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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

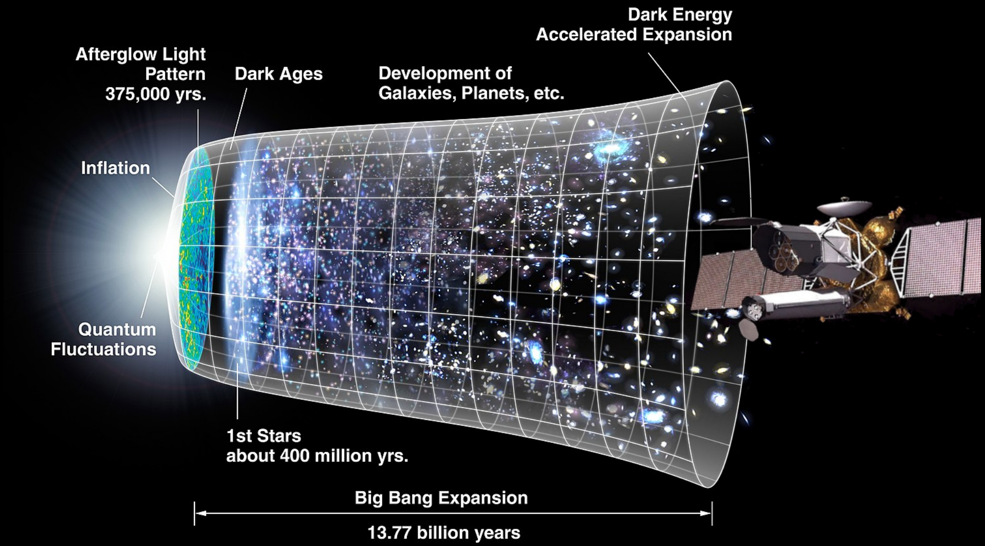
Cosmology with Galaxy Clusters: From Number Counts to Gas Physics

Vittorio Ghirardini

Outline

- What are “galaxy clusters”?
- What is “cosmology”?
- What is “cluster cosmology”?
  - Number counts
  - Beyond number counts

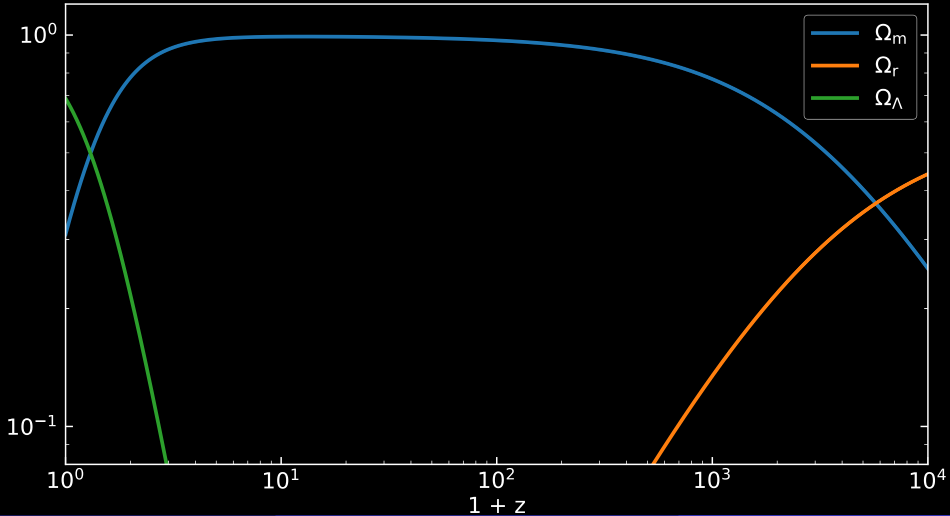
Cosmology



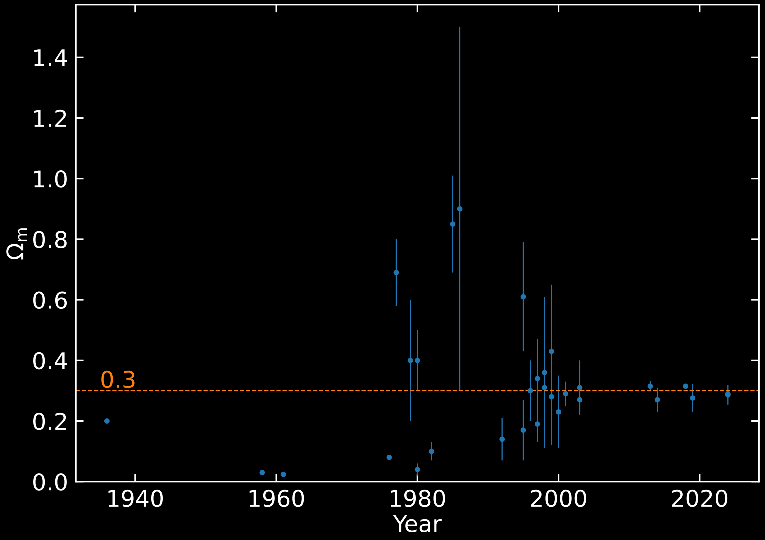
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Friedmann's equations

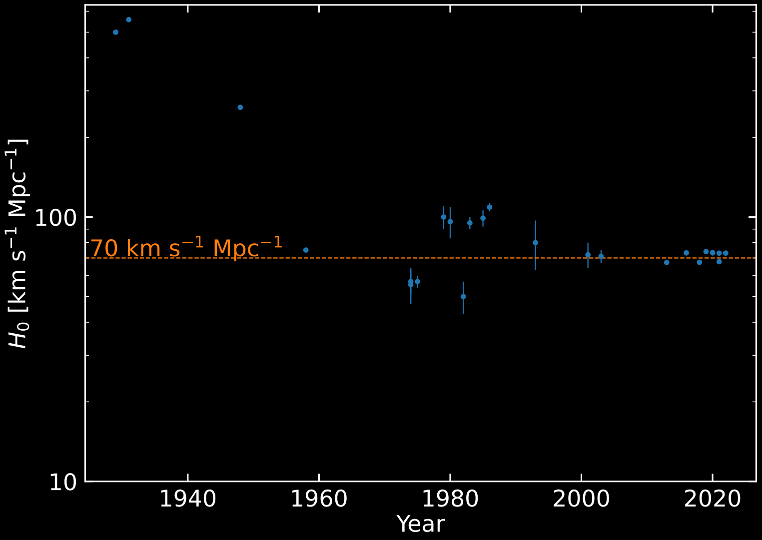
- ΛCDM: 6 parameters that govern formation and evolution of LSS



