

# Hot baryons is the largest cosmic structure

---

Nabila Aghanim (IAS, France)

With **V. Bonjean, H. Tanimura, N. Malavasi, G. Fabbian, M. Douspis,**  
and A. Kolodzig, E. Lecoq, D. Galarraga, C. Guin, T. Bonnaire, M. Ulmo, M. Langer, J.  
Grain, A. Decelle (LRI), A. Beelen (LAM)



# A Cosmic web of galaxies

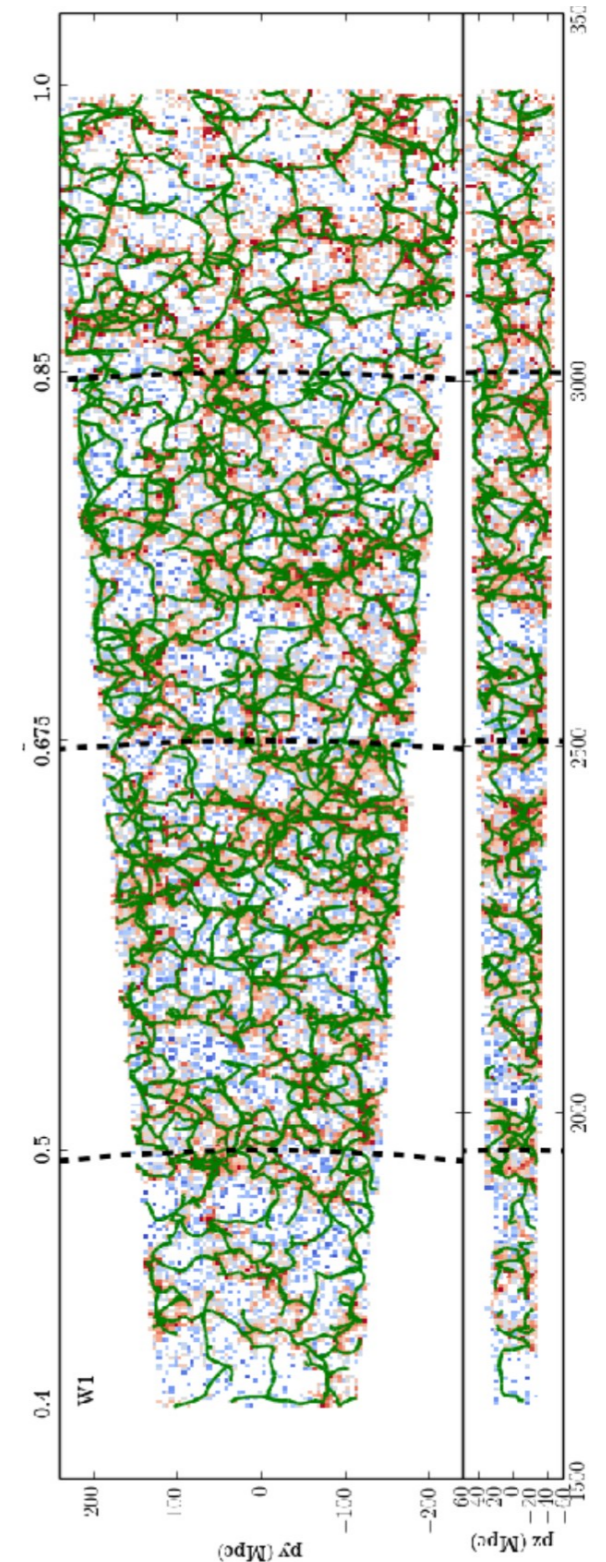
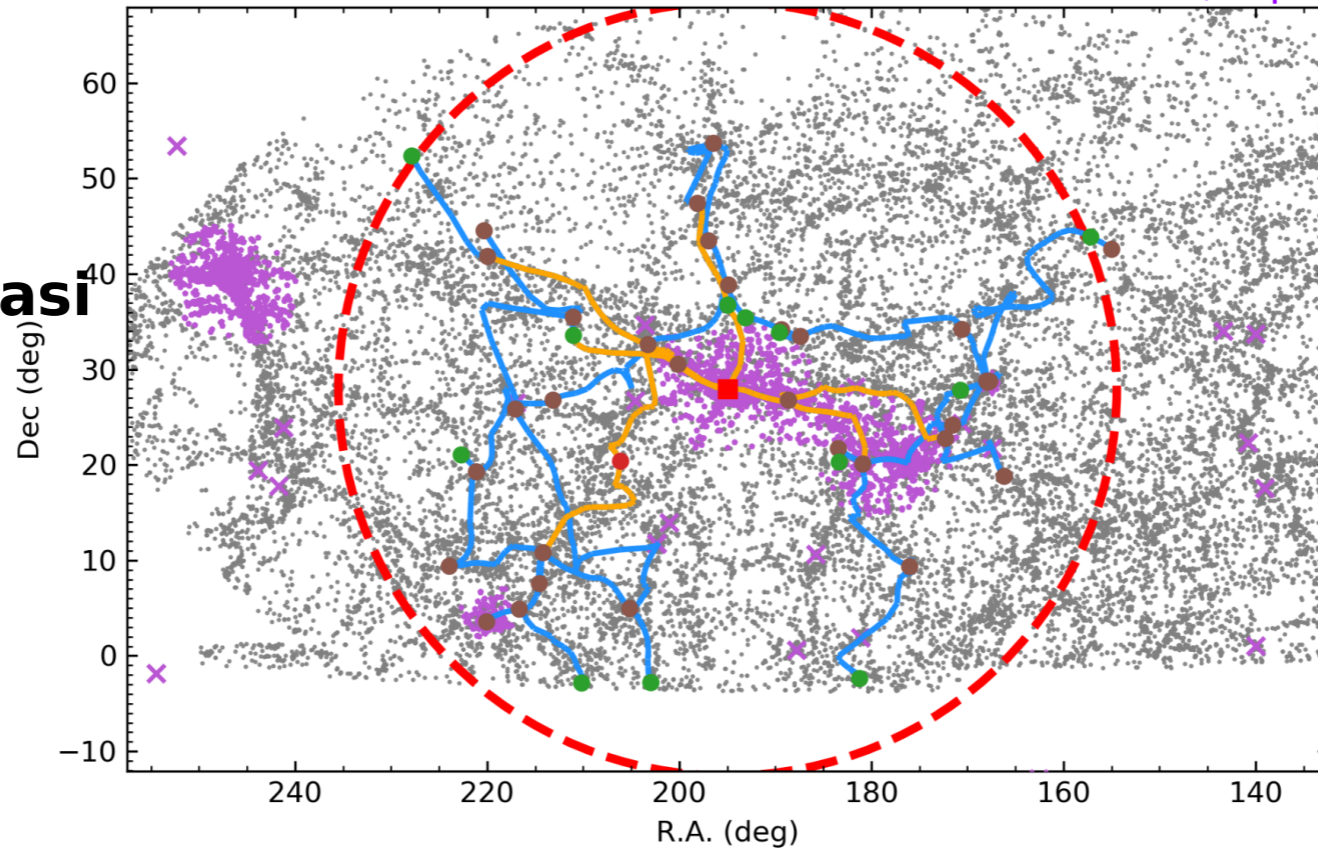
Cosmic web in VIPERS, Malavasi+ '17

