Galaxy cluster cosmology

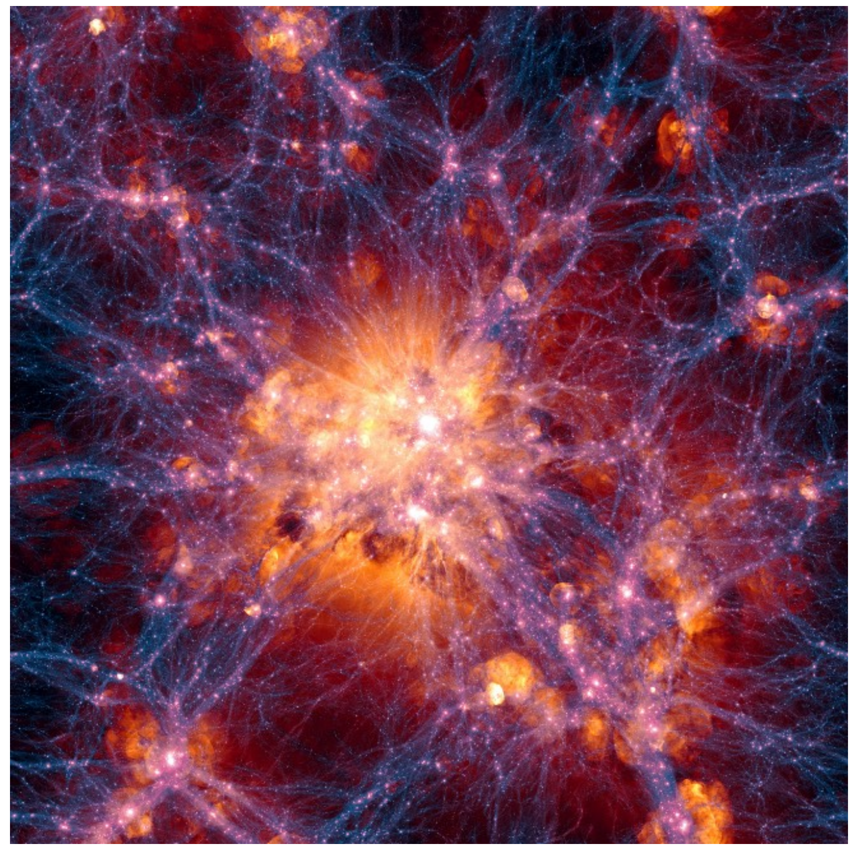
Céline Combet

on behalf of

R. Adam, D. Boutigny, T. Louis, J.F. Macías-Pérez, S. Maurogordato, F. Mayet, L. Perotto, C. Renault, M. Ricci, Y. Zolnierowski, R. Ansari, J. Bartlett, J. Bregeon, J. Cohen-Tanugi, S. Dagoret-Campagne, J. Delabrouille, K. Ganga, E. Gangler, B. Kubik, D. Maurin, J.Neveu, E. Nuss

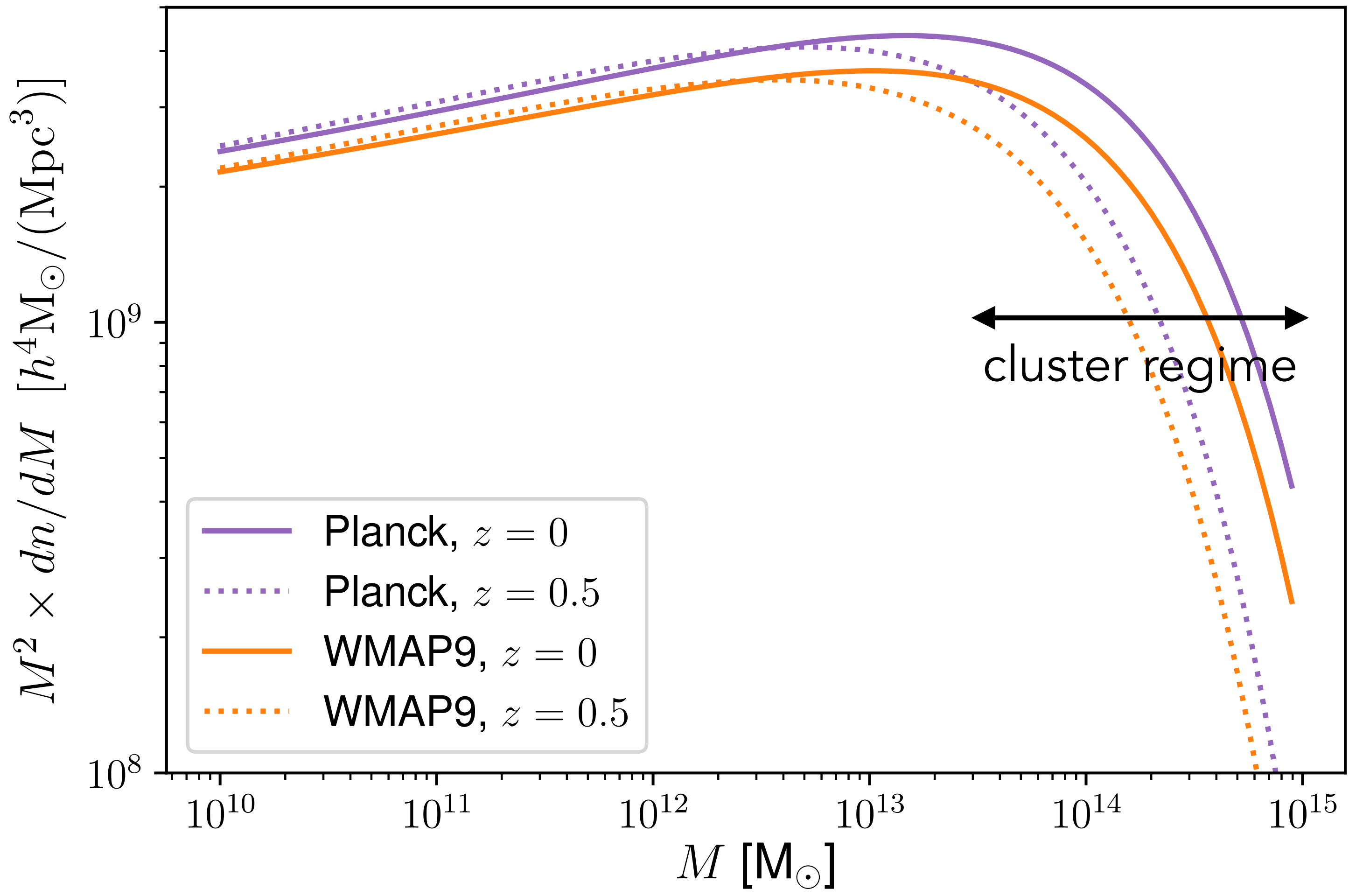
Galaxy clusters are…

…cosmological objects



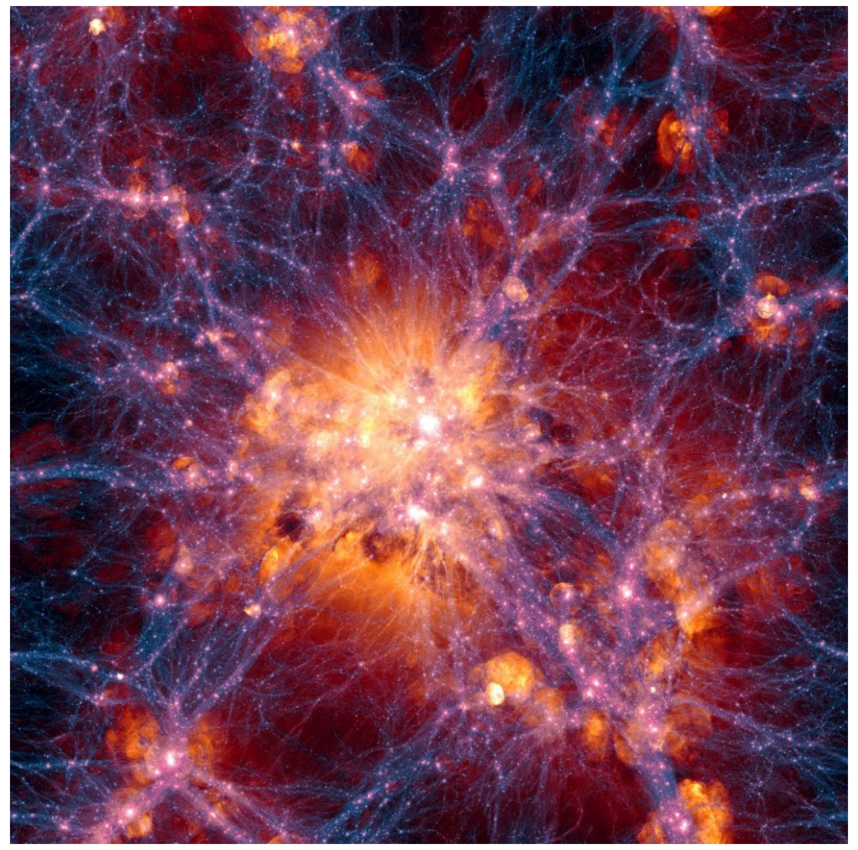
Illustris simulation

- Largest gravitationally bound structures in the Universe
- Formed by gravitational collapse at the intersection of cosmic filaments
- $M_{tot} = 10^{13}$-10^{16} M_{sun} (85% DM)
- $0 < z < 3$
- Mass and redshift distribution of clusters is sensitive to cosmology (expansion and growth of structure)



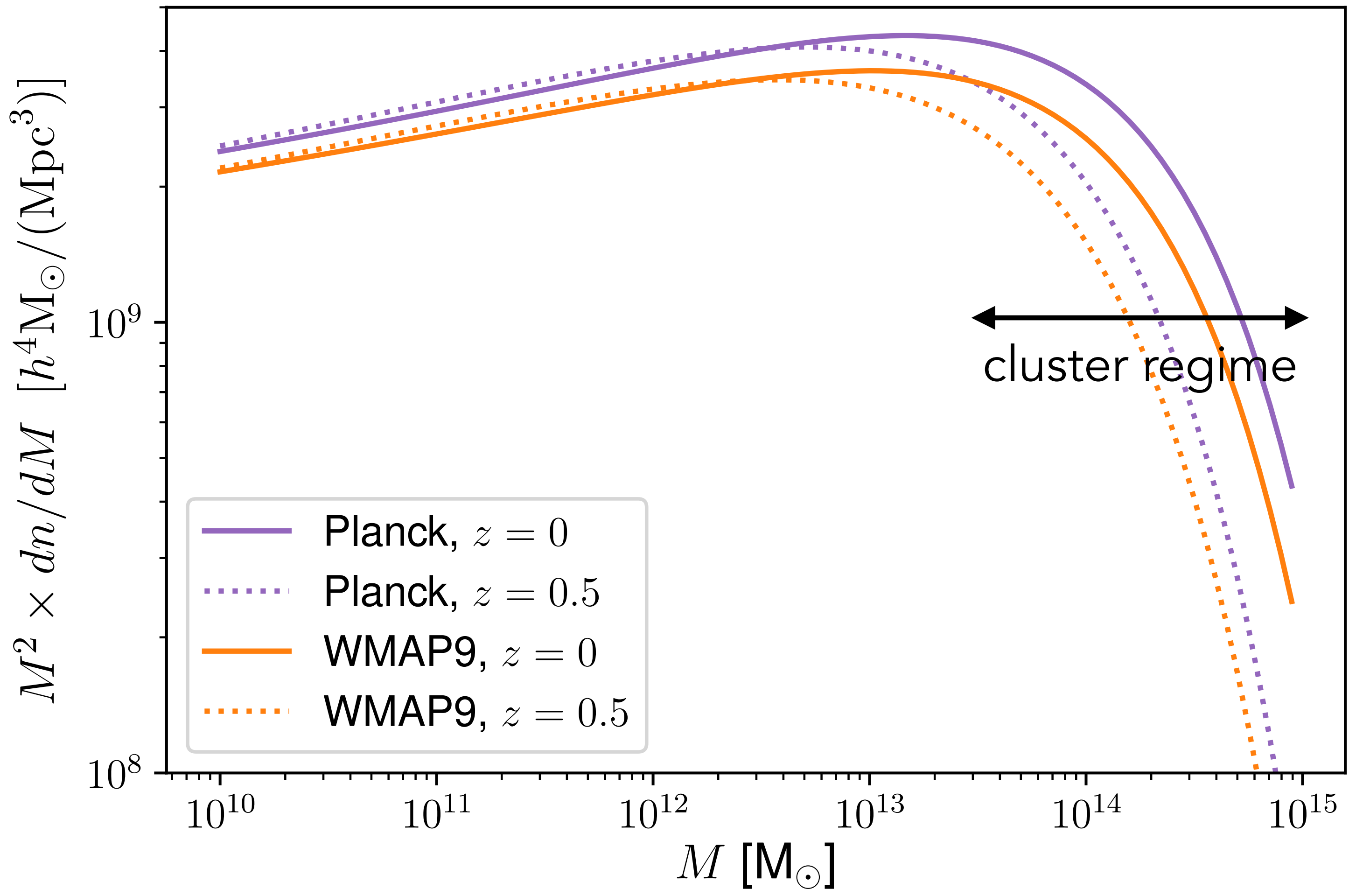
Galaxy clusters are…

…cosmological objects



Illustris simulation

- Largest gravitationally bound structures in the Univers
- Formed by gravitational collapse at the intersection of cosmic filaments
- $M_{tot} = 10^{13}\text{-}10^{16}\ M_{sun}$ (85% DM)
- $0 < z < 3$
- Mass and redshift distribution of clusters is sensitive to cosmology (expansion and growth of structure)



…rich multiwavelength astrophysical objects

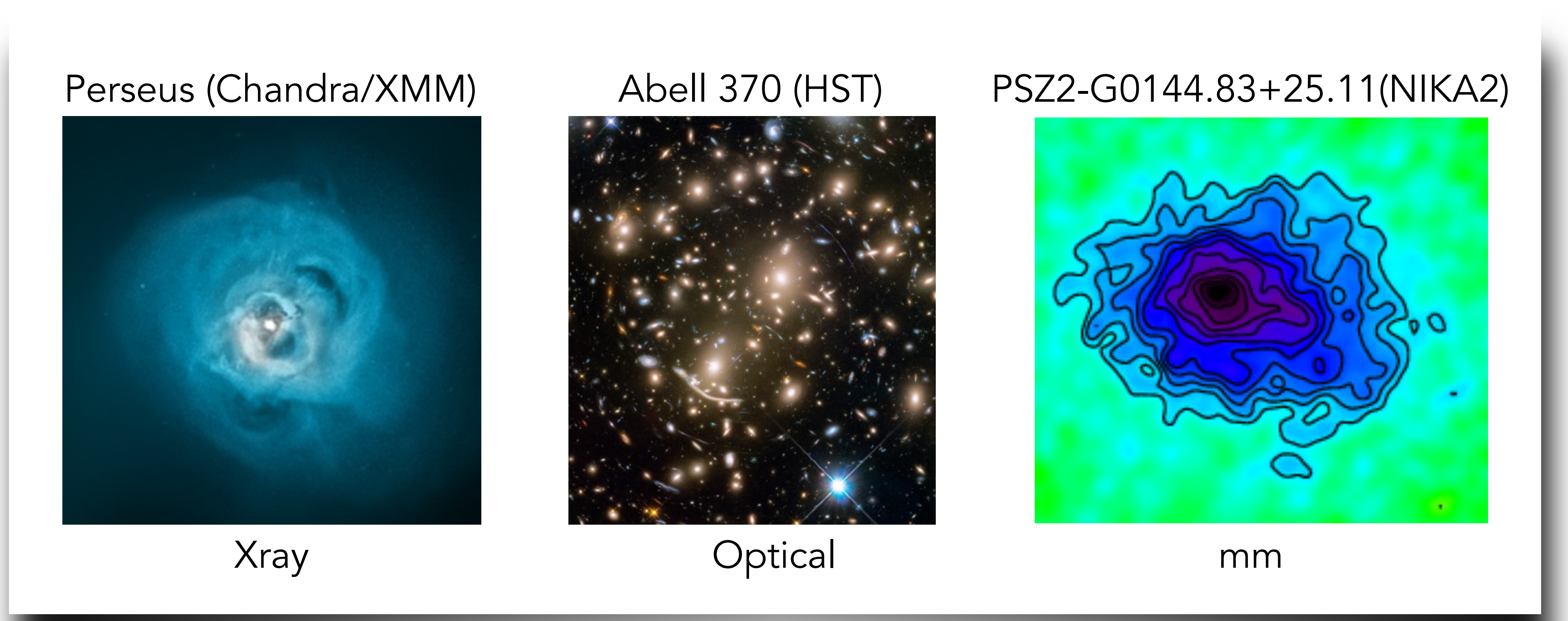
X-ray: free-free emission from ICM e-

Optical and infrared: light from galaxies

mm-wavelength: Inverse Compton of CMB photons on hot ICM e- (SZ)

