COSMOLOGY WITH CLUSTERING OF GALAXY CLUSTERS

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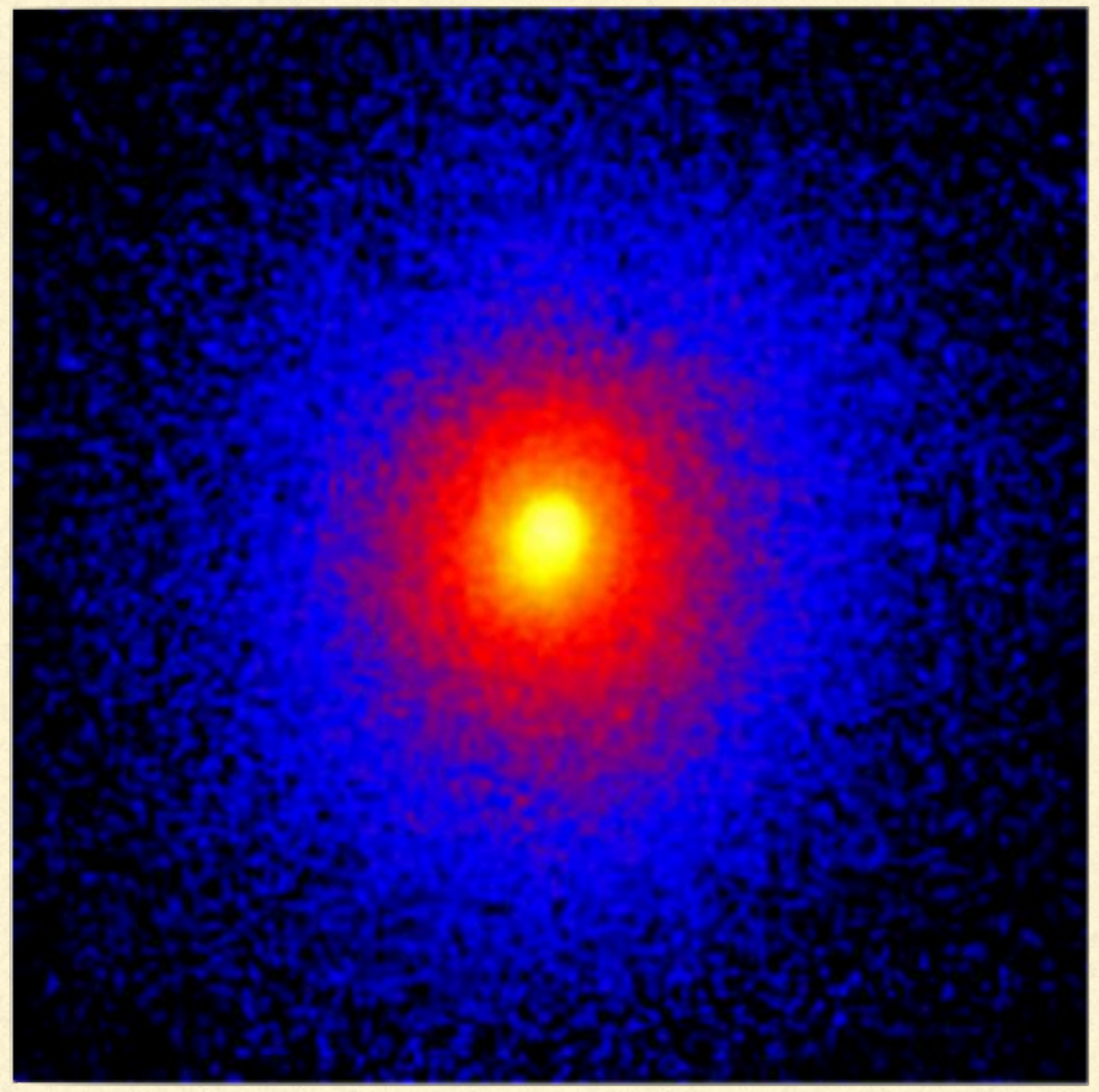
Sexten — 03.07.2024

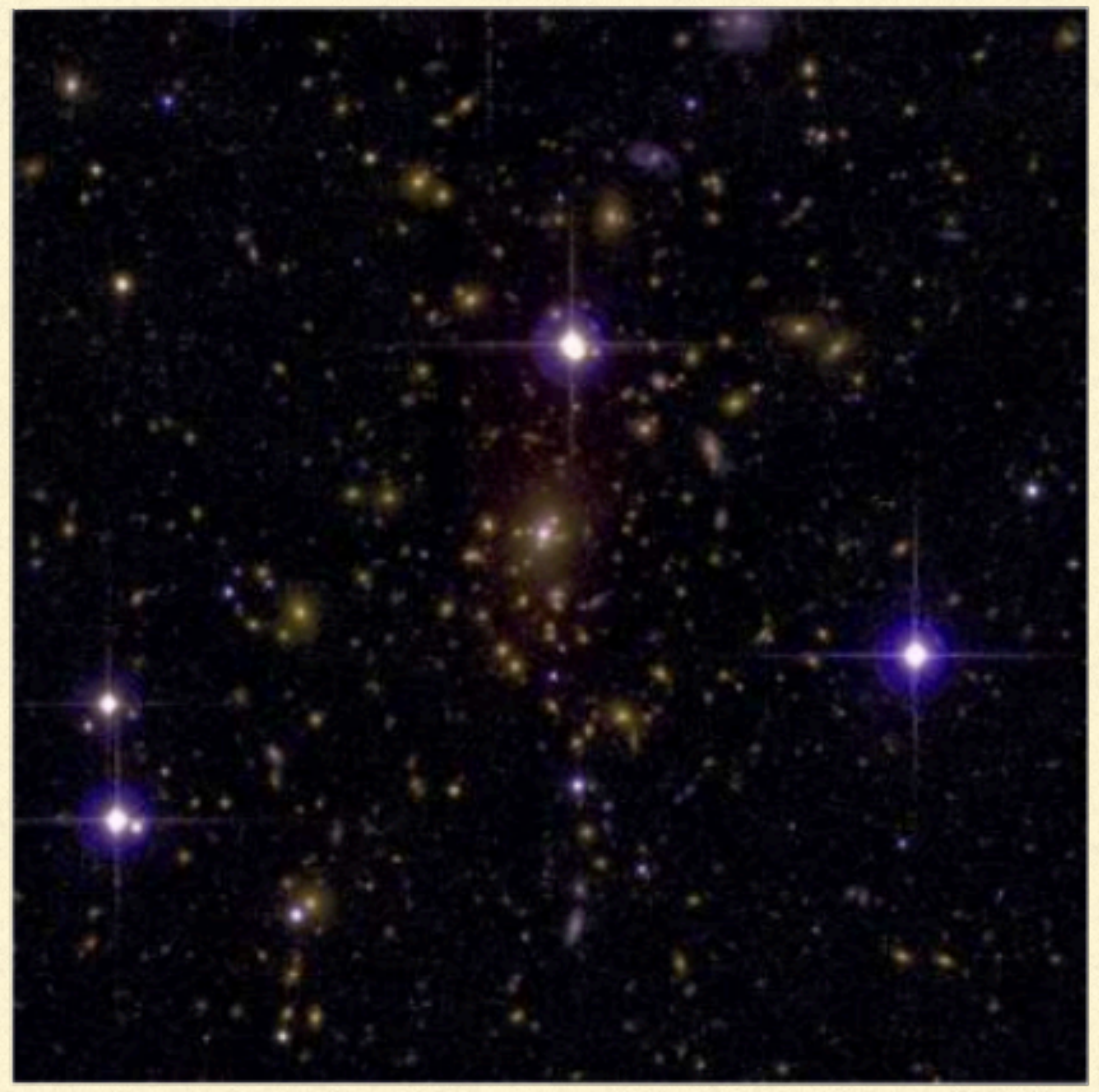
GALAXY CLUSTERS

- most massive gravitationally bound systems in the Universe (M ~10^{14} – 10^{15} M$\odot$)
- dark matter (85%) + hot ionised gas (12%) + stars (3%)
- detectable across the entire electromagnetic spectrum

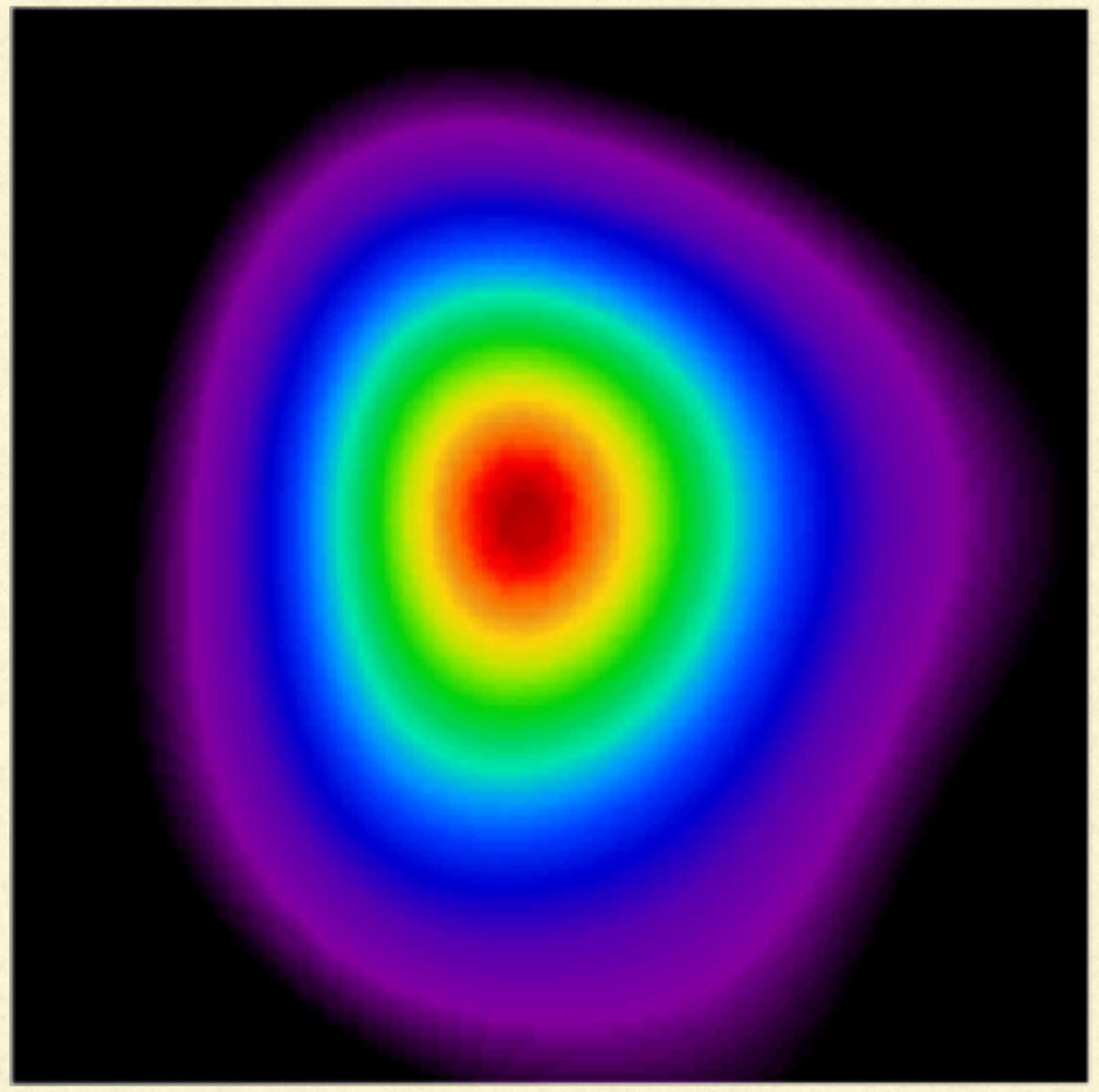
Intracluster gas:
X-ray



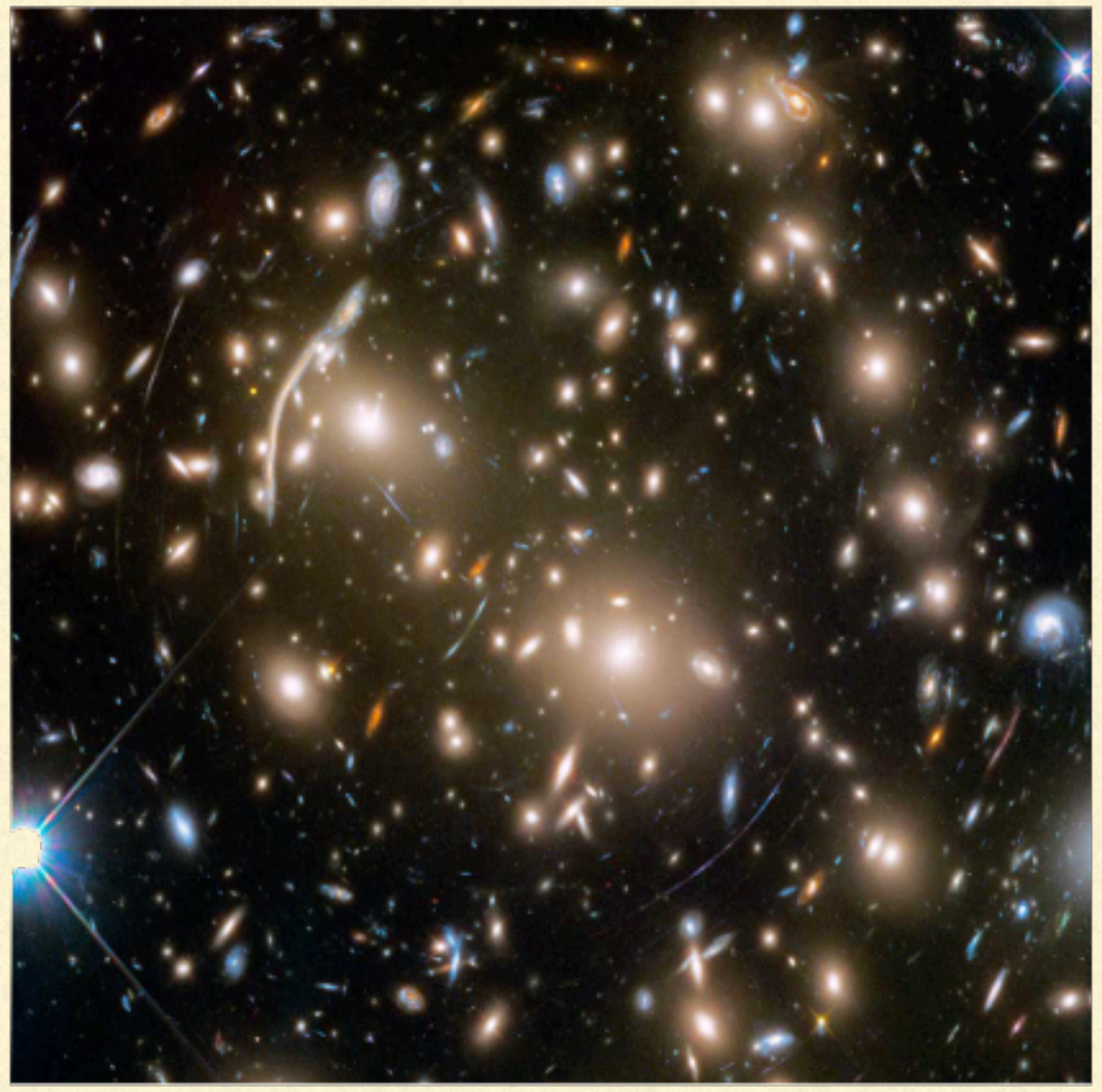
Stars in galaxies:
Optical and infrared



Sunayaev-Zeldovich effect
Millimiter band



Gravitational lensing



CLUSTER COSMOLOGY

Galaxy clusters reside in **dark matter halos**

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Trace the large-scale structure geometry and evolution

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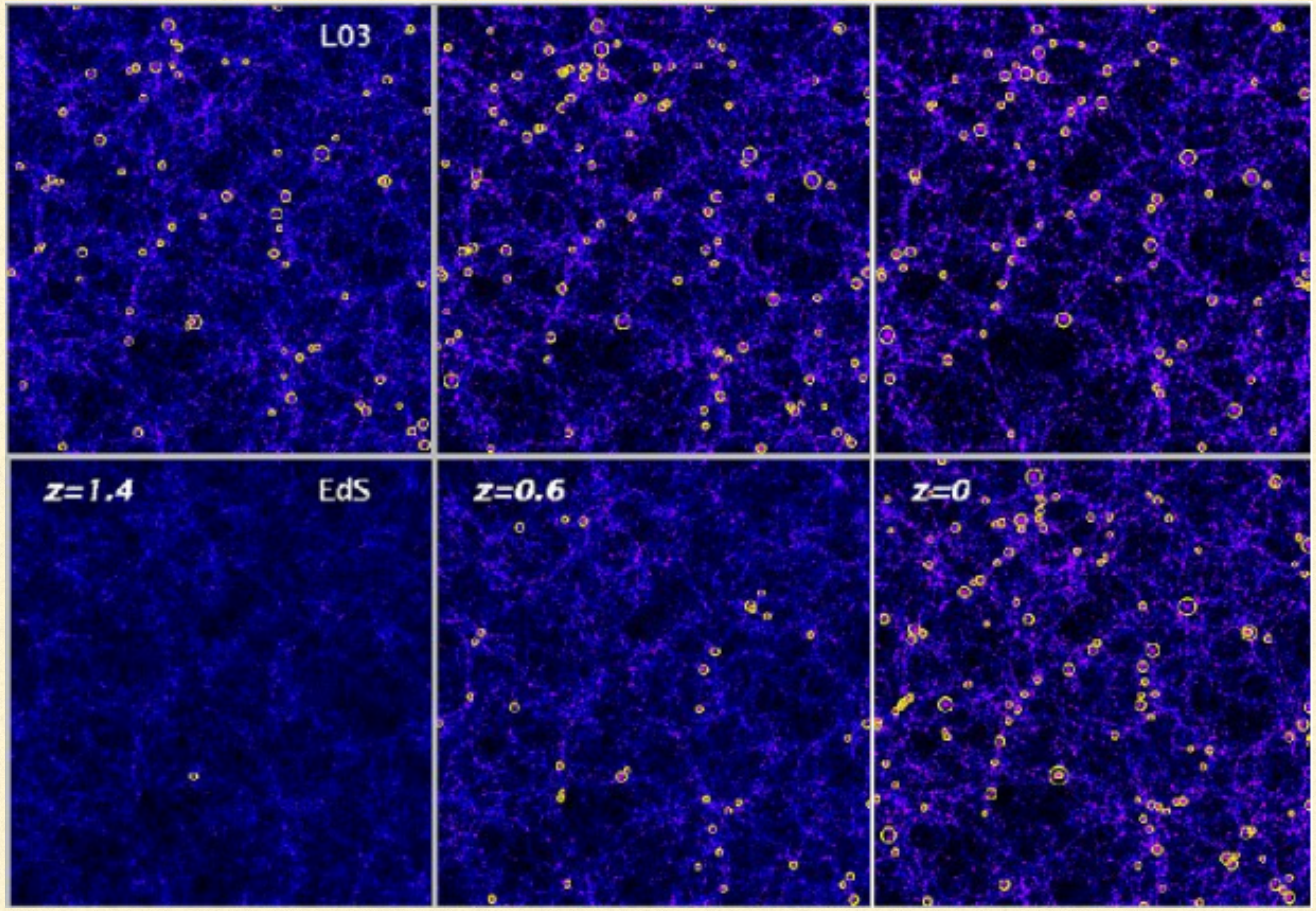
Constrain cosmological parameters, especially:

