Weak-Lensing Calibrated Cluster Cosmology

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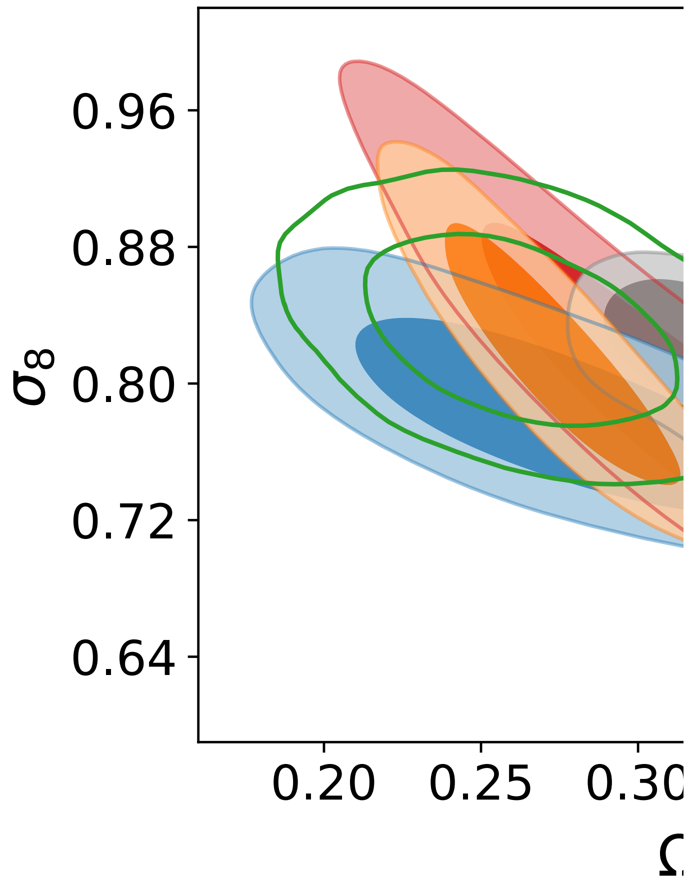
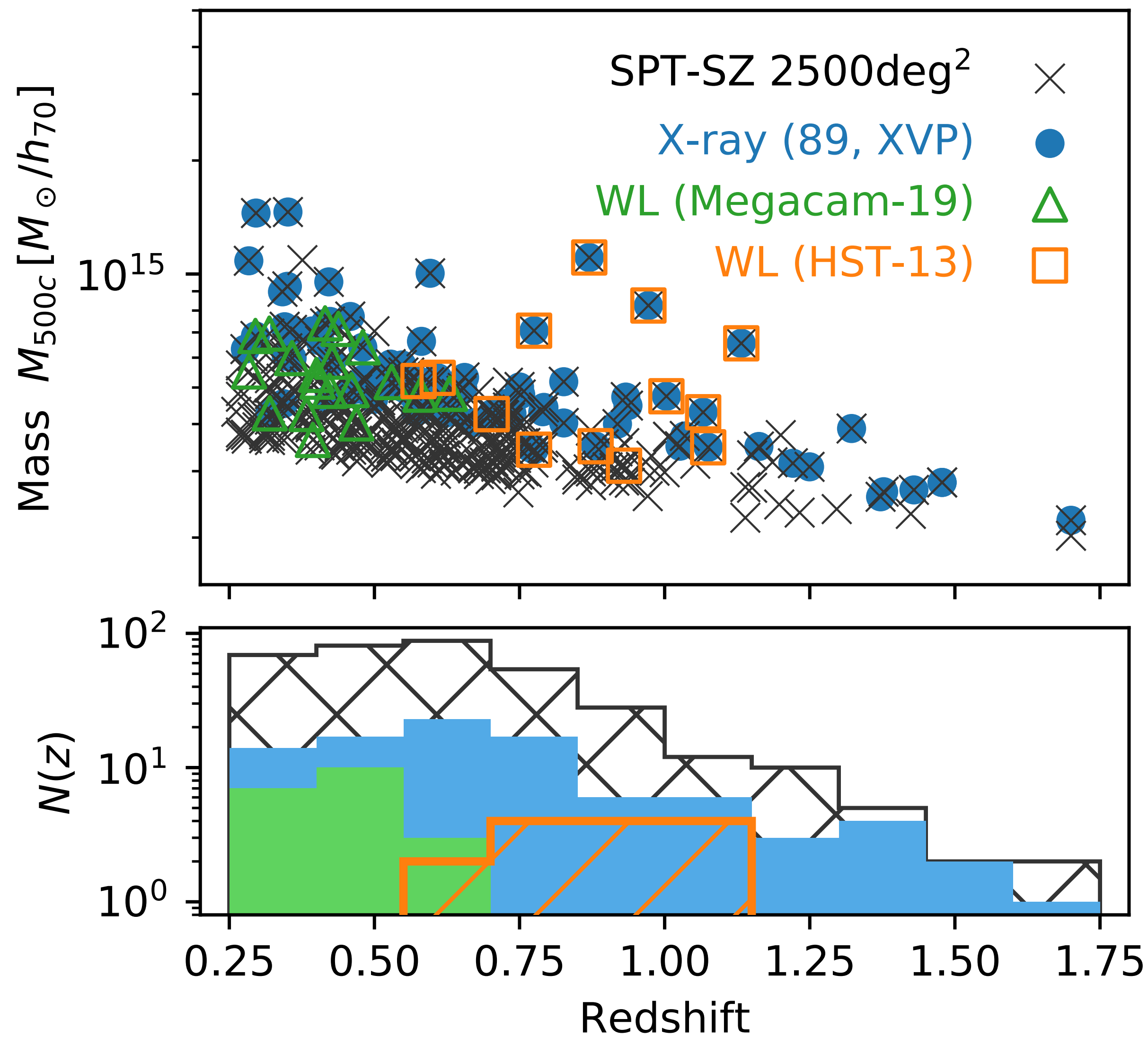
LCDM with varying sum of neutrino masses

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





How did we get here?

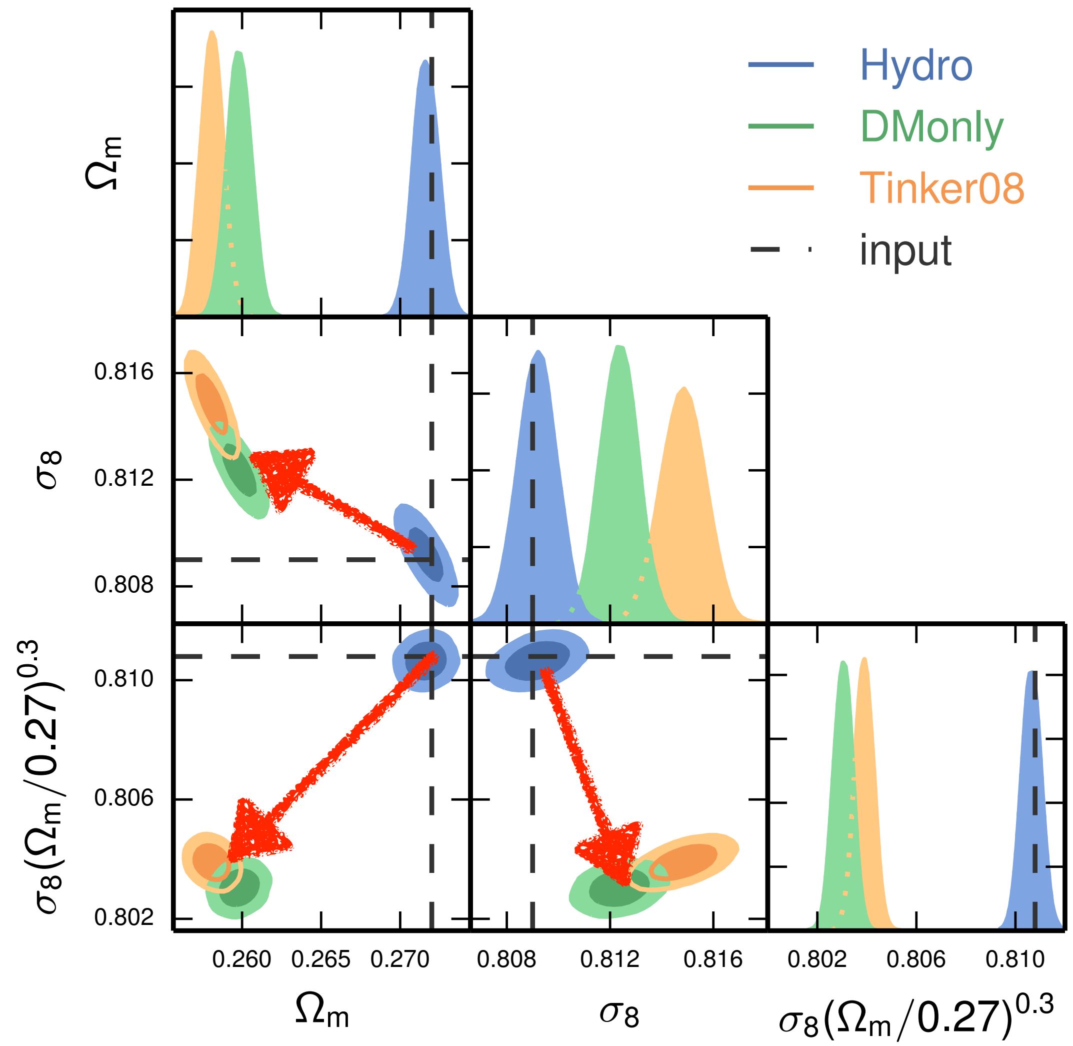
Premise: Modeling Framework

- 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 (yet?)
- **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 with %-level systematic uncertainty (calibrated against numerical simulations because we don't have perfectly centered NFW-profile halos)
  - We should account for correlated scatter between the different observables (correlation is introduced, e.g., by projecting onto the plane of the sky)
- Theory prediction for halo abundance from *N*-body simulations (Tinker+08)

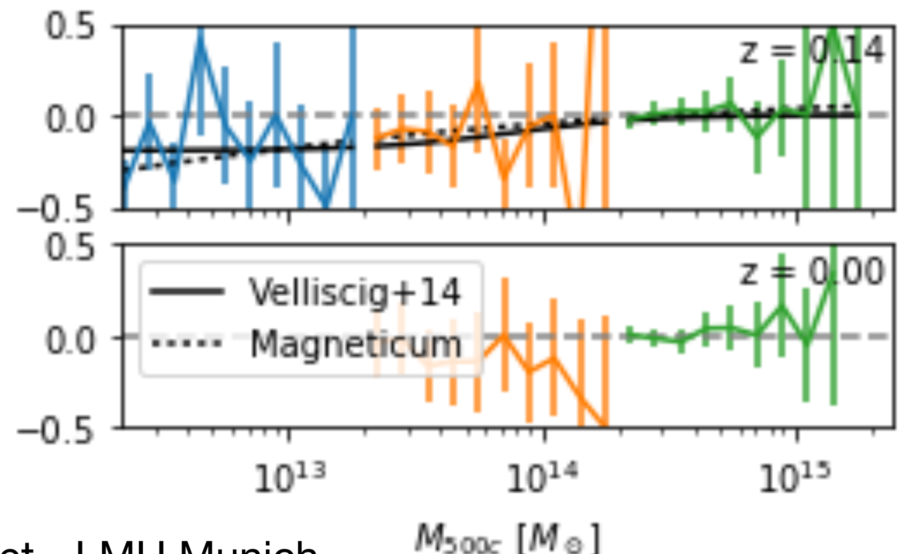
Baryons and the Halo Mass Function

Bocquet et al. 2016, MNRAS 456, 2361

- At fixed halo mass, feedback processes change the abundance
- Use hydrodynamical *Magneticum Pathfinder* simulation suite (Dolag et al., www.magneticum.org)
- Up to (2688 Mpc/h)^3 to sample high-mass halos
- Hydro effects are important for upcoming studies using M < ~1e14 Msun

