SPH simulations of Magnetic fields in Astrophysics

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Motivation: How we observe them

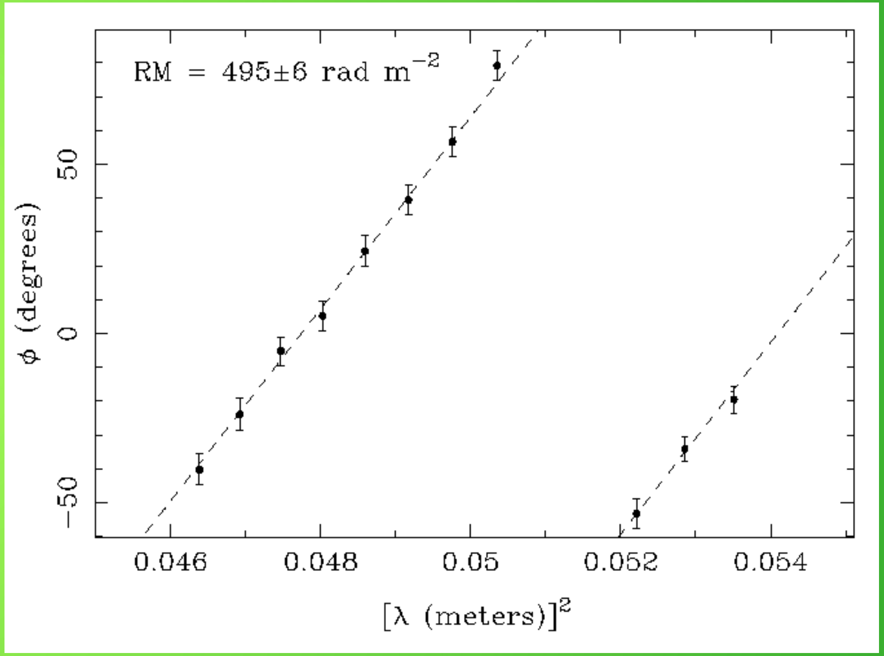
- Optical dust polarization
- Synchrotron emission / polarization
- Infrared dust polarization

$\Big\}\ B_\perp$

- Zeeman splitting $B_\parallel$

- ***Faraday rotation*** is a powerful probe of $B_\parallel$
  - no extinction
  - "absorption" experiment
  - provides direction of B
  - weighted by n_e

$$\mathrm{RM} = K \int n_e B \cdot dl\,,$$

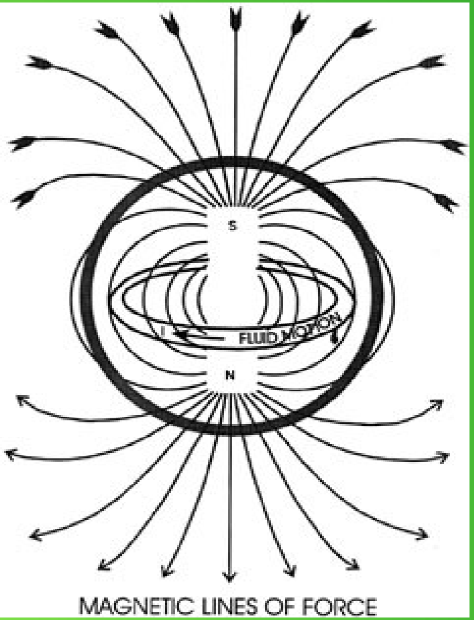


PSR B1154-62 (Gaensler et al 1998)

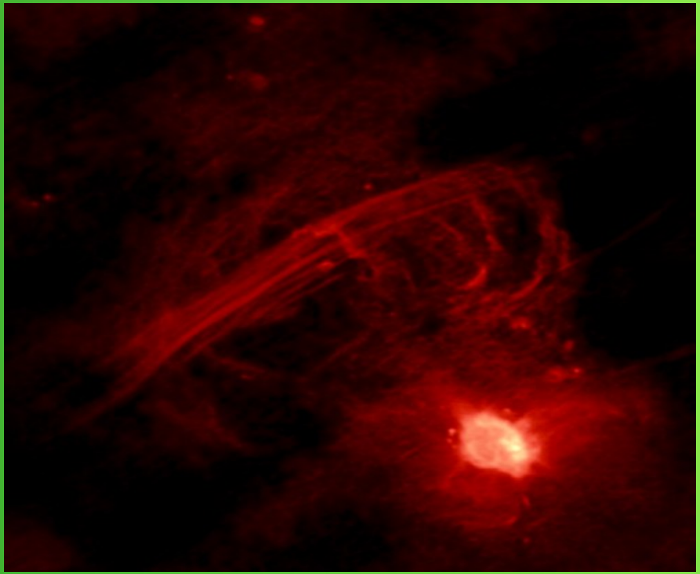
$$\Phi = \Phi_0 + \mathrm{RM}\ \lambda^2$$

ALMA / SKA !

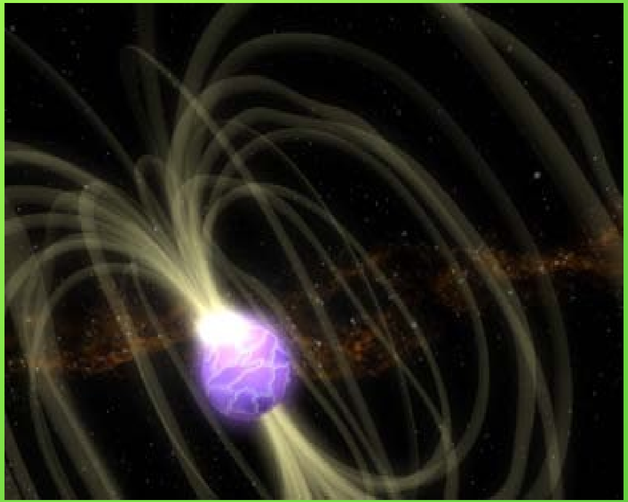
Now...
-From the “small” scale
(Star formation, stellar atmospheres, etc...)



Sol
(Charla de ayer!)



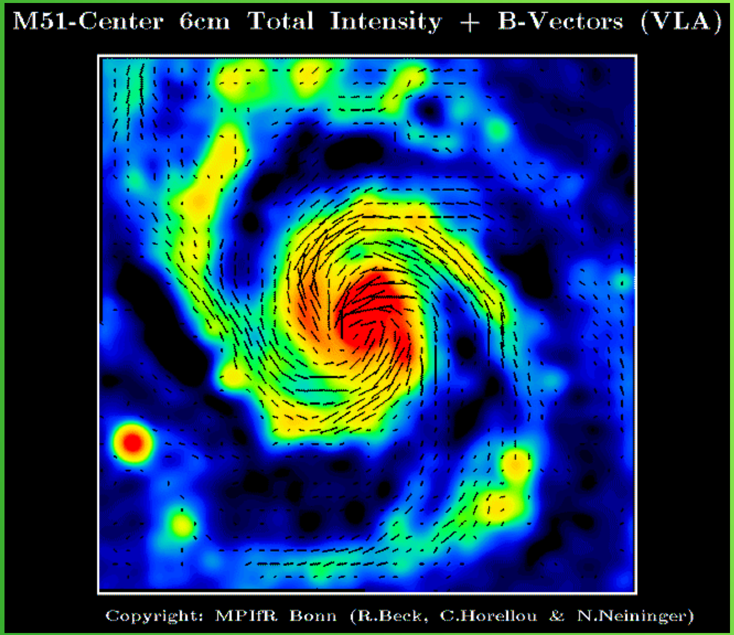
Galactic center
(Crocker 2010)

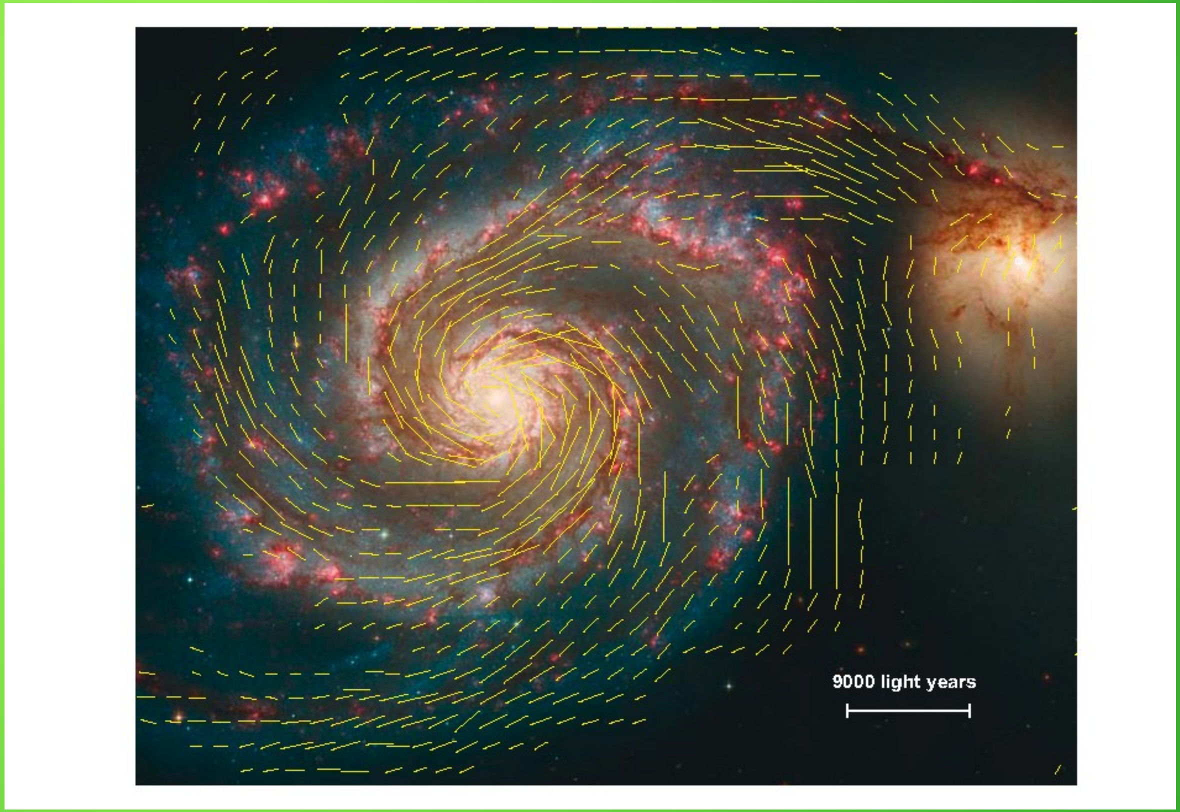


Magnetars
(Israel 2005)

- We can observe them.
- In Galaxies follow the arms with strength higher than 30 muG

- How they survive?
- There is an observational bias?
- Does effect star formation?

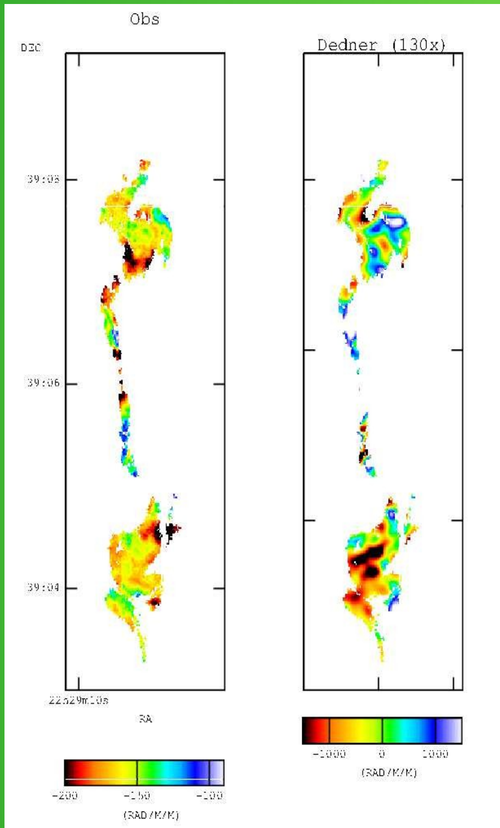




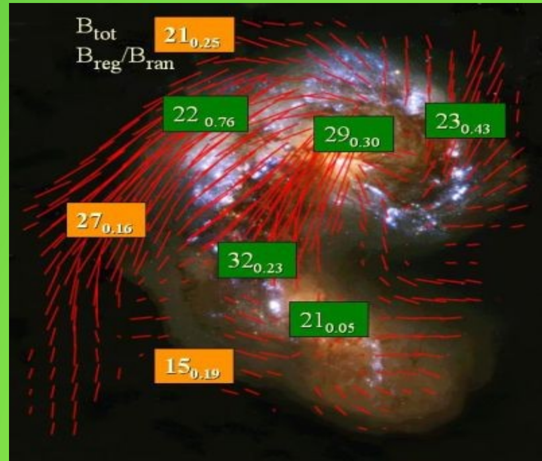
M51 (Fletcher et al 2005)

-To the “Large” scales

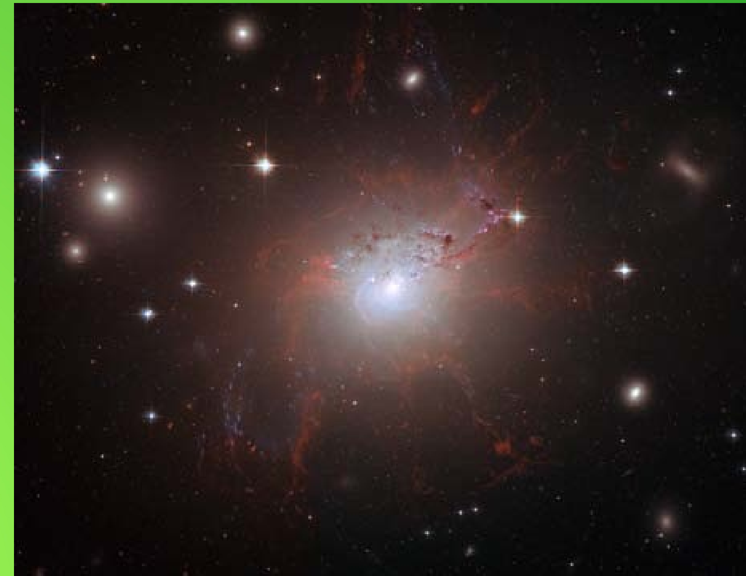
(Galaxies, Filaments, Galaxy Clusters)



