Lecture IV
MHD simulations Galaxis/Clusters

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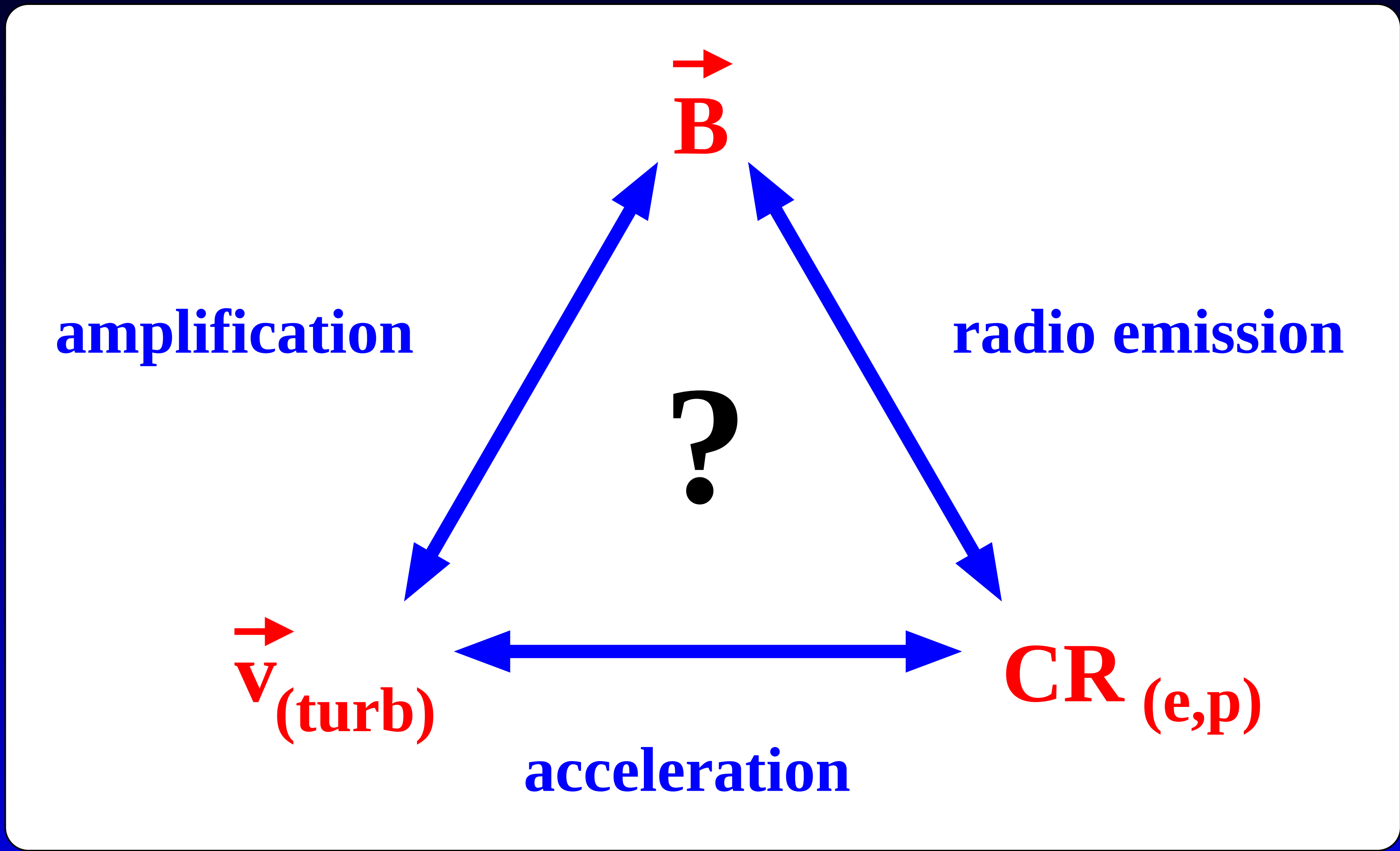
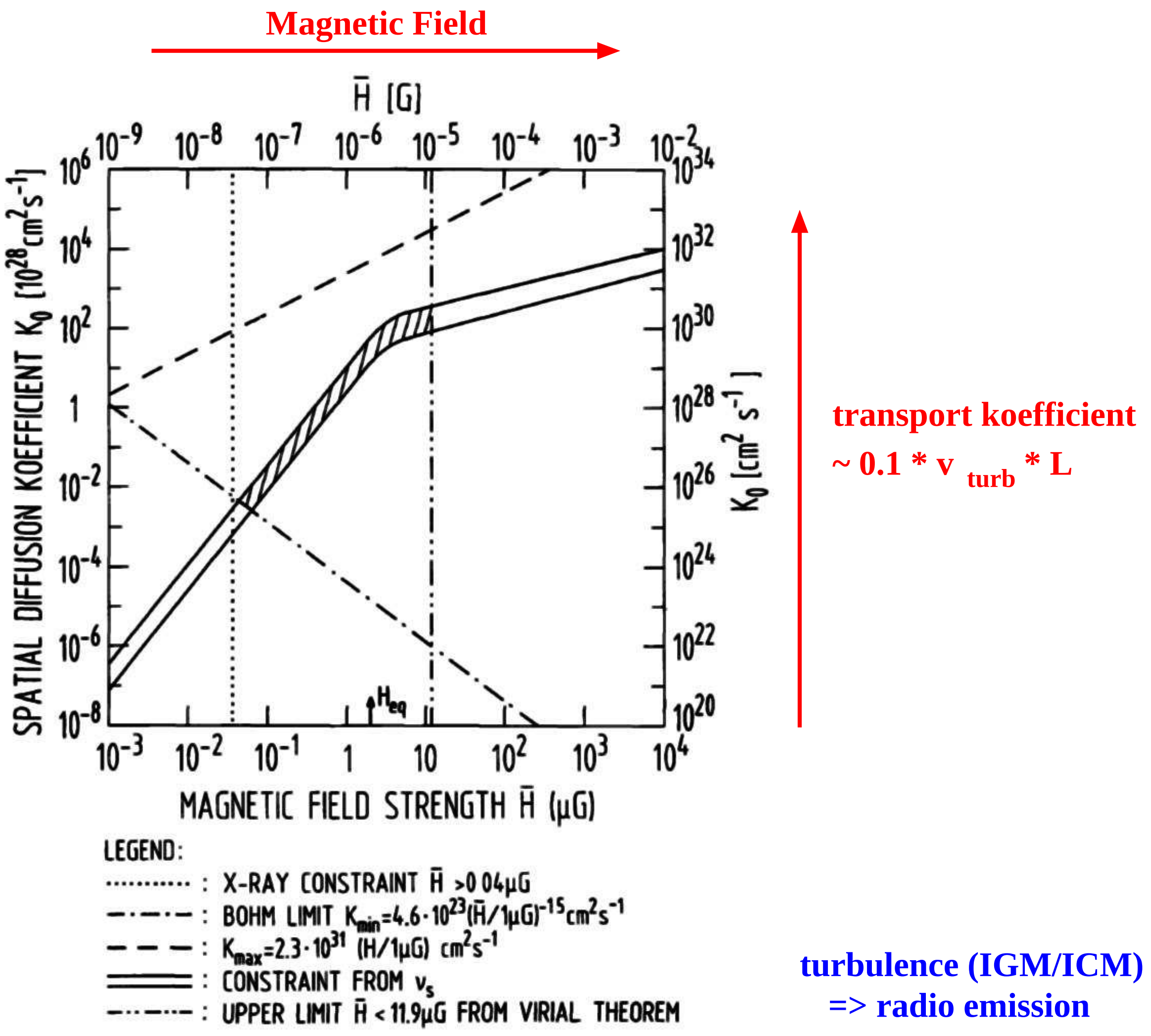
⇒

The Cluster Bermuda-Triangle



see lectures on the different individual aspects ...

Where are we ?



Schlickeiser et al. 1987

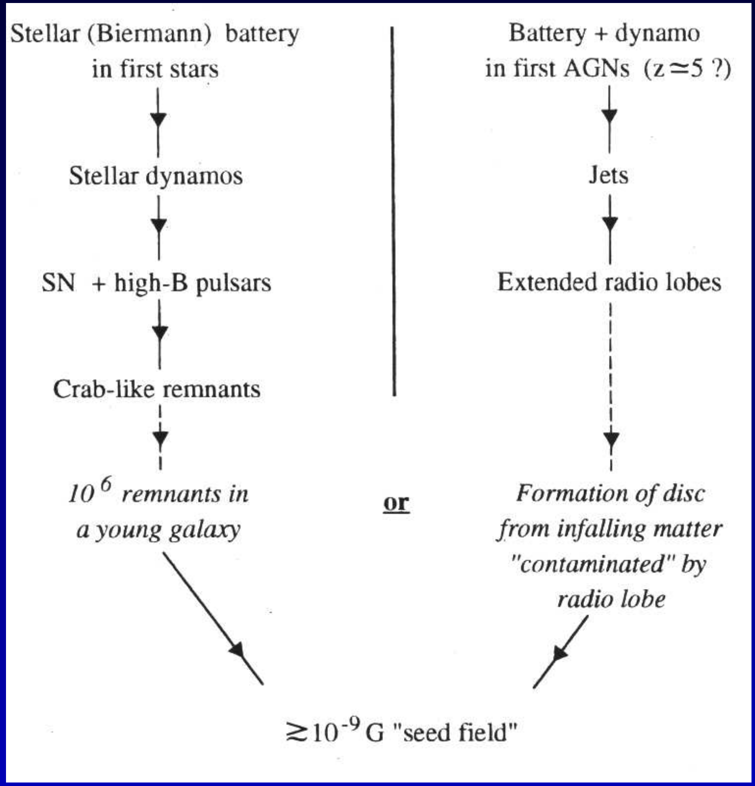
“If the intergalactic clouds [...] still containing some magnetic flux have random velocities [...], then particles will be accelerated by a variant of the original Fermi mechanism.”

(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 1: Origin of B

- 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) ?

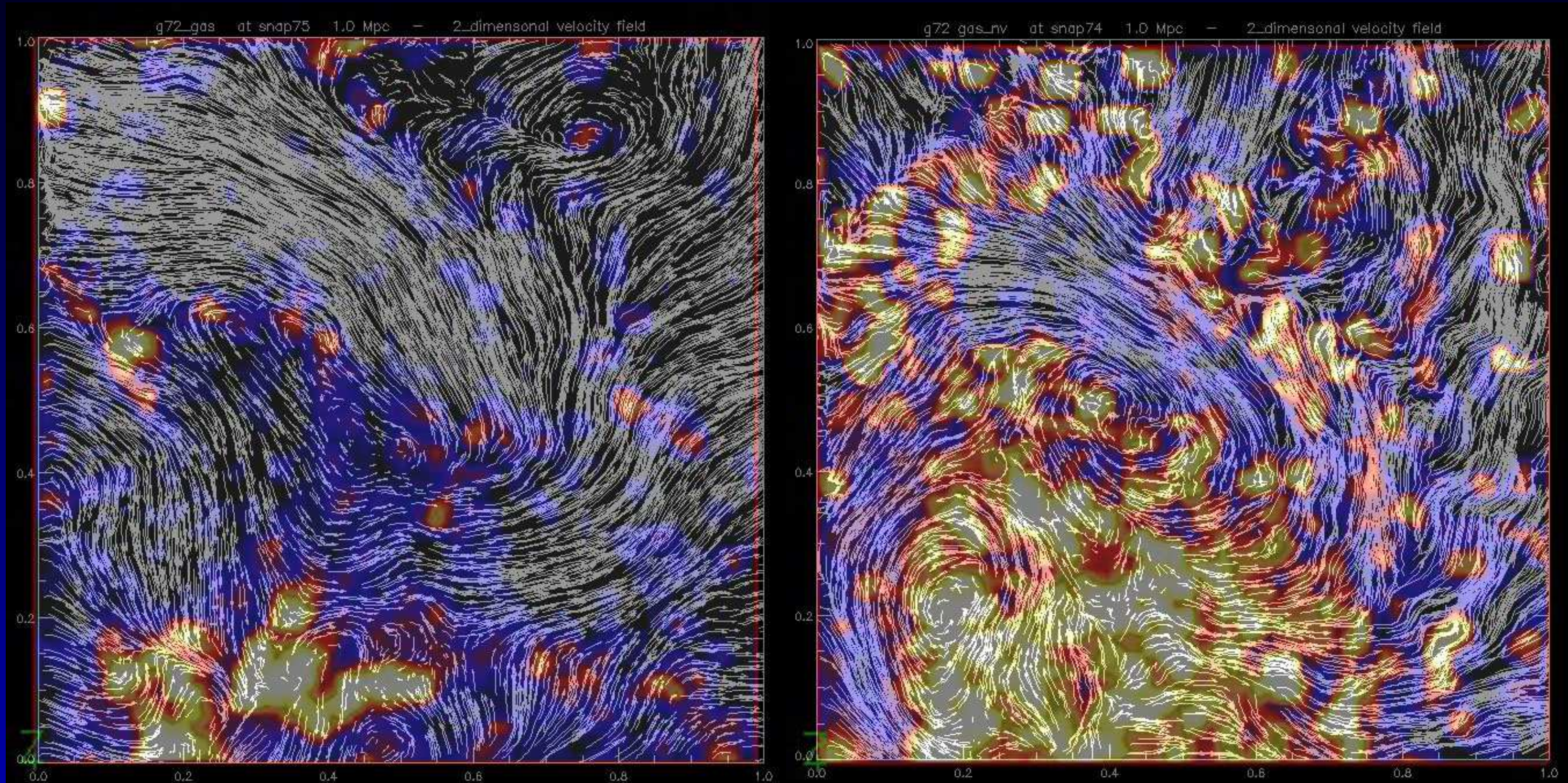
$\Rightarrow$ Relation to dynamics ?

  - Merger, Turbulence, cool Core, Bubbles ?

- Observations:
  - RM in clusters $\Rightarrow$ see Lecture Ia
  - Radio emission (halo and relics) $\Rightarrow$ see Lecture Ib

Problem 2: Turbulence

Old viscosity scheme **New viscosity scheme**



1Mpc × 1Mpc slice (Dolag et al. 2005)

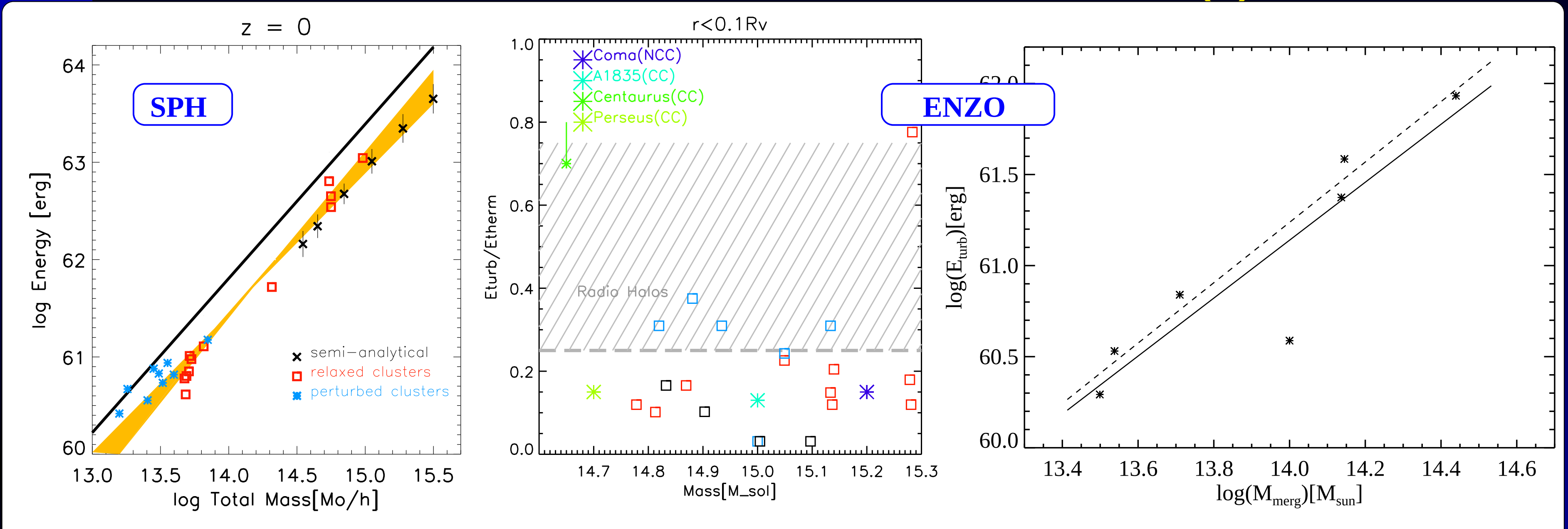
Huge dynamical range needed for LSS simulations:
From several 100 Mpc (LSS) to < 10kpc (cluster turbulence) !

- Resolution crucial (Adaptive methods, *zoomed* simulations)
- Numerical modifications to capture turbulence needed !

  Low artificial viscosity (SPH), refinement criteria (AMR), sub-grid models

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):

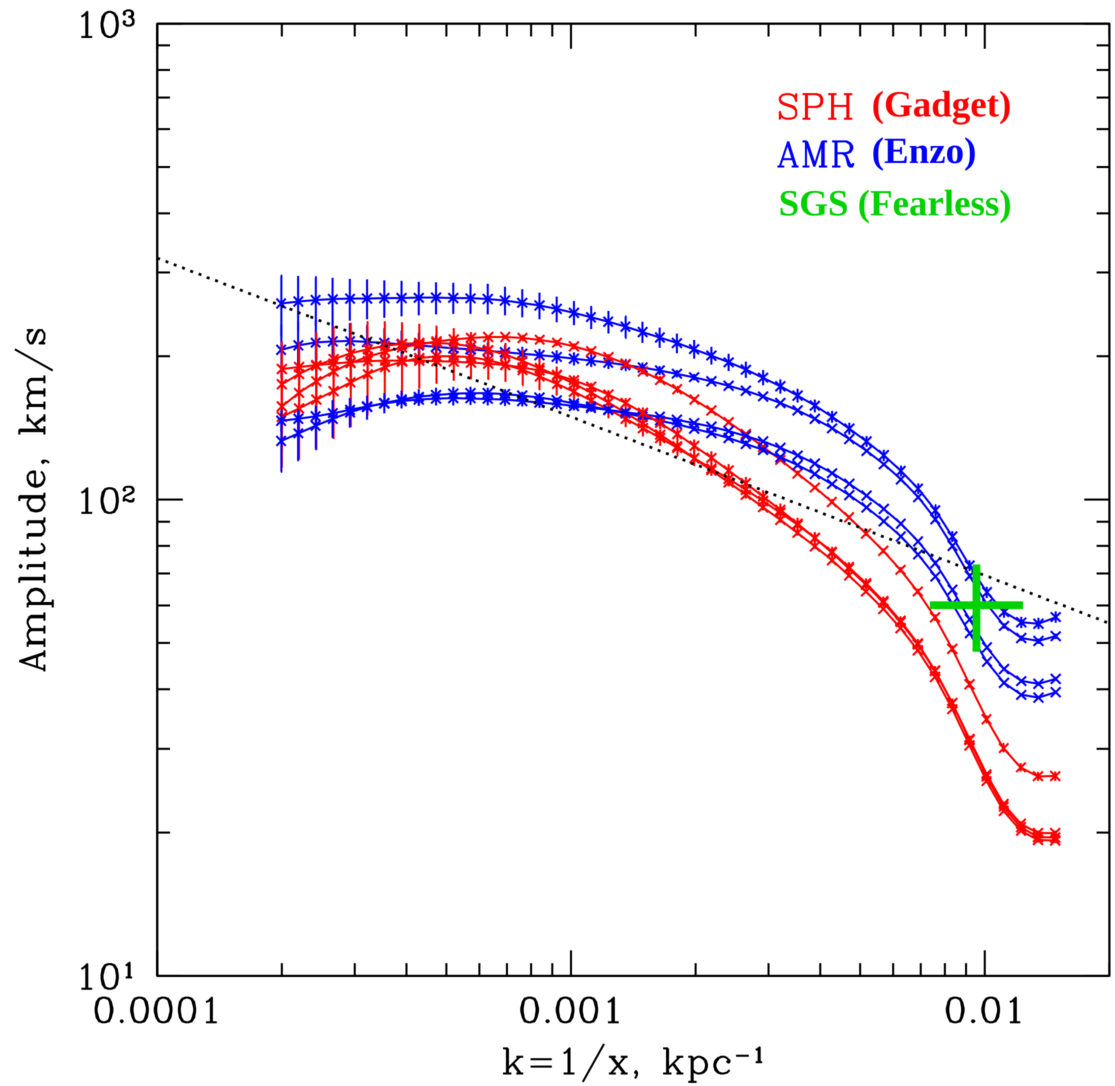
- Behind shocks (mostly beyond core radius)
- Passage of gas rich substructure (whole cluster)
- Passage of dm substructure (mostly cluster core)

Problem 2: Turbulence

Problem 2: Turbulence

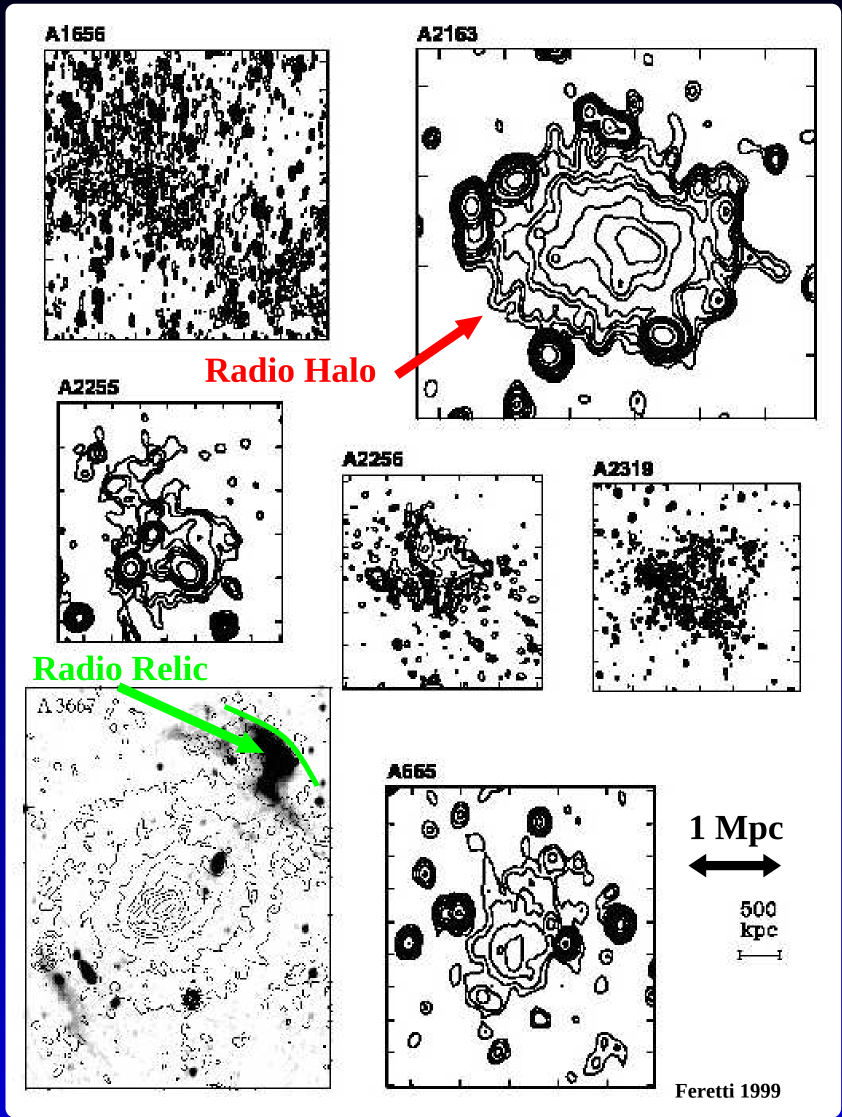
Simulated turbulece in clusters (II):

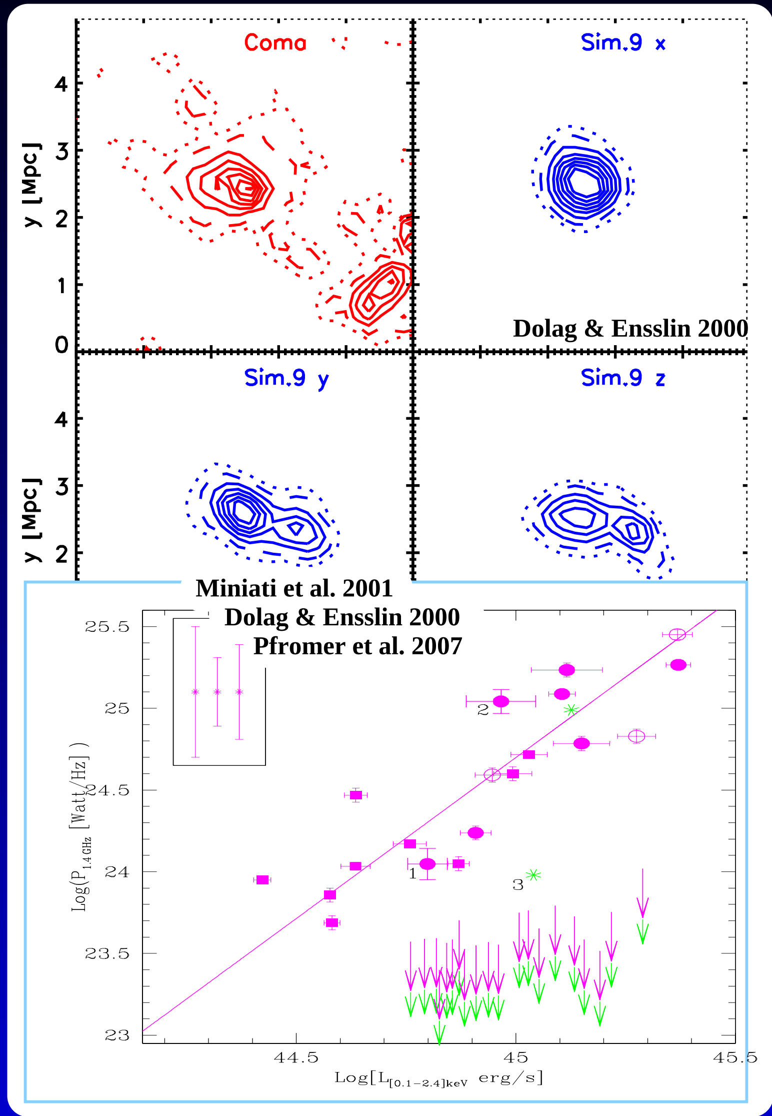
(Dolag et al 2005, Vazza et al 2009, Maier et al 2009, ...)



provided by I.Zhuravleva

Problem 3: Particle acceleration

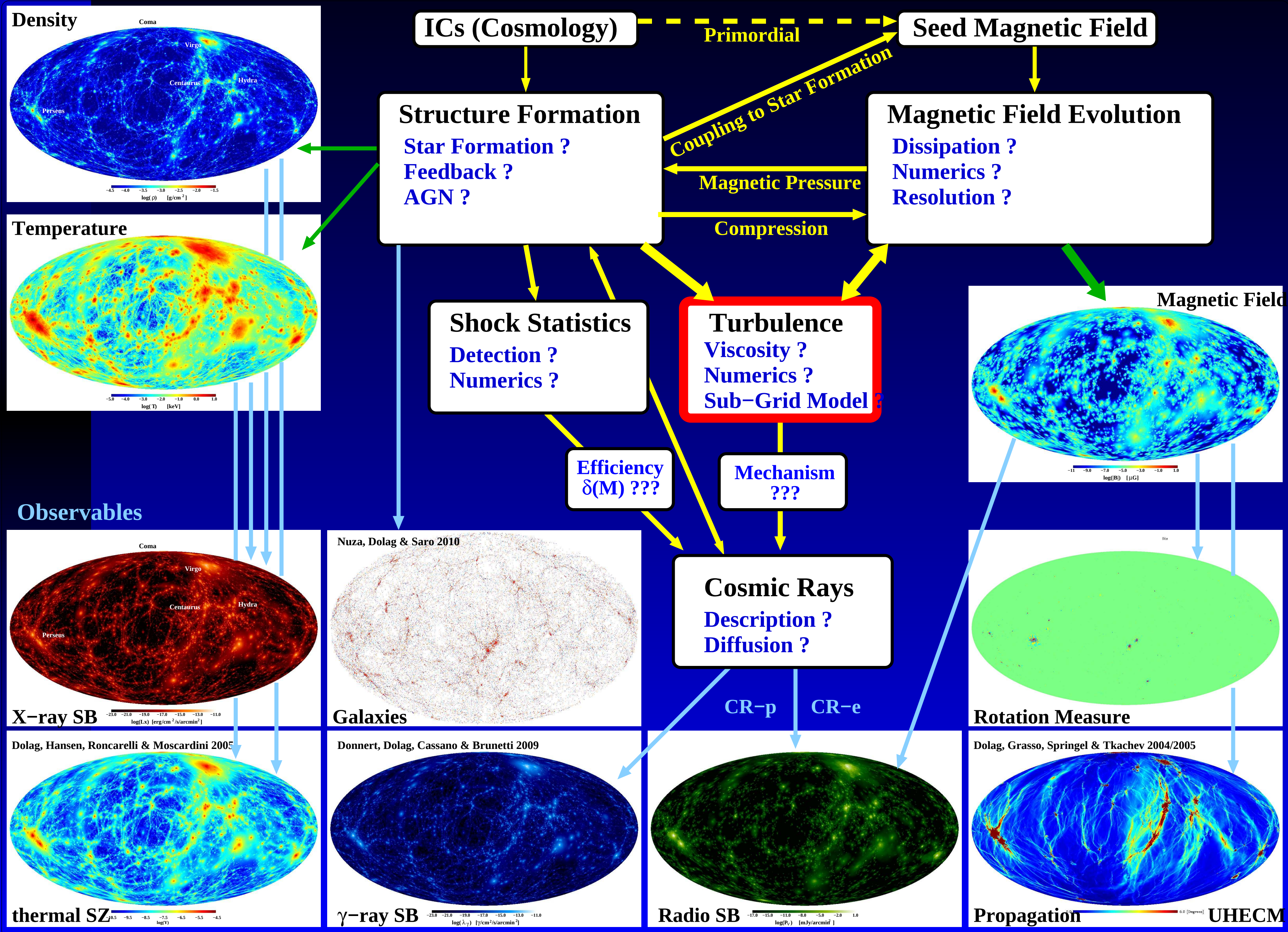




Cluster wide **diffuse synchrotron emission** connected to **merger** events, **periferal** emission directly connected to **shocks**.

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

Simulation Network



Pioneering Work

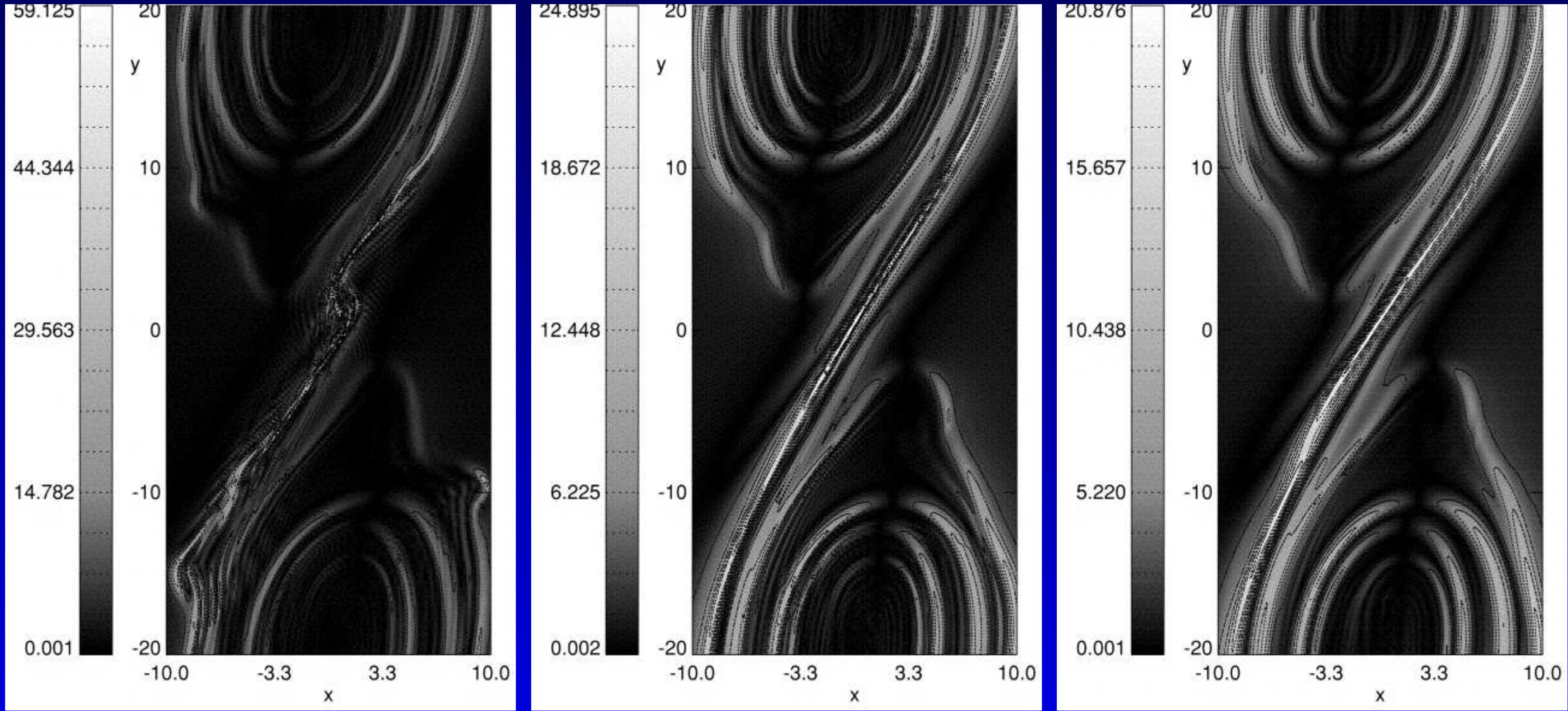
- Cloud collisions
  Jones et al. 1994/1996, Malagoli et al. 1996, Miniati et al. 1997/1999, Gregori et al. 2000, ...
- Buoyant radio lobes
  Churazov et al. 2001, Brüggen et al. 2002, Brüggen & Kaiser 2002, Robinson et al. 2004, Jones & De Young 2005, Reynolds et al. 2005, ...
- Kelvin-Helmholtz in galactic winds
  Birk et al. 1999, ...
- Merging galaxy clusters
  Roettiger et al. 1999a/1999b, Enßlin & Brüggen 2001, Hoeft et al. 2004, ...
- Large Scale Structure
  Kulsrud et al. 1992/1997, Ryu et al 1998 , Miniati 2001/2002, Dolag et al. 1999,2002,2005, Li et al. 2005 , Brüggen et al. 2005 , ...
- Non full MHD simulations
  Bruni et al. 2003, King & Coles 2005, Gazzola et al. 2005, ...

KH driven amplification

Winds in galactic Halo:

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

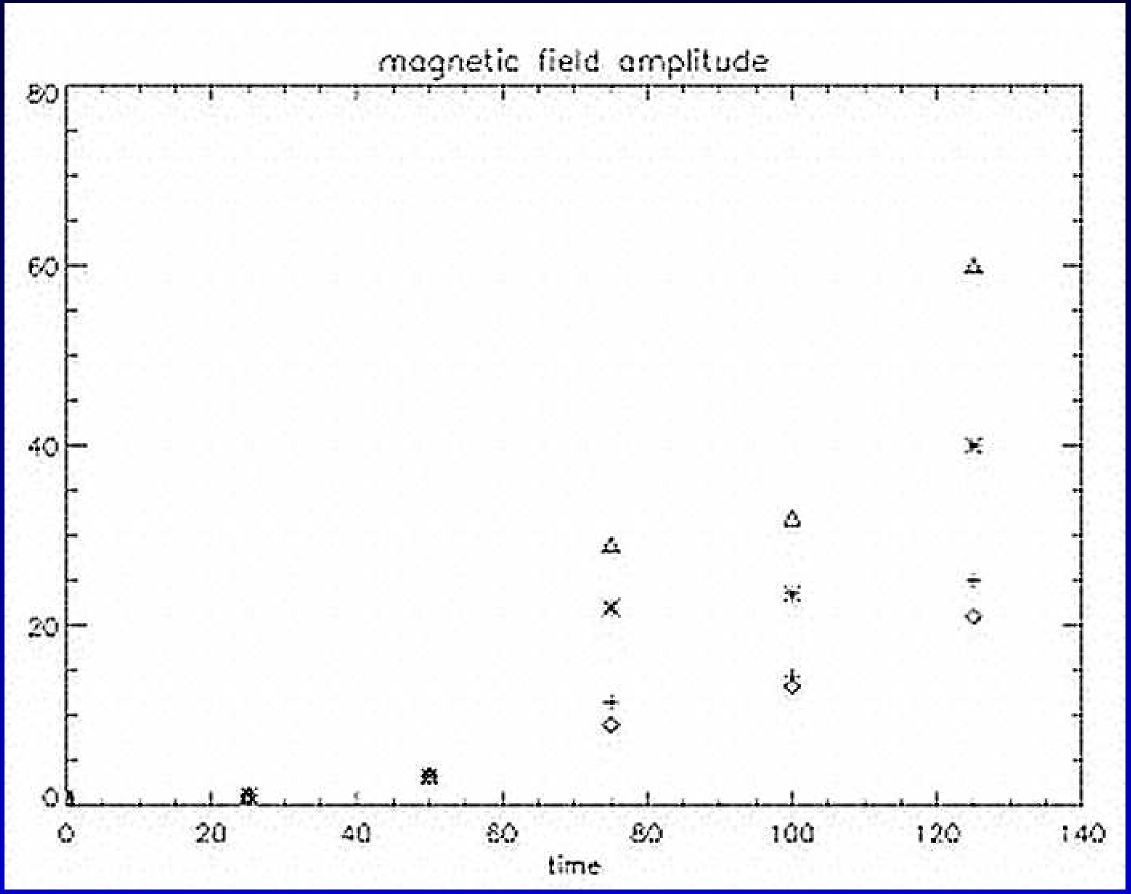
$\Rightarrow t_{\mathrm{KH}} \approx 4 \times 10^5\mathrm{Year}$



Birk et al. 1999

KH driven amplification

Large amplification of seed magnetic field !



