Magnetic Fields, Turbulence and Cosmic Rays in Galaxy Clusters

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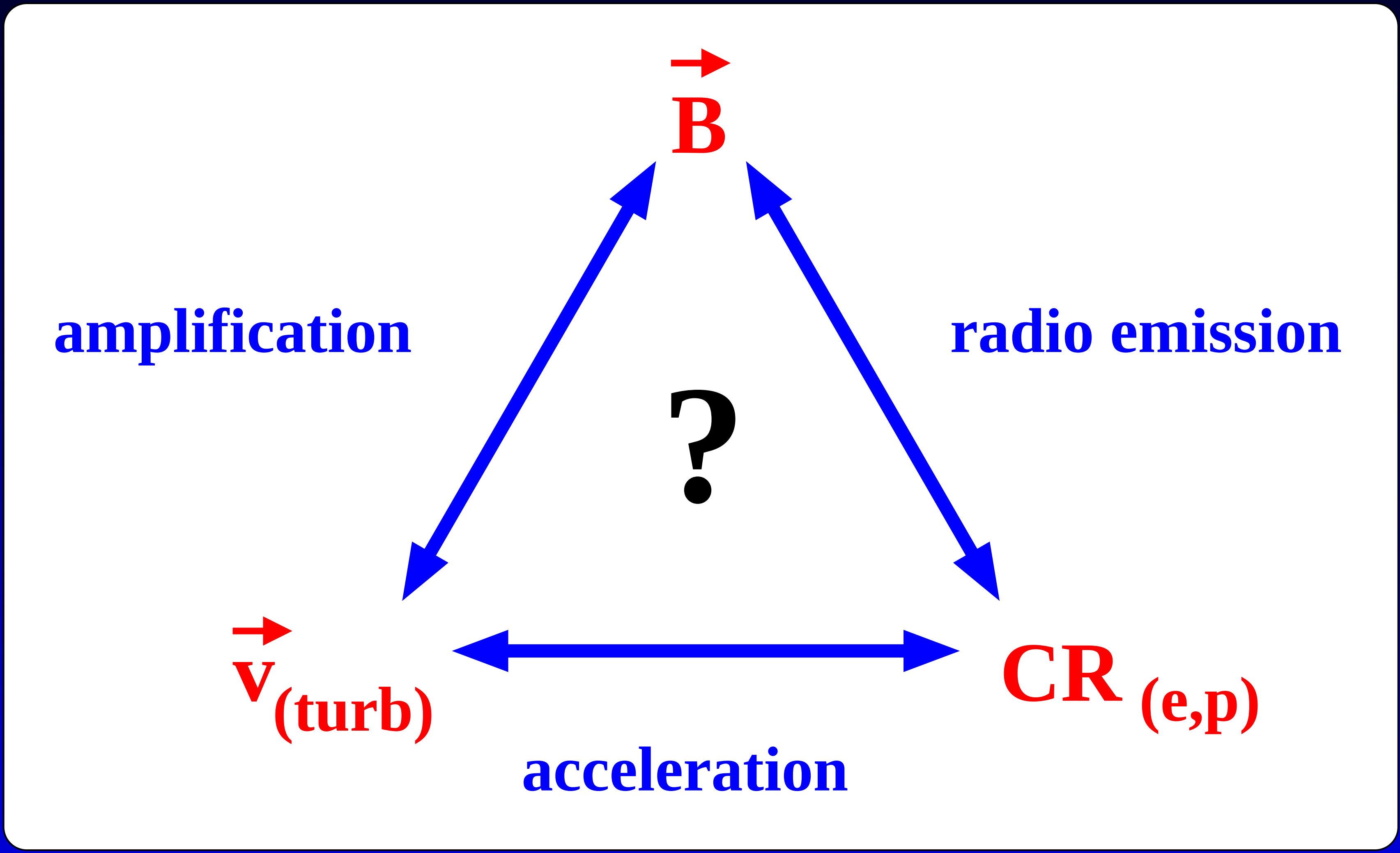
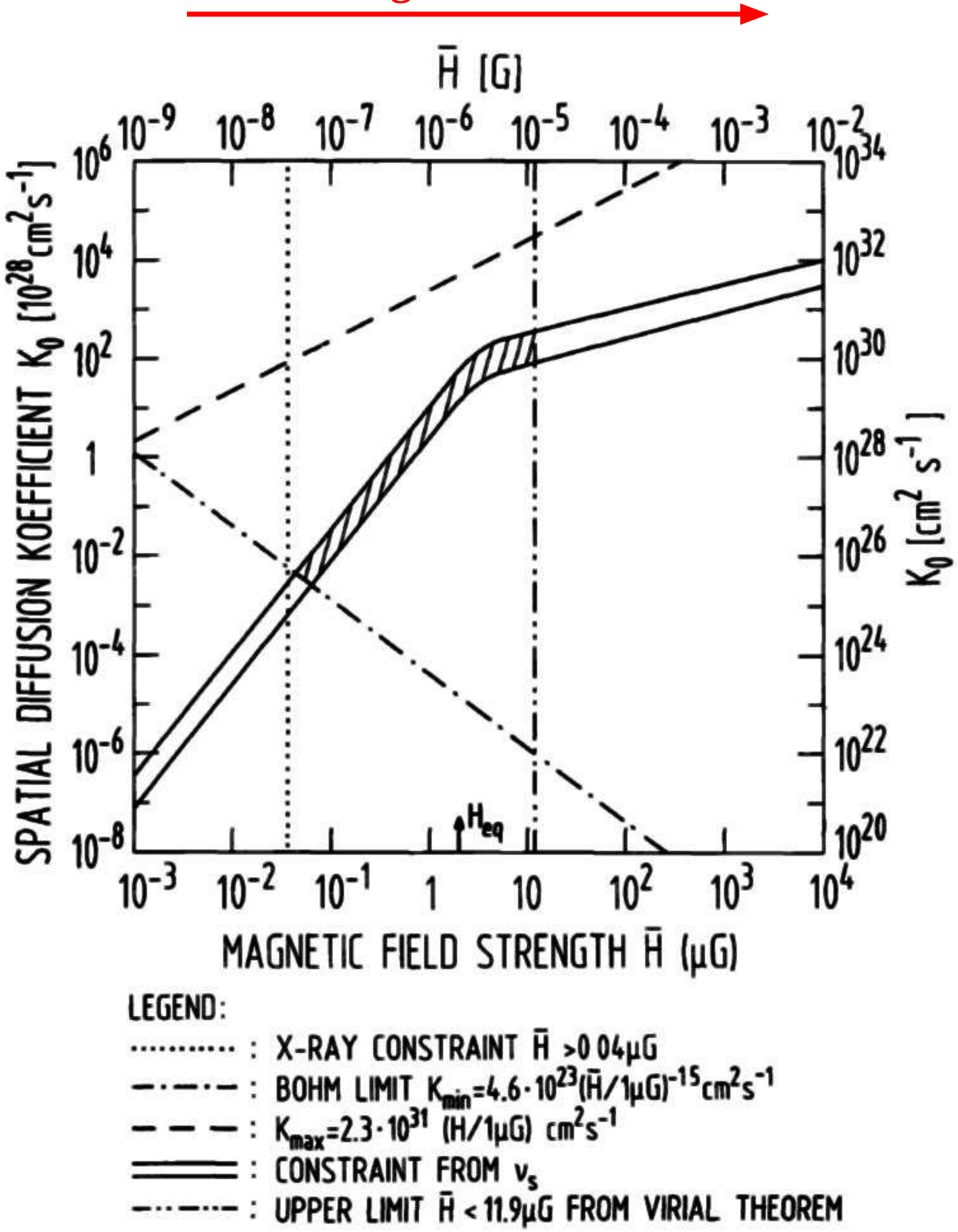
The Cluster Bermuda-Triangle



Where are we ?

Magnetic Field



Schlickeiser et al. 1987

transport koefficient

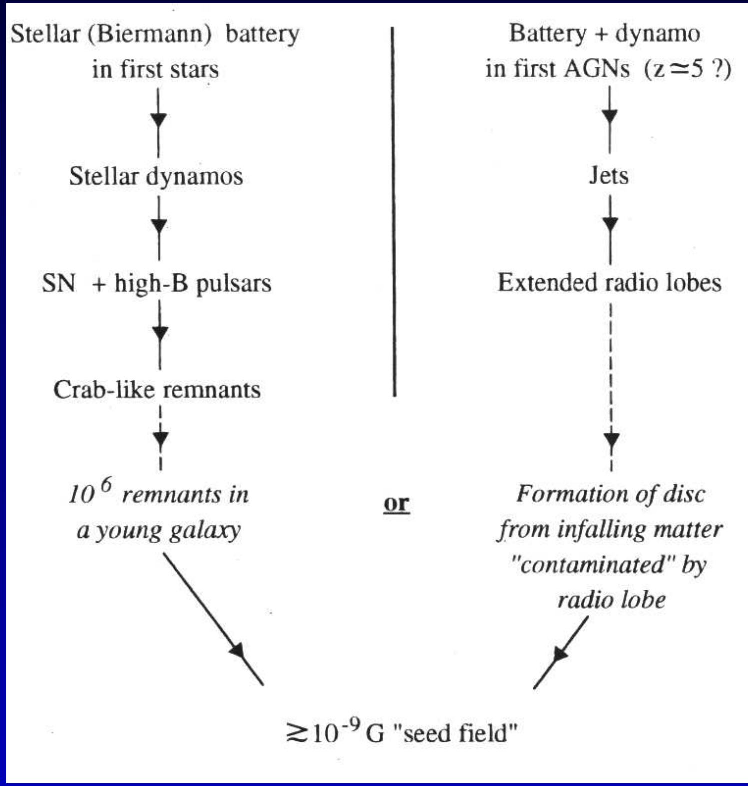
~ 0.1 * v $_{turb}$ * L

turbulence (IGM/ICM)
=> radio emission
Burbidge 1958 (!!)

Problem 1: Origin of B

Origin

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



Rees 1994

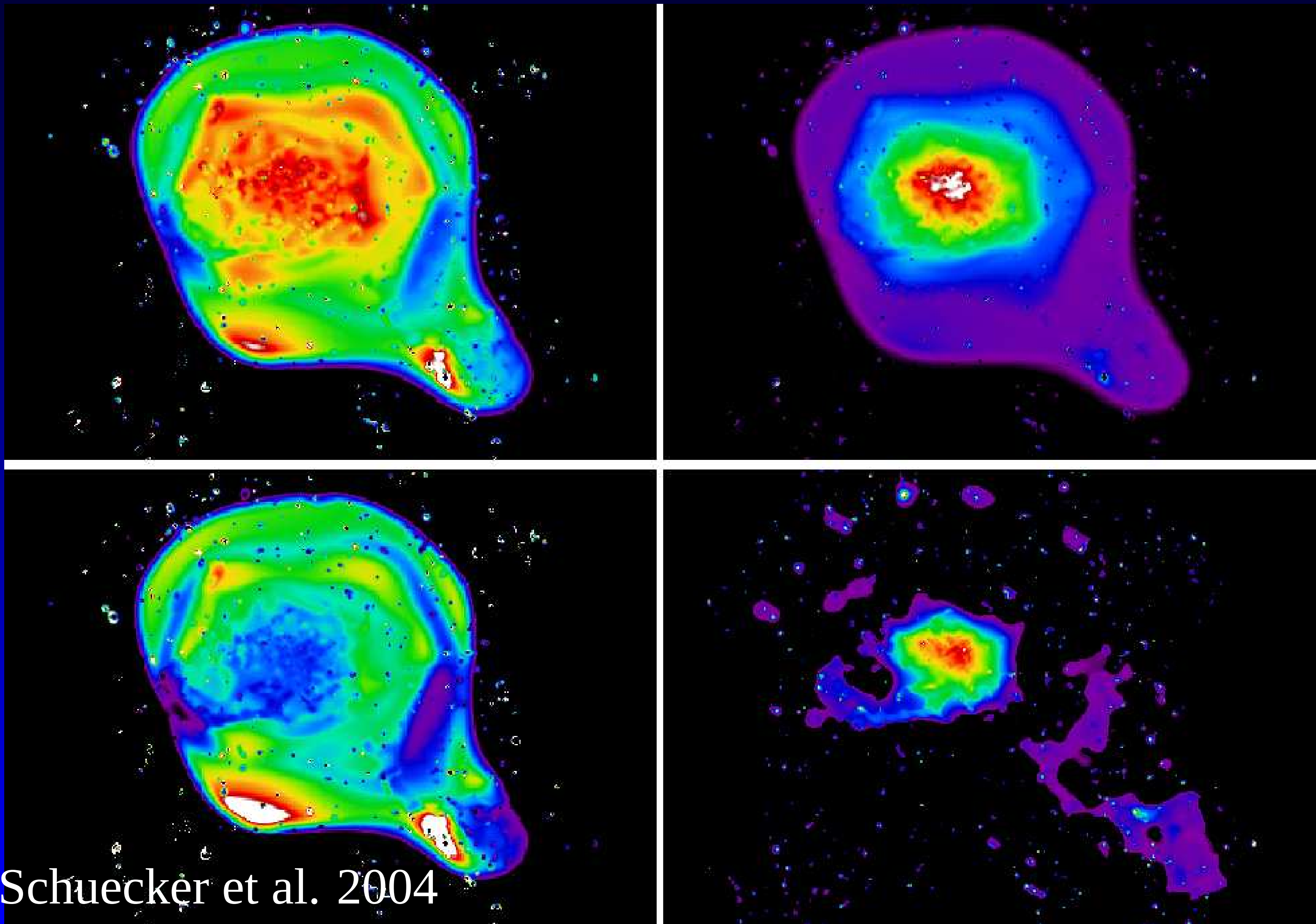
+ further amplification by **structure formation**

\- **dissipation** ?

Problem 2: Turbulence

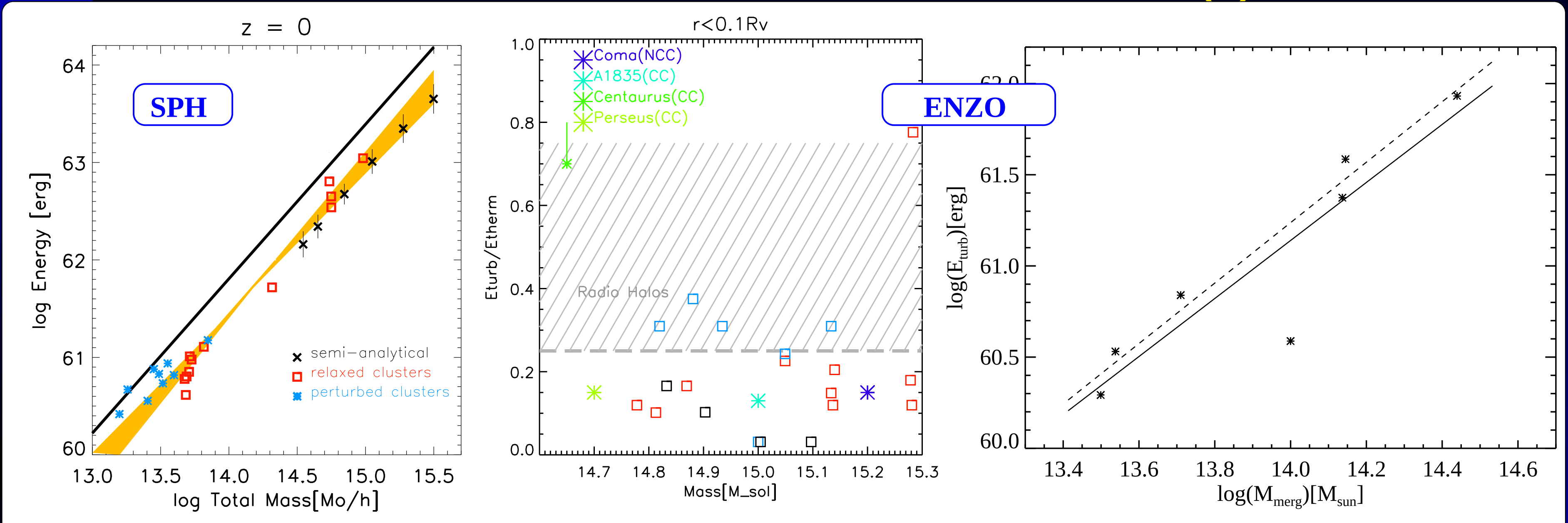
Observed turbulece in clusters: (see talk by de Plaa, ...)

$$D_{\rm diff} = 0.1 \times v_{\rm turb} \times \lambda_{\rm turb} \quad , \quad v_{\rm turb}(l) \propto \lambda_{\rm turb}^{(1/3)}$$



Problem 2: Turbulence

Simulations: **Simulated turbulece in clusters (I):**



Dolag et al. 2005 / Vazza et al. 2006 **Vazza et al. 2010** **Iapichino et al. 2009/2010**

Dolag et al. 2005 (see also Iapichino et al. 2008/2009, Vazza et al. 2006/2009/2010, ...)

Need to distinguish **bulk** and **turbulent** motions.

$\Rightarrow$ strongly depend on operational definitions !