Radio: synchrotron, non-thermal emission (shocks and turbulence)

Gamma-rays: cosmic rays (e.g., π^0 decay)



Perseus (Chandra/XMM) — Xray

Abell 370 (HST) — Optical

PSZ2-G0144.83+25.11(NIKA2) — mm

Cluster cosmology

Experimental landscape in the next decade

Conclusions

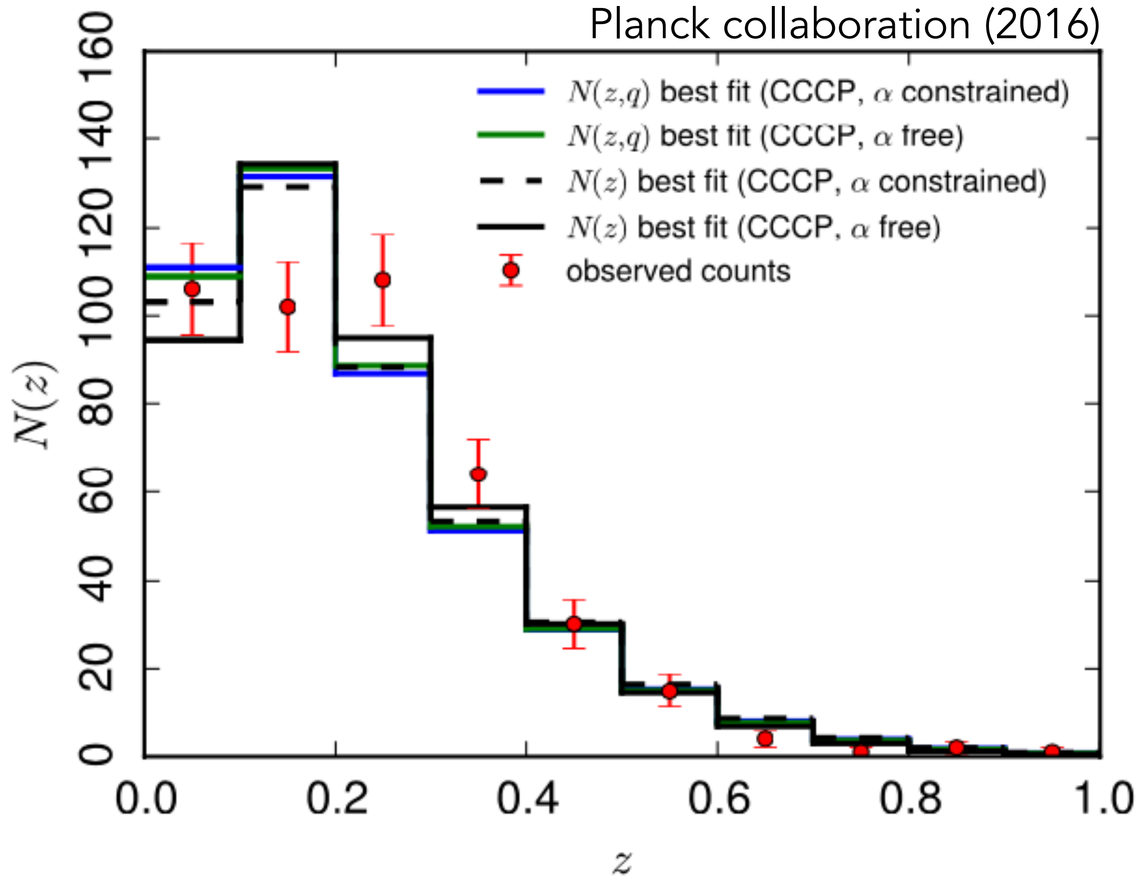
Probing cosmology with clusters I.

Cluster counts (SZ, X-ray, optical)

$$N_{a,i} = \frac{\Delta\Omega}{4\pi} \int_{z_i}^{z_{i+1}} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z} \int_{\ln M_a}^{\ln M_{a+1}} \frac{\mathrm{d}n(M,z)}{\mathrm{d}\ln M} \mathrm{d}\ln M$$

cosmology (expansion + structure growth)

Planck collaboration (2016)

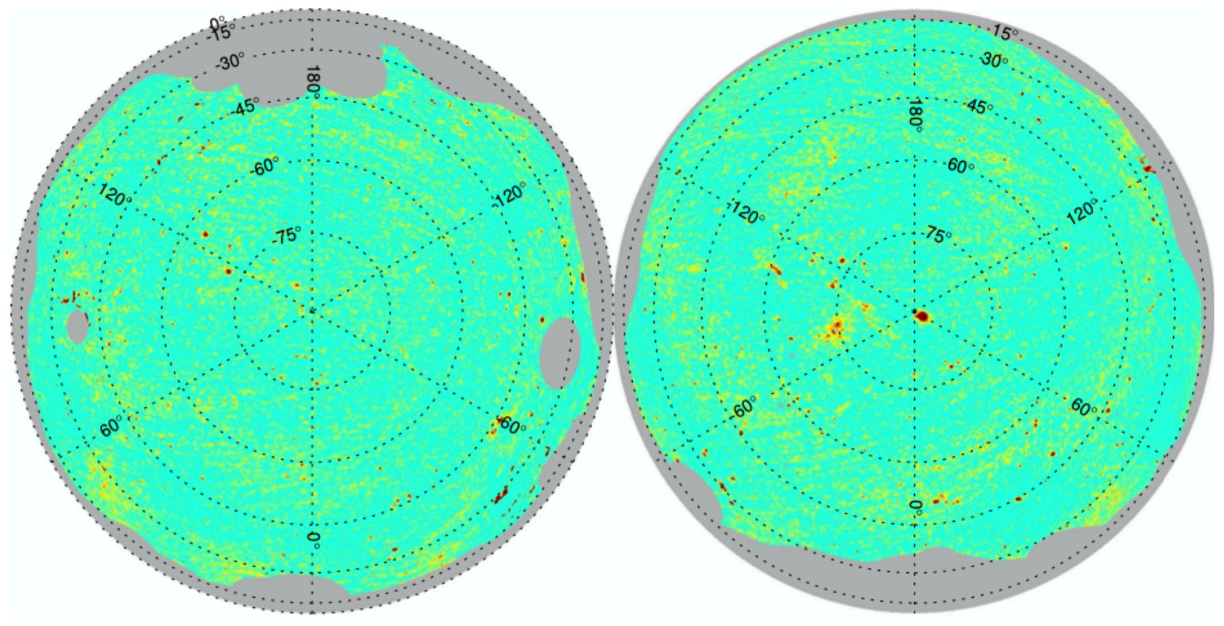


1. Find clusters in survey data
2. Estimate (M,z) of clusters + selection function
3. Compute cluster abundances
4. Mass function model = f (cosmo)
5. Likelihood analysis

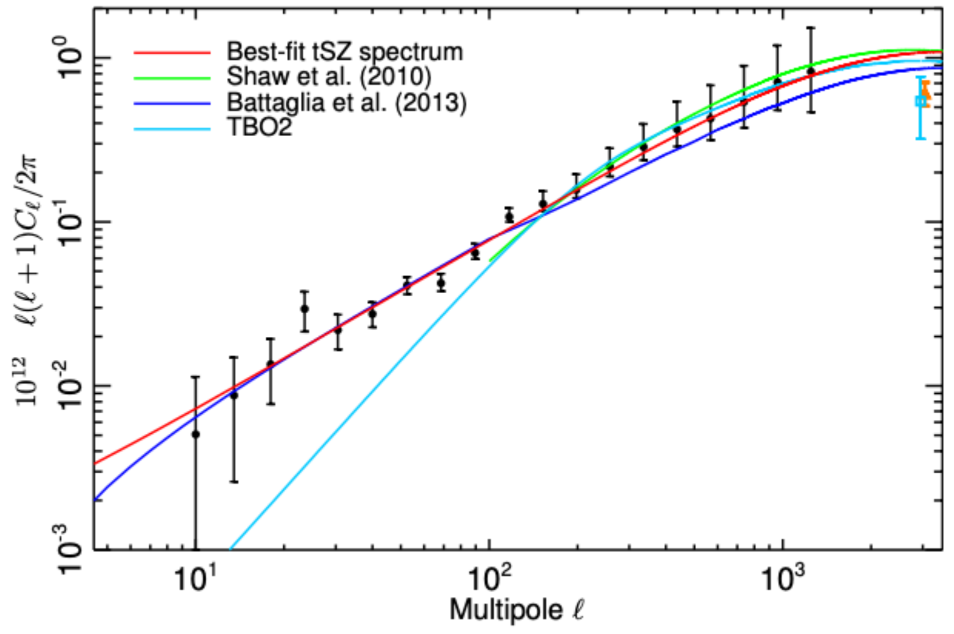
Cluster spatial distribution

SZ power spectrum

$$C_\ell \propto \int_0^{z_{\max}} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z} \int_{M_{\min}}^{M_{\max}} \frac{\mathrm{d}n(M,z)}{\mathrm{d}\ln M} \,|\, y_\ell(M,z) \,|^2 \,\mathrm{d}\ln M$$



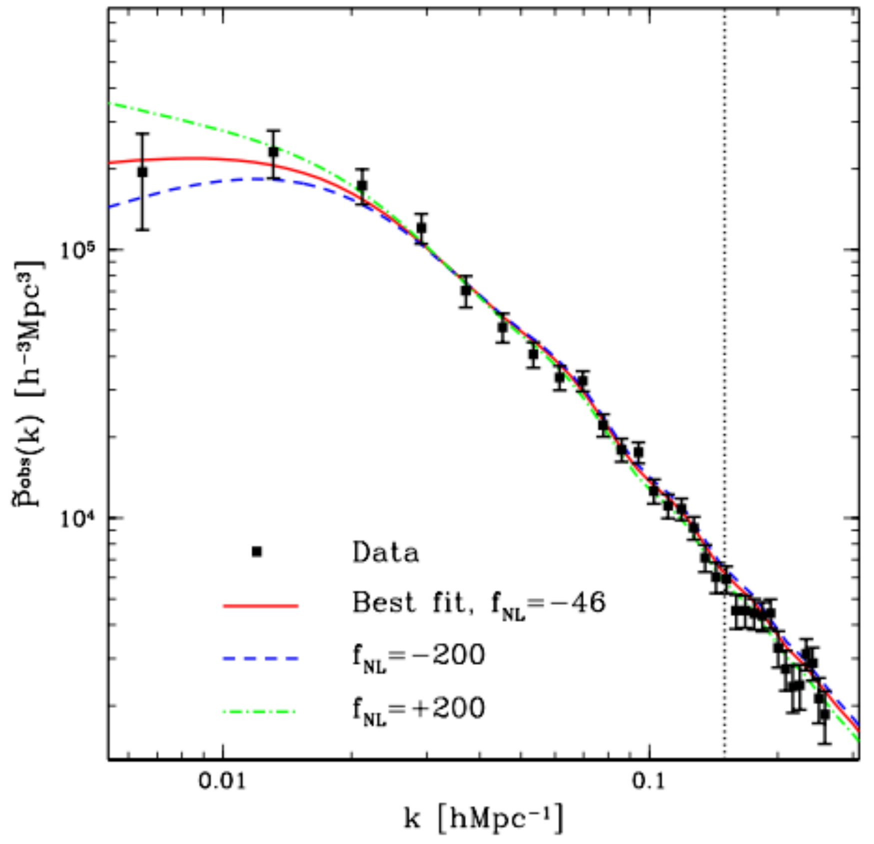
Planck collaboration (2015)



Cluster clustering

Use clusters (and not galaxies) as tracers of the cosmic web
→ 2pt-correlation function or power spectrum

Mana et al. (2013)

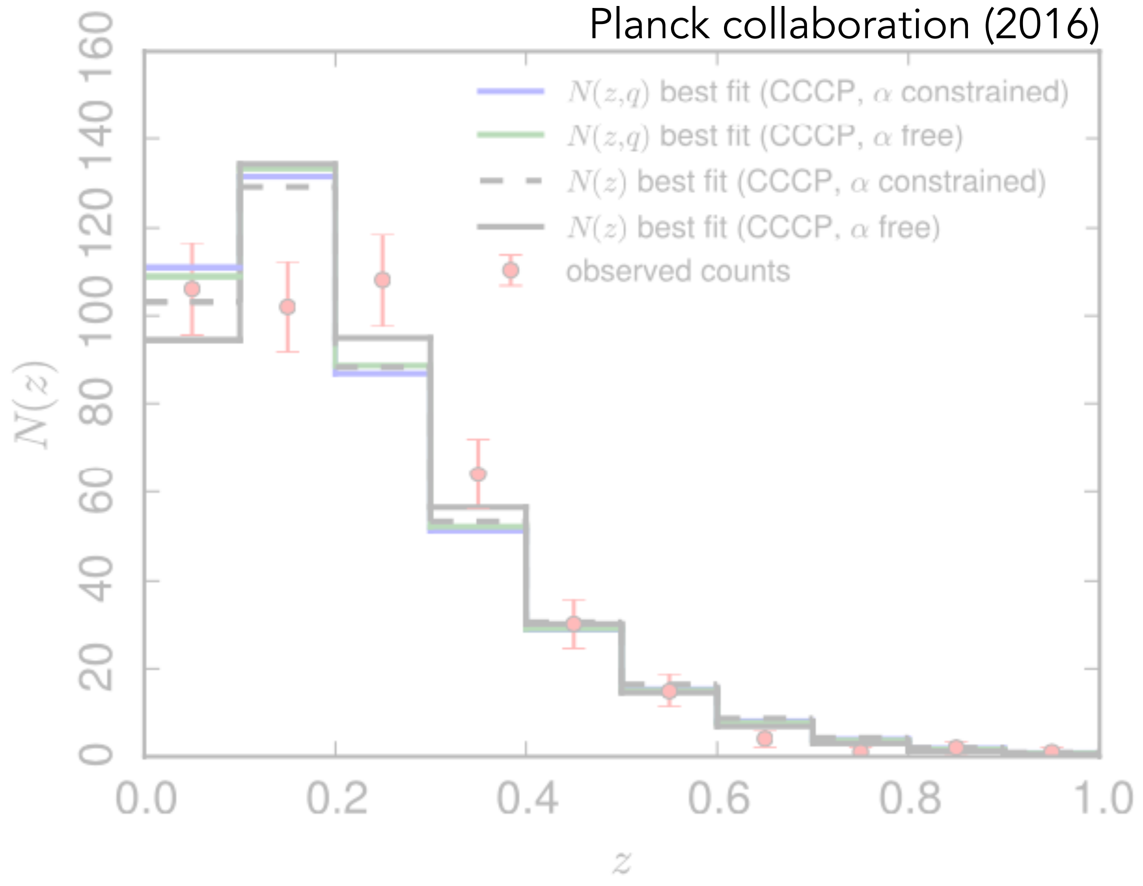


Probing cosmology with clusters I.

