

Search for Radio Emission from Cosmic Filaments with LOFAR

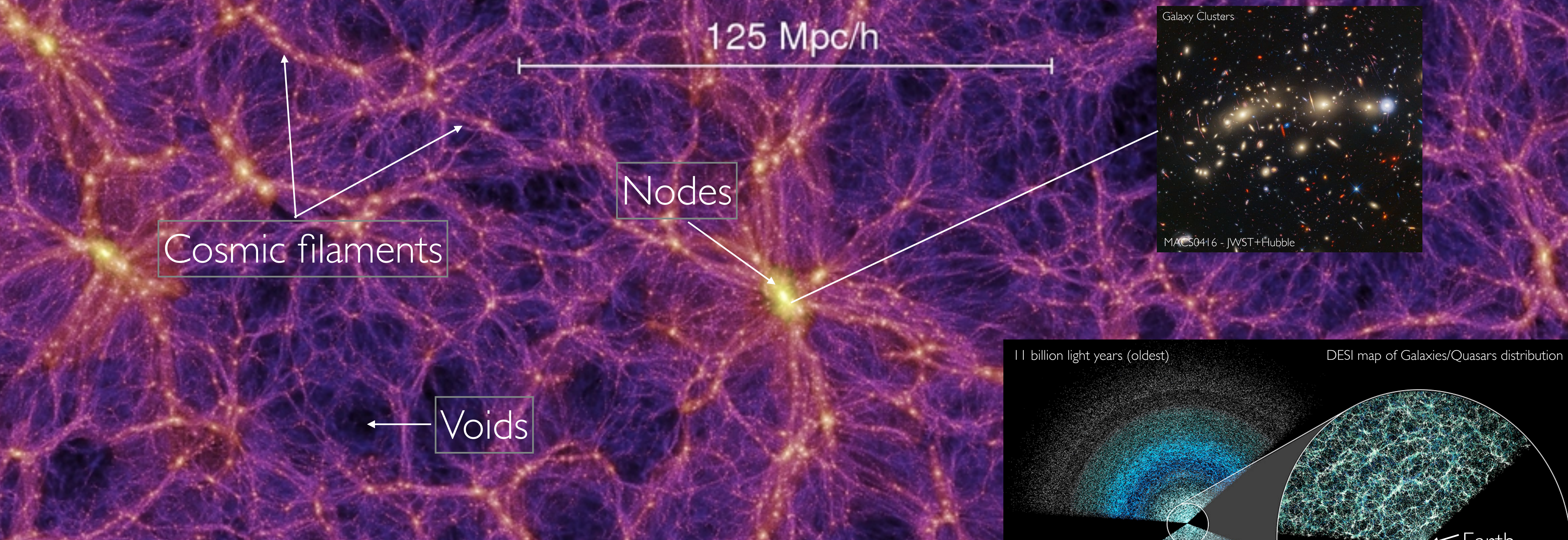
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Millennium Simulation Project

Springel et al. (2005)

Projected density field at $z = 0$

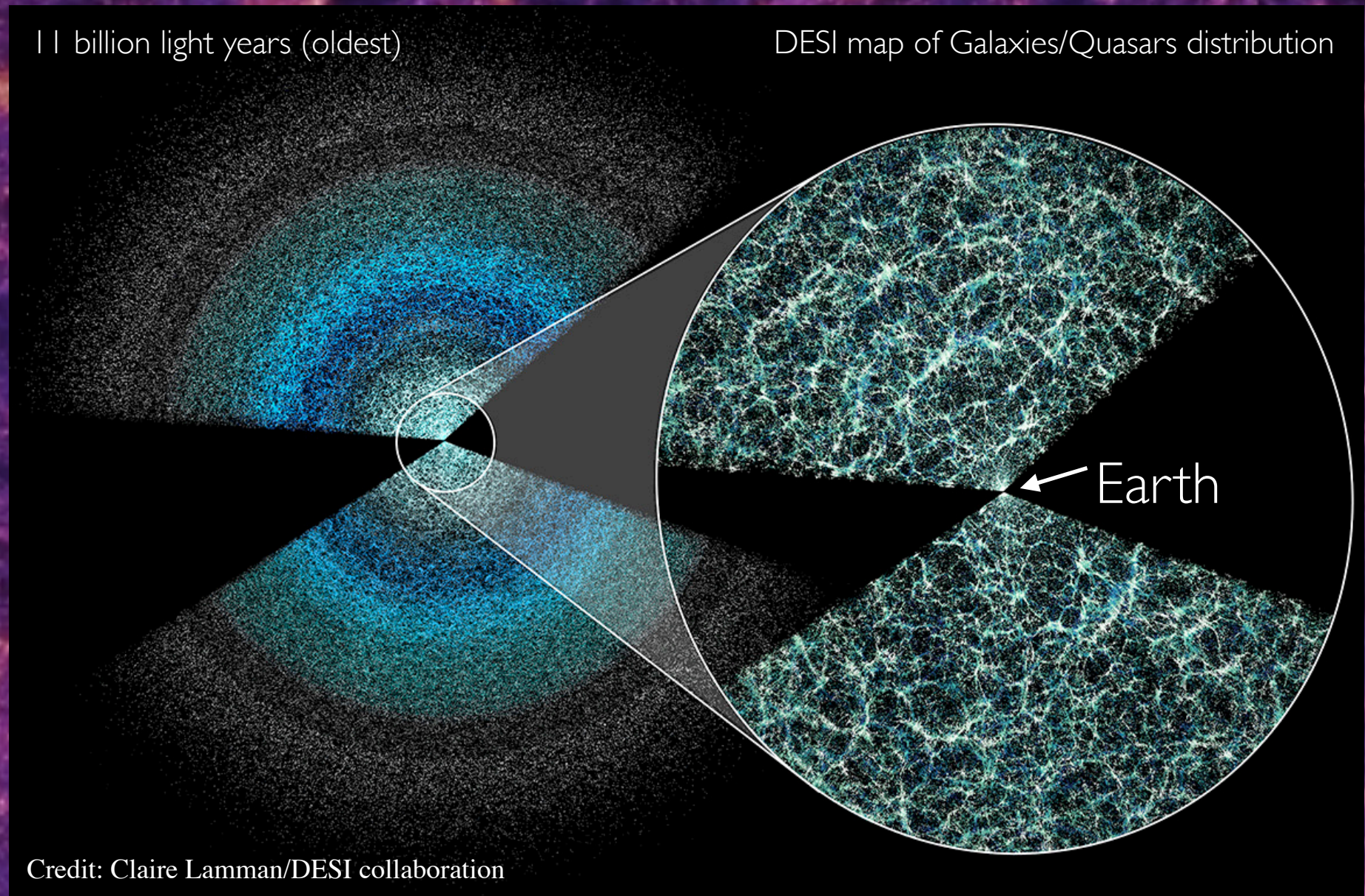


Filaments (WHIM):

- $n_e \approx 10^{-5} - 10^{-7} \text{ cm}^{-3}$
- $T \approx 10^5 - 10^7 \text{ K}$
- 30 – 40 % of missing baryons

Galaxy Clusters:

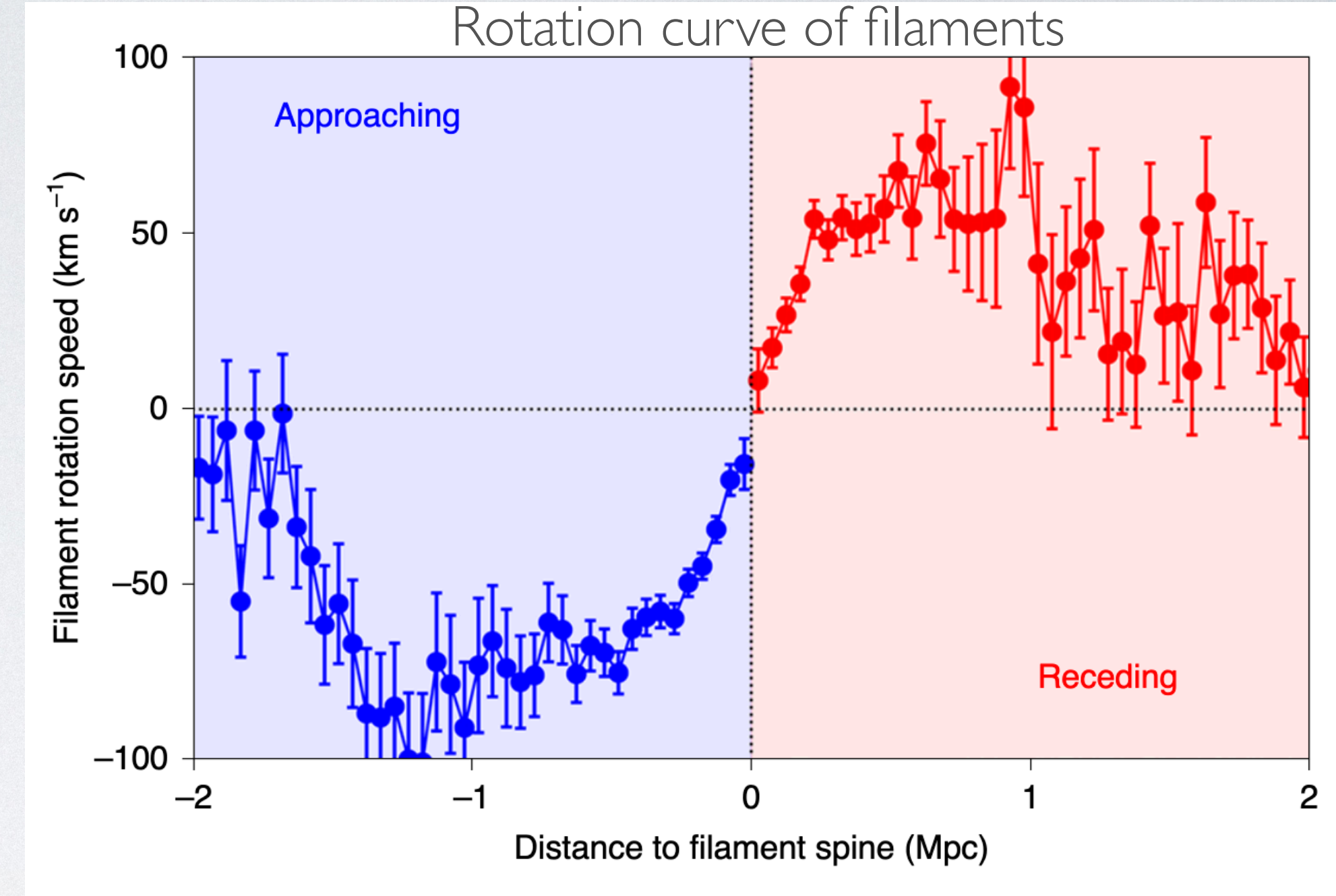
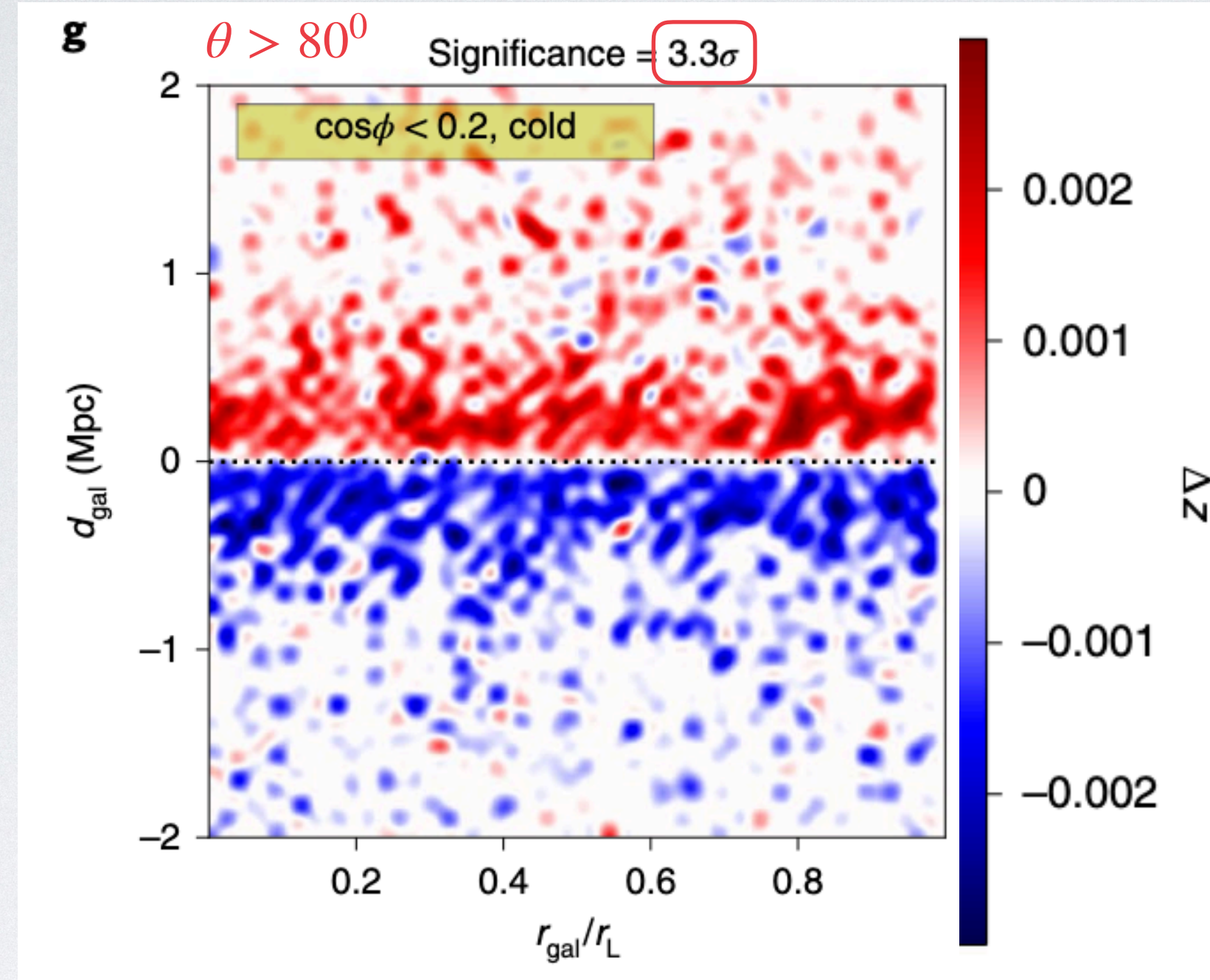
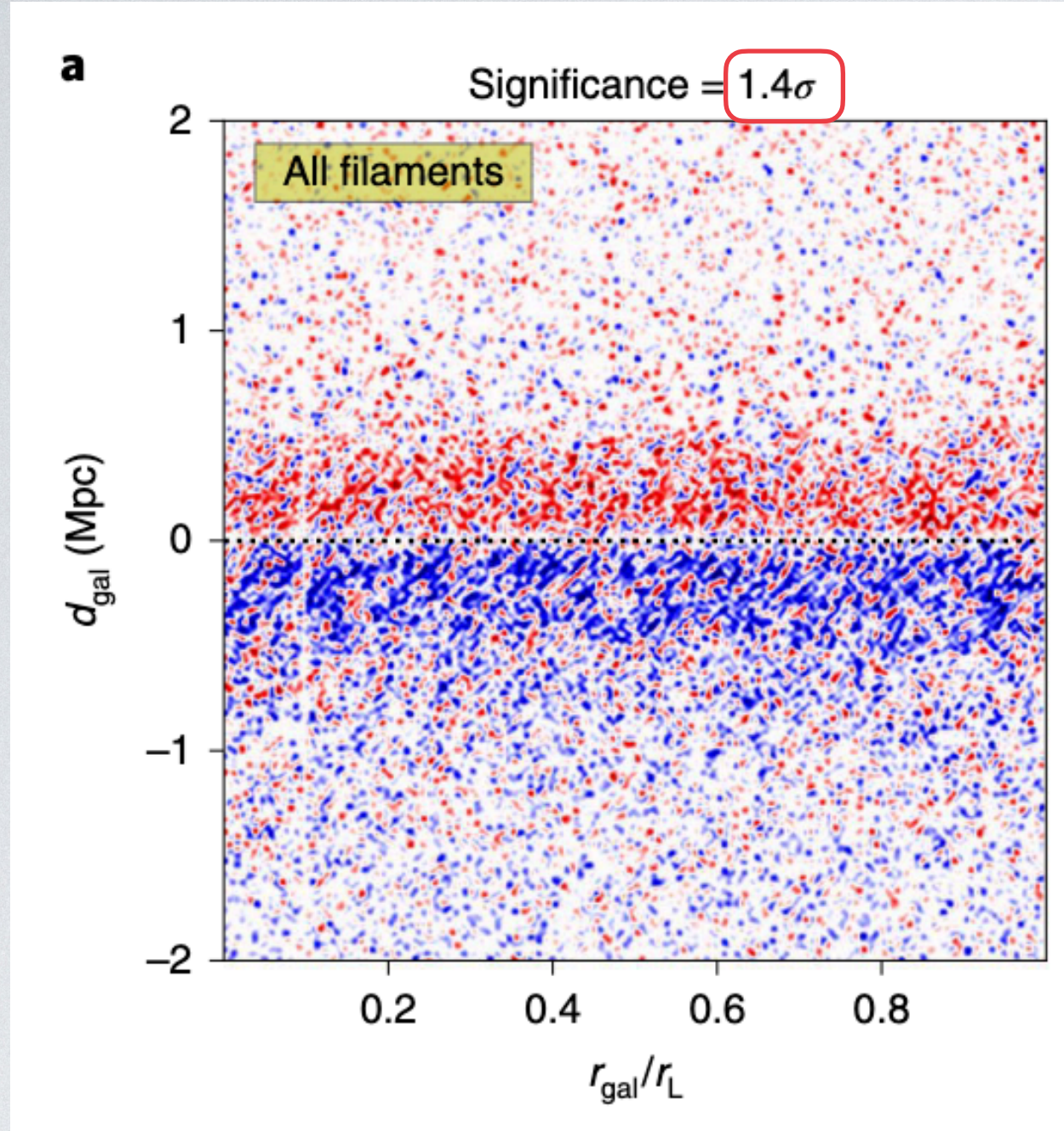
- $n_e \approx 10^{-3} - 10^{-4} \text{ cm}^{-3}$
- $T \approx 10^7 - 10^8 \text{ K}$



Credit: Claire Lamman/DESI collaboration

Credit: NASA

Cosmic Filament Rotation



Wang+21

- Stacking of $\sim 17k$ filaments which consists of more than 3 galaxies per each filaments with SDSS DR12 data.
- The detection is more significant for **dynamically cold** ($\frac{z_{\text{rms}}}{\Delta z_{\text{AB}}} < 1$) filaments with a **viewing angle** larger than 80° ($\cos(\phi) < 0.2$).
- Max speed of $\sim 100 \text{ km s}^{-1}$ at distance of $\sim 1 \text{ Mpc}$ from the spine.
- Filament width: $\sim 3 - 4 \text{ Mpc}$.