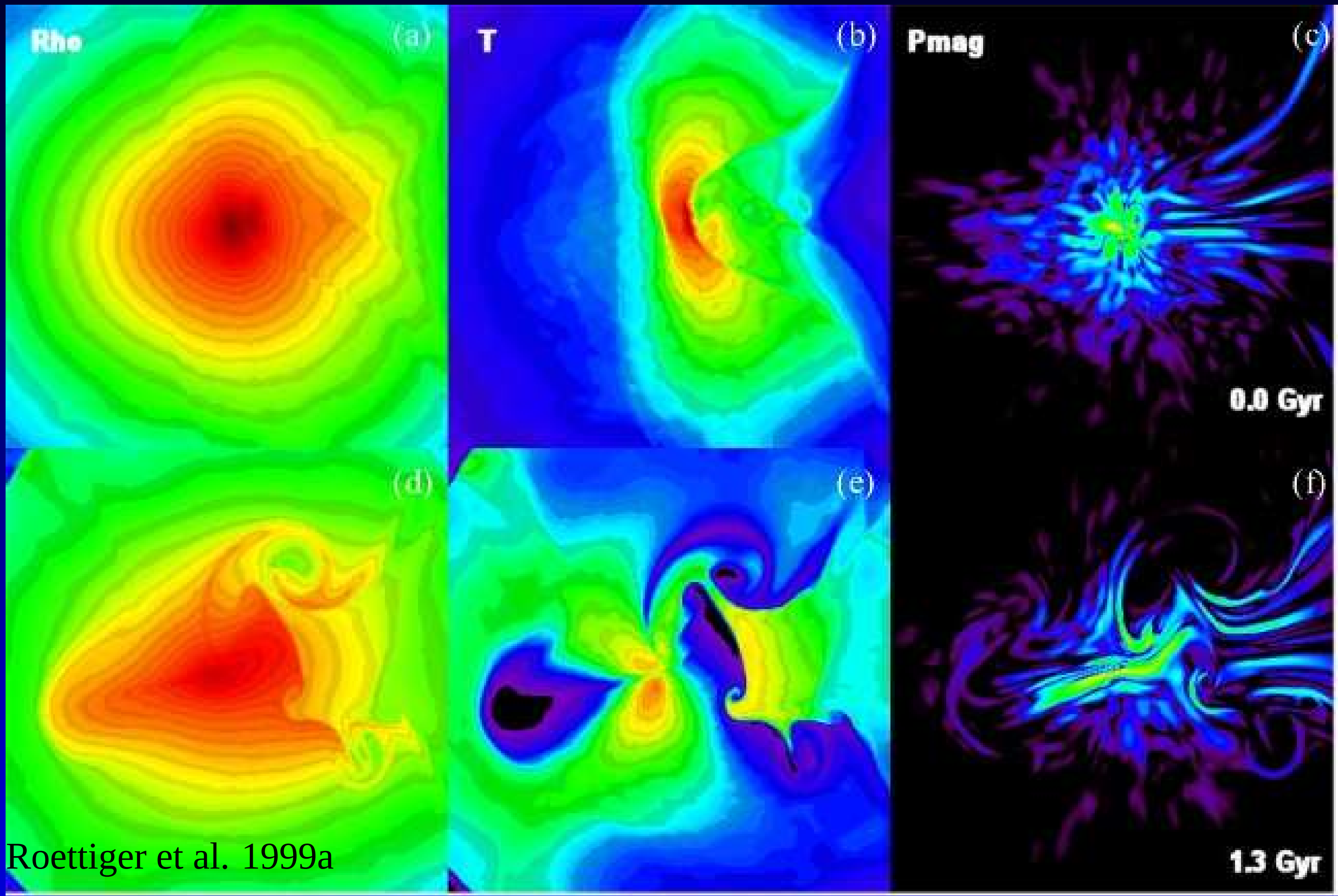
Birk et al. 1999

Should also work in galaxy cluster environment:

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

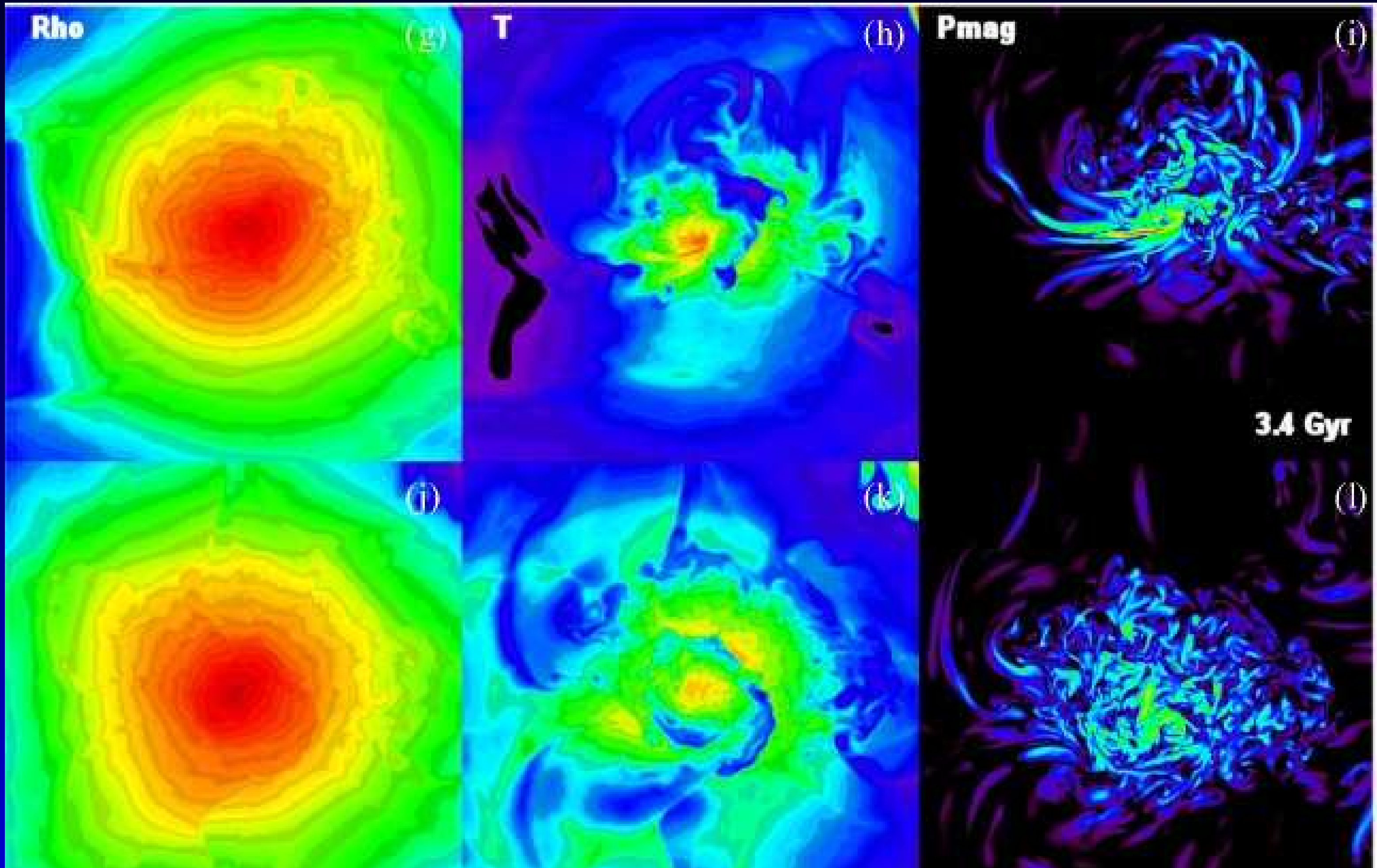
$\Rightarrow t_{\mathrm{KH}} \approx 0.1 \times 10^8\mathrm{Year}$

Merging Clusters



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

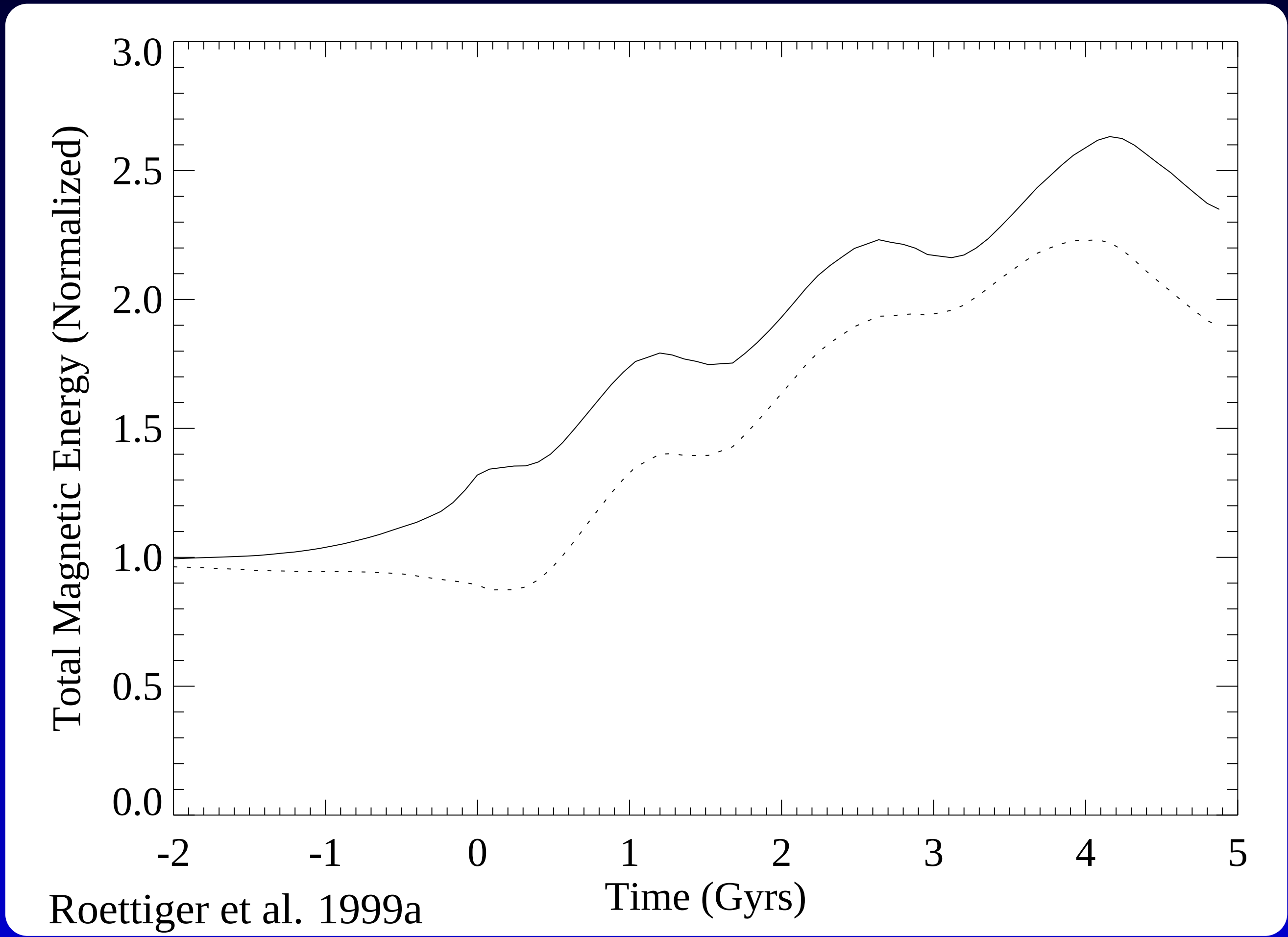
Merging Clusters



Roettiger et al. 1999a

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

Merging Clusters

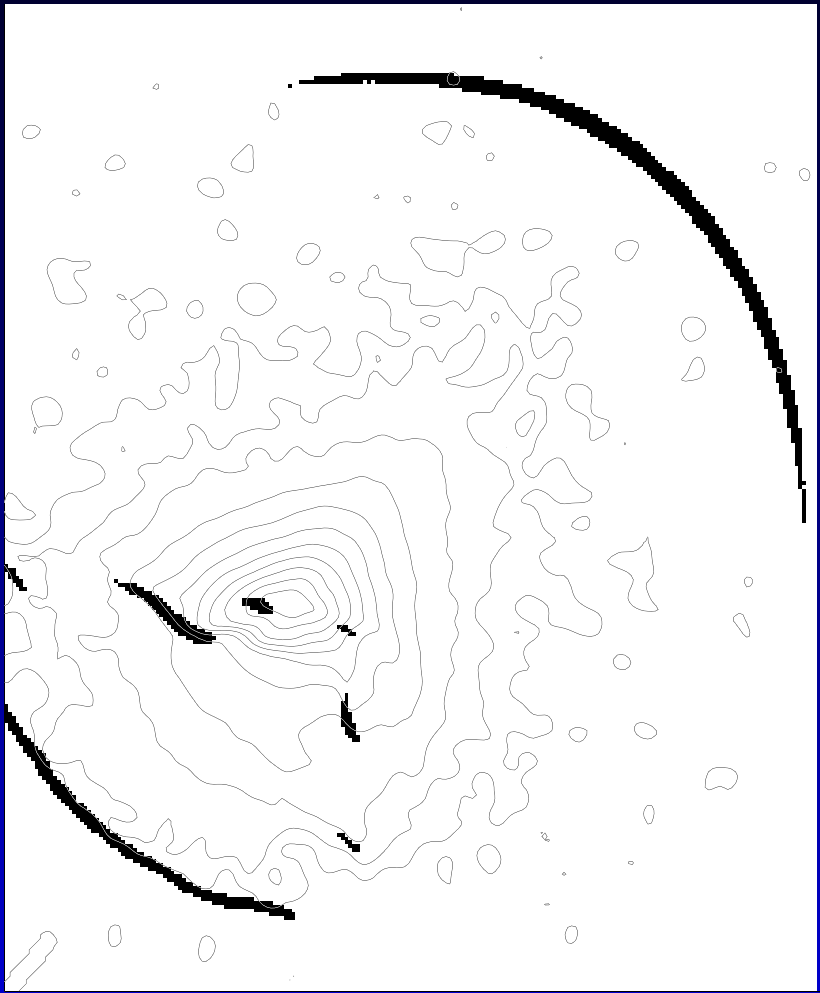


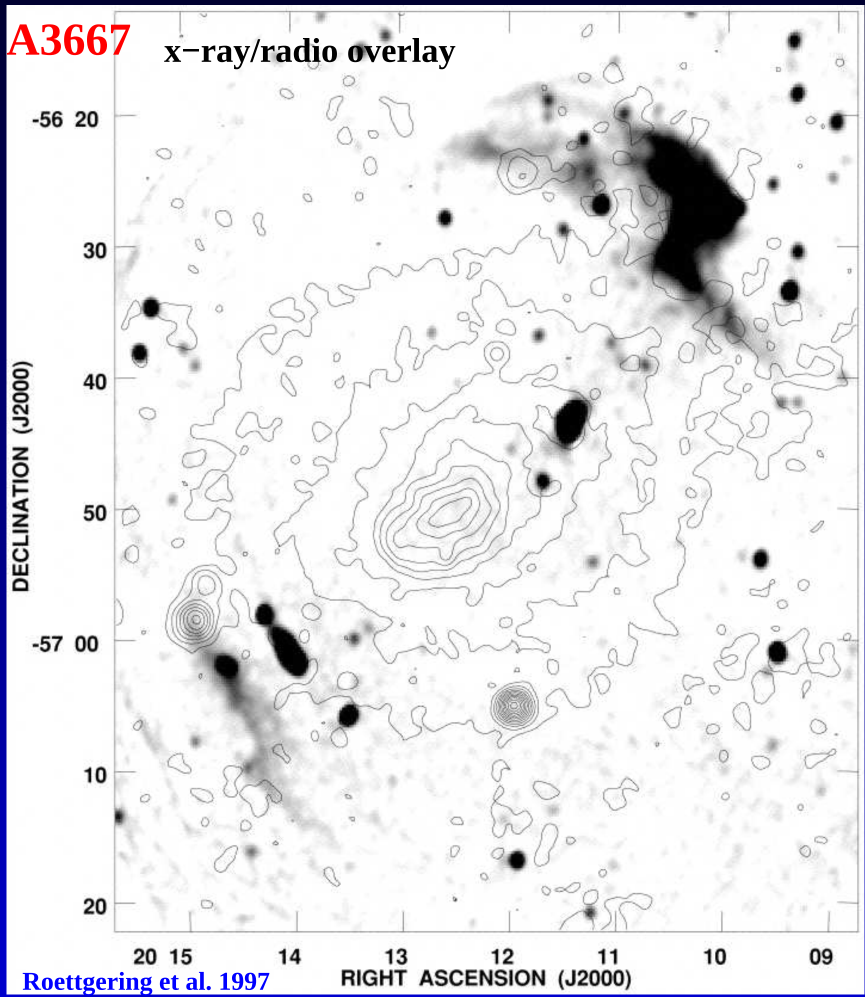
- Globally by a factor of 3 ($\vec{B}^2$!)
- But depends on resolution (12.5kpc here) !

Merging Clusters

Merging Clusters

Radio relics from mergers

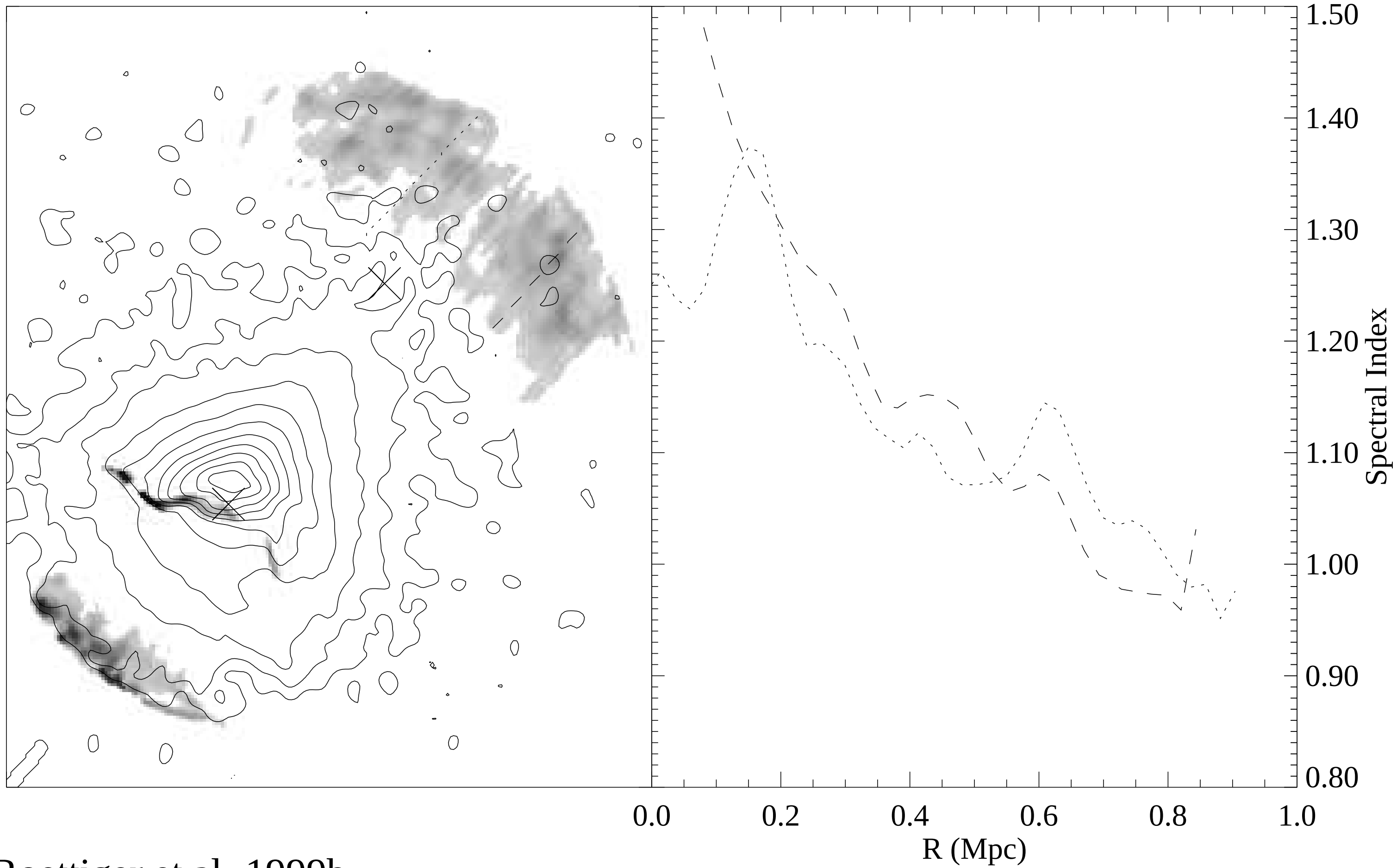




Roettiger et al. 1999b

- ZEUS, A3667 setup (5 : 1 merger)

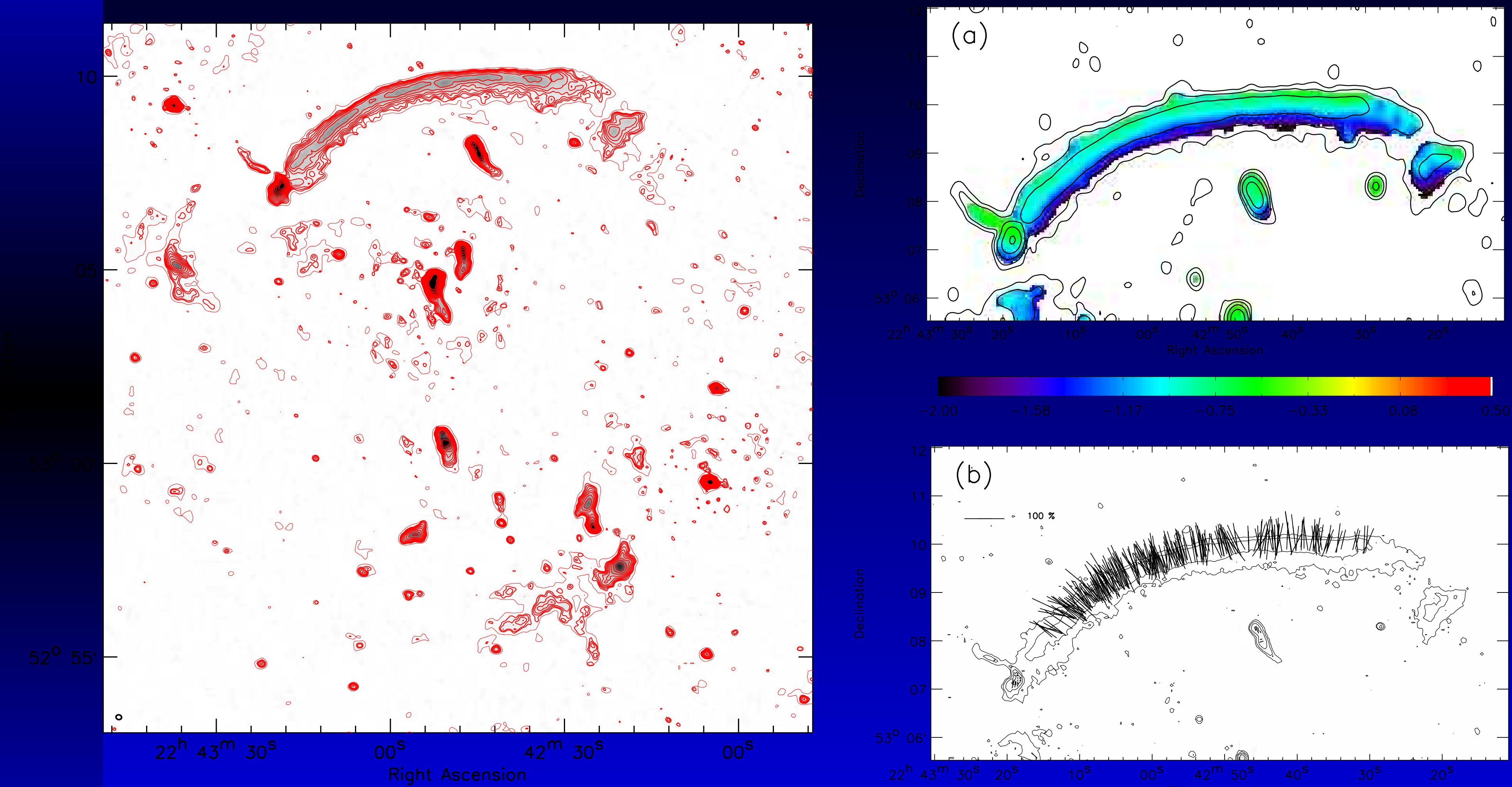
Radio relics from mergers



Roettiger et al. 1999b

- Injection by shocks (ρ_2/ρ_1), diffusion ($\kappa = 1$), aging
- emission zone width $\Rightarrow \vec{B} \approx 1\mu$G)

Radio relics from mergers



van Weeren et al. 2010

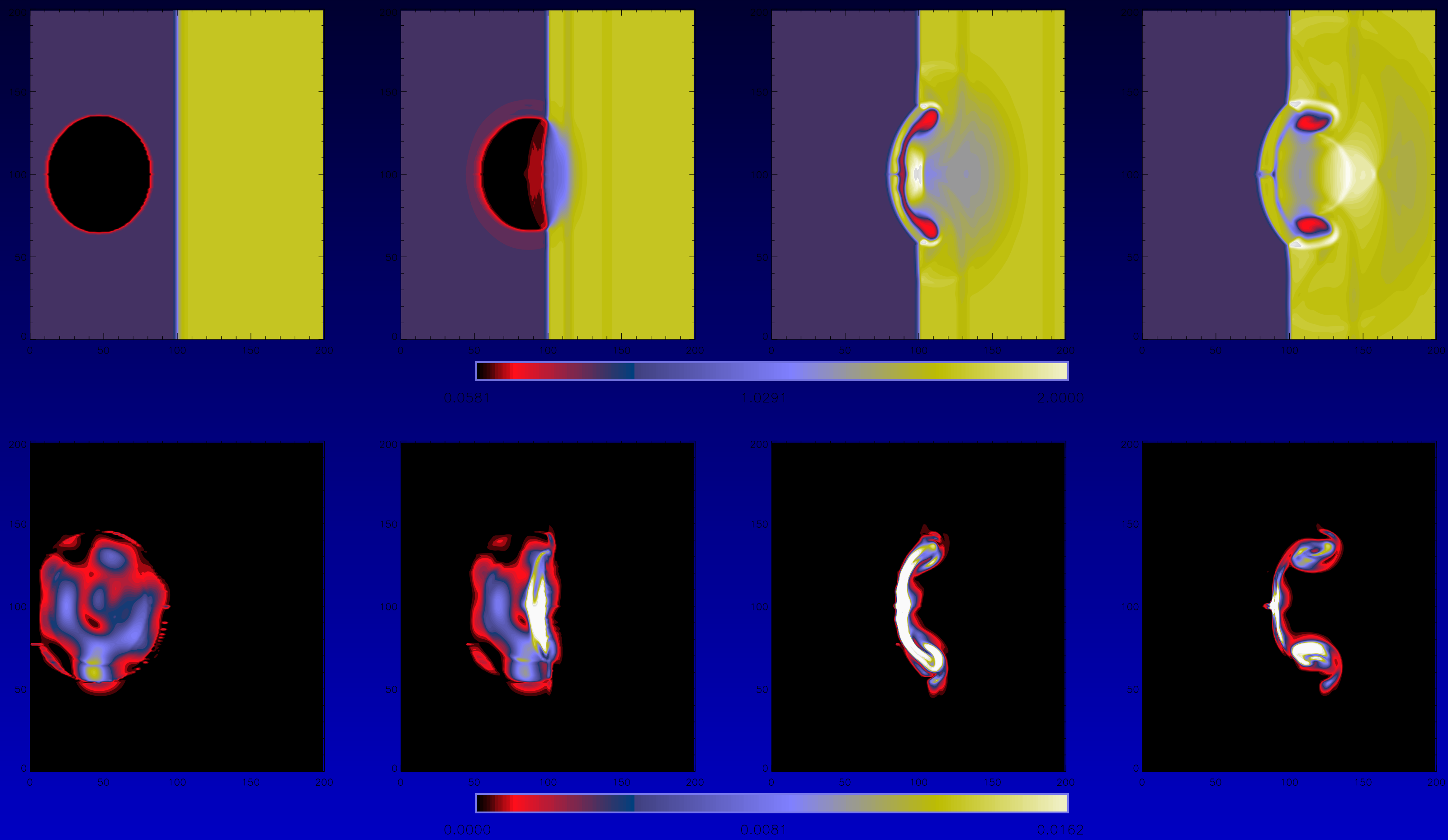
With of the relic suggest $\vec{B} \approx 5 - 7\mu$!

Radio relics from mergers

Why does not every cluster show relicts ?

- Shock structures too short lived ?
- Cluster mass ?
- More than the shock is needed ?
- Radial distribution ?
- Scaling relations ?
- CR protons ?

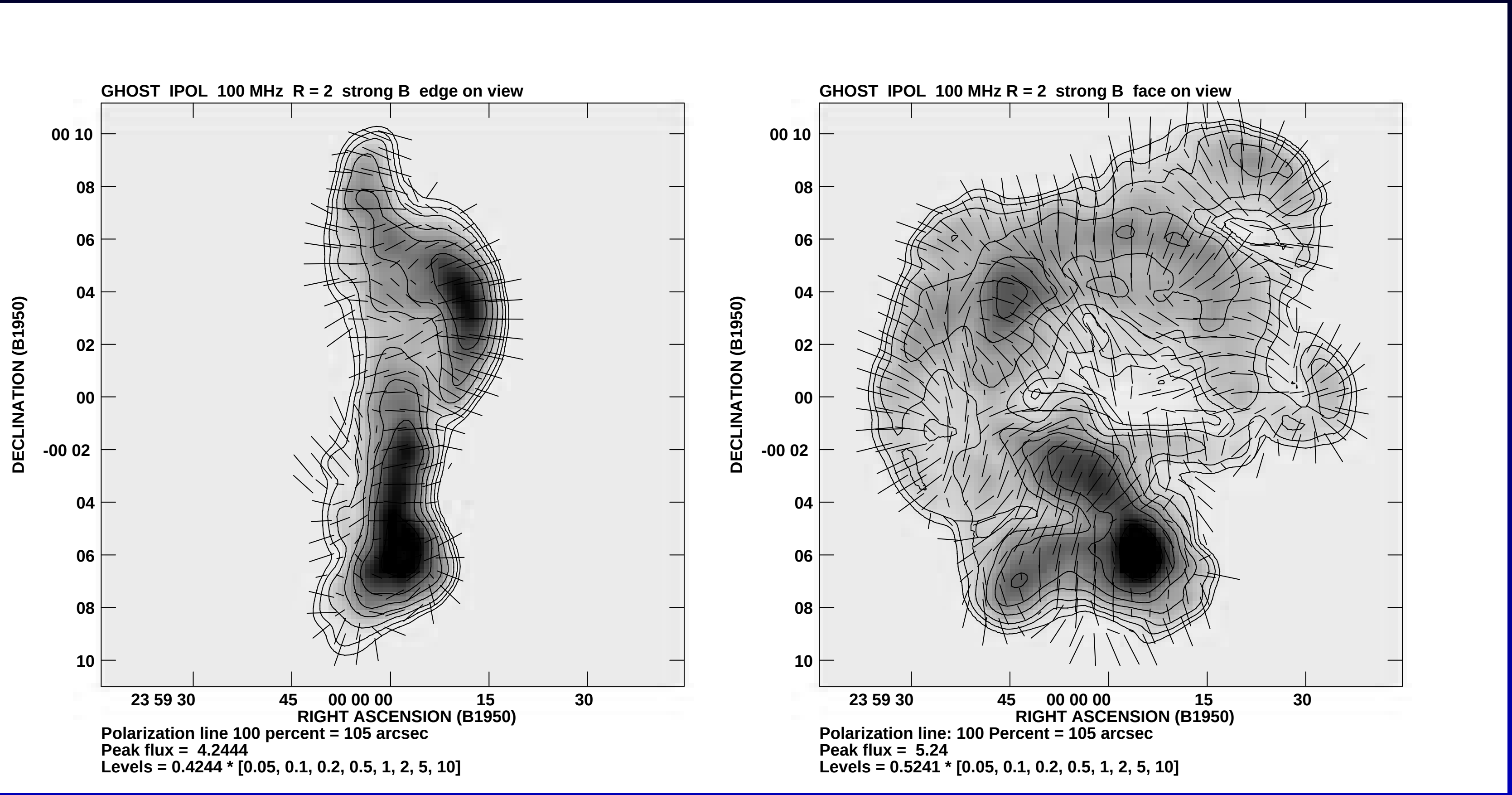
Fossil radio relics



Enßlin & Brüggen 2002

- ZEUS, bubble with tracer particles
- Shock compression of fossil radio plasma

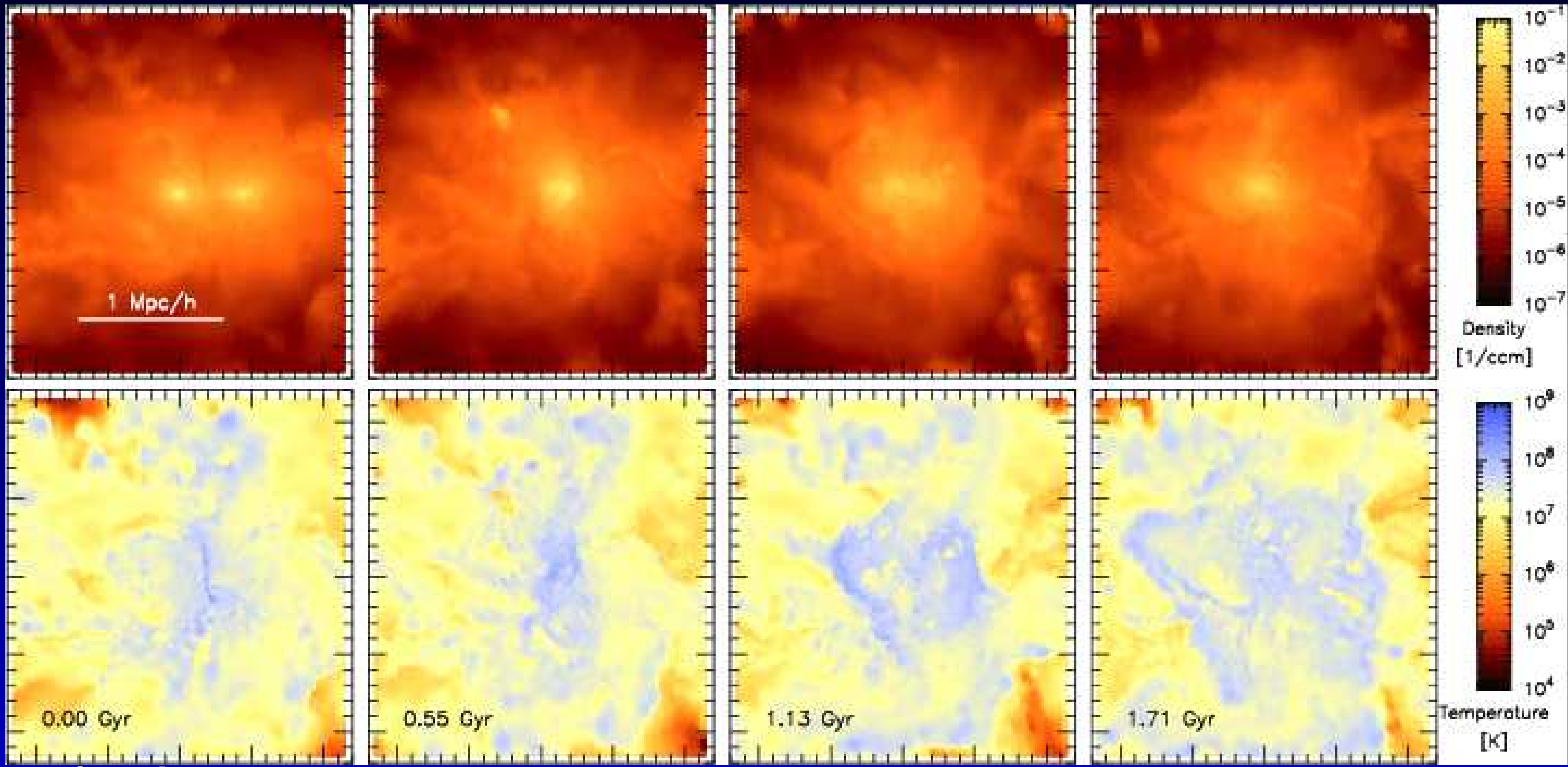
Fossil radio relics



Enßlin & Brüggen 2002

- Reproduce structure (toroidal) and $\vec{B}$ alignment
- Size ratios correlate with shock strength

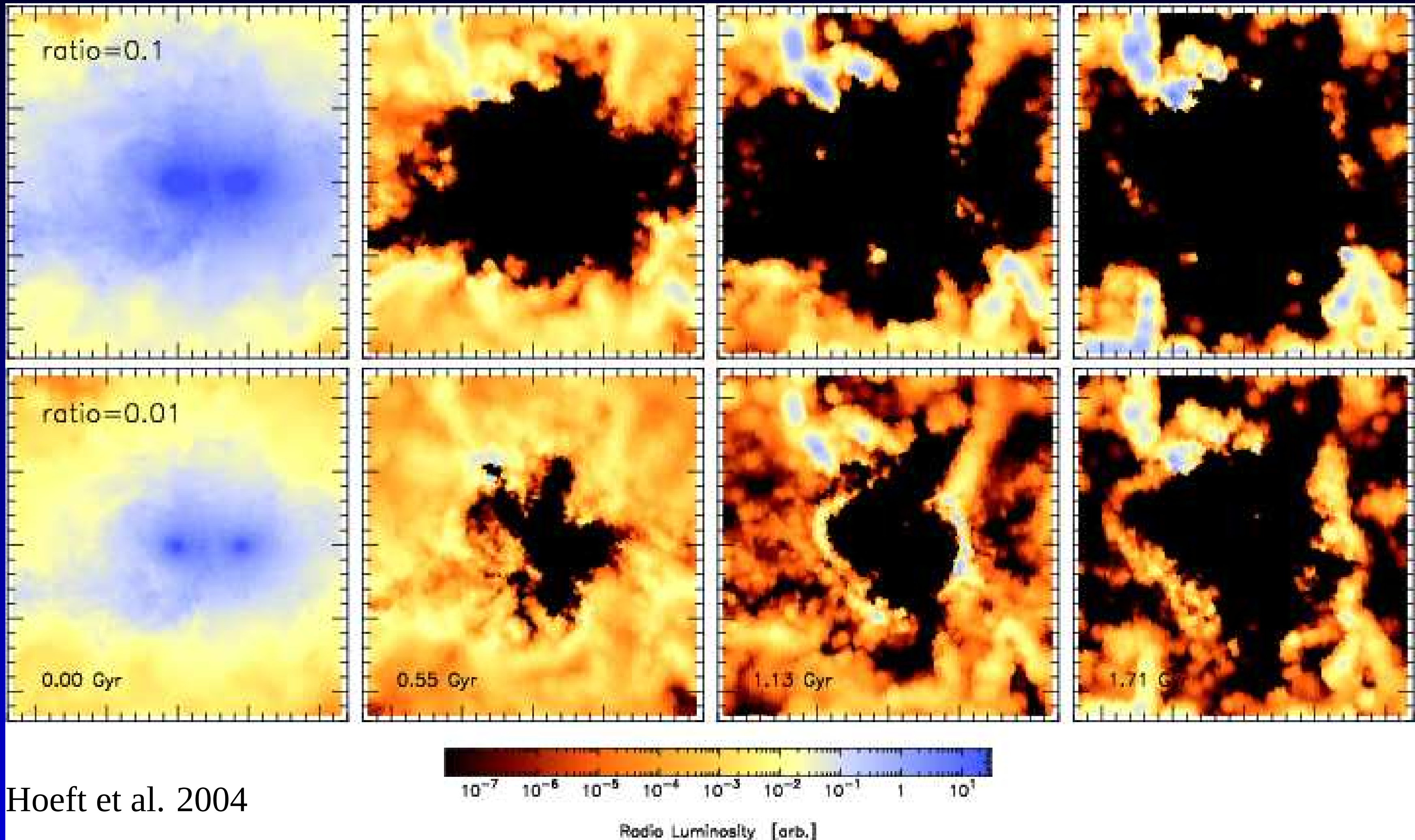
Fossil radio relics



Hoeft et al. 2004

- Gadget-2 (SPH), cluster merger simulation
- Pressure history ⇒ radio plasma evolution