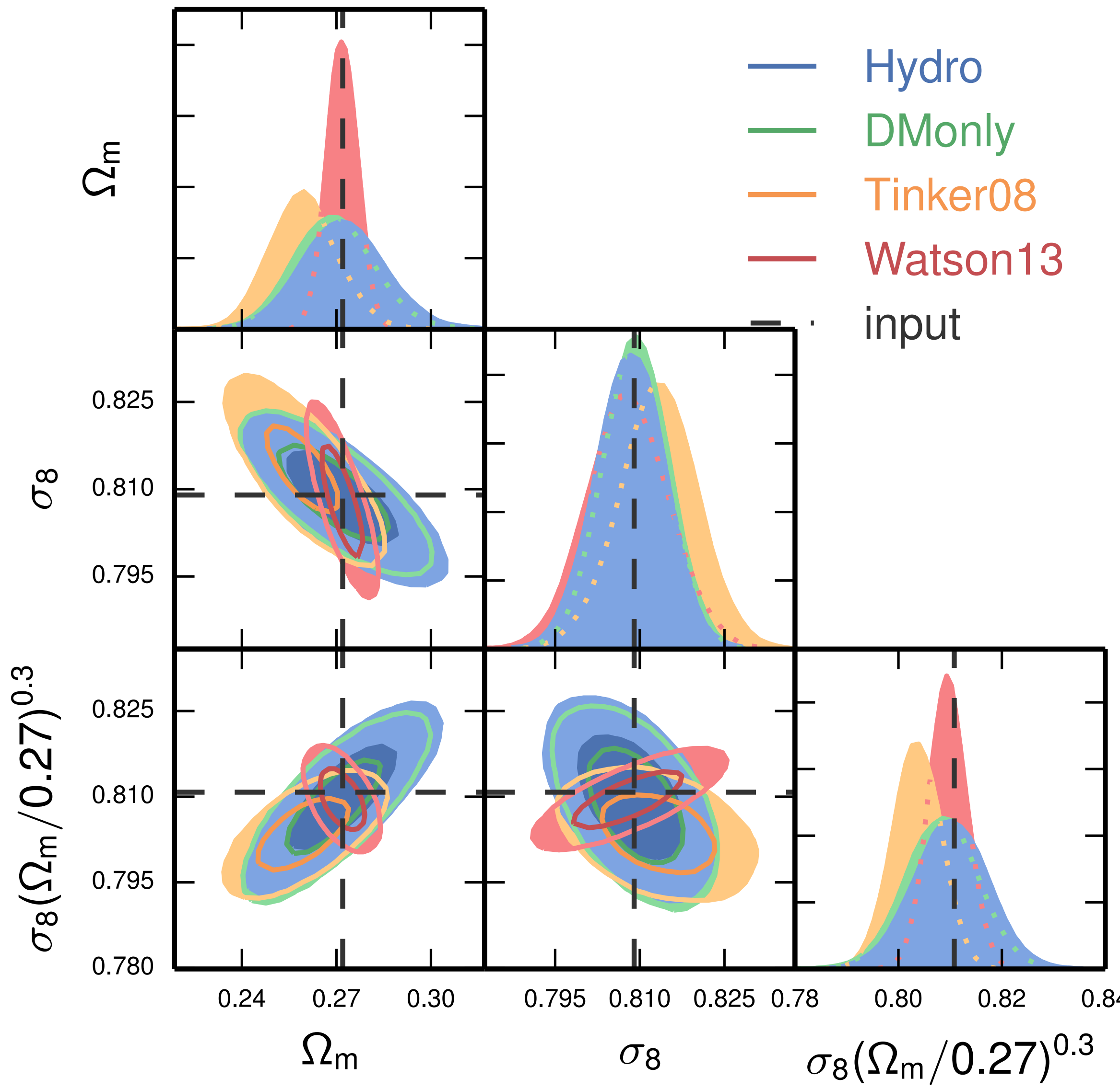


Biases if effect of hydro is ignored for eROSITA-like surveys with M > 7e13 Msun



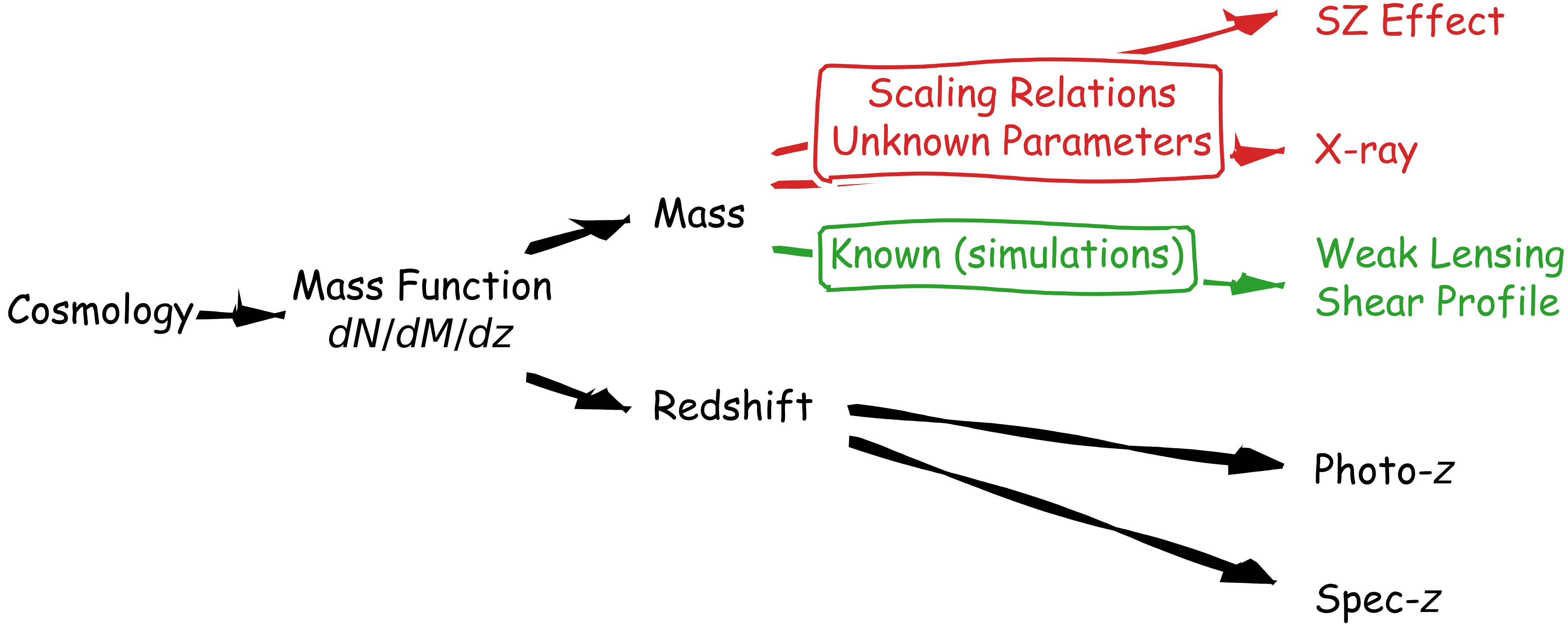
Impact of Feedback on HMF for SPT: None?

Bocquet et al. 2016, MNRAS 456, 2361



Magneticum Pathfinder **hydro simulations (Dolag et al.)**

Forward-Modeling Analysis Strategy



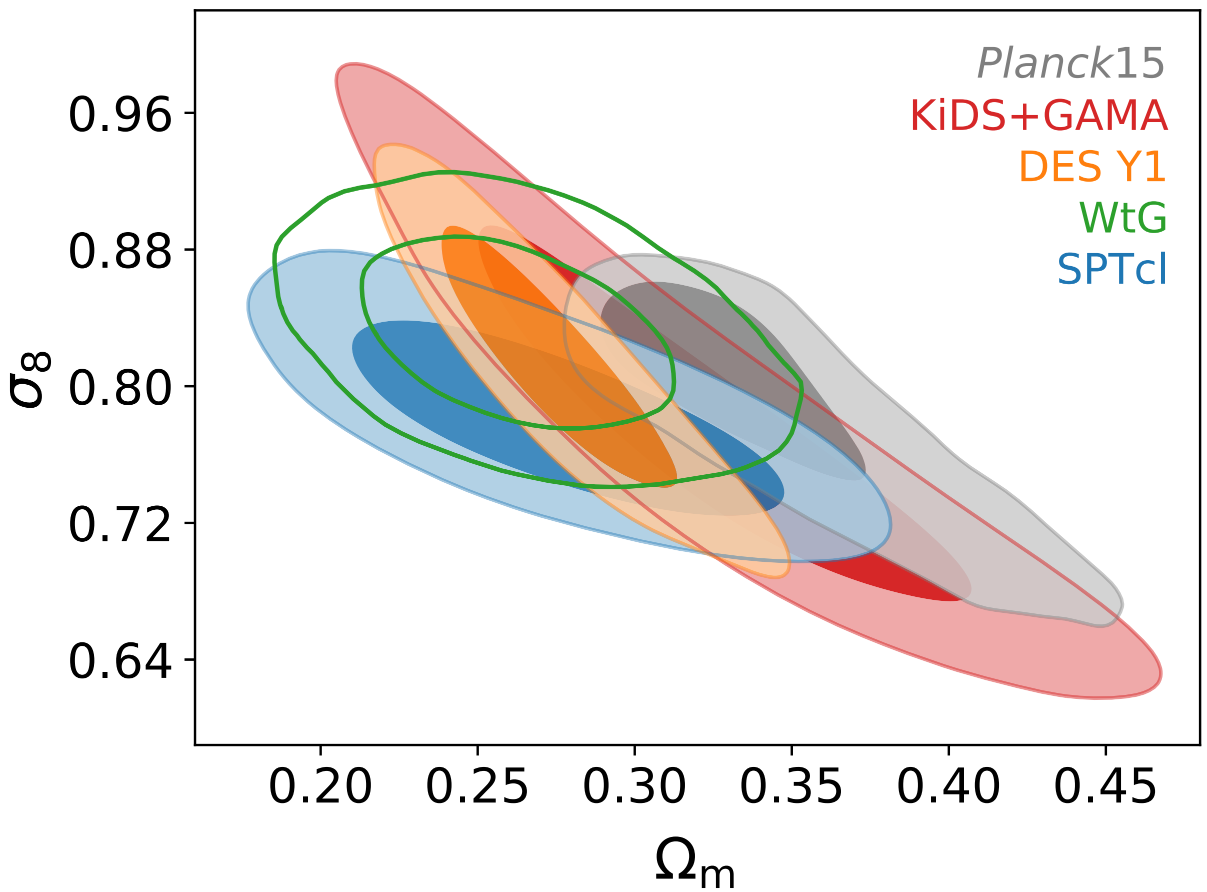
Use the known relation
mass -> weak lensing shear profile
to calibrate
mass -> SZ effect and mass -> X-ray

Simultaneous analysis of all observables and cosmology to capture all covariances

