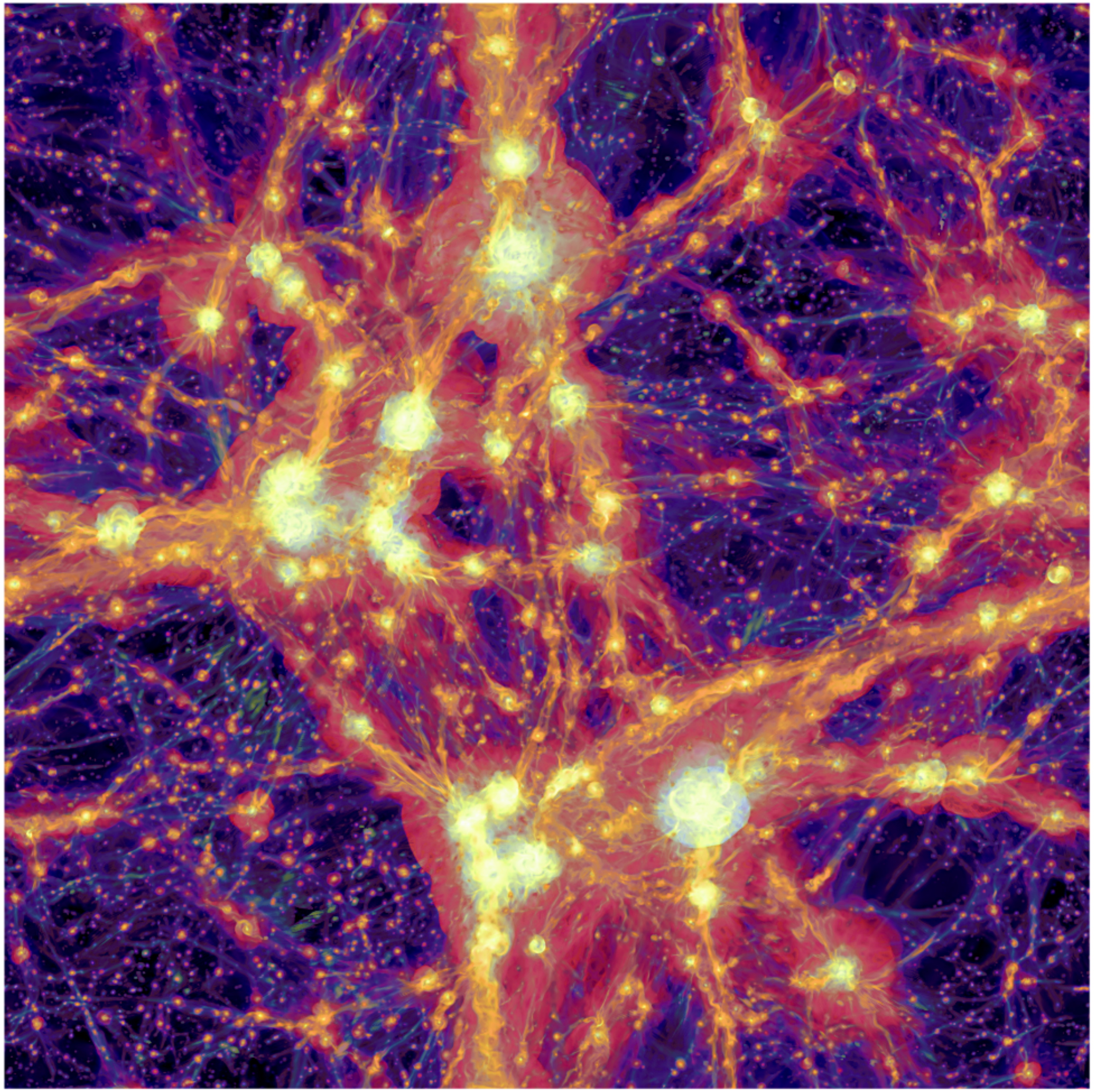
Traces of magnetogenesis in large-scale structures



Franco Vazza
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M. Brüggen, C. Gheller, G. Brunetti
D. Wittor, S.Hackstein, A. Bonafede,
P.M. Hinz, T. Jones, S. Ettori

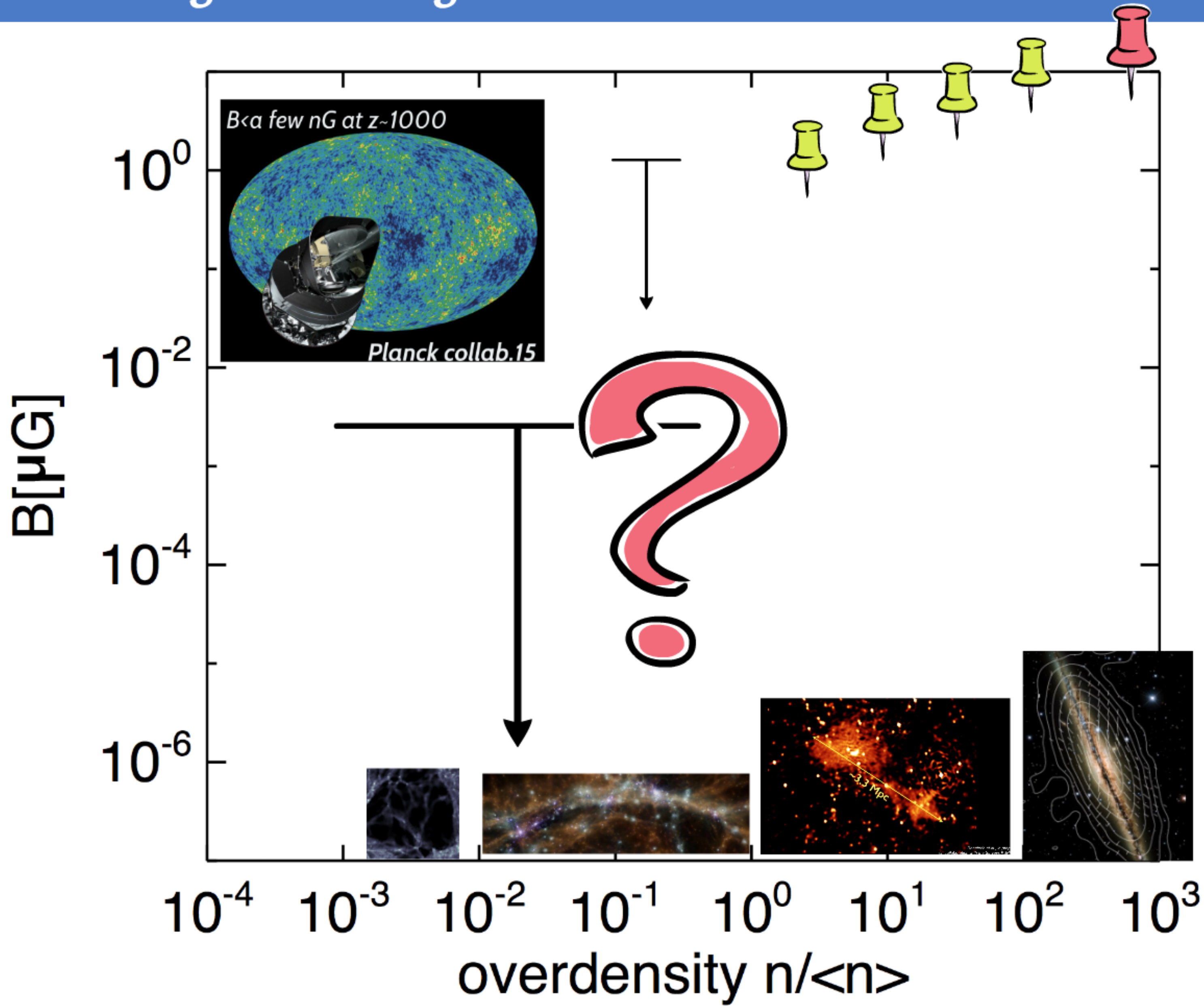
GSSI, 14. Feb 2018

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088

erc

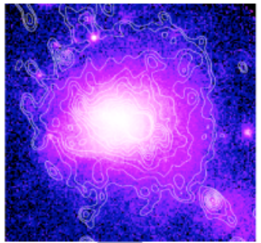
MAGCOW
ERC Starting Grant

Extragalactic magnetic fields: not much known.

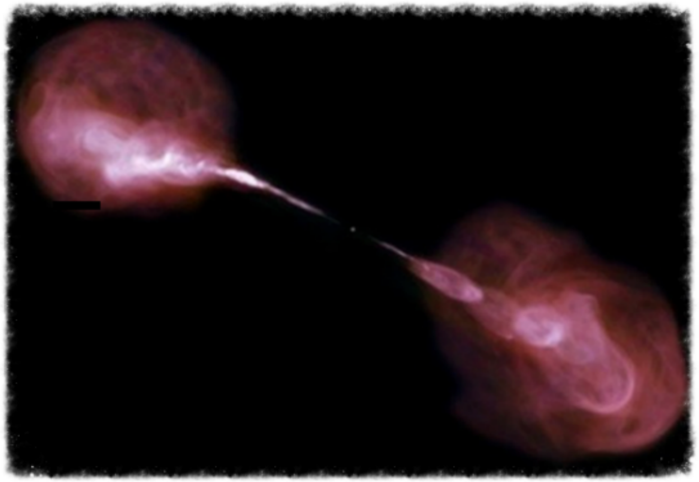


magnetic fields ~unknown for >99.99% of cosmic volume

Two scenarios for cosmogenesis



"ASTROPHYSICAL"

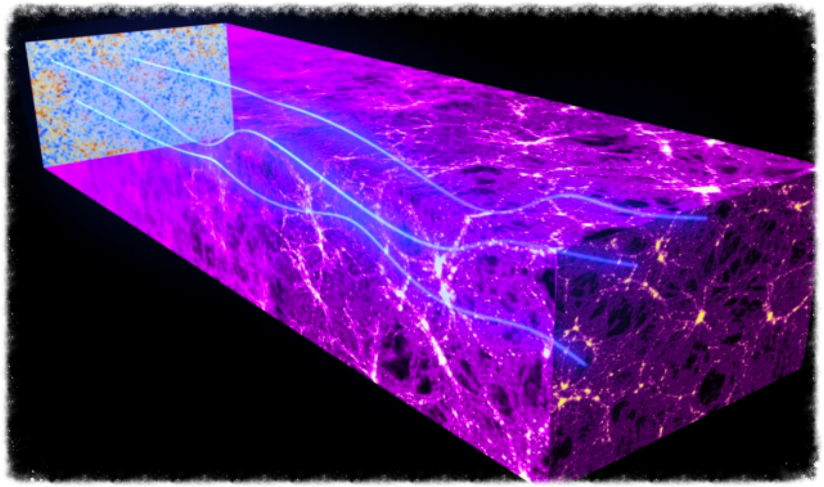


seeds from galaxy formation (z<6)

- "inside-out"
- star formation, AGN
- batteries, CR-dynamos

(sim: Kulsrud+98,Donnert+08,Xu+09,Beck+13)

"PRIMORDIAL"

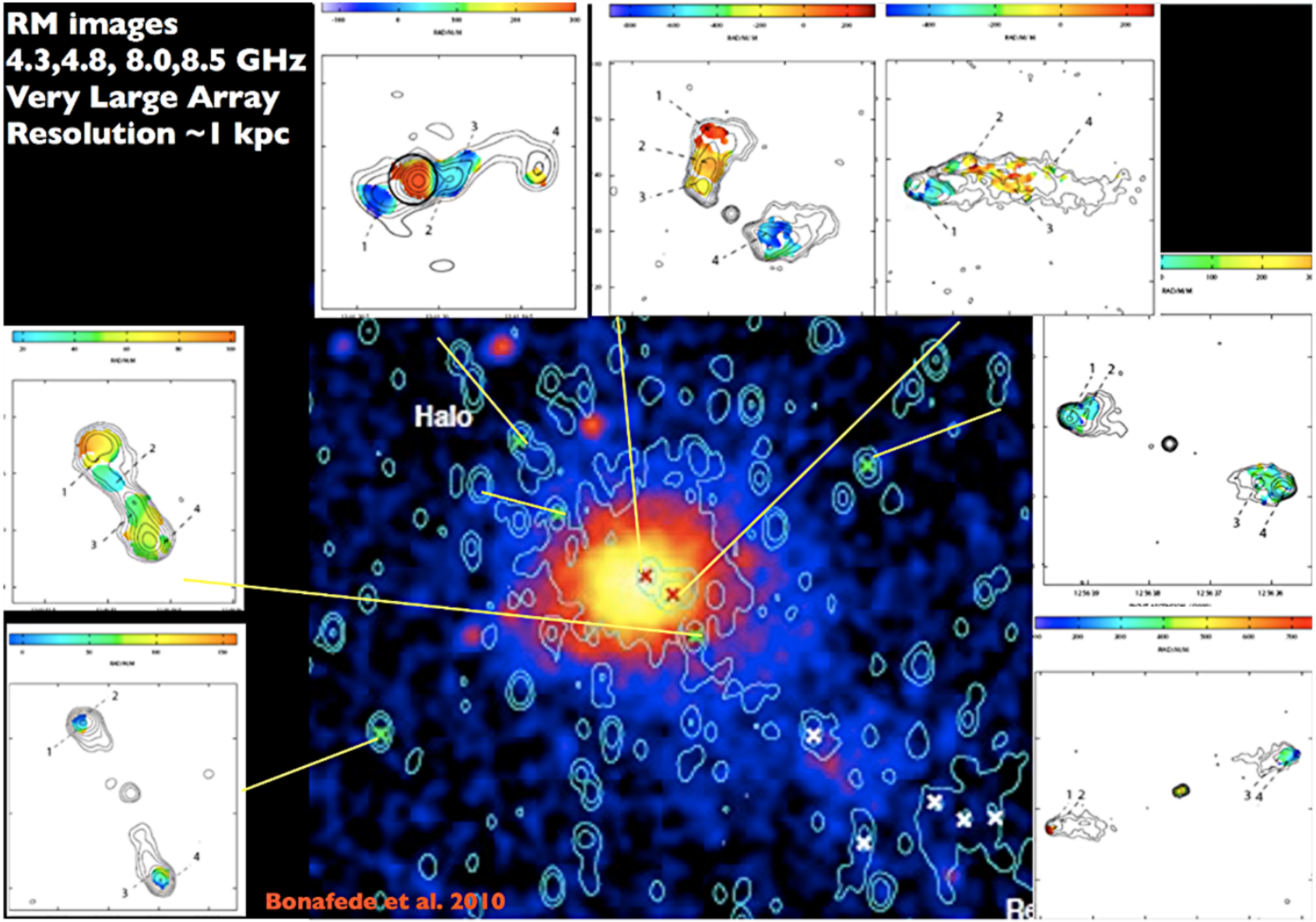


seeds from early Universe (z>1000):

- spatially unifrom
- inflation/phase transitions/baryogenesis...
- compression + amplification

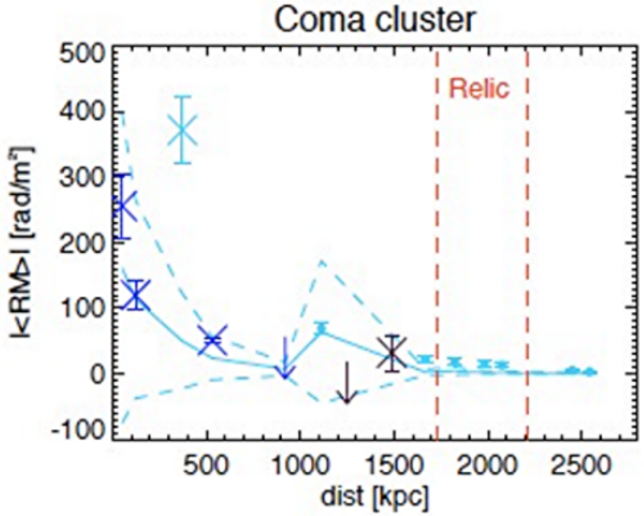
(sim: Dolag+99,Ryu+08,FV+14,Marinacci+15)

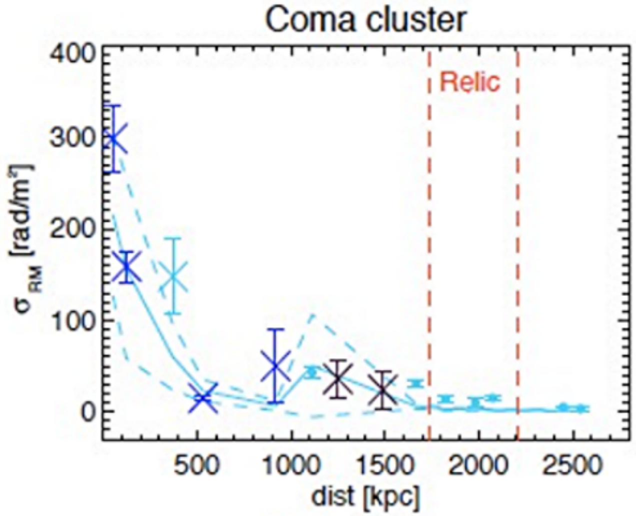
Faraday Rotation effect in the COMA cluster