Cluster counts (SZ, X-ray, optical)

$$N_{a,i} = \frac{\Delta\Omega}{4\pi}\int_{z_i}^{z_{i+1}} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z} \int_{\ln M_a}^{\ln M_{a+1}} \frac{\mathrm{d}n(M,z)}{\mathrm{d}\ln M} \mathrm{d}\ln M$$

cosmology (expansion + structure growth)



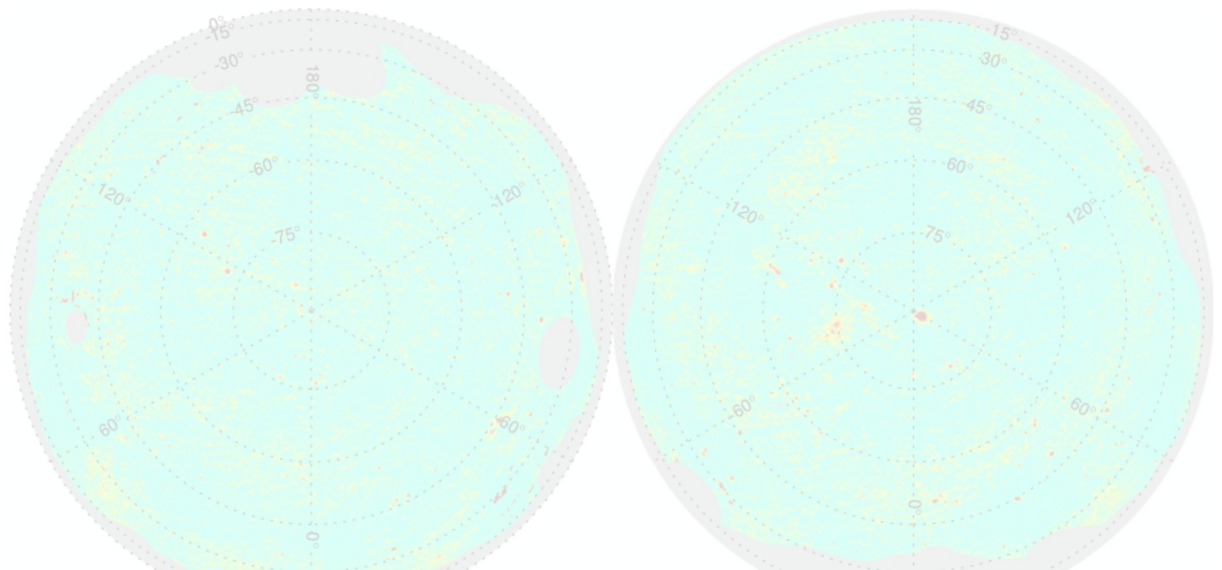
Planck collaboration (2016)

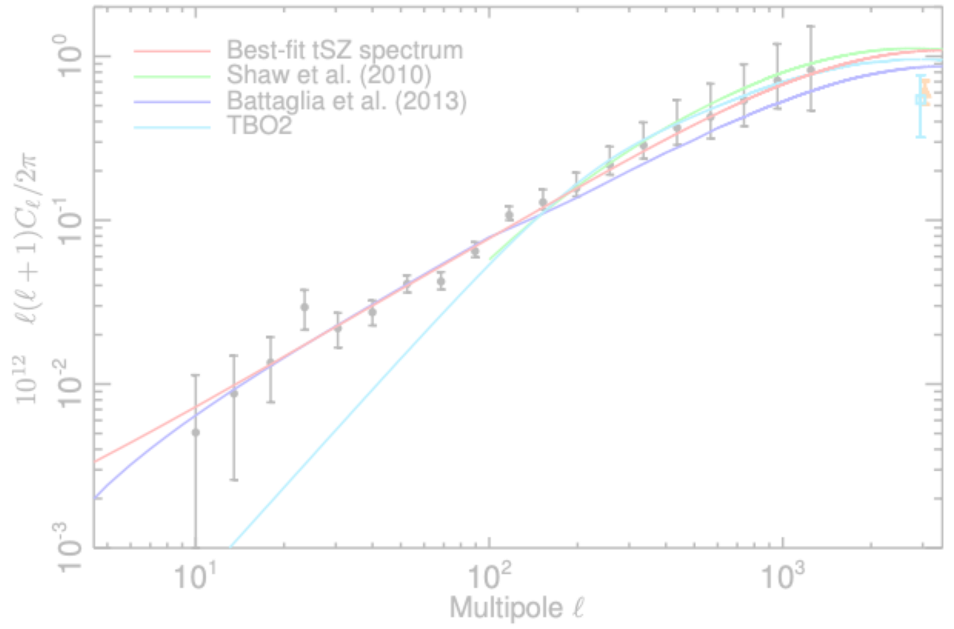
1. Find clusters in survey data
2. Estimate (M,z) of clusters + selection function
3. Compute cluster abundances
4. Mass function model = f (cosmo)
5. Likelihood analysis

Cluster spatial distribution

SZ power spectrum

$$C_\ell \propto \int_0^{z_{\max}} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z} \int_{M_{\min}}^{M_{\max}} \frac{\mathrm{d}n(M,z)}{\mathrm{d}\ln M} \,|\, y_\ell(M,z)\,|^2 \,\mathrm{d}\ln M$$



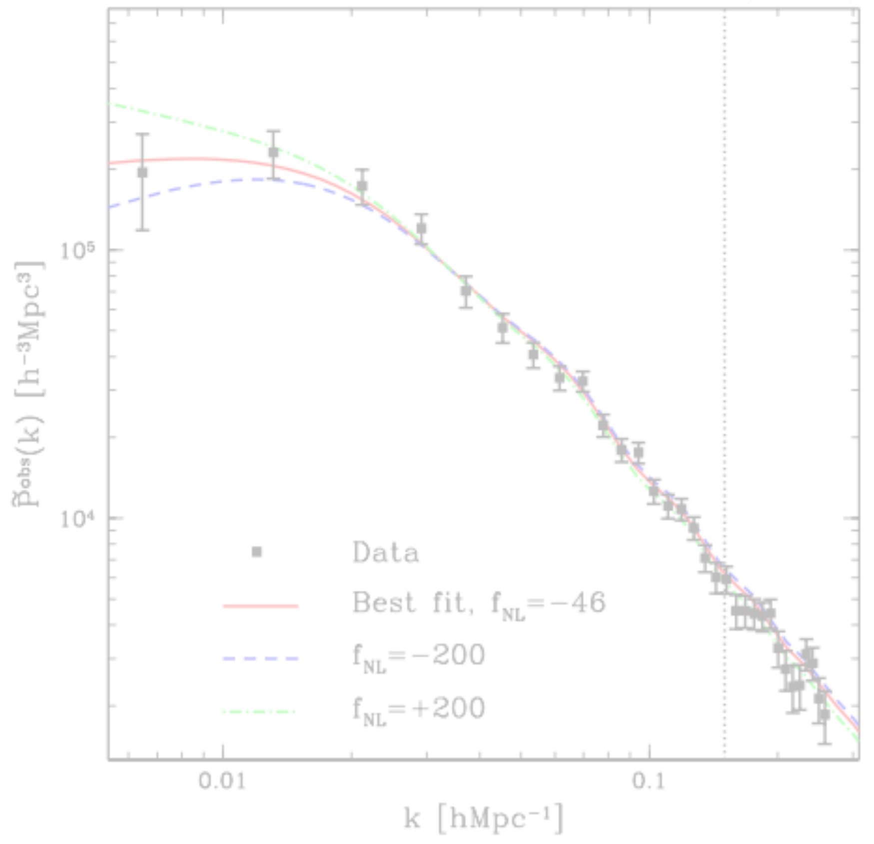


Planck collaboration (2015)

Cluster clustering

Use clusters (and not galaxies) as tracers of the cosmic web

→ 2pt-correlation function or power spectrum



Mana et al. (2013)

Problem: the mass is not an observable

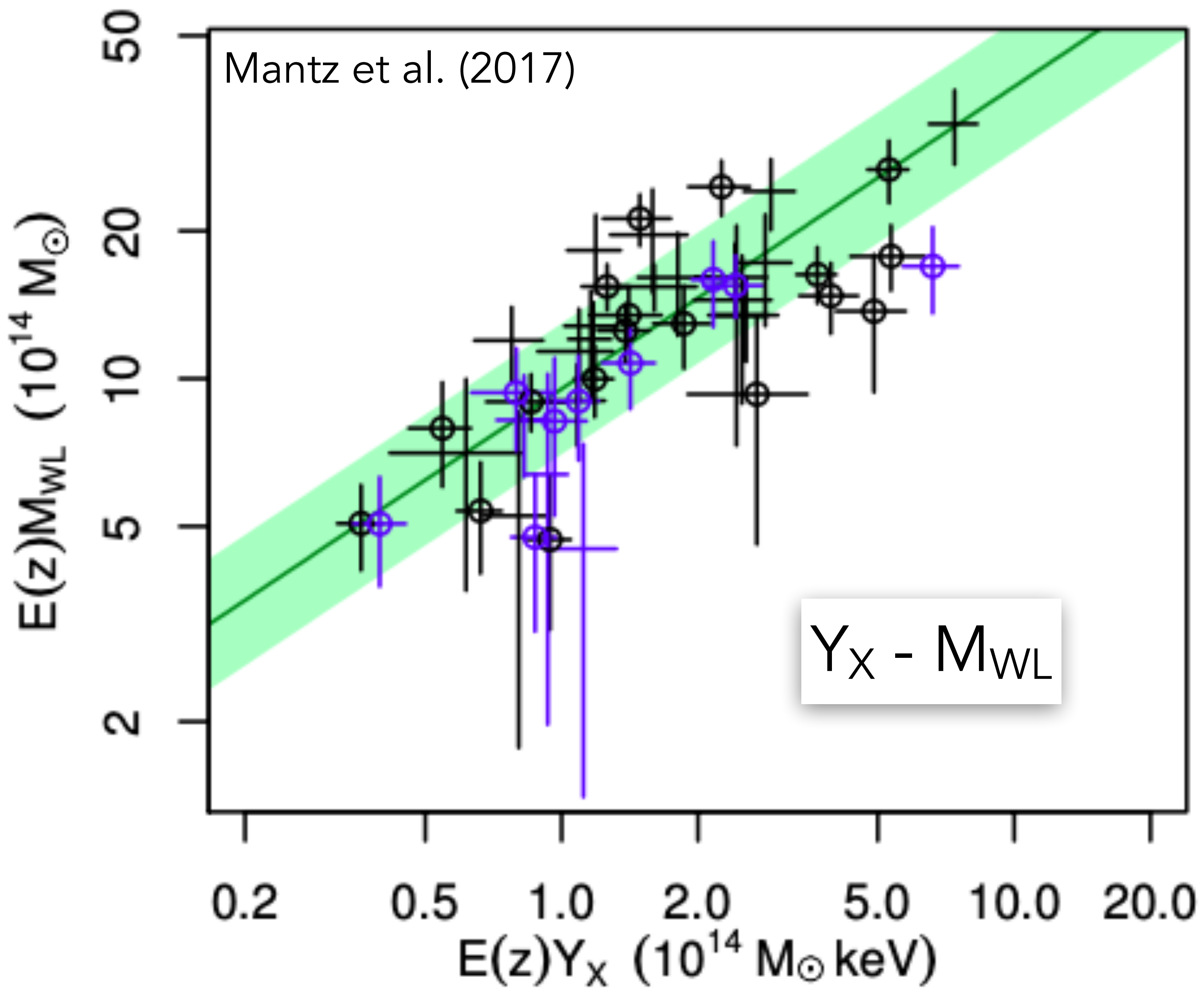
Determining the cluster mass - multi-λ effort

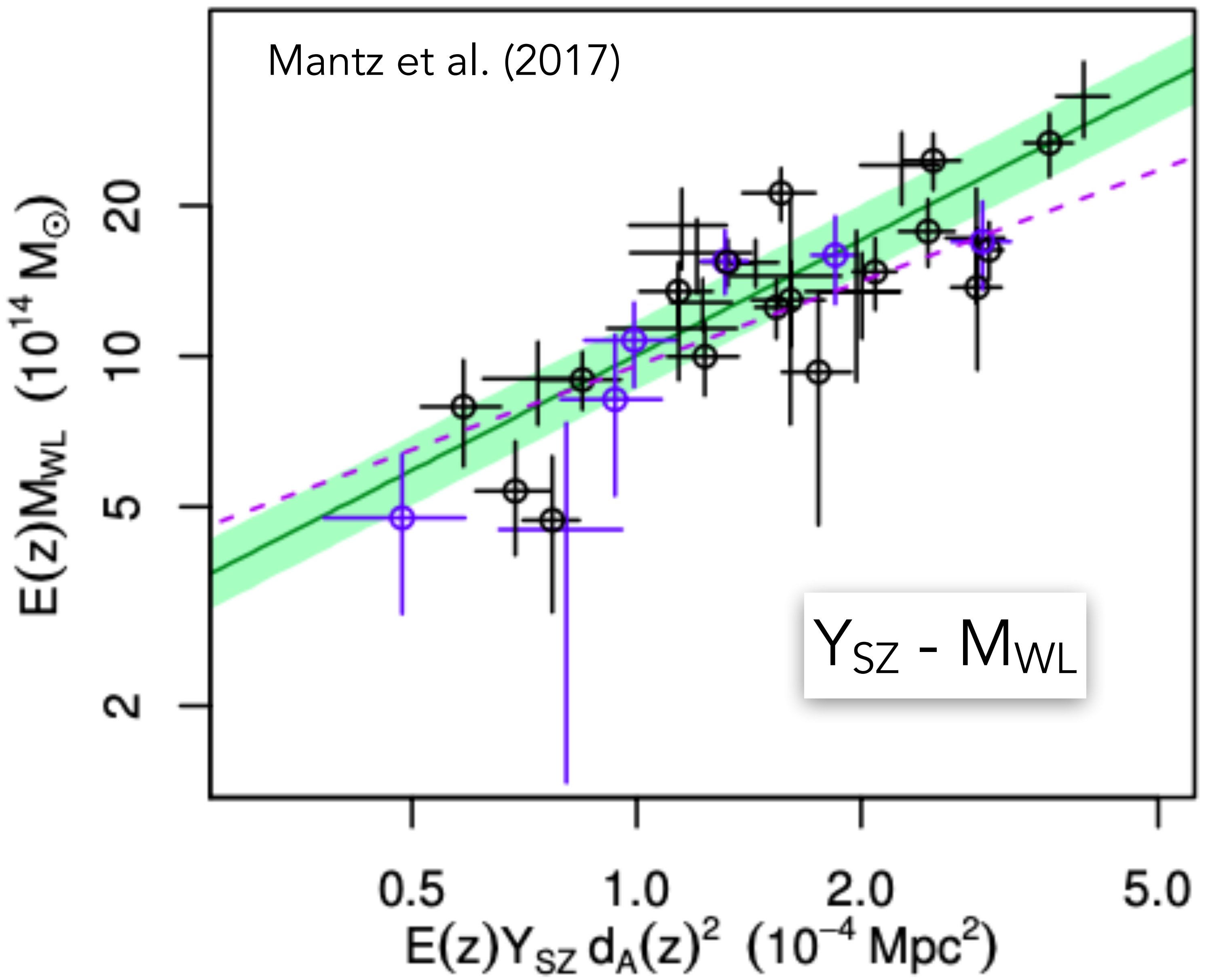
Cluster observable:

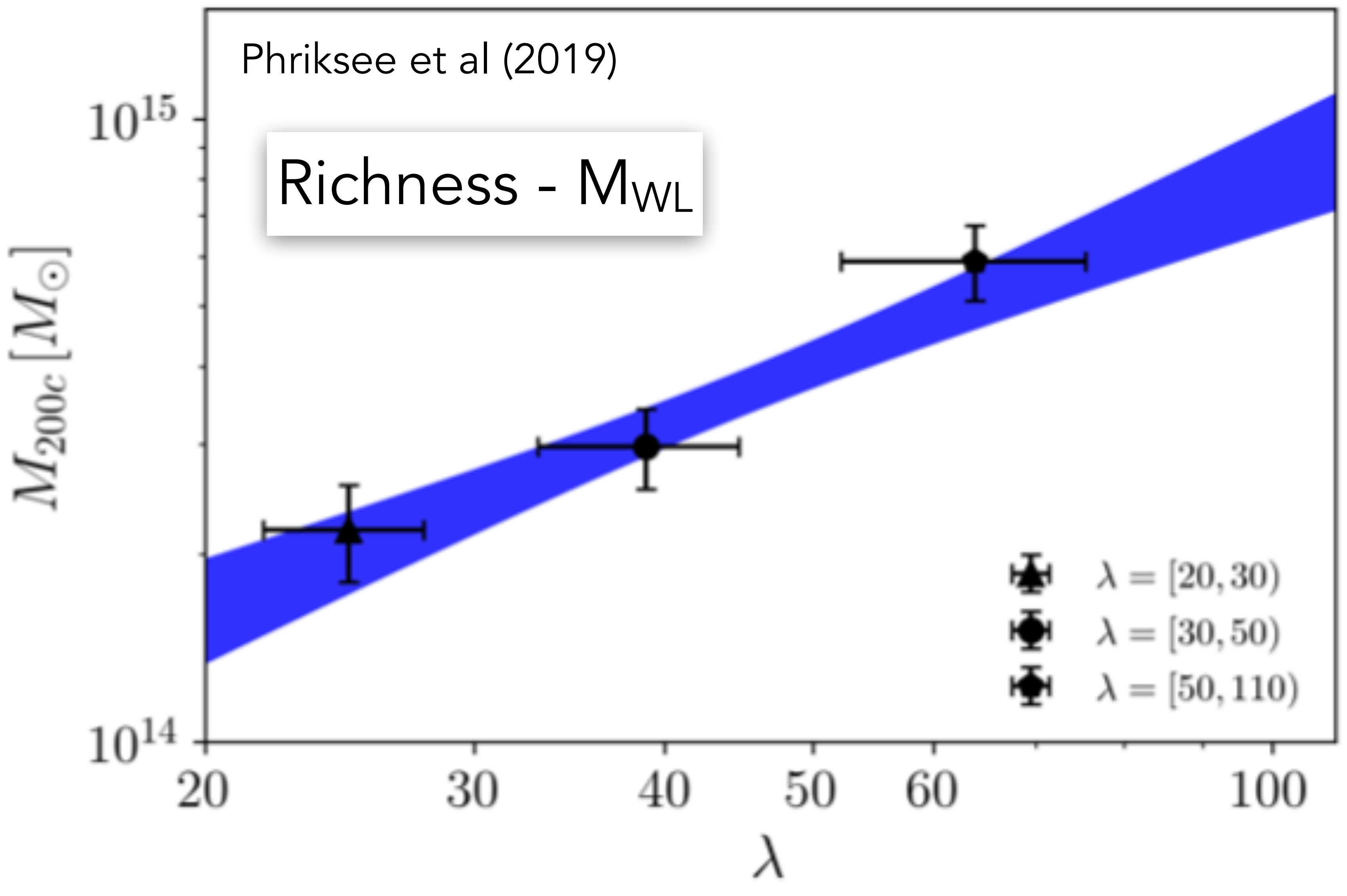
- X-ray: L_X, kT_X, Y_X
- mm: SZ decrement
- optical : richness (number of galaxies in a cluster), lensing

→ Determine a mass-observable relation on a representative selection of well-measured clusters

→ Apply it to the full sample







Determining the cluster mass - multi-λ effort

Cluster observable:

- X-ray: L_X, kT_X, Y_X
- mm: SZ decrement
- optical : richness (number of galaxies in a cluster), lensing

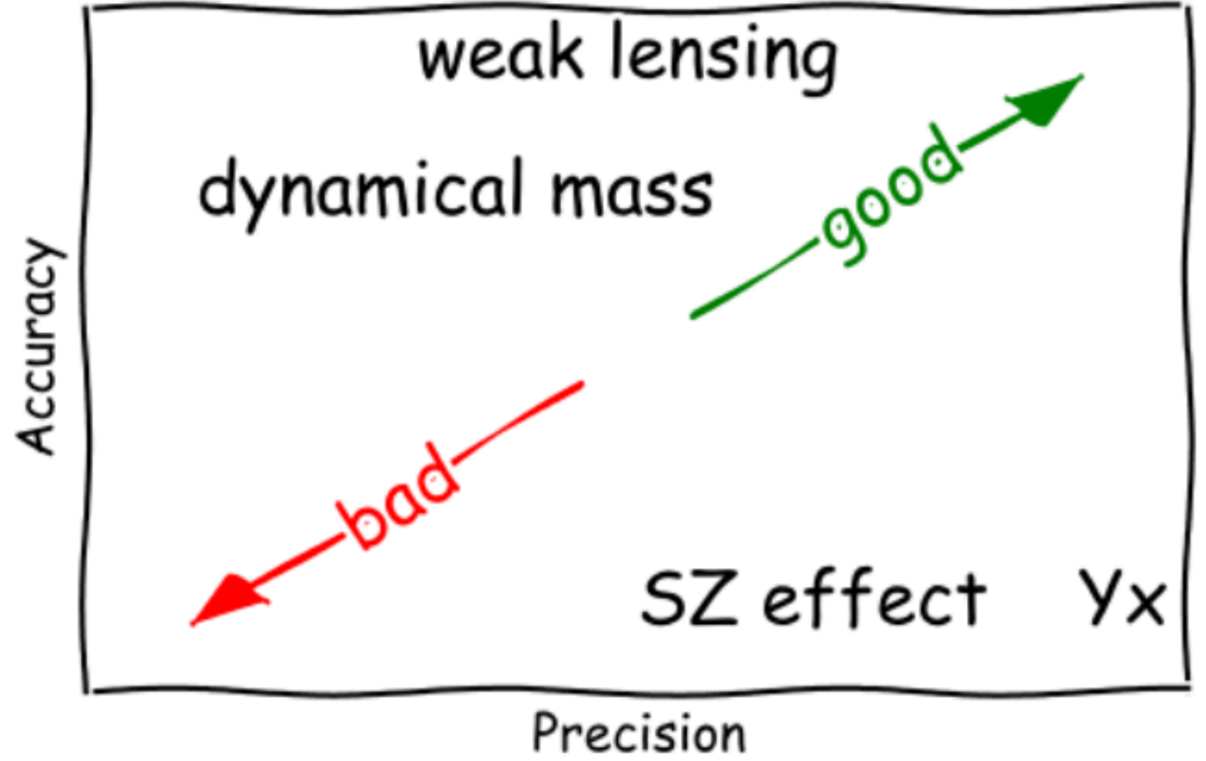
mass from spherical cluster in hydro. eq.

hydrostatic bias

lensing mass as absolute calibration

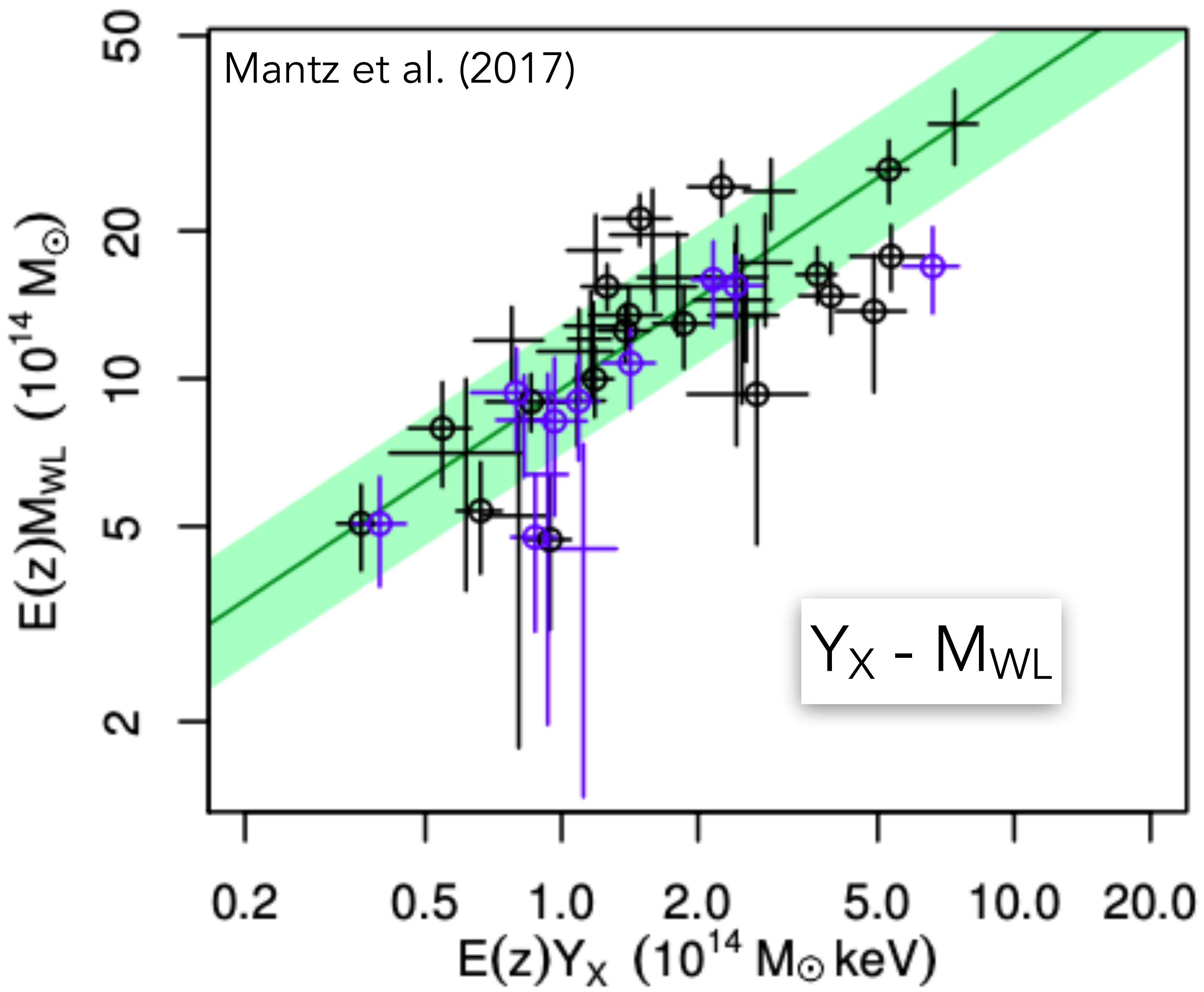
$$M_{obs} = (1\text{-}b)\, M_{true} \neq M_{true} \longleftrightarrow M_{lensing}$$

From S. Bocquet

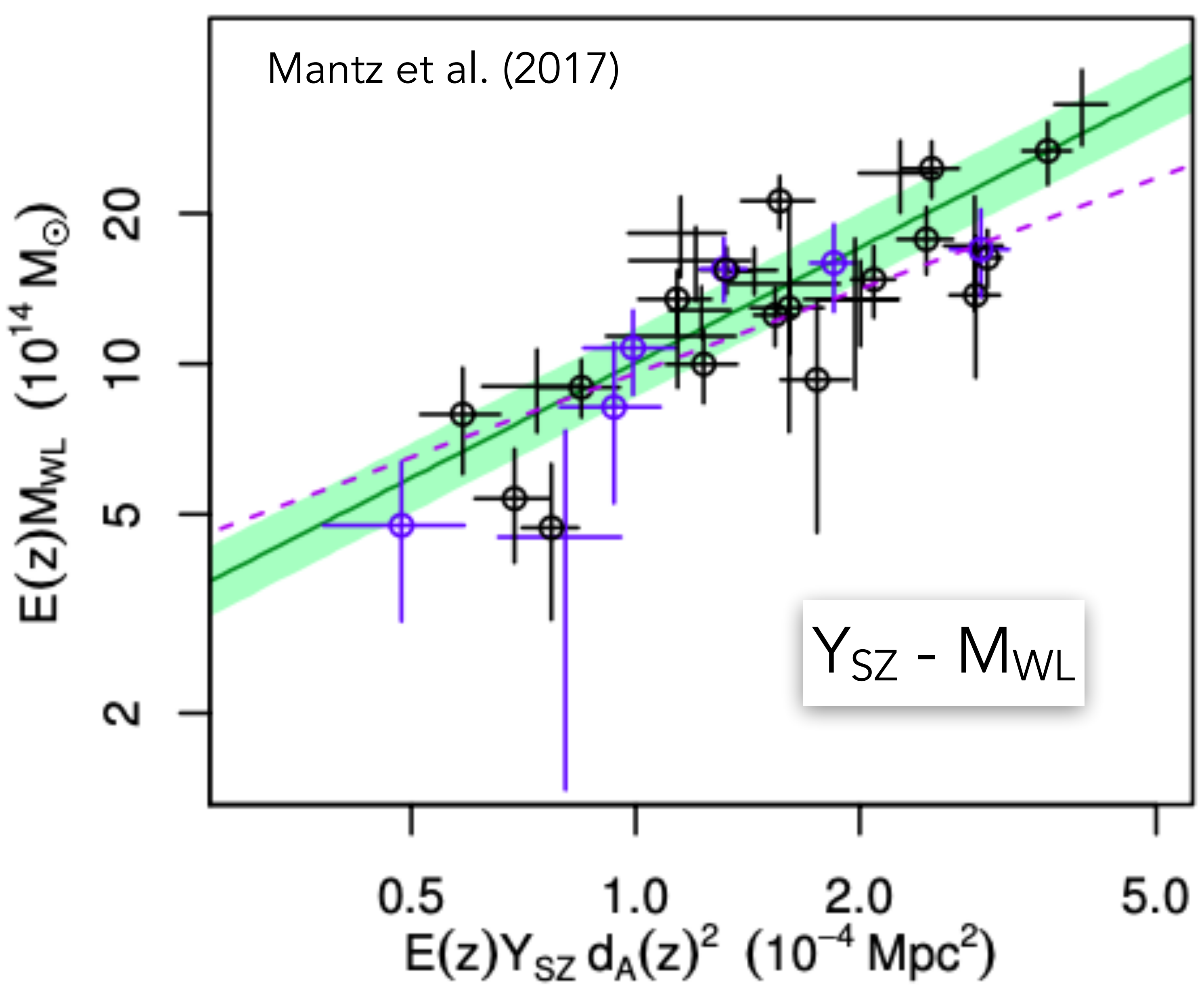


→ Determine a mass-observable relation on a representative selection of well-measured clusters

