Lecture II:
(*) Galaxy Clusters
(*) Filaments / Voids
(*) Magnetic Fields as Probe

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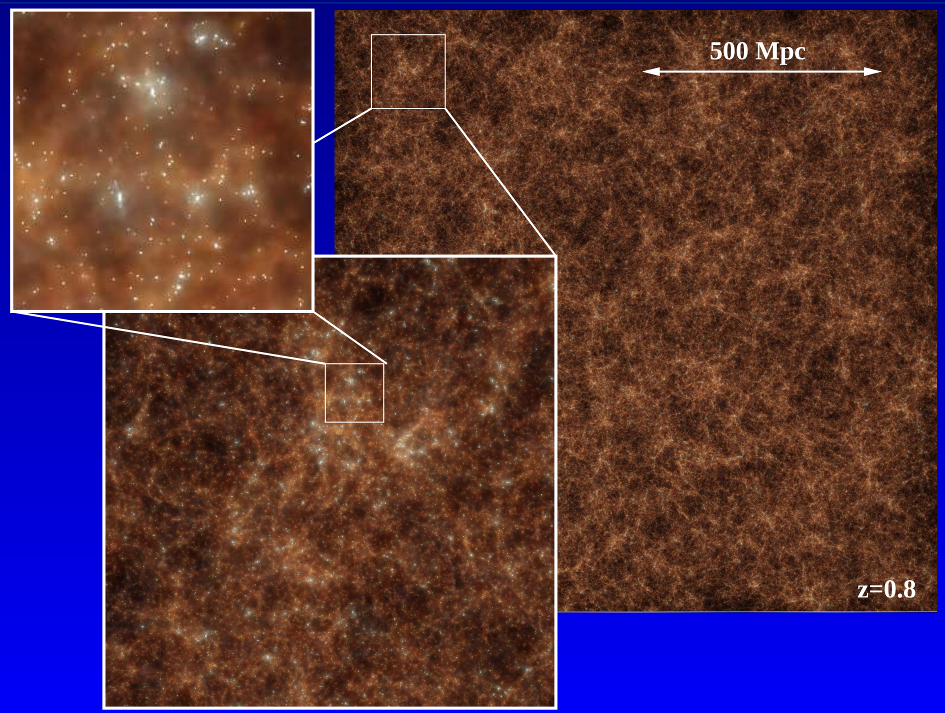
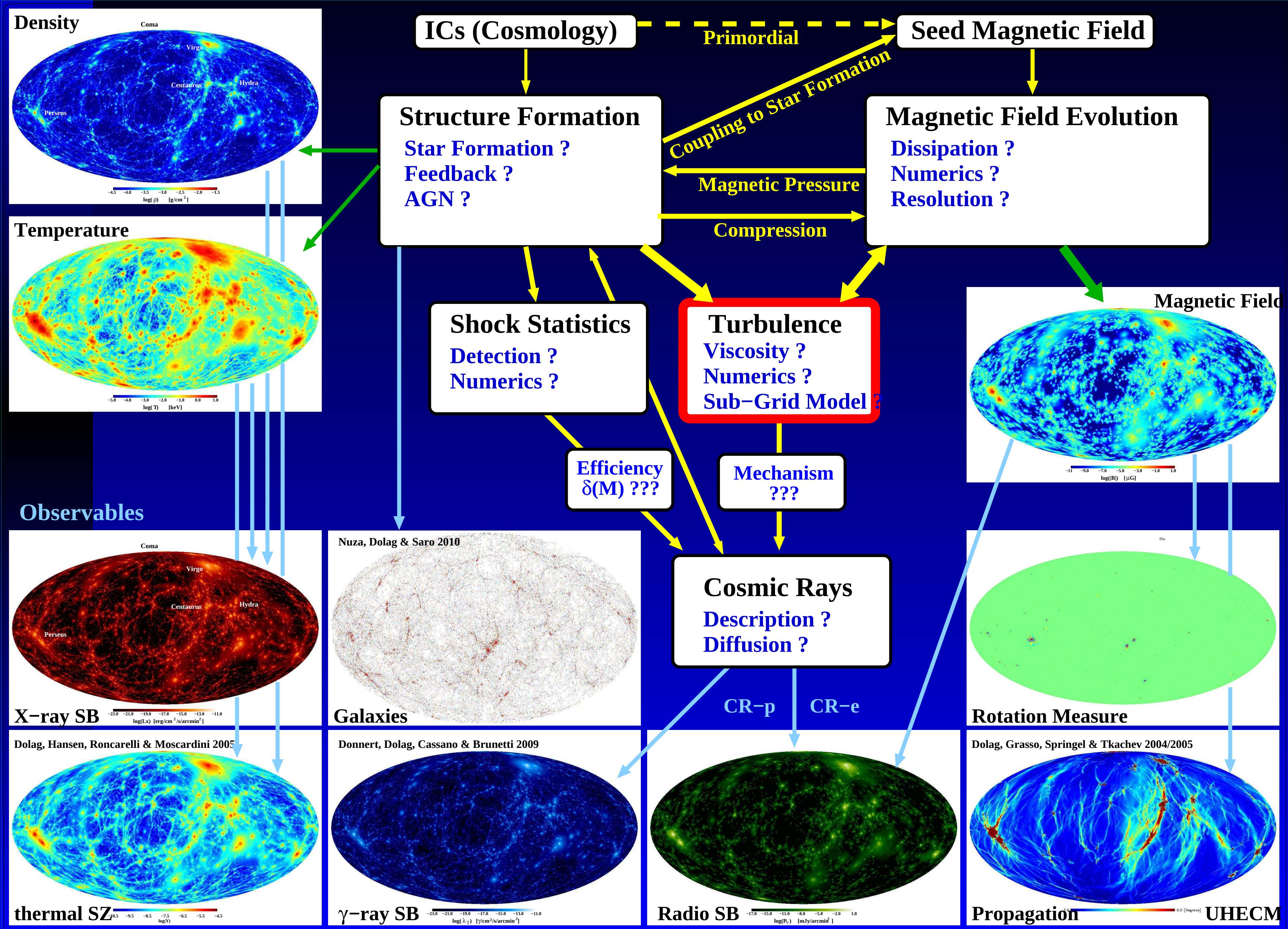
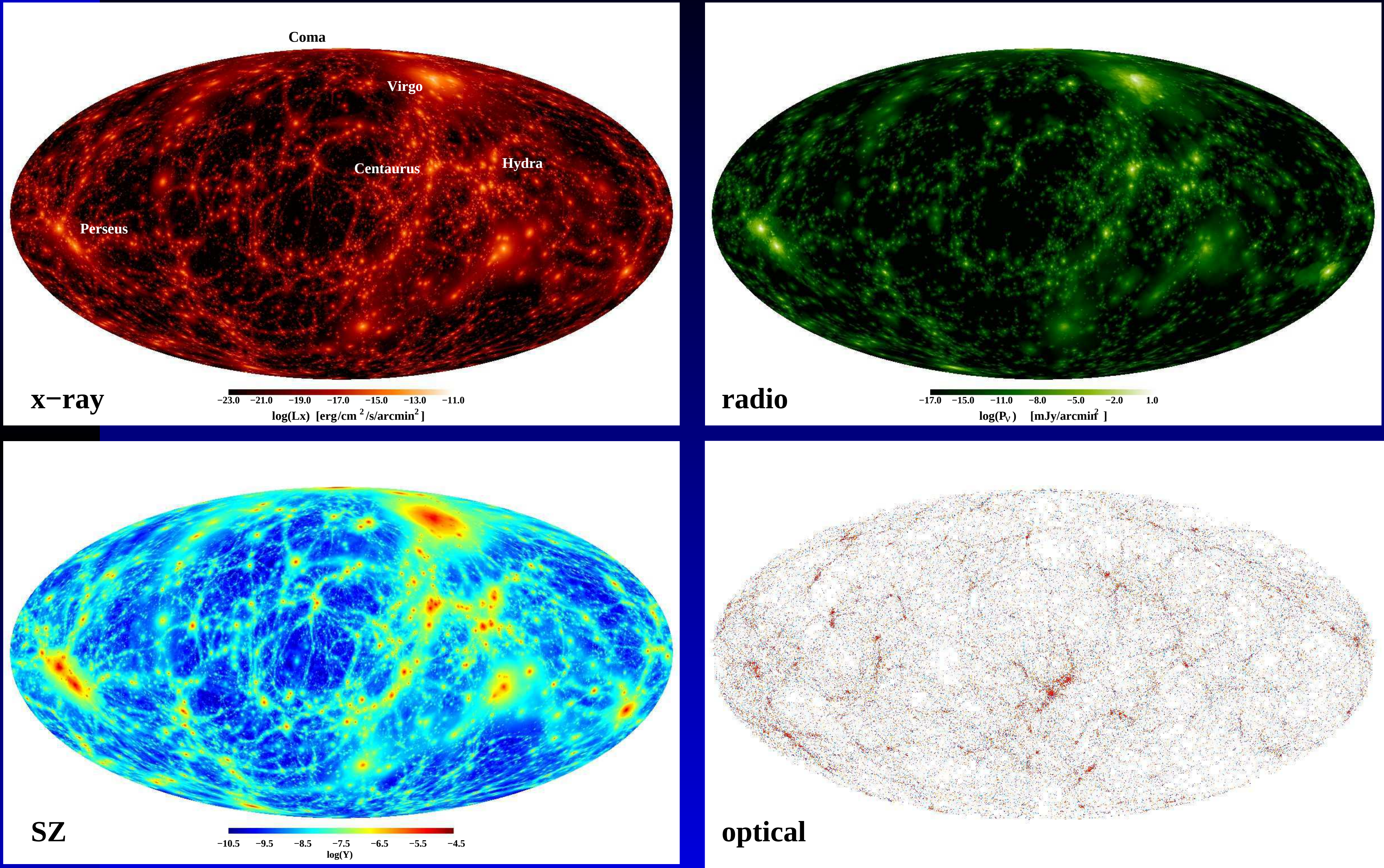


Process Network

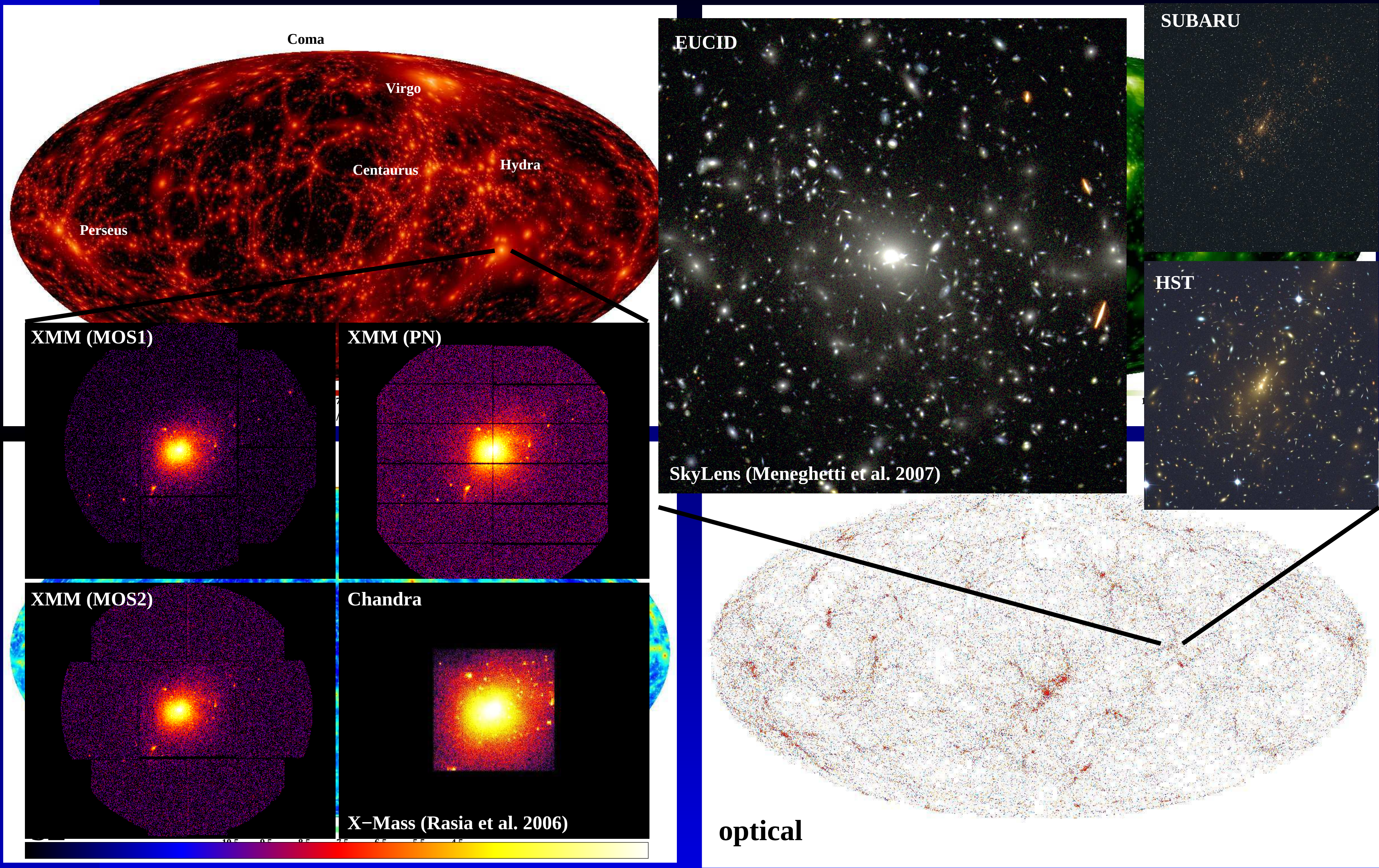


The Aim



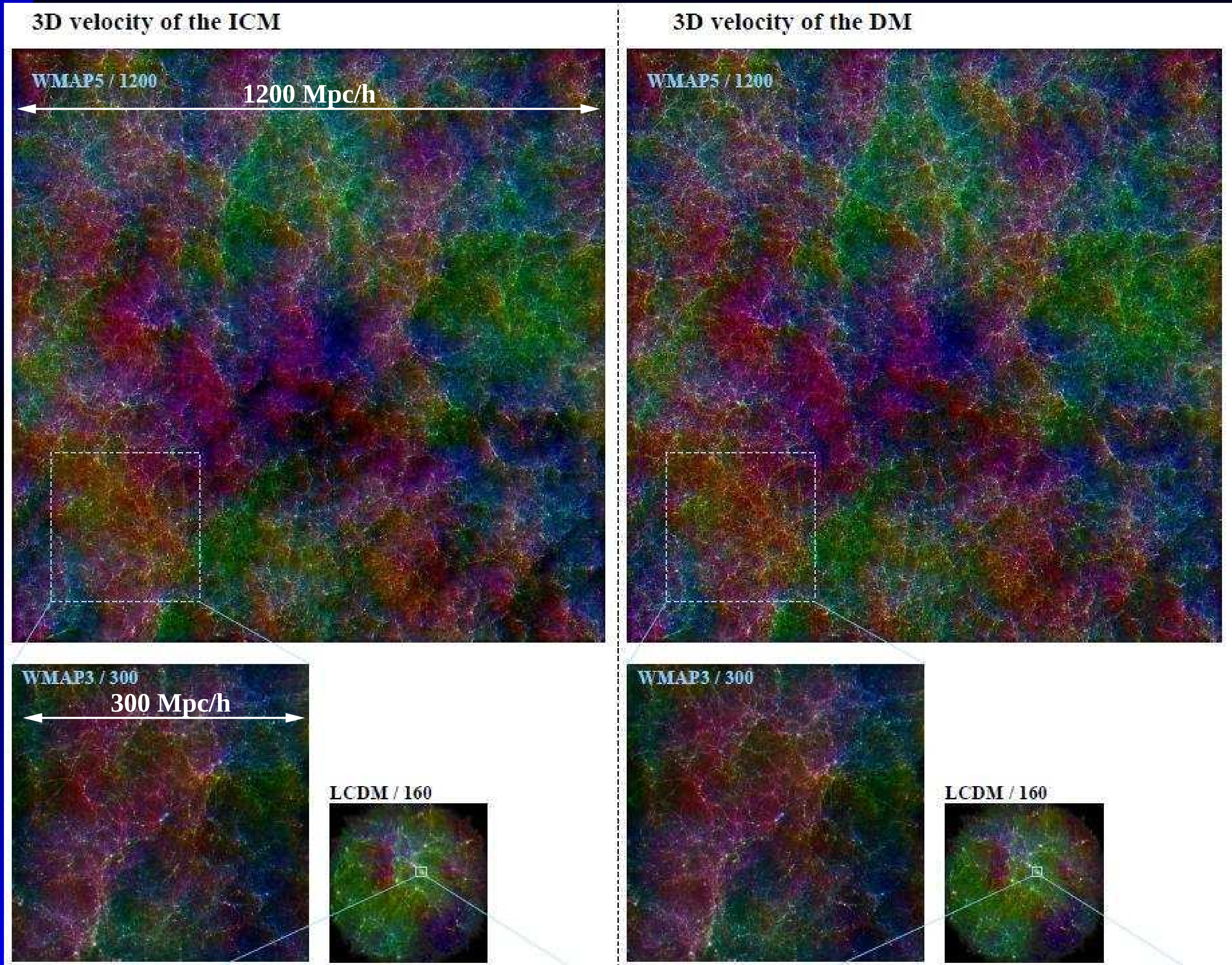
Cosmological, hydrodynamical simulations which at the same time allows predictions for ICM and stellar component for ongoing/future missions (Planck, SPT, LOFAR, eROSITA ...).

The Aim

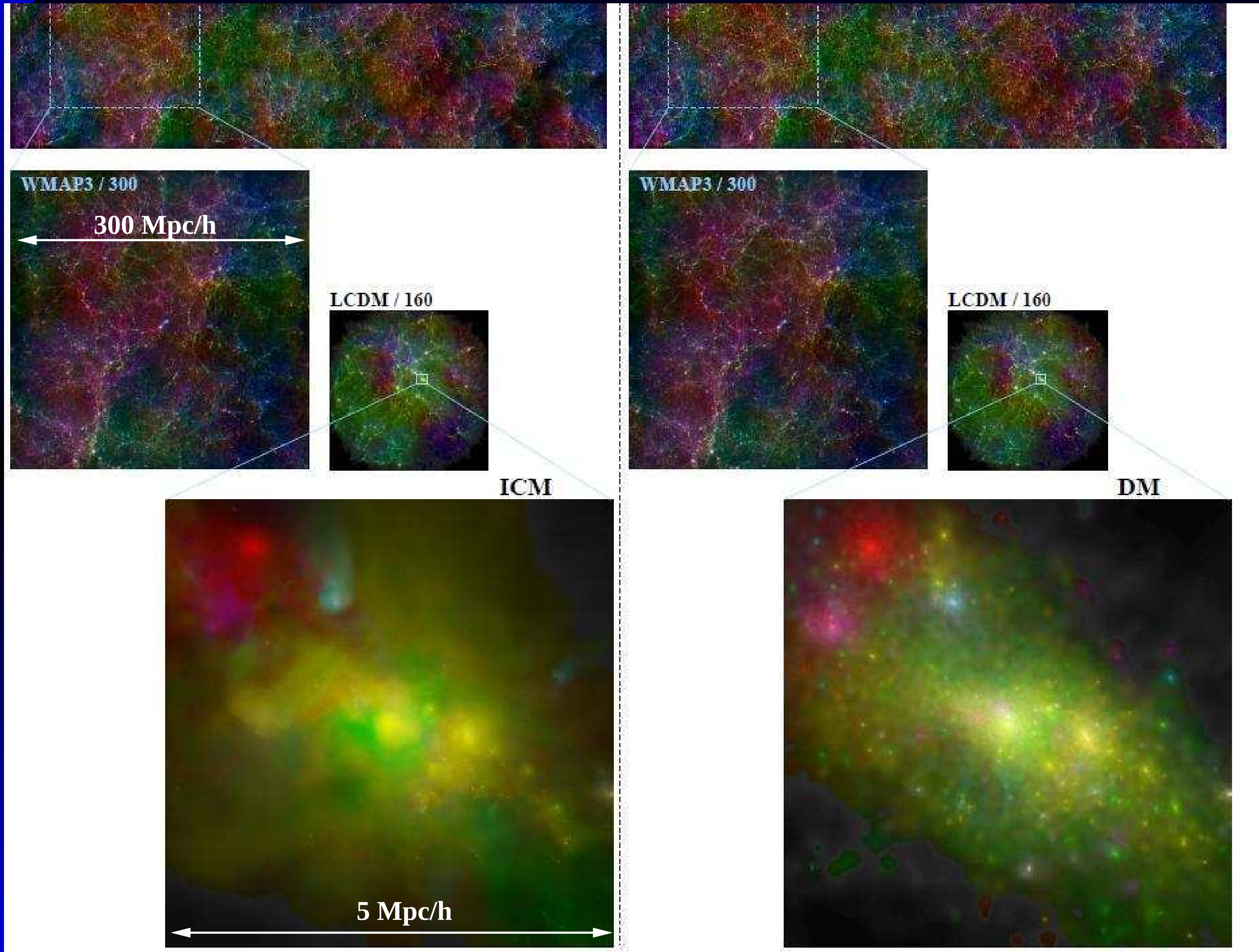


Mock optical/x-ray observations using SkyLens (Meneghetti 2010), X-Mass (Rasia 2007) and Phox (Biffi 2011).

Galaxy Clusters are Special



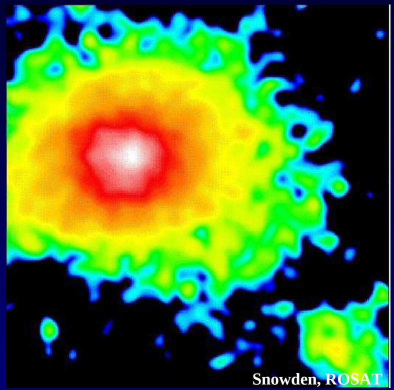
Galaxy Clusters are Special

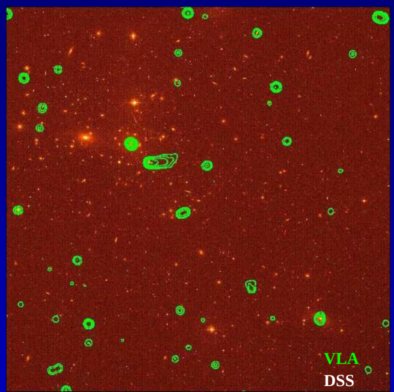


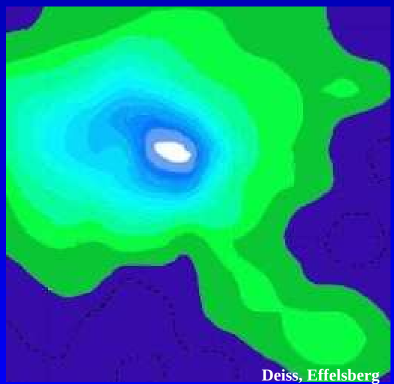
Dynamical difference between DM and baryons !

Galaxy Clusters are Special

Observations ($\Rightarrow$), Processes ($\Leftarrow$) and the role of $\vec{B}$:







ICM (X-ray, $T \approx 10^8$K, Bremsstrahlung):

- $\Rightarrow$ Dynamical state of ICM
- $\Leftarrow$ Non thermal **pressure** support
- $\Leftarrow$ **Turbulence**, **Viscosity**, Shocks

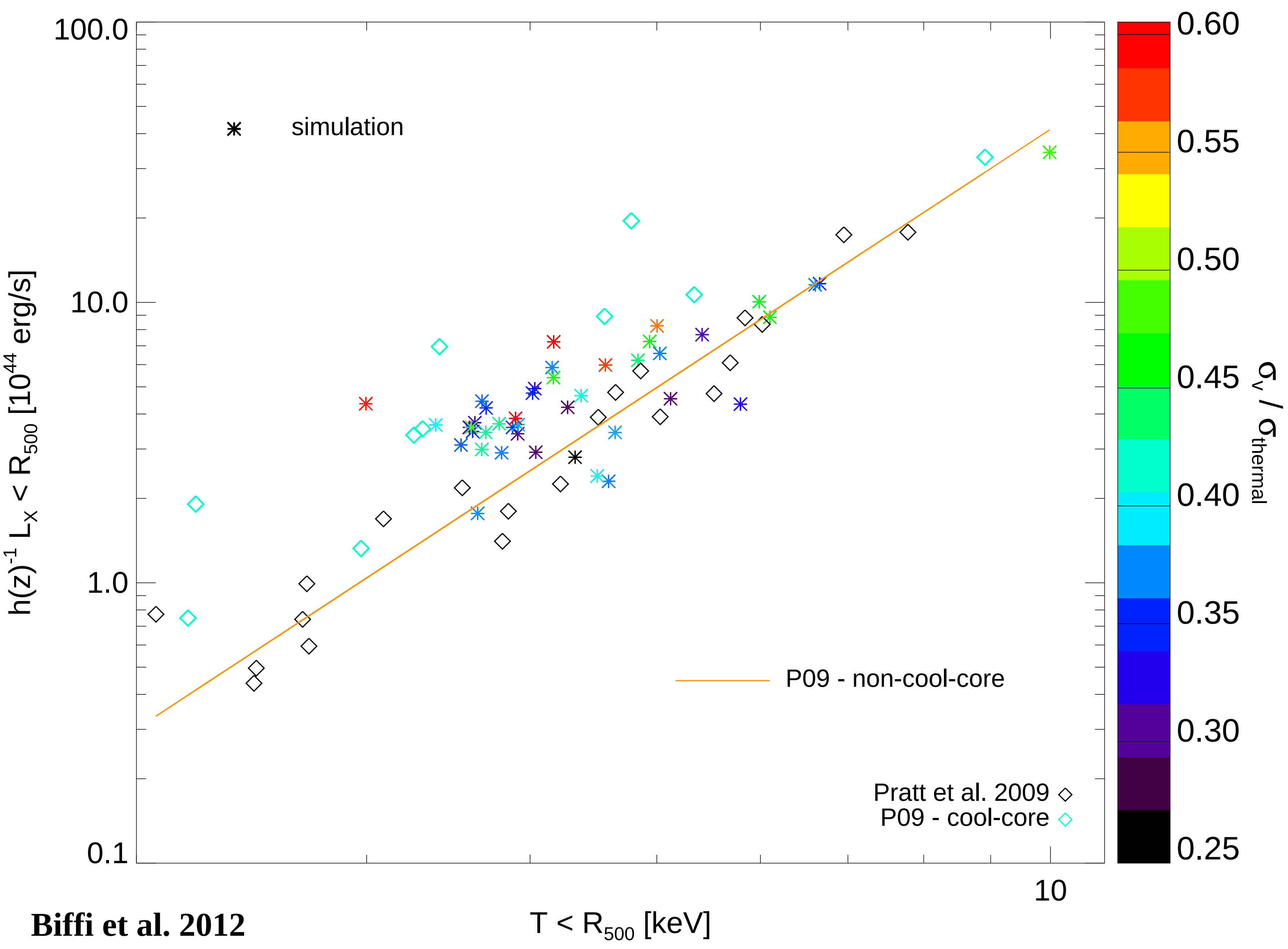
Galaxies (optical, radio, $N_{\rm gal} > 1000$):

- $\Rightarrow$ Interaction with the ICM
- $\Leftarrow$ Galaxies in dense environment (**stripping**, distribution of metals)
- $\Leftarrow$ Magnetic field **seeding** (outflows)

ICM (radio, synchrotron radiation, RM):

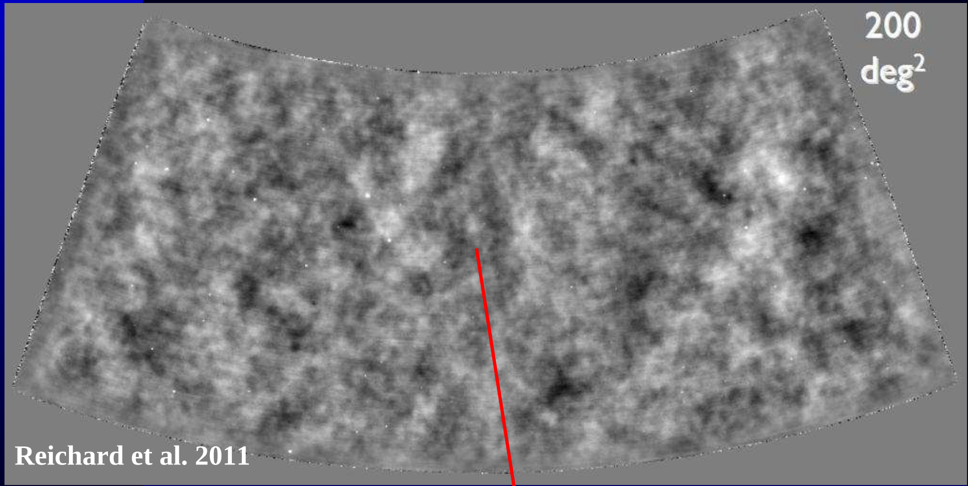
- $\Rightarrow$ Distribution of $\vec{B}$, CRs (diffuse + RM)
- $\Leftarrow$ **Evolution** and **buildup** of $\vec{B}$
- $\Leftarrow$ **Acceleration** and **propagation** of CRs

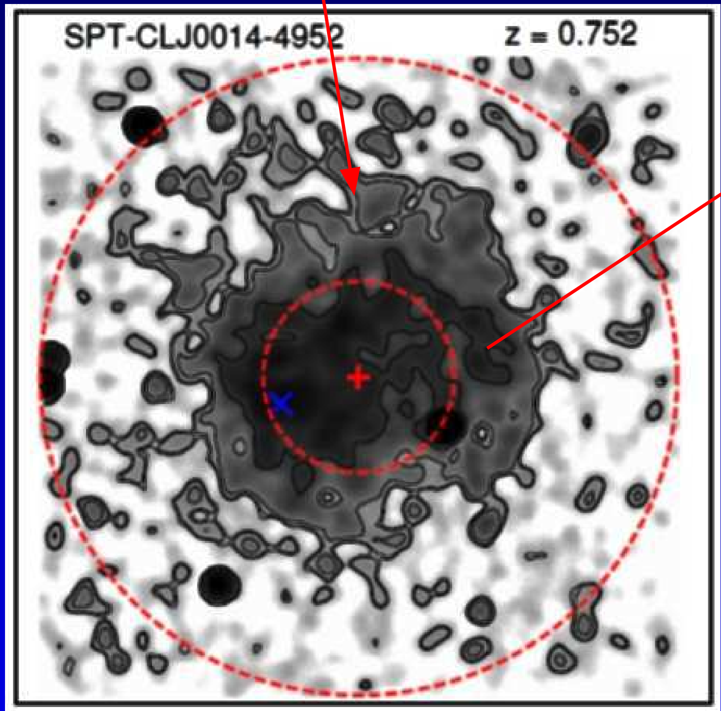
How does it work out ?

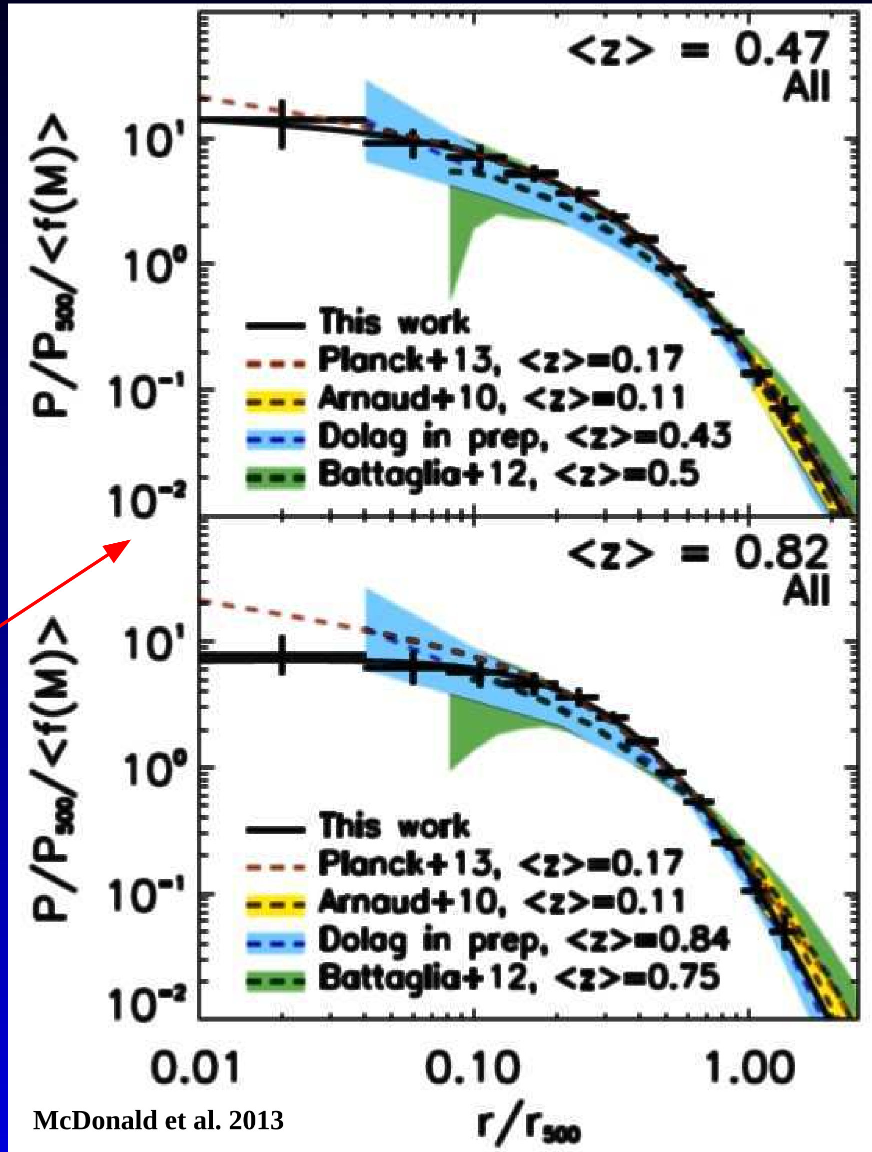


Biffi et al. 2012

How does it work out ?

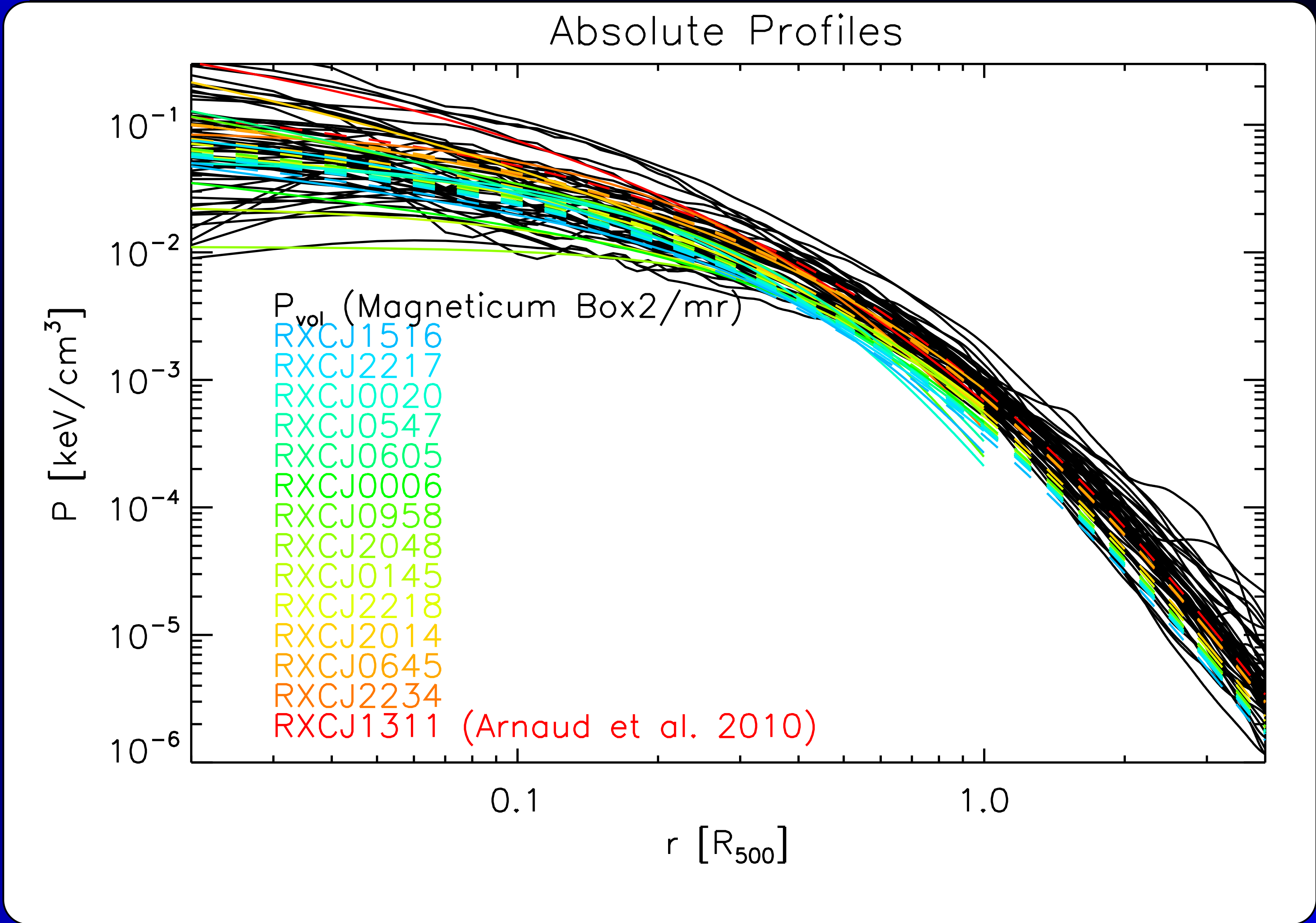






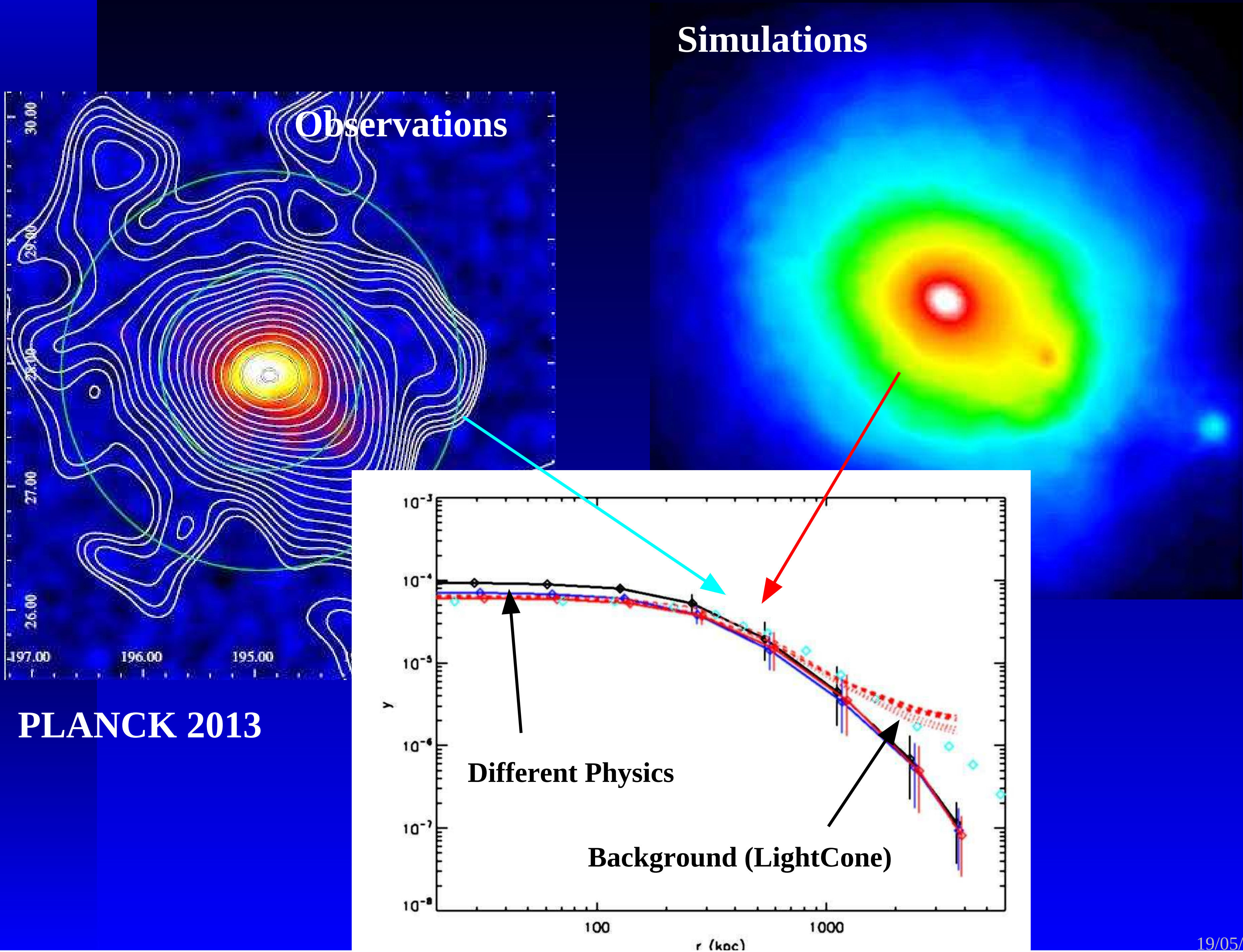
Mean ICM pressure profieles from CMB foreground (SPT).

