Magnetic fields in and beyond clusters of galaxies

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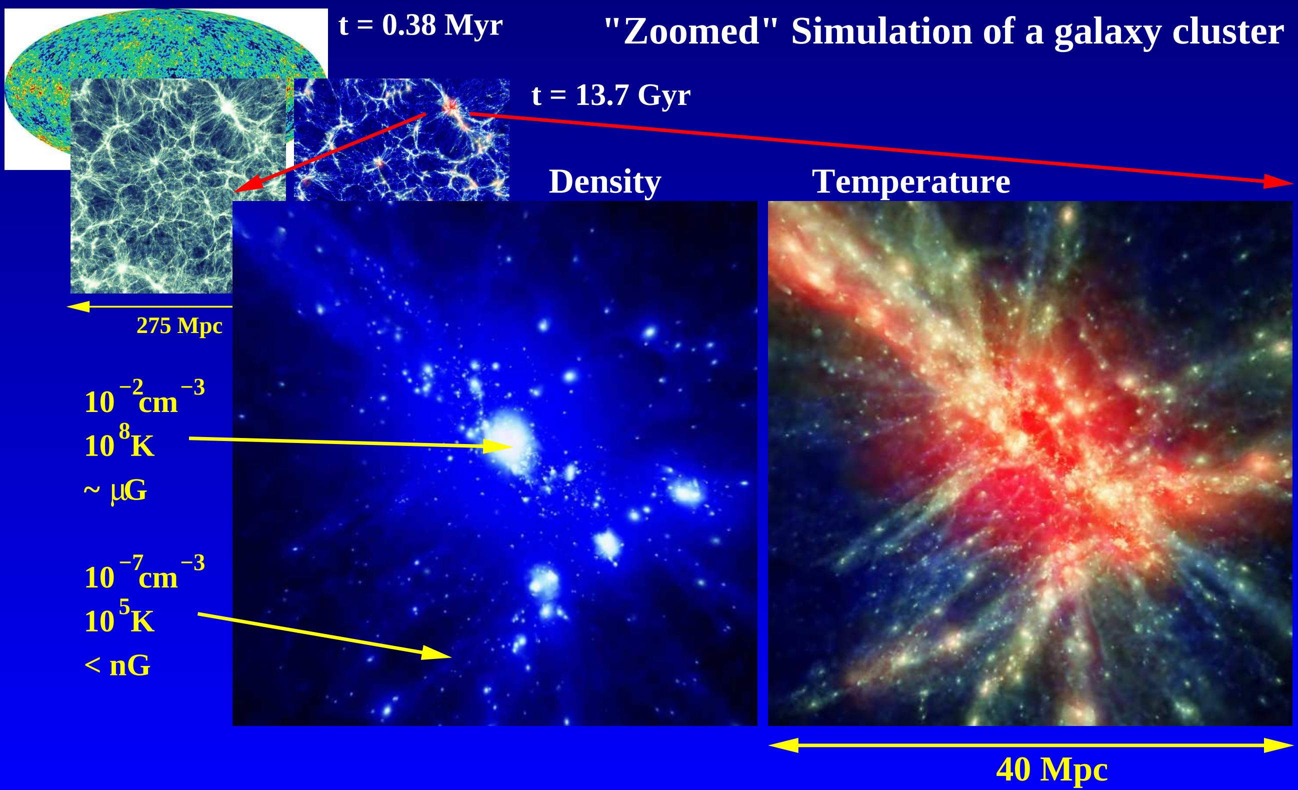


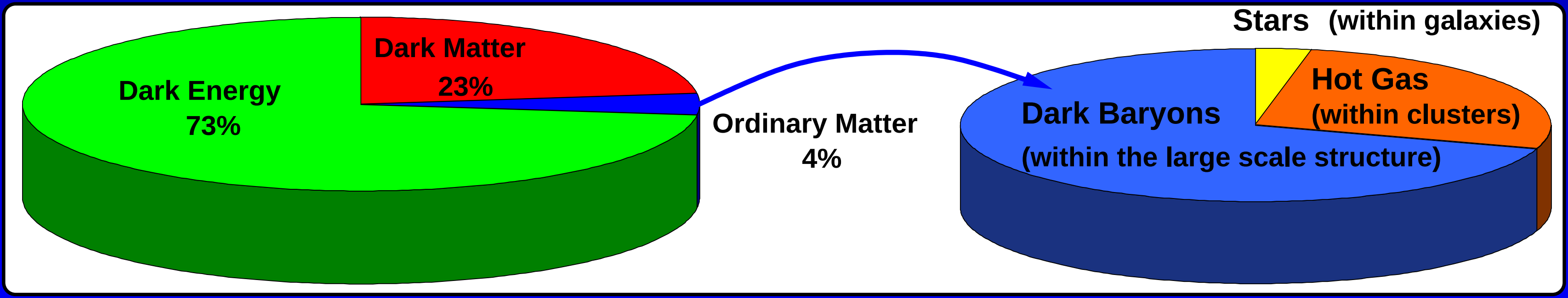
Galaxy Clusters in Numbers

Galaxy clusters are the largest, gravitational bound objects in the Universe and represent an almost fair sample of the cosmological composition.

- Up to thousands of galaxies with $\sigma_{\rm gal}$ up to $1000{\rm km/s}$
- Size ($R_{\rm cluster}$) of several Mpc
- Total mass ($M_{\rm tot}$) up to several $10^{15}M_\odot$ ($\Rightarrow$ dark matter)
- Nearly cosmic baryon fraction ($\approx 95\%$)
- ICM temperatures ($T_{\rm ICM}$) larger than 10^8K

Observed to be virialized:

$$3\sigma^2_{\rm galaxies} \approx \frac{GM_{\rm tot}}{R_{\rm cluster}} \approx \frac{3kT_{\rm ICM}}{2\mu m_p}$$



Historic Milestones

-100 Years:

Ein merkwürdiger Haufen von Nebelflecken.

Auf zwei mit dem Bruce-Teleskop genommenen Aufnahmen vom 24. März dieses Jahres, welche die Umgebung von 31 Comae Berenices darstellen, findet sich eine sehr interessante Gegend des Himmels. Um die Stelle

$$\alpha = 12^h\,52^m.6 \quad \delta = +28°\,42' \; (1855.0)$$

stehen nämlich zahlreiche kleine Nebelflecken so dicht beisammen, dass man beim Anblick der Gegend förmlich über das merkwürdige Aussehen dieses »Nebelhaufens« erschrickt. Ich habe die Anzahl der Nebel in einem Kreis von 30′ Durchmesser um die angegebene Stelle bestimmt und finde, dass mindestens 108 Nebelflecken auf dieser Fläche beisammen stehen, also auf einer Fläche etwa von der Grösse des Vollmondes. Darunter sind vier oder fünf grössere ausgedehnte und centralverdichtete Nebel, sowie mehrere langgestreckte. Die weitaus meisten haben aber rundliche Form und sind kleiner. *)

Heidelberg, 1901 März 27.

Max Wolf.

Max Wolf, 1901

“Die Nebelflecken am Pol der Milchstrasse”

Es ist sofort zu sehen, wenn man die Tabelle oder die Tafel betrachtet, dass das Zusammendrängen der Nebel immer stärker wird, je weiter man in's Innere der Hauptinsel eindringt. Je näher man dem Puncte grösster Dichtigkeit kommt, umso dichter treten auch die Nebel an einander, so dass auf dem innersten Quadratgrad mehr als 320 einzelne Nebelflecken beisammen stehen. An der dichtesten Stelle dieses »Weltpoles« finden sich mehr als 70 Nebel auf der Fläche von 1/16 Quadratgrad.

Wir finden also hier ein völlig gesetzmässiges Verhalten in der Anordnung dieser fernen Welten; und dieser ungeheure Reichthum führt uns so eine Ordnung im Weltsystem vor Augen, die sicher für die Erkenntniss des Universums von allergrösster Bedeutung ist, von der wir uns aber auch zugestehen müssen, dass wir noch lange keine erschöpfende Erklärung für sie werden finden können. *)

Max Wolf, 1902

-70 Years:

Unvisible matter needed to explain cluster dynamics

Zwicky 1936

Historic Milestones

-50 Years:

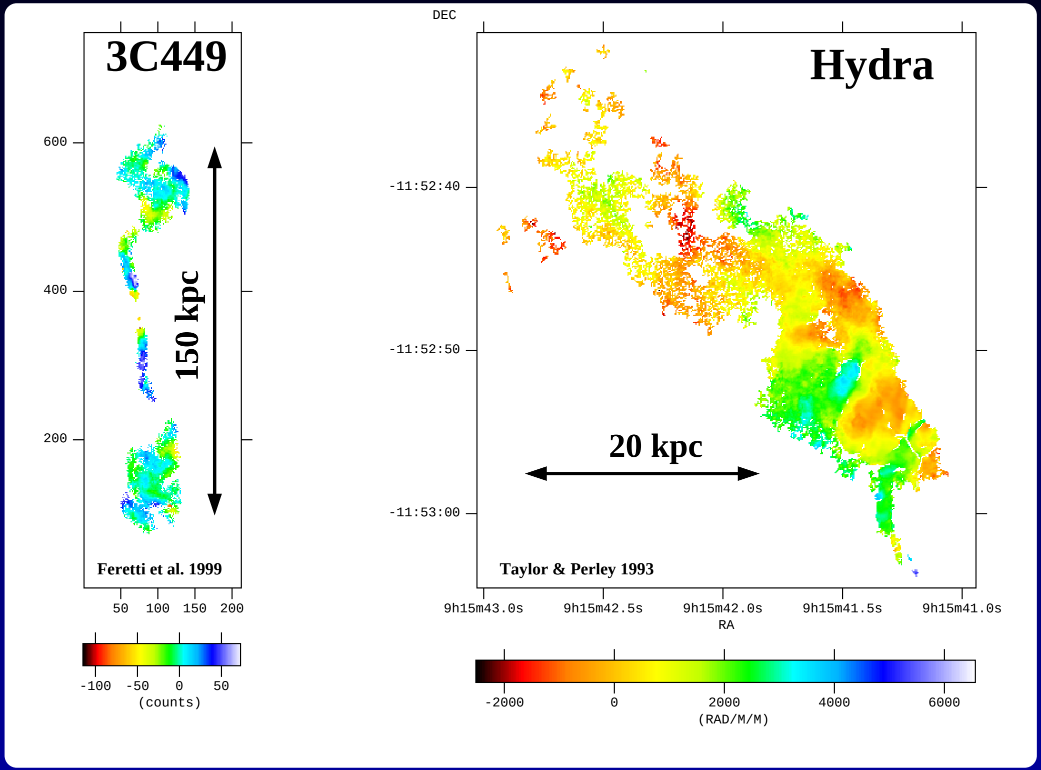
- Coma C detected as extended radio source
  Large, Masthewson & Haslam 1959
- Confirmed to be diffuse radio emission
  Willson 1970 ⇒ problem of large extend Jaffe 1977
- Diffuse X-ray emission detected
  Meekins, Fritz, Chubb & Friedman 1971
- Faraday Rotation (RM) of ICM detected
  Dennison 1979
- No similar emission found in 72 rich clusters
  Hanisch 1982

⇒ What is the origin of the magnetic field ?

⇒ What causes the diffuse radio emission ?

⇒ Magnetic fields on larger scales ?

Historic Milestones



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:

$<$ 10 extended RM sources within clusters

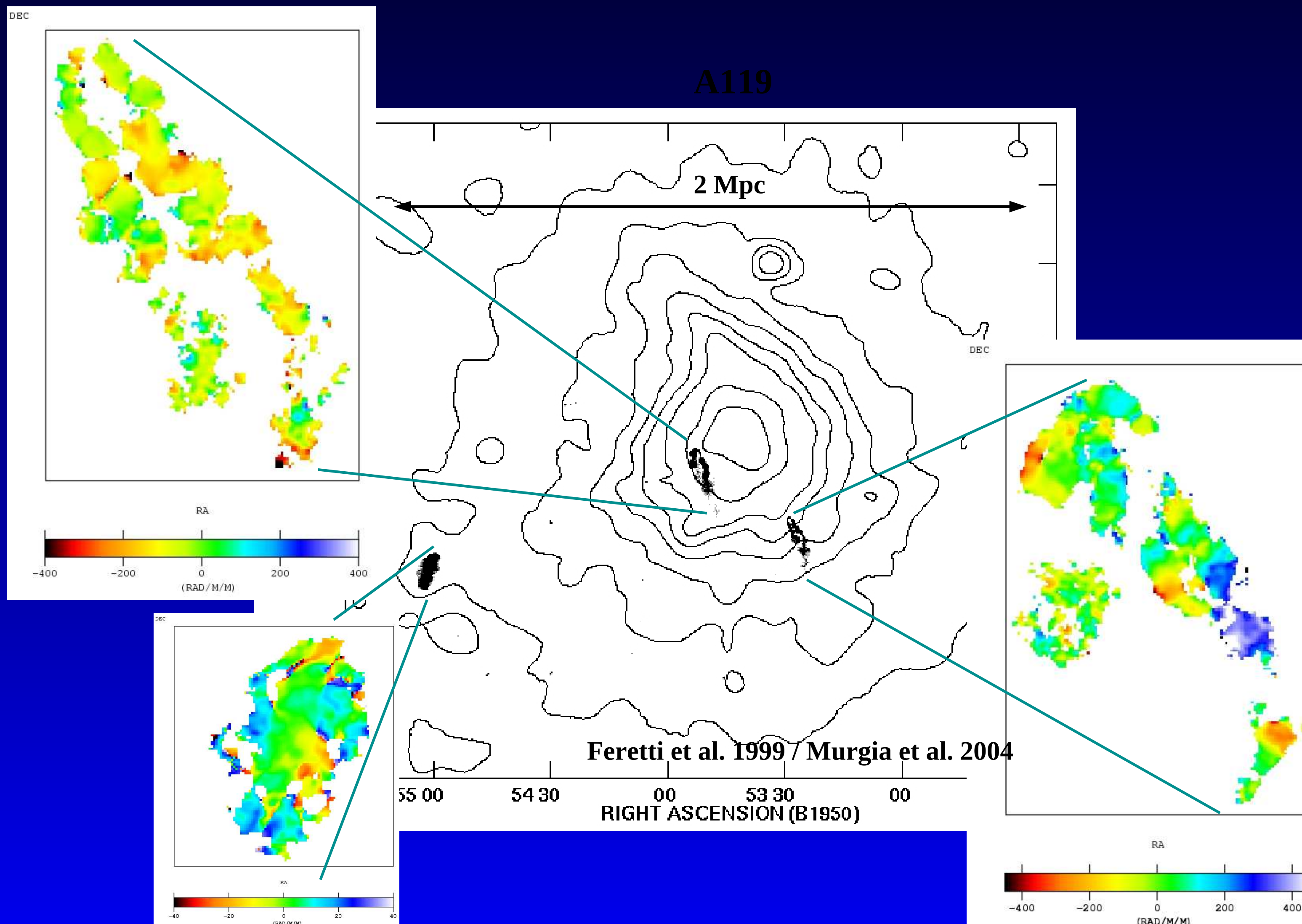
$<$ 100 point sources behind various clusters

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

Observations

-10 Years:

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

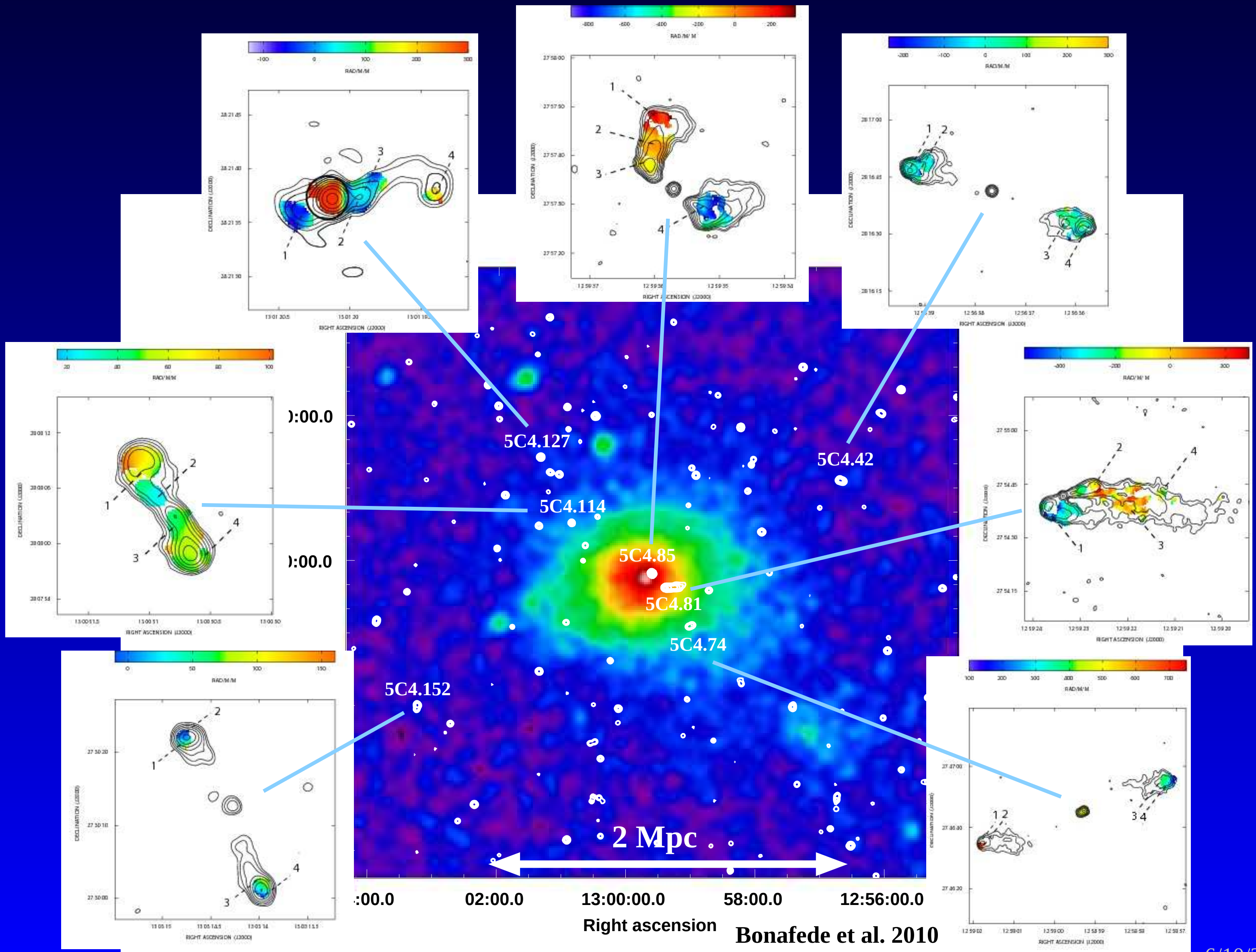


$$\Rightarrow B_0 = 5\mu\mathrm{G} \quad n = 2 \quad \mu = 0.5$$

Observations

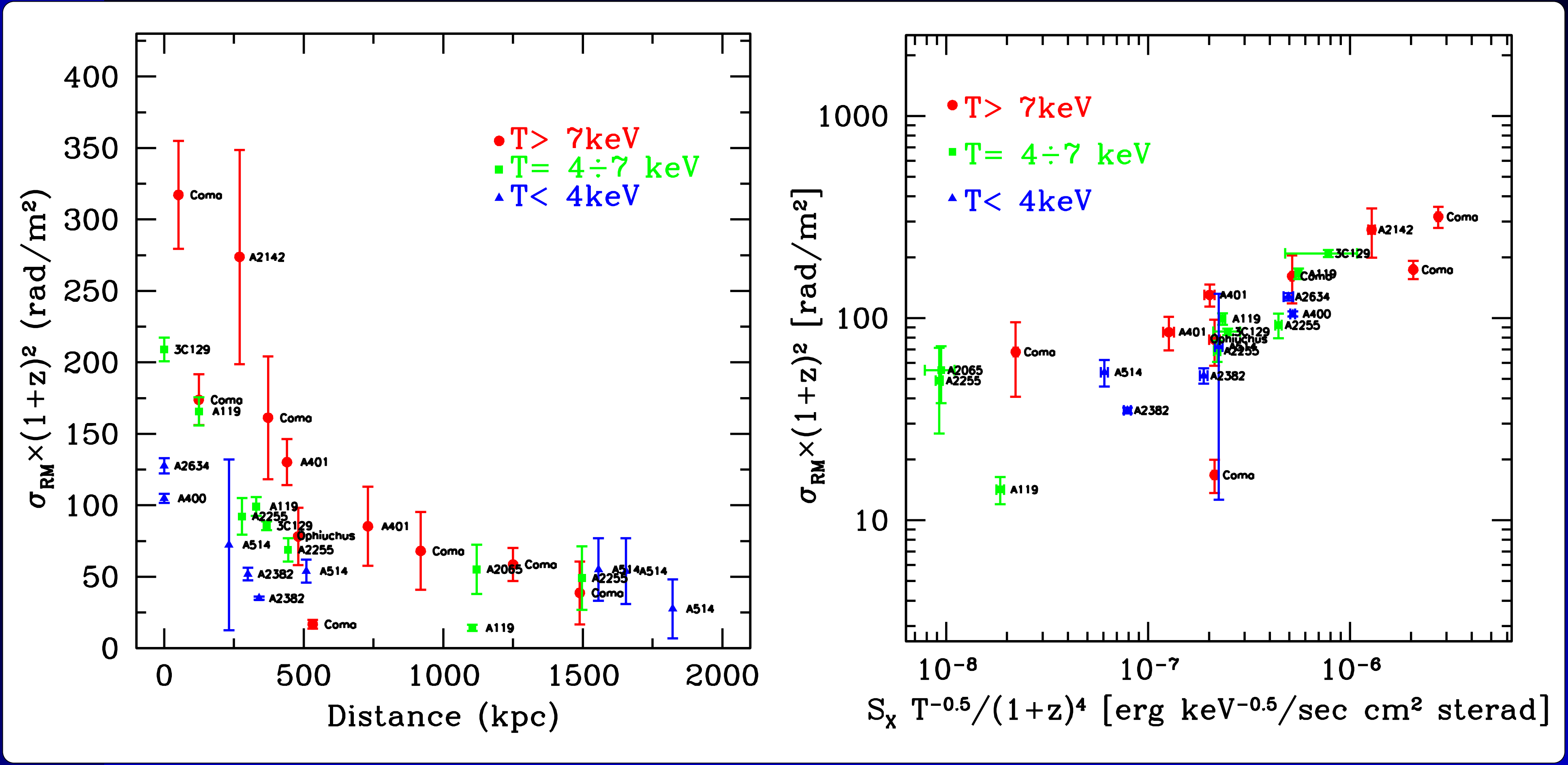
-0 Years: (See talk by A. Bonafede)

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



Bonafede et al. 2010

Observations

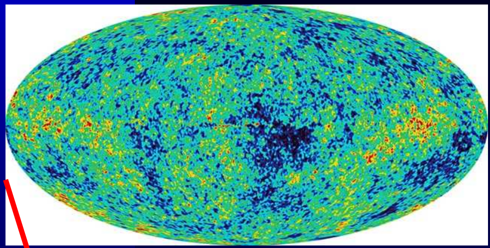


Govoni et al. 2010

- Four new RM maps within massive clusters.
- How does $\vec{B}$ scale with cluster temperature ?