How To Locate Cosmic Filaments?

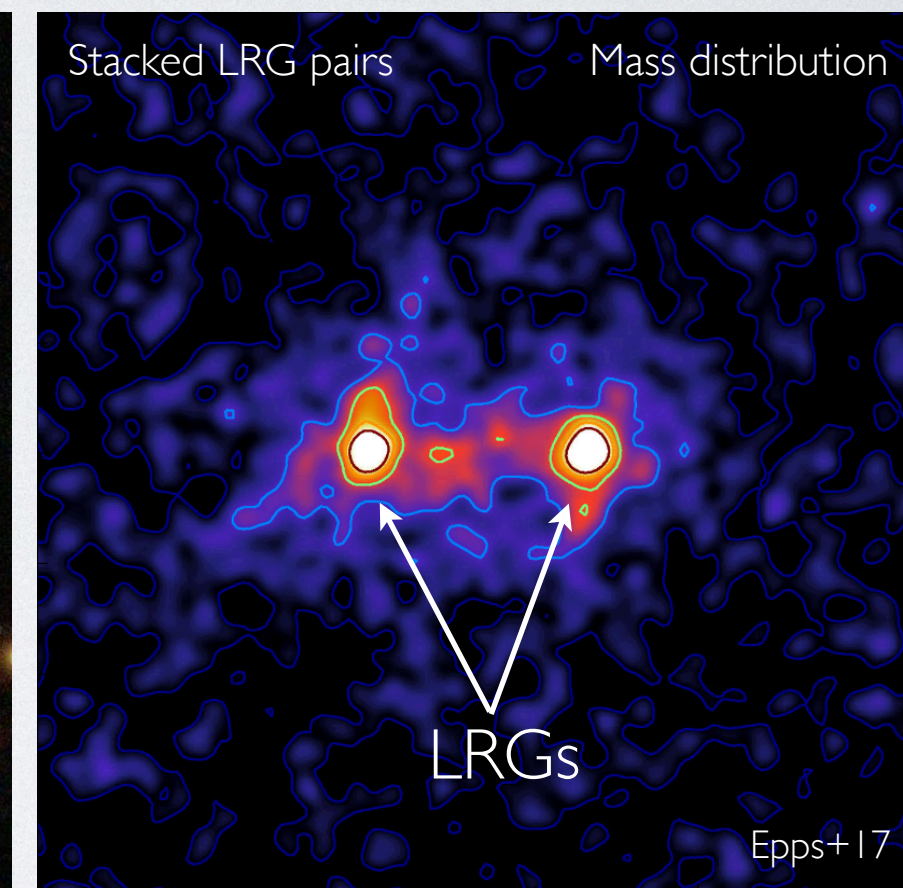
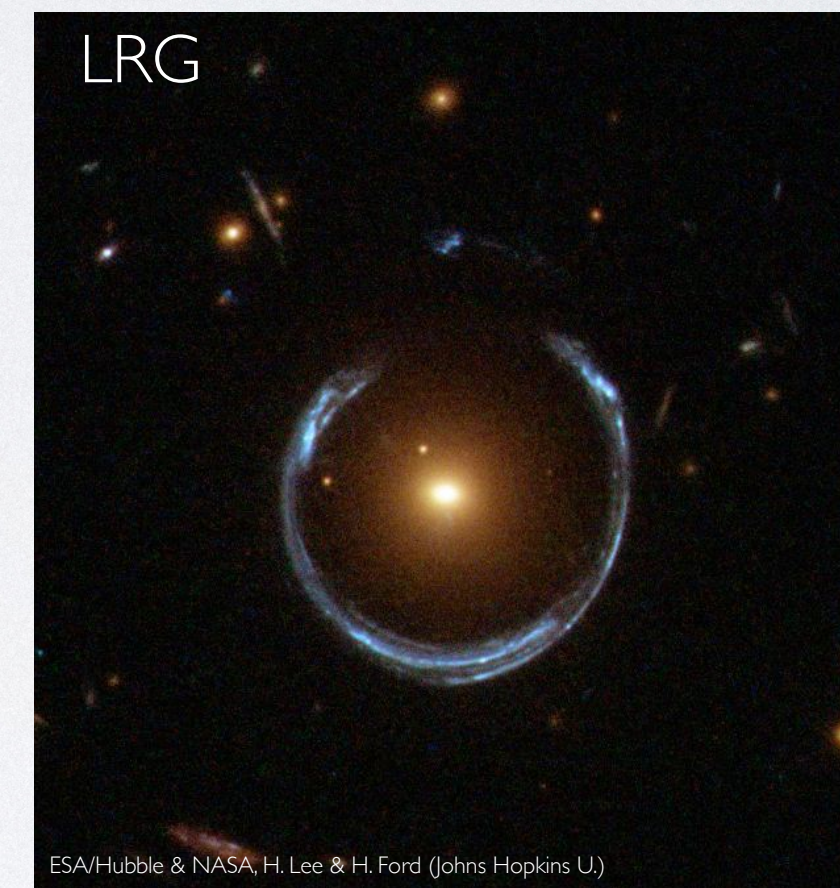
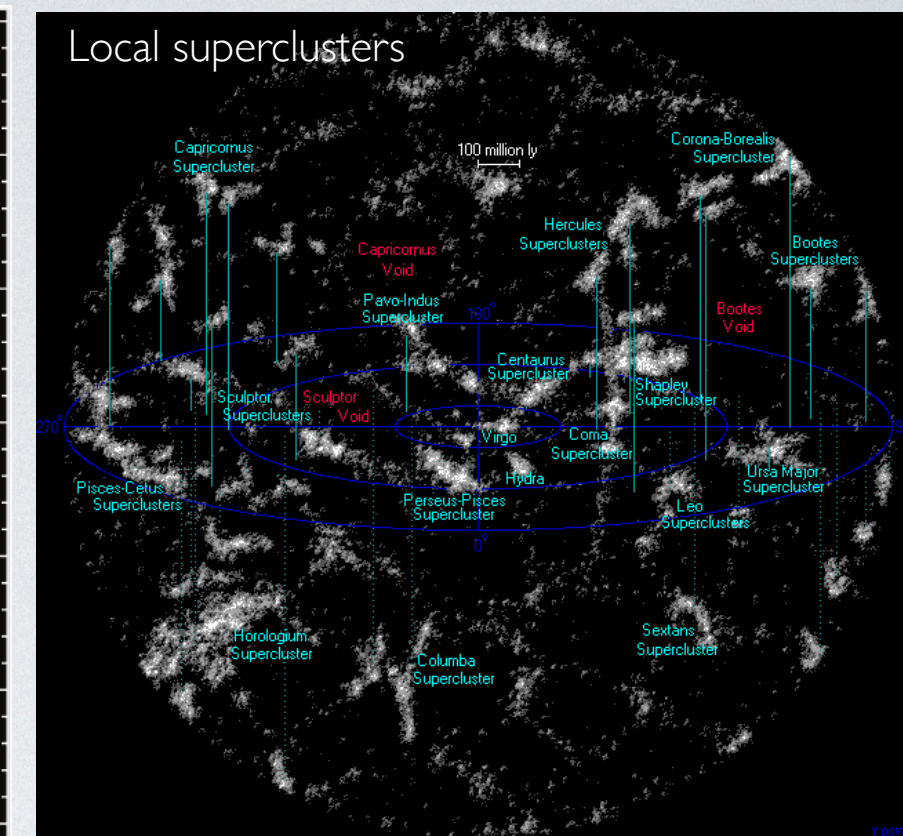
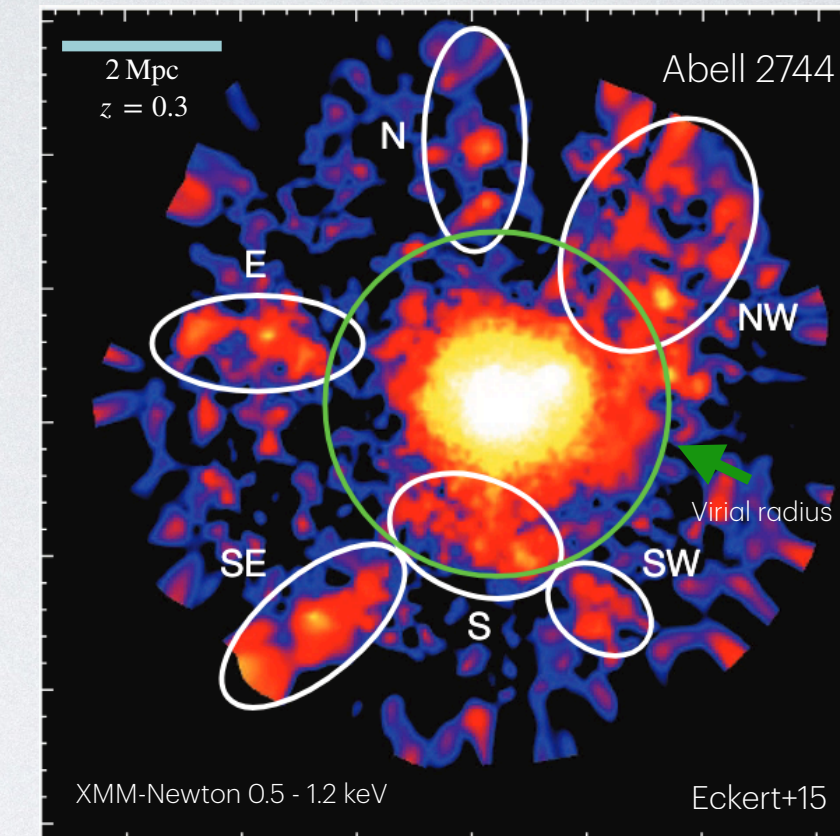
- ◎ Deep observations of **massive clusters beyond virial radius**
- ◎ **Inter-cluster regions** in superclusters which consists of more than 2 clusters/groups of galaxies.

→ Inter-cluster regions trace cosmic filaments

- ◎ **Luminous Red Galaxy (LRG) pairs**

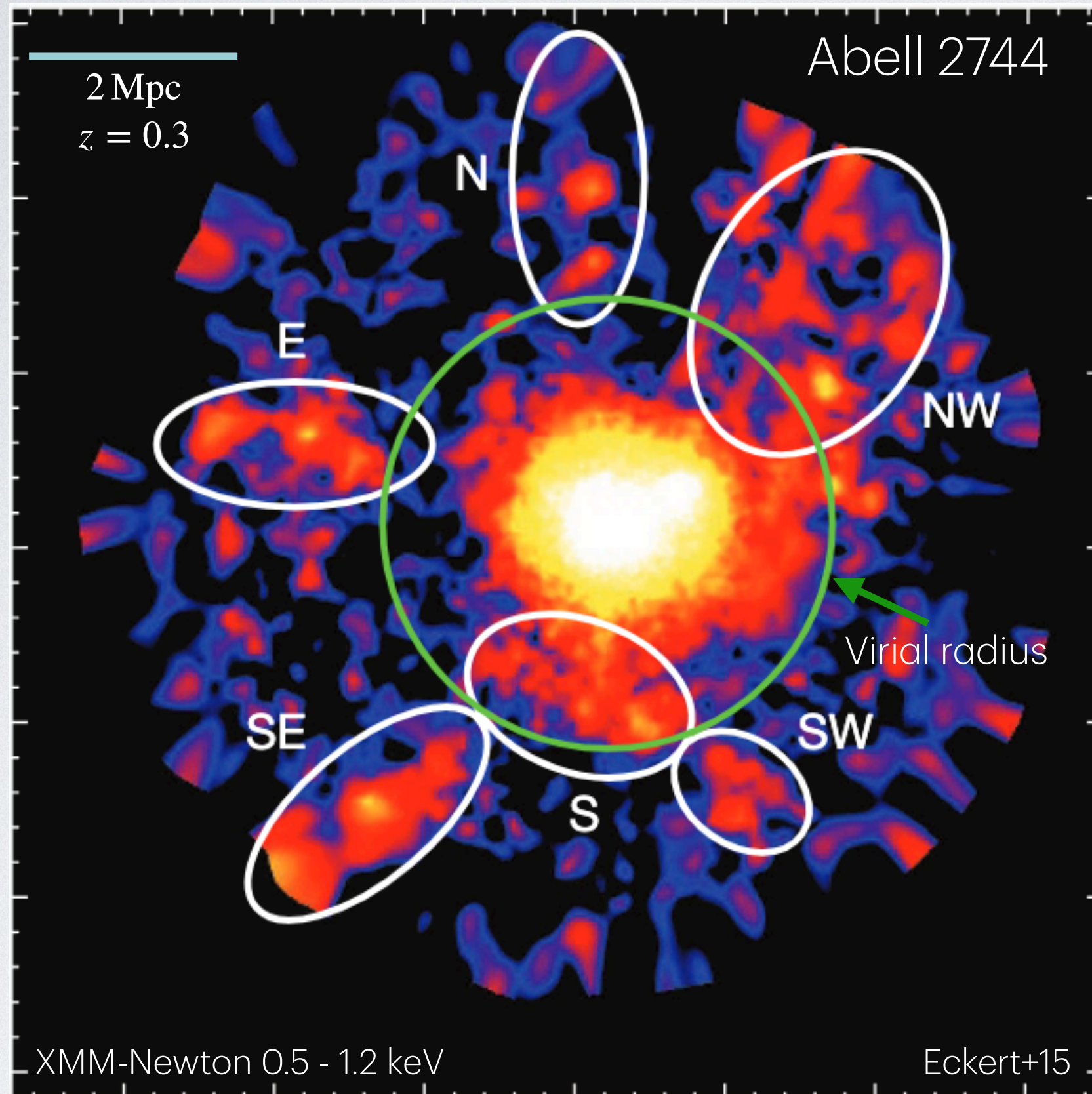
- LRG is typically giant, bright elliptical galaxies.
- Massive ($\gtrsim 10^{11} M_{\odot}$) galaxies with oldest stars and located at dark matter halos.

→ LRG pairs trace cosmic filaments



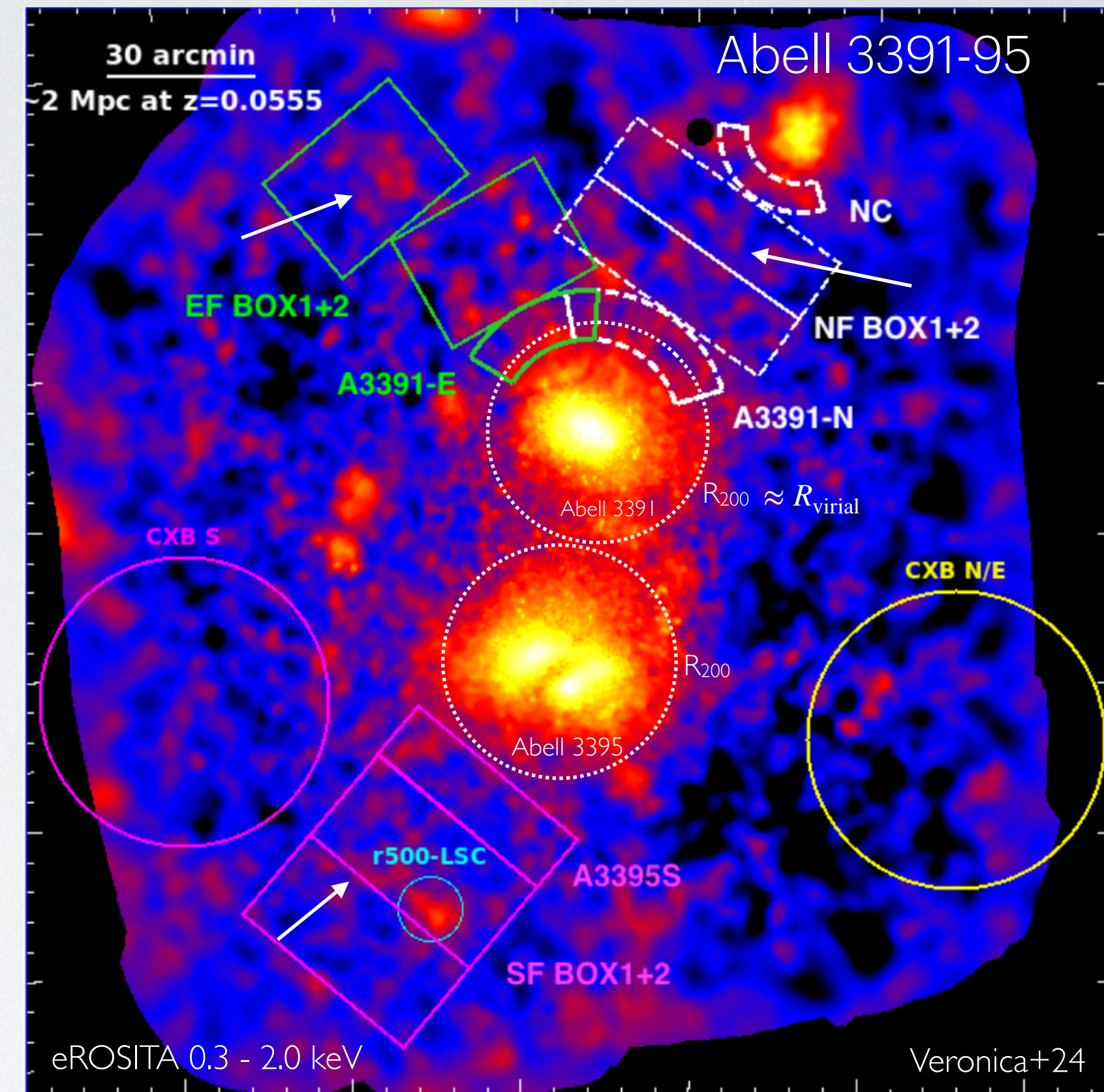
Baryonic Thermal Gas Beyond Cluster Virial Radius

XMM-Newton/EPIC
surface-brightness image



- Cluster mass: $9.5 \pm 1.0 \times 10^{14} M_{\odot}$
- Virial radius: $2.1 h_{70}^{-1} \text{ Mpc}$ (green circle)
- **Filaments:**
 - Size: up to 2 Mpc
 - Temperature: $\sim 0.8 - 1.7 \text{ keV}$ ($\sim 10 - 20 \times 10^6 \text{ K}$)
 - Mass fraction: $\sim 5 - 10 \%$

