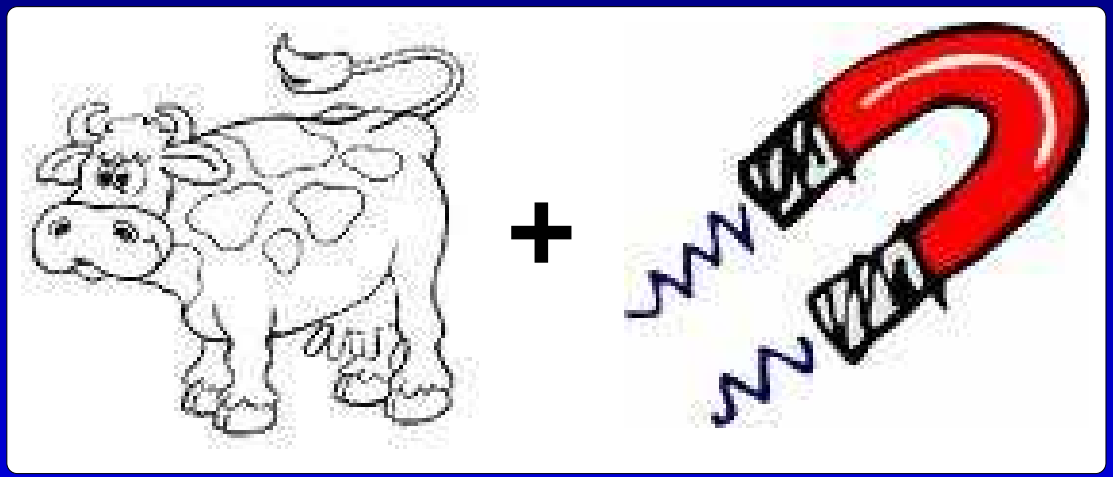
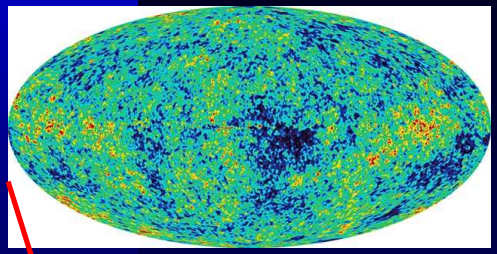
Magnetic Fields in galaxy clusters and beyond

Klaus Dolag

Universitäts-Sternwarte München



The Big Picture

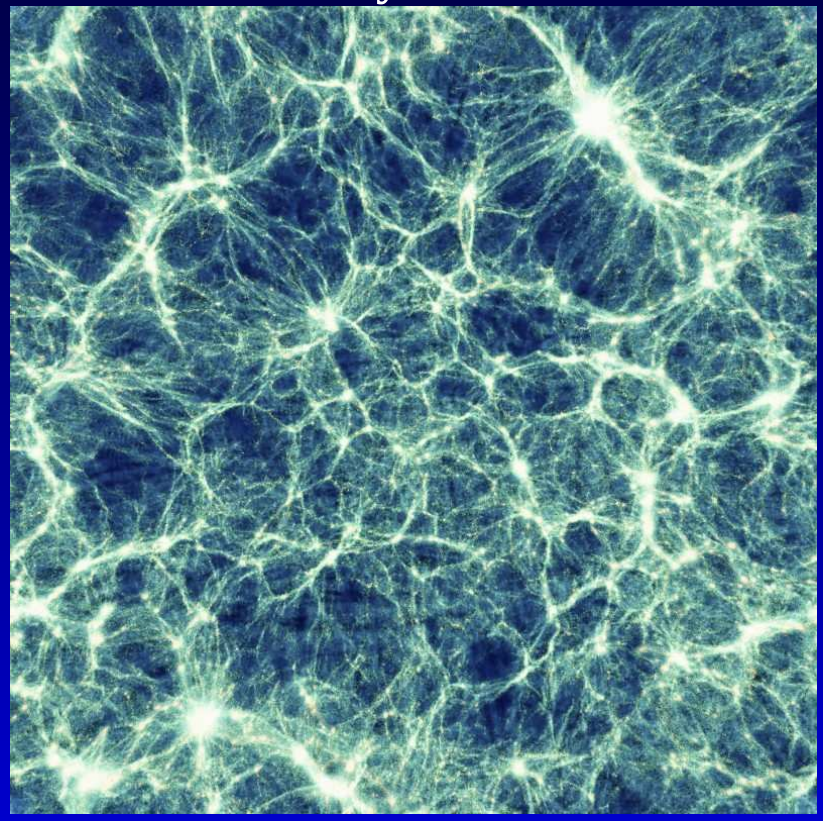


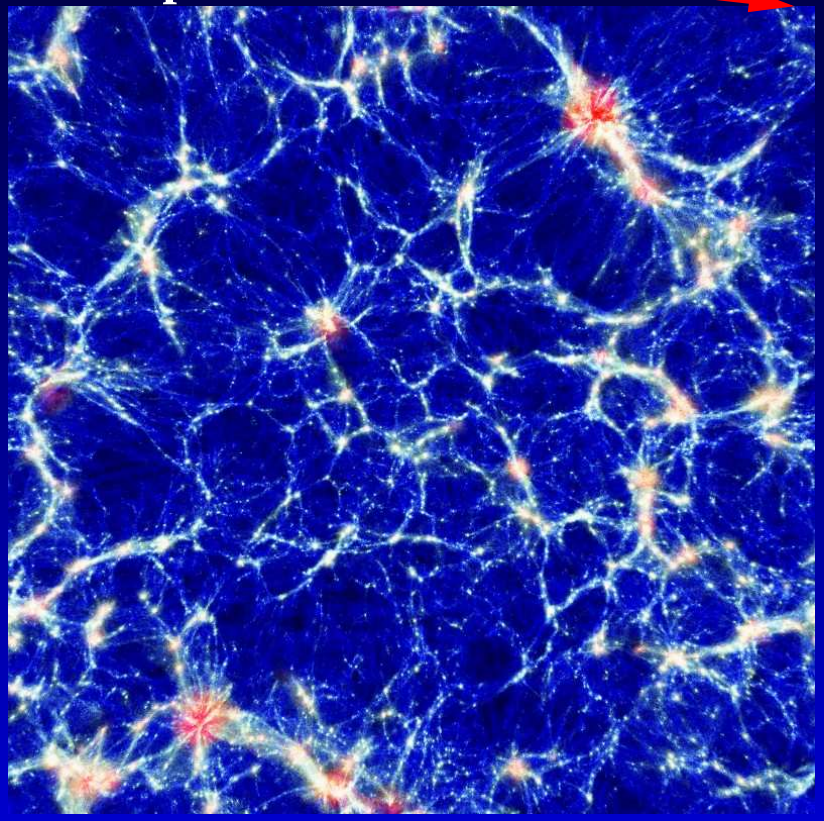
CMB (t = 0.38 Myr)

Cosmic structure today
(t = 13.7 Gyr)

Density

Temperature



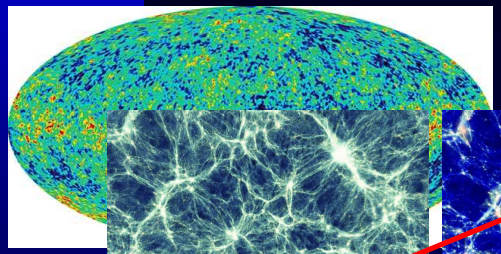


Borgani, Murante, Springel, Diaferio, Dolag et al. 2004

275 Mpc

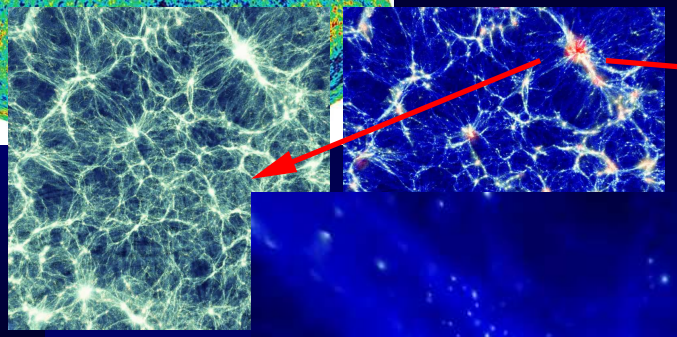
The cosmic web today ($z = 0$) is mainly accessible through simulations (warm, thin). Model predictions for $\vec{B}$ are important for propagation of ultra high energetic cosmic rays (UHECRs).

The Big Picture



t = 0.38 Myr

"Zoomed" Simulation of a galaxy cluster



t = 13.7 Gyr

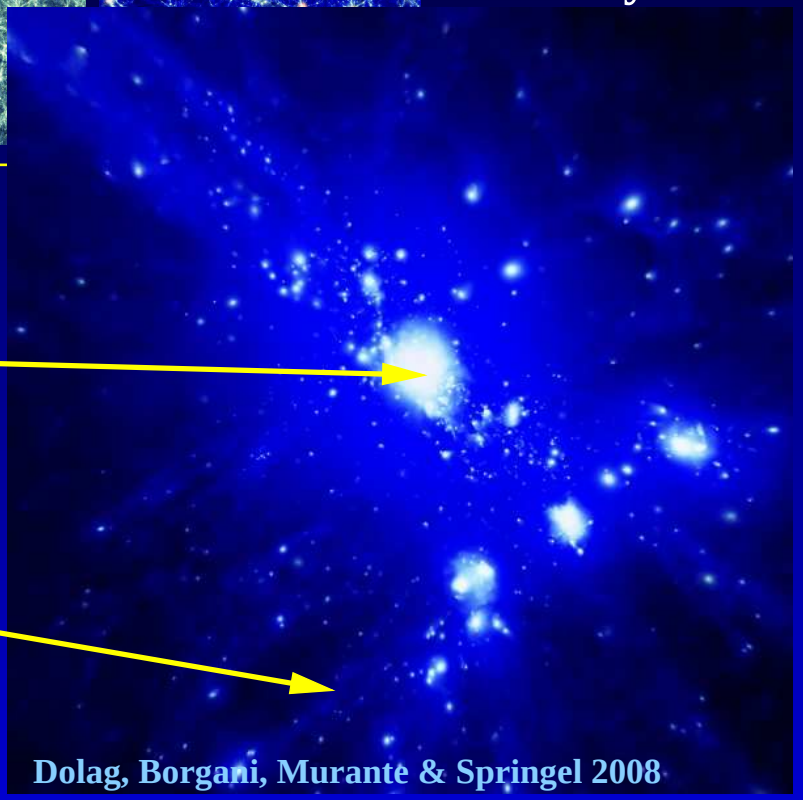
Density

Temperature

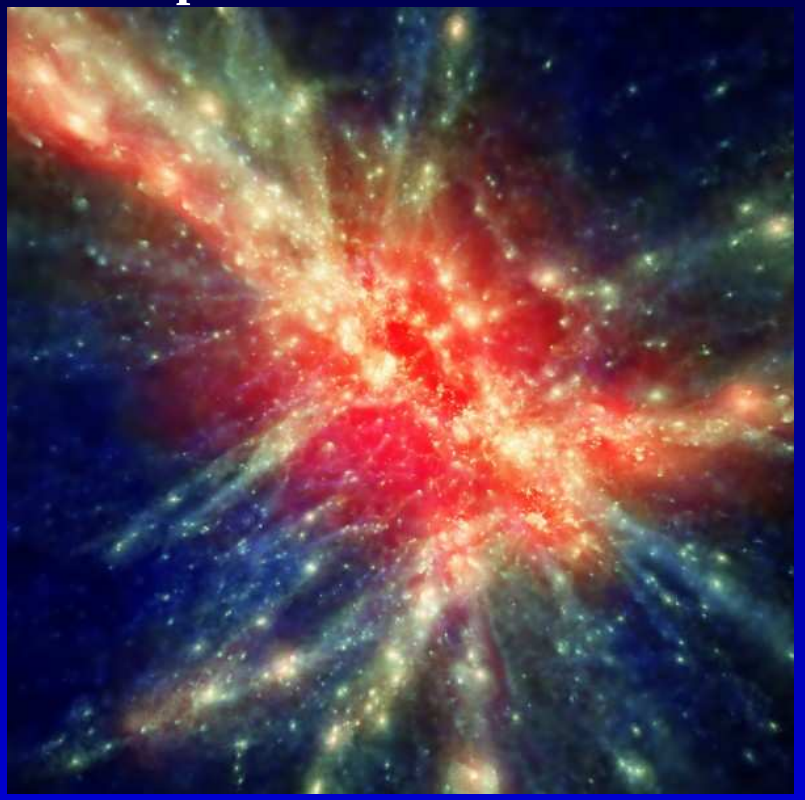
275 Mpc

10^{-2} cm^{-3}
10^{8} K
~ μG

10^{-7} cm^{-3}
10^{5} K
< nG



Dolag, Borgani, Murante & Springel 2008



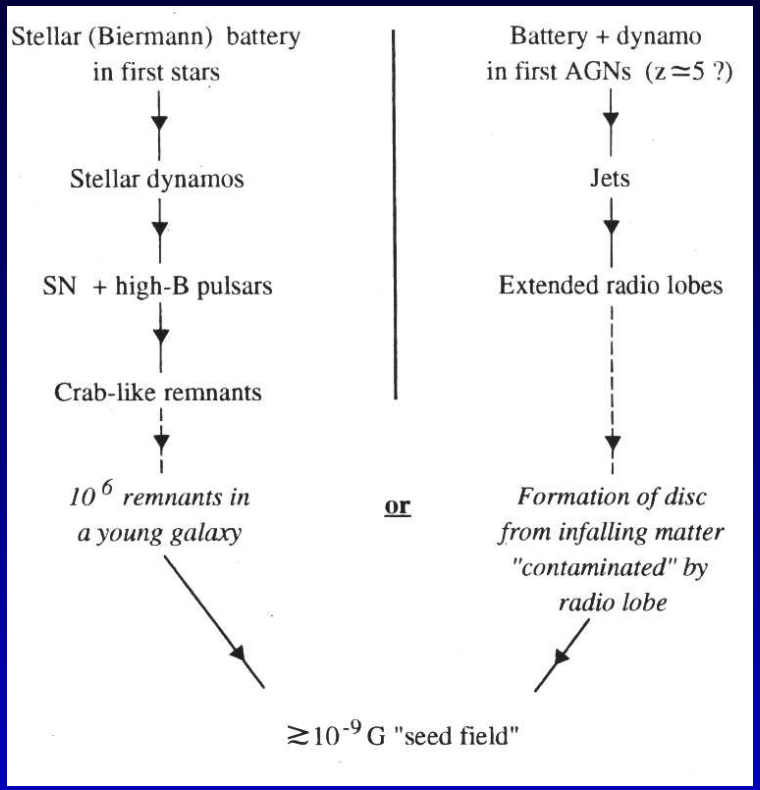
40 Mpc

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

Problem 1: Origin

Origin

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



Rees 1994

+ further amplification by **structure formation**

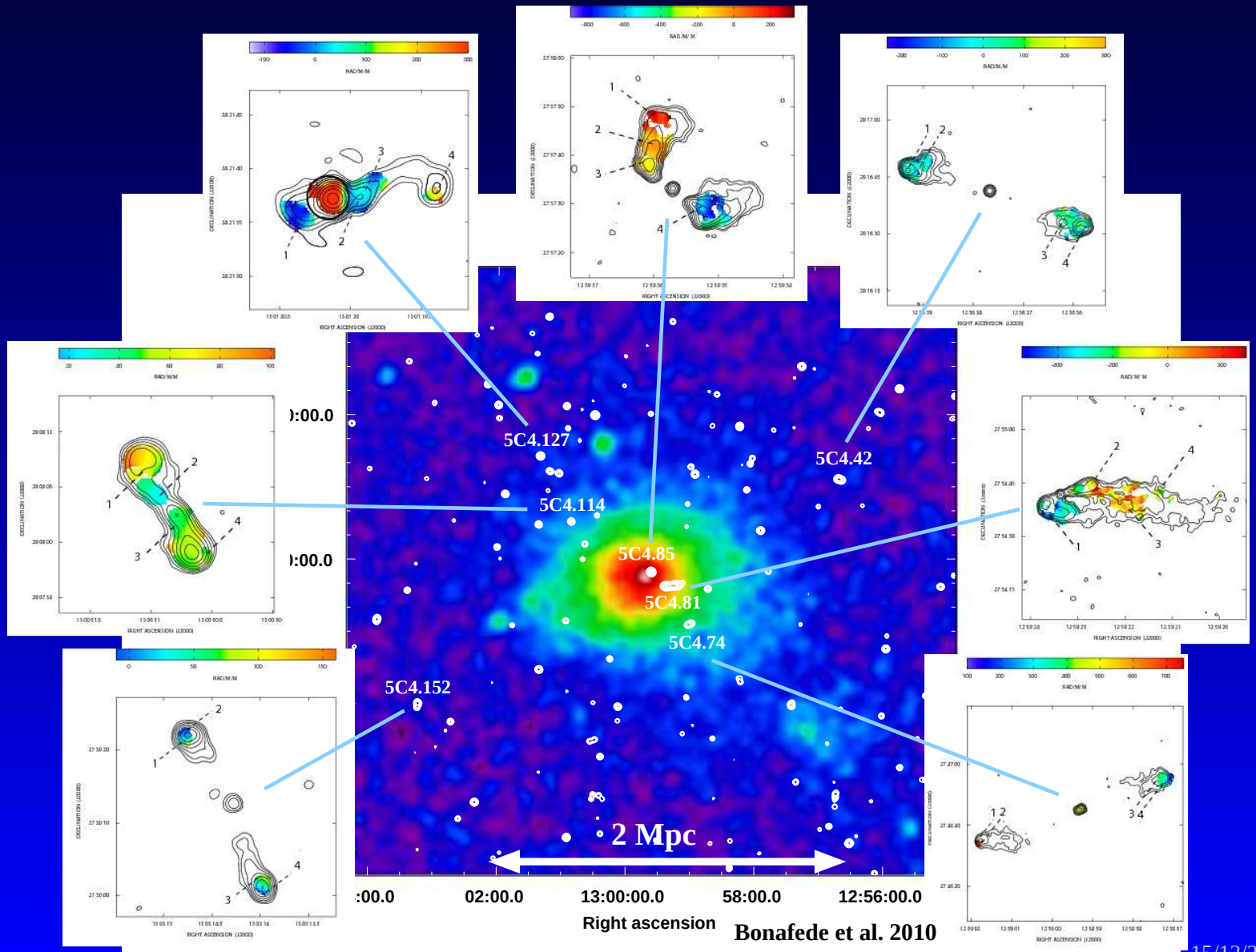
- dissipation ?

