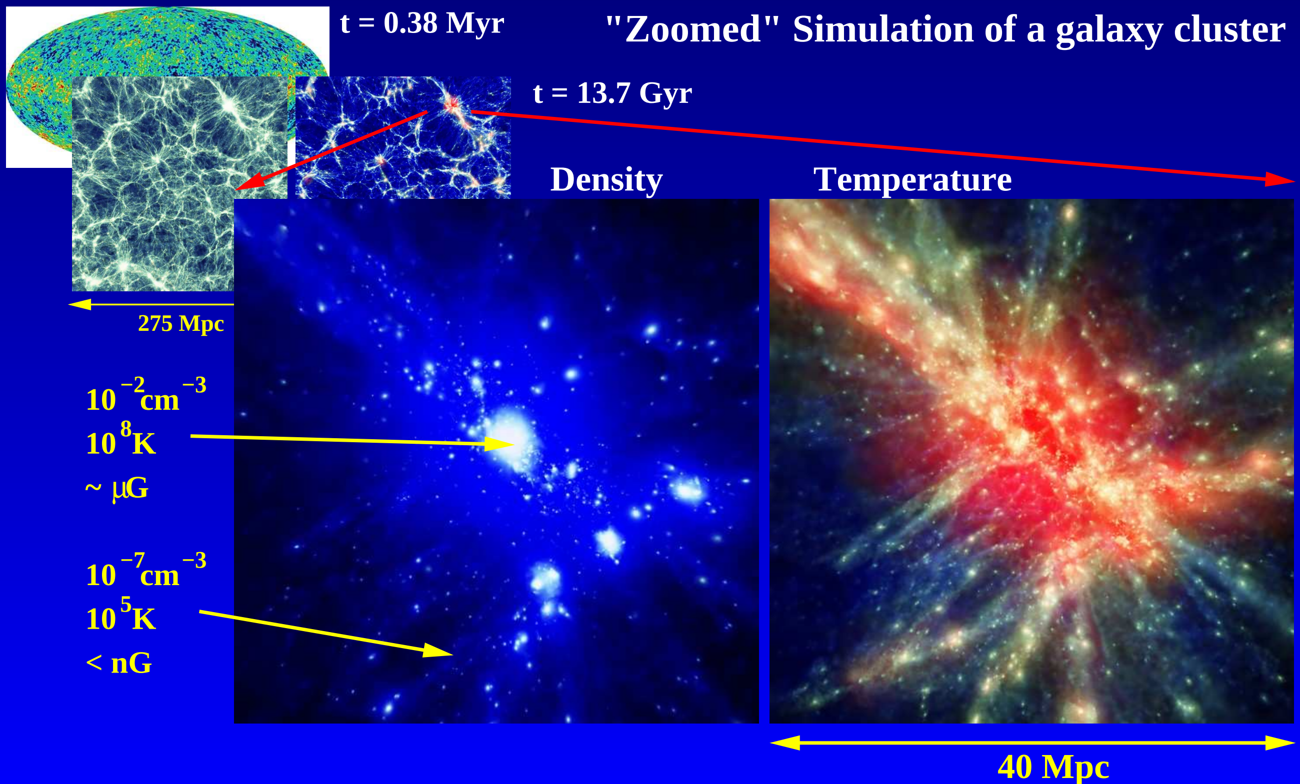
Magnetic fields in and beyond clusters of galaxies

Klaus Dolag

Max-Planck-Institut für Astrophysik



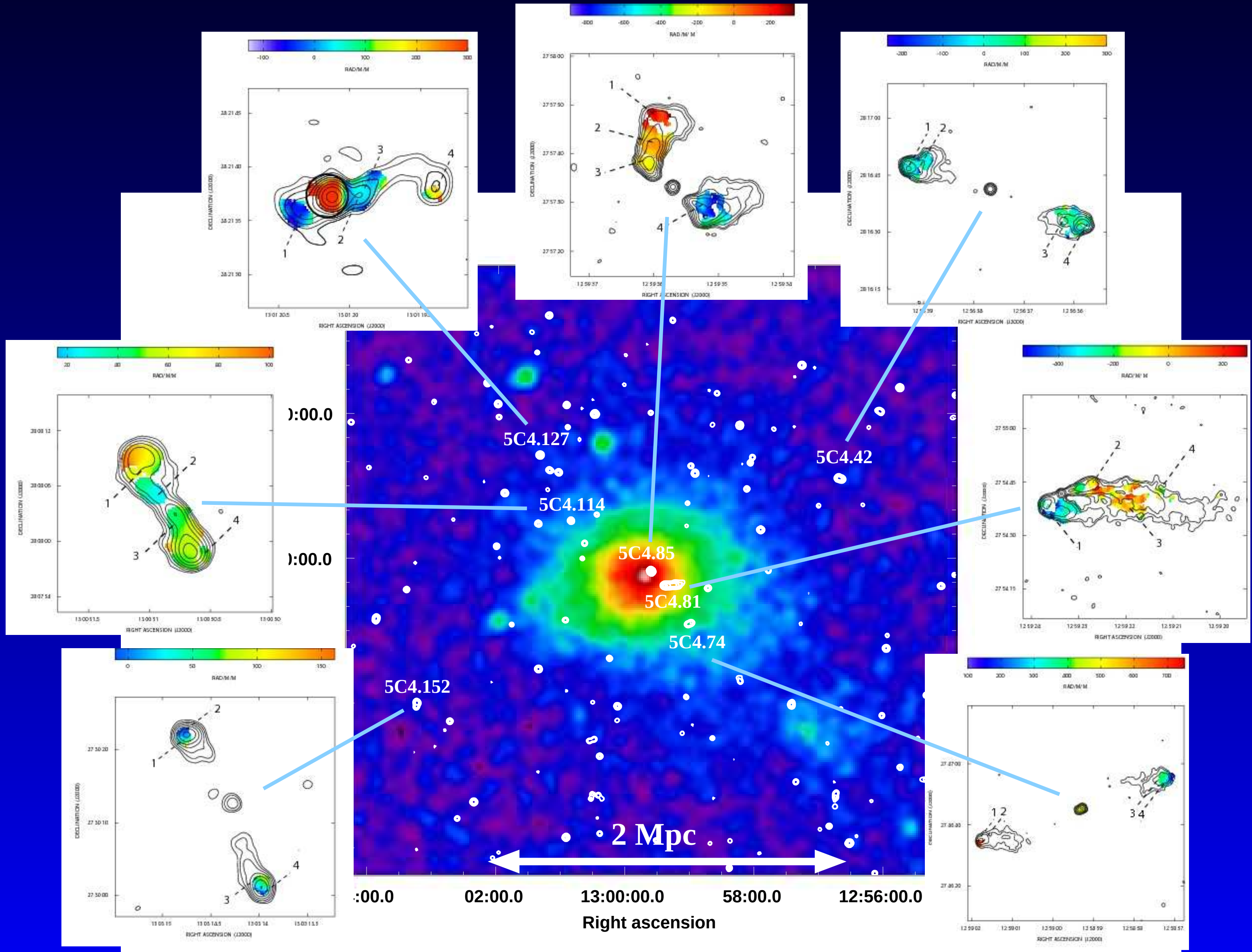
Outline

- Simulating magnetic fields in galaxy clusters
  - Observations of cluster magnetic fields
  - Hierarchical buildup of magnetic fields
- Applications
  - Propagation of UHECRs
  - RM-galaxy correlation to measure cosmic magnetization
  - Measuring low magnetic fields
- Constraining ICM properties
  - Profile of magnetic field ?
  - Minimal length-scale of cluster fields ?

F. Stasyszyn (MPA), J. Donnert (MPA) and A. Bonafede (IRA)

Observed Magnetic Fields

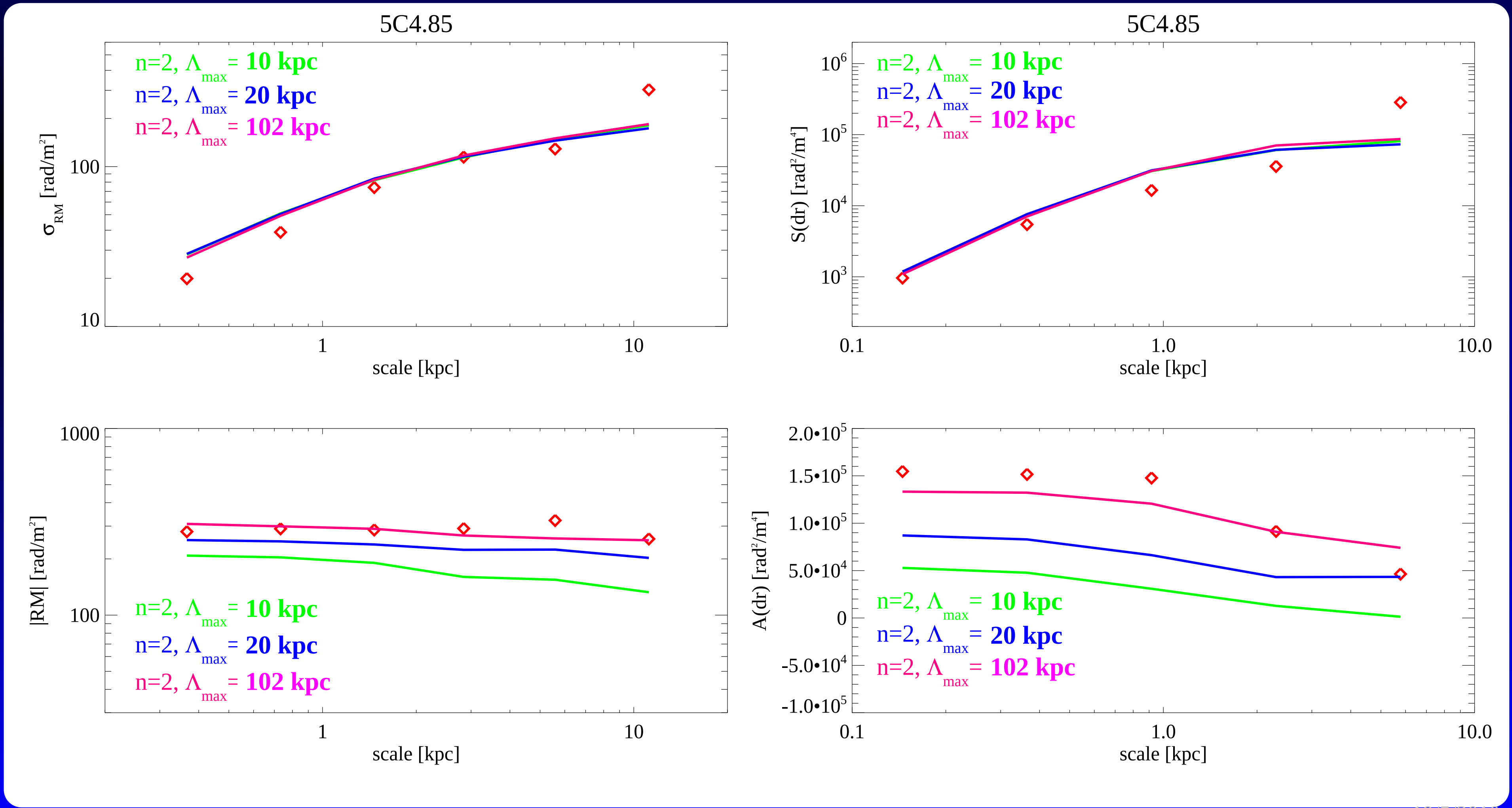
$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\mu}, \quad |B_k|^2 \propto k^{-n}, \quad (k_{\min}, k_{\max})$$



Bonafede et al. 2010

Observed Magnetic Fields

- $S(dx, dy) = \langle [RM(x, y) - RM(x + dx, y + dy)]^2 \rangle$
- $A(dx, dy) = \langle RM(x, y) \times RM(x + dx, y + dy) \rangle$
- $\langle |RM| \rangle_{\rm scale}$, $\langle \sigma_{\rm RM} \rangle_{\rm scale}$, $n = 2, \Lambda_{\rm max} = 102{\rm kpc}$



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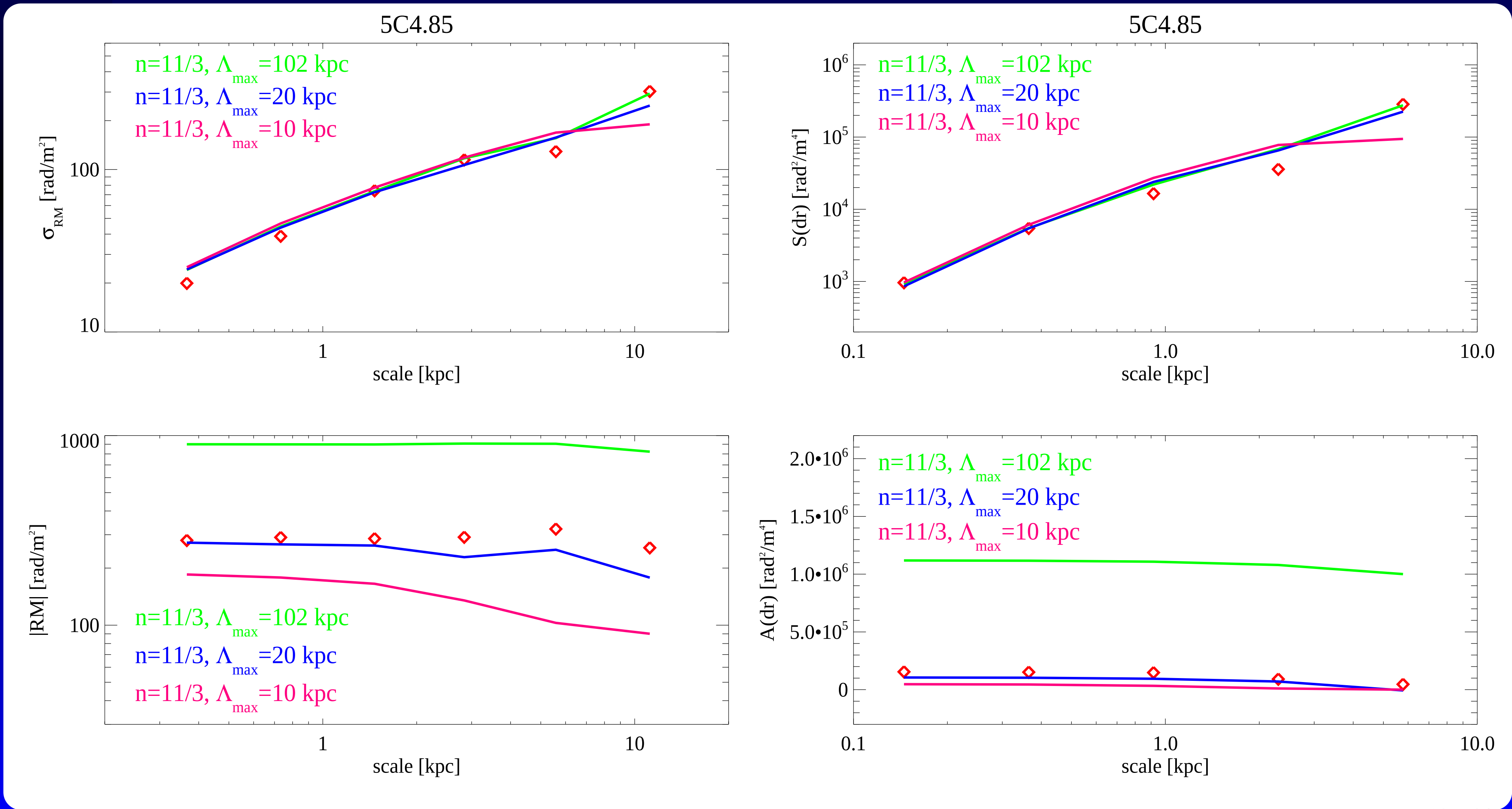
- $A(dx, dy) = \langle RM(x,y) \times RM(x+dx, y+dy) \rangle$
- $\langle |RM| \rangle_{\text{scale}}$, $\langle \sigma_{\text{RM}} \rangle_{\text{scale}}$, $n = 11/3, \Lambda_{\max} = 24\text{kpc}$



