

The Magnetised Cosmic Web: Joint RM and SZ Probes with AtLAST

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Movie: IllustrisTNG



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Iberian AtLAST days



POSSUM
POLARISATION SKY SURVEY OF THE UNIVERSE'S MAGNETISM

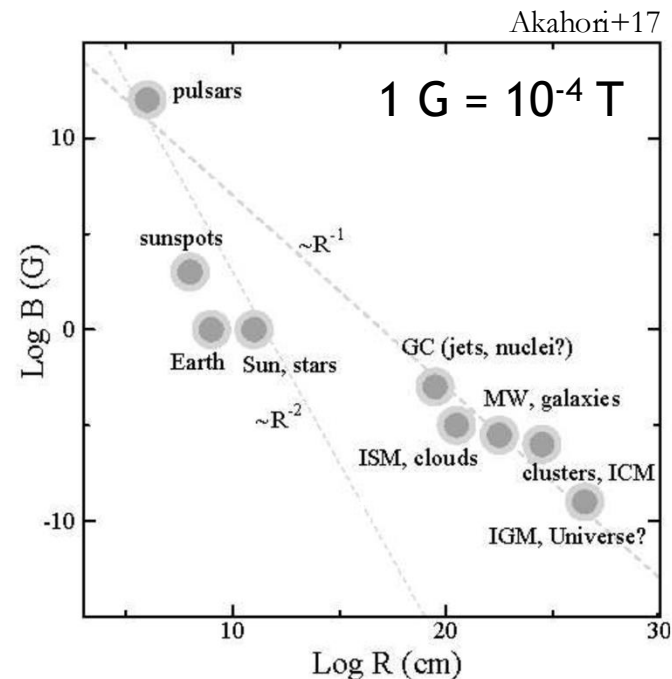


Cosmic magnetic fields

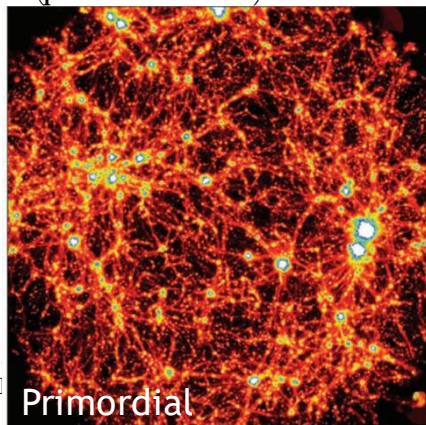
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eg. Neronov & Vovk 2010, Subramanian+19, Vachaspati+21, Mtchedlidze+24

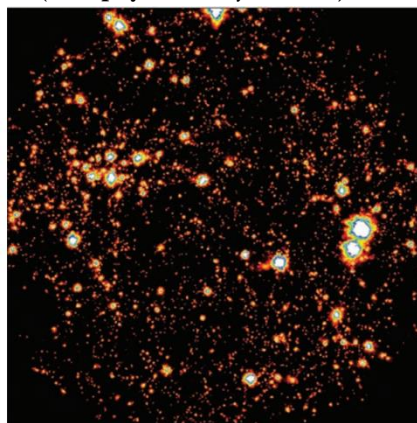
- Astrophysical magnetic fields play a crucial role on many different scales in the Universe
 - ▣ planetary habitability, star formation, extracting energy from black holes, affecting the thermodynamics of the ICM and the baryon cycle in CGM,
- Growing evidence of magnetic fields on the largest scales of the cosmic web of matter
 - ▣ $10^{-16} \text{ G} < B < 10^{-9} \text{ G}$
 - ▣ Primordial and/or “astrophysical” origin?



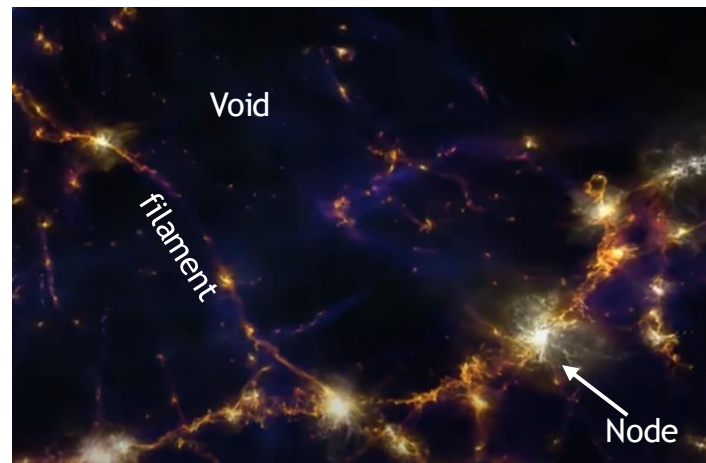
Magnetic field strength @ $z = 0$
(primordial scenario)



Magnetic field strength @ $z = 0$
(astrophysical-only scenario)



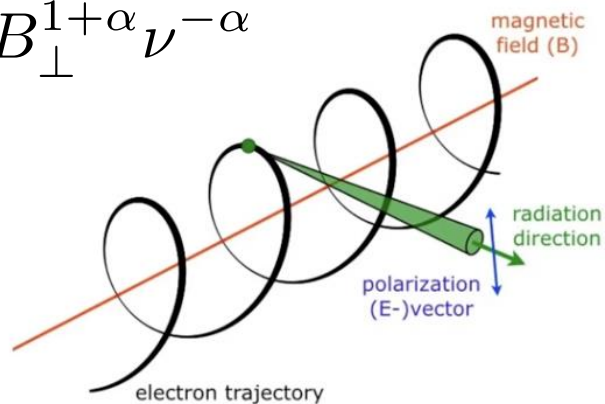
200 Mpc



Magnetism with radio telescopes

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$$I_\nu \propto B_\perp^{1+\alpha} \nu^{-\alpha}$$



G. Heald

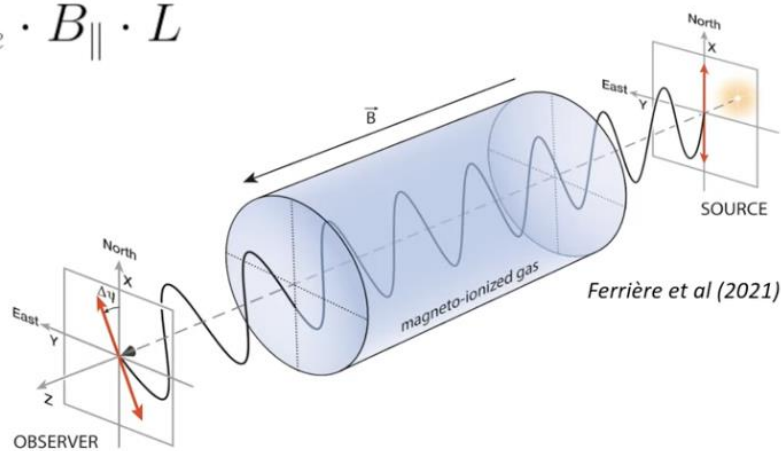


Fornalont+89

Orange: radio synchrotron emission from Fornax A

Synchrotron traces magnetic fields in the sky plane

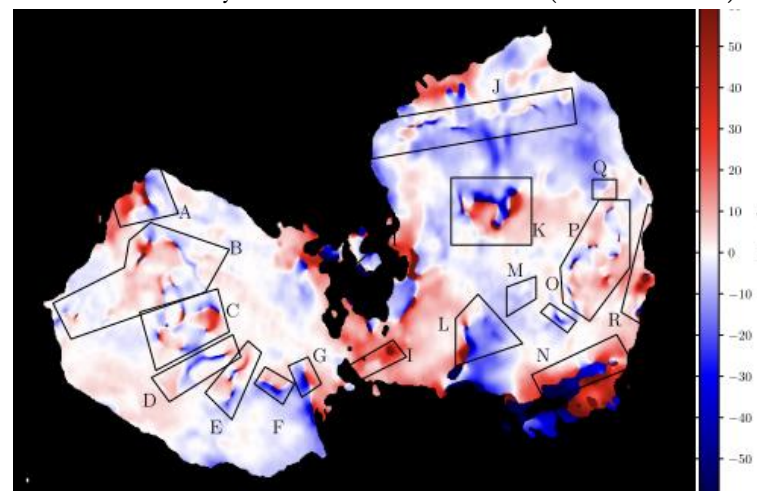
$$RM \propto n_e \cdot B_{\parallel} \cdot L$$



Ferrière et al (2021)

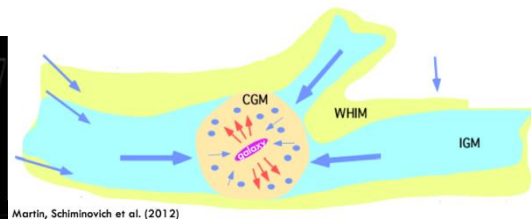
Faraday rotation traces magnetic fields along LOS

