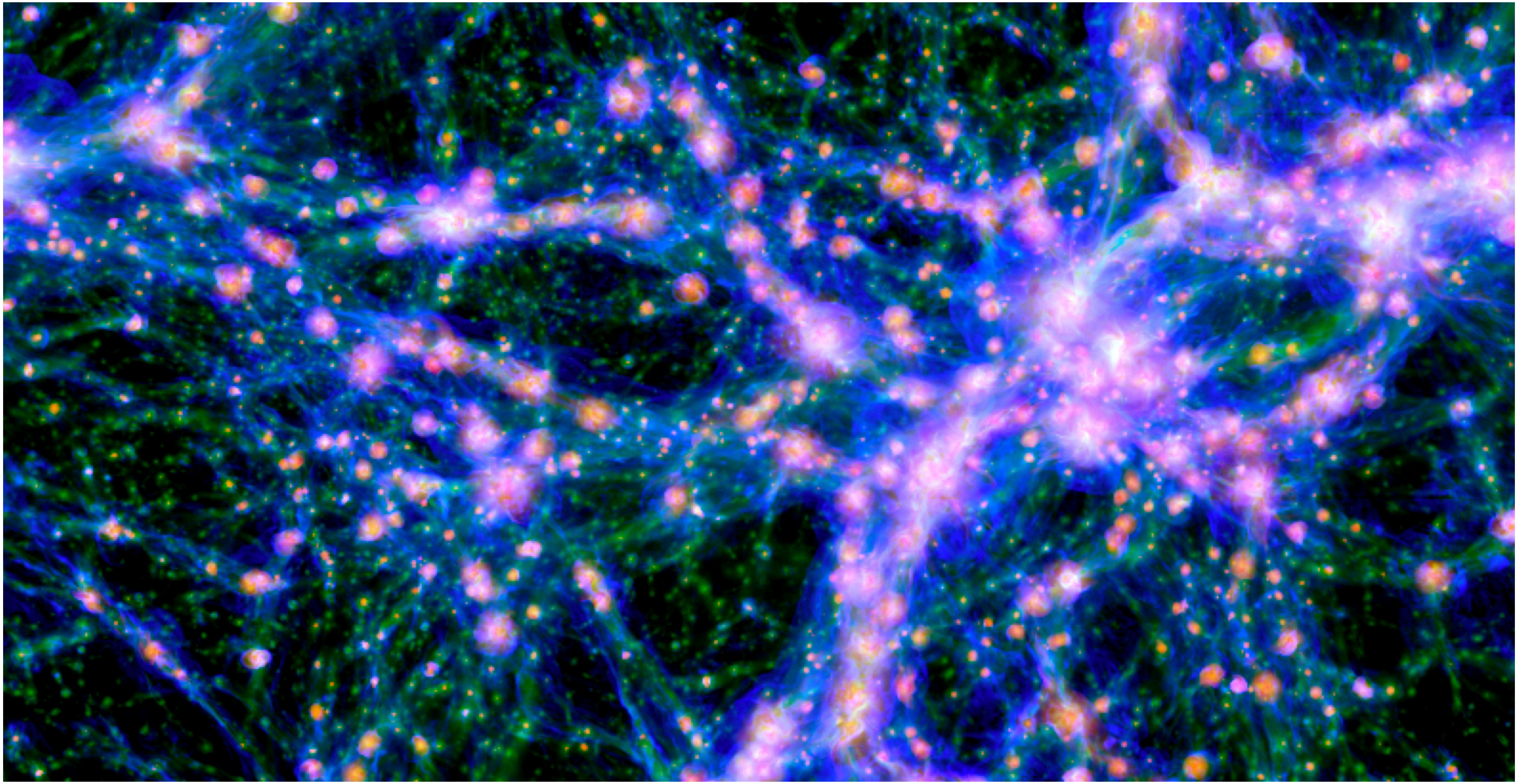


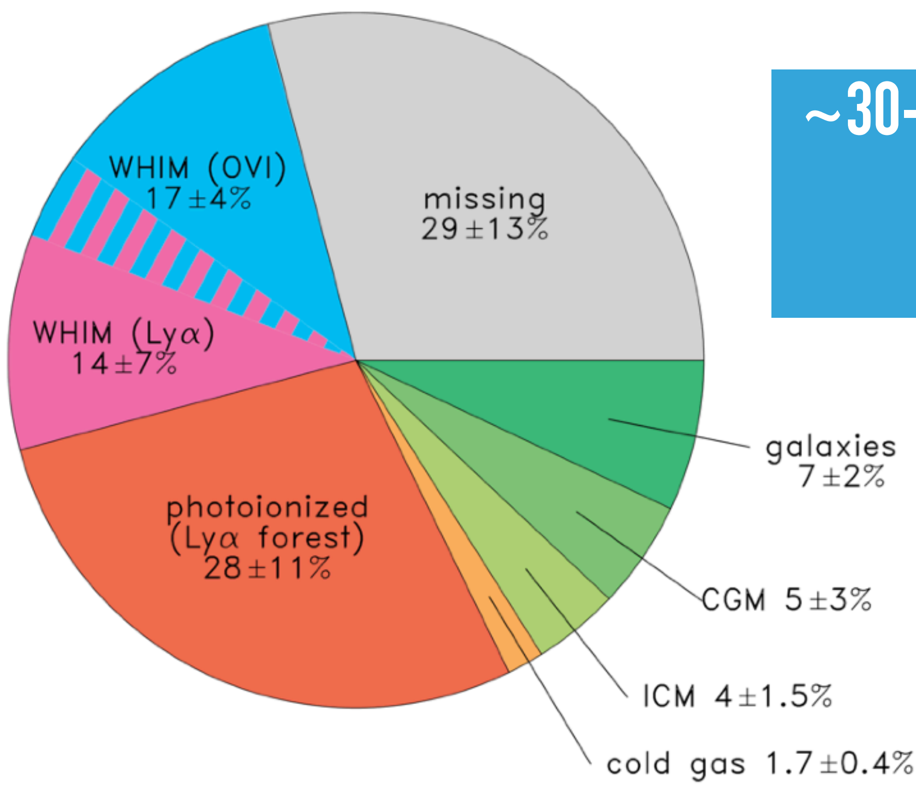
The fascinating periphery of galaxy clusters and its connection with the cosmic web

+ S. Ettori, C.Gheller, M. Roncarelli, M. Bruggen, M. Angelinelli,
G. Brunetti, P.Dominguez-Fernandez, N. Locatelli

A QUESTION:

CAN WE IMAGE THE WARM HOT IGM WITH X-RAYS?

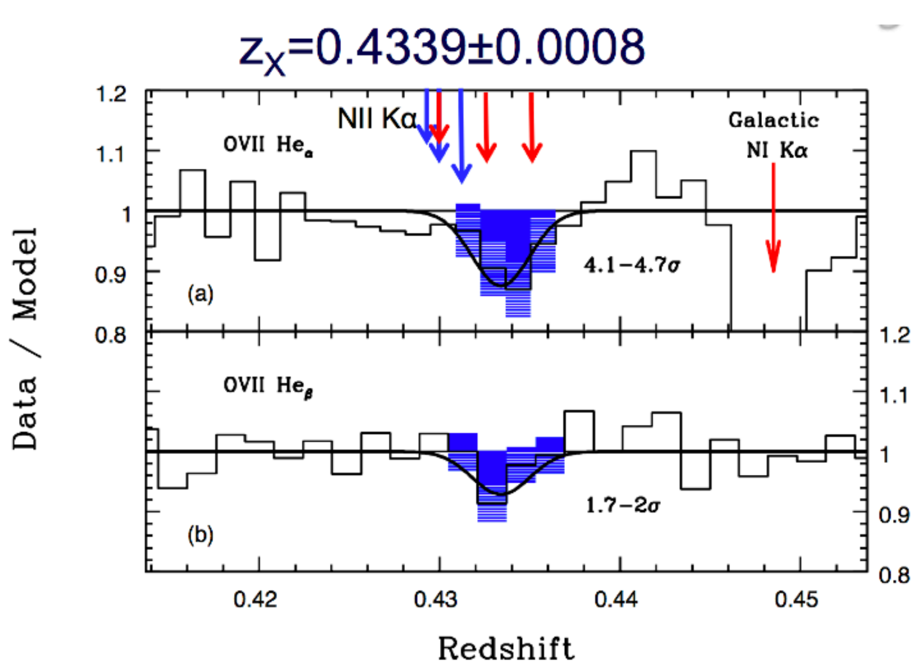
Shull+2012



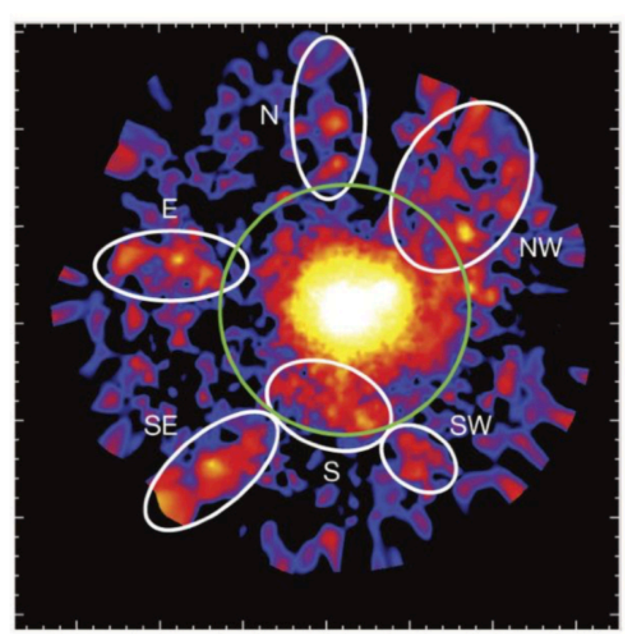
~30-50 % OF BARYONS PREDICTED TO BE IN FILAMENTS

(Cen & Ostriker 99,Davè+01...)

RECENT DETECTIONS:

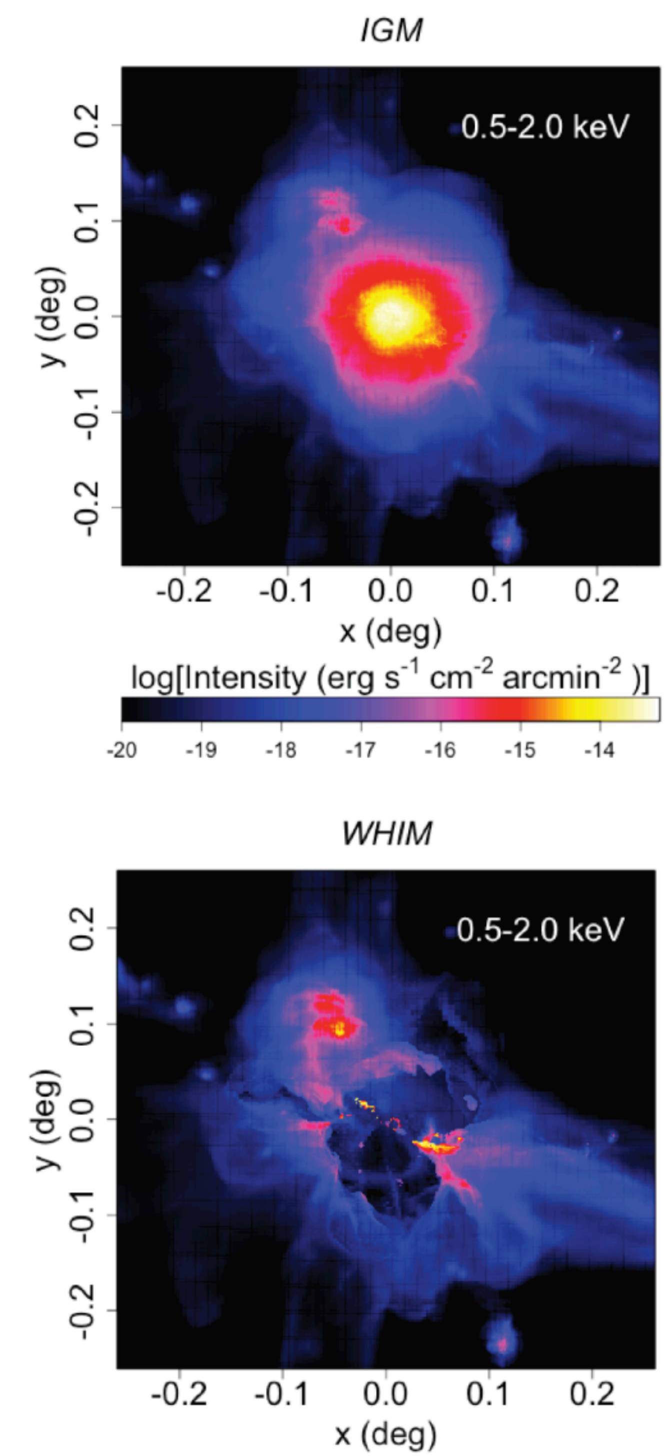


Nicastro+ 2019 Nature (see also Kovacs+2019)



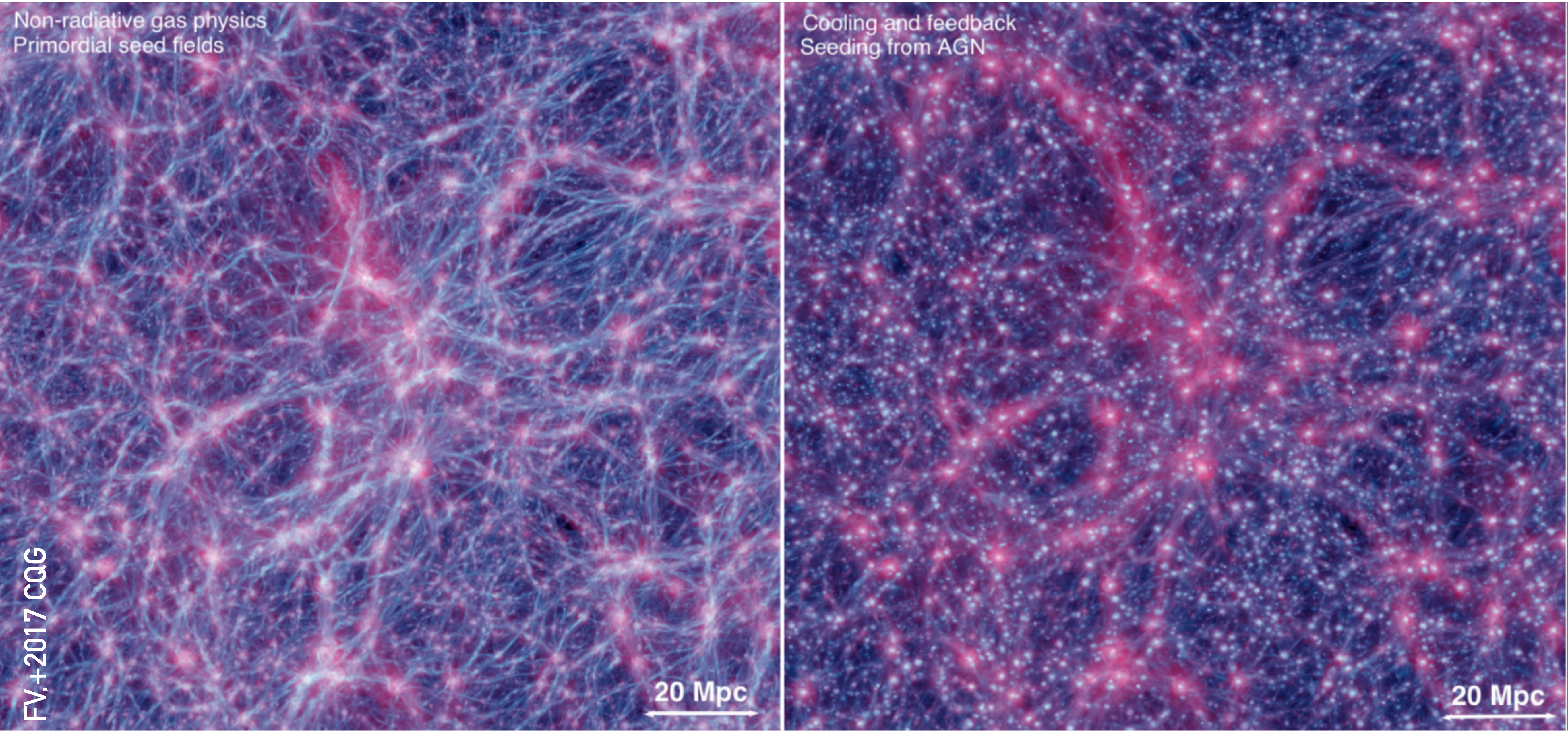
Eckert +. 2015 Nature

HYDRO SIMULATIONS:



Planelles+2018

THE RADIO COSMIC WEB

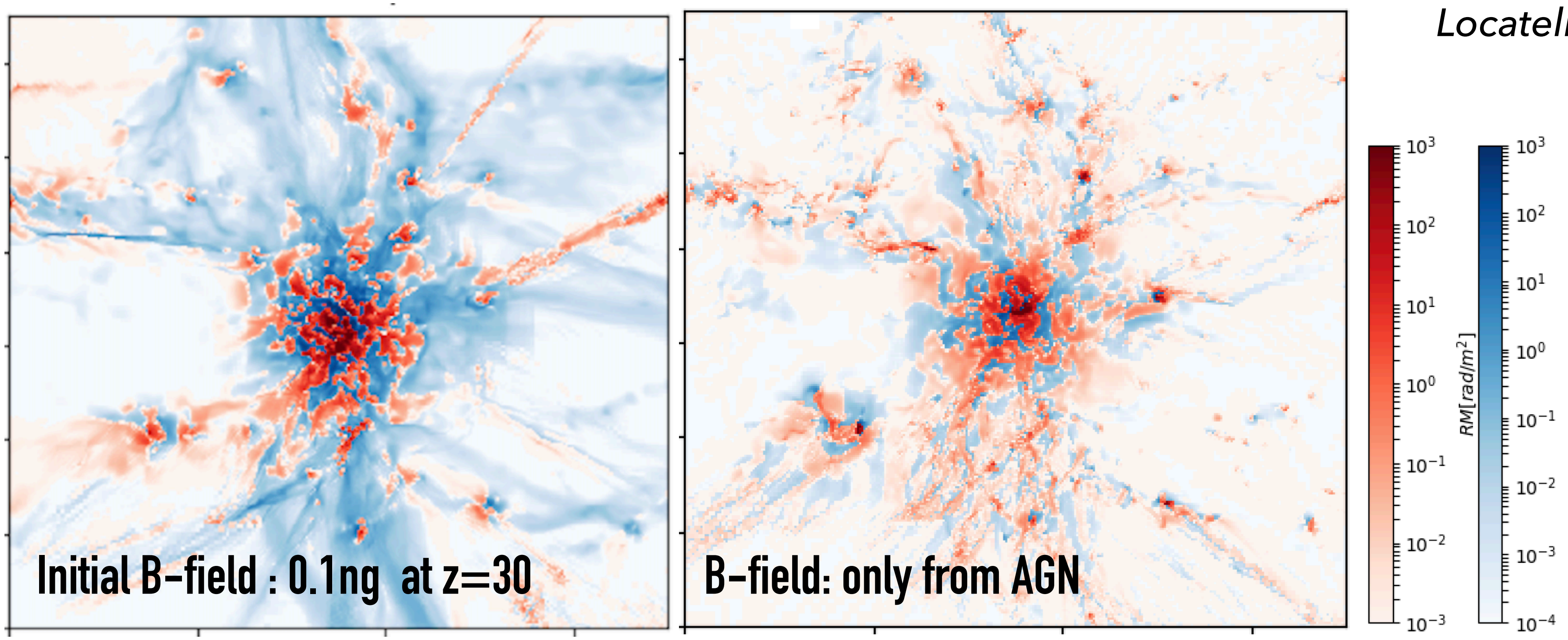


DIFFERENT SCENARIOS FOR THE ORIGIN OF EXTRAGALACTIC MAGNETIC FIELDS SHOULD DIFFER IN FILAMENTS

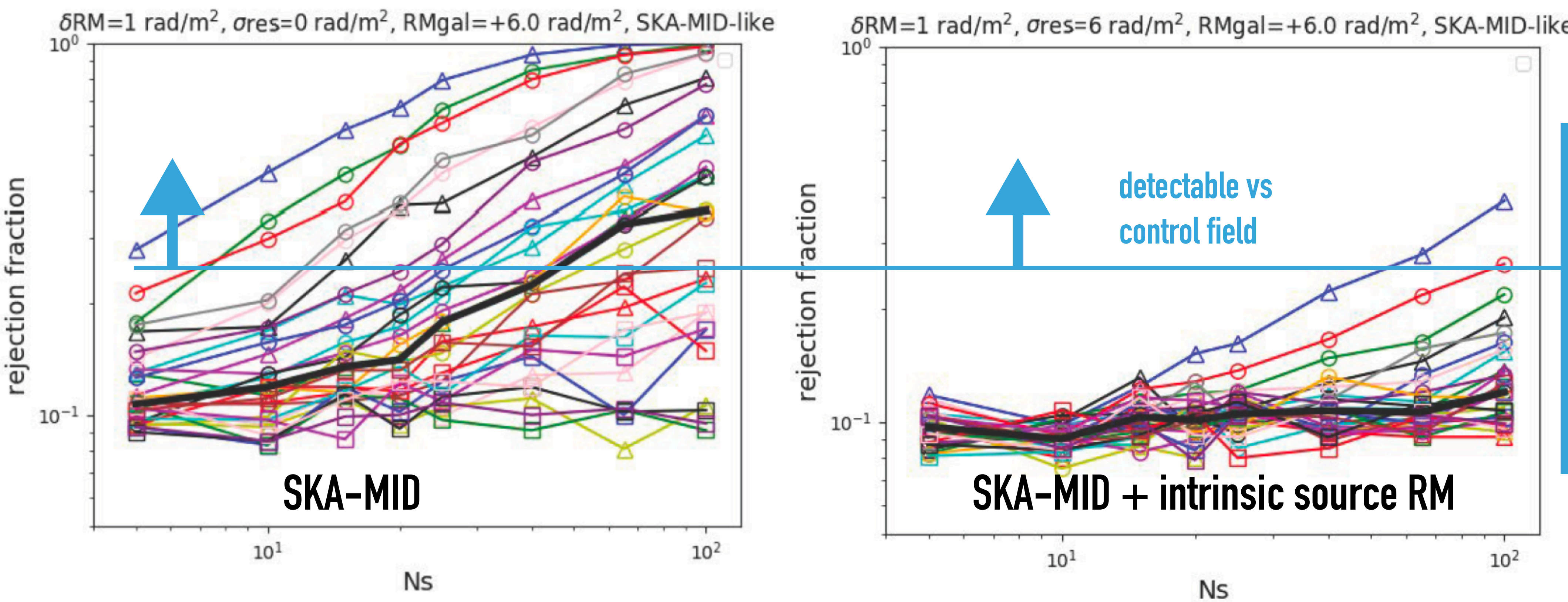
(A SIDE CHALLENGE: DETECTING THE COSMIC WEB WITH FARADAY ROTATION)

Locatelli, FV, Dominguez-Fernandez 2018

(see also Akahori+2014)

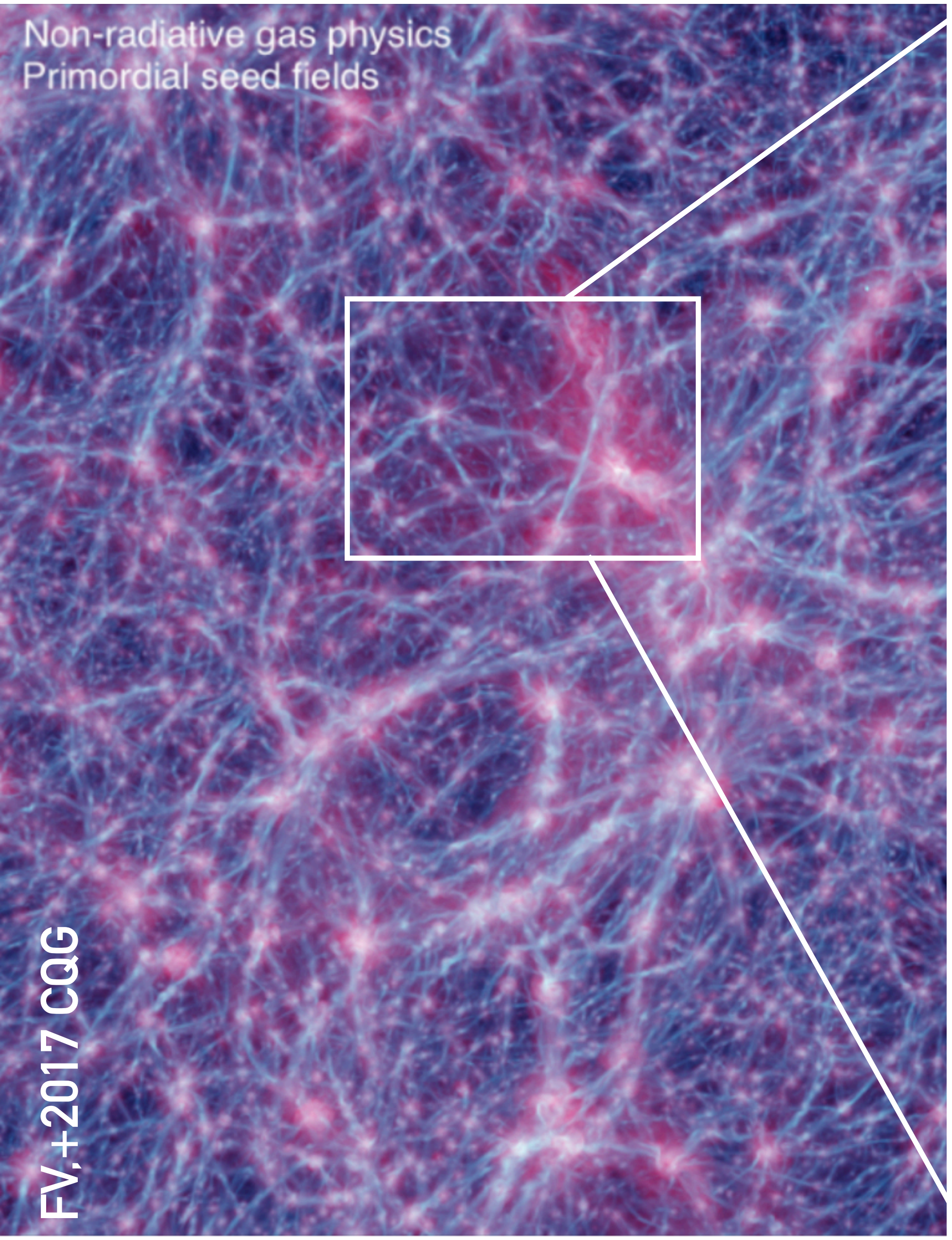


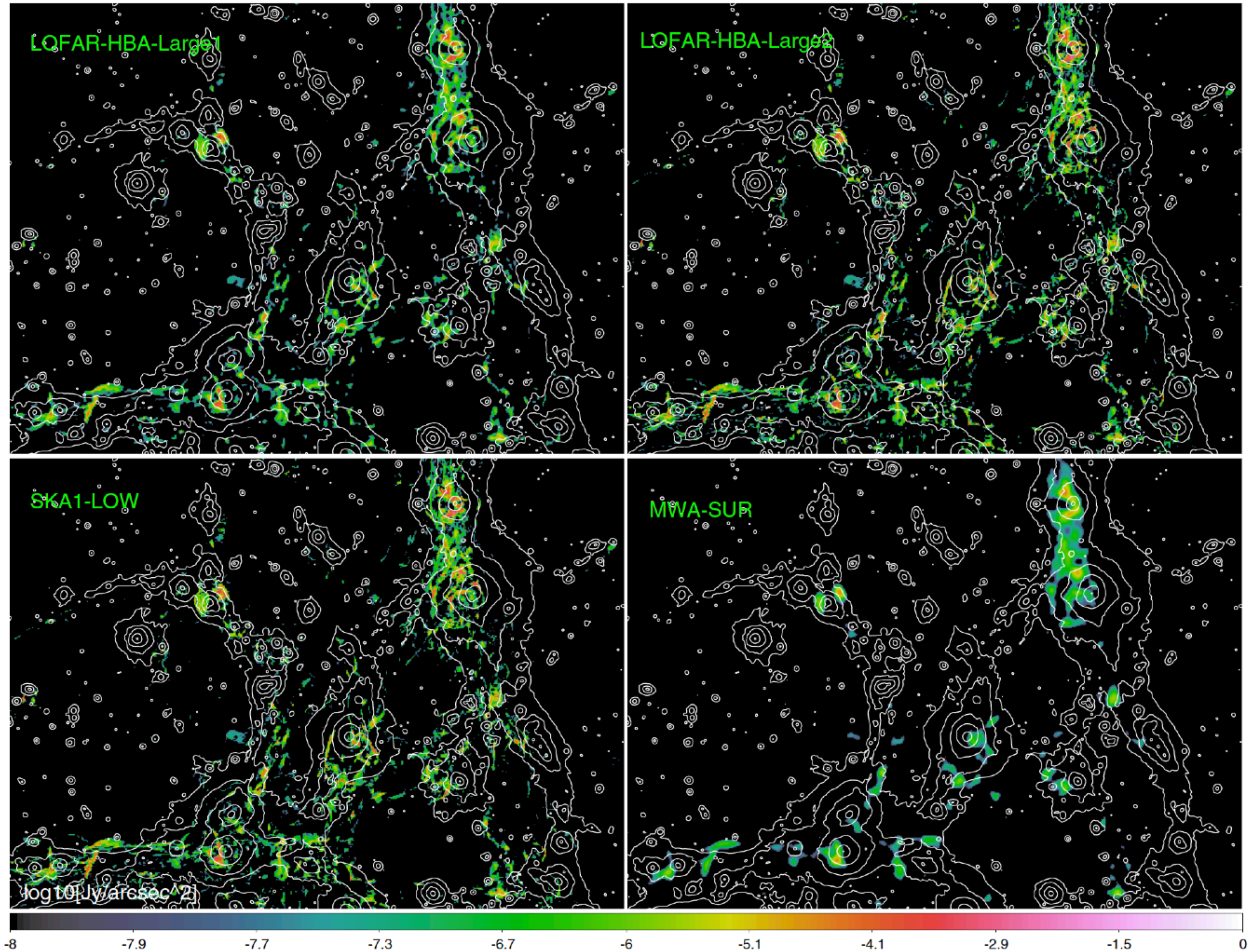
FARADAY ROTATION FROM INTRACLUSTER FILAMENTS DEPENDS ON MAGNETOGENESIS



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

THE RADIO COSMIC WEB





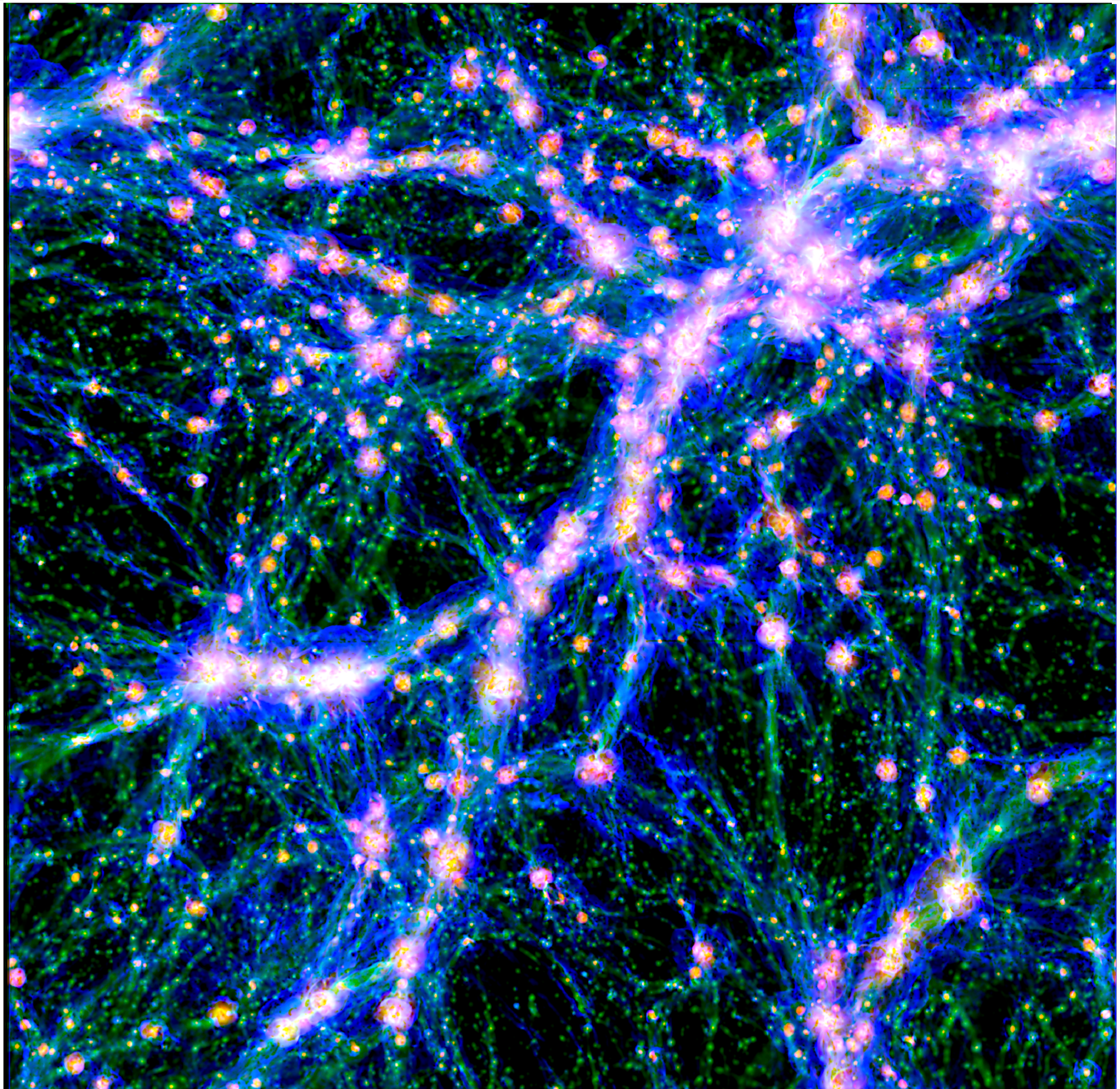
FV,+2015 A&A

DIFFERENT SCENARIOS FOR THE ORIGIN OF EXTRAGALACTIC MAGNETIC FIELDS SHOULD DIFFER IN FILAMENTS

LOW-FREQ. RADIO OBSERVATIONS MAY DETECT THE TIP OF THE ICEBERG OF THE COSMIC WEB

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

FV,Ettori,Roncarelli,Angelinelli,Bruggen,Gheller A&A sub.



RADIO EMISSION

X-RAY EMISSION

MAGNETIC FIELDS (B_0=0.1NG AT Z=50)

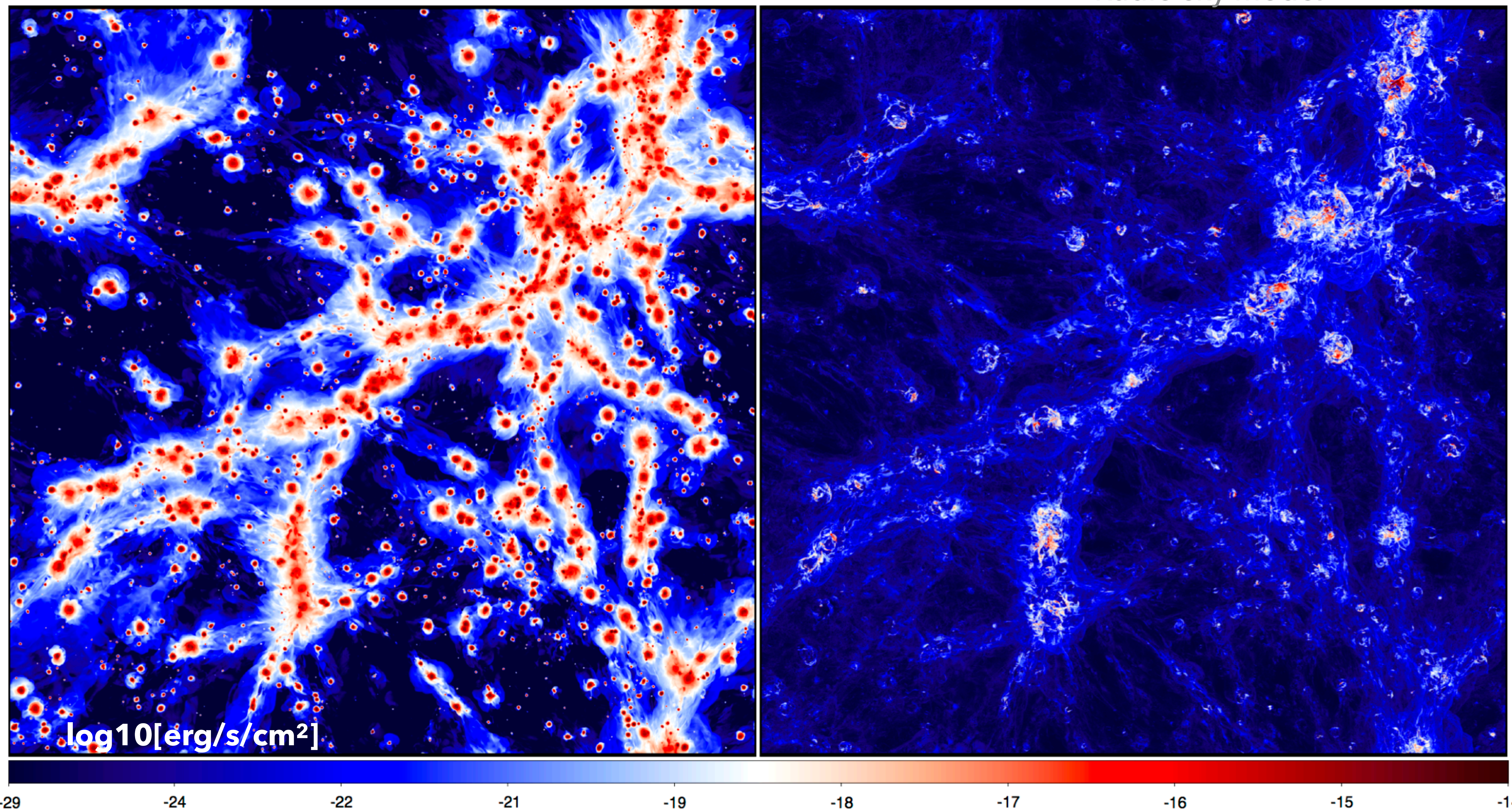
ENZO-MHD - 2400^3 cells simulation, 100Mpc - Δx=41.6kpc. ~2000kE on 2400 Daint nodes

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

FV,Ettori,Roncarelli,Angelinelli,Bruggen,Gheller A&A sub.