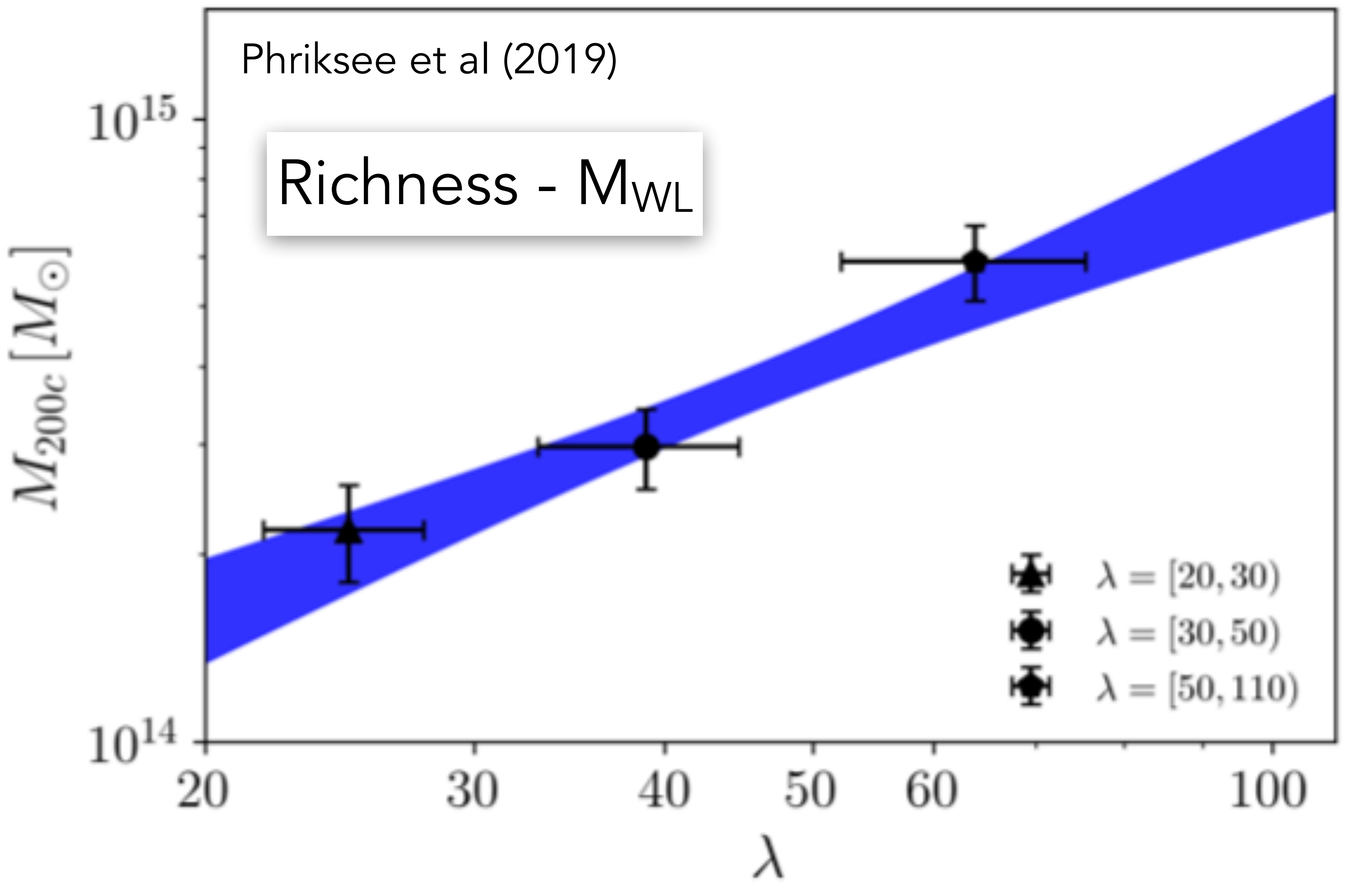
→ Apply it to the full sample


Mantz et al. (2017)

Y_X - M_{WL}


Mantz et al. (2017)

Y_{SZ} - M_{WL}

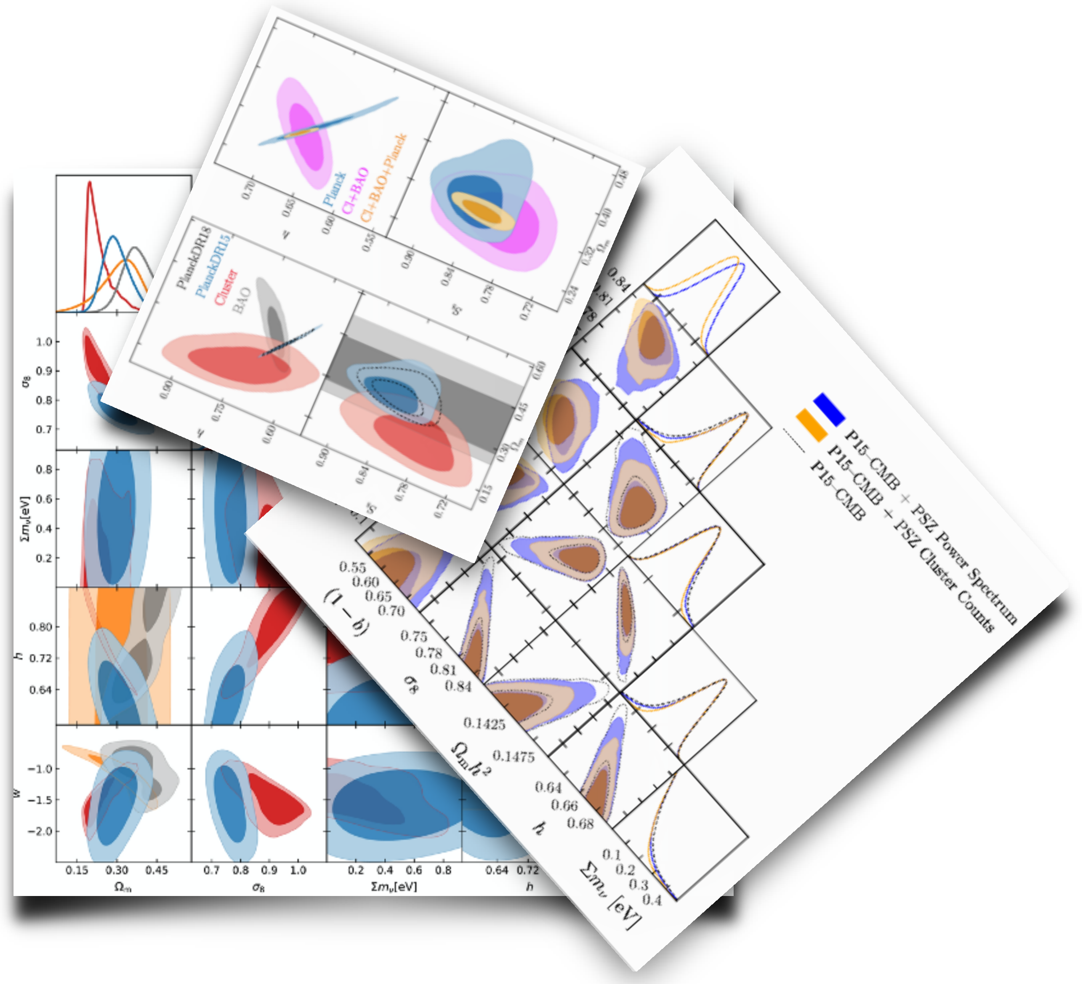

Phriksee et al (2019)

Richness - M_{WL}

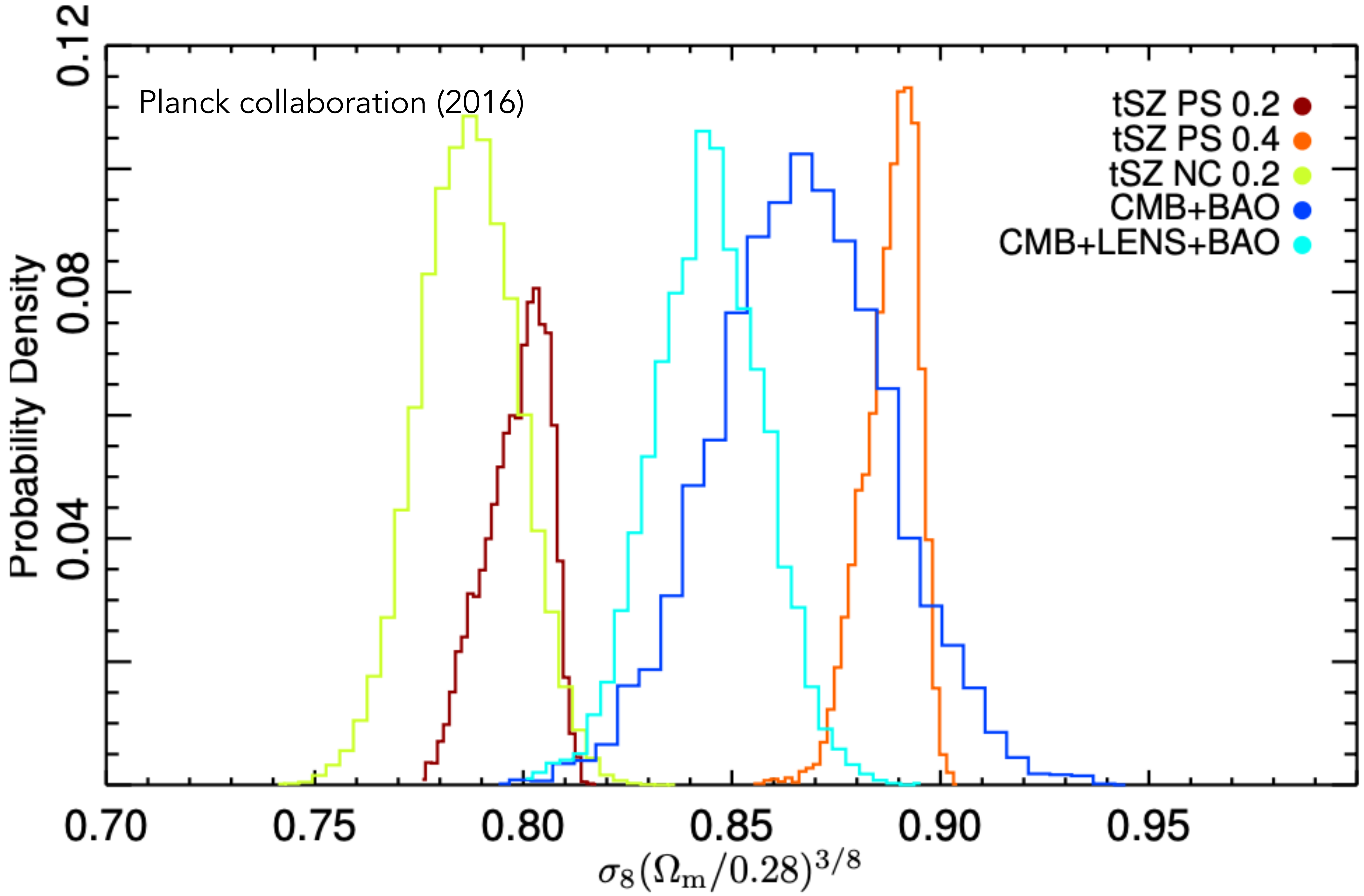
Current situation

Clusters are sensitive to various cosmological parameters: $\Omega_m, \sigma_8, w, \Sigma m_\nu, f_{\rm NL}$ + modified gravity

Results from wavelength: Planck, ACT, SPT, WtG, SDSS, DES, HSC, XXL,…



Central issue since Planck 2013: tension with CMB results



Origin of the tension in the literature:

"Systematics":

- **mass / hydro. bias value**
- normalisation of pressure profile (SZ)
- value of the reionisation optical depth

New physics:

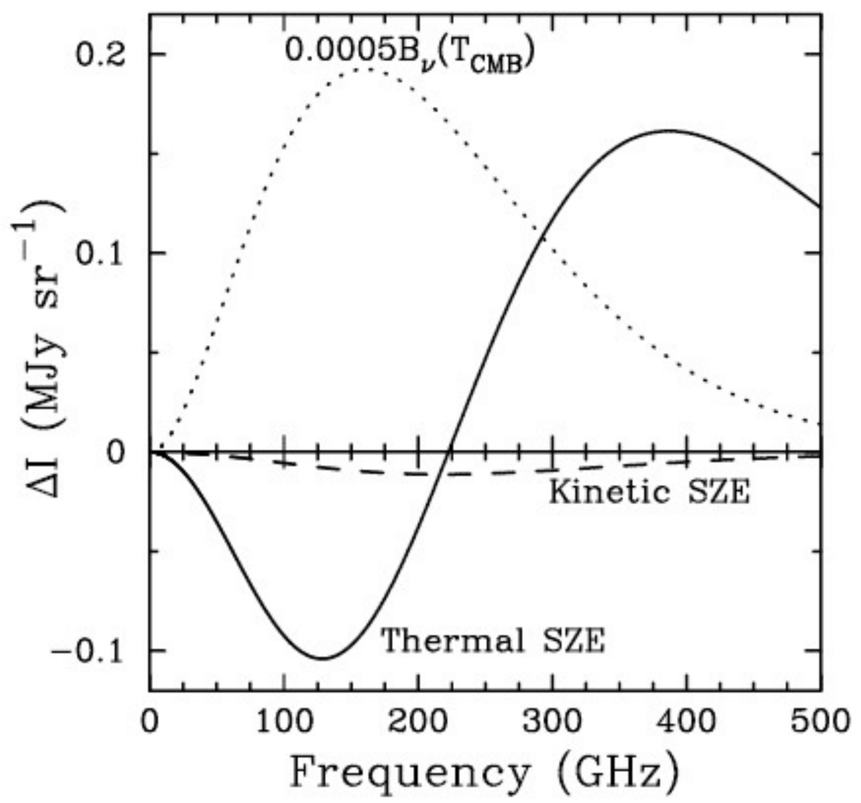
- neutrino mass
- modified gravity

Other approaches…

Kinetic SZ

Spectral signature of the motion of galaxy clusters in the CMB rest frame

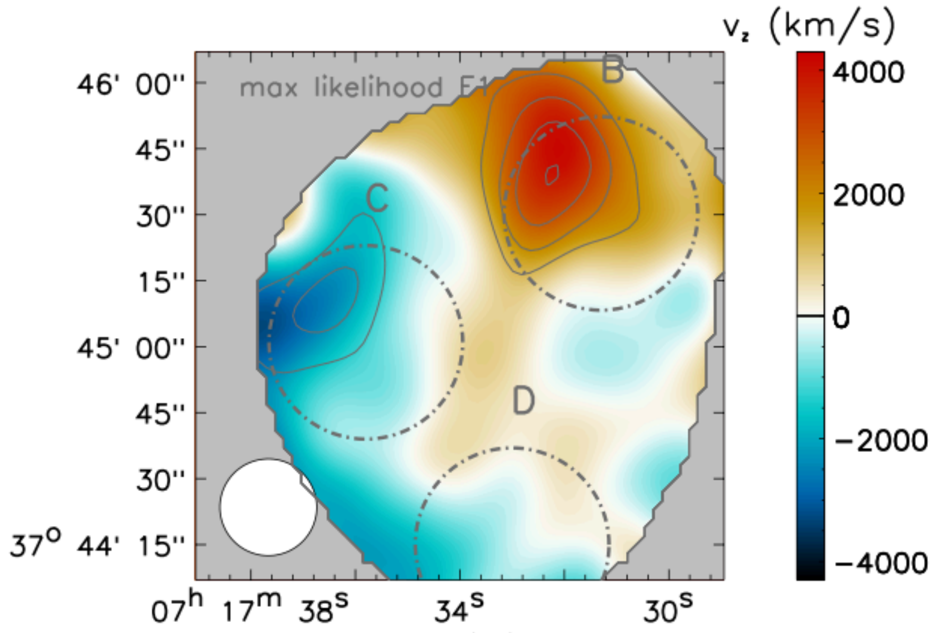
$$\frac{\Delta T_{\rm kSZ}}{T_{\rm CMB}} = -\,\tau \frac{v_z}{c}$$



The kSZ effect: a lot of potential
→ growth of structures
→ patchy reionization
→ thermodynamics of clusters

Allen et al. (2011) review: "*Although some initial results based on such measurements have been reported (…), the technique has not yet reached the maturity of those discussed above and is not discussed further in this review.*"

- Hand et al. (2012):
  → first detection (ACT + SDSS)
- Adam et al. (2017):
  → first map of the kSZ signal (NIKA)



