The Magnetic Universe through vector potential SPMHD

Federico Stasyszyn

Outline

- Astrophysical magnetic fields
- Numerical Methods - SPMHD
- Vector Potentials
- Applications
  - Isolated Galaxies
  - Galaxy Clusters
  - Accretion Discs
- Conclutions

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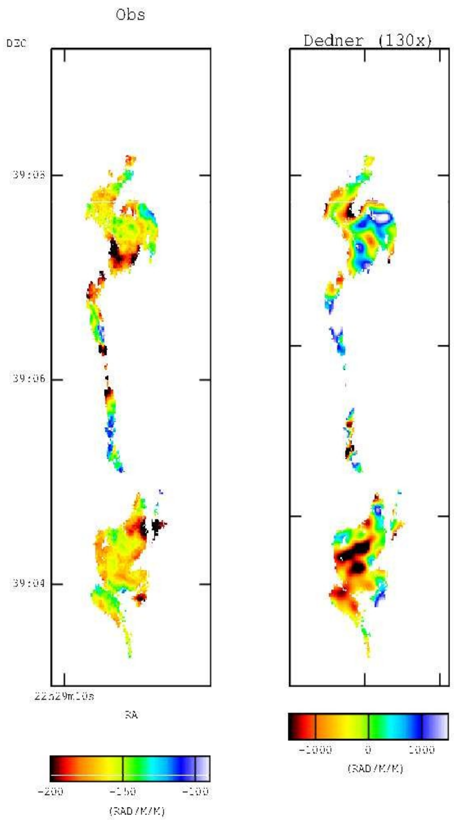
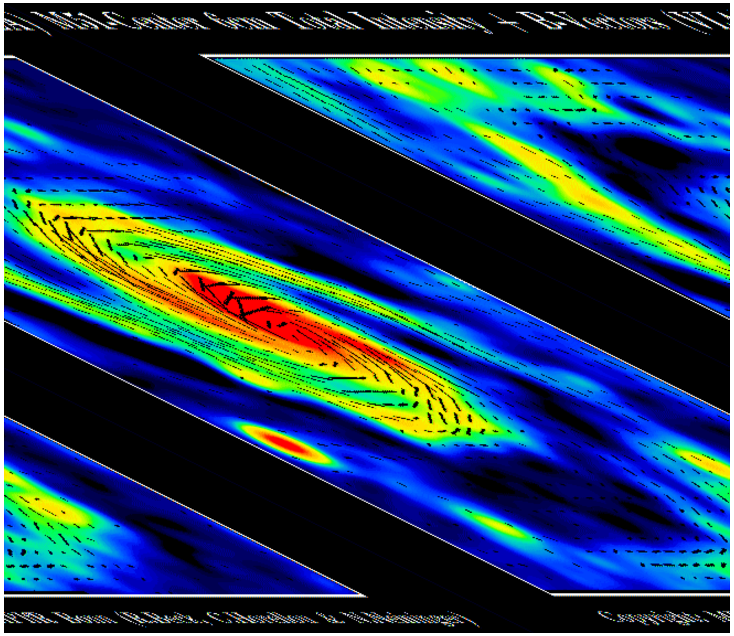
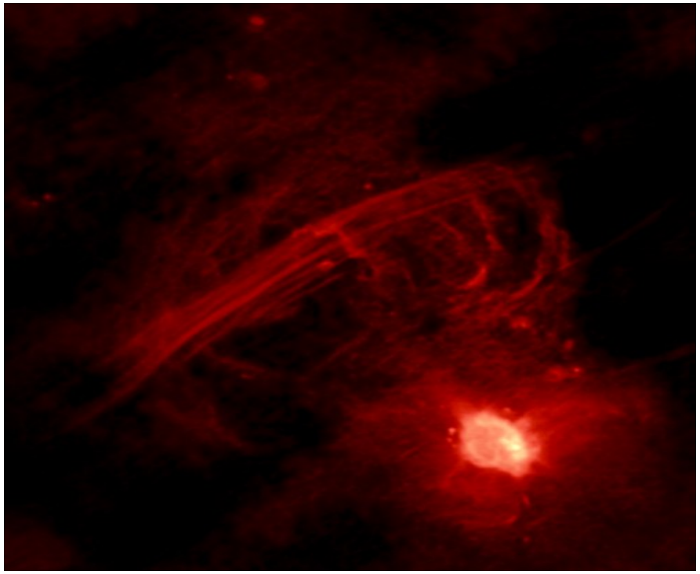
The magnetic Universe



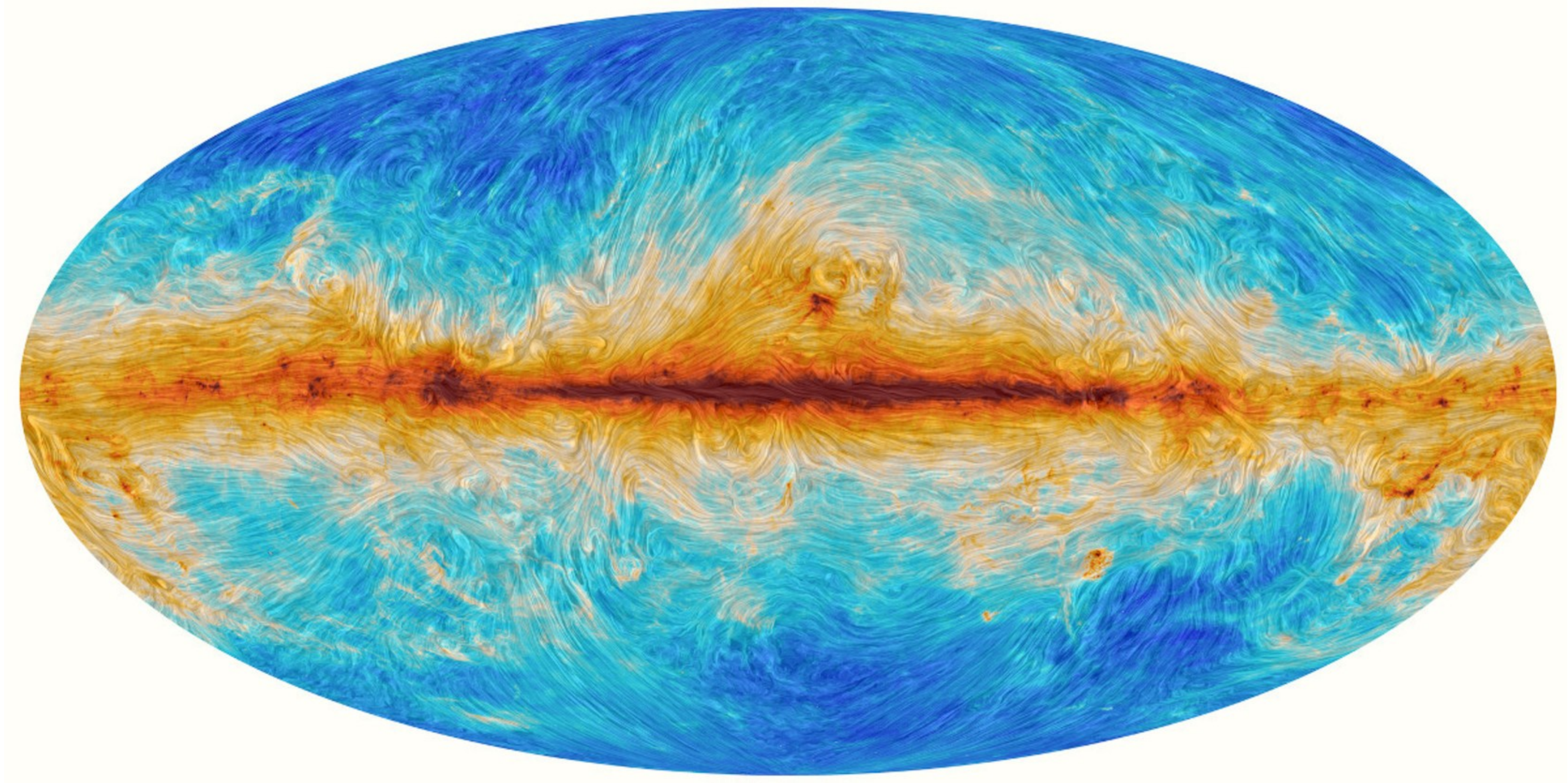
3C449
(Feretti et al 1999)





