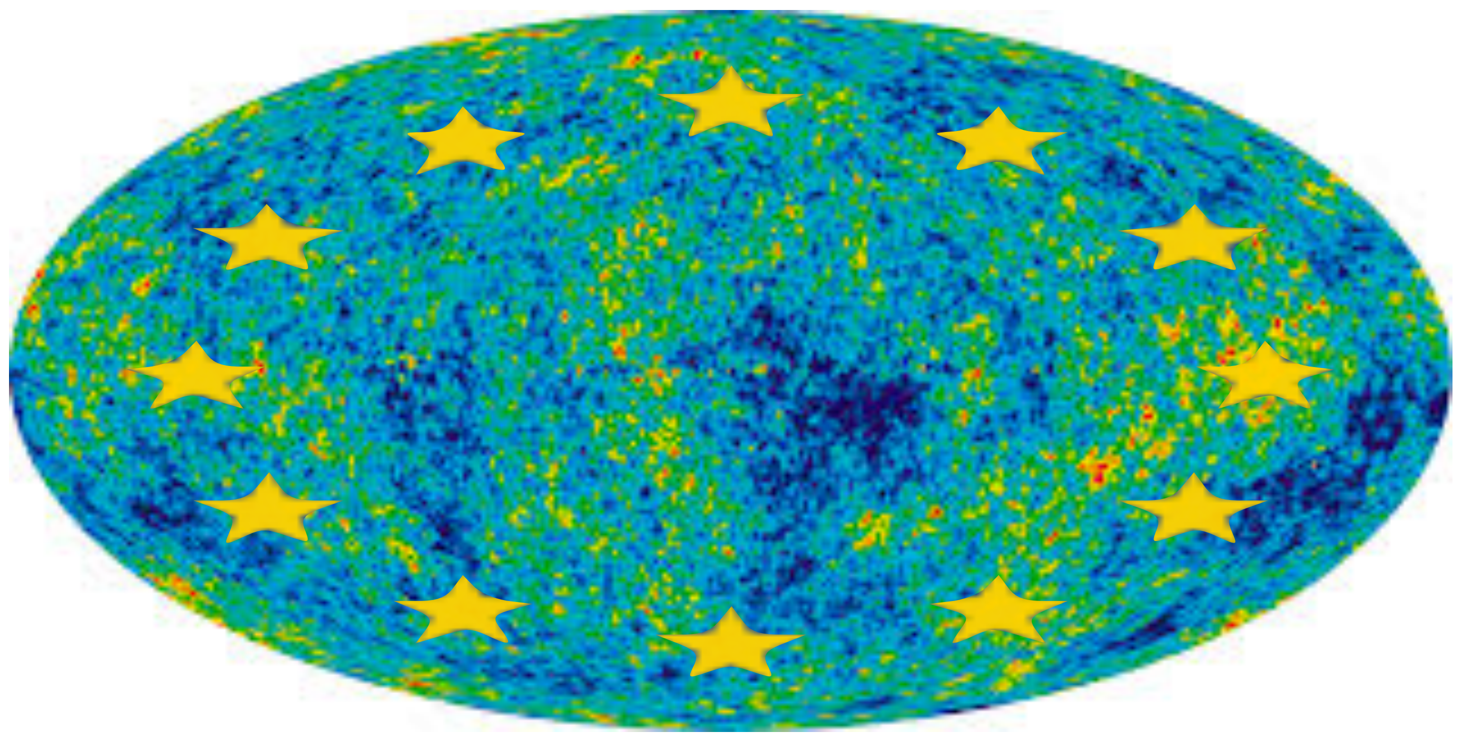
Sunyaev-Zel'dovich Effect-Based Neutrino Constraints



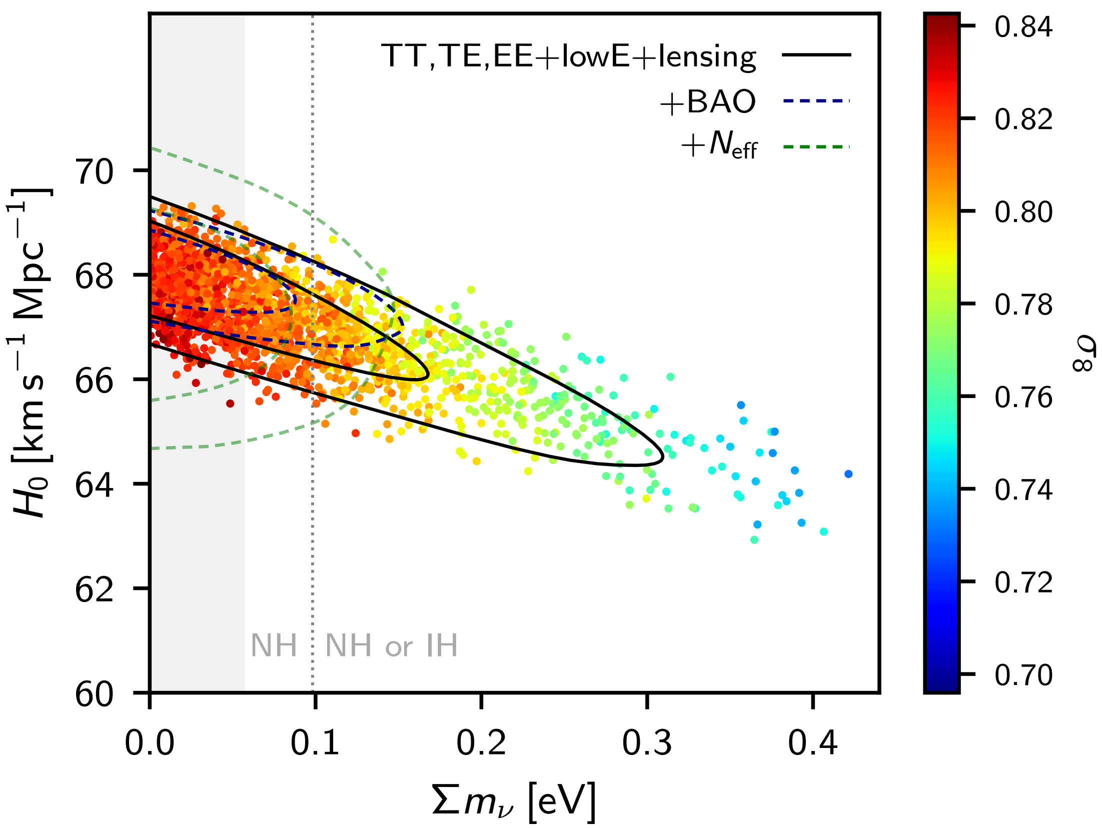
Sebastian Bocquet - LMU Munich

Outline

- Great introduction and theory overview by Massimiliano!
- Premise: Current constraints
- Statistical methods
- Baryons: Challenge or opportunity?
- Where we're going with SZ effect cosmology

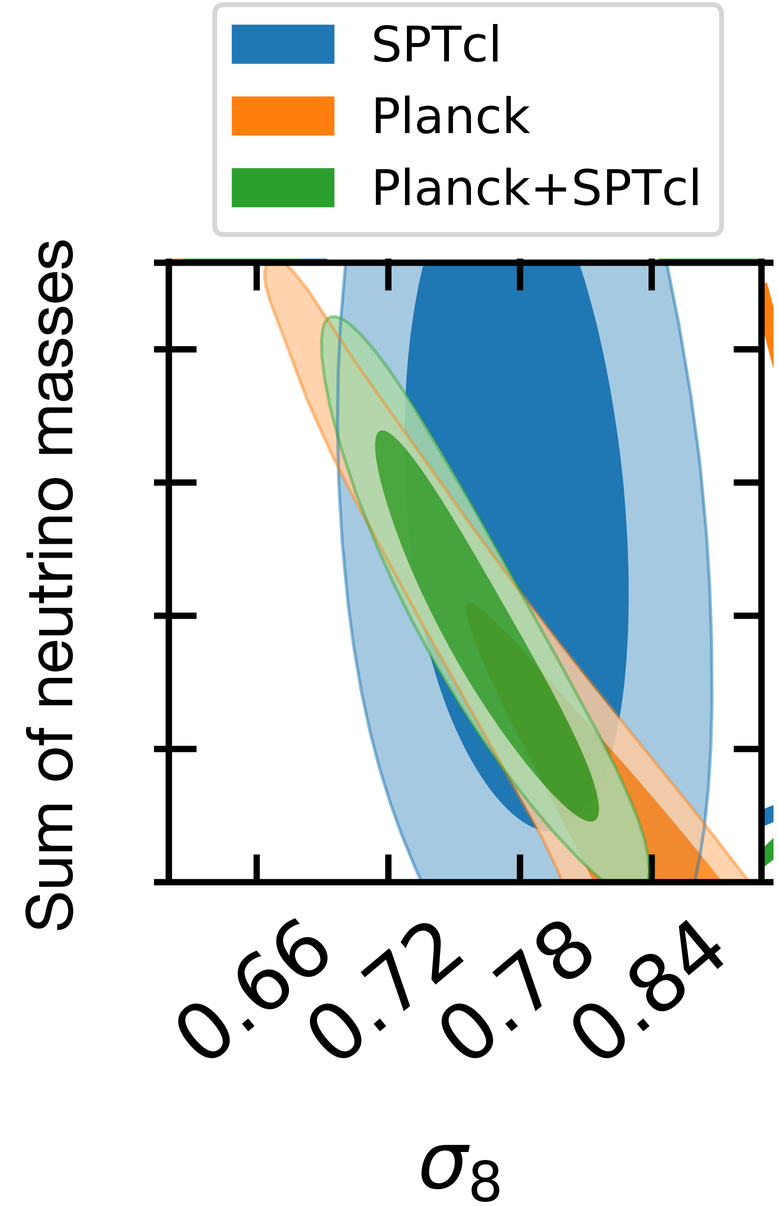
Sum of Neutrino Masses from CMB

- Presence of massive neutrinos change the angular diameter distance that is degenerate with H0 (Planck 18 VI)
- Mapping to low-z amplitude σ_8 also changes
- Therefore, combine with
  - BAO
  - Low-z LSS probe
  - H0 (caution)



Obtaining Neutrino Constraints

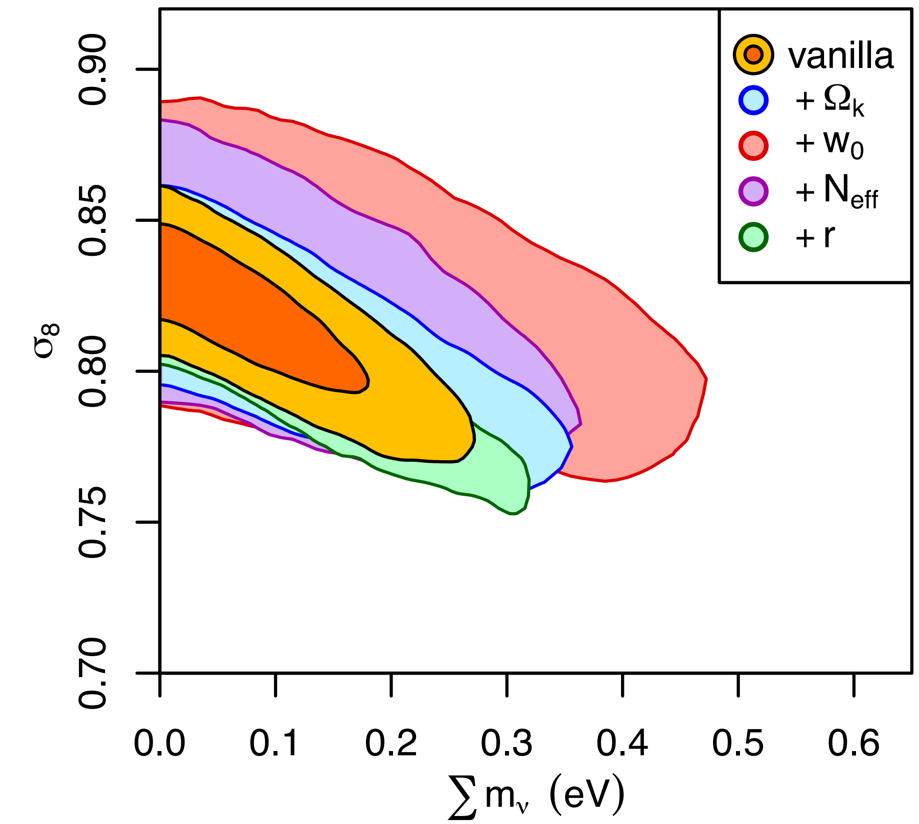
- Primary CMB and LSS probes provide weak constraints on their own
- For primary CMB, neutrino properties are degenerate with σ_8
- Break that degeneracy e.g., by analyzing CMB + cluster abundance
- (Other approaches are: CMB lensing, BAO, H_0)