From Faraday Rotation to the magnetic field profile

MOCK ROTATION MEASURE OBSERVATIONS



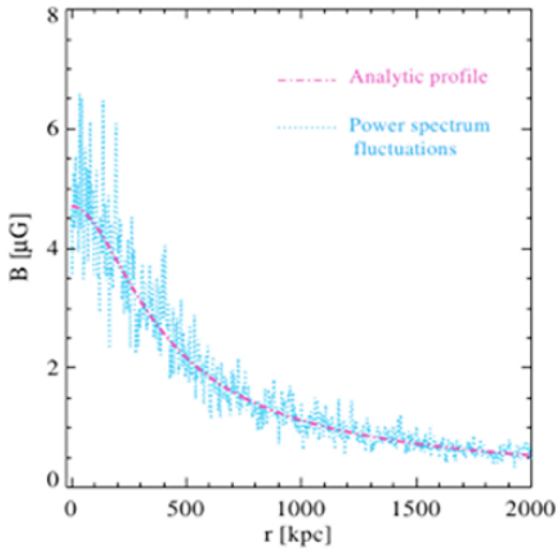


Results:

- field is tangled on <100kpc
- B scales as sqrt(n)

Assumptions to be tested:

- components are Gaussian
- power-law spectrum



$$B \propto B_0 n_{gas}^{\eta}$$

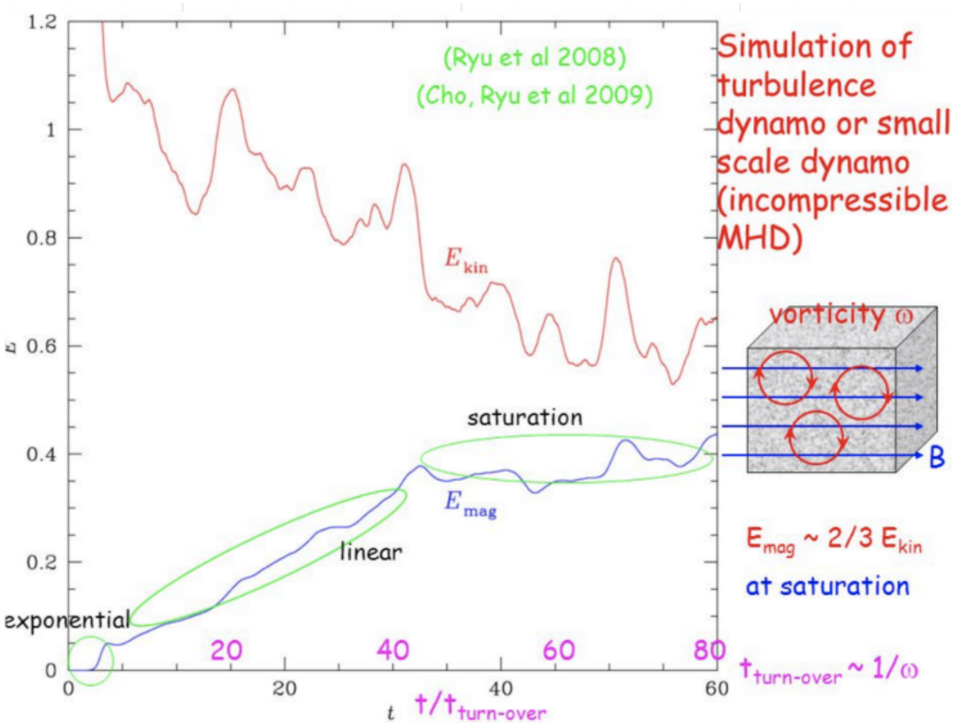
B0=4.7 μG,
η=0.5

from Bonafede+14

Small-scale dynamo in galaxy clusters

It seems necessary :

magnetic energy has grown >10,000 times from z~1000 >100 beyond gas compression



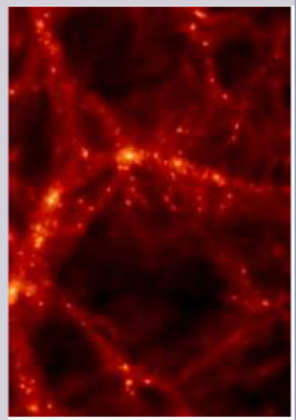
It is likely:

- gas continuously stirred by accretions/mergers
- low viscosity, large Reynolds number
- lots of seed fields

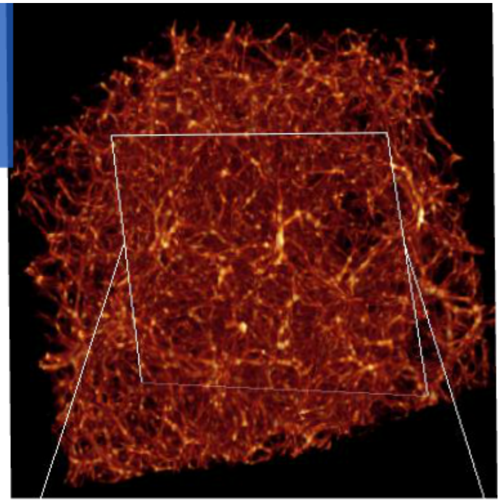
numerical simulations!

Challenging because high dynamical resolution is necessary:

$$R_e = \frac{\sigma_v L}{\nu} \approx \left(\frac{L}{2\Delta x}\right)^{4/3}$$



Structure formation on computers



INITIAL CONDITIONS: ~from CMB

INGREDIENTS: "baryons", dark matter

BASICS: expansion, gravity, & (mangeto)-hydrodynamics on a comoving stencil

$$\frac{\partial \rho}{\partial t} + \frac{1}{a}\nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \frac{1}{a}\nabla \cdot \left(\rho \mathbf{v}\mathbf{v} + \mathbf{I}p^* - \frac{\mathbf{B}\mathbf{B}}{a}\right) = -\frac{\dot{a}}{a}\rho \mathbf{v} - \frac{1}{a}\rho \nabla \phi$$

$$\frac{\partial E}{\partial t} + \frac{1}{a}\nabla \cdot \left[(E + p^*)\mathbf{v} - \frac{1}{a}\mathbf{B}(\mathbf{B}\cdot \mathbf{v})\right] = -\frac{\dot{a}}{a}\left(2E - \frac{B}{2}\right.$$

$$-\frac{\rho}{a}\mathbf{v}\cdot \nabla \phi - \Lambda + \Gamma + \frac{1}{a^2}\nabla \cdot \mathbf{F}_{\rm cond},$$

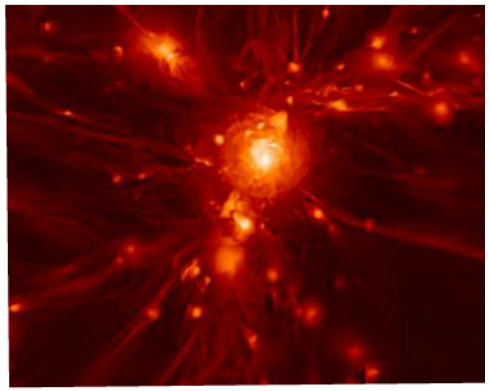
$$\frac{\partial \mathbf{B}}{\partial t} - \frac{1}{a}\nabla \times (\mathbf{v} \times \mathbf{B}) = 0.$$

FIXED/ADAPTIVE RESOLUTION

MORE PHYSICS: cooling, star formation, feedback, chemistry... and *magnetic fields*

MHD: *the* challenge is $\nabla \cdot B = 0$

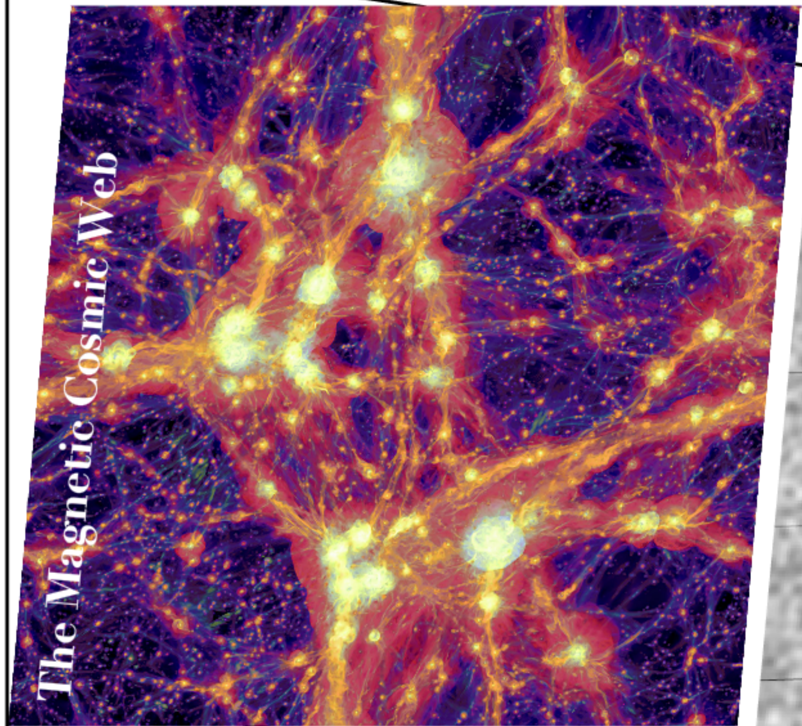
this talk: "**Dedner cleaning**" in the **ENZO CODE (Bryan+14)**

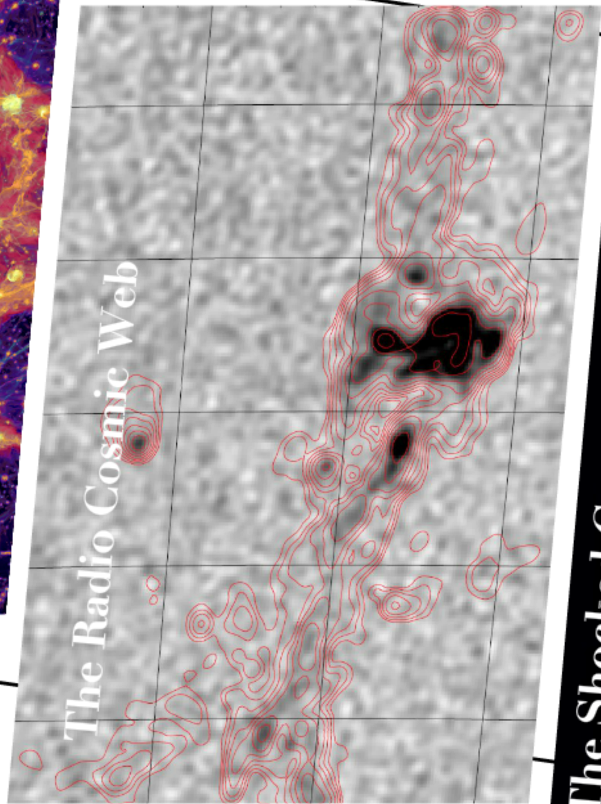


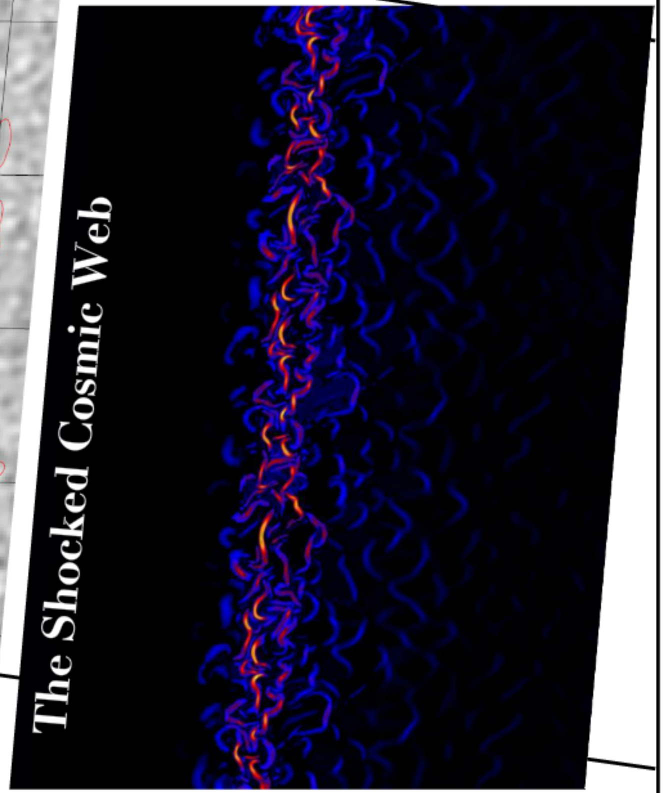
MAGCOW

Horizon 2020
European Union Funding
for Research & Innovation

What is the origin of extragalactic magnetic fields?
Can we detect the cosmic web in radio?







Università di Bologna
(Host Institution)

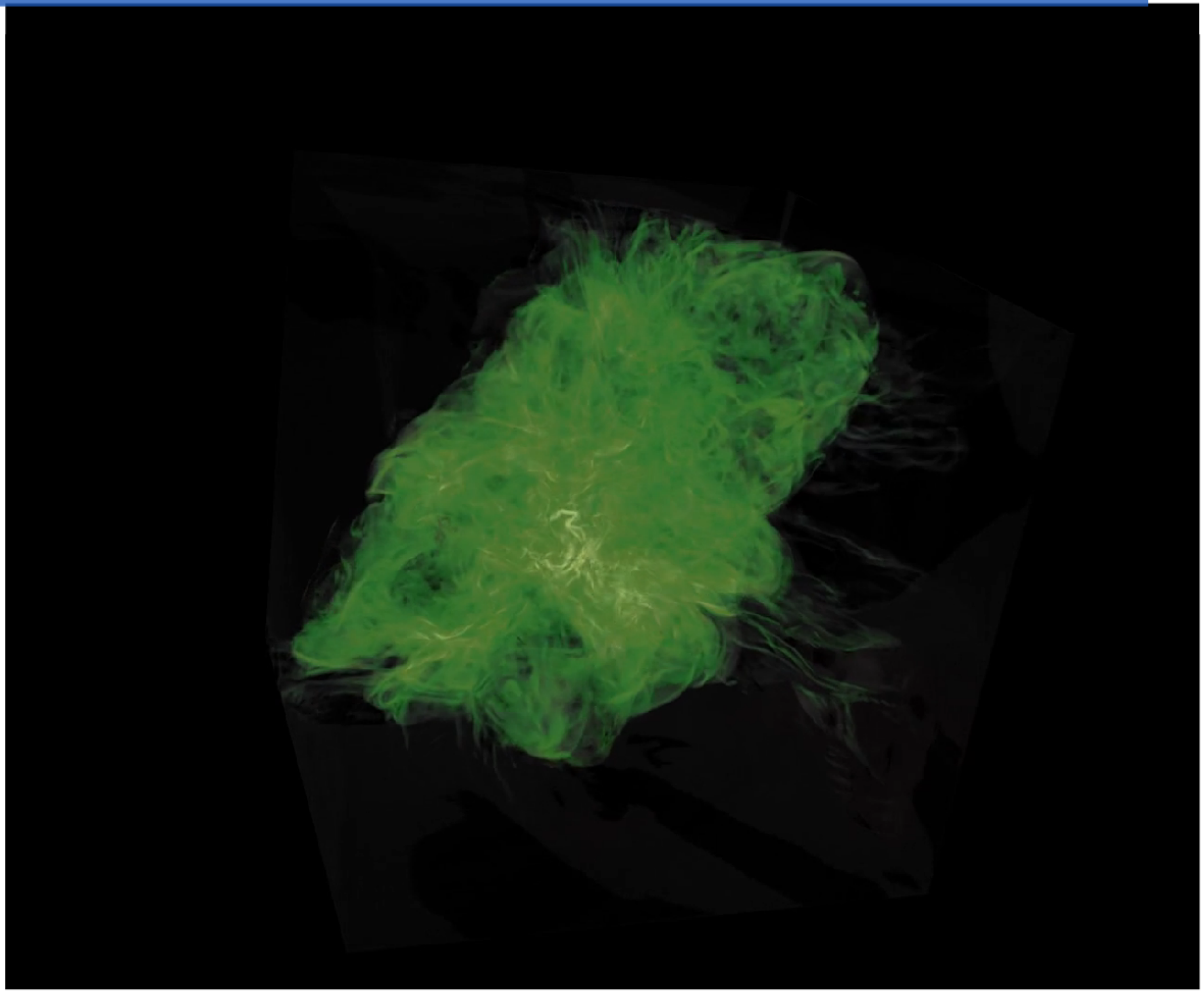
Universität Hamburg
(Secondary Host)

Principal Investigator:
Franco Vazza

ERC StG 2016

Turbulence (and vorticity) in the intracluster medium

FV, Jones et al. 2016 MNRAS
Wittor, Jones, FV & Bruggen+2017 MNRAS
(see also Beresnyak & Miniati 2015, Ryu+08)

