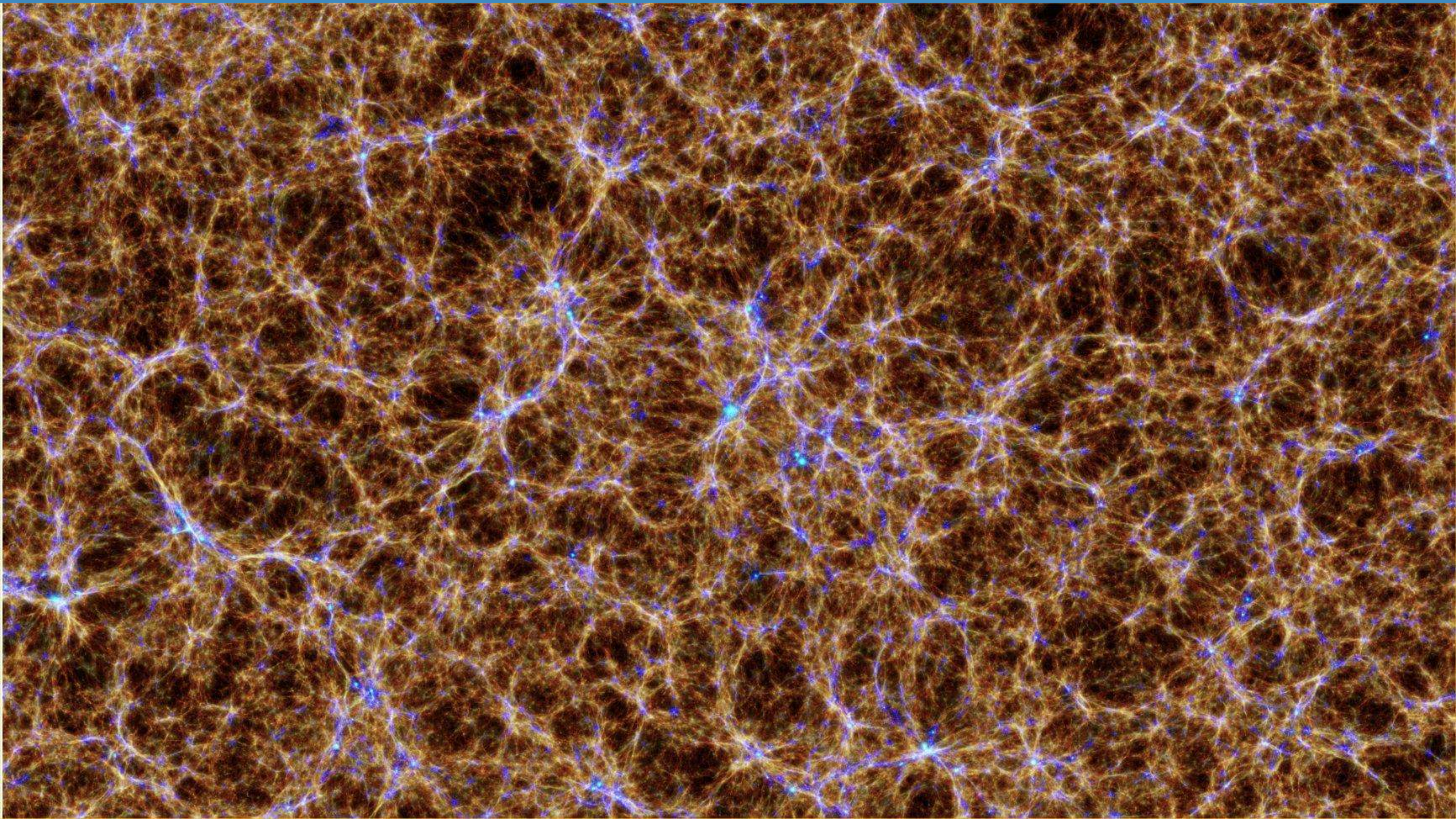
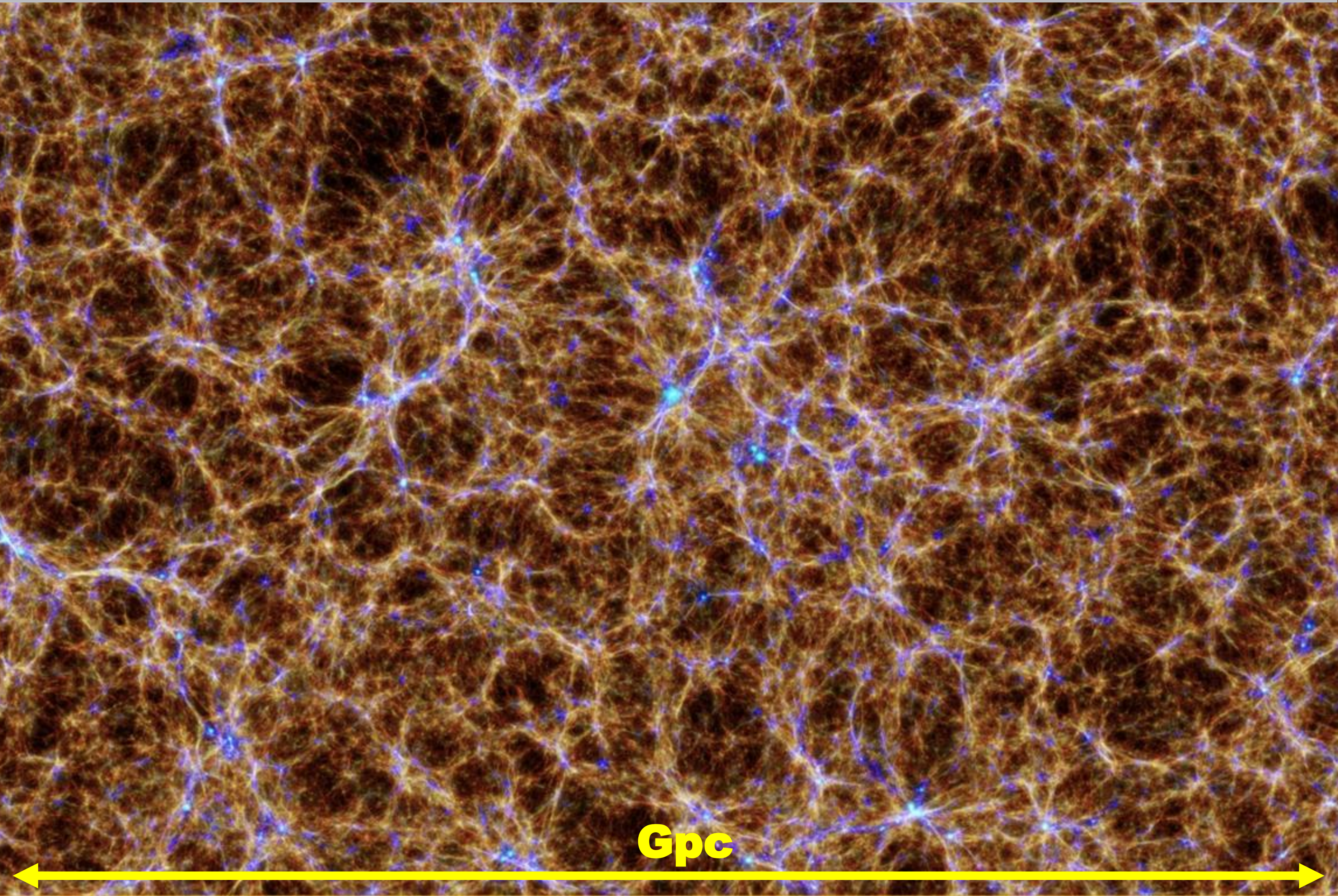
Magnetic Fields in Galaxy Clusters: Cosmological MHD Simulations

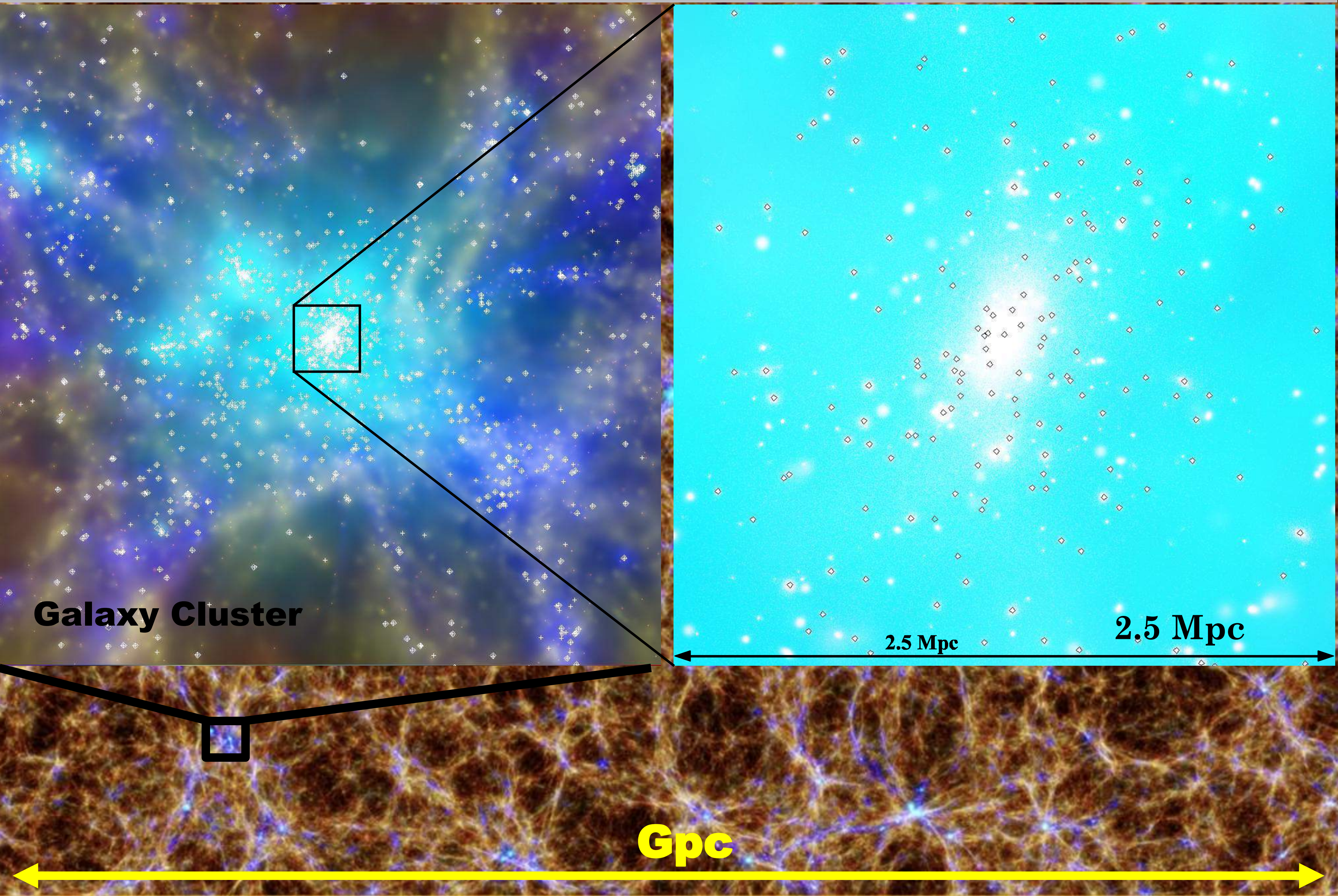
Klaus Dolag (USM)