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*15 TT+lowTEB

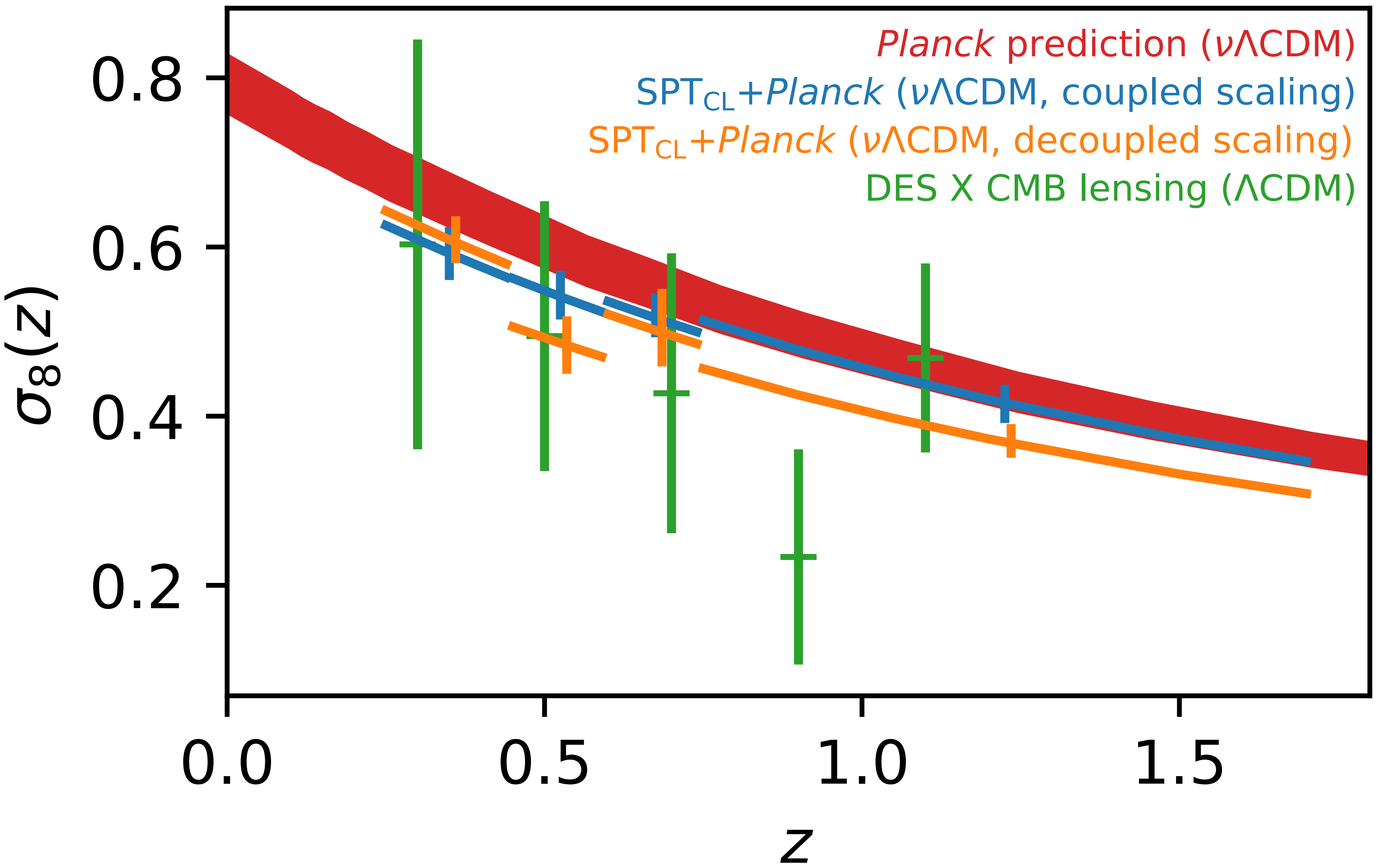


Linear Growth of Structure

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

Blue error bars: ***Planck*** **constrains the geometry of the Universe only, clusters constrain growth.**

Orange error bars: More freedom in observable—mass relation

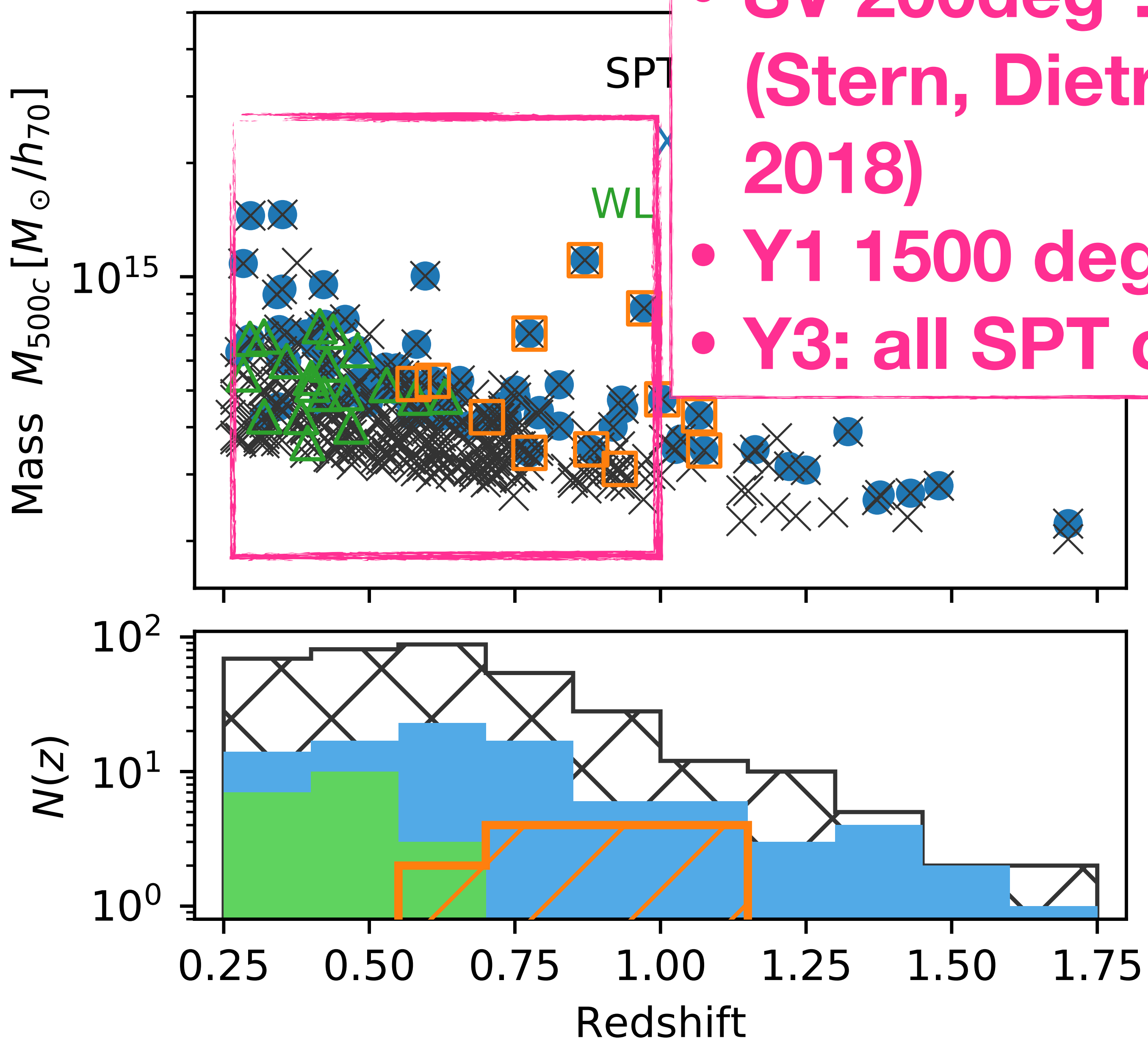


How are we going to improve?

The Dark Energy Survey

- CTIO Blanco Telescope
- 5000 square degrees in *grizy*
- Survey is complete — analysis of Y3 data ongoing
- Strategically overlaps the SPT survey

SPT Clusters + DES Weak Lensing

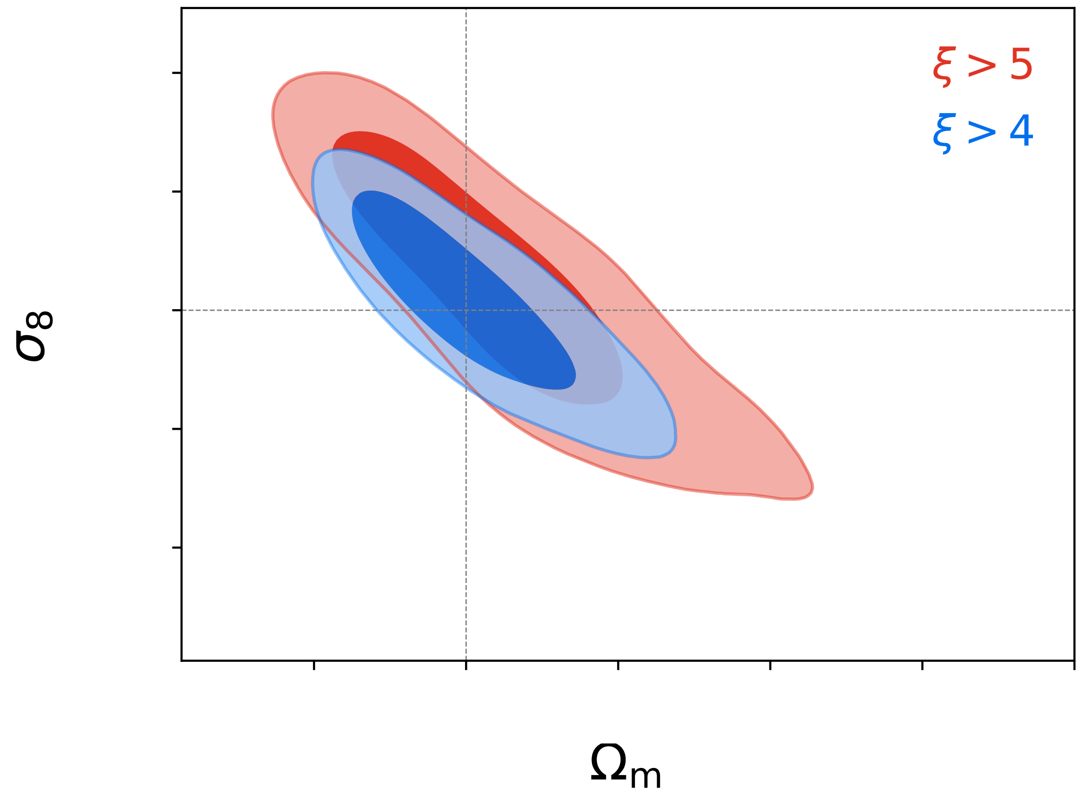


WL calibration from DES

- **SV 200deg²: 34 clusters (Stern, Dietrich, Bocquet+ 2018)**
- **Y1 1500 deg²**
- **Y3: all SPT clusters z < 1**