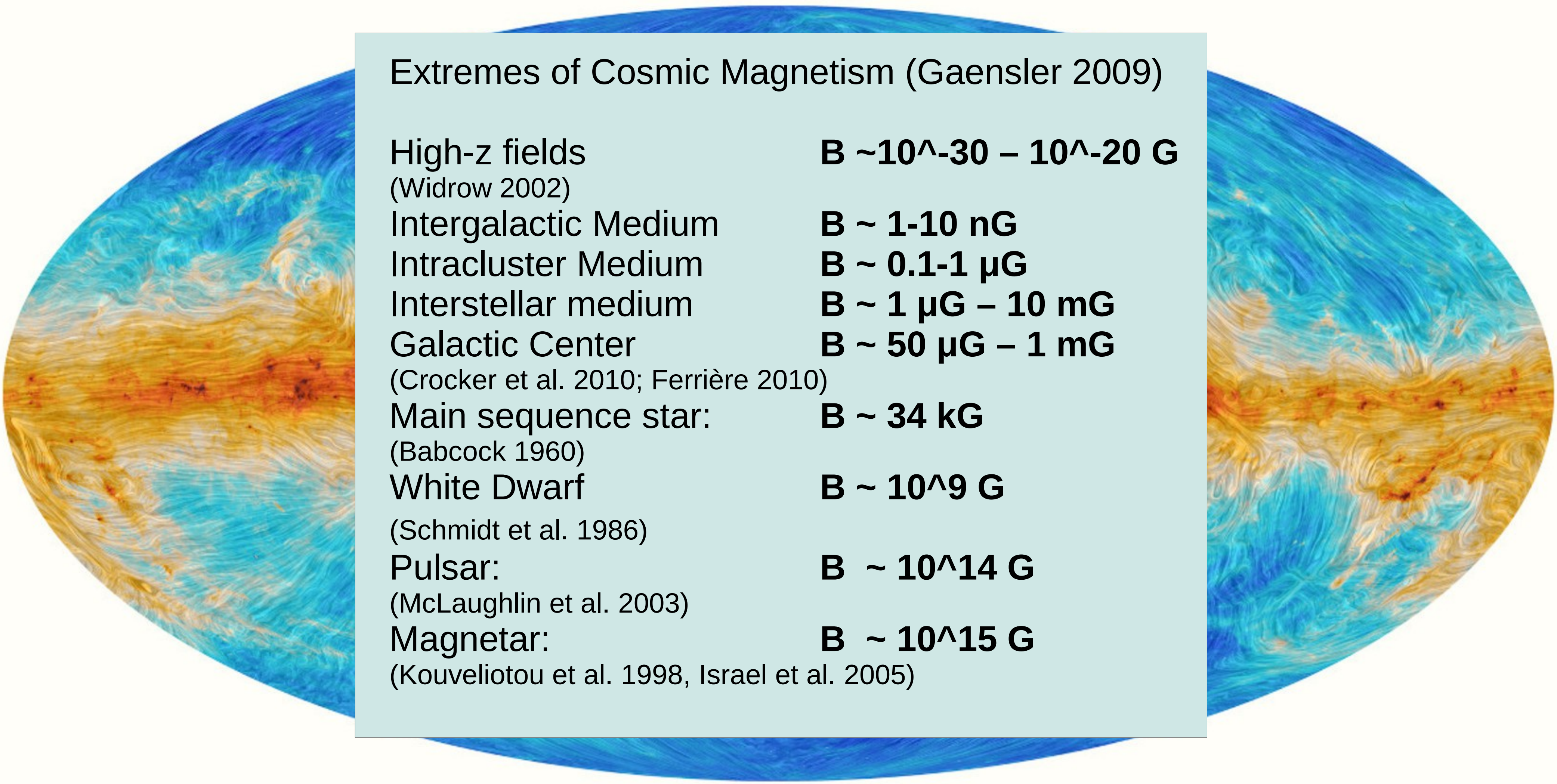
Galactic center
(Crocker 2010)

The magnetic Universe



Via Lactea
ESA & Planck (2015)

The magnetic Universe



Extremes of Cosmic Magnetism (Gaensler 2009)

High-z fields (Widrow 2002)	**B ~10^-30 – 10^-20 G**
Intergalactic Medium	**B ~ 1-10 nG**
Intracluster Medium	**B ~ 0.1-1 μG**
Interstellar medium	**B ~ 1 μG – 10 mG**
Galactic Center (Crocker et al. 2010; Ferrière 2010)	**B ~ 50 μG – 1 mG**
Main sequence star: (Babcock 1960)	**B ~ 34 kG**
White Dwarf (Schmidt et al. 1986)	**B ~ 10^9 G**
Pulsar: (McLaughlin et al. 2003)	**B ~ 10^14 G**
Magnetar: (Kouveliotou et al. 1998, Israel et al. 2005)	**B ~ 10^15 G**

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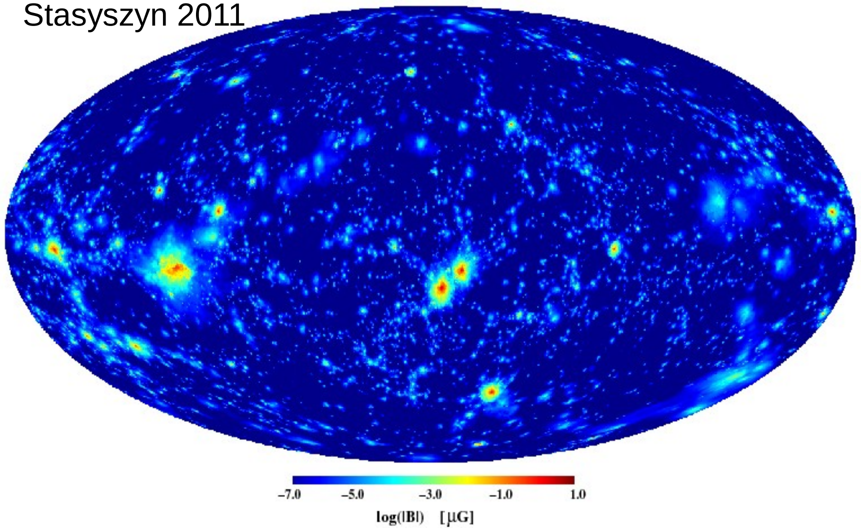
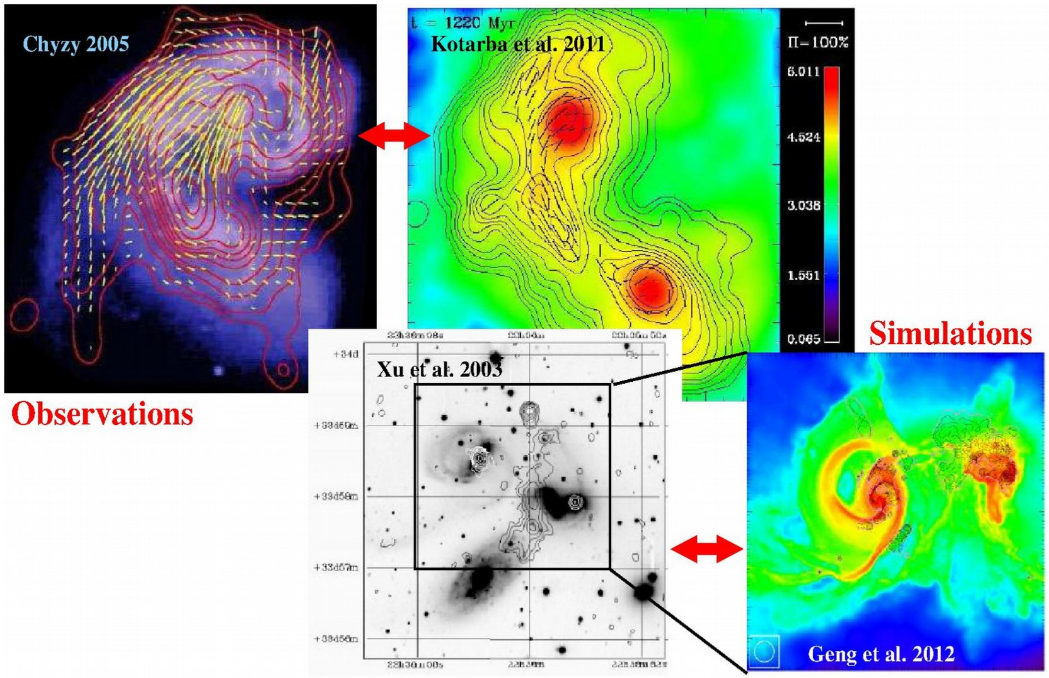
ESA & Planck (2015)