- Ω_m = matter content of the Universe
- σ_8 = amplitude of density fluctuations

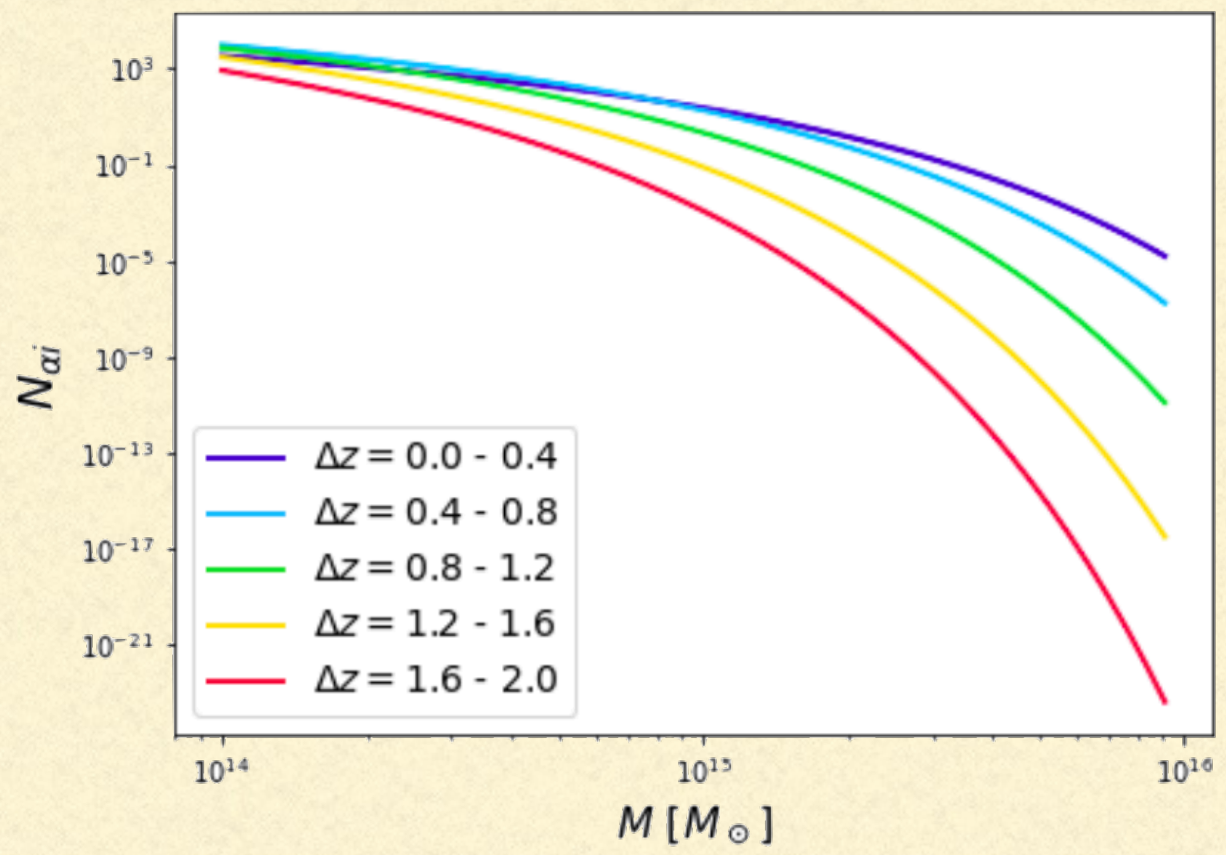


Borgani & Guzzo 2001

CLUSTER COSMOLOGY

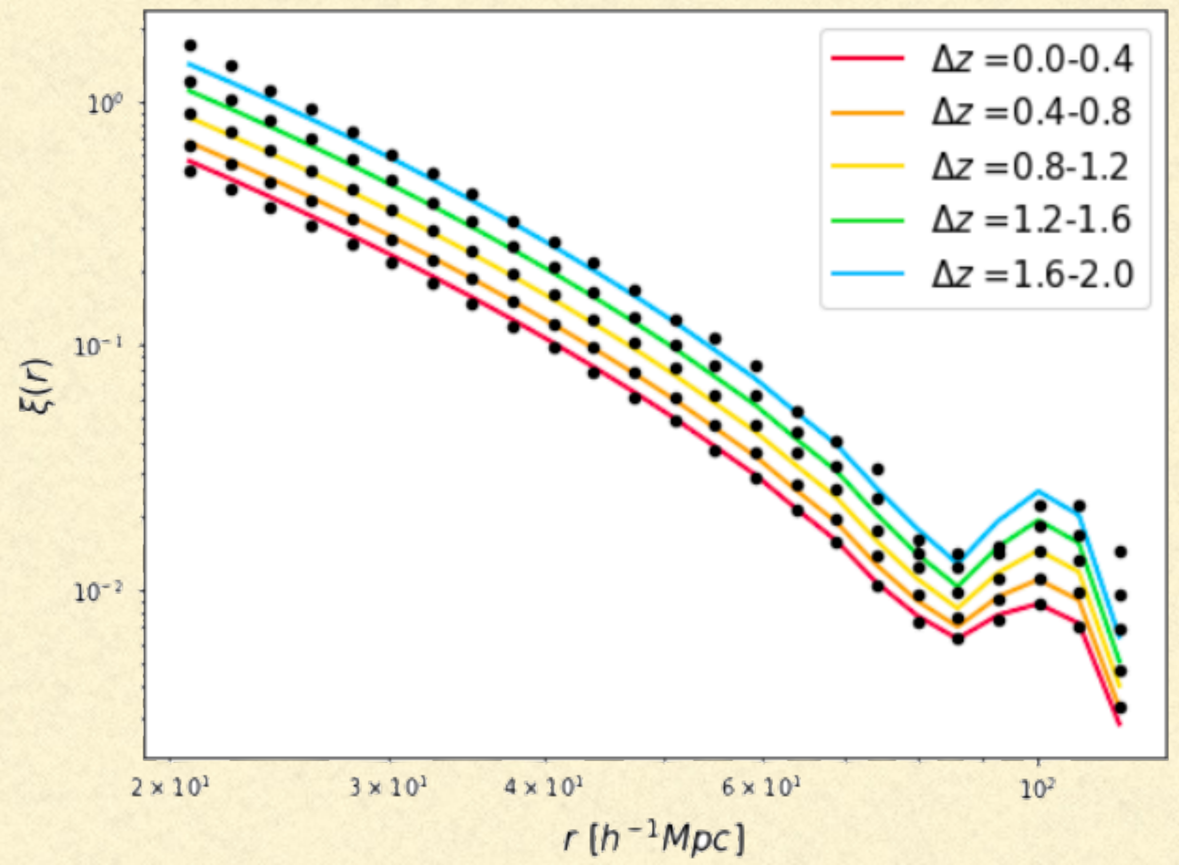
Cosmology with **cluster counts**:

- abundance of clusters in mass and redshift
- most widely used observable in cluster cosmology
- can constrain both cosmological and mass-observable relation parameters



Cosmology with **cluster clustering**:

- spatial distribution of clusters
- less used due to low statistics
- useful to break parameter degeneracies if combined to other probes (e.g., Borgani et al. 1999; Majumdar & Mohr 2004; Mana et al. 2013; Sereno et al. 2015; To et al. 2021; Lesci et al. 2022)



CLUSTER CLUSTERING

3D 2-point correlation function:

$$\xi_{\rm h}(r,z) = \int \frac{{\rm d}^3 k}{(2\,\pi)^3}\, P_{\rm h}(k,z)\, e^{i\,\mathbf{k}\cdot\mathbf{r}}$$

observational uncertainties: **RSD** and **photo-z**

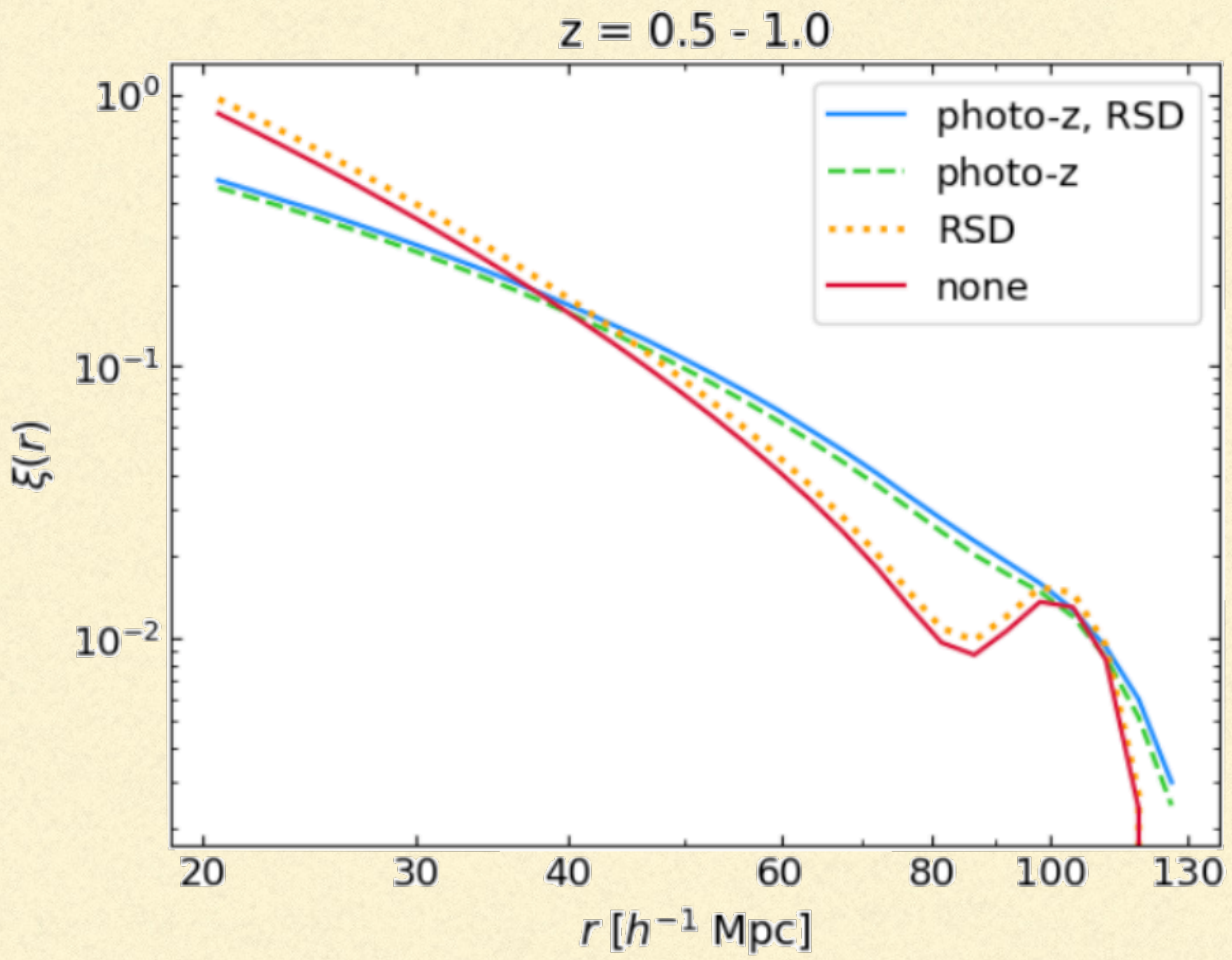
$$z_{\rm ob} = z + \boxed{\frac{v_{//}}{c}(1+z)} \boxed{\pm\ \sigma_z}$$

$$P_{\rm h}^{\rm ob}(k,\mu) = \boxed{(1+\beta\,\mu^2)^2} P_{\rm h}(k) \boxed{e^{-(k\,\mu\,\sigma)^2}} \qquad \sigma = \frac{\sigma_z\, c}{H(z)}$$

monopole

$$P_{\rm h}^{\rm ob,0}(k,z) = \left(A + B\,\beta + C\,\beta^2\right)\ P_{\rm h}(k,z)$$

$A = A(k\sigma)\quad B = B(k\sigma)\quad C = C(k\sigma)$



HALO BIAS

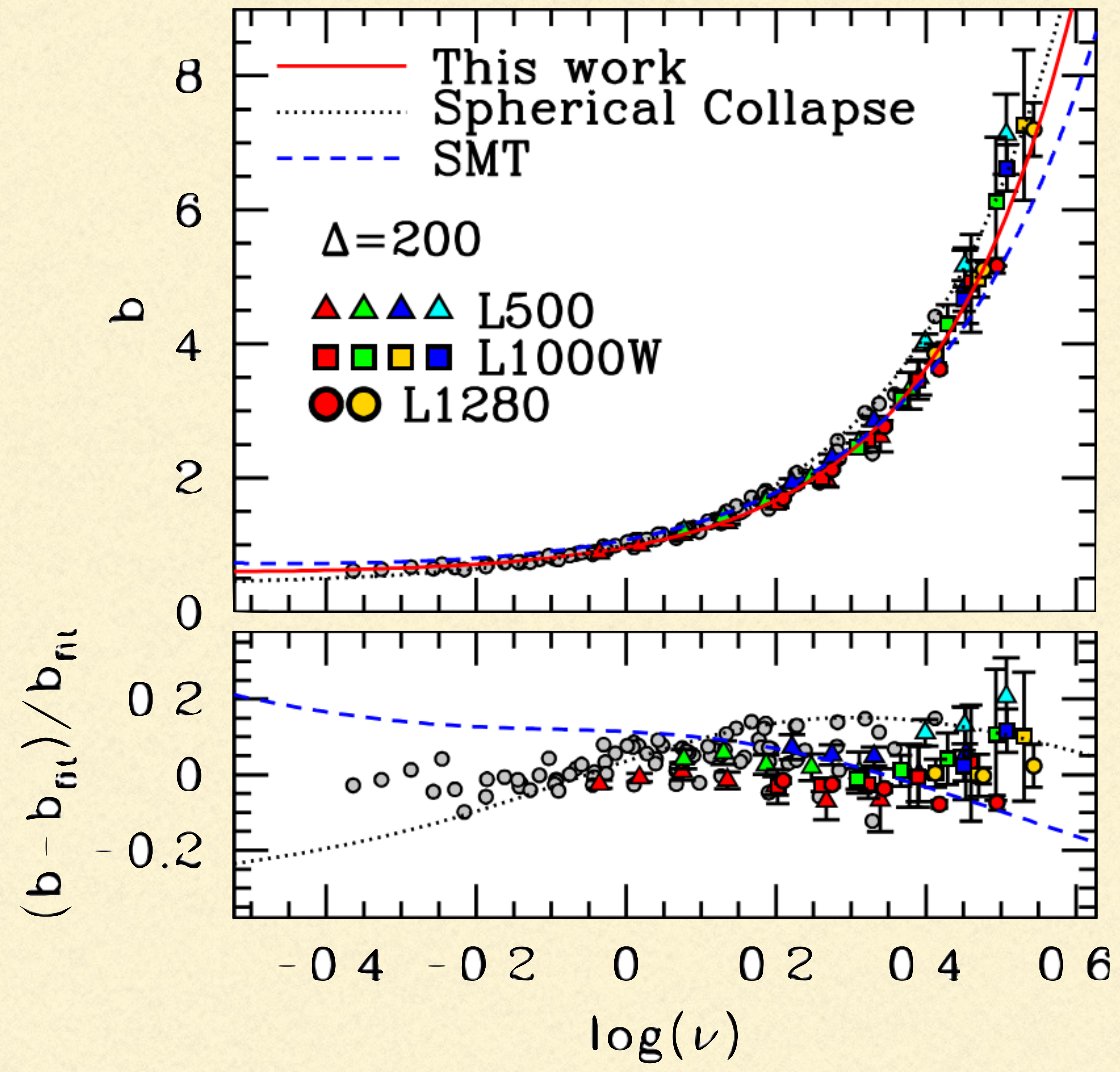
Clusters are **biased tracers** of matter distribution

$$\xi_{\rm h}(r) = b^2\,\xi_{\rm m}(r)$$

Halo bias:

- More linear and larger than galaxy bias
- Almost scale-independent (r>20 Mpc/h)
- Depends on mass, redshift and cosmology
- Can be fitted from simulations (e.g., Tinker+10, Castro+23)

