A multiwavelength study of WHIM in Planck-detected superclusters:

Searching for the missing baryons

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Venue XMM-Newton 2019 Science Workshop:
"Astrophysics of hot plasma in extended X-ray sources",
European Space Astronomy Centre (ESAC), Villafranca del Castillo, Madrid, Spain,
We.12 - Fr.14.06.2019

European Research Council
Established by the European Commission

THE BARYON PICTURE OF THE COSMOS (BYOPIC)

Main questions about the *hidden* baryons:

- Where are they today and what's their physical state ?
- How do they evolve and influence their environment?
- How can we detect and study them?

Main Focus:

- hot ionized baryons in "non/partially" virialised objects → **"super-clusters", "filaments", "bridges"**

Approaches:

- Developing and applying **statistical tools** (e.g. DISPERS, machine learning):
  - identify the largest cosmic structures (e.g. filaments)
  - reconstruct the cosmic web and assess their physical state
- **Multi-frequency analyses** to trace the hot baryons (tSZ, **X-rays**), and cold baryons (galaxies, optical/IR)
- Comparing and testing results with **cosmological simulations**


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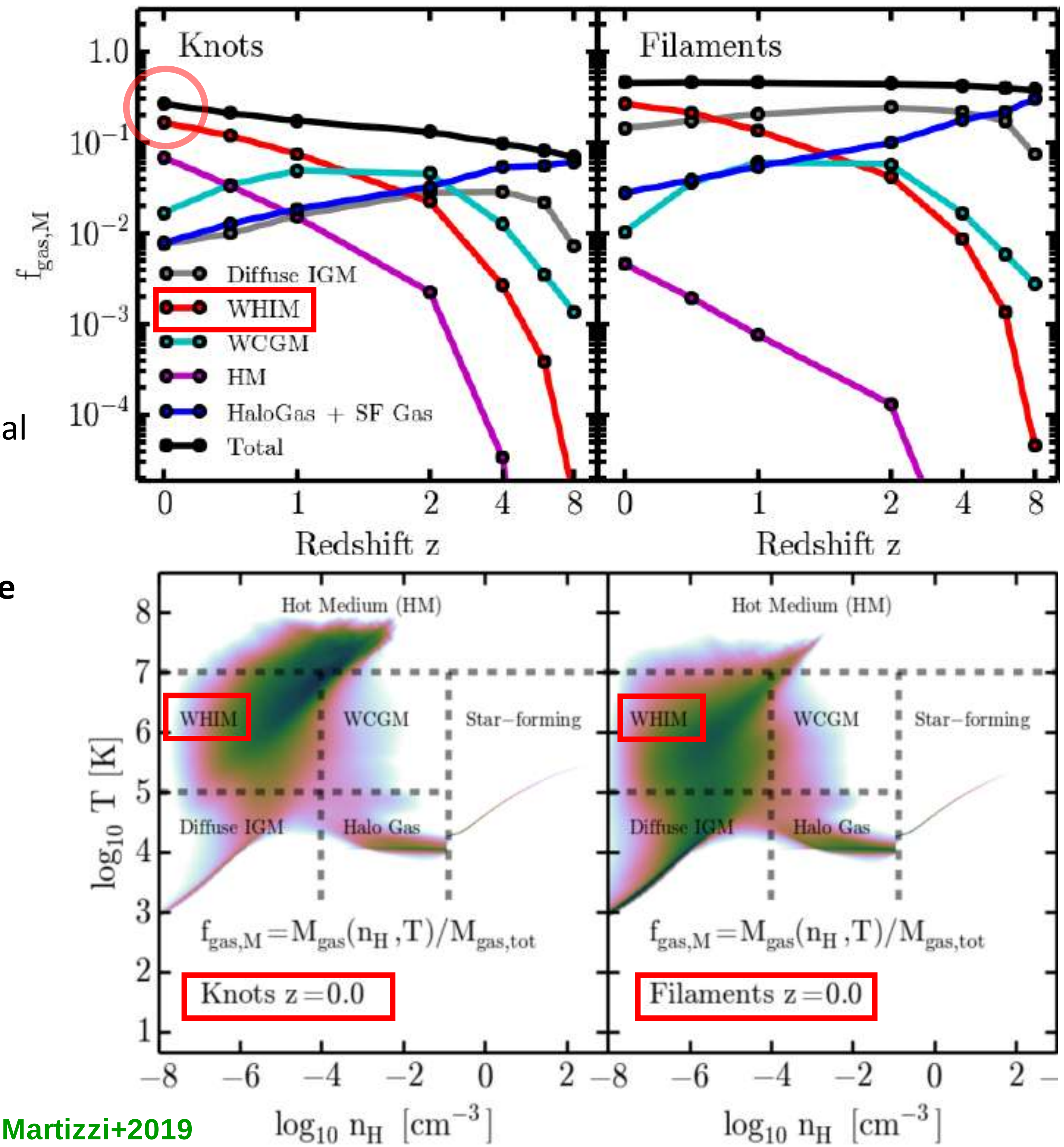
Intro

Knots & filaments: ideal structures to study WHIM



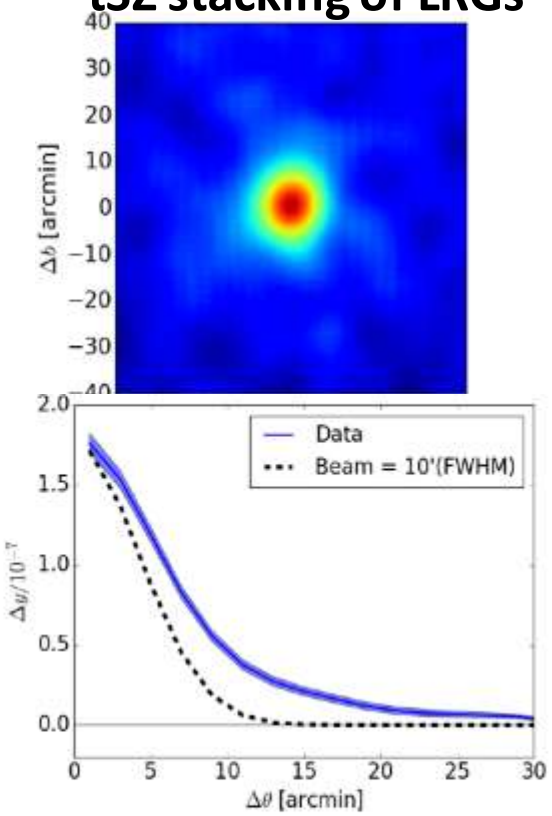
Prediction by cosmological, hydrodynamical simulations (e.g. IllustrisTNG):

WHIM is the dominant baryon mass contribution in knots and filaments in the local Universe

Martizzi+2019

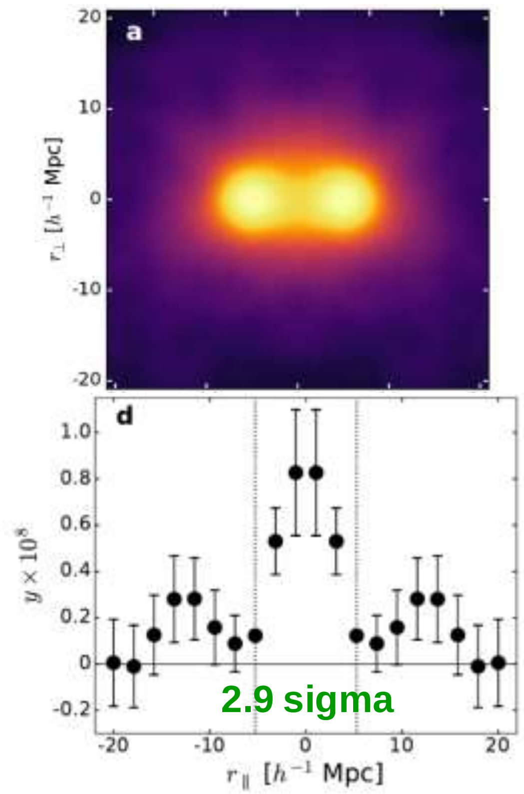
WHIM stacking analysis – an (incomplete) overview

