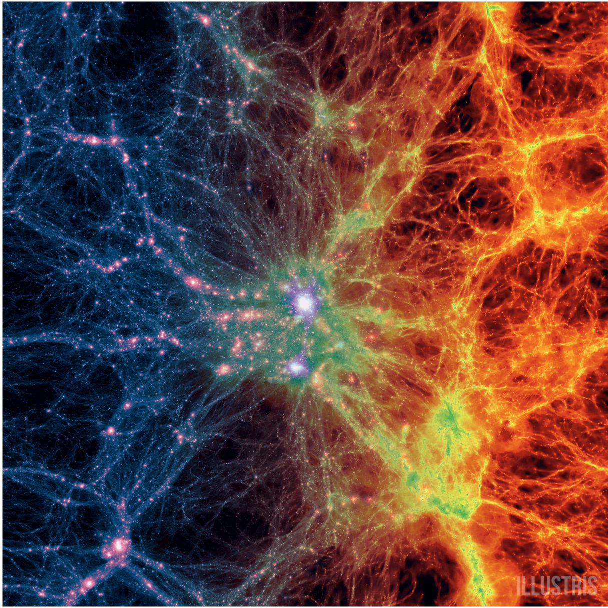
Properties of polarized synchrotron emission from Fluctuation dynamo action

Application to galaxy clusters

Sharanya Sur
Indian Institute of Astrophysics

Nordic Dynamo Seminar 2021



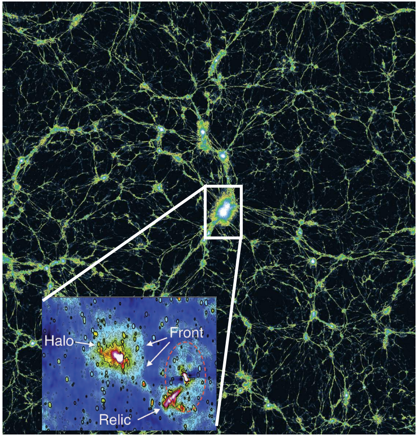
Outline

- Turbulence and magnetic fields in galaxy clusters
- Motivation and Key questions
- Methodology and basic physical parameters
- **Highlights of the key results**

  Sur, Basu & Subramanian, MNRAS, Vol. 501, 2021

  - The Faraday depth and connection to the properties of the magnetic field
  - Nature of total and polarized synchrotron intensity, correlation scales
  - Effects of beam smoothing
- Conclusions & Ongoing work
- **Collaborators :** Aritra Basu (Thüringer Landessternwarte) & Kandaswamy Subramanian (IUCAA)

Turbulence & magnetic fields in galaxy clusters



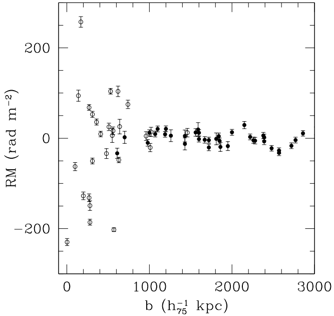
Illustris TNG, Brown & Rudnick, MNRAS, 2011

- Largest gravitationally bound systems
- Numbers : $M \sim 10^{14} - 10^{15}\, M_{\odot}$, size of several Mpc, hot X-ray emitting gas $T \simeq 10^{7} - 10^{8}\,\mathrm{K}$ with gas number densities $n \sim 10^{-2} - 10^{-4}\,\mathrm{cm}^{-3}$
- Drivers of turbulence : Structure formation, ongoing merger activity, other galactic scale processes
  - Turbulent velocity $v \sim 200 - 300\,\mathrm{km\,s}^{-1}$ in the cluster core (*Hitomi collaboration, PASJ, 2018*); Sound speeds $c_{\mathrm{s}} \approx 10^{3}\,\mathrm{km\,s}^{-1} \Rightarrow$ subsonic turbulence