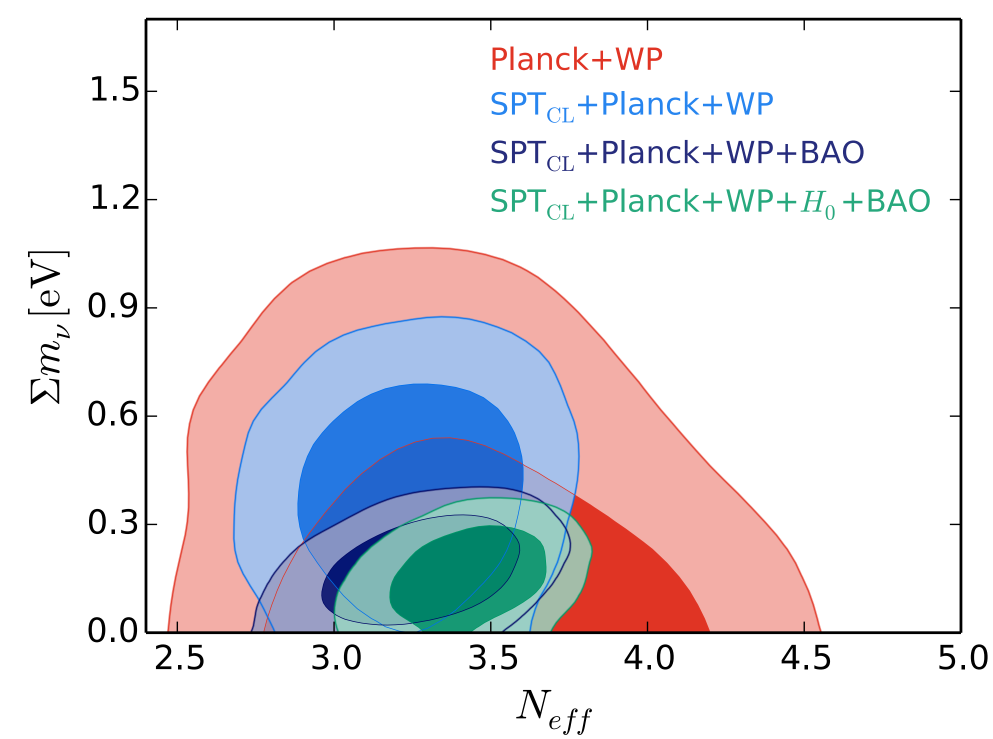
Example from Bocquet+19

Robustness to Choice of Cosmology

Allowing for additional freedom in the cosmological model (curvature, dark energy equation of state, $N_{\rm eff}$, r) does not significantly degrade the constraint on Σm_ν (Mantz+15).



Simultaneous constraints on Σm_ν and $N_{\rm eff}$ (de Haan+16)

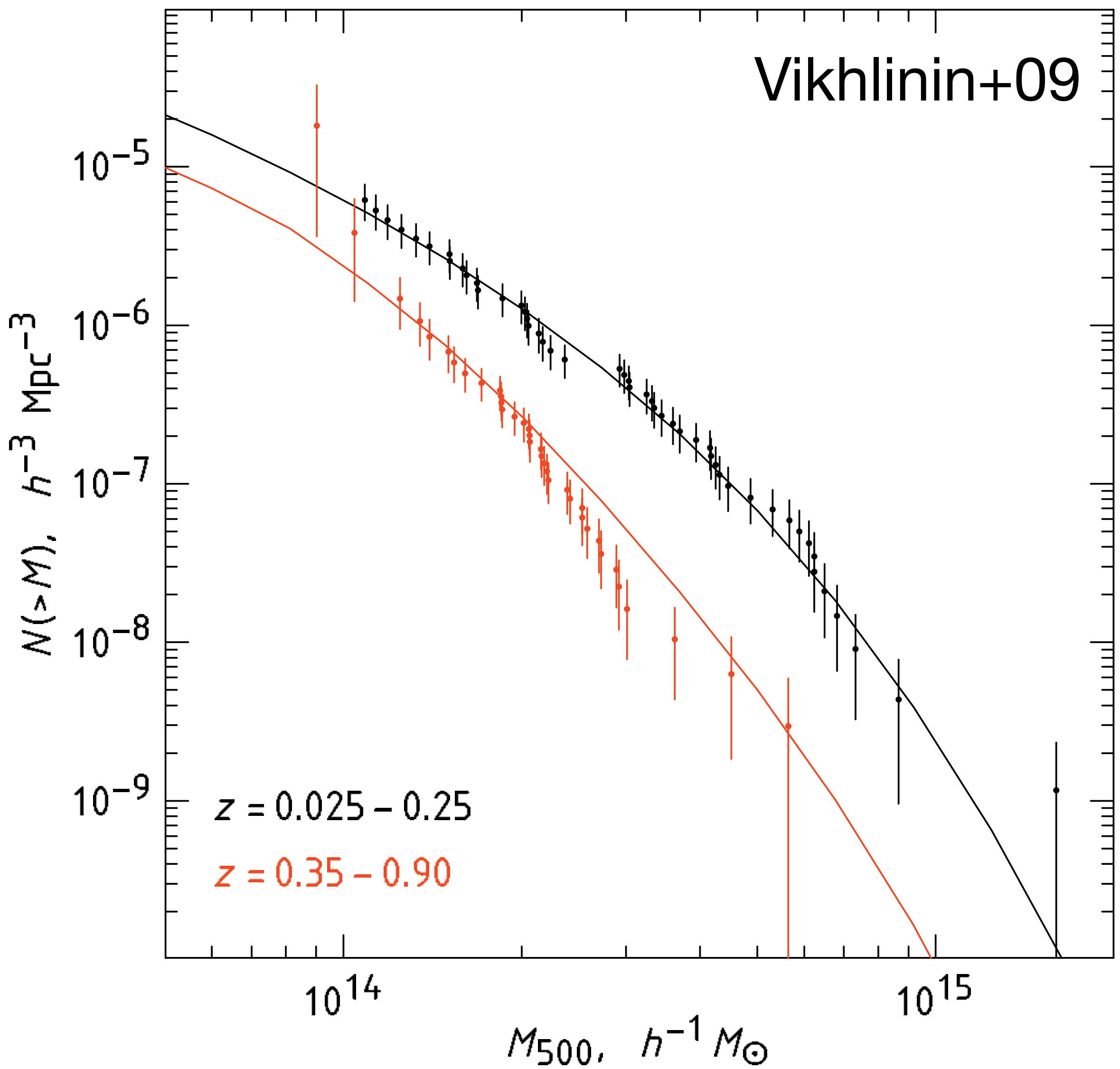


Methods: Self-Consistent, Data-Driven Statistical Modeling Framework

(*Hierarchical Bayesian modeling* for the cool kids)

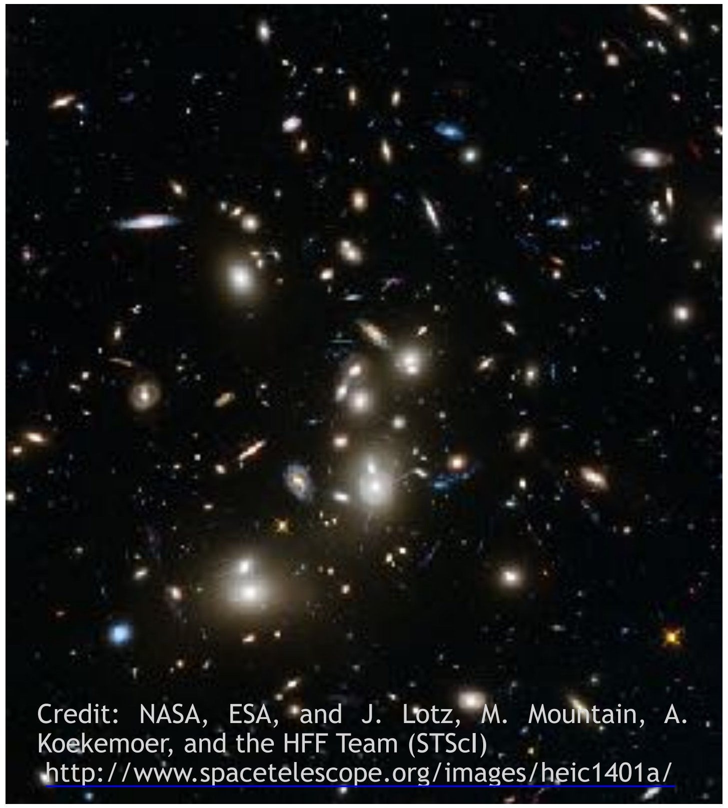
Basics of Cluster Cosmology

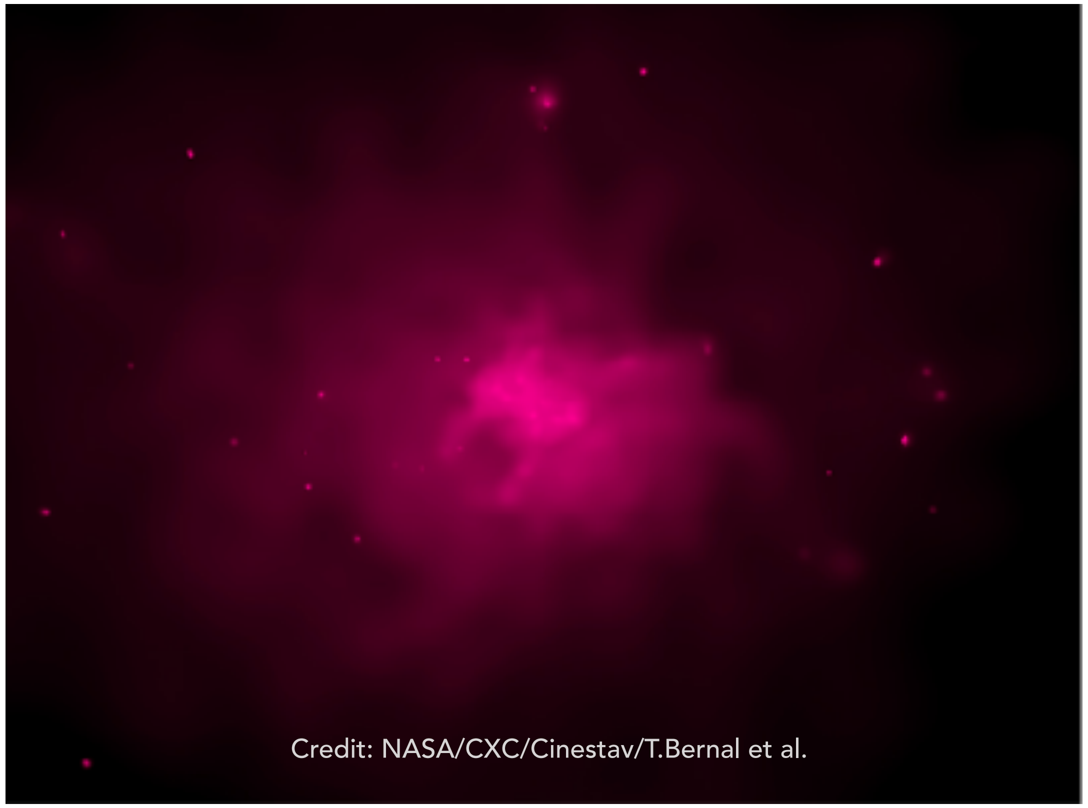
- Halo mass function is extremely sensitive to cosmology
- Measure cluster masses and redshifts
- Compare mass function measurement with model prediction
- Done
  - … or not?

