Simulation-Based Cosmological Mass Calibration of XXL Galaxy Clusters using HSC Weak Lensing

Sut-Ieng Tam 譚雪瑩 (National Yang Ming Chiao Tung University; NYCU)

Cluster Cosmology Inference

X-ray/Optical Observables → Cluster number counts; Cluster mass calibration (weak-lensing)

Bayesian Inference → Cosmological parameters (Ω_m, σ_8)

Intractable likelihood

Likelihood

Prior

Posterior (likely parameters given data)

$$p(\theta|d) = \frac{p(d|\theta)p(\theta)}{p(d)}$$

$$d = m(\theta) + n$$

Noise

Signal (model)

Simulation-based Inference: bypasses the need for an explicit likelihood. Instead, it relies on forward simulations and machine learning to learn the posterior:

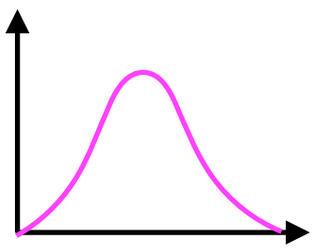
$$p(\theta \mid d) \approx \text{Neural Density Estimator (NDE)}$$

Simulation-based Inference

masked autoregressive flow (MAF)
+ mixture density network (MDN)

Simulator/
Forward Model

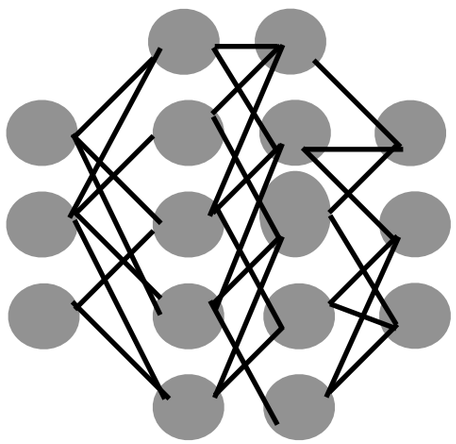
Prior



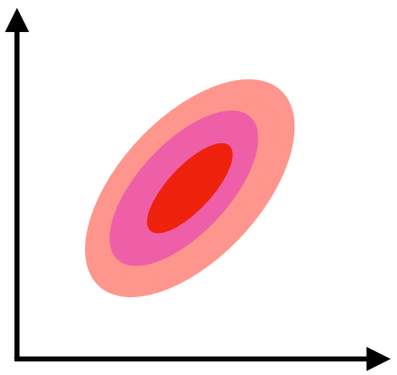
Observed
Data

Simulated
Data

Neural Network

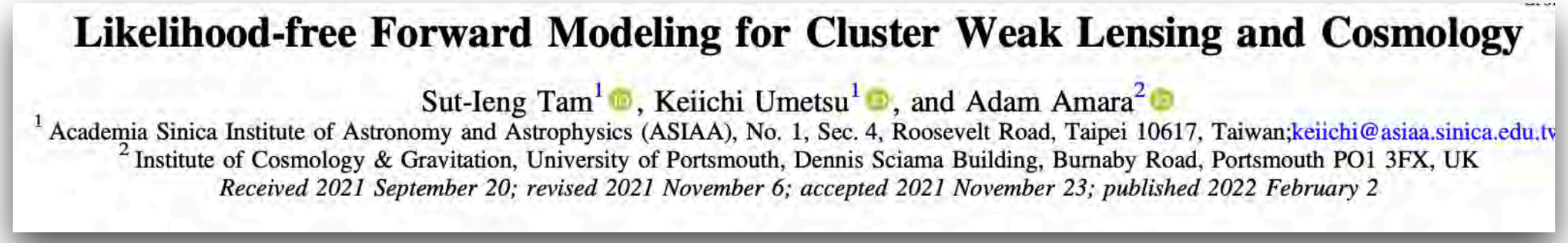


Posterior
Distribution



Generate new sims

Advantages: Forward model—> more flexible and complex for cluster modeling
—> no need to calculate the complex covariance matrix
—> no assumption of the functional form of the likelihood



Likelihood-free Forward Modeling for Cluster Weak Lensing and Cosmology

Sut-Ieng Tam[1], Keiichi Umetsu[1], and Adam Amara[2]
[1] Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan;keiichi@asiaa.sinica.edu.tw
[2] Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth PO1 3FX, UK
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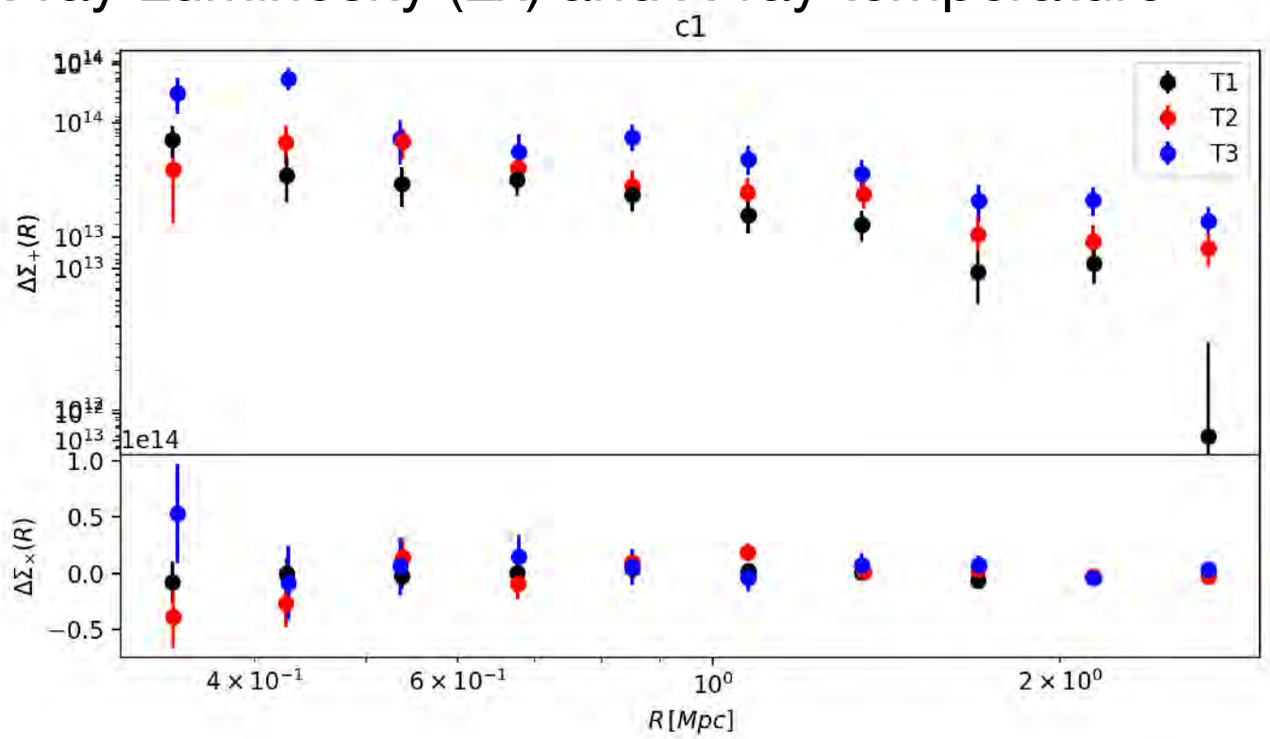
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Sut-Ieng Tam,[1] Keiichi Umetsu,[2] Adam Amara,[3] Dominique Eckert,[4] Manon Regamey,[4] I-Non Chiu,[5] Sunayana Bhargava,[6] Christian Garrel,[7] Fabio Gastaldello,[8] Elias Koulouridis,[9] Ben Maughan,[10] Mauro Sereno,[11] Marguerite Pierre,[6] XXL team, and HSC team