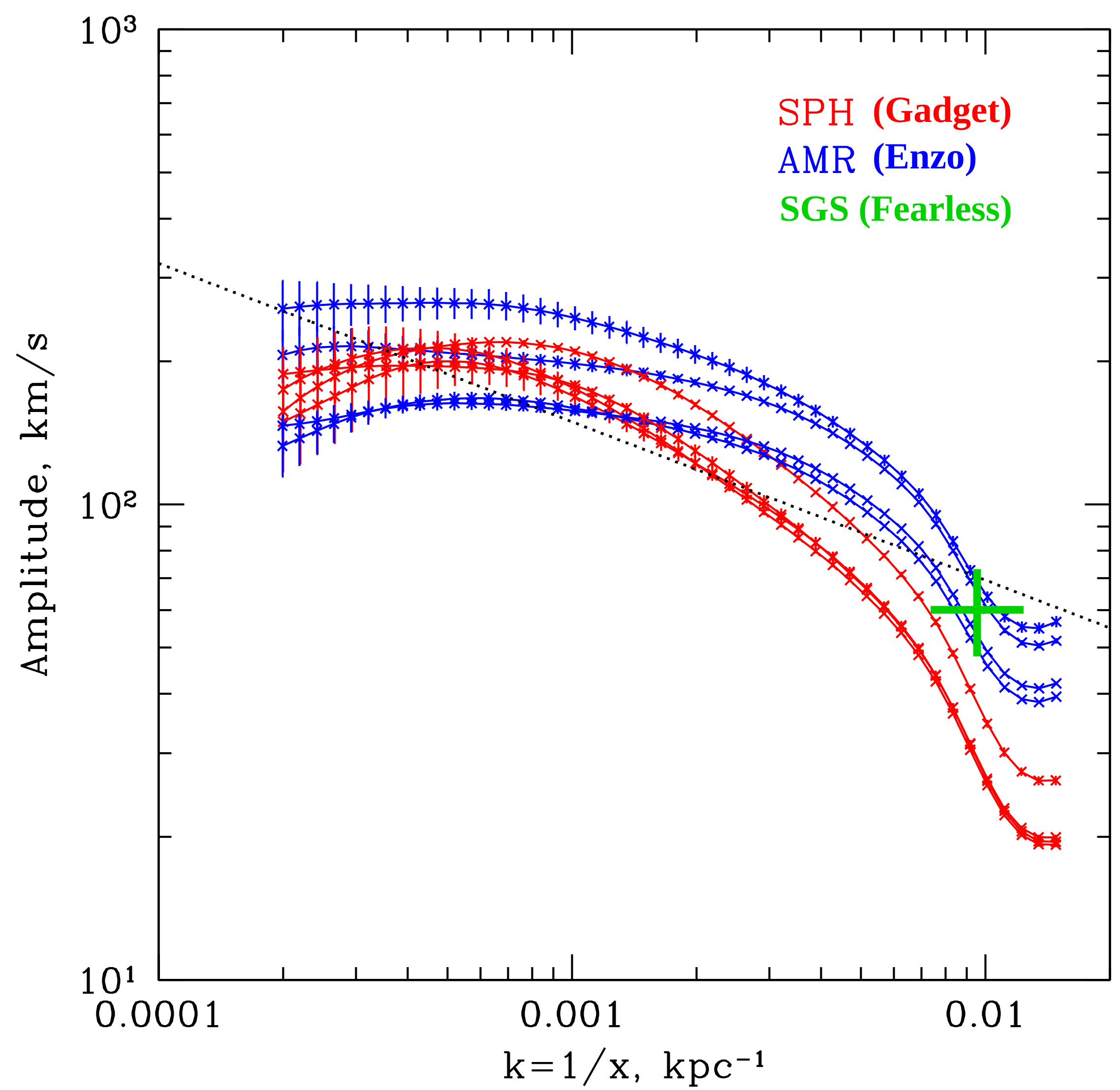
Origin (in cosmological context):

- Behind shocks (mostly beyond core radius)
- Passage of gas rich substructure (whole cluster)
- Passage of dm substructure (mostly cluster core)

Problem 2: Turbulence

Simulated turbulece in clusters (II):

(Dolag et al 2005, Vazza et al 2009, Maier et al 2009, ...)



see talk by I.Zhuravleva

Problem 3: Low B

Please: 

(numbers are from private communication)

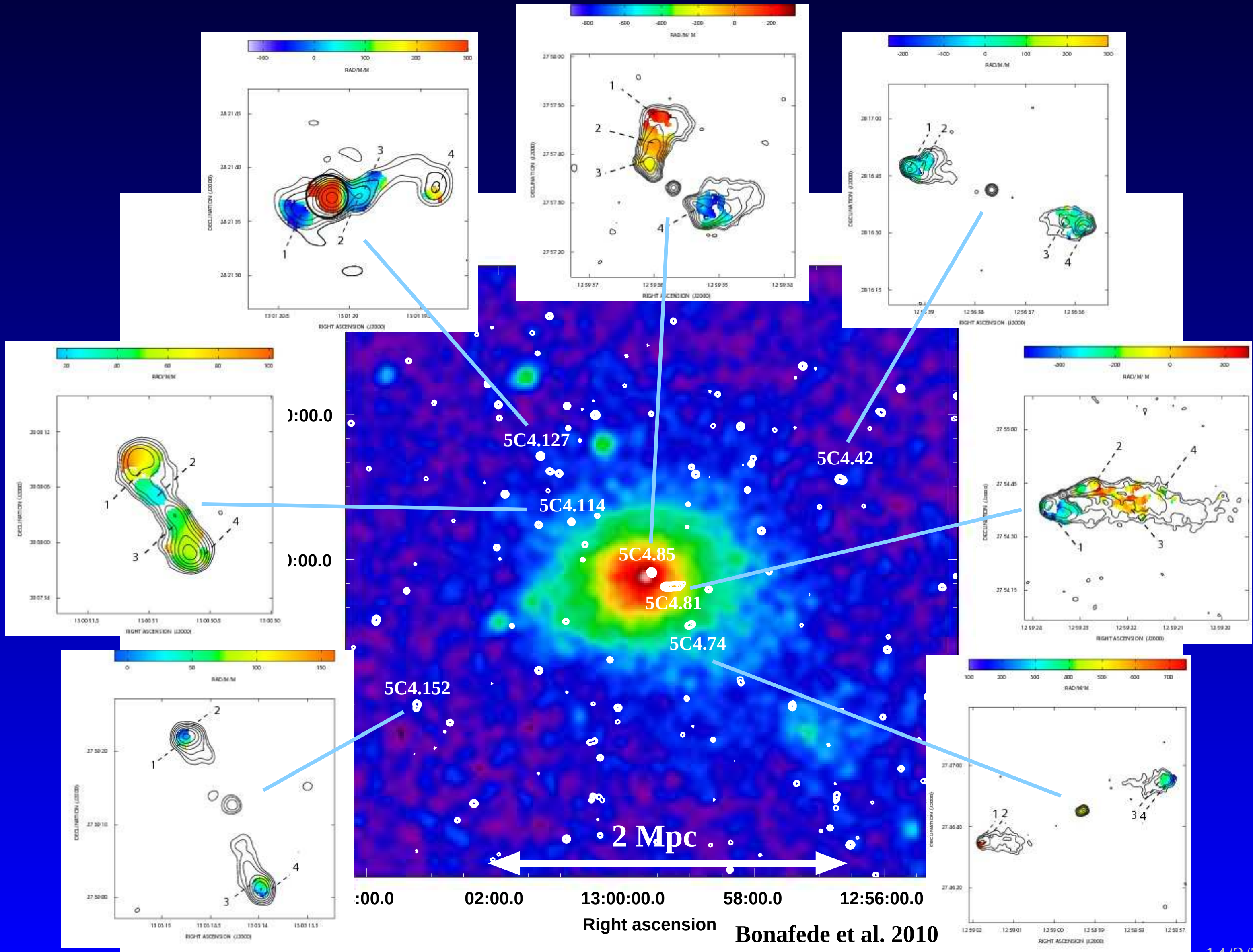
Cluster	$P_{\rm thermal}$	$B^2/8\pi$	β
Coma	1.02e-10	1.63e-12	1.6
A2255	5.016e-11	2.487e-13	0.5
A400	1.927e-11	1.681e-12	8.7
A119	3.63e-11	1.204e-12	3.3
A2382	1.21e-11	3.581e-13	3.0

Note on Turbulence:
10% (Observed, Coma)
10-20% (Simulations)

Problem 3: Low B

Observed B in clusters: (Bonafede et al. 2010, ...)

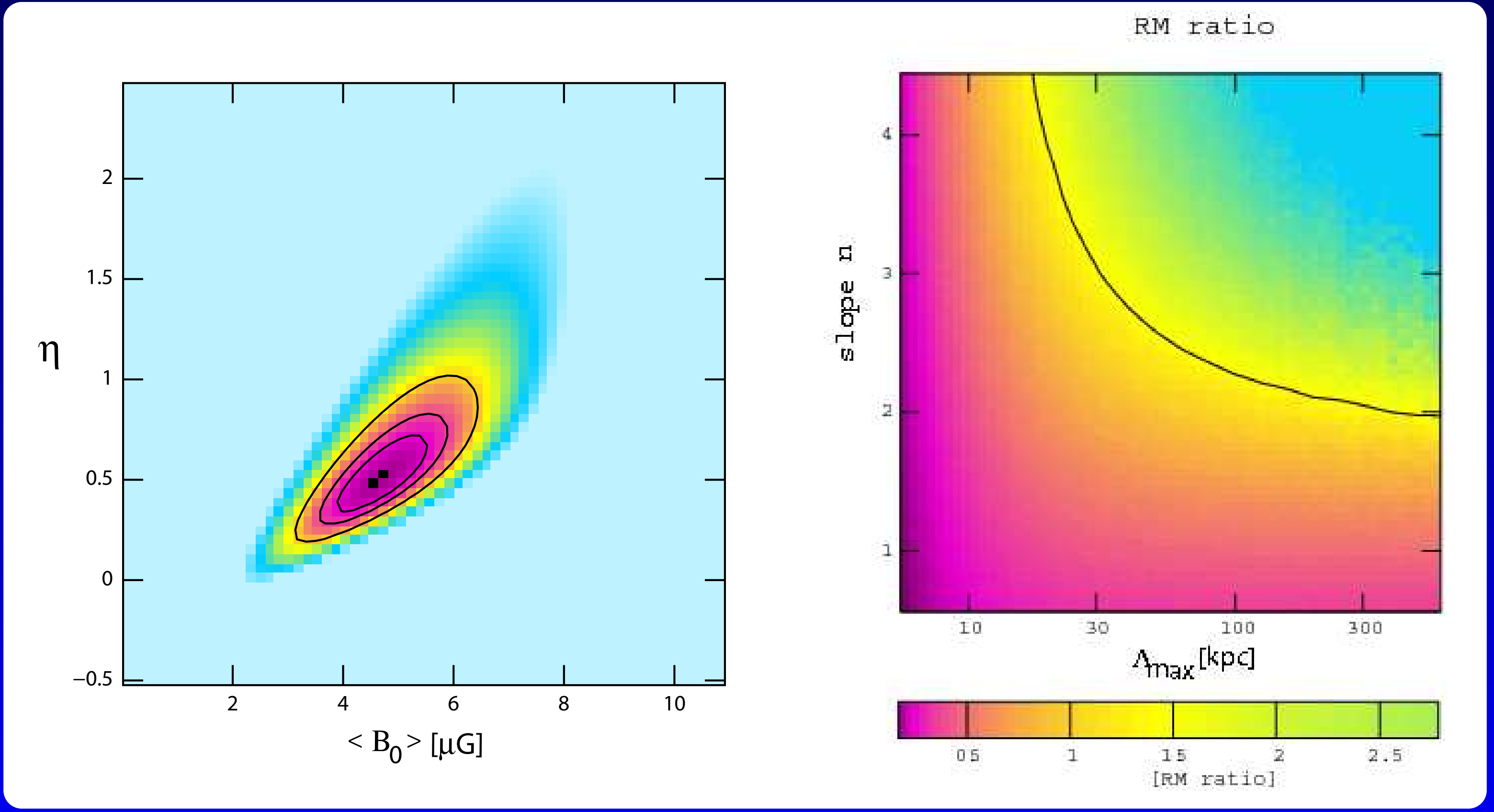
$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\eta}, \quad |B_k|^2 \propto k^{-n}, \quad (k_{\rm min}, k_{\rm max})$$



Problem 3: Low B

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

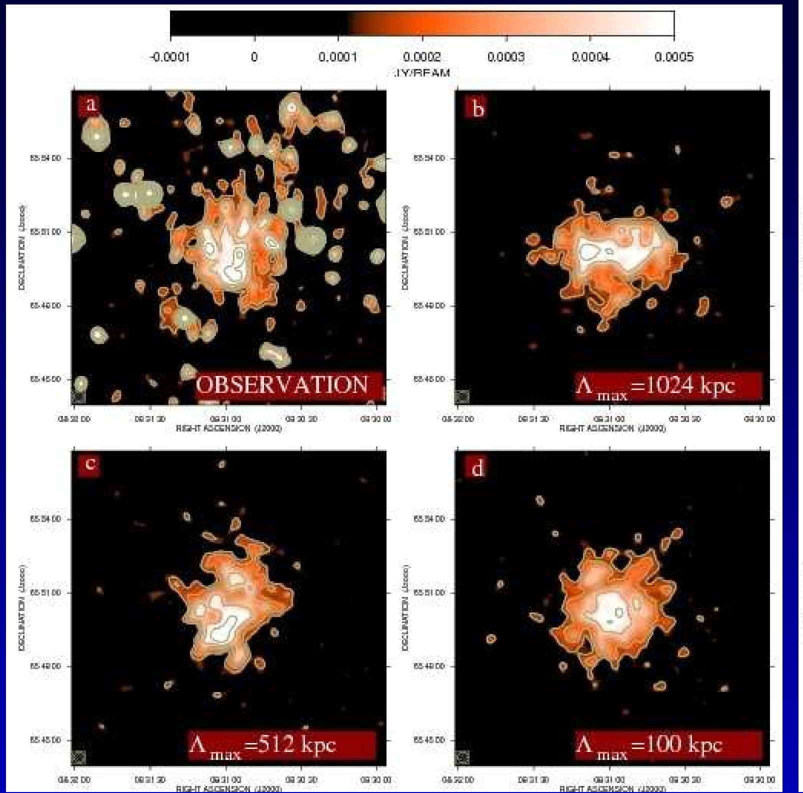
- $S(dx, dy) = \langle [RM(x,y) - RM(x+dx, y+dy)]^2 \rangle$
- $A(dx, dy) = \langle RM(x,y) \times RM(x+dx, y+dy) \rangle$
- $\langle |RM| \rangle_{\text{scale}}, \quad \langle \sigma_{\text{RM}} \rangle_{\text{scale}}$

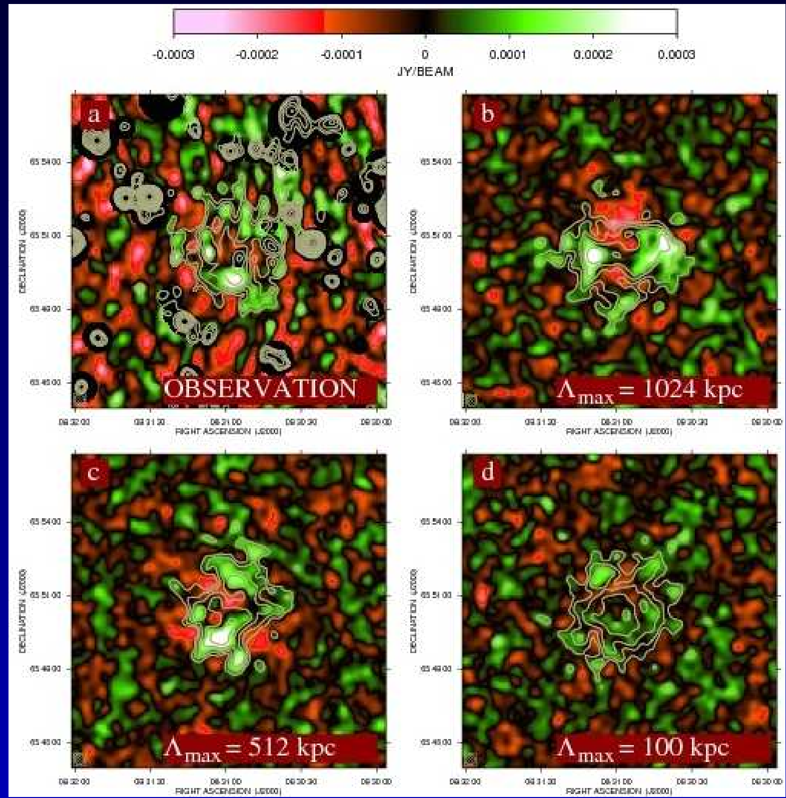


⇒ constrains on magnetic field strength !

Problem 3: Low B

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





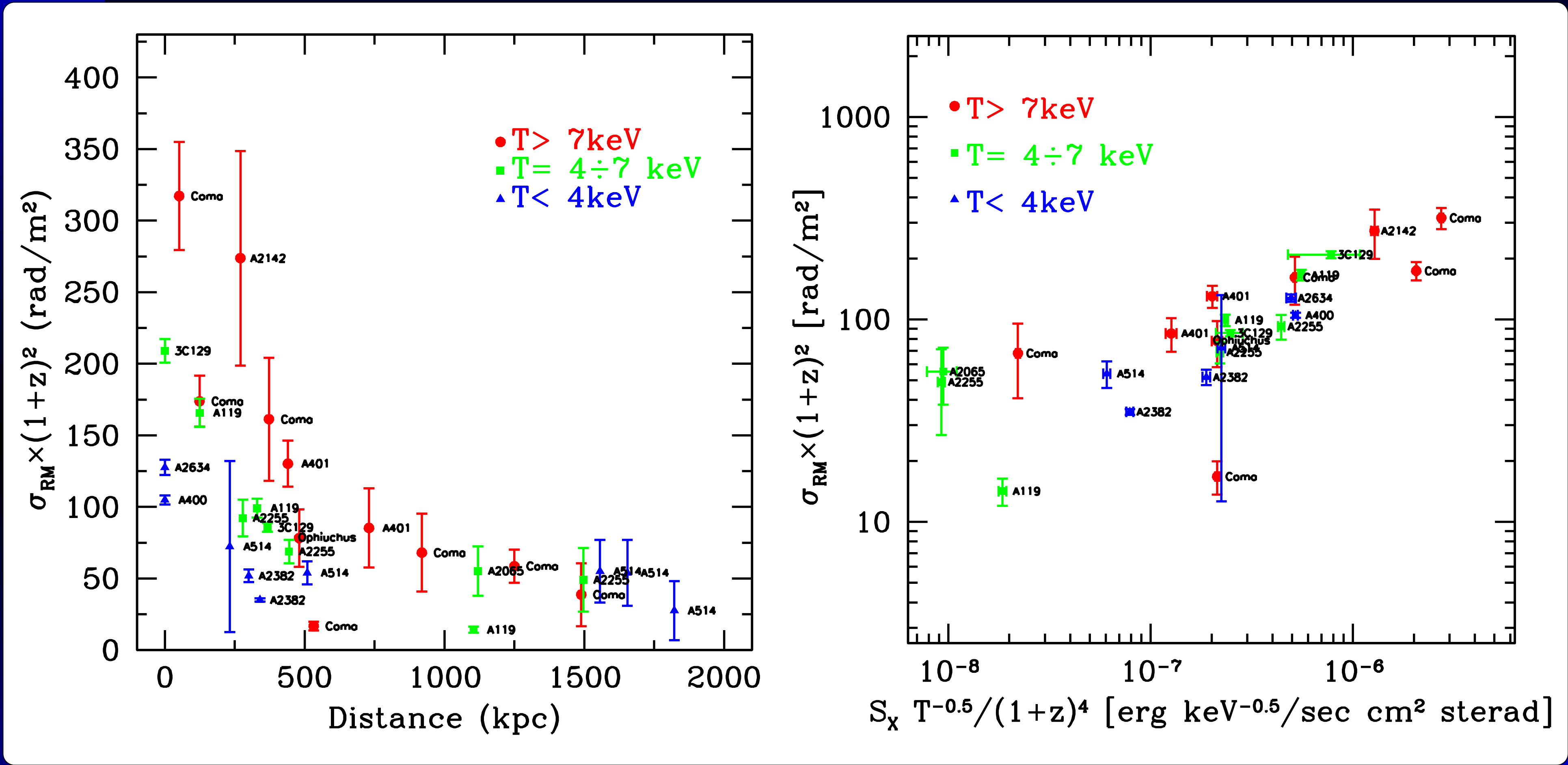
$\Rightarrow$ A655: Inferred outer scale $\approx$450 kpc (Vacca et al. 2010) !