Red/blue: Faraday rotation from Fornax A (Anderson+18)

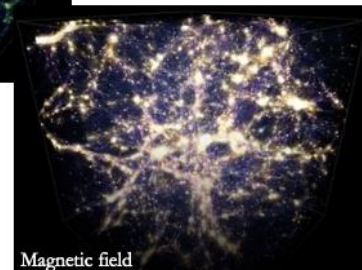
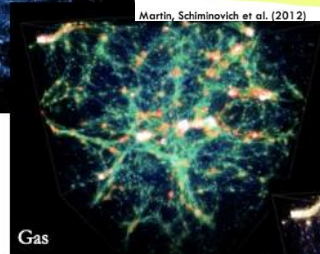


Motivation

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Martin, Schiminovich et al. (2012)



- Faraday rotation: tracer of the **inventory of matter** out to cosmic noon
 - ▣ Cluster outskirts & IGrM – IGM interface (Anderson+21,24)
 - ▣ Testing MHD models of the CGM (Heesen+23, Ramesh+24)
 - ▣ Constraining extent of AGN feedback (Blunier & Neronov 2024)

- Radio cosmic web: the **origin of cosmic magnetism** & properties of primordial magnetic fields

- ▣ Probe of early Universe physics (Vachaspati+21)
 - Inflation, Electroweak, QCD eras
- ▣ Stochastic Gravitational Wave Background (Neronov+21)
- ▣ Alleviate “Hubble Tension” (Jedamzik & Pogosian 2020)
- ▣ Influence on structure formation and reionisation (Ralegankar+24, Sanati+24)

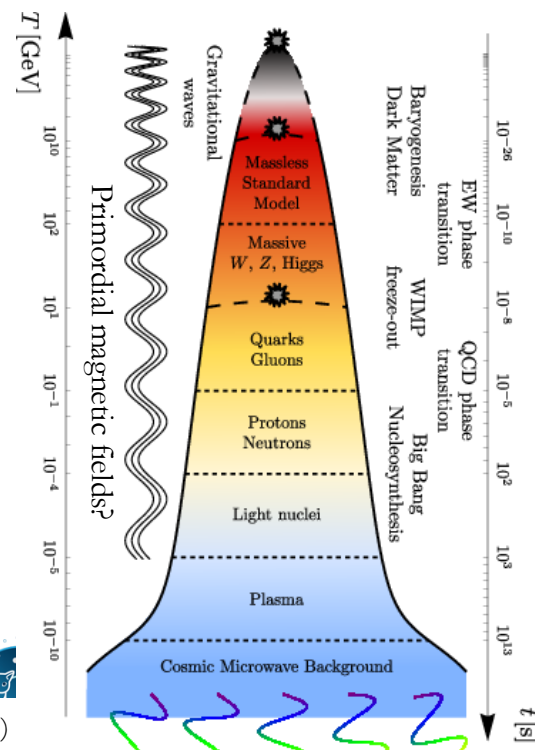


Image credit: Schmitz (2022)

RM values in different environments

$$\text{RM}_{[\text{rad m}^{-2}]} = 0.812 \int_0^L n_e [\text{cm}^{-3}] B_{\parallel} [\mu\text{G}] dl [\text{pc}]$$

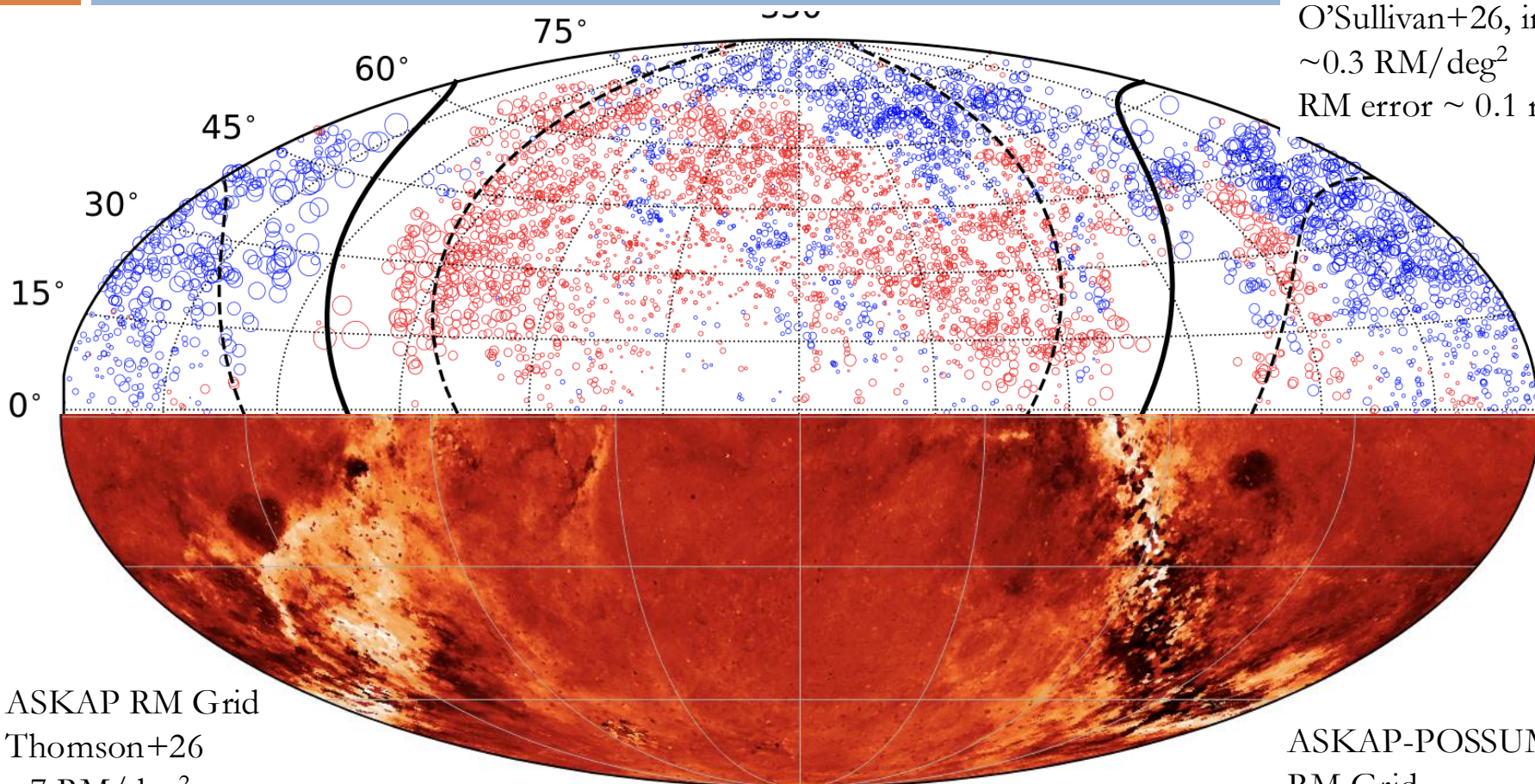
Environment	n_e (cm^{-3})	B_{\parallel} (μG)	L (kpc)	RM (rad m^{-2})
Cluster core	10^{-3}	3	100	~ 250
Cluster outskirts	10^{-4}	0.3	1000	~ 25
Galaxy ISM	0.03	3	1	~ 70
Galaxy group	10^{-4}	0.2	500	~ 8
Hot CGM	10^{-4}	0.5	50	~ 2
Cosmic-web filament	10^{-5}	0.1	1000	~ 1

- Combine RM with ionised gas tracers (eg. tSZ, kSZ, X-ray) to get more robust B estimates

$$y \propto \int n_e k_B T_e dl \quad \frac{\Delta T_{\text{kSZ}}}{T_{\text{CMB}}} \propto \int n_e v_{\parallel} dl \quad S_X \propto \int n_e^2 \Lambda(T, Z) dl$$

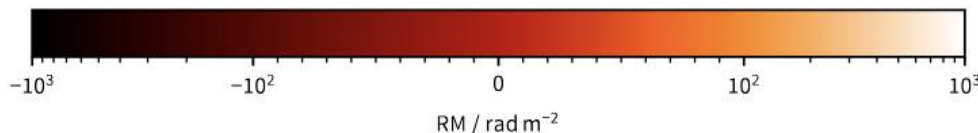
Next generation of RM Grids

LOFAR RM Grid
 O'Sullivan+26, in prep
 $\sim 0.3 \text{ RM/deg}^2$
 RM error $\sim 0.1 \text{ rad/m}^2$



