The hidden matter, some like it hot

Nabila Aghanim

Institut d'Astrophysique Spatiale,
CNRS & Univ. Paris Saclay (France)

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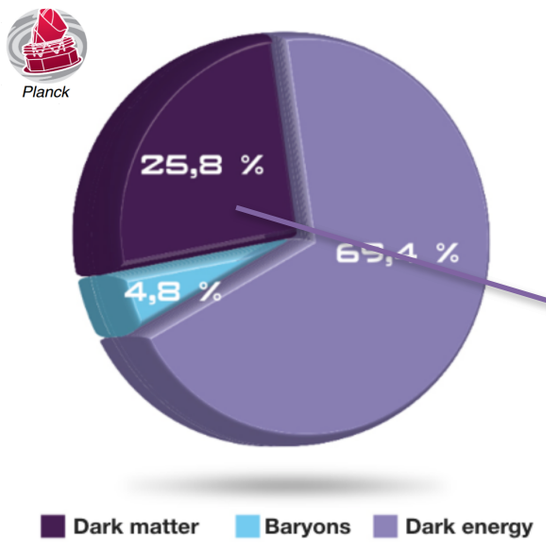
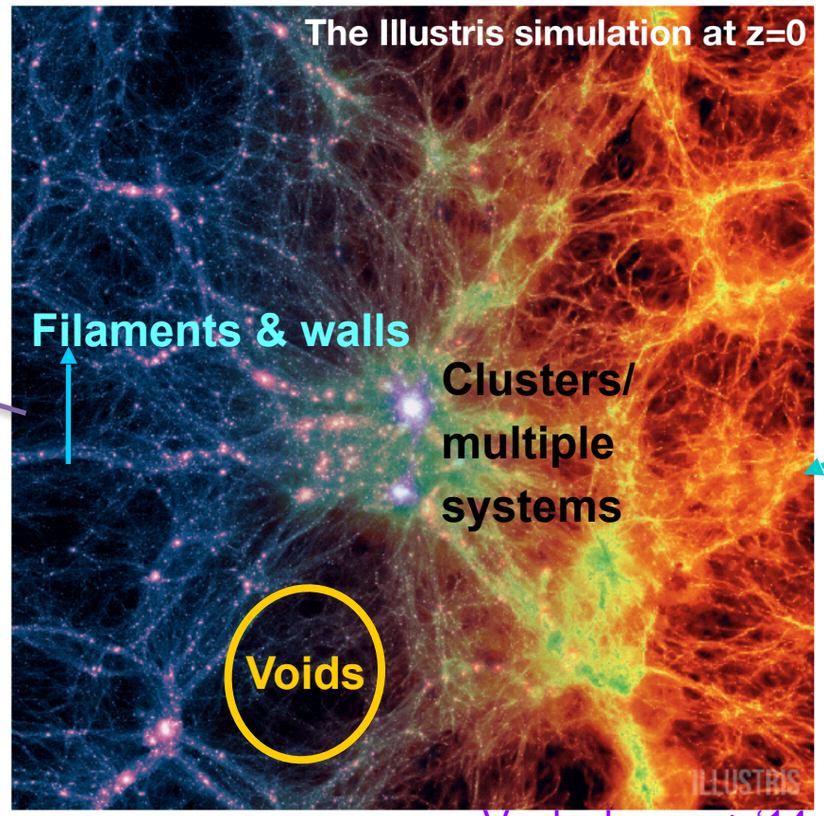
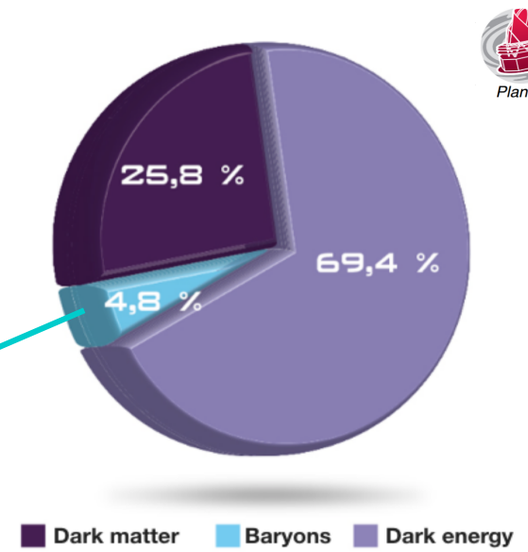
Matter in the cosmic web



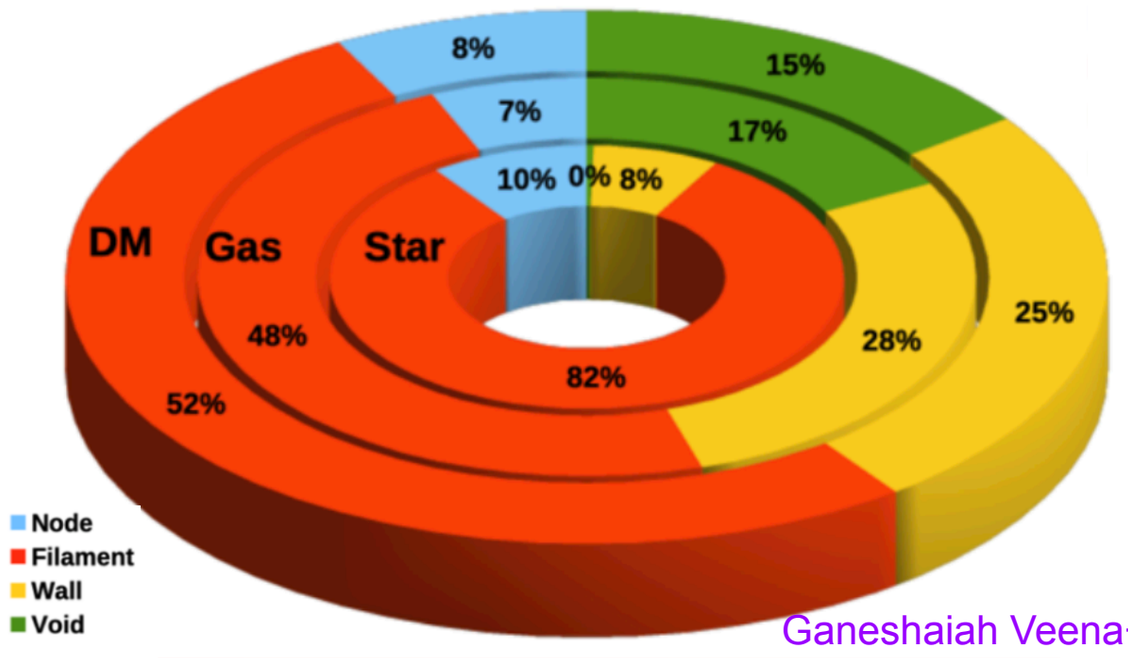




Dark matter

Baryonic matter

Voglesberger+ '14



Ganeshaiah Veena+ 19

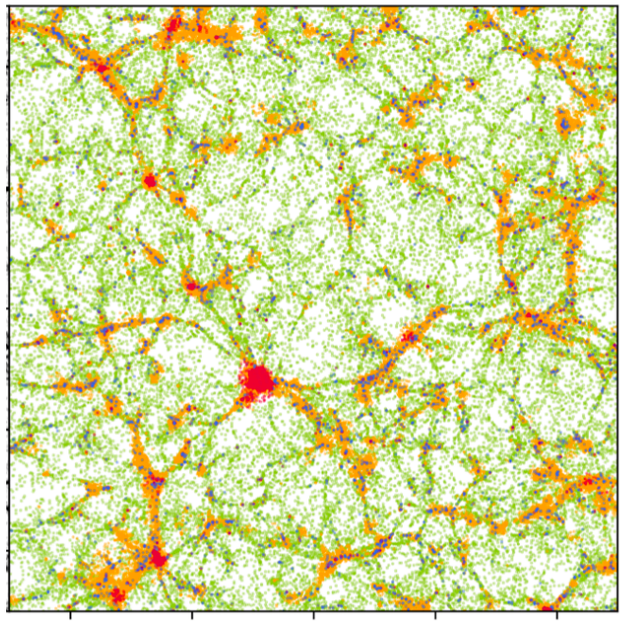
Filaments are:

- A dominant feature of the CW connecting nodes
- Contain most of the matter, in particular gas & stars

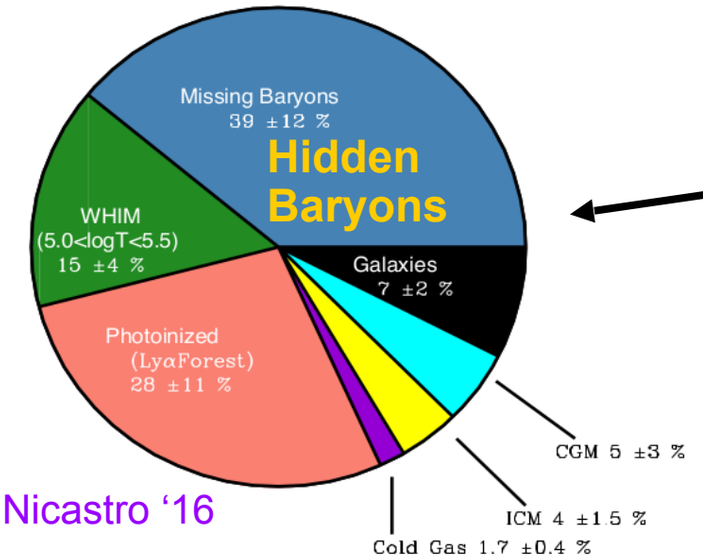
Baryonic matter in the cosmic web

Observations show that:
~10% baryonic matter in the form of galaxies
~90% baryonic matter in the form of gas
~40% baryonic matter not observed

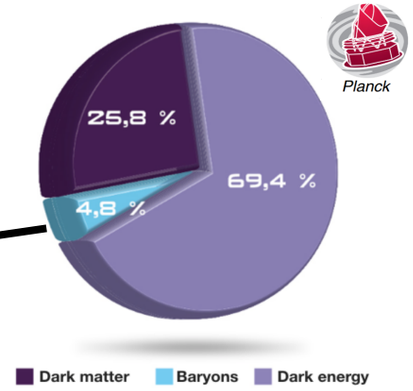
Simulations show that:
- Nodes contain hot (>10^7 K) baryons
- **Filaments contain warm/hot (10^5–10^7 K) baryons**

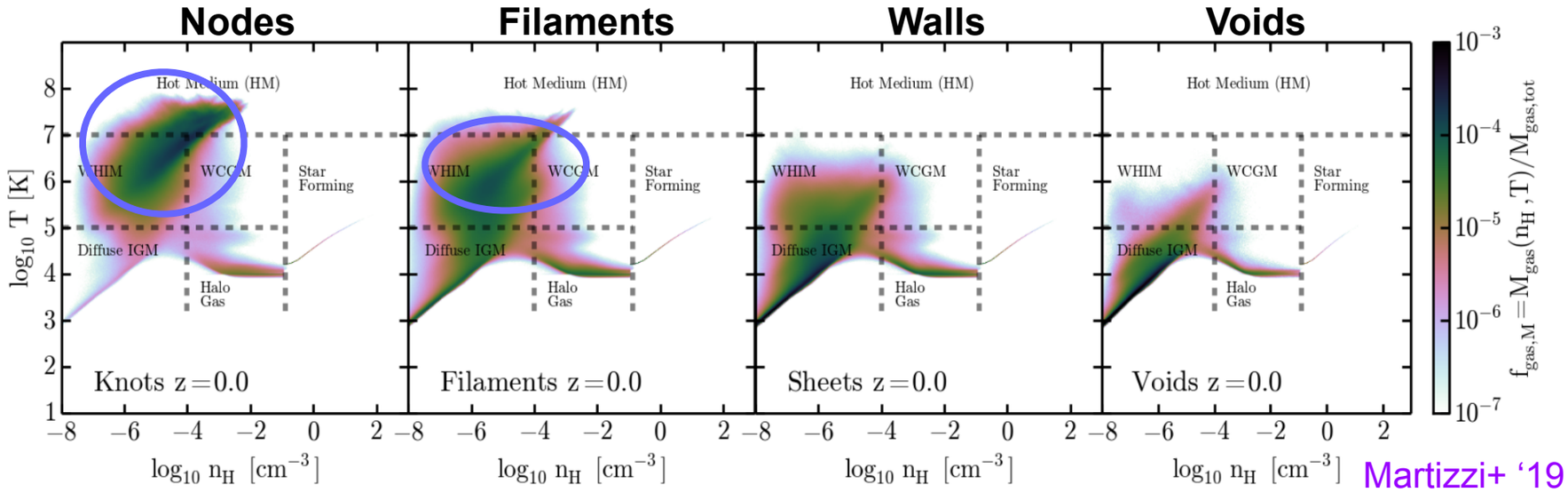


Galarraga PhD ‘21



Nicastro ‘16





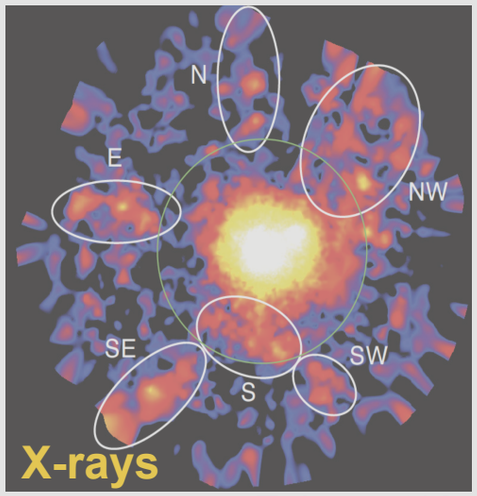
Martizzi+ ‘19

→ Filaments of the cosmic web are best reservoir for hidden matter as diffuse warm/hot ionised baryons

Searching for the hidden baryons in the cosmic web

Filaments everywhere!

Abell 2744



Eckert+ '16

"**Spider legs**"
connected to clusters

@small scale (~Mpc)

Pair A399-A401

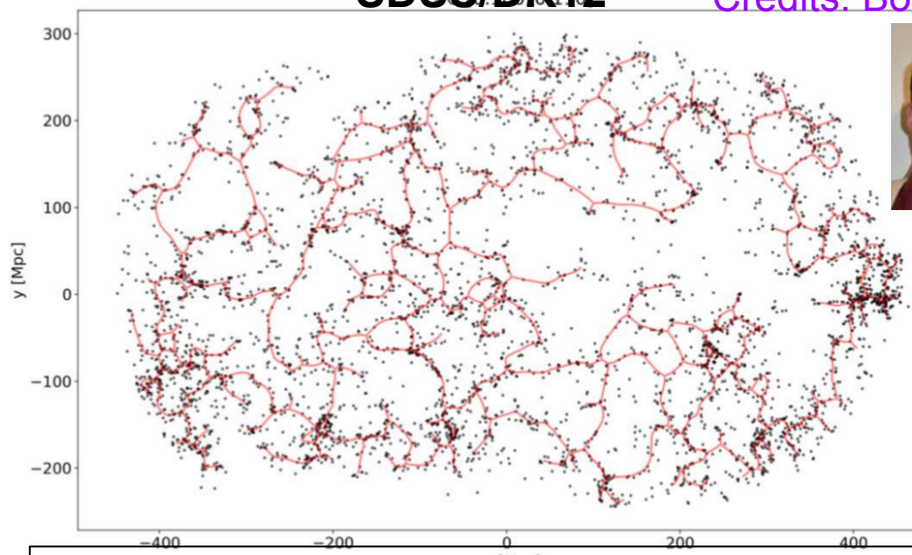
Credits: Planck collab

"**Bridges**"
between clusters

@intermediate (few Mpc)