How does it work out ?

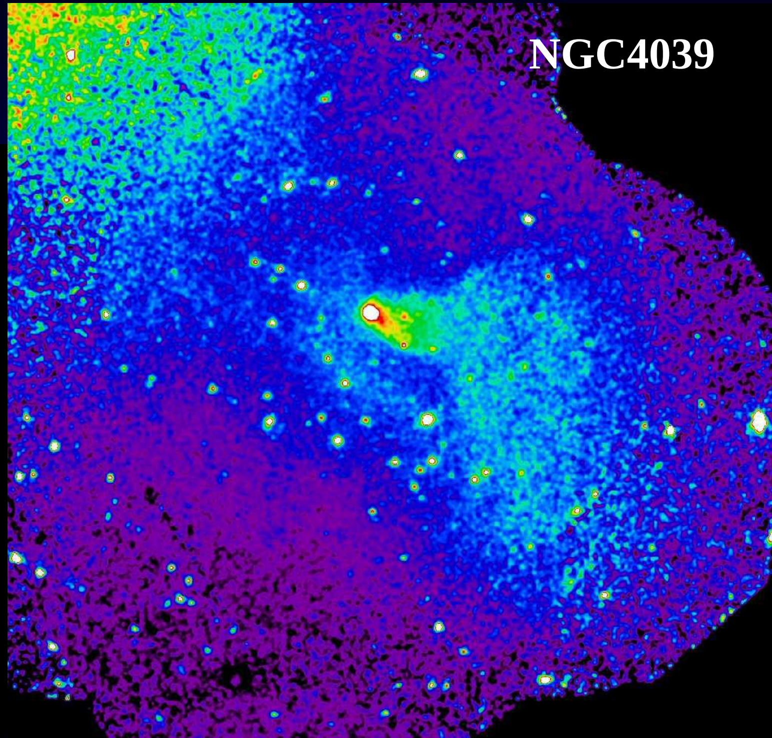


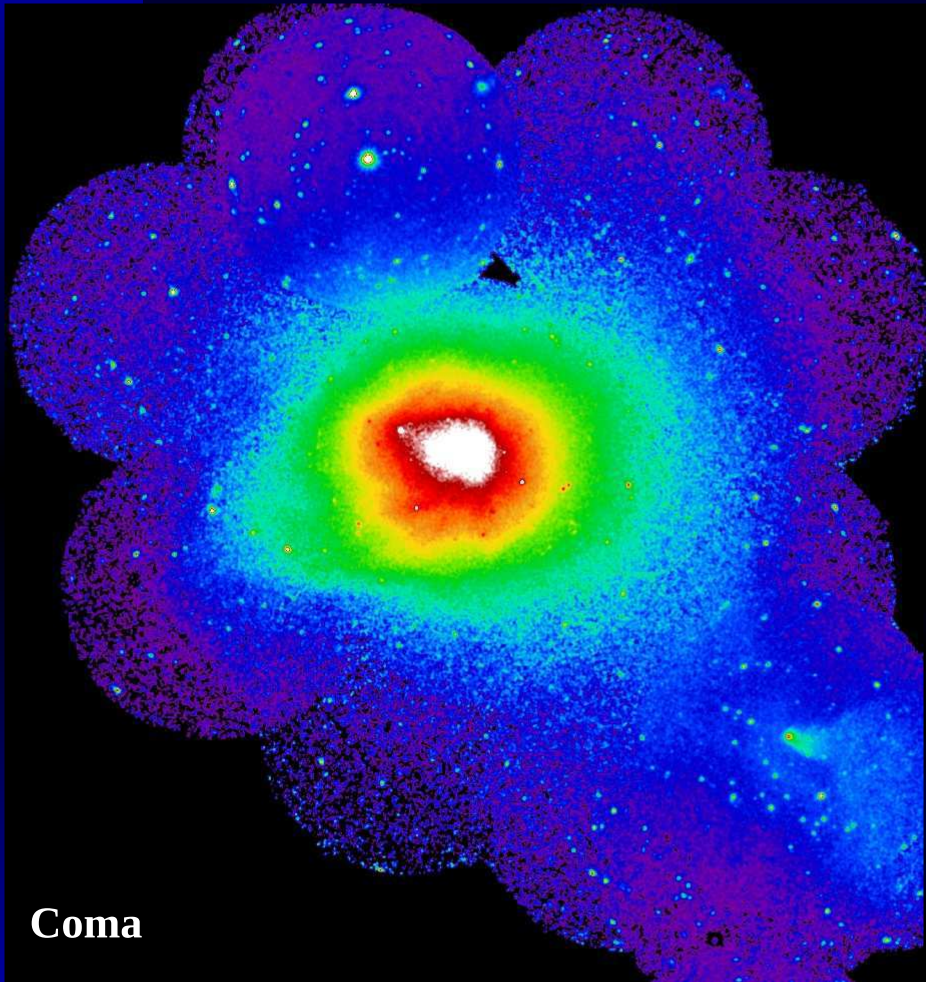
Comparison of simulated ICM pressure profiles with x-ray observations (matching shape and scatter !).

How does it work out ?

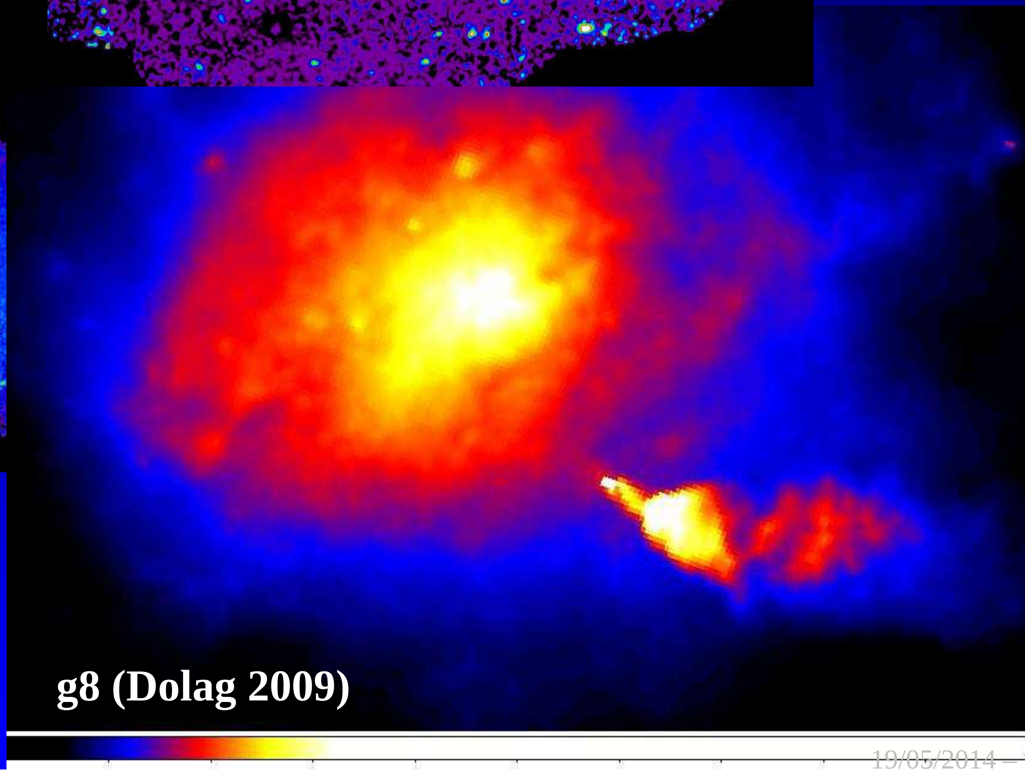


How does it work out ?



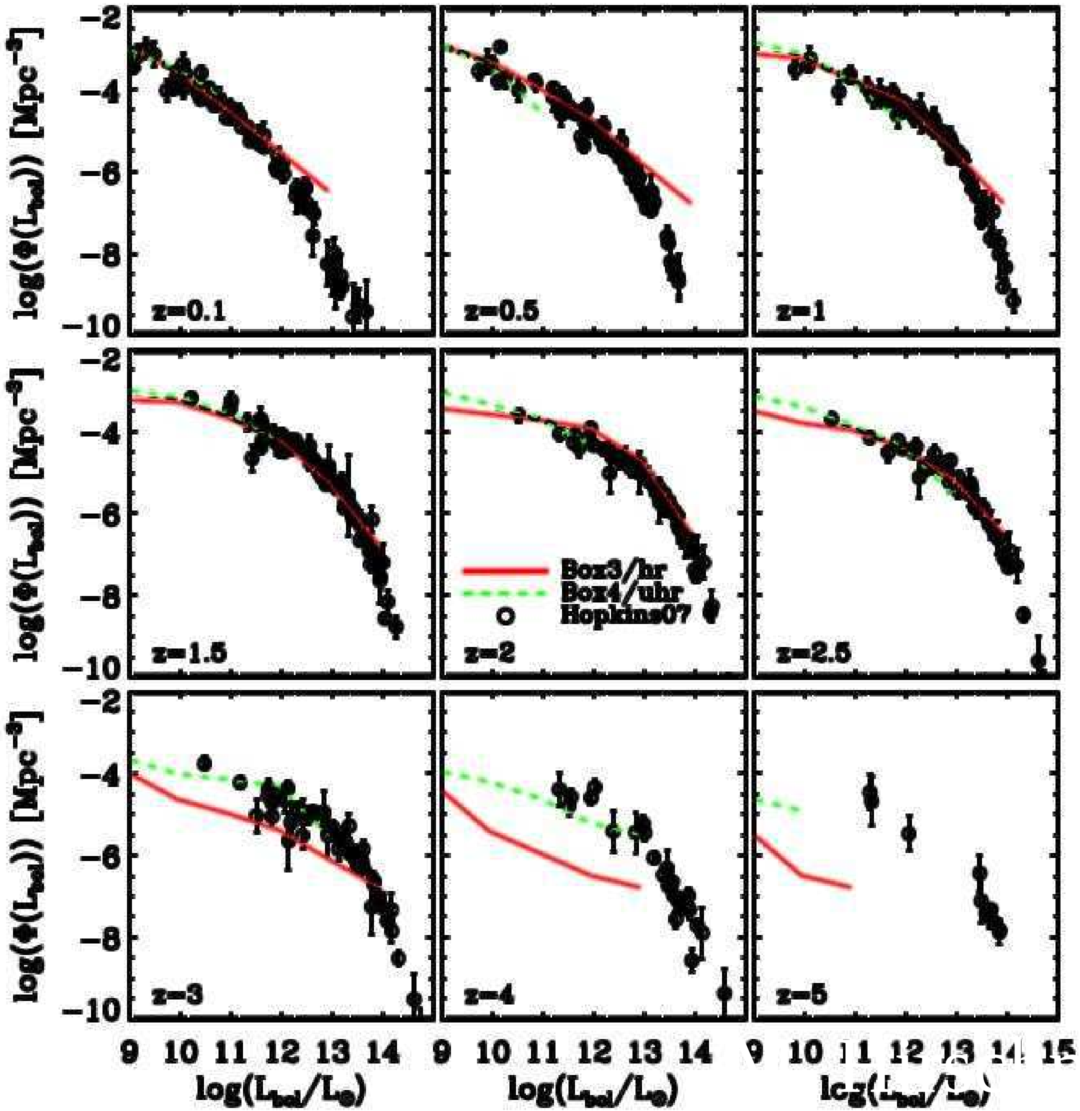


Provided by N. Lyskova & E. Churazov

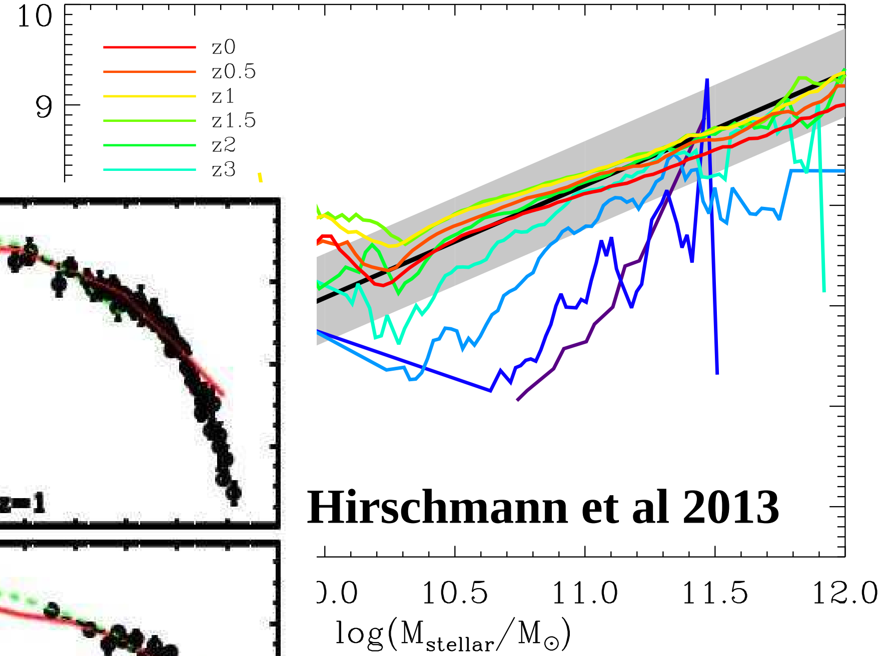


How does it work out ?

Bolometric LF

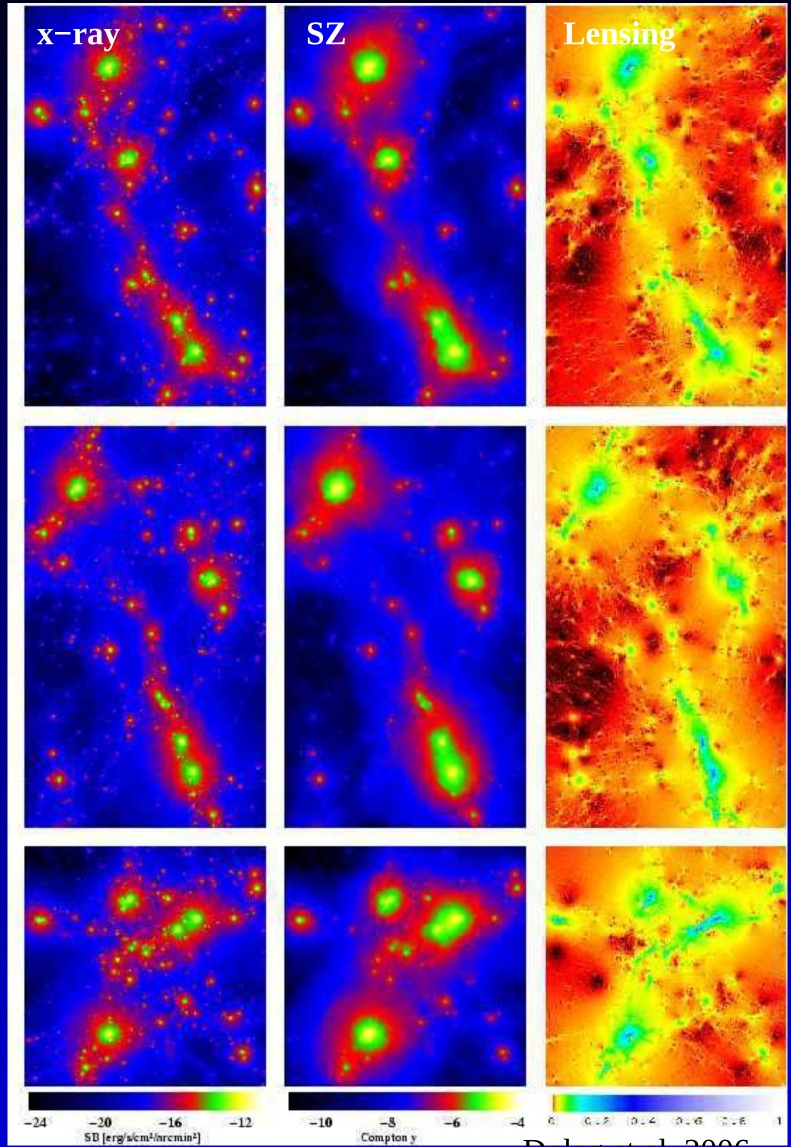


BH Mass -- Stellar Mass



Hirschmann et al 2013

Cosmological Filaments



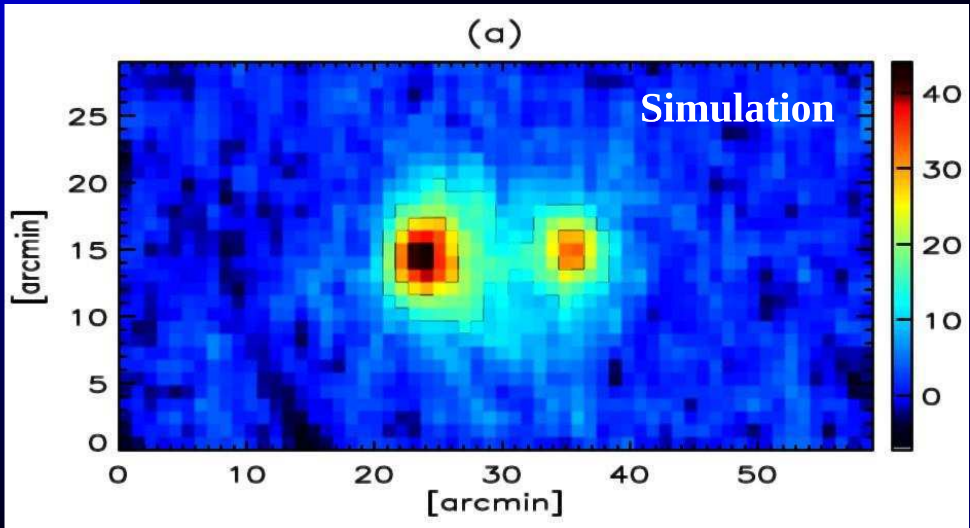
Dolag et al. 2006

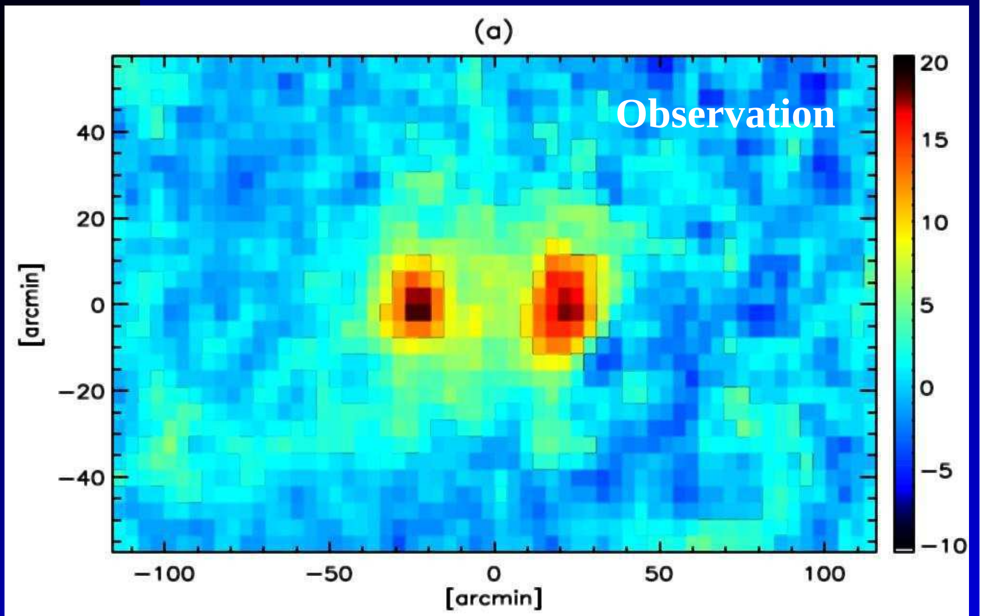
Planck detected bridge between two galaxy clusters !

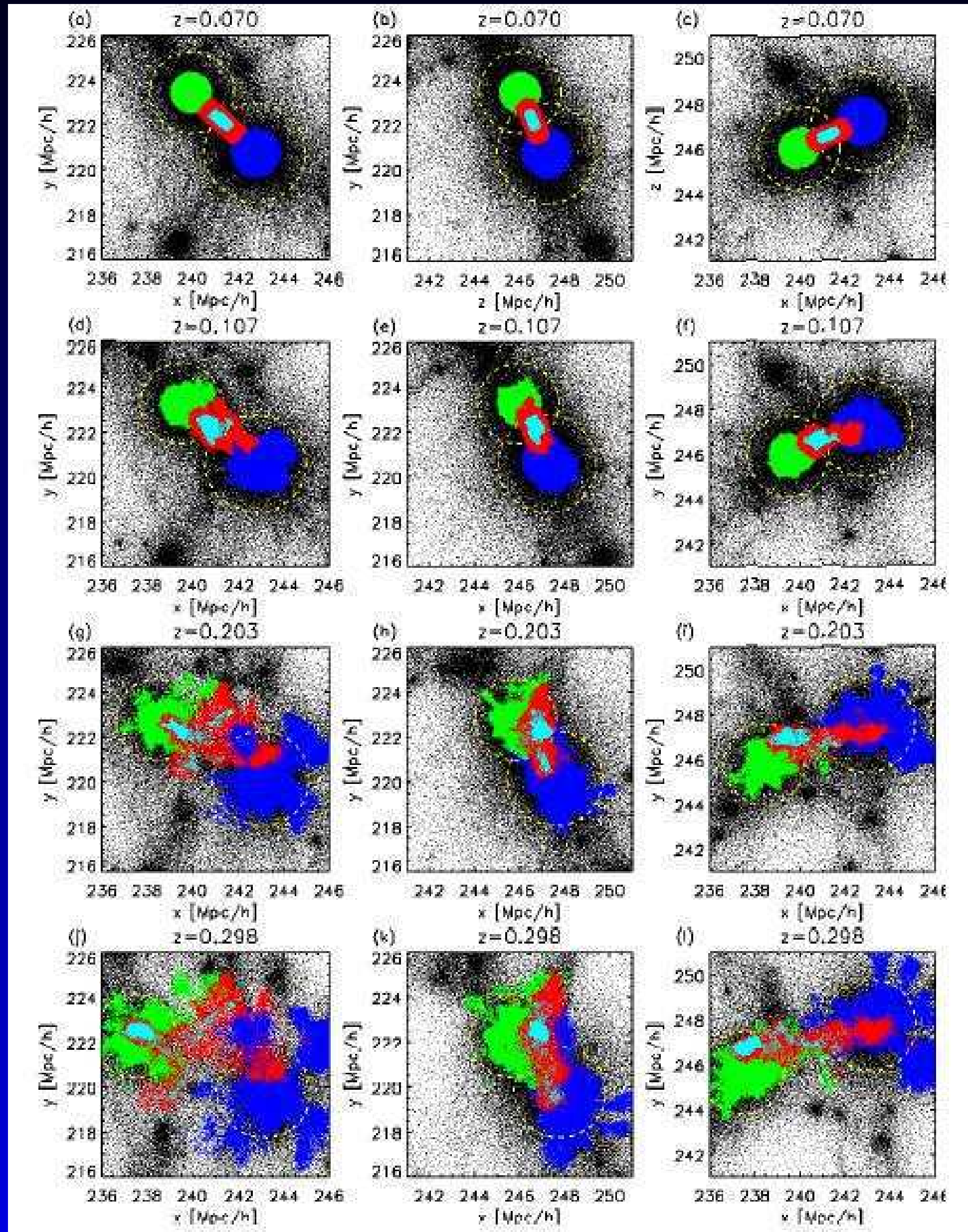
Real filament or “only” merger ?

⇒ compare to hydrodynamical simulations !

Cosmological Filaments



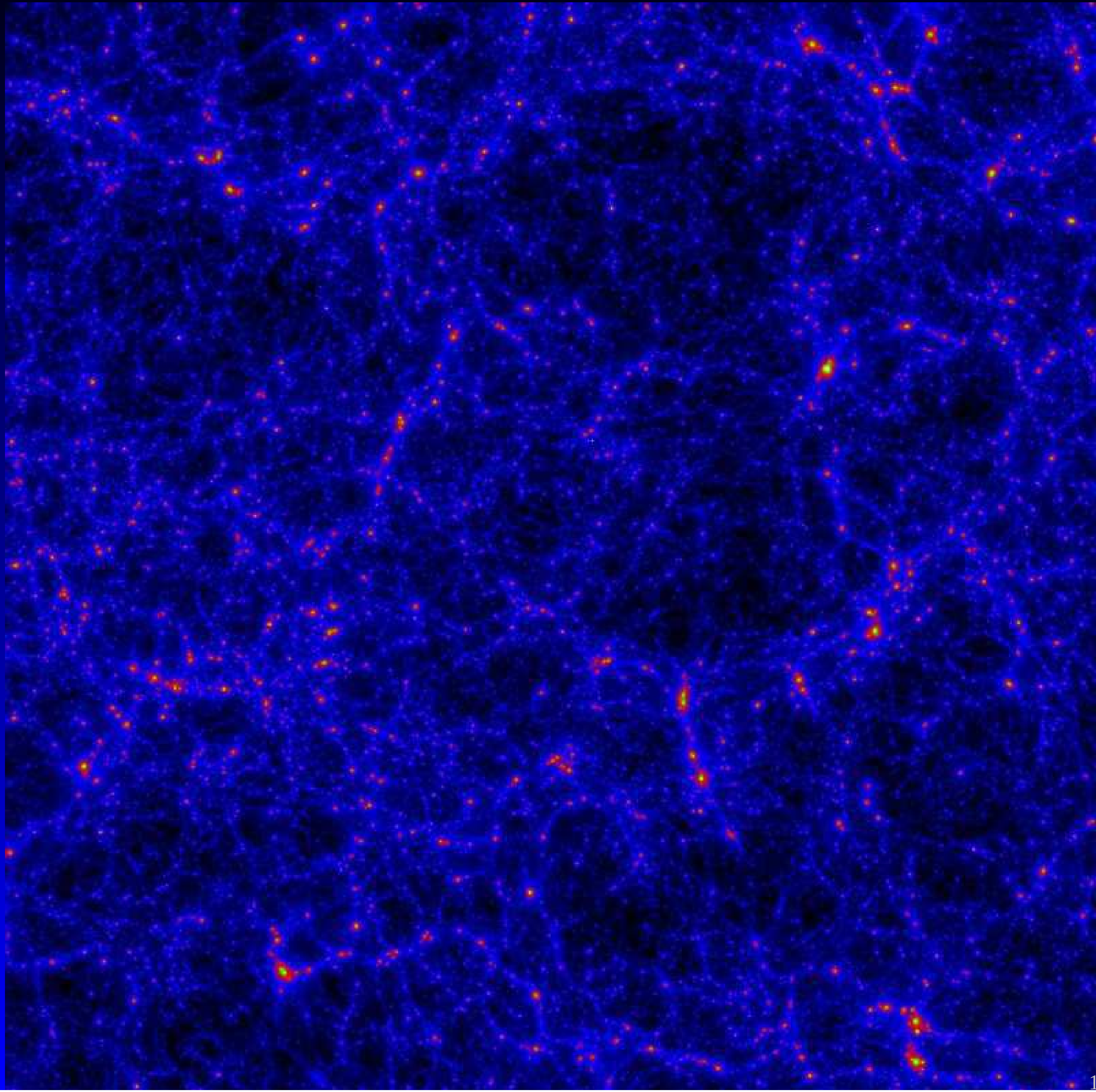




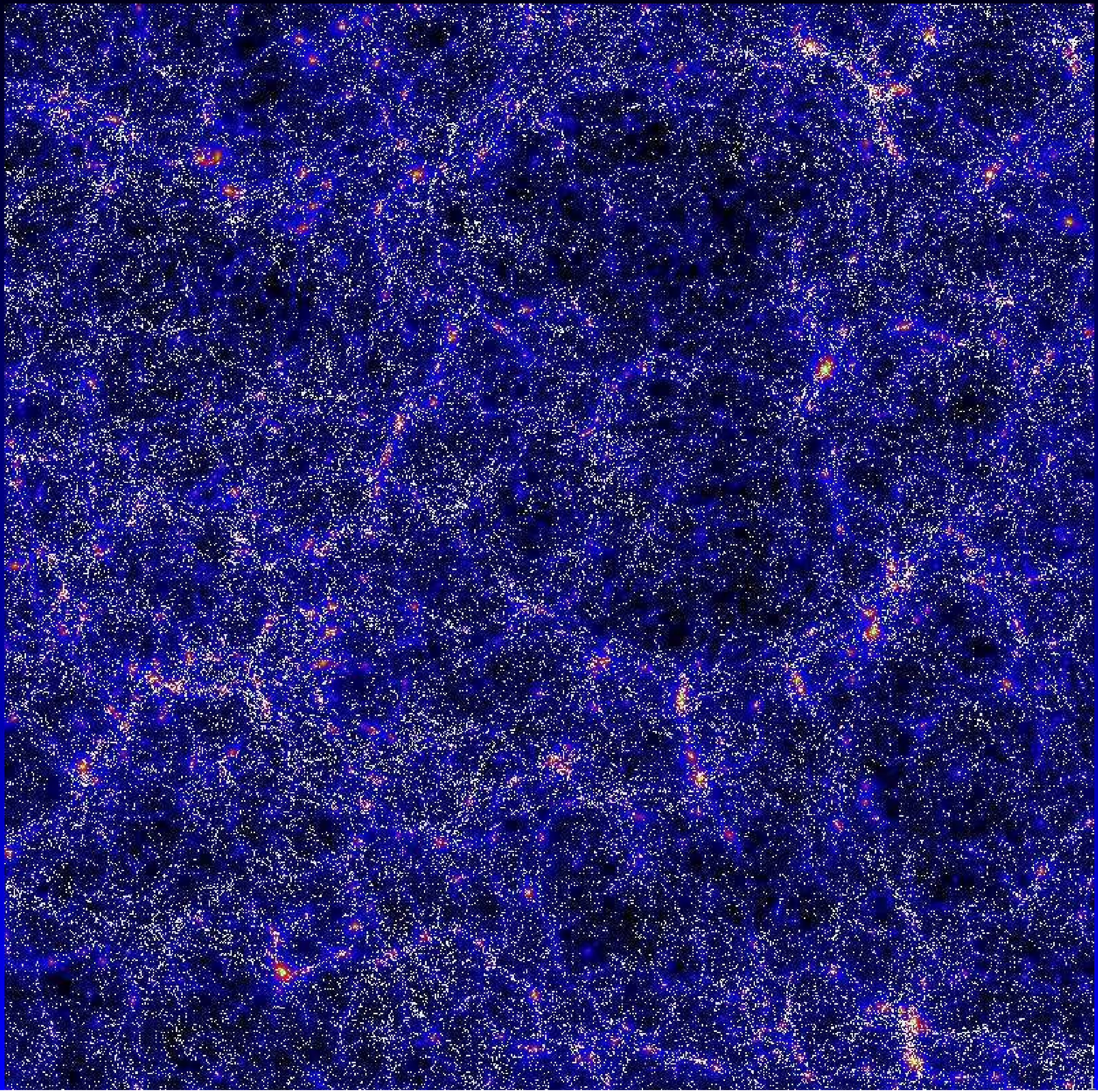
Planck collaboration, 2012

Tracing the particles in simulations suggest that significant fraction of the material comes from outside the clusters !