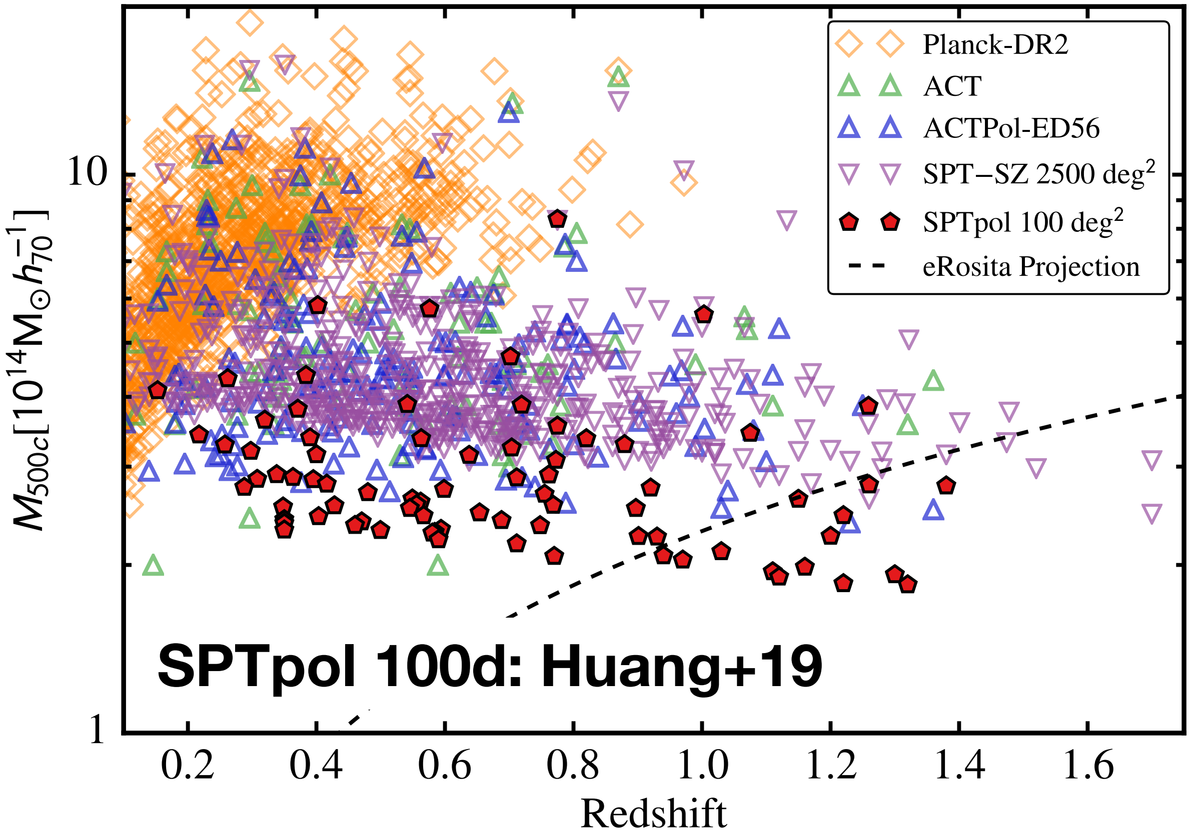
SPTcluster + DES WL Analysis Pipeline

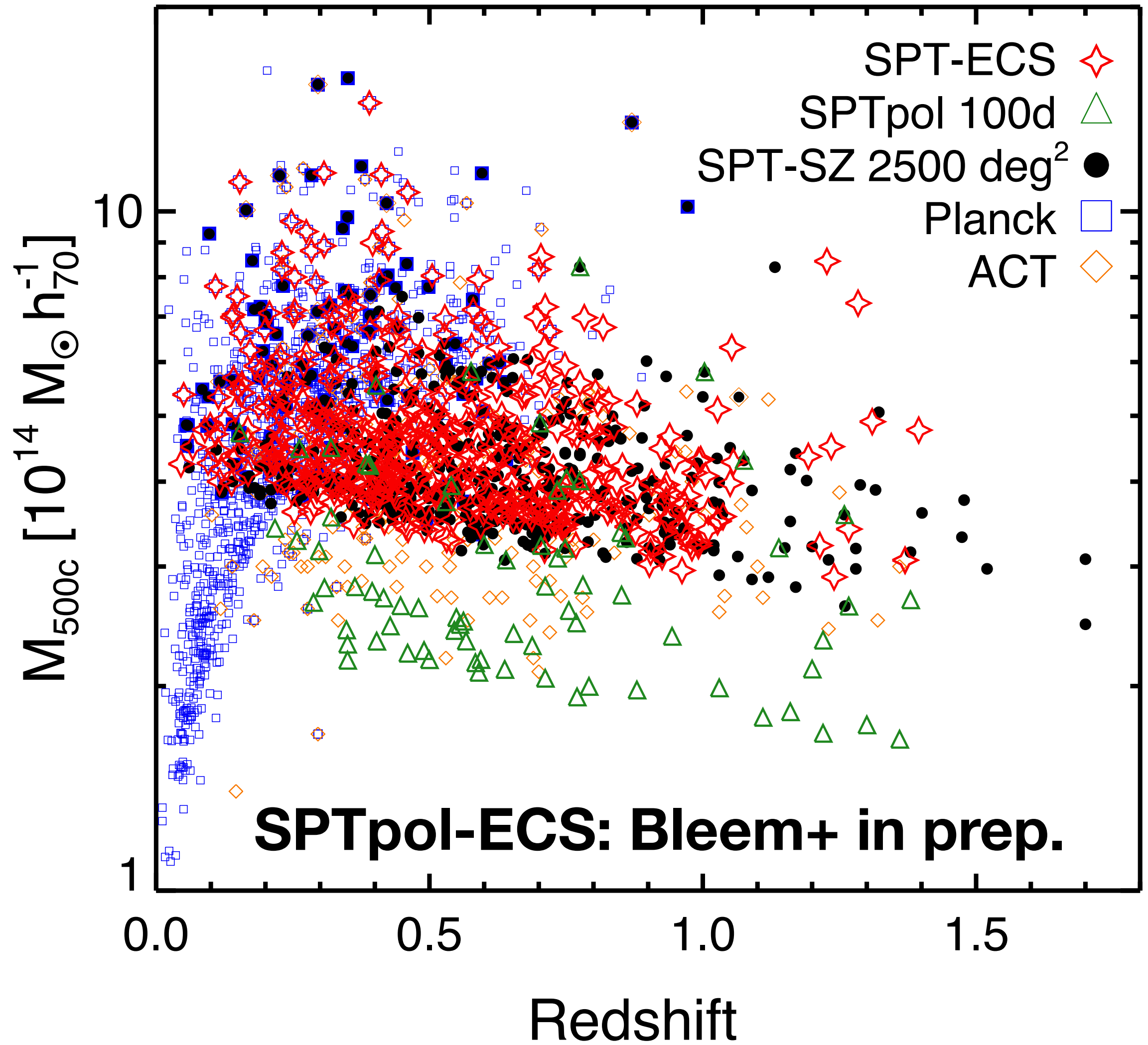
- Opportunity to make several improvements
  - Better cluster member contamination correction (Maria Paulus, Joe Mohr)
  - Explicitly marginalize over halo concentration for each halo
  - Forward-model lensing miscentering (more flexibility)
- Pipeline validation against full-scale mocks
- Data analysis will be performed blindly



Pipeline validation against complete mocks (Bocquet+ in prep.)

Clusters in the SPTpol Survey





SPTpol 100d "deep field"

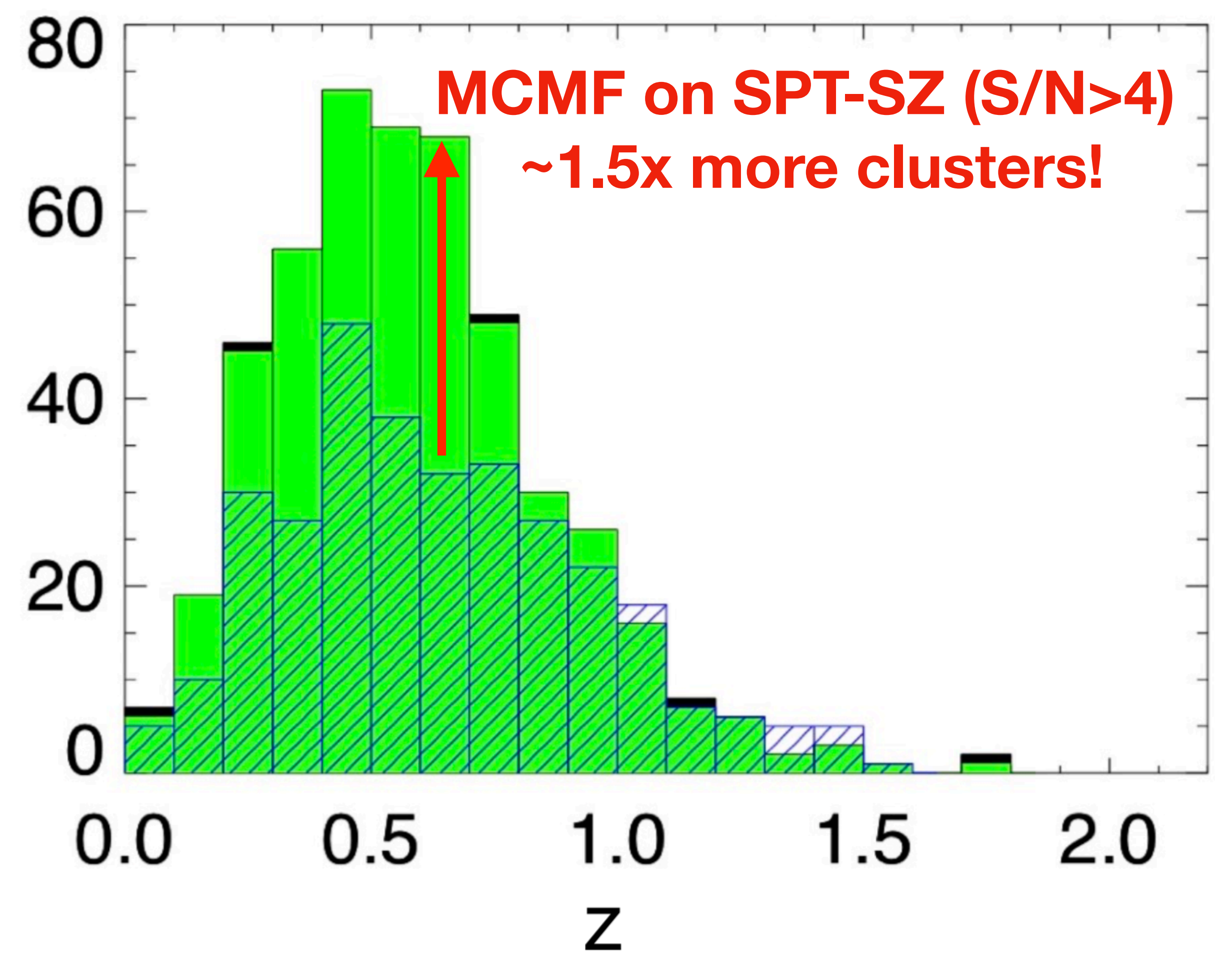
- 3—4x deeper than SPT-SZ
- deeper = lower-mass clusters
- ~1 cluster per deg2

SPTpol 2700d "Extended Cluster Survey"