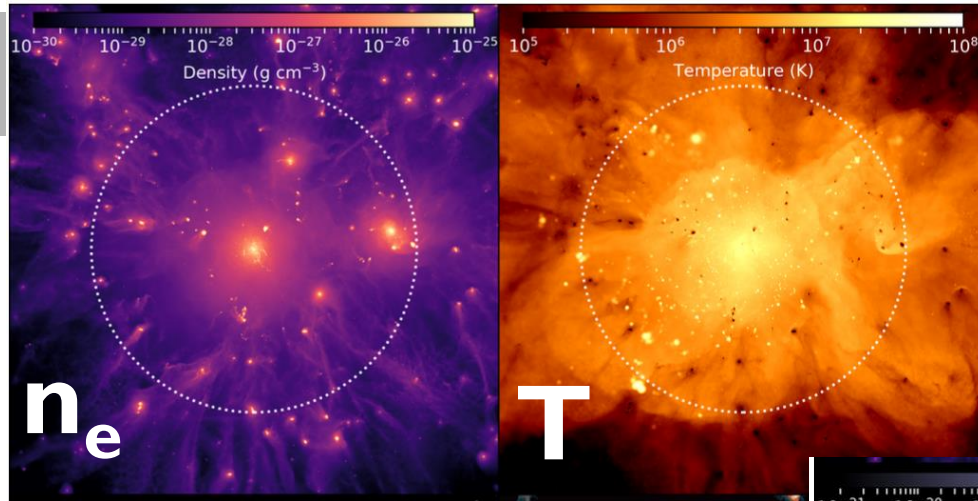
ASKAP RM Grid
 Thomson+26
 $\sim 7 \text{ RM/deg}^2$
 RM error $\sim 2 \text{ rad/m}^2$

ASKAP-POSSUM
 RM Grid
 $\sim 40 \text{ RM/deg}^2$
 RM error $\sim 2 \text{ rad/m}^2$

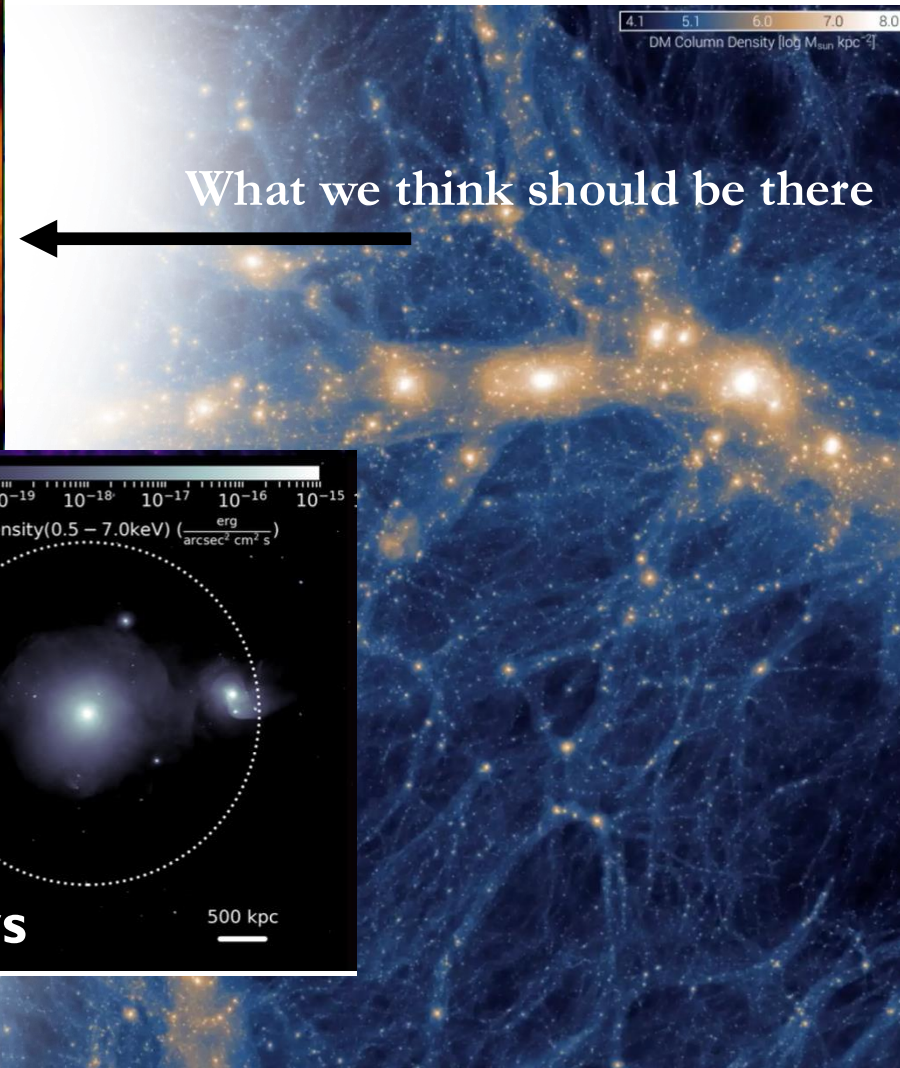


Mapping the baryon distribution

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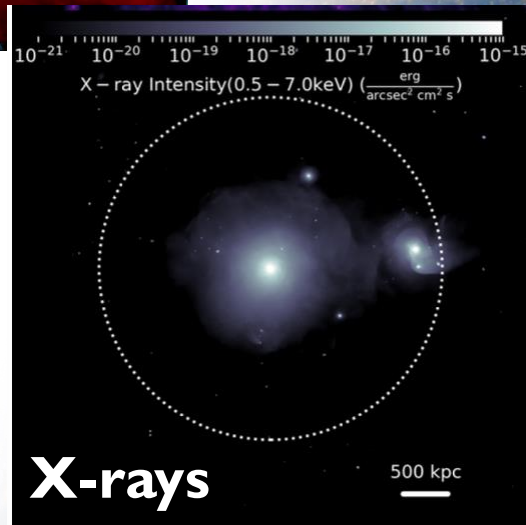


ROMULUSSC - c/o Oppenheimer+2021



What we think should be there

what we can typically observe



X-rays

500 kpc

“missing baryon” problem:
most normal matter not in stars or
galaxies or intracluster medium