- Depolarization indicates truncation at small scales !

$\Rightarrow$ **No** fluctuations at scales below $\approx (.1 - .5)$ kpc !

Govoni et al. 2010, Vacca et al. 2010, Guidetti et al. 2010, Bonafede et al. 2010, Guidetti et al. 2008, Govoni et al. 2006, Laing et al. 2006, Vogt & Ensslin 2005, Murgia et al. 2004, Ensslin & Vogt 2003, ... , Tribble 1991.

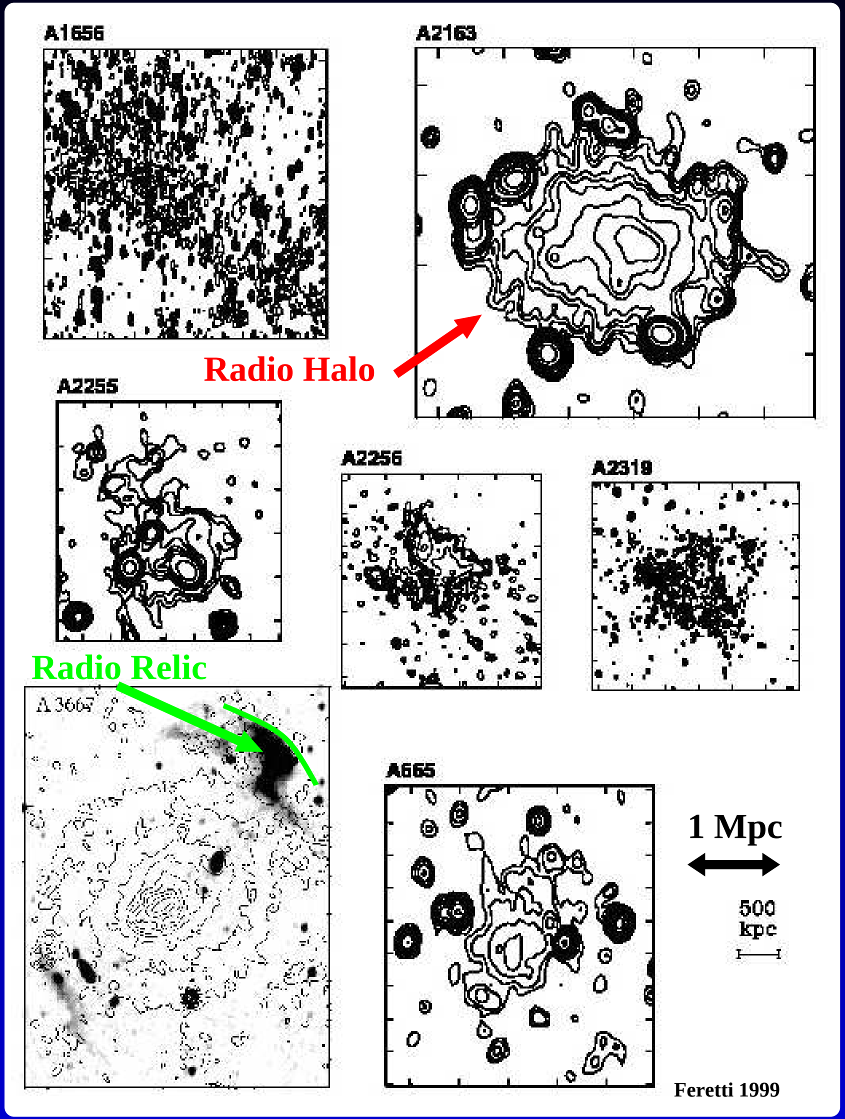
Problem 3: Low B

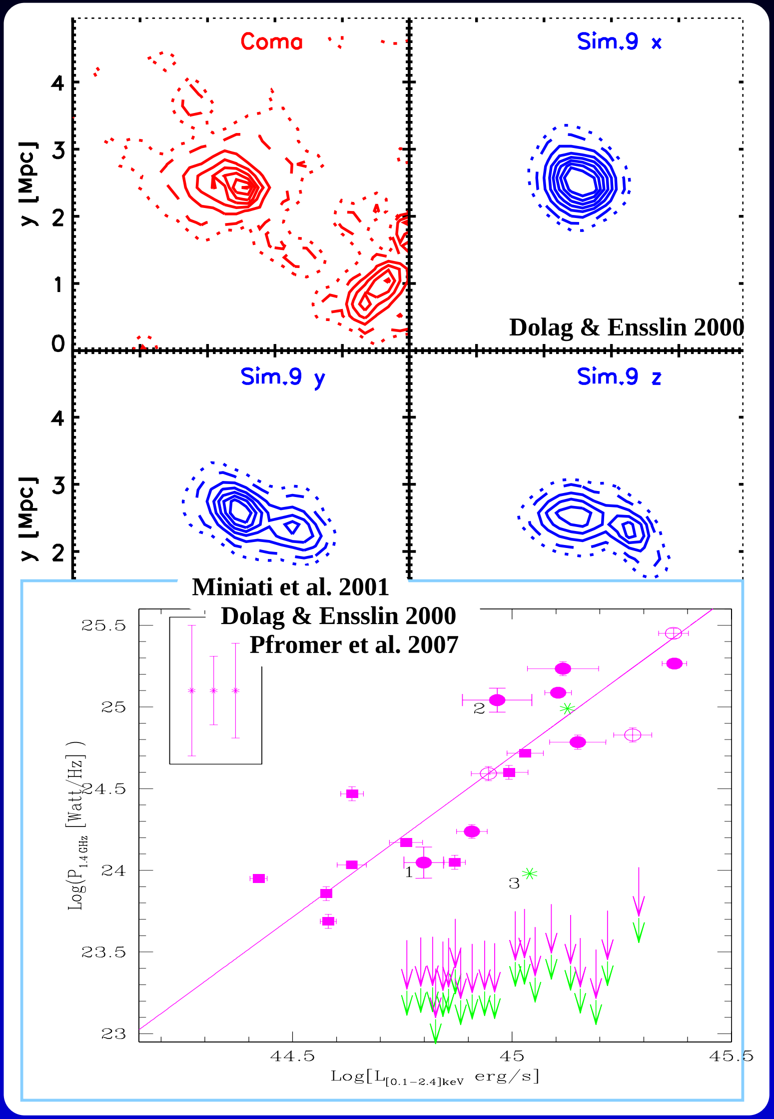


Govoni et al. 2010

- Combination of RM measured in many clusters.
- How does $\vec{B}$ scale with cluster temperature ?
- Magnetic Field in Radio quiet/active clusters ?

Problem 4: Radio Emission

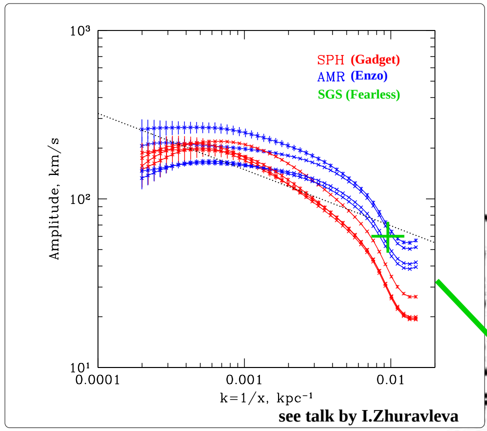




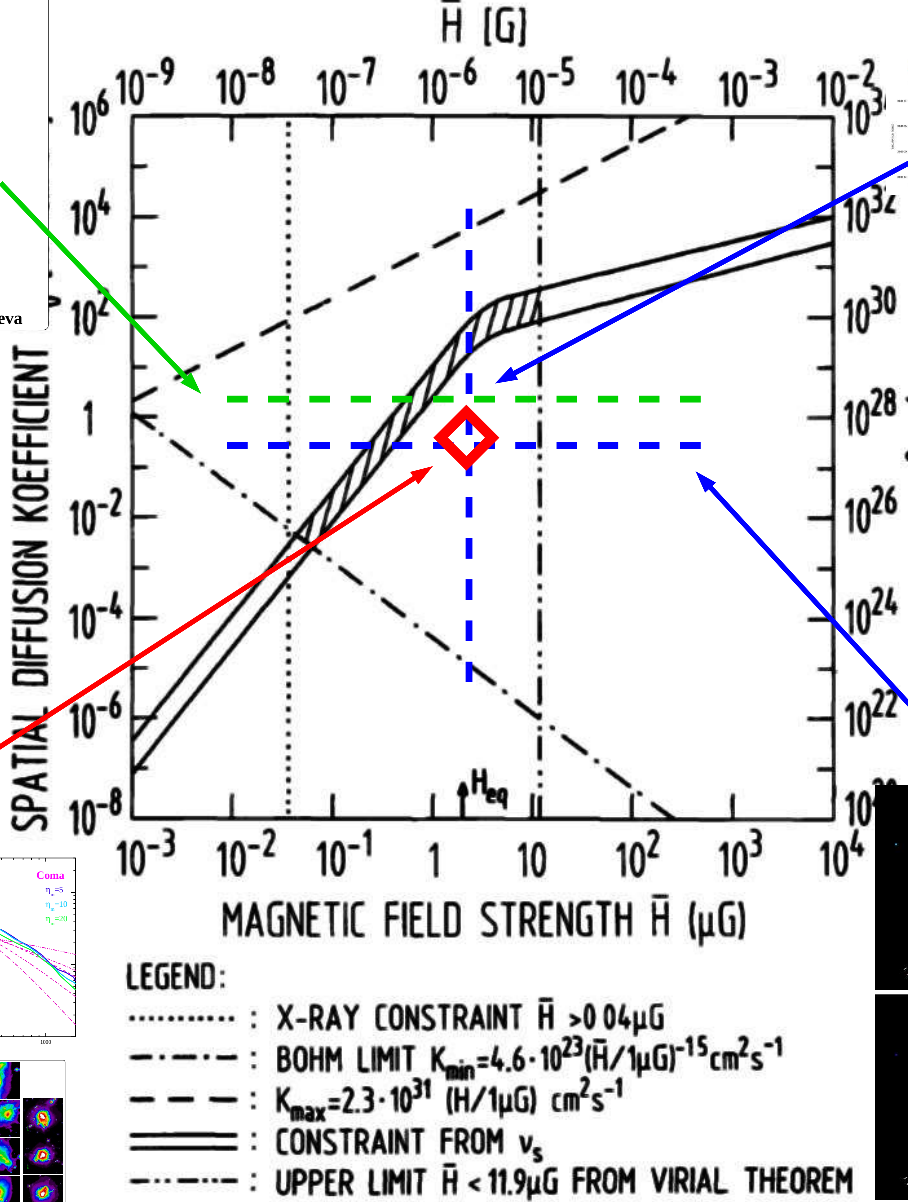
Cluster wide **diffuse synchrotron emission** connected to **merger** events, **periferal** emission directly connected to **shocks**.

- **Radio halo**: Turbulence, shocks, secondary ?
- **Relics**: Primary from shocks or compressed radio plasma ?

