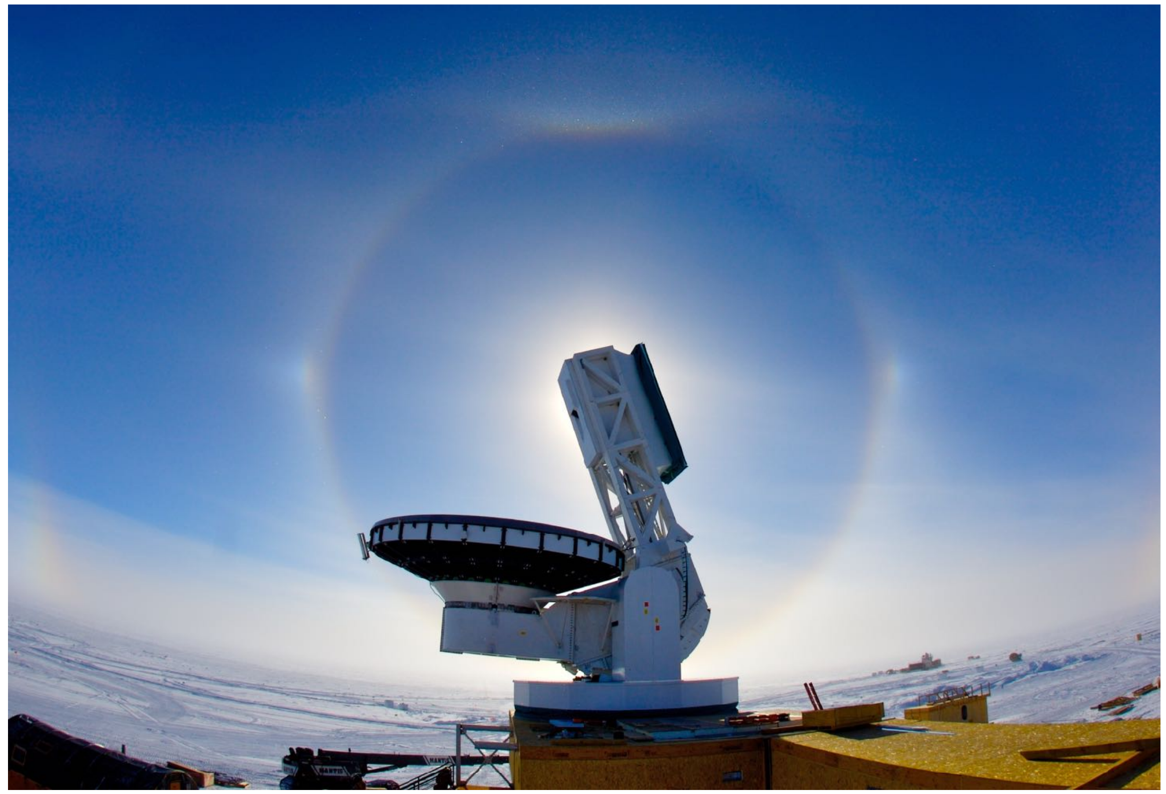
Galaxy Cluster Cosmology with the South Pole Telescope



Sebastian Bocquet - LMU Munich
and the SPT collaboration

Bocquet et al., 2018, ApJ submitted, arXiv:1812.01679

Stern, Dietrich, Bocquet et al., 2019, MNRAS accepted, arXiv:1802.04533
Dietrich, Bocquet, Schrabback et al., 2019, MNRAS 483, 2871, arXiv:1711.05344
Schrabback, Applegate, Dietrich, Hoekstra, Bocquet et al., 2018, MNRAS, 474, 2635, arXiv:1611.03866

de Haan et al., 2016, 2016, ApJ, 832, 95, arXiv:1603.06522
Bleem et al., 2015, ApJS, 216, 27, arXiv:1409.0850

Outline

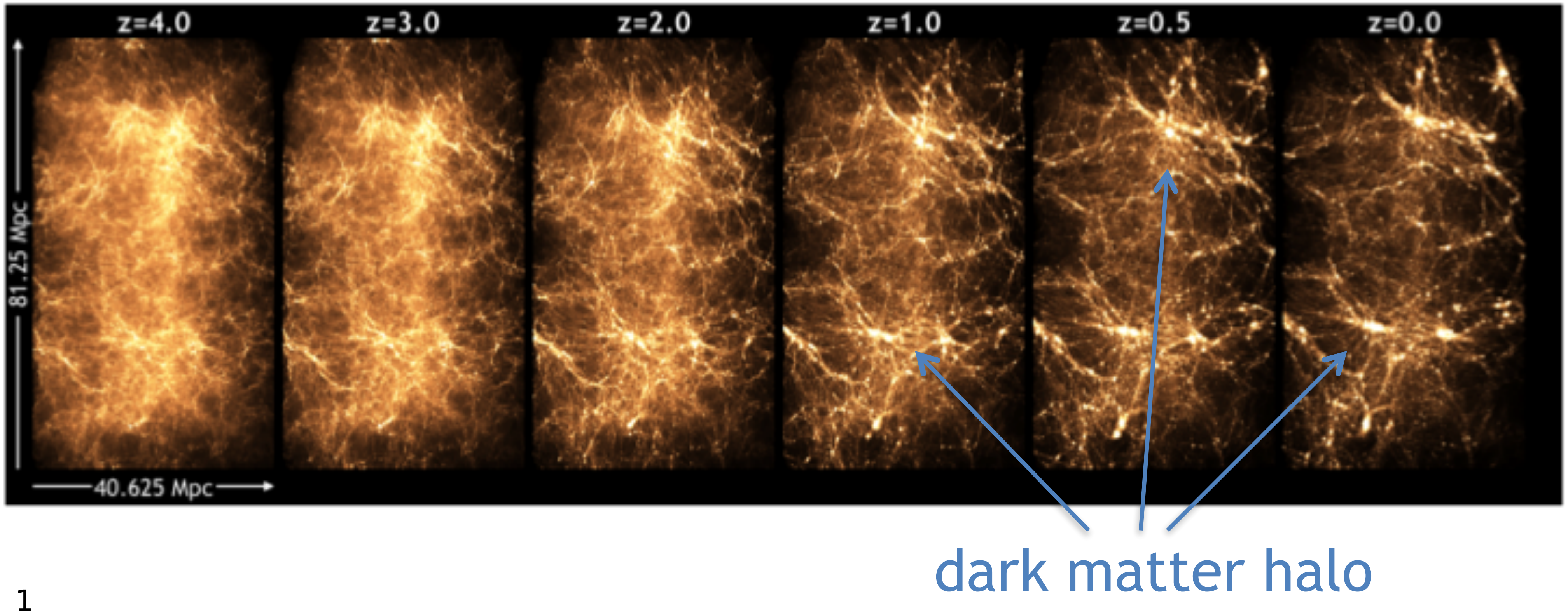
1. Cluster Cosmology in a Nutshell
2. Clusters in the South Pole Telescope Survey
3. Our Latest Cosmology Study
4. Outlook

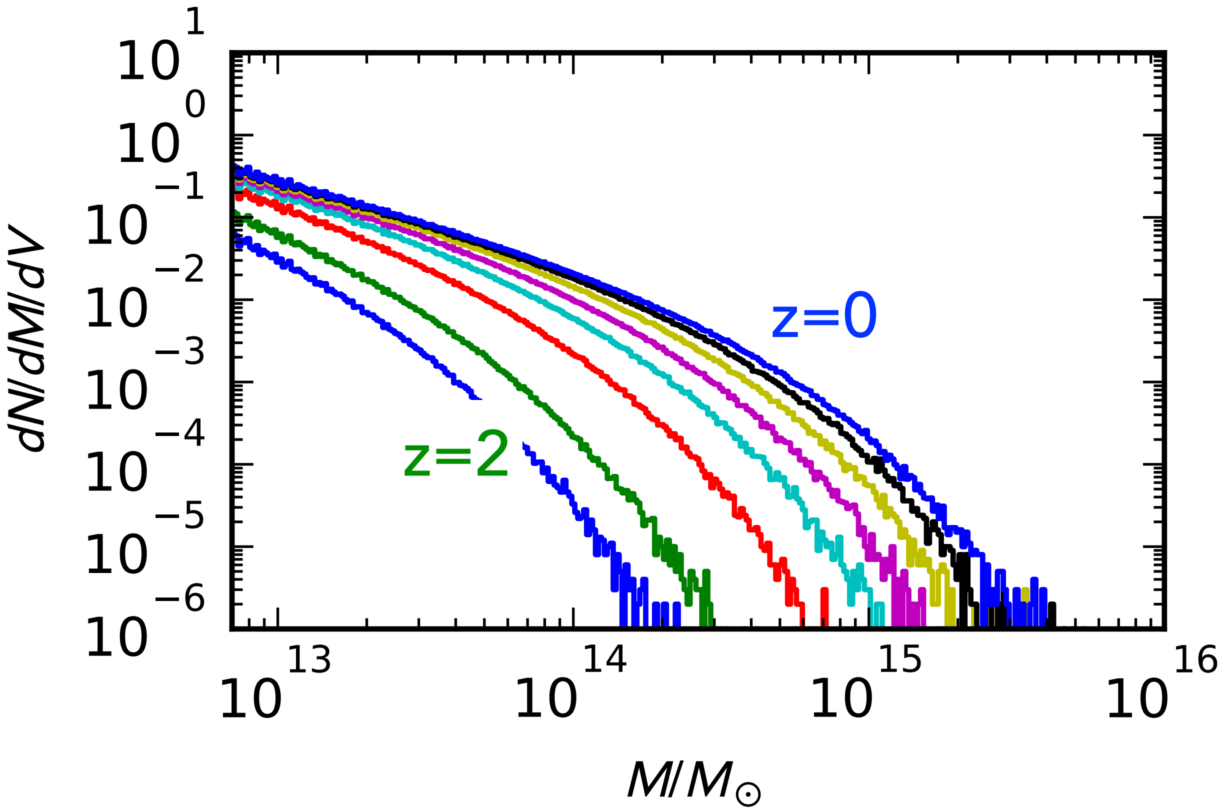
Take-Away Points

- **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 vast literature proving) that
  - cluster mass proxies correlate with mass
  - weak gravitational lensing measures halo mass on average with %-level systematic uncertainty

Cluster Cosmology in a Nutshell

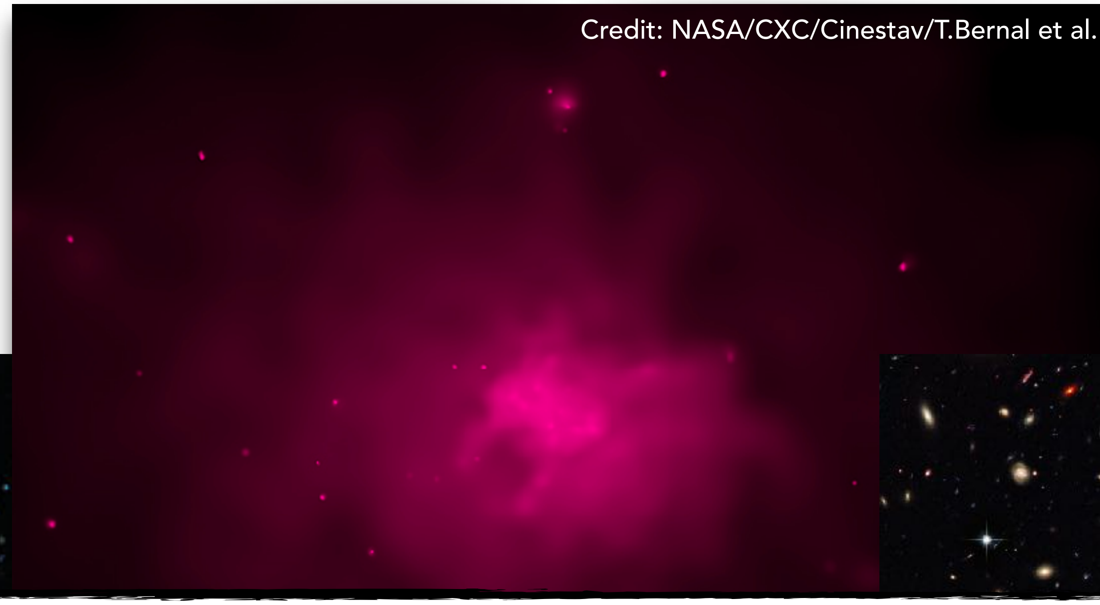
The Q Continuum Simulation: Heitmann+15 (arXiv:1411.3396)





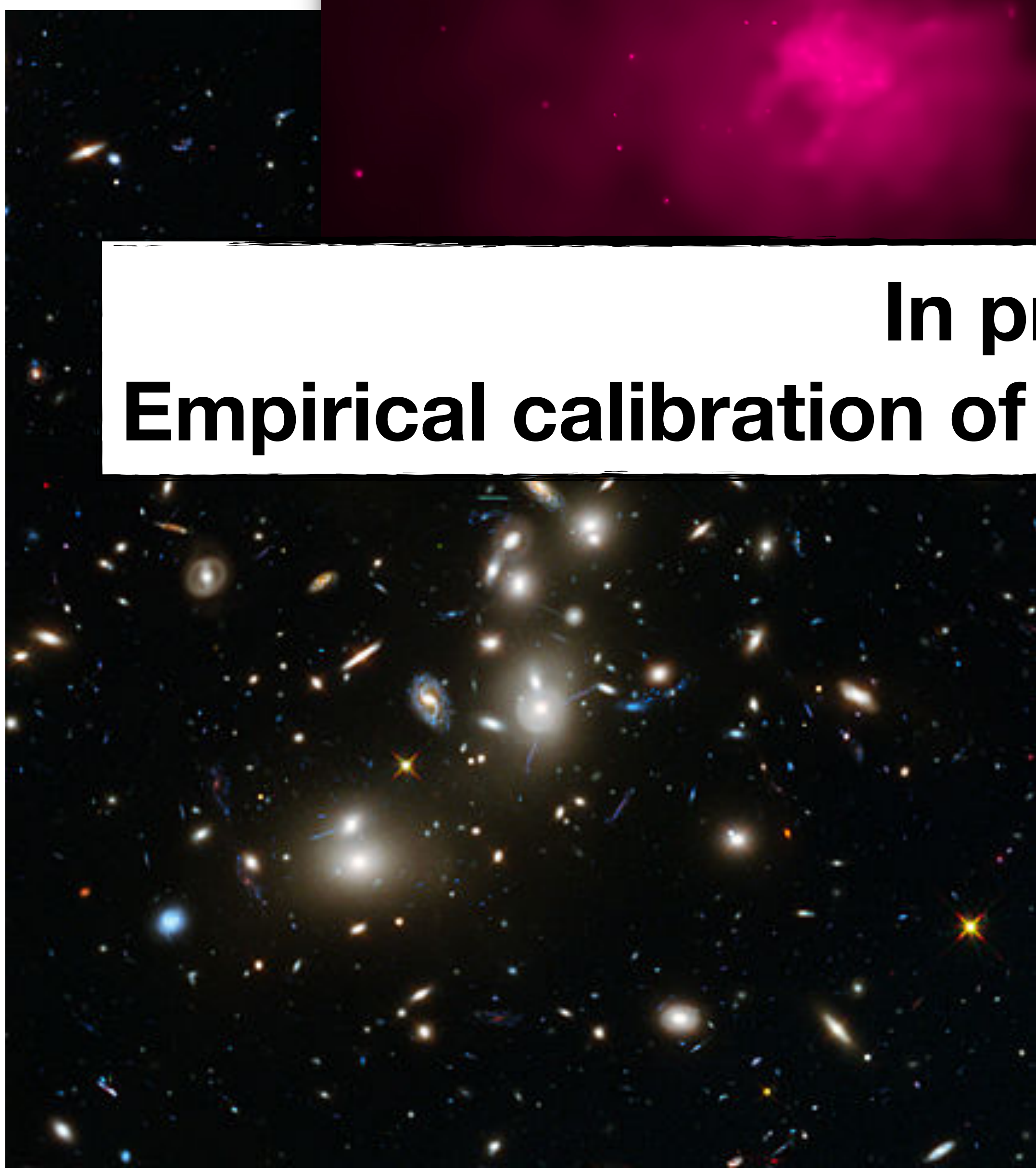
1. Predict abundance of halos as a function of cosmology using numerical simulations
2. Measure number of galaxy clusters in a given survey as a function of mass and redshift
3. Learn about cosmology

