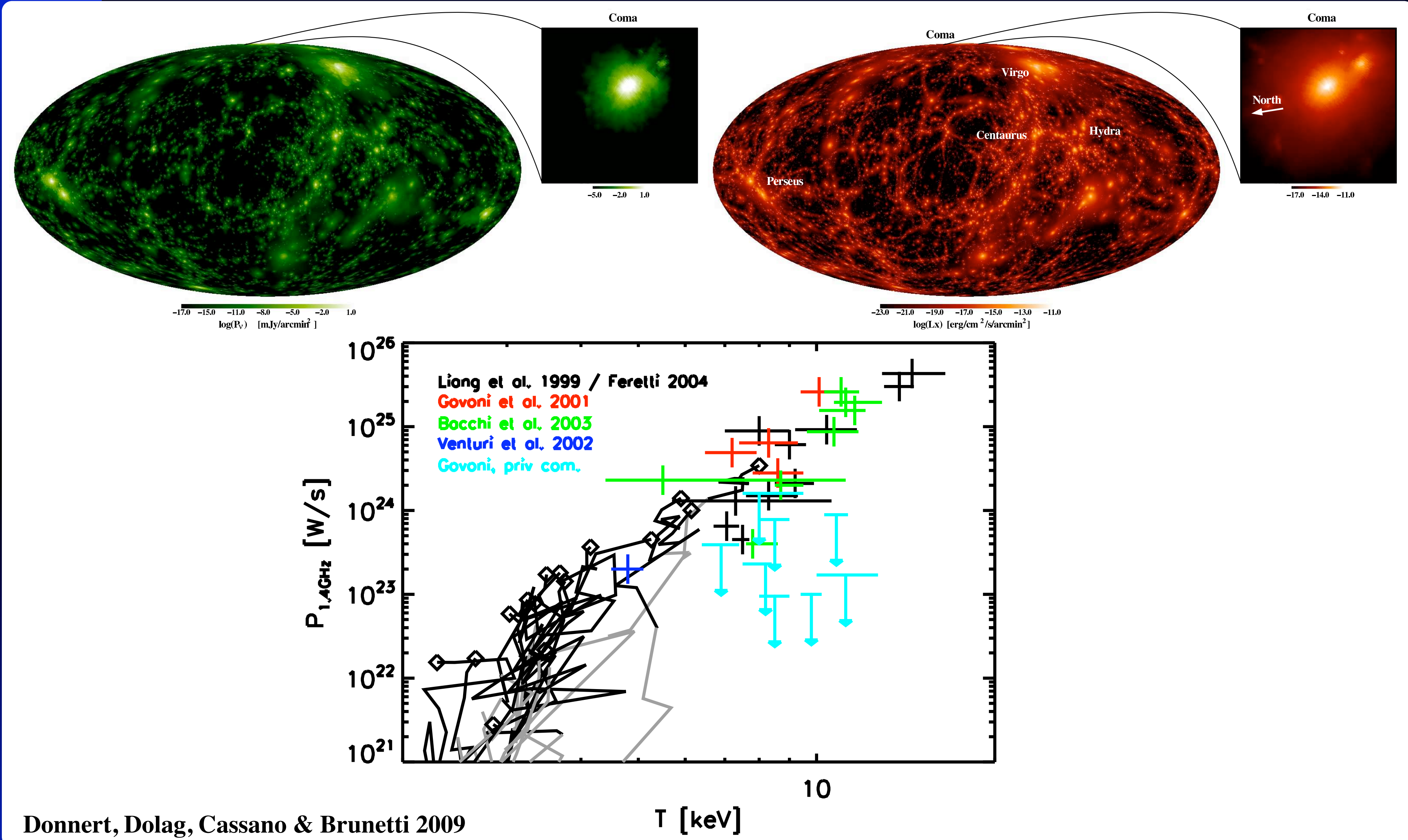
CRs and non-thermal Emission



CR-p^+ will have power law distribution $\Rightarrow$ power law spectra and negative SZ flux steepens spectra not enough

$\Rightarrow$ Sign of aging (e.g. indicates primary CR-e^-)

CRs and non-thermal Emission



Donnert, Dolag, Cassano & Brunetti 2009

Evolution track aligned to correlation

$\Rightarrow$ Strong evolution of CR-e^- needed

$\Rightarrow$ Secondaries from CR-p^+ disfavored

$\Rightarrow$ Need to investigate turbulent re-acceleration

CRs and non-thermal Emission

Evolution of D_{pp} in simulated galaxy cluster.