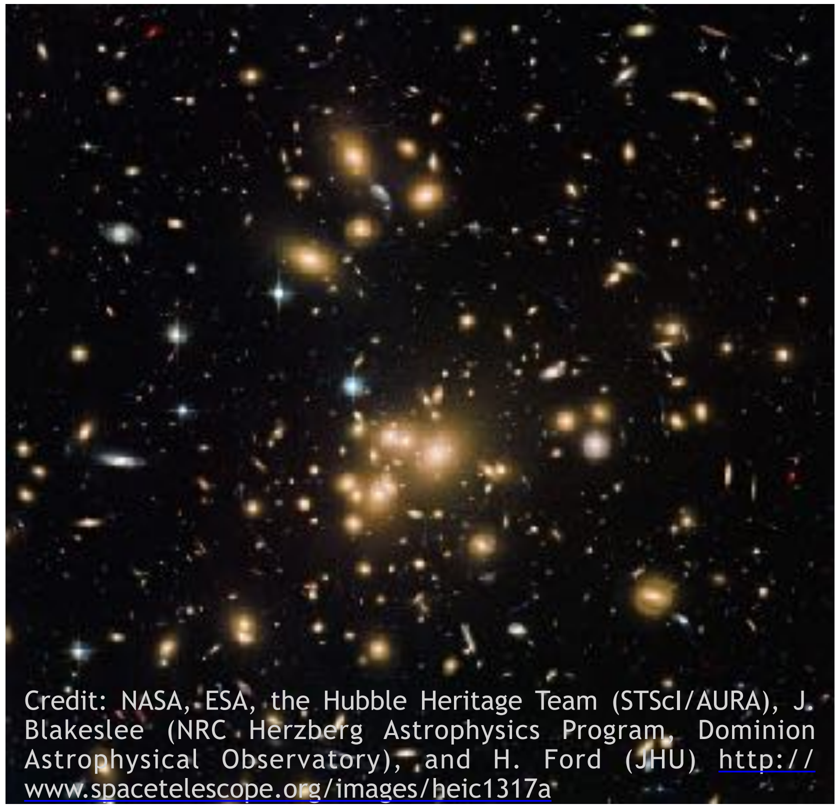


Observed Clusters ≠ Simulated Halos

In practice:
Empirical calibration of observable—mass relations







Cluster Cosmology Calls for Forward Modeling

Halo Mass Function
Abundance $dN/dM/dz$
from numerical simulations

↓

Observable — Mass Relation
Statistical description
$P(\mathrm{obs}\,|\,\mathrm{mass, redshift})$

↓

Model prediction in Observable-Space
$dN_{\mathrm{model}}/d\mathrm{obs}/dz$

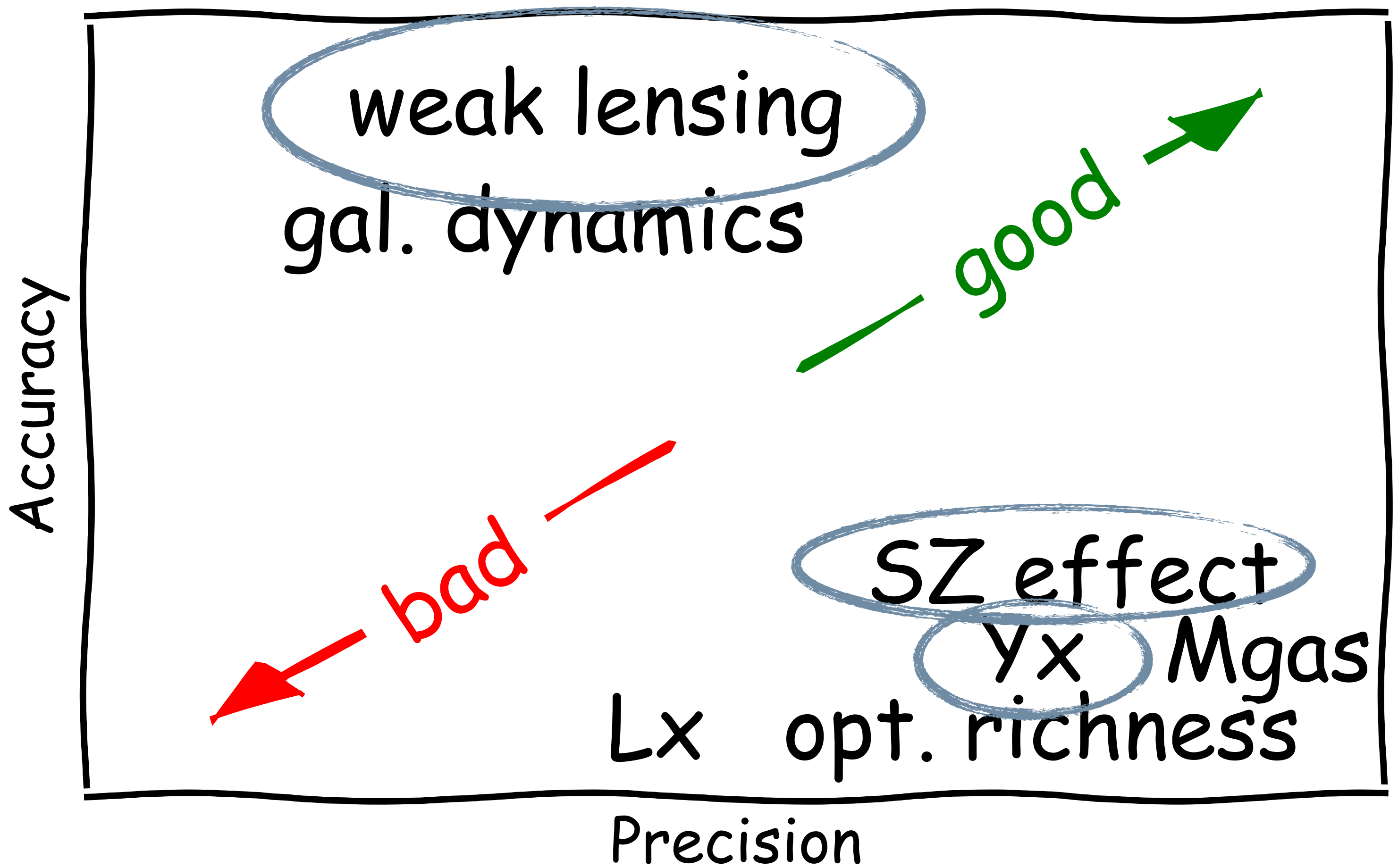
↓

Likelihood

↑

Observed Distribution in Observable-Space
$dN_{\mathrm{data}}/d\mathrm{obs}/dz$

Mass Proxies (correlate with halo mass)



- SZ effect and X-ray Y_X
  - Small intrinsic & measurement scatter < 20 %
  - Systematically limited by our (lack of) understanding of gas physics in clusters
- Weak gravitational lensing
  - Measures total mass
  - Mass modeling in *N*-body simulations
  - %-level systematics
  - Large intrinsic & measurement scatter > ~30 %

Weak-Lensing Bias and Scatter

- WL is a biased mass estimator (with intrinsic scatter) because we fit an NFW profile
- Mass modeling
  - NFW profile mismatch
  - Miscentering
  - Correlated LSS
- Other systematics:
  - Cluster member contamination
  - Shear and photo-z bias

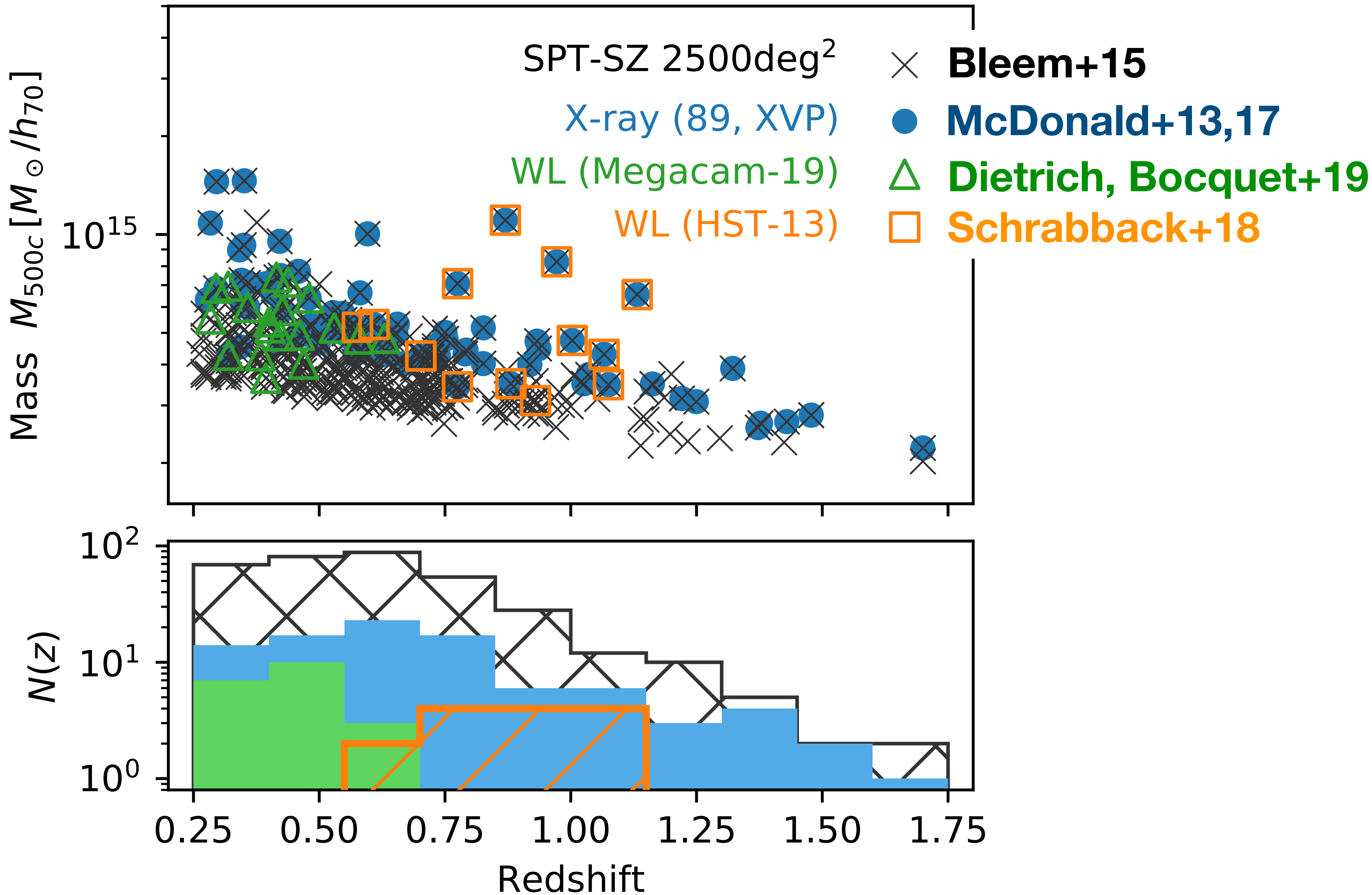
Source of systematic	SV Amplitude uncertainty	Y1 Amplitude Uncertainty
Shear measurement	4%	1.7%
Photometric redshifts	3%	2.6%
Modeling systematics	2%	0.73%
Cluster triaxiality	2%	2.0%
Line-of-sight projections	2%	2.0%
Membership dilution + miscentering	$\leqslant$ 1%	0.78%
Total Systematics	6.1%	4.3%
Total Statistical	9.4%	2.4%
Total	11.2%	5.0%

DES Y1: 4.3% systematic uncertainty (McClintock+19)

Premise & Modeling Framework

- Cluster cosmology is a modeling challenge.
- Be explicit about your assumptions!
- **We will not**
  - assume hydrostatic equilibrium
  - consider a hydrostatic bias extracted from hydro simulations (let’s discuss their predictivity/ validation over coffee/beer!)
- **We will** trust our intuition (and decades of research) that
  - cluster mass proxies correlate with mass
  - Mean observable—mass relation is well described by a power law in mass and redshift (with unknown parameters)
  - weak gravitational lensing measures halo mass on average with %-level systematic uncertainty (more on [known] biases later)

2500 deg² SPT-SZ Survey Cluster Catalog and Multi-Observable Follow-up Data



Multi-Observable—Mass Relation

e.g., Bocquet+19

Mean relations

SZ

$$\langle \ln \zeta \rangle = \ln A_{\mathrm{SZ}} + B_{\mathrm{SZ}} \ln \left(\frac{M_{500c}\, h_{70}}{4.3 \times 10^{14} M_\odot} \right) + C_{\mathrm{SZ}} \ln \left(\frac{E(z)}{E(0.6)} \right) \tag{1}$$

X-ray

$$\ln \left(\frac{M_{500c}\, h_{70}}{8.37 \times 10^{13} M_\odot} \right) = \ln A_{Y_{\mathrm{X}}} + B_{Y_{\mathrm{X}}} \langle \ln Y_{\mathrm{X}} \rangle + B_{Y_{\mathrm{X}}} \ln \left(\frac{h_{70}^{5/2}}{3 \times 10^{14} M_\odot \mathrm{keV}} \right) + C_{Y_{\mathrm{X}}} \ln E(z) \tag{2}$$

WL

$$\langle \ln M_{\mathrm{WL}} \rangle = \ln b_{\mathrm{WL}} + \ln M_{500c}. \tag{3}$$

Covariance matrix

$$\mathbf{\Sigma}_{\text{multi-obs}} = \begin{pmatrix} \sigma^2_{\ln \zeta} & \rho_{\mathrm{SZ-WL}}\sigma_{\ln\zeta}\sigma_{\mathrm{WL}} & \rho_{\mathrm{SZ-X}}\sigma_{\ln\zeta}\sigma_{\ln Y_{\mathrm{X}}} \\ \rho_{\mathrm{SZ-WL}}\sigma_{\ln\zeta}\sigma_{\mathrm{WL}} & \sigma^2_{\mathrm{WL}} & \rho_{\mathrm{WL-X}}\sigma_{\mathrm{WL}}\sigma_{\ln Y_{\mathrm{X}}} \\ \rho_{\mathrm{SZ-X}}\sigma_{\ln\zeta}\sigma_{\ln Y_{\mathrm{X}}} & \rho_{\mathrm{WL-X}}\sigma_{\mathrm{WL}}\sigma_{\ln Y_{\mathrm{X}}} & \sigma^2_{\ln Y_{\mathrm{X}}} \end{pmatrix} \tag{4}$$