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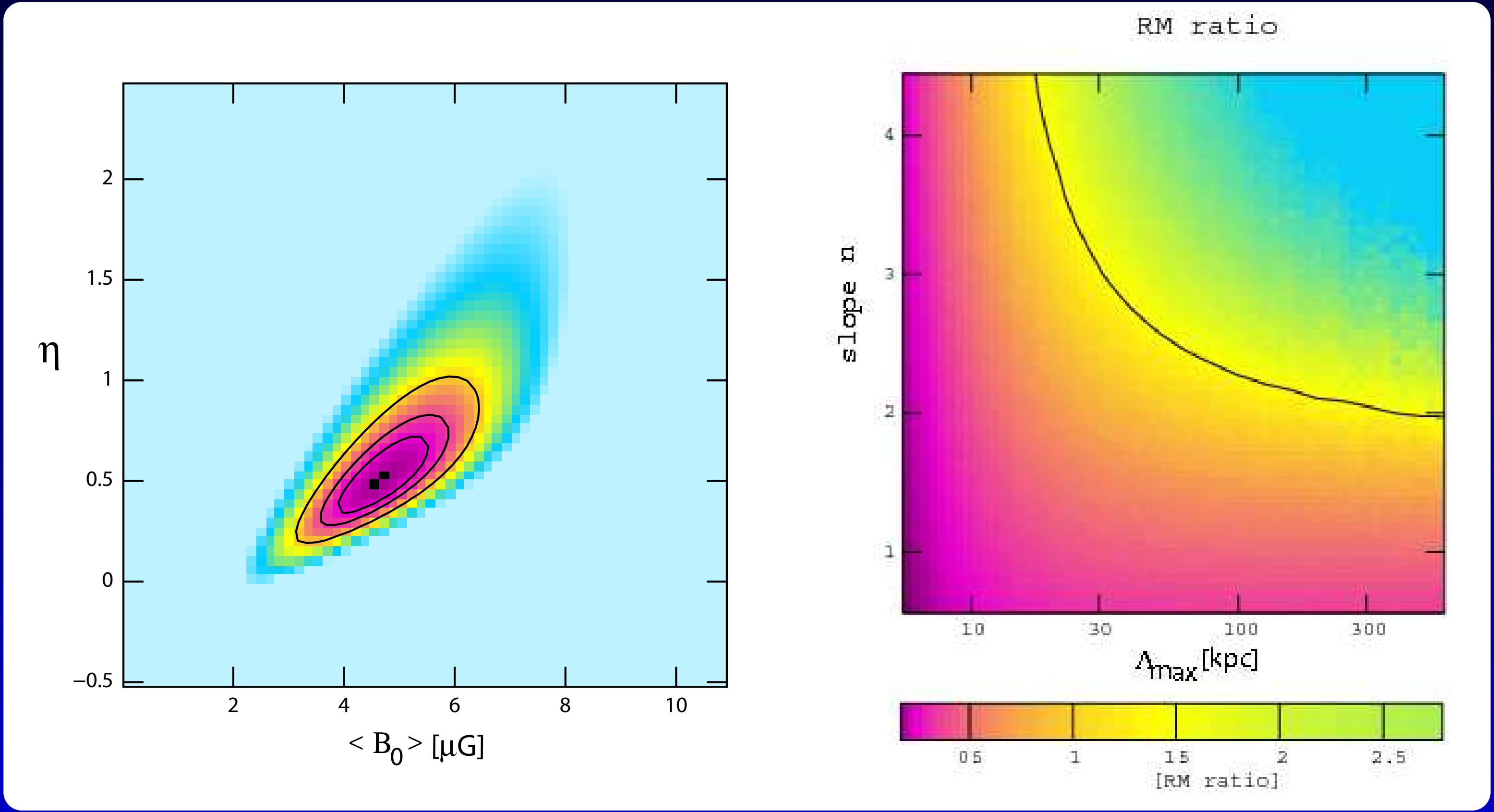


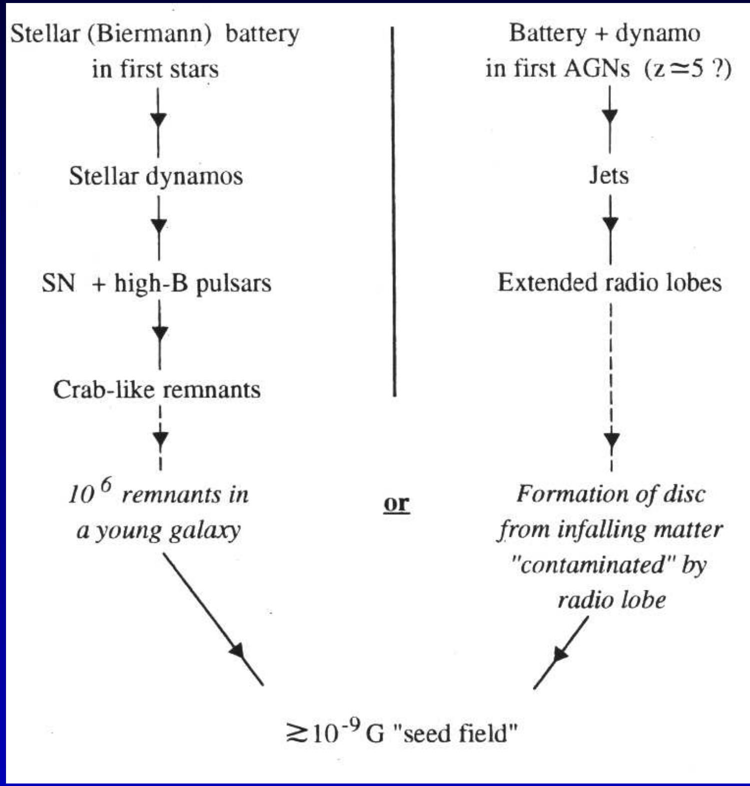
- Degeneration of injection scale $k_{\min}$ and spectral index n
- Knowing the spectrum constrains magnetic field

⇒ Cosmological MHD simulations

Origin of Magnetic Fields

Origin

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

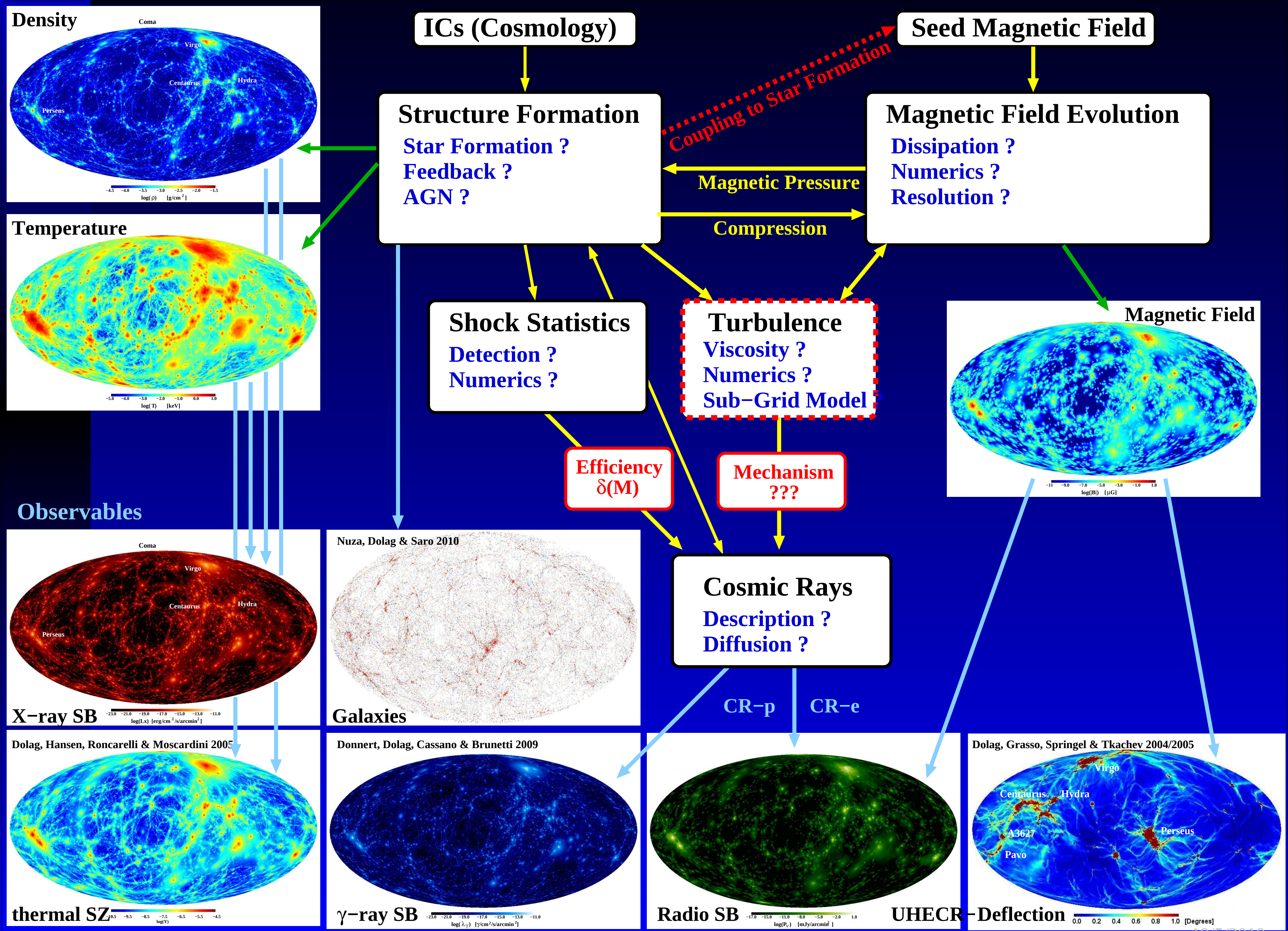


Rees 1994

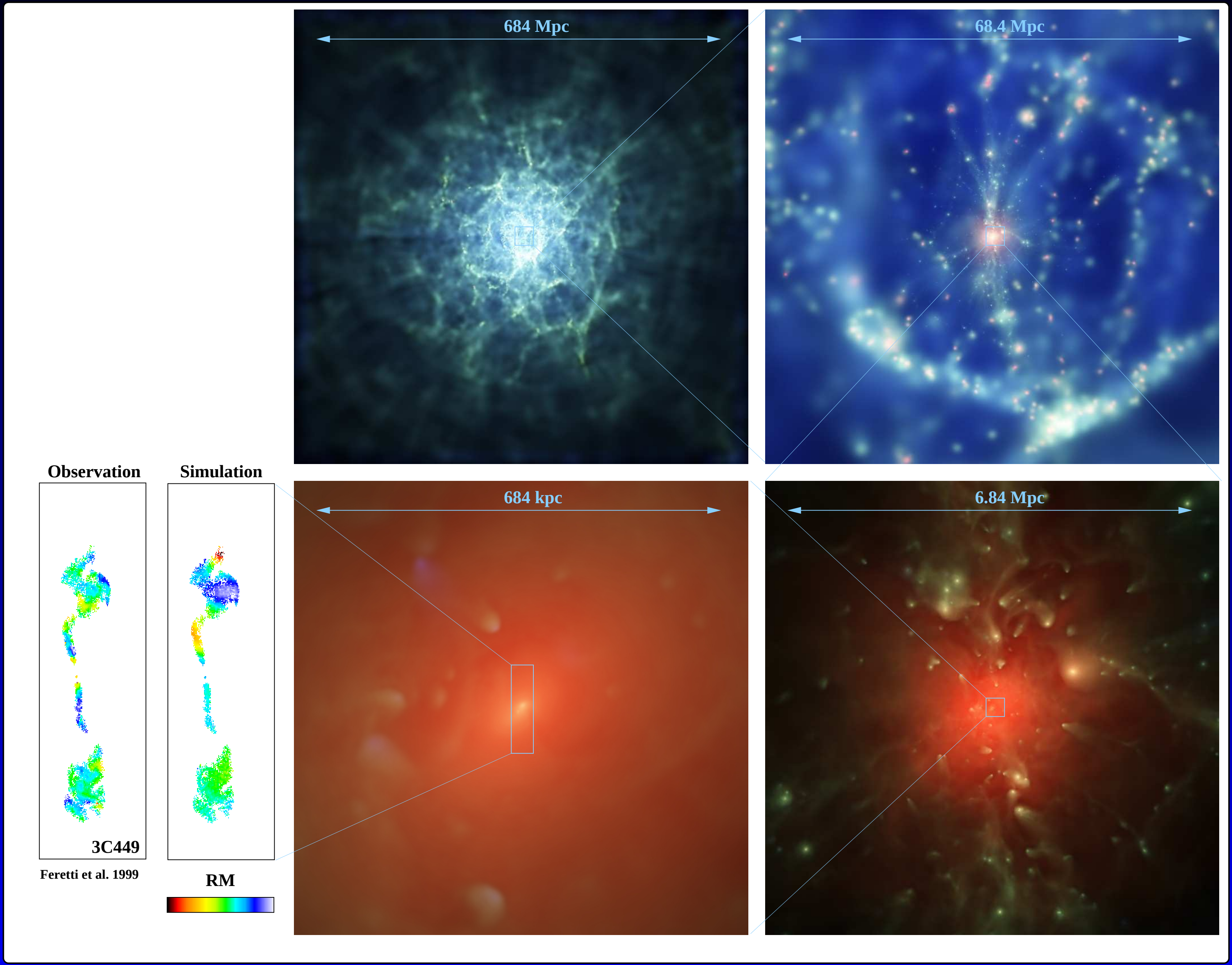
\+ further amplification by **structure formation**

\- dissipation ?

Simulation Network



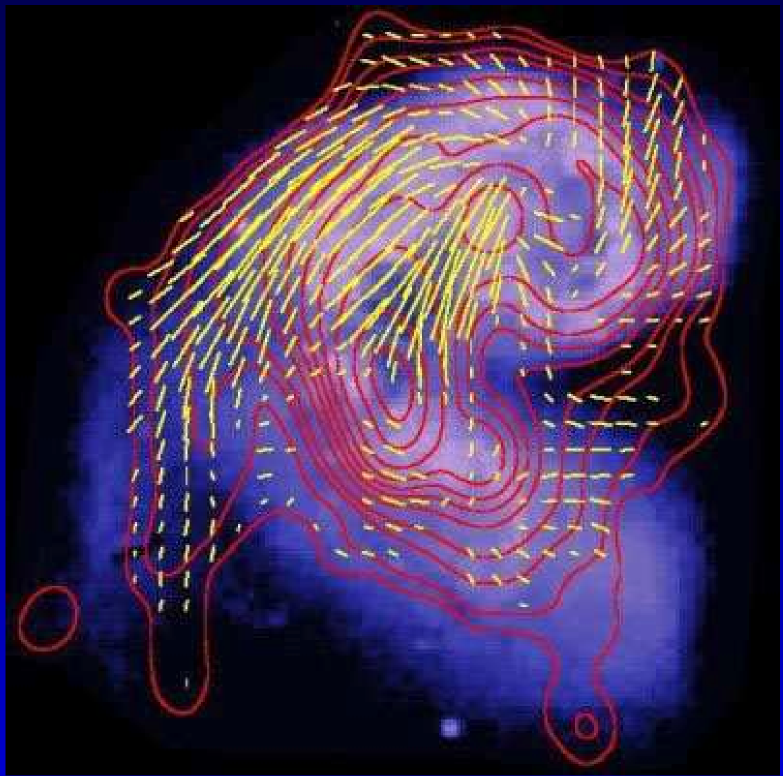
Cosmological MHD simulations

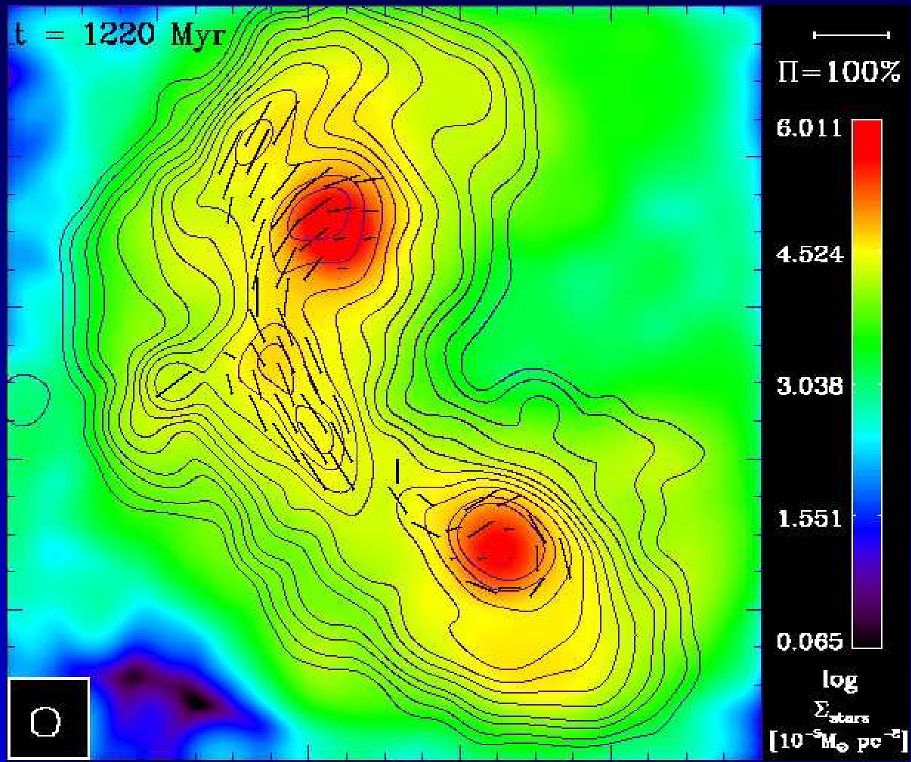


"Zoomed" cluster simulation (Dolag & Stasyszyn 2009). Movie: u,v

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

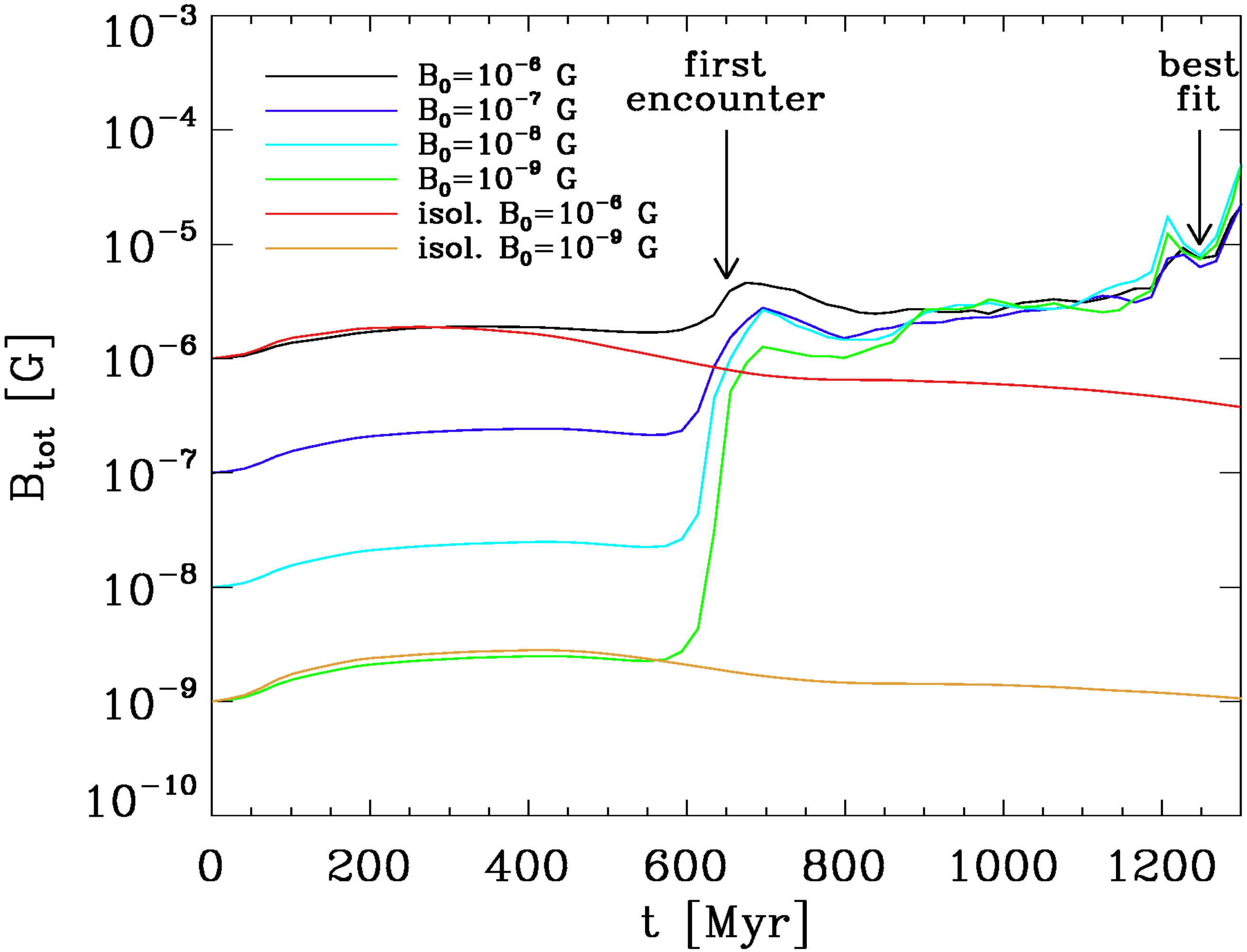
Simulating the magnetic field amplification during galaxy mergers like in the Antennae system. Final magnetic field strength and field configuration in broad agreement with observations.