Problem 2: Turbulence

Problem 2: Turbulence

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

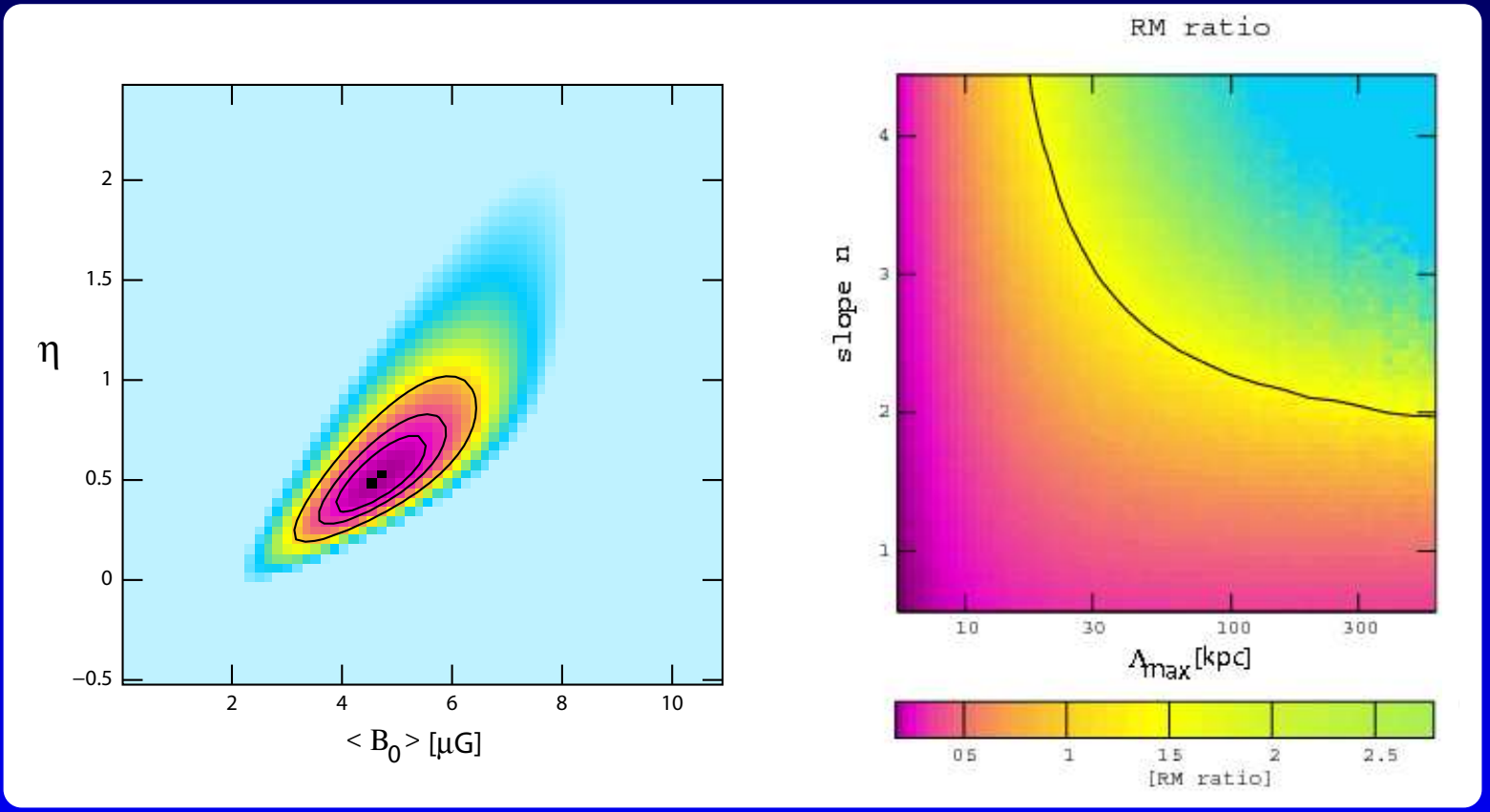
$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\eta}, \quad |B_k|^2 \propto k^{-n}, \quad (k_{\rm min}, k_{\rm max})$$



Problem 2: Turbulence

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

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



⇒ constrains on magnetic field strength !

Problem 3: Low B

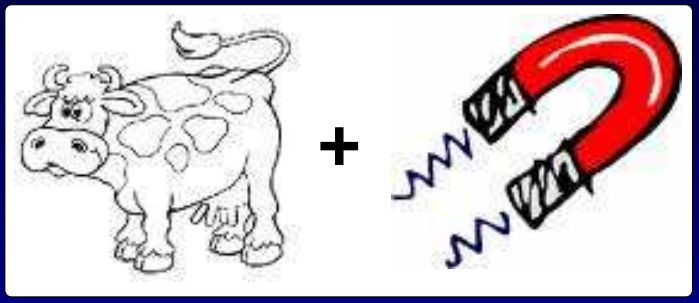
Please:
(numbers are from private communication)

Cluster	$P_{\rm thermal}$	$B^2/8\pi$	β
Coma	XXXXXXXXX	XXXXXXXXX	XXX
A2255	XXXXXXXXX	XXXXXXXXX	XXX
A400	XXXXXXXXX	XXXXXXXXX	XXX
A119	XXXXXXXXX	XXXXXXXXX	XXX
A2382	XXXXXXXXX	XXXXXXXXX	XXX

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

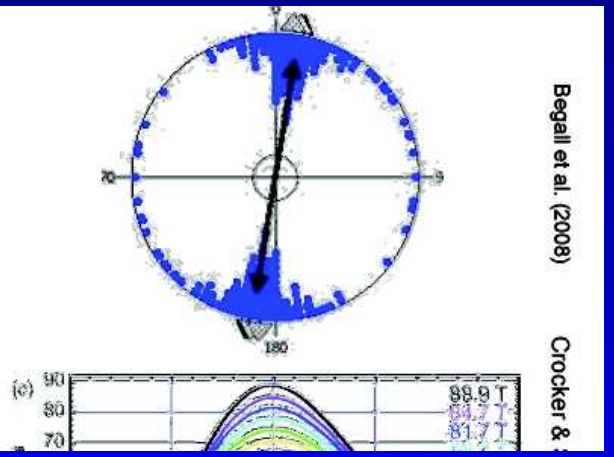
Note on low magnetic fields

Always be careful, as things can be much more complicated as you think, even if magnetic fields are low !



Example: **Magnetic Cows**

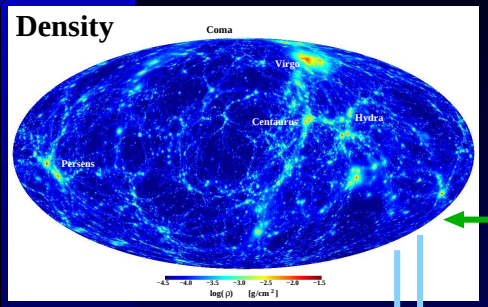
- Birds: retinal magneto-reception (Mouritsen et al. 2004; Ritz et al. 2004)
- Cows: align with Earth's field when grazing or resting (Begall et al. 2008)
- Humans! Bones in sinus contain ferric iron; duration of REM sleep depends on orientation (Baker et al. 1983; Ruhenstroth-Bauer et al. 1987)

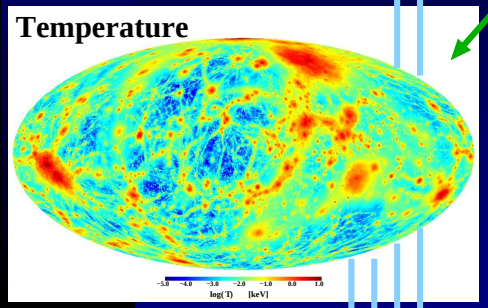


taken from Bryan Gaensler's Kiama 2010 talk

http://www.atnf.csiro.au/research/Astro2010/talks/gaensler.pdf

Simulation Network





ICs (Cosmology)

Primordial

Seed Magnetic Field

Coupling to Star Formation

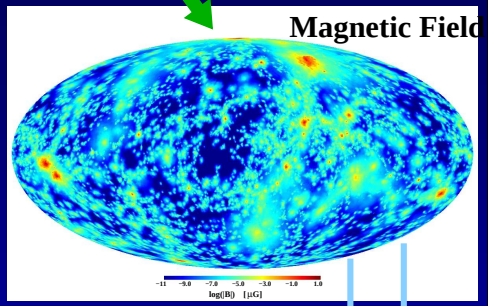
Structure Formation
- Star Formation ?
- Feedback ?
- AGN ?

Magnetic Pressure

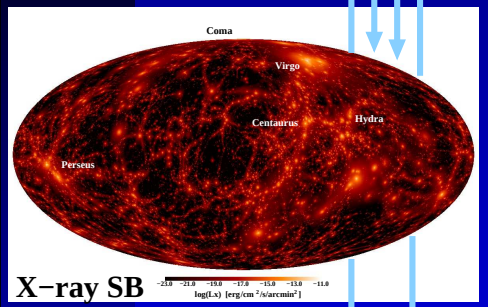
Compression

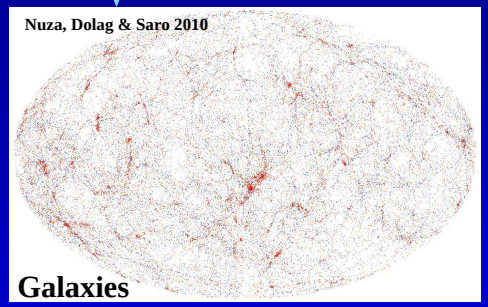
Magnetic Field Evolution
- Dissipation ?
- Numerics ?
- Resolution ?

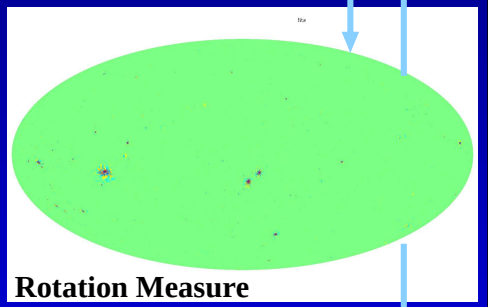
Turbulence
- Viscosity ?
- Numerics ?
- Sub−Grid Model ?

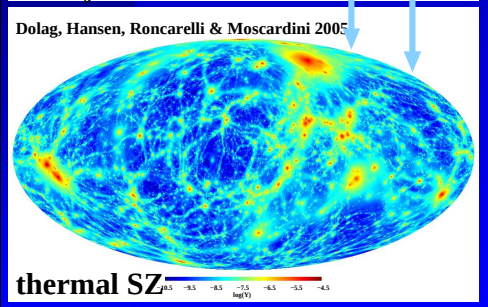


Observables

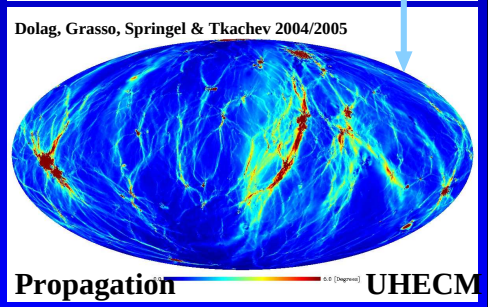




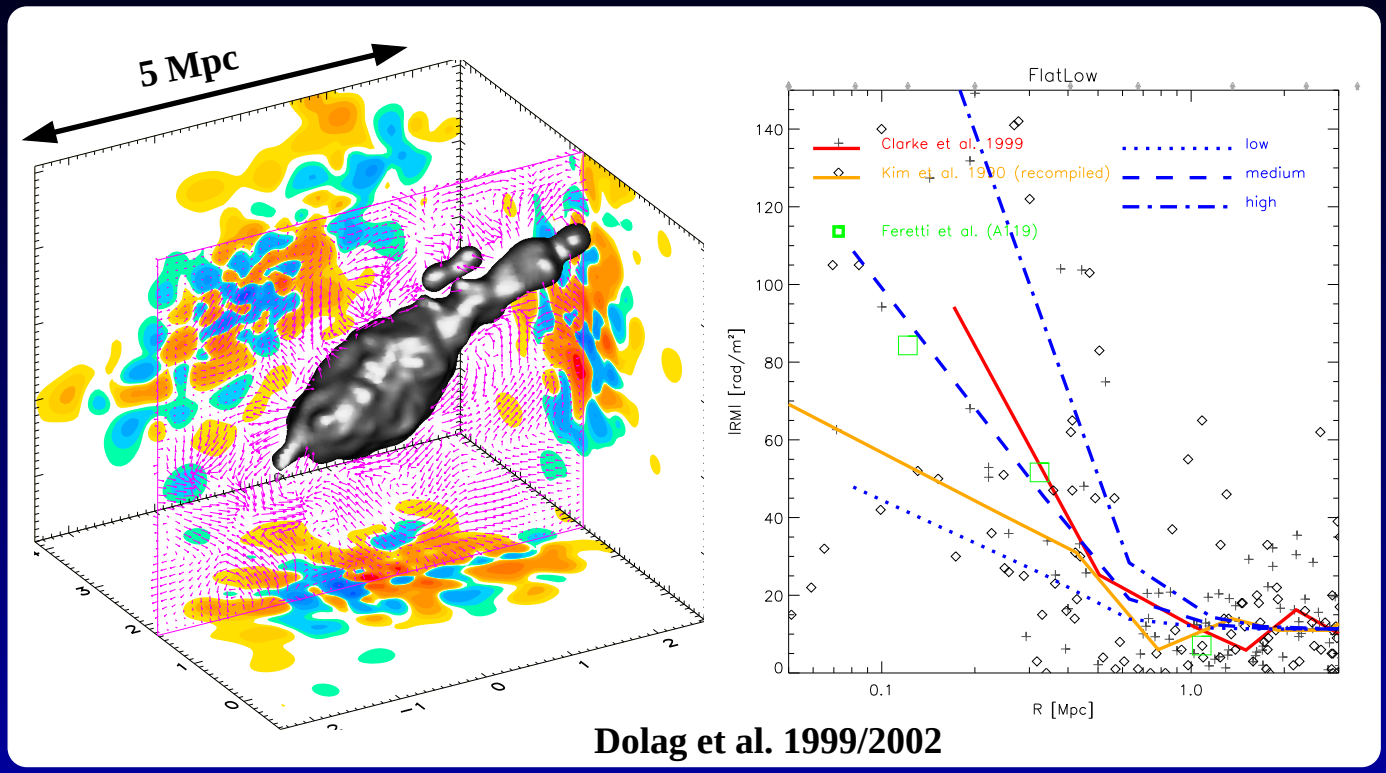




γ



Cosmological MHD Simulations

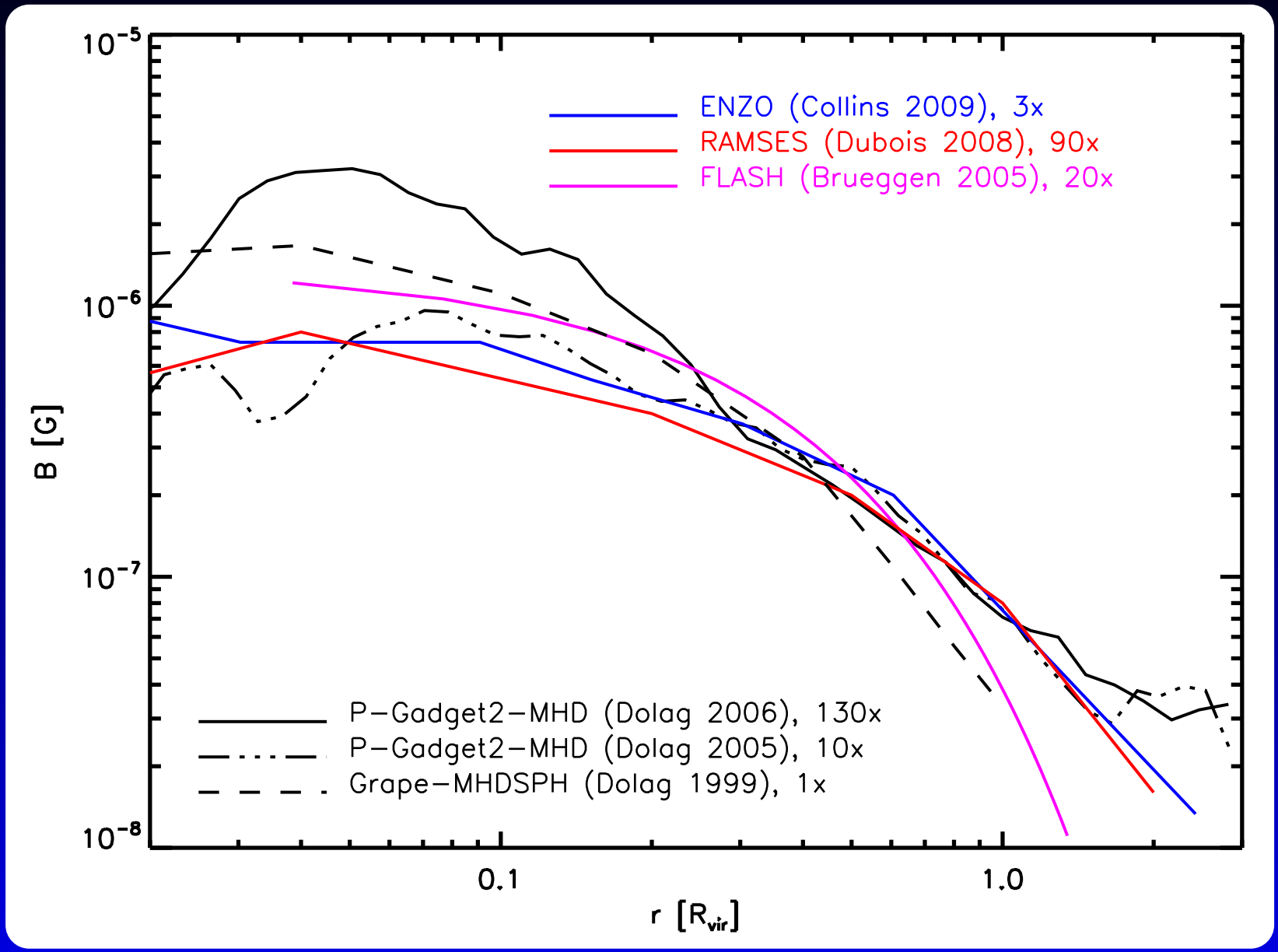


Dolag et al. 1999/2002

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
  $\Rightarrow$ values reached by many models for magnetic seed fields

Cosmological MHD Simulations

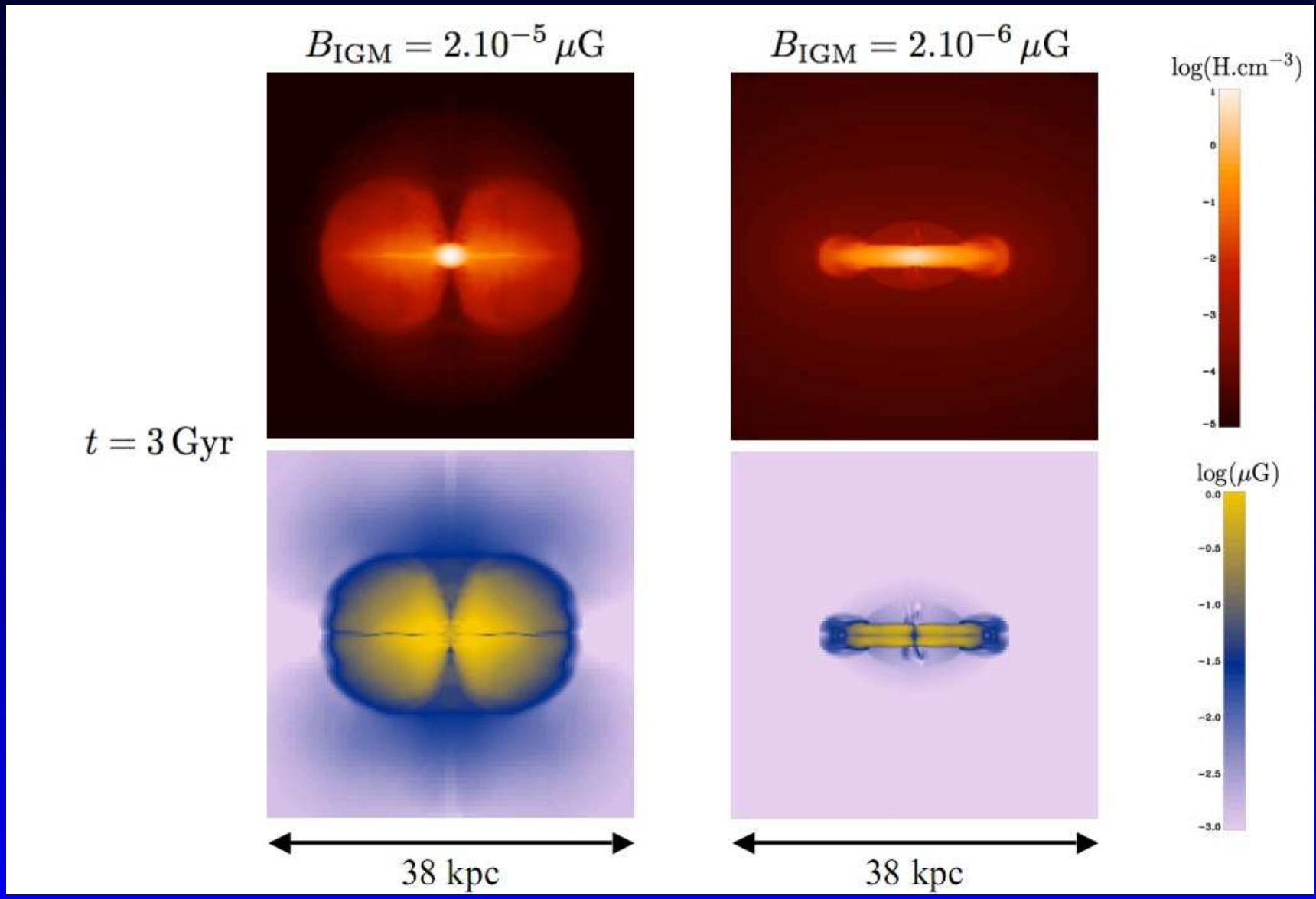


$\Rightarrow$ Radial shape **confirmed** by more recent works

$\Rightarrow$ **Generic** feature from structure formation for B_{ini} of $10^{-12}G$