X-ray sky model

Radio sky model



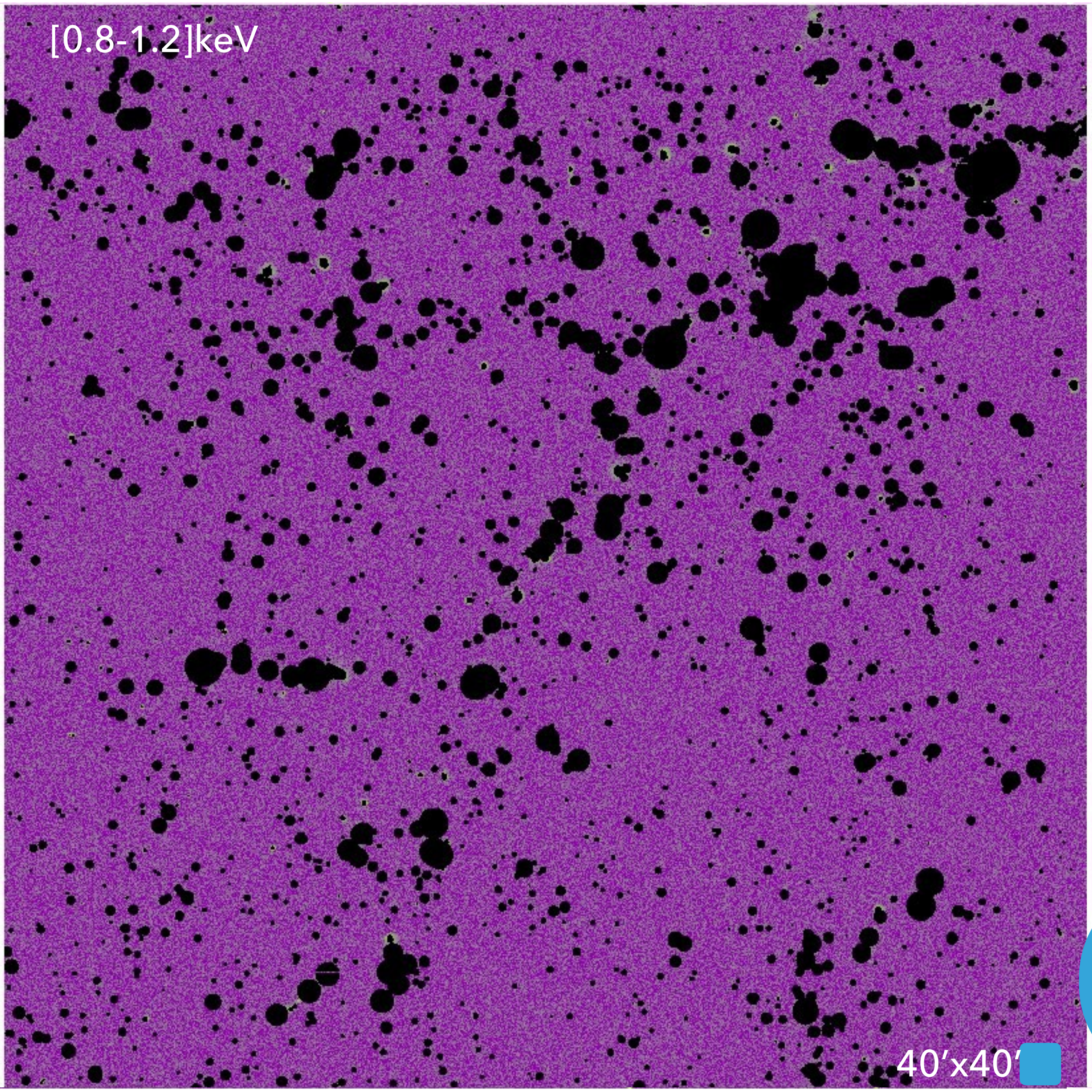
<u>X-ray emission model:</u>
equilibrium cooling, Z=0.3 solar,
bApec emission model

<u>Radio emission model:</u>
single injection DSA model (see <u>Kang's talk</u>),
max.efficiency ξ_e~7 10^{-4} ; 3D magnetic field from MHD simulation (~10-50 nG in filaments)

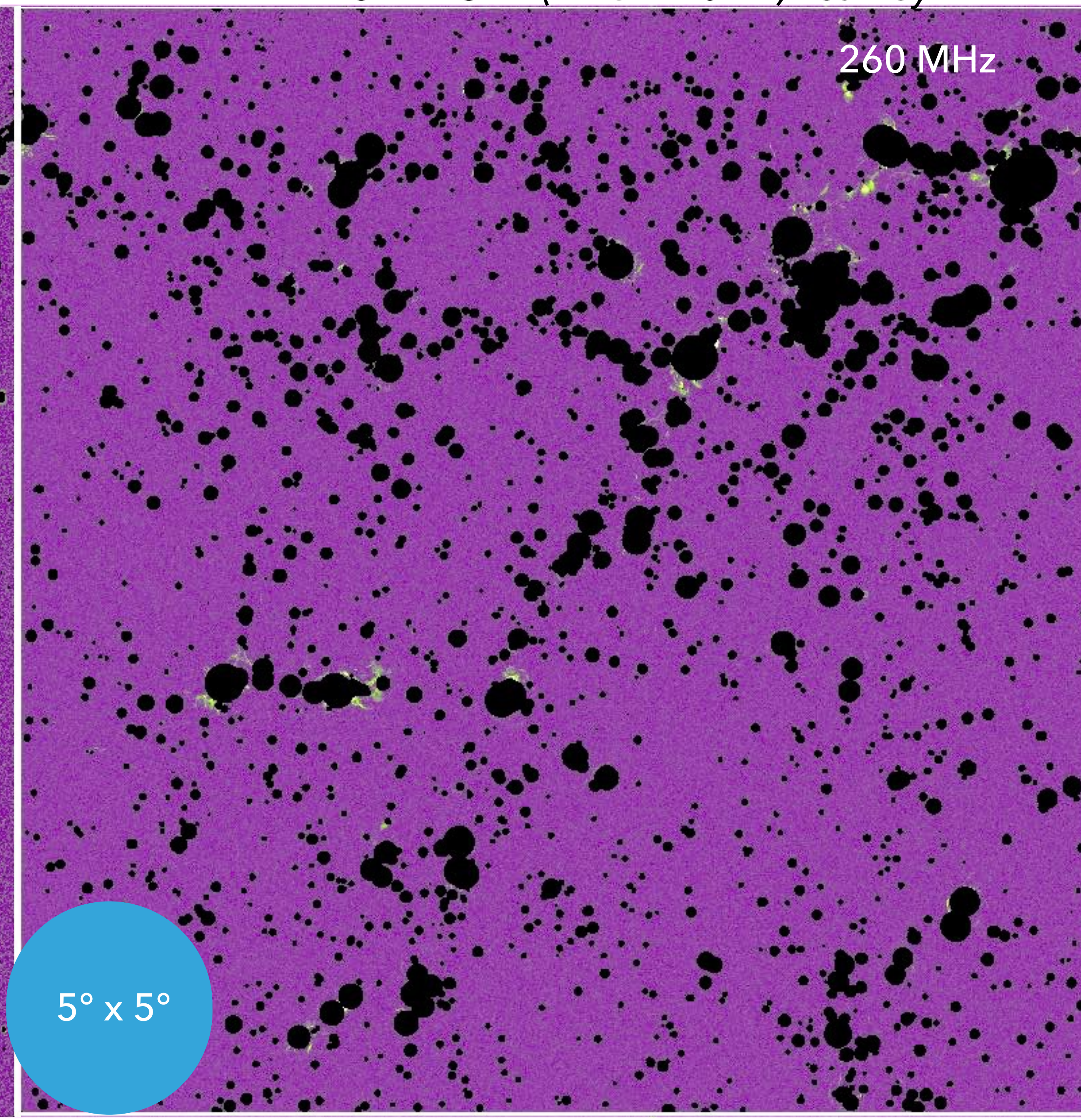
“DETECTING THE COSMIC WEB WITH X-RAY AND RADIO OBSERVATIONS”

FV,Ettori,Roncarelli,Angelinelli,Bruggen,Gheller A&A sub.

ATHENA-WFI “core” - 1Ms



SKA-LOW (Bmax=40km) - survey



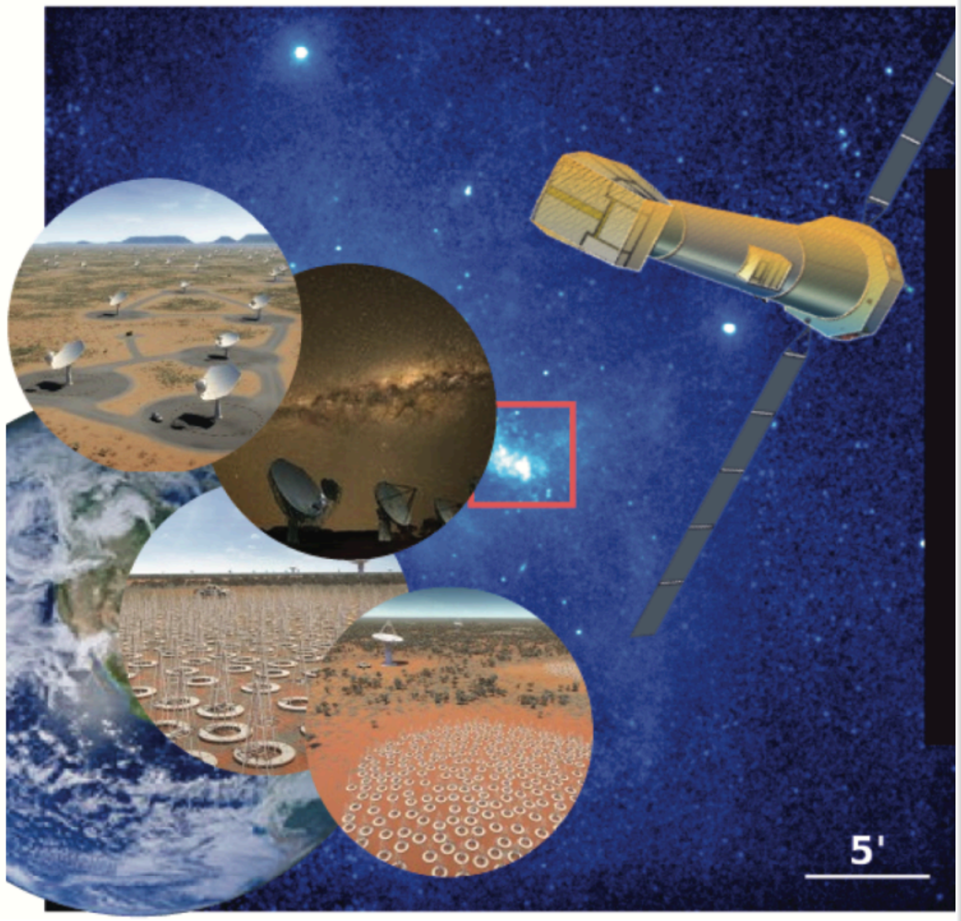
<u>mock X-ray observation</u> (Athena-WFI 0.8-1.2keV)

t=1Ms, instr.+ sky BG (3100 cnt/Ms arcmin^2)
nH=2 10^{20} cm^2 , A_{eff} = 12139 cm^2

<u>mock radio observation</u> (SKA-LOW 260MHz)

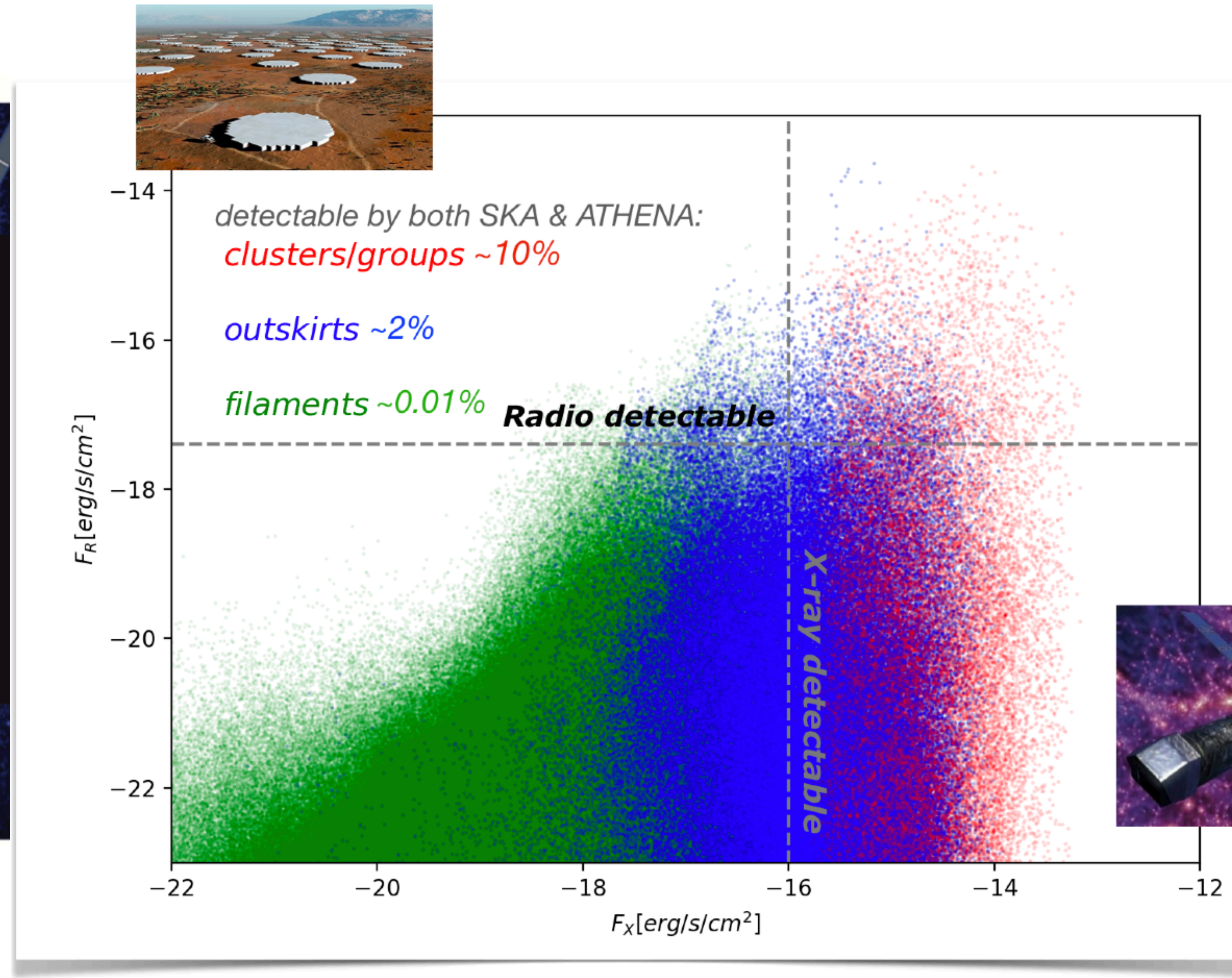
t=10hr, thermal+confusion noise (σ=4.8μJy/beam)
beam=7.3” , UV sampling

DETECTING THE COSMIC WEB WITH X-RAY AND RADIO OBSERVATIONS



ATHENA-SKA White Book

Cassano+2018



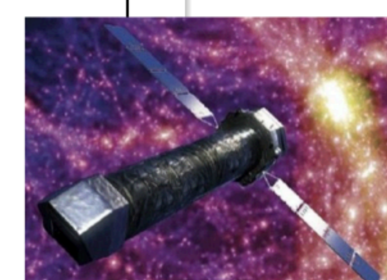


Table 5.1: Percentage of detected area covered by different simulated objects.