Cosmological Structure Formation



Cosmological Structure Formation



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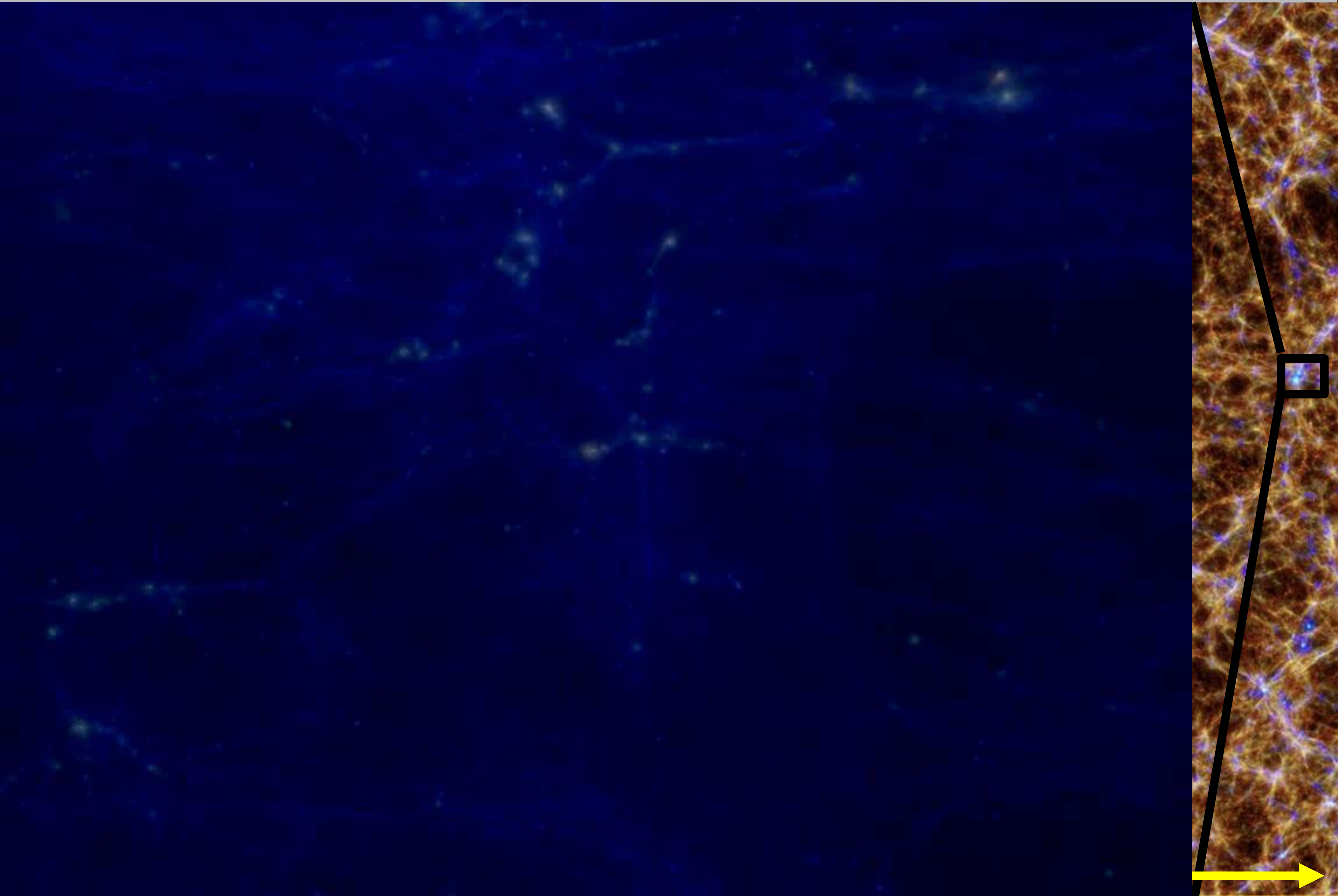
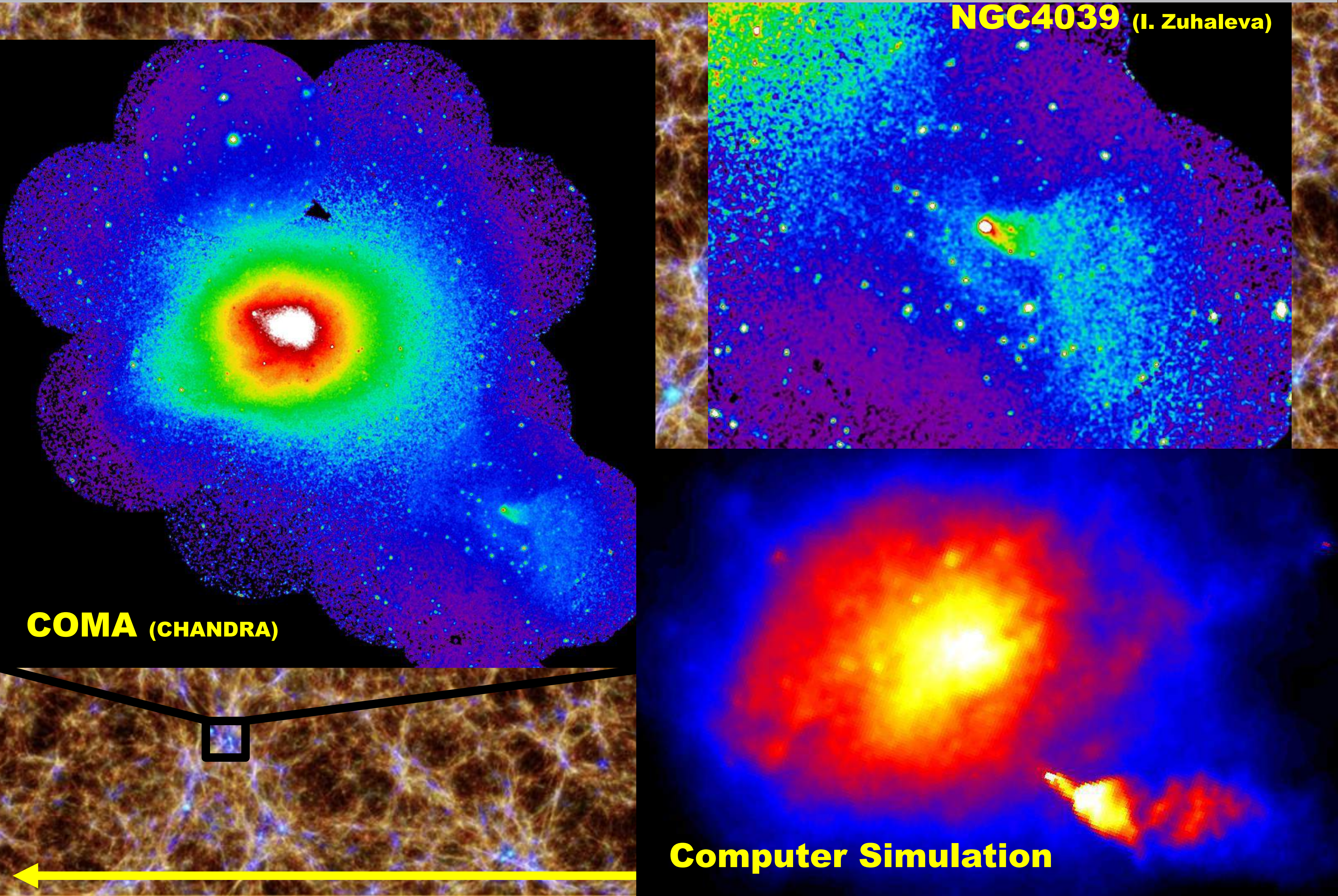
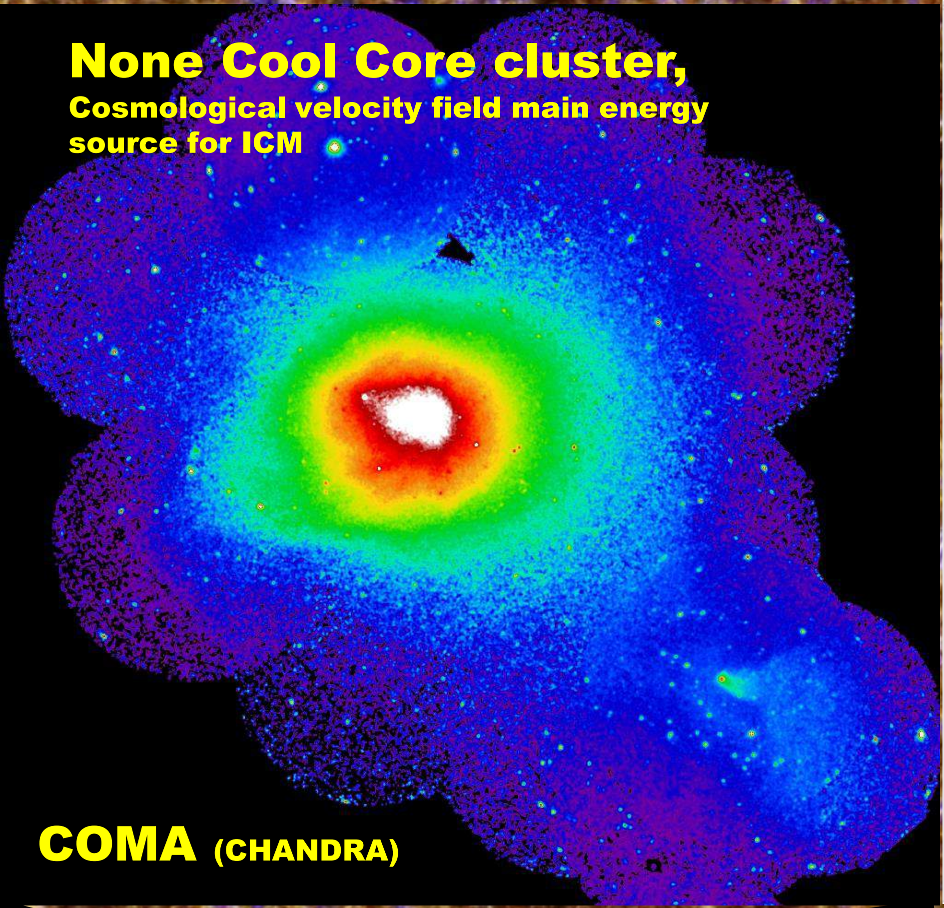
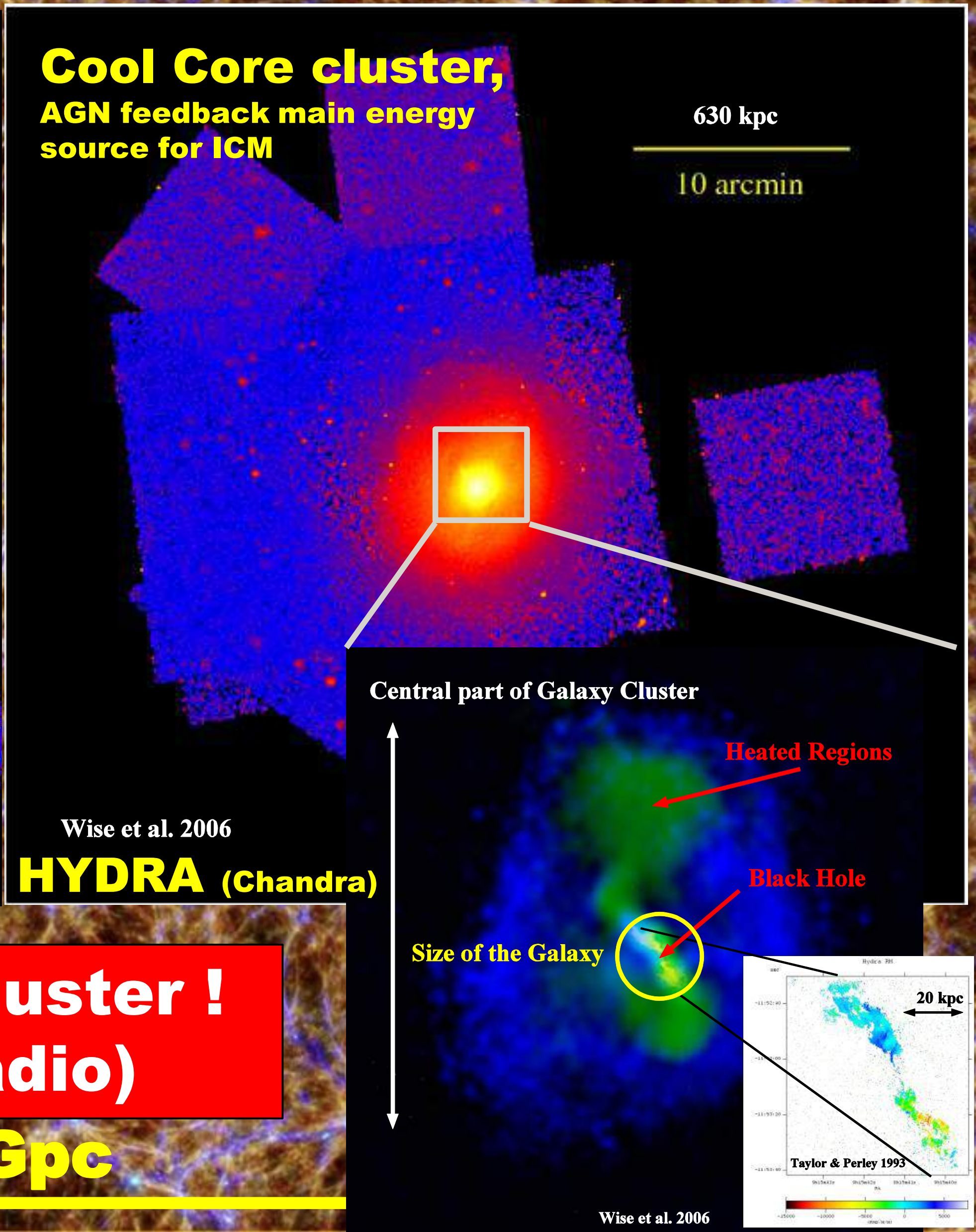


Cosmological Structure Formation



Cosmological Structure Formation

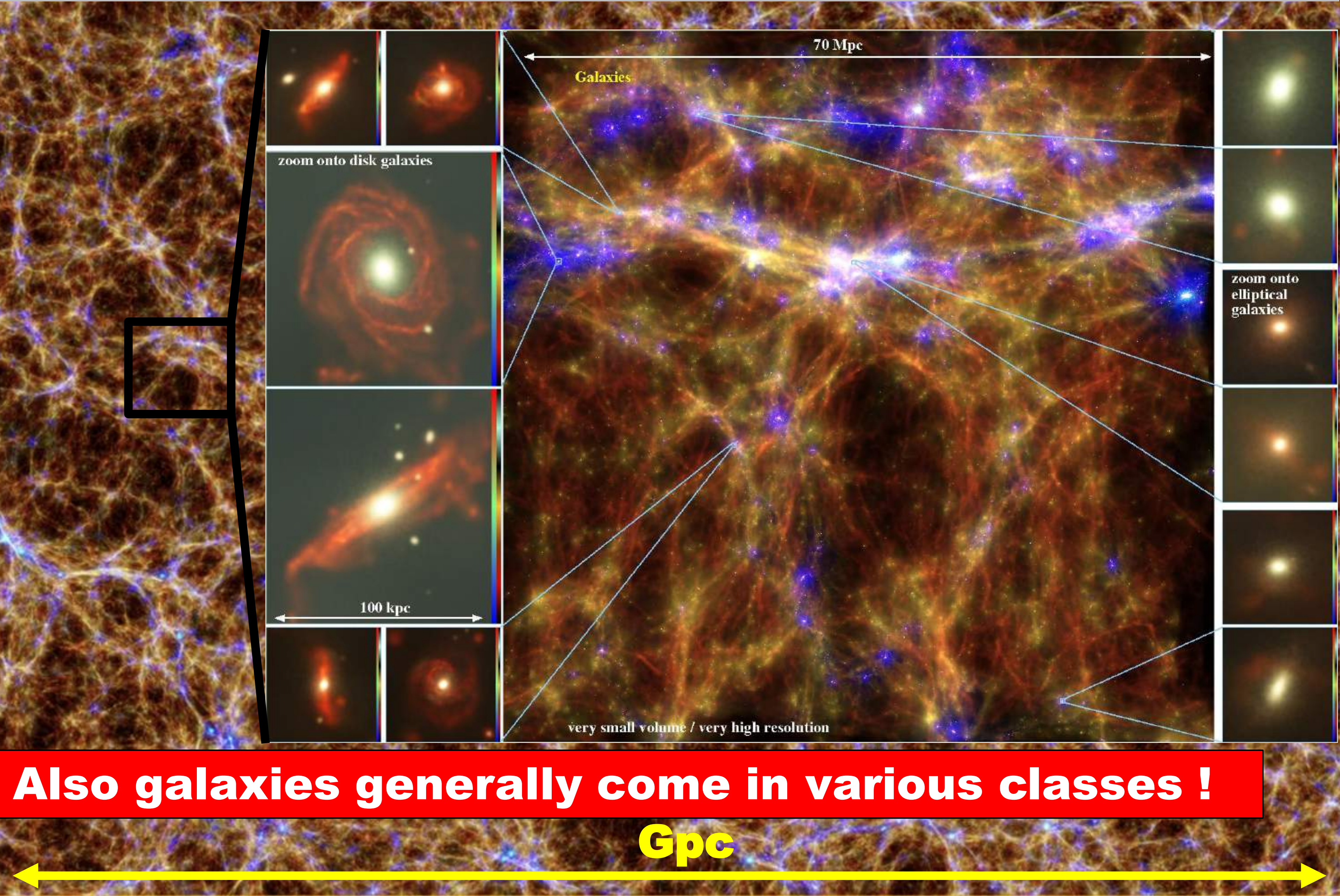




Two classes of Galaxy Cluster !
(also feature differnt B/radio)

Gpc

Galaxies in Cosmological Context



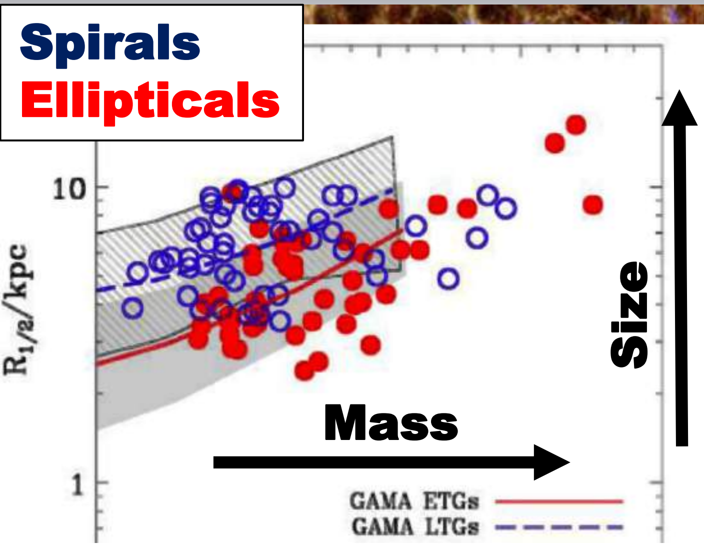
Also galaxies generally come in various classes !