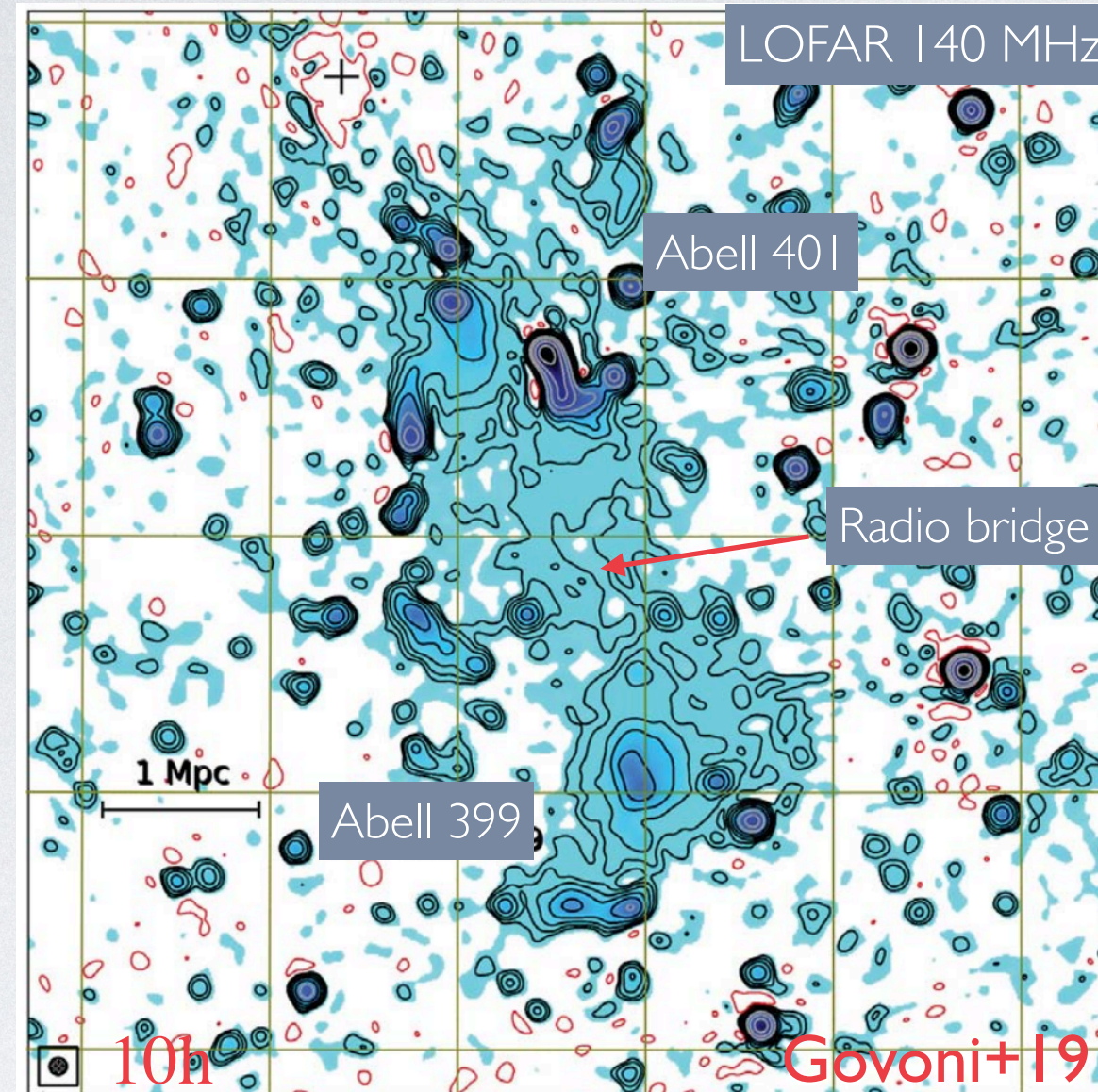
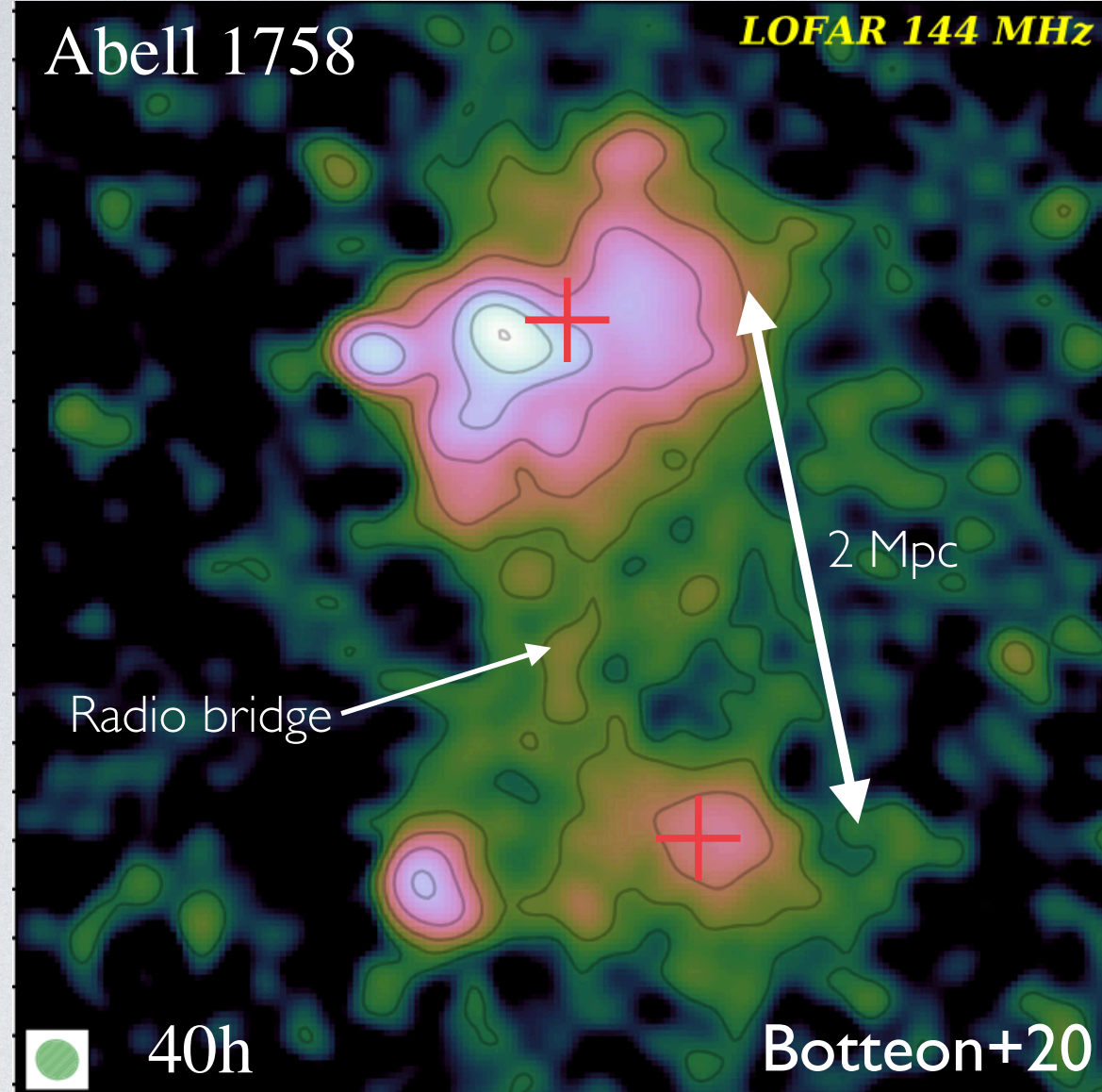
→ a large fraction of **missing baryonic matter** resides in the cosmic web of filaments



eROSITA PIB-subtracted,
exposure- and Galactic-
absorption corrected
image

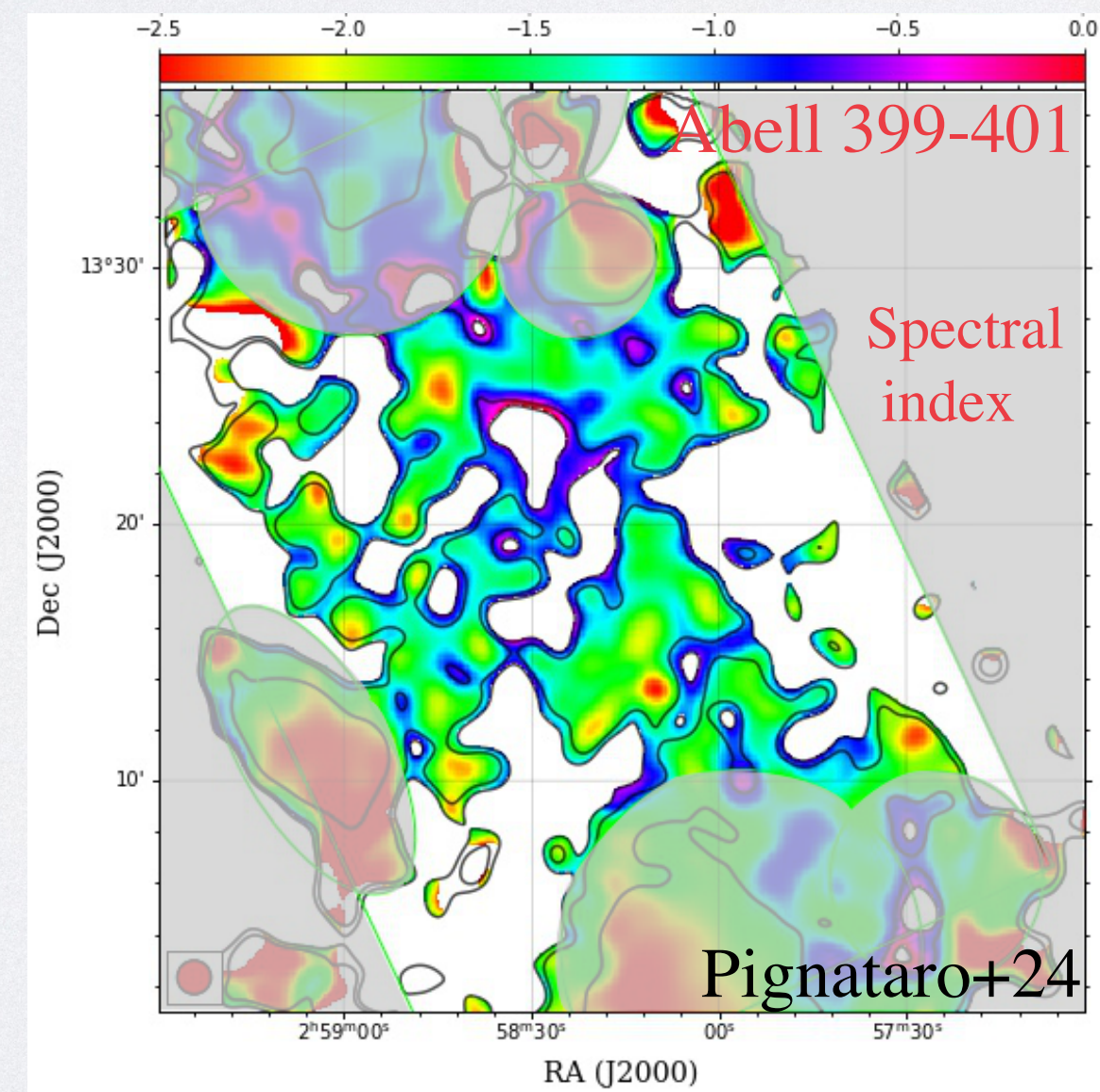
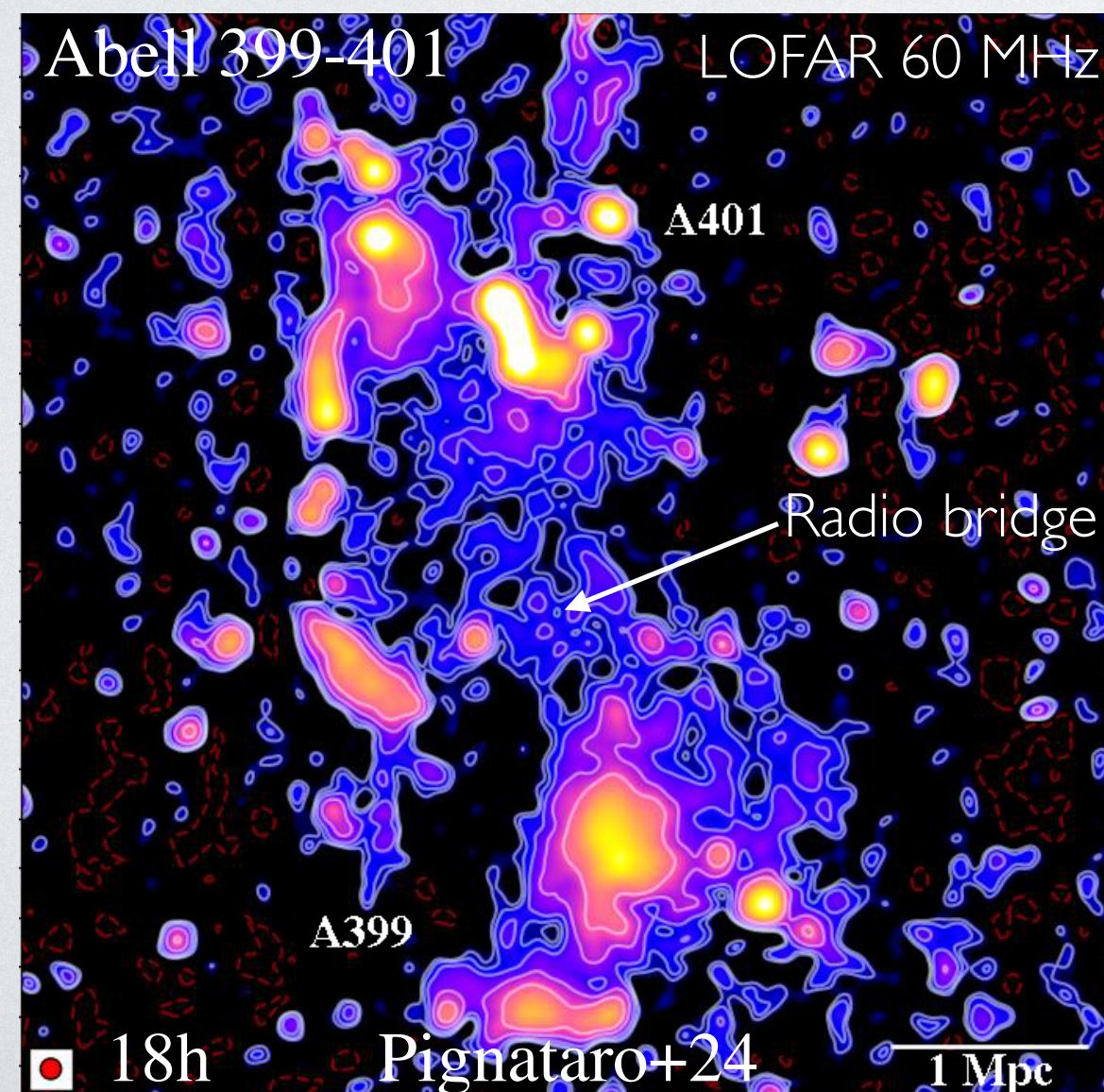
- Cluster mass: $\sim 4 \times 10^{14} M_{\odot}$
- Bridge of X-ray emission connecting the sub-clusters, within R_{200} , without radio emission (ASKAP/EMU Early Science observation; Brüggner+21).
- **X-ray emission beyond virial radii:** SF, NF, & EF
- **Temperature (Fil.):** $\sim 1 - 2 \text{ keV}$ (**within the clusters** $\sim 2 - 3 \text{ keV}$)
- **Size (Fil.):** $\sim 1 - 2 \text{ Mpc}$

Radio Bridges Between Interacting Galaxy Clusters



● **Abell 1758N - 1758S** ($z = 0.279$):

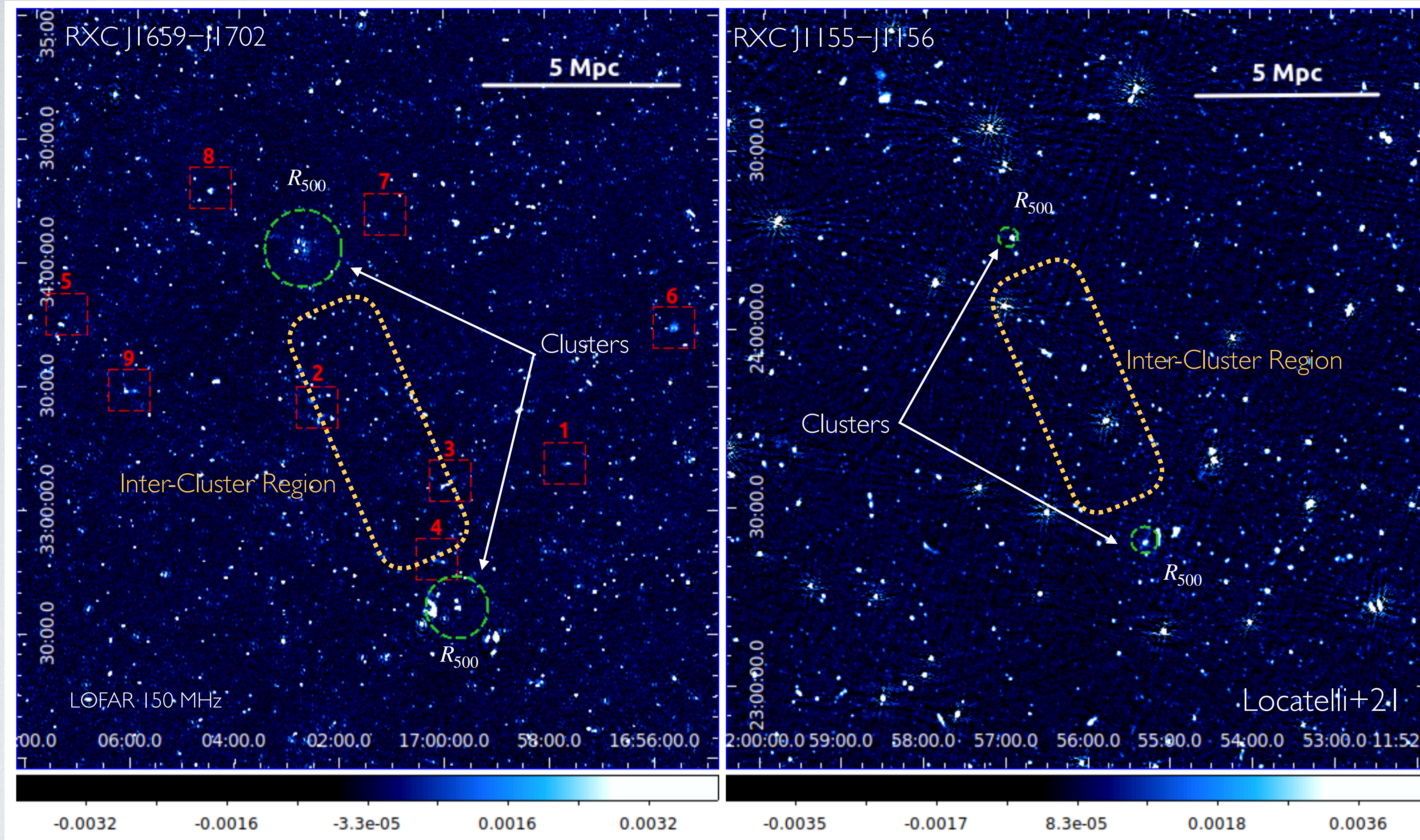
- Total Mass: $\sim 10^{15} M_{\odot}$ (Planck Collaboration XXVII 2016)
- Separation: 2 Mpc. Virial radii: 2.6 Mpc and 2.2 Mpc (David & Kempner+04)
- **Spectral index** (bridge): $\alpha_{53\text{ MHz}}^{144\text{ MHz}} = -1.65 \pm 0.27$
- **Radio emissivity** (bridge): $4 \times 10^{-43} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ cm}^{-3}$ (144 MHz)