Tinker+10



CLUSTER MASSES

Cluster **masses non directly measurable**

↓

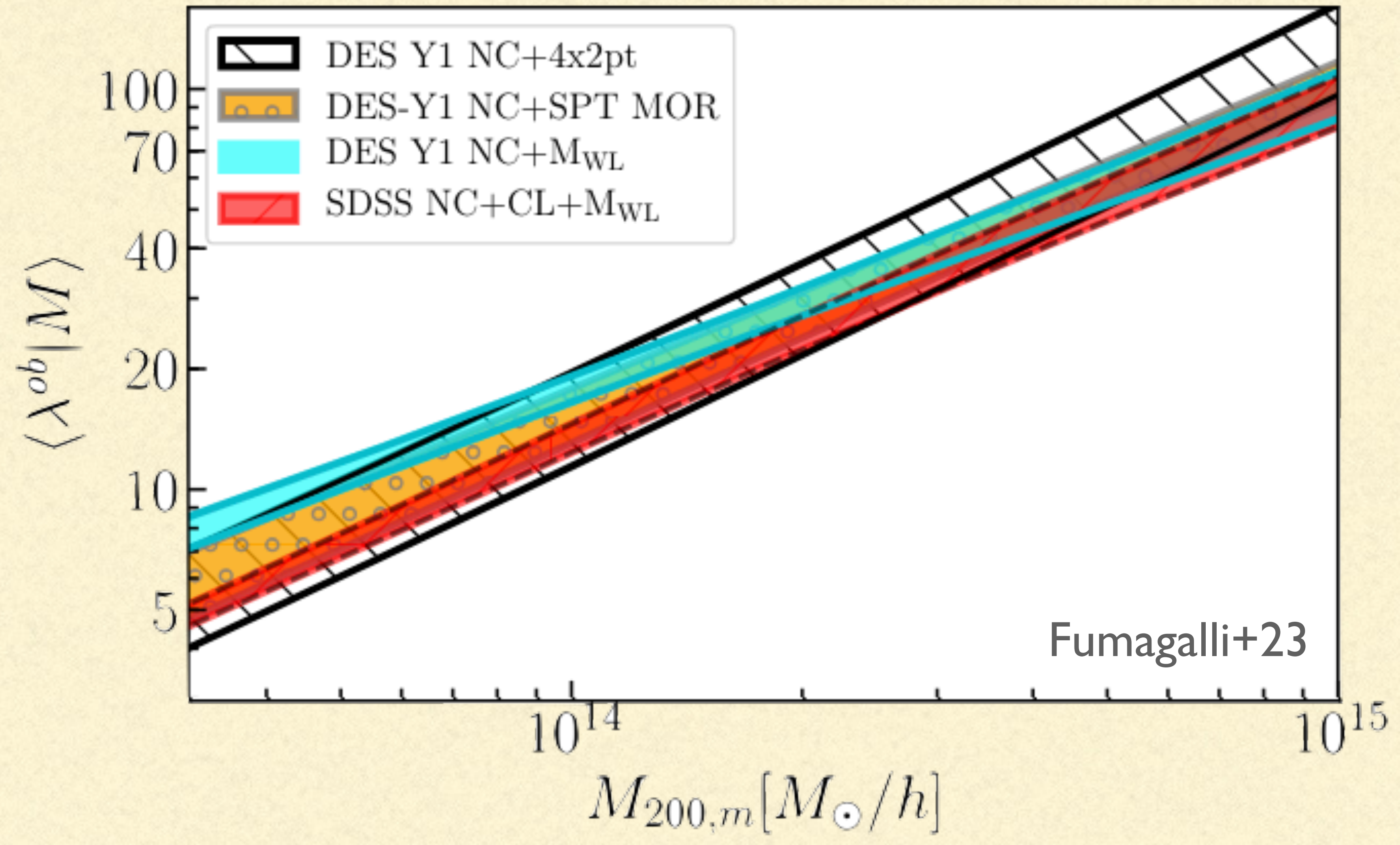
must be inferred through measurable properties of clusters (**mass proxy** like richness)

↓

observable-mass relation to be **calibrated** (usually with the help of weak-lensing masses)

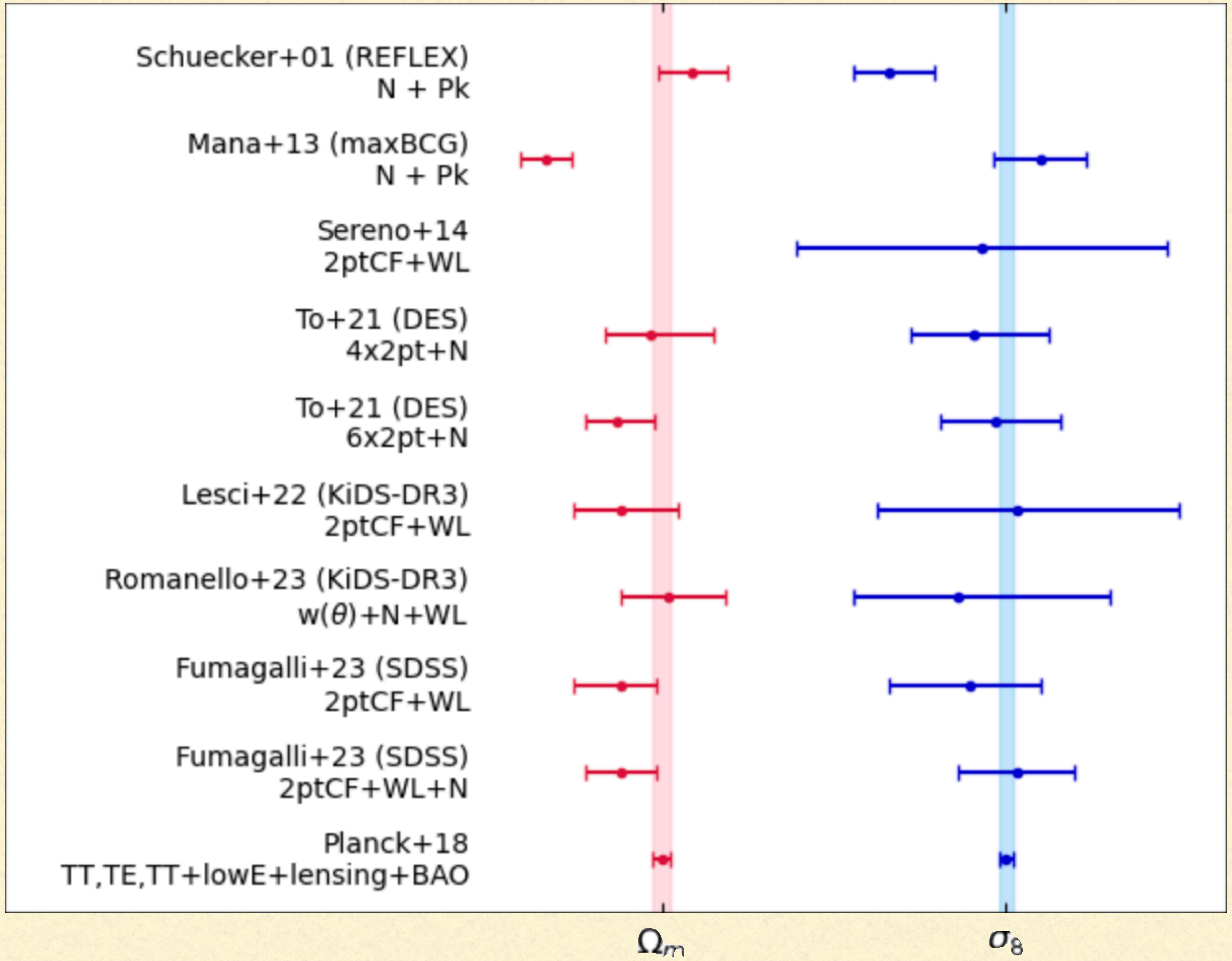
$$\langle \ln \lambda | M_{\rm vir}, z\rangle = \ln A_\lambda + B_\lambda \ln\left(\frac{M_{\rm vir}}{3\times 10^{14}\,M_\odot}\right) + C_\lambda \ln\left(\frac{E(z)}{E(z=0.6)}\right),$$

$$\sigma^2_{\ln \lambda | M_{\rm vir}, z} = D^2_\lambda.$$



STATE-OF-THE-ART

- Cluster clustering (CC) first used by Borgani+99 to constrain σ_8 ($0.8 < \sigma_8 < 2.0$ for $\Omega_m = 0.3$)
- CC first combined with cluster counts by Schuecker+03 to constrain Ω_m and σ_8
- CC useful to help constraining scaling relations and cosmology (e.g., Majumdar&Mohr04; Mana+13; Sereno+14, To+21; Lesci+22, Romanello+23,Fumagalli+23)
- CC useful to identify BAO (Miller+01; Angulo+05; Huetsi+10; Veropalumbo+14; Moresco+21)

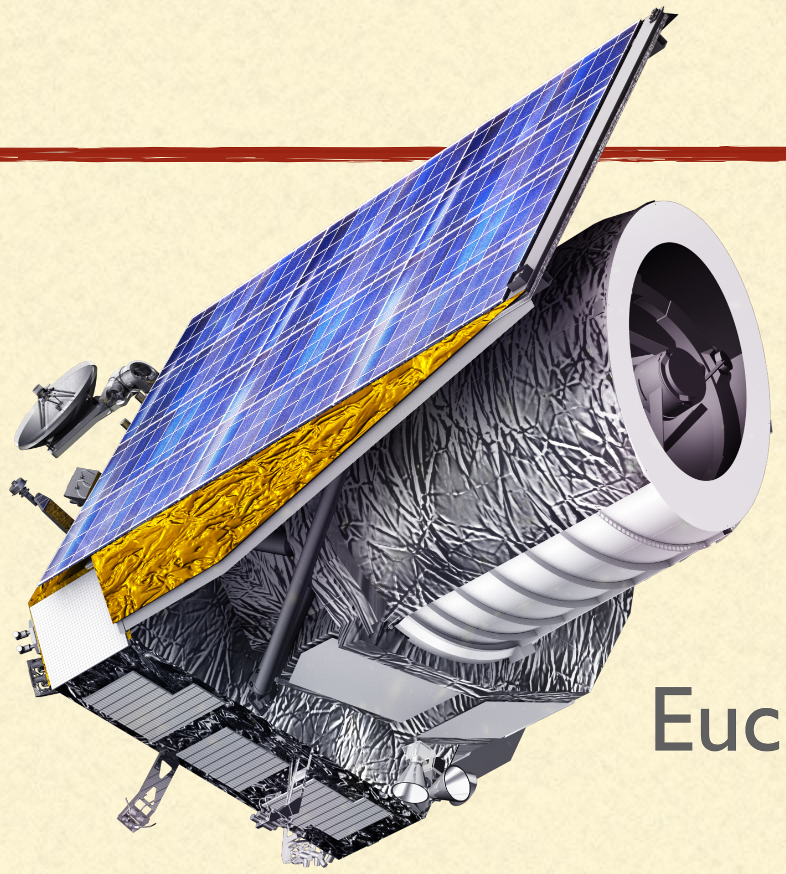


CLUSTER SURVEYS

- Recent cluster surveys (e.g., **SDSS, DES, SPT, KiDS**, …) have significantly expanded our catalogs of galaxy clusters

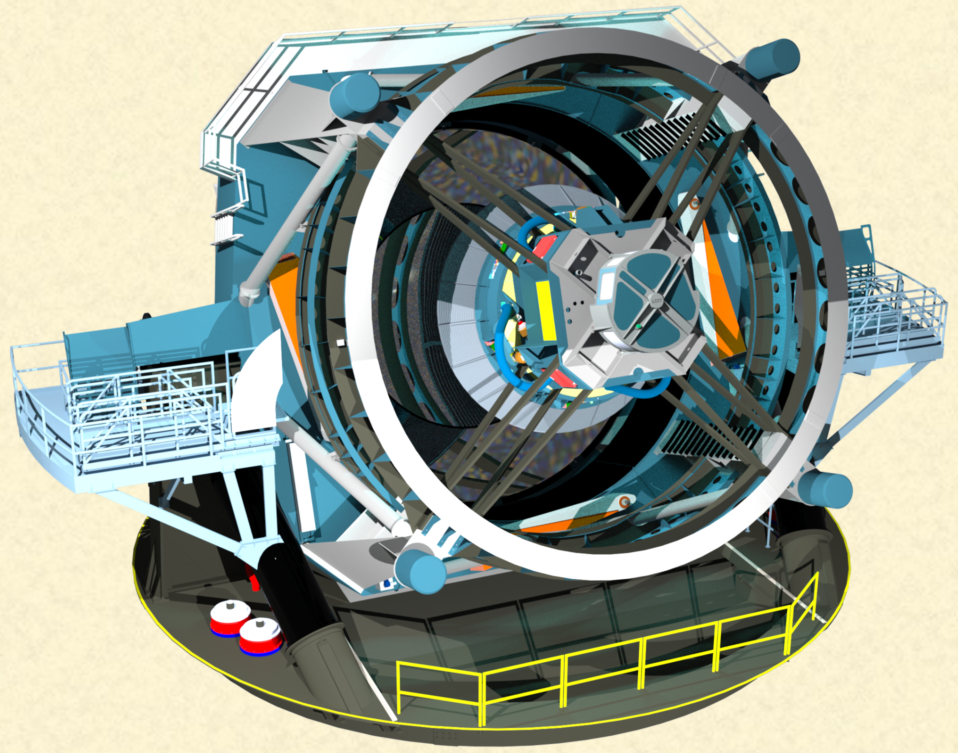
- Upcoming cluster surveys (e.g., **Euclid, LSST, eROSITA**, …) will provide cluster catalogs with **unprecedented statistics**:
  - Increase number of clusters (up to ~10^5)
  - Wider redshift ranges (up to $z \simeq 2$)
  - Large survey volumes
  - Multi-wavelength surveys to be combined

→ main problem in cluster cosmology: **control of systematic** uncertainties



Euclid

Rubin/LSST



eROSITA

SYSTEMATICS AND UNCERTAINTIES

$$\xi(\Delta r_a, \Delta z_i^{\mathrm{ob}}) = \frac{1}{N_i^2}\int_0^\infty \mathrm{d}z_1\,\mathrm{d}z_2 \boxed{\frac{\mathrm{d}V}{\mathrm{d}z}(z_1)} \frac{\mathrm{d}V}{\mathrm{d}z}(z_2)\,\bar{n}(z_1)\,\bar{n}(z_2)\,\bar{b}(z_1)\,\bar{b}(z_2) \boxed{\bar{\xi}_{\mathrm{m}}(\Delta r_a, z_1, z_2)} \int_{\Delta z_i^{\mathrm{ob}}} \mathrm{d}z_1^{\mathrm{ob}}\,\mathrm{d}z_2^{\mathrm{ob}} \boxed{P(z_1^{\mathrm{ob}}\;\; z_1)} P(z_2^{\mathrm{ob}}\;\; z_2)$$

$$\bar{b}(z\;\; \lambda^{\mathrm{ob}}) = \frac{1}{\bar{n}}\int_0^\infty \mathrm{d}M \boxed{n(M,z)}\boxed{b(M,z)} \int_0^\infty \mathrm{d}\lambda \int_{\lambda_{\min}}^\infty \mathrm{d}\lambda^{\mathrm{ob}} \boxed{P(\lambda^{\mathrm{ob}}\;\; \lambda)}\boxed{P(\lambda\;\; M,z)},$$

cosmology-dependent quantities ⇒ constrain cosmological parameters

semi-analytical models ⇒ calibrate on numerical simulations

mass-observable relation ⇒ cluster mass not directly observable, to be inferred through mass proxies (e.g. richness)

selection functions ⇒ observational inaccuracy (photo-z error, projection effects, …)

+ cluster detection ⇒ catalog's completeness and purity

+ covariance matrix ⇒ statistical errors (shot-noise, sample variance, …).

COVARIANCE MATRIX

Inclusion of uncertainties of statistical quantities fundamental to constrain cosmological parameters

- **Numerical matrix** from a large set of simulations

$$\hat{C}_{ij} = \frac{1}{N-1} \sum_{a=1}^{N} \left(\hat{d}_i^a - \langle \hat{d}_i \rangle \right) \left(\hat{d}_j^a - \langle \hat{d}_j \rangle \right)$$

  + all the contributes are included
  − noisy due to finite number of simulations / high computational resources
  − cosmology-independent matrix

- **(Semi-)analytical models**

$$C_{ij} = C_{ij}(\Theta), \quad \Theta = \{\Omega_{\mathrm{m}}, \sigma_8, \dots\}$$

  + noise free
  + cosmology-dependent
  − difficult to include all the terms (non-linearities, non-Gaussianity, window functions...)

to be validated/calibrated with simulations

COVARIANCE MATRIX MODEL

Euclid Collaboration: Fumagalli+22 (arXiv:2211.12965)

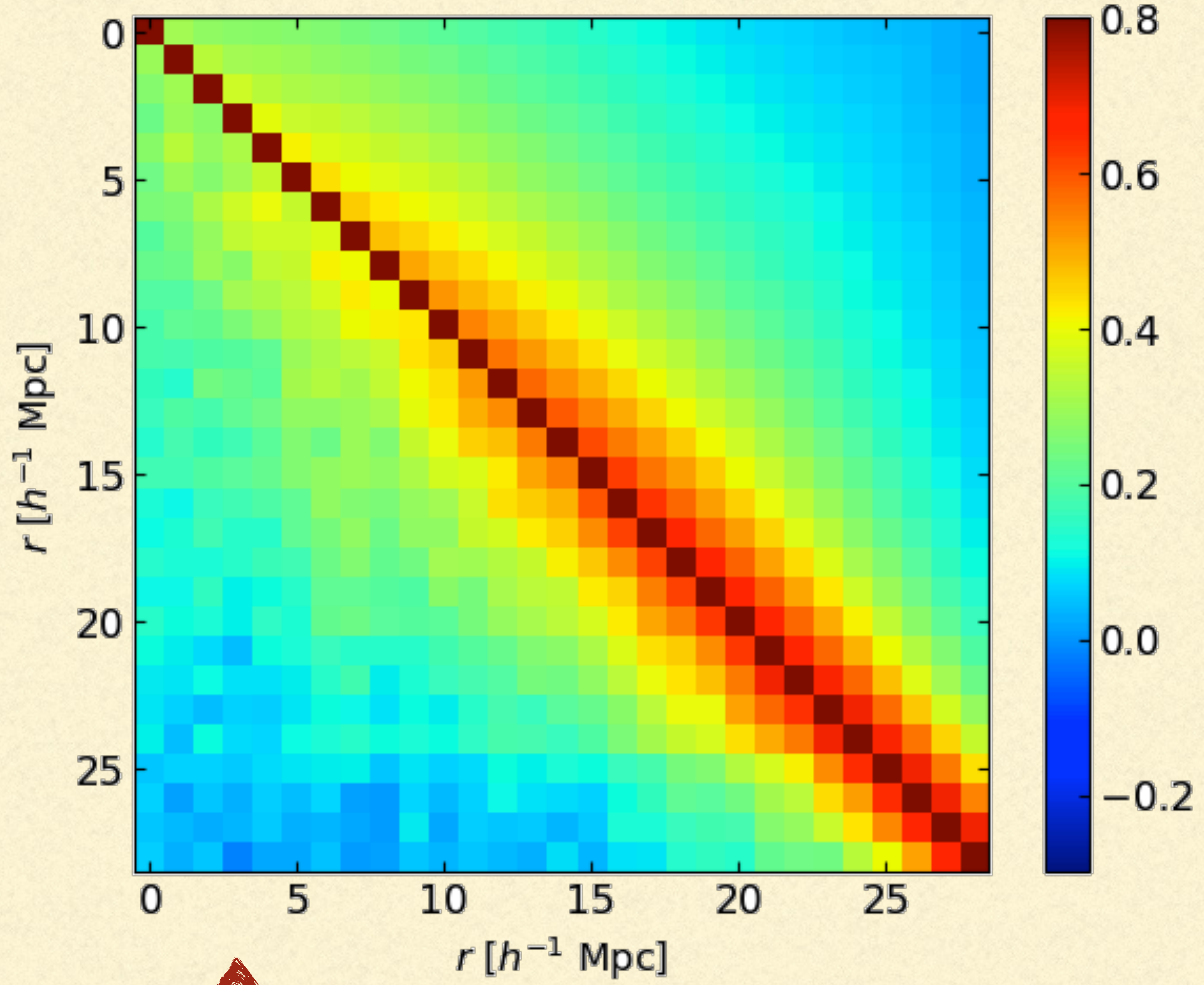
$$C(\Delta z_a, \Delta r_i, \Delta r_j) = \frac{2}{V_{\Delta z}} \int \frac{\mathrm{d}k\, k^2}{2\pi^2} \left\langle \bar{b}^2 P_\mathrm{m}(k) + \frac{1}{\bar{n}} \right\rangle^2_{\Delta z_a} W_i(k)\, W_j(k)$$

$$+ \frac{2}{V_{\Delta z_a} V_i} \int \frac{\mathrm{d}k\, k^2}{2\pi^2} \left\langle \bar{b}^2 P_\mathrm{m}(k) \left(\frac{1}{\bar{n}}\right)^2 \right\rangle_{\Delta z_a} W_j(k)\; \delta^\mathrm{D}_{ij}$$

$$\cancel{+ \text{ high order terms}(\propto B, T)}$$

Validated against **1000 Euclid-like lightcones** generated with LPT-based **PINOCCHIO** algorithm (Monaco et al. 2021)