Multi-obs relation

$$P\left(\begin{bmatrix} \ln \zeta \\ \ln M_{\mathrm{WL}} \\ \ln Y_{\mathrm{X}} \end{bmatrix} \Bigg| M, z, \boldsymbol{p} \right) = \mathcal{N}\left(\begin{bmatrix} \langle \ln \zeta \rangle (M, z, \boldsymbol{p}) \\ \langle \ln M_{\mathrm{WL}} \rangle (M, z, \boldsymbol{p}) \\ \langle \ln Y_{\mathrm{X}} \rangle (M, z, \boldsymbol{p}) \end{bmatrix}, \mathbf{\Sigma}_{\text{multi-obs}} \right)$$

Multi-Observable—Mass Relation

e.g., Bocquet+19

Mean relations

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$$\langle \ln \zeta \rangle = \ln A_{\mathrm{SZ}} + B_{\mathrm{SZ}} \ln \left(\frac{M_{500c} h_{70}}{4.3 \times 10^{14} M_\odot} \right) + C_{\mathrm{SZ}} \ln \left(\frac{E(z)}{E(0.6)} \right) \quad (1)$$

X-ray

$$\ln \left(\frac{M_{500c} h_{70}}{8.37 \times 10^{13} M_\odot} \right) = \ln A_{Y_\mathrm{X}} + B_{Y_\mathrm{X}} \langle \ln Y_\mathrm{X} \rangle + B_{Y_\mathrm{X}} \ln \left(\frac{h_{70}^{5/2}}{3 \times 10^{14} M_\odot \mathrm{keV}} \right) + C_{Y_\mathrm{X}} \ln E(z) \quad (2)$$

WL

$$\langle \ln M_{\mathrm{WL}} \rangle = \ln b_{\mathrm{WL}} + \ln M_{500c}. \quad (3)$$

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Multi-obs relation

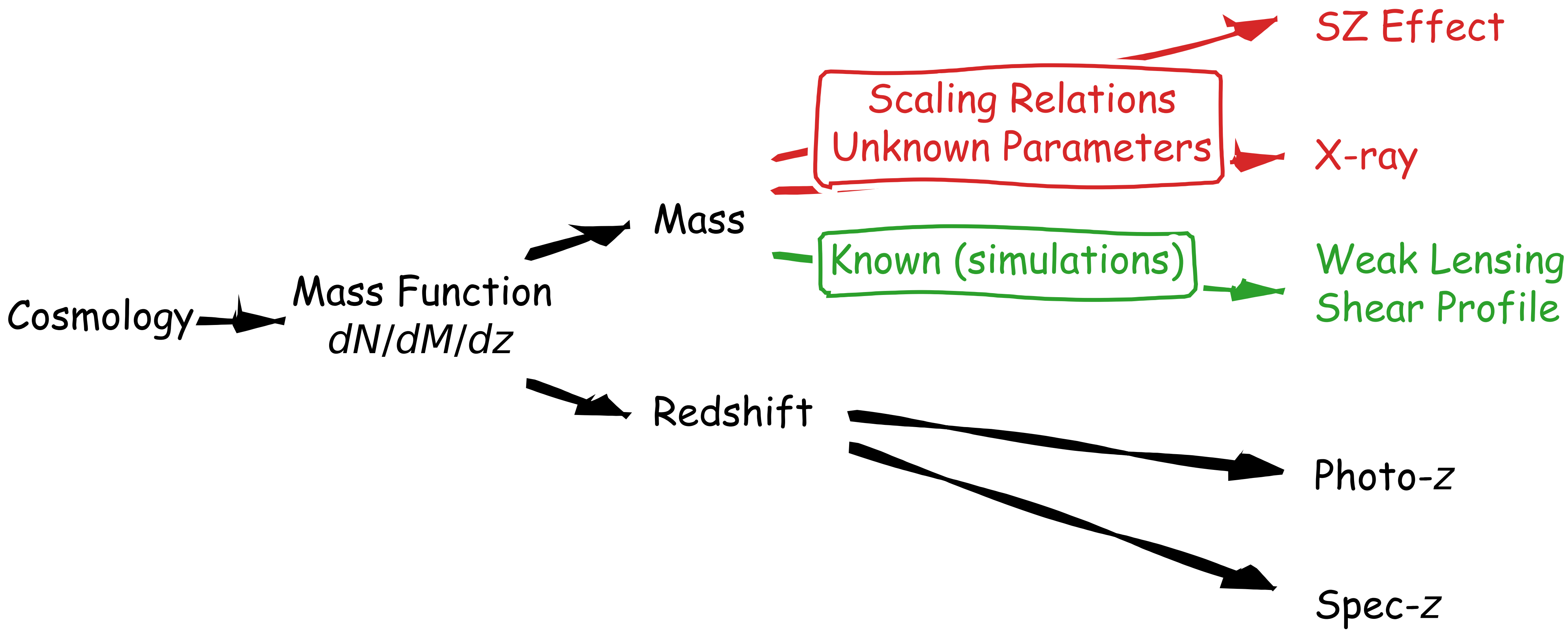
$$P\left(\begin{bmatrix} \ln\zeta \\ \ln M_{\mathrm{WL}} \\ \ln Y_\mathrm{X} \end{bmatrix} | M, z, \boldsymbol{p} \right) = \mathcal{N}\left(\begin{bmatrix} \langle \ln\zeta \rangle (M,z,\boldsymbol{p}) \\ \langle \ln M_{\mathrm{WL}} \rangle (M,z,\boldsymbol{p}) \\ \langle \ln Y_\mathrm{X} \rangle (M,z,\boldsymbol{p}) \end{bmatrix}, \mathbf{\Sigma}_{\text{multi-obs}} \right)$$

3 + 3 + 1 parameters for mean relations

3 + 3 parameters for covariance matrix (correlated intrinsic scatter)

Forward-Modeling Analysis Strategy

e.g., Bocquet+19



Use the known relation
mass -> weak lensing shear profile
to calibrate
mass -> SZ effect and mass -> X-ray

Simultaneous analysis of all observables to capture all covariances

Likelihood Function in Observable Space

Poisson likelihood for cluster abundance

Selection
xi >5, z>0.25

$$\ln \mathcal{L}(\vec{p}) = \boxed{\sum_i \ln \frac{dN(\xi,z,\vec{p})}{d\xi dz}\Big|_{\xi_i,z_i} - \iint d\xi dz \Theta_{\rm survey} \frac{dN(\xi,z,\vec{p})}{d\xi dz}} + \boxed{\sum_j P(Y_{\rm X}, g_{\rm t}|\xi_j, z_j, \vec{p})\Big|_{Y_{{\rm X}_j}, g_{{\rm t}j}}}$$

Total predicted number

Mass calibration

$$\frac{dN(\xi,z|\boldsymbol{p})}{d\xi dz} = \iint dM\, d\zeta\, \Big[\, P(\xi|\zeta) P(\zeta|M,z,\boldsymbol{p}) \frac{dN(M,z|\boldsymbol{p})}{dM dz} \Omega(z,\boldsymbol{p})\, \Big]$$

$$P(Y_{\rm X}^{\rm obs}, g_{\rm t}^{\rm obs}|\xi,z,\boldsymbol{p}) = \iiiint dM\, d\zeta\, dY_{\rm X}\, dM_{\rm WL}\, \Big[P(Y_{\rm X}^{\rm obs}|Y_{\rm X}) P(g_{\rm t}^{\rm obs}|M_{\rm WL}) P(\xi|\zeta) P(\zeta, Y_{\rm X}, M_{\rm WL}|M,z,\boldsymbol{p}) P(M|z,\boldsymbol{p})\, \Big]$$

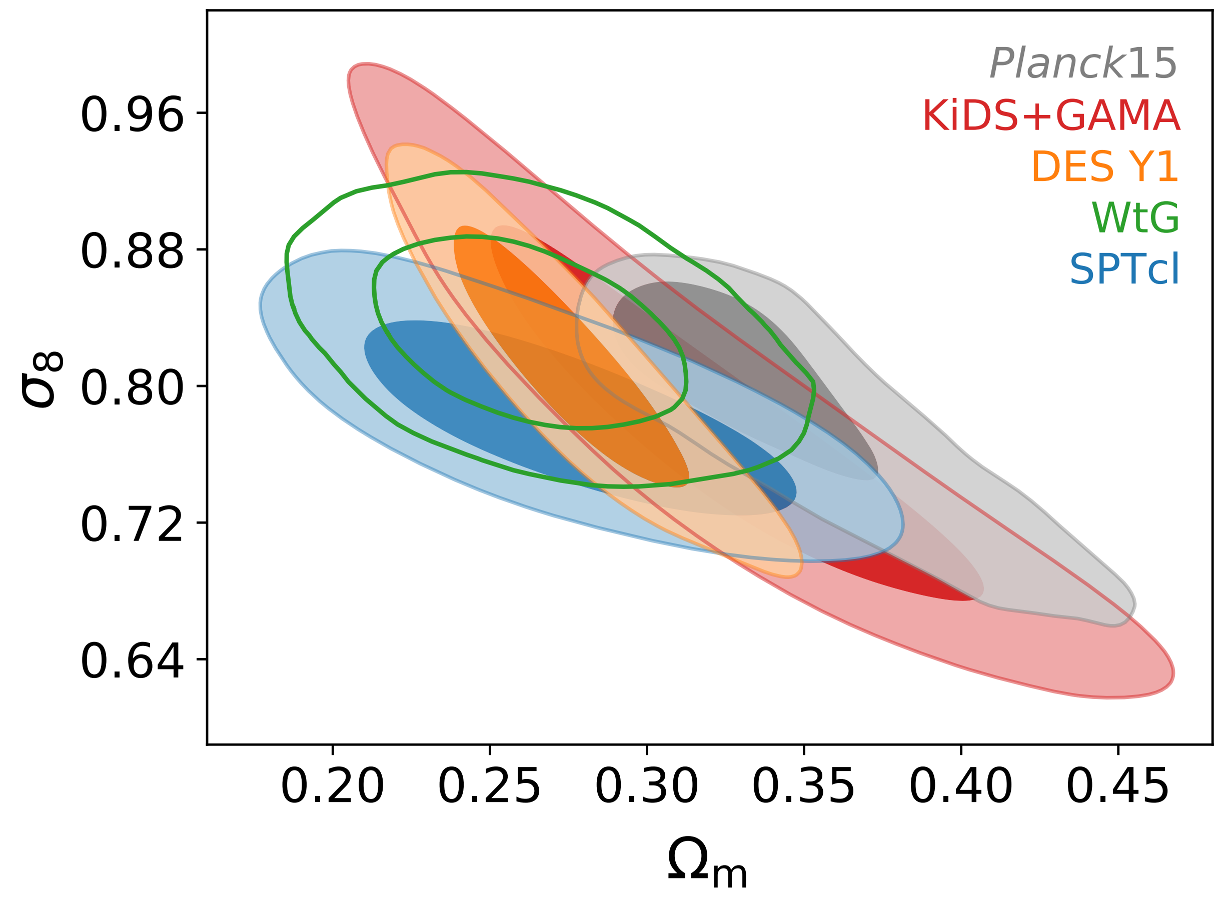
LCDM with varying sum of neutrino masses

Bocquet et al. [2019ApJ...878...55B]