tSZ stacking of LRGs



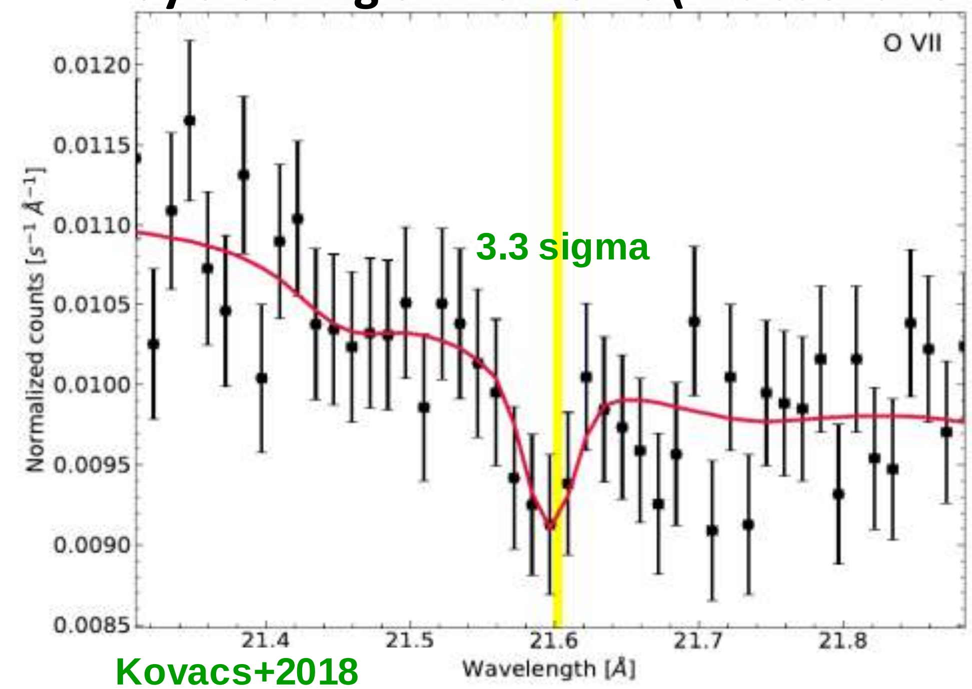
Tanimura+2019a

tSZ stacking of galaxie pairs



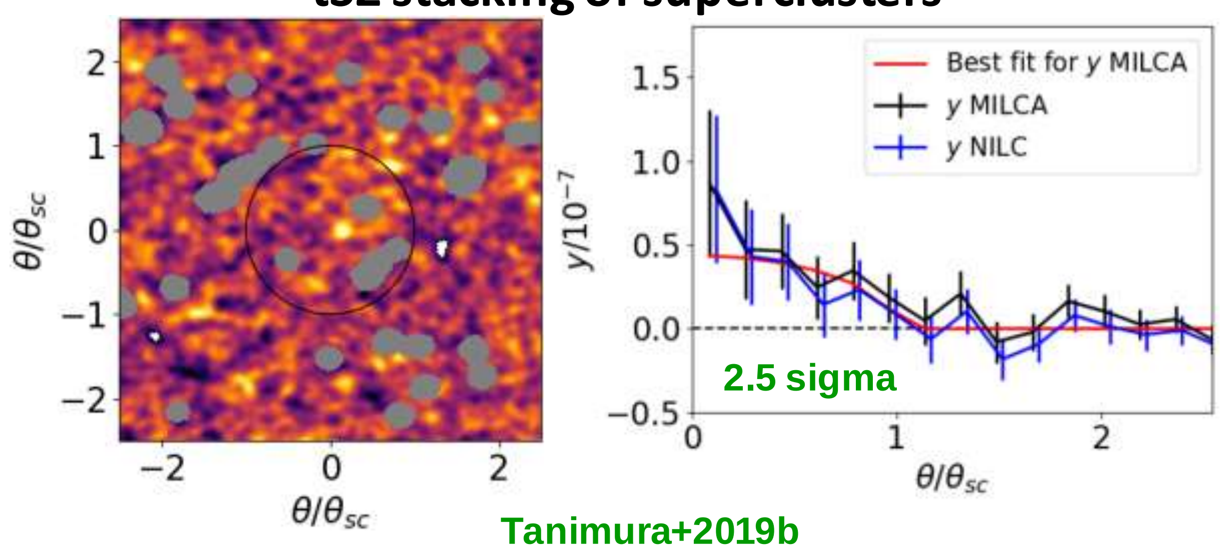
deGraaff+2019

X-ray stacking of filaments (in absorbtion)



Kovacs+2018

tSZ stacking of superclusters



Tanimura+2019b

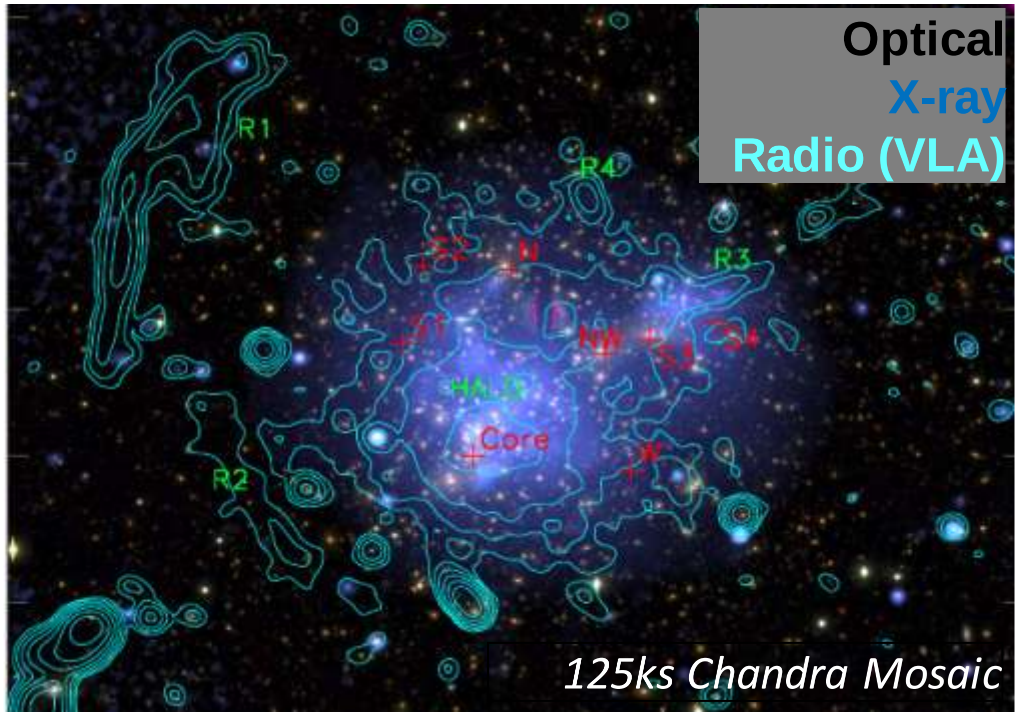
Stacking versus individual-object studies

- **Stacking analyses** of a source type (e.g. filaments):
  - Small cosmic variance
  - Great for obtaining a census
  - Blind to many physical properties
  - Limited knowledge of connection to the cosmic web
  - Rather exhausted field

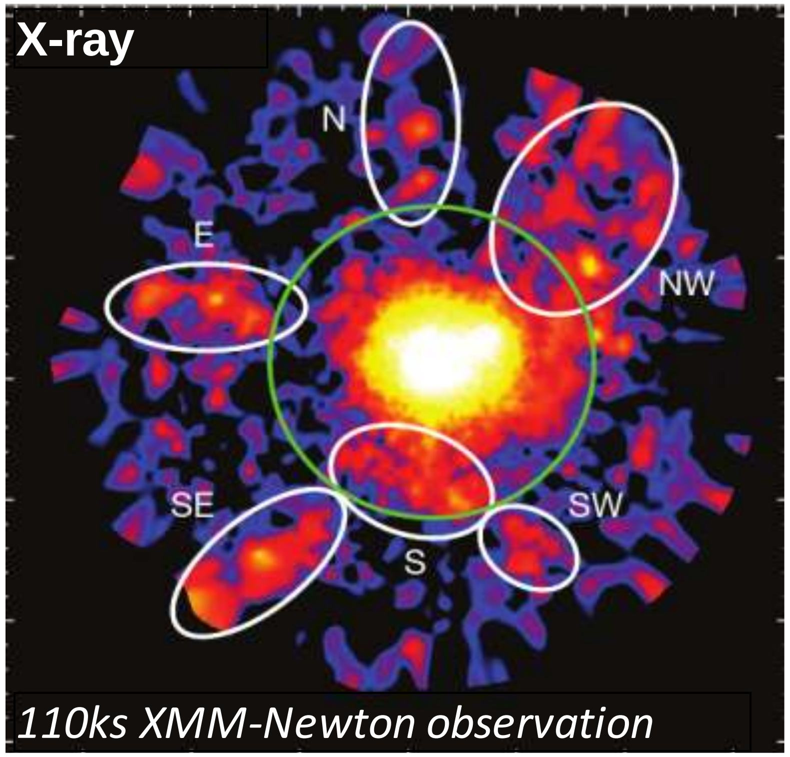
    → new survey data needed (e.g. eROSITA all-sky survey, LSST)
- **Multiwavelength studies** of individual large-scale structures:
  - High cosmic variance
  - Require deep survey data
  - More direct access to physical properties
  - Clear knowledge of connection to the cosmic web
  - Many interesting sources available

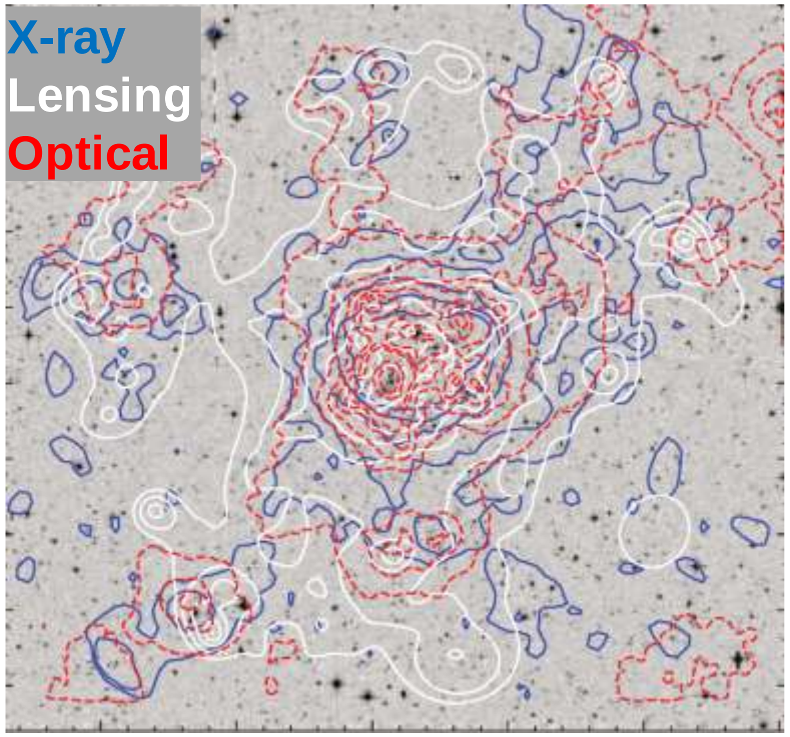
Filaments around a single cluster (e.g. Abell 2744)