Goal: Extend the forward model for weak lensing mass calibration for the galaxy clusters in XMM-XXL survey, using blind HSC weak lensing catalogue —> constrain the X-ray observables - cluster mass scaling relation

Data

- spectroscopically confirmed X-ray-selected systems from XMM-XXL survey
- select XXL clusters that overlap with the HSC survey in its HSC-XMM field.
- A total of 86 XXL-c1 clusters with spectroscopic confirmation + WL.
- Blind weak lensing catalogue from HSC —Unblinded in Feb 2025
- XXL DR2 cluster catalog including X-ray Luminosity (Lx) and X-ray temperature (Tx)



Forward Modeling

$$\frac{T_{300\,\mathrm{kpc}}}{T_{\mathrm{piv}}} = \alpha_{T-M} \left(\frac{M_{500}}{M_{\mathrm{piv}}}\right)^{\beta_{T-M}} \left(\frac{E(z)}{E(z=0.3)}\right)^{\gamma_{T-M}}, \tag{26}$$

$$\frac{L_{500}}{L_{\mathrm{piv}}} = \alpha_{L-T} \left(\frac{T_{300\,\mathrm{kpc}}}{T_{\mathrm{piv}}}\right)^{\beta_{L\ T}} \left(\frac{E(z)}{E(z=0.3)}\right)^{\gamma_{L\ T}}, \tag{27}$$

Cosmology (Ω_m, σ_8)

↓

Halo mass function + **Observables - mass scaling relations** + **Cluster halo model**

NFW

↓

Creation of synthetic clusters (M_{500}, c_{500}, $T_{300\,kpc}$, L_{500}, r_c) + **Survey selection function**

↓

Observable selected clusters

↓

Implementation of weak-lensing (WL) mass bias

$$M_{500}^{\mathrm{WL}}/M_{500} = a \tanh M_{500}/b + c.$$

↓

Creation of synthetic WL signals

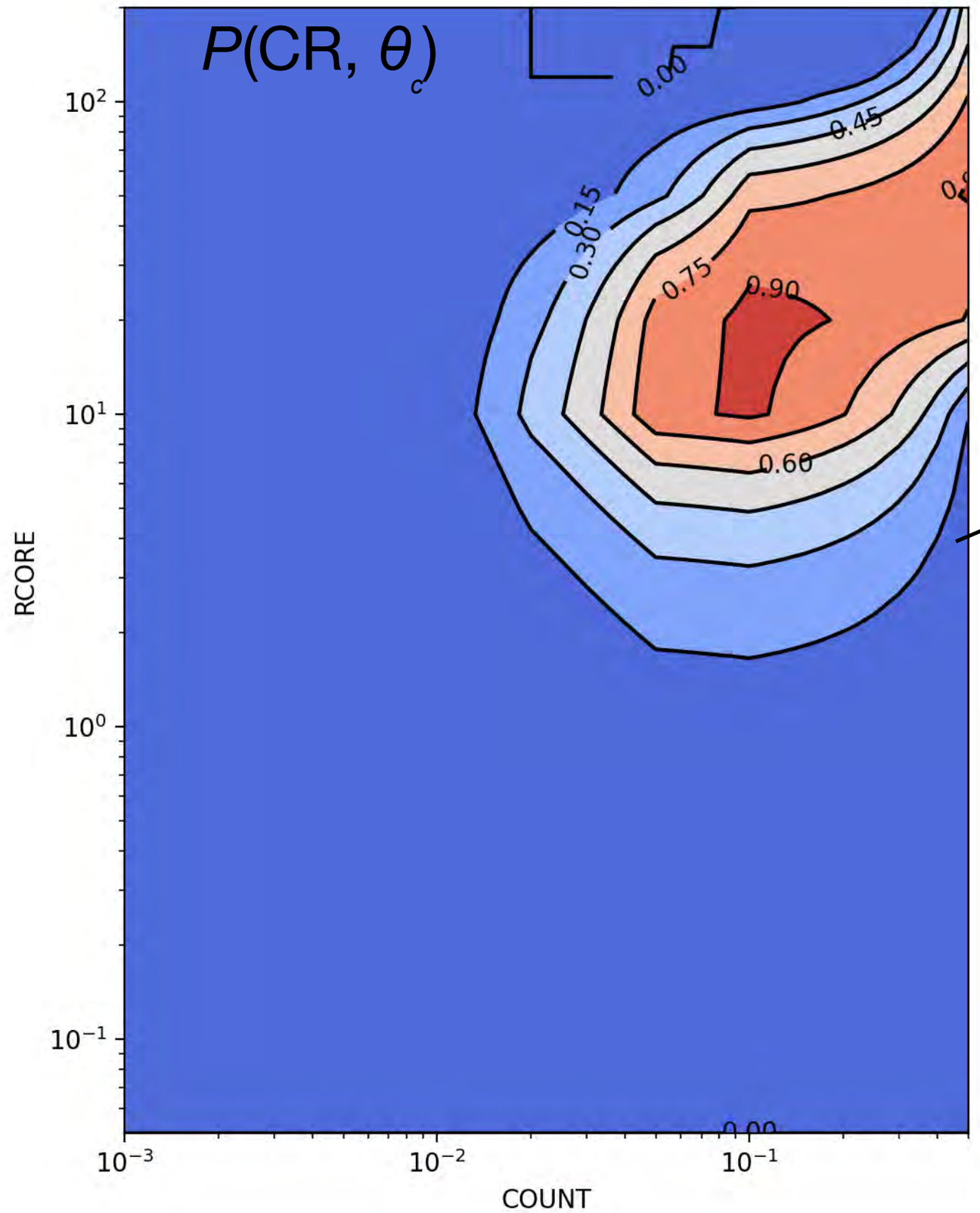
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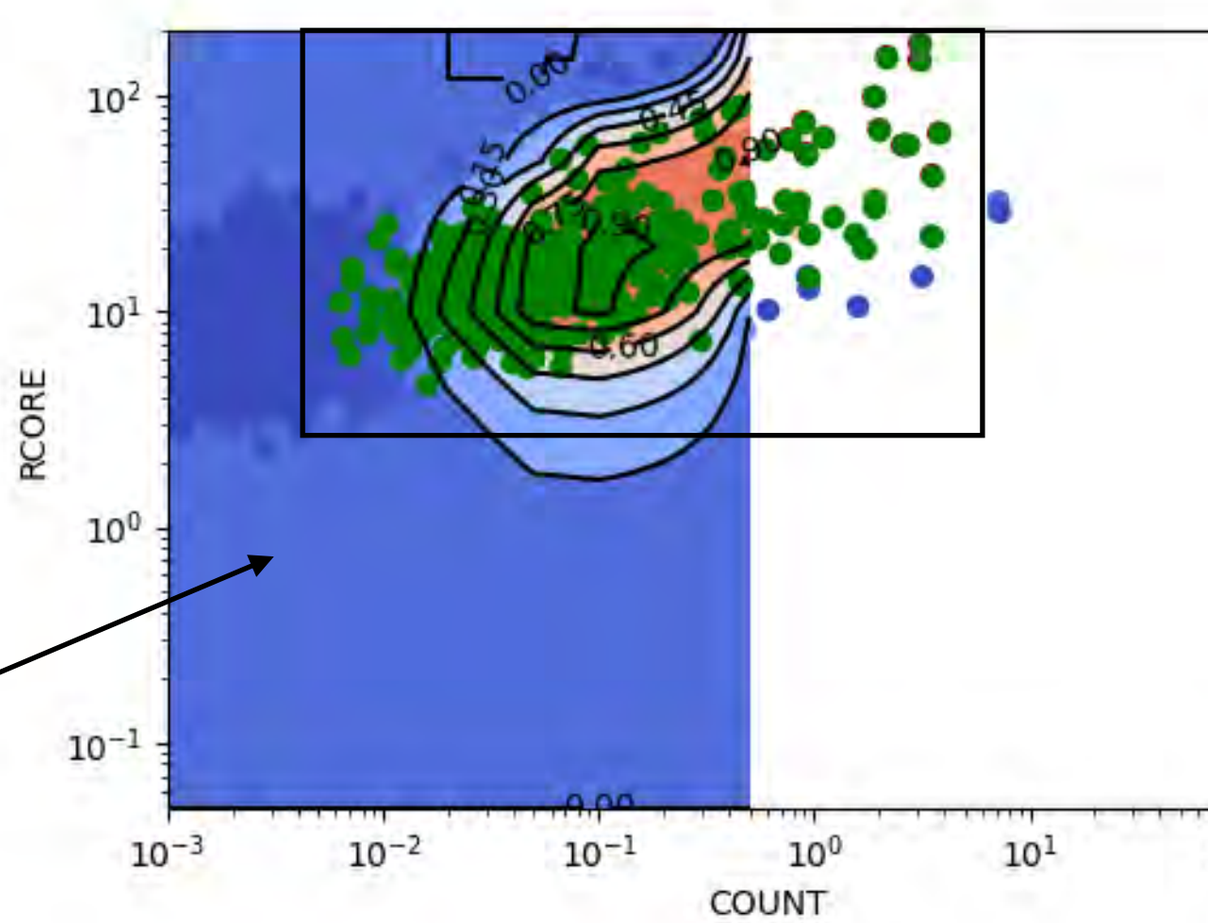
Implementation of miscentering effect, photo-z bias, shape noise, cosmic noise due to LSS

