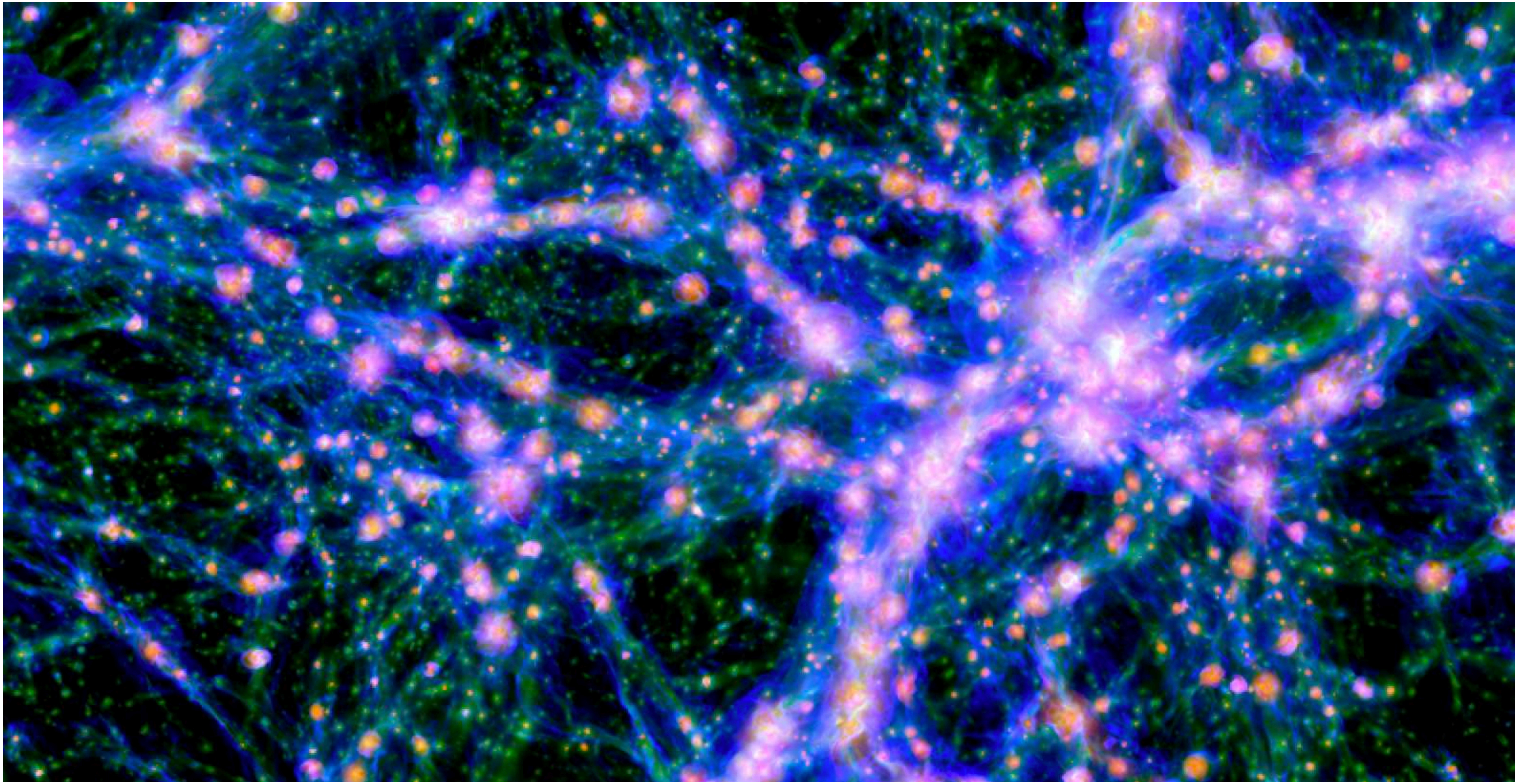


The Magnetic Cosmic Web

Franco Vazza

- **WHAT'S INTERESTING IN THE COSMIC WEB?**
- **MYSTERIES & PUZZLES**
- **RECENT AND FUTURE OBSERVATIONS**

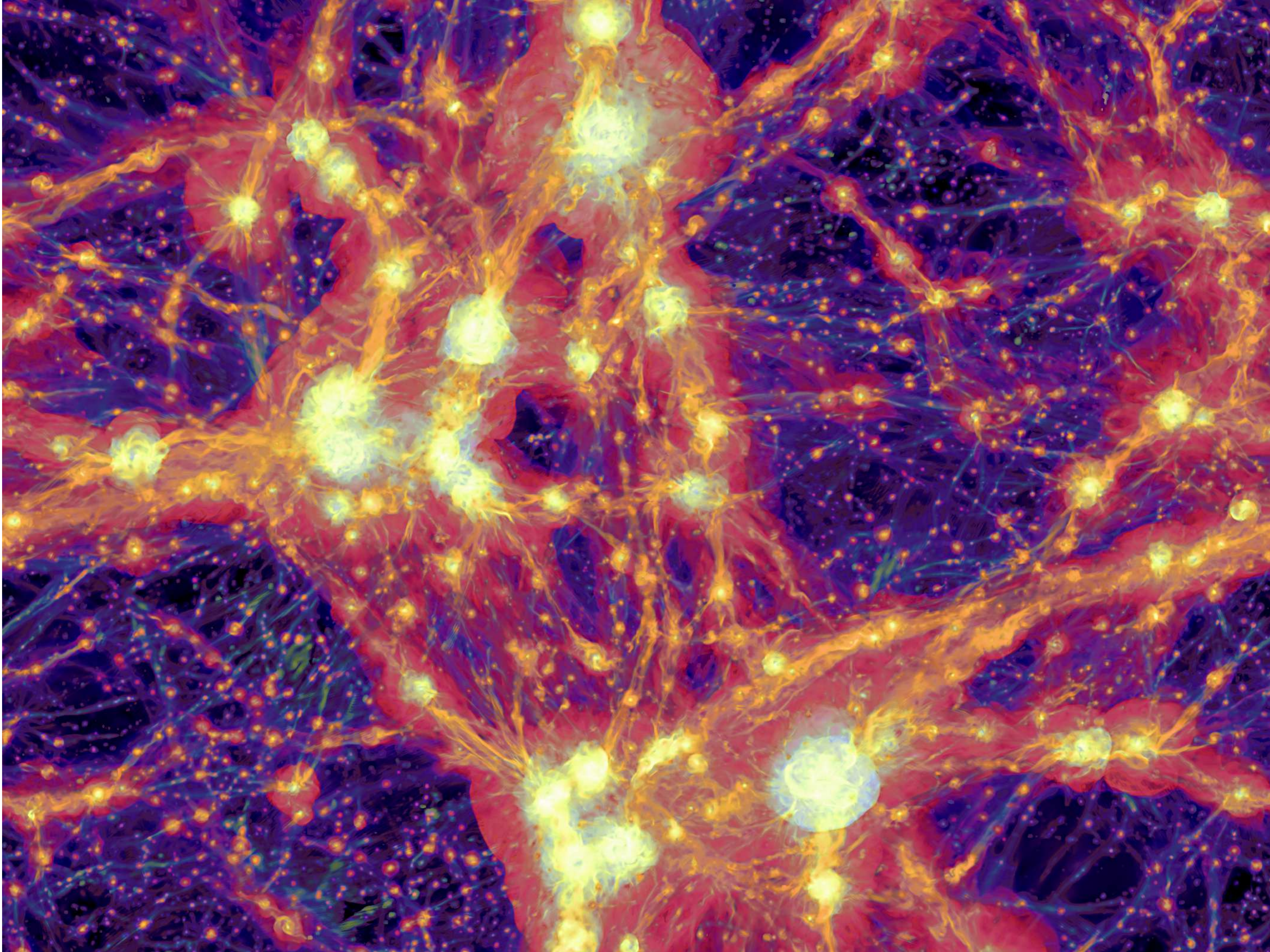
ERC-STG funded group in Bologna/Hamburg 2017–2022

Post-Docs: D.Wittor, K. Rajpurohit,N. Locatelli

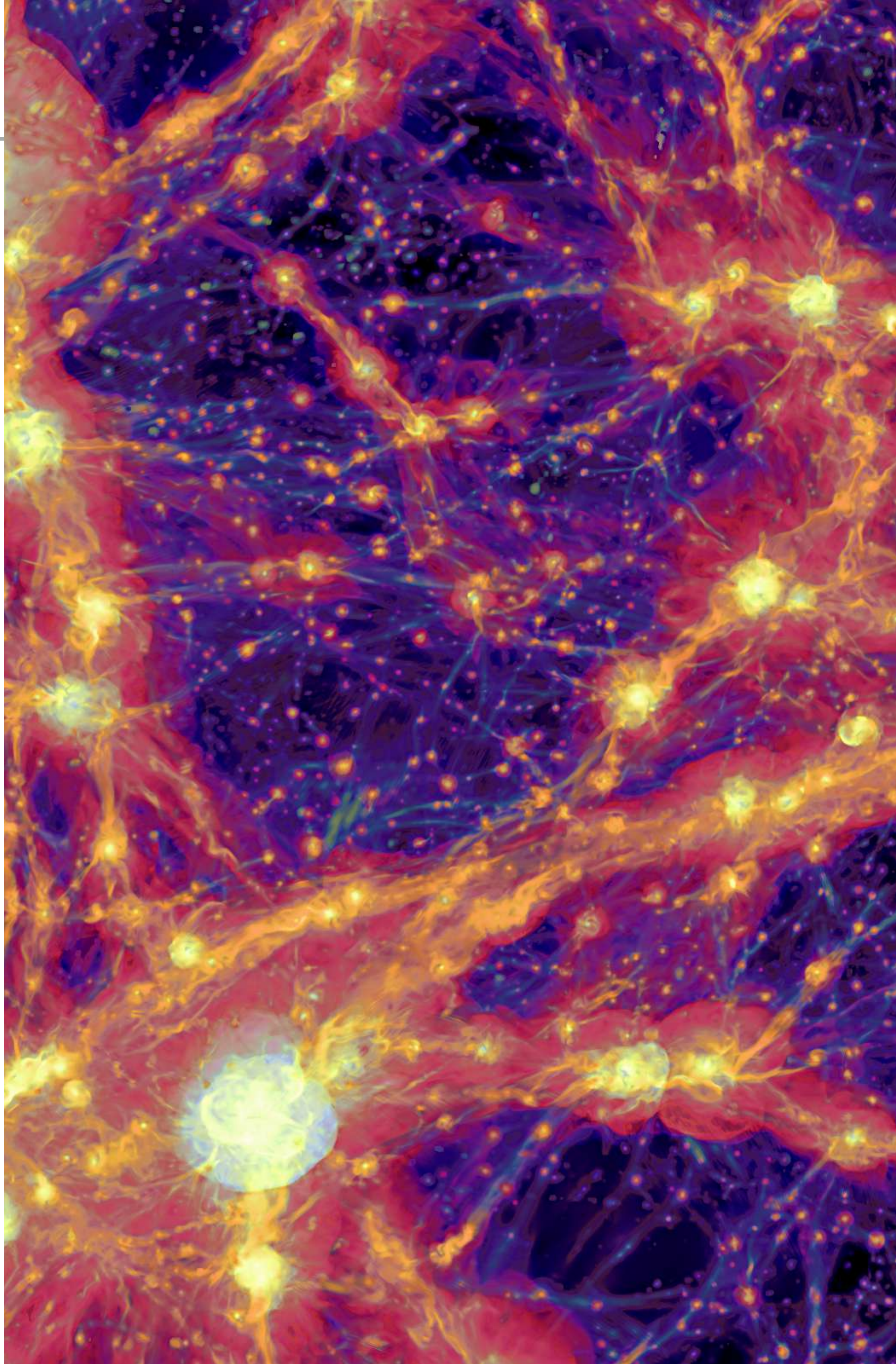
PhDs: N. Locatelli, S.Banfi, M.Angelinelli, P. Dominguez-Fernandez (in Hamburg)

Master: M.Simonte, E. Cilia

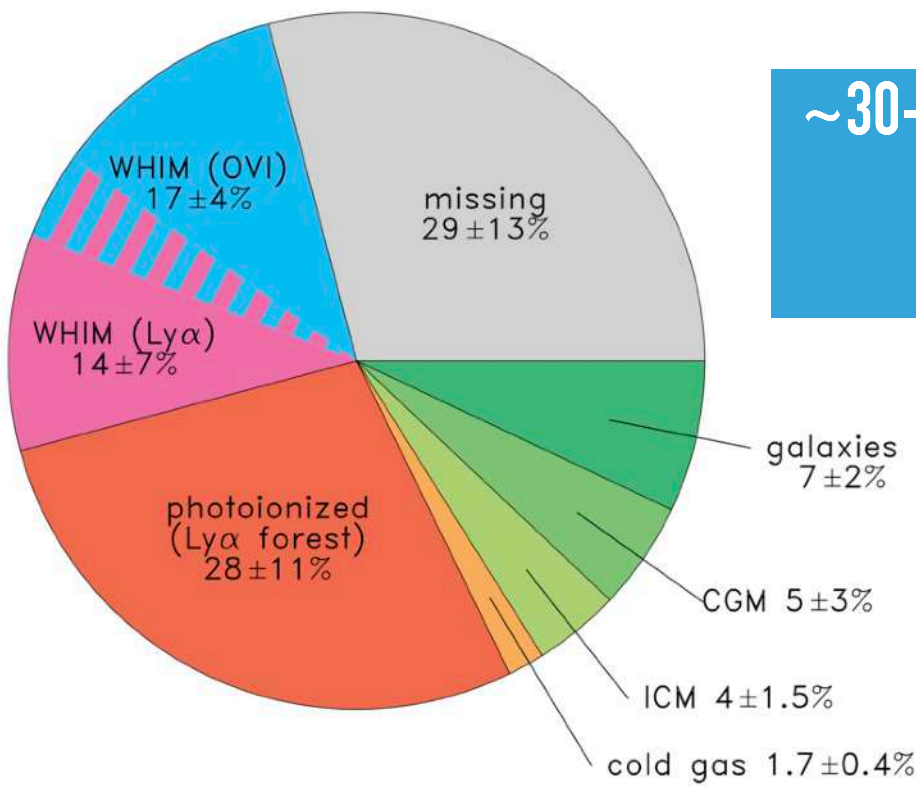
https://cosmosimfrazza.myfreesites.net/erc-magcow



- missing baryons
- chemical evolution
- fuelling of galaxies
- link between spin of galaxies and large-scale structures
- out of equilibrium plasmas
- non-thermal phenomena
- magnetic fields amplification
- …



1. A GREAT PORTION OF COSMIC MATTER IS MISSING

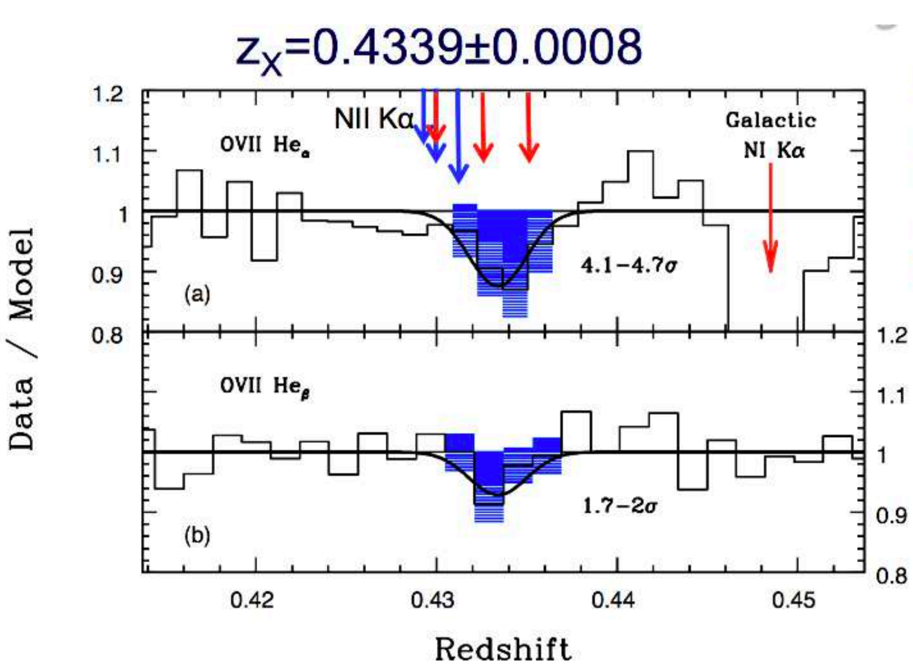


Shull+2012

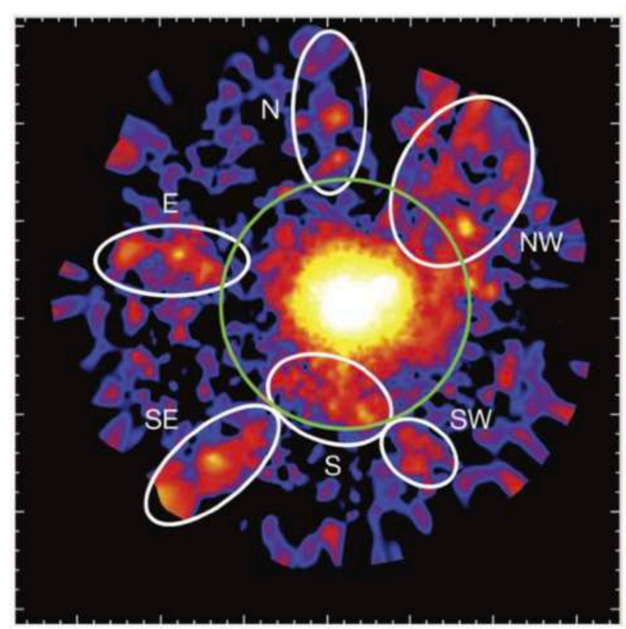
~30-50 % OF BARYONS PREDICTED TO BE IN FILAMENTS

(Cen & Ostriker 99,Davè+01…)

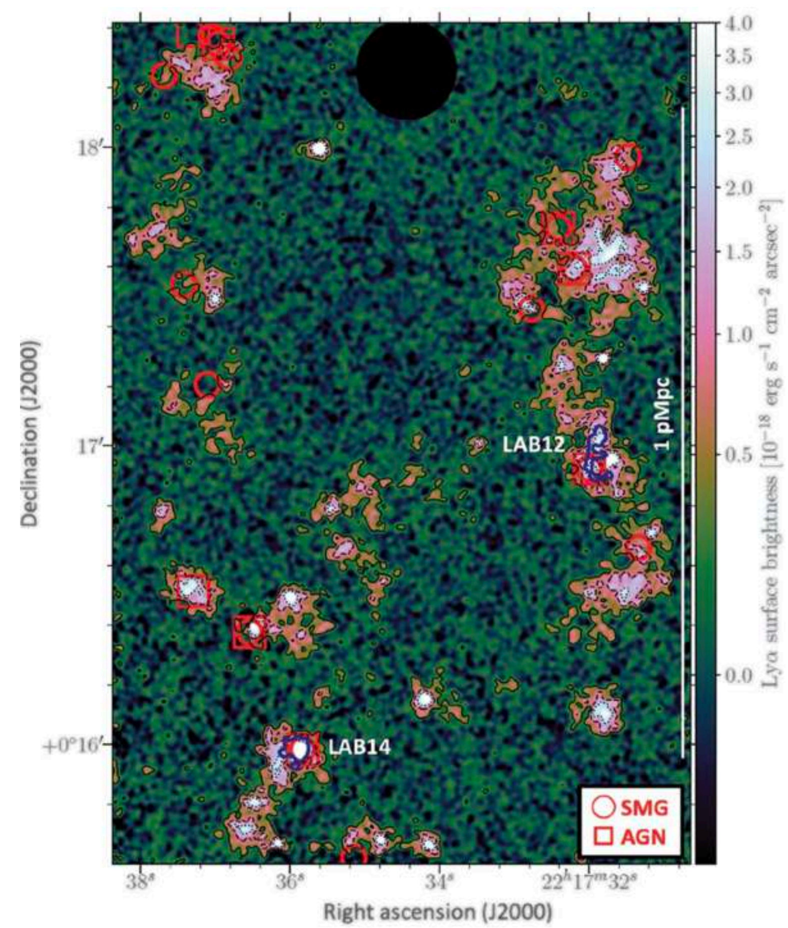
RECENT DETECTIONS:



Nicastro+ 2018 Nature (see also Kovacs+2019)