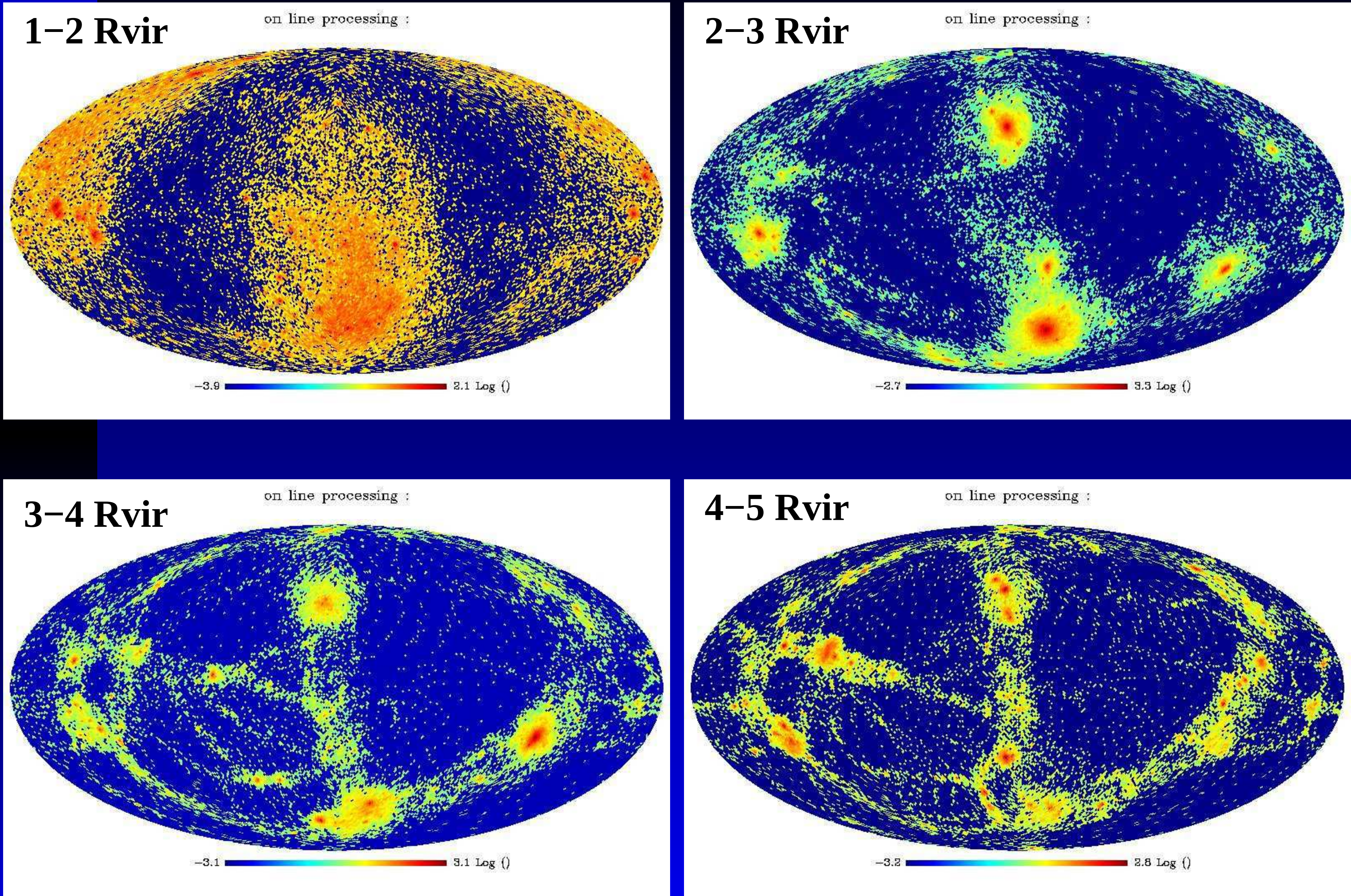
The Cosmic Web



The Cosmic Web

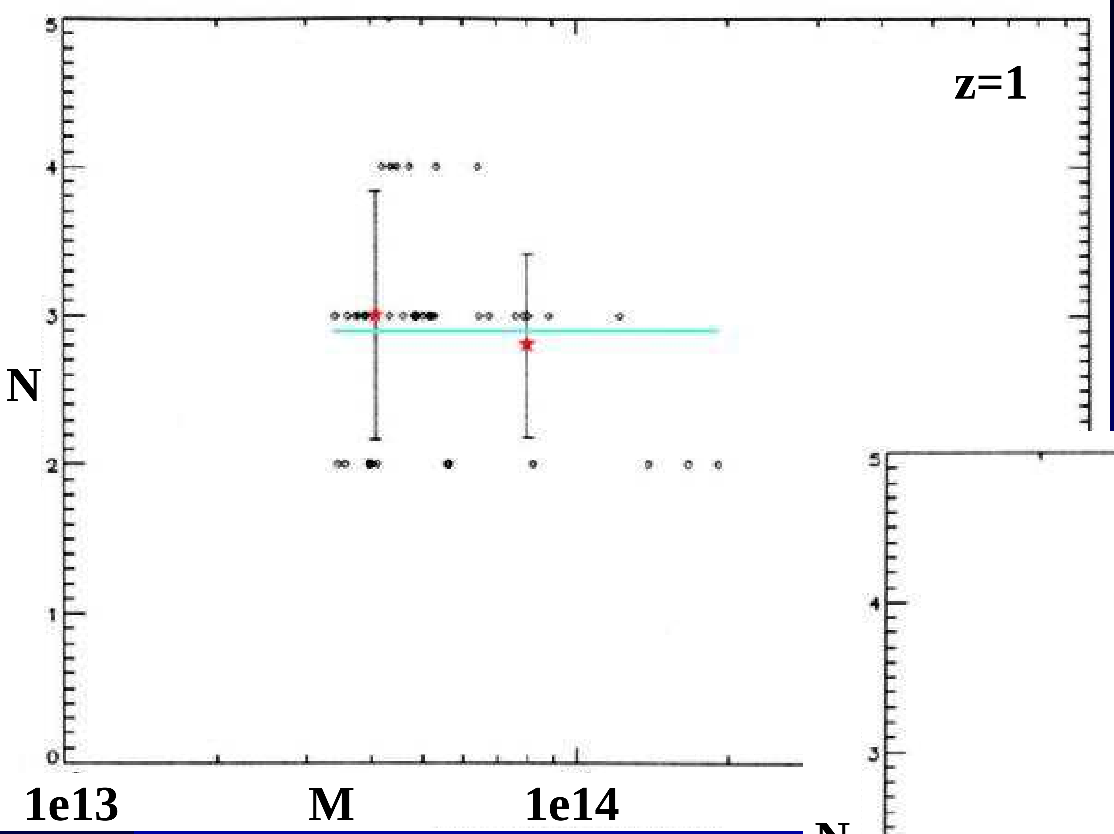


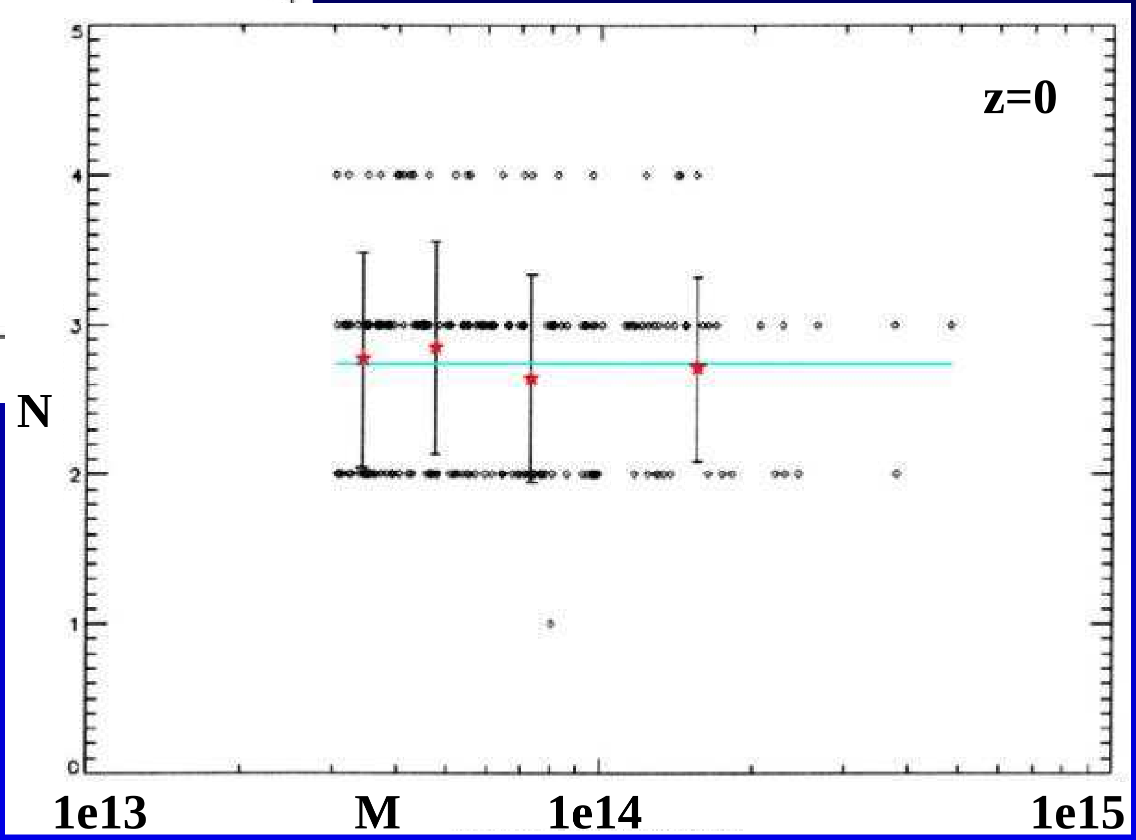
1. Filaments per Halo



Filaments and sheets arround halos (BA, Szymon Styrnik)

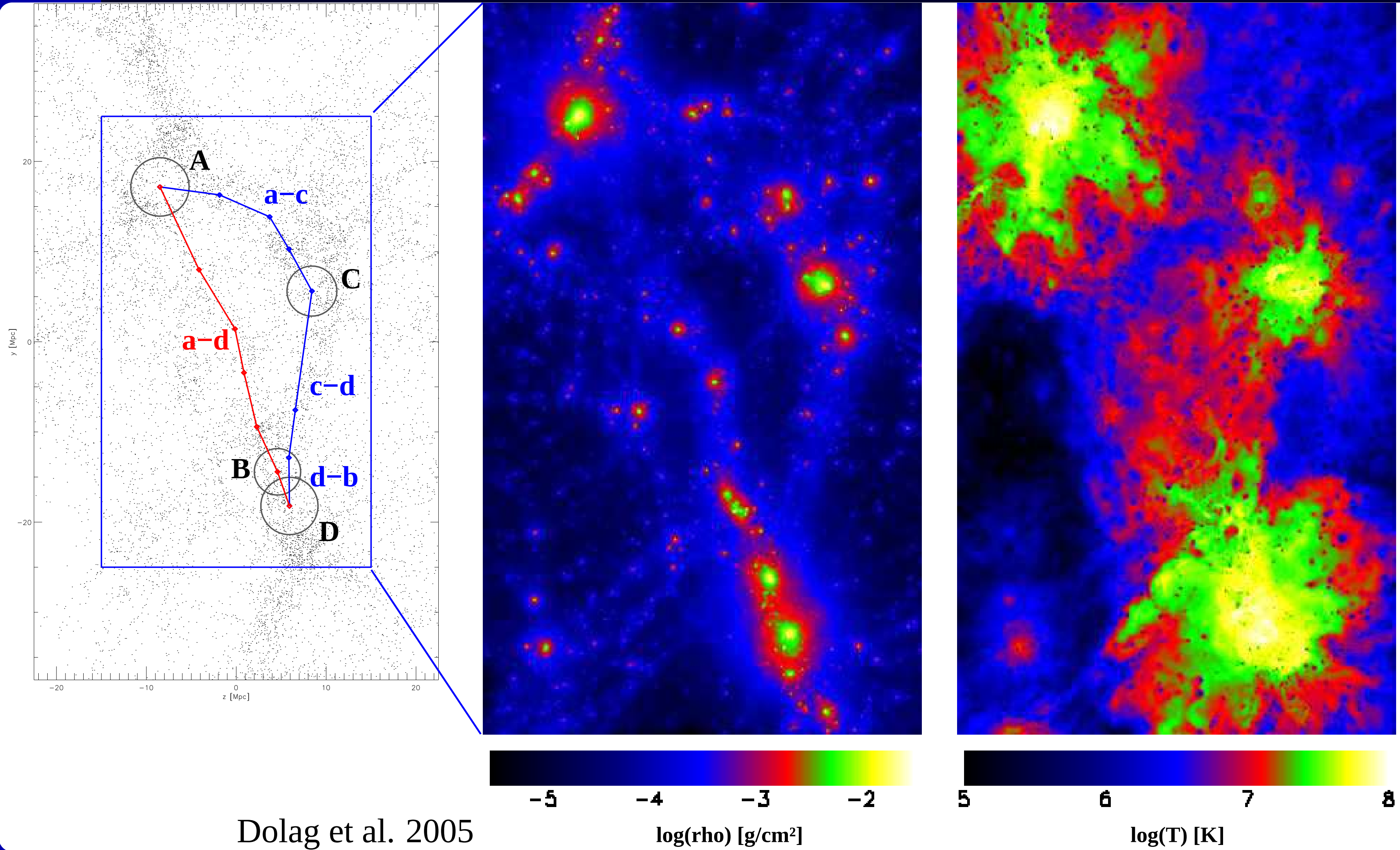
1. Filaments per Halo





Number of Filaments arround halos (BA, Szymon Styrnik)

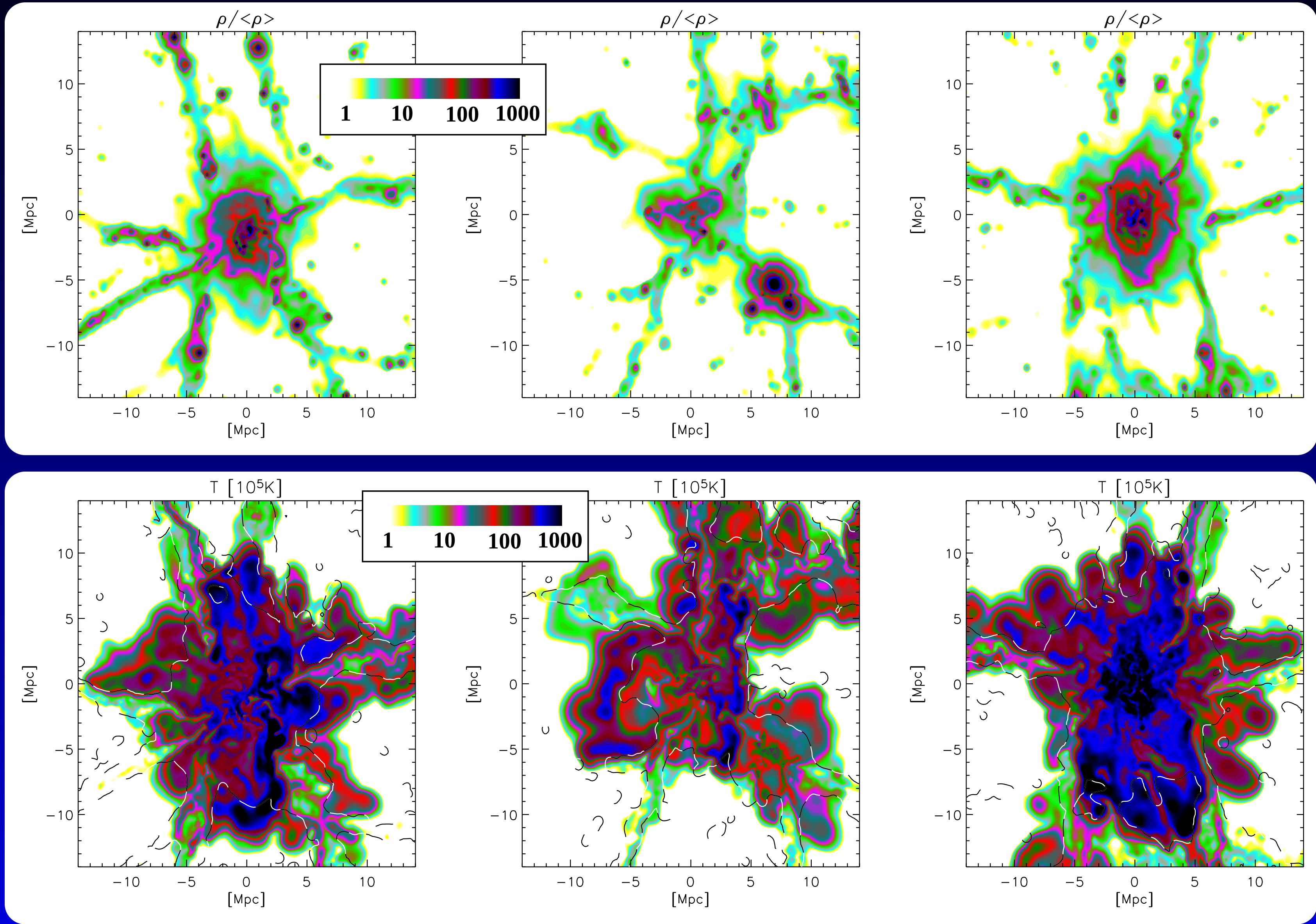
2. An example Filament



Dolag et al. 2005

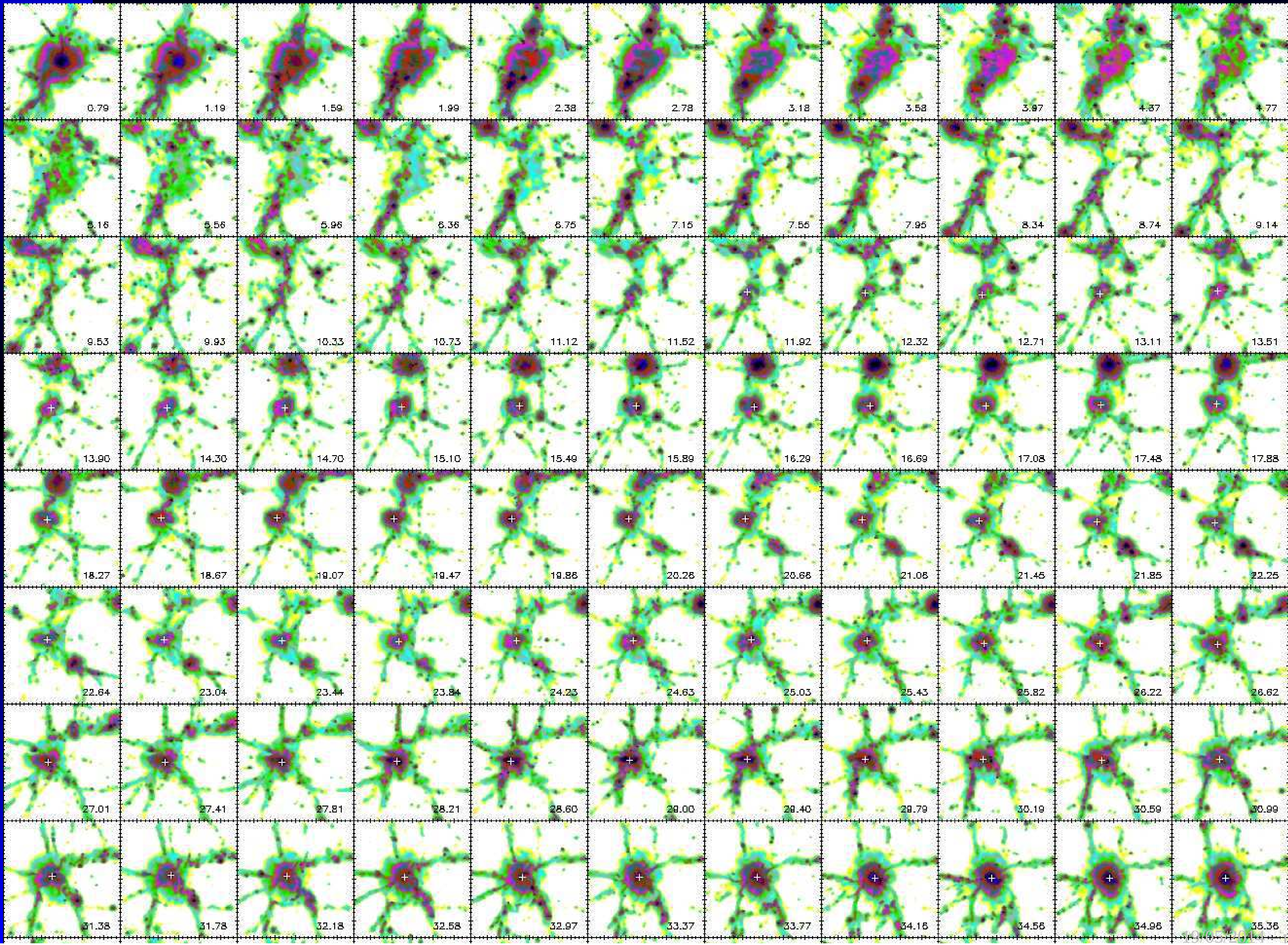
Filaments connecting massive galaxy clusters (environment).

2. An example Filament

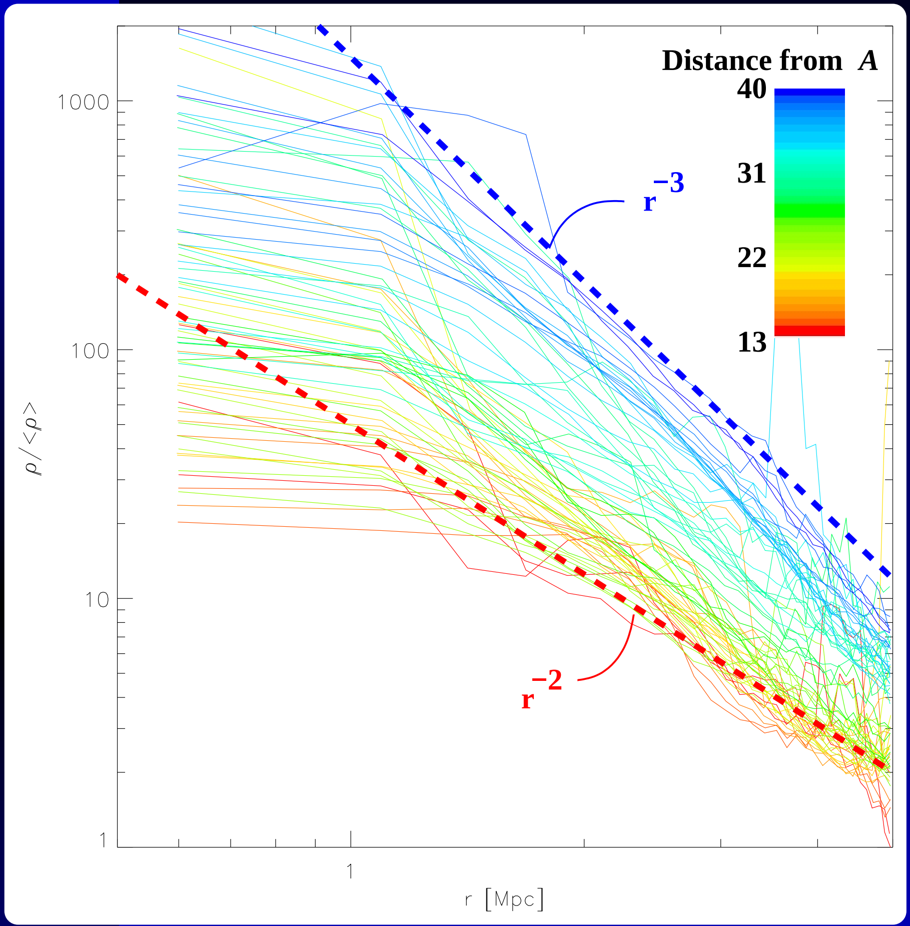


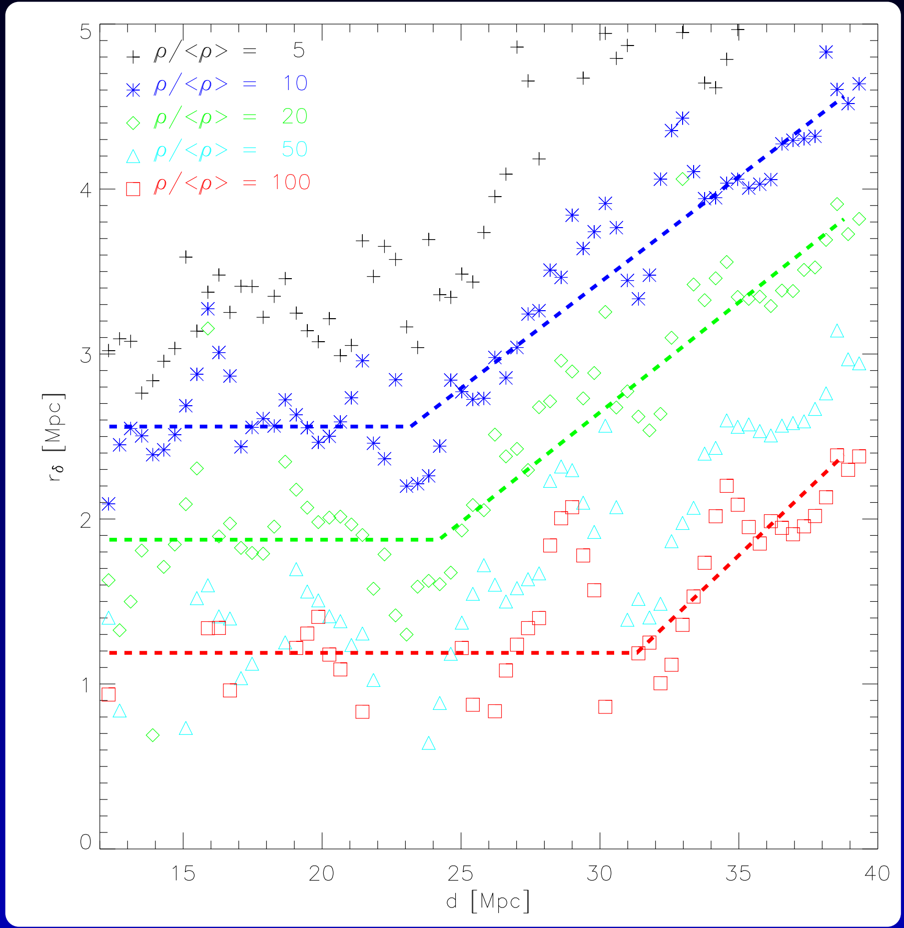
Density dominates over sheets till ≈5 Mpc.
Higher temperature in the outskirts / towards voids.

2. An example Filament



2. An example Filament

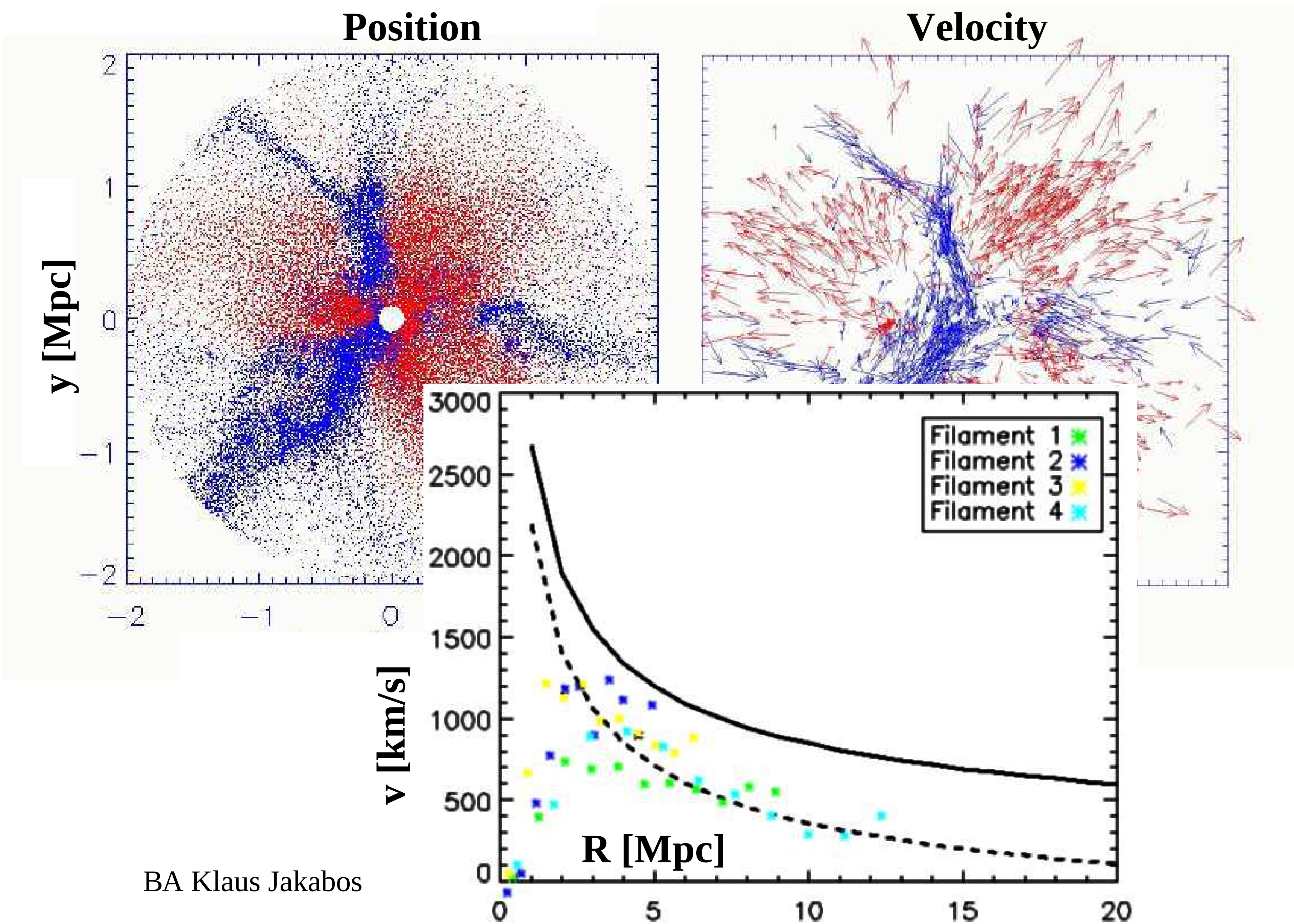




Radial density profile along the filament.

- Filament $\propto r^{-2}$, Cluster $\propto r^{-3}$, Outskirts steeper ($\propto r^{-4}$?)
- Cluster felt at $\approx$ 15 Mpc, region of influence 3-5 R_{vir} !?

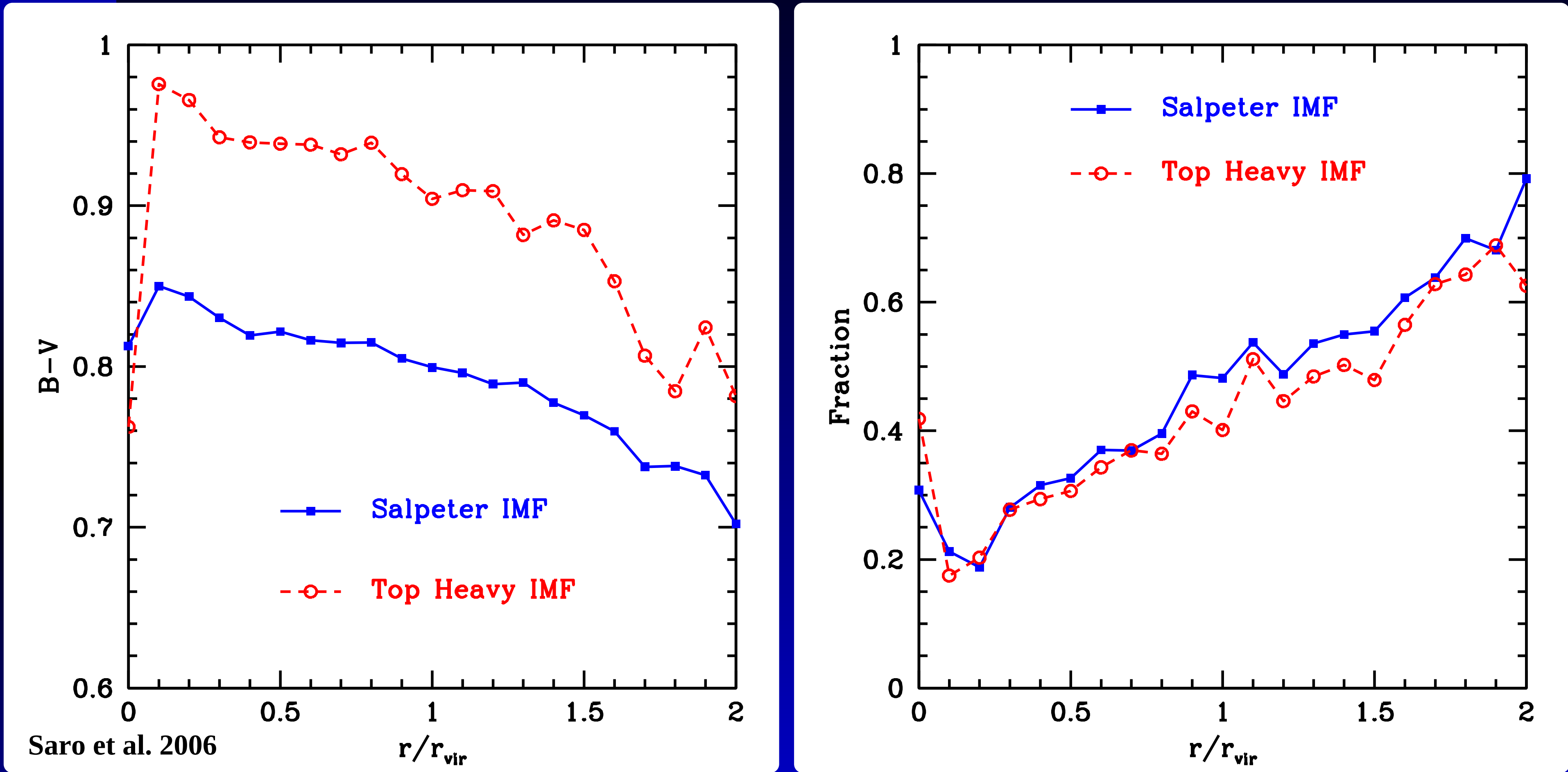
2. An example Filament



BA Klaus Jakabos

2. An example Filament

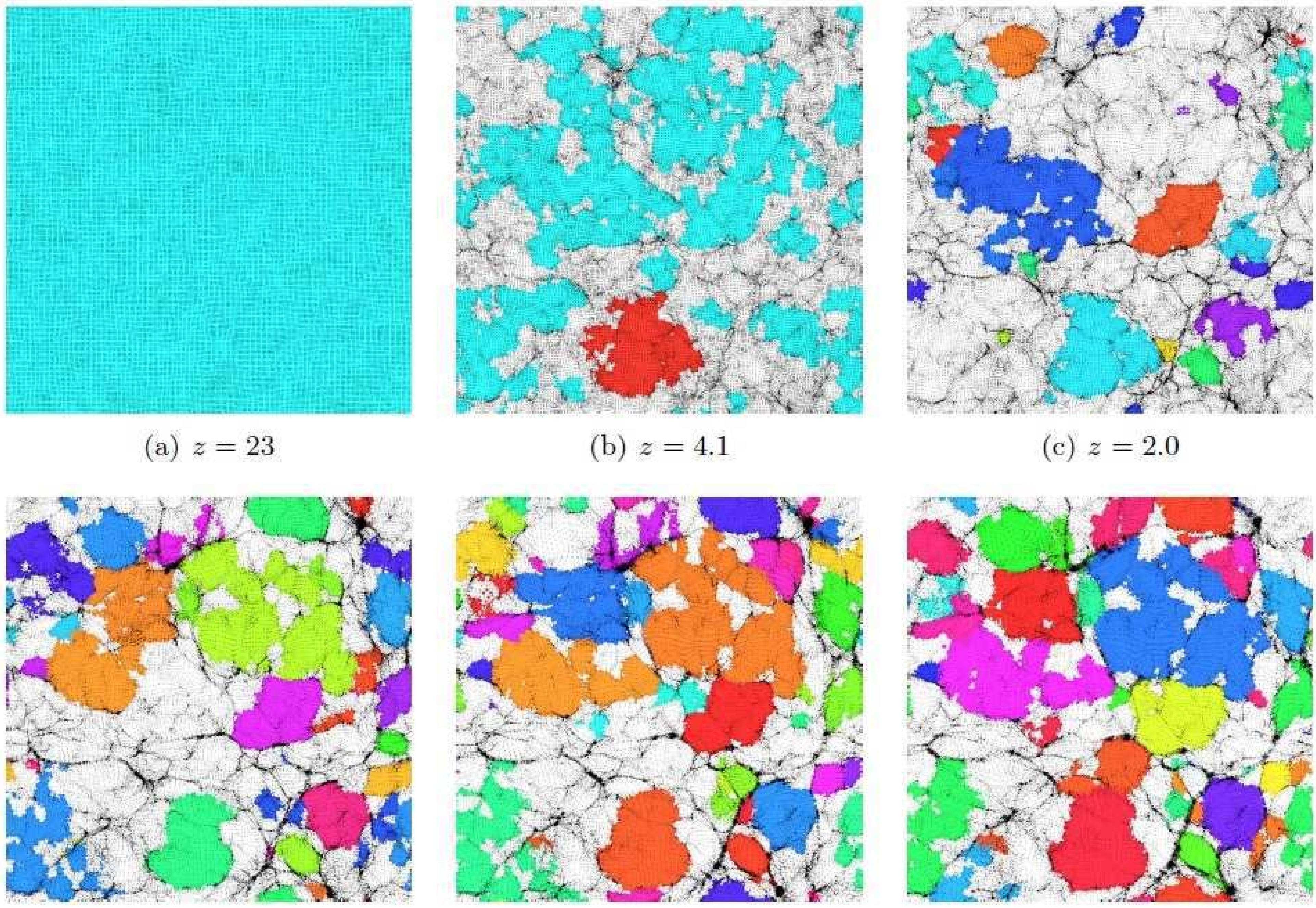
Environmental effects in hydrodynamical simulations:



Properties of galaxies from hydrodynamical simulations.
Galaxies feel environment at 3 R_{vir} and bejond !

- ⇒ General observational trends are naturally reproduced.
- ⇒ Details depend on IMF (and maybe on other parameters).