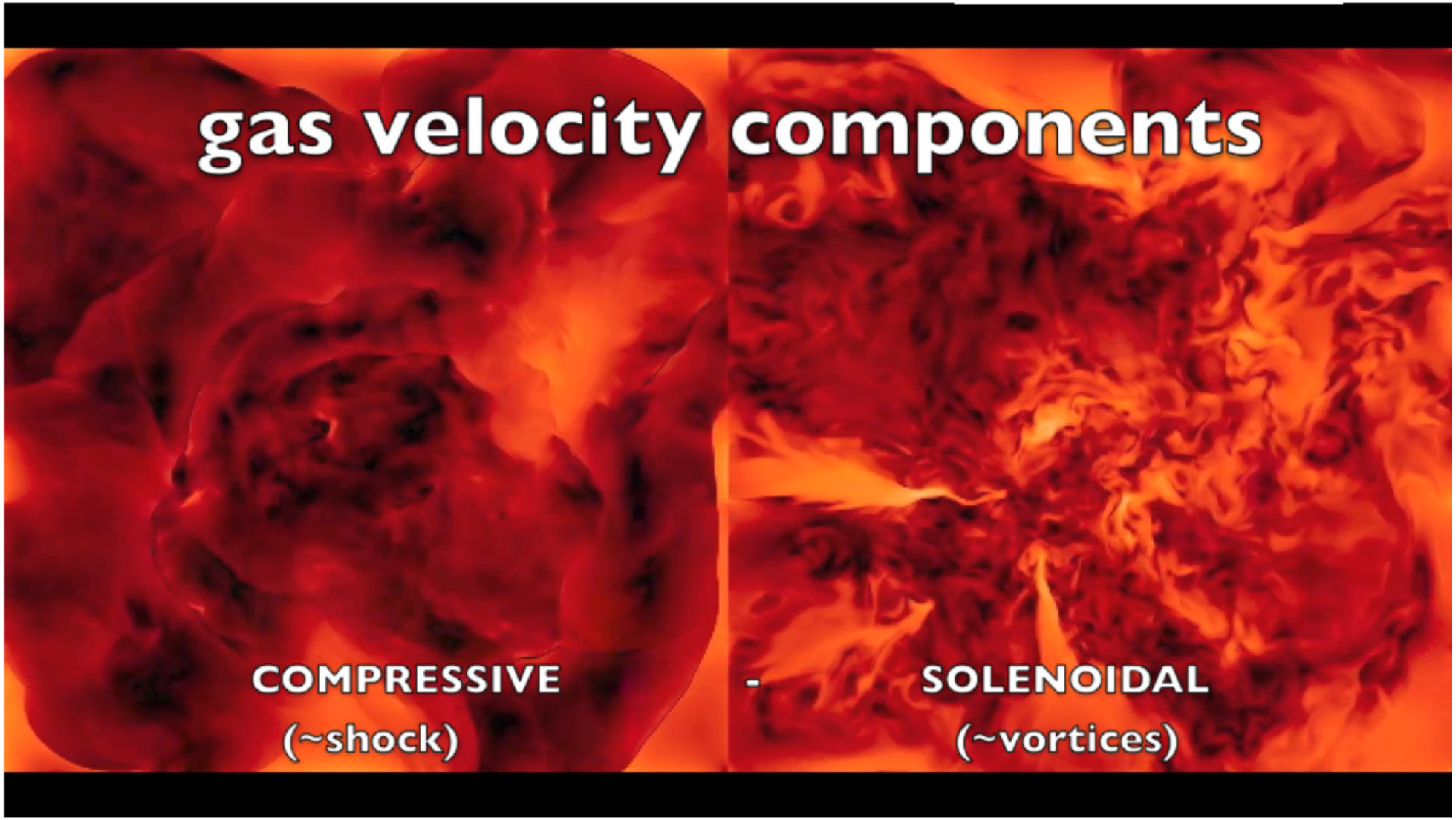


20 clusters, res=20kpc (static ref.), ~260,000 core hours on ITASCA (Uni.Minnesota)

Compressive vs Solenoidal turbulent modes

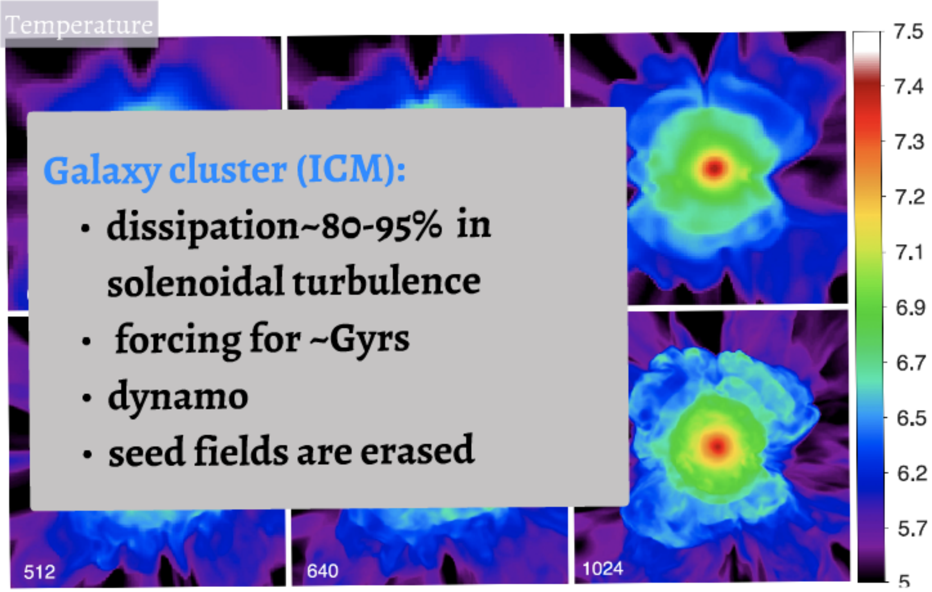
flux is soleno
available fo
dynamo

$$\nabla \times \vec{v}_c = 0 \qquad \nabla \cdot \vec{v}_s = 0$$



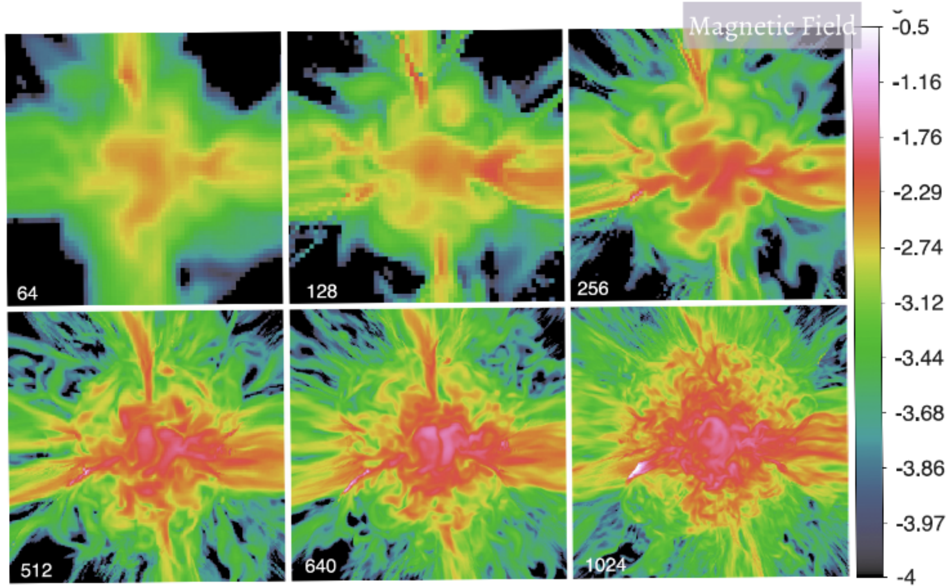
FV, Jones et al. 2016 MNRAS

Amplification in clusters and in filaments



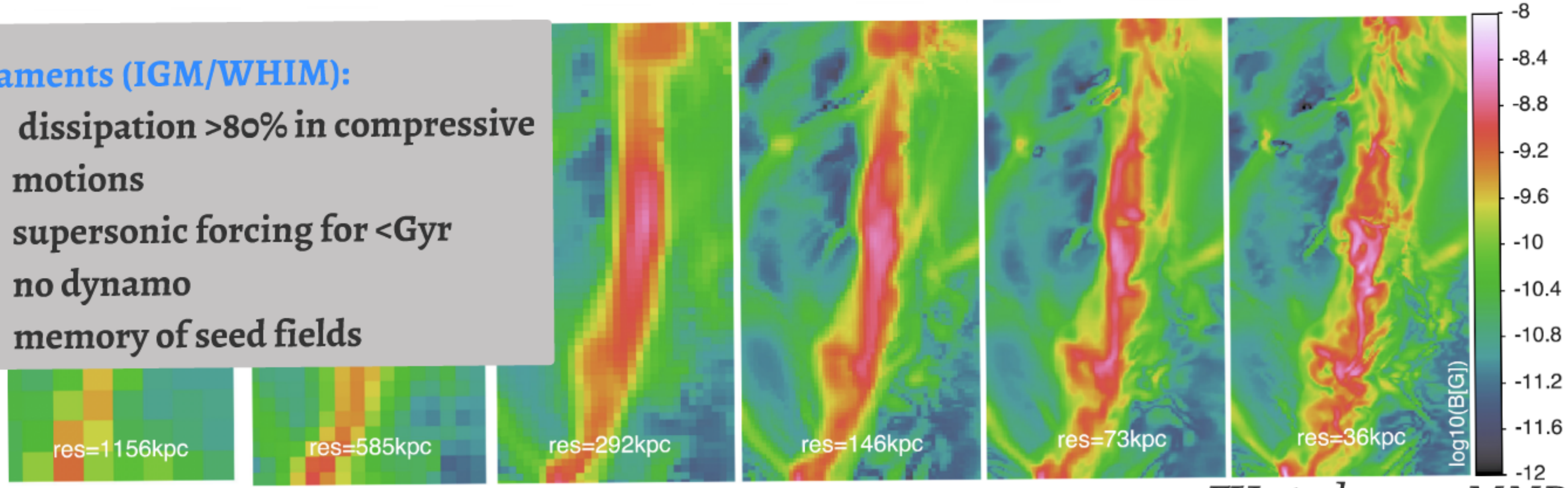
Galaxy cluster (ICM):

- dissipation~80-95% in solenoidal turbulence
- forcing for ~Gyrs
- dynamo
- seed fields are erased



Filaments (IGM/WHIM):

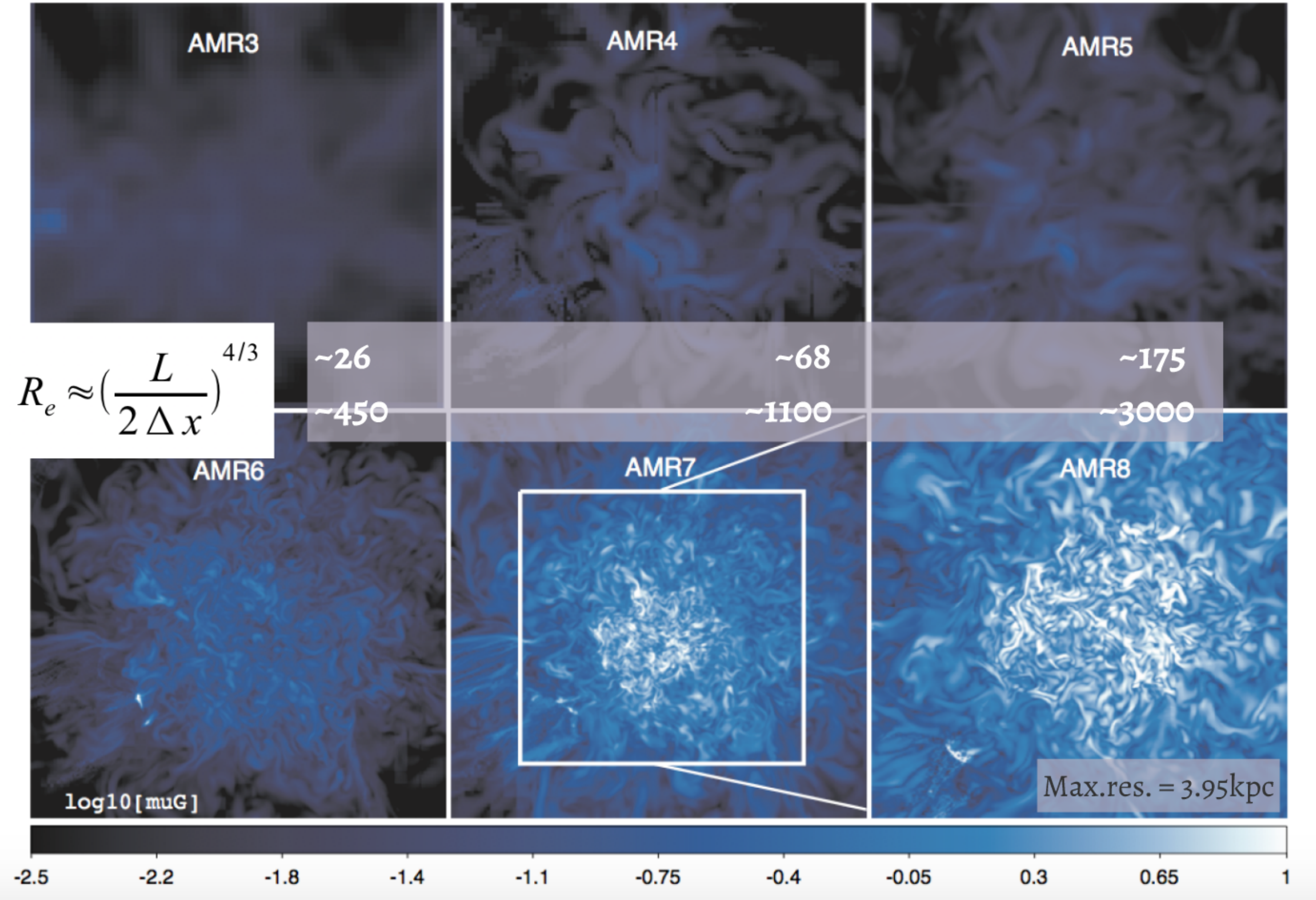
- dissipation >80% in compressive motions
- supersonic forcing for <Gyr
- no dynamo
- memory of seed fields

