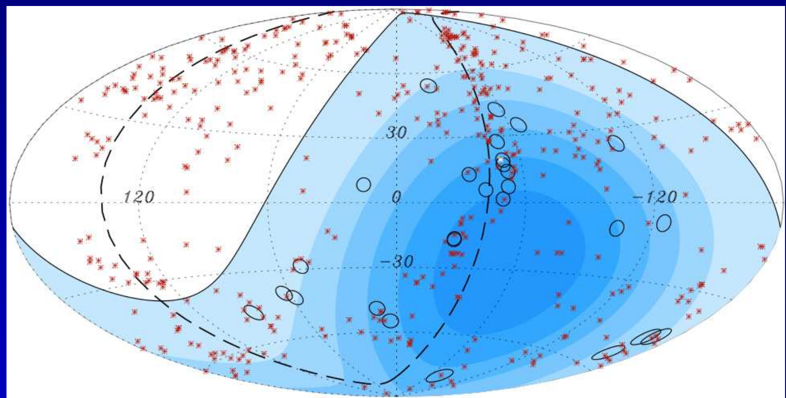
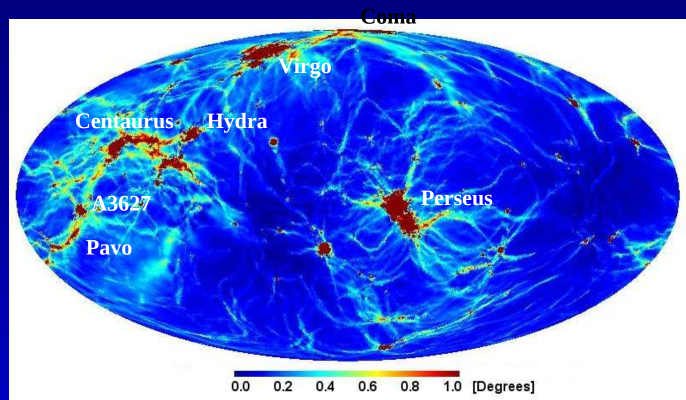
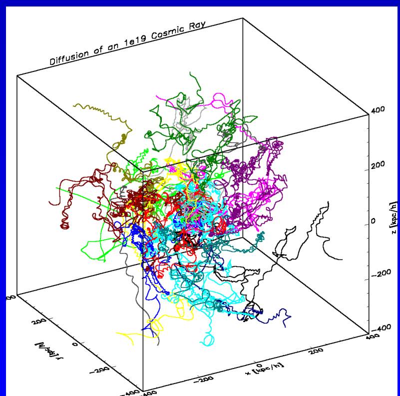
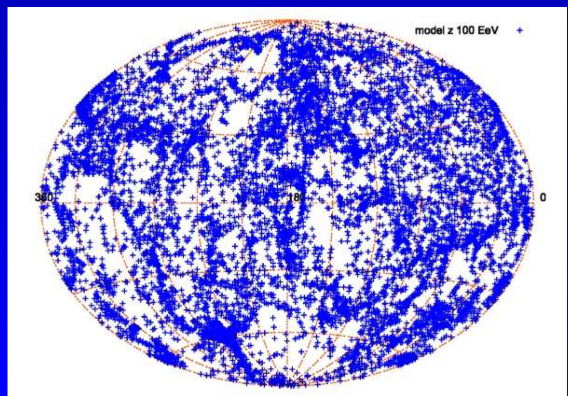
Magnetic fields in and beyond clusters of galaxies

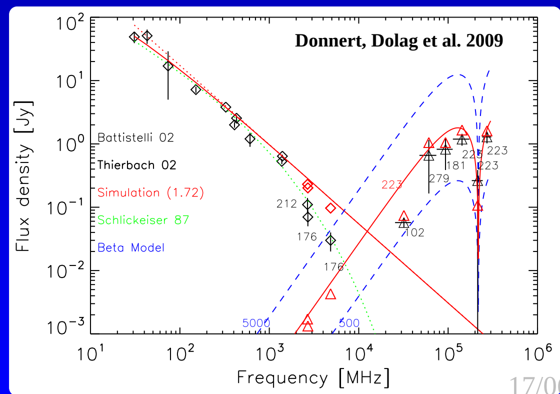
Klaus Dolag



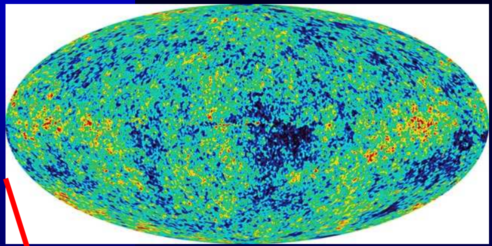








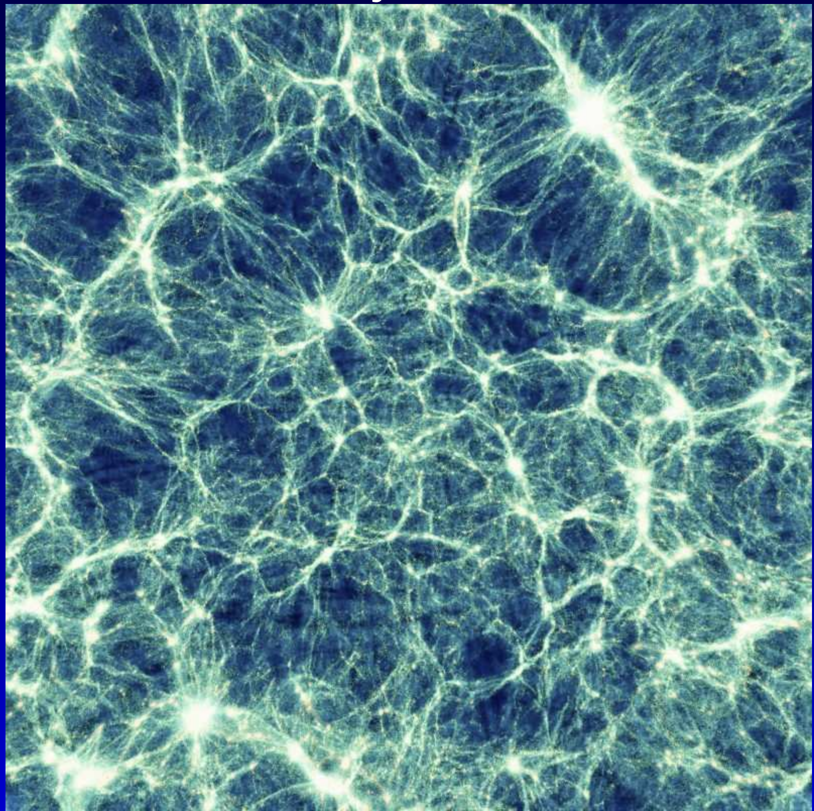
Introduction



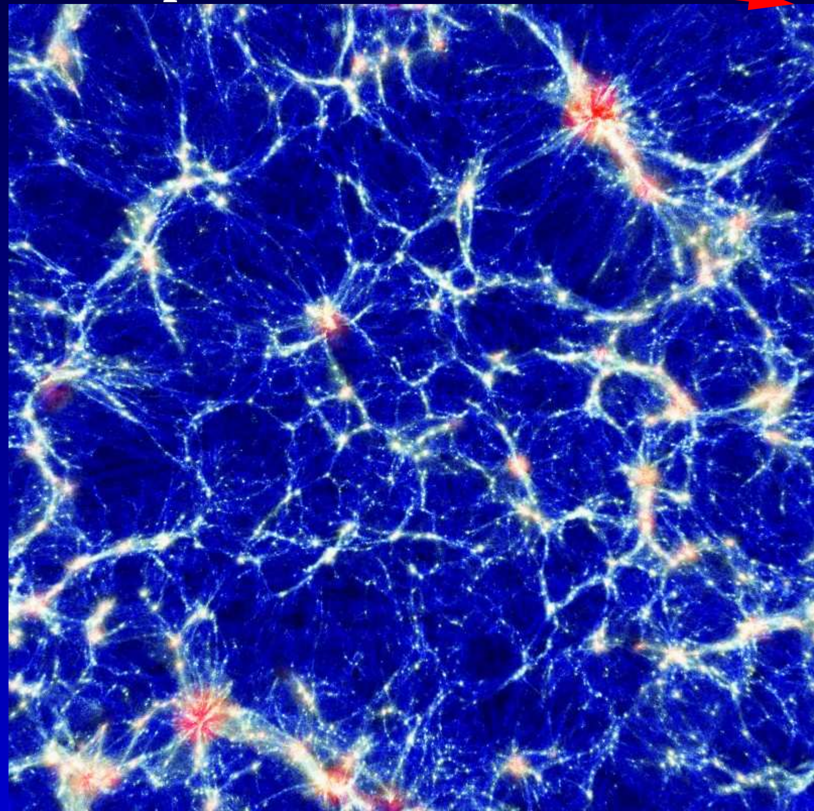
CMB (t = 0.38 Myr)

Cosmic structure today (t = 13.7 Gyr)

Density



Temperature

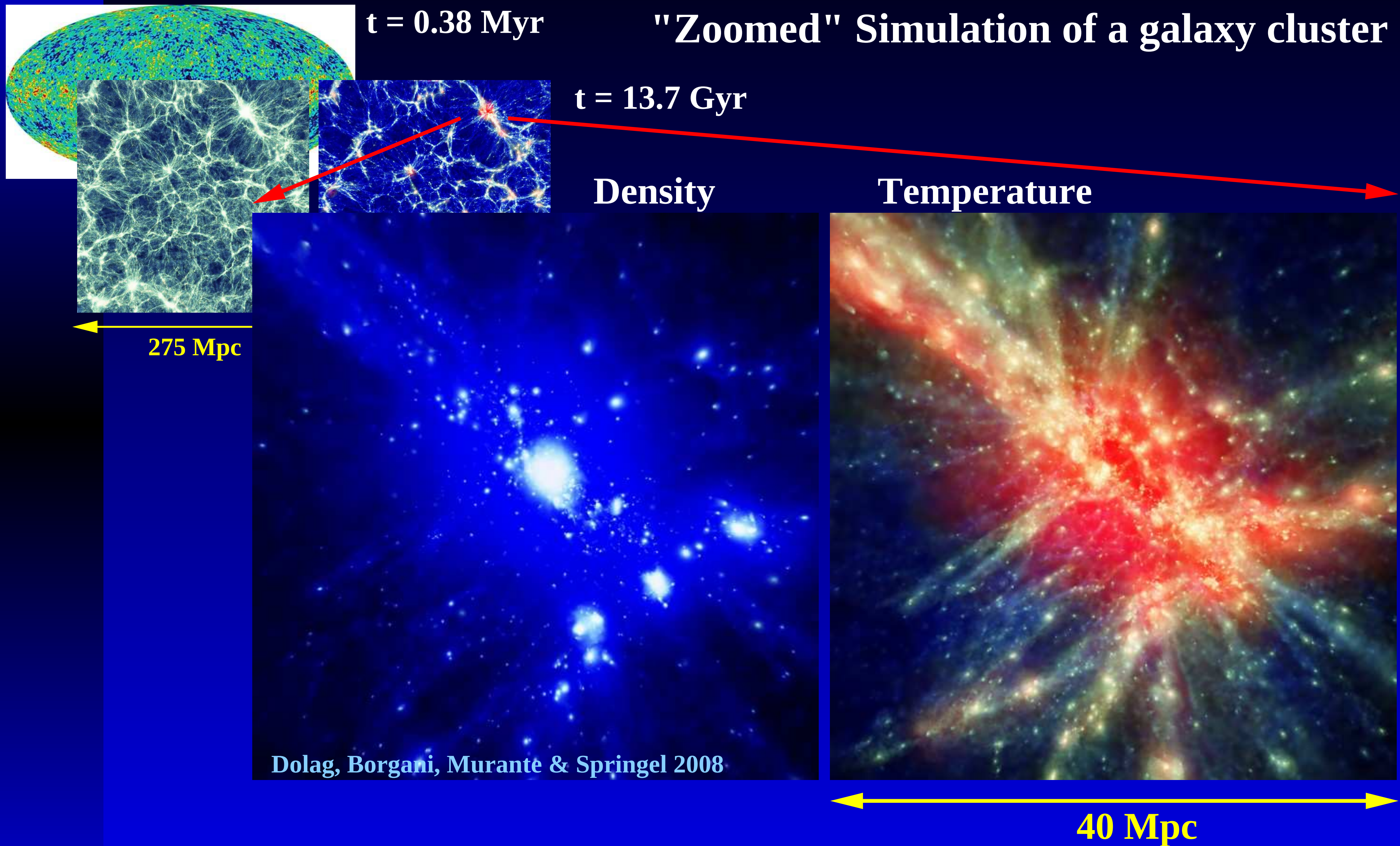


Borgani, Murante, Springel, Diaferio, Dolag et al. 2004

275 Mpc

The cosmic web today ($z = 0$) is mainly accessible through simulations (warm, thin). Model predictions for $\vec{B}$ are important for propagation of ultra high energetic cosmic rays (UHECRs).

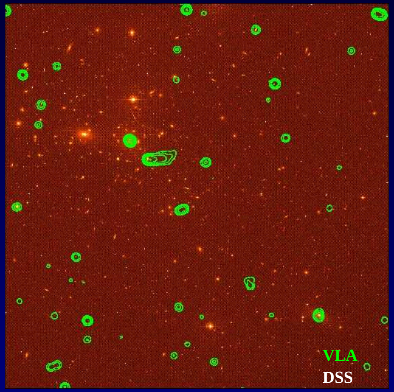
Introduction



Clusters form at the nodes of the cosmic web and can be used as a tool to understand the physical state of diffuse baryons.

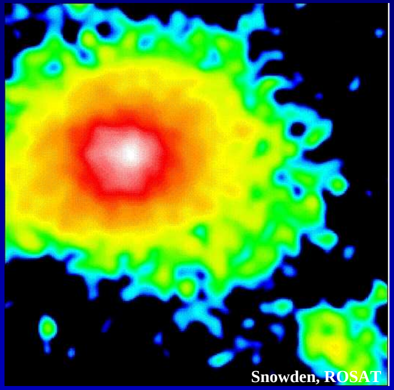
Introduction

Observations (⇒), Simulations (⇐) and the role of $\vec{B}$:



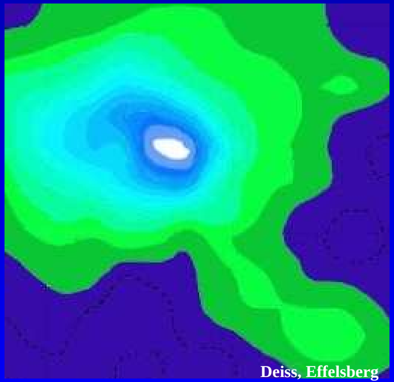
Galaxies (optical, radio):

- ⇒ Interaction with the ICM
- ⇐ Galaxies in dense environment (**stripping**, distribution of metals)
- ⇐ Magnetic field **seeding** (outflows)



ICM (X-ray, thermal bremsstrahlung):

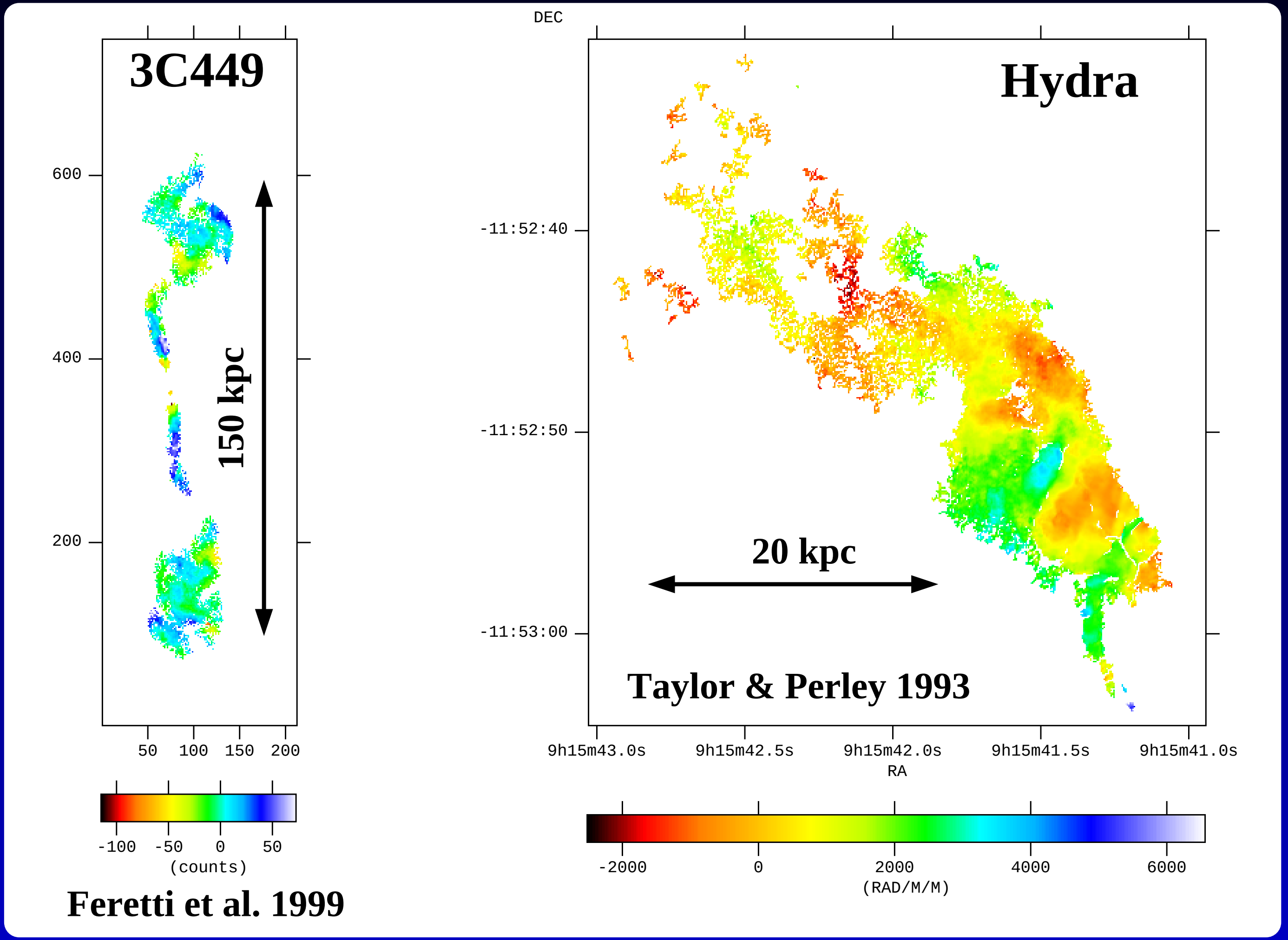
- ⇒ Dynamical state of ICM
- ⇐ Non thermal **pressure** support
- ⇐ **Turbulence**, **viscosity**, shocks