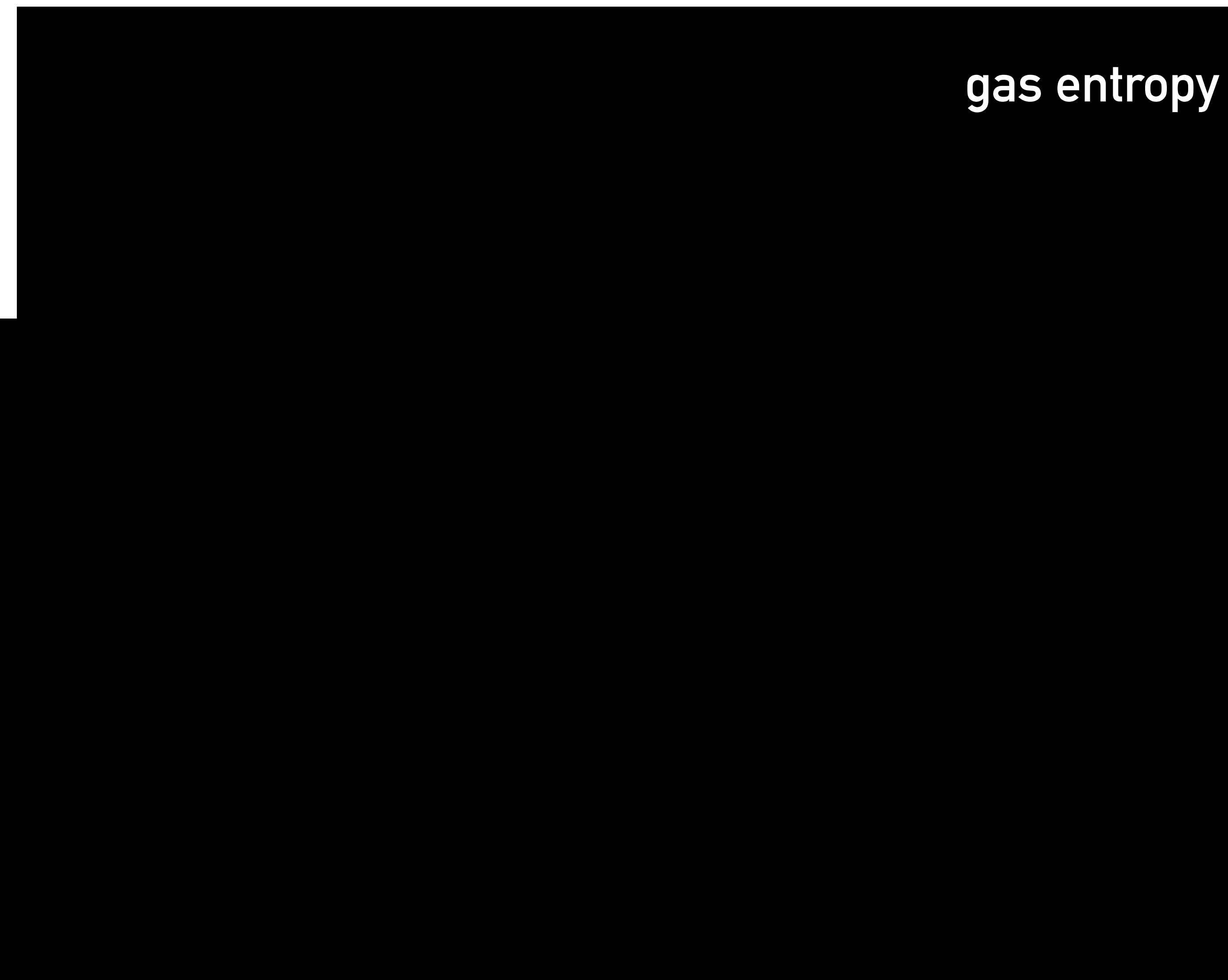
Eckert +. 2015 Nature

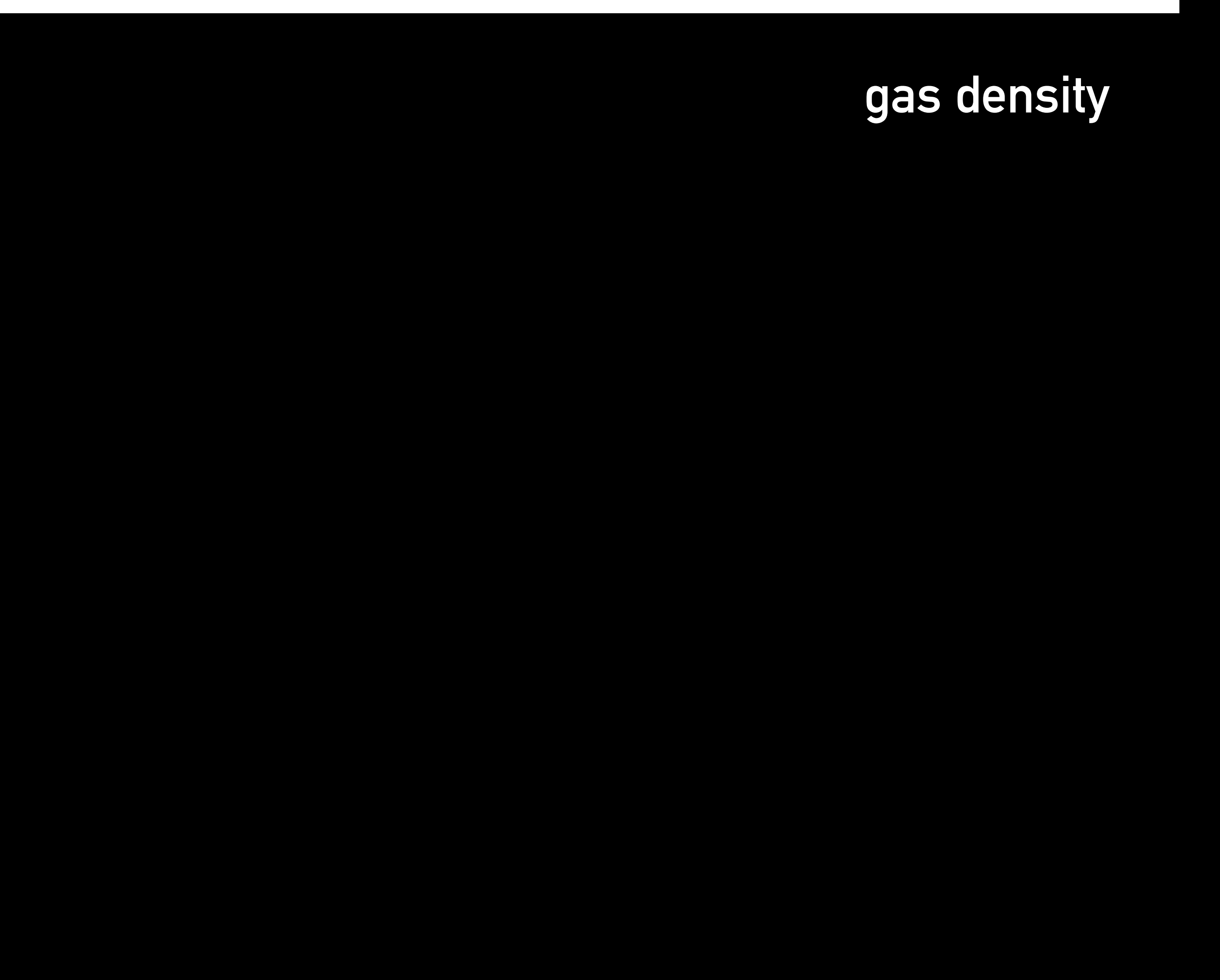


Umehata +. 2019 Science

2. THE COSMIC WEB: NOT SO QUIET, NOT SO SIMPLE

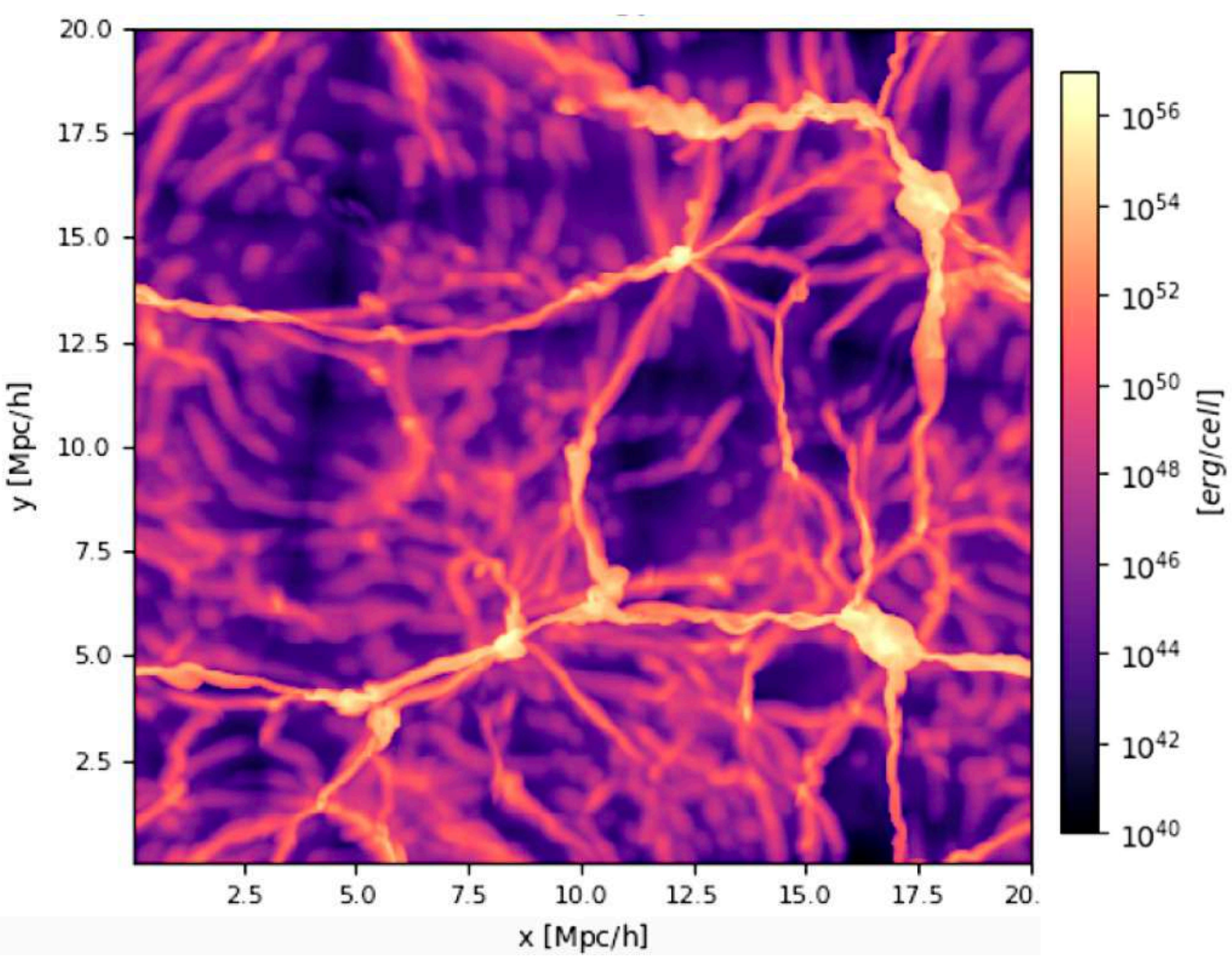
- Ongoing accretions across the entire cosmic history
- Violent energy transitions (from potential to kinetic/thermal/magnetic/turbulent/CR energy)

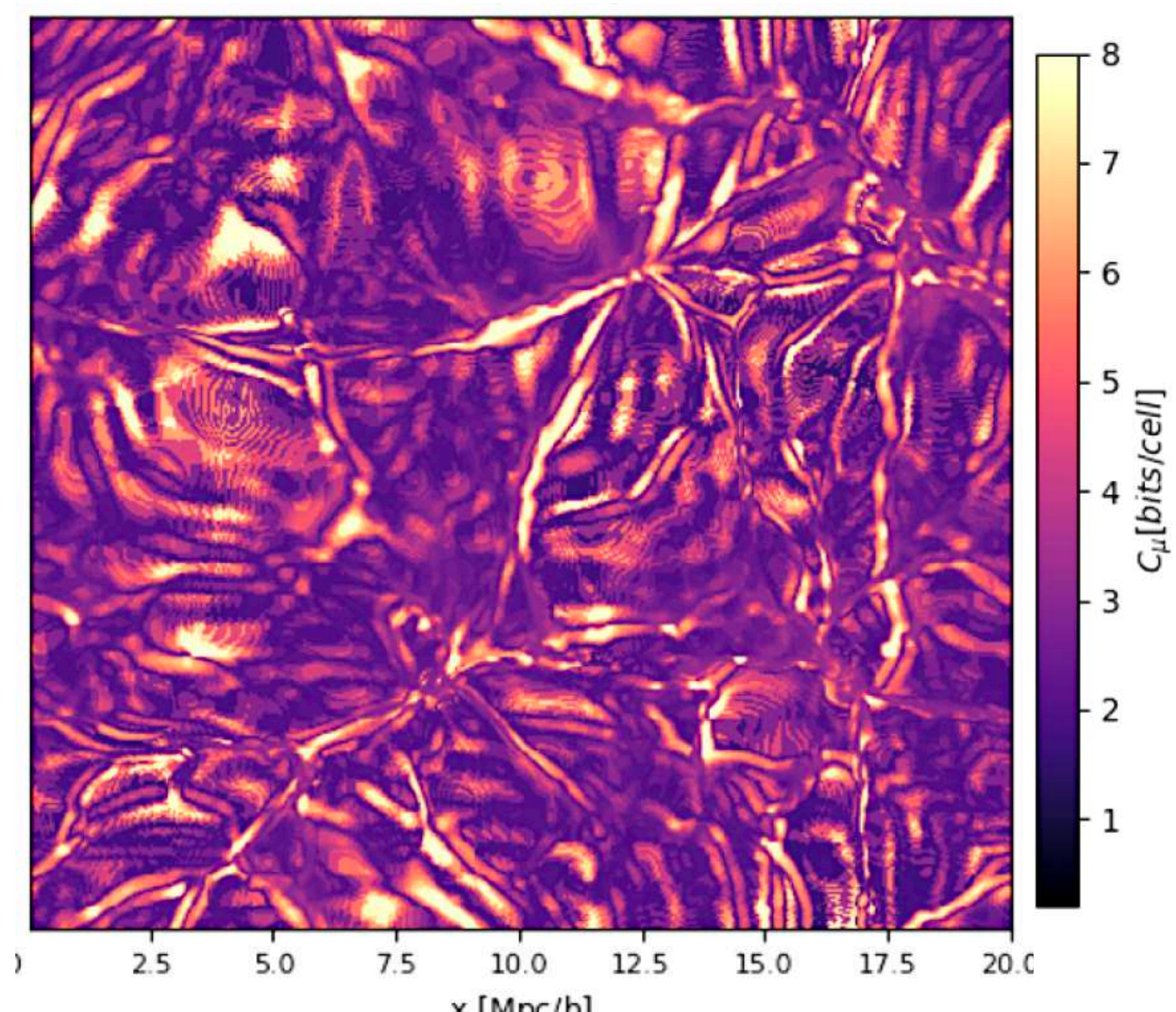




3-dimensional rendering by T.Jones

2. THE COSMIC WEB: NOT SO QUIET, NOT SO SIMPLE



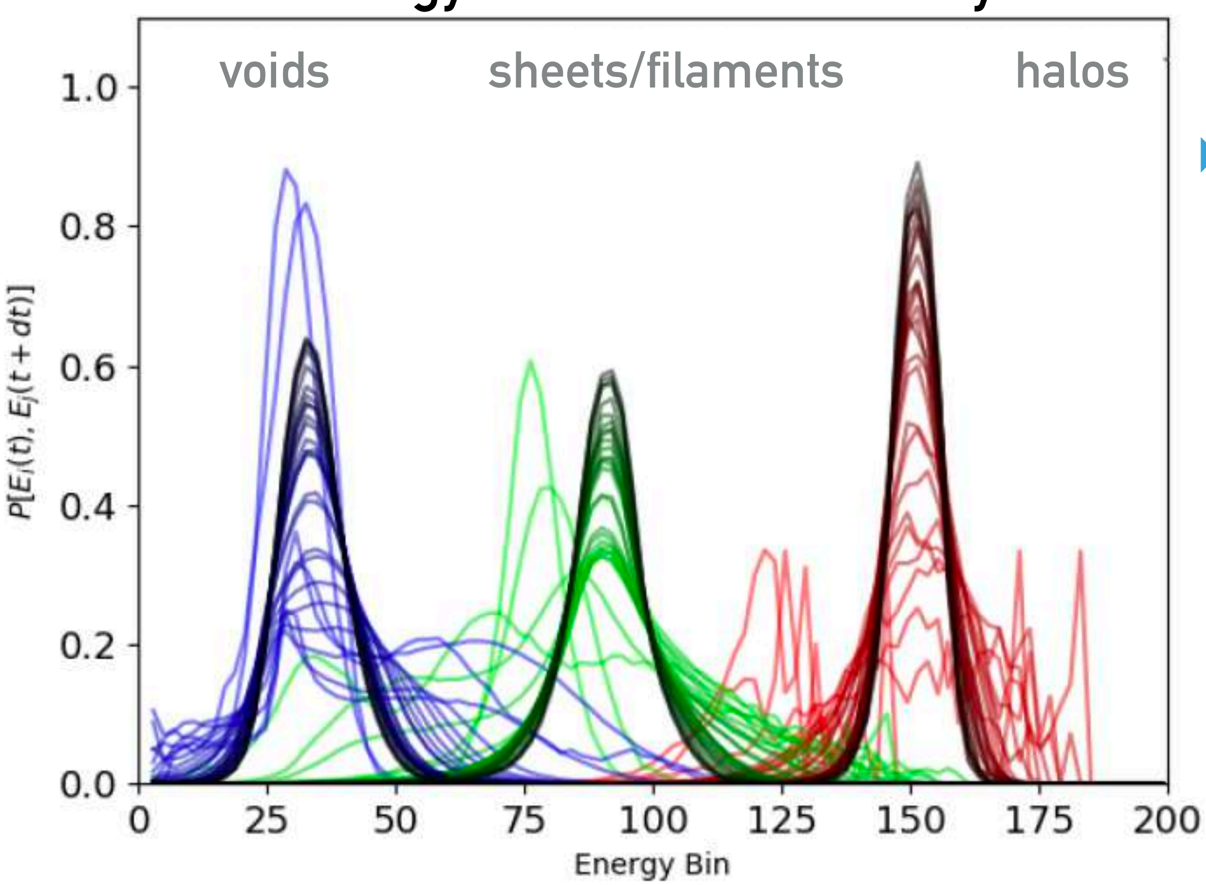


FV 2019 MNRAS "How Complex is the Cosmic Web?"

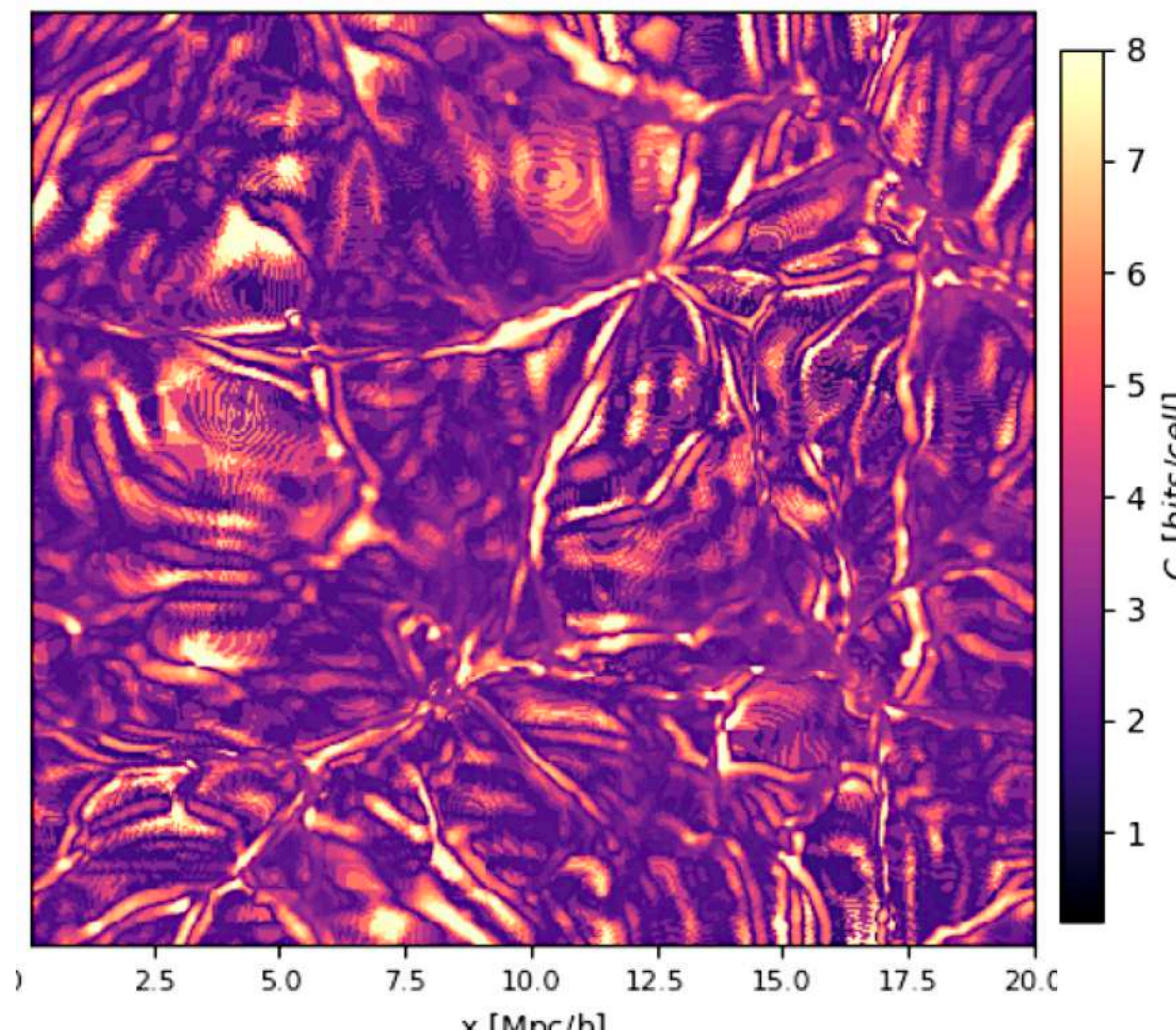
2. THE COSMIC WEB: NOT SO QUIET, NOT SO SIMPLE

- <u>Statistical complexity</u> measures how many bits of information are needed to predict the evolution of a system/object/environment.
- This can be measured from the datastream of the simulation

Energy Transition Probability

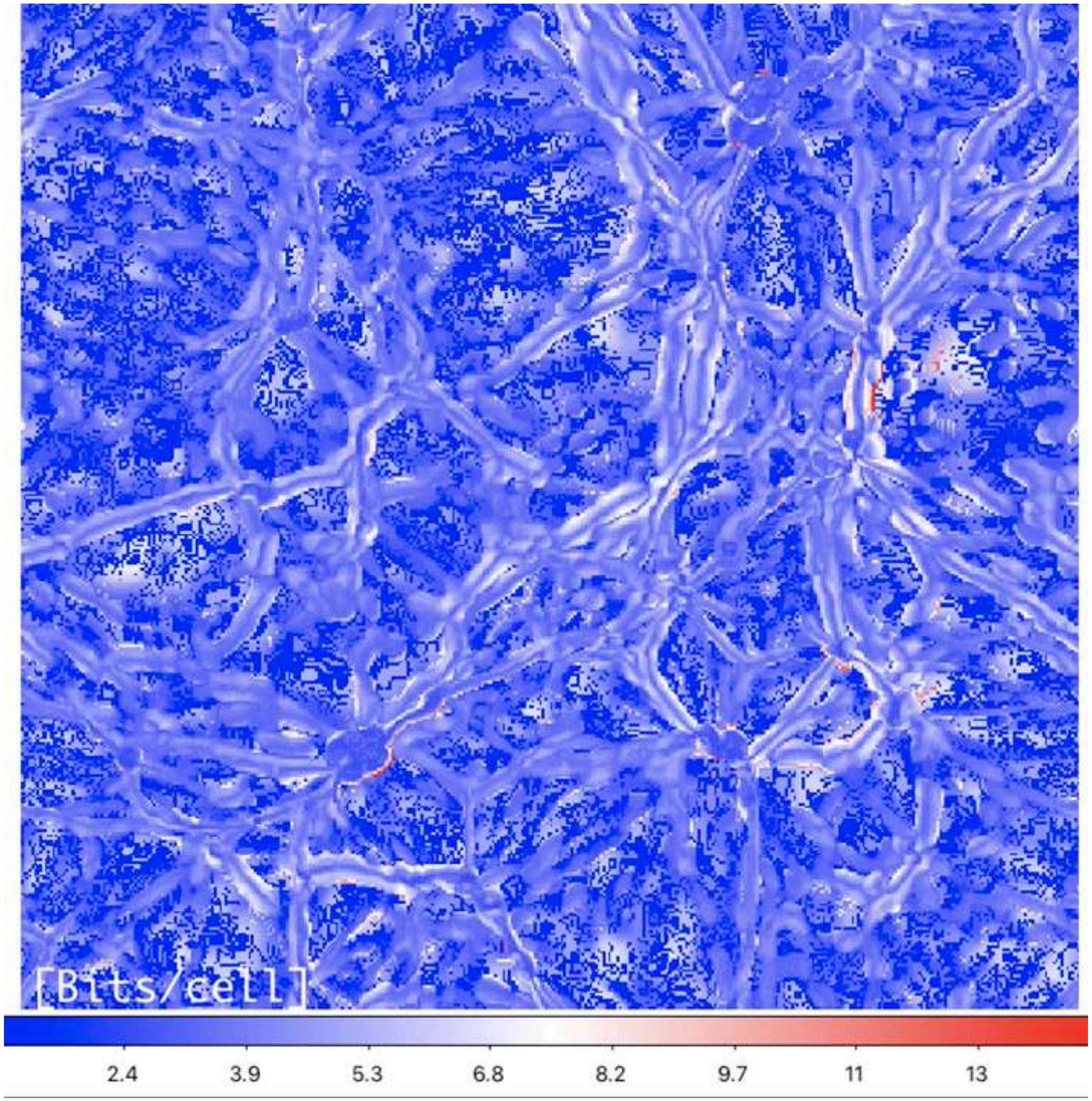


$$C_{\mu,xyz} = -P_{xyz} \log_2 P_{xyz}$$



FV 2019 MNRAS "How Complex is the Cosmic Web?"