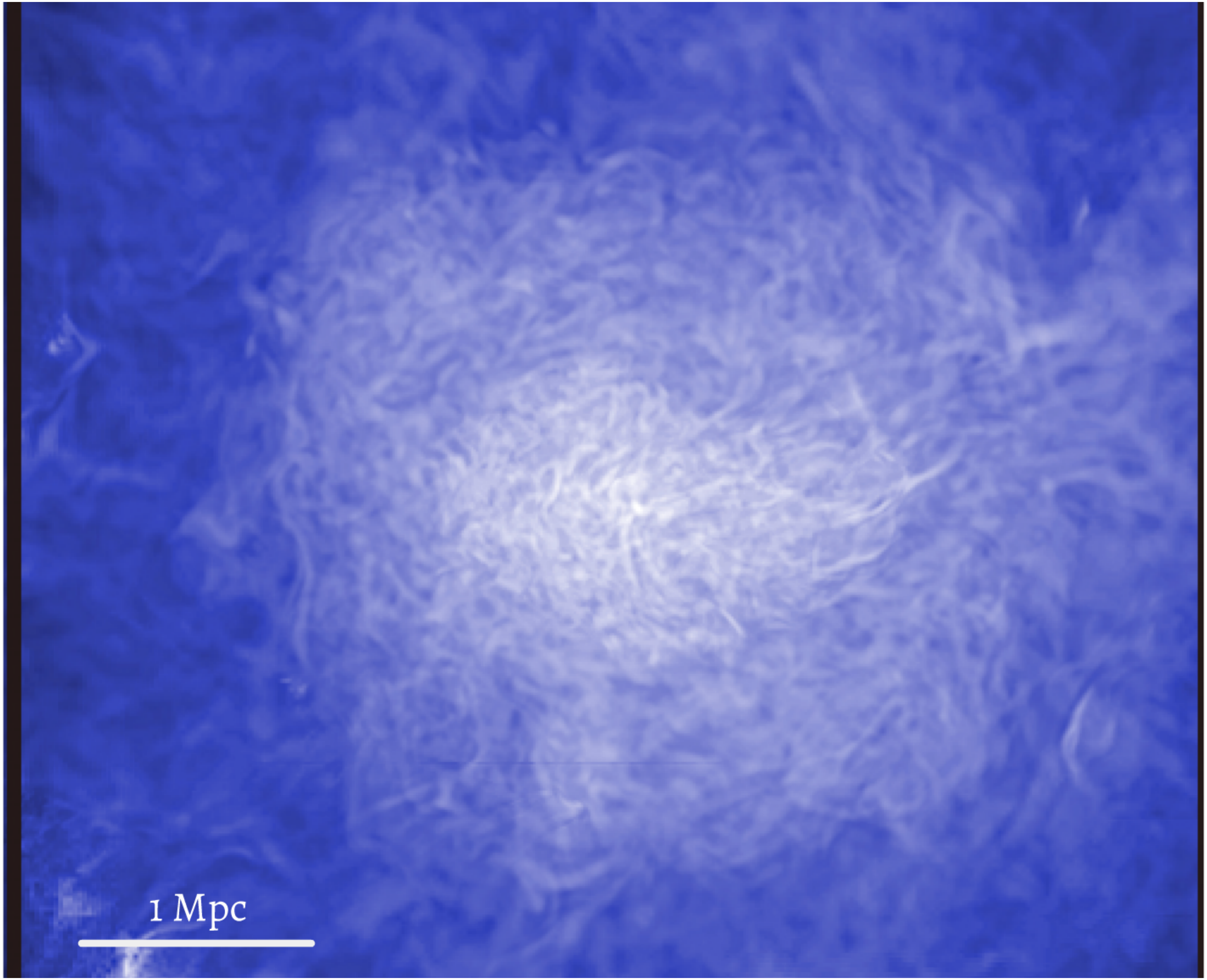


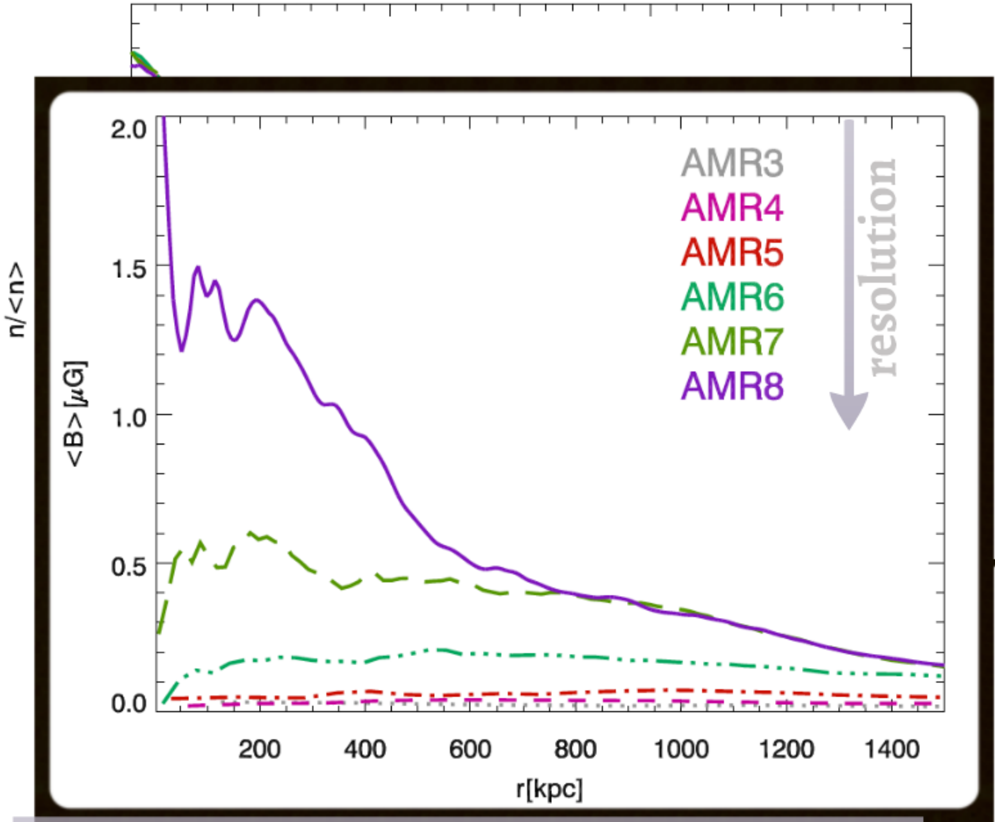
FV et al. 2014 MNRAS

(Recently) resolved non-linear dynamo in clusters

FV, Brunetti, Brüggen, Bonafede 2017 MNRAS



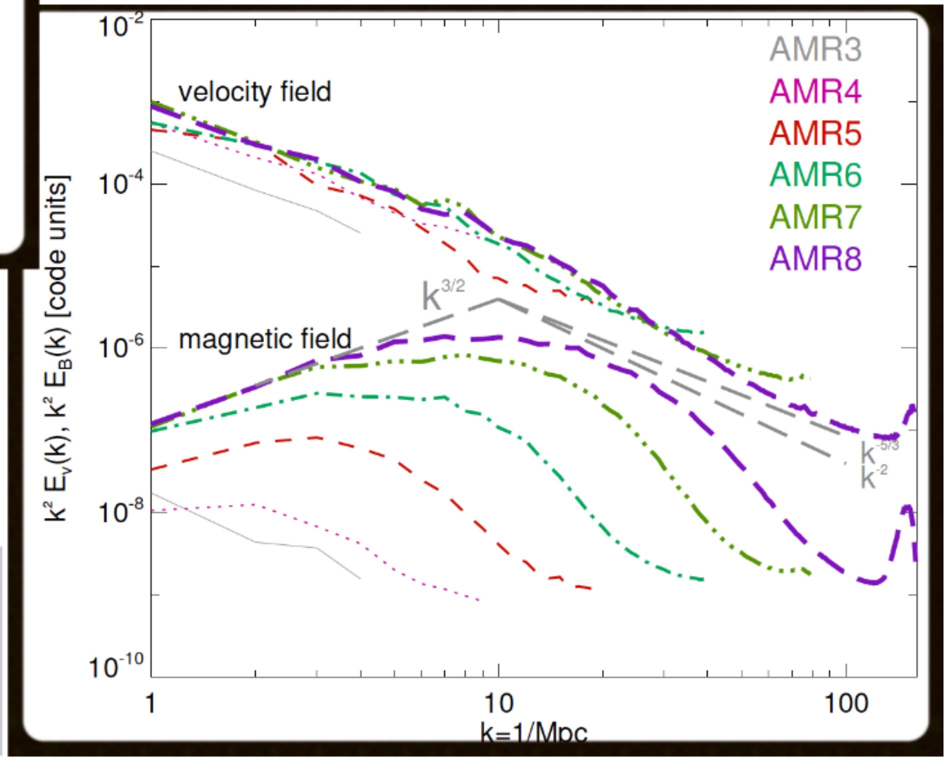

1 Mpc



Magnetic field PROFILE:
field grows up to ~2μG

PDF of magnetic field strength:
increasingly *less* Maxellian

Magnetic POWER SPECTRA:
not a power law



Are we sure this is a dynamo?

"MHD-scale" resolved in ~50% of volume

$$l_A \approx 0.3\text{kpc}(\frac{B}{\mu\text{G}})^3 \frac{L}{\text{kpc}}(\frac{n}{10^{-3}\text{part}/\text{cm}^3})^{-3/2}(\frac{\sigma_L}{\text{km/s}})^3$$

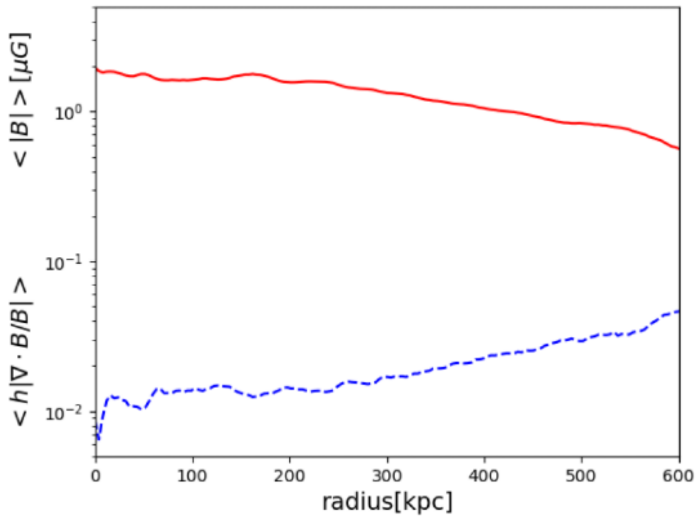
Curvature of field lines as in dynamo

$$\vec{K} = \frac{(\vec{B}\cdot\nabla)\vec{B}}{|B^2|}$$

Magnetic energy follows dissipation of turbulent kin. energy

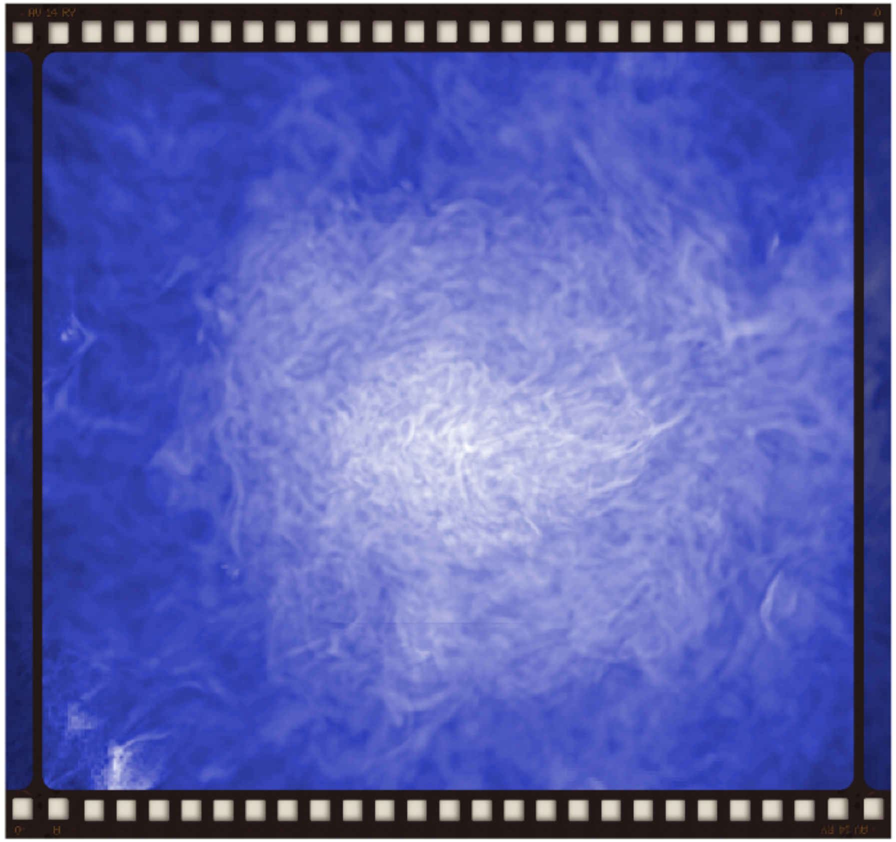
$$B_{\text{turb}} = [8\pi \int_t C_E \epsilon_s dt]^{0.5}$$

Spurious magnetic divergence is small

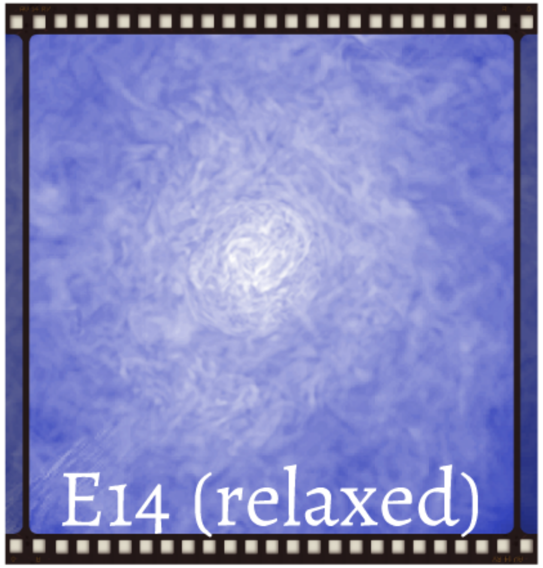


It looks very plausible.

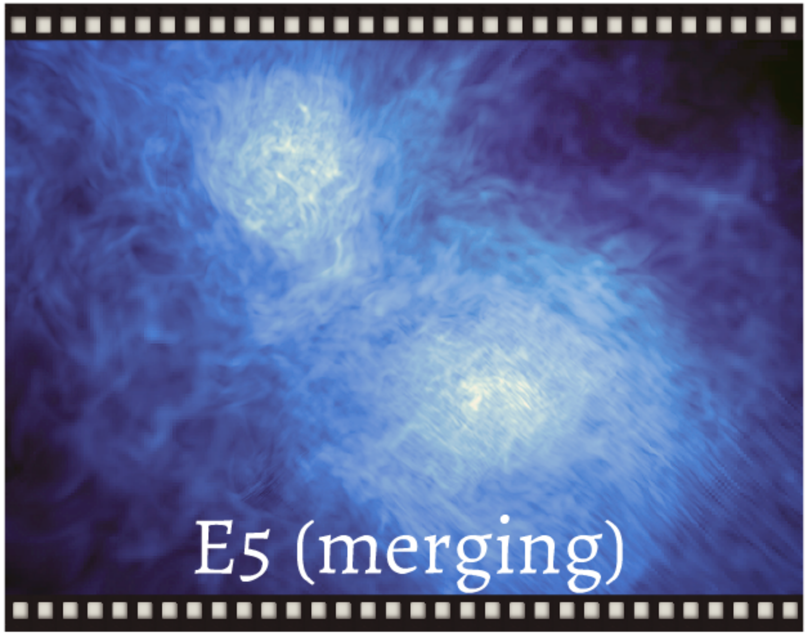
What about other clusters? (work in prog.)



E18B (post-merger)

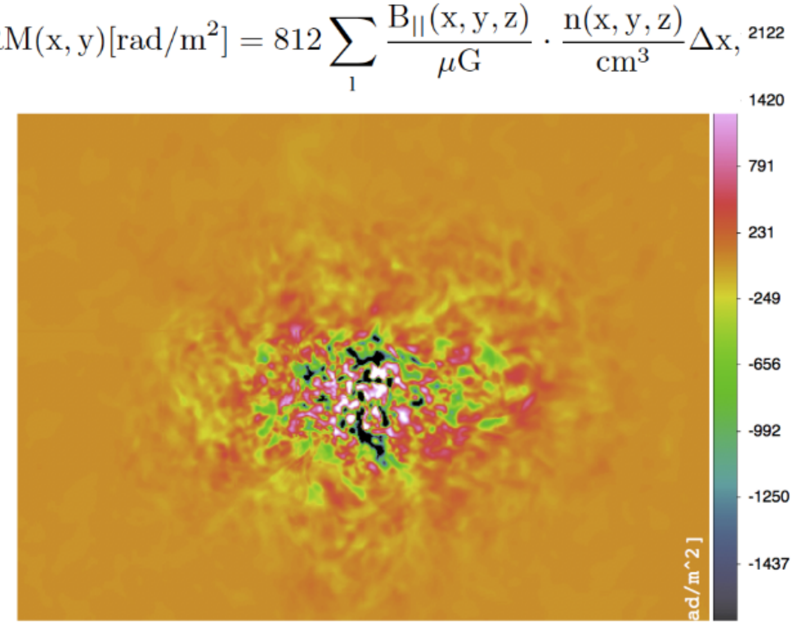


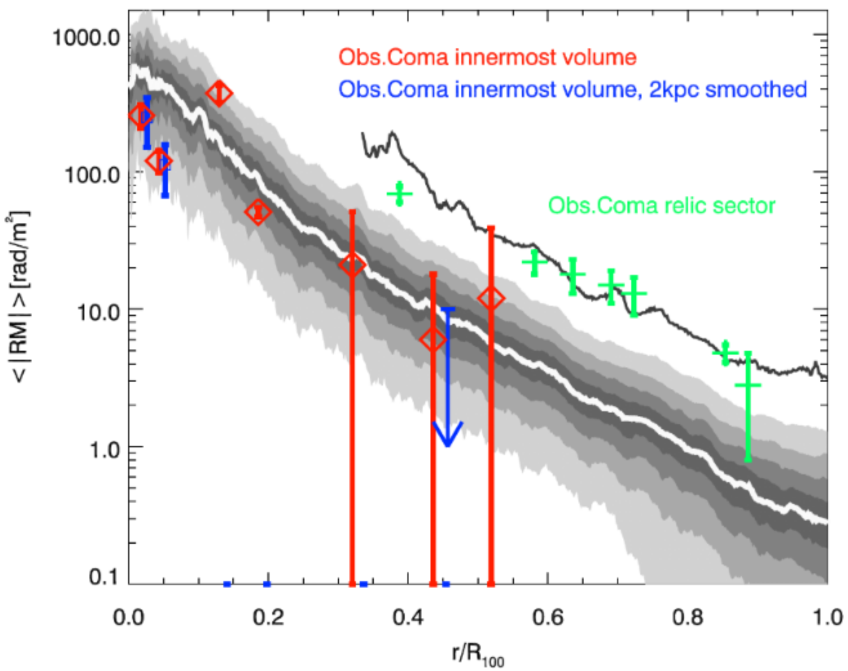
E14 (relaxed)



E5 (merging)

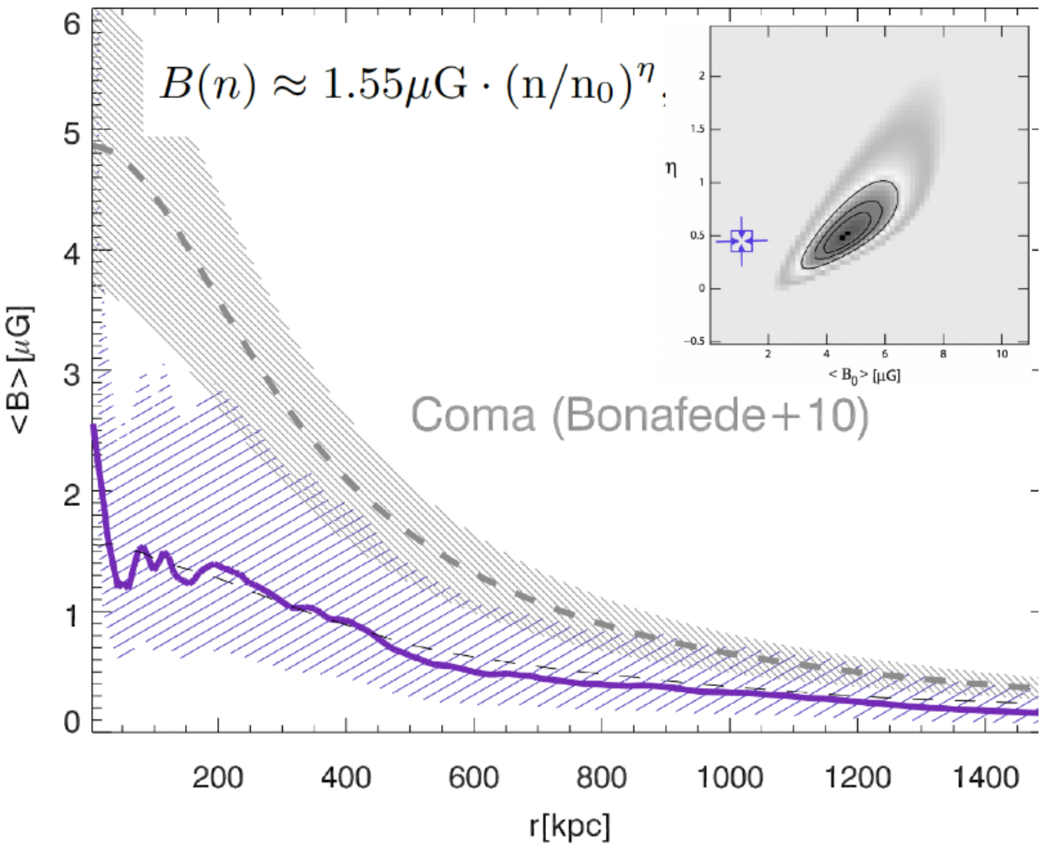
$$\mathrm{RM}(x,y)[\mathrm{rad/m^2}] = 812 \sum_{l} \frac{B_{||}(x,y,z)}{\mu G} \cdot \frac{n(x,y,z)}{cm^3} \Delta x,$$