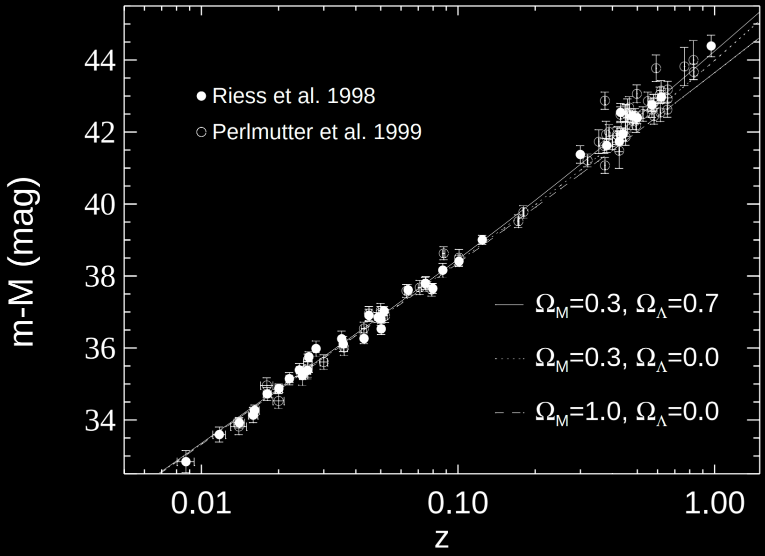
$\Omega_{\rm m}$: Mean matter density



H_0: Expansion rate

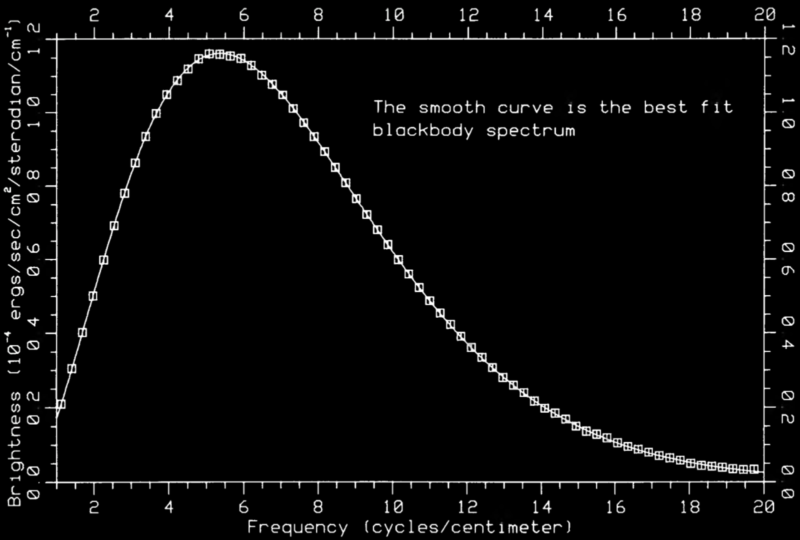


Ω_Λ: Dark energy



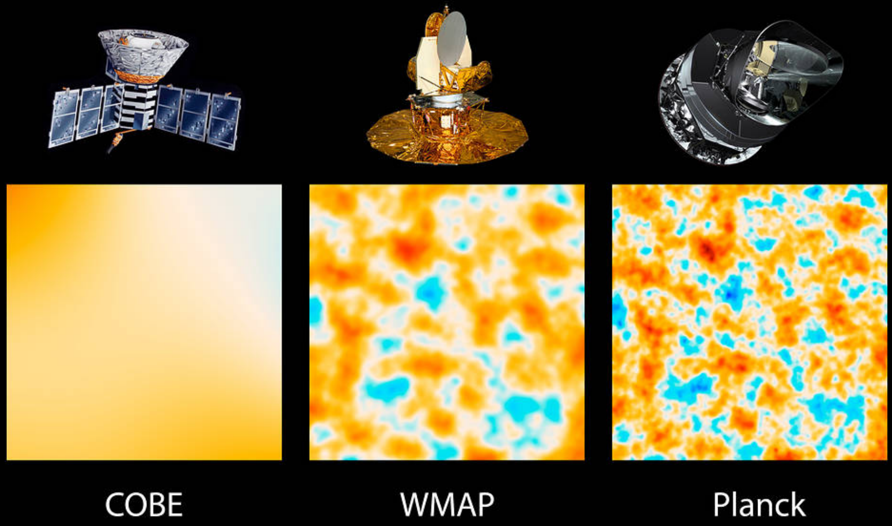
Riess+ 2000

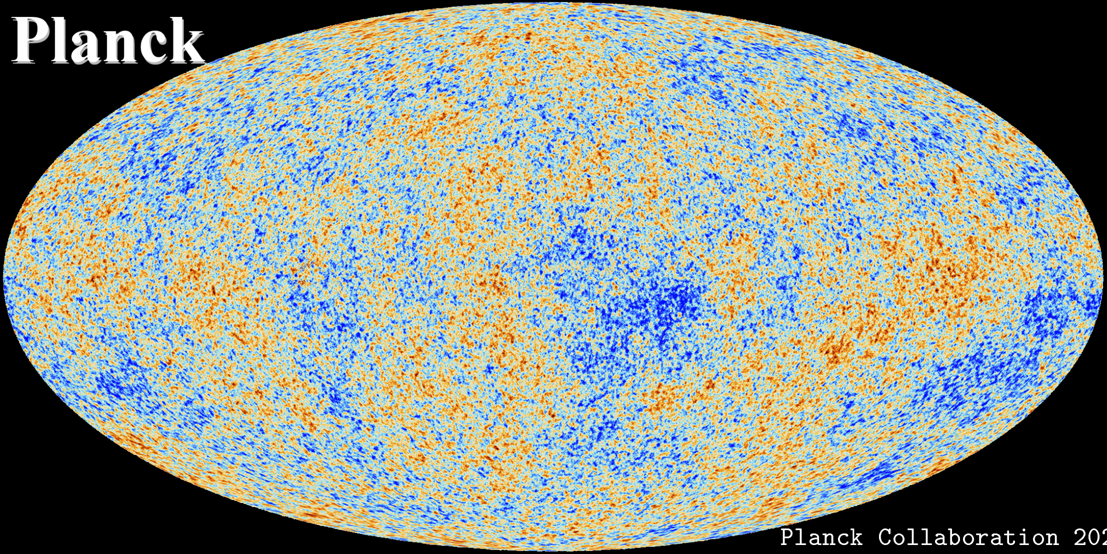
Cosmic Microwave Background



Mather+ 1990

Cosmic Microwave Background

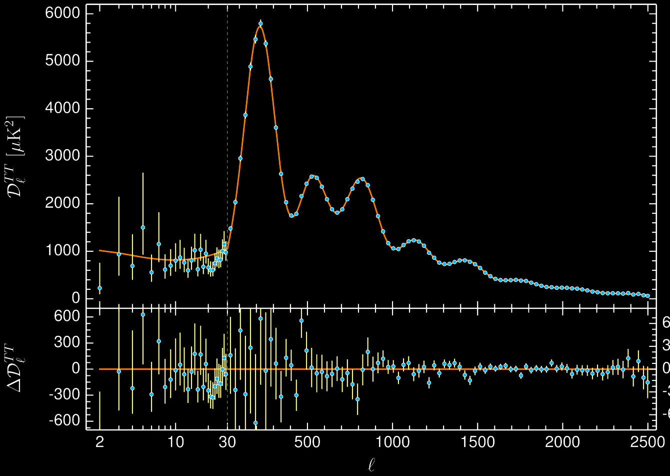



Planck
Planck Collaboration 2020

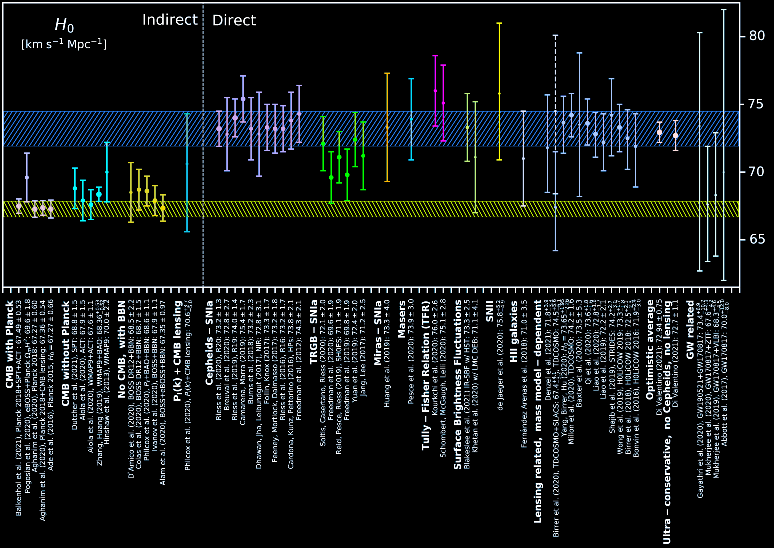
Planck results

Parameter	Constraint
$\Omega_{\rm m}$	0.3153 ± 0.0073
Ω_Λ	0.6847 ± 0.0073
H_0	67.36 ± 0.54
σ_8	0.8111 ± 0.0060
$\Omega_{\rm k}$	0.0007 ± 0.0019
w_0	-1.028 ± 0.031

Planck Collaboration 2020

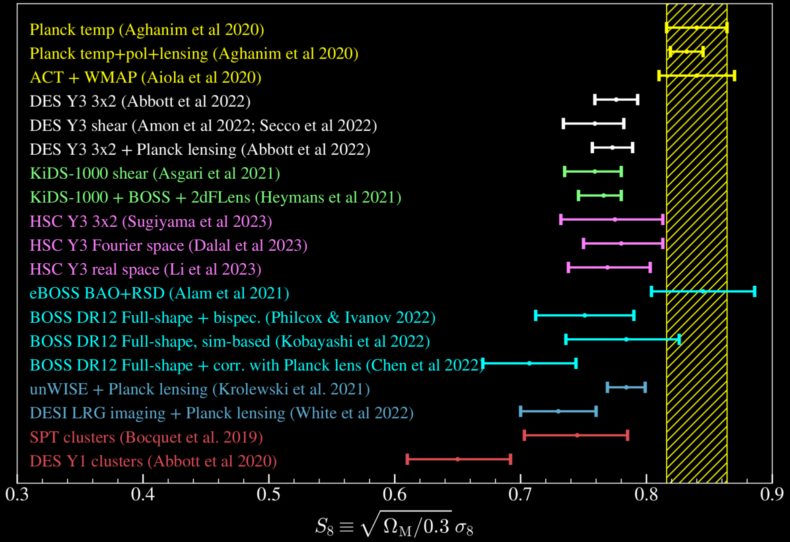


H_0 tension



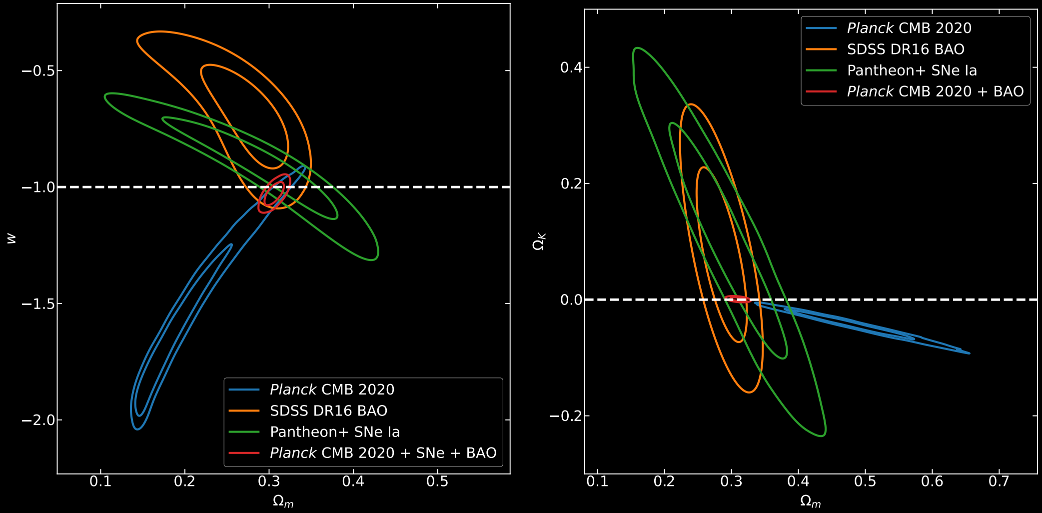
Di Valentino et al. 2021

S_8 tension



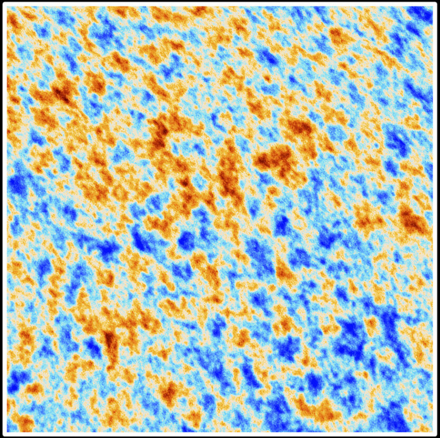
Huterer 2023

Some parameters need external datasets

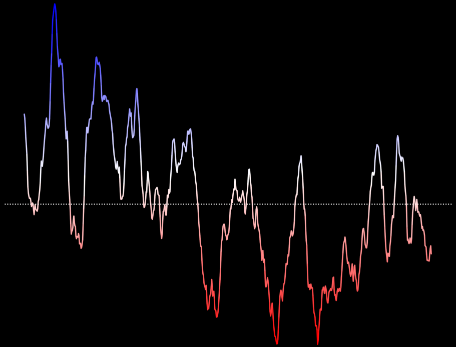


Planck Collaboration 2020

Why clusters?

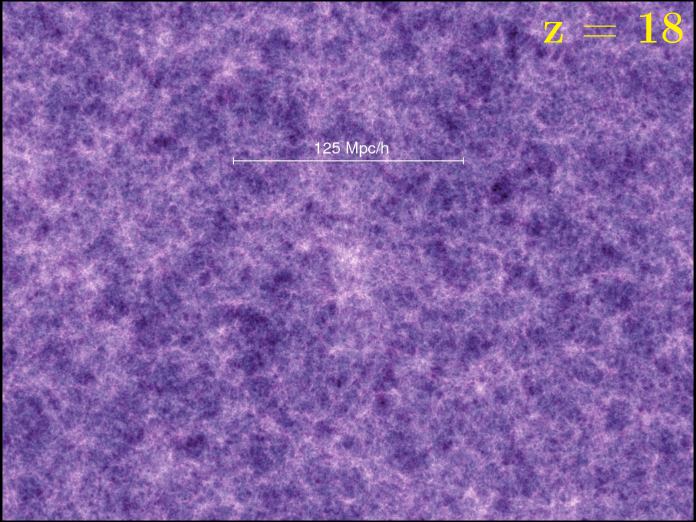


Planck



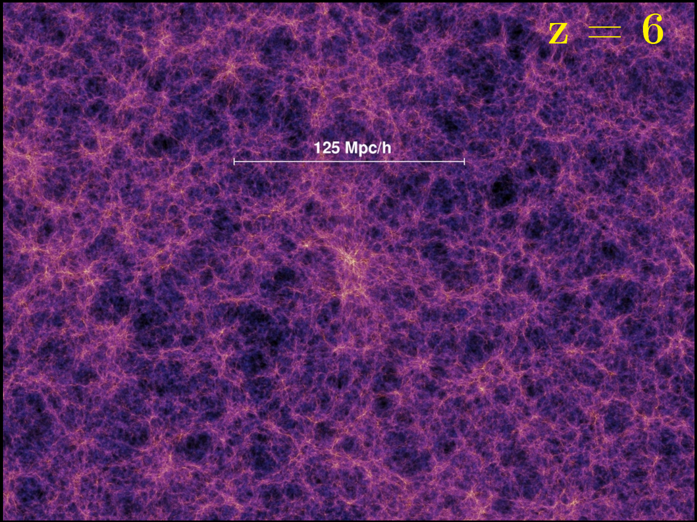
Density field

Why clusters?