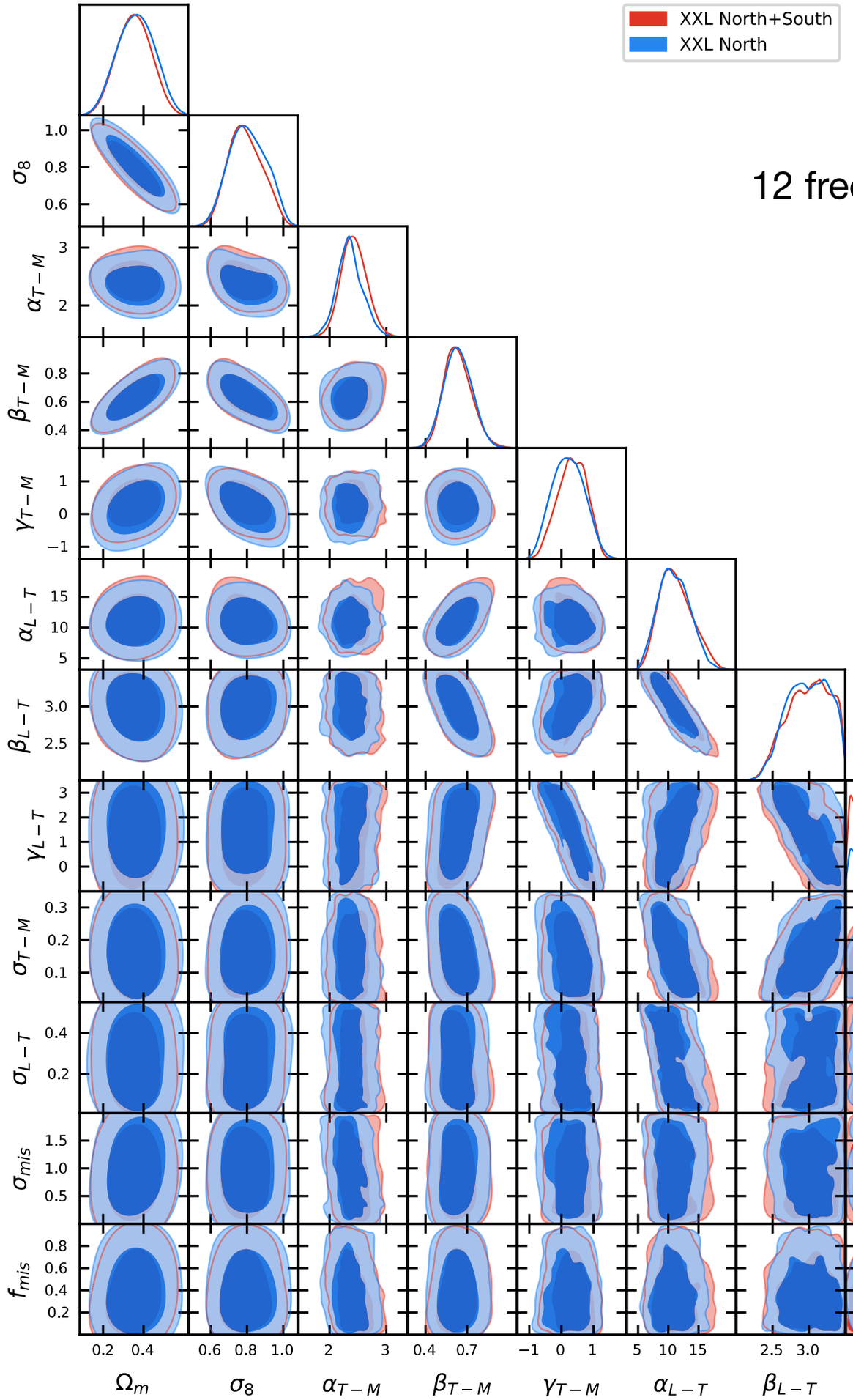
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Summary statistics: cluster number counts, stacked WL signals, distribution of $T_{300\,kpc}$, L_{500}