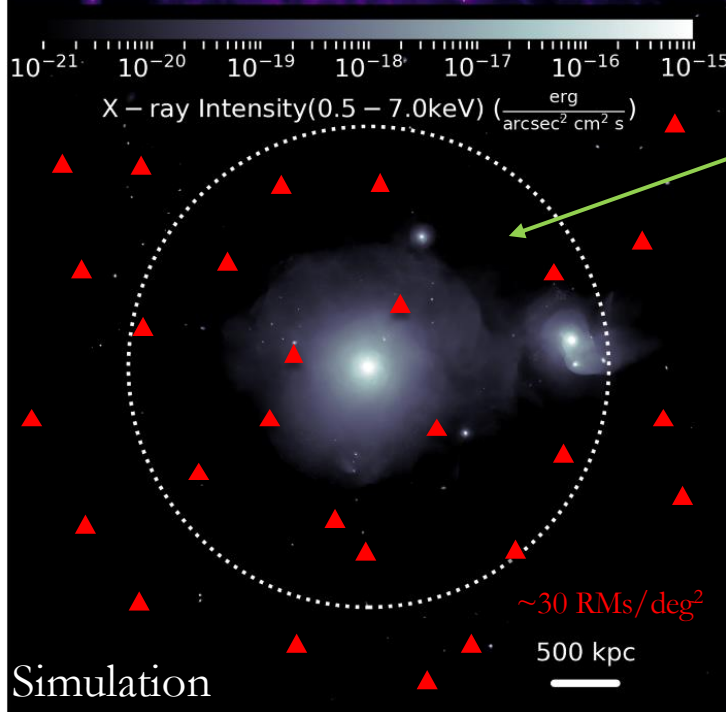
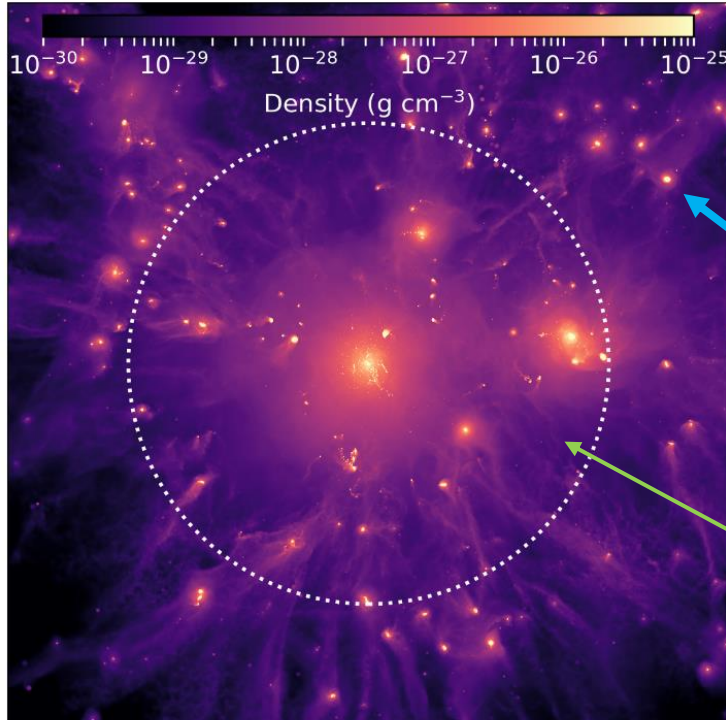
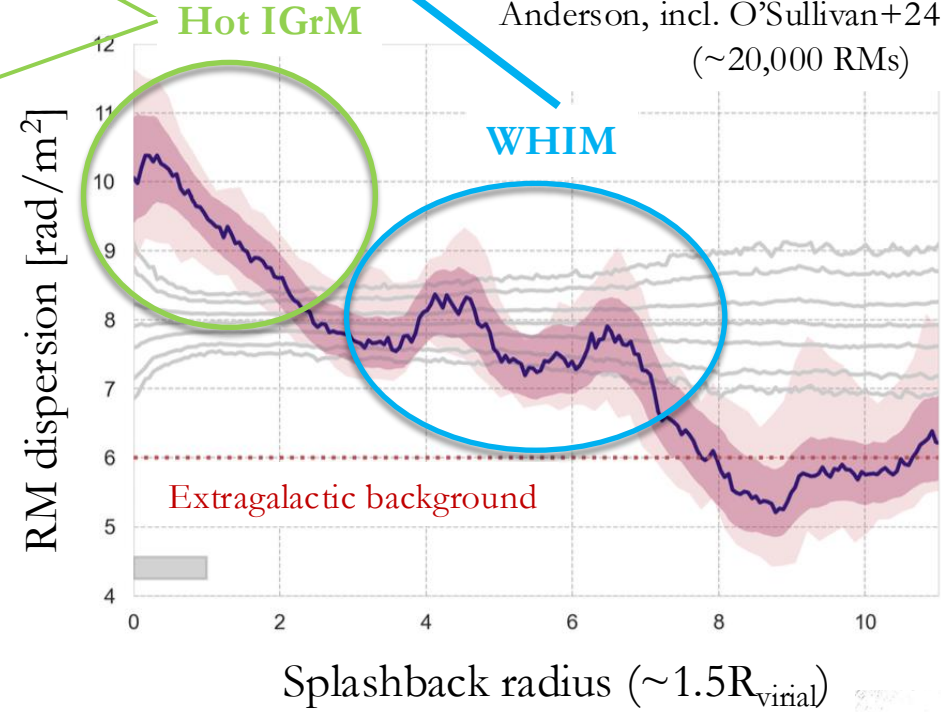
Can be up to $15R_{\text{vir}}$ until universal
baryon fraction is reached Ayromlou+23

Galaxy groups

- Excess σ_{RM} from hot intragroup medium (IGrM) & connecting filaments (WHIM) in **55 nearby groups**
- Magnetised thermal gas at interfaces of galaxy groups and the cosmic web: $0.1 < B_{\text{IGrM/WHIM}} [\mu\text{G}] < 1$

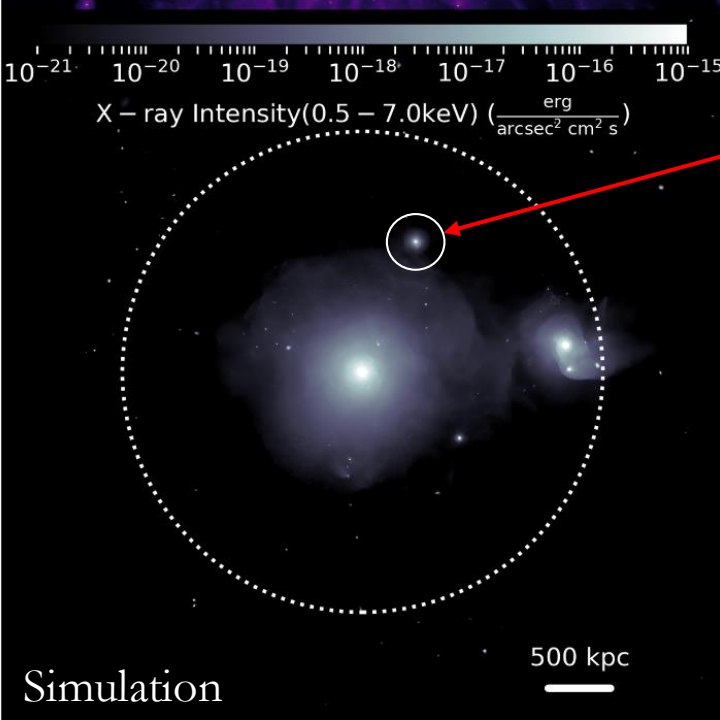
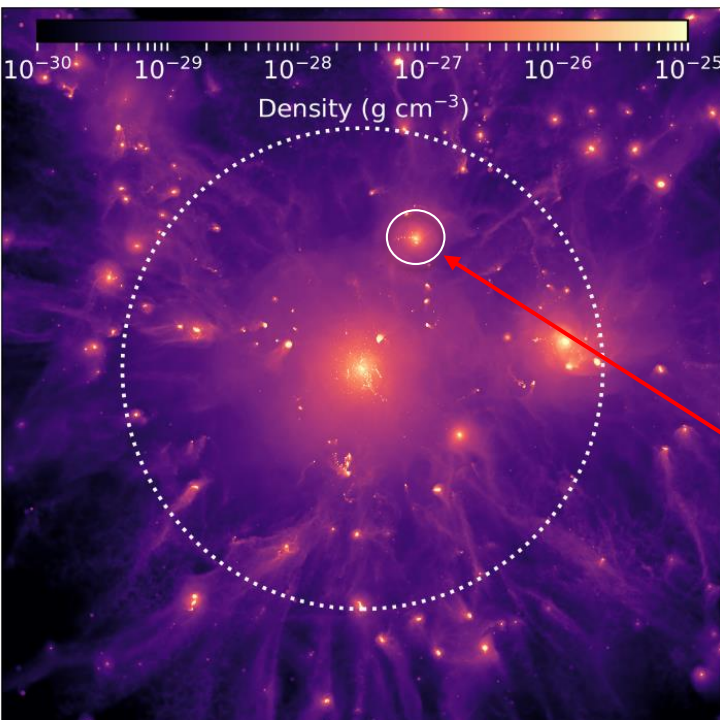
ASKAP-POSSUM: cm RM Grid

Anderson, incl. O'Sullivan+24
(~20,000 RMs)



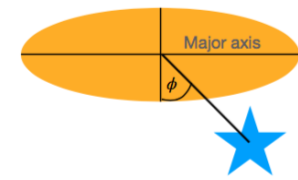
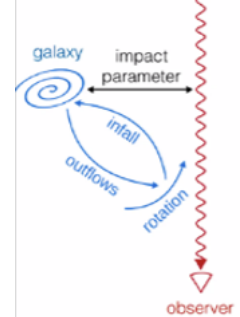
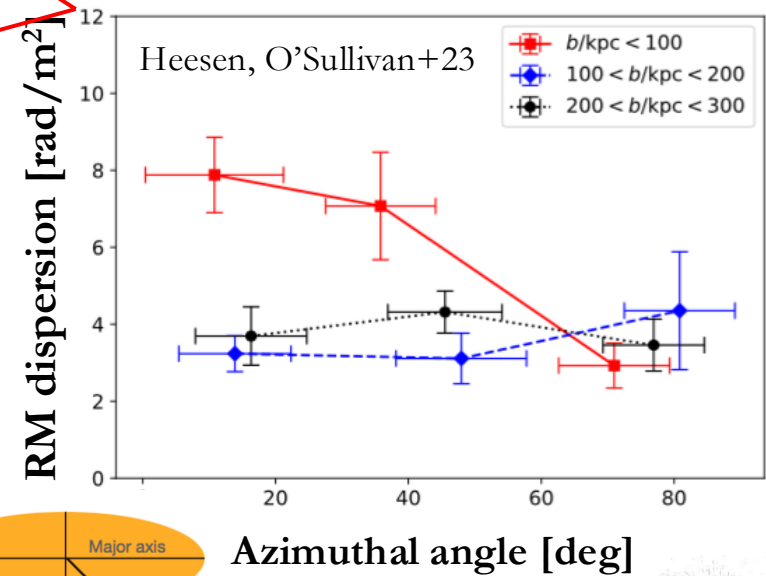
Simulation