$\Rightarrow$ Cosmological MHD simulations

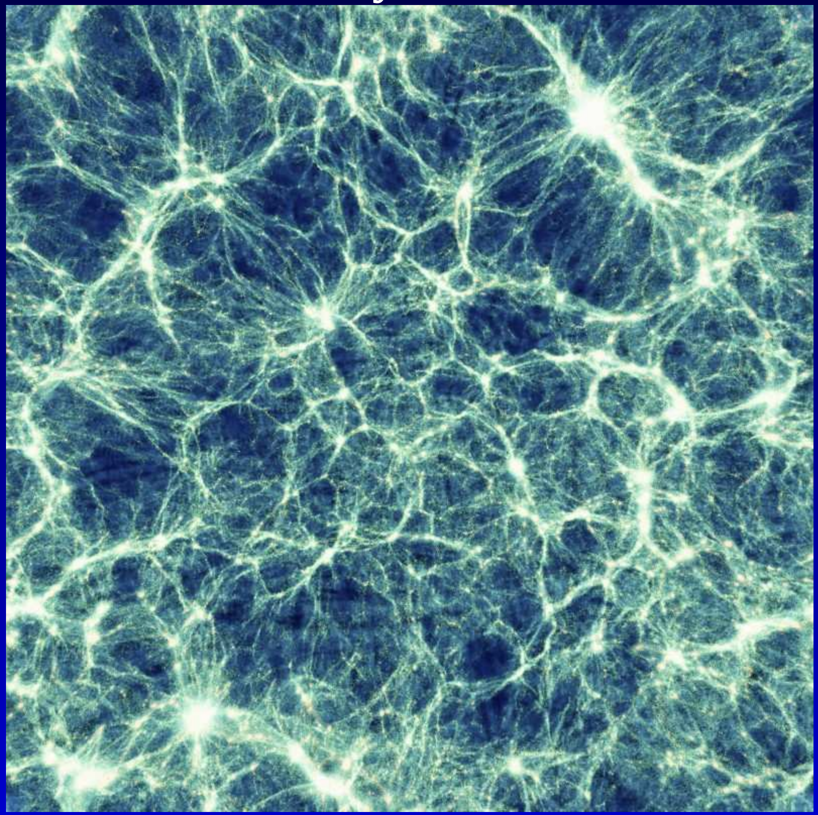
The Big Picture



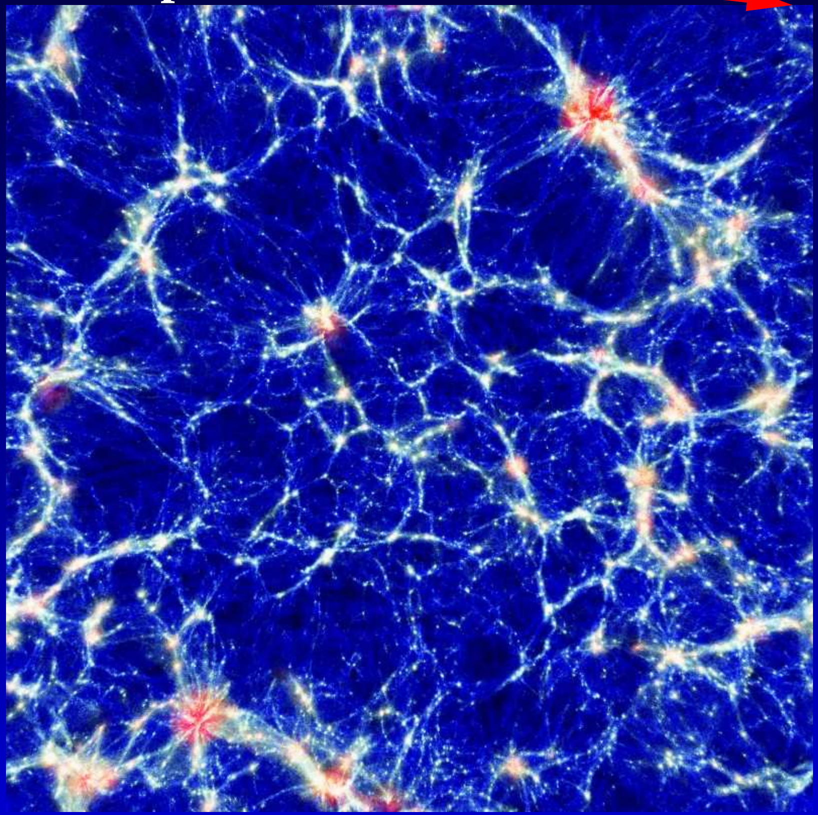
CMB (t = 0.38 Myr)

Cosmic structure today (t = 13.7 Gyr)

Density



Temperature

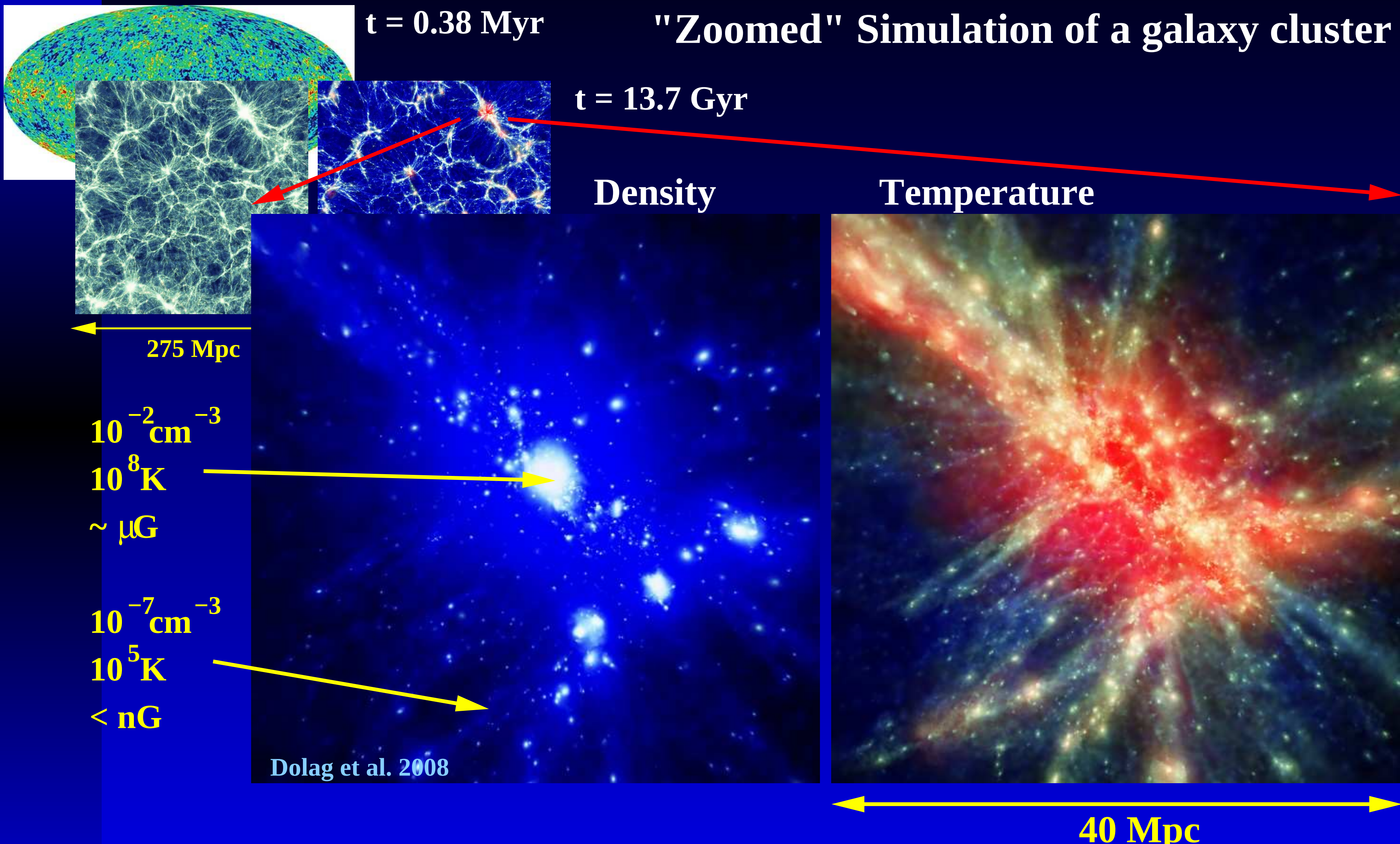


Borgani et al. 2004

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

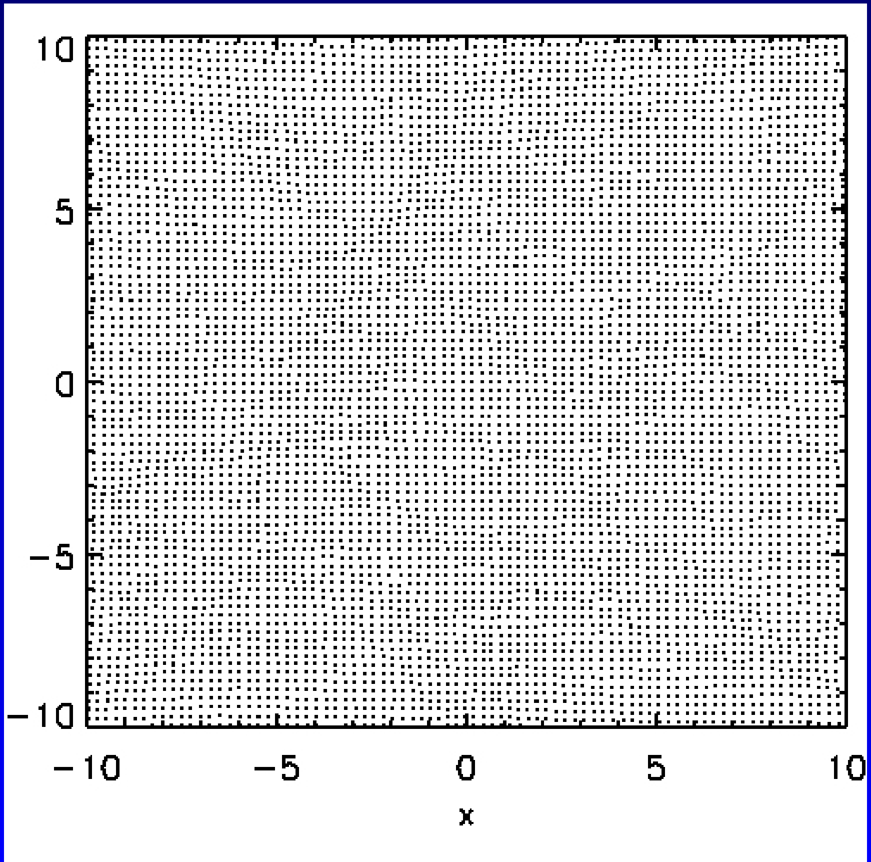


Clusters form at the nodes of the cosmic web and can be used as a tool to understand the physical state of diffuse baryons.

Simulating the Universe

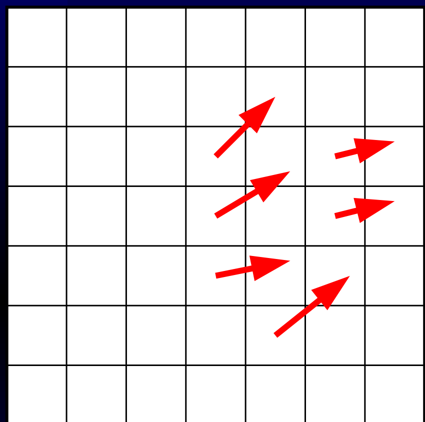
N-body simulation: Integrate the equation of motion using tracer particles, within the ΛCDM framework.

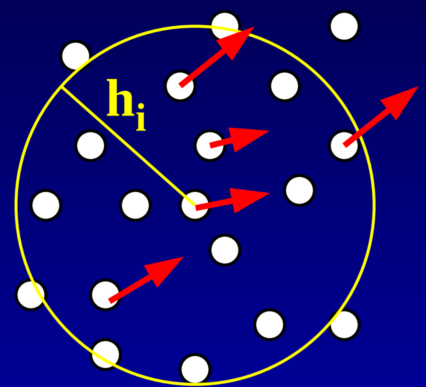
$\Rightarrow$ formation of typical, cosmic structures like voids, filaments and collapsed objects (e.g. galaxies and galaxy clusters)



Simulating the Universe

Eulerian	Langrangian	SPH
discretize space	**discretize mass**	**kernel estimate**

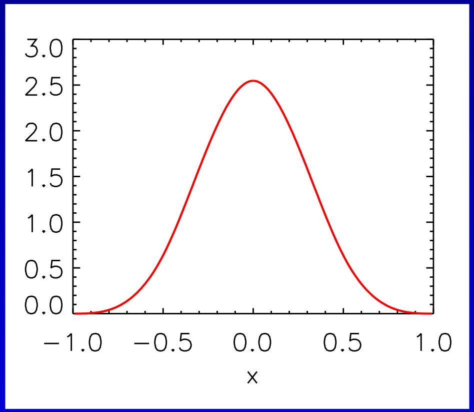




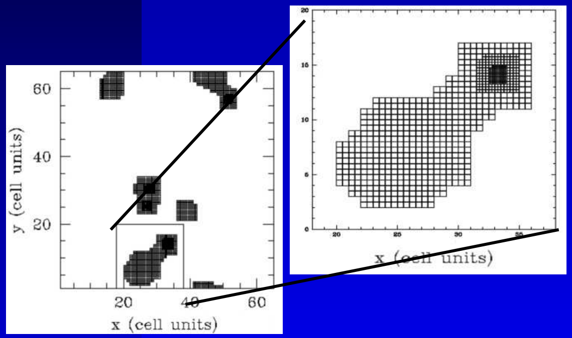
$$\langle A(\mathbf{r})\rangle = \int W(\mathbf{r}-\mathbf{r}', h)\, A(\mathbf{r}')\, \mathrm{d}^3 r'$$

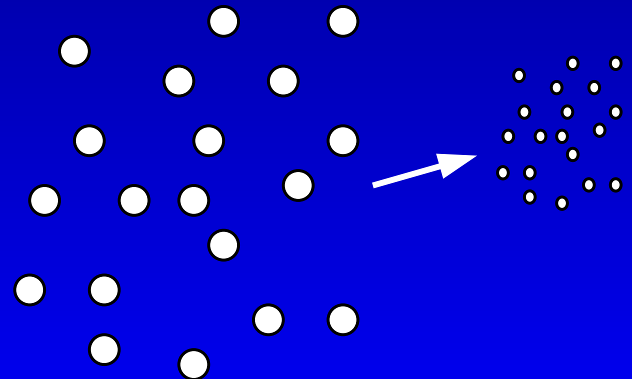
$$\mathrm{d}^3 r' \mapsto \frac{m_j}{\rho_j}$$

$$\langle A_i\rangle = \sum_{j=1}^{N} \frac{m_j}{\rho_j} A_j\, W(\mathbf{r}_{ij}; h_i)$$



Collapse:

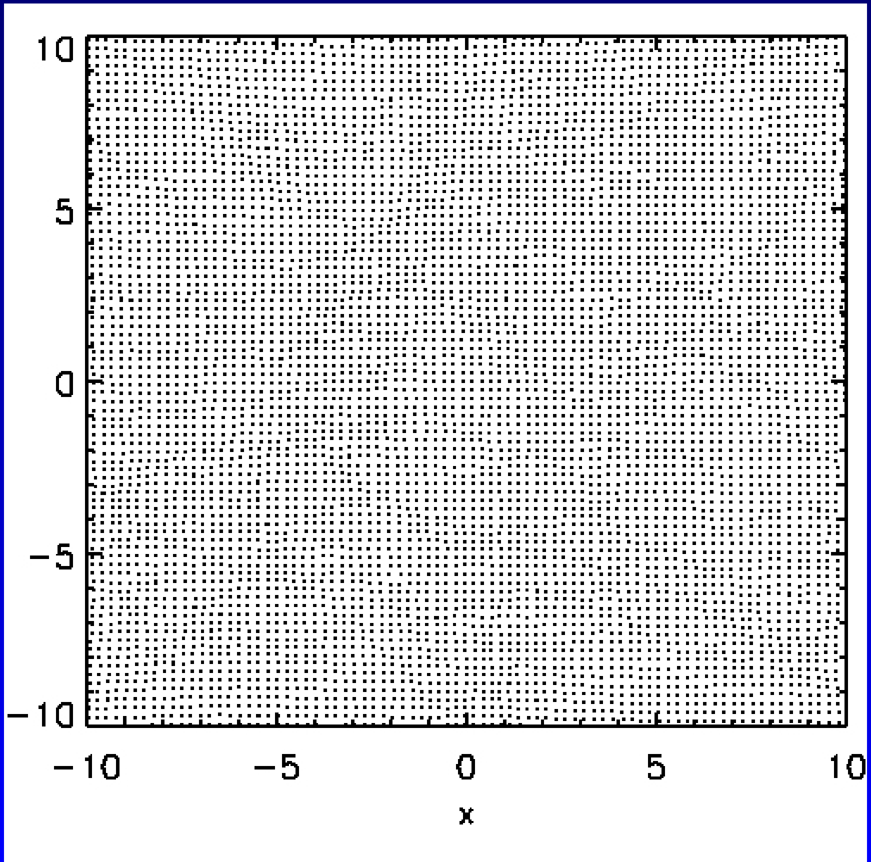




Simulating the Universe

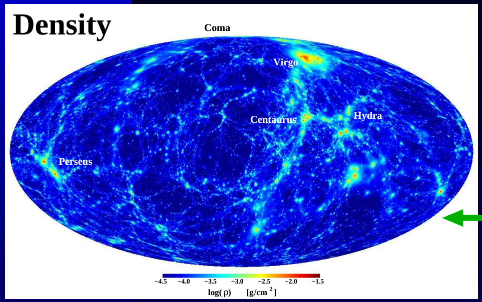
Now we can follow the equation of motion of two species of particle, but for the gas additional terms appear.

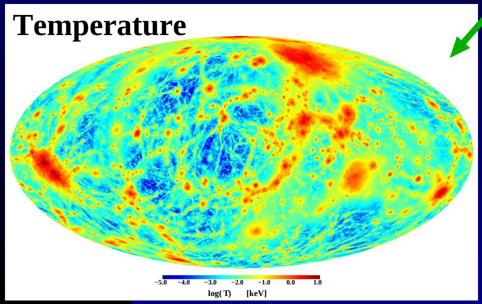
$$\left(\frac{\mathrm{d}\vec{v}}{\mathrm{d}t}\right)_{\mathrm{D}M} = -\vec{\nabla}\Phi, \quad \left(\frac{\mathrm{d}\vec{v}}{\mathrm{d}t}\right)_{gas} = -\frac{\vec{\nabla}P}{\rho} - \rho\vec{\nabla}\Pi_{ij} - \vec{\nabla}\Phi$$



Simulating the Universe

Simulation Network



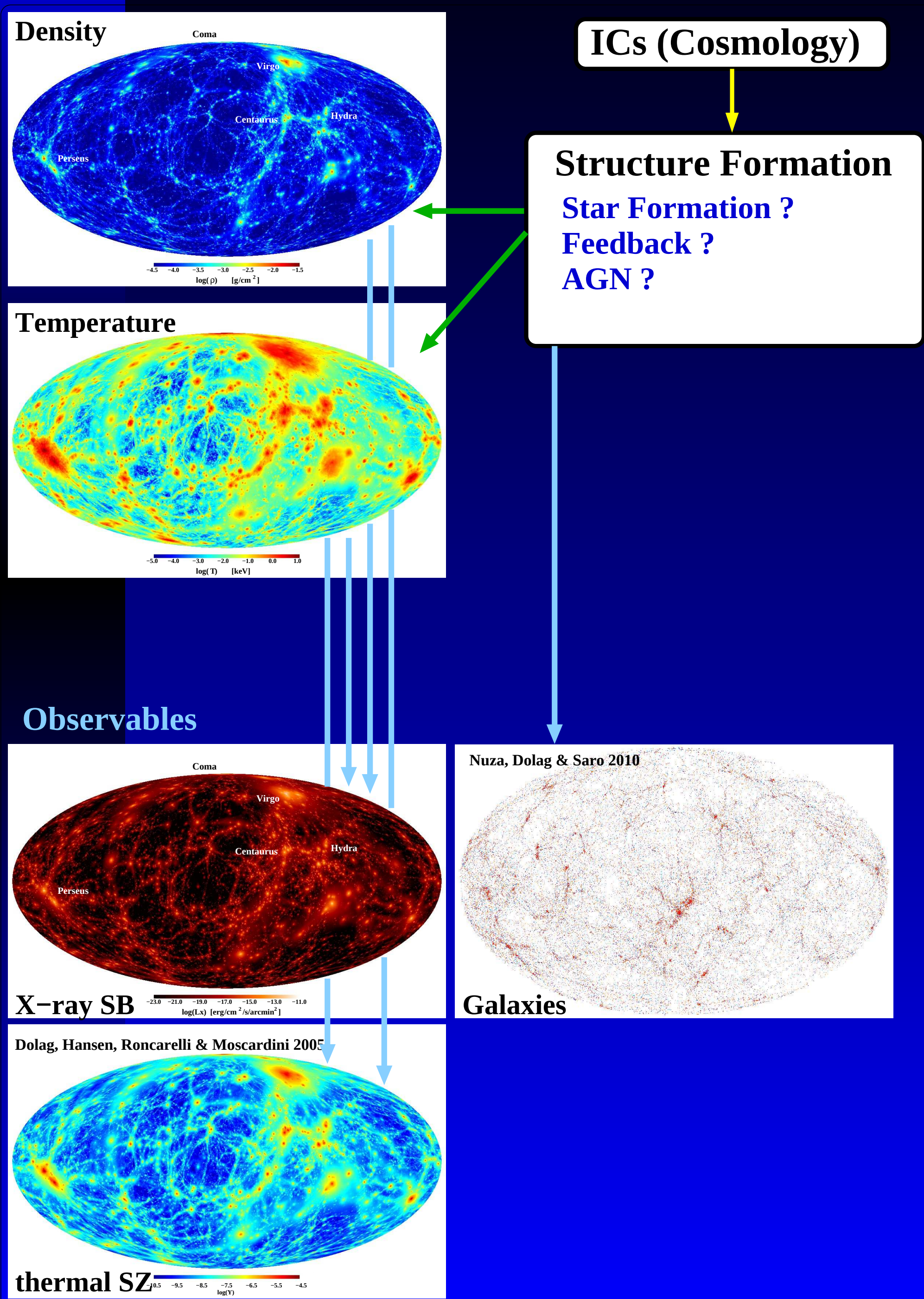


ICs (Cosmology)

Structure Formation

Star Formation ?
Feedback ?
AGN ?

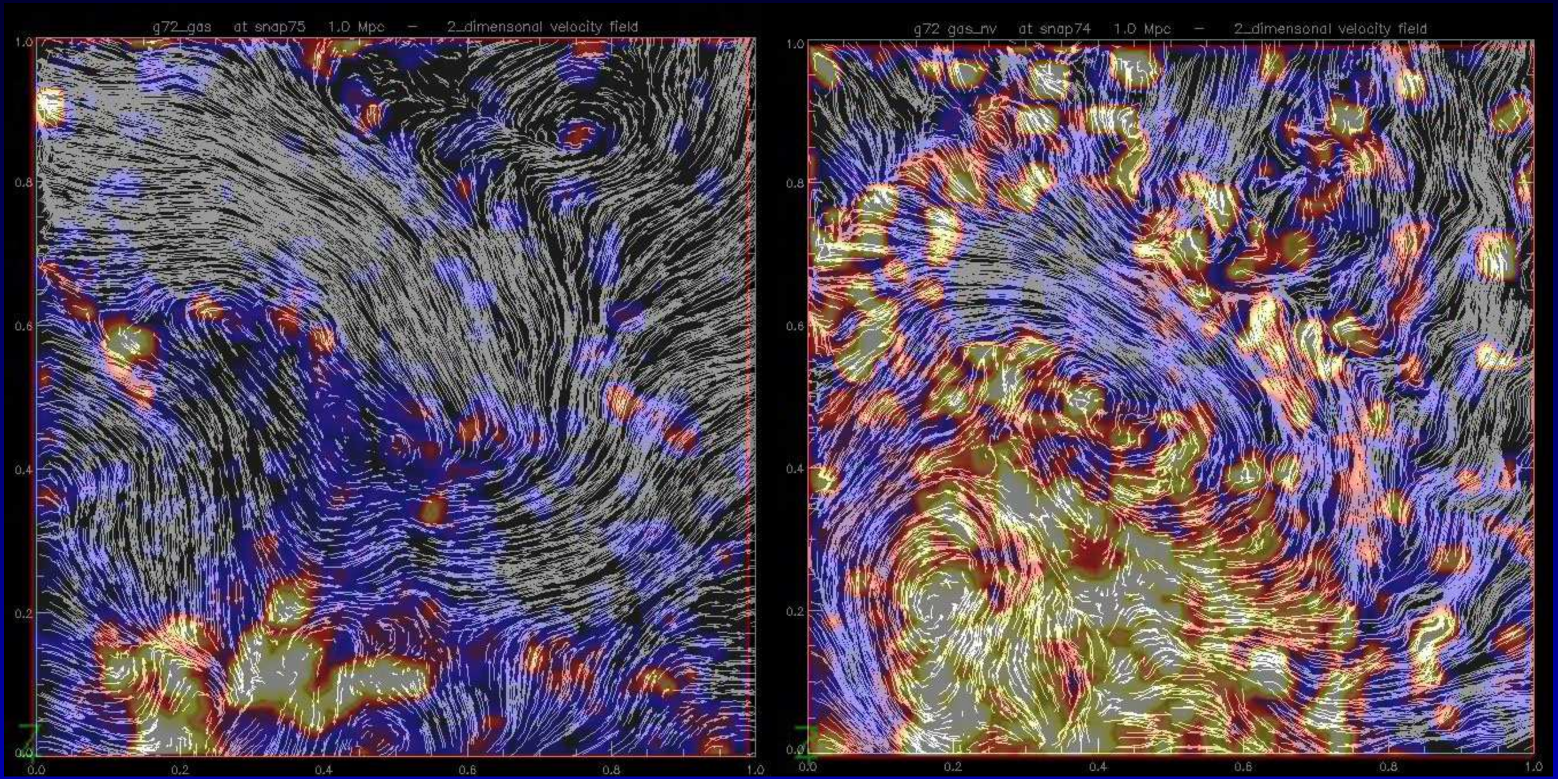
Simulation Network



Turbulent motions in the ICM

An example of turbuent velocity fields from simulations:

Old viscosity scheme **New viscosity scheme**



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

⇒ Inset of turbulence (transient phenomena)

⇒ Enlarged energy-fraction in gas velocity (10%)

See talk by F. Vazza ...

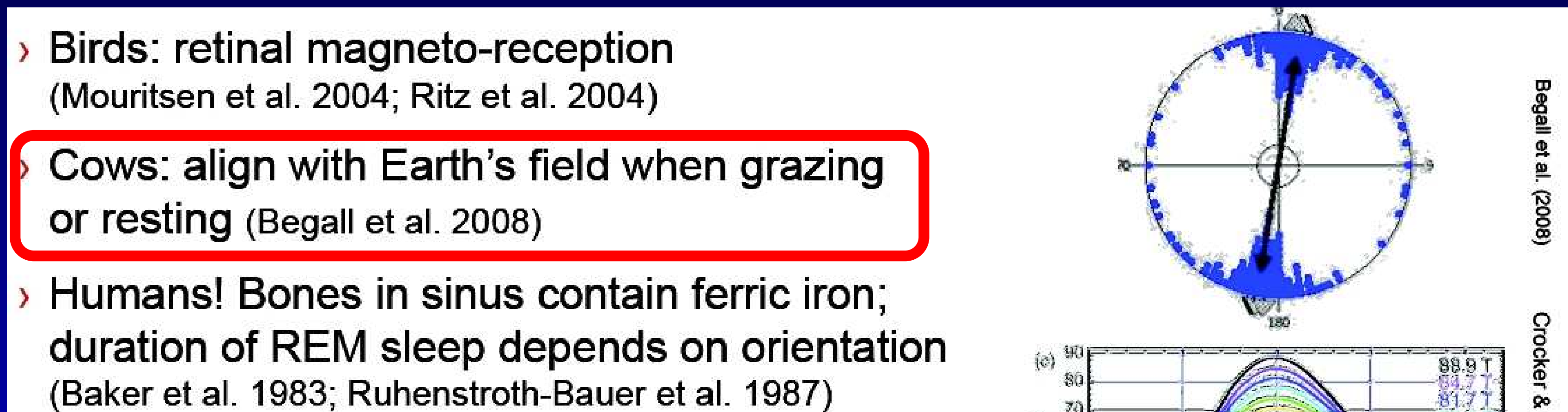
⇒ Observed in Coma (Schuecker et al. 2004)

⇒ Will steer magnetic fields ...