XXL Survey Selection Function







12 free parameters:

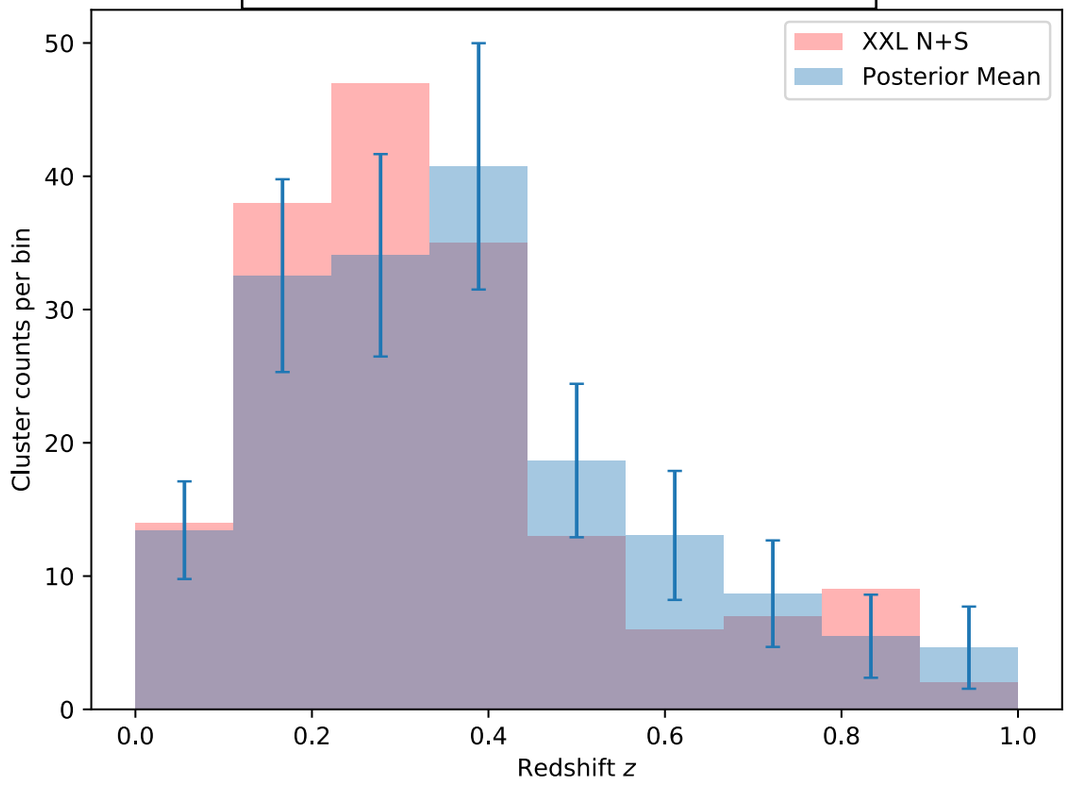
$$\boldsymbol{p} = \{\Omega_m, \sigma_8, \alpha_{T-M}, \beta_{T-M}, \gamma_{T-M}, \alpha_{L-T}, \beta_{L-T}, \gamma_{L-T}, \sigma_{T-M}, \sigma_{L-T}, f_{\rm mis}, \sigma_{\rm mis}\}.$$

$$\frac{T_{300\,\rm kpc}}{T_{\rm piv}} = \alpha_{T-M} \left(\frac{M_{500}}{M_{\rm piv}}\right)^{\beta_{T-M}} \left(\frac{E(z)}{E(z=0.3)}\right)^{\gamma_{T-M}}, \tag{26}$$

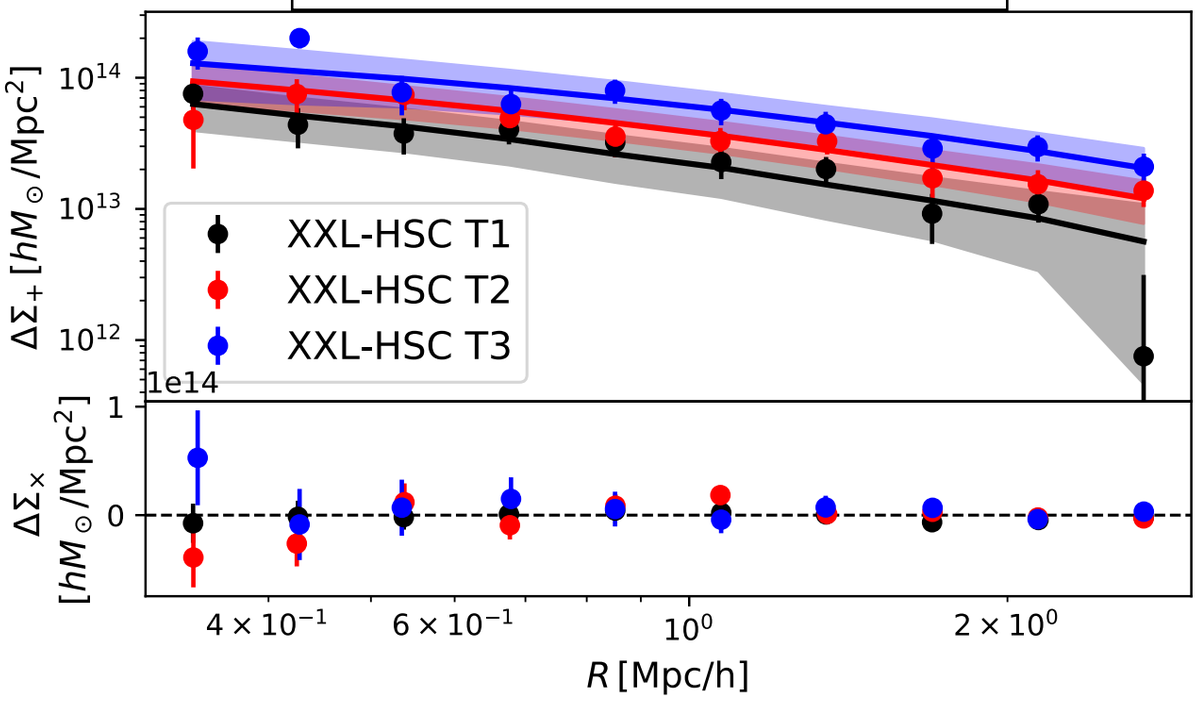
$$\frac{L_{500}}{L_{\rm piv}} = \alpha_{L-T} \left(\frac{T_{300\,\rm kpc}}{T_{\rm piv}}\right)^{\beta_{L-T}} \left(\frac{E(z)}{E(z=0.3)}\right)^{\gamma_{L-T}}, \tag{27}$$