The many Lives of Galaxies

Gyr = 0.28
z = 15.304

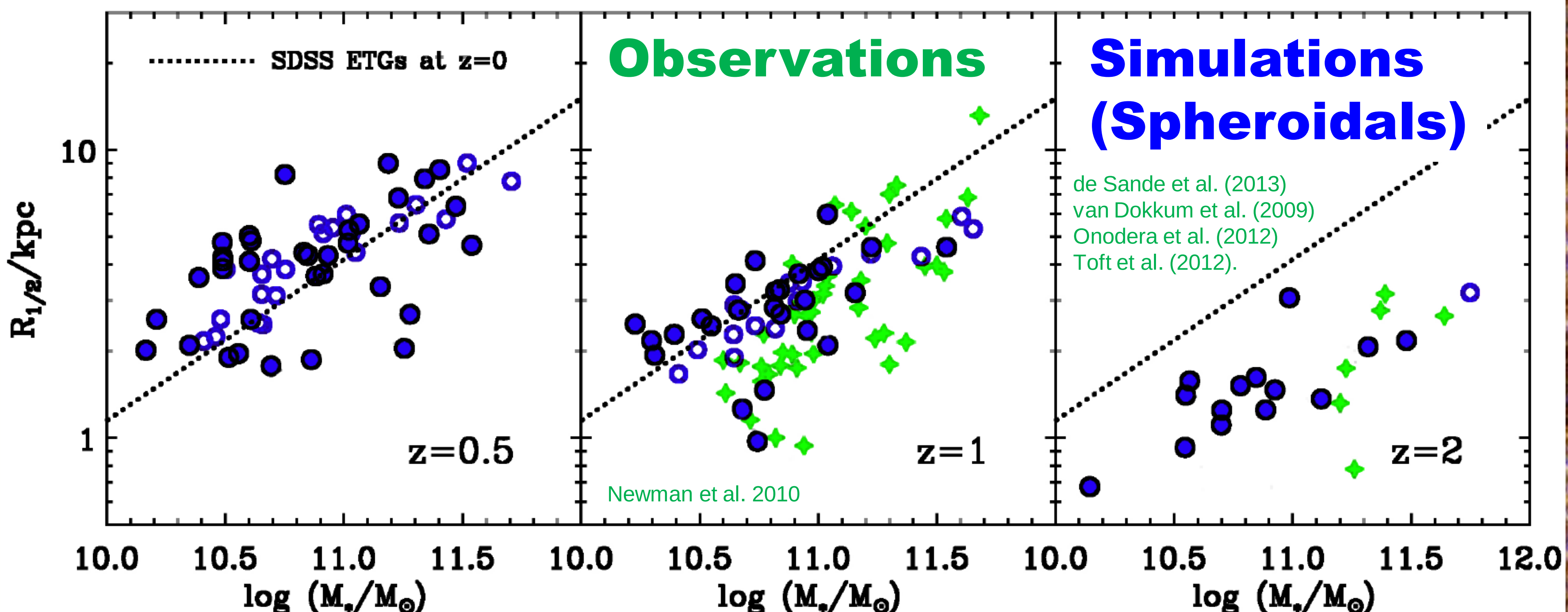
Galaxies undergo a strong and violent evolution !

The many Lives of Galaxies



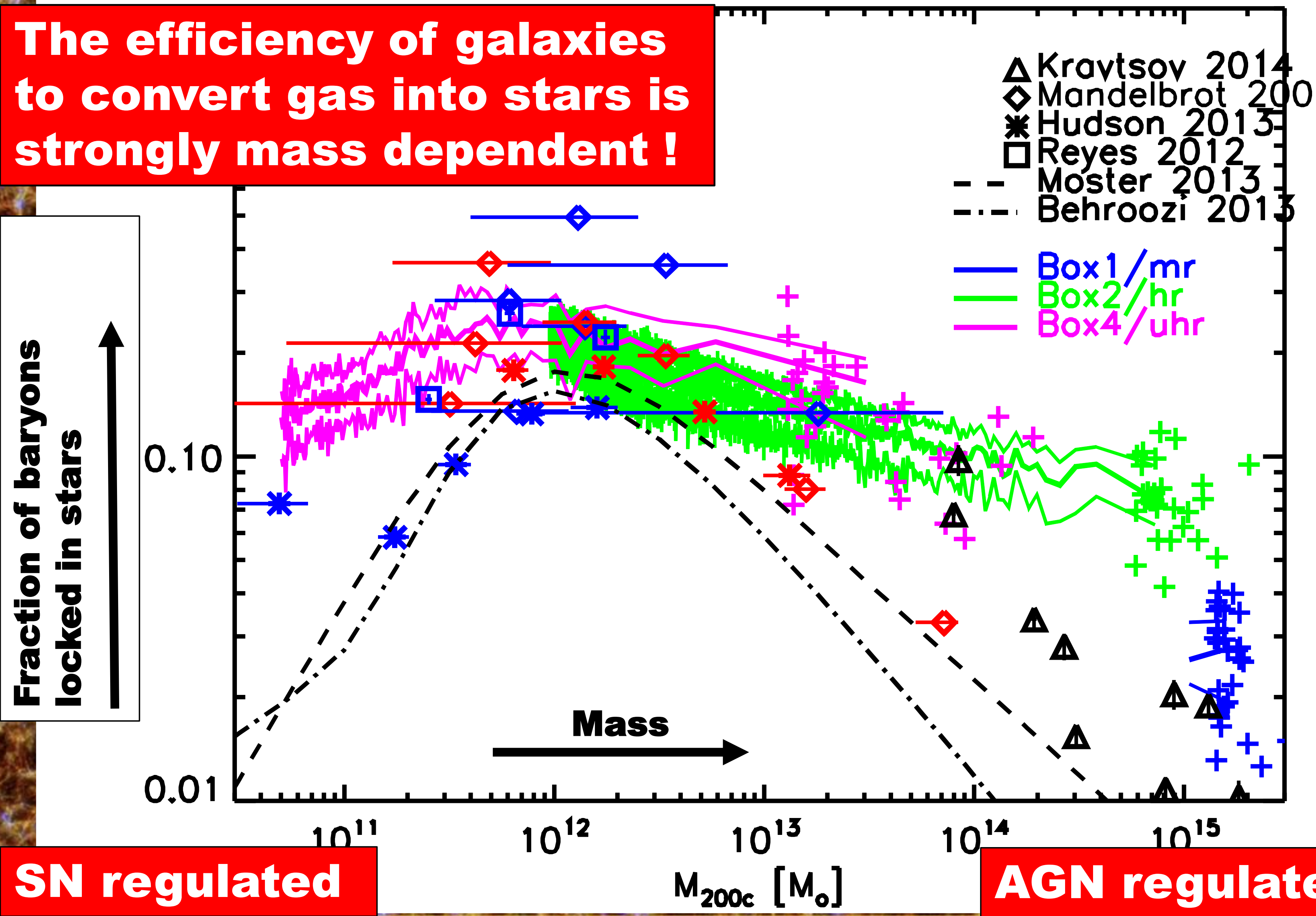
Galaxies at high redshift are:

a) much more compact
b) much more gas rich
c) at z=2 discs very clumpy
d) at z>2 very irregular



The many Lives of Galaxies

The efficiency of galaxies to convert gas into stars is strongly mass dependent !

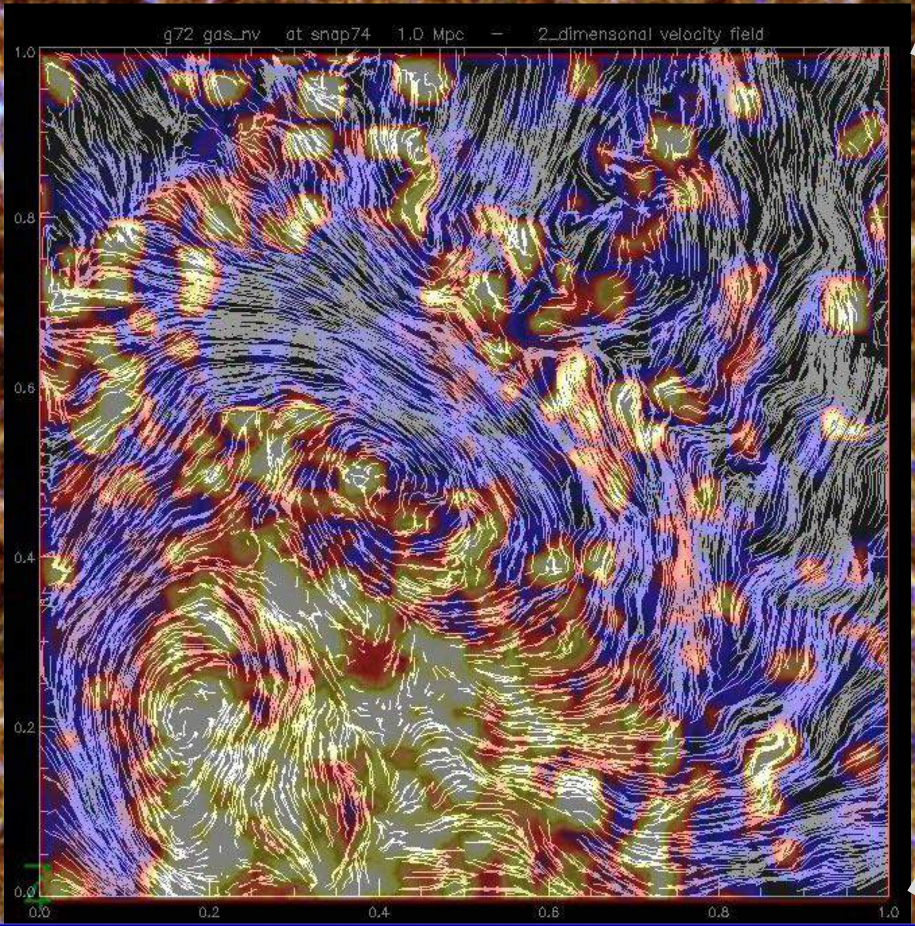


SN regulated

AGN regulated

Finally, lets try with Magnetic Fields

1 Mpc



Here, many details discussed on this conference (should) go in.

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) - \vec{\nabla} \times (\eta_{mag} \vec{\nabla} \times \vec{B}) + \left.\frac{\partial \vec{B}}{\partial t}\right|_{\mathrm{seed}}$$

Cosmology (structure formation)

Microphysics (plasma physics)

magnetic seeding (star formtion)