2. THE COSMIC WEB: NOT SO QUIET, NOT SO SIMPLE



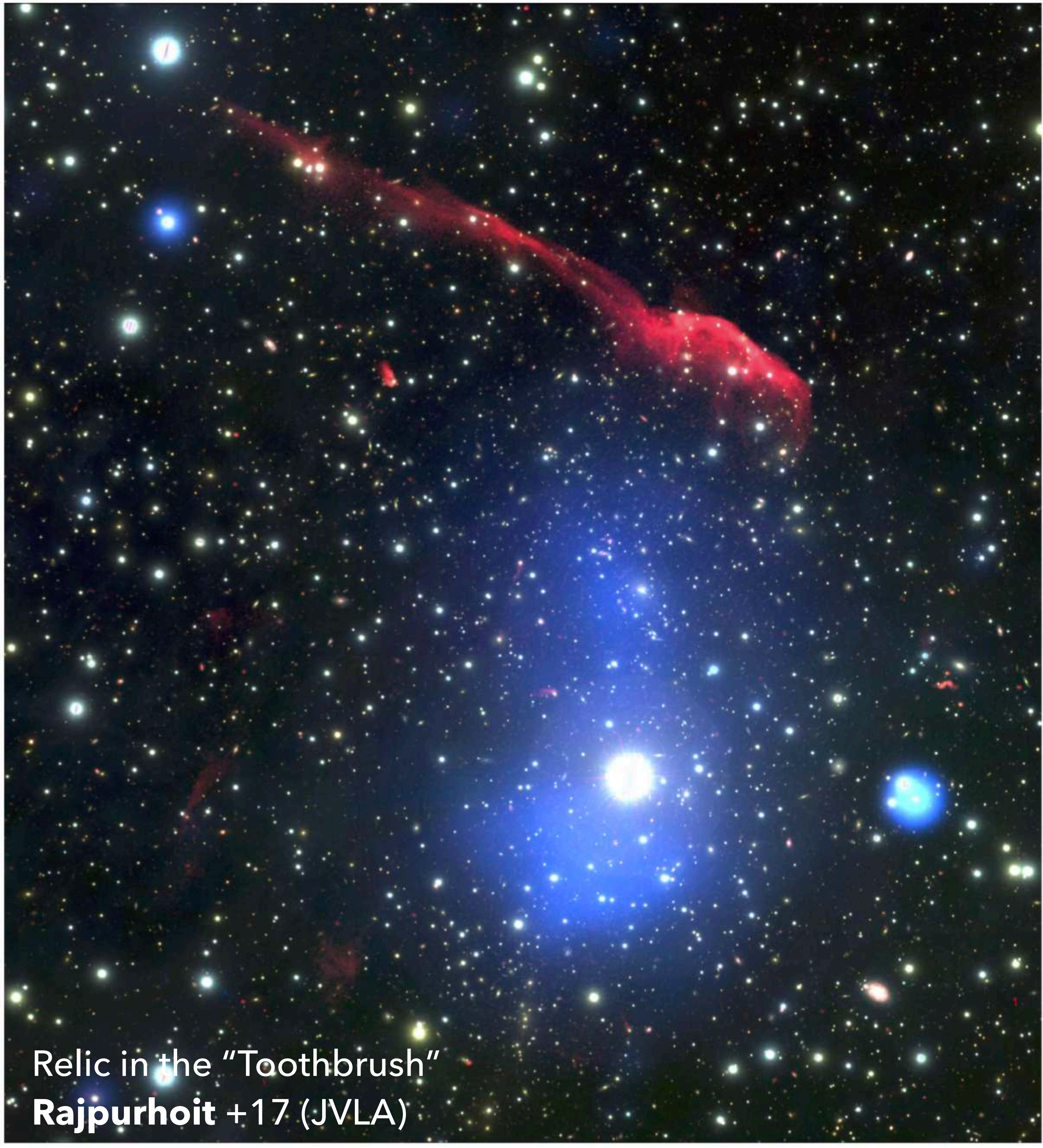
FV 2019 MNRAS “How Complex is the Cosmic Web?”

3.WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

RADIO EMISSION

Optical emission

X-RAY EMISSION



3.WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

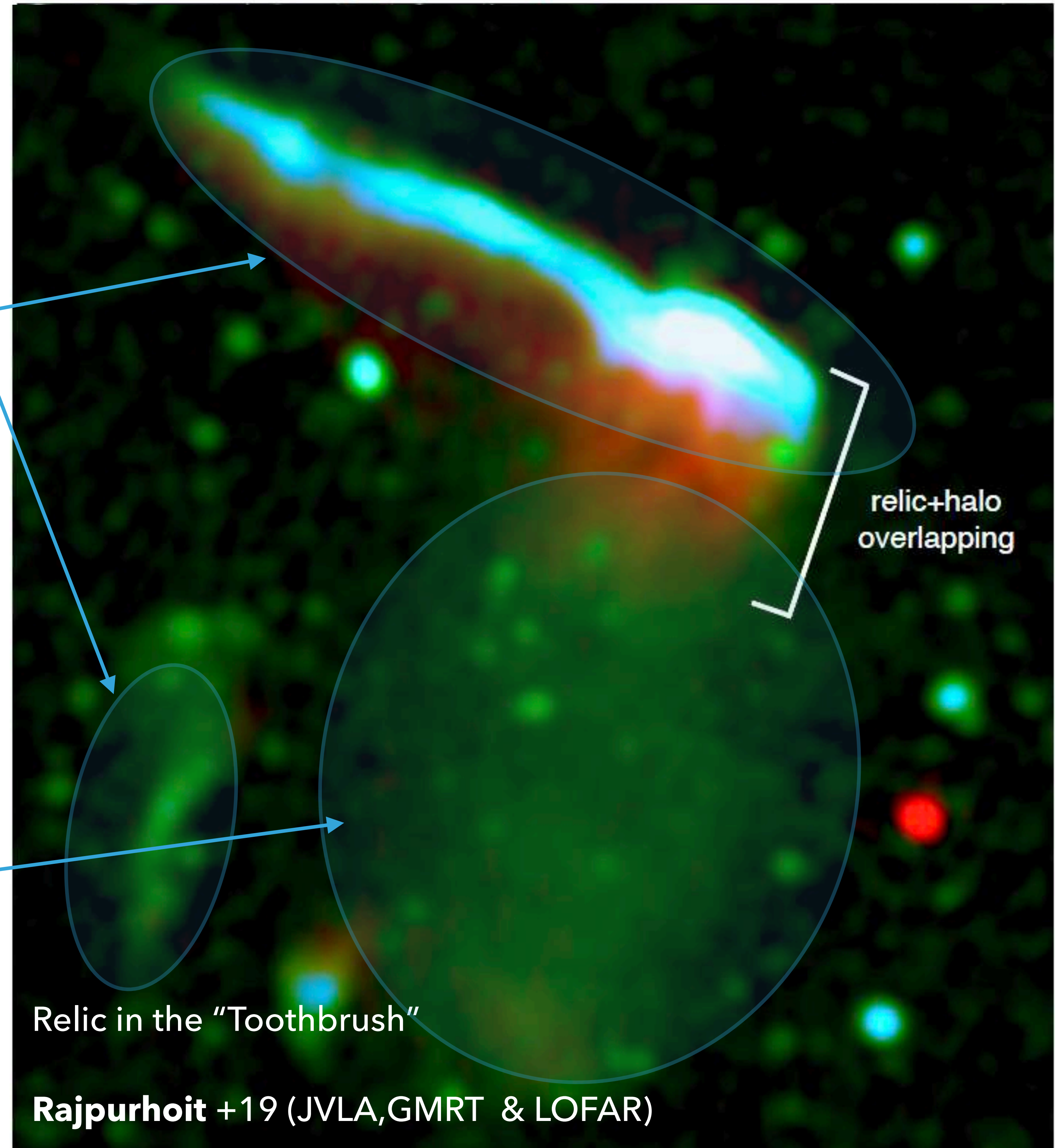
"RADIO RELICS"

- Magnetic fields: B~μG over ~1-2Mp
- 2-3 Mpc from the cluster centre
- associated with mergers/shocks
- polarized

"RADIO HALOS"

- Magnetic fields: B~μG over ~1-2Mp
- centrally located
- associated with mergers/turbulence
- unpolarized

(e.g. Brunetti & Jones 2014, Vanweeren+19)

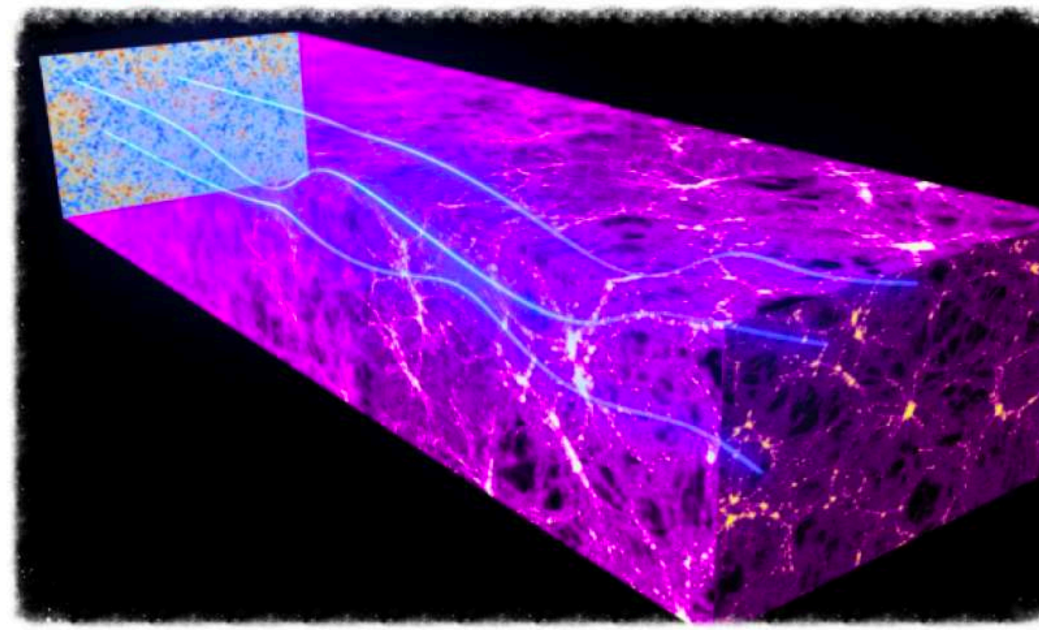


WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

astrophysical origin

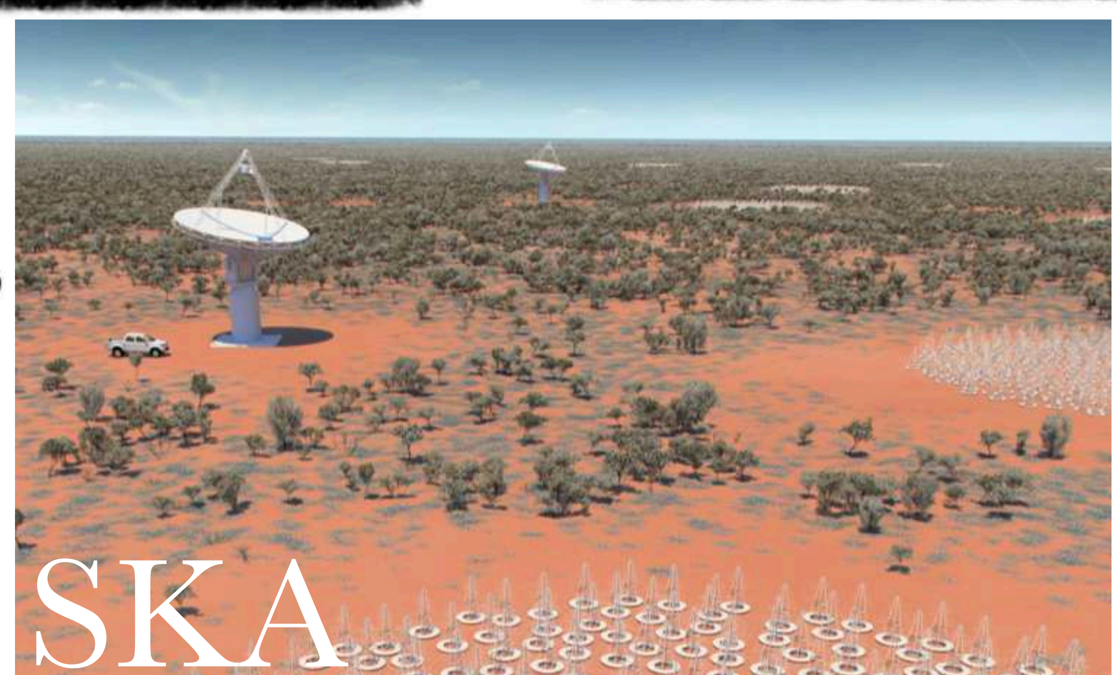
VS

primordial origin



galaxy evolution & compact objects

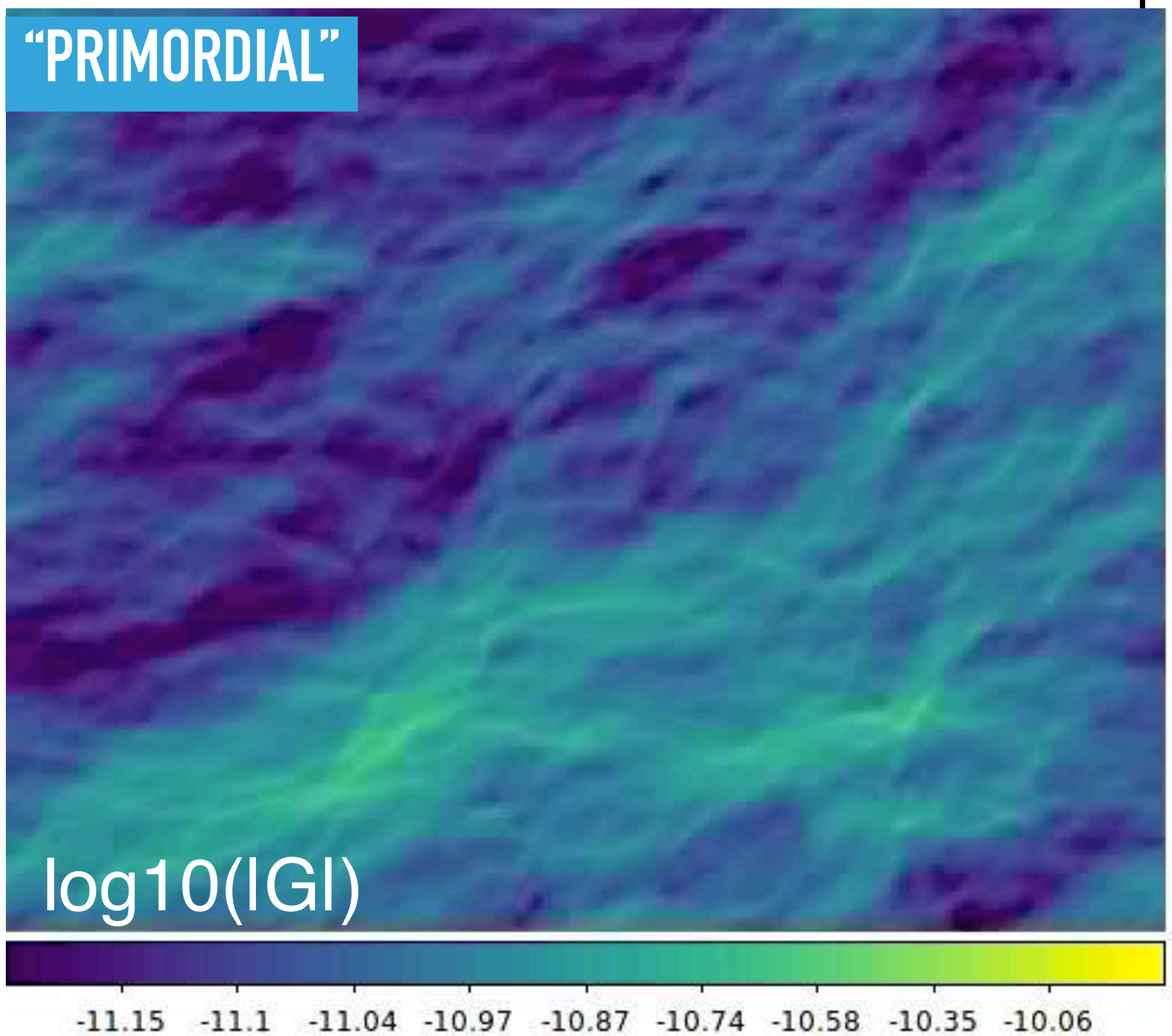
(e.g. Donnert+08, Xu+09, Marinacci+15)



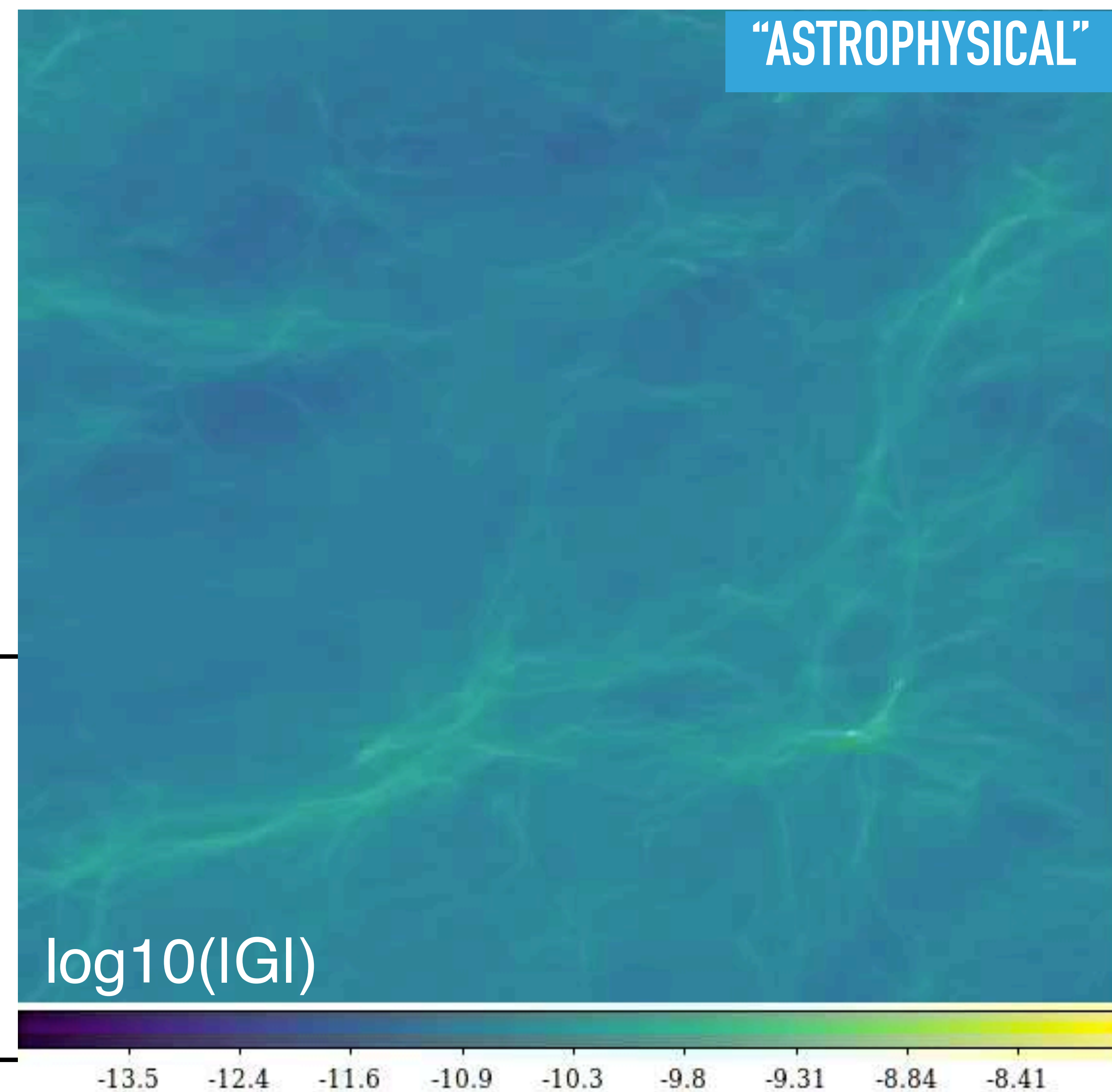
cosmology & particle physics

(e.g. Ryu+08, Subramanian+14)