Optimal summary statistics

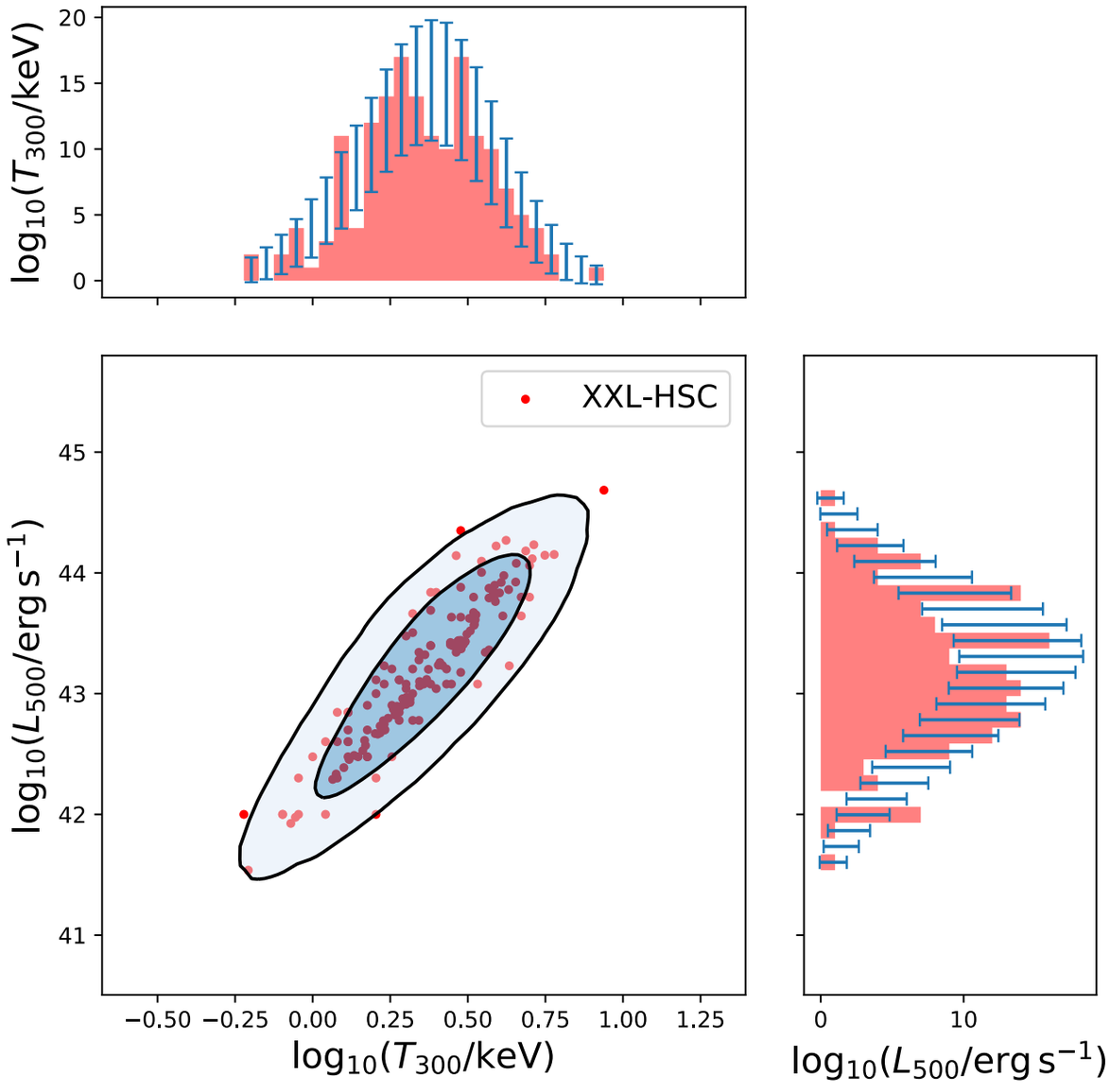
Cluster abundance Ncl(z)