Coma cluster in its LSS environment

Malavasi+ '19, in prep

Filaments connecting  
Maxima, saddles,  
bifurcations

Poster by N. Malavasi



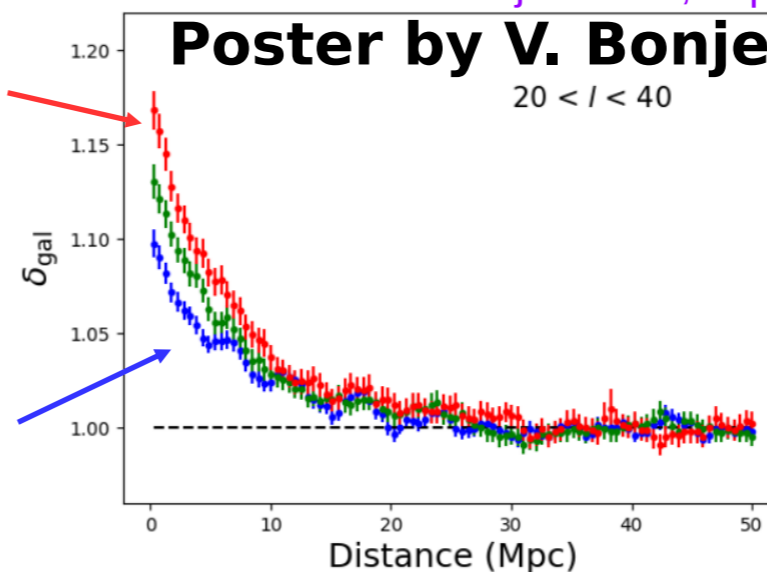
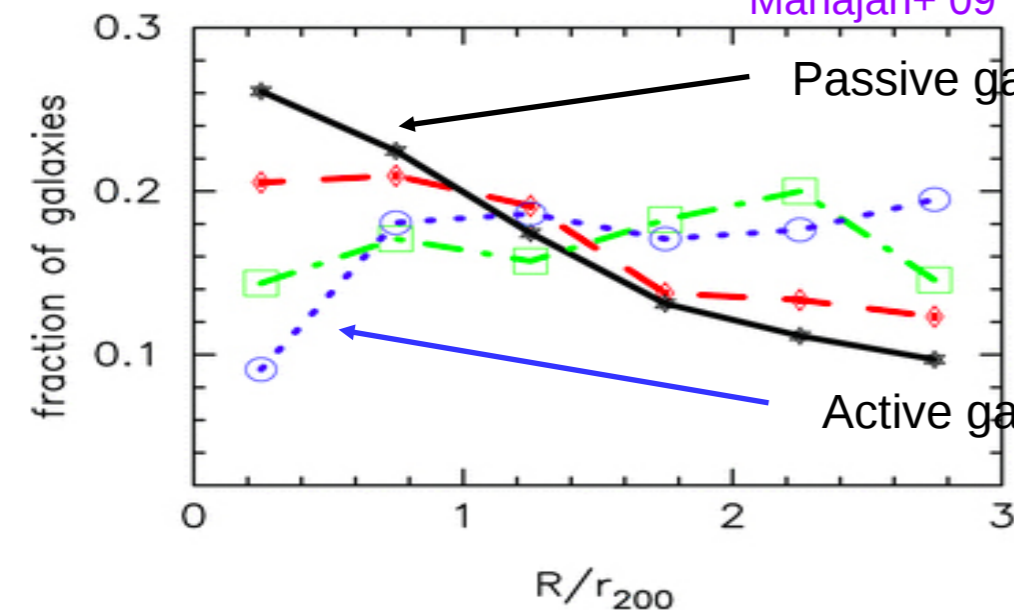
Galaxies in clusters ...