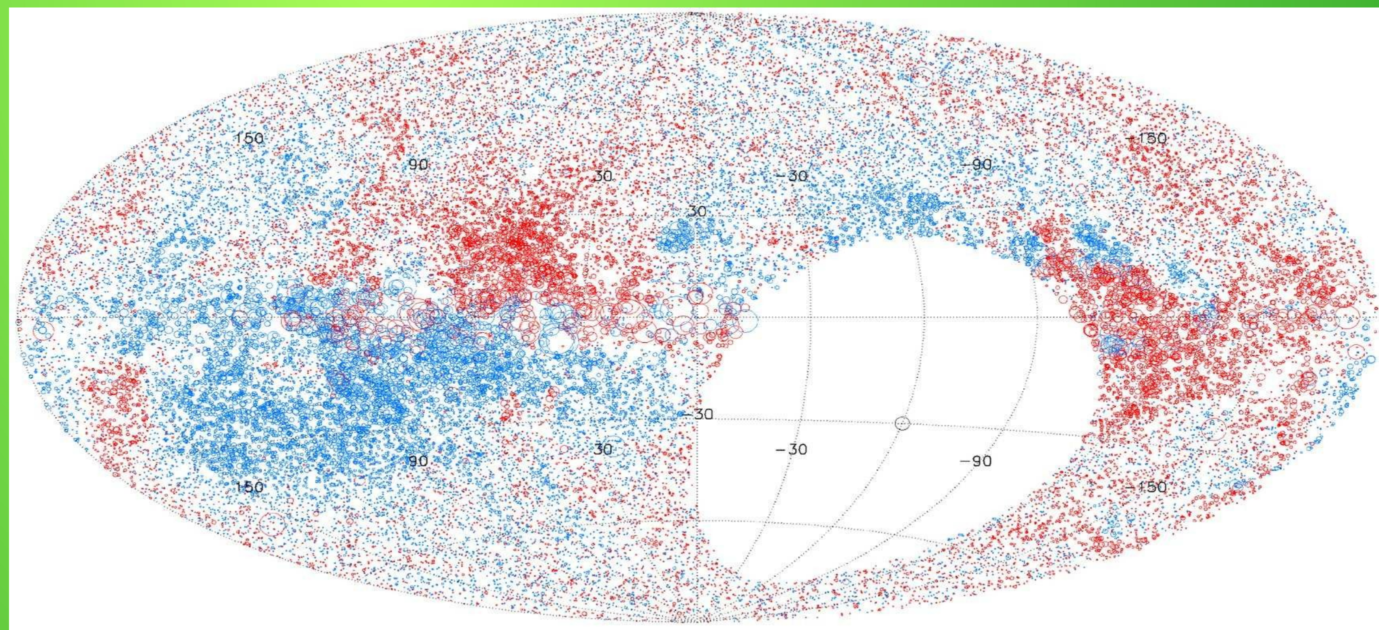
3C449
(Feretti et al 1999)



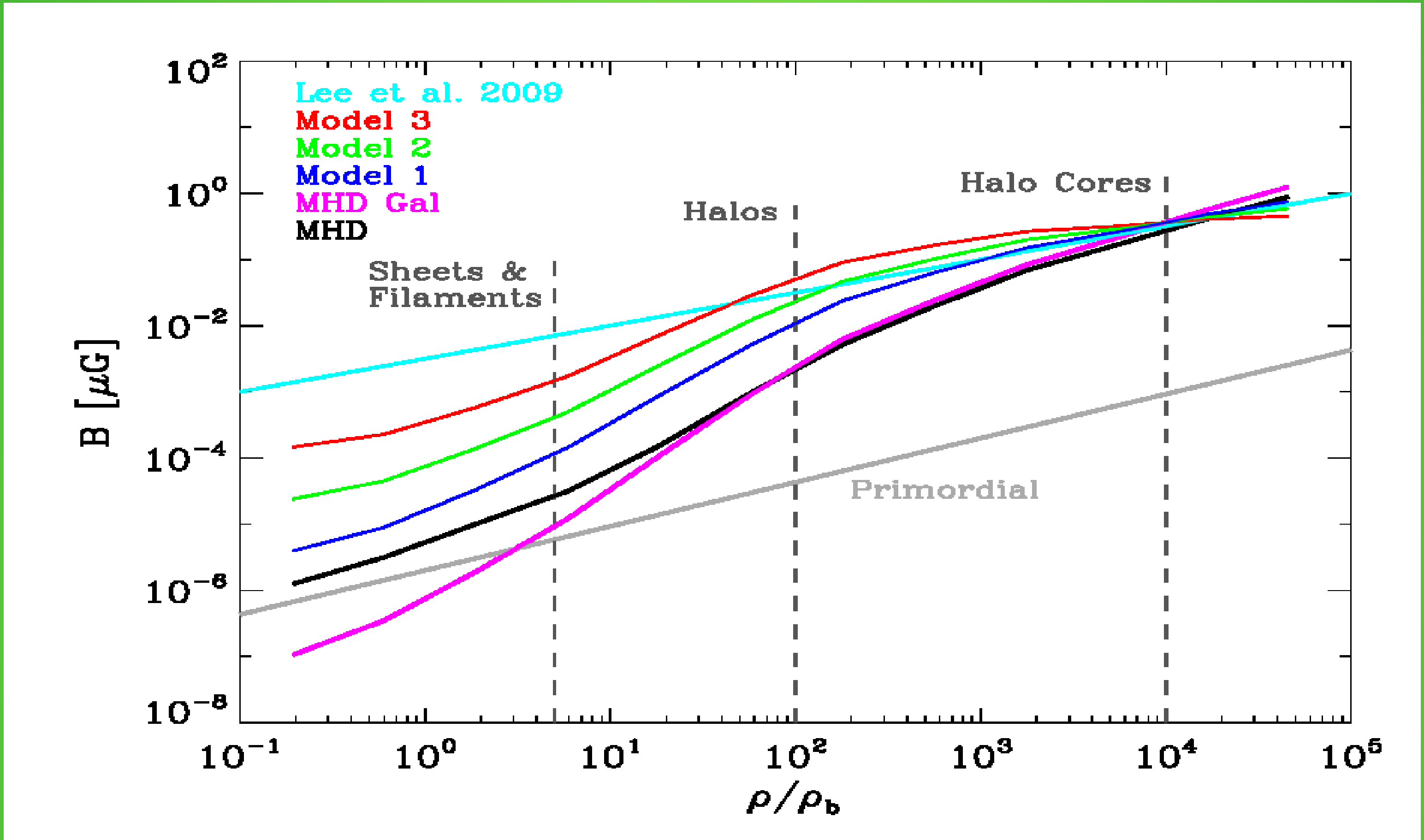
Antenae systems
(Chyzy et al 2005)



Magnetic filaments in Perseus A
(Fabian et al 2008)



RM catalog (Tayler 2008)



Brief Cosmic Magnetic problems:
-Galaxies: the actual MF should be vanished at 10^8 years.
-Galaxy Clusters: Only Gravitational Collapse does not explain their fields
-Stars/Sun: explanations of Acivity Cycle and MF reversals

Motivation

Extremes of Cosmic Magnetism (Gaensler 2009)

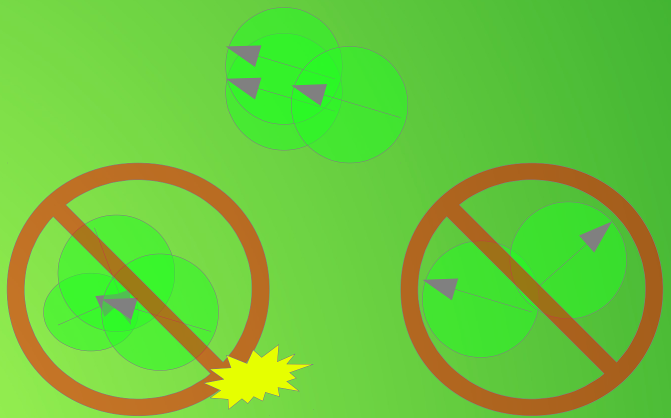
High-z fields (Widrow 2002)	**B ~10^-30 – 10^-20 G**
Intergalactic Medium	**B ~ 1-10 nG**
Intracluster Medium	**B ~ 0.1-1 μG**
Interstellar medium	**B ~ 1 μG – 10 mG**
Galactic Center (Crocker et al. 2010; Ferrière 2010)	**B ~ 50 μG – 1 mG**
Main sequence star: (Babcock 1960)	**B ~ 34 kG**
White Dwarf (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**

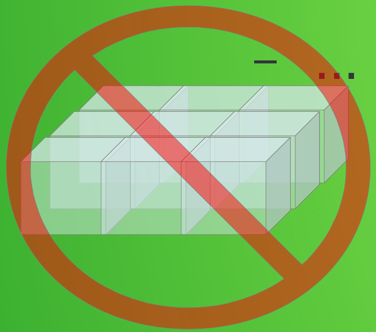
How we deal with this...

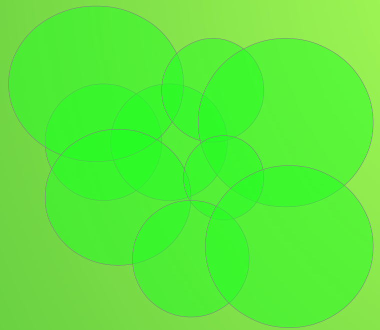
…. SPH simulations of Magnetic fields

Numerical MHD

- Smoothed Particles Hydrodynamics:
  - Natural Adaptivity and Huge Dynamical Range
  - Perfect self Gravity Calculation
  - Scalability
  - Galilean Invariant
  - ...







Approaches

- Suppression instabilities
  - Cleaning Schemes
  - Smoothing of the Field
  - Art. Dissipation
- Euler Potentials $\mathrm{B} = \nabla\alpha_E \times \nabla\beta_E .$
- Vector Potential (?)

$$\frac{\delta\phi}{\delta t} = -\left({c_h}^2 \nabla \cdot \mathbf{B} + \frac{{c_h}^2}{{c_p}^2}\phi \right)$$

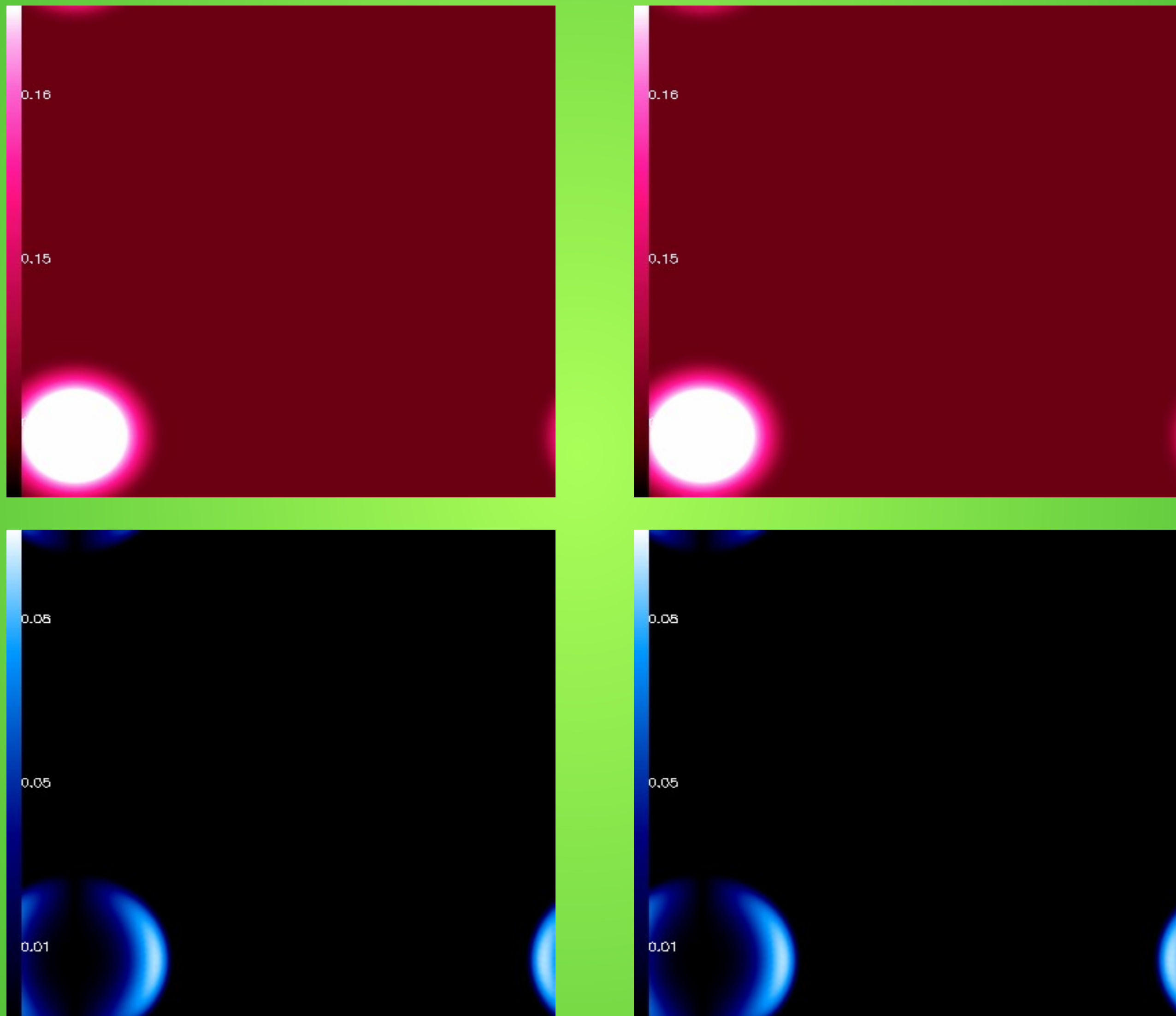
Normal Run

Divergence Cleaning

$$\frac{d\mathbf{B_p}}{dt}^{Dedner} = -\nabla_p \phi_p$$

B*B

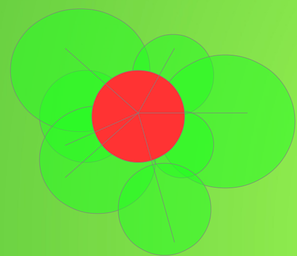
|Div(B)|



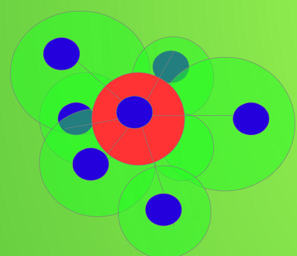
Orzang-Tang Vortex

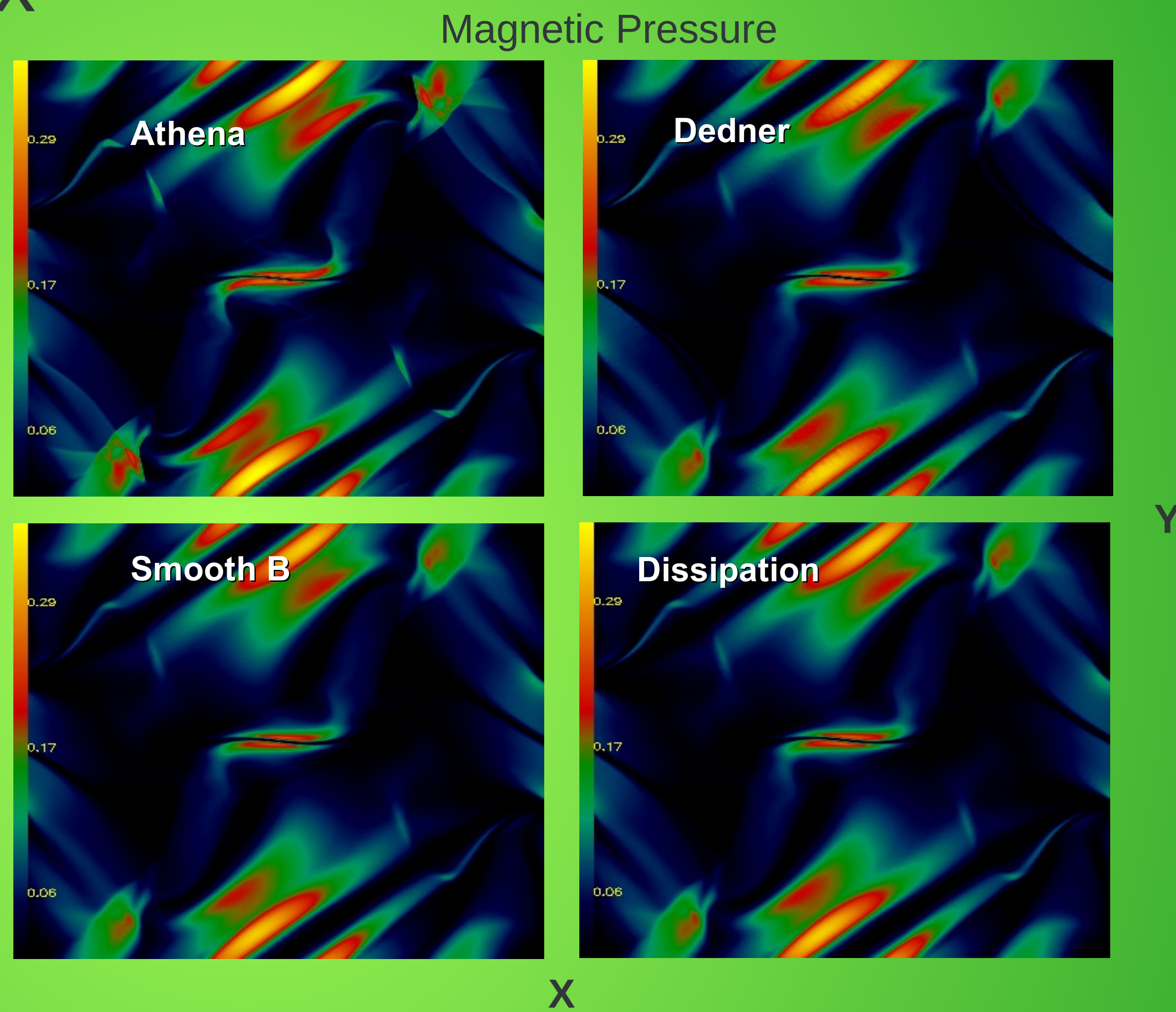
Smoothing:

Art. Dissipation:



Cleaning Scheme (Dedner):





To a code or scheme be reliable has to complete resolution convergence and pass the full 1D/2D/3D test suite.