- Wide flat priors on SZ scaling relation parameters fully encompass posterior

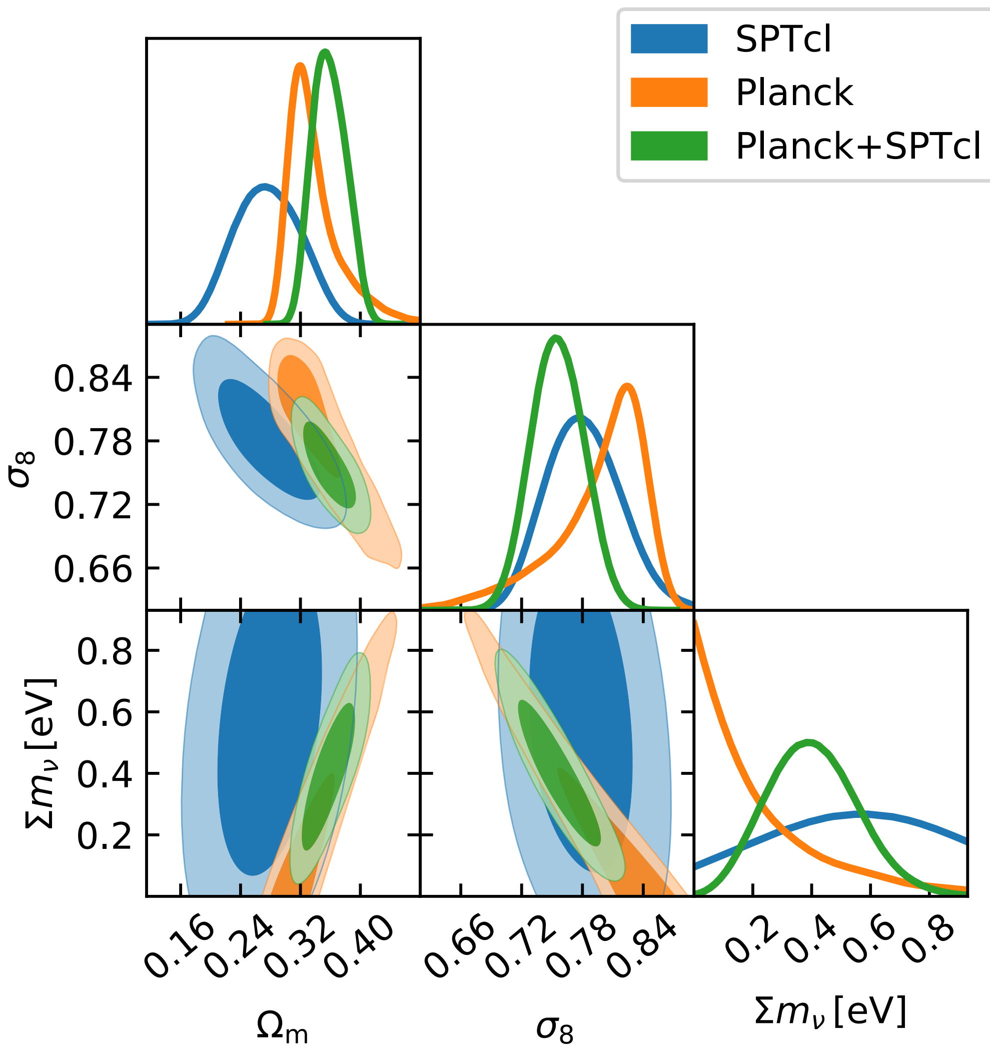
- Cluster constraint statistically limited by mass calibration: need more (weak lensing) data! (currently 32 clusters)

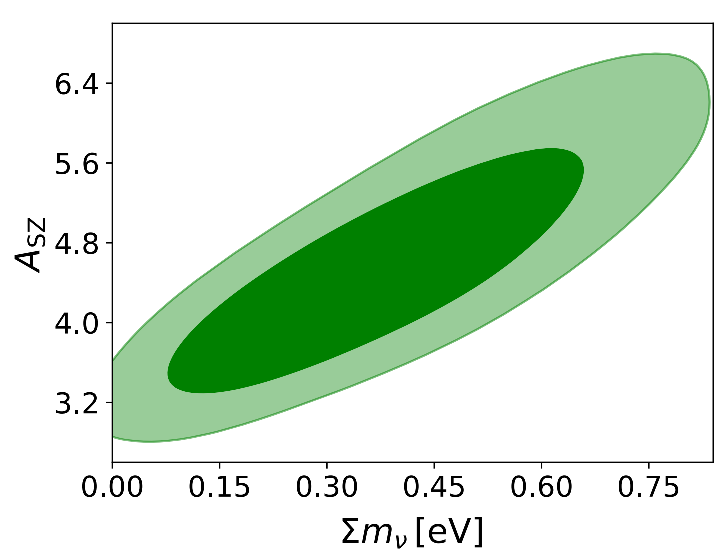
- 1.5 σ agreement with *Planck* TT+lowTEB



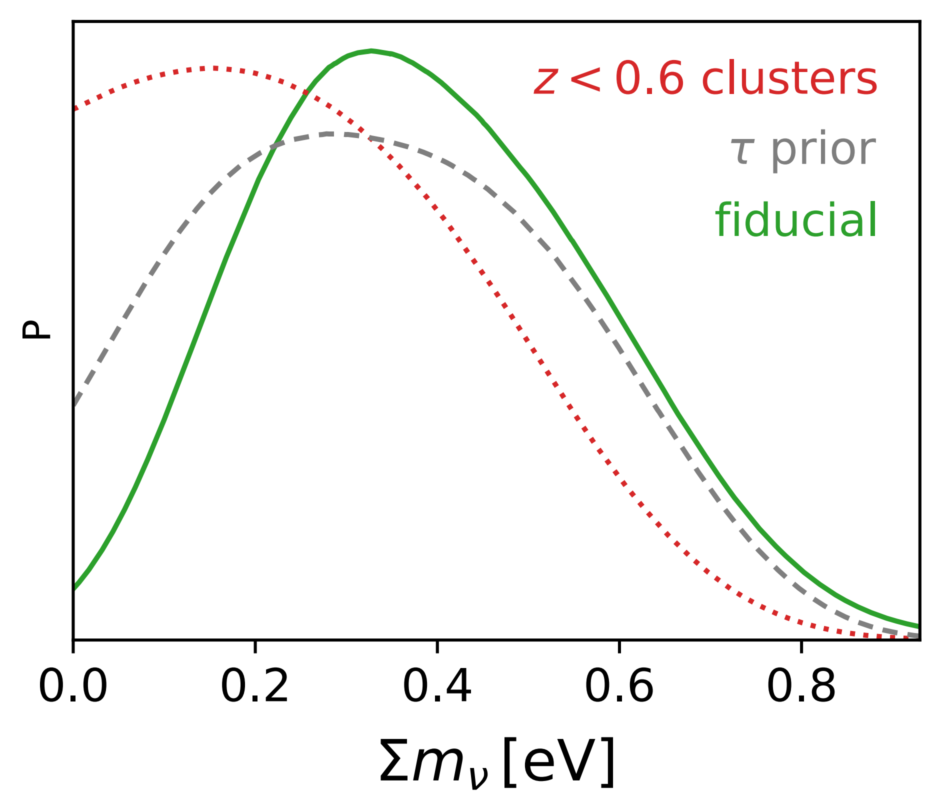
Neutrino Masses

Bocquet et al. 2019ApJ...878...55B





- Combination with Planck primary CMB measurements yields 2 σ preference for non-zero sum of neutrino masses
- Again, limited by mass calibration uncertainties
- Using τ prior from Planck 2018 gives 1.7 σ preference
- Using only the $z < 0.6$ cluster sample gives no preference for non-zero sum of neutrino masses



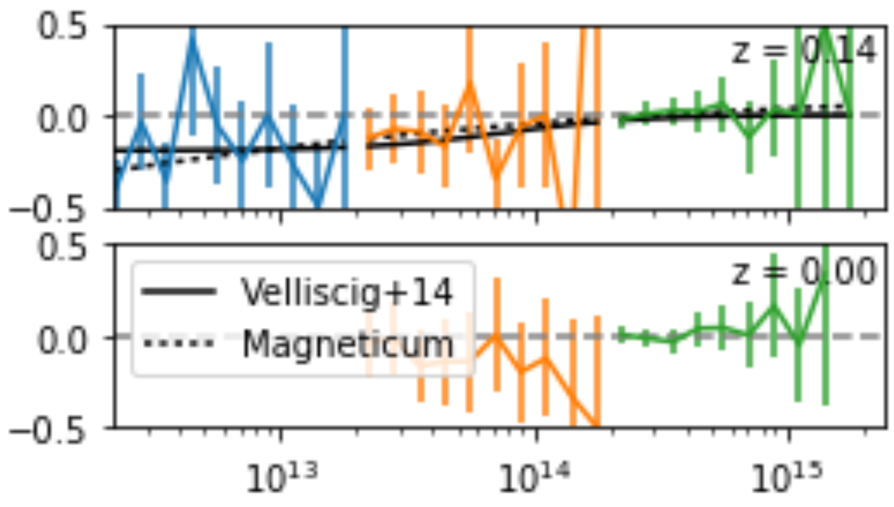
Outlook for SPT Cluster Cosmology

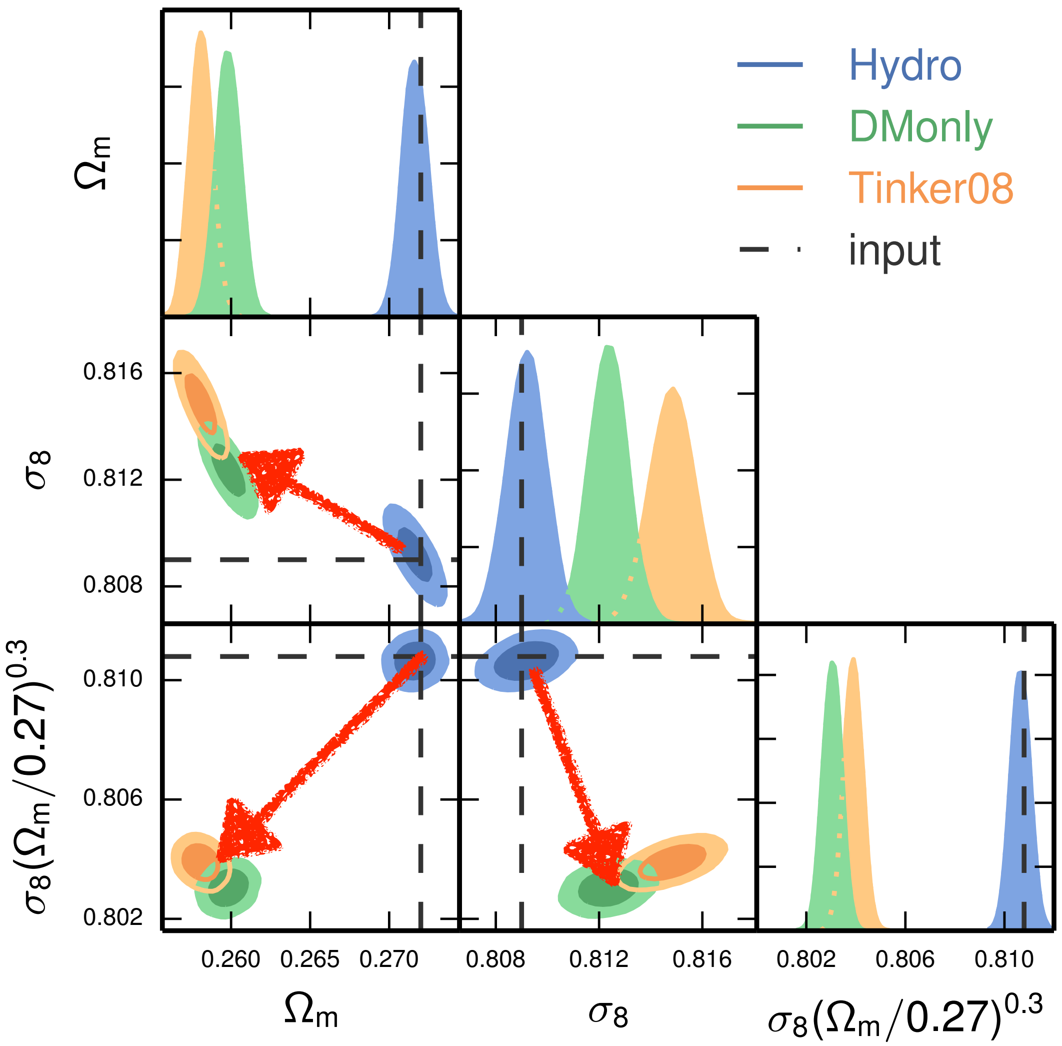
- Weak-lensing mass calibration of SPT clusters
  - Currently limited by number of WL observations
  - Use overlap of SPT and the Dark Energy Survey (DES) to get WL data for all SPT clusters at z <~ 1 (Paulus+, Bocquet+, both in prep.)
  - Ongoing HST programs for high-*z* clusters (Schrabback+)
  - CMB lensing
- SPTpol (2nd generation camera) analyses ongoing
  - Wide survey extension (another 2700 square deg: SPTpol-ECS, Bleem+ to be submitted)
  - Main, deep fields: Push to lower-mass clusters (more abundant)
    - Deepest 100d catalog is published: Huang+19
- SPT-3G: ongoing, deep 1500 square degree survey
  - Planck + SPT-3G clusters: $\sigma(\Sigma m_\nu) \sim 0.06$ eV

Baryons: Challenges and Opportunities

Baryons and the Halo Mass Function

- At fixed halo mass, feedback processes change the abundance (e.g., Cui+12, Cui+14, Cusworth+14, Martizzi+14, Velliscig+14, Vogelsberger+14, Schaller+15)
- Hydro effects are important for upcoming studies using M < ~1e14 Msun
- From *Magneticum Pathfinder*: for eROSITA, bias in Ω_m as large as total error (Bocquet+16, Dolag+16)





Biases if effect of hydro is ignored for eROSITA-like surveys!