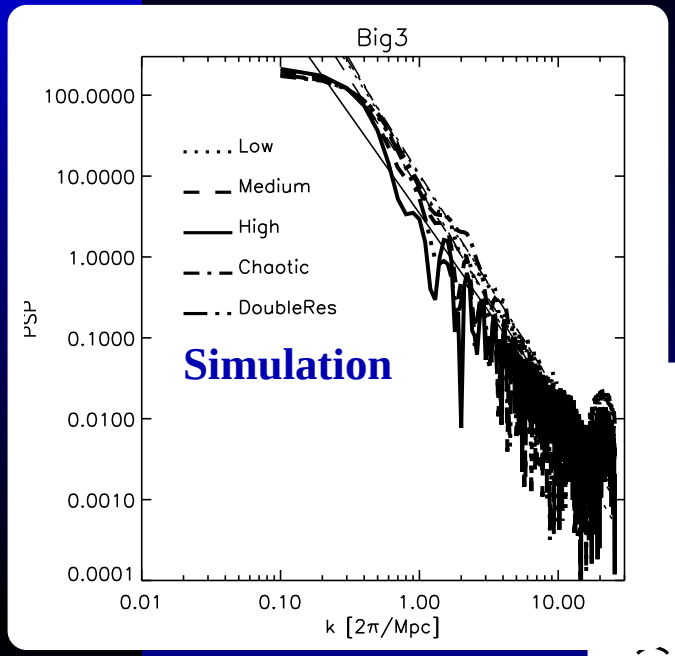
Cosmological MHD Simulations

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



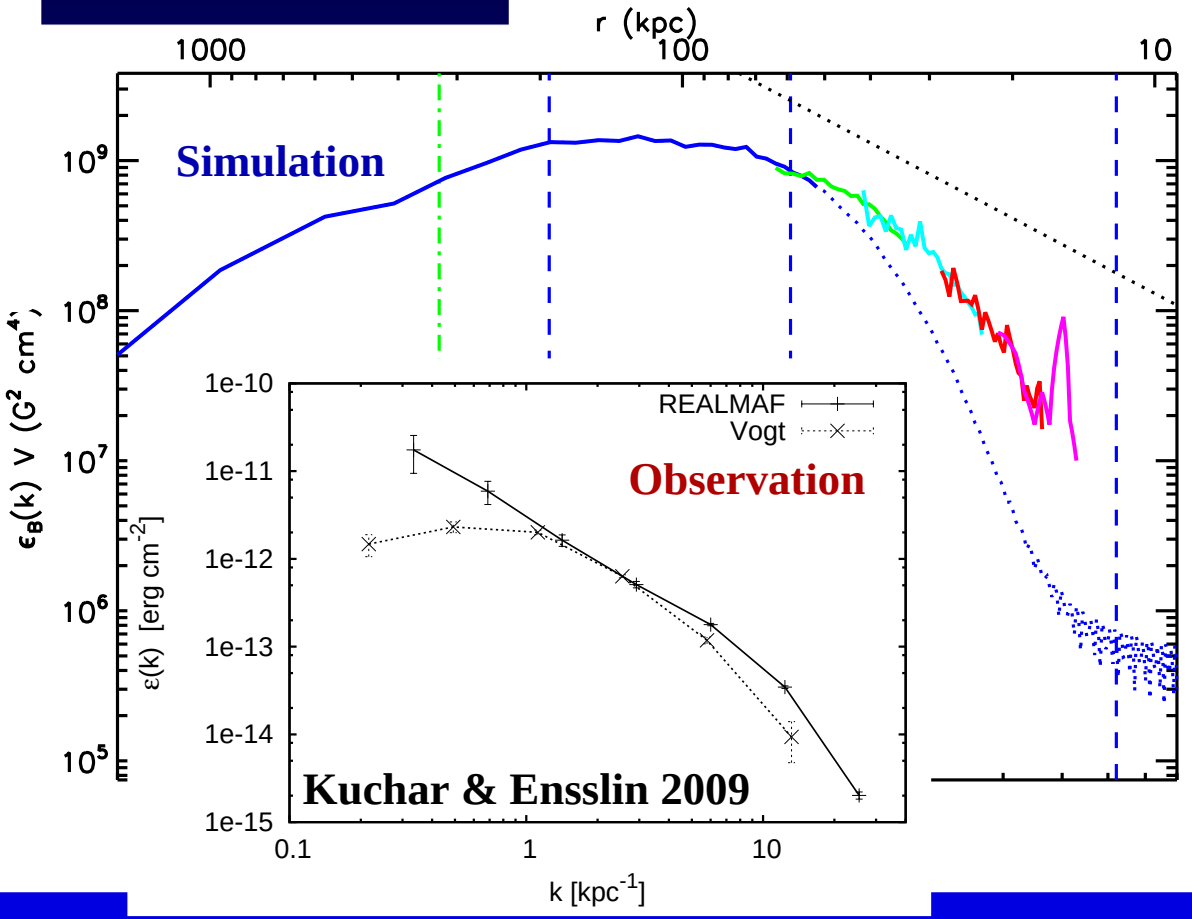
(RAMSES, Teyssier 2009)

Cosmological MHD Simulations



Dolag et al. 2002

Pakmor & Dolag 2006

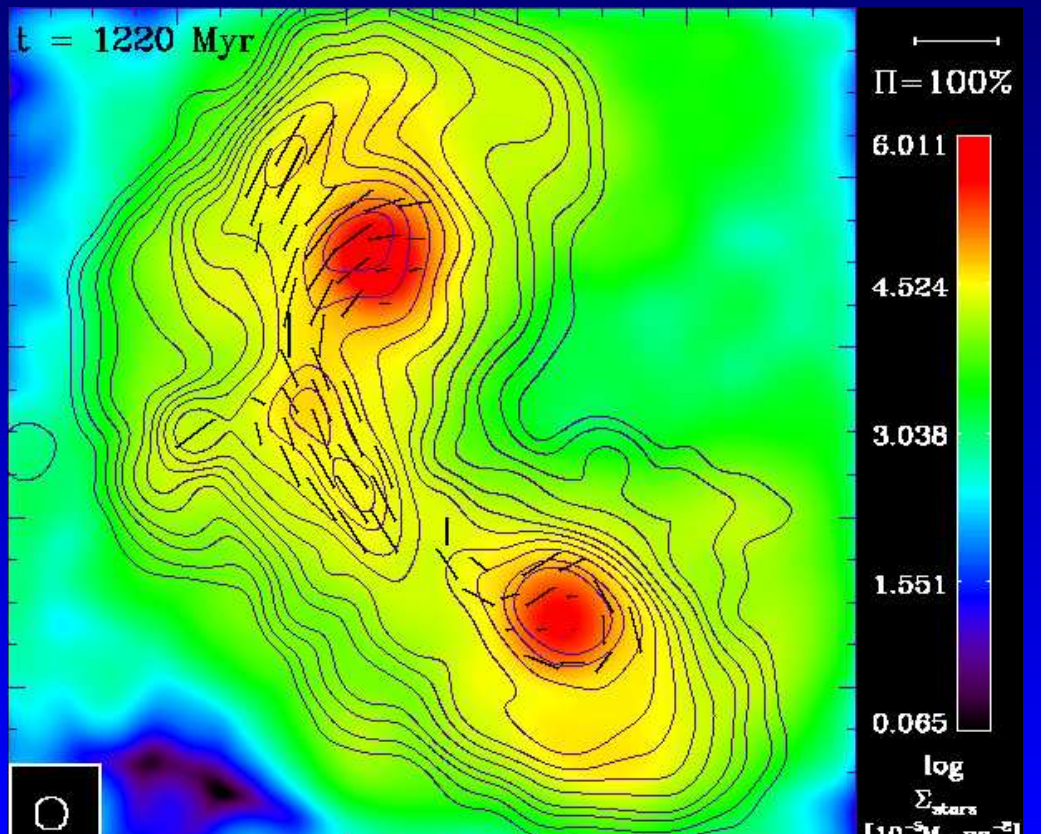


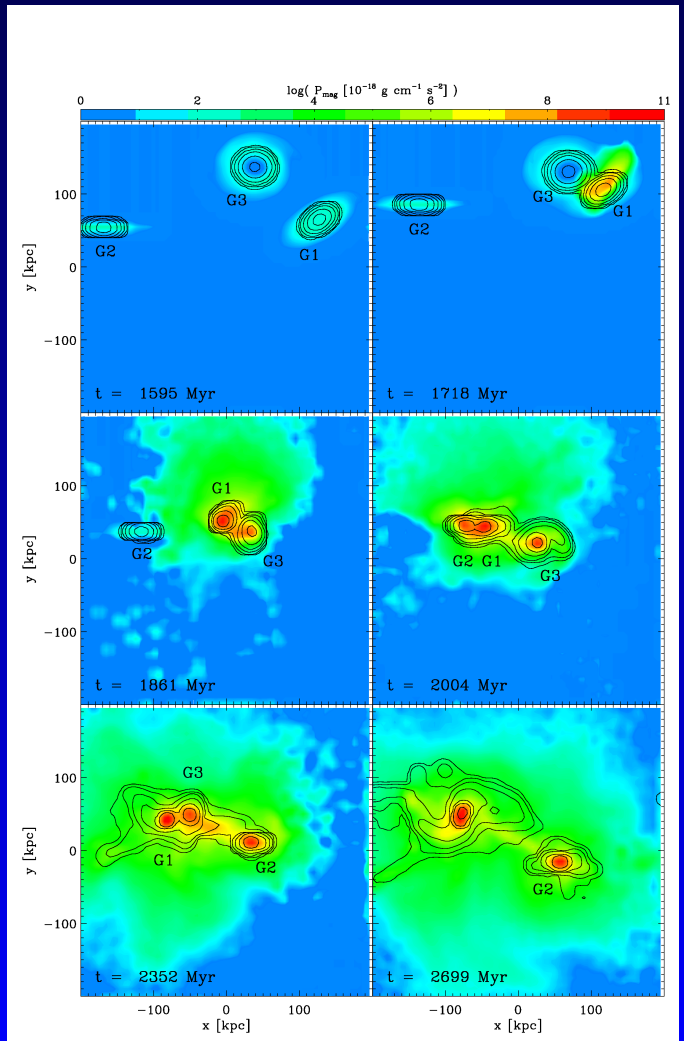
Magnetic field **power spectra**: predictions vs. observations.

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

Magnetic Field buildup

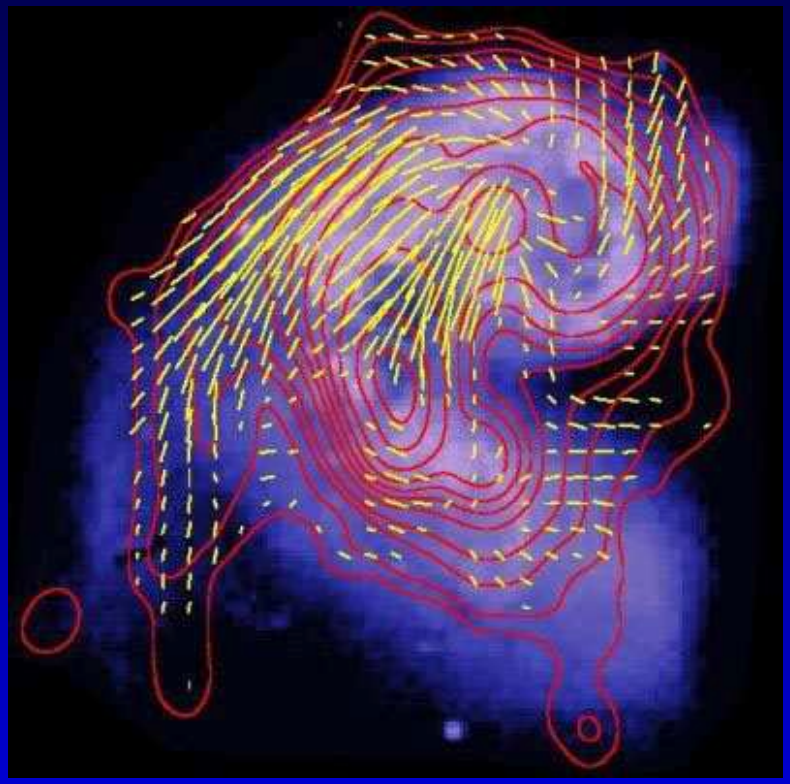
Simulating the magnetic field amplification during galaxy mergers like in the Antennae system. Final magnetic field strength and field configuration in broad agreement with observations.

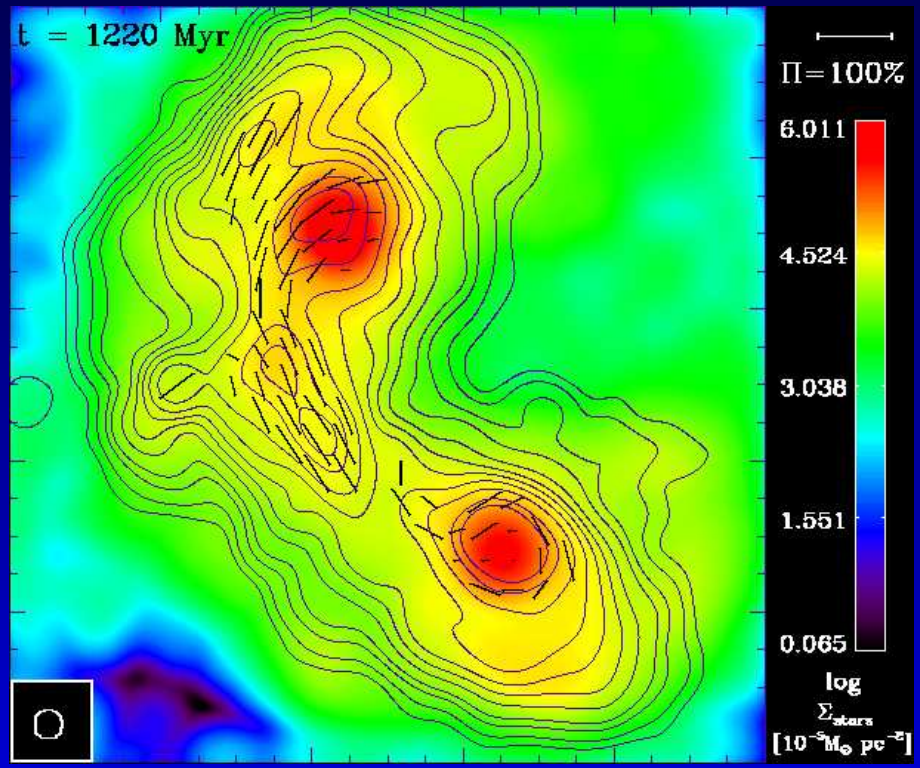




Magnetic Field buildup

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.

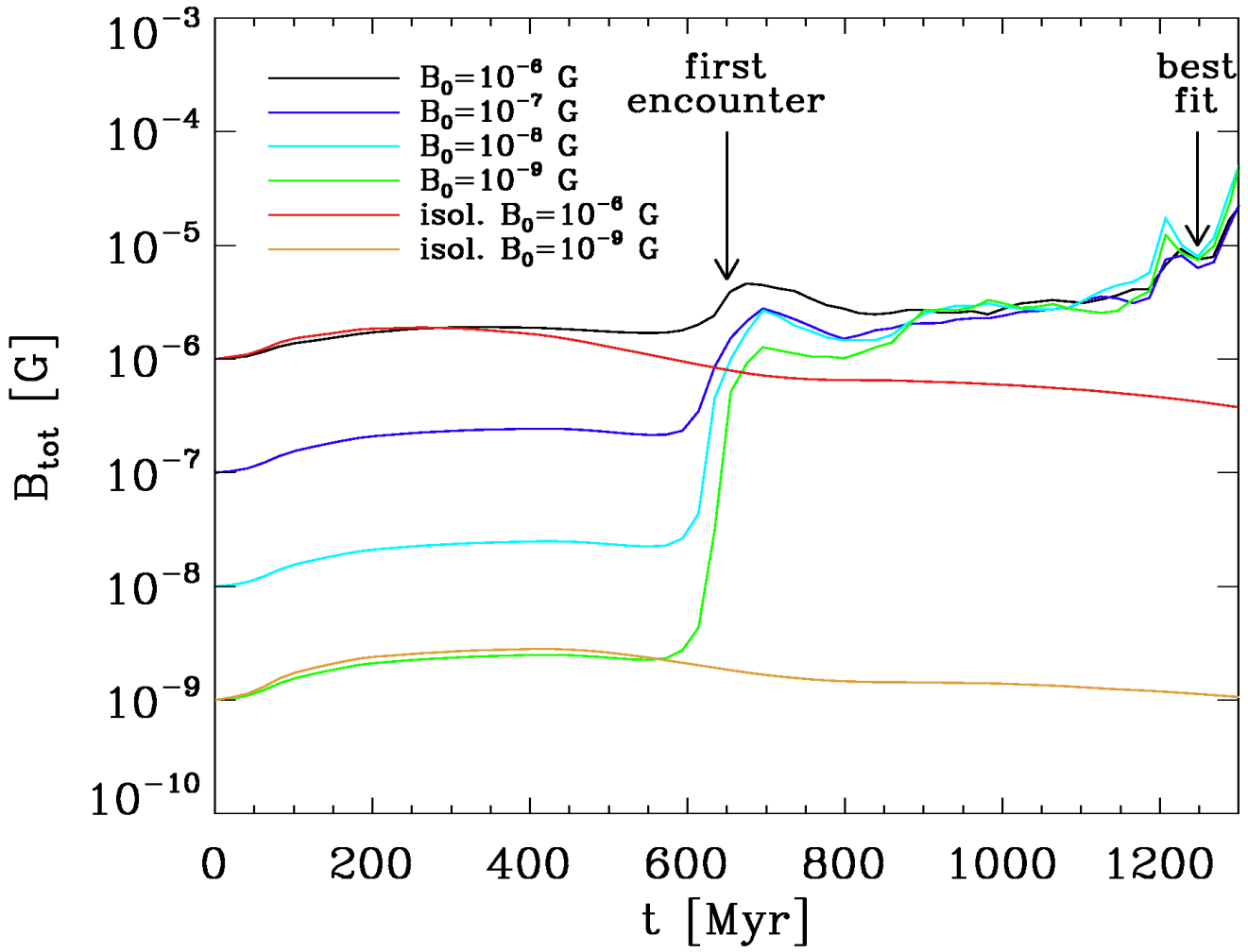




(Chyzy & Beck 2005 Kortarba et al. 2010)