Note on adding magnetic fields

Always be careful, as things can be much more complicated as you think !

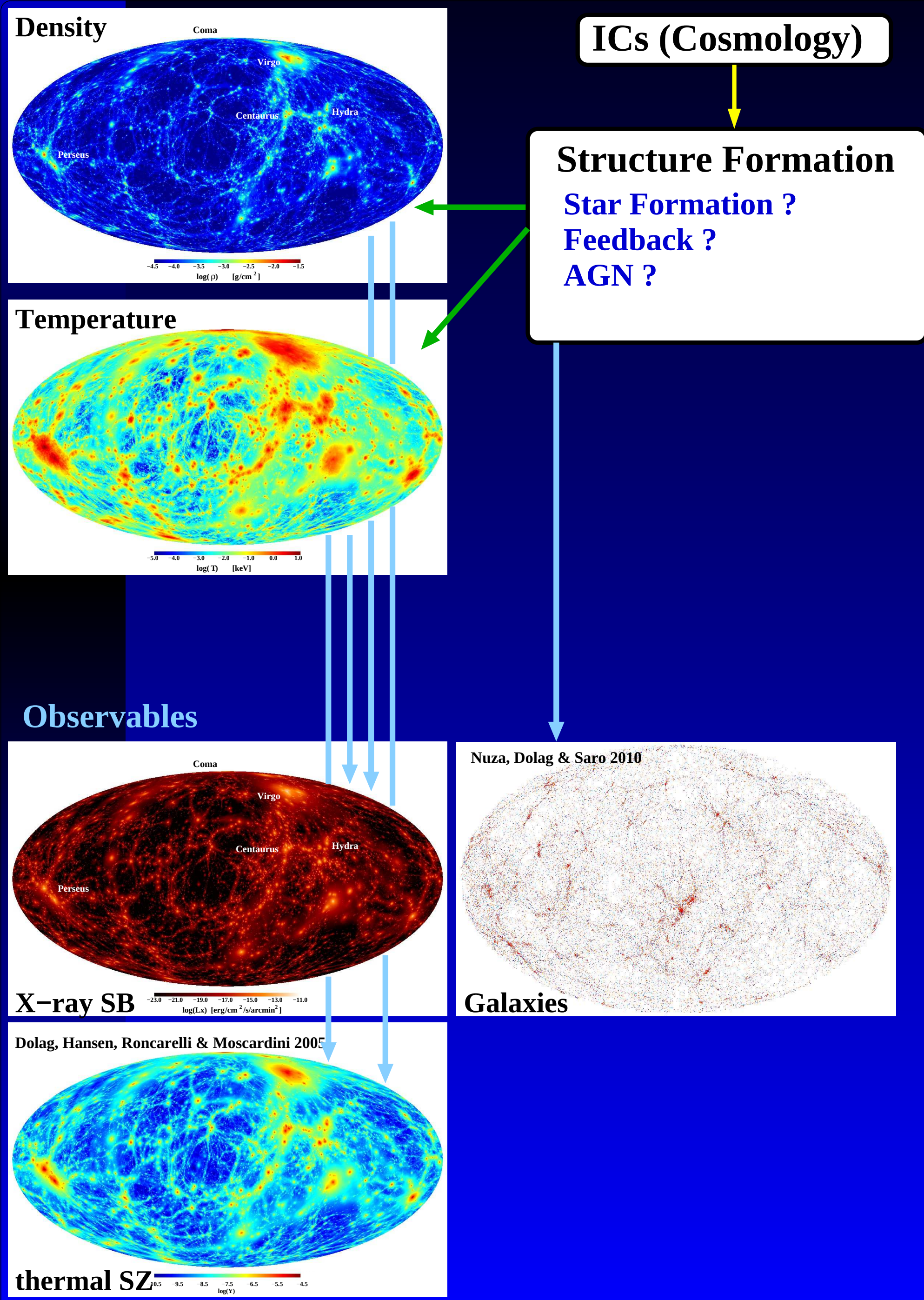
Example: **Magnetic Cows**



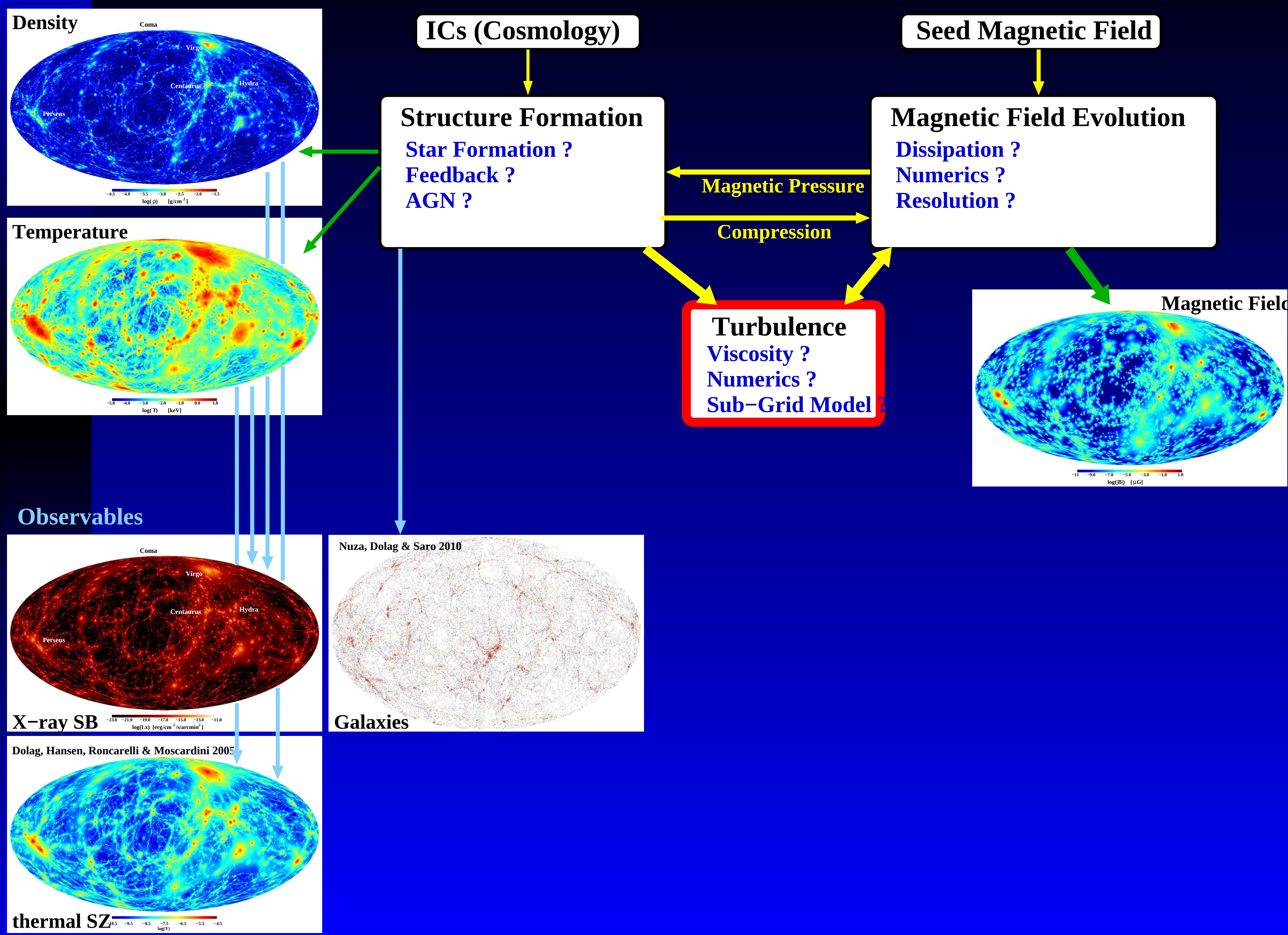
taken from Bryan Gaensler's Kiama 2010 talk

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

Simulation Network



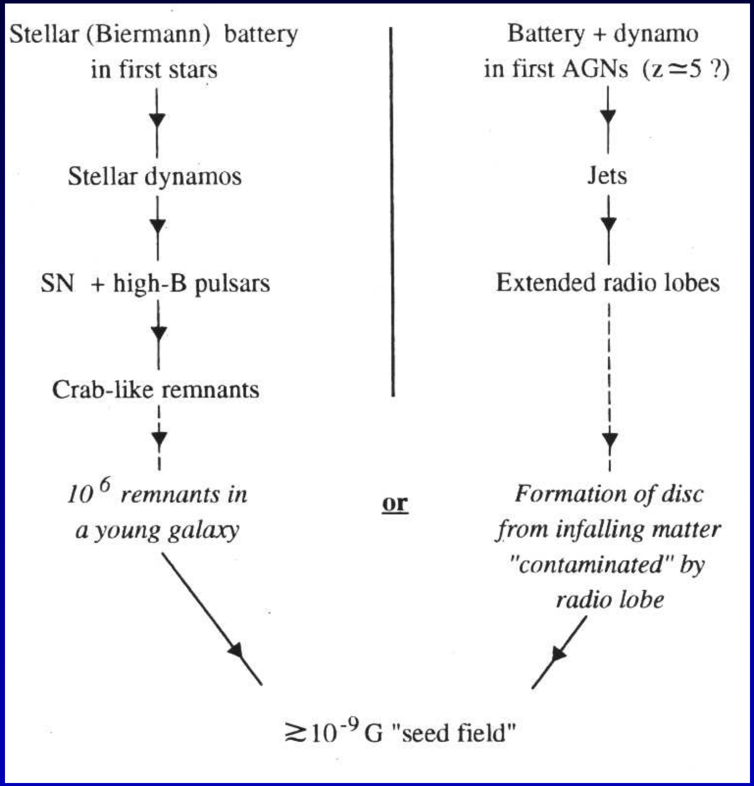
Simulation Network



Origin of Magnetic Fields

Origin

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

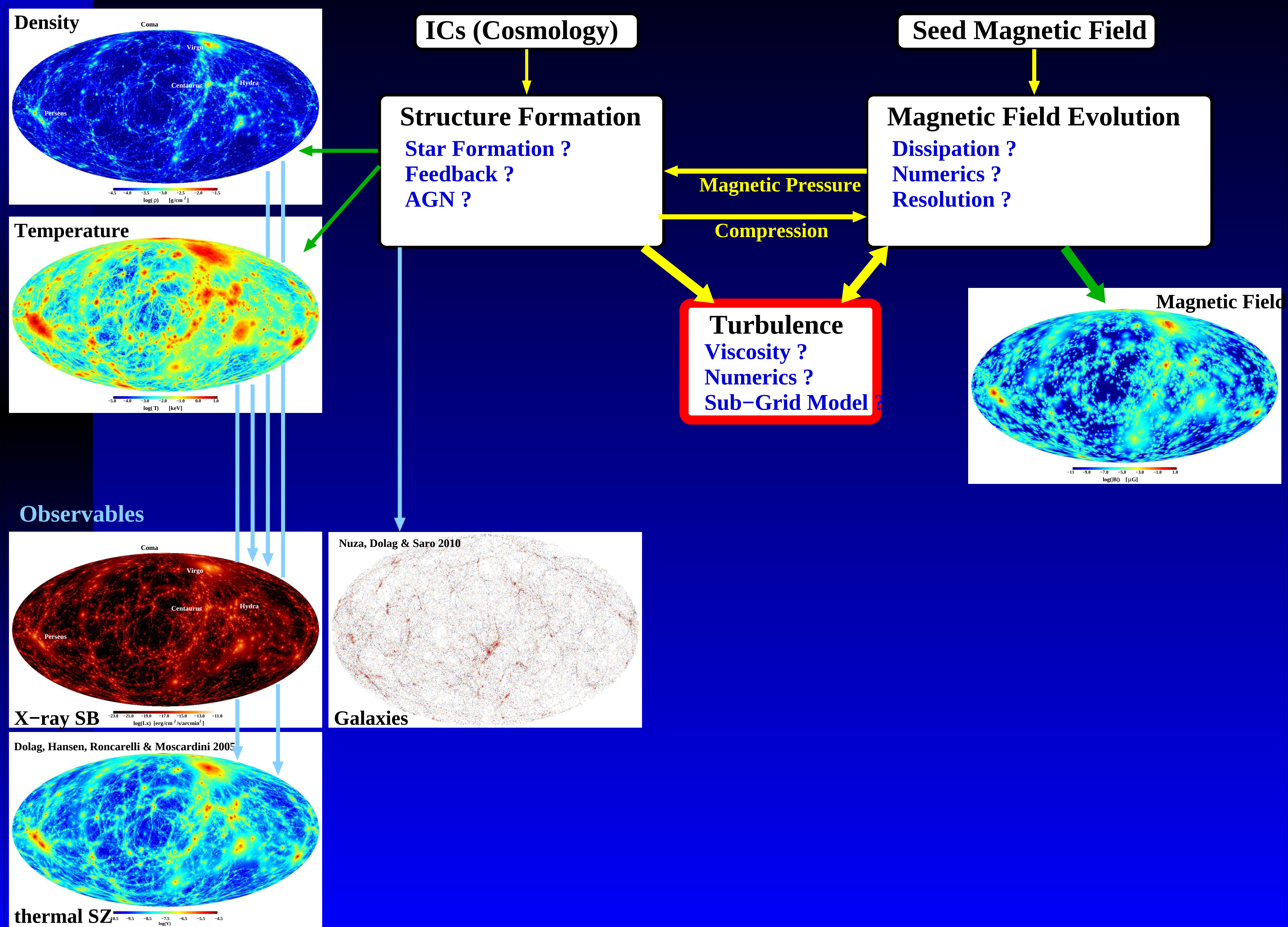


Rees 1994

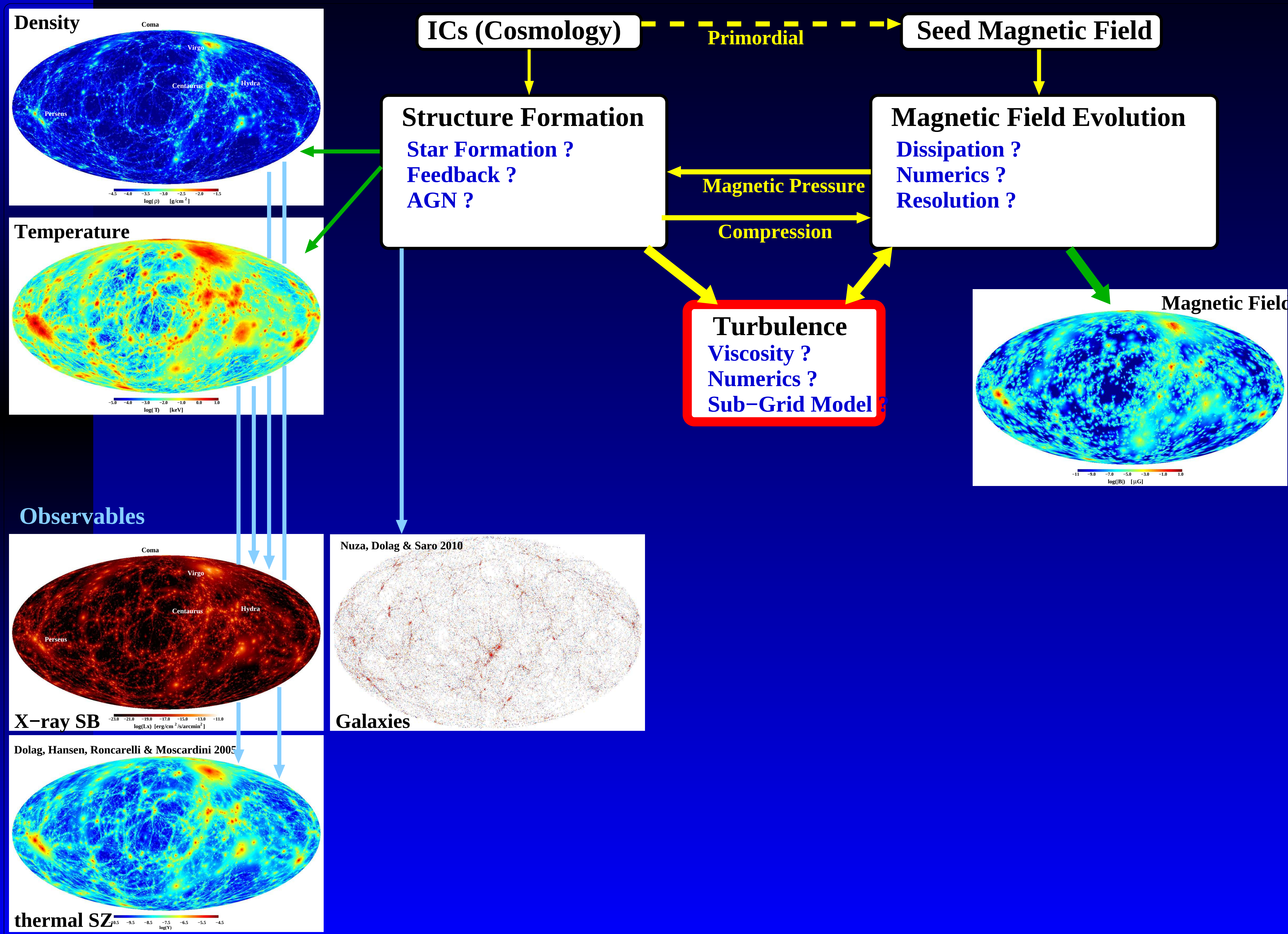
+ further amplification by **structure formation**

- dissipation ?