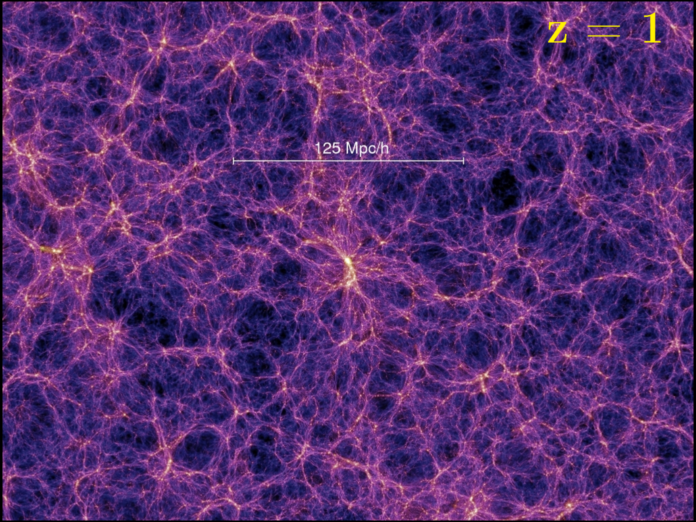
Millenium, Springel et al. 2006

Why clusters?



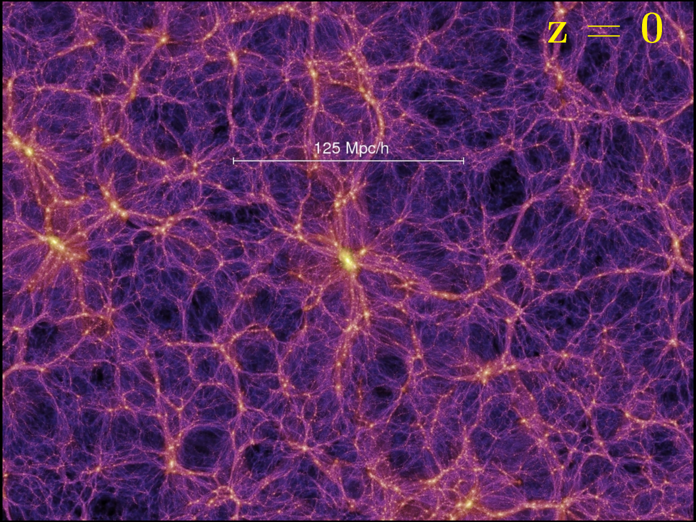
Millenium, Springel et al. 2006

Why clusters?



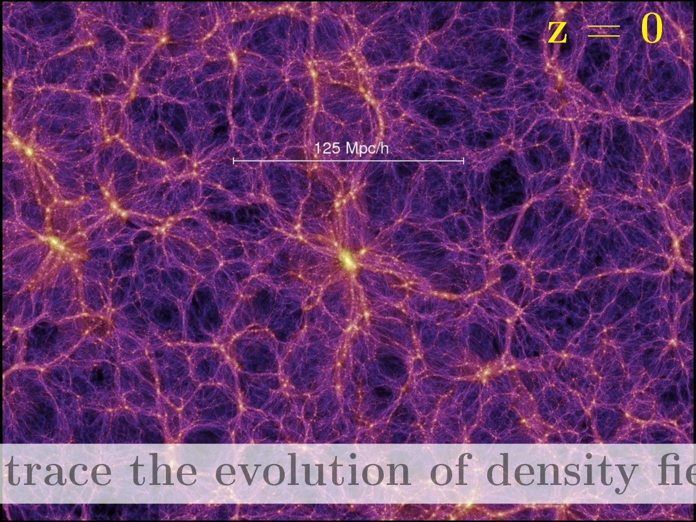
Millenium, Springel et al. 2006

Why clusters?



Millenium, Springel et al. 2006

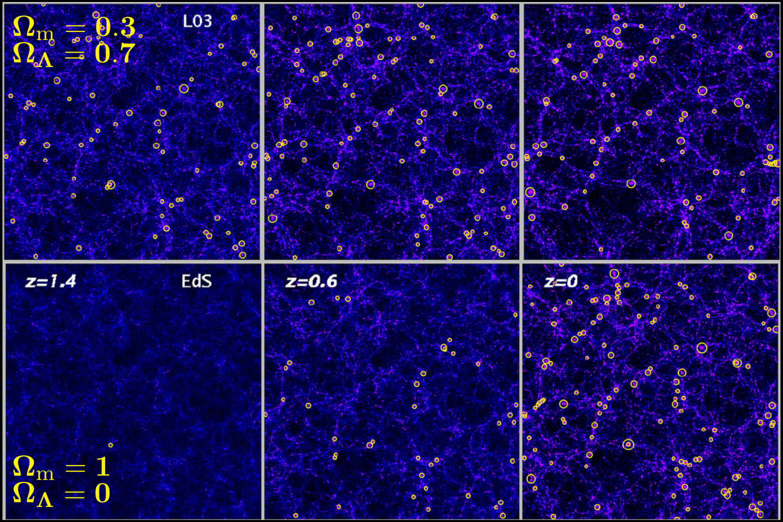
Why clusters?