SDSS/DR12

Credits: Bonnaire



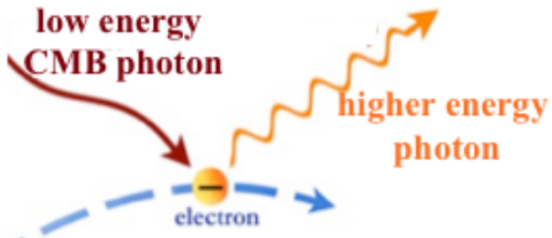
"**Cosmic filaments**"
surrounding voids & shaping the CW

@large (tens Mpc)

- Identify the **filaments** at different scales
- Search for evidence of hidden matter via **signatures of the hot baryons** at the location of the filaments
- Characterise the properties of the hot ionised baryons

Observables of the matter components

Inverse Compton
→ SZ effect

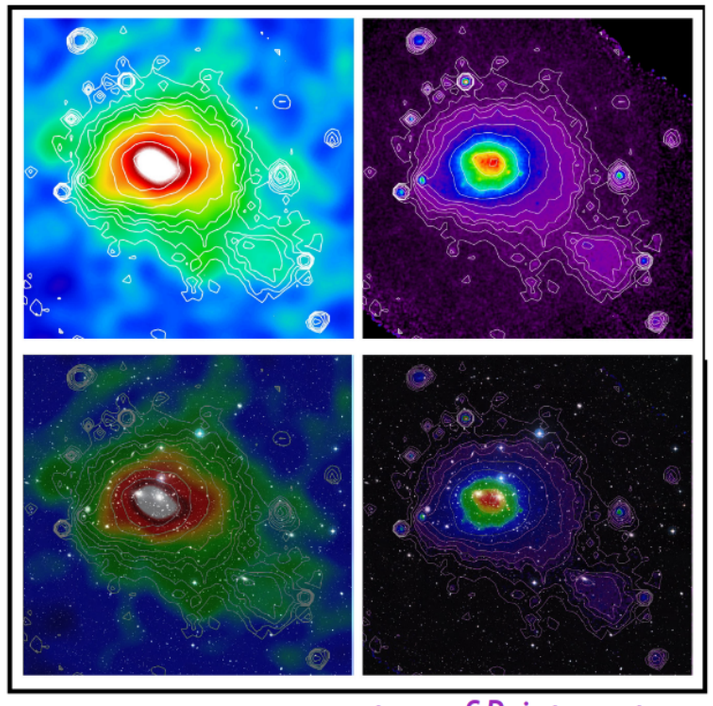


$$F_\nu \propto \int_\Omega (P = n_e T) d\Omega$$

Number of galaxies
→Optical/IR

Cold Gas

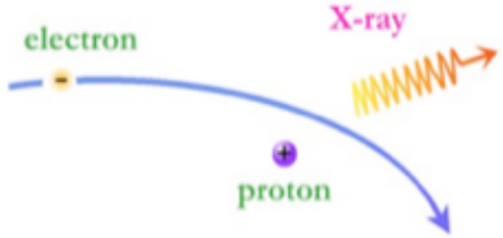
Hot Gas



courtesy of Pointecouteau

non thermal emission
→radio

Bremsstrahlung
→ X-ray emission



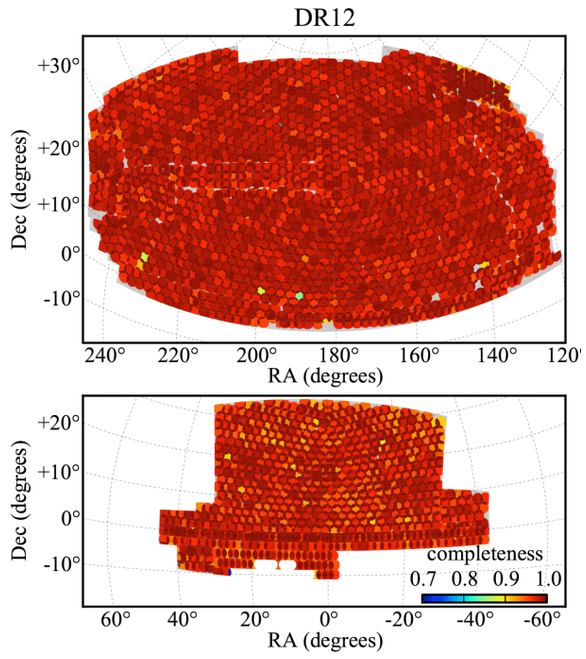
$$E_X \propto \int_V n_e^2 \Lambda(T) dV$$

Weak/Strong lensing
velocity dispersion
→Optical/IR

+Dark Matter

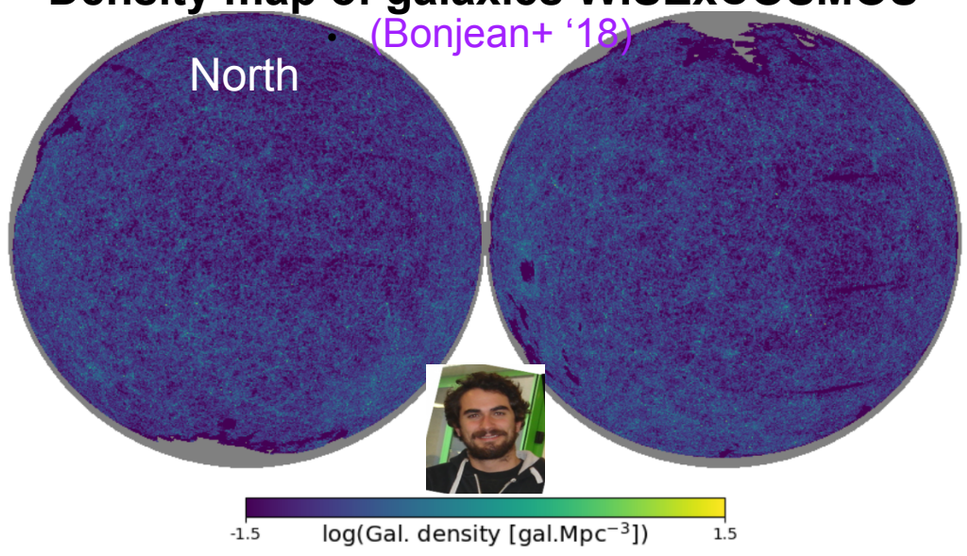
Observations of the matter components

SDSS DR12



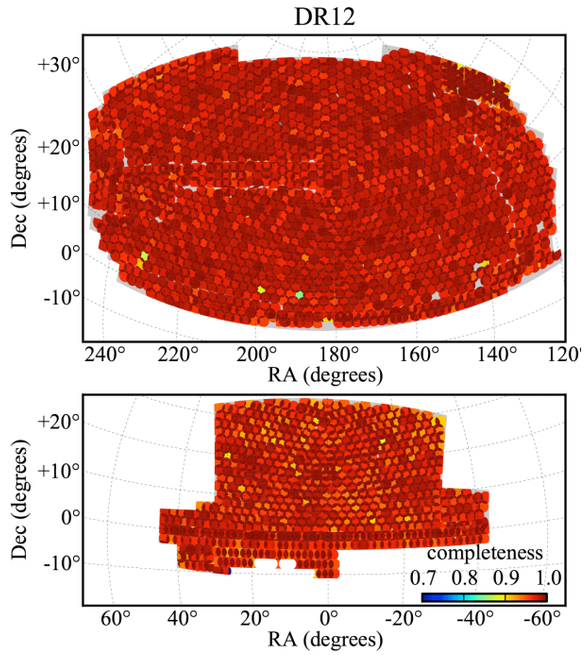
Density map of galaxies WISExCOSMOS

(Bonjean+ '18)