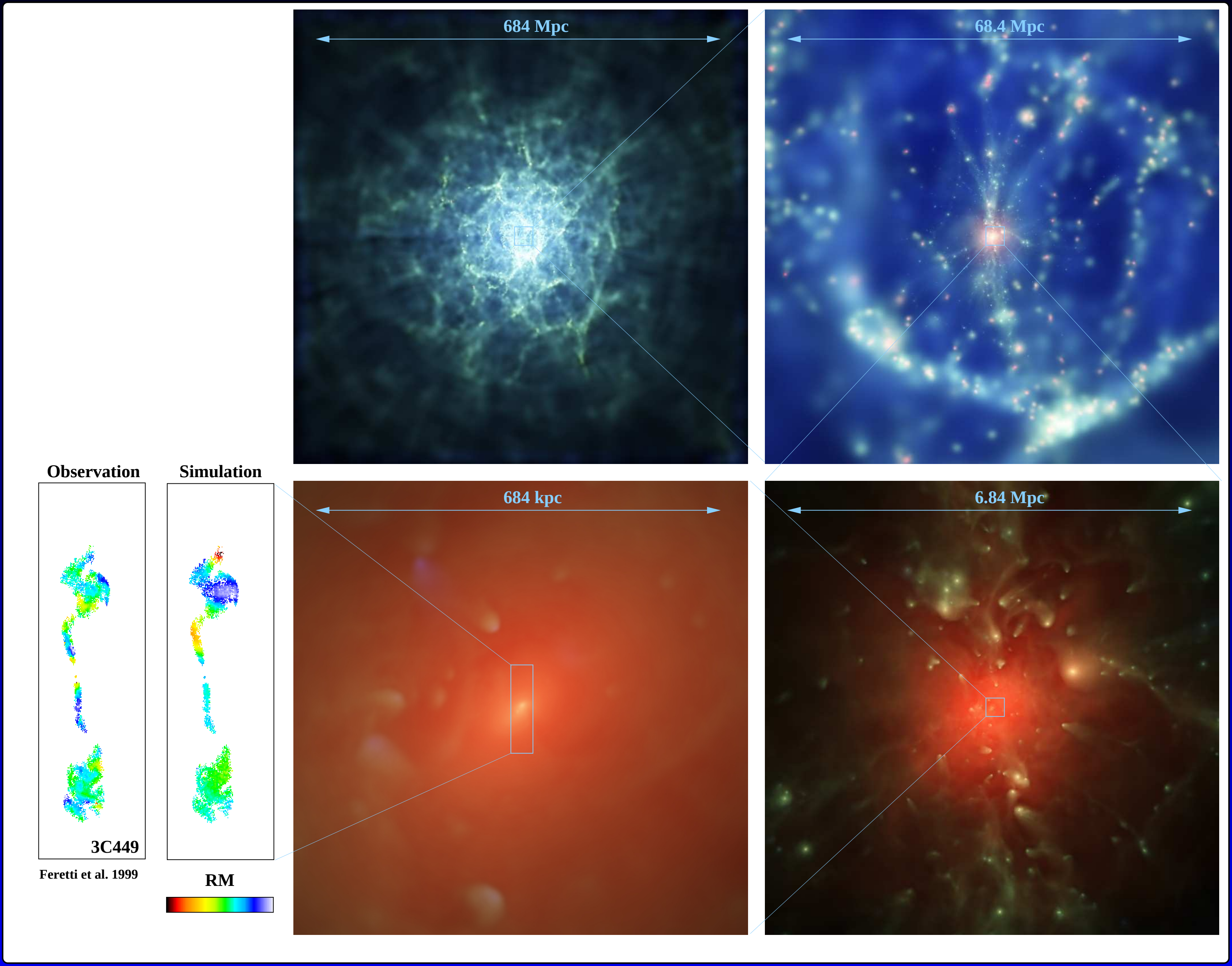
Simulation Network



Simulation Network

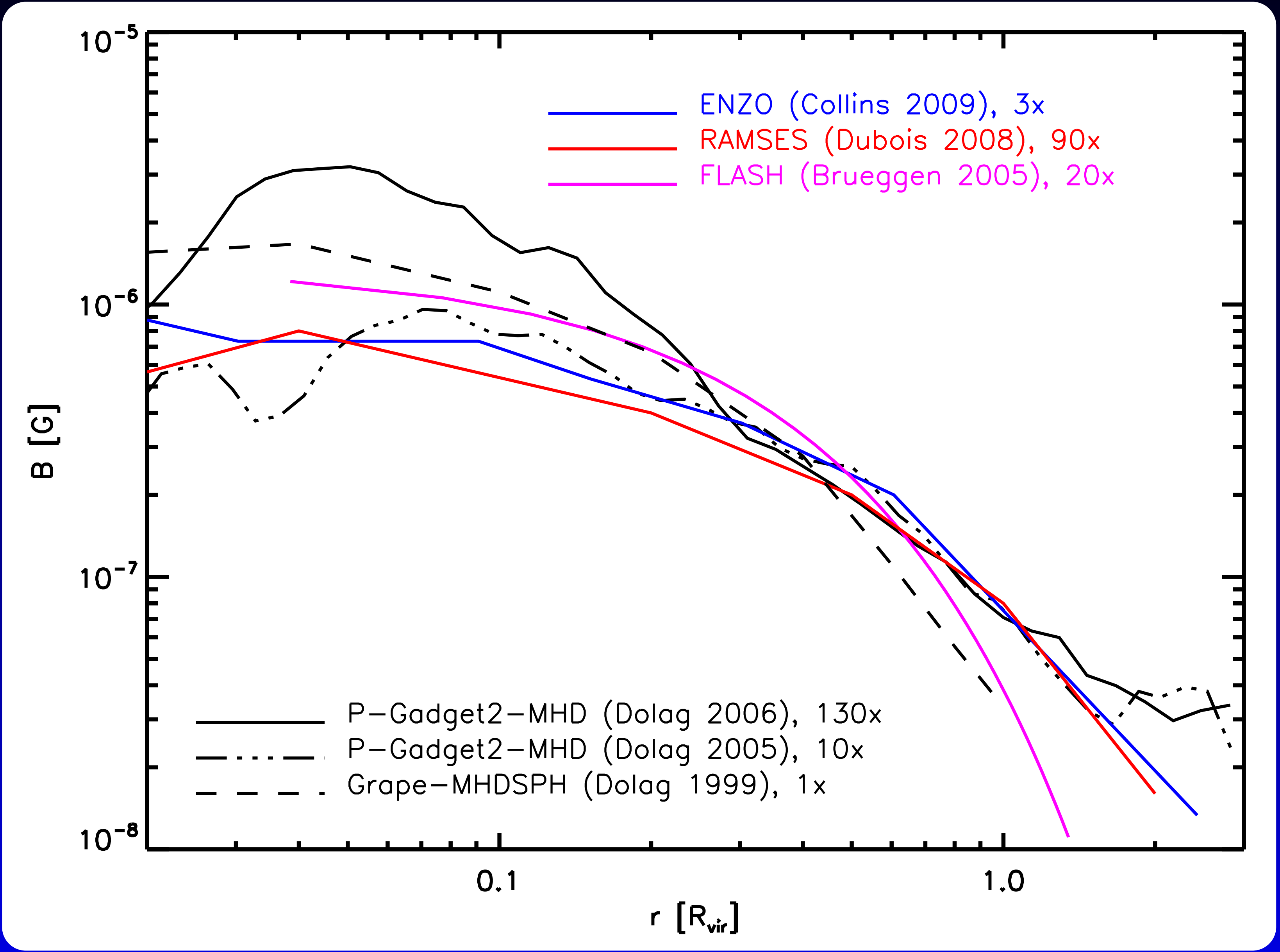


Cosmological MHD Simulations



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

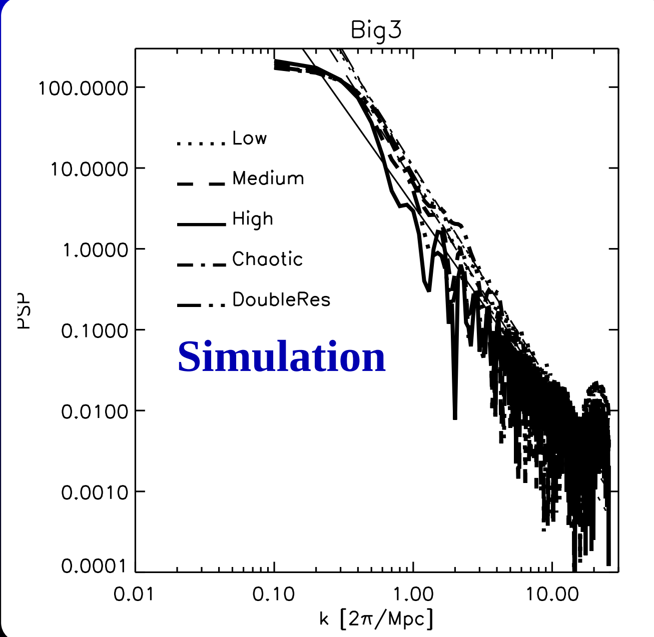
Cosmological MHD Simulations



⇒ Radial shape confirmed by more recent works

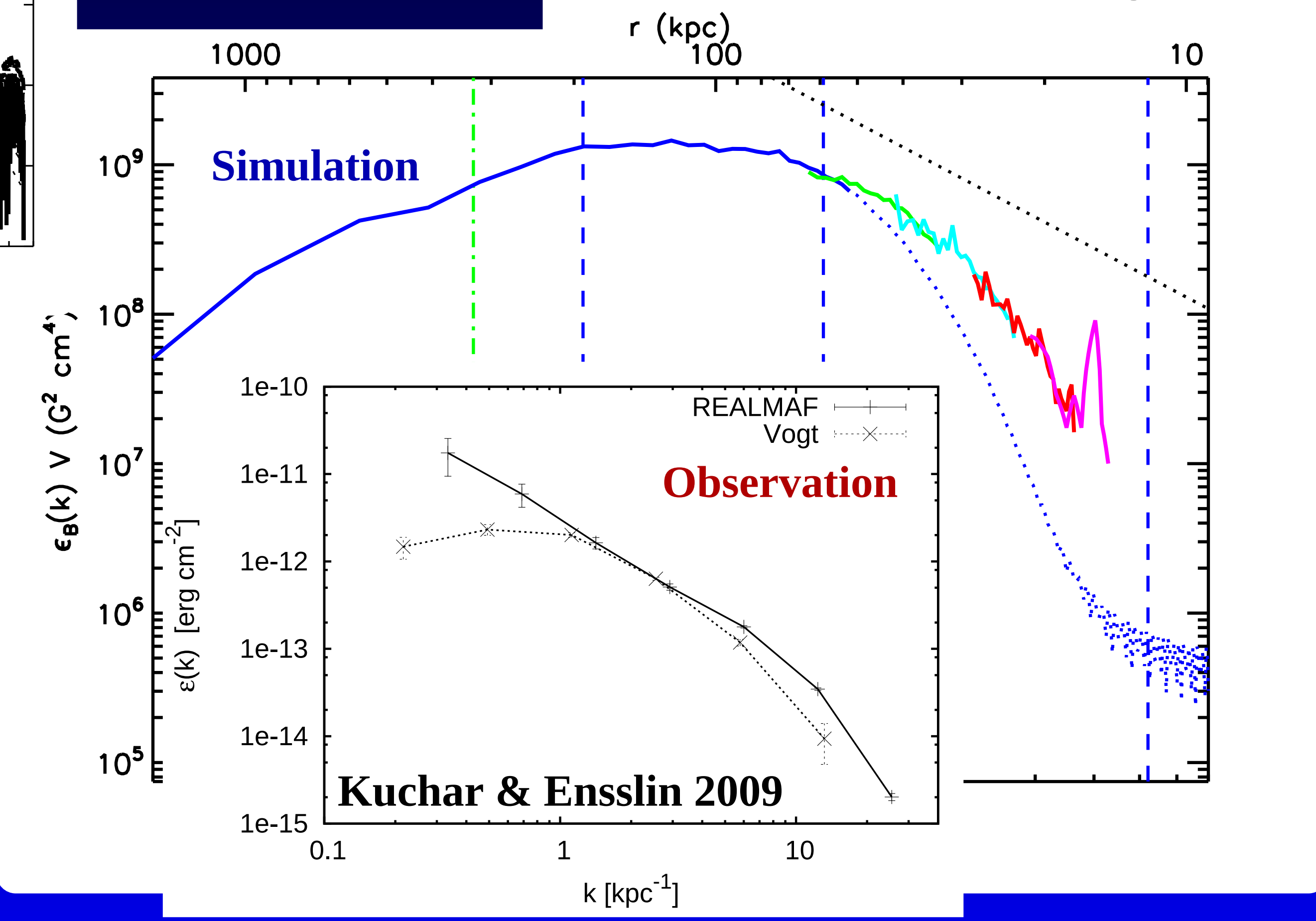
⇒ Generic feature from structure formation

Cosmological MHD Simulations



Dolag et al. 2002

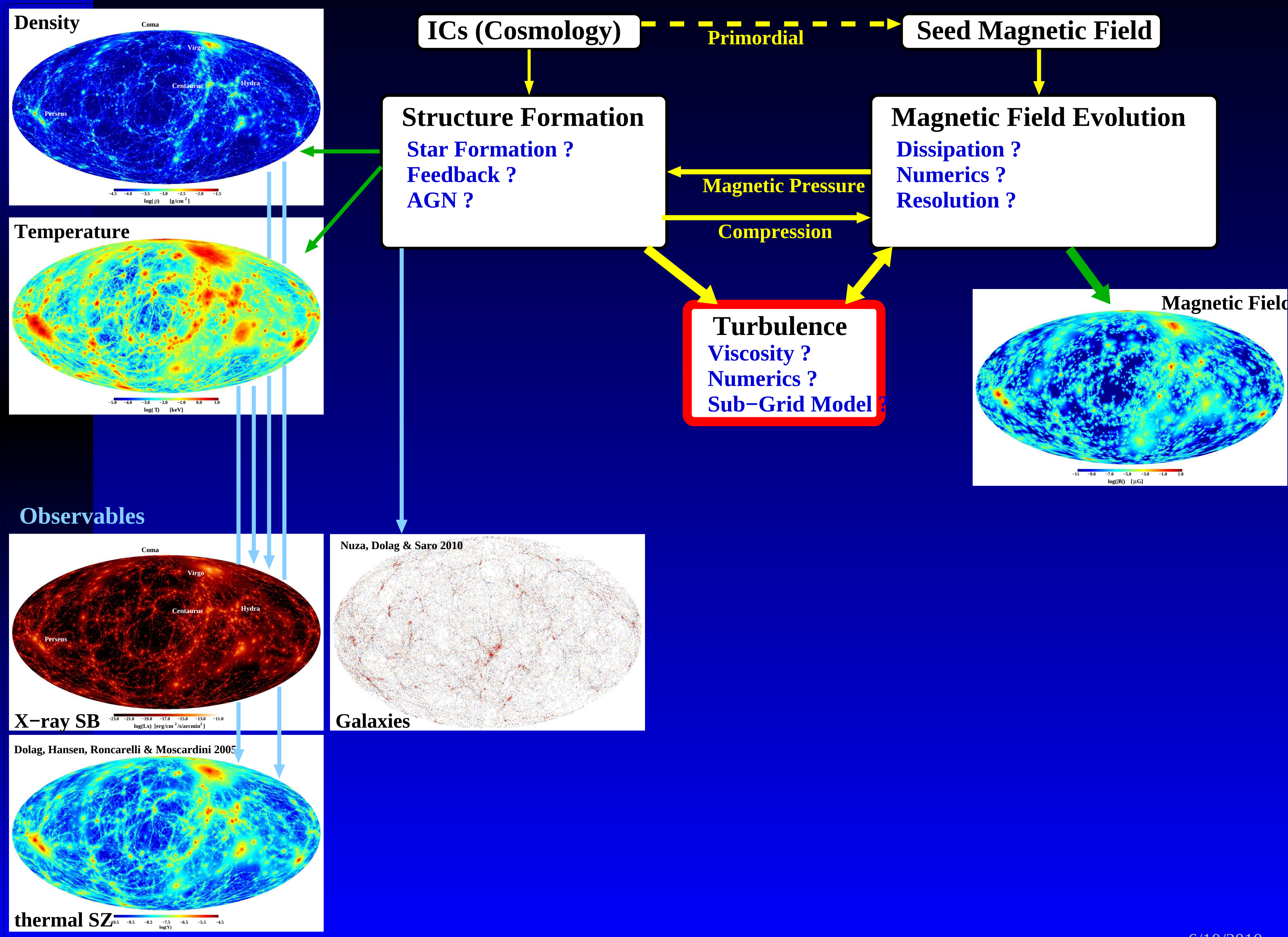
Pakmor & Dolag 2006



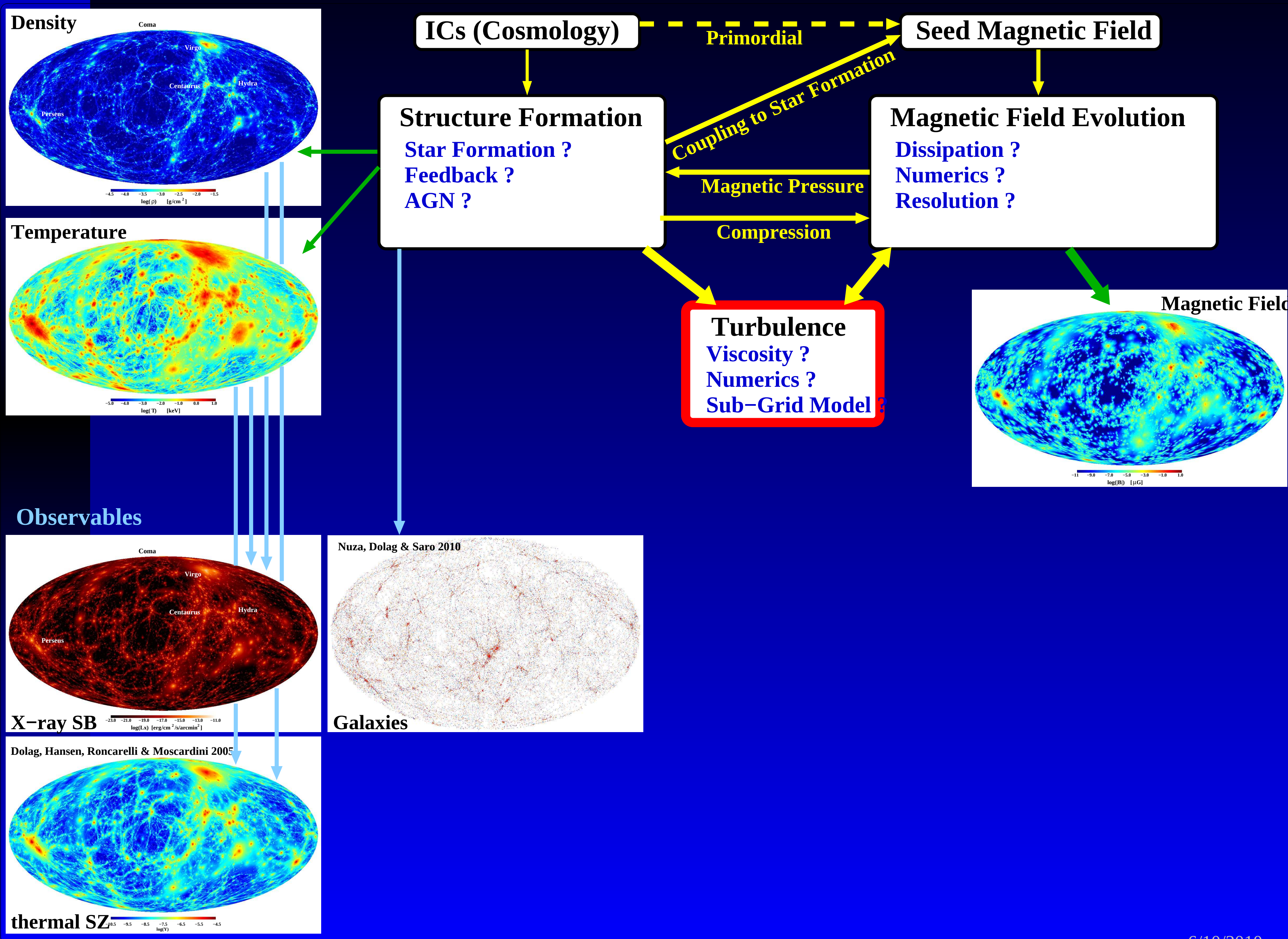
Magnetic field power spectra: predictions vs. observations.

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

Simulation Network

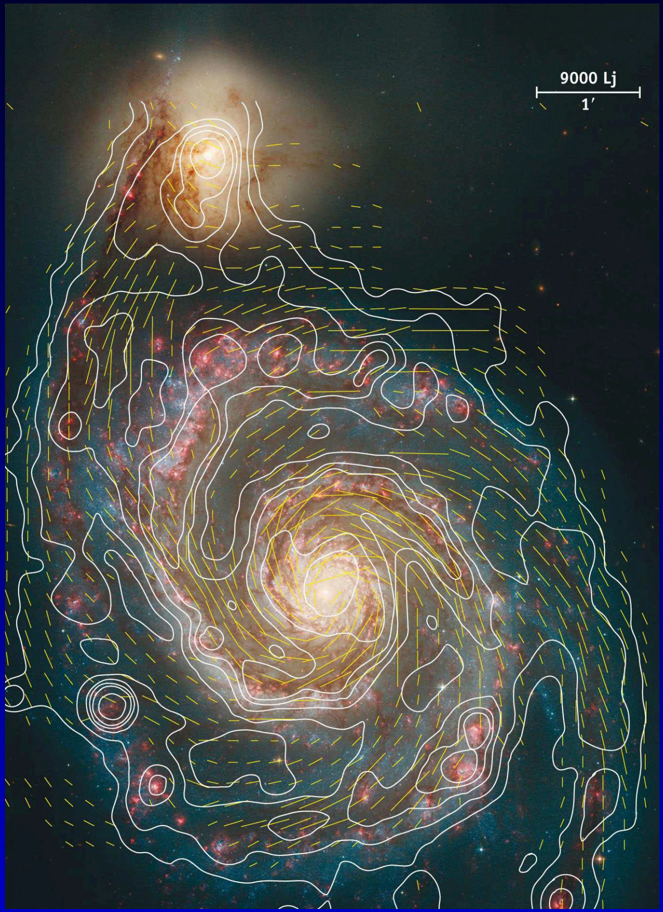


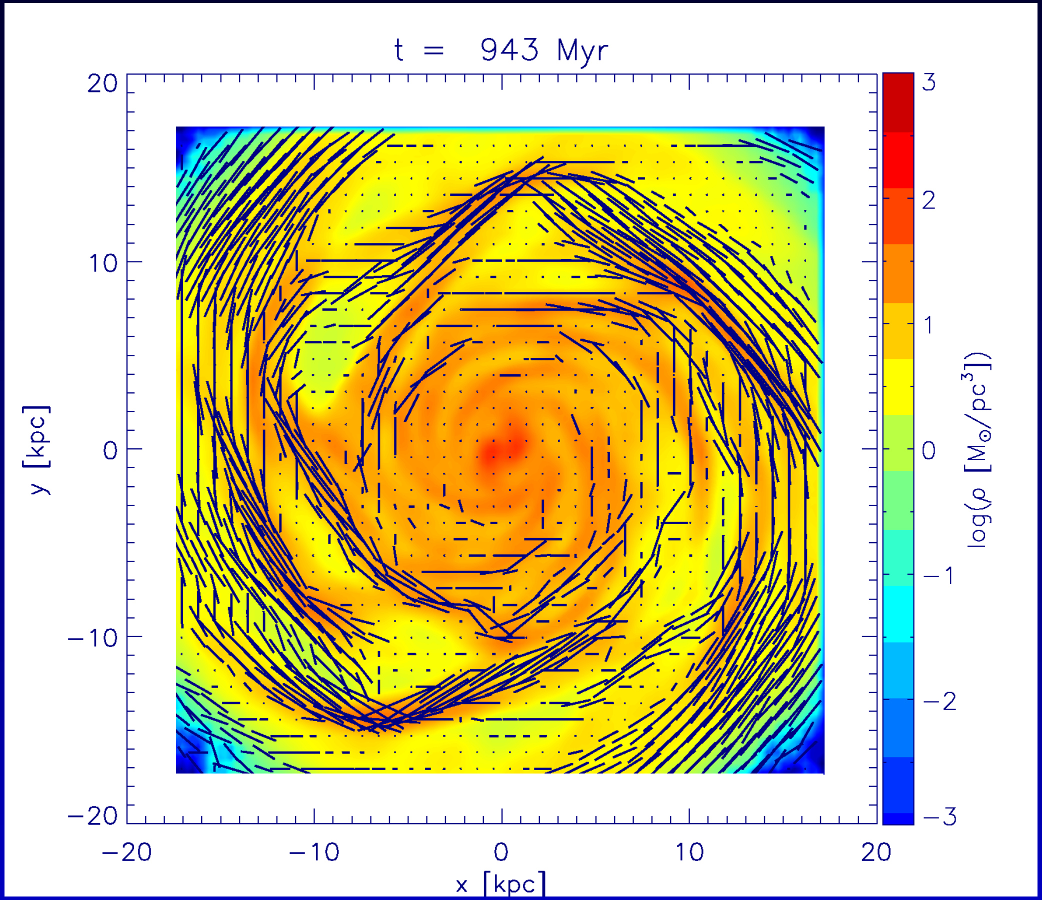
Simulation Network



Magnetic Field buildup

Simulations on galaxy scales ...

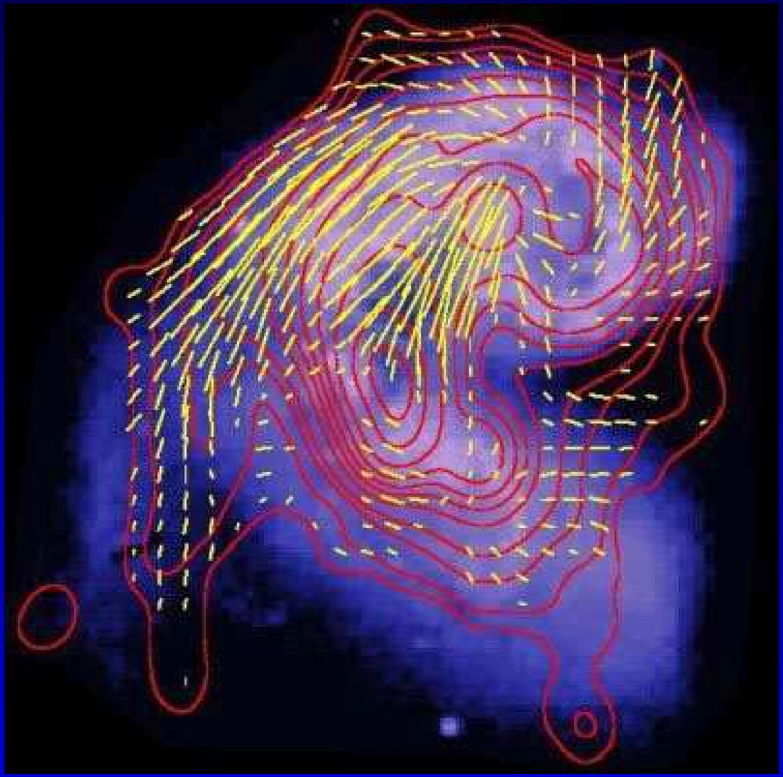


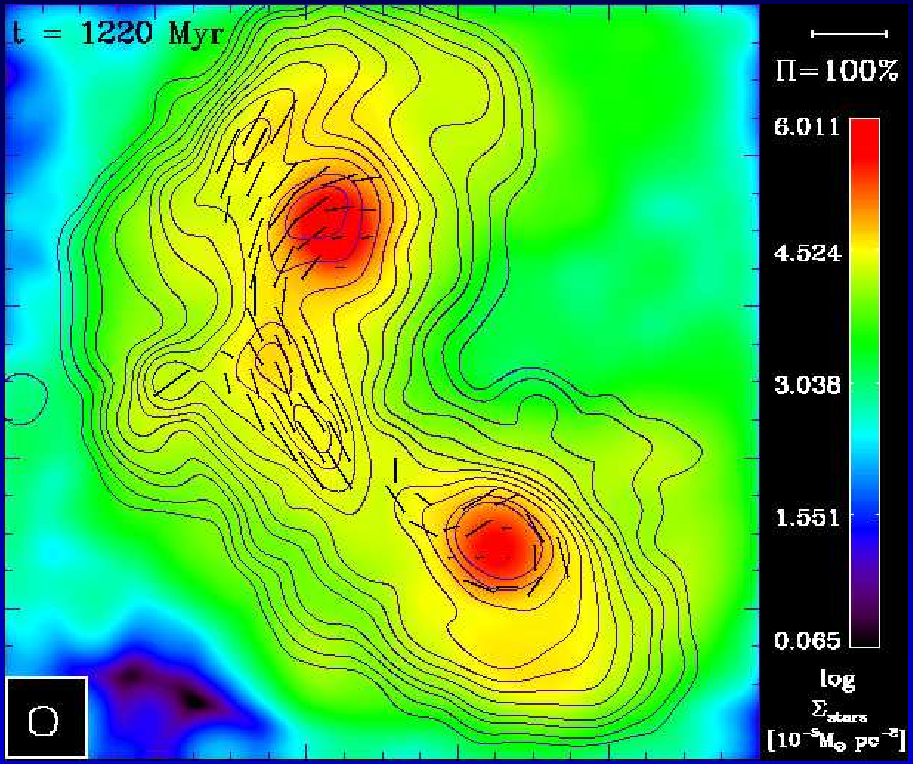


M51 (Fletcher & Beck 2006) and a simulation using the MHD implementation in Gadget (Kotarba et al. 2009).

Magnetic Field buildup

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.

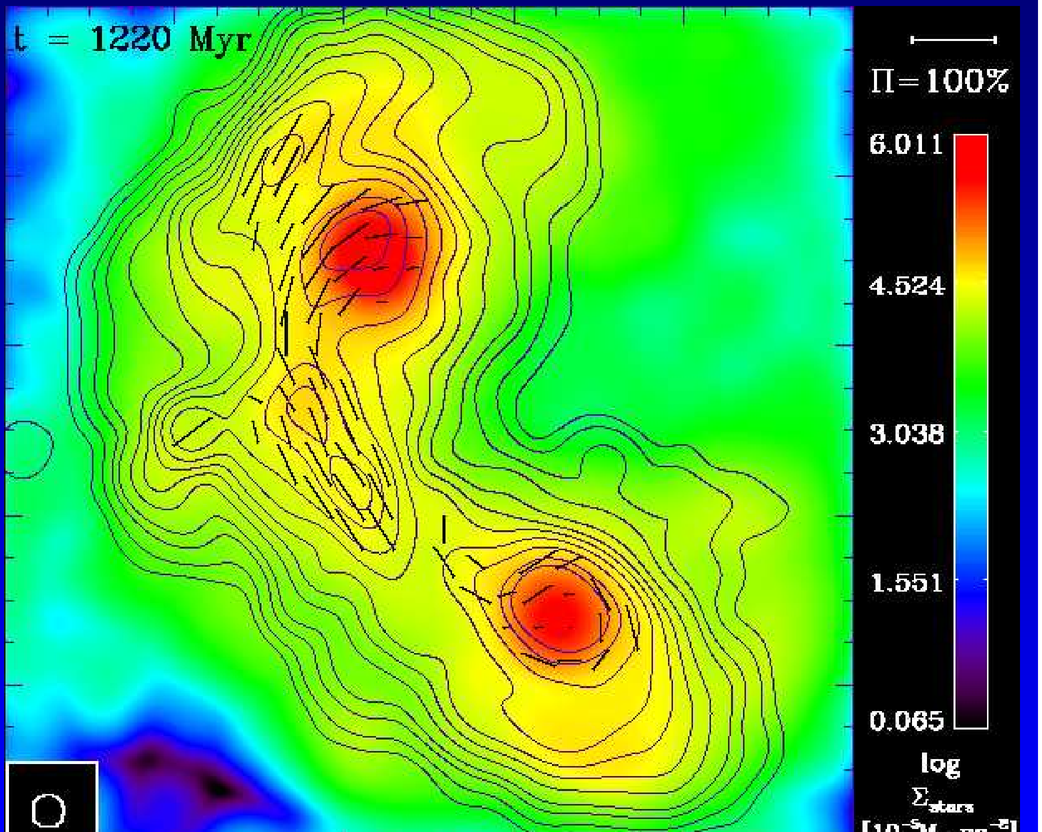


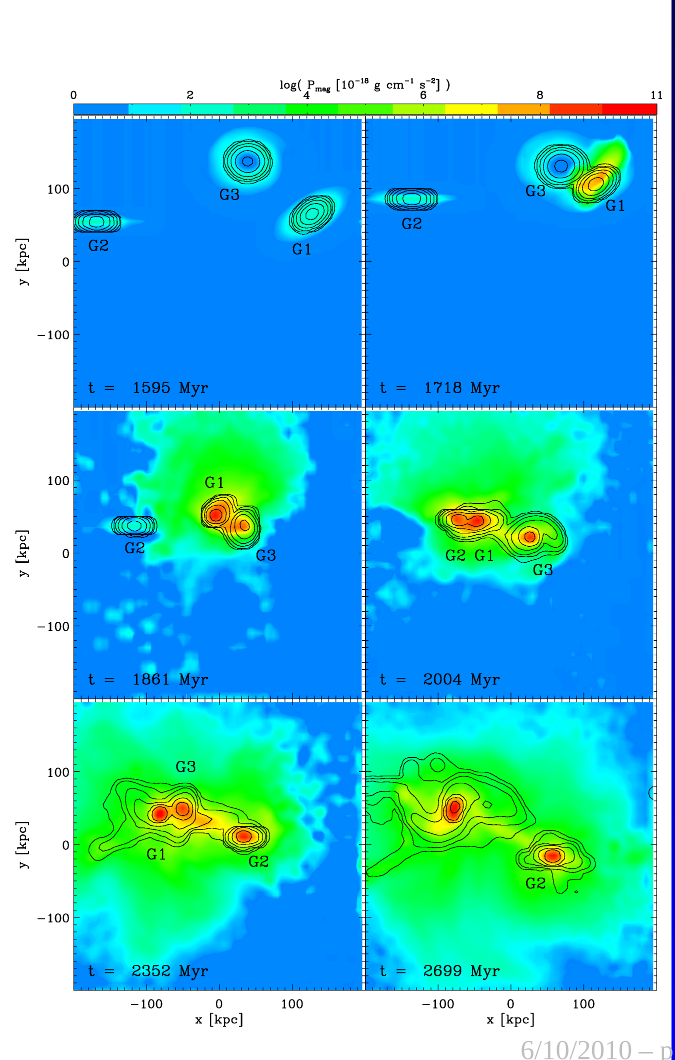


(Chyzy & Beck 2005 Kortarba et al. 2010)

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.