Orzang-Tang Vortex

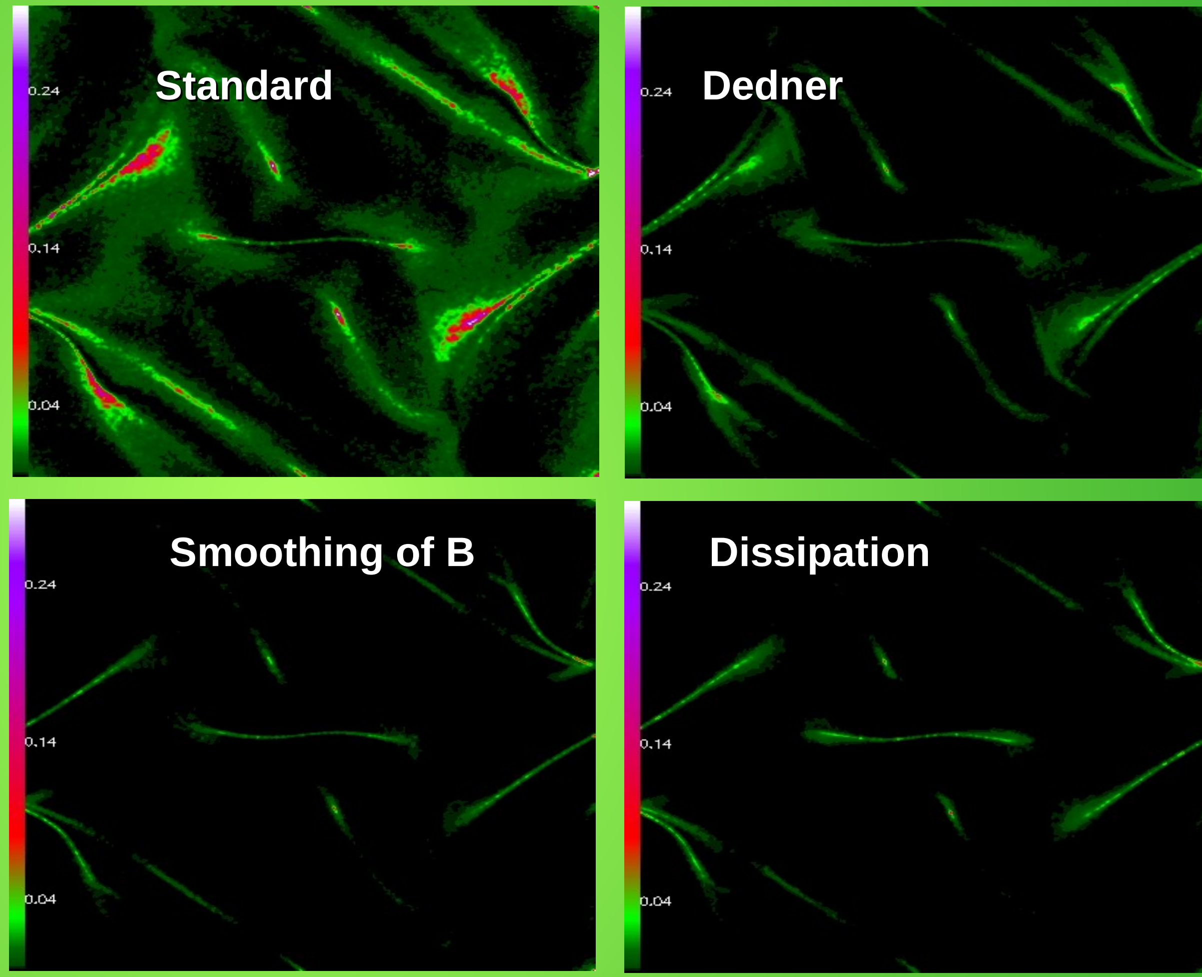
Div(B) errors

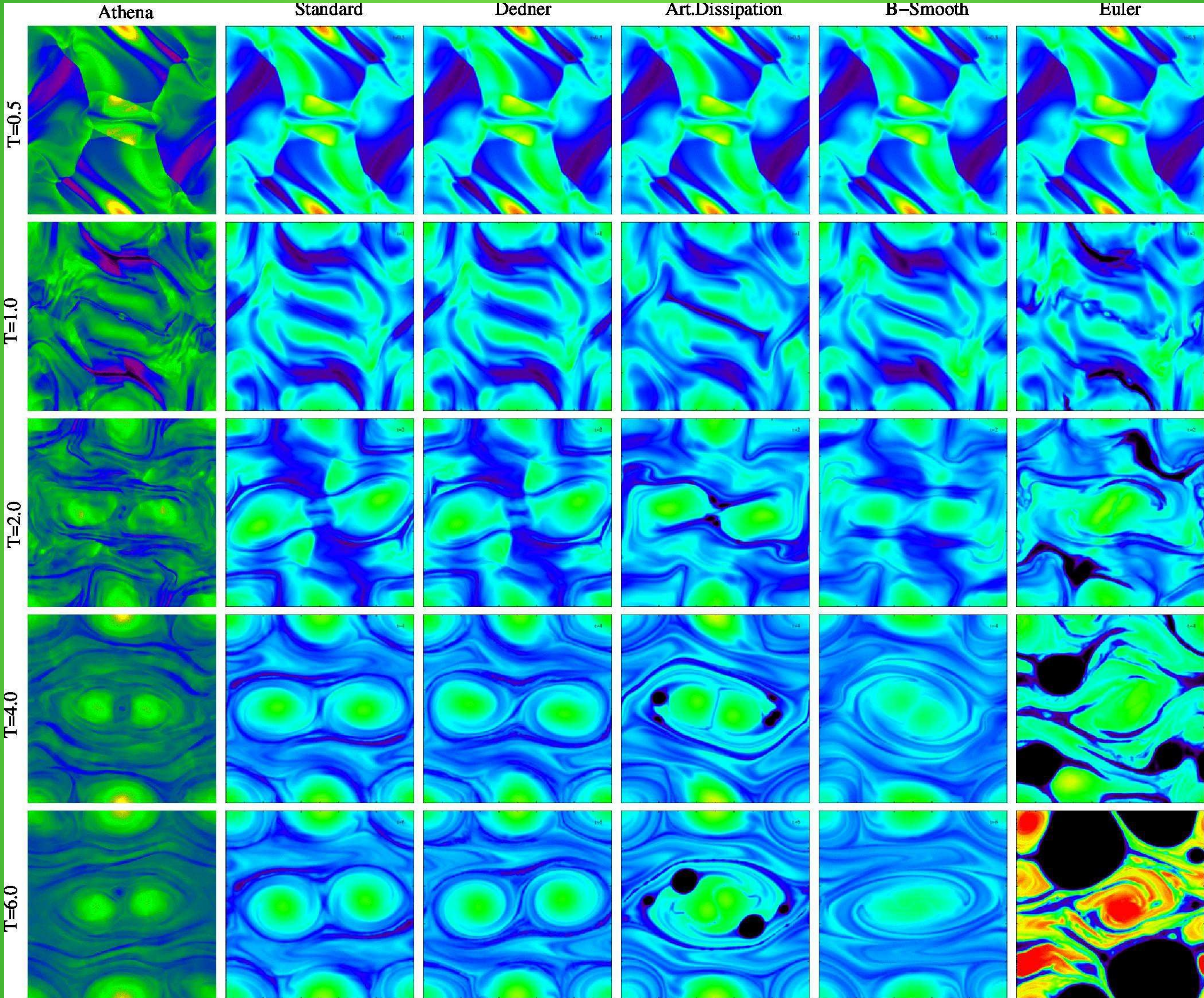
The div(B) is globally suppressed

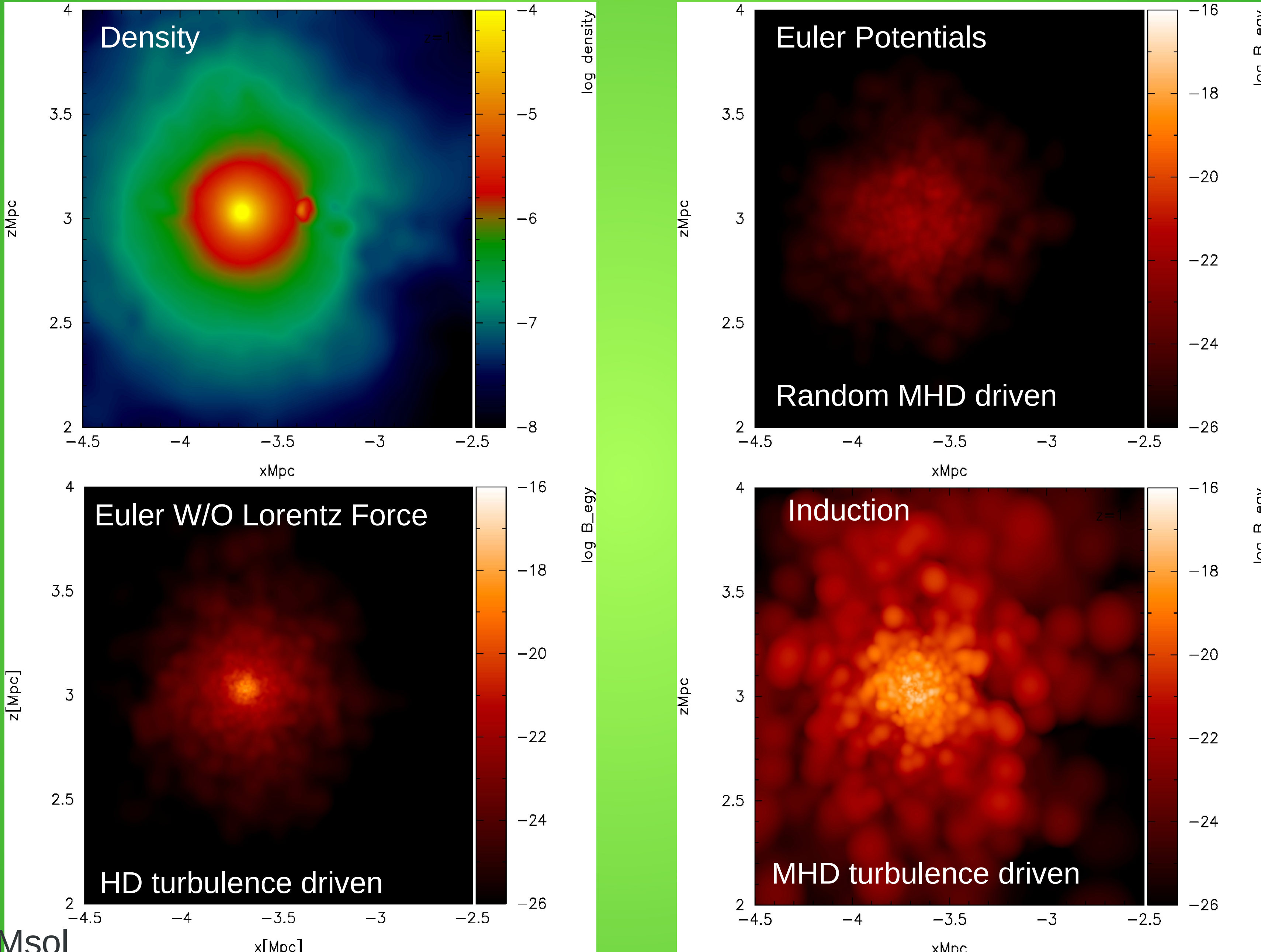
The front Shocks are a problem, in particular Dissipation and Smoothing still Oversmooth them.