Baryons and Halo Profiles

- For weak-lensing analyses: need mapping from halo mass to (projected) mass profile
- *N*-body simulations sufficient for mapping halo structure outside of the core
- Hydro effects most important for r<~100kpc
- "Trick": Impact of hydro effects can effectively be captured by a change in halo concentration
- No need to calibrate that change in concentration if we treat it as free parameter

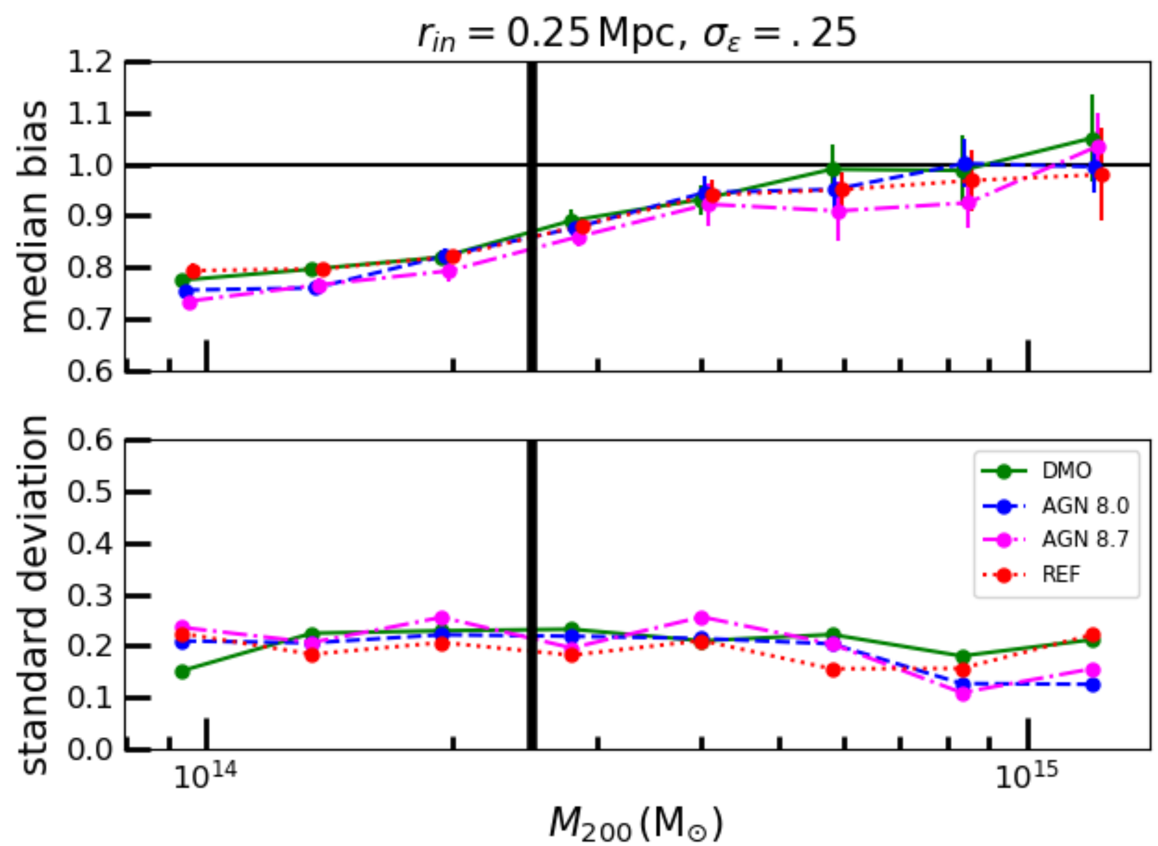


Fig.: Choice of sub grid physics model not important if concentration is a free parameter (Lee+18)

Cluster Constraints on Feedback Models

- At high *k*, correlation function analyses are limited by uncertainties in feedback models

- We study the relation between halo mass and gas observables (X-ray gas mass (fraction), X-ray temperature, SZ effect)

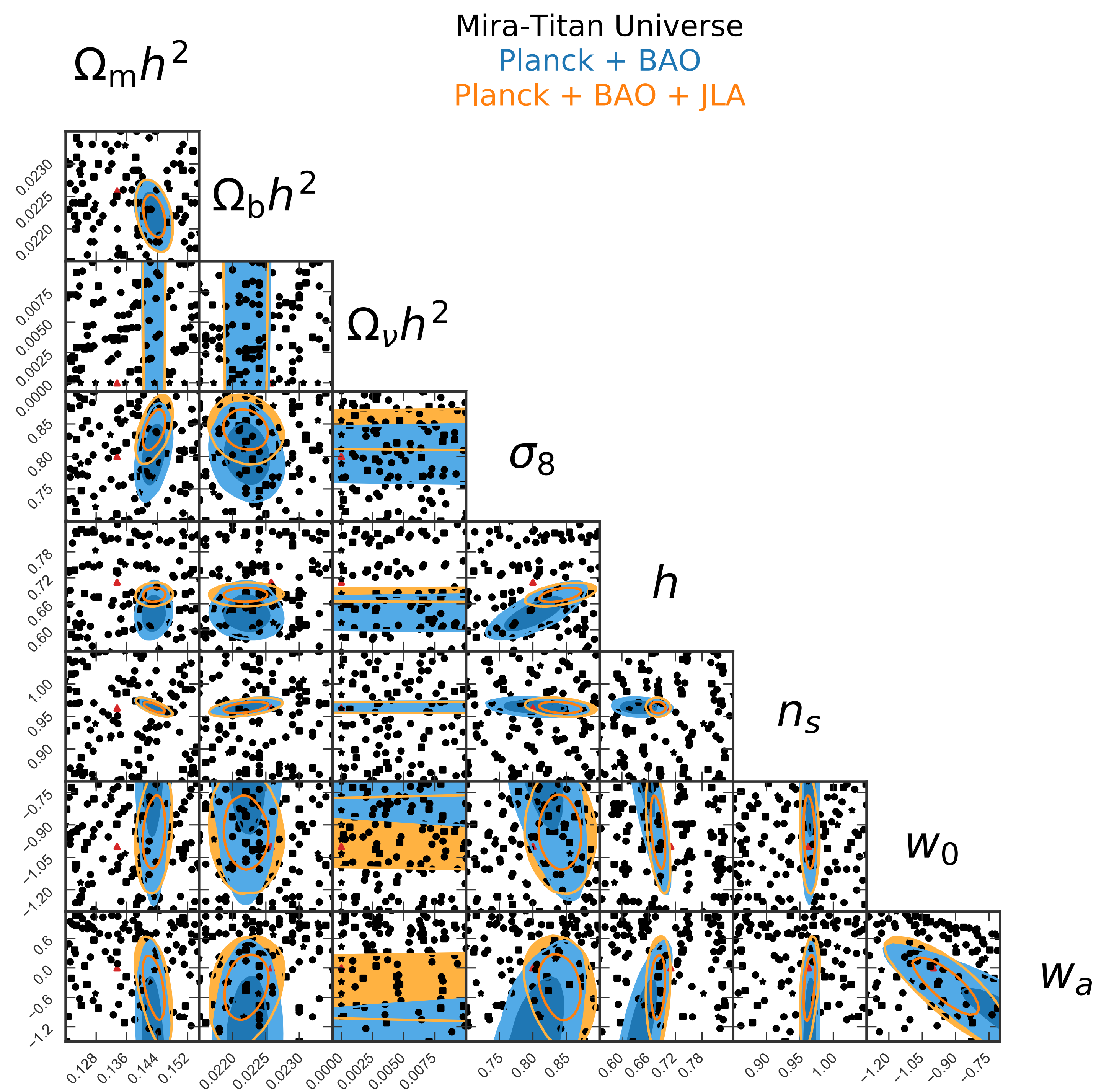
  - Validation dataset for hydro simulations

  - Measured cluster profiles can directly feed into “baryonification” models (e.g., Schneider+19)

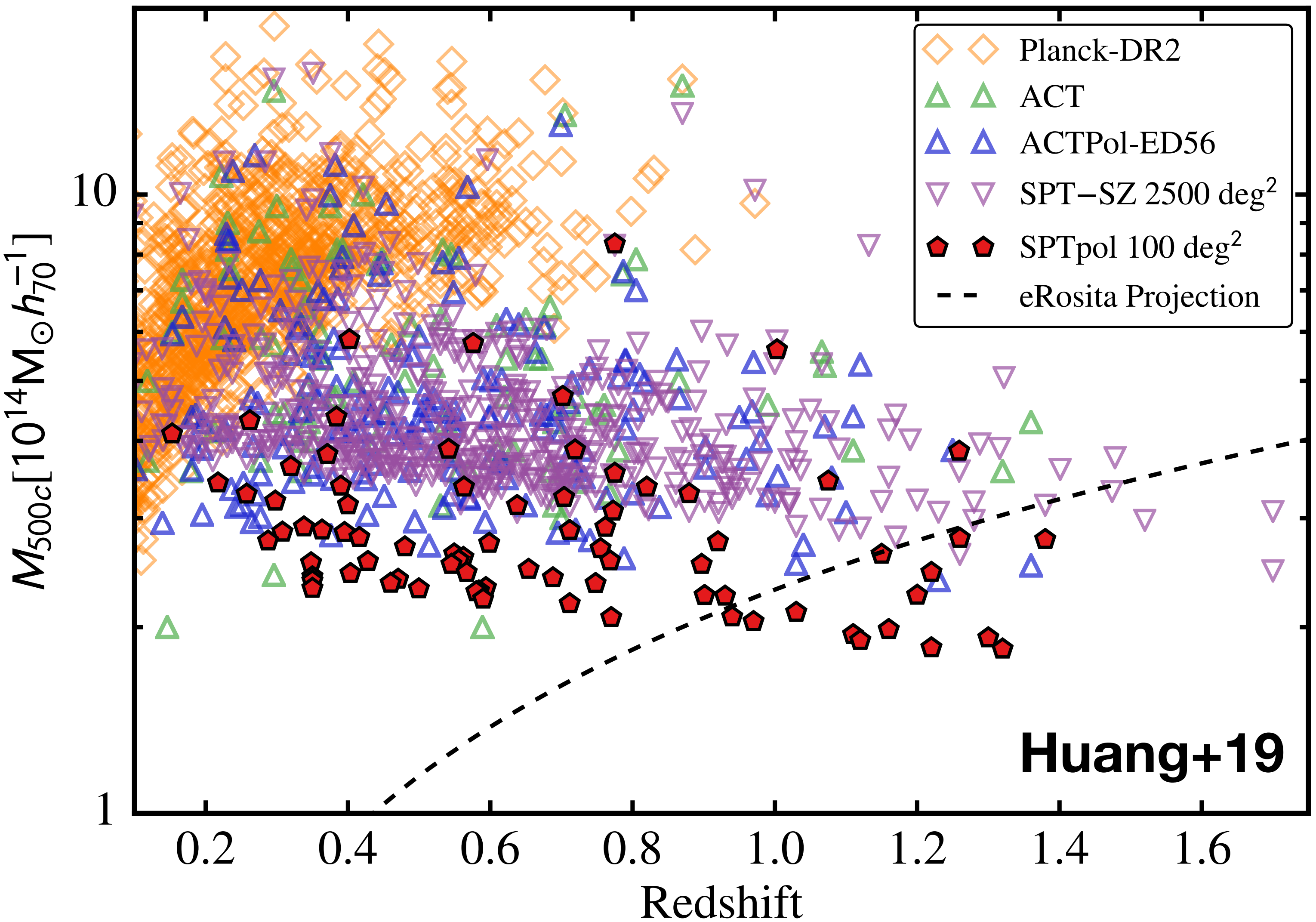
Where we are going

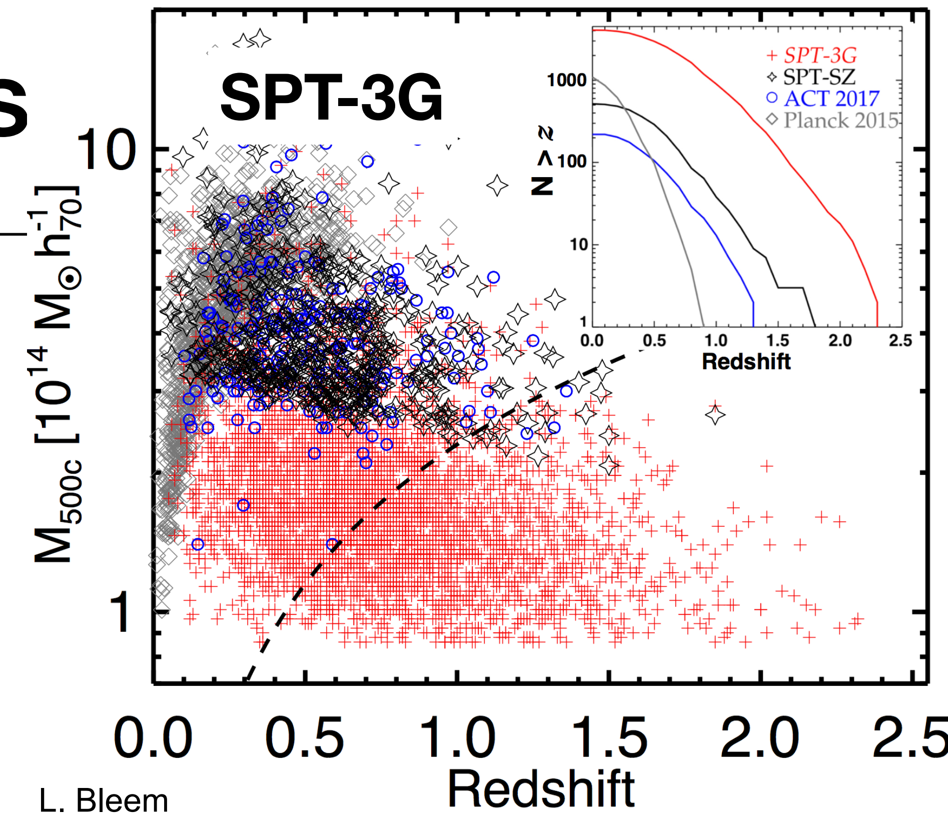
Cosmology Dependence of Halo Mass Function