(Donnert et al., in prep)

Conclusions

Motions within the ICM:

- Bulk motions: Dominant (independent on dissipation)
- Turbulence: Transient (depend strongly on dissipation)
- Rotation: Unimportant (unless strong over-cooling)

Magnetic field within the ICM:

- Hierarchical buildup
- Central profiles: Need for ohmic dissipation
- Small scale structures: Need for viscosity (?)

Cosmic Rays:

- Radio Halo: Secondary Models fail

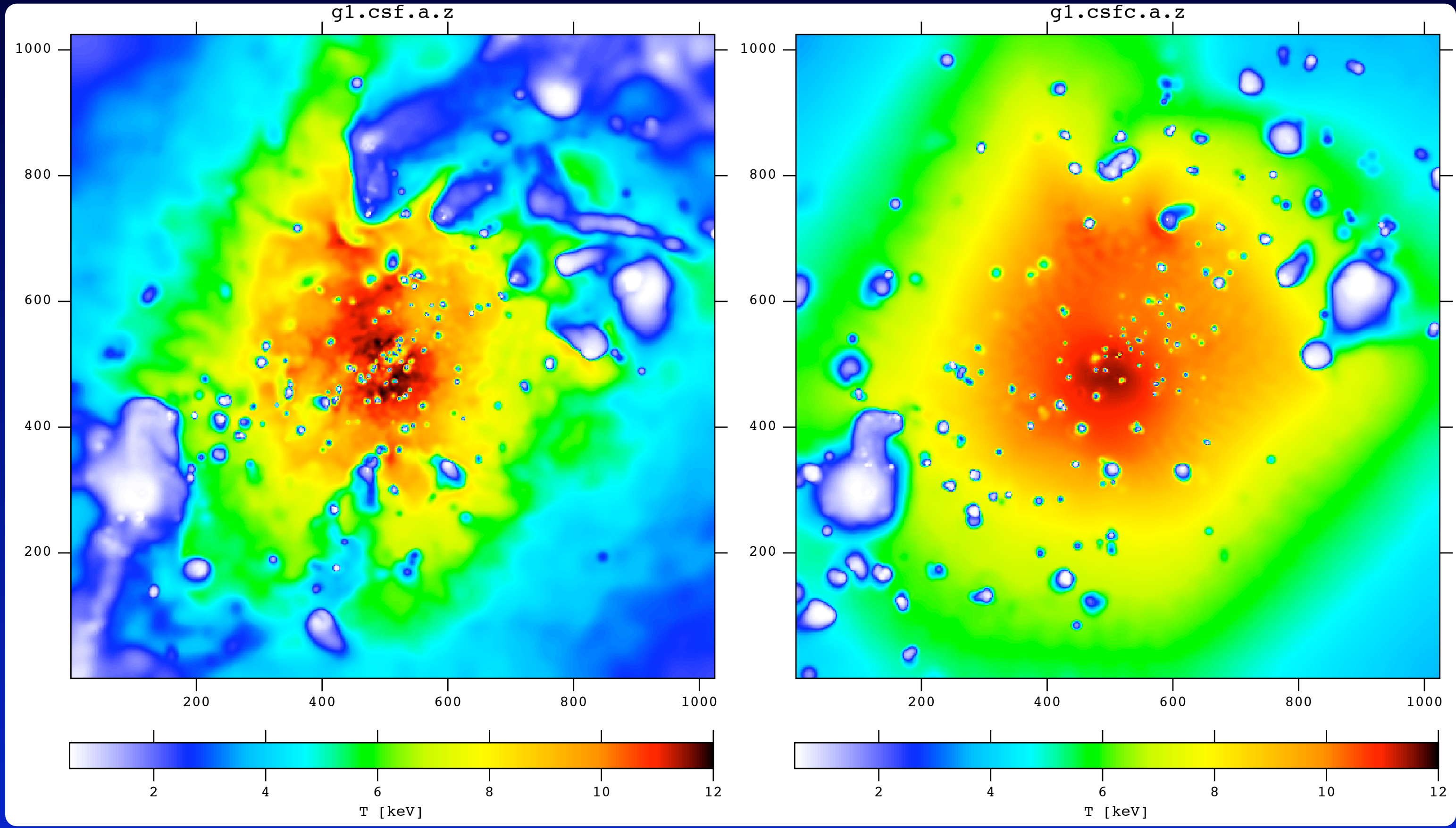
$\Rightarrow$ No significant CRp population (but why ?)