Back to reality…

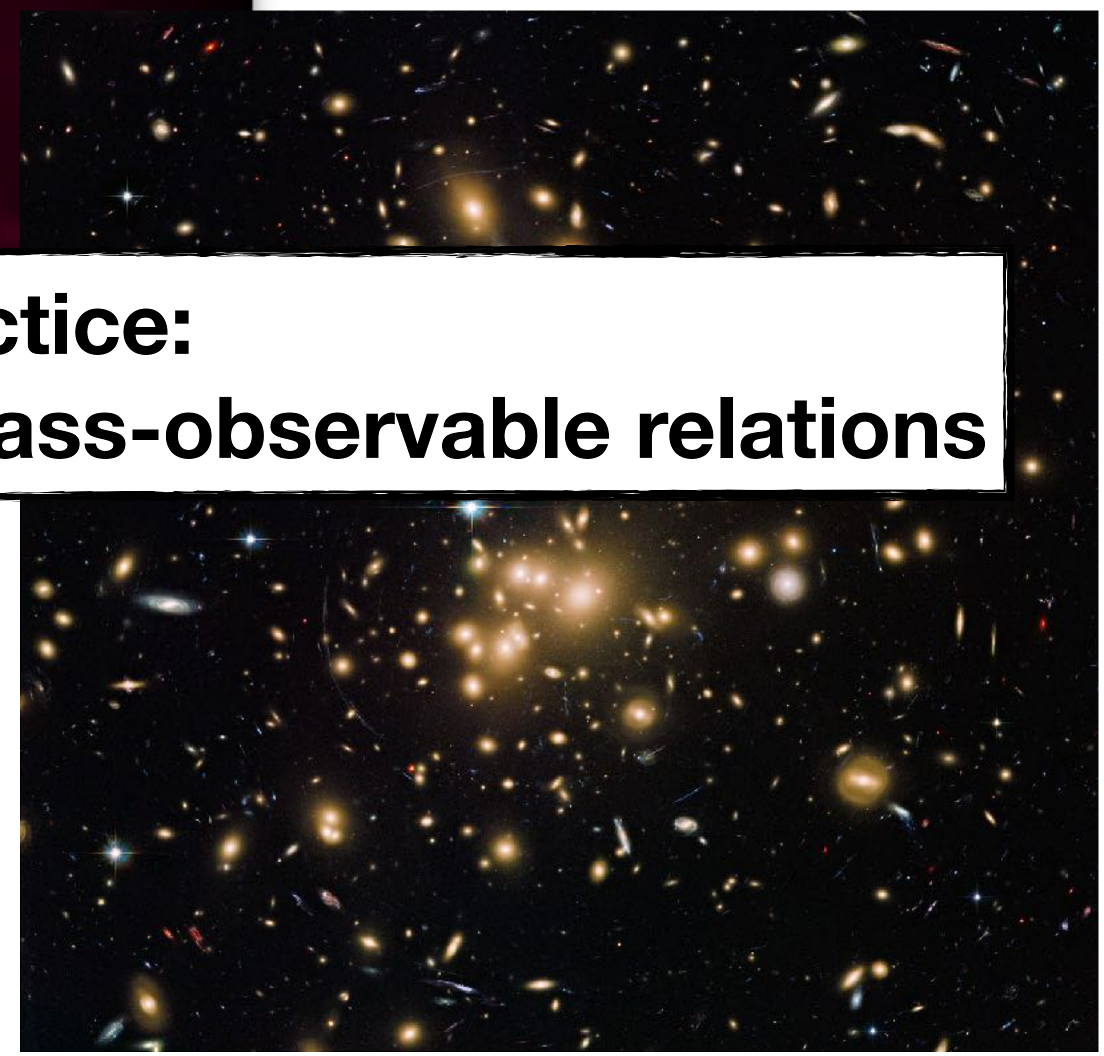


Credit: NASA/CXC/Cinestav/T.Bernal et al.

In practice:
Empirical calibration of mass-observable relations

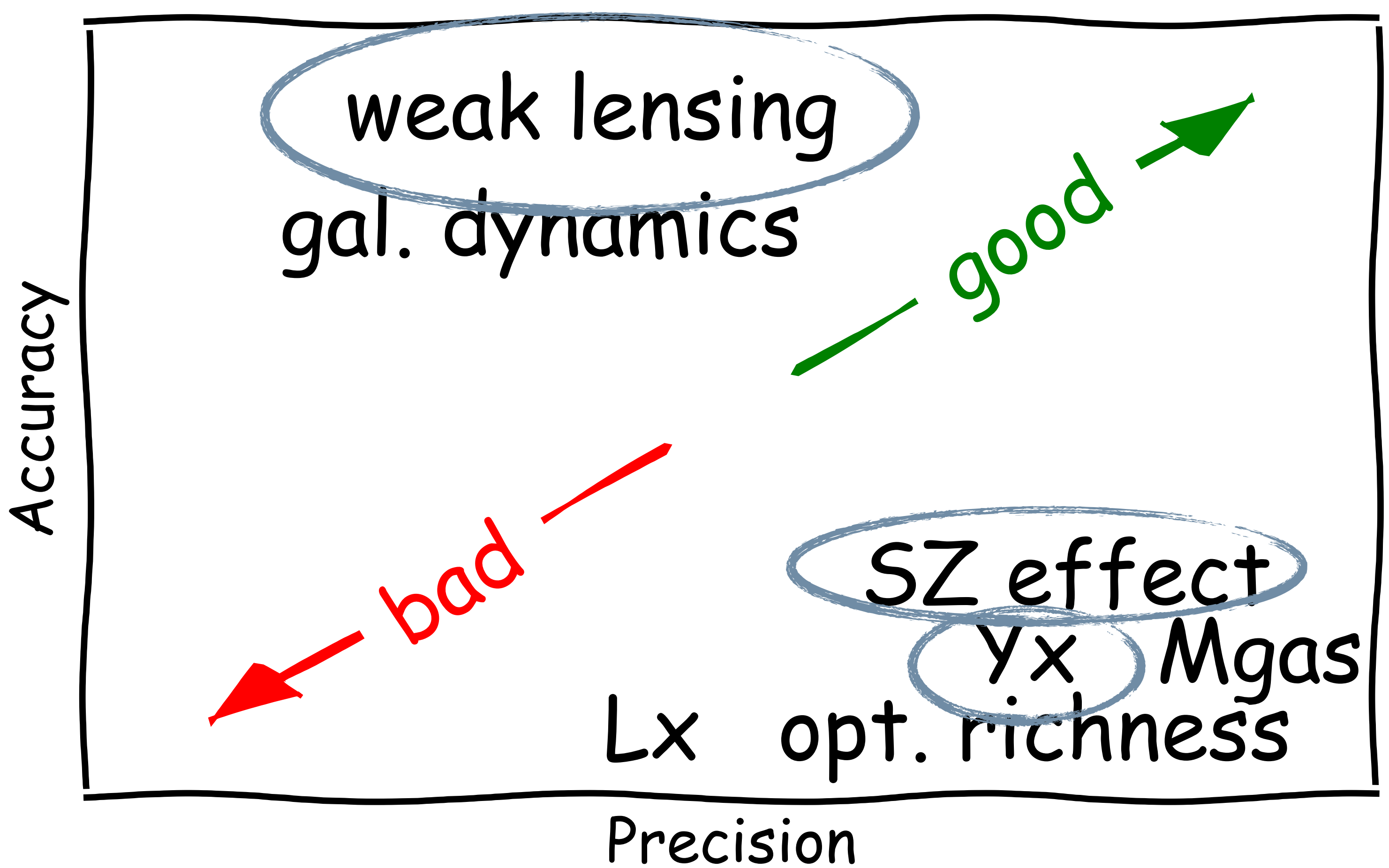


Credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)
http://www.spacetelescope.org/images/heic1401a/



Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), J. Blakeslee (NRC Herzberg Astrophysics Program, Dominion Astrophysical Observatory), and H. Ford (JHU) http://www.spacetelescope.org/images/heic1317a

Mass Proxies



- 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 modelling in *N*-body simulations
  - %-level systematics
  - Large intrinsic & measurement scatter > ~30 %

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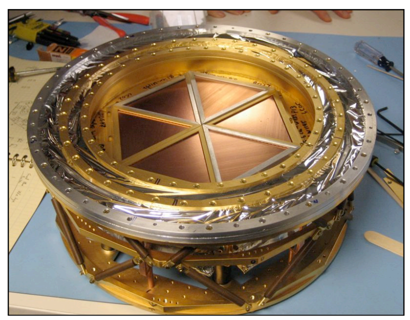
The South Pole Telescope (SPT)

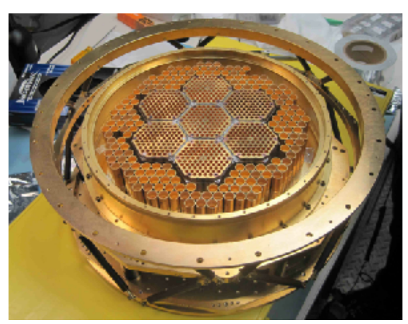
10-meter sub-mm quality wavelength telescope

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

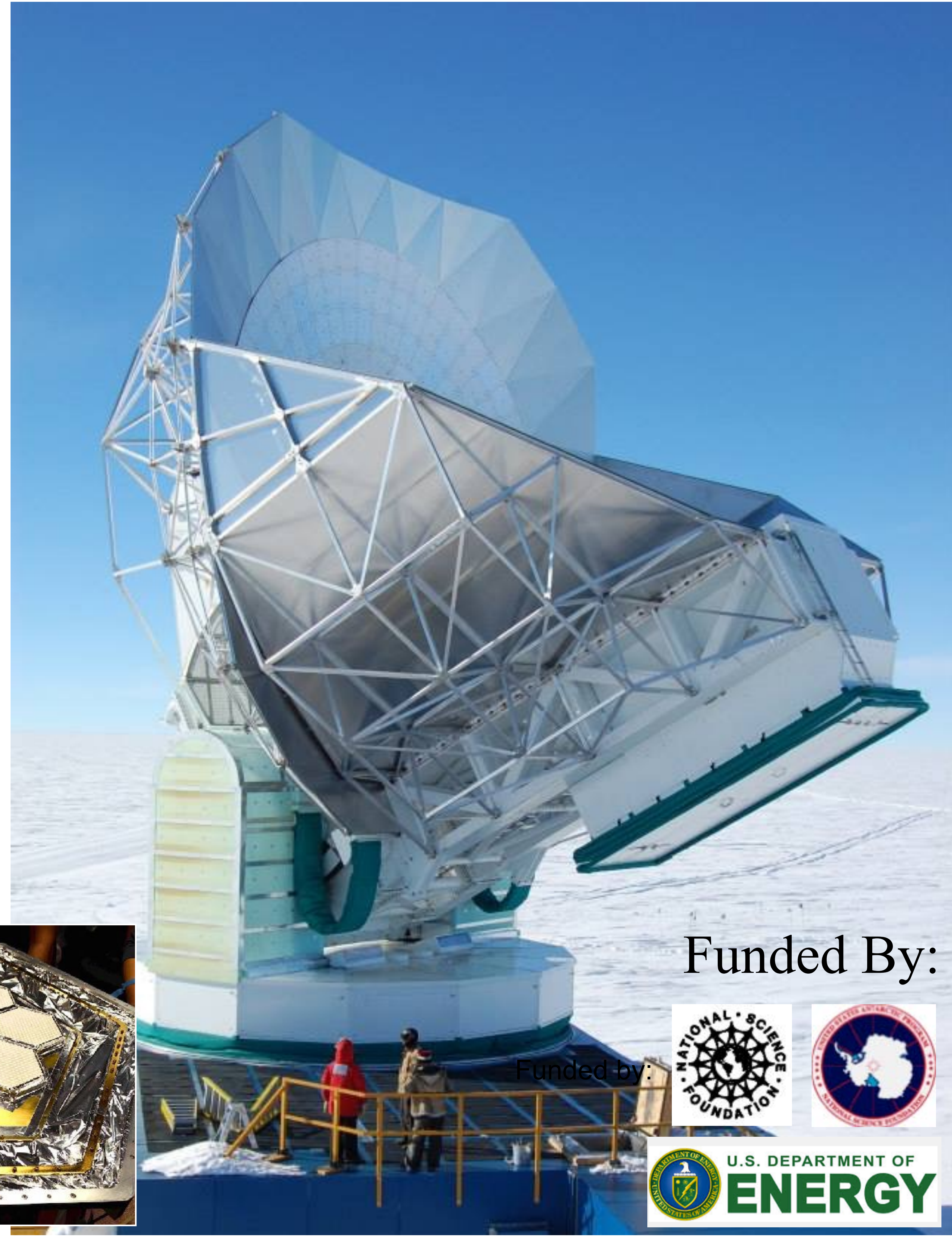
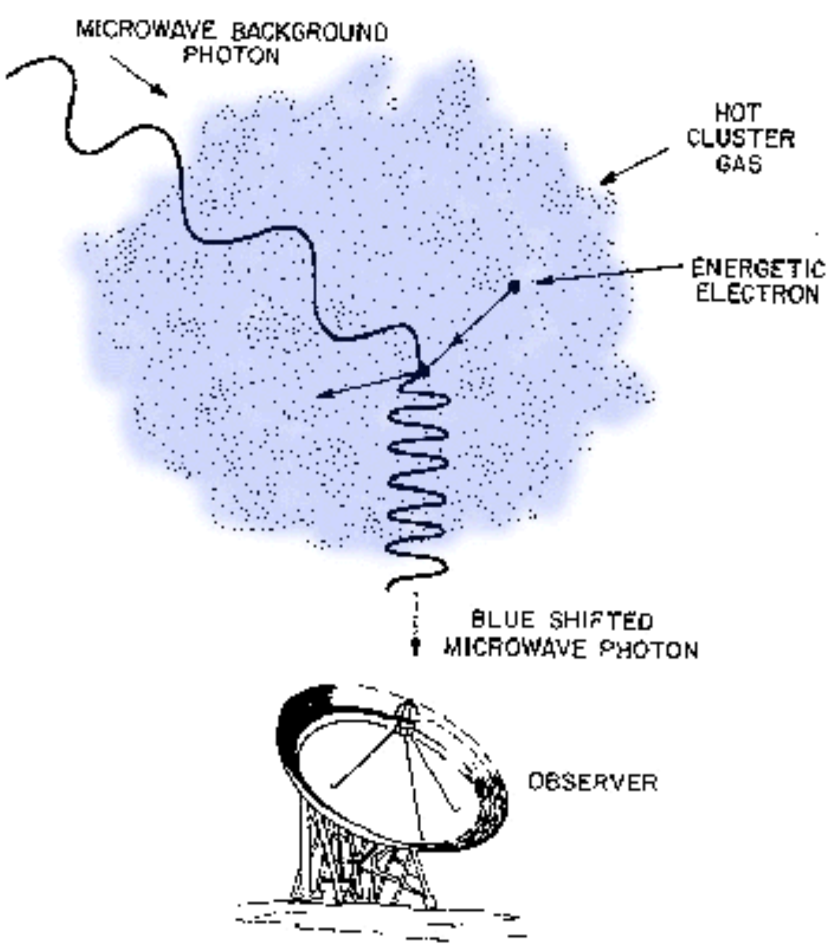
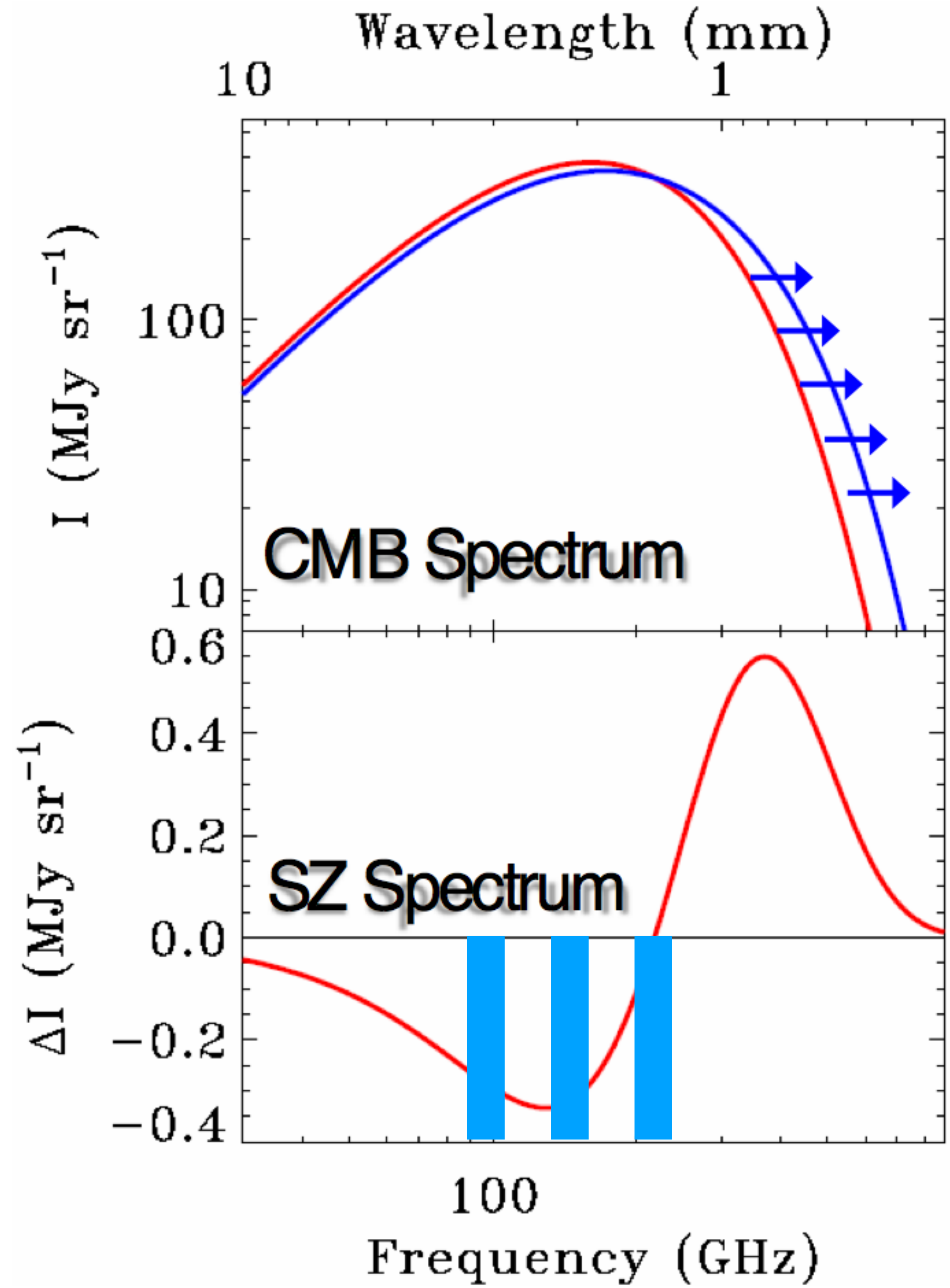