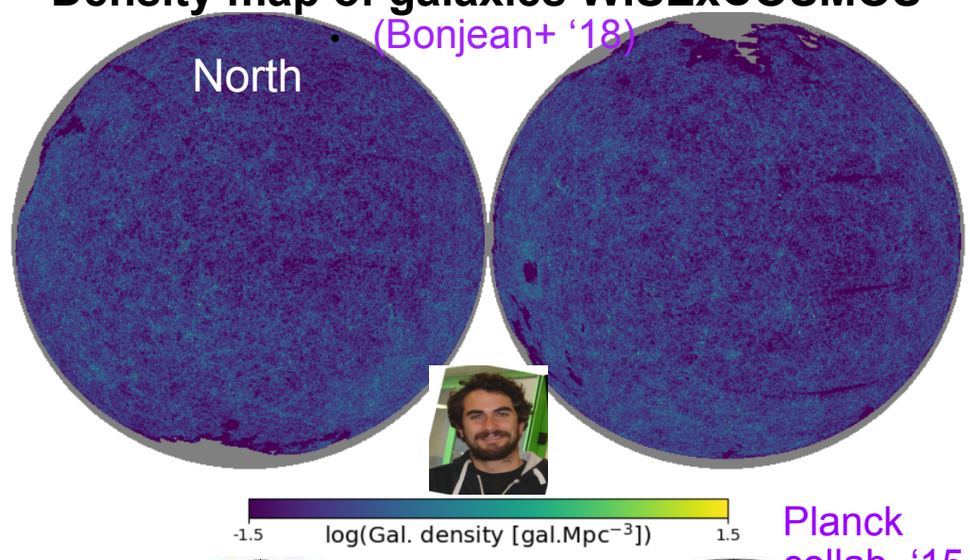


Observations of the matter components

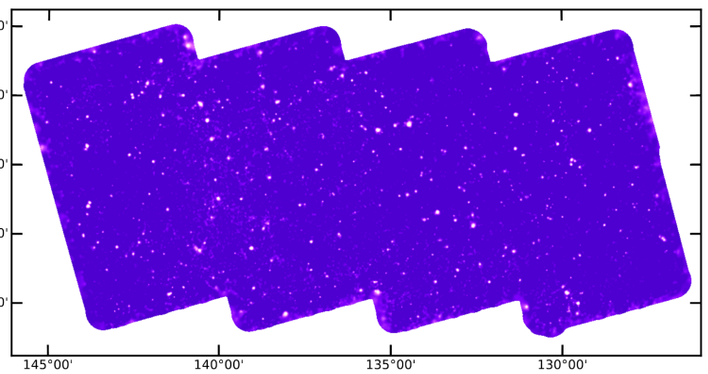
SDSS DR12

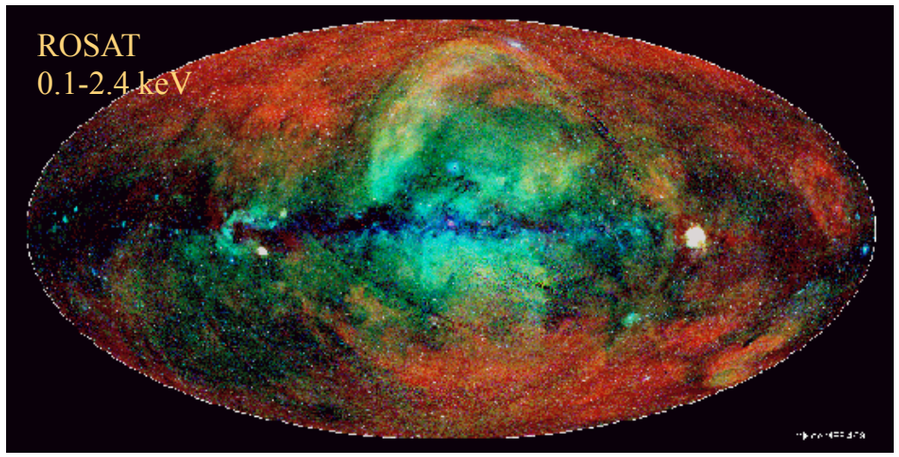


Density map of galaxies WISExCOSMOS (Bonjean+ '18)