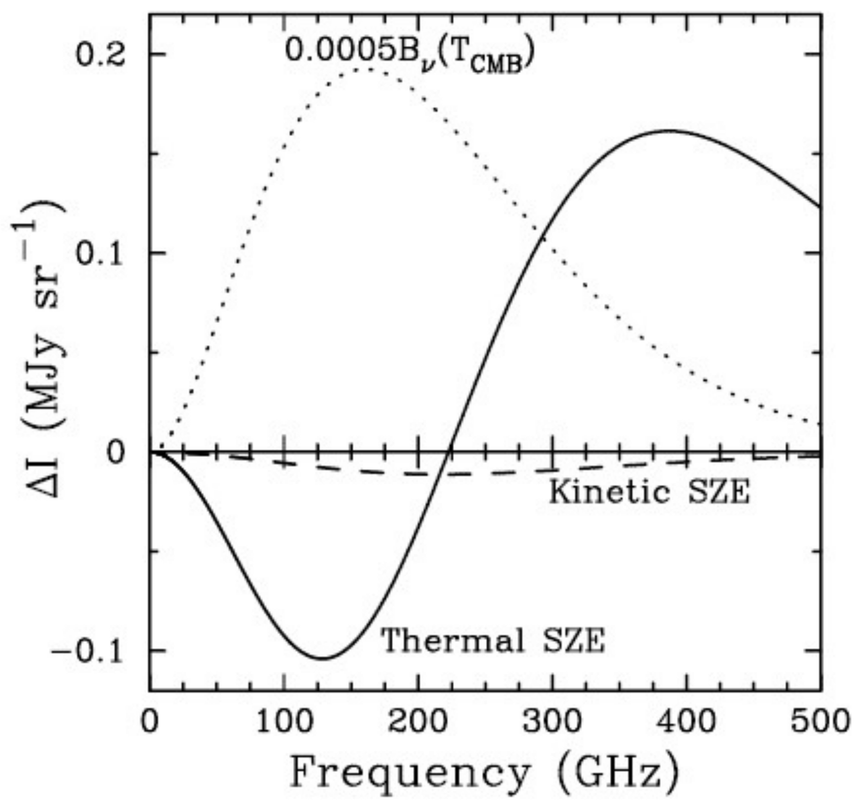
Adam et al. (2017)

Other approaches…

Kinetic SZ

Spectral signature of the motion of galaxy clusters in the CMB rest frame

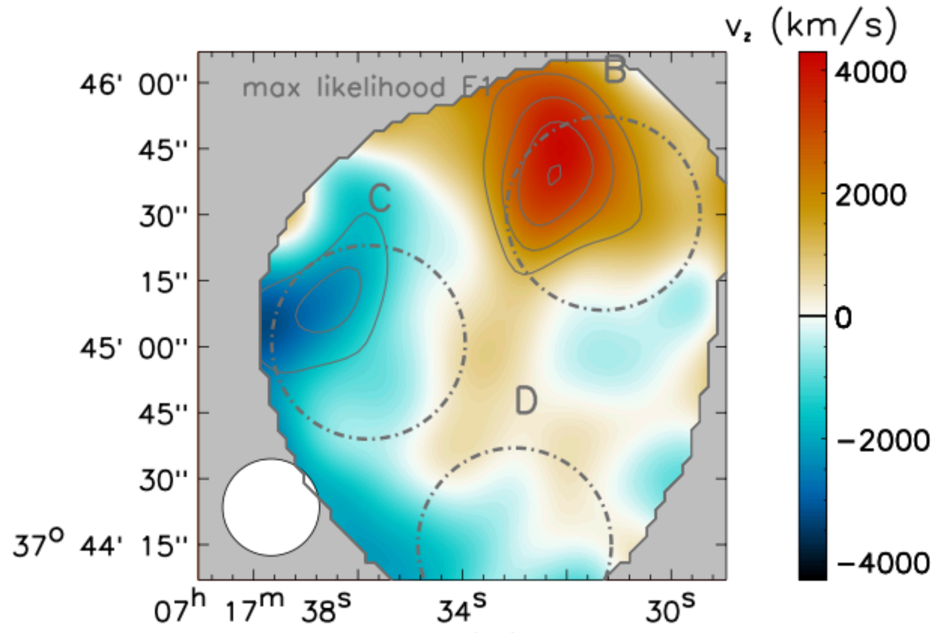
$$\frac{\Delta T_{\rm kSZ}}{T_{\rm CMB}} = -\tau \frac{v_z}{c}$$



The kSZ effect: a lot of potential
→ growth of structures
→ patchy reionization
→ thermodynamics of clusters

Allen et al. (2011) review: "*Although some initial results based on such measurements have been reported (…), the technique has not yet reached the maturity of those discussed above and is not discussed further in this review.*"

- Hand et al. (2012):
  → first detection (ACT + SDSS)
- Adam et al. (2017):
  → first map of the kSZ signal (NIKA)



Adam et al. (2017)

Gas fraction (X-rays)

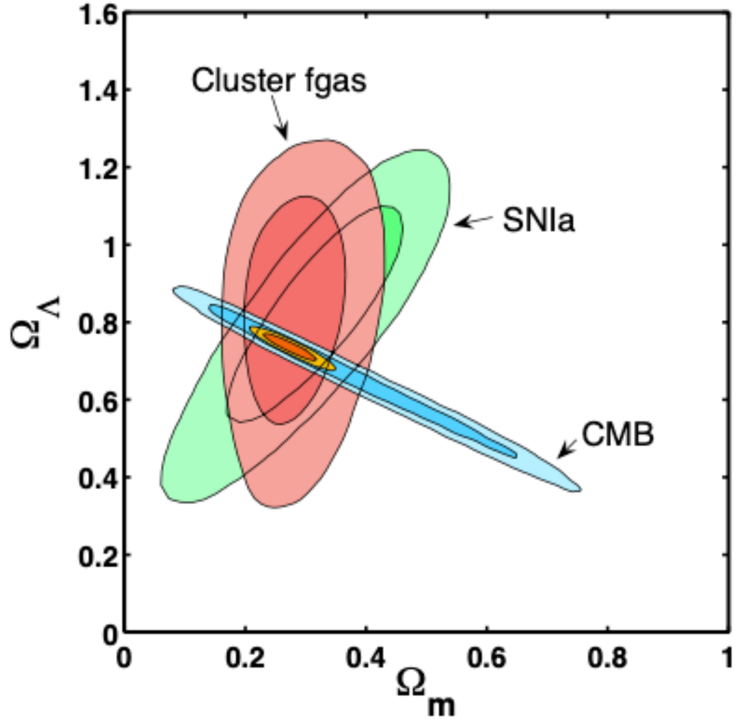
CMB prior

$$1.\ f_{\rm gas}(z) = \Upsilon(z)\left(\frac{\Omega_b}{\Omega_m}\right) \rightarrow \Omega_m$$

baryonic effects

$$2.\ f_{\rm gas}(z) \propto d_A(z)^{3/2} \rightarrow \Omega_\Lambda$$

Allen et al. (2008)



Distance measurement, H$_0$ (X-rays + SZ)

SZ decrement

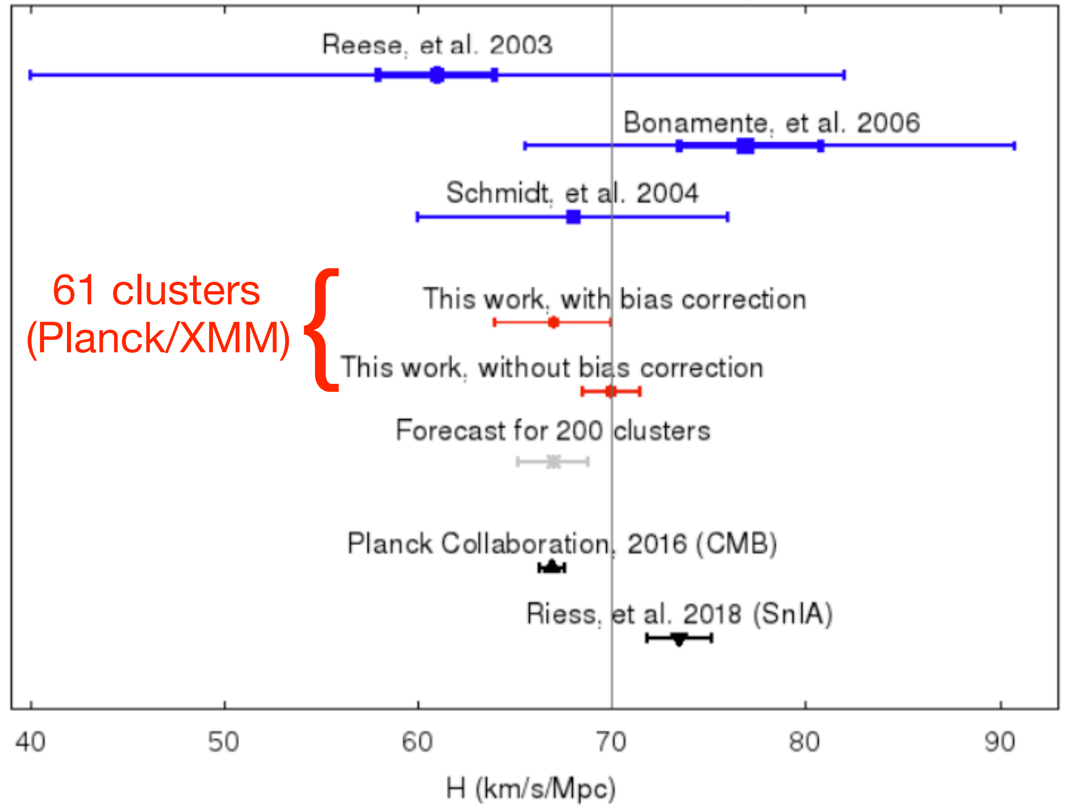
$$d_A \propto \frac{\Delta T^2_{\rm CMB}}{S_X}$$

X-ray surface brightness

Use a sample of clusters at various z:

$$d_A(z) \propto \frac{1}{H_0} \times f(z, \Omega_m, \Omega_\Lambda, \Omega_k)$$

Kozmanyan et al. (2019)



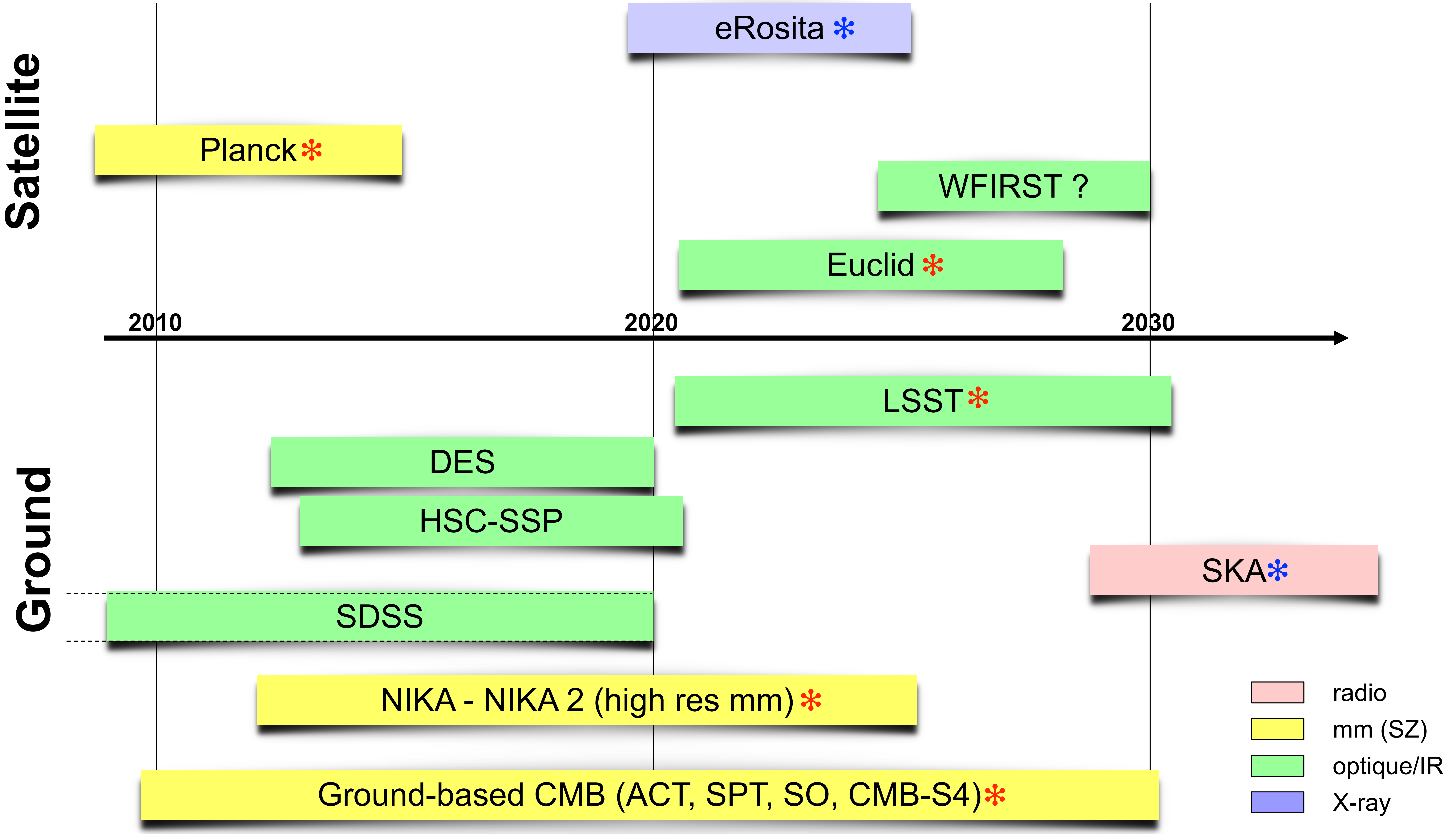
Cluster cosmology

Experimental landscape in the next decade

Conclusions

Cluster-relevant experimental landscape and timeline

✻ cluster-related work (past or ongoing at IN2P3)
✻ interest or possible collaboration



Satellite

eRosita ✻

Planck ✻

WFIRST ?

Euclid ✻

2010

2020

2030

Ground

LSST ✻

DES

HSC-SSP

SKA ✻

SDSS

NIKA - NIKA 2 (high res mm) ✻

Ground-based CMB (ACT, SPT, SO, CMB-S4) ✻

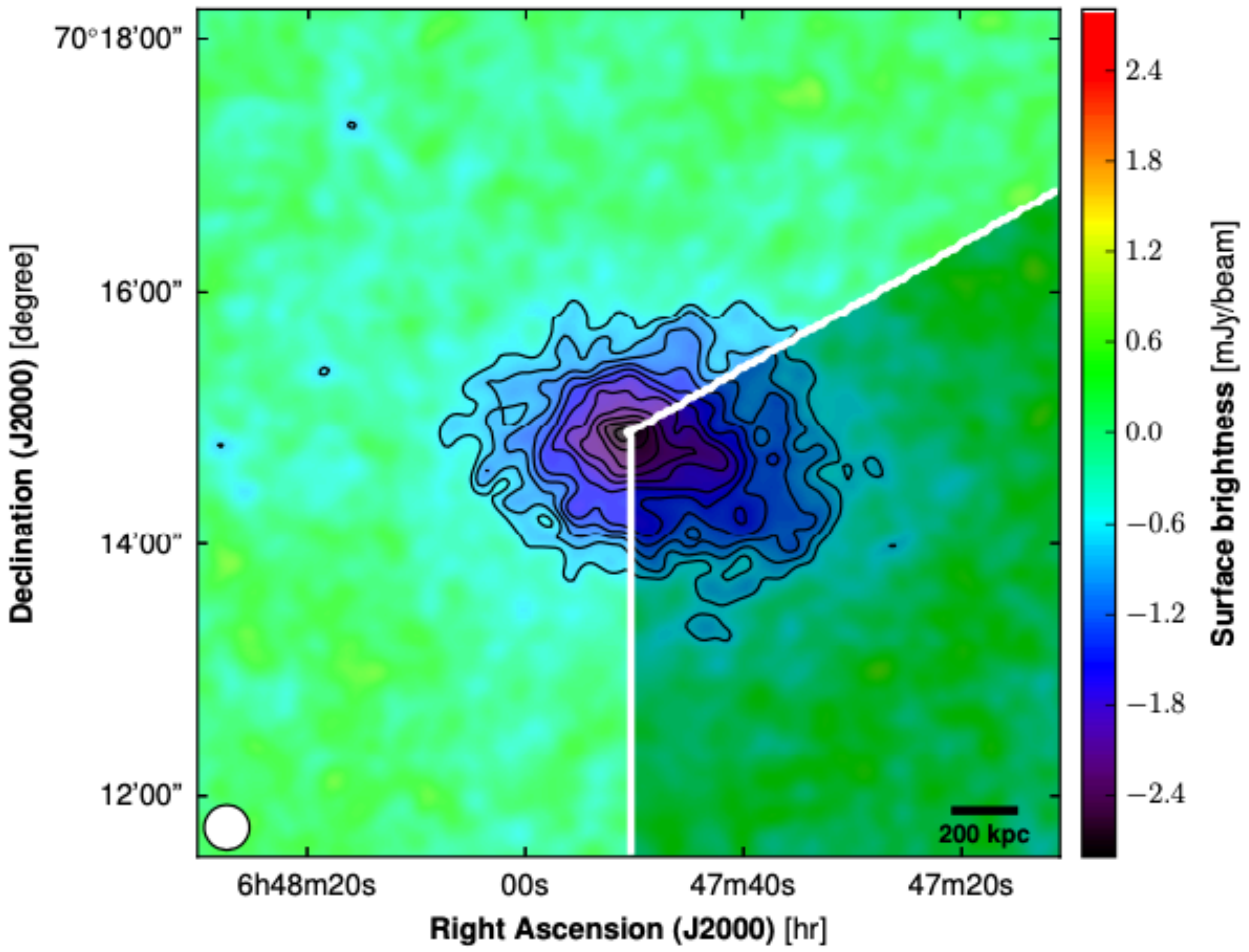
🟥 radio
🟨 mm (SZ)
🟩 optique/IR
🟦 X-ray

NIKA2 (2016 - ~2025)