Clusters trace the evolution of density field peaks

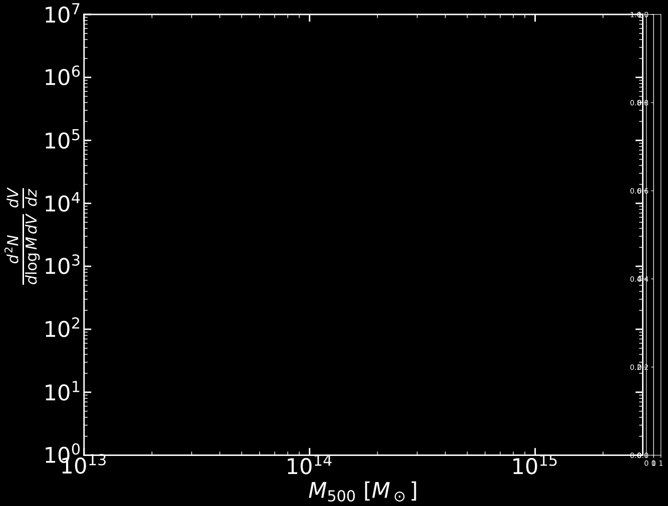
Millenium, Springel et al. 2006

Cluster number count evolution

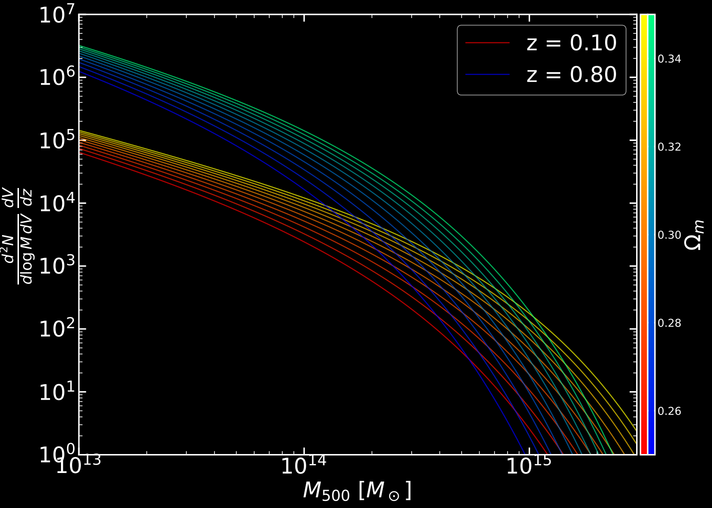


Borgani+ 2001

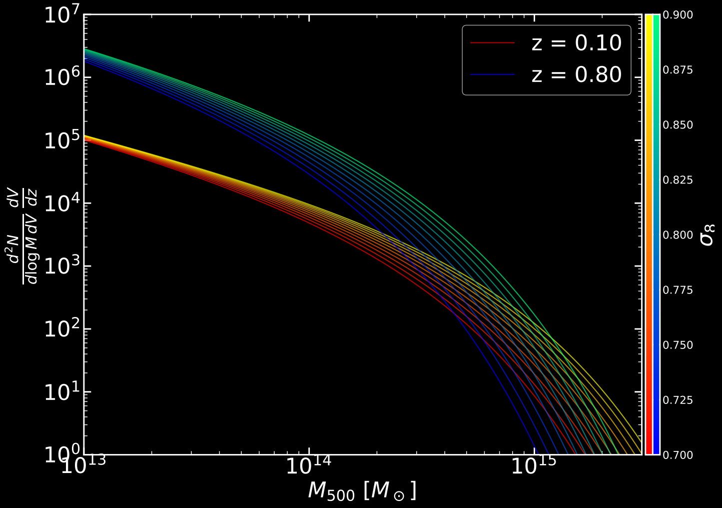
Halo Mass Function



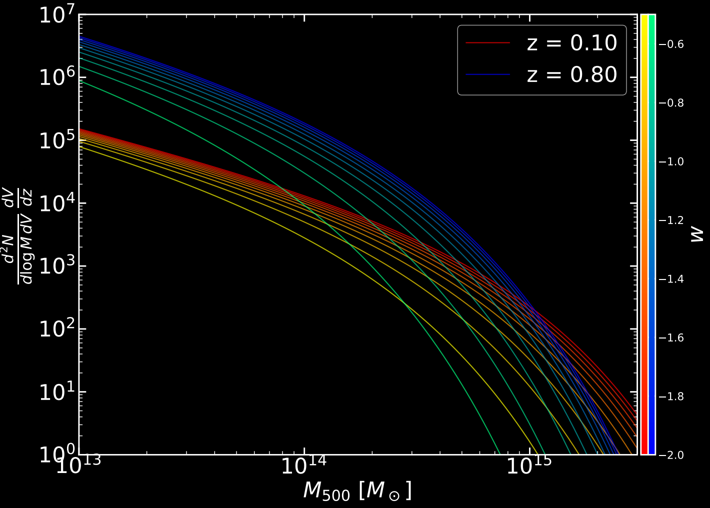
Halo Mass Function



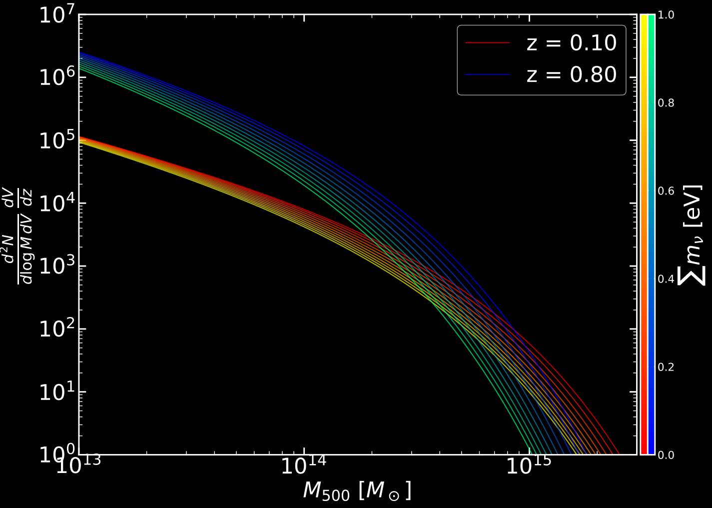
Halo Mass Function



Halo Mass Function

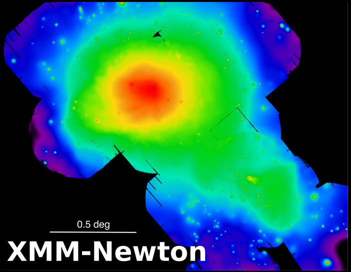


Halo Mass Function

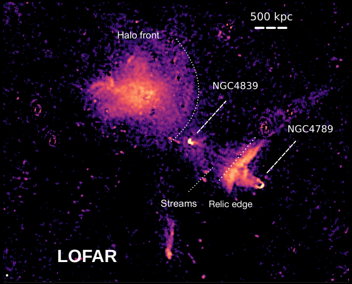


Observation of galaxy clusters

- Galaxies (5-10 %)
- Optical



- Intra-Cluster Medium (ICM) (85-90 %)
- X-ray/SZ



- Relativistic electrons
- Radio

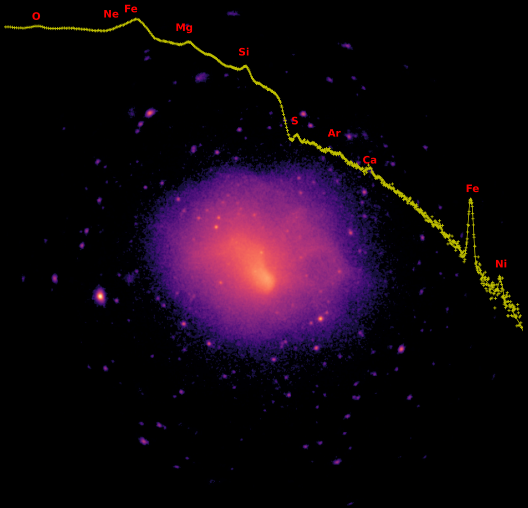
What is the ICM?

- Primordial gas falls into deep gravitational potential
- Very hot gas (10^7 - 10^8 K $\sim$ keV)
- Fully ionized gas (bremsstrahlung plus recombination)
- Tenuous gas (10^{-5} - 10^{-3} cm^{-3})
- Optically thin
- Almost ideal gas ($P_e = n_e T_e$, $K_e = T_e n_e^{-2/3}$)

-> Emits in X-ray via bremsstrahlung radiation $S_X \propto \int n_e^2 \Lambda(T_e) dl$

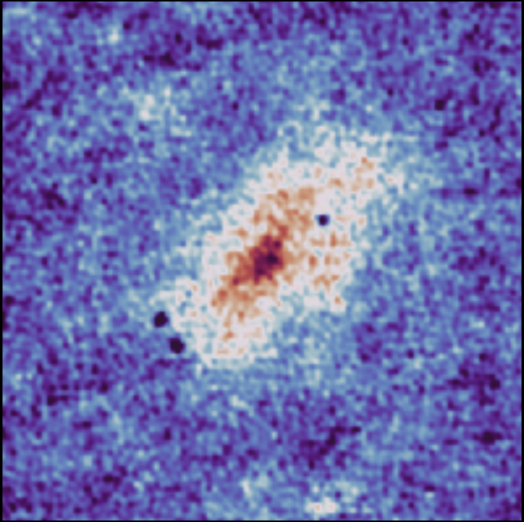
-> Distorts the CMB signal via the SZ effect $Y_{SZ} \propto \int n_e T_e dl$

X-ray - ICM



Sanders+ 2022

- $S_X \propto \int n_e^2 \Lambda(T_e) dl$
  - imaging capability
  - spectra capability
- Concentrated signal
  - high-constrast in X-ray sky
  - bound systems are selected
- Flux-limited samples
  - selection function is easy to model
  - L_X scales with mass
- <u>Limitation</u>:
  - surface brightness dimming with z
  - fast signal loss in outskirts



Bleem+ 2022

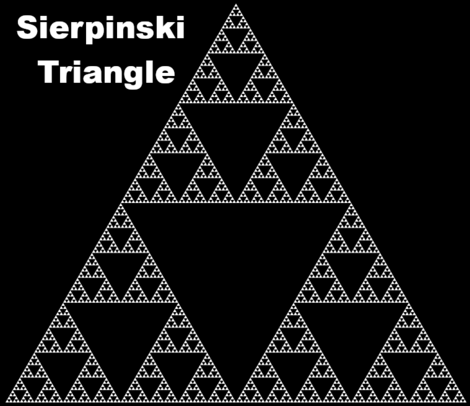
- $Y_{SZ} \propto \int n_e T_e dl$
- Signal independent on redshift
- Less S/N loss in the outskirts
- S/N selected samples ≈ mass-limited
- Limitation:
  - only one thermodynamic property
  - lower contrast in sky

Why do we measure ICM properties?

- Tight connection with cluster cosmology

$$\frac{dN(X,z)}{dX\,dz} = \underbrace{\frac{dN(M,z,\theta_c)}{dM\,dV}\frac{dV}{dz}(\theta_c)}_{\text{cosmology dependence}}\underbrace{\frac{dM}{dX}(z,\theta_p)}_{\text{astrophysics}}$$

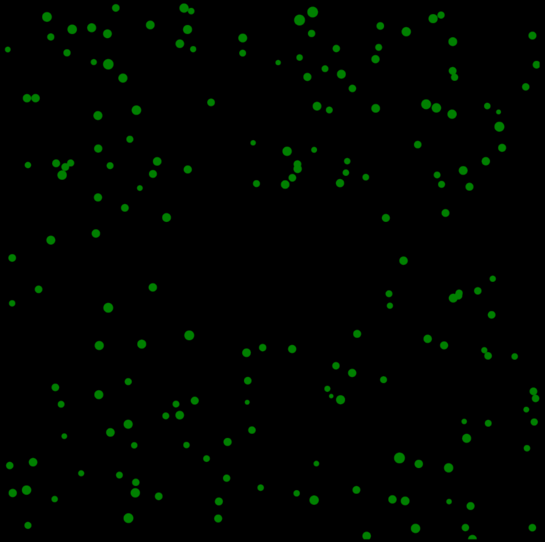
- Structure formation
- Astrophysics
  - AGN-feedback
  - cooling
  - magnetic field
  - non-thermal energy
  - ...



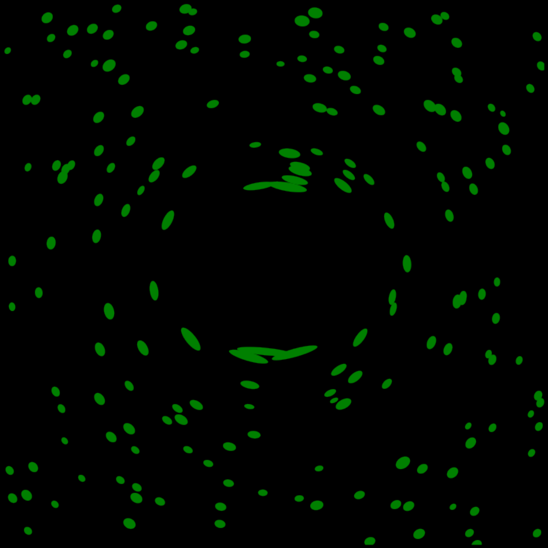
$M \curvearrowright \bar{X}$

- Self-similarity of cluster properties
  - Kaiser 1986
  - $\langle \bar{X} \rangle \sim M^{\alpha}$
    - $L_X \sim M^1$
    - $T_X \sim M^{2/3}$
    - $Y_{SZ} \sim M^{5/3}$

Gravitational lensing



Gravitational lensing



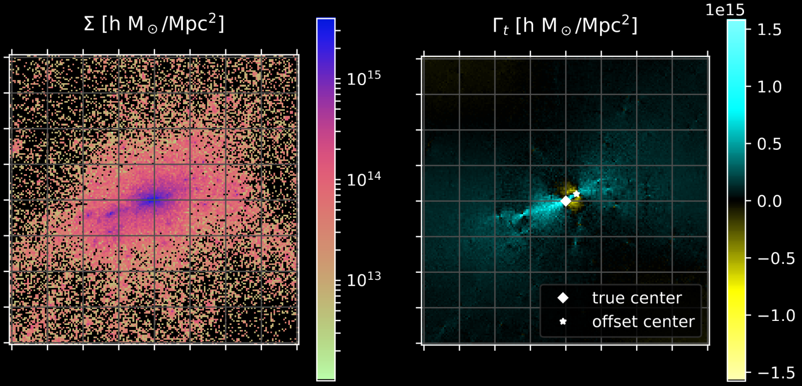
Weak lensing mass proxy

- All mass proxy are biased!
- The factors contributing to the WL bias are under control
  - Photo-z calibration
  - Triaxiality
  - Substructures
  - Miscentering
  - Baryonic effects
  - Uncorrelated structures
- They can be calibrated using simulations

Weak lensing mass proxy

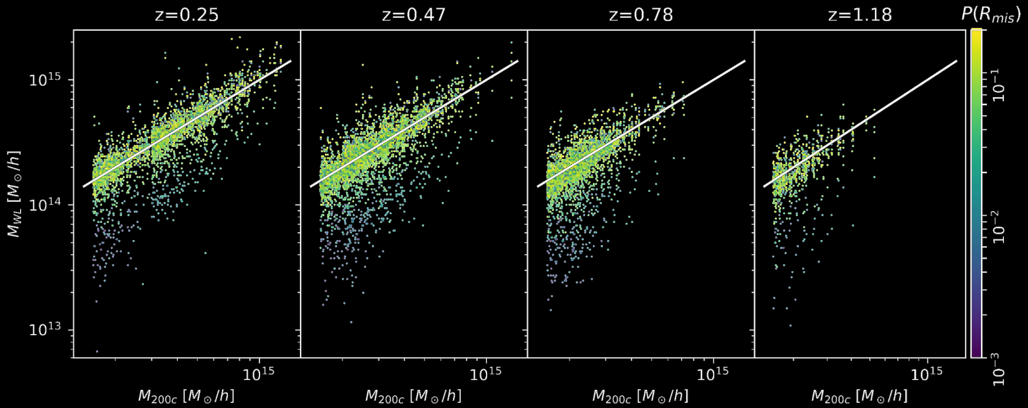
- **pre-2014**: unbiased WL used for calibration before cosmological analysis
- **Mantz et al. 2014**: directly use WL masses as unbiased mass proxy in cosmology pipeline
- **Dietrich et al. 2019**: first calibration of WL bias for cosmological inference
- **Grandis et al. 2021**: explicitly marginalizing over known WL systematics and using hydrodynamical simulations to simulate realistic shear profiles