Finally, lets try with Magnetic Fields

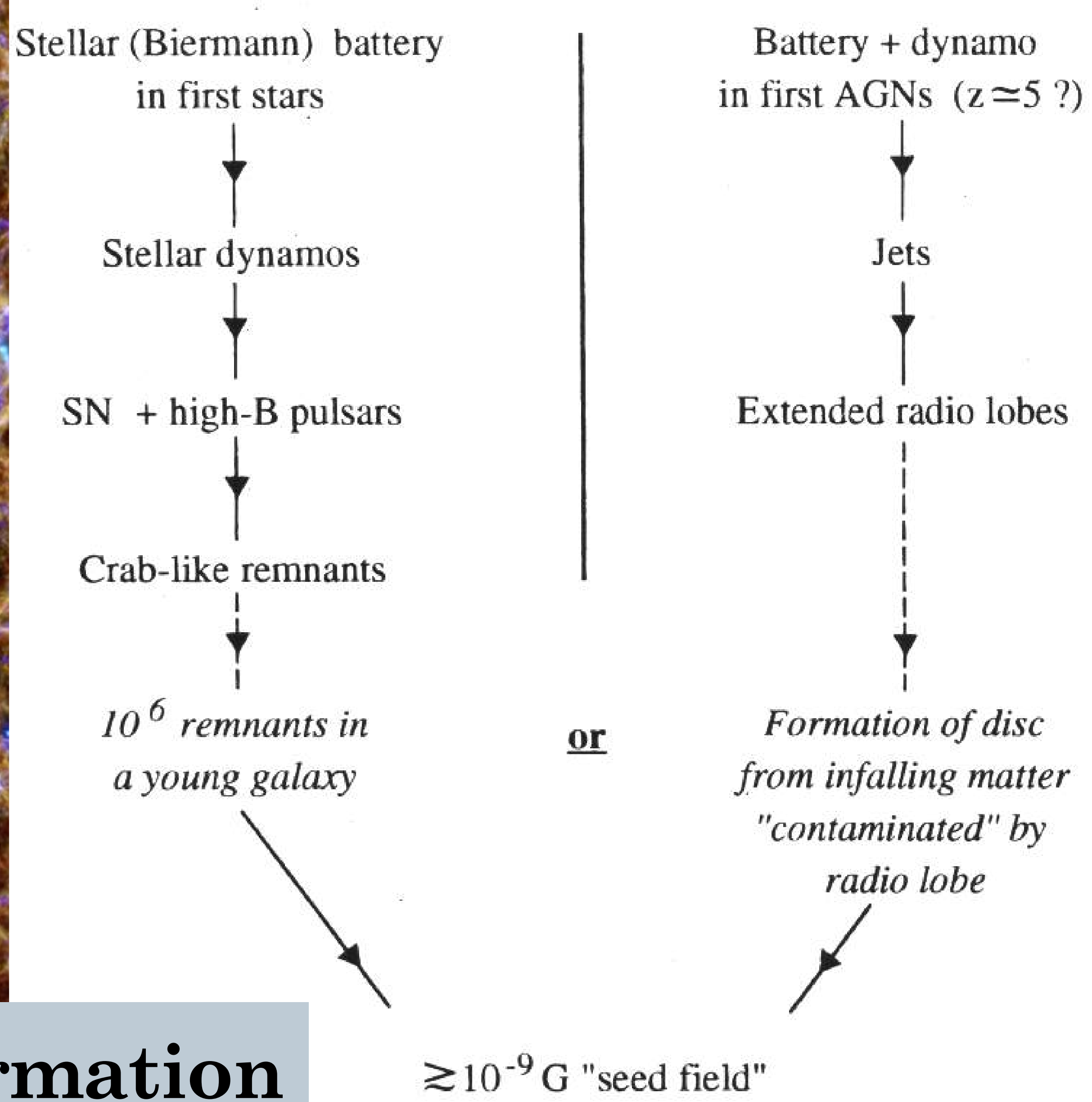
Seeds:
Primordial
Battery
Shocks

Generators:
Stars
Supernovae

Propagators:
Galactic Winds
AGN, Jets

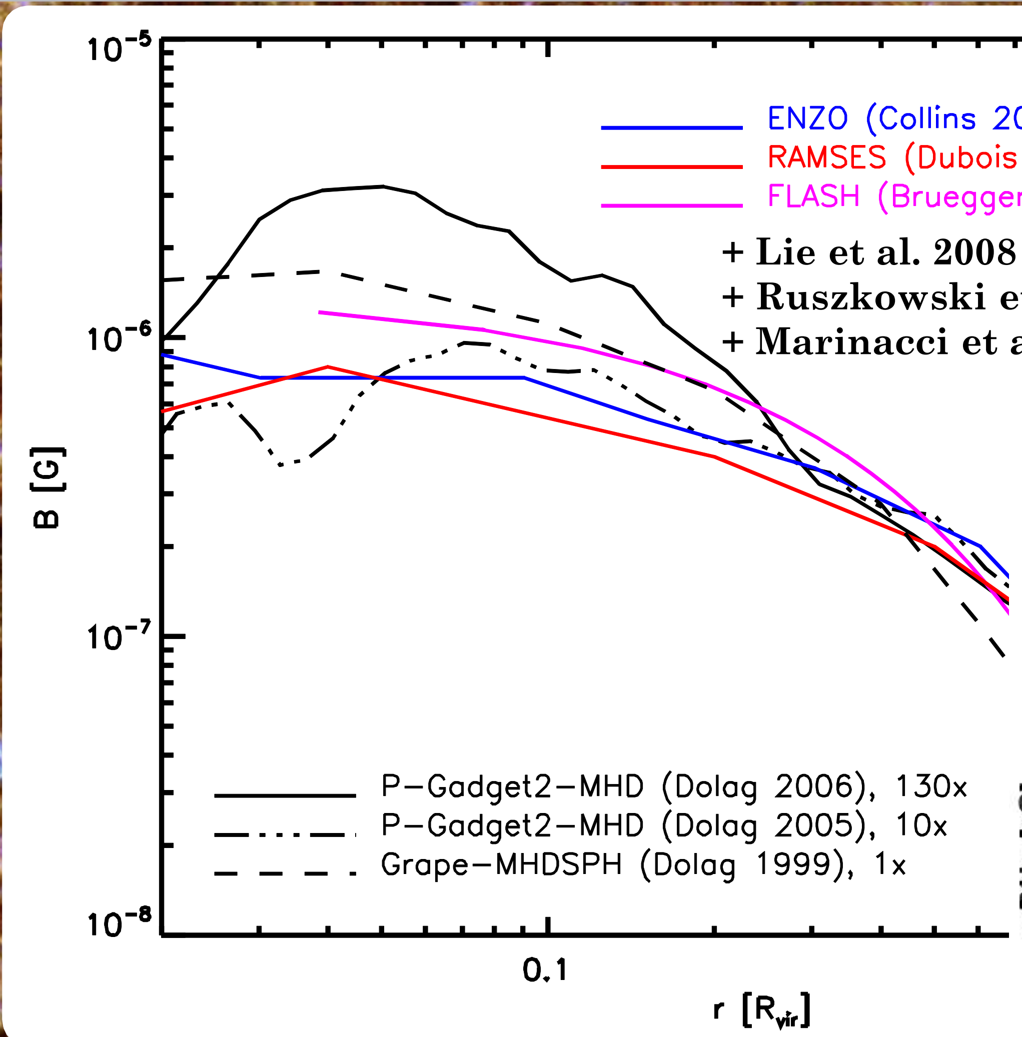
Moderators:
Dynamo
Turbulence

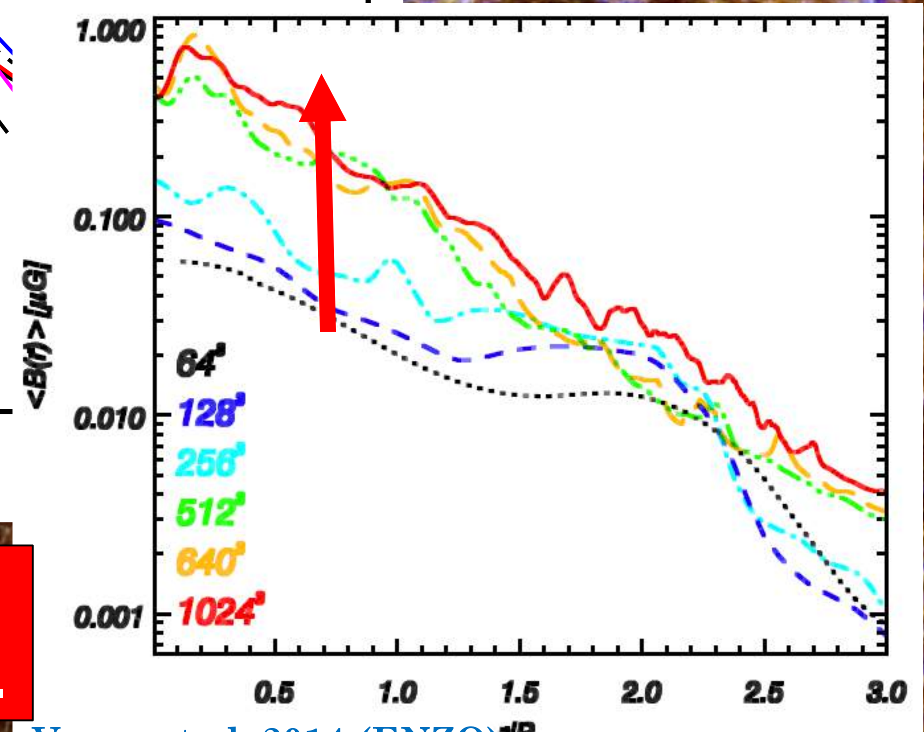
+ Structure formation



Rees 1994

15 years of cluster MHD simulatios

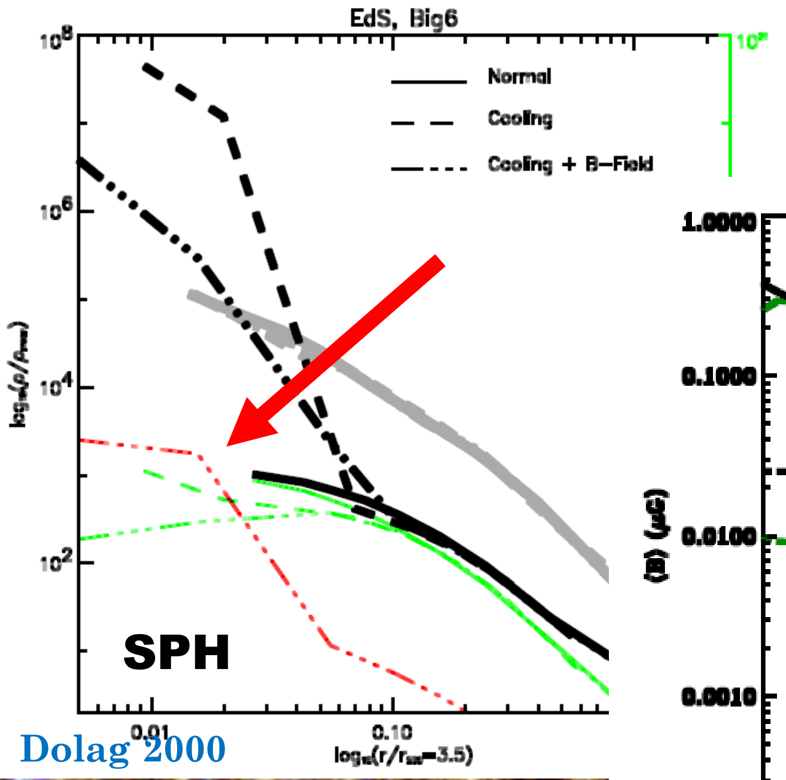


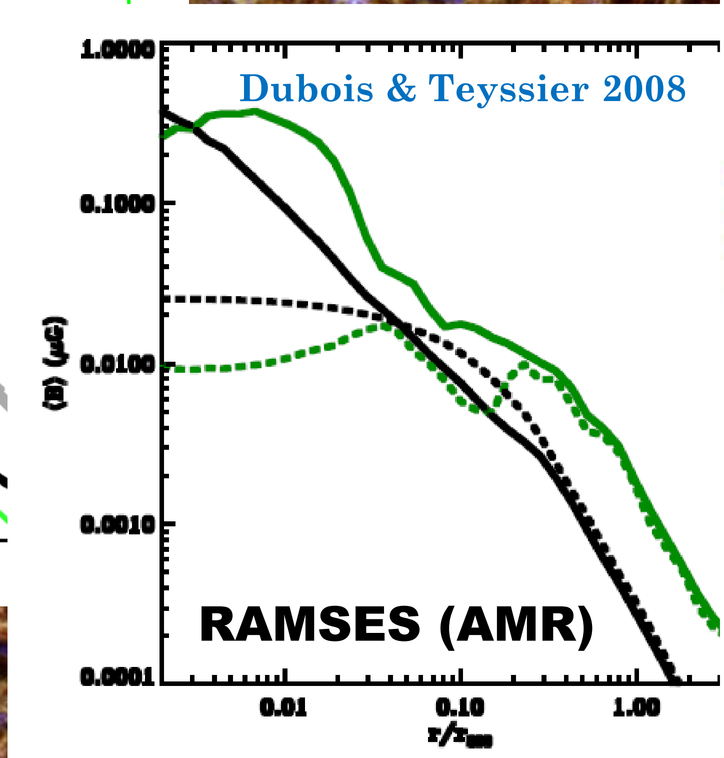


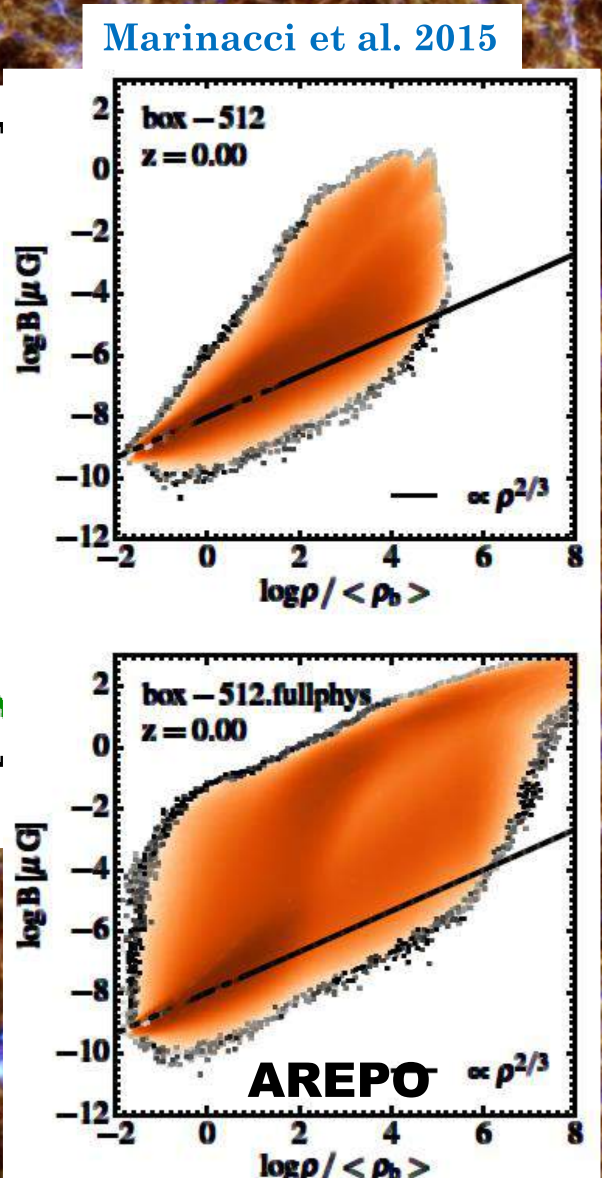
Non radiative runs give amplification to seed fields which are strongly resolution dependent, reaching μG levels in clusters.

Vazza et al. 2014 (ENZO)

15 years of cluster MHD simulatios





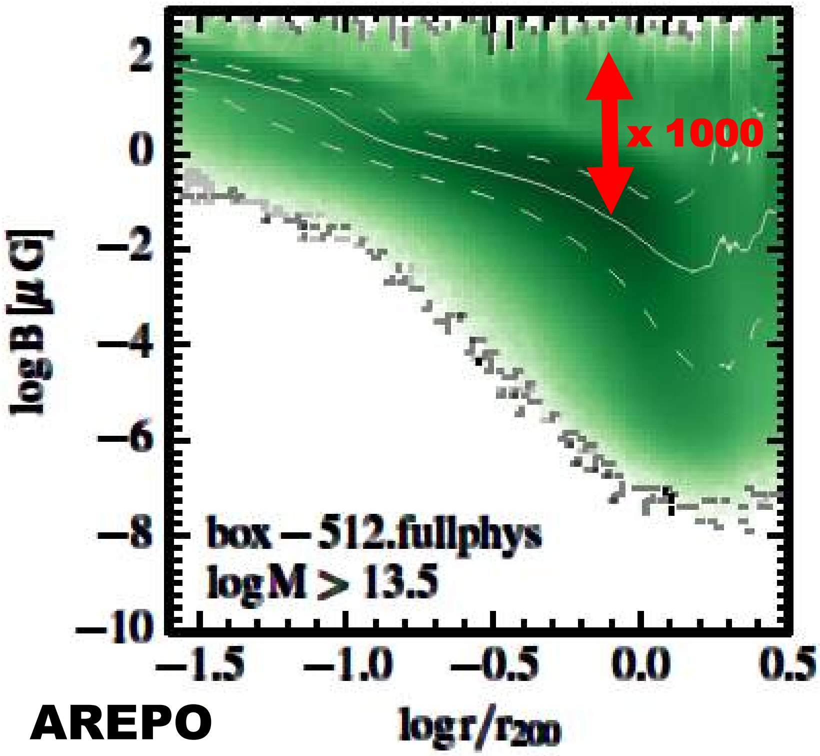


Including cooling give strong amplification up to equipatition:

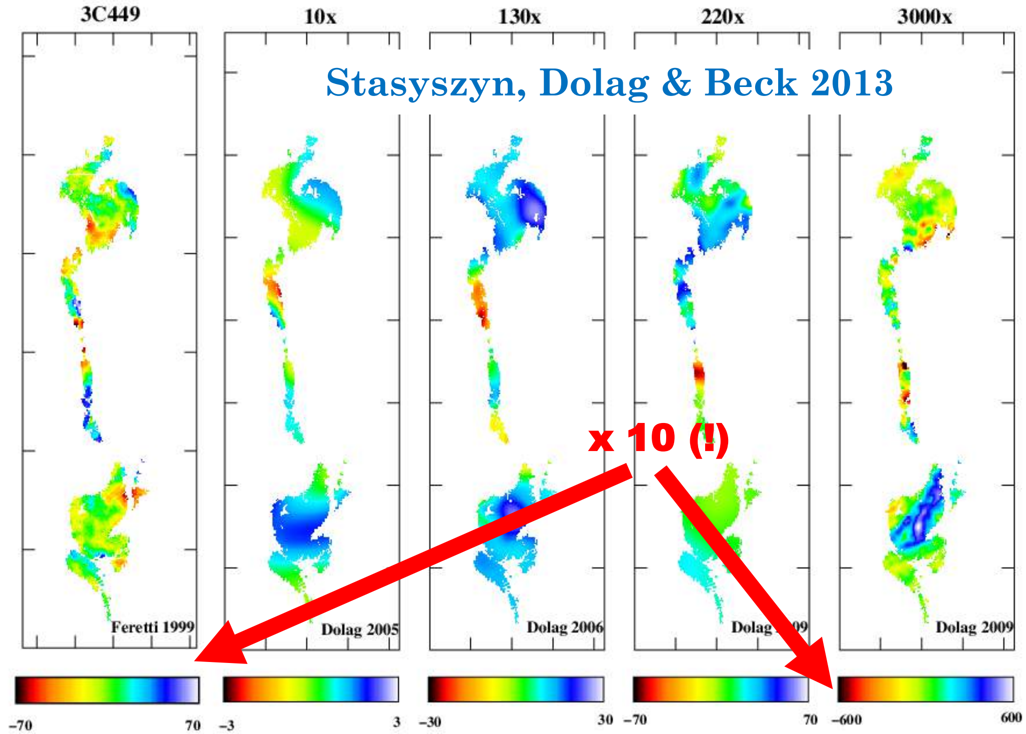
a) smaller/more compact sub-structures

b) feedback related to star-formation

15 years of cluster MHD simulatios

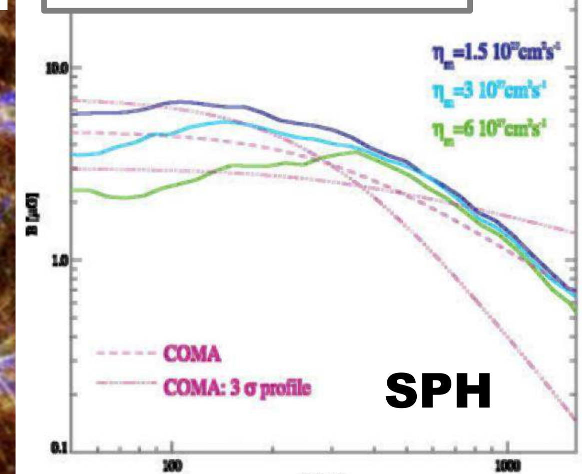


Marinacci et al. 2015



see also Xu et al. 2012

Bonafede et al. 2011



Simulatins predict magnetic field topology which matches observations quite well. But:

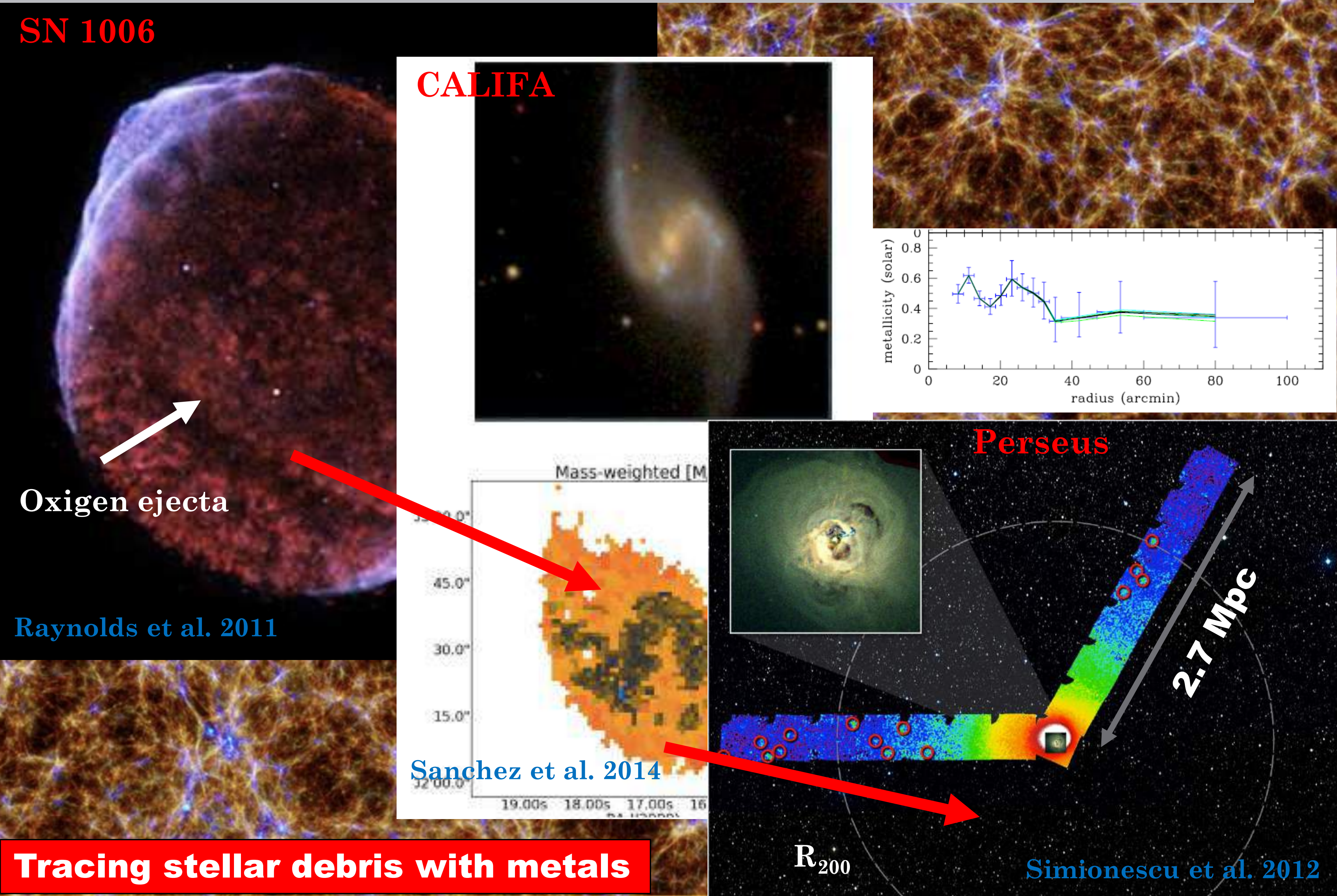
a) produce too strong B fields in the centre

b) too steep gradients outwards

Possible solution: Diffusion/Dissipation

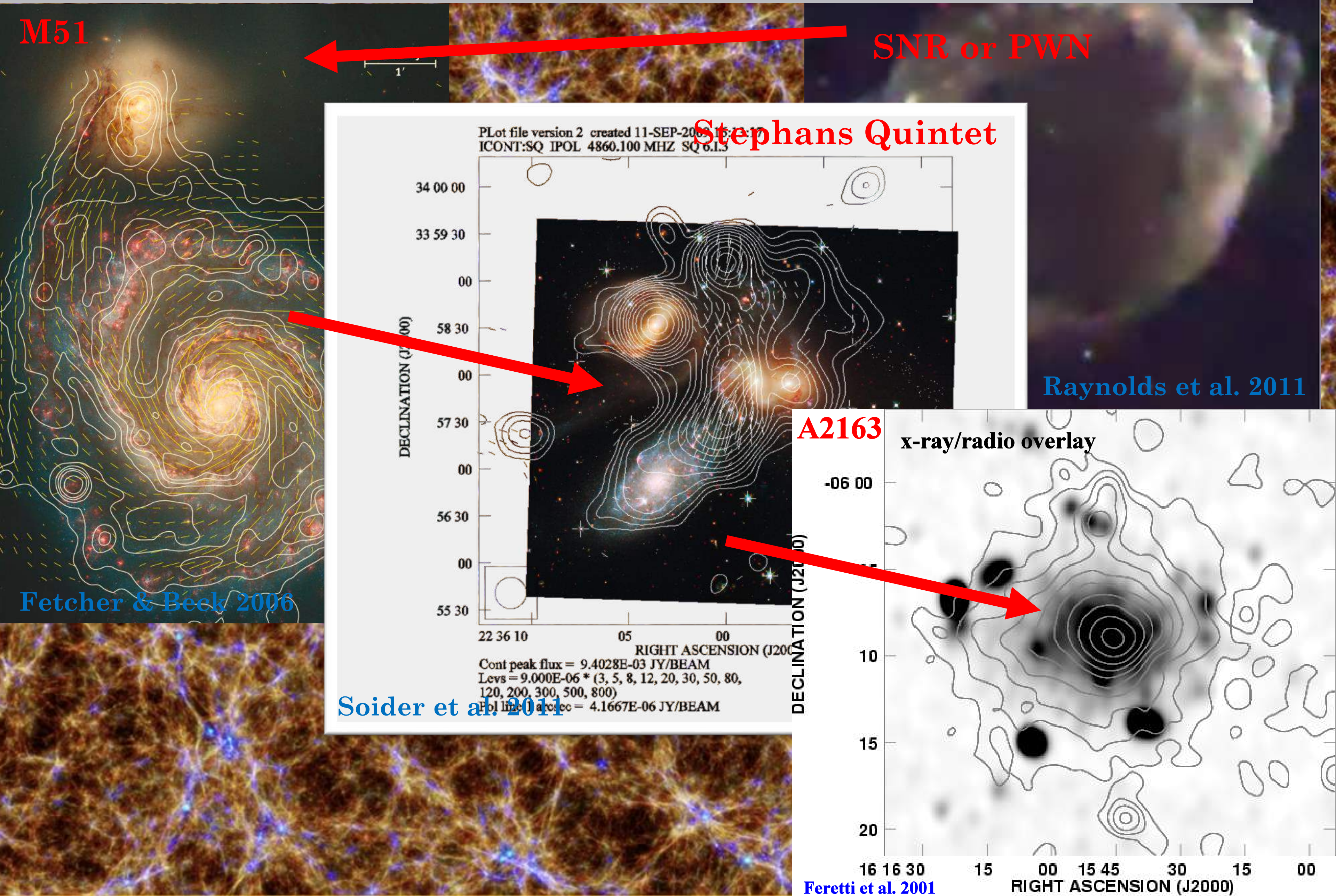
But: details unclear (plasma physics)

Linking things across all scales

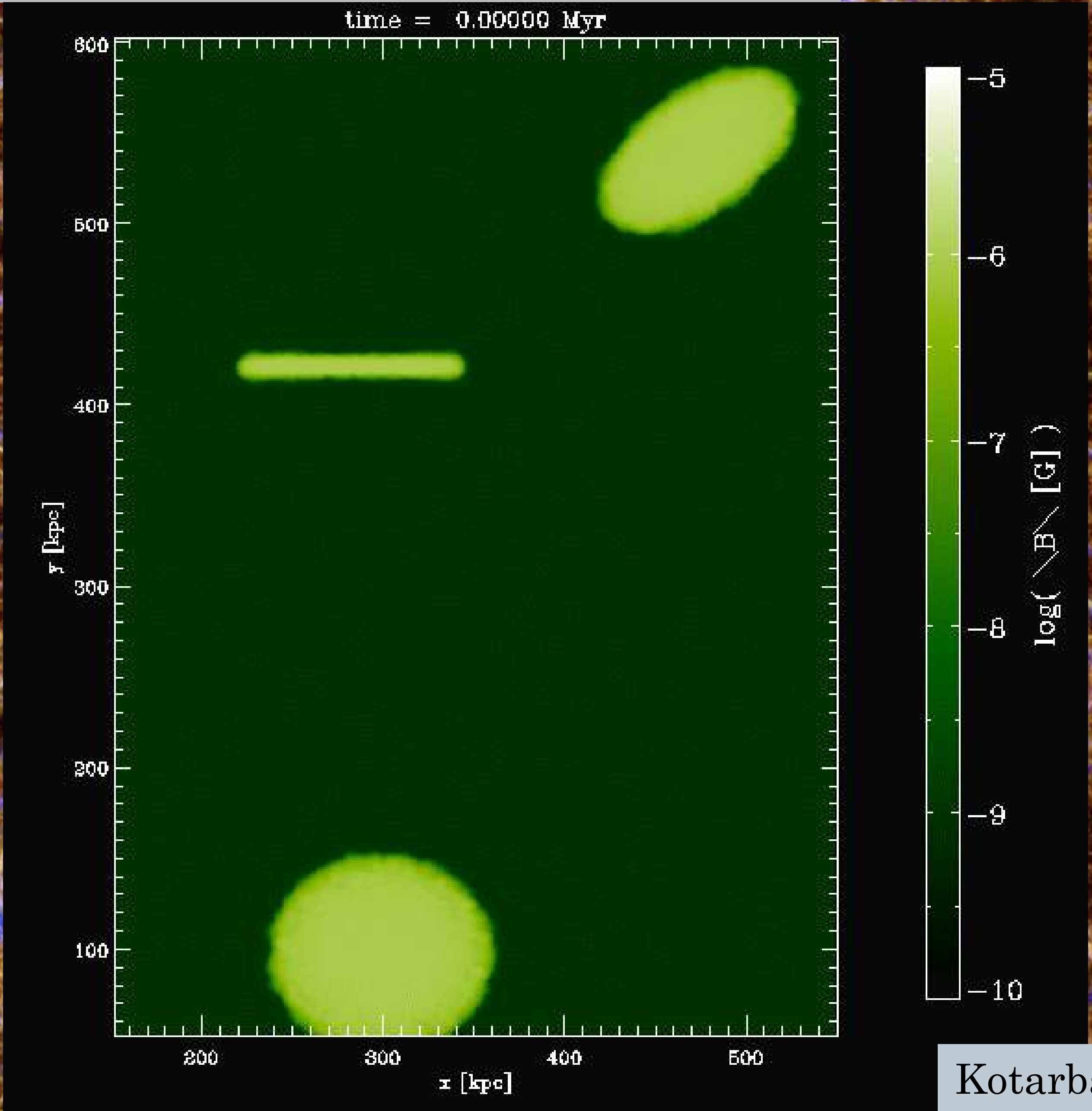


Tracing stellar debris with metals

Linking things across all scales



A very simple example

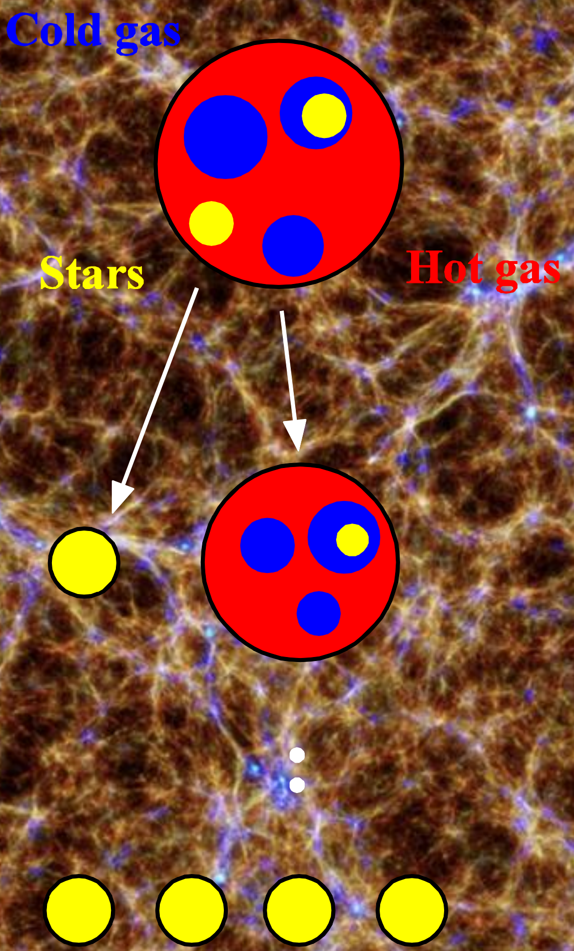


Kotarba et al. 2011

Sub-resolution star-formation:

Multi phase model (sub-scale)

Springel & Hernquist 2002



Star formation

$$\frac{d\rho_\star}{dt} = (1-\beta)\frac{\rho_c}{t_\star}$$

supernova mass fraction

star formation timescale

Cloud evaporation

$$\left.\frac{d\rho_h}{dt}\right|_{\rm evap} = A\beta\frac{\rho_c}{t_\star}$$

cloud evaporation parameter

Here, all you heared on this conference (should) go in.