$\Rightarrow$ No gamma rays to expect

Outlook

- Dissipation (Spitzer / Ohmic)
- Magnetic fields in cool cores
- Direct coupling of magnetic field seeding to star formation
- Cosmological, magnetized galaxy formation
- Correlation functions of RM (magnetic fields in filaments)
- Jets in realistic galaxy clusters environment

Clusters with Conduction

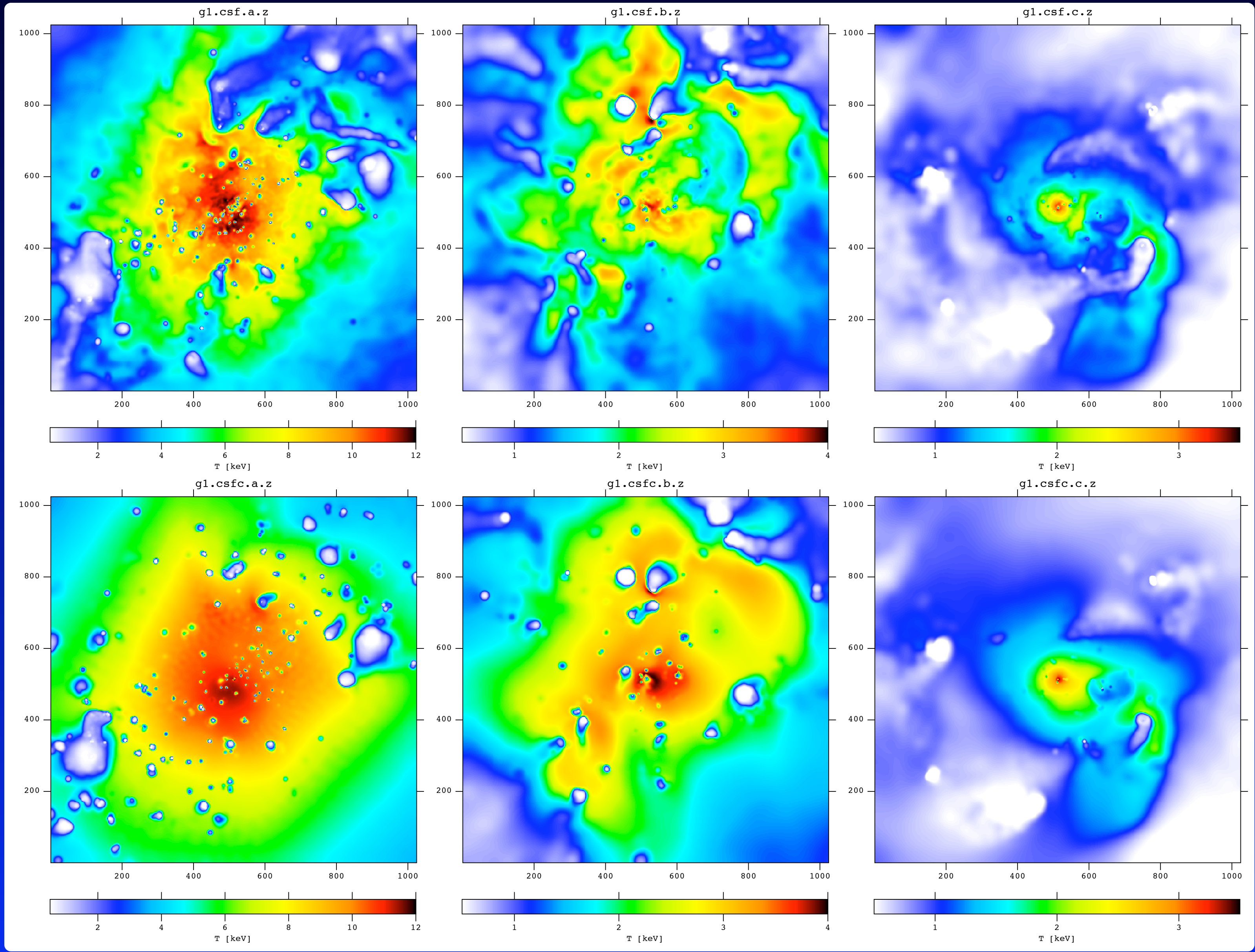


Cosmological simulations including thermal conduction.