- Joined analysis of **X-ray, optical and lensing** by **Eckert+2016**
  - Gas in **filament structure**:
    - $T_{X\text{-ray}} \sim 10^7$ K, $n_e \sim 10^{-5}$ cm^{-3}
    - **Gas mass fraction: M_{gas}/M_{DM+b} = 5-10%**
- Radio (VLA): merging & accretion history



Pearce+2017



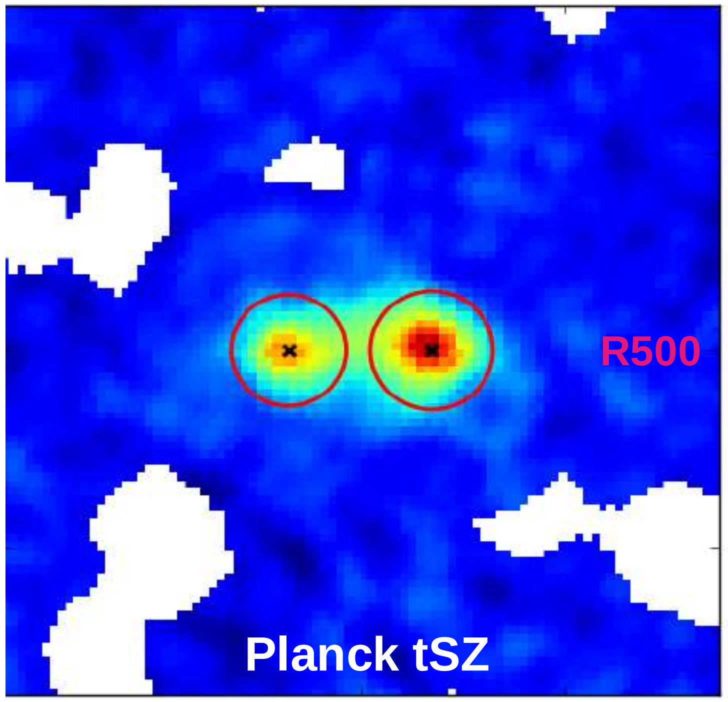


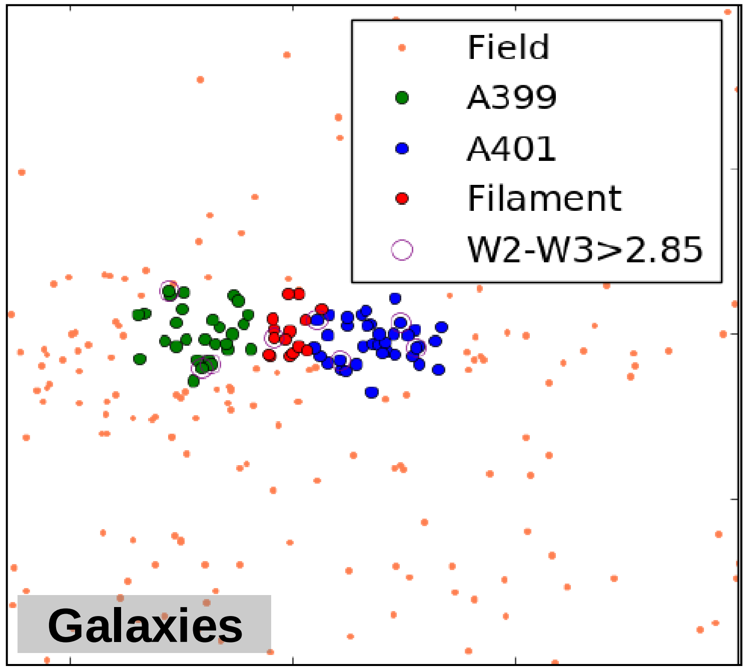
Eckert+2016

Bridge between two clusters (e.g. Abell 399 & 401)

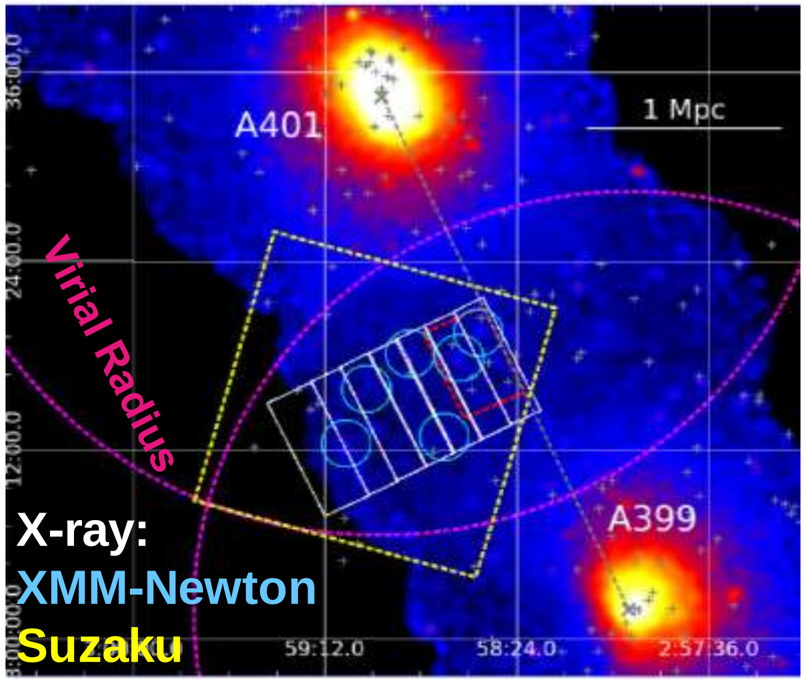
- Separated analysis of X-ray, tSZ+optical/IR & Radio
- **Bridge**:
  - $T_{X\text{-ray}} > 10^7$ K, $Z_{Sun} \sim 0.3$
  - tSZ + $T_{X\text{-ray}}$: $n > 10^{-4}$ cm^{-3}
  - optical/IR: early type galaxy population
- Radio (LOFAR): merging process and history

→ **No WHIM detection but exemplary study for it**

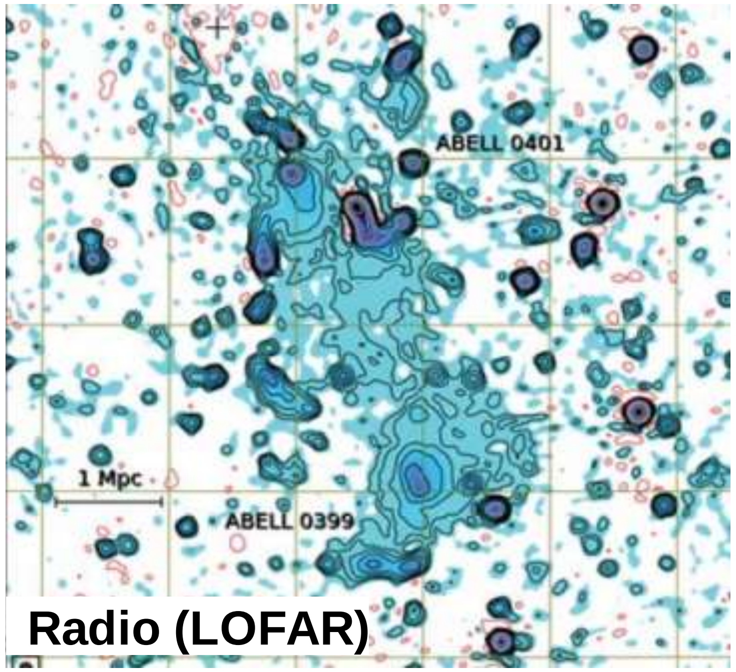




Bonjean+2018



Akamatsu+2017



Govoni+2019

Superclusters (e.g. PLCKG 214.6+37.0)

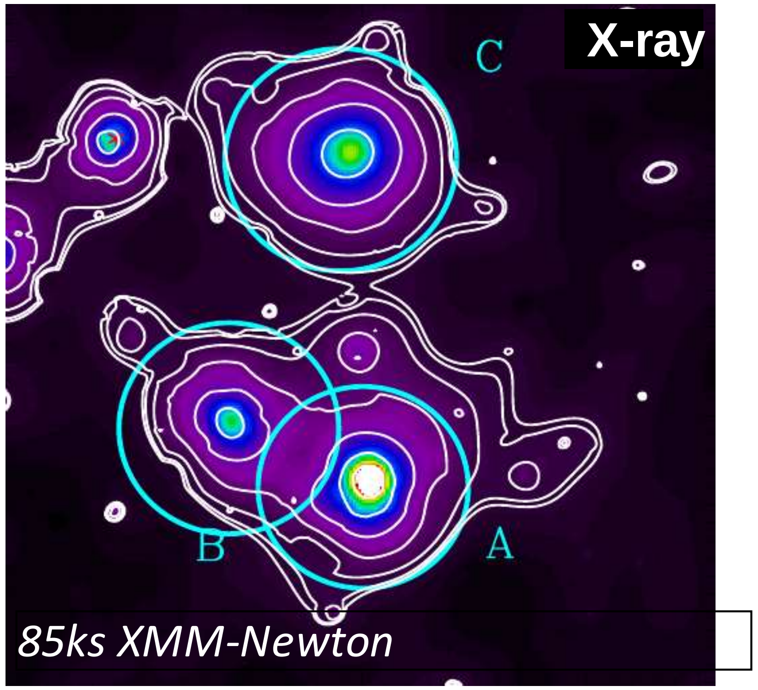
- Joined analysis of tSZ, X-ray, optical by **Planck Int. VI 2013**
  - Cluster members:

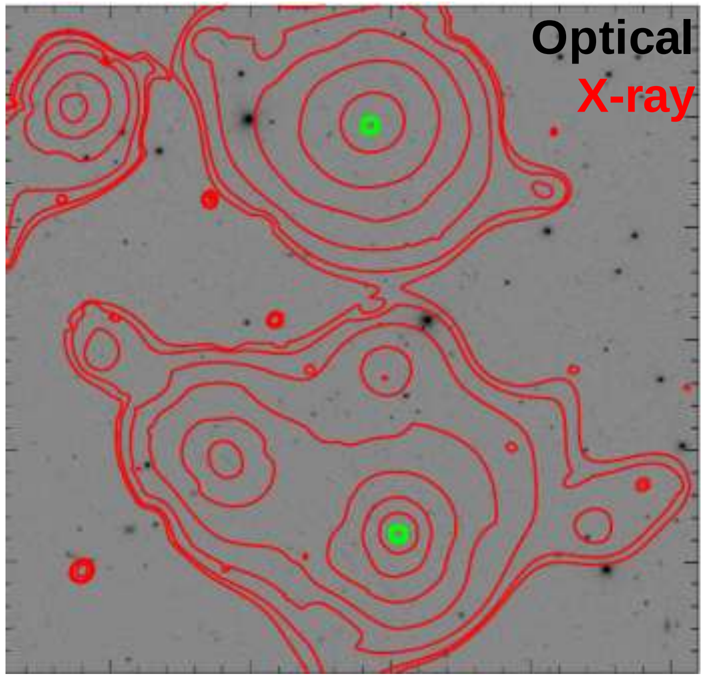
    $T_{X\text{-ray}} \sim (4\text{-}5) \times 10^{7}$ K

    $M_{500} \sim (2\text{-}3) \times 10^{14}\ M_{sun}$

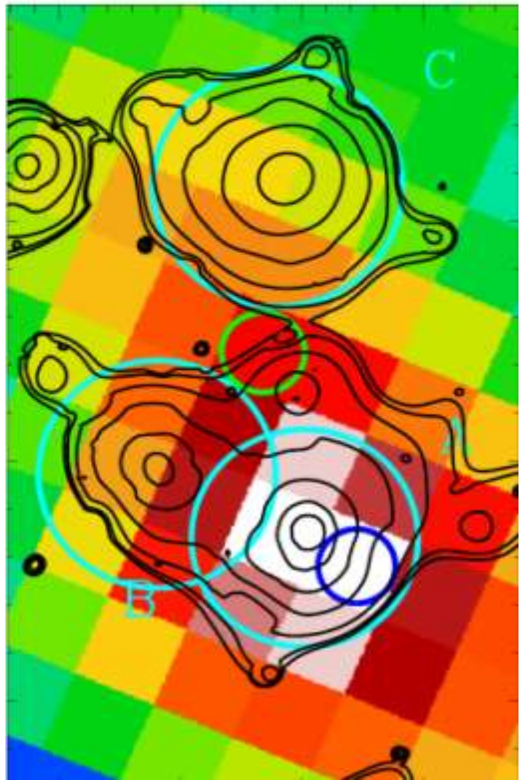
    $z \sim 0.45\text{-}0.48$

→ **Pioneering study but focus only on cluster physics**





tSZ (Planck Intermediated data)



Our study

A multiwavelength study of WHIM in
Planck-detected superclusters

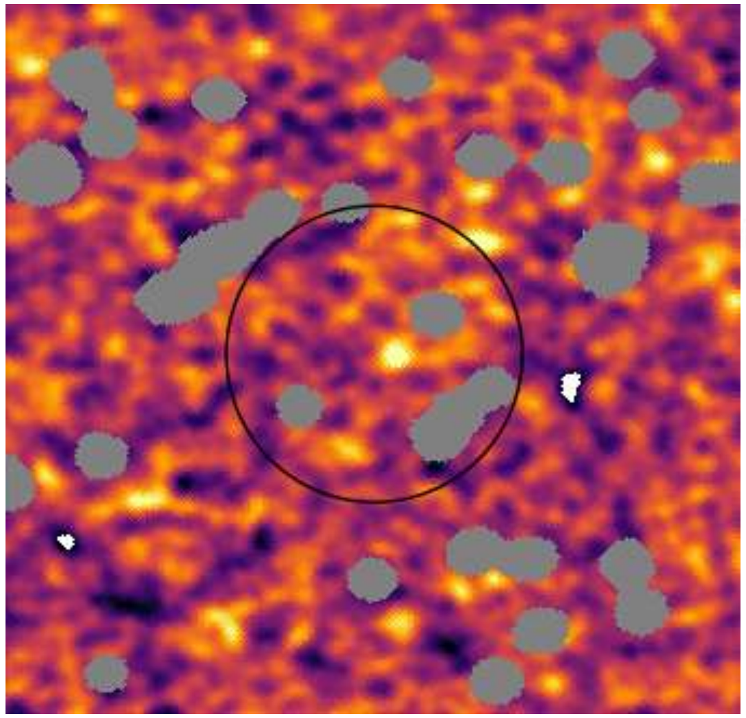
Our motivation

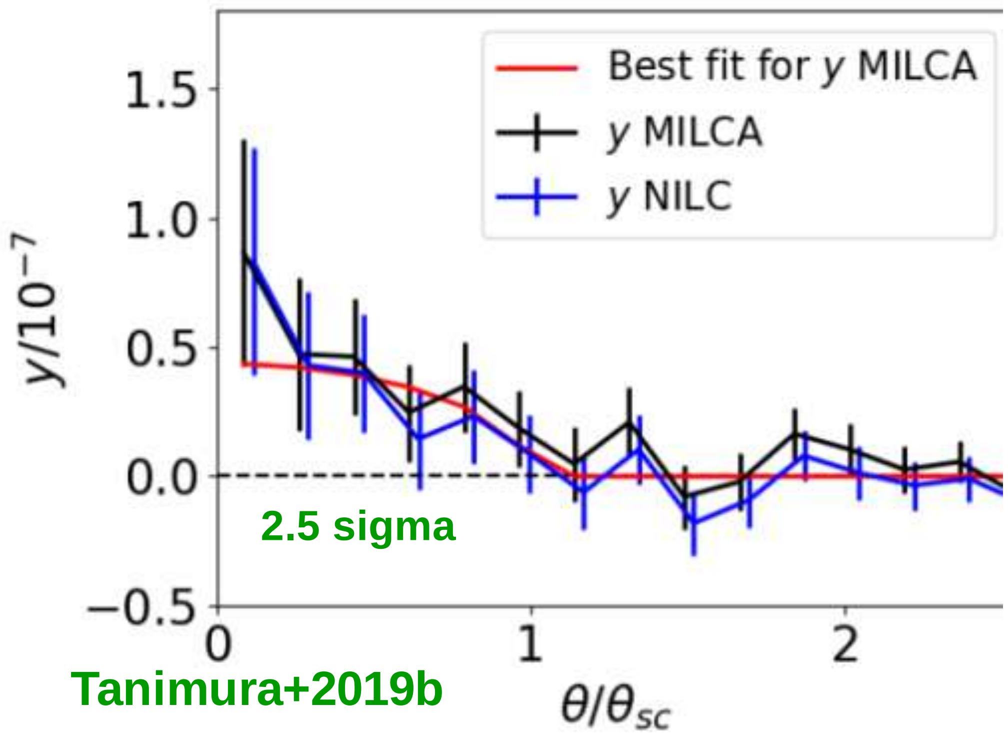
- Study WHIM directly within large-scale structures
  - Access its physical state
  - Study its evolution and interaction with environment
- Develop new methods to study WHIM
- Possible Targets:
  - Bridges: typically too hot & dense to be WHIM (e.g. **Bonjean+2018)**
  - Filaments: typically too faint → stacking (absorption & emission) best channel
  - Superclusters: most promising candidates

Supercluster: encouragement from stacking analysis

- Planck tSZ Stacking,
  (assuming $T_e = 8 \times 10^6$ K):
  - $n_e = (1\text{-}3) \times 10^6\ \mathrm{cm}^{-3}$
  - **baryon density:**
    $(\Omega_{gas}/\Omega_b) \sim 10\%$
  - ~17% of missing baryons
- RASS Stacking:
  no significant detection
- But for **filament stacking:**
  significant detection in
  tSZ and X-ray!