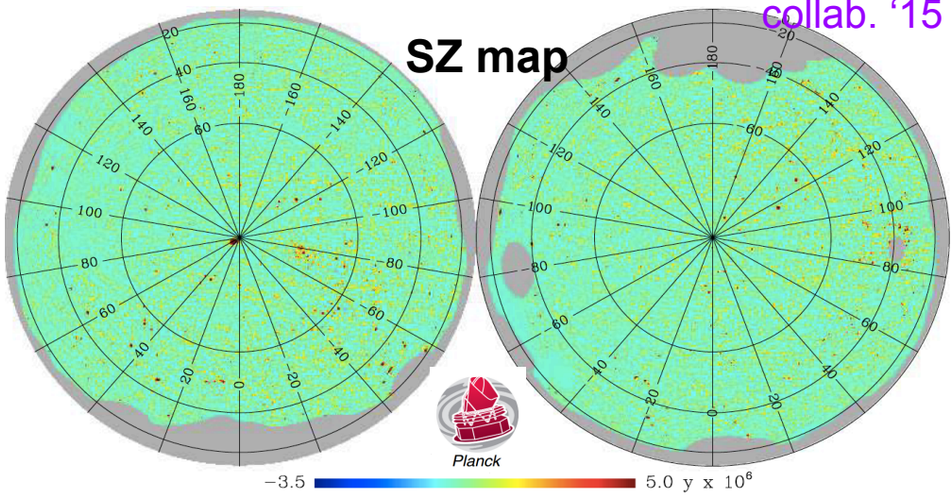
SRG/eROSITA eFEDS





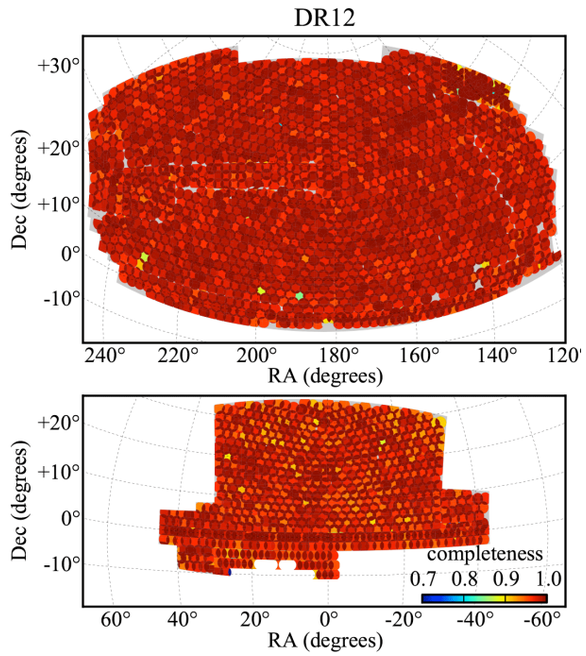
SZ map

Planck collab. '15



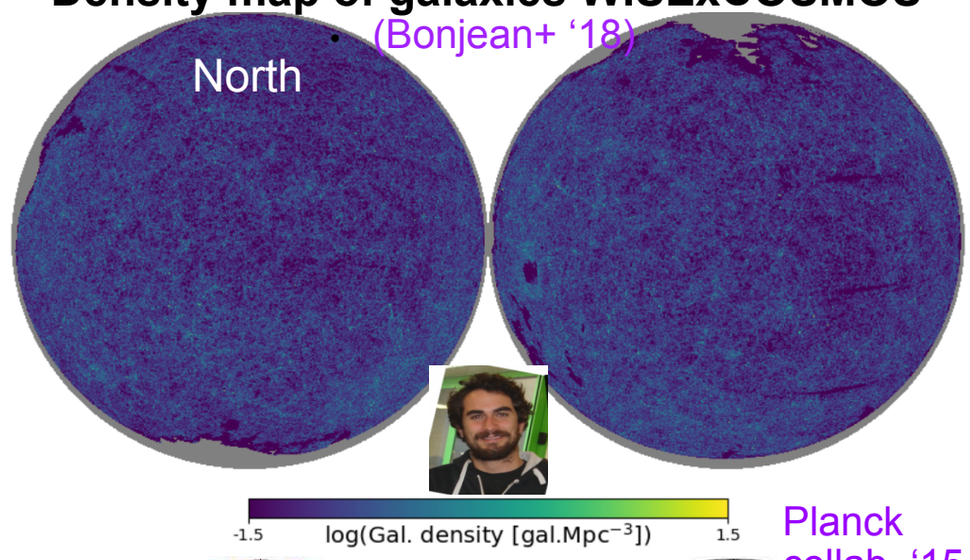
Observations of the matter components

SDSS DR12

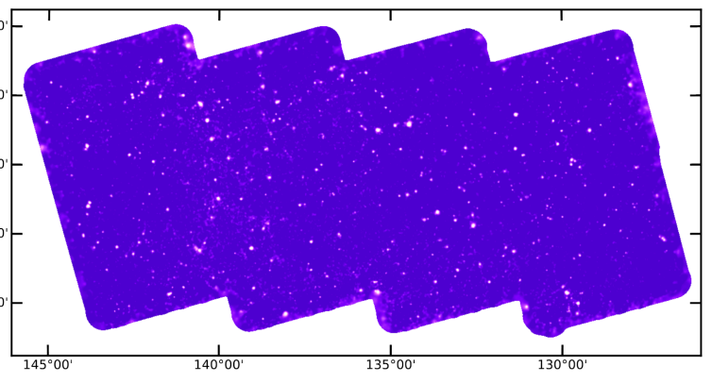


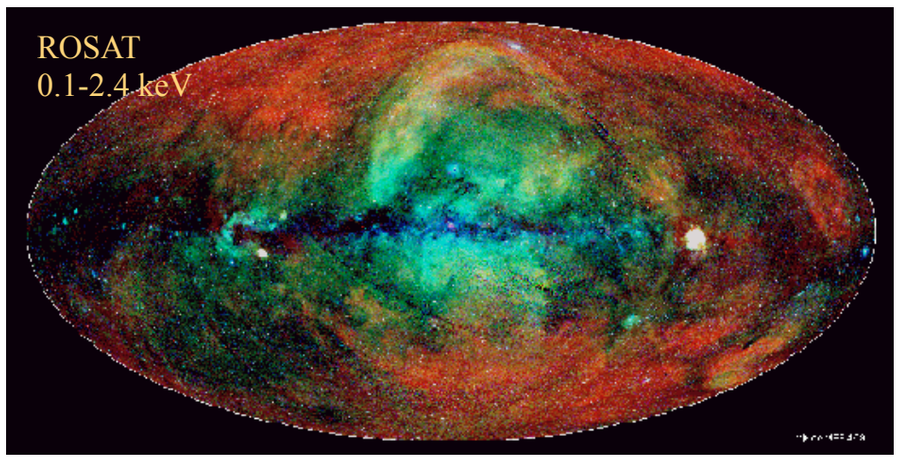
Density map of galaxies WISExCOSMOS

(Bonjean+ '18)