Mahajan+ 09

Bonjean+ 19, in prep

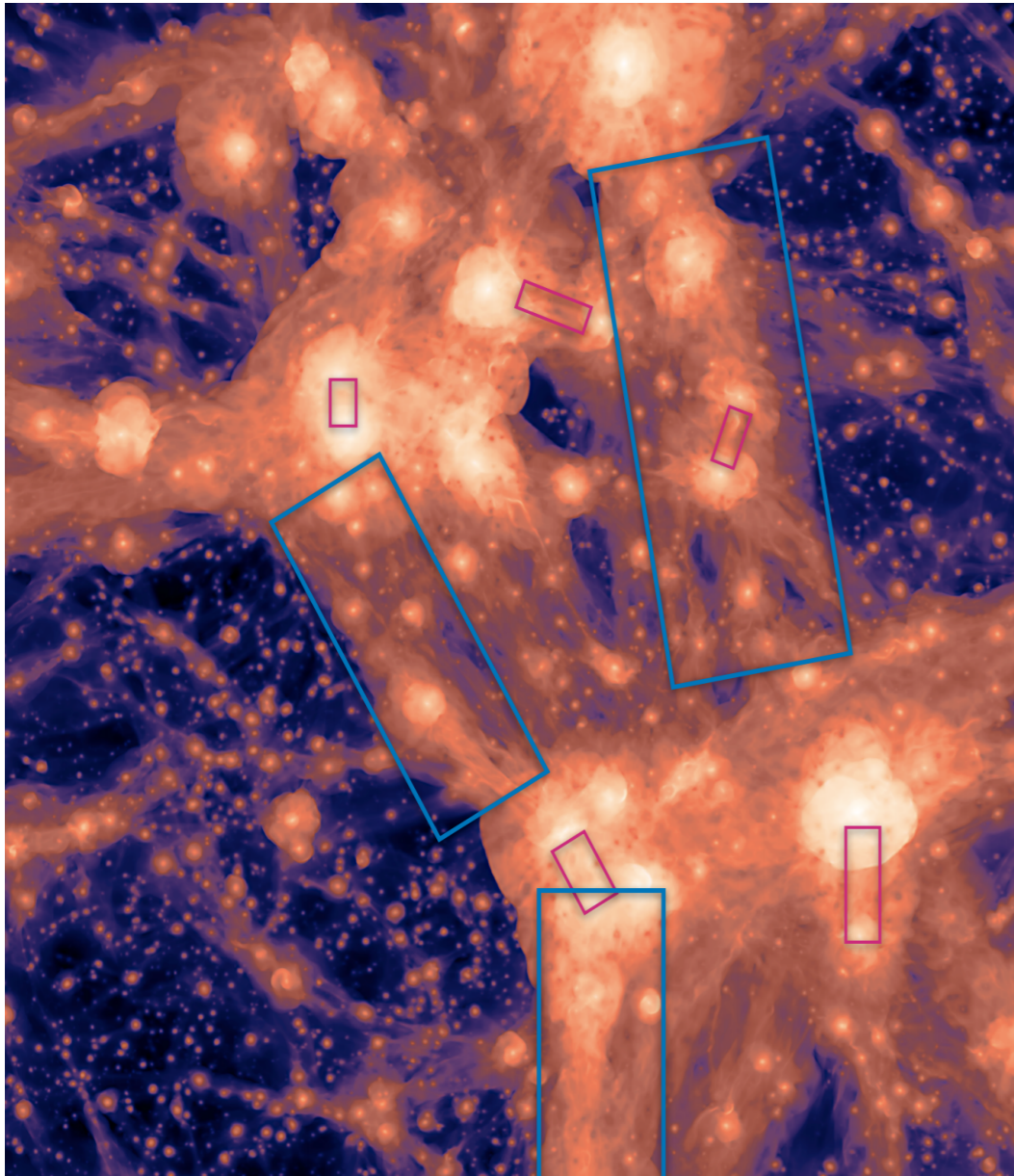
Poster by V. Bonjean

20 < l < 40



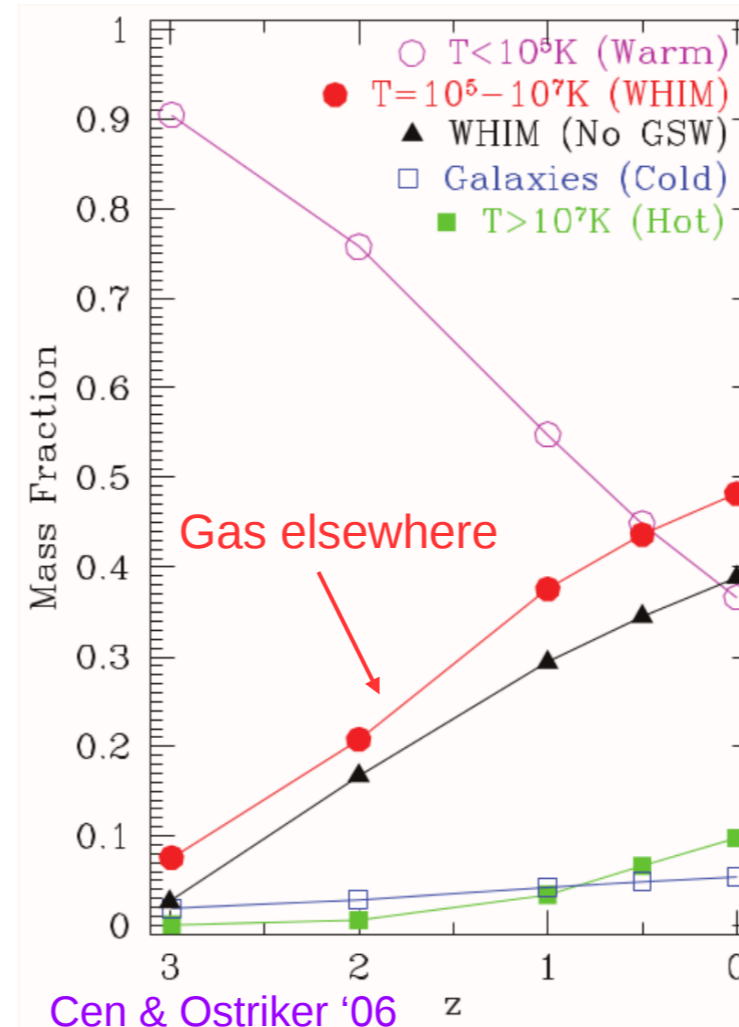
With DISPERSE (Sousbie+ '11):  
Geometric 3D ridge extractor

# A Cosmic web of gas

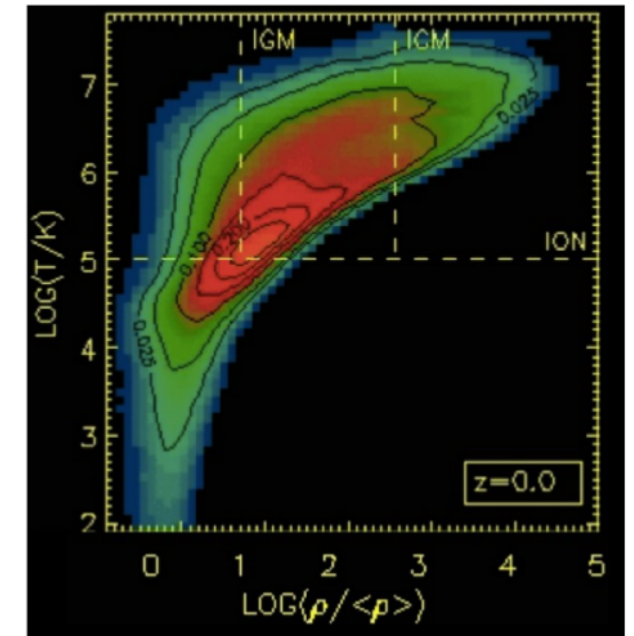


Courtesy F. Vazza

Clusters = nodes  
 Superclusters = multiple systems  
 Bridges between (interacting) clusters  
 Cosmic filaments



Cen & Ostriker '06



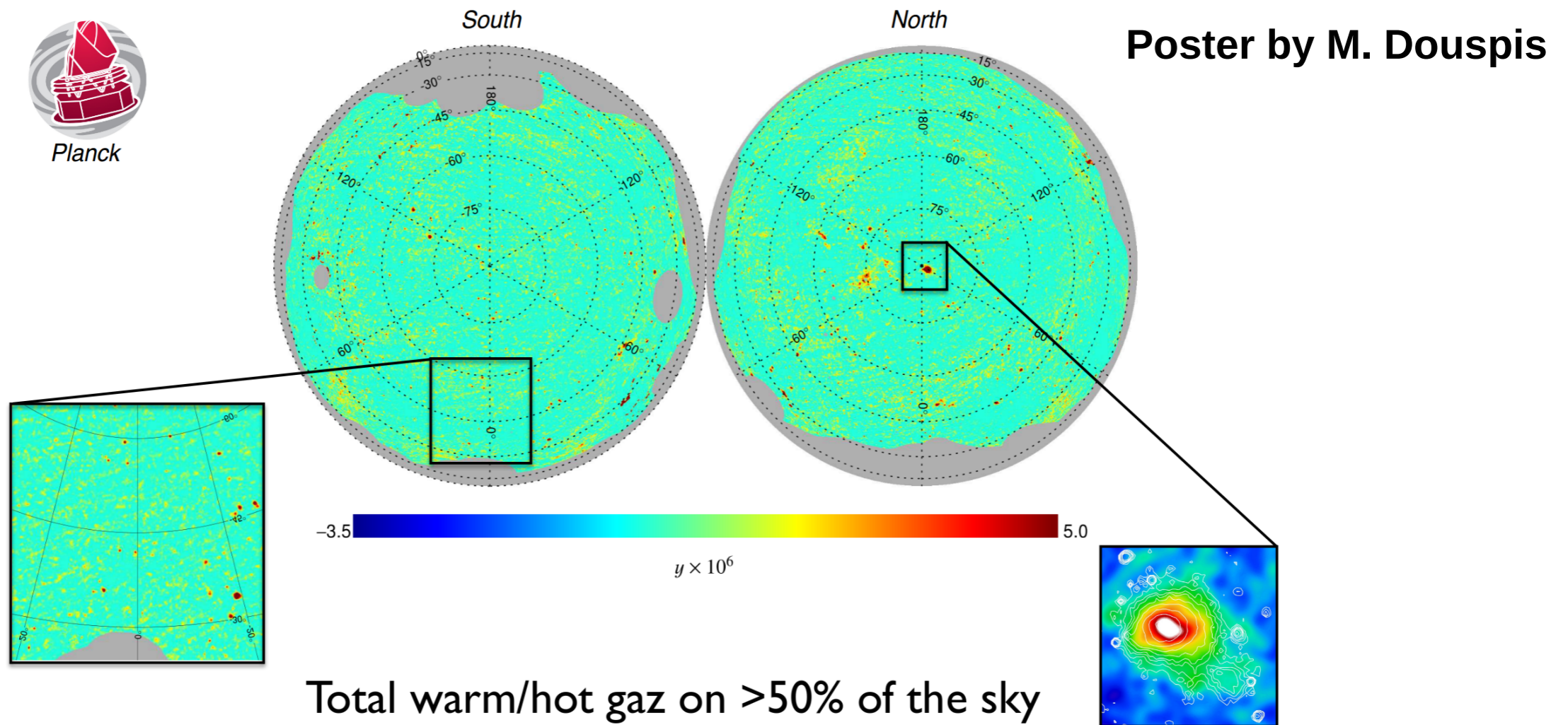
CLEF sim: Da Silva & NA '04

Gas in clusters  
 galaxies

- Temperature/density phase distribution from hydrodynamic simulations suggests that a large fraction of the baryons are
- in the cosmic web outside virialised structures
  - at densities  $\sim 10$ - $100$  average cosmic density
  - temperature of  $10^5$  -  $10^7$  K