- ~*Planck* depths
- Brings total number of SPT clusters to >1000

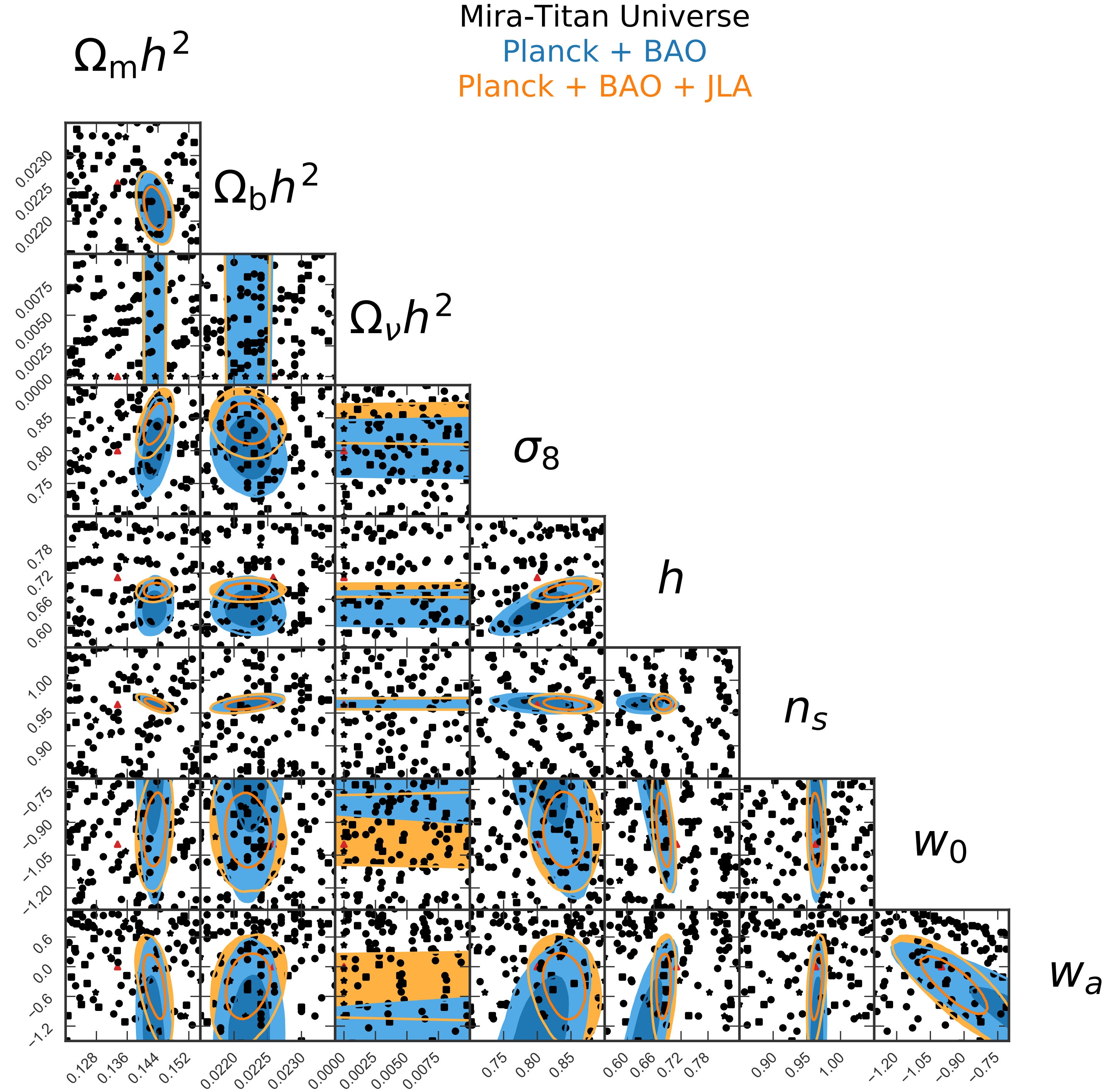
Better Exploitation of SZ Data: Multi-Component Matched Filter (MCMF)

- Use DES+WISE to identify OIR counterparts near SPT cluster candidates
- Enables ~1.5x more clusters to lower detection SNR
- Klein+18, Klein+19



Cosmology Dependence of Halo Mass Function

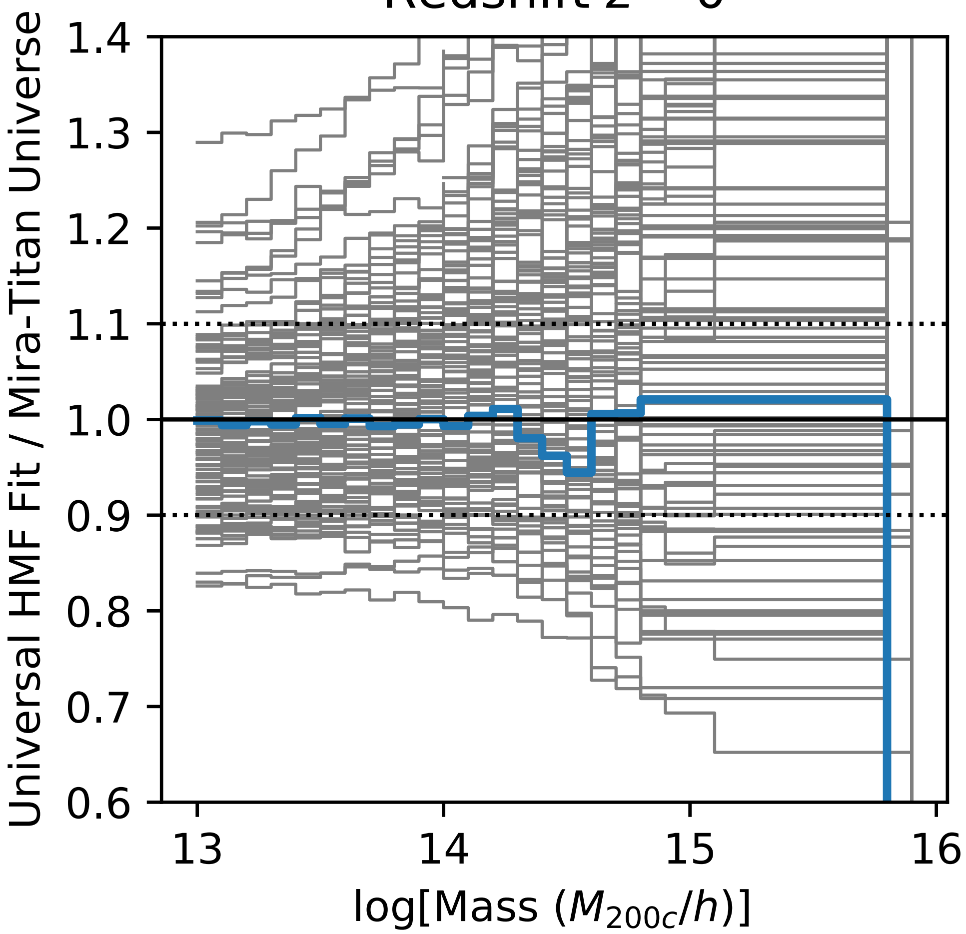
- Current "universal HMF" approach: extrapolate cosmology dependence
- Better: Use emulators to interpolate between numerical simulations of different cosmologies
(Aemulus: McClintock+18, Dark Quest: Nishimichi+19)
- *Mira-Titan Universe*: first emulator suite to include massive neutrinos and dynamical 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)



The Need for an HMF Emulator: Extreme example for $w_0 w_a$CDM + Σm_ν

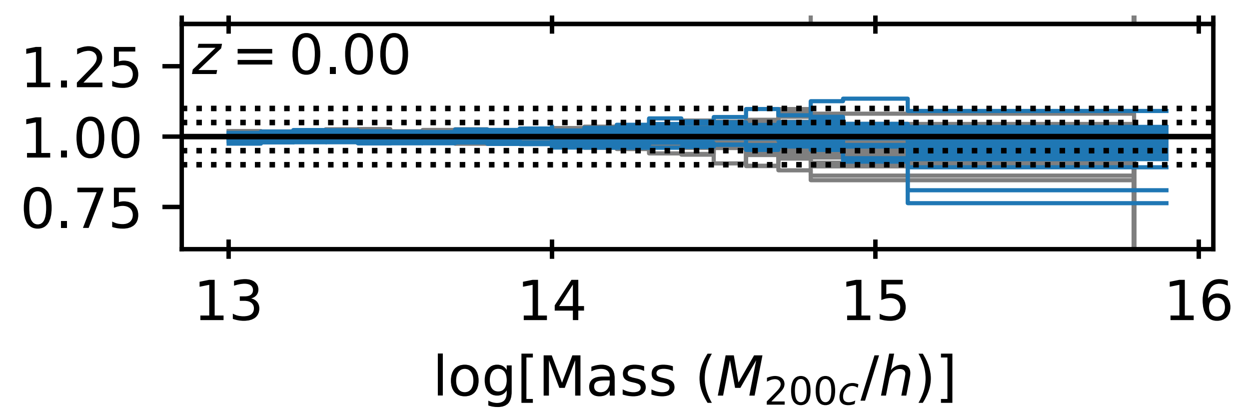
Universal HMF

Redshift $z = 0$



Emulator

(Bocquet, Habib, Heitmann, in prep.)



Summary

- Data-driven cosmology from SPT galaxy clusters
  - Multi-observable modeling framework
  - Weak-lensing mass calibration
- WL sample is expanding thanks to the Dark Energy Survey, HST programs, and CMB lensing
- SPTpol cluster catalogs being published
  - Optical follow-up of SPT-3G high-*z* clusters started tonight!
- HMF emulation
- Exciting times ahead!

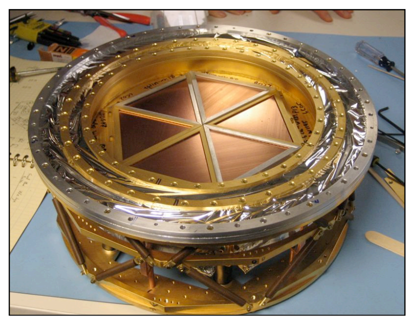
Backup Slides

The South Pole Telescope (SPT)

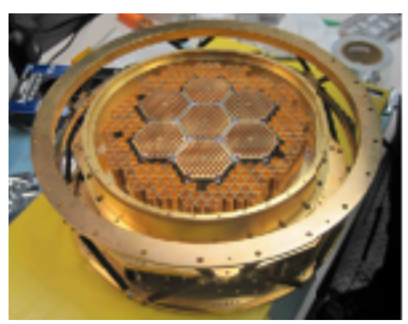
10-meter sub-mm quality wavelength telescope

95, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

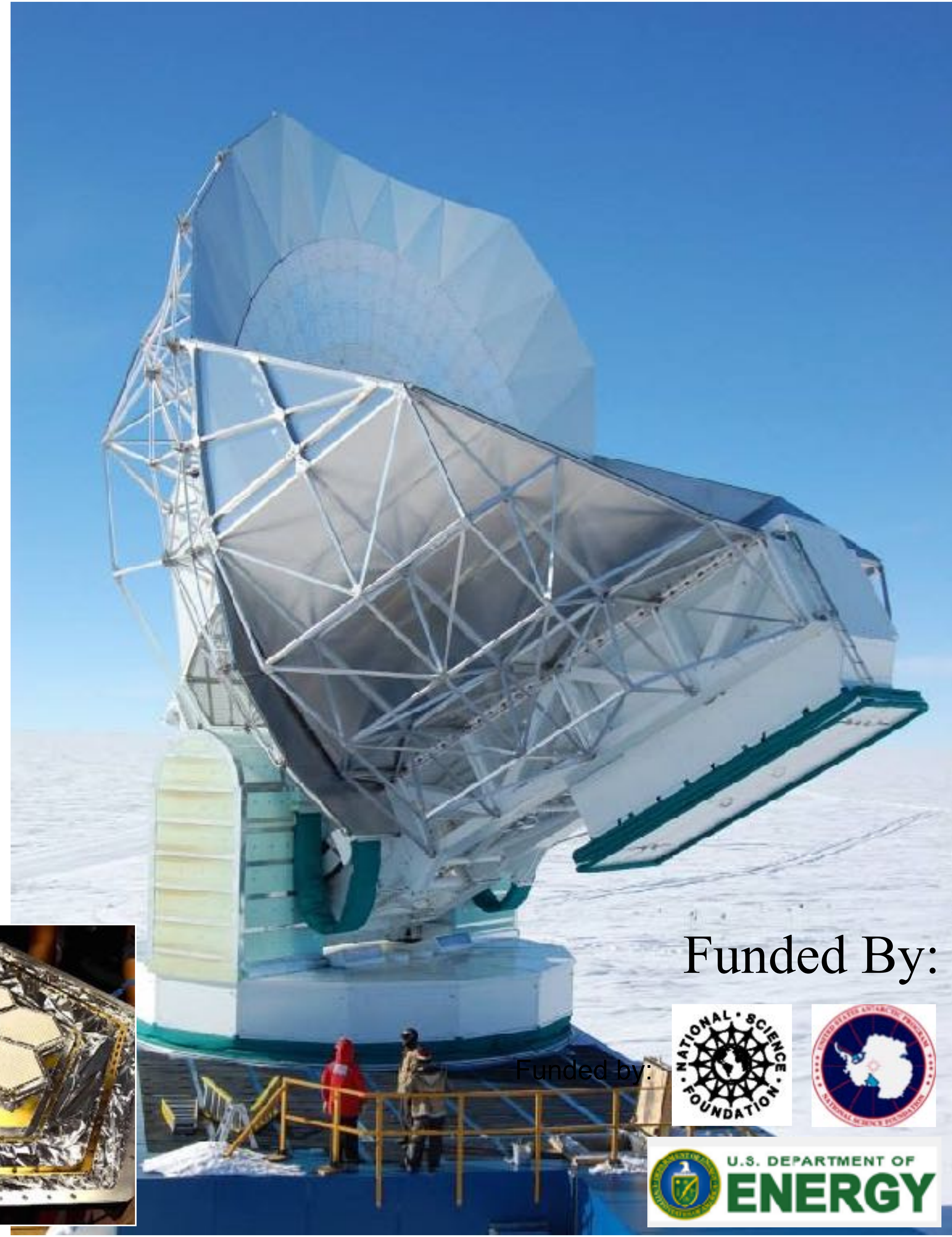
2007: SPT-SZ
960 detectors
95,150,220 GHz