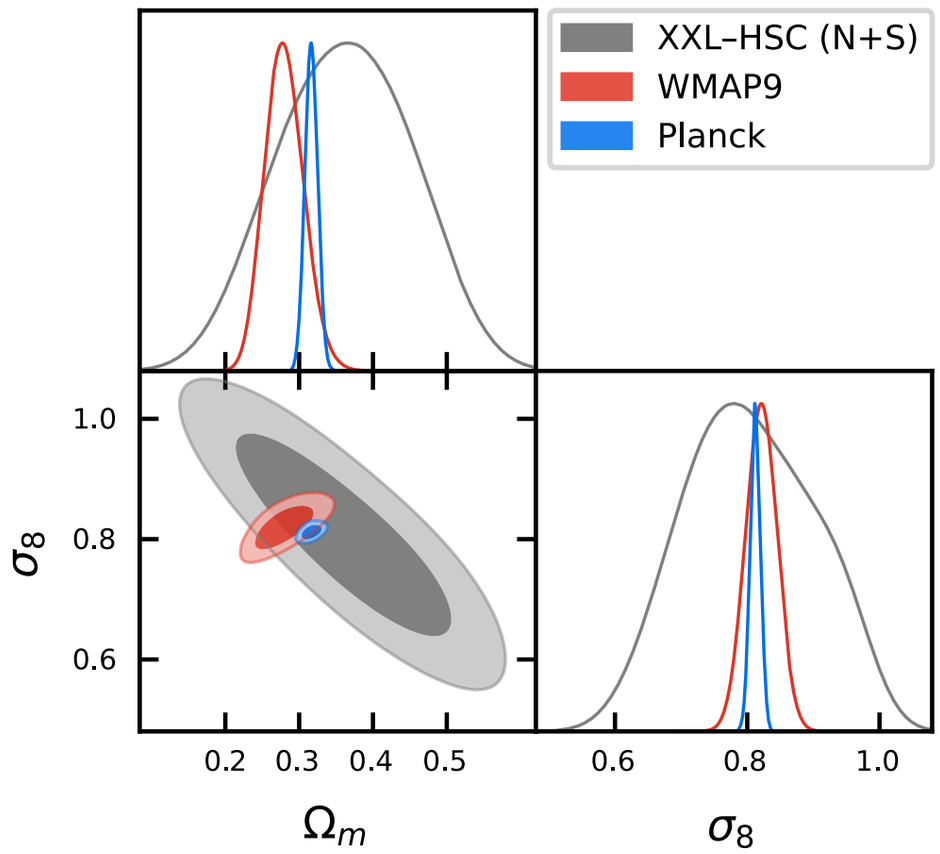
Stacked weak lensing profile



X-ray temperature/ luminosity distribution



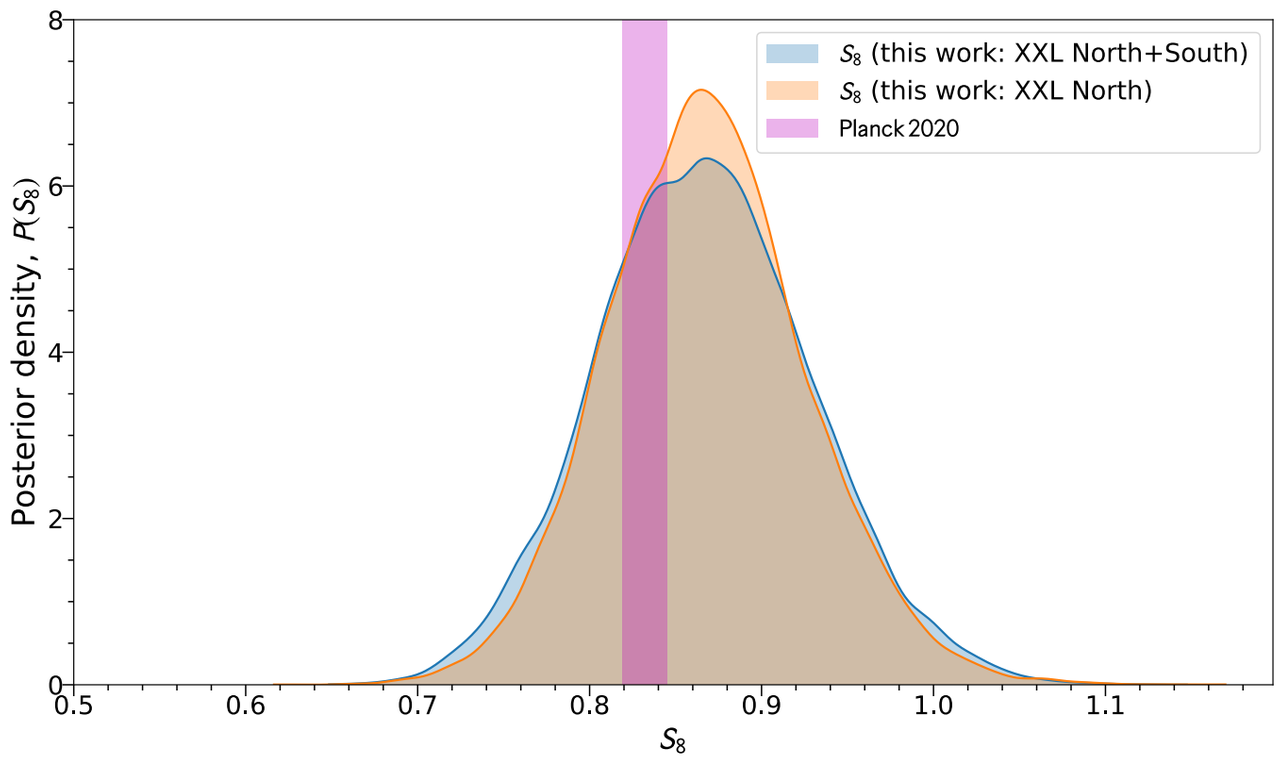
Cosmological Constraints



$$\Omega_m = 0.366 \pm 0.091$$

$$\sigma_8 = 0.80 \pm 0.10$$

$$S_8 = \sigma_8(\Omega_{\rm m}/0.3)^{0.5} = 0.867 \pm 0.063$$

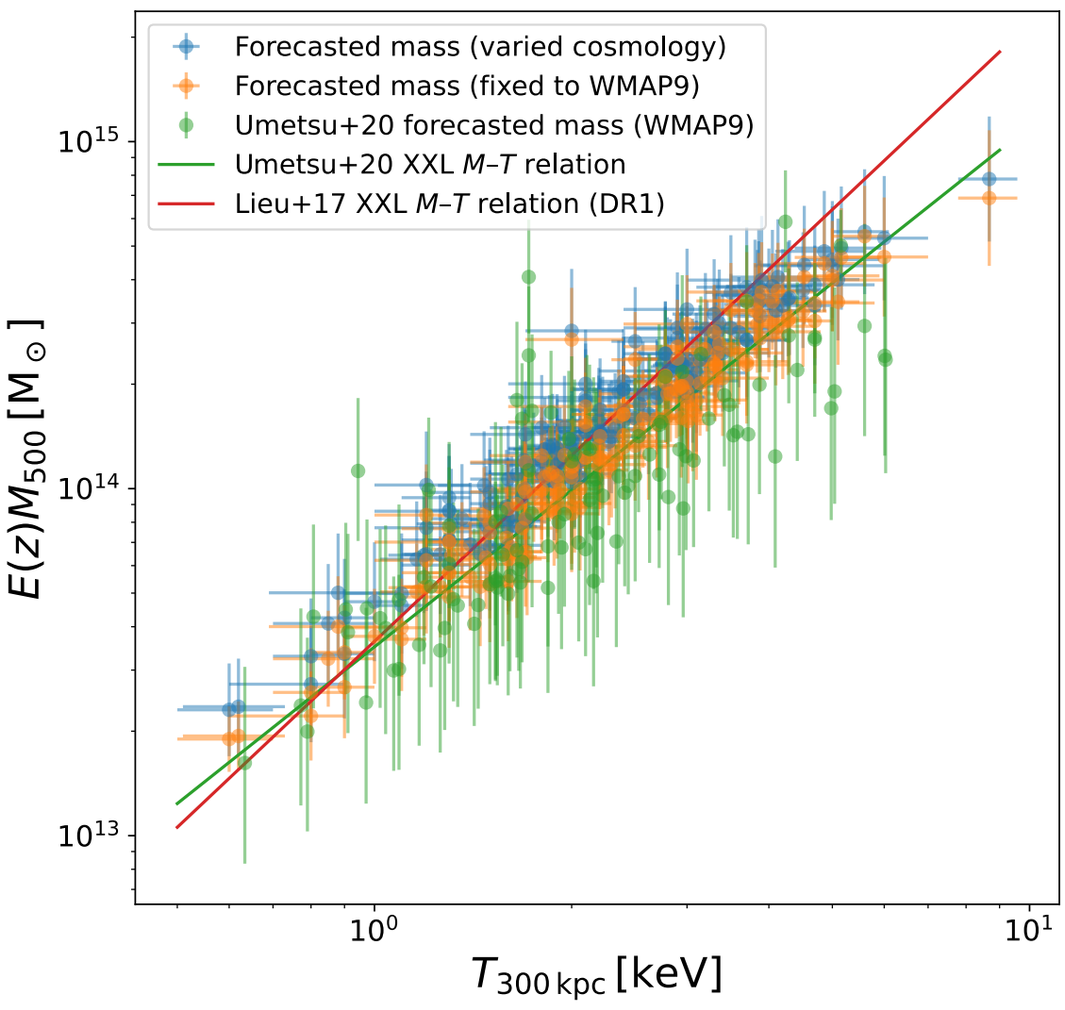


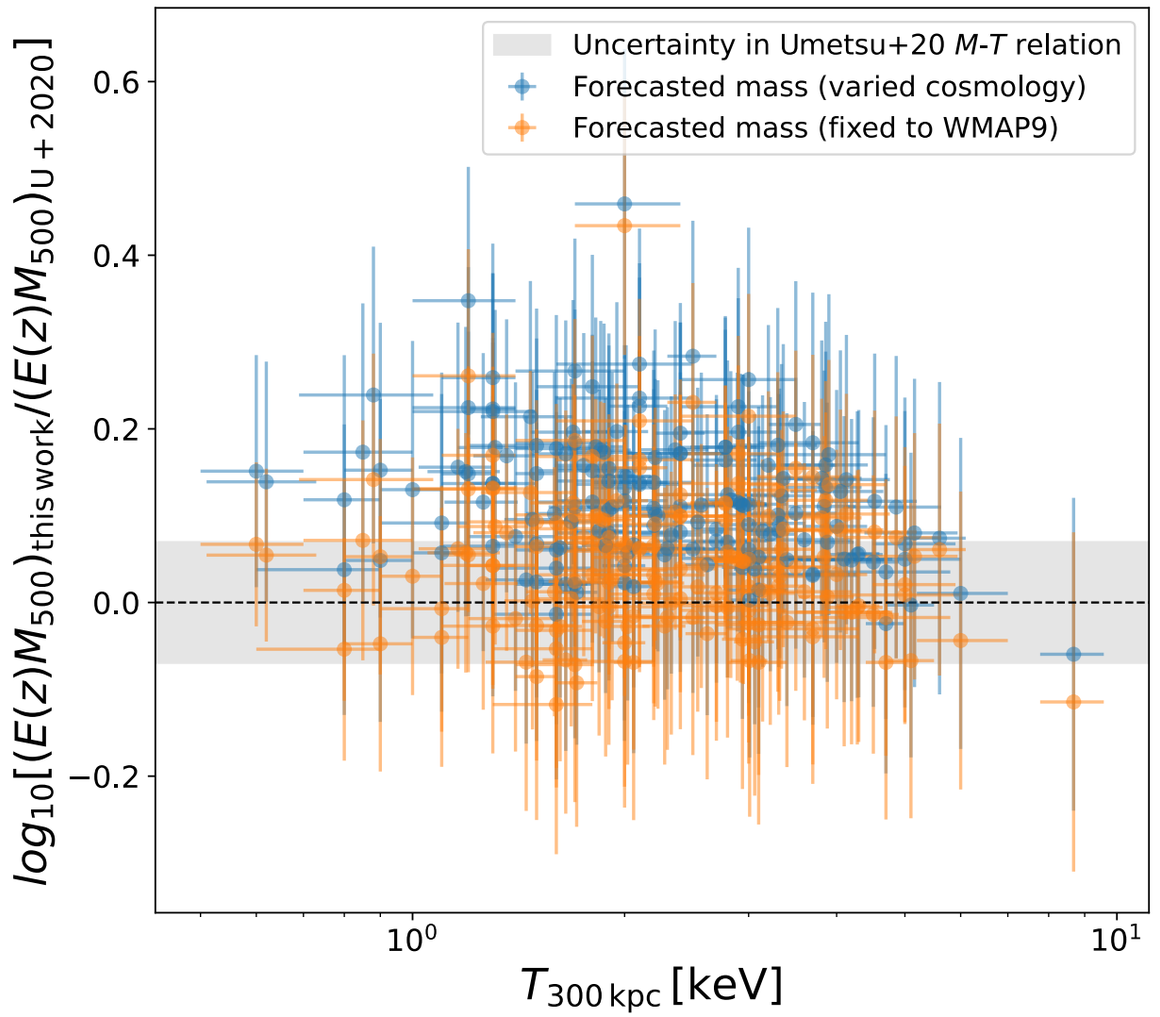
Best-fit Scaling Relations

$$\frac{T_{300\,\mathrm{kpc}}}{T_{\mathrm{piv}}} = (2.34 \pm 0.228)\left(\frac{M_{500}}{M_{\mathrm{piv}}}\right)^{0.634\pm0.100} \times \left(\frac{E(z)}{E(z=0.3)}\right)^{0.213\pm0.493}$$

$$\frac{L_{500}}{L_{\mathrm{piv}}} = (10.9 \pm 2.54)\left(\frac{T_{300\,\mathrm{kpc}}}{T_{\mathrm{piv}}}\right)^{2.99\pm0.285} \times \left(\frac{E(z)}{E(z=0.3)}\right)^{1.61\pm1.21}$$

Forecasted Mass for XXL-C1 clusters





Conclusion

- **Simulation-Based Inference (SBI)** offers a flexible, likelihood-free framework for cosmological analysis using forward modeling.