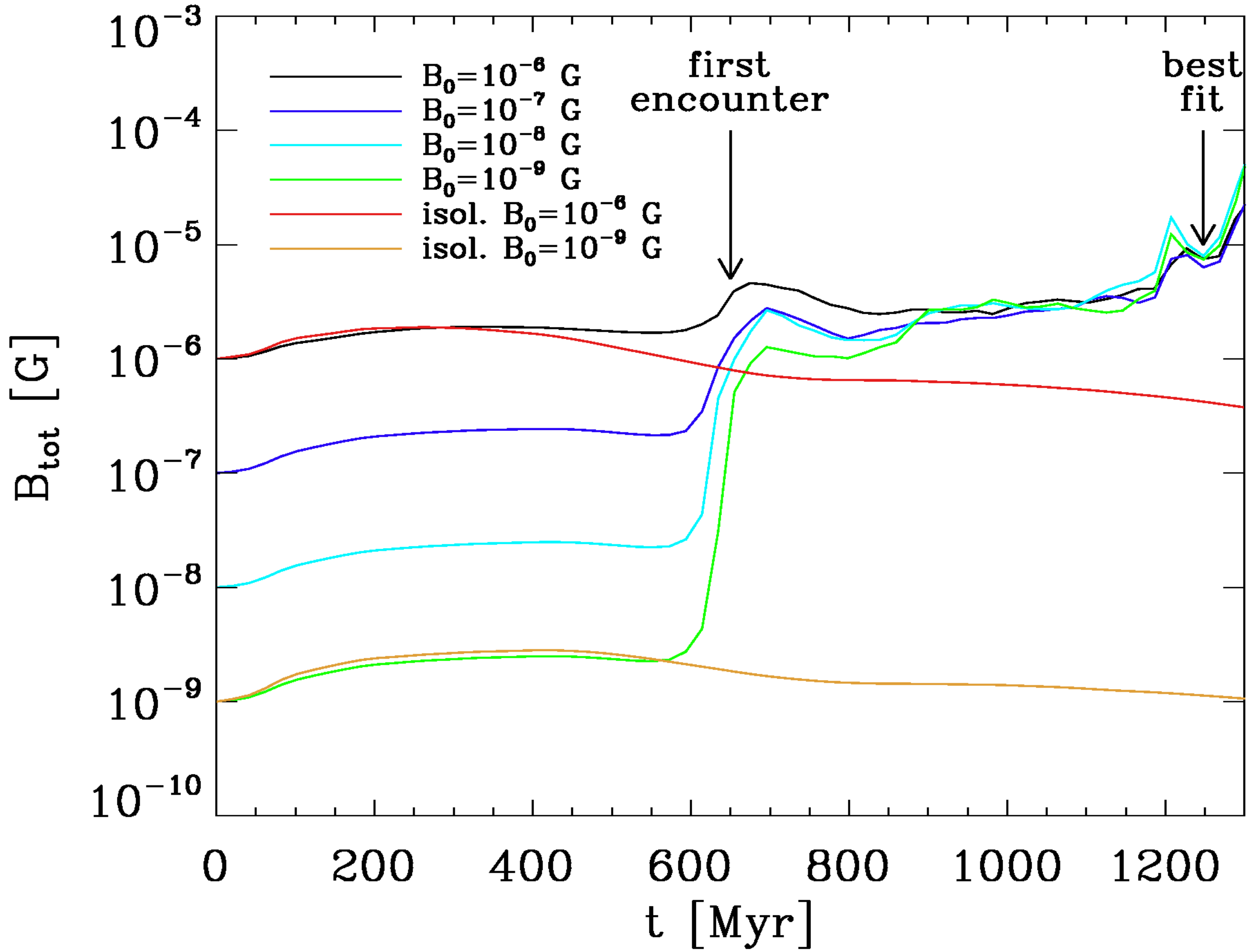




Magnetic Field buildup

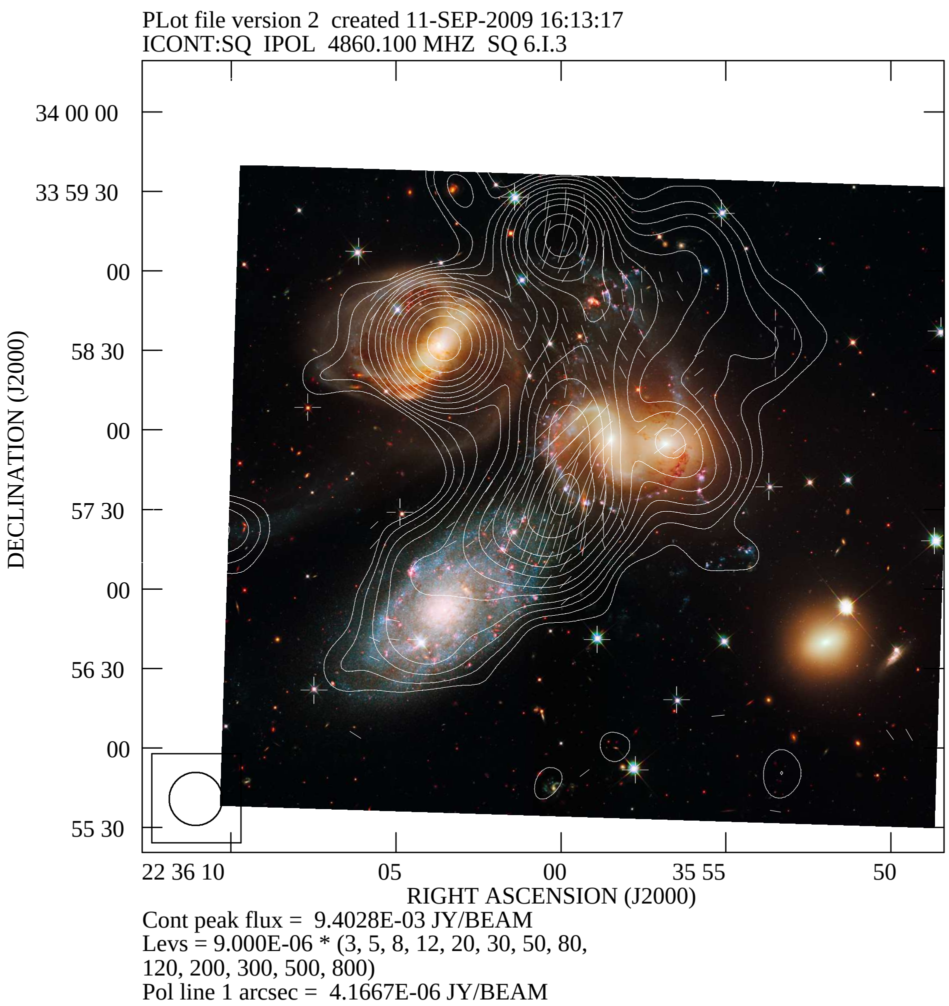
Final magnetic field close to equipartition with turbulent velocity component, largely independent of initial field values.

$\Rightarrow$ Hierarchical buildup of magnetic field

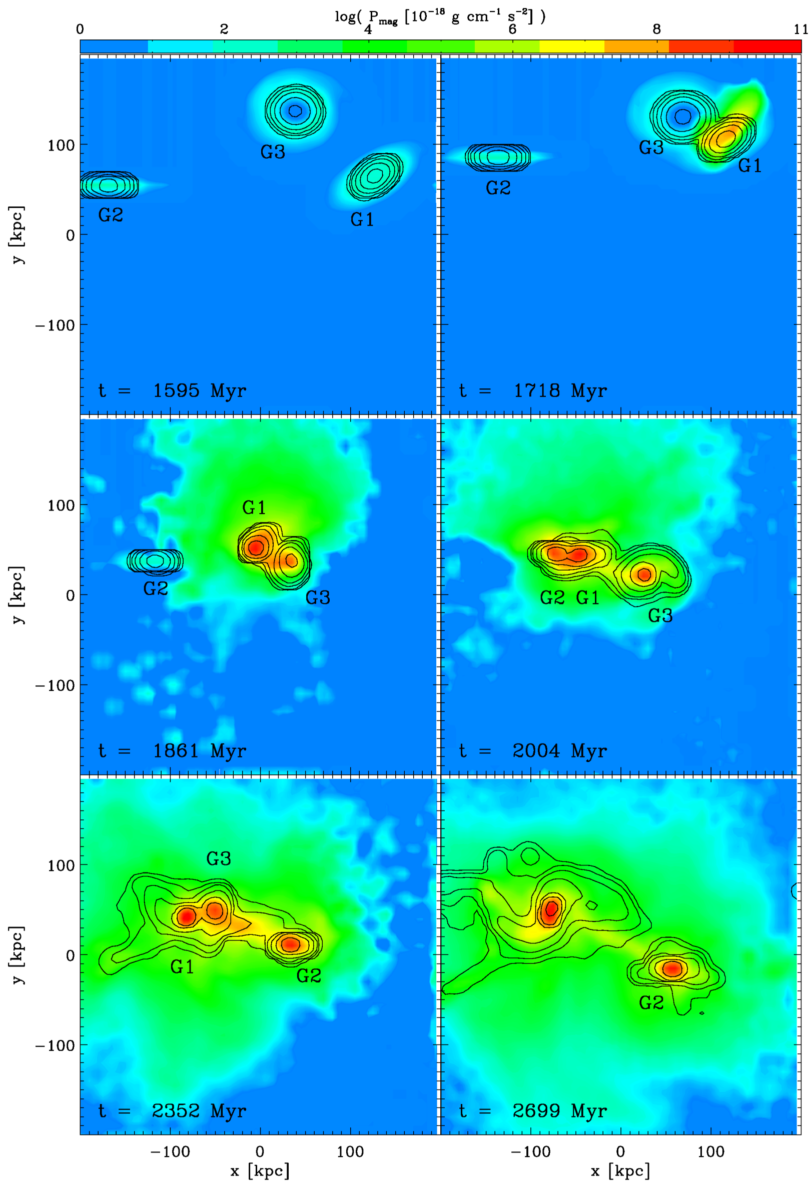


(Kortarba et al. 2010)

Magnetic Field buildup

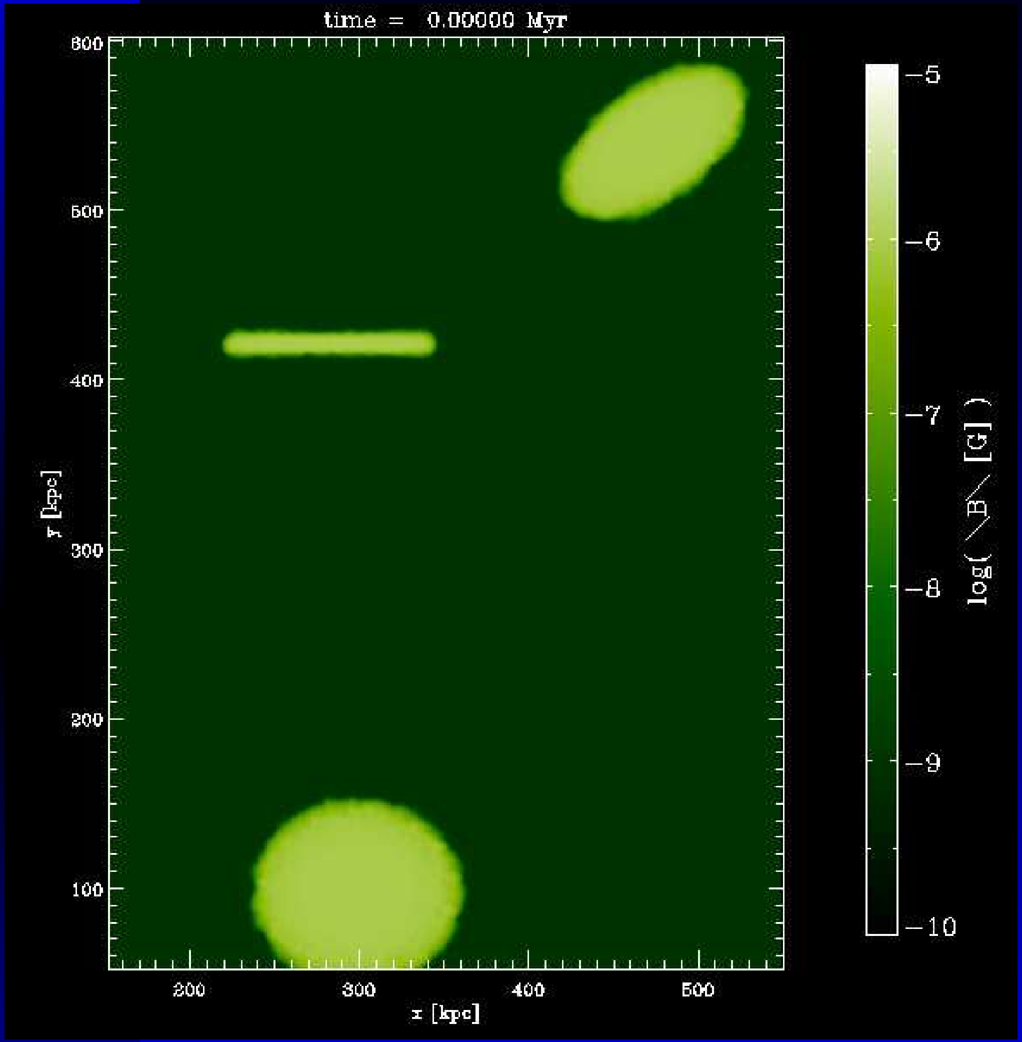


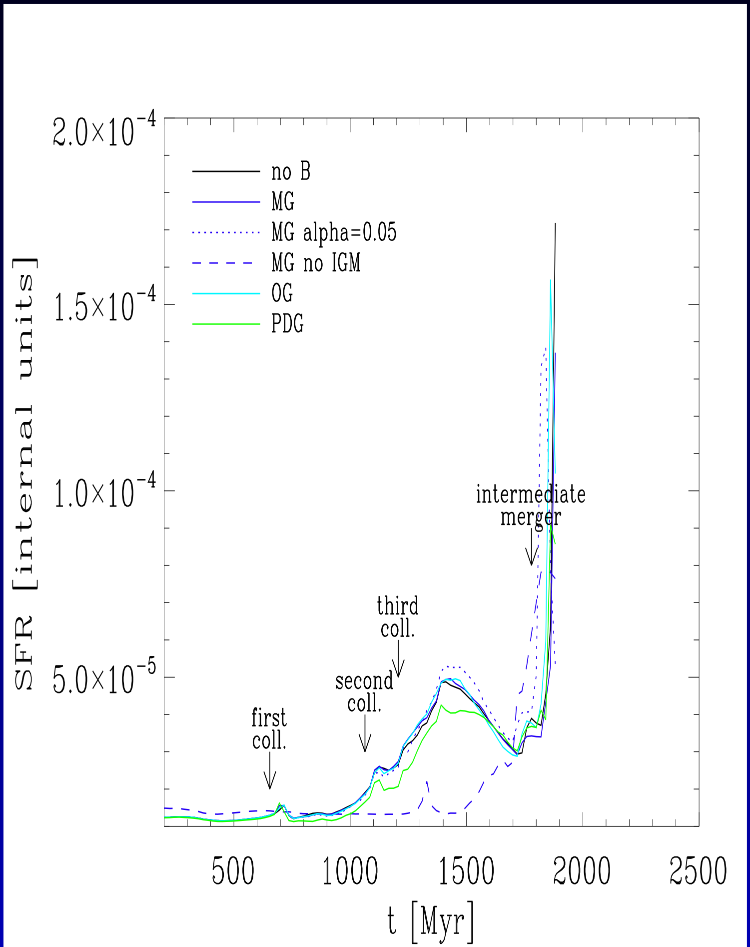
Soida et al., in prep.



Kortarba et al., in prep.

Magnetic Field buildup

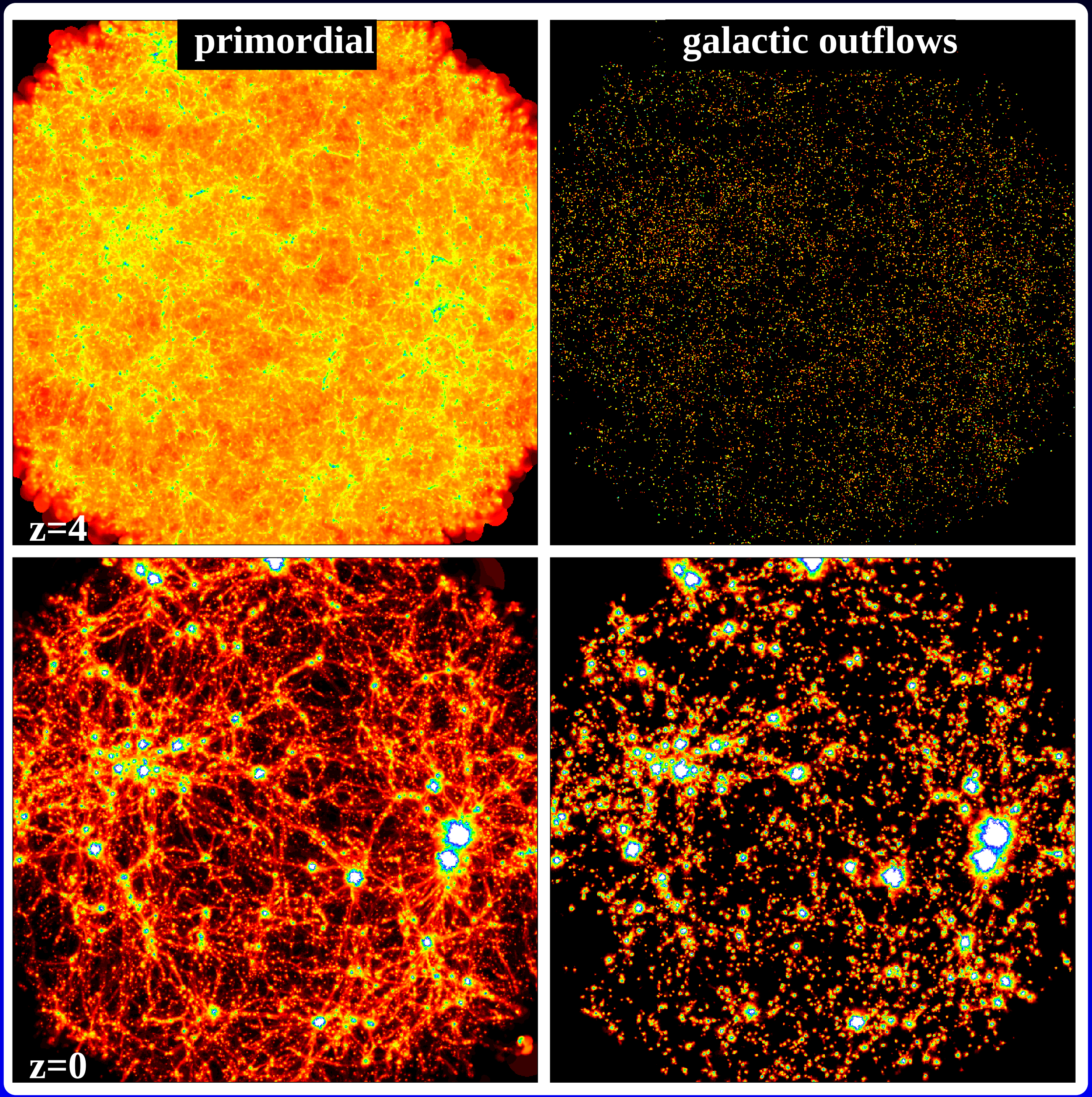




Kortarba et al., in prep

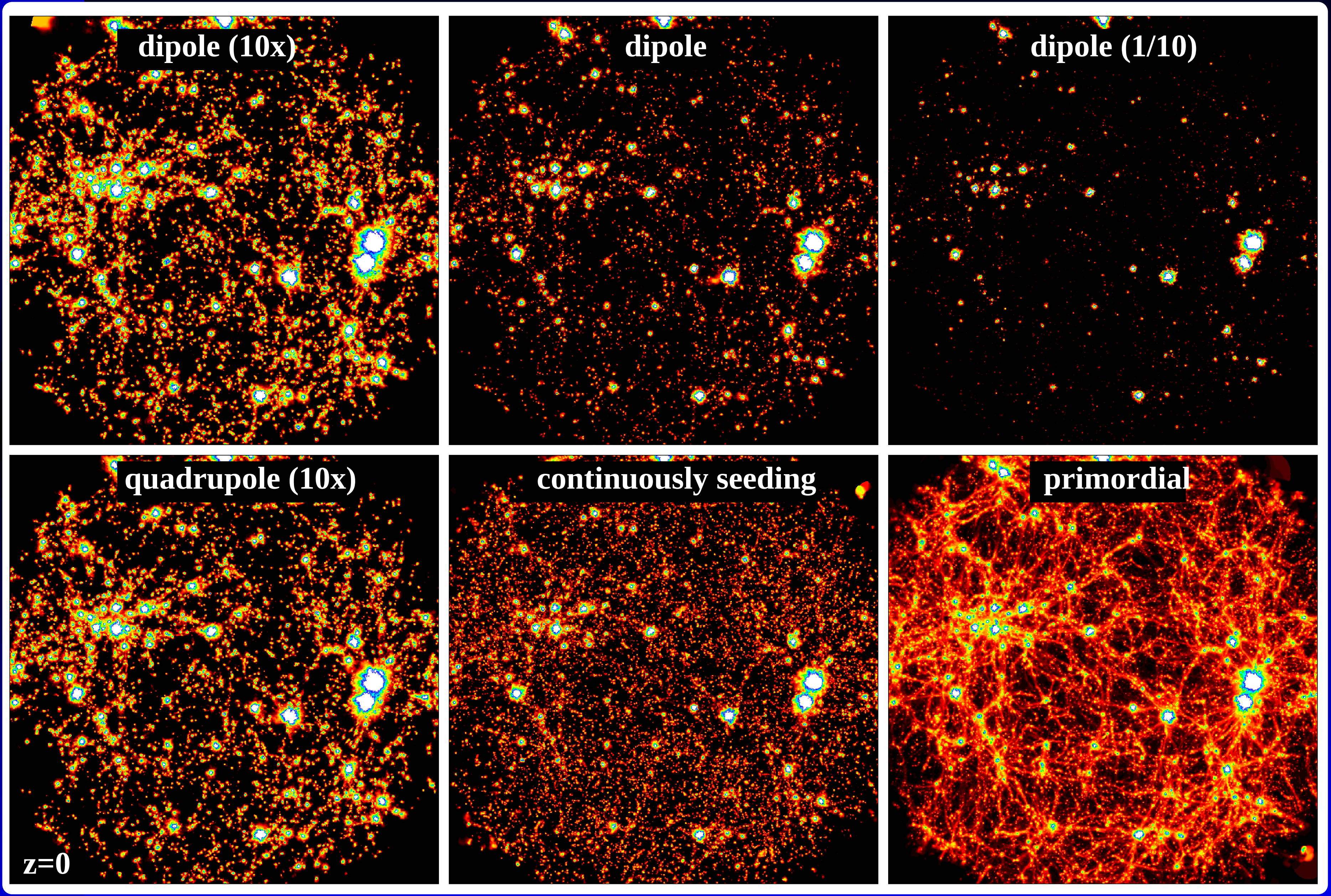
- Merging drives shocks, turbulence and star-formation
- Star-formation drives winds
- Winds transport out magnetic fields