ICM (radio, synchrotron radiation):

- ⇒ Distribution of $\vec{B}$, CRs (diffuse + RM)
- ⇐ **Evolution** and **buildup** of $\vec{B}$
- ⇐ **Acceleration** and **propagation** of CRs

Faraday Rotation (RM)

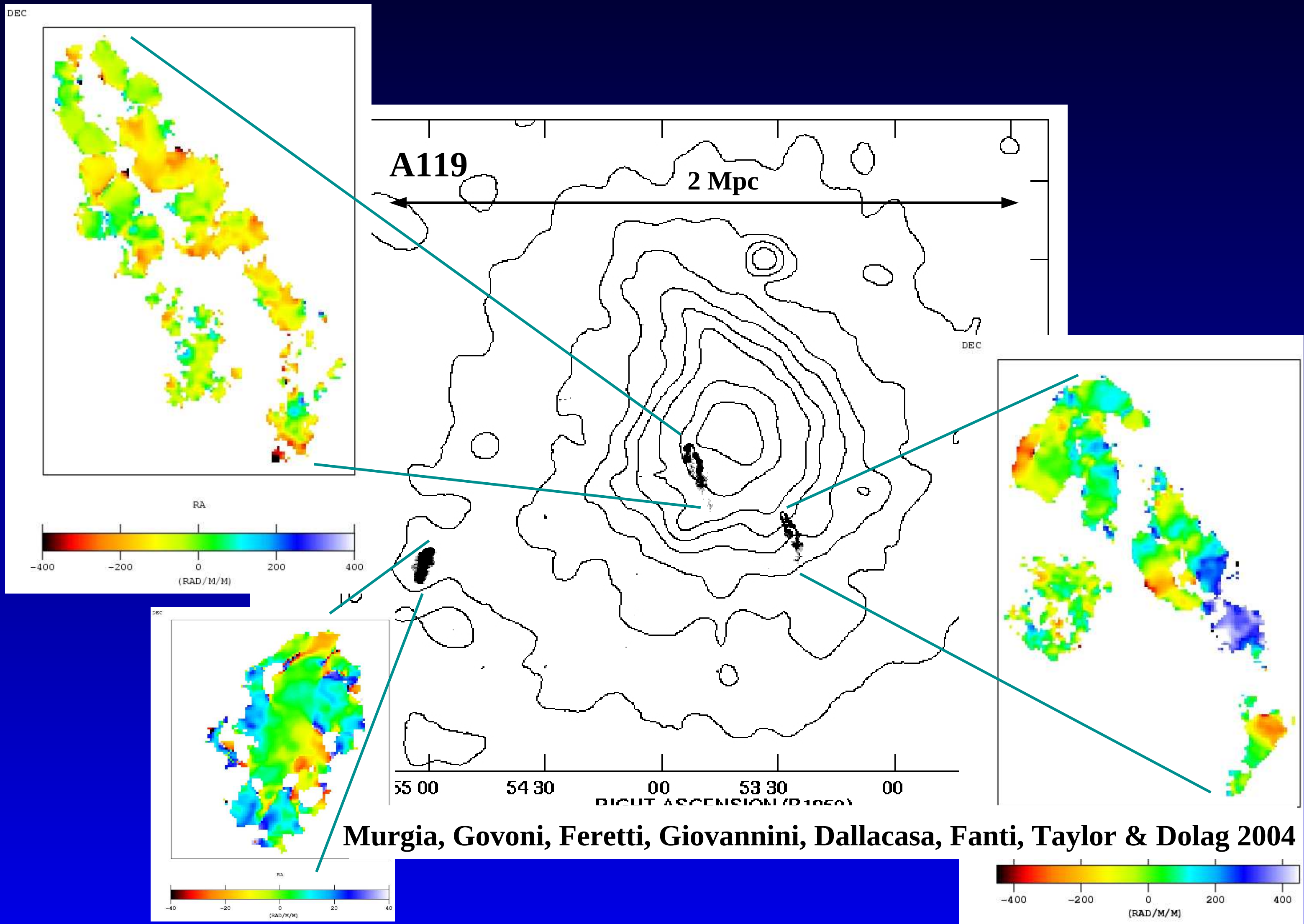


High quality Rotation Measure maps across the lobes of the central radio source in 3C449 (left) and Hydra (right).

- Cool core versus cluster wide turbulence / fields structure ?
- Origin of cosmological magnetic fields ?
- Extension, structure and evolution of magnetic fields ?

Faraday Rotation (RM)

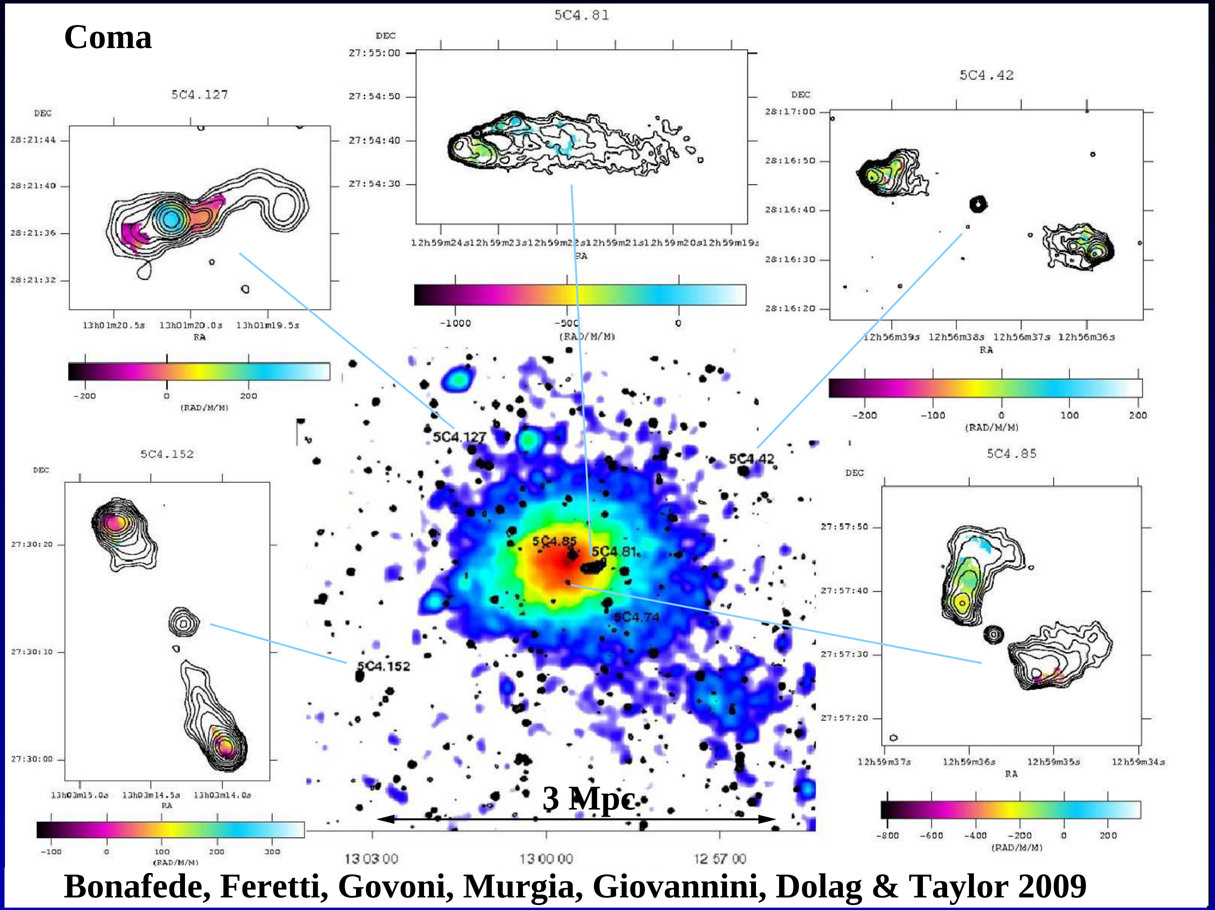
$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\mu}, \quad |B_k|^2 \propto k^{-n}$$

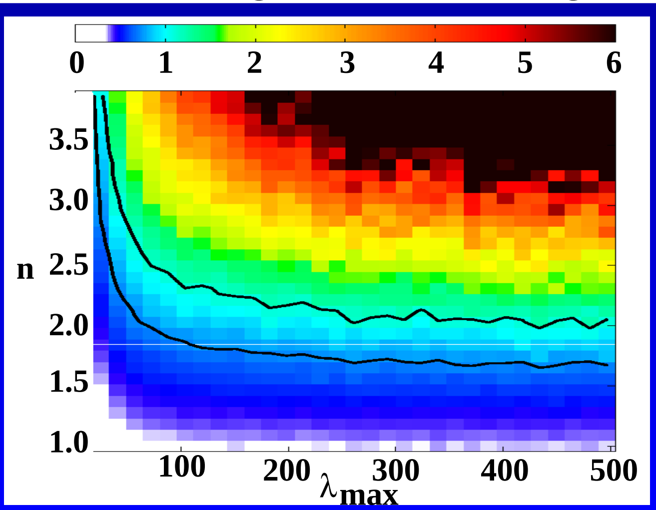


Murgia, Govoni, Feretti, Giovannini, Dallacasa, Fanti, Taylor & Dolag 2004

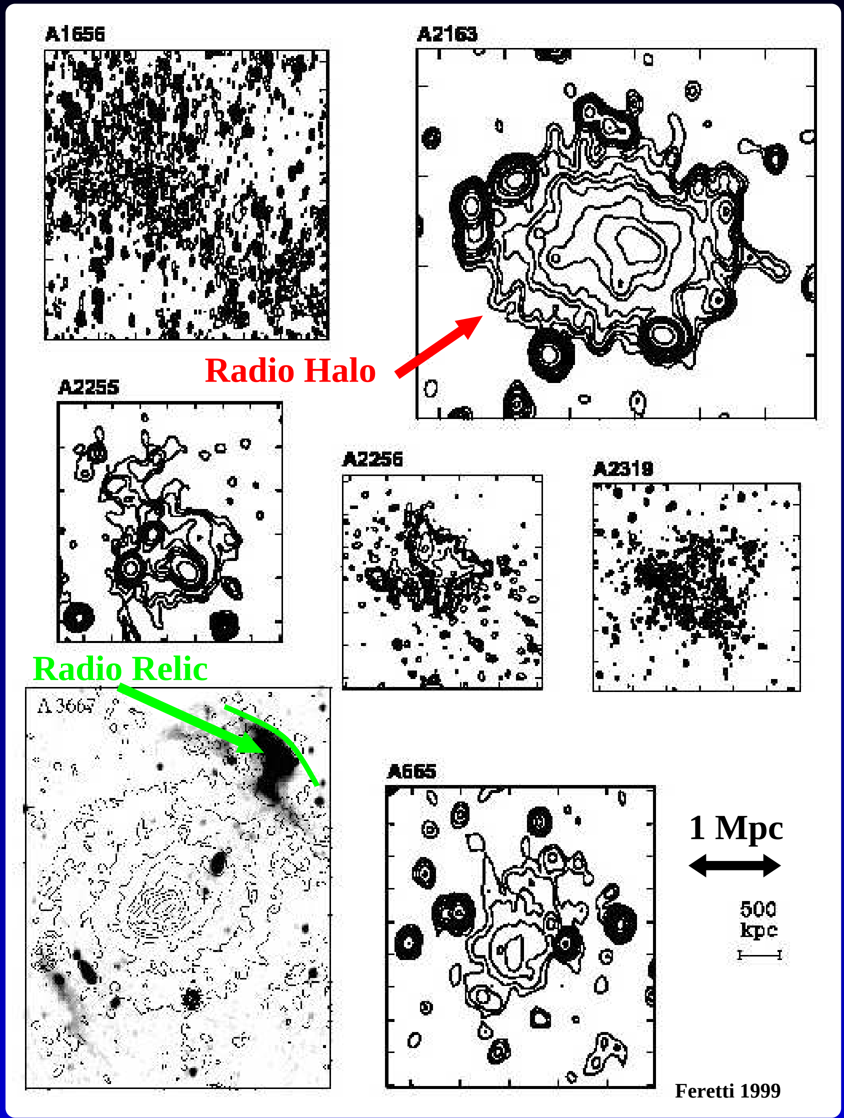
$$\Rightarrow B_0 = 5\mu\text{G} \quad n = 2 \quad \mu = 0.5$$

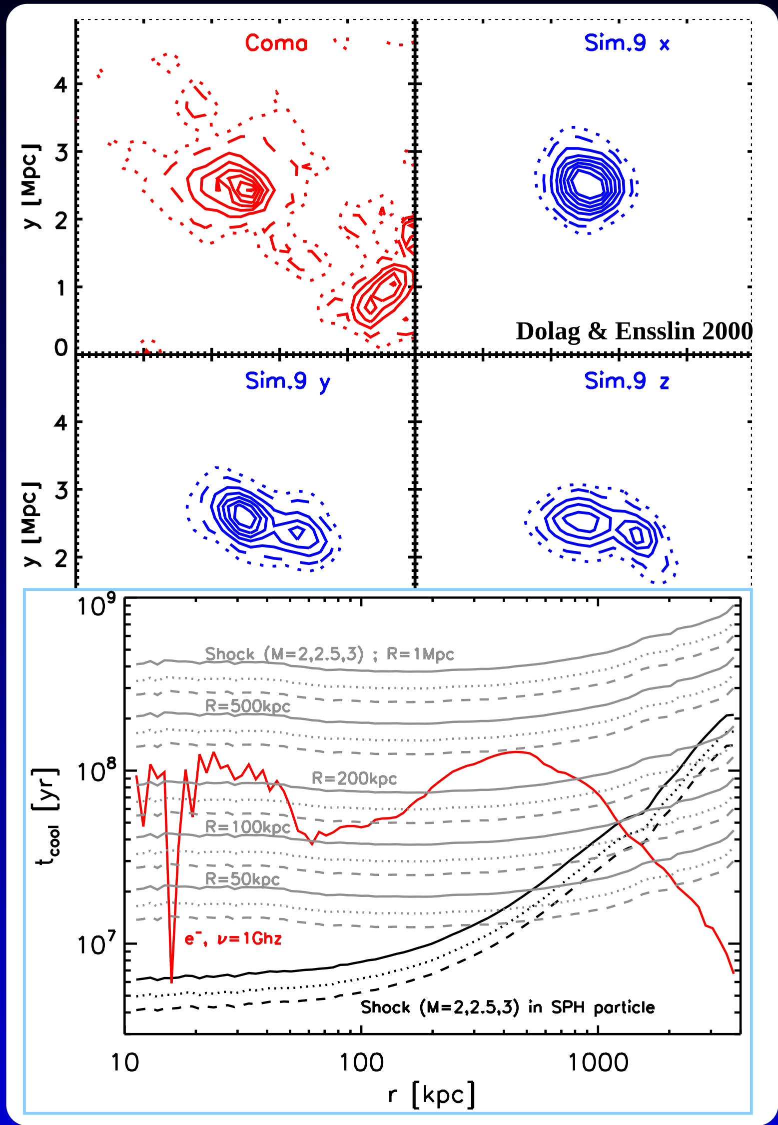
Faraday Rotation (RM)





Radio Halos (synchrotron)

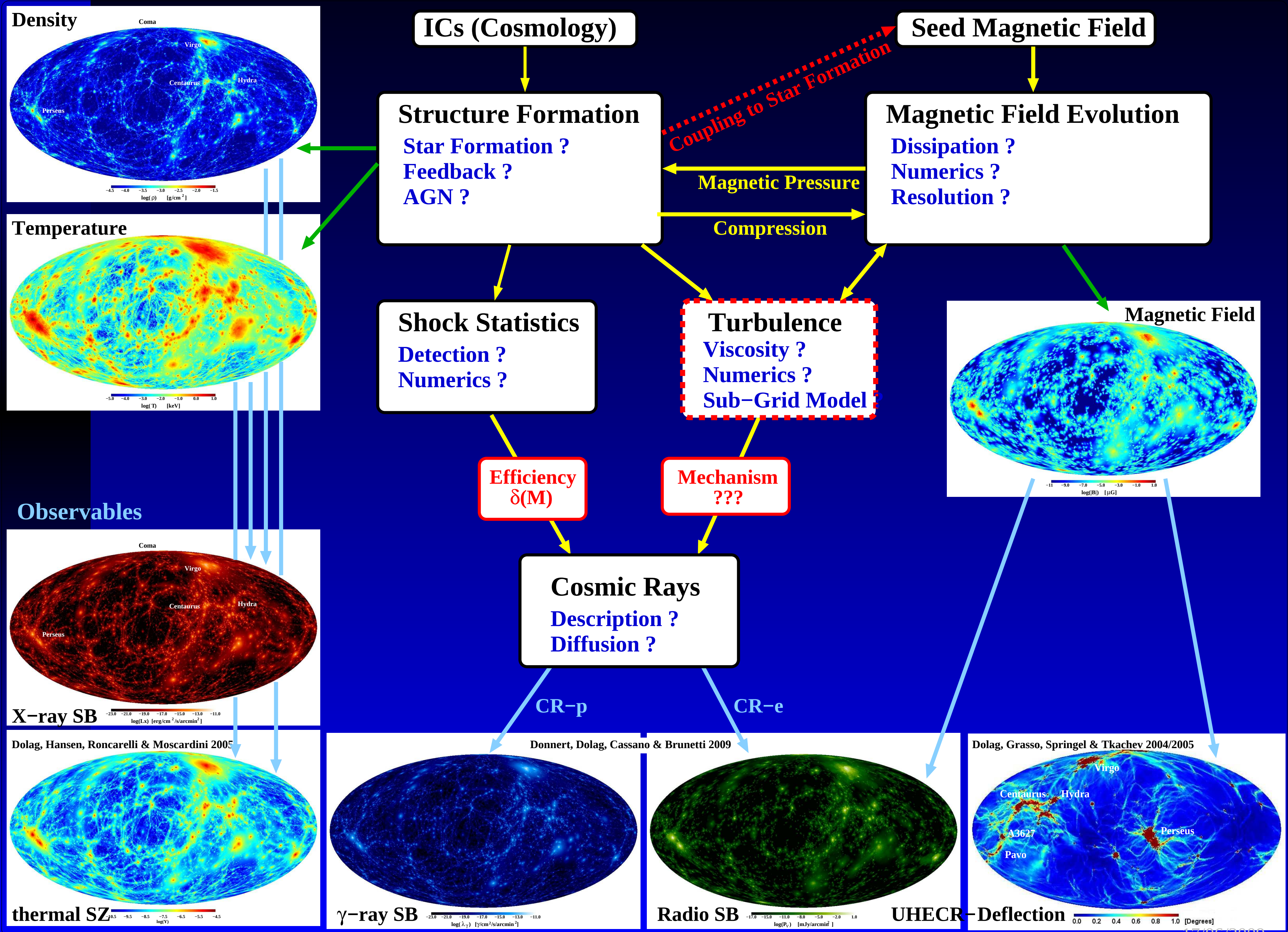




Cluster wide **diffuse synchrotron emission** connected to **merger** events, **periferal** emission directly connected to **shocks**.

