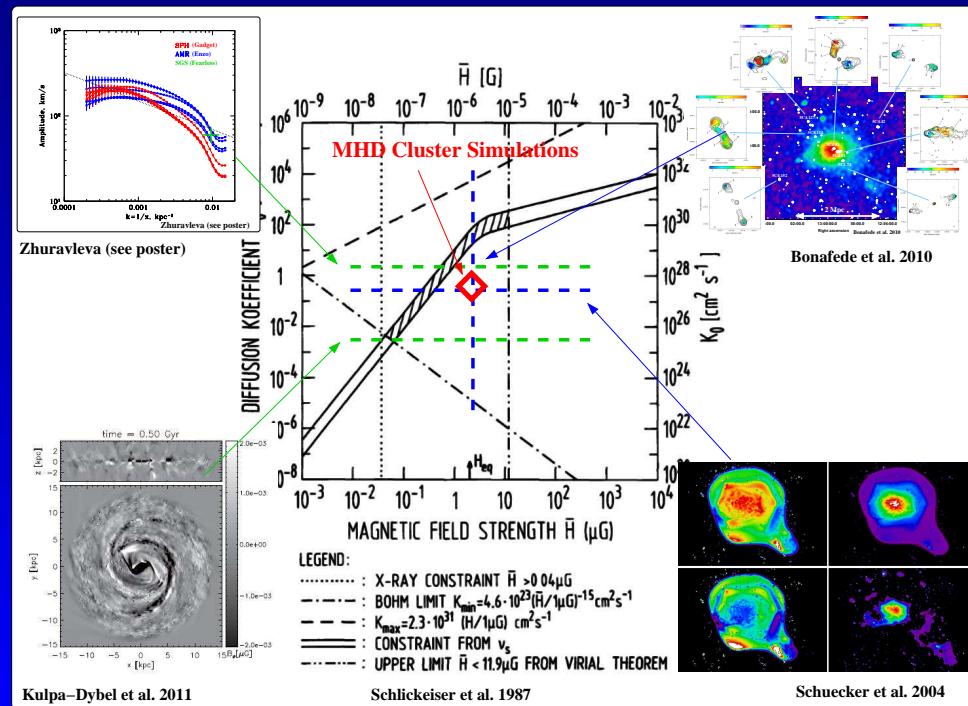


Magnetic Fields, Turbulence and Cosmic Rays in Galaxy Clusters

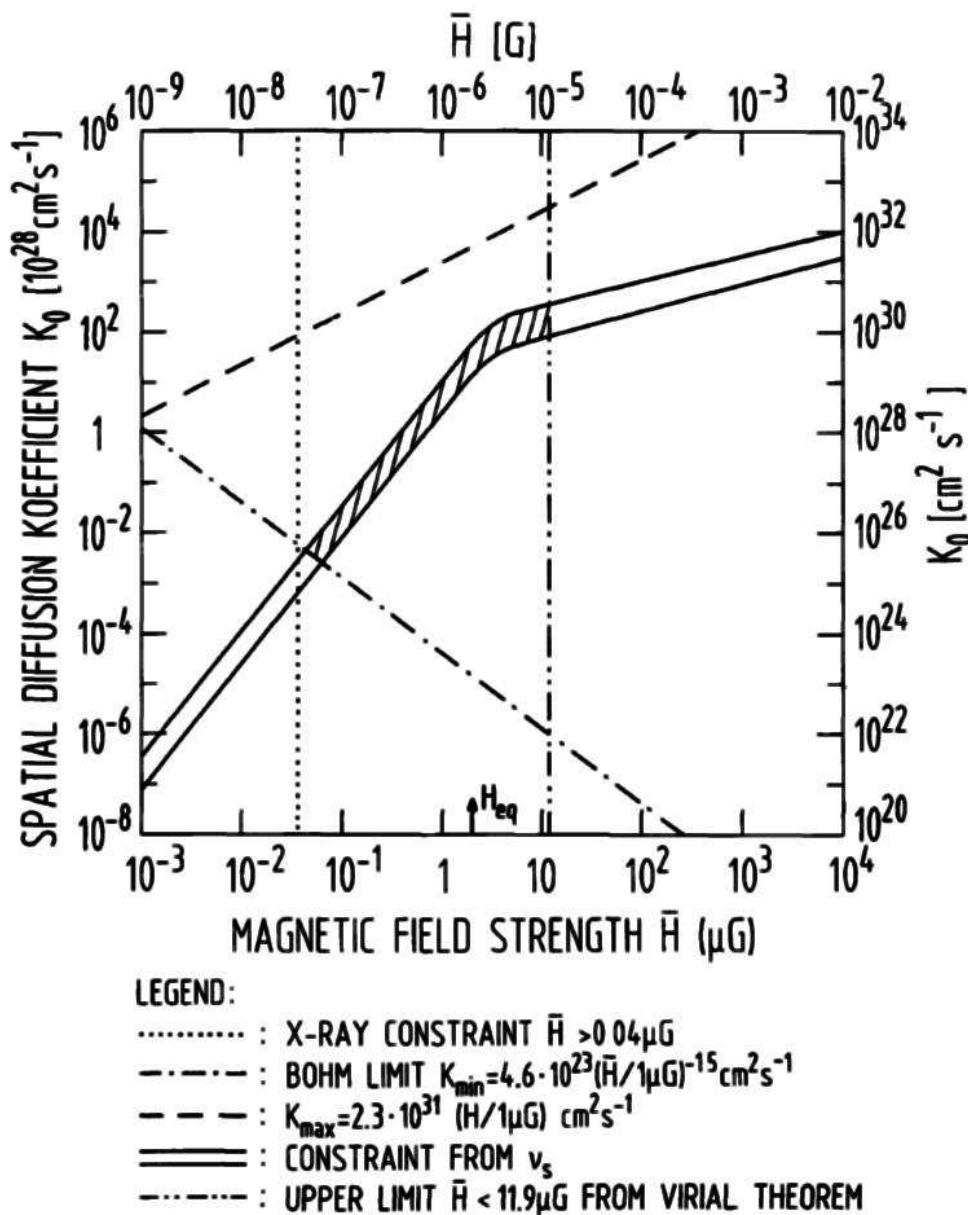
Klaus Dolag^(*)