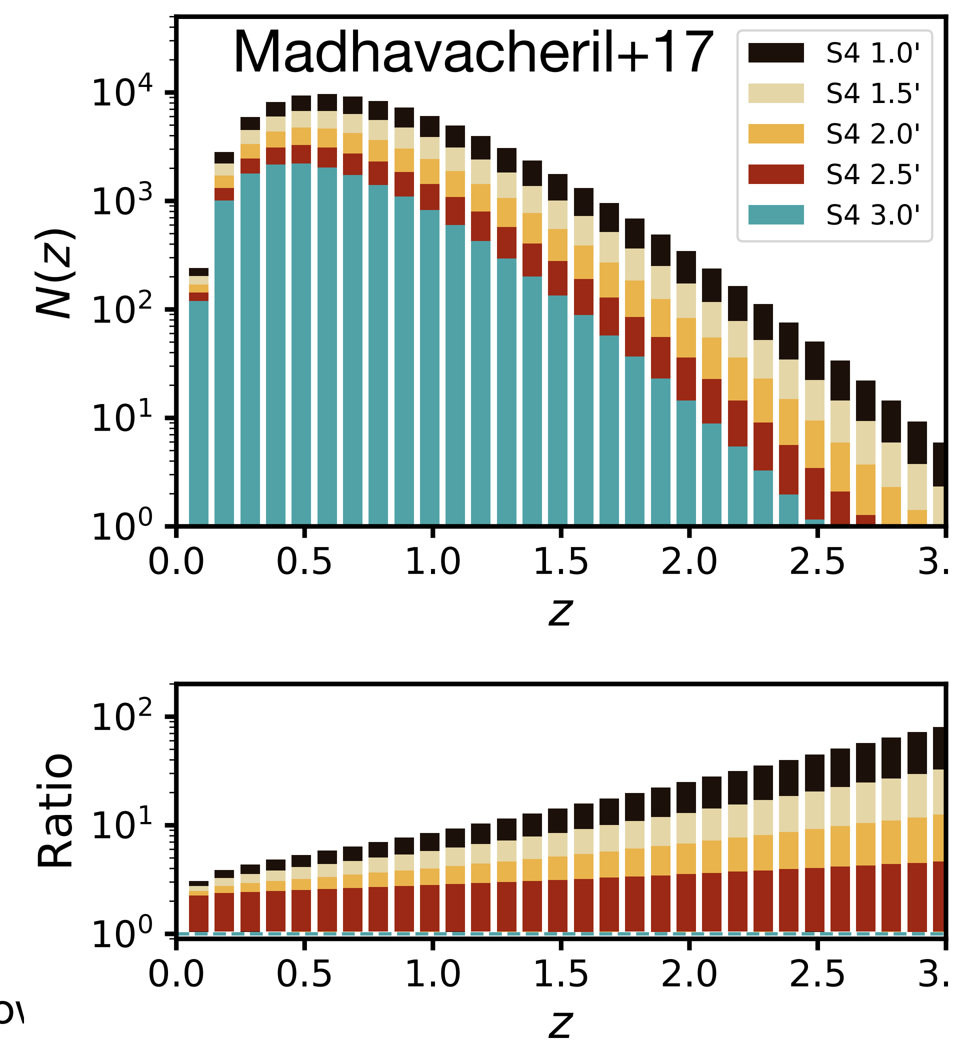
- Current “universal HMF” approach: extrapolate cosmology dependence
- Better: Use emulators to interpolate between numerical simulations of different cosmologies (for HMF: McClintock+18, Nishimichi+19)
- *Mira-Titan Universe*: first emulator suite to include massive neutrinos and dynamical dark energy (Heitmann+16)
- Use 111 (2.1 Gpc)^3 and (5 Gpc)^3 simulations covering 8 cosmological parameters and interpolate using Gaussian process (Bocquet+ to be submitted)
- Percent-level accuracy



SZ Effect-Selected Cluster Catalogs



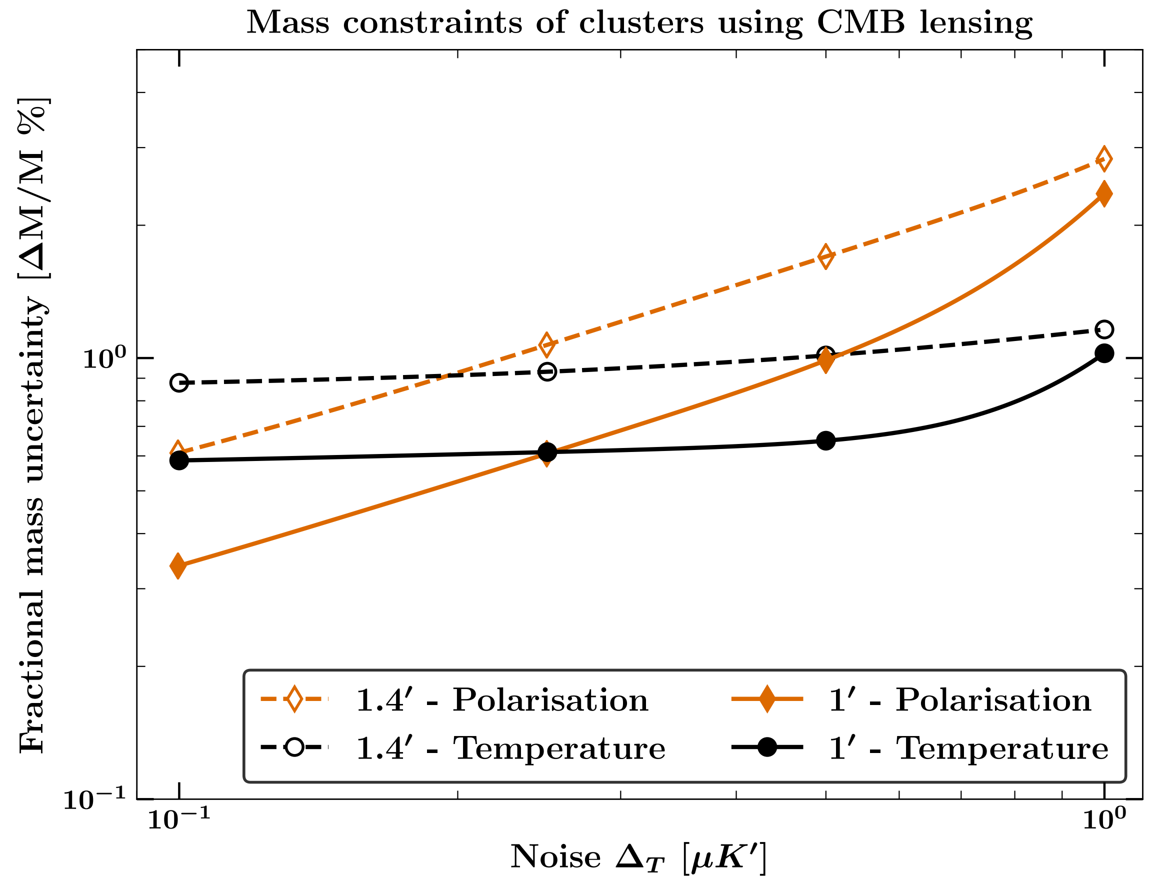




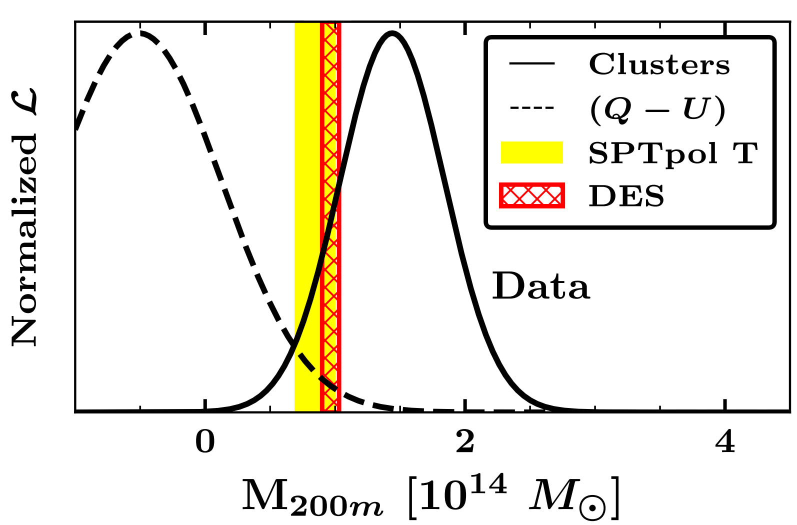
- Planck DR 2 ~1700 clusters
- ACT + ACTpol ~270
- SPT-SZ + SPTpol (deep 100d, shallow 2700d) ~1e3 clusters
- advACT and SPT-3G will each detect several 1e3 clusters

CMB Cluster Lensing

- CMB lensing not affected by galaxy lensing systematics such as shear or photo-*z* calibration
- Measurements now routinely performed using *Planck*, ACT, SPT temperature data
- CMB lensing using polarization detected (SPT, Raghunathan+19)

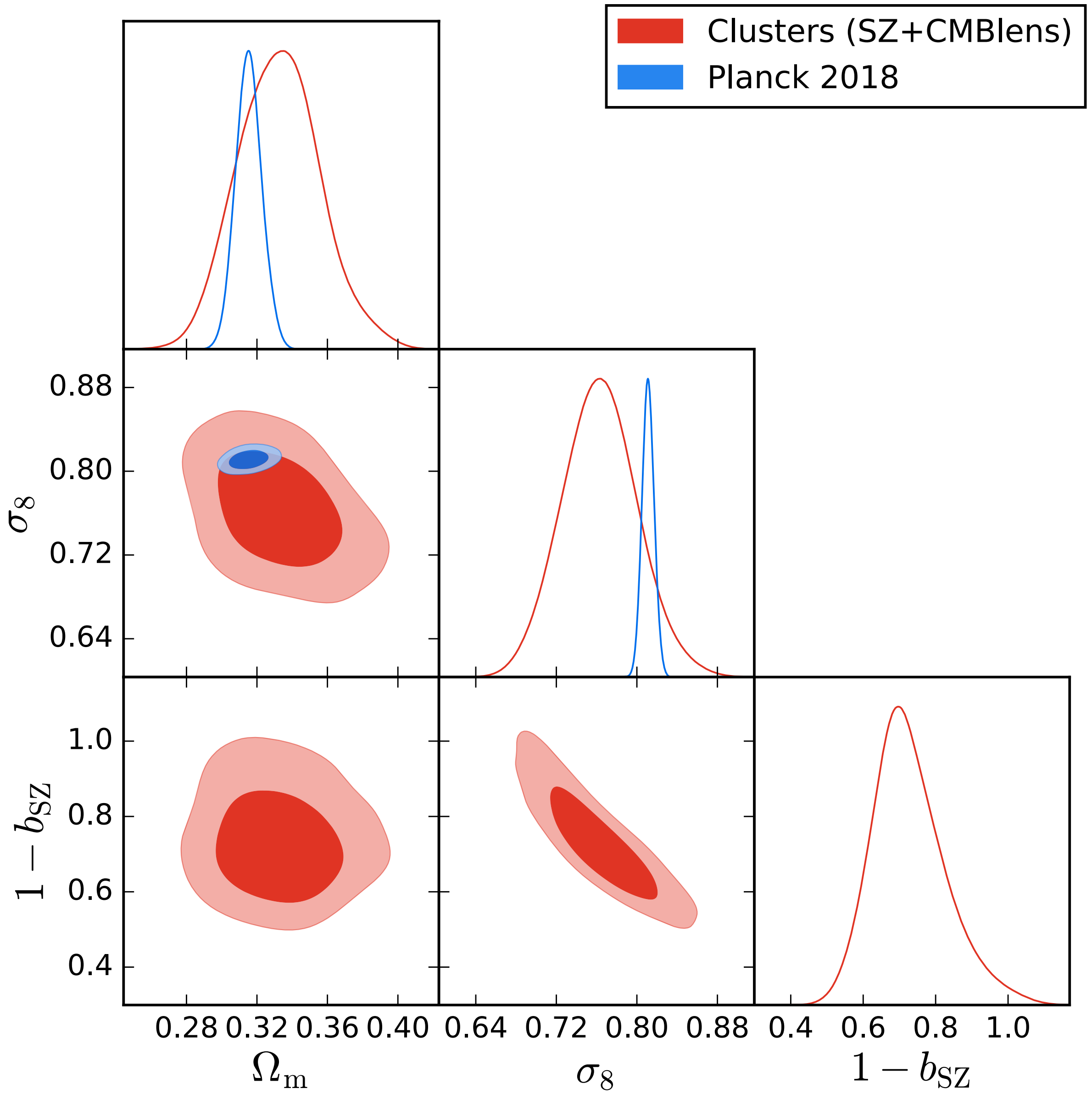


Future of CMB lensing (Basu+19, Delabrouille+19)