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

Simulation Network



MHD with SPH

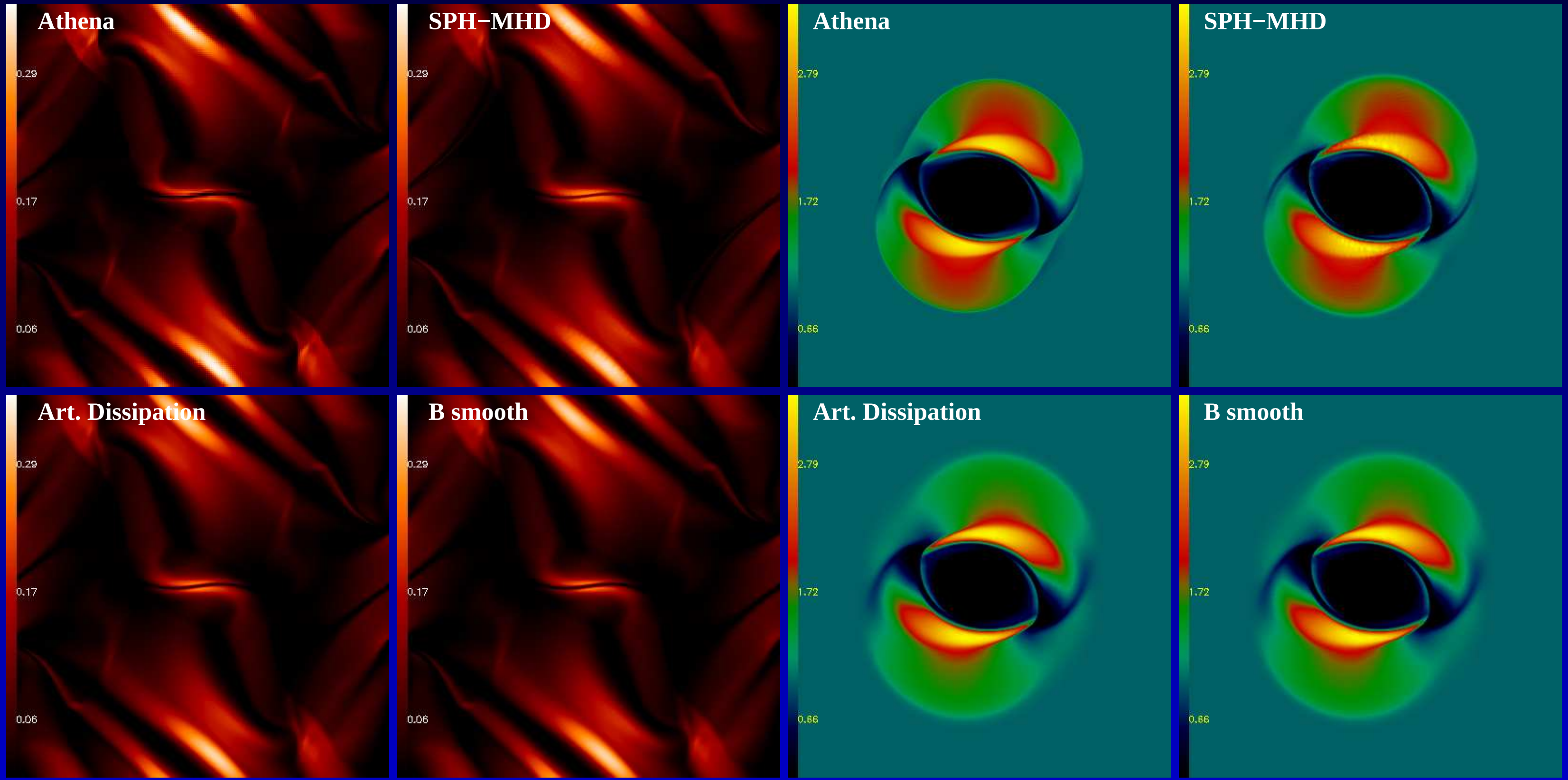
Why SPH ?

- Perfect self gravity $\Rightarrow$ excellent to capture structure formation
- Lagrangian $\Rightarrow$ excellent advection
- Highly adaptive $\Rightarrow$ large dynamical range
- Low dissipation $\Rightarrow$ no numerical mixing
- Efficient $\Rightarrow$ large simulations
- Simple $\Rightarrow$ allows to include various physical processes
- Ideal MHD: **+ Induction equation + Lorenz force**
  $\Rightarrow$ Many details to obtain stable and reliable implementation

MHD with SPH

Code verification in 1D shock tube tests (Ryu & Johns 1995) (Dolag et al. 1999, 2001, 2005) ...

Code verification in various 2D tests

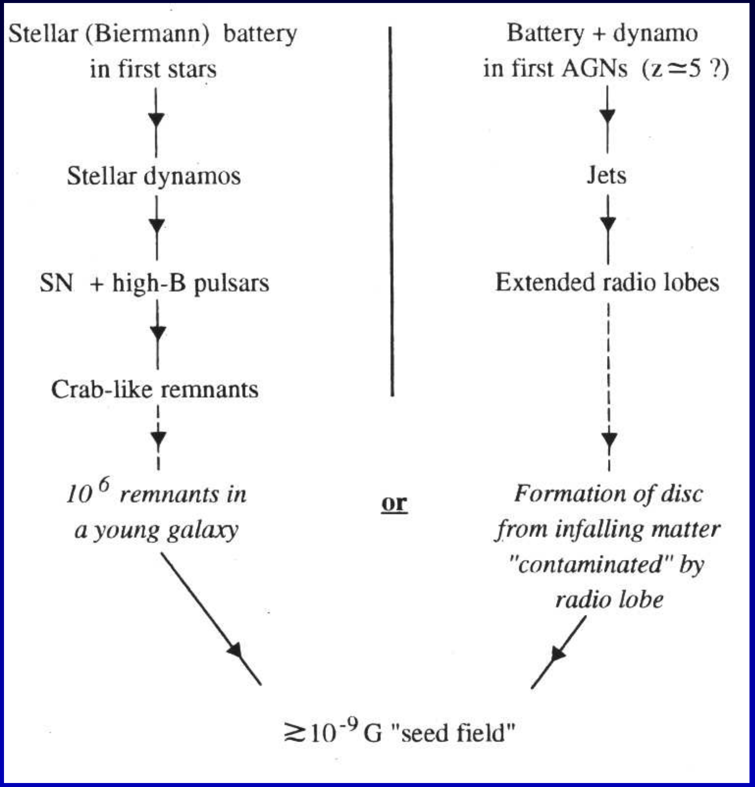


Magnetic field in the vortex (Orszag & Tang 1979) and the rotor (Balsare & Spicer 1999) test problem. Results for Anthena (top left) and SPH-MHD runs (Dolag & Stasyszyn 2008).

Cosmological MHD simulations

Origin

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

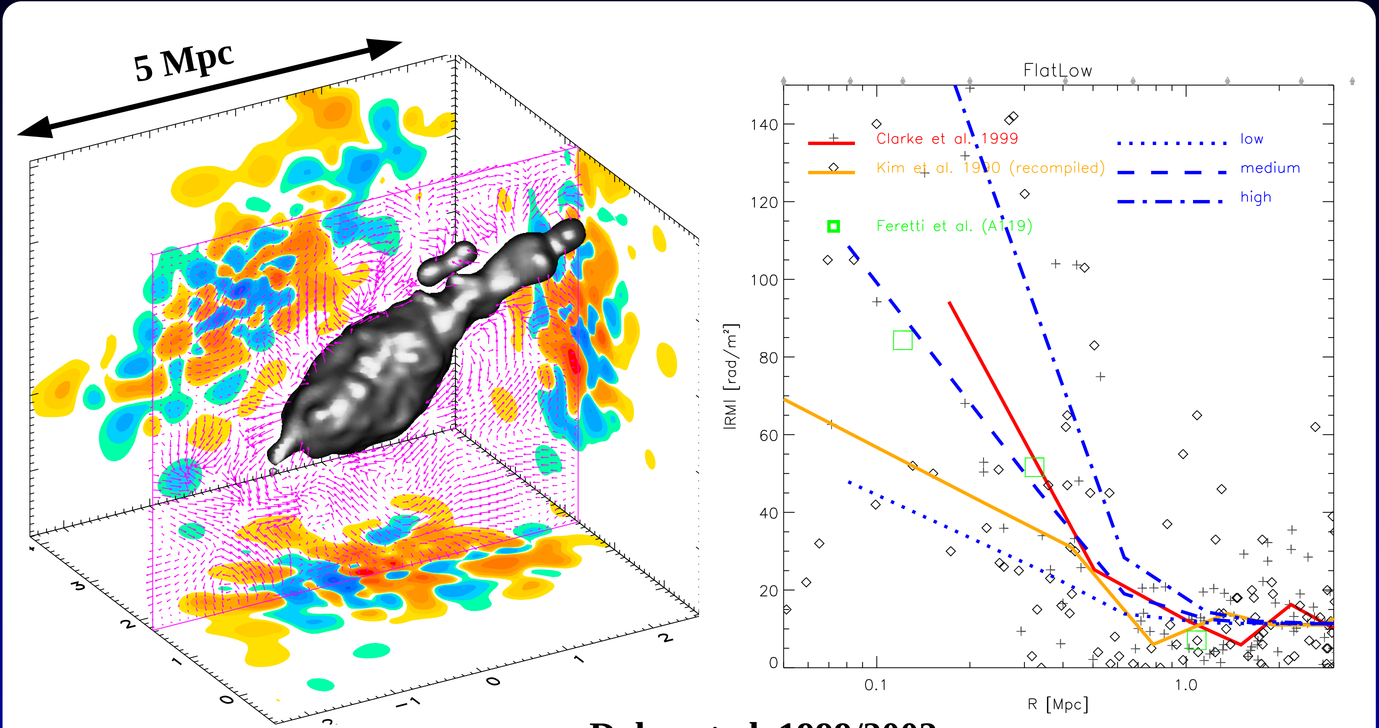


Rees 1994

+ further amplification by **structure formation**

- dissipation ?

Cosmological MHD simulations

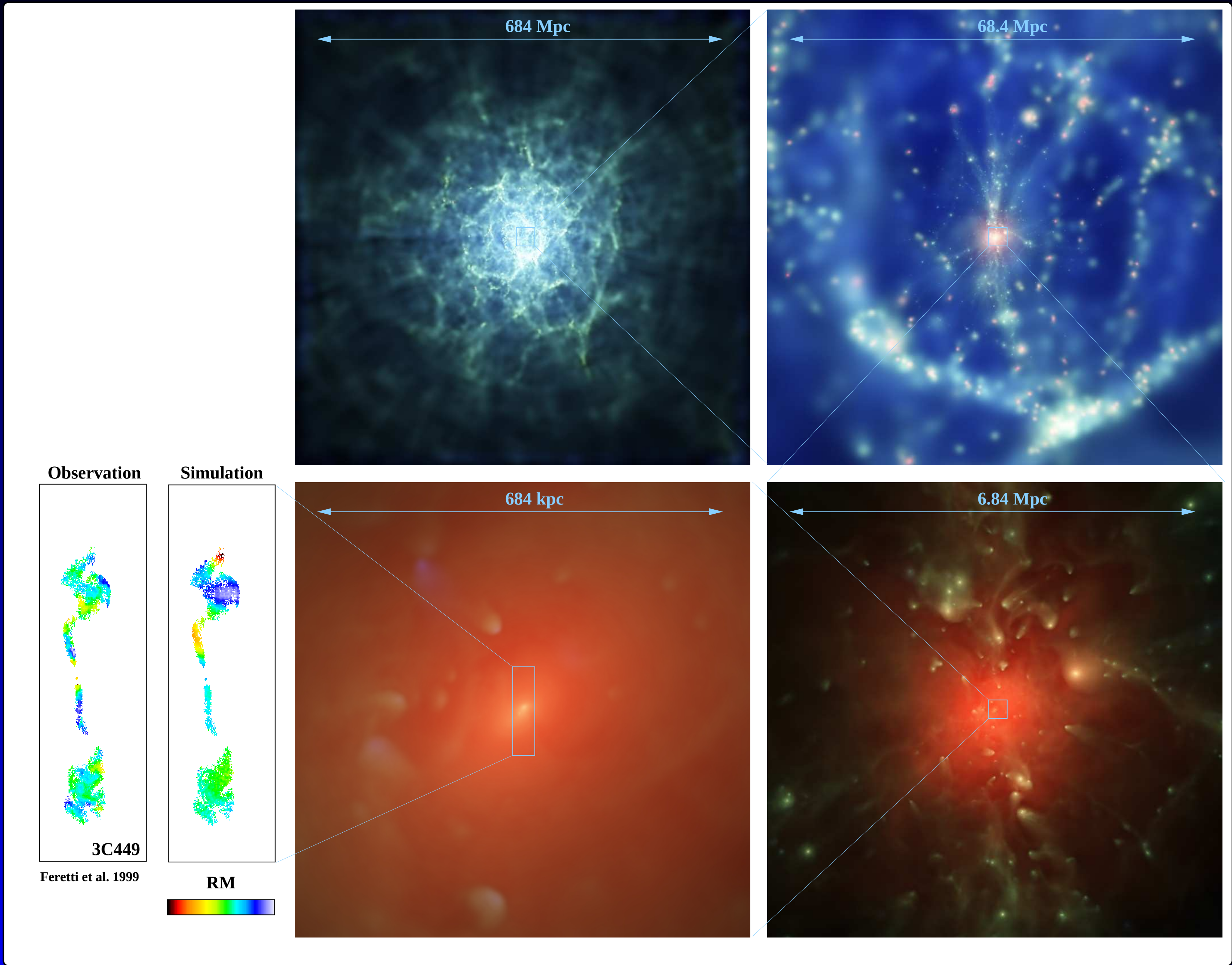


Dolag et al. 1999/2002

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

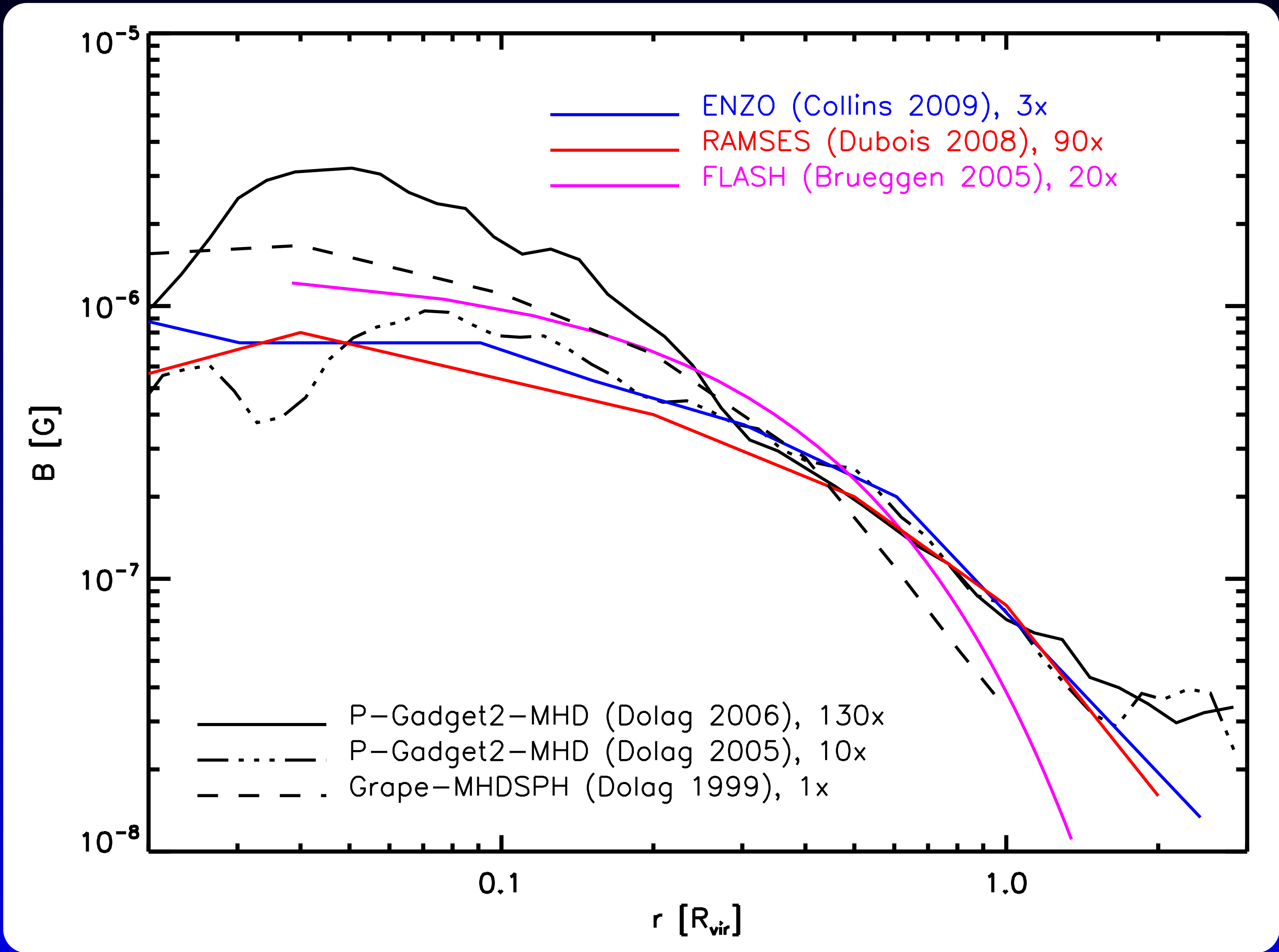
- Simulations reproduce the radial shape of the RM signal
  $\Rightarrow$ Magnetic power spectrum of clusters $n \approx 2.3 - 3.1$
- Magnetic field configuration driven by cluster dynamics
  $\Rightarrow$ Initial magnetic field structure not important
- Initial fields of $\approx (0.2 - 1) \times 10^{-11}$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