MYSTERIES & PUZZLES

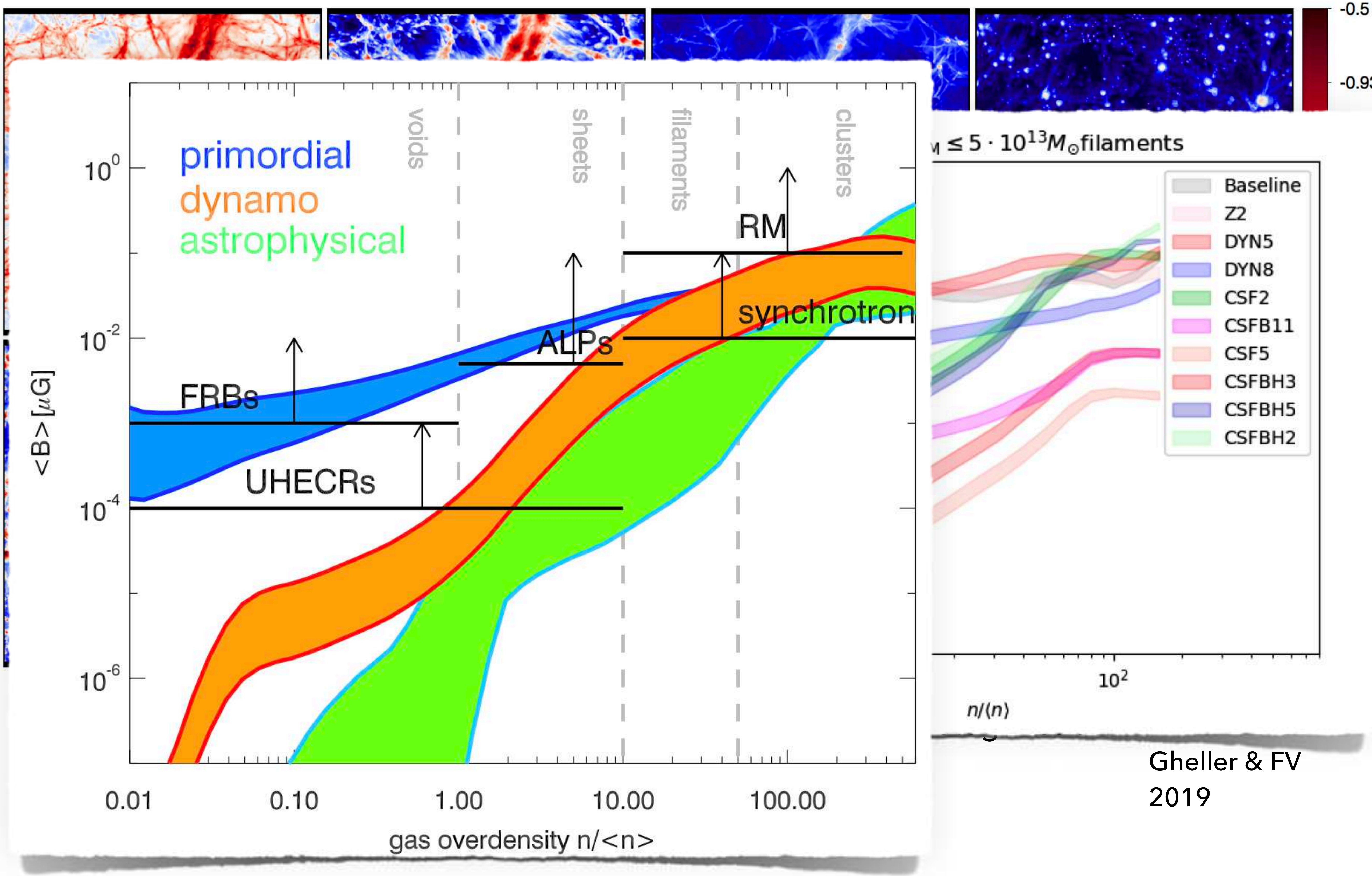


- **Weak** (<nG) B-fields in place at $z>10^3$
- Growth by: **compression**, **dynamo** (depending on Reynolds number)
- **Volume filling**



- **Strong** (>μG) B-fields in place at $z<10$
- Evolve by: **compression/rarefaction**, dynamo
- **Little volume filling**

The CHRONOS++ suite: 20 models of magnetism

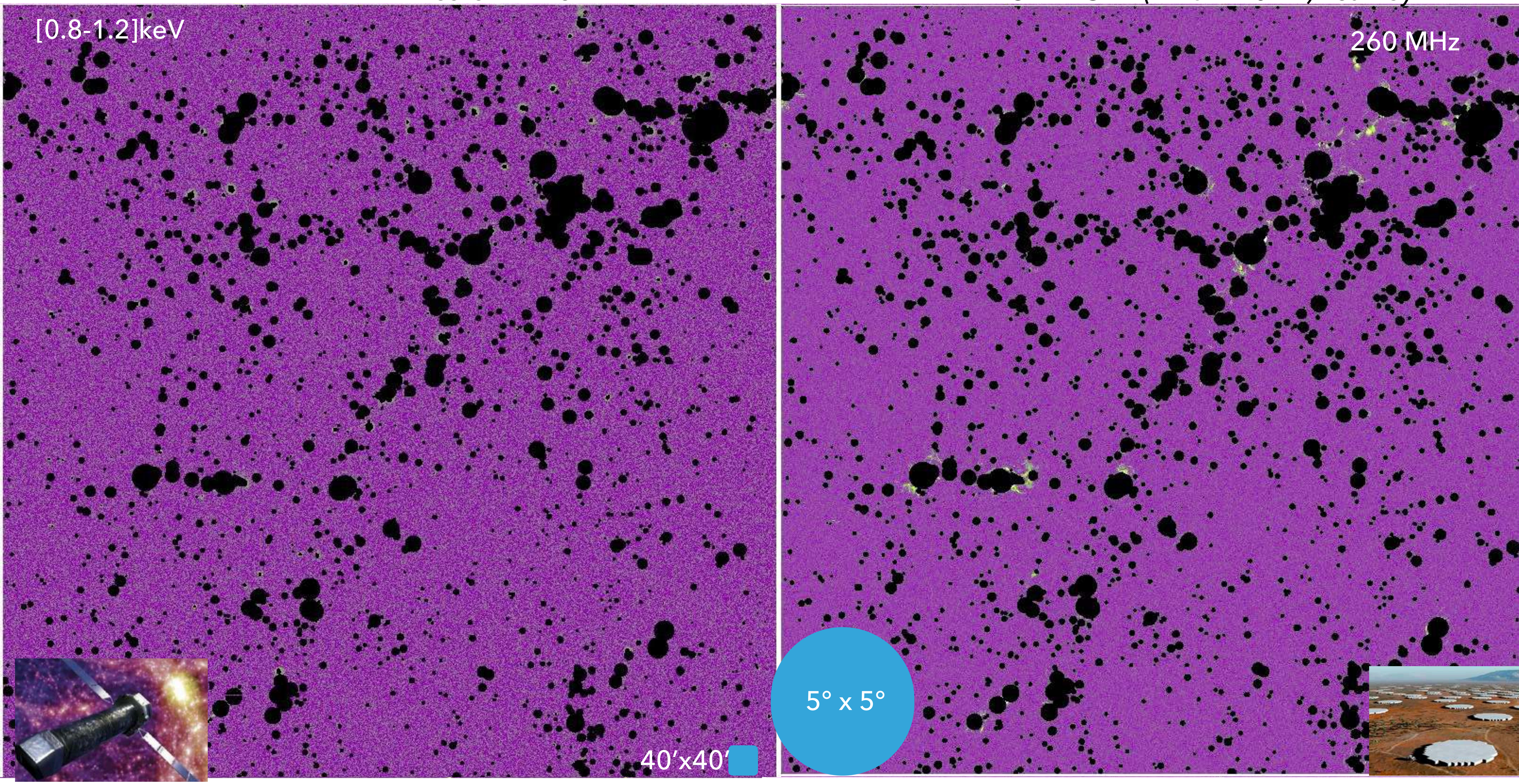


Gheller & FV 2019

"DETECTING THE COSMIC WEB WITH X-RAY AND RADIO OBSERVATIONS"

FV,Ettori,Roncarelli,Angelinelli,Bruggen,Gheller A&A 2019

ATHENA-WFI "core" - 1Ms *SKA-LOW (Bmax=40km) - survey*



mock X-ray observation (Athena-WFI 0.8-1.2keV)	mock radio observation (SKA-LOW 260MHz)
t=1Ms, instr.+ sky BG (3100 cnt/Ms arcmin^2) nH=2 10^{20} cm^2 , A_{eff} = 12139 cm^2	t=10hr, thermal+confusion noise (σ=4.8μJy/beam) beam=7.3" , UV sampling

“DETECTING THE COSMIC WEB WITH X-RAY AND RADIO OBSERVATIONS”

FV,Ettori,Roncarelli,Angelinelli,Bruggen,Gheller A&A 2019

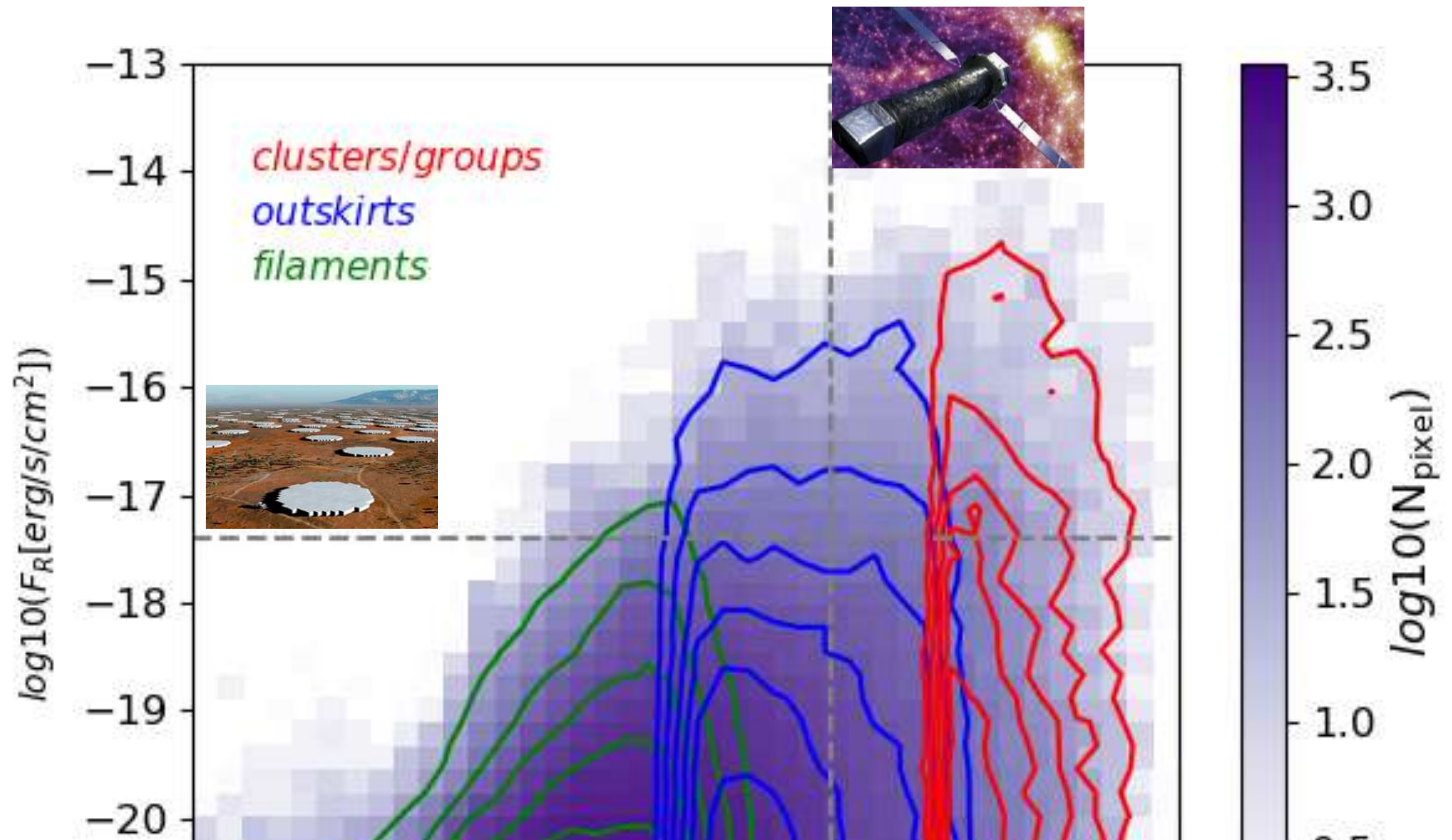
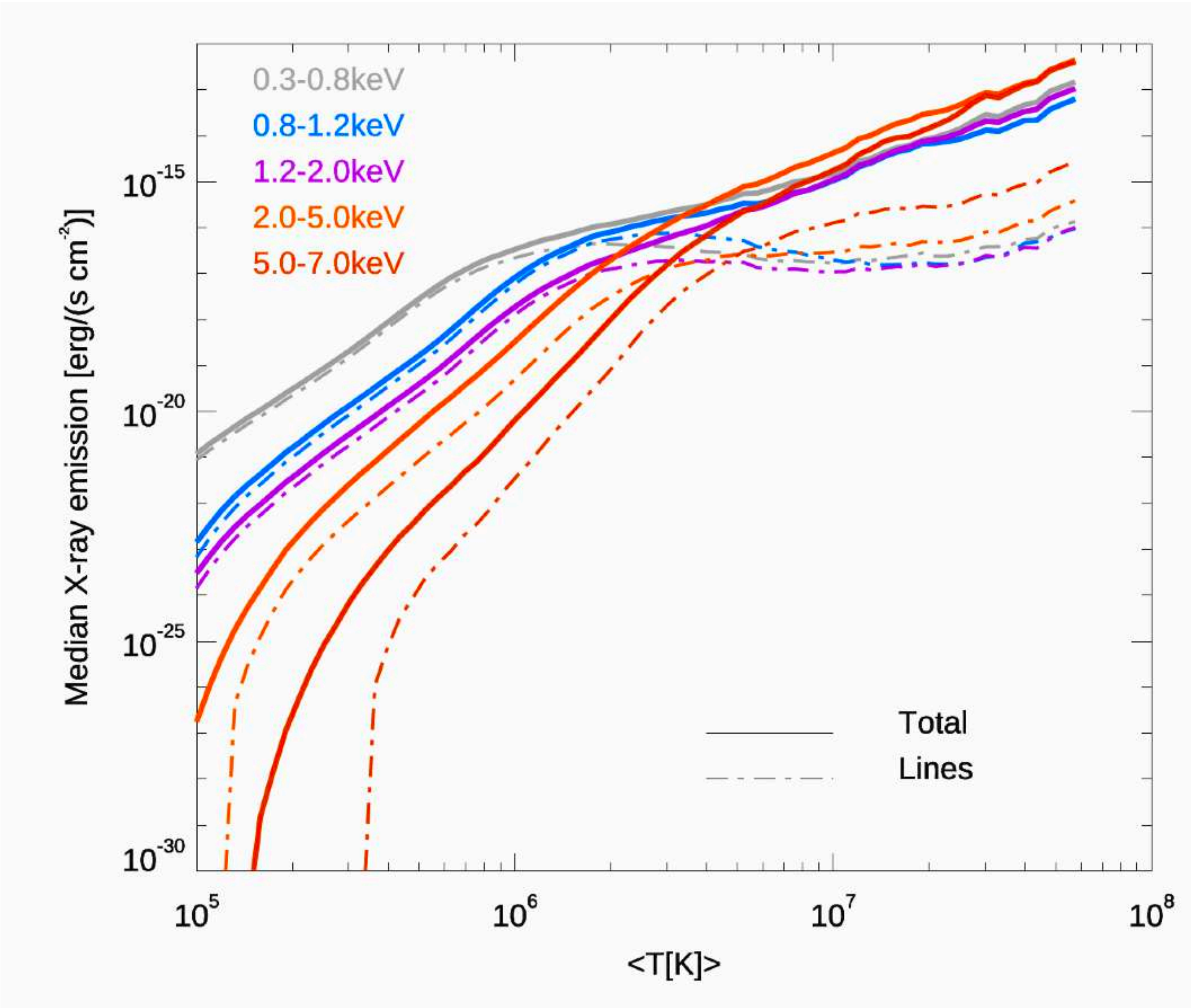
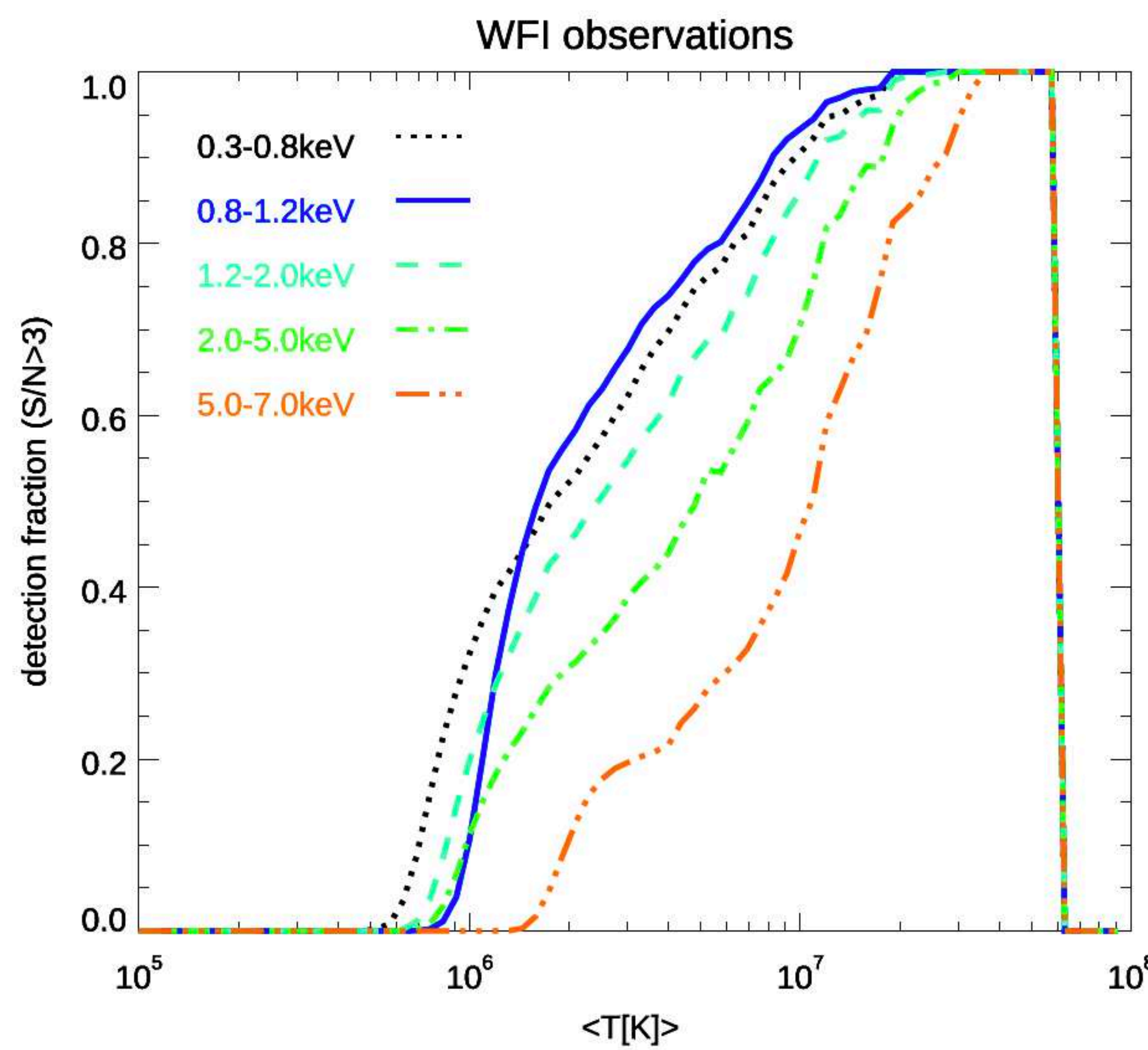


Table 5.1: Percentage of detected area covered by different simulated objects.

	Athena	SKA1-LOW	*Athena* ∩ SKA1-LOW
galaxy clusters	50%	19%	11%
outskirts	10%	19%	1.4%
filaments	0.1 %	1.8%	0.01%



- More photons from the WHIM in the 0.3-0.8keV

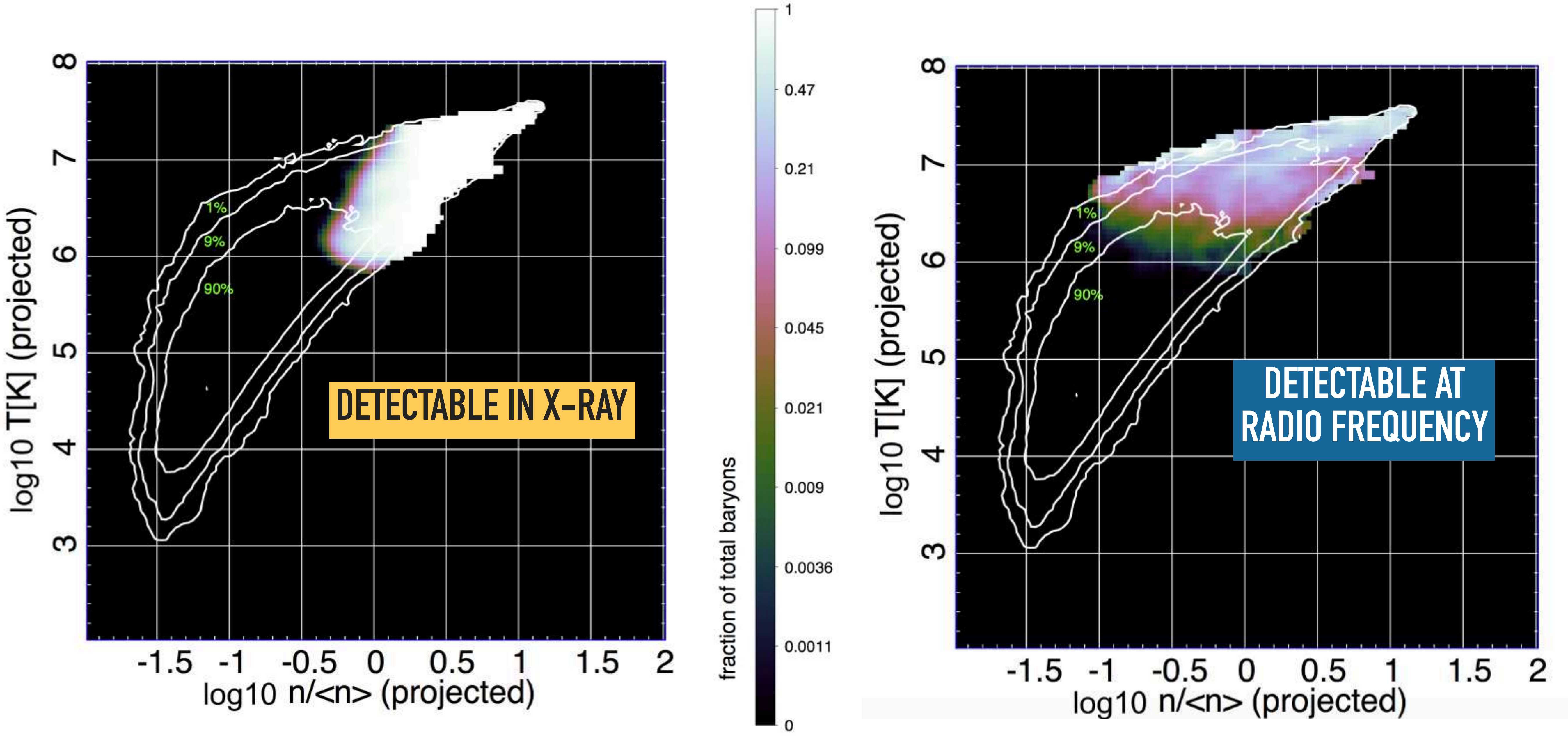


- More chances of detection in the 0.8-1.2keV band (S/N>3)