Overall good performance of Dedner Method

In general at most still 10% errors in Front shocks

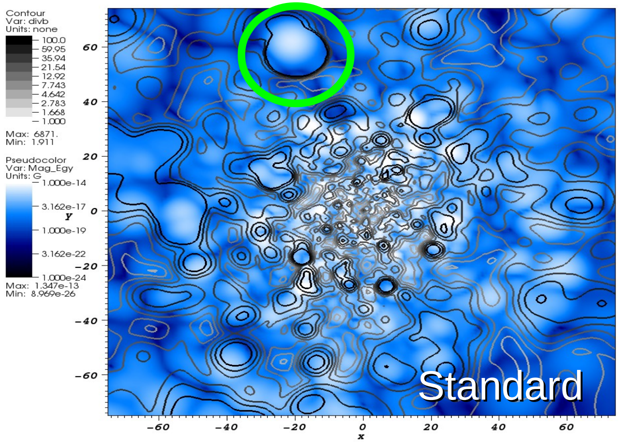



Athena
Standard
Dedner
Art.Dissipation
B−Smooth
Euler
T=0.5
T=1.0
T=2.0
T=4.0
T=6.0

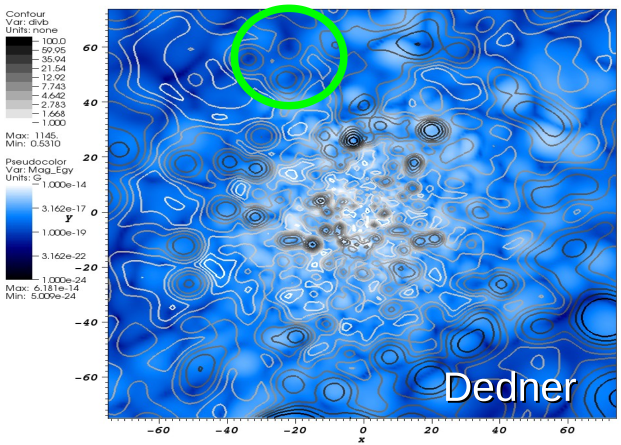

Density
log density
zMpc
xMpc
Euler Potentials
Random MHD driven
log B_egy
zMpc
xMpc
Euler W/O Lorentz Force
HD turbulence driven
log B_egy
z[Mpc]
x[Mpc]
Induction
MHD turbulence driven
log B_egy
zMpc
xMpc

10^14 Msol

Low Resolution (1x)

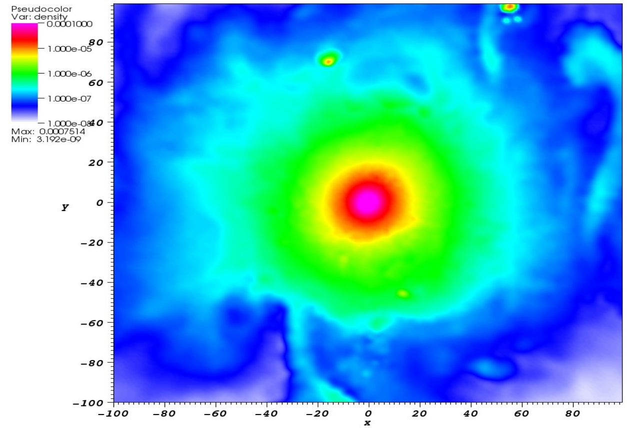


Magnetic Field

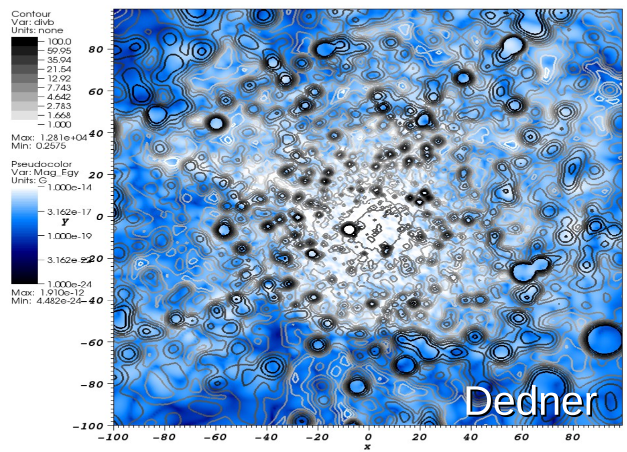


Magnetic Field

2.4x10^8 Msol



Density



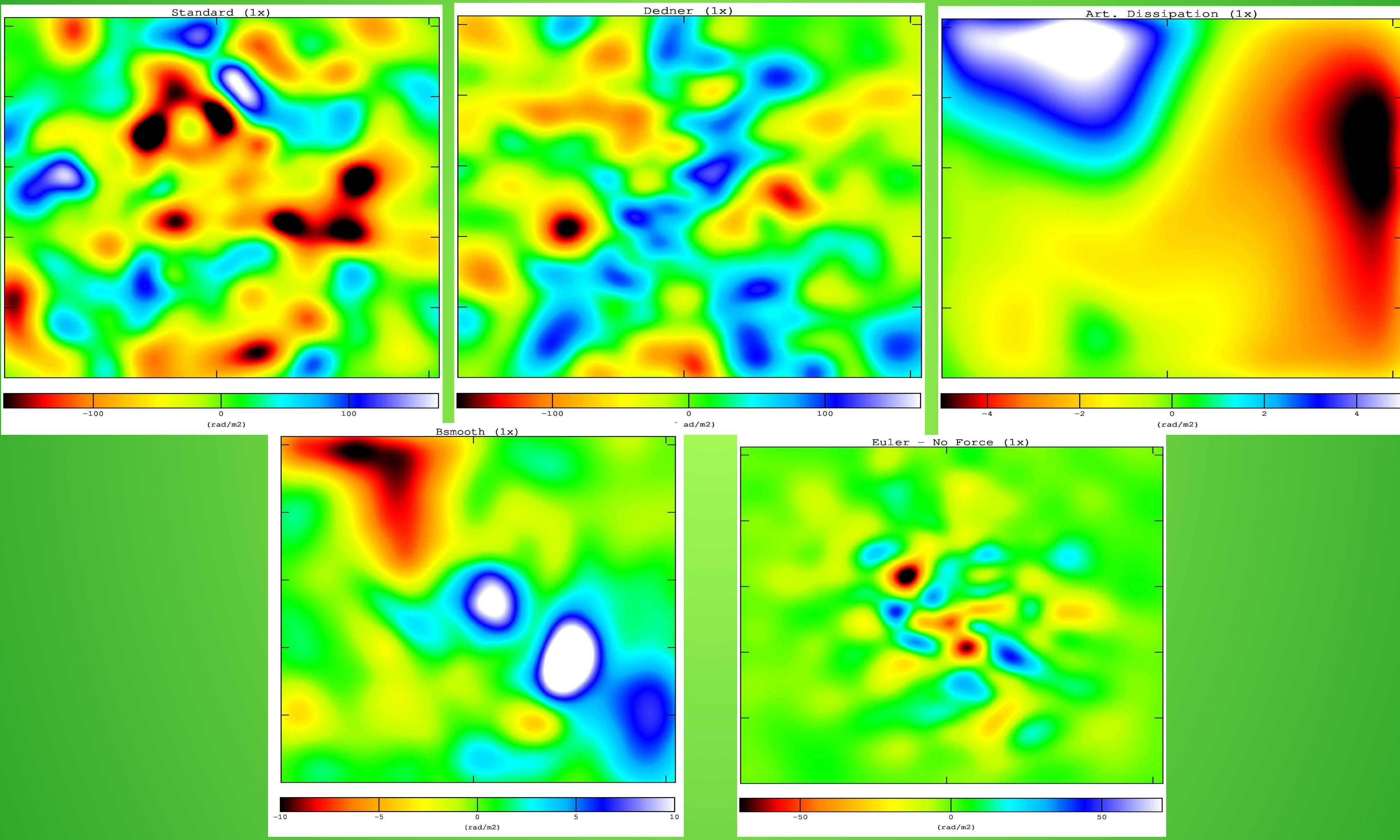
Magnetic Field

High Resolution (10x)

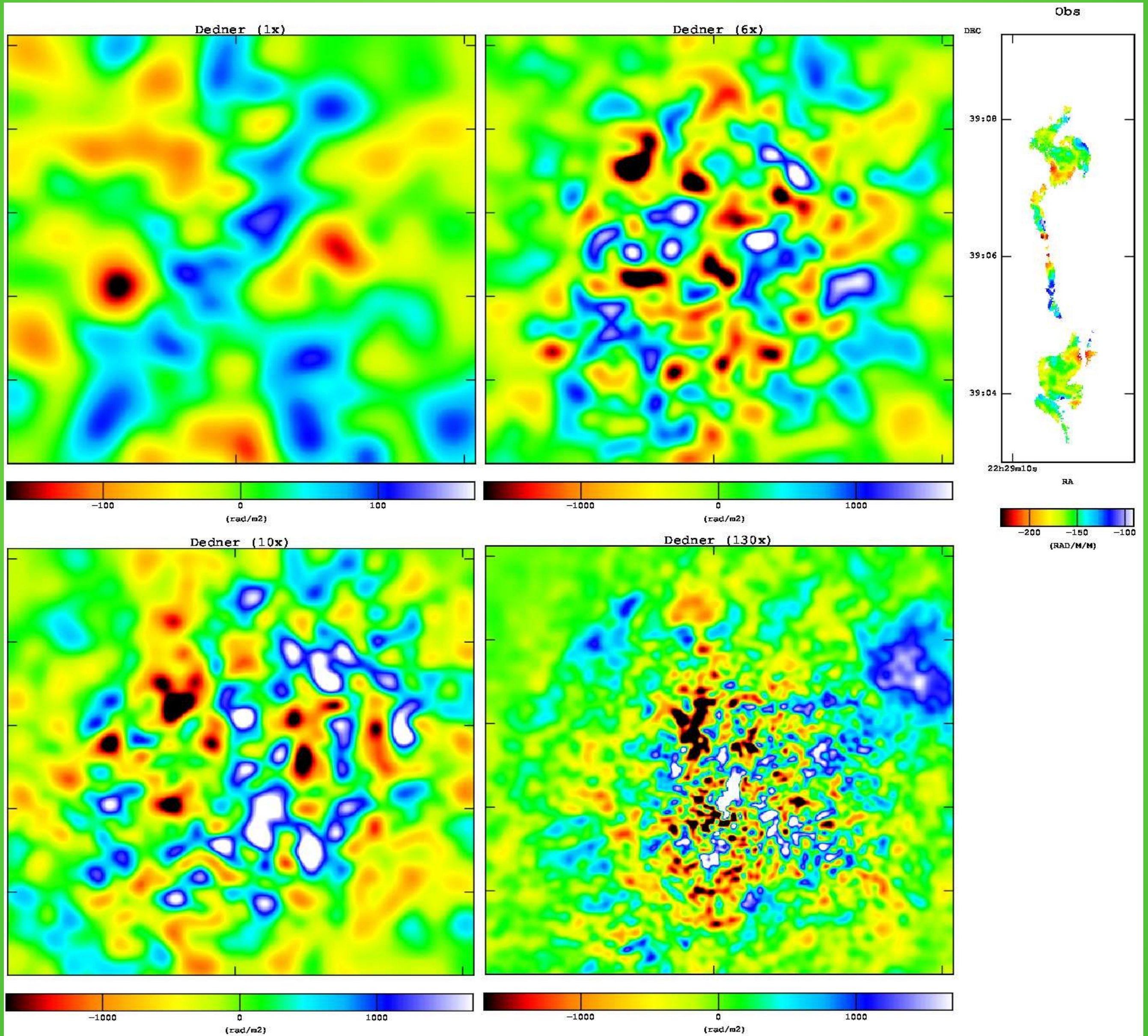
3.0x10^7 Msol

Cleaning scheme confines the DivB errors in smaller volumes, and diffuse them quickly.

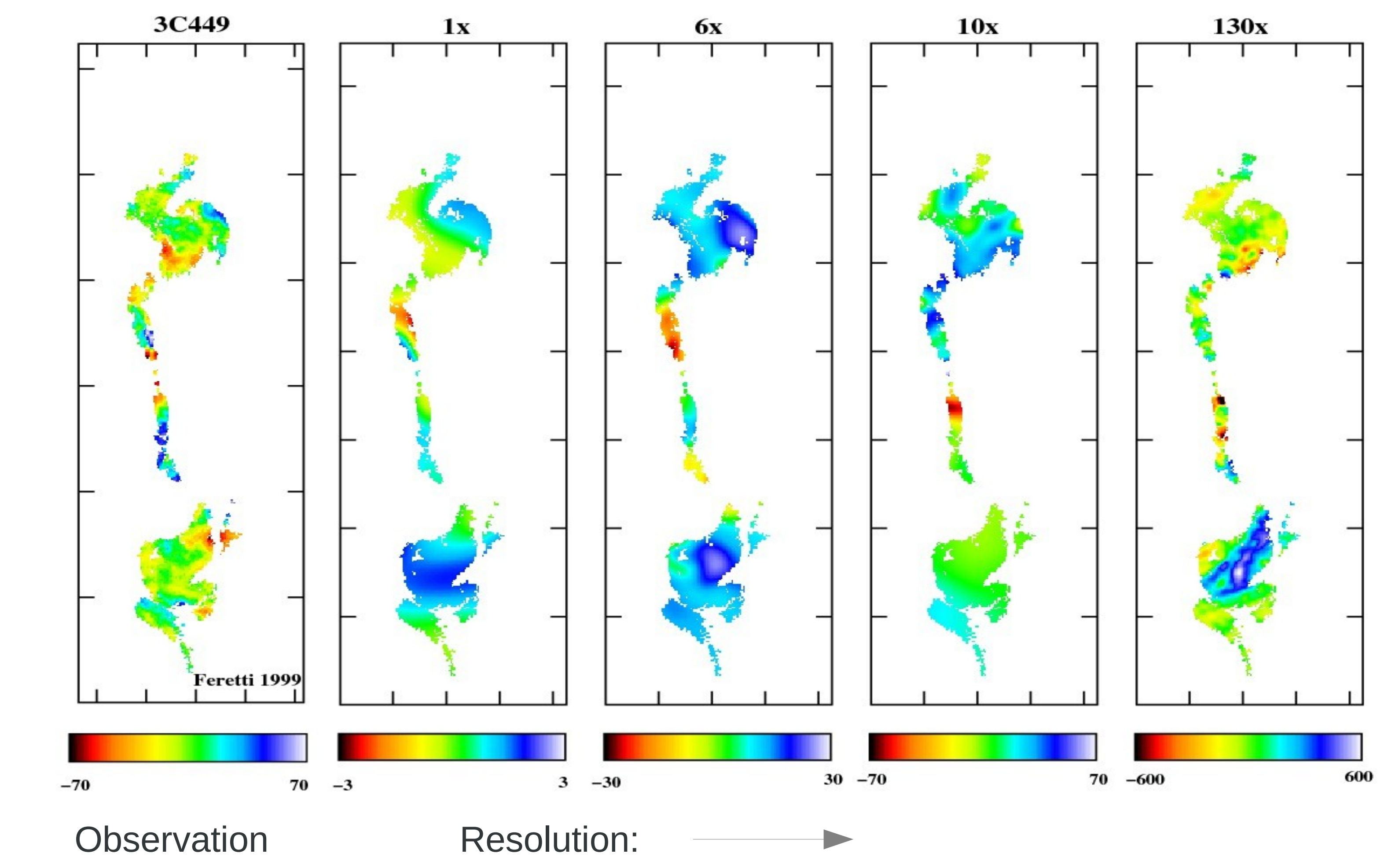
Synthetic RM



Synthetic RM – Resolution Dep.