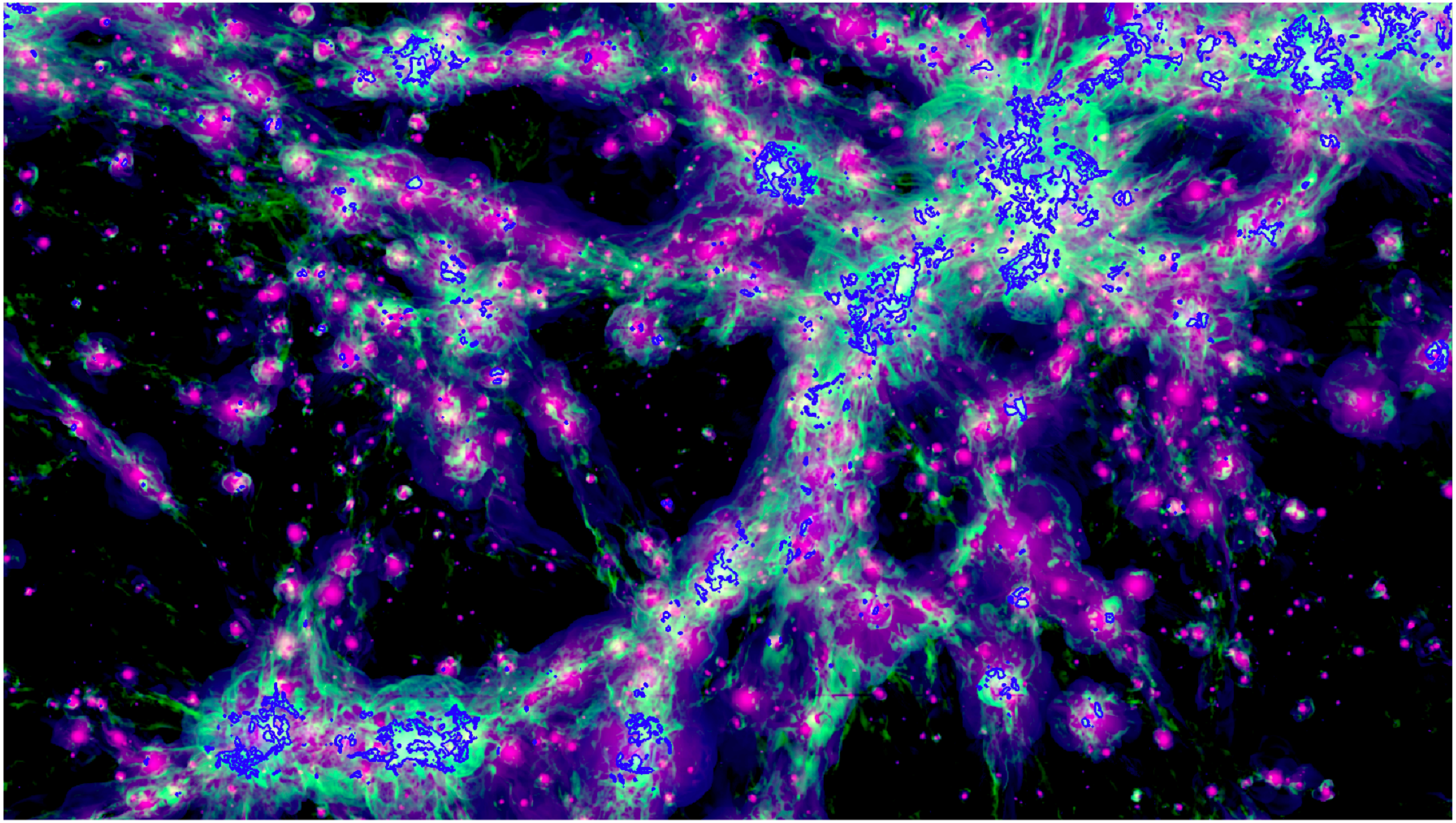
	Athena	SKA1-LOW	*Athena* ∩ SKA1-LOW
galaxy clusters	50%	19%	11%
outskirts	10%	19%	1.4%
filaments	0.1 %	1.8%	0.01%

WHERE ARE DOUBLE DETECTIONS MORE LIKELY?

X-ray emission

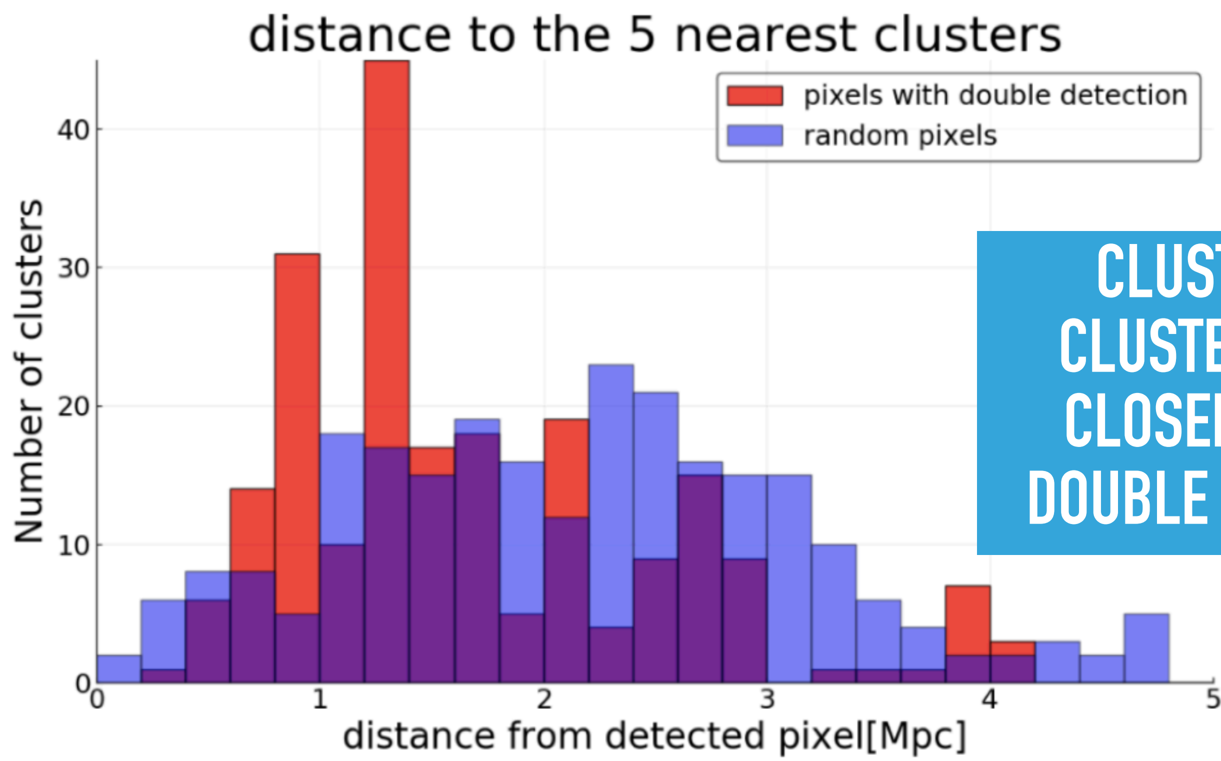
Radio emission

Double detections



Vazza, Ettori & Ferrari, "Athena Nugget 22"

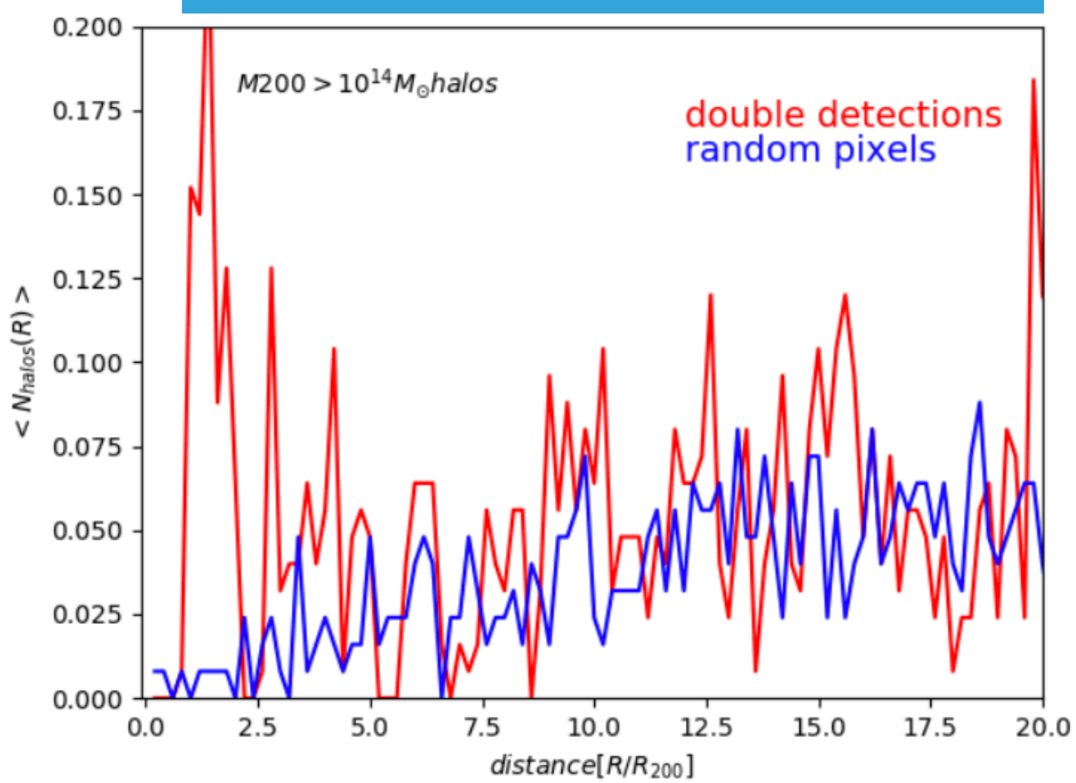
WHERE ARE "DOUBLE DETECTIONS" MORE LIKELY?

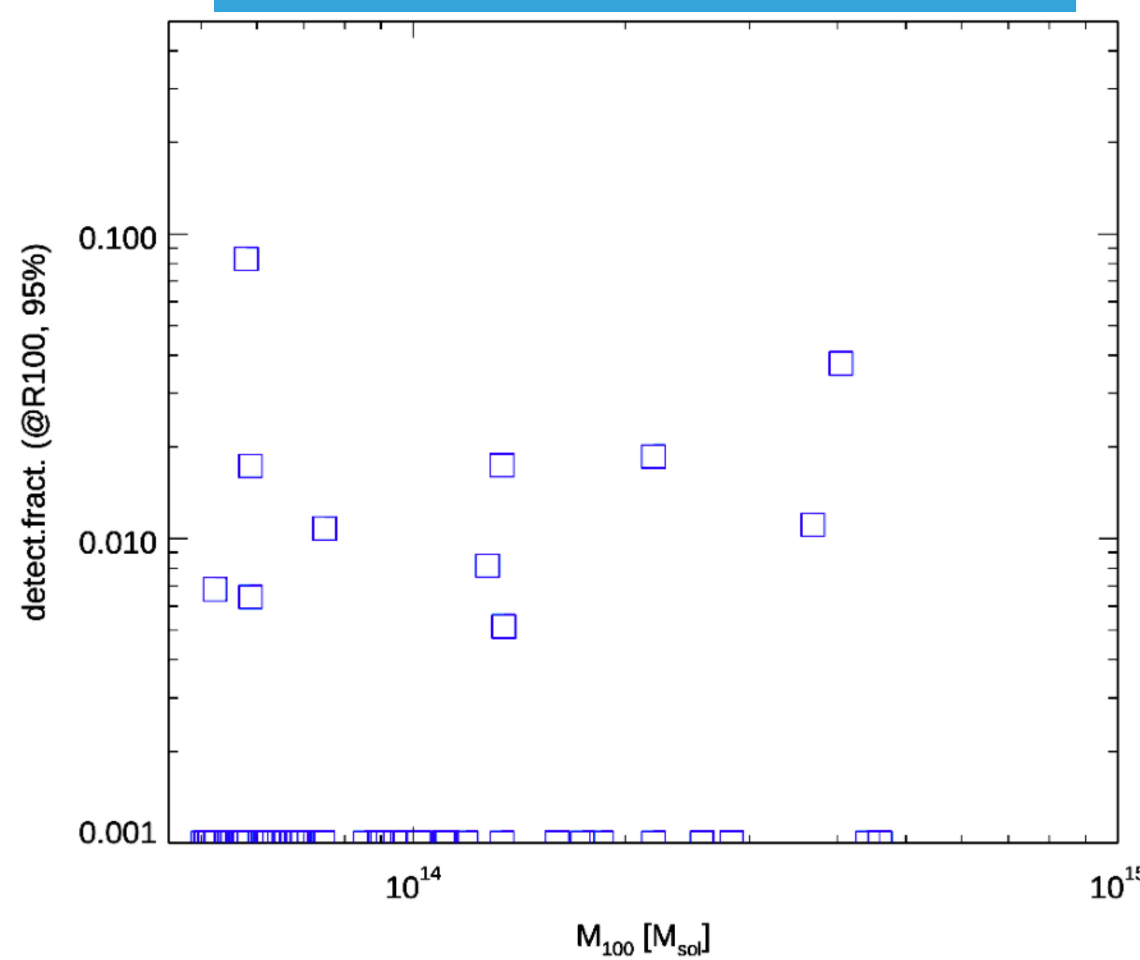


CLUSTERS ARE CLUSTERED MORE CLOSELY AROUND DOUBLE DETECTIONS

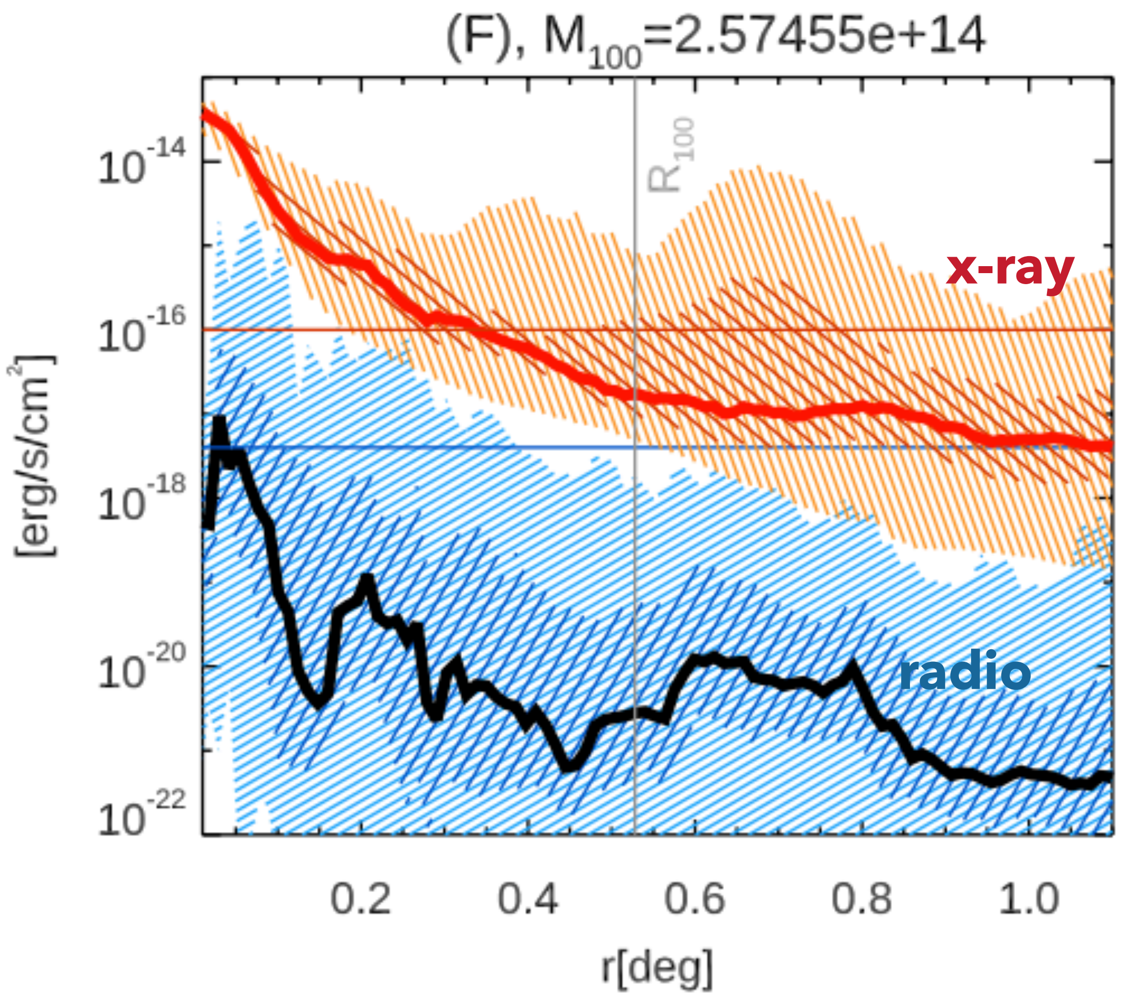
DOUBLE DETECTABLE REGIONS DOT CORRELATE WITH CLUSTER MASSES OR INTERNAL DYNAMICS