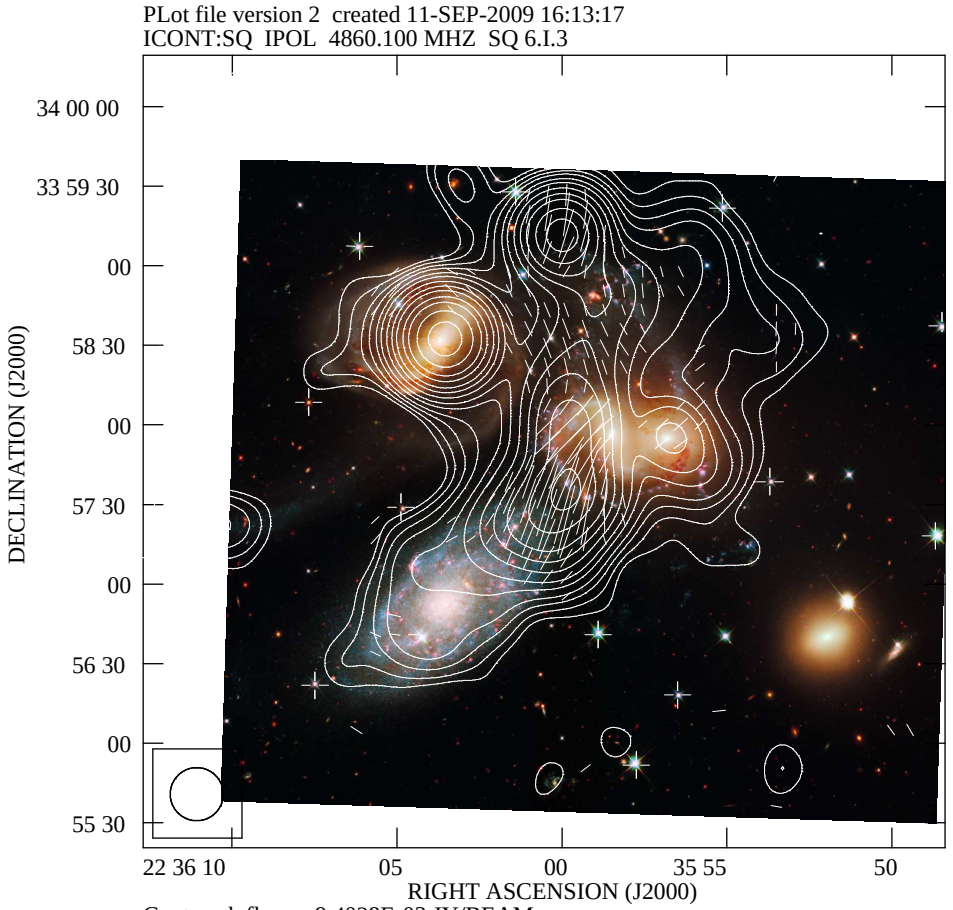
Magnetic Field buildup

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

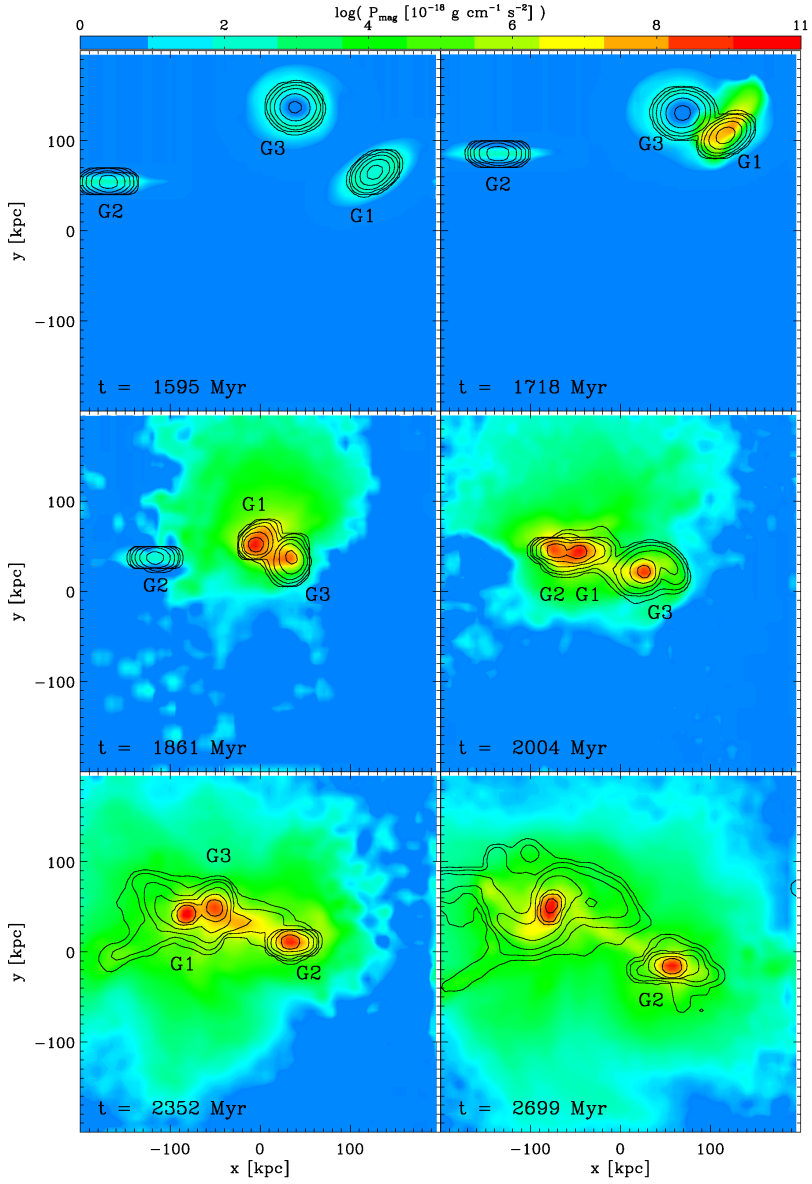


(Kortarba et al. 2010)

Magnetic Field buildup

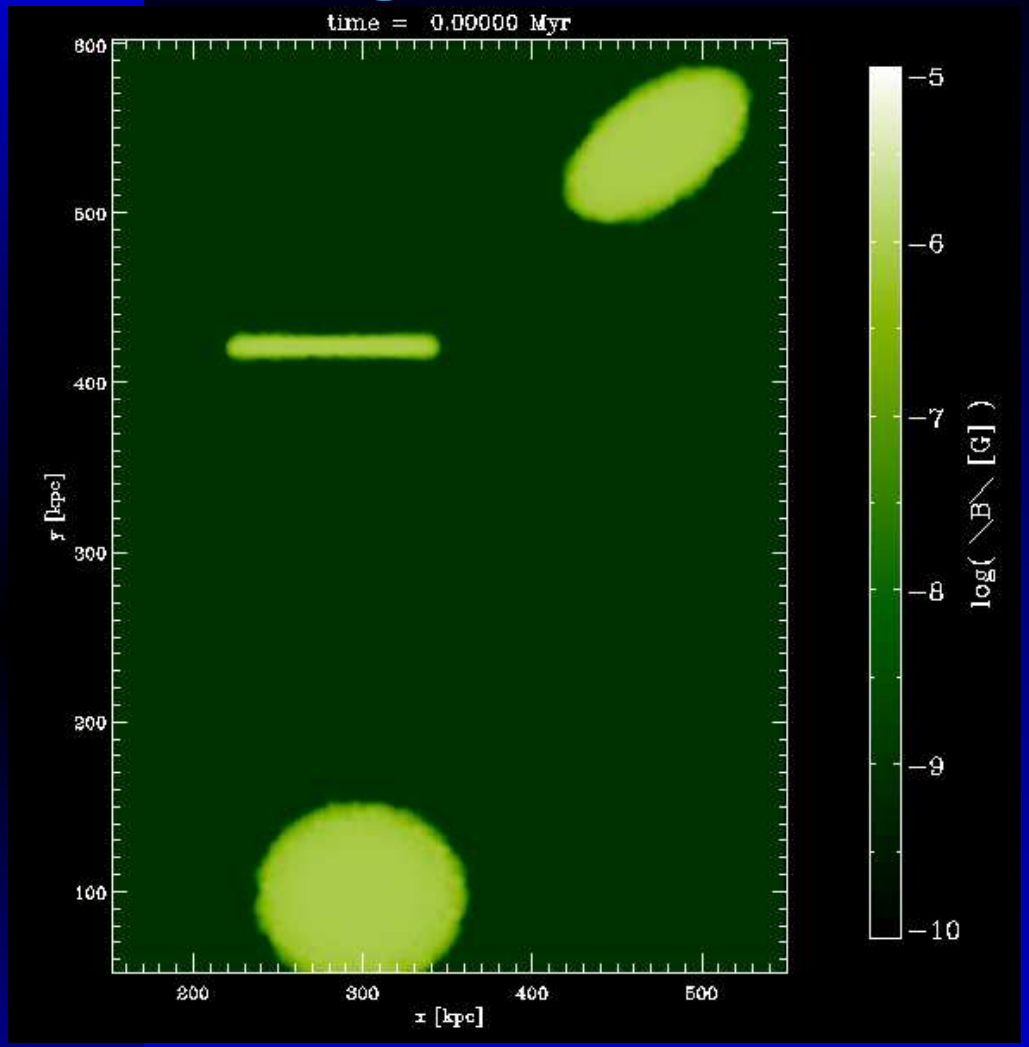


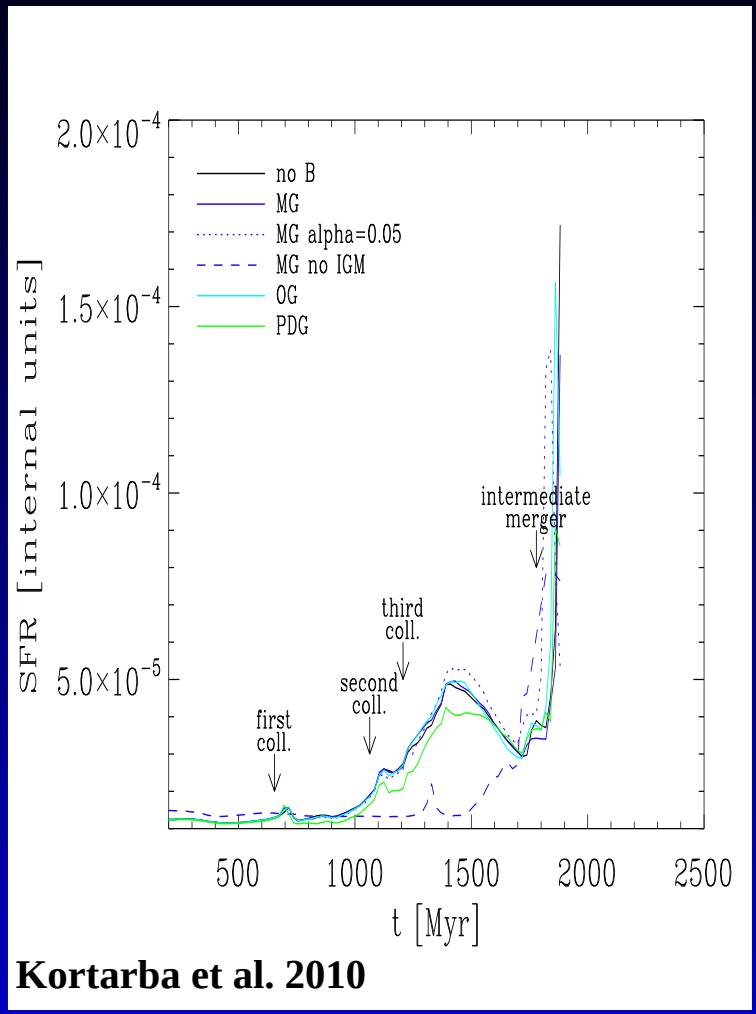
Soida et al., in prep.



Kortarba et al. 2010

Magnetic Field buildup

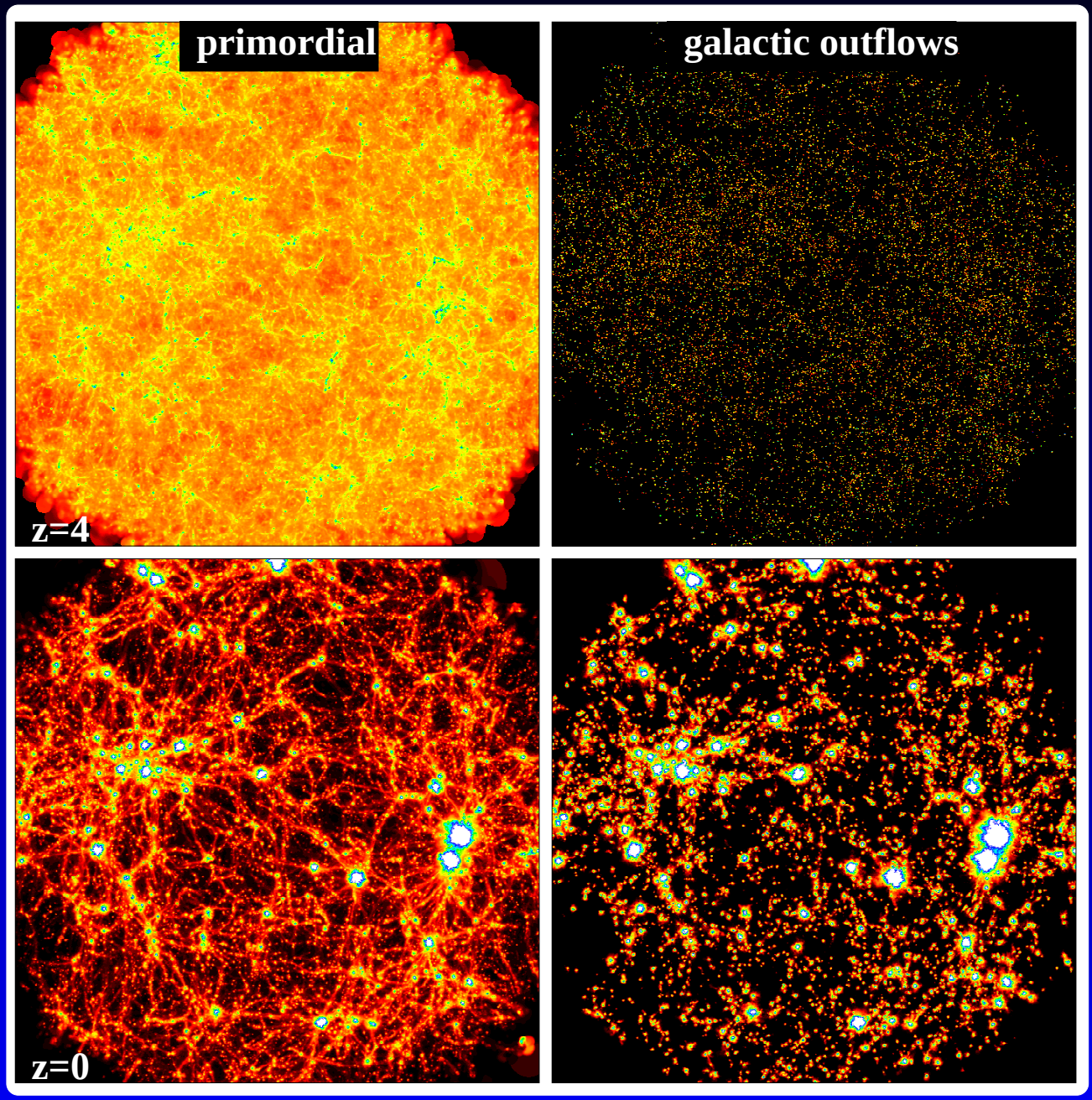




Kortarba et al. 2010

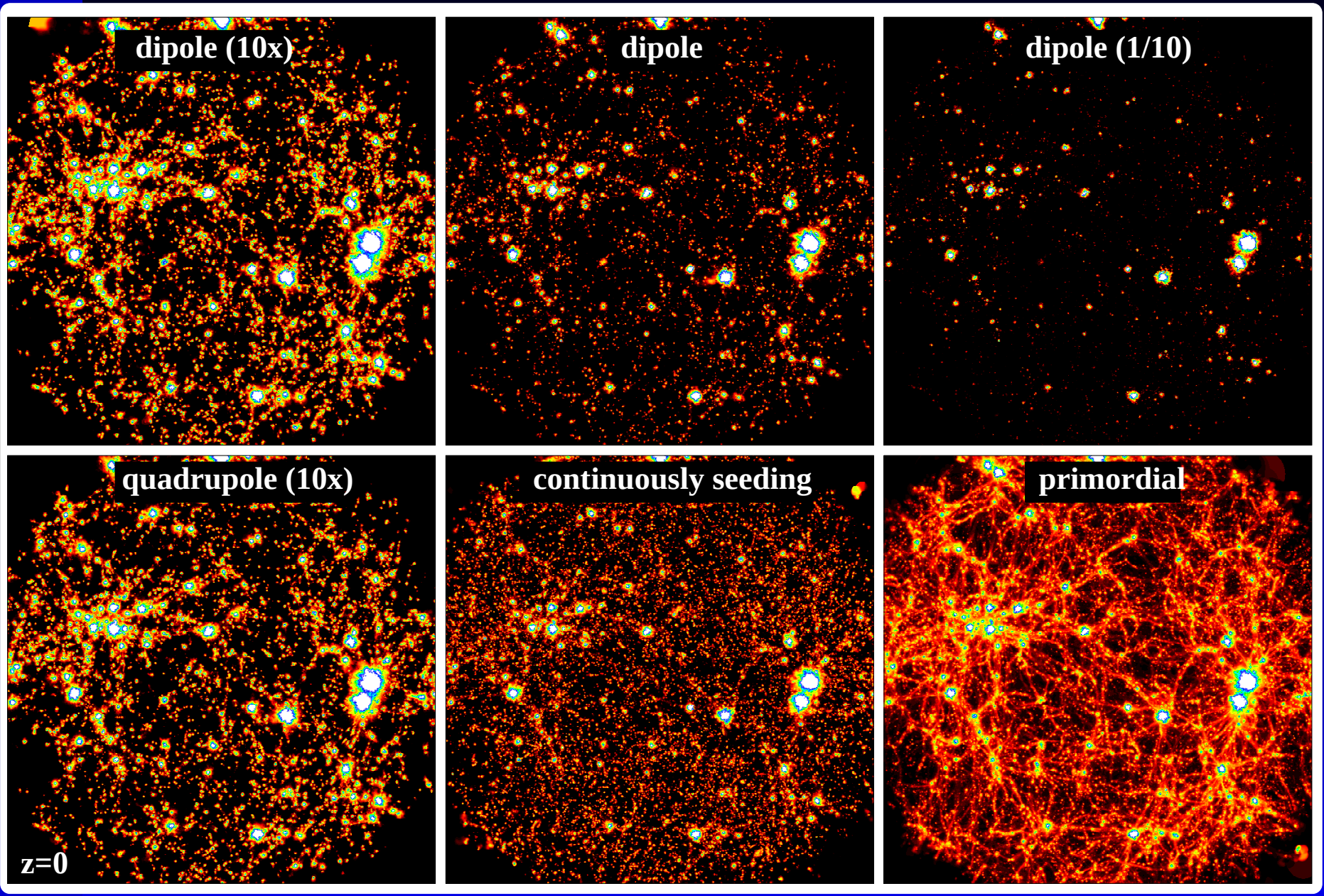
- **Merging** drives shocks, **turbulence** and **star-formation**
- Star-formation drives **winds**
- Winds **transport** out **magnetic fields**