- Validations on synthetic data confirm robustness of the inference pipeline

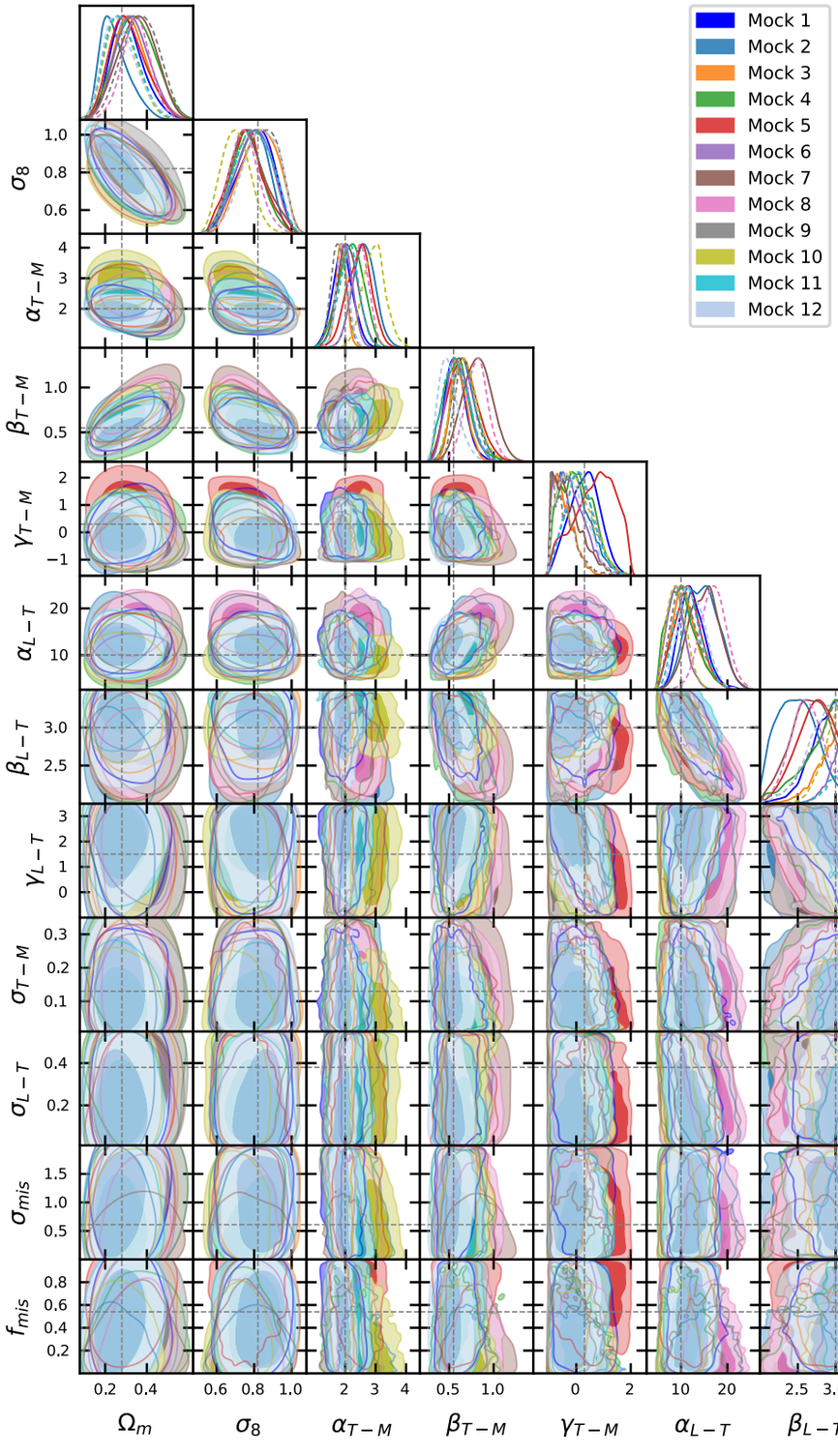
- Applied to the XXL–HSC cluster sample, jointly modeling:
  cluster abundance, weak-lensing shear, and X-ray observables
  —> X-ray scaling relations marginzaling over cosmology
  —> Forecasted cluster masses

- Results demonstrate SBI's potential for precision cluster cosmology

- The modular nature of the framework makes it easily adaptable to other surveys (e.g., SZ, optical) by modifying specific components of the forward model.

Validation with mocks

Robust test with 12 synthetic XXL-N surveys



Median of posterior mean:

$$\Omega_m = 0.311 \pm 0.042$$

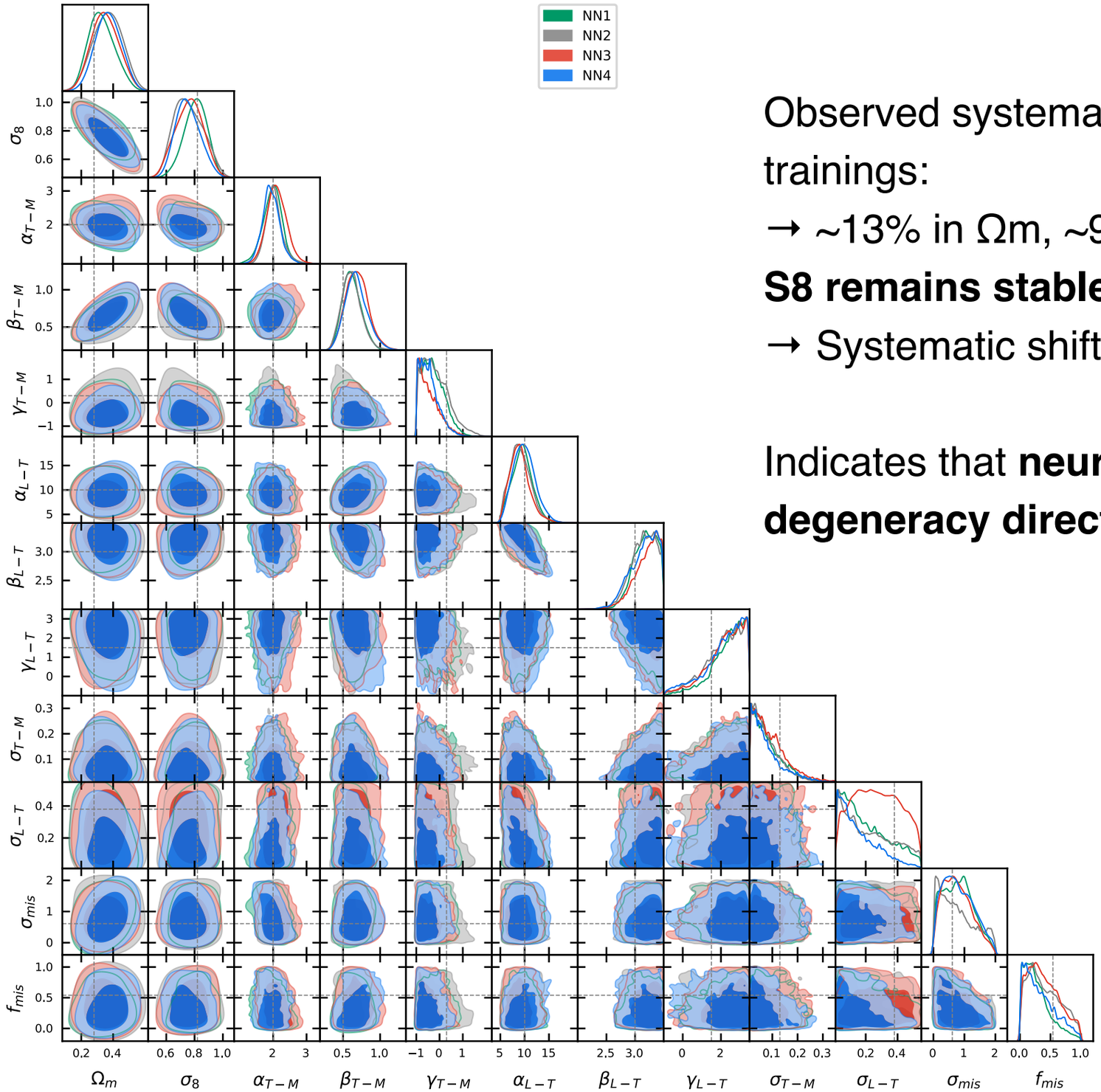
$$\sigma_8 = 0.790 \pm 0.039$$

Fiducial values lie within ~0.75 σ of ensemble means

→ Indicates statistically consistent and unbiased inference under realistic noise

Validation with mocks

Sensitivity of our results to he choice of neural network architecture



Observed systematic shifts across 4 independent NDE trainings:

→ ~13% in Ωm, ~9% in σ8 posterior means

S8 remains stable:

→ Systematic shift < 3%

Indicates that **neural network variability affects the degeneracy direction** in the (Ωm, σ8) plane