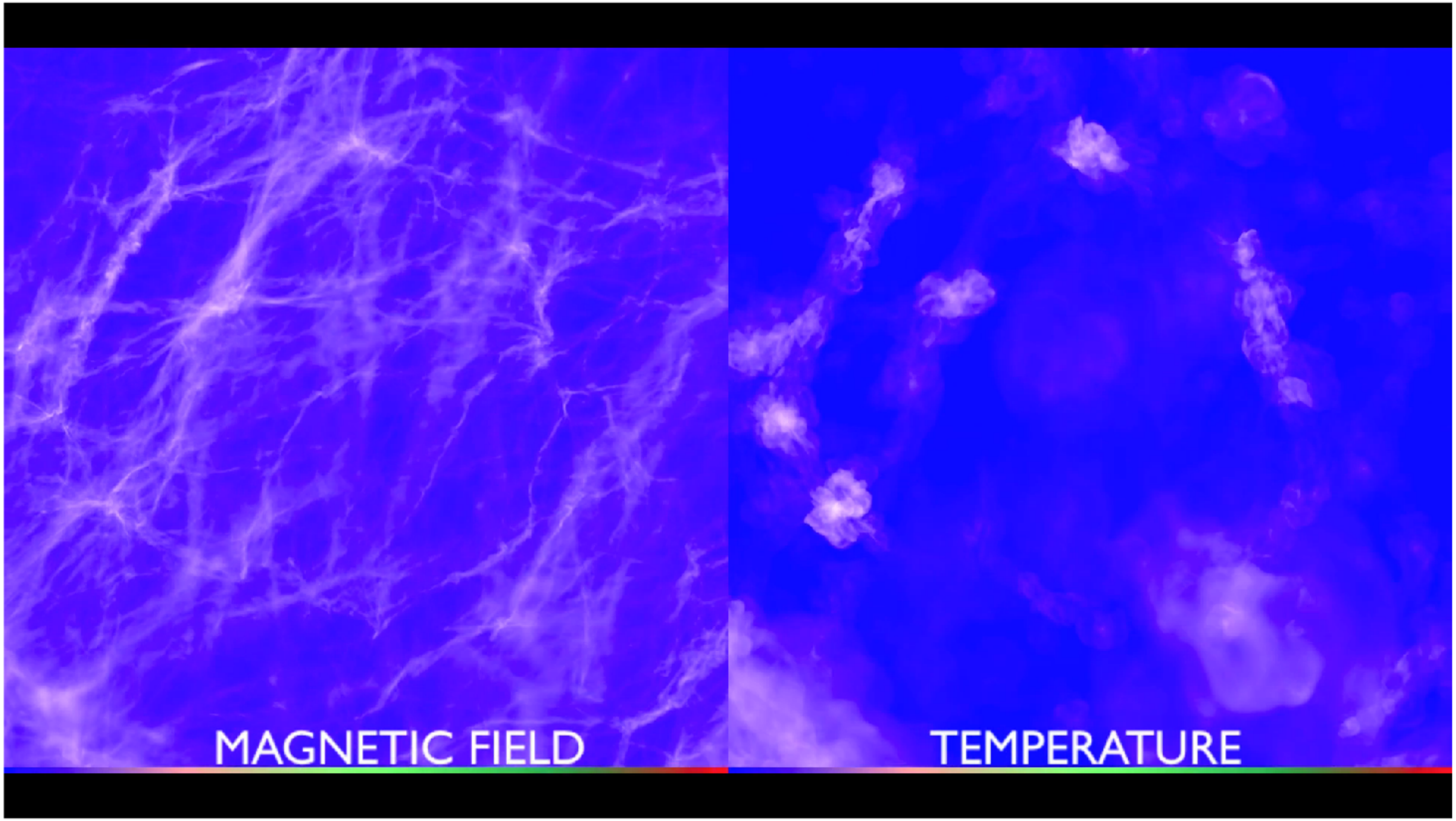


Faraday Rotation Measure:

- good match with observations
- "standard" model of B-field in Coma **needs to be revised?**



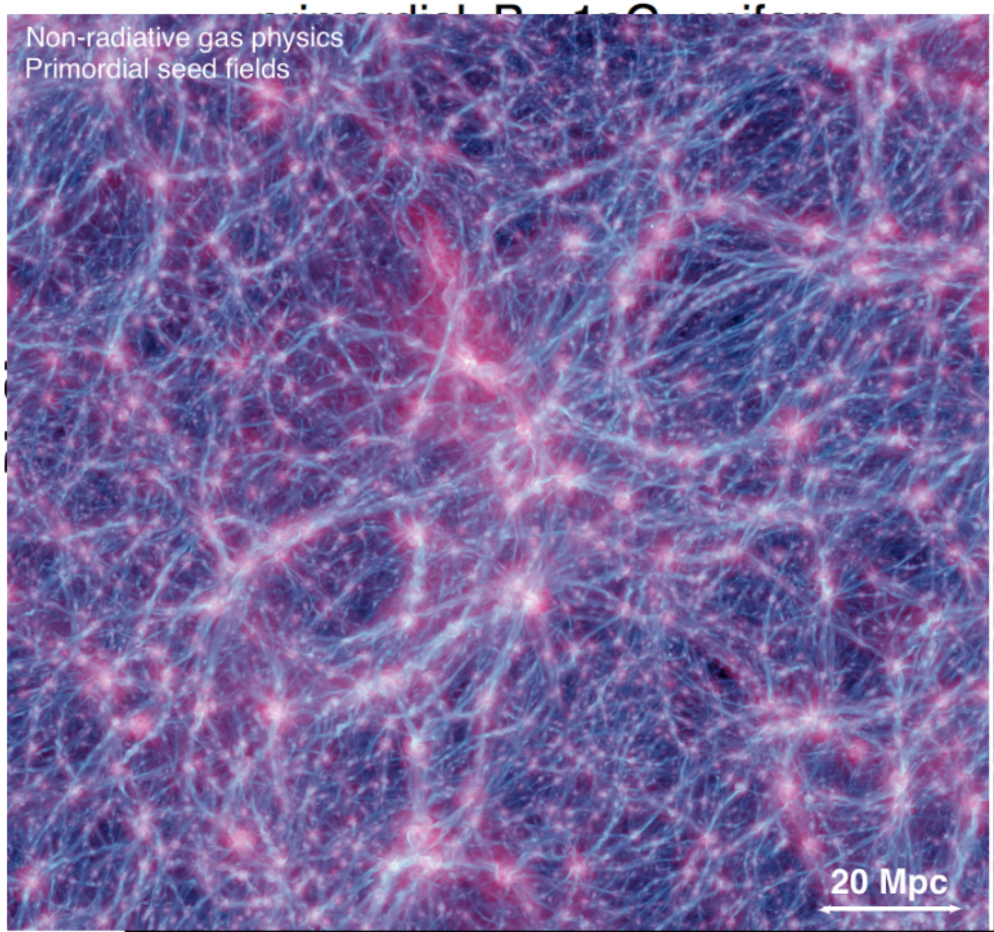
CHRONOS++: new large simulations of extragalactic magnetic fields

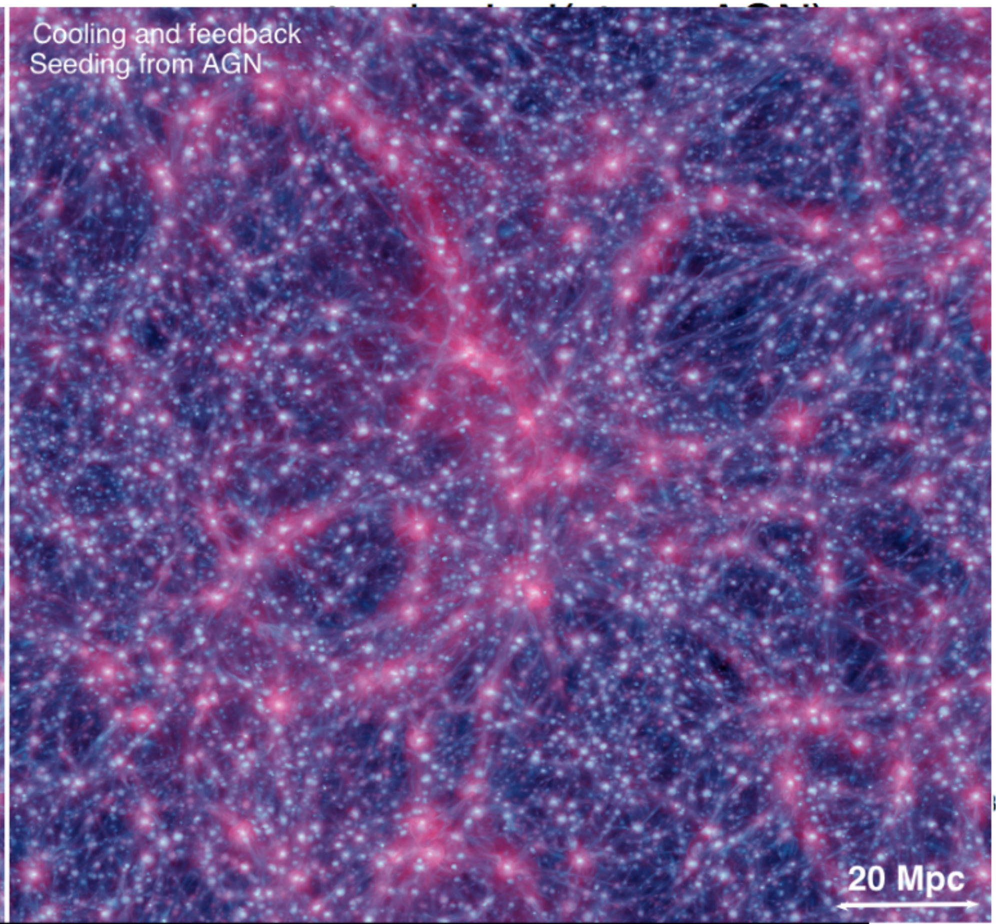


- ENZO-MHD on the GPU: ~32 million core hours on Piz-Daint CSCS (Lugano)
- Largest (grid) simulations of magnetism to-date (2400^3).   A 3460^3 run is underway…

"Primordial" vs "Astrophysical" scenarios to the test

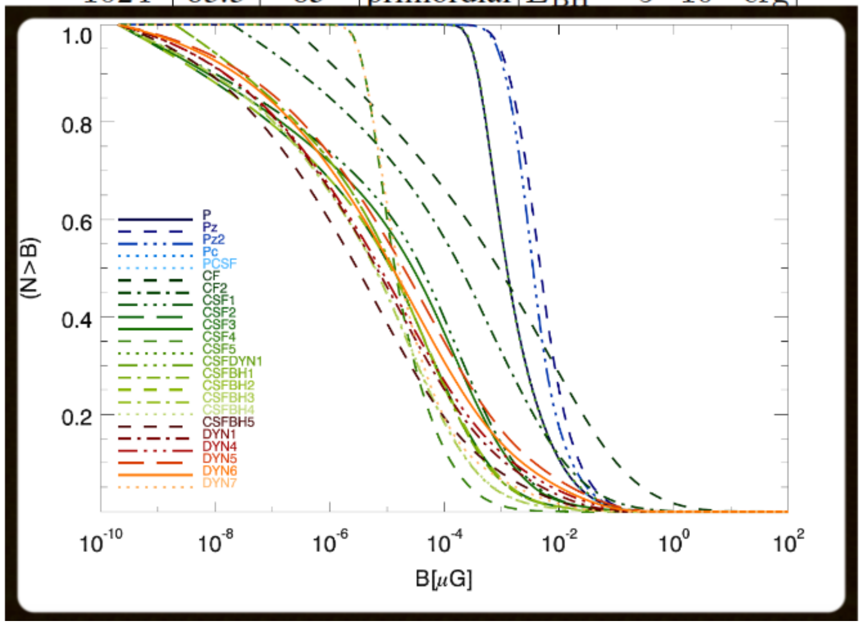
FV et al. 2017, Classical and Quantum Gravity





- Galaxy formation coupled to seeding of magnetic fields (res~80kpc)
- >20 seeding models magnetic fields.

$N_{\rm grid}$	Δx [kpc]	$L_{\rm box}$ [Mpc]	cooling	BH feedback	SF feedback	B_0 [nG]	other sources of B	ID
2400^3	83.3	200	n	n	n	1	n	P
2400^3	83.3	200	primordial	$E_{\rm BH} = 10^{58}$erg	n	0.01	AGN ($\epsilon_B = 0.01$)	CF1
2400^3	83.3	200	primordial	$E_{\rm BH} = 5 \cdot 10^{59}$erg	n	0.01	AGN ($\epsilon_B = 0.01$)	CF2
1024^3	83.3	85	n	n	n	1	no	P
1024^3	83.3	85	n	n	n	1 (Zeld.)	no	Pz
1024^3	83.3	85	n	n	n	1 (Zeld. 2nd)	no	Pz2
1024^3	83.3	85	n	n	n	10^{-9}	dynamo, $\epsilon_{\rm dyn}(\mathcal{M})$	DYN1
1024^3	83.3	85	n	n	n	10^{-9}	dynamo, $\epsilon_{\rm dyn} = 0.02$	DYN4
1024^3	83.3	85	n	n	n	10^{-9}	dynamo, $10 \cdot \epsilon_{\rm dyn}(\mathcal{M})$	DYN5
1024^3	83.3	85	n	n	n	10^{-9}	dynamo, $\epsilon_{\rm dyn} = 0.1$	DYN6
1024^3	83.3	85	n	n	n	10^{-9}	dynamo, $\epsilon_{\rm dyn}(\mathcal{M}) = 0.04$	DYN7
1024^3	83.3	85	n	n	n	1	dynamo, $\epsilon_{\rm dyn}(\mathcal{M})$	DYN8
1024^3	83.3	85	primordial	n	n	1	n	C
1024^3	83.3	85	primordial	$E_{\rm BH} = 10^{58}$erg	n	10^{-9}	AGN($\epsilon_b = 0.01$)	CF1
1024^3	83.3	85	primordial	$E_{\rm BH} = 5 \cdot 10^{59}$erg	n	10^{-9}	AGN($\epsilon_b = 0.01$)	CF2
					$= 10^{-8}$	10^{-9}	$\epsilon_{b,SF} = 0.01$	CSF1
					$= 10^{-7}$	10^{-9}	$\epsilon_{b,SF} = 0.1$	CSF2
					$= 10^{-6}$	10^{-9}	$\epsilon_{b,SF} = 0.1$	CSF3
					$= 10^{-7}$	1	no	CSF4
					$= 10^{-8}$	0.01	$\epsilon_{b,SF} = 0.1$	CSF5
					$= 10^{-8}$	10^{-9}	$\epsilon_{b,SF} = 0.1$, $\epsilon_{b,BH} = 0.01$	CSFBH1
					$= 10^{-8}$	10^{-9}	$\epsilon_{b,SF} = 0.1$, $\epsilon_{b,BH} = 0.01$	CSFBH2
					$= 10^{-6}$	10^{-9}	$\epsilon_{b,SF} = 0.1$, $\epsilon_{b,BH} = 0.1$	CSFBH3
					$= 10^{-6}$	10^{-9}	$\epsilon_{b,SF} = 0.1$, $\epsilon_{b,BH} = 0.1$	CSFBH4
					$= 10^{-6}$	10^{-9}	$\epsilon_{b,SF} = 0.1$, $\epsilon_{b,BH} = 0.1$	CSFBH5
					$= 10^{-6}$	1	$\epsilon_{b,SF} = 0.1$, dynamo $\epsilon_{\rm dyn}(\mathcal{M})$	CSFDYN1



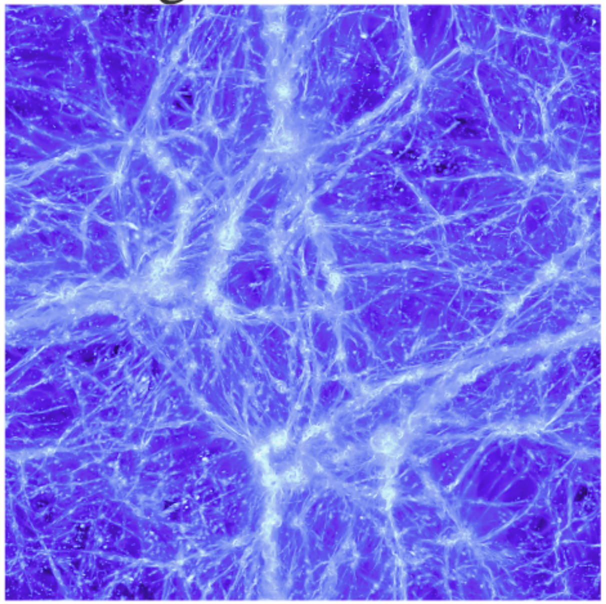
Magnetogensis is a key driver of the SKA (and precursors)