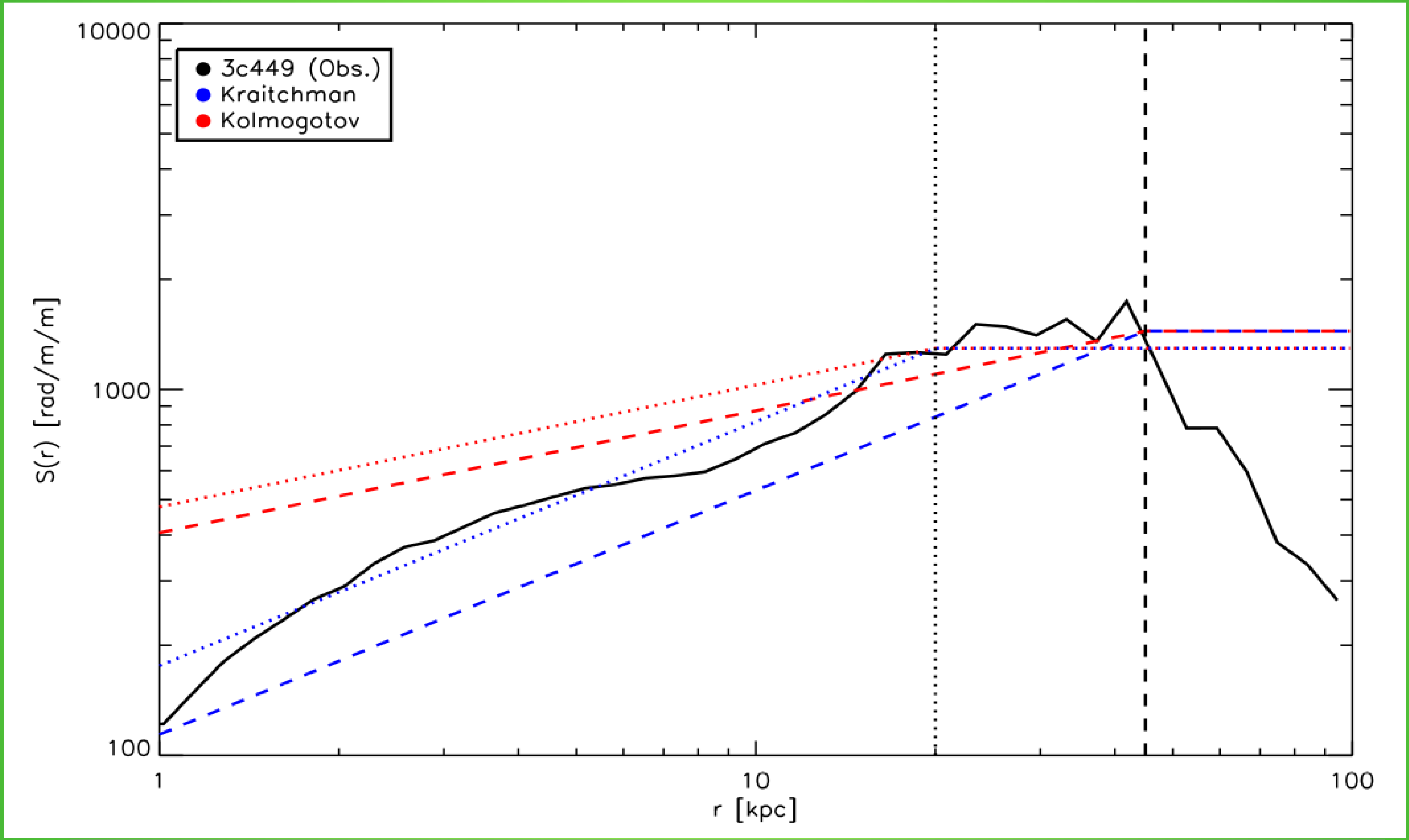
Synthetic RM



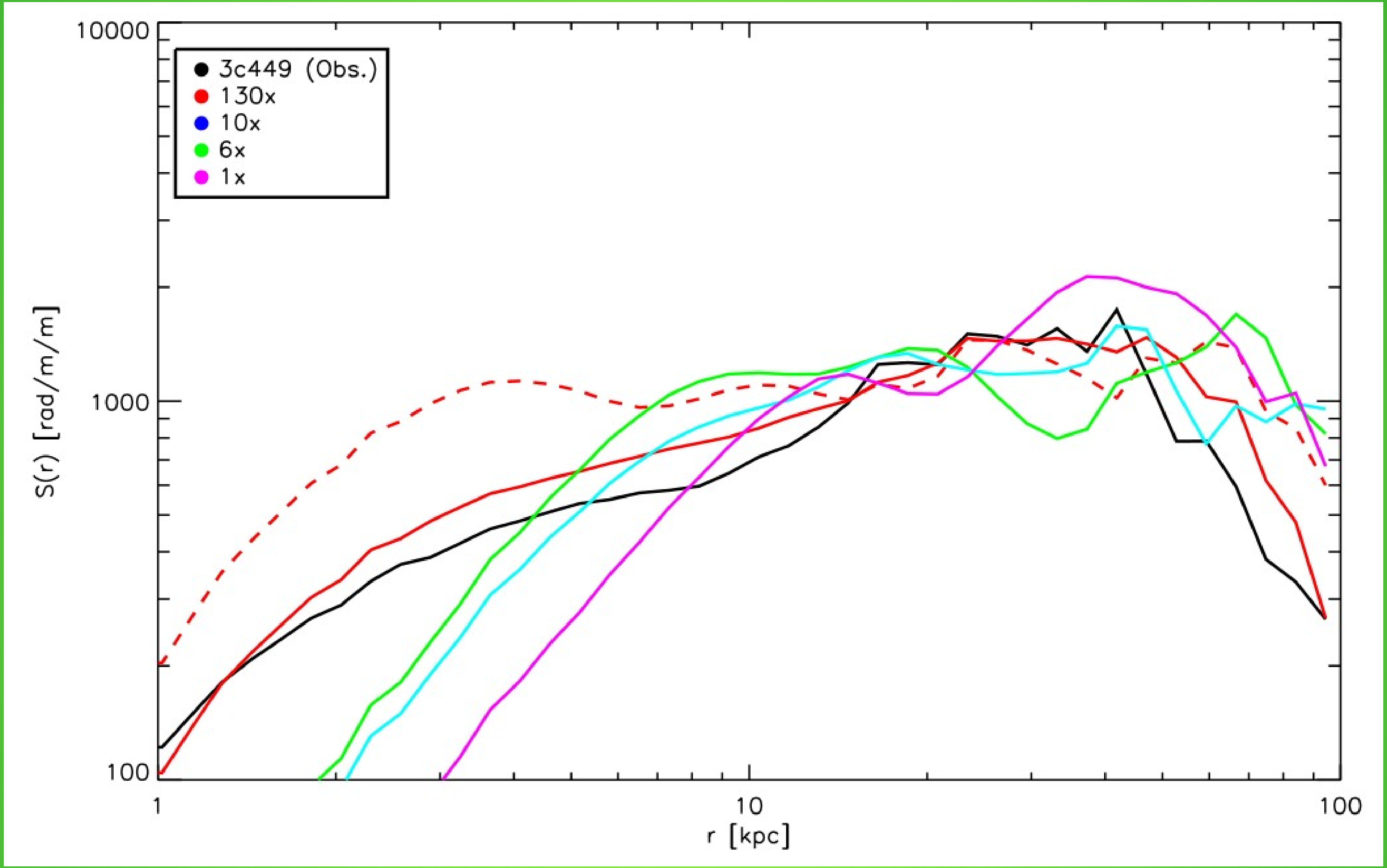
Currently we can compare with direct obervations.

Structure Function

$$S(r) = \langle (RM(r') - RM(r+r'))^2 \rangle$$



Structure function help us to define the statistical properties of the ICM, as Choerence length and slope of the turbulent casade.



Increasing the resolution we recover the observed SF.
However we have too much small structures.

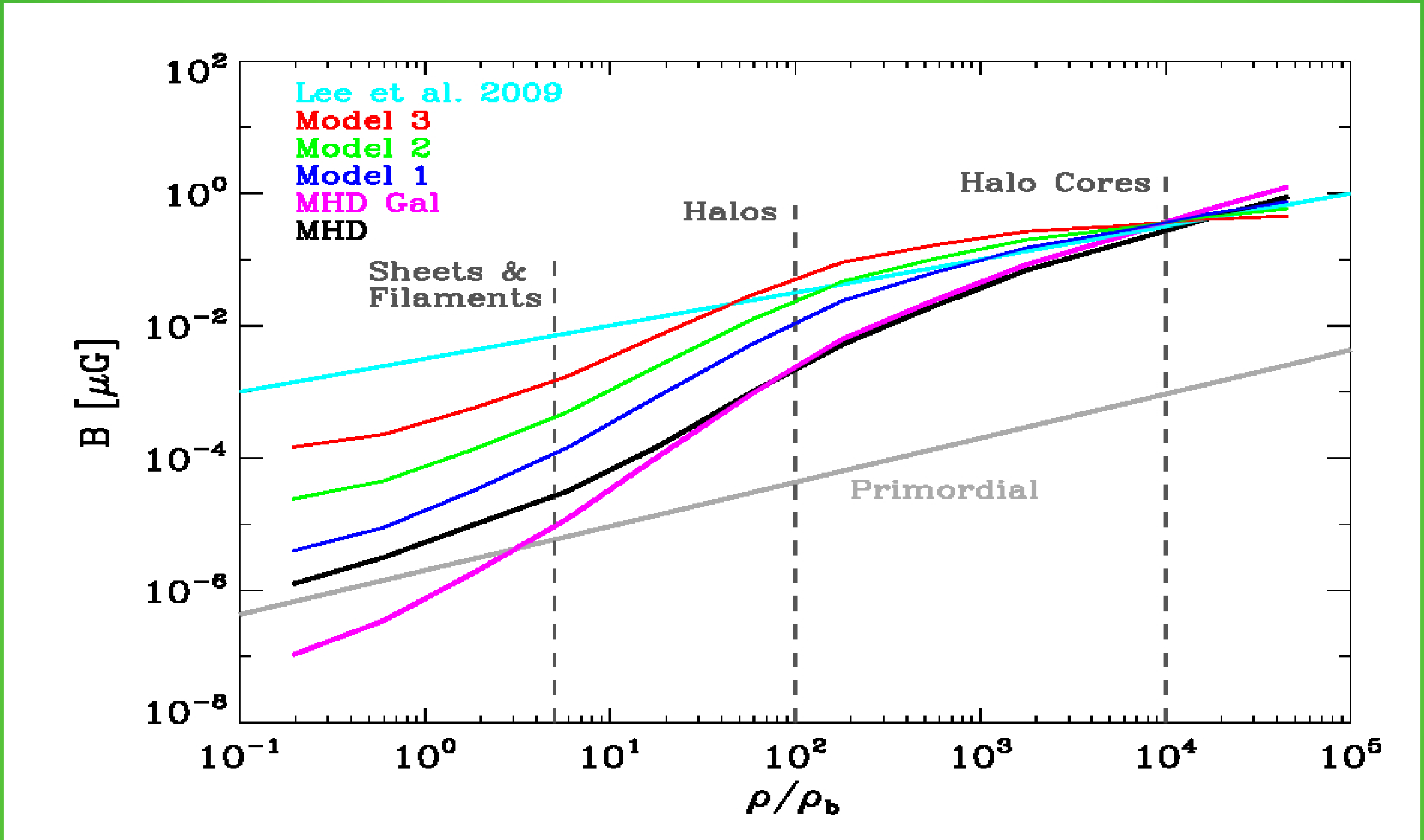
We were able to test several implementations, with different features.

The cleaning schemes seems to be the most close to the Ideal MHD case, improving stability. However the dissipative implementations can be interpreted missing physics.

Increasing the resolution, allow us resolve better smaller structures which are linked with a better resolution of the turbulence.

However, at current resolution and accuracy we over predict the structure, which head us towards additional physics needed.

Turbulent diffusion helps (Bonafede 2012), but difficult to justify.



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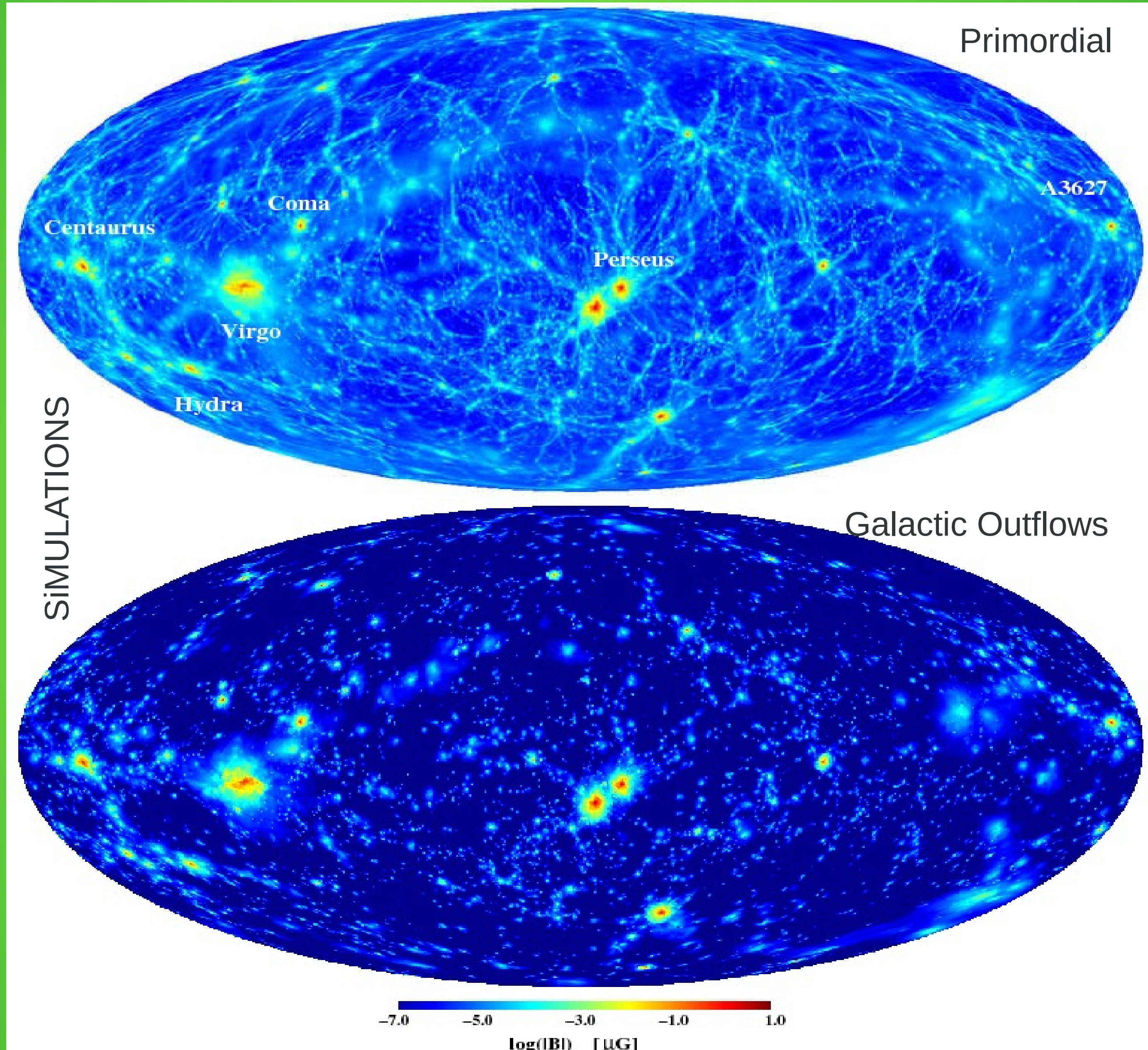
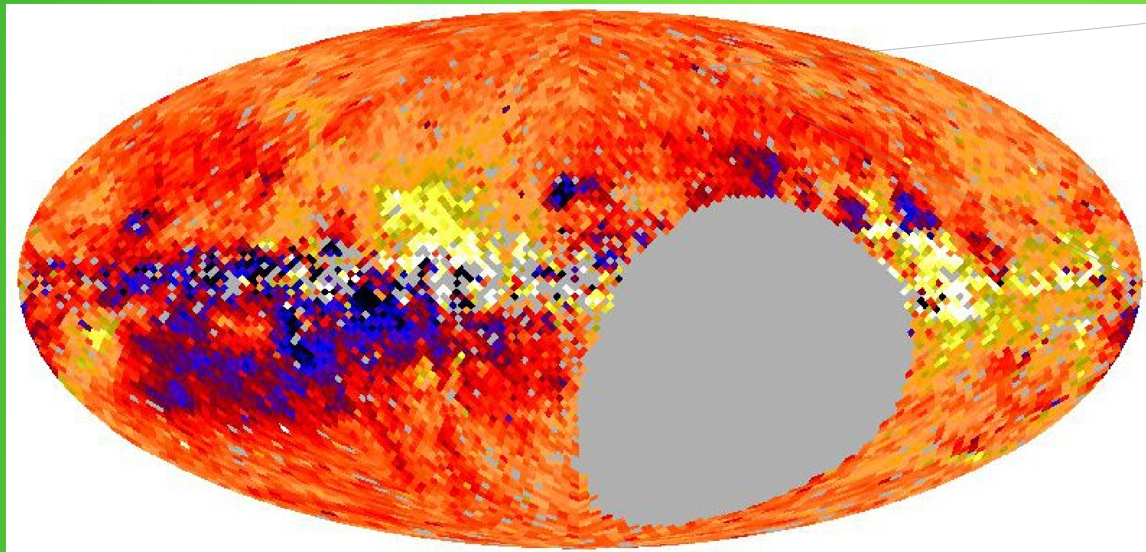
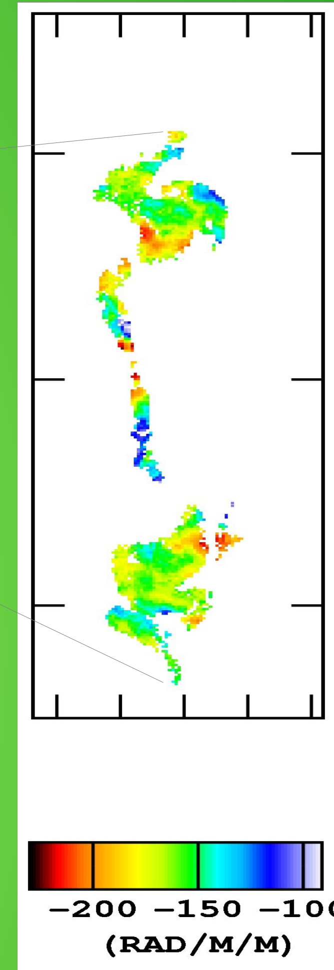
-Stars/Sun: explanations of Activity Cycle and MF reversals