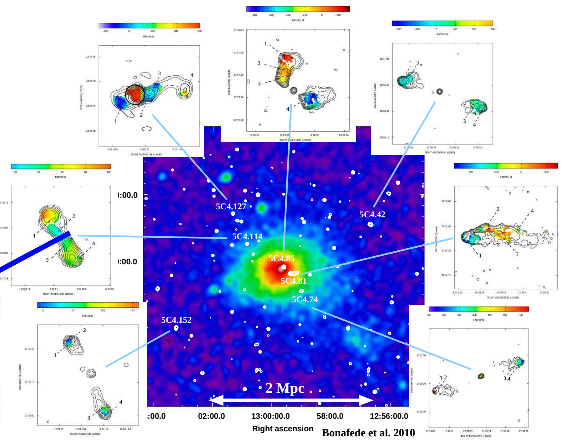
The Big Picture



see talk by I.Zhuravleva



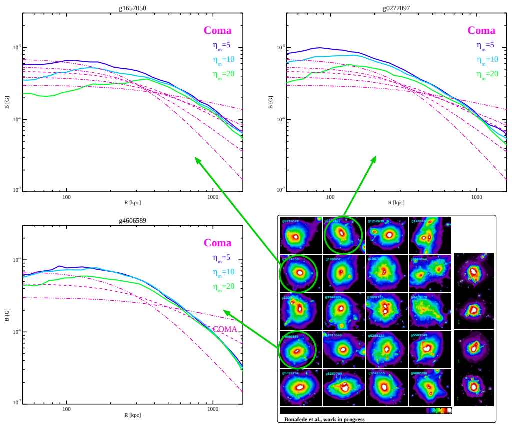
Schlickeiser et al. 1987

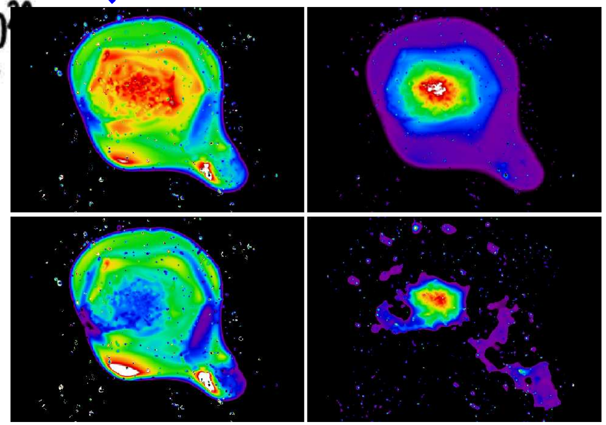


Bonafede et al. 2010

MHD Simulations

Bonafede et al. 2011

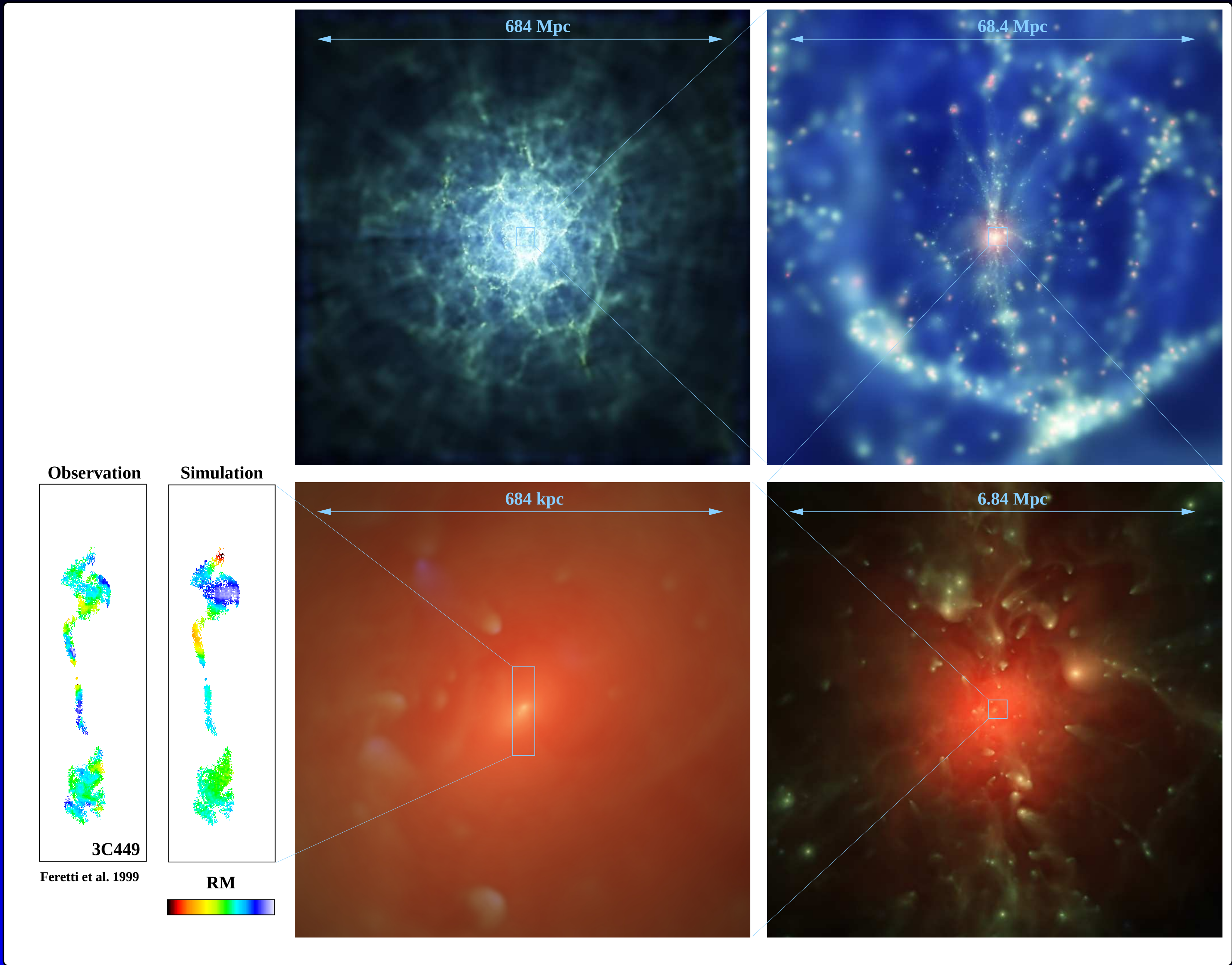




Schuecker et al. 2004

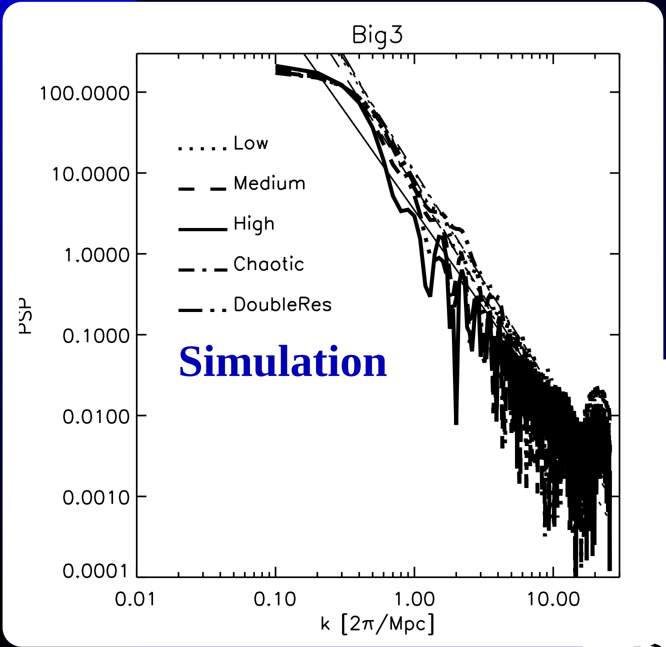
Cluster MHD simulations

Cluster MHD simulations

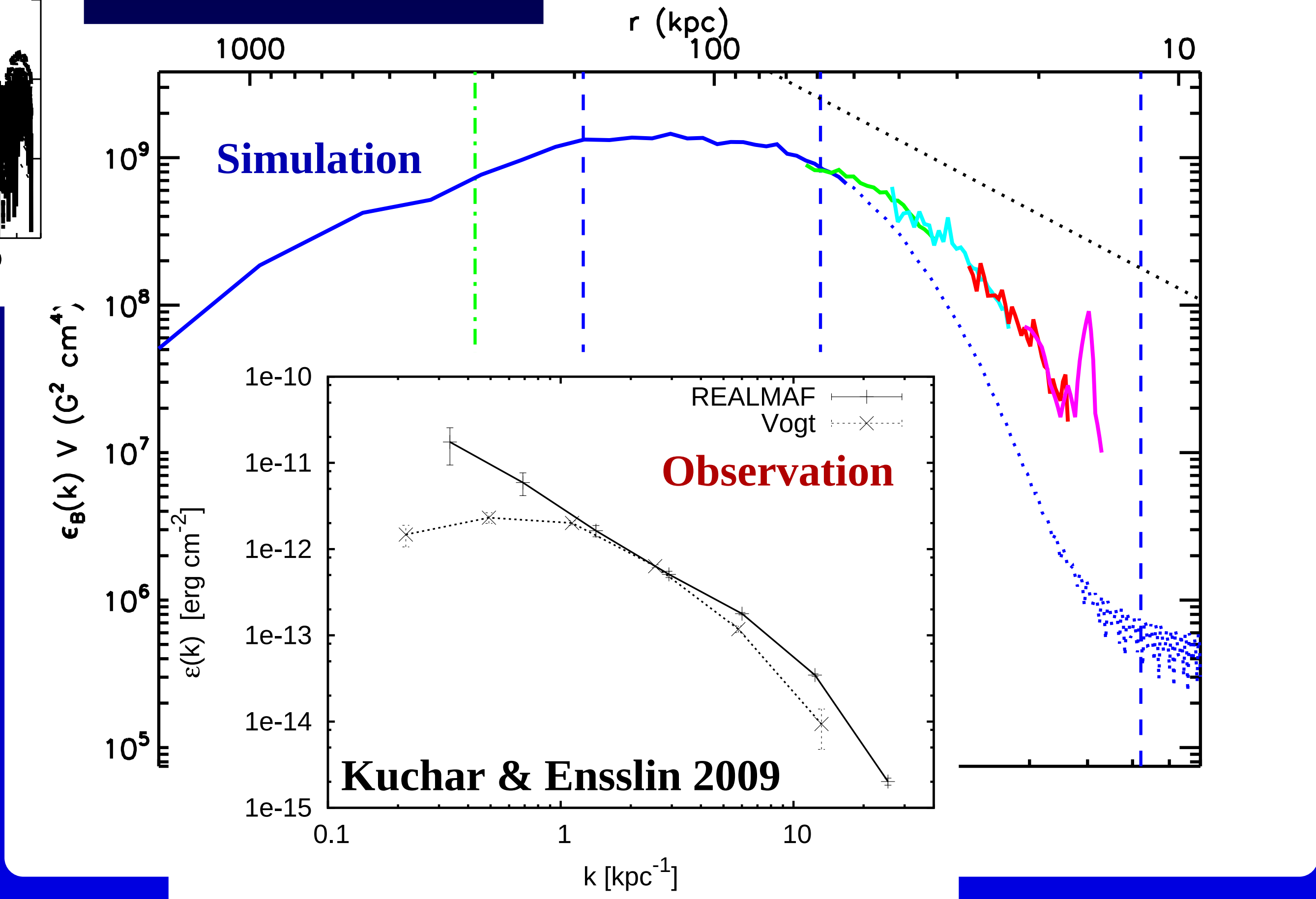


"Zoomed" cluster simulation (Dolag & Stasyszyn 2009). Movie: u,v

Cluster MHD simulations



Dolag et al. 2002

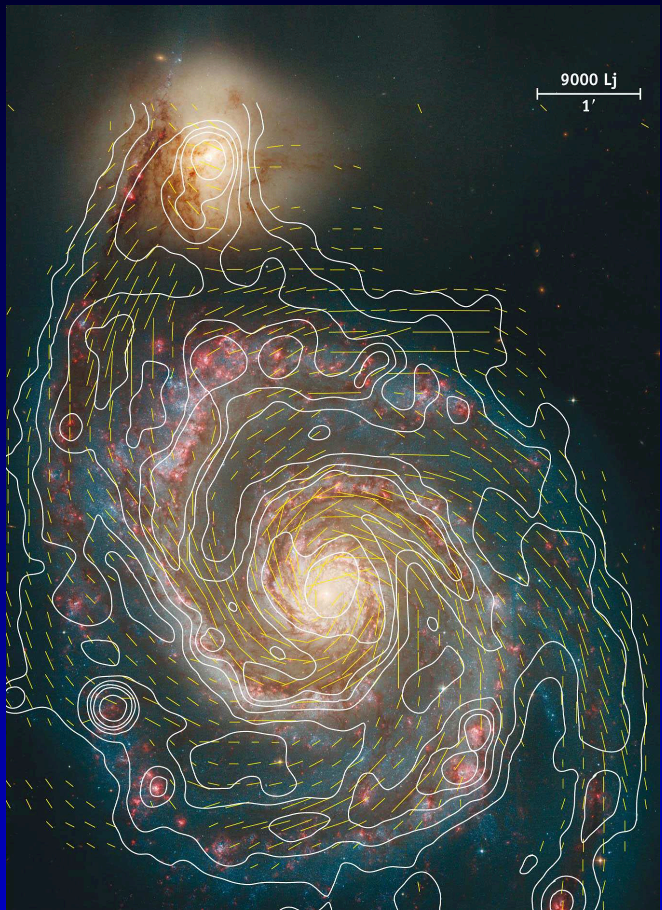


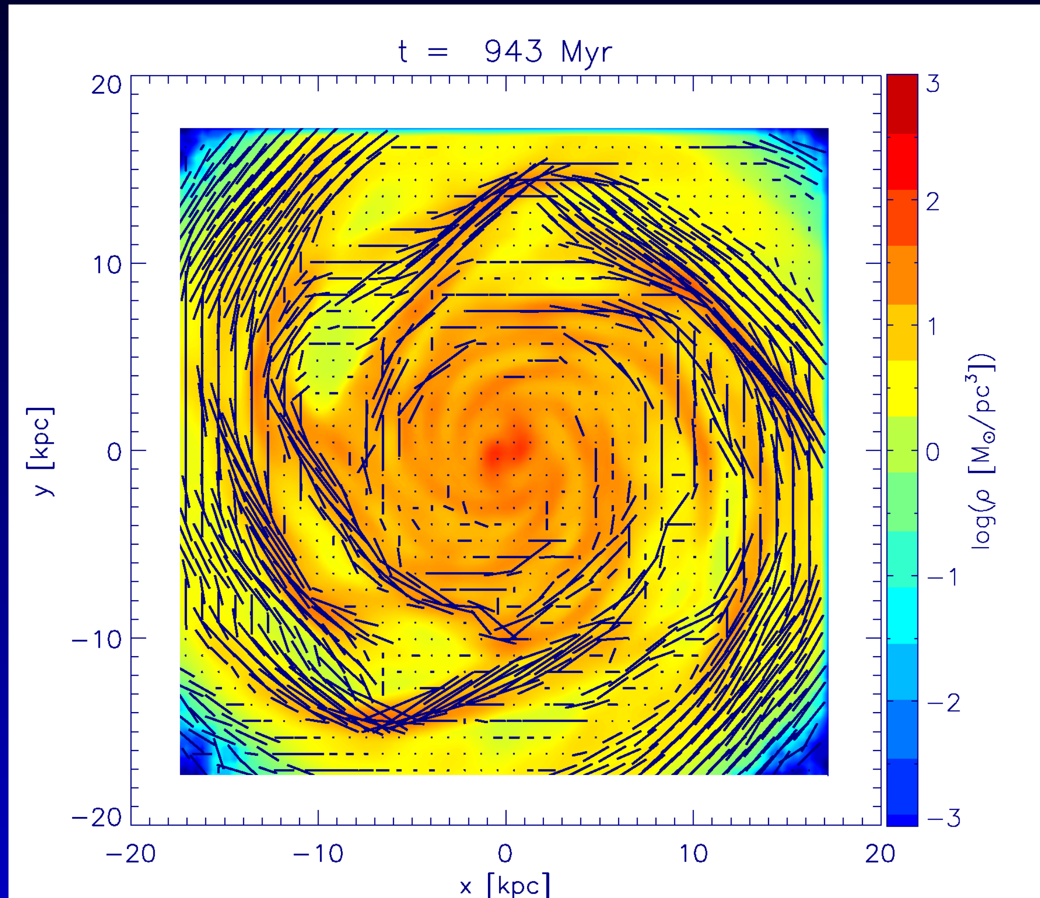
Magnetic field power spectra: predictions vs. observations.

See also Brüggen et al. 2005, Xu et al. 2009

Magnetic Field buildup

Simulations on galaxy scales ...

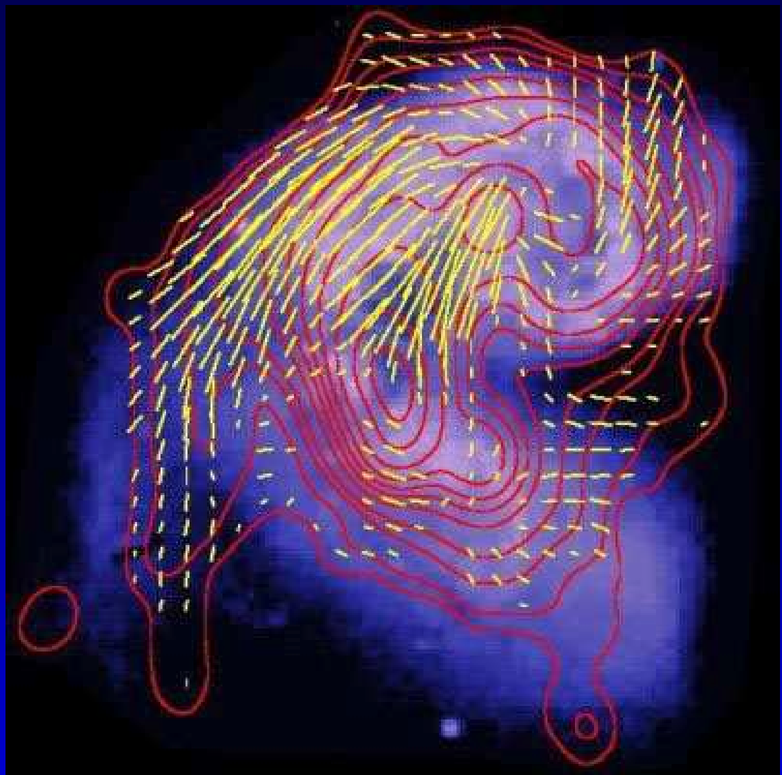


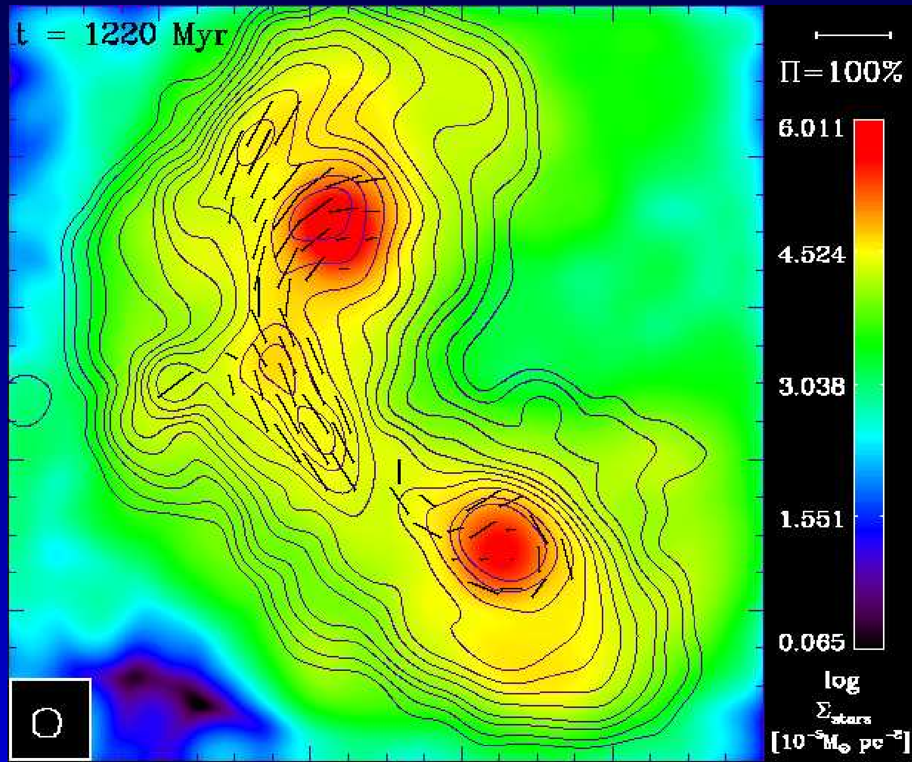


M51 (Fletcher & Beck 2006) and a simulation using the MHD implementation in Gadget (Kotarba et al. 2009).

Magnetic Field buildup

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.



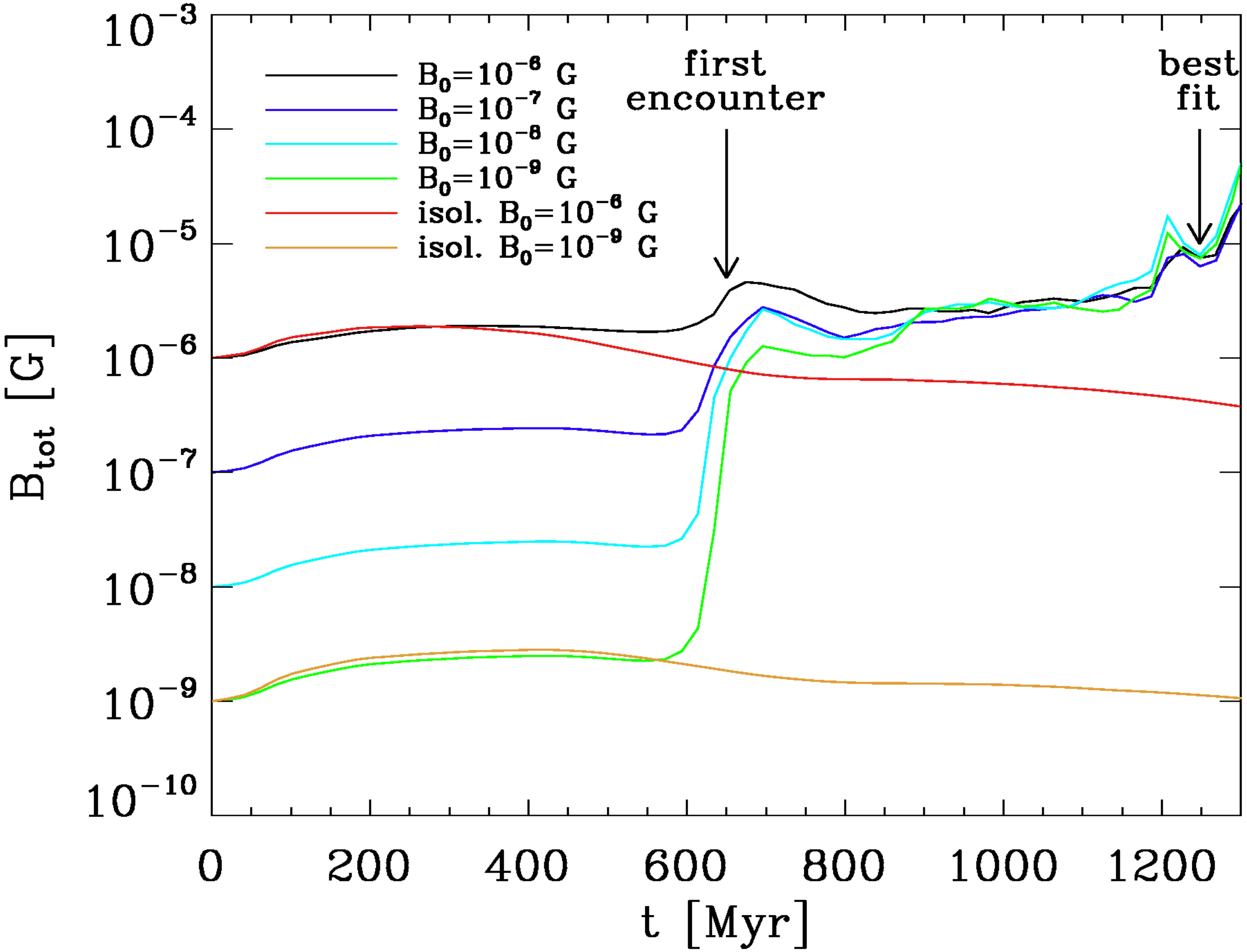


(Chyzy & Beck 2005 Kortarba et al. 2010)

Magnetic Field buildup

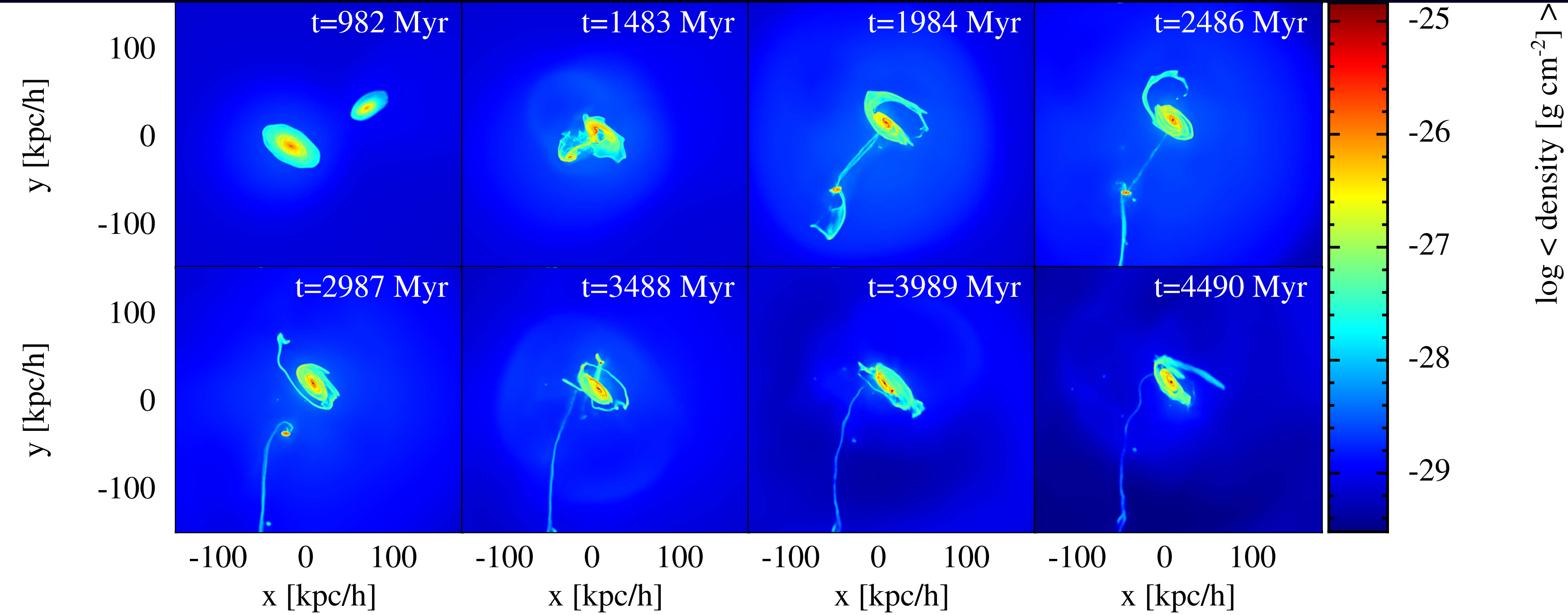
Final magnetic field close to equipartition with turbulent velocity component, largely independent of initial field values.