Image credit: SPT 2018 winter-overs Adam & Joshua

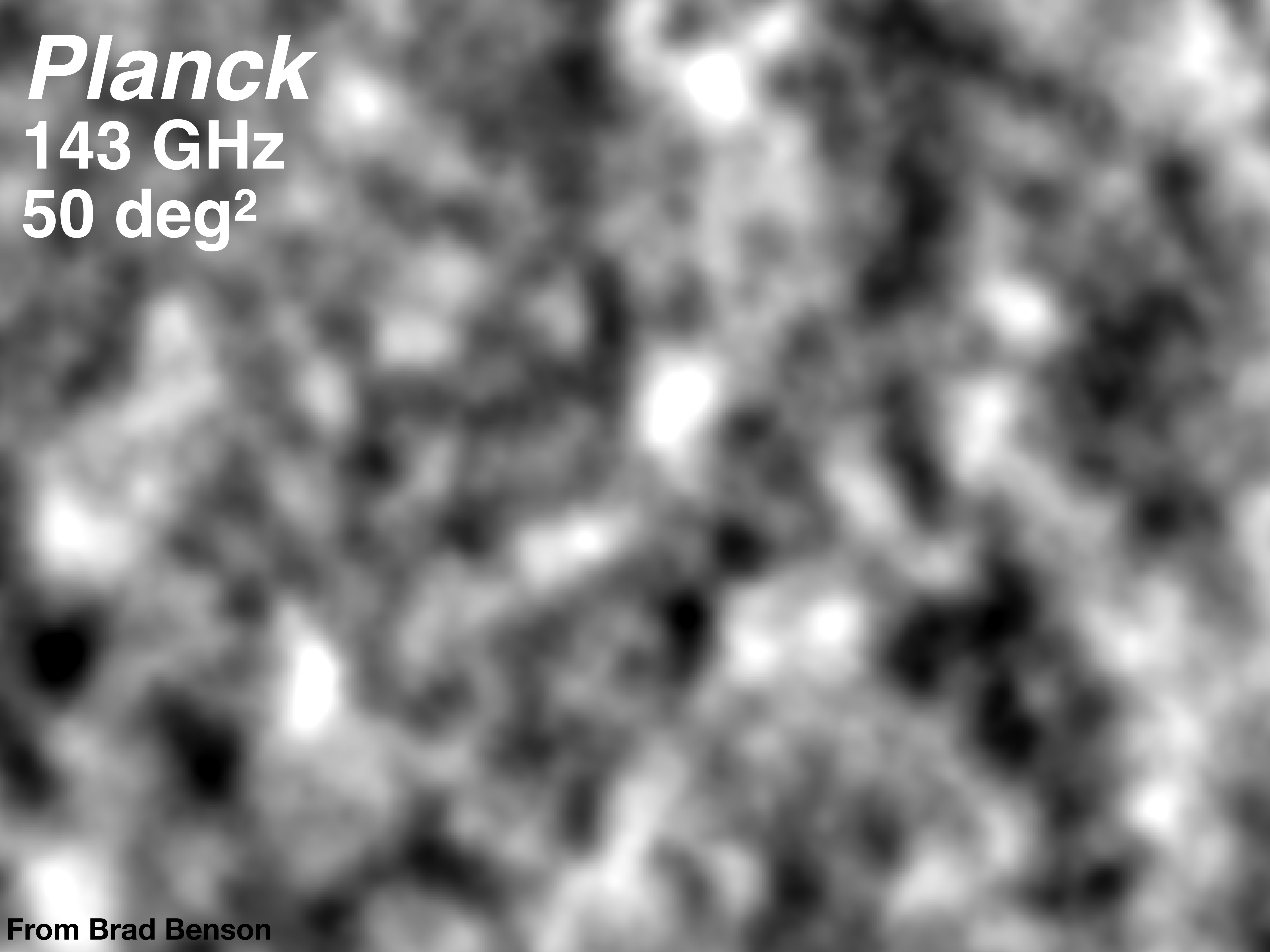
Sunyaev-Zel'dovich Effect (1972)