Cosmological MHD simulations



"Zoomed" cluster simulations (Dolag & Stasyszyn 2008)

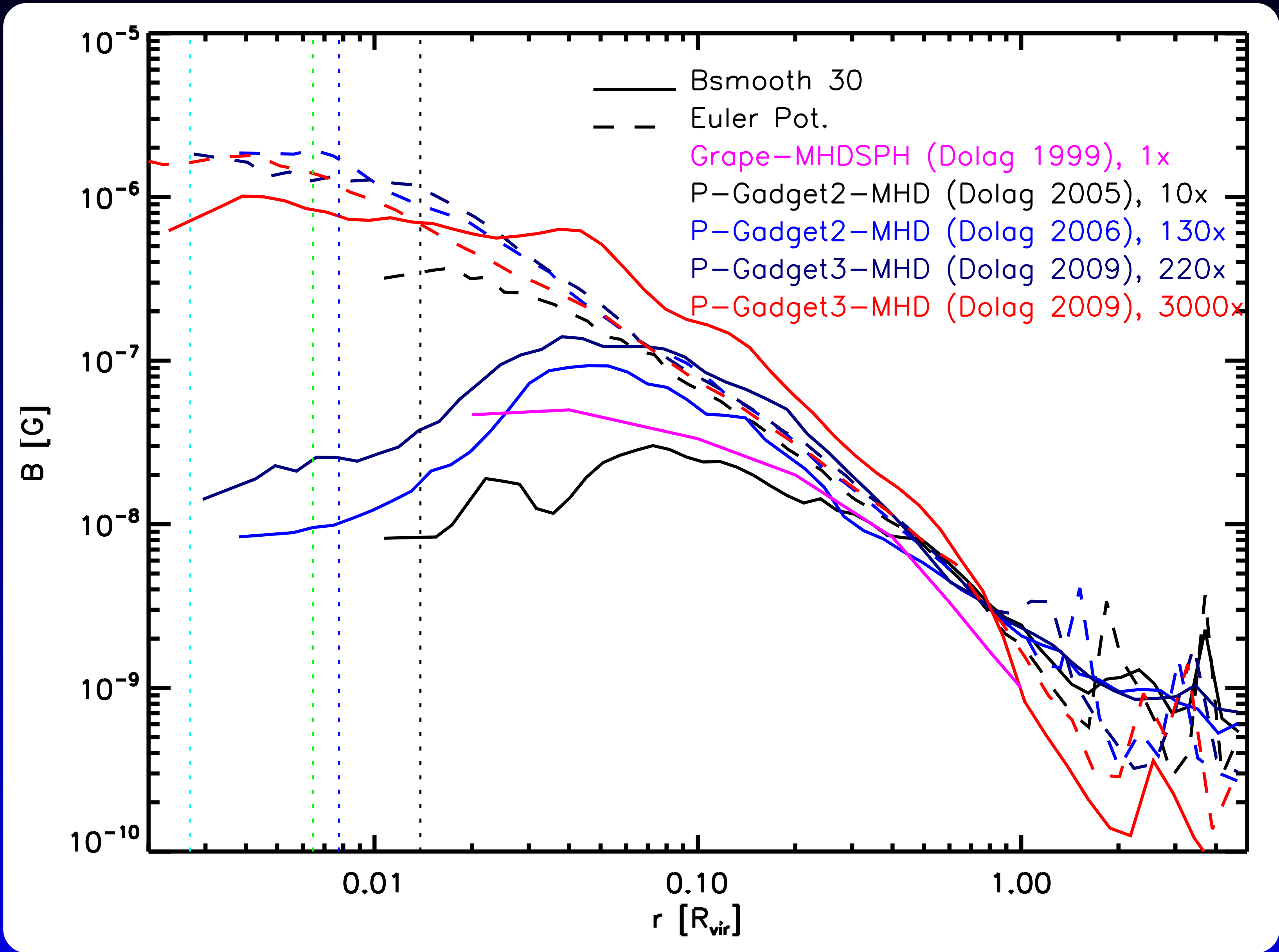
Cosmological MHD simulations



⇒ Several times confirmed since early work

⇒ Generic feature from structure formation

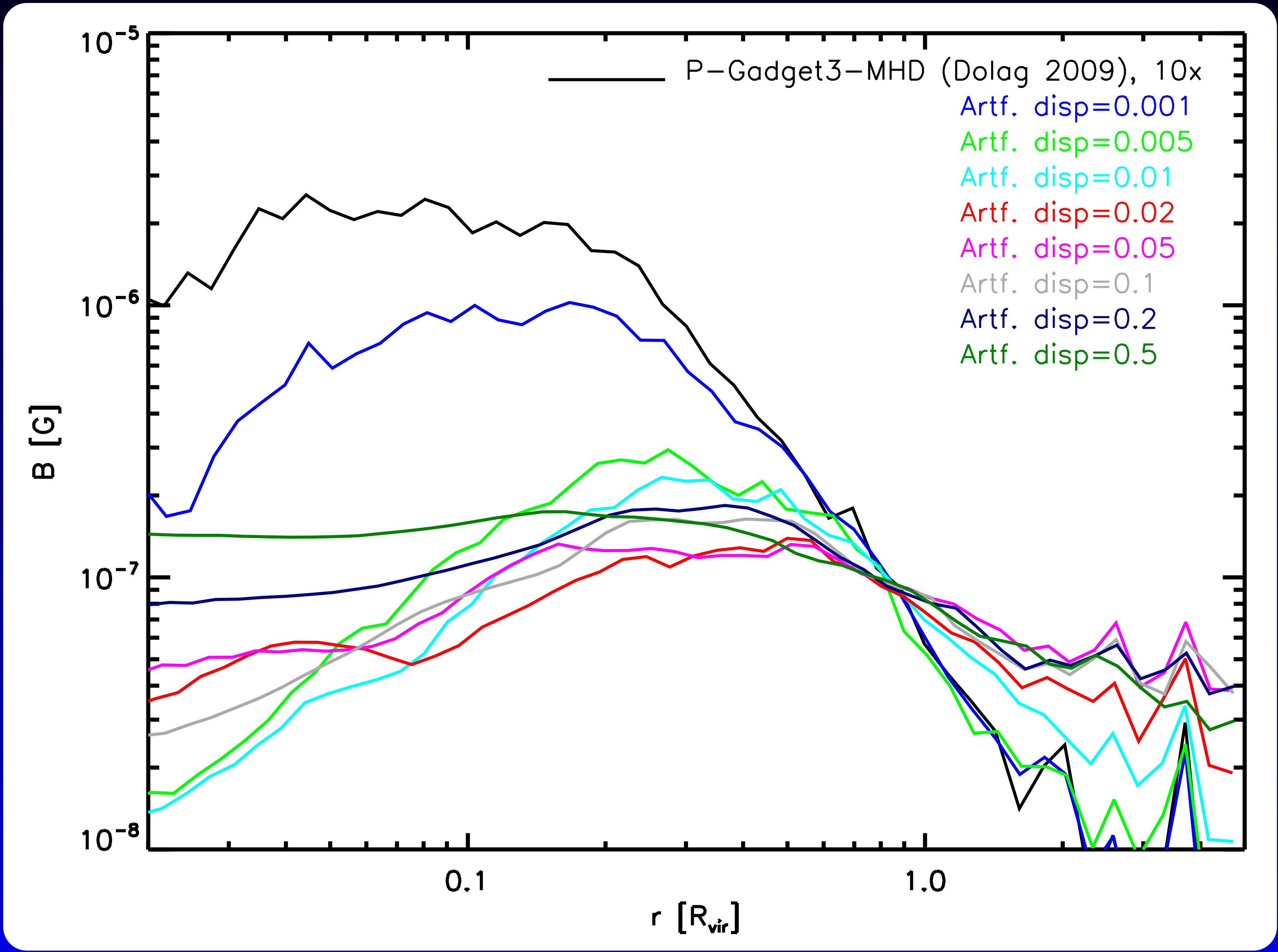
Cosmological MHD simulations



But: Central part steepens strongly with resolution.