Fossil radio relics

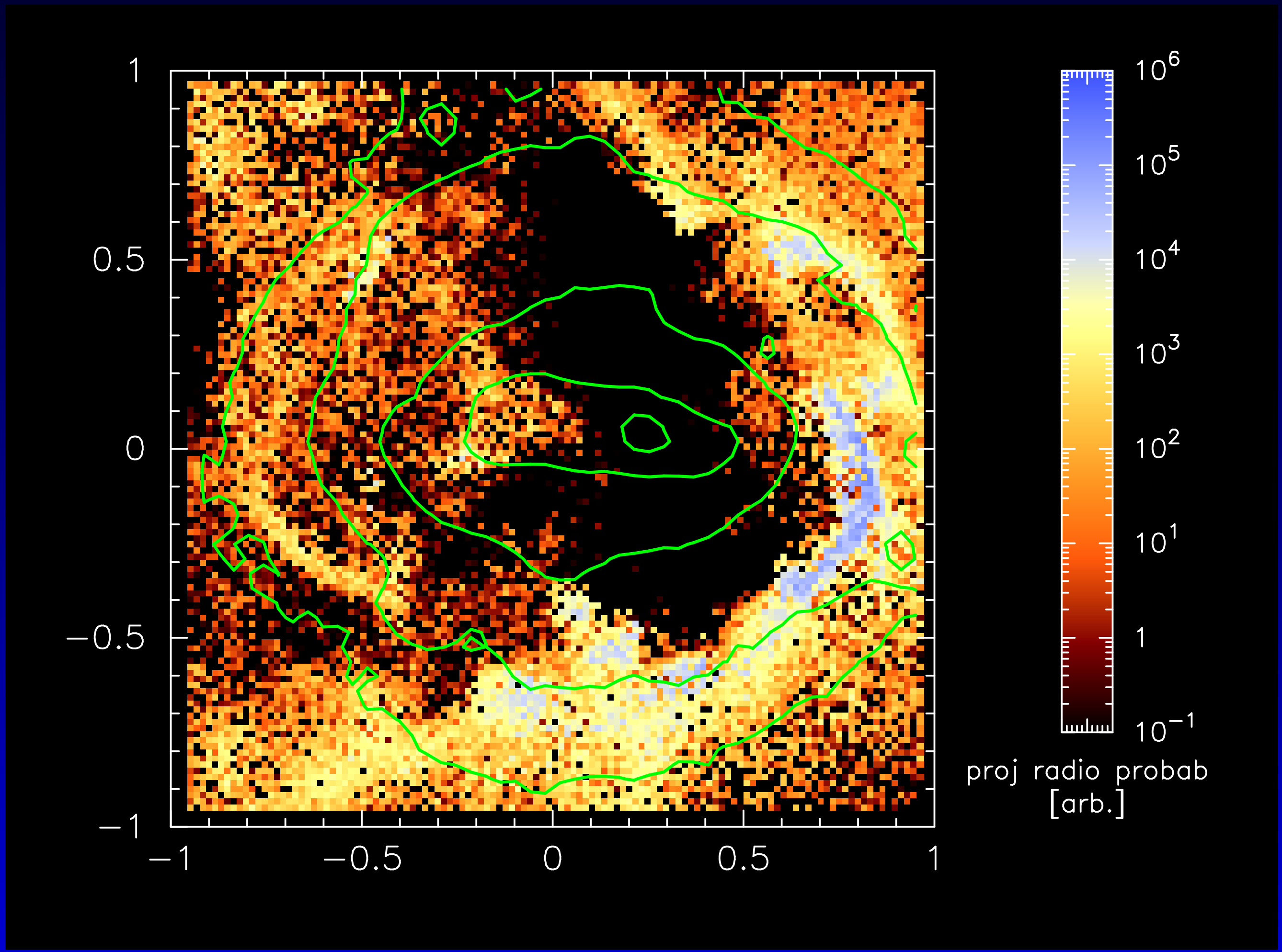


Hoeft et al. 2004

- Result depends on ratio of P_B/P_{gas}
- Relics only outside the cluster

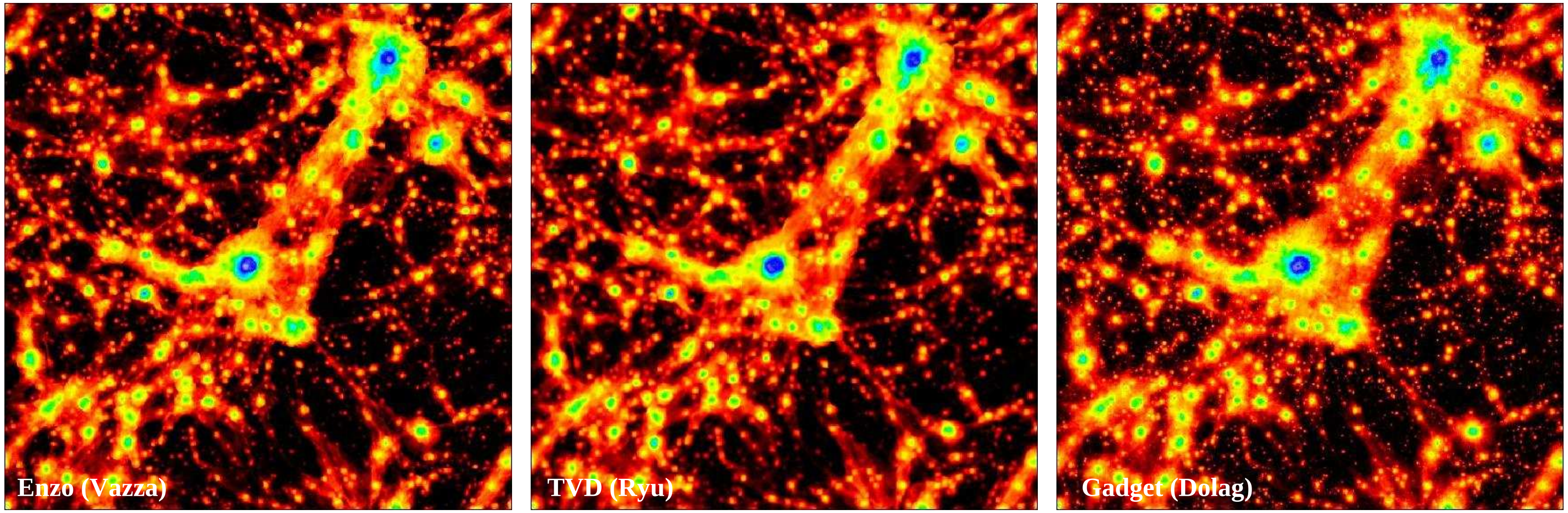
Fossil radio relics

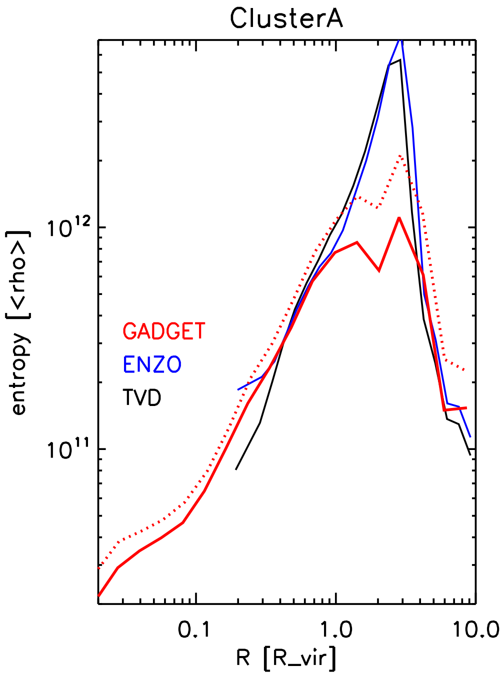
Hoeft et al. 2004

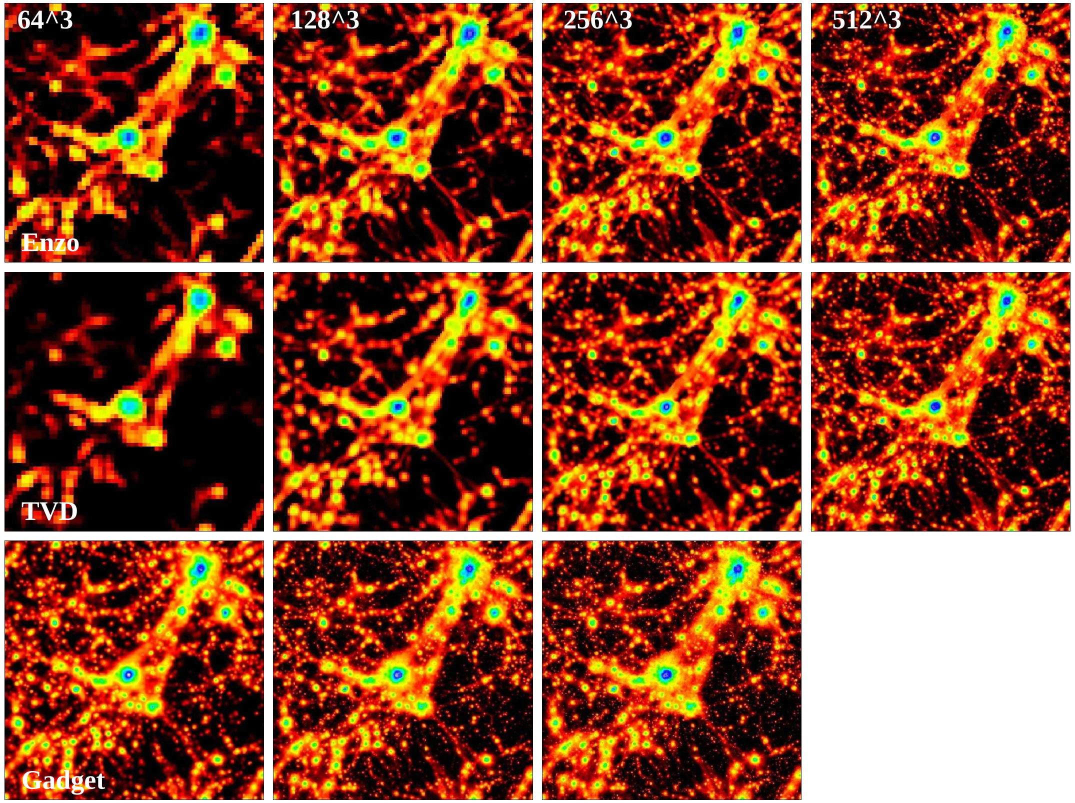


- Cooling efficient inside cluster
- Timing and P_B/P_{gas} crucial for relics

Comparison Project



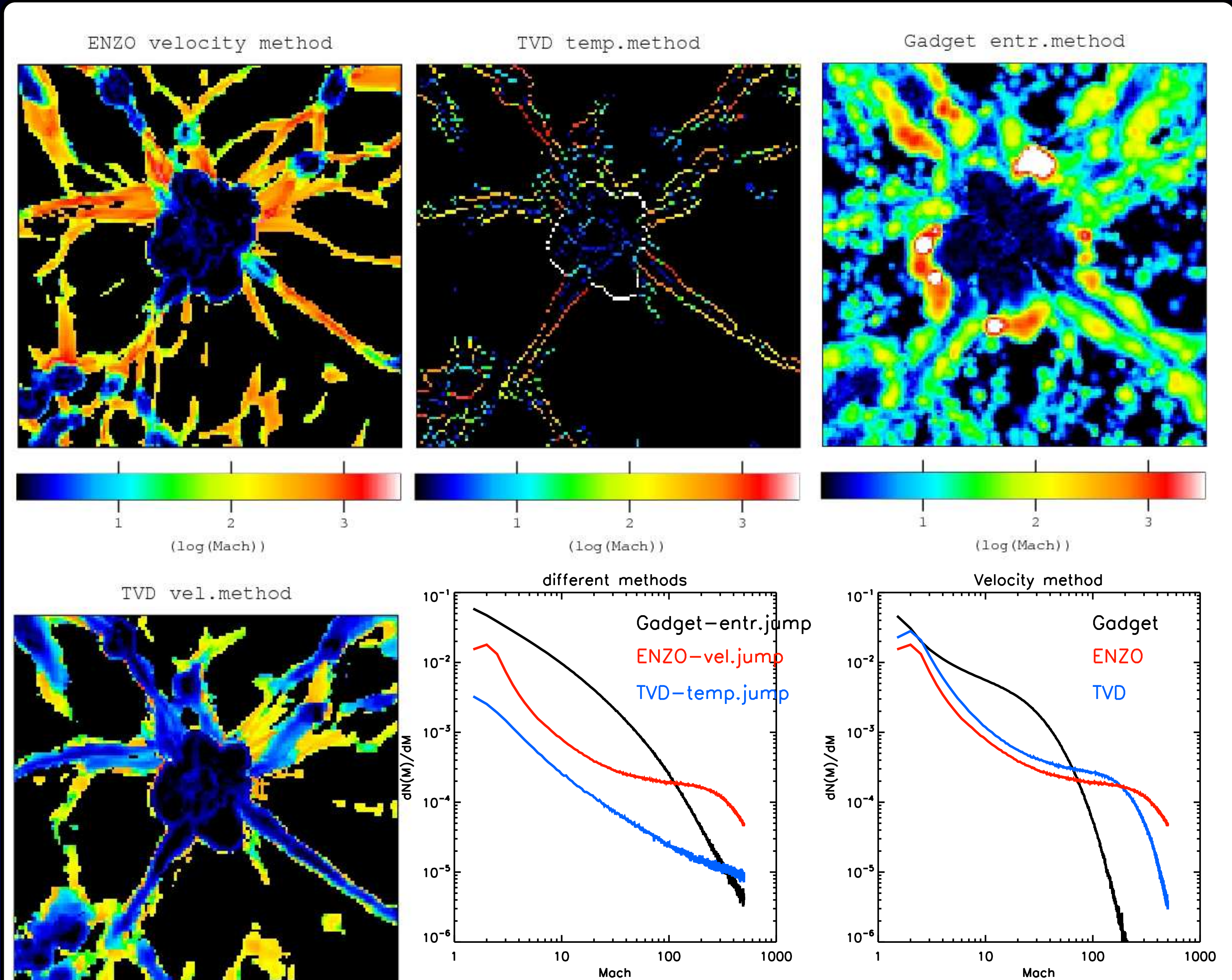




Franco Vazza
Gianfranco Brunetti
Claudi Gheller

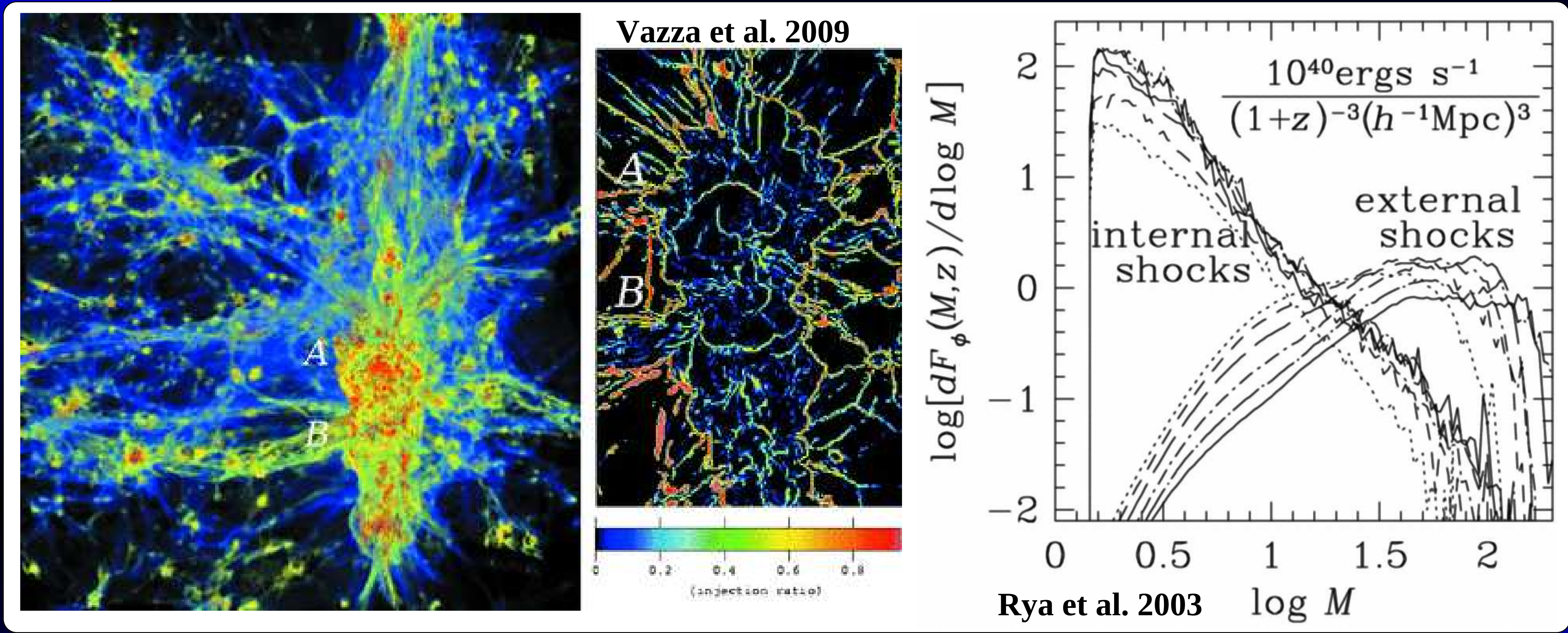
Dongsu Ryu
Hyesung Kang
Cristoph Pfrommer
Klaus Dolag

Comparison Project



provided by F. Vazza

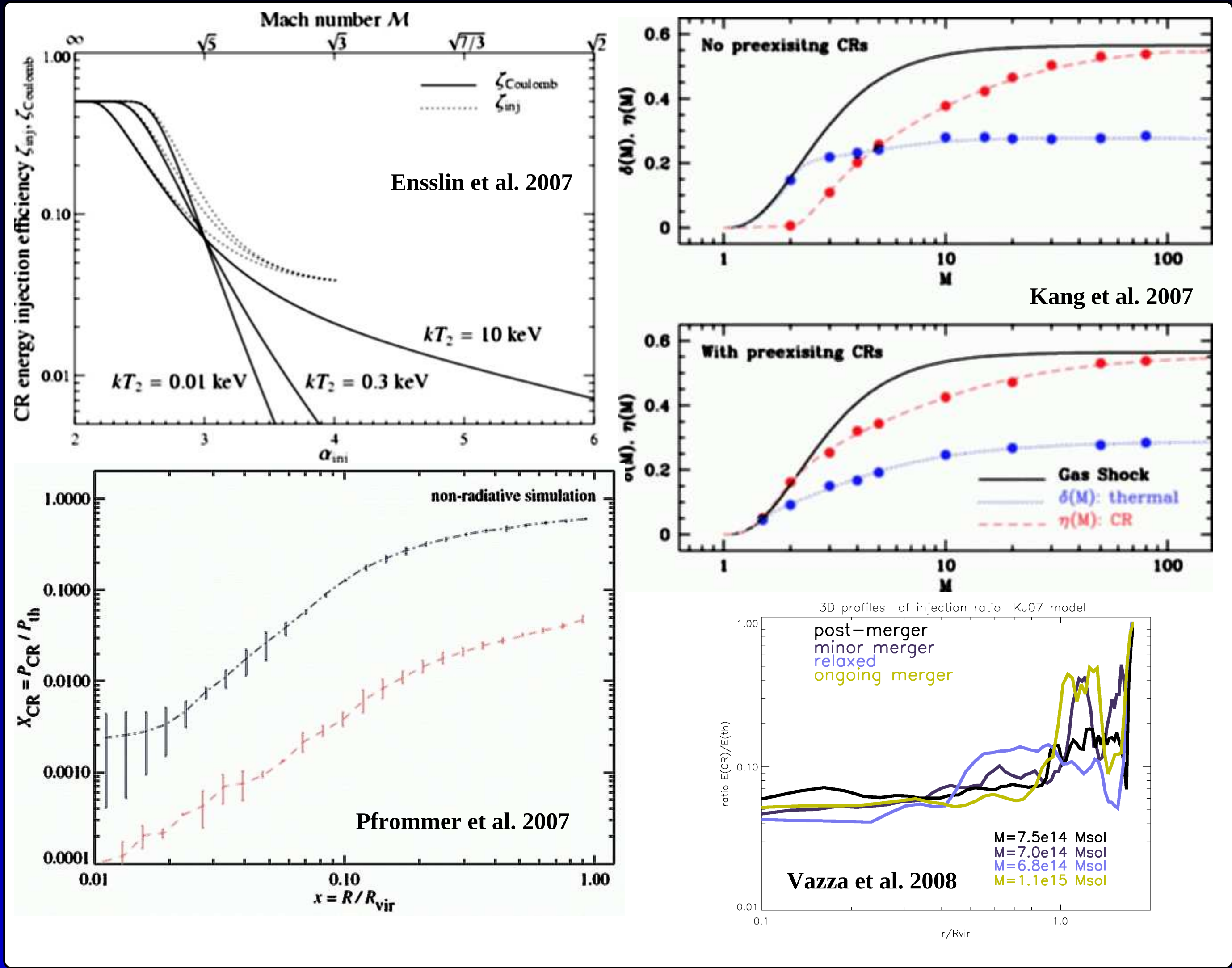
Shocks in LSS



See discussions in Miniati et al. 2000, Ryu et al. 2003, Pfrommer et al. 2006, Hoeft et al. 2008, Skillman et al 2008, Vazza et al. 2009, Paul et al. 2011, Skillman et al. 2011, Vazza et al. 2012, Araya-Melo et al. 2012, Planelles et al. 2013

See also Reviews: Dolag et al. 2008, Brueggen et al. 2012

Shocks in LSS



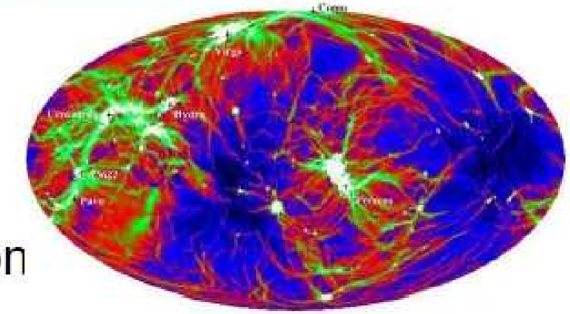
Used/Infered efficiency of CR acceleration at shocks.

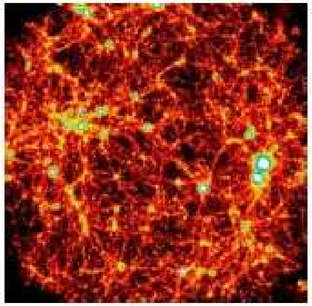
$\Rightarrow$ strong inversion of CRp^+/thermal energy ratio predicted by non radiative simulations.

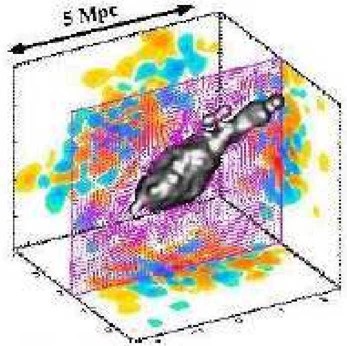
What we do ...

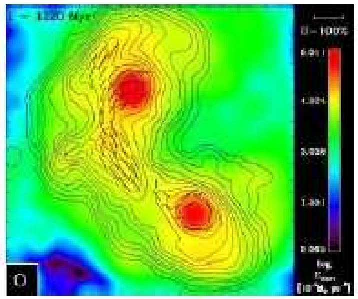
Simulating cosmic magnetism (past to present):

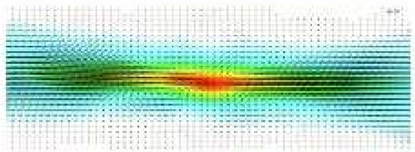
SPH MHD (Dolag, Bartelmann, Lesch 1999)	1999	Galaxy clusters (Dolag, Bartelmann & Lesch 1999,2002)
	2000	Radio Haloes & CR propagation (Dolag & Enßlin 2000; Dolag et al. 2004,2005)
Gadget1 MHD (Dolag et al. 2004)	2005	Galactic seeding models (Donnert et al. 2009)
Gadget3 MHD (Dolag & Stasyszyn 2009)	2008	Isolated galaxies (Kotarba et al. 2009)
Non-ideal MHD (Bonafede et al. 2011)	2010	Major & Minor merger (Kotarba et al. 2011; Geng, Beck A. et al. 2012)
Cleaning schemes (Stasyszyn, Dolag & Beck A. 2012)	2011	Antennae & Stephan's Quintet (Kotarba et al. 2010; Geng, Beck A. et al. 2012)
Dynamo models (Stasyszyn & Elstner, in prep.)	2012	Galactic halo formation (Beck A., et al. 2012)
		First dynamos (Stasyszyn & Elstner, in prep.)

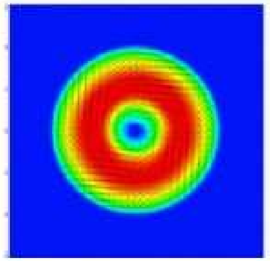












What we do ...

Simulating cosmic magnetism (present to future):

2010

2012

Non-ideal MHD
(Bonafede et al. 2011)

Cleaning schemes
(Stasyszyn, Dolag & Beck A. 2012)

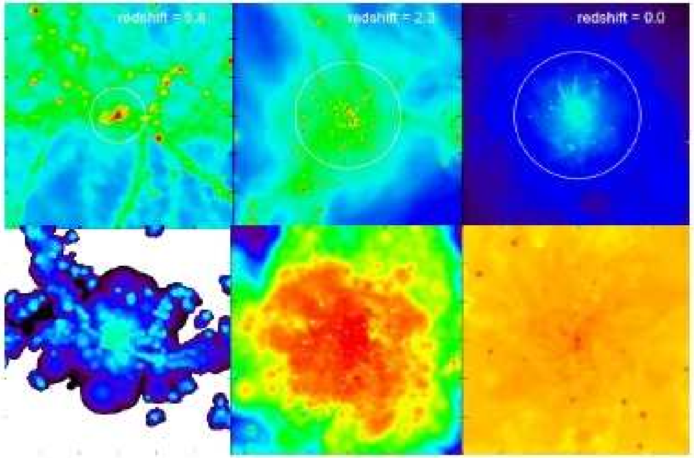
Dynamo models
(Stasyszyn & Elstner, in prep.)

Shock detection
(Beck A. et al., in prep)

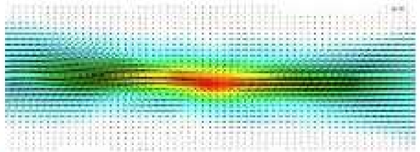
Sub-grid physics
(Arth et al., in prep)

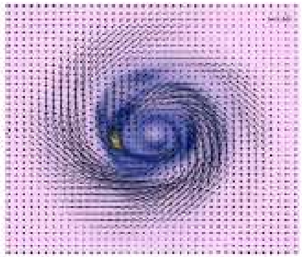
Galactic halo formation
(Beck A. et al. 2012)

Supernova seeding
(Beck A.,et al., 2013)



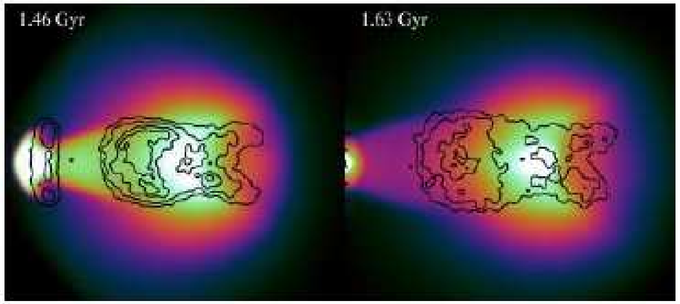
First dynamos
(Stasyszyn & Elstner, in prep.)





CR shock injection
(Pasternak, Beck A., in prep.)

CR reacceleration
(Donnert et al., 2012)



Combining various aspects of cosmological simulations (LSS, ICM, Galaxies, AGNs) allow to improve our sub-scale models.

What we do ...

$$\frac{\mathrm{d}\vec{v}_a}{\mathrm{d}t} = - \sum_b m_b \left(f_b^{\mathrm{co}} \frac{P_b}{\rho_b^2} + f_a^{\mathrm{co}} \frac{P_a}{\rho_a^2} + \Pi_{ab} \right) \nabla_a W(\vec{r}_a - \vec{r}_b, h)$$

$$+ \sum_b m_b \left[\left(\frac{\mathcal{M}_{ij}}{\rho_{ab}^2} \right)_a + \left(\frac{\mathcal{M}_{ij}}{\rho^2} \right)_b \right] \nabla_{a,j} W(\vec{r}_a - \vec{r}_b, h)$$

$$- \sum_b \frac{m_b}{(|\vec{r}_a - \vec{r}_b|^2 + \epsilon_a^2)^{1.5}} (\vec{r}_a - \vec{r}_i)$$

$$\frac{\mathrm{d}A_a}{\mathrm{d}t} = \frac{1}{2} \frac{\gamma - 1}{\rho_a^{\gamma-1}} \sum_b m_b \Pi_{ab} \vec{v}_{ab} \cdot \nabla_a \bar{W}_{ab}$$

$$+ \frac{2\mu}{k_B} \frac{\gamma - 1}{\rho_a^{\gamma-1}} \sum_b \frac{m_b}{\rho_a \rho_b} \frac{4\kappa_a \kappa_b}{\kappa_a + \kappa_b} \left(\frac{A_b}{\rho_b^{\gamma-1}} - \frac{A_a}{\rho_a^{\gamma-1}} \right) \frac{\nabla_a W(\vec{r}_a - \vec{r}_b, h)}{(x_a - x_b)^2}$$

$$- \frac{\eta_m (\gamma - 1)}{2\mu_0 \rho_a^{\gamma-1}} \sum_b \frac{m_b}{\rho_{ab}^2} \left(\vec{B}_a - \vec{B}_b \right)^2 \nabla_a W(\vec{r}_a - \vec{r}_b, h)$$

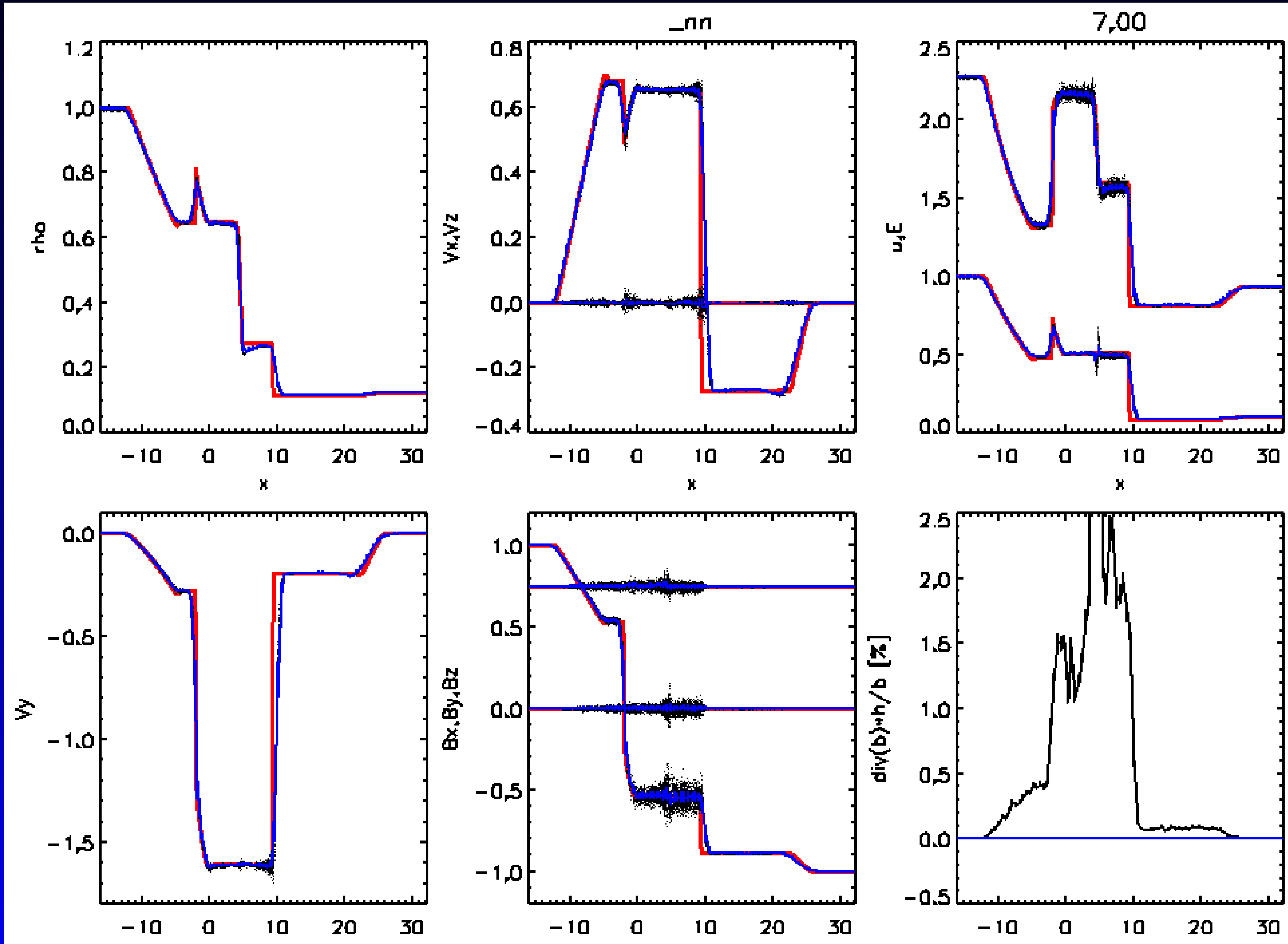
$$- \Lambda(T, \vec{z}) + \epsilon_{\mathrm{SN}} + \epsilon_{\mathrm{AGN}}$$

$$\frac{\mathrm{d}\vec{B}_{a,j}}{\mathrm{d}t} = \frac{f_i^{\mathrm{co}}}{\rho_a} \sum_b m_b (\vec{B}_{a,j} \vec{v}_{ab} - \vec{v}_{ab,j} \vec{B}_a) \nabla_a W(\vec{r}_a - \vec{r}_b, h)$$

$$+ \eta_m \rho_a \sum_b \frac{m_b}{\rho_{ab}^2} \left(\vec{B}_a - \vec{B}_b \right) \nabla_a W(\vec{r}_a - \vec{r}_b, h)$$

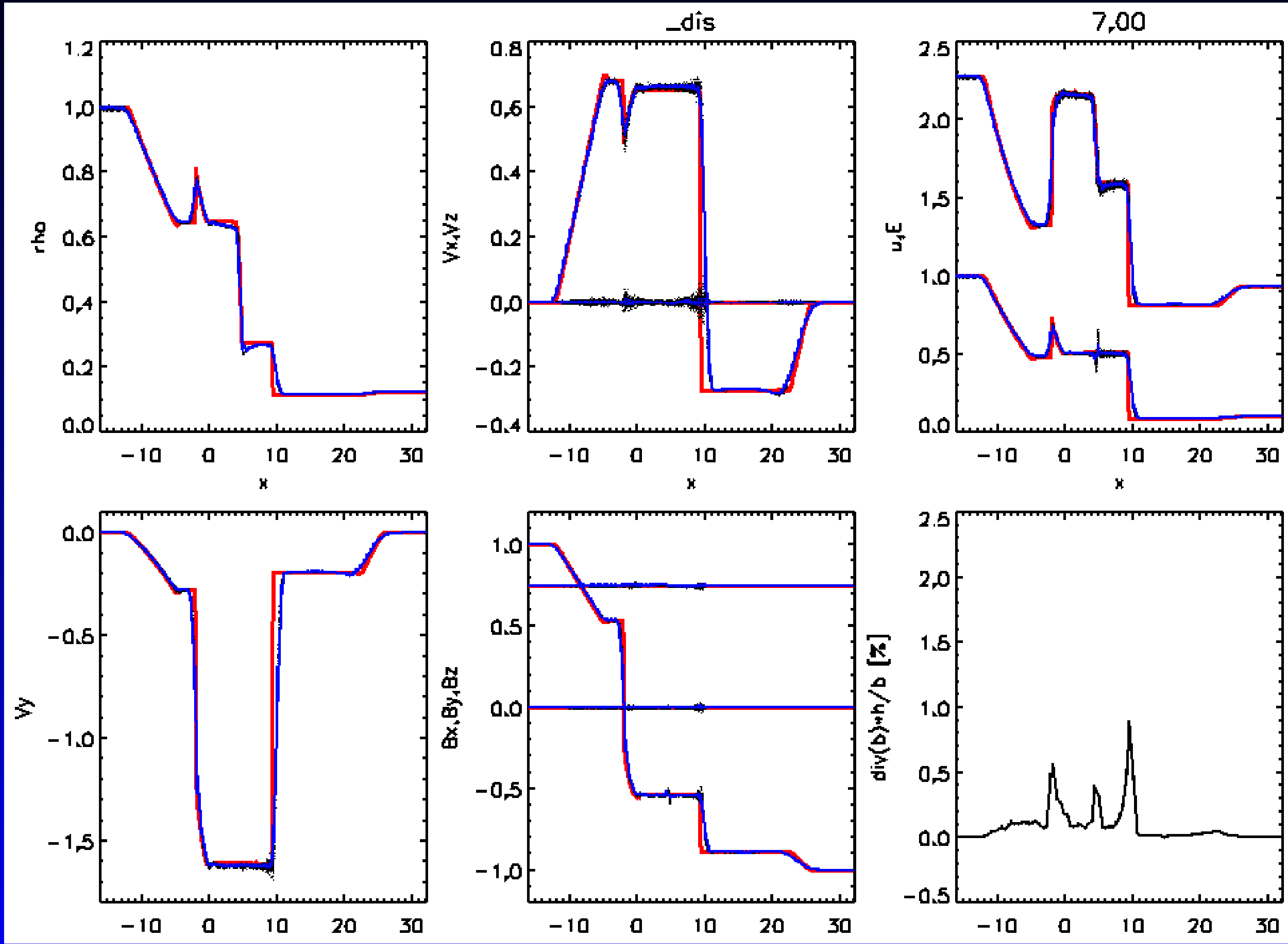
$$+ \frac{\sqrt{\dot{N}_{\mathrm{SN}} \Delta t}}{\Delta t} B_{SN} \left(\frac{r_{\mathrm{SN}}}{r_{\mathrm{SB}}} \right)^2 \left(\frac{r_{\mathrm{SB}}}{r_{\mathrm{inj}}} \right)^3 e_B$$

Performance (I)



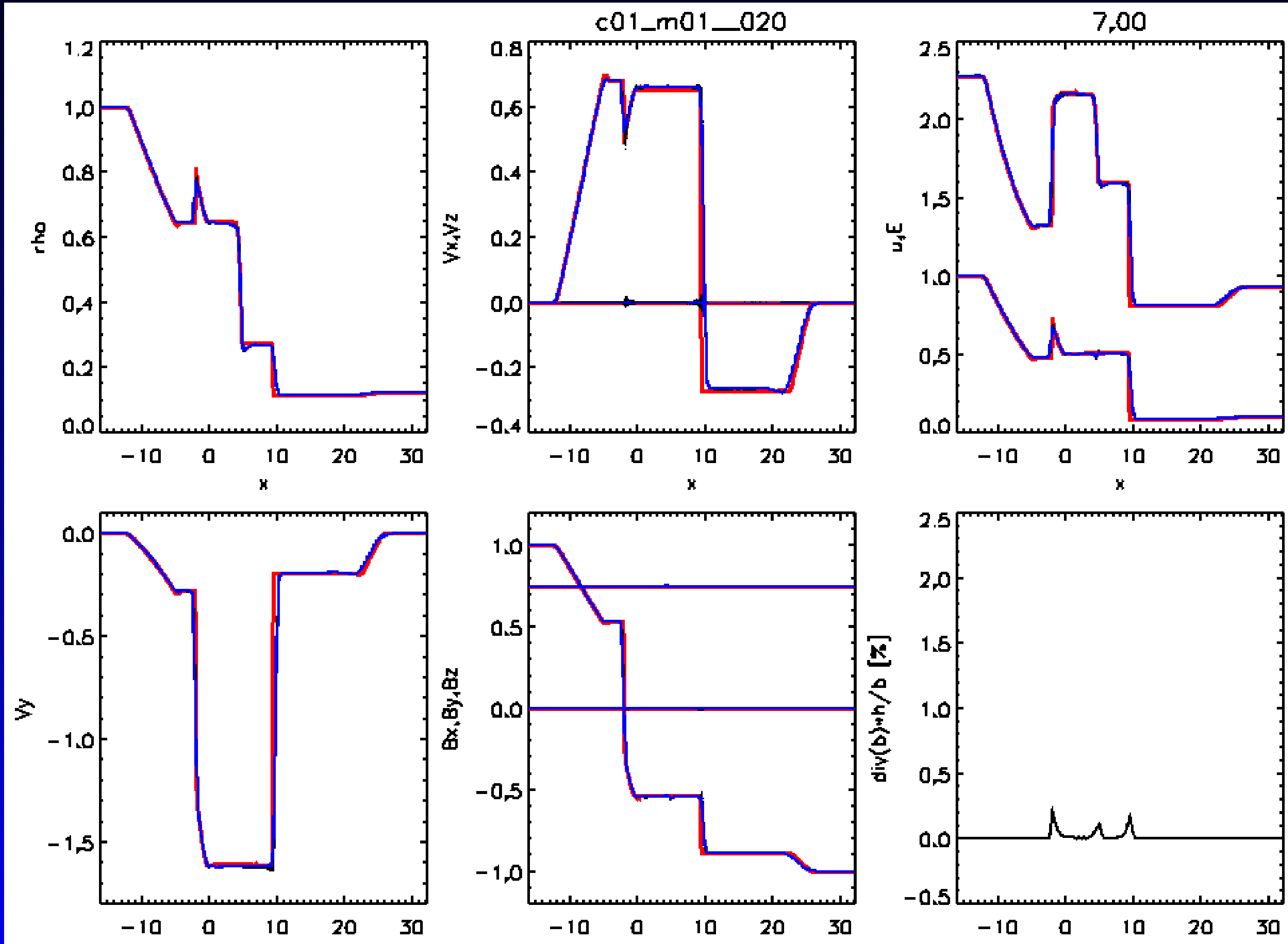
Tube 5A (Ryu & Johns 1995) std SPH MHD (Dolag et al 2005) in 3D.