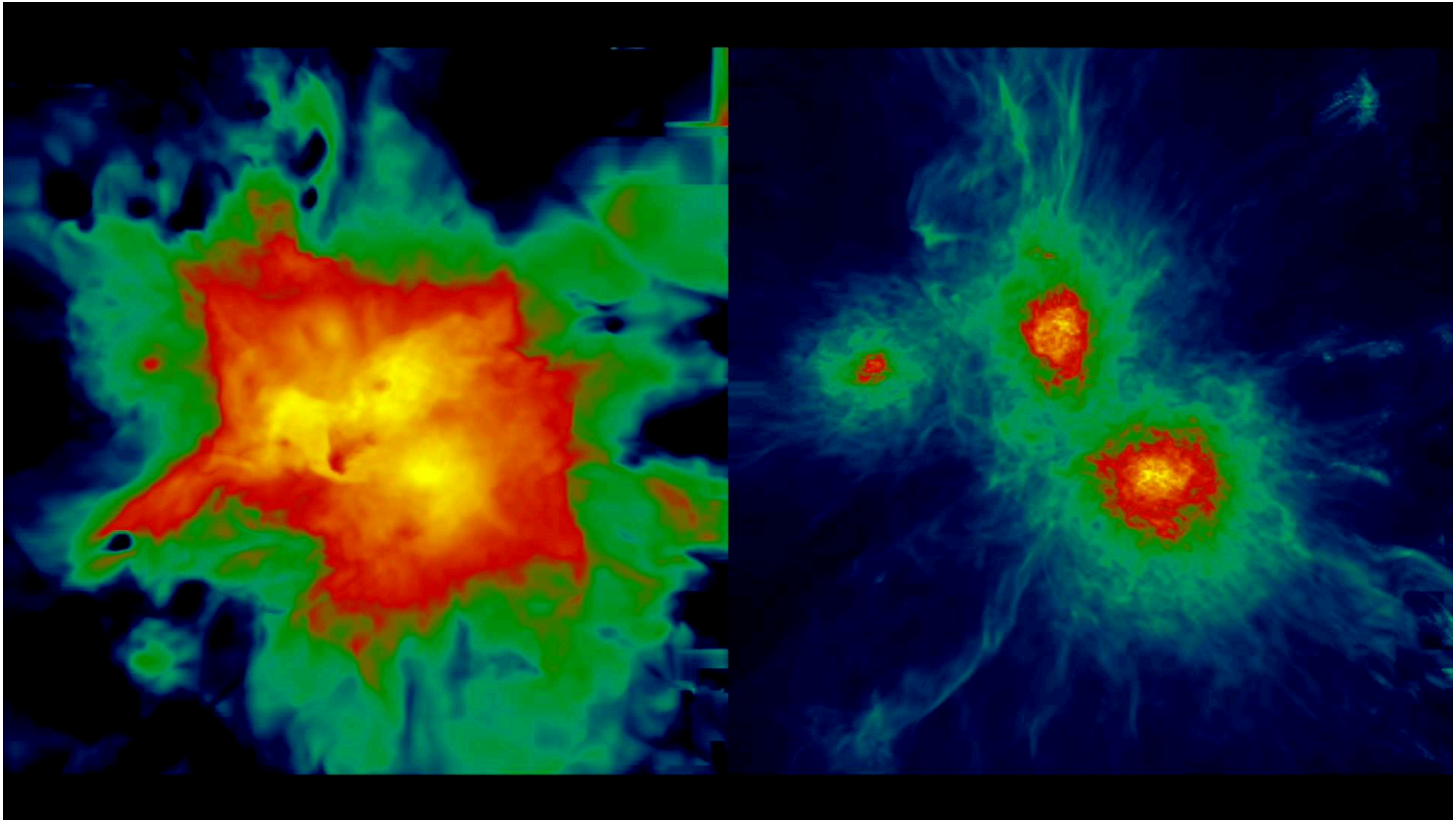
$$S/N = \frac{f_{\rm abs} \cdot S}{\sqrt{f_{\rm abs}(S + 2B_{\rm bg})}}$$

WHICH TECHNIQUE WILL DETECT MOST BARYONS?

- X-ray will detect most of the hot plasma in clusters. This where only ~10% of baryons are.
- Radio observation will detect a fraction (shock filling factors) of baryons.
- This is the phase where ~90% of baryons are

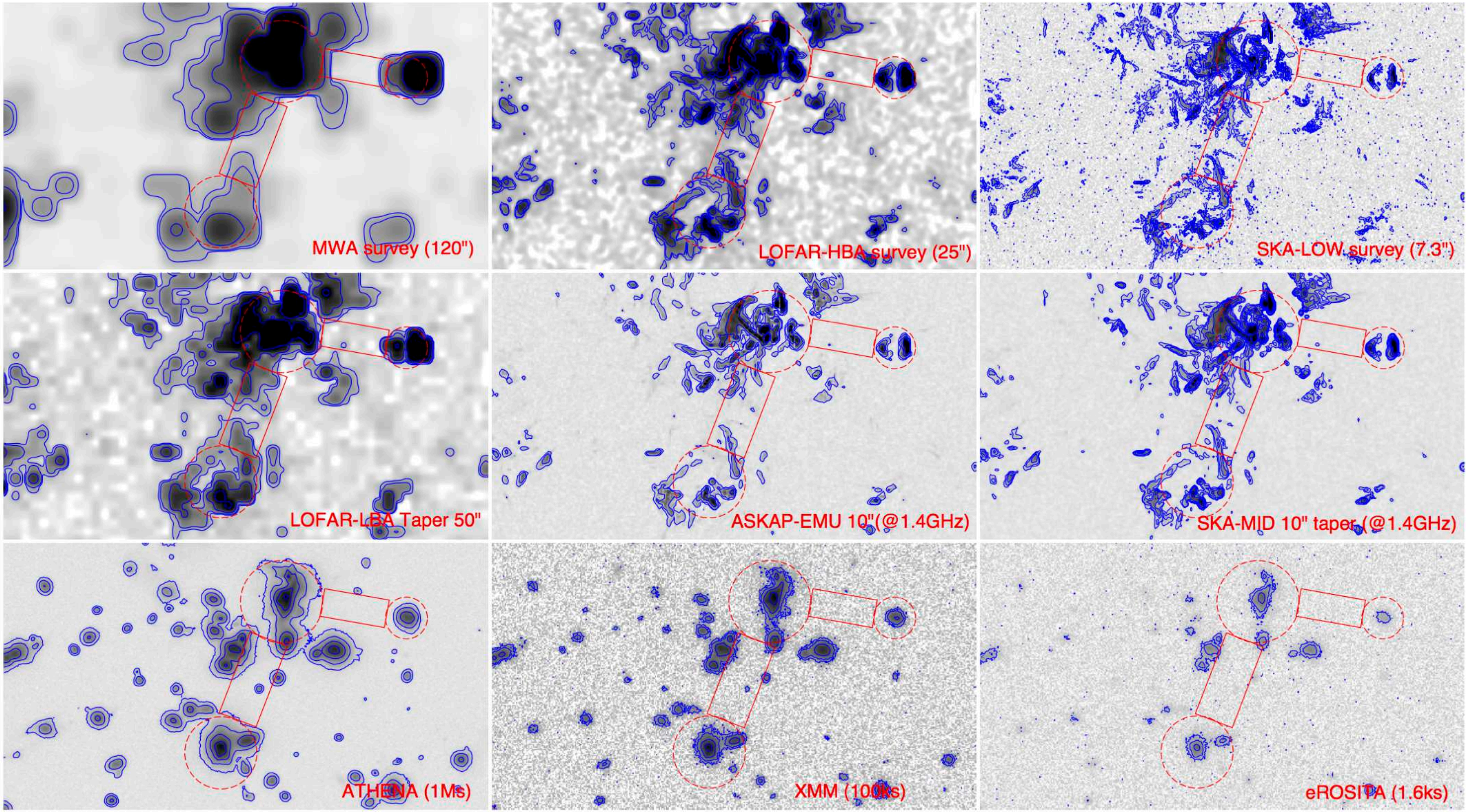


WHERE ARE “DOUBLE DETECTIONS” (X-RAY + RADIO) POSSIBLE?



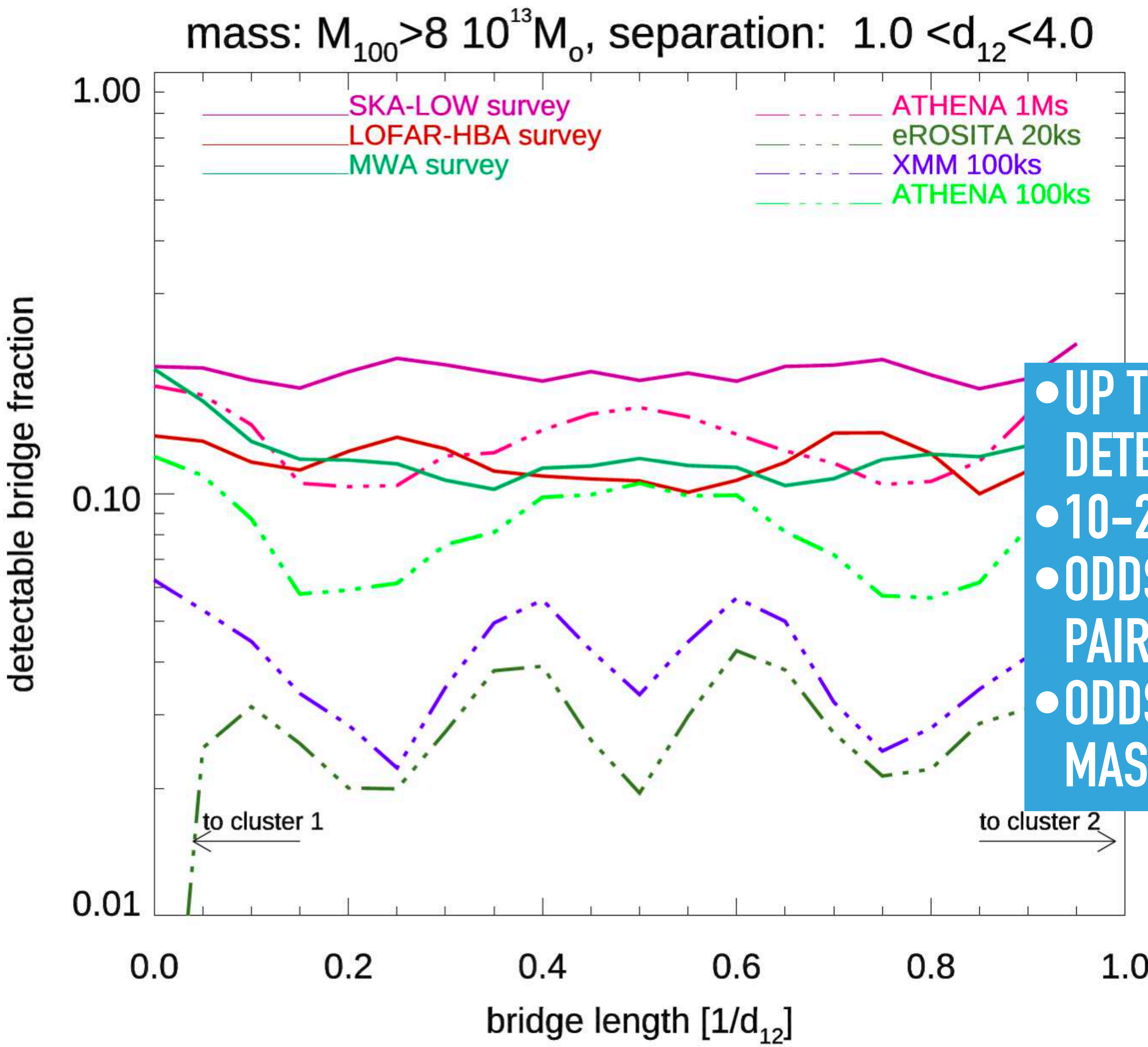
- cluster pairs in pre-merger condition “boost” the WHIM between them (transient <Gyr stage) to T~keV

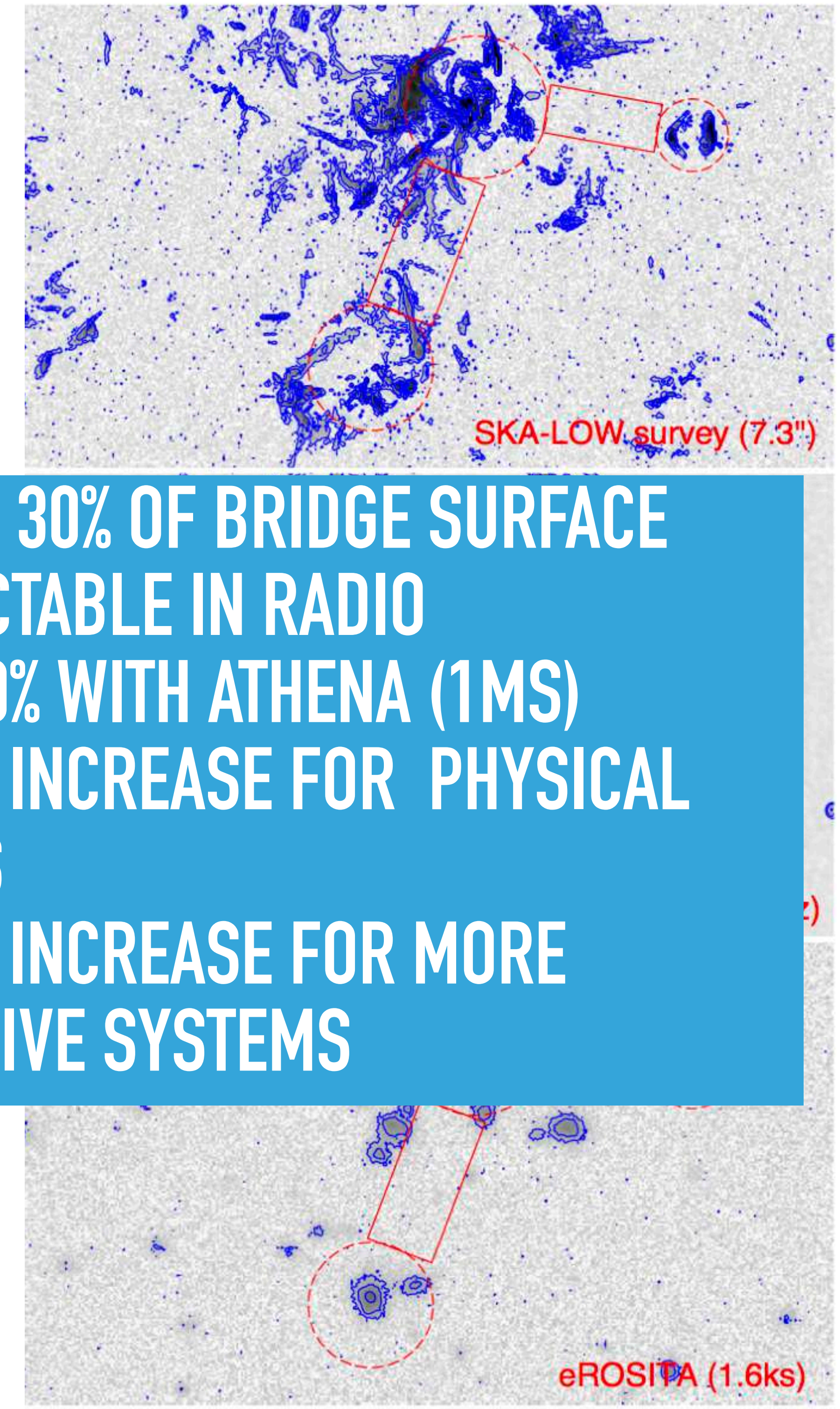
WHERE ARE "DOUBLE DETECTIONS" (X-RAY + RADIO) POSSIBLE?



- study of ~50 pairs of simulated pre-merger pairs
- scan of ~5′ wide bridges connecting their R100

WHERE ARE "DOUBLE DETECTIONS" (X-RAY + RADIO) POSSIBLE?

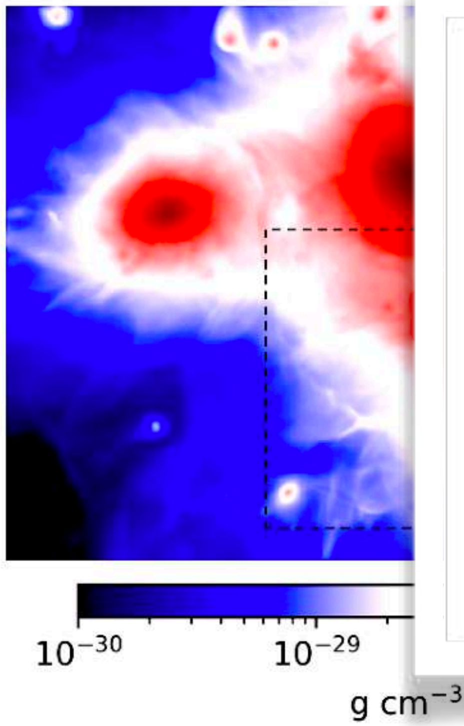




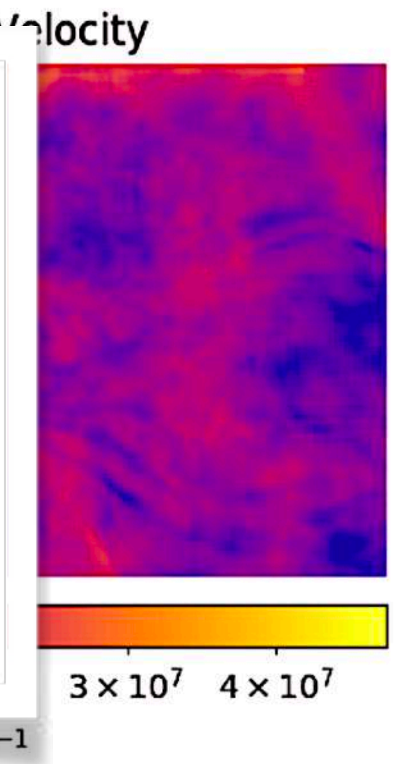
- UP TO 30% OF BRIDGE SURFACE DETECTABLE IN RADIO
- 10-20% WITH ATHENA (1MS)
- ODDS INCREASE FOR PHYSICAL PAIRS
- ODDS INCREASE FOR MORE MASSIVE SYSTEMS

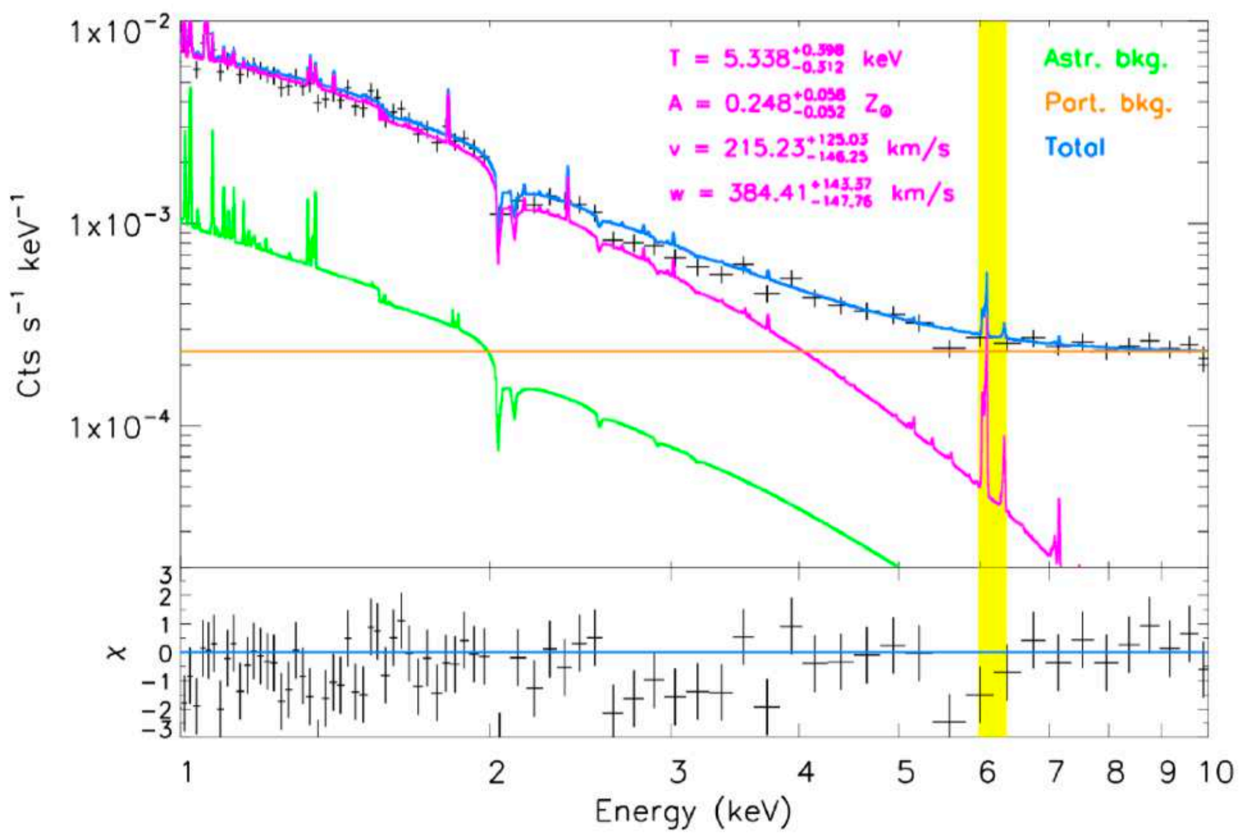
- study of ~50 pairs of simulated pre-merger pairs
- scan of ~5′ wide bridges connecting their R100

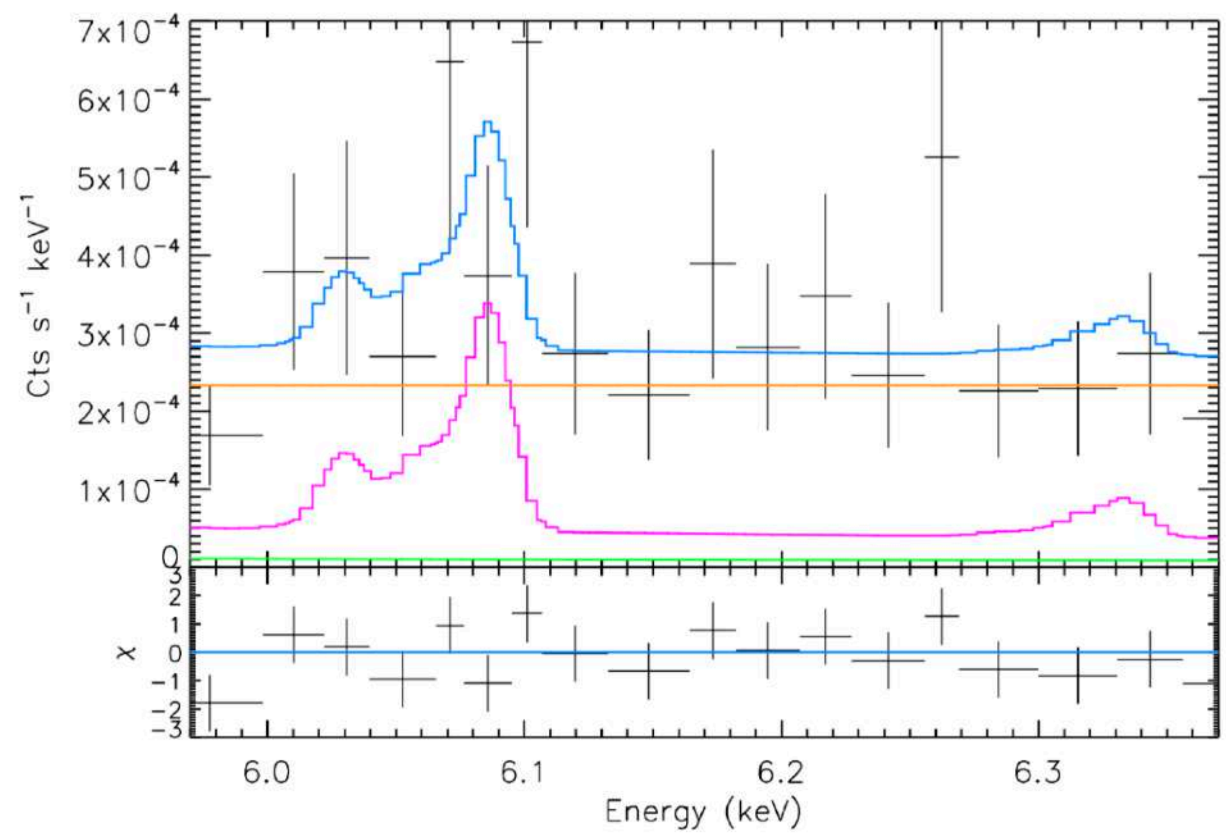
WHAT STUDY CAN WE DO WITH DOUBLY DETECTED BRIDGES?