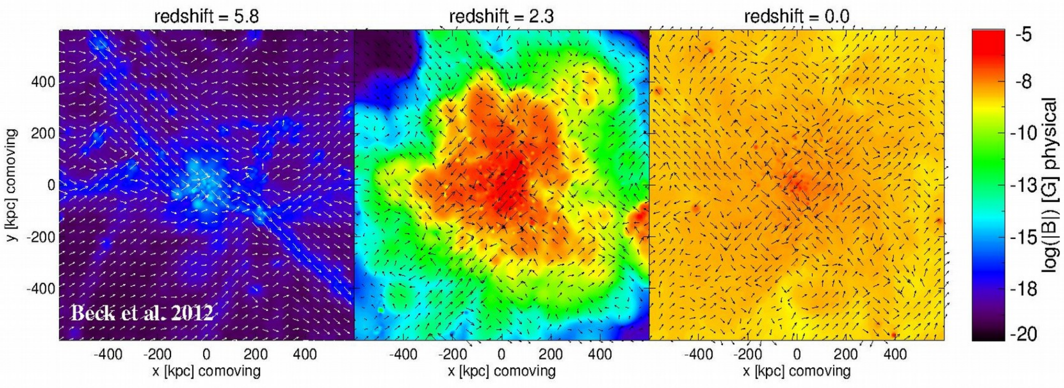
Numerical Methods

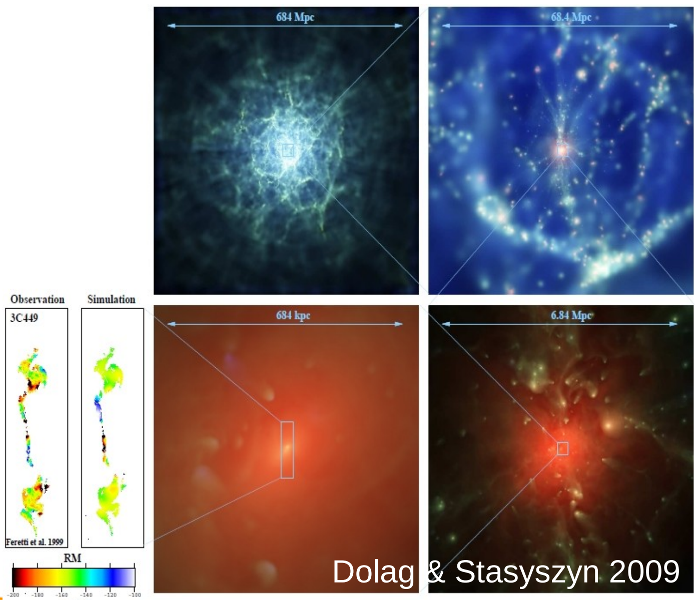
Outcome from previous works

Stasyszyn 2011







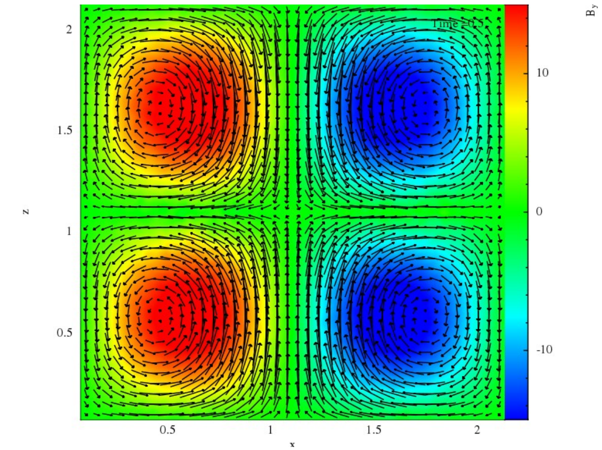


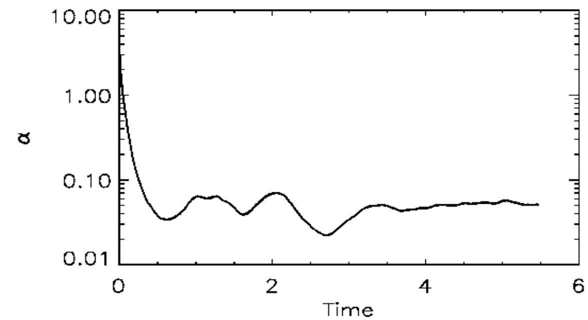
Dolag & Stasyszyn 2009

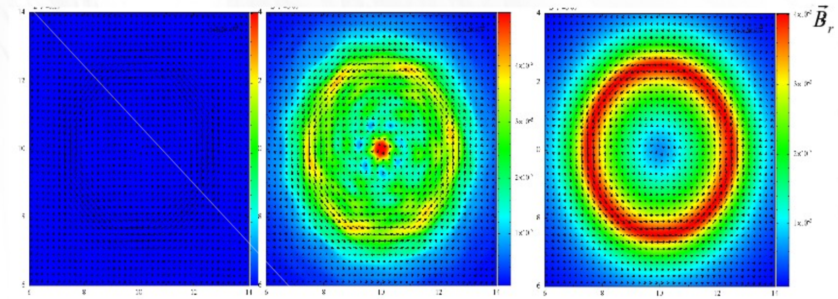
LSS → Galaxy Clusters → Galaxies

So far so good..

- So we start to study Galactic Dynamos, and the solutions I found are not stable
- We sisolated the problem to the induction equation, or at least the way we solve it.
- So we have to find another way.....







Advection | NonPredicted | Standard

Error(Br/Bphi): 0.0001% | Error(Br/Bphi): 0.005% | Error(Br/Bphi): 0.1%

Vector potentials

-Is a clean method by construction and quite easy to implement… or so...

$$\vec{B} = \nabla \times \vec{A} \qquad \frac{\delta \vec{A}}{\delta t} = \vec{v} \times \vec{B}$$

-Price D. (2010) deeply tried to implement it in SPH. Concluding that, if stable in 2D, untable in 3D.