(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

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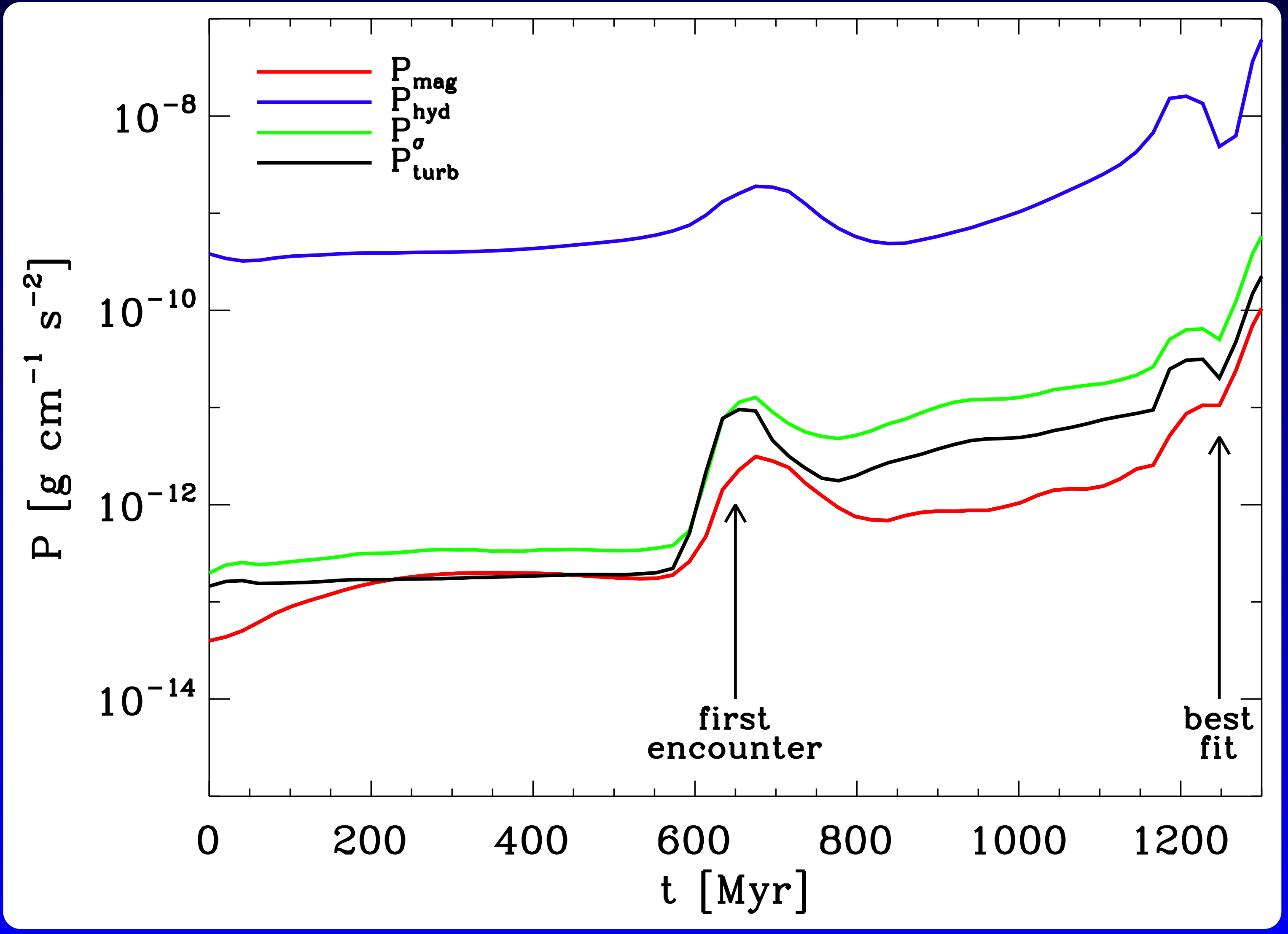
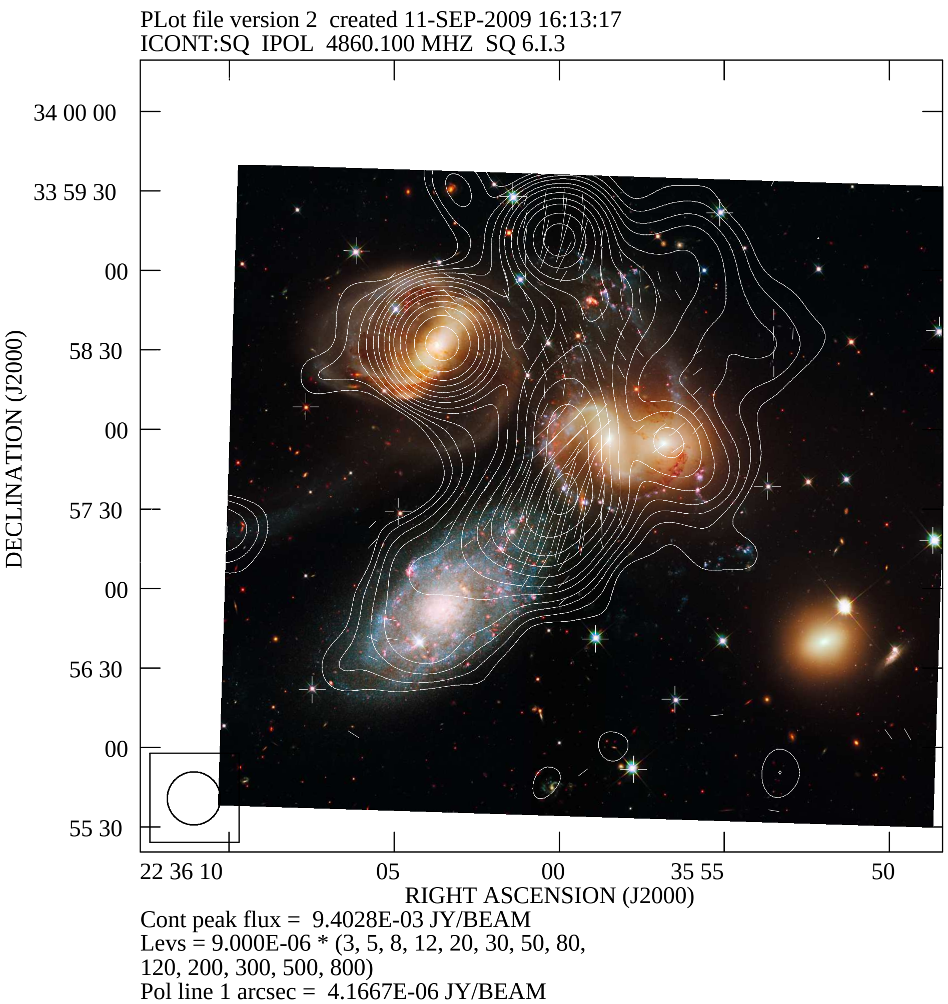
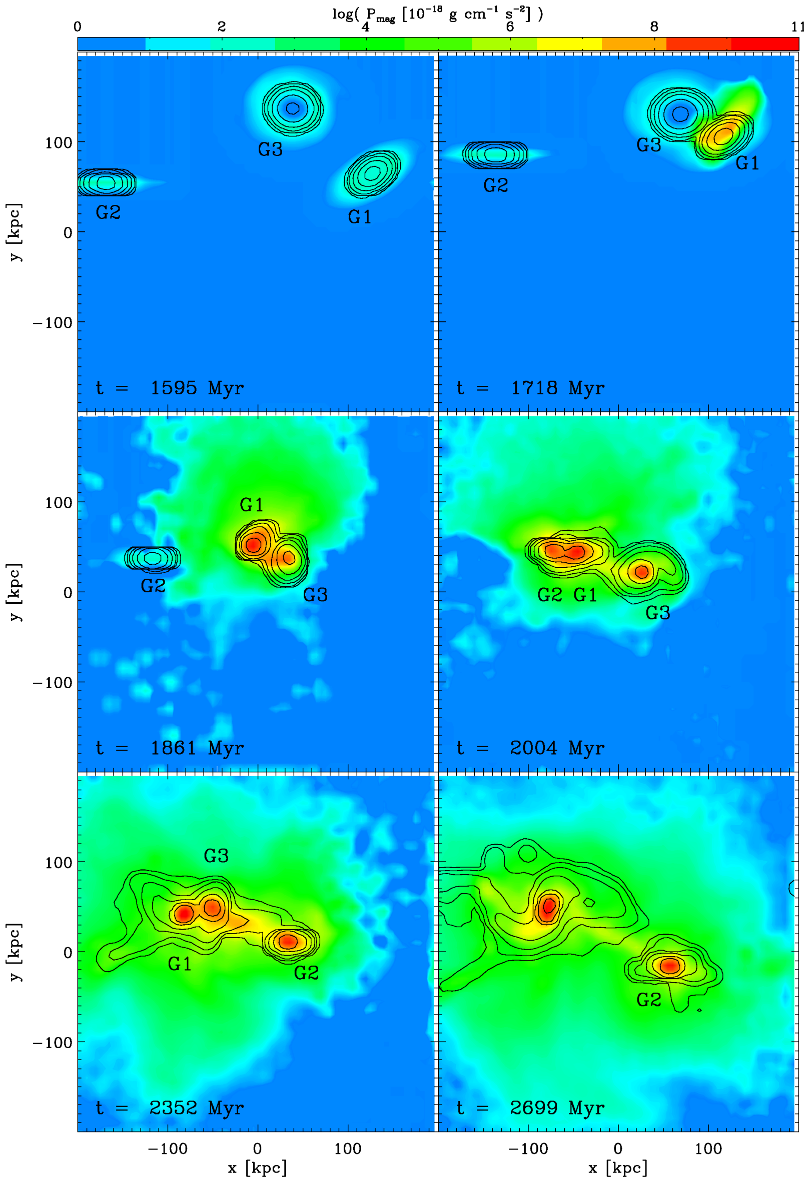


(Kortarba et al. 2010)

Magnetic field buildup



Soida et al., in prep.



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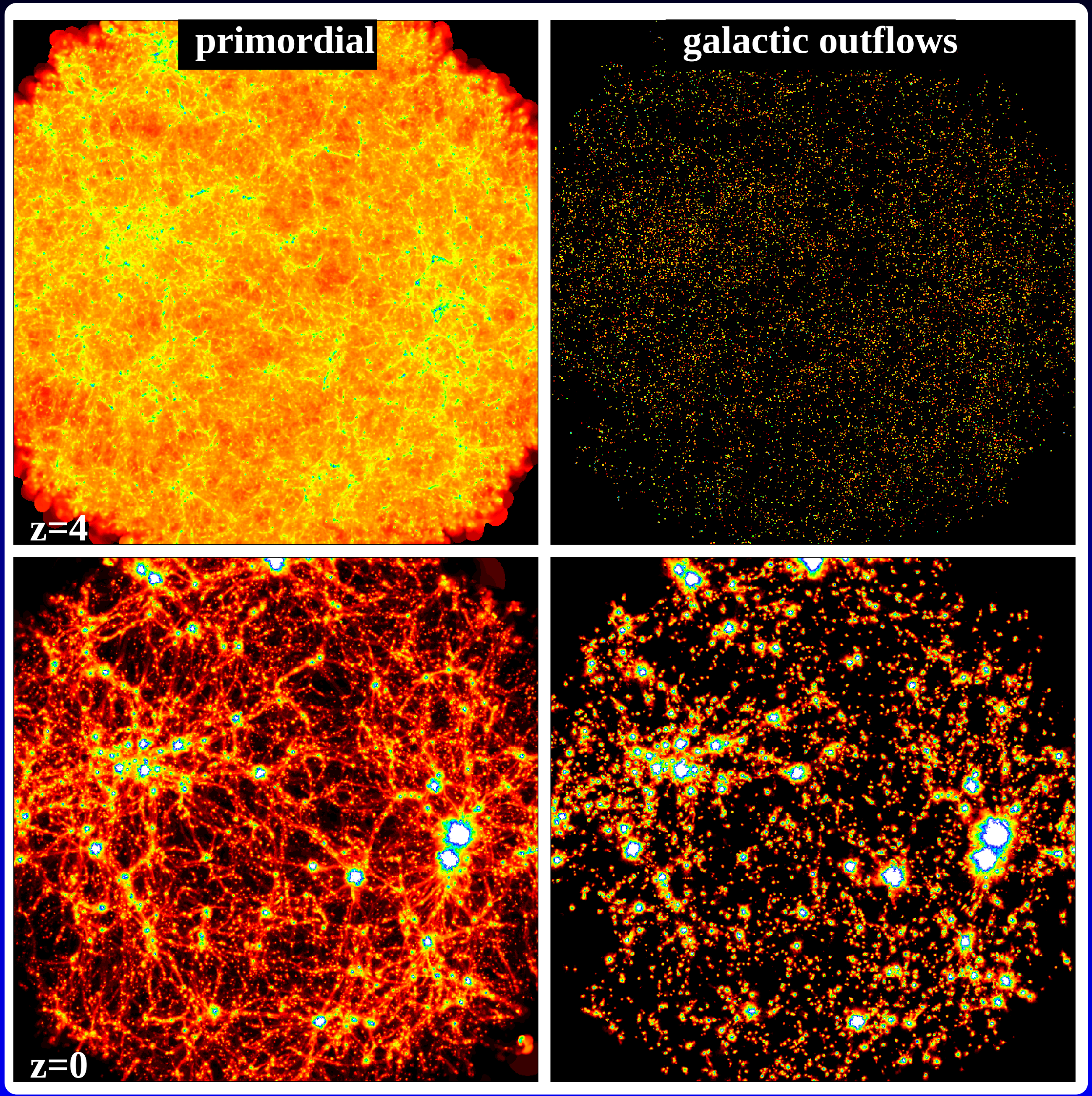
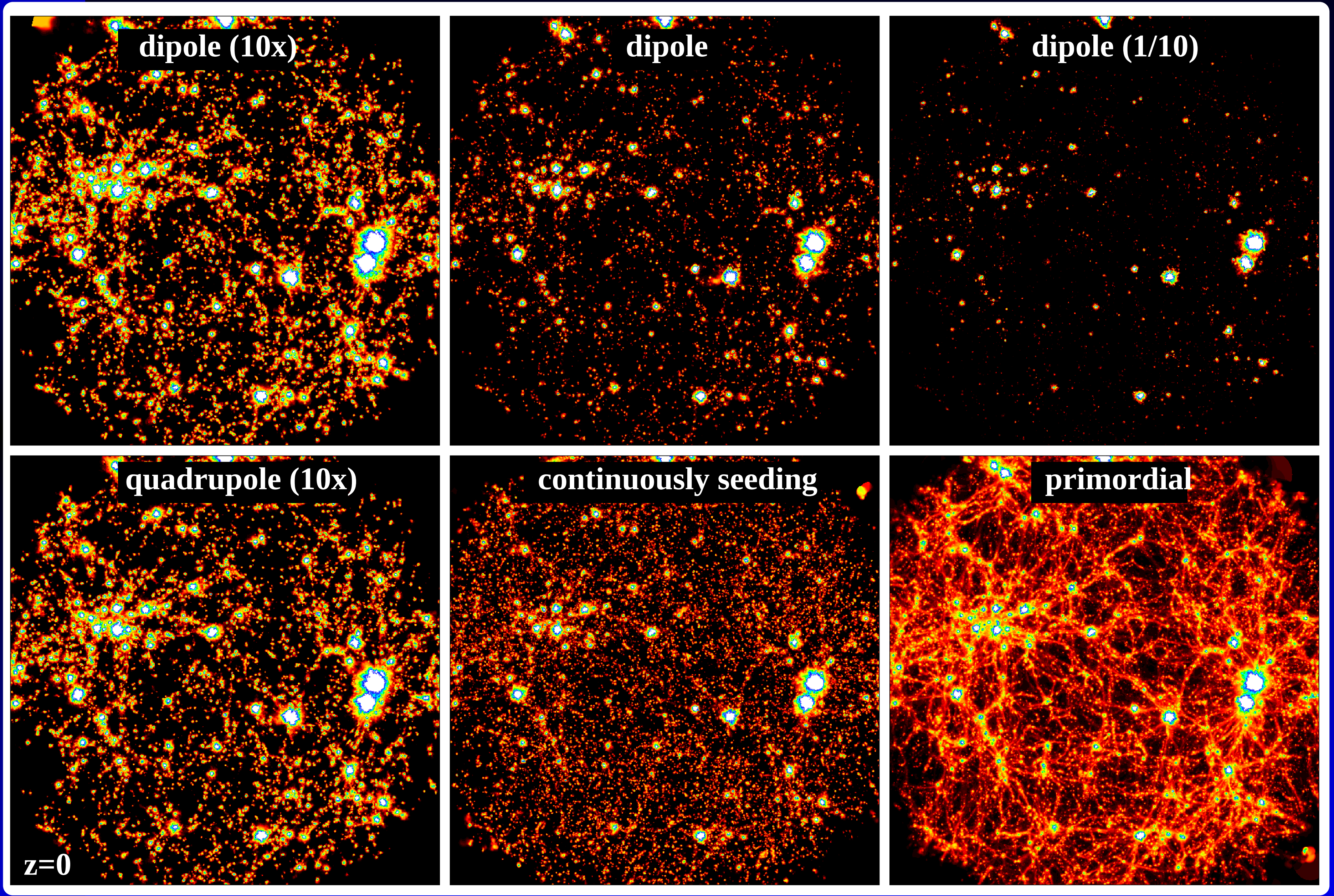
Magnetic field buildup