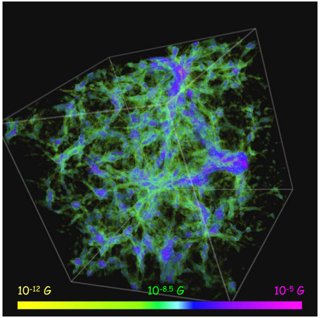
turb

Turbulence & magnetic fields in galaxy clusters

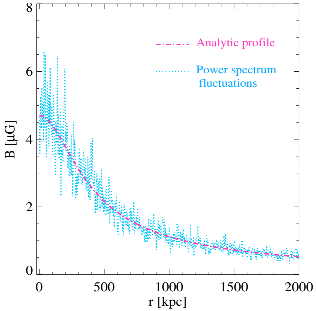
- Observations of the Faraday rotation measure (RM) suggest that the intracluster medium (ICM) is magnetized
  - Field strengths $\sim$ few μG, correlated on several kpc scales



Clarke et al., ApJL, 2001



Ryu et al., Science, 2008



Bonafede et al., A&A, 2010

Motivation

- In the absence of rotation Fluctuation dynamos ideally suited for amplifying fields to observable strengths
- **Faraday RM** only provides info about the line-of-sight magnetic field
- Synchrotron emission and it's polarization are the other two observables
  - Furnish info about magnetic fields in the plane of the sky
  - Stokes I, Q and U can be measured by a radio telescope
- Polarized emission from radio halos have been difficult to detect (*Vacca et al., A&A, 2010, Govoni et al., A&A, 2013*)
  - Observed only in bright filaments in A2255 and in MACS J0717+1345 *Govoni et al., A&A, 2005, Bonafede et al., A&A, 2009*

Motivation

- Stokes parameters are related to magnetic field components in a non-linear manner (see *Waelkens, Schekochihin & Enßlin, MNRAS, 2009*)
- **Fluctuation dynamos :** Spatially intermittent fields, field components are non-Gaussian (*Haugen et al. 2004, Schekochihin et al. 2004, Brandenburg & Subramanian 2005, Vazza et al., 2018, Seta et al. 2020*)
- Explore and extract information from simulations of Fluctuation dynamos

Fundamental Questions

- Can one relate the power spectrum of Faraday depth to the magnetic field?
- What is the statistical nature of total and polarized synchrotron emission?
- How are these affected by Faraday depolarization?
- What is the effect of beam smoothing on the observables?

Methodology and basic physical parameters

- Non-ideal subsonic simulation using the compressible FLASHv4.2 code
  - Forced turbulence ($k_\mathrm{f} \sim 2$), Periodic boundaries, solenoidal forcing
  - $512^3, \mathcal{M} \approx 0.18, \mathrm{Rm} = \mathrm{Re} = 1080$
  - Weak seed fields of the form $\boldsymbol{B} = B_0[0, 0, \sin(10\pi x)], \beta \sim 10^6$

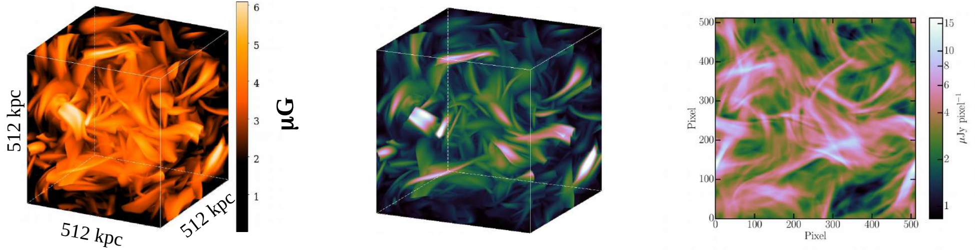
Parameter name	Value
Mean electron density	$\langle n_\mathrm{e} \rangle = 10^{-3}\,\mathrm{cm}^{-3}$
Isothermal sound speed	$c_\mathrm{s} = 10^3\,\mathrm{km\,s}^{-1}$
Turbulent rms velocity	$u_\mathrm{rms} \approx 180\,\mathrm{km\,s}^{-1}$
Rms field strength	$b_\mathrm{rms} \approx 1.3\,\mu\mathrm{G} \sim B_\mathrm{eq}/2$
Box size	$512 \times 512 \times 512\,\mathrm{kpc}^3$
Resolution	$\Delta x = \Delta y = \Delta z = 1\,\mathrm{kpc}$
Turbulence driving scale	$256\,\mathrm{kpc}$
Spectral index	$\alpha = -1$
Frequency range	$\nu_\mathrm{min} = 0.5\,\mathrm{GHz},\ \nu_\mathrm{max} = 7\,\mathrm{GHz}$
Total flux density	1 Jy at $1\,\mathrm{GHz}$