Analytical model



Numerical matrix from simulations

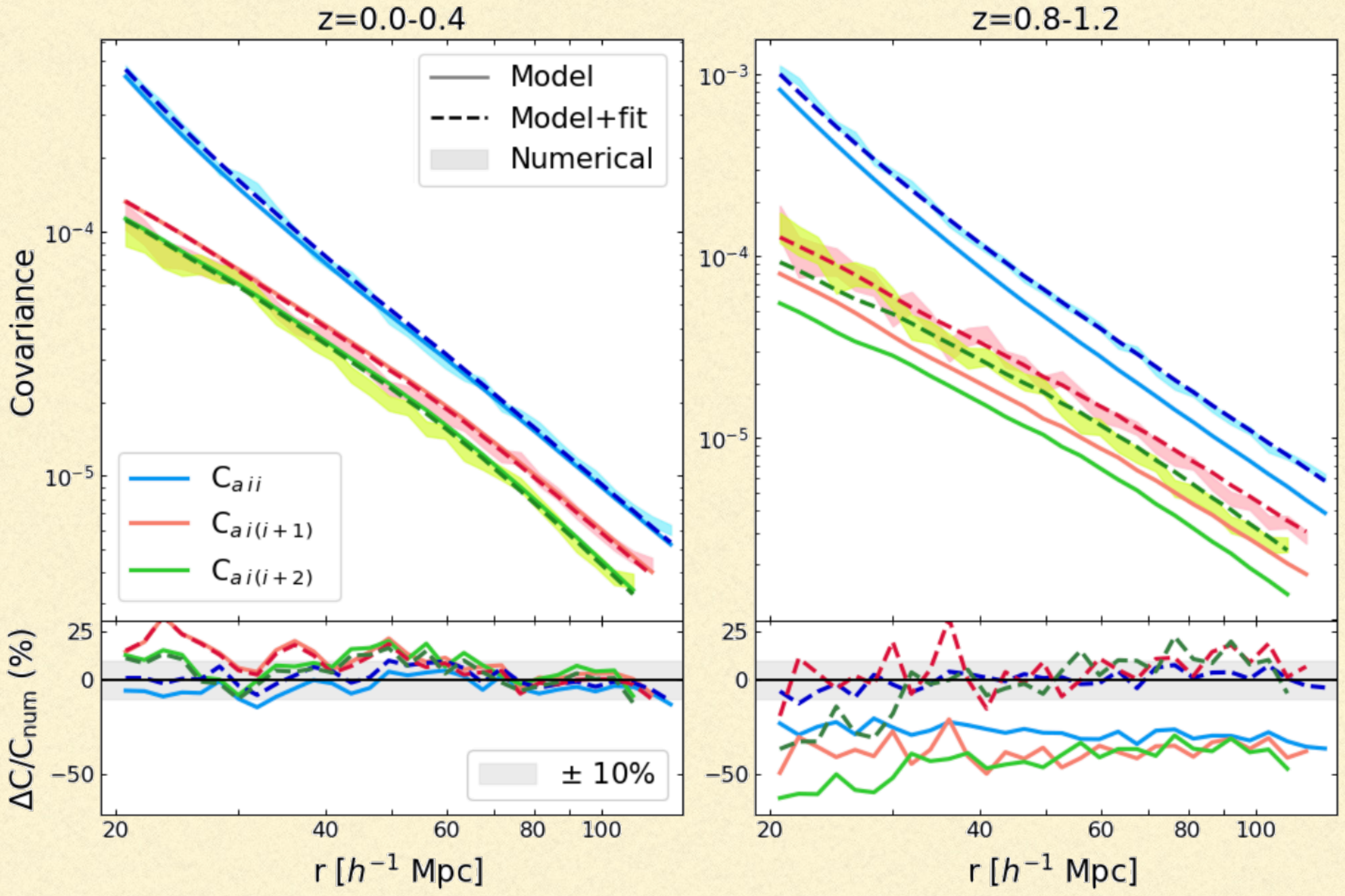
COVARIANCE MATRIX MODEL

Euclid Collaboration: Fumagalli+22 (arXiv:2211.12965)

$$C(\Delta r_i, \Delta r_j) = \frac{2}{V_{\Delta z}} \int \frac{\mathrm{d}k\, k^2}{2\pi^2} \left\langle (\beta \bar{b})^2 P_\mathrm{m}(k) + \frac{1+\alpha}{\bar{n}} \right\rangle^2_{\Delta z} W_i(k)\, W_j(k)$$
$$+ \frac{2}{V_{\Delta z} V_i} \int \frac{\mathrm{d}k\, k^2}{2\pi^2} \left\langle (\beta \bar{b})^2 P_\mathrm{m}(k) \left(\frac{1+\gamma}{\bar{n}} \right)^2 \right\rangle_{\Delta z} W_j(k)\; \delta^\mathrm{D}_{ij}$$

α, β, ɣ fitted from few (~10[2]) simulations
following Fumagalli+22 (arXiv:2206.05191v2)

accurate, noise-free, cosmo-dependent
covariance matrix

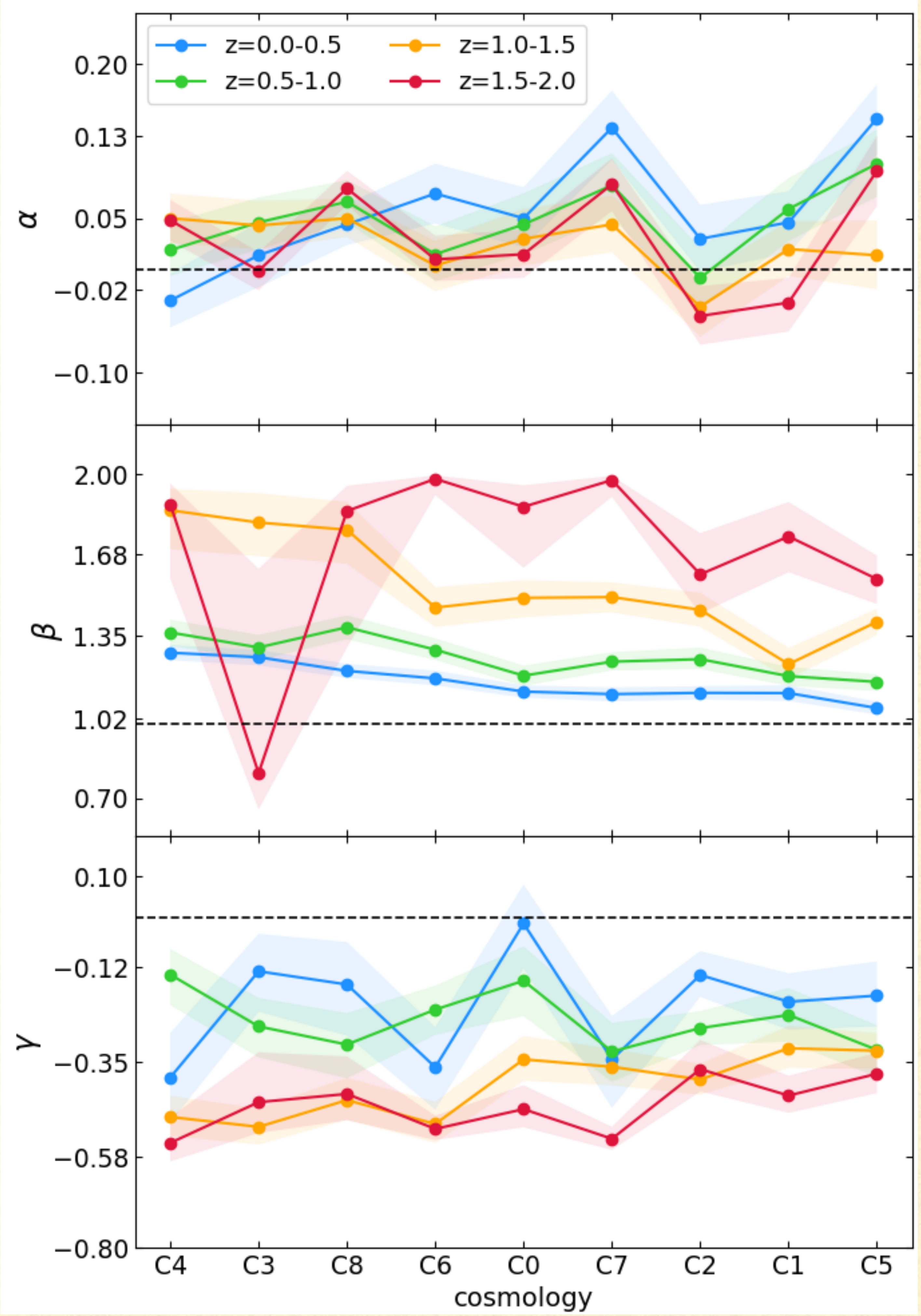


COVARIANCE FIT PARAMETERS

$$C(\Delta r_i, \Delta r_j) = \frac{2}{V_{\Delta z}} \int \frac{\mathrm{d}k\, k^2}{2\pi^2} \left\langle (\beta \bar{b})^2 P_\mathrm{m}(k) + \frac{1+\alpha}{\bar{n}} \right\rangle_{\Delta z}^2 W_i(k)\, W_j(k)$$

$$+ \frac{2}{V_{\Delta z} V_i} \int \frac{\mathrm{d}k\, k^2}{2\pi^2} \left\langle (\beta \bar{b})^2 P_\mathrm{m}(k) \left(\frac{1+\gamma}{\bar{n}} \right)^2 \right\rangle_{\Delta z} W_j(k)\, \delta_{ij}^\mathrm{D}$$

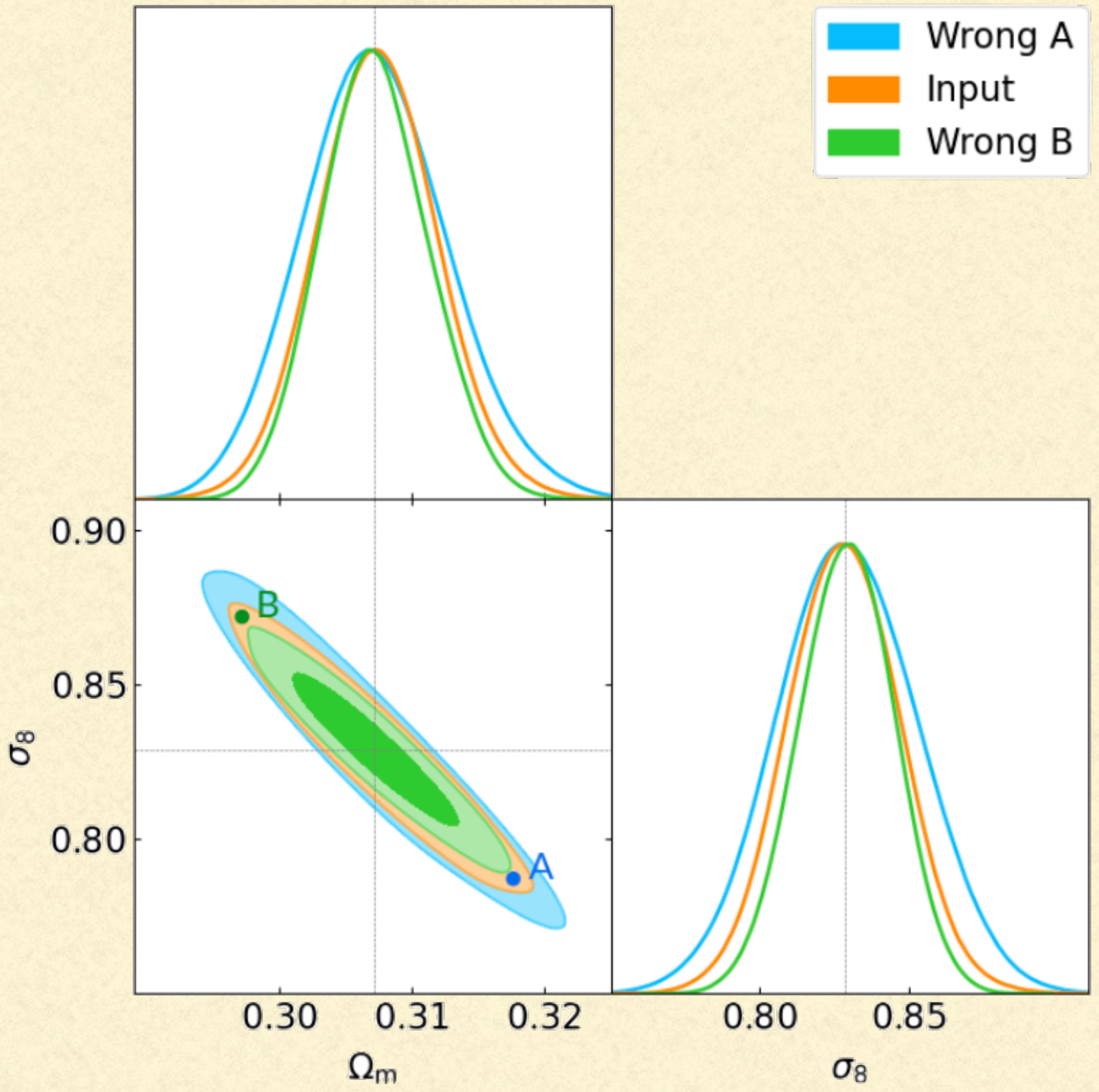
α, β, ɣ independent on cosmology



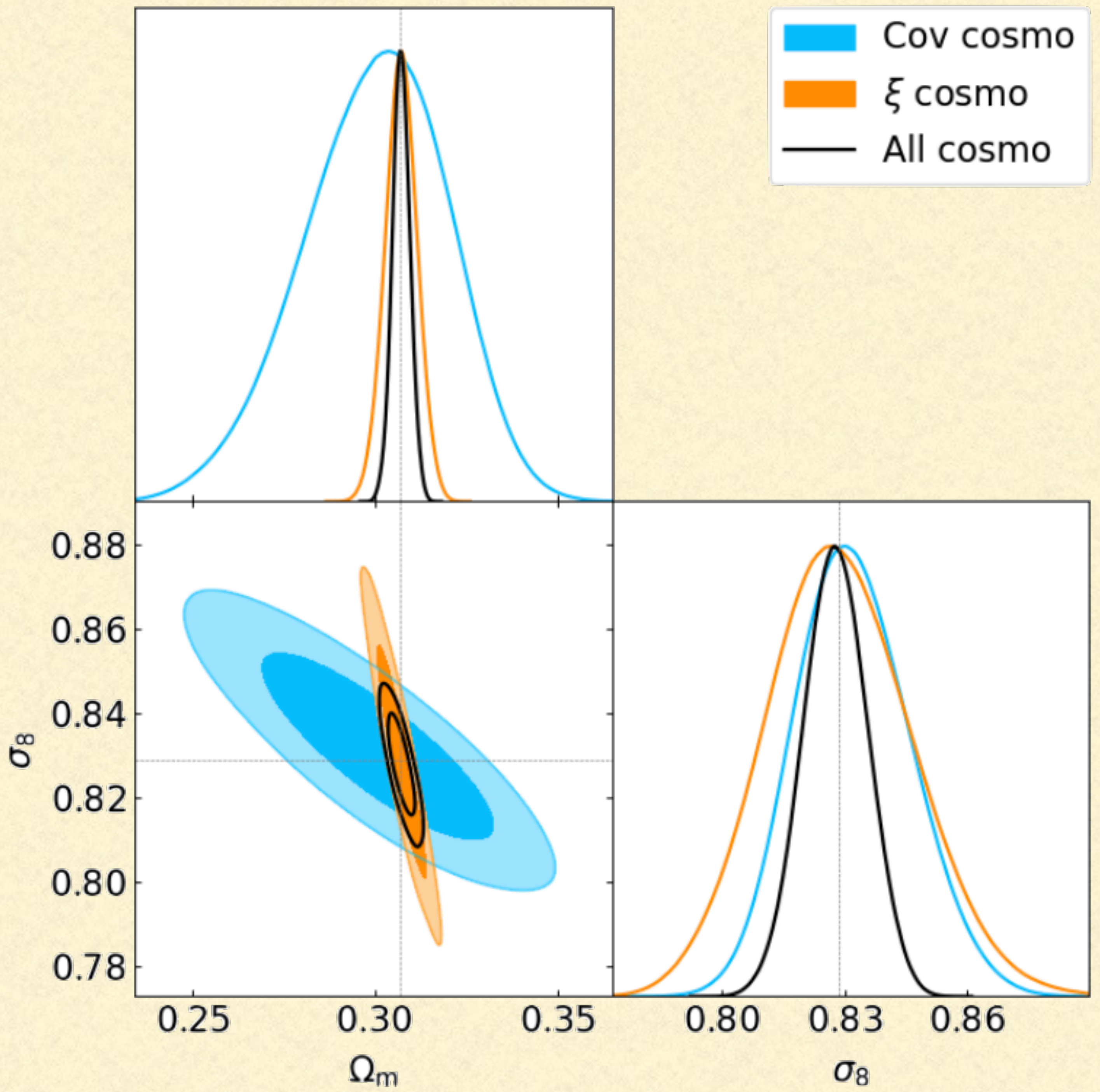
COSMO-DEPENDENT COVARIANCE

Covariance with different degeneracy on parameters w.r.t. ξ due to shot-noise ∝ mass function

$$C(\Delta r_i, \Delta r_j) = \frac{2}{V_{\Delta z}} \int \frac{\mathrm{d}k\, k^2}{2\pi^2} \left\langle (\beta \bar{b})^2 P_\mathrm{m}(k) + \boxed{\frac{1+\alpha}{\bar{n}}} \right\rangle^2_{\Delta z} W_i(k)\, W_j(k)$$
$$+ \frac{2}{V_{\Delta z} V_i} \int \frac{\mathrm{d}k\, k^2}{2\pi^2} \left\langle (\beta \bar{b})^2 P_\mathrm{m}(k) \boxed{\left(\frac{1+\gamma}{\bar{n}}\right)^2} \right\rangle_{\Delta z} W_j(k)\, \delta^\mathrm{D}_{ij}$$