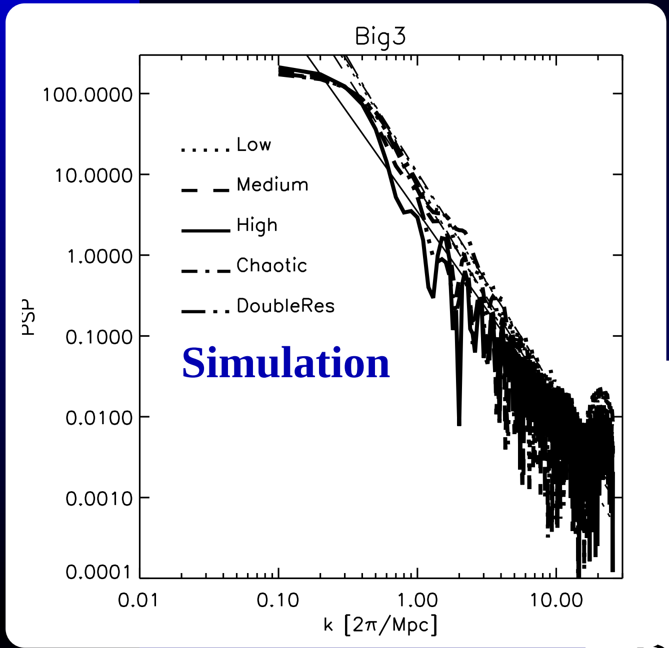
Seeding from galactic outflows (Donnert et al. 2009)

Magnetic field buildup



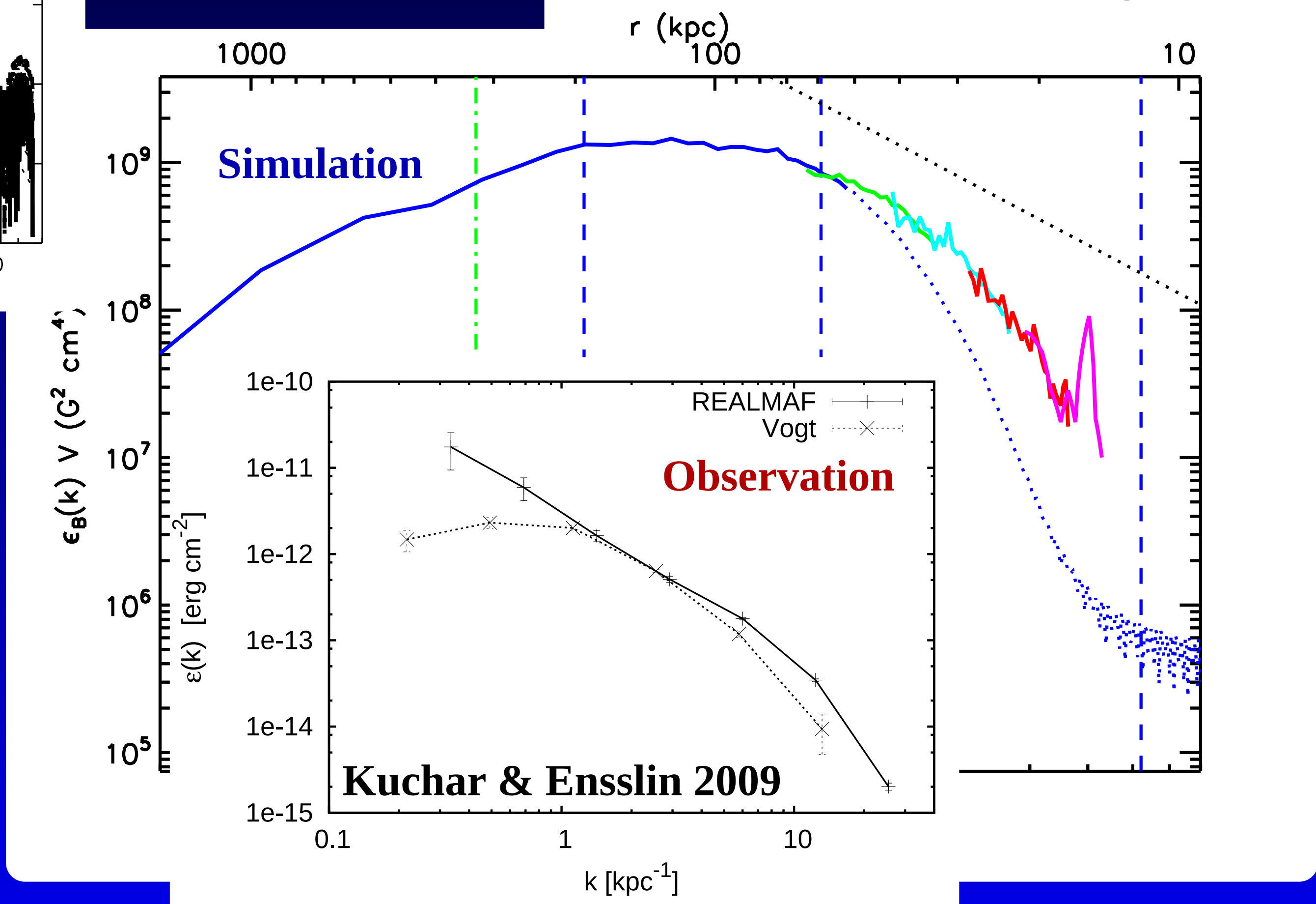
Different wind parameters (Donnert et al. 2009)

Magnetic field buildup



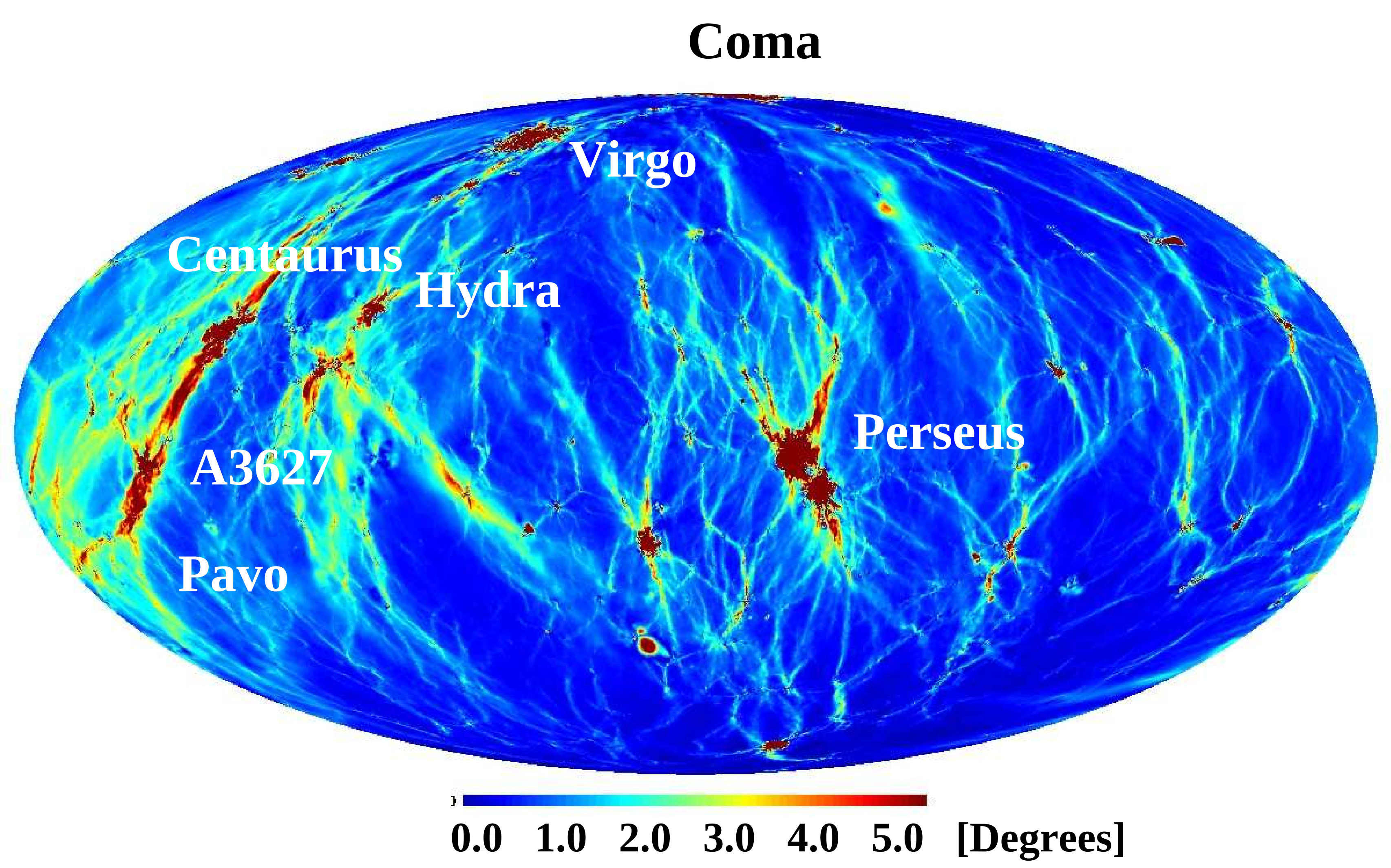
Dolag et al. 2002

Pakmor & Dolag 2006



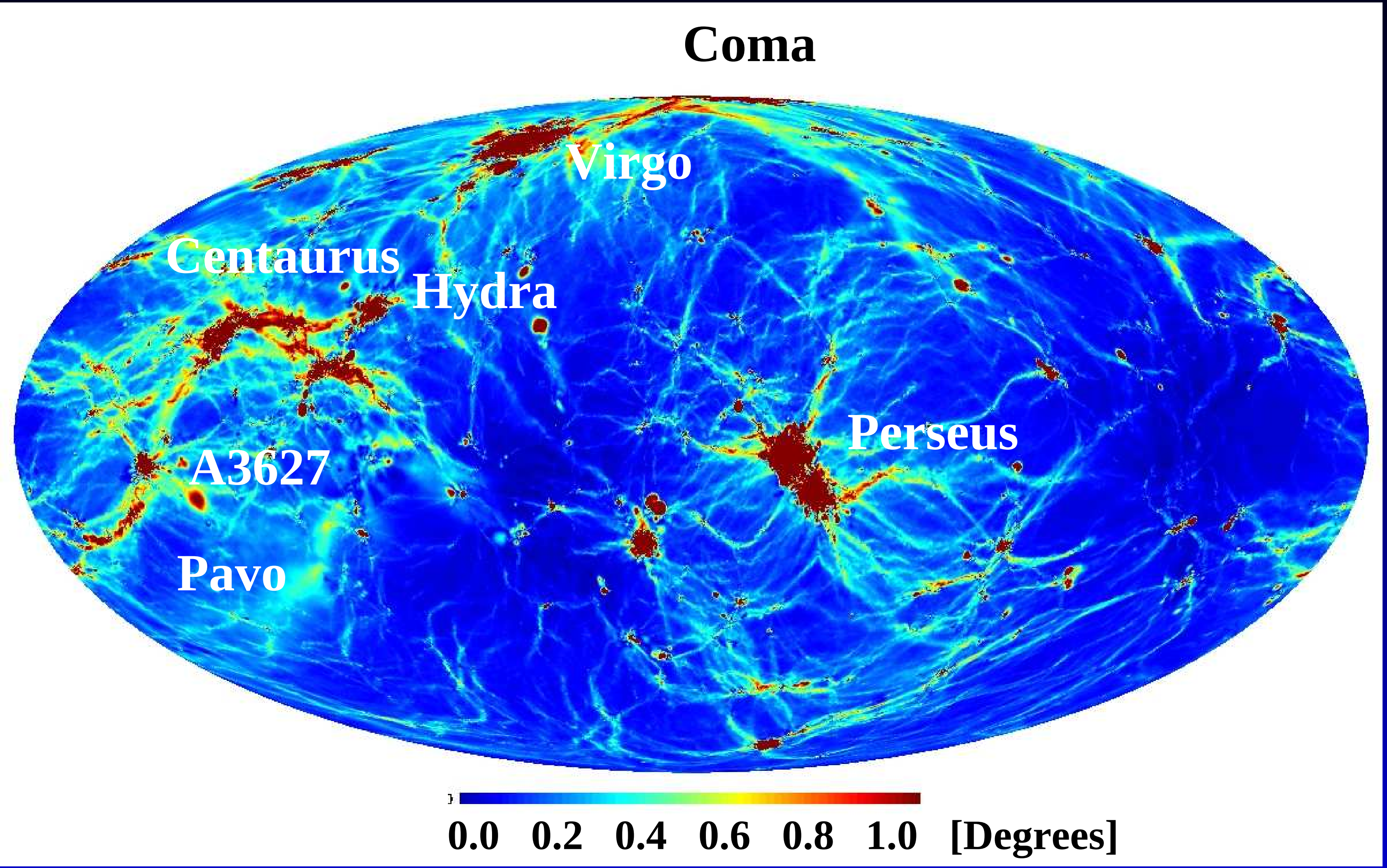
Magnetic field power spectra: predictions vs. observations.

Propagation of UHECRs



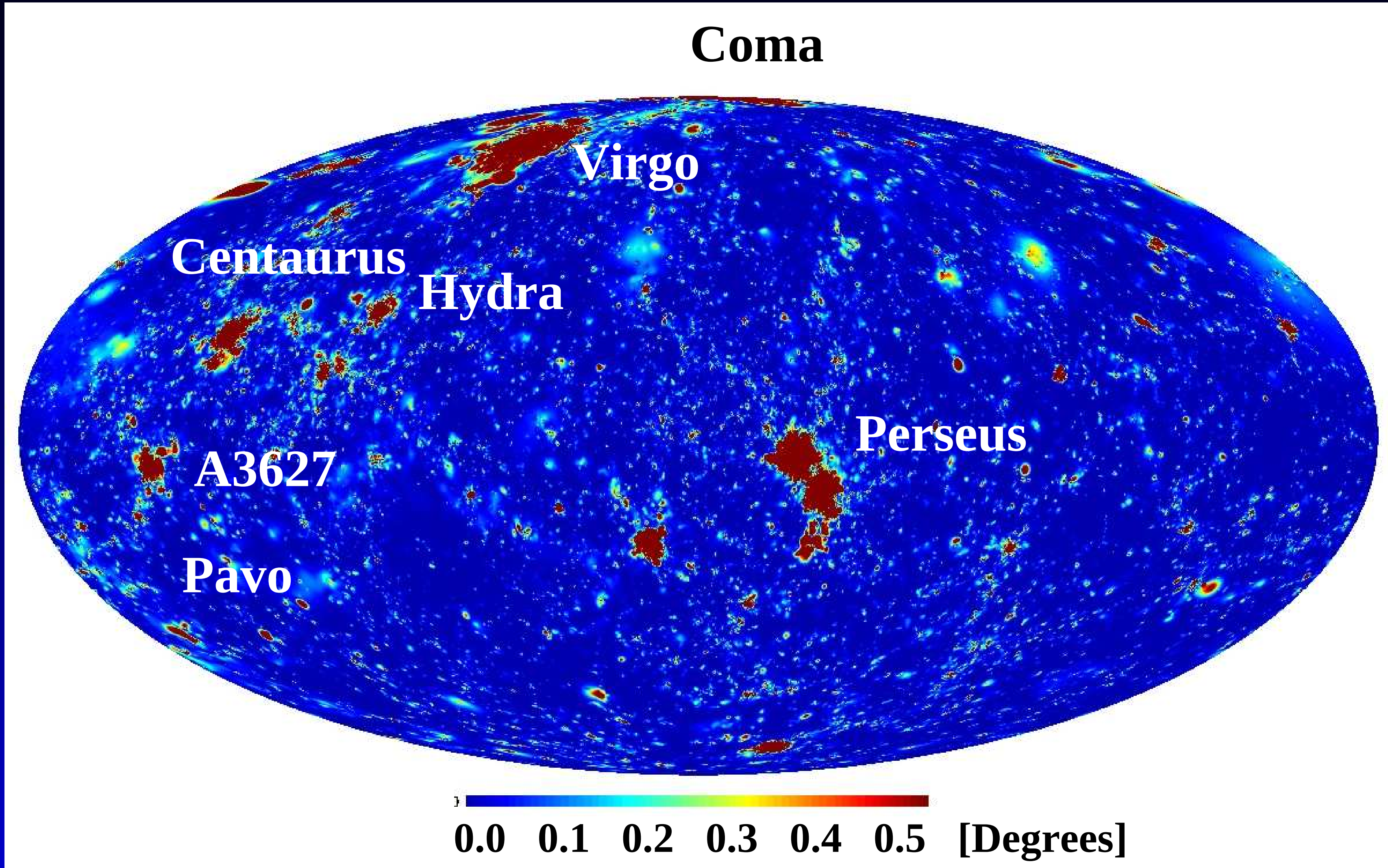
Full sky deflection signal for 4×10^{19}eV Cosmic Rays without losses, using a sphere of 110 Mpc radius and $B_0 = 10^{-5}\mu$G (Dolag, Grasso, Springel & Tkachev 2004)