- n_CRE assumed to be constant at mesh points
  - Follows a power law energy spectrum $n_\mathrm{CRE}(E)dE = n_0 E^\gamma\, dE; \gamma = -3$
- $B_\perp = (B_x^2 + B_y^2)^{1/2}, B_\parallel = B_z$
- Results at three representative frequencies : $0.5, 1$ & $6\,\mathrm{GHz} \Rightarrow \lambda : 60, 30$ & $5\,\mathrm{cm}$

Methodology and basic physical parameters

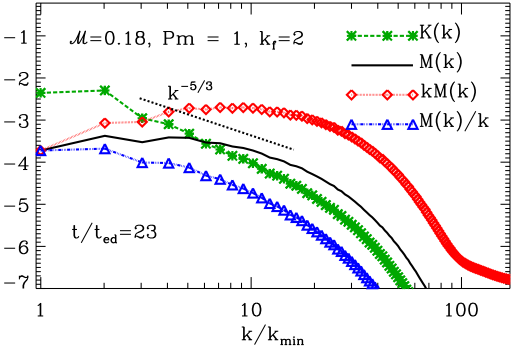
- Simulation output ⇒ input to `COSMIC` (*Basu et al., Galaxies, 2019*)
  - `COSMIC` : **C**omputerized **O**bservations of **M**HD **I**nferred **C**ubes
  - Computes a variety of observables that characterize the nature of the polarized emission; benchmarked with analytic models of magneto-ionic media (e.g., *Sokoloff et al., MNRAS, 1998*)

3D $B_{x,y,z}$ cube ⟶ **3D spatial synchrotron** **2D Maps**



Power spectra

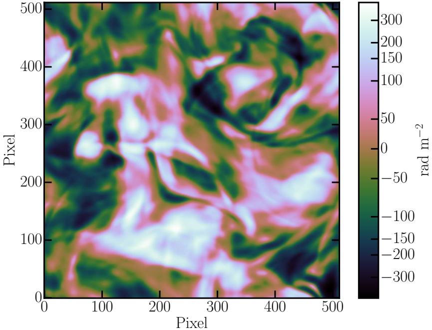
- Power spectrum of kinetic energy $K(k)$, magnetic energy $M(k)$, the magnetic integral scale $M(k)/k$ and $kM(k)$

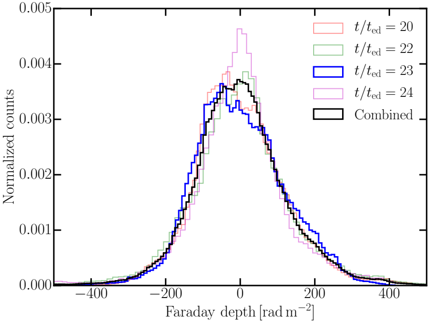


- $M(k)$ exceeds $K(k)$ on all but the largest scales
  - $M(k)$ peaks at $\sim 1/4 - 1/6$ of the box size; physical scales of $\sim 128 - 85\,\mathrm{kpc}$
- $kM(k)$ peaks on scales $\sim 51\,\mathrm{kpc}$; smaller than that of $M(k)$
- Peak of $M(k)/k$ occurs on the scale of turbulent driving

Faraday depth (FD) map and spectra

- Faraday depth : $FD = K \int n_e B_{\|} \, dl$, $\delta n_e / n_e \sim \mathcal{M}^2 \sim 3\% \Rightarrow n_e$ is nearly uniformly distributed





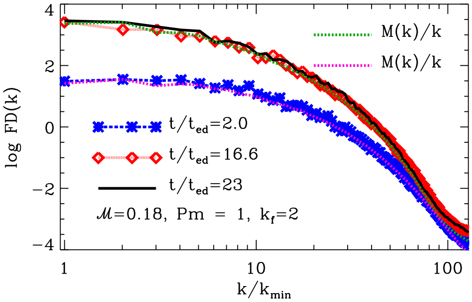
- Structures arise purely from the spatial fluctuations of $B_{\|}$