⇒ Resolution is important

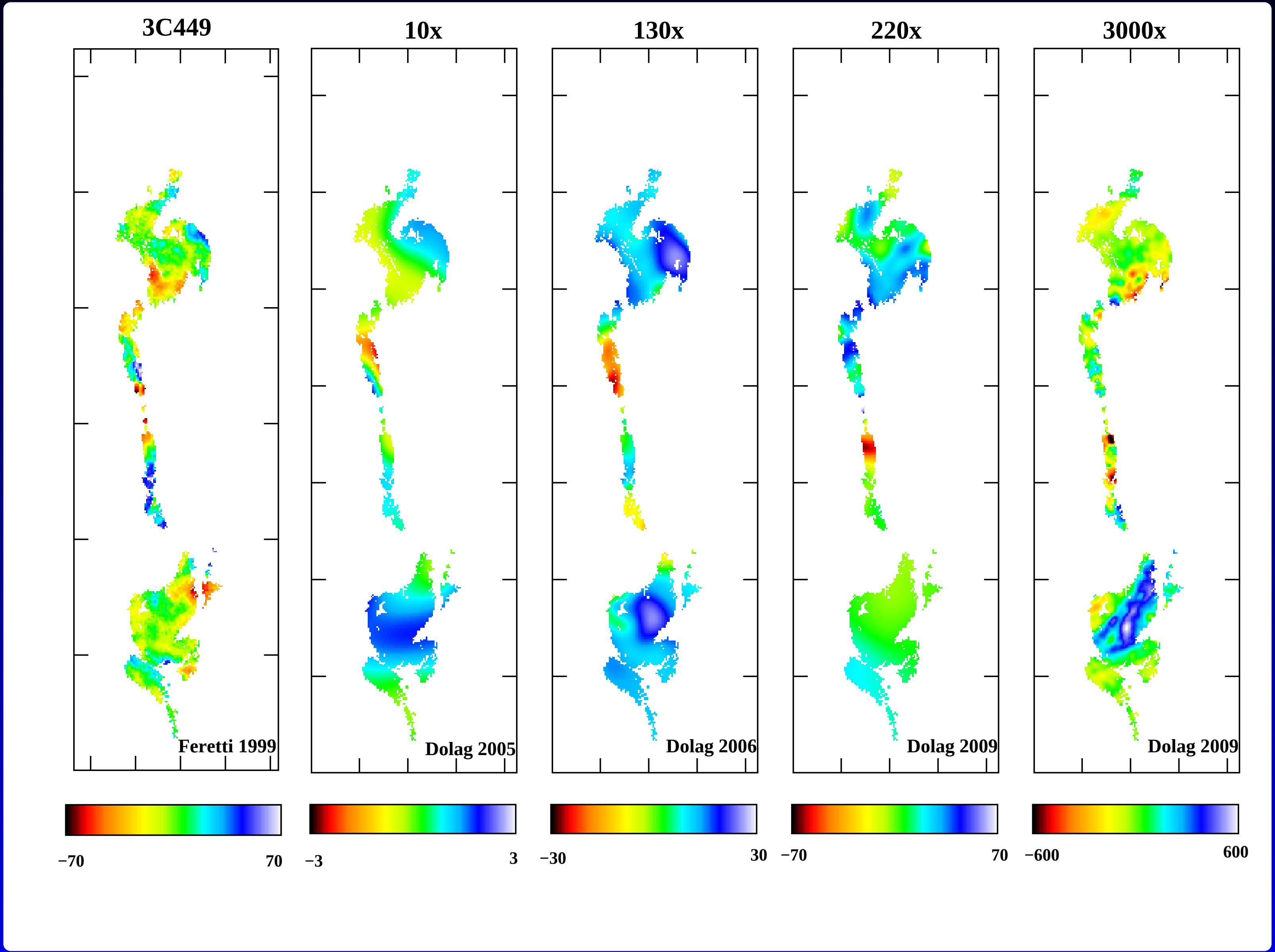
Cosmological MHD simulations



Attention: Also depends strongly on dissipation

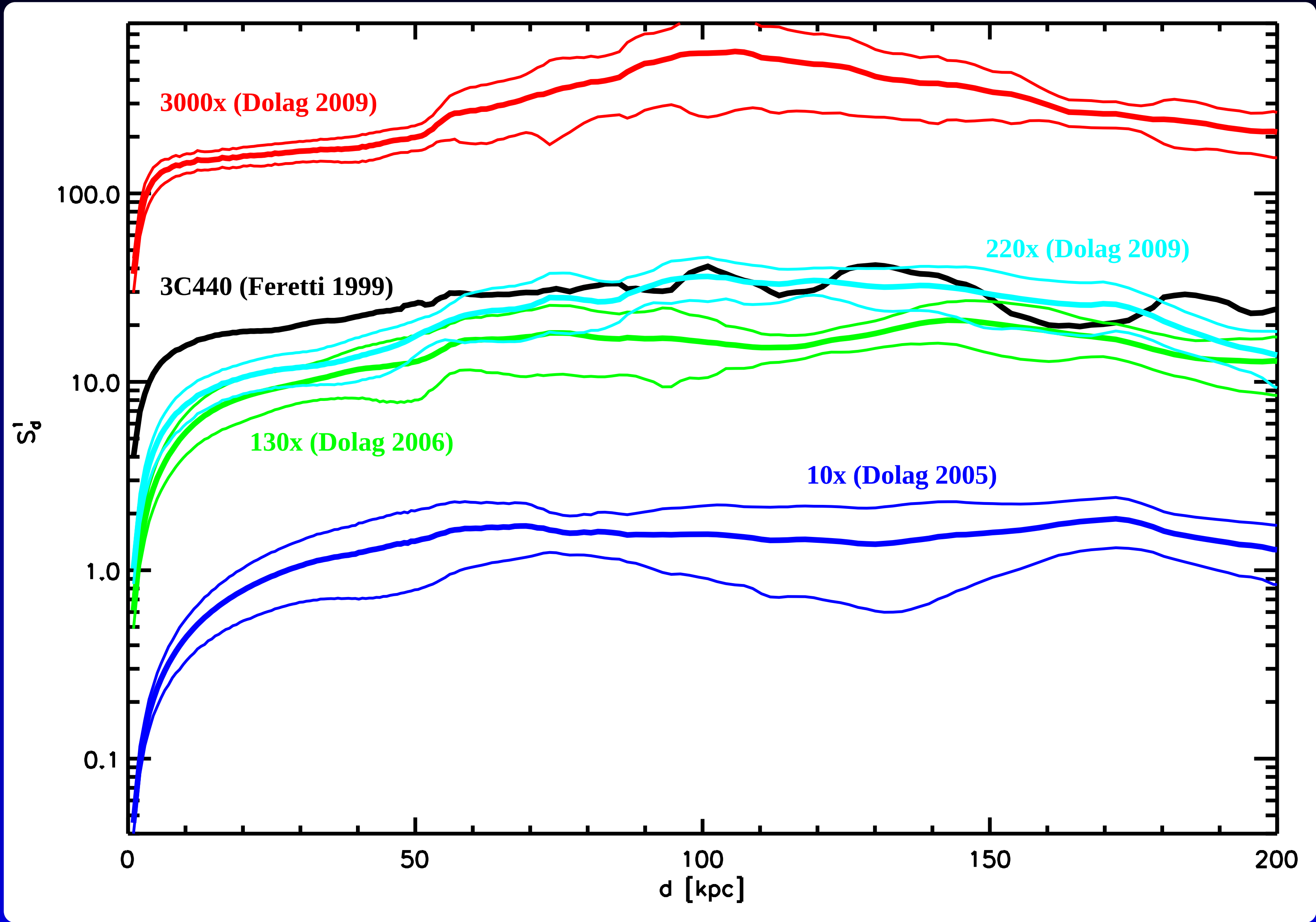
⇒ Numerical dissipation is important

Cosmological MHD simulations



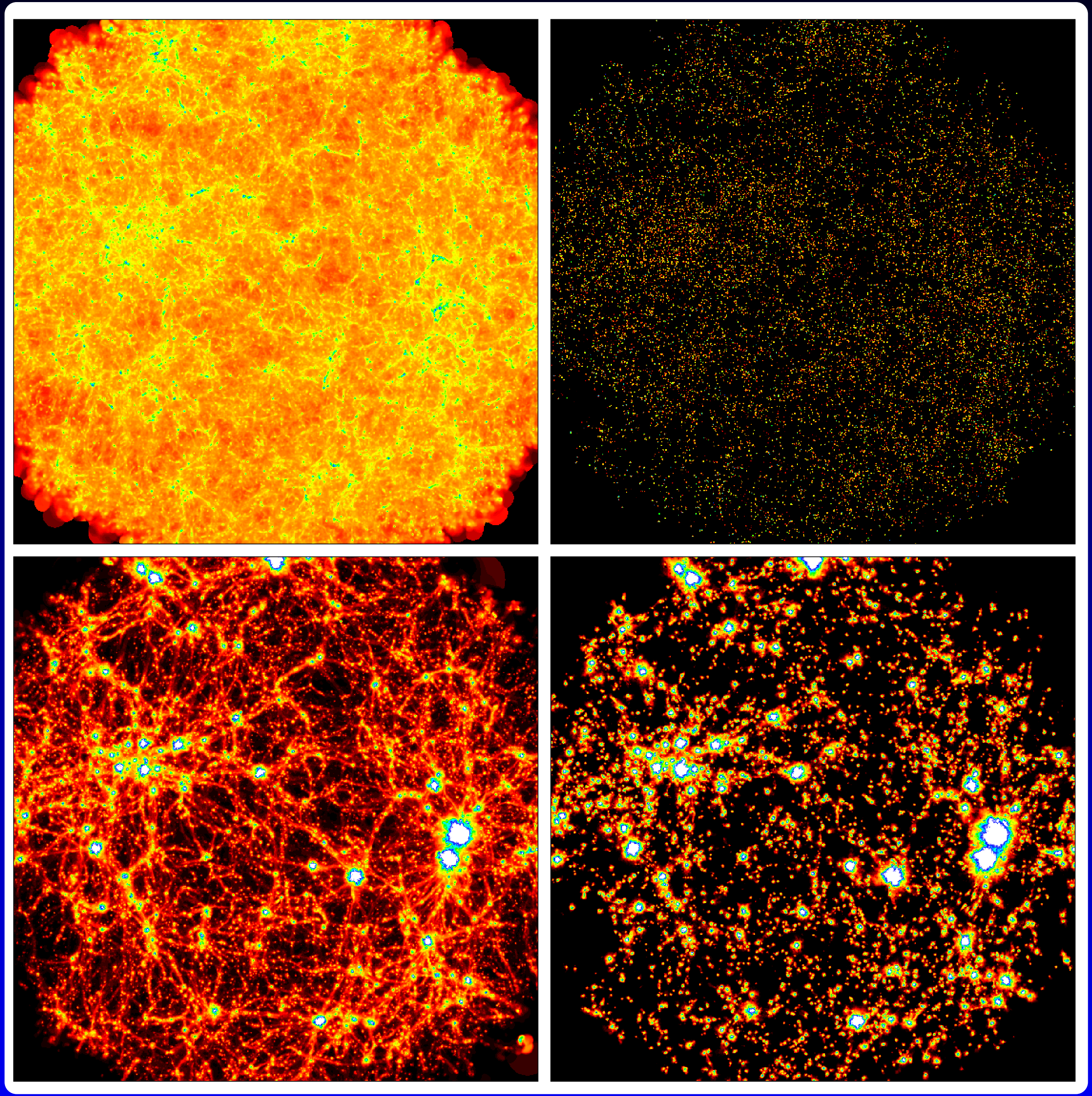
Observed and simulated RM maps up to highest resolution simulation: MHD, 20 Million particles within R_{vir}, $m_{DM} = 10^7 M_\odot/h$, $\epsilon_{Grav} = 1$kpc/h (work in progress).

Cosmological MHD simulations



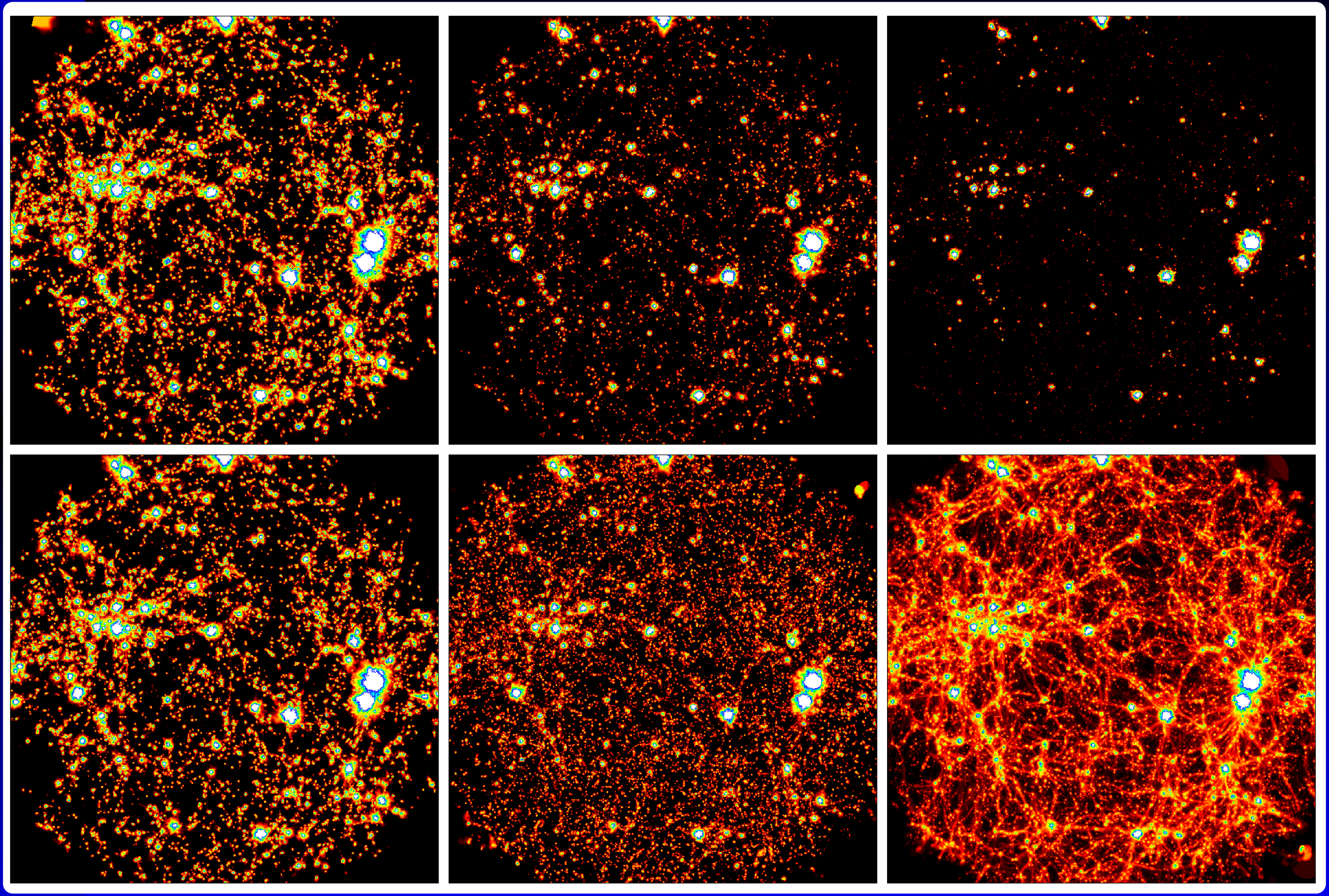
Structure function derived from observed and simulated RM maps up to highest resolution simulation: Indication for need of magnetic dissiation (work in progress).

Origin of Magnetic Fields



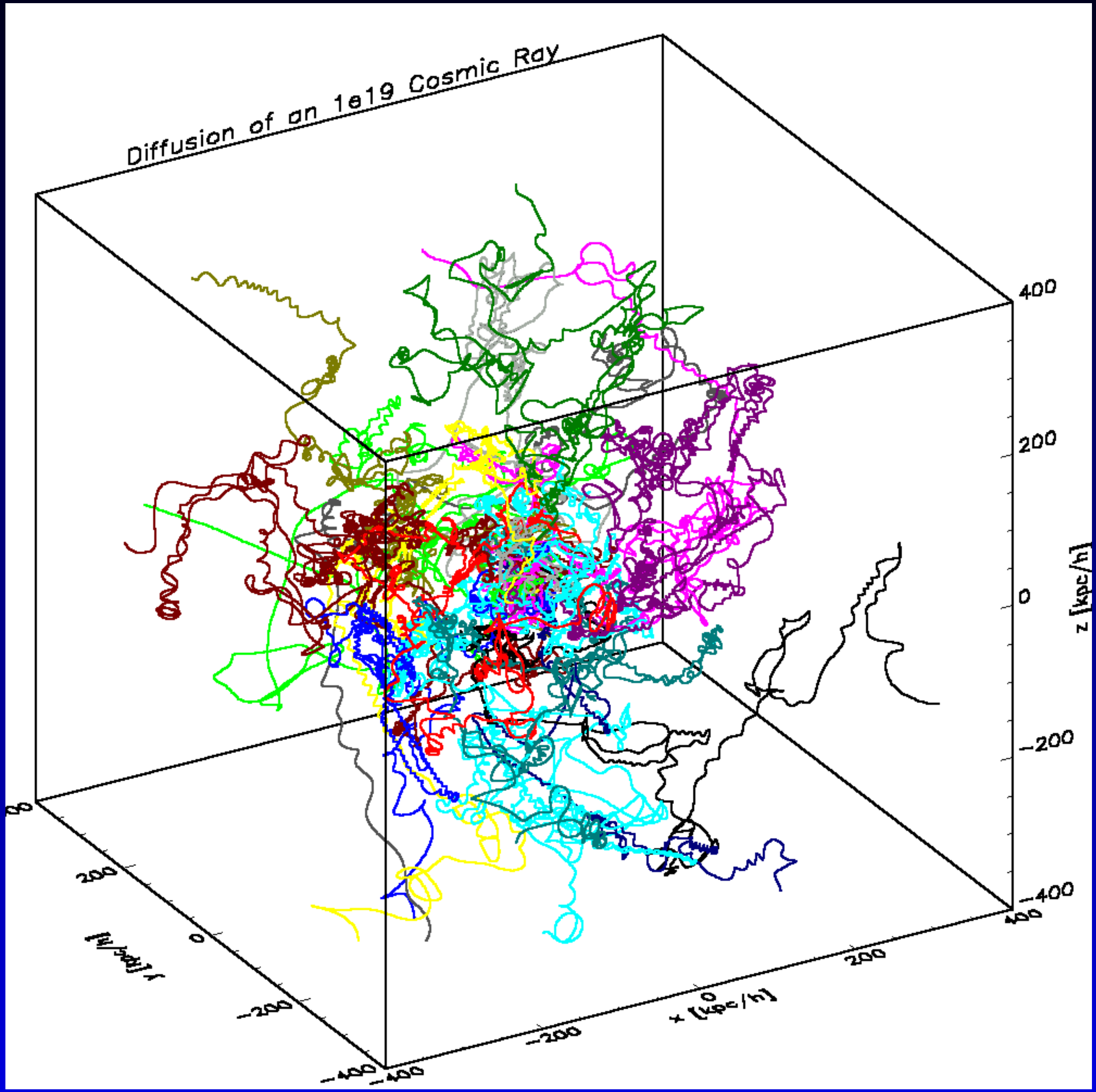
Seeding from galactic outflows (Donnert, Dolag et al. 2008)

Origin of Magnetic Fields



Different wind parameters (Donnert, Dolag et al. 2008)

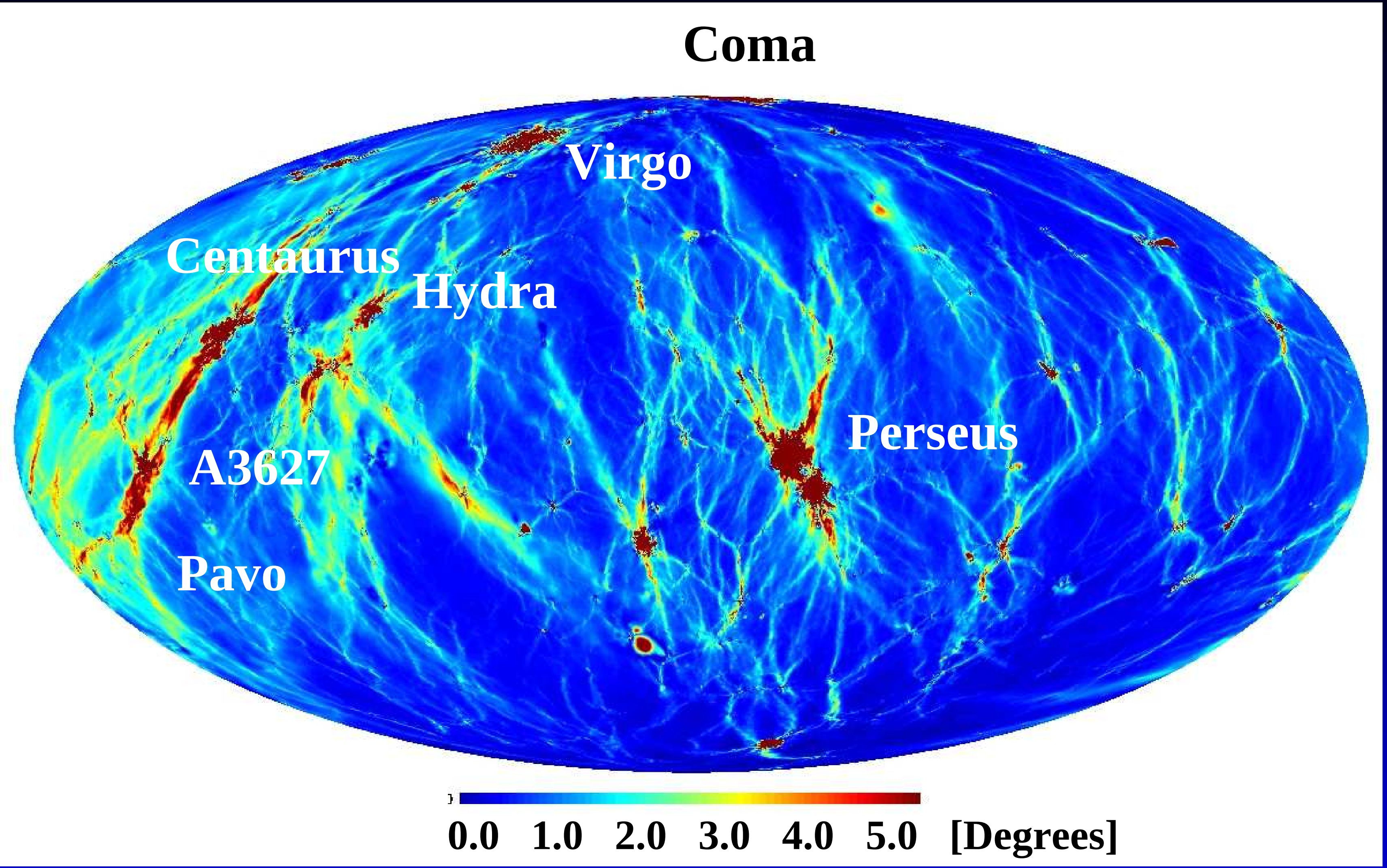
Propagation of UHECRs



Trajectories of Cosmic Rays diffusing through the cluster core

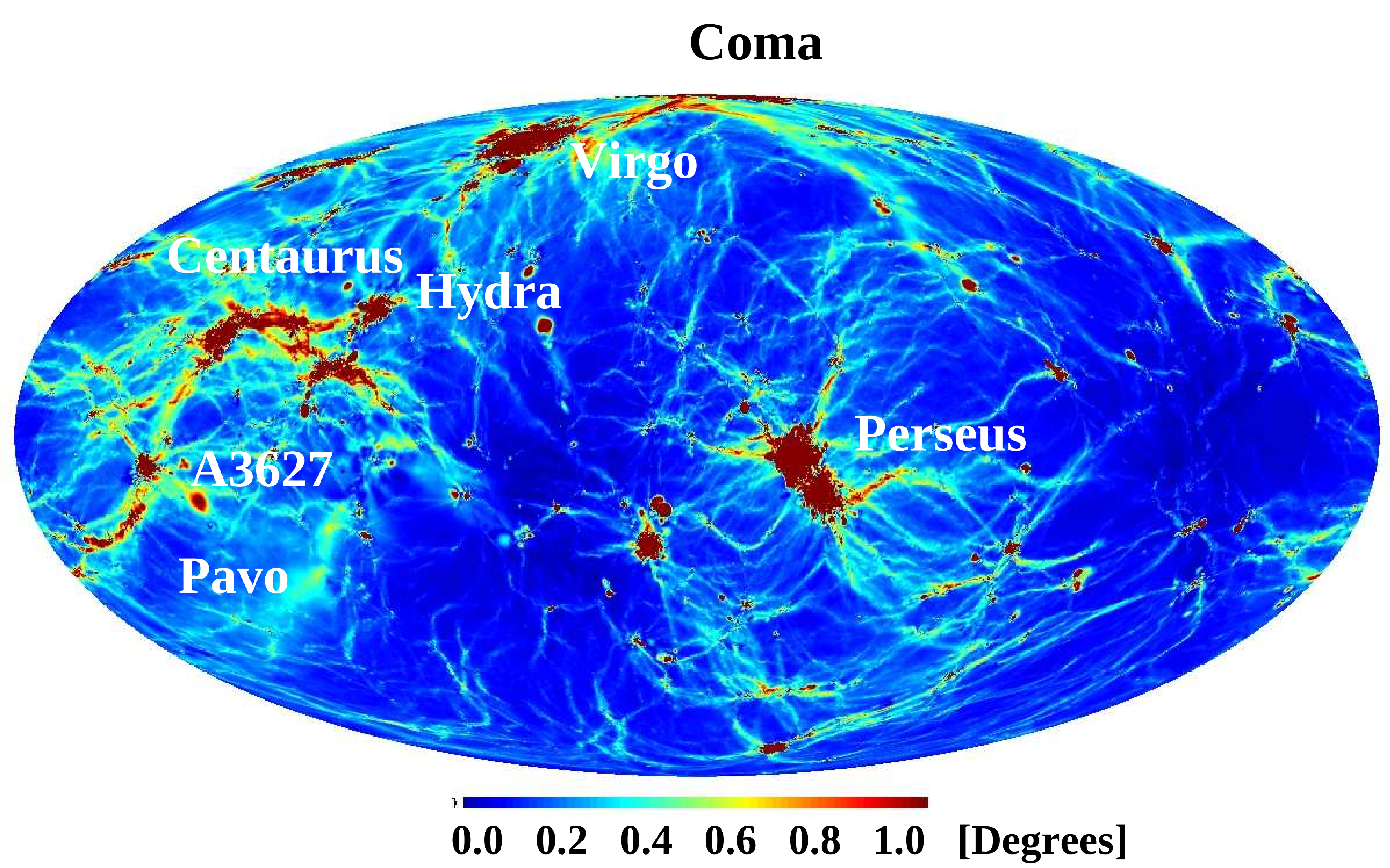
(Rordorf, Grasso & Dolag 2004)