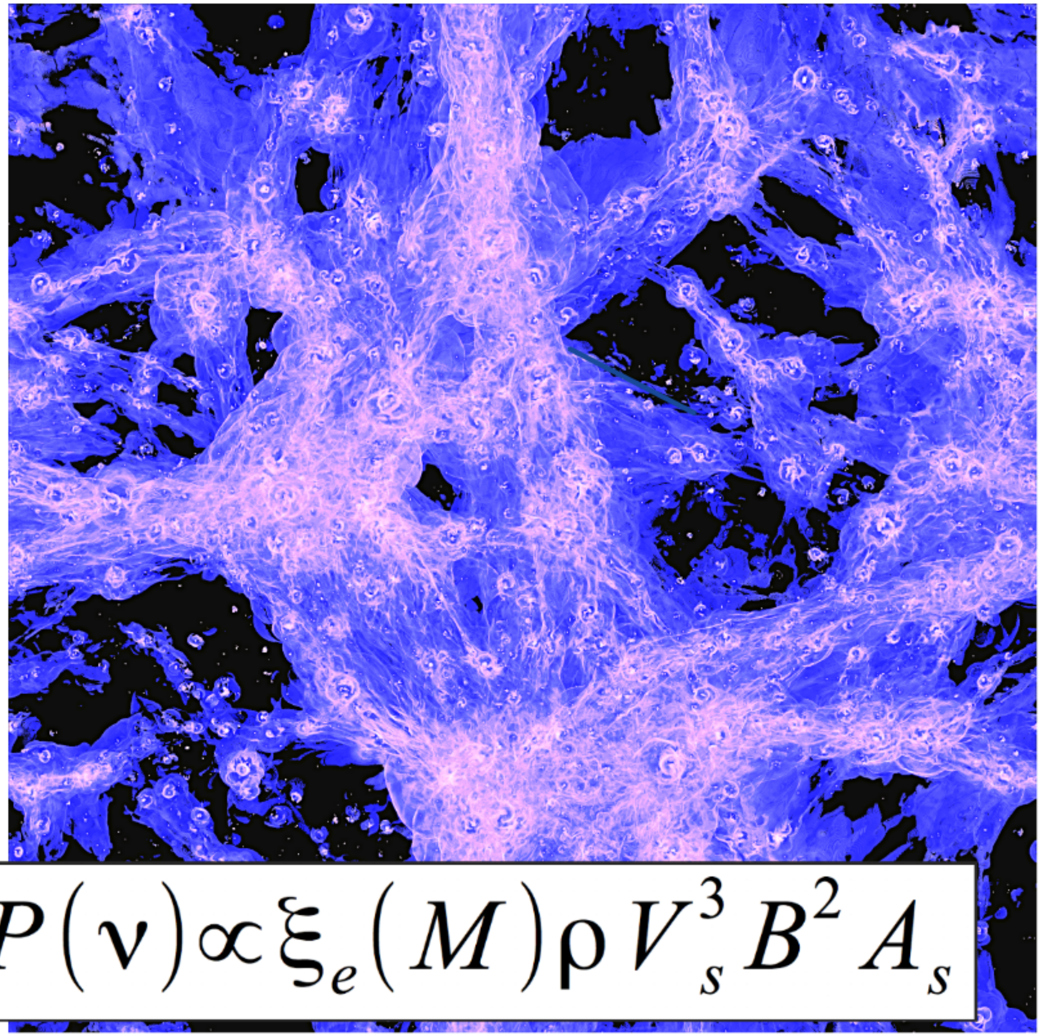
Can radio telescopes detect the tip of the "radio cosmic web"?

The radio/shocked cosmic web

FV, Ferrari, Brüggen+2015 AA

Magnetic fields





Synchrotron from shock-accelerated electrons:

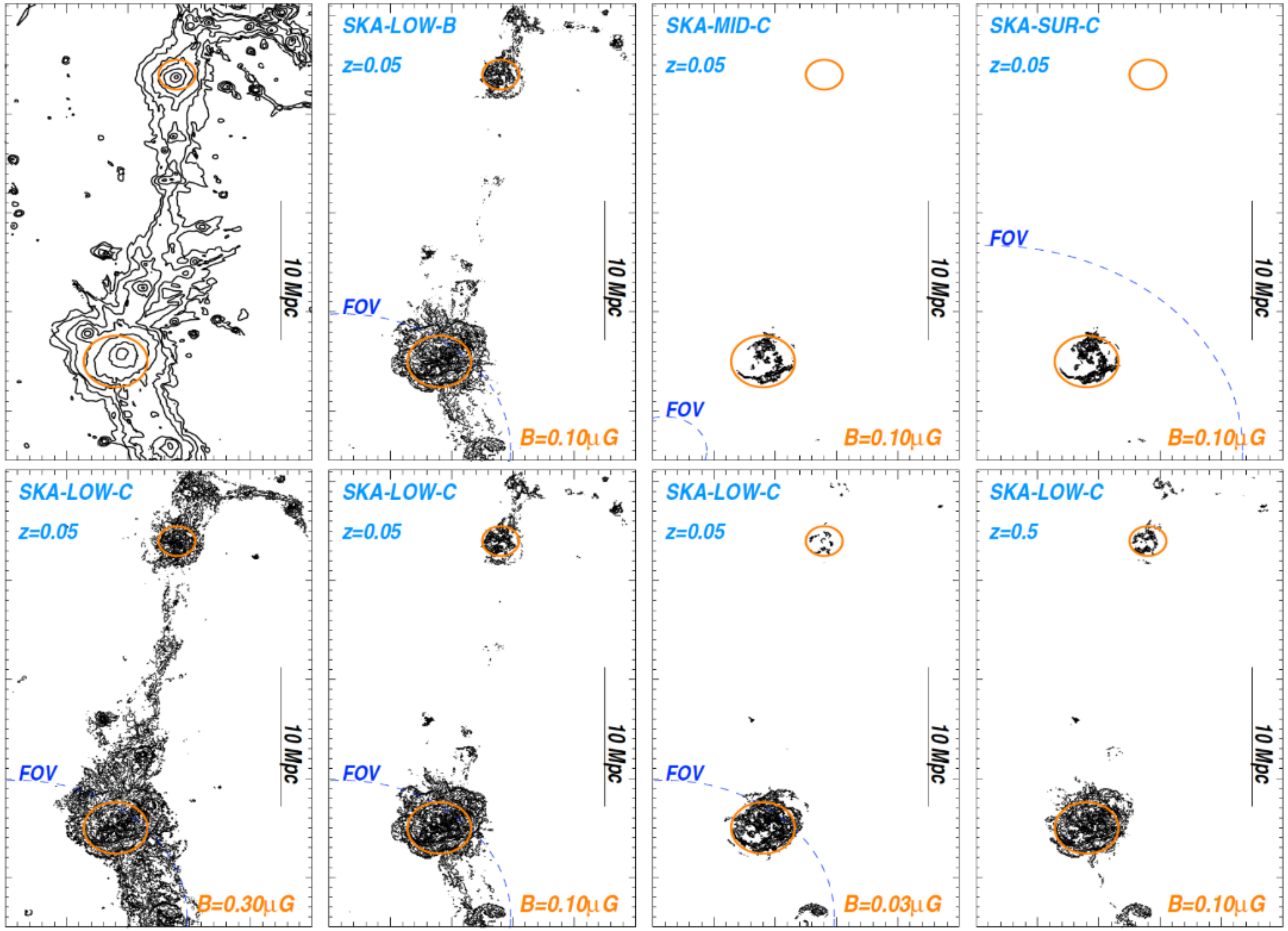
$$P(\nu) \propto \xi_e(M)\,\rho\, V_s^3 B^2 A_s$$

Emission model tuned to reproduce observed statistics of radio relics

How much difficult will it be to observe the radio web?

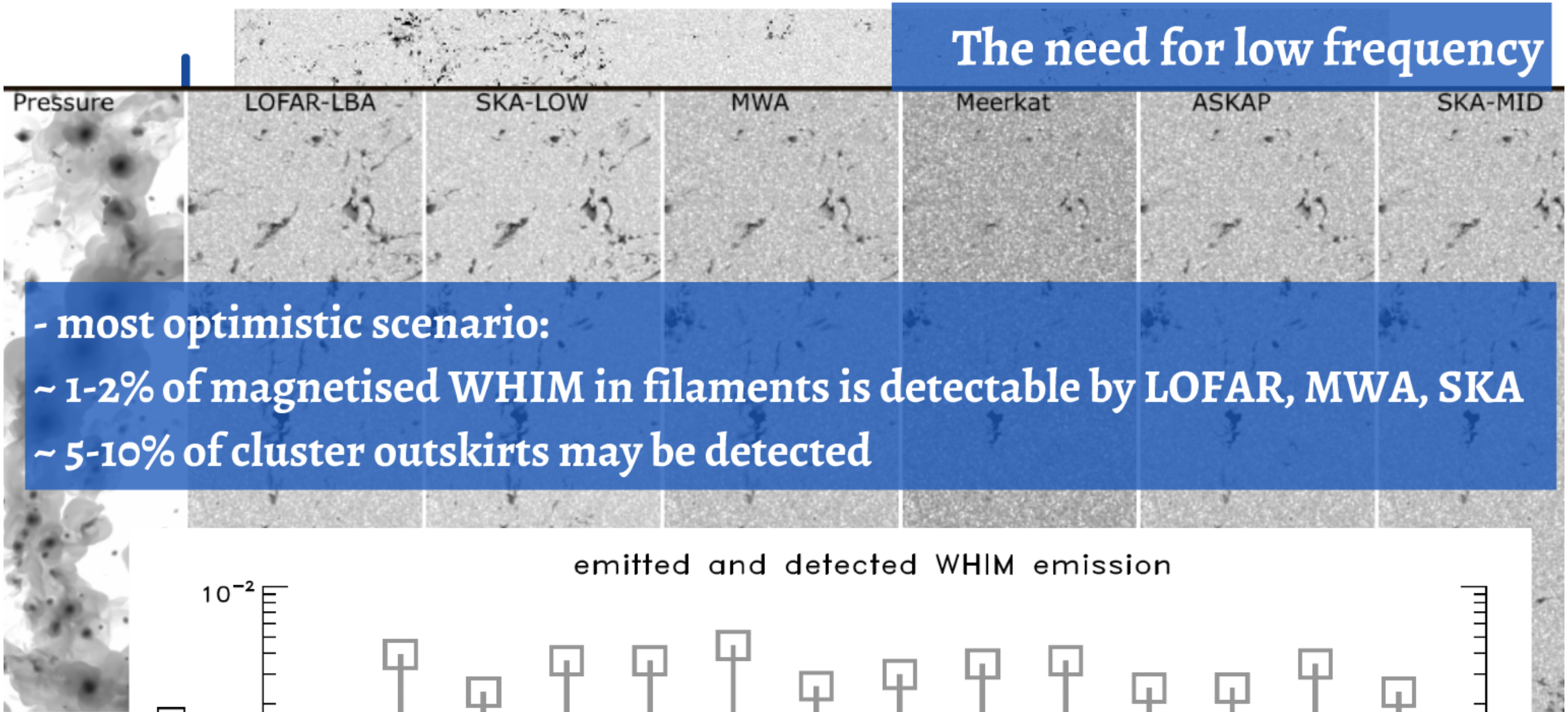
Detecting filaments with SKA (LOW)

FV, Ferrari+2015 SKA White Book

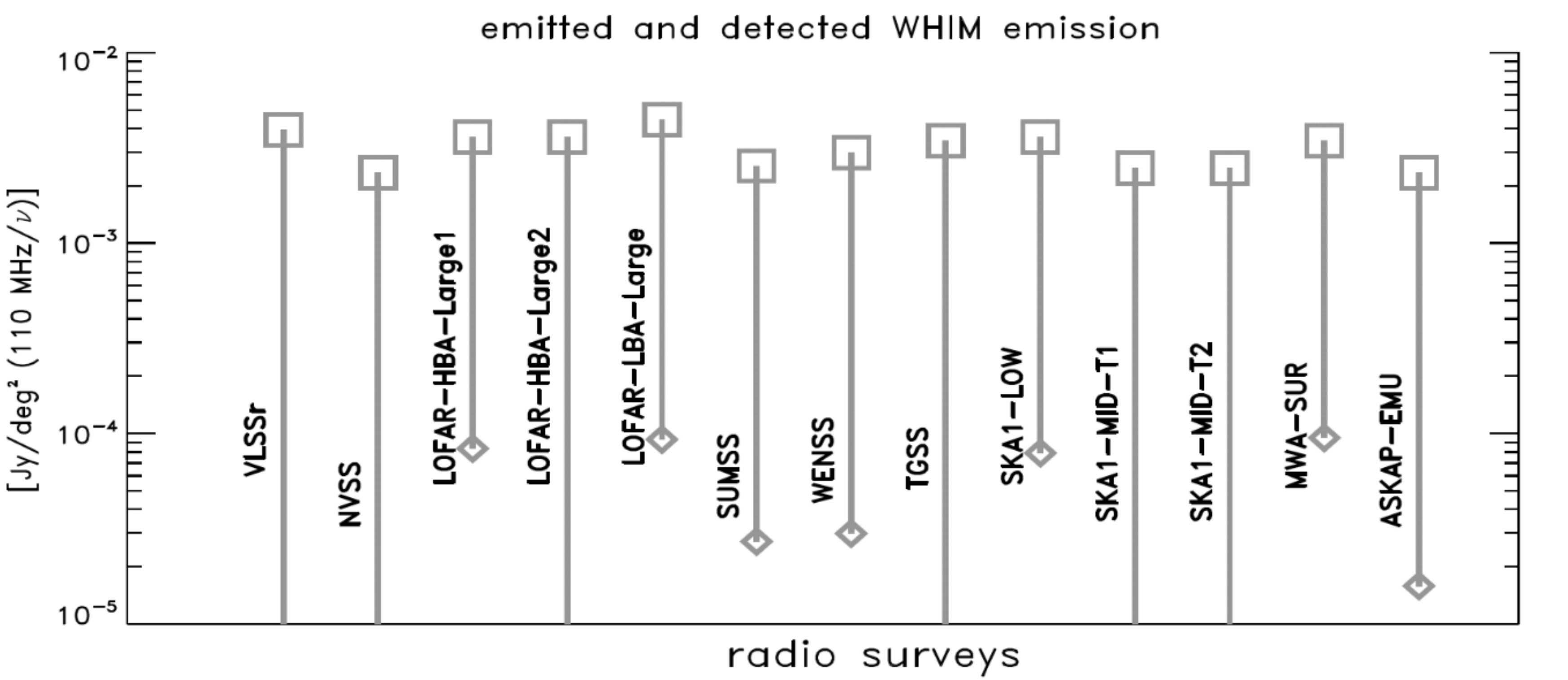


SKA-LOW (<300 MHz) is better than SKA-MID (>1 GHz):
higher sensitivity to ~deg structures, ~ 0.02 mJy/beam (beam ~10")

The need for low frequency



- most optimistic scenario:
~ 1-2% of magnetised WHIM in filaments is detectable by LOFAR, MWA, SKA
~ 5-10% of cluster outskirts may be detected



X-ray vs Radio observations of the cosmic web

FV,Ettori et al.
in prep.