- PDF of FD is Gaussian

Faraday depth (FD) map and spectra

- $\sigma_{\rm FD} \approx 110 - 130\,{\rm rad\,m^{-2}}$; related to the magnetic integral scale $L_{{\rm int},M}$ (see *Cho & Ryu, ApJL, 2009, Bhat & Subramanian, MNRAS, 2013*)

$$\sigma_{\rm FD} = K\,\langle n_{\rm e}\rangle \frac{b_{\rm rms}}{2}\sqrt{L\,L_{{\rm int},M}}\,, \quad L_{{\rm int},M} = \frac{2\,\pi\int (M(k)/k)\,dk}{\int M(k)\,dk}$$

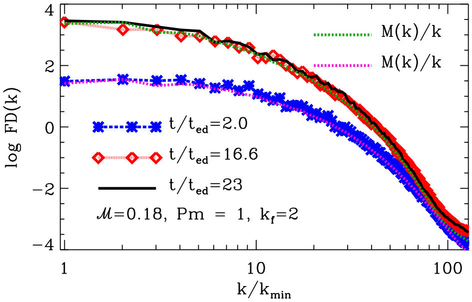


- Power spectrum of FD remarkably similar to that of $M(k)/k$
- Can infer about random magnetic fields in the ICM, provided fluctuations in $n_{\rm e}$ are small
- Information on the evolutionary stage of the turbulent dynamo

Faraday depth (FD) map and spectra

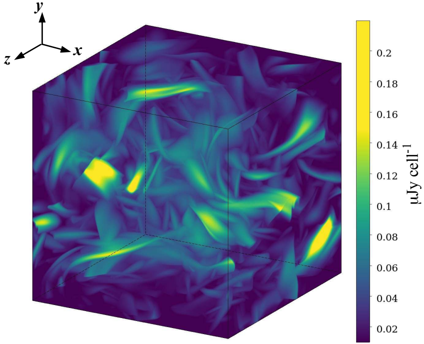
- $\sigma_{\rm FD} \approx 110 - 130\,{\rm rad\,m^{-2}}$; related to the magnetic integral scale $L_{\rm int},M$ (see *Cho & Ryu, ApJL, 2009, Bhat & Subramanian, MNRAS, 2013*)

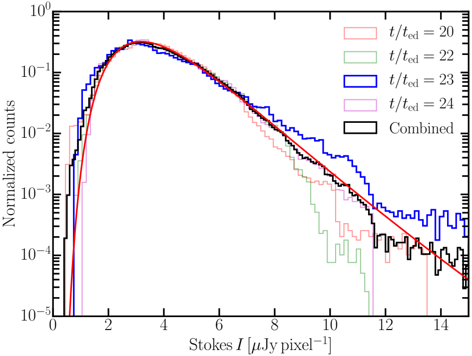
$$\sigma_{\rm FD} = K\,\langle n_{\rm e}\rangle\,\frac{b_{\rm rms}}{2}\,\sqrt{L\,L_{{\rm int},M}}\,, \quad L_{{\rm int},M} = \frac{2\,\pi\int (M(k)/k)\,dk}{\int M(k)\,dk}$$



- Power spectrum of FD remarkably similar to that of $M(k)/k$
  - At $t/t_{\rm ed} = 23$, $L_{\rm int},M = 112.4\,{\rm kpc}$
  - For $b_{\rm rms} \approx 1.3\,\mu{\rm G}, L = 512\,{\rm kpc}$ and $n_{\rm e} = 10^{-3}\,{\rm cm}^{-3} \Rightarrow \sigma_{\rm FD} \approx 127\,{\rm rad\,m^{-2}}$

Synchrotron emissivity and total intensity





- $\varepsilon_{\rm sync} \propto \nu^\alpha B_\perp^2$, $I_{\rm sync} \propto \nu^\alpha \int B_\perp^2 \, dl$; structures essentially arises due to magnetic fields being randomly stretched and twisted due to turbulent driving
- Unlike FD, the PDF is well represented by a log-normal distribution

Polarization parameters

- Focus on how the polarization parameters depend on frequency
- The linearly polarized intensity (PI) map at a frequency ν computed from the Stokes Q and U parameters

$$\mathrm{PI}_\nu(i,j) = \sqrt{Q^2_\nu(i,j) + U^2_\nu(i,j)}, \;\; p_\nu = \mathrm{PI}_\nu / I_\nu$$

- The Stokes Q and U parameters at a frequency ν

$$Q_\nu(i,j) = \sum_k p_{\max}\, \varepsilon_{\mathrm{sync},\nu}(i,j,k)\, l_{\mathrm{cell}}\, \cos\left[2\,\theta(i,j,k)\right],$$