Performance (I)



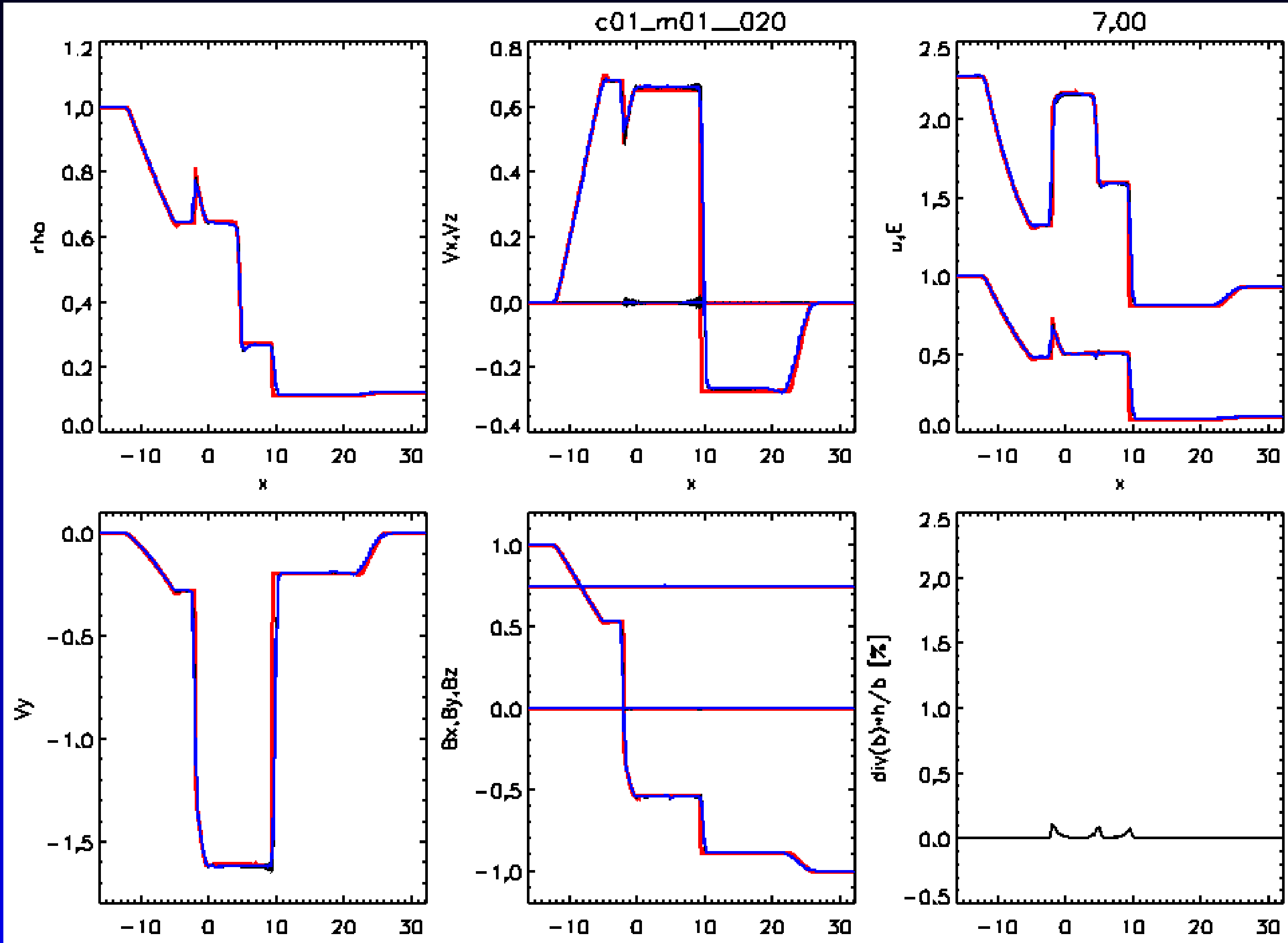
SPH MHD with art. $\vec{B}$ diffusion (Dolag & Stasyszyn 2009).

Performance (I)



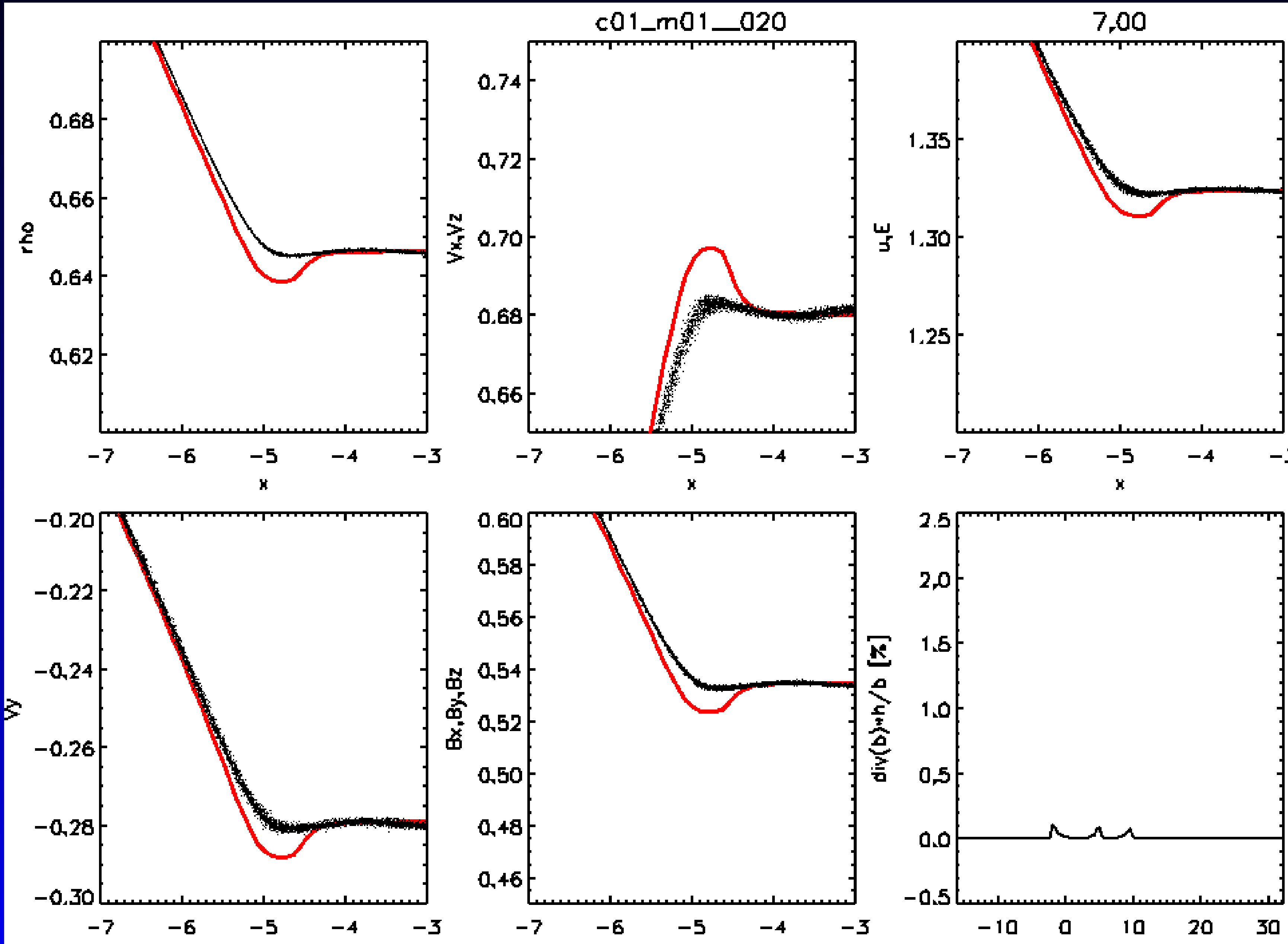
SPH MHD with quintic kernel (Beck et al, in prep).

Performance (I)



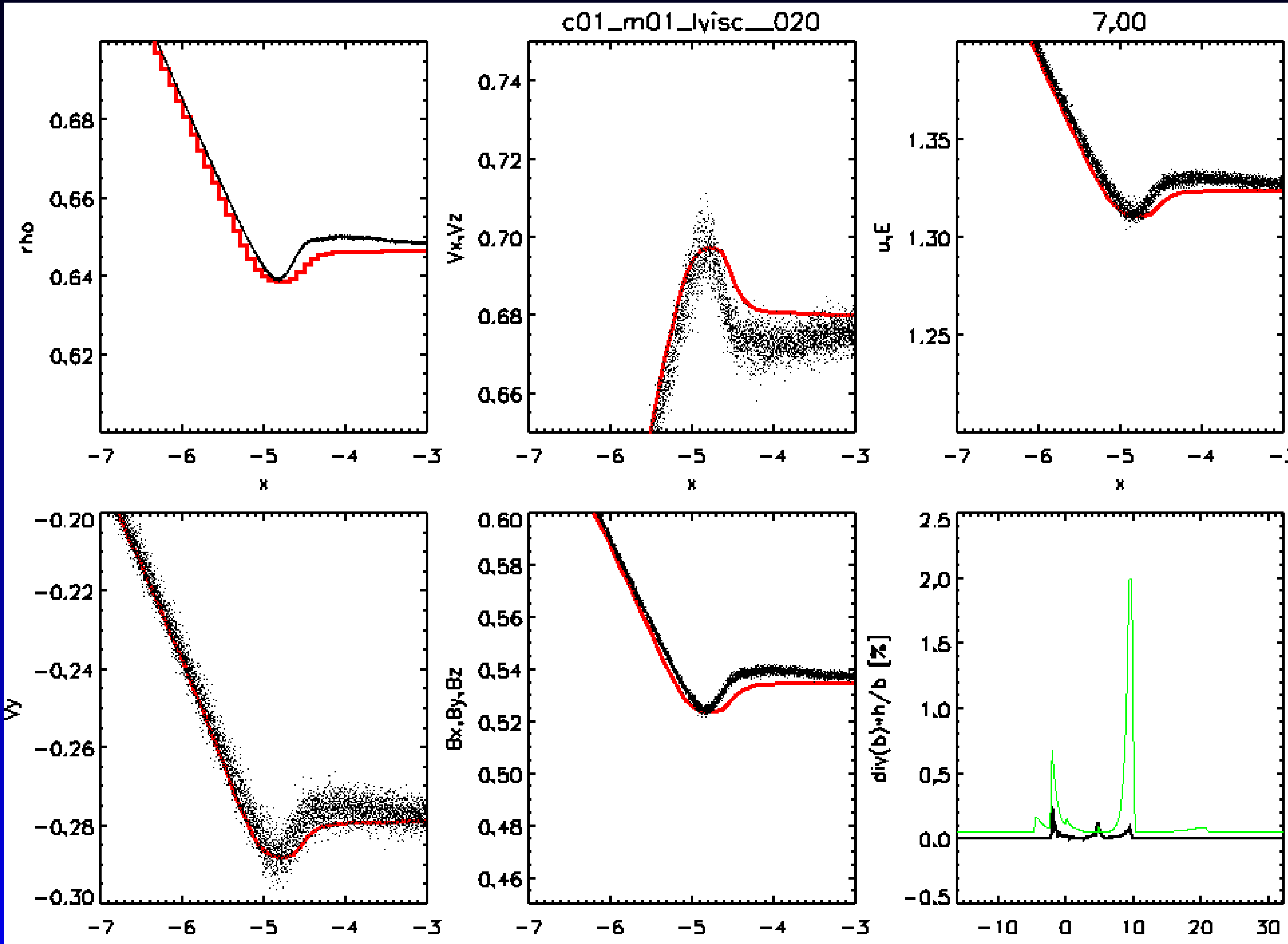
SPH MHD with WC4 kernel (Beck et al, in prep).

Performance (I)



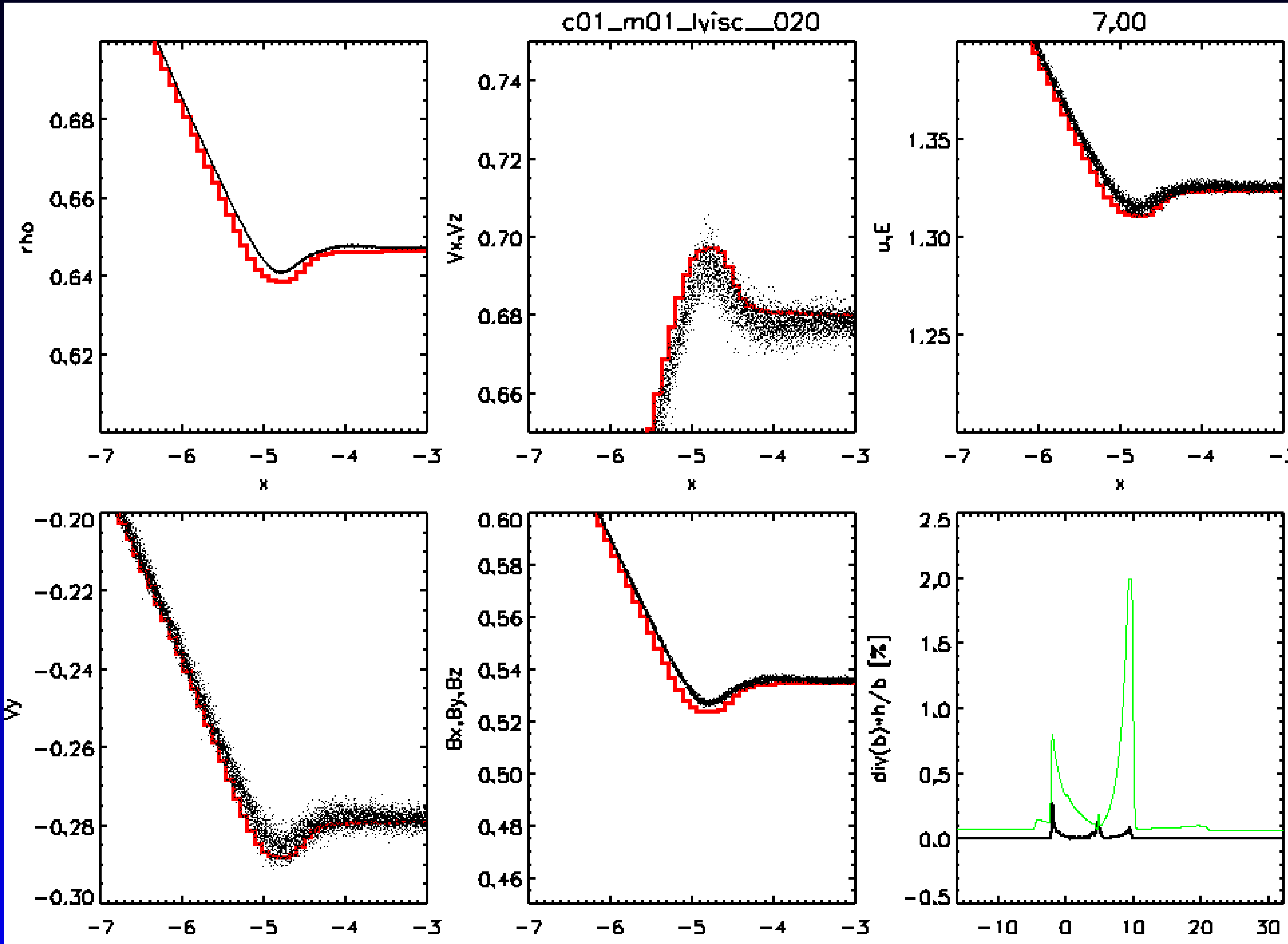
SPH MHD with WC4 kernel (Beck et al, in prep).

Performance (I)



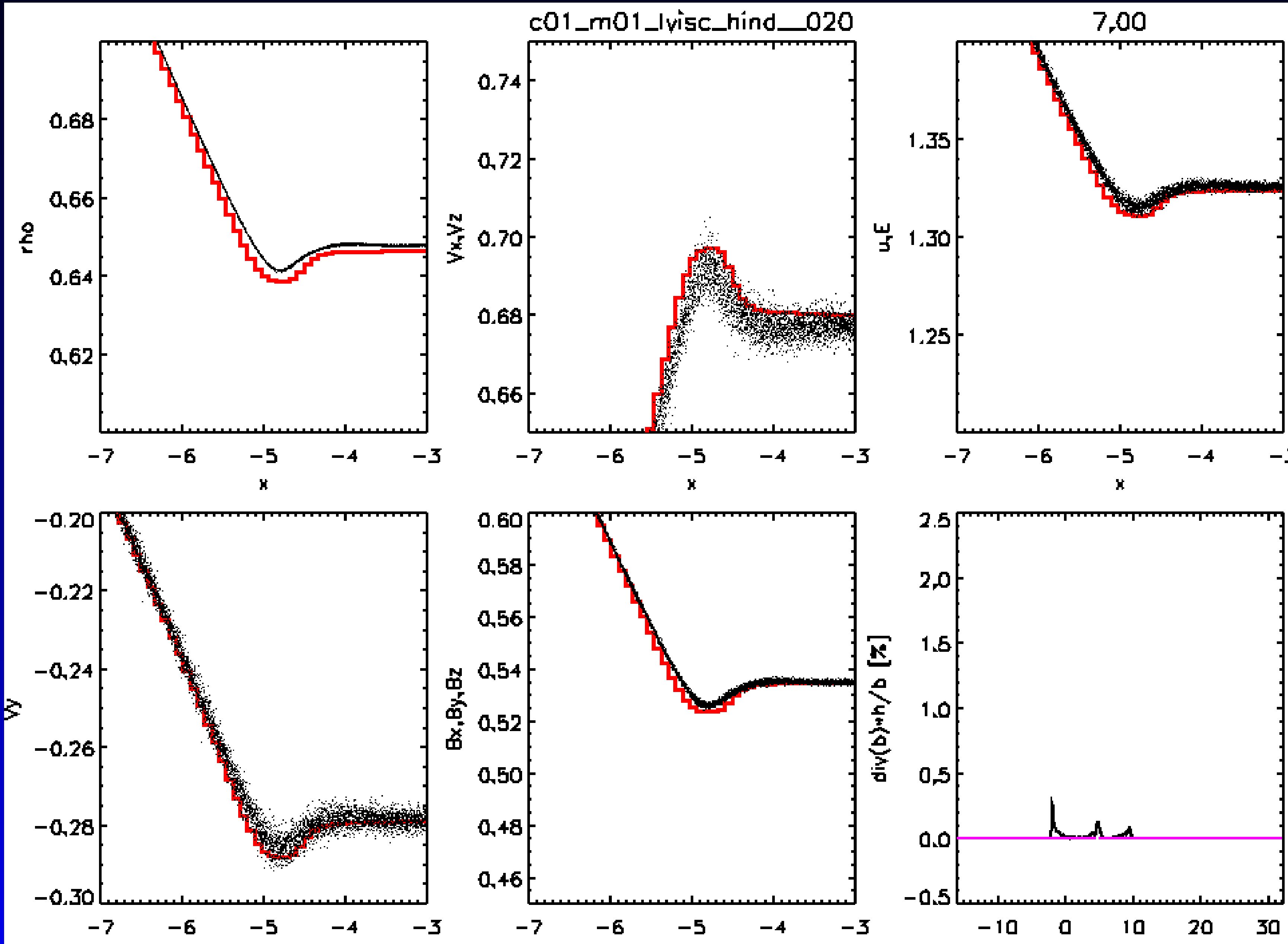
SPH MHD with WC4 kernel + viscosity switch (Beck et al, in prep).

Performance (I)



SPH MHD with WC6 kernel + viscosity switch (Beck et al, in prep).

Performance (I)



Including higher order terms in induction equation (Beck et al, in prep).

Performance (I)

High order terms for derivatives:

$$\nabla A(\vec{r}) = \sum_j \frac{m_j}{\rho}(A - A_j - (\vec{r_j} - \vec{r})^\alpha \frac{\partial A}{\partial r^\alpha})\nabla W(\vec{r} - \vec{r_j}, h)$$

for $\frac{\partial \vec{v}}{\partial r^\alpha}$ in idnduction equation we need to invert

$$X^{\alpha\beta} = \sum_j \frac{m_j}{\rho}(\vec{r_j} - \vec{r})^\alpha \nabla^\beta W(\vec{r} - \vec{r_j}, h)$$

which leads to

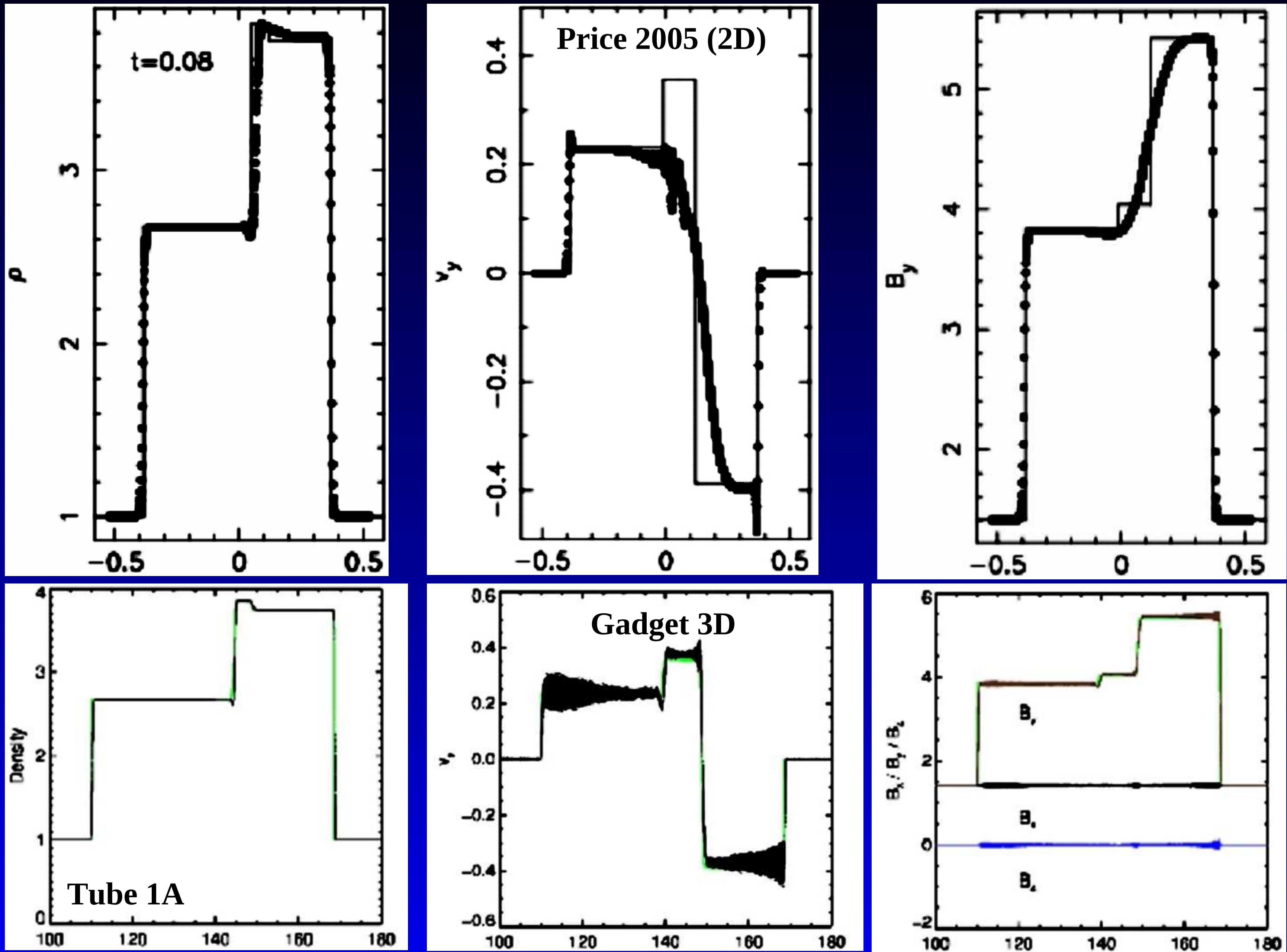
$$\frac{dB_i^k}{dt} = \sum_j \frac{m_j}{\rho_i}\left((\Delta v)^k B_i^l - B_i^k (\Delta v)^l\right)\frac{\partial W_{ij}}{\partial r}\frac{r_{ij}^l}{|r_{ij}|}$$

with

$$\Delta v = \left(\vec{v}_i - \vec{v}_j - (\vec{r_j} - \vec{r_i})^\alpha \frac{\partial \vec{v}}{\partial r^\alpha}\right)$$

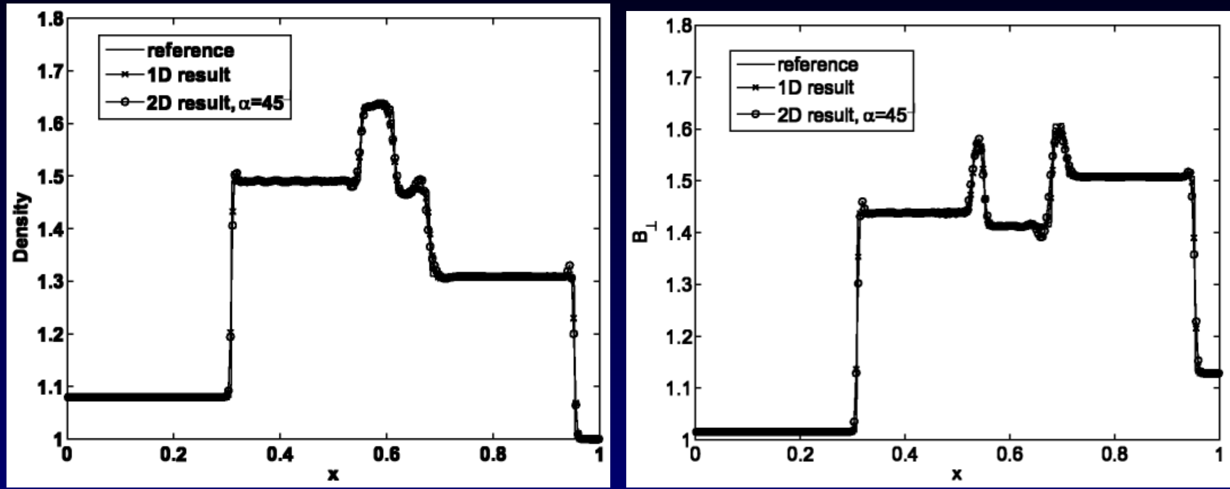
(Beck et al, in prep).

Performance (I)

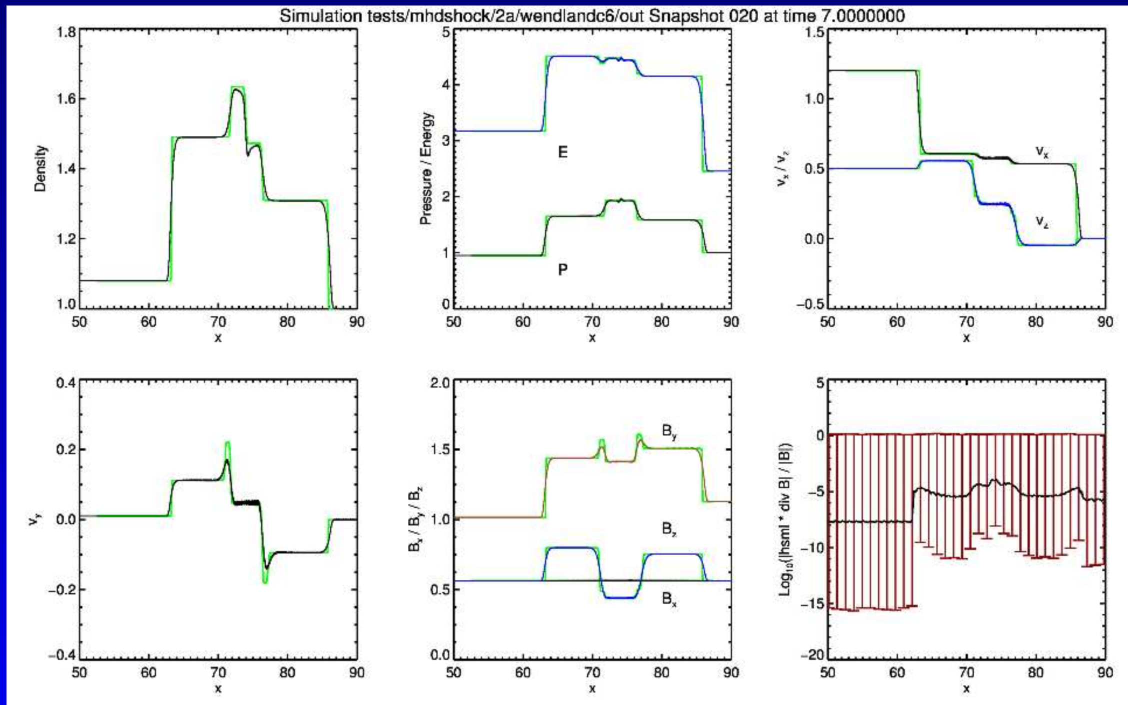


SPH MHD with WC6 kernel + viscosity switch (Beck et al, in prep).

Performance (I)



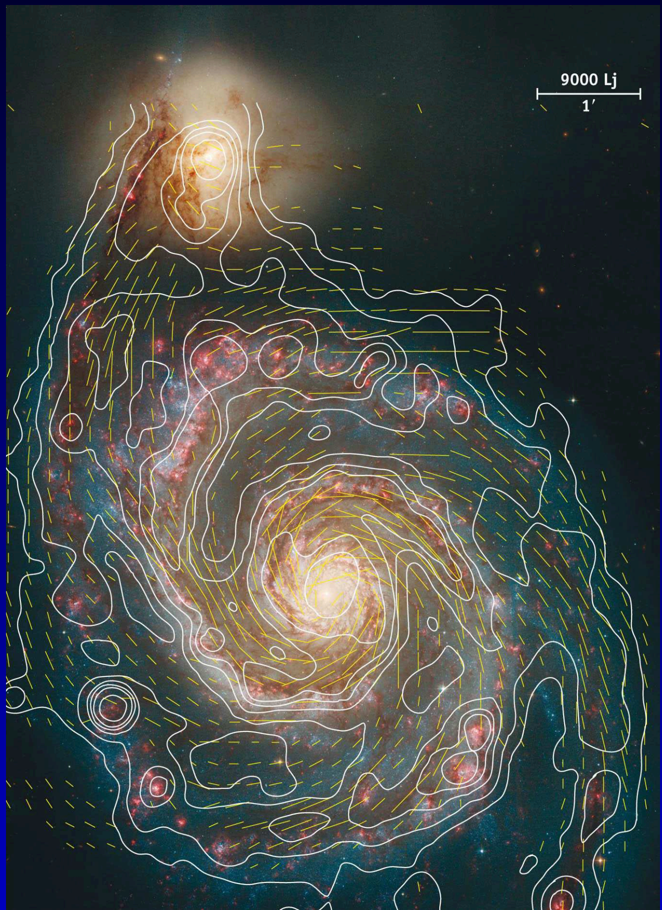
CosmoMHD (Li, Li & Cen 2006) in 2D and in 45 degree.

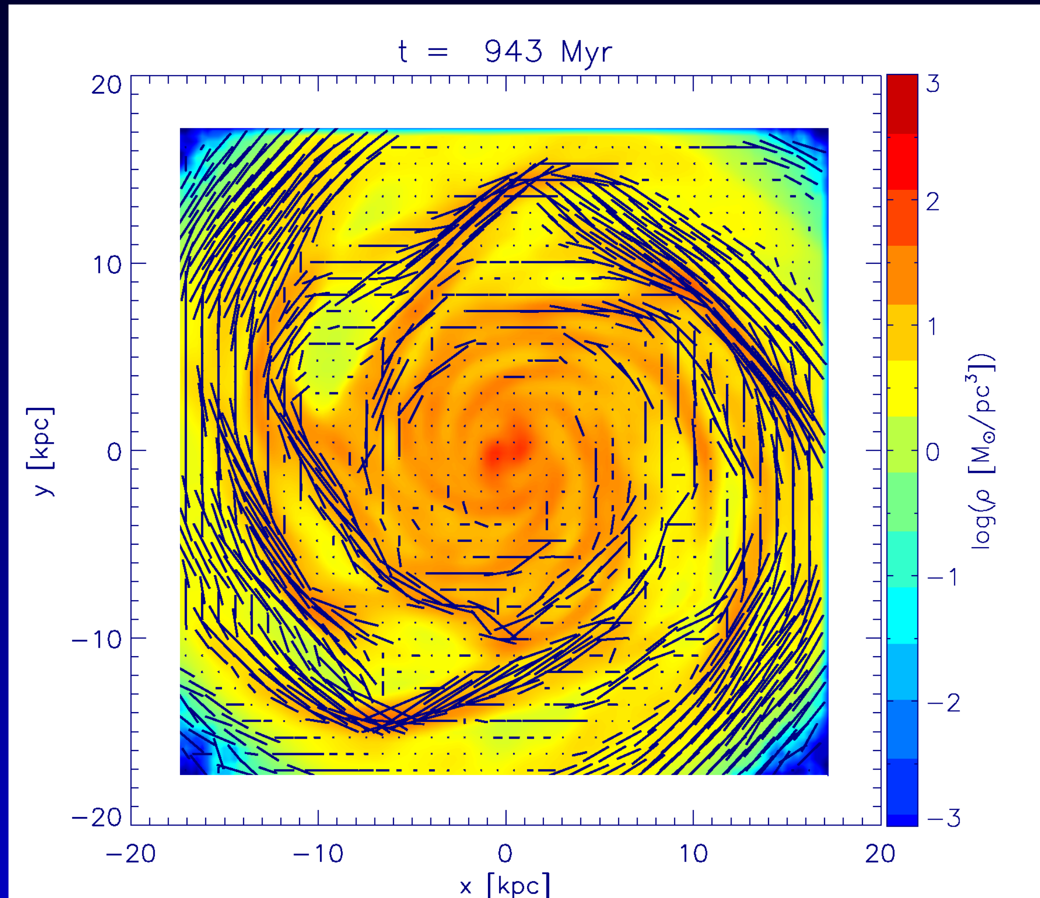


SPH MHD with WC6 kernel + viscosity switch (Beck et al, in prep).