2012: SPTpol
1600 detectors
90,150 GHz
+Polarization



2016: SPT-3G
~16,200 detectors
95,150, 225 GHz
+Polarization



Funded By:

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Weak-Lensing Bias and Scatter

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

- WL is a biased mass estimator because we fit an NFW profile
- Simulation calibration:
  - NFW profile mismatch
  - Miscentering
  - Correlated LSS
- Other systematics:
  - Cluster member contamination
  - Shear and photo-z bias
- We are currently limited by the number of WL clusters, but that will change!

Effect	Impact on Mass	
	Megacam	HST
WL mass bias	0.938	0.81 – 0.92
Intrinsic scatter	0.214	(0.26 – 0.42)
Δ(intrinsic scatter)	0.04	0.021 – 0.055
Uncorr. LSS scatter [$M_\odot$]	9×10^{13}	8×10^{13}
Δ(Uncorr. LSS scatter) [$M_\odot$]	10^{13}	10^{13}
Mass modeling uncertainty	4.4%	5.8 – 6.1%
Systematic measurement uncert.	3.5%	7.2%
Total systematic uncertainty	5.6%	9.2 – 9.4%

19 clusters **13 clusters**

Multi-Observable—Mass Relation

Mean relations

SZ

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

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

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

Covariance matrix

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

Multi-obs relation

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

3 + 3 + 1 parameters for mean relations

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

Likelihood Function in Observable Space

Poisson likelihood for cluster abundance

Selection
xi >5, z>0.25

$$\ln \mathcal{L}(\vec{p}) = \sum_i \ln \frac{dN(\xi, z, \vec{p})}{d\xi dz}\Big|_{\xi_i, z_i} - \iint d\xi dz \Theta_{\text{survey}} \frac{dN(\xi, z, \vec{p})}{d\xi dz}$$

$$+ \sum_j P(Y_{\text{X}}, g_{\text{t}} | \xi_j, z_j, \vec{p})\Big|_{Y_{\text{X}_j}, g_{\text{t}j}}$$

Total predicted number

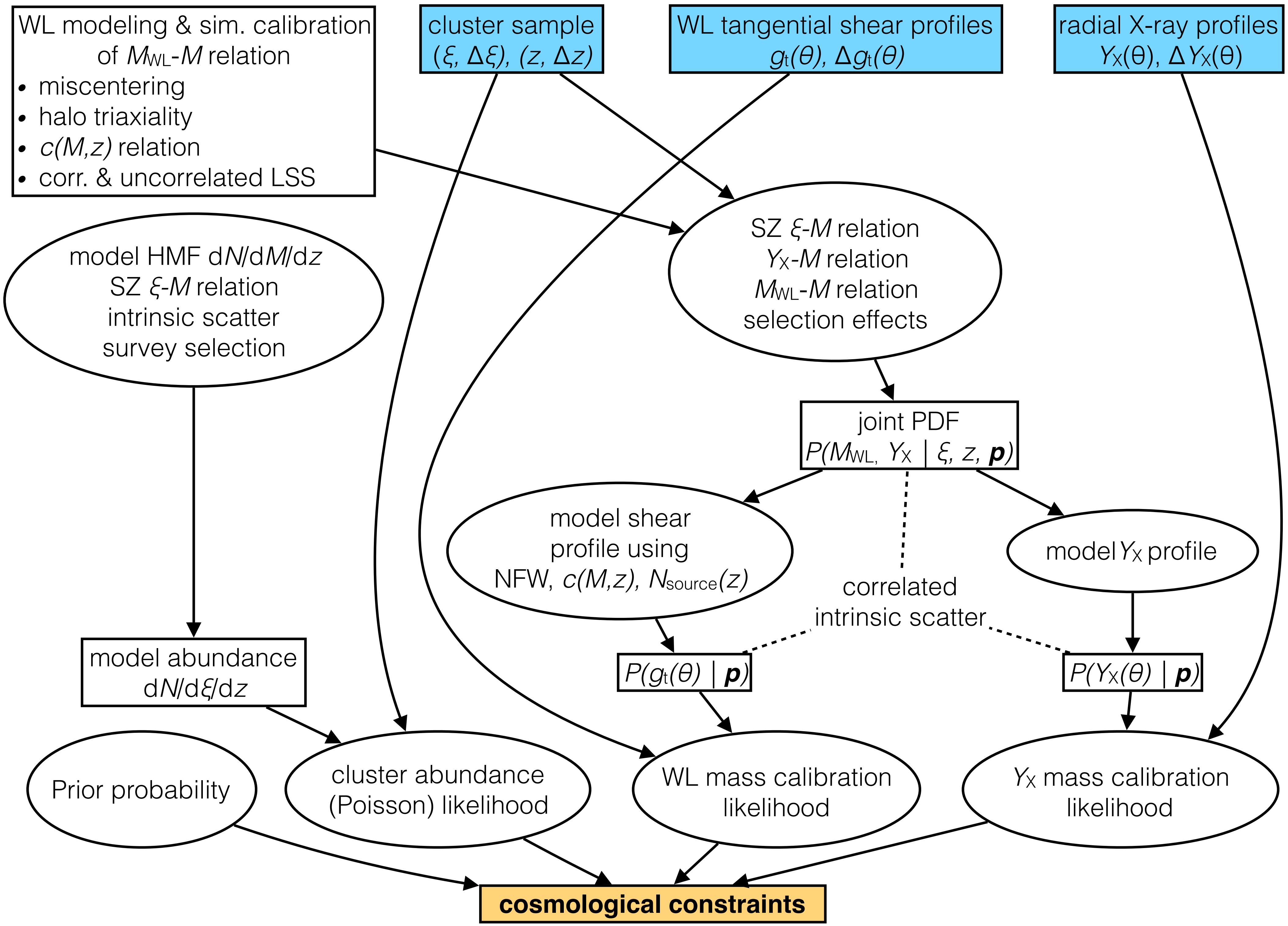
Mass calibration

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

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

Analysis workflow

Bocquet+ (arXiv: 1812.01679)



Pipeline Validation, Parameters, and Priors

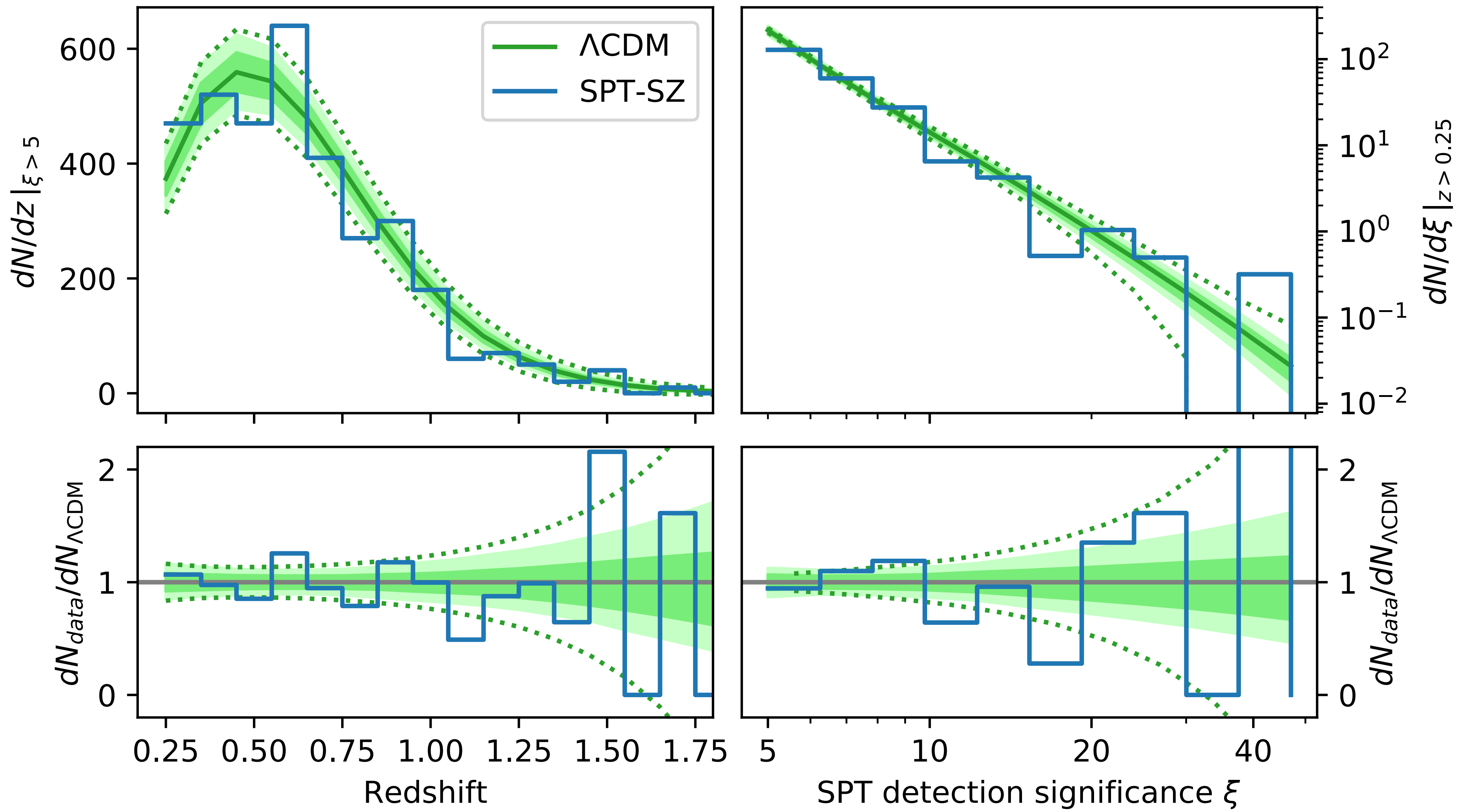
Bocquet et al. 2019ApJ...878...55B

- Pipeline validation against mocks:
  - Draw halos from HMF
  - Assign multivariate observable distribution
  - Mock creation is easier than actual analysis (otherwise, this test is pointless!)
- Any remaining bias in analysis pipeline is small compared to uncertainty from real data
- Validate zero point (HMF) against independent implementations