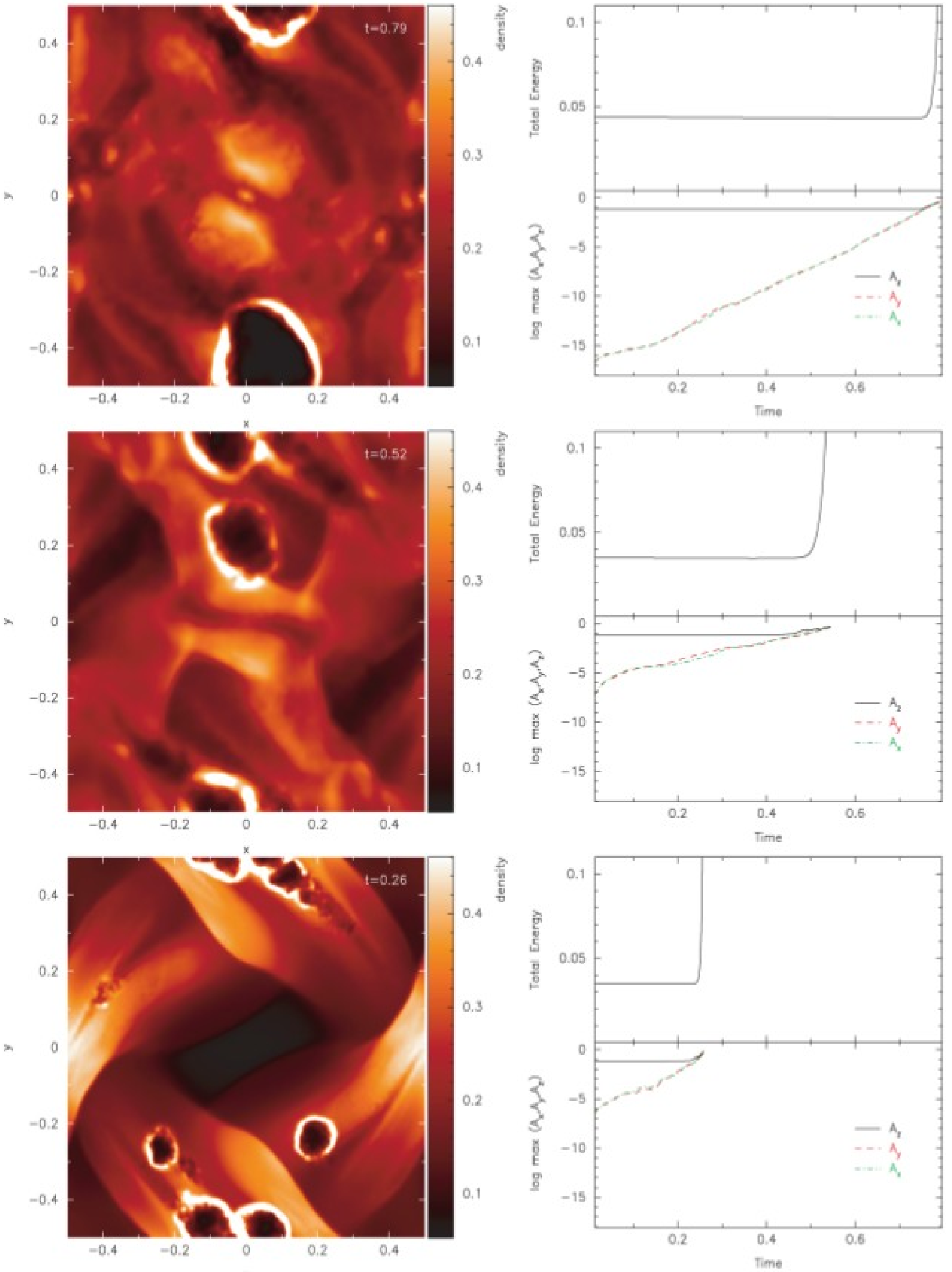


Figure 8. Results of the Orszag–Tang vortex evolution in 3D, using 128 × 128 × 16 particles (top, using our NDSPMHD code) 100 × 100 × 10 particles (middle, using PHANTOM) and 200 × 200 × 20 particles (bottom, using PHANTOM). Here we have adopted the hybrid vector potential formulation that is stable to clumping instabilities and gives good results in 2D. In 3D, we observe the exponential growth of the A_x and A_y components of the vector potential (right-hand panel, showing the maximum value as a function of time, alongside the evolution of total energy). When these components grow to the same order of magnitude as A_z, large, low-density voids appear in the solution (left-hand panels) together with an exponential divergence in total energy (right-hand panels).

Gauge Conservation

- Full set of Equations

$$\vec{B} = \nabla \times \vec{A}$$

$$\frac{\delta \vec{A}}{\delta t} = \vec{v} \times \vec{B} + \nabla \phi$$

$$\frac{d \phi}{d t} = -\left(c_h^2 \nabla \cdot \vec{A} + c_h \frac{\phi}{h}\right)$$

Pseudo-Lorenz Gauge

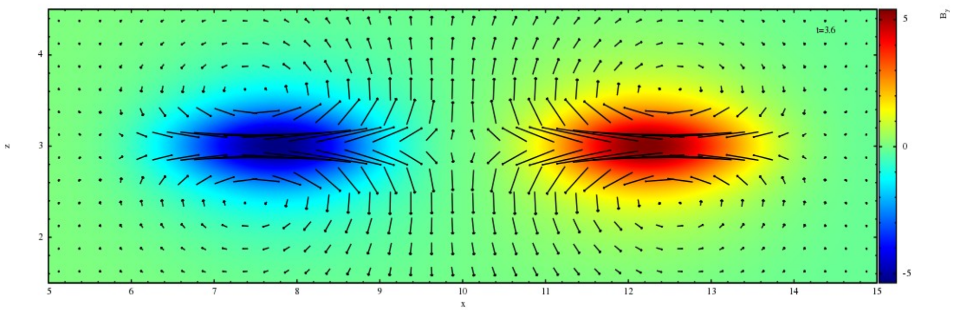
- Extras:
  - No change for the Lorentz force implementation
  - Trivial physical diffusion:

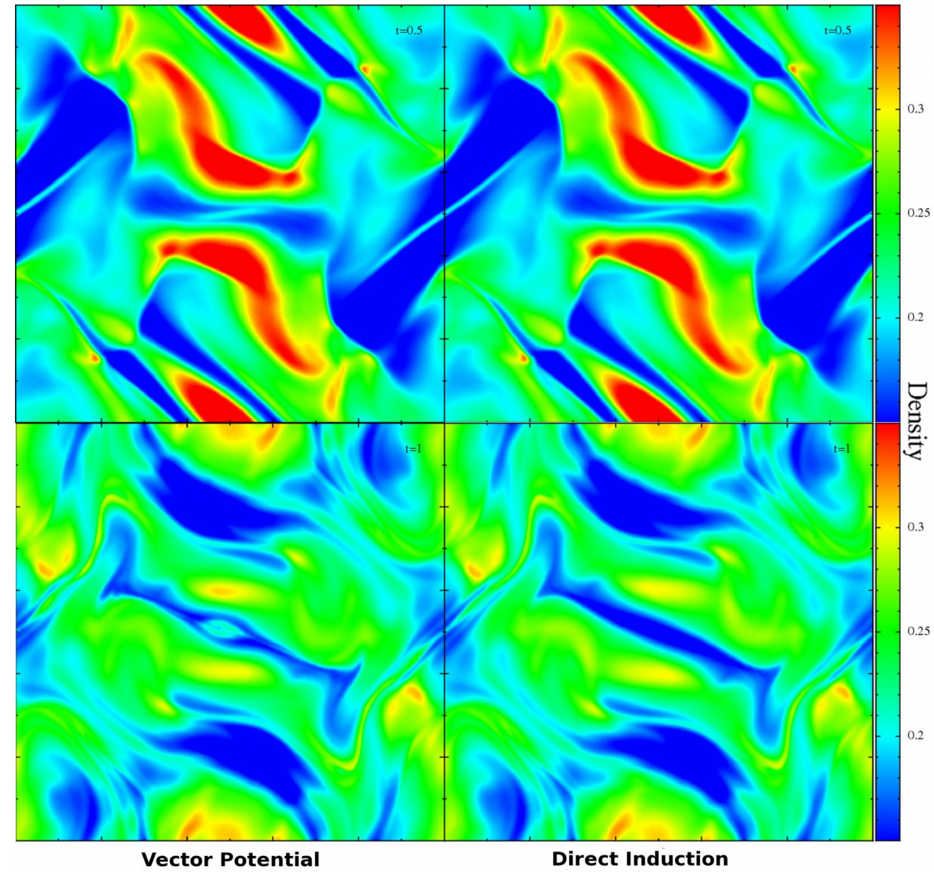
$$\frac{\delta \vec{A}}{\delta t} = \eta \nabla^2 \vec{A}$$

It works! (now in 3D!)