Magnetic Field buildup

Simulations on galaxy scales ...

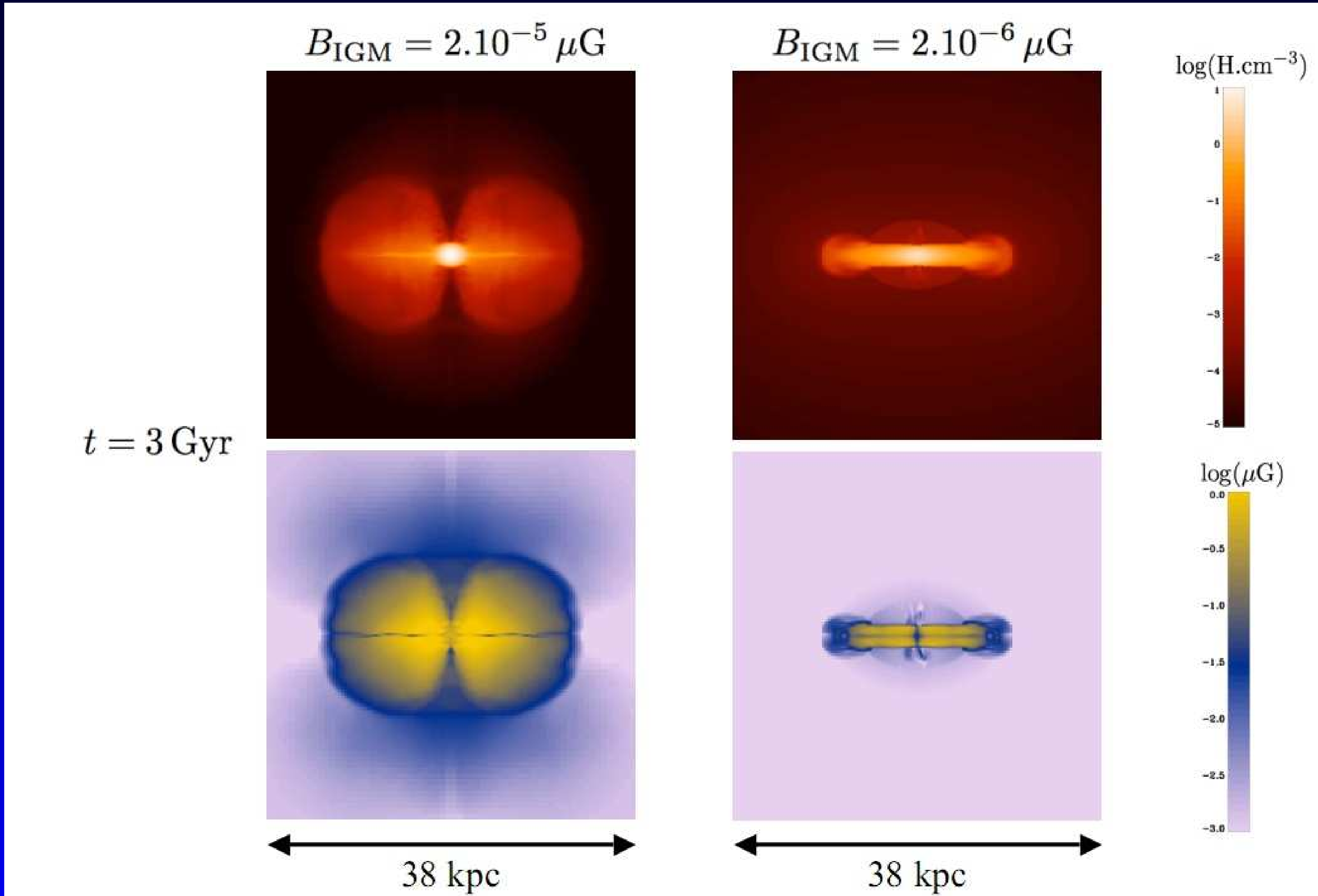




M51 (Fletcher & Beck 2006) and a simulation using the MHD implementation in Gadget (Kotarba et al. 2009).

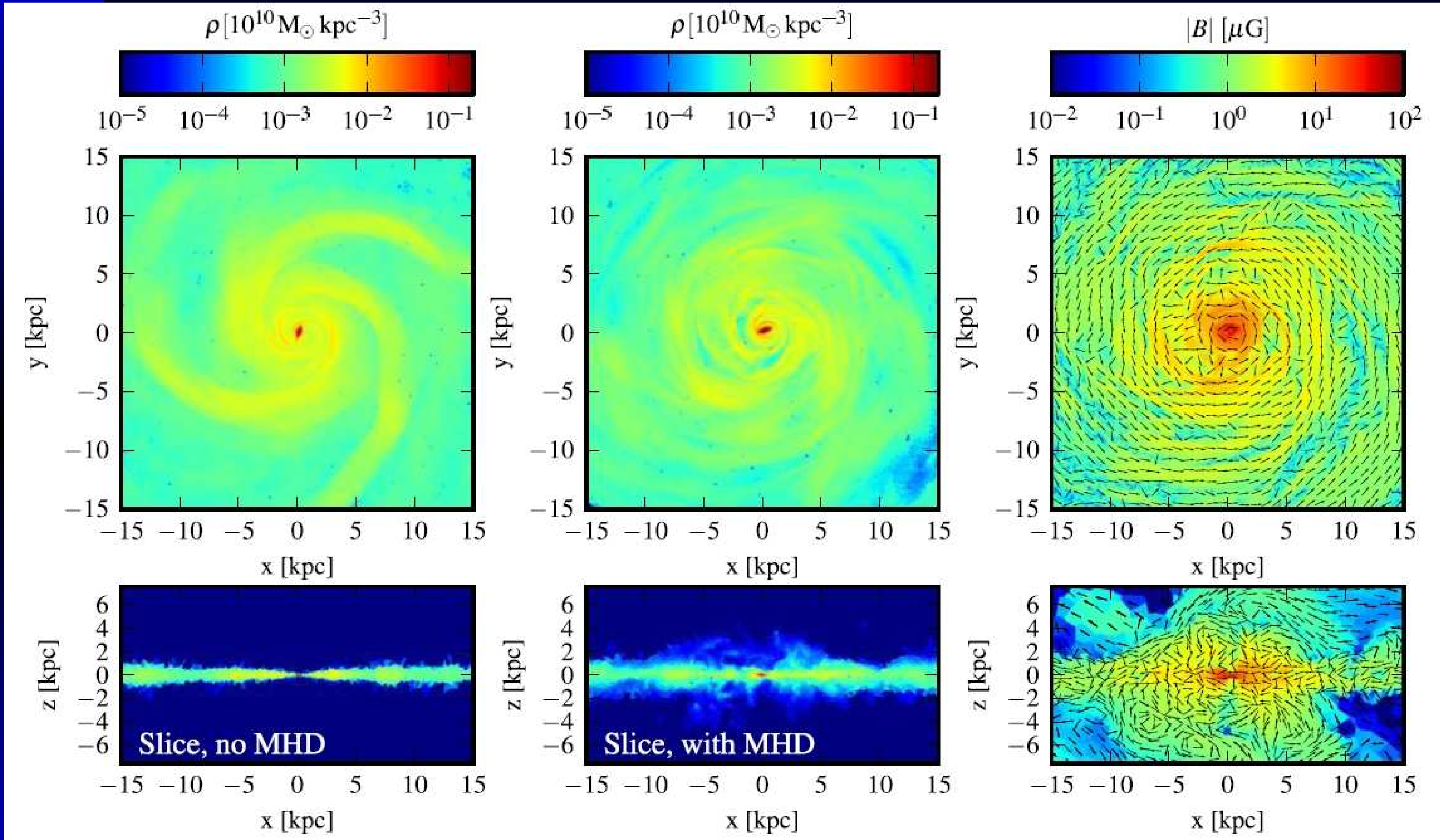
Magnetic Field buildup

Problems with **formation** of dwarf **galaxies** if $B_{back} > 10^{-5} \mu G$



(RAMSES, Teyssier 2009)

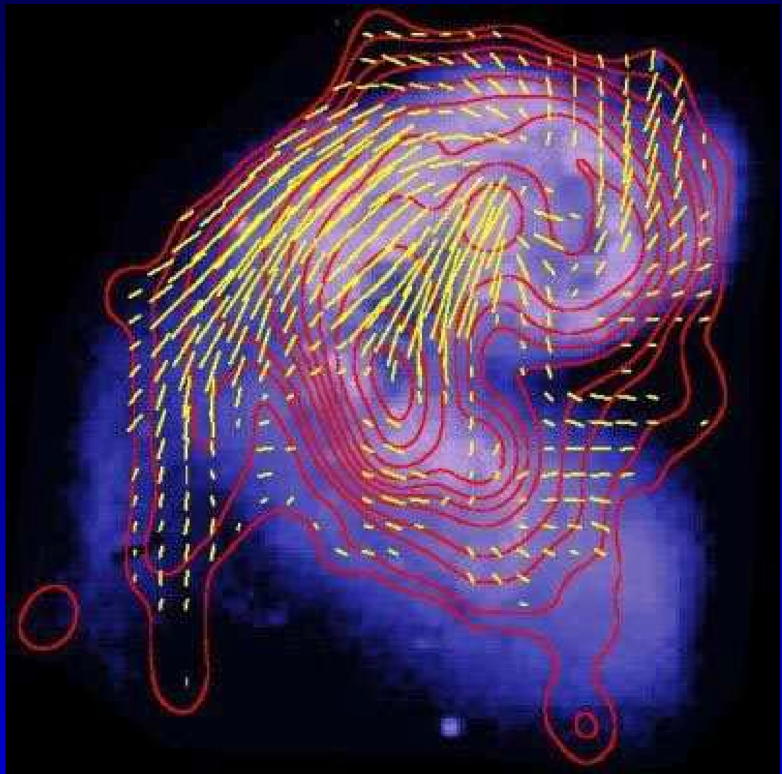
Magnetic Field buildup

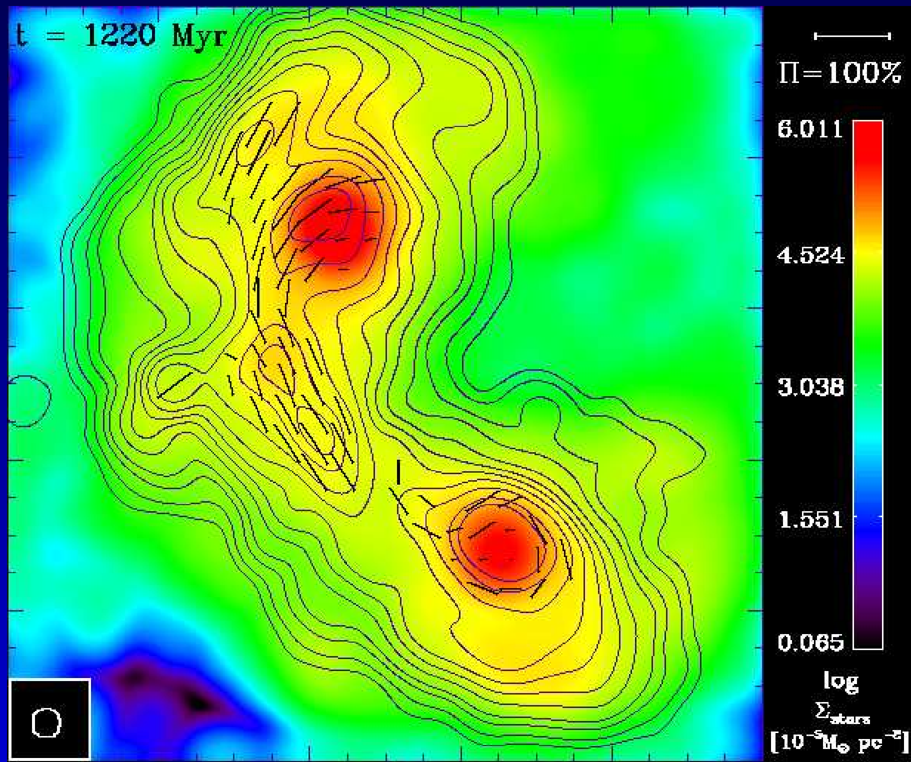


See also Wang & Abel 2009, Dubois & Teyssier 2010, Packmor & Springel 2013 and work on CR driven dynamo Hanasz 2004, Kulpa-Dybel 2011, ...

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

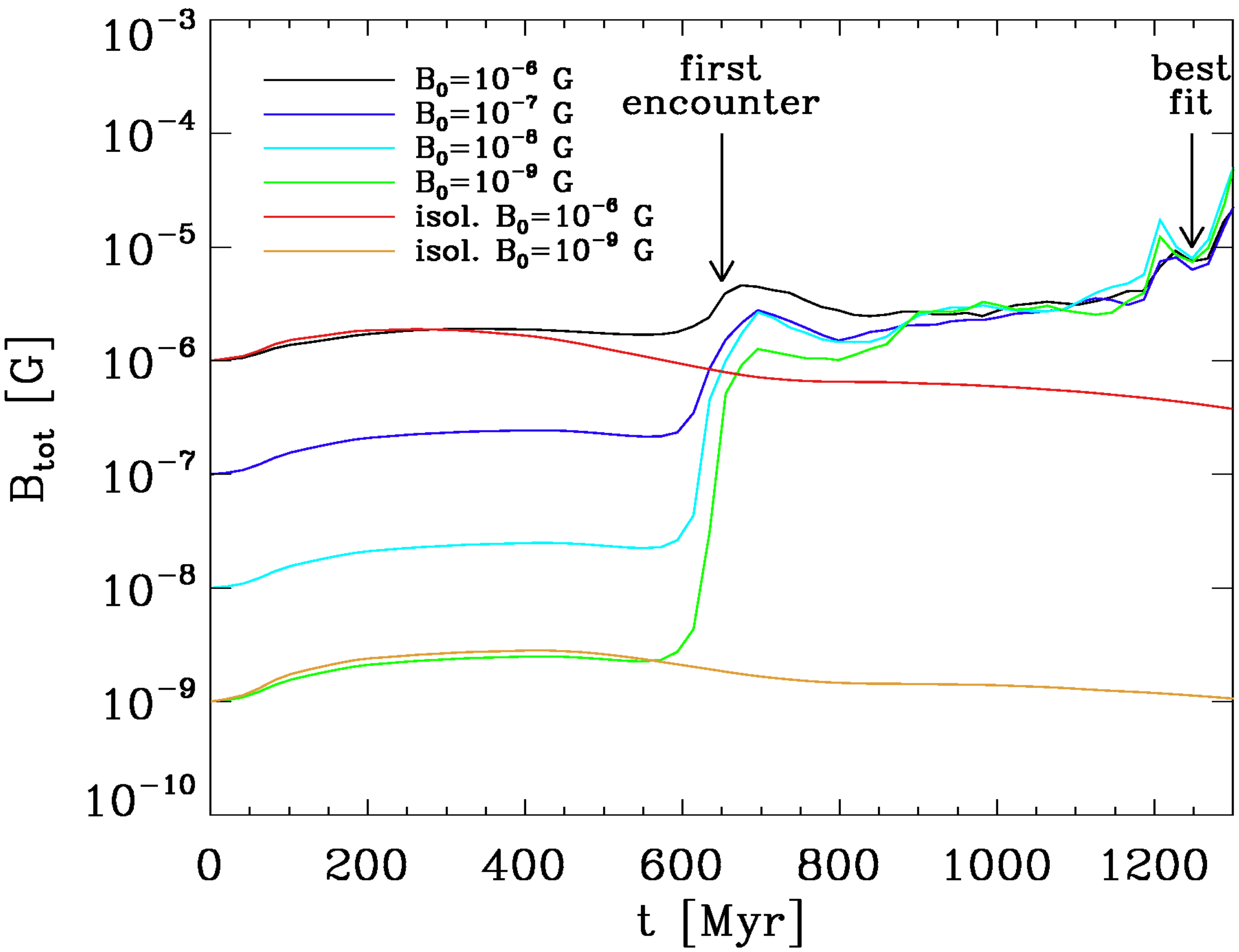
Simulating the magnetic field amplification during galaxy mergers like in the Antennae system. Final magnetic field strength and field configuration in broad agreement with observations.

(Kotarba 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

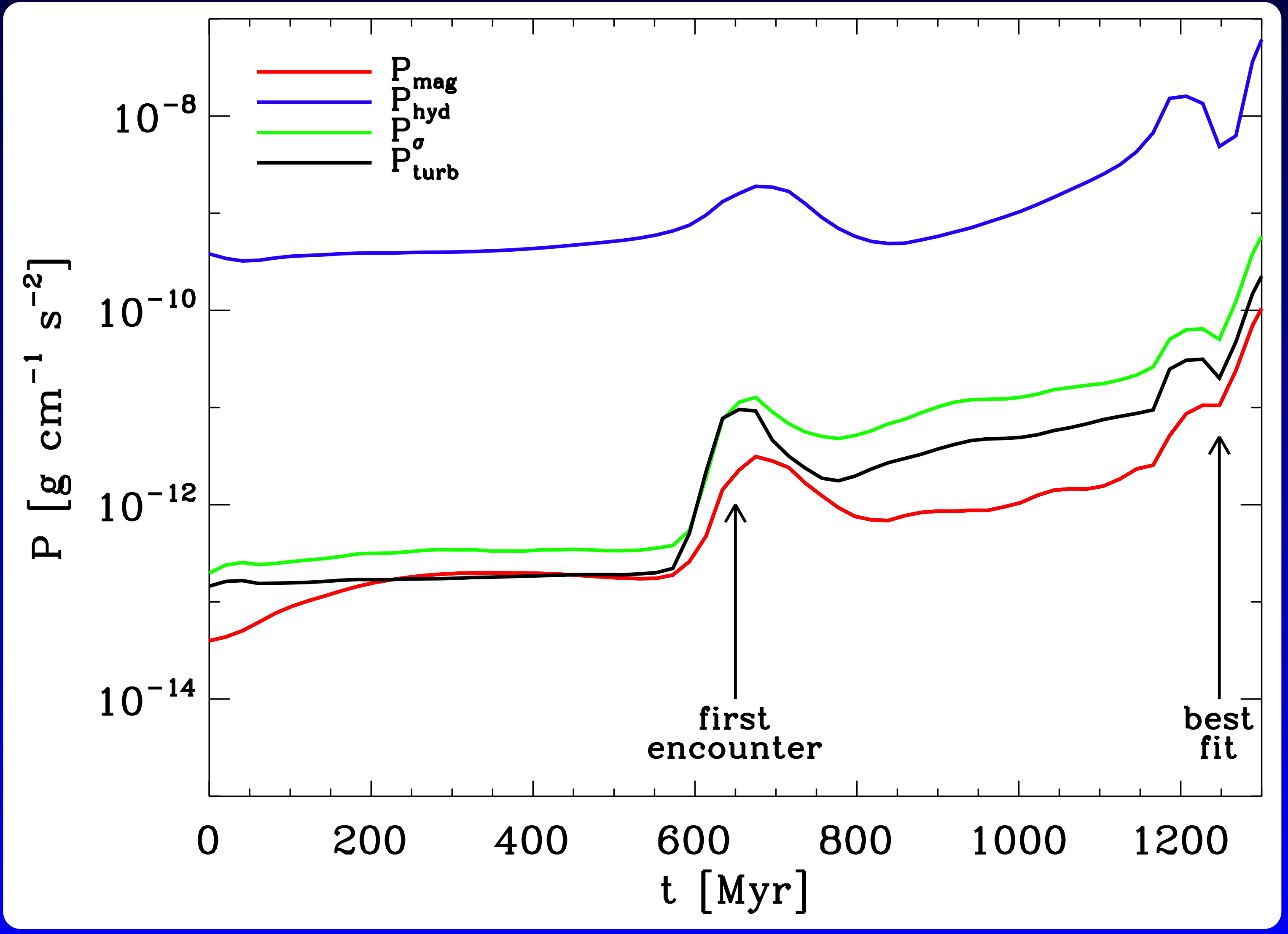


(Kortarba et al. 2010)

Magnetic Field buildup

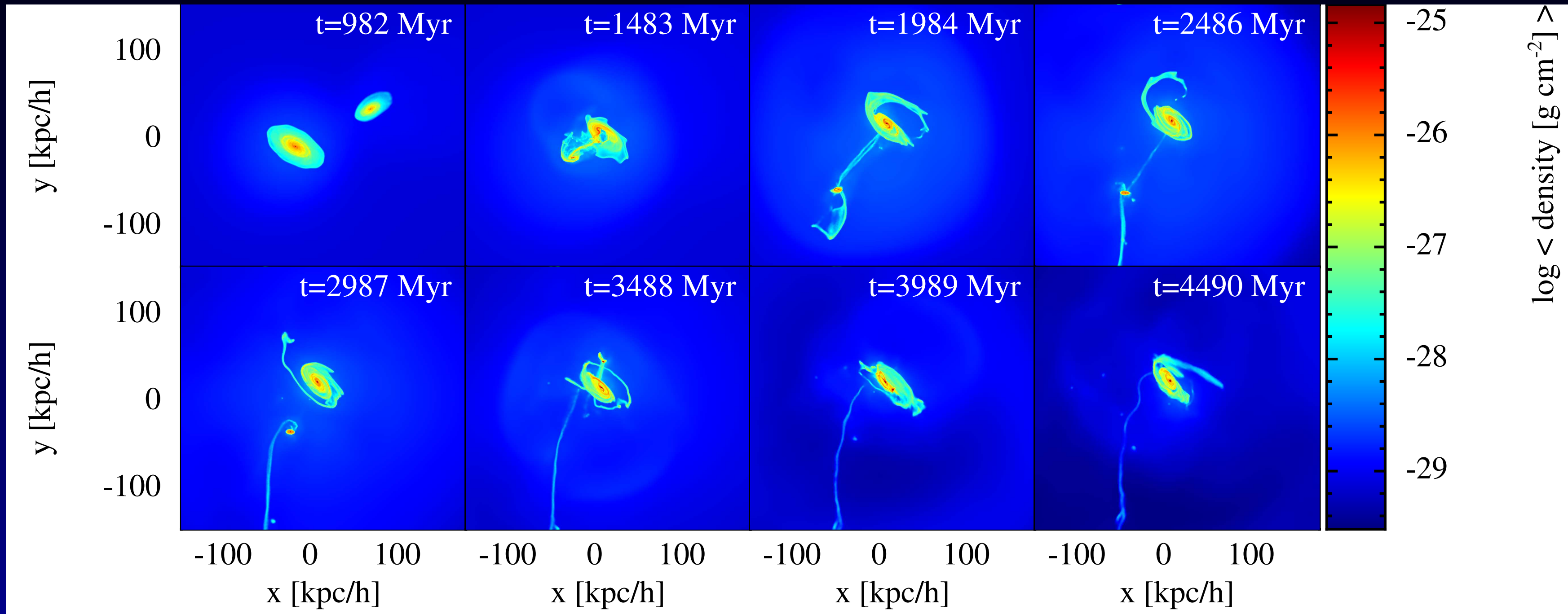
Final magnetic field close to equipartition with turbulent velocity component, quasi independent of initial field values.

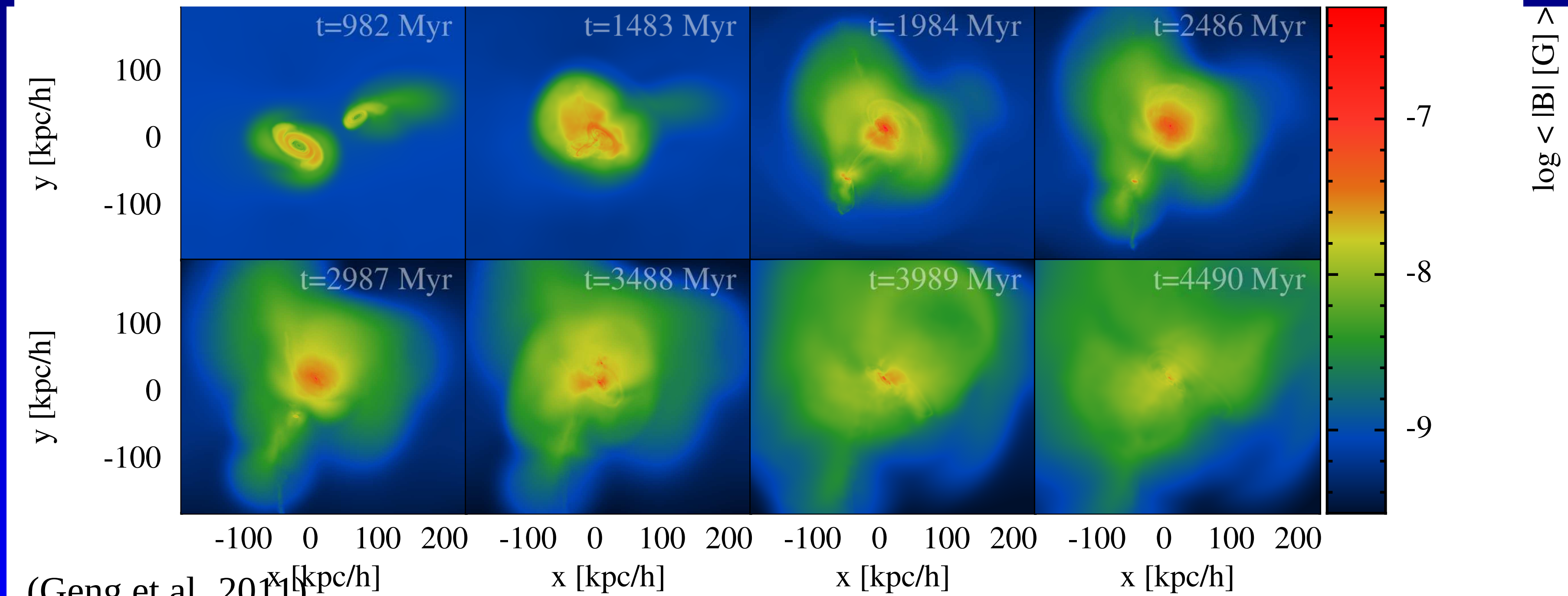
⇒ Hierarchical buildup of magnetic field



(Kortarba et al. 2010)

Magnetic Field buildup





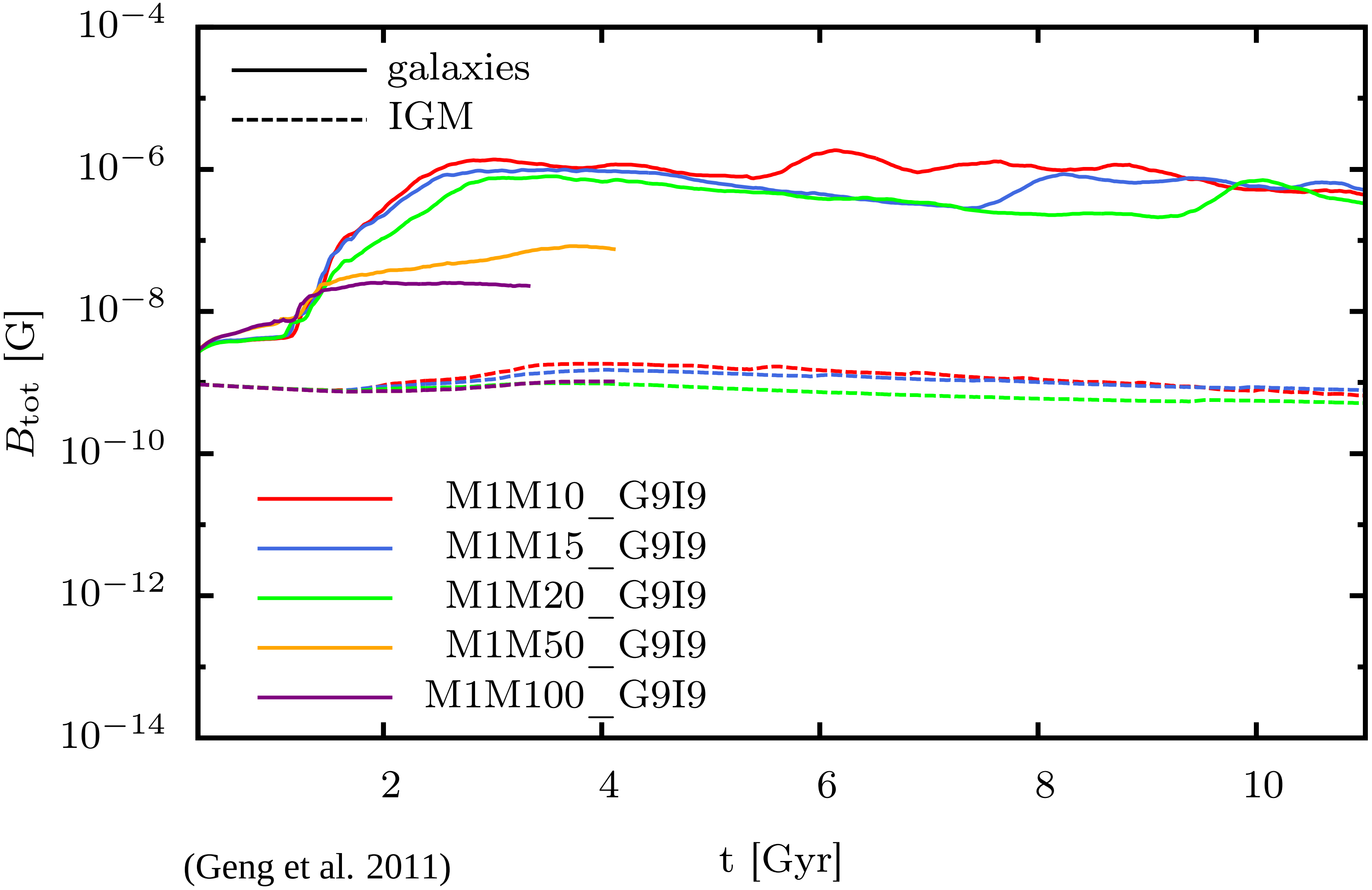
(Geng et al. 2011)

Magnetic Field buildup

(Geng et al. 2011)

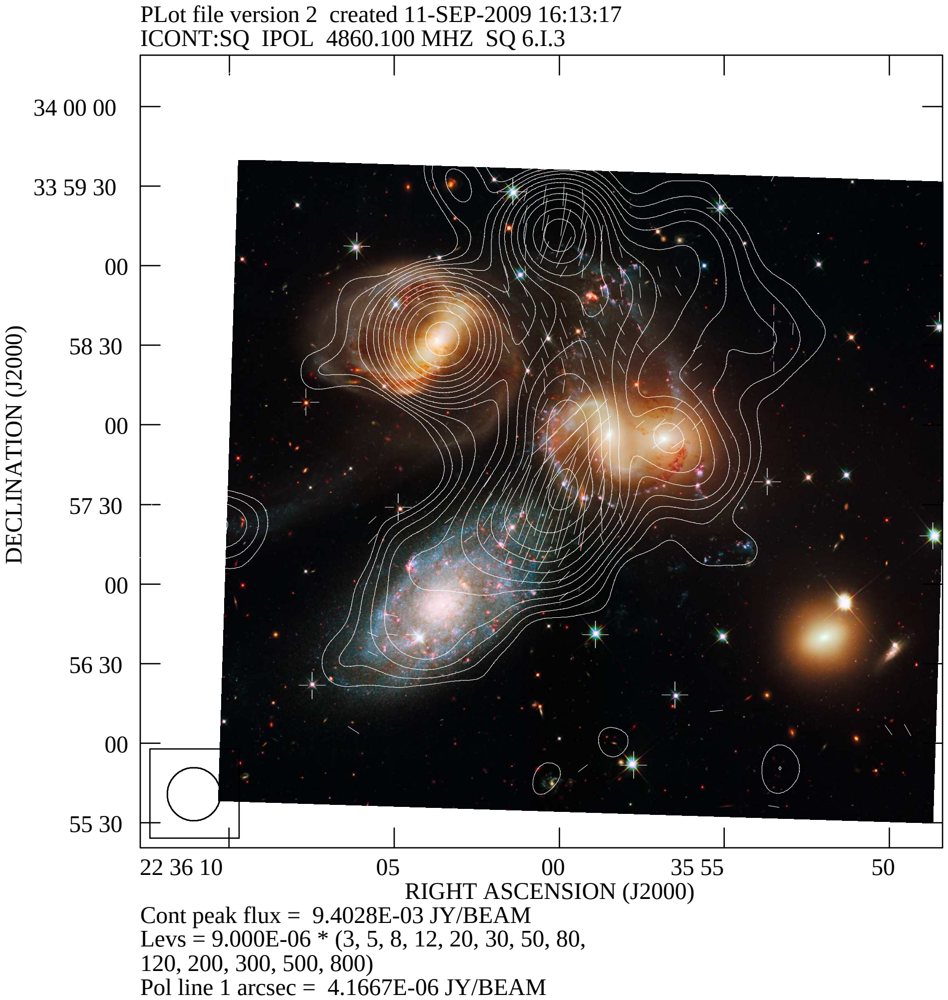
Magnetic Field buildup

Smaller merger less efficient in driving turbulence.

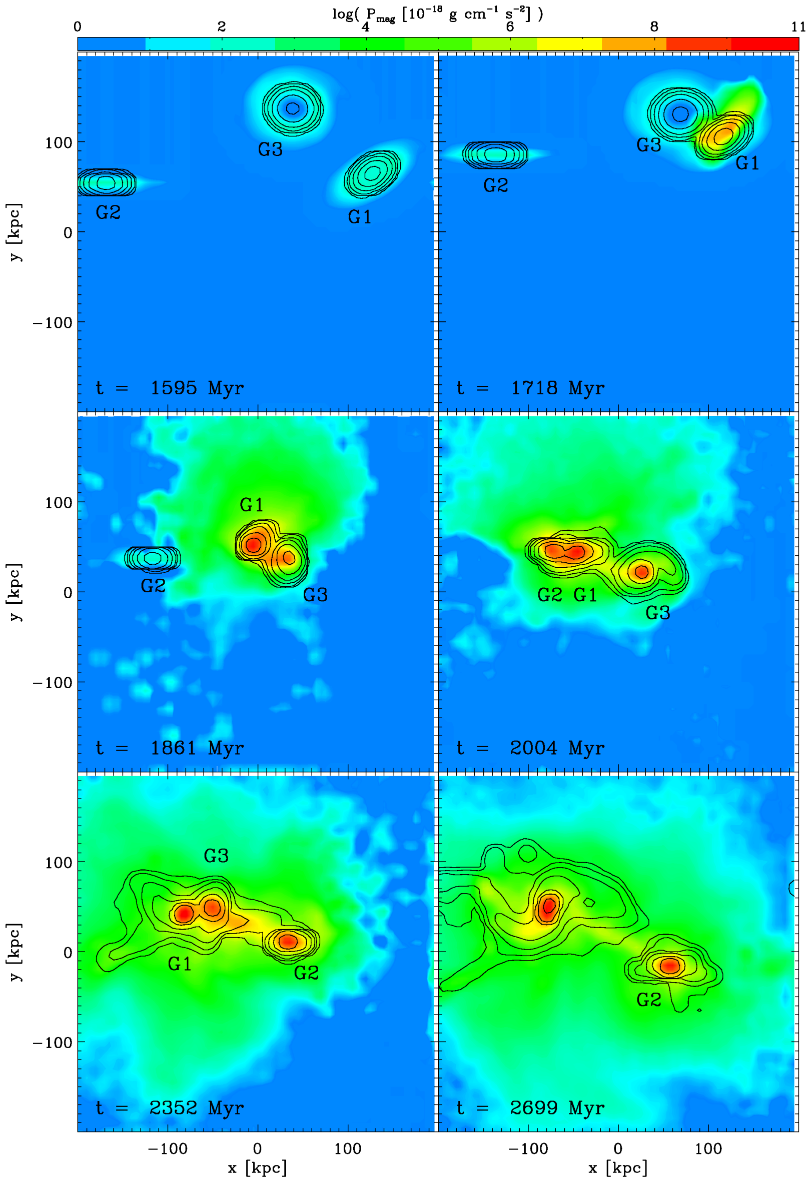


(Geng et al. 2011)

Magnetic Field buildup

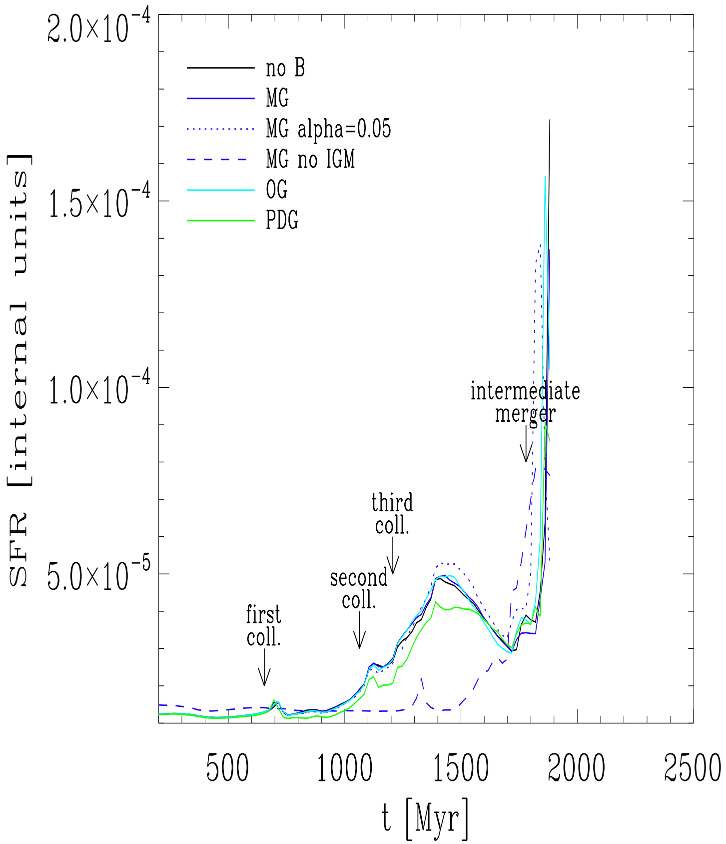


Soida et al., in prep.