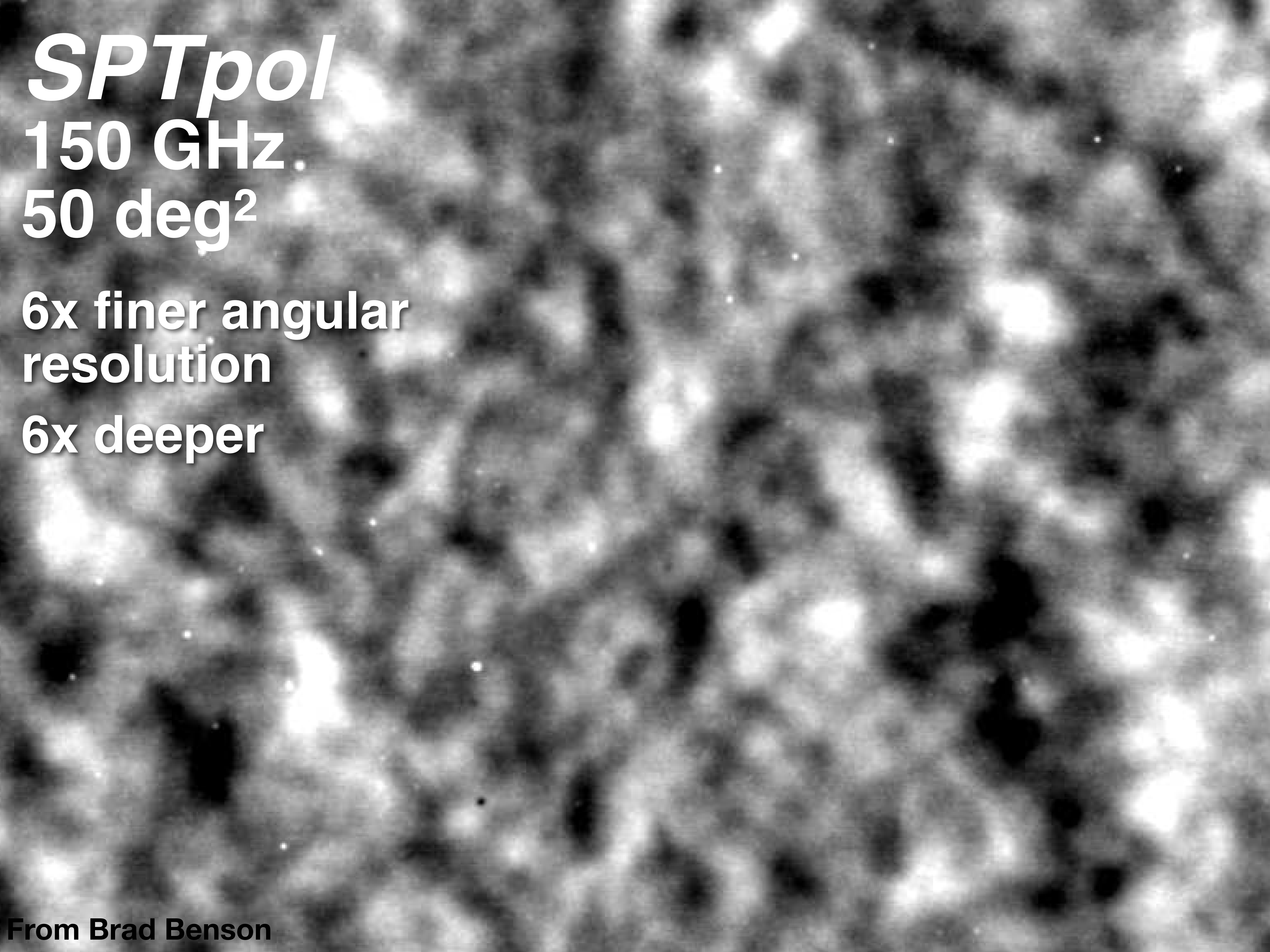


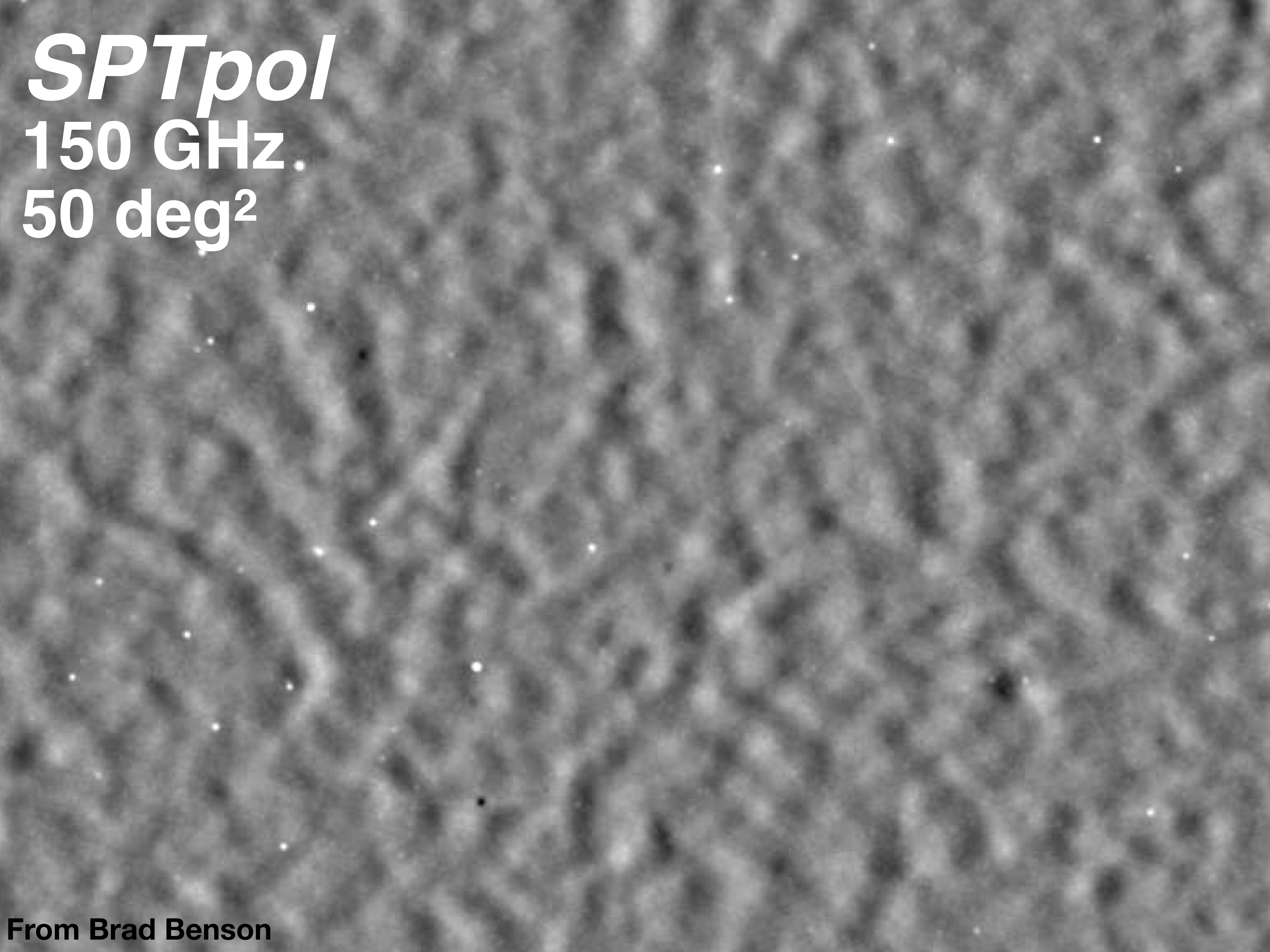
from L. Van Speybroeck

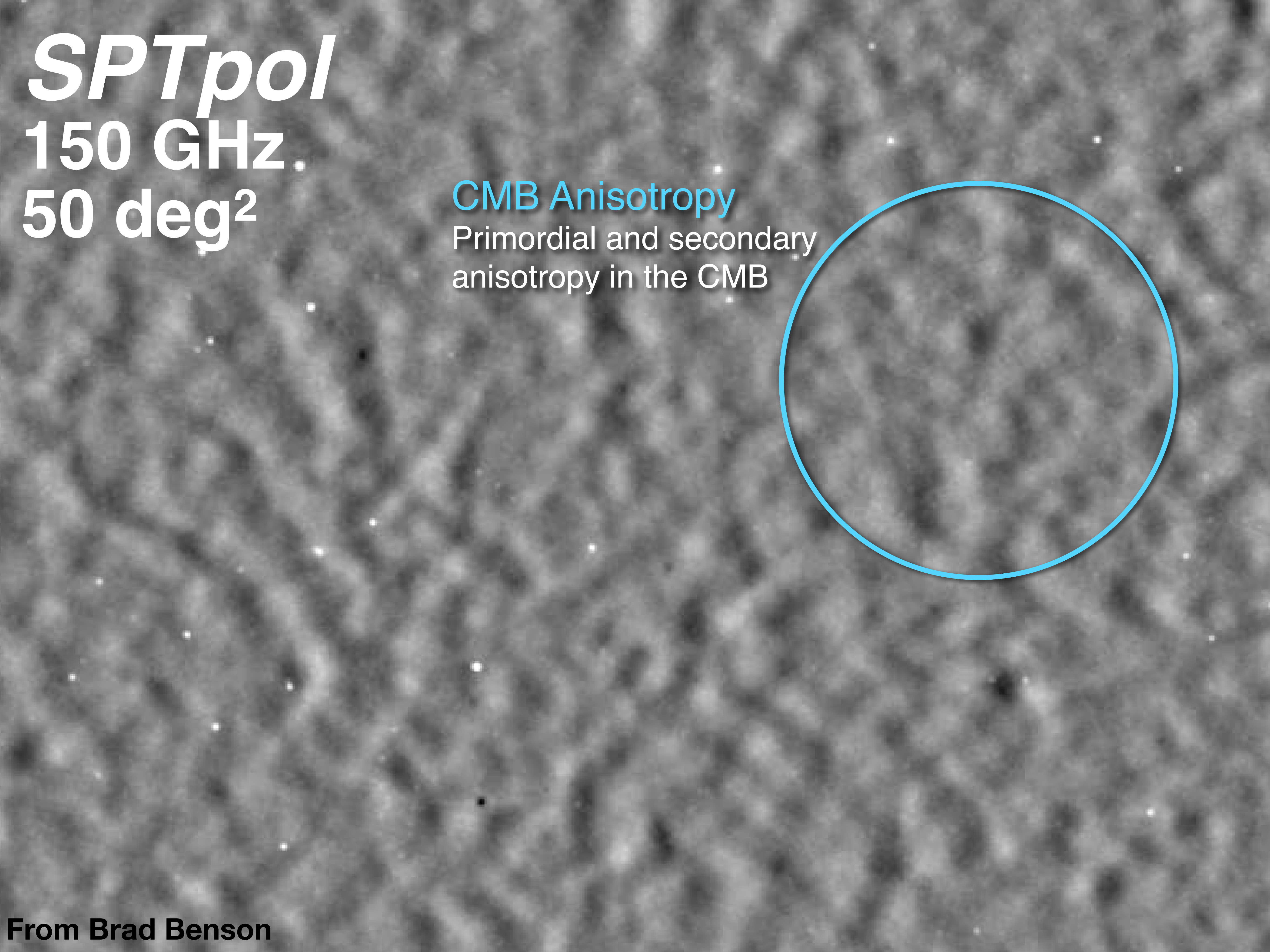


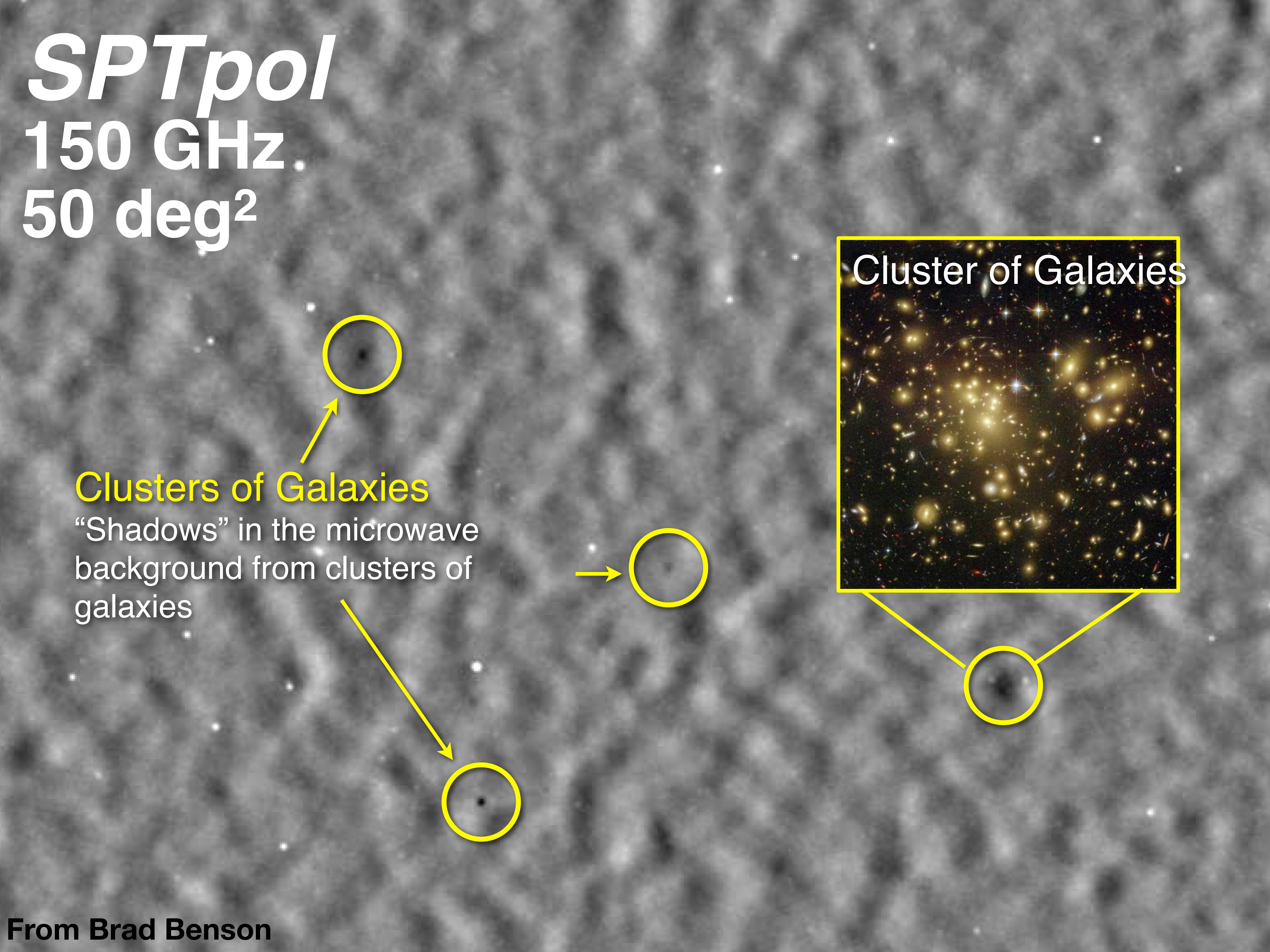
- About 1% of CMB photons scatter
- SZE flux proportional to total thermal energy in the electron population
- SZE surface brightness is independent of redshift


Planck
143 GHz
50 deg^2
From Brad Benson

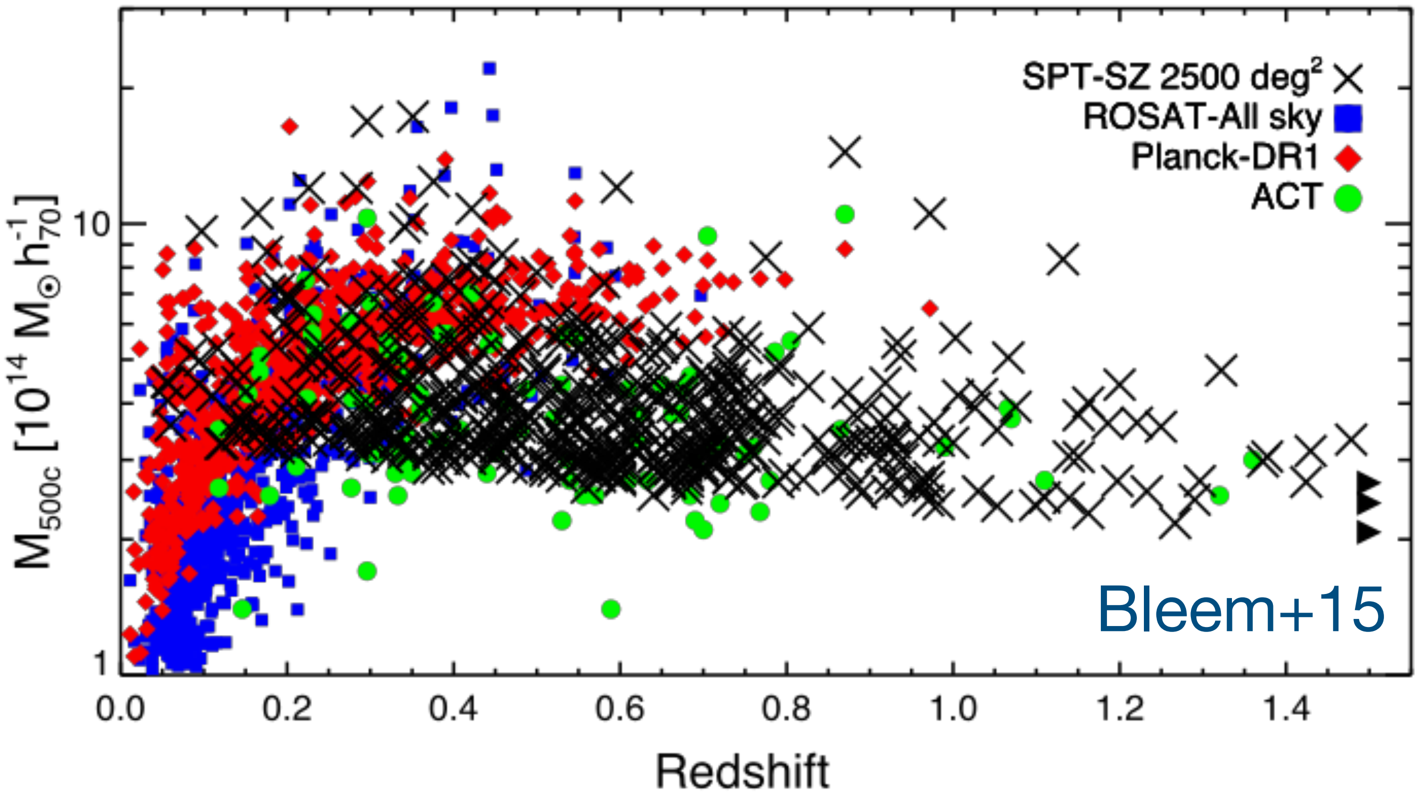

SPTpol
150 GHz
50 deg²
6x finer angular resolution
6x deeper
From Brad Benson


SPTpol
150 GHz
50 deg²
From Brad Benson


SPTpol
150 GHz
50 deg²
CMB Anisotropy
Primordial and secondary anisotropy in the CMB
From Brad Benson


SPTpol
150 GHz
50 deg²
Cluster of Galaxies
Clusters of Galaxies
"Shadows" in the microwave background from clusters of galaxies
From Brad Benson

SPT Cluster Catalogs



- High-resolution SZ survey means large redshift range
  - Galaxy populations
    - Zenteno+16, Hennig+17, Strazzullo+18
  - Galaxy dynamics
    - Ruel+14, Bocquet+15, Capasso+18
  - (X-ray) gas physics
    - Chiu+16,18, Bulbul+18, McDonald+13-18
  - Radio galaxies
    - Gupta+17
  - Cosmology
    - Benson+13, Reichardt+13, Bocquet+15, de Haan+16, Bocquet+18