Magnetic Field buildup



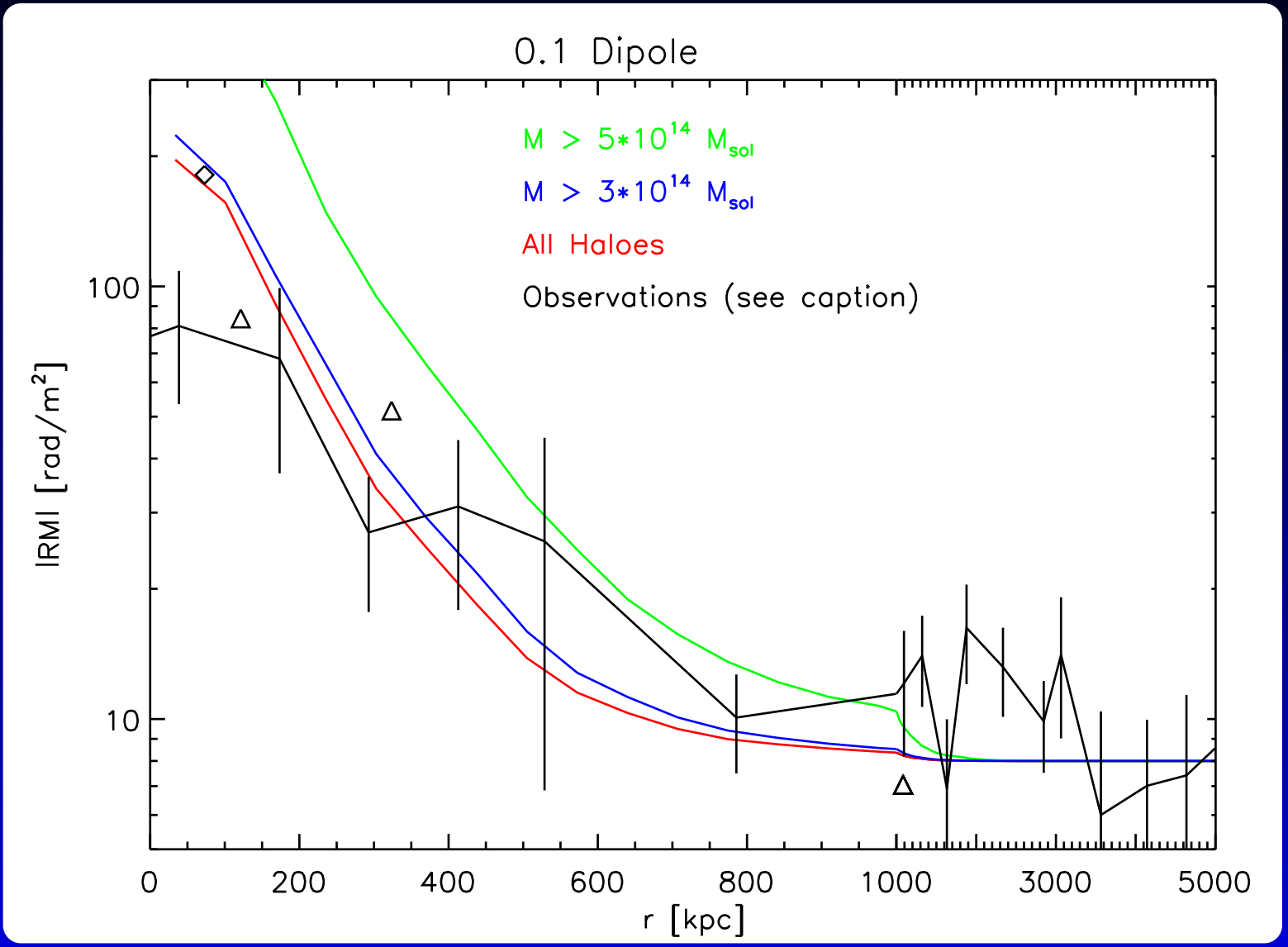
Seeding from **galactic outflows** (Donnert et al. 2009)

Magnetic Field buildup



Different wind **parameters** (Donnert et al. 2009)

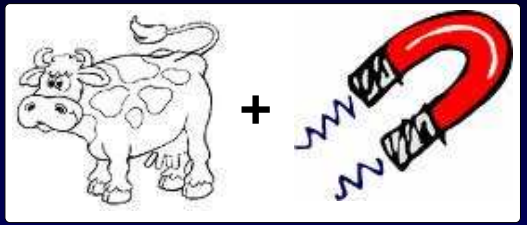
Magnetic Field buildup



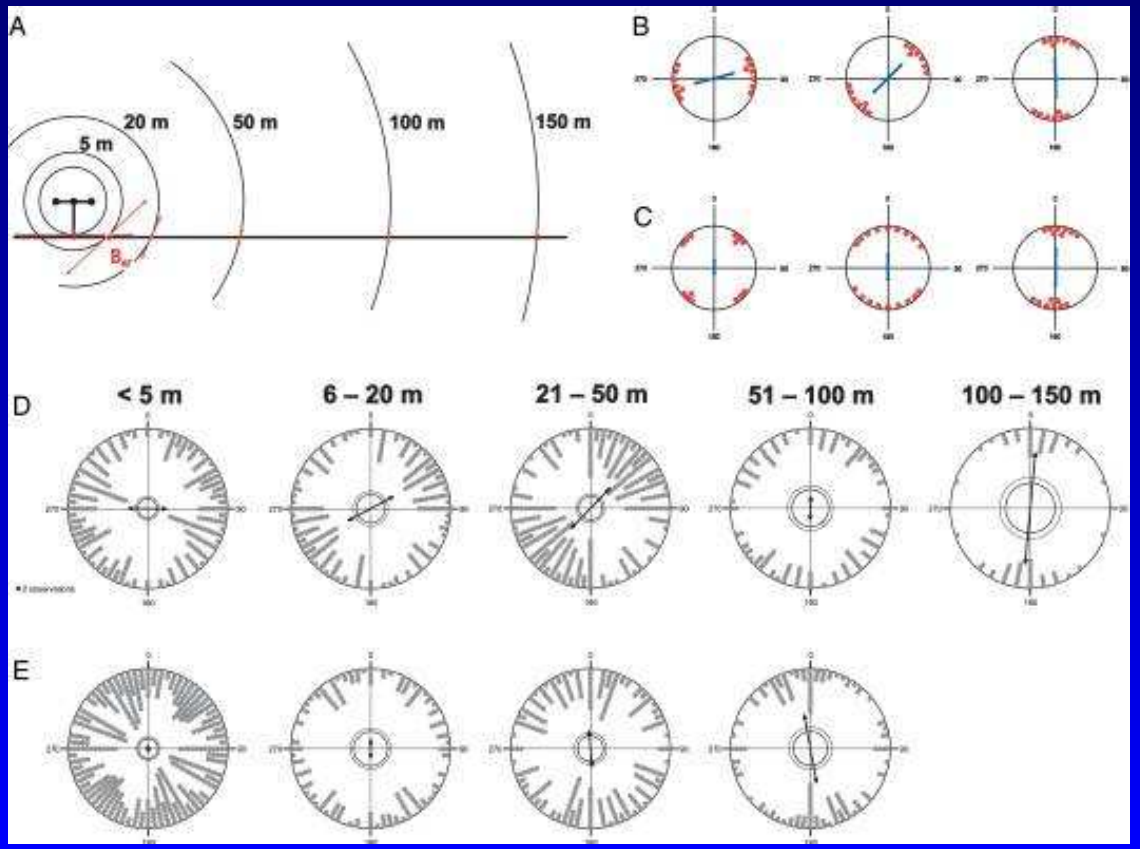
⇒ **Galactic seeding** models also **reproduce** observed **RM profile** within galaxy clusters (Donnert et al. 2009)

Note on magnetic field details

Details in magnetic field structure can reveal interesting effects !

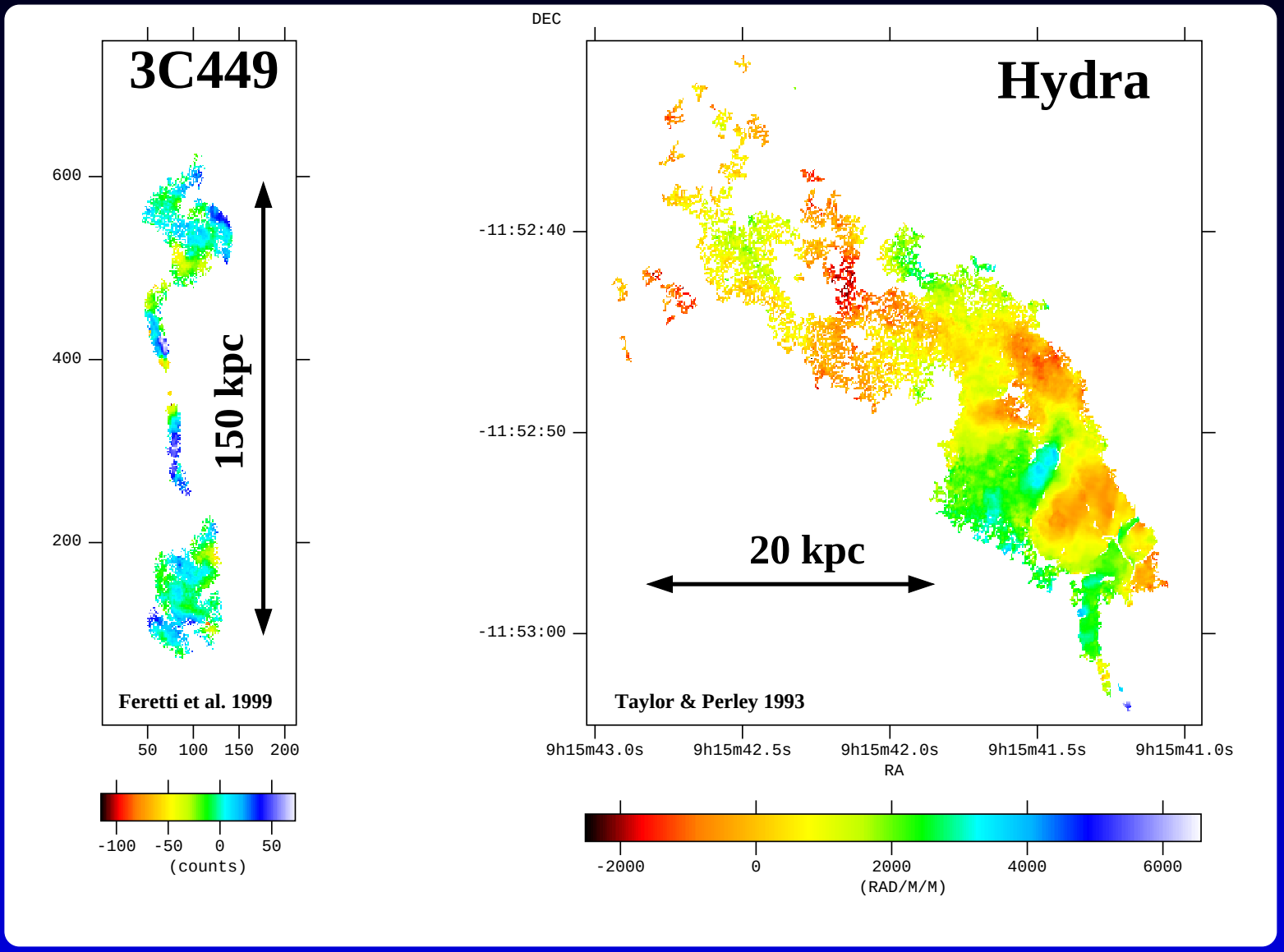


Example **Disturbed Magnetic Cows**: “Extremely low-frequency electromagnetic fields disrupt magnetic alignment of ruminants”