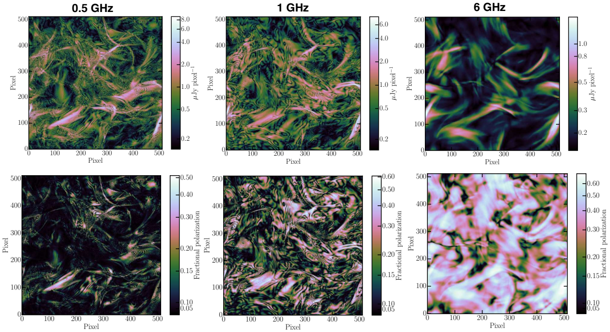
$$U_\nu(i,j) = \sum_k p_{\max}\, \varepsilon_{\mathrm{sync},\nu}(i,j,k)\, l_{\mathrm{cell}}\, \sin\left[2\,\theta(i,j,k)\right], p_{\max} = 0.75$$

- $\theta(i,j,k) = \theta_0(i,j,k) + \mathrm{FD}'(i,j,k)\, c^2/\nu^2$ and $\theta_0 = \pi/2 + \arctan\left(B_y/B_x\right)$

Polarization parameters

- Polarized intensity (PI_ν) and the fractional polarization $p_\nu = \mathrm{PI}_\nu / I_\nu$

spectra



Quantity	Resolution	Mean		
		0.5 GHz	1 GHz	6 GHz
PI_ν (μJy/pixel)	Native	0.67	0.638	0.228
p_ν	Native	0.09	0.17	0.345

- Small scale structures in PI_ν at low frequencies

- $\langle \mathrm{PI}_\nu \rangle$ progressively decreases from $0.67 \rightarrow 0.23$ as frequency increases
- Opposite trend for p_ν; $\langle p \rangle$ increasing from $9\% \rightarrow 34\%$

Correlation scales in a magneto-ionic medium

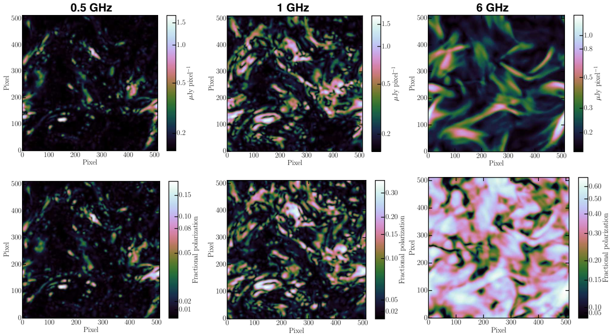
- How do the correlation scales of the observables compare with that of the magnetic field?
  - Can be measured directly from the simulation

$t/t_{\rm ed}$	$L_{{\rm int},V}$ (kpc)	$L_{{\rm int},M}$ (kpc)	$L_{\rm int,FD}$ (kpc)	$L_{{\rm int},I}$ (kpc)	$L_{{\rm int},PI}$ (kpc) 0.5 GHz	1 GHz	6 GHz
16.6	320	106	212.5	224	122	155	199
23.0	340	112.4	216	227.6	138	128	182

  - $L_{{\rm int},V} \sim 3\,L_{{\rm int},M}$, Integral scales of $\rm FD$, $I_{\rm sync}$ and $\rm PI$ are all comparable and larger than $L_{{\rm int},M}$ by a factor of about two

Smoothed polarization parameters

- Smoothing performed with a Gaussian kernel with FWHM $10 \times 10\,\mathrm{pixel}^2$



Quantity	Resolution	Mean		
		0.5 GHz	1 GHz	6 GHz
PI_ν	Native	0.67	0.638	0.228
(μJy/pixel)	10 pixels	0.099	0.227	0.222
p_ν	Native	0.09	0.17	0.345
	10 pixels	0.013	0.06	0.337

- Noticeable differences seen at 0.5 and $1\,\mathrm{GHz}$
  - Bright filamentary structures seen at native resolution are lost in the smoothed maps