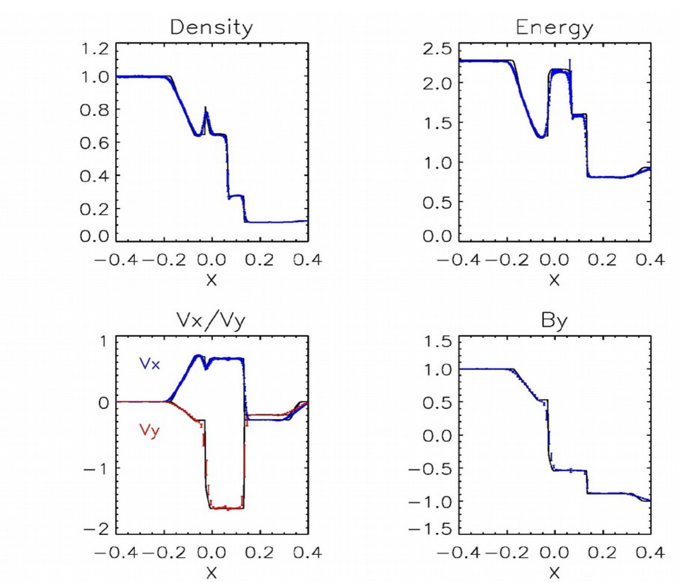
α^2 and α-ω dynamo!

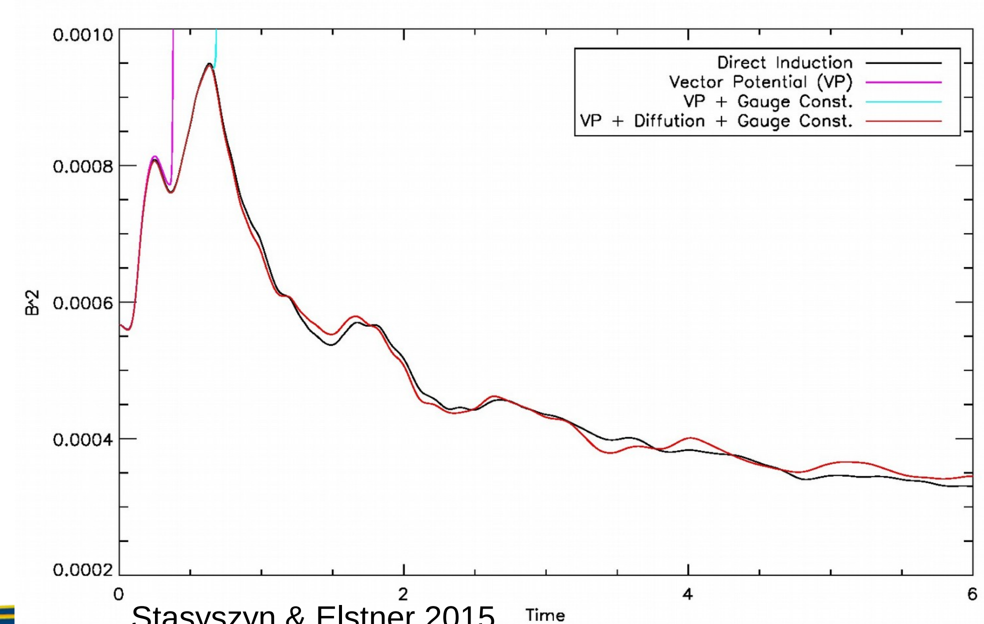
2D tests





Shock Tube tests





Stasyszyn & Elstner 2015

Roberts Flow Dynamo

- Definition:

$$\vec{v}=U_0[\sin(ky)\cos(kx)\hat{x},\sin(kx)\cos(ky)\hat{y},\frac{1}{\sqrt{(2)}}\cos(ky)\cos(kx)\hat{z}]$$

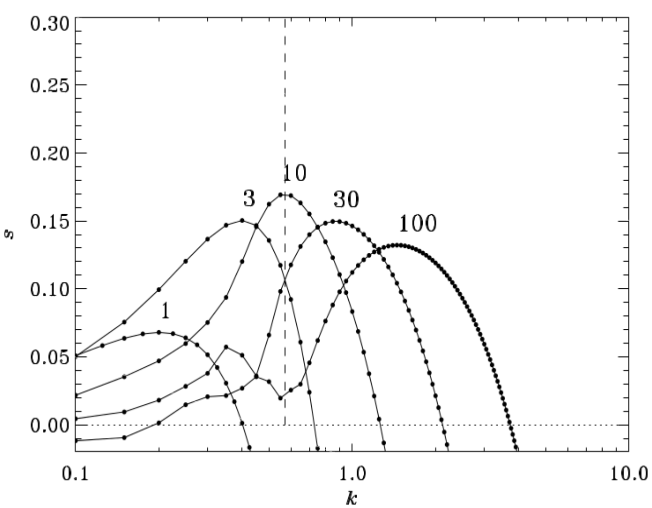
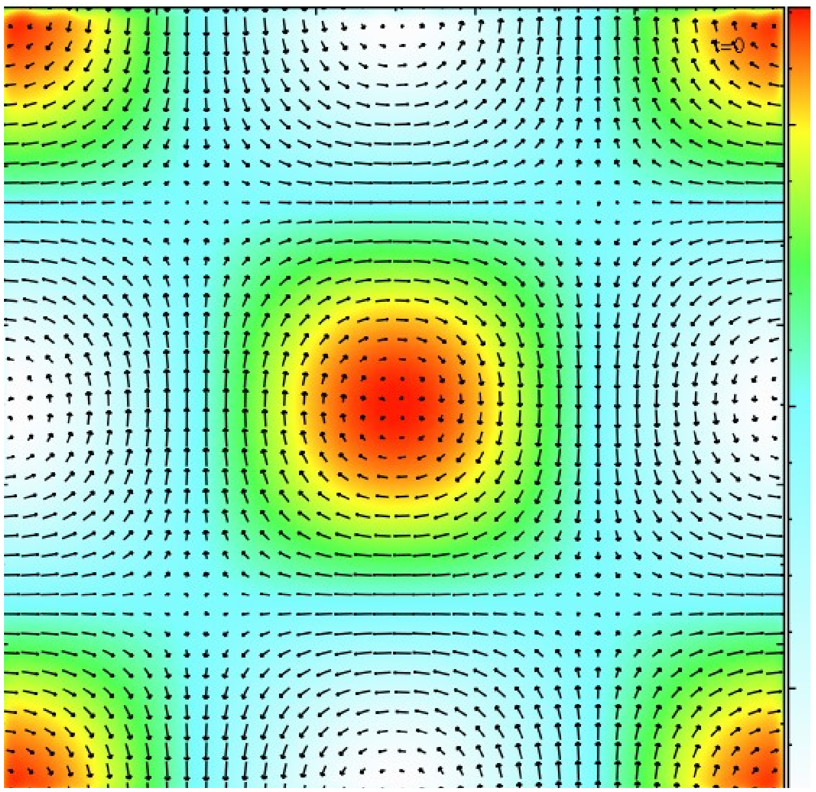


Fig. 2.16 Growth rates of the magnetic energy in the Roberts cell, for sequences of solutions with increasing k and various values of R_m, as labeled near the maxima of the various curves. Growth typically occurs for a restricted range in k, and peaks at a value k_{max} that increases slowly with increasing R_m. Note however how the corresponding maximum growth rate decreases with increasing R_m. The small "dip" left of the main peaks for the high-R_m solutions is a real feature, although here it is not very well resolved in k.