# Observing Hot baryons in the LSS

Ideal tracer of the hot/warm ionised gas → tSZ signal (available cluster catalog & tSZ map)



- Focus on the hot ionised baryons in cosmic web elements such: bridges, filaments, superclusters  
→ Complementary to the approach focusing on cluster outskirts
- Informed (combined) search of the hot ionised baryons → search for tSZ signal using the galaxy distribution

# Hot baryons from cross-correlation

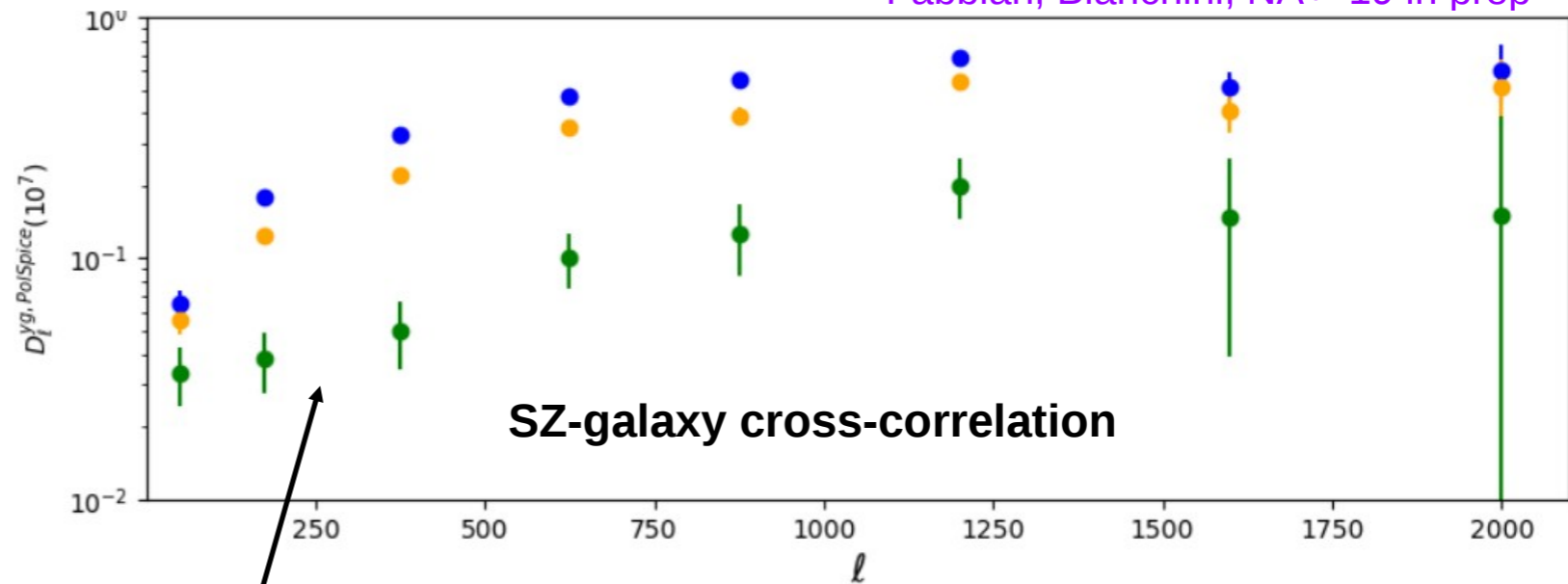
Correlation of Planck tSZ map with WISExSCOSMOS galaxies in  $0.1 < z < 0.3$   
(added value catalog from Bonjean+ 2019)

Cross-correlation detected with **S/N~40: dominated by signal from clusters**

SZ map contaminated at small scales by foregrounds e.g. CIB  
→ **Statistical detection of tSZ gas outside clusters with S/N~4** (after group and cluster masking & foreground cleaning)

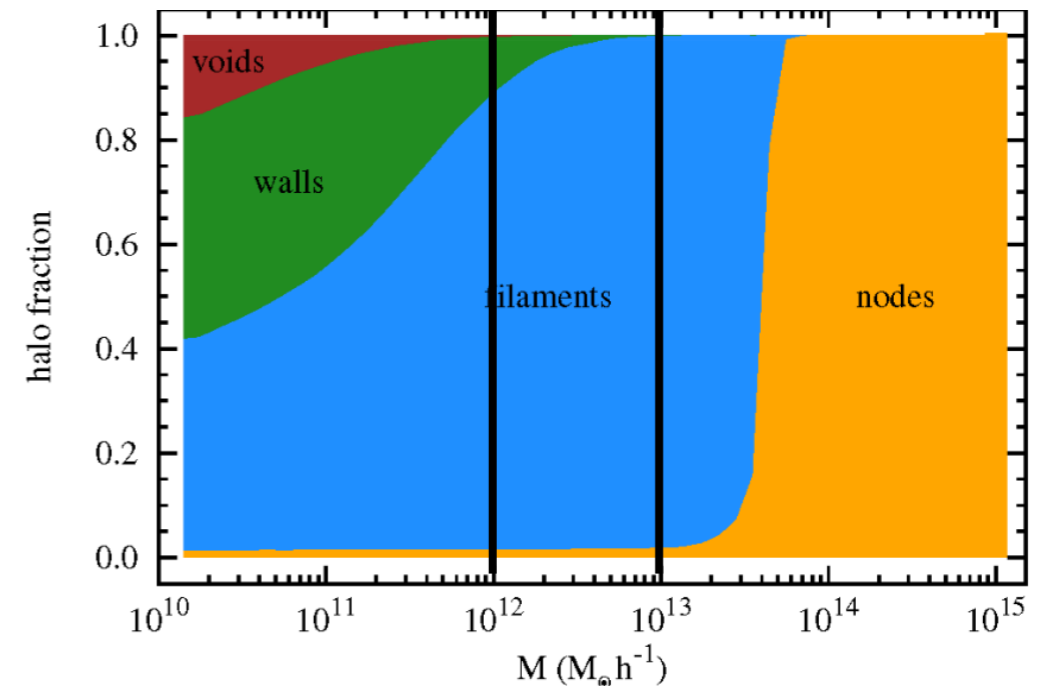
DM halos used for the correlation with estimated masses from  $10^{12}$  to  $10^{13} M_{\text{sun}}$  → representative of the halos populating filaments