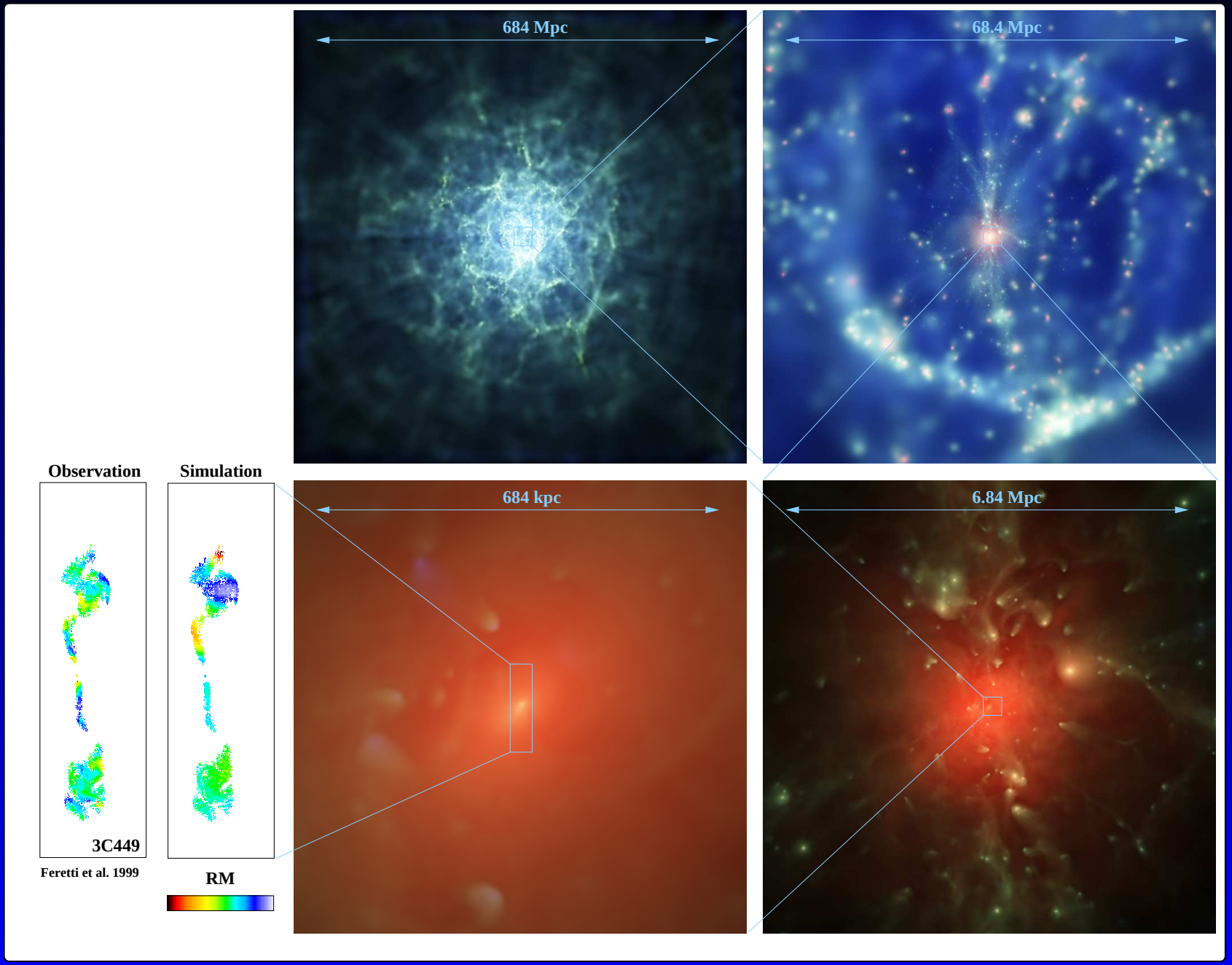
Burda et al. 2009

Simulation RM maps



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

Simulation RM maps



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

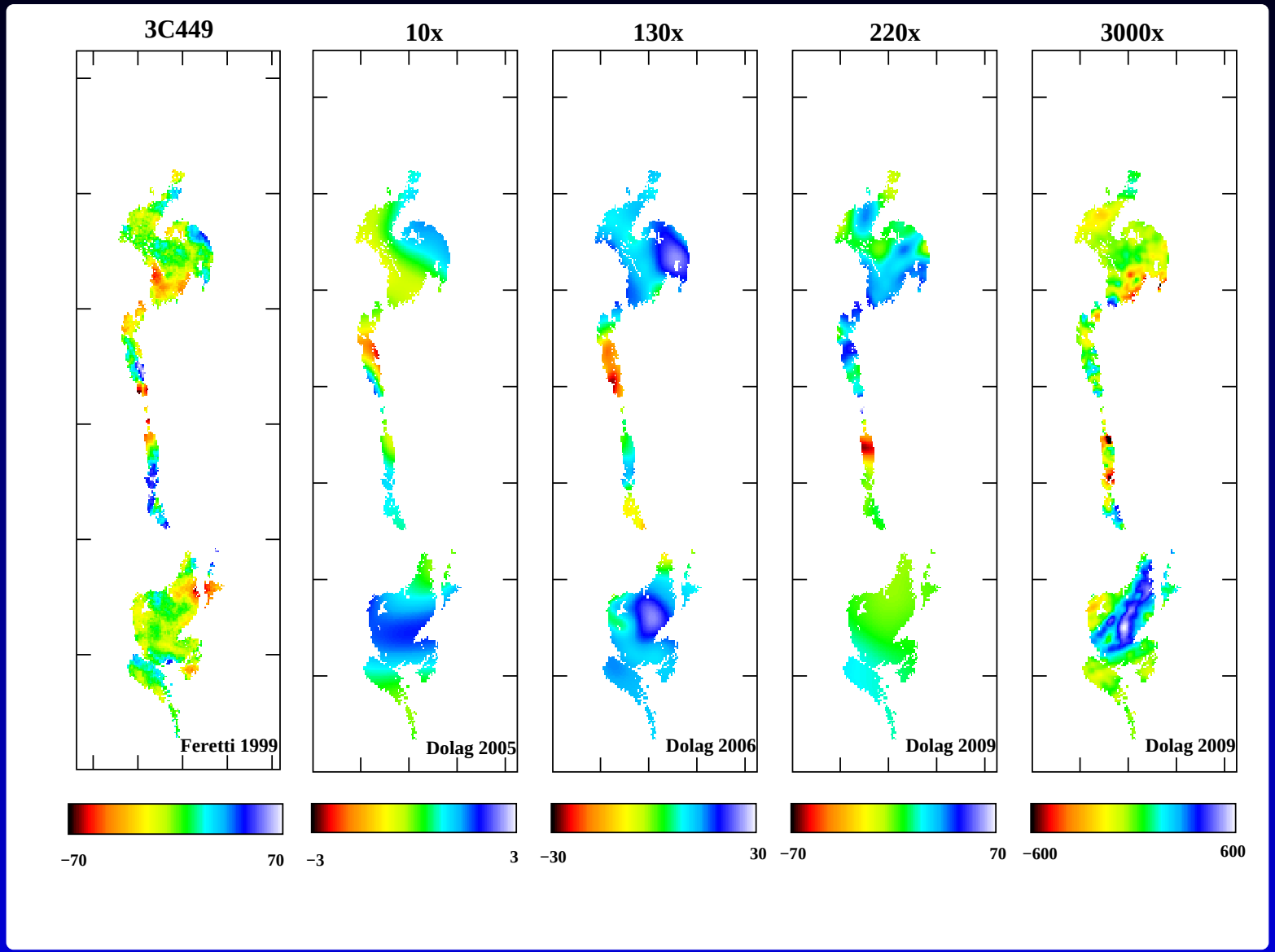
Simulation RM maps

Structure of **simulated magnetic field** in galaxy cluster

Embeded Movie

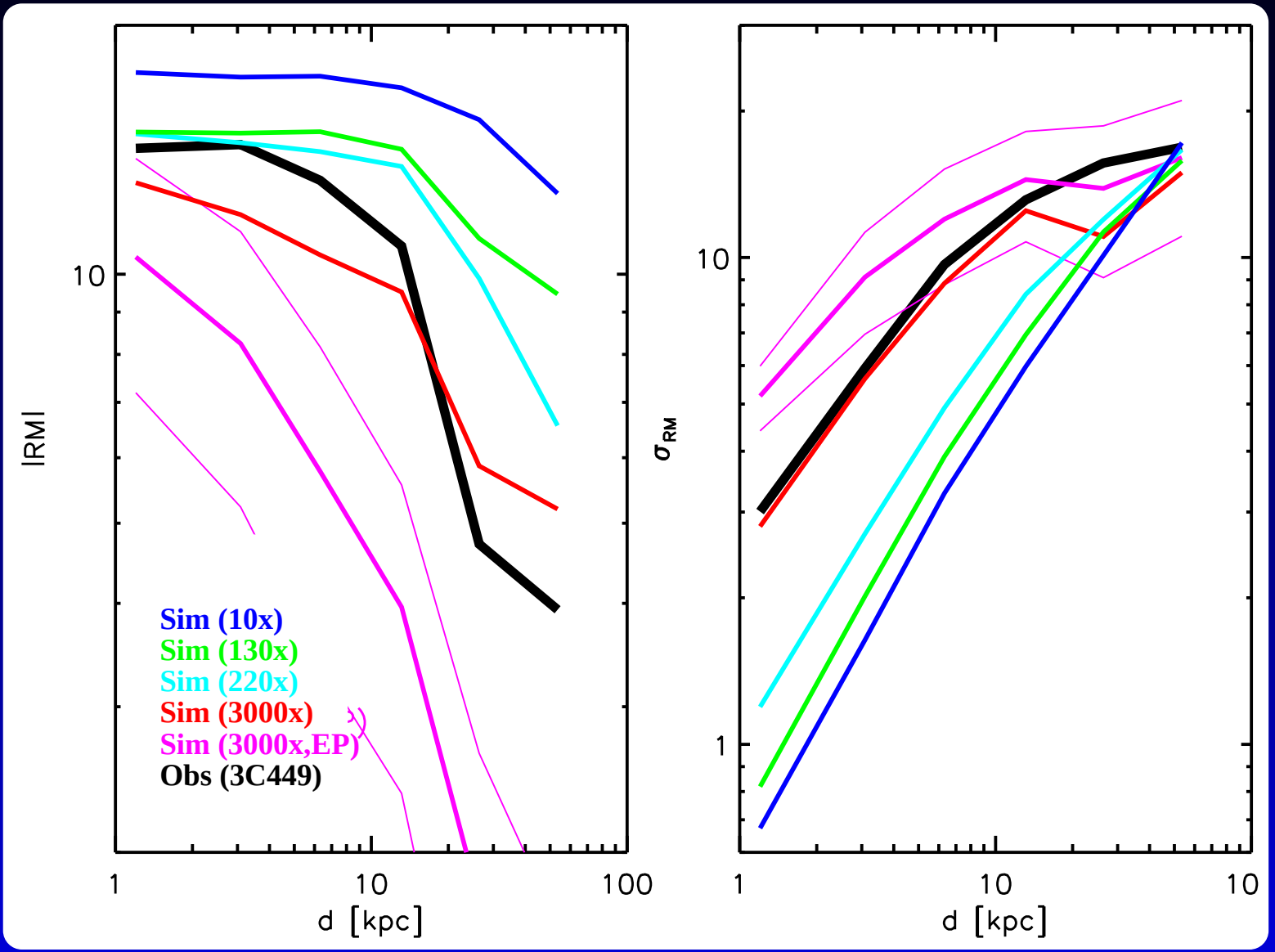
Movie & Simulation by P. Mendygral

Simulation RM maps



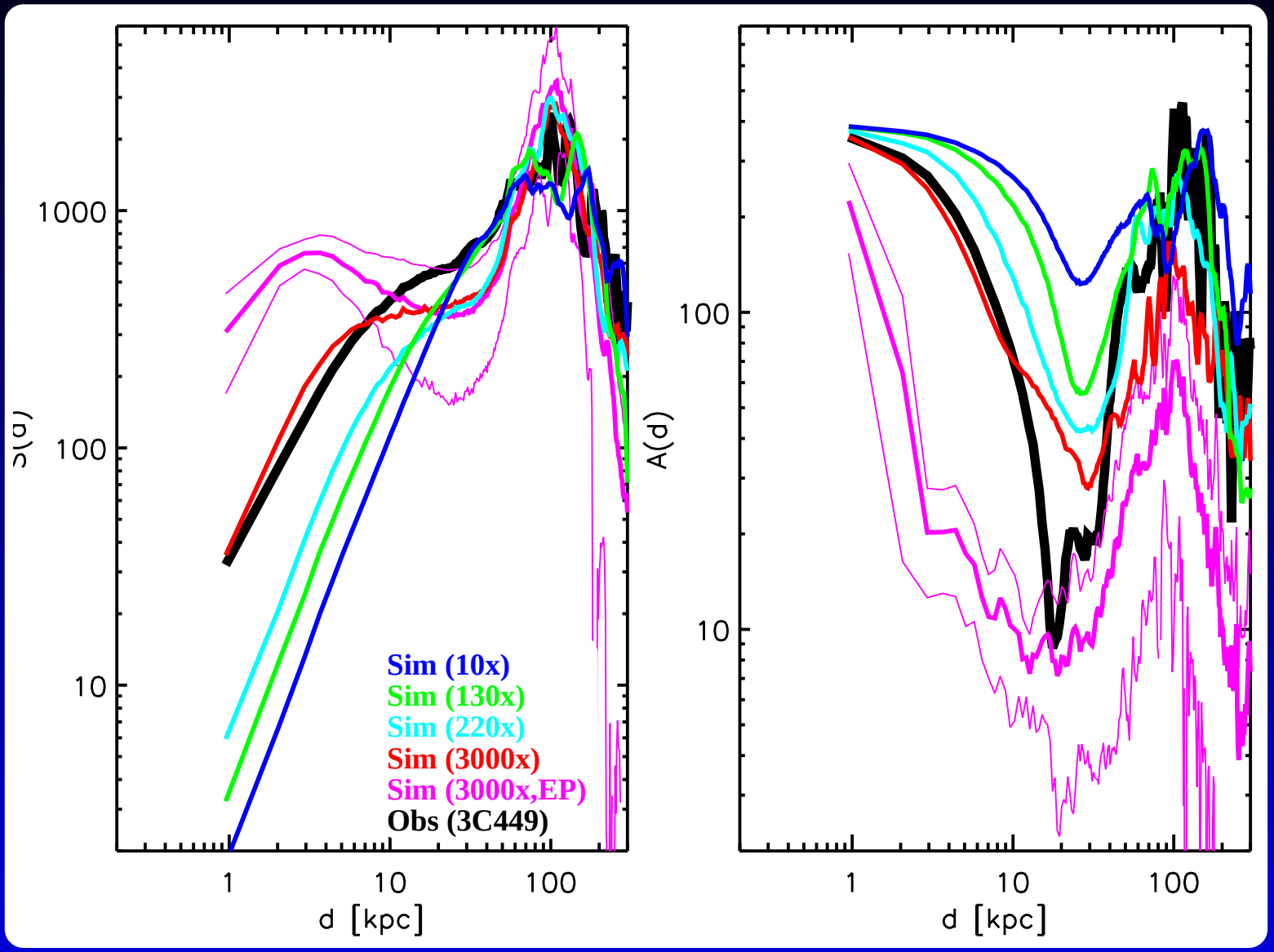
Observed and **simulated RM maps** up to the highest resolution simulation: 20 Million particles within R_{vir}, $m_{DM} = 10^7 M_\odot/h$, $\epsilon_{Grav} = 1$kpc/h (Stasyszyn & Dolag, work in progress)

Simulation RM maps



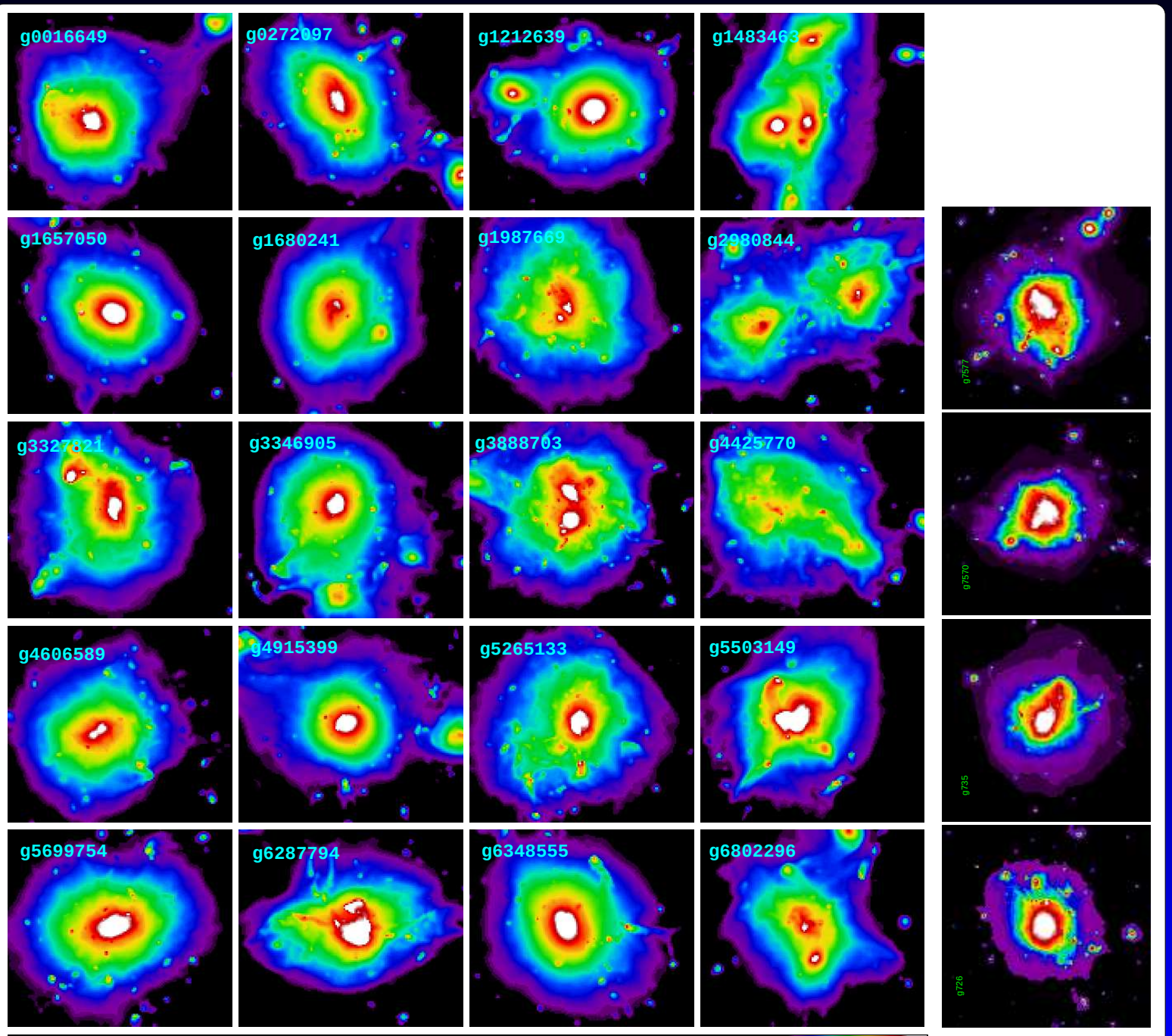
$$S(dx, dy) = \left\langle [RM(x, y) - RM(x + dx, y + dy)]^2 \right\rangle$$
$$A(dx, dy) = \langle RM(x, y) \times RM(x + dx, y + dy) \rangle$$

Simulation RM maps



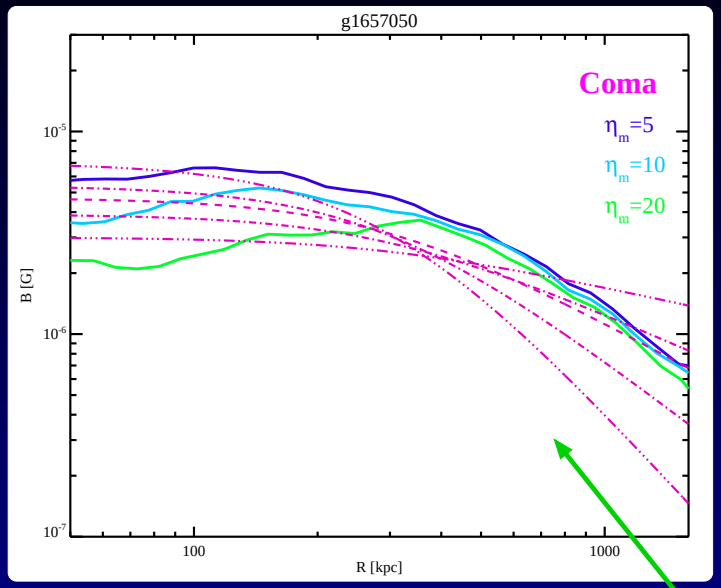
Structure functions derived from **observed** and simulated RM maps up to the highest resolution simulation: Indication for need of magnetic dissipation (Stasyszyn & Dolag, work in progress)

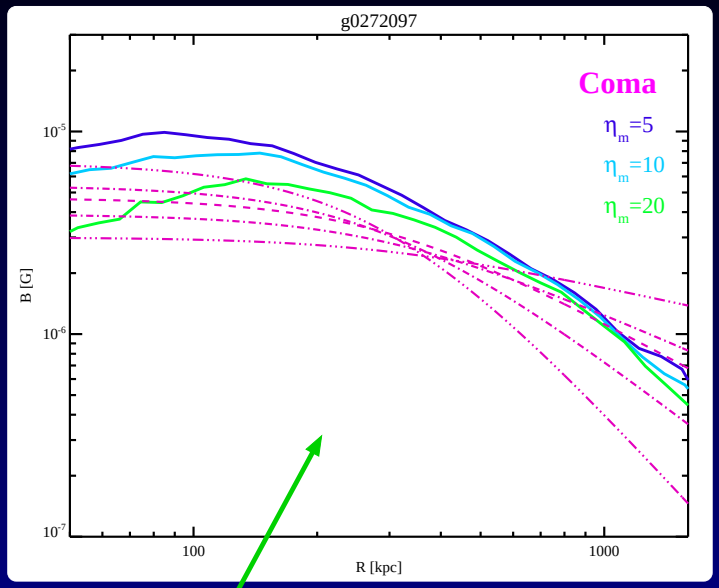
Beyond ideal MHD

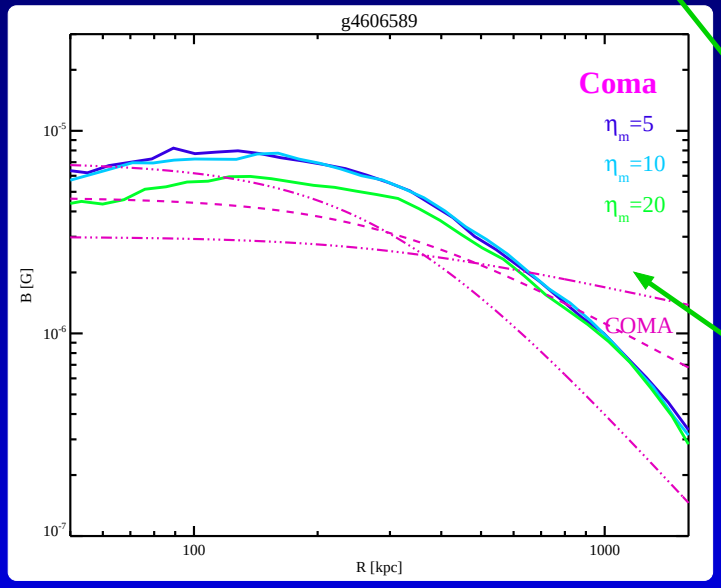


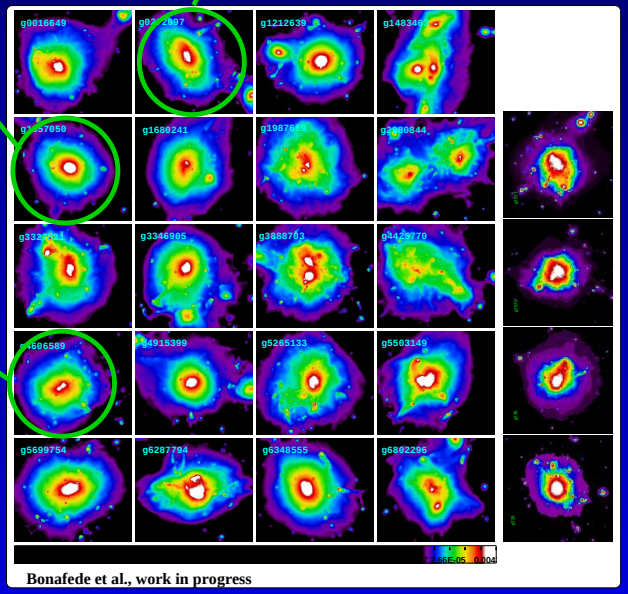
Bonaldede et al., work in progress

Beyond ideal MHD



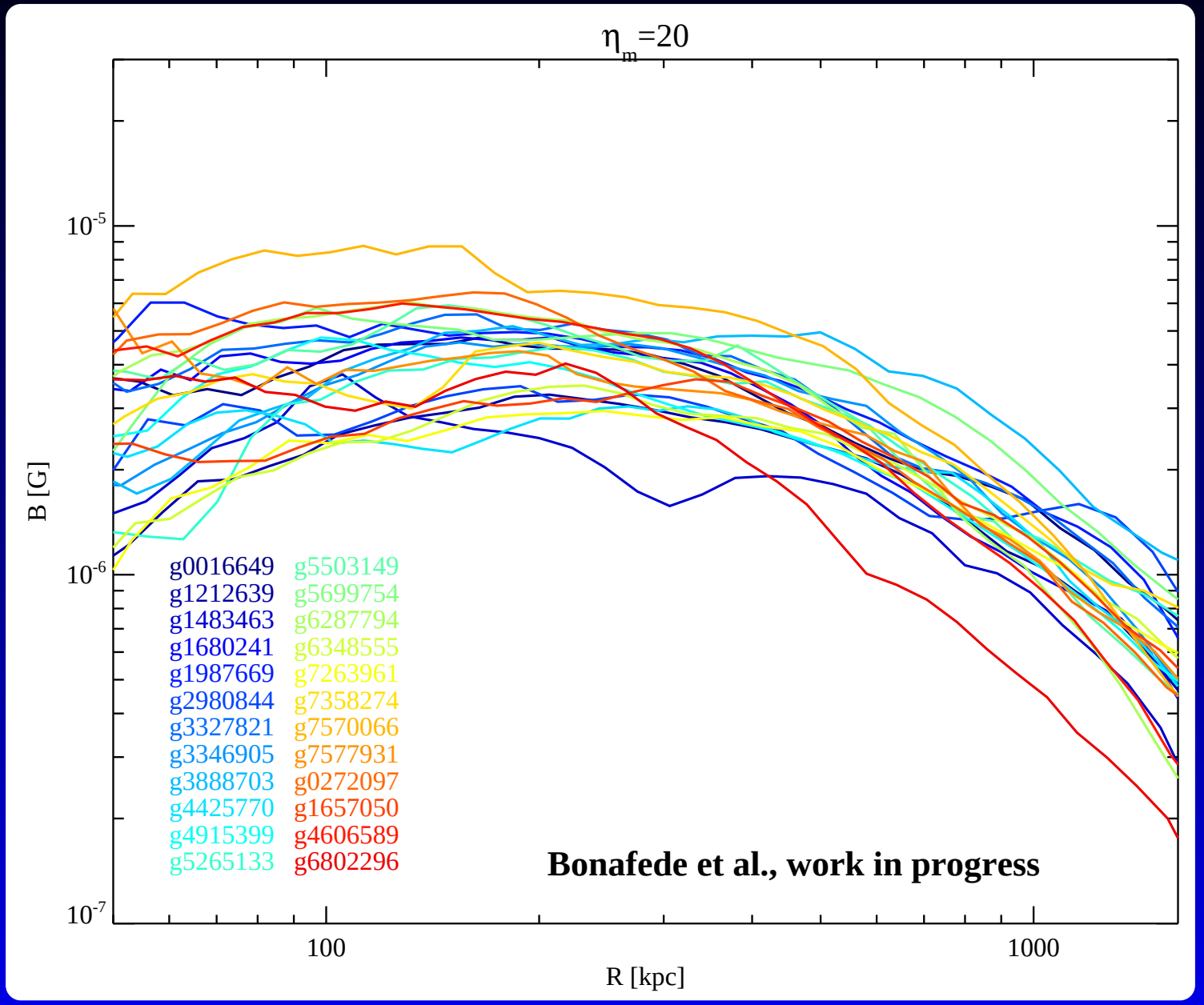






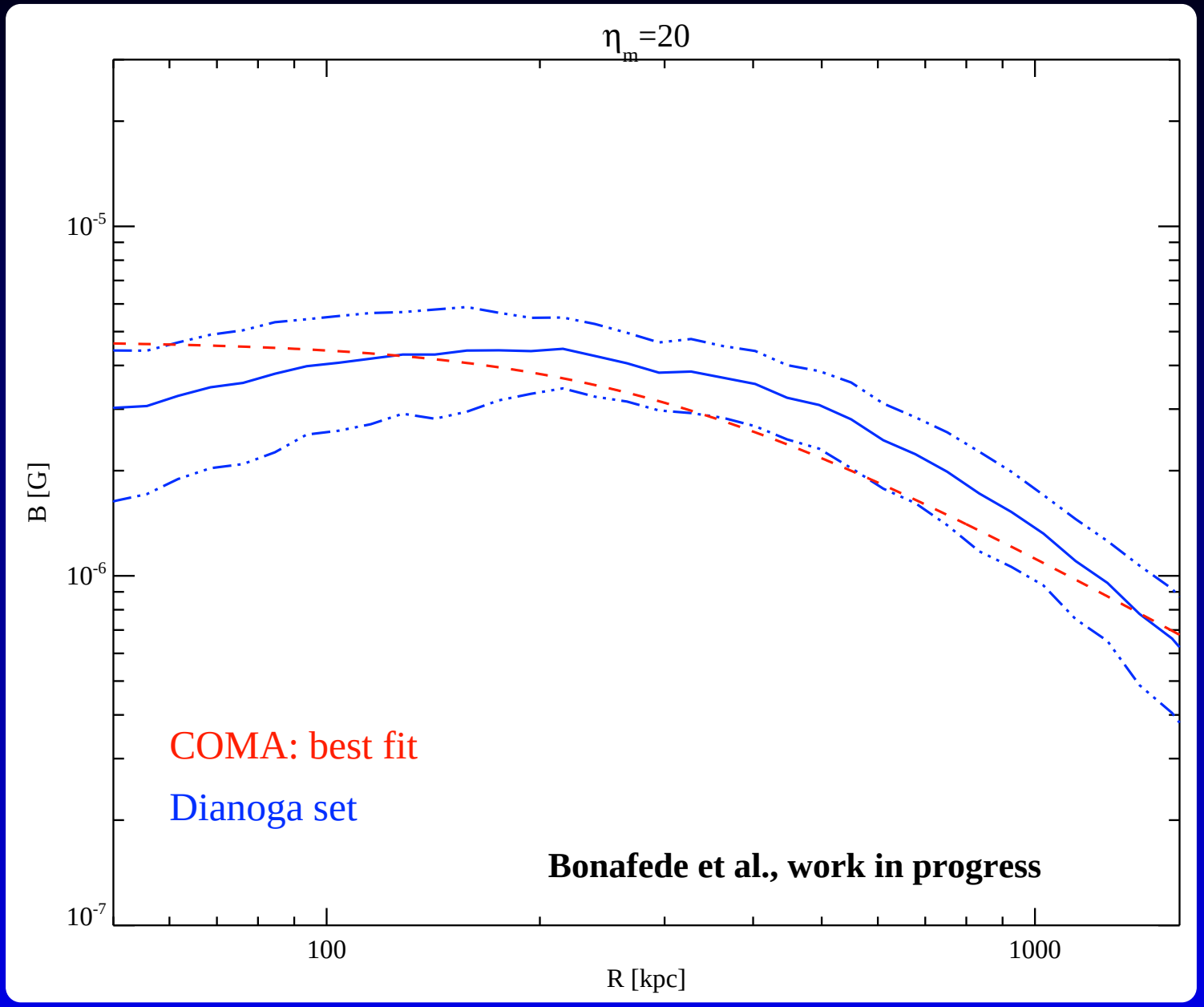
$$\frac{\mathrm{d}\vec{B}}{\mathrm{d}t} = (\vec{B}\cdot\vec{\nabla})\vec{v} - \vec{B}(\vec{\nabla}\cdot\vec{v}) + \eta\vec{\nabla}^2\vec{B}$$