SDSS Supercluster stacking with Planck tSZ





Our first targets

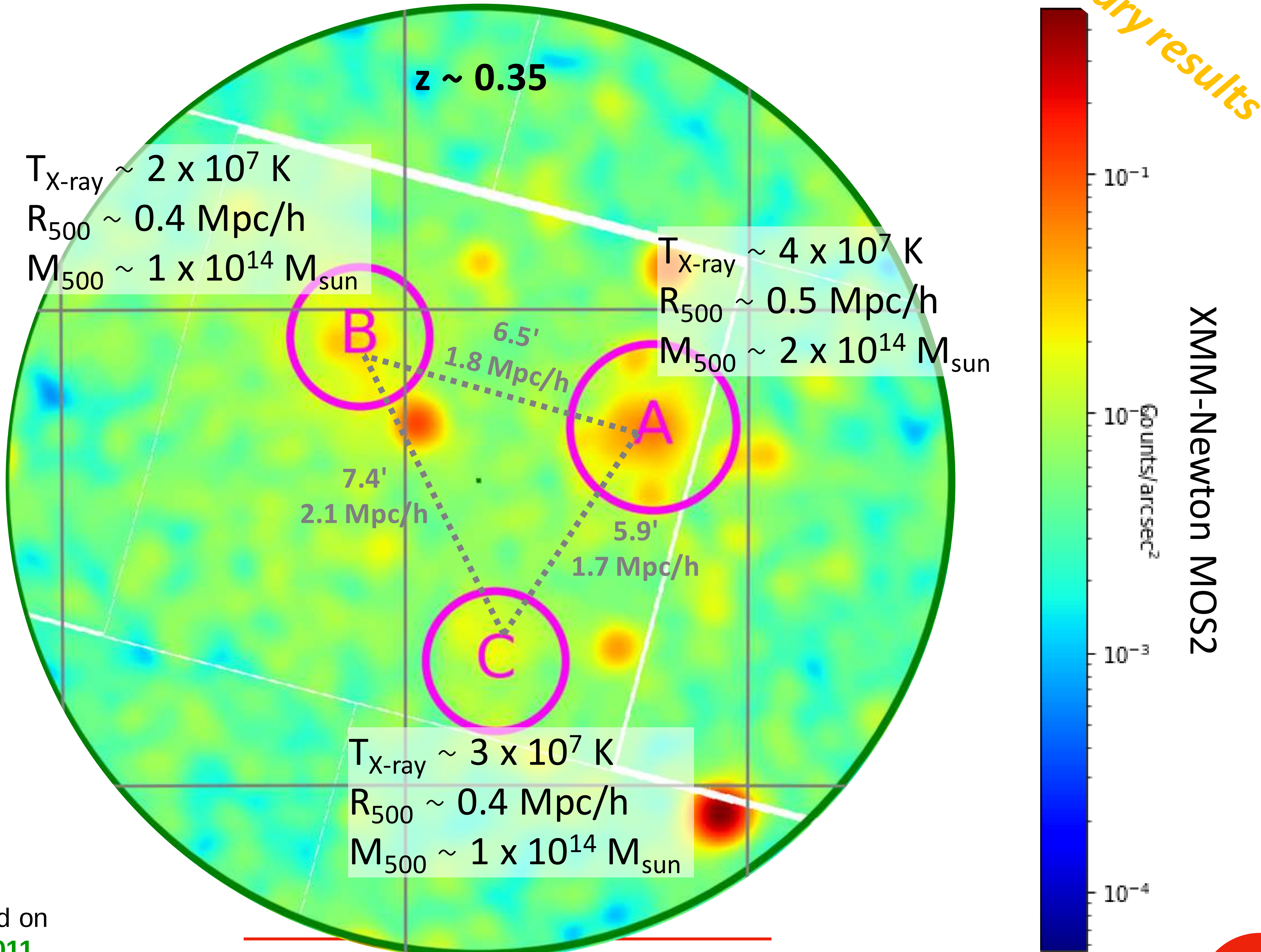
- Two **triplet-cluster** systems
  1. Supercluster "**Planck #1**": PLCKG214.6+36.9

     $z \sim 0.46$, $M_{500} \sim (2\text{-}3) \times 10^{14}\, M_{sun}$ / cluster
  2. Supercluster "**Planck #2**": PLCK G334.8−38.0

     $z \sim 0.35$, $M_{500} \sim (1\text{-}2) \times 10^{14}\, M_{sun}$ / cluster
- 1st detection in tSZ cluster search with Planck's 1st sky scan (**Planck Early VIII 2011**)
- Confirmed by XMM-Newton snapshot (~10-20ks) and identified as the only two triplet systems (**Planck Early IX 2011**)
- Led to successful VLT – XMM-Newton proposal (2012)
- "**Planck #1**": Joined tSZ , X-ray, optical analysis (**Planck Int. VI 2013**)

  → re-analyzed by Edouard Lecoq
- "**Planck #2**": Data was never analyzed → focus of this talk

Planck #2: Introduction



Some values based on
Planck Early IX 2011

Planck #2: available data

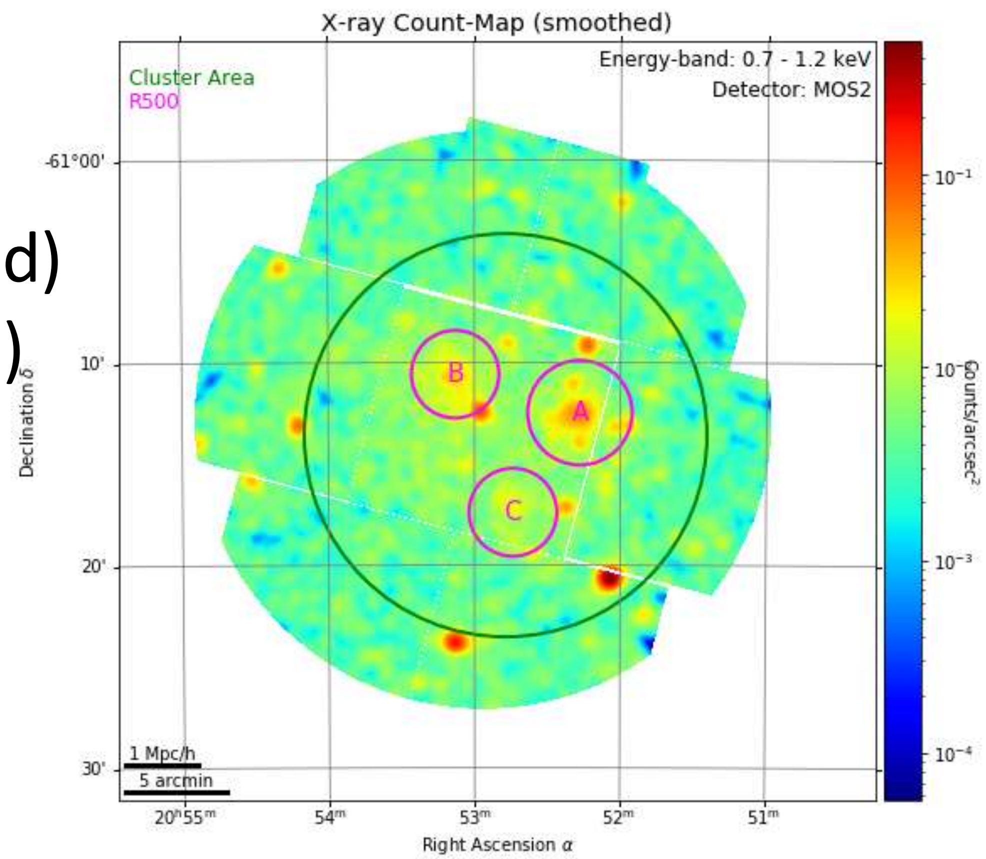
Preliminary results

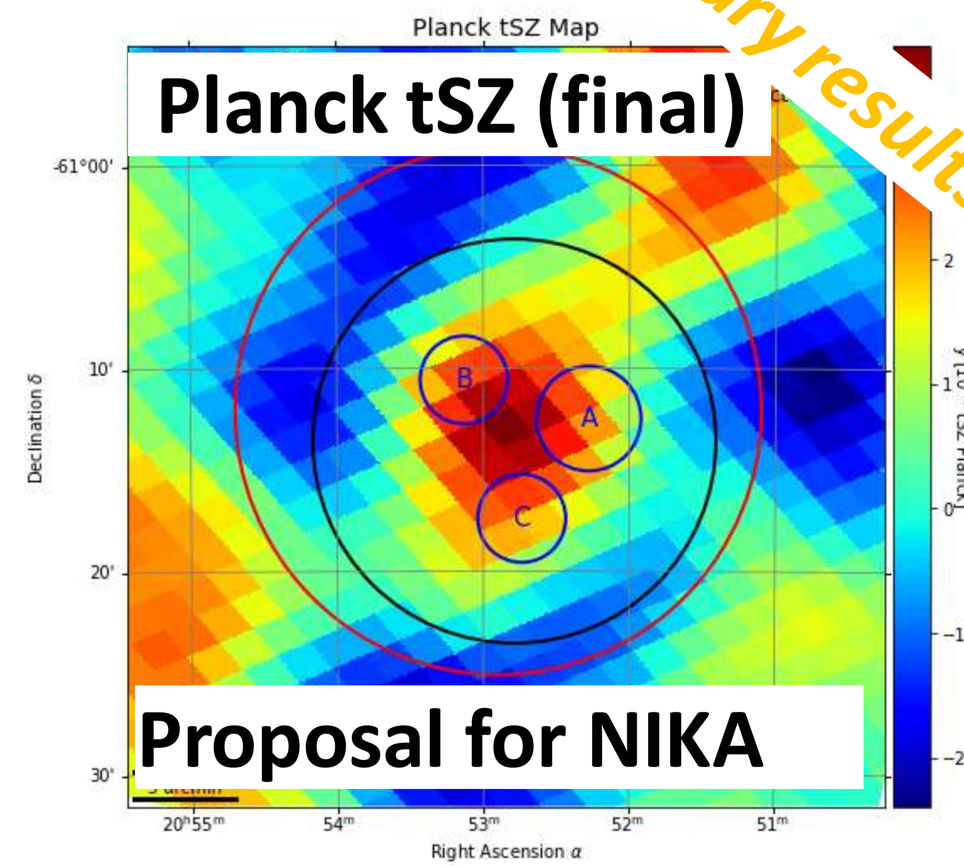
X-ray:

XMM-Newton

110ks (~50% flared)