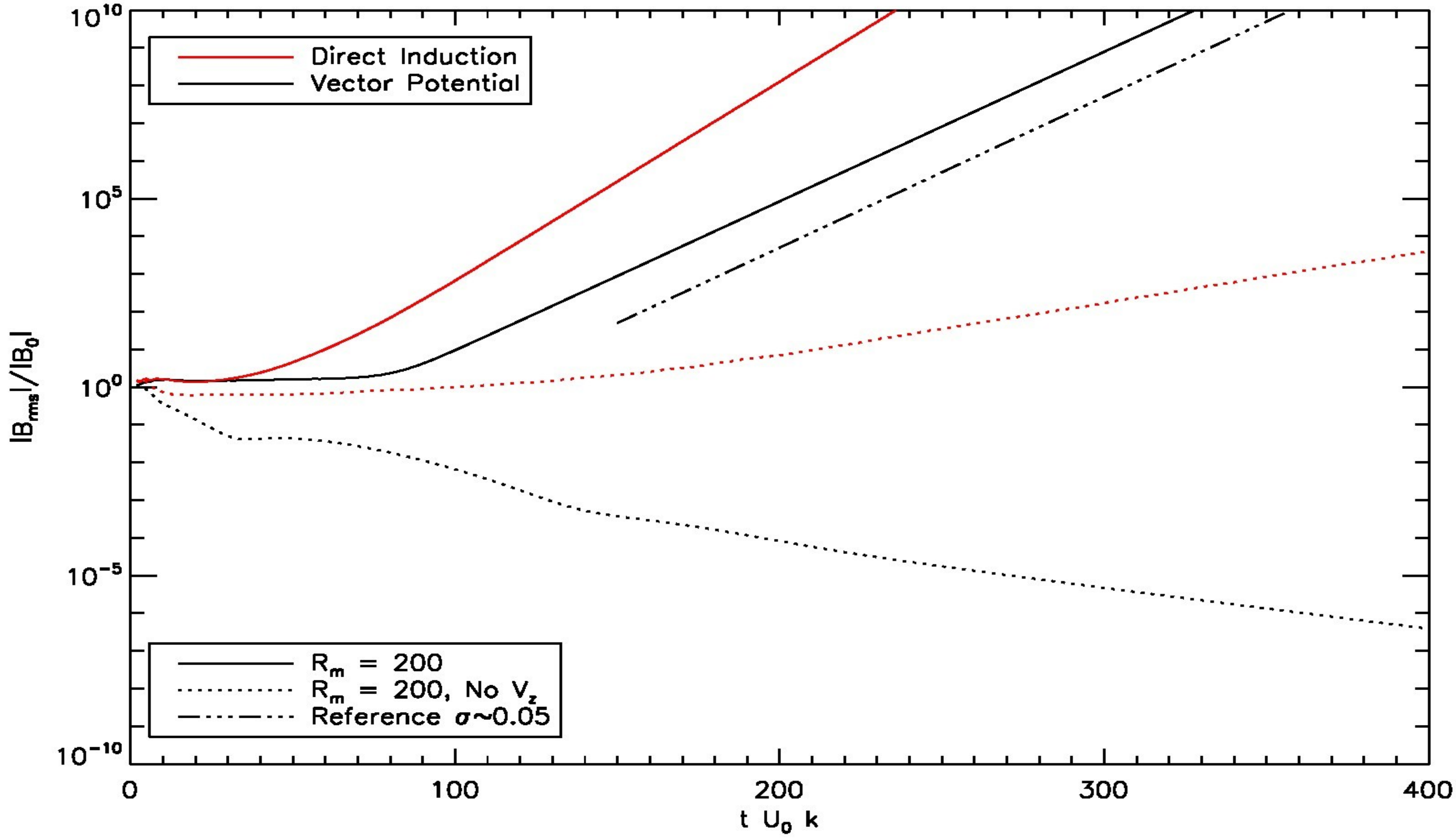
Charboneau (2012)