Propagation of UHECRs



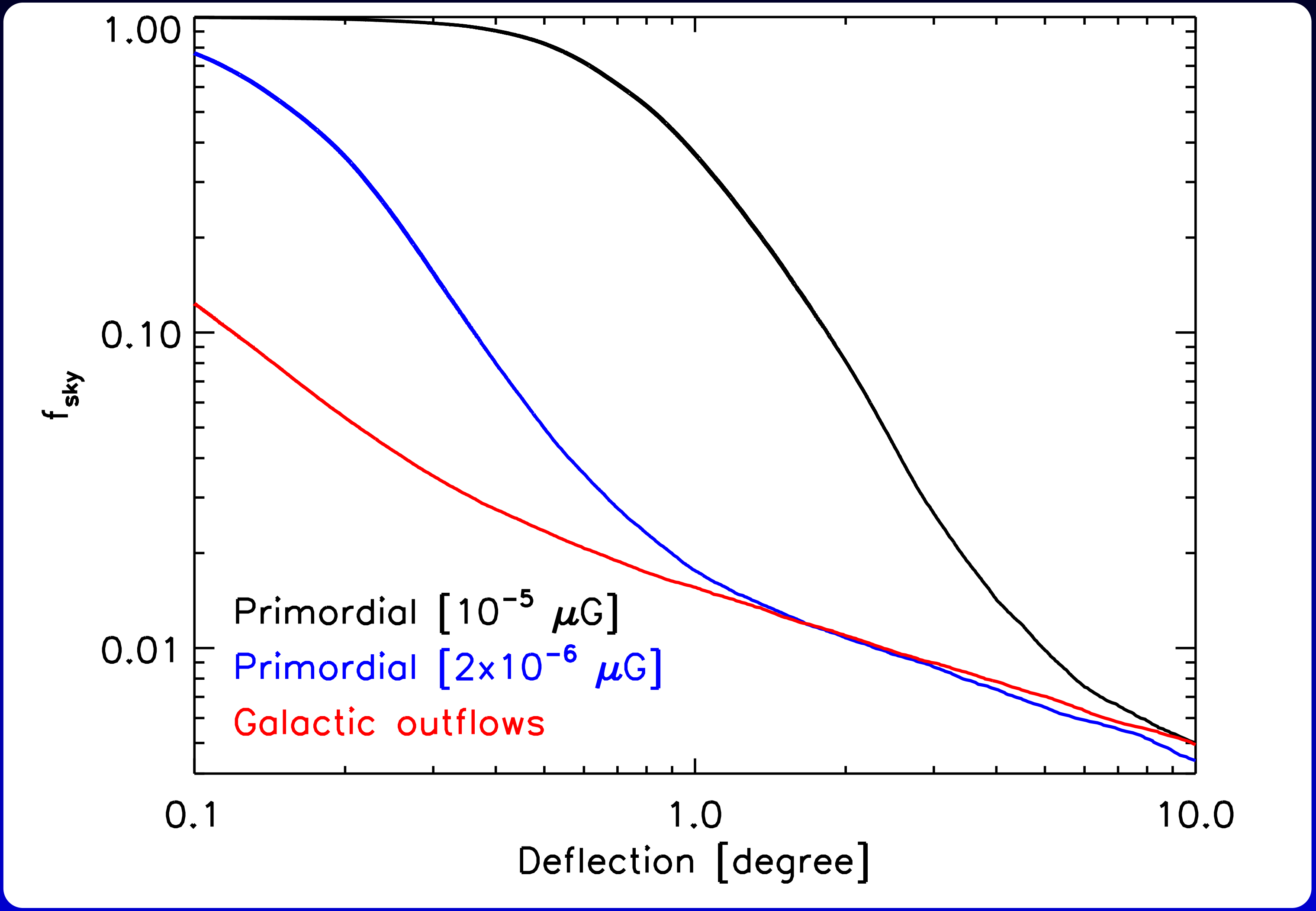
Full sky deflection signal for 4×10^{19}eV Cosmic Rays without losses, using a sphere of 110 Mpc radius $B_0 = 0.2 \times 10^{-5} \mu$G (Dolag, Grasso, Springel & Tkachev 2005)

Propagation of UHECRs



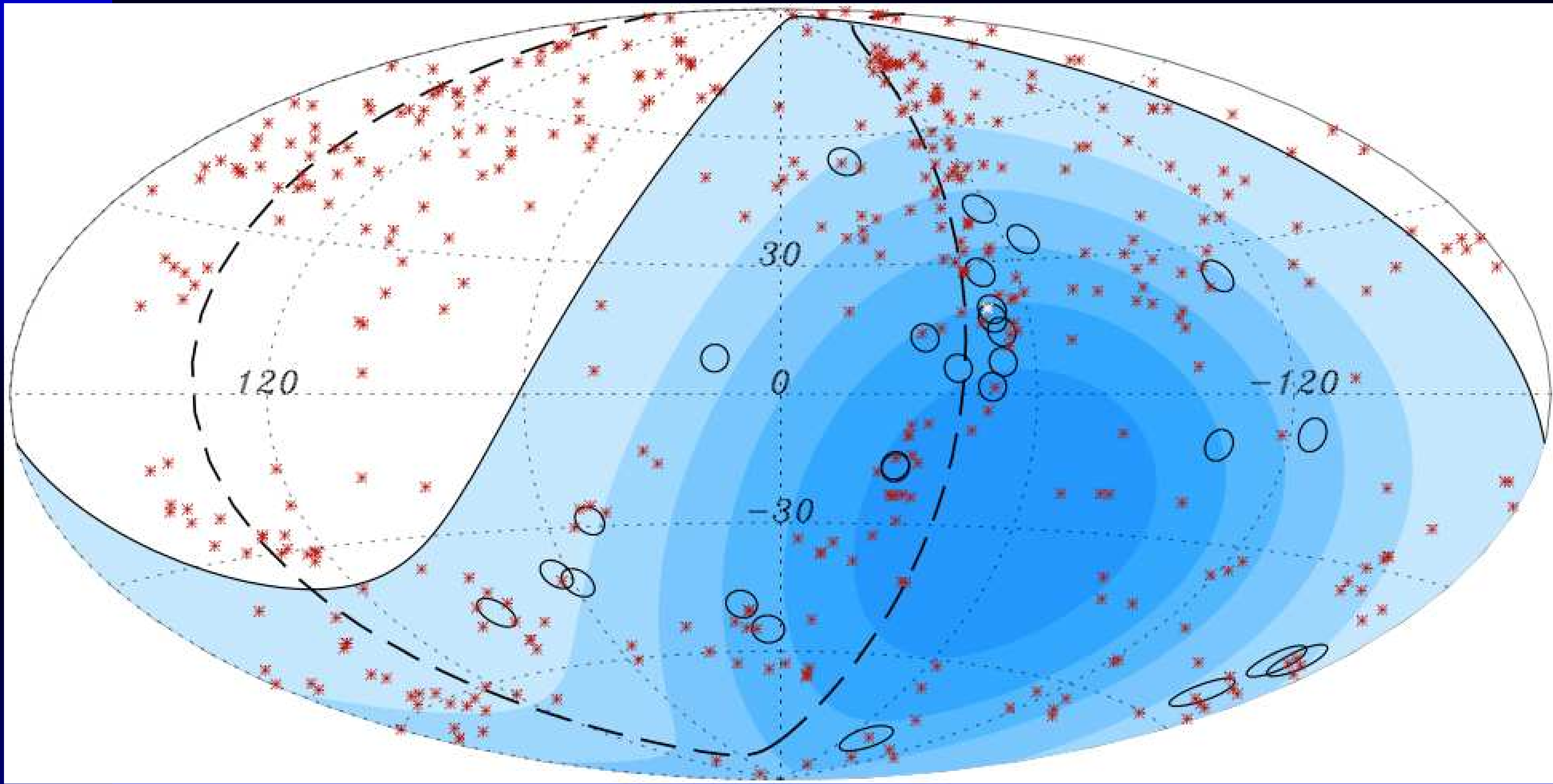
Full sky deflection signal for 4×10^{19}eV Cosmic Rays without losses, using a sphere of 110 Mpc radius from galactic outflows (Just for you !)

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 !)

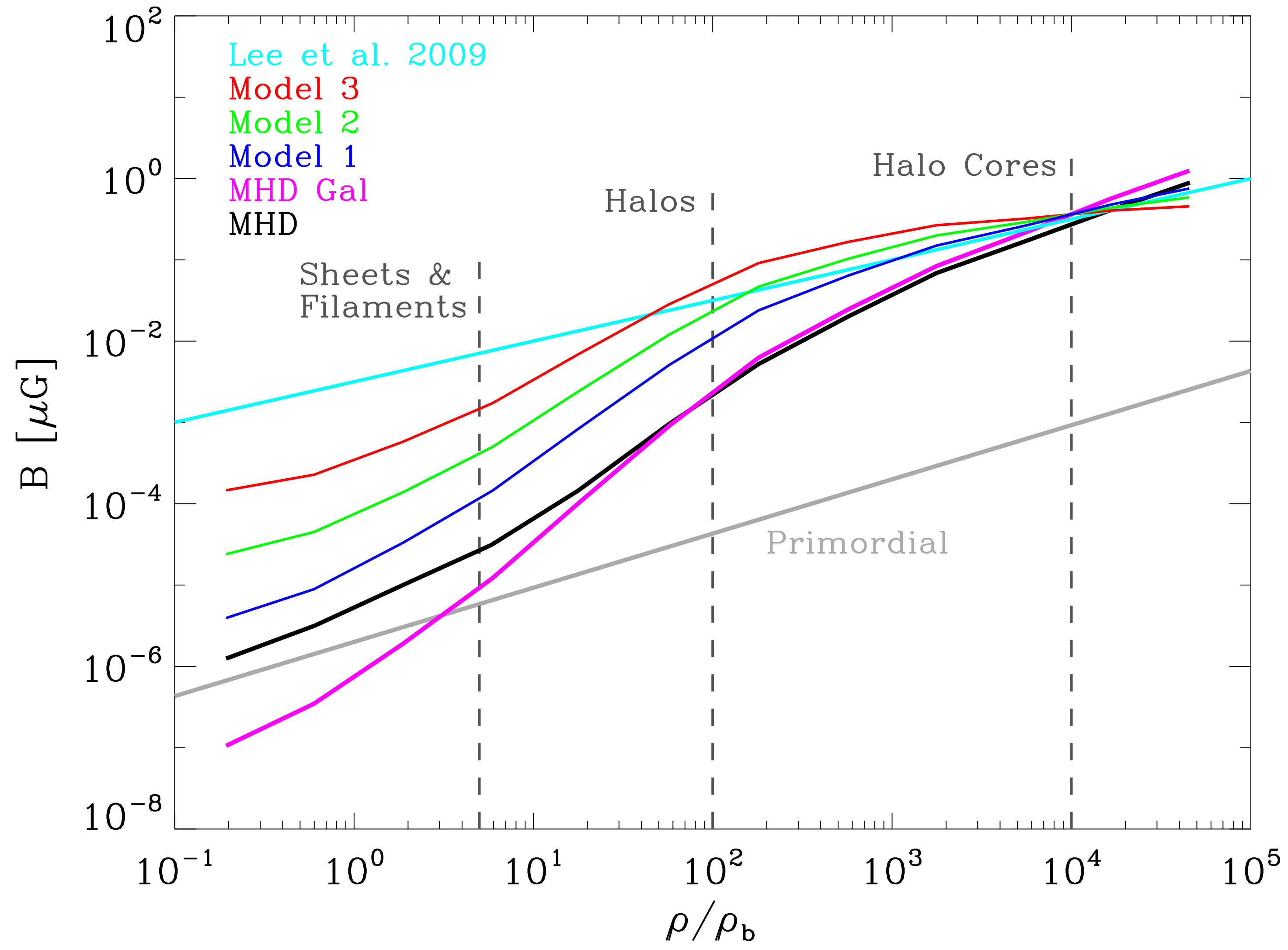
Propagation of UHECRs



Pierre Auger Observatory provides evidence for anisotropy in the arrival directions of the Cosmic Rays with the highest energies, which are correlated with the positions of relatively nearby active galactic nuclei (AGNs).

(Pierre Auger Collaboration 2008)

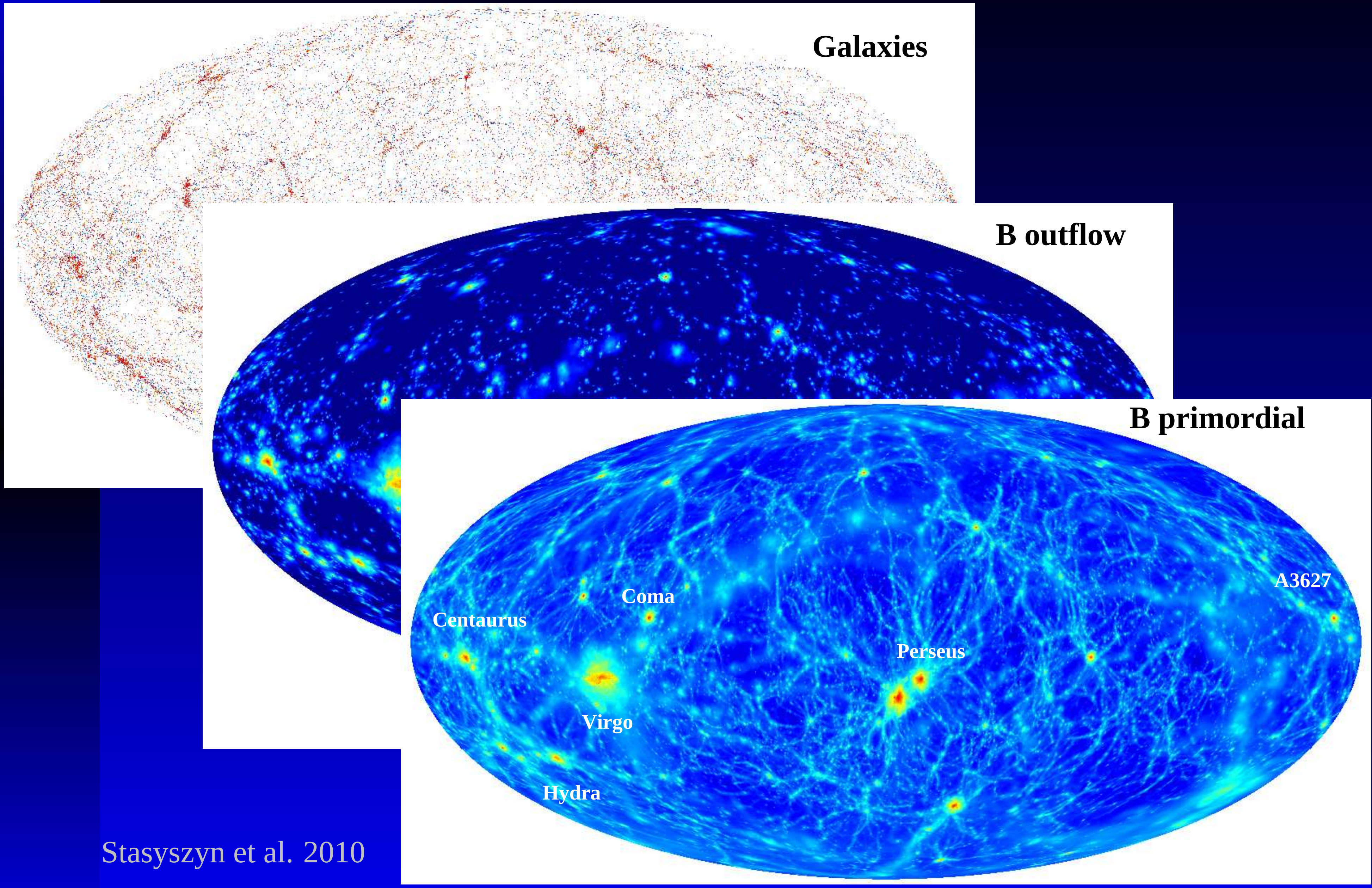
RMs in large scale structures



Stasyszyn et al. 2010

Mean magnetic field as a function of density for various models.