Magnetic Field buildup



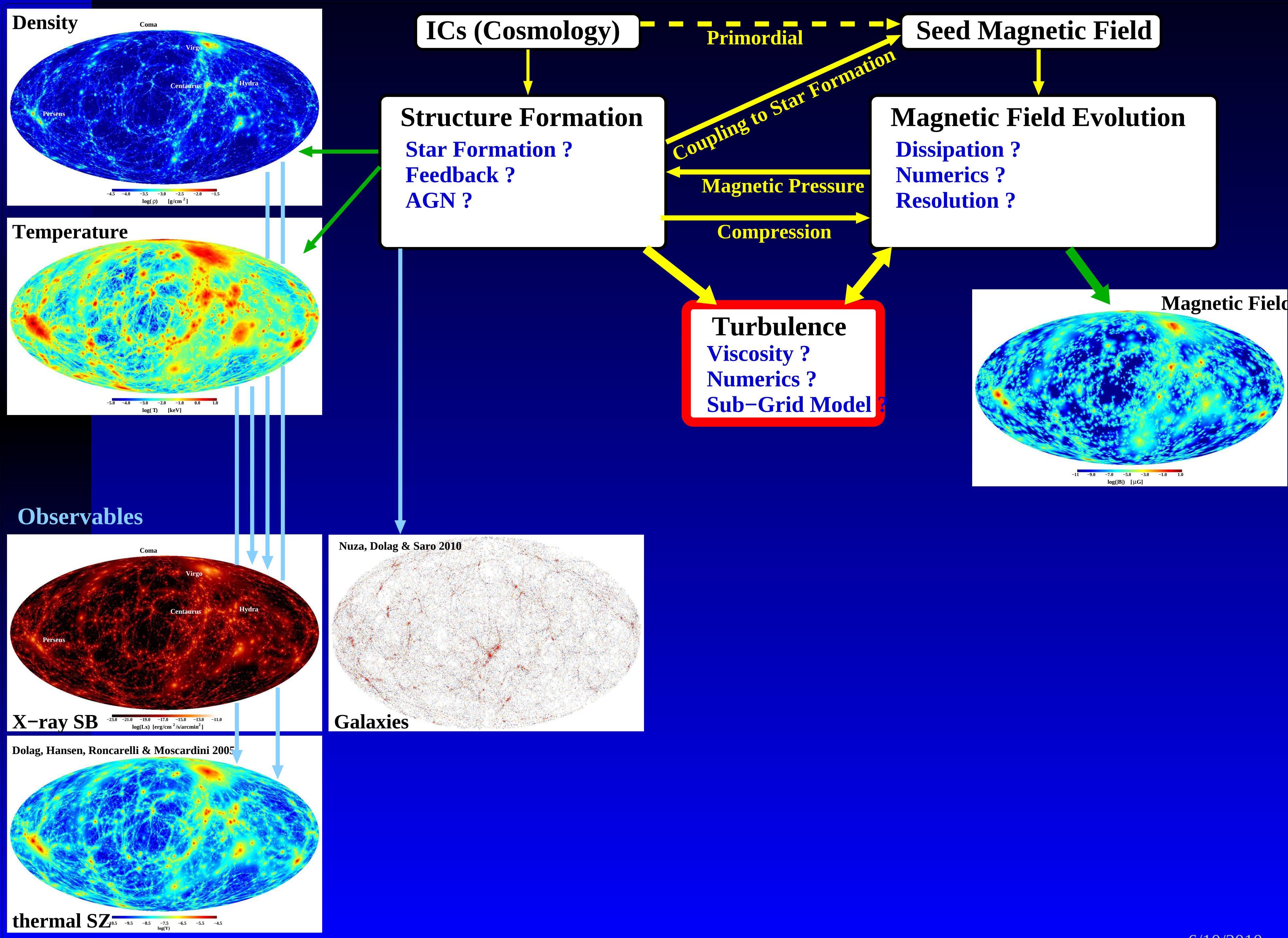
Seeding from galactic outflows (Donnert et al. 2009)

Magnetic Field buildup

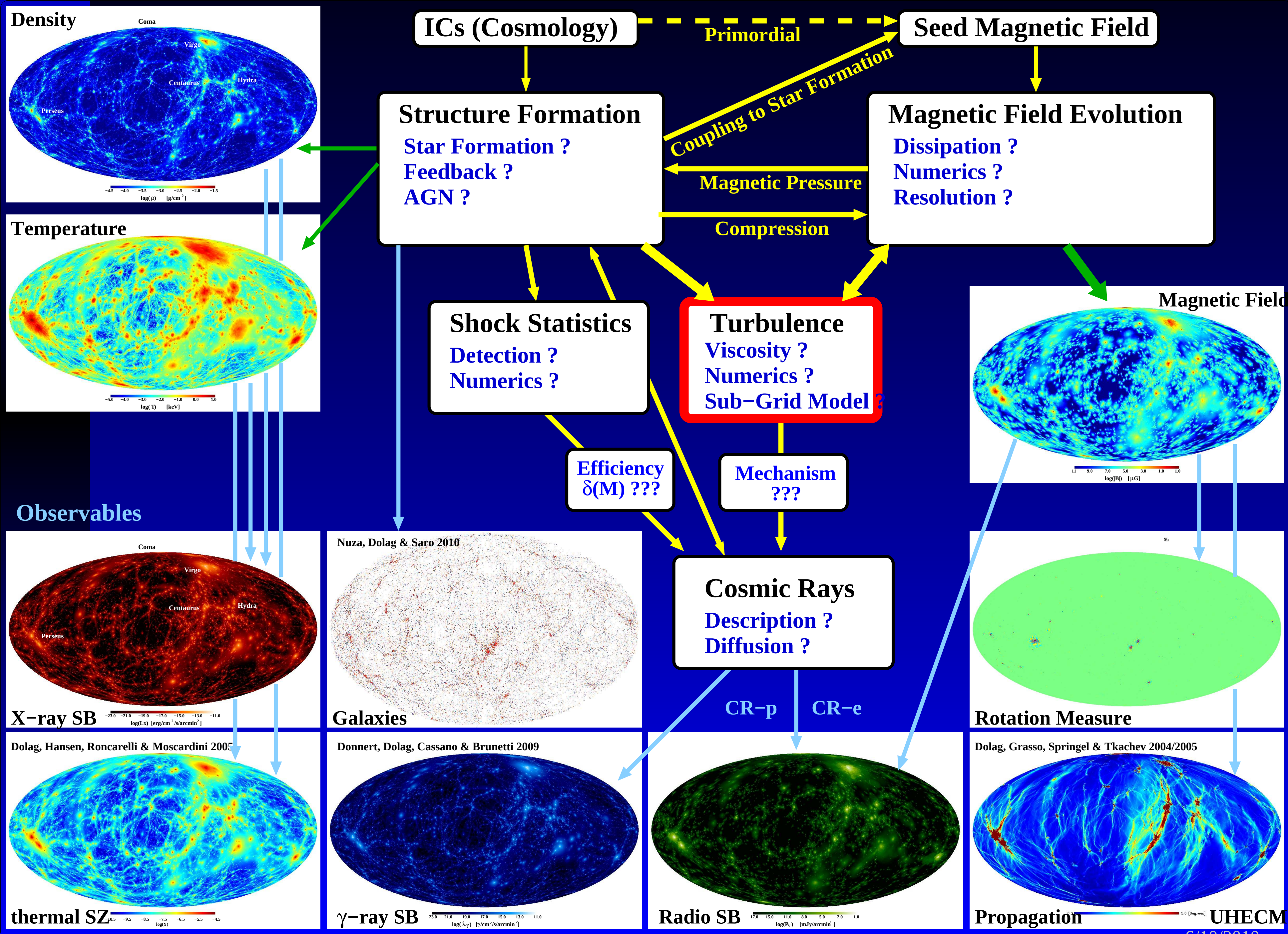


Different wind parameters (Donnert et al. 2009)

Simulation Network

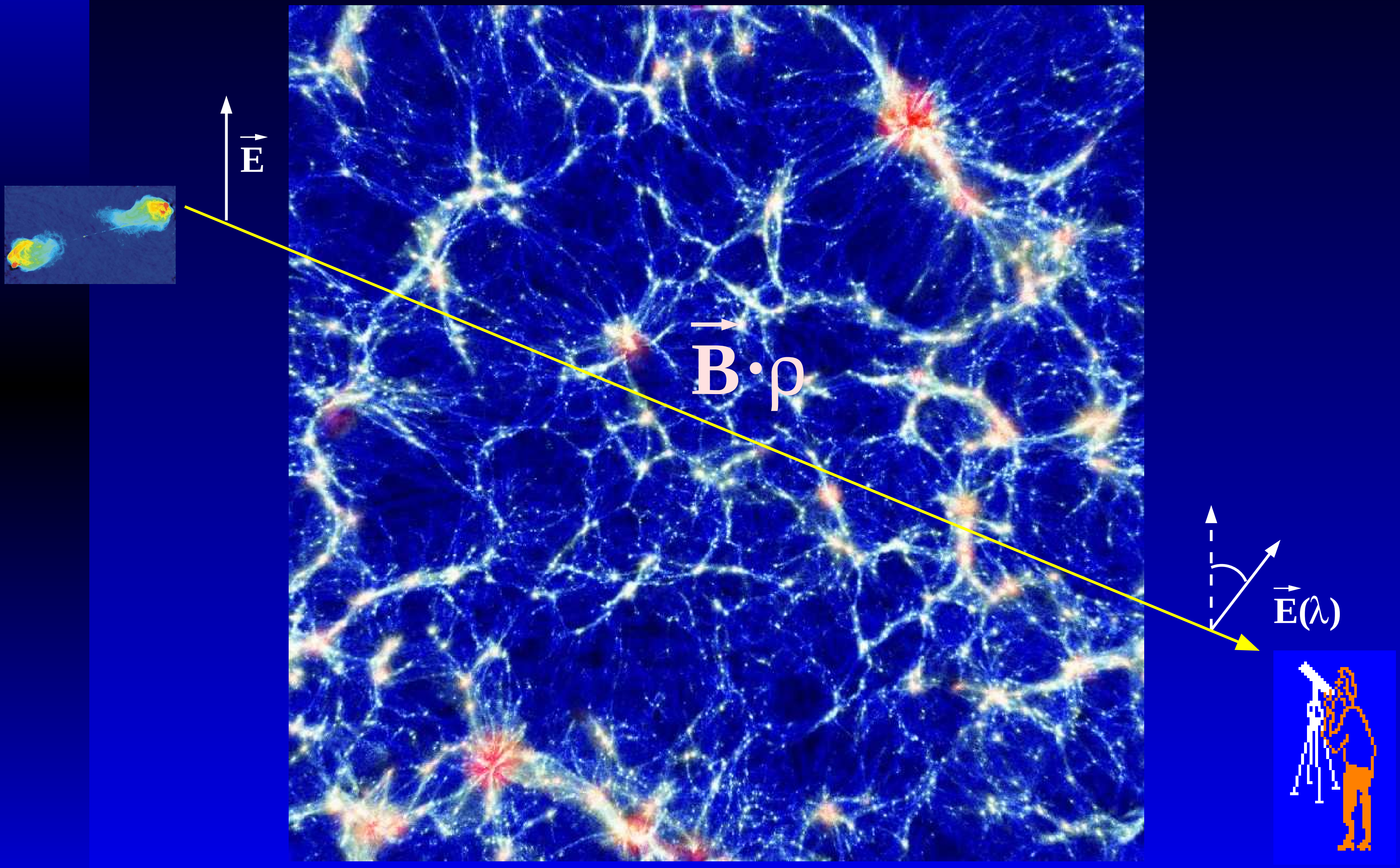


Simulation Network



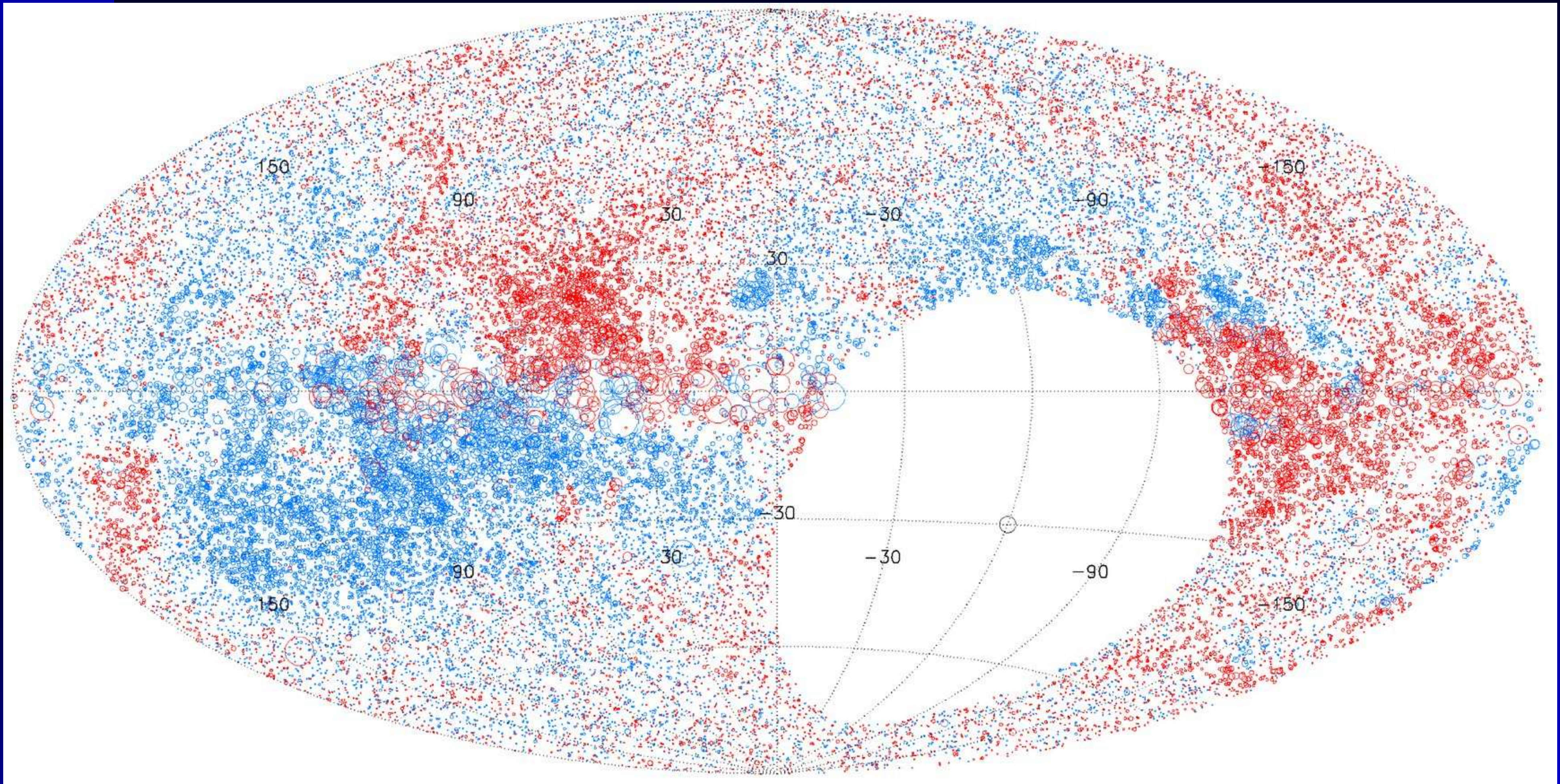
Measure cosmic magnetization

Faraday Rotation (RM) of polarized radio emission



Measure cosmic magnetization

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



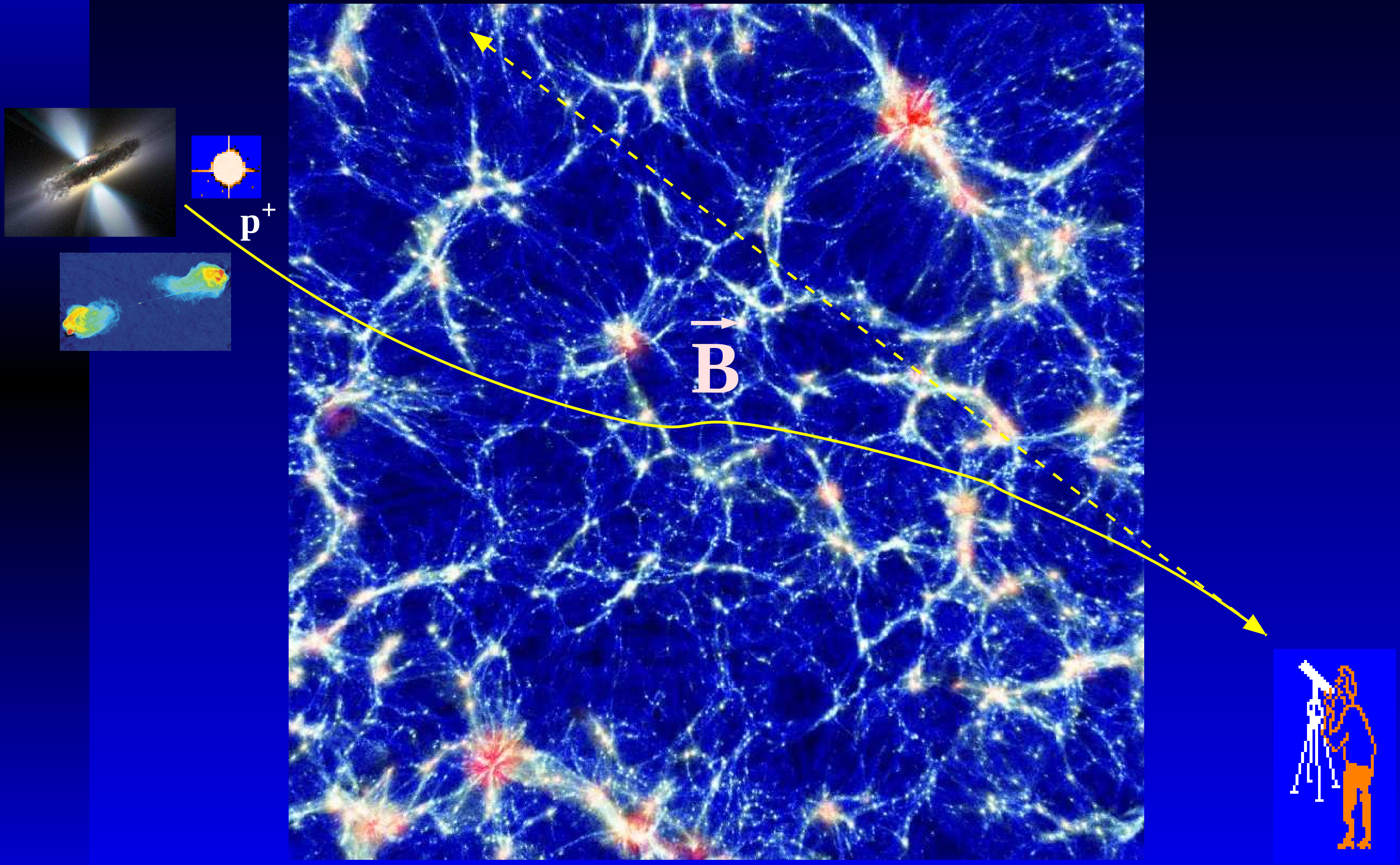
Observed, full sky RM signal (Taylor et al. 2009)

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

But Galactic foreground critical !!! (See talk by F. Stasyszyn)

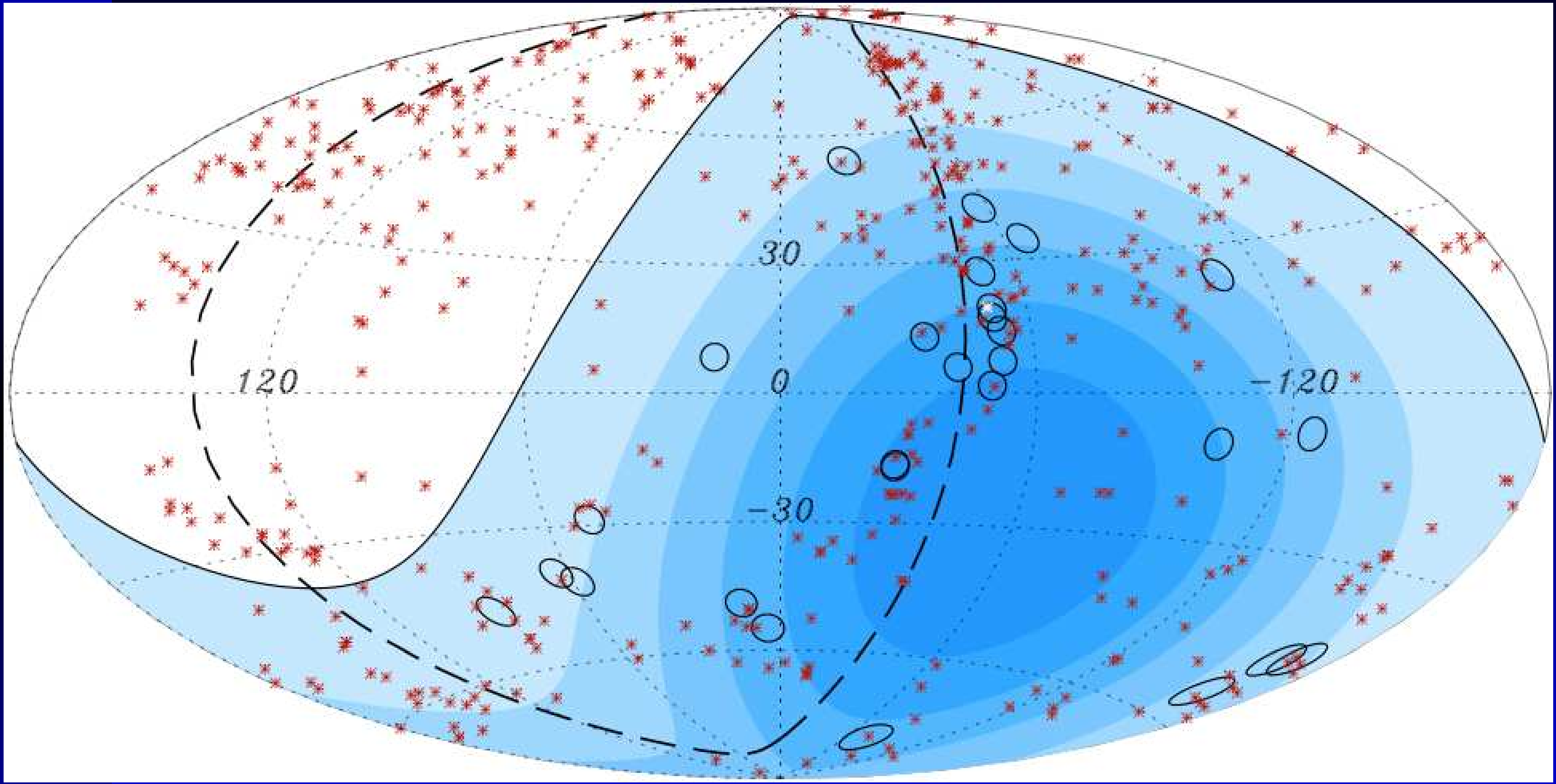
Measure cosmic magnetization

Propagation of ultra high energy cosmic rays (UHECR)



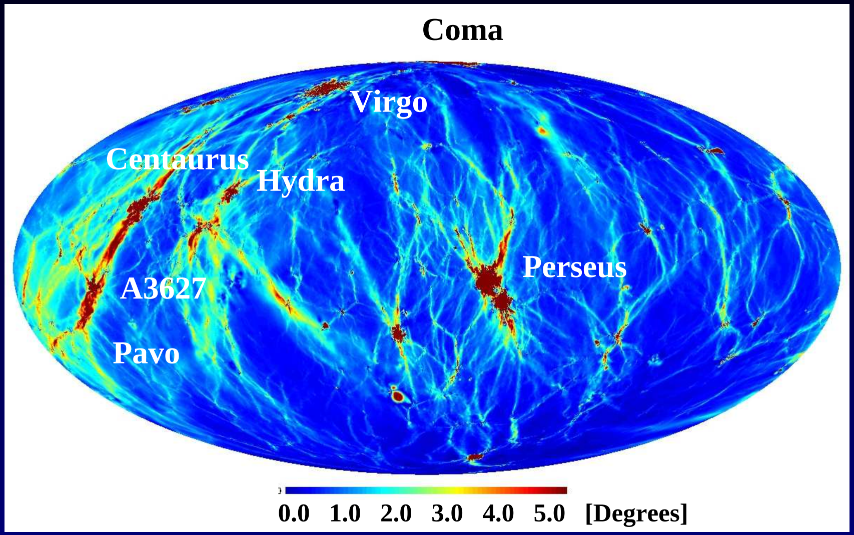
Measure cosmic magnetization

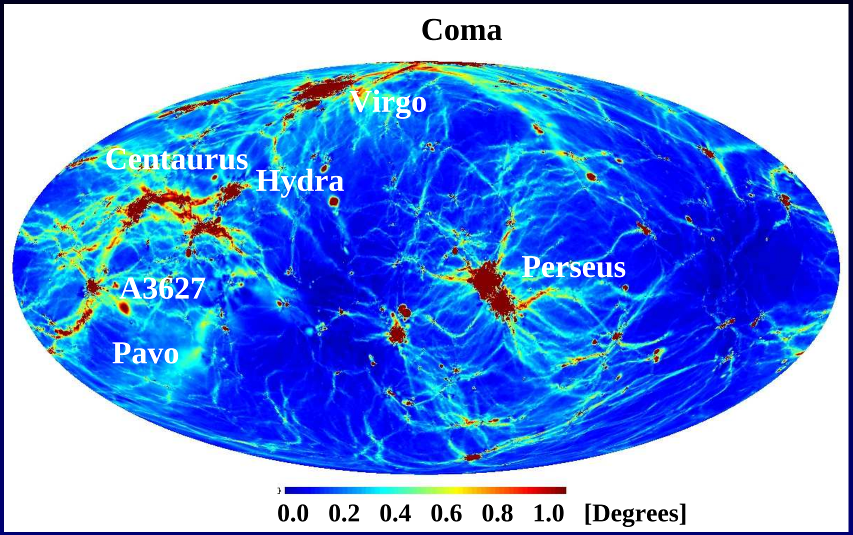
Propagation of CRp, sensitive to $(10^{-9} - 10^{-12})$G