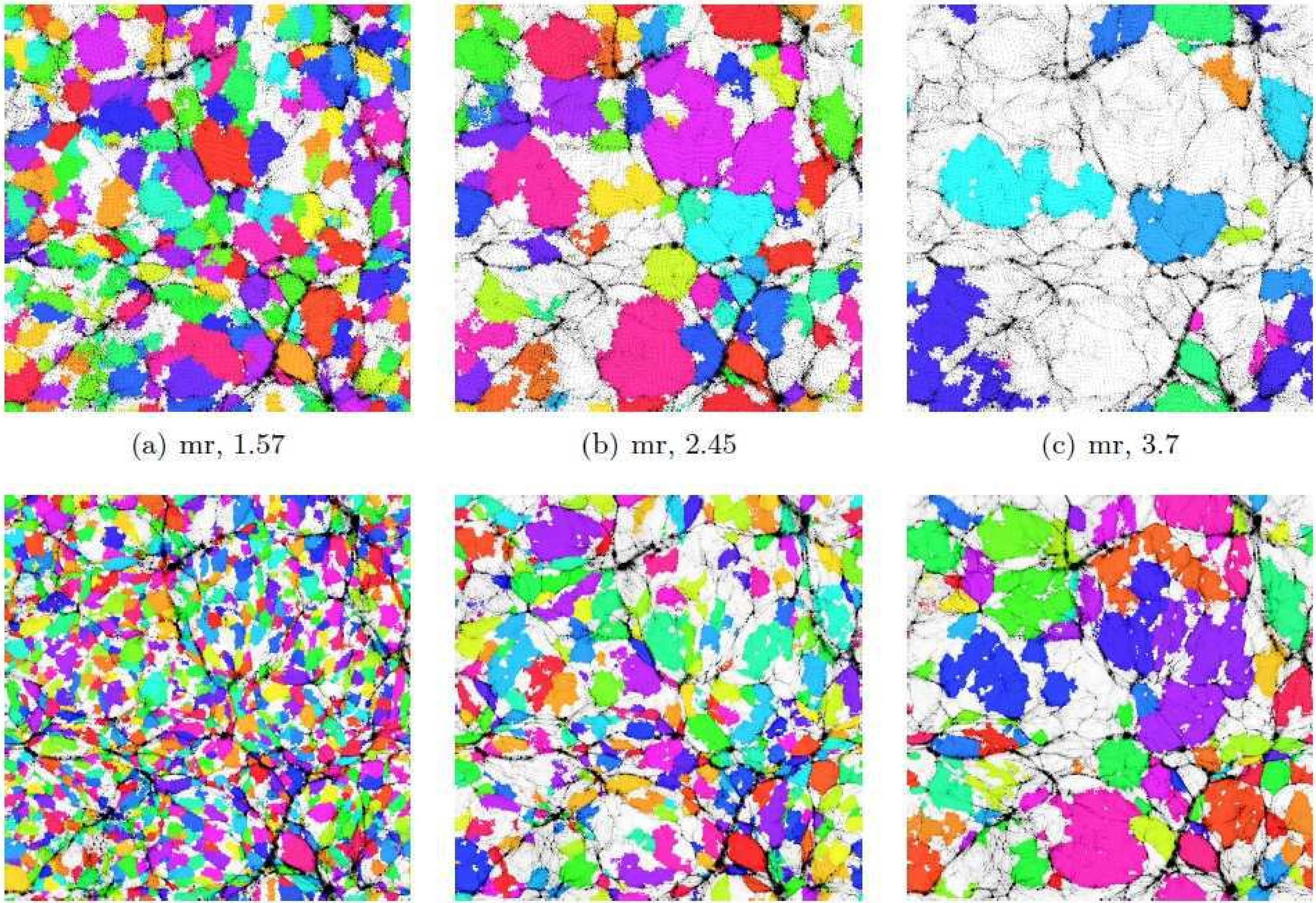
ZOBOV Voids



(a) $z = 23$ (b) $z = 4.1$ (c) $z = 2.0$

(d) $z = 0.78$ (e) $z = 0.34$ (f) $z = 0$

ZOBOV Voids

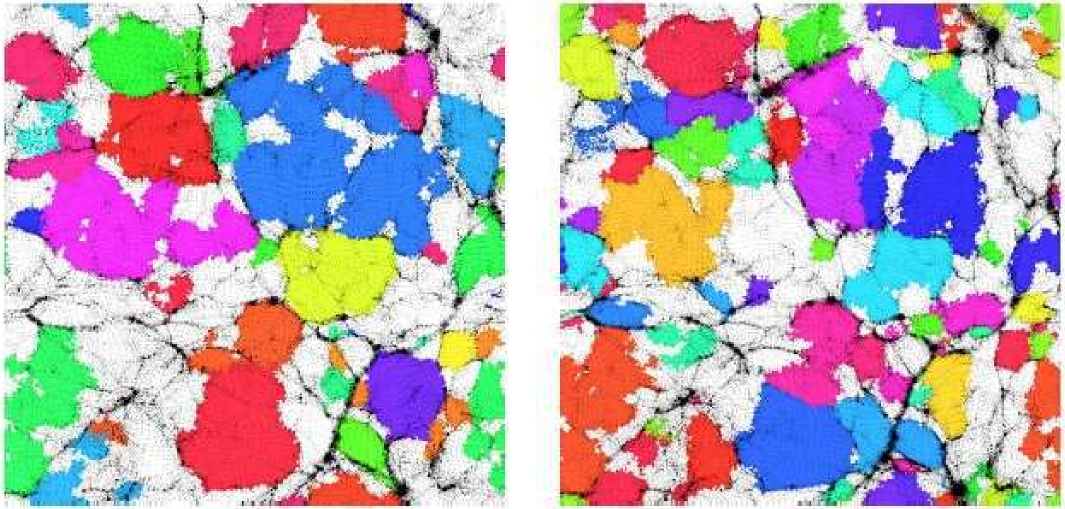


(a) mr, 1.57 (b) mr, 2.45 (c) mr, 3.7

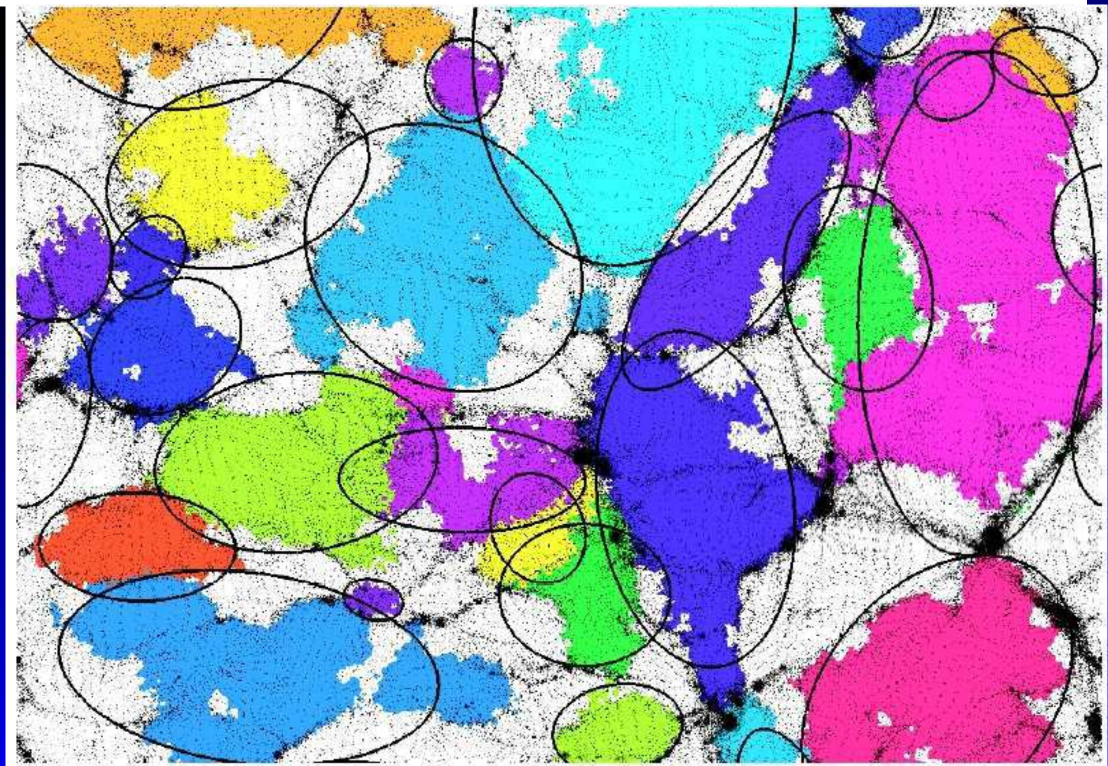
(d) hr, 1.57 (e) hr, 2.45 (f) hr, 3.7

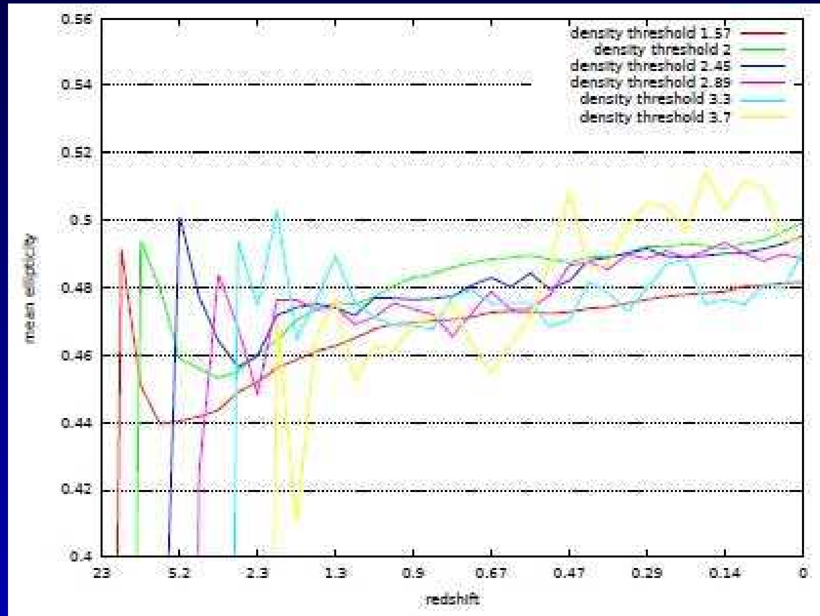
BA Florian Stecker

ZOBOV Voids



(a) dark matter (b) gas





BA Florian Stecker

ZOBOV Voids

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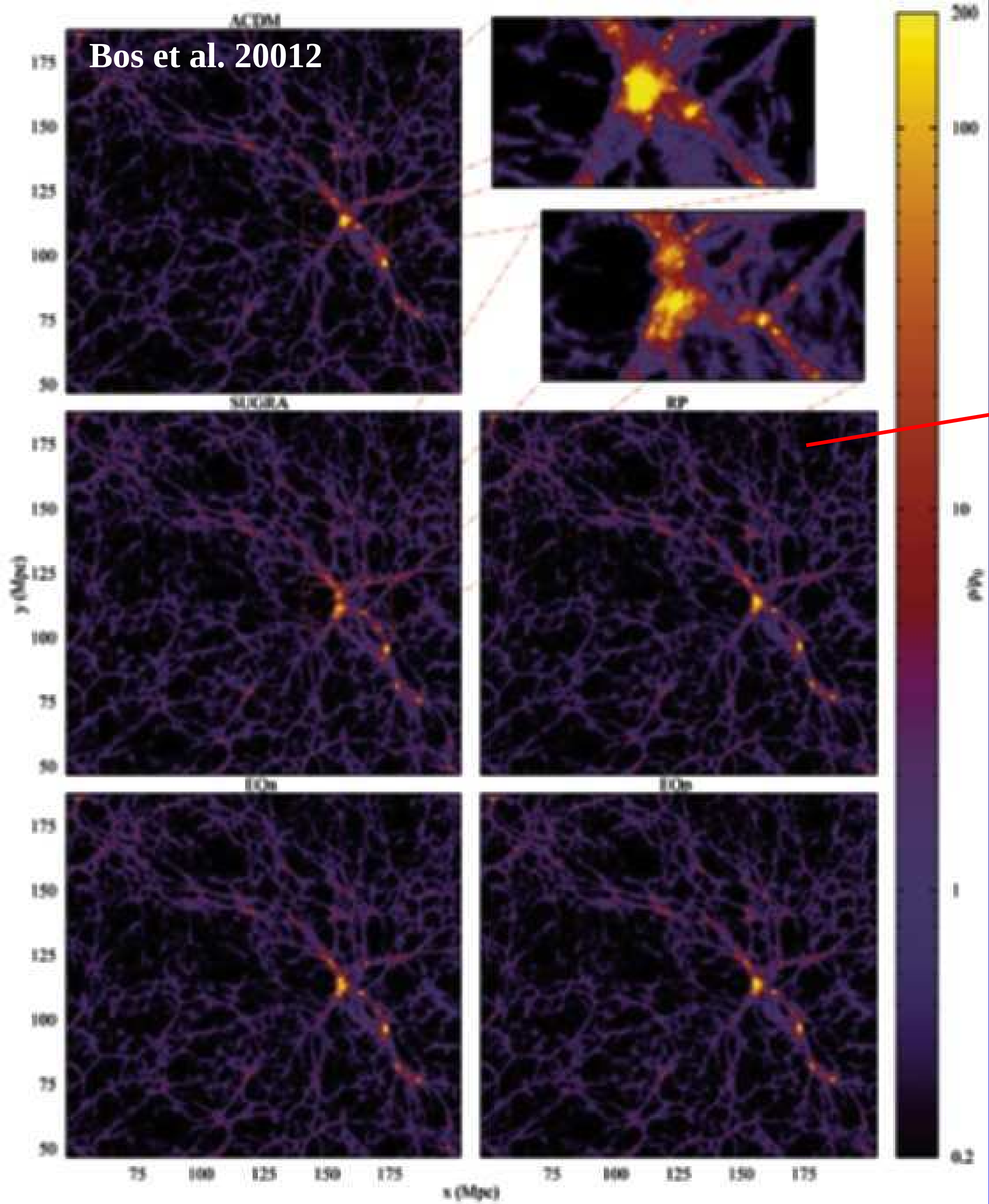
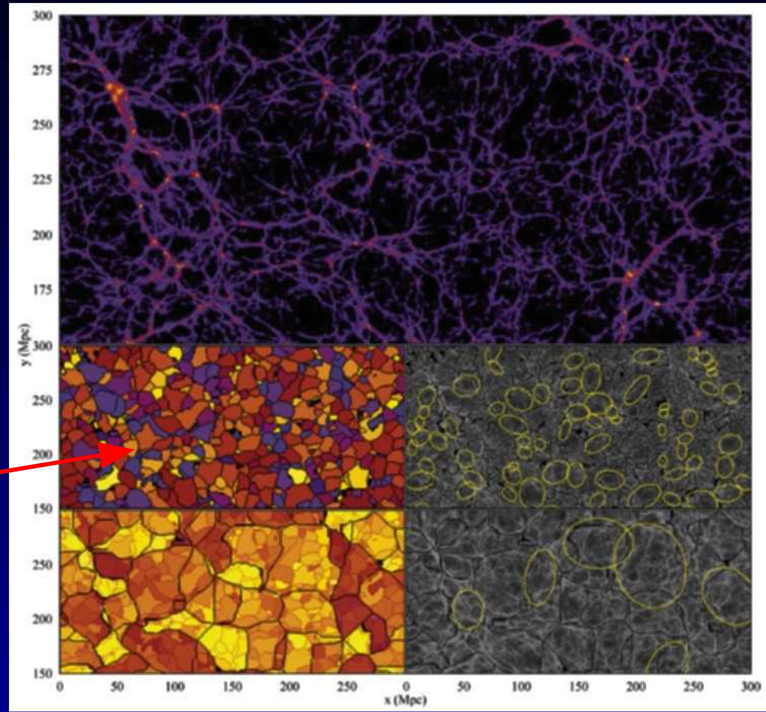
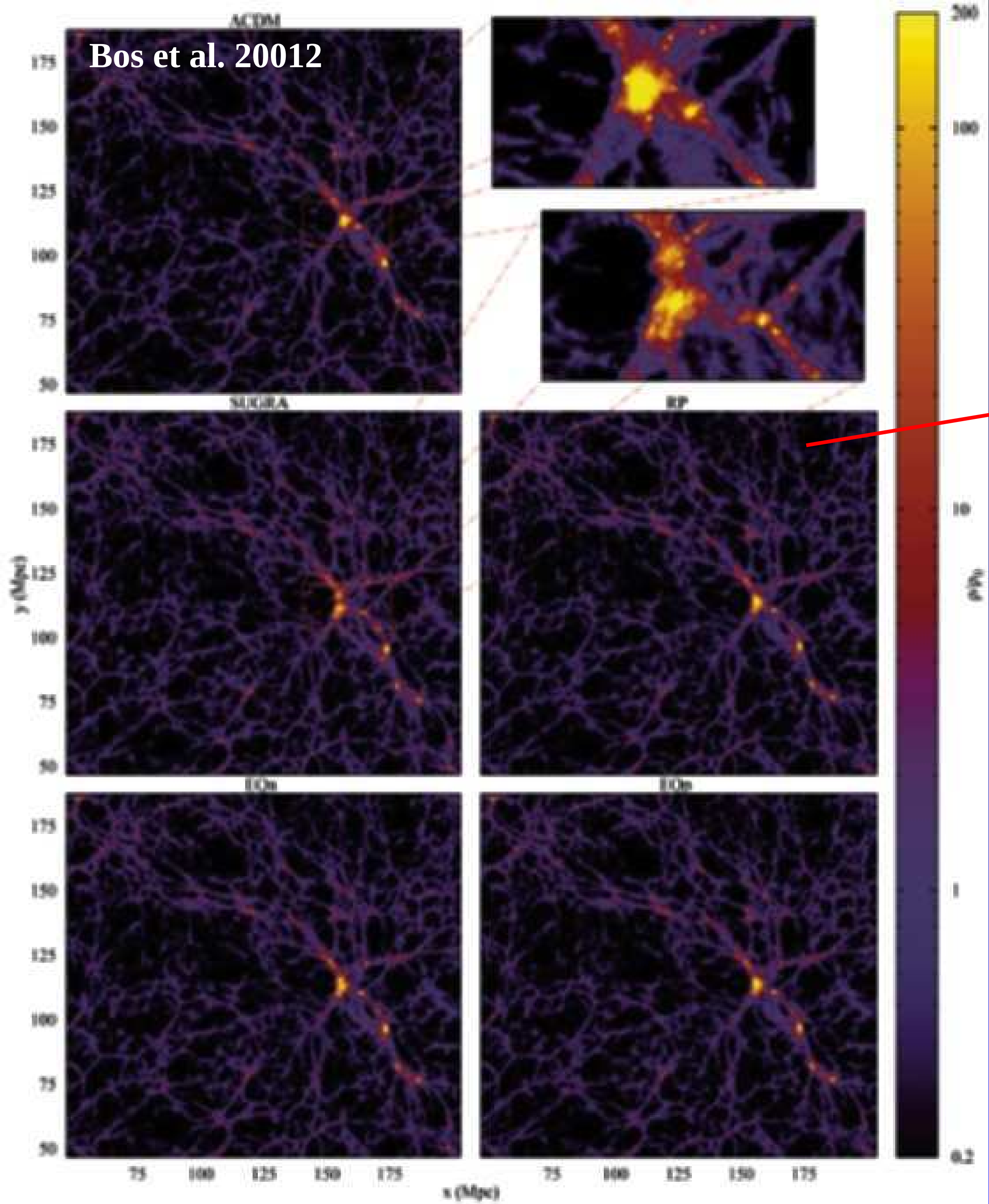
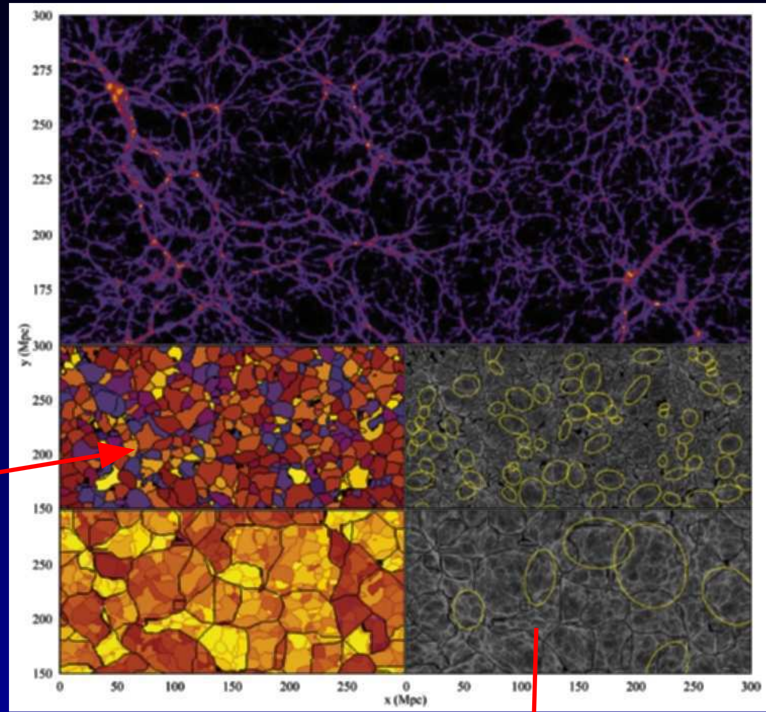
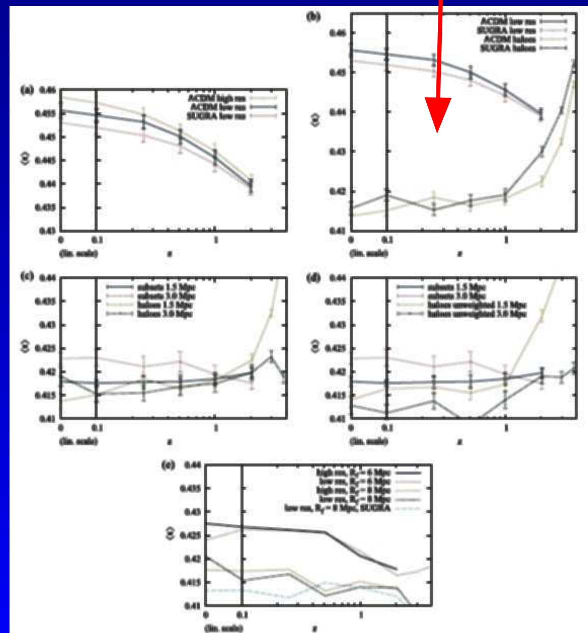

Bos et al. 20012
ΛCDM
SUGRA
RP
175
150
125
100
75
50
x (Mpc)
y (Mpc)
200
100
10
1
0.2


300
275
250
225
200
175
150
y (Mpc)
x (Mpc)
0
50
100
150
200
250
300

ZOBOV Voids







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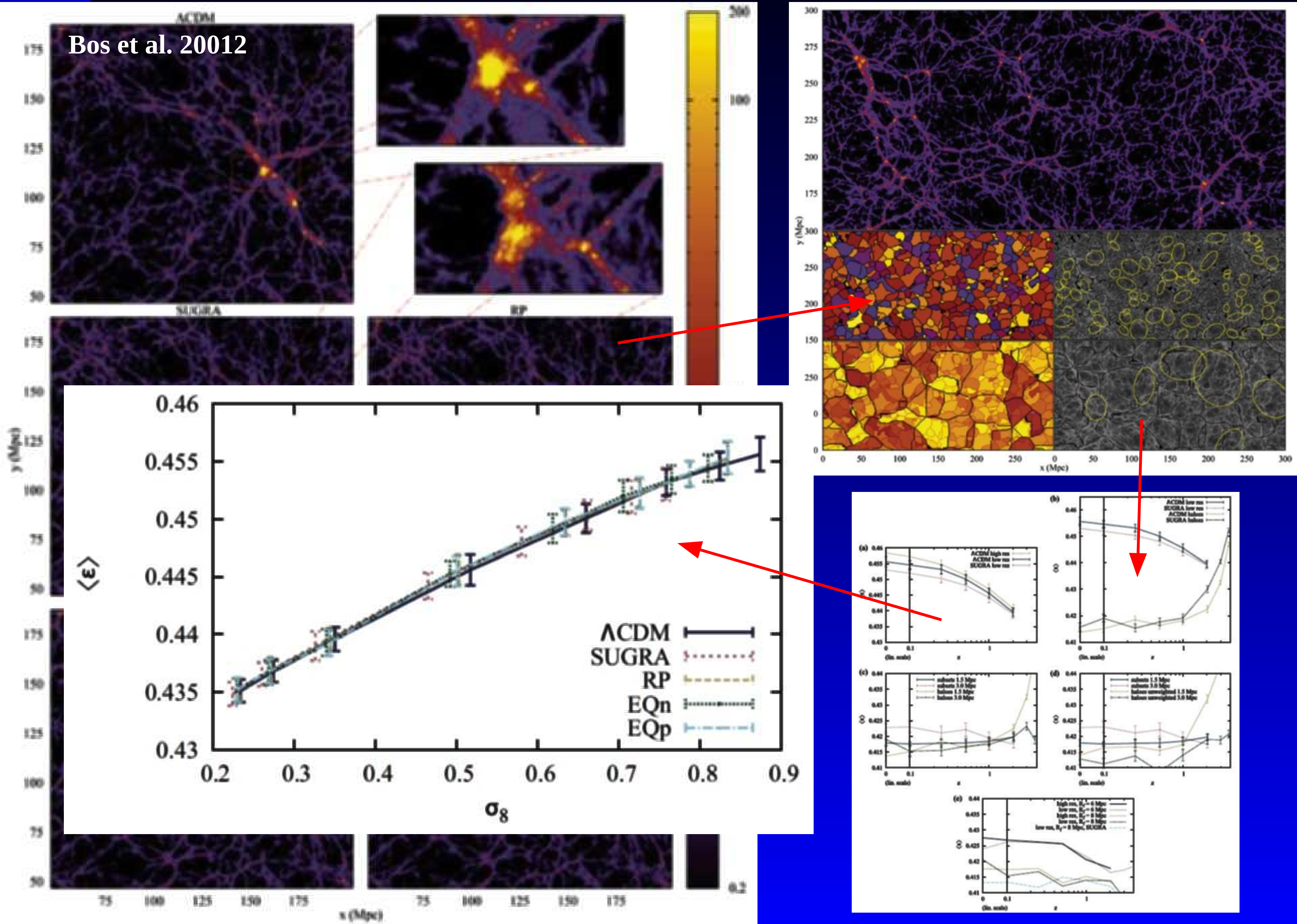
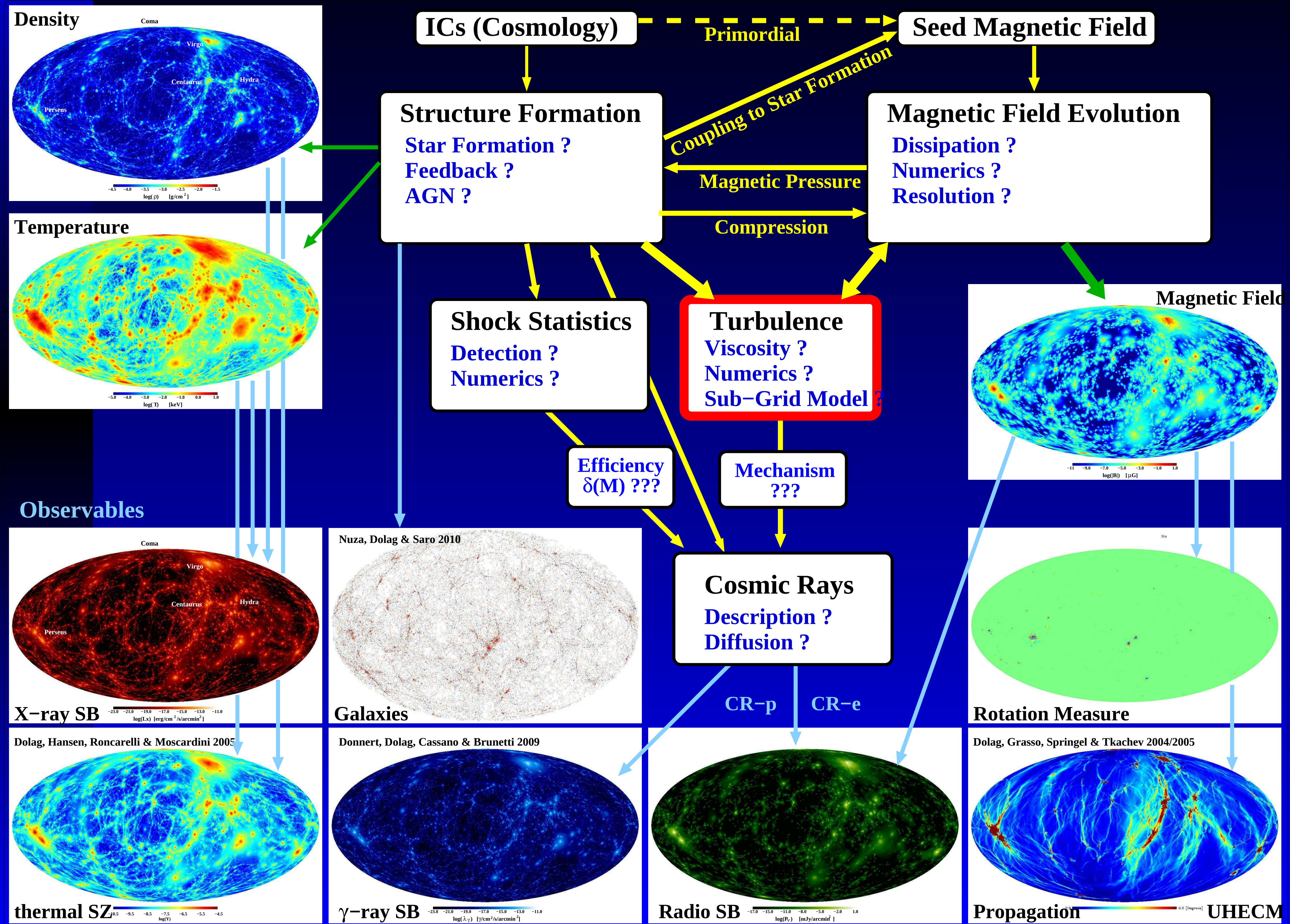
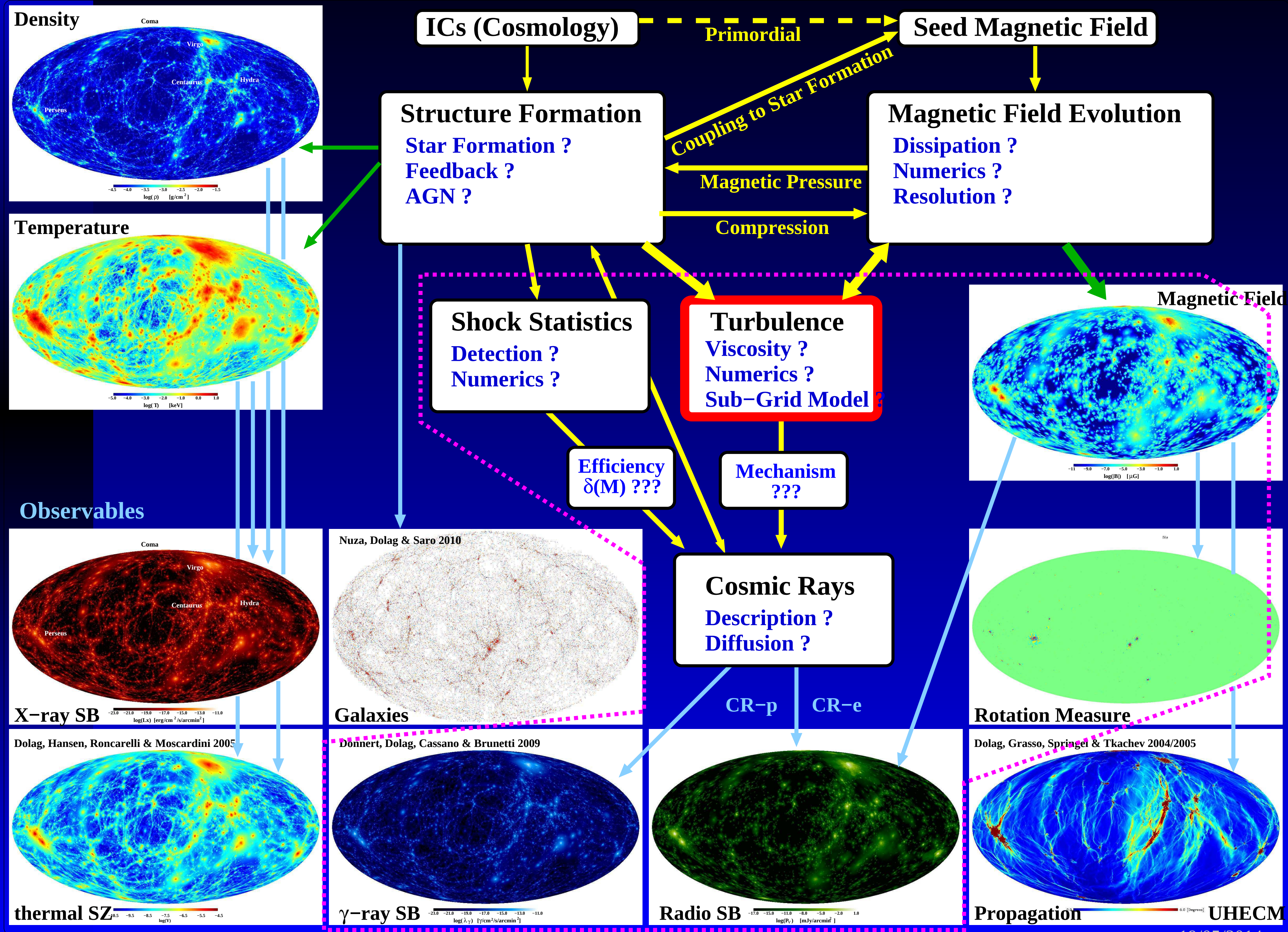


Bos et al. 20012
ΛCDM
SUGRA
RP
0.46
0.455
0.45
0.445
0.44
0.435
0.43
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
⟨ε⟩
σ8
ΛCDM
SUGRA
RP
EQn
EQp

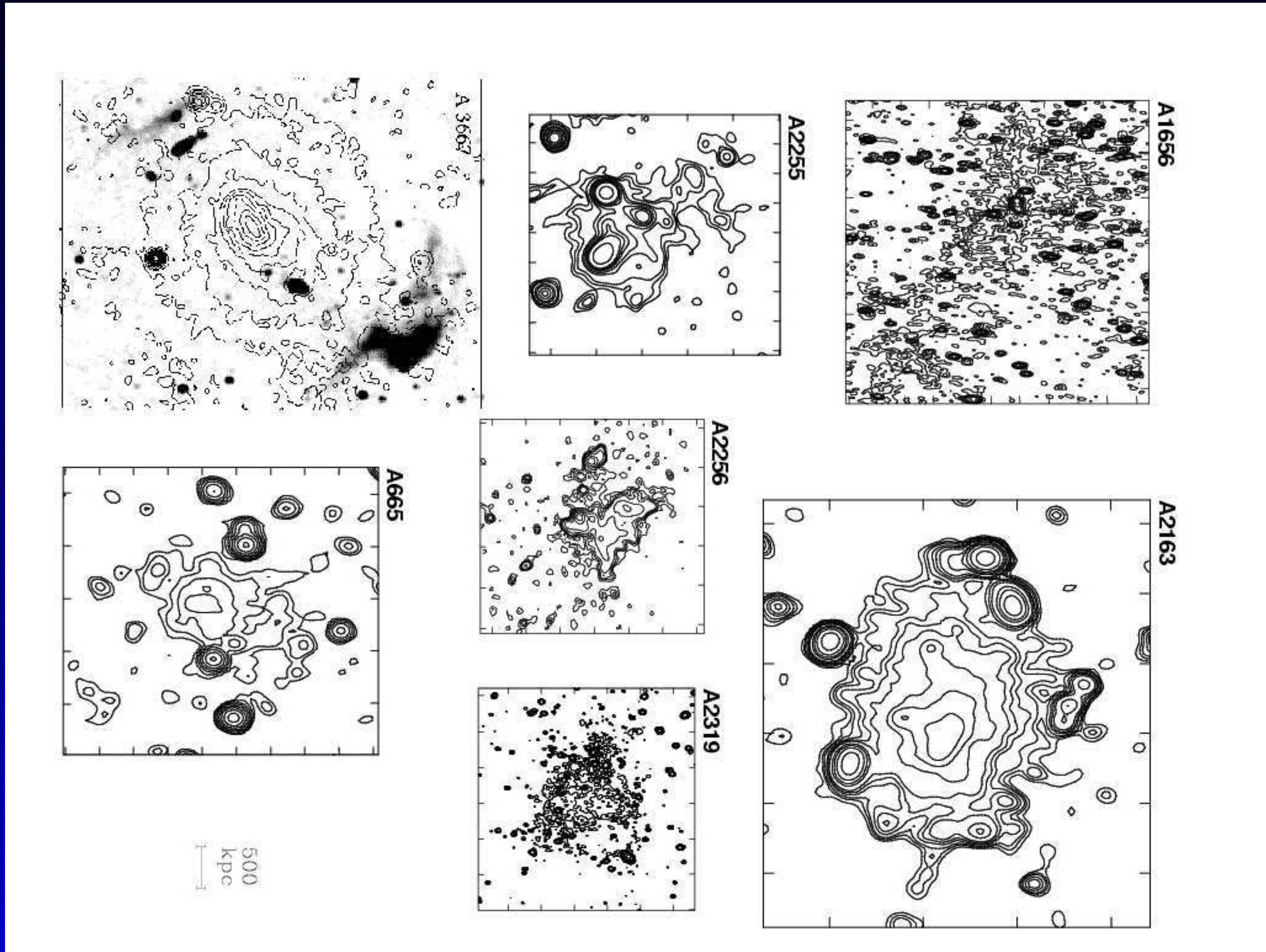
Process Network



Process Network

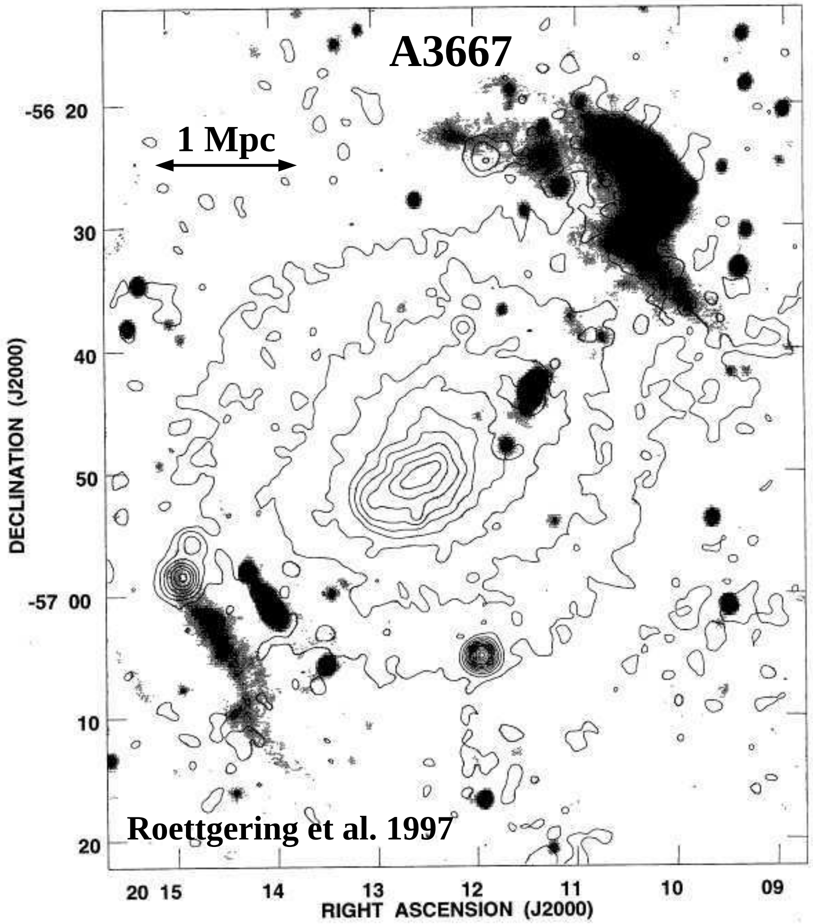


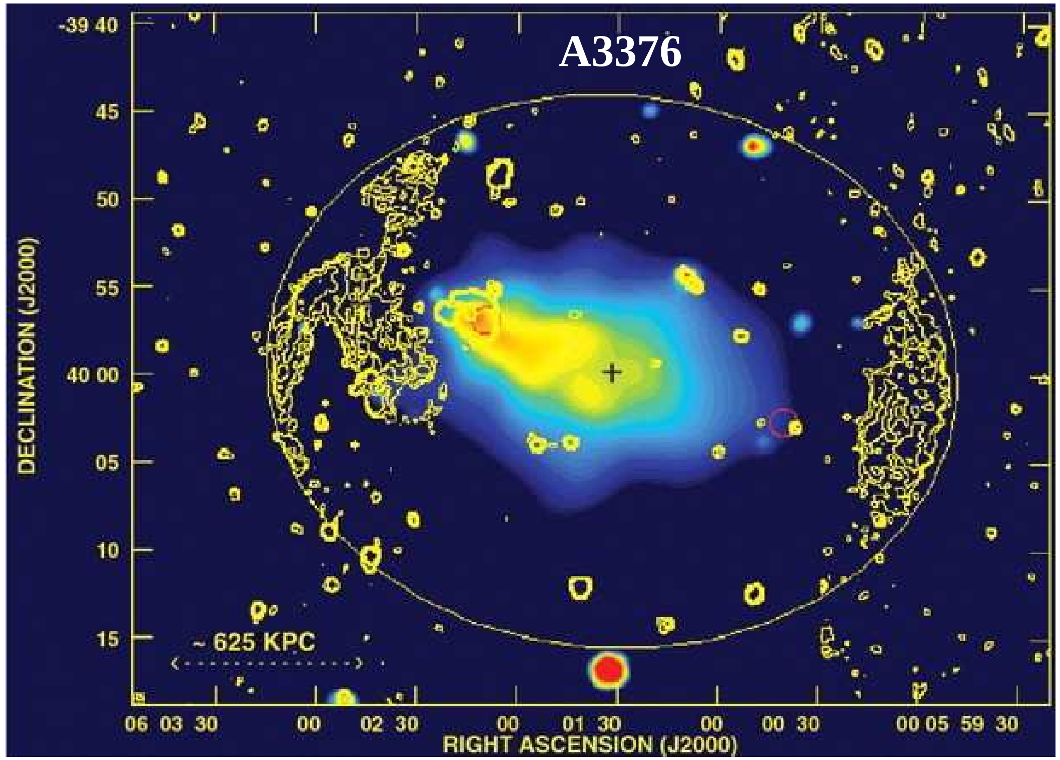
Radio Clusters



Cluster wide diffuse synchrotron emission (radio halos) of relativistic electrons in cluster magnetic fields. **Origin of relativistic electrons** (secondary, shocks, turbulence, ...) ?

Radio Clusters





Bagchi et al. 2006

Peripheral synchrotron emission (radio relics) of A3667 (left) and A3376 (right).

- Related to **merger** or accretion **shock** ?
- Acceleration of electrons in shock ?
- Revival of (old) relativistic plasma ?

Magnetic Field Questions

- Strength, Structure, Origin, Evolution

$\Rightarrow$ Common Origin ?
Filament vs. Cluster, Cluster vs. cool Core, ...

$\Rightarrow$ Relation to other LSS ”properties” ?