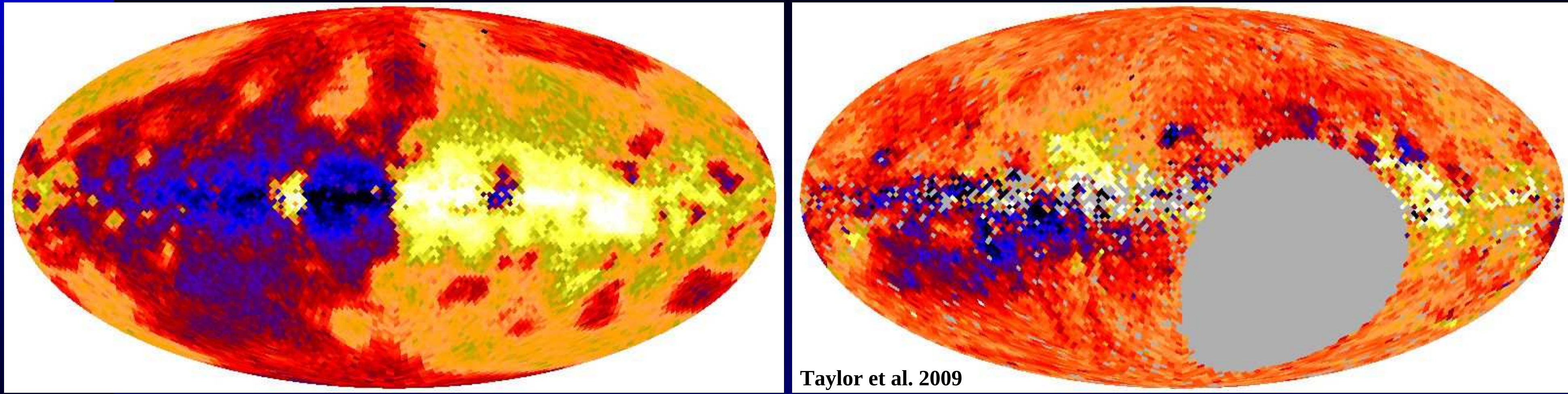
RMs in large scale structures



Stasyszyn et al. 2010

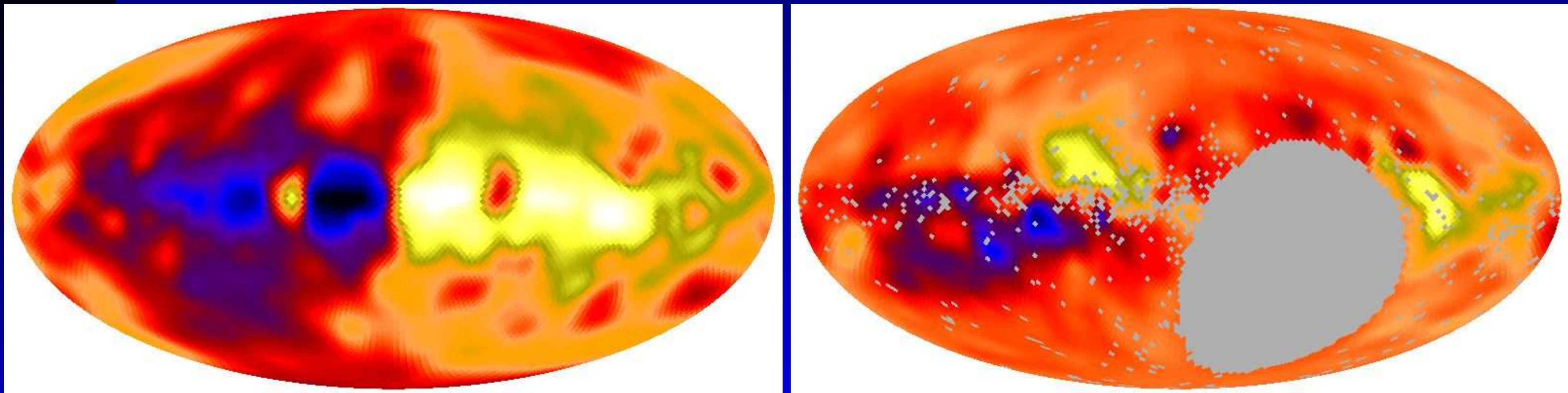
Full sky maps for the local universe showing the magnetic field and galaxy distribution.

RMs in large scale structures



Taylor et al. 2009

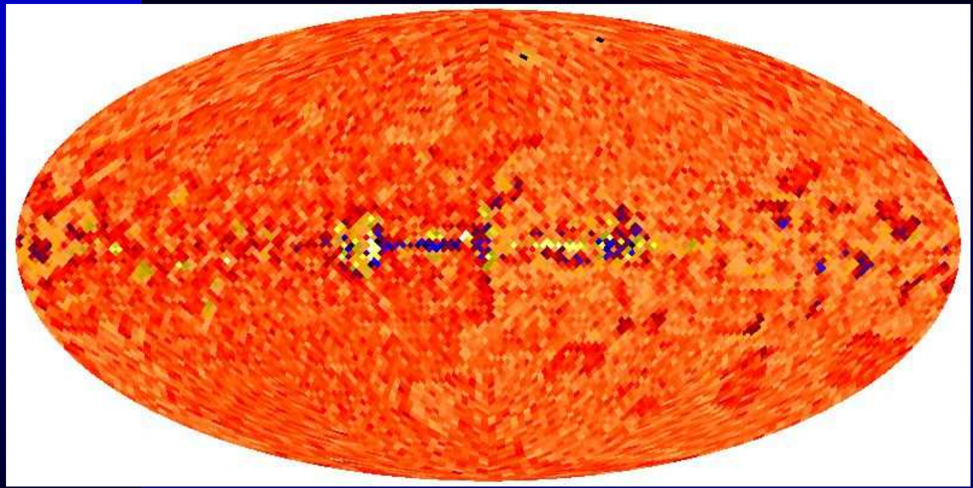
Model foreground based on HAMMURABI (Waelkens et al. 2009), cosmic signal and observational noise compared to observations.

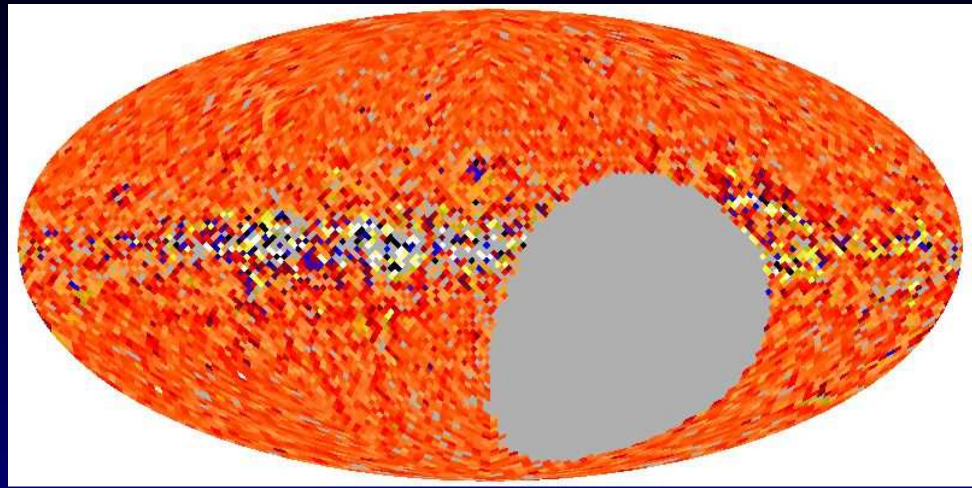


Same but smoothed by 8 degrees.

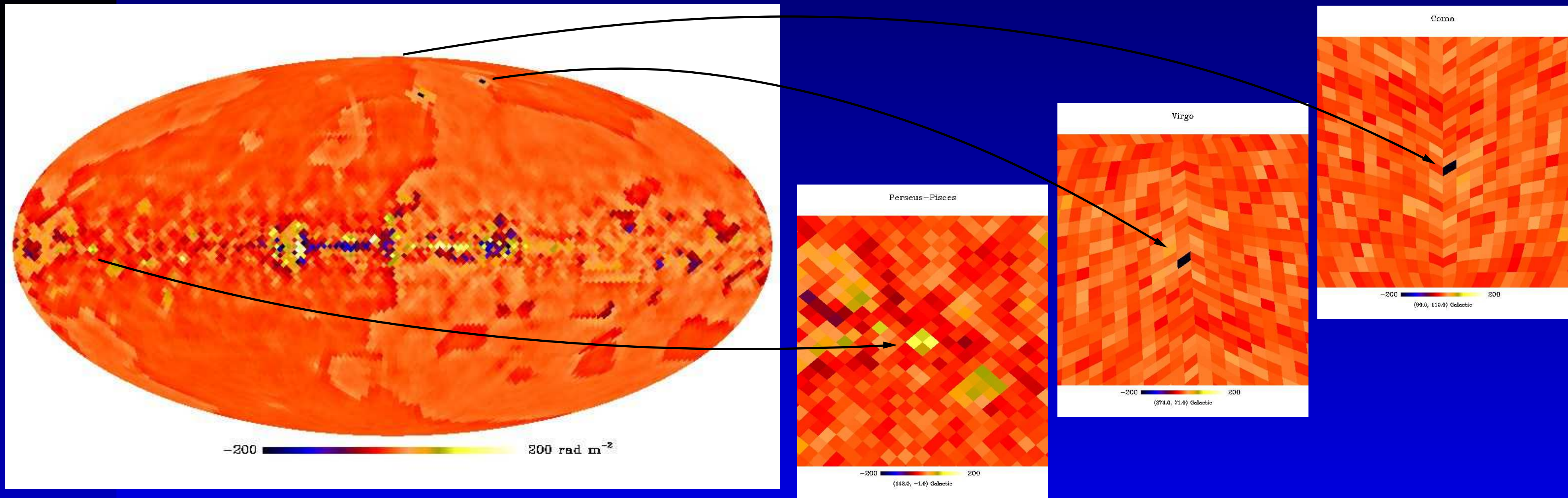
Stasyszyn et al. 2010

RMs in large scale structures





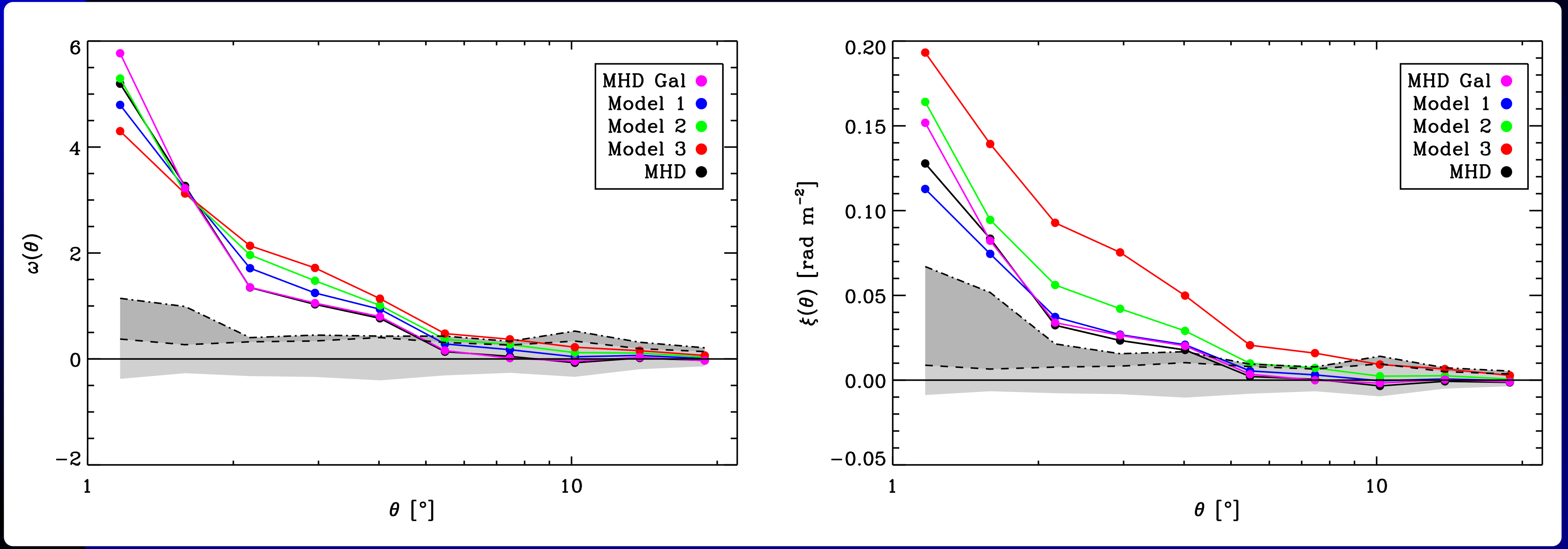
Same as before, but with foreground removal.



Reduced noise (1 rad$/m^2$) and zoom on several clusters.

Stasyszyn et al. 2010

RMs in large scale structures



Correlation functions (based on 3072 RMs):

$$\omega_{\rm RM}(\theta) \equiv \frac{\langle \Delta n(\theta)|{\rm RM}|\rangle}{\bar{n}\overline{|{\rm RM}|}},$$

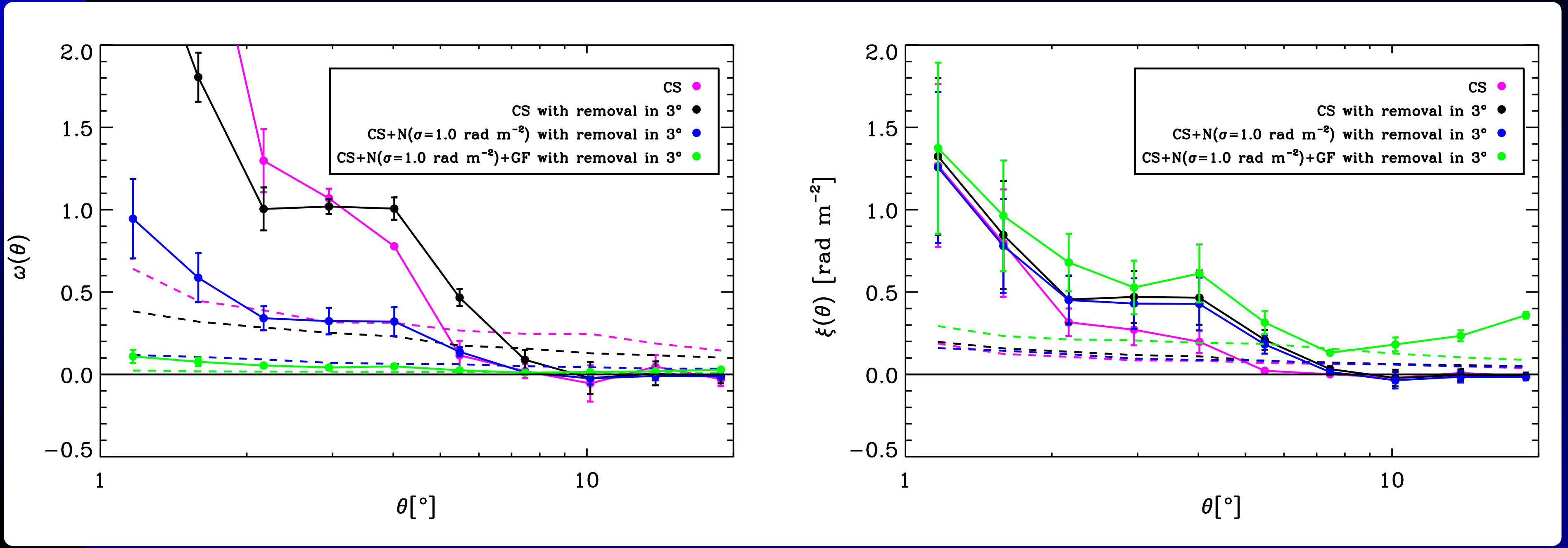
(normalized)

$$\xi_{\rm RM}(\theta) \equiv \frac{\langle \Delta n(\theta)|{\rm RM}|\rangle}{\bar{n}}.$$

(unnormalized).