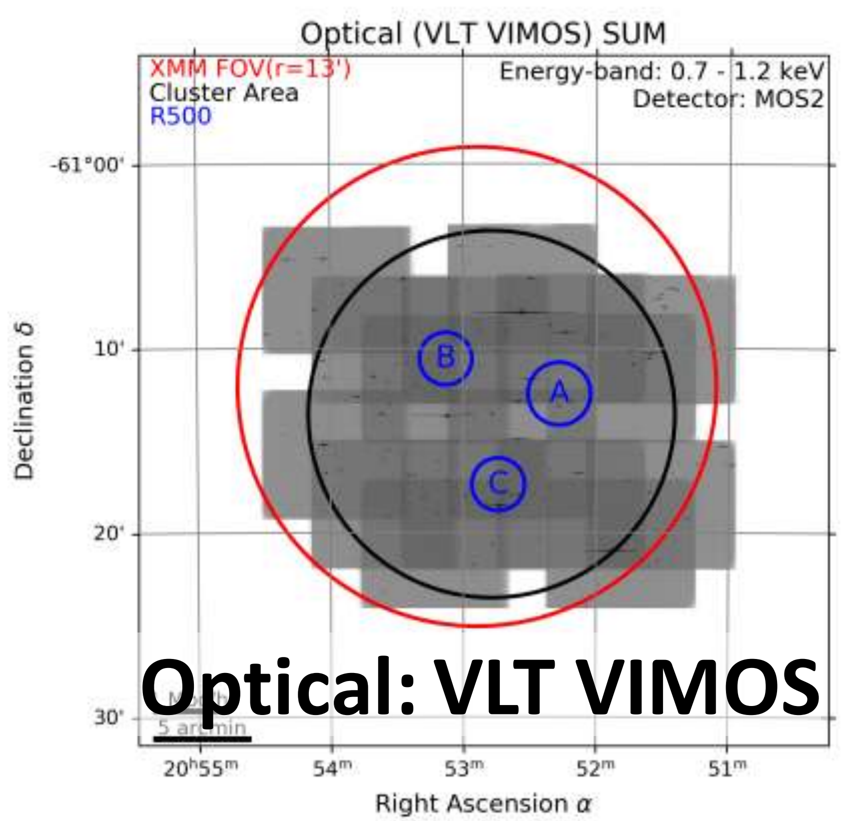
25ks (~40% flared)



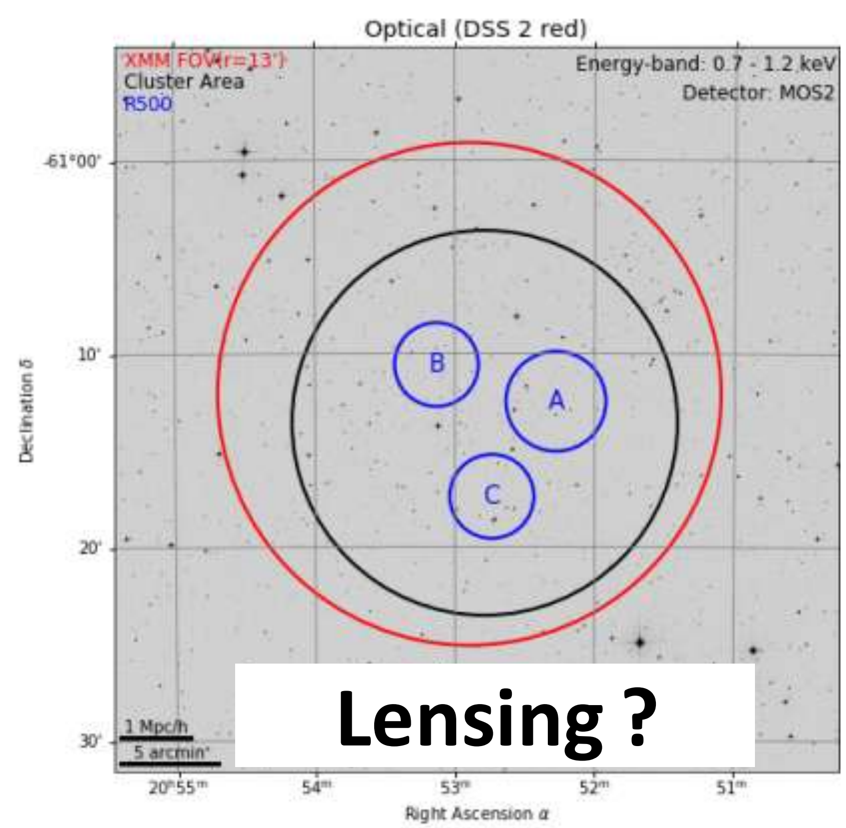


Planck tSZ (final)

Proposal for NIKA



Optical: VLT VIMOS



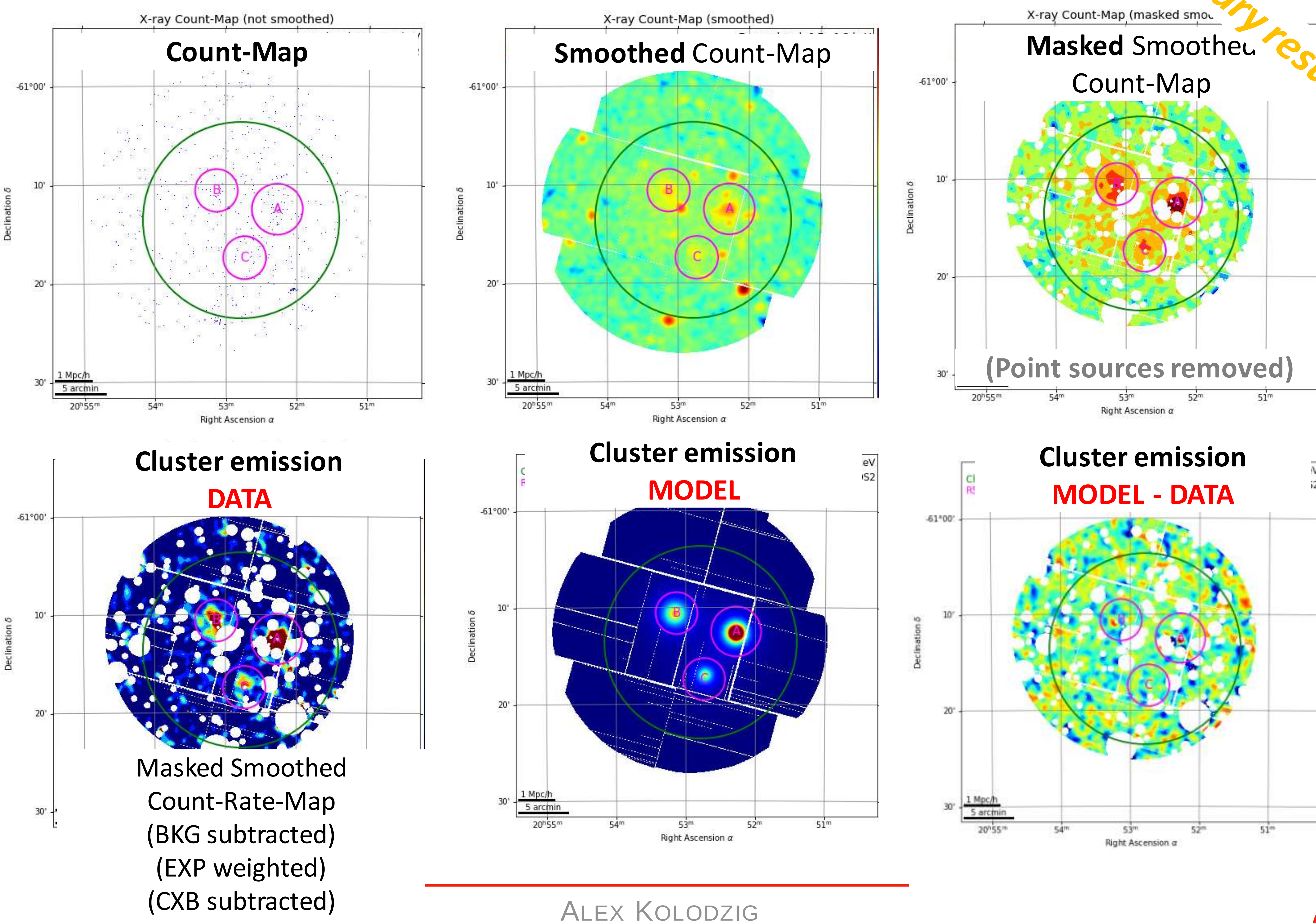
Lensing ?

Major analysis steps

1. **X-ray** analysis:
   - Modeling cluster gas emission (via surface brightness and energy spectra)
   - Studying WHIM emission, if detected
2. **Jointed X-ray – tSZ** analysis:
   - Modeling tSZ emission with X-ray model (based on spectral fitting)
   - Studying WHIM emission, if detected
3. **Joint X-ray – tSZ – optical** analysis:
   - Studying galaxy population in WHIM region
   - Lensing study, if data permits
4. **Forecast** for current and future instruments and missions:
   - Simulating X-ray observation for XMM-Newton, Athena, …
   - Making observation proposals for suitable candidates