Field	Input (sim)	Output (X-IFU)
T [keV]	5.52	5.33 ± [-0.31, 0.40]
v	65	215 ± [-146, 123]
w	465	384 ± [-148, 144]
A [$1/Z_\odot$]	0.20	0.25 ± [-0.05, 0.06]

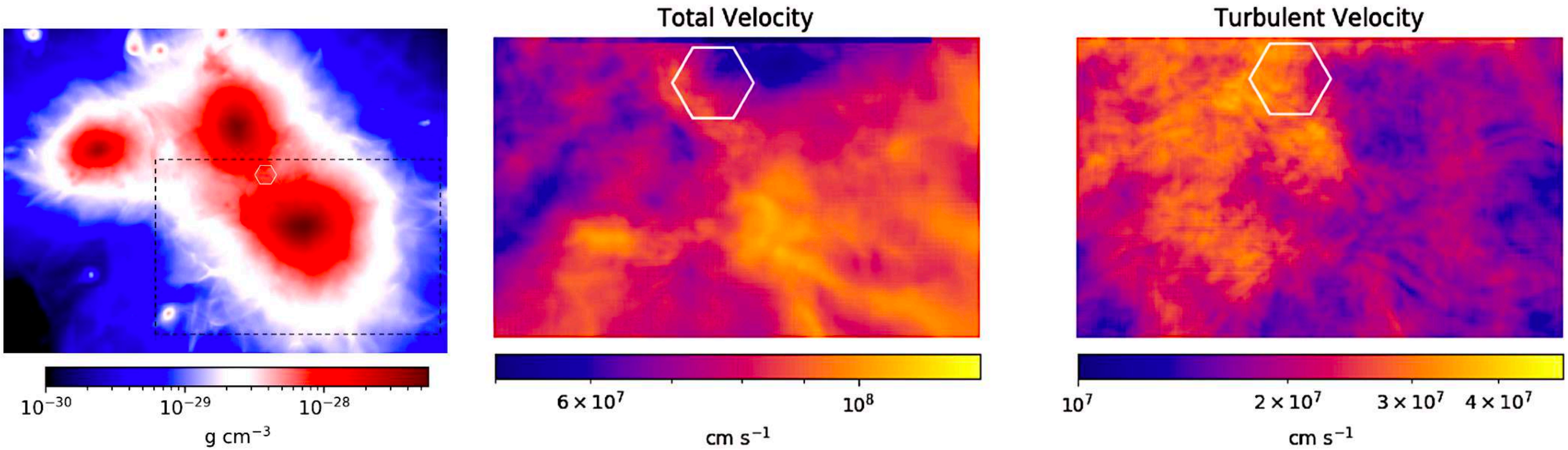






SIXTE simulation of a 1Ms integration

WHAT STUDY CAN WE DO WITH DOUBLY DETECTED BRIDGES?



If $w \sim \sigma_v$, and shock normal is ~0-45° along the LOS:

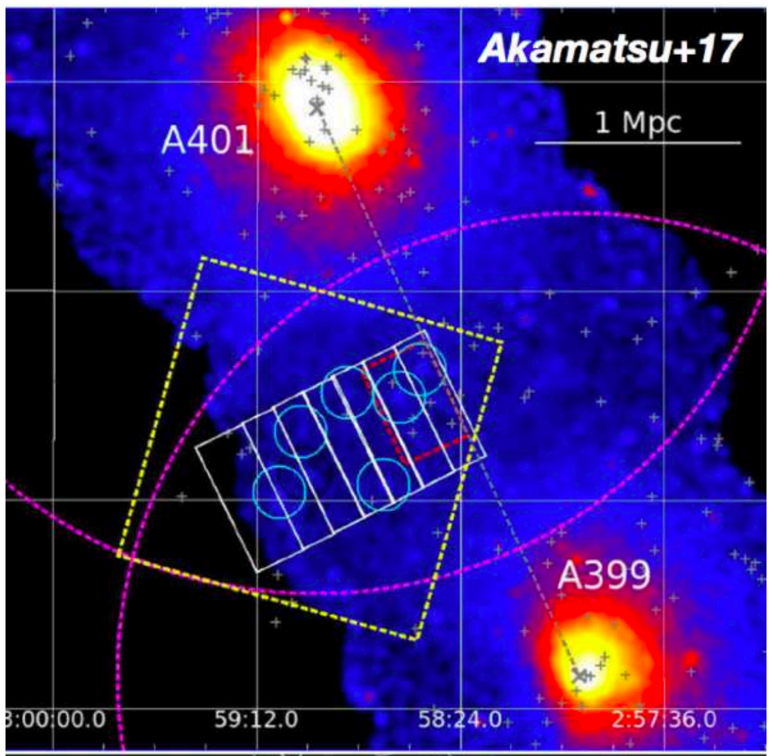
"Velocity Jump": $$\mathcal{M}_{spec} = \frac{2}{3}\left(\frac{\sigma_v}{c_s} + \sqrt{\frac{4\sigma_v}{c_s} + 9}\right)$$

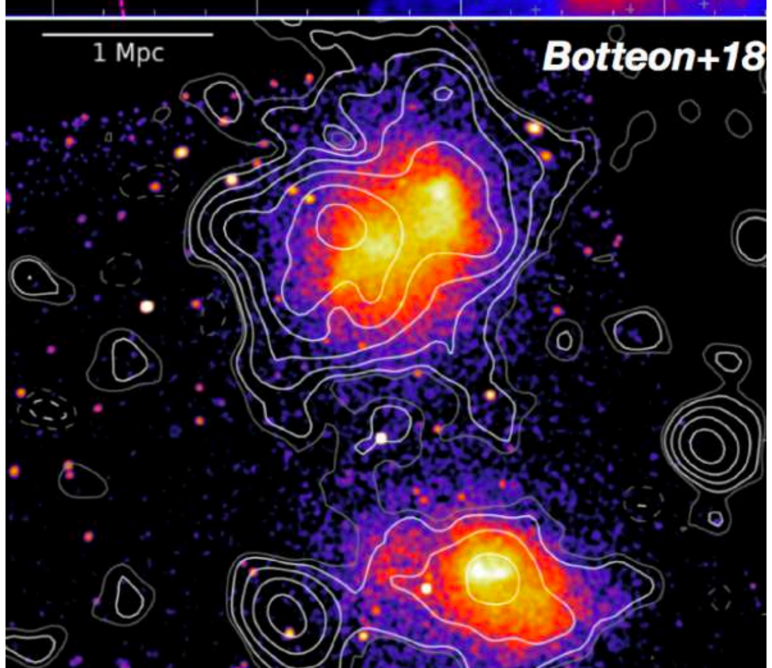
$$\mathcal{M}_{spec} \approx 2.3 \sim \mathcal{M}_{3D} = 2.5 - 3$$

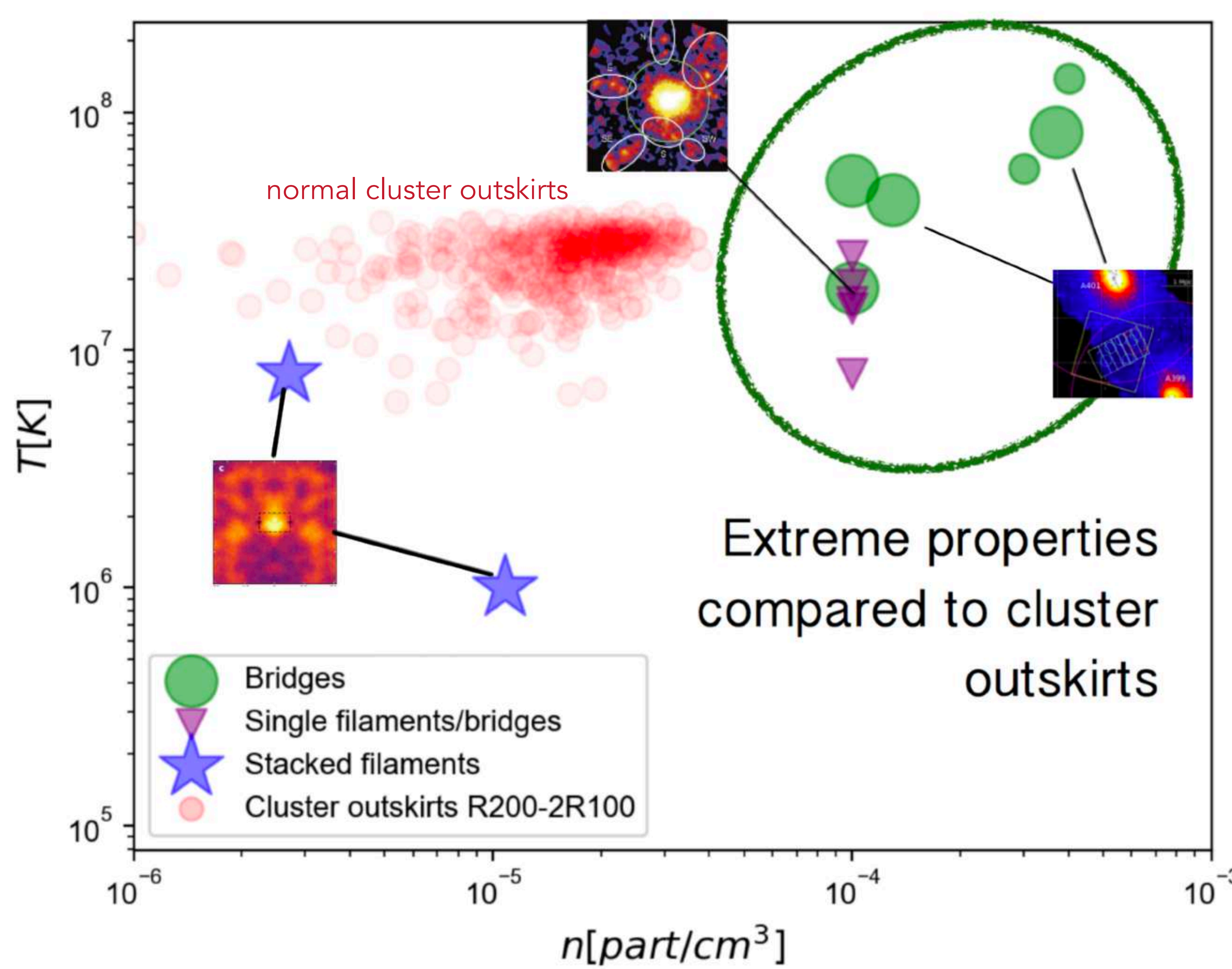
X-RAY SPECTROSCOPIC MEASUREMENTS OF MACH NUMBERS WILL ALLOW CONSTRAINING SHOCK ACCELERATION PHYSICS

THE “BOOSTED” WHIM

- standard WHIM gas that used to be in filaments ~1-2Gyr ago. Now squeezed and compressed.
- X-ray emission boosted as $L_{WHIM,boost} \sim L_{\rm WHIM} \cdot (\frac{\rho_2}{\rho_1})^{11/4}$
- transonic regime, short dynamical time, volume filling M<4 shocks, uncertain composition





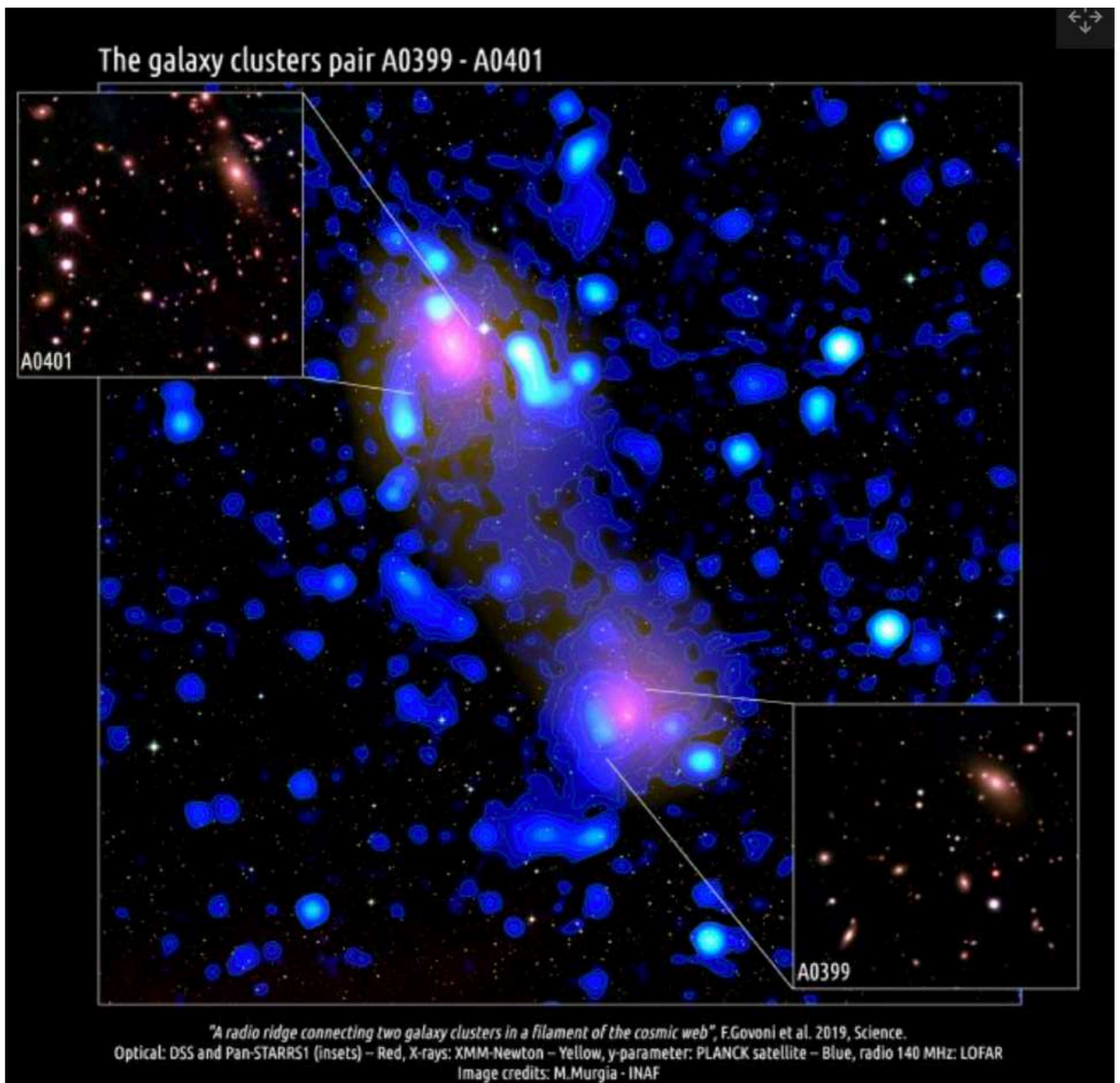


Science AAAS

Submitted Manuscript: Confidential

A vast magnetic ridge illuminated by fossil electrons in a filament of the cosmic web

Authors: F. Govoni[1*], E. Orrù[2], A. Bonafede[3,4], M. Iacobelli[2], R. Paladino[3], F. Vazza[4,3,11], M. Murgia[1] ,V. Vacca[1], G. Giovannini[3,4], L. Feretti[3], F. Loi[1,5], G. Bernardi[3,6,7], C. Ferrari[8], R.F. Pizzo[2], C. Gheller[9], S. Manti[10], M. Brüggen[11], G. Brunetti[3], R. Cassano[3], F. de Gasperin[11,12], T.A. Enßlin[13], M. Hoeft[14], C. Horellou[15], H. Junklewitz[16], H.J.A. Röttgering[12], A.M.M Scaife[17], T.W. Shimwell[2,12], R.J. van Weeren[12], M. Wise[2].



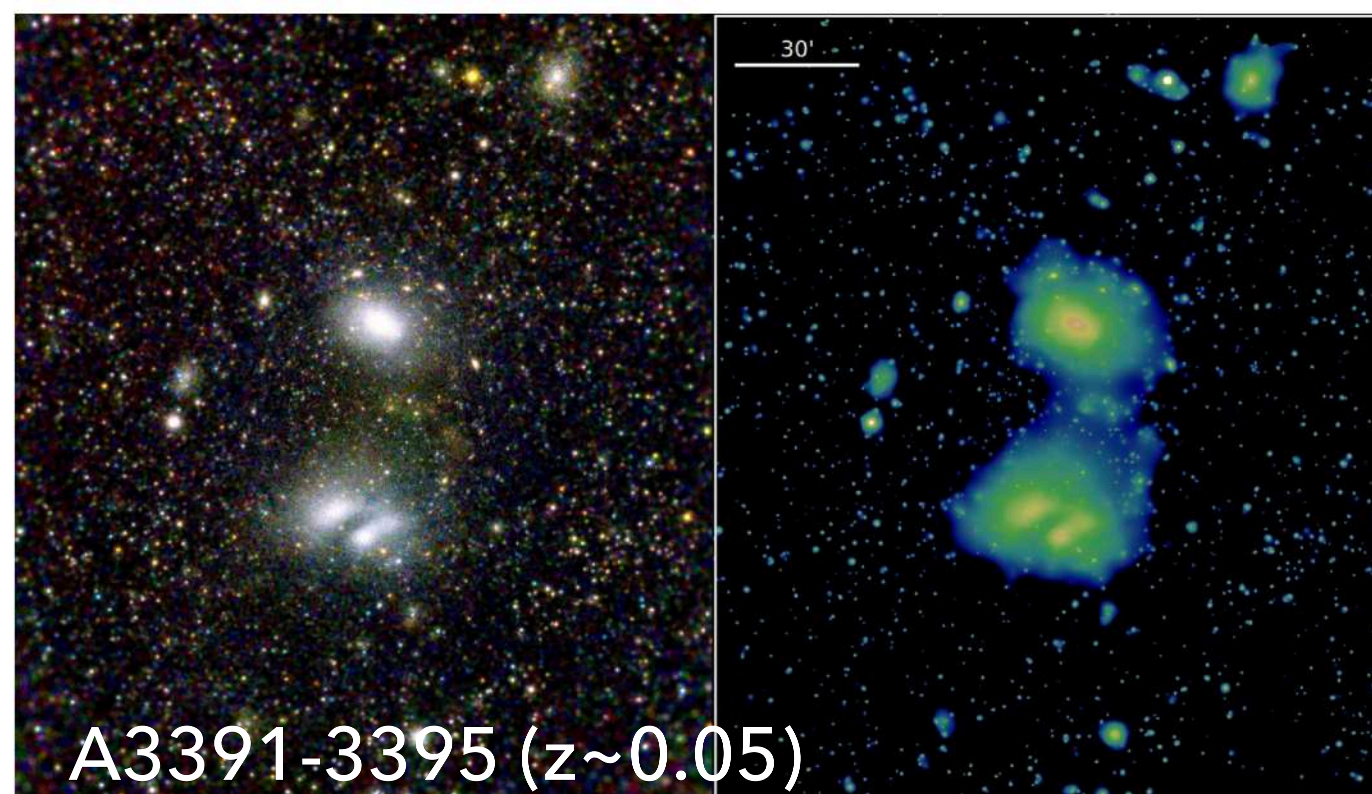
X-ray scout sees first light

Observations with eRosita promise a breakthrough in our understanding of the energetic universe

OCTOBER 22, 2019

Astronomy | Astrophysics | Cosmology | Galaxies

Astronomers are excited: the first images of the eRosita telescope launched in July reveal an impressive performance. After an extended commissioning phase, all seven X-ray telescope modules with their custom-designed CCD cameras have been observing the sky simultaneously since 13 October. The first composite images show our neighbouring galaxy, the Large Magellanic Cloud, and two interacting clusters of galaxies at a distance of about 800 million light years in remarkable detail.