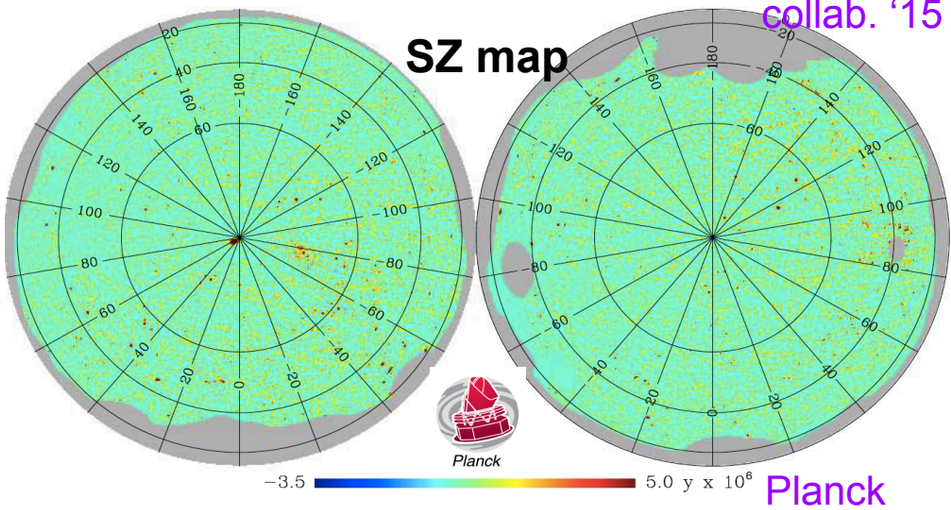
SRG/eROSITA eFEDS





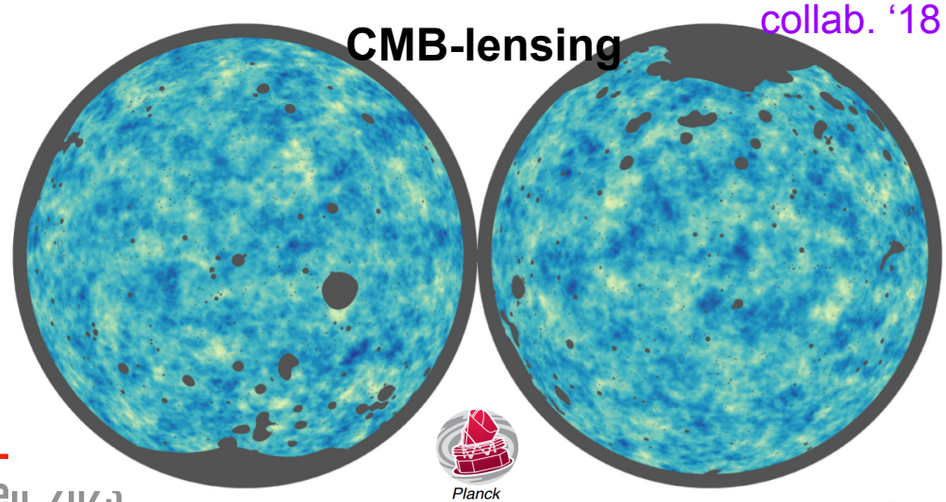
SZ map

Planck collab. '15



CMB-lensing

Planck collab. '18

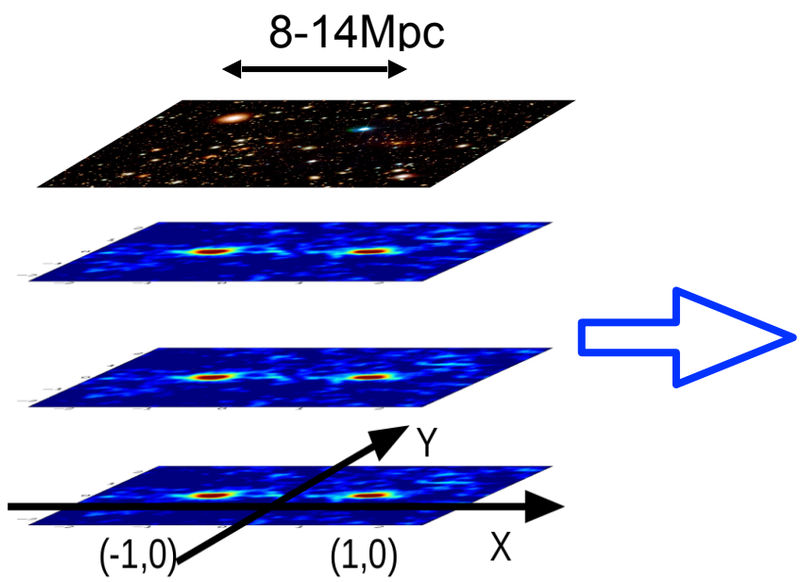


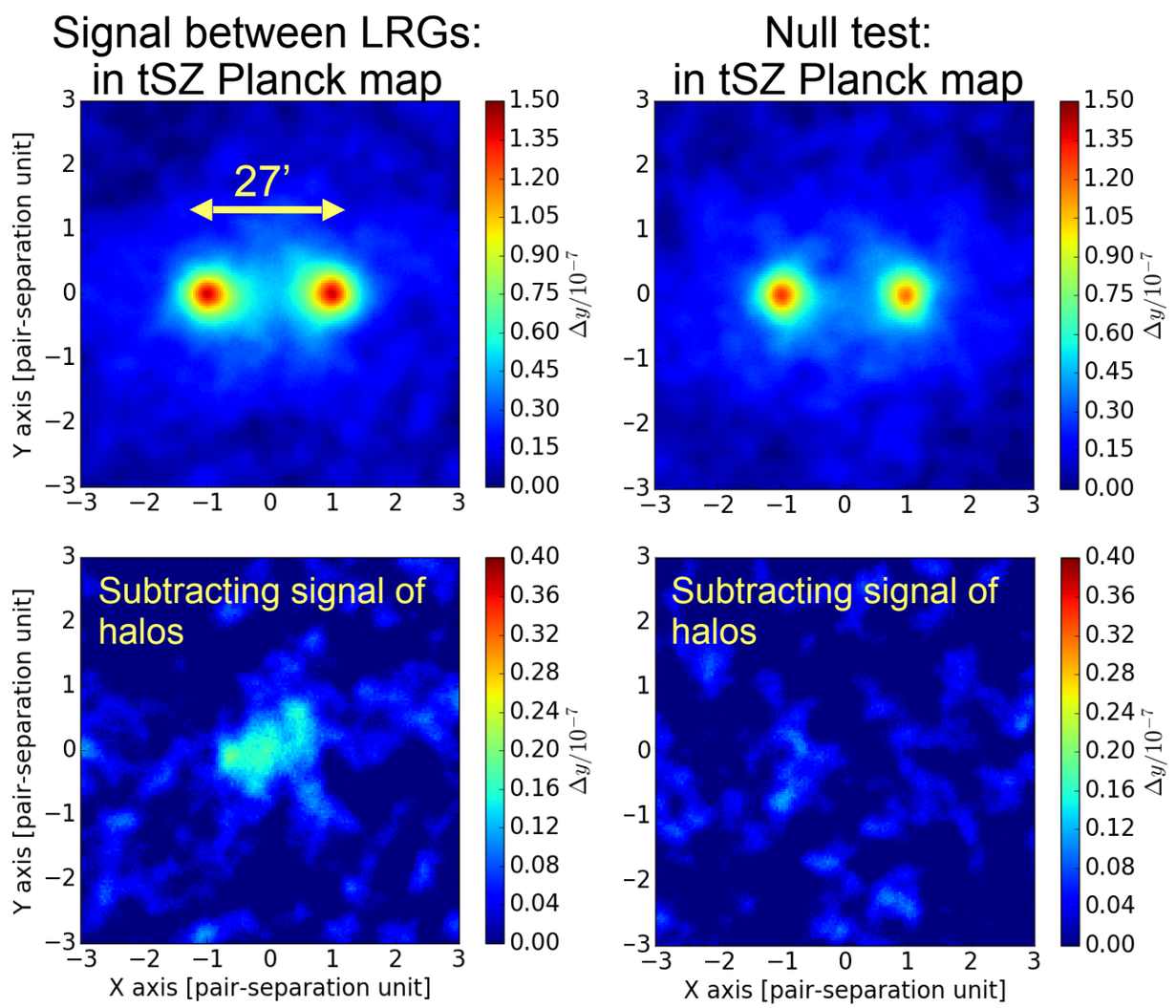
Searching for hidden matter in filaments between cluster pairs

LRG → ~Cluster center
In SDSS: 2.6 X 10^5 LRG/cluster pairs [0.05<z<0.40, M > $10^{11.3}$ M_{sun}]