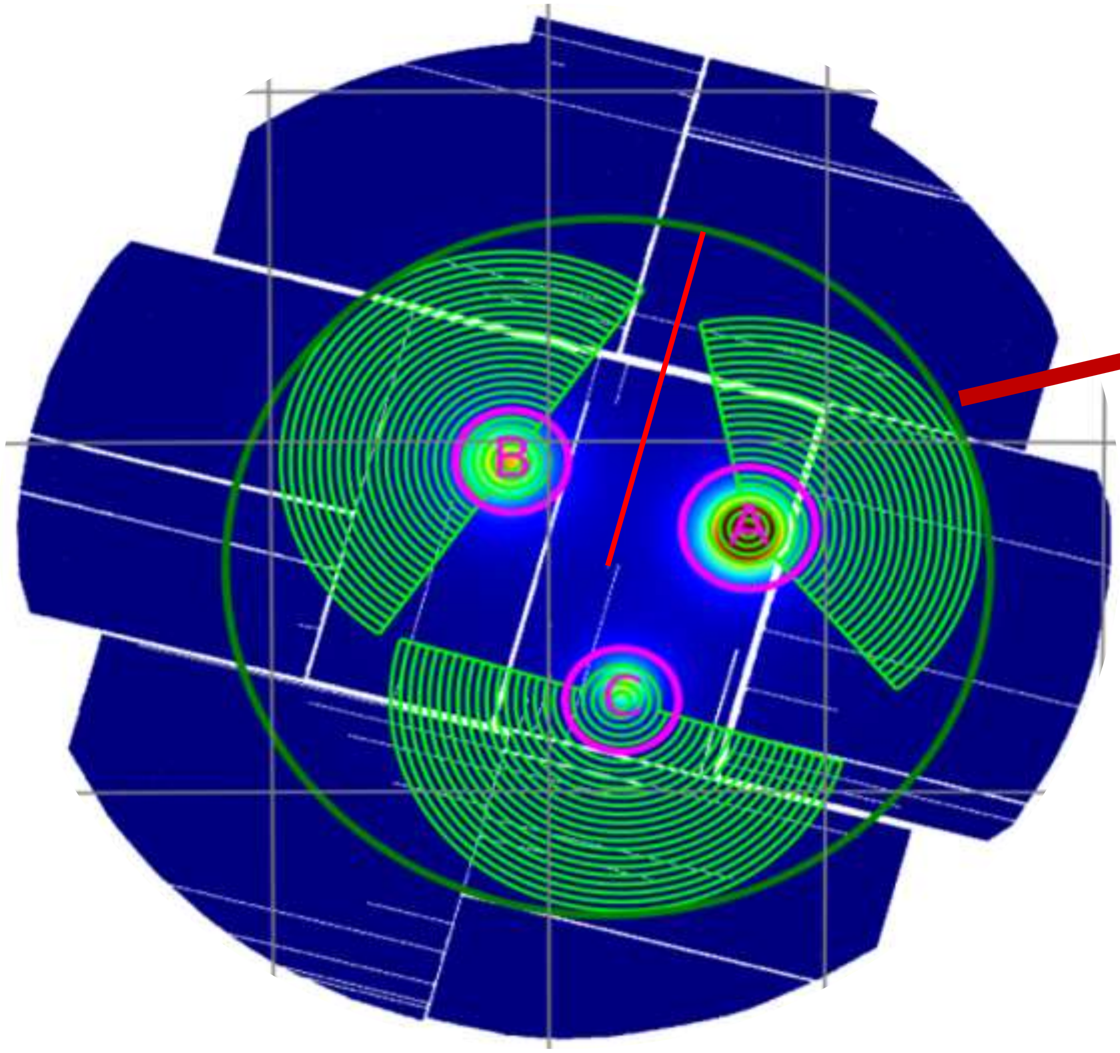
X-ray Analysis: Overview

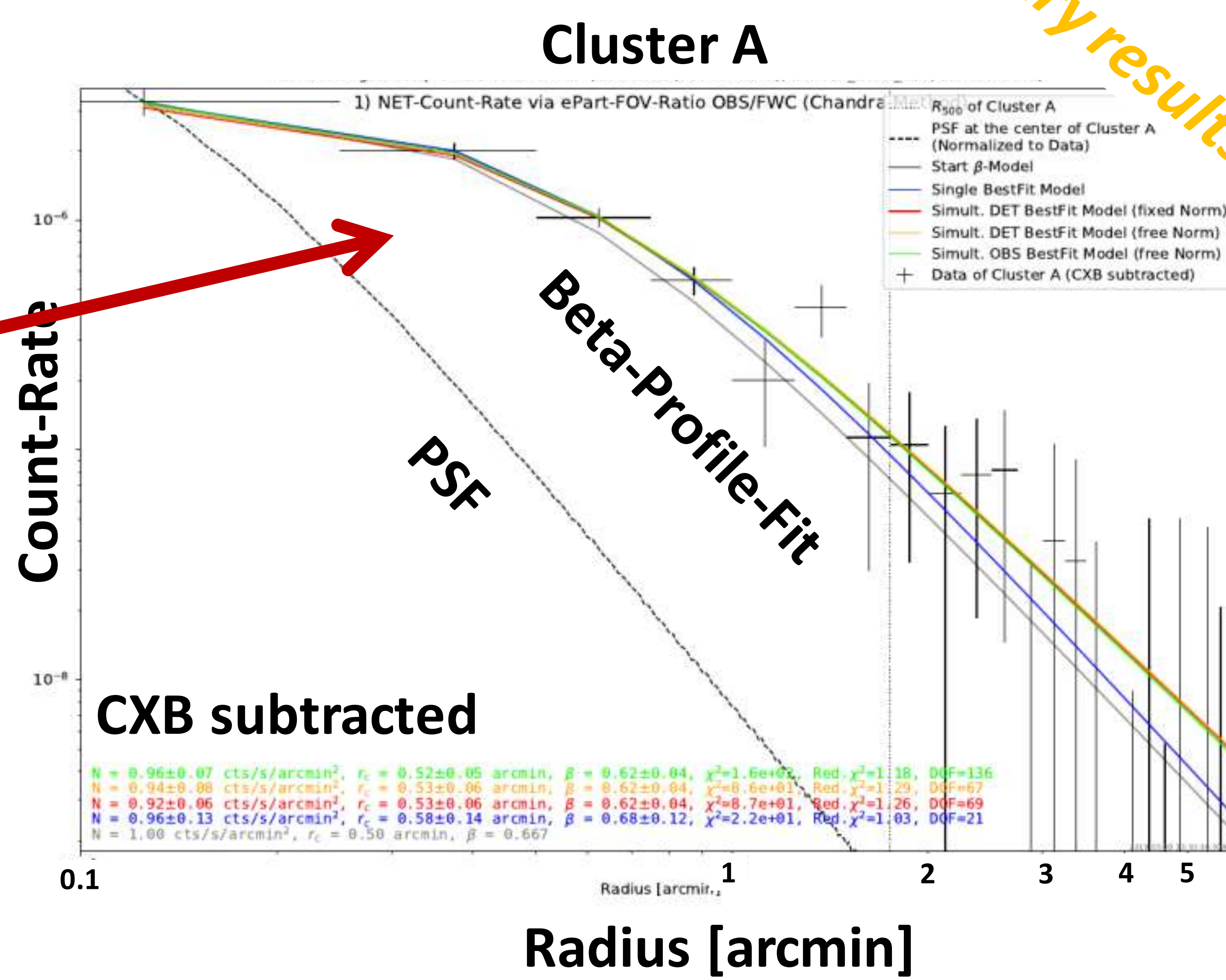
Preliminary results



X-ray Analysis: Surface brightness profile

Preliminary results

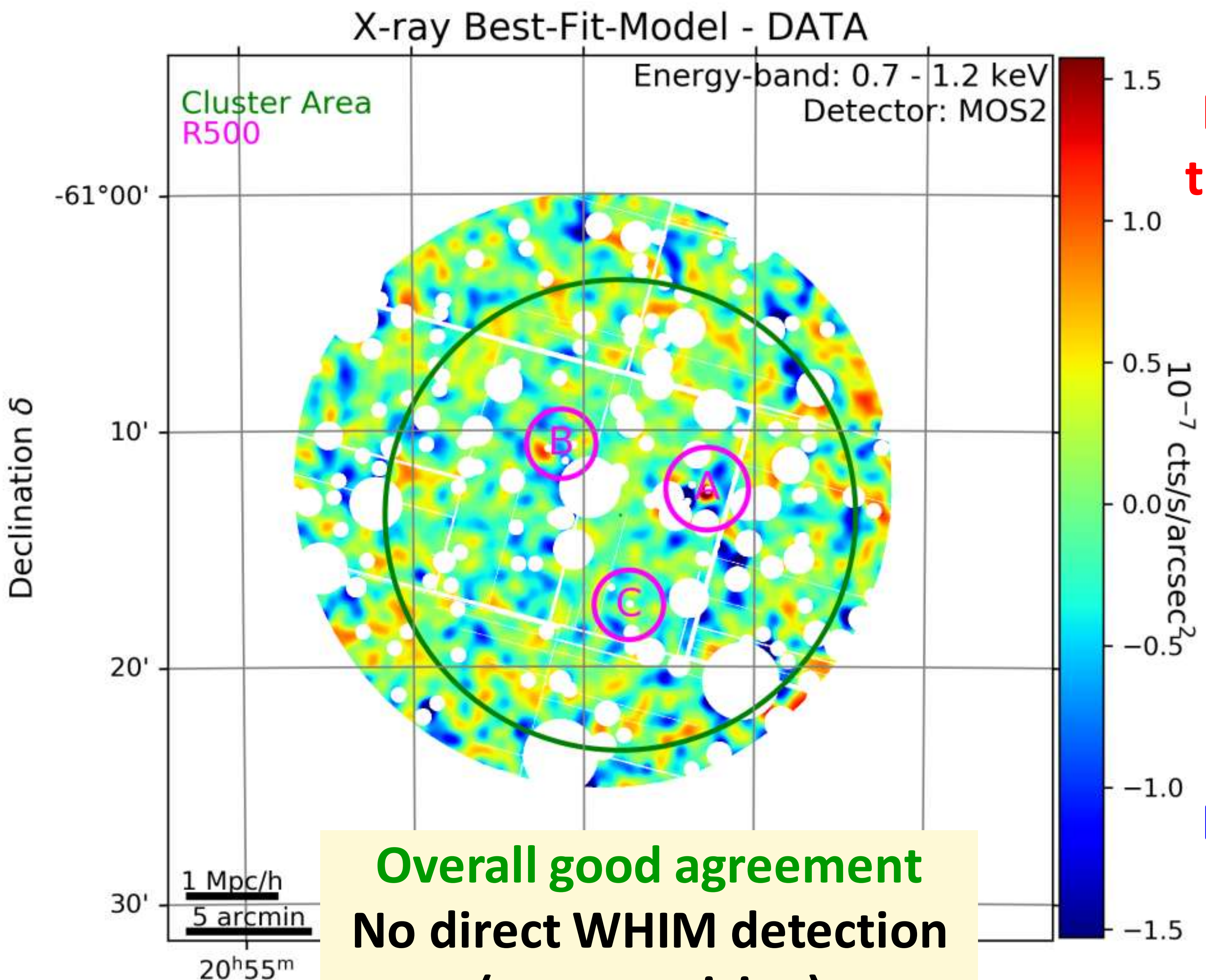




- Profiles measured up to 6 arcmin = 1.7 Mpc/h = (3.4-4.1) x R_{500}
- Profiles drops below CXB for > ~3 arcmin = ~2 x R_{500}
- Simple beta-profile fit (jointly with all observations & detectors)
- Two different Inst.BKG estimates give consistent results