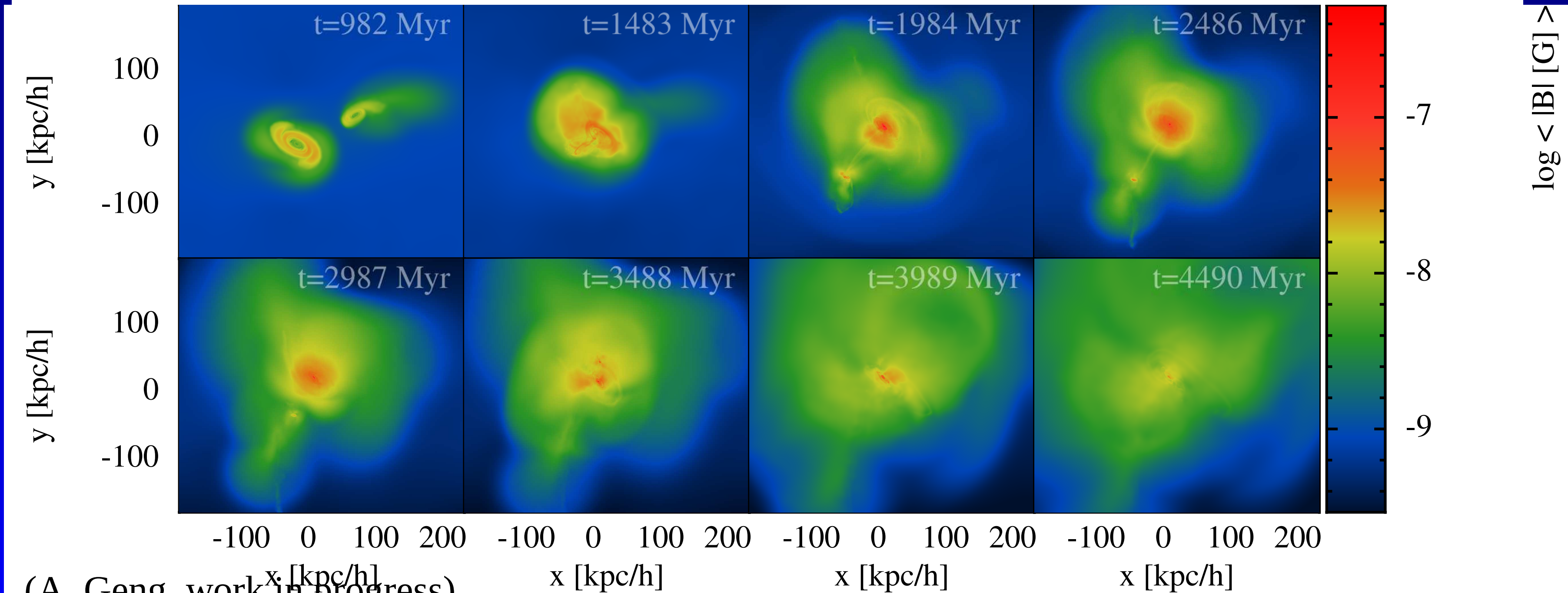
$\Rightarrow$ Hierarchical buildup of magnetic field



(Kortarba et al. 2010)

Magnetic Field buildup

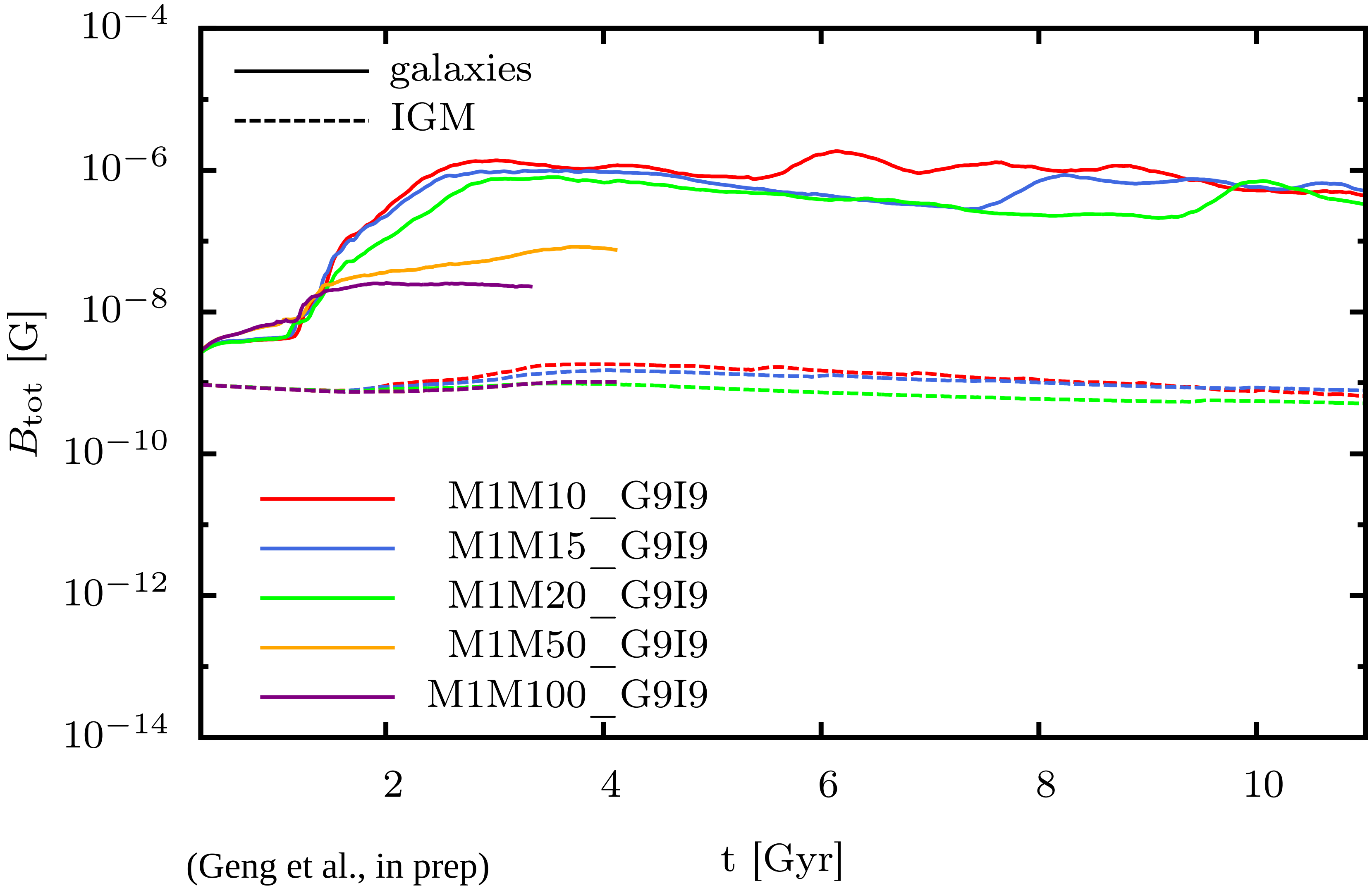




(A. Geng, work in progress)

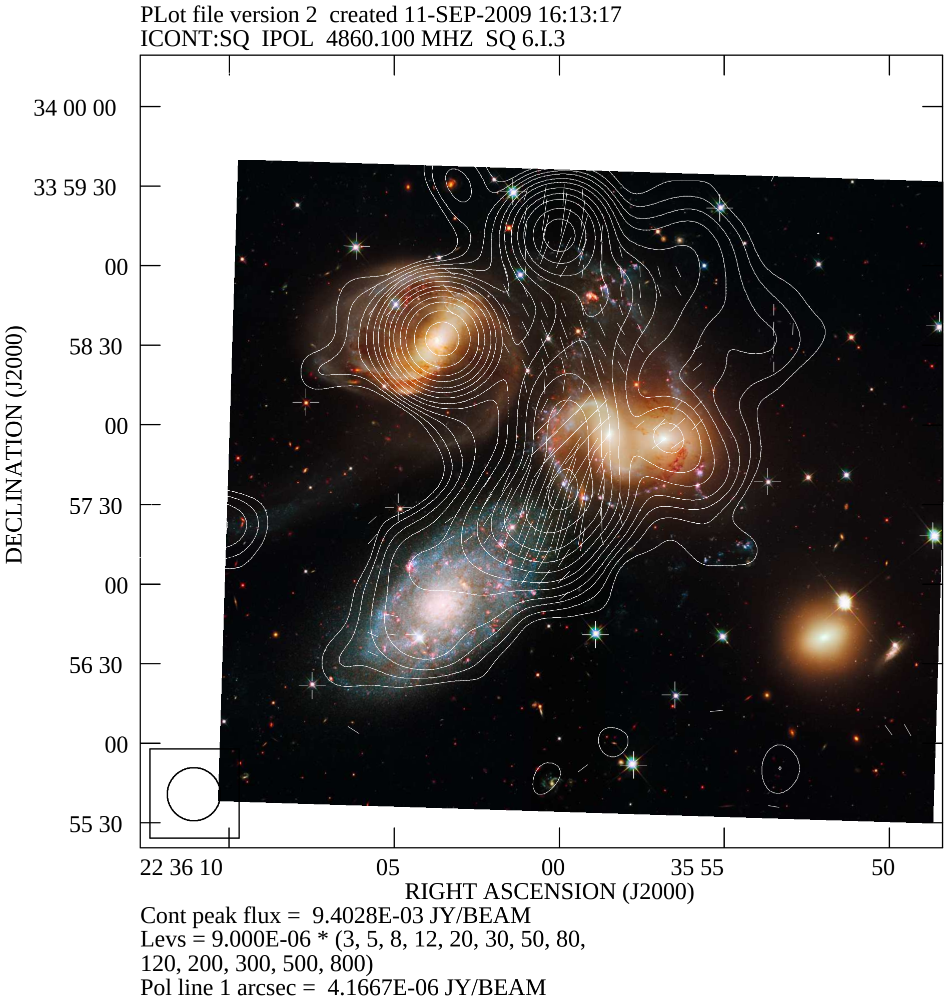
Magnetic Field buildup

Smaller merger less efficient in driving turbulence.

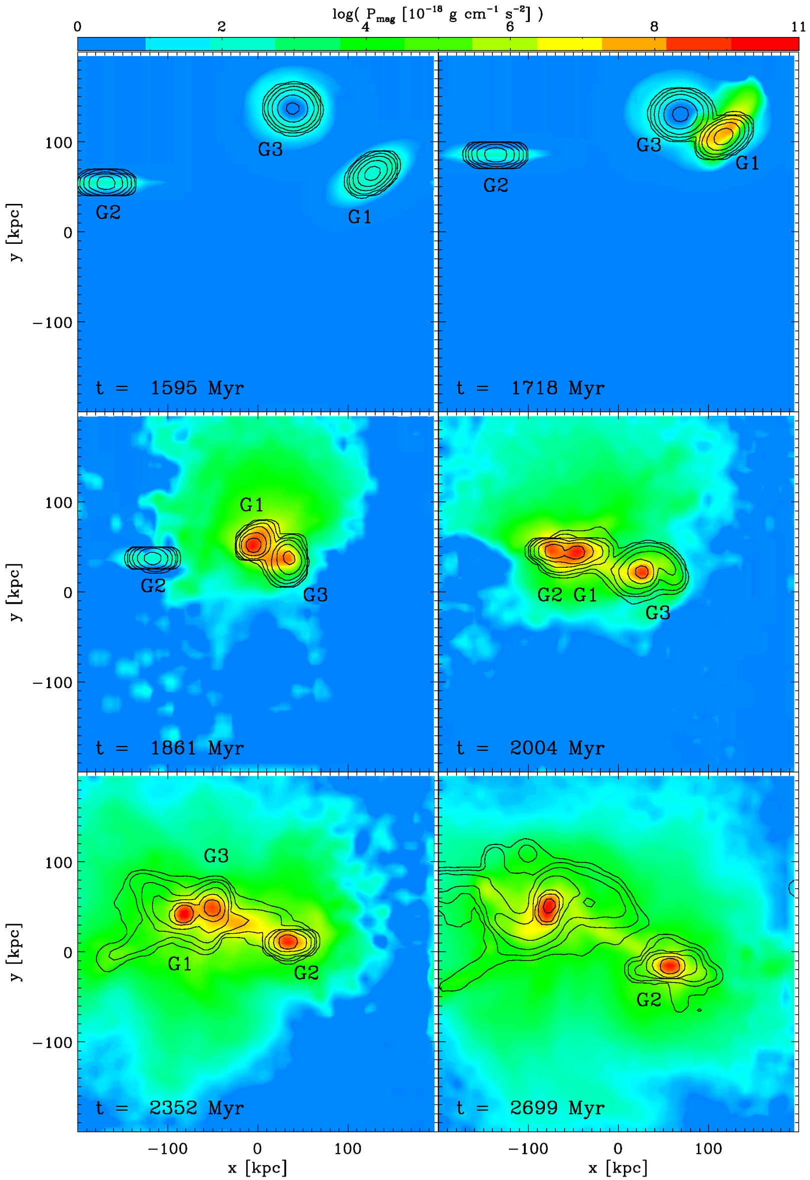


(Geng et al., in prep)

Magnetic Field buildup

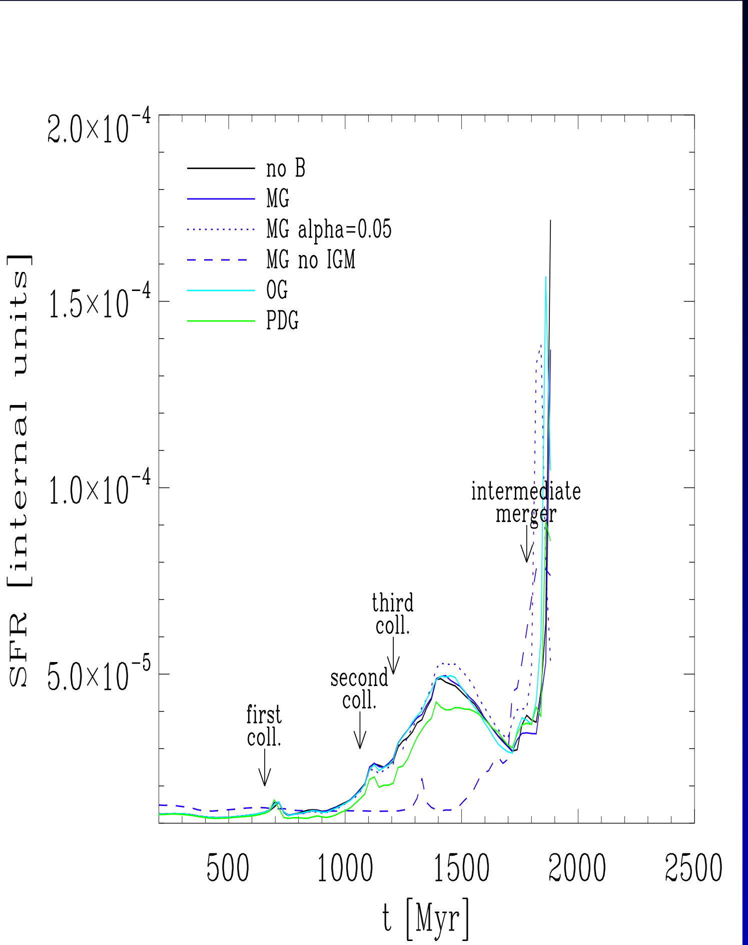


Soida et al., in prep.