Parameter	Prior
Cosmological	
Ω_m	$\mathcal{U}(0.05, 0.6)$, $\Omega_\mathrm{m}(z > 0.25) > 0.156$
$\Omega_\mathrm{b} h^2$	$\mathcal{U}(0.020, 0.024)$
$\Omega_\nu h^2$	$\mathcal{U}(0, 0.01)$
Ω_k	fixed (0)
A_s	$\mathcal{U}(10^{-10}, 10^{-8})$
h	$\mathcal{U}(0.55, 0.9)$
n_s	$\mathcal{U}(0.94, 1.00)$
w	fixed (-1) or $\mathcal{U}(-2.5, -0.33)$
Optical depth to reionization	
τ	fixed or $\mathcal{U}(0.02, 0.14)$
SZ scaling relation	
A_SZ	$\mathcal{U}(1, 10)$
B_SZ	$\mathcal{U}(1, 2.5)$
C_SZ	$\mathcal{U}(-1, 2.5)$
$\sigma_{\ln\zeta}$	$\mathcal{U}(0.01, 0.5)$ $(\times\mathcal{N}(0.13, 0.13^2))$
X-ray Y_X scaling relation	
A_{Y_X}	$\mathcal{U}(3, 10)$
B_{Y_X}	$\mathcal{U}(0.3, 0.9)$
C_{Y_X}	$\mathcal{U}(-1, 0.5)$
$\sigma_{\ln Y_\mathrm{X}}$	$\mathcal{U}(0.01, 0.5)$
$d\ln M_\mathrm{g}/d\ln r$	$\mathcal{U}(0.4, 1.8) \times \mathcal{N}(1.12, 0.23^2)$
WL modeling	
$\delta_\mathrm{WL,bias}$	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
δ_Megacam	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
δ_HST	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
$\delta_\mathrm{WL,scatter}$	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
$\sigma_{\mathrm{WL,LSS}_\mathrm{Megacam}}$	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
$\sigma_{\mathrm{WL,LSS}_\mathrm{HST}}$	$\mathcal{U}(-3, 3) \times \mathcal{N}(0, 1)$
Correlated scatter	
$\rho_\mathrm{SZ-WL}$	$\mathcal{U}(0, 1)$
$\rho_\mathrm{SZ-X}$	$\mathcal{U}(0, 1)$
$\rho_\mathrm{X-WL}$	$\mathcal{U}(0, 1)$
	$\det(\mathbf{\Sigma}) > 0$

Goodness of Fit Test: Passed

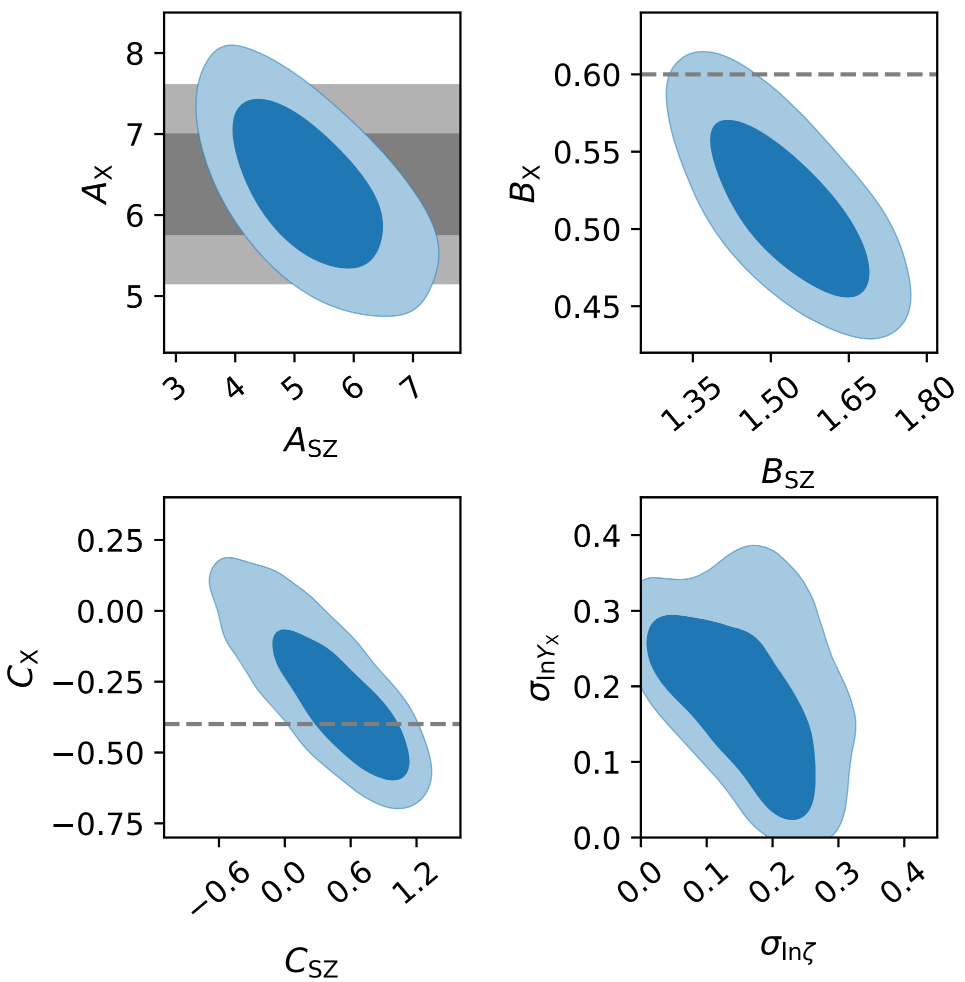
Bocquet et al. 2019ApJ...878...55B

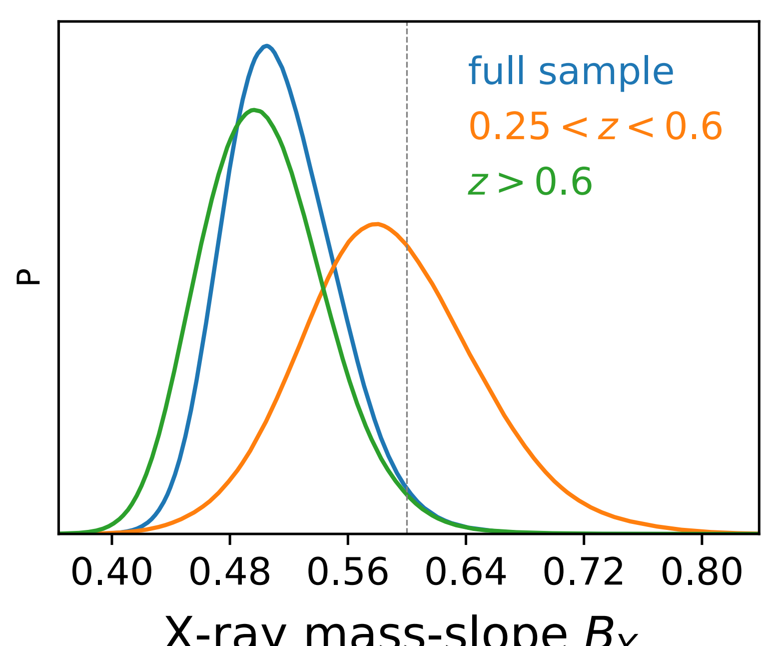


- Number counts test statistic (Kaastra 17)
  - *C*(model) = 439.8 +/- 26.8
  - *C*(data) = 449.3

X-ray Scaling Relation

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

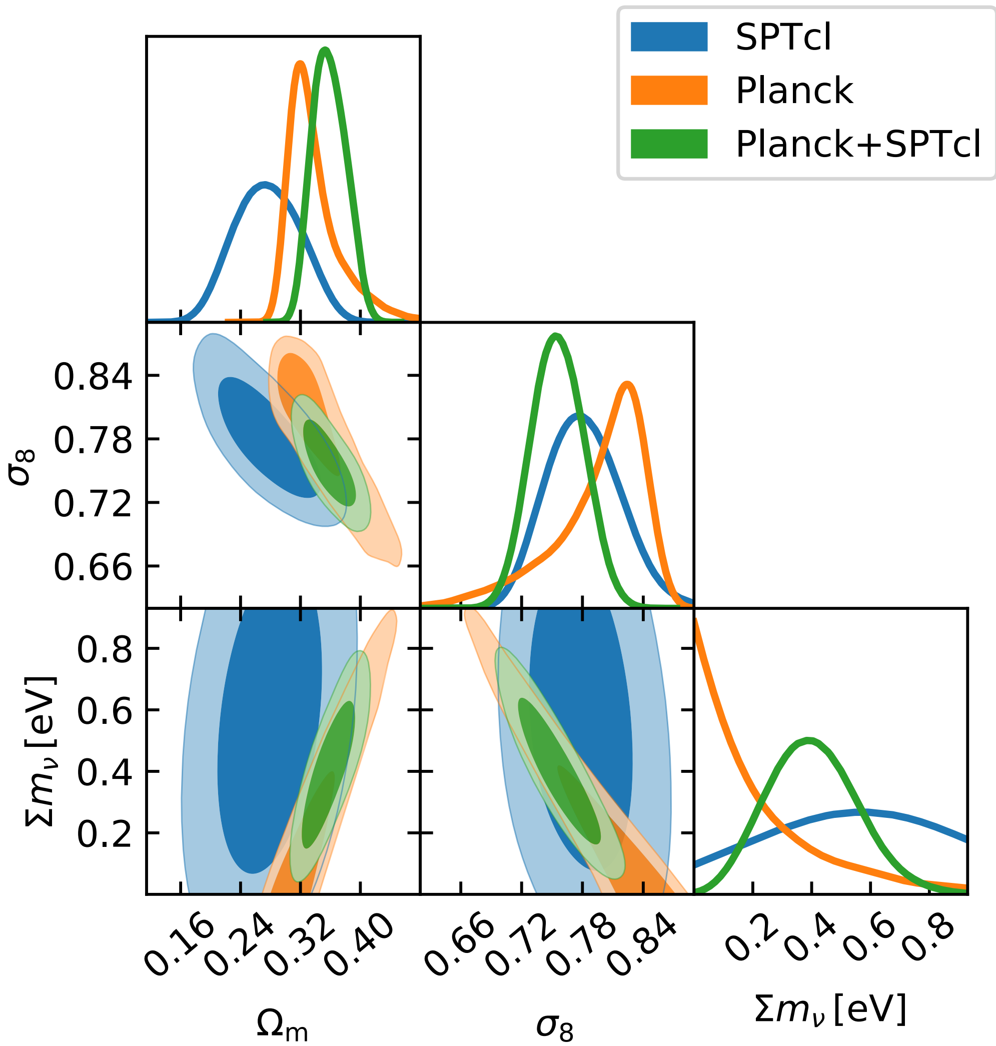


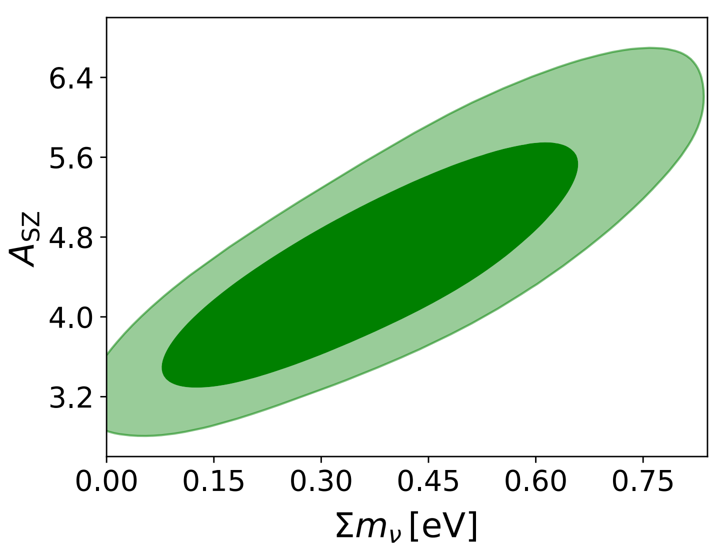


- Constraints on X-ray scaling relations as a “byproduct”
- Self-similar model prediction if non-thermal pressure support is negligible
- Redshift evolution is self-similar
- Mass evolution is steeper than self-similar
    - Low-redshift half ($0.25 < z < 0.6$) in $< 1\ \sigma$ agreement with the standard self-similar evolution
    - High-redshift half ($z > 0.6$) shows signs of departure at ~3 σ level
- Very similar story when using M_{gas} instead of Y_X
- Also consistent with XMM results for SPT clusters (Bulbul et al. 2018)