X-ray Analysis: (Best-Fit-Model) **minus** (DATA)

Preliminary results



Excess in the model

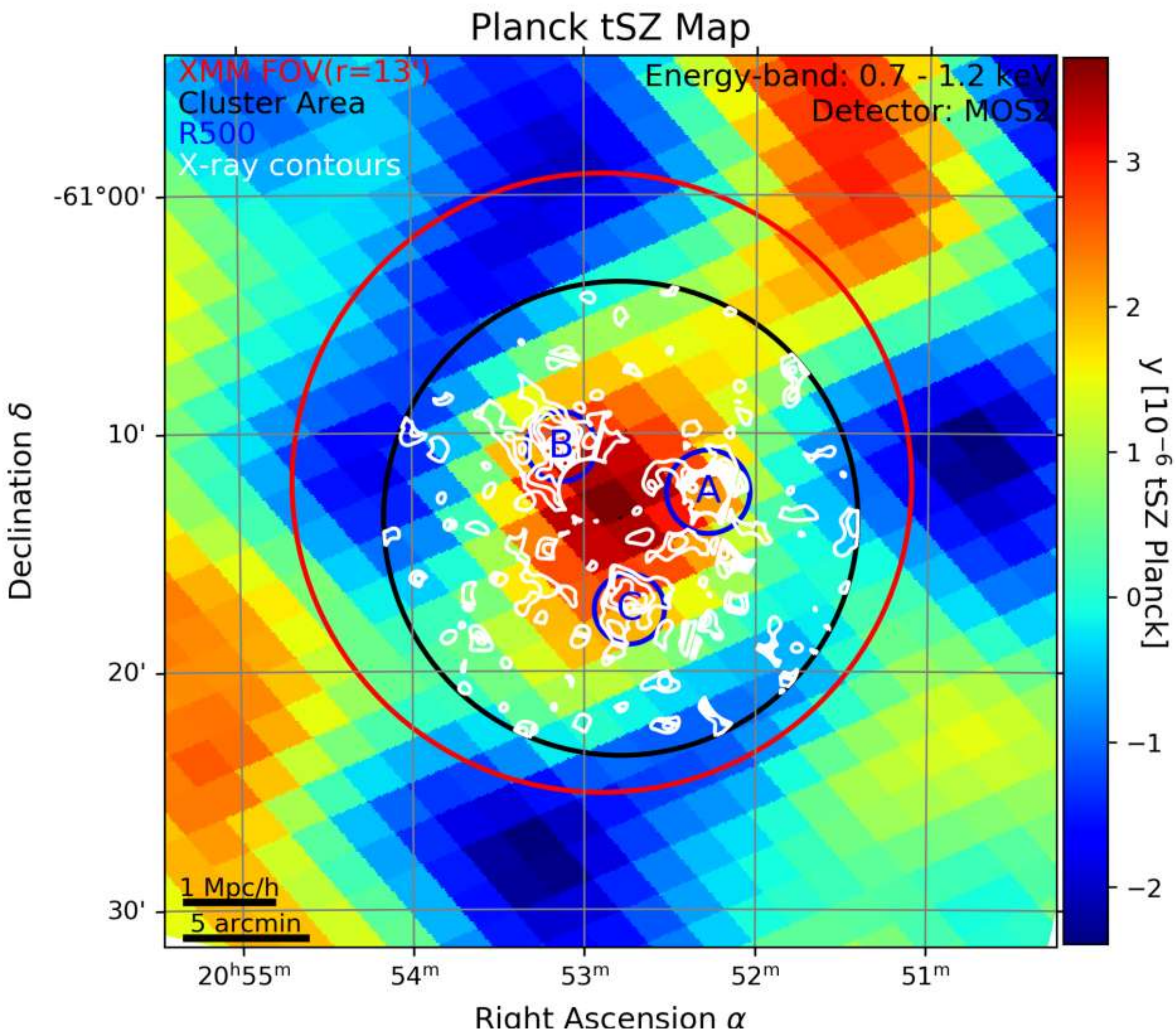
Excess in the data

Overall good agreement

No direct WHIM detection (not surprising)

Jointed X-ray – tSZ analysis: An outlook

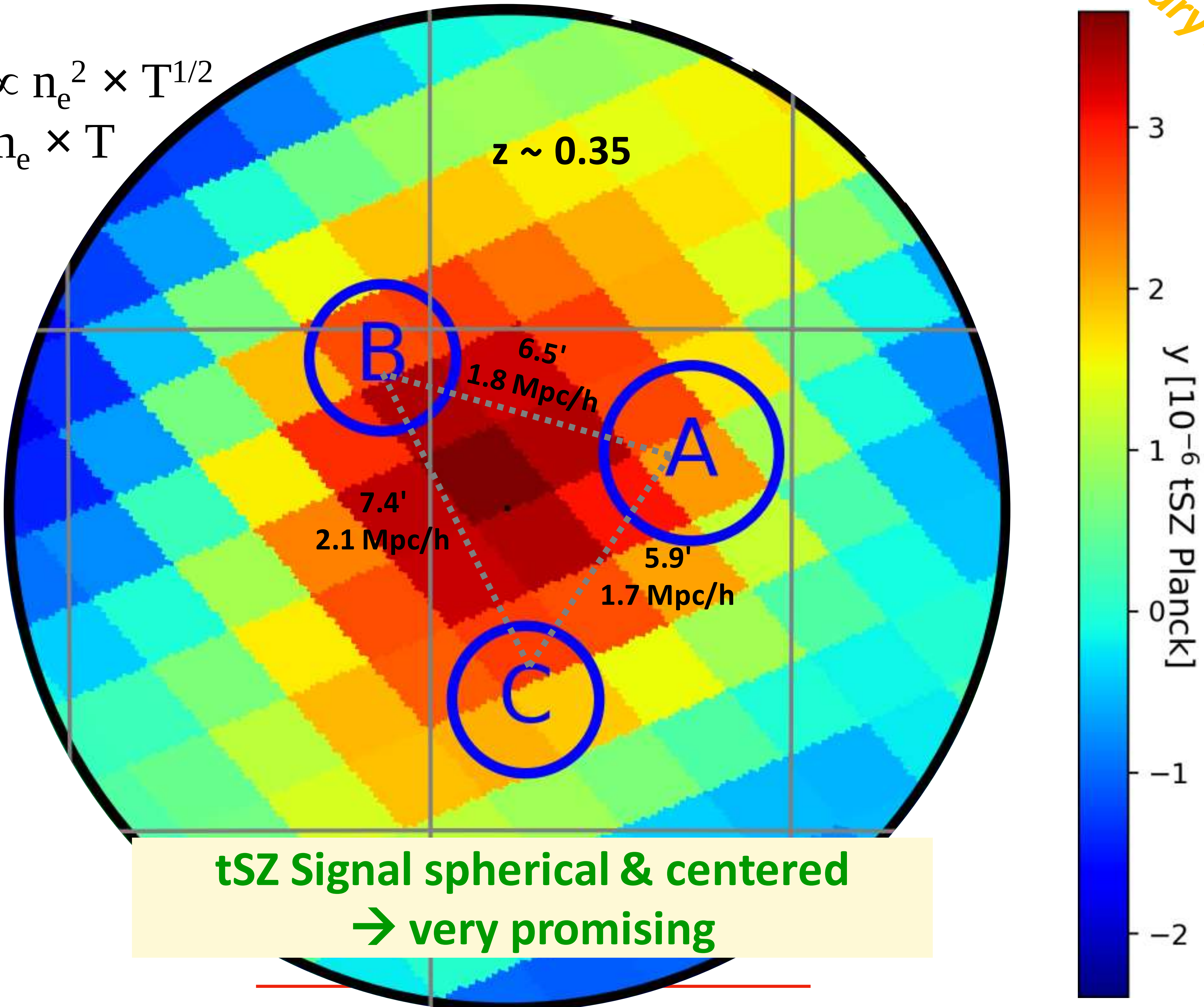
Preliminary results



Jointed X-ray – tSZ analysis: An outlook

Preliminary results

X-ray: $\propto n_e^2 \times T^{1/2}$
tSZ: $\propto n_e \times T$



tSZ Signal spherical & centered
→ very promising

Take-home messages

- WHIM stacking studies great success but blind to many of its physical properties
- Need complementary multiwavelength studies of individual structures
- Superclusters ideal target
- Interesting sources available
  → our study hopefully emphasis deeper X-ray follow-ups
- Accurate XMM-Newton BKG knowledge crucial!
  → Thank you S. Molendi, F. Gastaldello, D. Eckert, the XMM-Newton Team et al.