Propagation of UHECRs



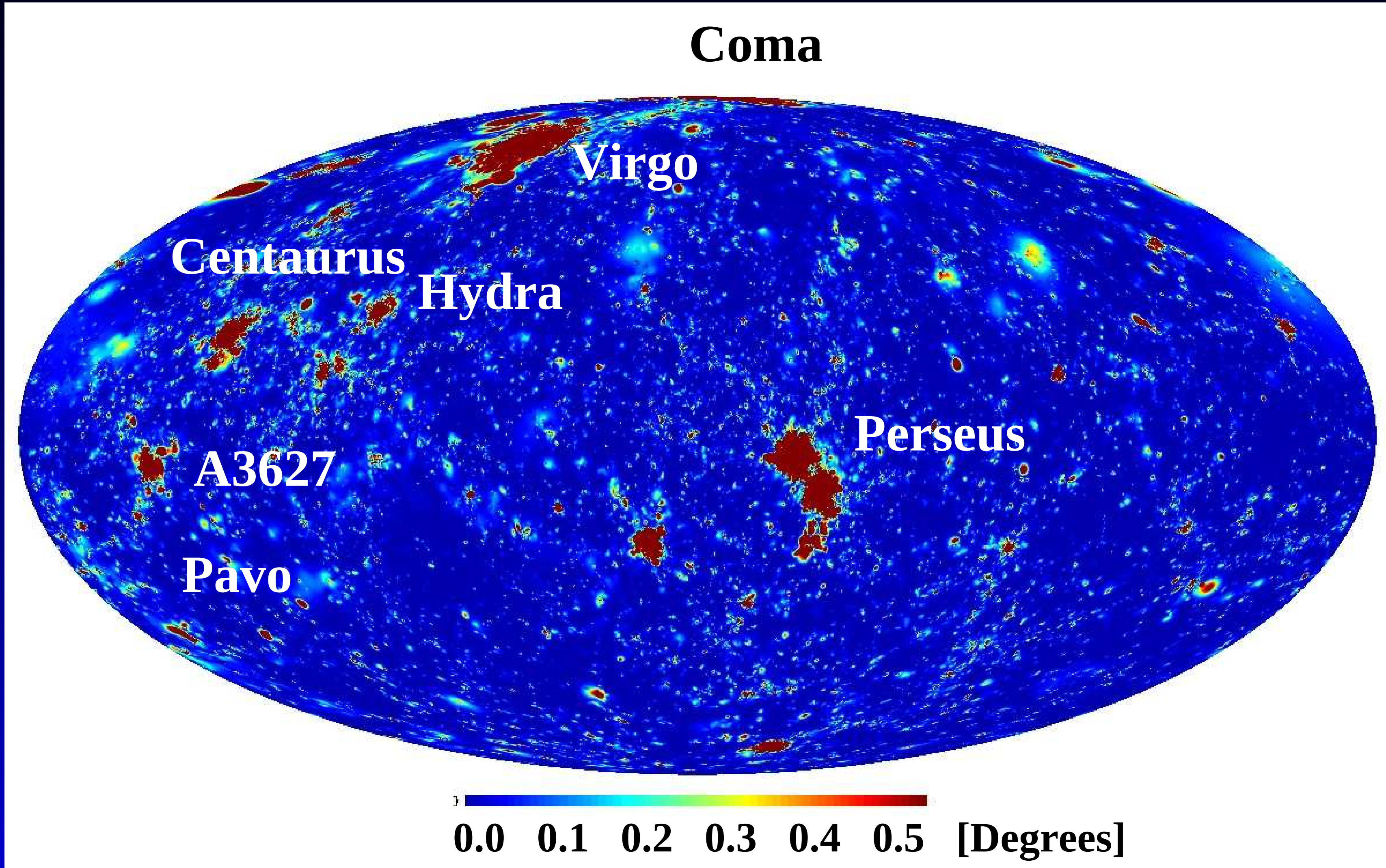
Full sky deflection signal for 4×10^{19}eV Cosmic Rays without losses, using a sphere of 110 Mpc radius and $B_0 = 10^{-5} \mu$G (Dolag, Grasso, Springel & Tkachev 2004)

Propagation of UHECRs



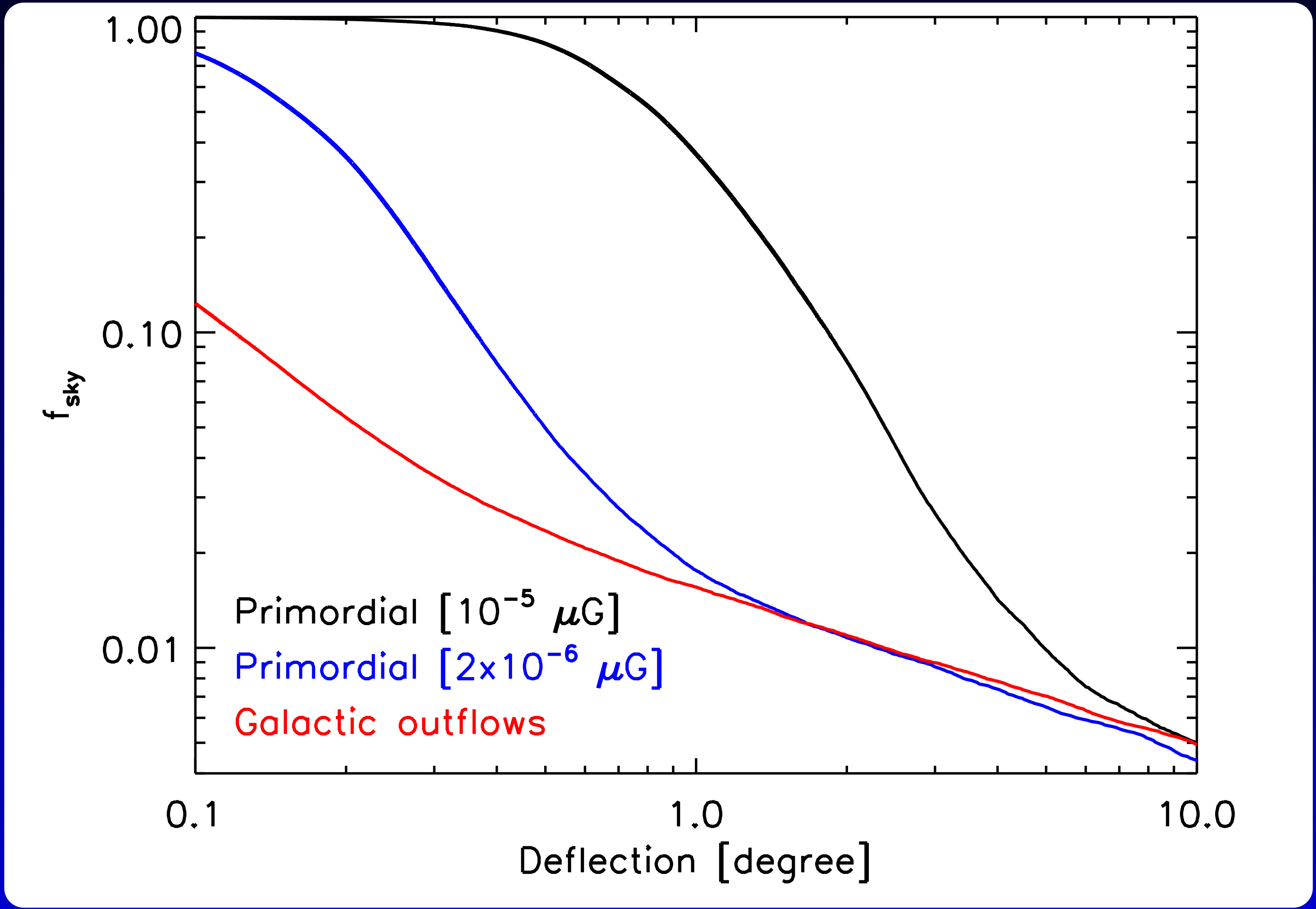
Full sky deflection signal for 4×10^{19}eV Cosmic Rays without losses, using a sphere of 110 Mpc radius $B_0 = 0.2 \times 10^{-5}\mu$G (Dolag, Grasso, Springel & Tkachev 2005)

Propagation of UHECRs



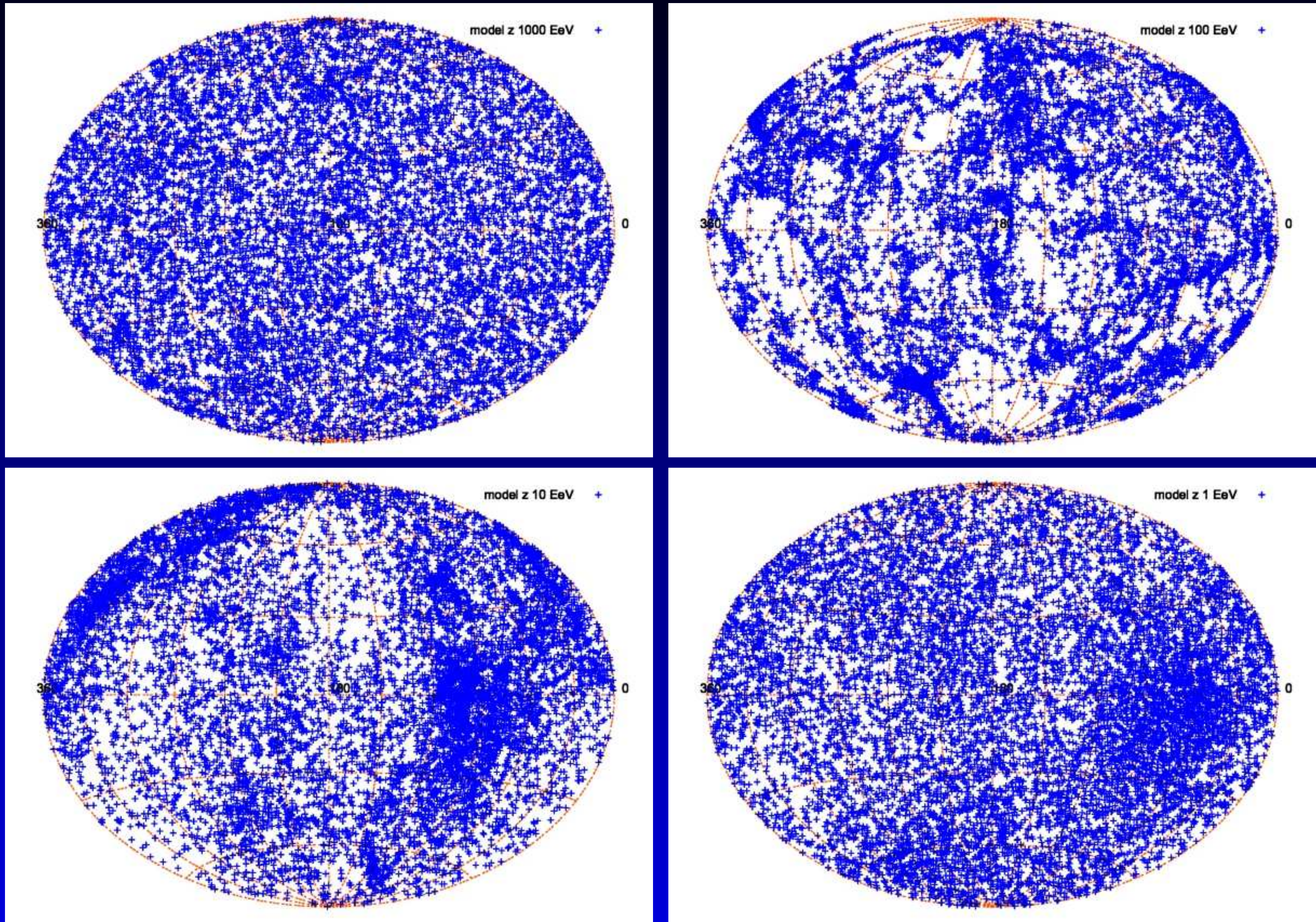
Full sky deflection signal for 4×10^{19}eV Cosmic Rays without losses, using a sphere of 110 Mpc radius from galactic outflows (Just for you !)

Propagation of UHECRs



Sky coverage of deflection signal for 4×10^{19}eV Cosmic Rays without losses, using a sphere of 110 Mpc radius for all models (Also just for you !)

Propagation of UHECRs



Sky maps of UHECRs emitted uniformly from M87 with 1000 (upper right), 100, 10 and 1 EeV (lower left) (Dolag, Kachelriess, Semikoz 2008), see talk by Dimitri Semikoz.

Investigating magnetic fields

Rotation Measure:

$$\mathrm{RM} \propto \int n_{\mathrm{e}} \, B_{\|} \, \mathrm{d}l$$

$\Rightarrow$ additional proportionality to density

$\Rightarrow$ not very good for low density regions

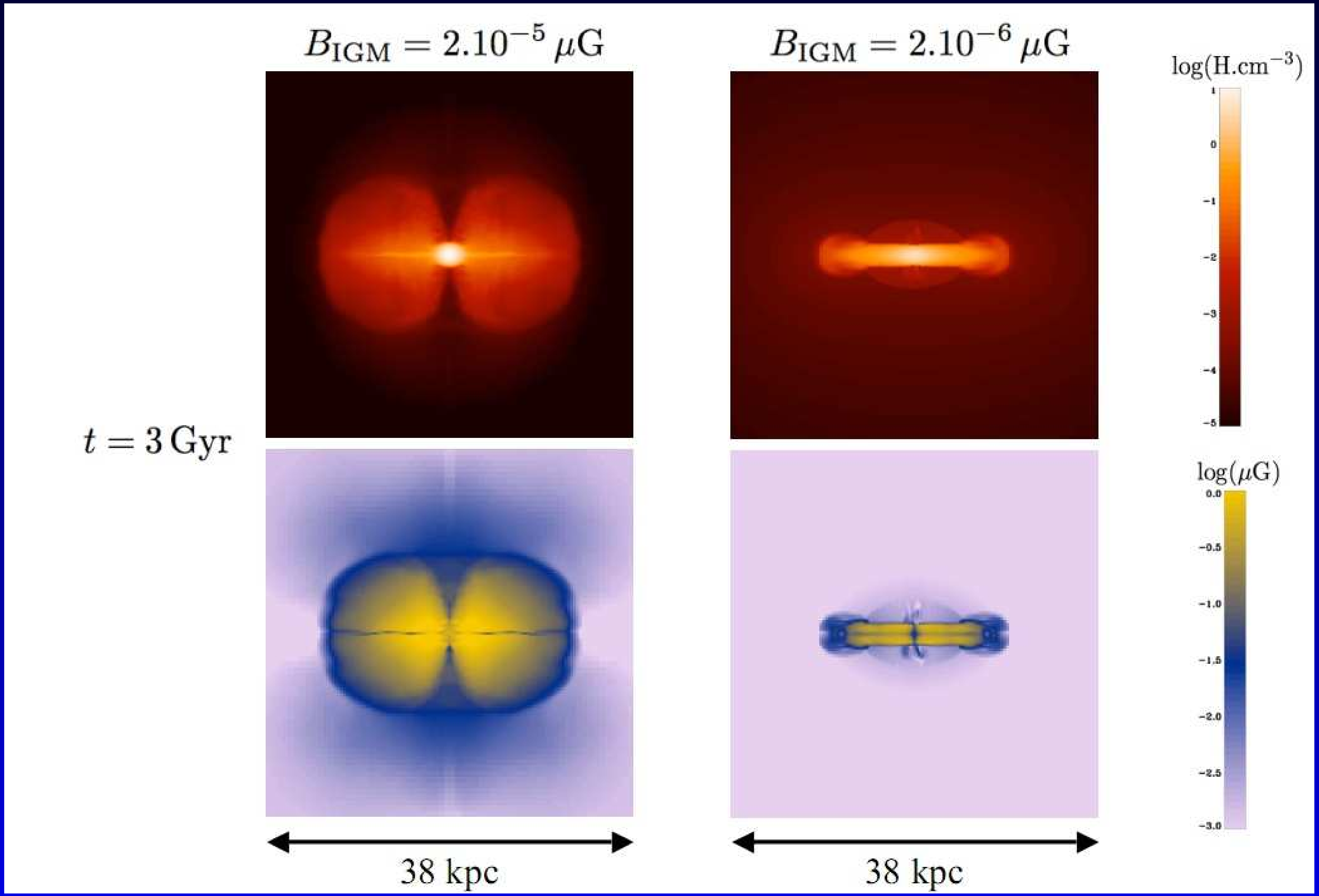
Also background/foreground subtraction not trivial for next generation of instruments like LOFAR, SKA or EVLA !