Primordial
Coma
Centaurus
A3627
Perseus
Virgo
Hydra
SiMULATIONS
Galactic Outflows
−7.0
−5.0
−3.0
−1.0
1.0
log(|B|) [μG]

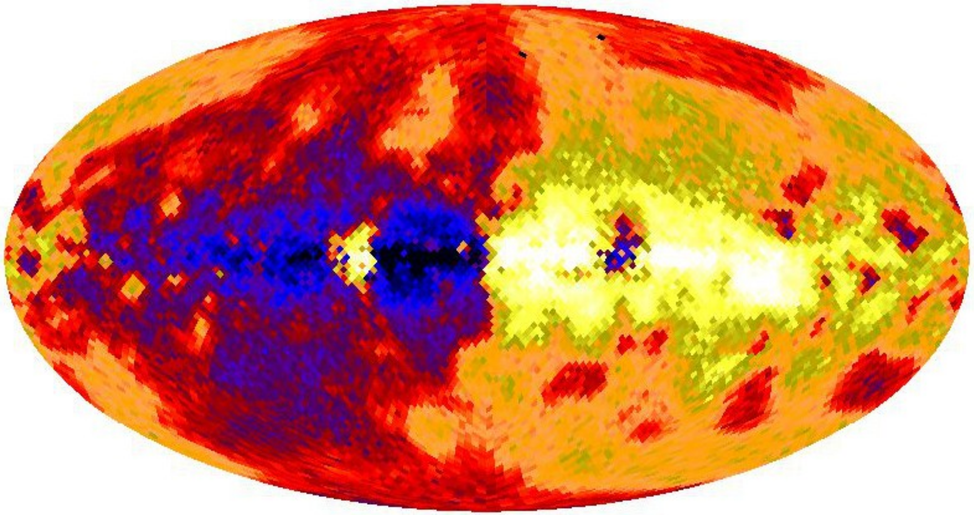
Cosmological RM Statistics



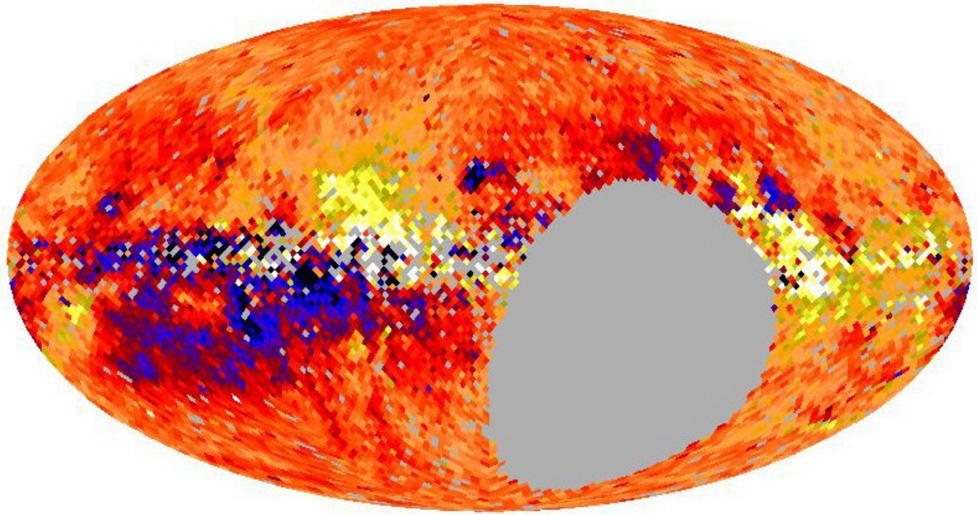


Structure Functions	$S(r) := \langle (a(s) - a(s+r))^2 \rangle$
Autocorrelation Functions	$A(r) := \langle a(s) * a(s+r) \rangle$
Marc Correlation Functions	$M(r) := \langle a(s) * b(s+r) \rangle / (\bar{a}\,\bar{b}\,n(r))$
	$omega(r) := \langle Del_n(r) * B \rangle / (\bar{n}\,\bar{B})$

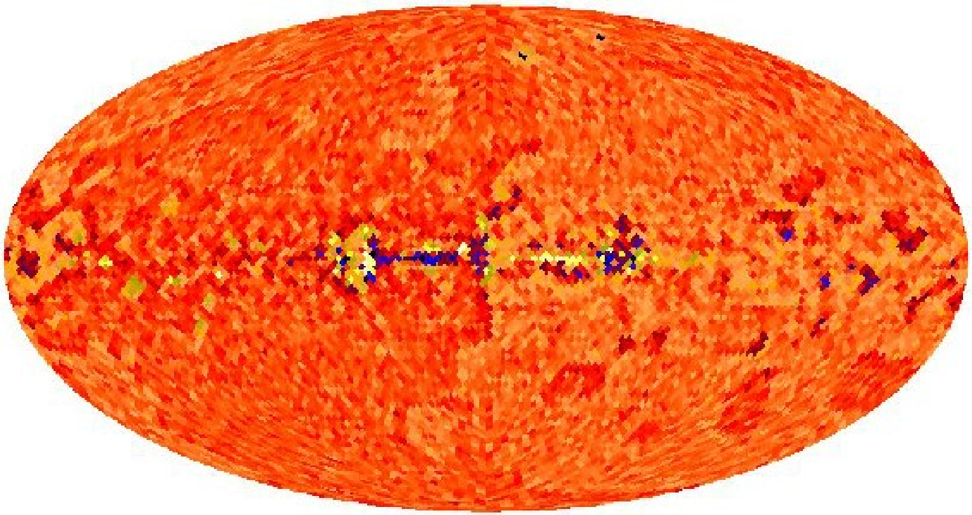
Simulation + Galactic Foreground
(Hammurabi)



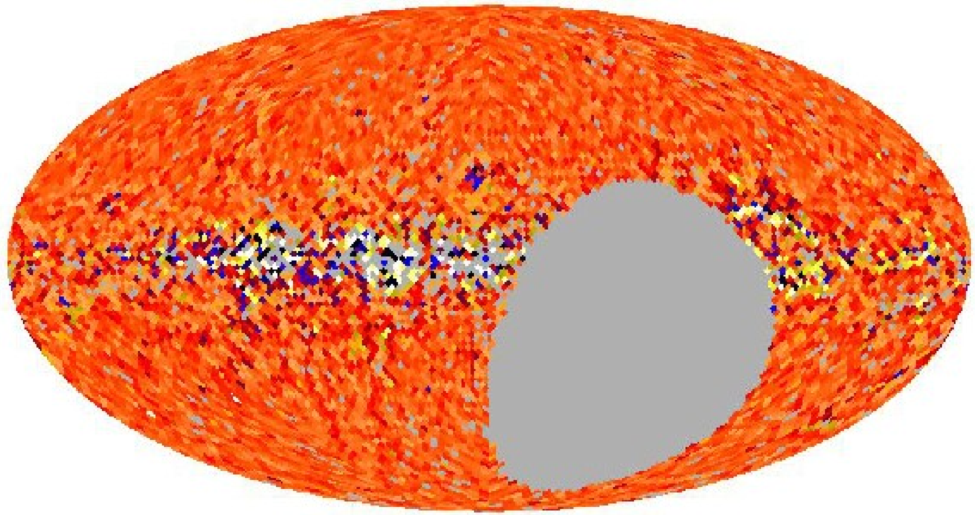
Observation (Taylor 2009)

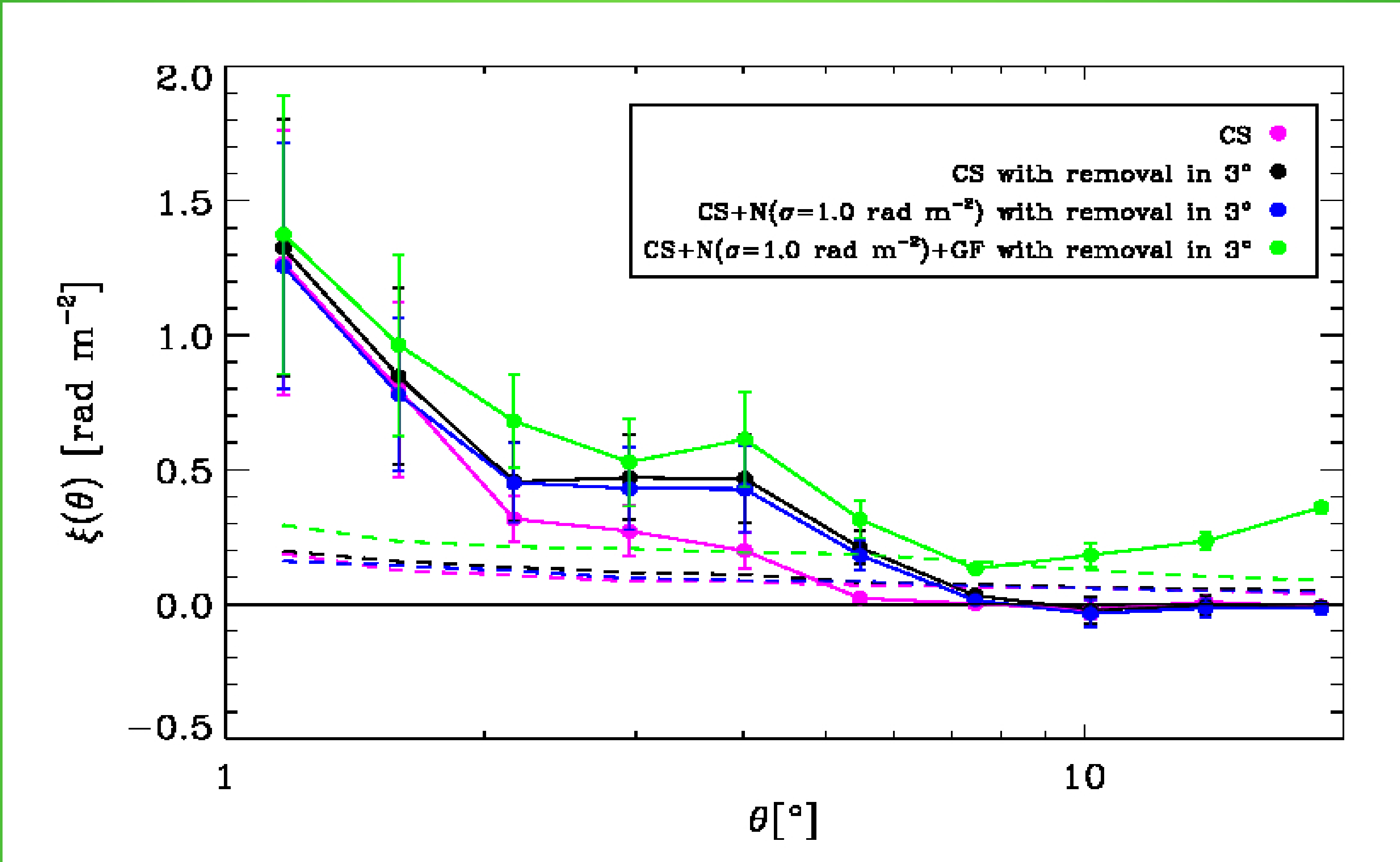


Simulation + Galactic Foreground – Substraction + Noise



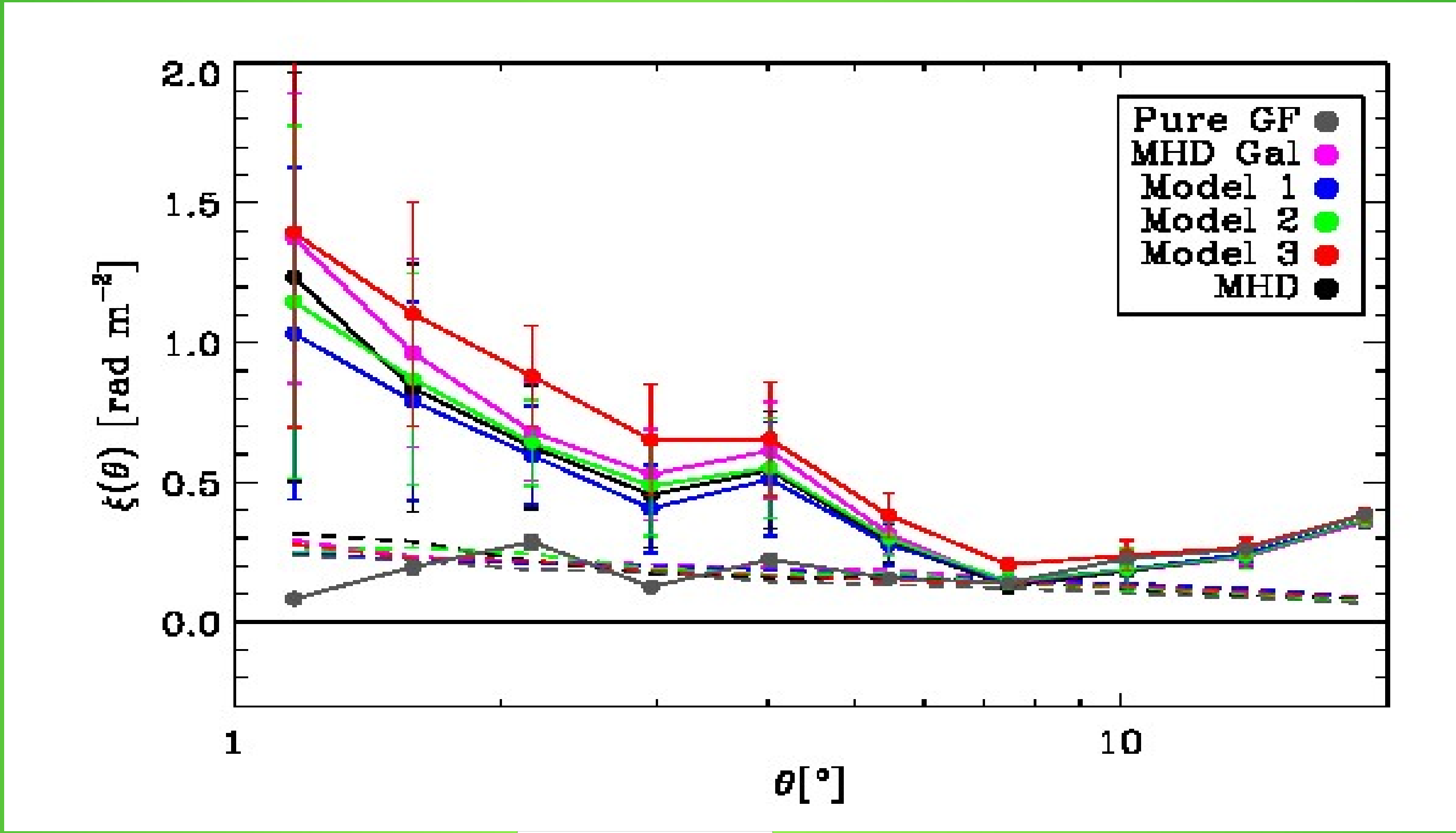
Observation – Substraction





We can prove, how the different aspects of the processing affects the cosmological signal.