Hot CGM



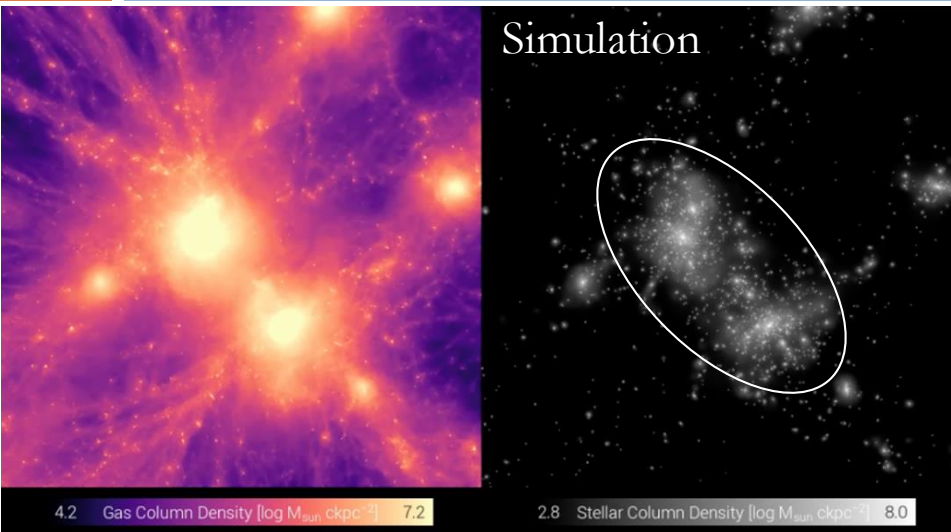
- Excess σ_{RM} ($3.7 \pm 0.9 \text{ rad/m}^2$) from circumgalactic medium along minor axis of 183 nearby galaxies
- Implies $\sim 0.5 \mu\text{G}$ for $n_e \sim 10^{-4} \text{ cm}^{-3}$ at $\sim 50 \text{ kpc}$
 - Magnetised galaxy outflows

LOFAR: m RM Grid



Gas between galaxy clusters

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ASKAP-POSSUM: cm RM Grid

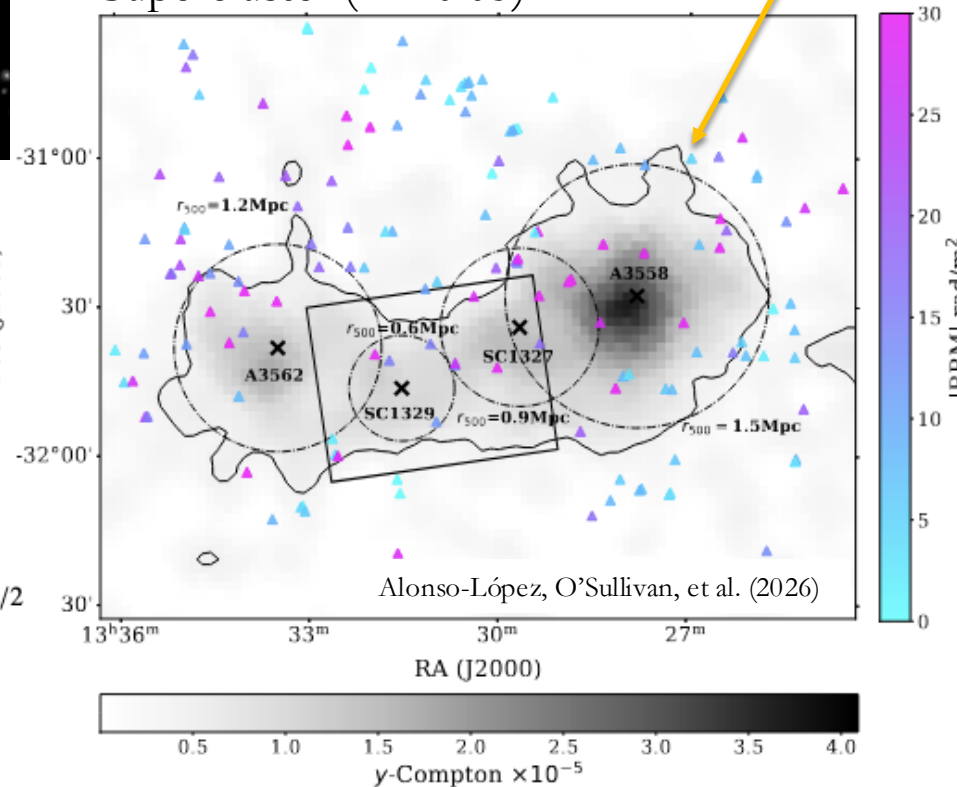
Planck tSZ contour:
tracer of gas density

Observations of the
centre of the Shapley
Supercluster ($z \sim 0.05$)

- Excess σ_{RM} from intercluster matter bridge at the core of the Shapley Supercluster

$$\sigma_{\text{RM}}^{\text{SSC}} = \sqrt{\sigma_{\text{RM,on-target}}^2 - \sigma_{\text{RM,off-target}}^2} = 30.52 \pm 4.55 \text{ rad/m}^2$$

$$B \approx 1 \mu\text{G} \left(\frac{\sigma_{\text{RM}}[\text{rad/m}^2]}{30} \right) \left(\frac{\bar{n}_e[\text{cm}^{-3}]}{4 \times 10^{-4}} \right)^{-1} \left(\frac{L[\text{Mpc}]}{1.8} \frac{\Lambda[\text{kpc}]}{50} \right)^{-1/2}$$



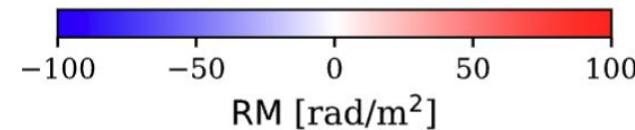
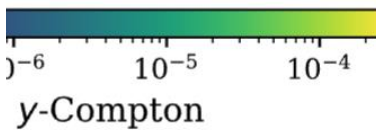
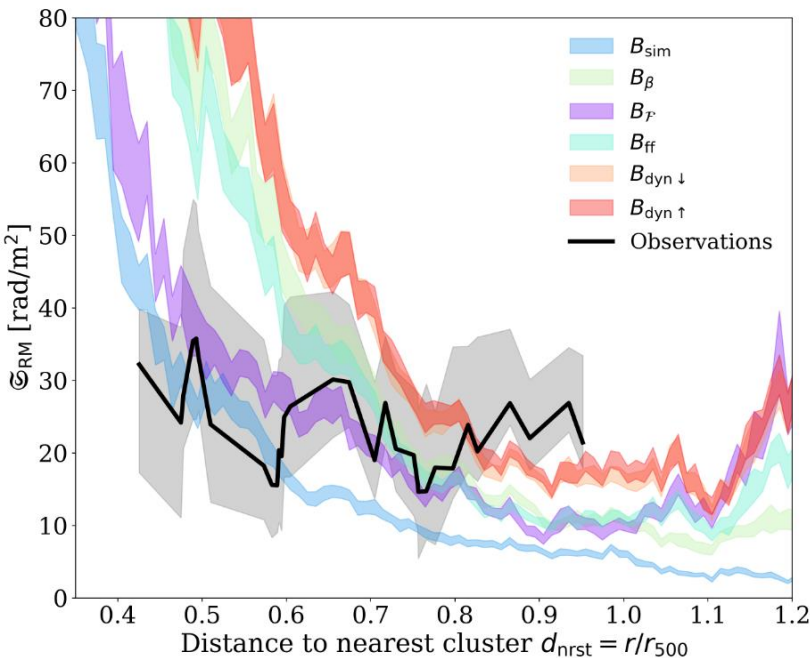
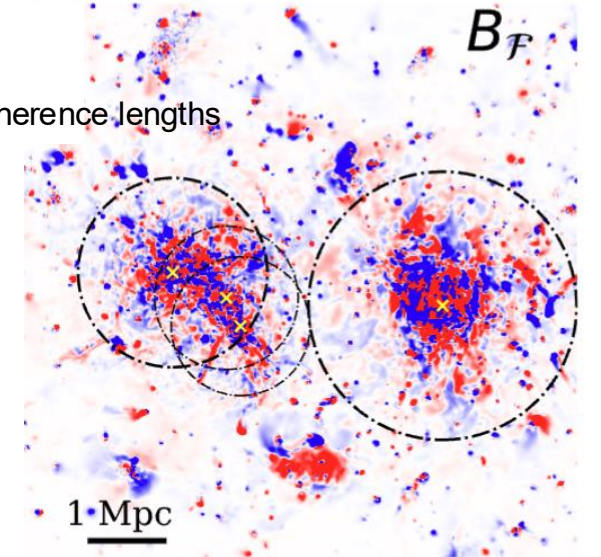
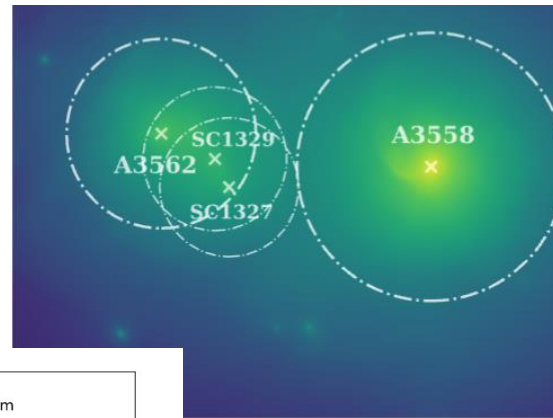
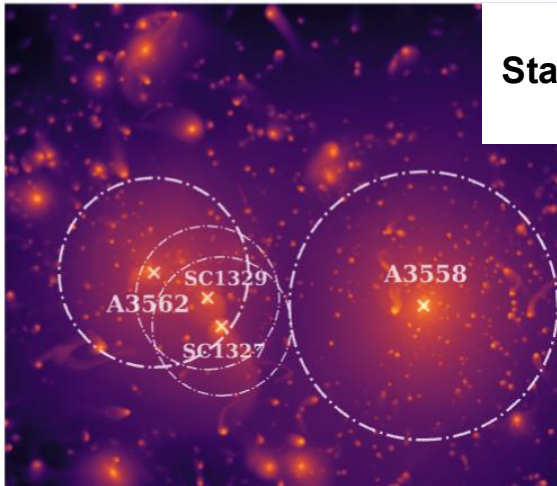
SLOW MHD simulation of the Shapley supercluster