Euclid Collaboration: Fumagalli+22

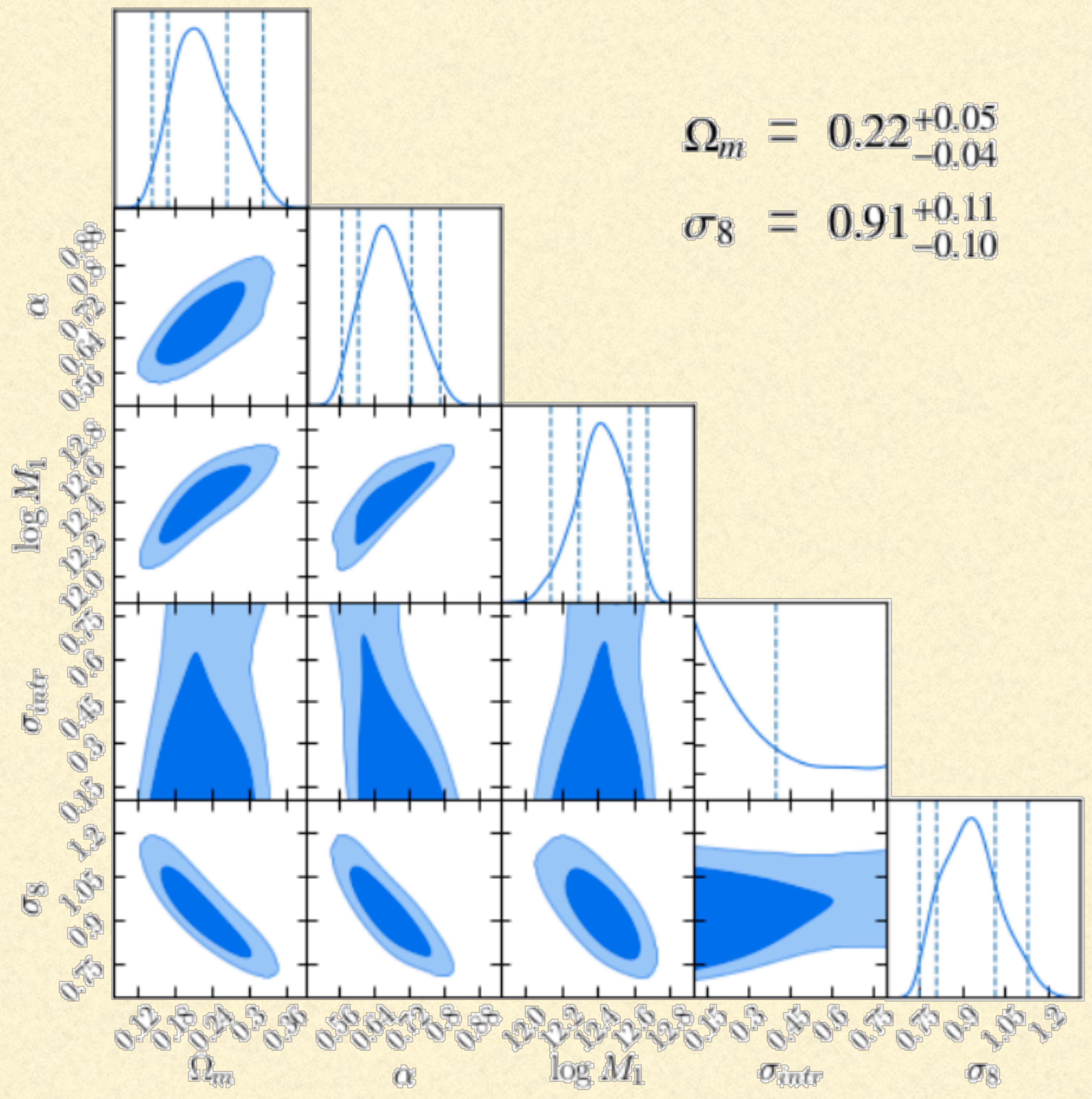


CLUSTER CLUSTERING ON REAL DATA: SDSS

Cosmological and richness-mass relation constraints from:

- cluster abundance and weak lensing mass (Costanzi et al. 2019)

- cluster abundance and weak lensing mass **+ 3D cluster clustering**



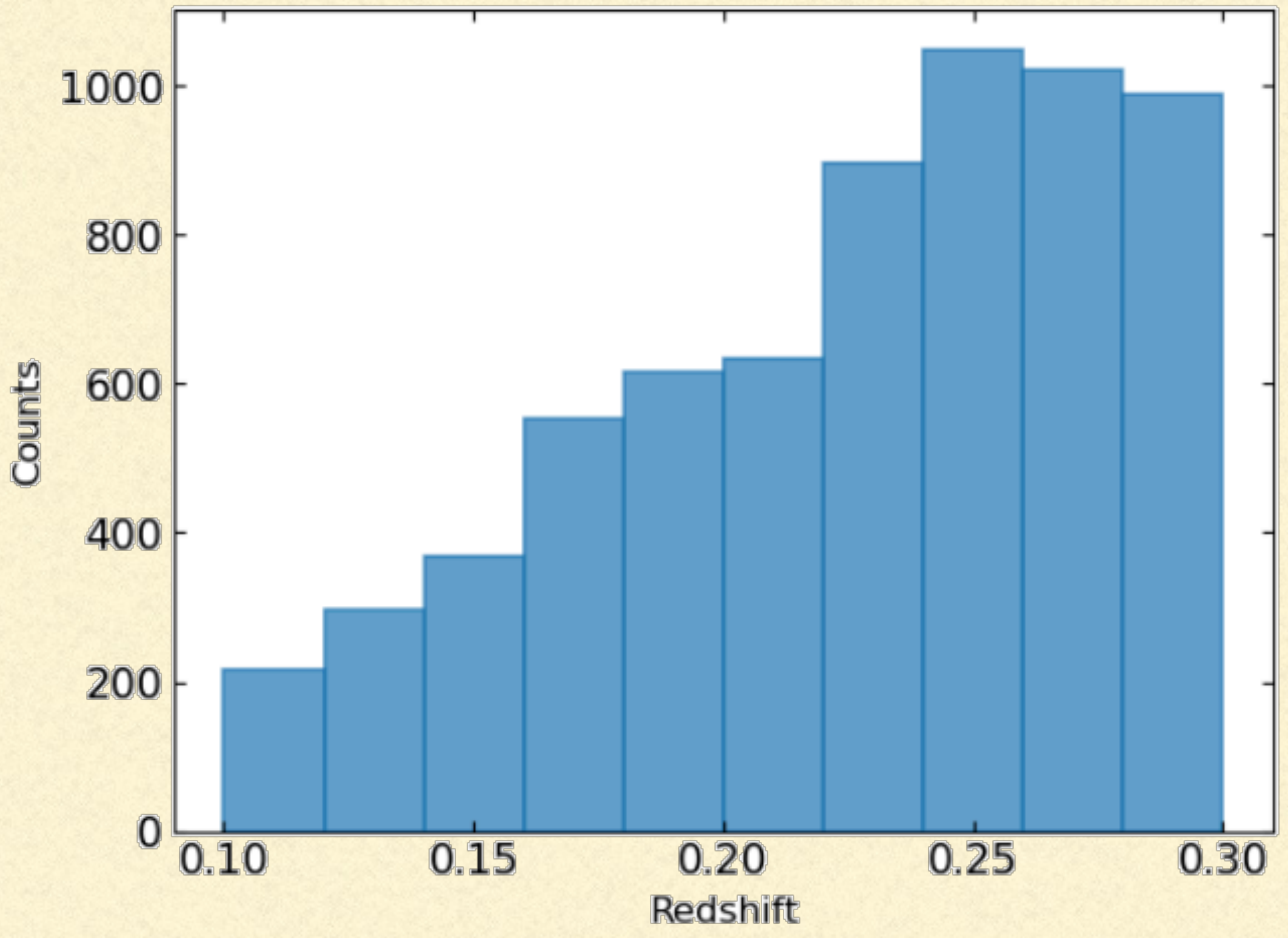
Cosmological constraints from abundance, weak-lensing and clustering of galaxy clusters: application to the SDSS, arXiv:2310.09146

A. Fumagalli, M. Costanzi, A. Saro, T. Castro, S. Borgani

DATASET

Data: redMaPPer cluster catalog (Rozo+15) from SDSS DR8 (Aihara+11)

- 6964 photometrically-selected clusters
- Sky area of 10 000 deg^2
- Richness range $\lambda \geq 20$
- Redshift range $z = 0.1 - 0.3$
- Photo-z uncertainty $\sigma_z/(1+z) \lesssim 0.01$
  ($\sigma_z \approx 0.005$ at $z = 0.15$ to $\sigma_z \approx 0.014$ at $z = 0.3$)



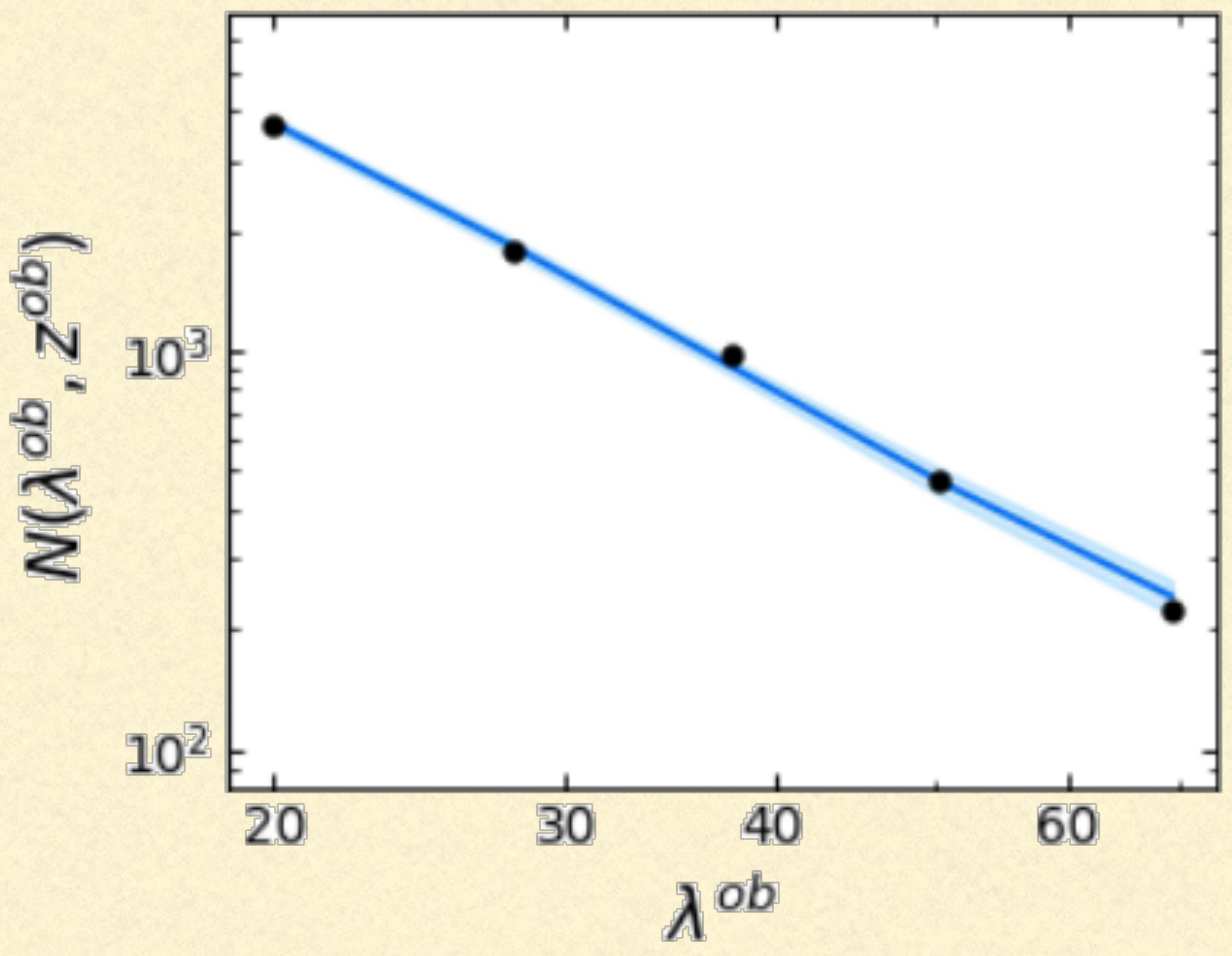
Stacked WL mass profiles from Simet+17

- ~39 million galaxies
- ~9000 deg^2 of SDSS footprint (Reyes+12) from SDSS DR8

COSMOLOGICAL PROBES

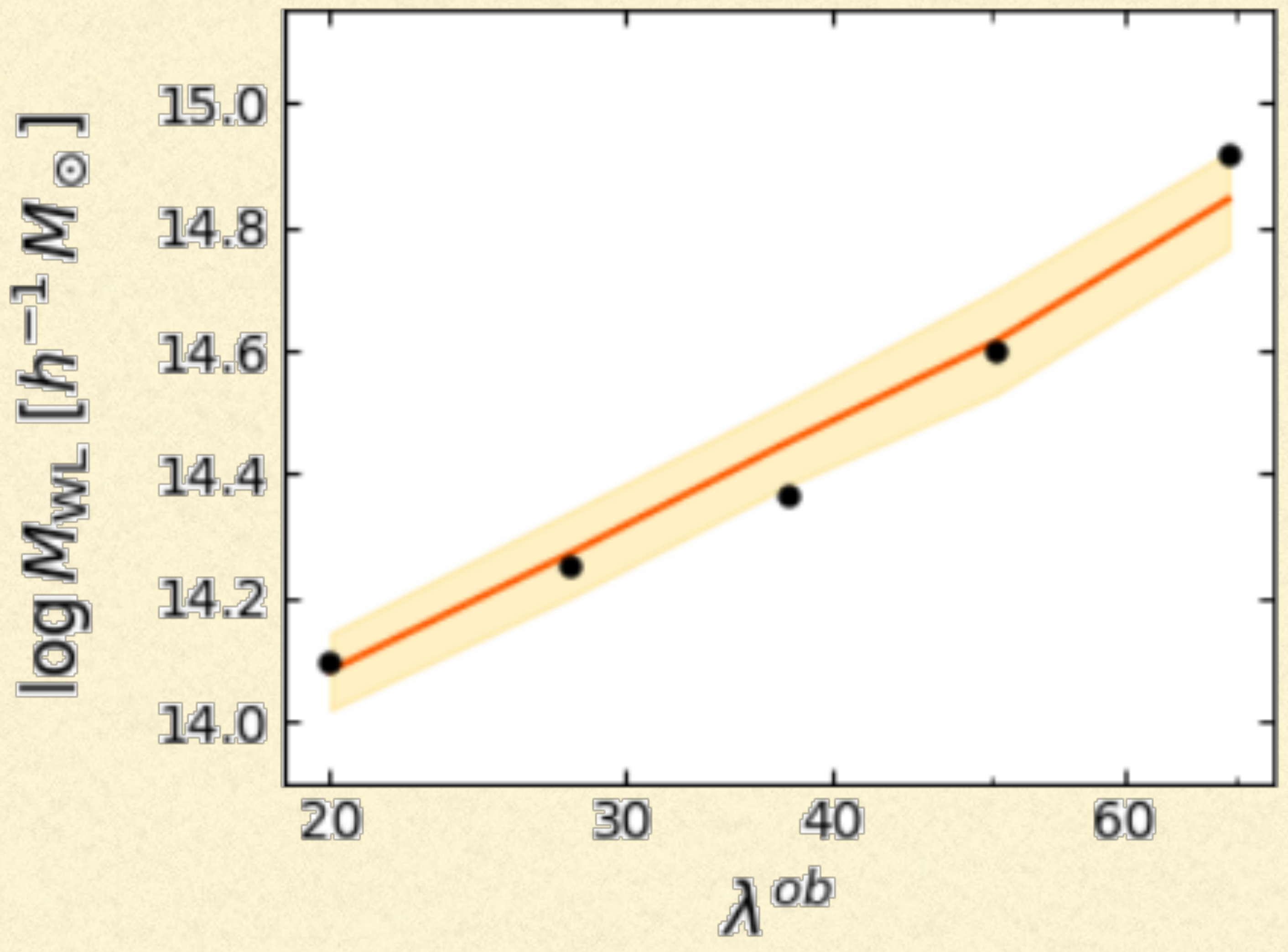
Cluster abundance

$$N(\Delta\lambda_j^{\mathrm{ob}}) = \int dz^{\mathrm{tr}}\, \Omega_{\mathrm{mask}}(z^{\mathrm{tr}})\, \frac{dV}{dz\, d\Omega}(z^{\mathrm{tr}}) \times \langle n(z^{\mathrm{tr}}, \Delta\lambda_j^{\mathrm{ob}})\rangle \int_{\Delta z} dz^{\mathrm{ob}} P(z^{\mathrm{ob}} \quad z^{\mathrm{tr}})$$