A.Bonafede, J.Donnert, I. Zhuravleva

(*) Universitäts-Sternwarte München



The Big Picture

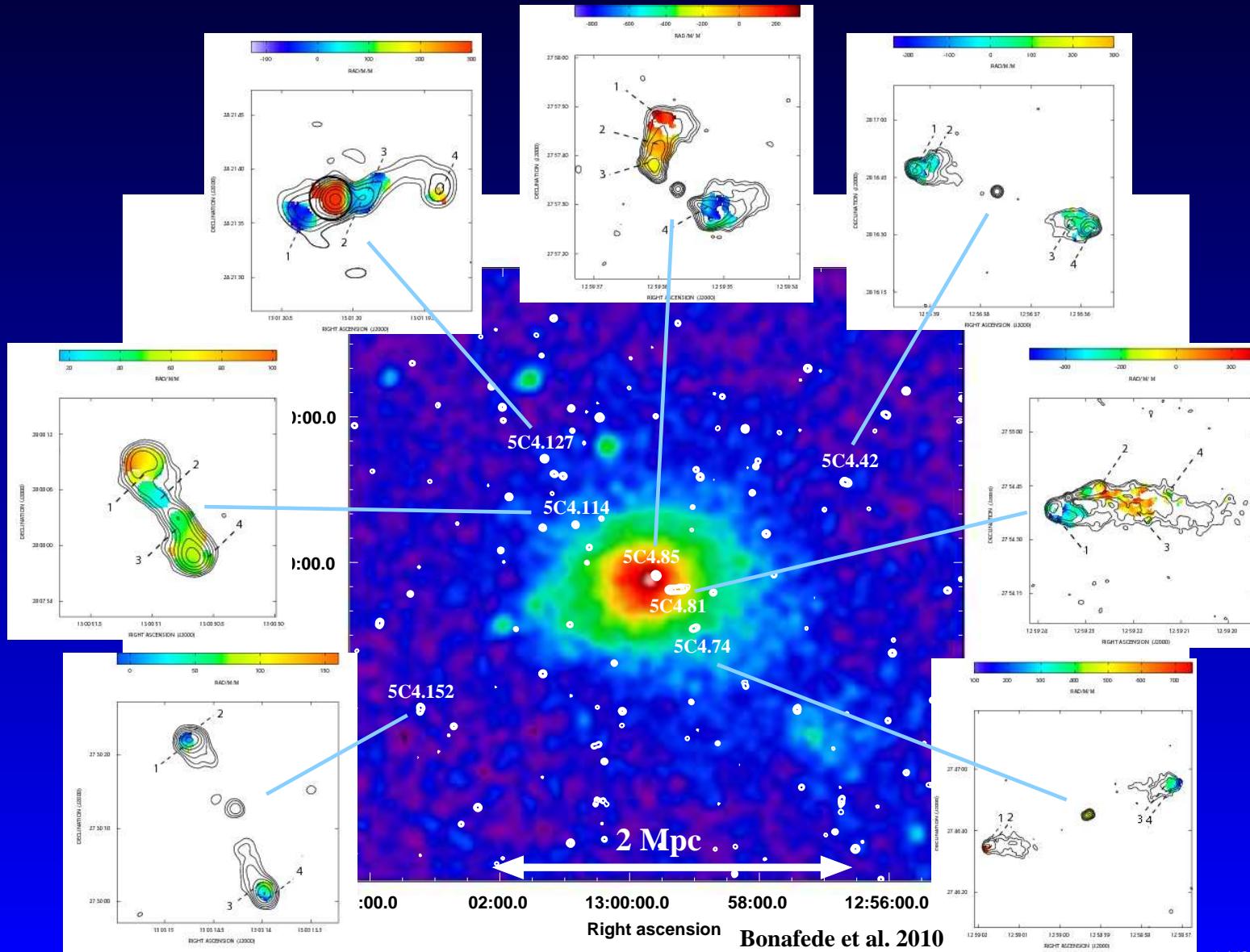


Schlickeiser et al. 1987

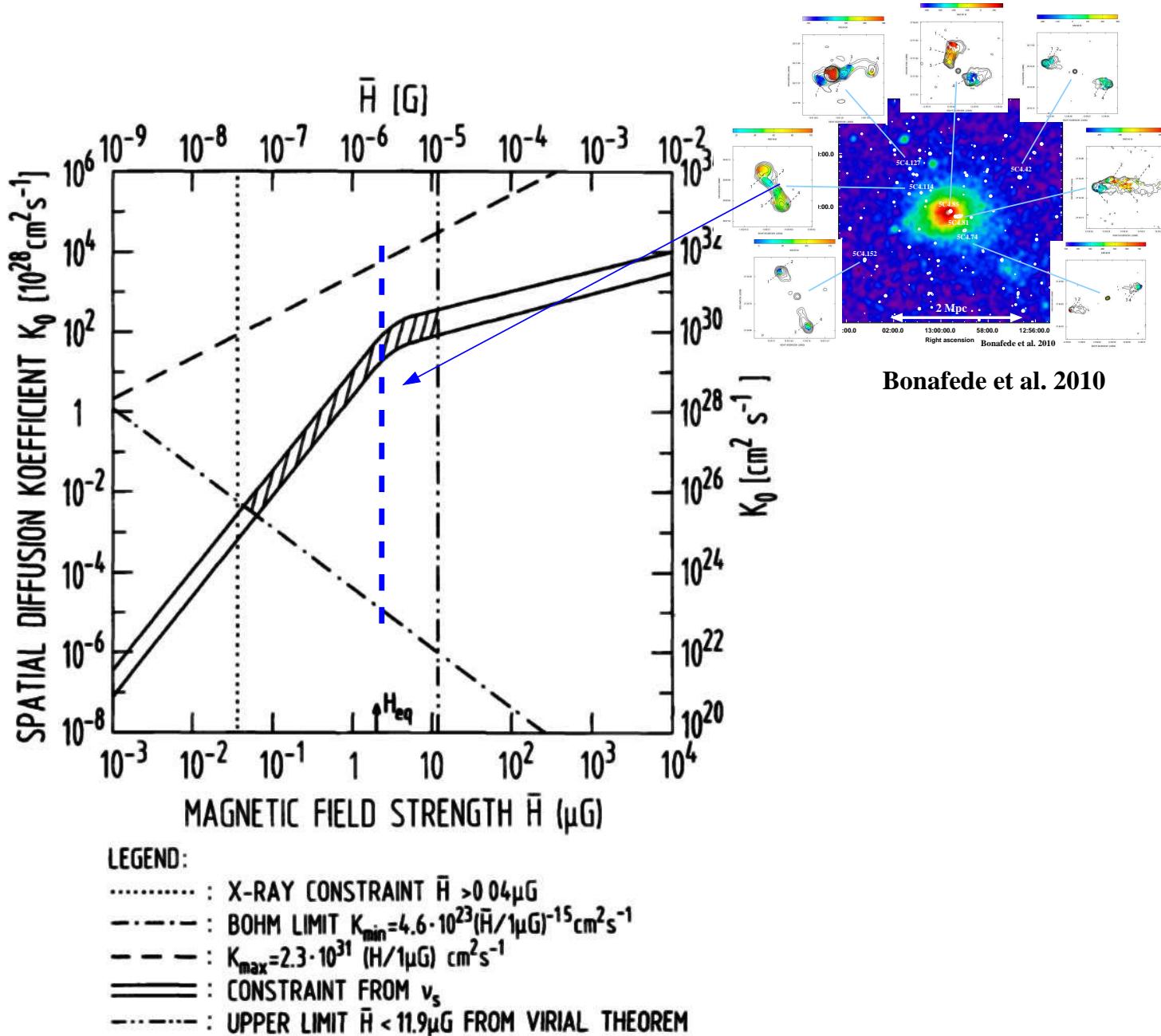
The Big Picture

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

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



The Big Picture

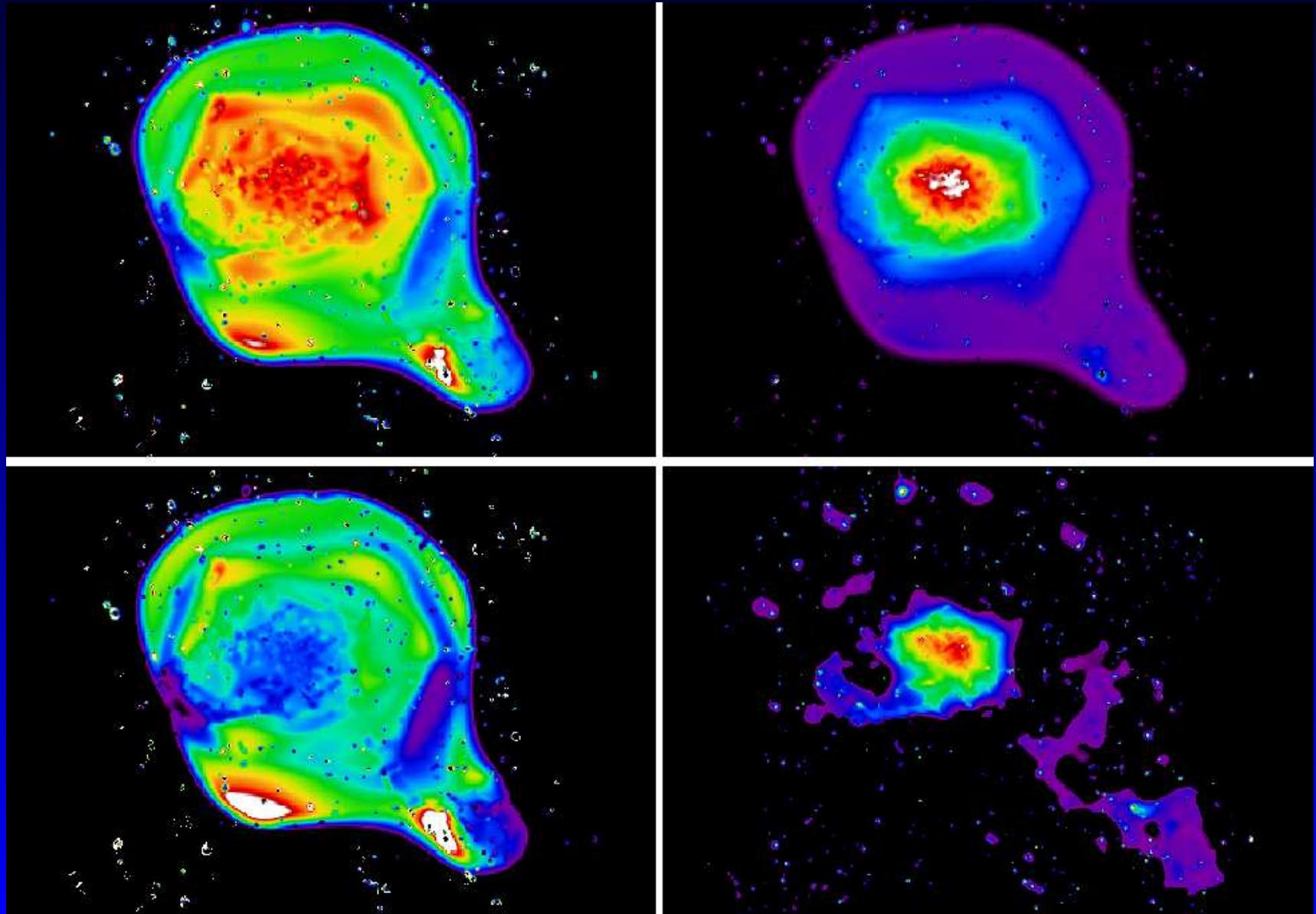


Schlickeiser et al. 1987

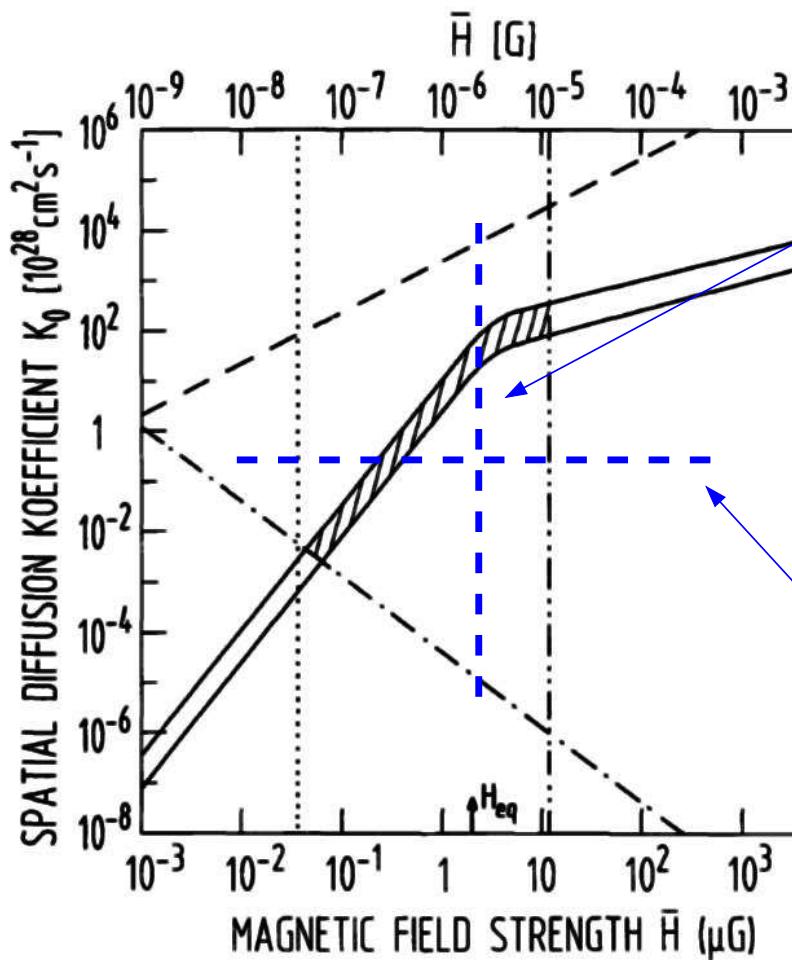
The Big Picture

Observed turbulence in clusters: (Schuecker et al. 2004, ...)

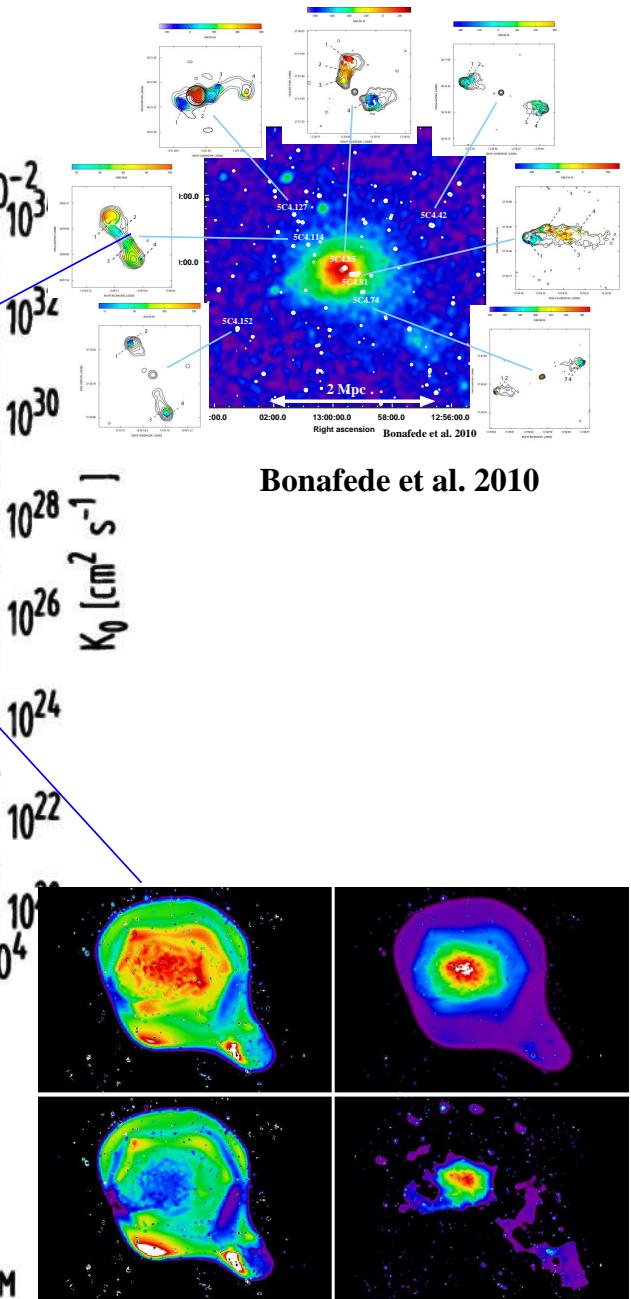
$$D_{\text{diff}} = 0.1 \times v_{\text{turb}} \times \lambda_{\text{turb}} \quad , \quad v_{\text{turb}}(l) \propto \lambda_{\text{turb}}^{(1/3)}$$