Growth of clouds

$$\left.\frac{d\rho_c}{dt}\right|_{\rm TI} = -\left.\frac{d\rho_h}{dt}\right|_{\rm TI} = \frac{\Lambda_{\rm net}(\rho_h, u_h)}{u_h - u_c}$$

cooling function

A very simple model

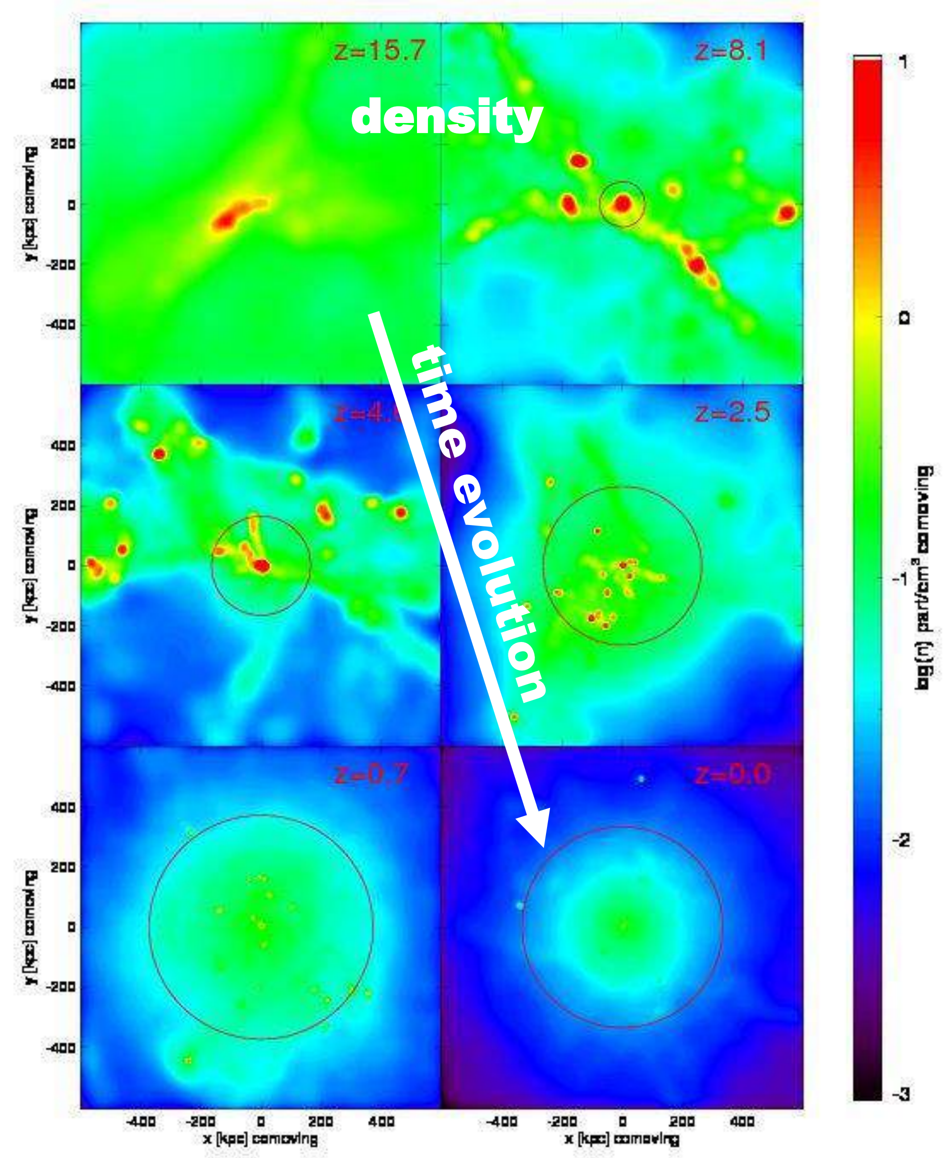
A sub-resolution seeding model based on supernovae

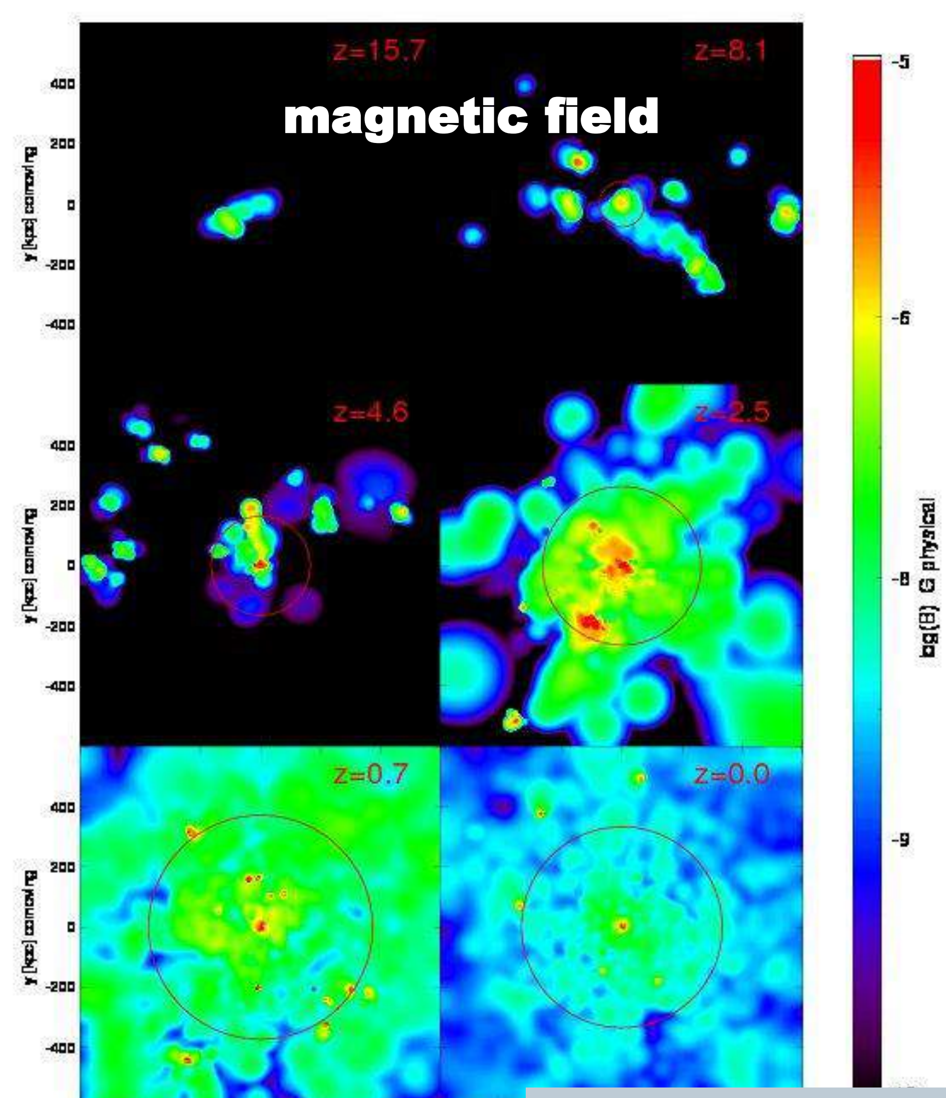
$$\left.\frac{\partial \vec{B}}{\partial t}\right|_{\text{seed}} = \frac{\sqrt{\dot{N}_{\text{SN}}\Delta t}}{\Delta t} B_{SN} \left(\frac{r_{\text{SN}}}{r_{\text{SB}}}\right)^2 \left(\frac{r_{\text{SB}}}{r_{\text{inj}}}\right)^3 e_B$$

- Supernova remnant: $r_{\text{SN}} \approx 5\text{pc}$, $B_{\text{SN}} \approx 10^{-4}\text{G}$
- Bubble: $r_{\text{SB}} \approx 25\text{pc}$
- Injection: $r_{\text{inj}} = h_i$ (e.g. numerical resolution)
- e_B: normalized dipole vector
- $\dot{N}_{\text{SN}}\Delta t < 1 \Rightarrow$ stochastic approach
- Limit diffusion: $L_d = v_D \Delta t$, $v_D = \sqrt{0.5(c_s^2 + v_a^2)}$
- $\eta = 10^{27}\text{cm}^2\text{s}^{-1}$

Beck et al. 2013

Exploring a galactic halo forming

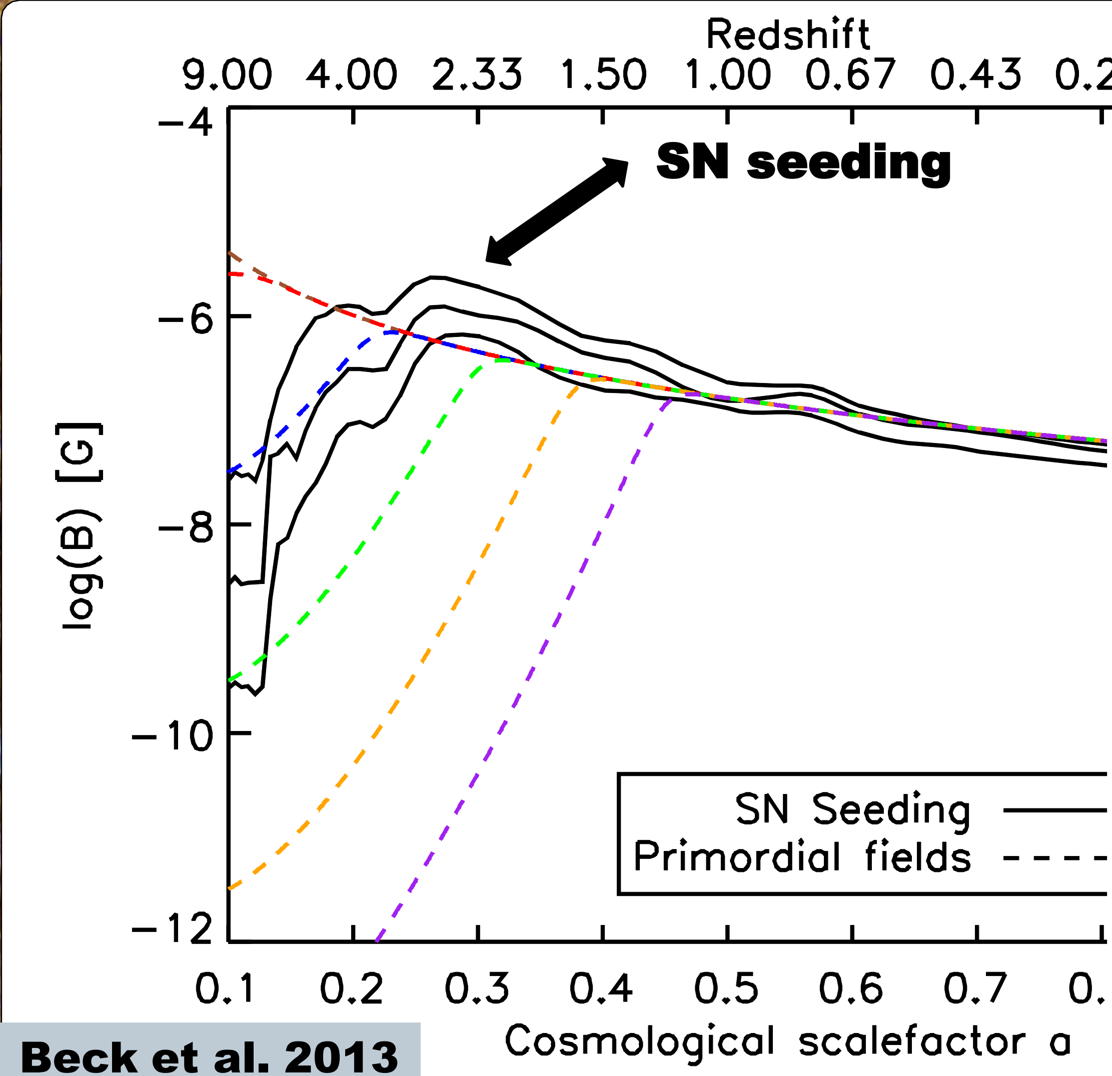


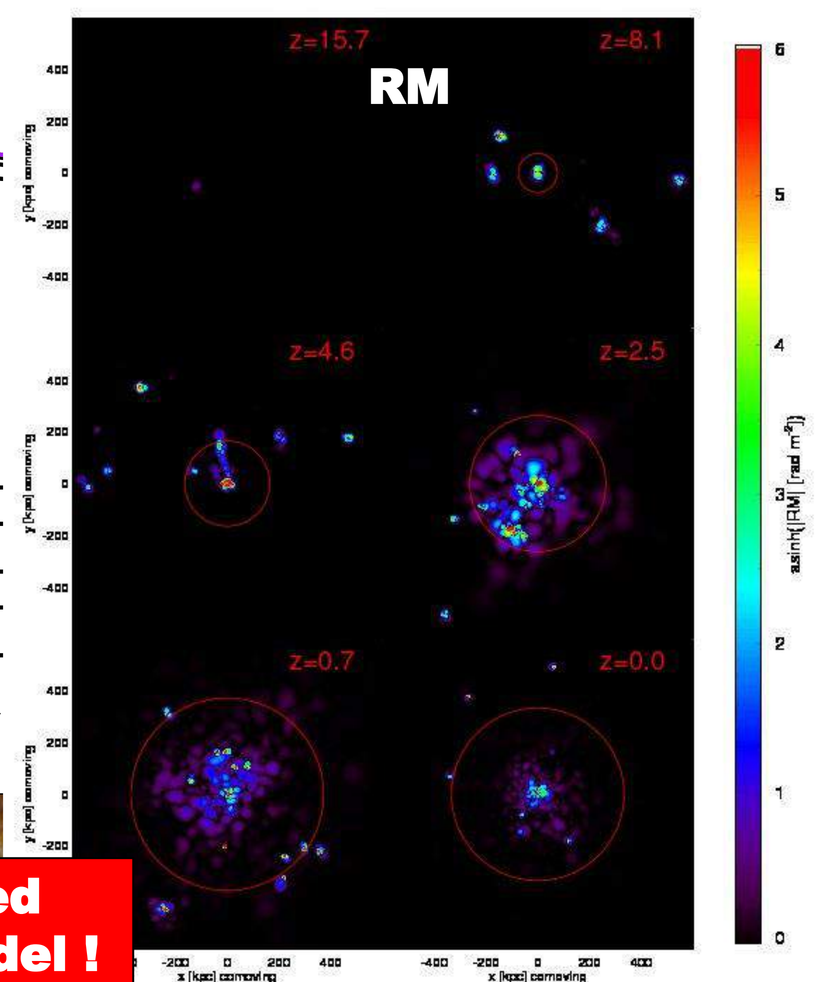


Beck et al. 2013

Magnetic fields build up quiet early in proto-galactic halo

Exploring a galactic halo forming

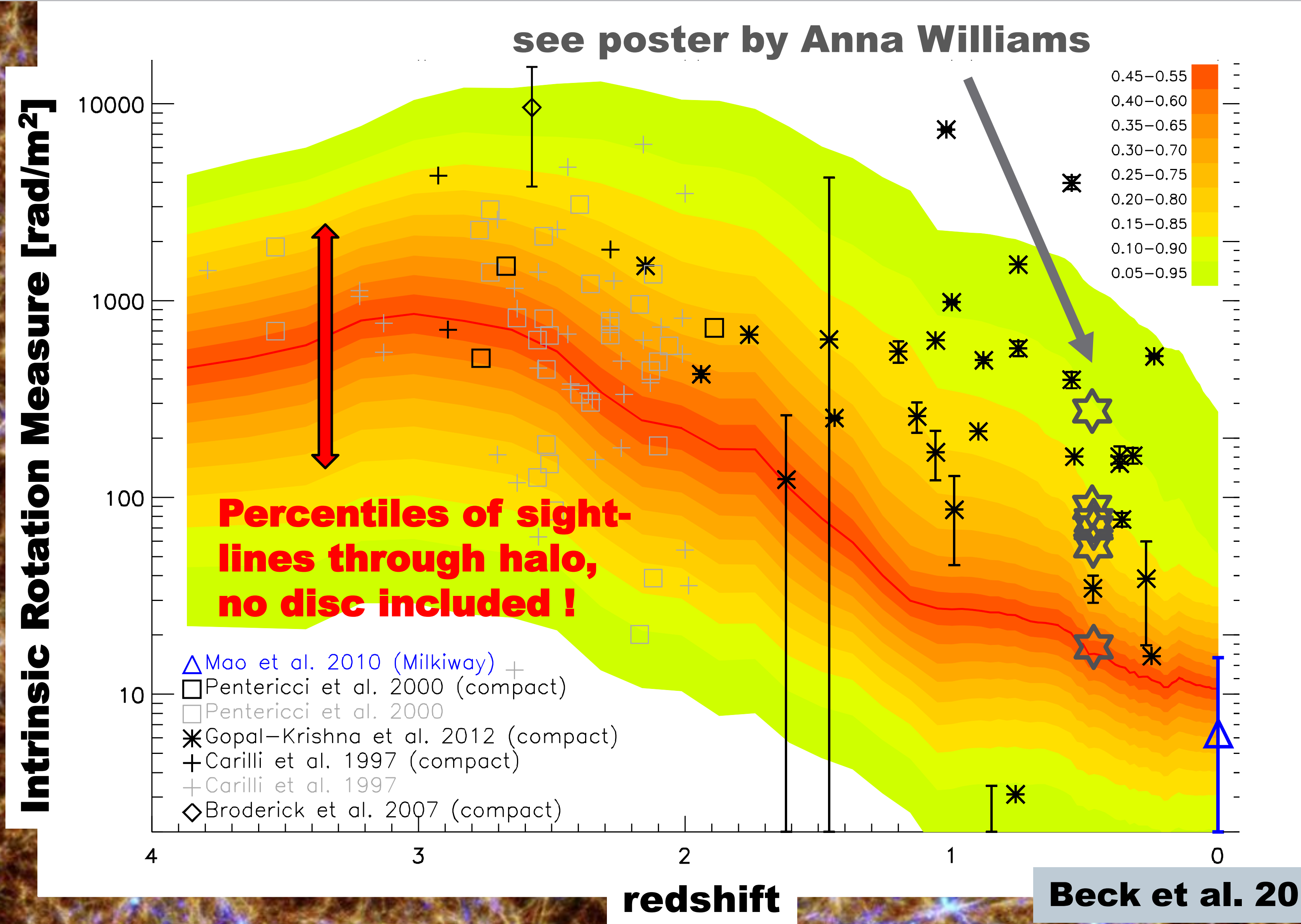




Beck et al. 2013

Results do not strongly depend on detailed parameter choices of the SN seeding model !