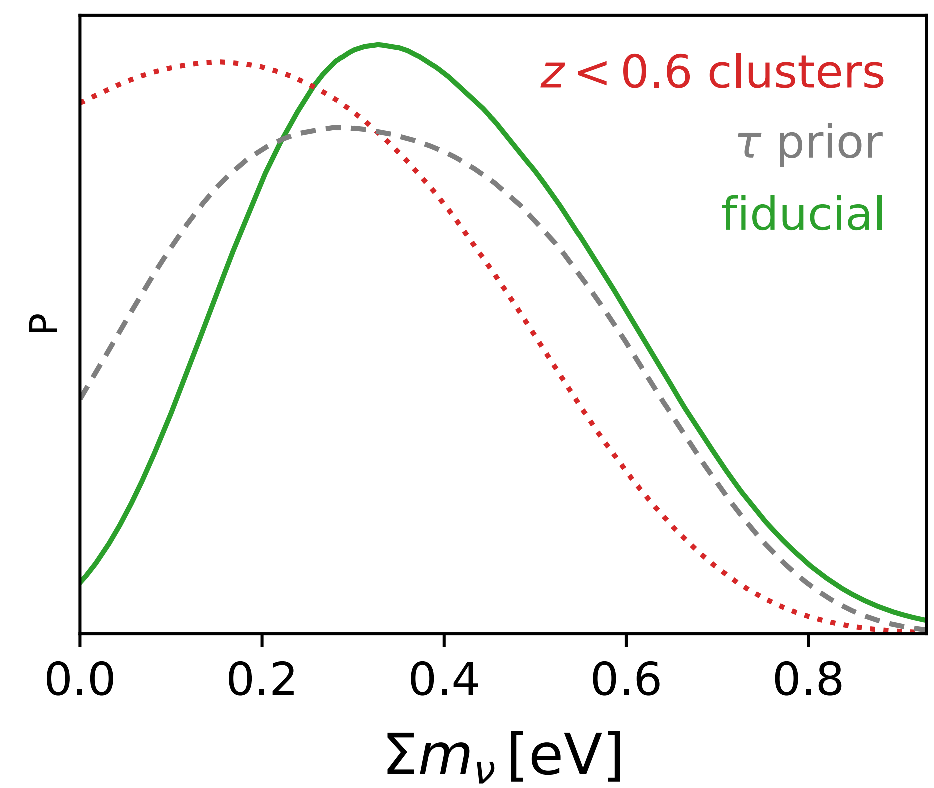
Neutrino Masses

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



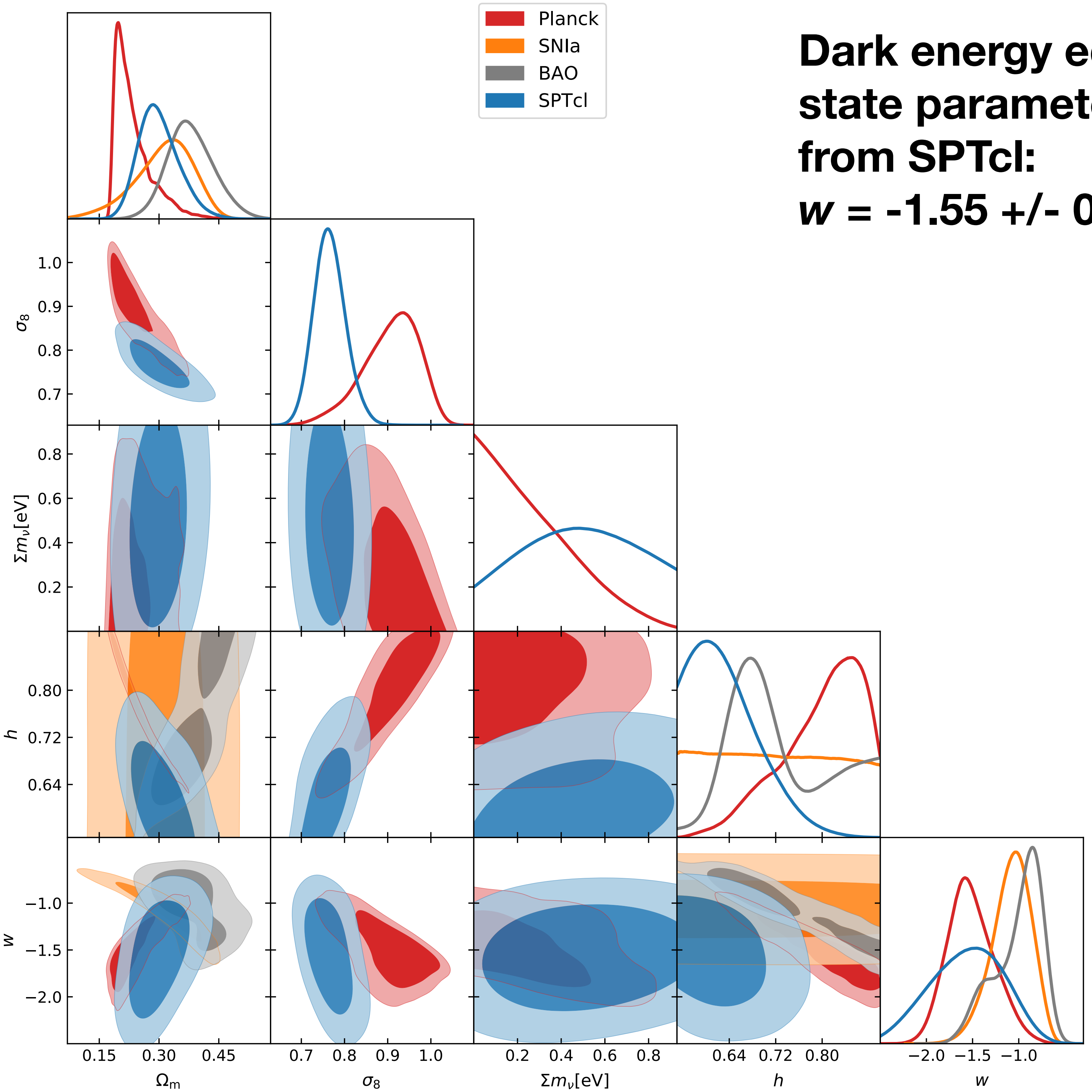


- Combination with Planck primary CMB measurements yields 2 σ preference for non-zero sum of neutrino masses
- Again, limited by mass calibration uncertainties
- Using τ prior from Planck 2018 gives 1.7 σ preference
- Using only the $z < 0.6$ cluster sample gives no preference for non-zero sum of neutrino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



*w*CDM

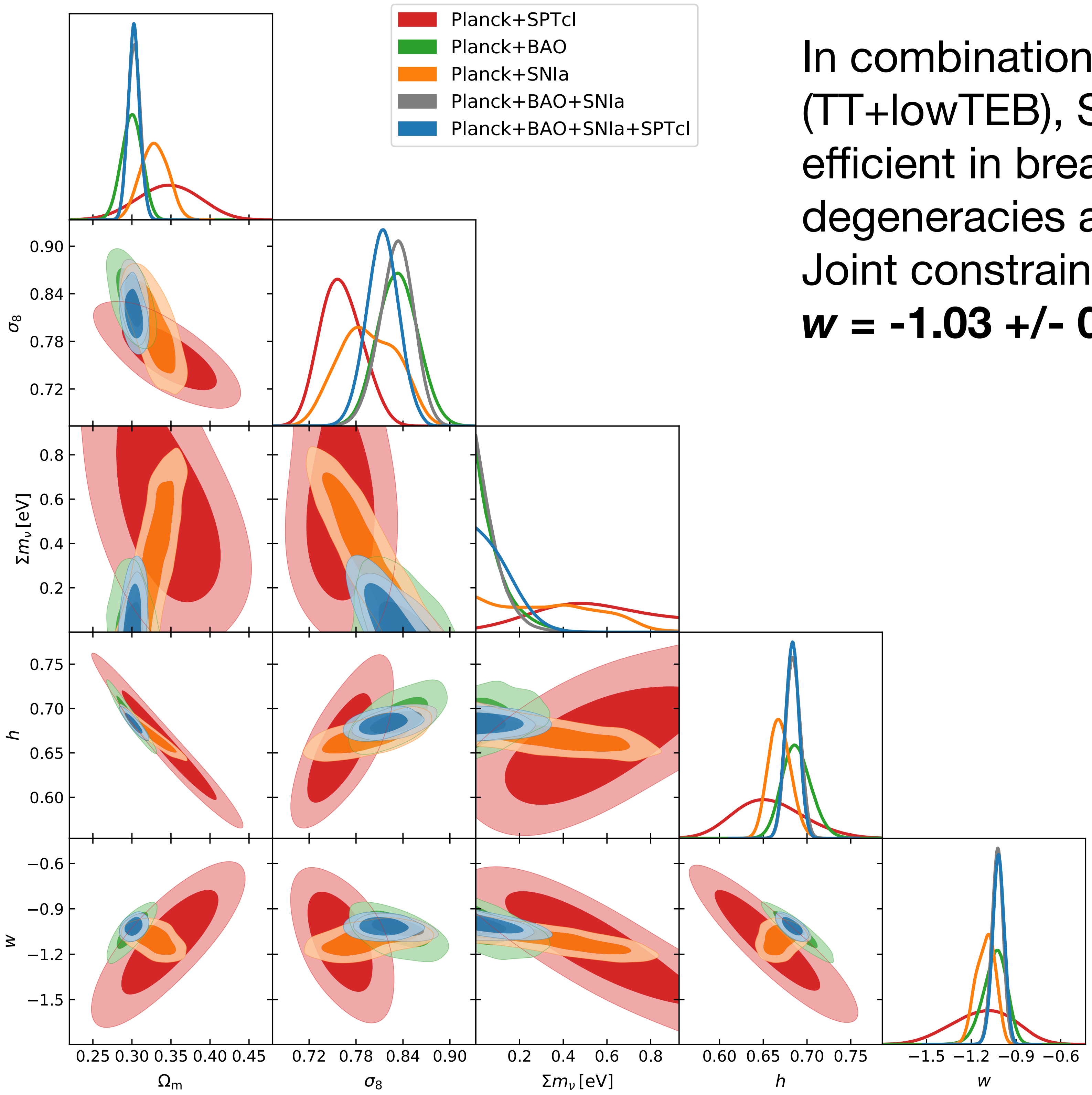
Bocquet et al. 2019ApJ...878...55B



Dark energy equation of state parameter from SPTcl:
w = -1.55 +/- 0.41

*w*CDM

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



In combination with Planck (TT+lowTEB), SPTcl is not as efficient in breaking degeneracies as BAO or SNIa. Joint constraint:

***w* = -1.03 +/- 0.04**