Outline

1. Cluster Cosmology in a Nutshell
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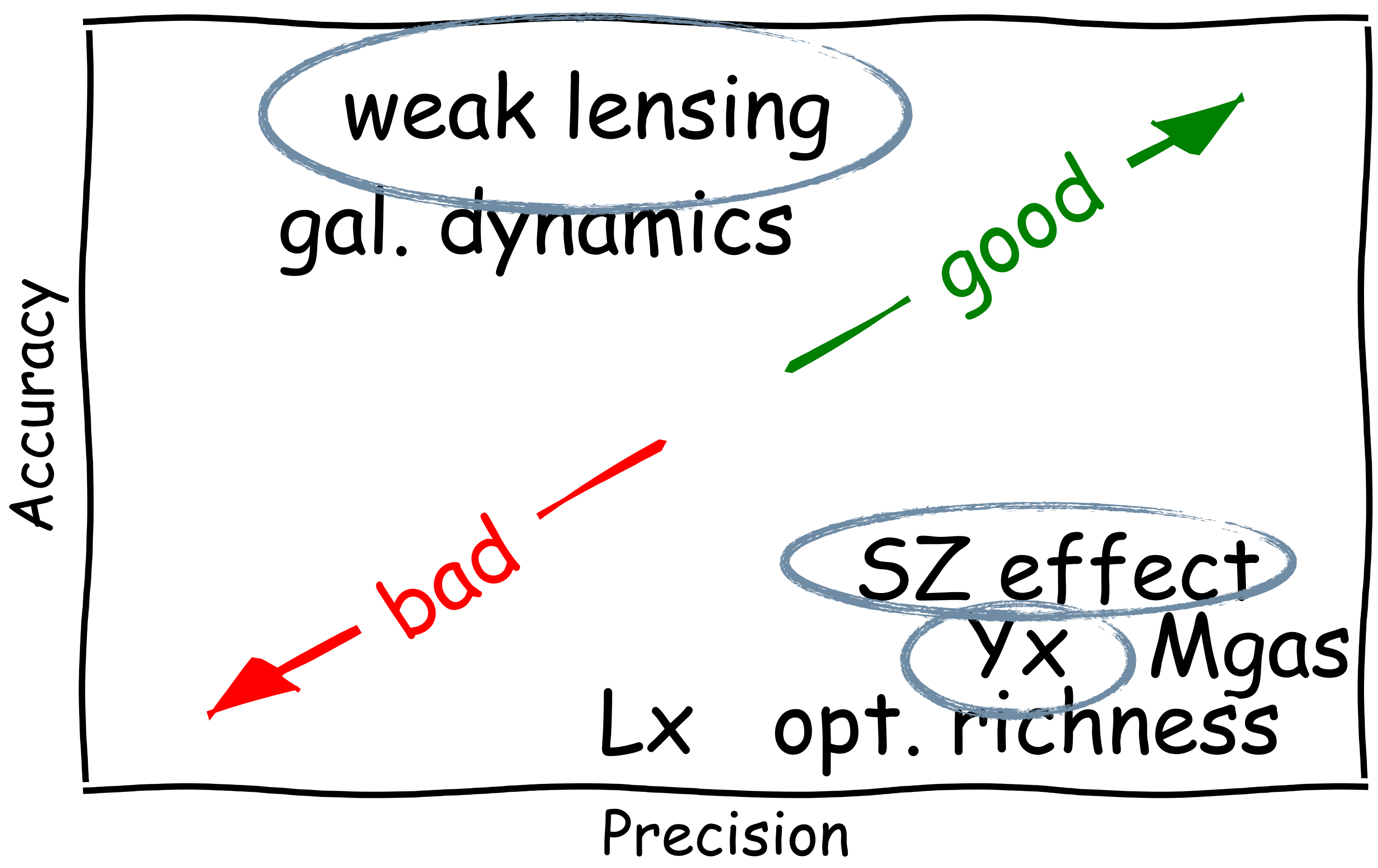
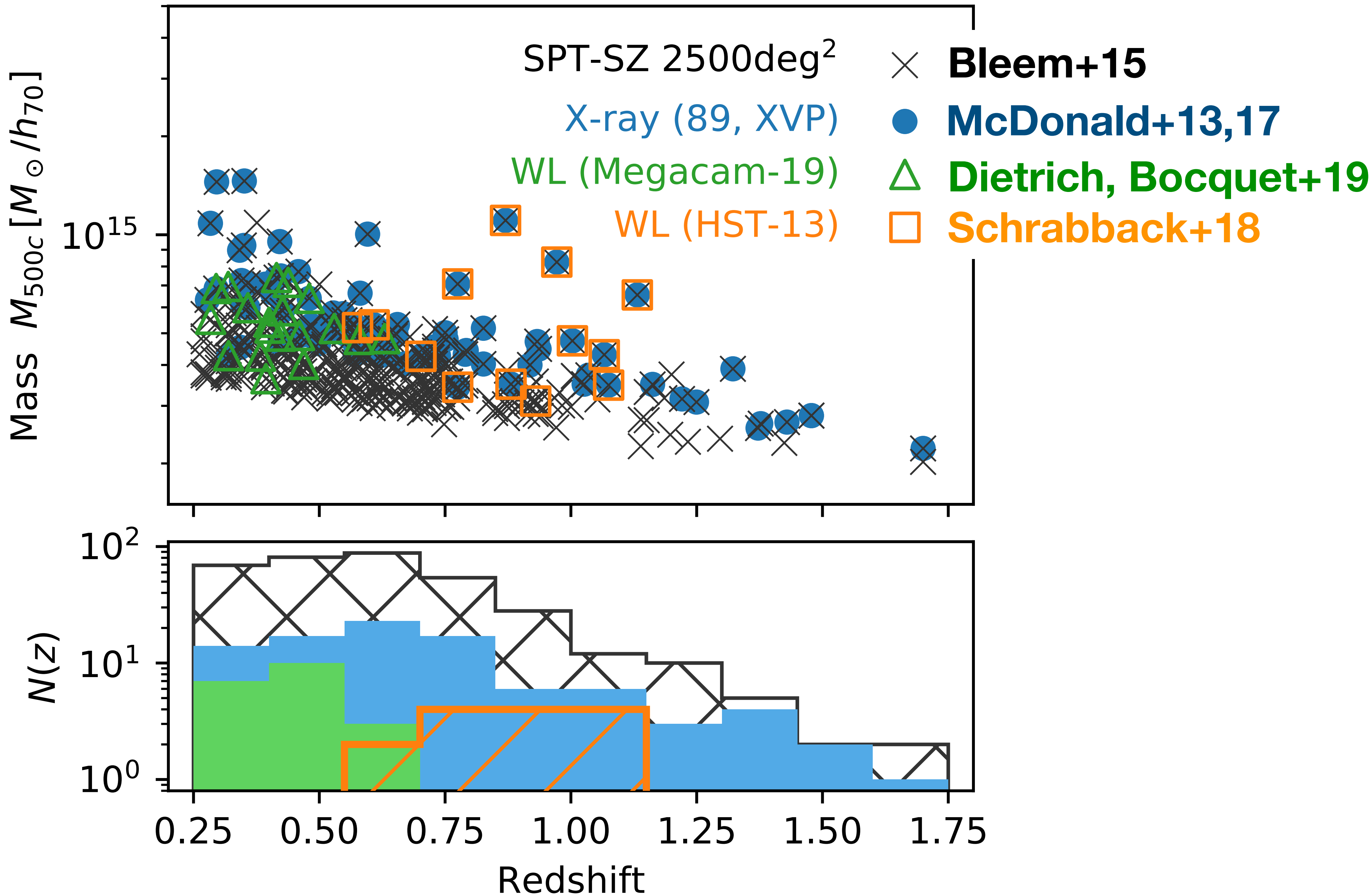
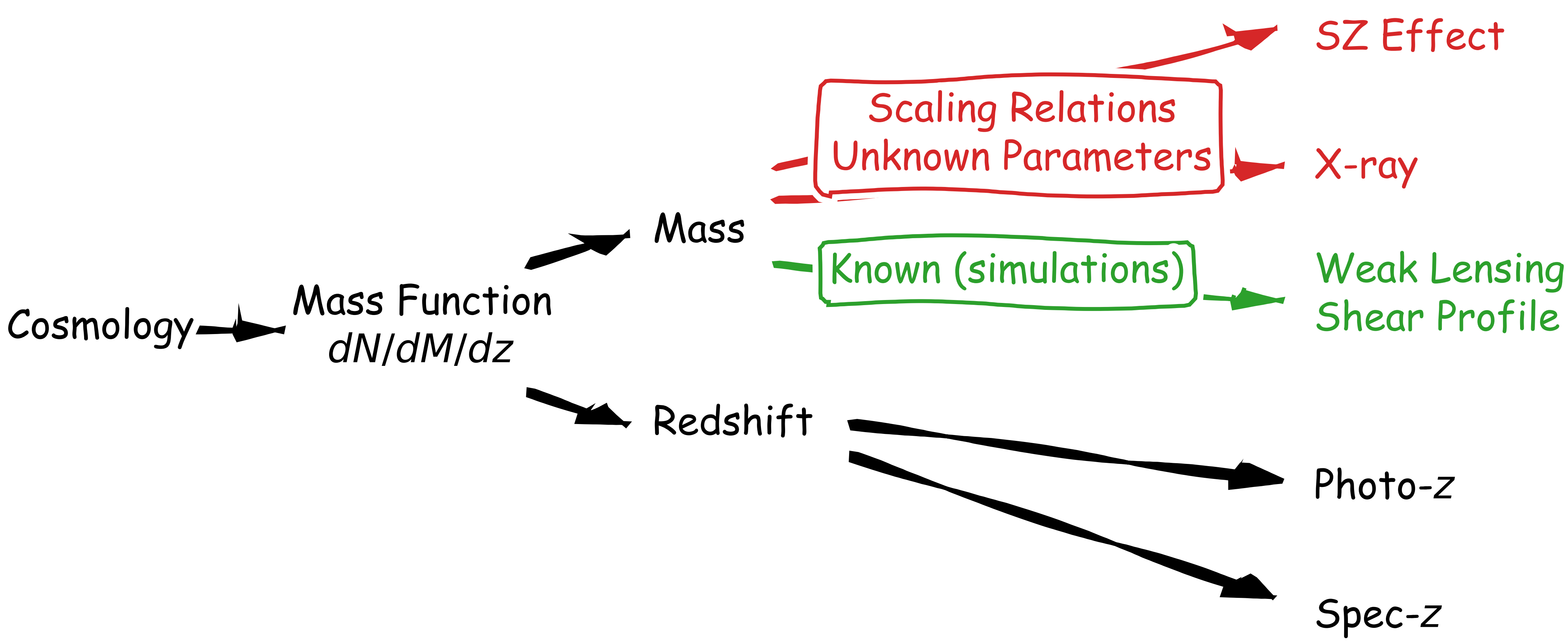
Mass Proxies (Reminder)



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



Mass Proxies and Observable—Mass Scaling Relation Calibration Strategy



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

Modeling Framework

Bocquet+ (arXiv: 1812.01679)

- Mean scaling relation between SZ signal and mass is described by power-law in mass and redshift with a priori unknown parameters
- Simulation calibration of mass-to-WL shear profile (because we don't have perfectly centered NFW halos)
- Correlated intrinsic lognormal scatter in SZ, WL, and X-ray
- Halo mass function (theory prediction for halo abundance, Tinker+08)
    - Baryonic effects should not matter for us (explicitly shown in Bocquet+16, but see also Cui+14, Cusworth+14, Velliscig+14, Vogelsberger+14, Schaller+15)

Weak-Lensing Bias and Scatter

Bocquet+ (arXiv: 1812.01679)

We are limited by the low number of clusters with WL data, not systematics!

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**

Likelihood function

Poisson likelihood for cluster abundance

Selection
xi >5, z>0.25

HMF

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

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

Mass calibration

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

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

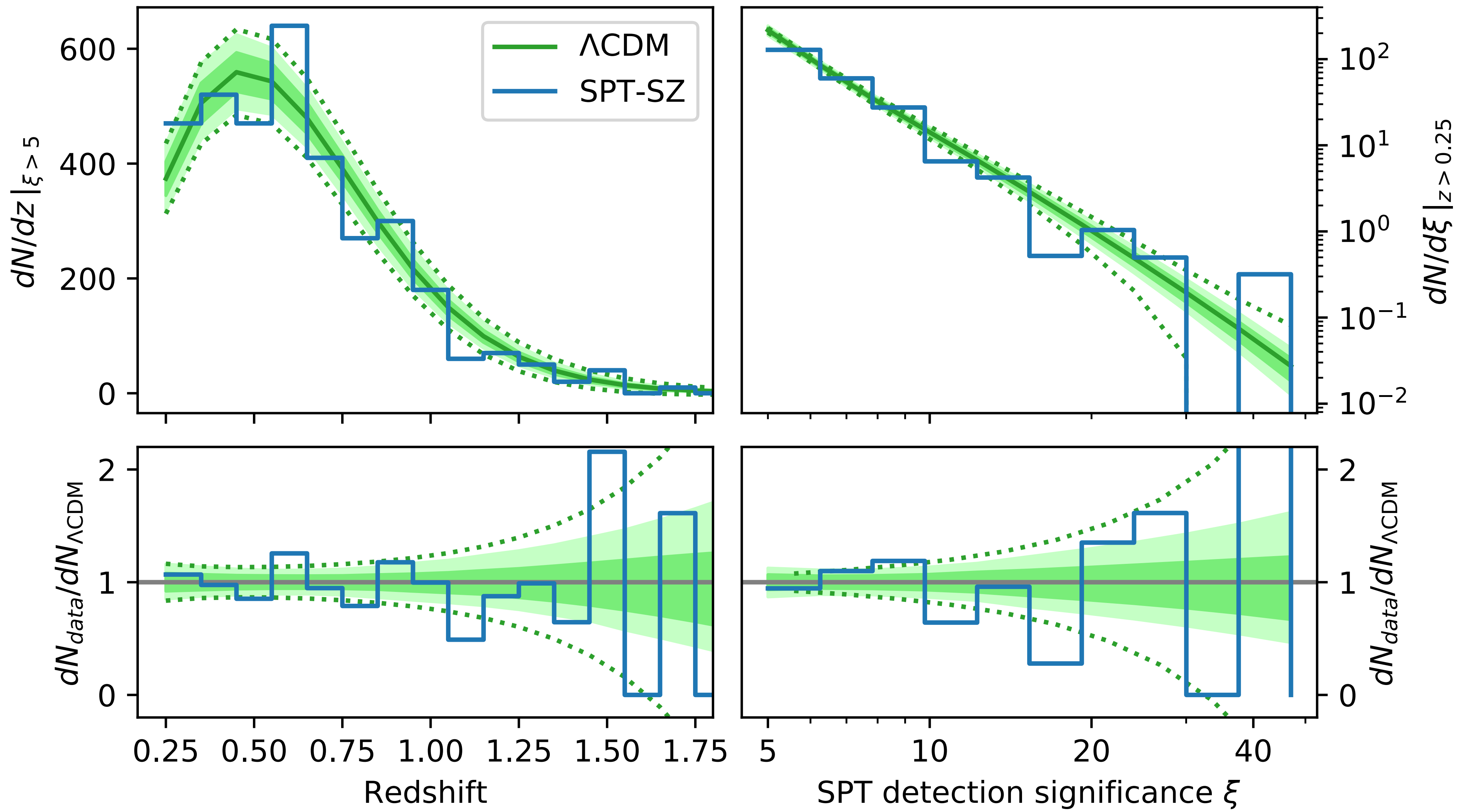
Parameters and Priors

Bocquet+ (arXiv: 1812.01679)

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

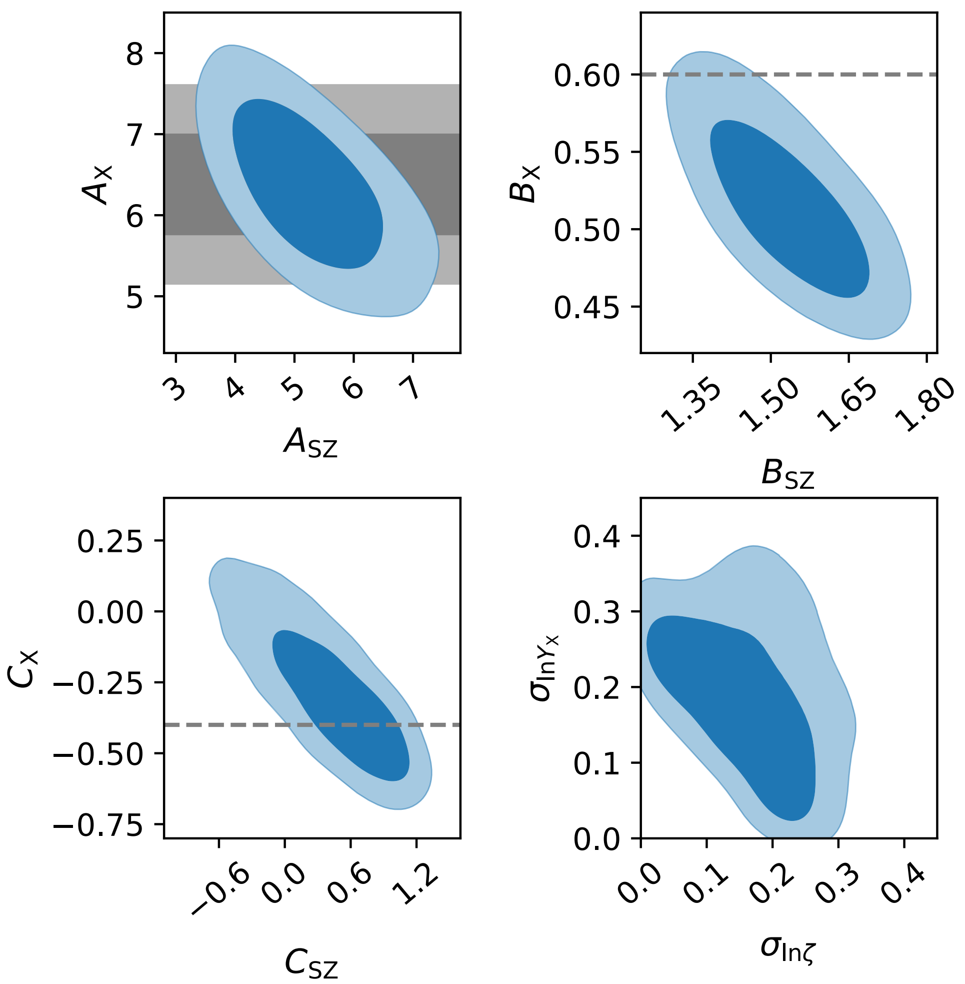
Bocquet+ (arXiv: 1812.01679)