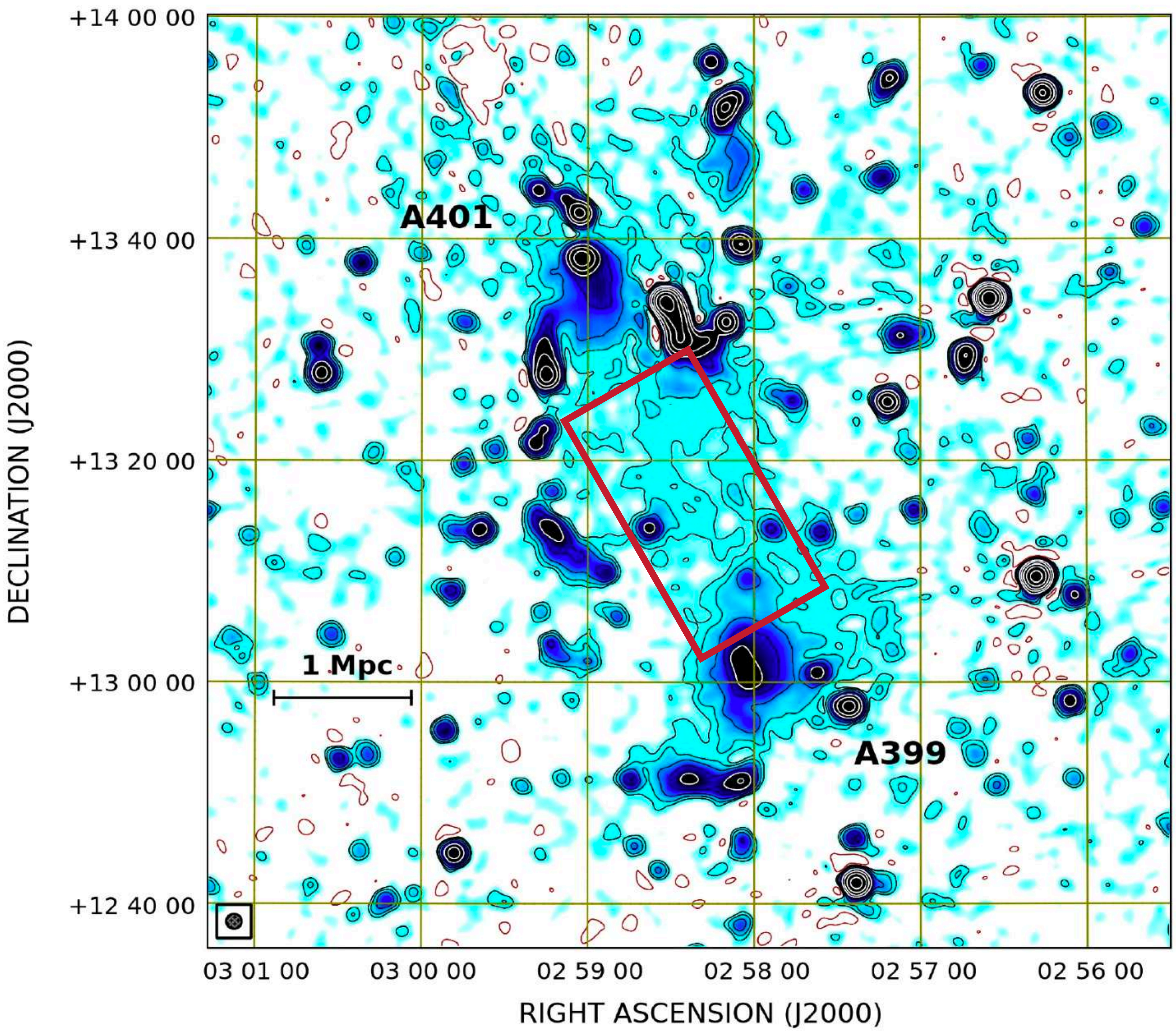


A399-A401 WITH LOFAR HBA (140 MHZ)

θ~80″

σ_{rms}~1mJy/beam

t~10 hours



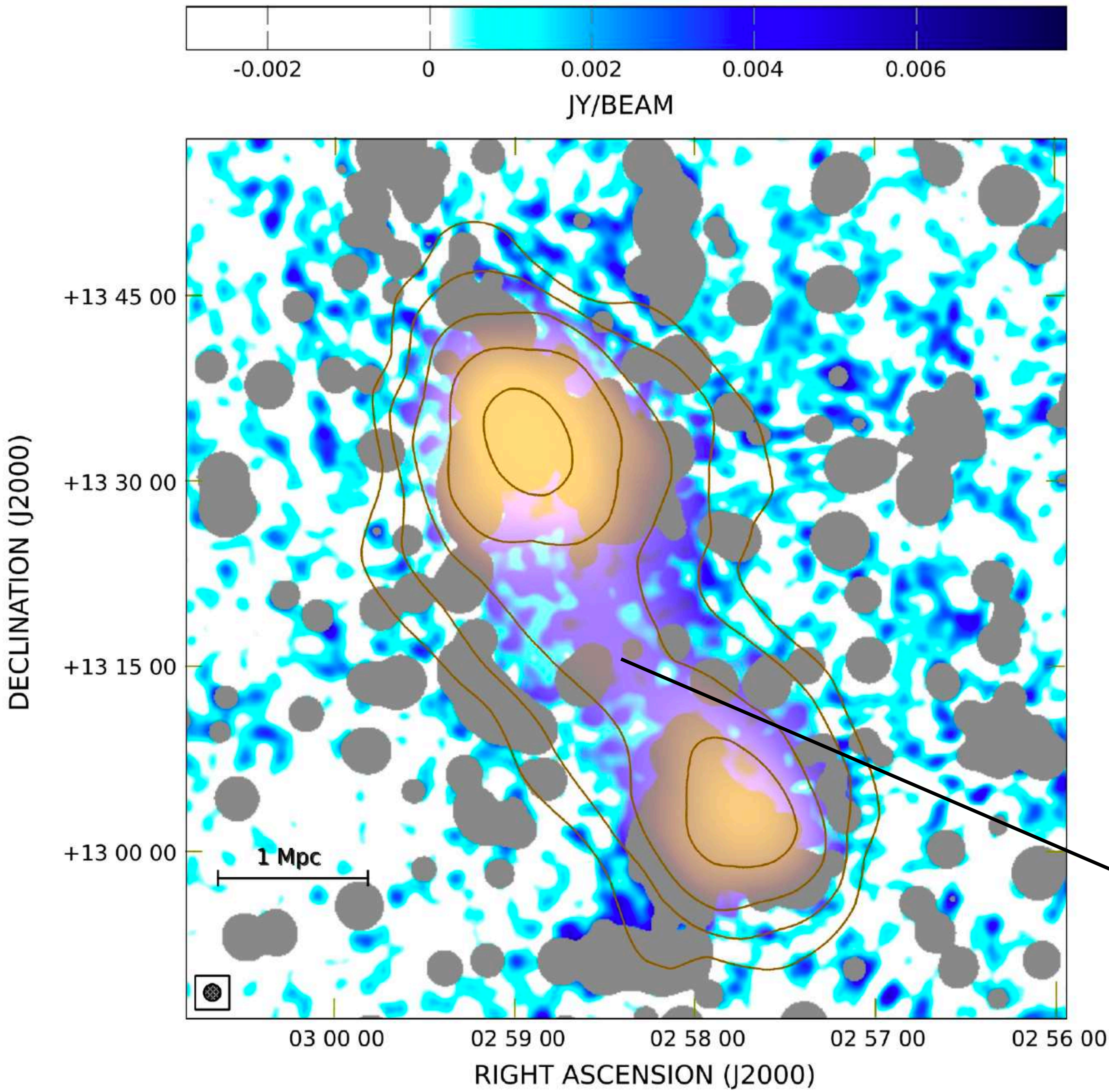
Flux~0.8Jy

Power~1e25 W/Hz

Size ~1.3 x 3 Mpc^2

α>1.3 (?)

A399-A401 WITH LOFAR HBA (140 MHZ)



θ~80″

σ_{rms}~1mJy/beam

t~10 hours

Flux~0.8Jy

Power~1e25 W/Hz

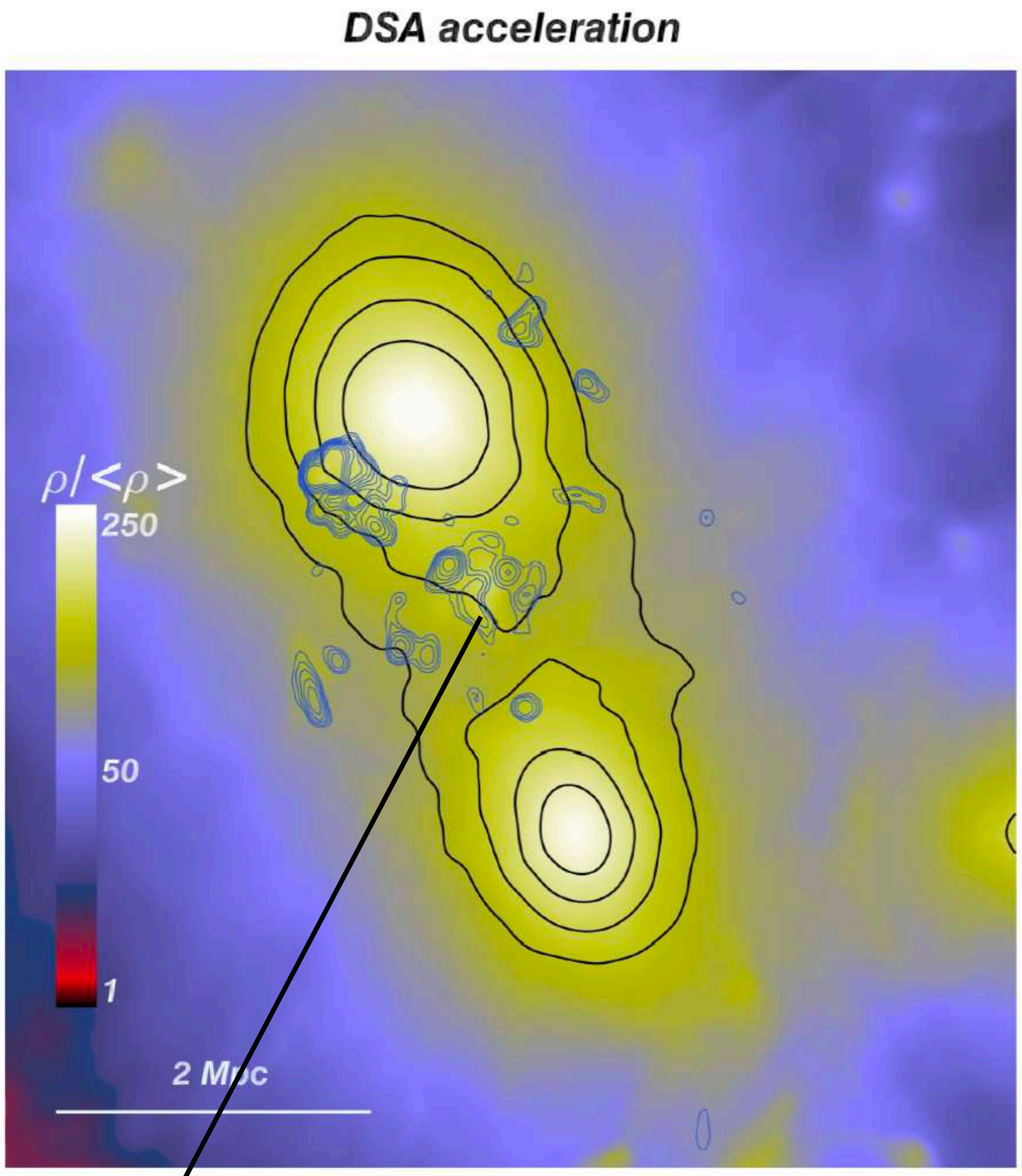
Size ~1.3 x 3 Mpc^2

α>1.3 (?)

n ~3 x 10^{-4}

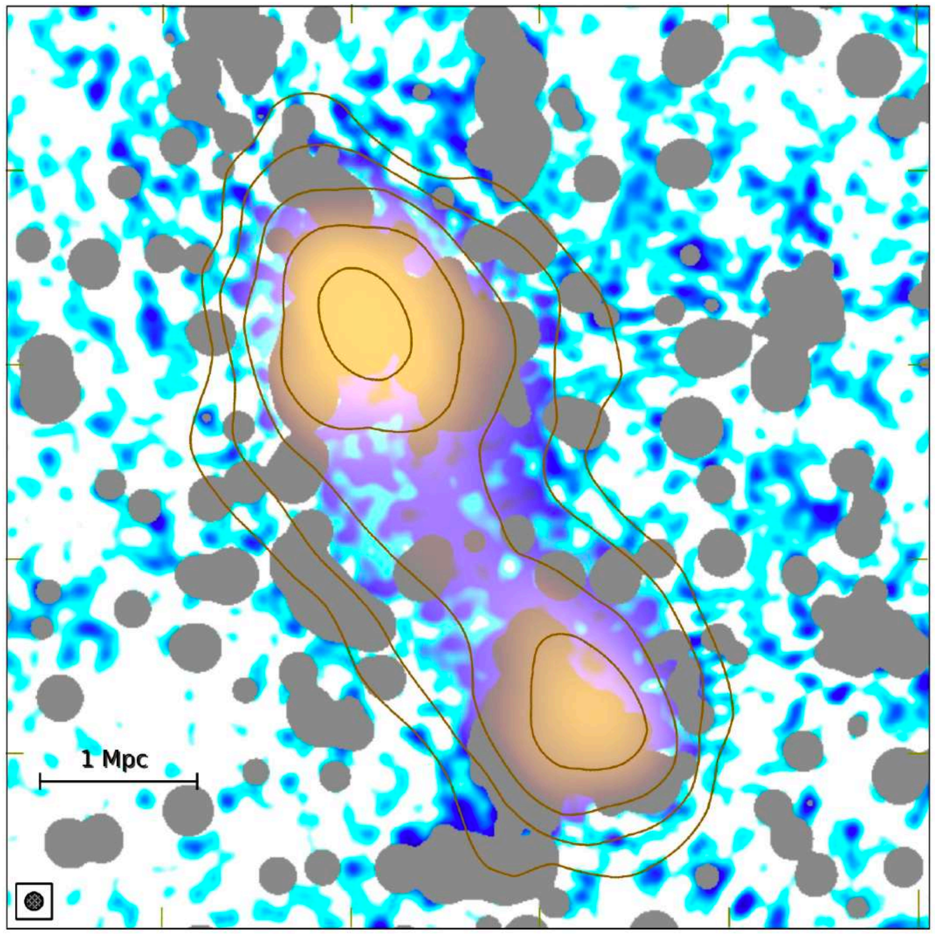
T~6keV

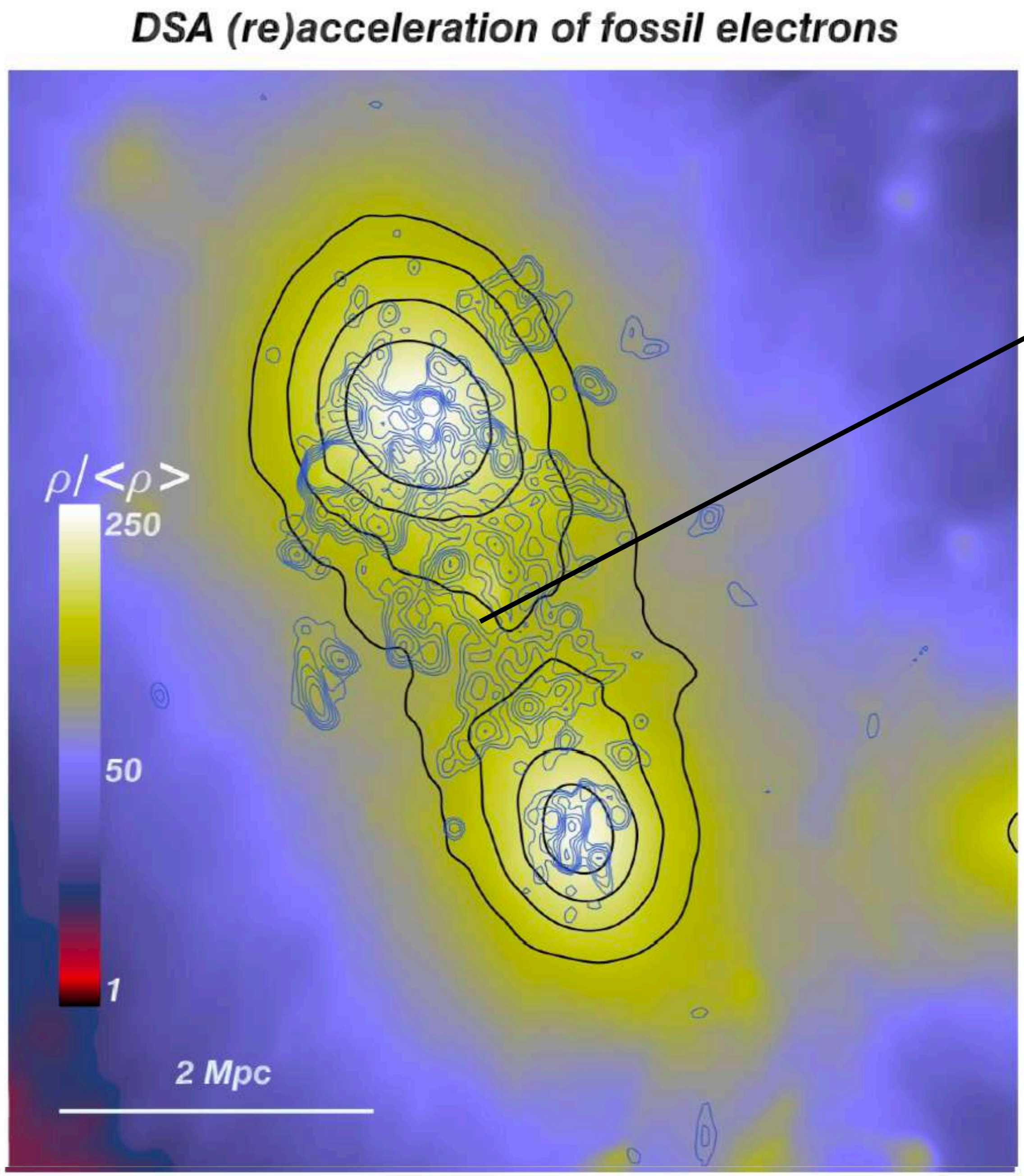
A399-A401 WITH LOFAR HBA (140 MHZ) - ENZO NUMERICAL SIMULATIONS



Diffusive Shock Acceleration by M~2-4 shocks: <u>not efficient enough</u> ($\xi_e < 10^{-5}$)

for B~0.2μG: cannot explain LOFAR obs.





if we assume "fossil electrons"+DSA

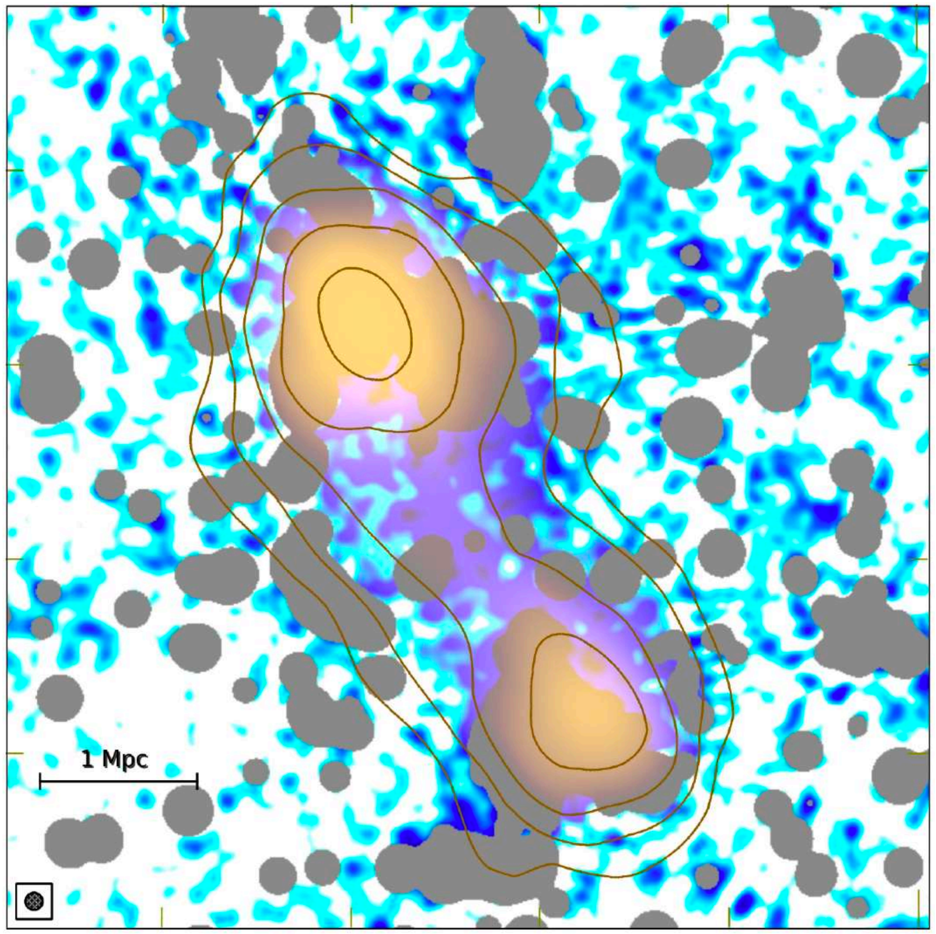
$\xi_e \sim 10^{-5}$ for M~2.5

can match LOFAR observation

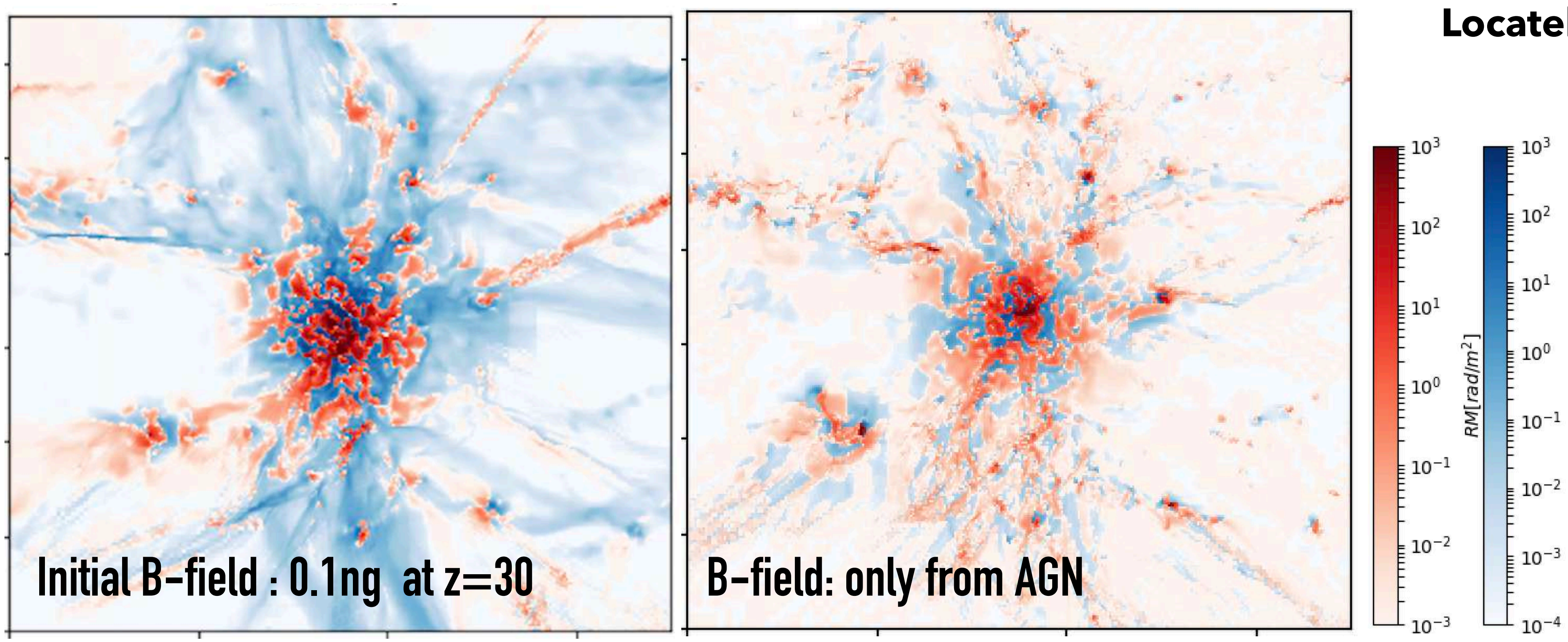
However, this scenario requires some fine tuning on timing (<Gyr) and volume filling