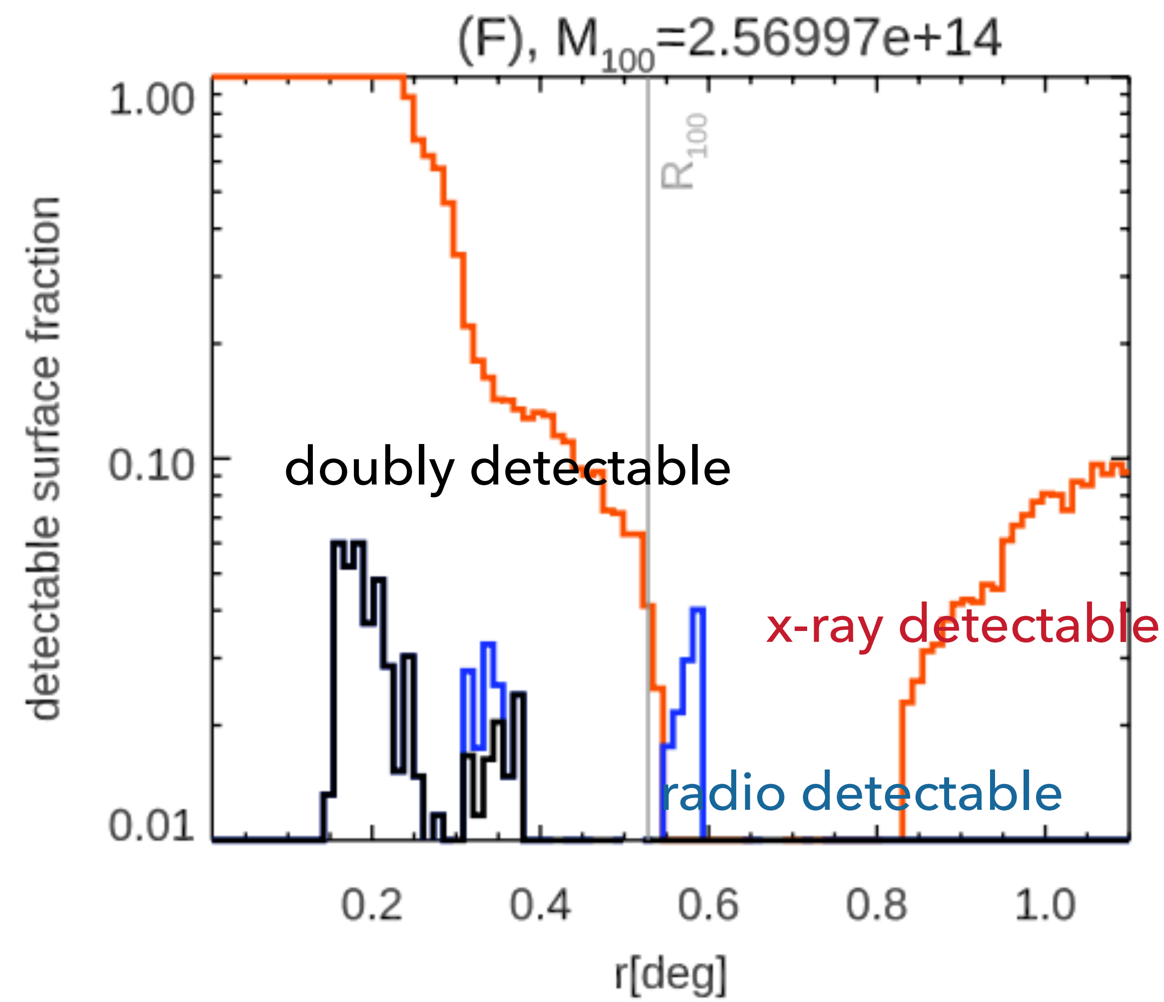
CLUSTERING LARGER DOWN TO ~10R200



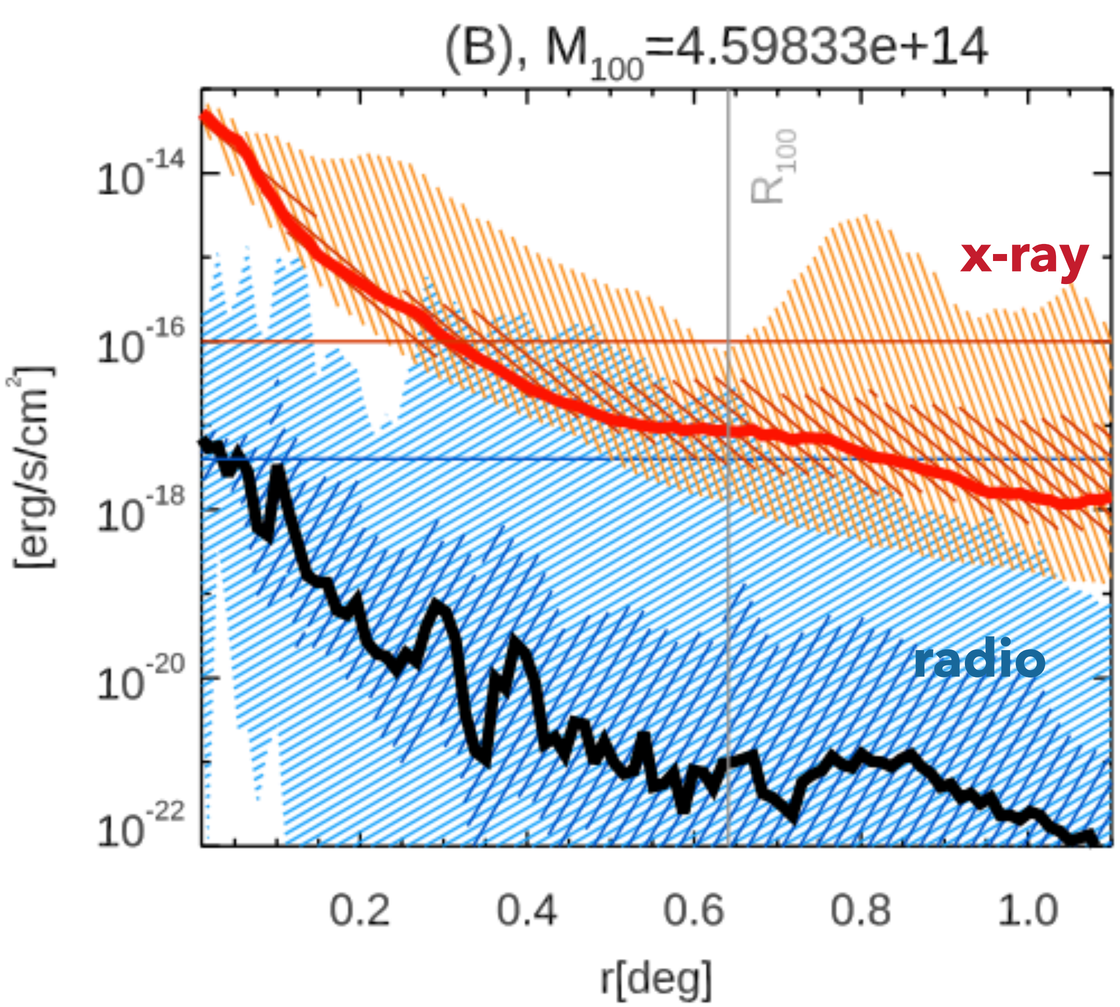


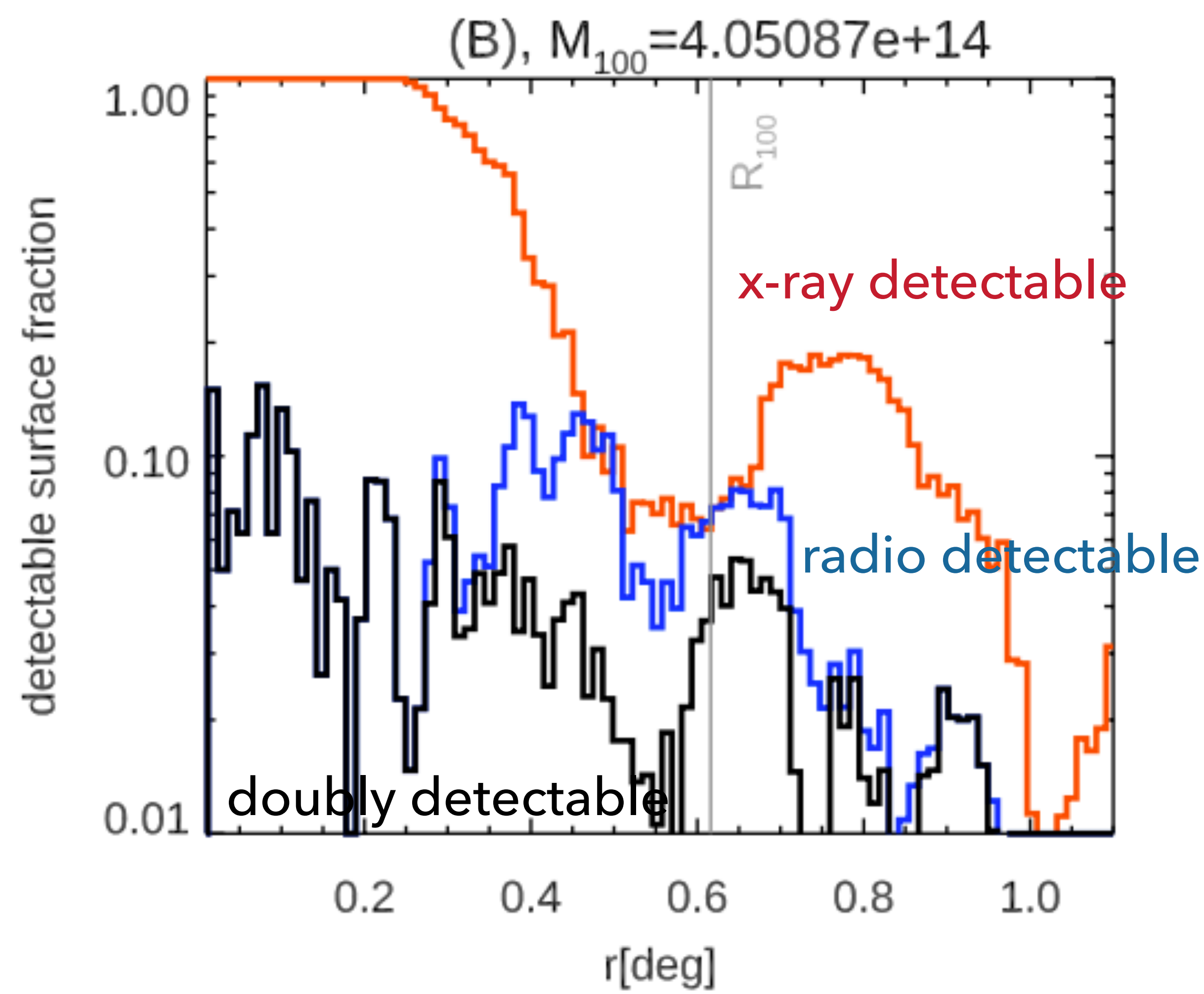
WHERE ARE “DOUBLE DETECTIONS” MORE LIKELY?





WHERE ARE "DOUBLE DETECTIONS" MORE LIKELY?





ASSOCIATION WITH CLUSTERS WITH A LARGE SCALE (>R100) COMPANION UNDERGOING MERGER

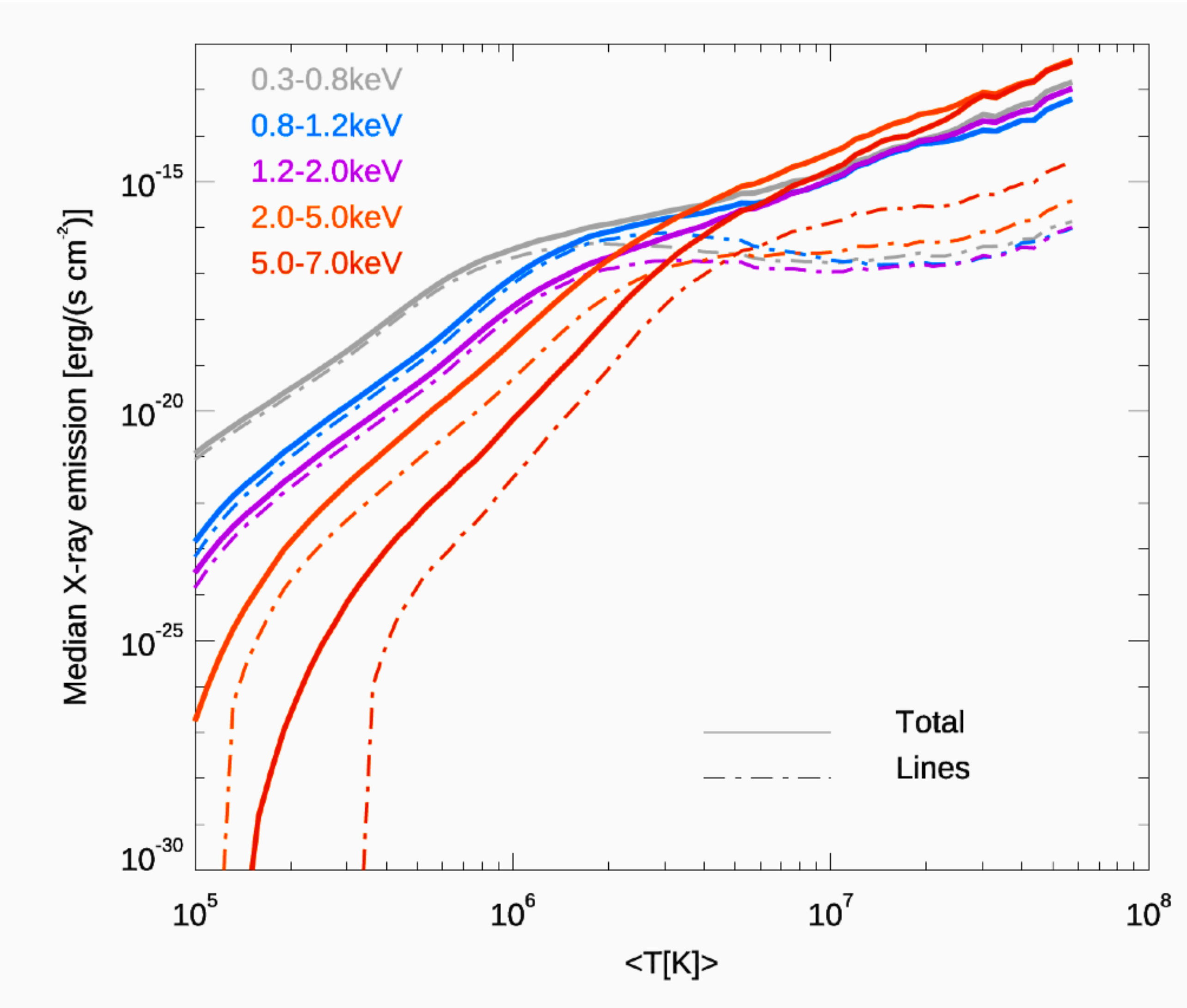
PERFORMANCES OF DIFFERENT X-RAY/RADIO INSTRUMENTS

Table 1: Values adopted for our mock X-ray observations with *Athena*, eROSITA and XMM-Newton. For each different energy band we give the count rate due to the effective (sky+instrumental) background, the fraction $f_{\rm abs}$ of source counts un-absorbed by the galactic column density (assuming $n_H = 2 \cdot 10^{20} {\rm cm}^{-2}$), and the mean effective collecting area $A_{\rm eff}$ in that energy range [6].

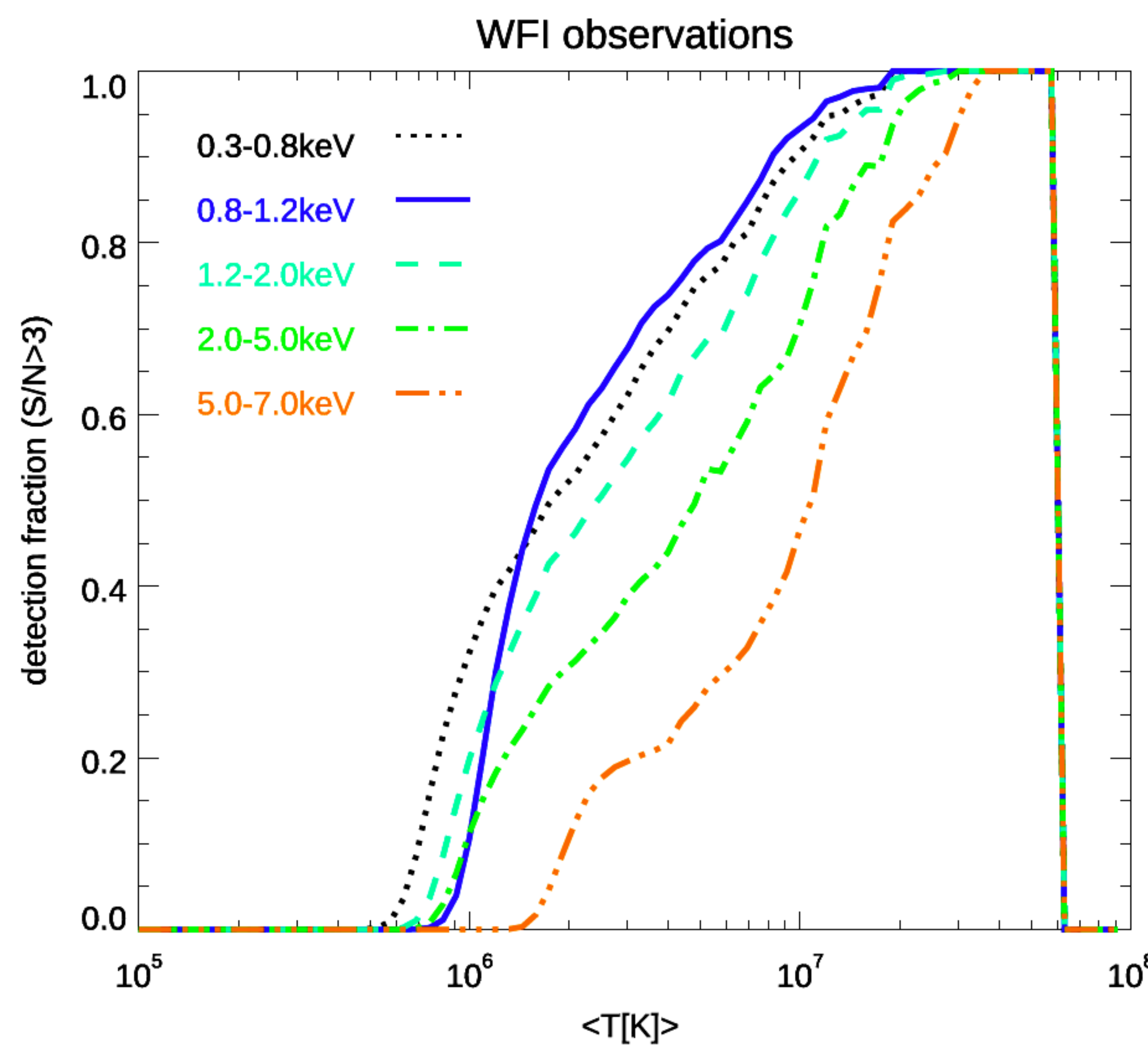
Instrument	Energy Band [keV]	$B_{\rm bg}$ $\frac{\rm counts}{\rm arcmin^2 Msec}$	$f_{\rm abs}$	$A_{\rm eff}$ [cm^2]
Athena-WFI	0.3-0.8	$2.1 \cdot 10^4$	0.83	9511
	0.8-1.2	$3.1 \cdot 10^3$	0.95	12139
	1.2-2.0	$1.4 \cdot 10^3$	0.98	10841
	2.0-5.0	$3.4 \cdot 10^3$	0.99	4673
	5.0-7.0	$2.0 \cdot 10^3$	1.00	2131
eROSITA	0.3-0.8	$2.2 \cdot 10^3$	0.83	610
	0.8-1.2	$4.6 \cdot 10^2$	0.95	1243
	1.2-2.0	$4.2 \cdot 10^2$	0.98	1267
	2.0-5.0	$4.1 \cdot 10^2$	0.99	287
	5.0-7.0	$3.0 \cdot 10^2$	1.00	88
XMM (PN + 2MOS)	0.3-0.8	$4.6 \cdot 10^3$	0.83	1056
	0.8-1.2	$1.4 \cdot 10^3$	0.95	1655
	1.2-2.0	$1.8 \cdot 10^3$	0.98	1894
	2.0-5.0	$3.4 \cdot 10^3$	0.99	1337
	5.0-7.0	$1.7 \cdot 10^3$	1.00	998

Table 2: Assumed values for the radio observing parameters considered in this work: central observing frequency, beam resolution, thermal rms noise per beam and detection threshold considered in our analysis (considering a 3σ detection, also including confusion noise) .