Weak lensing mass proxy



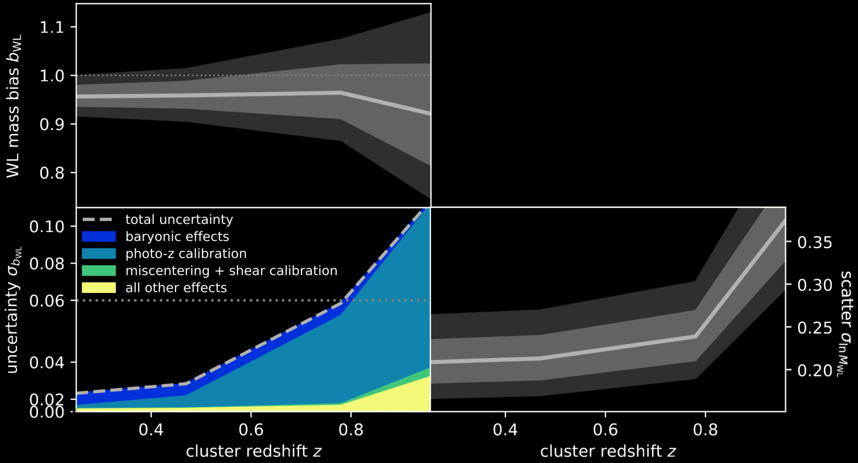
Grandis+21

Weak lensing mass proxy



Grandis+21

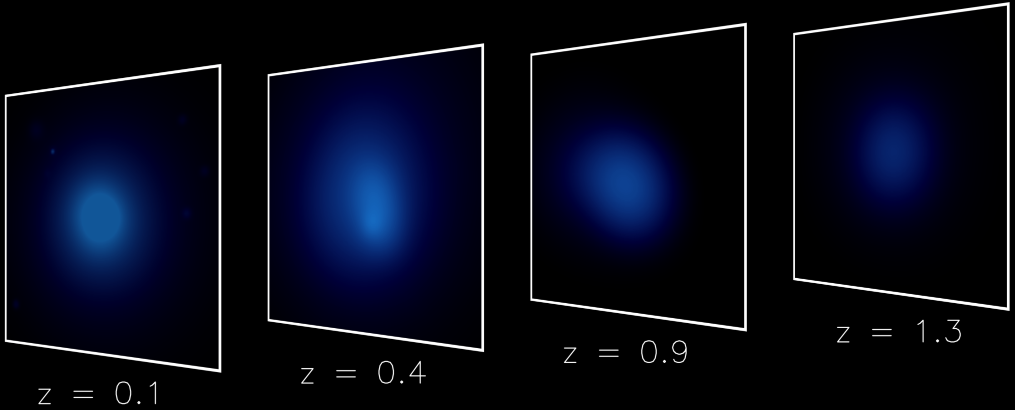
Weak lensing mass proxy



Grandis+24, Bocquet+24

What we see

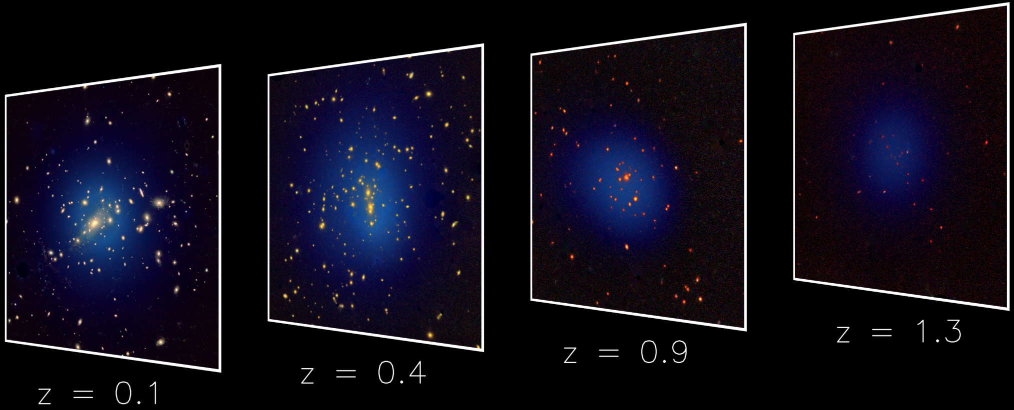
X-ray



Credit: C. Garrel, M. Kluge, S. Grandis

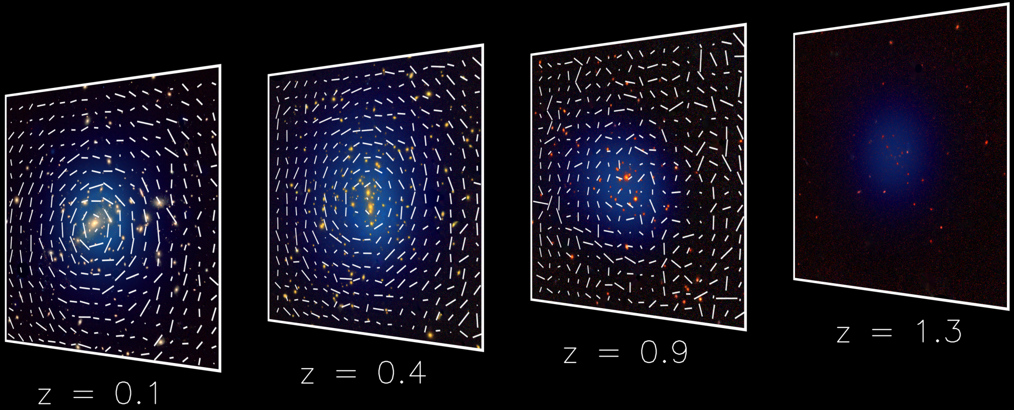
What we see

X-ray + optical



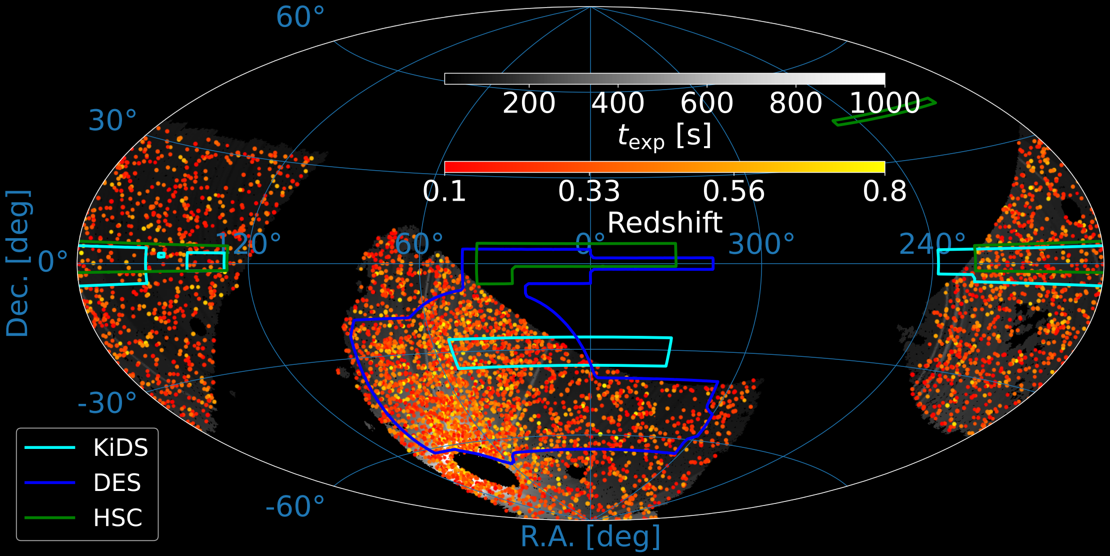
Credit: C. Garrel, M. Kluge, S. Grandis

X-ray + optical + shear

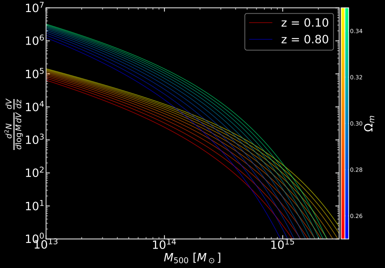


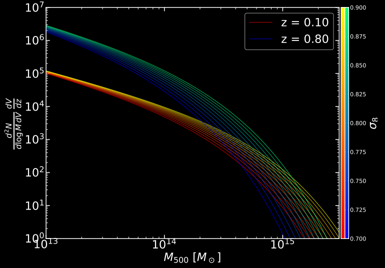
Credit: C. Garrel, M. Kluge, S. Grandis

eROSITA_DE weak lensing overlap

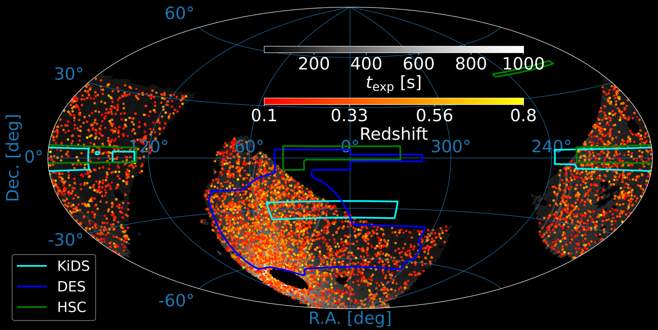


Forward model



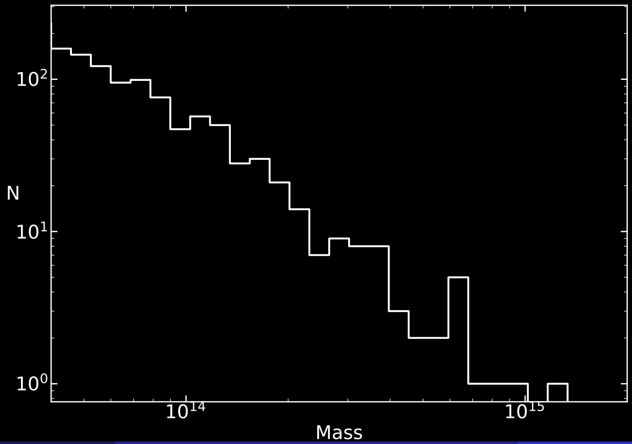


? ⇔



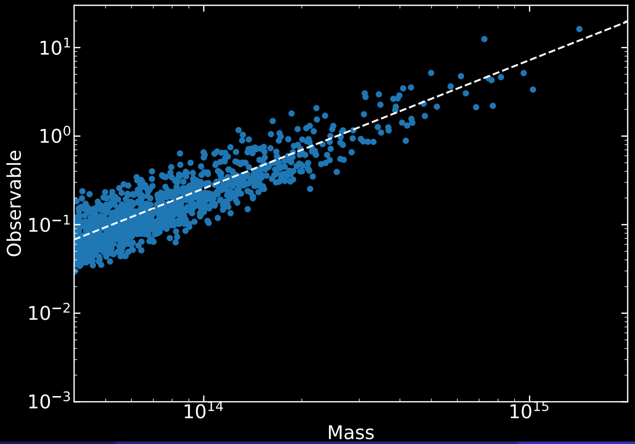
Forward model

$$\underbrace{\frac{d^2N(M,z,\theta_c)}{dMdV}\frac{dV}{dz}(\theta_c)}_{\text{cosmology dependence}}$$