$$R_m=\frac{U_0}{\eta k}$$

Colors: Vz



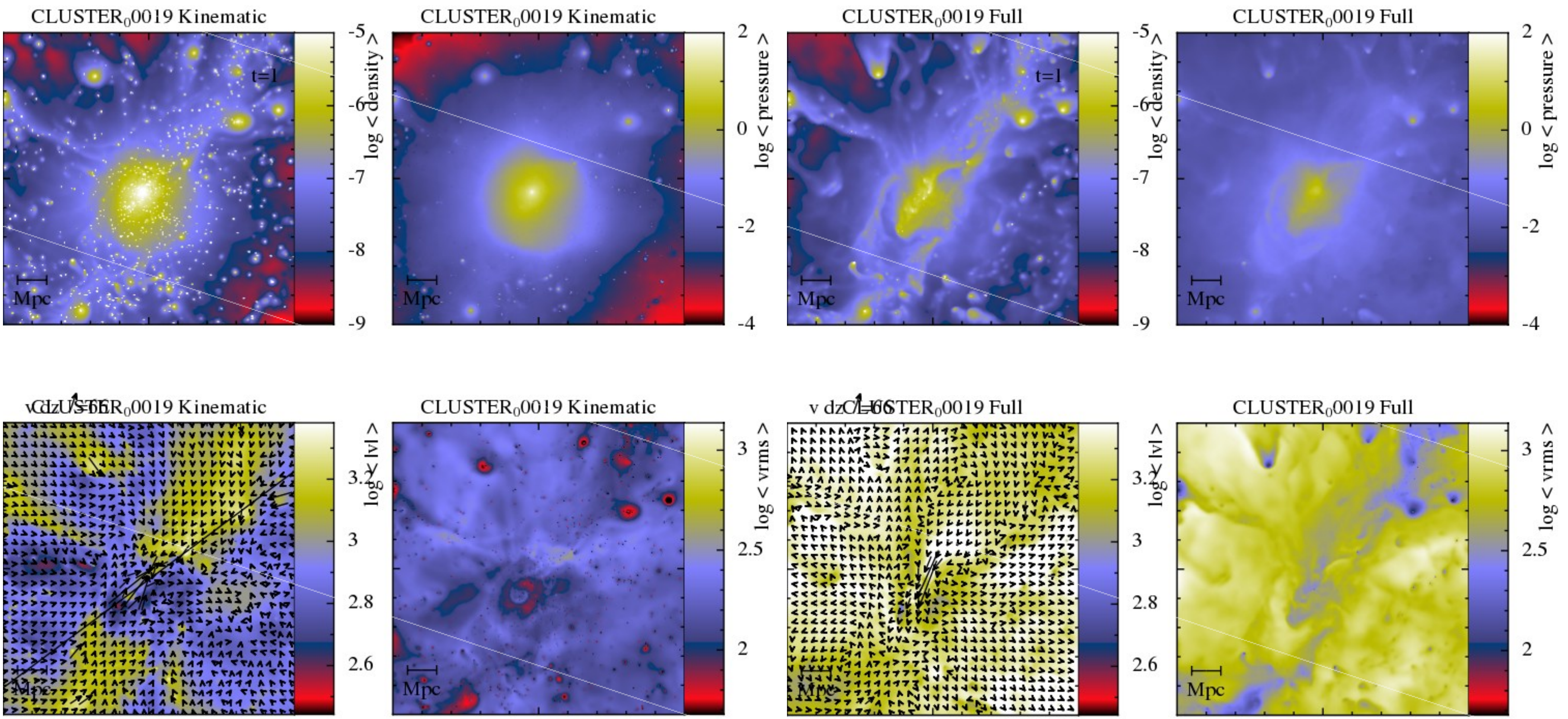
Roberts Flow



Galaxy Clusters

Application

- MUSIC Galaxy Clusters



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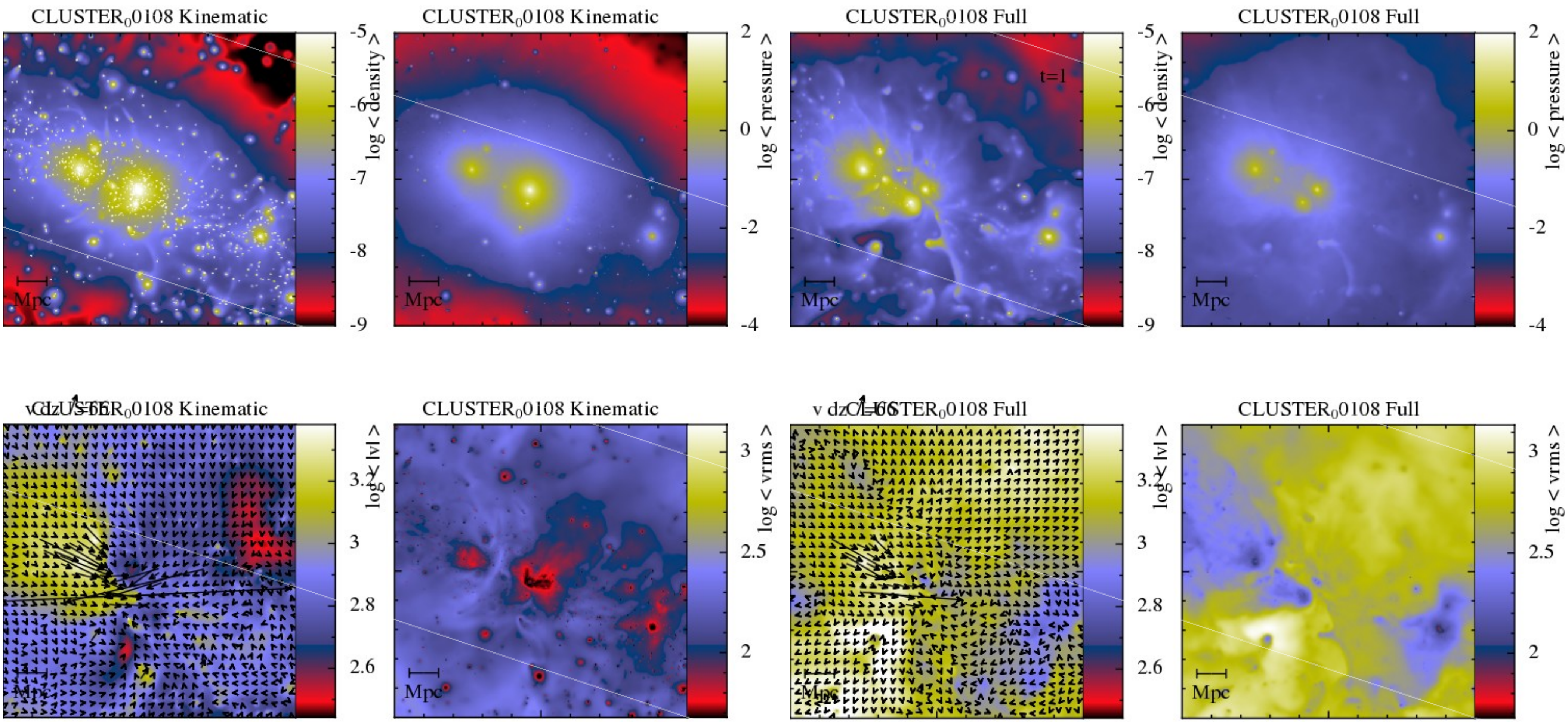

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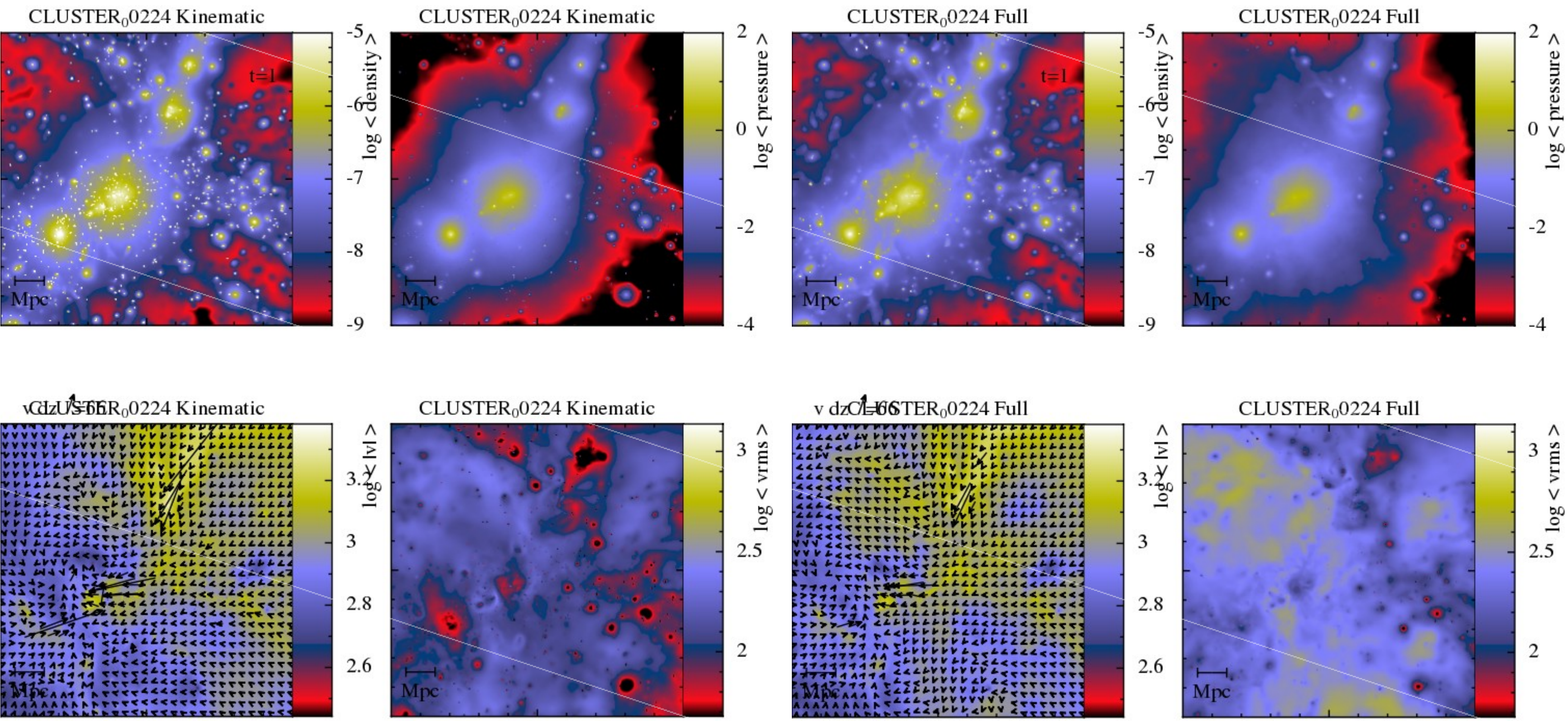
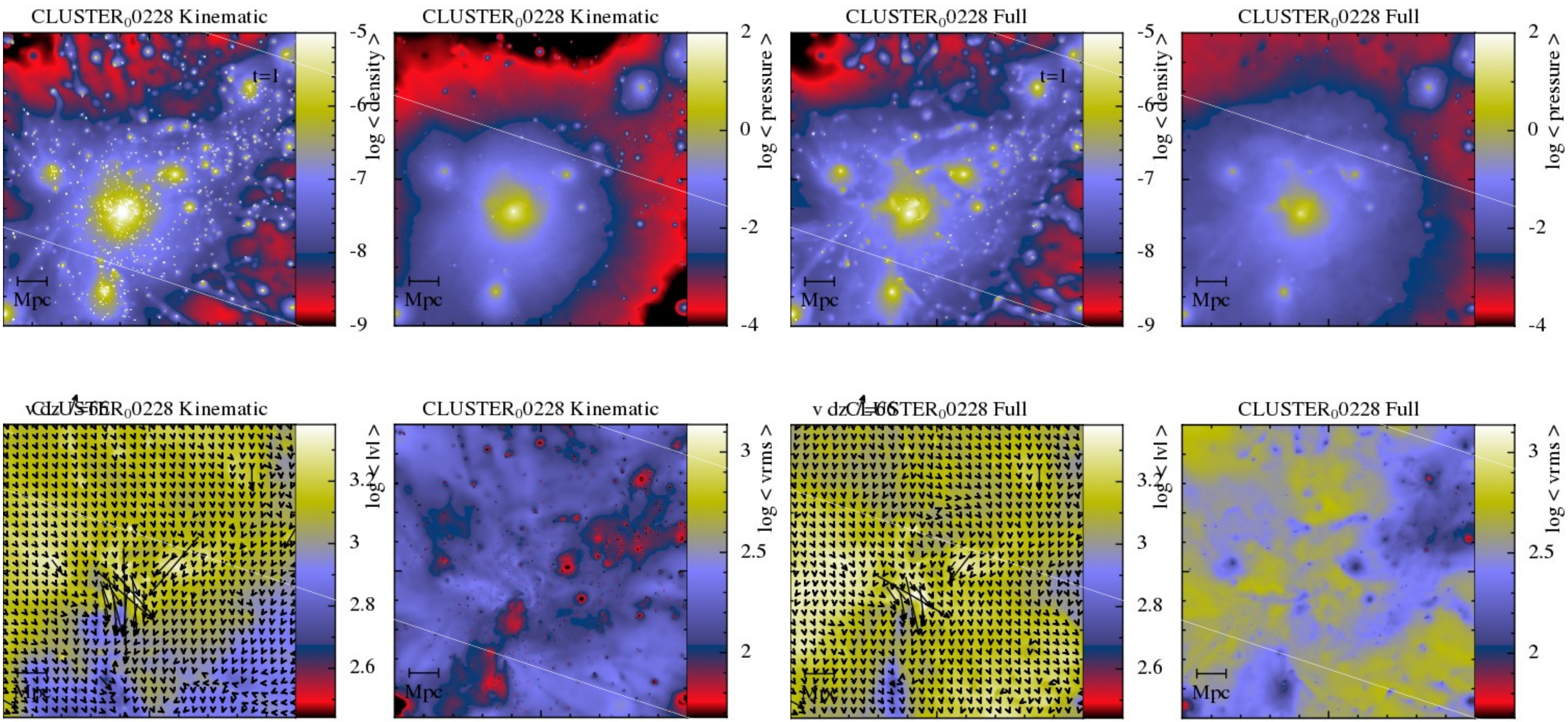