The Big Picture



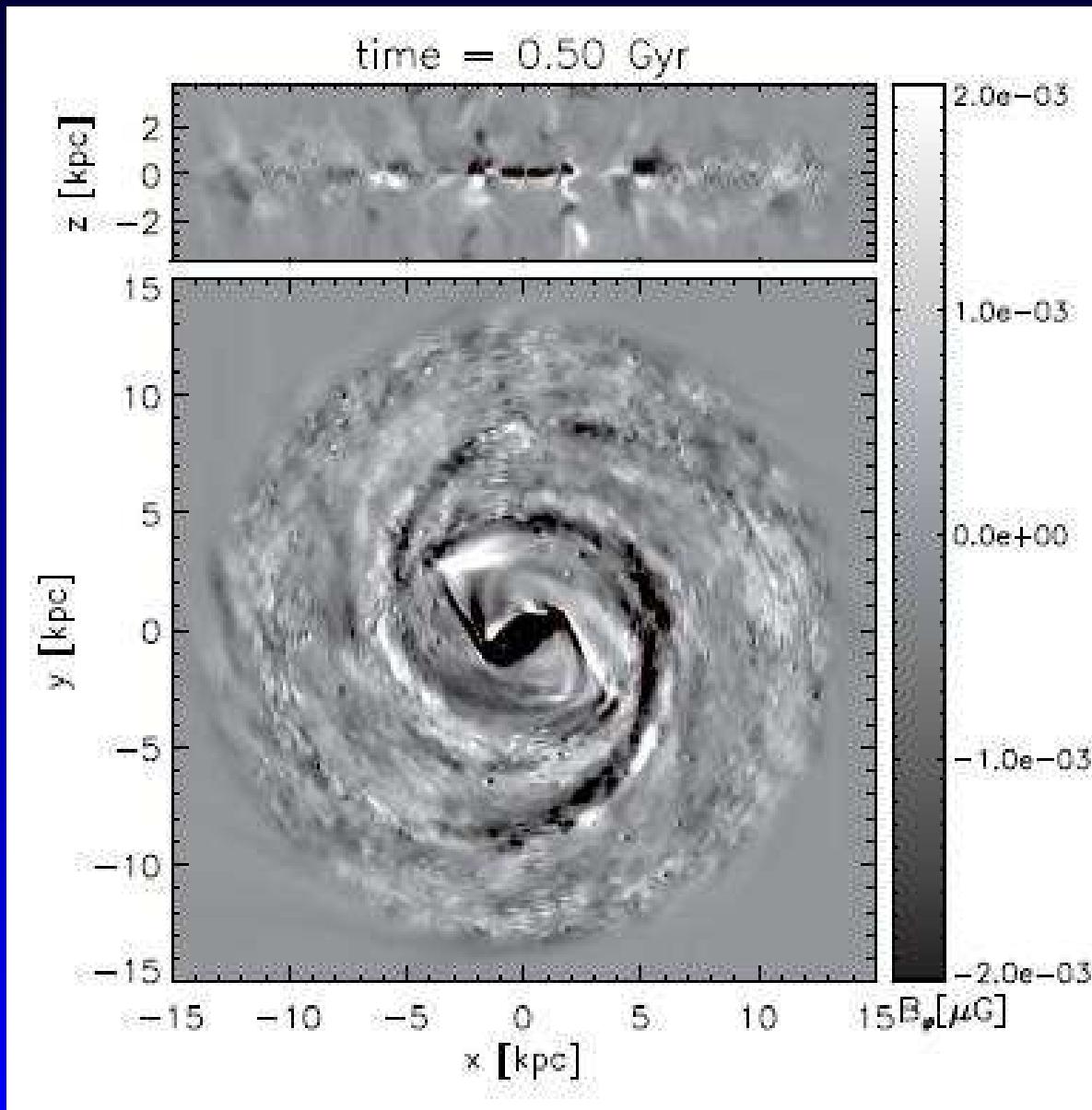
Schlickeiser et al. 1987



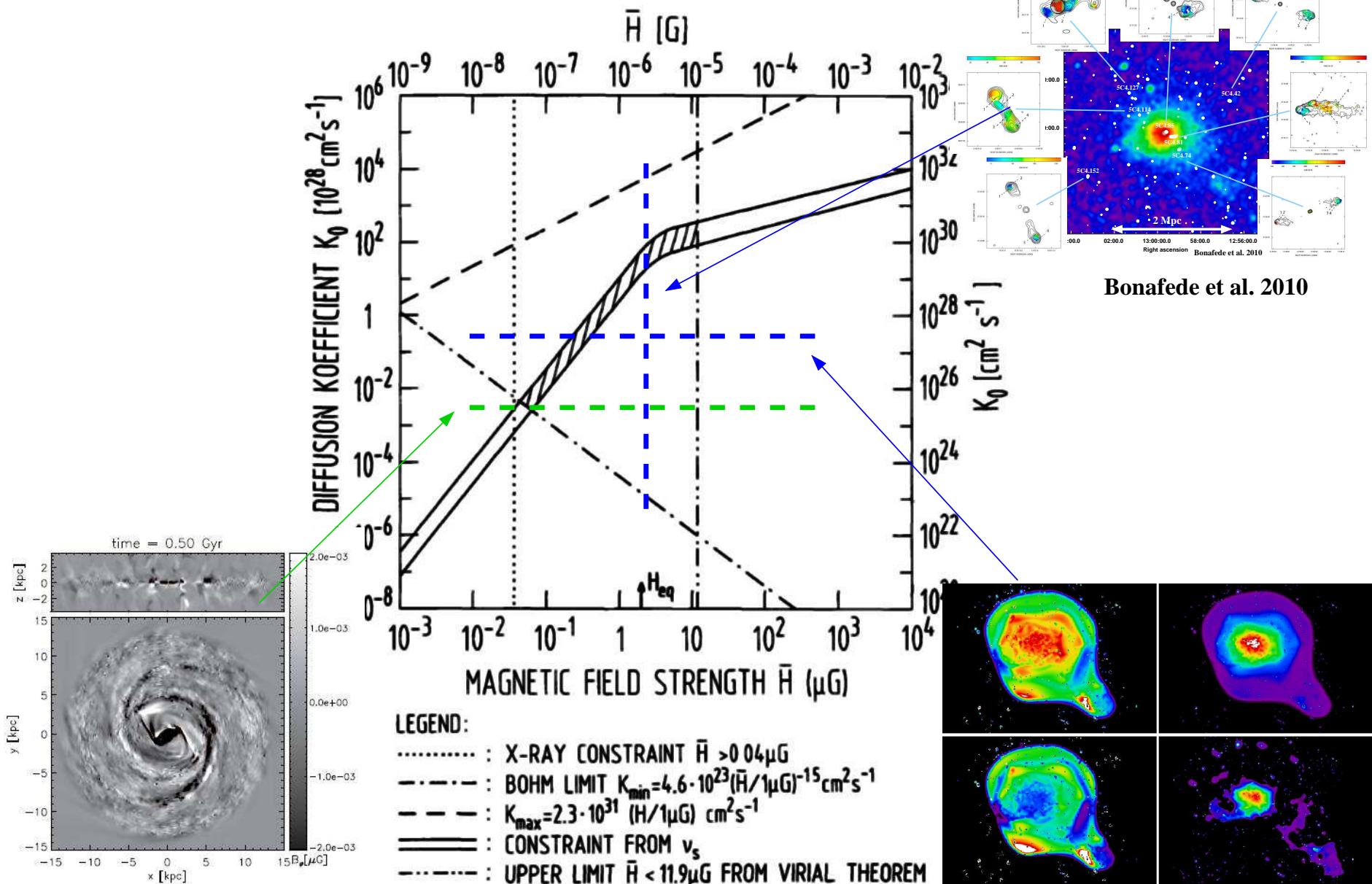
The Big Picture

Cosmic Ray driven Dynamo in Galaxies:

(Lesch & Hanasz et al. 2003, Hanasz et al. 2010, ...)



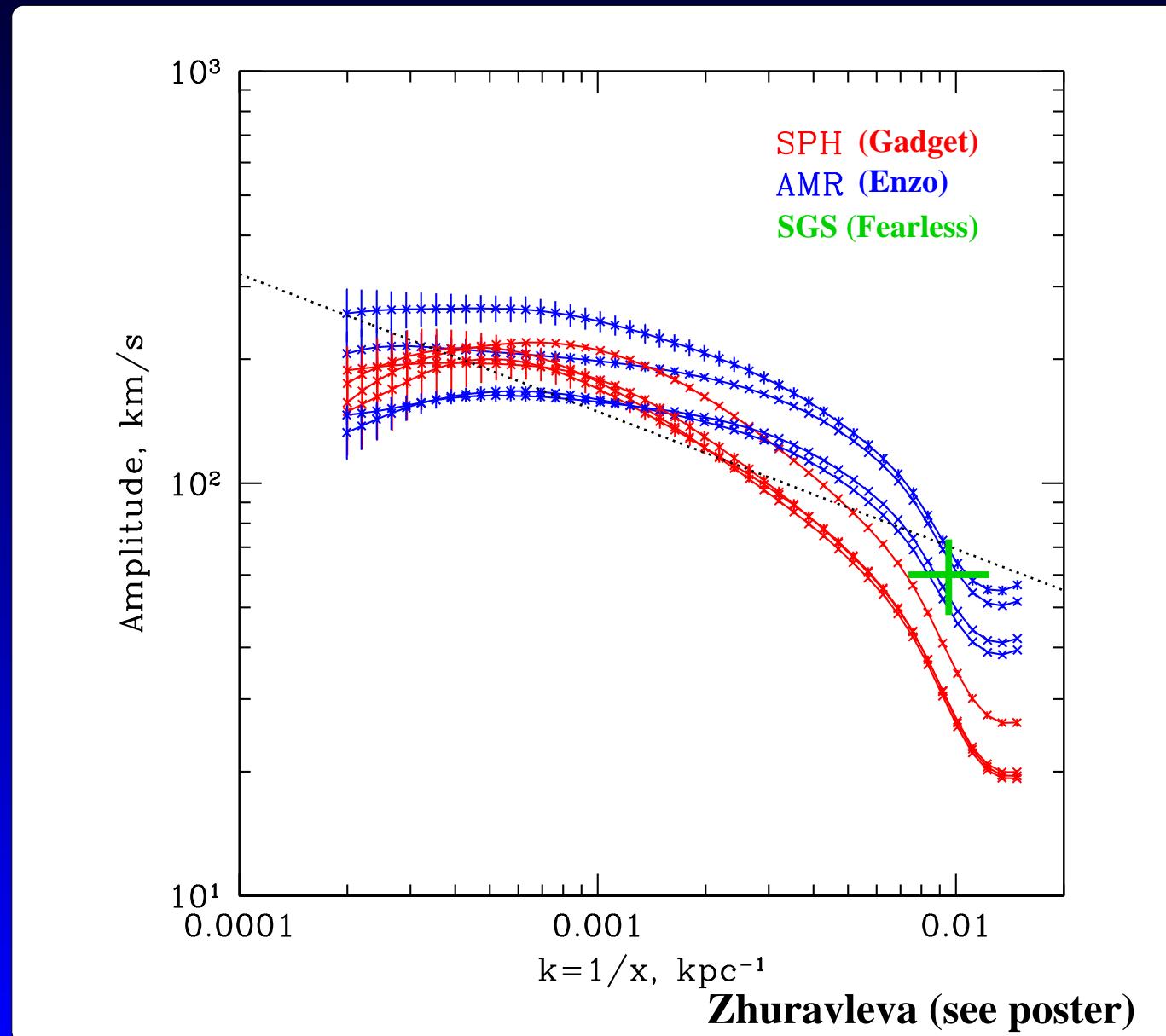
The Big Picture



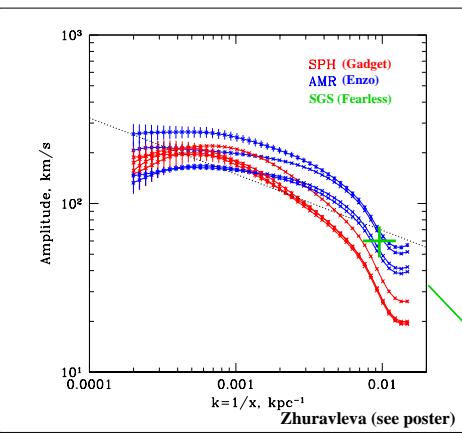
The Big Picture

Simulated turbulence in clusters:

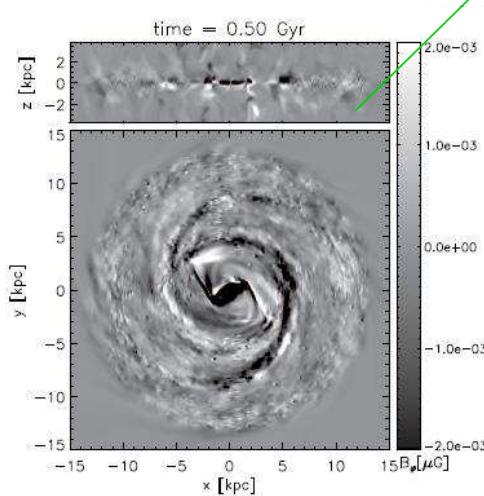
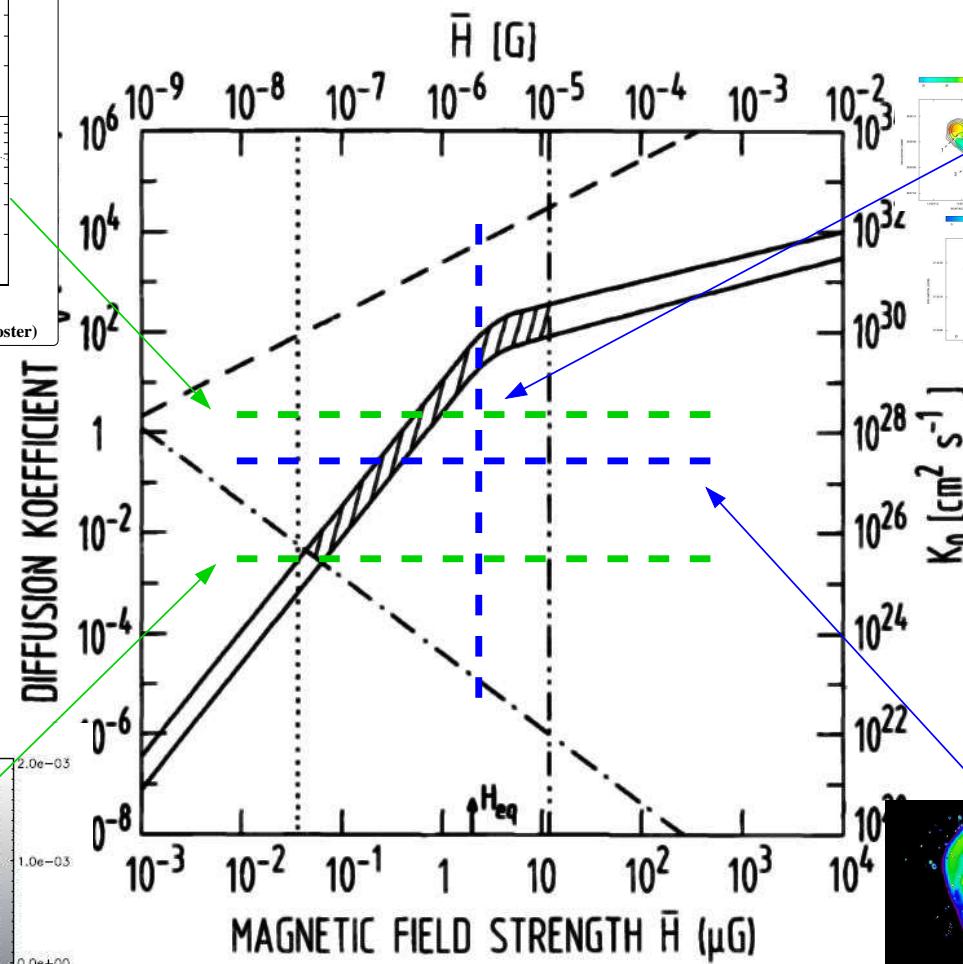
(Dolag et al 2005, Vazza et al 2009, Maier et al 2009, ...)