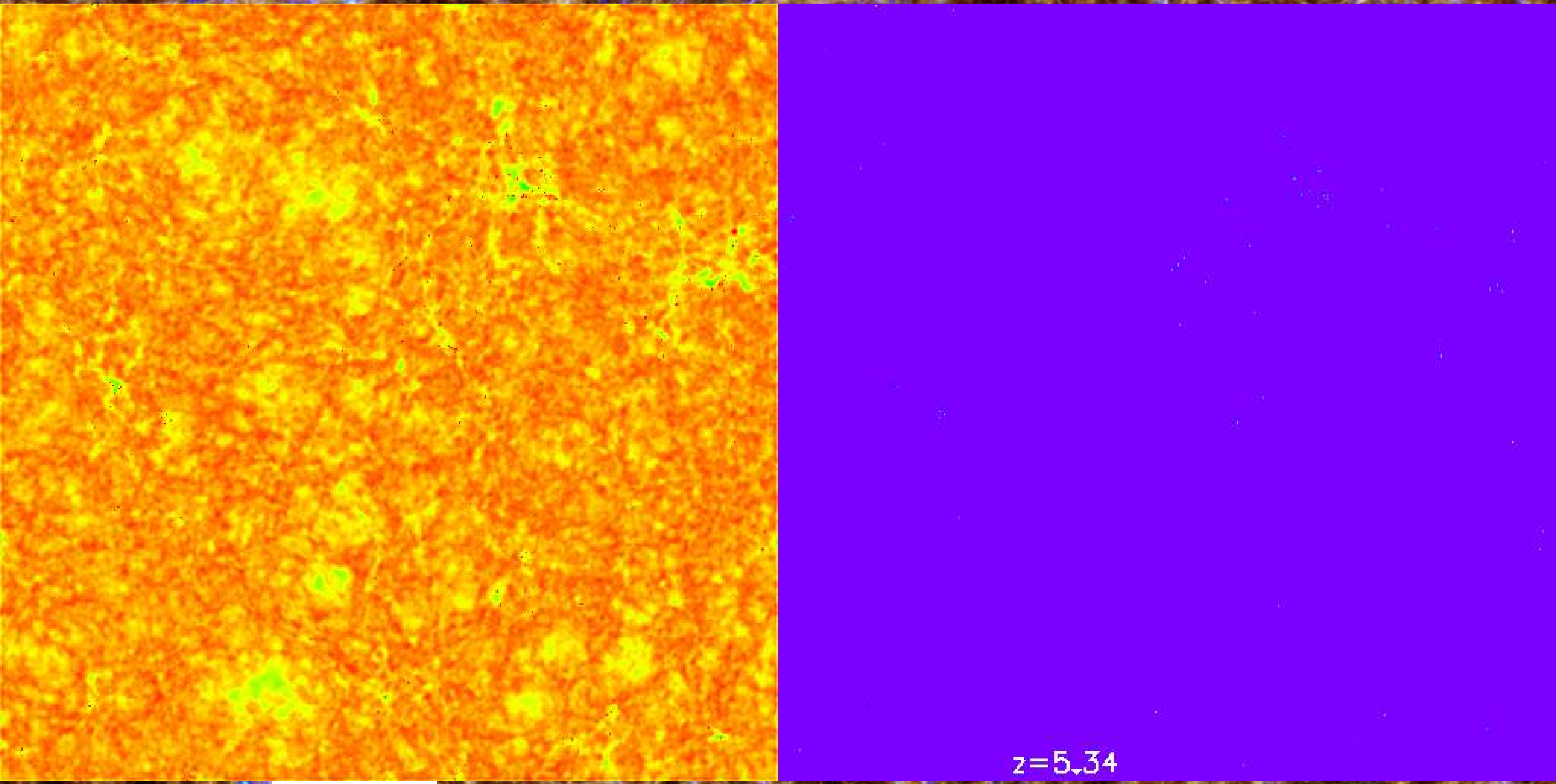
Exploring a galactic halo forming



Beck et al. 2013

Evolution of intrinsic RM of the SN seeding model vs Observations !

Applying to a cosmological volume

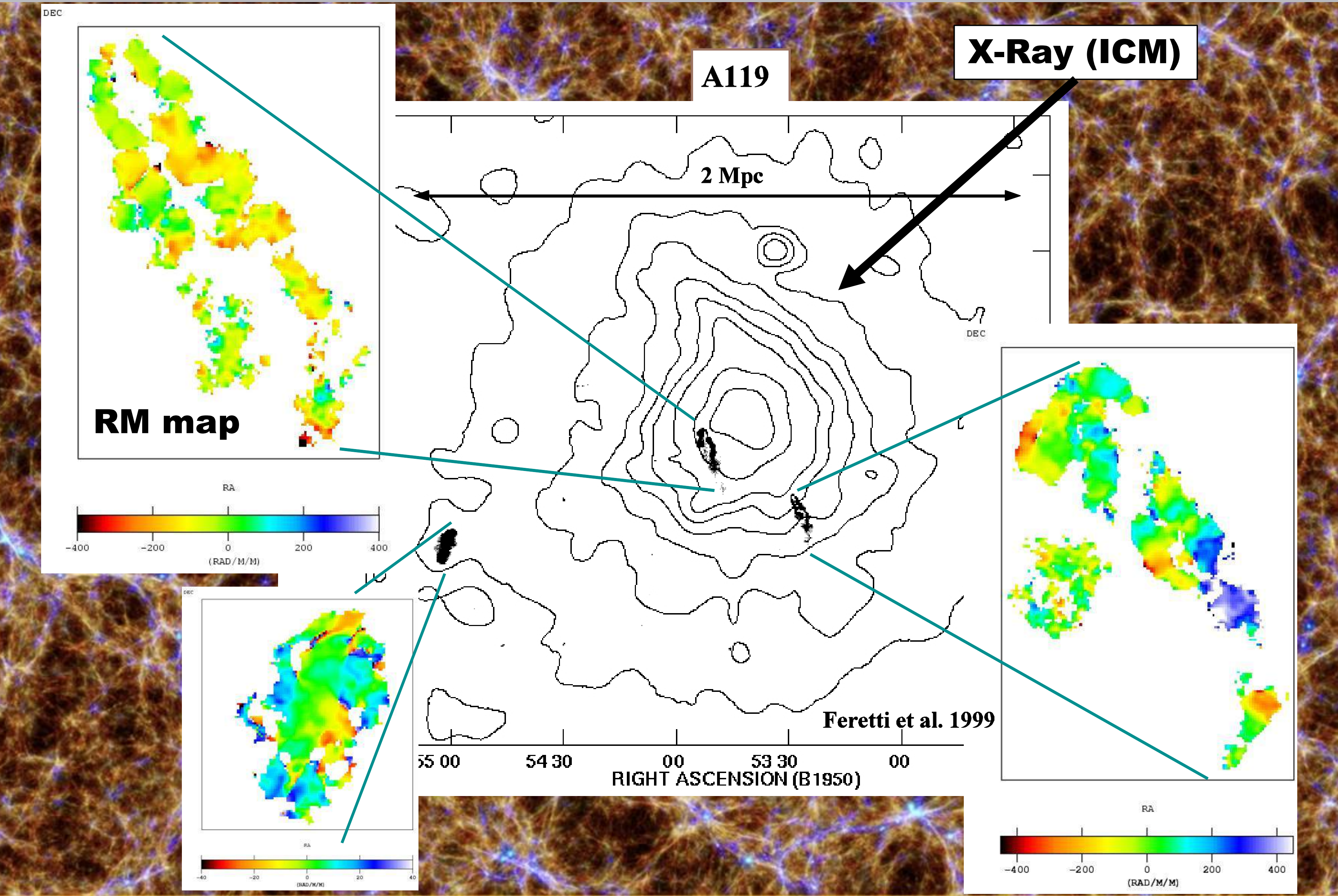


density

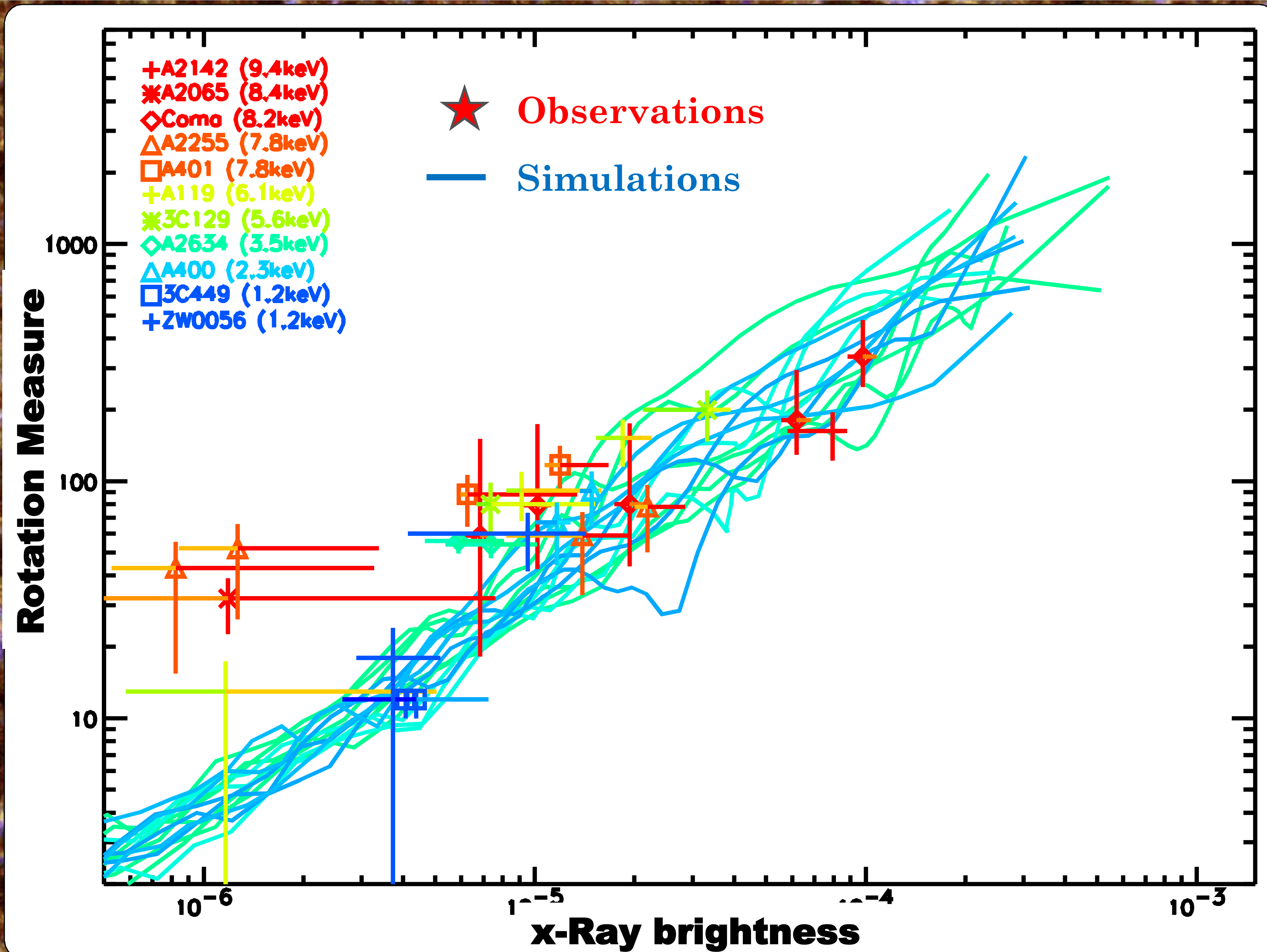
magnetic field

Box3/hr (128 Mpc/h) of the Magneticum Pathfinder set.