Telescope	Frequency [MHz]	beam ["]	$\sigma_{\rm rms}$ [μJy/beam]	detection thr. [μJy/arcsec^2]
SKA-LOW	260	7.3	4.8	0.24
LOFAR-HBA	120	25	250	1.05
MWA Phase I	200	120	10,000	1.83



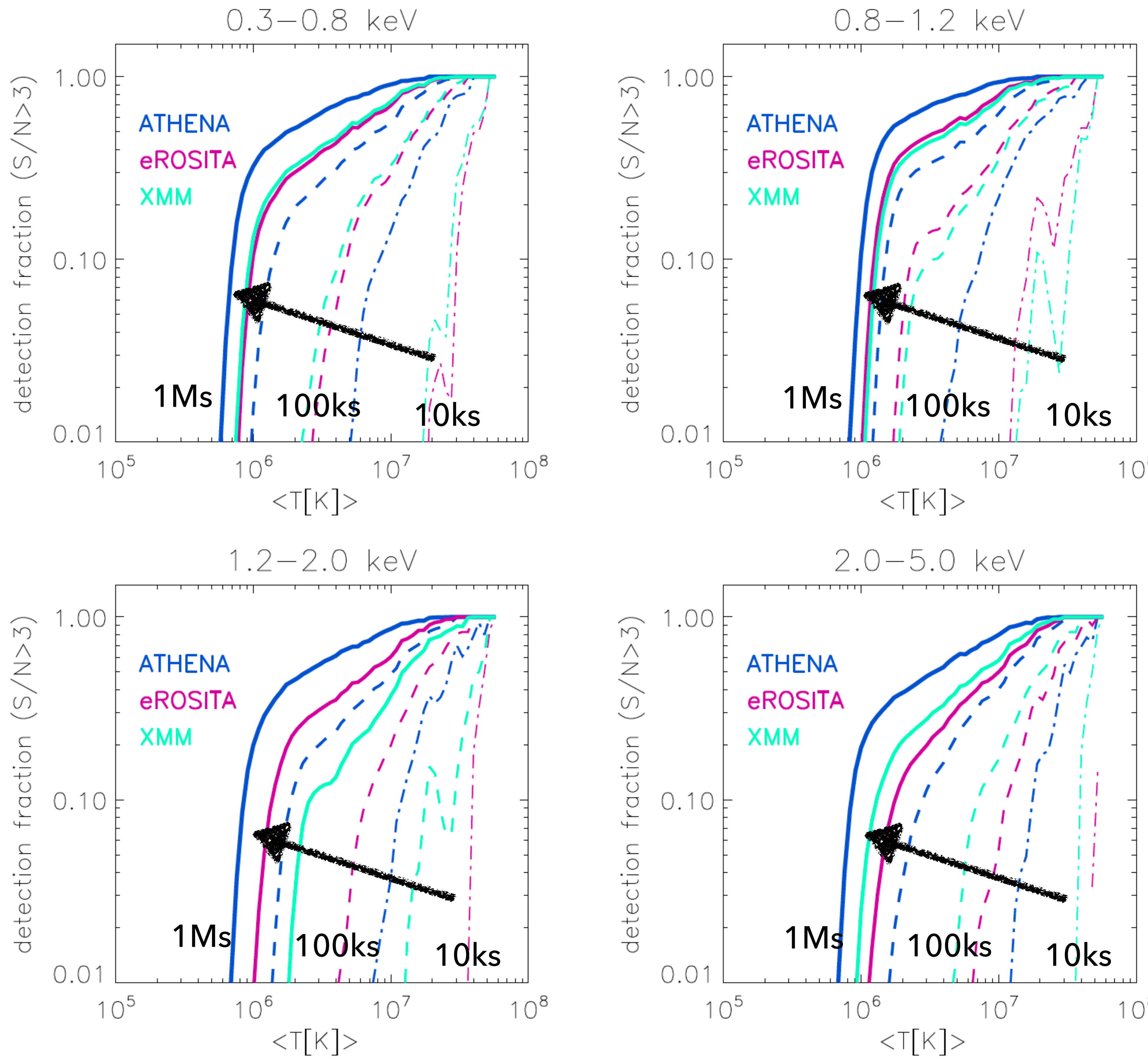
- More photons from the WHIM in the 0.3-0.8keV



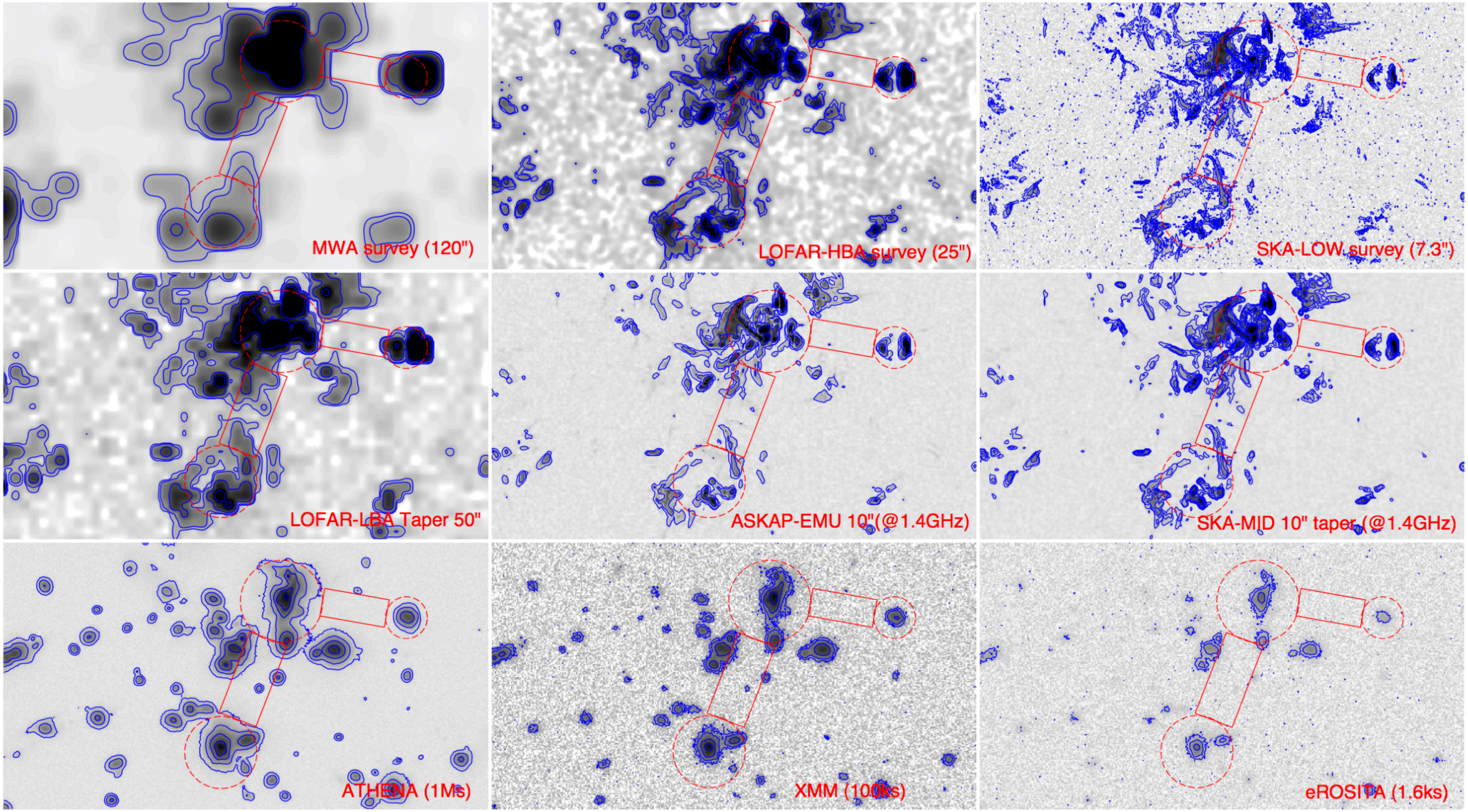
- More chances of detection S/N>3 in the 0.8-1.2keV band

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

PERFORMANCES OF DIFFERENT X-RAY/RADIO INSTRUMENTS

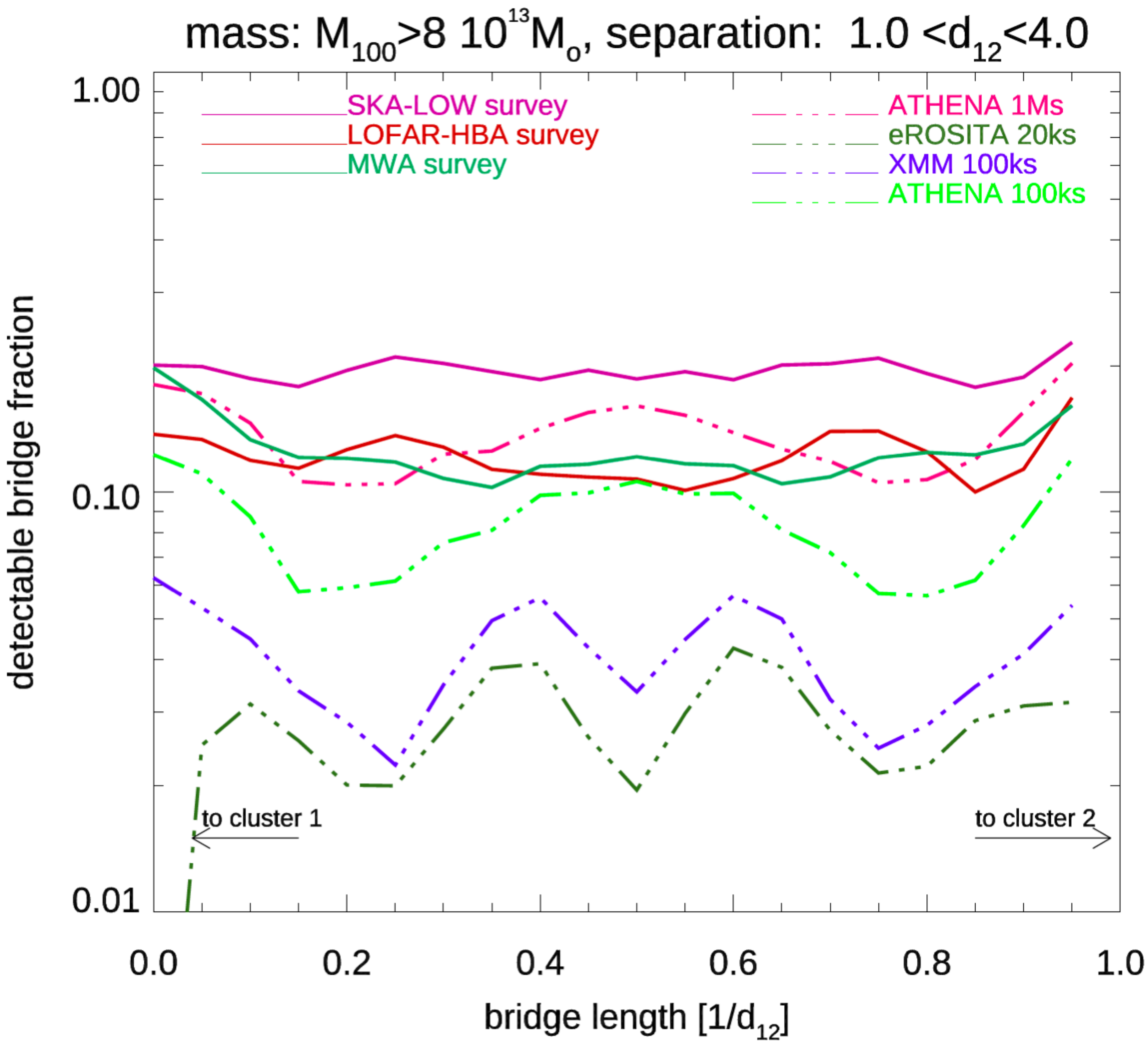


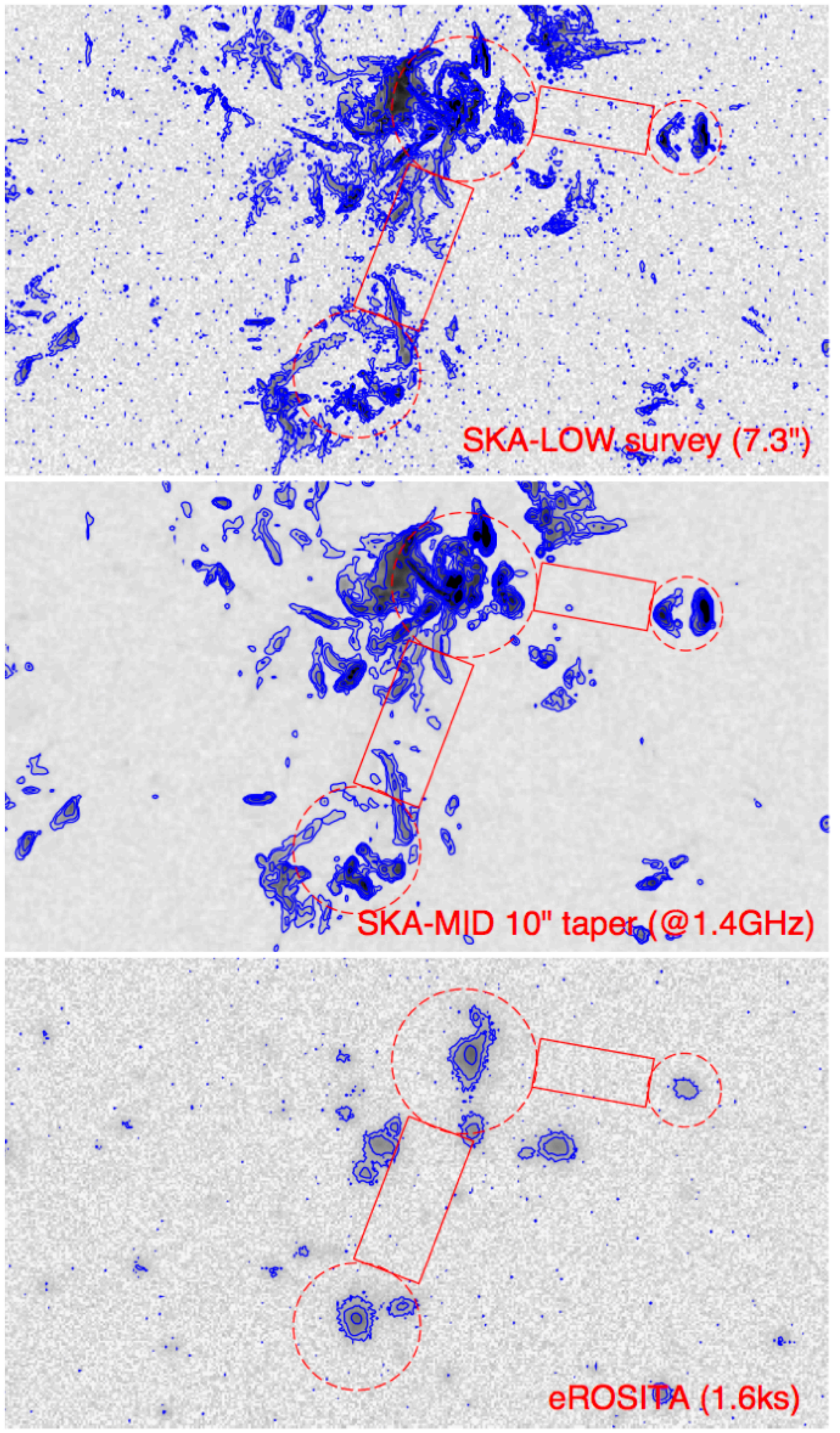
WHERE ARE “DOUBLE DETECTIONS” MORE LIKELY?



STATISTICS OF ~50 PAIRS OF PRE-MERGING CLUSTERS
5′ THICK BRIDGES CONNECTING CLUSTERS OUTSIDE THEIR R100

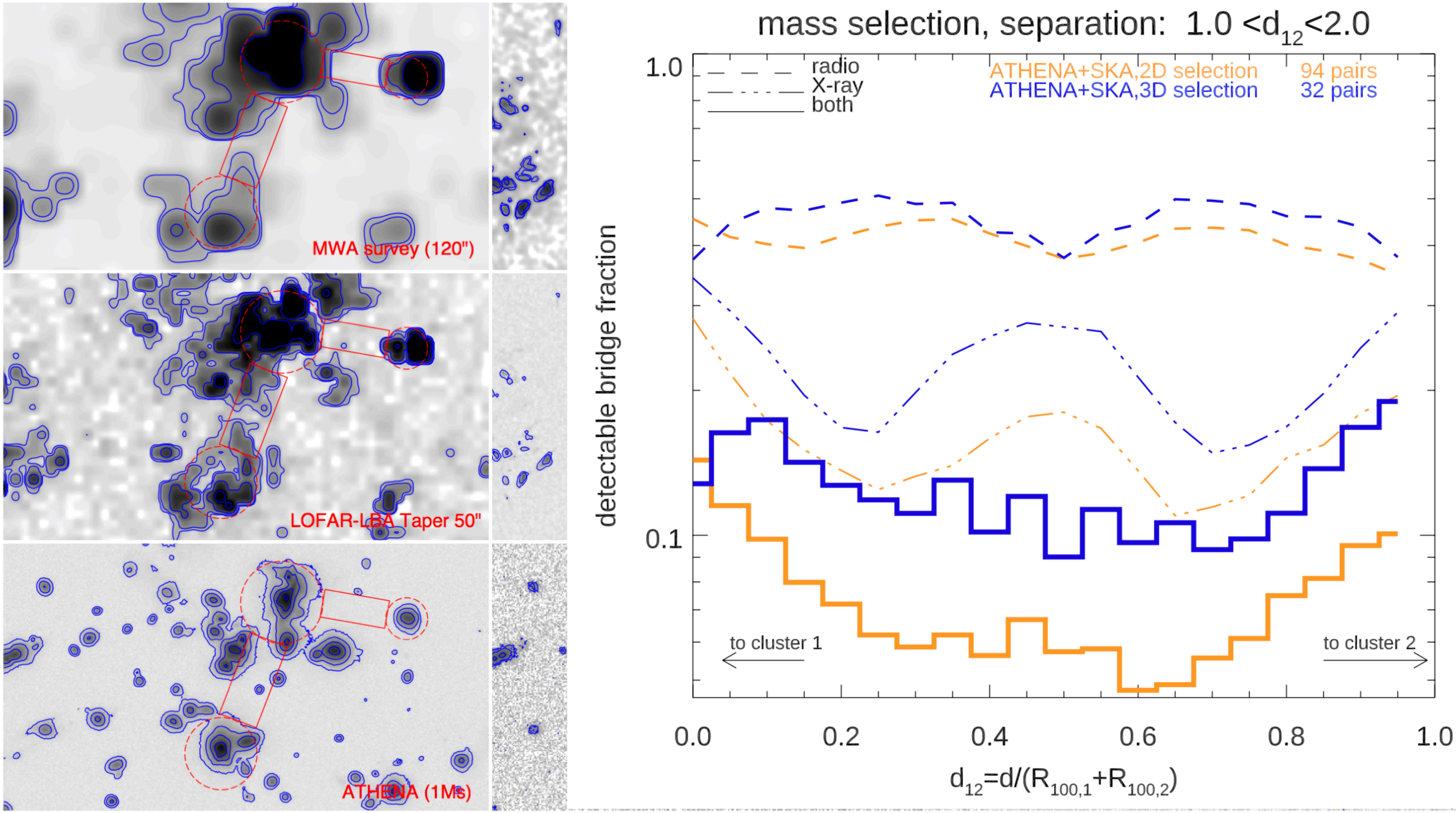
WHERE ARE "DOUBLE DETECTIONS" MORE LIKELY?