The Big Picture

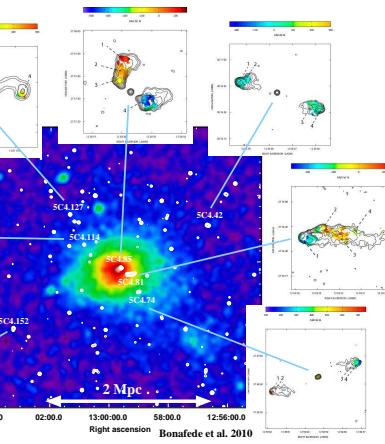


Zhuravleva (see poster)

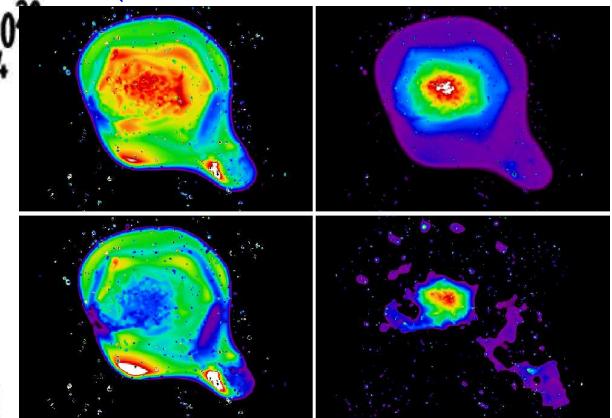


Kulpa-Dybel et al. 2011

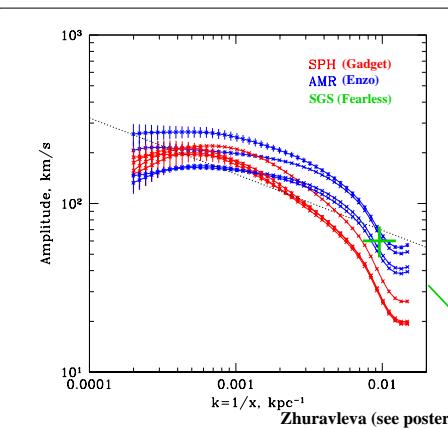
Schlickeiser et al. 1987



Bonafede et al. 2010



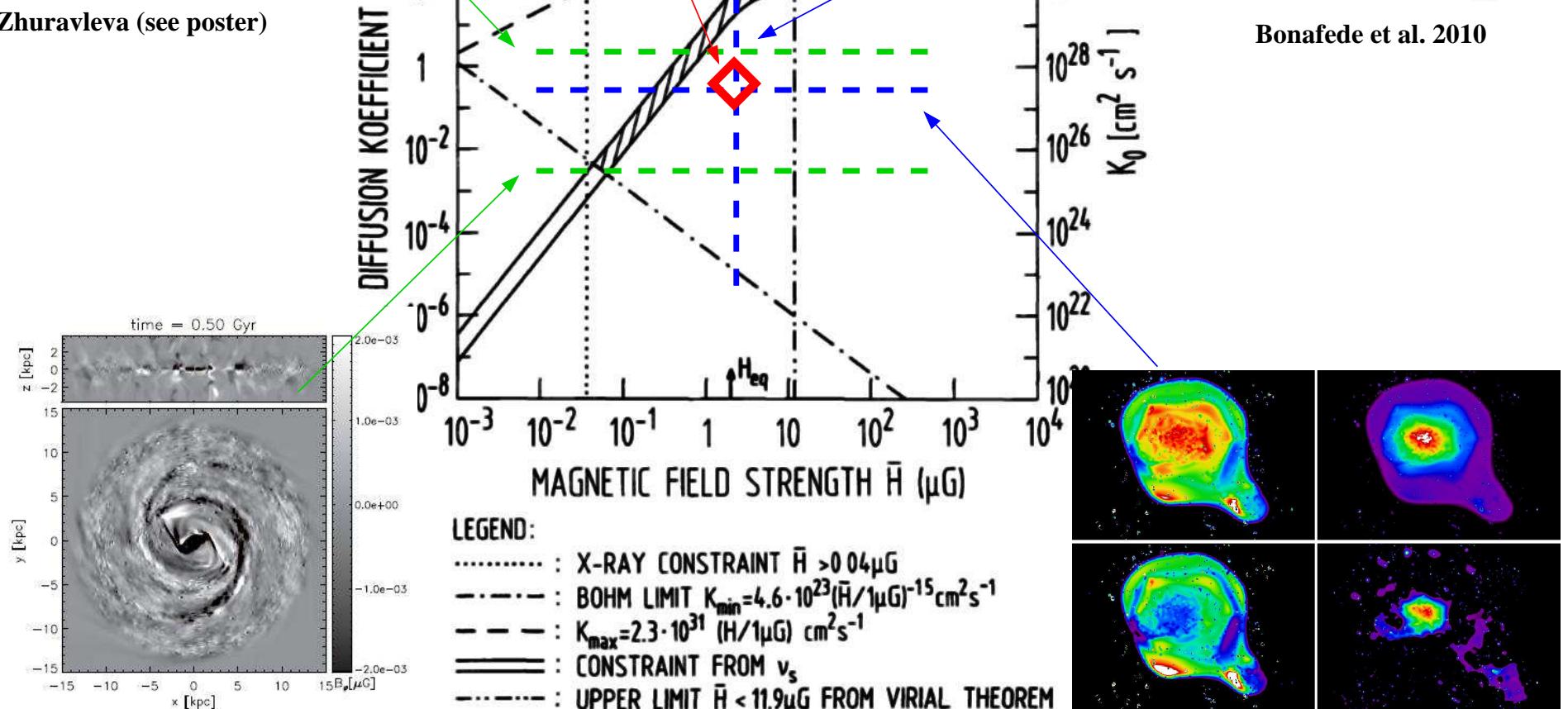
The Big Picture



Zhuravleva (see poster)

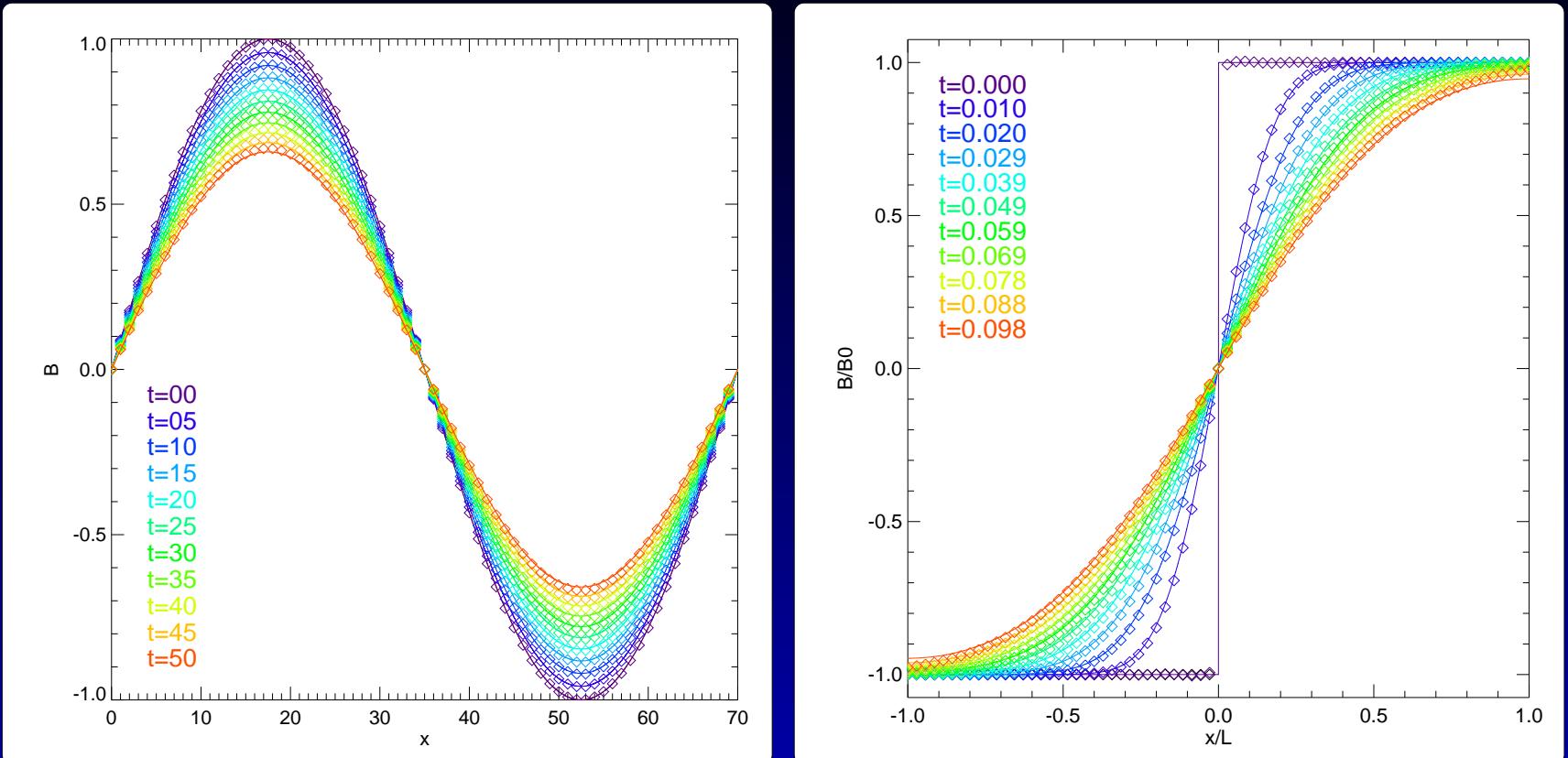
$\bar{H} [\mu\text{G}]$

MHD Cluster Simulations



Kulpa-Dybel et al. 2011

Magnetic diffusion in clusters

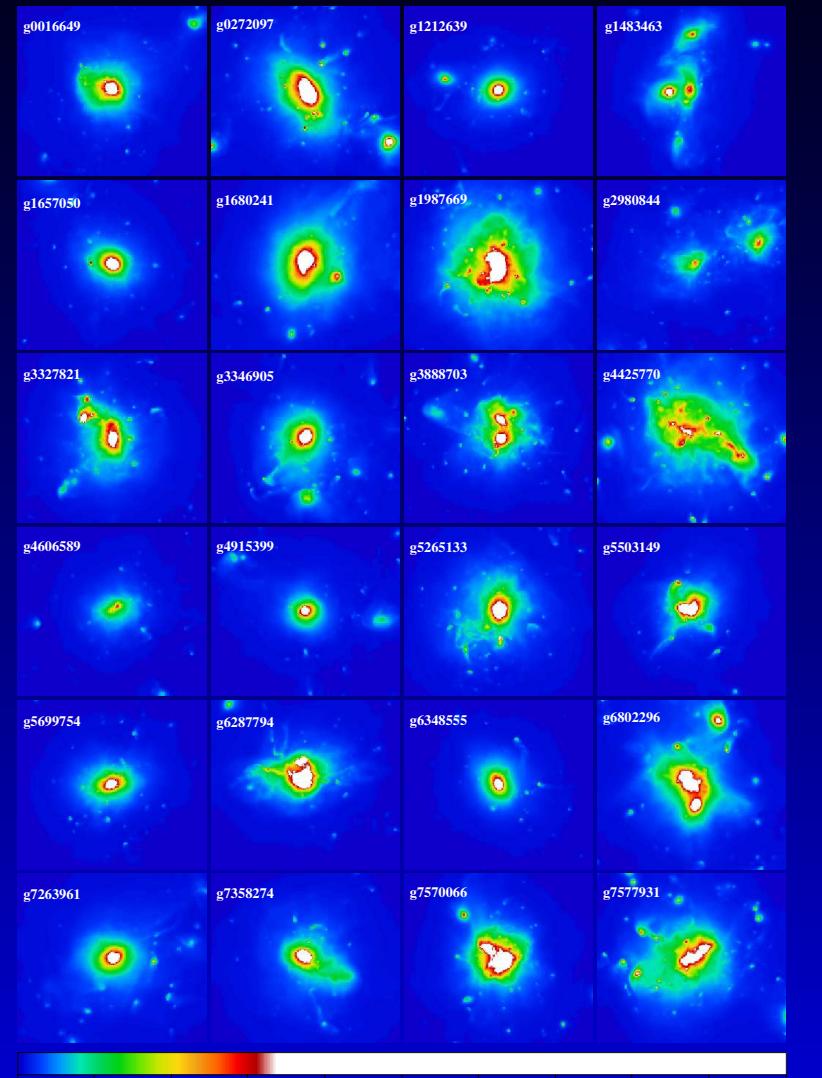
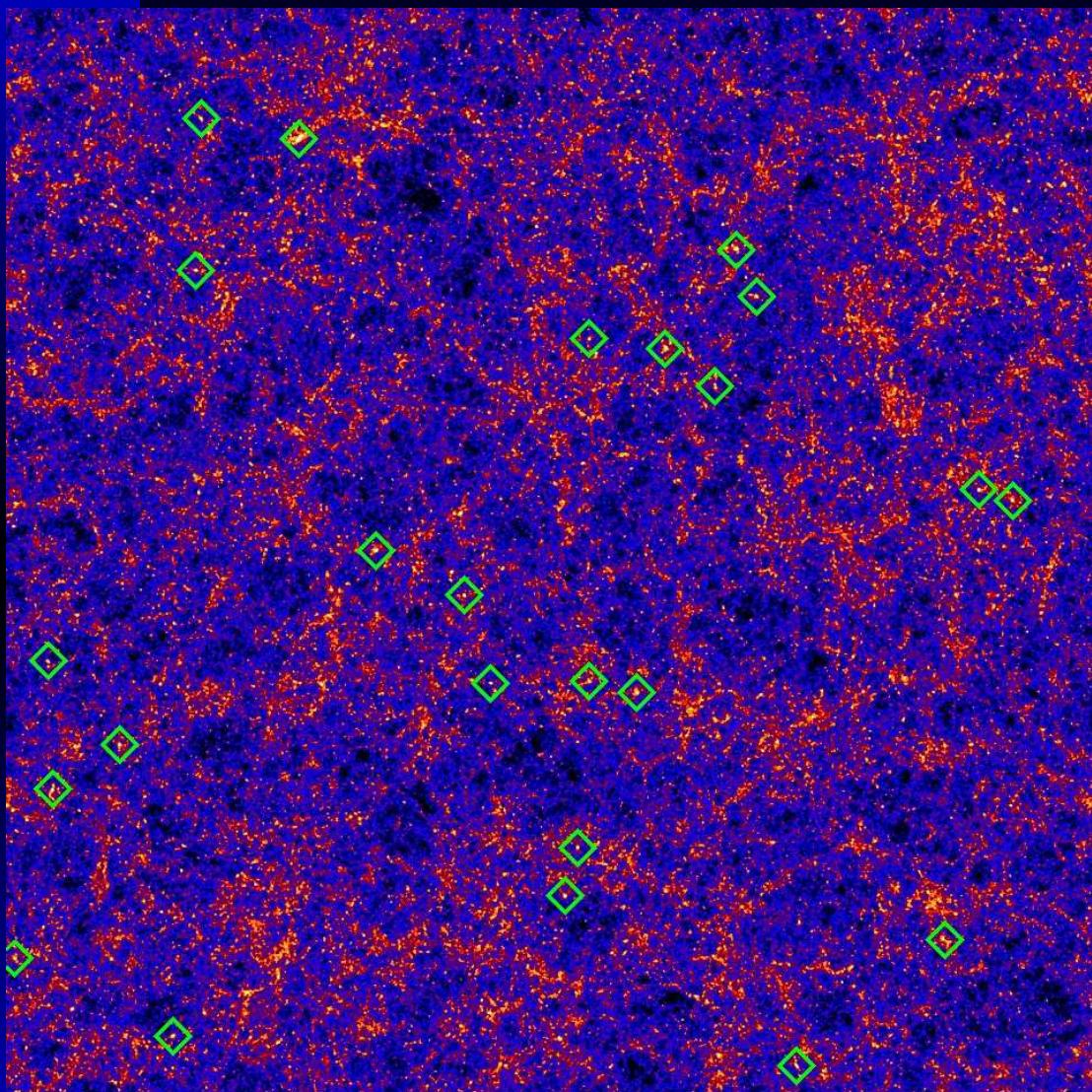


$$\frac{d\vec{B}}{dt} = (\vec{B} \cdot \vec{\nabla})\vec{v} - \vec{B}(\vec{\nabla} \cdot \vec{v}) + \eta \vec{\nabla}^2 \vec{B}$$