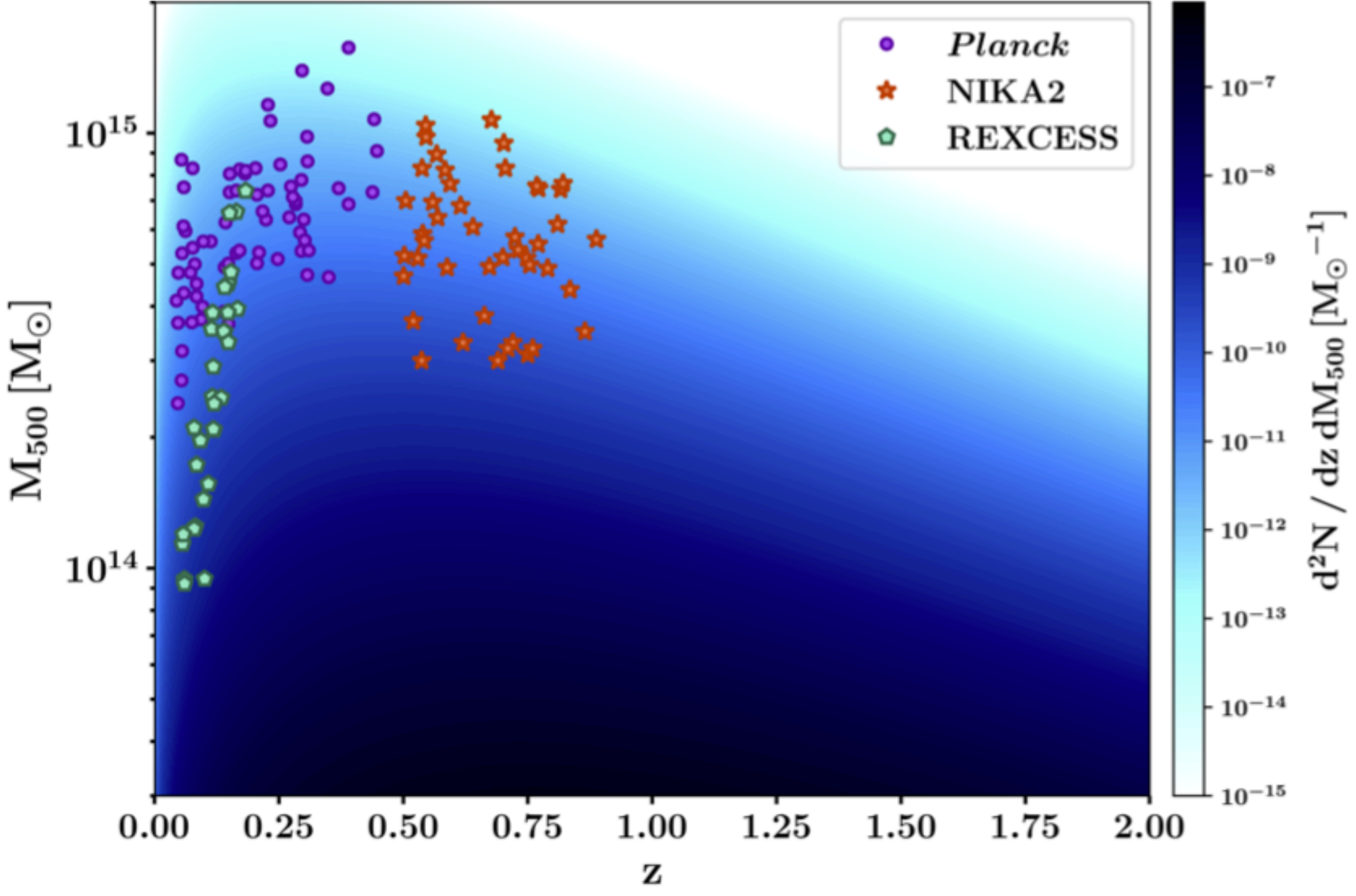
targeted SZ observations, mass-observable relation

- KIDs camera at IRAM 30m telescope
- 150 GHz, 260 GHz → SZ!
- pointed observations (6.5' fov)
- dedicated SZ program (300 hr)

SZ large program, Ruppin et al. (2018)



Ruppin et al. (2019)



SZ large program for cluster cosmology

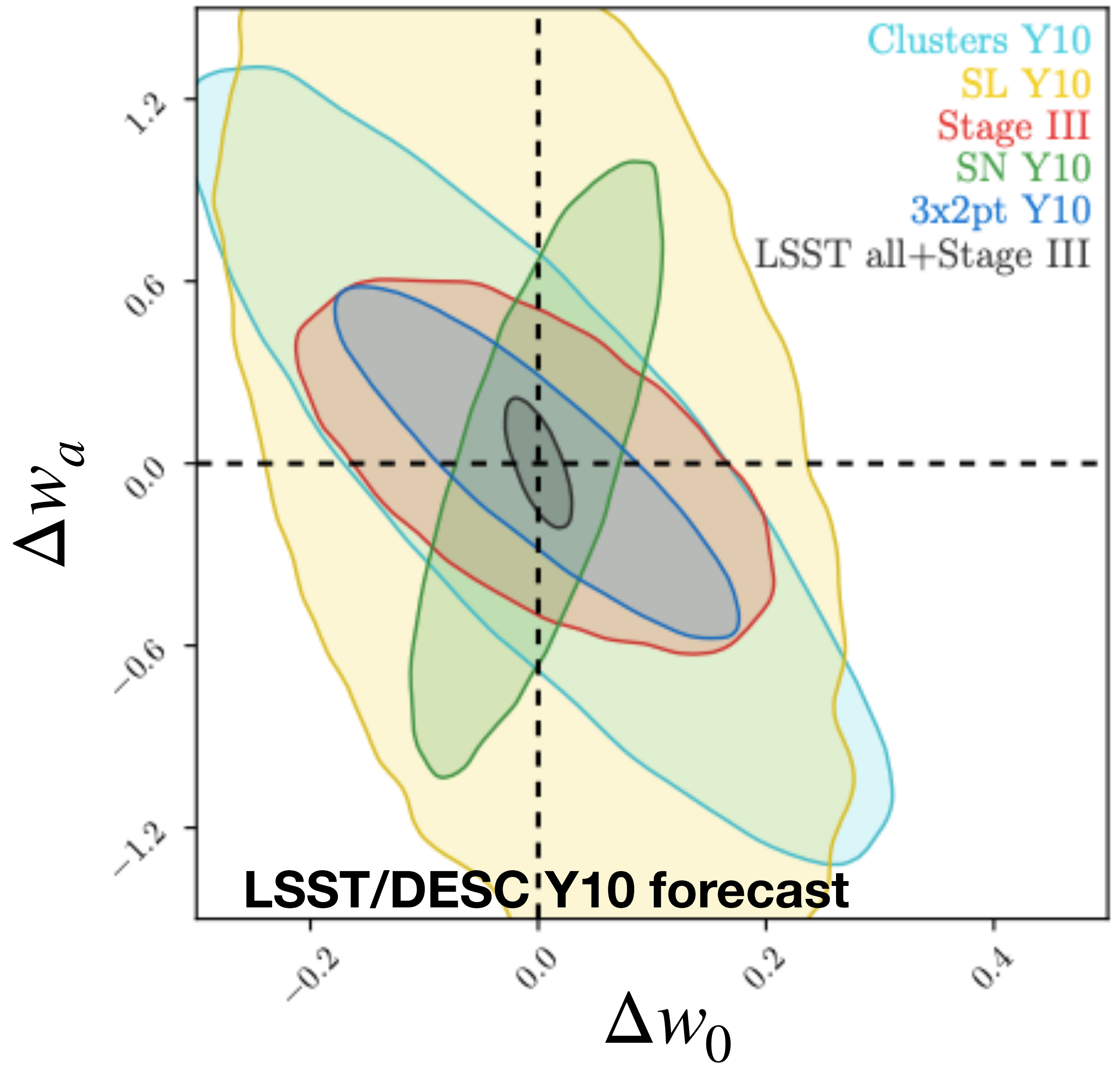
- Follow-up of 50 *Planck* and ACT-selected clusters (z=0.5 - 0.9)
- Combination with ancillary data
  - ✴ X-rays → thermodynamics (density, pressure, temperature, entropy)
  - ✴ Optical (WL) → mass bias
- Mass-observable scaling relation at high redshift, mean pressure profile
- (Re-)analysis of existing survey data with this new scaling relation

LSST / Euclid (2022 -)

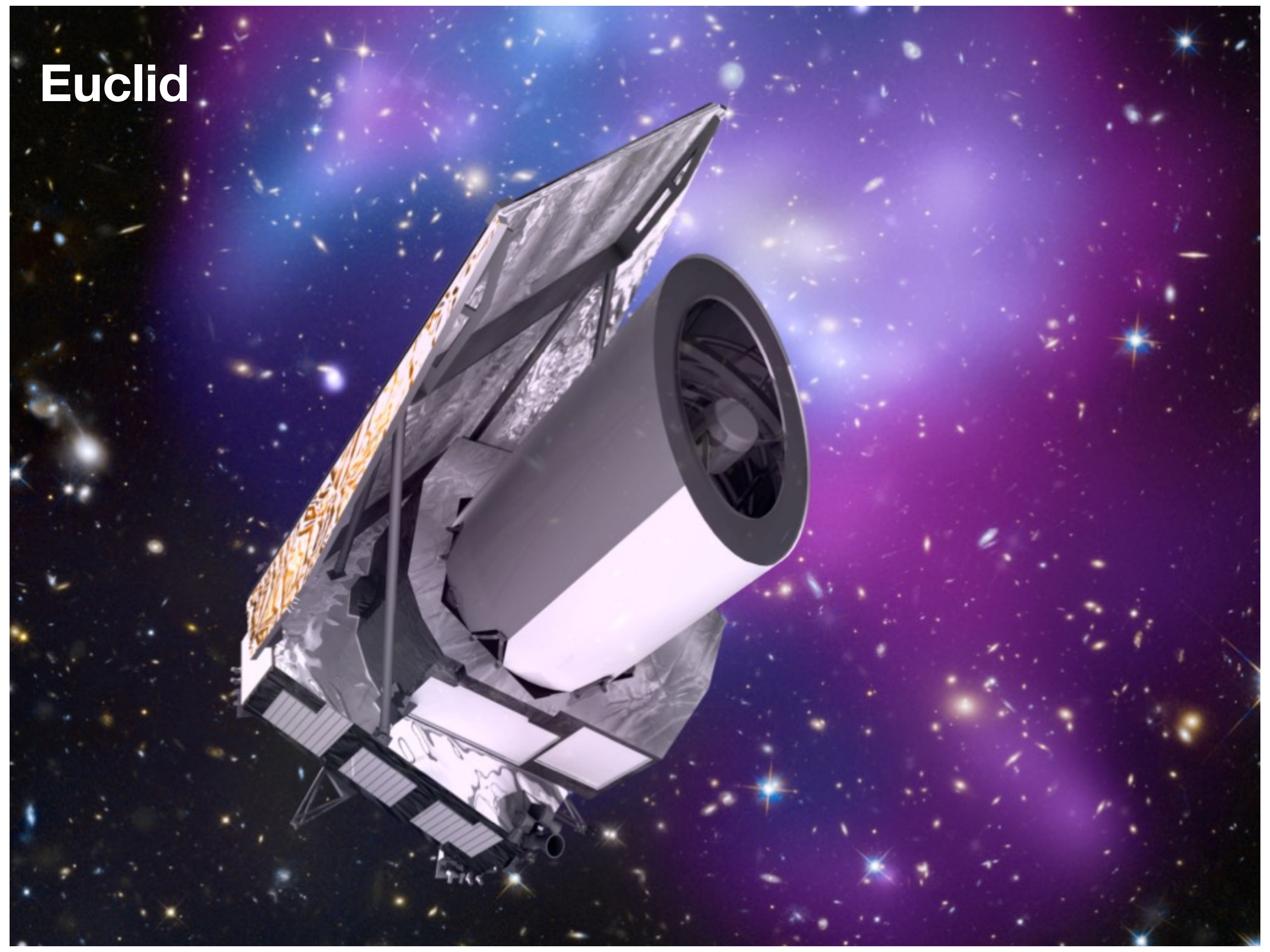
Cluster counts, cluster clustering, WL masses

- 6 optical bands
- 9.2 deg^2 f-o-v
- 18000 deg^2 main survey
- limit r ~ 27.5 (10 yr)
- time domain
- **> 300,000 clusters 0.1 < z < 1.2**

DESC collaboration (2018)



Common problematics: cluster finding, mass-richness relation, WL mass reconstruction,…



- 2 instruments: near-infrared spectrometer, visible imager
- 15000 deg^2 extragal survey
- limit H~24
- **~200,000 clusters 0.2<z<2**
  ~40,000 clusters at z>1

Synergy LSST / Euclid

- 7000 deg^2 sky overlap (minimum)
- Blending
- Improved photometric redshifts (> z=1.4)
- WL mass pushed to z=1-1.3 !