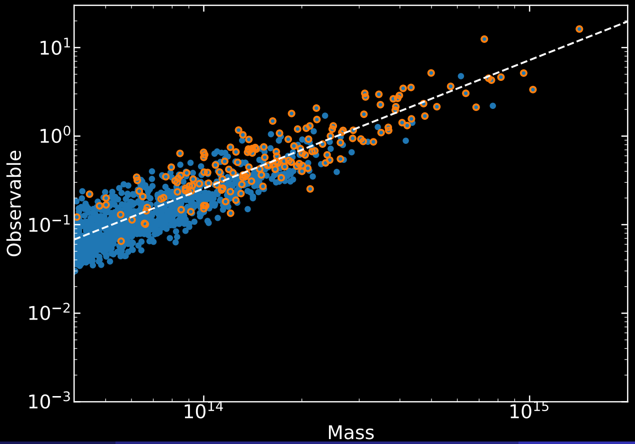
Forward model – Scaling relation

$$\underbrace{\frac{d^2N(M,z,\theta_c)}{dMdV}\frac{dV}{dz}(\theta_c)}_{\text{cosmology dependence}}\underbrace{\frac{dM}{dX}(z,\theta_p)}_{\text{astrophysics}}$$



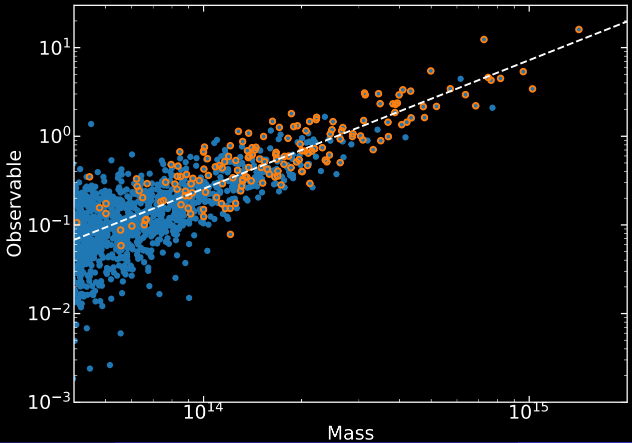
Forward model – Selection function

$$\underbrace{\frac{d^2N(M,z,\theta_c)}{dMdV}\frac{dV}{dz}(\theta_c)}_{\text{cosmology dependence}}\underbrace{\frac{dM}{dX}(z,\theta_p)}_{\text{astrophysics}}\underbrace{P(I|X,M,z,\theta_s)}_{\text{selection function}}$$



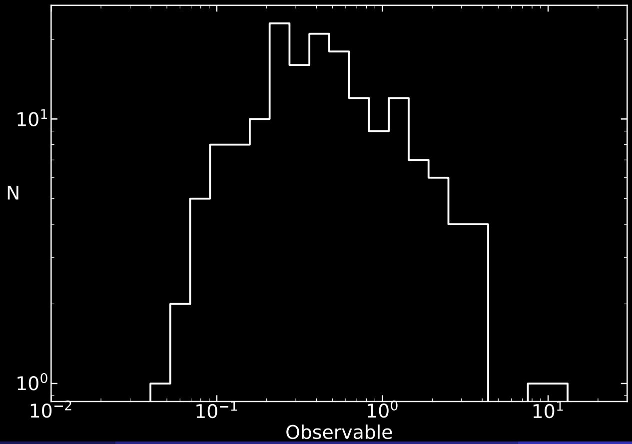
Forward model – Measurement uncertainty

$$\underbrace{\frac{d^2N(M,z,\theta_c)}{dMdV}\frac{dV}{dz}(\theta_c)}_{\text{cosmology dependence}}\underbrace{\frac{dM}{dX}(z,\theta_p)}_{\text{astrophysics}}\underbrace{P(I|X,M,z,\theta_s)}_{\text{selection function}}\underbrace{P(\hat{X}|X)}_{\text{uncertainty}}$$



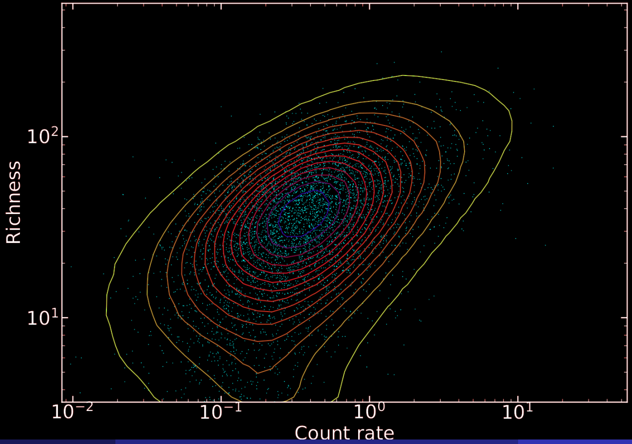
Forward model – Marginalization

$$\iint \underbrace{\frac{d^2N(M,z,\theta_c)}{dMdV}\frac{dV}{dz}(\theta_c)}_{\text{cosmology dependence}} \underbrace{\frac{dM}{dX}(z,\theta_p)}_{\text{astrophysics}} \underbrace{P(I|X,M,z,\theta_s)}_{\text{selection function}} \underbrace{P(\hat{X}|X)}_{\text{uncertainty}} \underbrace{dMdX}_{\text{marginalize}}$$

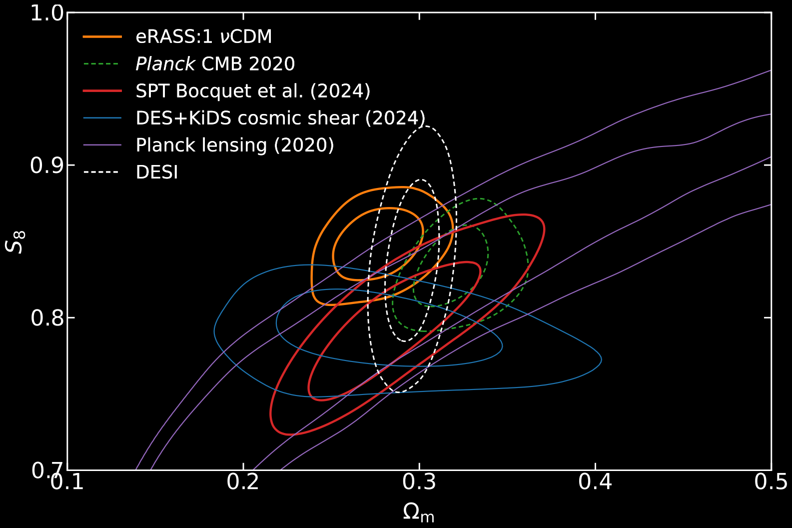


Forward model – Multiple observables

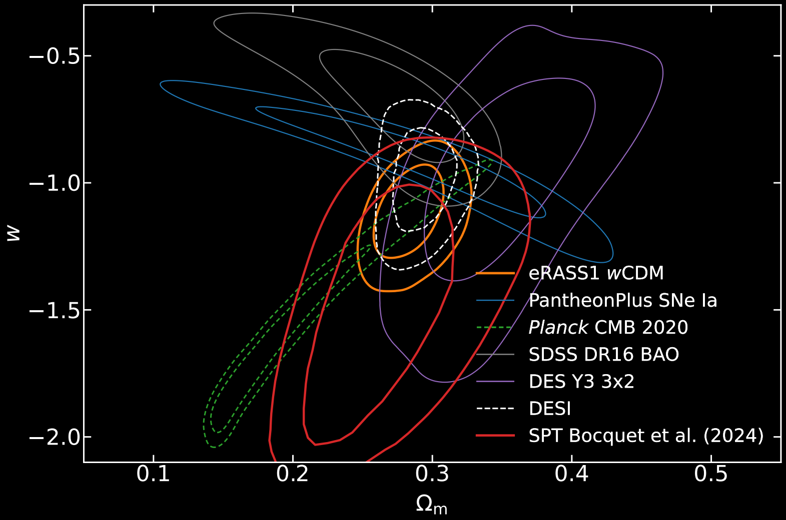
$$\iint \underbrace{\frac{d^2N(M,z,\theta_c)}{dMdV}\frac{dV}{dz}(\theta_c)}_{\text{cosmology dependence}} \underbrace{\frac{dM}{d\bar{X}}(z,\theta_p)}_{\text{astrophysics}} \underbrace{P(I|\bar{X},M,z,\theta_s)}_{\text{selection function}} \underbrace{P(\hat{\bar{X}}|\bar{X})}_{\text{uncertainty}} \underbrace{dMd\bar{X}}_{\text{marginalize}}$$



Clumpiness - Matter density



Dark energy - Matter density



Beyond number counts

Cosmology from the gas distribution

- **Gas mass fraction** — Allen+ 2007, Ettori+ 2009, Mantz+ 2014,2022
- **Size temperature relation** — Mohr+ 2000
- **SZ vs X-ray pressure** — Bonamente+ 2006, Kozmanyan+ 2019
- **Emission measure profile** — Arnaud+ 2002, Morandi+ 2016

Cosmology from the gas distribution

- **Clusters are representative chunks of the Universe** — Allen+ 2007, Ettori+ 2009, Mantz+ 2014,2022
- **Redshift independent relation for self-similar scenario** — Mohr+ 2000
- **Angular diameter distance proxy** — Bonamente+ 2006, Kozmanyan+ 2019
- **Gravity is self-similar $\Rightarrow$ minimal scatter profiles** — Arnaud+ 2002, Morandi+ 2016

Gas mass fraction

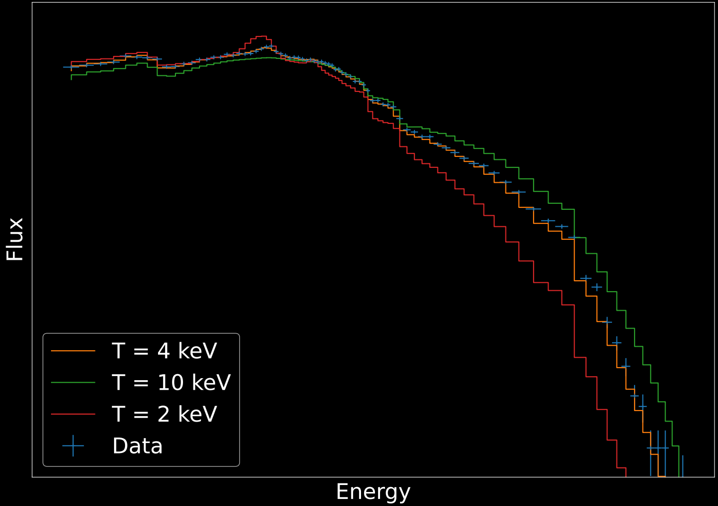
- Clusters are representative chunks of the whole Universe
- 85-90 % of baryons are in the ICM
- $\begin{cases} \Omega_m(z) = \Omega_{m,0}\frac{(1+z)^3}{E(z)^2} \\ \Omega_b(z) = \Omega_{b,0}\frac{(1+z)^3}{E(z)^2} \end{cases} \Rightarrow \frac{\Omega_b(z)}{\Omega_m(z)} = \frac{\Omega_{b,0}}{\Omega_{m,0}}$ is constant