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

Bonafede et al. 2011

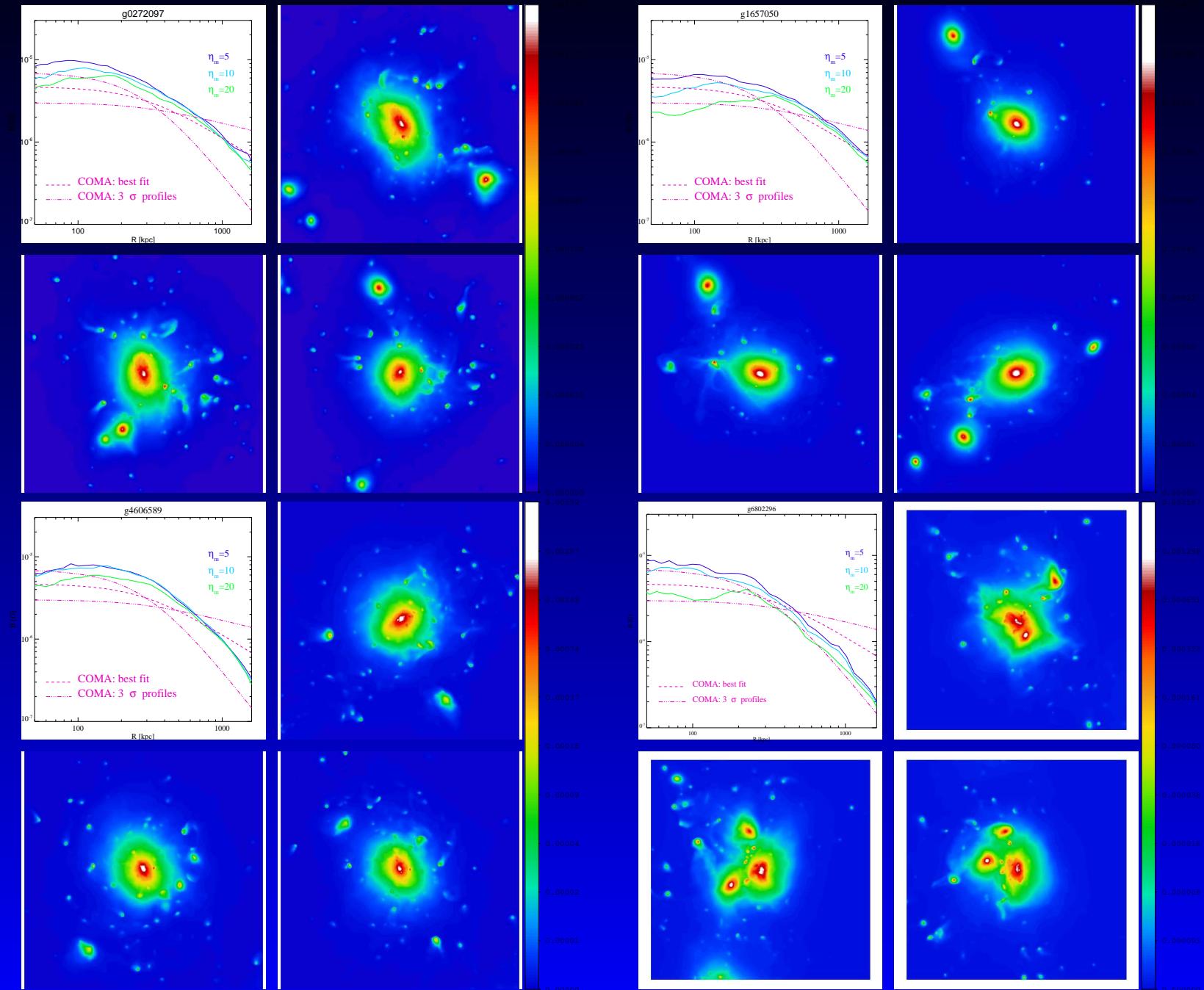
Magnetic diffusion in clusters



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

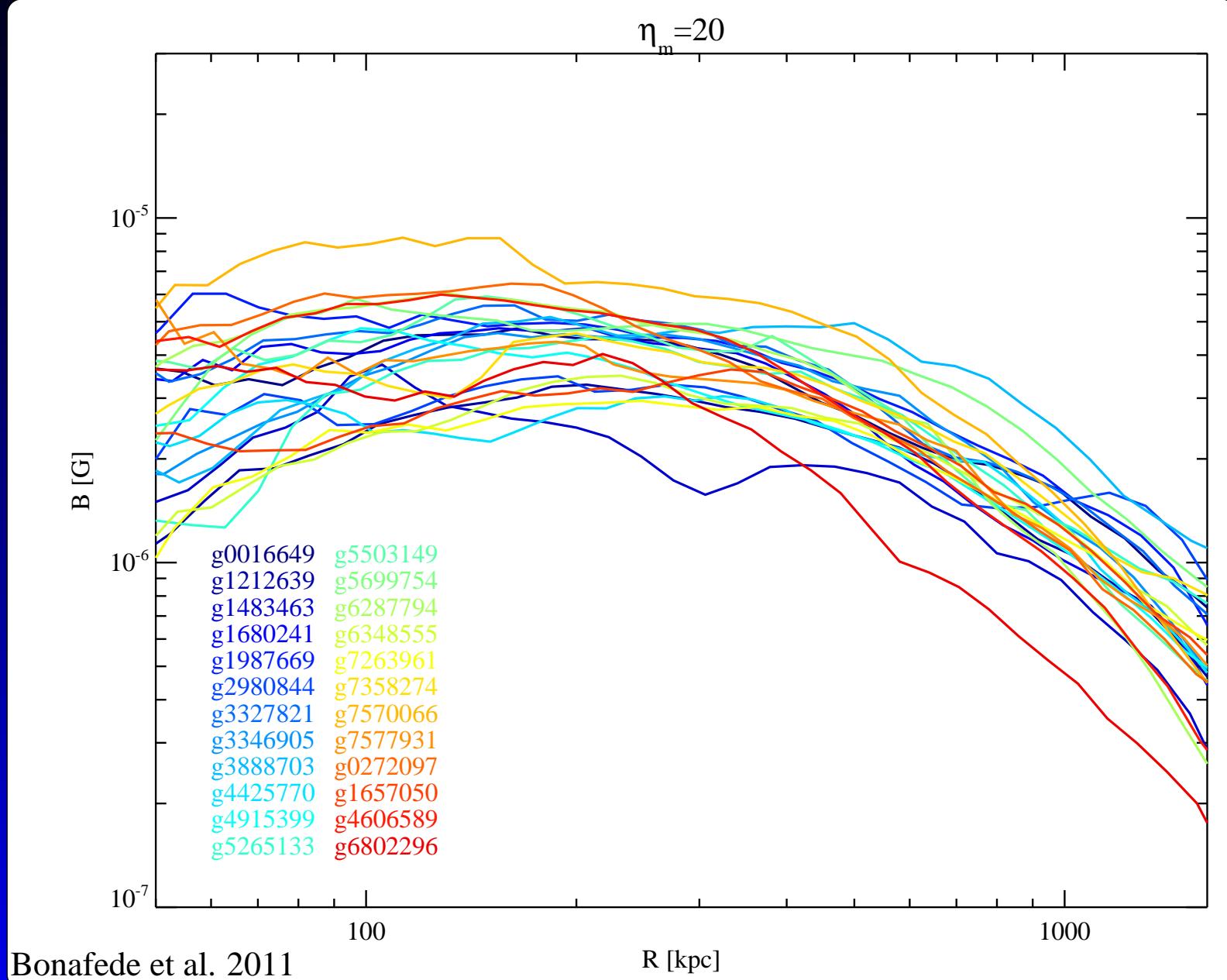
Bonafede et al. 2011

Madgetic diffusion in clusters



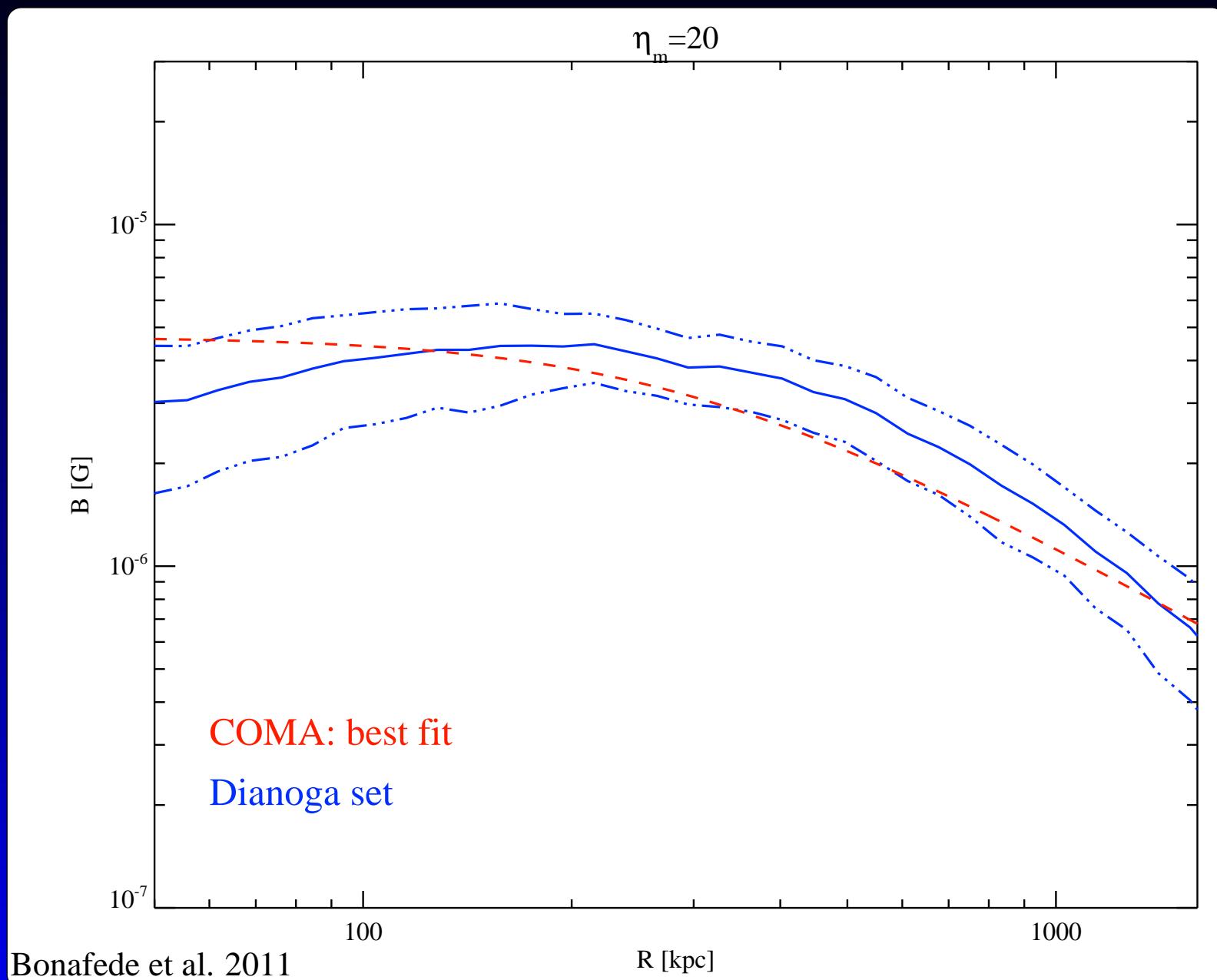
Subset of 4 Coma-like clusters with $\eta = 1.5, 3, 6 \times 10^{27} \text{ cm}^2/\text{s}$. (Bonafede et al. 2011)