Fabbian, Bianchini, NA+ '19 in prep



Masked groups & clusters

Cautun+ '14

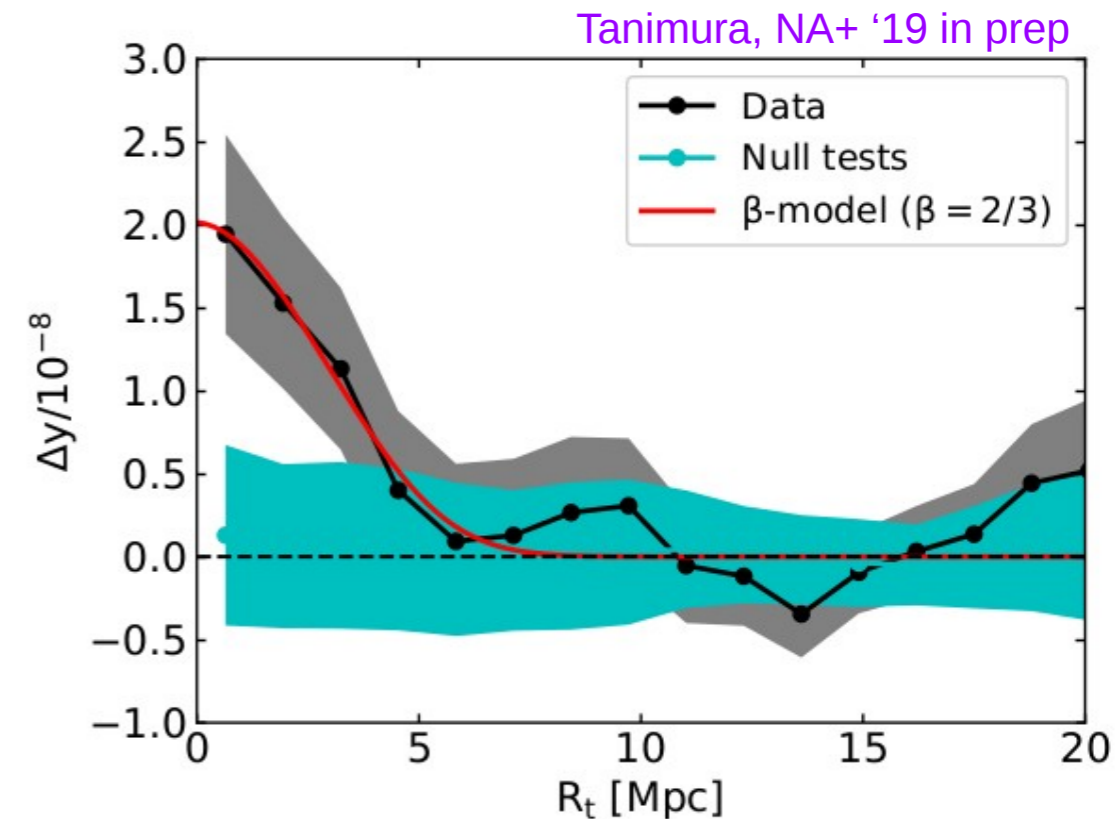


# Hot baryons in cosmic filaments

From cross-correlation analysis to stacking analysis

Poster by H. Tanimura

Stacking analysis based on a catalog of  $\sim 23000$  filaments extracted with DISPERSE from SDSS DR12 (cf. N. Malavasi)  
Length 30 to 100Mpc, redshift  $0.2 < z < 0.6$   
Clusters down to  $10^{13} M_{\text{sun}}$  masked by  $3 \times R_{500}$ .



**tSZ signal from hot baryons in cosmic filaments** statistically detected with **S/N $\sim$ 3**  $\rightarrow$  consistent with tSZ-galaxy cross-power spectrum

Stacking analysis provides a description of the cosmic filaments

- Average filament width  $\sim 5$  Mpc
- Average Density  $\delta \sim 4$
- Average temperature  $\sim 10^6$  K

# Hot baryons in cluster-pair bridges

Stacking  $2.6 \times 10^5$  LRG pairs: centers of groups and clusters ( $0.05 < z < 0.40$ ,  $M > 10^{11.3} M_{\text{sun}}$ )

Cluster separation = 6 – 10 Mpc

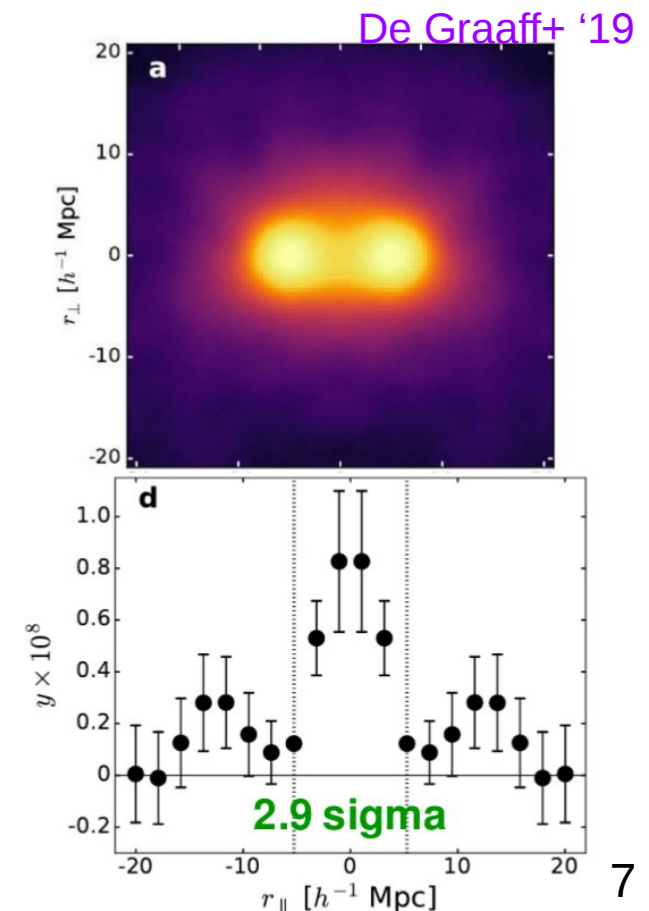
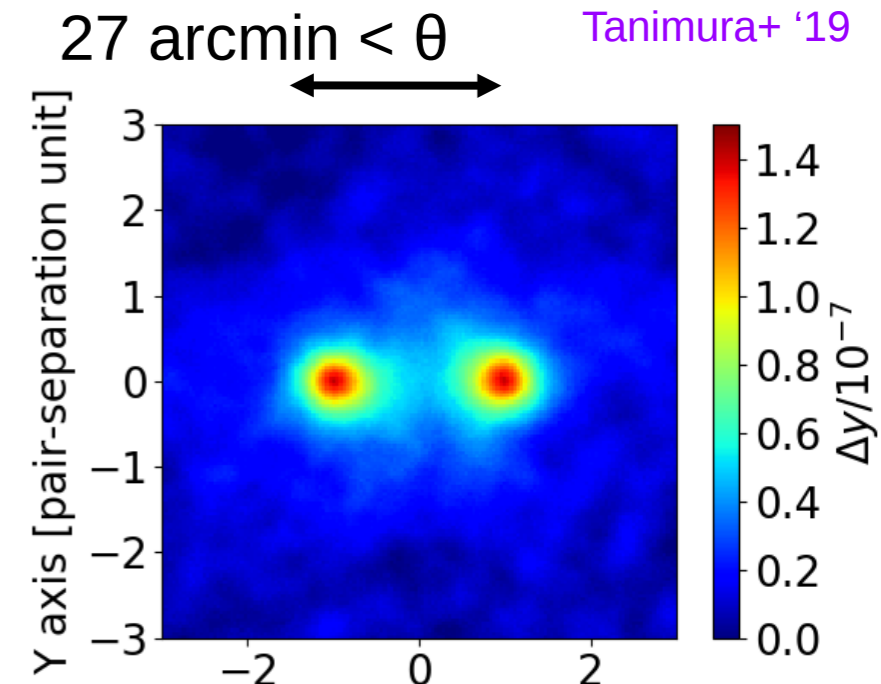
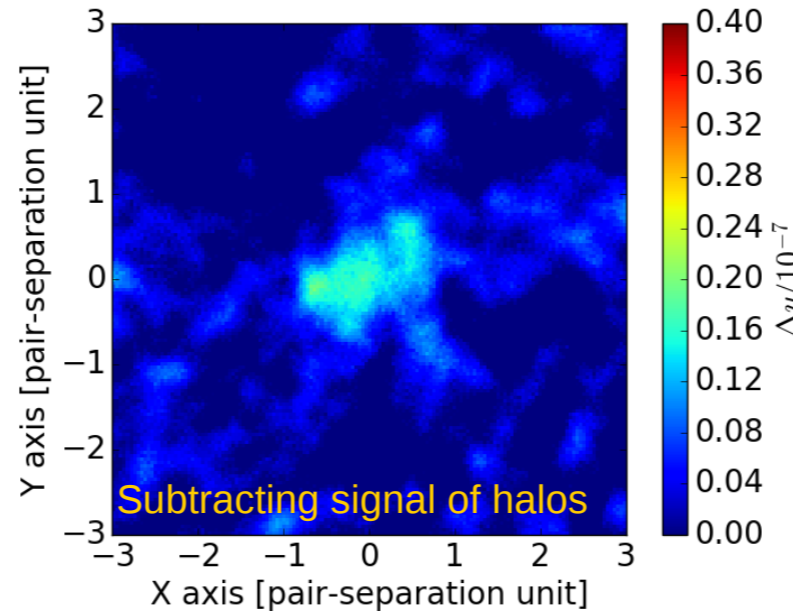
**tSZ signal between LRGs** →  
 $y = 1.31 \times 10^{-8}$  detected at  $5.3\sigma$