Kortarba et al. 2010

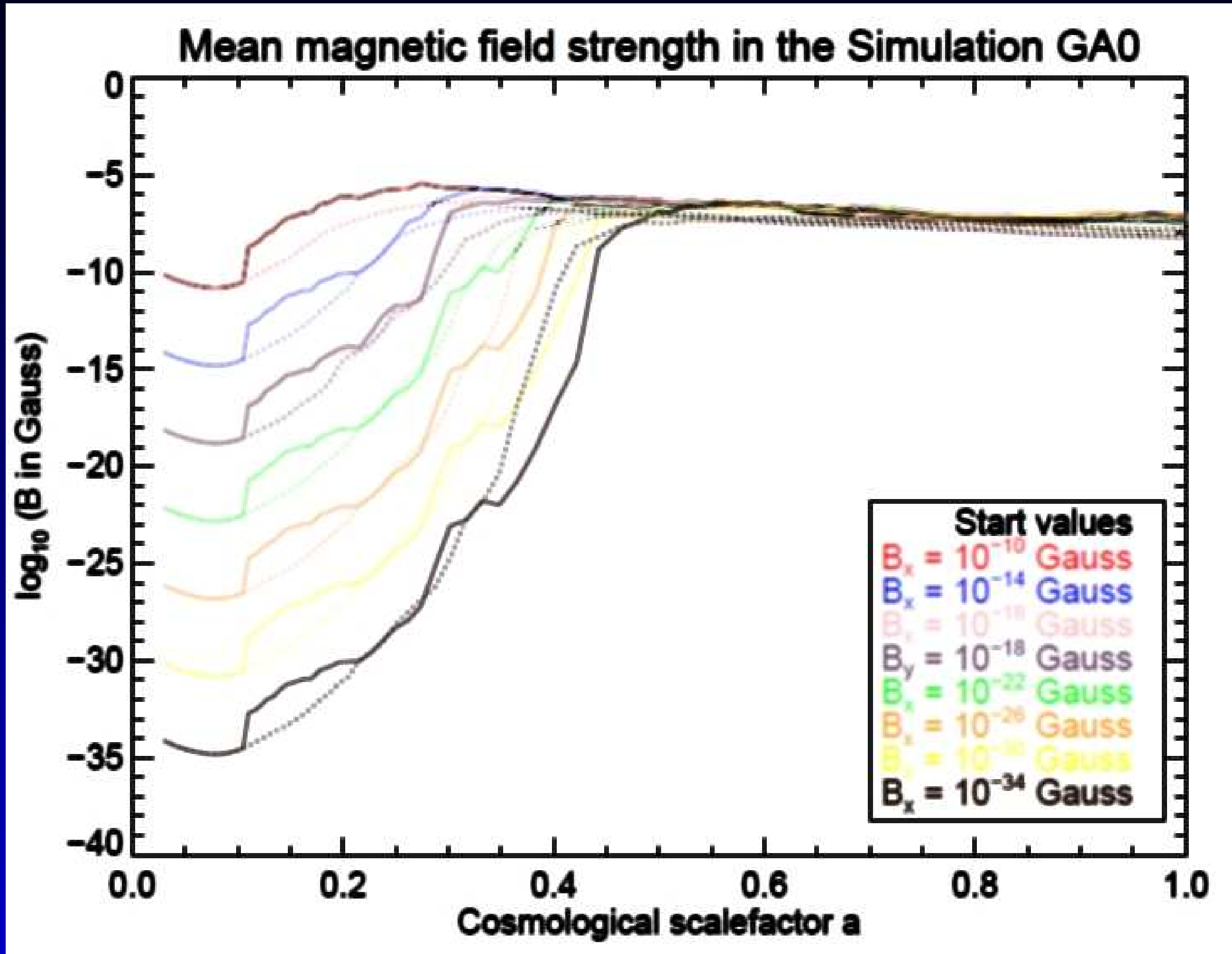
Magnetic Field buildup



Kortarba et al. 2010

- Merging drives shocks, turbulence and star-formation
- Star-formation drives winds
- Winds transport out magnetic fields

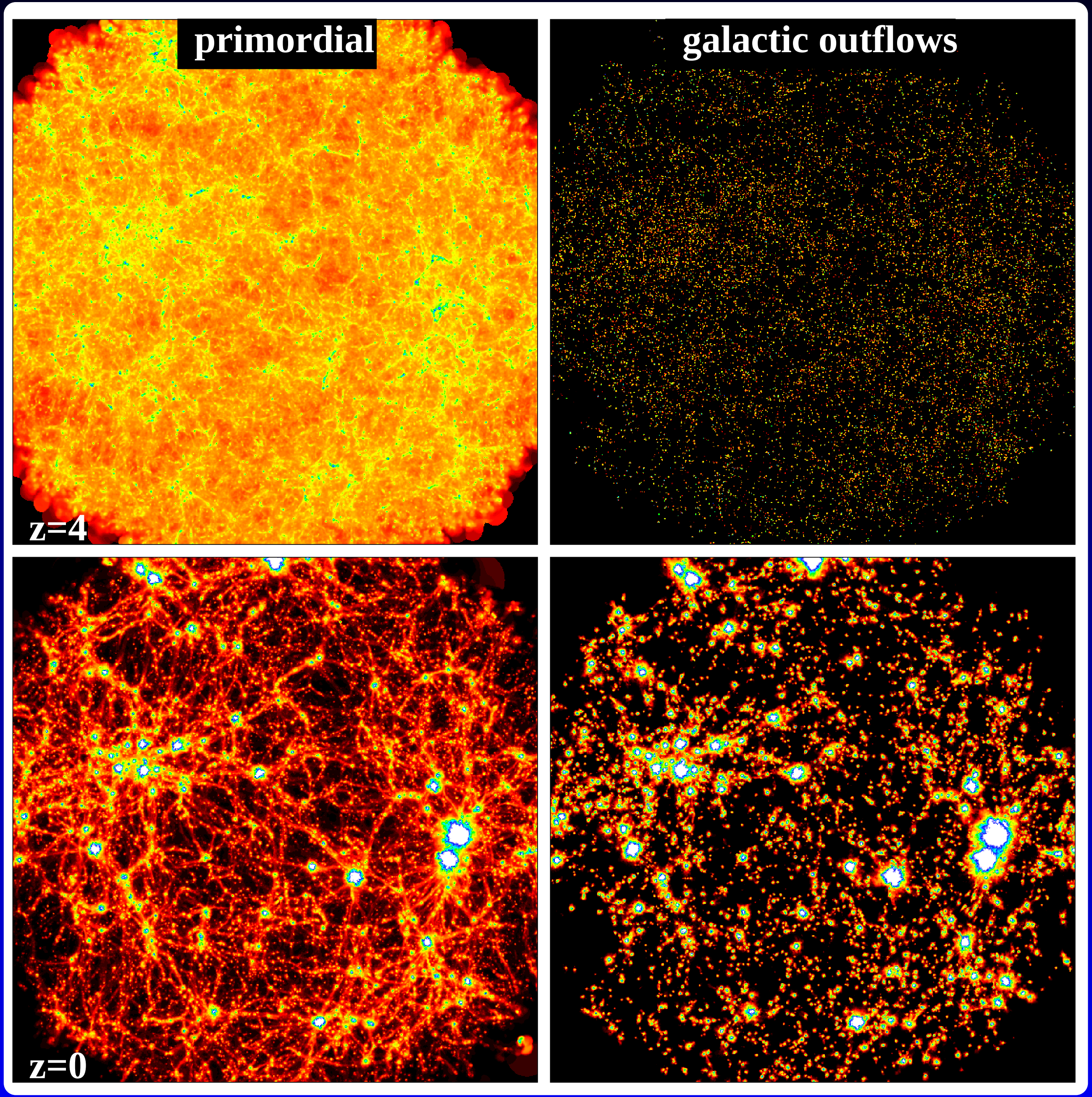
Magnetic Field buildup



Comparison of magnetic growth and simple expectation for $v_{turb} = 100$km/s and $\lambda = 25$kpc.

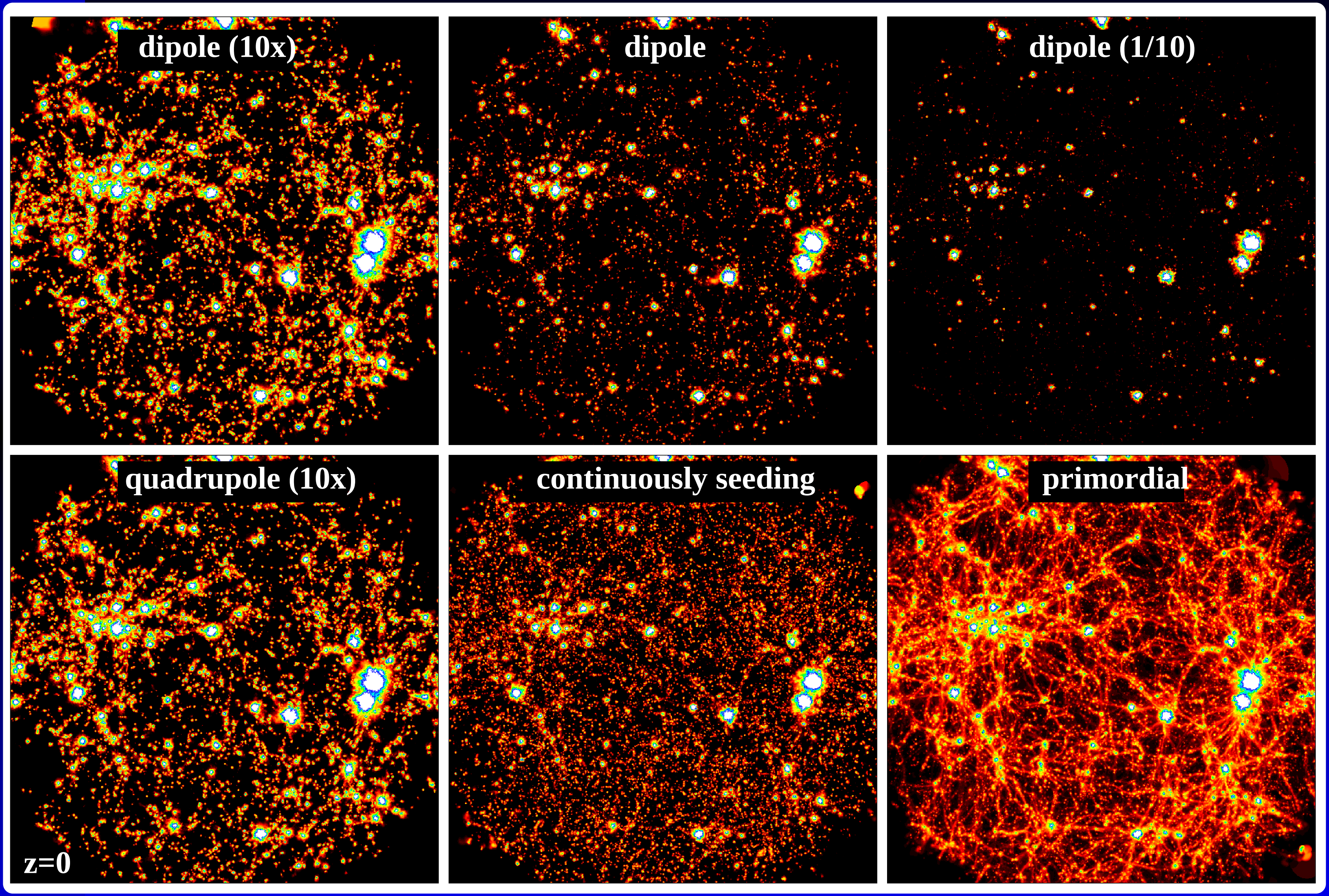
A. Beck, diploma thesis

Magnetic Field buildup



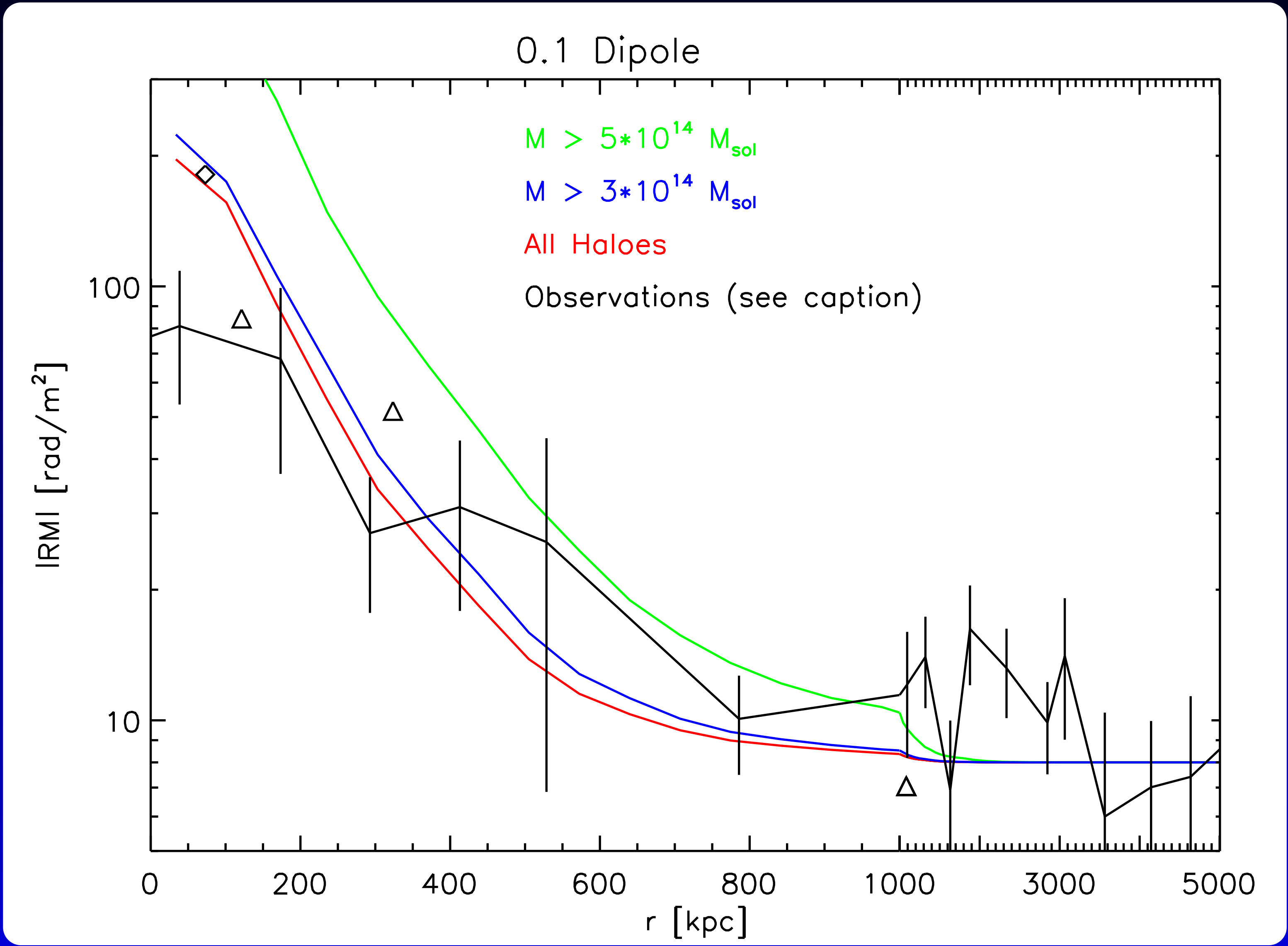
Seeding from galactic outflows (Donnert et al. 2009)

Magnetic Field buildup



Different wind parameters (Donnert et al. 2009)

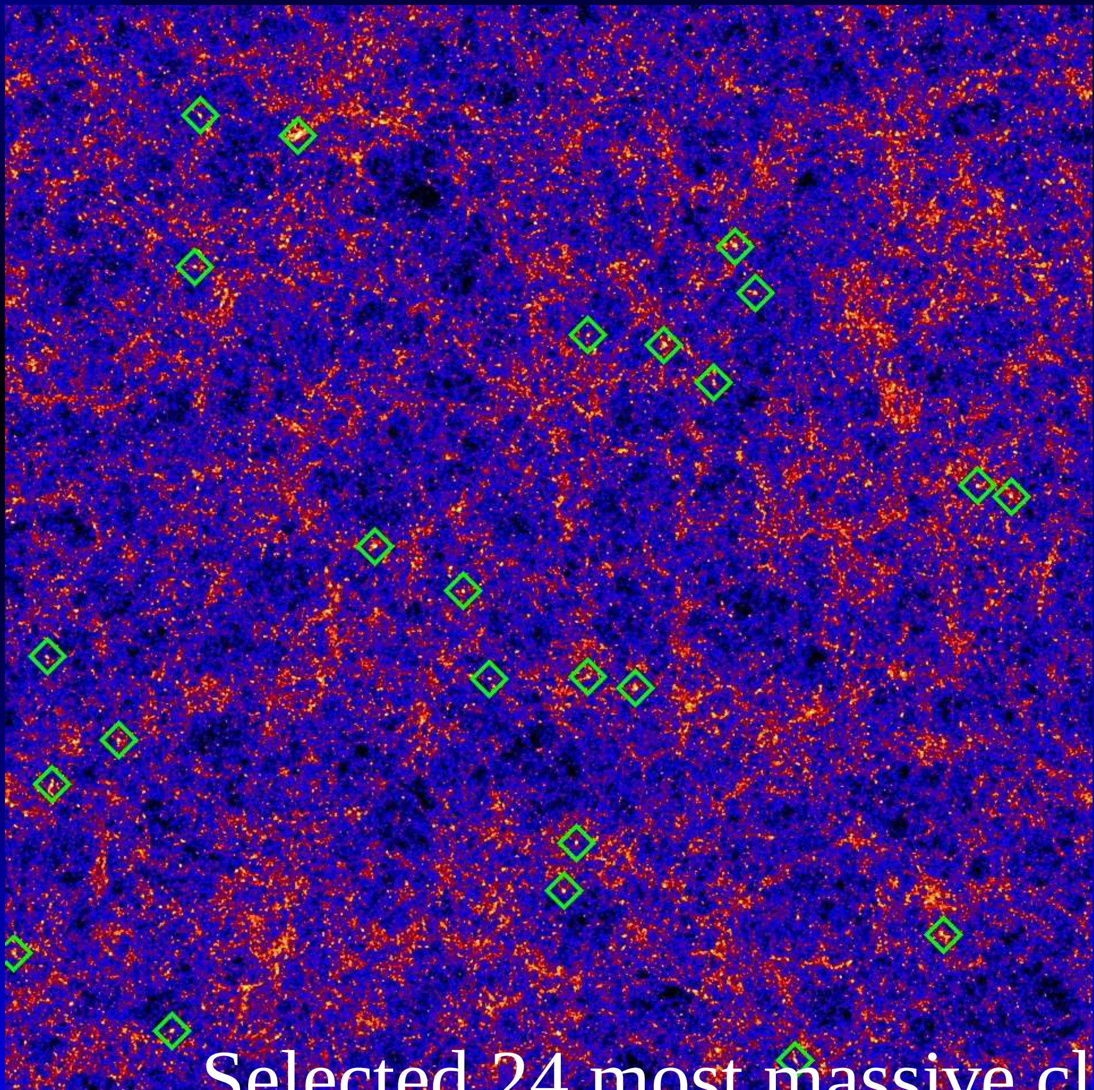
Magnetic Field buildup

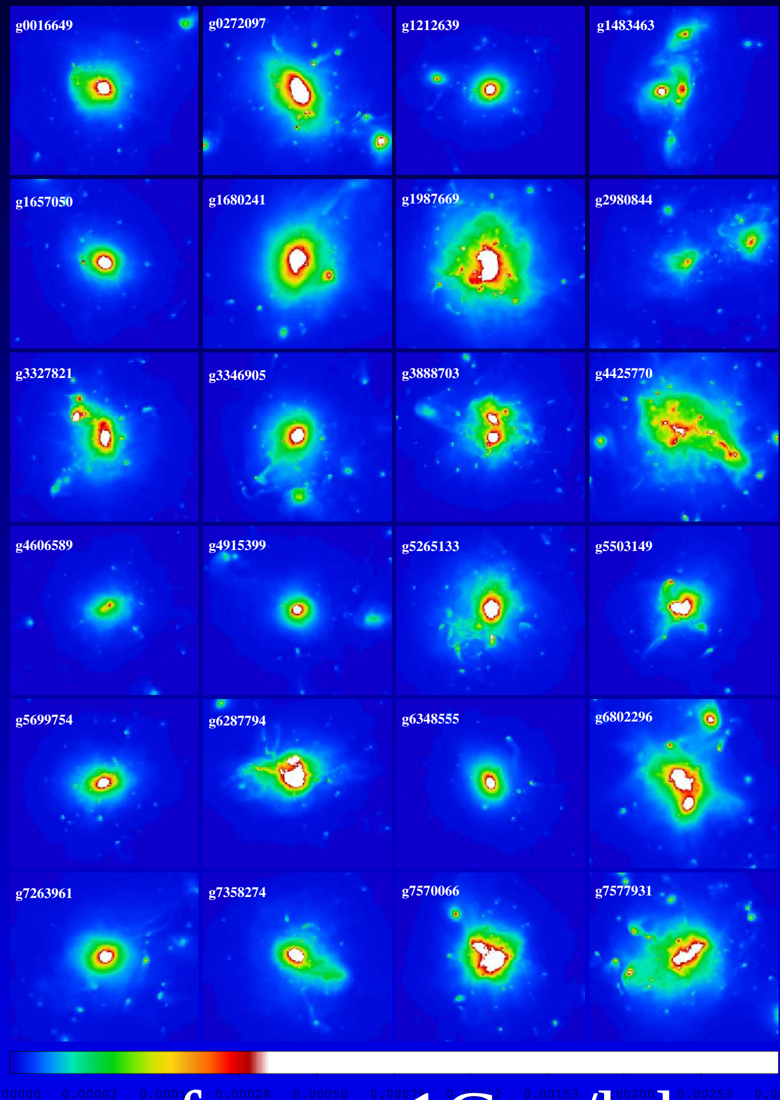


⇒ **Galactic seeding** models also **reproduce** observed **RM profile** within galaxy clusters (Donnert et al. 2009)