And at witch noise level we should expect significance.



Predictions

The Observational Data is close to be Statistically important (if not already).

The Numerical simulations are able to help to understand theses new sets of data and improve predictions for the new generation of telescopes

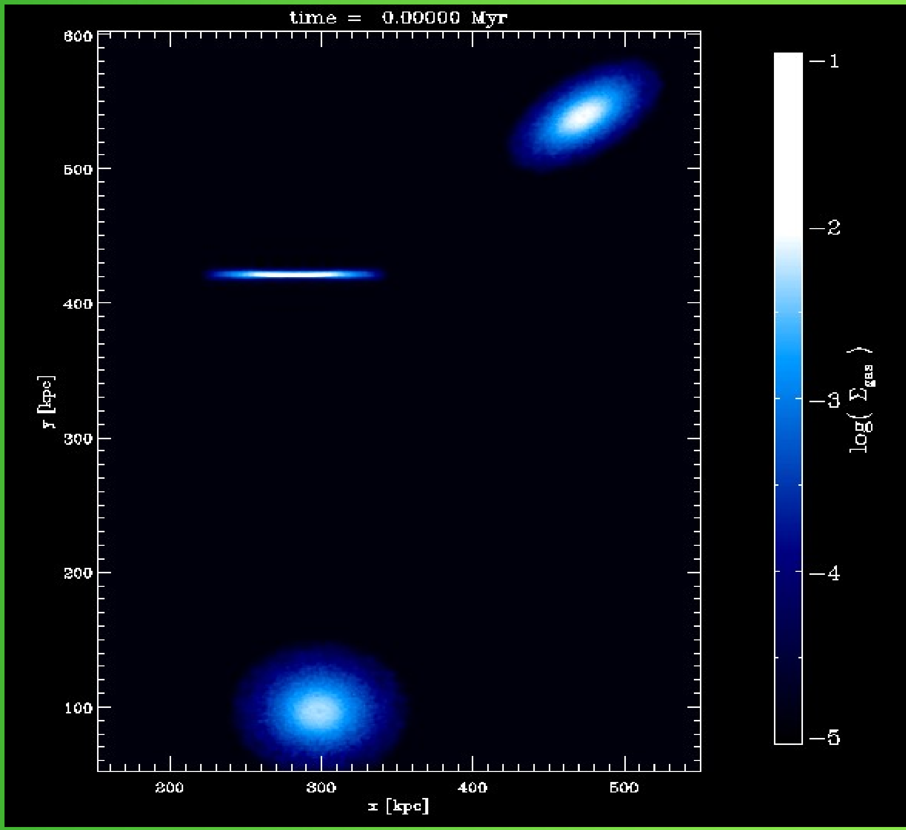
Summary

-We are able to build statistical tools to study the significance of Cosmological MF signal. We calculate the noise level needed in future instruments for detections.

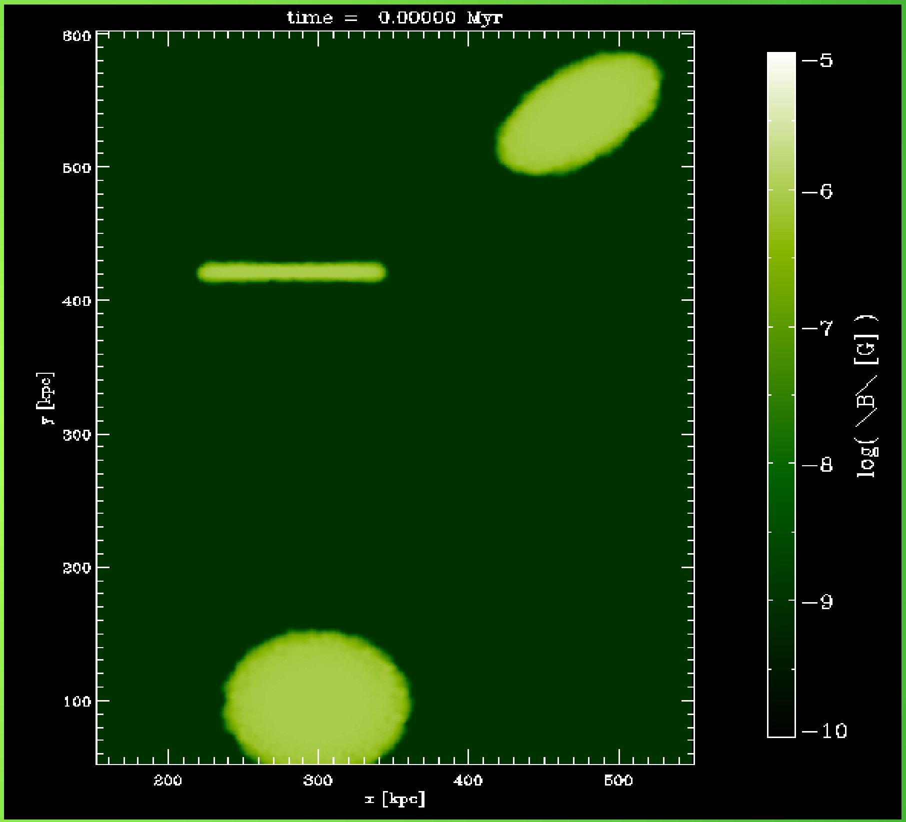
-However current cosmological simulations are not “FULL” MHD, which is needed, to a real comparison.

Galaxies!

now with IGM



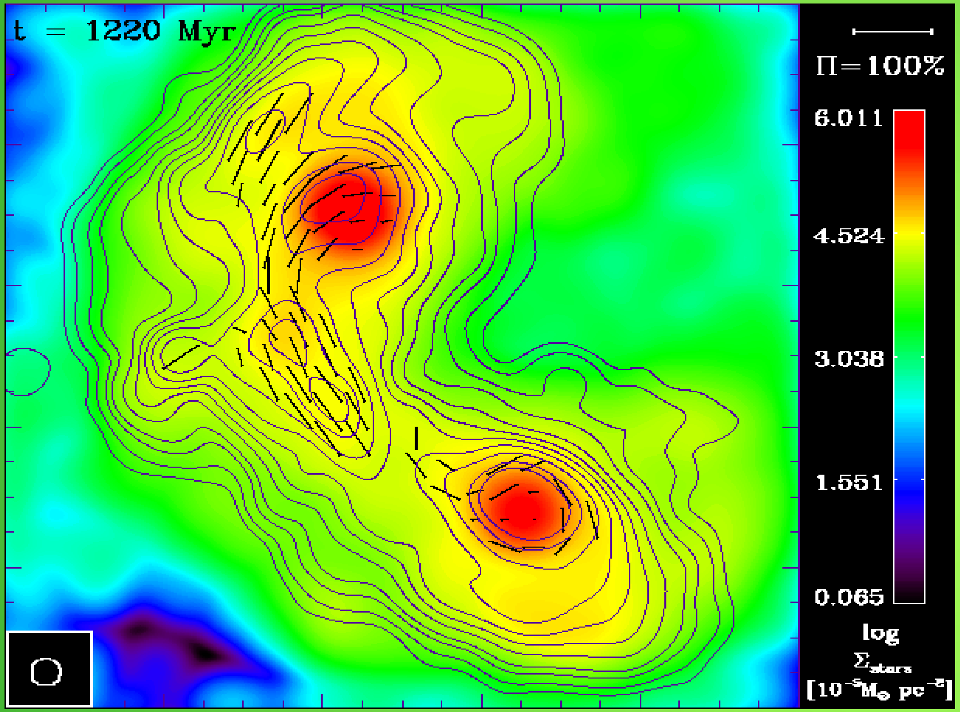
Gas density



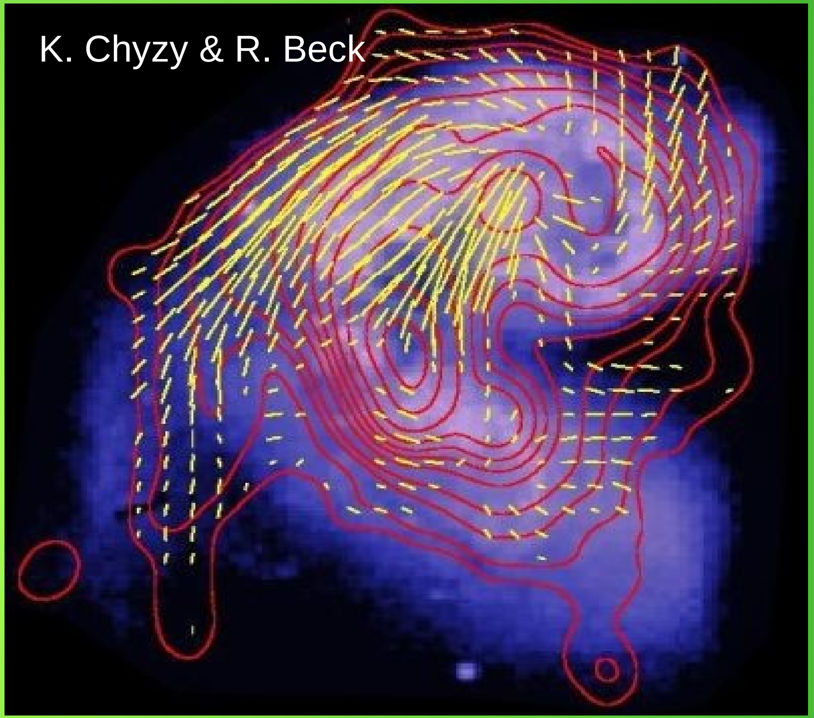
Magnetic field strength

Kotarba et al. 2010b, submitted

The Antennae System



star density, total intensity, field vectors

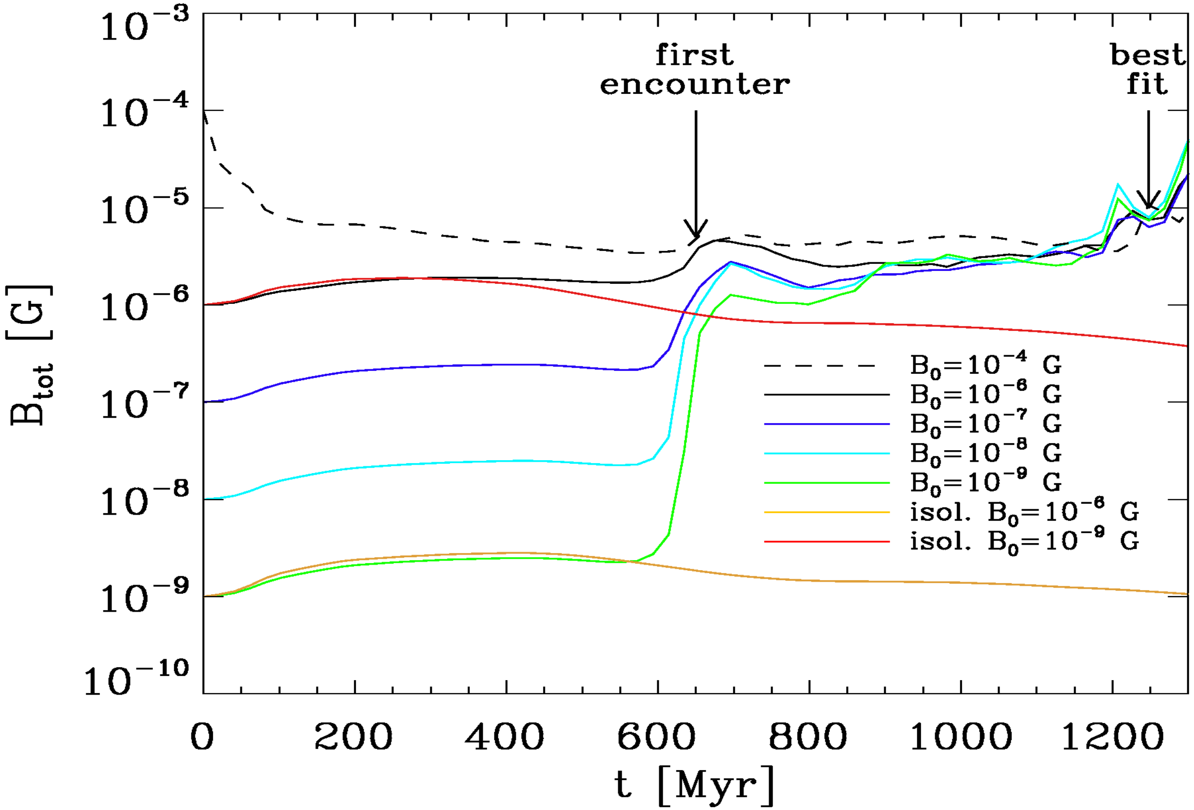


optical, total intensity, field vectors

Kotarba et al. 2010

- Total synchrotron intensity traces total magnetic field
- Polarized synchrotron emission reveals direction of magnetic field

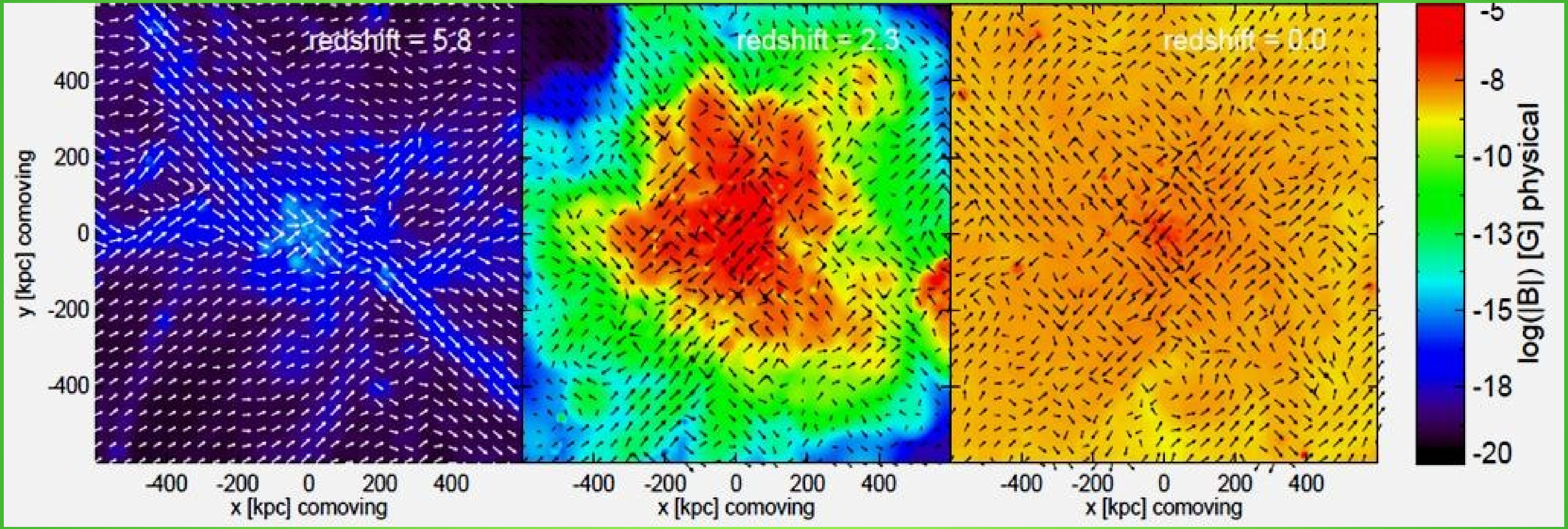
The Antennae System



several μG independent of the initial field!