Other methods:

- Propagation of UHECRs (this talk)
- Blazar halos (Dolag, Kachelriess, Ostapchenko & Tomas 2009) (see talk by Dimitri Semikoz)
- Dynamics in structure formation !

Investigating magnetic fields

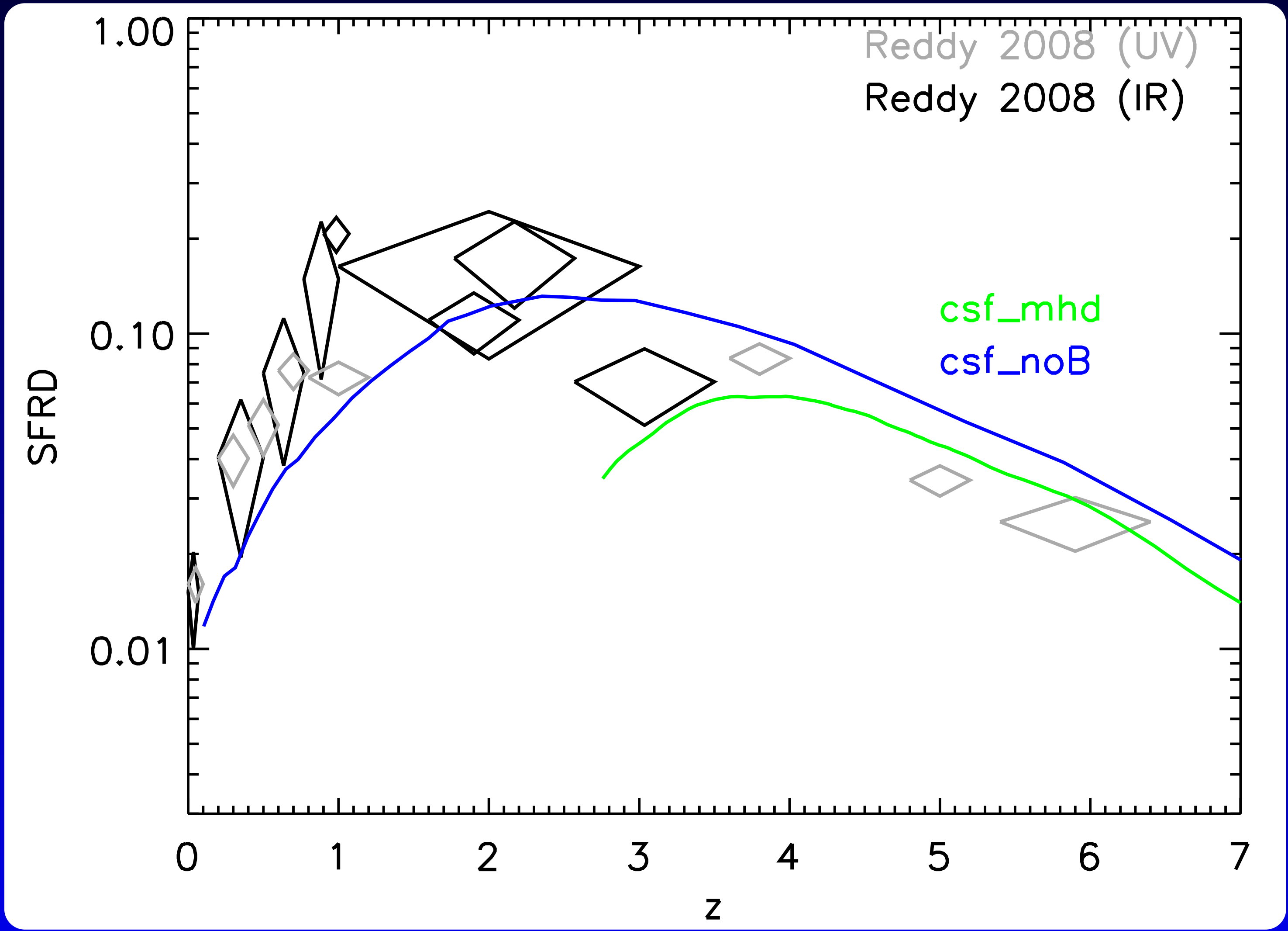
Galaxy formation studies with RAMSES:



Teyssier 2009

Investigating magnetic fields

Cosmological simulation with Gadget:



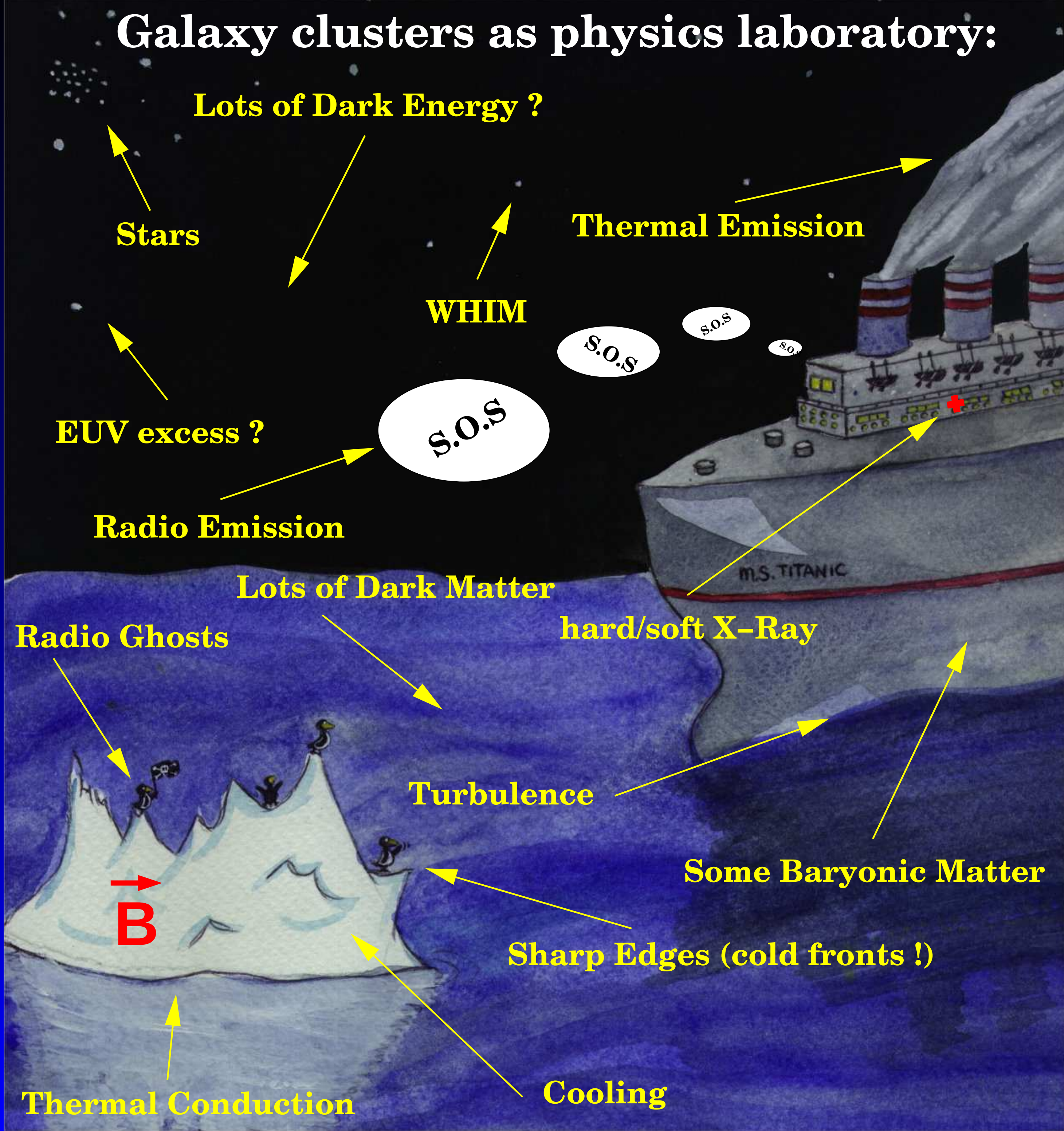
$B_{ini} = 10^{-5} \mu G$, work in progress, (Stasyszyn & Dolag 2009)

Conclusions

- Predicted magnetic field structure reflects formation of galaxy clusters
- Galactic outflows are valid sources for cluster fields
- Predicted (complex) field structure in galaxy clusters is compatible with RM measures
- Filaments might host remaining signatures of magnetic field origin
- UHECR propagation very promising
  $\Rightarrow$ Pointing back to sources might be possible
  $\Rightarrow$ Complications from propagation in nearby clusters
  $\Rightarrow$ non defection of UHECRs measure small $\vec{B}$-fields
- Blazar halos allow to probe even lower $\vec{B}$-fields

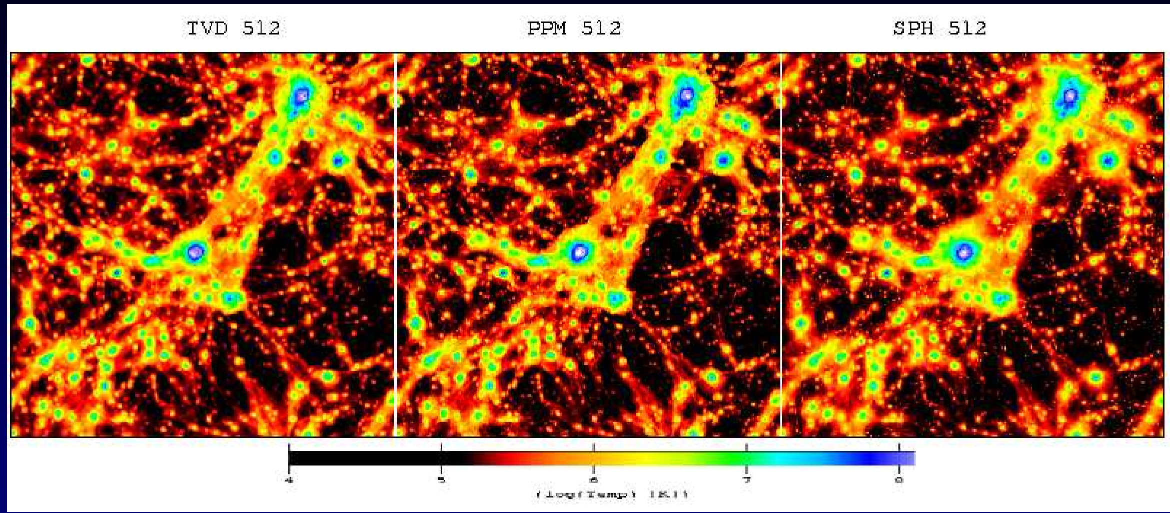
  $\Rightarrow$ see talk by Dimitri Semikoz

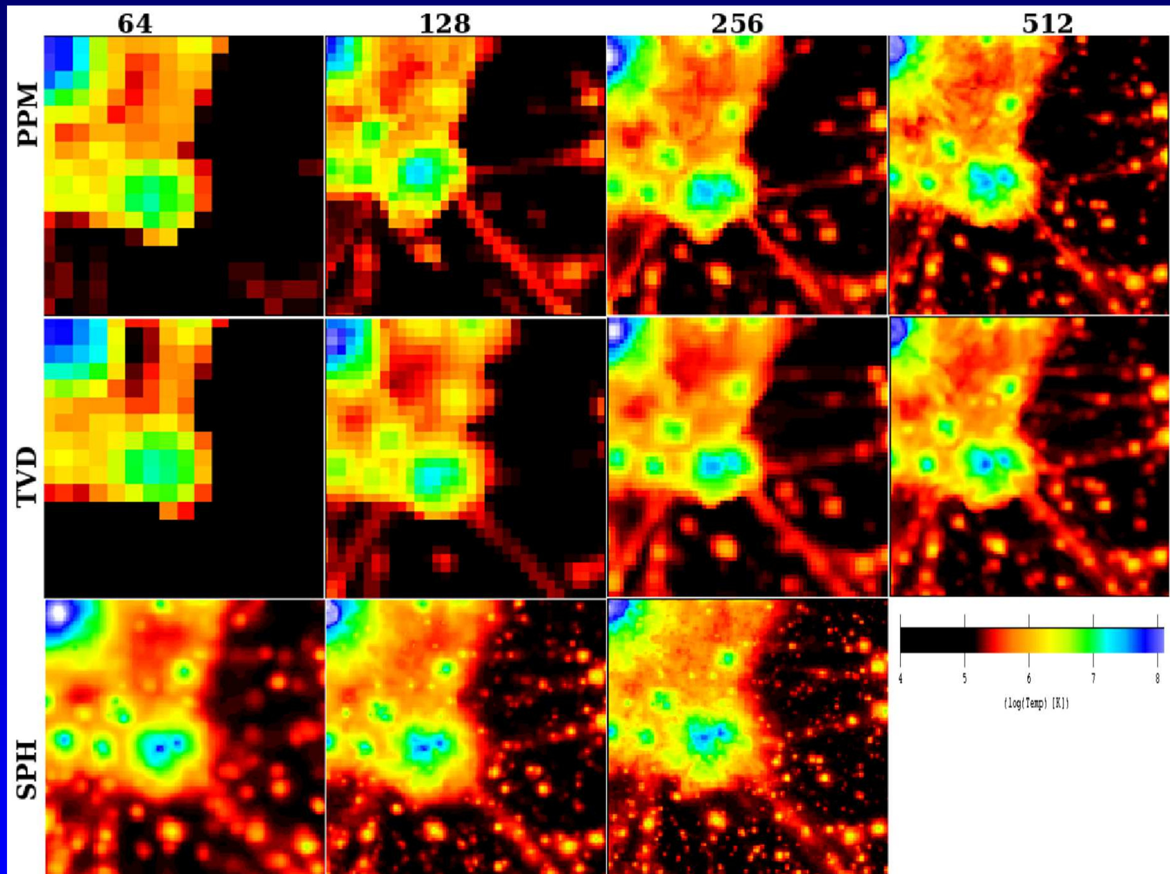
Galaxy clusters as physics laboratory:



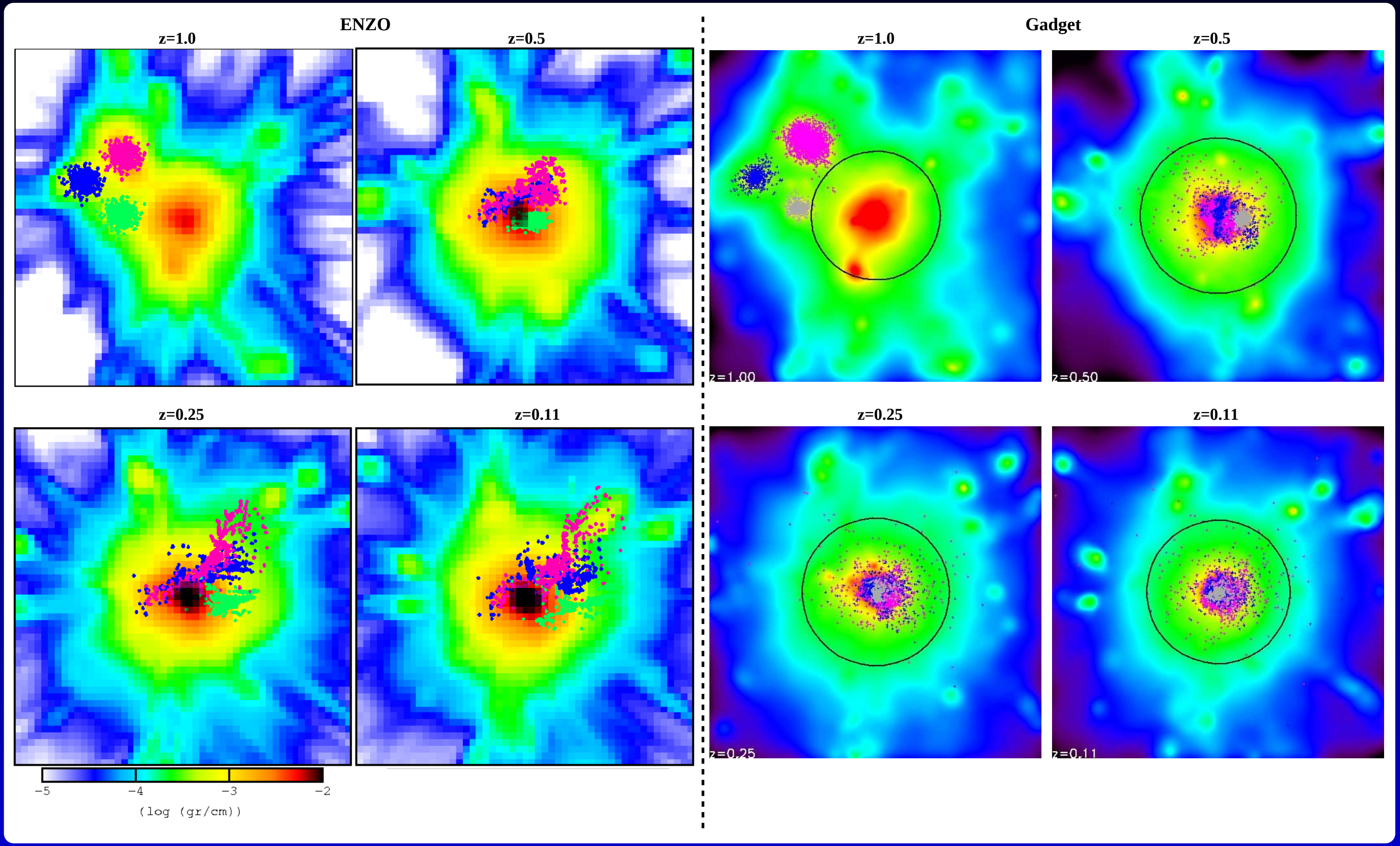
Do we understand our "world" !?