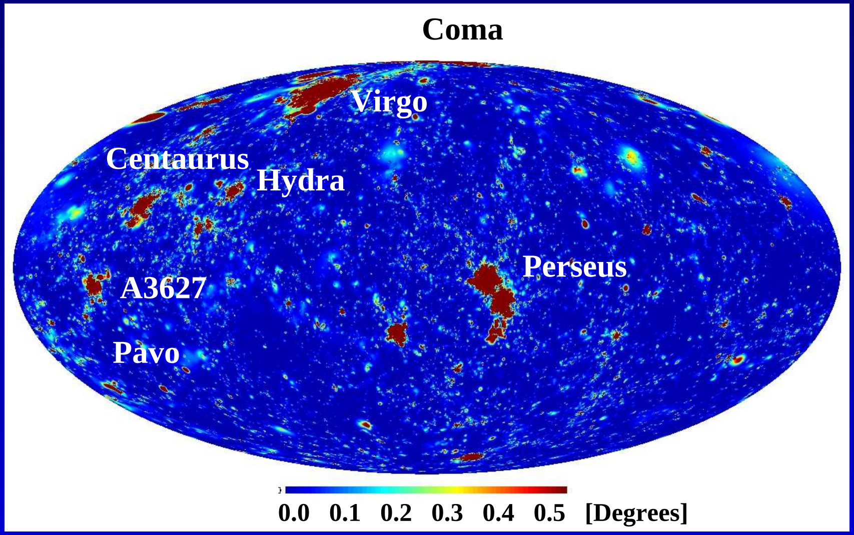


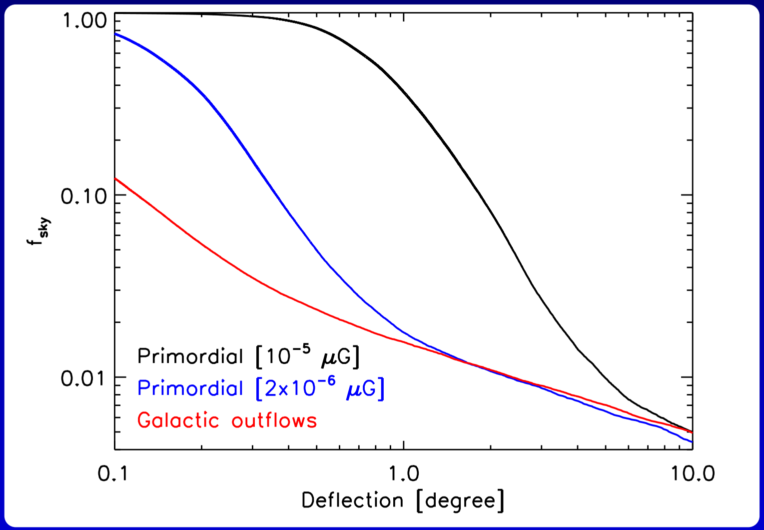
Pierre Auger Observatory provides evidence for anisotropy in the arrival directions of the Cosmic Rays with the highest energies, which are correlated with the positions of relatively nearby active galactic nuclei (AGNs). **But still under discussion !**

Measure cosmic magnetization



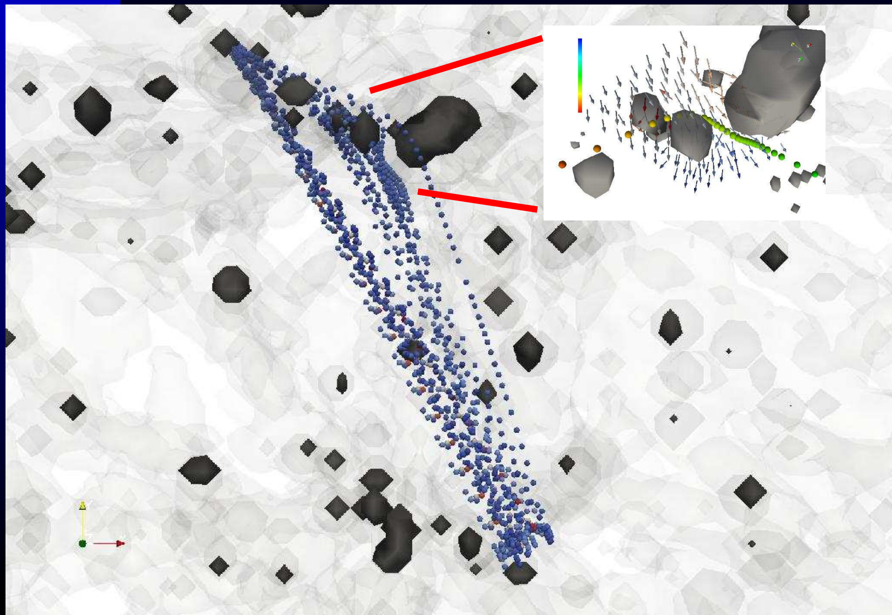


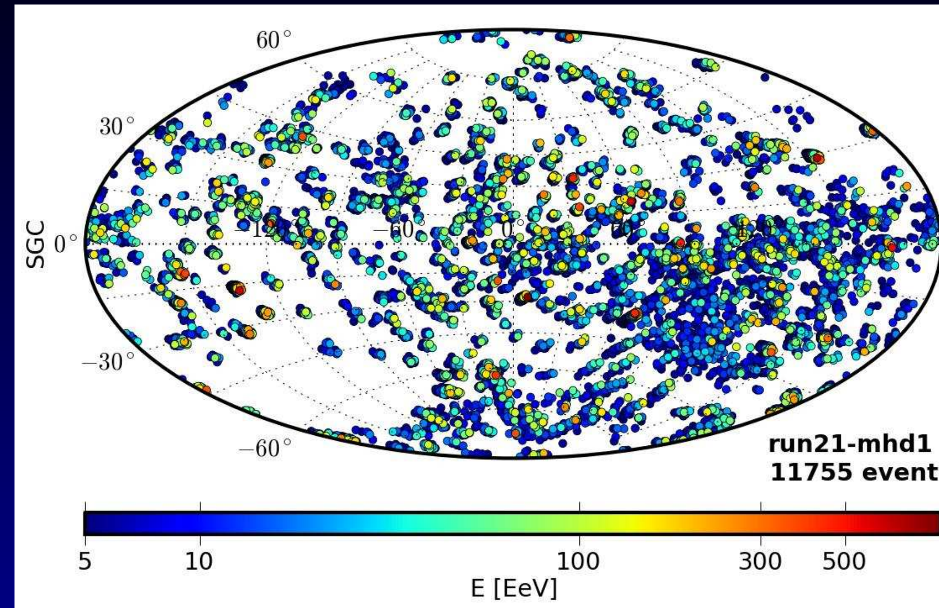


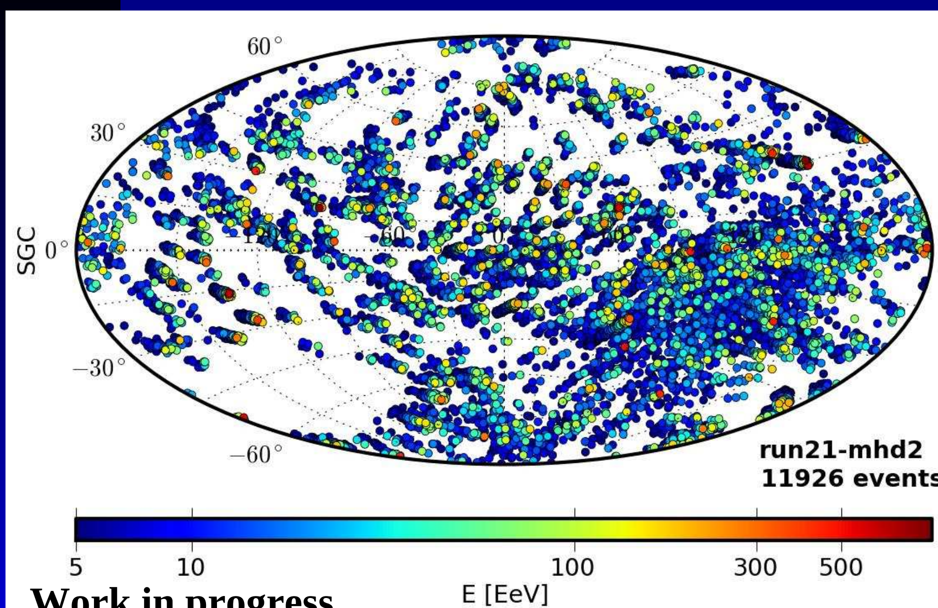


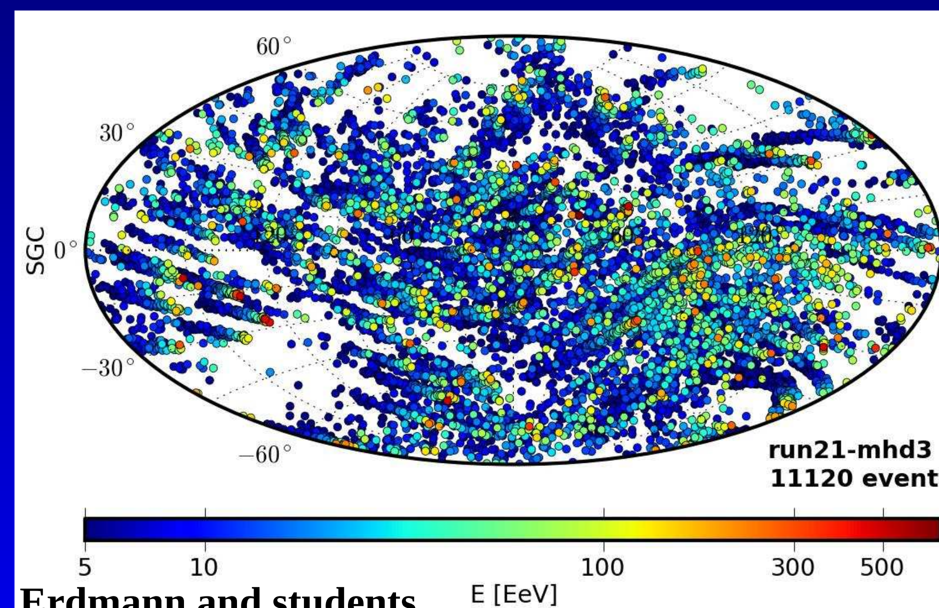
Full sky deflection signal for 4×10^{19}eV **Cosmic Rays** without losses, using a sphere of 110 Mpc radius for **different** magnetic seed models (Dolag, Grasso, Springel & Tkachev 2004/2005).

Measure cosmic magnetization





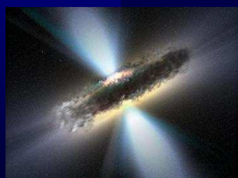


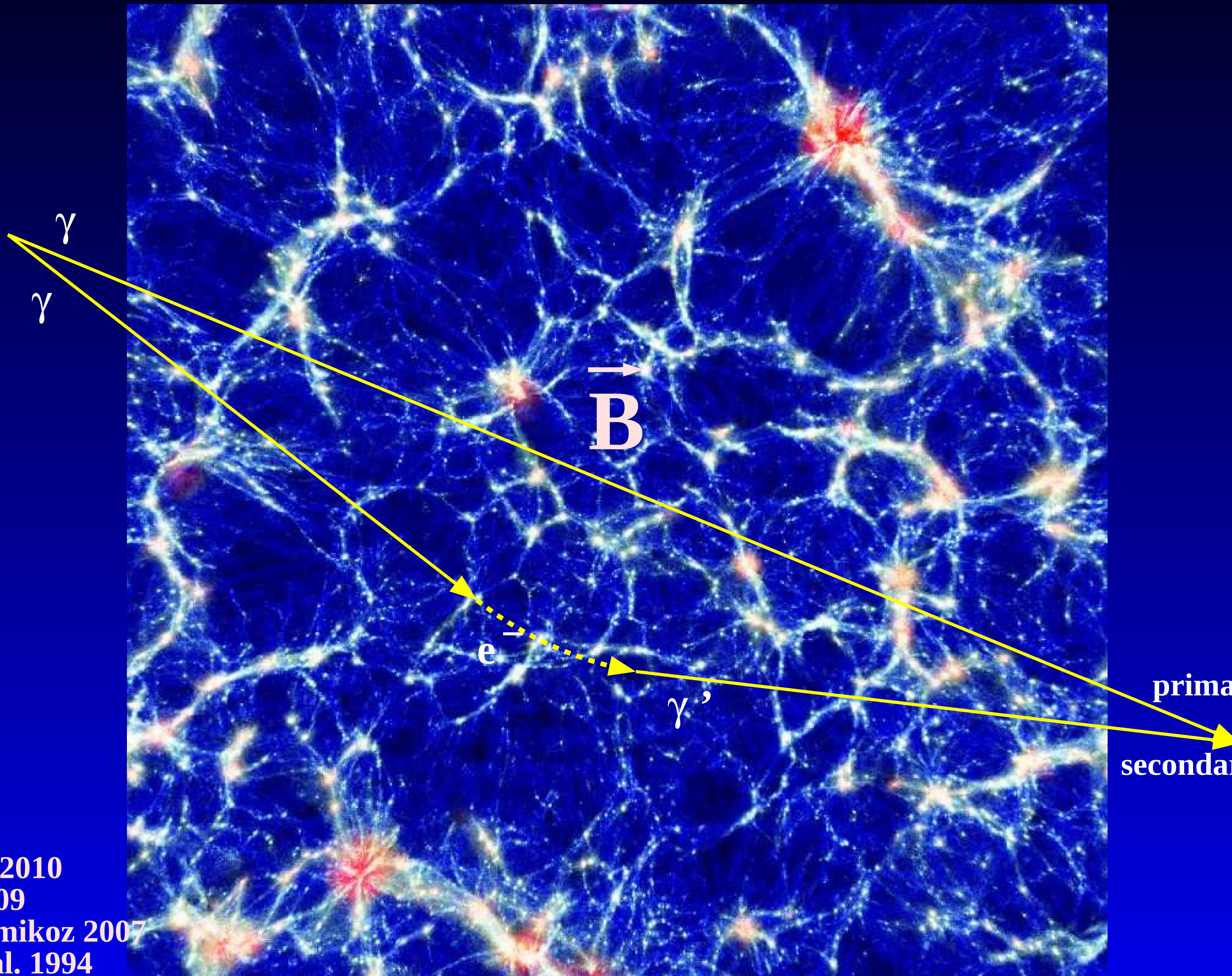


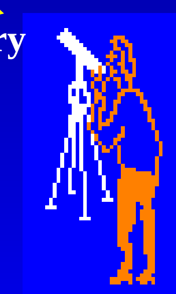
Full tracking of UHECRs in cosmological MHD simulation.

Measure cosmic magnetization

Deflection of electromagnetic cascade of TeV photons



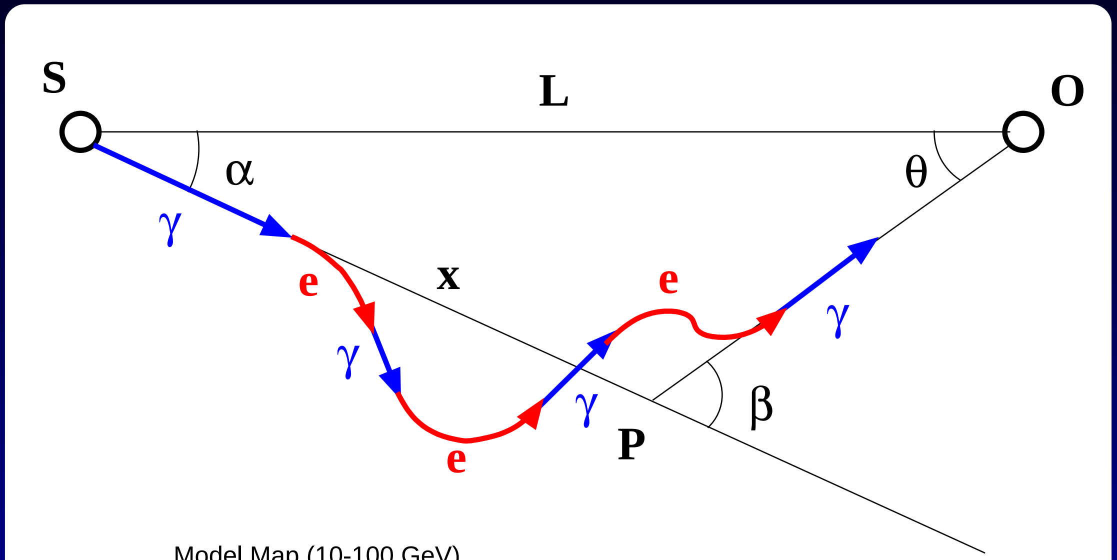


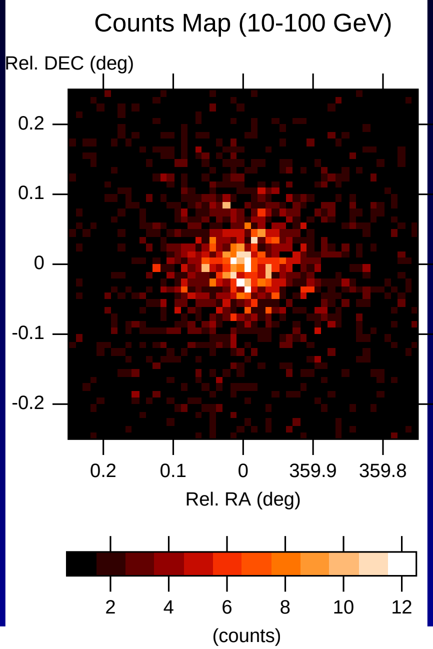


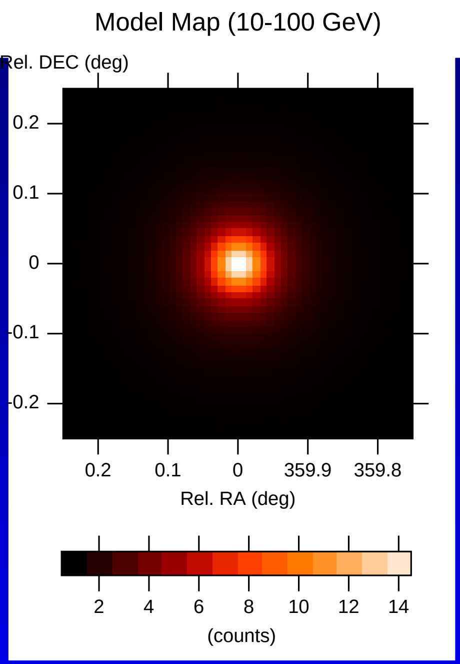
Neronov et al. 2010
Dolag et al. 2009
Neronov & Semikoz 2007
Aharonian et al. 1994

Measure cosmic magnetization

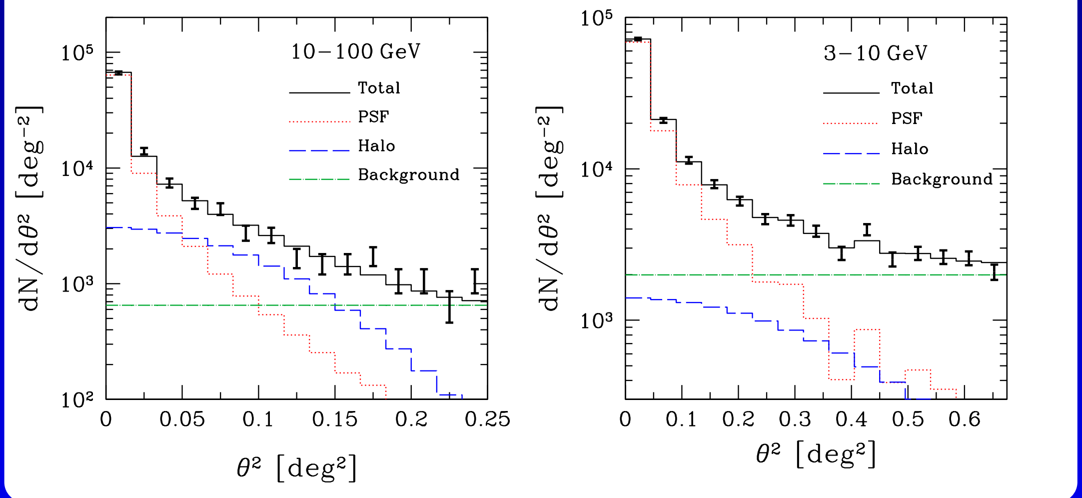
Propagation of γ-rays, sensitive to $(10^{-12} - 10^{-16})$G





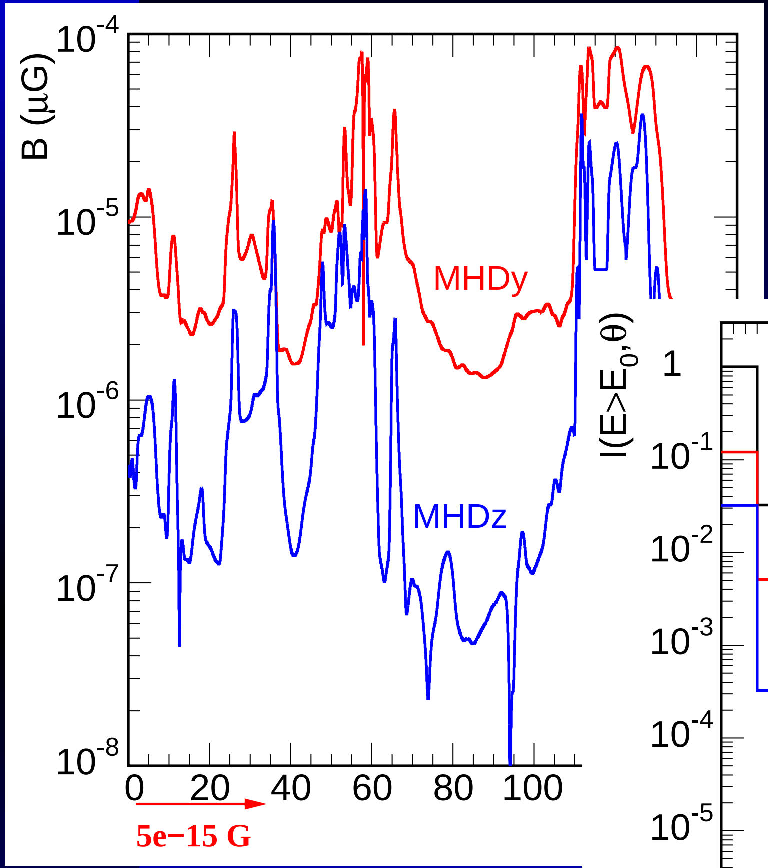


Ando & Kusenko 2010

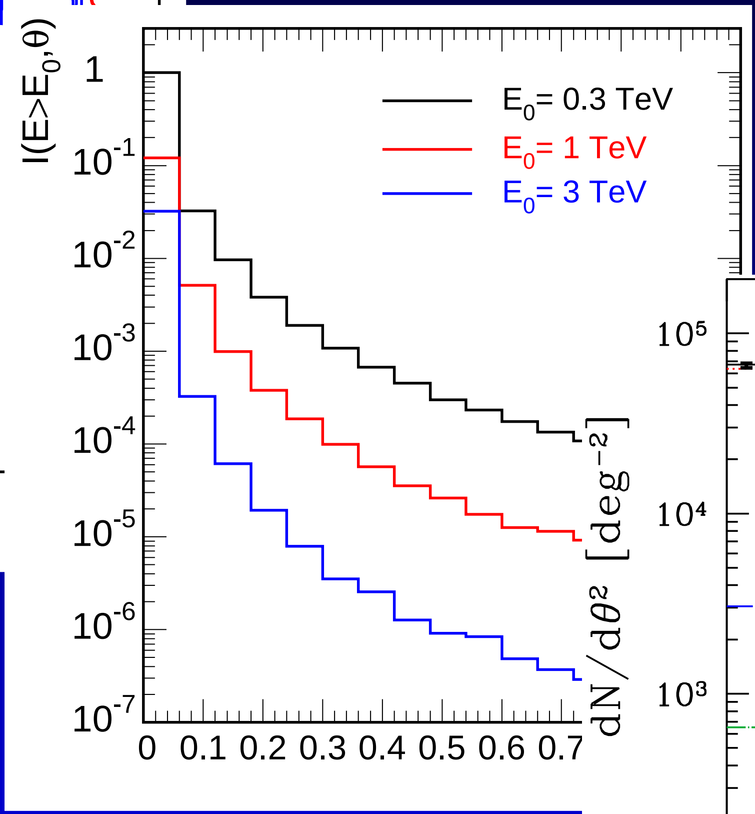


Halo found stacking 170 AGNs with FERMI: $B \approx 10^{-15}$G.