Kotarba et al. 2010

Galaxy Formation + MHD



Beck 2012

Take home

-Current SPH schemes are suitable to study Magnetic fields in Galaxies.

There is an incredible good agreements with observations.

The Simulation goes toward an equipartition between turbulence and Magnetic energy.

-Additional Physics is needed to understand observations

Structure formation simulations fail dramatically.

From α-effect to radiative cooling and star formation and their feedback.

A real coupling between the different sub-grid physics is needed.

Mean Field Theory.....

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{V} \times \vec{B} - \eta \nabla \times \vec{B})$$

$$\vec{B} = \langle \vec{B} \rangle + \vec{b} \qquad \vec{V} = \langle \vec{V} \rangle + \vec{v}$$

Statistical Properties

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{V} \times \vec{B} - \eta \nabla \times \vec{B} + \vec{\xi})$$

$$\vec{\xi} = \alpha \vec{B} + \gamma \times \vec{B} - \beta \nabla \times \vec{B} - \delta \times \nabla \times \vec{B} + \ldots$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{V} \times \vec{B} + \alpha \vec{B} - \beta \nabla \times \vec{B})$$

Nice model and workhorse for theoreticians

Theory

Non Linear Approach

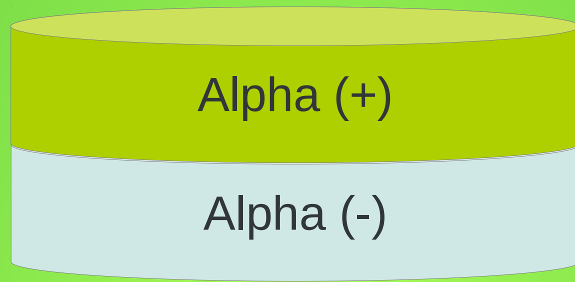
(from B,V get alpha,beta, etc)

Kinematic approach

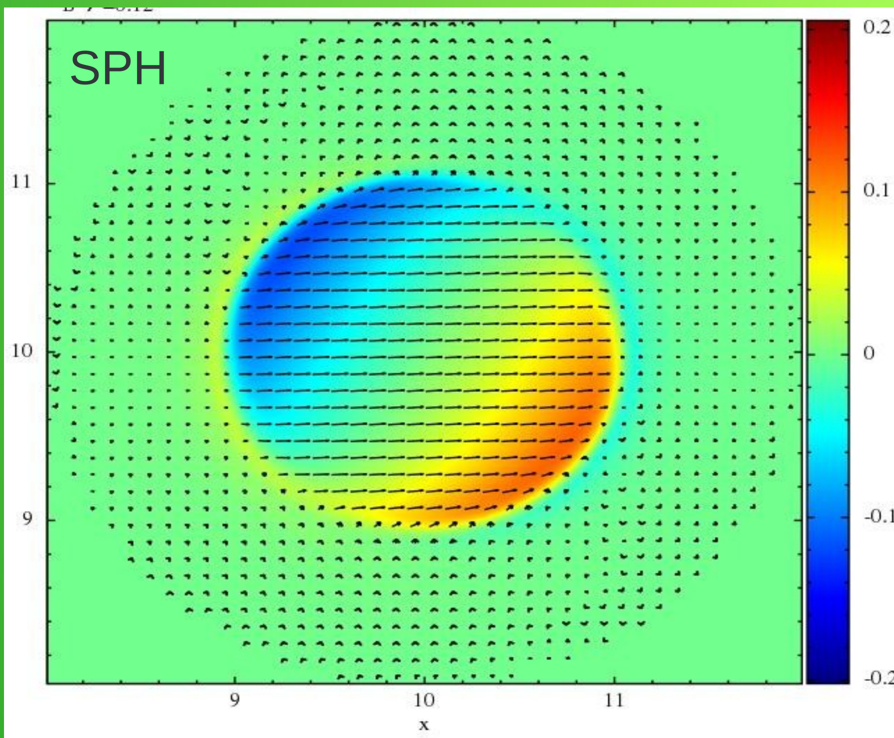
(from alpha, beta, etc get B,V)

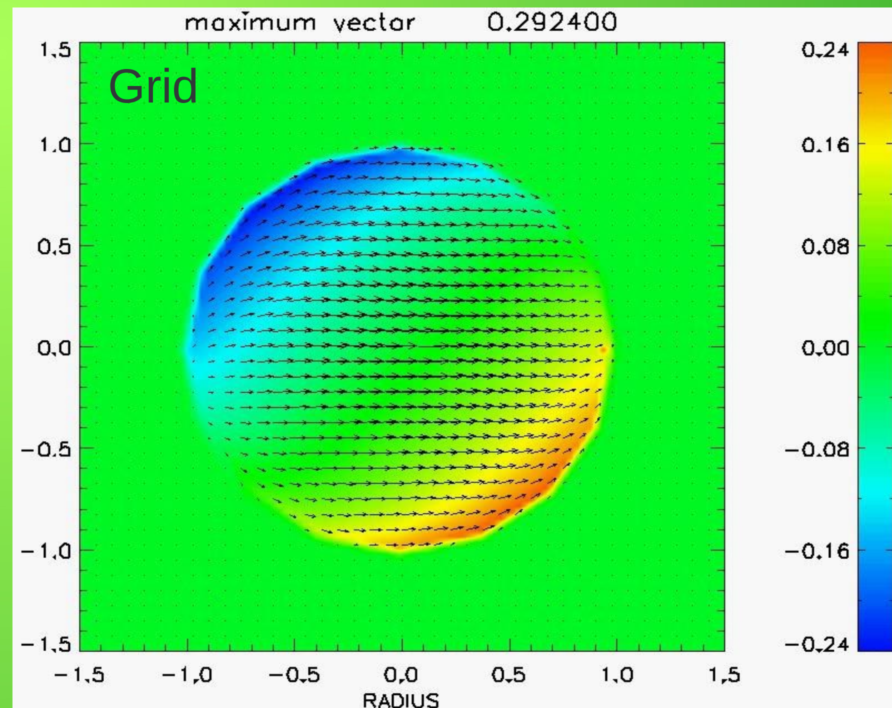
SPMHD - Tests

- Anisotropic α



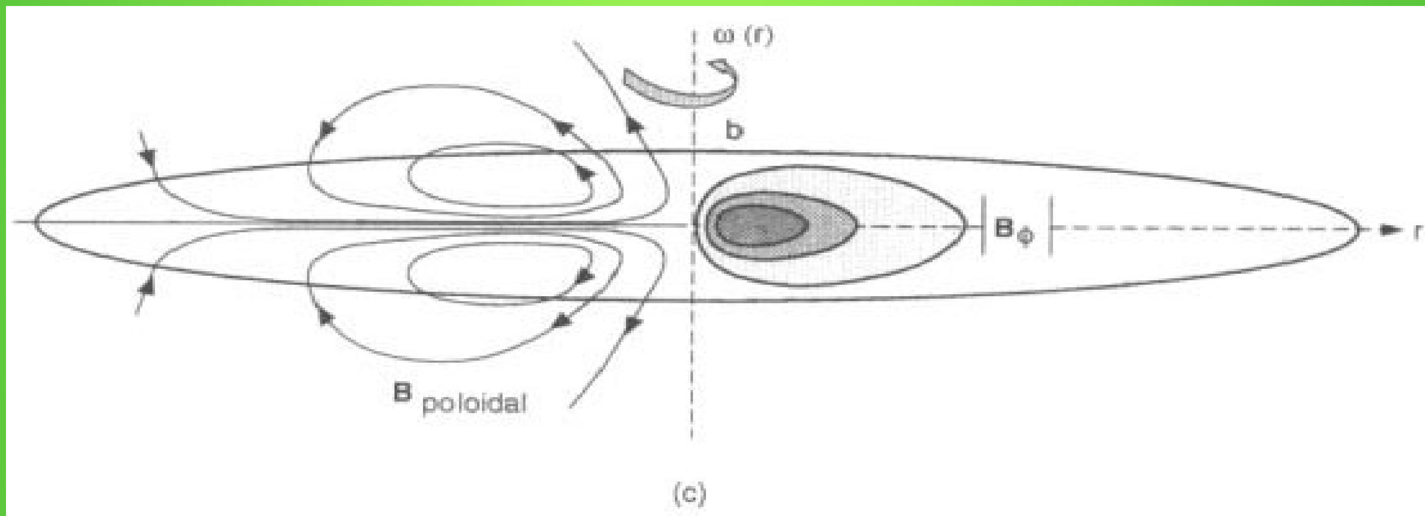
$$\vec{\alpha}=[\alpha,\alpha,0]$$

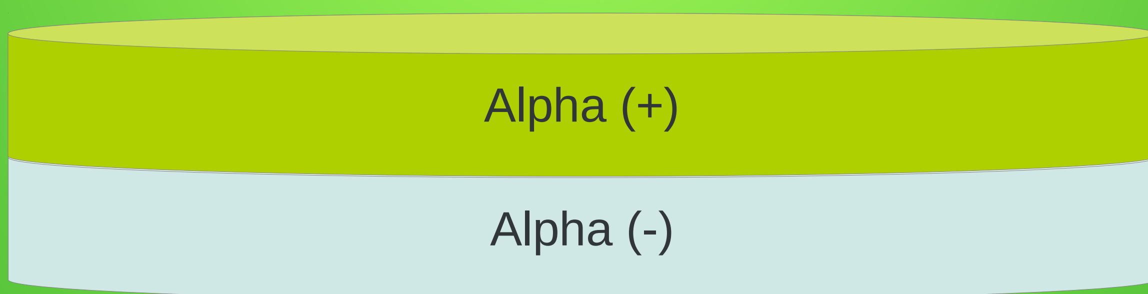




SPMHD - Tests

- Alpha-Omega
  - Mean field equations + Differential rotation



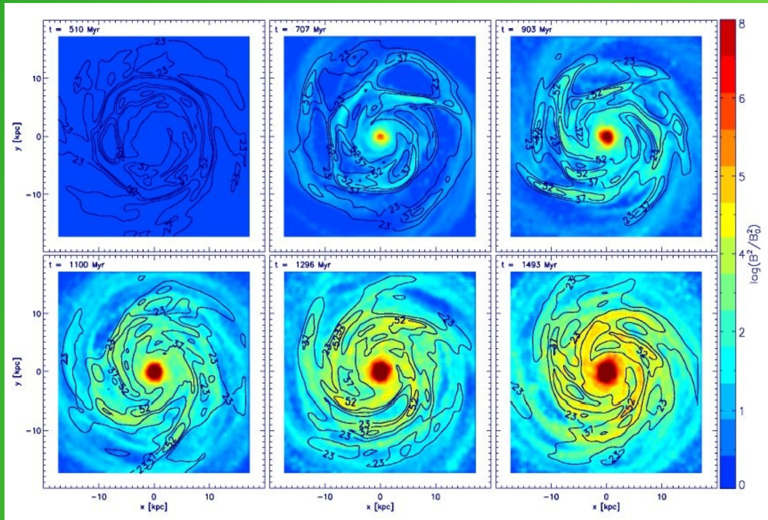


Summary

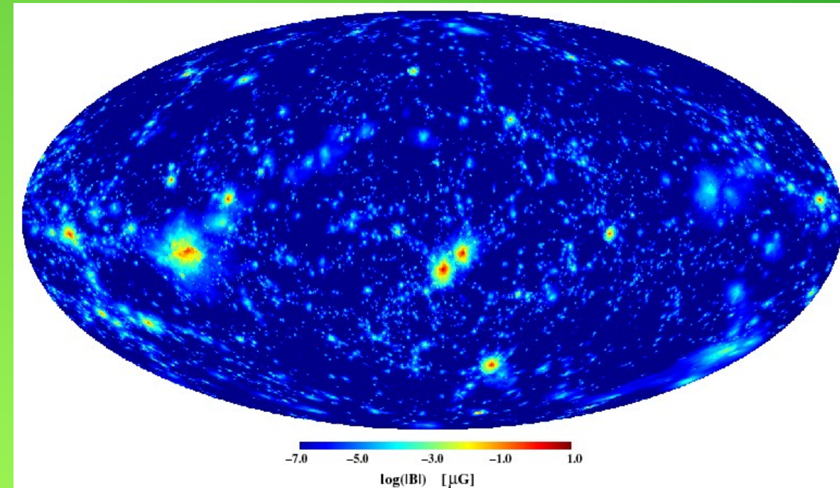
-SPH scheme is ready for Non-Ideal MHD.

-Testing and contrast with known solutions, “certifies” the code to be used in astrophysical simulations.

-The “new” approach is to work closely to validate and understand the physical process that are observed.



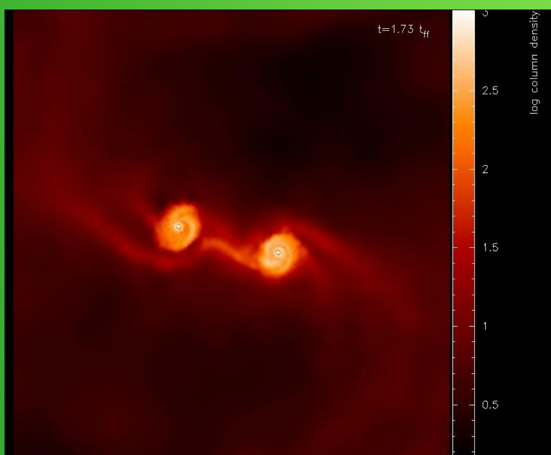
Galactic & Dynamo Action



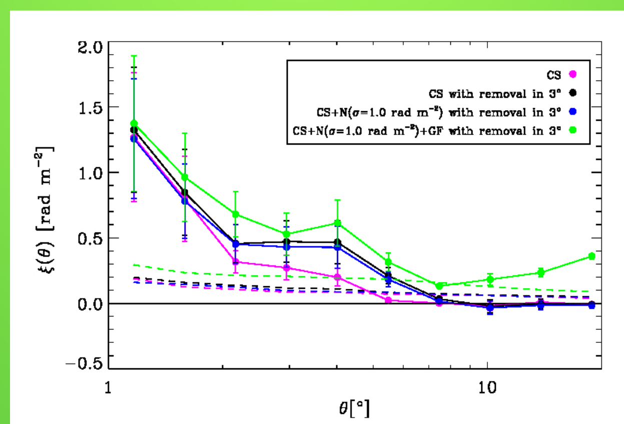
Cosmological MHD

Tools to study MF in a Global scope

Star Formation



RM Statistics



Galaxy Clusters