$\Rightarrow f_{\mathrm{gas}} = \frac{\Omega_{b,0}}{\Omega_{m,0}} Y_{\mathrm{bar}} - f_\star$

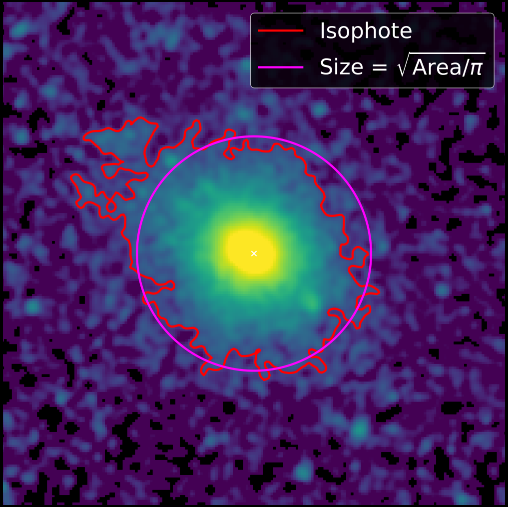
$\Rightarrow$ Standard ruler

Allen+ 2007, Ettori+ 2009

Cluster "temperature"



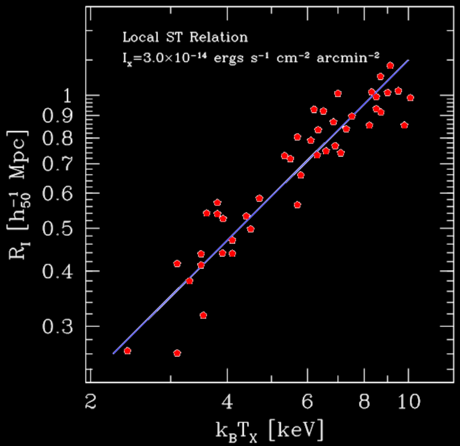
Cluster “size”



Size temperature relation

- Temperature is cosmology independent
- $R_{\mathrm{I,fit}} = R_0 \left(\frac{T_X}{6\,\mathrm{keV}}\right)^{\phi} E(z)^{\gamma}$
  - with $\gamma \approx 0$ for a β-model with $\beta = 2/3$

$\Rightarrow$ Standard ruler



Mohr+ 2000

X-ray - SZ ratio

$$\epsilon_{\text{X-ray}} = \int n_e n_{\text{H}} \Lambda(T_e) \left(\sum_i Z_i^2 \frac{n_i}{n_{\text{H}}} \right) dl$$

$$= \left[\int n_e n_{\text{H}} \Lambda(T_e) \left(\sum_i Z_i^2 \frac{n_i}{n_{\text{H}}} \right) d\theta \right] d_A(z)$$

$$\Rightarrow n_e \sim d_A^{-1/2}(z) \Rightarrow \mathbf{P_X \sim d_A^{-1/2}(z)}$$

$$y_{\text{SZ}} = \frac{\sigma_T}{m_e c^2} \int P_{\text{SZ}}(r) dl$$

$$= \left(\frac{\sigma_T}{m_e c^2} \int P_{\text{SZ}}(r) d\theta \right) d_A(z)$$

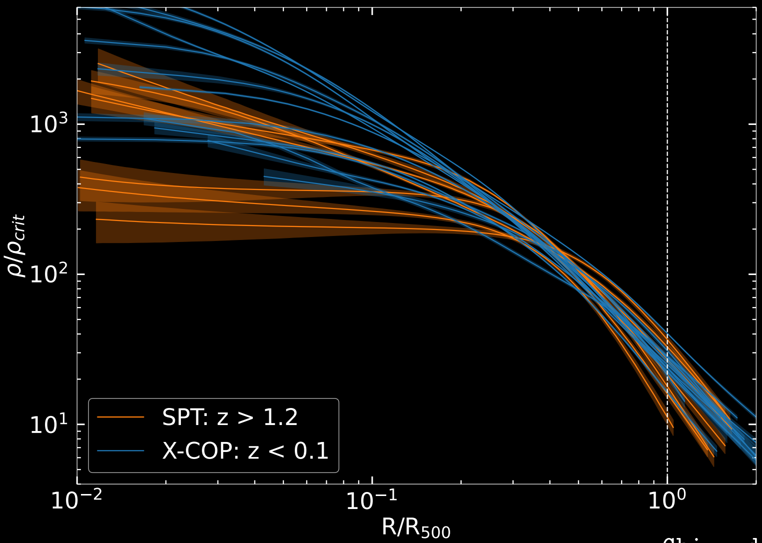
$$\Rightarrow \mathbf{P_{SZ} \sim d_A^{-1}(z)}$$

X-ray - SZ ratio

$$\eta = \frac{P_{\mathrm{SZ}}}{P_{\mathrm{X}}} \sim [d_A(z)]^{-1/2}$$

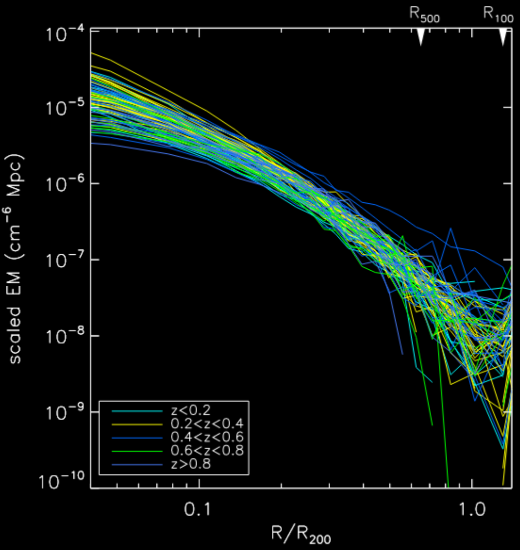
$\Rightarrow$ Standard ruler

Universal profile



Ghirardini+ 2019,2020

Universal emission measure profile

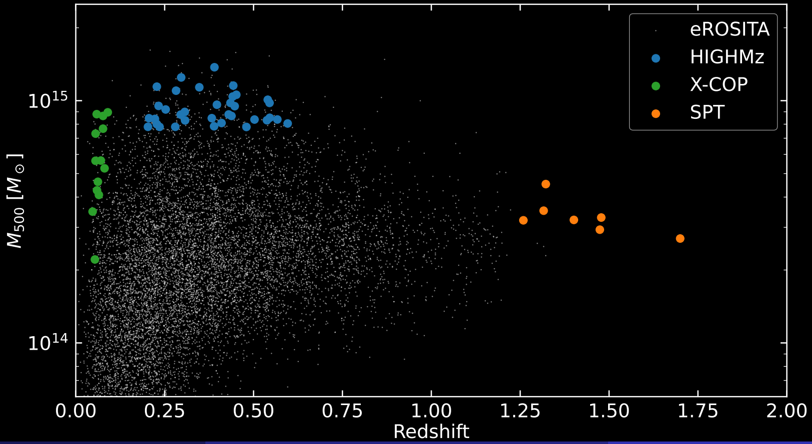


$\Rightarrow$ Standard ruler

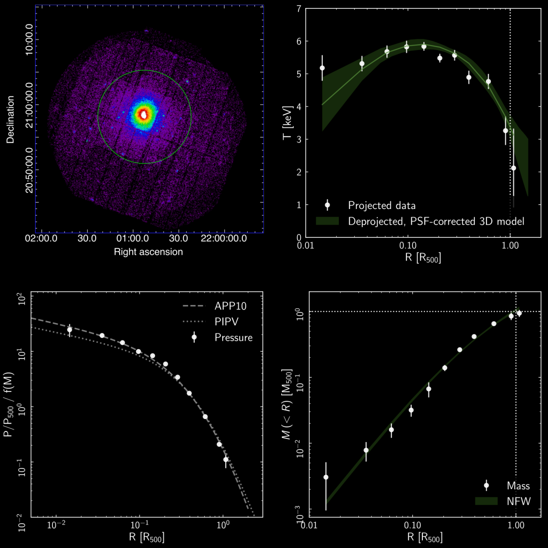
Morandi+ 2016

Dataset

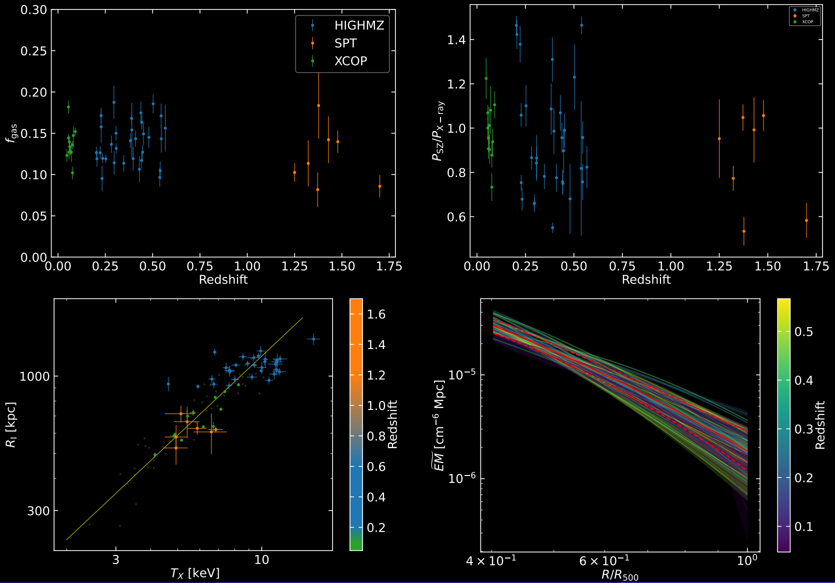
- X-COP: 12 massive clusters ($M_{500} > 4 \times 10^{14}\, M_{\odot}$) at $0.05 < z < 0.1$
- HIGHMz: 32 massive clusters ($M_{500} > 7.75 \times 10^{14}\, M_{\odot}$) at $0.2 < z < 0.6$
- SPT: 7 massive clusters ($M_{500} > 3 \times 10^{14}\, M_{\odot}$) at $z > 1.2$



Data


Declination
10:00:0.0
21:00:00.0
20:50:00.0
02:00.0
30.0
01:00.0
30.0
22:00:00.0
Right ascension
T [keV]
Projected data
Deprojected, PSF-corrected 3D model
R [R500]
APP10
PIPV
Pressure
P/P500 / f(M)
R [R500]
M(< R) [M500]
Mass
NFW
R [R500]