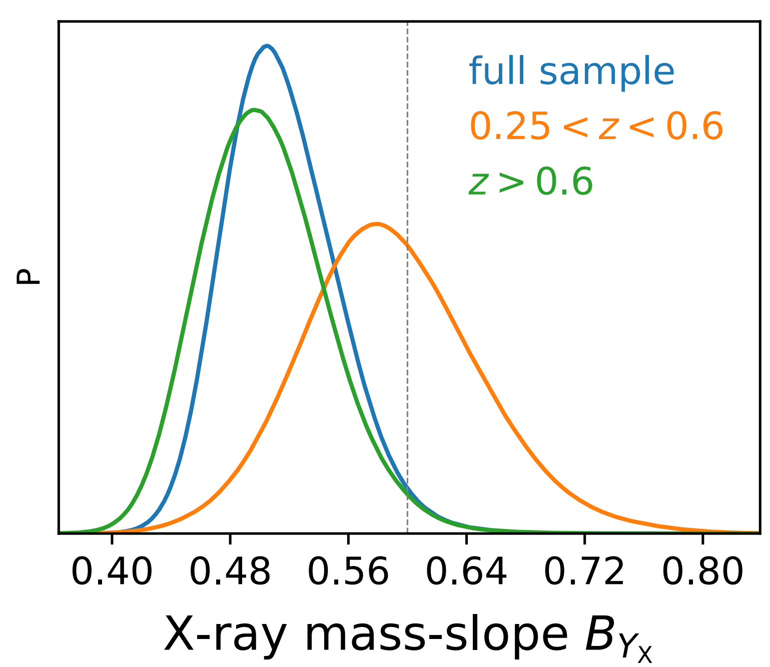


- Number counts test statistic (Kaastra 17)
  - C(model) = 439.8 +/- 26.8
  - C(data) = 449.3

X-ray Scaling Relation

Bocquet+ (arXiv: 1812.01679)



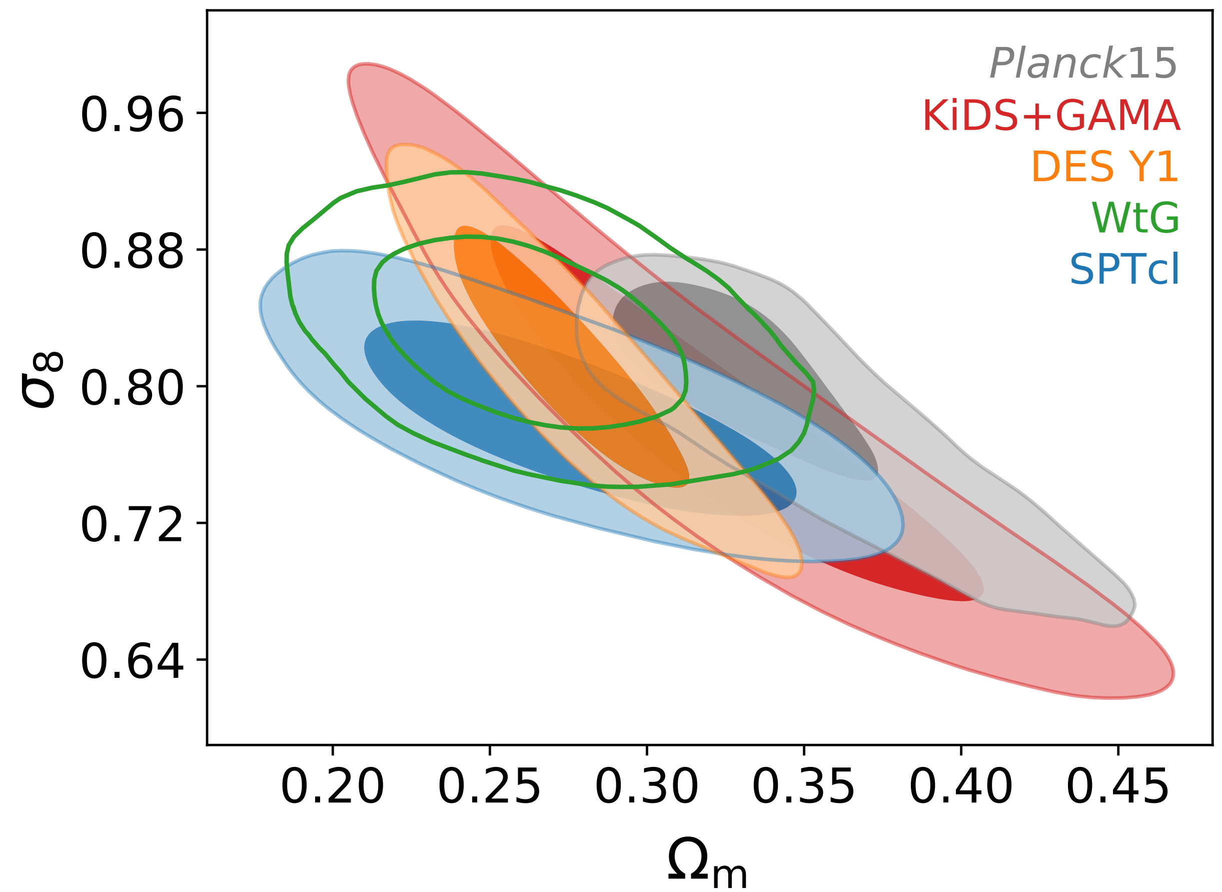


- Constraints on X-ray scaling relations as a "byproduct"
- **Why care: This feeds back into hydro simulations!**
- Self-similar model prediction if non-thermal pressure support is negligible
- Redshift evolution is self-similar
- Mass evolution is steeper than self-similar
    - Low-redshift half (0.25 < z < 0.6) in < 1 σ 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

LCDM with varying sum of neutrino masses

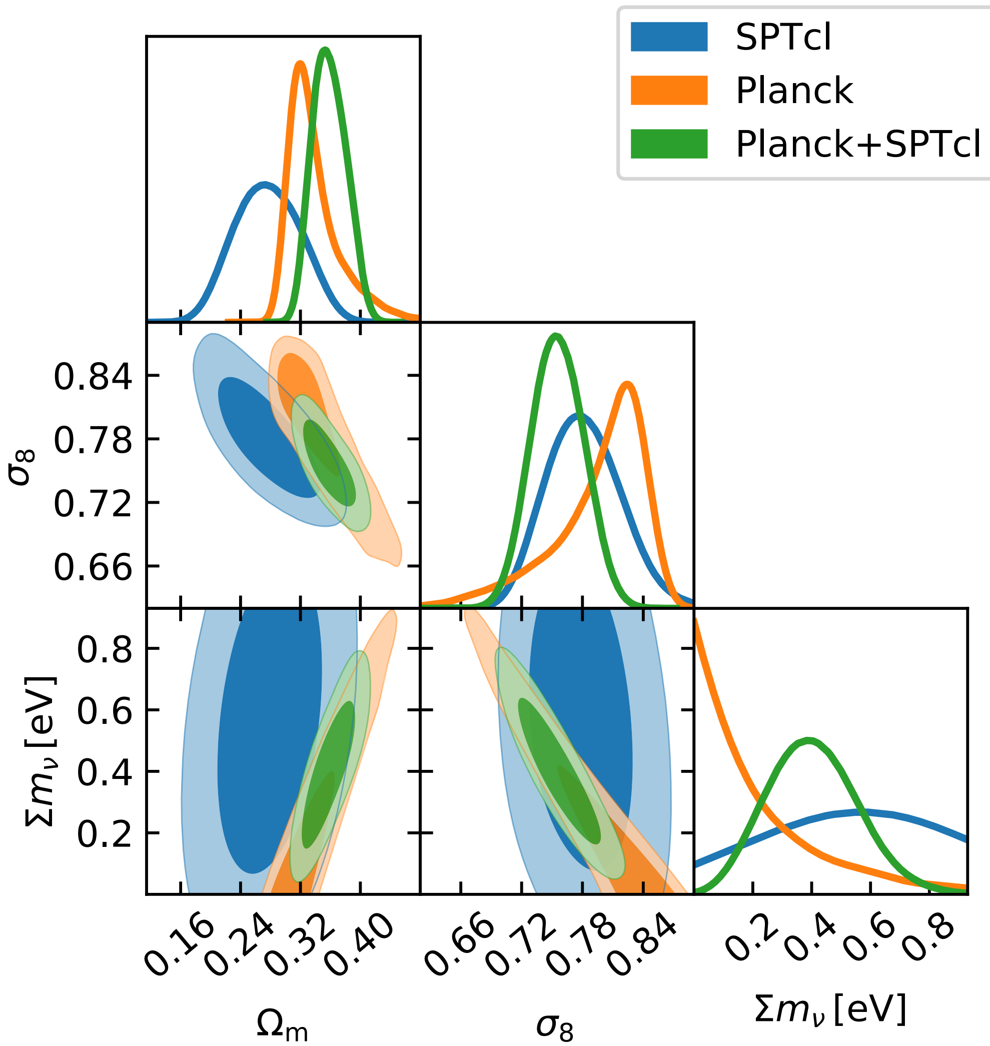
Bocquet+ (arXiv: 1812.01679)

- 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

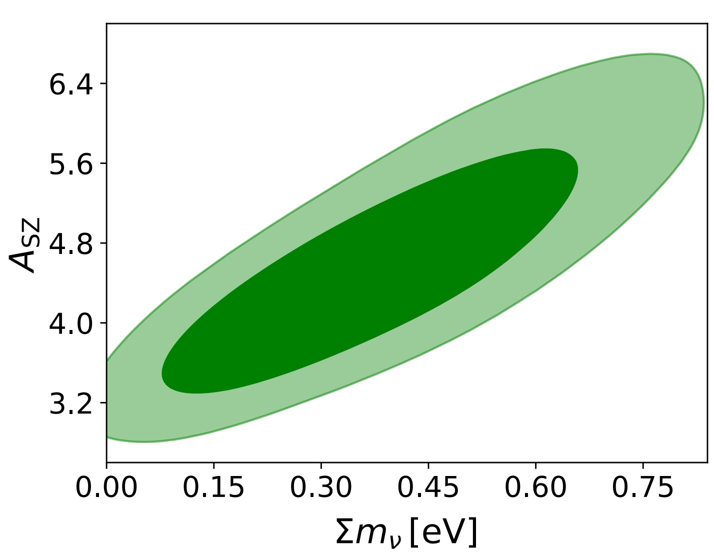


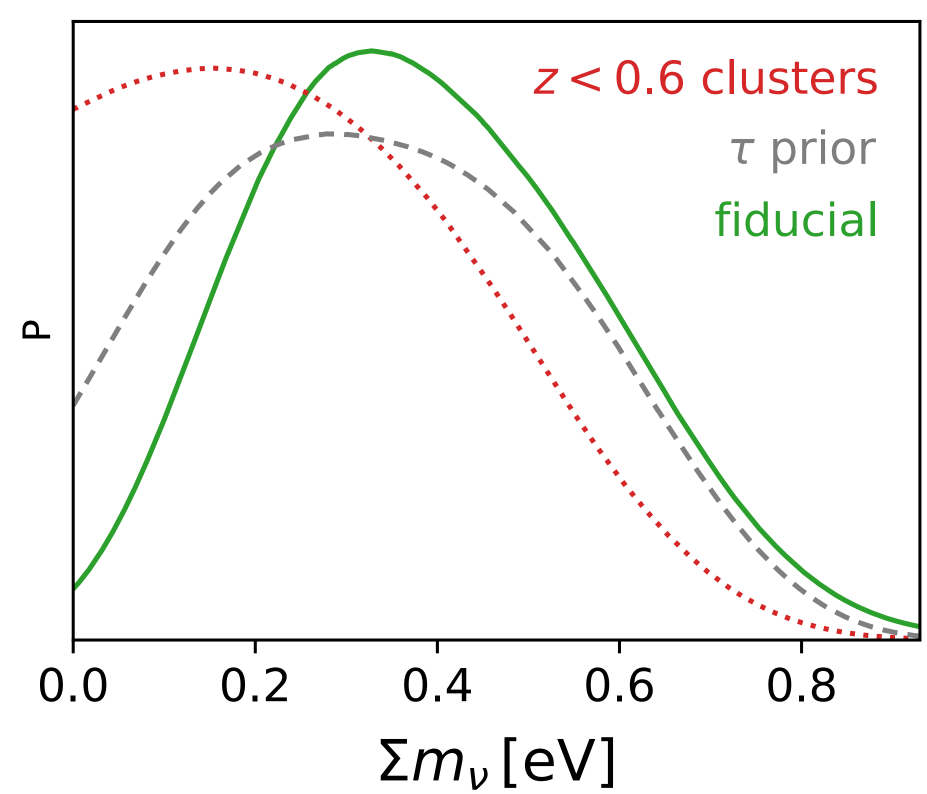
Neutrino Masses

Bocquet+ (arXiv: 1812.01679)