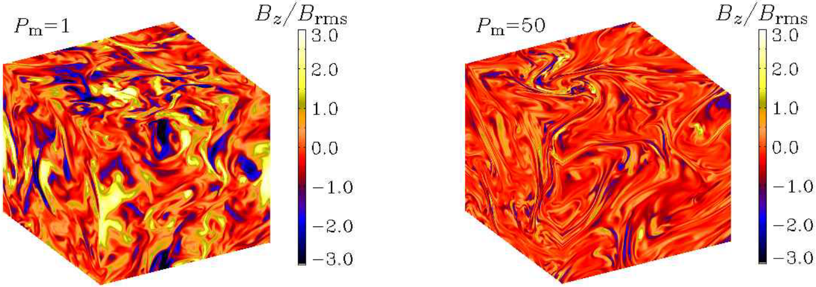
- At higher frequencies : Both native resolution and smoothed maps show similar structures

Conclusions

- Faraday depth maps contain information on the evolutionary stage of the dynamo
  - Can reconstruct the power spectrum of random magnetic fields from FD power spectrum
- Faraday depolarization affects polarized structures at $\nu \lesssim 1.5\,\mathrm{GHz}$
- Effects of Beam smoothing
  - Significantly affects statistical properties of polarized emission below $\lesssim 1.5\,\mathrm{GHz}$
  - Properties at higher frequencies ($\gtrsim 5\,\mathrm{GHz}$) remains largely unaffected
- **High frequency ($\nu \gtrsim 5\,\mathrm{GHz}$) observations needed to effectively probe the properties of polarized emission in the ICM**
  - At resolution of $1\,\mathrm{kpc}$: $p_{6\,\mathrm{GHz}} \simeq 30\%, p_{0.5\,\mathrm{GHz}} \simeq 9\%$

Ongoing work

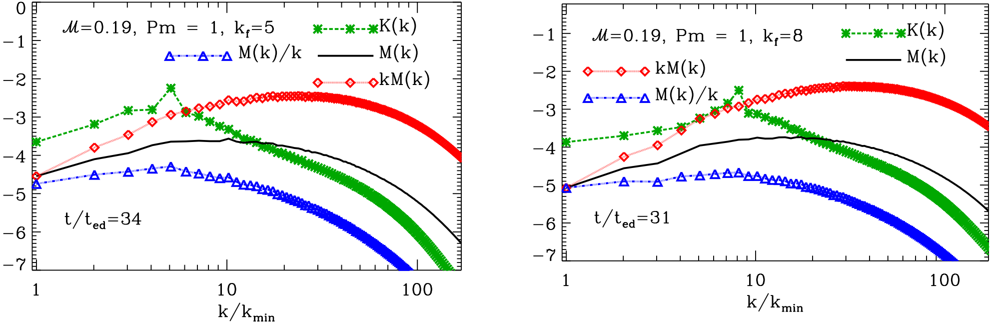
- Probe the effect of intermittency of the field structure
  - Left : $\mathcal{M} \approx 0.1, \mathrm{Pm} = 1$, Right : $\mathcal{M} \approx 0.1, \mathrm{Pm} = 50$



- Turbulent driving at half the scale of the box, more intermittent and less volume filling fields for $\mathrm{Pm} = 50$ (*Brandenburg & Subramanian 2005*)

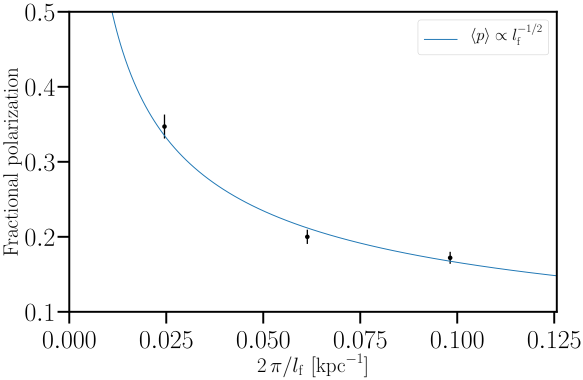
Ongoing work

- How does p change due to beam smoothing on different scales?
  - Additional simulations at $\mathcal{M} \approx 0.19$ with $k_{\rm f} = 5, 8$