Beyond ideal MHD



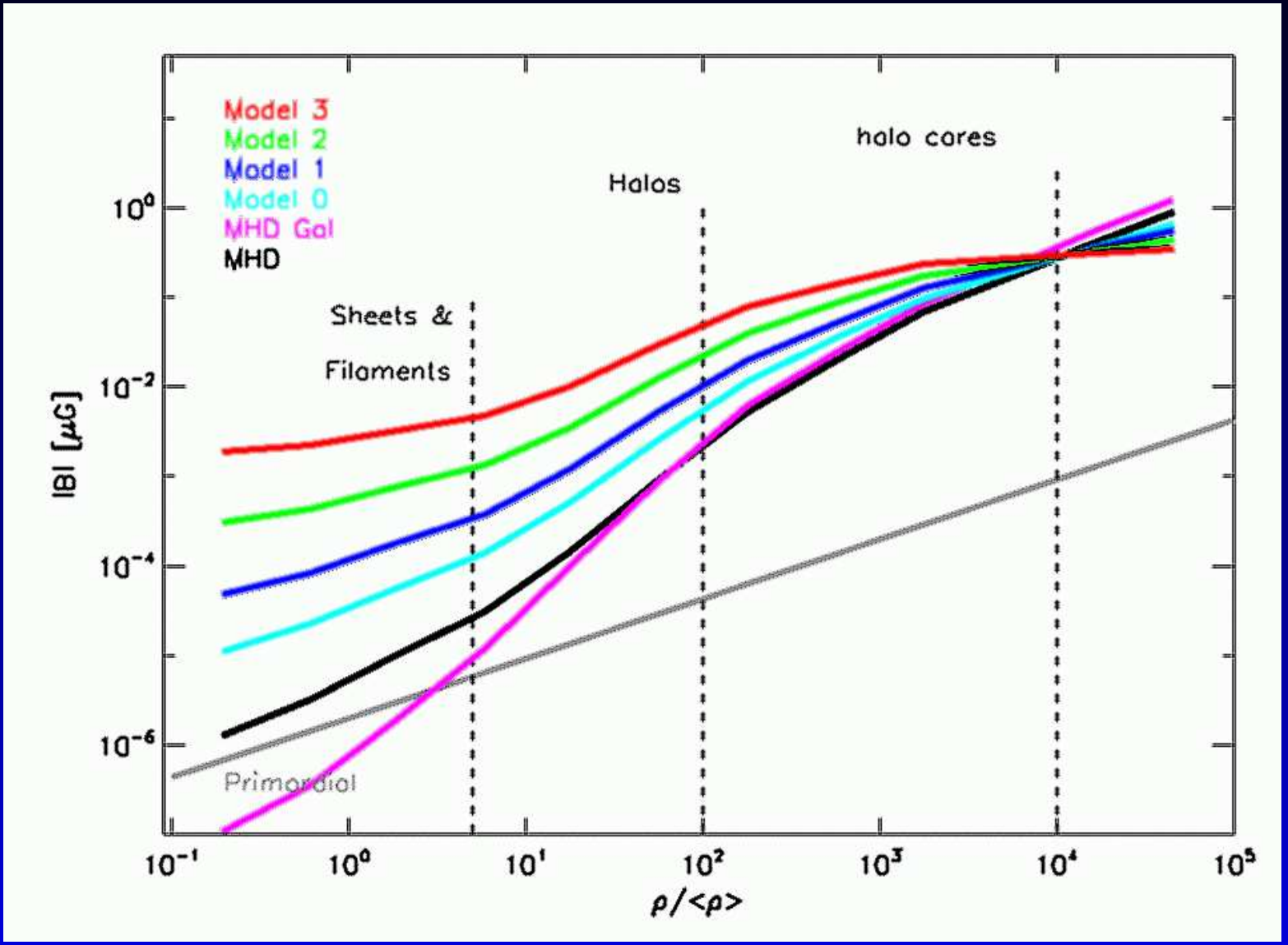
⇒ **Profiles** of 24 **Coma-like** galaxy clusters

Beyond ideal MHD



$\Rightarrow$ Magnetic **dissipation needed** to explain profiles

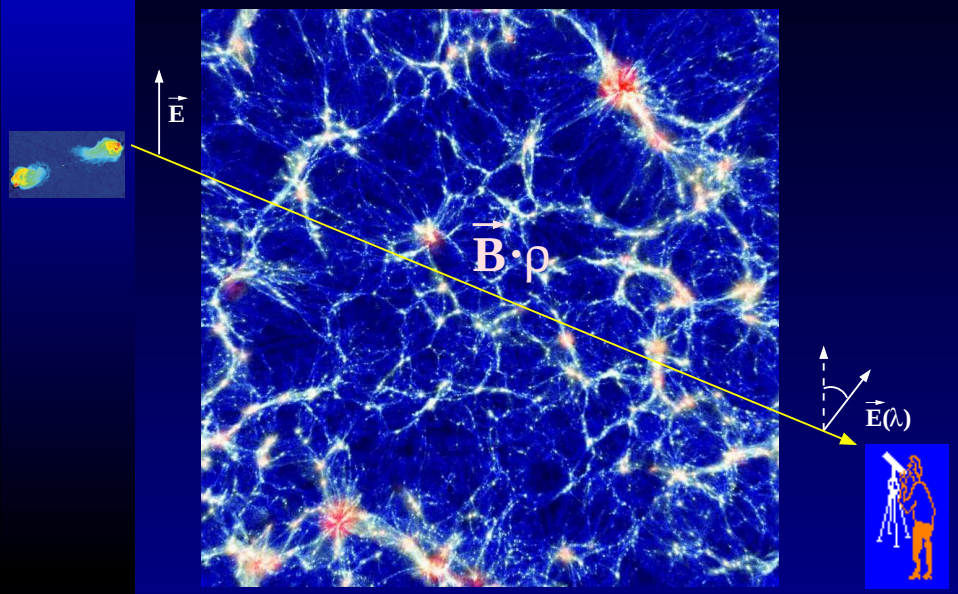
Discussion



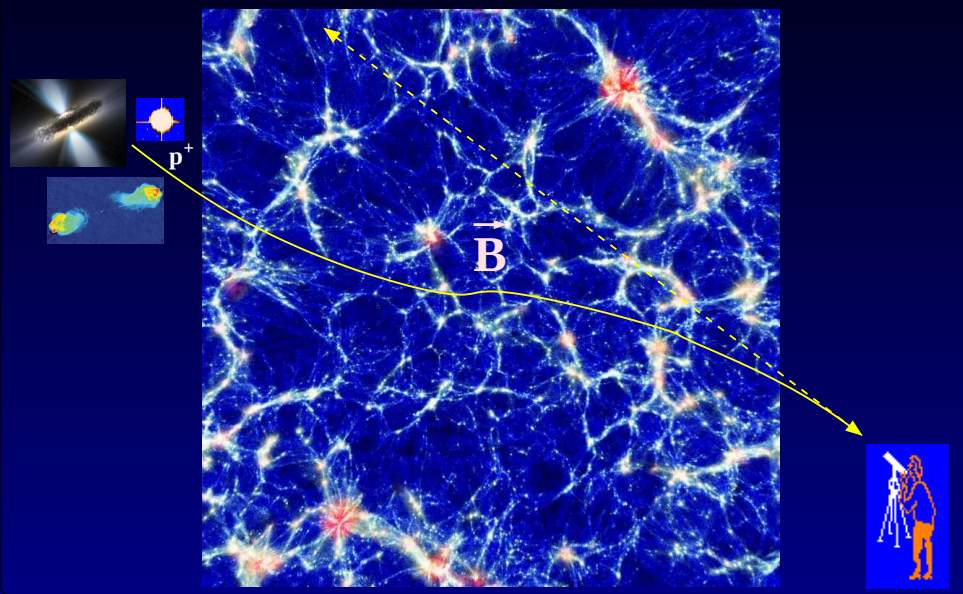
Predictions from **different** models for **origin** of cosmic magnetism.

Discussion

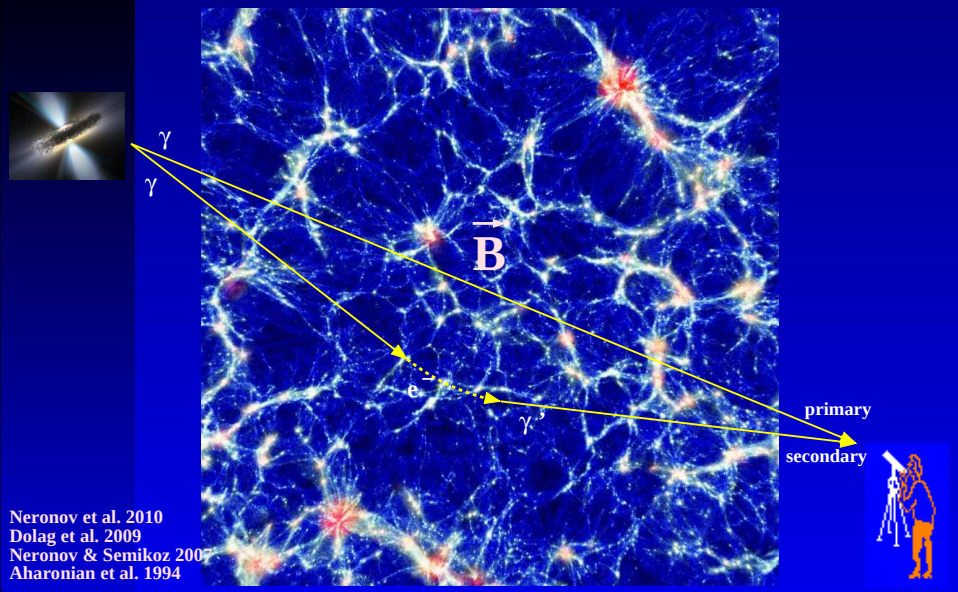
Faraday Rotation (RM) of polarized radio emission



Propagation of ultra high energy cosmic rays (UHECR)

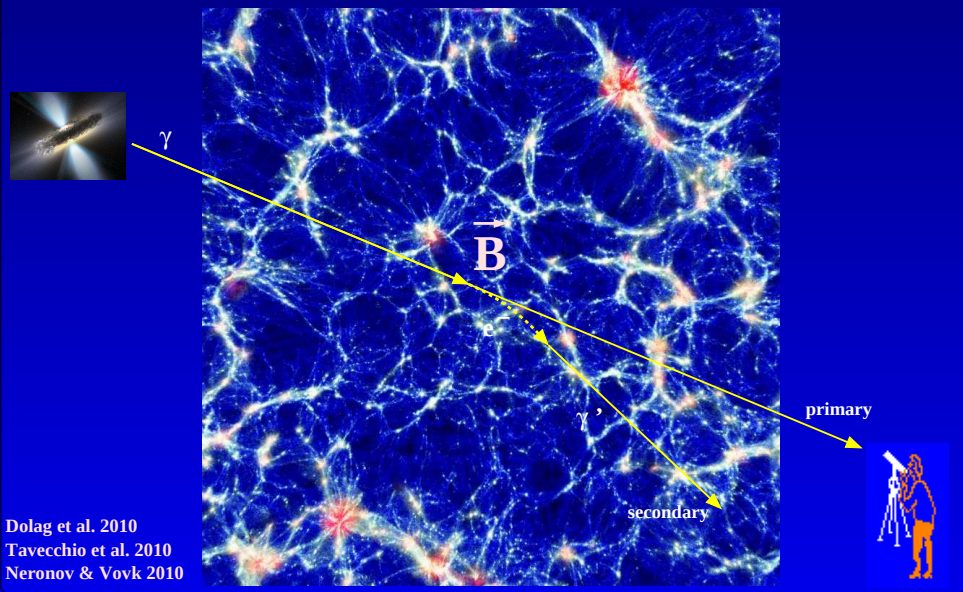


Deflection of electromagnetic cascade of TeV photons



Neronov et al. 2010
Dolag et al. 2009
Neronov & Semikoz 2007
Aharonian et al. 1994

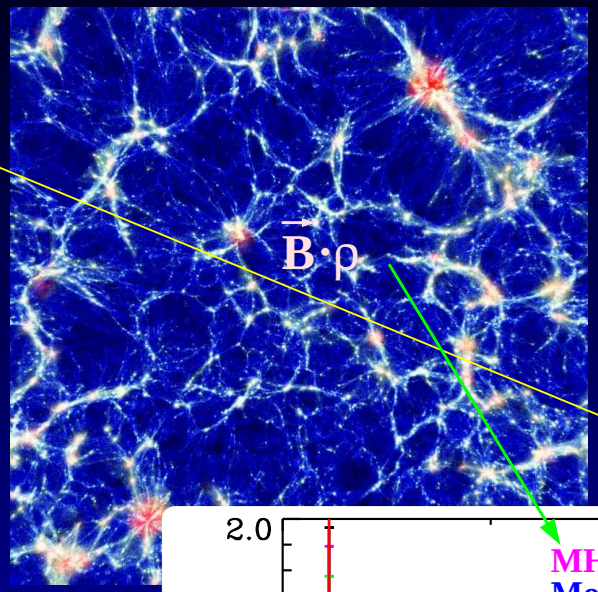
Attenuation from electromagnetic cascade of TeV photons

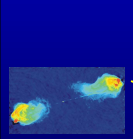


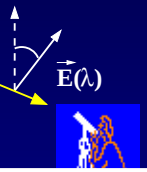
Dolag et al. 2010
Tavecchio et al. 2010
Neronov & Vovk 2010

Discussion

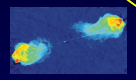
Faraday Rotation (RM) of polarized radio emission

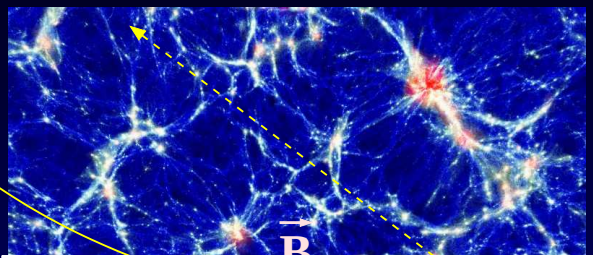


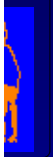




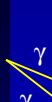
Propagation of ultra high energy cosmic rays (UHECR)

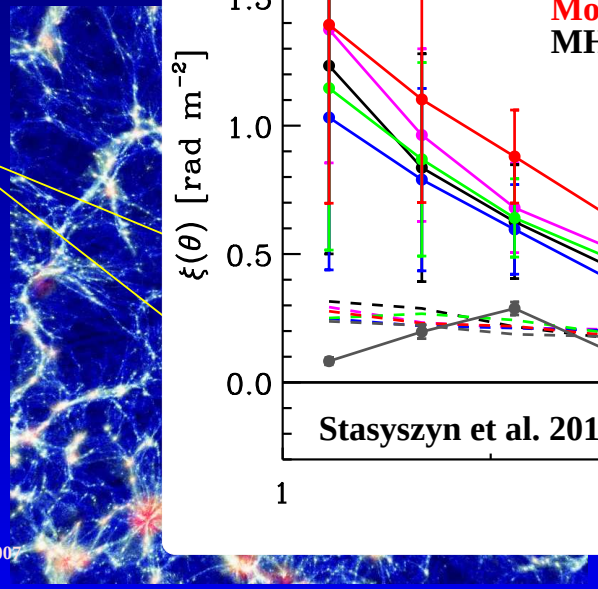


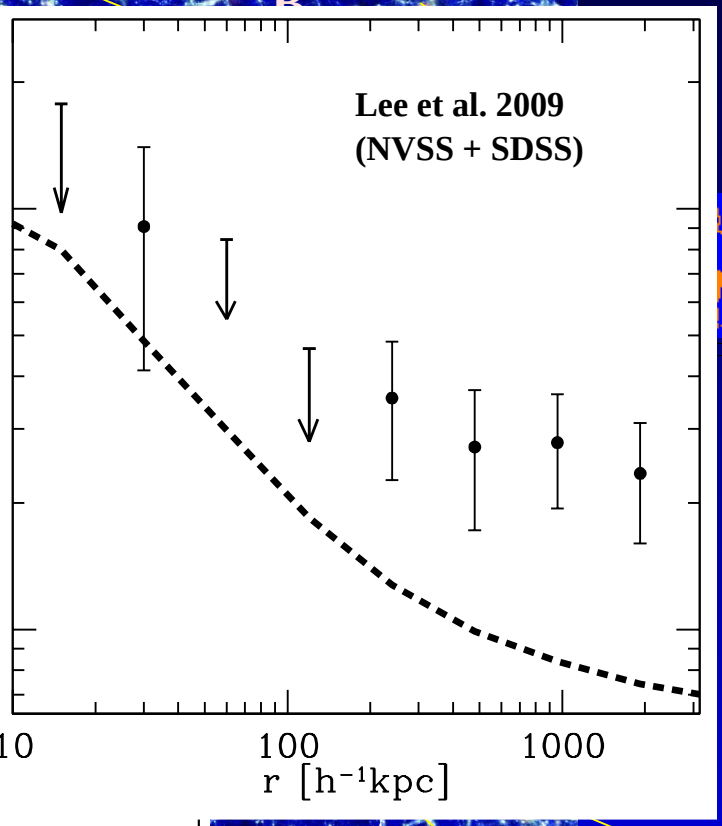


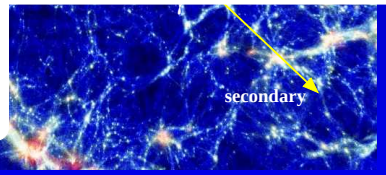


Deflection of ele







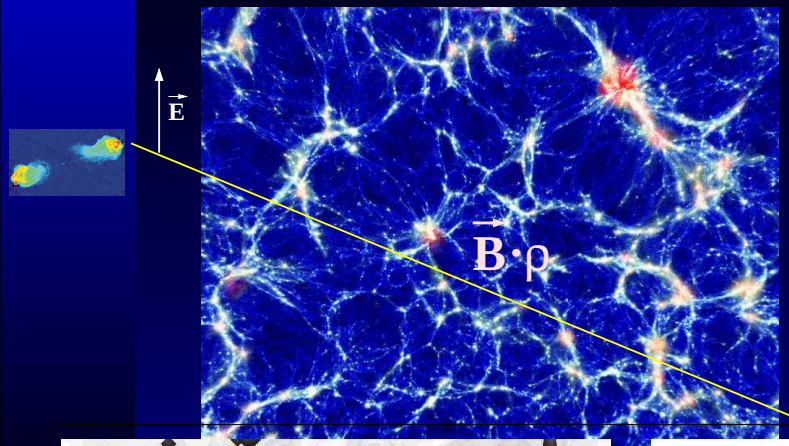


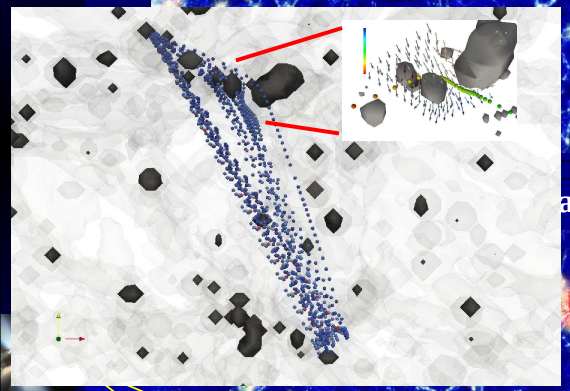
Neronov et al. 2010
Dolag et al. 2009
Neronov & Semikoz 2007
Aharonian et al. 1994