Madgetic diffusion in clusters



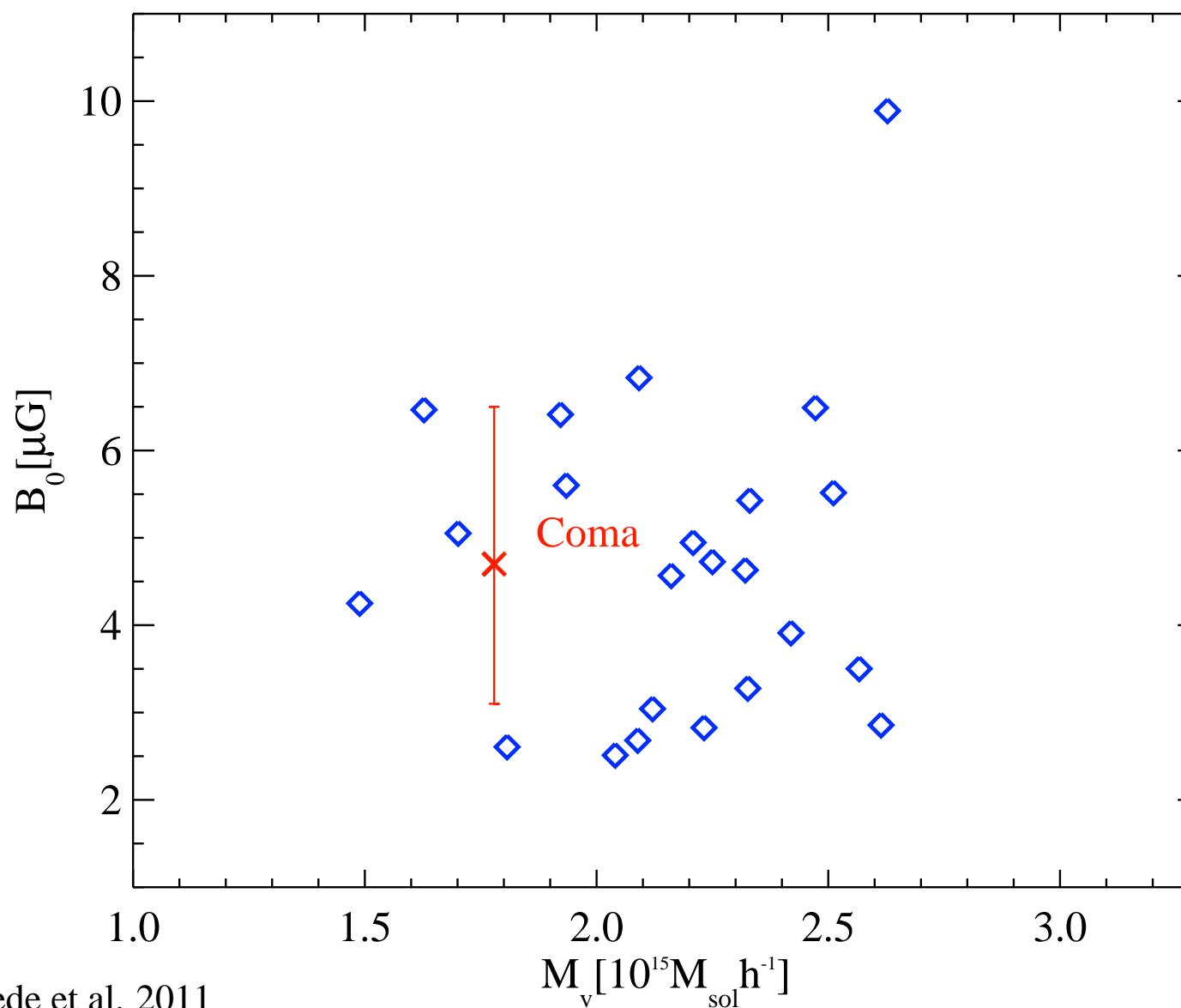
⇒ Profiles of 24 **Coma-like** galaxy clusters

Magnetic diffusion in clusters



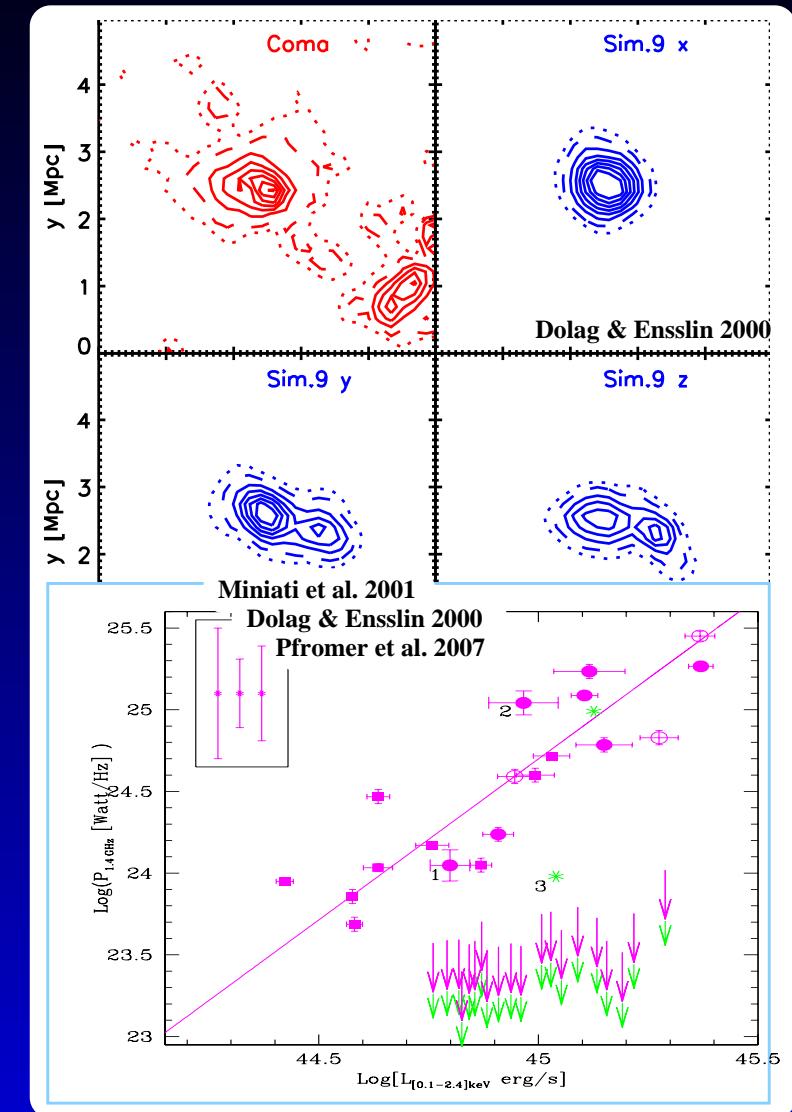
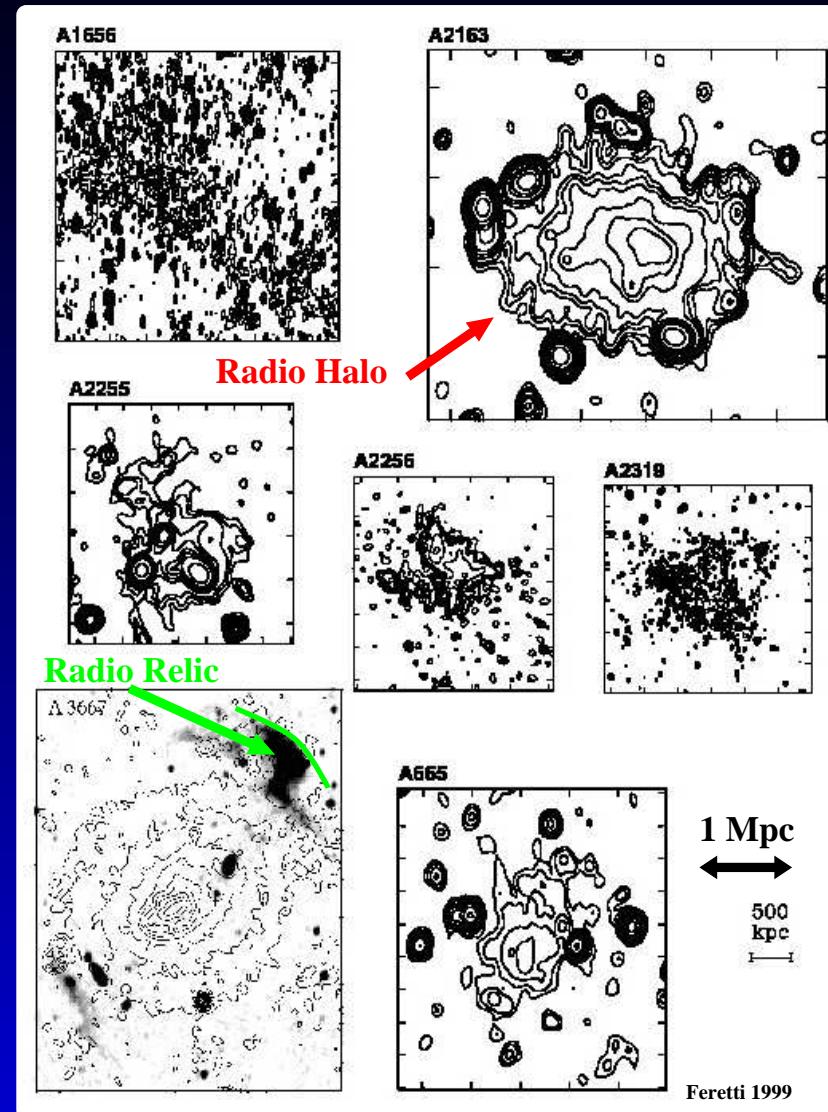
⇒ Profiles of 24 Coma-like galaxy clusters