Consistent with numerical simulations

See also de Graaff+ '19 at higher redshift

- Cylindrical bridges of length 6 – 10 Mpc
- Temperature  $T_e \sim 3 \times 10^6 \text{K}$
- Average over-density  $\delta \sim 3$  → consistent with stacking analysis of CFHTLenS mass map from Epps & Hudson '17 ( $\delta \sim 4$ )

In pairs and multiple systems (e.g. superclusters) clusters are linked by bridges of matter



# Hot baryons in superclusters

689 superclusters (Liivamägi+ '12) SDSS [ $z < 0.2$ ;  $R_{sc} \sim 18$  Mpc] →  
**tSZ signal at  $6.4\sigma$** , mainly from cluster contribution

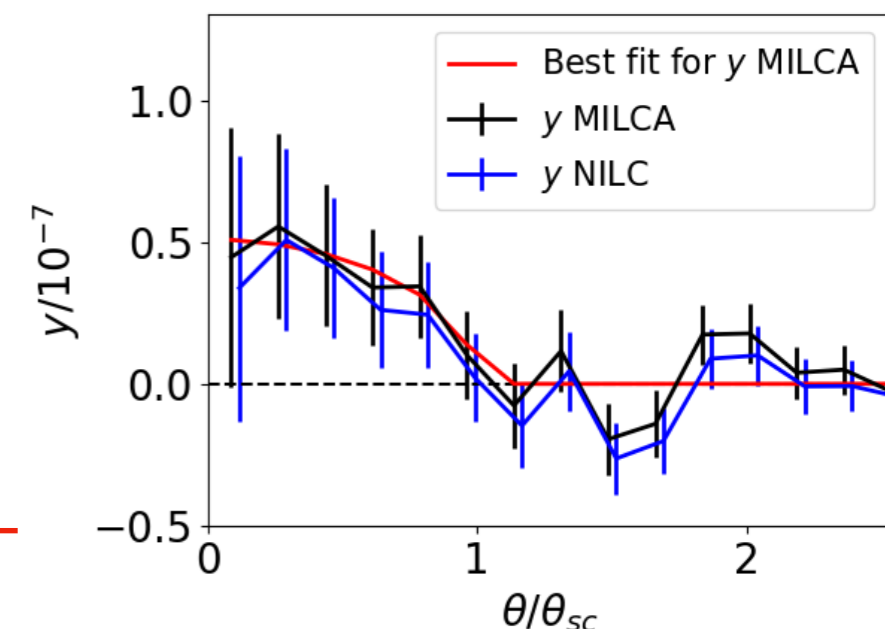
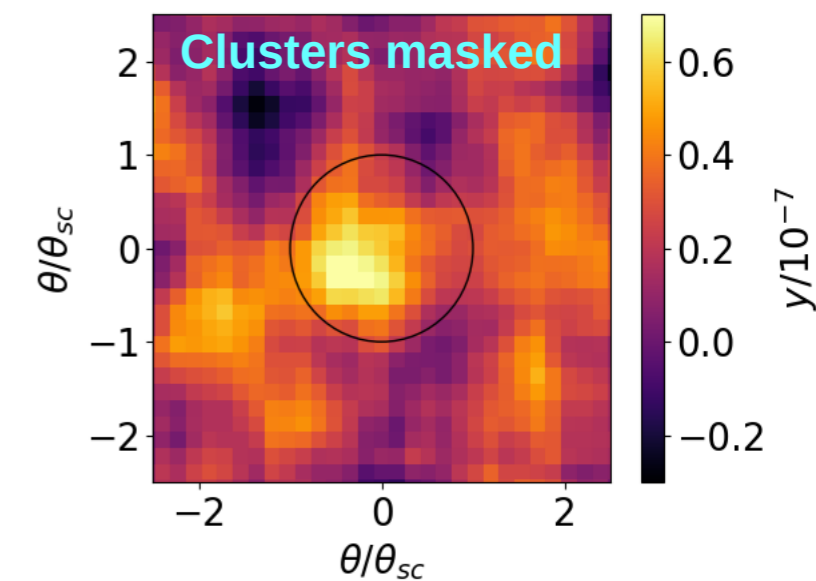
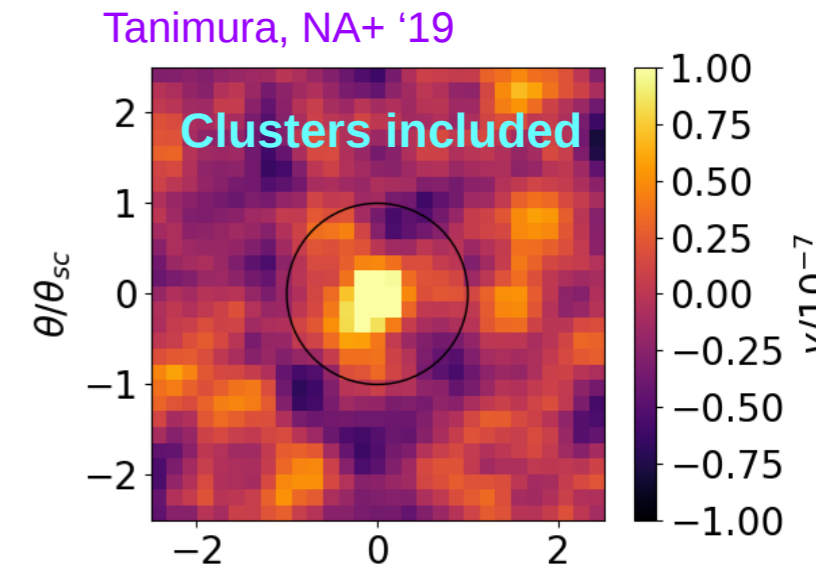
Groups & clusters down to  $10^{13} M_{sun}$  masked by  $3 \times R_{500}$ .