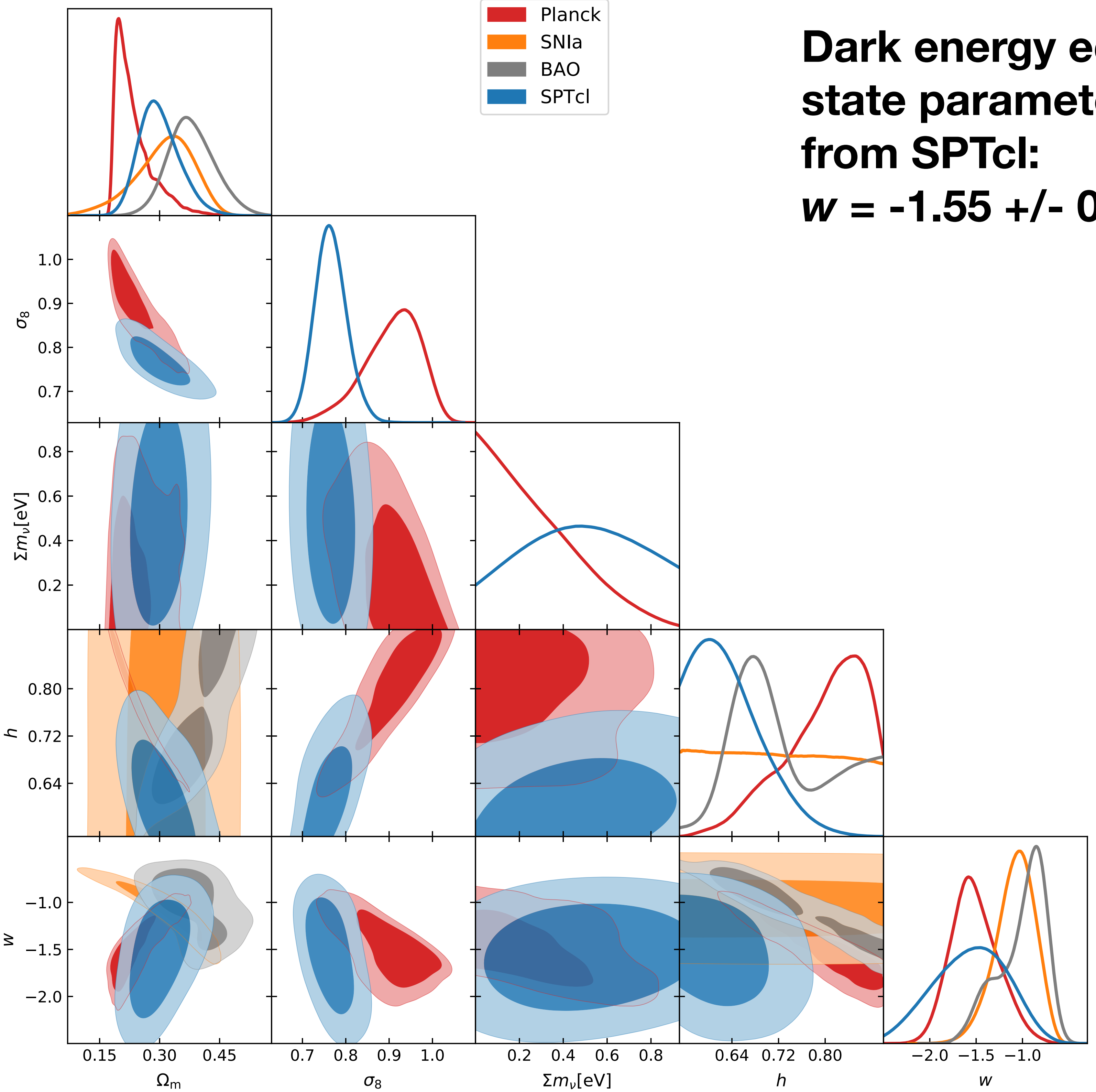
- Combination with Planck primary CMB measurements yields 2 σ preference for non-zero sum of neutrino masses
- Again, limited by mass calibration uncertainties
- Using τ prior from Planck 2018 gives 1.7 σ preference
- Using only the $z < 0.6$ cluster sample gives no preference for non-zero sum of neutrino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





*w*CDM

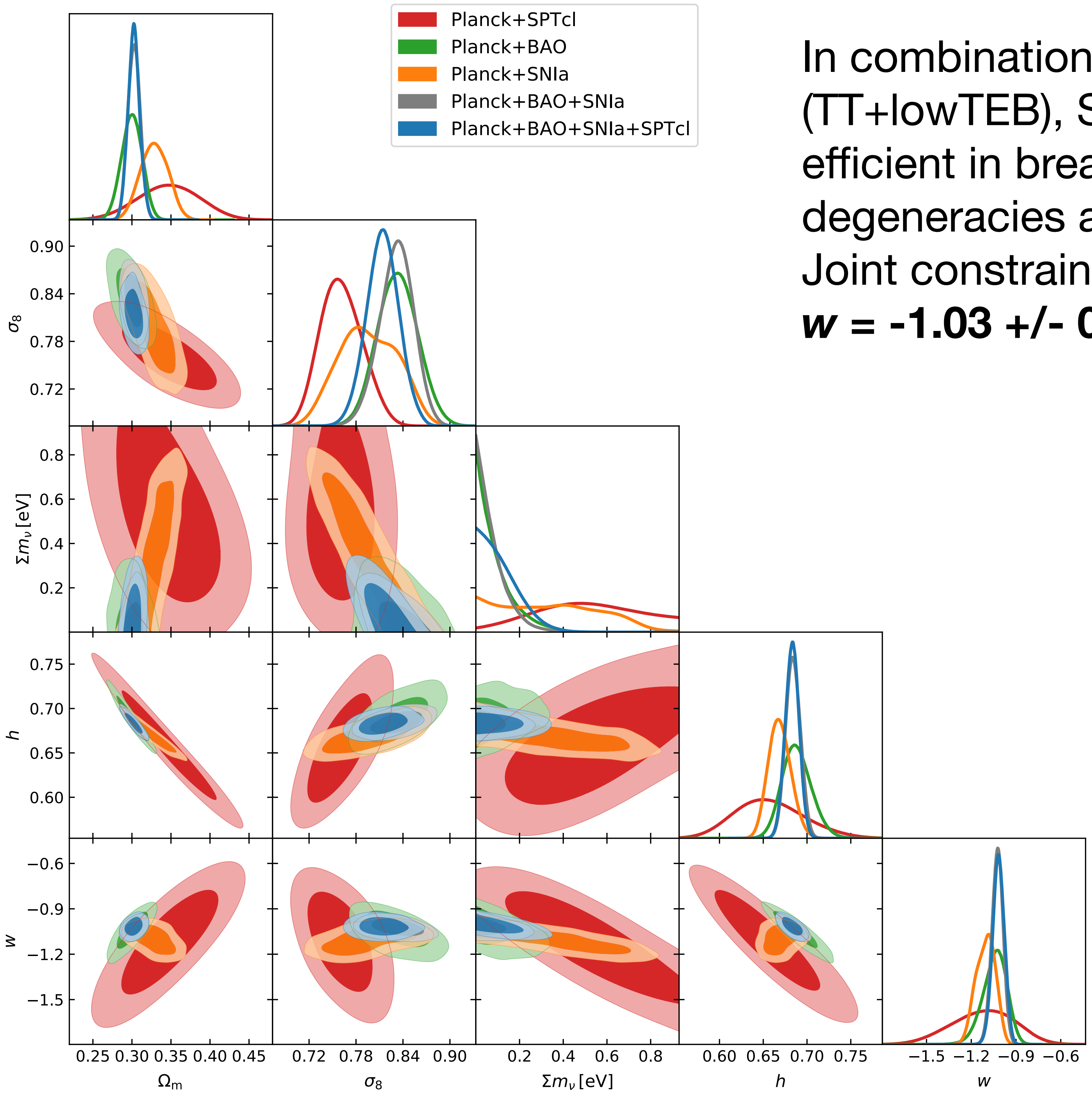
Bocquet+ (arXiv: 1812.01679)



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

*w*CDM

Bocquet+ (arXiv: 1812.01679)



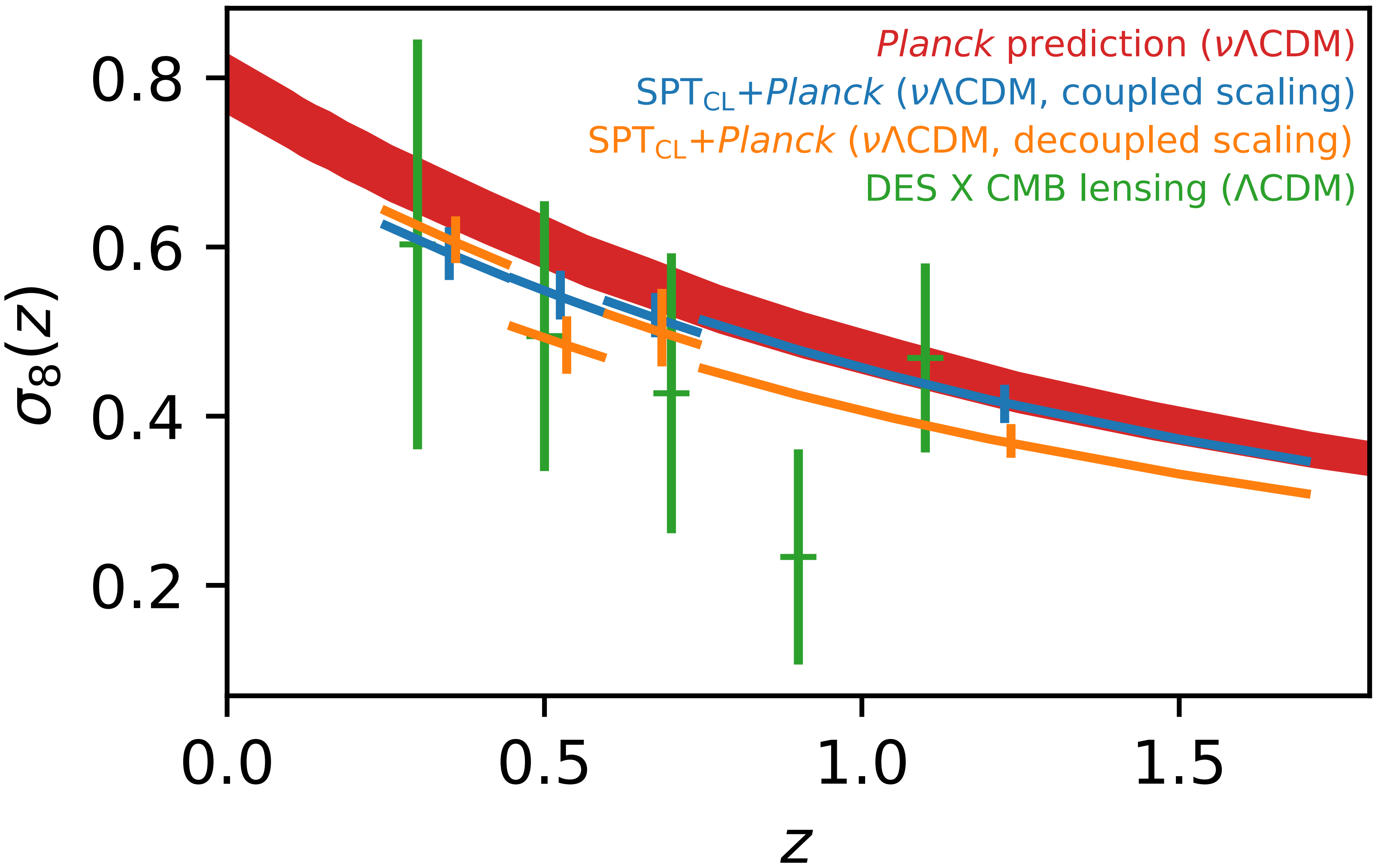
In combination with Planck (TT+lowTEB), SPTcl is not as efficient in breaking degeneracies as BAO or SNIa.
Joint constraint:
***w* = -1.03 +/- 0.04**

Linear Growth of Structure

Bocquet+ (arXiv: 1812.01679)

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

Orange error bars: More freedom in mass—observable relation



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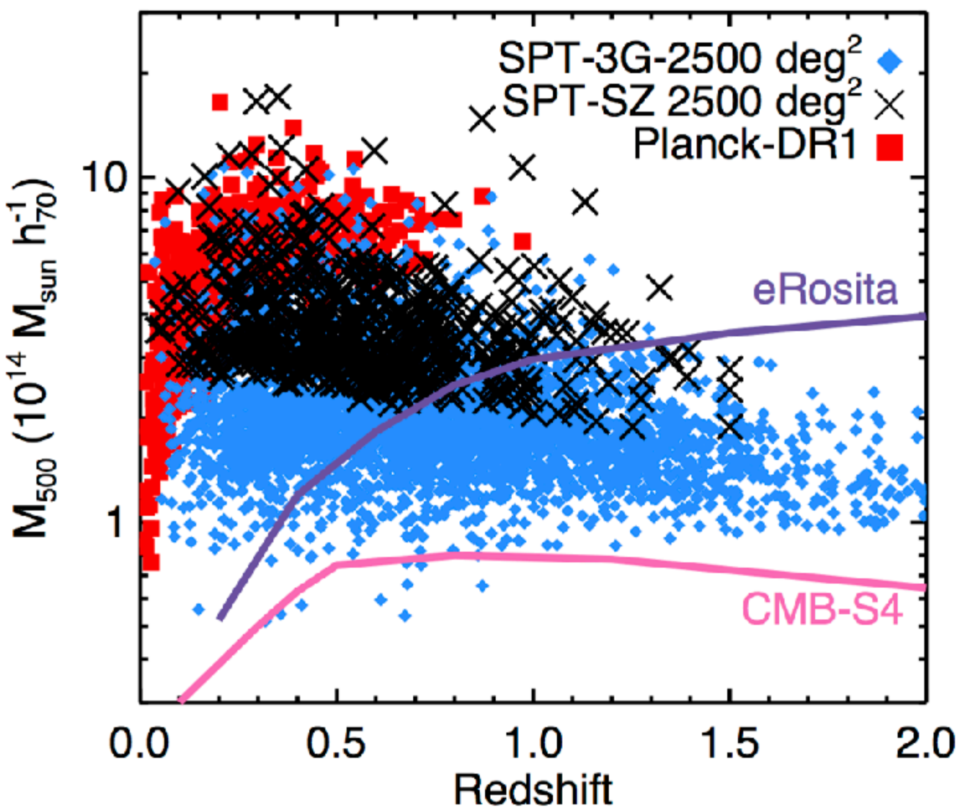
Outlook: Ongoing Work

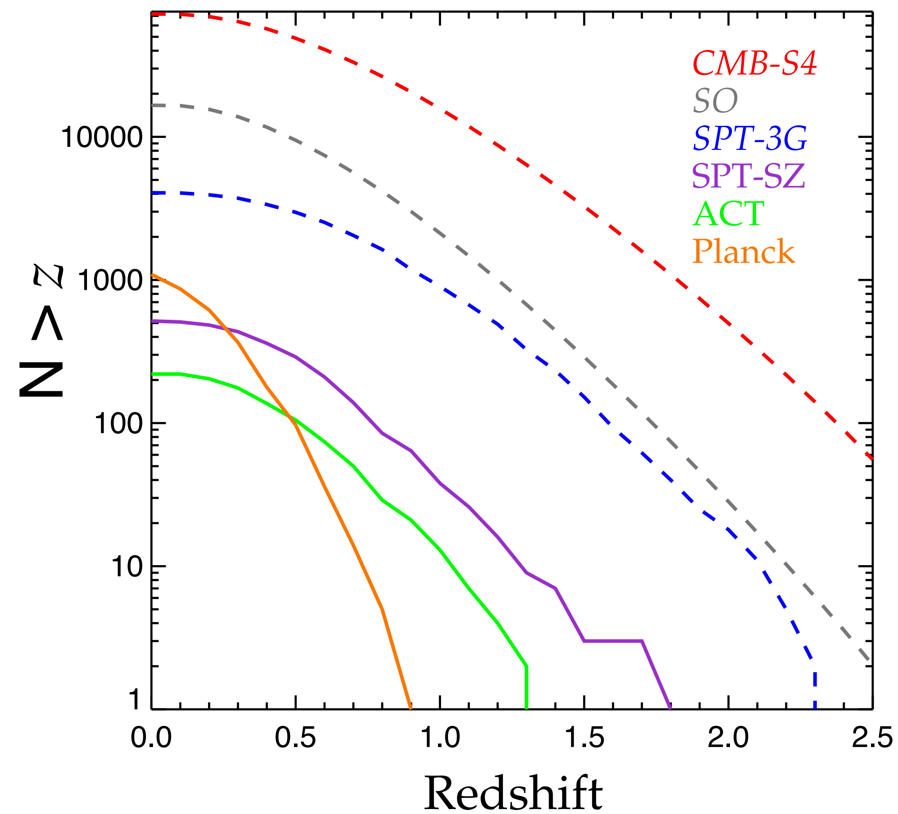
- Weak-lensing mass calibration of SPT clusters
  - Currently limited by number of WL observations
  - Use overlap of SPT and the Dark Energy Survey (DES) to get WL data for all SPT clusters at z <~ 1 (Paulus, Bocquet, Mohr+ in prep.)
  - Ongoing HST programs for high-z clusters
- SPTpol (2nd generation camera) analyses ongoing
  - Wide survey extension (another 2500 square deg: SPECS)
  - Main, deep fields: Push to lower-mass clusters (more abundant)
- SPT-3G: deep 1500 square degree survey