→ ***joint analysis highly-desirable***

Simons Observatory (2021-), CMB-S4 (~2027-)

Cluster counts, SZ power spectrum, kSZ

Simons Observatory

- SO = 1 Large Aperture Telescope (6m), 3 Small AT (0.5m)
- LAT: 30000 TES, 6 bands in 27 - 280 GHz
- SAT: 30000 TES, 93/145 GHz and 225/280 GHz
- LAT survey: 40% sky, maximal overlap with LSST
- ~20,000 SZ-detected clusters (Planck x 10)

CMB halo lensing to calibrate the mass-observable relation

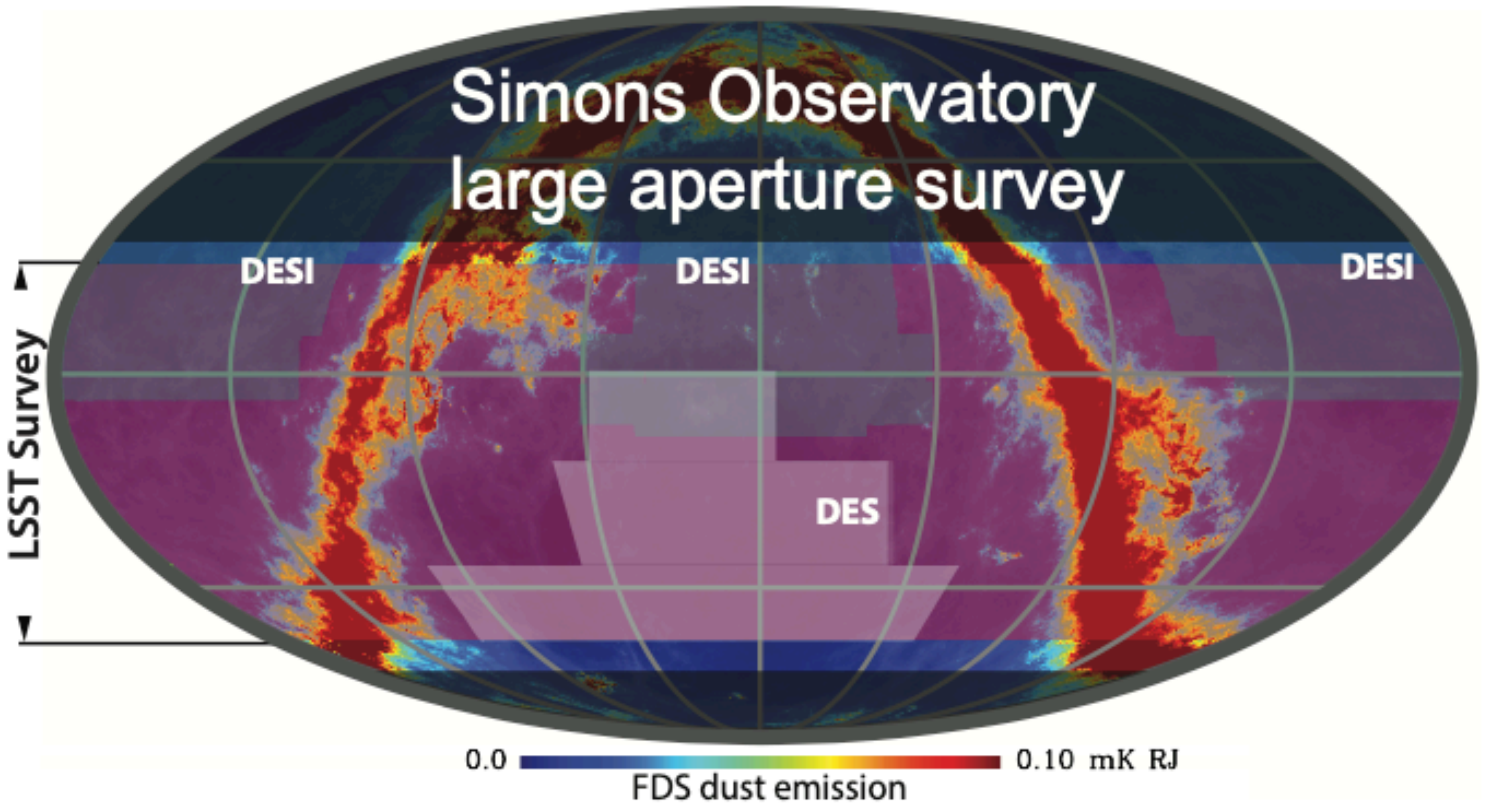
Cluster cosmology

[dark energy, neutrino mass, growth of structures, non-gaussianity, EoR]

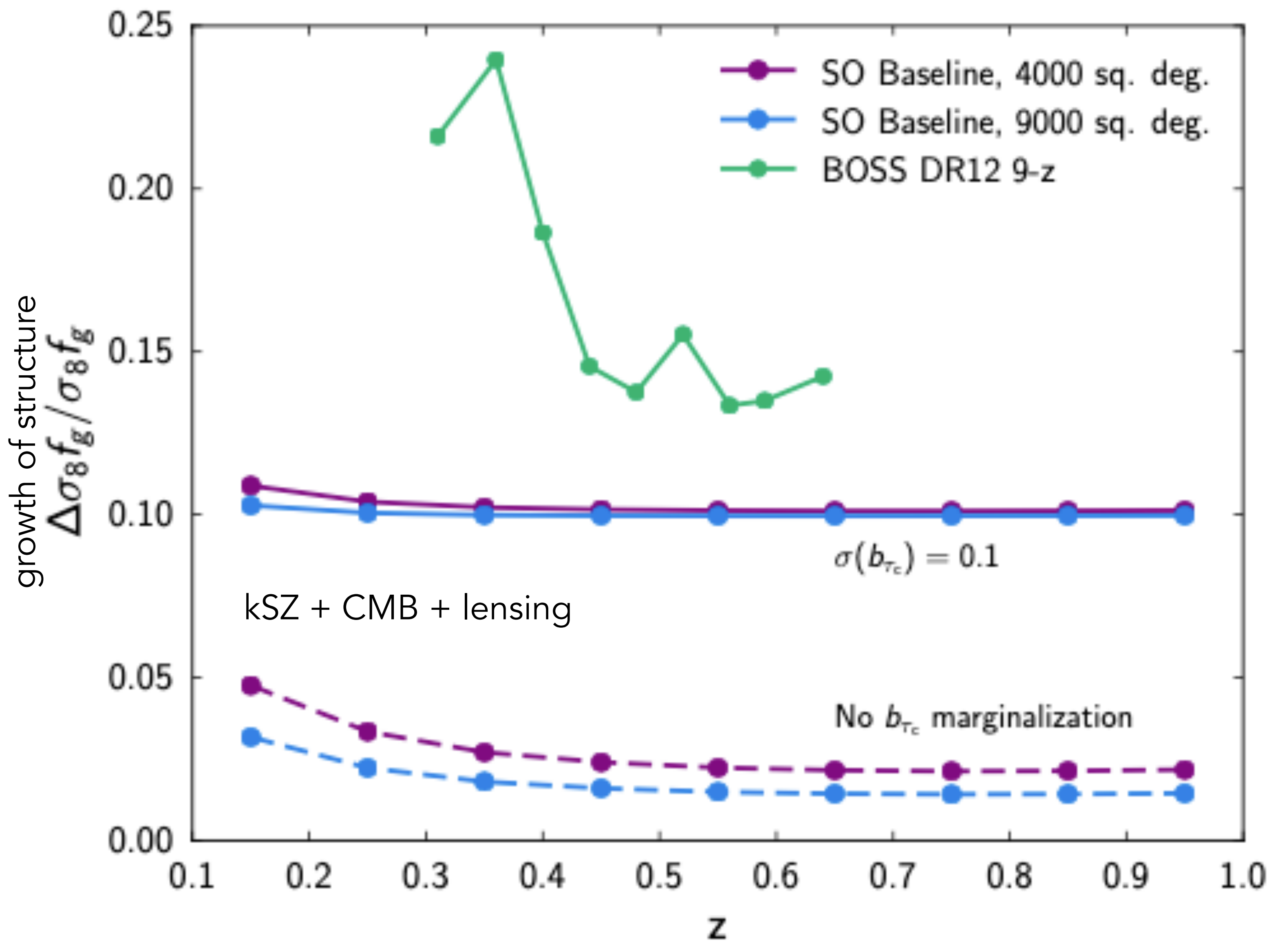
- tSZ cluster counts
- tSZ power spectrum
- kSZ: growth of structures, non-gaussianity, EoR

Cluster physics

- tSZ x kSZ: cluster physics - feedback efficiency, non-thermal support



SO collaboration (2019)



Cluster cosmology

Experimental landscape in the next decade

Conclusions

Conclusions

Clusters are sensitive to various cosmological parameters: $\Omega_m, \sigma_8, w, \Sigma m_\nu, f_{\mathrm{NL}}$ + modified gravity

Understanding of cluster astrophysics is mandatory for their use in cosmology

Cluster cosmology is a multi-wavelength endeavour

- State-of-the-art analysis combine information from SZ, X-ray and optical data
- 2020s: major projects in all wavelengths

IN2P3: strategically involved in several cluster-friendly experiments in 2020-2030

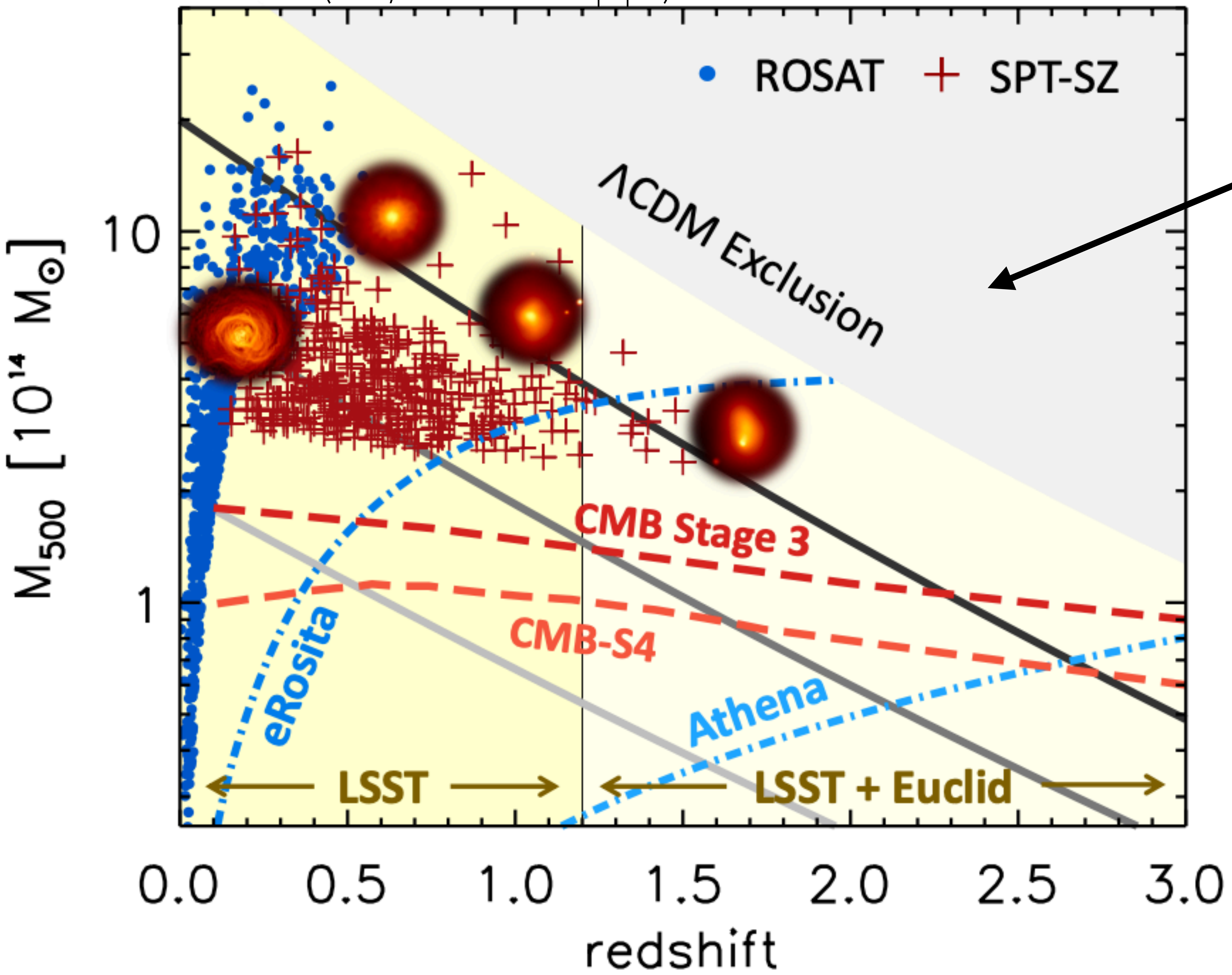
- NIKA 2 SZ large program
- Preparation of cluster analyses in LSST/Euclid
- Involvement in SO - CMB-S4

2020 - 2030 Exploit the large synergistic potential at IN2P3 for cluster cosmology

Bonus track

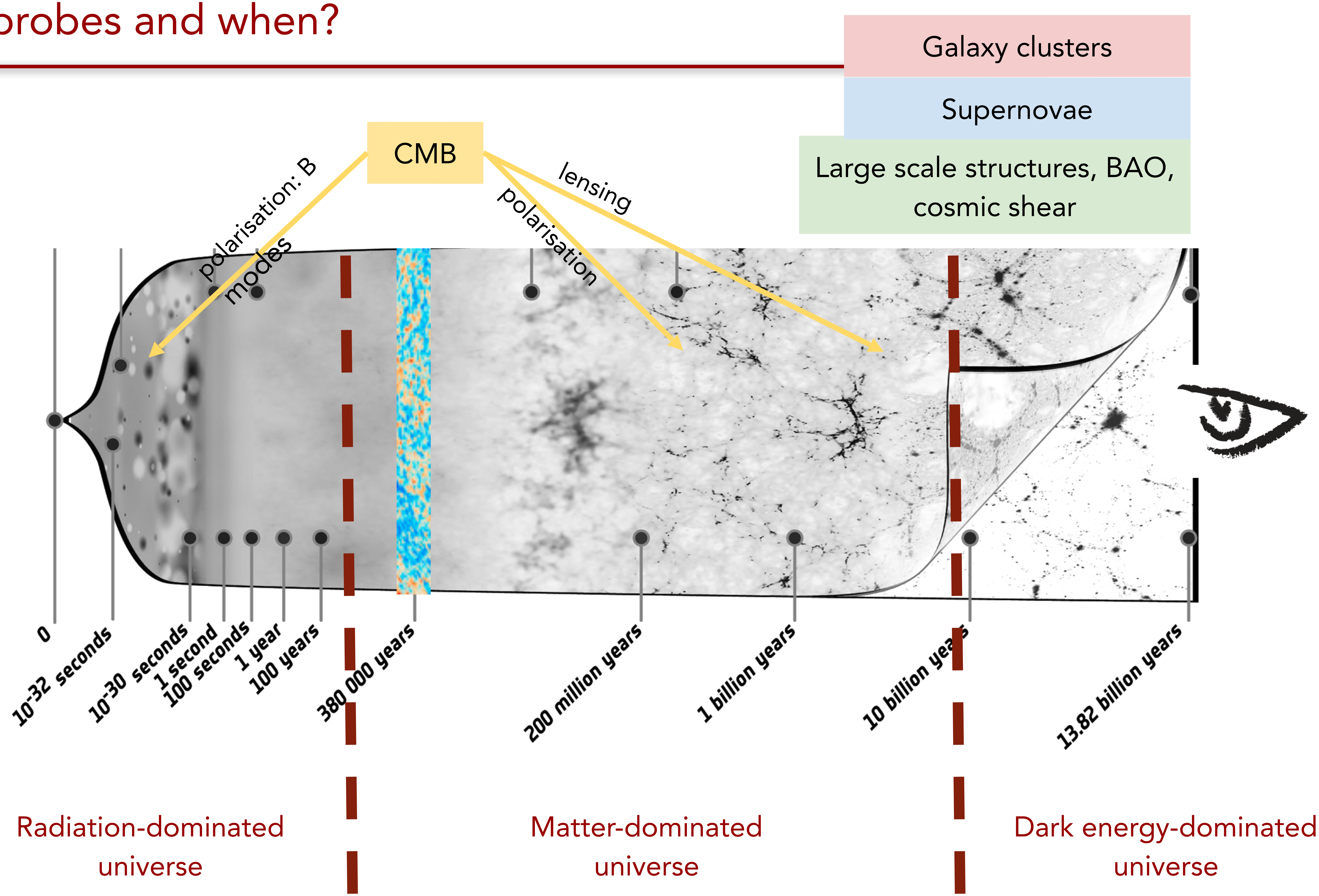
Future cluster catalogs… A busy plot

Mantz et al. (2019, Astro2020 white paper)



Finding a single cluster here would rule out ΛCDM

What probes and when?



Galaxy clusters

Supernovae

Large scale structures, BAO, cosmic shear

CMB

Radiation-dominated universe

Matter-dominated universe

Dark energy-dominated universe