Simulations:

res=40kpc (fixed)

vol=100Mpc^3

MHD, non radiative

z=0.024

SKA-LOW (2yr survey)

260MHz , ~10"

UV sampling, noise

~20μJy/beam (μJy/arcsec2)

no fg, no pointlike sources

ATHENA-XIFU (1Ms)

[0.8-1.2] keV, 5' x 5'

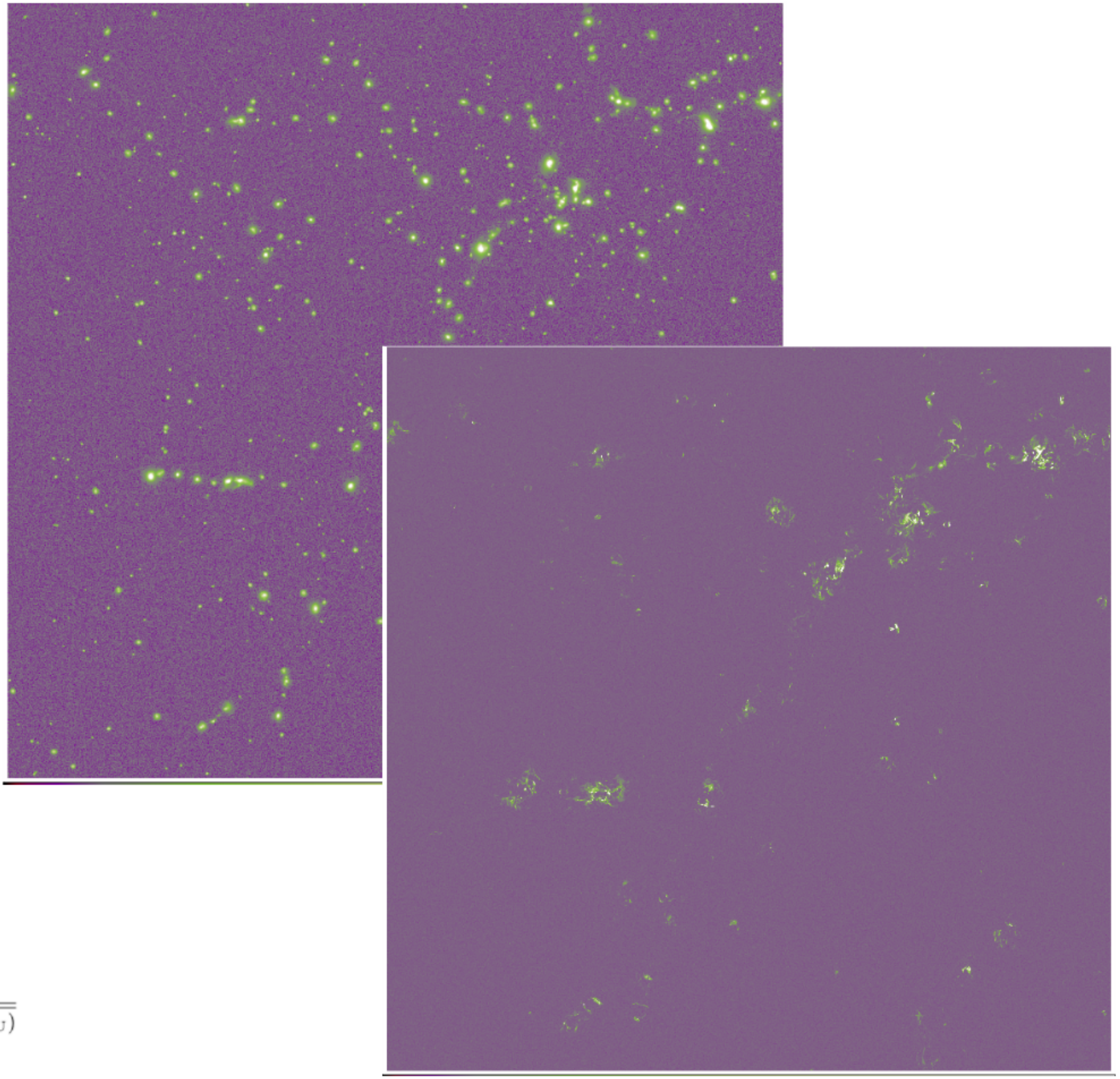
Eff.Area=9947 cm2 (core)

Bg=2.9e3counts/Ms/arcmin2

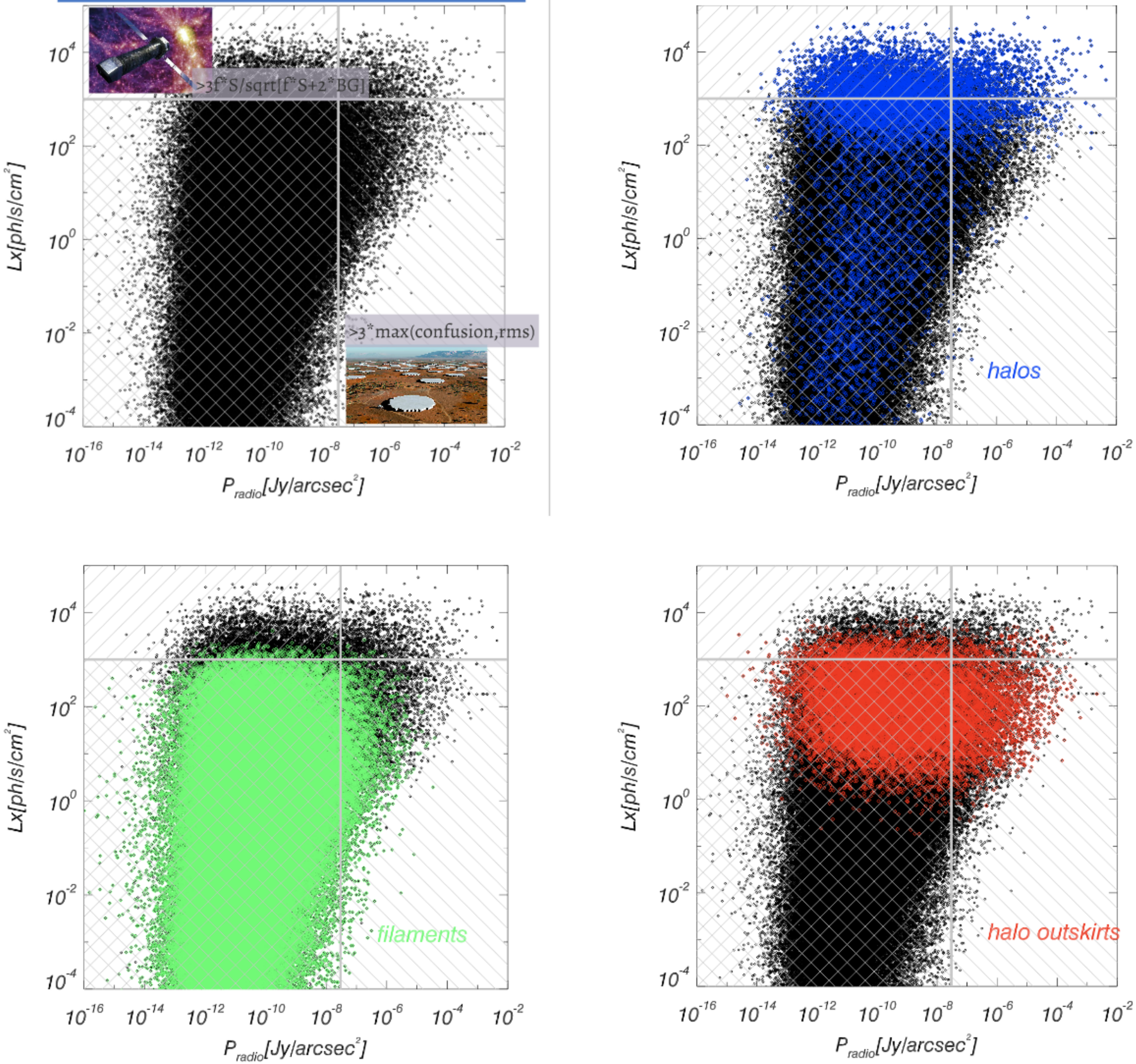
nH=2e20 cm2

Z=0.3Zsol, APEC

$$\sigma_{S/N} = \frac{f_{\rm abs} \cdot S}{\sqrt{f_{\rm abs}(S + 2B_{\rm XIFU})}}$$



Where do we expect "double detections"?



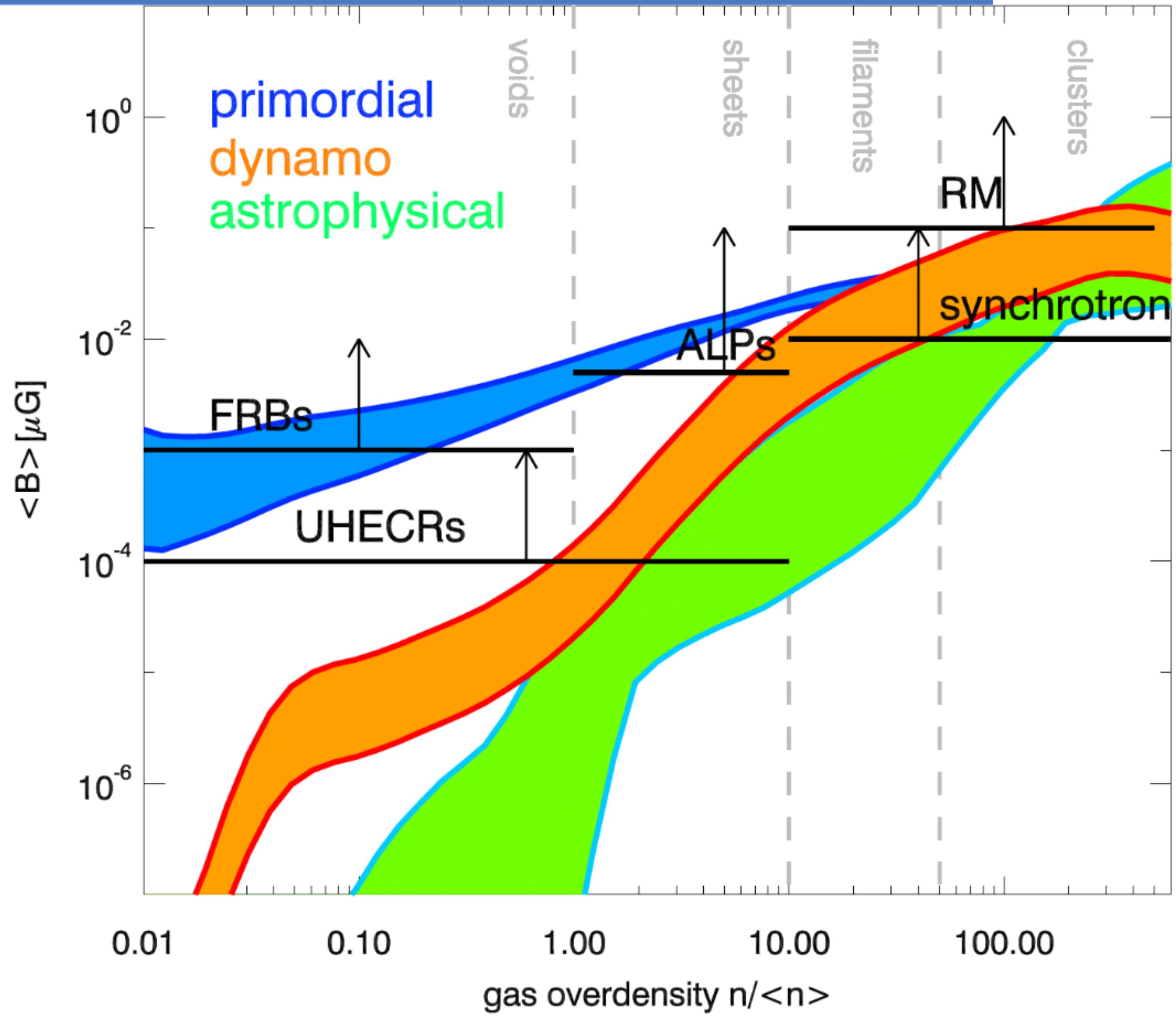
Complementary probes of magnetic fields in the low density Universe

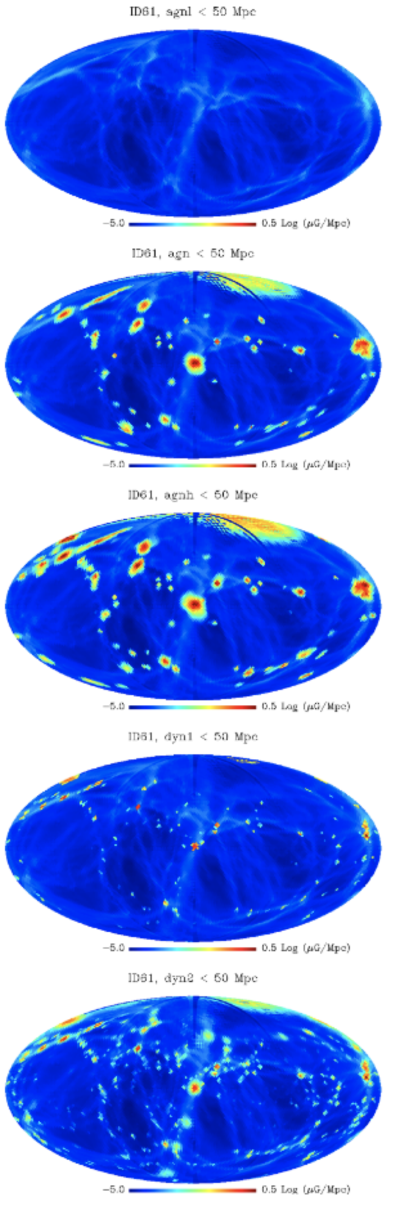
ULTRA HIGH ENERGY COSMIC RAYS

AXIONLIKE PARTICLES

FAST RADIO BURSTS

(also: Inverse Compton Cascade)



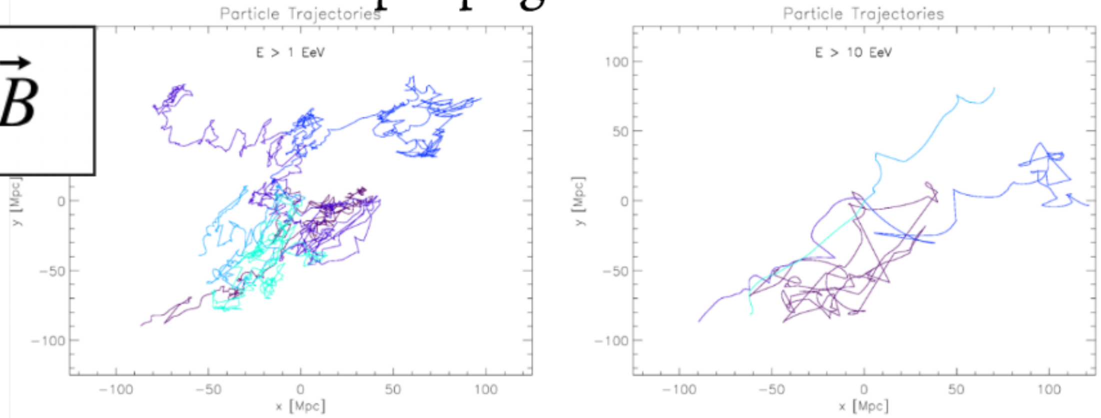


Propagation of Ultra-High Energy Cosmic Rays

ENZO+CRPROPA simulations:

Extragal.mag.field affect the propagation of UHECR:

$$\vec{F}_L = q\,\vec{V} \times \vec{B}$$



- 6 magnetic field models, pure proton comp., different source models
- ~1e8 injected CRs in the [1e18-1e21 eV] range

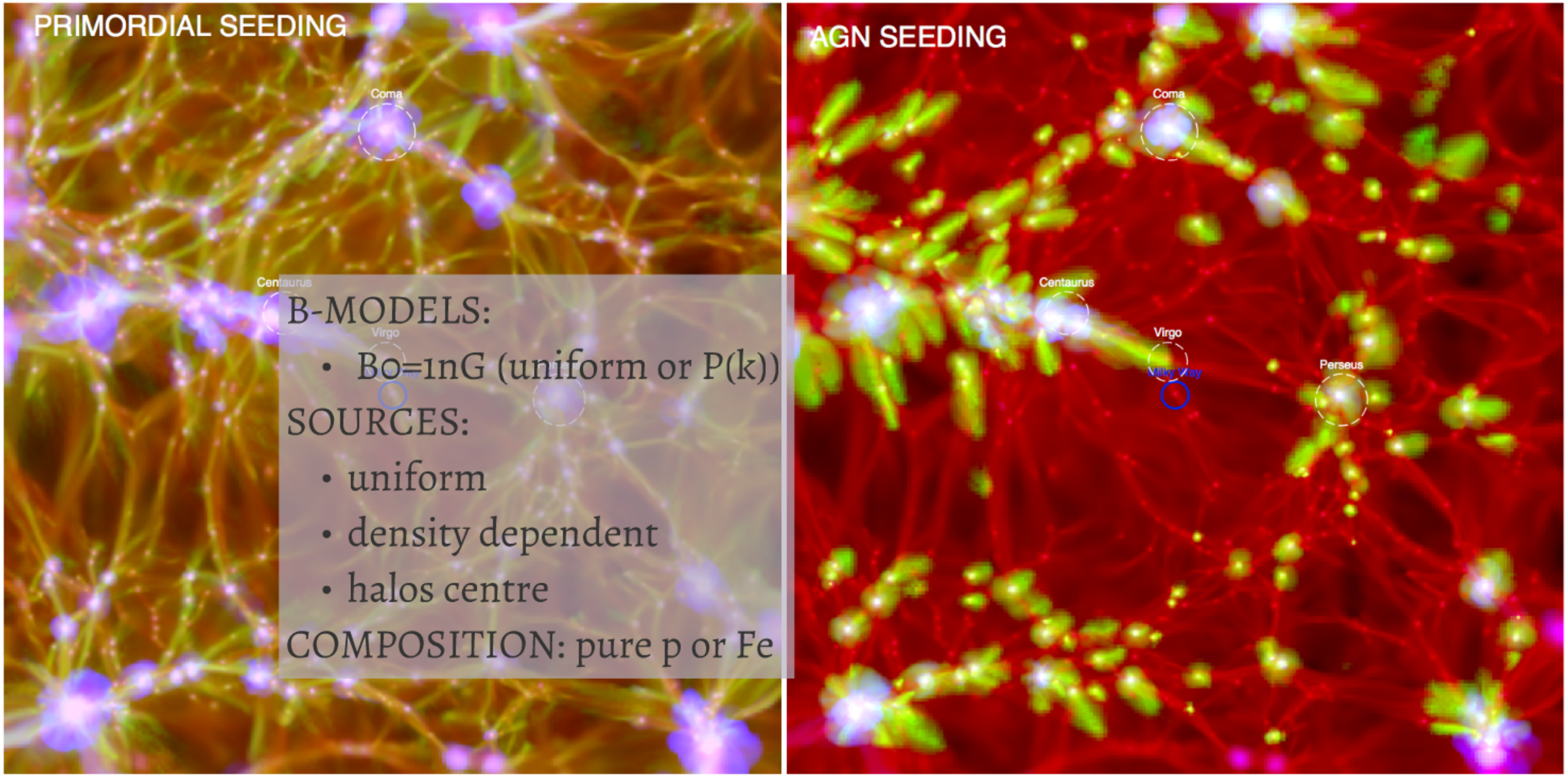
Results:

- B0>0.1nG produce too large anisotropies for E>4e19 eV
- uncertainties in source distribution dominate any B-field signal