● **Abell 401 - 399** ($z = 0.07$):

- Total mass: $\sim 1.5 \times 10^{15} M_{\odot}$ (Govoni+19)
- Separation: 3 Mpc. Radius $R_{200} \sim 2.2$ Mpc each
- **Spectral index** (bridge): $\alpha_{60\text{ MHz}}^{144\text{ MHz}} = -1.44 \pm 0.16$
- **Radio emissivity** (bridge): $8 \times 10^{-43} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ cm}^{-3}$ (144 MHz)

Inter-Cluster Filament Regions

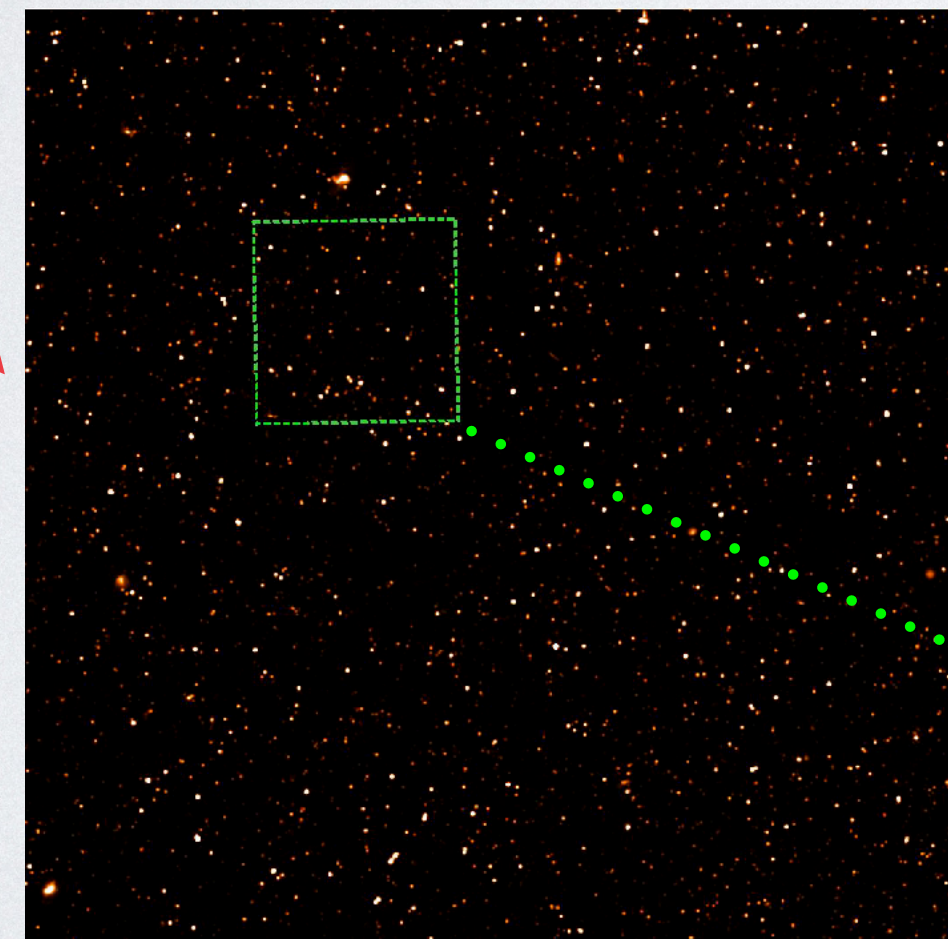
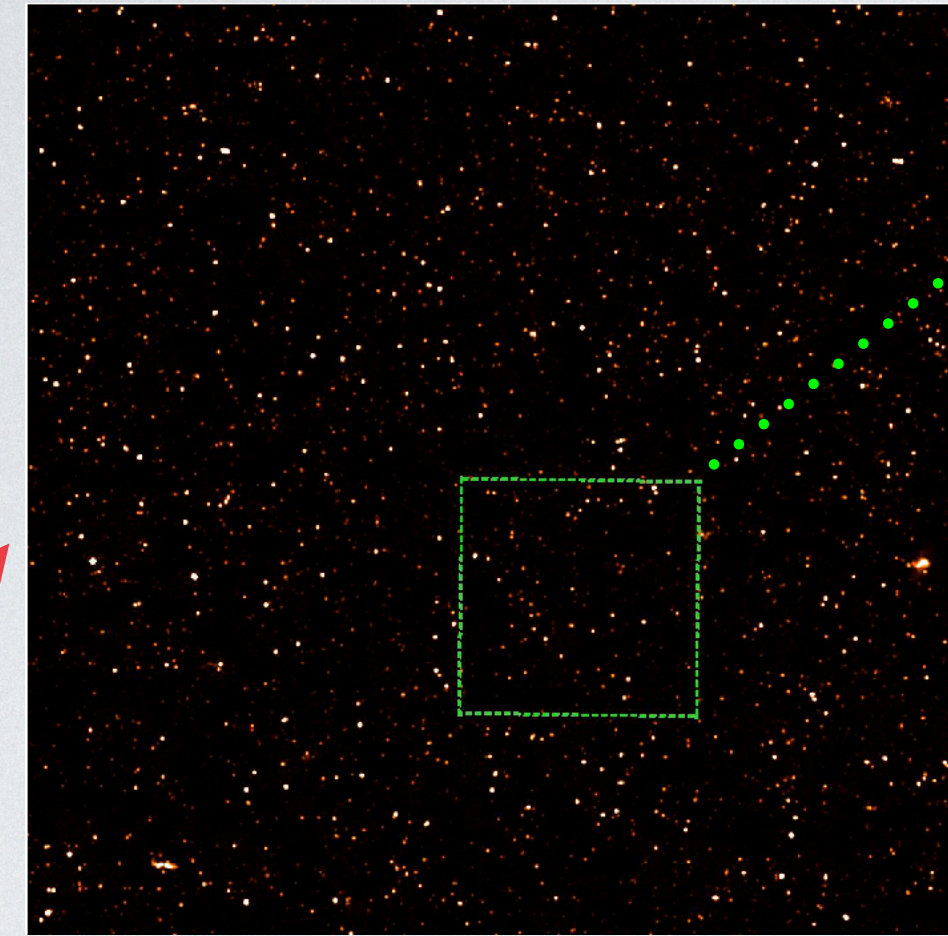


- Clusters: RXC J1659-J1702 and RXC J1155-J1156
 - LOFAR HBA 8h
 - Total mass: $\sim 5 - 8 \times 10^{14} M_{\odot}$
 - Filament region: ~ 8 Mpc
 - No detection of diffuse radio emission in the filament regions
- $\rightarrow B(10 \text{ Mpc}) < 250 \text{ nG}$

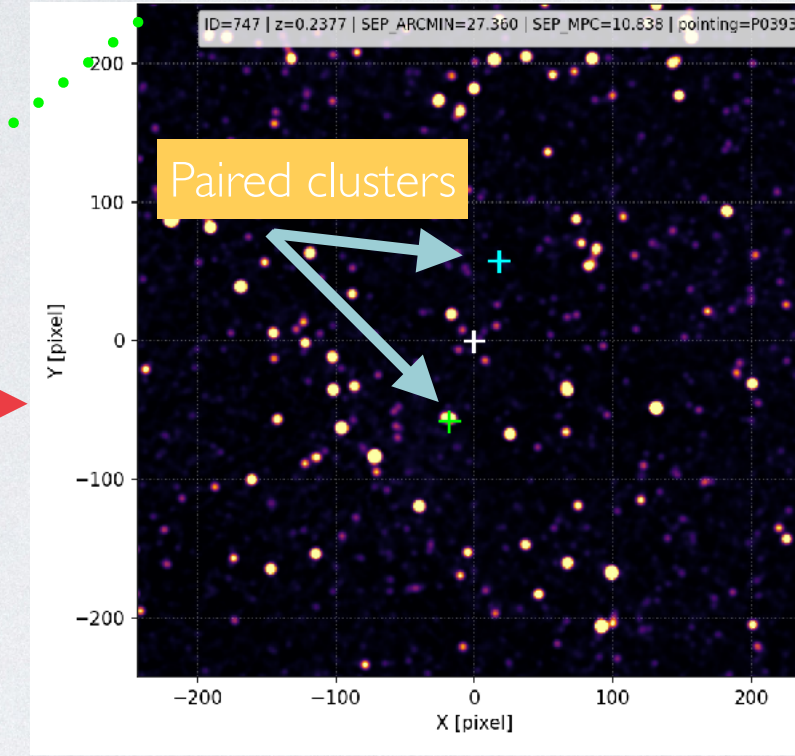
Stacking of Cosmic Filaments

imaging

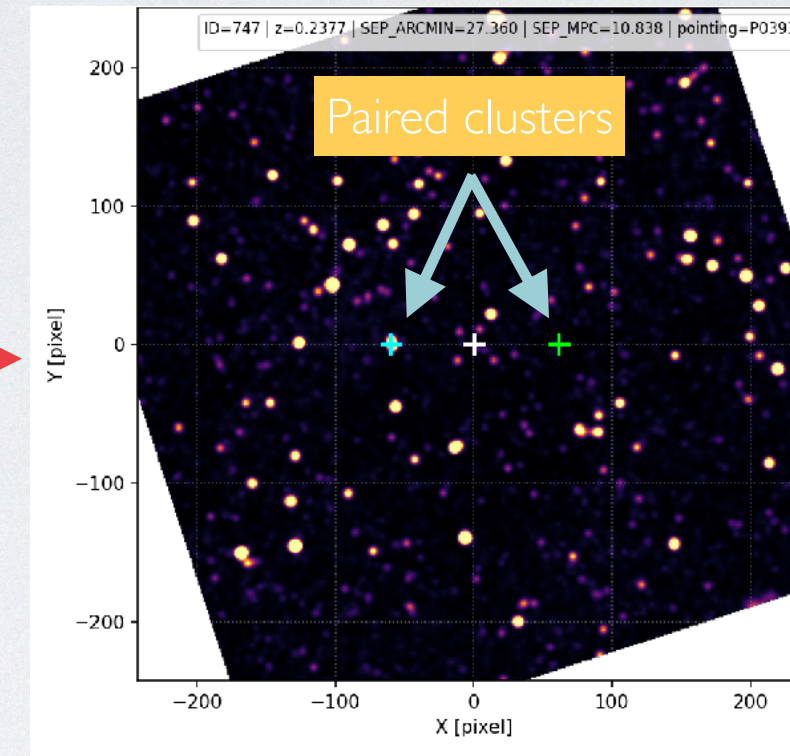
UV
data



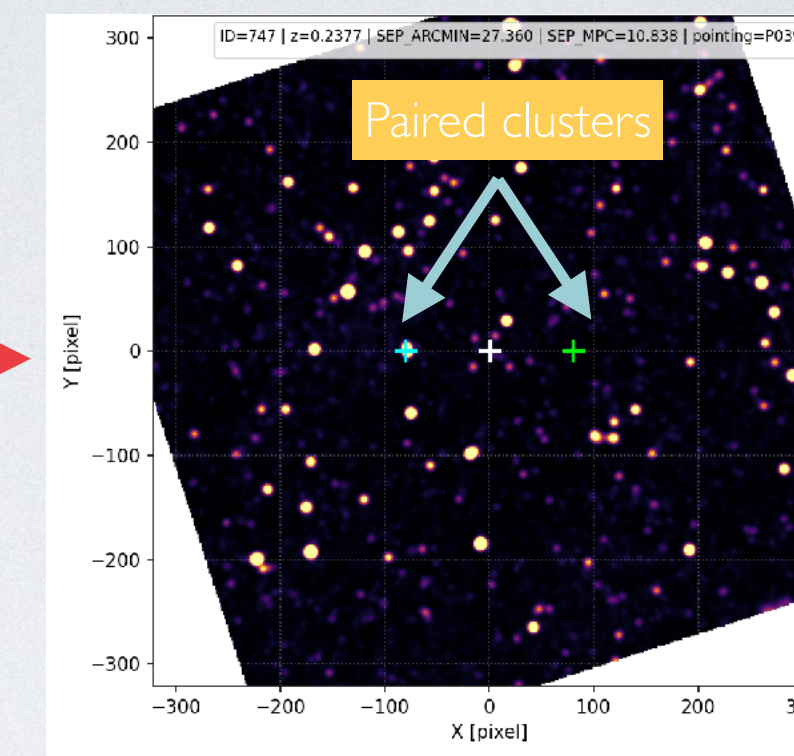
Mosaic



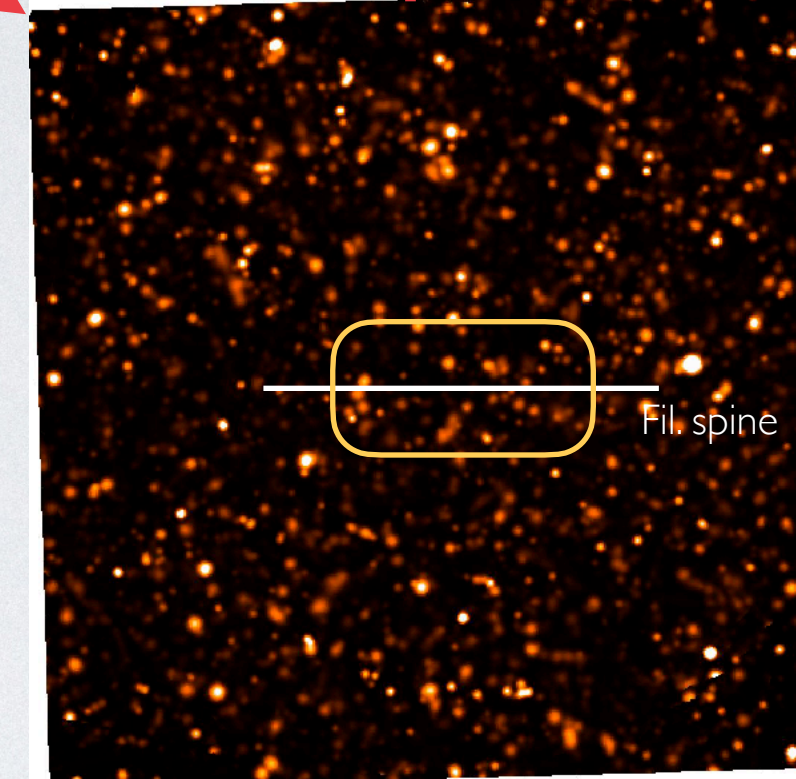
Cutouts



Rotation



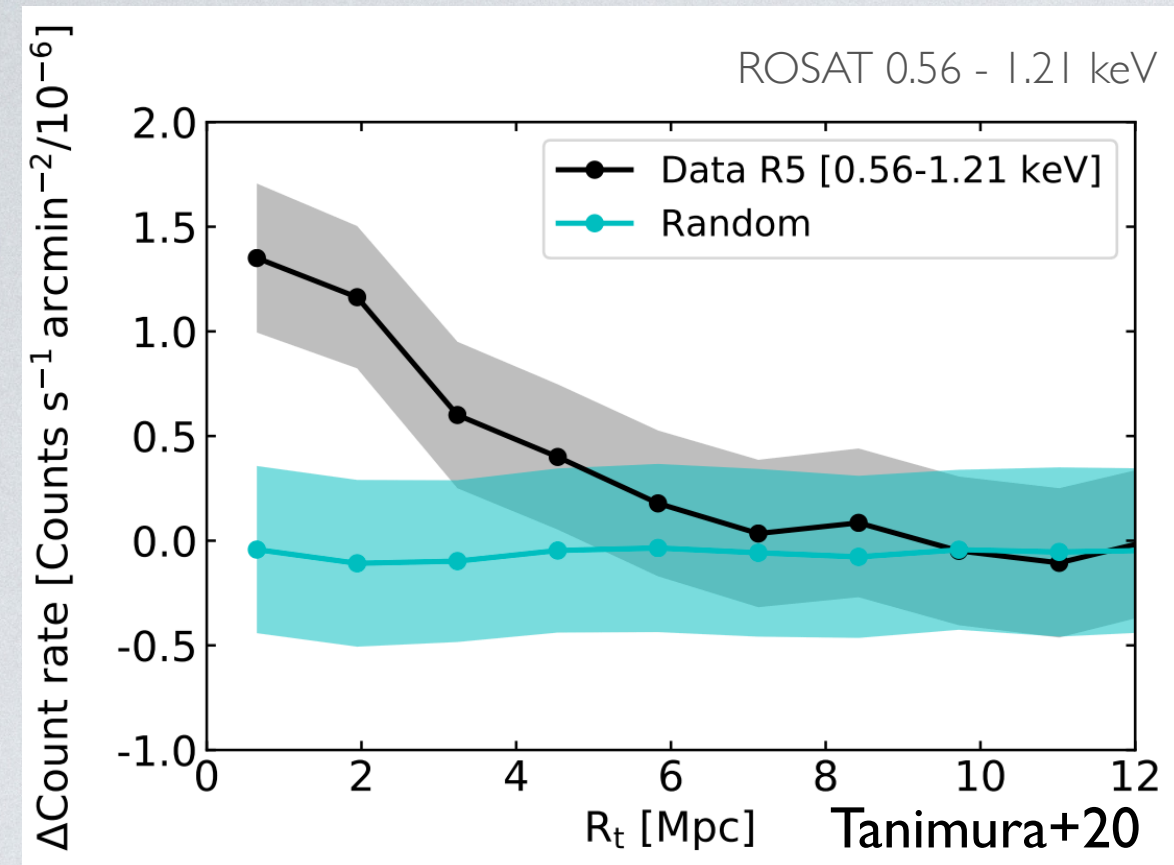
Regrid



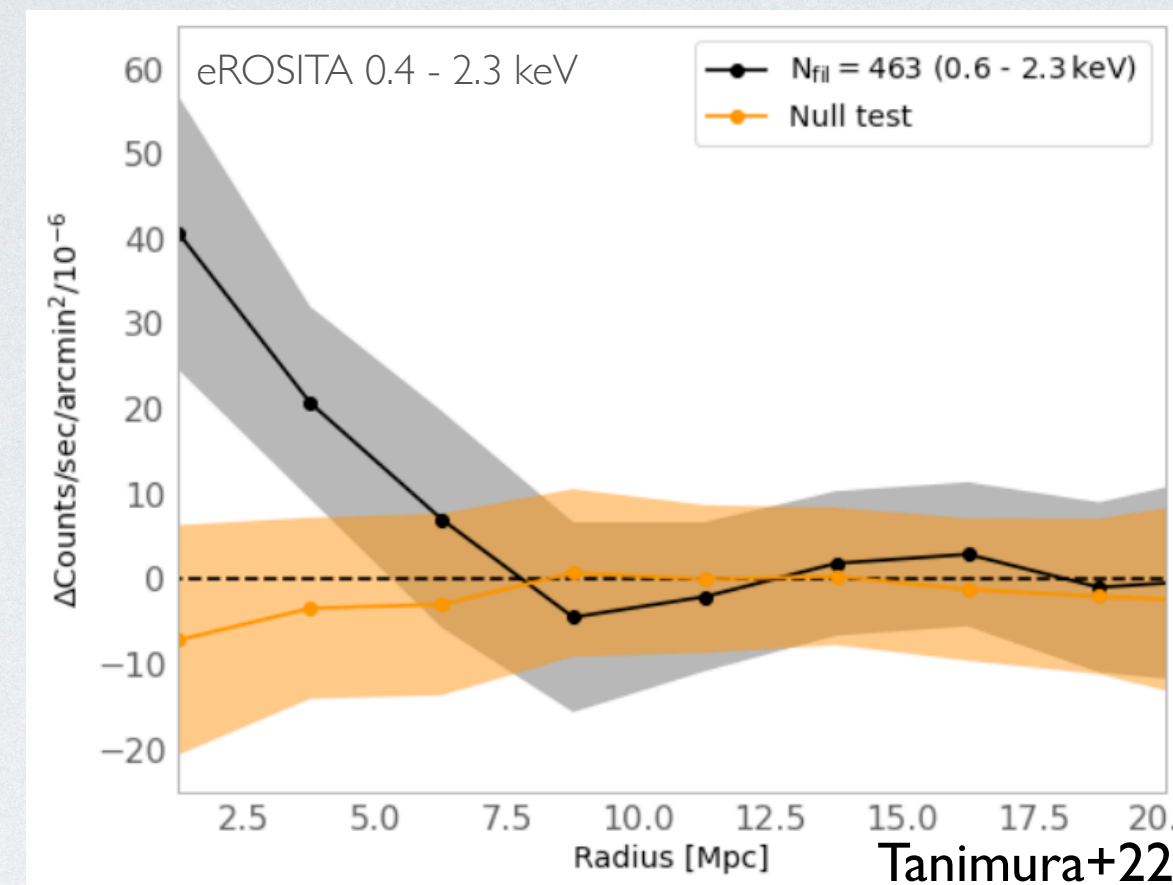
Stacked

- $\sigma_{\text{stacked}} = \sigma / \sqrt{N_{\text{fil}}}$
- $I_{\text{stacked}} = \sum (I_i) / N_{\text{fil}}$