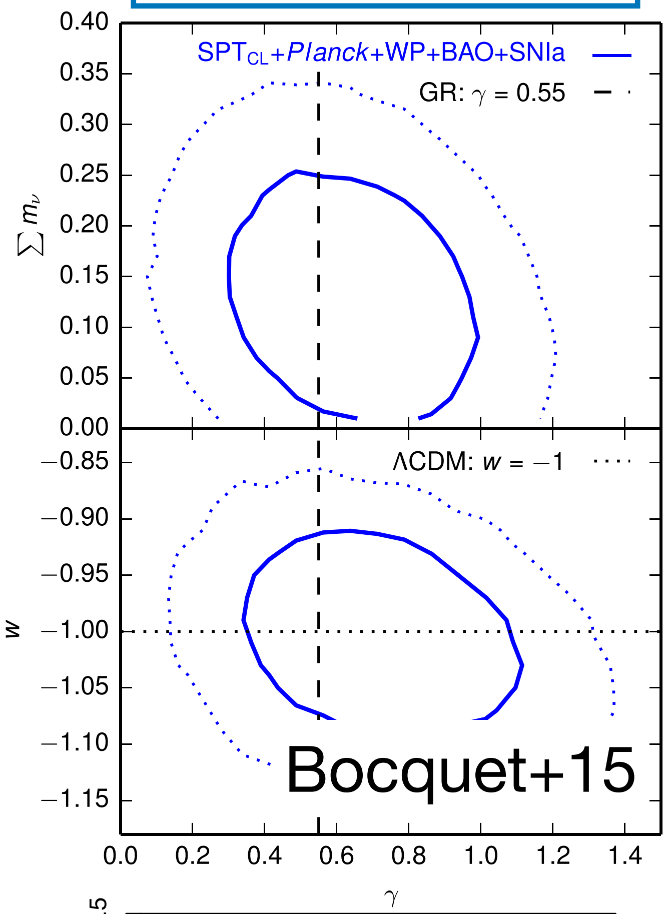
CMB lensing-calibrated cluster cosmology

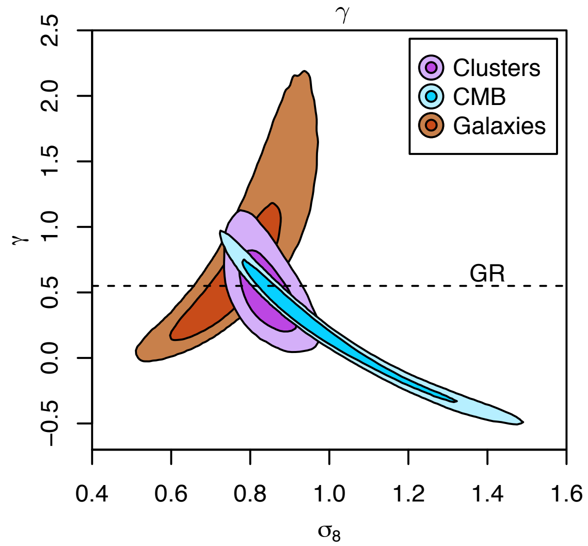
- First self-consistent cluster cosmology with mass calibration from CMB lensing (Zubeldia & Challinor 19)
- Cluster sample and lensing from *Planck* data

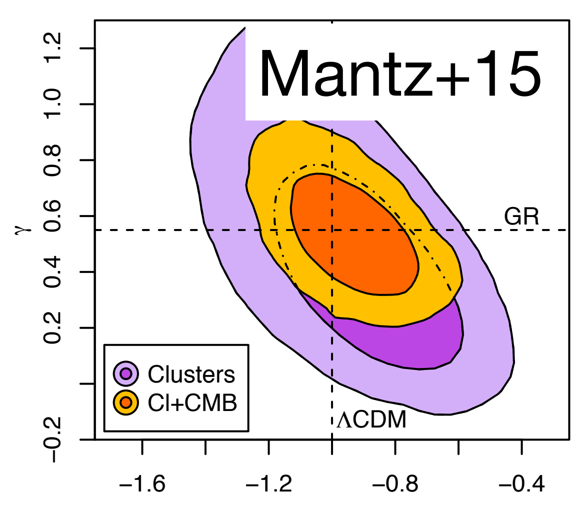


Growth of Structure: Present and Future

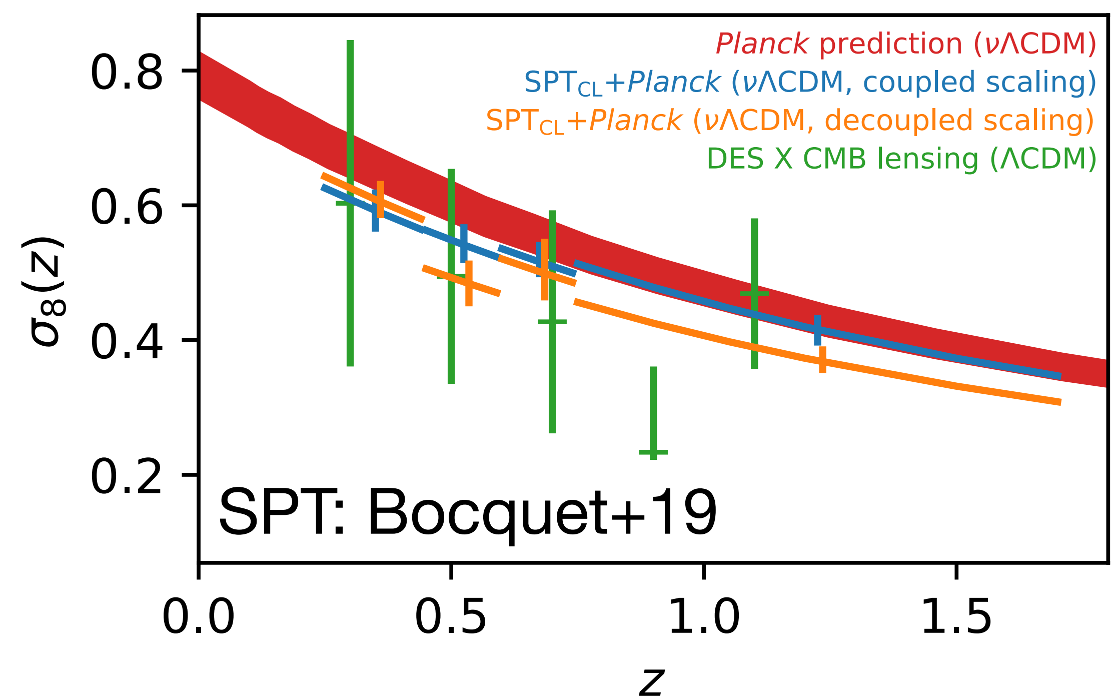
$$f(a) \equiv \frac{d\ln\delta}{d\ln a} = \Omega_m(a)^\gamma$$

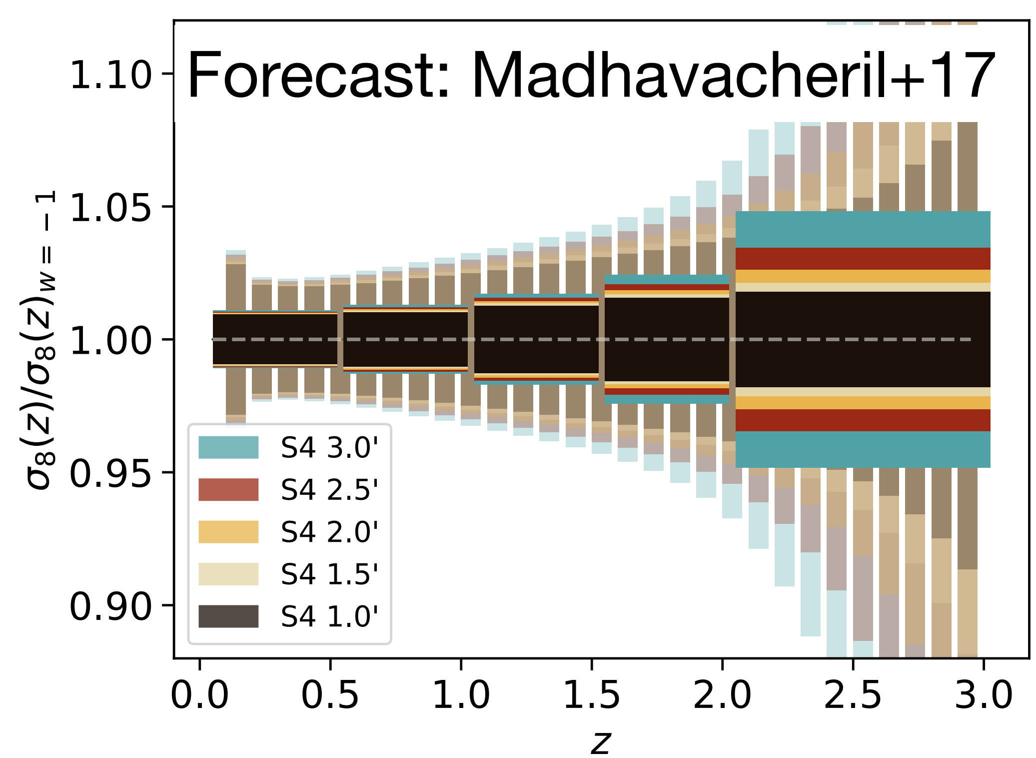




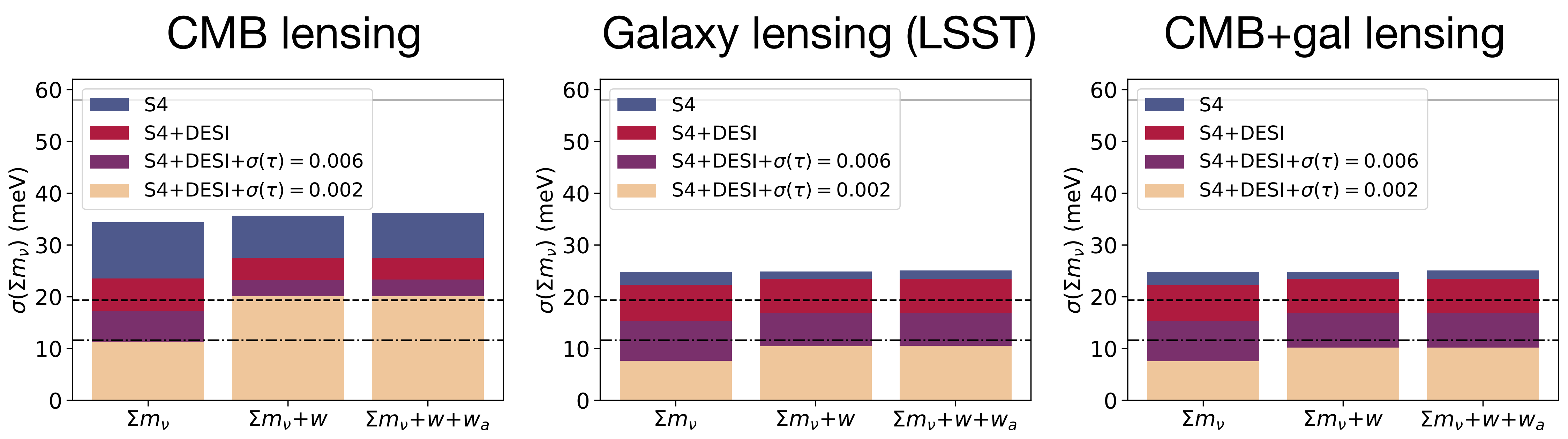


σ_8 as function of redshift





Sum of Neutrino Masses: Future



Bottomline (reminder): constraints on sum of neutrino masses do not significantly degrade when opening up cosmological parameter space (Madhavacheril+17)

Summary

- Data-driven cosmology from SZ effect-selected galaxy clusters
  - Multi-observable modeling framework
  - Weak-lensing mass calibration
- Galaxy WL samples are expanding thanks to the Dark Energy Survey, KiDS, HSC
- CMB lensing is catching up!
- First CMB stage 2 catalogs are available
- Expect tremendous improvements!