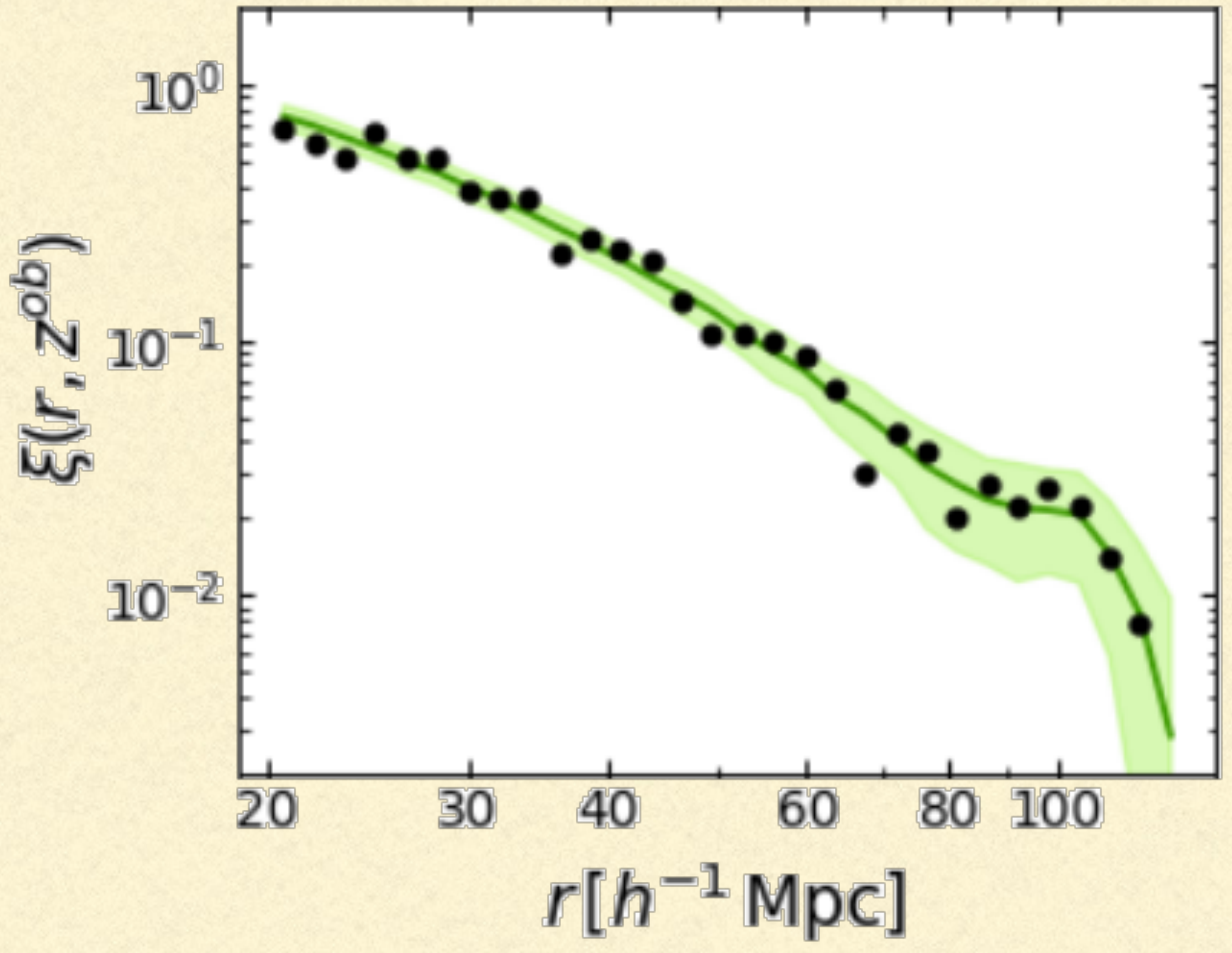
Weak lensing mass

$$\overline{M}(\Delta\lambda_j^{\mathrm{ob}}) = \frac{M^{\mathrm{tot}}(\Delta\lambda_j^{\mathrm{ob}})}{N(\Delta\lambda_j^{\mathrm{ob}})}$$



3D cluster clustering

$$\xi_{\mathrm{h}}(\Delta r_i) = \int \frac{\mathrm{d}k\, k^2}{2\pi^2} \left\langle \overline{b}^2 P_{\mathrm{m}}(k) \right\rangle_{\Delta_z} W_i(k)$$

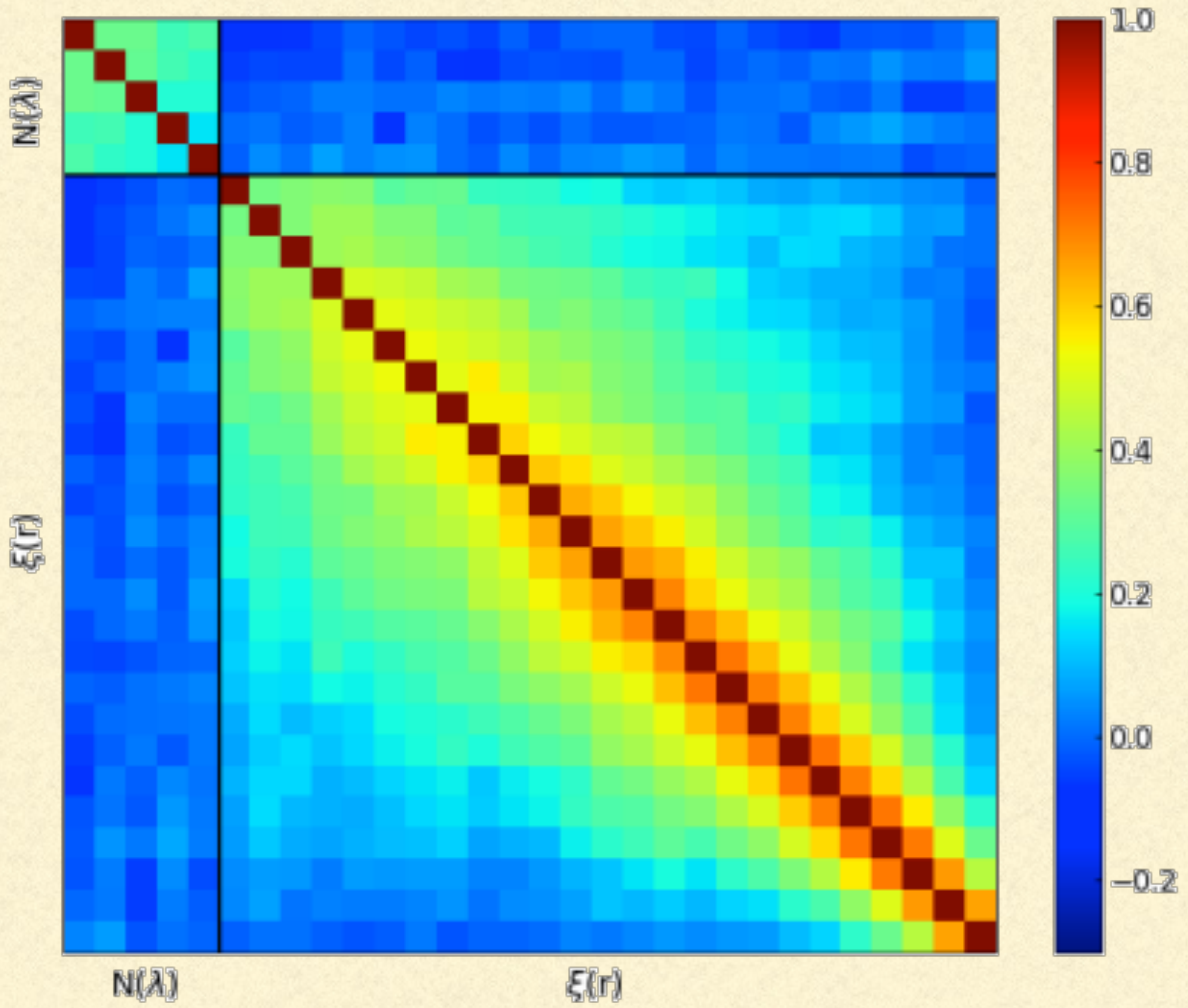


LIKELIHOOD SETUP

$$\mathcal{L}(\mathbf{d}|\,\boldsymbol{\theta}) = \frac{\exp\left\{-\frac{1}{2}[\mathbf{d}-\mathbf{m}(\boldsymbol{\theta})]^T C^{-1}[\mathbf{d}-\mathbf{m}(\boldsymbol{\theta})]\right\}}{\sqrt{(2\pi)^N |C|}}$$

Likelihood:

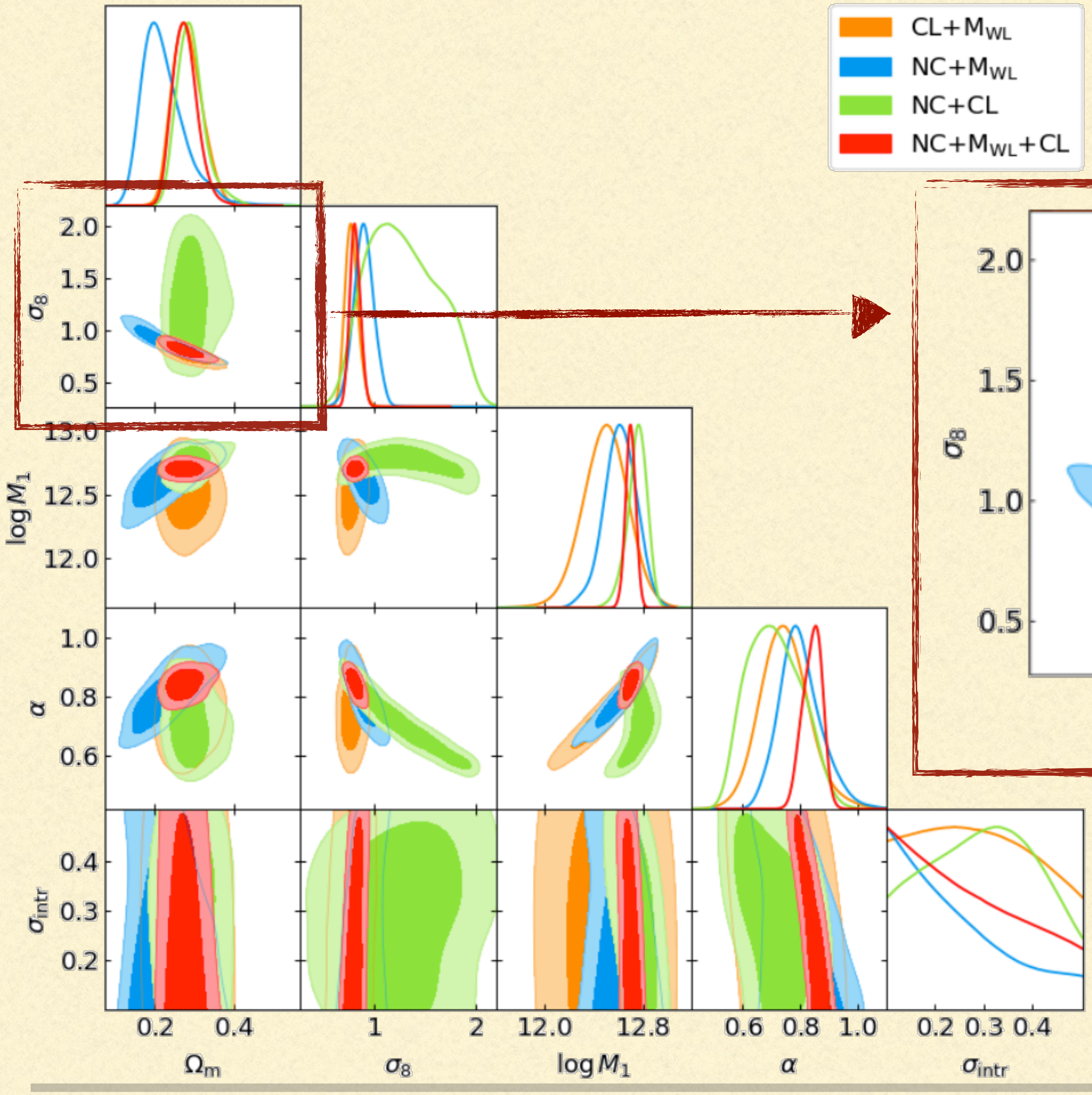
- Three **independent Gaussian likelihoods**
- Analytical **cosmo-dependent covariance** for counts (EC:Fumagalli+21)
- Analytical **cosmo-dependent covariance** for clustering (EC: Fumagalli+22)
- Numerical fixed covariance for WL masses (Costanzi+19)

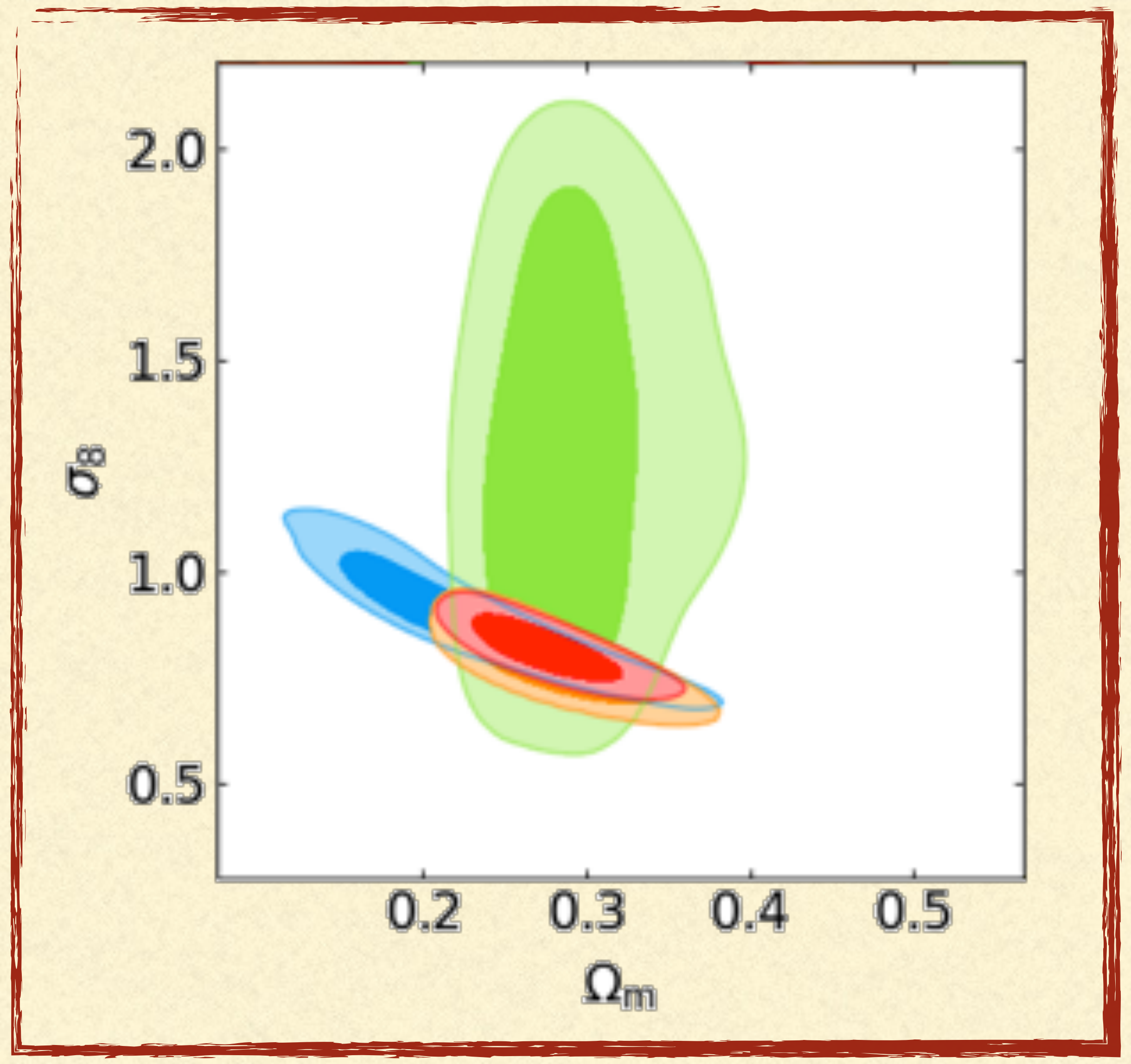


Free parameters:

- $\underbrace{\mathbf{\Omega_m, A_s\ (\sigma_8)}, h, \Omega_\nu h^2, \Omega_b h^2, n_s,}_{\text{cosmology}}$ $\underbrace{\alpha, M_1, M_{min}, \sigma_{intr},}_{\text{scaling relation}}$ $\underbrace{s_{hmf}, q_{hmf}}_{\text{model calibration}}$