Diffusive Shock Acceleration by M~2.5 shocks: <u>not efficient enough</u> ($\xi_e < 10^{-7}$)

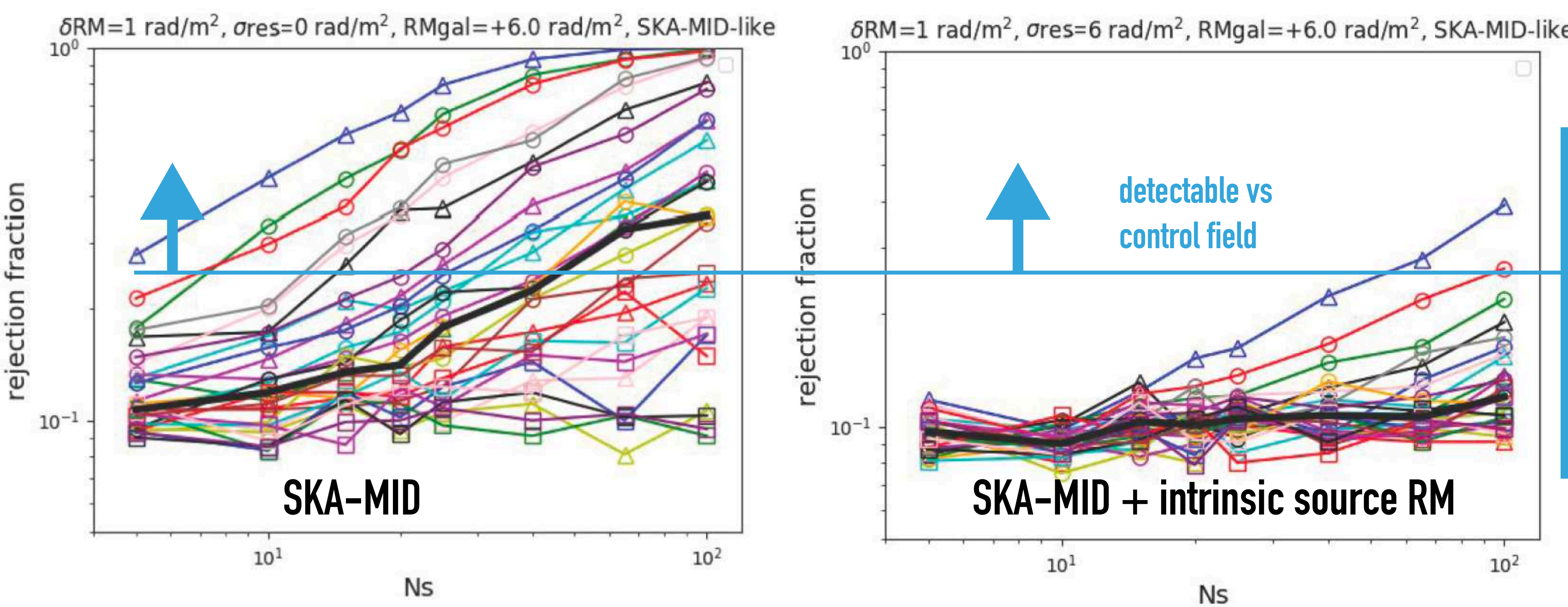
for B~0.2μG: cannot explain LOFAR obs.



Locatelli, FV, Dominguez-Fernandez 2018
(see also Akahori+2014)



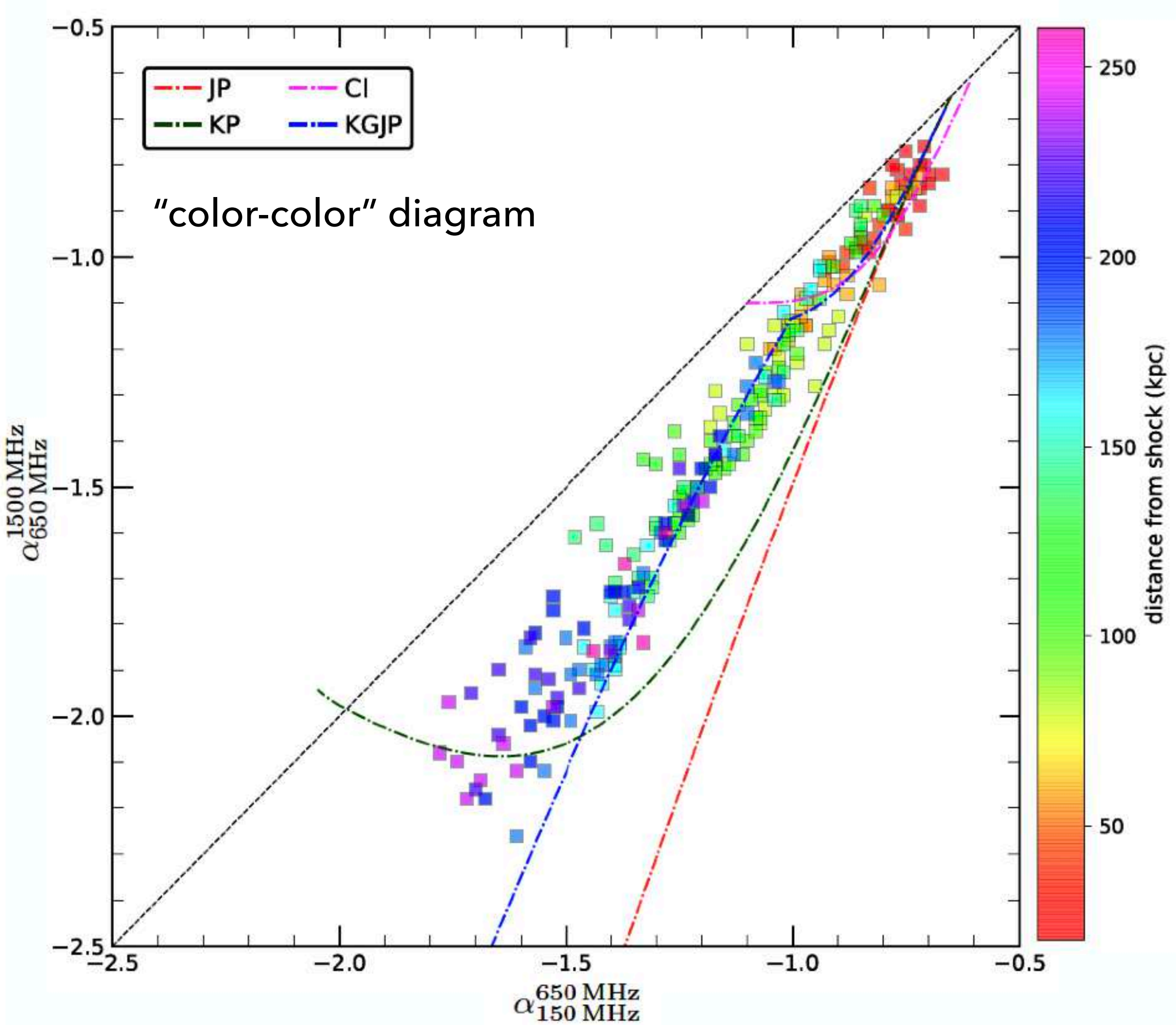
FARADAY ROTATION FROM INTRACLUSTER FILAMENTS DEPENDS ON MAGNETOGENESIS



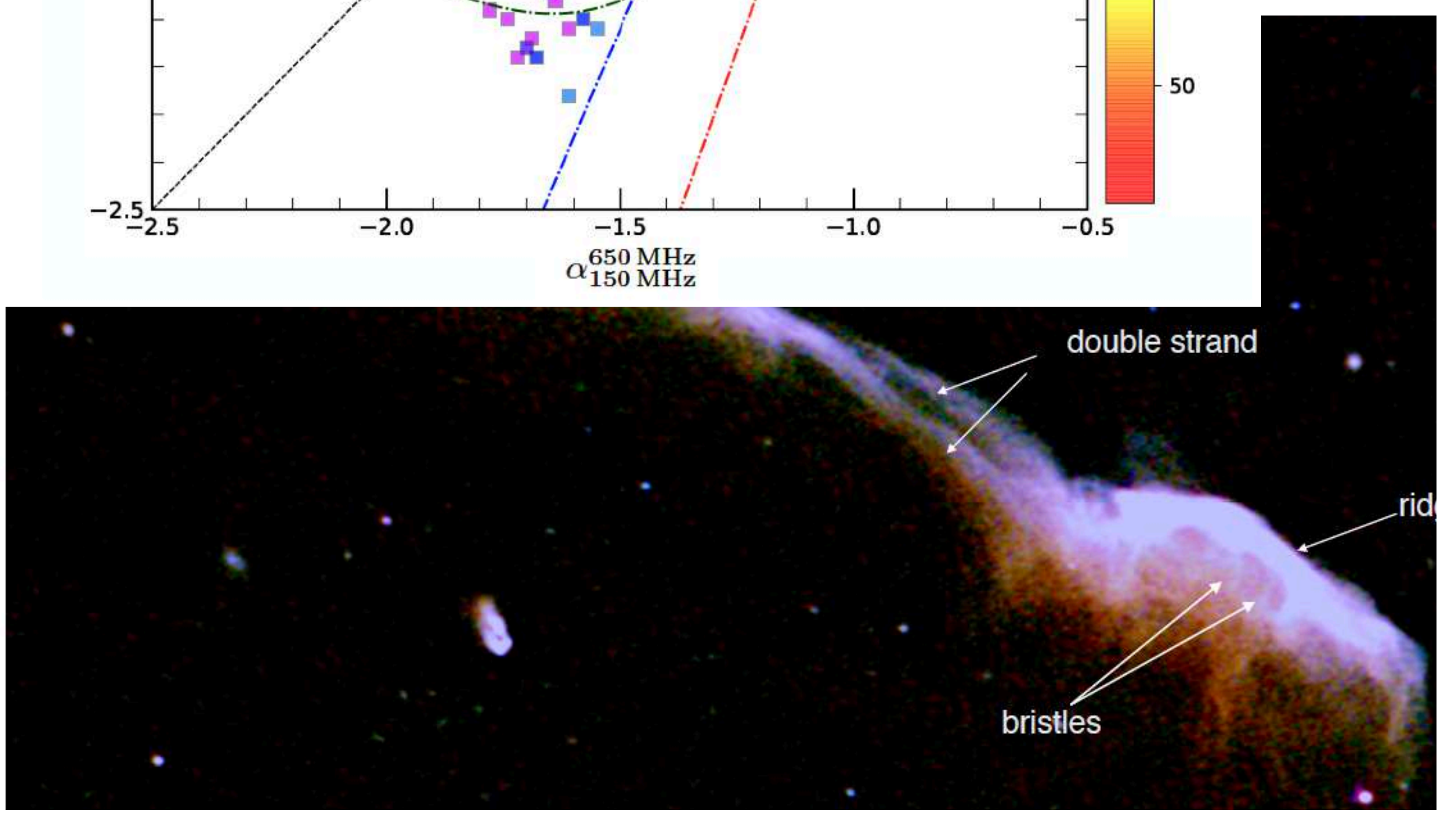
AT LEAST ~100 RM SOURCES ARE NEEDED FOR A DETECTION INTRINSIC RM FROM SOURCES IS <u>A BIG LIMITER</u>

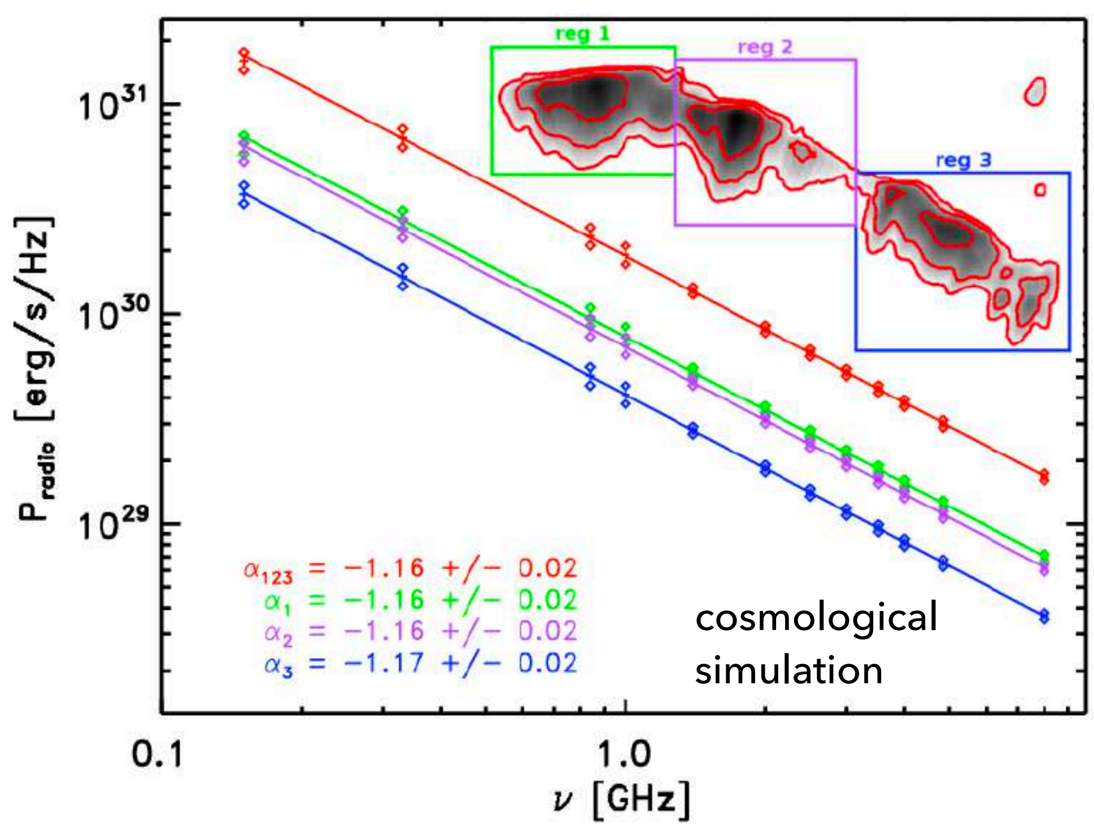
New mysteries and challenges from the Toothbrush relic: wideband observations from 550 MHz to 8 GHz

K. Rajpurohit[1,2], M. Hoeft[3], F. Vazza[1,2,4], L. Rudnick[5], R. J. van Weeren[6], D. Wittor[1,2,4], A. Drabent[3]

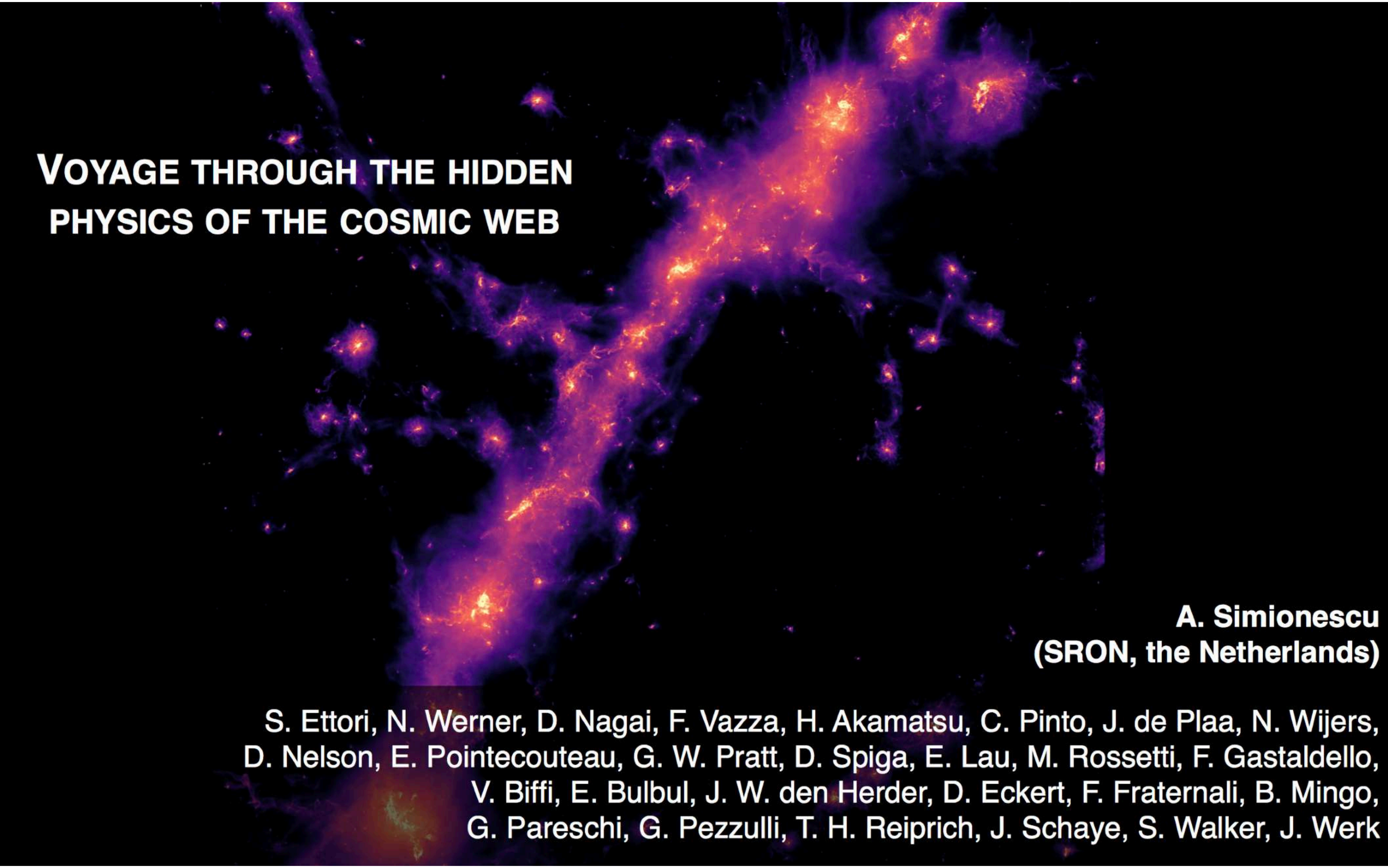


- *Perfect power law spectrum* (α=-1.16) across 2 frequency decades, 2Mpc in size and despite complex morphology.
- observed power requires higher accel. efficiency than DSA (~1%) and B~1-2μG
- downstream cooling not fitted by any simple model



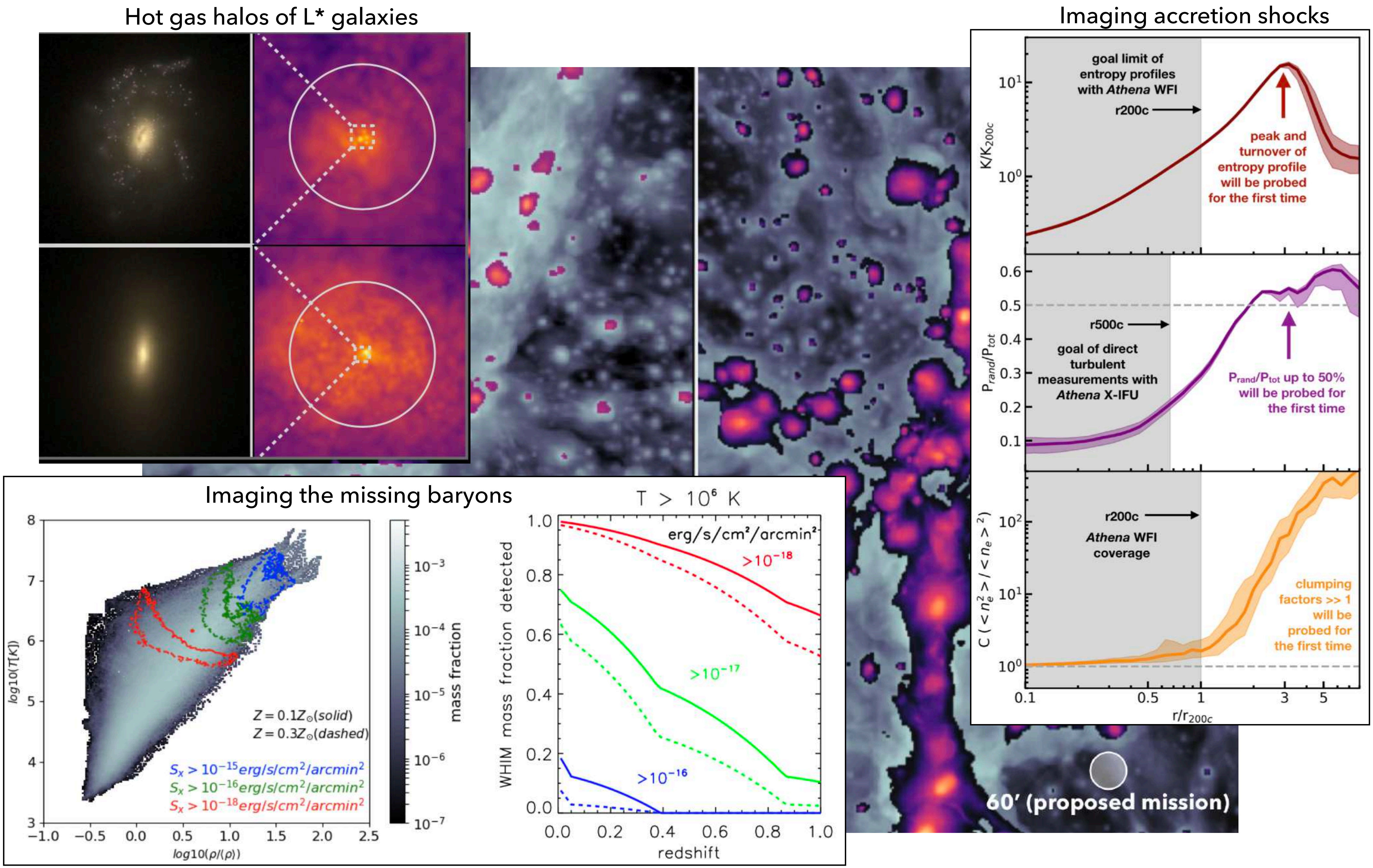


THE FAR FUTURE (>2050): X-RAY



https://arxiv.org/abs/1908.01778

THE FAR FUTURE (>2050): X-RAY



https://arxiv.org/abs/1908.01778

CONCLUSIONS:

- The cosmic web is a dynamic environment where drastic changes happen in the life of baryons
- Only future X-ray satellite will probe thermal baryons of the CW. Radio observations can help.
- Radio observations will constrain the origin of cosmic magnetism
- In this challenge, we are also learning about how diluted plasmas can accelerate cosmic rays