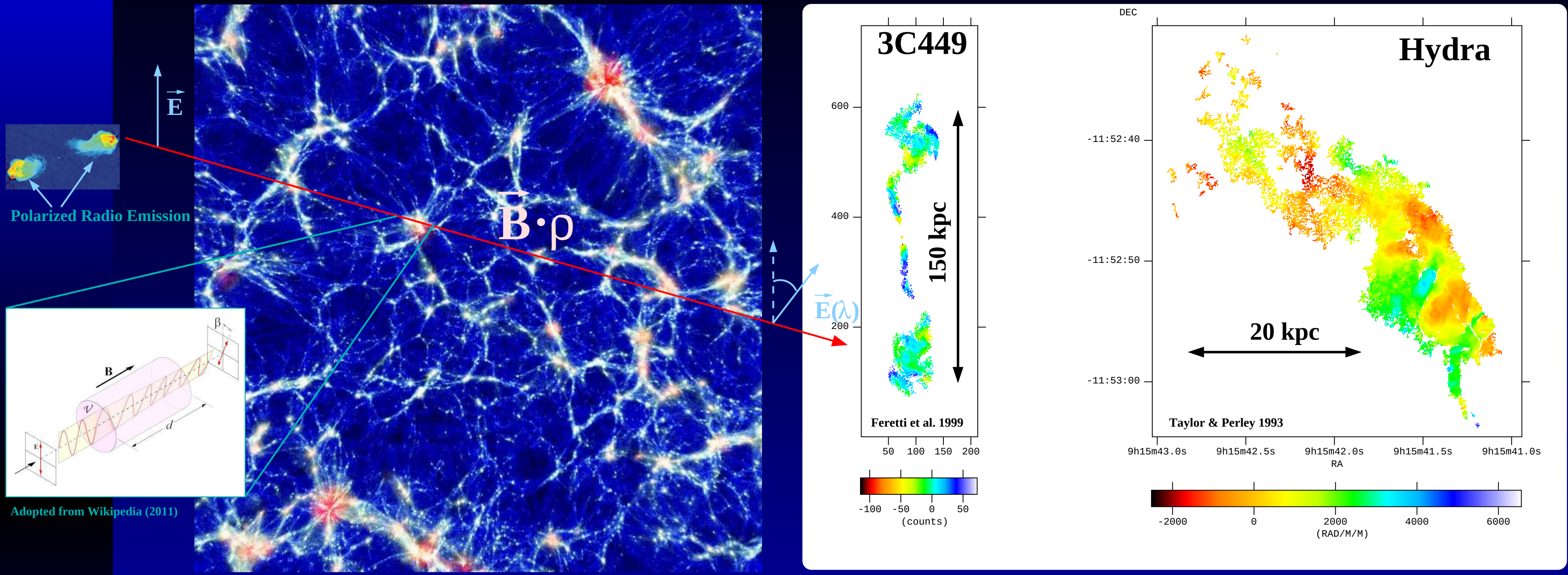
  - scaling with density ($\propto \rho^{\alpha}$) ?
  - scaling with temperature/mass ($\propto T^{\beta}$) ?
  - length scales, $P_B(k)$ (Filaments, Cluster, cool Core) ?

$\Rightarrow$ Relation to dynamics ?

  - Merger, Turbulence, cool Core, Bubbles ?

- Observations:
  - RM in clusters
  - Radio emission (halo and relics)

What do we know ?



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

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

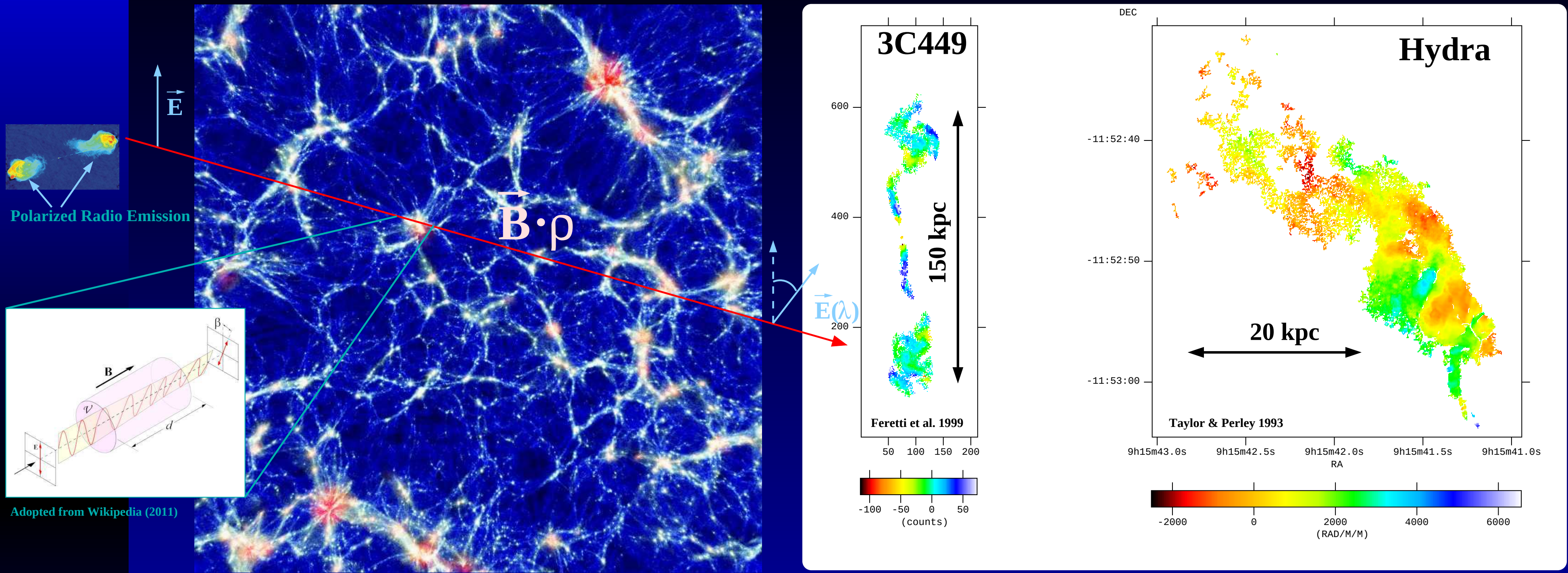
≈20 Years ago:

$<$ 10 extended RM sources within clusters

$<$ 100 point sources behind various clusters

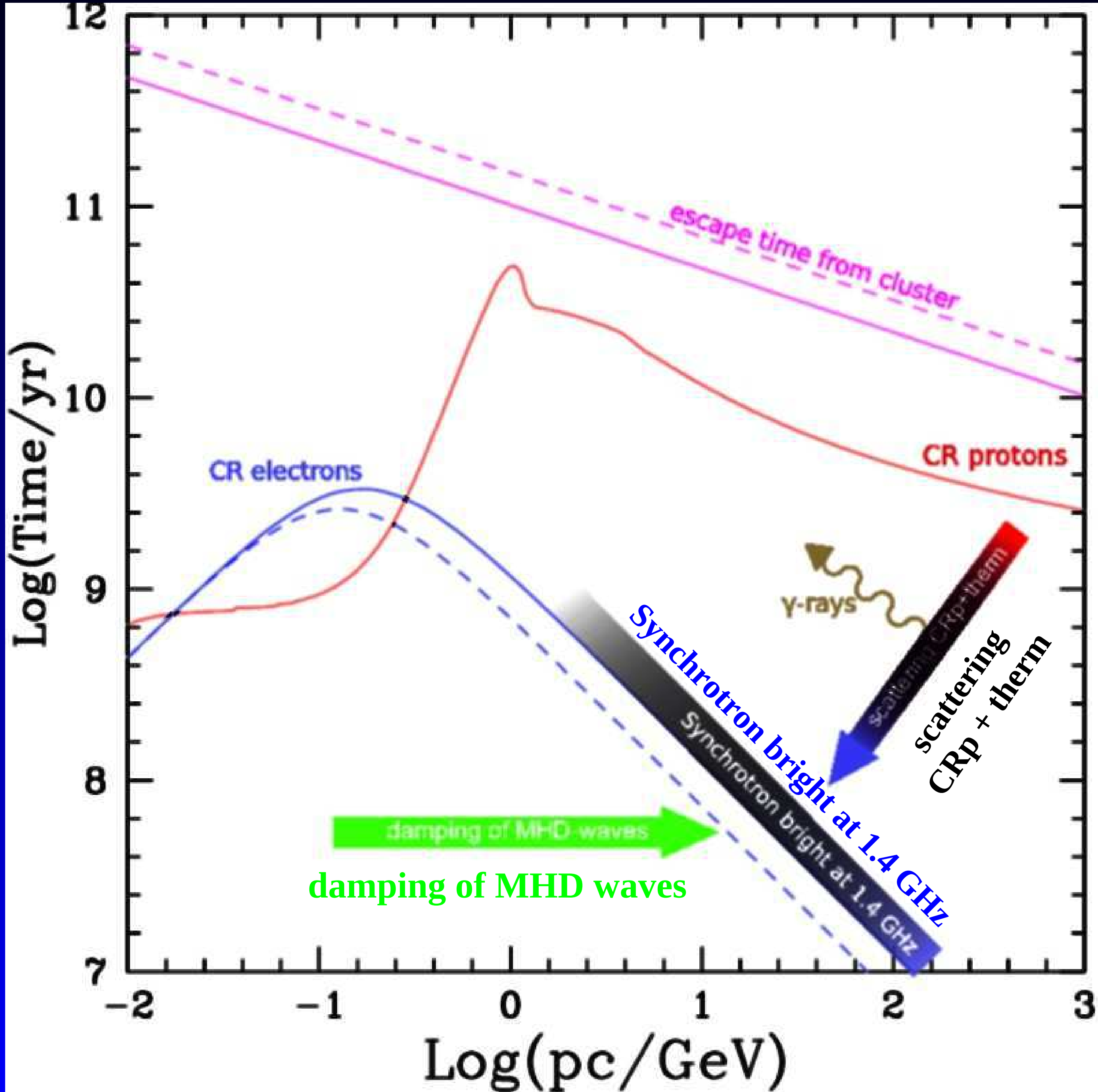
$\Rightarrow$ very simplified models: $\sim (0.1 - 10)\mu\mathrm{G}$, $l \sim (4 - 100)\mathrm{kpc}$.

What do we know ?



- A119: $\vec{B}$ with radial declining profile and fixed power spectrum (Murgia et al. 2004)
- Hydra: direct reconstruction of power spectrum (e.g. $|B_k|^2$) (Vogt & Ensslin 2005, Kuchar & Ensslin 2010)
- A2255: $\vec{B}$ with radial declining profile and variable power spectrum (Govoni et al. 2006)
- Coma: RMs from 7 extended sources constraining magnetic field and power spectrum (Bonafede et al. 2009)
- A401, A2142, A2065, Ophiuchus: magnetic field for clusters with different temperature (Govoni et al. 2009)

What do we know ?

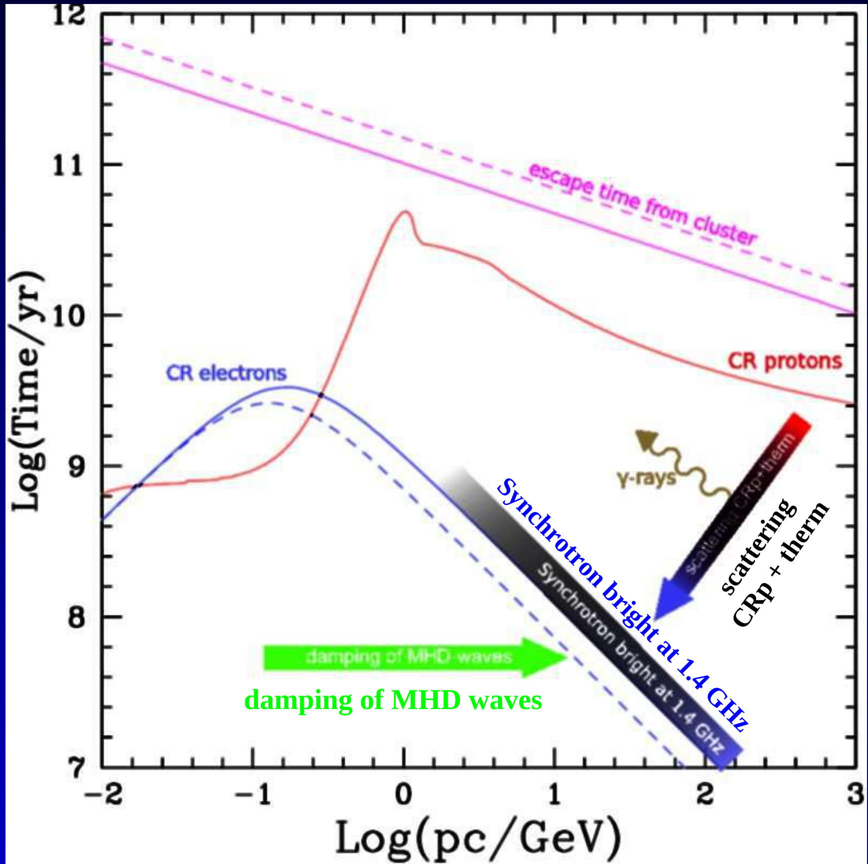


taken from Donnert 2013

What do we know ?

- Early work on radio halos (individual clusters)

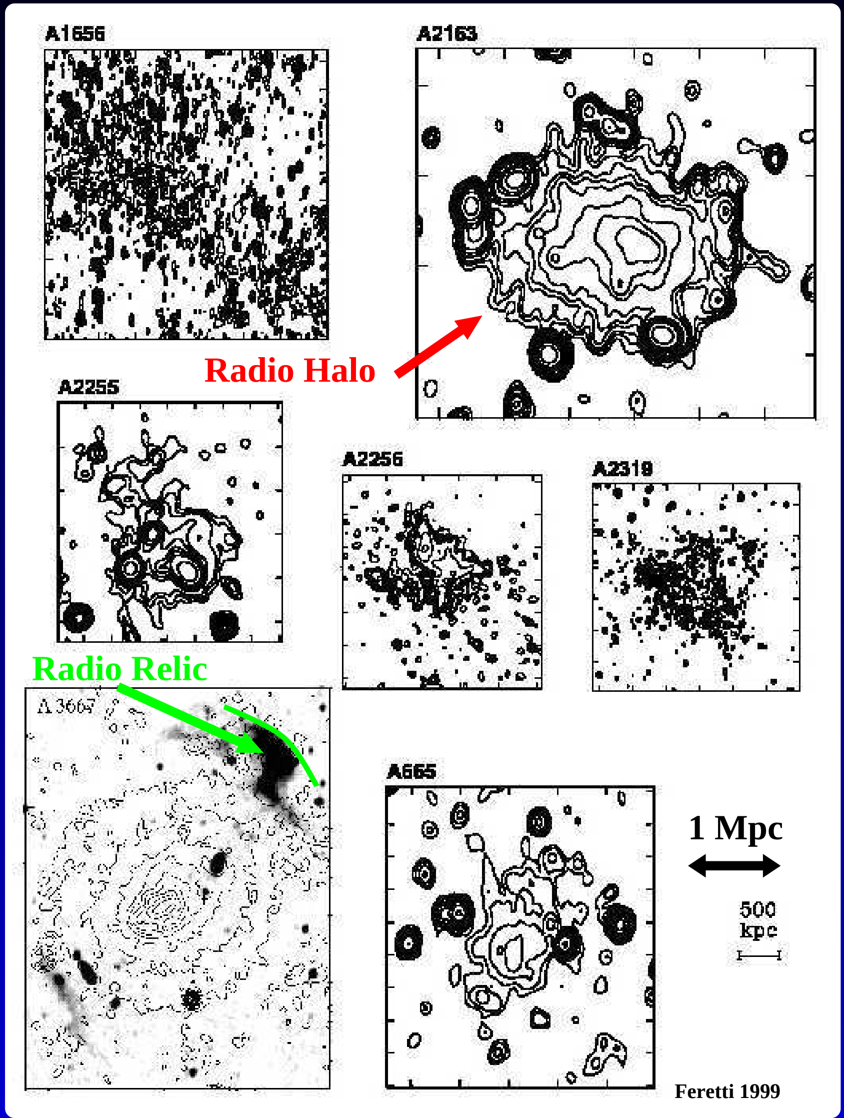
  ≈ 10 clusters with diffuse emission: $> (0.05 - 0.5)\mu G$

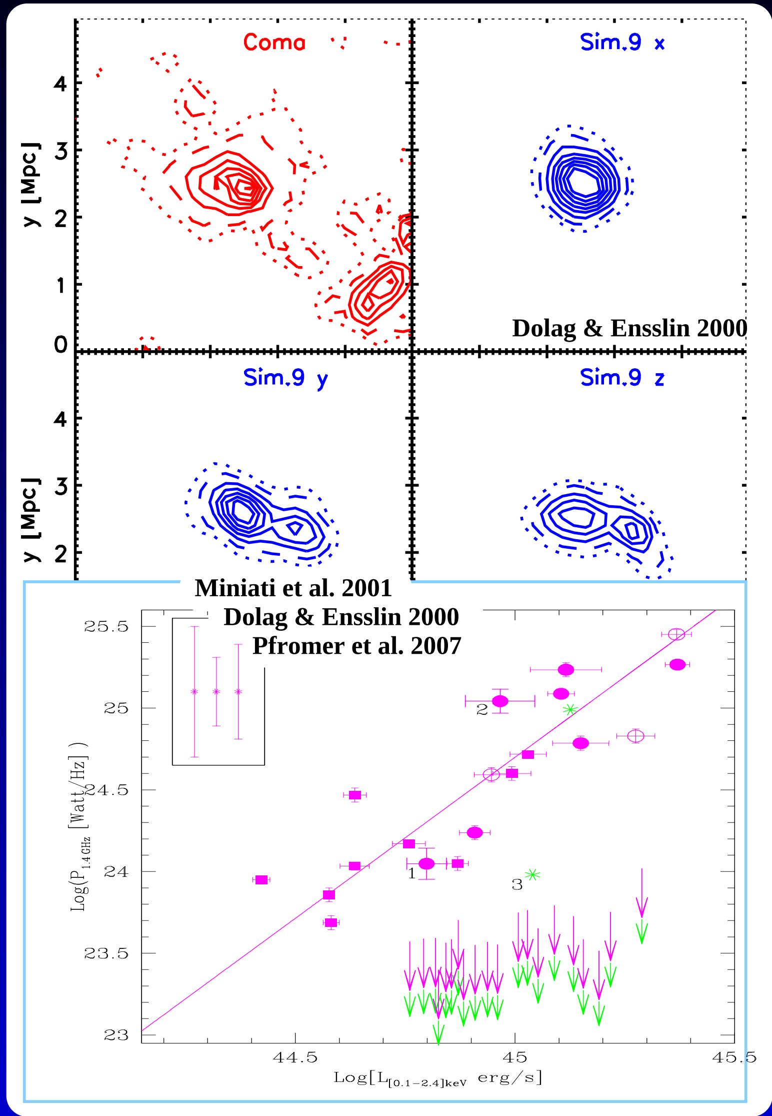


⇒ **Increased numbers and complexity:**

- Global spectral index steepening / local index maps
- Radial radio emission profile for many clusters
- Probability for clusters to host a radio halo

What do we know ?

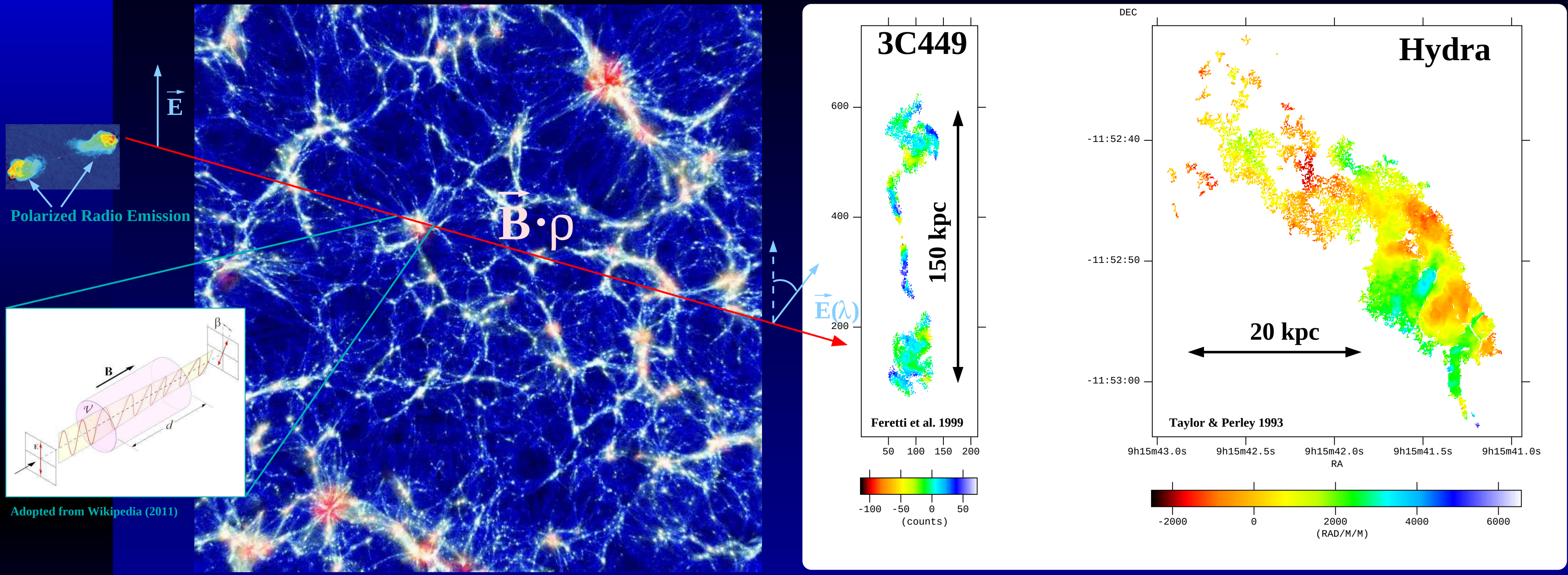




Cluster wide **diffuse synchrotron emission** connected to **merger** events, **periferal** emission directly connected to **shocks**.

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

Observations

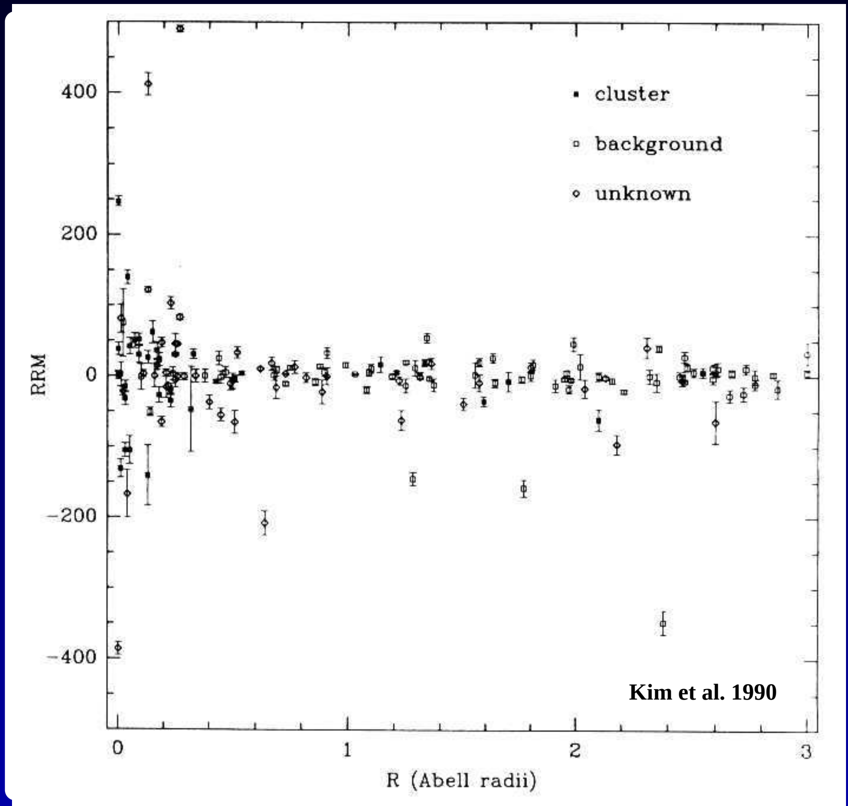


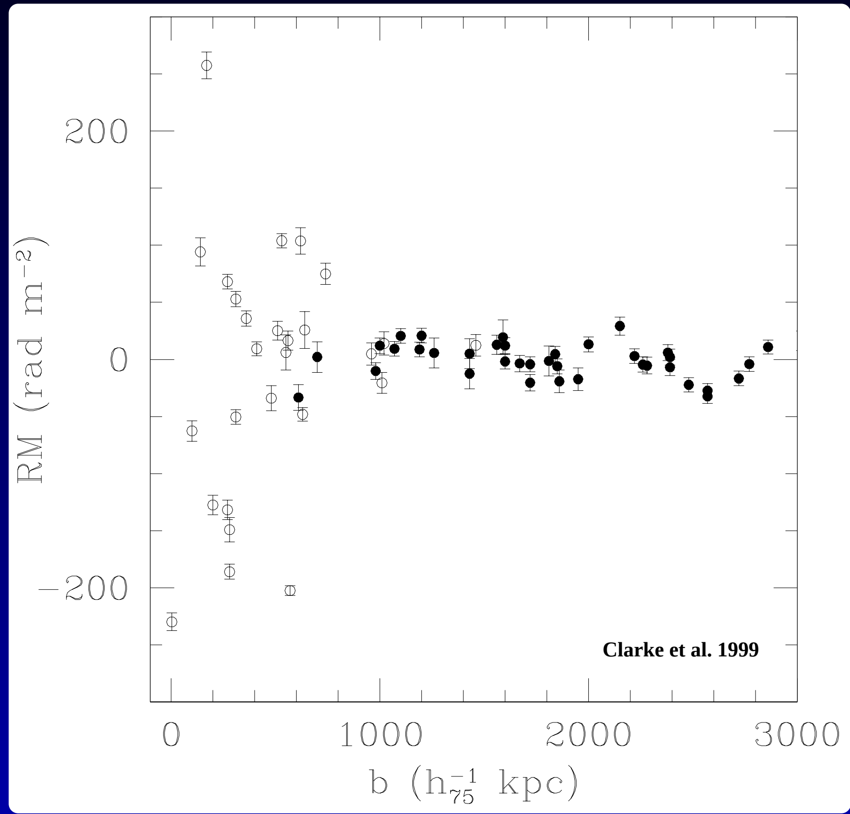
High quality Rotation Measure maps across the lobes of the central radio source in 3C449 (left) and Hydra (right).

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

- **Simple interpretation**
- **Direct inversion**
- **Modeling**

Observations



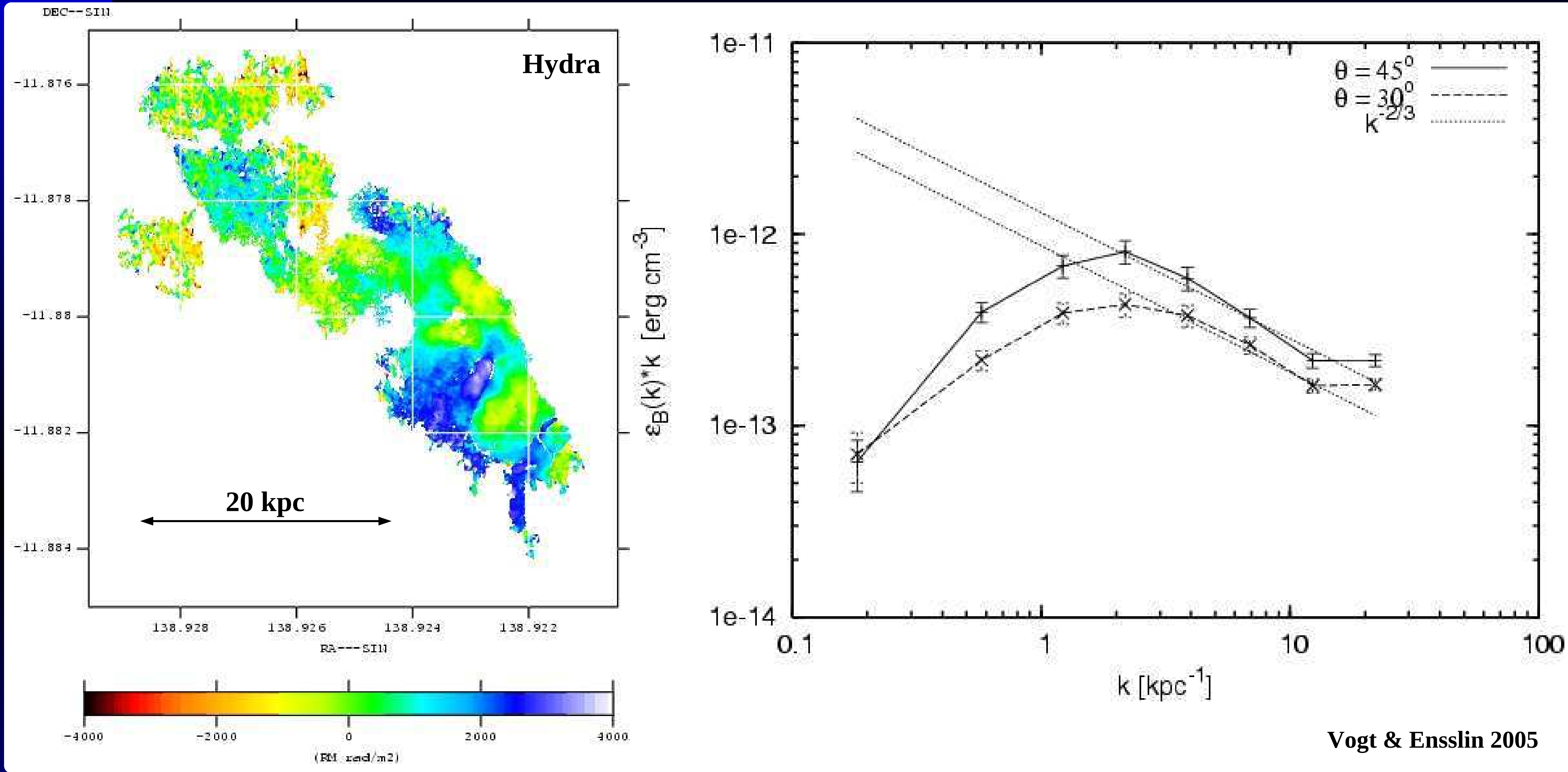


Rotation Measure as function of distance to the center of galaxy clusters.

$$\mathrm{RM} = 812\,\frac{\mathrm{rad}}{\mathrm{m}^2}\int \frac{n_\mathrm{e}}{\mathrm{cm}^{-3}}\,\frac{B_\parallel}{\mu\mathrm{G}}\,\frac{\mathrm{d}l}{\mathrm{kpc}}$$

Clear signature of **cluster magnetic fields** !

Observations

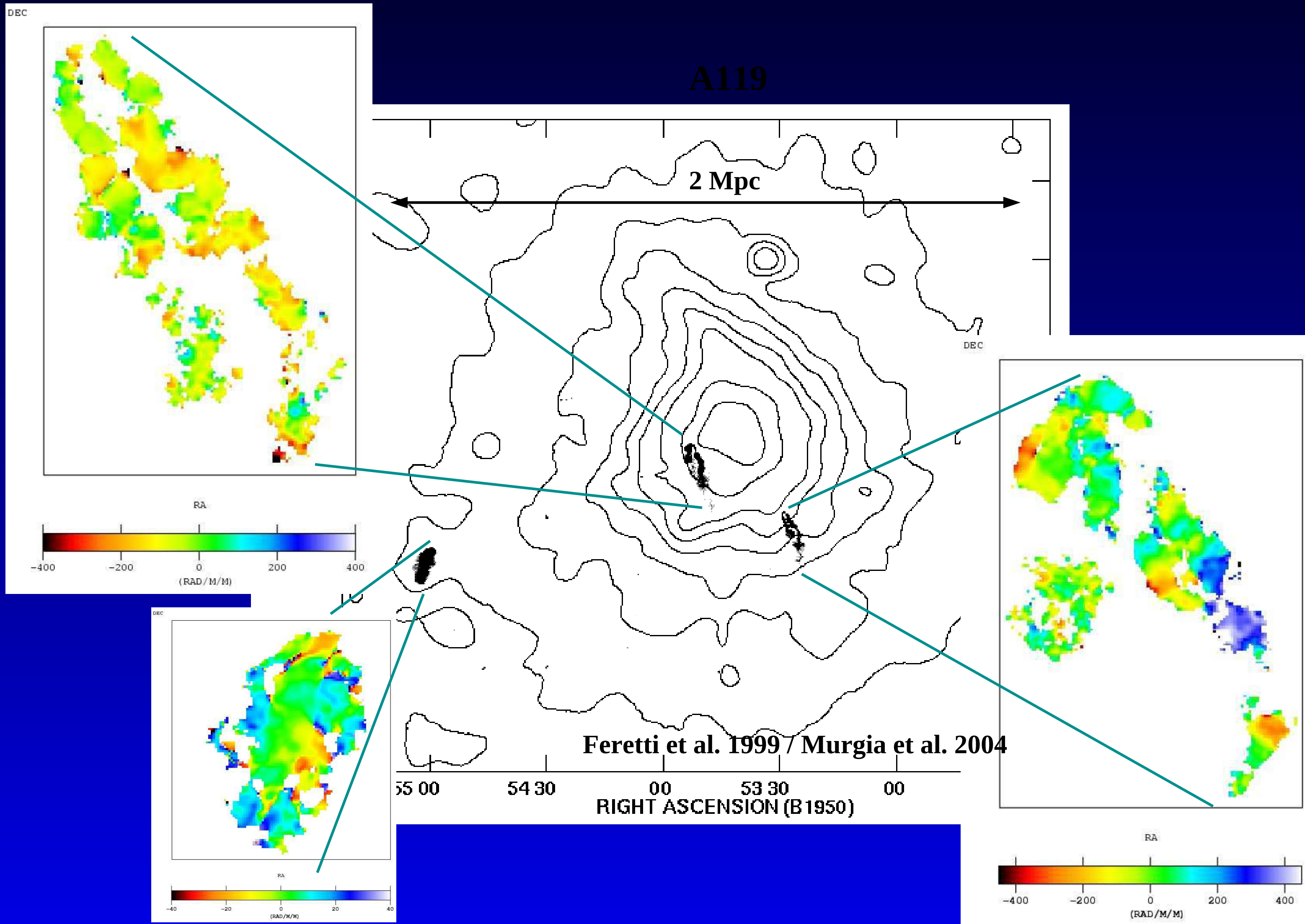


Rotation Measure of Hydra (left) and inferred power spectrum of the underlying magnetic field (Vogt & Ensslin 2005).

- Follows a **Kolmogorov-like** power spectrum !
- Magnetic field correlation length ≈ 3 kpc !
- Cool core turbulence or cluster wide field ?

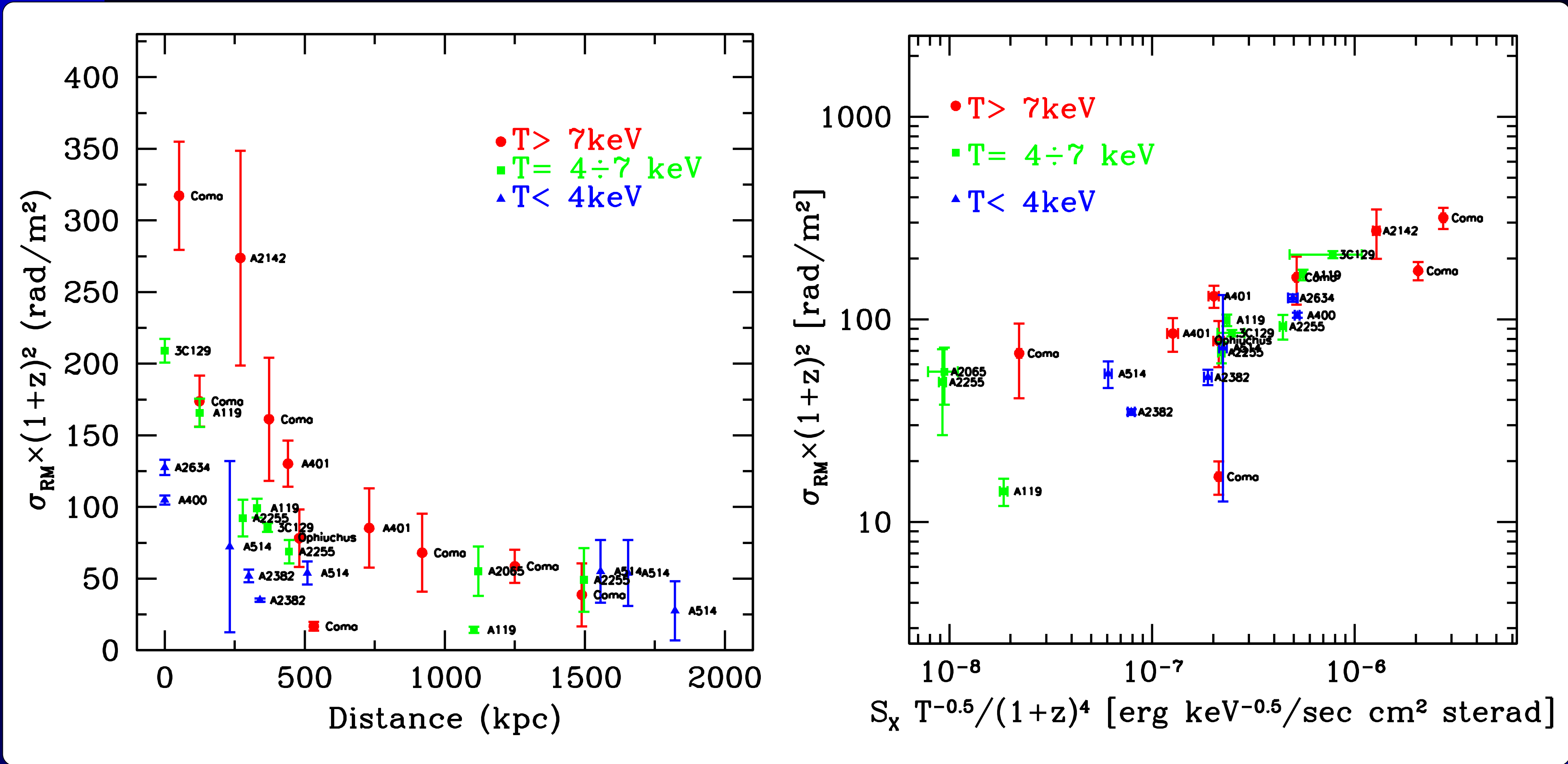
Observations

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



Composite of X-ray map and Rotation Measure in 3 extended radio sources in A119.