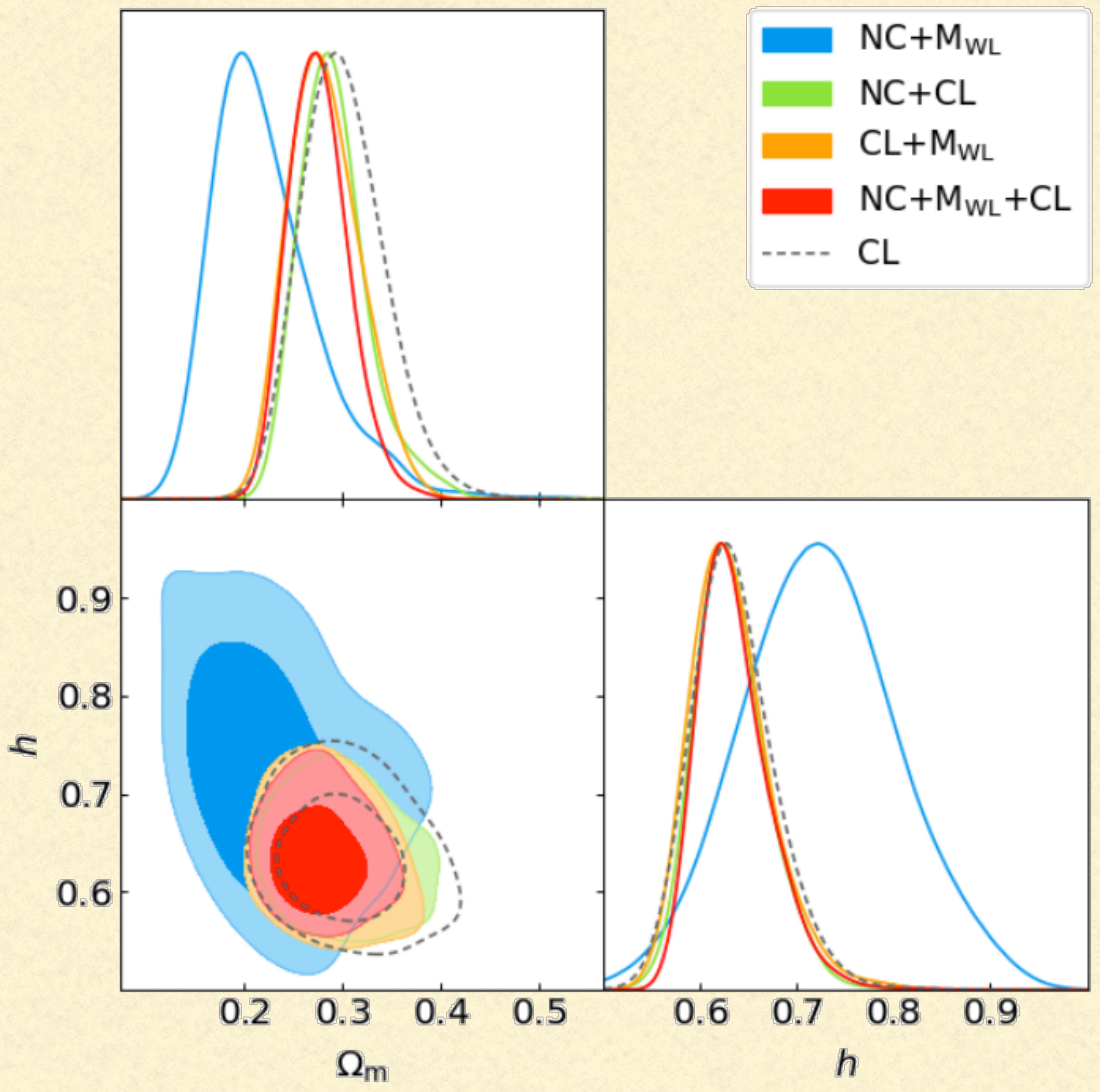
RESULTS: PARAMETER CONSTRAINTS





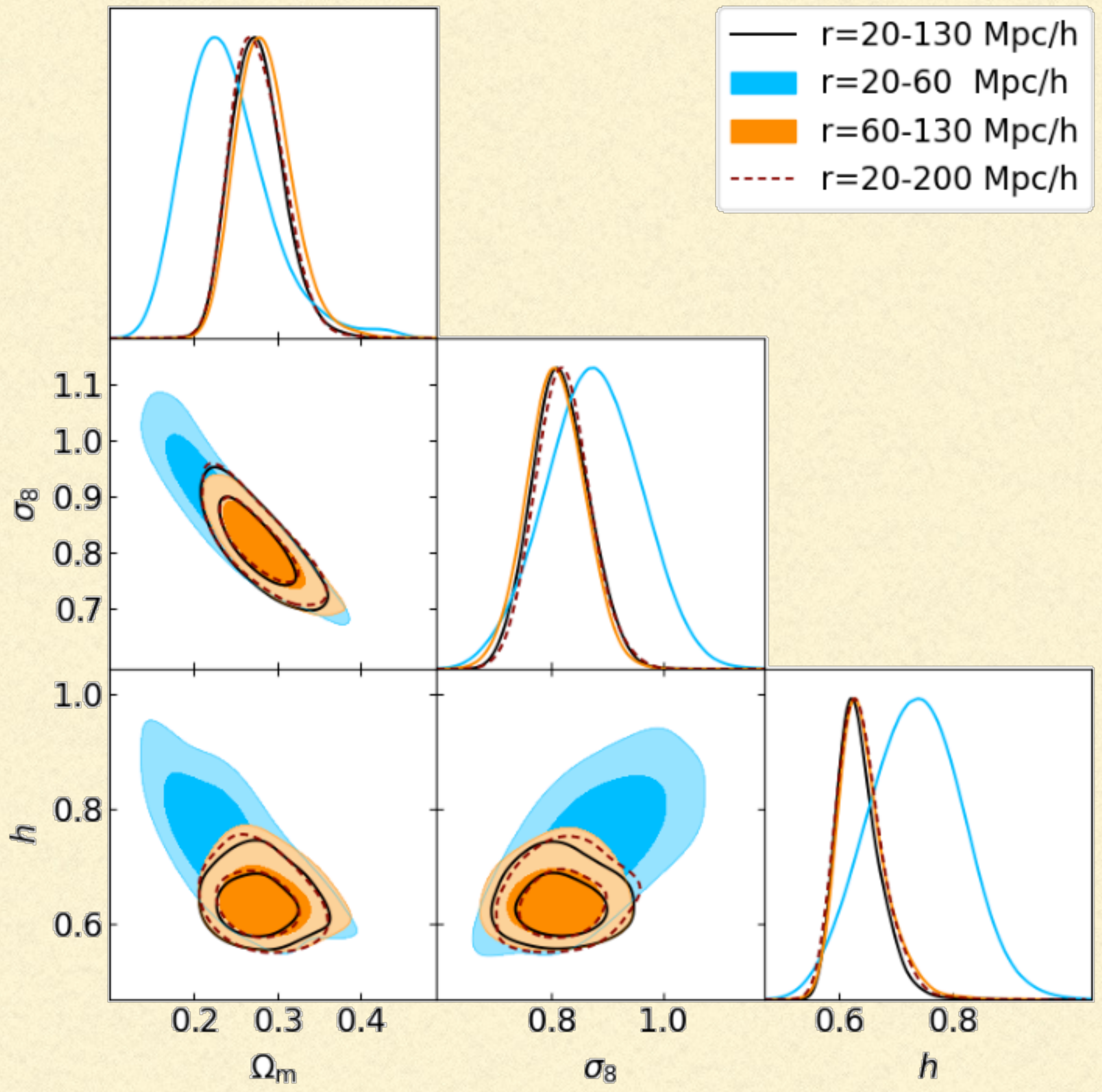
- CL helps to constrain Ω_m
- NC+CL don't constrain σ_8
- M_{WL}+CL better than NC+M_{WL}
- high improvement from NC+CL+M_{WL}

RESULTS: PARAMETER CONSTRAINTS

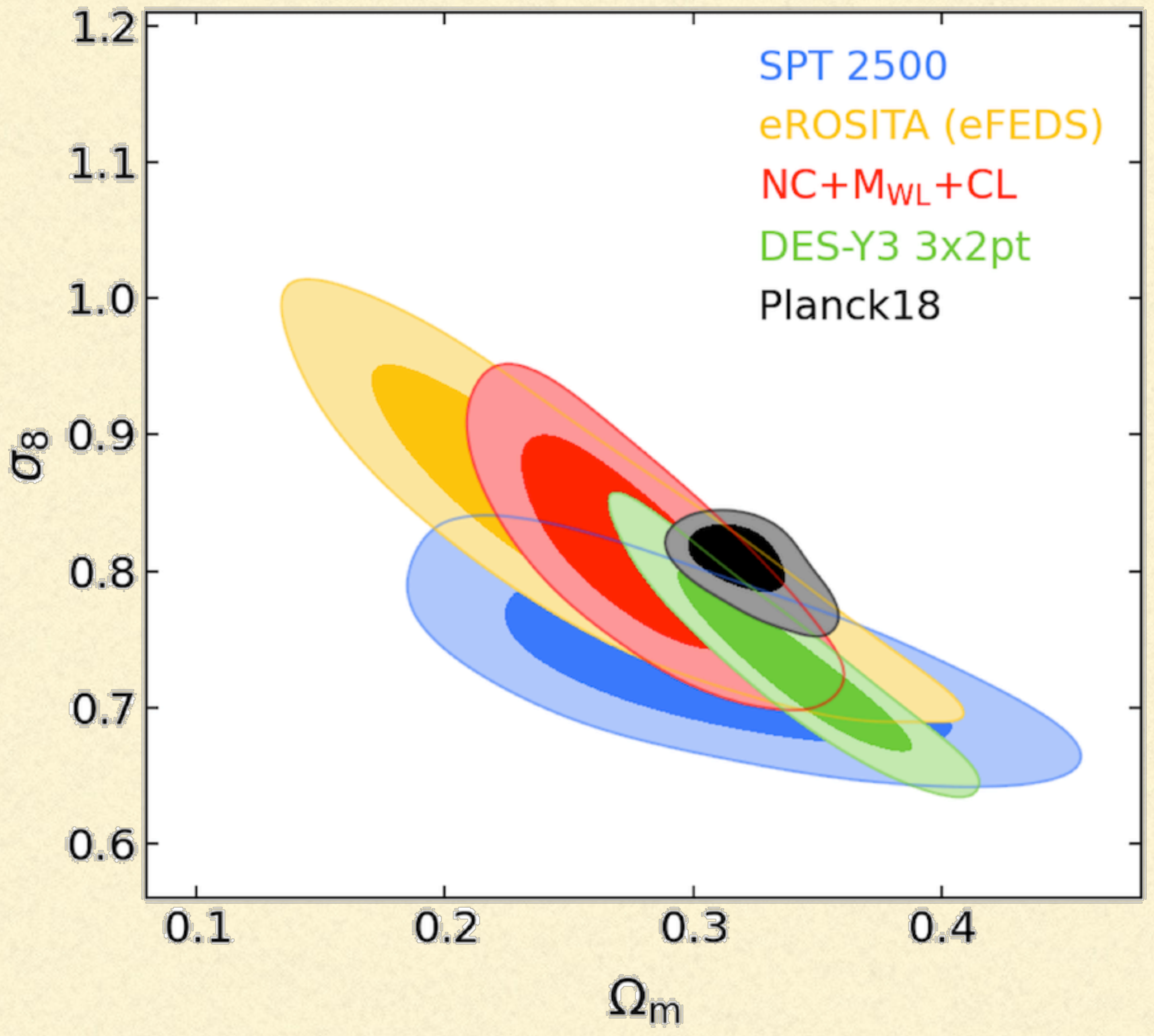


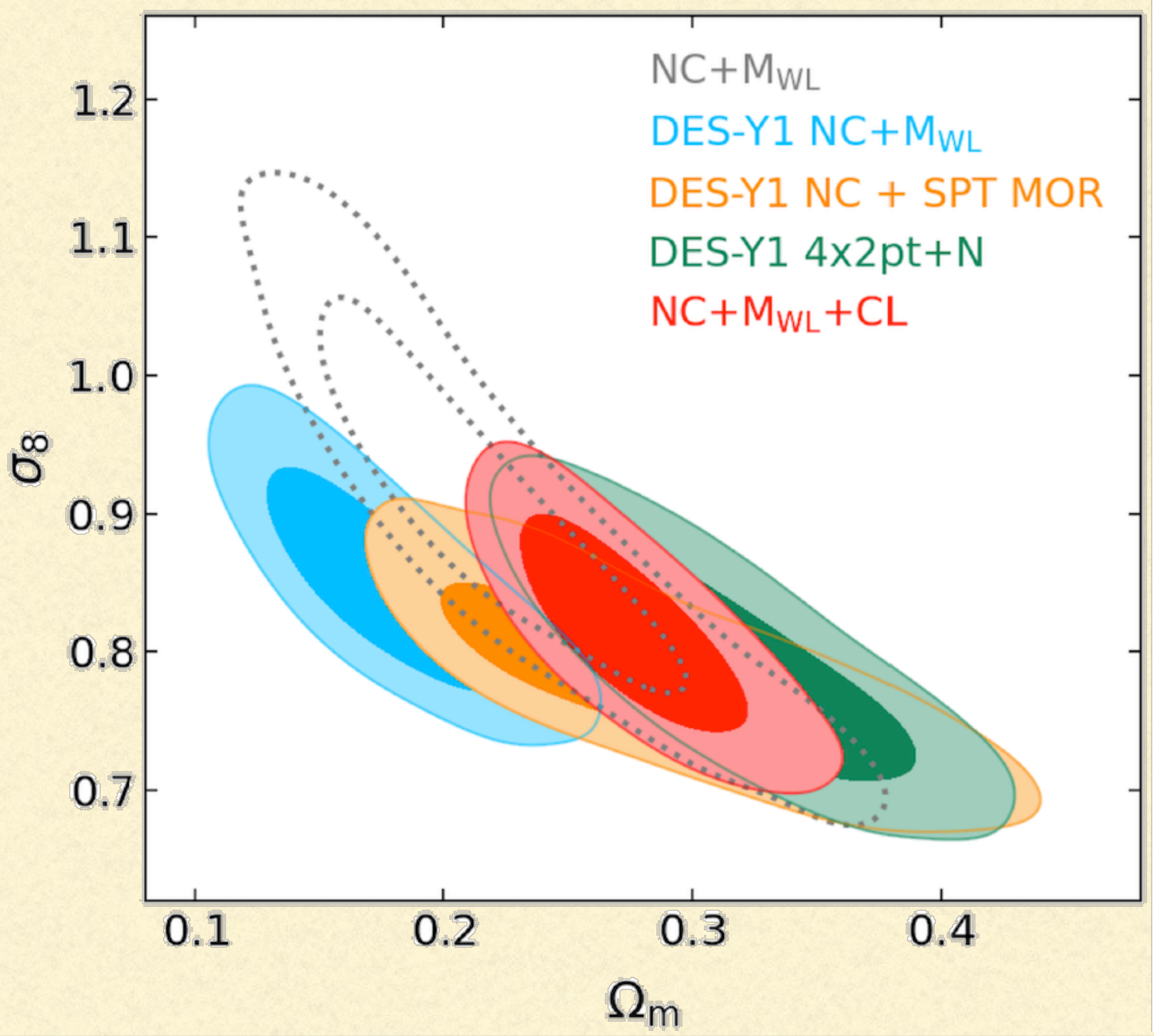
Cluster clustering helps to constraints the Hubble parameter (h = 0.64±0.04)

Information mainly from the BAO scales (~110 Mpc/h)



RESULTS: LITERATURE COMPARISON





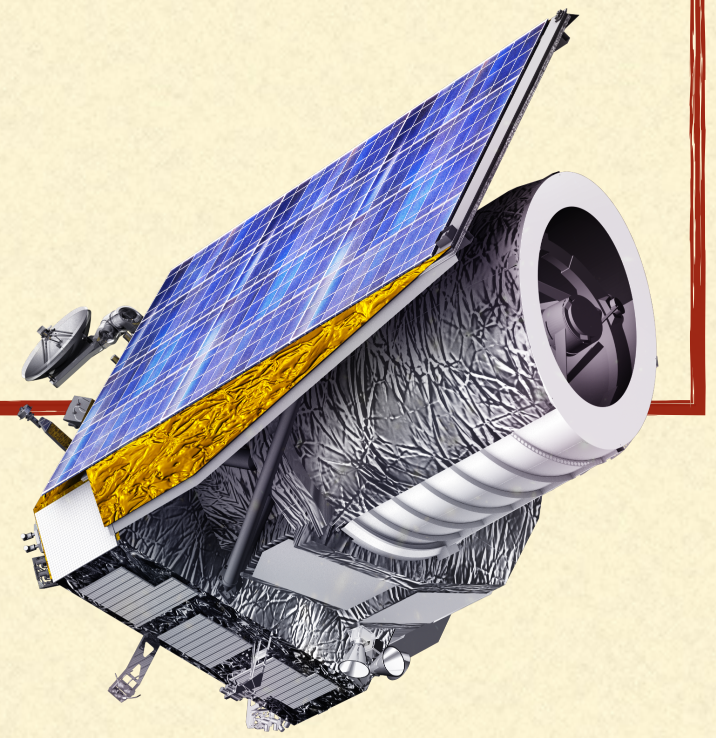
- Consistent with other cluster and non-cluster surveys
- Tension with DES-Y1 NC+M_{WL} (different WL modelling ⇒different scaling relation)
- Competitive constraining power
- Tighter than DES-Y1 4x2pt (different CL and WL scales)

CONCLUSIONS

- Cluster clustering helps to constrain **cosmological parameters** (mainly Ω_m) and **scaling relations**, already from currently available catalogs (e.g. SDSS)
- Constraints from cluster cosmology including cluster clustering are **competitive** with other cosmological probes
- **Future surveys** (Euclid, LSST, …) will allow us to better exploit cluster clustering information (redshift/richness binning, lower photo-z uncertainties,..)
- More information can be extracted by extending the analysis to **quadrupole and hexadecapole** and/or **higher-order statistics**

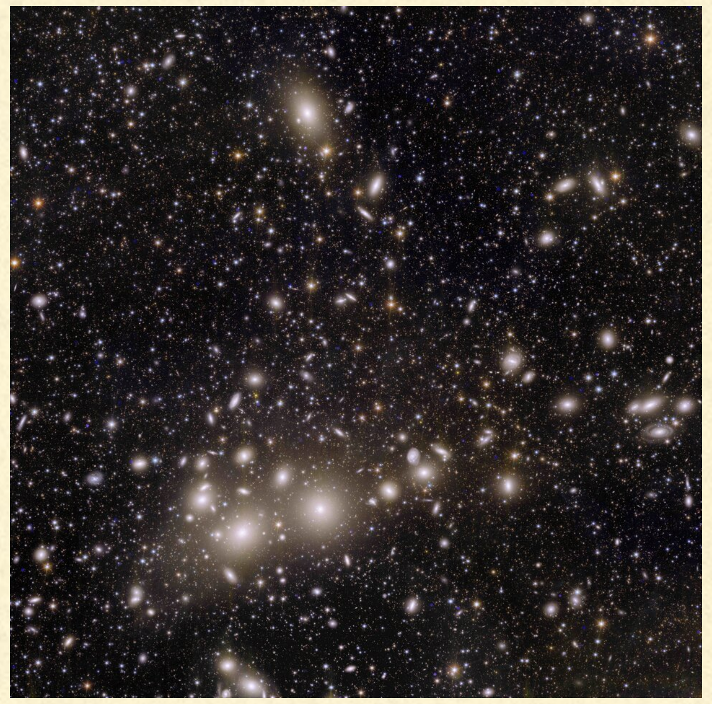
BACKUP SLIDES

EUCLID

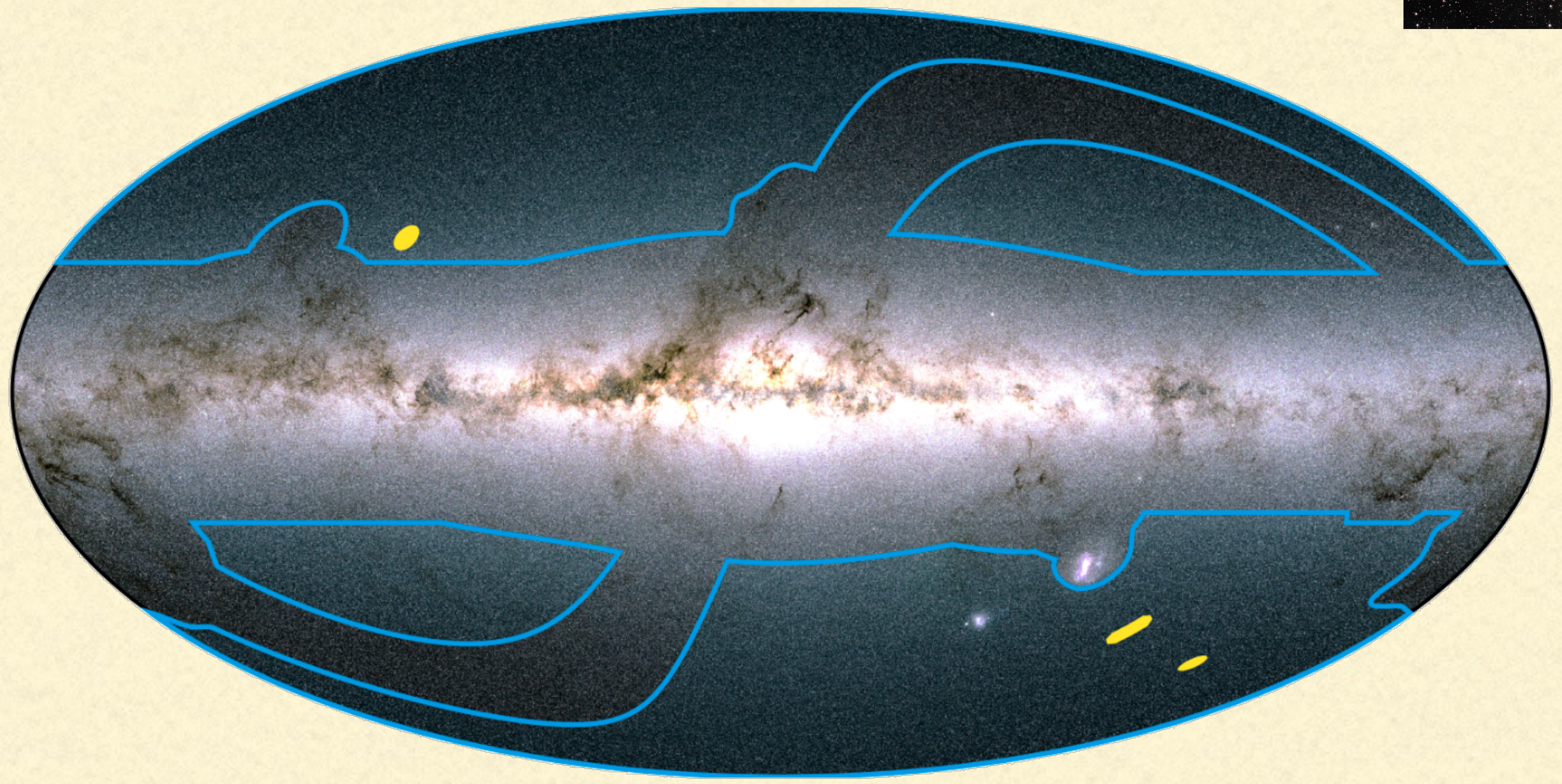


- **Visible/near-infrared** space telescope by the European Space Agency (**ESA**)
- Launched on July 1, 2023
- Two major surveys:
  - **Euclid Wide Survey**: 15 000 deg^2 of the extra-galactic sky
  - Euclid Deep Survey: ~53 deg^2 split over three fields
- Primary probes: weak lensing and galaxy clustering