Kortarba et al. 2010

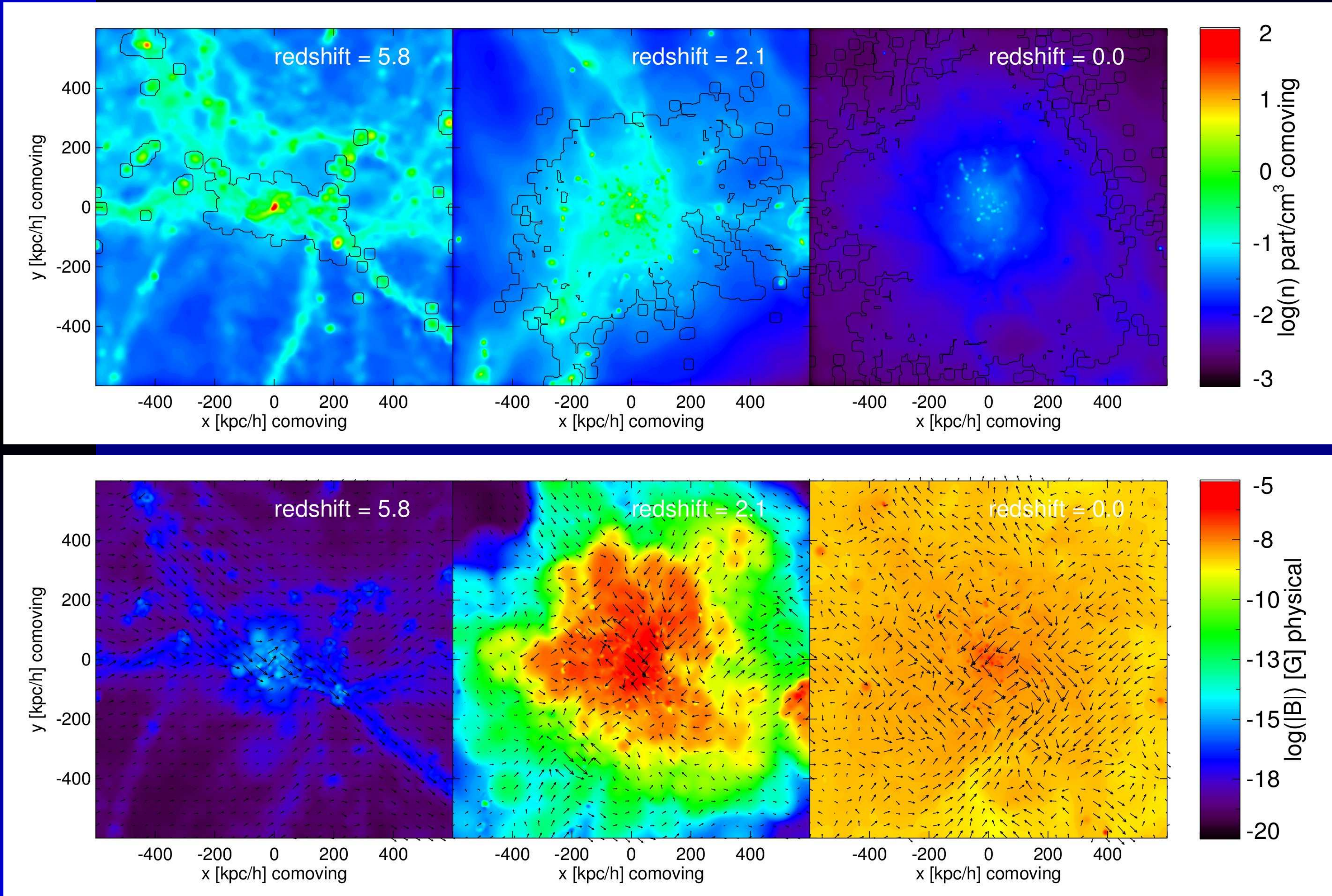
Magnetic Field buildup



Kotarba et al. 2010

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

Magnetic Field buildup



Growth of a magnetic field in **galactic halo** (Beck et al. 2012)

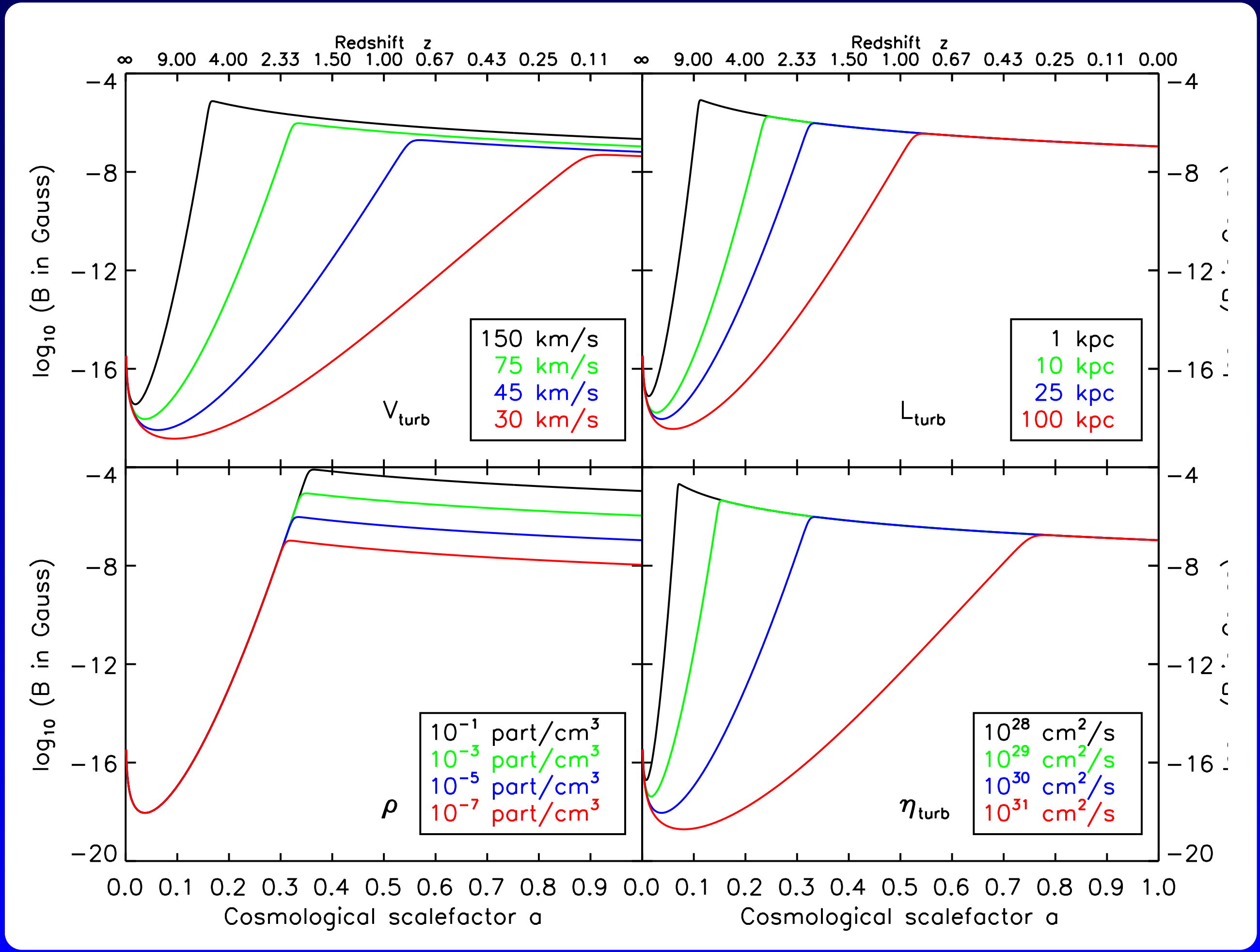
Magnetic Field buildup

Local perturbation ansatz leads to (Beck et al. 2012):

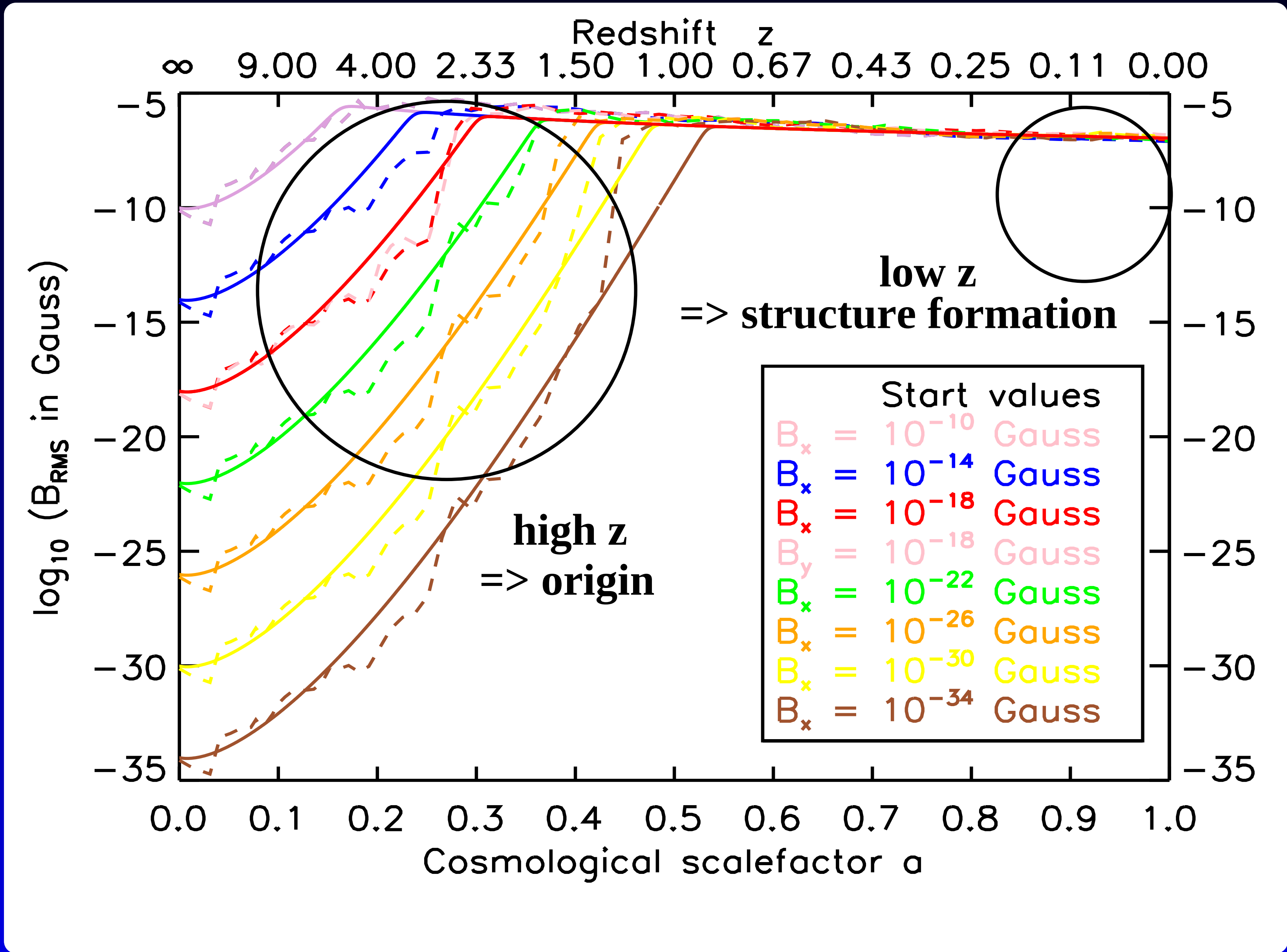
$$B_t(a) = \frac{1}{a^2}\left[(4\pi\rho v_{\rm turb}^2)^{-1} + B_0^{-2} e^{-2\gamma t(a)}\right]^{-\frac{1}{2}}$$

with

$$\gamma = 2.050 \frac{v_{\rm turb}^{3/2} k_{\rm turb}^{1/2}}{\eta_{\rm turb}^{1/2}}$$



Magnetic Field buildup



Comparison of **magnetic growth** and simple expectation for $v_{turb} = 100$km/s and $\lambda = 25$kpc. (Beck et al. 2012)

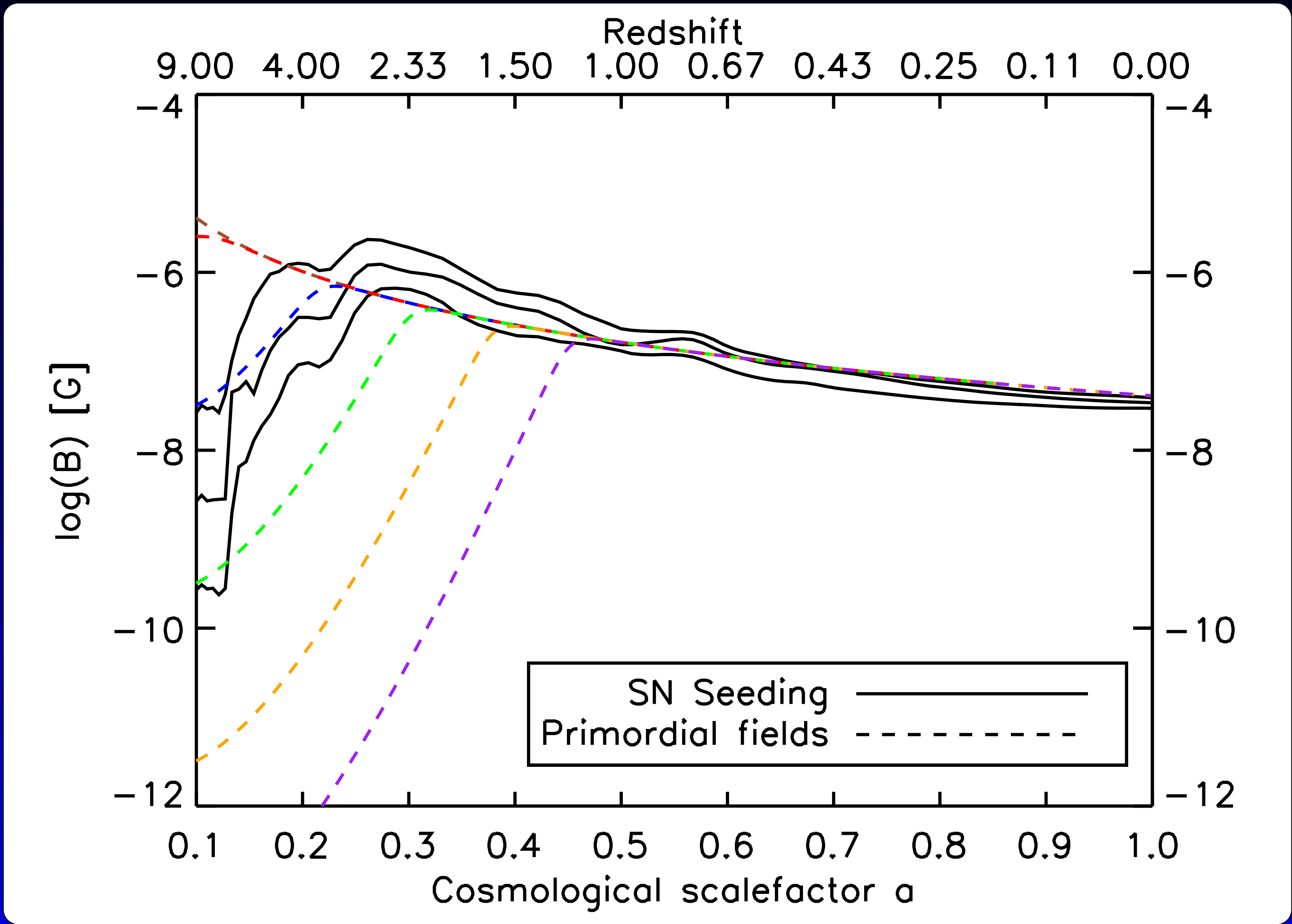
Magnetic Field buildup

A **sub-grid seeding** model based on **SN**:

$$\left.\frac{\partial \vec{B}}{\partial t}\right|_{\rm seed} = \frac{\sqrt{\dot{N}_{\rm SN}\Delta t}}{\Delta t} B_{SN} \left(\frac{r_{\rm SN}}{r_{\rm SB}}\right)^2 \left(\frac{r_{\rm SB}}{r_{\rm inj}}\right)^3 e_B$$

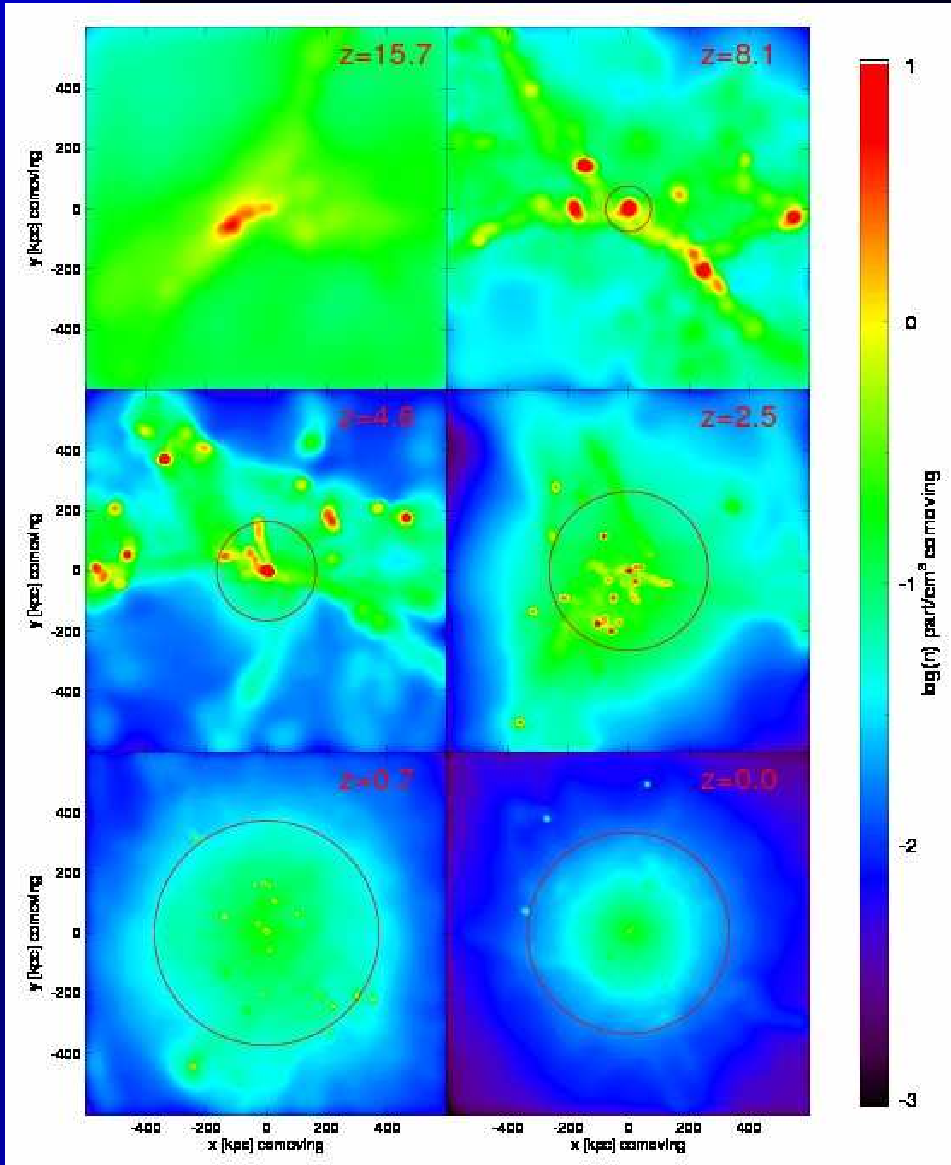
- Supernova remnant: $r_{\rm SN} \approx 5$pc, $B_{\rm SN} \approx 10^{-4}$G
- Bubble: $r_{\rm SB} \approx 25$pc
- Injection: $r_{\rm inj} = h_i$ (e.g. numerical resolution)
- e_B: normalized dipole vector
- $\dot{N}_{\rm SN}\Delta t < 1 \Rightarrow$ stochastic approach
- Limit diffusion: $L_d = v_D \Delta t$, $v_D = \sqrt{0.5(c_s^2 + v_a^2)}$
- $\eta = 10^{27}{\rm cm}^2{\rm s}^{-1}$

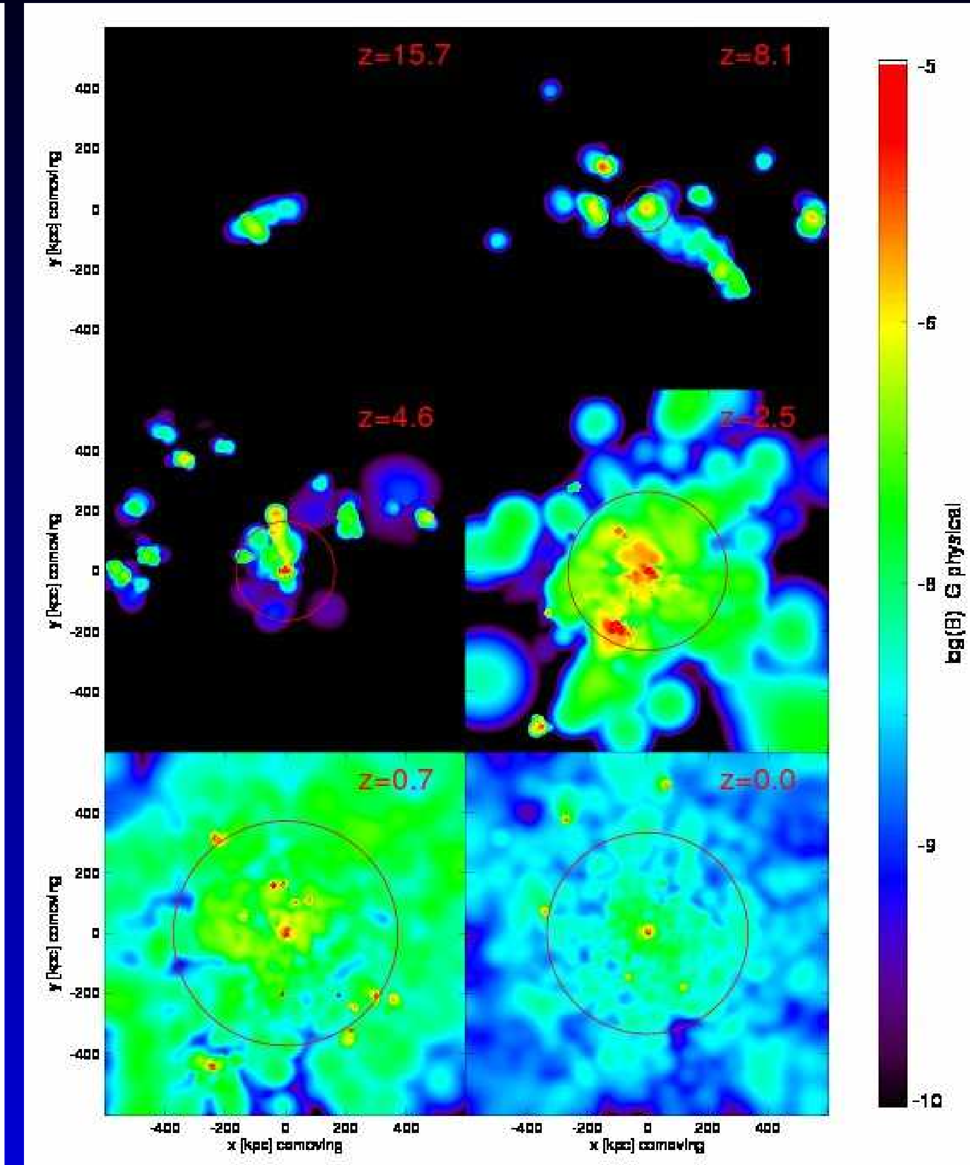
Magnetic Field buildup



Comparison of **magnetic growth** for **primordial** and for **seeding** from **star-formation**. (Beck et al., submitted)

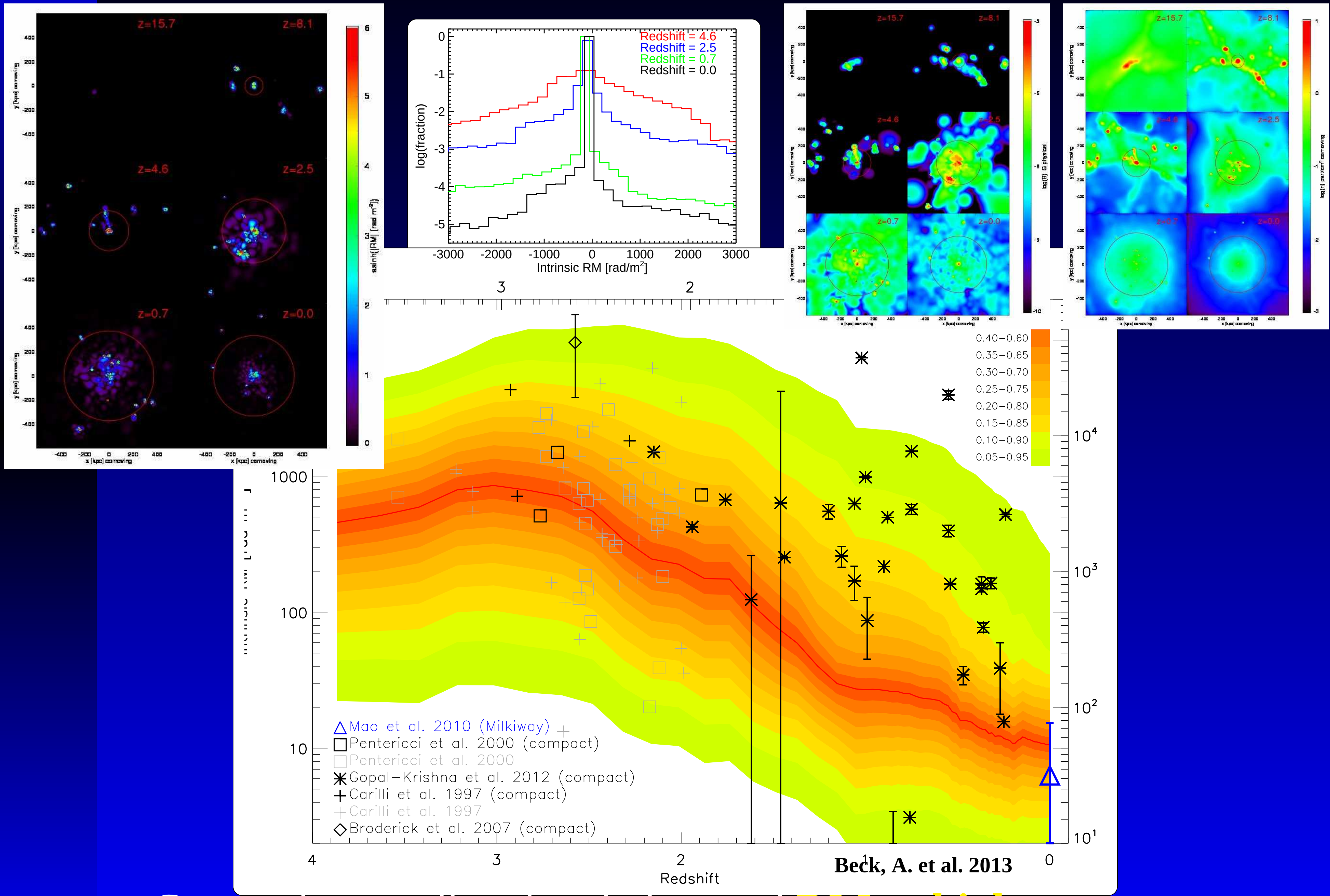
Magnetic Field buildup





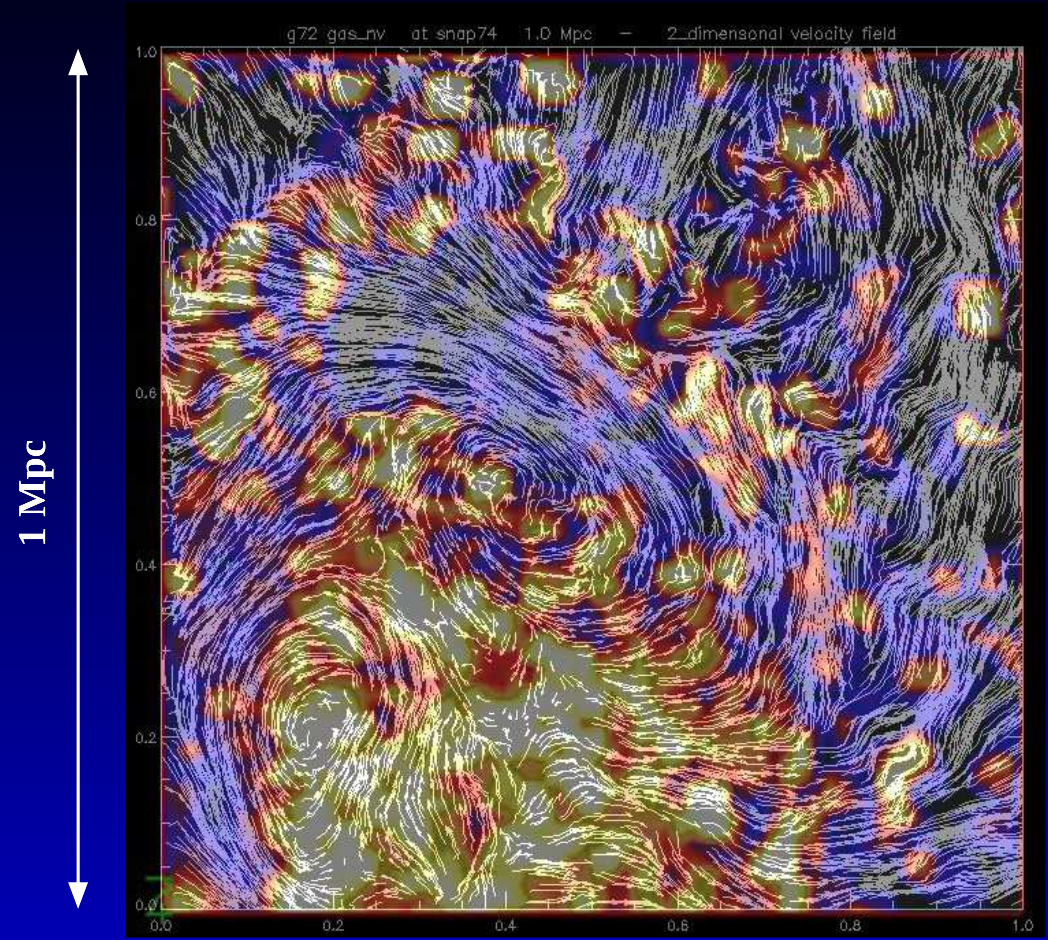
Direct **seeding** from **star-formation** process (e.g. every SN in simulation induces a idealized seed magnetic field with a local dipole shape) (Beck et al., submitted)

Magnetic Field buildup



Comparing predicted and observed **RM at high z**

Magnetic Field buildup



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

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) - \vec{\nabla} \times (\eta_{mag} \vec{\nabla} \times \vec{B}) + \left.\frac{\partial \vec{B}}{\partial t}\right|_{\mathrm{seed}}$$

Cosmology (structure formation)

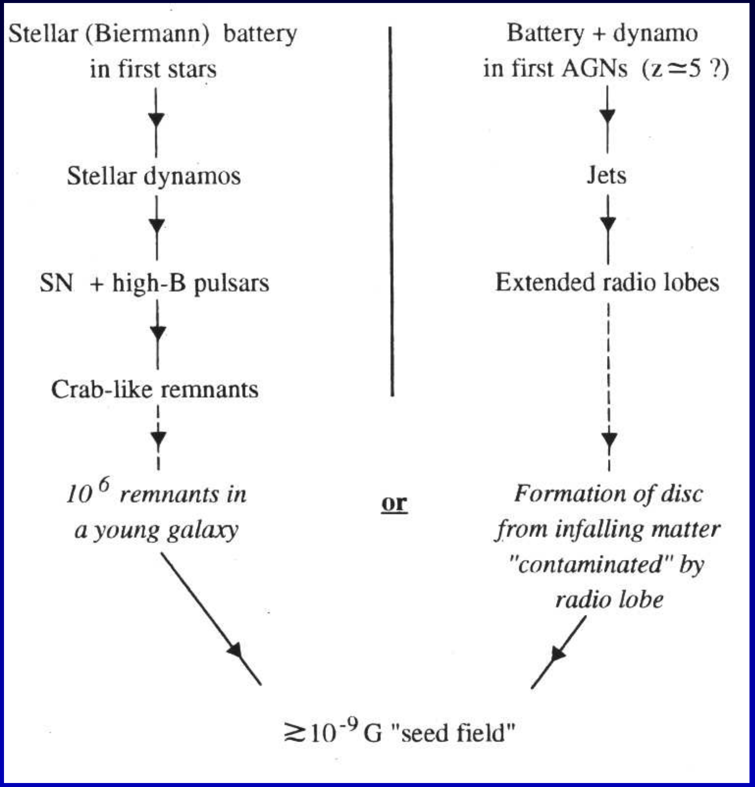
Microphysics (plasma physics)

magnetic seeding (star formtion)

Magnetic Field buildup

Origin

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

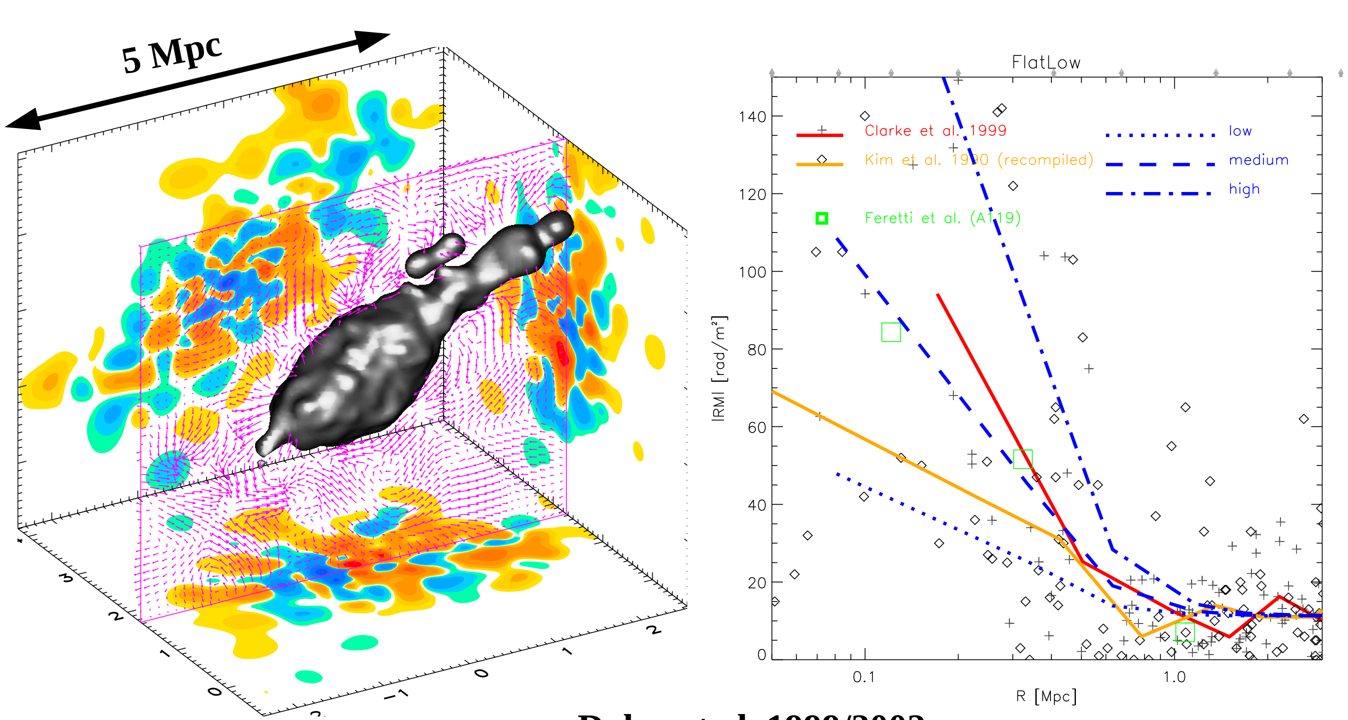


Rees 1994

+ further amplification by **structure formation**

- **dissipation** ?