Outlook: Future Cluster Samples from CMB

SPT

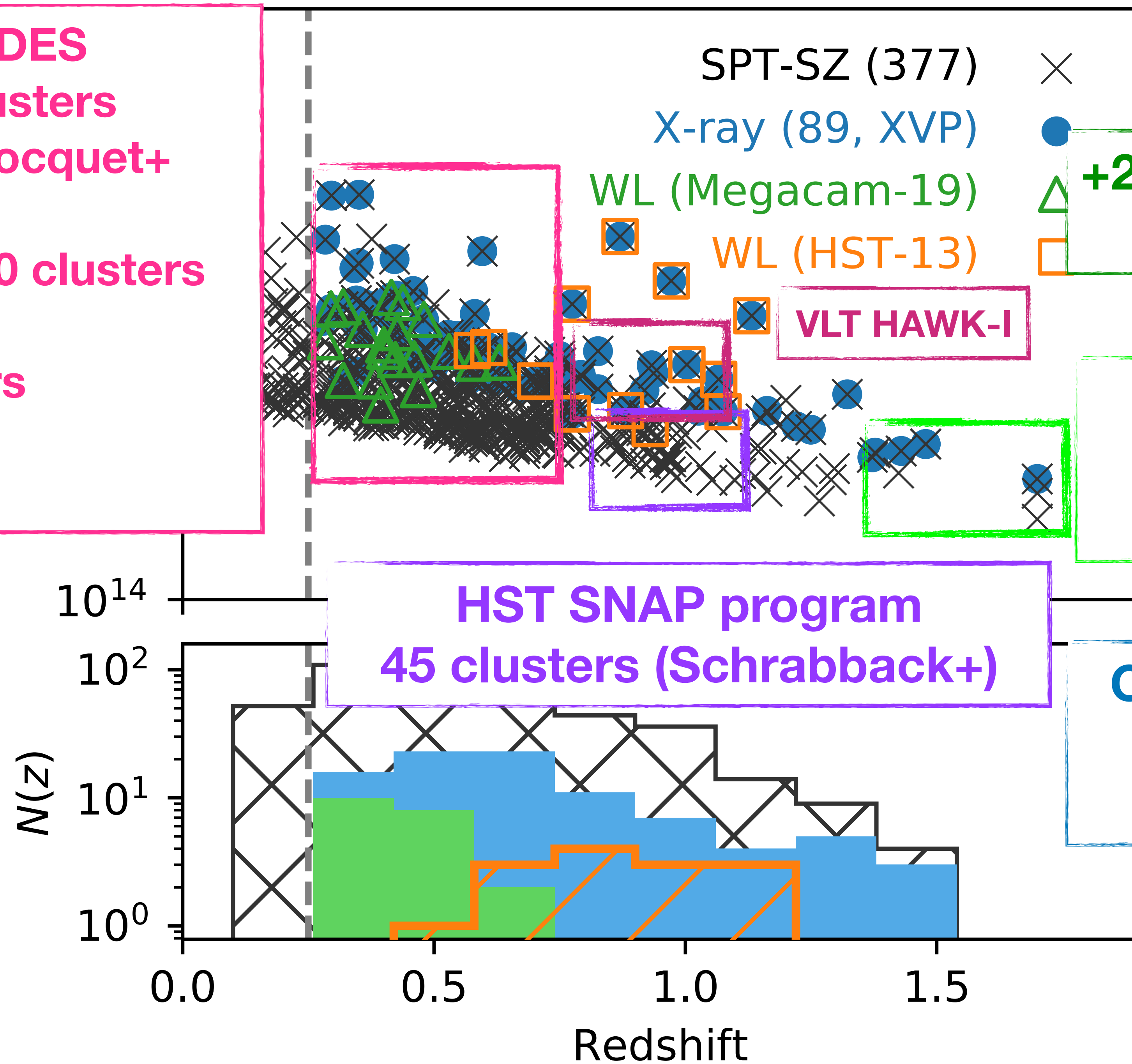


M. Madhavacheril



OUTLOOK: ONGOING (OPTICAL) WEAK LENSING FOLLOW-UP

WL calibration from DES
- **SV 200deg²: 34 clusters (Stern, Dietrich, Bocquet+ 2018)**
- **Y1 1500 deg²: ~200 clusters (Maria Paulus)**
- **Y3: all SPT clusters @ z < ~0.7 (Maria Paulus)**



+29 Megacam clusters analysis ongoing

9 high-z clusters (HST) (PI Schrabback)

HST SNAP program 45 clusters (Schrabback+)

CMB cluster lensing (Raghunathan, Bocquet+)

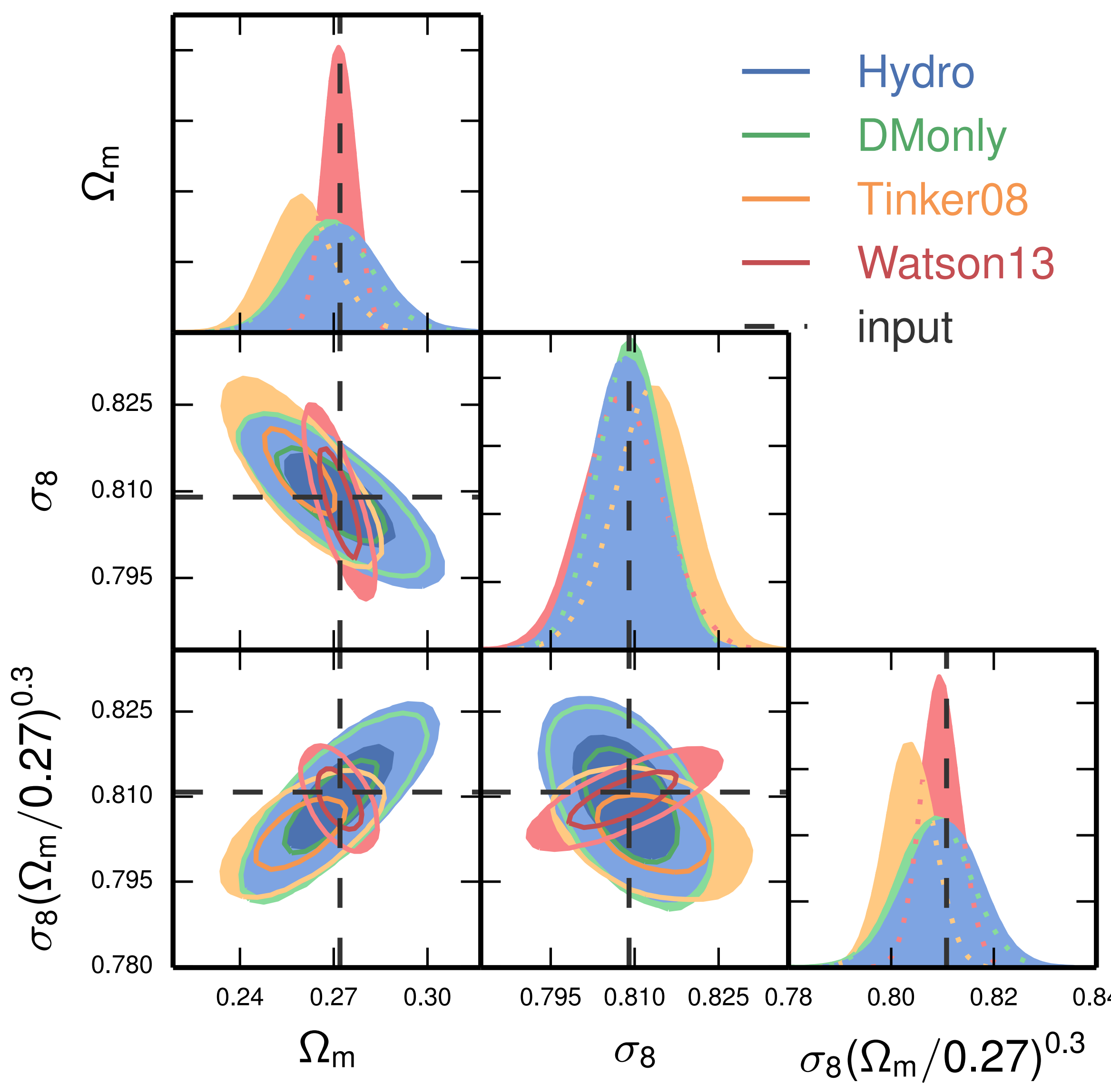
Summary

- Data-driven cosmology from SPT galaxy clusters
- WL data plays key role
- WL sample is expanding thanks to the Dark Energy Survey, HST programs, and CMB lensing
- Next-gen CMB surveys ongoing and planned
  - SPTpol, SPT-3G
  - Advanced ACTpol
  - Simons Observatory
  - CCAT-prime
  - CMB-S4

Backup slides…

Impact of hydro HMF for SPT

Bocquet+ (2016), MNRAS 456, 2361 (arXiv: 1502.07357)

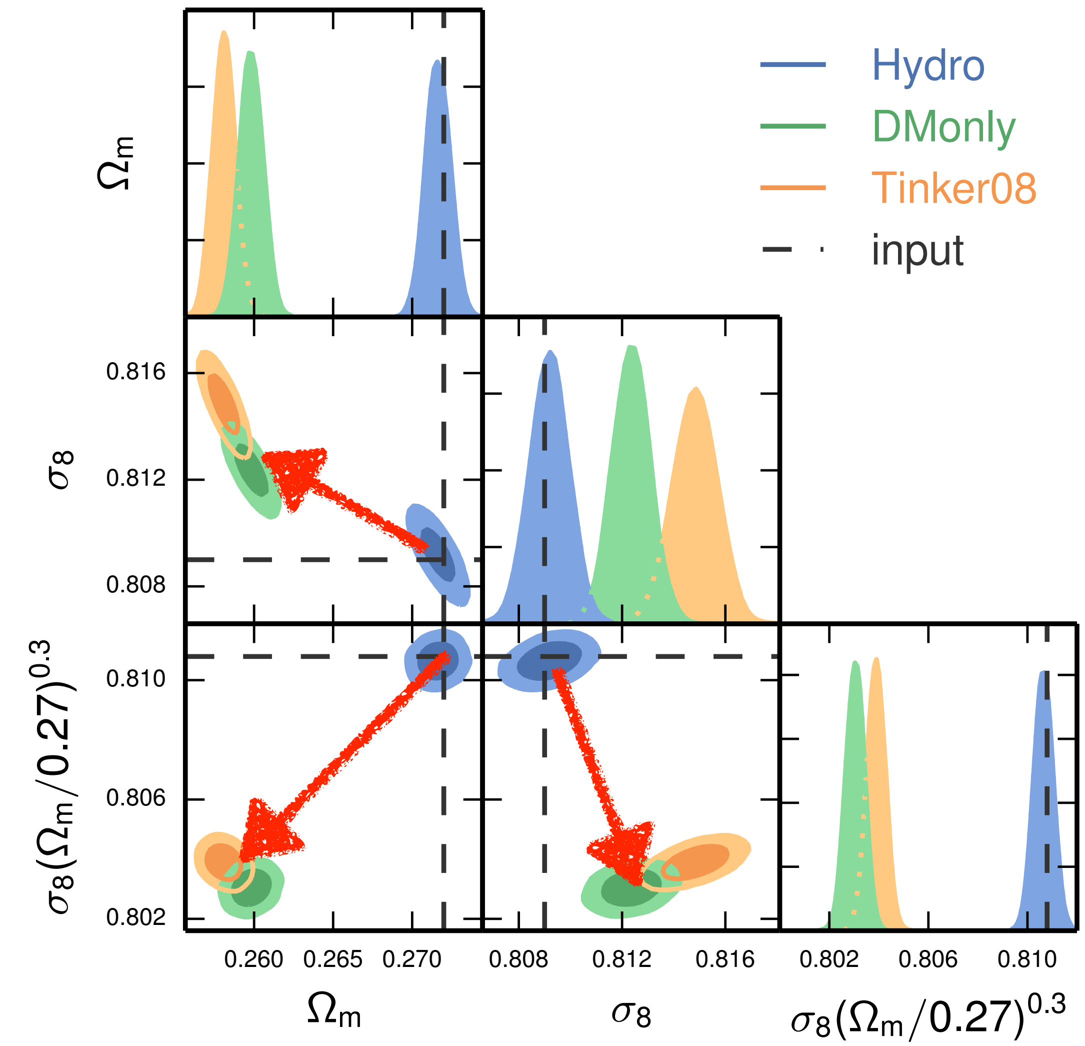


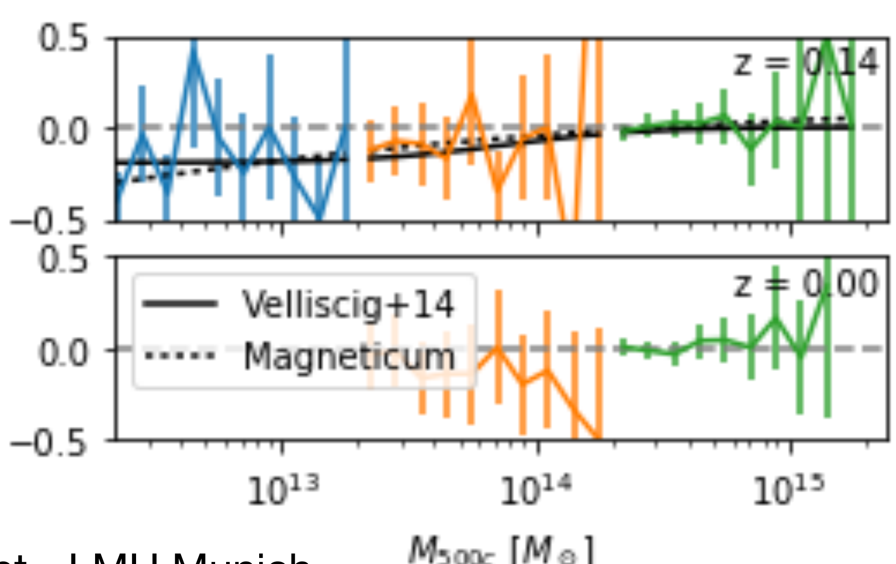
Magneticum Pathfinder **hydro simulations (Dolag et al.)**

Baryons and the Halo Mass Function

Bocquet+ (2016), MNRAS 456, 2361 (arXiv: 1502.07357)

- At fixed halo mass, feedback processes change the abundance
- Use hydrodynamical *Magneticum Pathfinder* simulation suite
- 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!

Cosmology dependence of halo mass function

- Current approach: extrapolate cosmology dependence
- Use 26 (2 & 5 Gpc)^3 simulations covering 8 cosmo params and "interpolate" using Gaussian process (Bocquet, Habib, Heitmann+ in prep.)
- See also Habib+07, Heitmann+ 16, McClintock+18, Nishimichi+19