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Alonso-López et al. (2026)

State of the art

- Interaction + Merger history
- ➔ Detailed ICM physics
- Realistic range of magnetic field coherence lengths

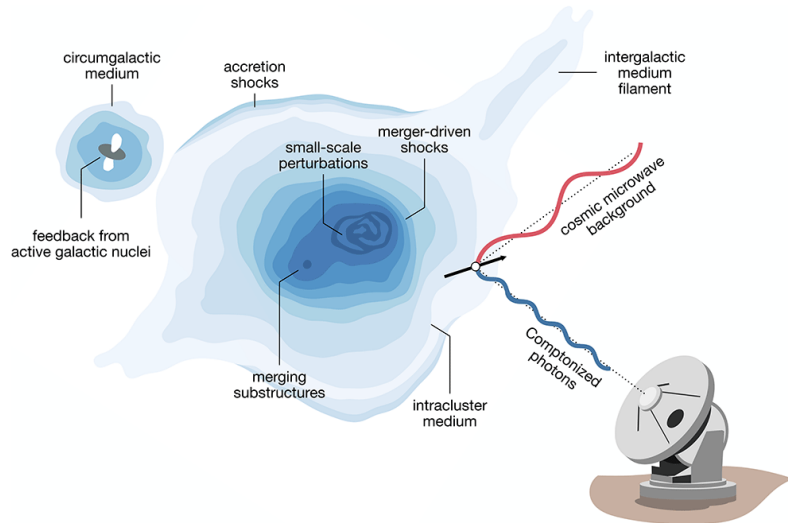


Systematically flatter-than-expected RM scatter profiles from observations compared SLOW profiles.

Challenging to explain: cluster substructure with coherent fields? Magnetic reconnection?

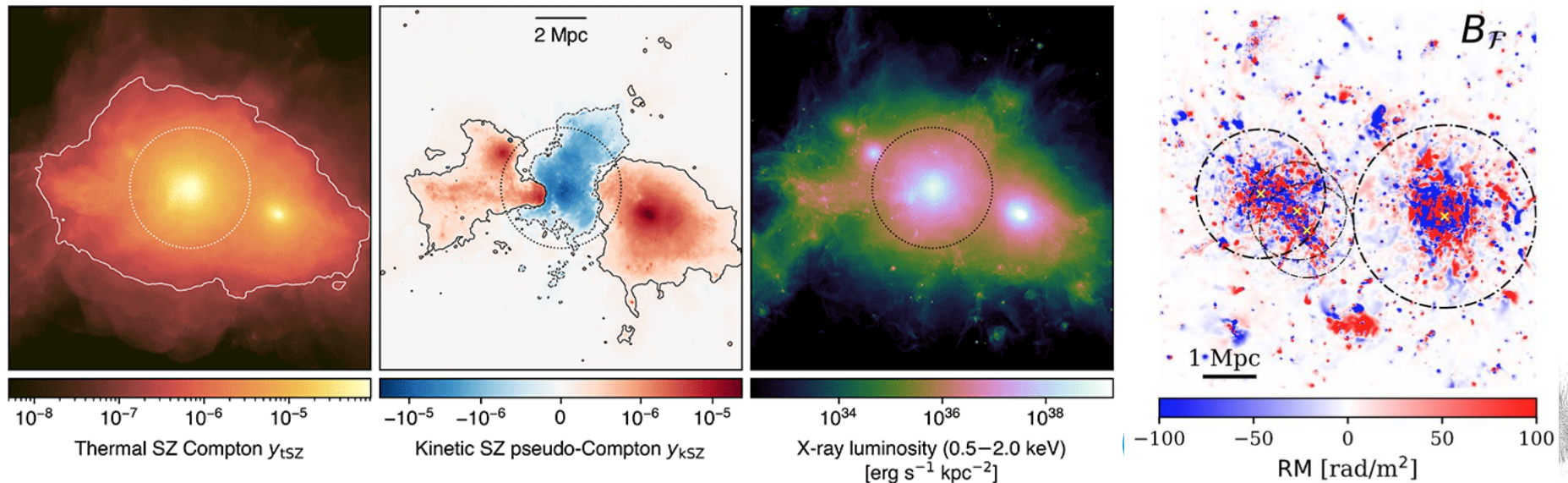
See also Osigna+25, Khadir+26

Probing cluster substructure with AtLAST



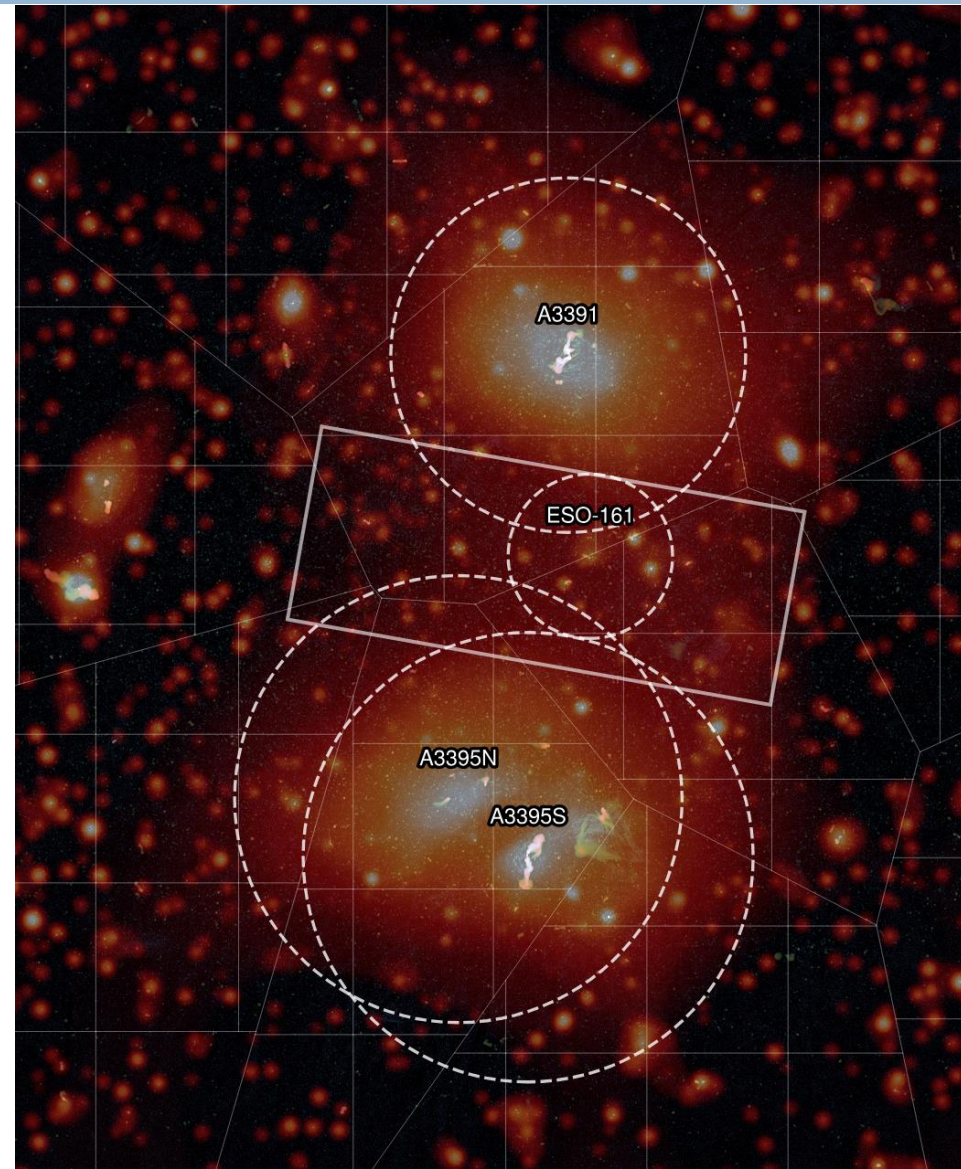
- Detailed mapping of the tSZ and kSZ will probe shocks, gas motion and substructure
- Invaluable to understand the magnetic field amplification process and RM distribution