$\Rightarrow$ but no solution for the catastrophic cooling !

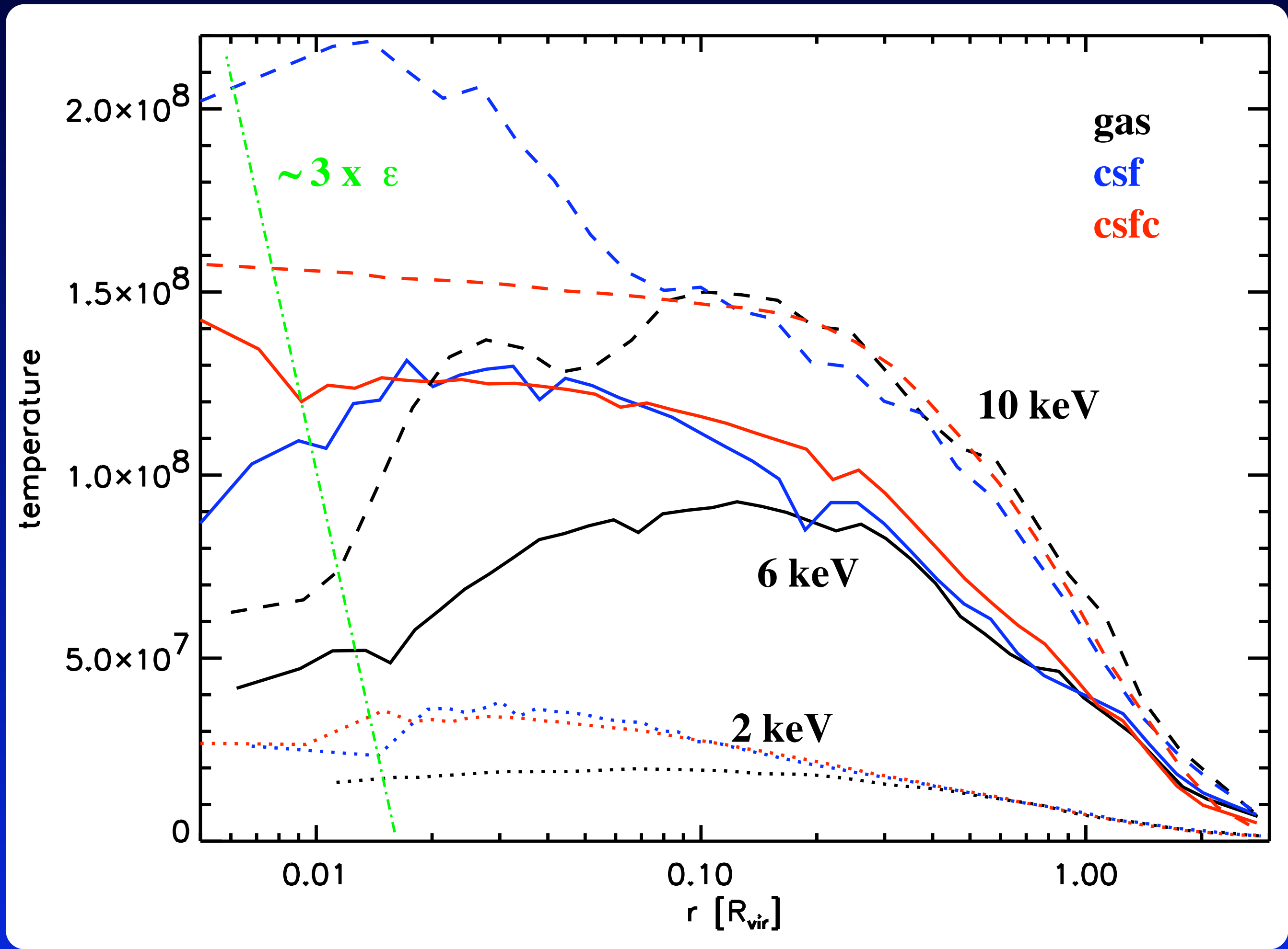
Dolag et al. 2004

Clusters with Conduction



Conduction efficiency scales with $T^{2.5}$.