Magnetic diffusion in clusters



⇒ Central B of 24 Coma-like galaxy clusters

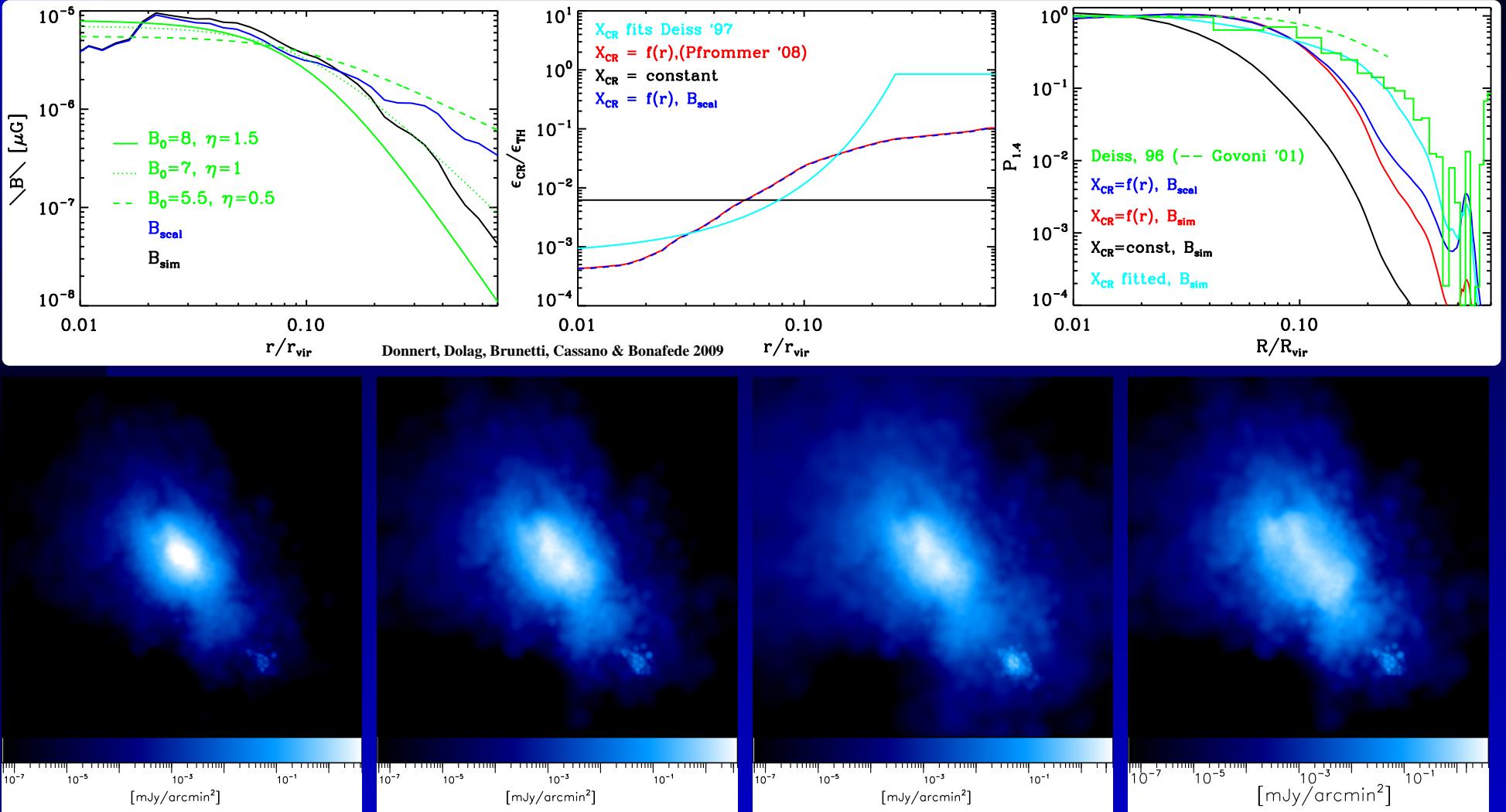
Radio emission of cluster



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

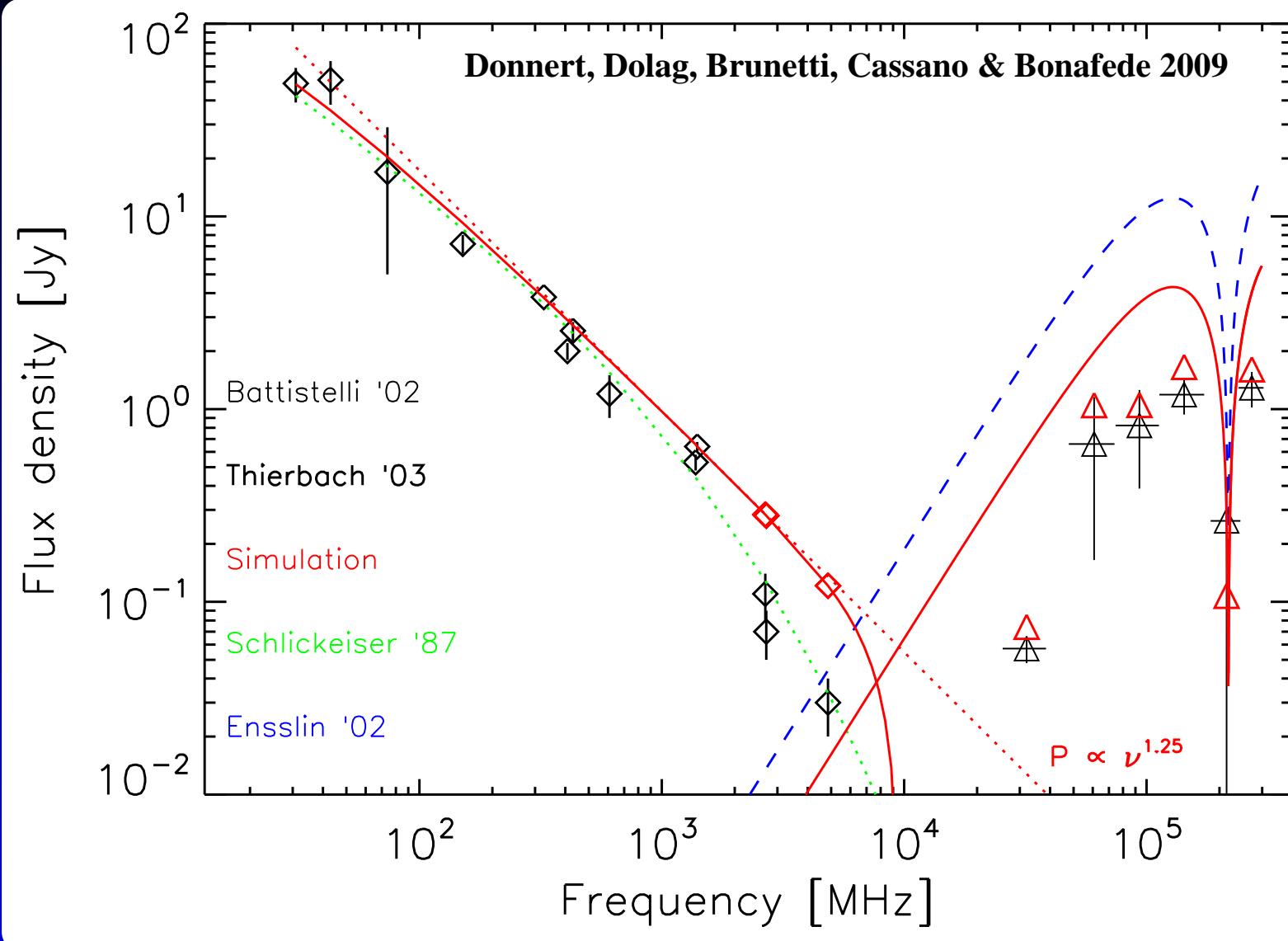
- **Radio halo:** Turbulence, shocks, secondary ?
- **Relics:** Primary from shocks or compressed radio plasma ?

Radio emission of cluster



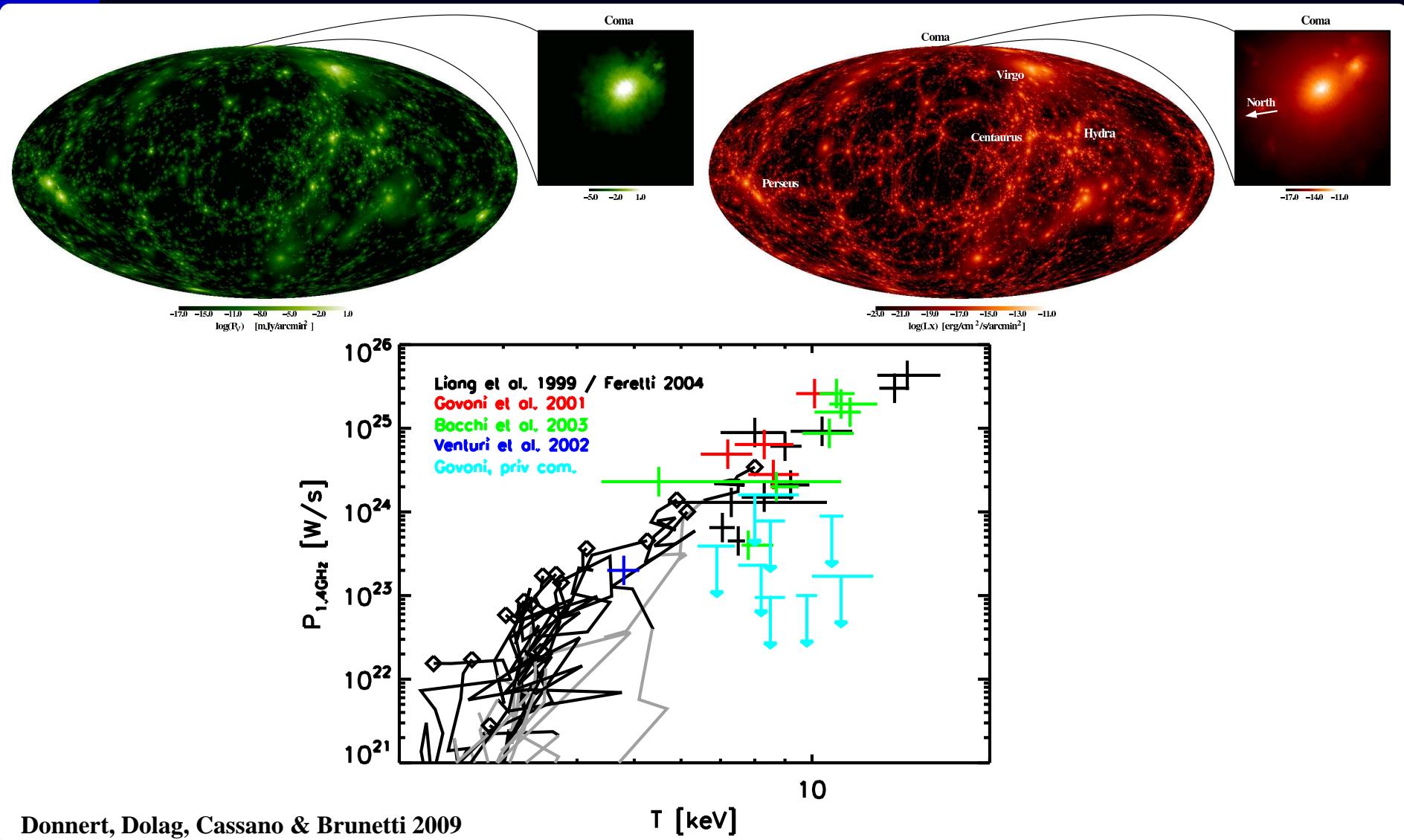
Hadronic interactions of CR- p^+ ($>\text{GeV}$) with ICM- p^+ will produce pions. The charged pions decay into secondary electrons producing synchrotron emission.
 ⇒ Radial energy distribution / emission disfavors model !

Radio emission of cluster



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^-)

Radio emission of cluster



Evolution track parallel to correlation

- ⇒ Strong evolution in CR- e^- needed
- ⇒ Secondaries from CR- p^+ disfavored
- ⇒ Need to investigate turbulent re-acceleration

Radio emission of cluster

⇒ Solve Fokker-Planck equation for CRe population

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

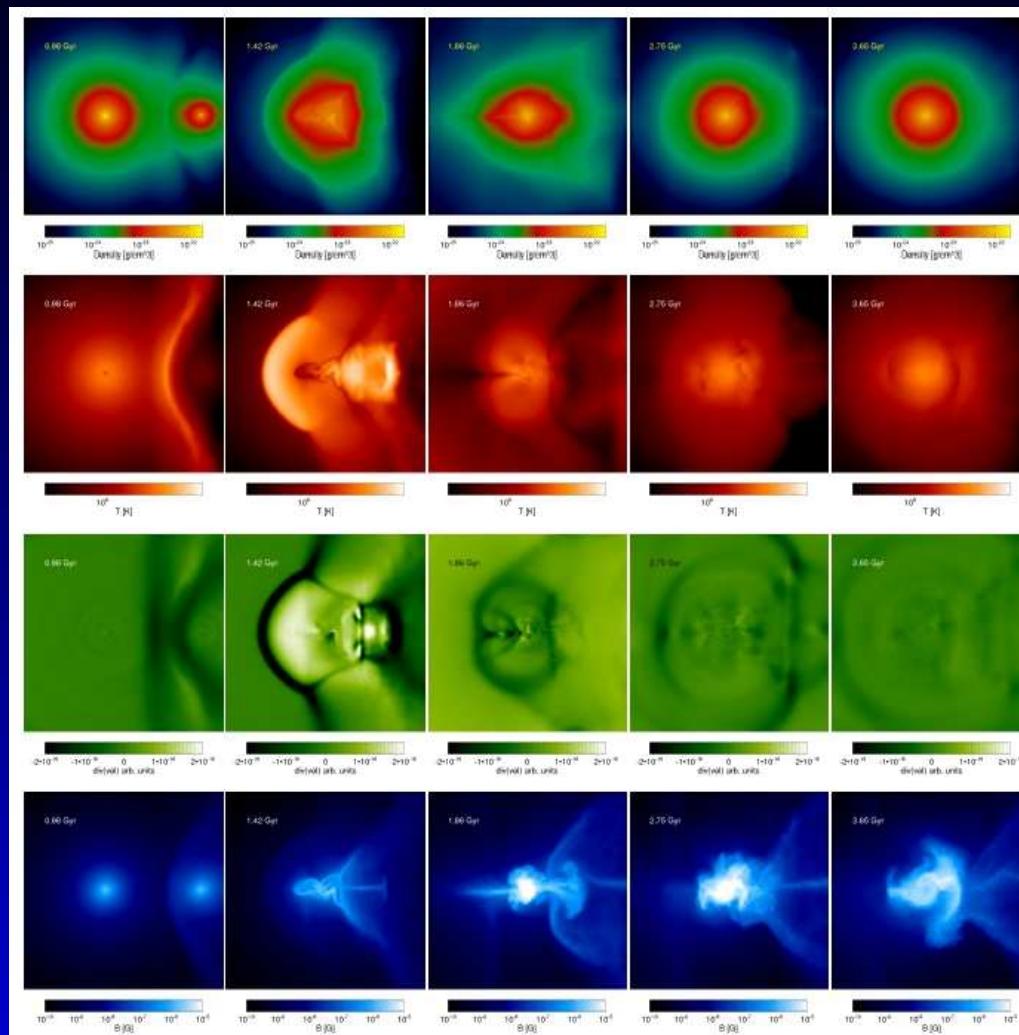
- 10% turbulent energy in fast mhd modes and reacceleration by those only
- Momentum Diffusion Coefficient

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

- cooling with inverse compton, synchrotron and bremsstrahlung
- See also Cassano & Brunetti 05, Brunetti & Lazarian 2007