Stasyszyn et al. 2010

RMs in large scale structures

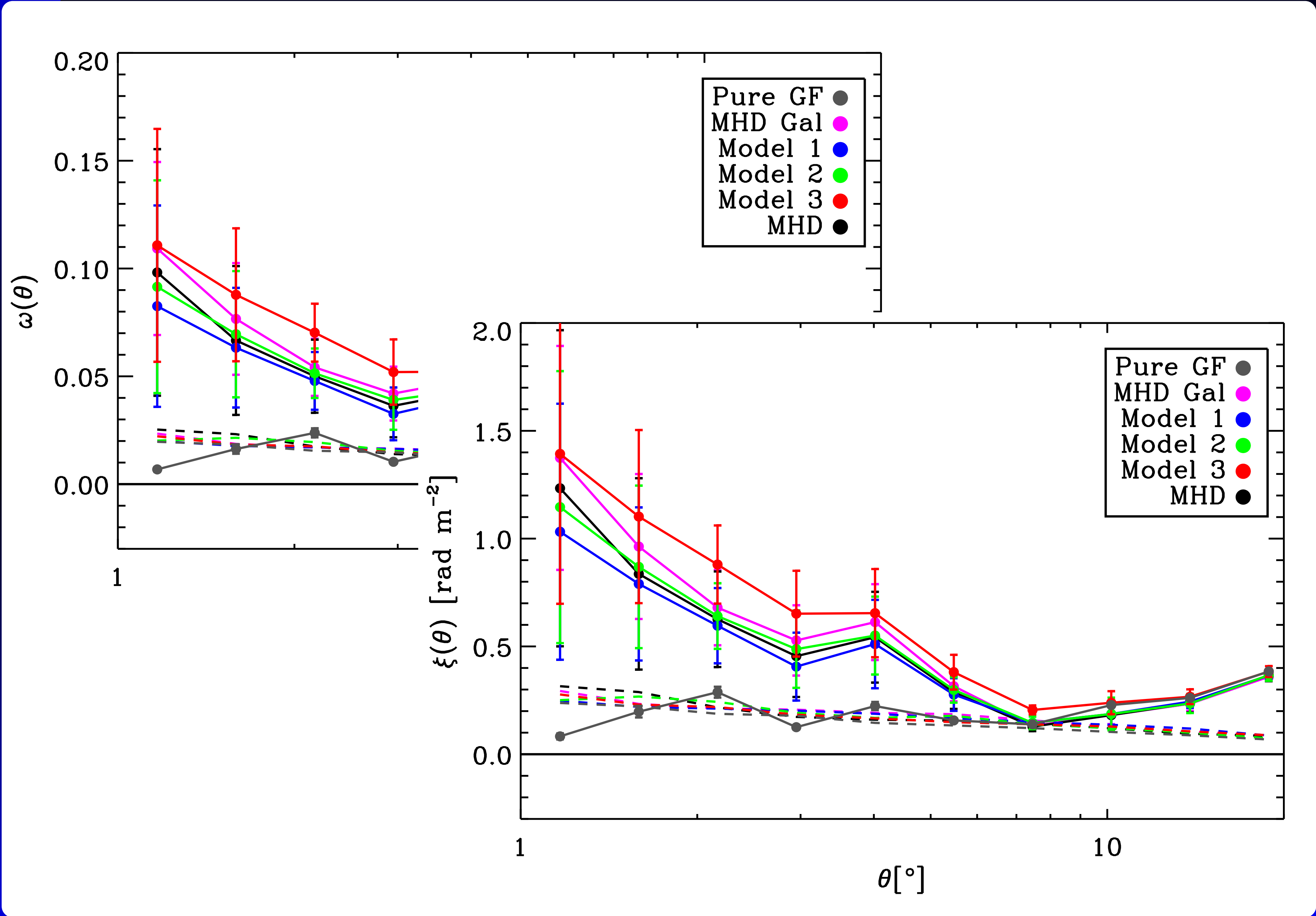


Influence of the different components onto the correlation signal:

- Cosmological signal (CS)
- Including galactic foreground and applying removal
- Adding only noise (1 rad/m^2) to the signal (CS+N)
- All effects together

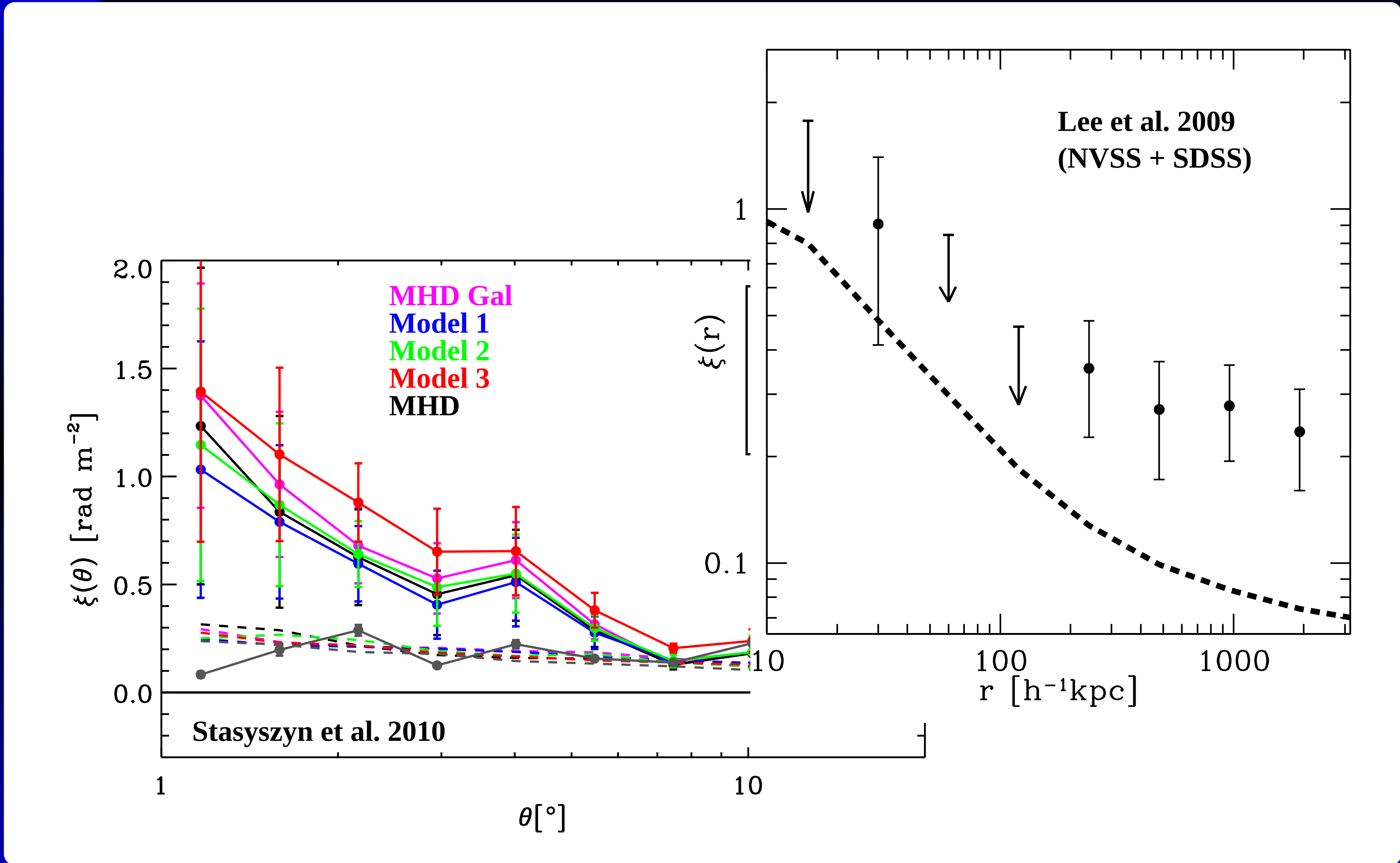
Stasyszyn et al. 2010

RMs in large scale structures



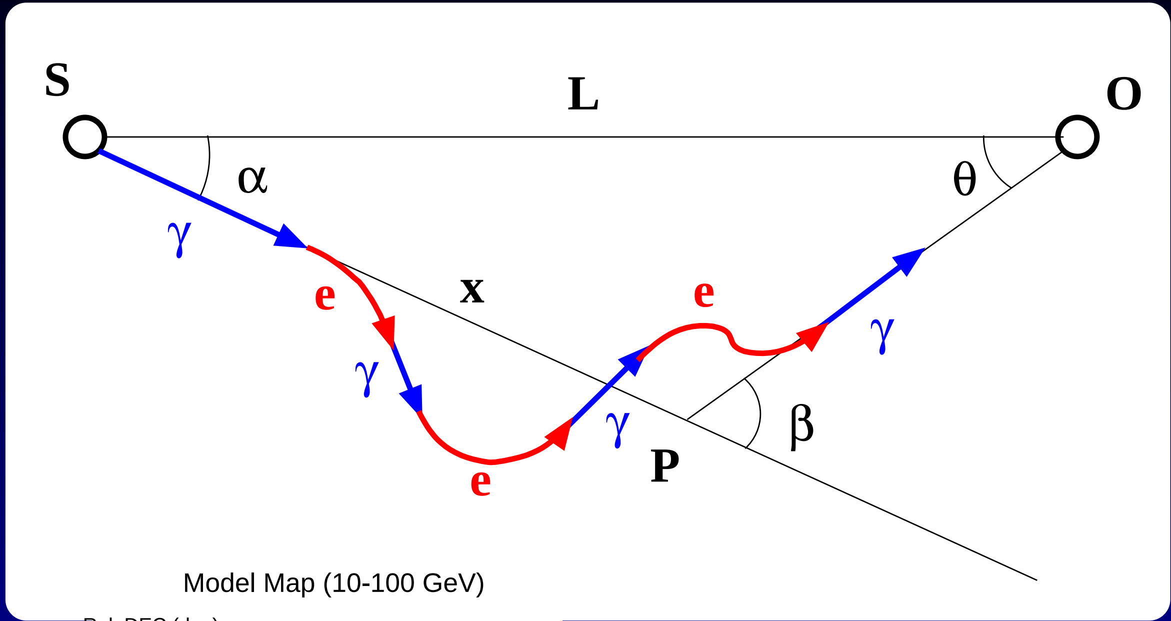
Correlation signal from different model (Stasyszyn et al. 2010).

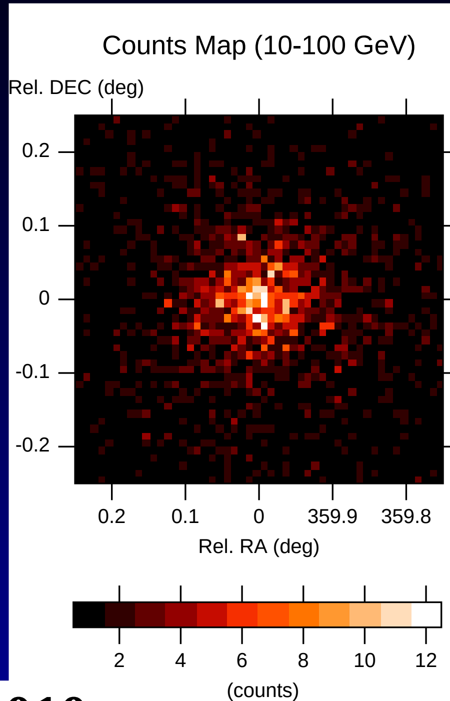
RMs in large scale structures

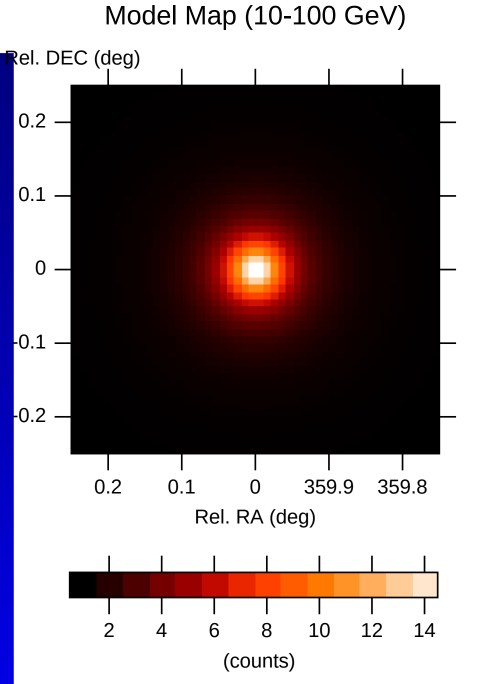


Correlation signal predicted by simulations, but the amplitude is driven by the foreground and observational noise !

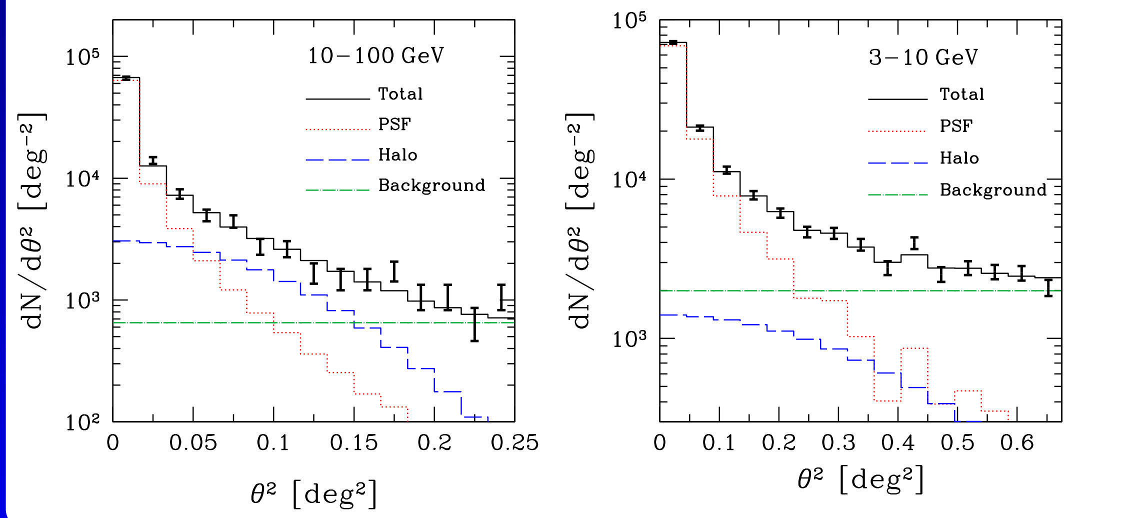
Measuring low magnetic fields





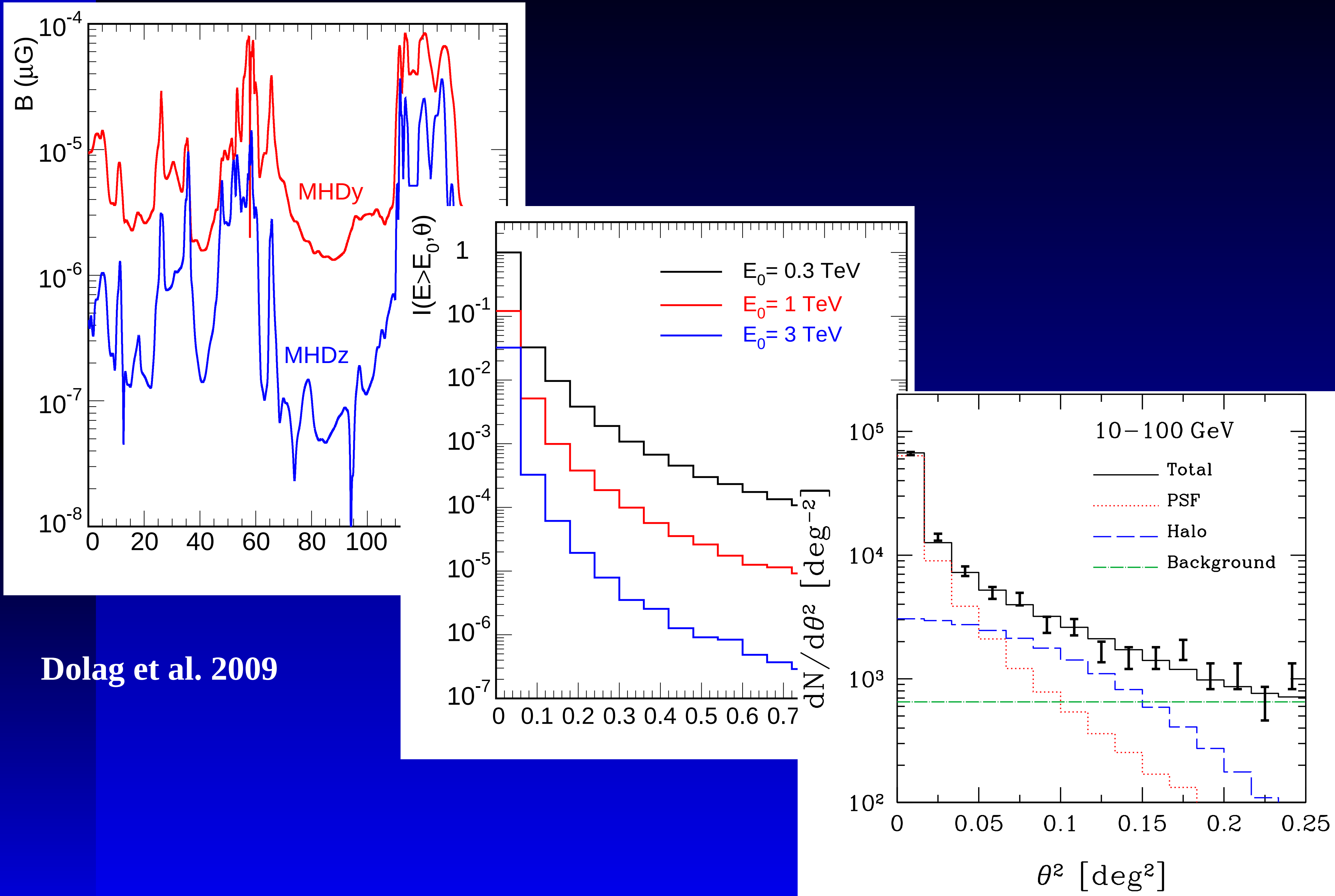


Shinichiro & Kusenko 2010



Halo found stacking 170 AGNs with FERMI: $B \approx 10^{-15}$G.

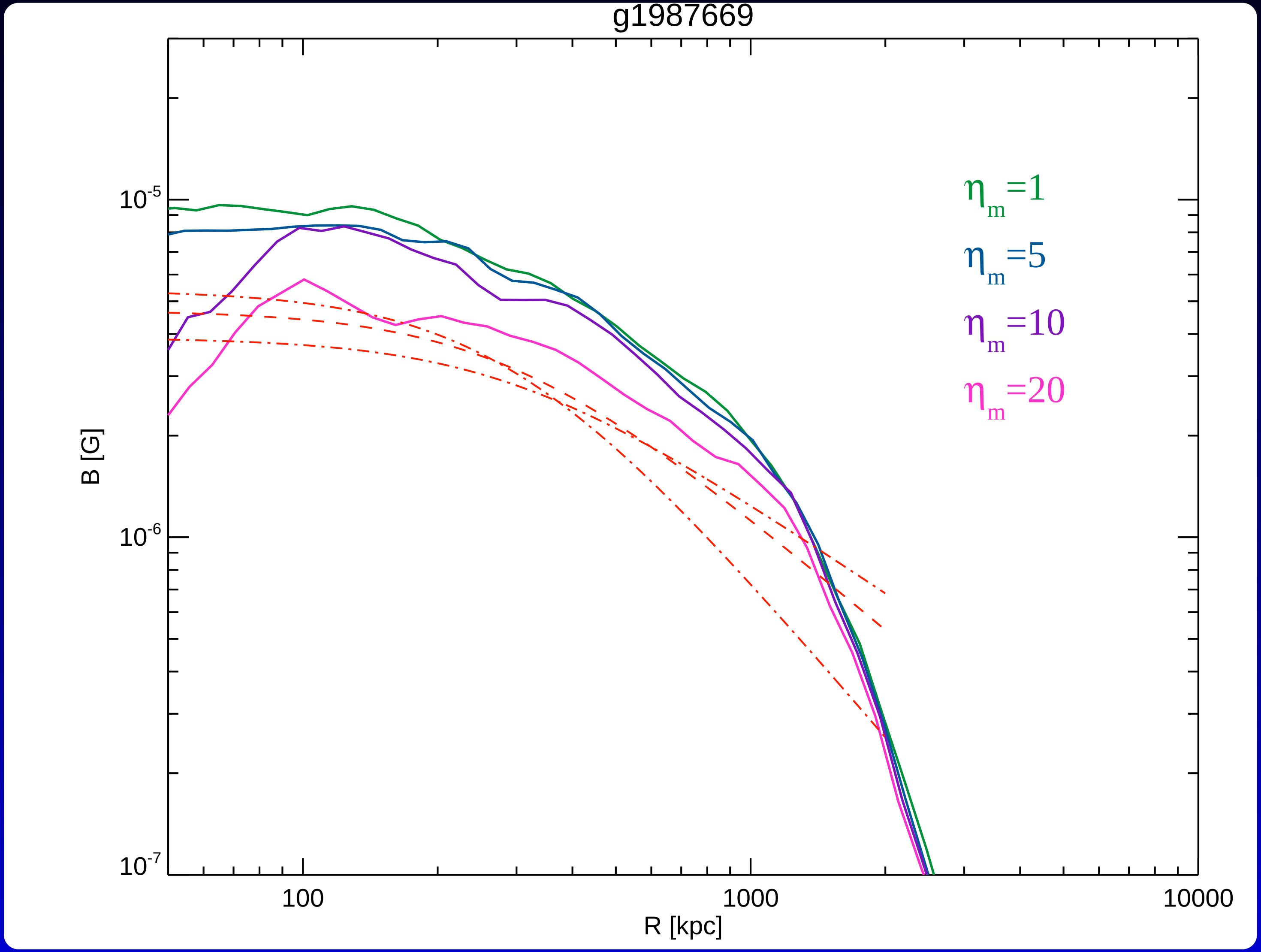
Measuring low magnetic fields



Dolag et al. 2009

Perfectly in line with predictions by simulations.