Di Mascolo+24



Abell 3391-3395 cluster bridge

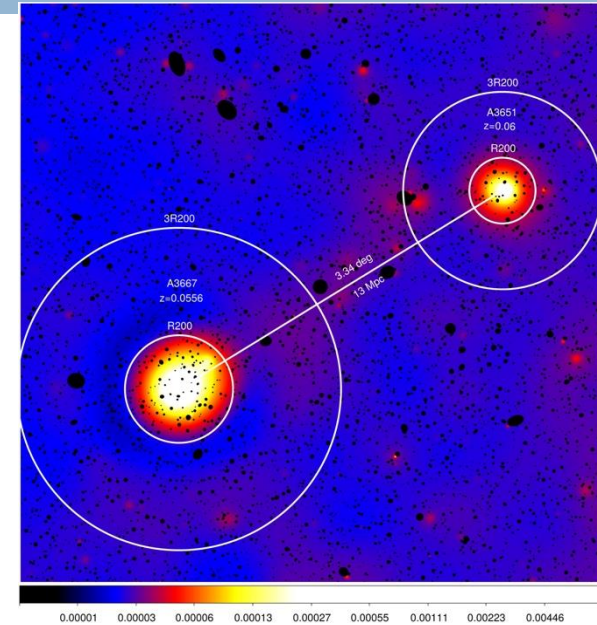
- Gustafsson et al. (2026)
- SKA-Mid equivalent RM Grid of 110 RMs/deg²
- Both clusters and “bridge” detected in RM
 - Implies an ordered bridge magnetic field (in tension with turbulent amplification models; maybe explains why no diffuse radio bridge)
- Need larger sample of X-ray, radio and tSZ-detected cluster bridges



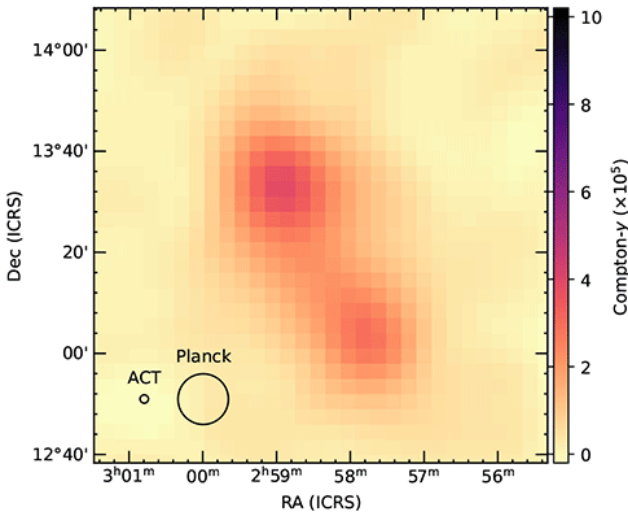
Cluster bridges to filaments?

- A399-A401 cluster bridge
 - ▣ Detected in X-ray, radio synchrotron and tSZ
 - ▣ AtLAST can detect more & provide better detail

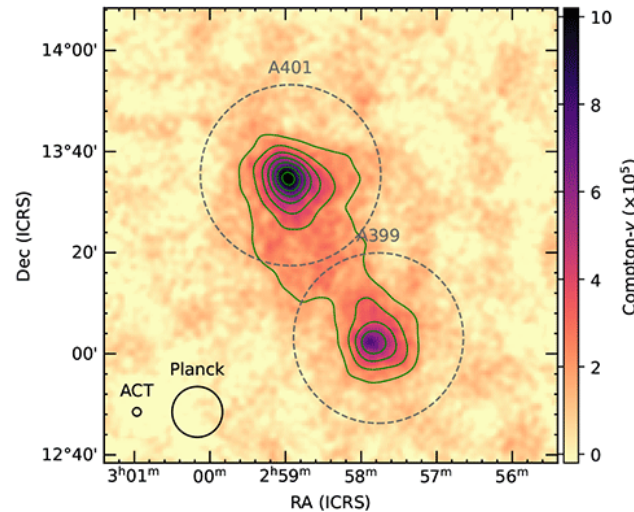
- Dense filaments?
 - ▣ 13 Mpc X-ray filament between A3667 - A3651
 - ▣ Dietl+24 ($\delta \sim 210$, $T \sim 0.9$ keV): predicted $y \sim 10^{-6}$



Planck A399-A401 Compton-y Map



Abell 399-401 Compton-y Map



Di Mascolo+24

Cosmic web filaments with AtLAST?

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Carretti, Vacca, O'Sullivan, et al. (2022), MNRAS, 512, 945. arXiv:2202.04607 (Paper I)

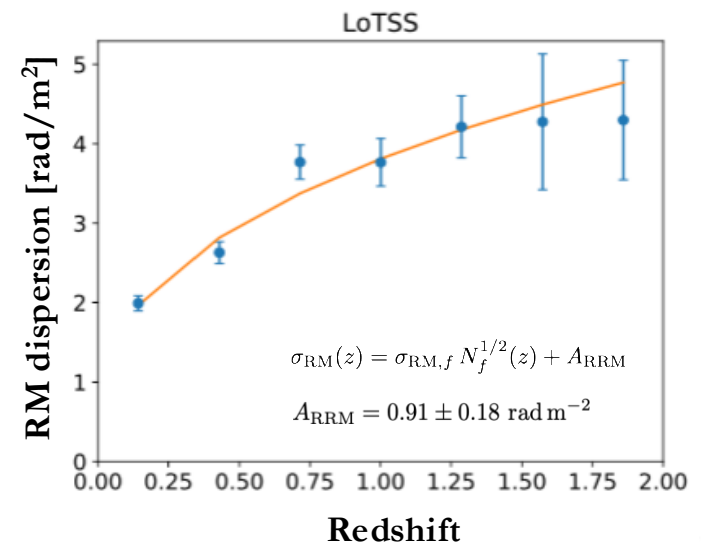
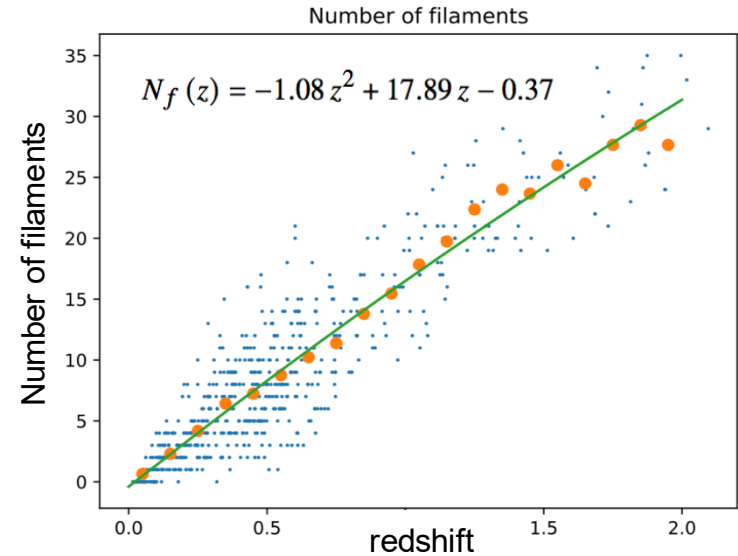
- $\sigma_{(R)RM}$ vs z analysis for 1003 RMs, $z < 2$
- Compare with number of filaments along each line of sight
 - Chen+15, Carrón-Duque+21