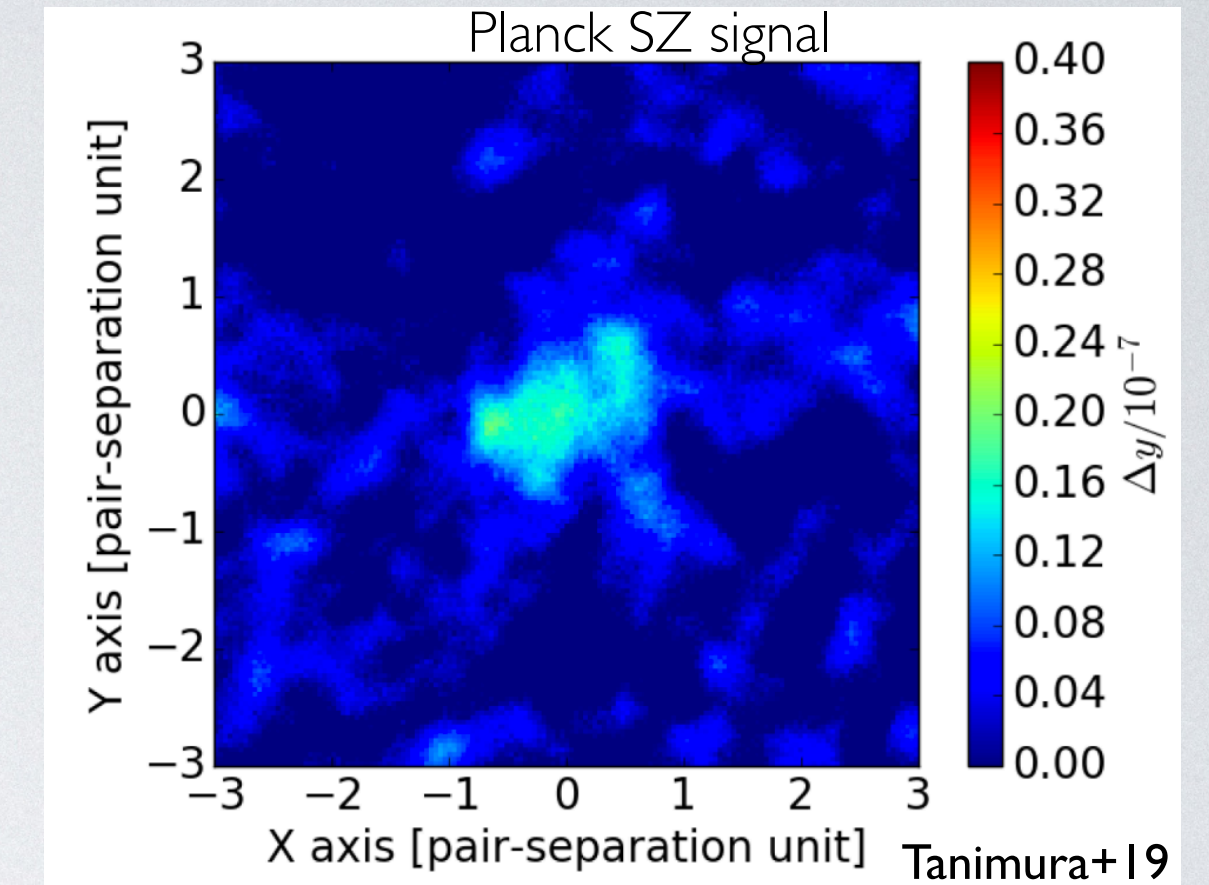
Stacked Thermal Cosmic Filaments via X-Rays & SZ



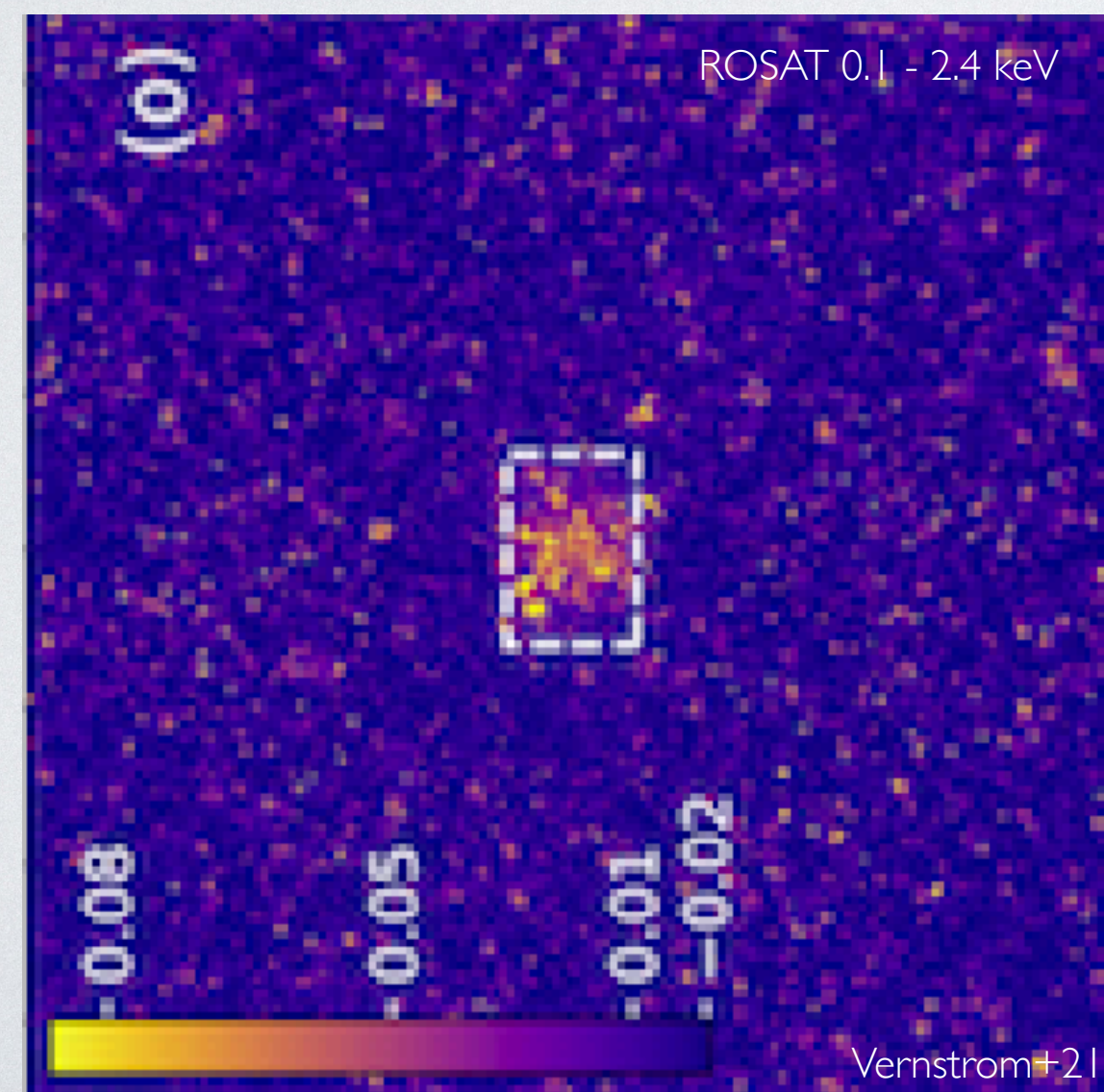
- LRG pairs: 15k
- $z = 0.2 - 0.6$
- $L = 30 - 100$ Mpc
- $\sigma = 4.2$
- $T = 0.9^{+1}_{-0.6}$ keV



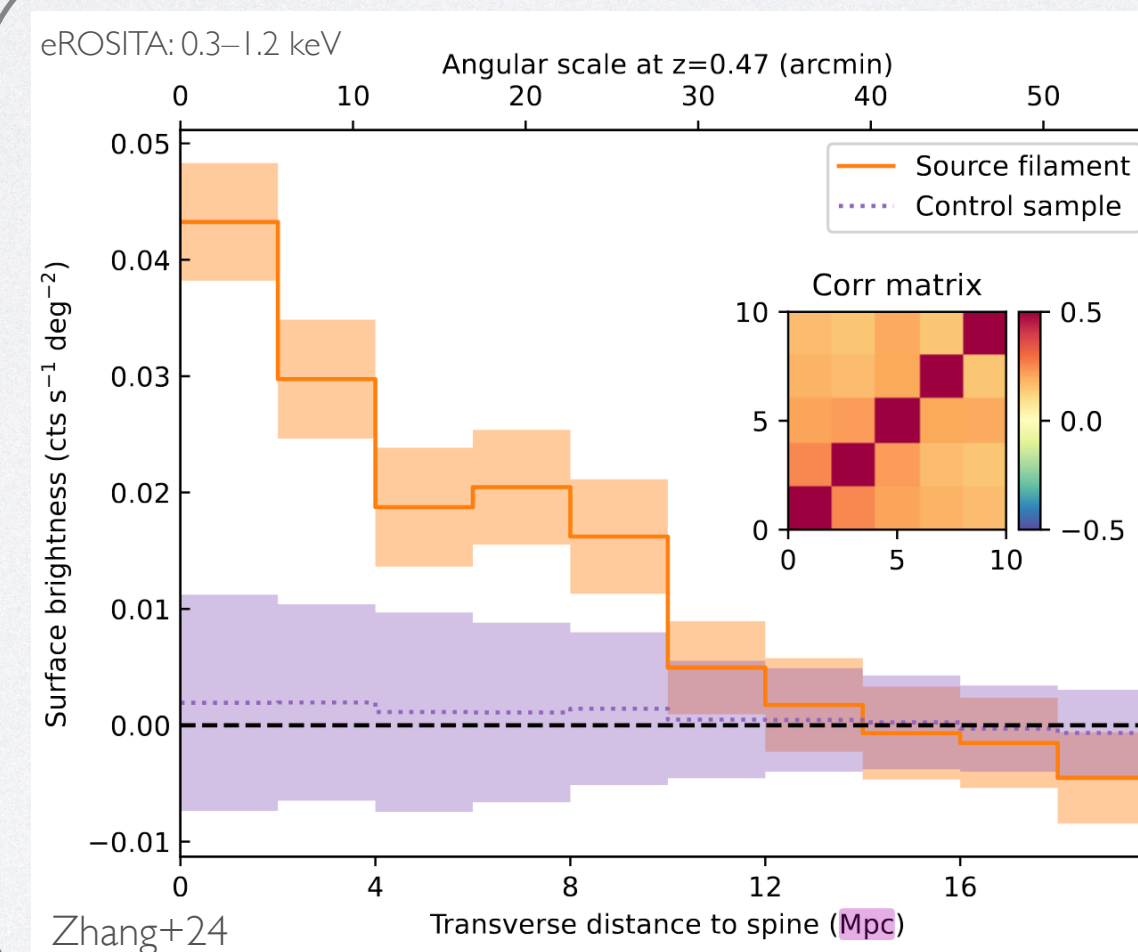
- Filaments (BOSS): 463
- $z = 0.2 - 0.6$
- $L = 30 - 100$ Mpc
- $\sigma = 3.8$
- $T = 1.0^{+0.3}_{-0.2}$ keV



- LRG pairs: 260k
- $z = 0.05 - 0.4$
- $L = 6 - 10 h^{-1}$ Mpc
- $\sigma = 5.3$
- $\Delta y = 1.31 \pm 0.25 \times 10^{-8}$

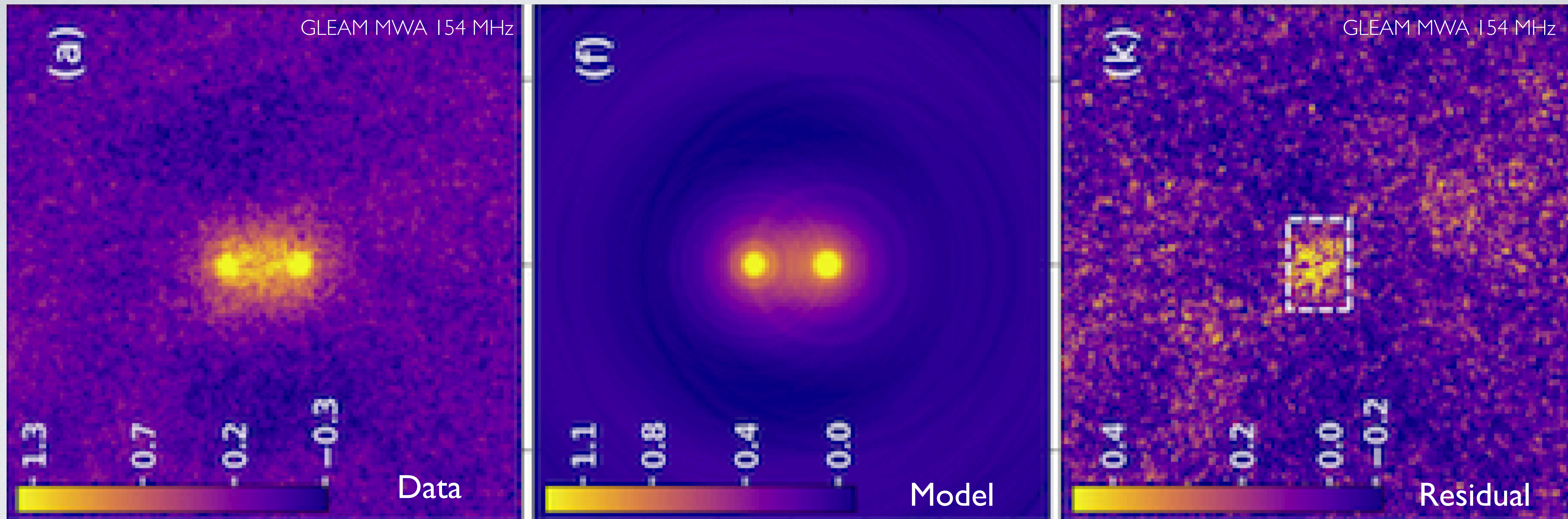


- LRG pairs: 390k
- $z < 0.7$
- $L < 14$ Mpc
- $\sigma > 3$



- SDSS filaments: 7817
- $L = 20 - 100$ Mpc
- $z = 0.2 - 0.6$
- $T = 0.58 \pm 0.1$ keV
- $\sigma = 5.4$
- 60% of the signals from cosmic filaments (others X-ray halos, AGNs, XRBs)

First Indirect Detection of Cosmic Non-Thermal Gas?



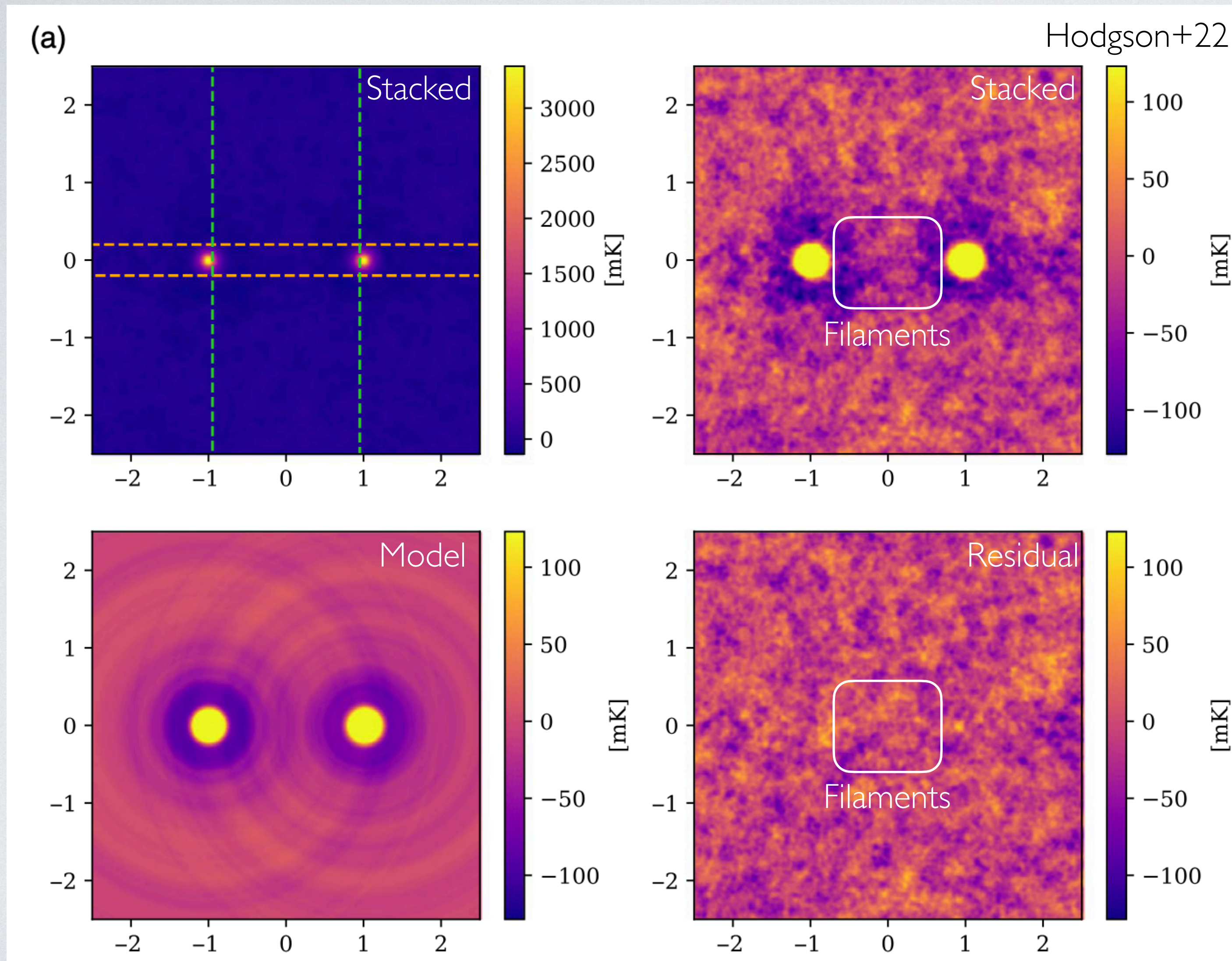
Vernstrom+21

- Stacking of 390 k pairs of LRGs ($\bar{z} = 0.14$). Shorter than 14 Mpc.
- GLEAM 88, 118, 154 MHz (MWA Phase I), LWA 73 MHz data.
- Detection of radio diffuse emission from filaments with $> 5\sigma$ significance.