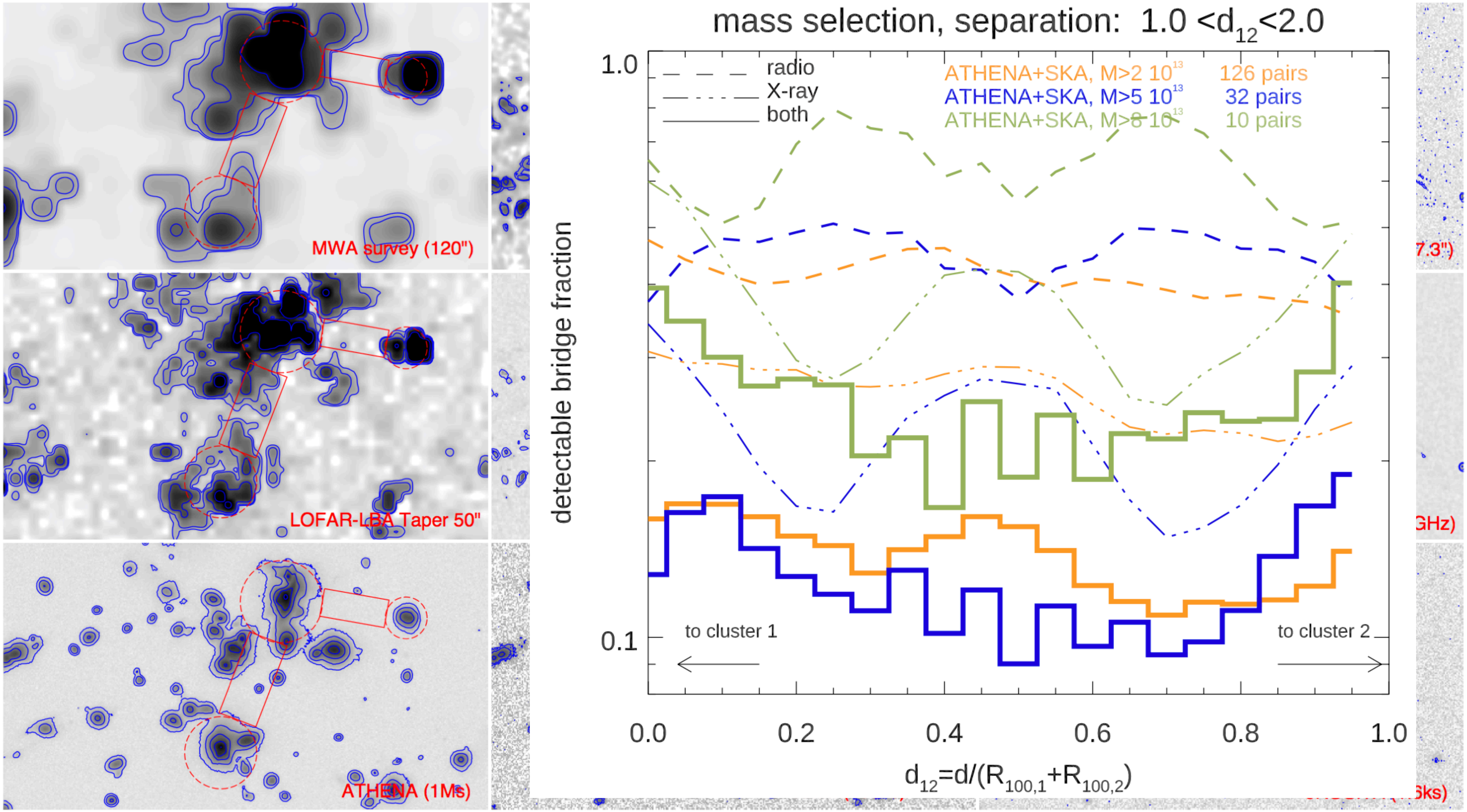
~10-30% OF BRIDGE SURFACE DETECTABLE AT LOW FREQ.
ATHENA (1MS TO 100KS) SHOULD YIED ~10-20% DETECTION

WHERE ARE “DOUBLE DETECTIONS” MORE LIKELY?



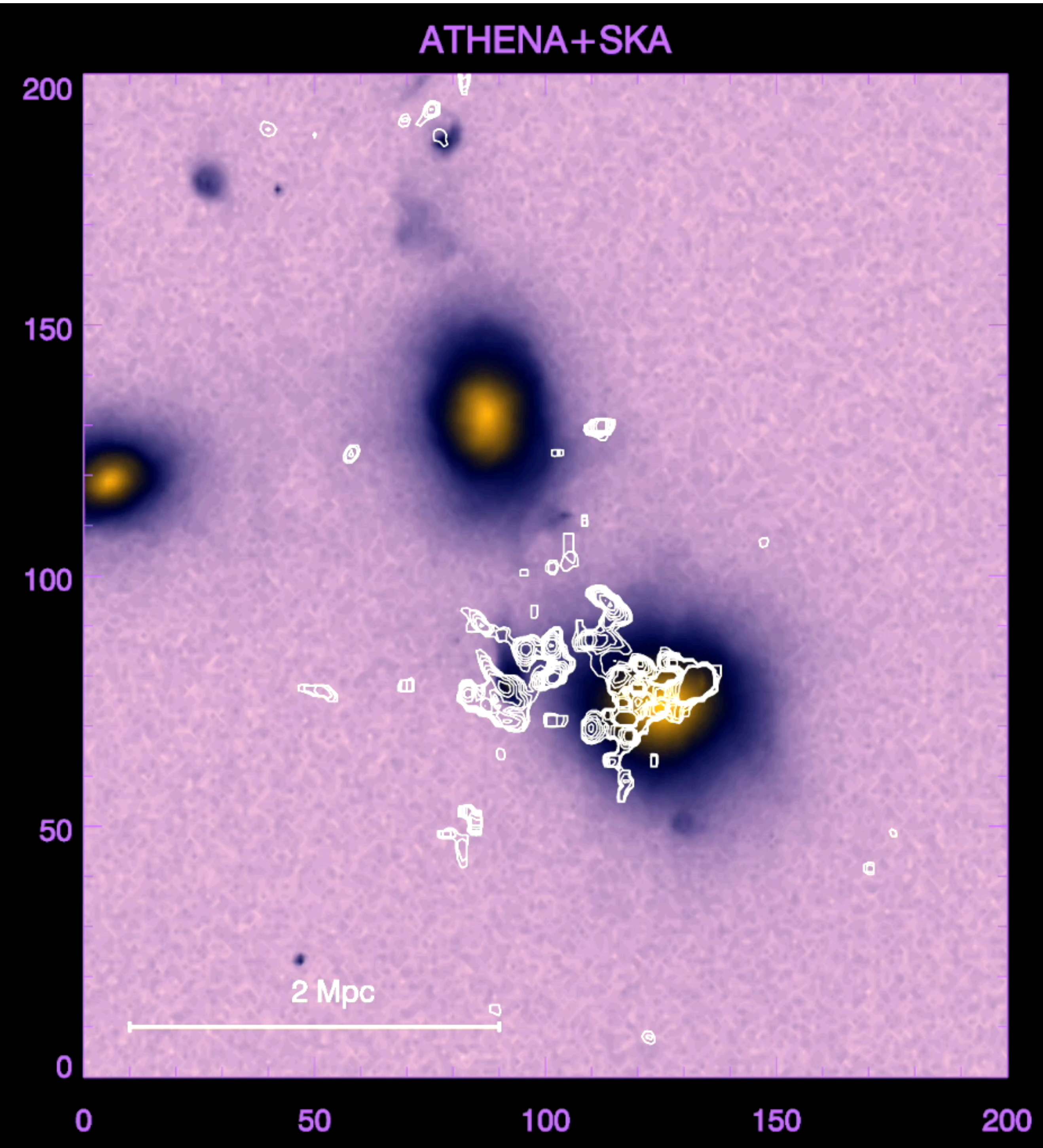
DOUBLE DETECTIONS INCREASE BY SELECTING PHYSICALLY ASSOCIATED SYSTEMS

WHERE ARE "DOUBLE DETECTIONS" MORE LIKELY?



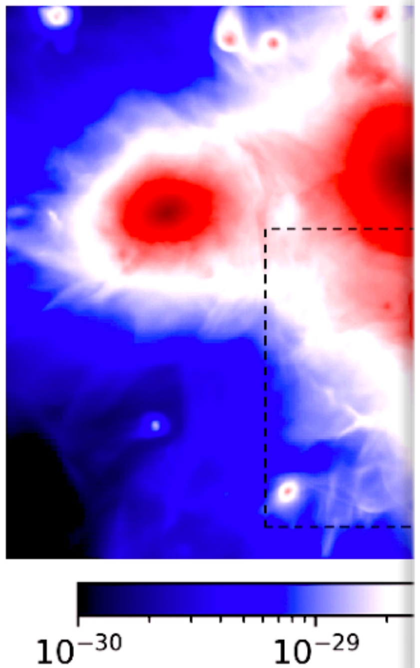
DOUBLE DETECTIONS INCREASE BY SELECTING MORE MASSIVE INTERACTING SYSTEMS

A PILOT STUDY WITH SIXTE: ENOUGH PHOTONS FOR SCIENCE WITH XIFU?



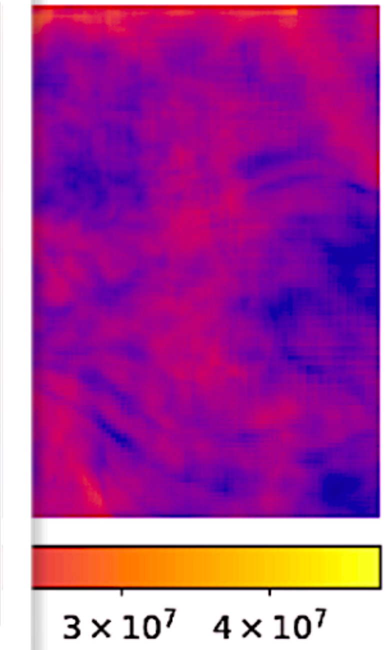
z=0.1 snapshot, ATHENA & SKA-LOW mock observation

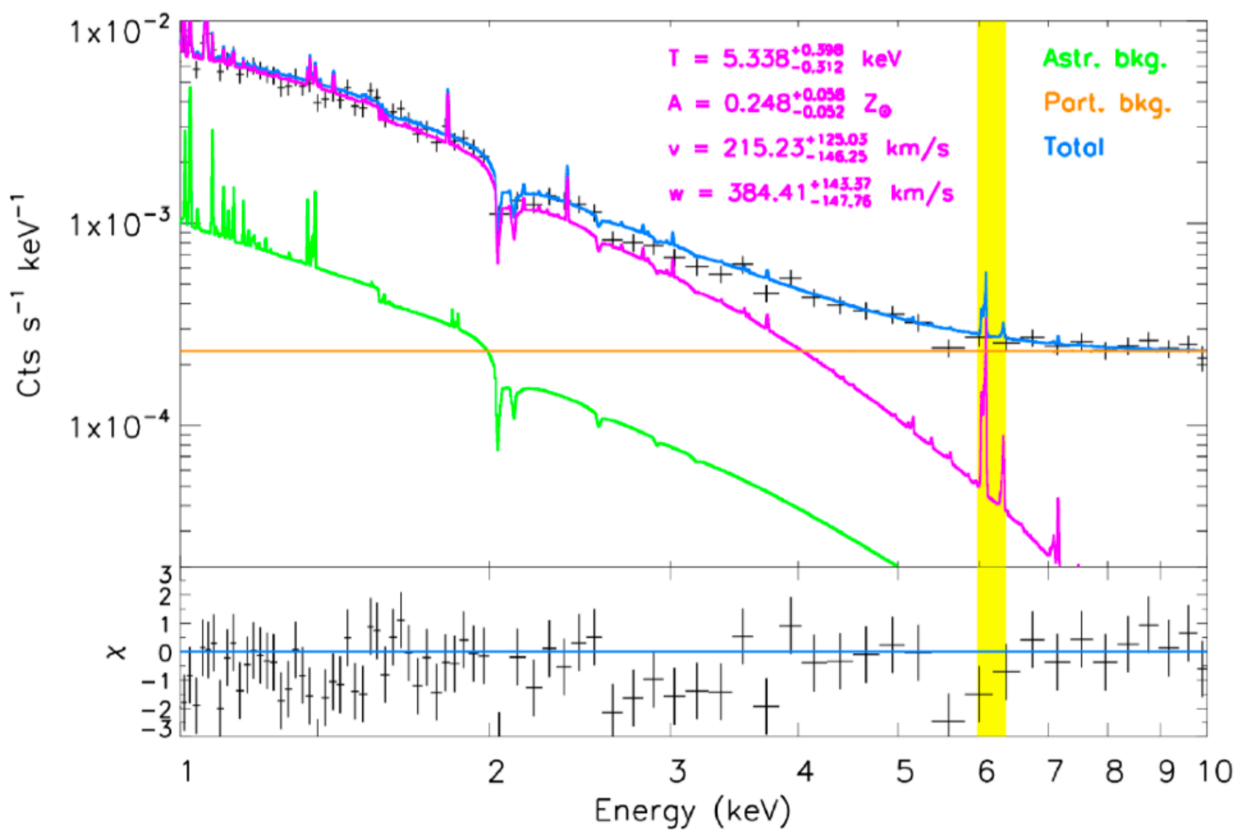
A PILOT STUDY WITH SIXTE: A MOCK XIFU OBSERVATION

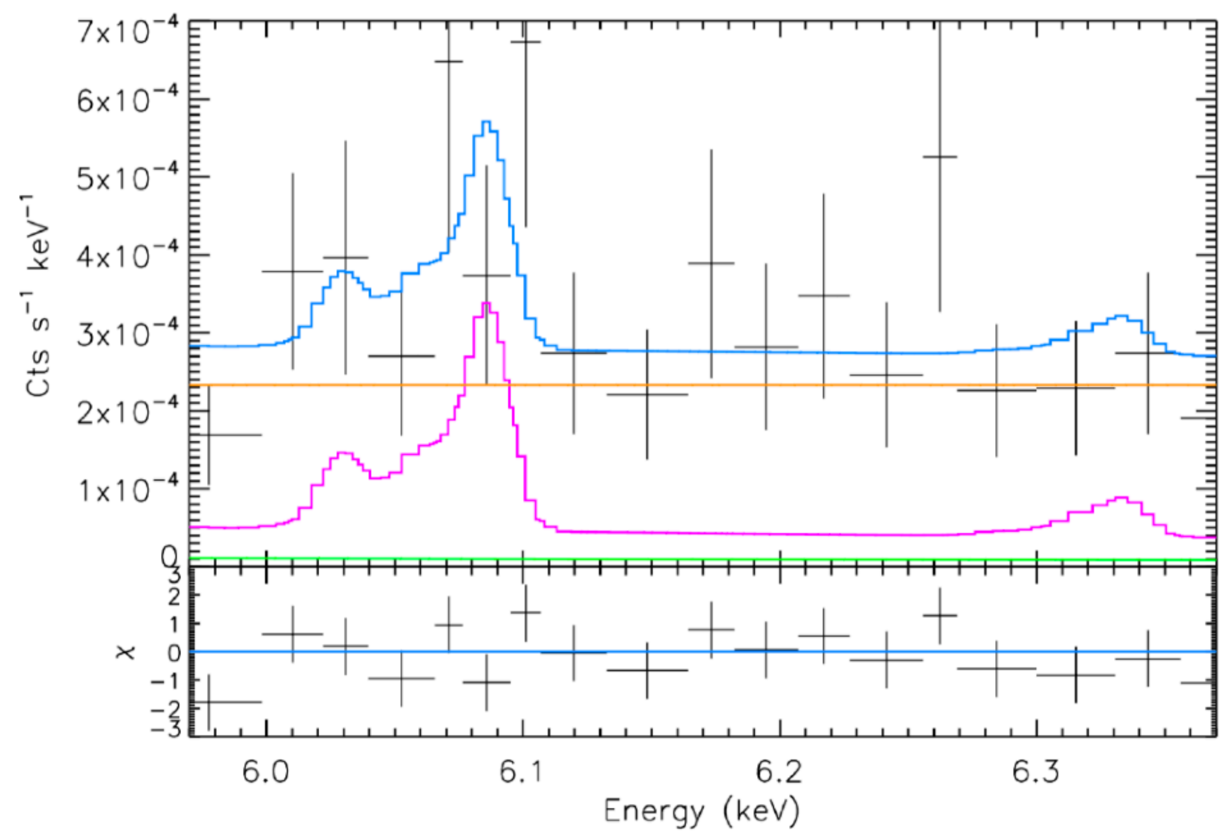


Field	Input (sim)	Output (X-IFU)
T [keV]	5.52	5.33 ± [-0.31, 0.40]
v	65	215 ± [-146, 123]
w	465	384 ± [-148, 144]
A [$1/Z_\odot$]	0.20	0.25 ± [-0.05, 0.06]