Madgetic diffusion in clusters

$$\eta = \eta_{\rm coulomb} + \eta_{\rm turb} \approx 0.1 \times v_{\rm turb} \times \lambda_{\rm vturb}$$

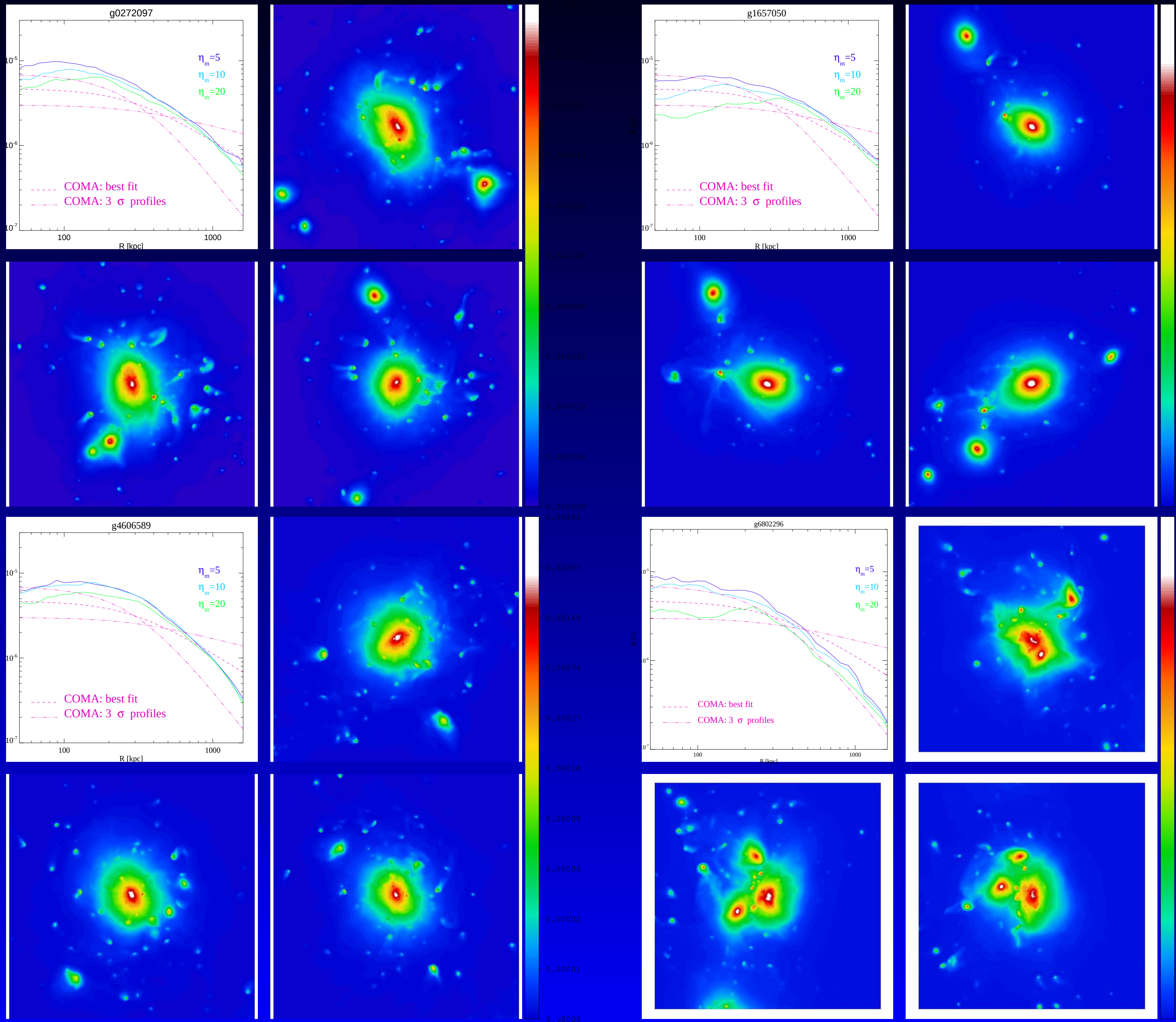




Selected 24 most massive clusters from a 1Gpc/h box.

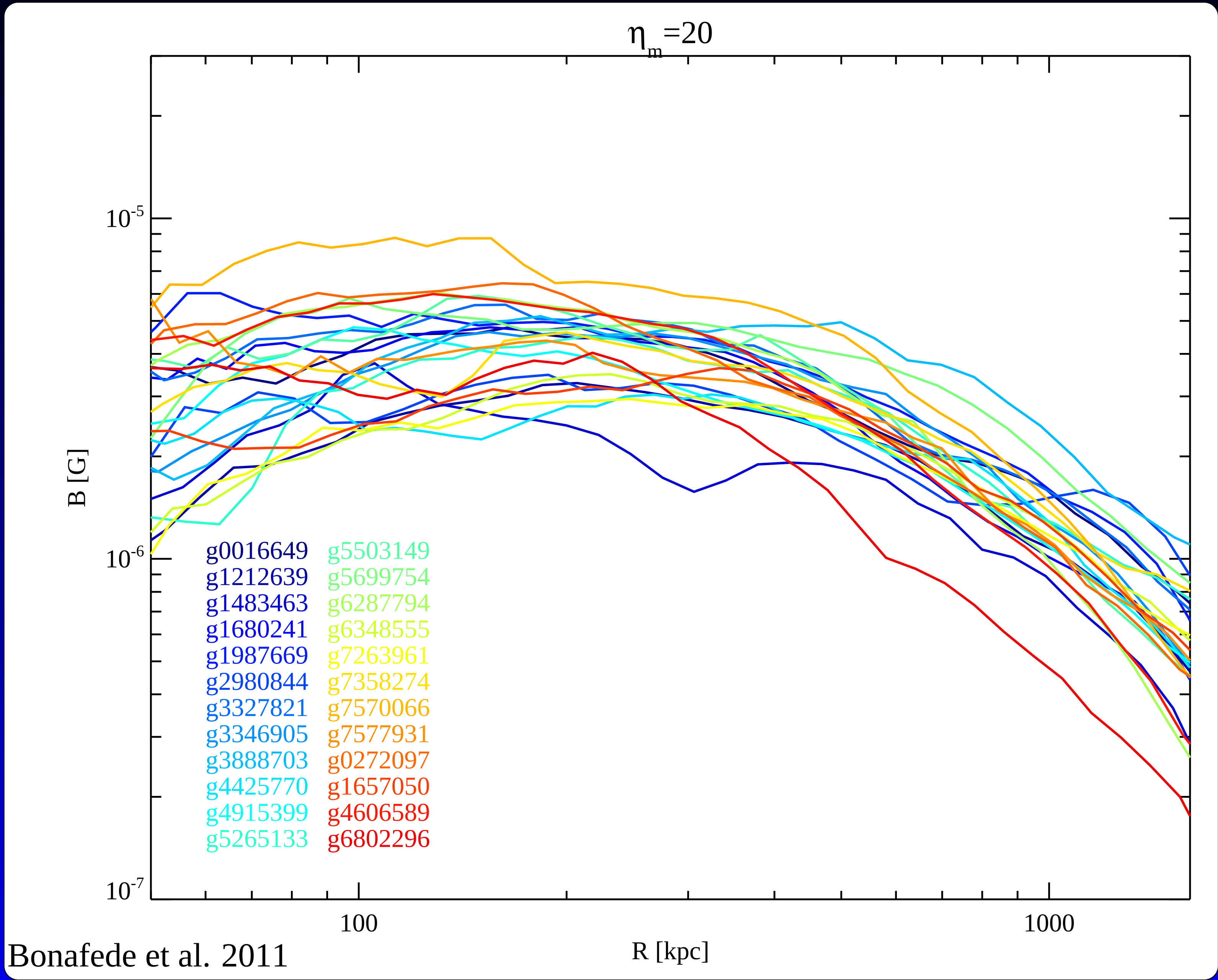
Bonafede et al. 2011

Madgetic diffusion in clusters



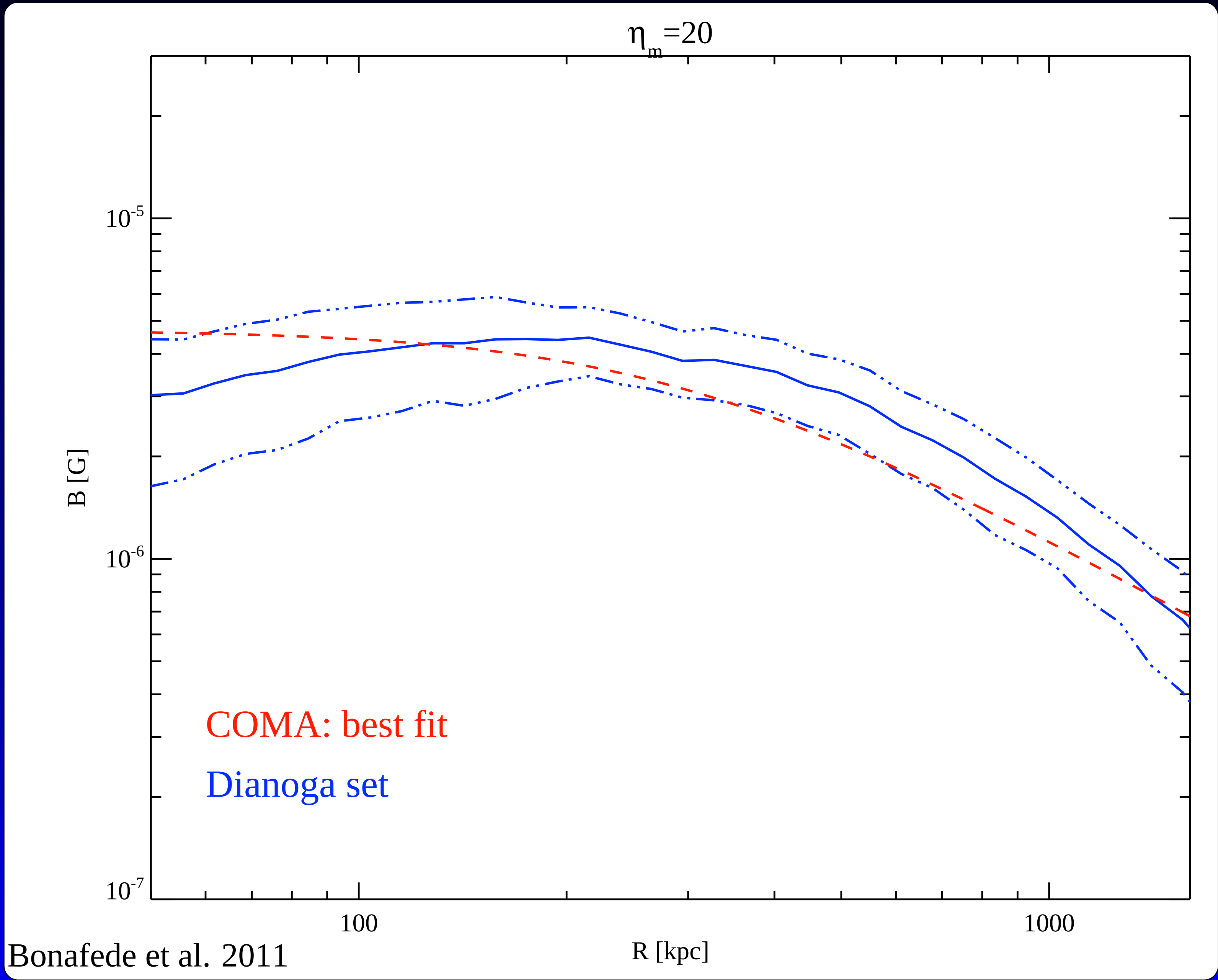
Subset of 4 Coma-like clusters with $\eta = 1.5, 3, 6 \times 10^{27} cm^2/s$. (Bonafede et al. 2011)

Madgetic diffusion in clusters



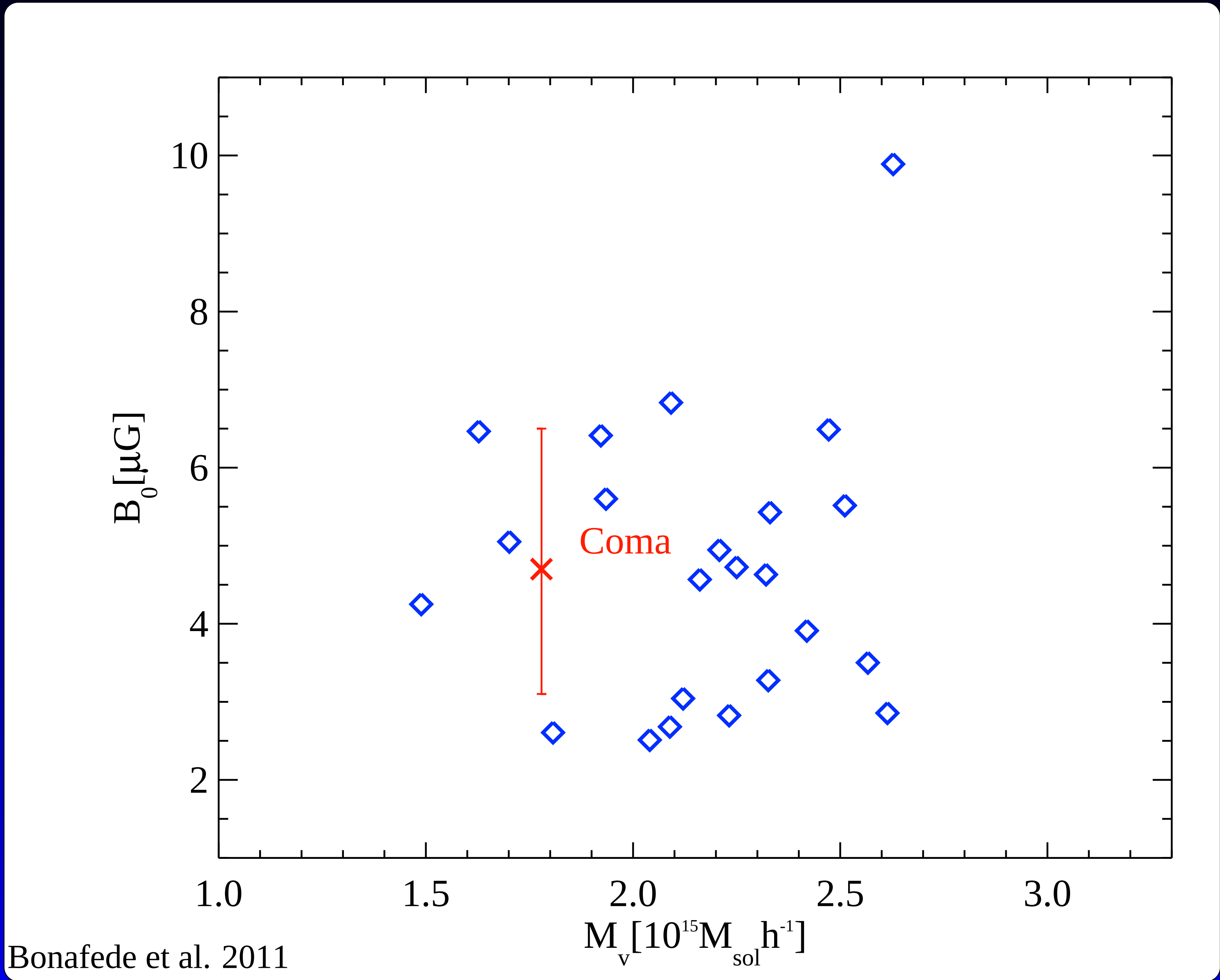
⇒ **Profiles** of 24 **Coma-like** galaxy clusters

Madgetic diffusion in clusters



⇒ **Profiles** of 24 **Coma-like** galaxy clusters

Madgetic diffusion in clusters



⇒ **Central B** of 24 **Coma-like** galaxy clusters

Radio emission of cluster

⇒ Solve Fokker-Planck equation for CRe population

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial p}\left(D_{\rm pp}\frac{\partial n}{\partial p} + H(p)n\right) - \frac{n}{T(t)} + Q(t)$$