- $\langle S_{\text{Fil.}} \rangle_{\text{physical}} = 0.06 \pm 0.02 \text{ mJy beam}^{-1}_{2.75' \times 2.75'}$ [154 Mhz]

- Spectral index: $\alpha = -1(?)$

Stacking of Upgraded MWA Phase II Data



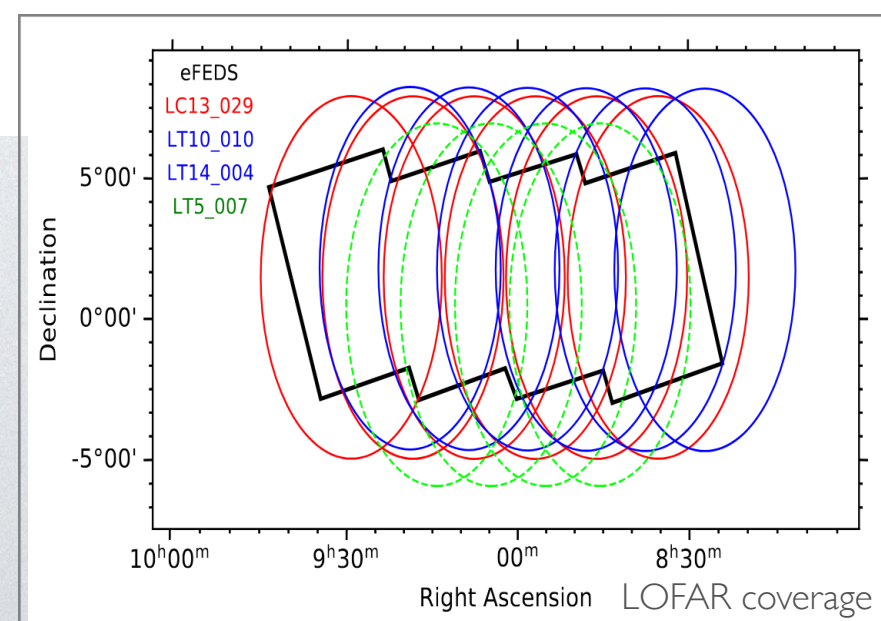
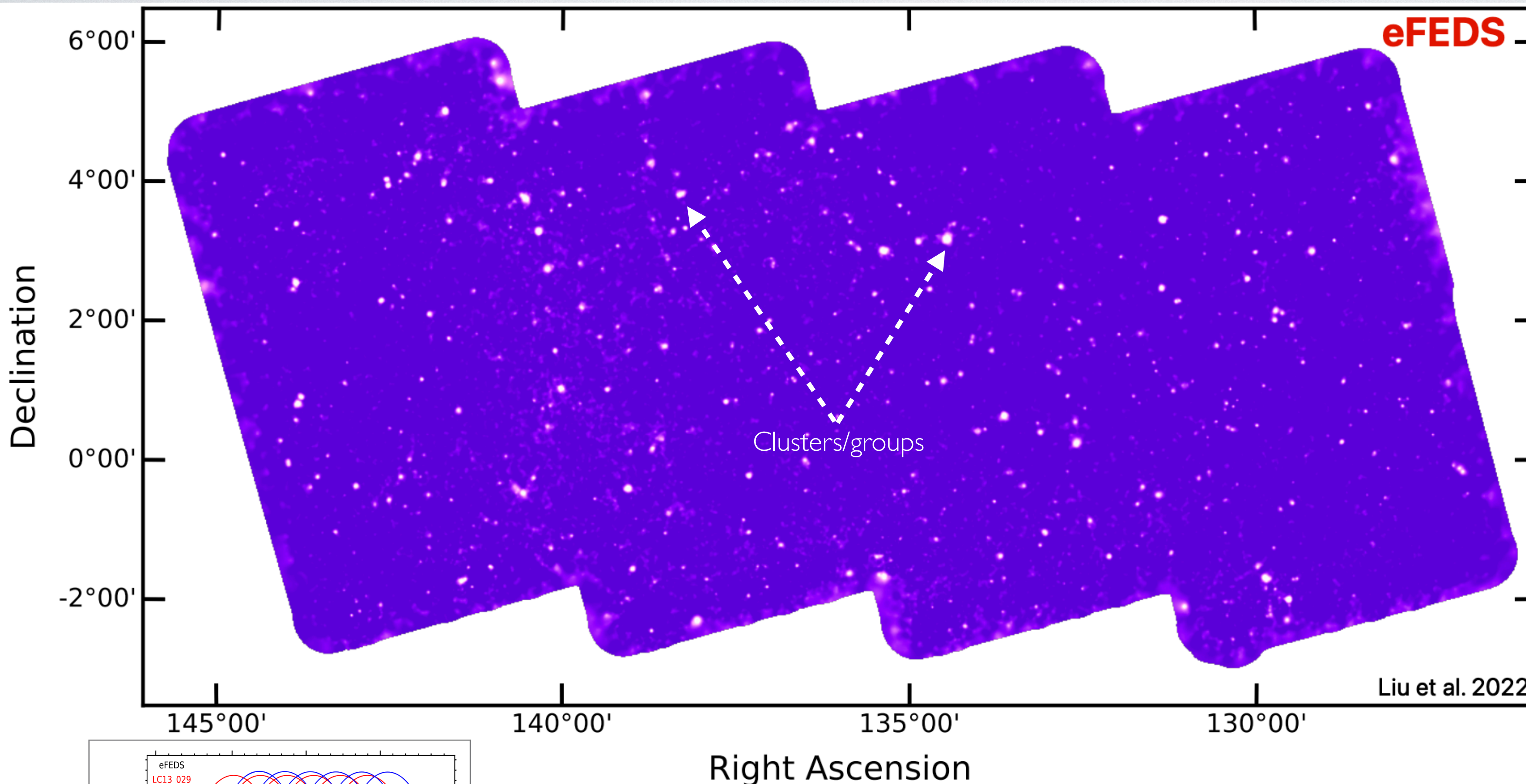
- New observations with the Phase II, extended configuration of the Murchison Widefield Array at 118.5 MHz
- Use LRGs pairs: 600k
- Length: < 15 Mpc
- Two times deeper than that in Vernstrom's data. Should detect the signal at 8σ .
- Use Vernstrom's data sets (ROSAT, MWA 118.5 MHz): X-ray detection confirmed, but not the radio.

Hodgson+22
unable to confirm the
Vernstrom's radio detection!

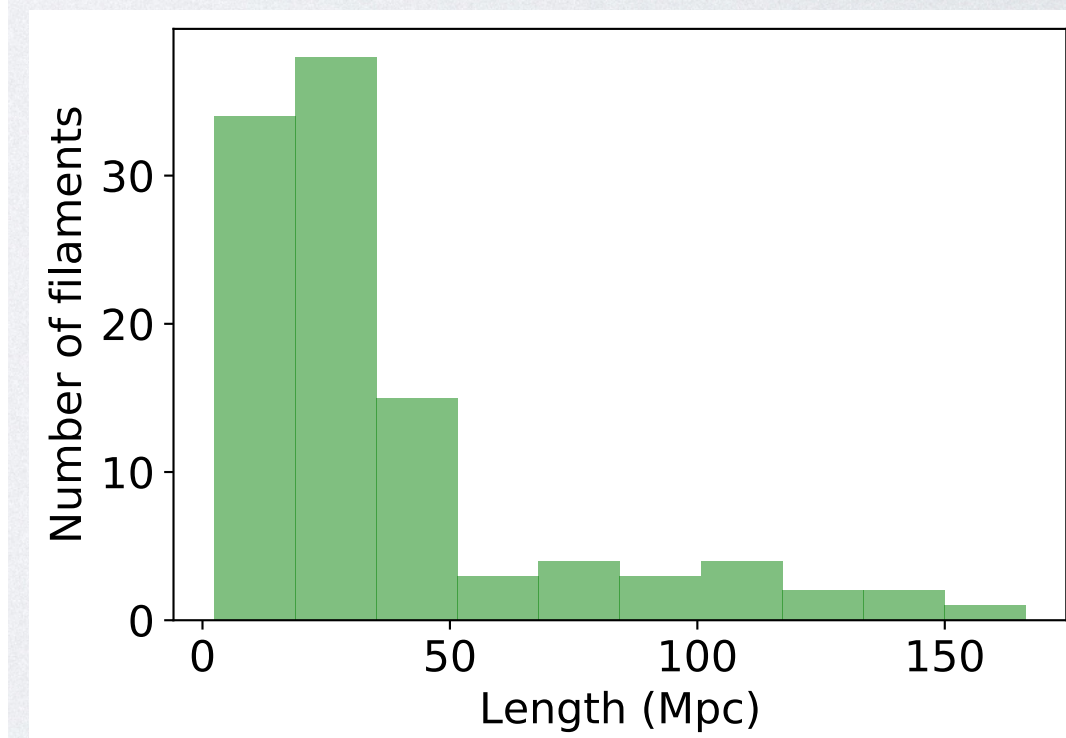
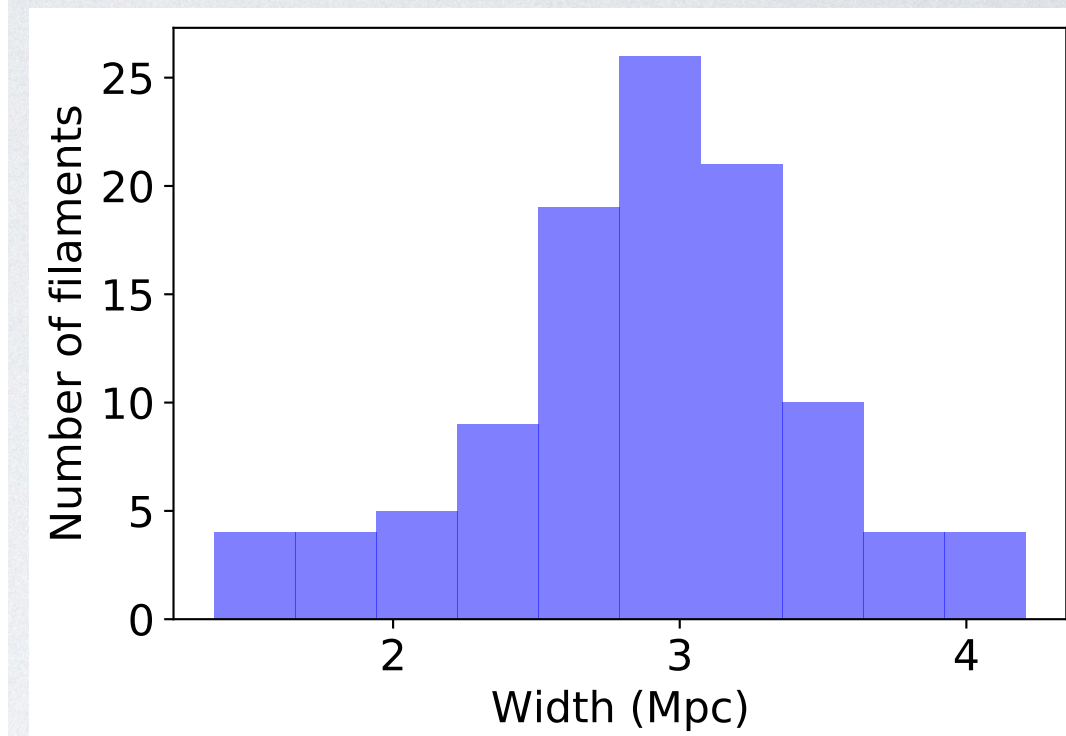
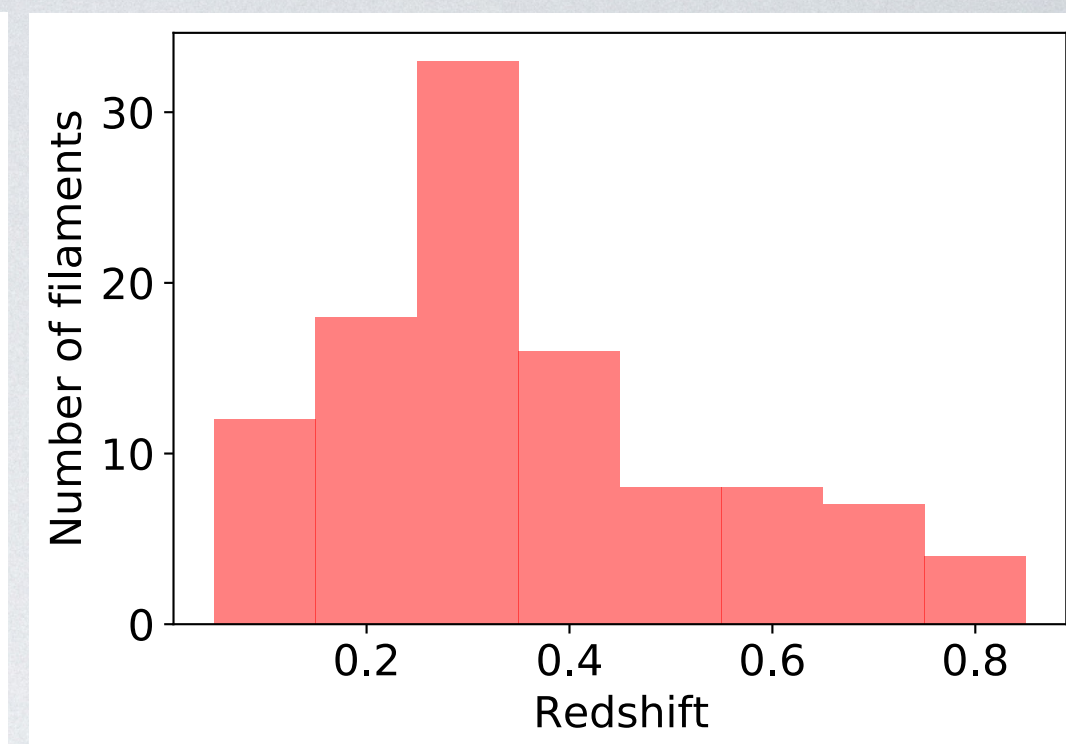
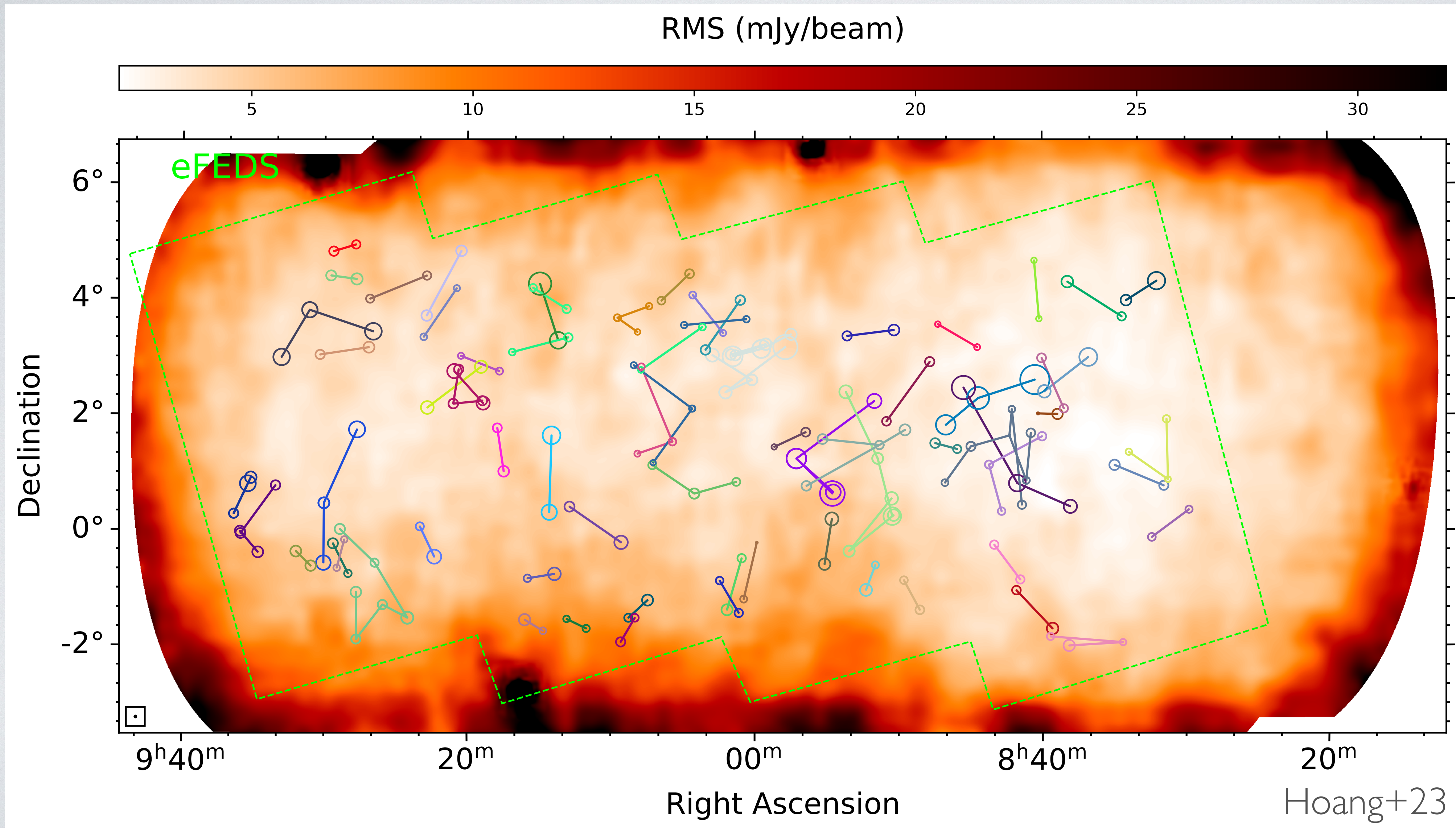
LOFAR Search for Non-Thermal Cosmic Filaments in the eROSITA Final Equatorial-Depth Survey (eFEDS) Field

eROSITA X-Ray Map of the eFEDS Field

- eFEDS: eROSITA Final Equatorial-Depth Survey
- Area: **~140 square degree**
- Location: overlay the GAMA09 and has rich multi-wavelength (optical, X-ray, radio) data
- Exposure-corrected point-source subtracted 0.2-2.3 keV image (adaptively smoothed)
- # of clusters/groups: 524
- # superclusters: **84** (245 clusters/groups)