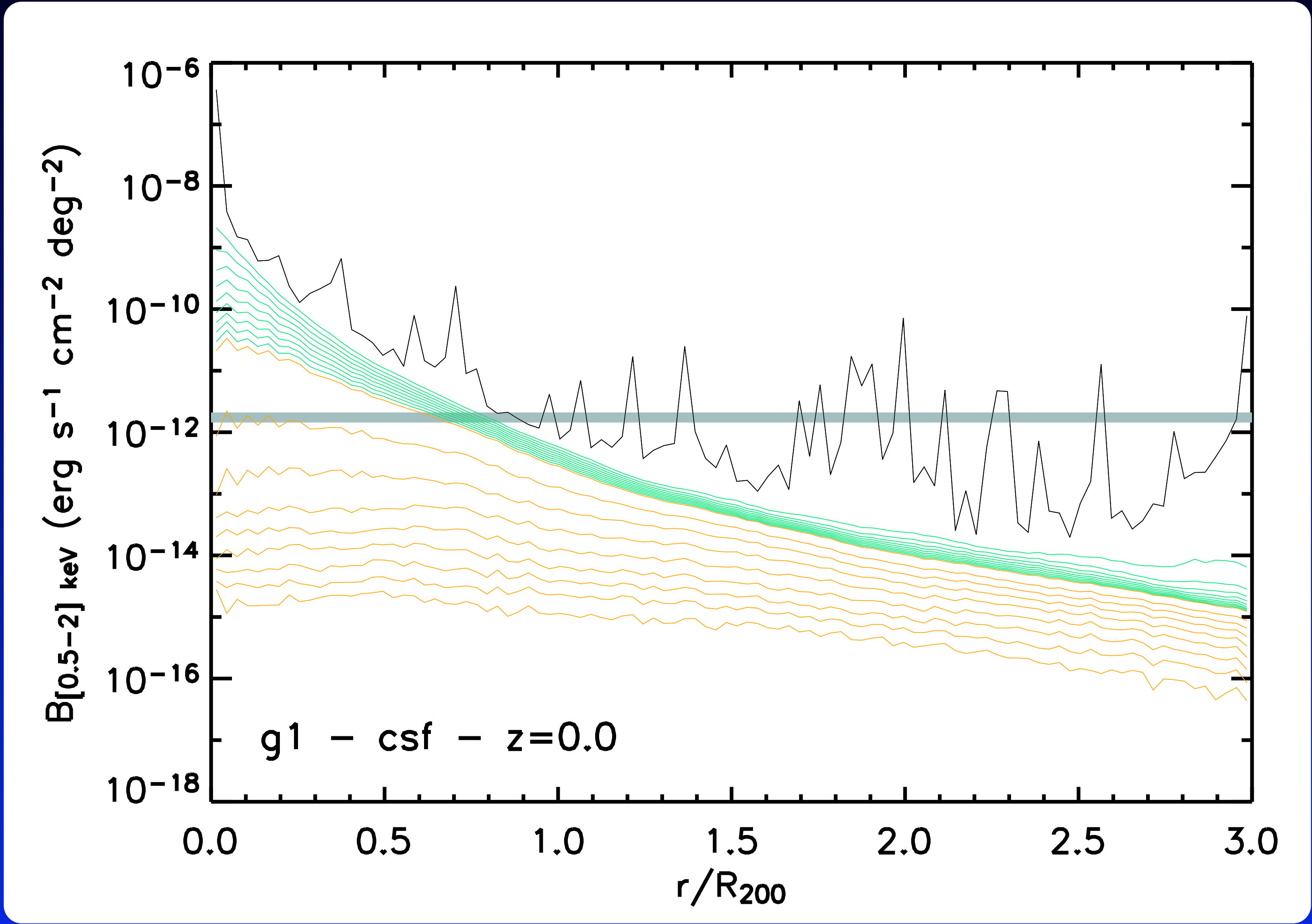
Clusters with Conduction



⇒ radial profiles change, depending on cluster temperature !