cm s^{-1}

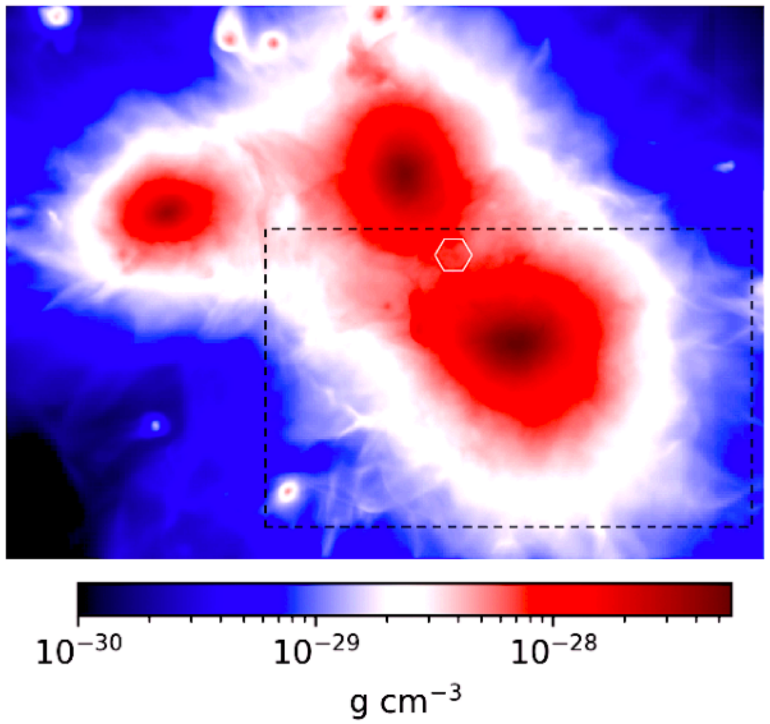


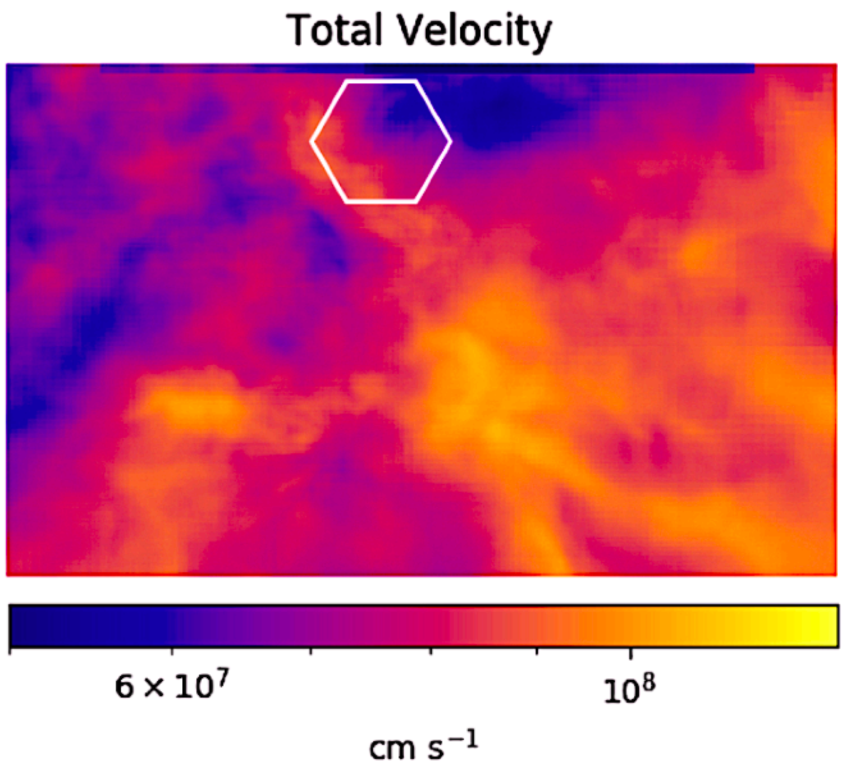


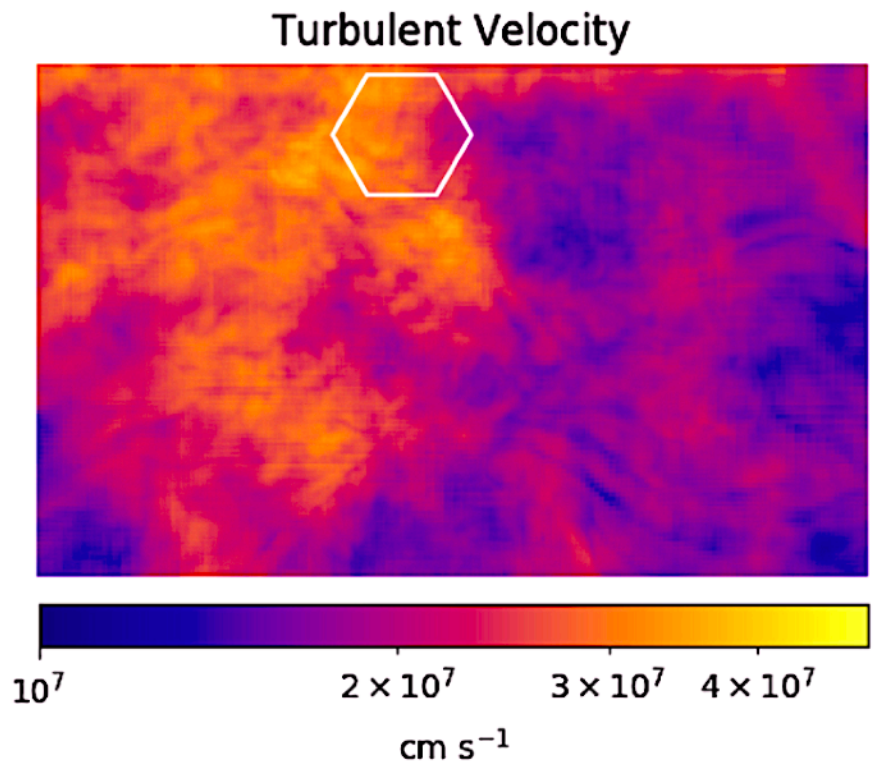


SIXTE simulation of a 1Ms integration

A NEW WAY OF MEASURING SHOCK MACH NUMBERS?







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

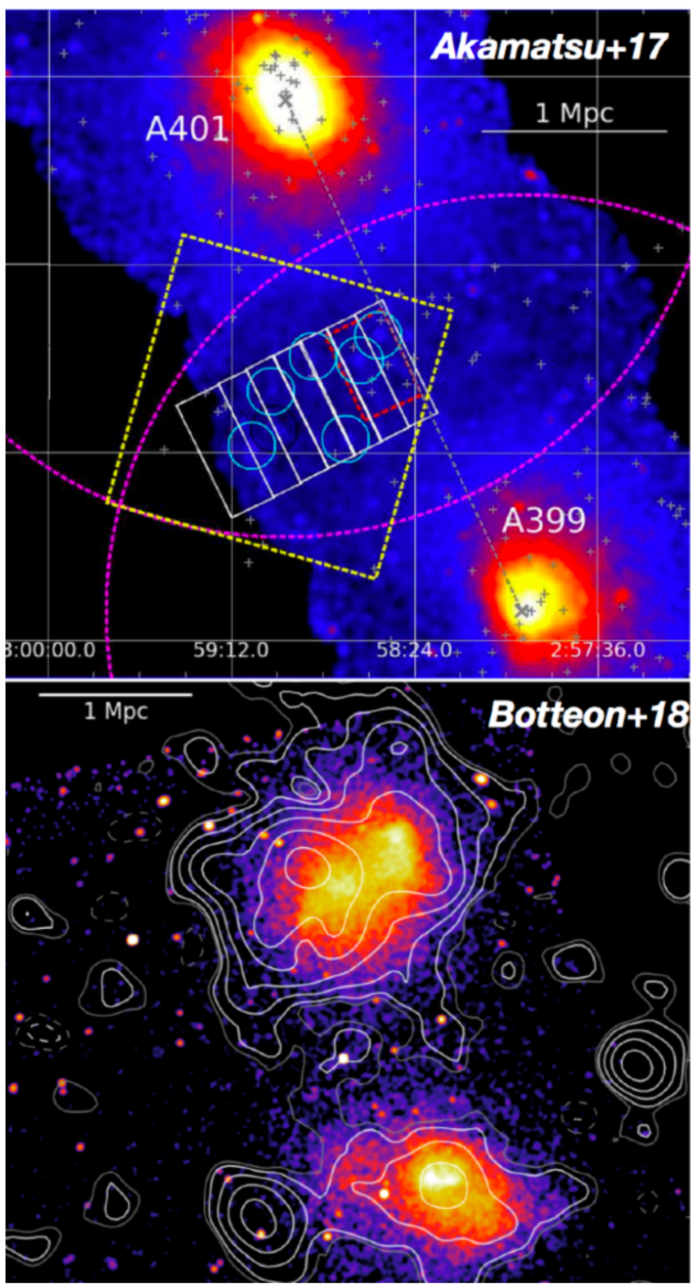
"Velocity Jump": $$\mathcal{M}_{spec} = \frac{2}{3}\left(\frac{\sigma_v}{c_s} + \sqrt{\frac{4\sigma_v}{c_s} + 9}\right)$$

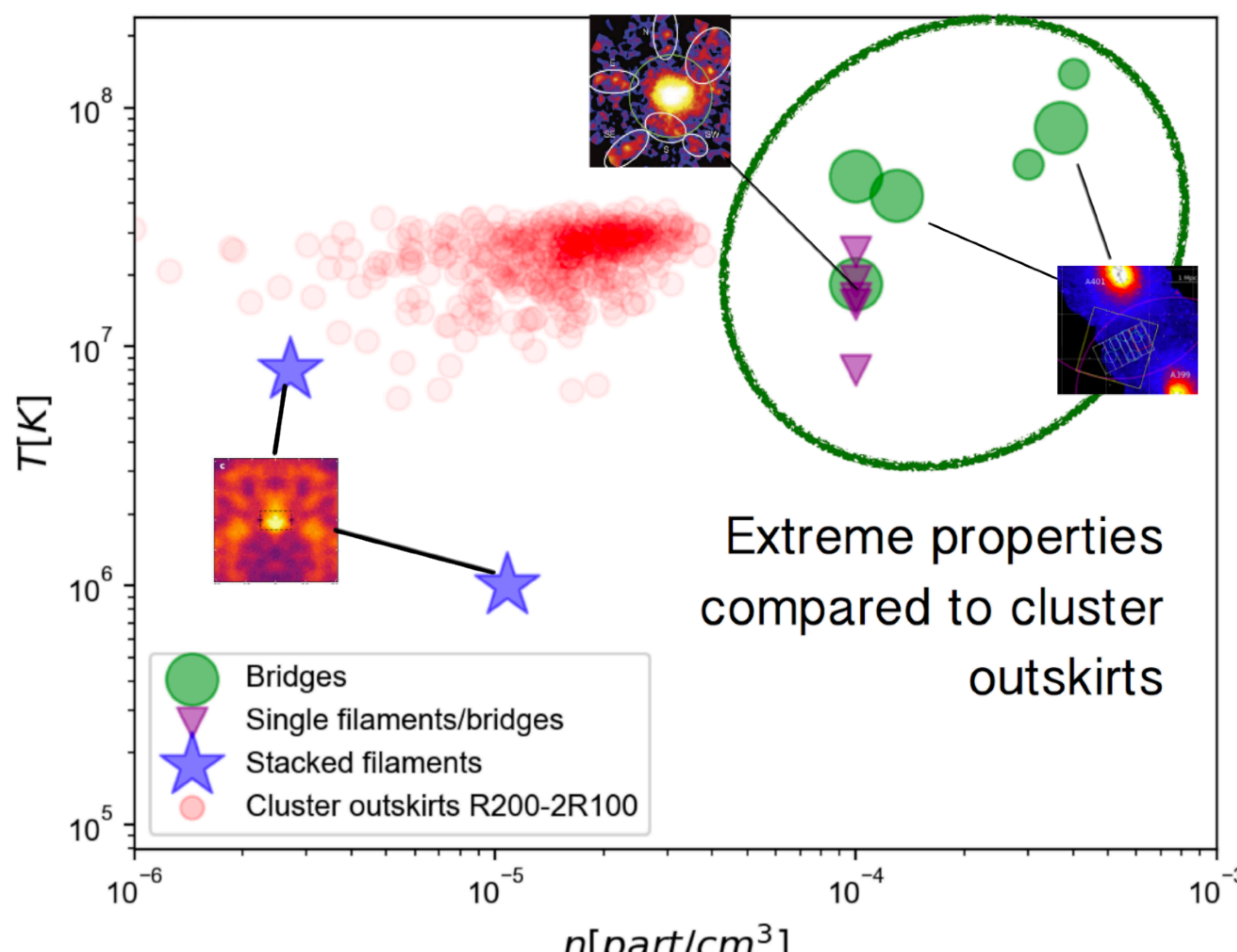
$$\mathcal{M}_{spec} \approx 2.3 \sim \mathcal{M}_{3D} = 2.5 - 3$$

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

IS THIS WHIM? I'D SAY IT IS A "BOOSTED WHIM"

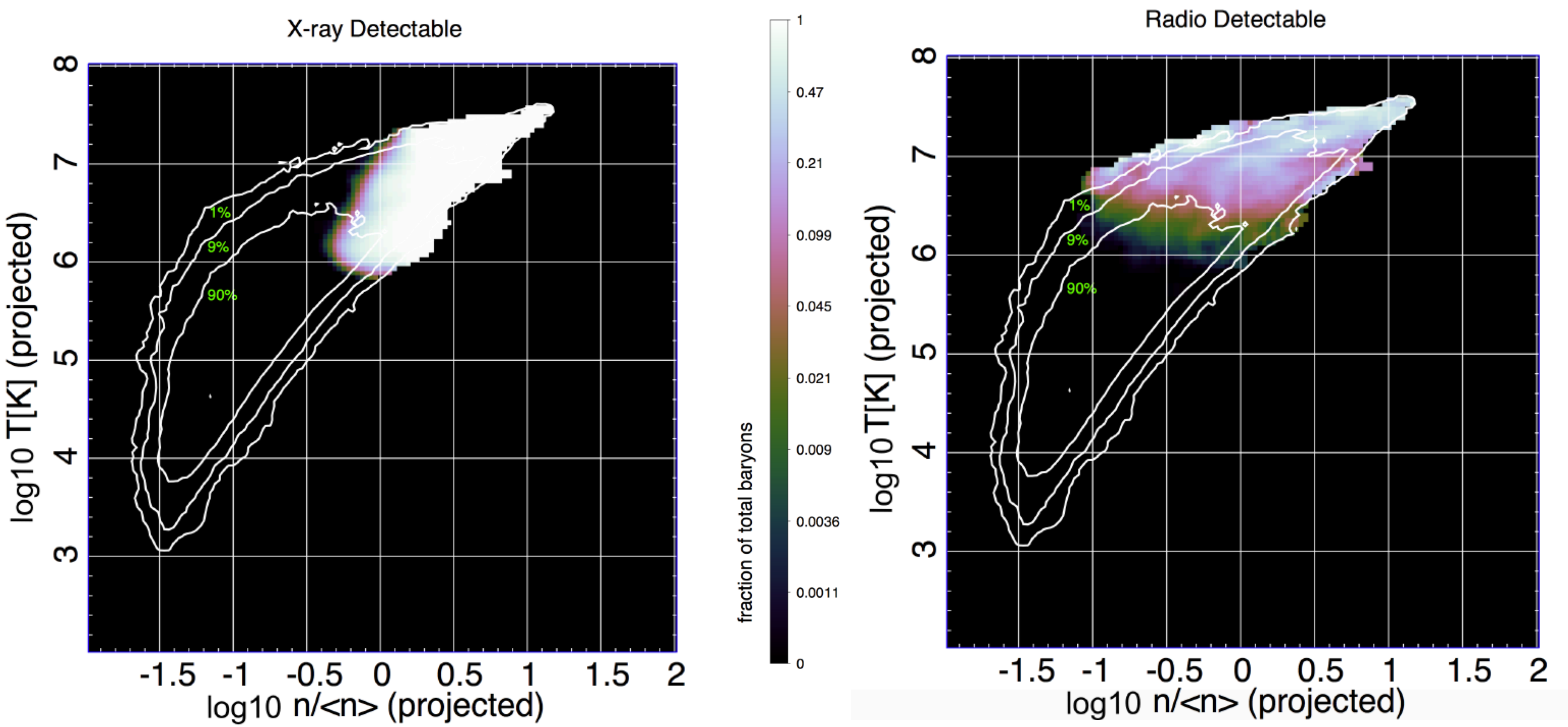
- standard WHIM gas that used to be in filaments ~1-2Gyr ago. Now squeezed and compressed.
- X-ray emission boosted as $L_{WHIM,boost} \sim L_{\mathrm{WHIM}} \cdot (\frac{\rho_2}{\rho_1})^{11/4}$
- transonic regime, short dynamical time, volume filling M<4 shocks, uncertain composition





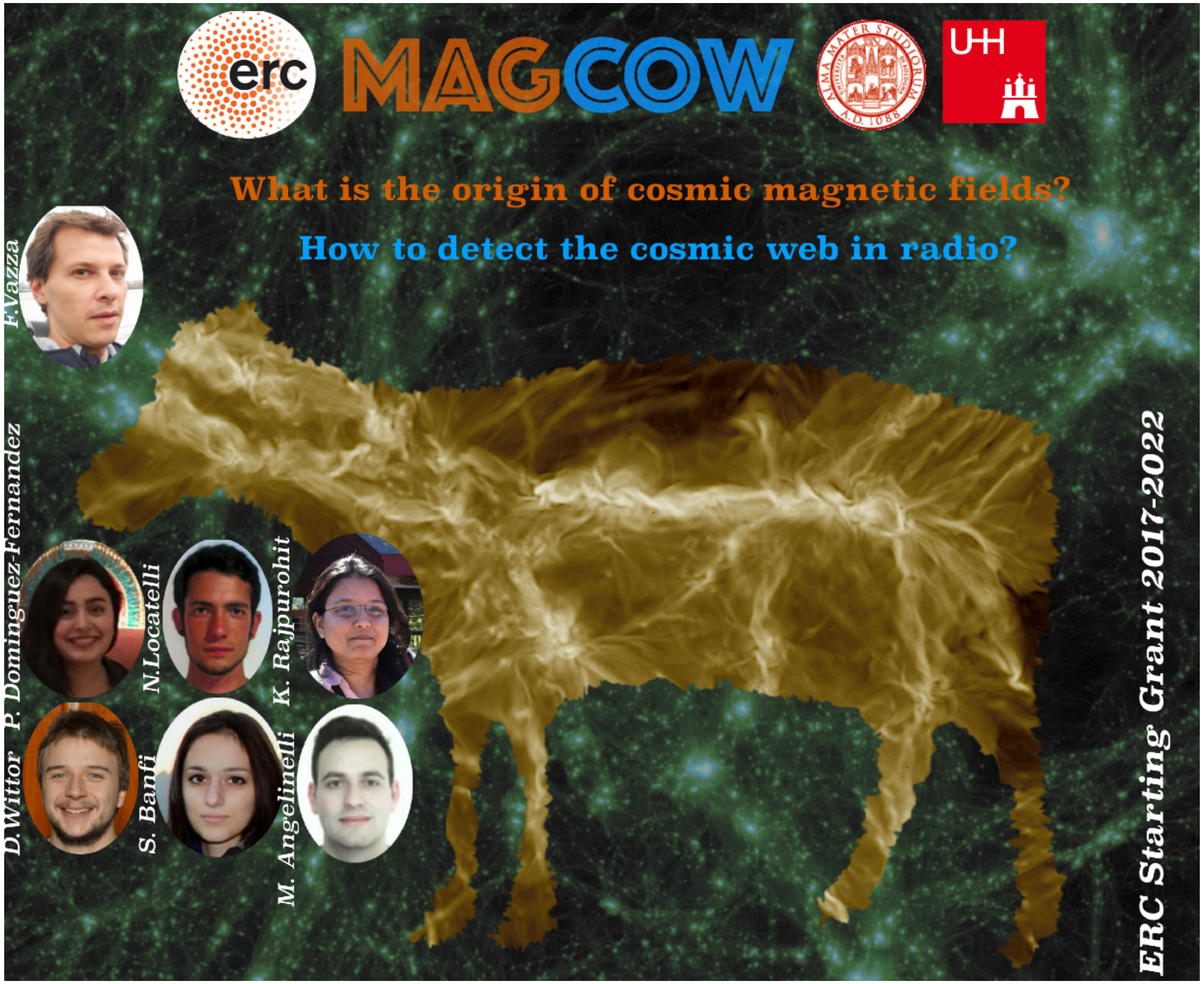
ARE RADIO DETECTIONS USEFUL FOR MISSING BARYON STUDIES?

- X-ray obs. can detect most of the hot plasma in clusters. This only is where ~10% of baryons are.
- Radio obs. can only detect a fraction (shock filling factors) of baryons. But even in the phase which contributes to ~90% of the baryon budget.



SUMMARY

- Detecting the WHIM is crucial to investigate missing baryons and cosmic magnetism
- Low freq.radio observations should detect more WHIM than X-ray obs.
- Small overlap between X-ray and radio (ATHENA+SKA or precursors) will allow new lines of research.
- The "boosted WHIM" in cluster-cluster bridges is a new environment to explore.



- Thanks