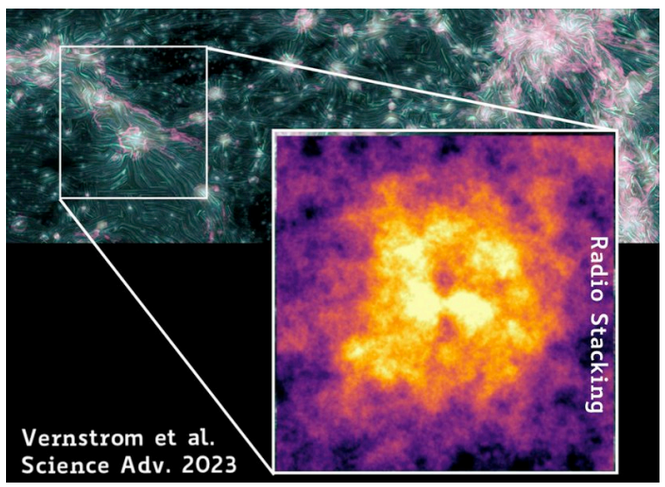
Tanimura+ '19

Stacking the tSZ signal at position of the LRG pairs





Detected tSZ excess signal between LRG pairs at 5.3σ

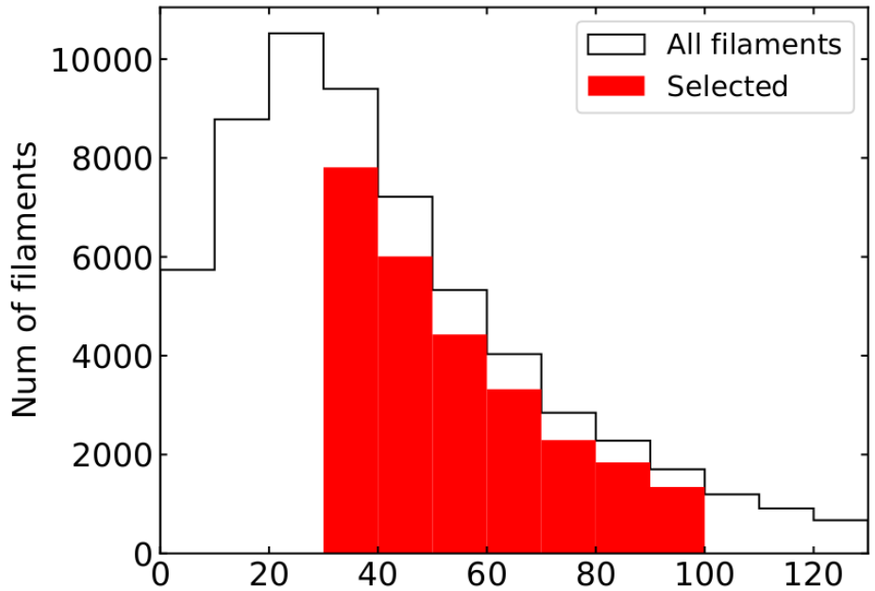


Radio emission from strong accretion shocks around filaments

$y=(1.31\pm0.25)\ 10^{-8}$

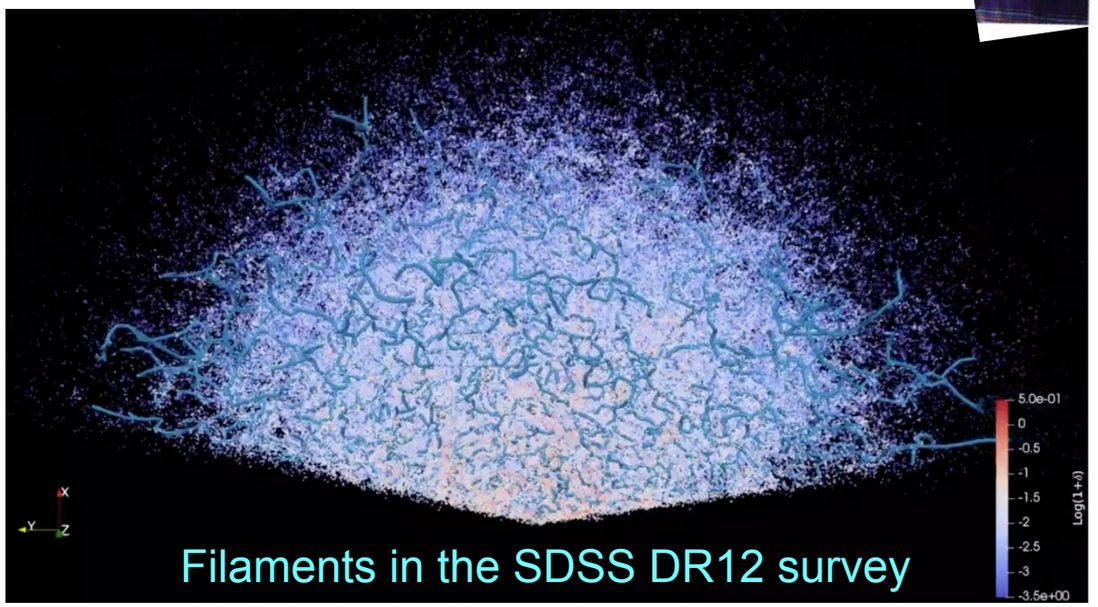
Searching for hidden matter in large cosmic filaments

~24,000 filaments, with length 30–100Mpc in the SDSS



Tanimura, NA+ ‘20a Length of filaments [Mpc]

Filament finder DisPerSE Sousbie+ ’11



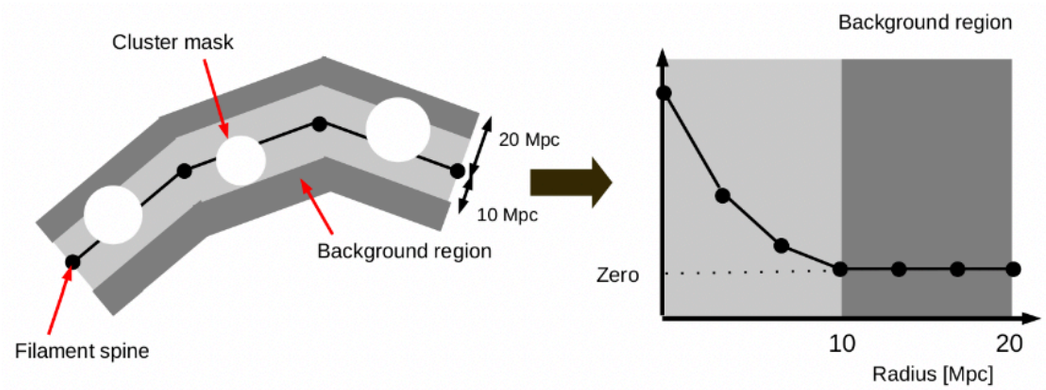
Malavasi, NA+ ‘20

Goal: Detect hot baryons phase in large cosmic filaments in tSZ and in X-rays

→ Avoid contribution from
- Clusters by masking known clusters down to 10^{13} M_{sun}
- Nodes of CW by masking maxima critical points
- X-ray sources by masking sources from ROSAT, Chandra, XMM-Newton
- Large scale background by subtracting signal >10Mpc

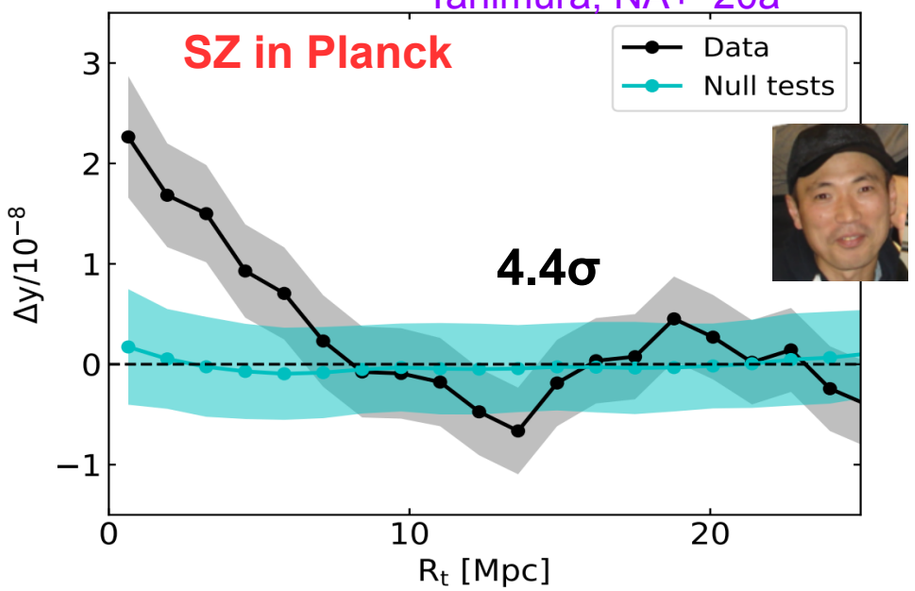
→ Stack signal maps at filaments position

→ Compute radial profiles (background subtracted) around filaments spines

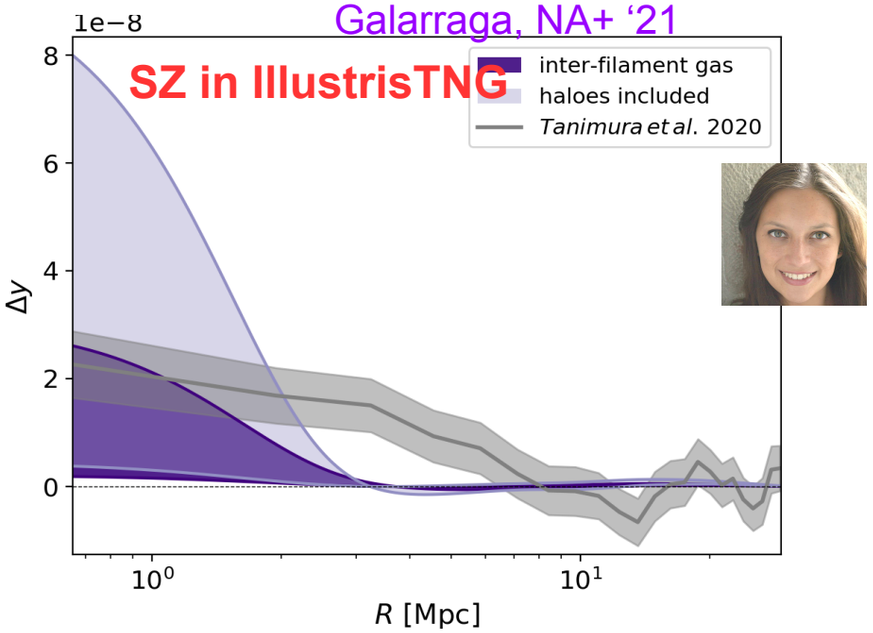


Hot baryons in cosmic filaments via the tSZ signal

Tanimura, NA+ ‘20a



Galarraga, NA+ ‘21



tSZ from hot baryons detected at 4.4σ from stacked 24,000 filaments
CMB-lensing detected at 8σ from 24,000 filaments