Observations

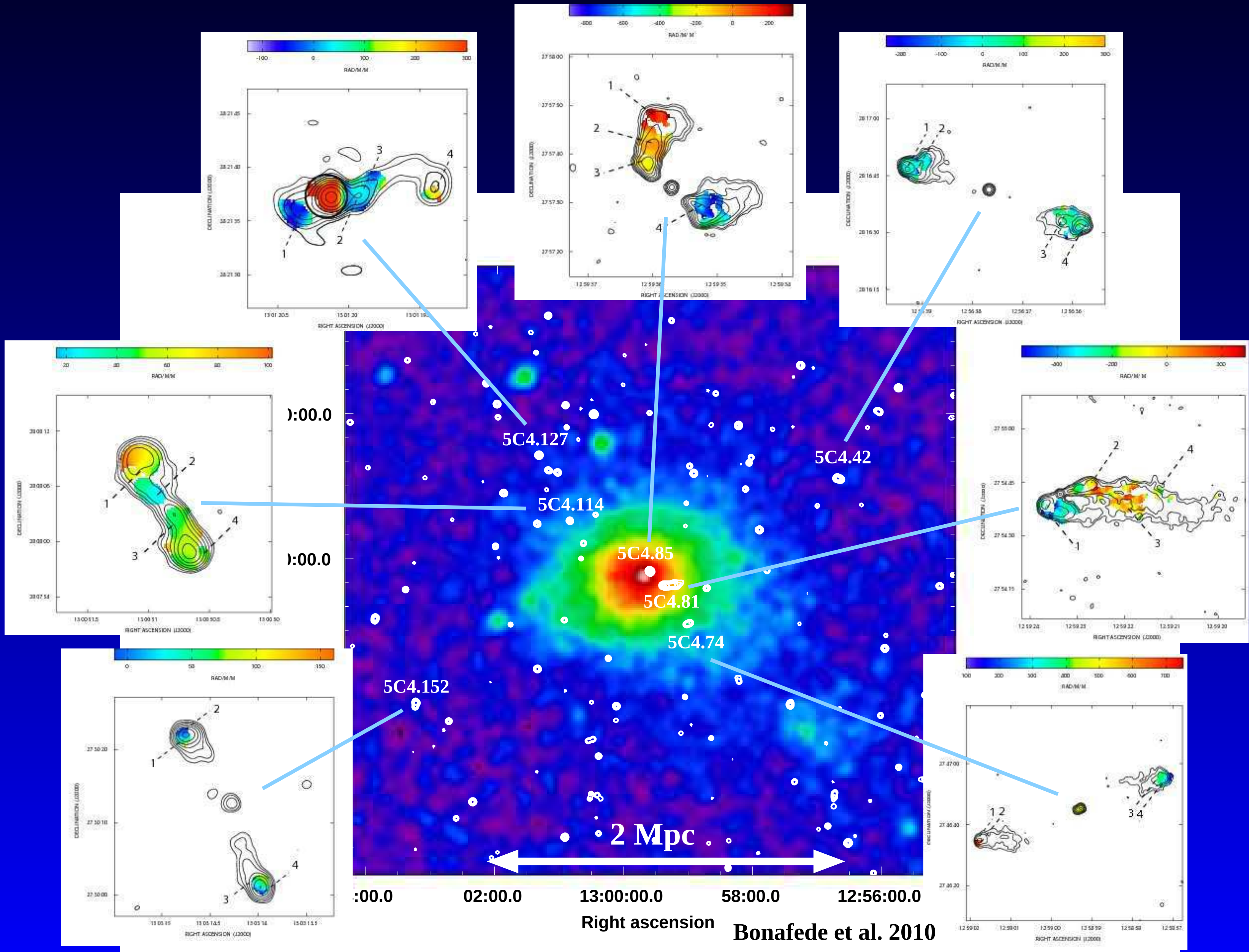


Govoni et al. 2010

- **Combination** of RM measured in **many clusters**.
- How does $\vec{B}$ scale with cluster temperature ?
- Magnetic Field in Radio quiet/active clusters ?

Observations

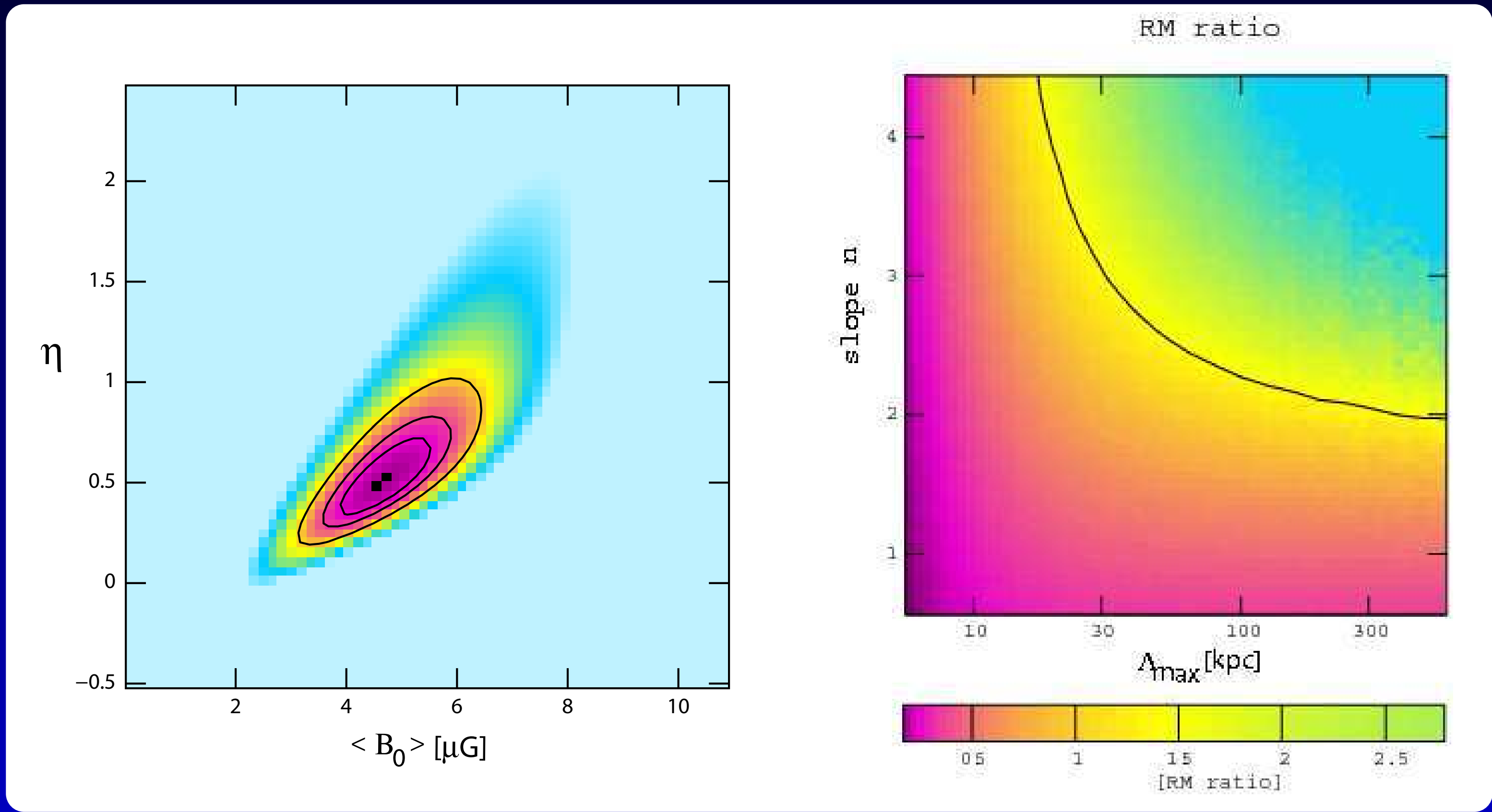
$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\eta}, \quad |B_k|^2 \propto k^{-n}, \quad (k_{\min}, k_{\max})$$



Bonafede et al. 2010

Observations

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

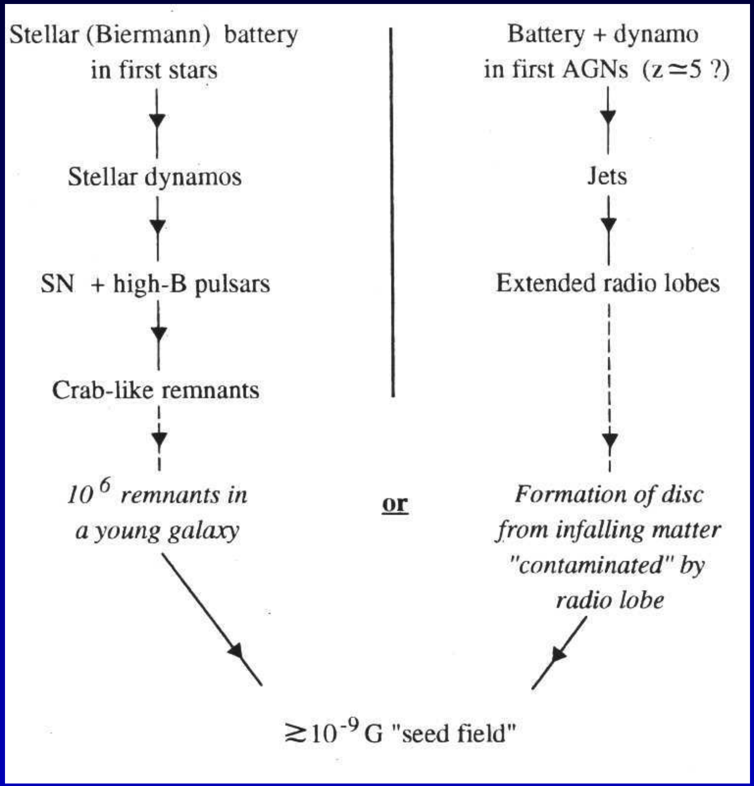


- Degeneration of injection scale $k_{\min}$ and spectral index n
- Knowledge of the spectrum constrains magnetic field
- How does $\vec{B}$ scale with cluster temperature ?

Origin of B

Origin

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

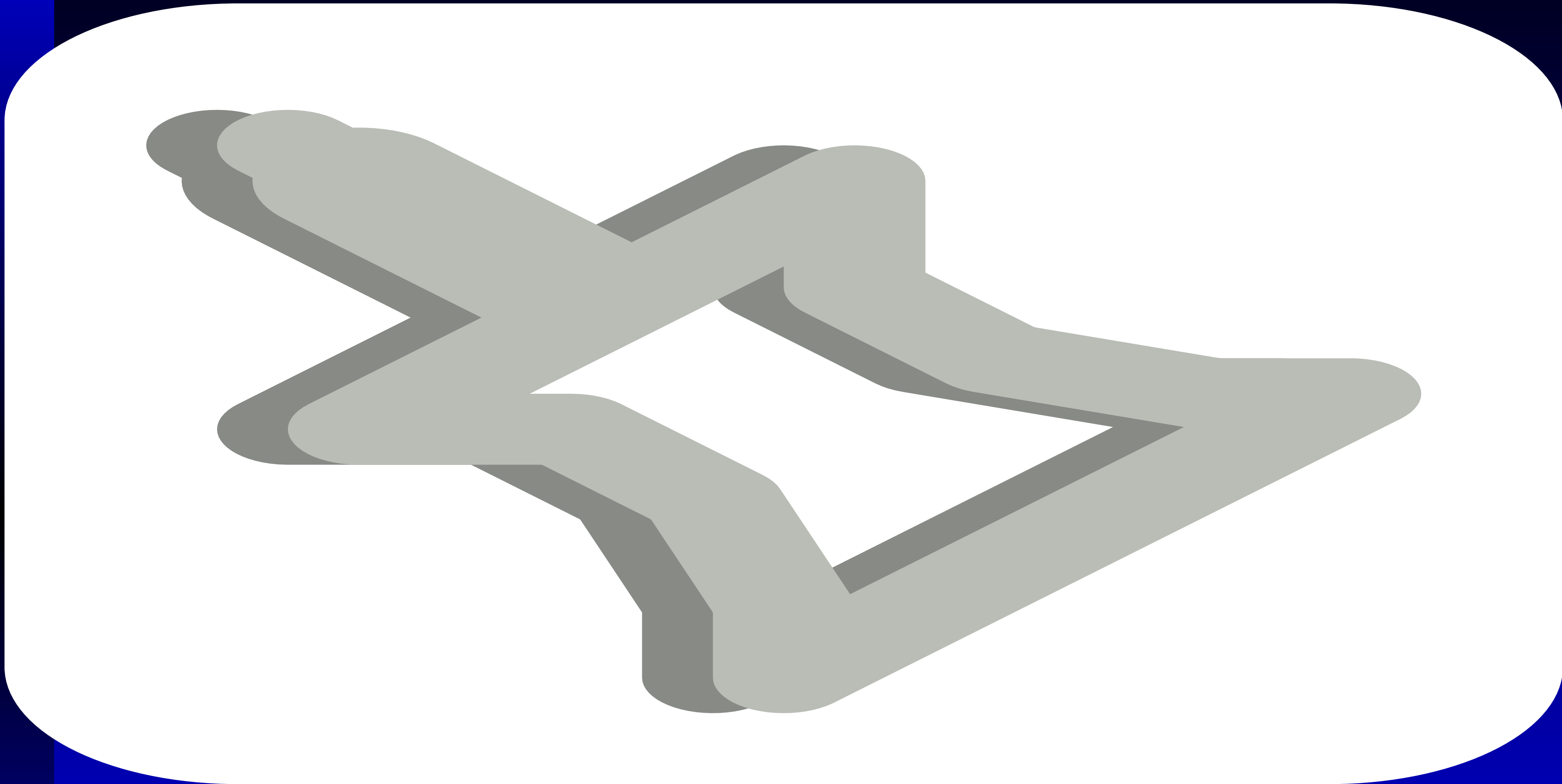


Rees 1994

+ further amplification by **structure formation**

- **dissipation** ?

Origin of B

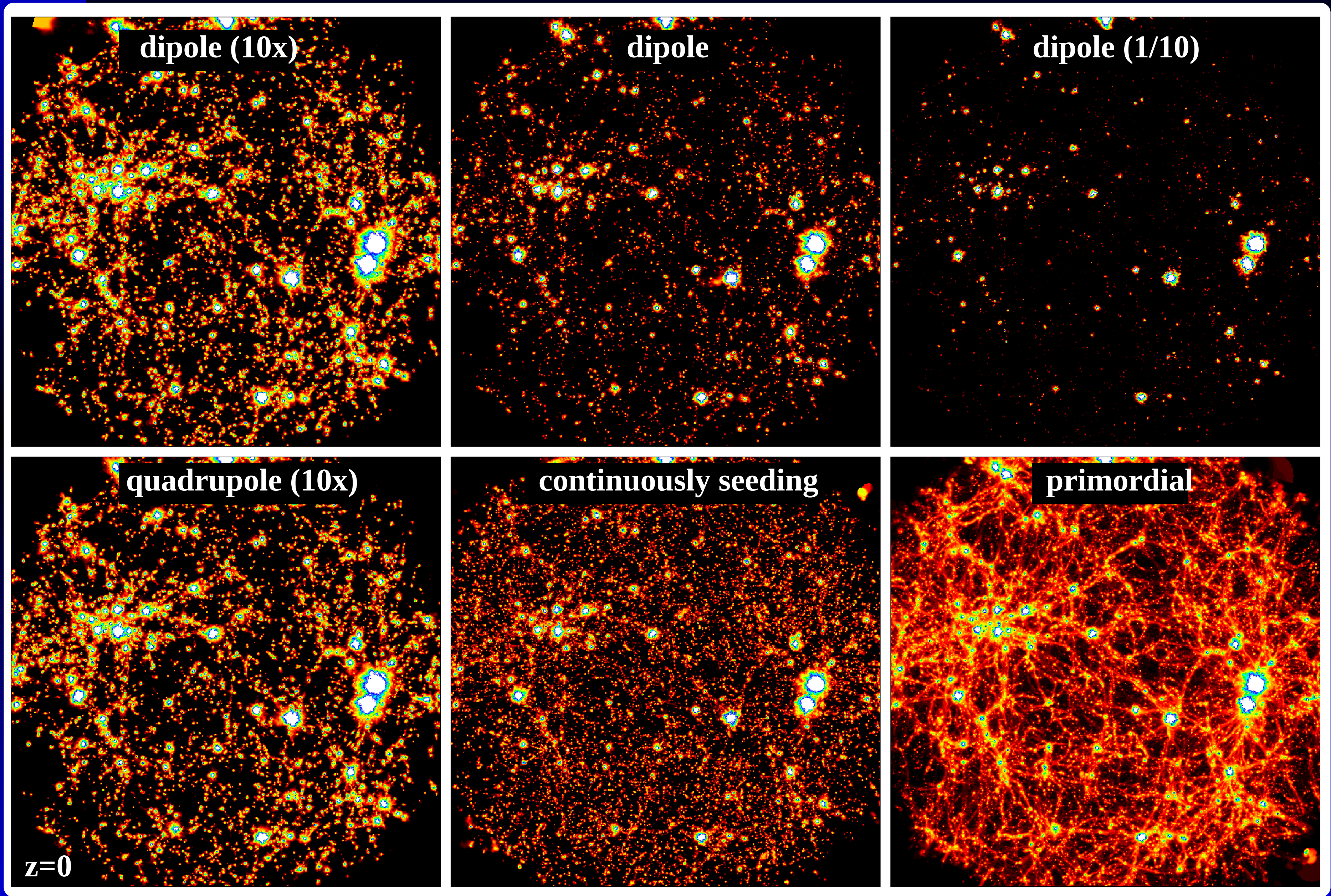


density | **magnetic field**

180 Mpc | 180 Mpc

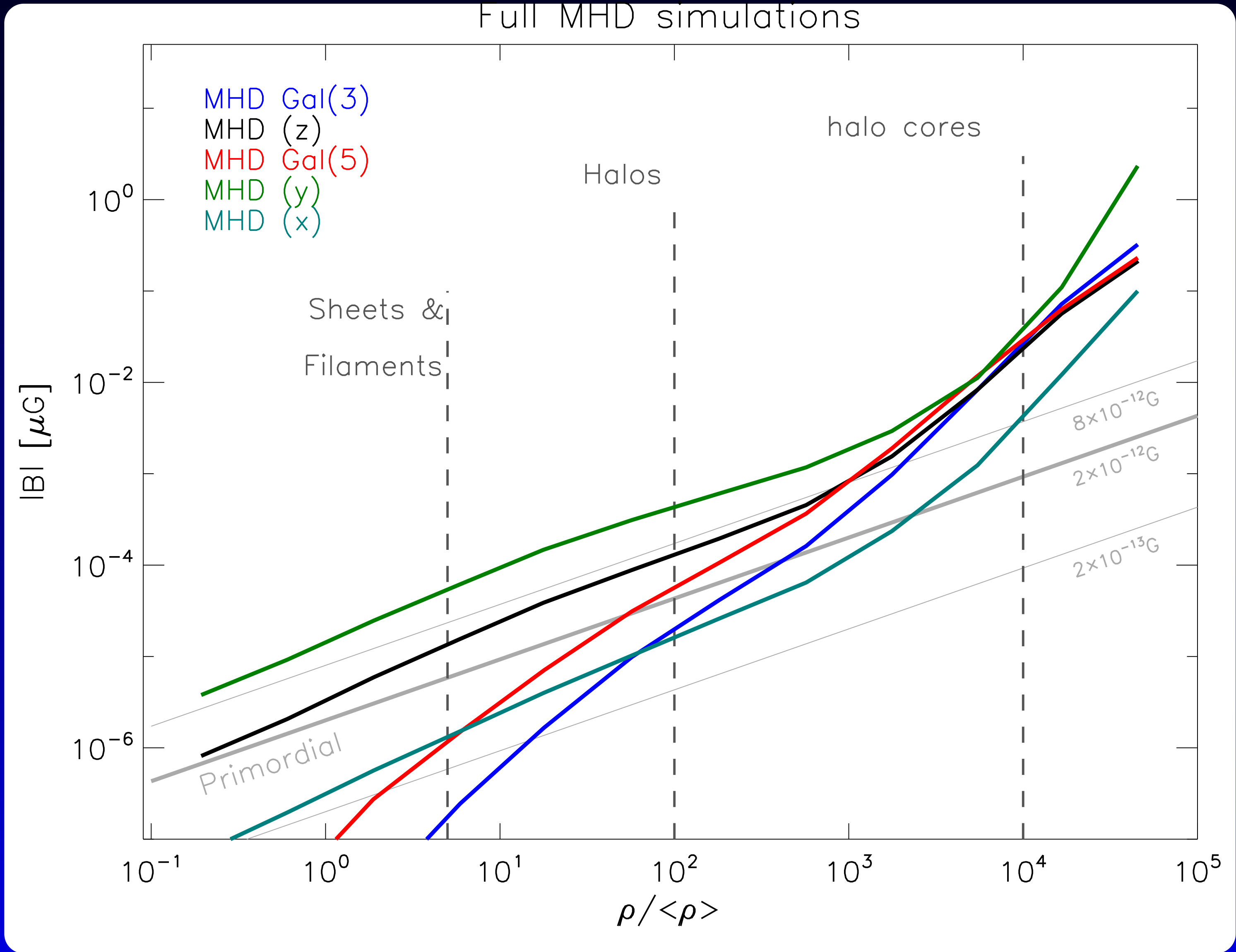
Buildup of **cosmological magnetism** through **seeding** by **SN**.

Cosmic Magnetization Quest



Different wind parameters (Donnert et al. 2009)

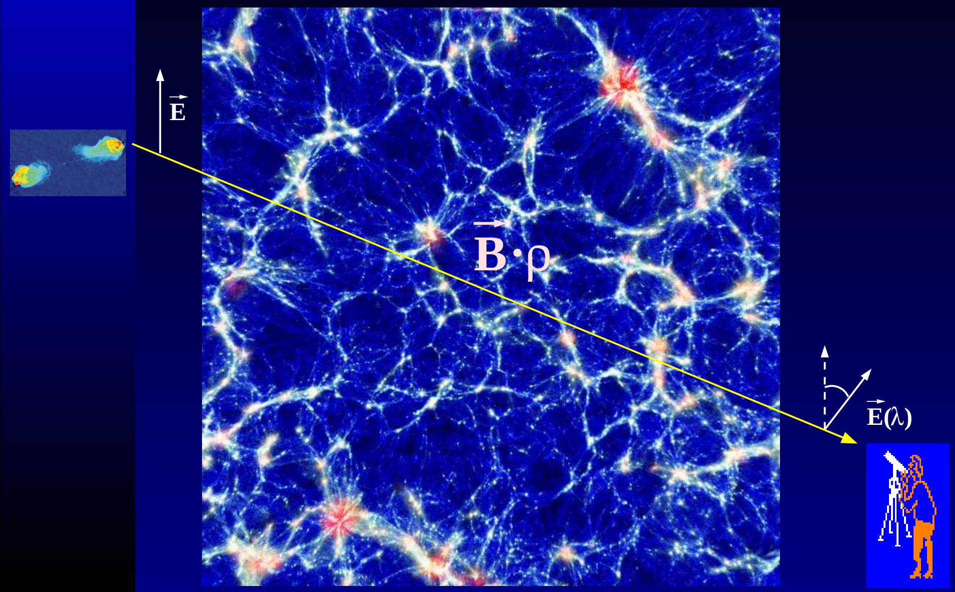
Cosmic Magnetization Quest



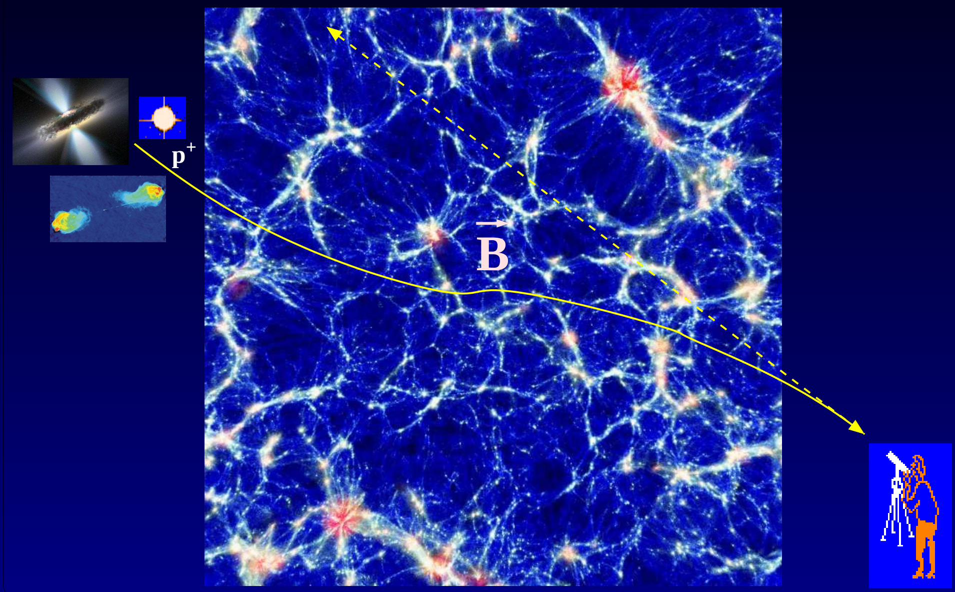
Predictions from **different** models for **origin** of cosmic magnetism.

Cosmic Magnetization Quest

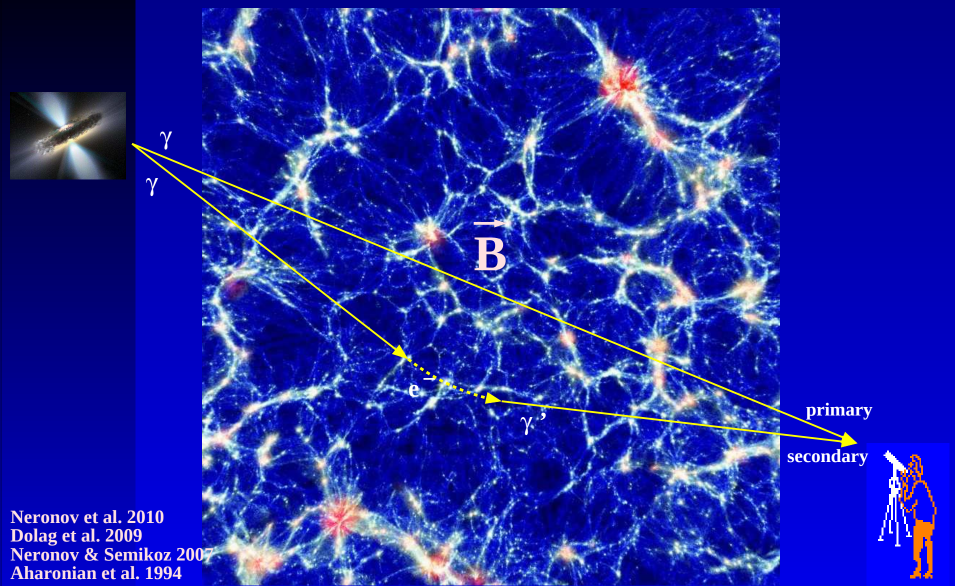
Faraday Rotation (RM) of polarized radio emission



Propagation of ultra high energy cosmic rays (UHECR)

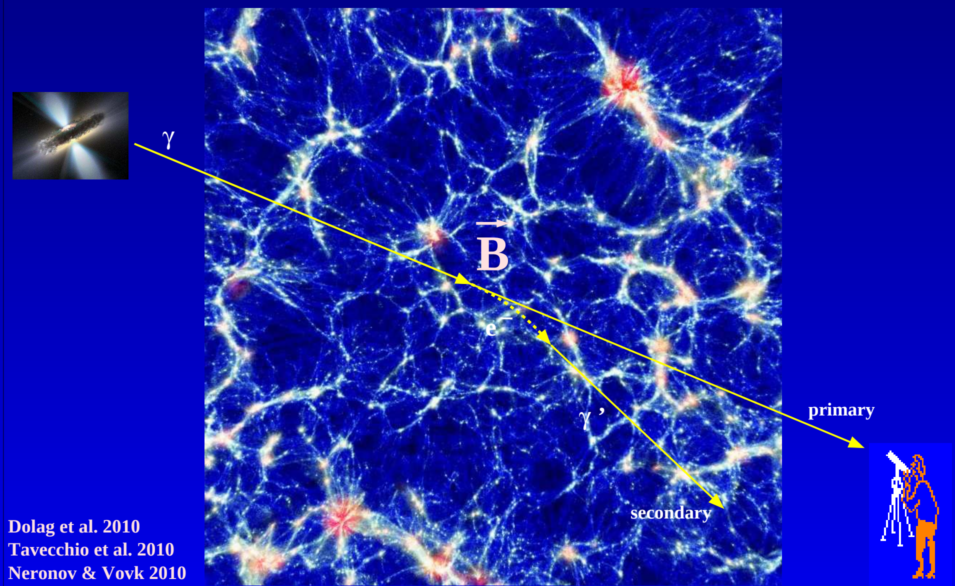


Deflection of electromagnetic cascade of TeV photons



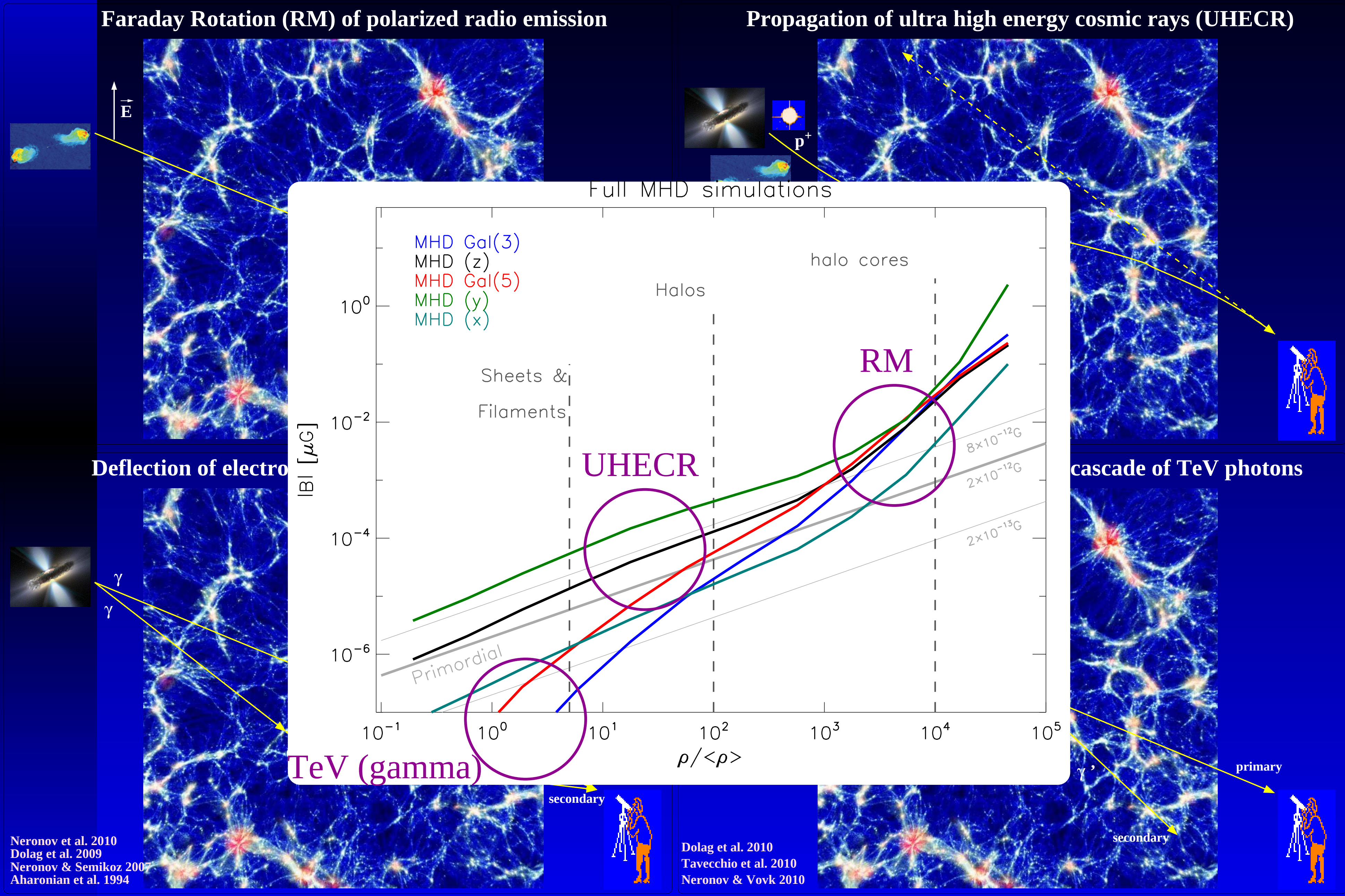
Neronov et al. 2010
Dolag et al. 2009
Neronov & Semikoz 2007
Aharonian et al. 1994

Attenuation from electromagnetic cascade of TeV photons



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

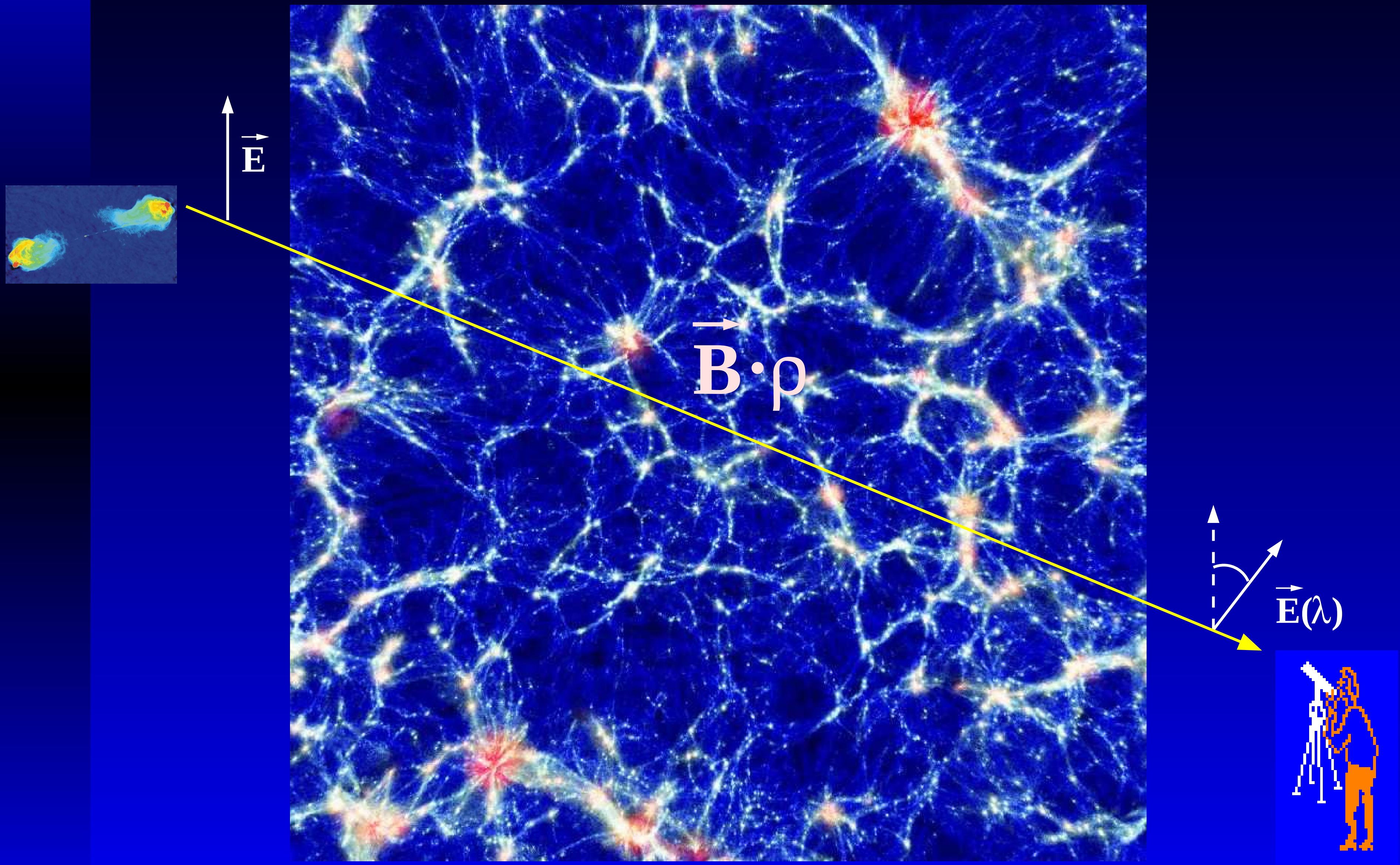
Cosmic Magnetization Quest



UHECMessengers open **new** window to Cosmic Magnetism !

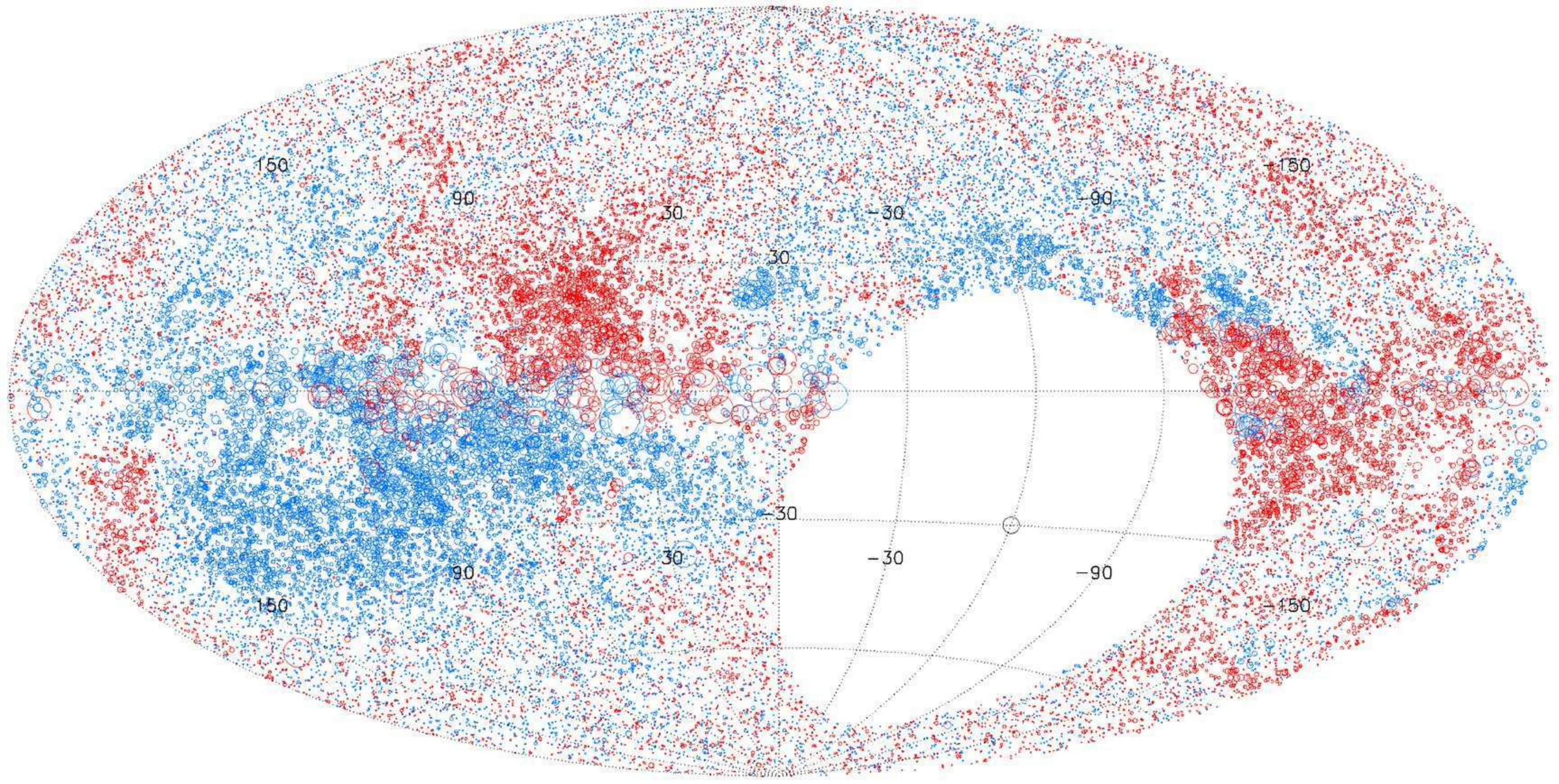
Method I: RM statistics (μG)

Faraday Rotation (RM) of polarized radio emission



Method I: RM statistics (μG)

RMs sensitive to $(.1 - 1) \times 10^{-6}$G, statistical methods 10^{-9}G (?)