**tSZ signal from intercluster baryons** in superclusters detected at  **$2.5\sigma$**

tSZ profile fitted with an isothermal constant density profile for the intercluster gas → Average density  $\delta \sim 10$

- tSZ signal from hot baryons observed in all cosmic web elements (filaments, bridges, superclusters)
- Hot baryons in the cosmic web elements account for large fractions of the hidden baryons ( $\sim 17$  to  $50\%$ )

→ Range reflects “unknowns” about the models → need construct models from observation of individual systems and from simulations



# Bridges: Exceptional pair A399-A401

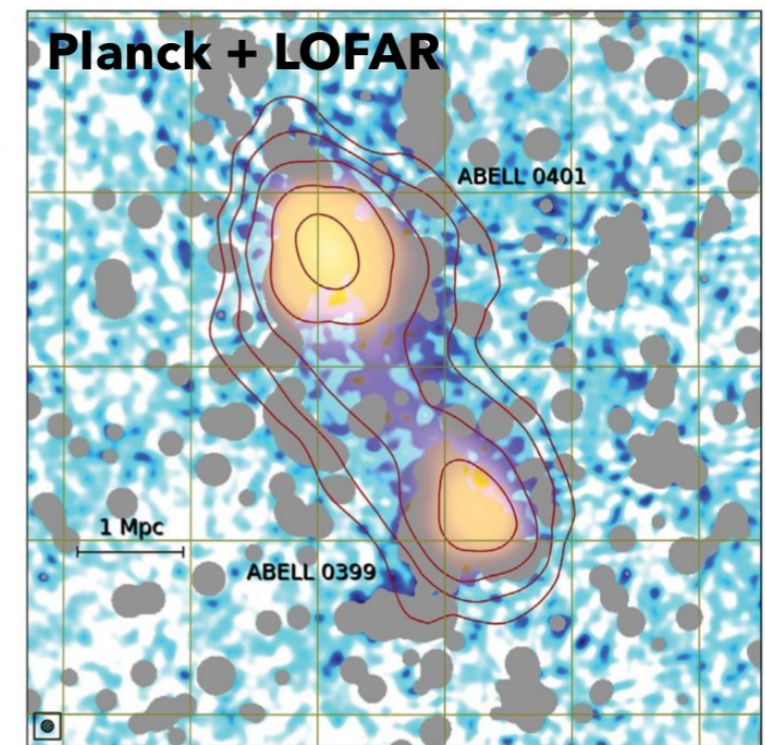
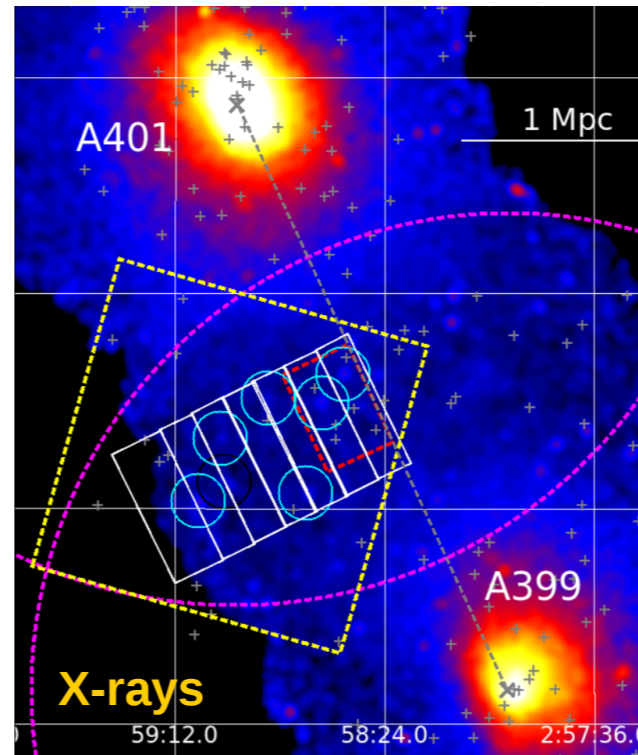
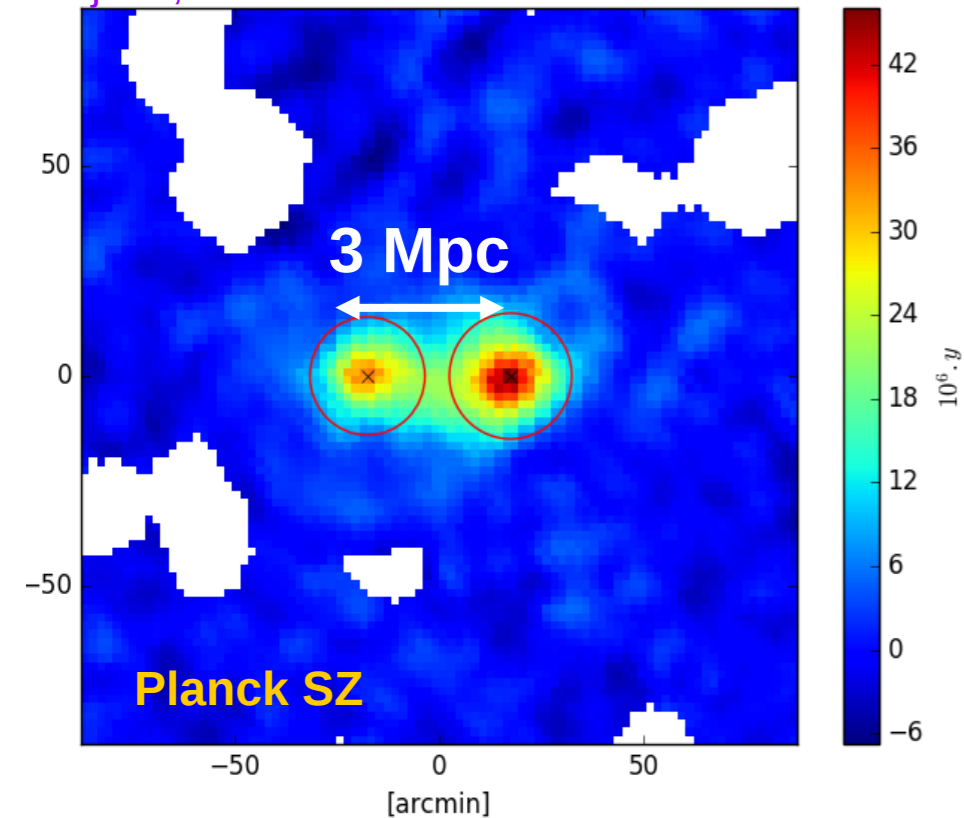
Observation in X-rays, SZ, radio Detailed characterisation of the gas between clusters

(Fujita et al. '96, '08, Sakelliou et al. '04, Planck collab. VIII '13)