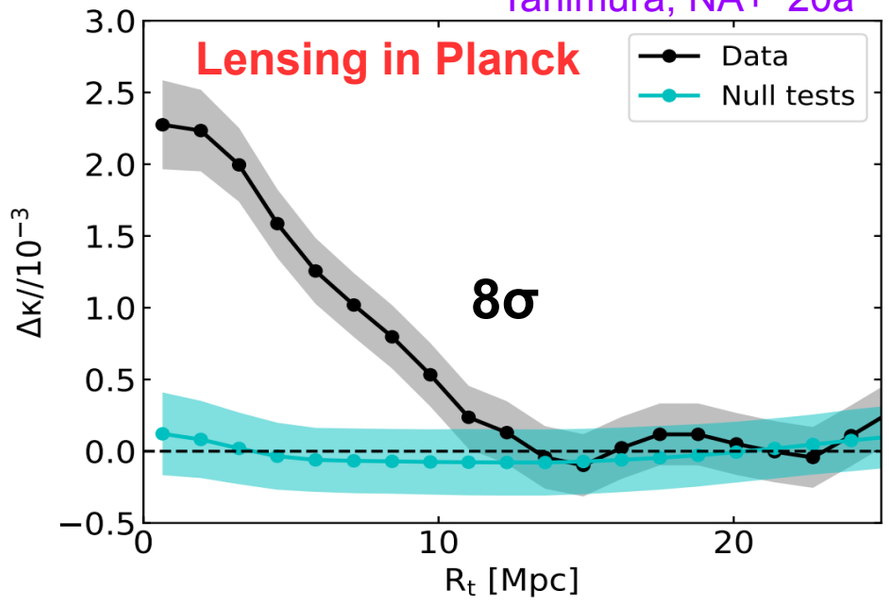
Observed tSZ agrees with simulations → signal mostly due to warm/hot gas in filaments

Joint fit of tSZ & CMB-lensing data assuming isothermal cylindrical filament

→ Average properties of the cosmic filaments:

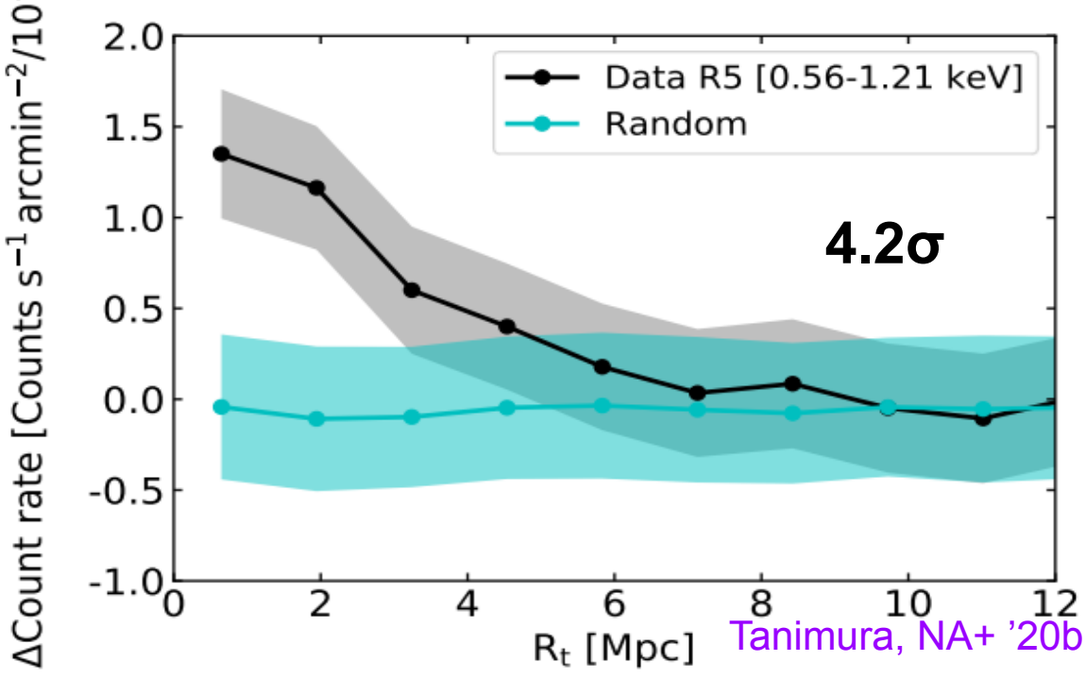
- Thickness ~ 6 Mpc
- Temperature: T ~ 1 – 2.10^6 K
- Over-density: δ ~ 7 – 39

Tanimura, NA+ ‘20a



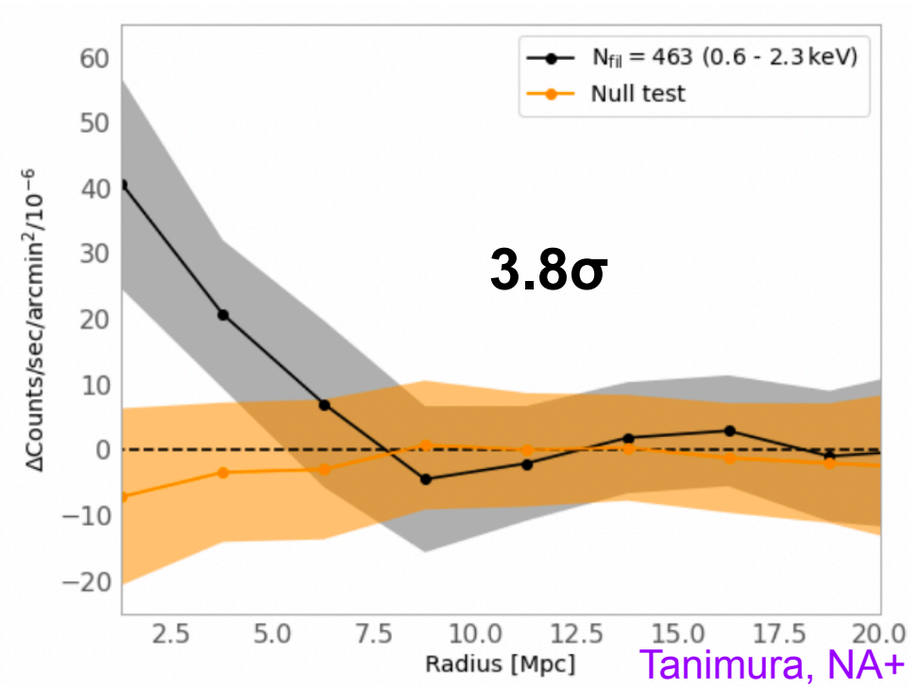
Hot baryons in cosmic filaments emitting in X-rays

ROSAT:
- 15,000 stacked filaments count maps
- S/N in filaments' "cores" (< 2 Mpc)



Tanimura, NA+ '20b

SRG/eROSITA (eFEDS):
- 463 stacked filaments count maps
- S/N in filaments' "cores" (< 2.5 Mpc)



Tanimura, NA+ '22

For the first time X-ray excess emission from cosmic filaments detected in ROSAT at 4.2σ & in eROSITA at 3.8σ

X-ray spectral analysis in ROSAT and SRG/eROSITA & cylindrical filament cores with β-model:
- Temperature: T_{ROSAT} ~ 0.9 (+1/-0.6)keV and $T_{eROSITA}$ ~ 0.8 (**+0.3/-0.2**)keV
- Over-density δ_{ROSAT} ~ 30 (+/-15) and $\delta_{eROSITA}$ ~ 41 (+/-11)

Summary

Radial profiles of the matter content around cosmic filament spines:

- Galaxy over-density at **S/N ~ 32** (Bonjean+ '20)
- Total matter via CMB-lensing at **S/N ~ 8** (Tanimura+ '20a), also between cluster pairs (Epps & Hudson '17)
- Hot ionised baryons via **tSZ at S/N ~ 4–5** (Tanimura+ '20a), also between cluster pairs (Tanimura+ '19; de Graaff+ '19), and for the first time via **X-ray** emission **in ROSAT at S/N ~4.2** (Tanimura+ '20b) and **eROSITA at S/N ~3.8** (Tanimura+ '22)

Direct and indirect evidence of ionised hot baryons in large cosmic filaments

Properties of the hot baryons in cosmic filaments:

Within ~2Mpc from the spine via spectral analysis of X-ray emission:
- Over-density: **~15 to 50**
- Temperature: **~ 3 – 20. 10^6K**

Within ~6Mpc from the spine combining CMB-lensing & tSZ:
- Over-density: **~7 to 40**
- Temperature: **~ 1 – 2. 10^6K**

Hot baryons in cosmic filaments should account for a large fraction of the hidden baryons
→ Coming next a detailed budget of these hidden baryons

Thank you