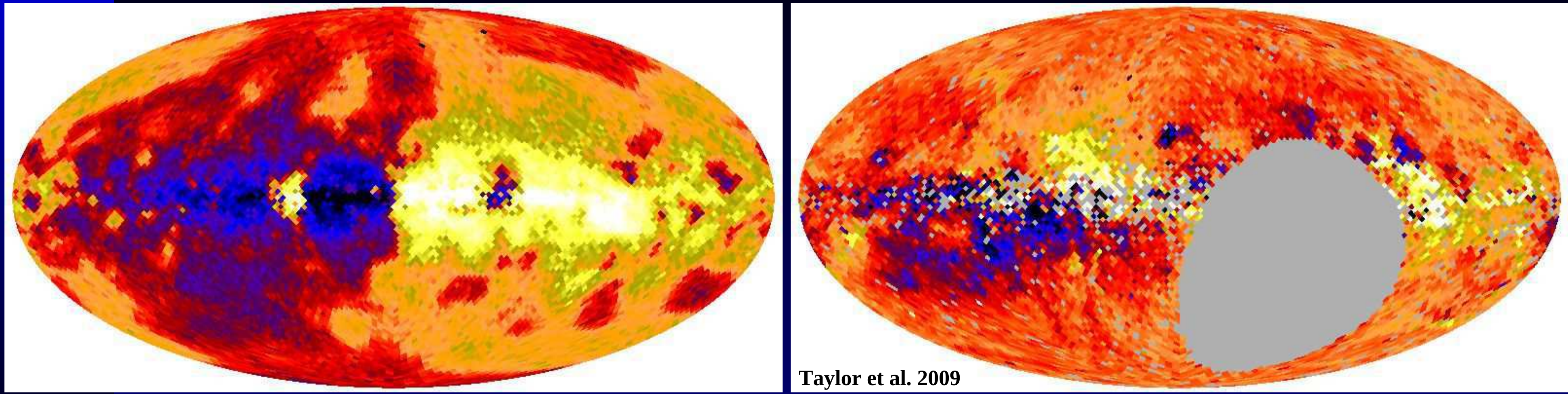


Observed, full sky RM signal (Taylor et al. 2009)

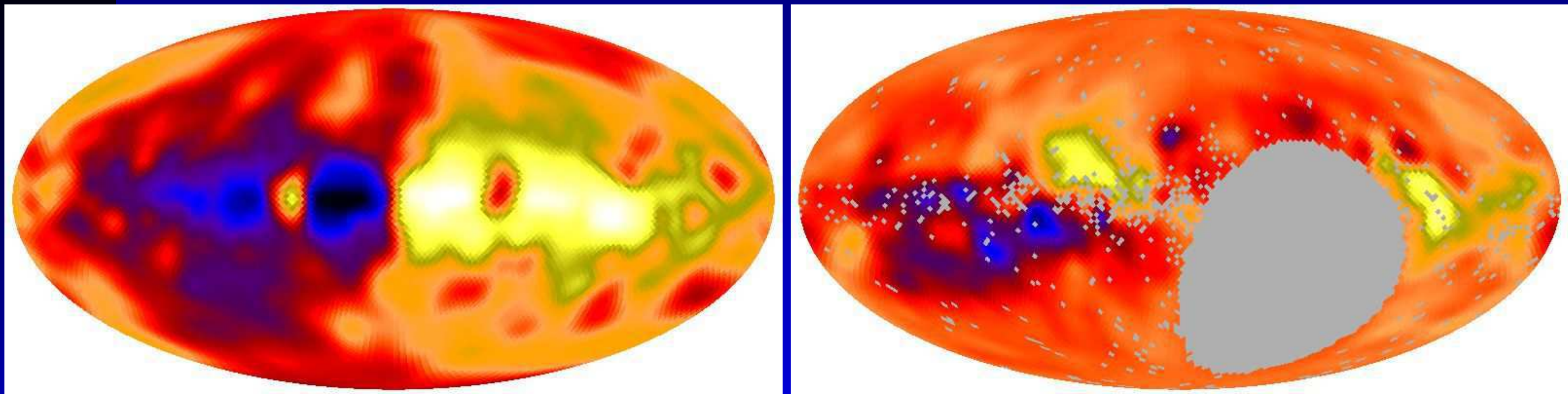
$\Rightarrow B_{cosmic} \approx 30 \times 10^{-9}$G (Lee et al. 2009) **???**.

But **Galactic foreground** critical !!!

Method I: RM statistics (μG)



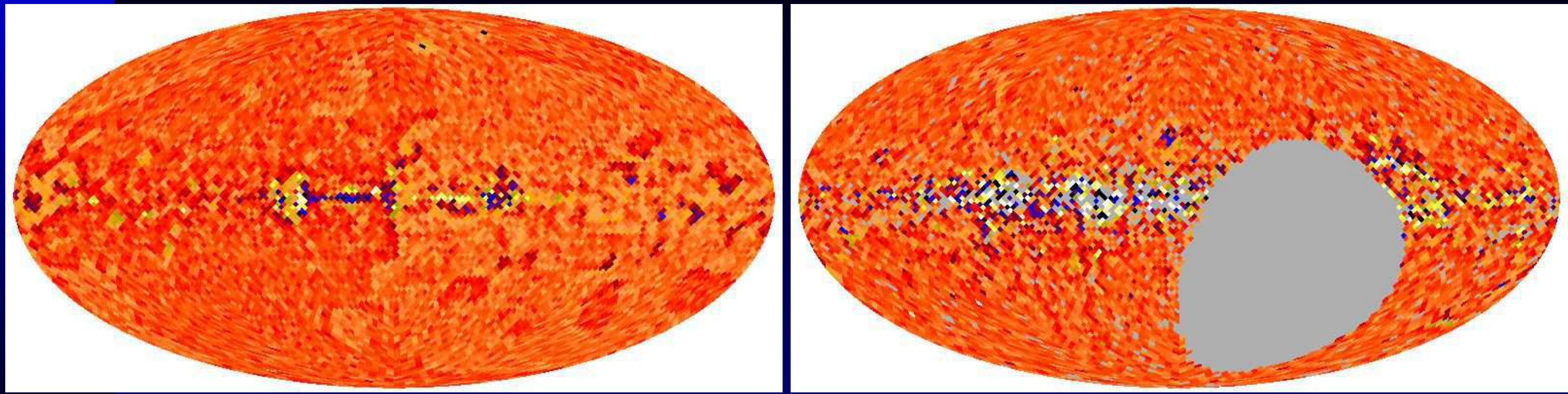
Model foreground based on HAMMURABI (Waelkens et al. 2009), cosmic signal and observational noise compared to observations.



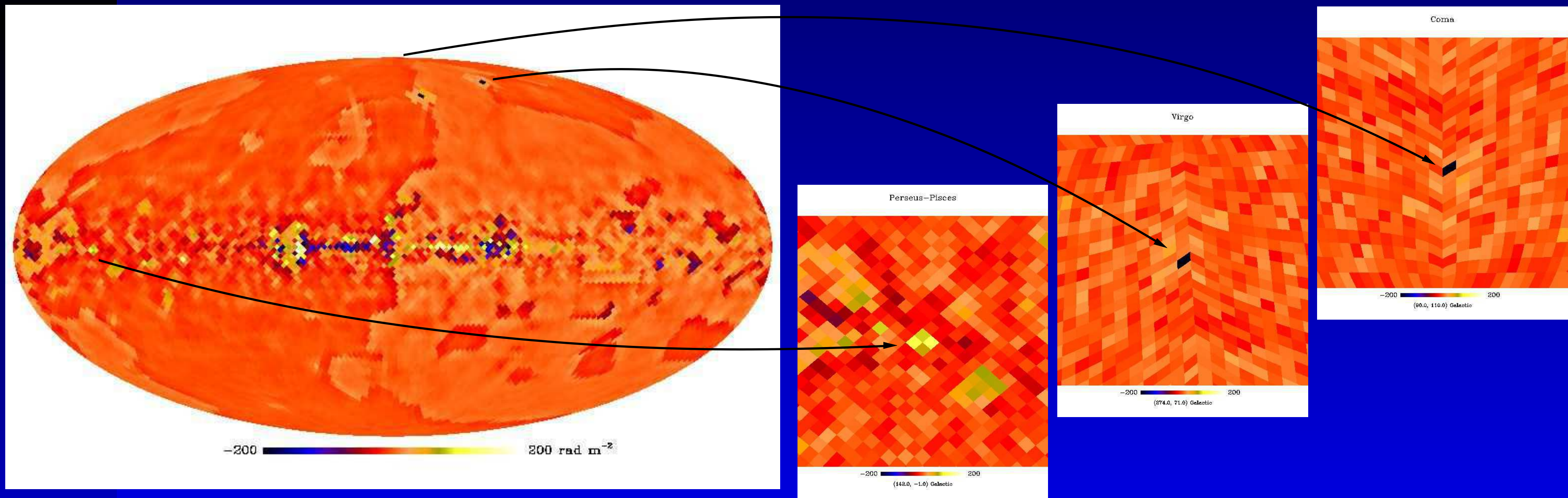
Same but smoothed by 8 degrees.

Stasyszyn et al. 2010

Method I: RM statistics (μG)



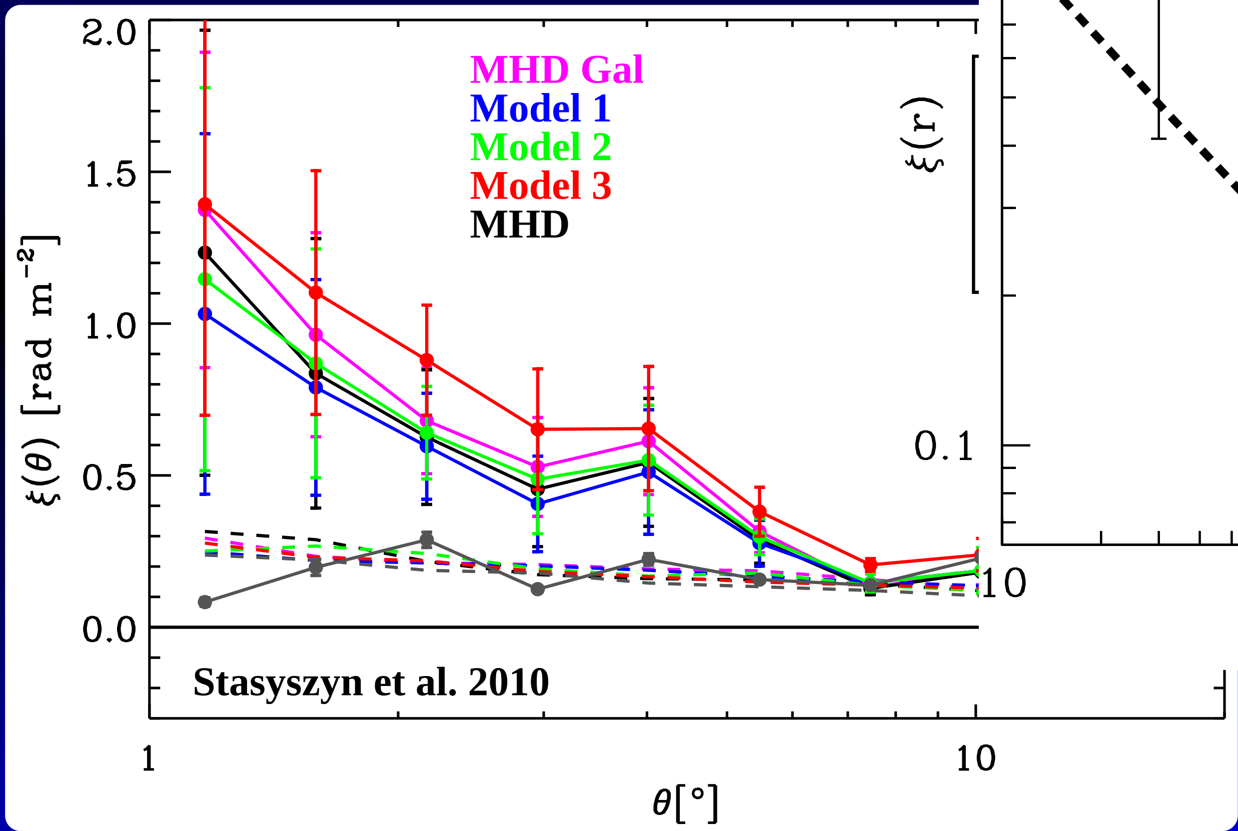
Same as before, but with foreground removal.

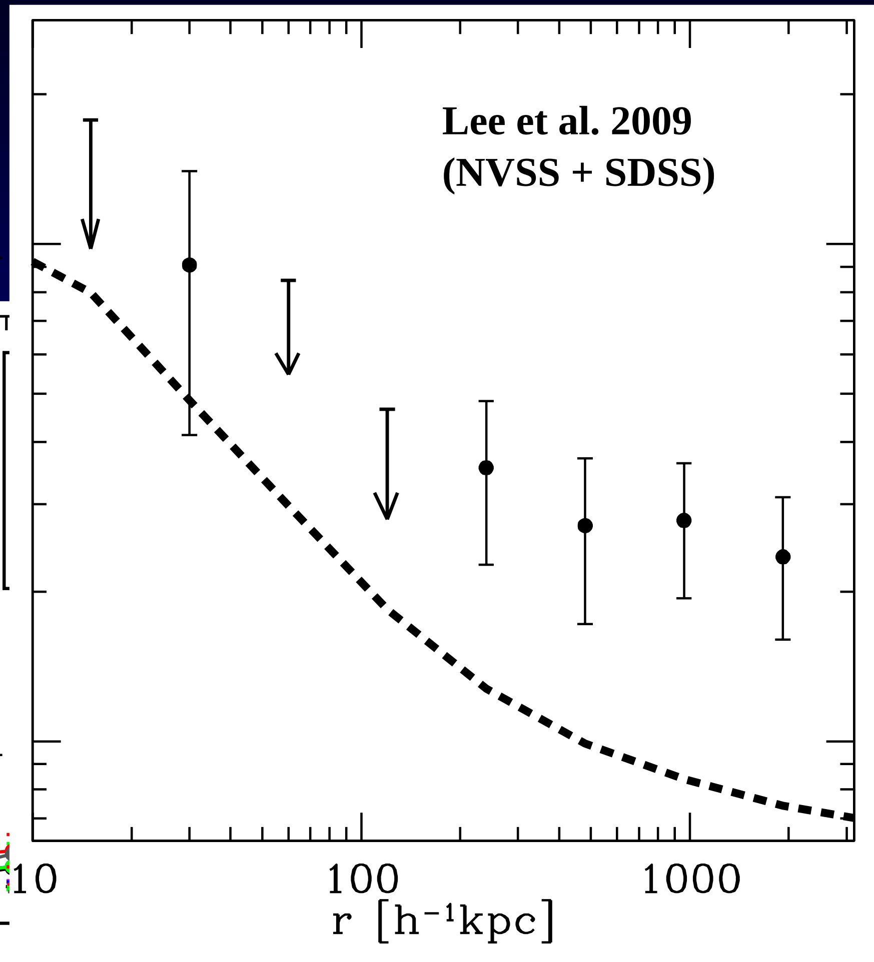


Reduced noise (1 rad$/m^2$) and zoom on several clusters.

Stasyszyn et al. 2010

Method I: RM statistics (μG)

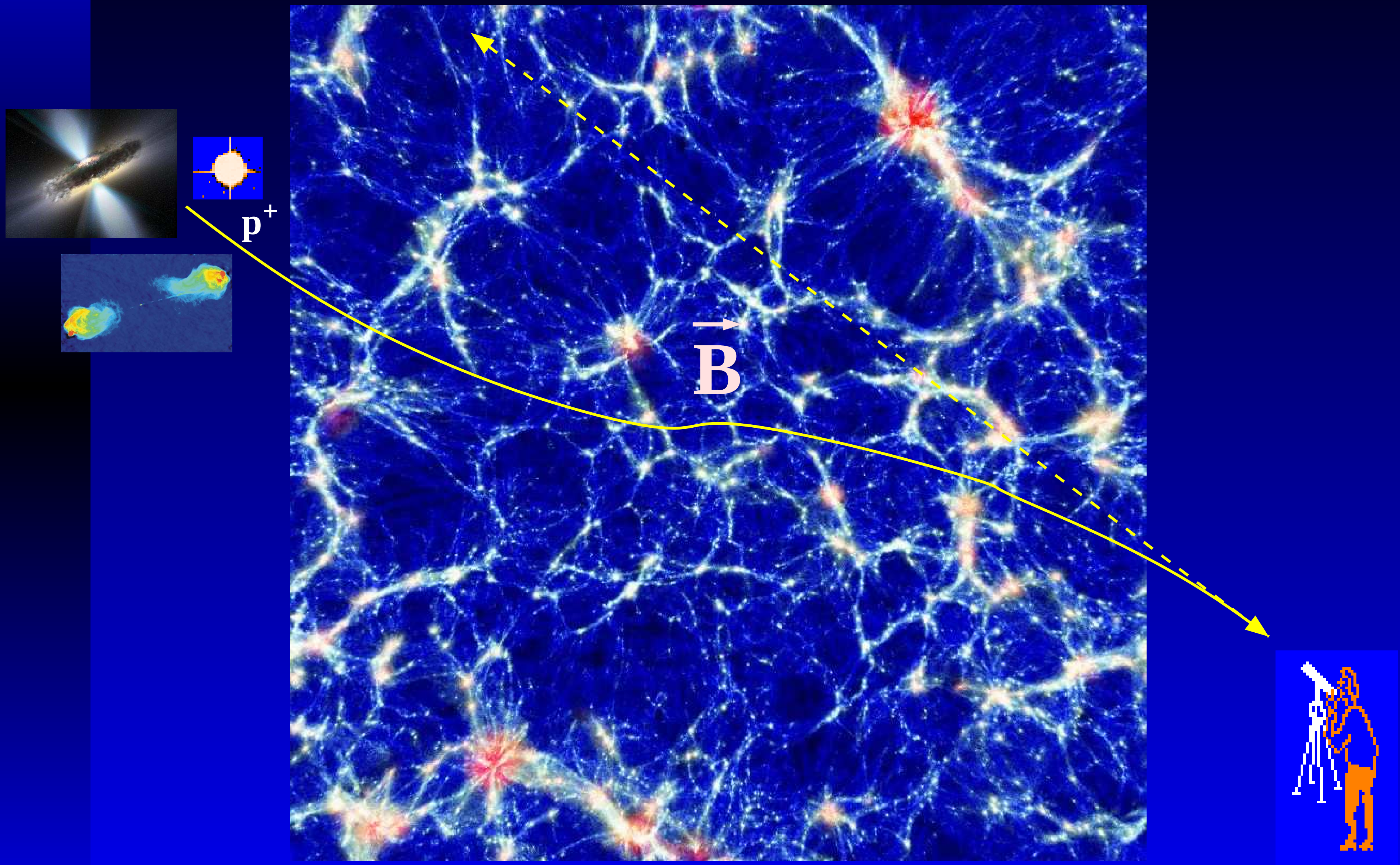




Correlation signal predicted by simulations, but the amplitude is driven by the foreground and observational noise !

Method II: UHECR defl. (nG)

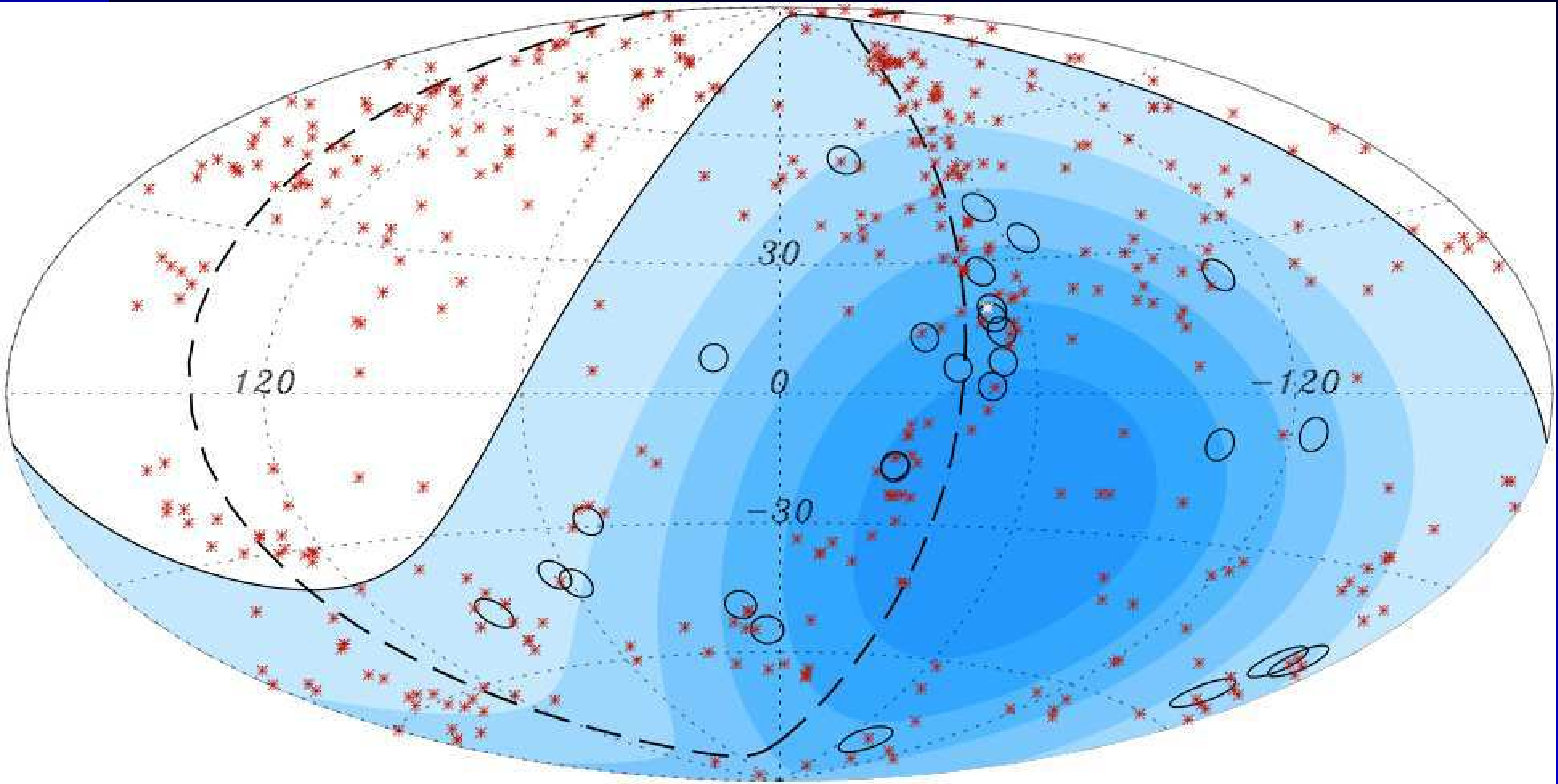
Propagation of ultra high energy cosmic rays (UHECR)



Cooling: photo-pion production in collisions with CMB
Secondary particles: ν from pion decay

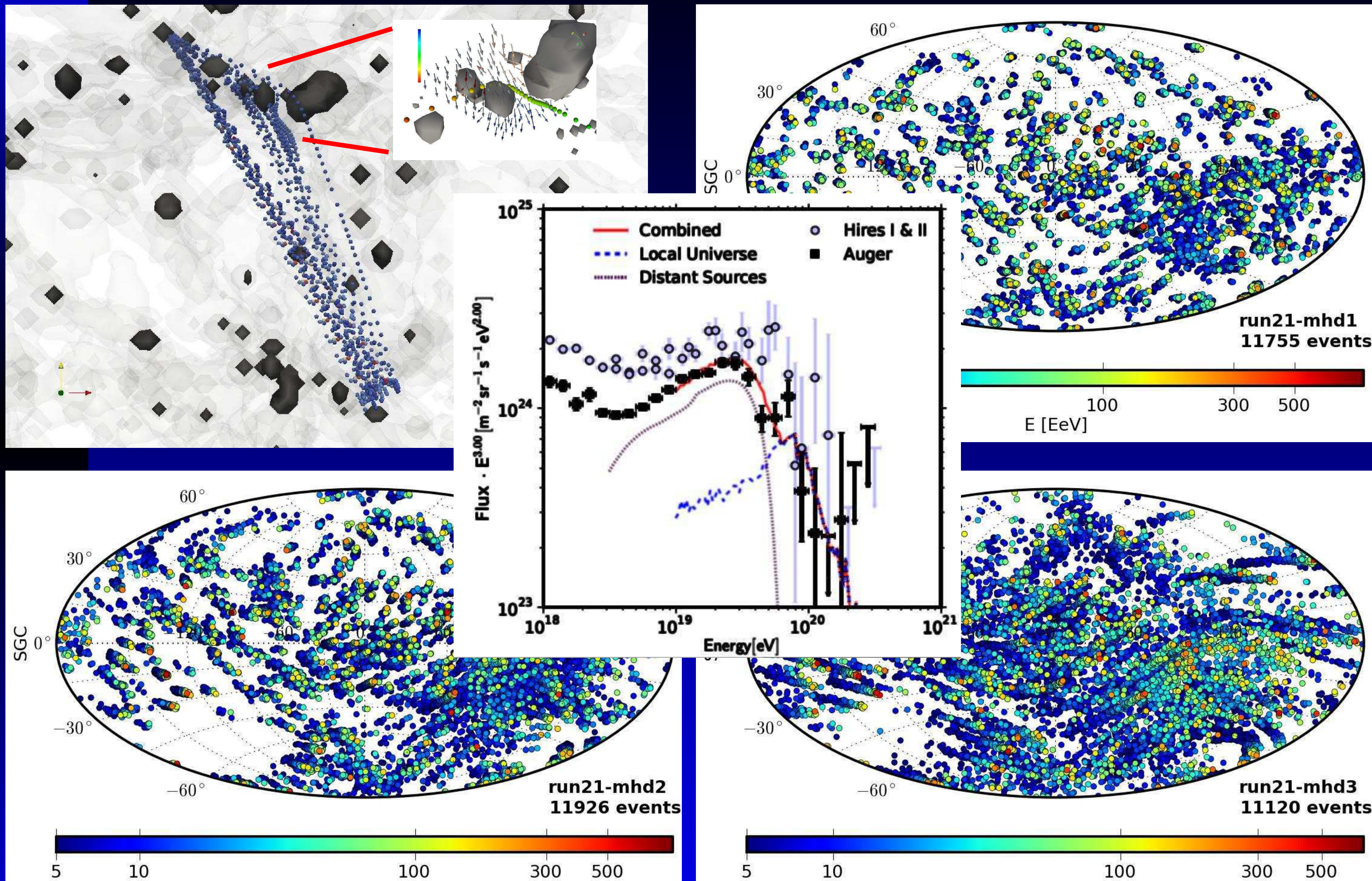
Method II: UHECR defl. (nG)

Propagation of CRp, sensitive to $(10^{-9} - 10^{-12})$G



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). **But still under discussion !**

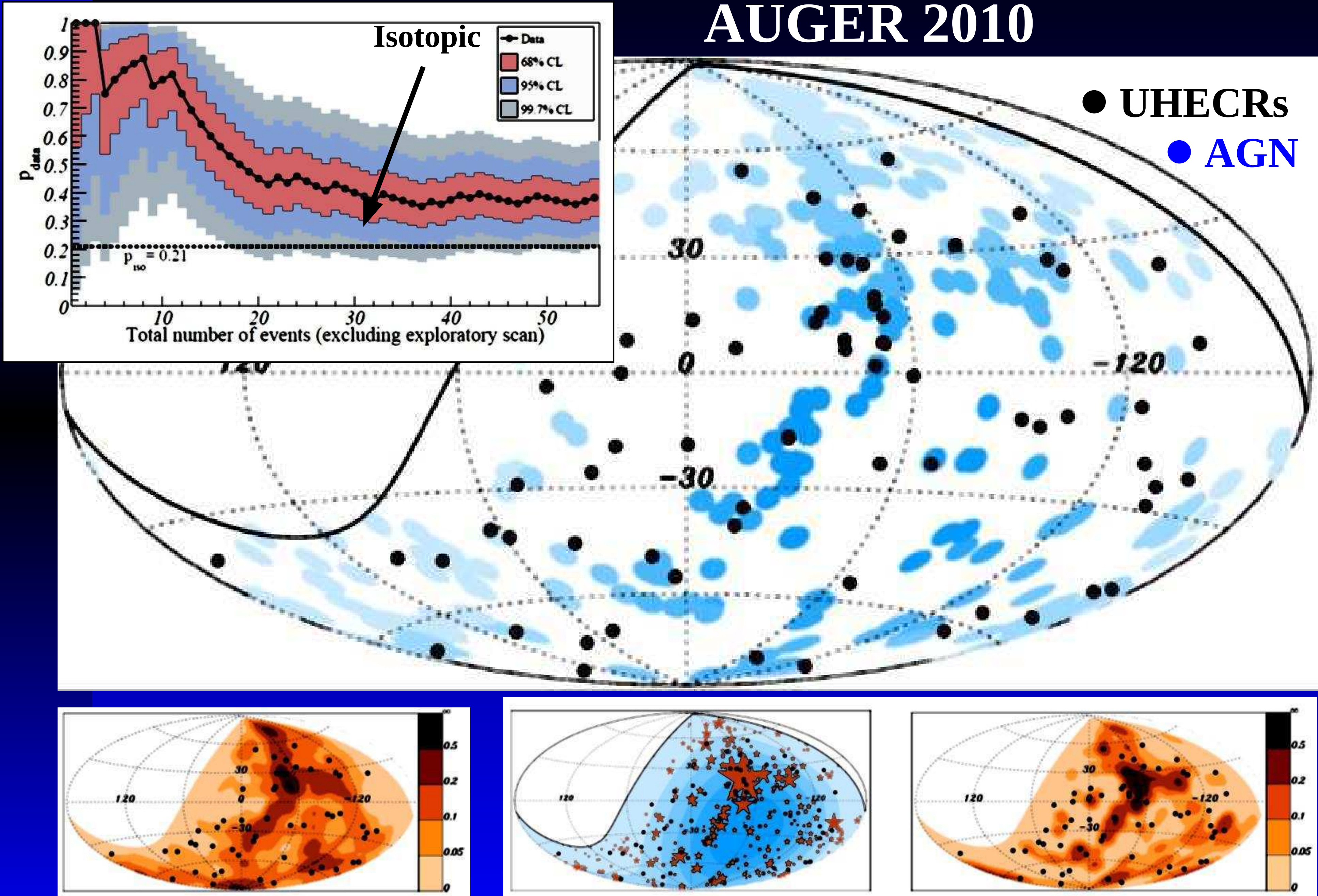
Method II: UHECR defl. (nG)



Dolag, Erdmann, Mueller, Walz & Winchen 2012

Full **tracking** of UHECRs in cosmological MHD simulation.

Method II: UHECR defl. (nG)

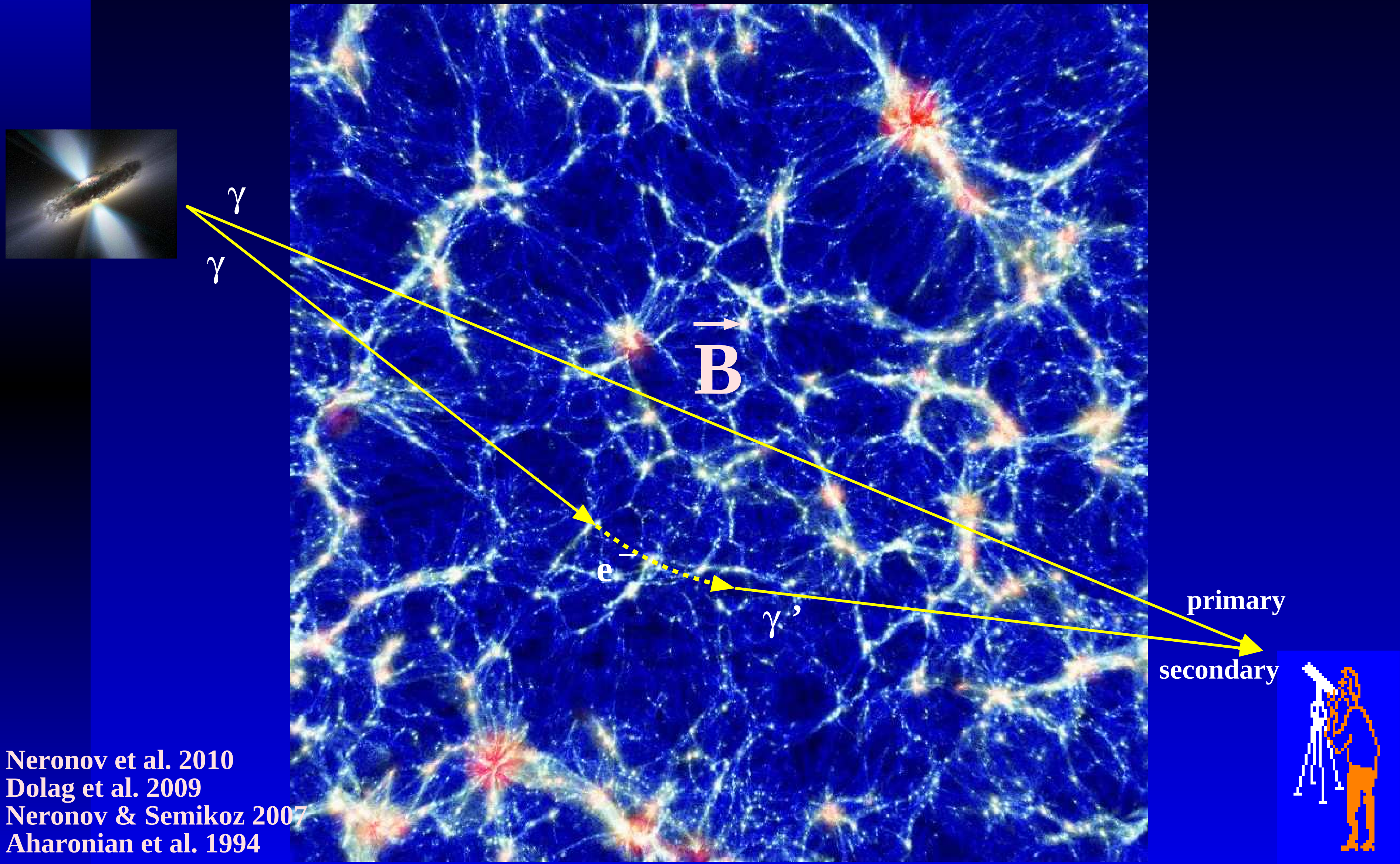


2MASS

Swift−BAT (AGNs)

Method III: γ-rays (pG-fG)

Deflection of electromagnetic cascade of TeV photons

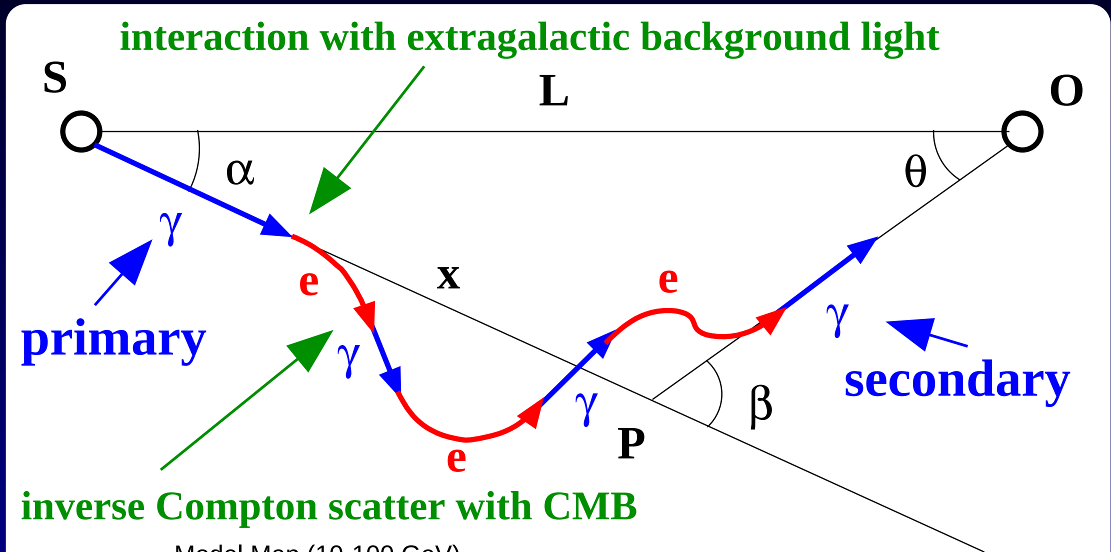


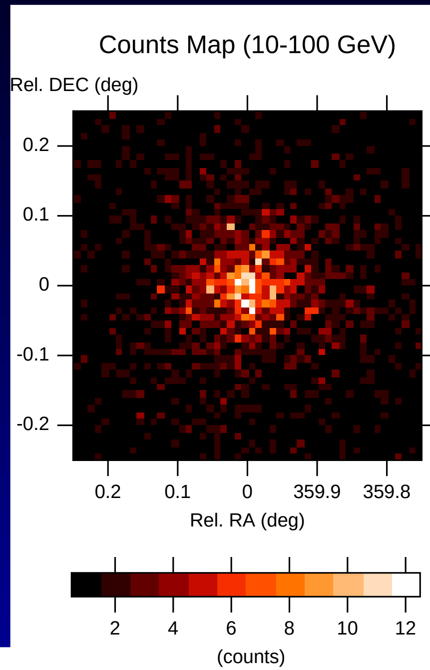
Neronov et al. 2010
Dolag et al. 2009
Neronov & Semikoz 2007
Aharonian et al. 1994

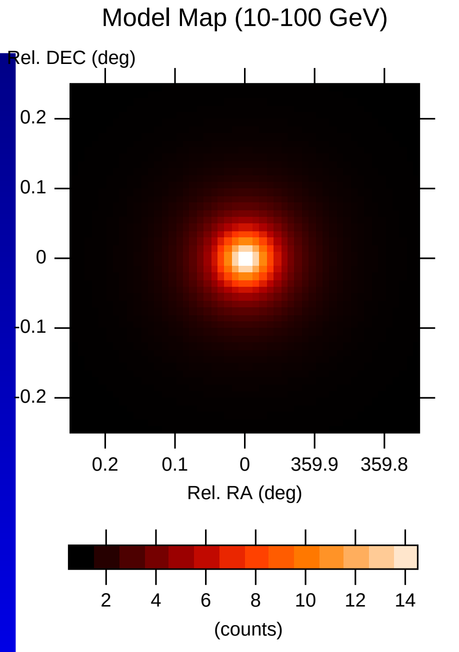
electromagnetic cascade: electron pair production interaction with EBL
cooling of electrons: inverse compton scatter with CMB photons