Aplicaciones

- MUSIC Galaxy Clusters



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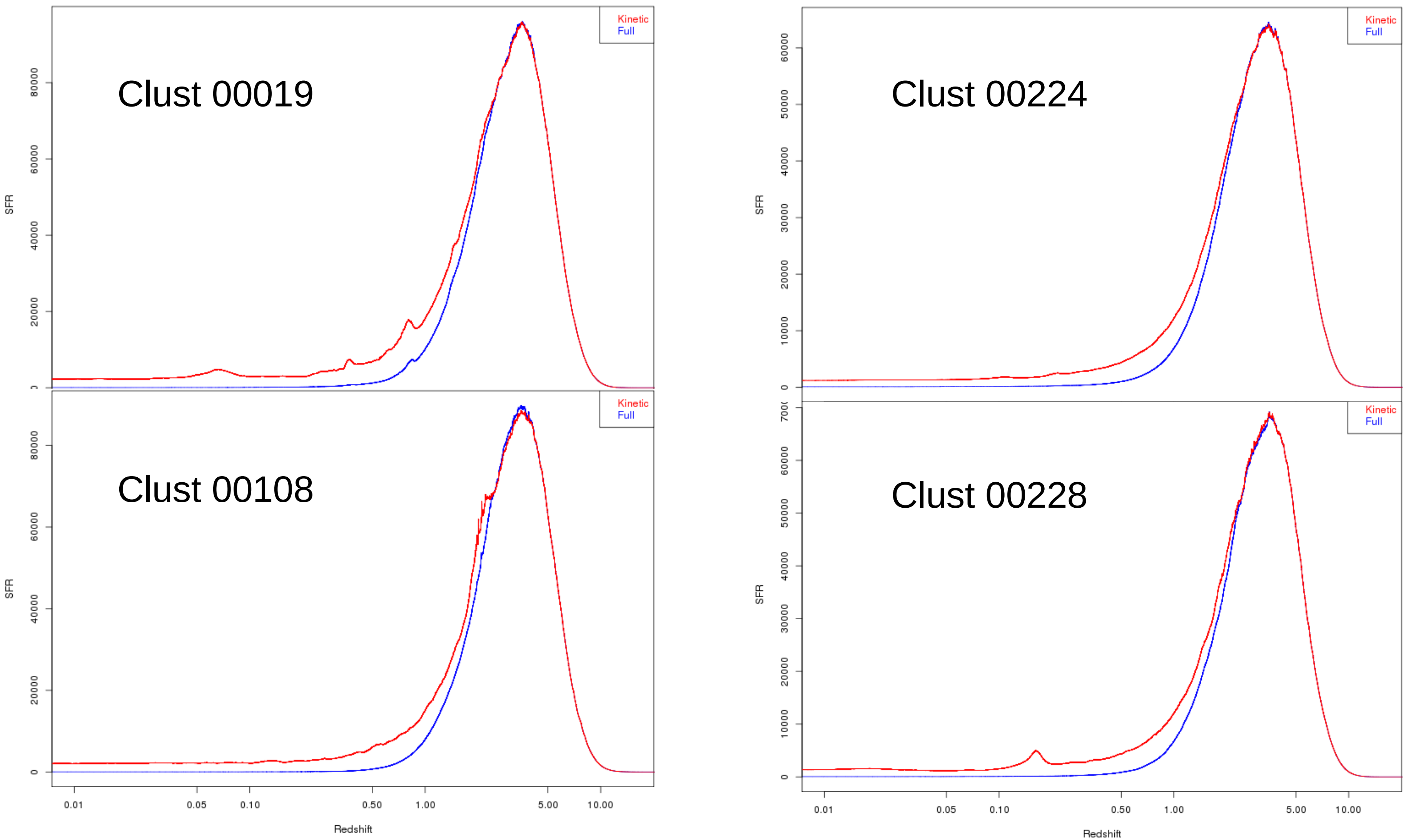

Take home….

- Carefull! Numerical errors can be miss interpreted as Dynamo action, and DivB cleaning does not help!
- Vector potential implementations, overcomes that issues with a clean magnetic field evolution by construction (first Dynamo Simulated with SPH).

- Galaxy Clusters (cualitative):
  - For first time there are radiative SPH simulations with SF and MF in a self-consistent way, without DivB related issues.
  - The inclution of MF modifies the Star formation history.
  - At the same time, the structure formation, define the evolution of MF and therefore the gas dynamics.

Thank You !