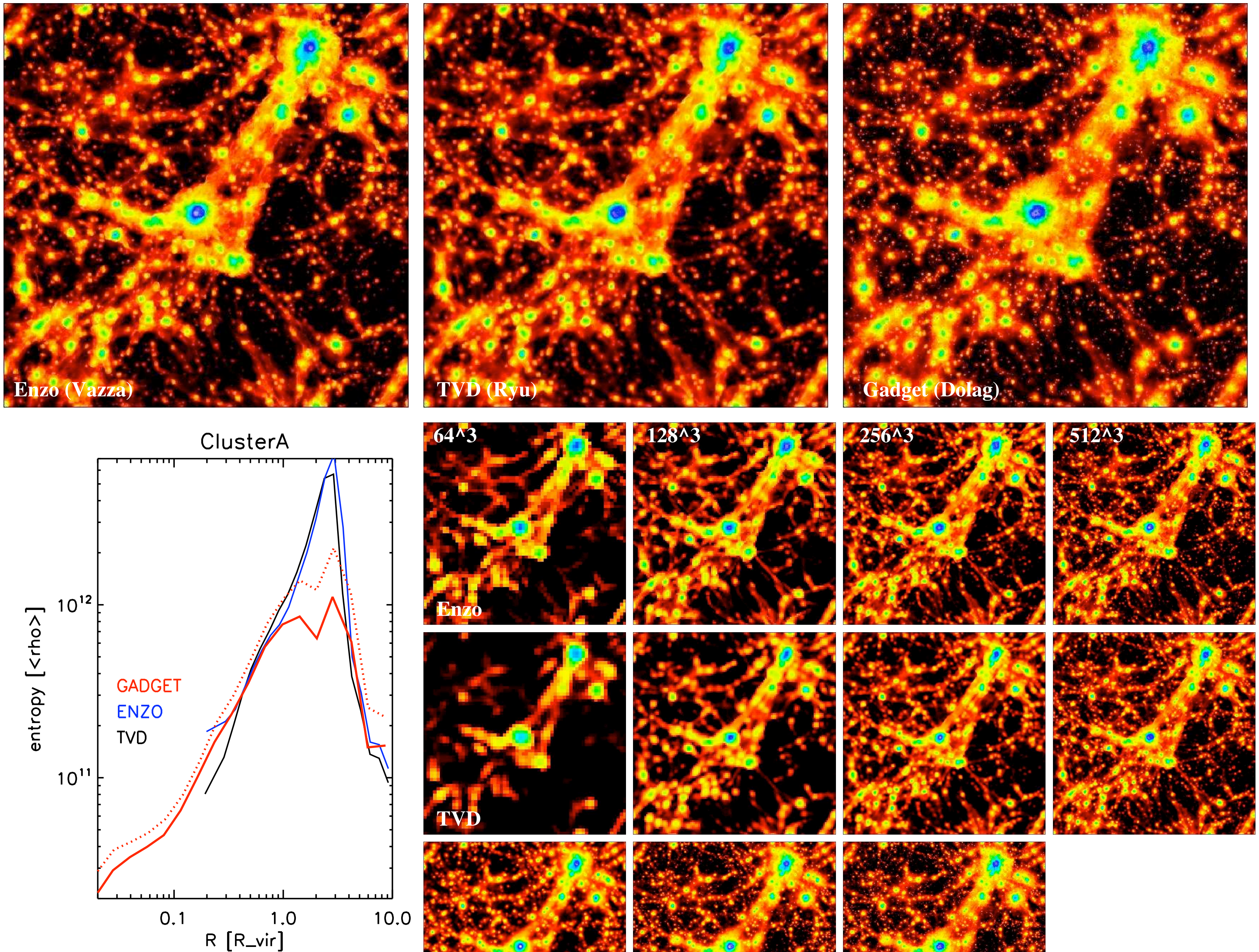
Dolag et al. 2004

Cluster Outskirts



Roncarelli et al. 2006

Cluster Outskirts



Franco Vazza
Gianfranco Brunetti
Claudi Gheller

Dongsu Ryu
Hyesung Kang
Cristoph Pfrommer
Klaus Dolag

Outtakes

Exploding galaxies:

To high ($\approx \times 10^6$) initial magnetic seed field

Outtakes

Exploding cluster:

Missing, cosmological factor ($\approx \times 10^{-5}$) when dissipating magnetic fields

Outtakes

Exploding void:

Time step of accreting particles too large ($\approx \times 10^4$) for a correct integration of induction equation