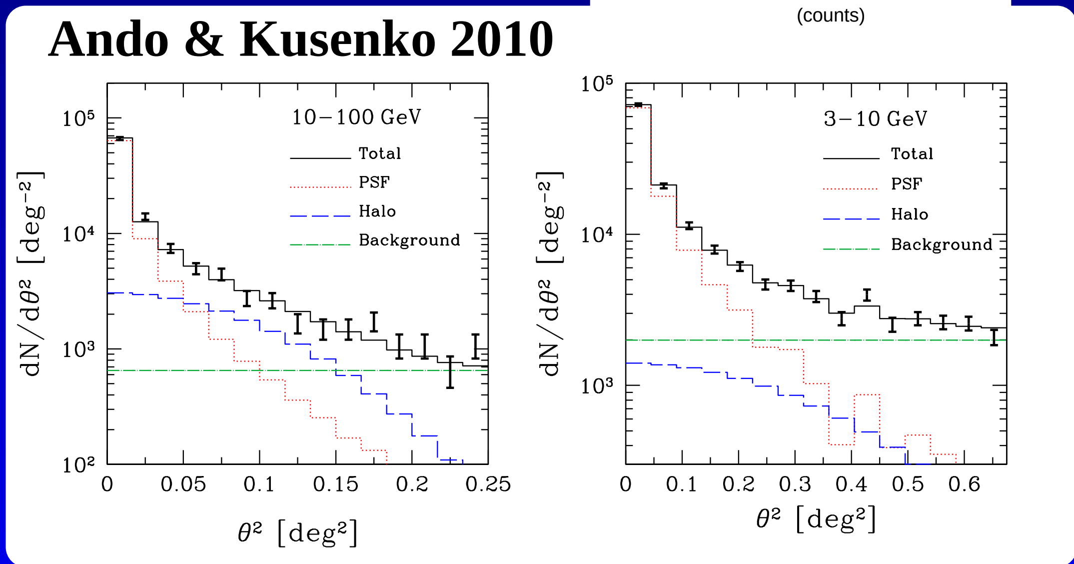
Method III: γ-rays (pG-fG)

Propagation of γ-rays, sensitive to $(10^{-12} - 10^{-16})$G



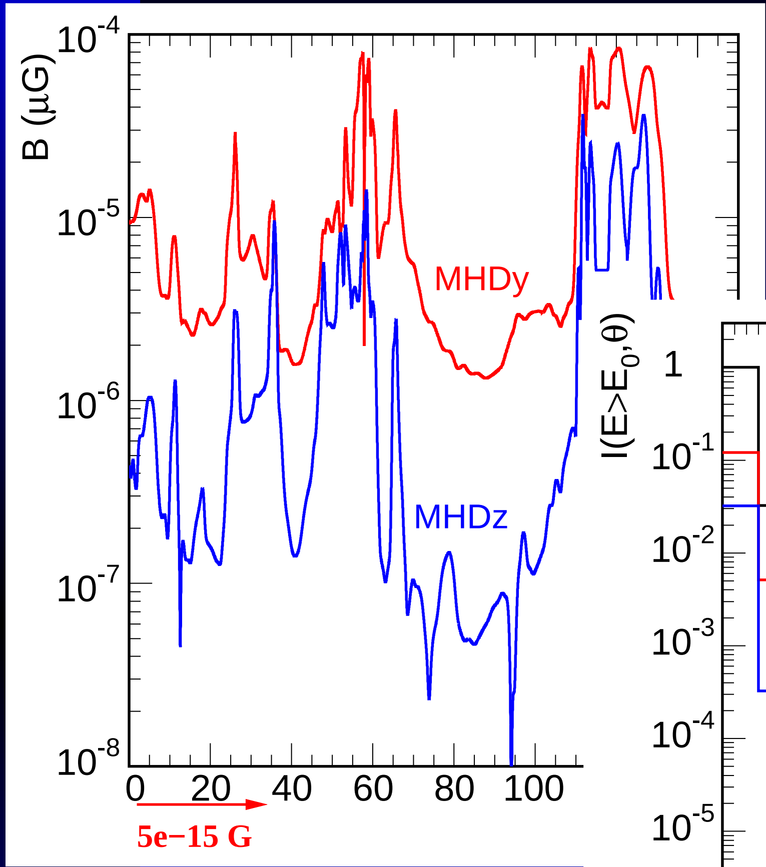






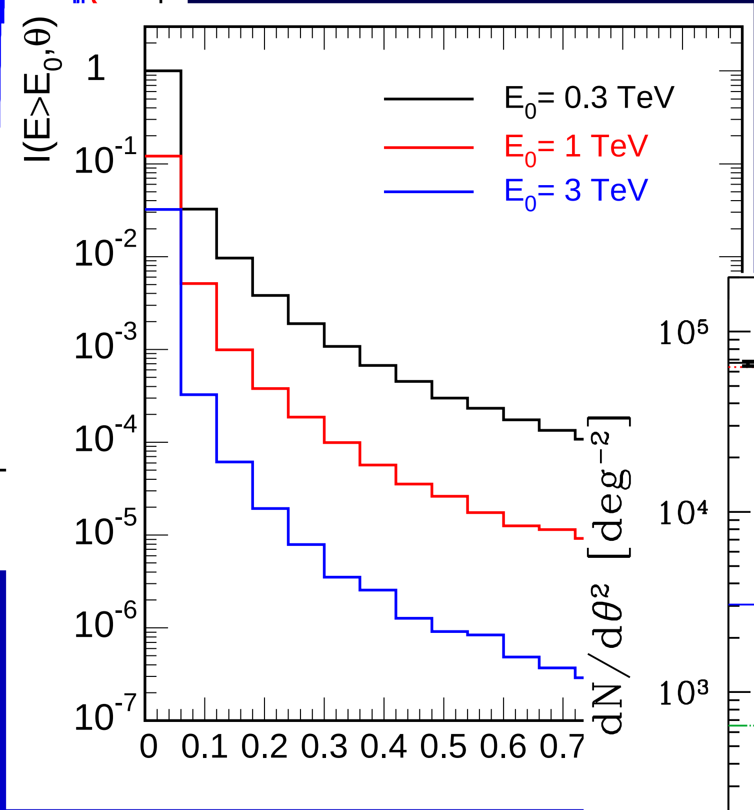
Halo found **stacking** 170 AGNs with FERMI: $B \approx 10^{-15}$G.

Method III: γ-rays (pG-fG)

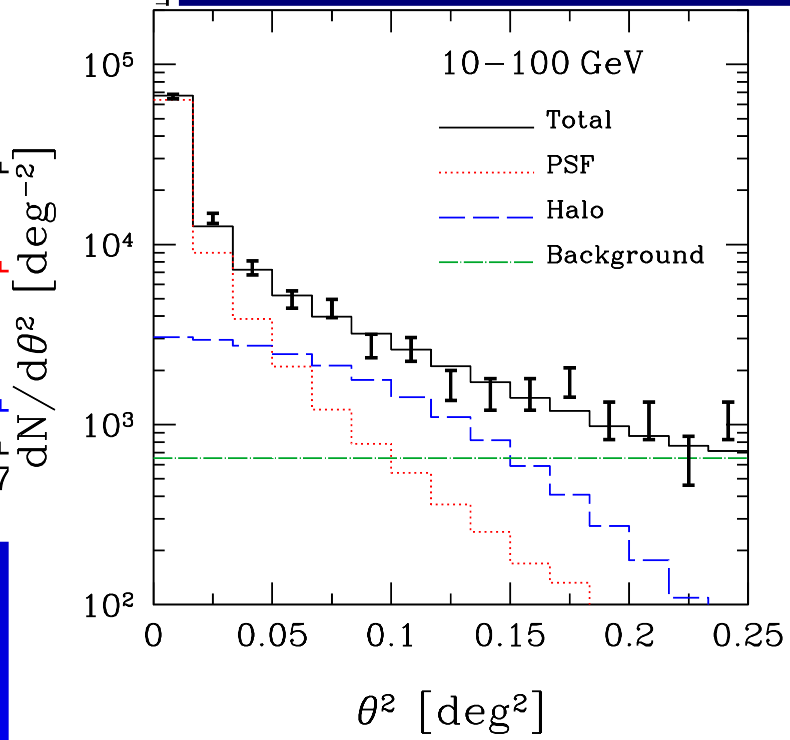


Dolag et al. 2009

1e−15 G

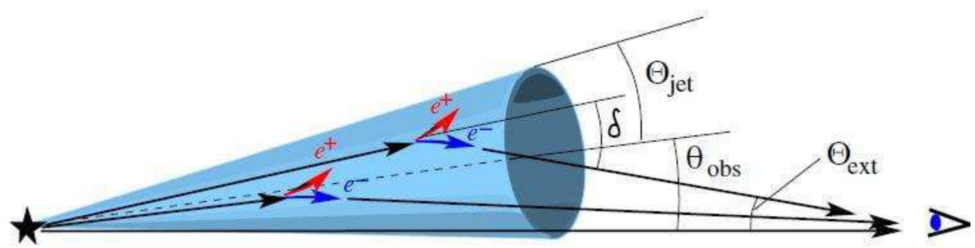


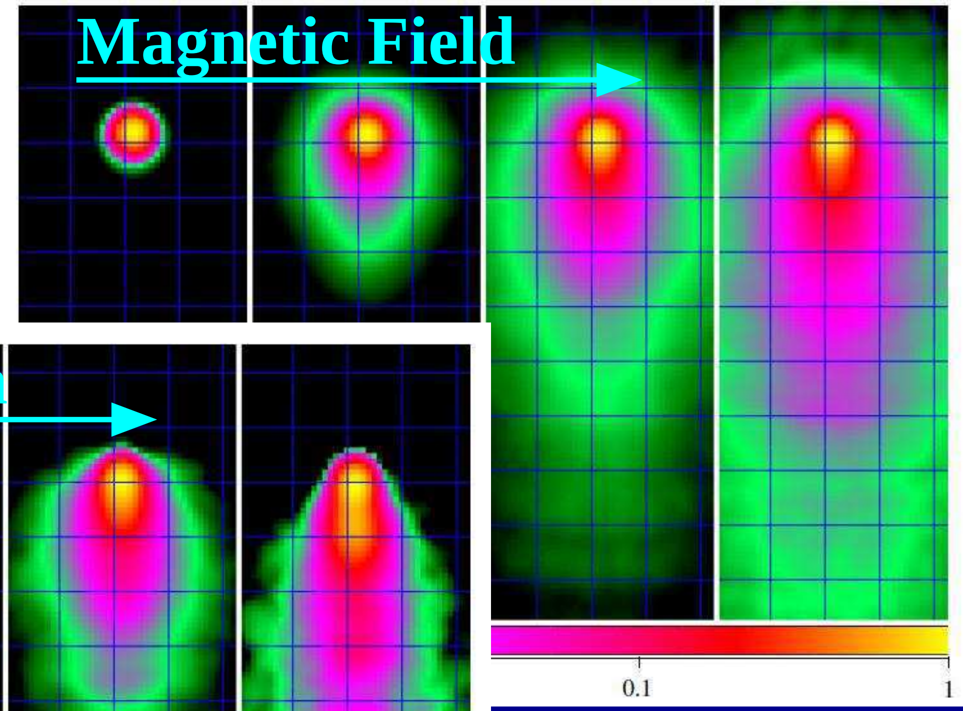
Ando & Kusenko 2010

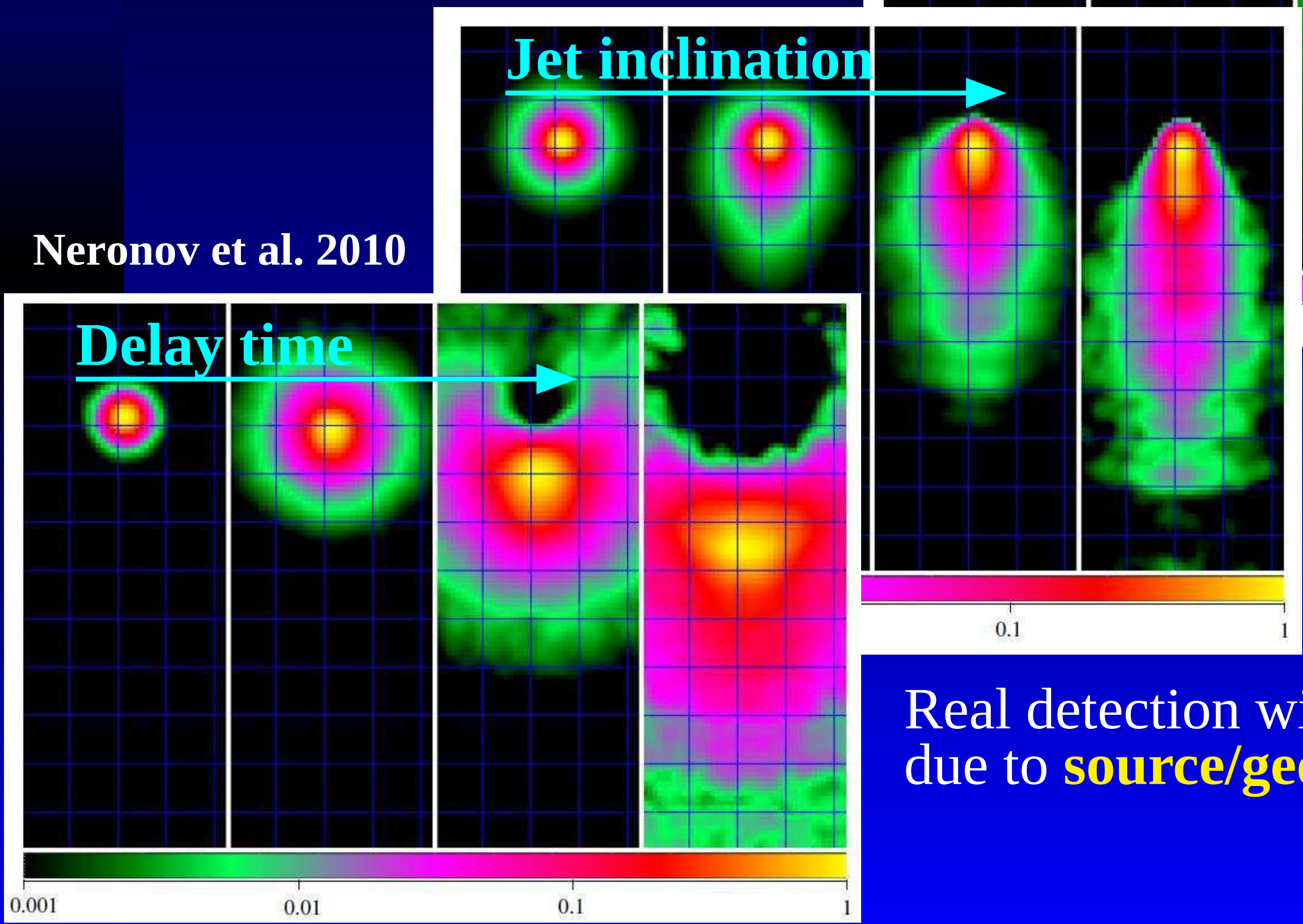


But false detection due to inperfect beam ! (Neronov et al. 2010)

Method III: γ-rays (pG-fG)





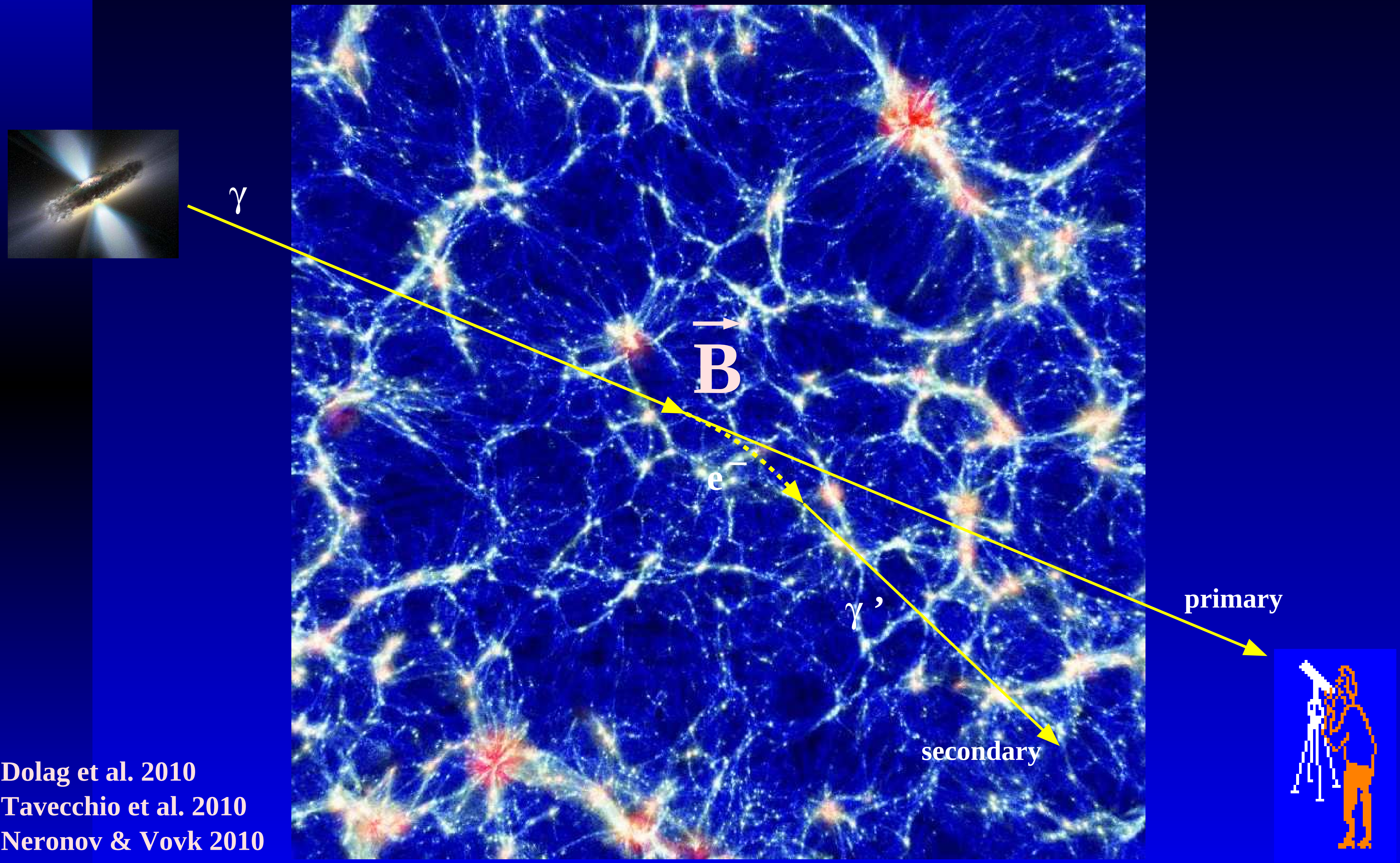


Neronov et al. 2010

Real detection will be difficult due to **source/geometry** details.

Method IV: γ-rays (fG)

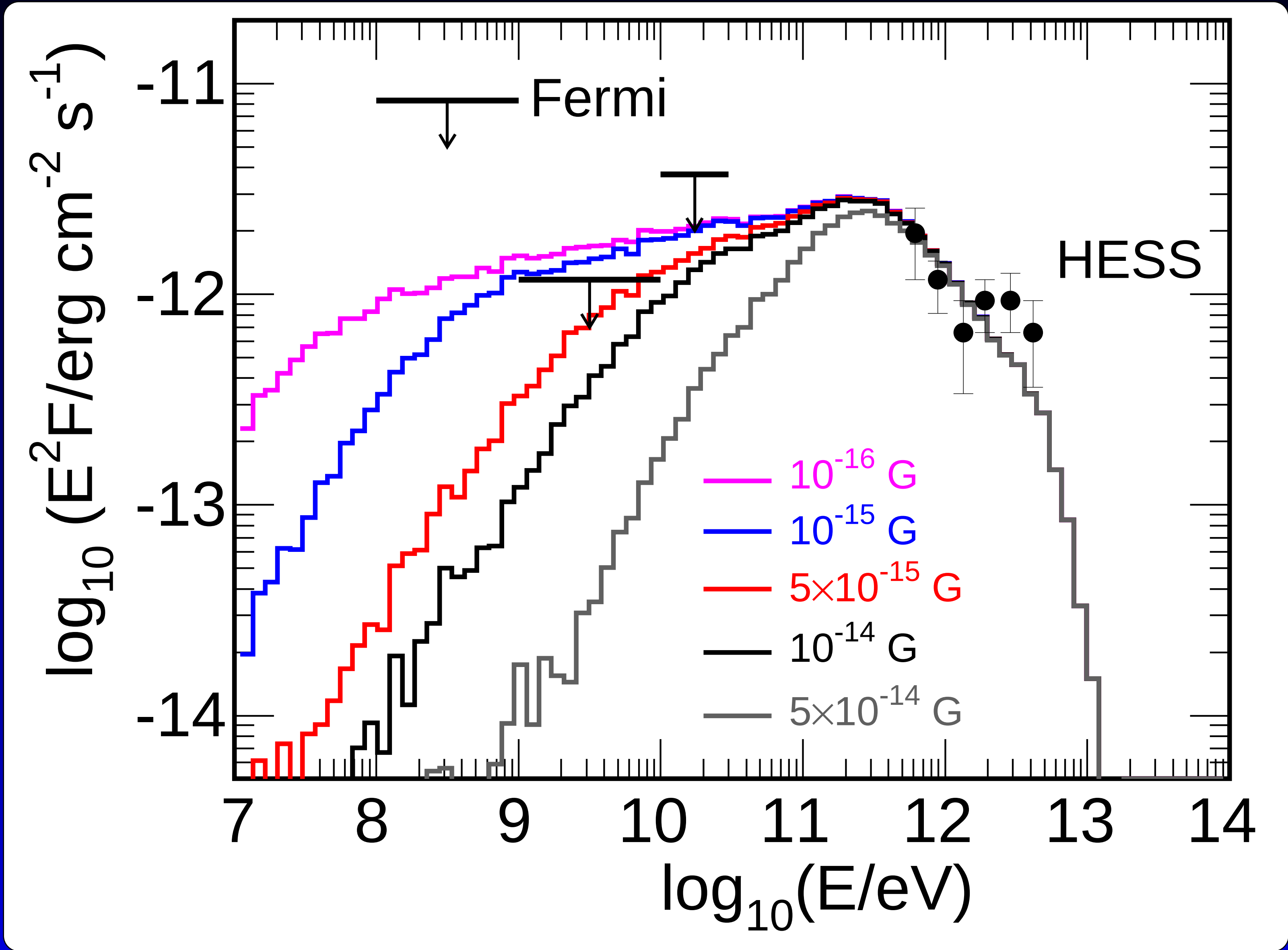
Attenuation from electromagnetic cascade of TeV photons



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

electromagnetic cascade: electron pair production interaction with EBL
cooling of electrons: inverse compton scatter with CMB photons

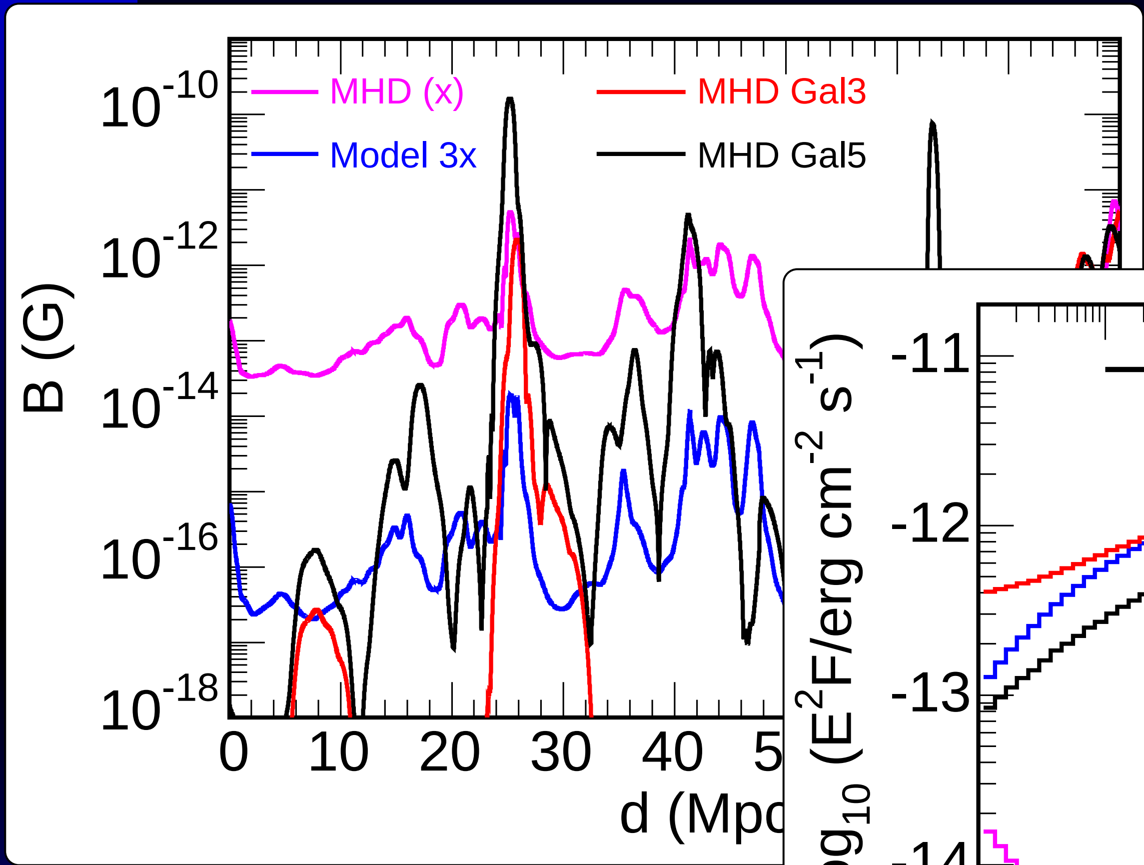
Method IV: γ-rays (fG)

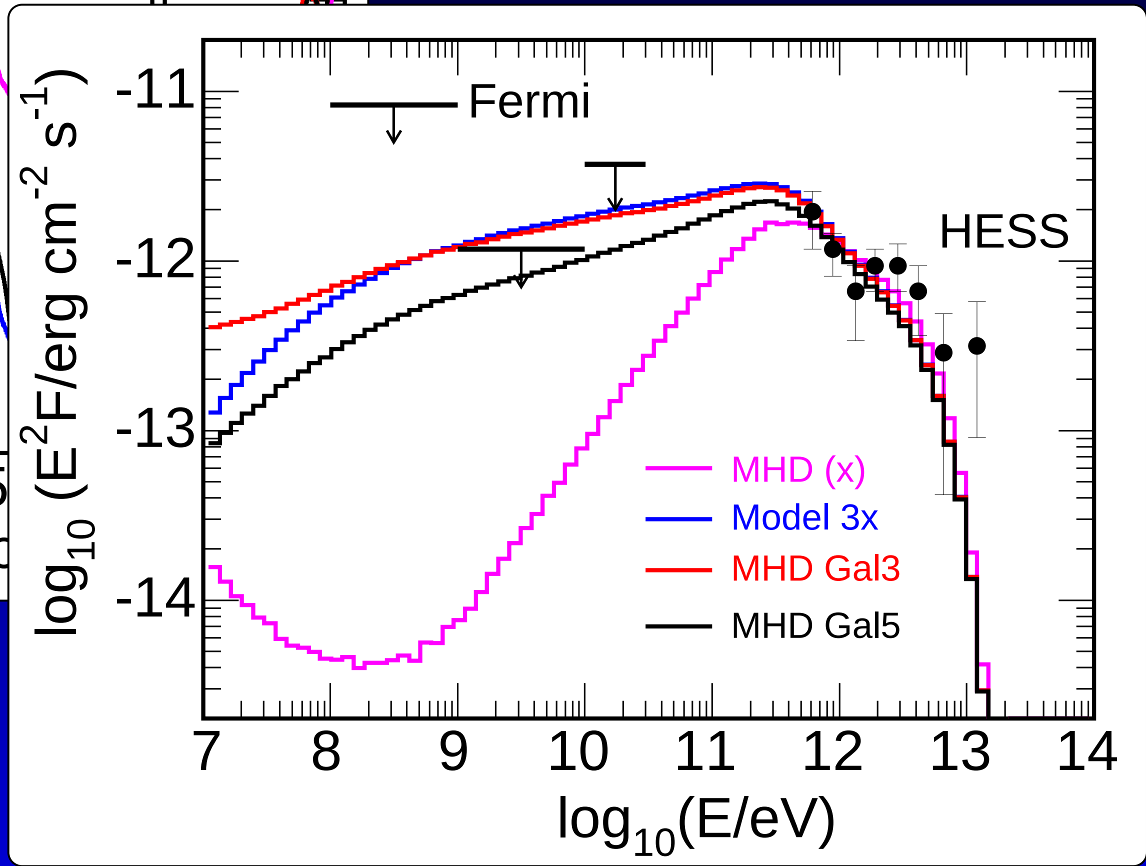


Combing FERMI and HESS give **lower limit** of

$B > 5 \times 10^{-15}$G (Neronov & Vovk 2010, Tavecchio et al. 2010)

Method IV: γ-rays (fG)



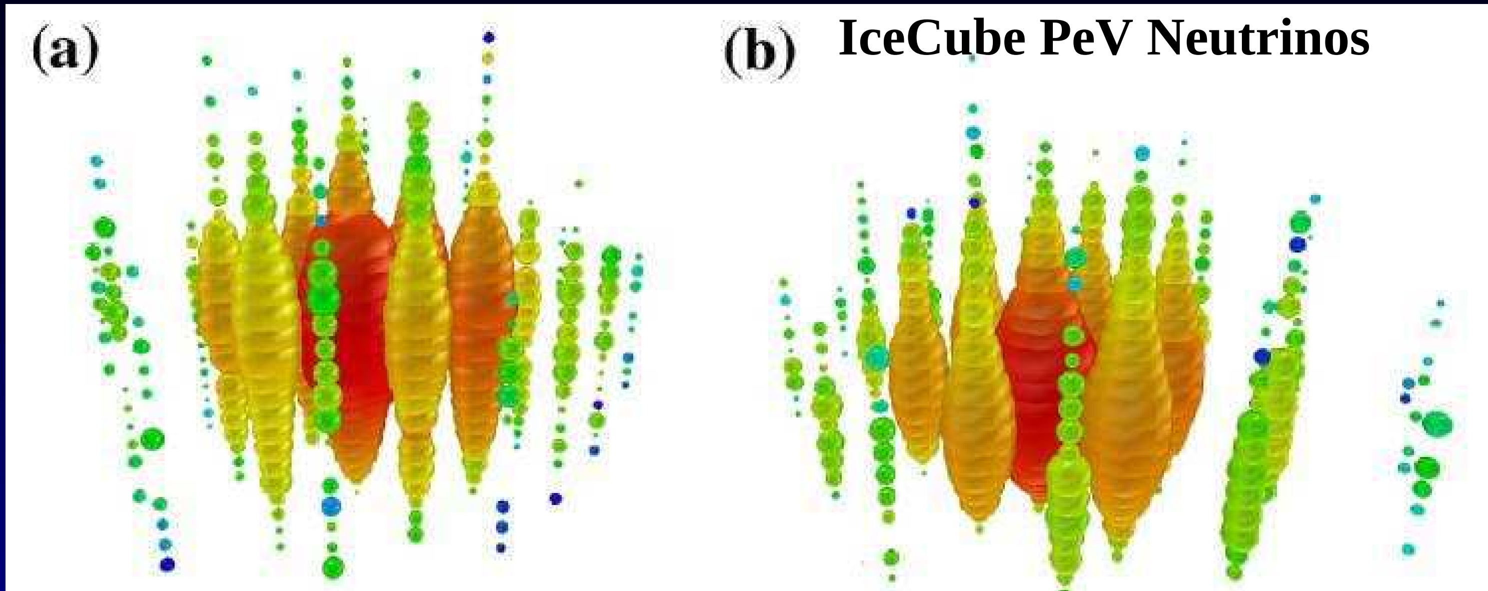


$\Rightarrow B > 3 \times 10^{-15}$ G in at least 40% of space !

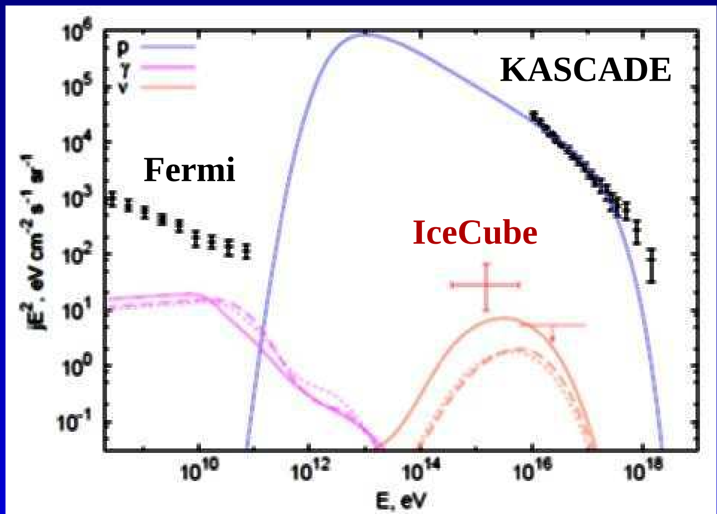
$\Rightarrow$ Strong **constrains** on the **origin** of EGMFs

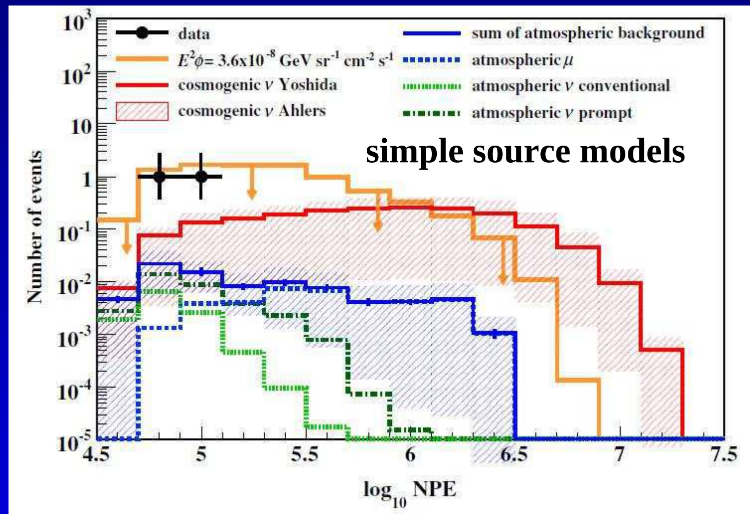
(Dolag, Kachelriess, Ostapchenko & Tomàs 2010)

Method V: Neutrinos



Aartsen et al. 2013





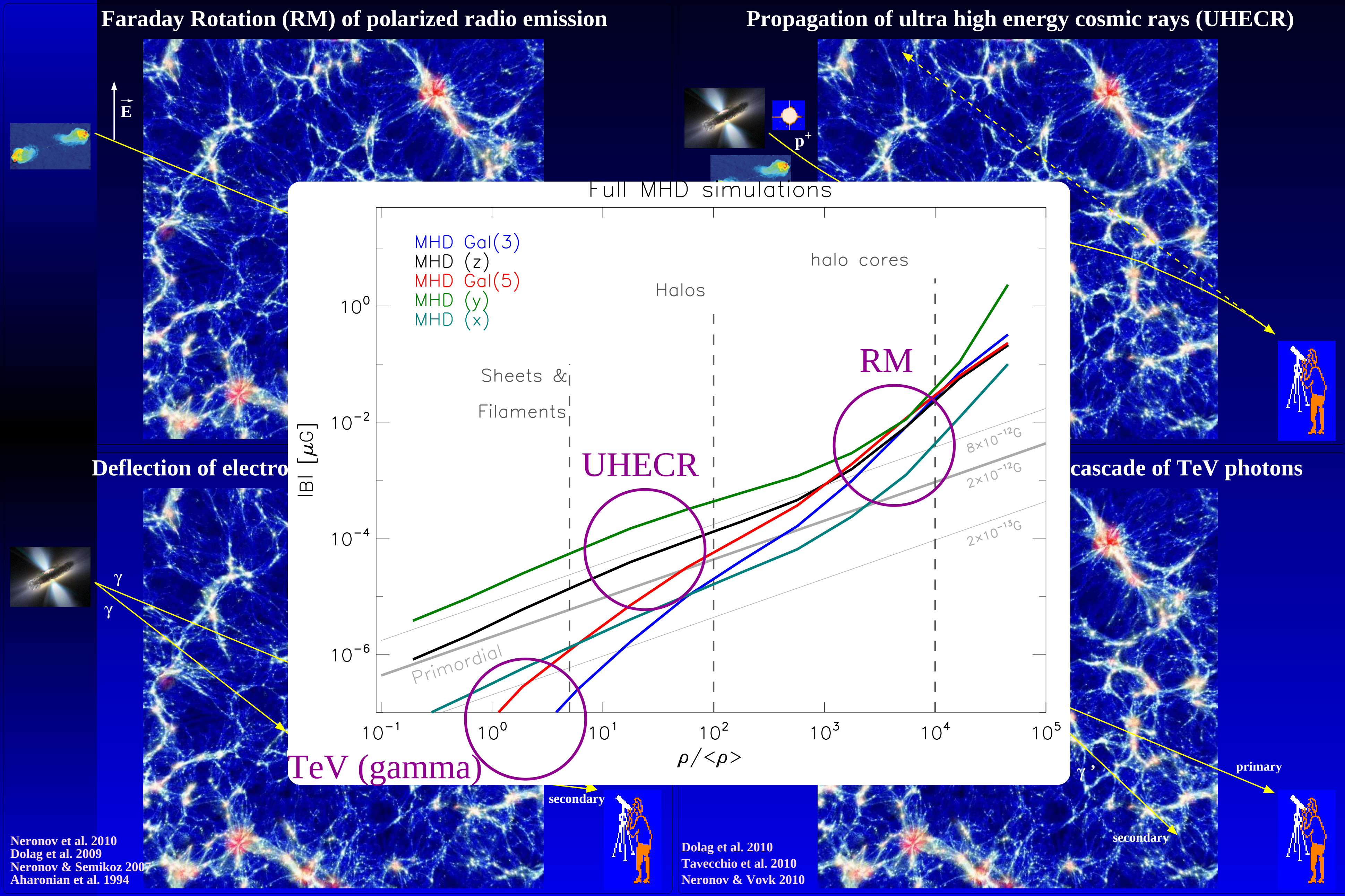
Kalashev, Kusenko & Essey 2013

Electromagnetic cascade will also produce neutrino signal.

IceCube detected 2 Neutrinos with PeV energies !

⇒ Compatible with attenuation signal !

Summary



UHECMessengers open **new** window to Cosmic Magnetism !

Summary

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

- Measurement of magnetic field power spectra
- Clear indication of magnetic field topology
- Indications for minimum/maximum length scale
- RM-Galaxy correlation consistent (but foreground / noise)

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

- High Energy Astronomy helps probing their origin
- UHECR propagation consistent (still under discussion)
- TeV observations of halos would exclude significant contribution from primordial fields (but observations challenged)
- TeV observations of attenuation probes filling factor in voids (but observations challenged by plasma physics)
- First cosmological neutrinos detected (ICE cube) opens independent probe of UHECRM propagation.

$\Rightarrow$ **growing field of research !**