Hackstein, FV, Bruggen, Sigl & Dundovic 2016 MNRAS

−6.0 0.5 Log [μG/Mpc]

Propagation of UHECRs : Local Universe Constrained Simulations



B-MODELS:

- B0=1nG (uniform or P(k))

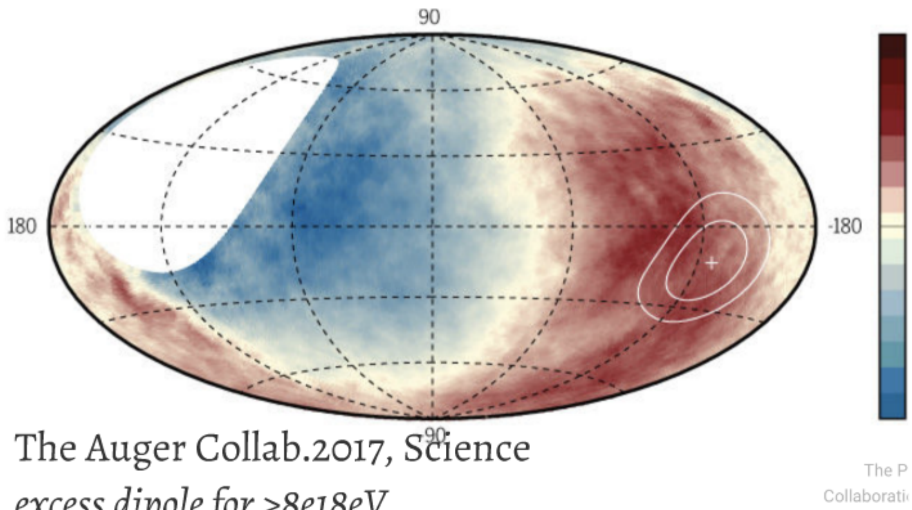
SOURCES:

- uniform
- density dependent
- halos centre

COMPOSITION: pure p or Fe

Hackstein, FV, Bruggen, Sorce & Gottlober 2018 MNRAS

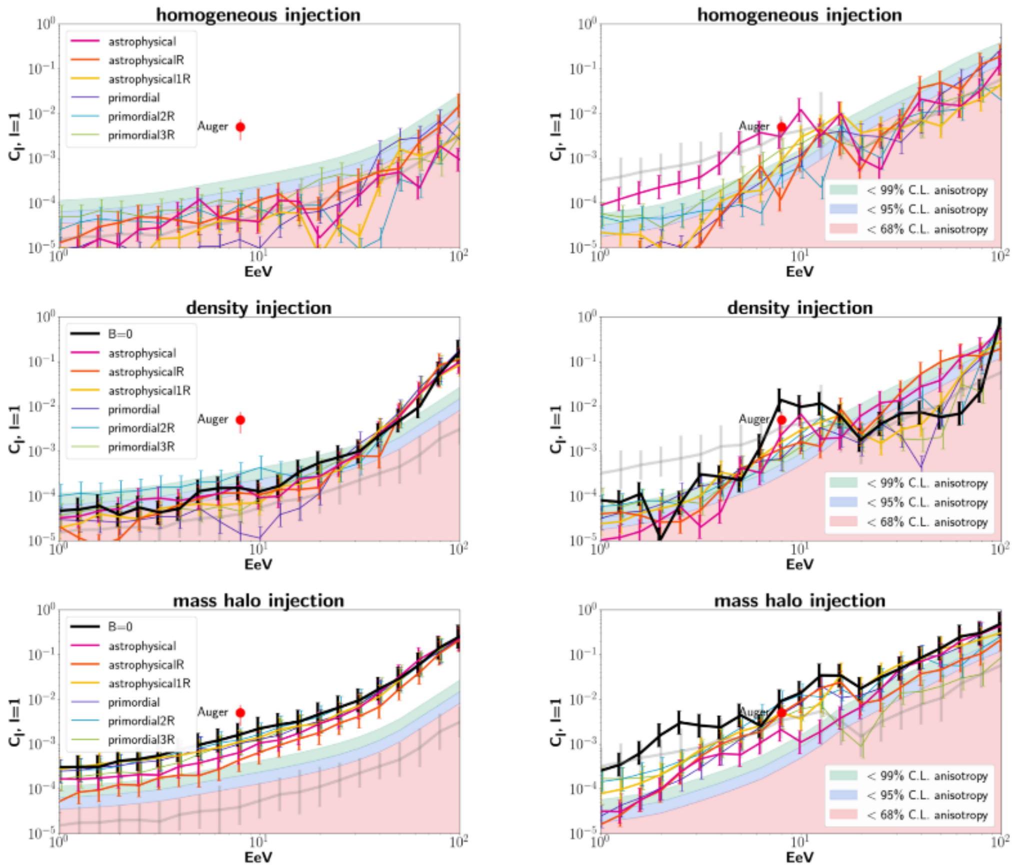
Propagation of Ultra-high energy cosmic rays



The Auger Collab.2017, Science

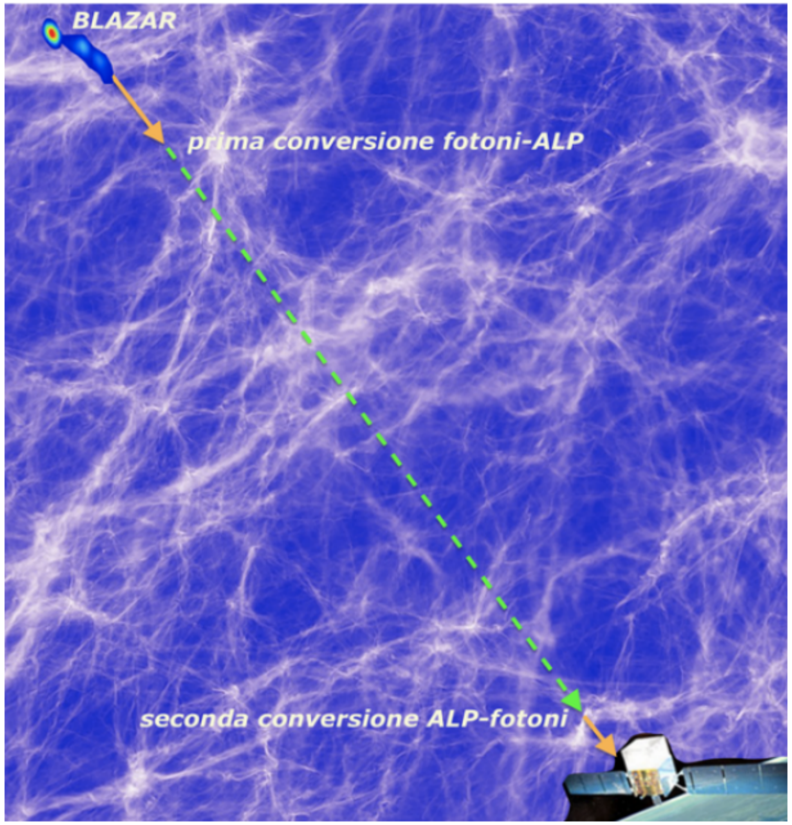
excess dipole for >8e18eV

- Little effect of B-field models
- source distribution dominates signal
- Auger dipole reproduced only for Fe composition and clustered sources

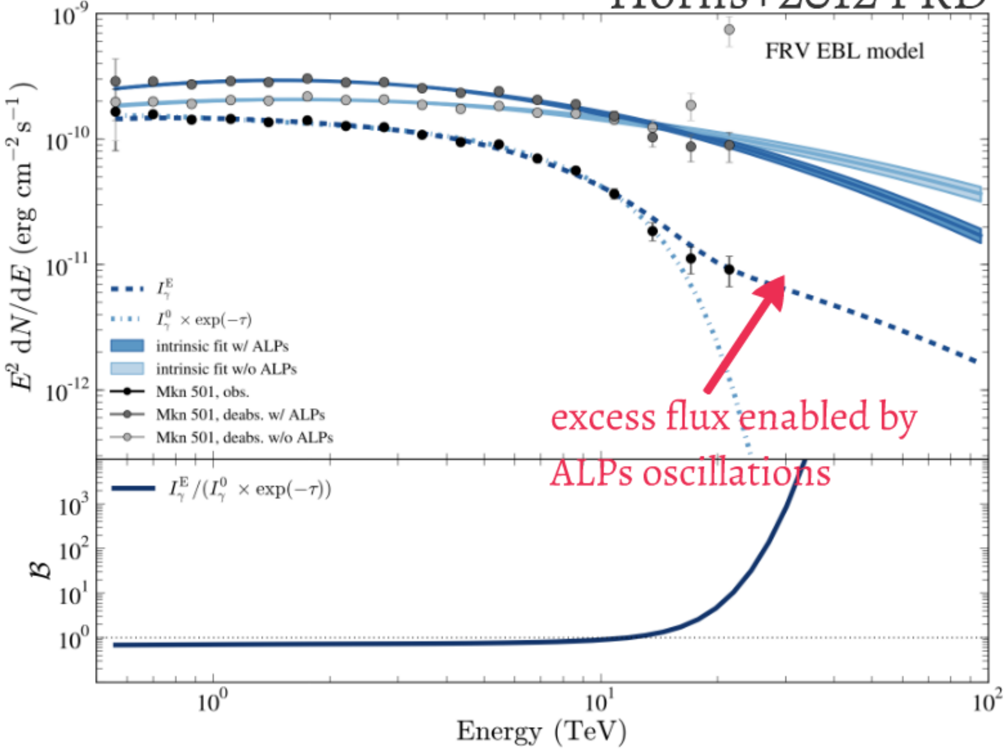


Hackstein, FV, Bruggen, Sorce & Gottlober 2018 MNRAS

Conversion of TeV photons into ALPS (in external B-fields)



Horns+2012 PRD



- "Realistic" 3D cosmological simulations, 1000 beams up to z=0.3, B0=1nG

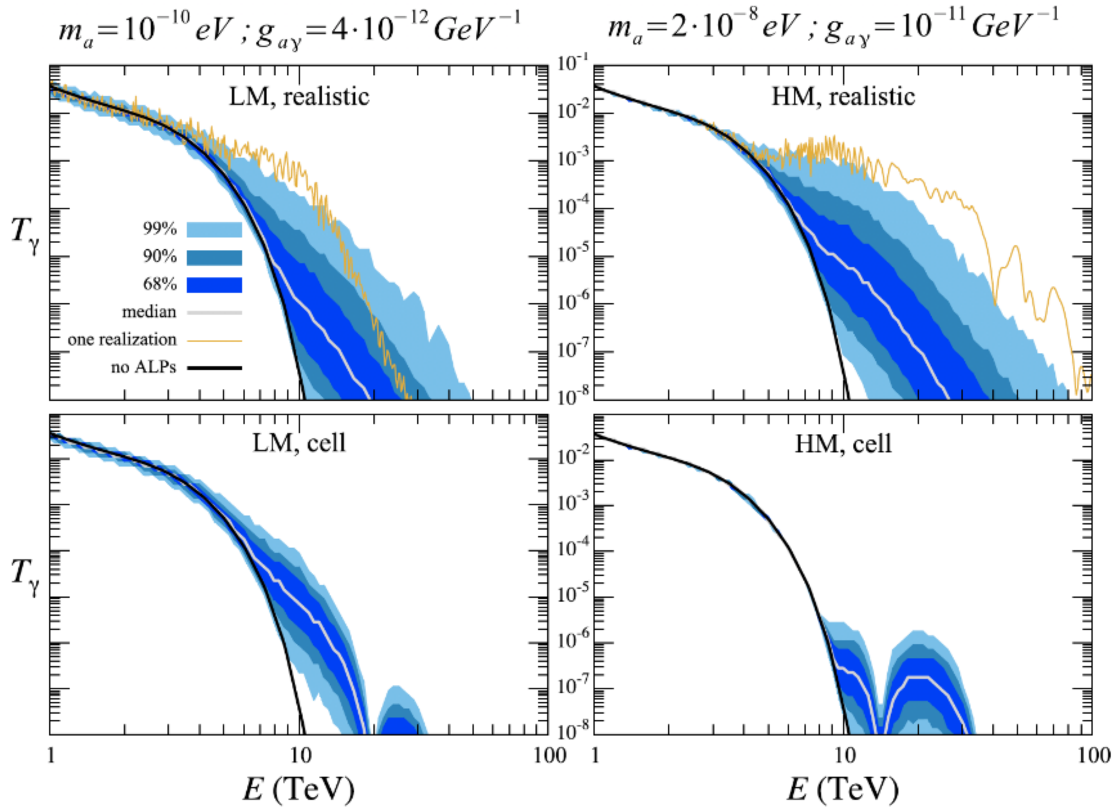
Montanino, FV, Mirizzi & Viel 2017 PRL

Conversion of TeV photons into ALPS (in external B-fields)

Threshold energy to enter the strong mixing regime:

$$E_c \simeq \frac{500\ m_a^2}{(10^{-9}\ \text{eV})^2} \left(\frac{10^{-9}\ \text{G}}{B_T}\right) \left(\frac{5 \times 10^{-11}}{g_{a\gamma}}\right)\ \text{GeV}$$

- Non-gaussian tail of magnetic fluctuations in simulations
- Higher conversion probability into ALPs for the same <B>



"Reopening of the hard gamma-ray window" thanks to ALPs?

Montanino, FV, Mirizzi & Viel 2017 PRL

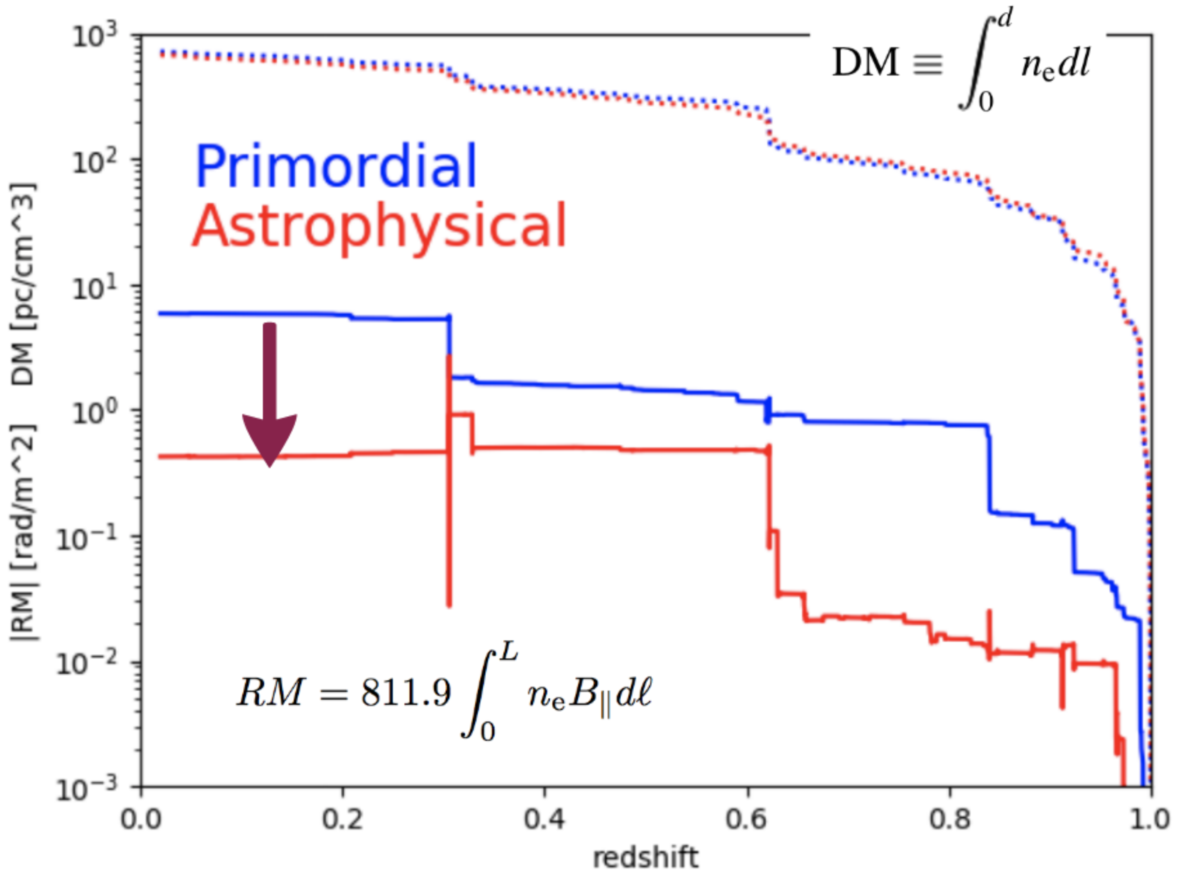
Fast Radio Bursts and their Dispersion/Rotation measure

- Strong radio pulses from extragalactic distances probe the magneto-ionic cosmic gas
- the RM-DM relation can be used to infer the value of magnetic fields:

$$B_{\|}^{\dagger} = \frac{\langle 1+z \rangle}{f_{DM}} \frac{C_{\rm D} RM}{C_{\rm R} DM}$$

(Akahori+2016)

- Inversion of DM-RM relation depends on assumed model!
- physics of sources unknown
- too small statistics



FV,Hinz, Bruggen et al., in prep.

Summary:

The origin of cosmic magnetism is unknown. Clues for this puzzle probably await in the rarefied in the cosmic web.

Filaments are may be soon detected by low frequency radio observations.

Other probes are complementary: UHECRs, FRBs, ALPs...

Simulations may enable very complex observations to turn into discoveries!

Thanks

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