Ongoing work

- Nature of the dependence of p on the scale of turbulent driving

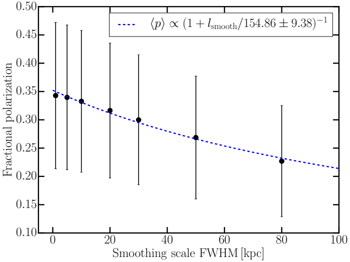


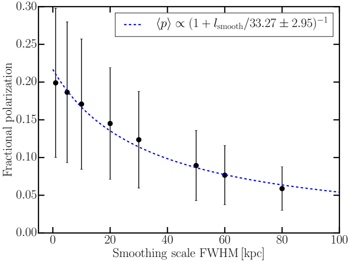
- Simulation domain kept fixed at $512\,{\rm kpc}$
- Turbulent driving at $l_{\rm f} = 256, 102$ and $64\,{\rm kpc}$

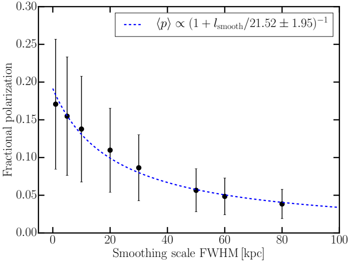
- Fractional polarization scales as : $\langle p \rangle \propto l_{\rm f}^{-1/2}$

Ongoing work

- Variation of p_ν as a function of the smoothing scale







- $\nu = 5\,\mathrm{GHz}, k_\mathrm{f} = 2$
- $\nu = 5\,\mathrm{GHz}, k_\mathrm{f} = 5$
- $\nu = 5\,\mathrm{GHz}, k_\mathrm{f} = 8$

- $p = A/(1 + l/l_s)$, l is the smoothing scale and l_s is the scale at which p reduces by $1/2$

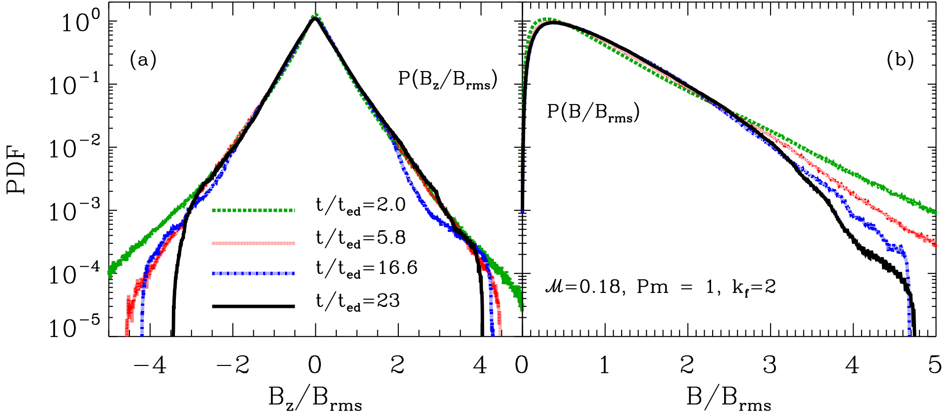
Thanks!

Other Slides

PDFs of the magnetic field

- **Left :** PDF of $B_z/B_{\rm rms}$, **Right :** PDF of the normalized field strength

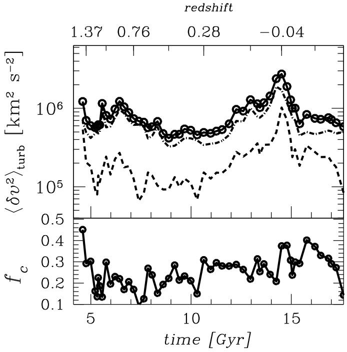
back



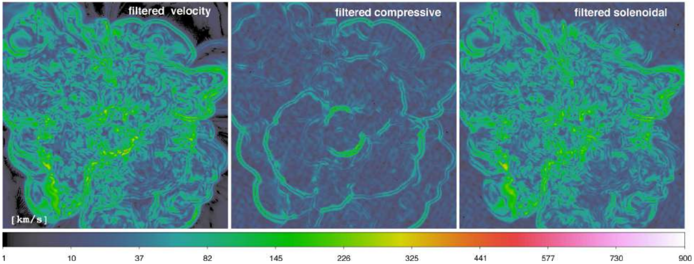
Nature of turbulence in galaxy clusters

- Cluster turbulence dominated by solenoidal modes
  - Predominance more clearly revealed when large-scale motions are filtered out