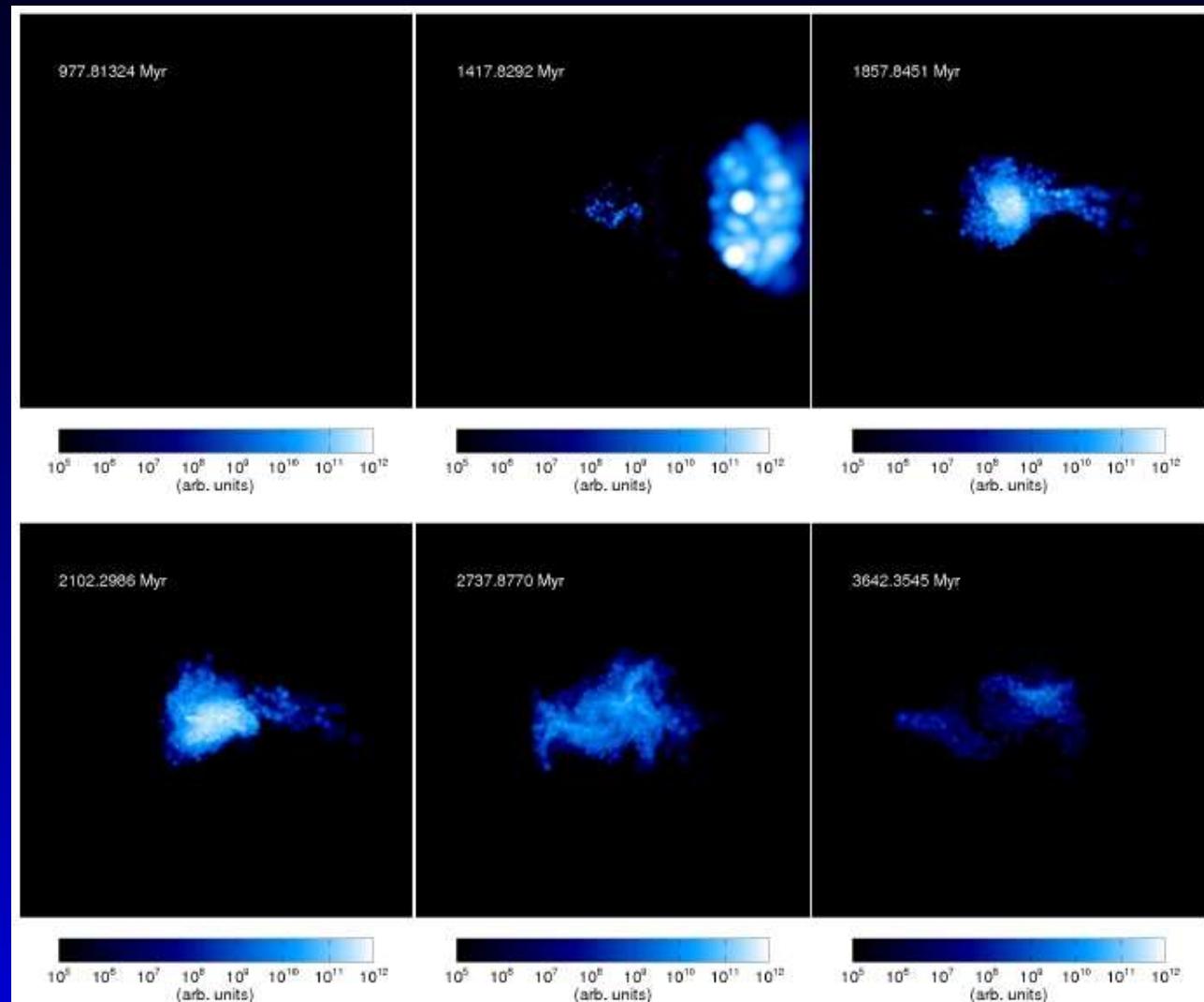
Donnert et al. 2011

Radio emission of cluster



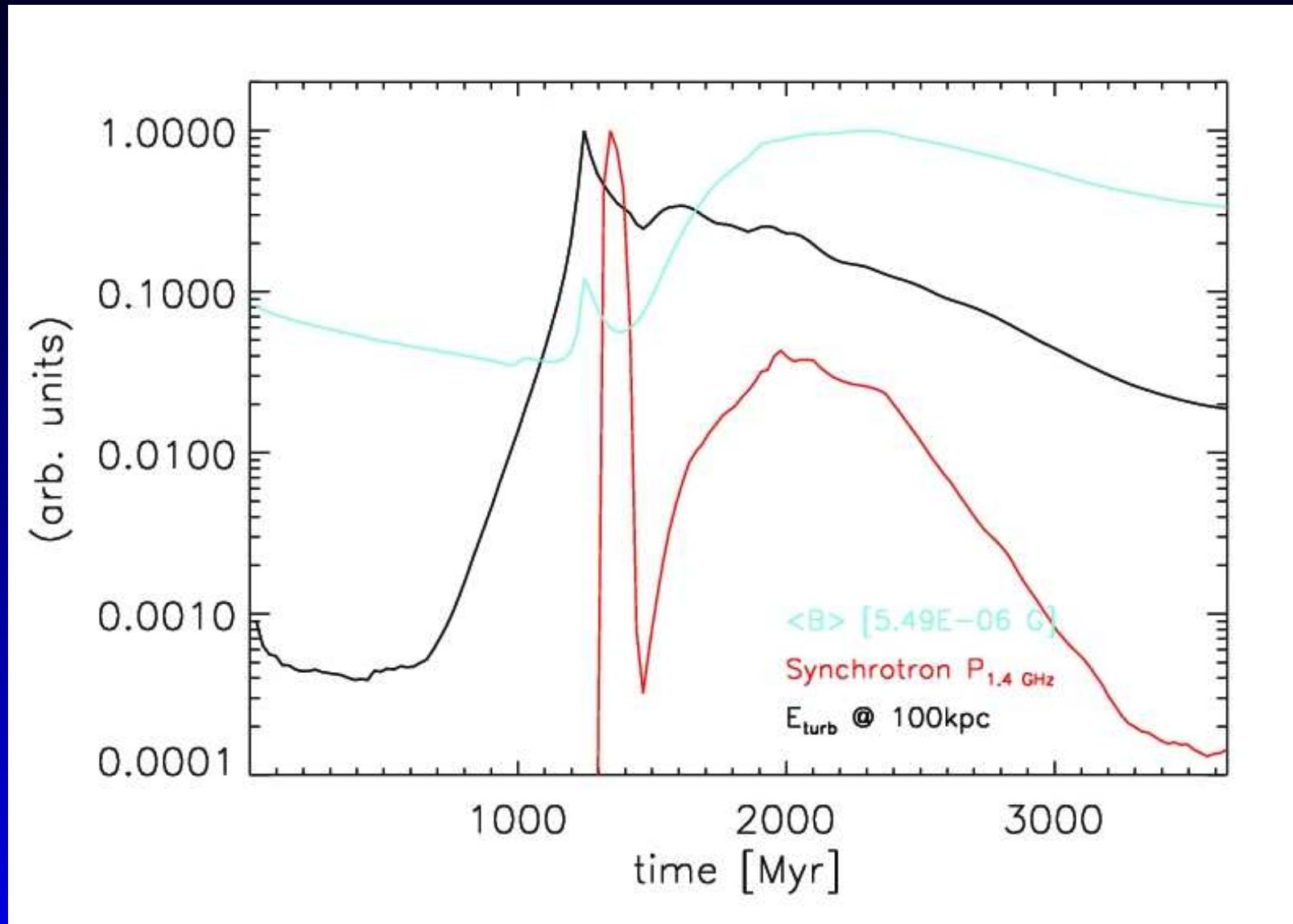
Idealized 1:4 merger, solving Fokker-Planck equation for all particles. (2×128^3). (Donnert et al. 2011)

Radio emission of cluster



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

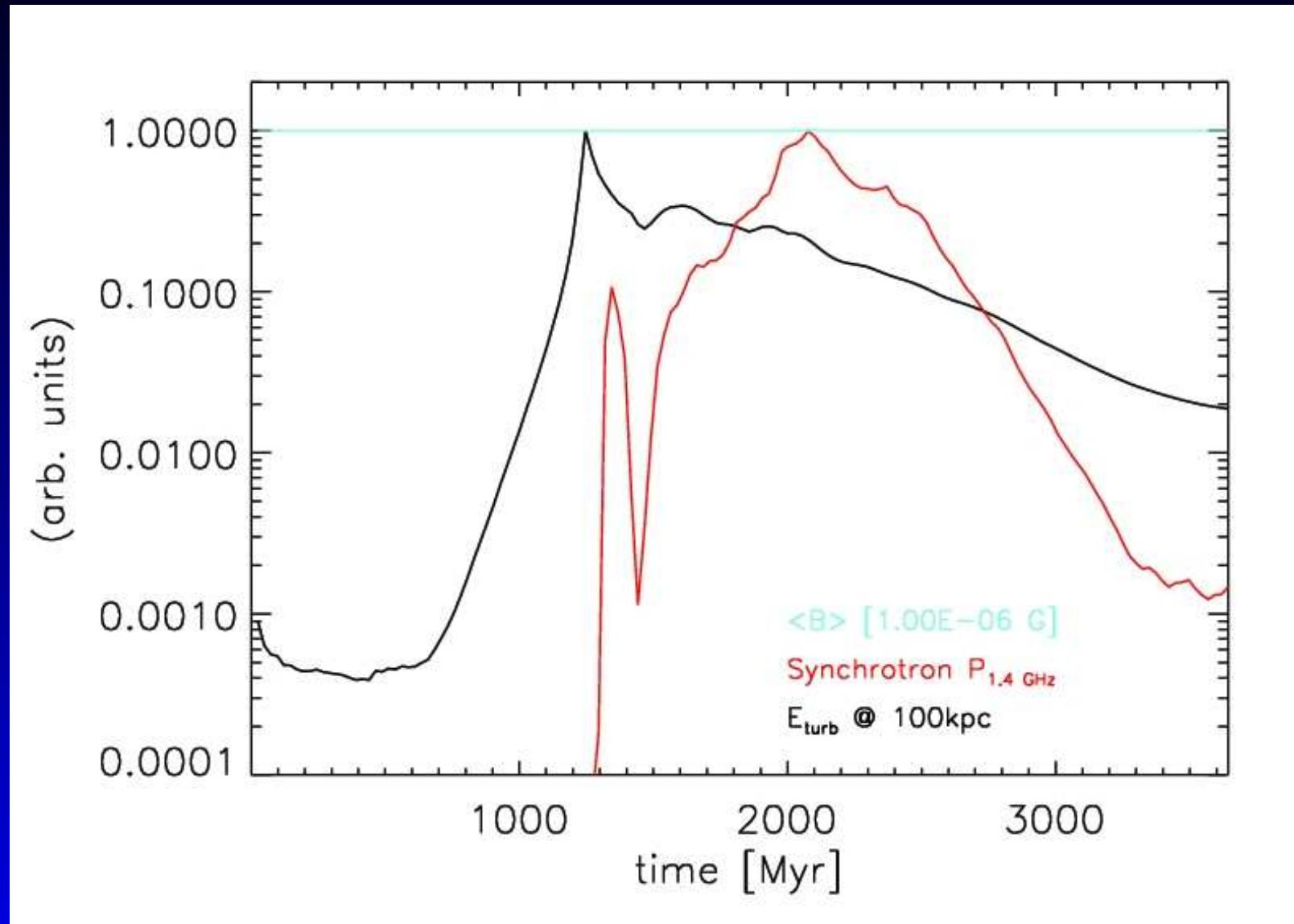
Radio emission of cluster



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

Donnert et al. 2011

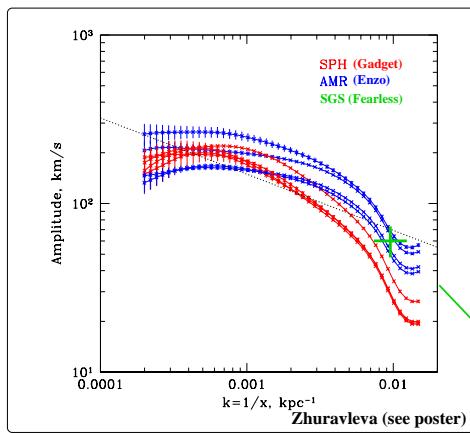
Radio emission of cluster



Evolution of $P_{1.4}$ (red) for constant B .

Donnert et al. 2011

Conclusions

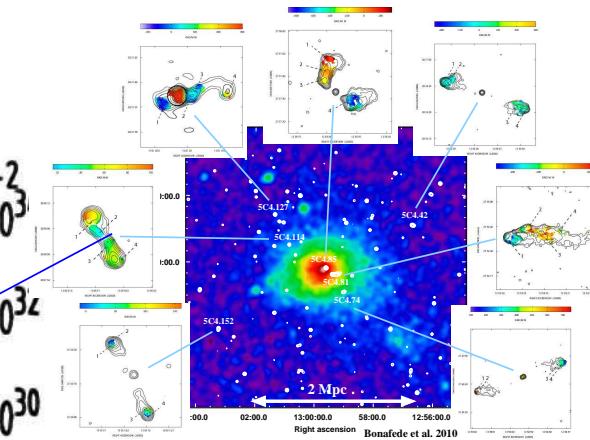


Zhuravleva (see poster)

$\bar{H} [\mu\text{G}]$

MHD Cluster Simulations

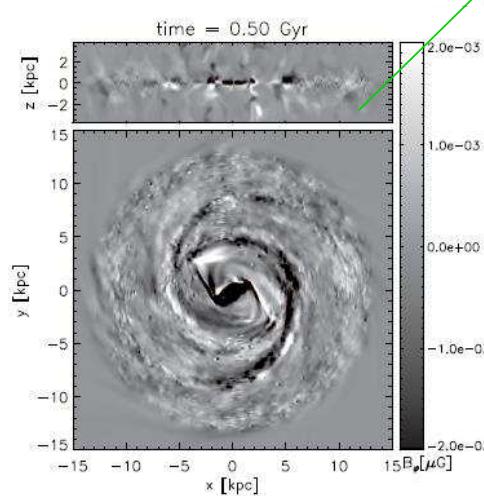
DIFFUSION KOEFFICIENT



Bonafede et al. 2010

$K_0 [\text{cm}^2 \text{s}^{-1}]$

MAGNETIC FIELD STRENGTH $\bar{H} (\mu\text{G})$



LEGEND:

- : X-RAY CONSTRAINT $\bar{H} > 0.04 \mu\text{G}$
- : BOHM LIMIT $K_{\min} = 4.6 \cdot 10^{23} (\bar{H}/1\mu\text{G})^{-15} \text{ cm}^2 \text{s}^{-1}$
- - - : $K_{\max} = 2.3 \cdot 10^{31} (\bar{H}/1\mu\text{G}) \text{ cm}^2 \text{s}^{-1}$
- : CONSTRAINT FROM v_s
- : UPPER LIMIT $\bar{H} < 11.9 \mu\text{G}$ FROM VIRIAL THEOREM

Kulpa-Dybel et al. 2011

Schlickeiser et al. 1987

Schuecker et al. 2004

Conclusions