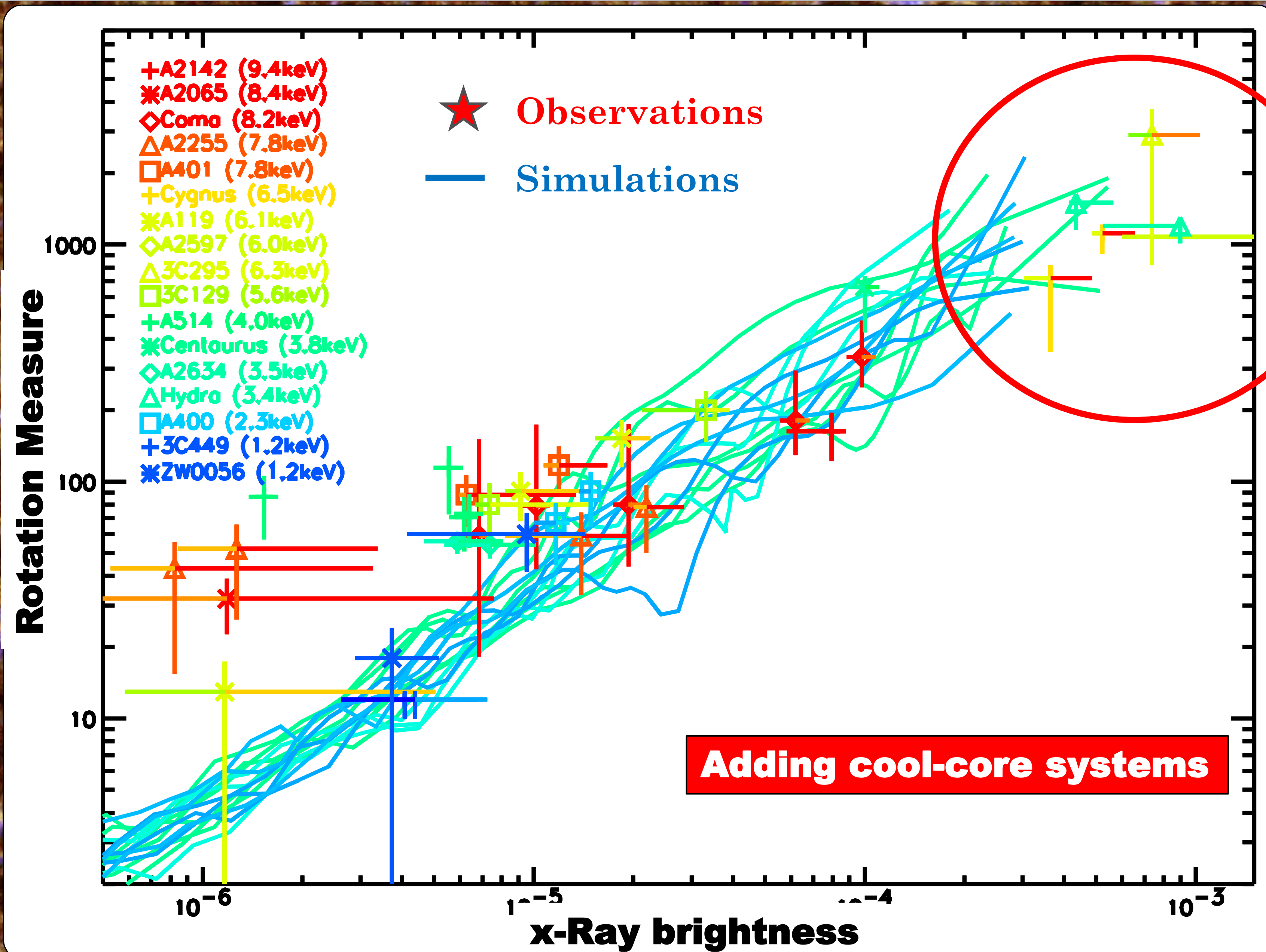
Rotation Measure in Clusters (I)



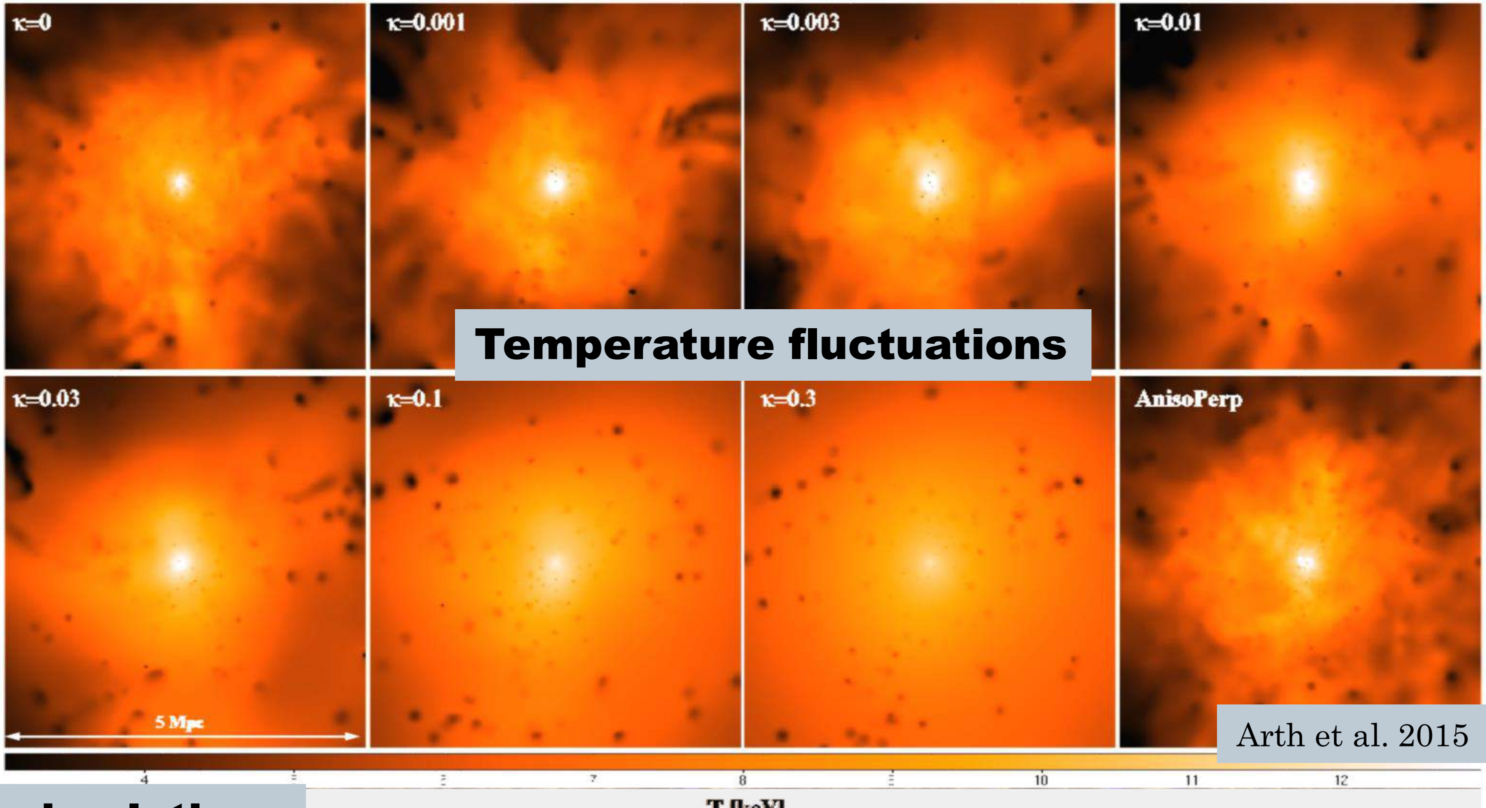
Rotation Measure in Clusters (II)



Rotation Measure in Clusters (III)



Heat transport with Magnetic Fields



Temperature fluctuations

Arth et al. 2015

simulations

$$\kappa \sim \frac{l^2}{\tau} \cdot n k_B \sim D \cdot n k_B$$

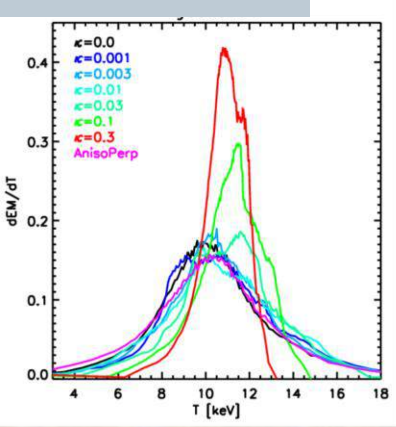
$$D_\perp \approx \frac{v^2}{\omega_g} \approx \frac{k_B T c}{eB}$$

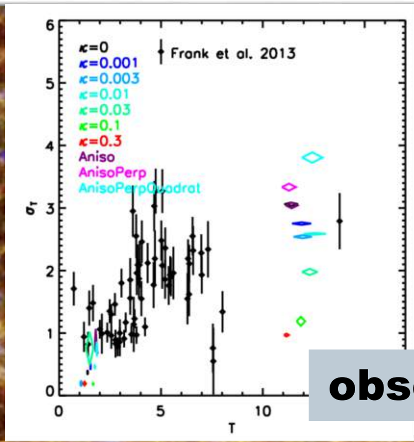
Gyroradius < Mean-free path

$$\frac{D_\perp}{D_\parallel} \approx \frac{1}{\omega_g^2 \tau^2} \propto B^{-2}$$

Gyroradius == Mean-free path

$$\frac{D_\perp}{D_\parallel} \approx \frac{1}{1 + \omega_g^2 \tau^2}$$



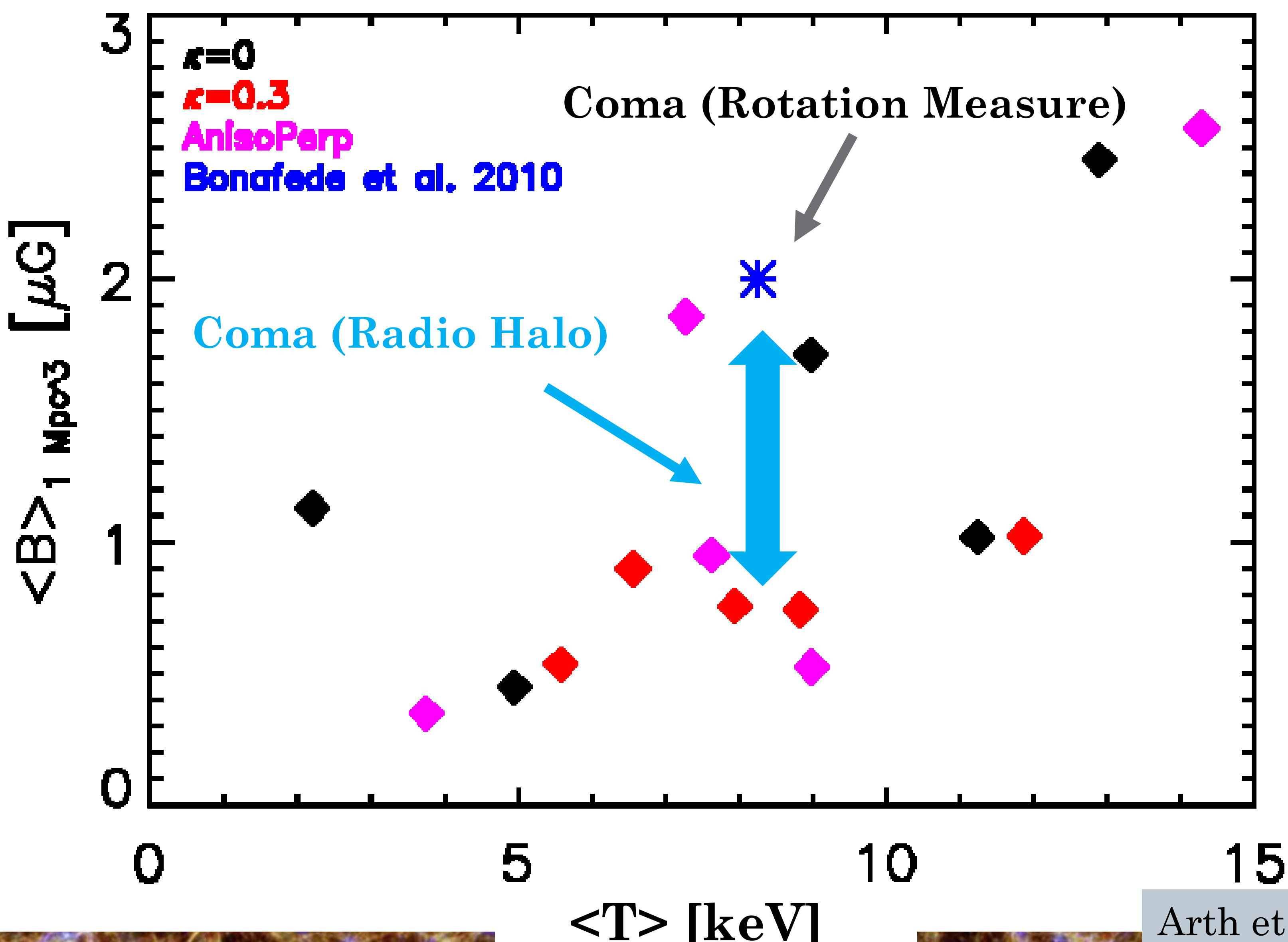


$$\frac{du}{dt} = \frac{1}{\rho} \nabla \cdot \left[\kappa_\parallel \left(\hat{B} \cdot \nabla T \right) \hat{B} + \kappa_\perp \left(\nabla T - \left(\hat{B} \cdot \nabla T \right) \hat{B} \right) \right]$$

observations

Now magnetic fields can be Included to guide treatment of micro physics processes !

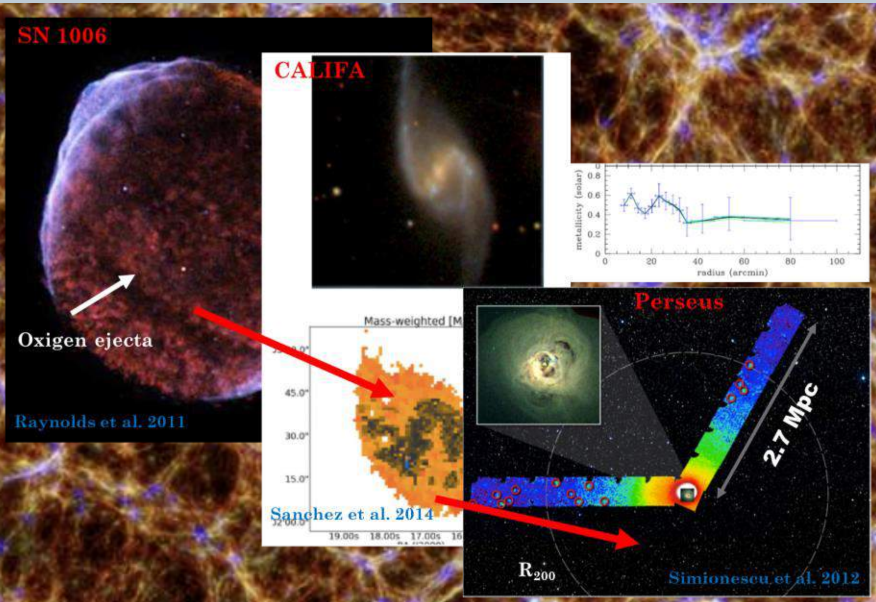
A small sample: final comparison

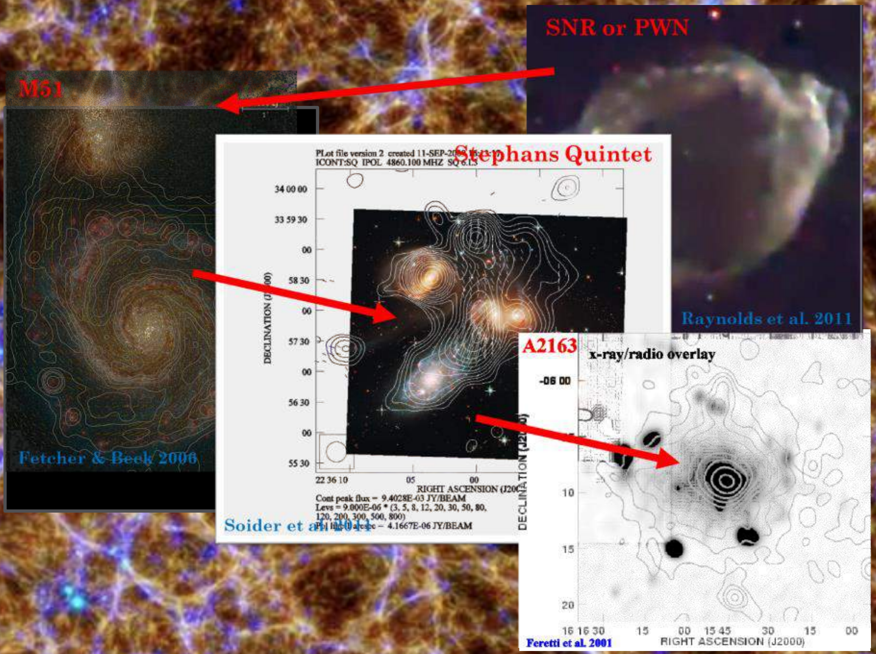


Arth et al. 2015

Conclusions

Metals & Star-formation ⟷ **Magnetic Fields**





Galaxies evolve in complex way, with close interplay between cosmic flows, star-formation and AGNs.

Linking magetic fields to star-formation (SN seeding):

a) **Works on galactic scale => evolution of RM !**
b) **Works on cluster scale, => RM-Lx relation !**
c) **Voids stay free from magnetic fields (but Galactic winds, Cosmic Rays need to be modeled more explicitly) !**
d) **Allows for magnetic field topology dependent transport !**