Measure cosmic magnetization

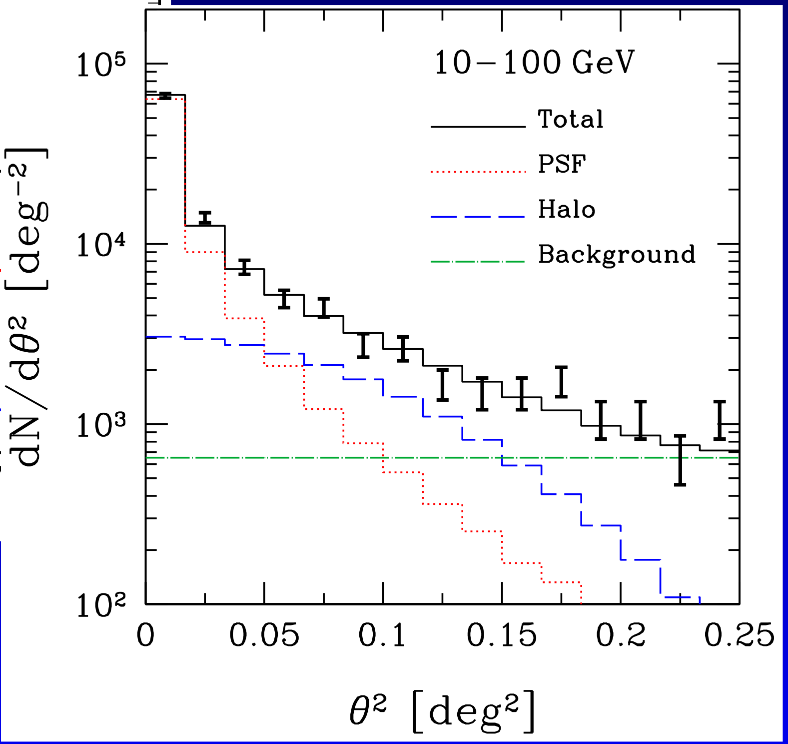


Dolag et al. 2009



1e−15 G

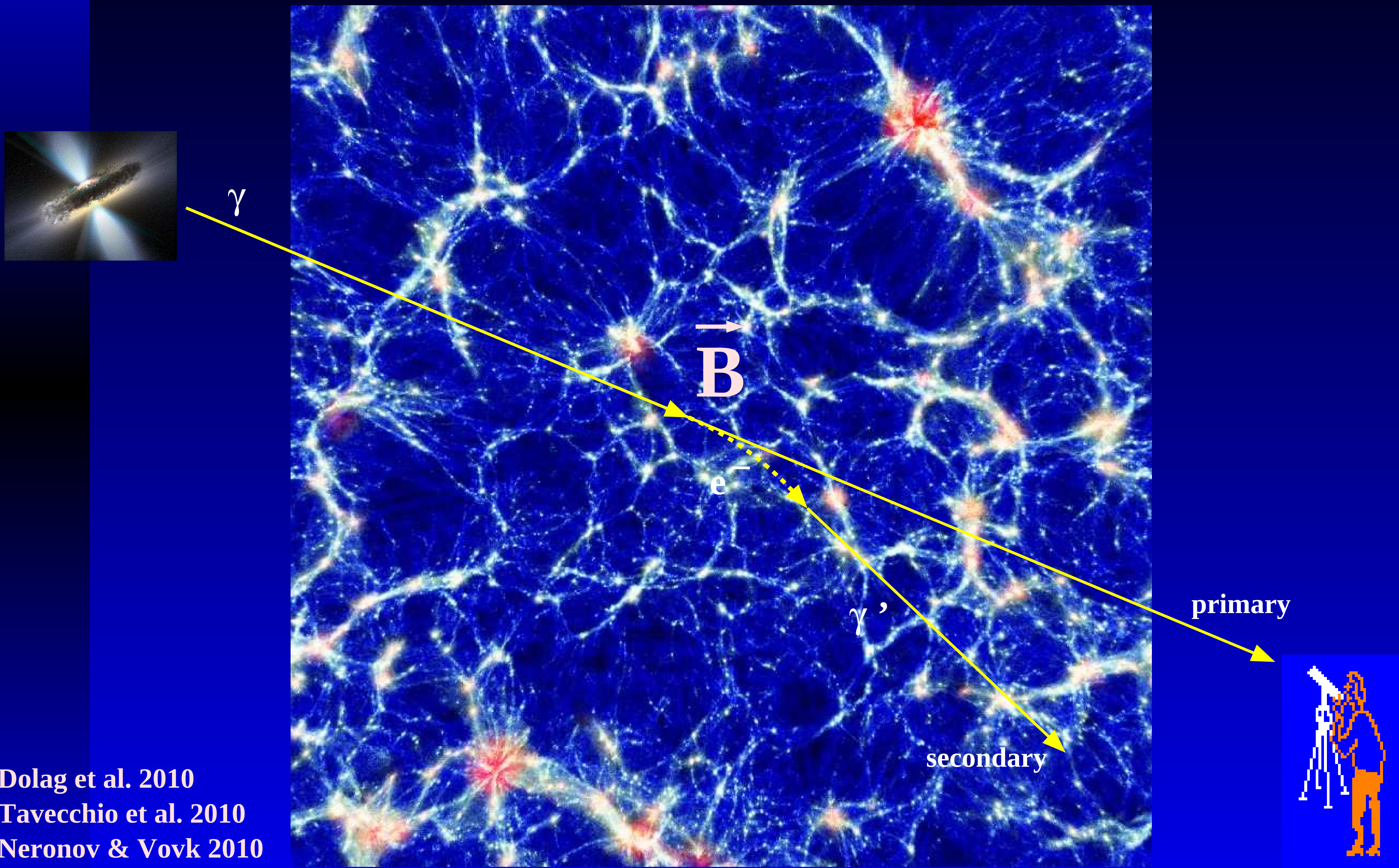
Ando & Kusenko 2010



But maybe inperfect beam ? (Neronov et al. 2010)

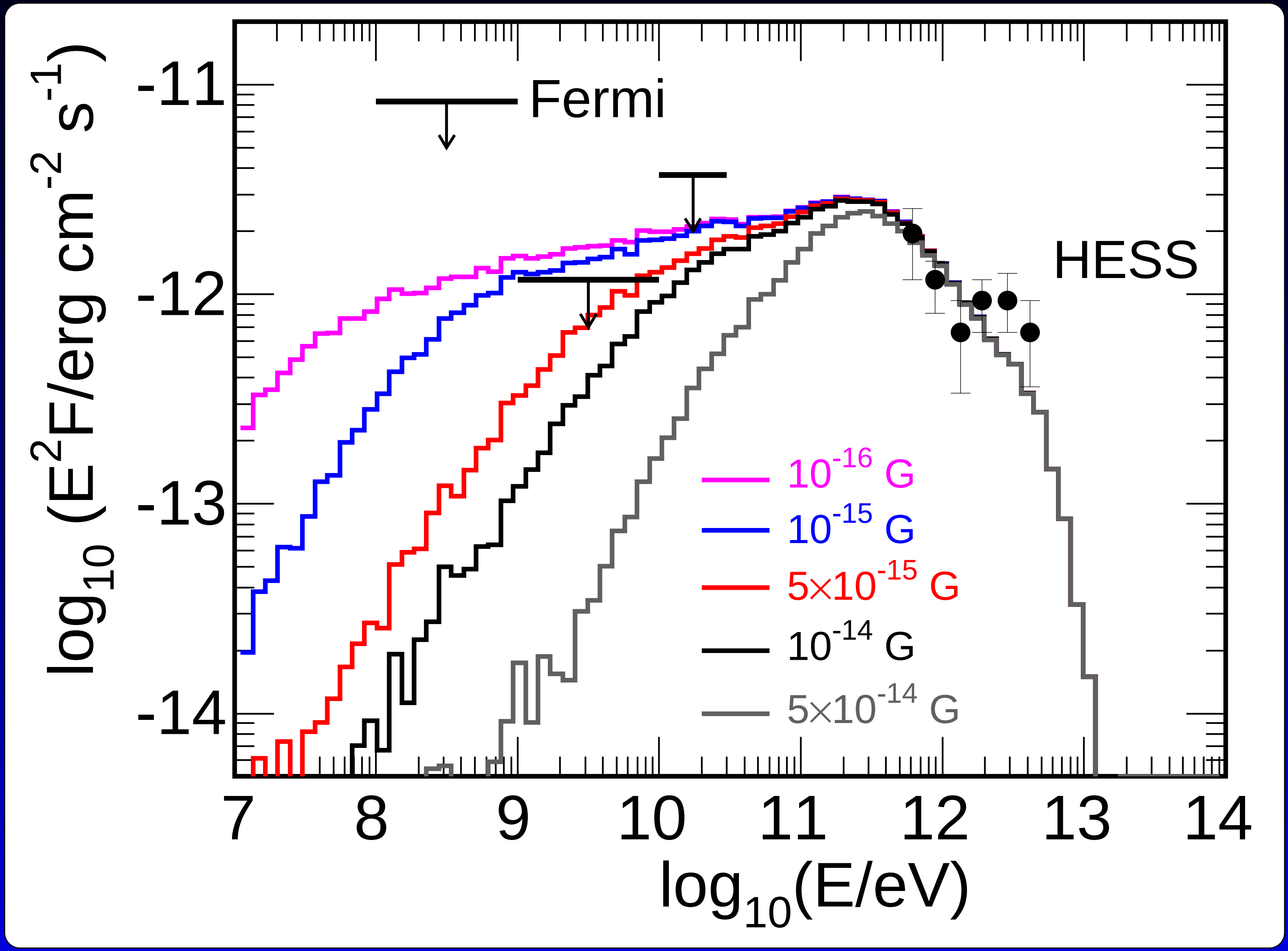
Measure cosmic magnetization

Attenuation from electromagnetic cascade of TeV photons



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

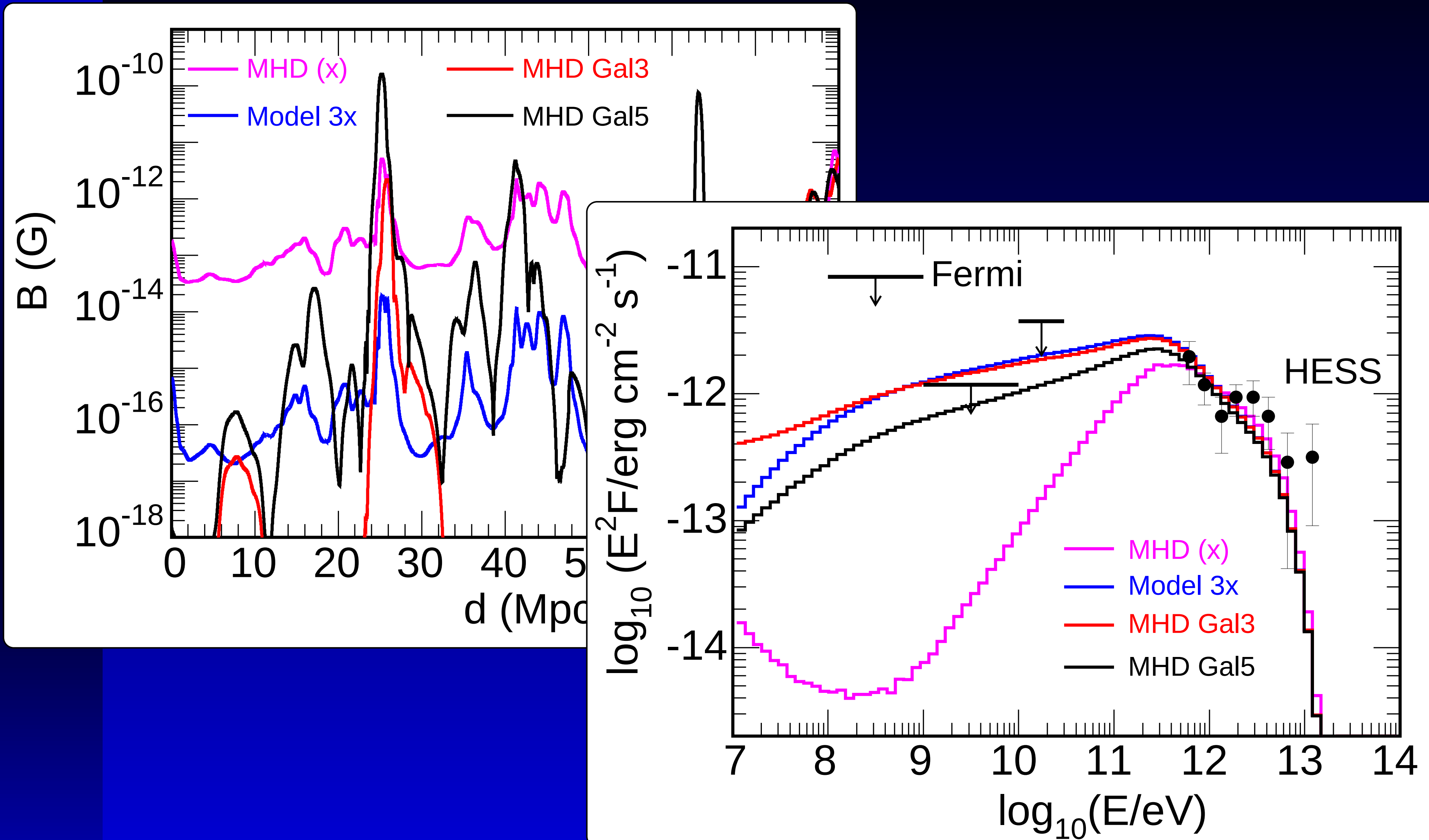
Measure cosmic magnetization



Combing FERMI and HESS give lower limit of $B > 5 \times 10^{-15}$G

(Neronov & Vovk 2010, Tavecchio et al. 2010)

Measure cosmic magnetization

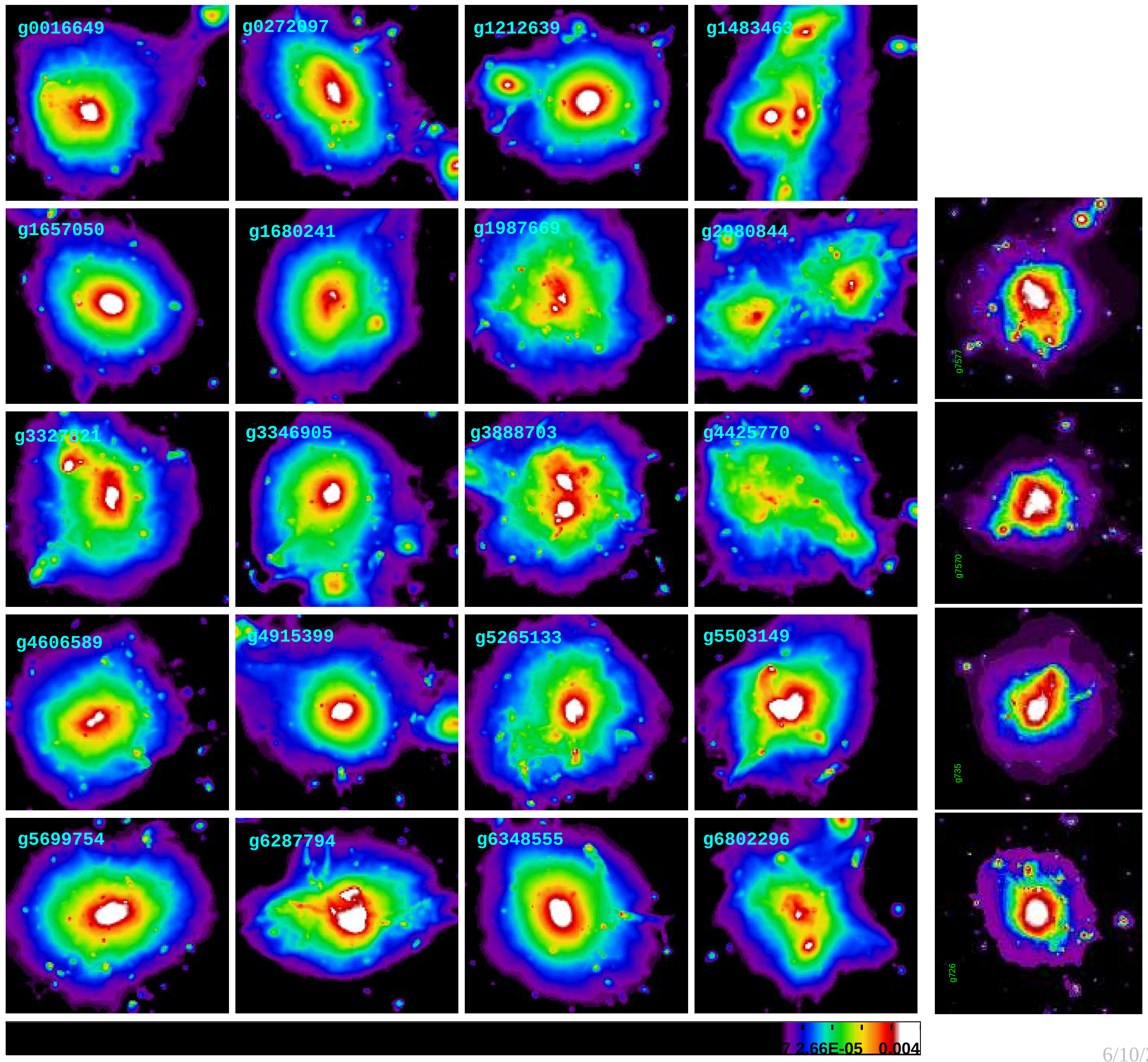


$\Rightarrow$ $B > 3 \times 10^{-15}$ G in at least 40% of space !

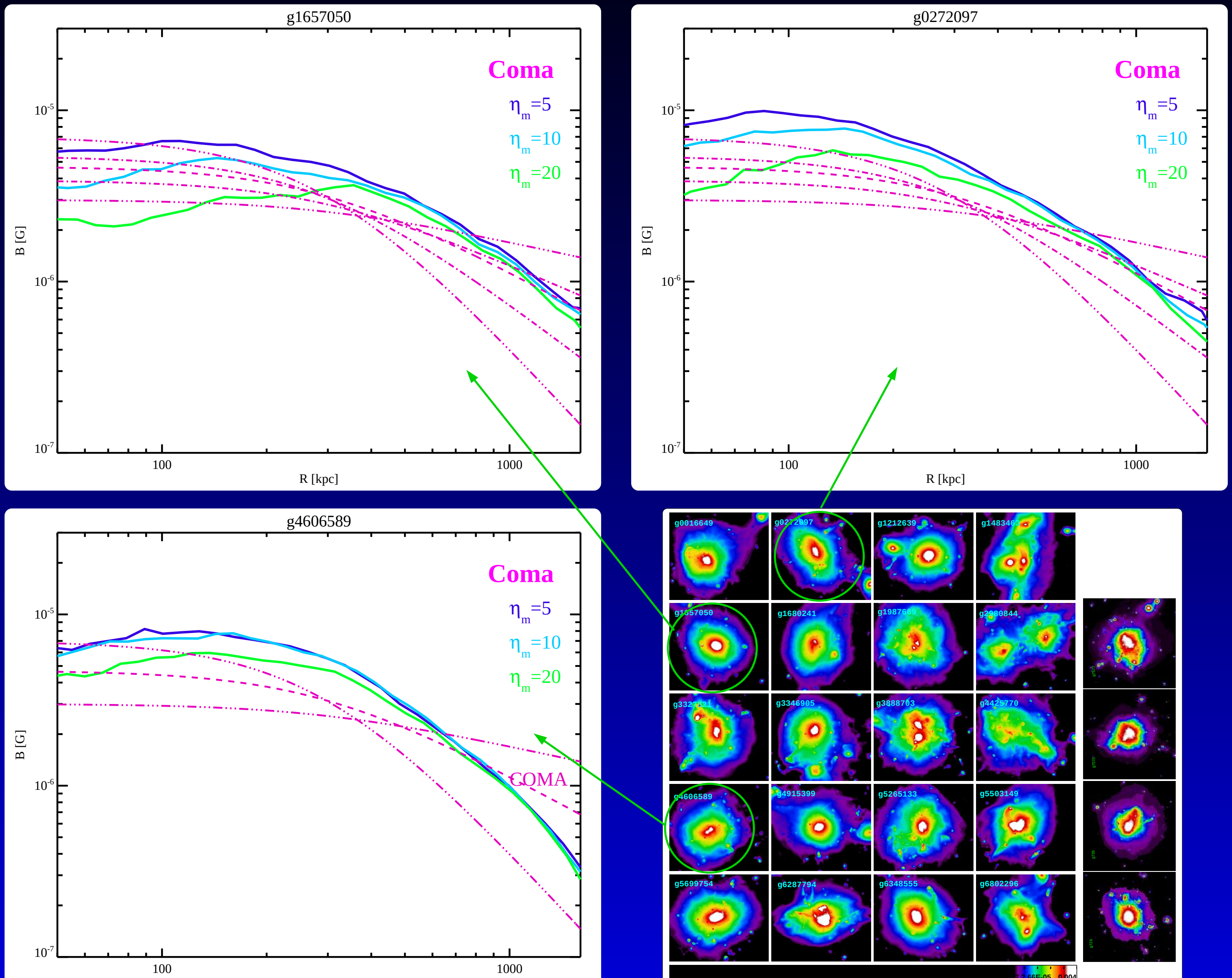
$\Rightarrow$ Strong constrains on the origin of EGMFs

(Dolag, Kachelriess, Ostapchenko & Tomàs 2010)

Beyond ideal MHD



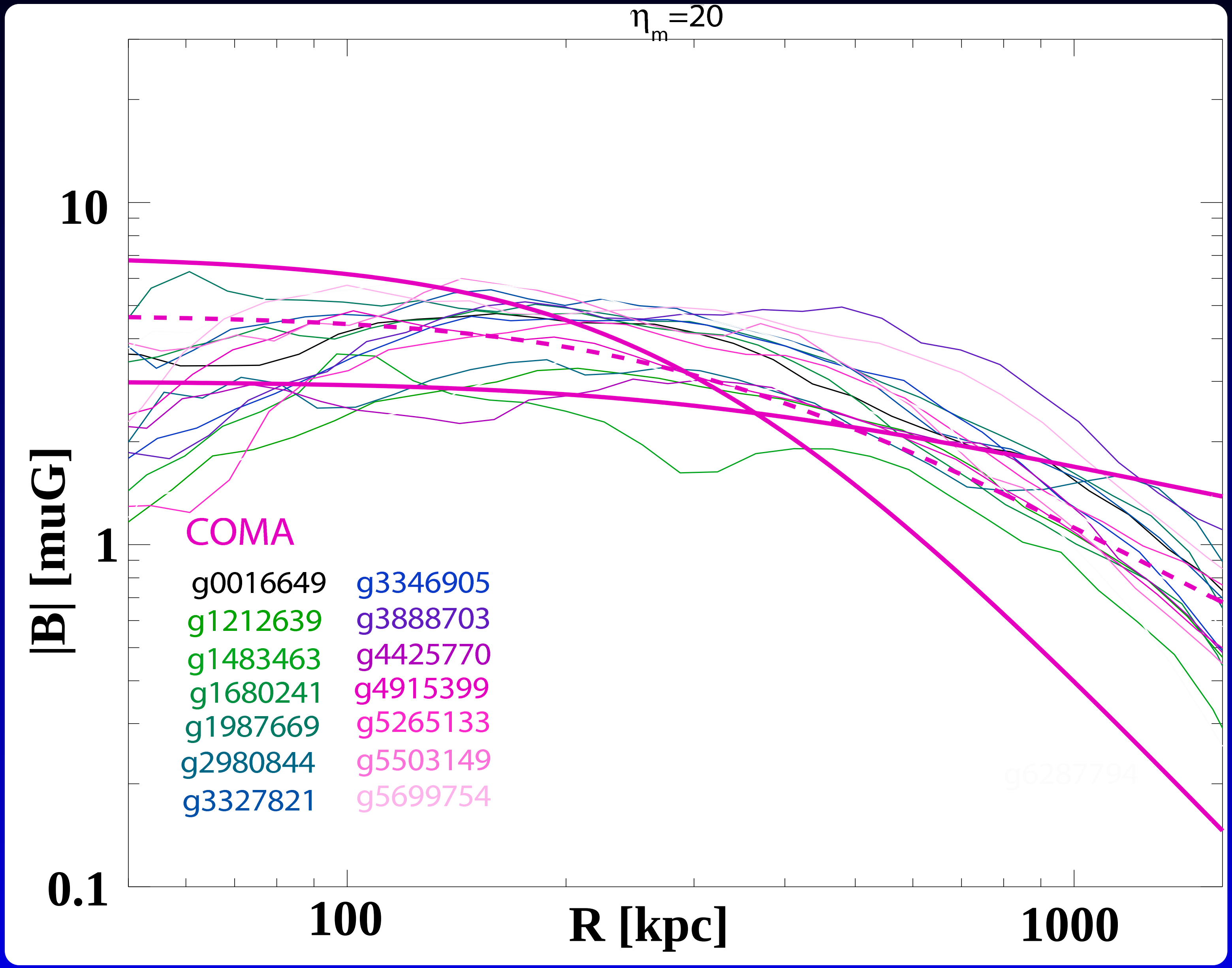
Beyond ideal MHD



Bonafede et al., work in progress

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

Beyond ideal MHD



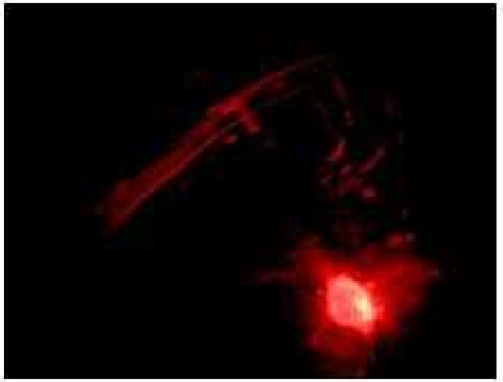
Bonafede et al., work in progress

⇒ Magnetic dissipation needed to explain profiles

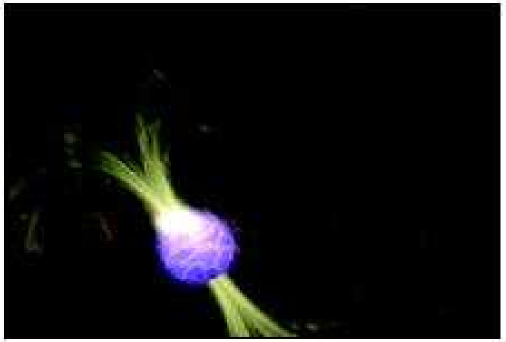
What is next ?

- High-z seed fields — $B \sim 10^{-30} – 10^{-20}$ G
  (Widrow 2002; Subramanian 2007)
- Intergalactic Medium — $B \sim$ 1-10 nG ?
- Intracluster Medium — $B \sim$ 0.1-1 μG
- Interstellar medium — $B \sim$ 1 μG – 10 mG
- Galactic Centre — $B \sim$ 50 μG – 1 mG
  (Crocker et al. 2010; Ferrière 2010)
- Main sequence star: HD 215441 — $B_0 \approx$ 34 kG
  (Babcock 1960)
- White dwarf: PG 1031+234 — $B_0 \approx 10^9$ G
  (Schmidt et al. 1986)
- Pulsar: PSR J1847-0130 — $B_0 \approx 9 \times 10^{13}$ G
  (McLaughlin et al. 2003)
- Magnetar: SGR 1806-20 — $B_0 \approx 2 \times 10^{15}$ G, $B_i \approx 10^{16}$ G
  (Kouveliotou et al. 1998, Israel et al. 2005)
- Cosmic strings (Ostriker et al. 1986) — $B \sim 10^{30}$ G
- Planck-mass monopoles — $B \sim 10^{55}$ G
  (Duncan et al. 2000)

Magnetic filaments in Perseus A (Fabian et al. 2008)



Galactic Centre (Yusef-Zadeh et al. 1984)



SGR 1806-20 giant flare (NASA)

taken from Bryan Gaensler's Kiama 2010 talk

... just climb the astronomical $\vec{B}$ scale !