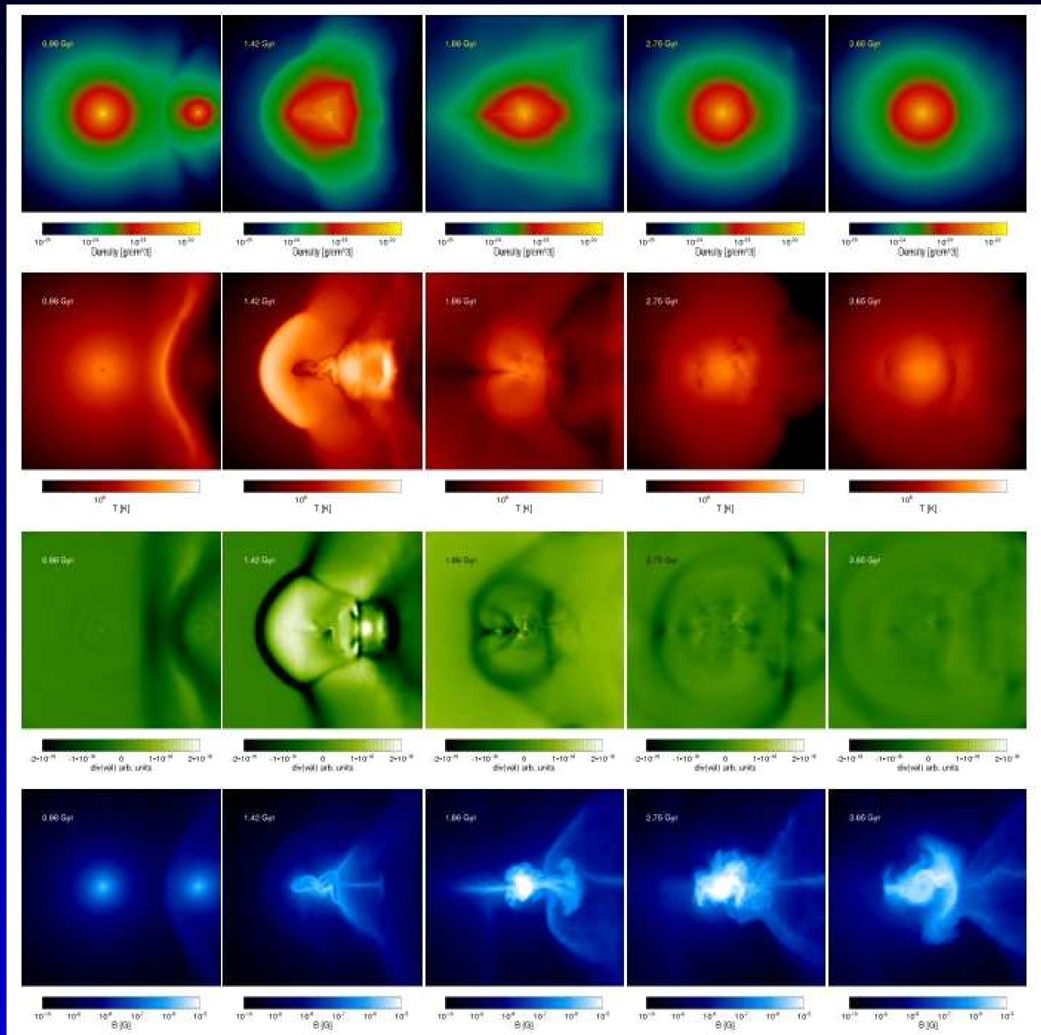
- 10% turbulent energy in fast mhd modes and reacceleration by those only
- Momentum Diffusion Coefficient

$$D_{\rm pp} \propto v_{\rm turb}^4 / h_{\rm sml} / c_{sound}$$

- cooling with inverse compton, synchrotron and bremsstrahlung
- See also Cassano & Brunetti 05, Brunetti & Lazarian 2007
- 1% CRp as seed for CRe (hadronic background)

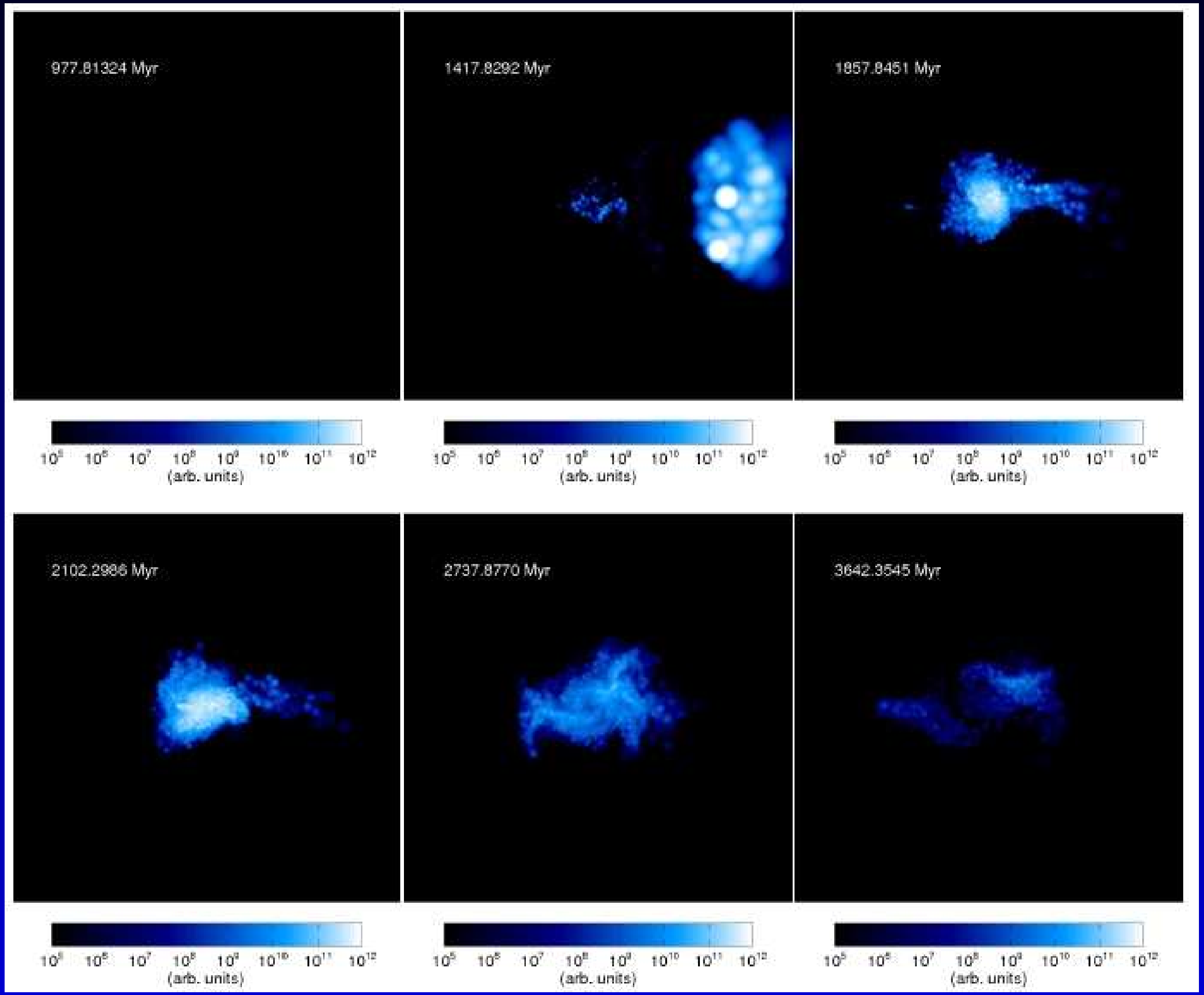
Donnert et al. 2011

Radio emission of cluster



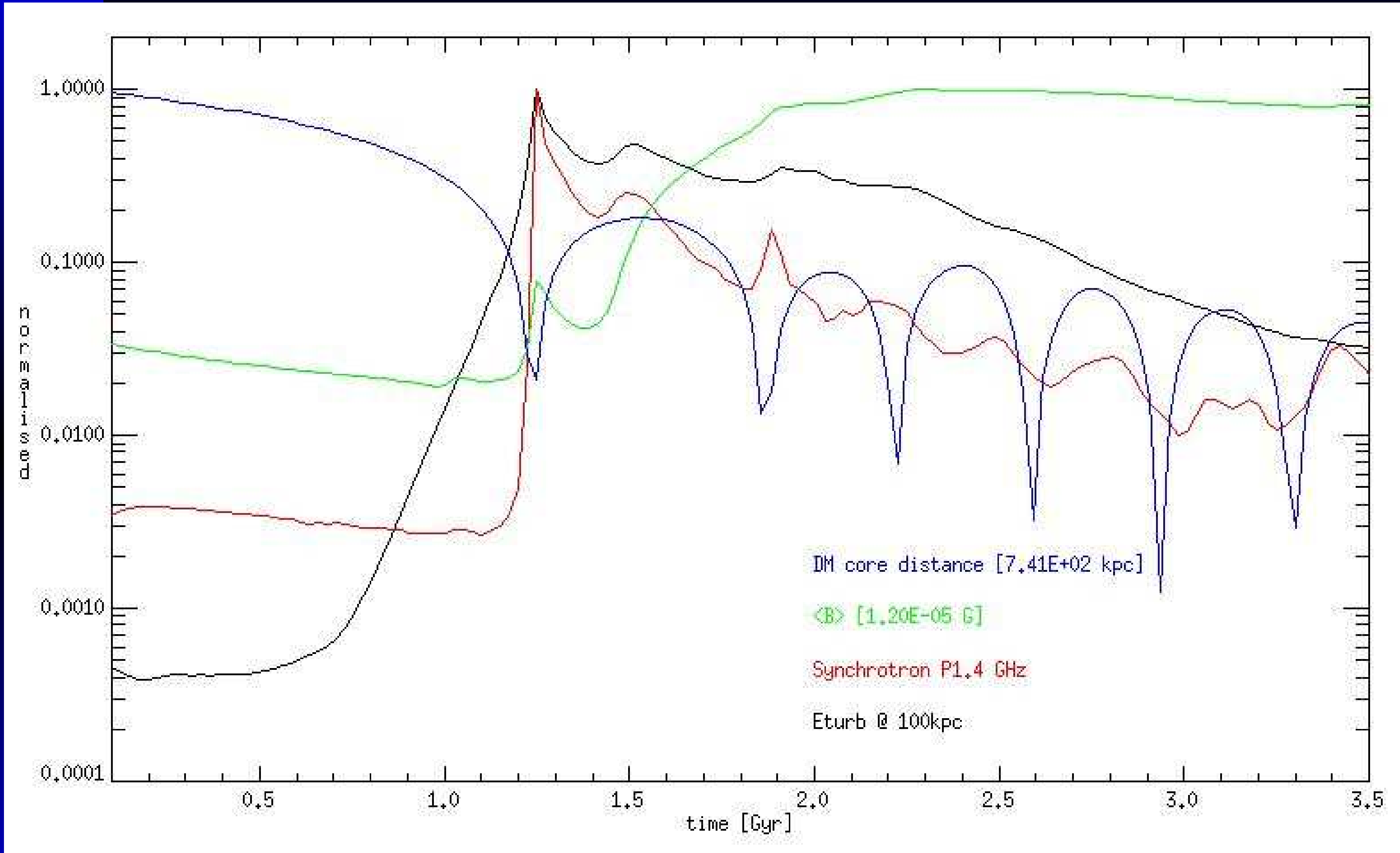
Idealized 1:4 merger, solving Fokker-Planck equation for all particles. ($2x128^3$). (Donnert et al. 2011)

Radio emission of cluster



Synthetic radio emission, smoothed to coma observation by Deiss et al. 1996 (right). (Donnert et al. 2011)

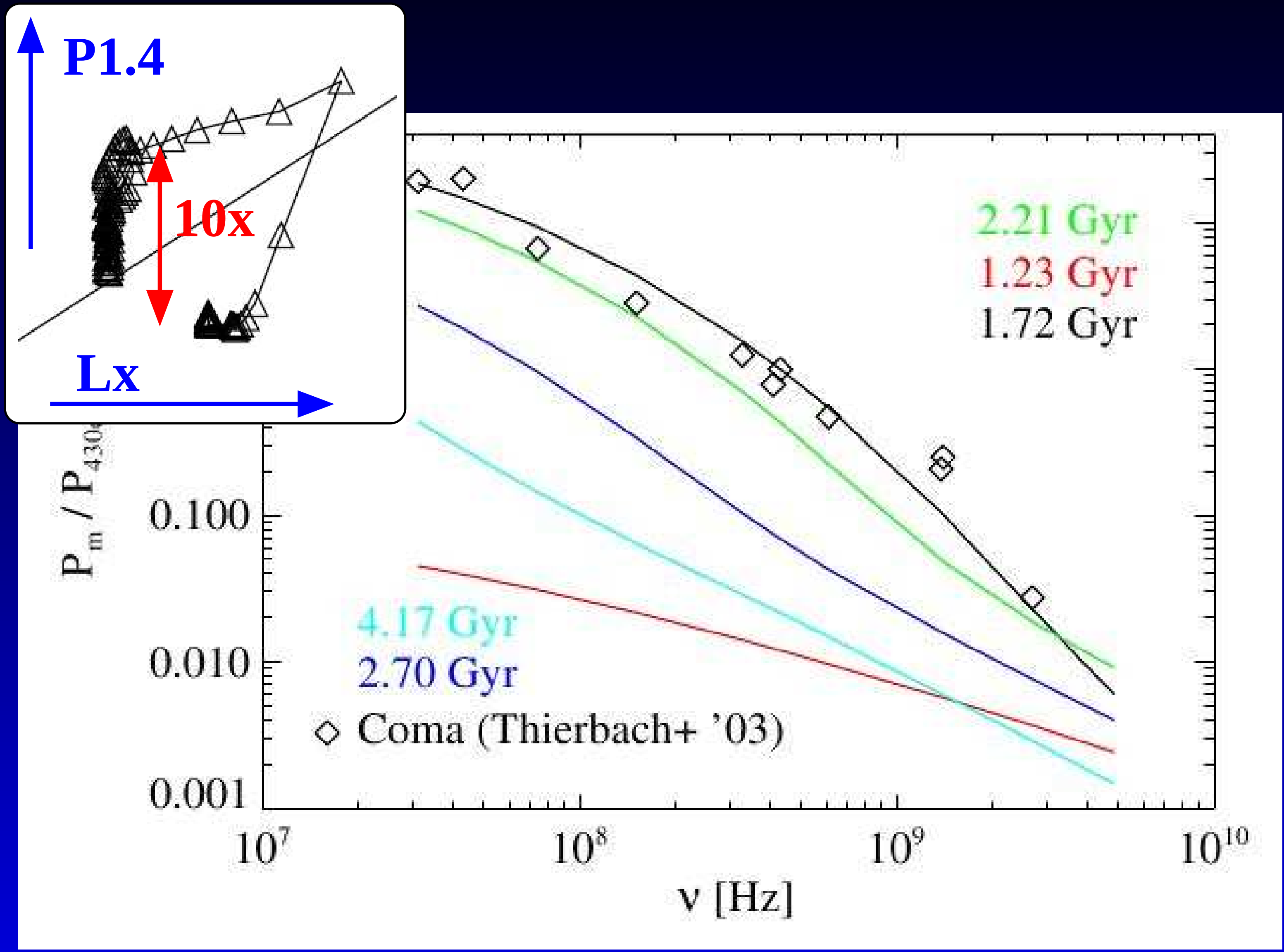
Radio emission of cluster



Evolution of v_{turb} (black), B (green) and $P_{1.4}$ (red).

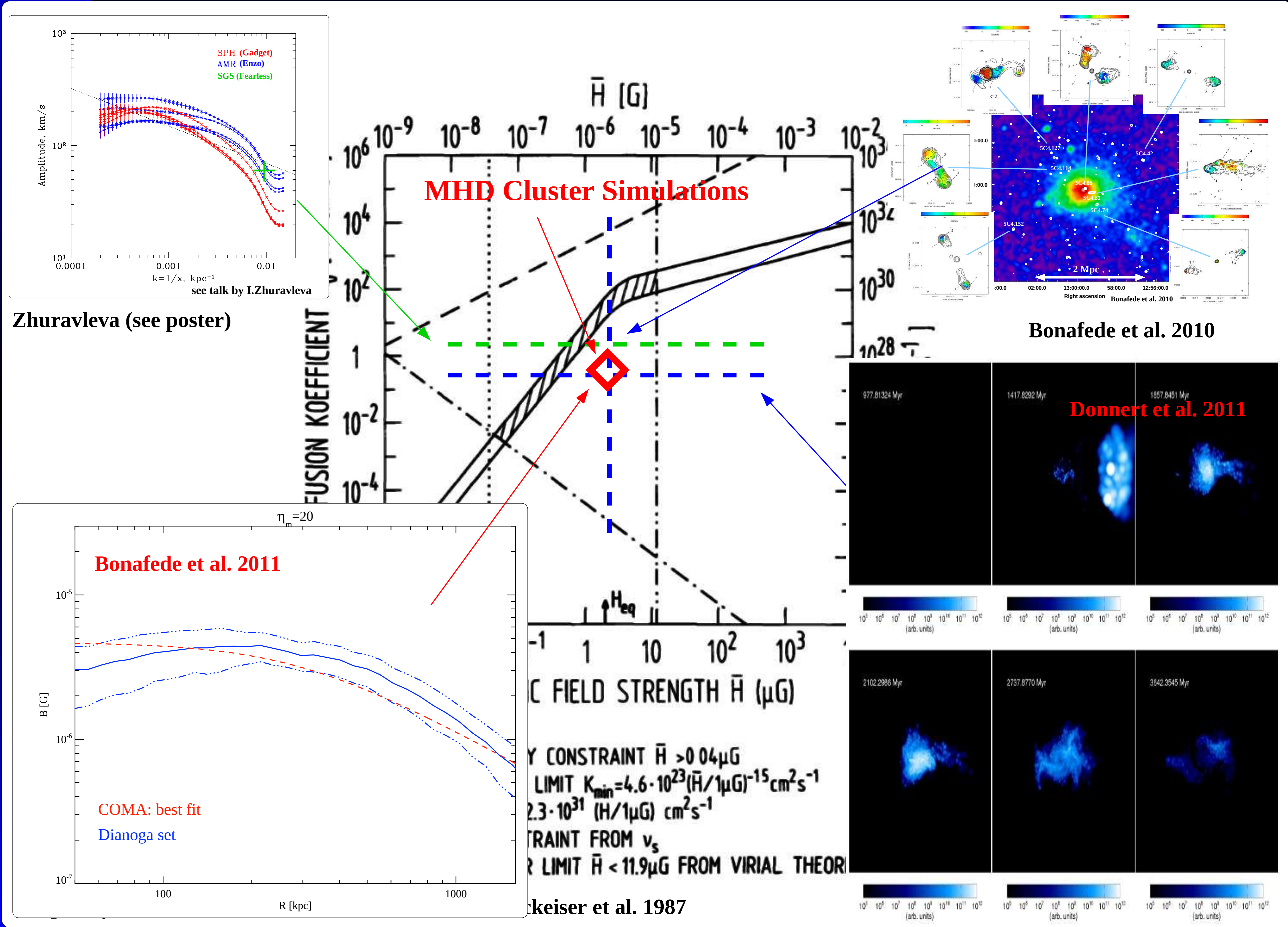
Donnert et al. 2011

Radio emission of cluster



Evolution of the spectrum of the radio emission and the Lx-P1.4 relation (inlay). Donnert et al. 2011

Conclusions



Conclusions

Observations (**RM & Radio probes μG**)

- Measurement of magnetic field power spectra
- Clear indication of magnetic field shape
- Indications for minimum/maximum length scale

Simulations (hydro):

- Motions within the ICM are unavoidable (> 100 km/s)
- Overall good agreement with (rare) observations
- Overall good agreement between different simulations

Simulations (MHD):

- Overall good agreement with observed magnetic fields
- Detailed comparison reveal dissipative processes

Simulations (Radio Halo):

- Turbulent re-acceleration reproduce on/off and spectra
- Secondary floor emission at best at 10% level