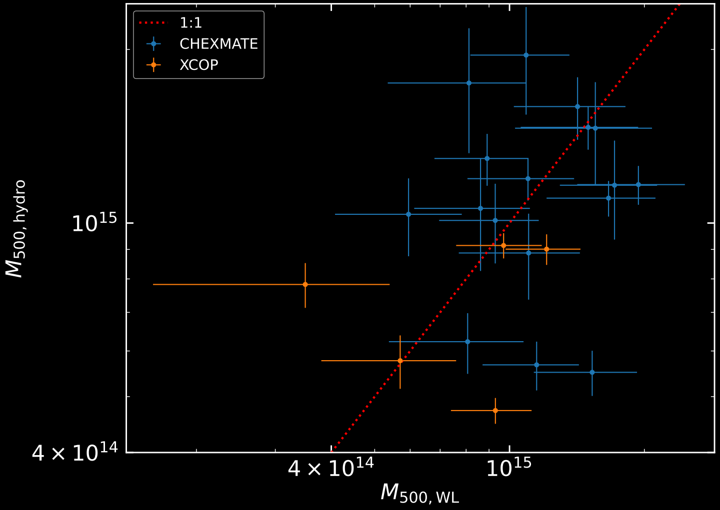
Data


HIGHMZ
SPT
XCOP
f_{gas}
Redshift
P_{SZ}/P_{X-ray}
Redshift
R_l [kpc]
T_X [keV]
Redshift
$\widetilde{EM}$ [cm^{-6} Mpc]
R/R_{500}
Redshift

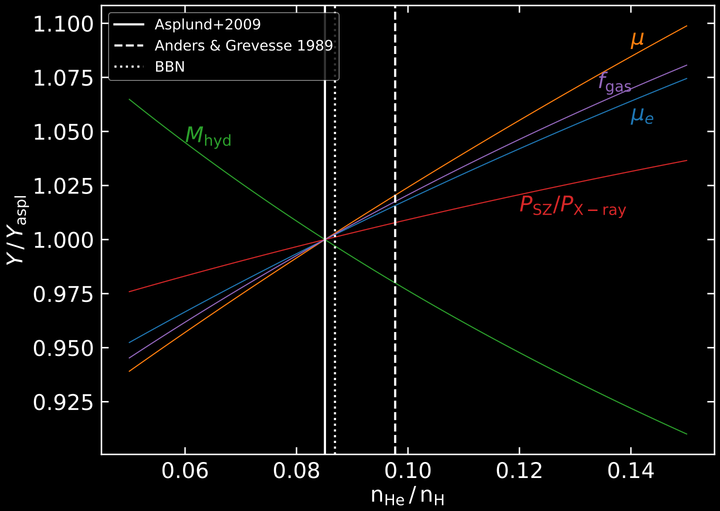
Modeling of systematics

- Mass bias
  - the adopted hydrostatic mass has to be calibrated
- Helium abundance
  - strongly connected with X-ray emissivity
    $\epsilon \approx \int n_e n_{\rm H} \Lambda(T_e) \left(1 + 4\frac{n_{\rm He}}{n_{\rm H}}\right) dl$
- Correlation between methods
- Size temperature evolution
- Emission measure scaling

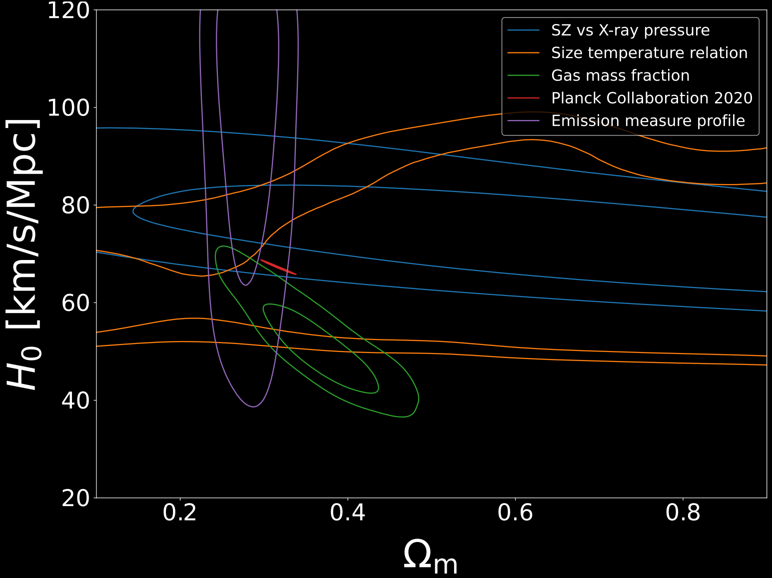
Mass calibration



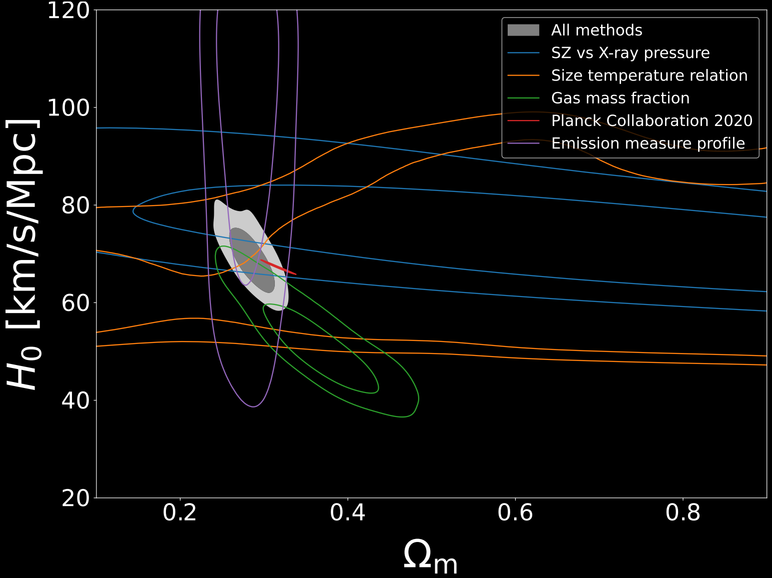
Helium abundance



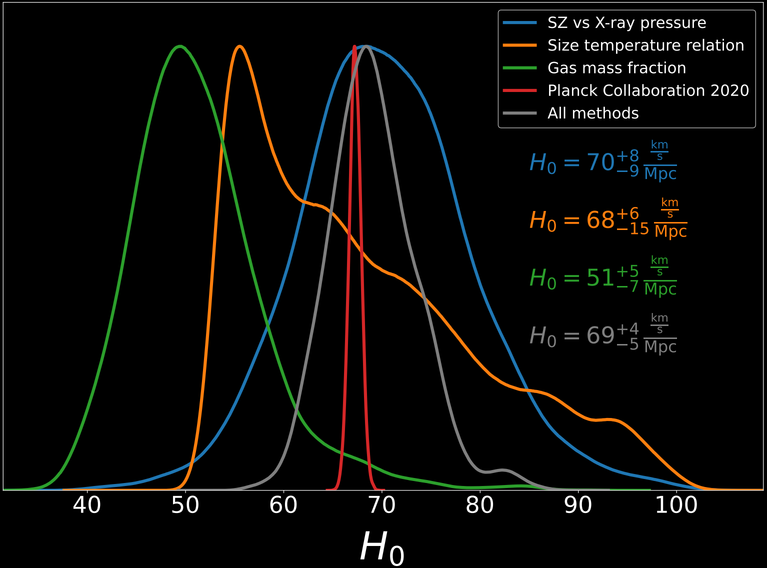
Preliminary results: flat ΛCDM



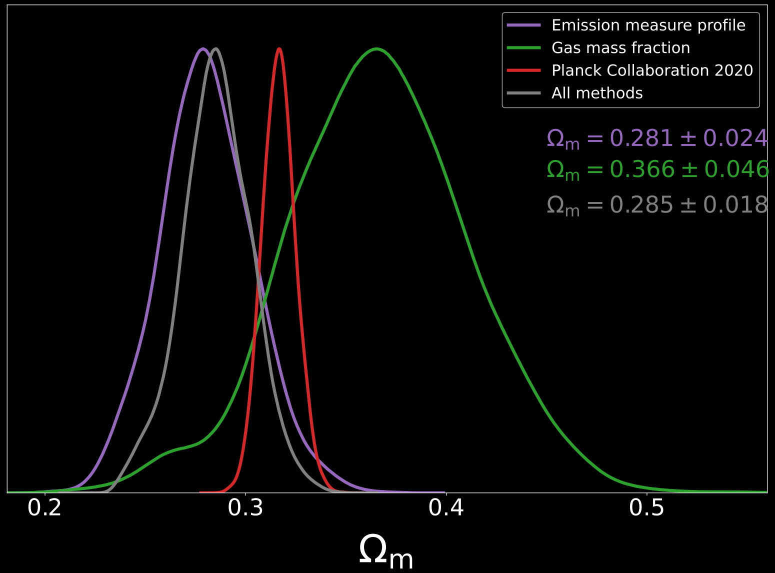
Preliminary results: flat ΛCDM



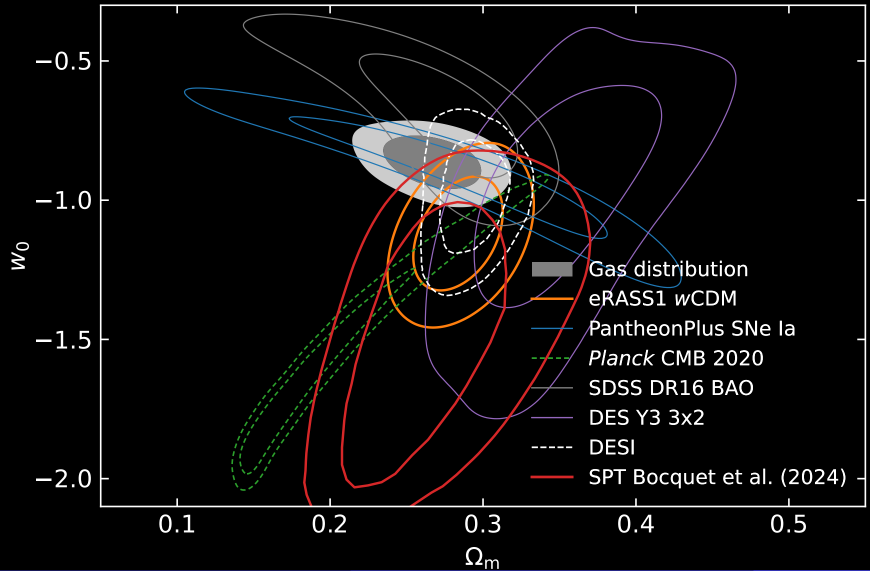
Preliminary results: flat ΛCDM - H_0



Preliminary results: flat ΛCDM - Ω_m



Preliminary results - w



Conclusion - why these results matter?

- Clusters are precision cosmological probes!
- Late-time parameters are measured with high precision
- Gas distribution can provide excellent constraints with just few clusters (32+12+7)
- No significant tension with *Planck* ΛCDM
- Constraints on dark energy equation of state are consistent with -1
- Future eROSITA surveys will return ground-breaking results on cosmology
- Systematics are accounted for and marginalized in the analysis