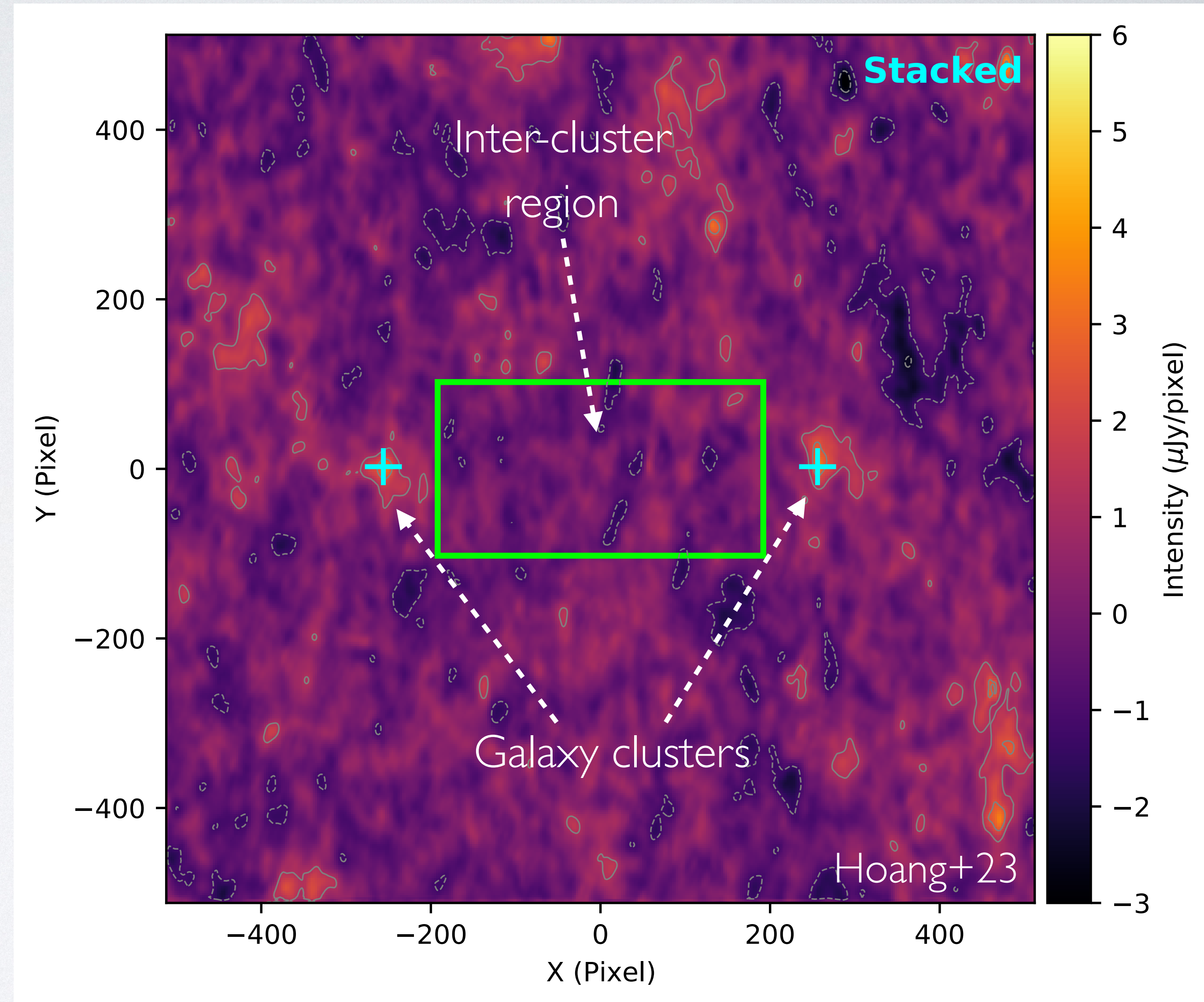


Inter-Cluster Filaments With LOFAR



Stacked LOFAR Image

- Stacked image of 106 inter-cluster pairs (filaments)
- Detection of radio emission from the paired clusters (cyan plus signs)
- No detection of radio diffuse emission from the stacked inter-cluster filaments (green box)

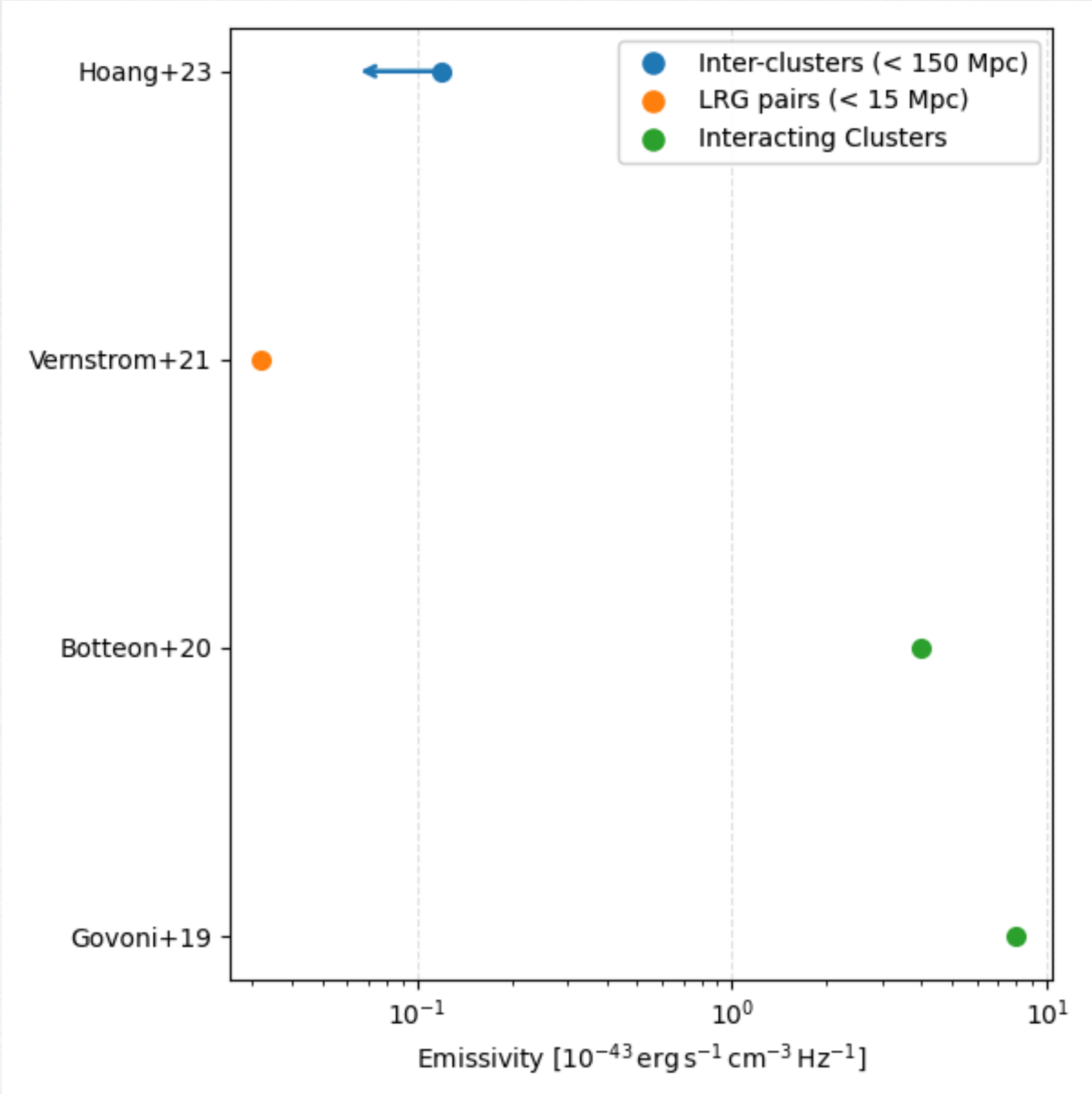


Upper Limit for Radio Emissivity

Table 1. The statistics for the two-sample KS test for the comparison between the means of the emission in the inter-cluster filaments before and after the injection of filament models.

ϵ_{inj} [$10^{-44} \text{ erg s}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1}$]	Statistic	p -value	Detection
1	0.4	0.08	N
1.2	0.45	0.03	Y
1.4	0.5	0.01	Y
1.6	0.55	0.004	Y
1.8	0.55	0.004	Y
2	0.6	0.001	Y
3	0.75	<0.001	Y
4	0.85	<0.001	Y
5	0.9	<0.001	Y

Upper limit for the radio emissivity of the filaments: $\epsilon < 1.2 \times 10^{-44} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ cm}^{-3}$



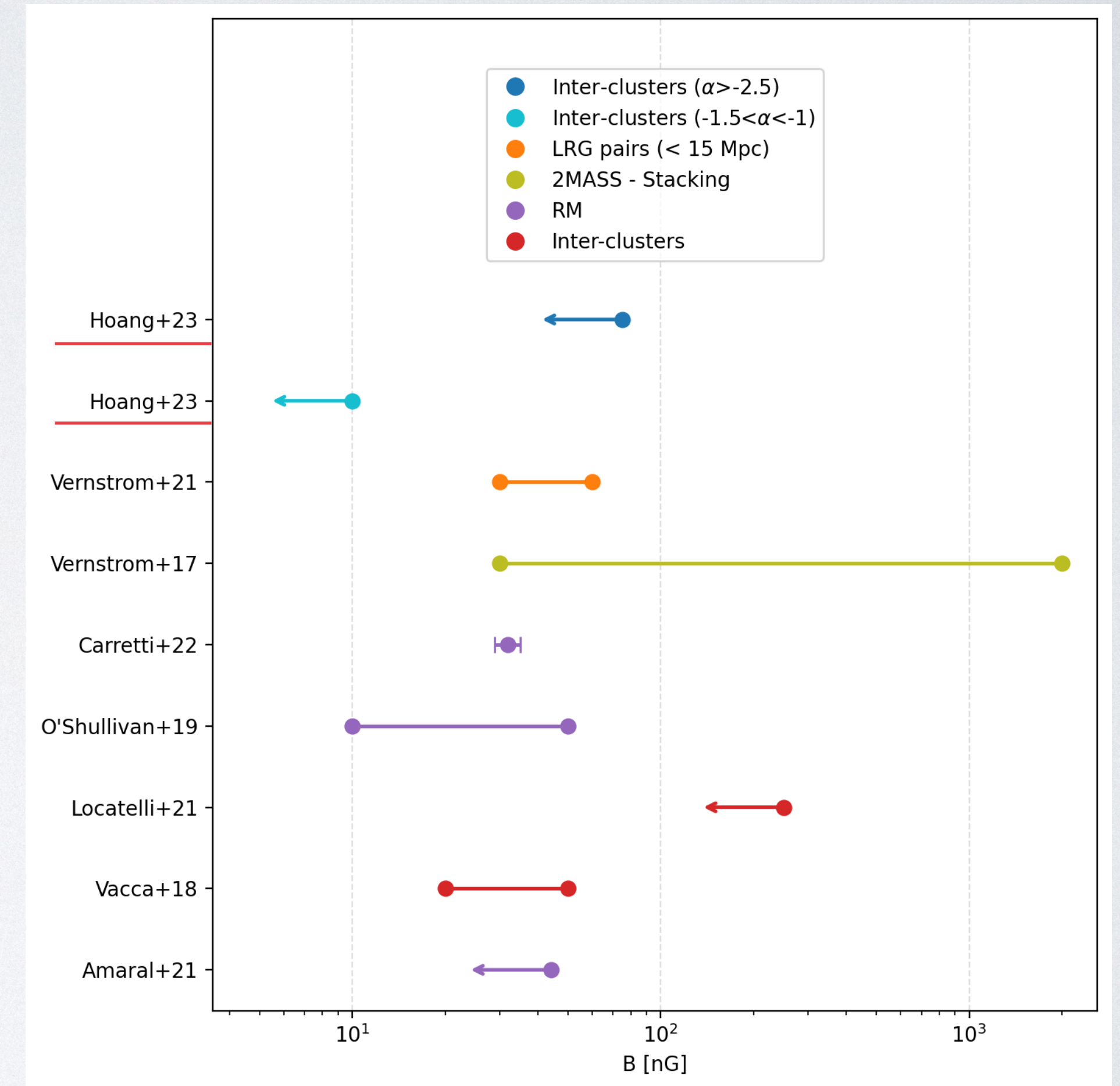
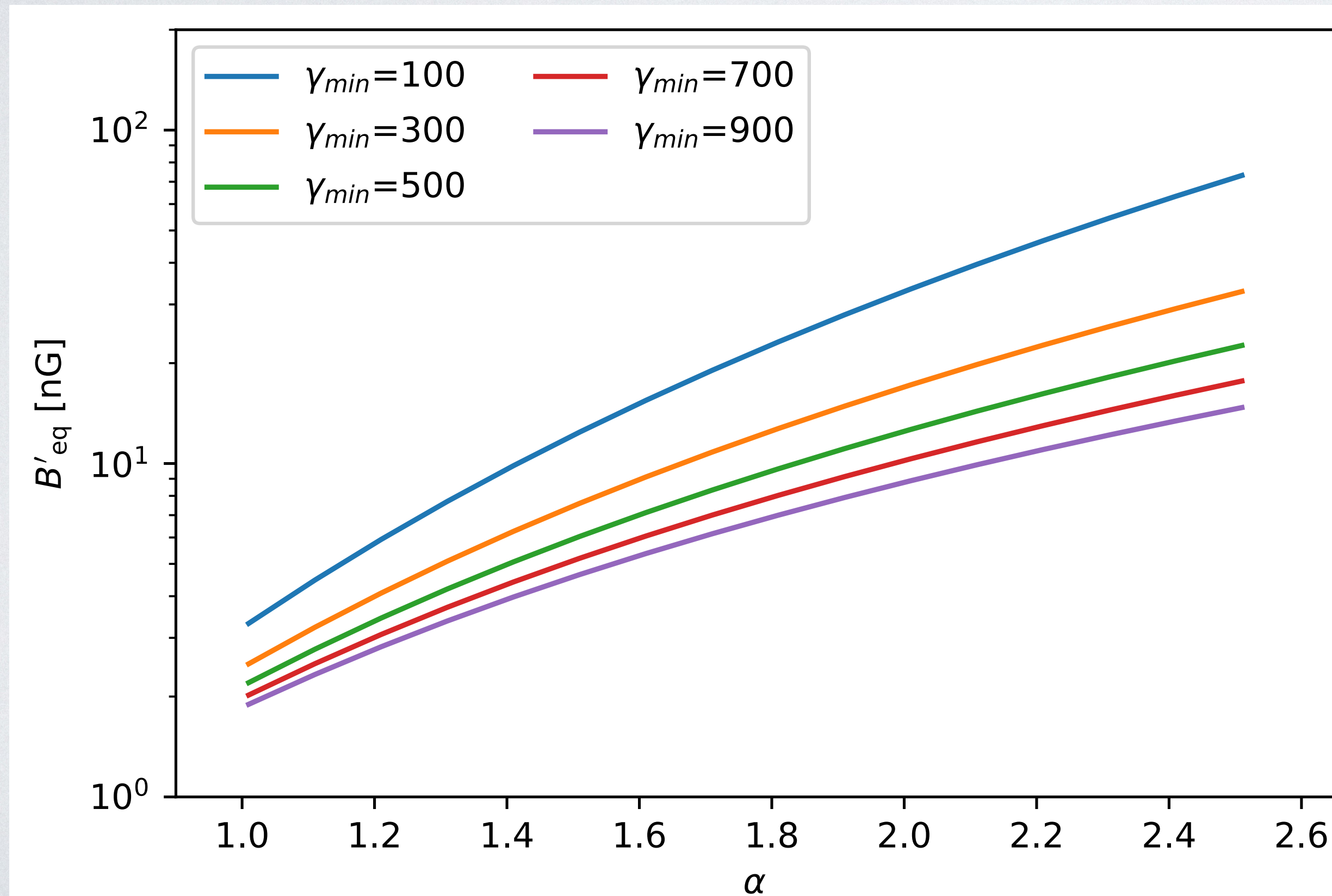
Hoang+23

B Field Strength Under Equipartition Conditions

● The equipartition B field:

$$B_{\text{eq}} = \left(6\pi(1+k)c_{12}K_{\text{bol}}\Phi^{-1}\epsilon \right)^{2/7}$$

$$B'_{\text{eq}} \approx 1.1\gamma_{\text{min}}^{\frac{1-2\alpha}{3+\alpha}} B_{\text{eq}}^{\frac{7}{2(3+\alpha)}}$$