Magnetic Field buildup

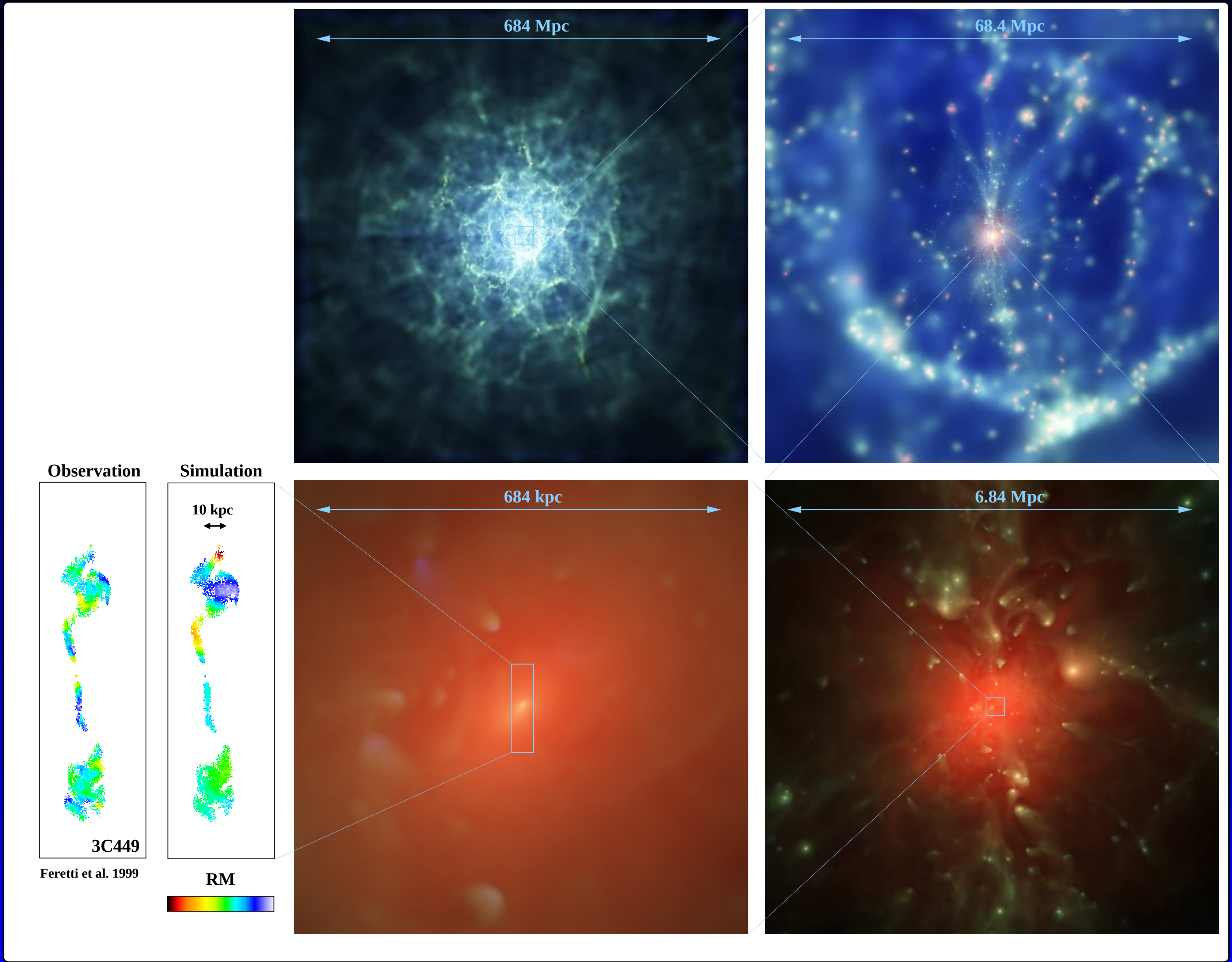


Dolag et al. 1999/2002

First cluster MHD simulations (Dolag et al. 1999/2002)

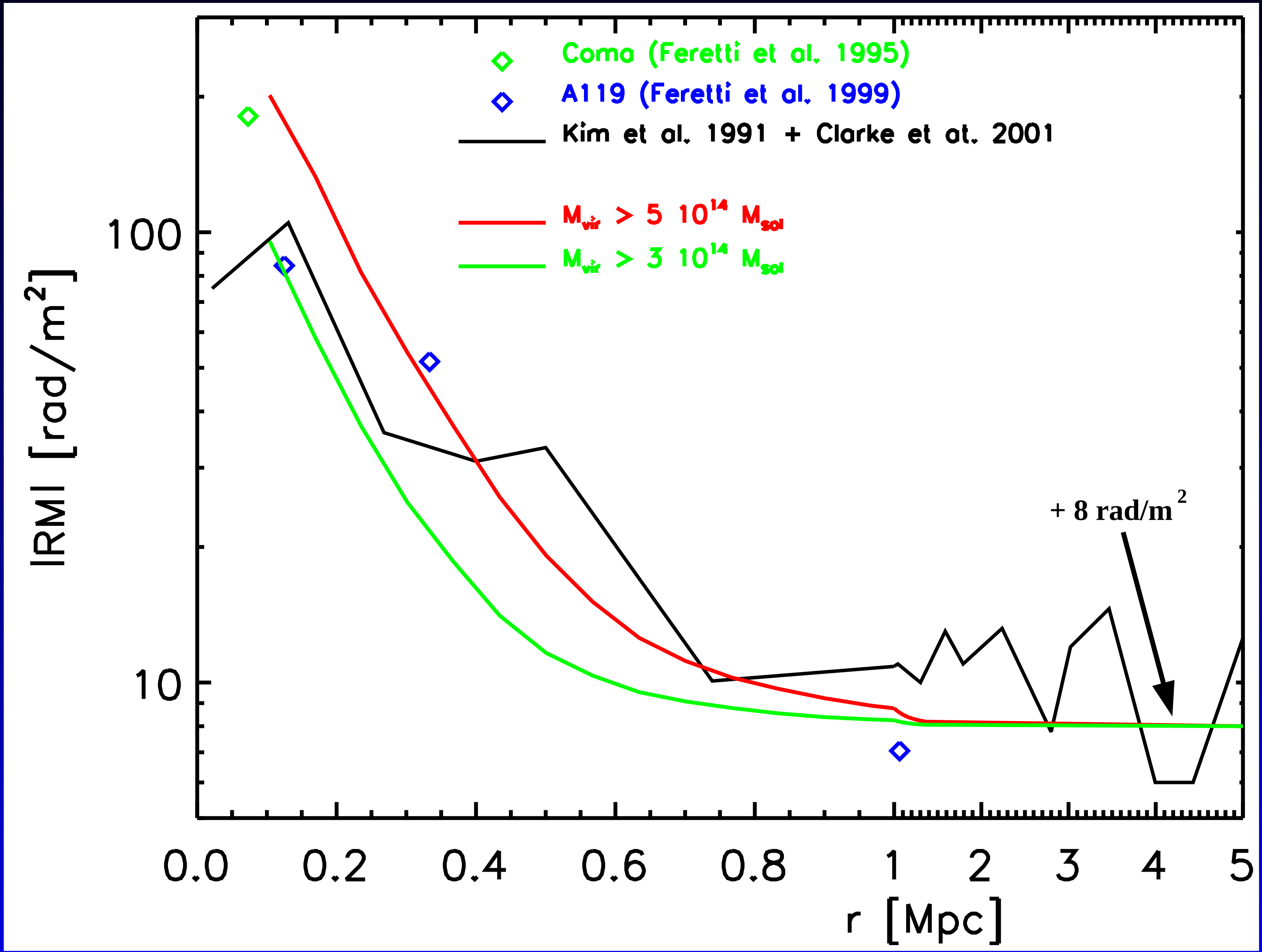
- Simulations reproduce the radial shape of the RM signal $\Rightarrow$ Magnetic power spectrum of clusters ($n \approx 2.3 - 3.1$)
- Magnetic field configuration driven by cluster dynamics $\Rightarrow$ Initial magnetic field structure not important
- Initial fields of $\approx (0.2 - 1) \times 10^{-11}$ G are sufficient $\Rightarrow$ values reached by many models for magnetic seed fields

Magnetic Field buildup



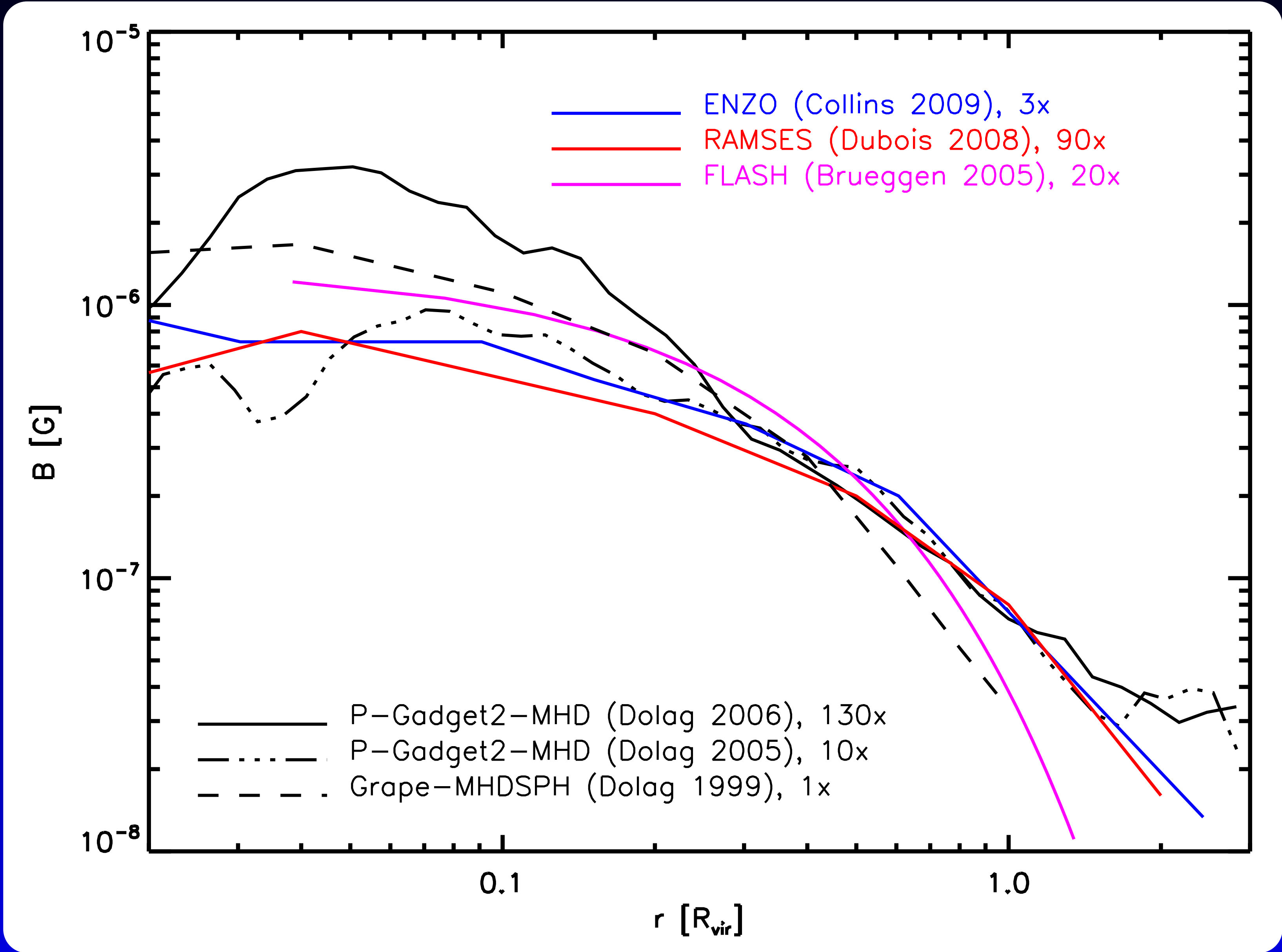
“Zoomed” cluster simulation (Dolag & Stasyszyn 2009).

Magnetic Field buildup



Comparing **RM** from **observations** with MHD **simulations** (Dolag et al. 1999/2001/2004/2005).

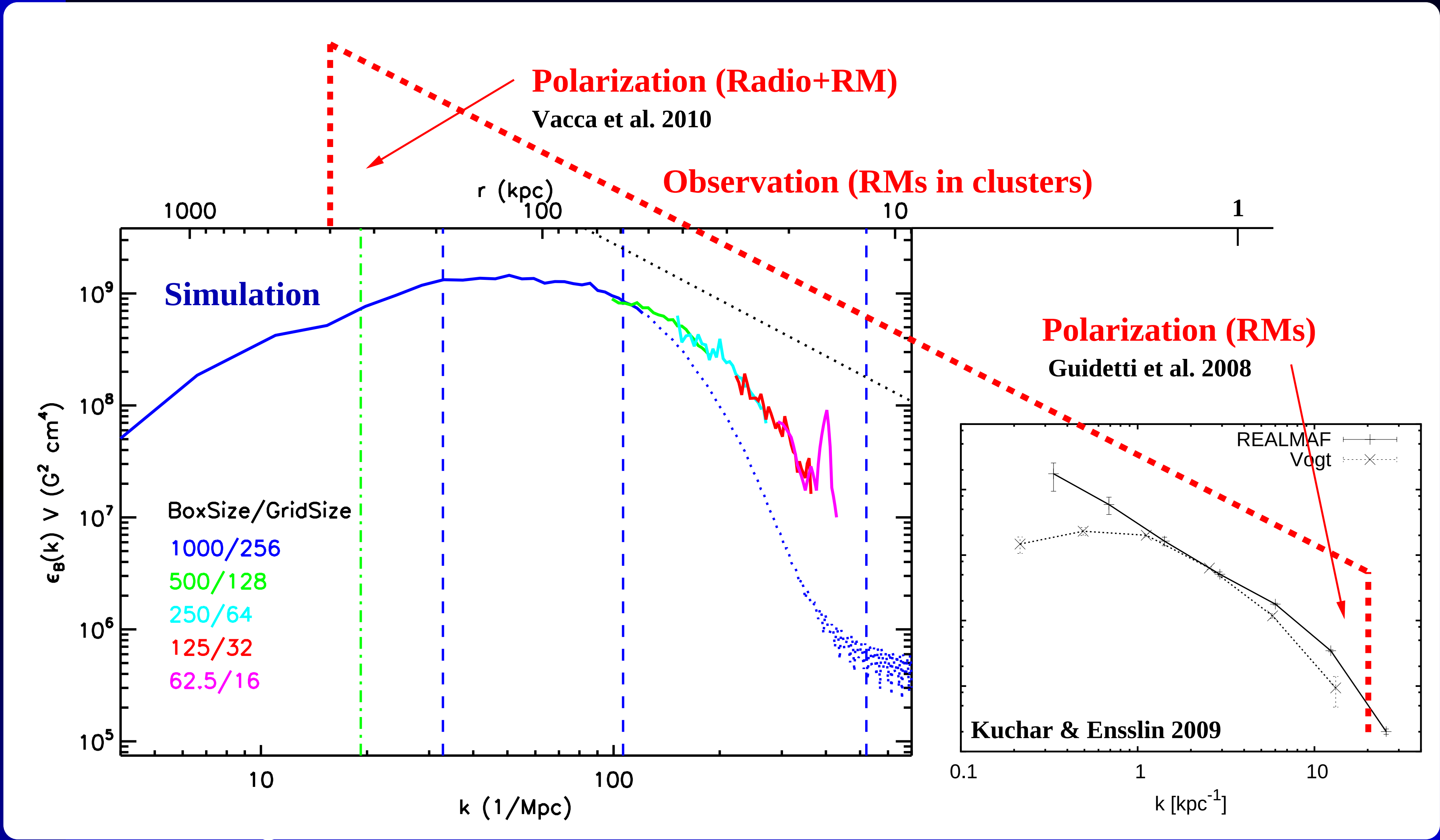
Magnetic Field buildup



⇒ Radial shape confirmed by more recent works

⇒ Generic feature from structure formation

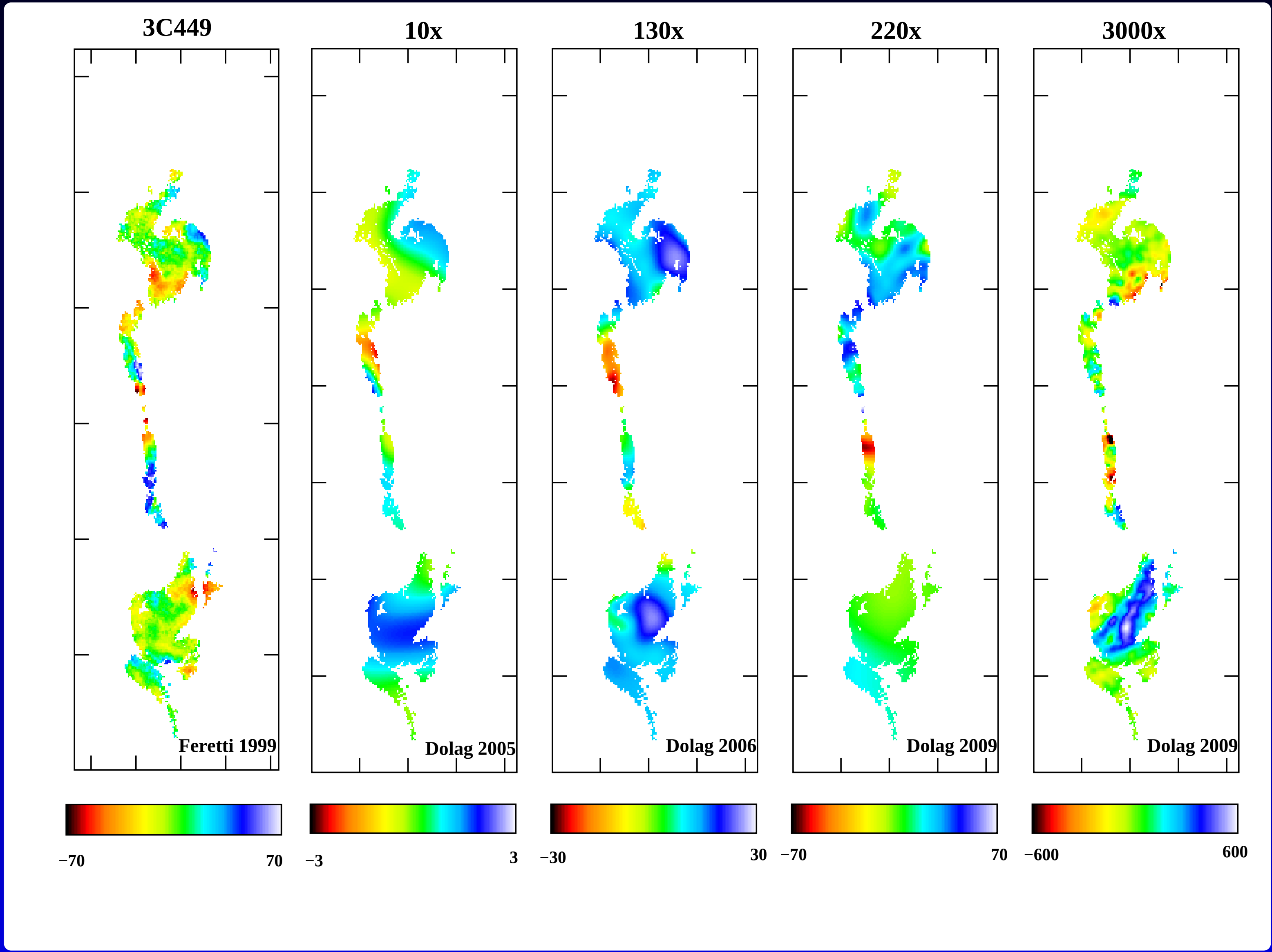
Magnetic Field buildup



Magnetic field power spectra: predictions vs. observations.

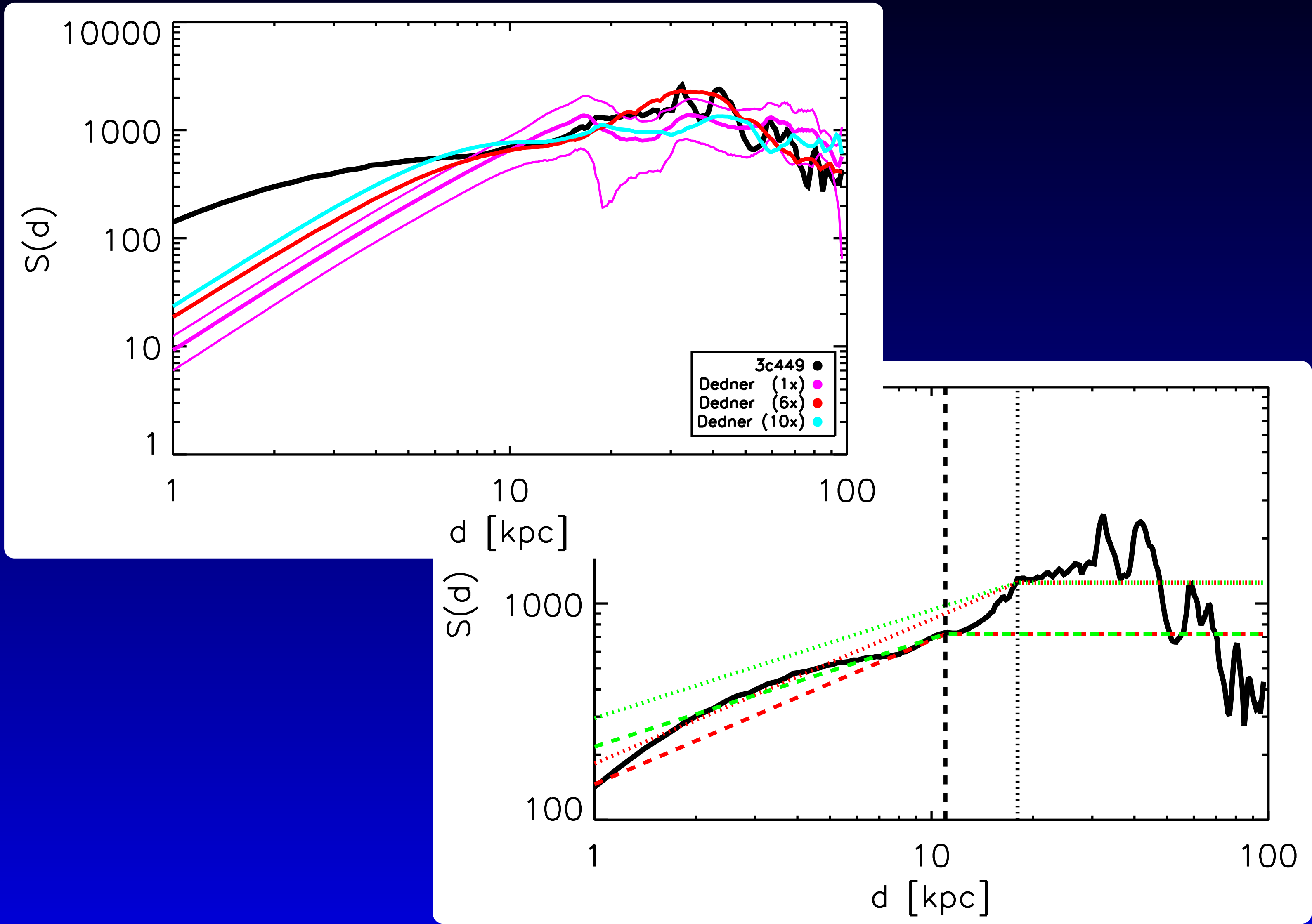
See also Brüggen et al. 2005, Xu et al. 2009,2011,2012 ...

Magnetic Field buildup



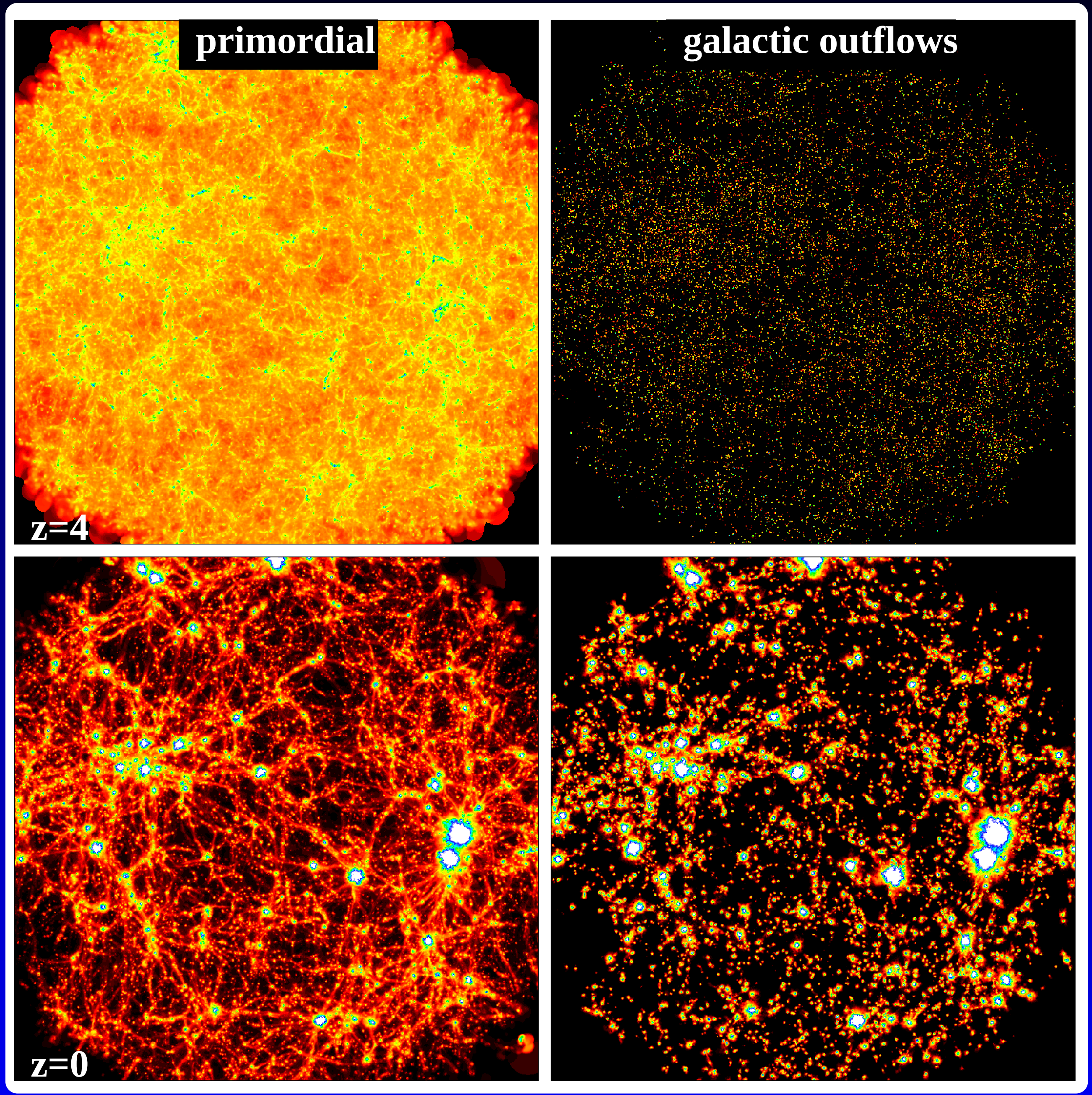
Observed and simulated RM maps up to the highest resolution simulation: 20 Million particles within R_{vir}, $m_{DM} = 10^7 M_\odot/h$, $\epsilon_{Grav} = 1$kpc/h (Stasyszyn, Dolag, Beck 2013)

Magnetic Field buildup



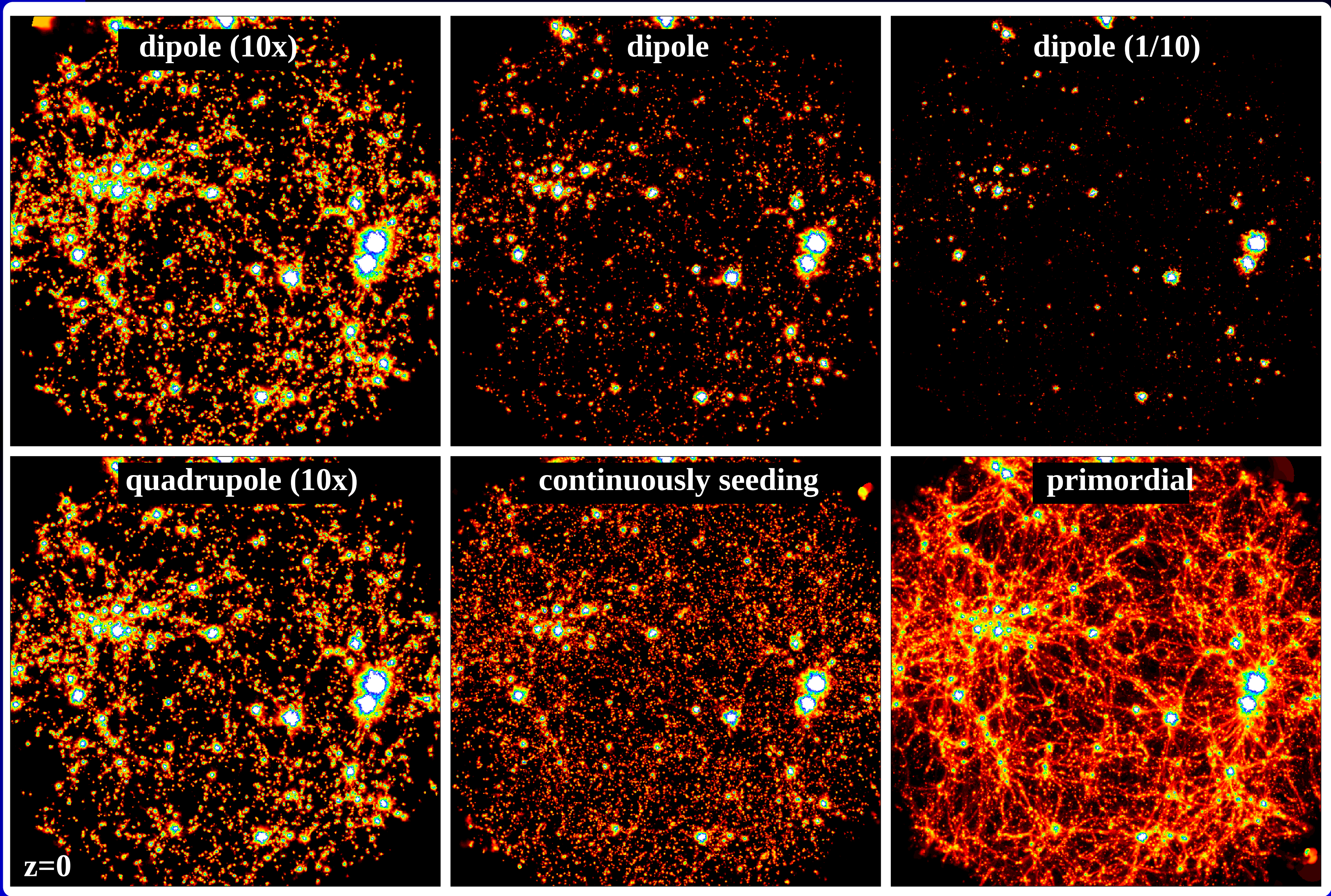
Structure functions derived from observed and simulated RM maps with increasing resolution.
(Stasyszyn, Dolag, Beck 2013)

Magnetic Field buildup



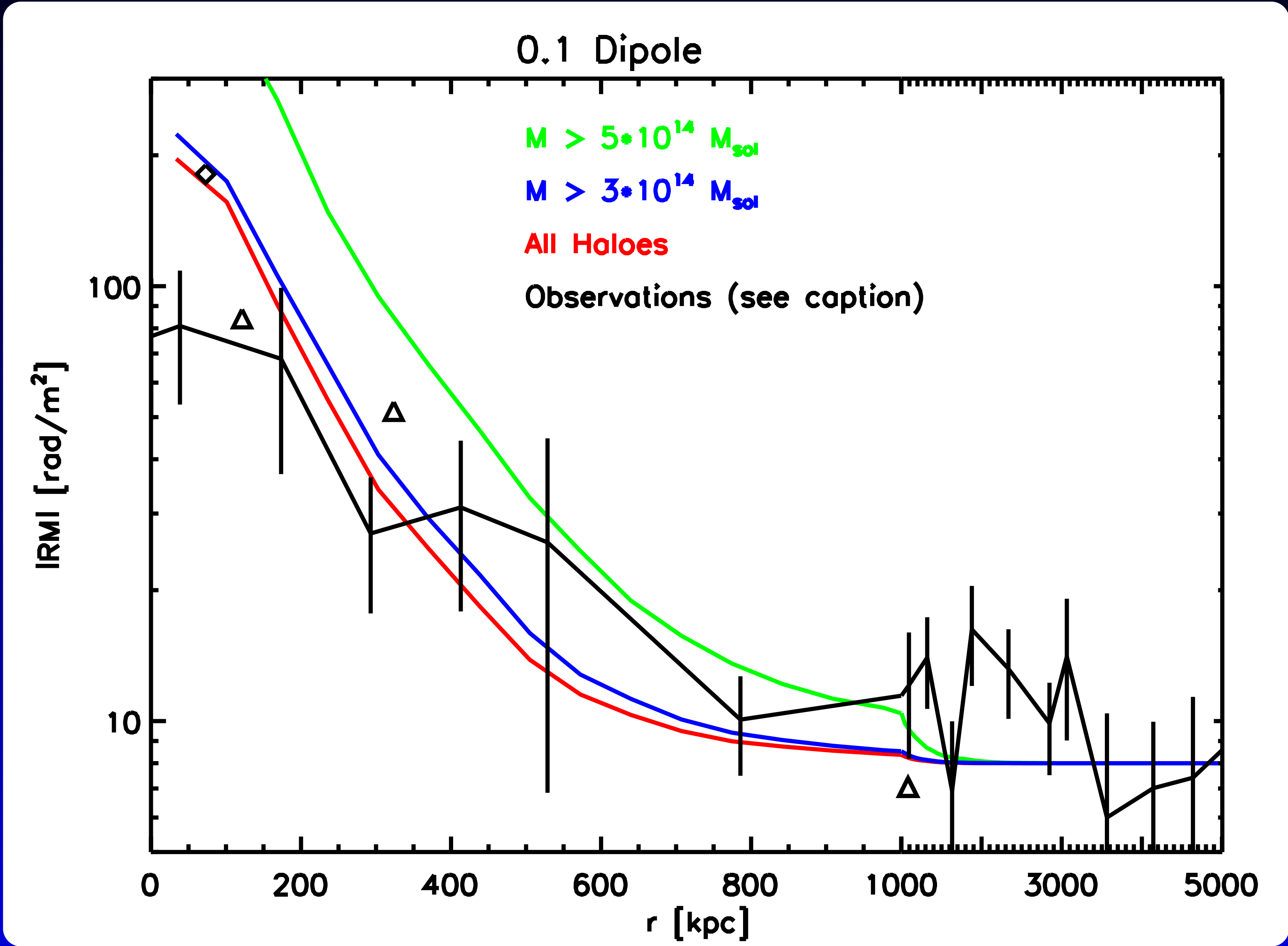
Seeding from galactic outflows (Donnert et al. 2009)

Magnetic Field buildup



Seeding from galactic outflows, different models (Donnert et al. 2009)

Magnetic Field buildup



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

Magnetic Field buildup

density

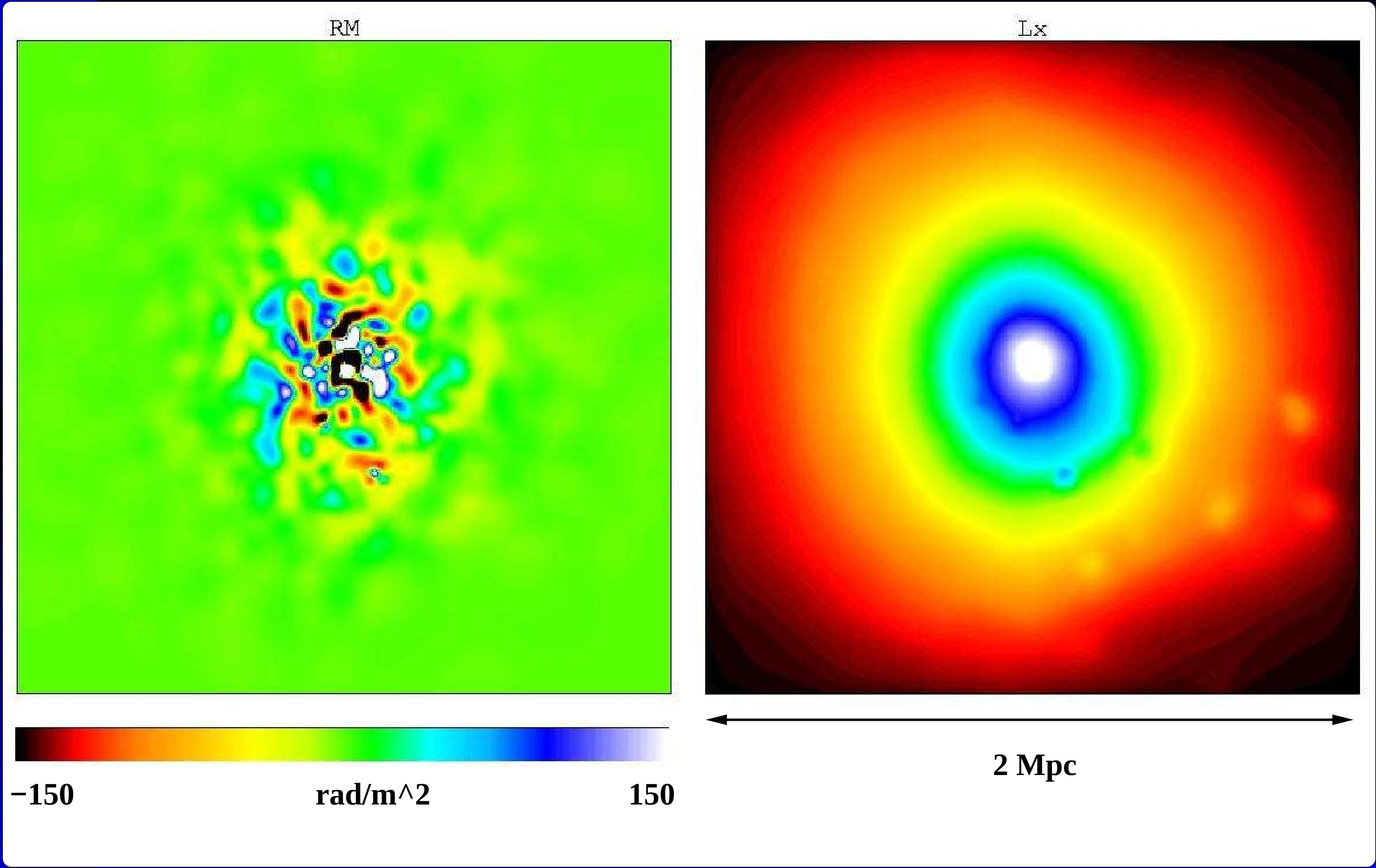
180 Mpc

magnetic field

180 Mpc

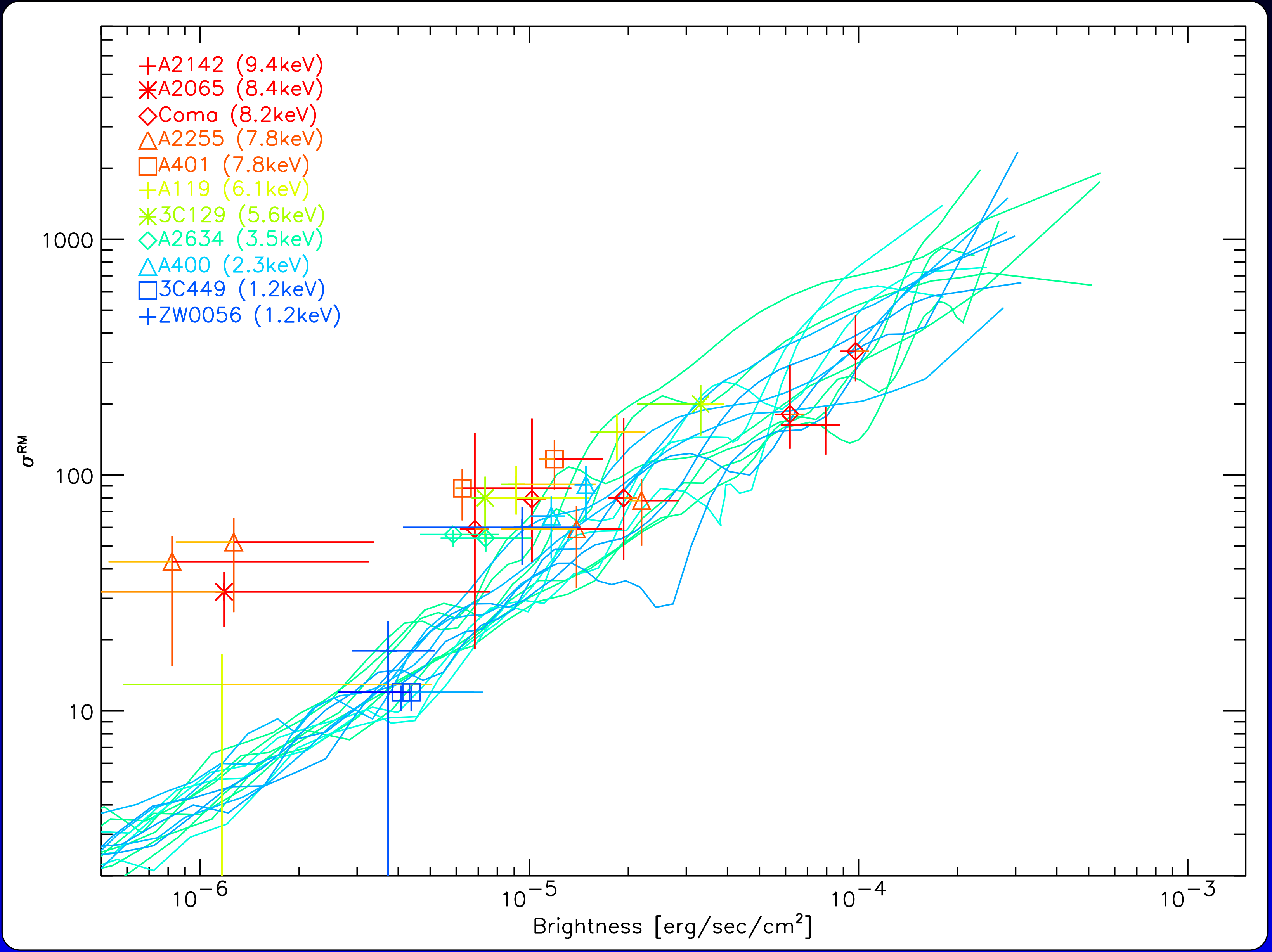
Buildup of **cosmological magnetism** through **seeding** by **SN**.