Bonjean, NA+ '18 **S/N<sub>fil</sub>=8.7**

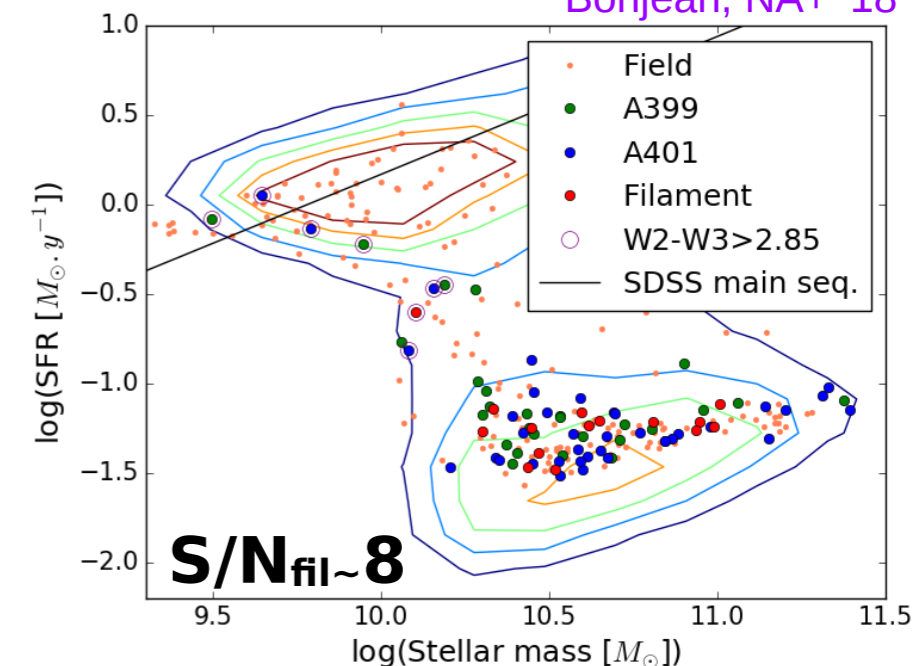
Akamatsu+ '17

Govoni+ '19



Bonjean, NA+ '18

- Planck's SZ signal:  $P_0 = (2.8 \pm 0.27) \times 10^{-3} \text{ keV cm}^{-3}$
- SUZAKU's Xrays: metallicity; Temperature break from isothermal  $T_e = 6.5 \pm 0.5 \text{ keV}$ ,  $n_e = (4.3 \pm 0.7) \times 10^{-4} \text{ cm}^{-3}$
- WISExCOSMOS: Passive galaxies in bridge & clusters
- LOFAR: radio ridge indicates magnetic field
- Simulations: 50% gas particles in bridge come from cluster outskirts  $>R_{\text{vir}}$



# Superclusters: individual systems

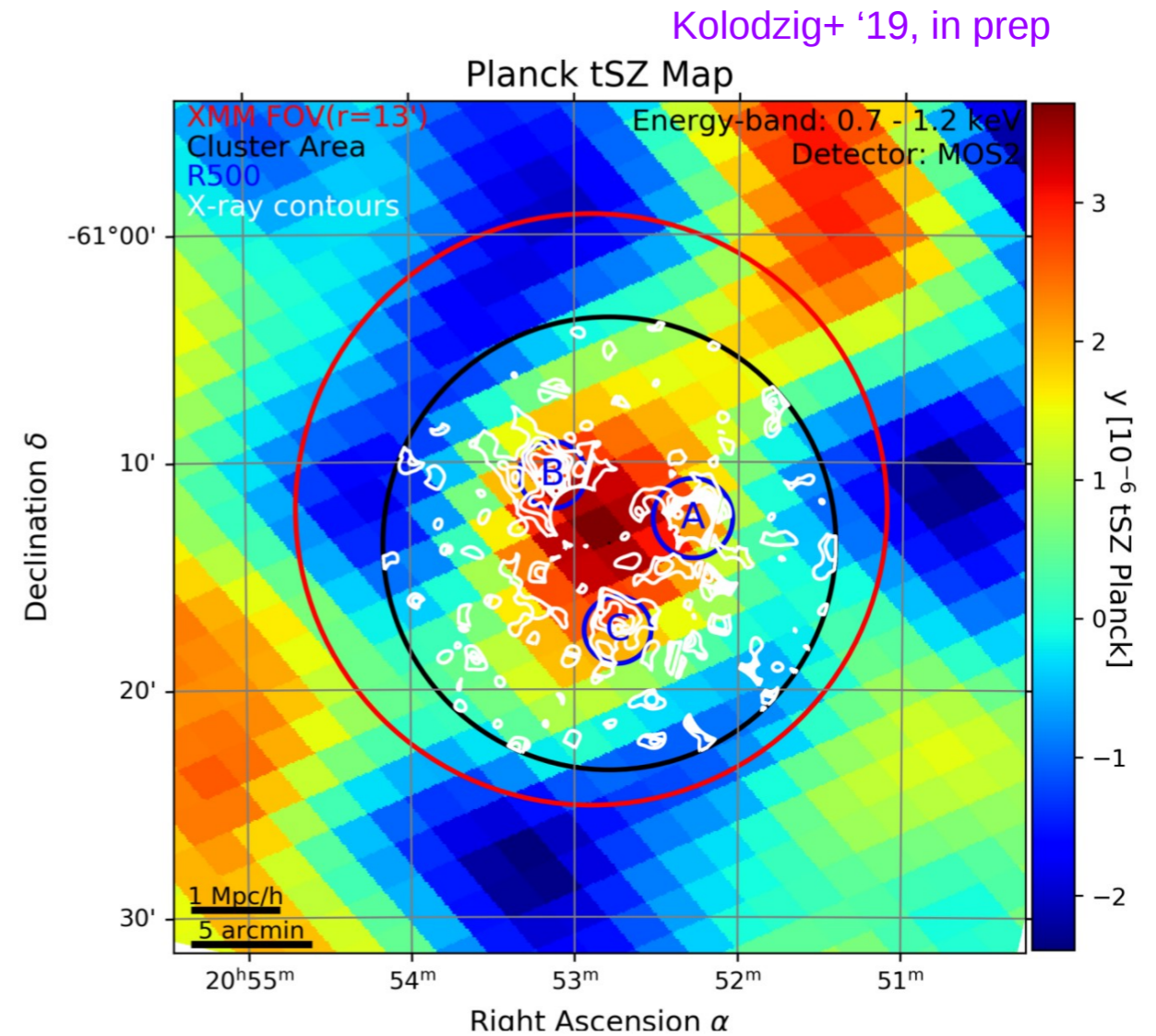
Multi-frequency analysis of superclusters  
with X-rays, tSZ and optical data

Example PLCK G334.8–38.0

$z \sim 0.35$

$M_{500} \sim (1 \text{ to } 2) \times 10^{14} M_{\text{sun}} / \text{cluster}$

- Very few pairs or multiple systems have suitable data for joint analyses
- What is the representativity of the selected systems
- Simulations should be used to help constructing realistic models



# Summary & Conclusions

Eckert+ 16

- Galaxy distribution → key tracer of the cosmic web & mature research topic
- Study of the hot gas in Cosmic web at low redshifts in its infancy with already **promising results**:
  - From first detection of filaments in A2744 outskirts to evidence of hot baryons in the largest cosmic structure (superclusters, filaments, etc.)
  - Hot baryons in the cosmic web elements account for large fractions of the hidden baryons
  - Detailed studies of individual structures (cluster pairs, superclusters) as benchmark for physical models calibrated with simulations & Systematic, statistical analyses of large sample of filaments, superclusters, etc. for baryon to DM scaling/calibration
- ... and **open questions**:
  - What is the connection between bridges/filaments and cluster outskirts? Are they filled with ICM or WHIM?
  - How can they trace non-thermal processes from turbulence or/and cosmic rays?
  - How do gas affect galaxy evolution?
- Bright prospects from the data side in X-rays [Athena, XARM]; Radio [LOFAR, SKA]; SZ [NIKA2, SPTPol/AdvACT, Simons Obs.]