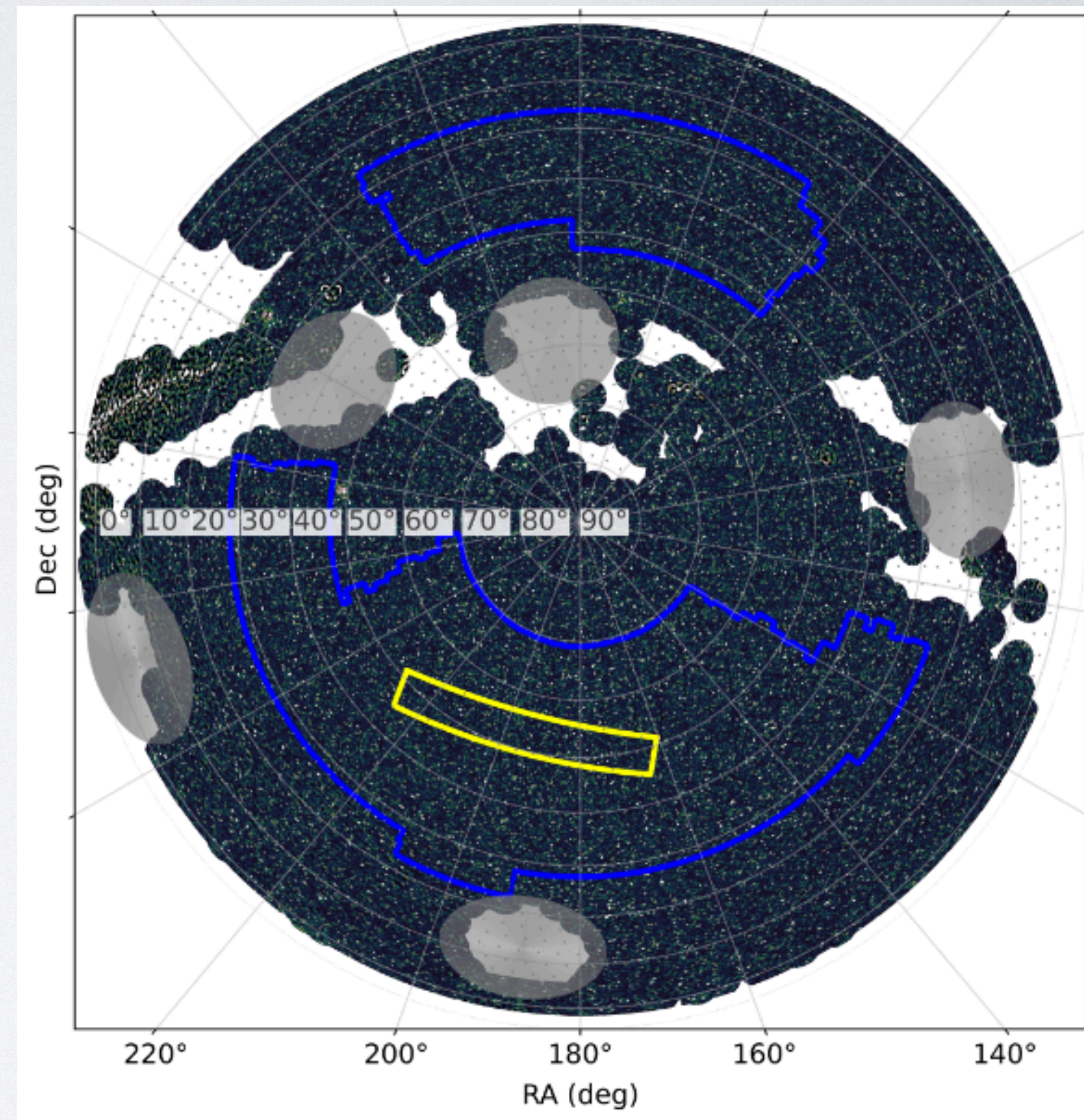
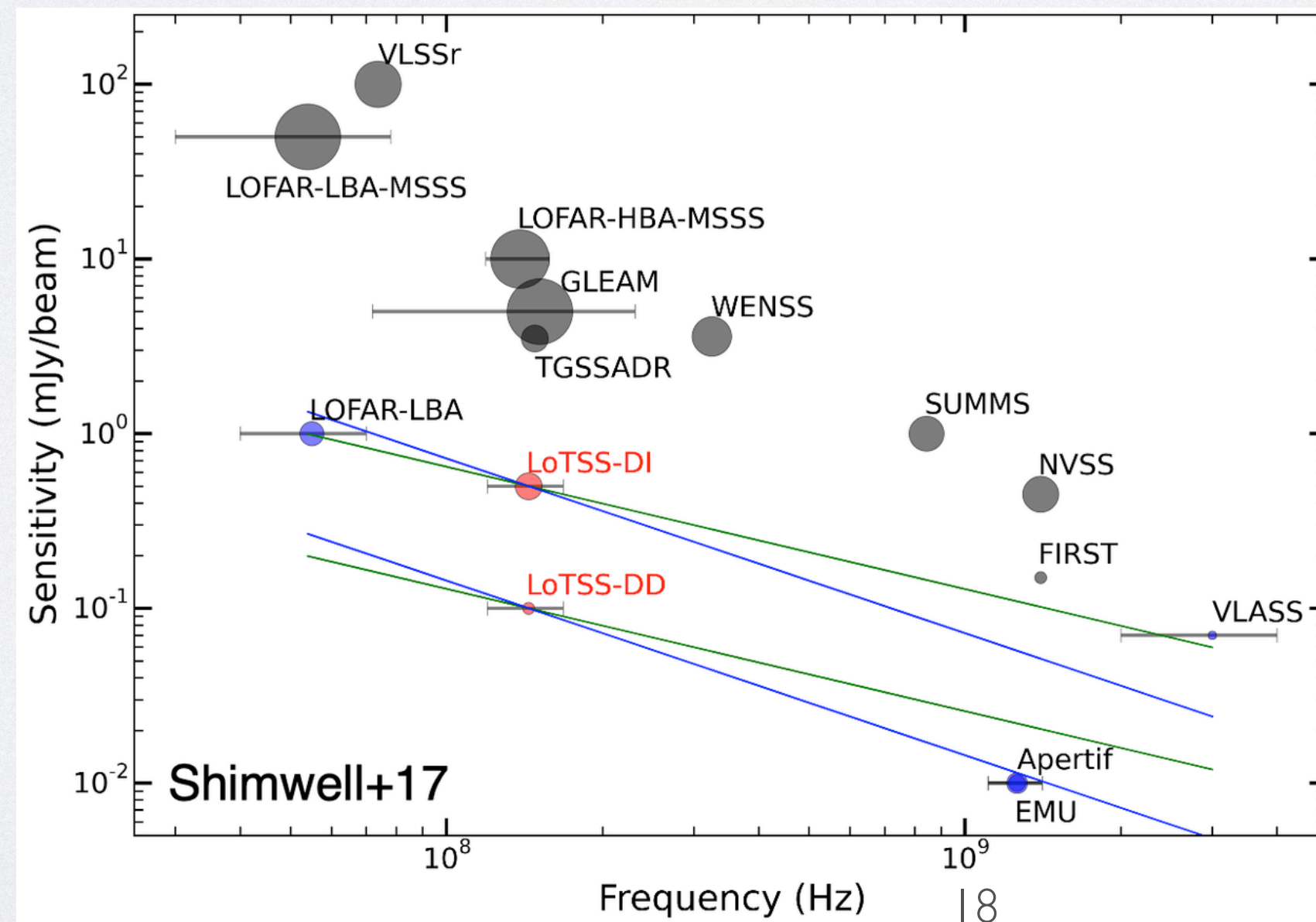


- Boss+23: simulations of local cosmic web. $-1.5 \lesssim \alpha \lesssim -1$

LoTSS-DR3

© LOFAR Two-Metre Sky Survey (LoTSS) - Data Release 3 (Shimwell+26)

- ✓ Sky coverage: **18k deg²** (88% of Northern sky)
- ✓ Frequency: 120 - 168 MHz
- ✓ Sensitivity: $\sim 100 \mu\text{Jy}/\text{beam}$
- ✓ Resolutions: 6'', 20'', sub-arcsec (w/ further processing)
- ✓ Source detected: ~ 13.7 milion



Cosmic Filaments Traced by LRG Pairs

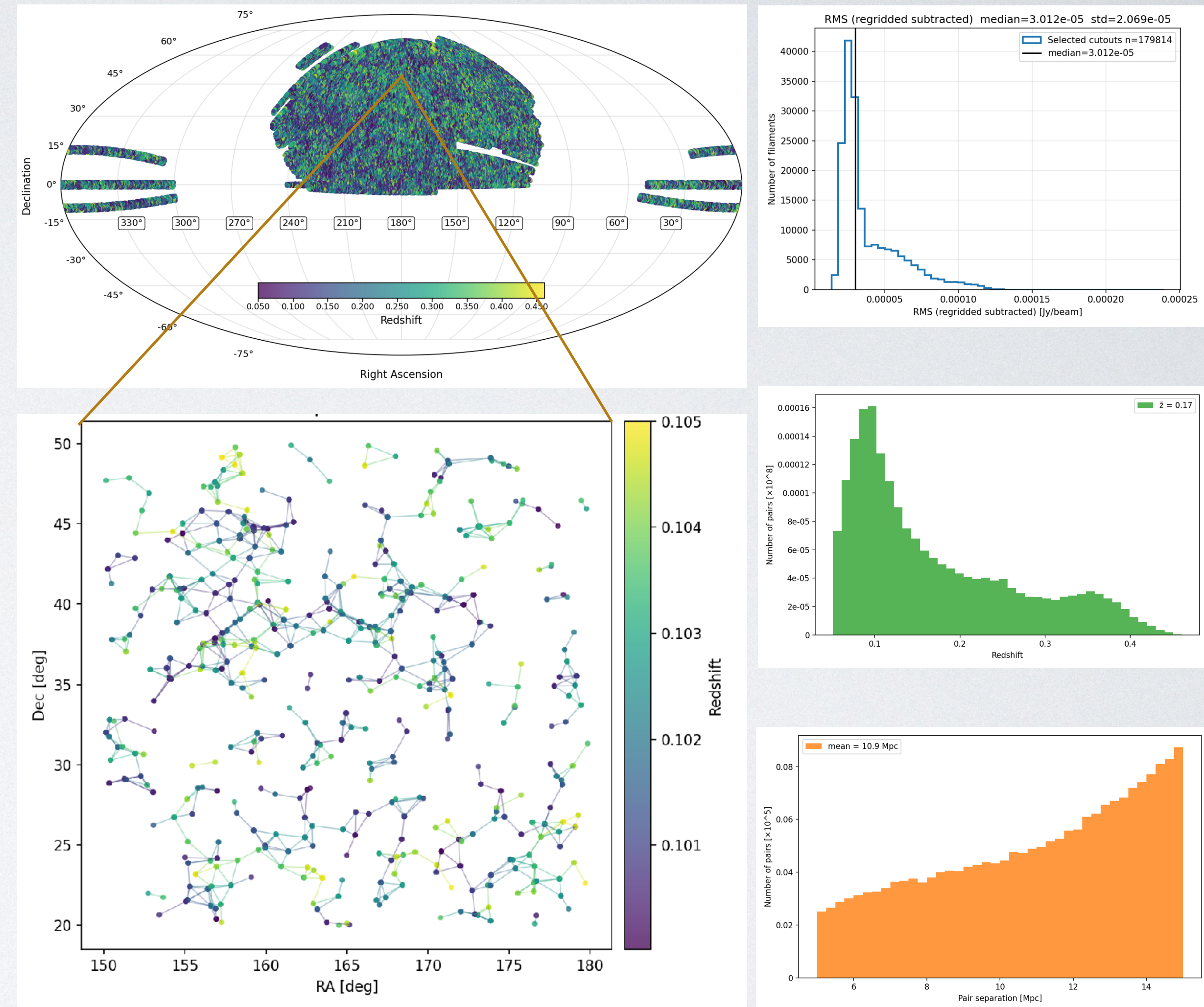
- LRG (Luminous Red Galaxies) catalogue (Lopes+07). 1.4 milion LRGs.

(LRGs are massive, luminous galaxies located at **centre of massive dark matter halos**)

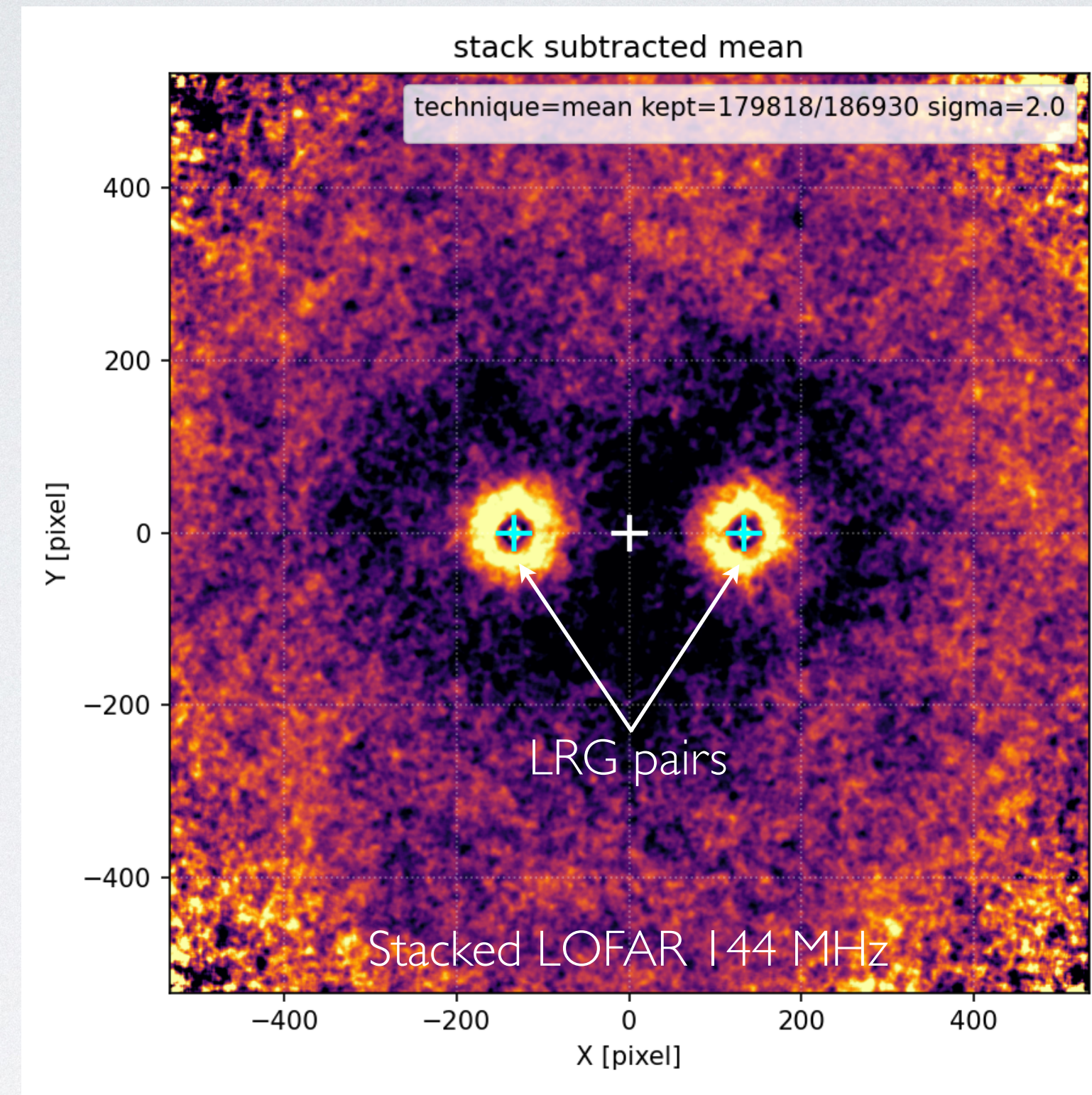
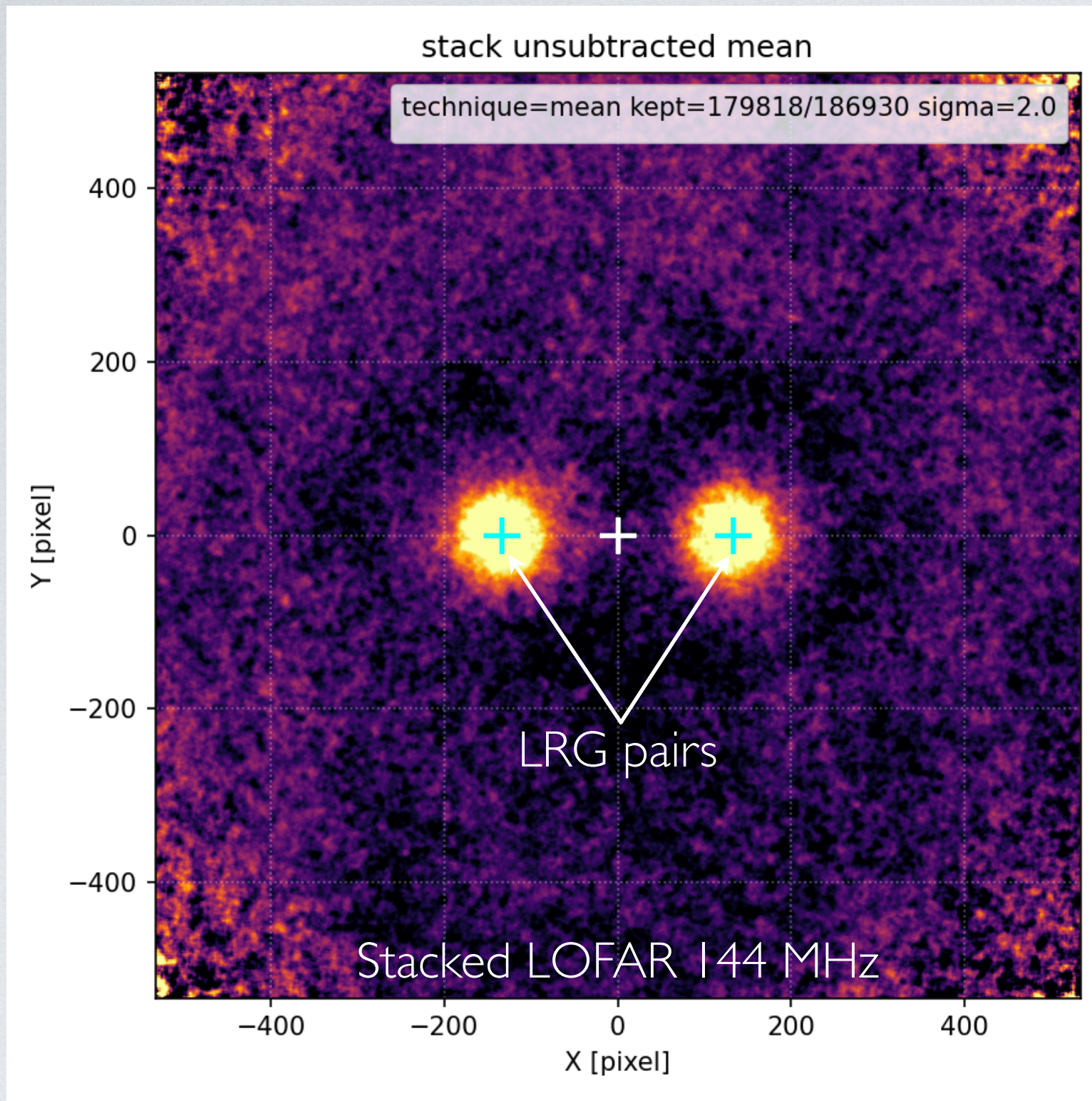
- Pairing LRGs

- ✓ Physical separation: 5 - 15 Mpc
- ✓ Spatial separation: 20 - 60 arcmin (180k pairs)
- ✓ Redshift: 0.05 - 1.0

- Data: LoTSS-DR3



LoTSS-DR3 Stacked Images



- What's next?
- **Subtraction in *uv* space** with high-resolution source models
- **Examine different filament catalogues** (Lobes+07, Malavasi+20, Temple+14, Duque+21)
- Extract **physical measurements** from stacked image

- LOFAR stacked image for 180k cutouts using original mosaics.
- Mosaics are smooth to 60 arcsec resolution
- Sources are masked out above 9 sigma

- LOFAR stacked image for 180k source-subtracted cutouts.
- Sources are subtracted with PyBDSF at 6 arcsec
- Residual images are smoothed to 60 arcsec resolution.

Thanks very much for
your attention!