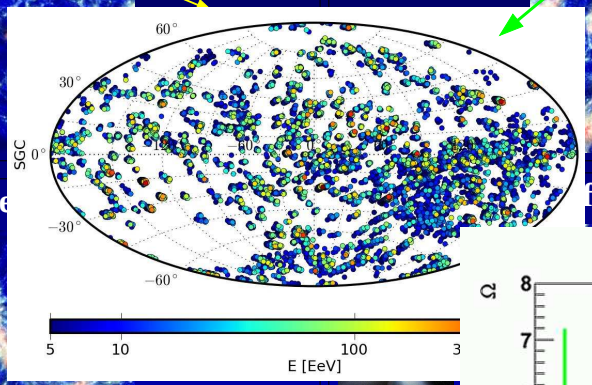
Neronov & Vovk 2010

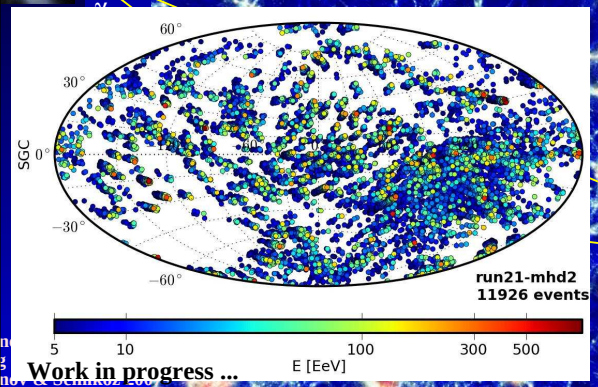
Discussion

Faraday Rotation (RM) of polarized radio emission

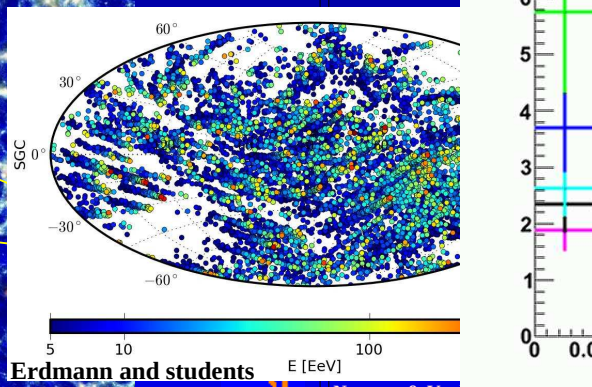








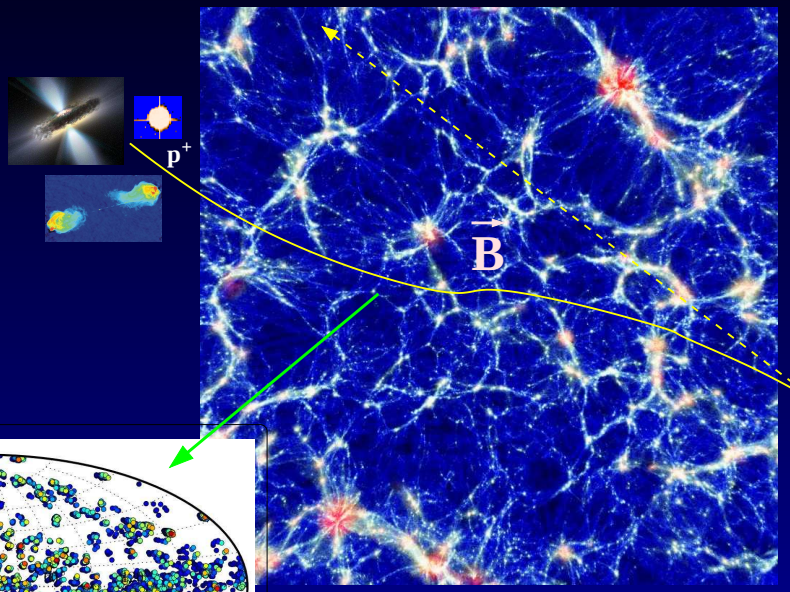
Work in progress ...



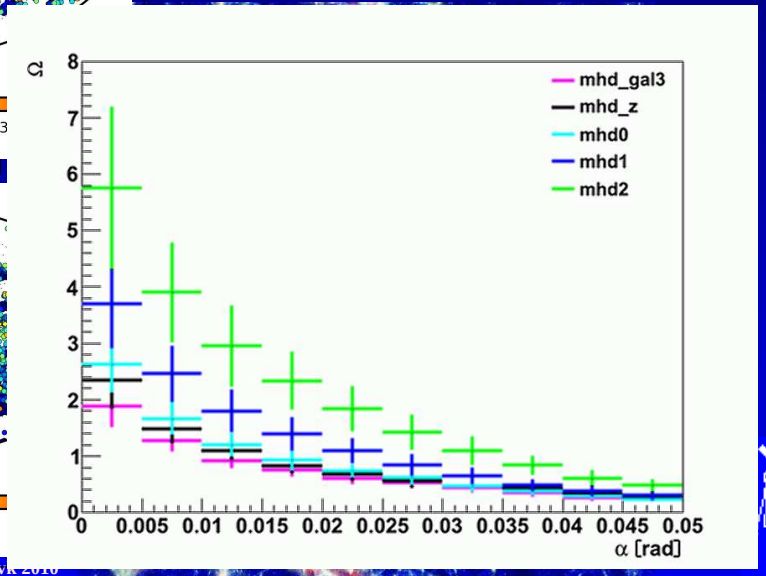
Erdmann and students

Neron
Dolag
Neronov & Vovk 2010
Aharonian et al. 1994

Propagation of ultra high energy cosmic rays (UHECR)



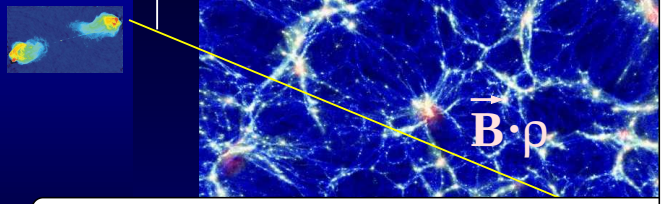
from electromagnetic cascade of TeV photons

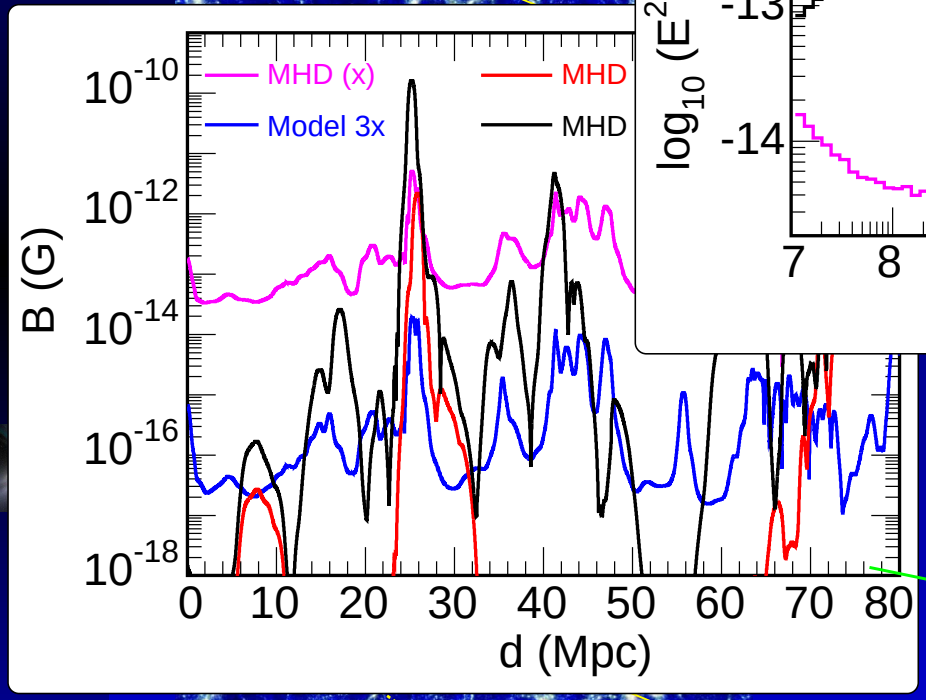


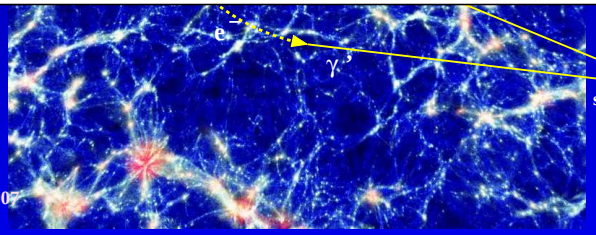
Neronov & Vovk 2010

Discussion

Faraday Rotation (RM) of polarized radio emission

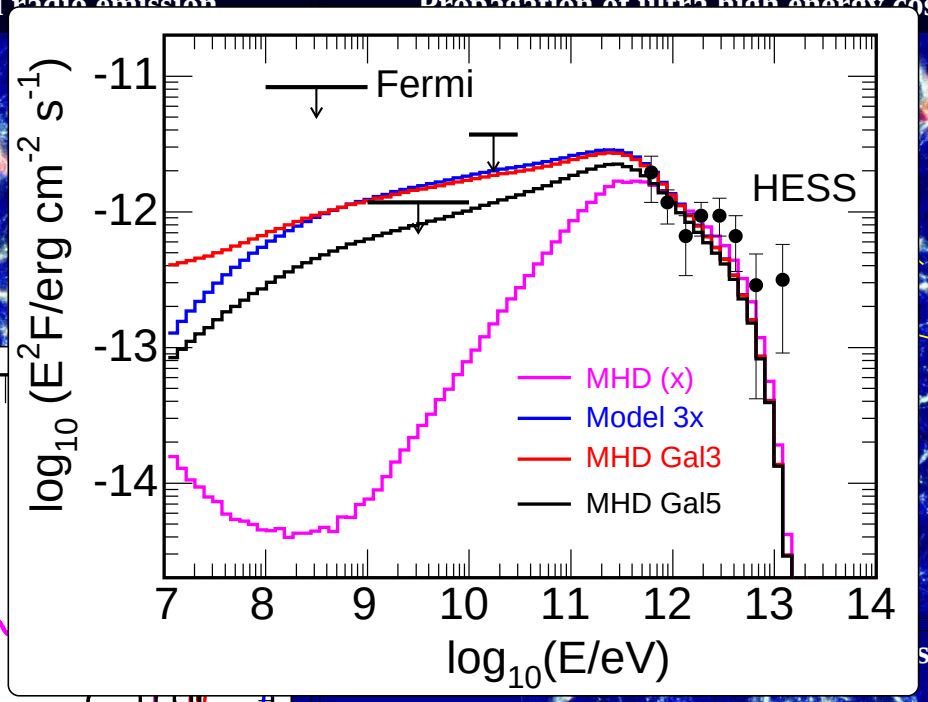


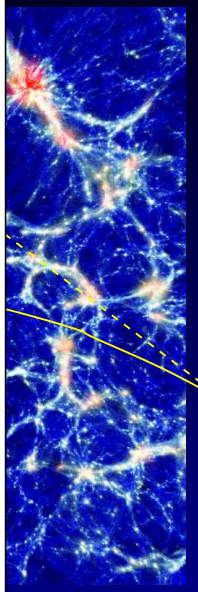




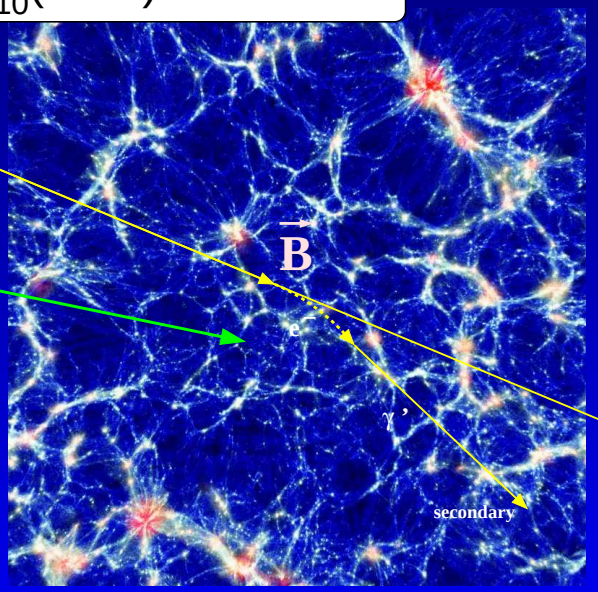
Neronov et al. 2010
Dolag et al. 2009
Neronov & Semikoz 2007
Aharonian et al. 1994

Propagation of ultra high energy cosmic rays (UHECR)



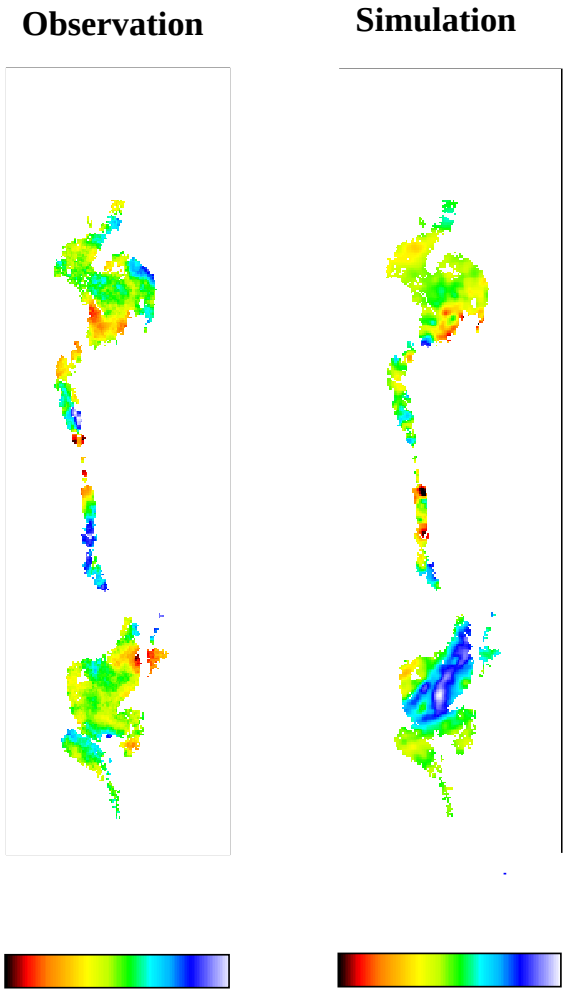


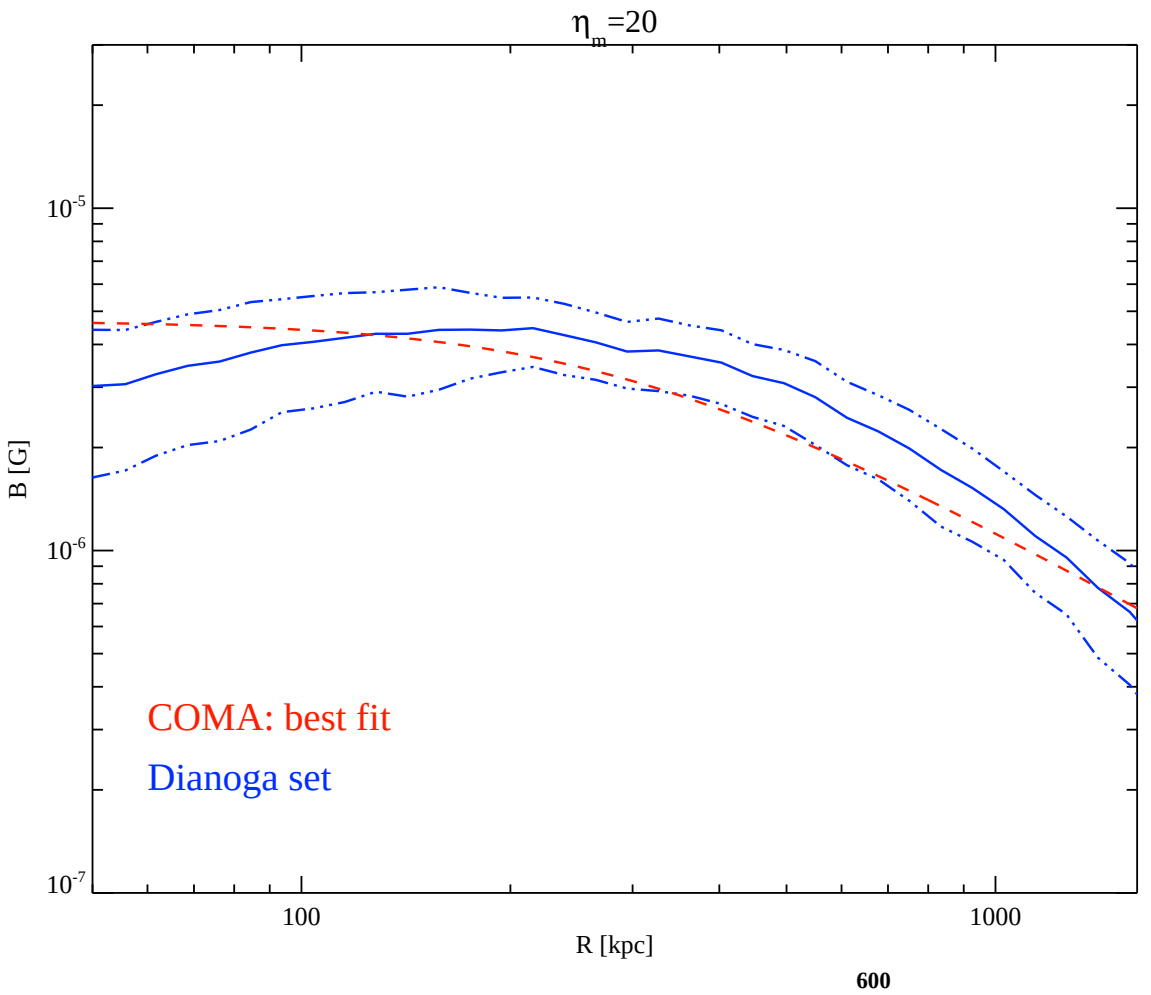
Cascade of TeV photons



Dolag et al. 2010
Tavecchio et al. 2010
Neronov & Vovk 2010

Conclusions





Magnetic field in galaxy **clusters** reflects structure formation and plasma properties, but **do not tell** anything on **origin** of **cosmic magnetism**.

Conclusions

Observations (**RM & Radio probes μG, maybe nG**)

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

Observations (**UHECR & γ-rays probes $10^{-16} - 10^{-9}$G**)

- High Enery Astronomy helps probing their origin

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

Clusters: $E_{Mag}(1-3\%) < E_{Turb}(10-20\%) < E_{Therm} \approx E_{pot}$