$$\sigma_{RM}(z) = \sigma_{RM,f} N_f^{1/2}(z) + A_{RRM}$$

$$\sigma_{RM,f} = 0.71 \pm 0.07 \text{ rad m}^{-2}$$

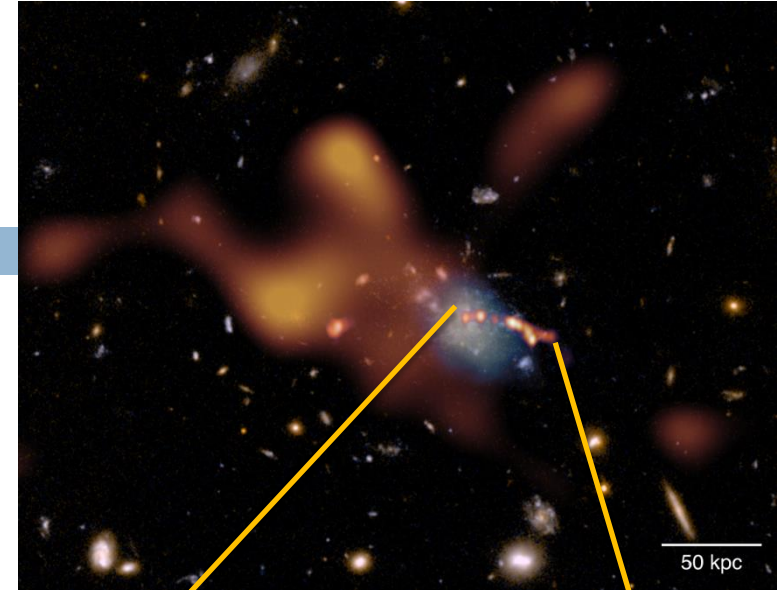
- Assuming typical $n_{e,f} \sim 10^{-5} \text{ cm}^{-3}$ and mean path length through a filament $L_f \sim 3 \text{ Mpc}$
 \Rightarrow average $B_f \sim 30 \text{ nG}$
- y-map stacking ($z > 0.5$) with AtLAST?
 $y < \sim 10^{-8}$

- eg. Tanimura+19, de Graaff+19

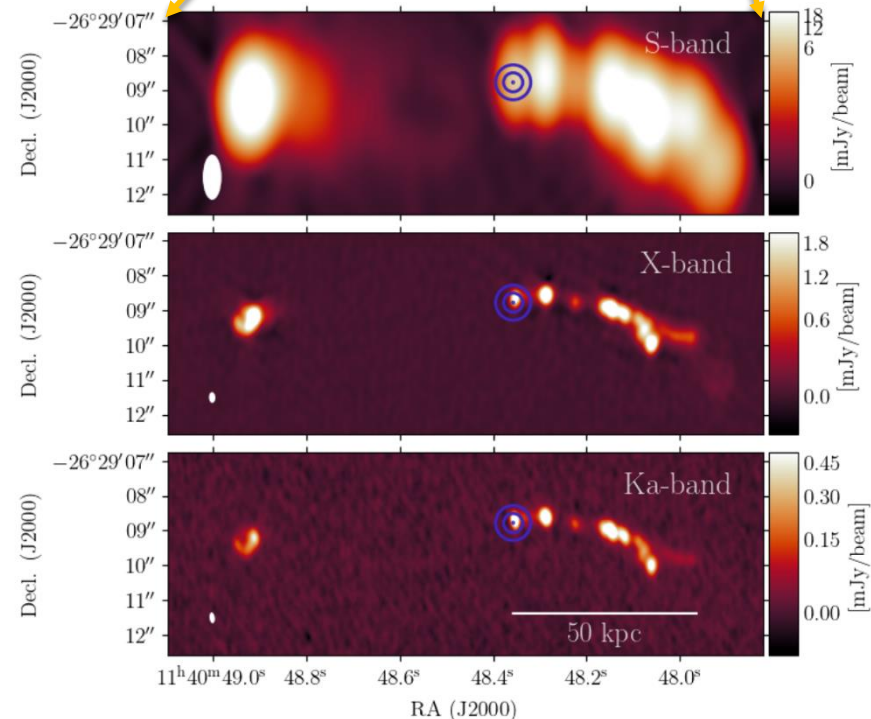


Proto-clusters

- Spiderweb proto-cluster: being magnetized by its central radio jet?
 - ▣ Anderson et al. (2022)
- RM and SZ effect remain observable to high redshift
 - ▣ complementary probes of the co-evolution of magnetic fields and baryons during cluster assembly
- Can AtLAST provide a better view of the gas thermodynamics in proto-clusters?
 - ▣ Jet feedback on proto-cluster gas
 - ▣ Is the high-RM/jet-bend region coincident with overpressured gas?
 - ▣ Are jet-gas interaction regions visible as tSZ enhancements?



Di Mascolo+24



Summary

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- Current Faraday rotation surveys are able to probe diffuse (magnetised) gas from the CGM to IGM
 - magnetised CGM in nearby galaxies (< 0.1 Mpc) Heesen+24
 - IGrM – WHIM interface ($0.1 - 5$ Mpc, $0.1 - 1 \mu\text{G}$) Anderson+24
 - Supercluster of galaxies ($\sim 1 \mu\text{G}$, < 5 Mpc) Alonso-López+26
 - cosmic web filaments (WHIM, > 5 Mpc), $B \sim 10$ nG ($z \sim 0$) Carretti+23

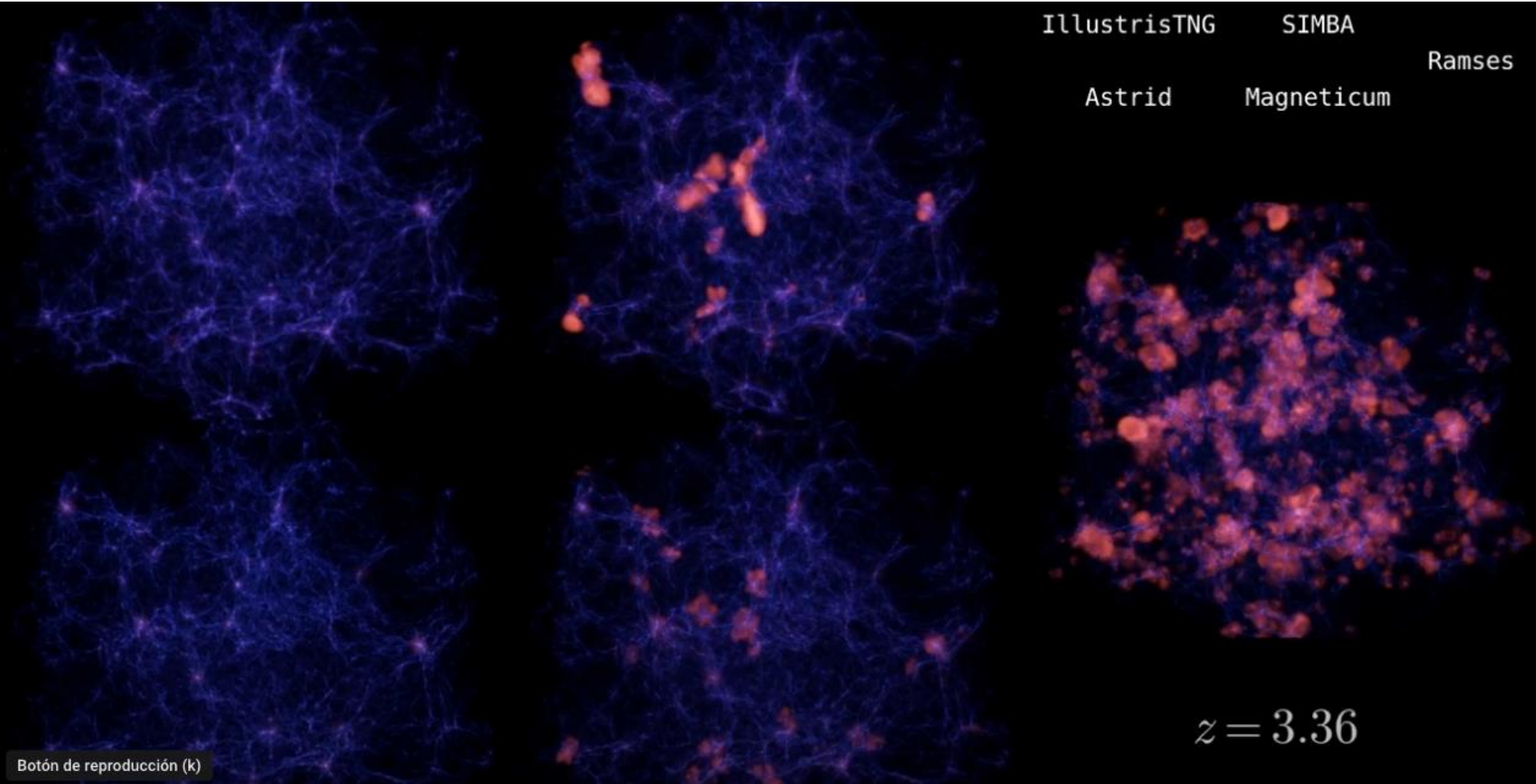
- tSZ and kSZ from AtLAST can break degeneracies in order to more reliably infer the magnetic field properties across a wide range of cosmic scales

- Future is bright with SKA-Mid and SKA-Low (2029+)
 - ▣ AtLAST as the perfect buddy?



Differences in simulation predictions

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gas density (blue) and gas temperature (red), 25 Mpc³ box