back



Miniati, ApJ, 2015



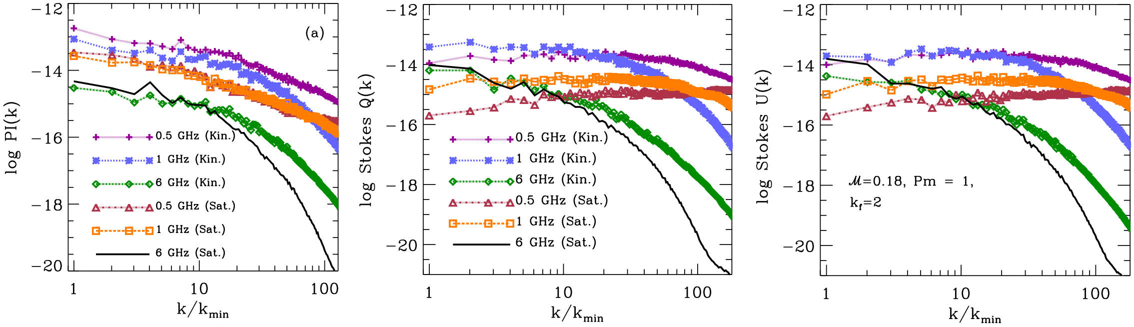
Vazza et al., MNRAS, 2017

- Contribution from compressional modes becomes important during merger events

Power spectra of PI_ν, Stokes Q and U

- Power spectra of PI_ν (left), Stokes Q (middle) and U (right) at different frequencies

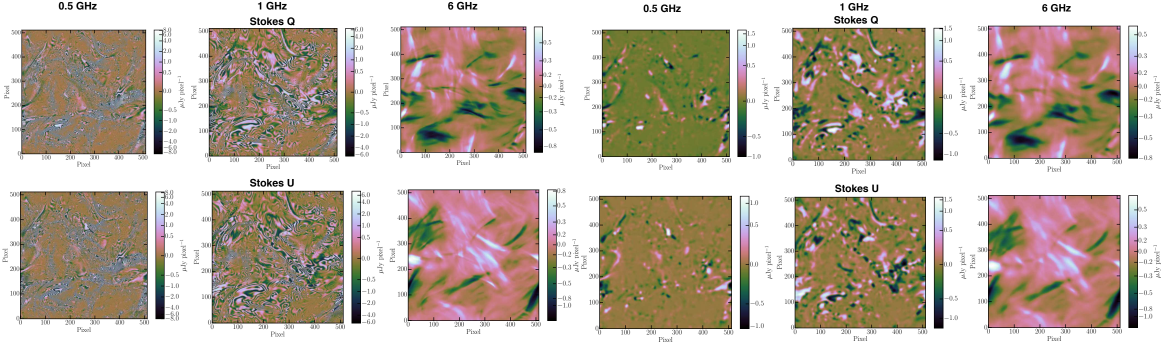
back



2D maps of Stokes Q and U

- 2D maps of Stokes *Q* and *U*
  - **Left :** At native resolution, **Right :** Smoothed maps

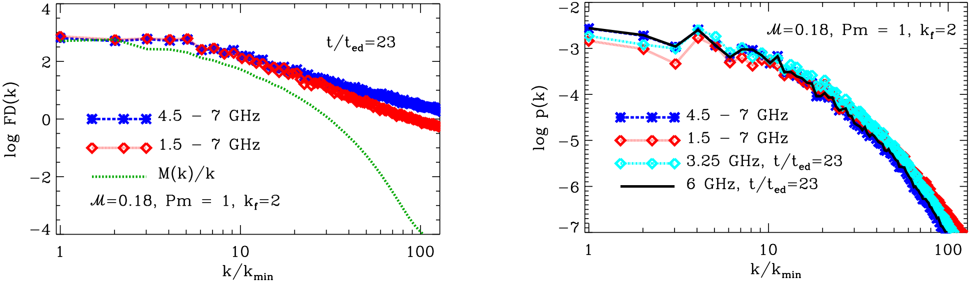
back



Spectra using RM Synthesis

- **Left :** Power spectra of $\mathrm{FD}_{\mathrm{RM\,synth}}$ and $M(k)/k$, **Right :** power spectra of $p_{\mathrm{RM\,synth}}$ and p

back



- Power spectra of the recovered $\mathrm{FD}_{\mathrm{RM\,synth}}$ deviate significantly from $M(k)/k$
- In contrast, excellent match between the power spectra of $p_{\mathrm{RM\,synth}}$ and that of p