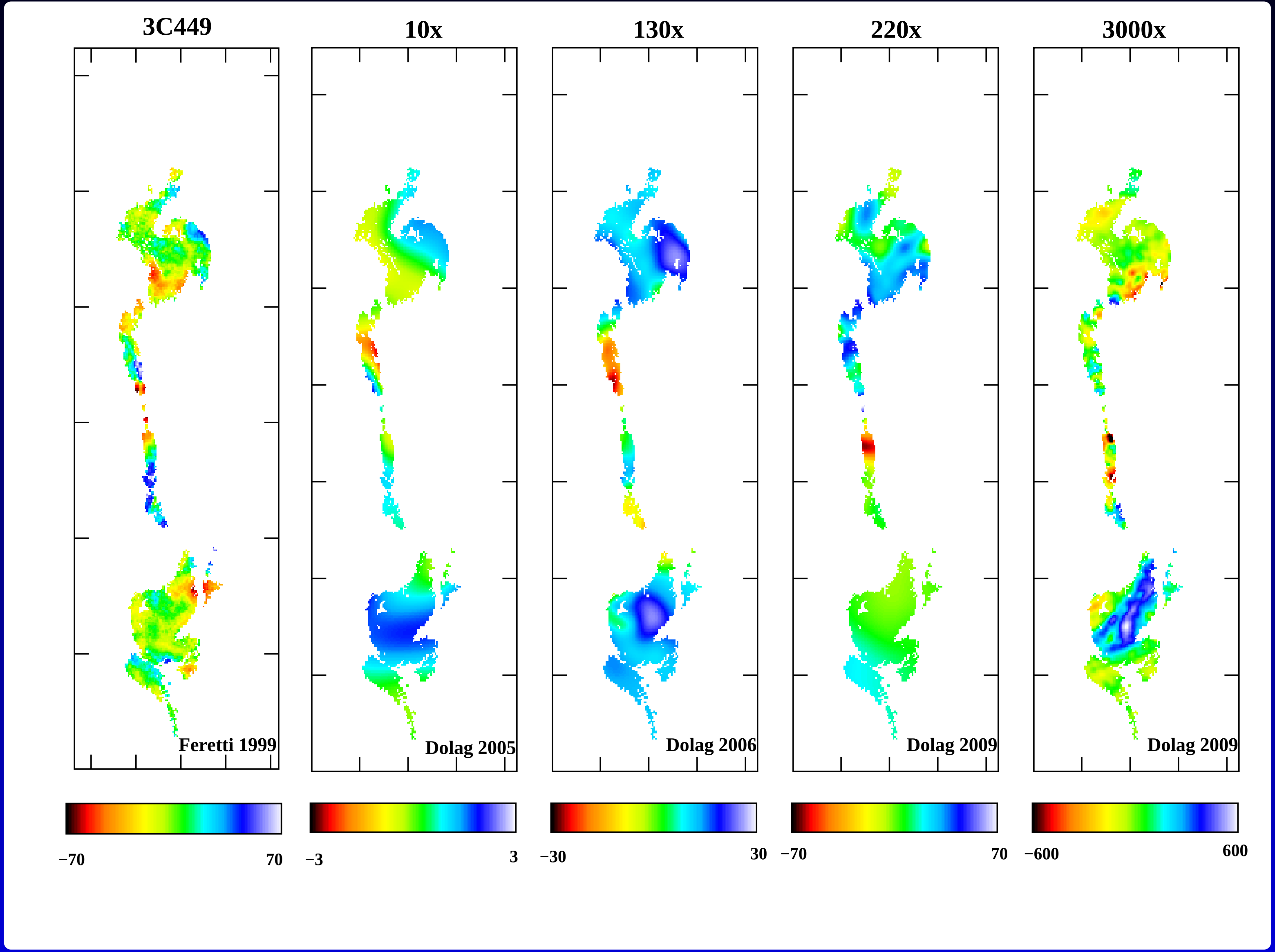
Constraining ICM properties



Bonafede et al., work in progress

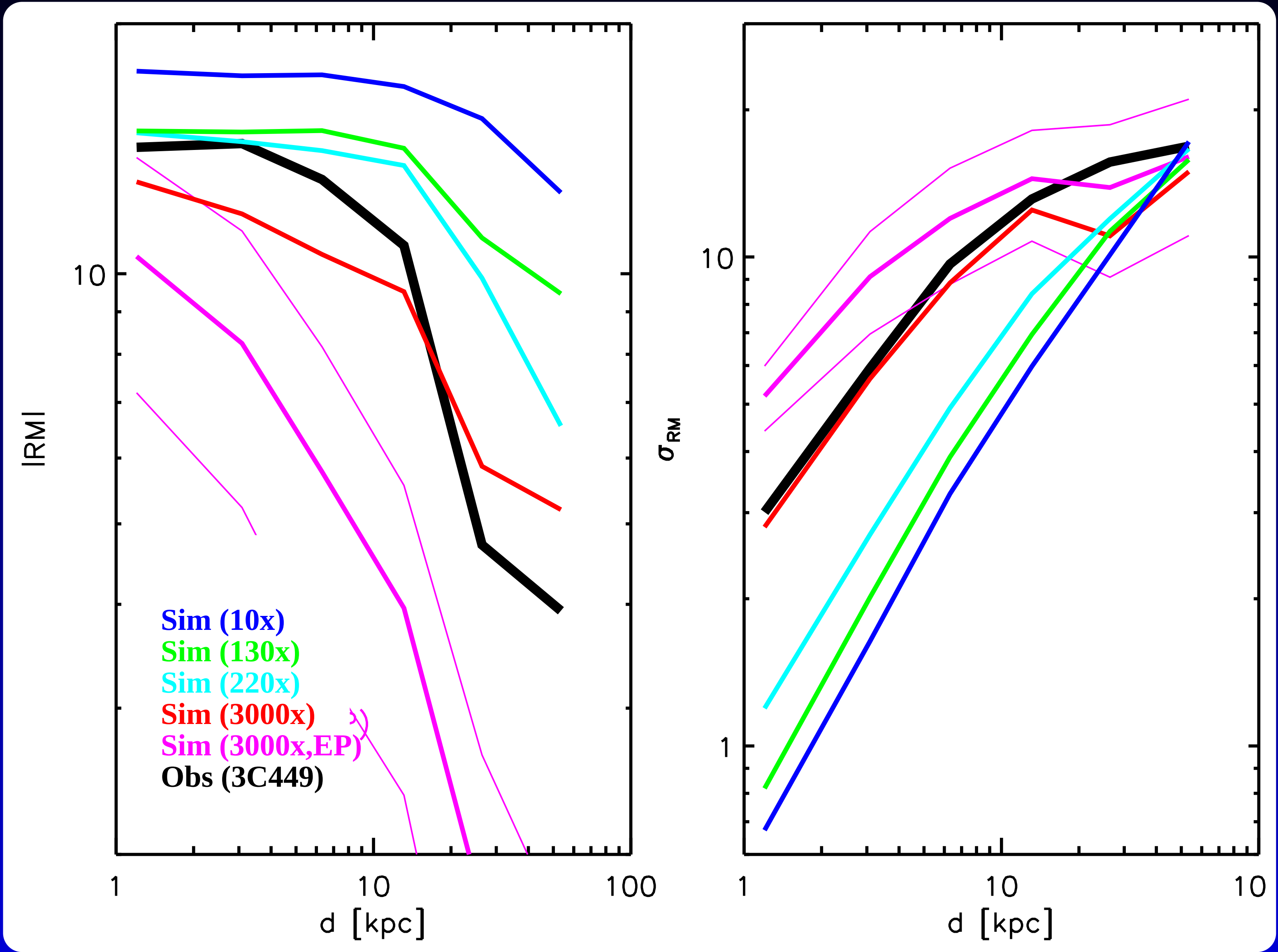
$$\frac{\mathrm{d}\vec{B}}{\mathrm{d}t} = (\vec{B} \cdot \vec{\nabla})\vec{v} - \vec{B}(\vec{\nabla} \cdot \vec{v}) + \eta \vec{\nabla}^2 \vec{B}$$

Constraining ICM properties



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)

Constraining ICM properties



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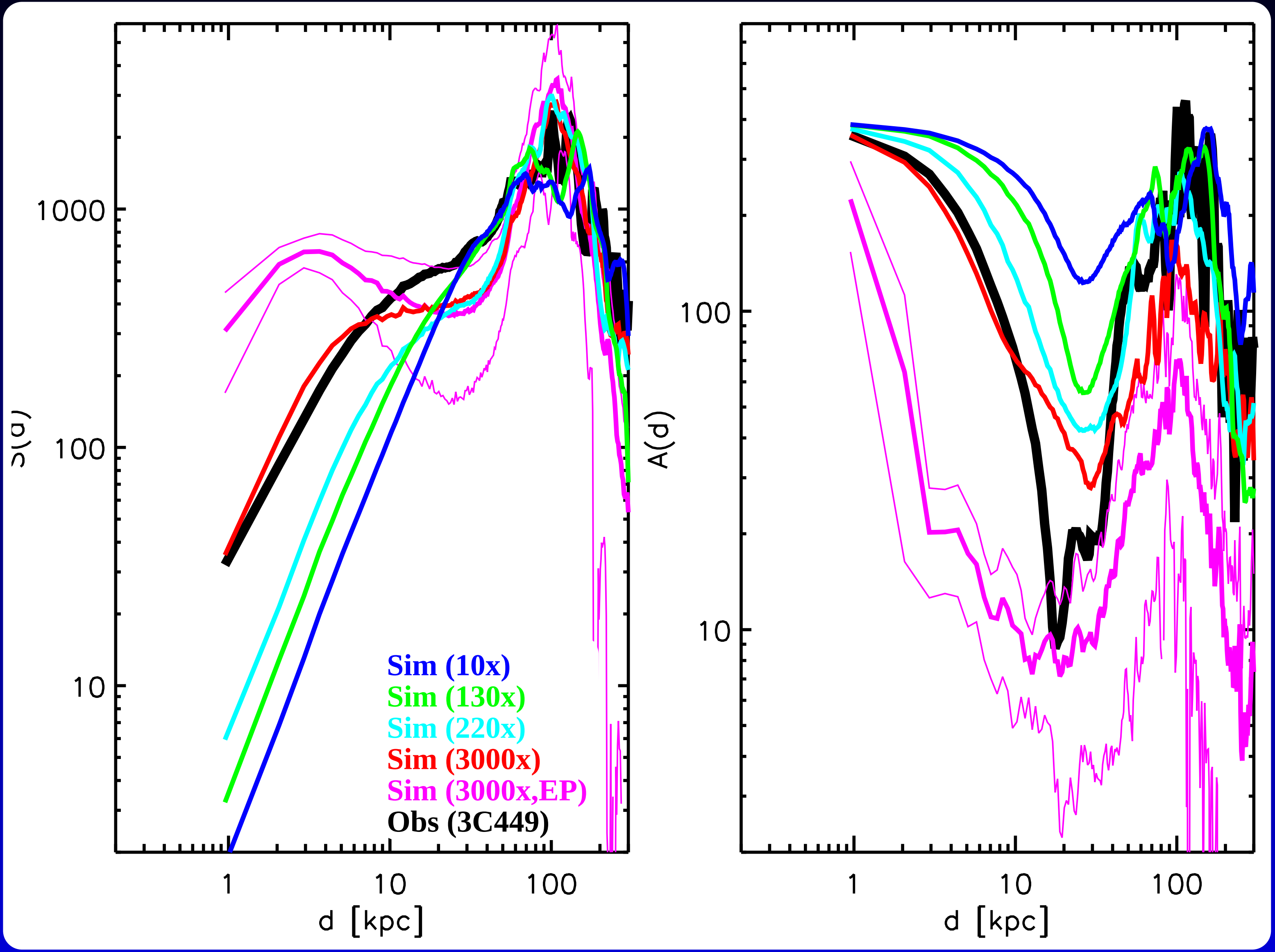
Constraining ICM properties



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)

Conclusions

Cosmological MHD simulations

- Reproduce overall picture well
- Low density regions encode origin if magnetic field
- Details need better understanding of dissipative processes
- Important to test observational strategies

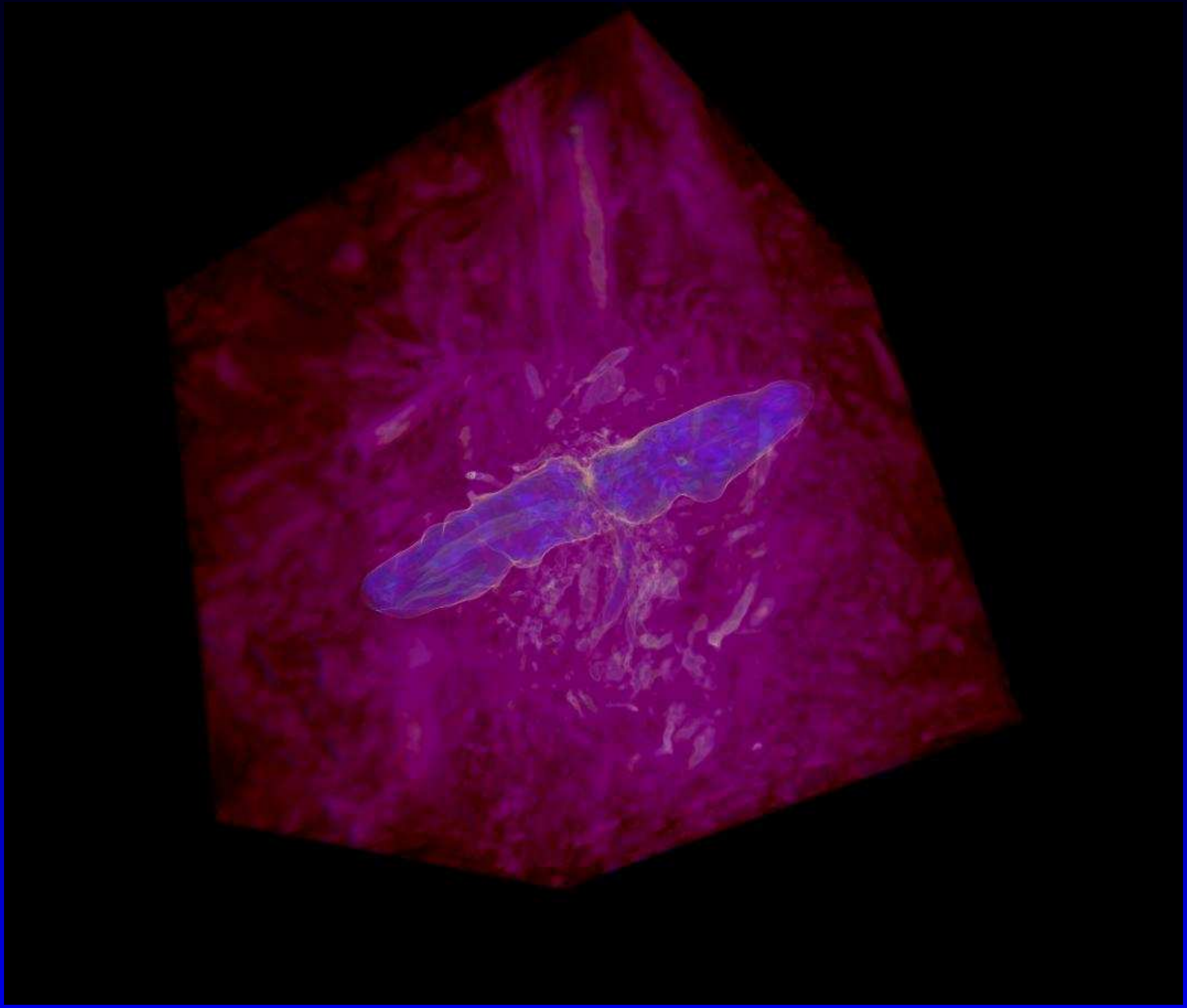
Applications:

- UHECR propagation consistent with observations
- RM-Galaxy correlation consistent (foreground / noise !)
- Observed Blazar halos consistent with predictions

Questions on magnetic fields:

- Minimal length-scale of cluster fields ?
- Detailed magnetic field profile shape ?

Outlook



Simulation by P. Mendygral