Comparison Project





Comparison Project



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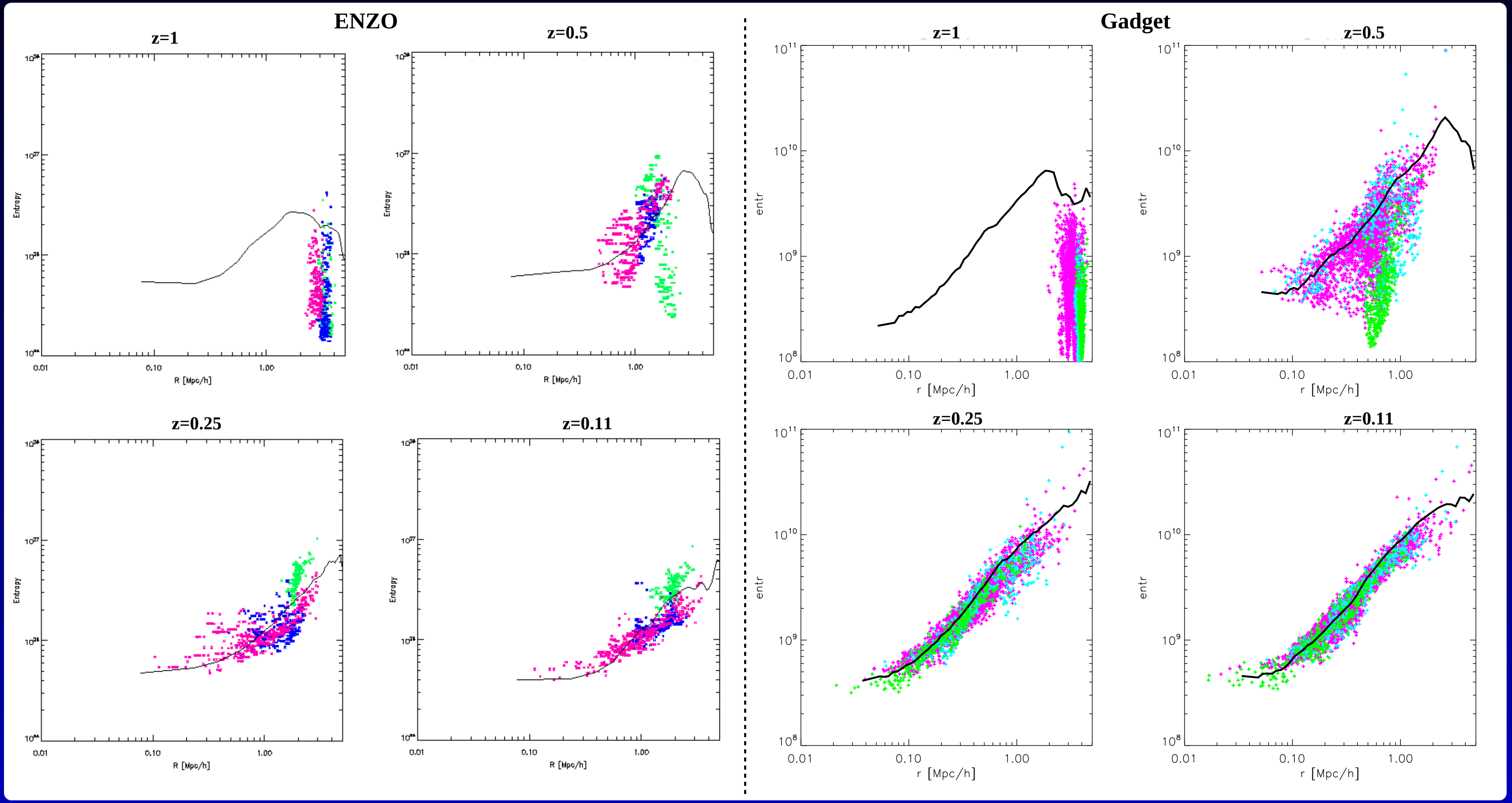
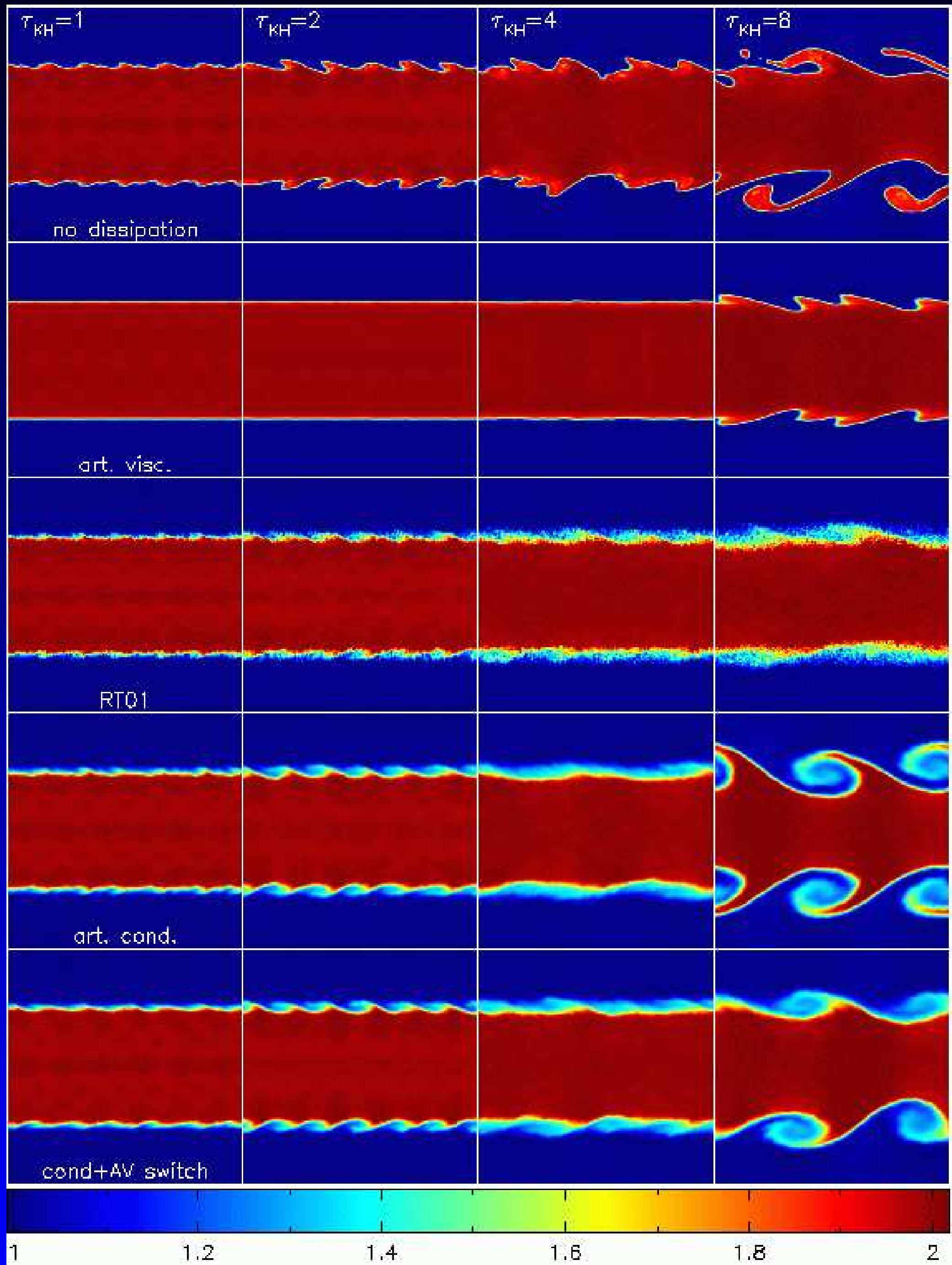
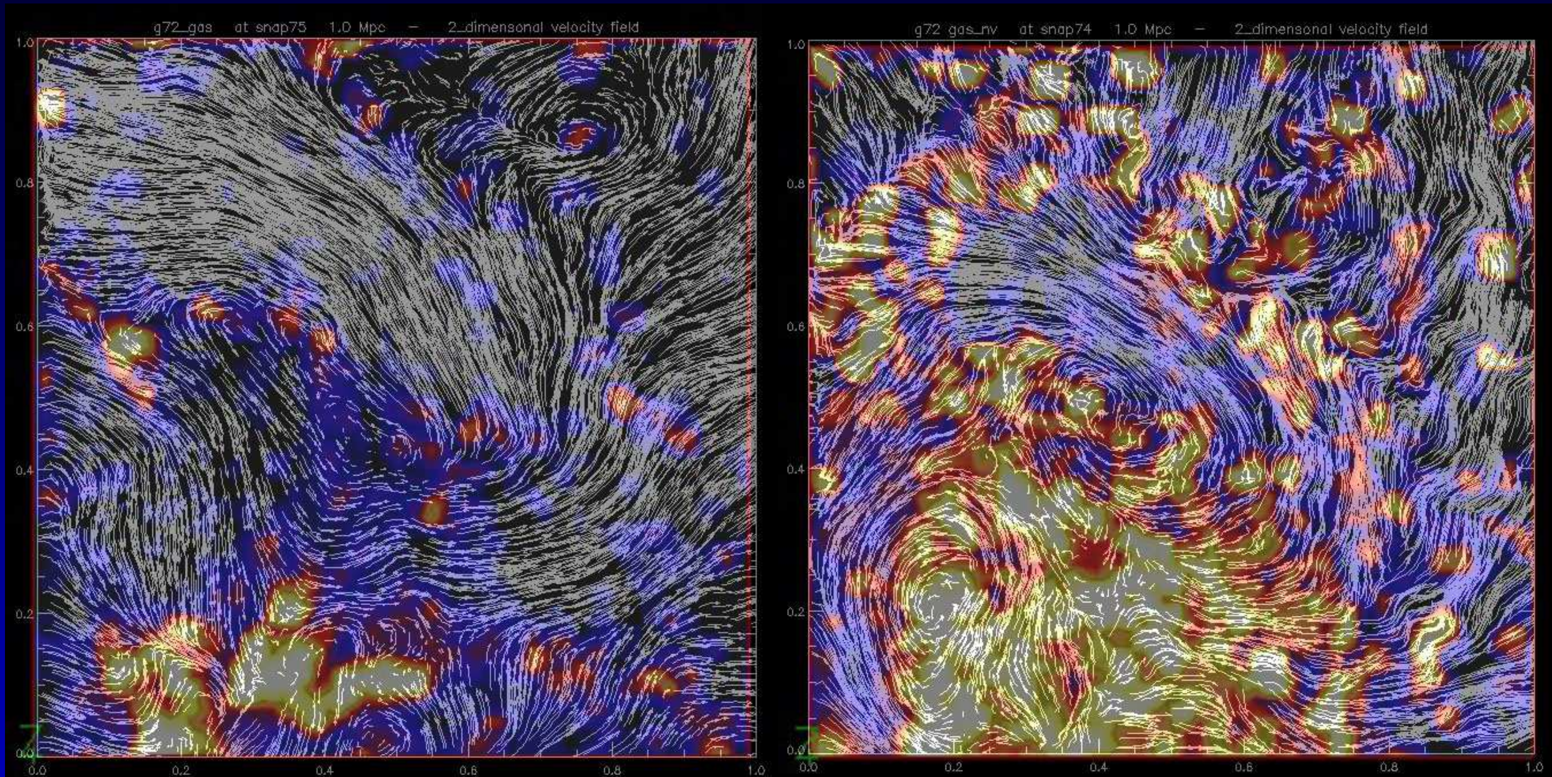


Comparison Project



Turbulence in Clusters

Old viscosity scheme **New viscosity scheme**



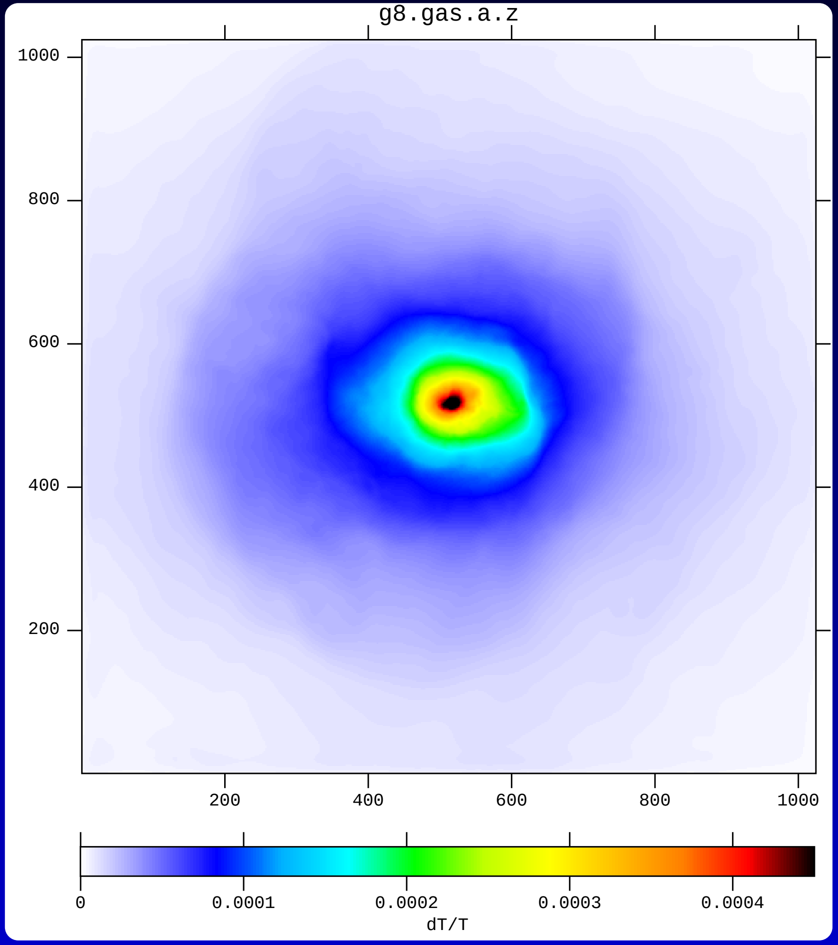
- Instabilities less damped (e.g. Kelvin-Helmholtz).

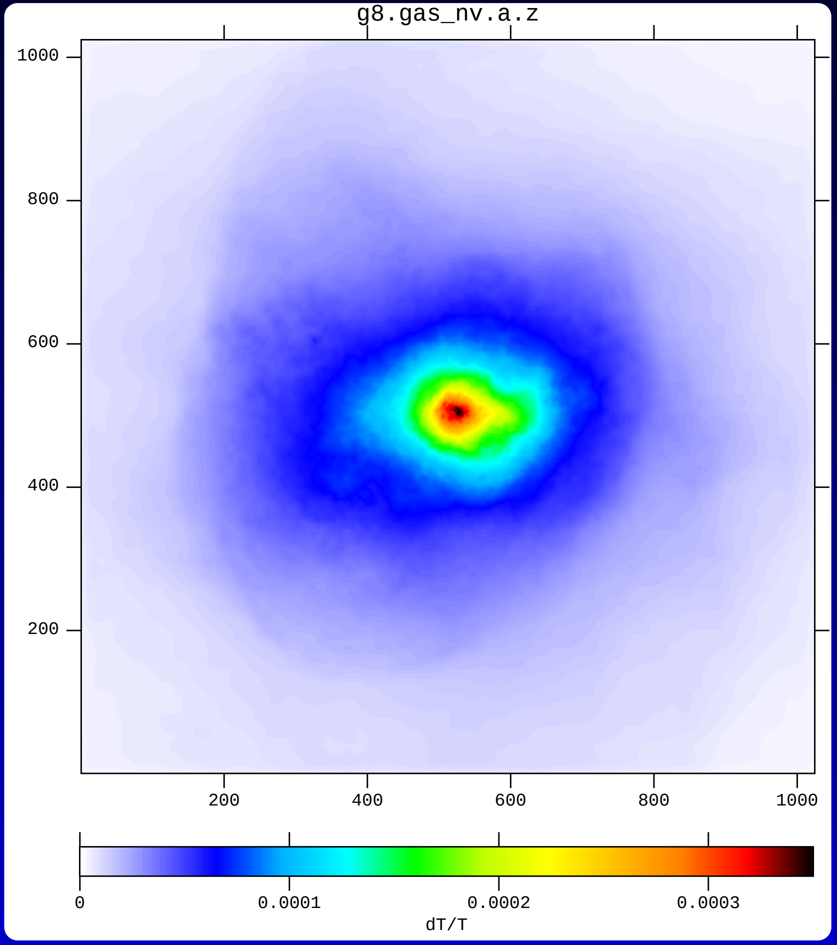
⇒ Inset of turbulence

⇒ Enlarged energy-fraction in gas velocity

Dolag, Vazza, Brunetti, Tormen & Springel 2004

Turbulence in Clusters





Standard (left) and reduced (right) Viscosity, Compton-y map