Magnetic Field buildup



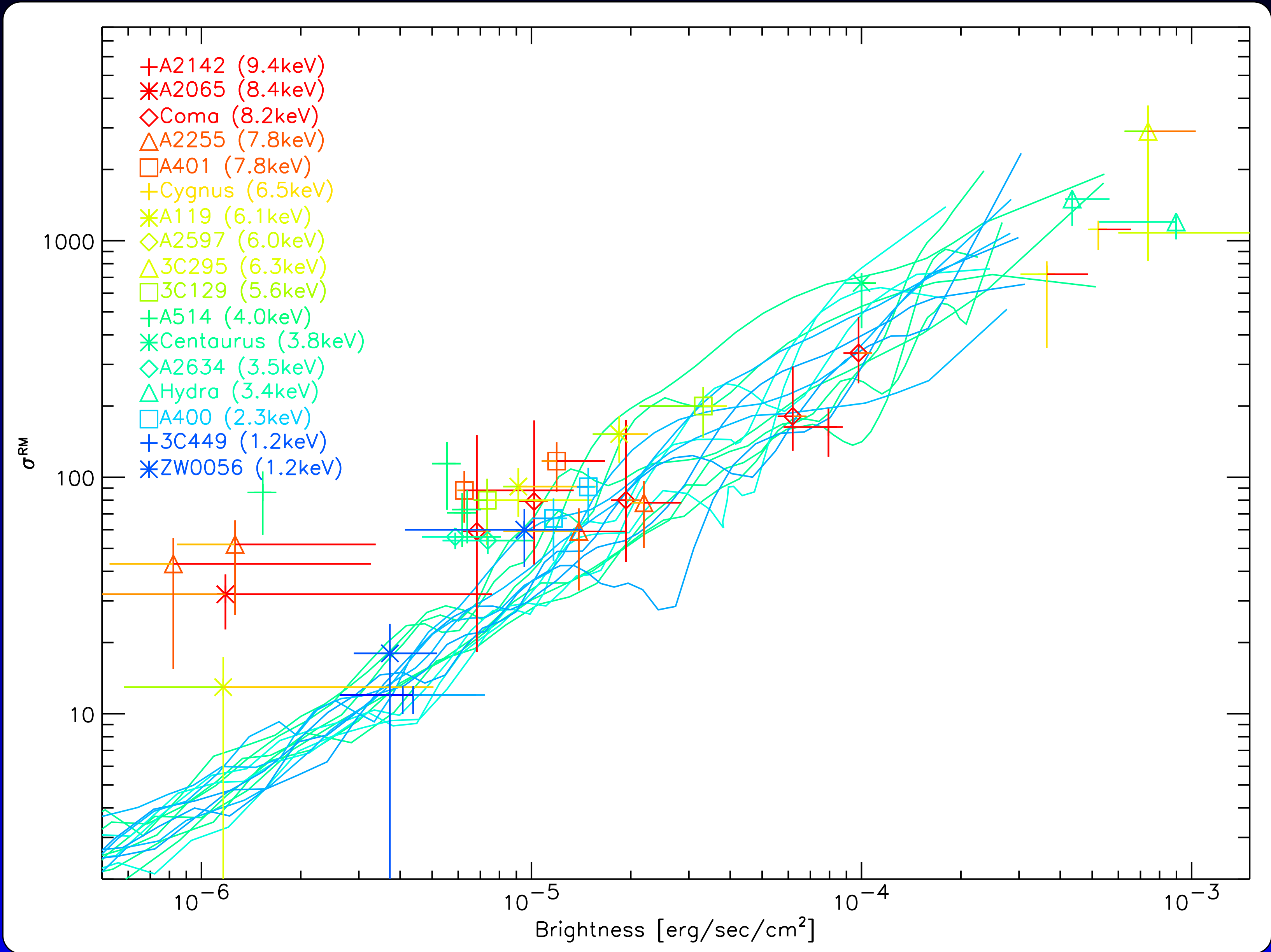
RM and **X-ray** Maps for a relaxed cluster.

Magnetic Field buildup



Comparison of **RM-Lx correlation** from **observatios** (Govoni et al. 2010) and results from **star-formation seending**.

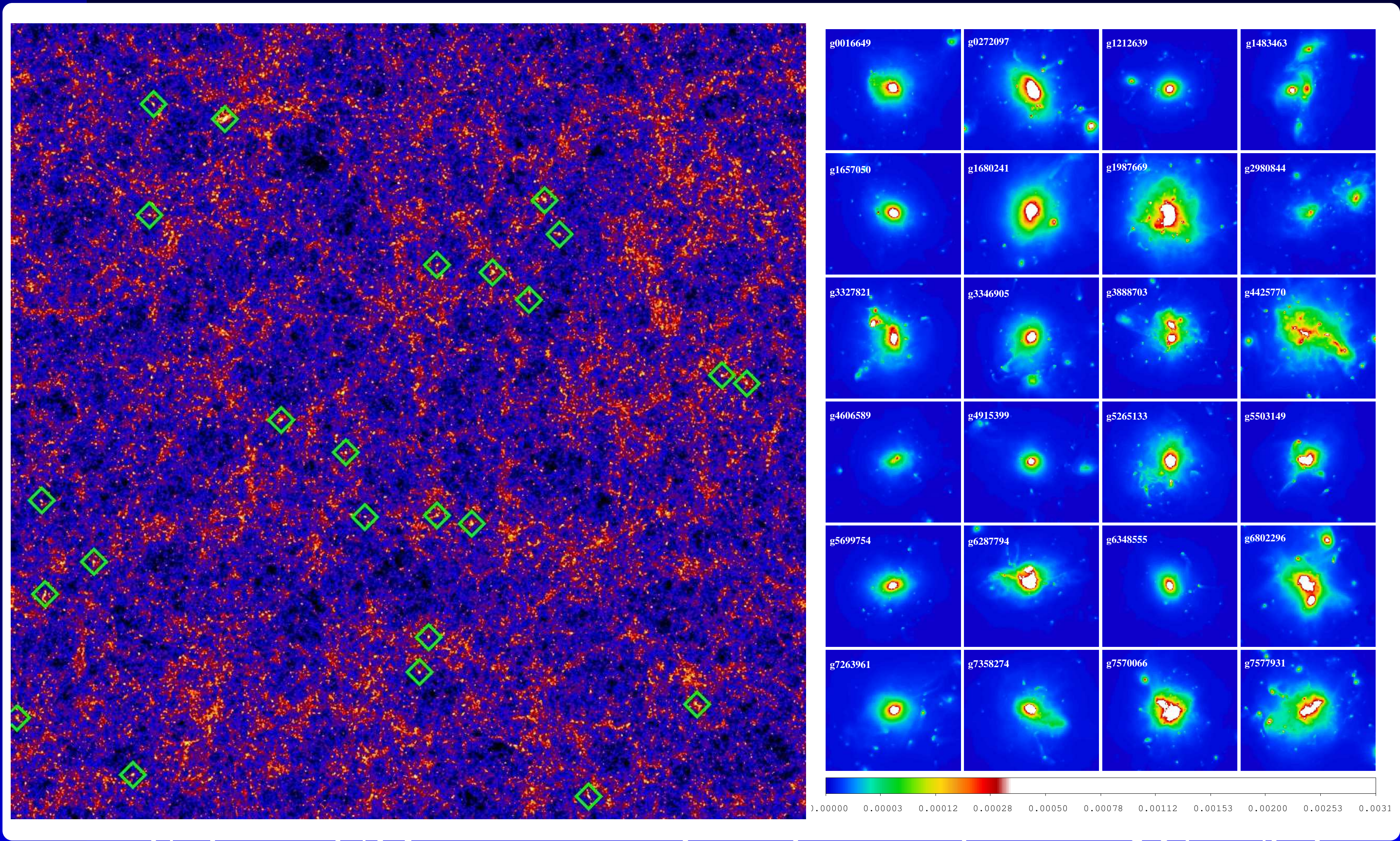
Magnetic Field buildup



Adding **cool-core clusters** ...

A simple subscale model

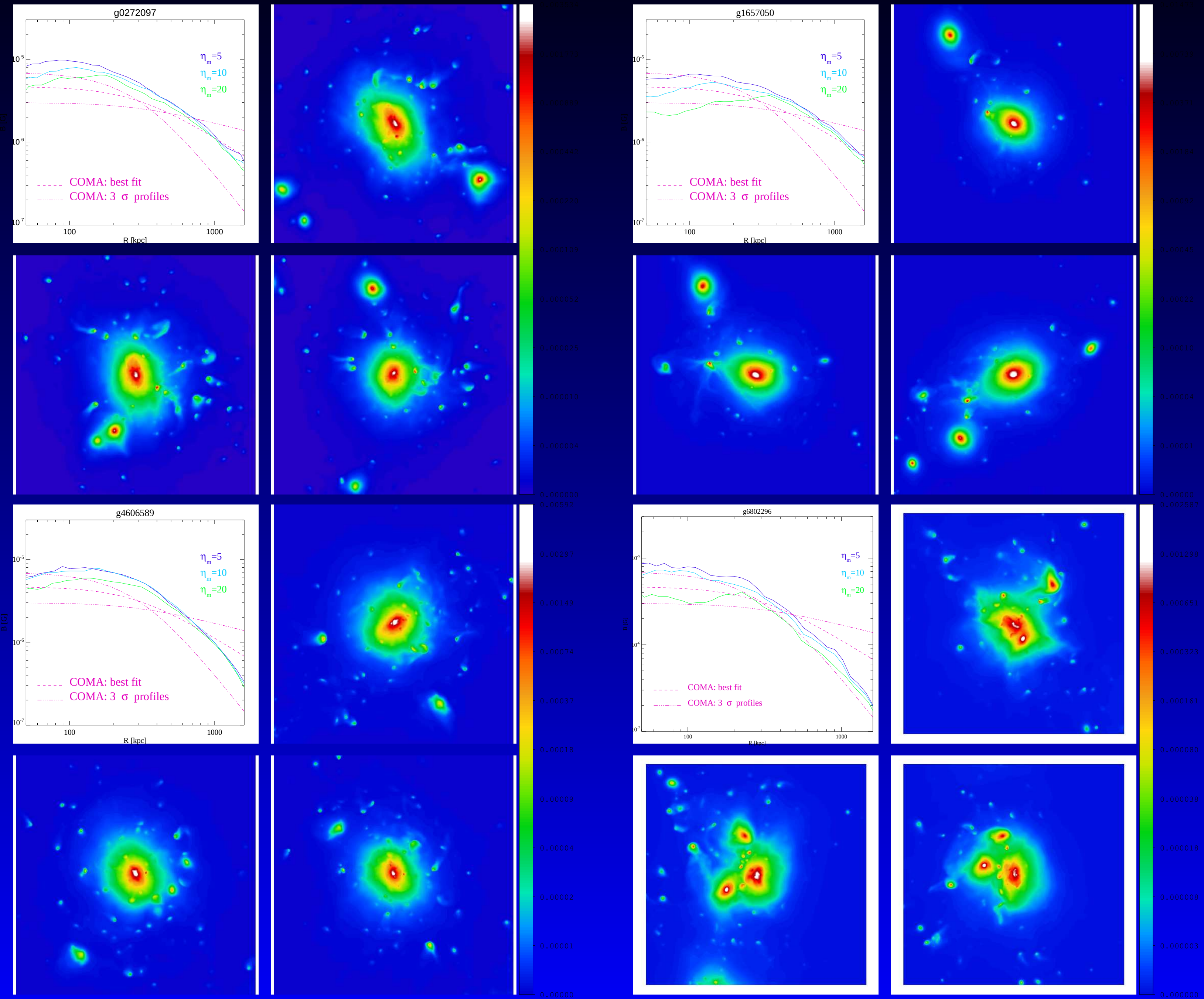
$$\eta = \eta_{\mathrm{coulomb}} + \eta_{\mathrm{turb}} \approx 0.1 \times v_{\mathrm{turb}} \times \lambda_{\mathrm{vturb}}$$



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

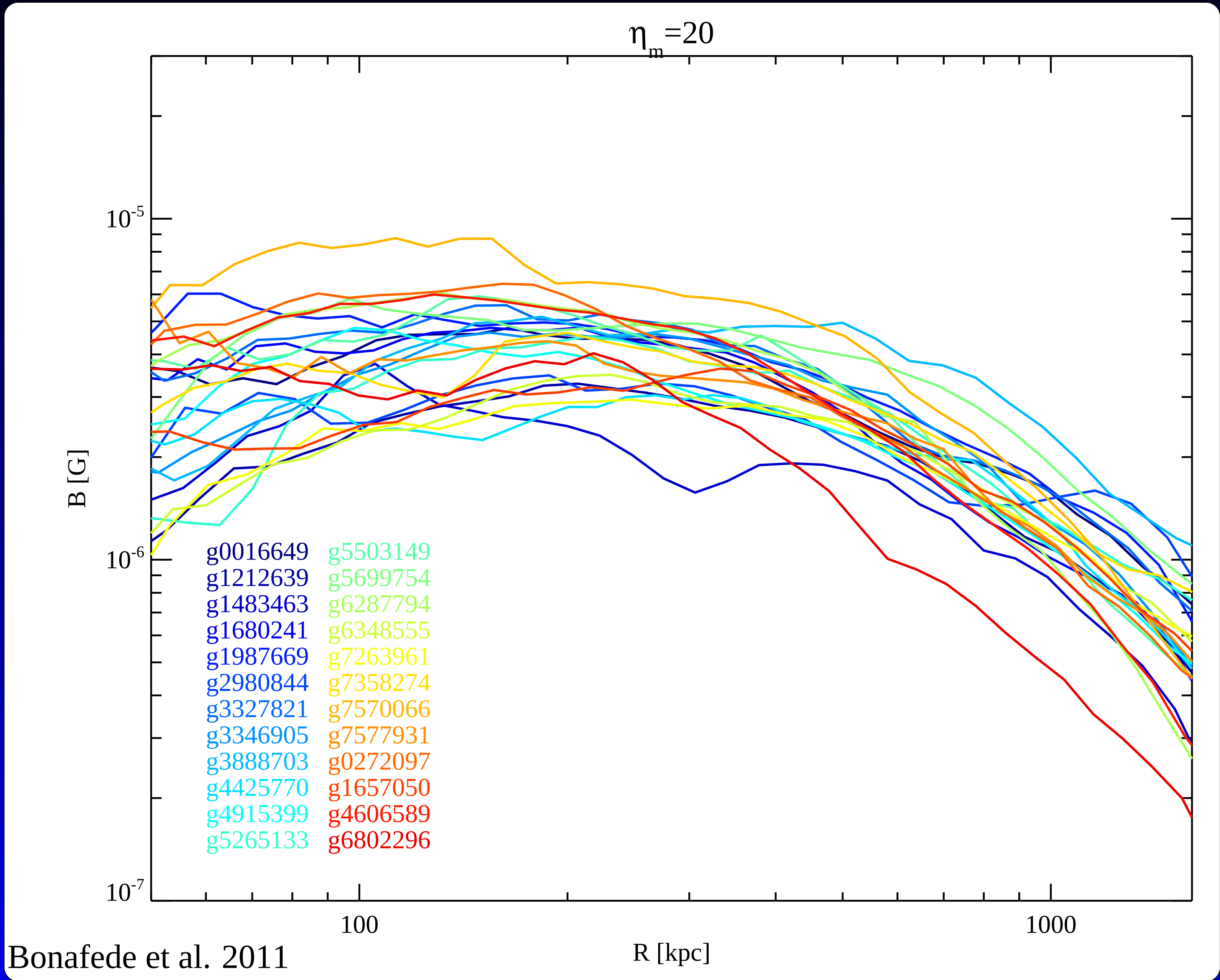
Bonafede et al. 2011

A simple subscale model



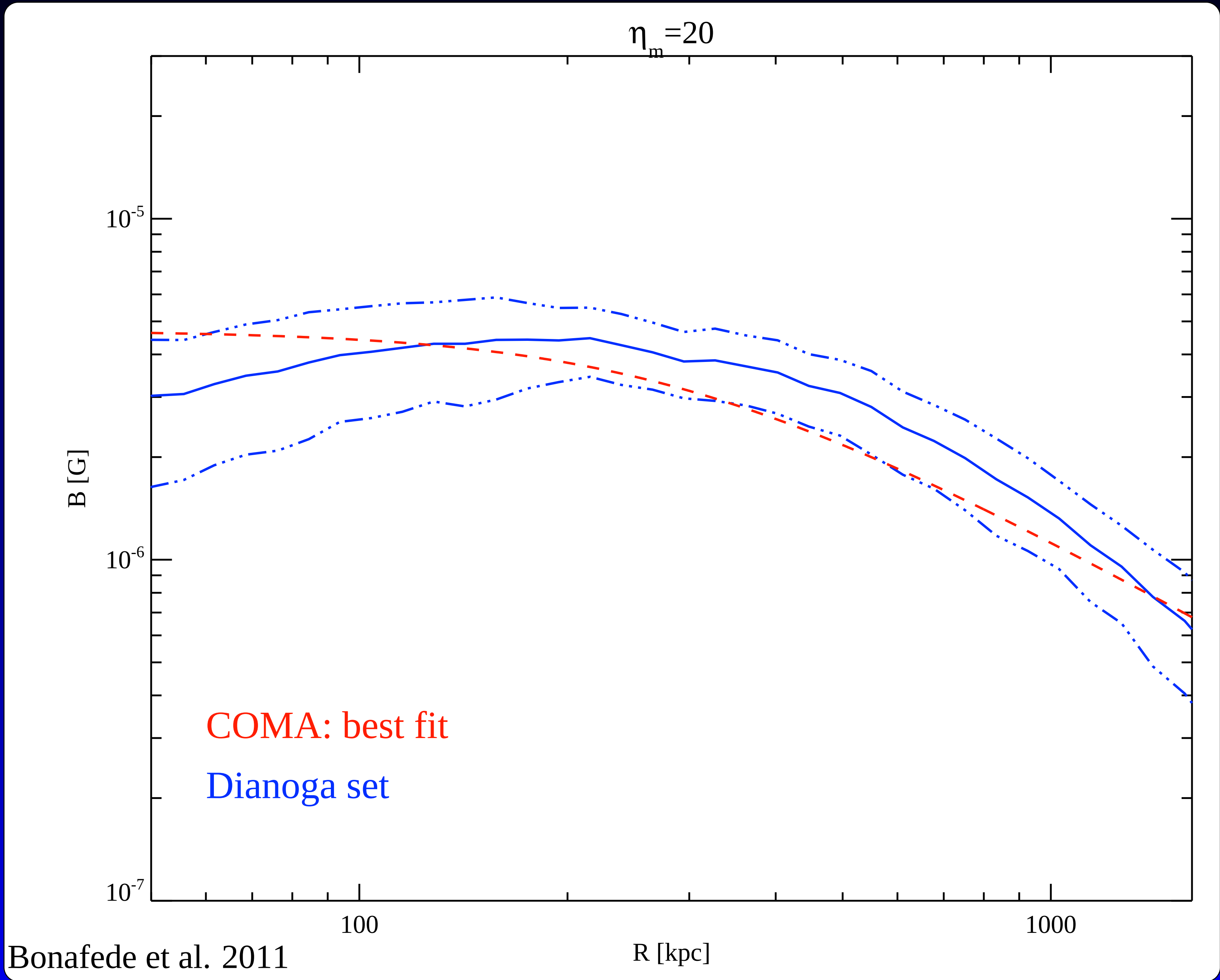
Subset of 4 Coma-like clusters with $\eta = 1.5, 3, 6 \times 10^{27} \mathrm{cm}^2/\mathrm{s}$. (Bonafede et al. 2011)

A simple subscale model



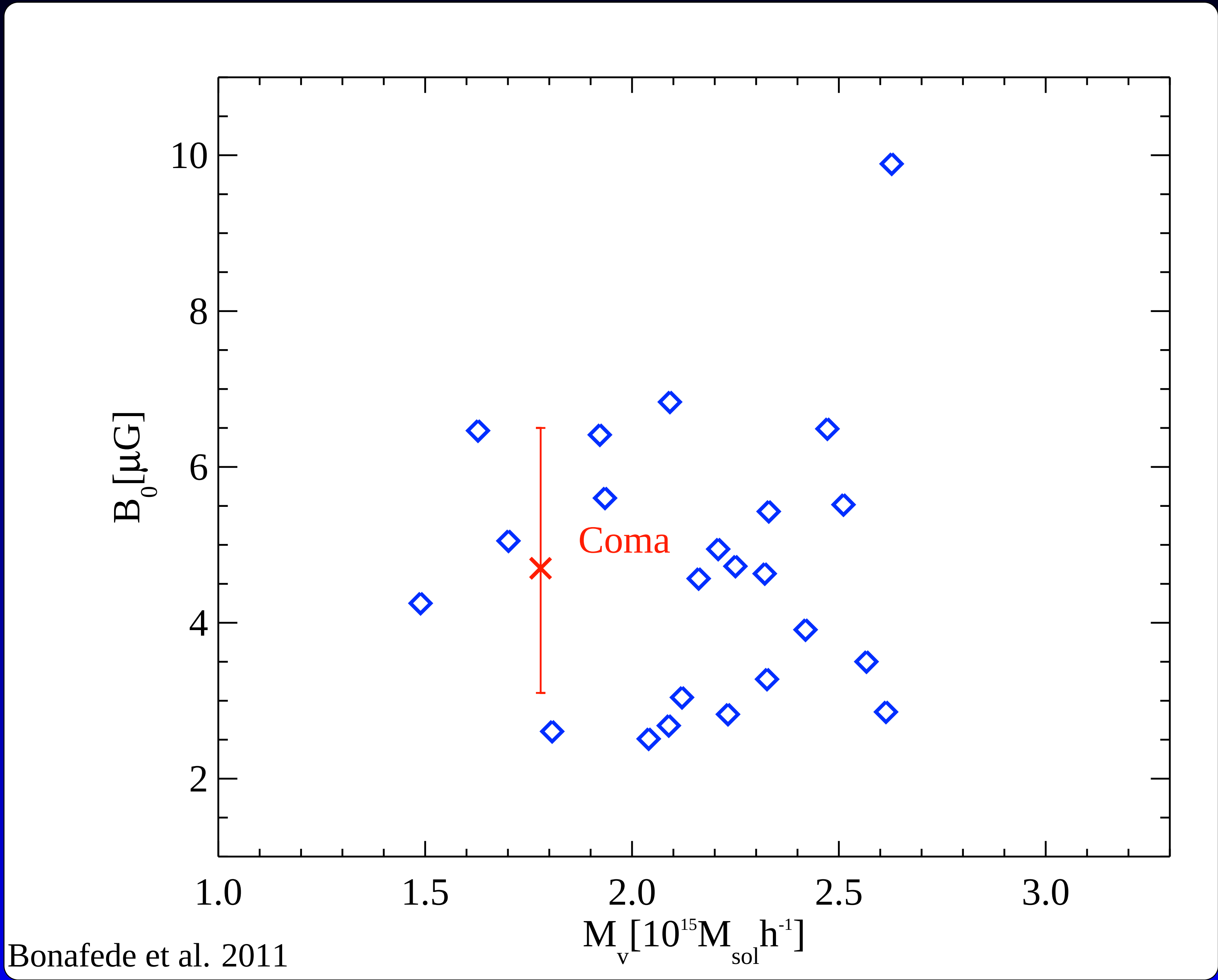
⇒ **Profiles** of 24 **Coma-like** galaxy clusters

A simple subscale model



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

A simple subscale model



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

Anisotropic Conduction

$$\frac{du}{dt} = \frac{1}{\rho}\nabla \cdot \left[\kappa_\parallel \left(\hat{B}\cdot\nabla T\right)\hat{B} + \kappa_\perp\left(\nabla T - \left(\hat{B}\cdot\nabla T\right)\hat{B}\right)\right]$$

$$\kappa \sim \frac{l^2}{\tau}\cdot n k_B \sim D \cdot n k_B$$

$$D_\perp \approx \frac{v^2}{\omega_g} \approx \frac{k_B T c}{eB}$$

Gyroradius < Mean-free path

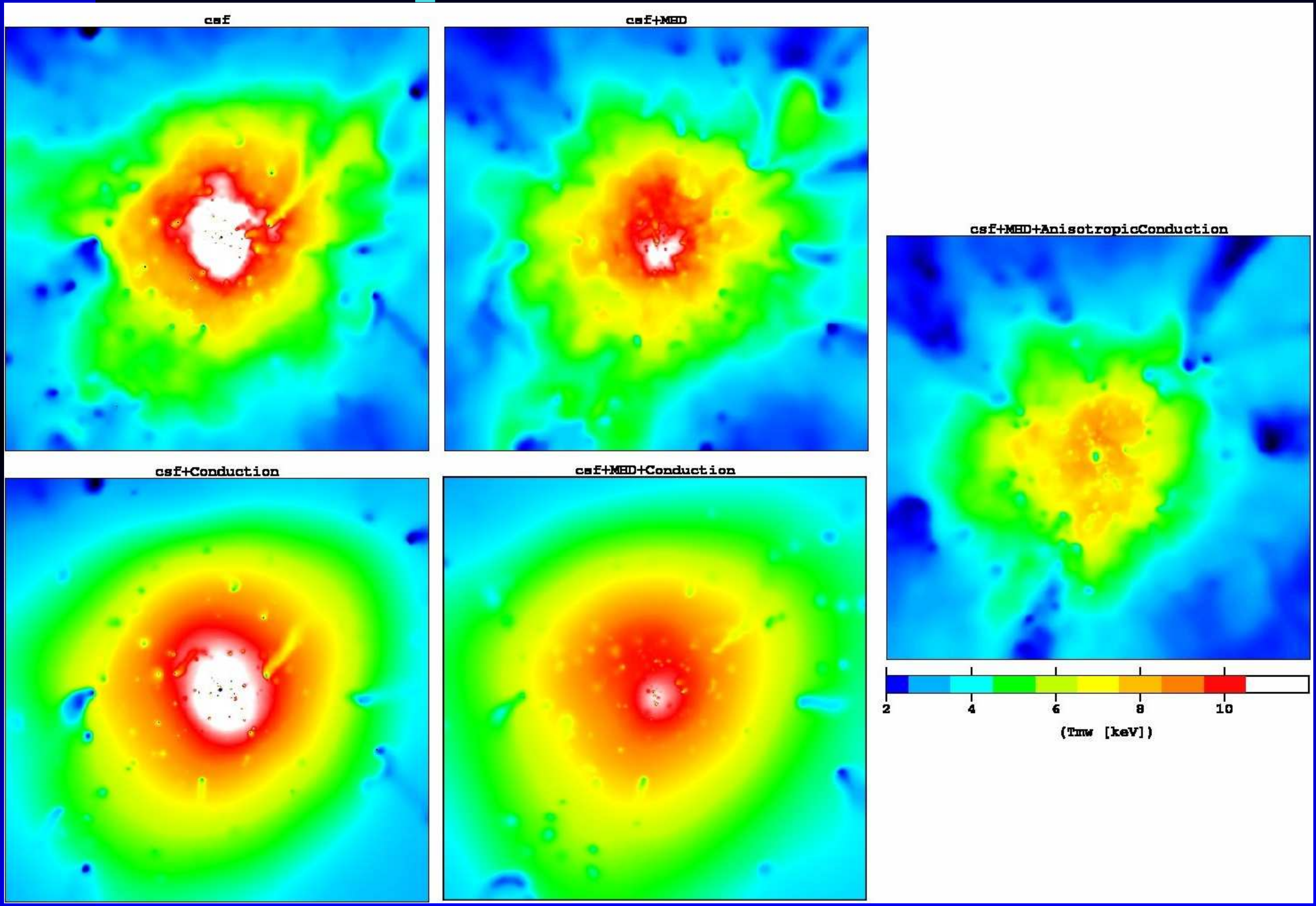
$$\frac{D_\perp}{D_\parallel} \approx \frac{1}{\omega_g^2\tau^2} \propto B^{-2}$$

Gyroradius == Mean-free path

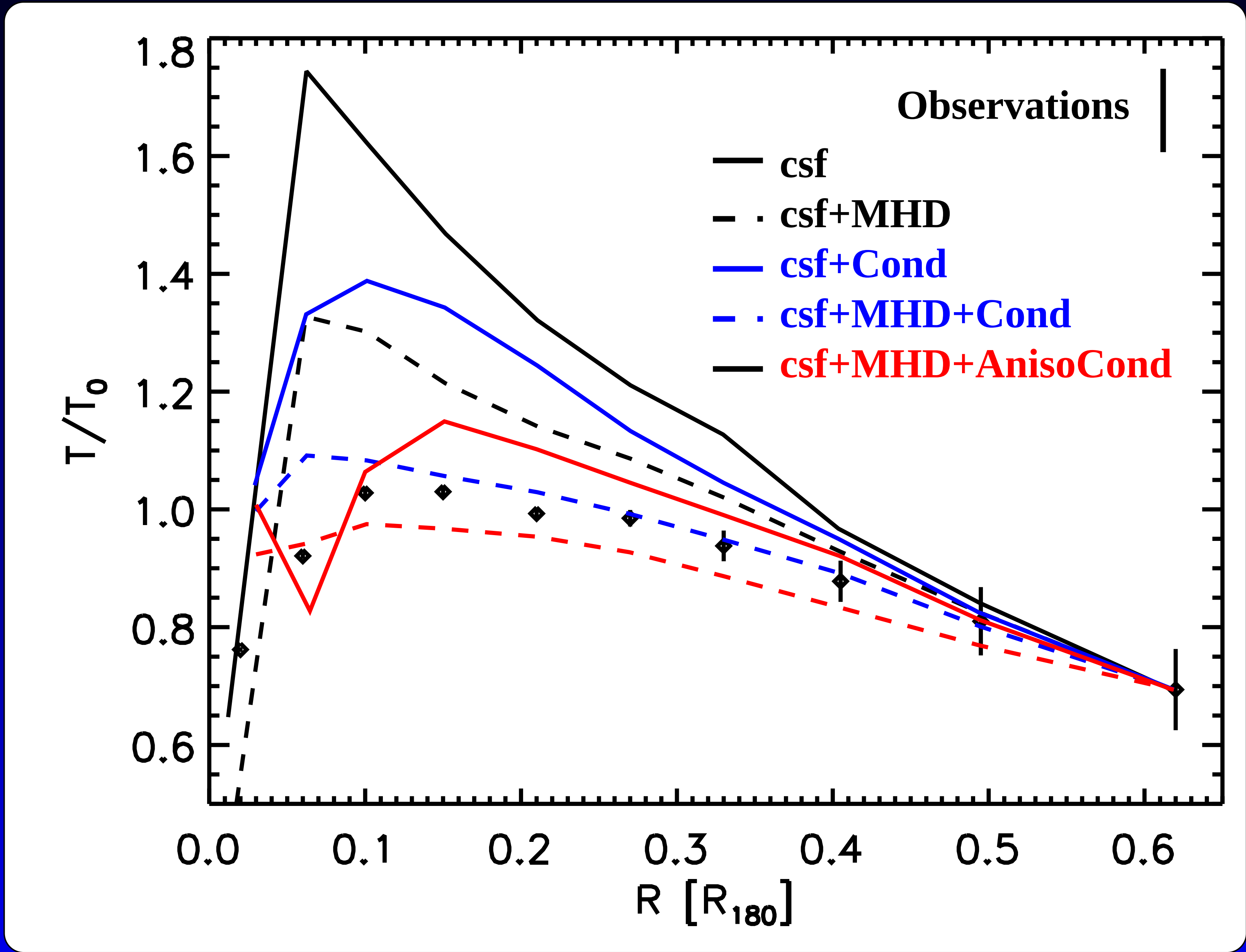
$$\frac{D_\perp}{D_\parallel} \approx \frac{1}{1+\omega_g^2\tau^2}$$

A. Arth (master thesis), see also Ruszkowski et al. 2011.

Anisotropic Conduction

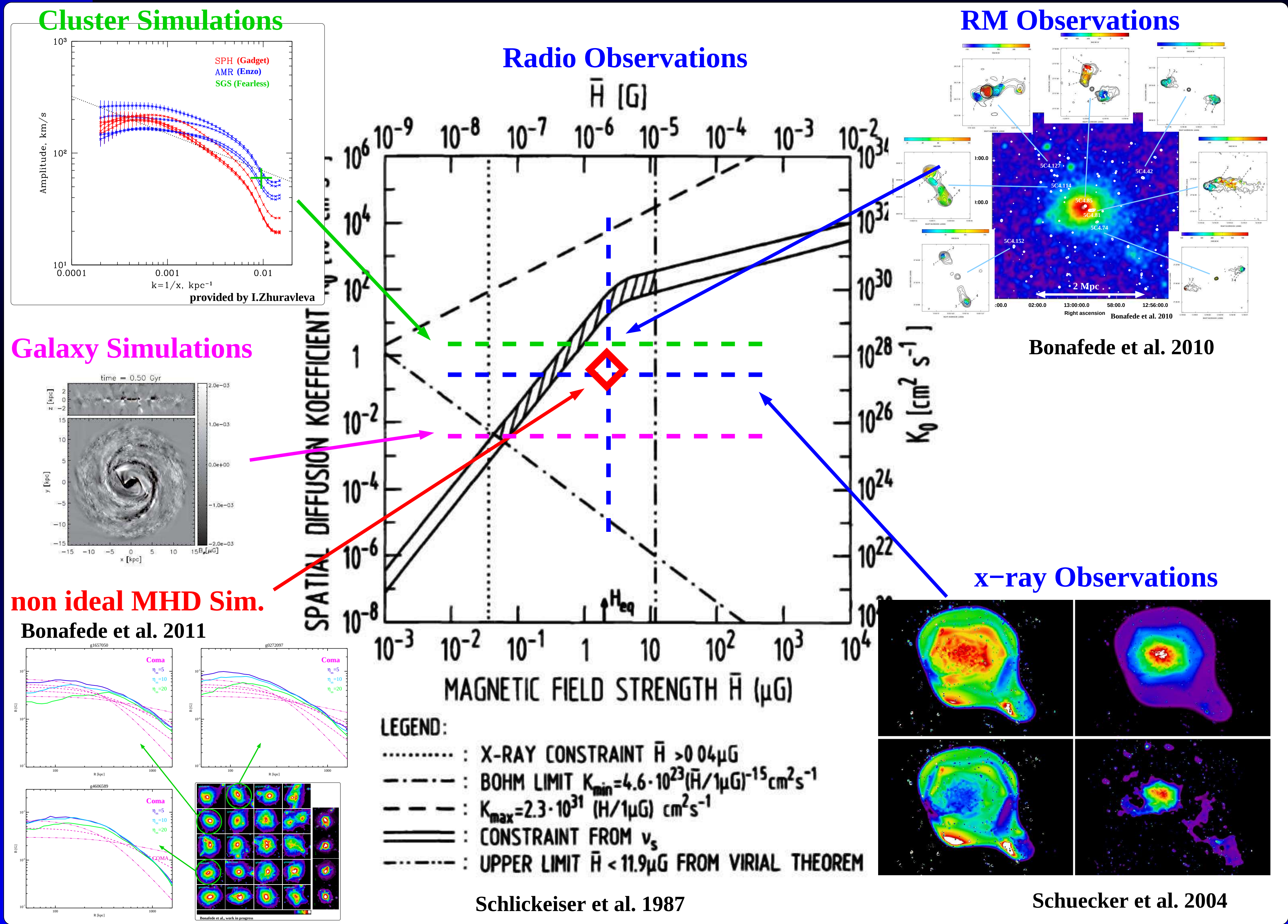


Anisotropic Conduction



⇒ Changes profiles but keeps structre in maps !

What we learned



Conclusions (MHD)

- Predicted magnetic field structures reflect formation of galaxy clusters
- Hierarchical buildup of magnetic fields from galaxy formation
- Galactic outflows are valid sources of cluster fields
- Predicted (complex) field structures in galaxy clusters is compatible with RM measures
- Filaments might host remaining signatures of magnetic field origin
- Radio emission + magnetic field models allow to constrain CR origin
- Numerics strongly improved, now to be applied to different scales
- Sub-grid models to connect $\vec{B}$ to transport processes are important.

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