Secondary probes: **galaxy clusters**, strong lensing, …



- Redshift range z = 0.2 - 2
- Mass range $M > 1.0 \times 10^{14}\ M_\odot$
- Number of clusters $\gtrsim 10^5$
- Cluster detected via photometric data, spectroscopic data, weak gravitational lensing



SIMULATIONS

Covariance matrices requires **large sets of simulations (~10^3)**:

- not feasible with N-body simulations due to high computational costs
- approximate methods: less accurate but faster

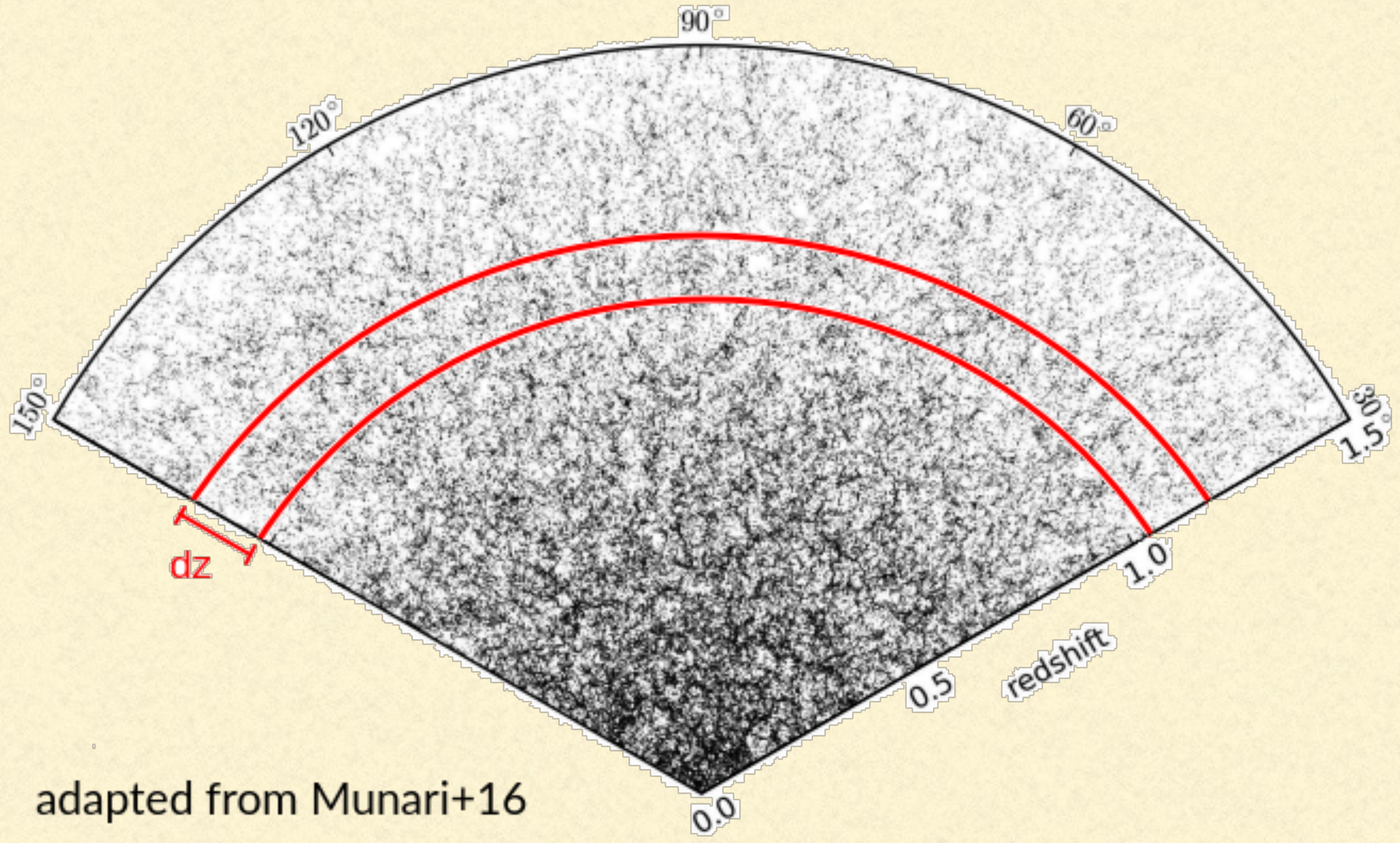
In this work (Euclid Collaboration: Fumagalli+22):

dark matter halo catalogs from cosmological simulations generated with LPT-based methods by the **PINOCCHIO** algorithm

↓

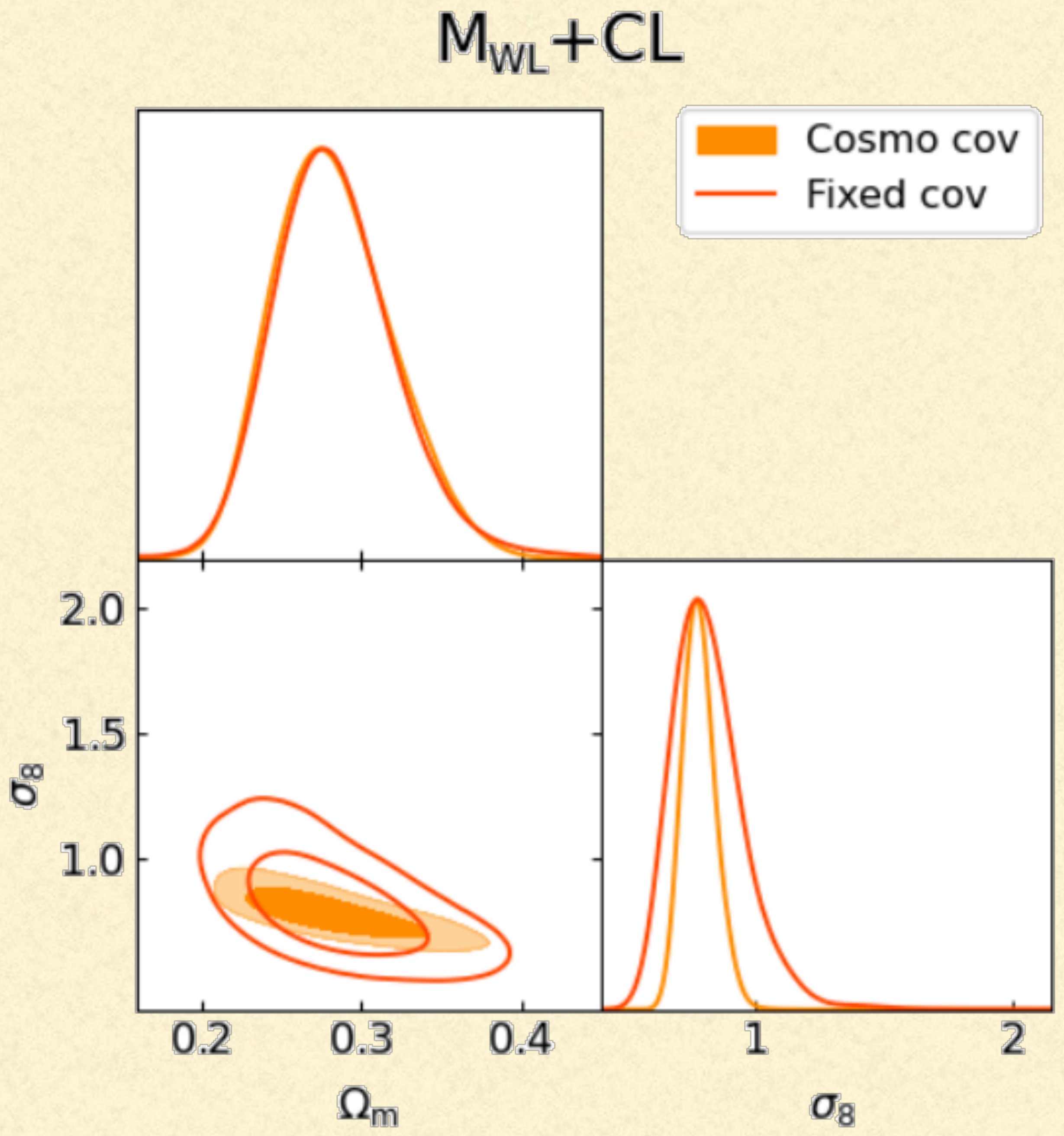
1000 Euclid-like lightcones with

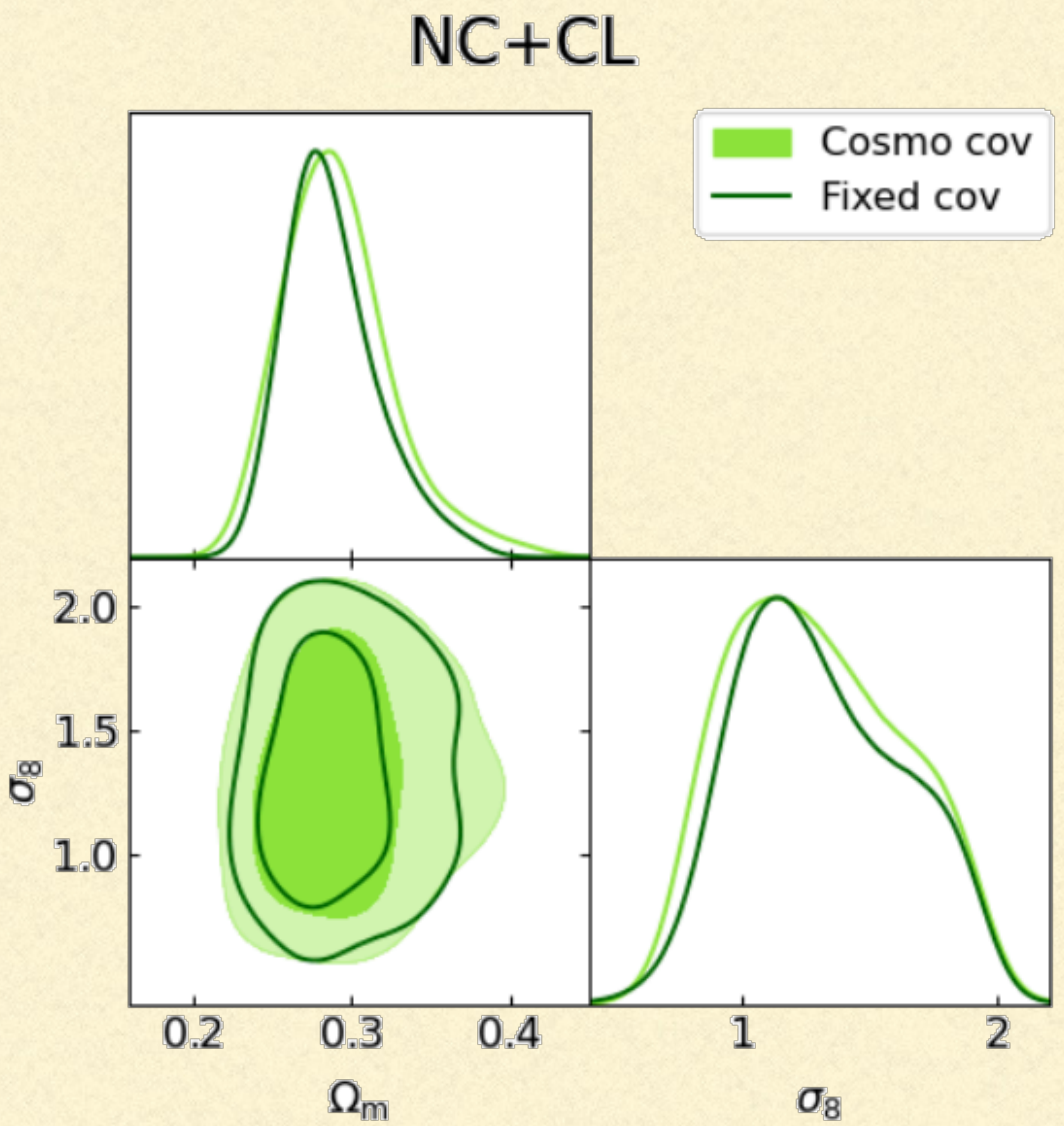
- Redshift range z = 0 − 2
- Mass range $M_{vir} \geq 5 \times 10^{13}\ M_\odot/h$
- Number of objects ~3×10^5

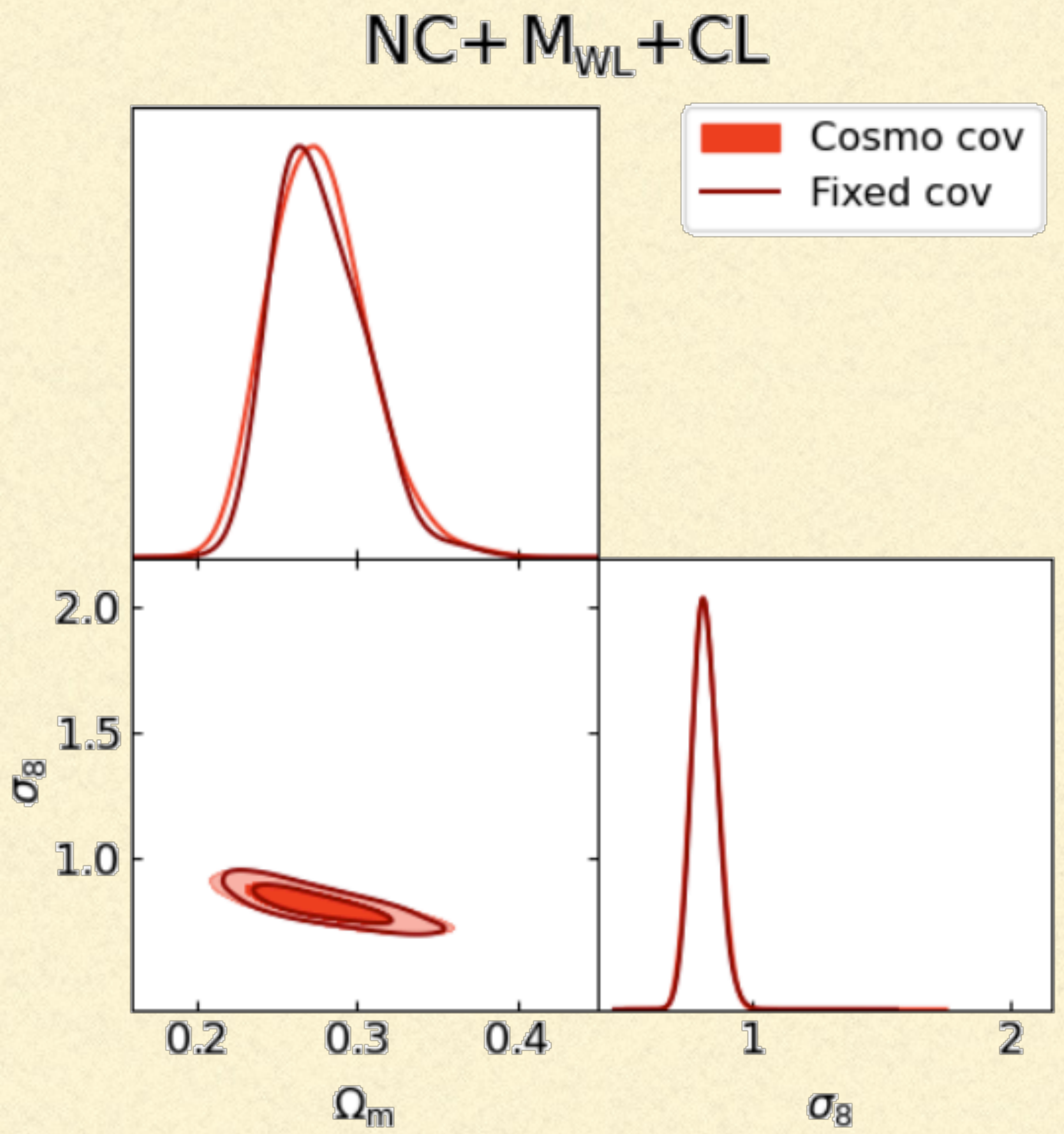


adapted from Munari+16

RESULTS: COSMO-DEPENDENT COVARIANCE







- ~ 100% improvement
- Information from shot-noise (integrated HMF)
- Only brings information on σ_8

- No difference between fixed and cosmo-dep covariance
- Information already extracted from number counts data
- No further tightening (= no double count of information)