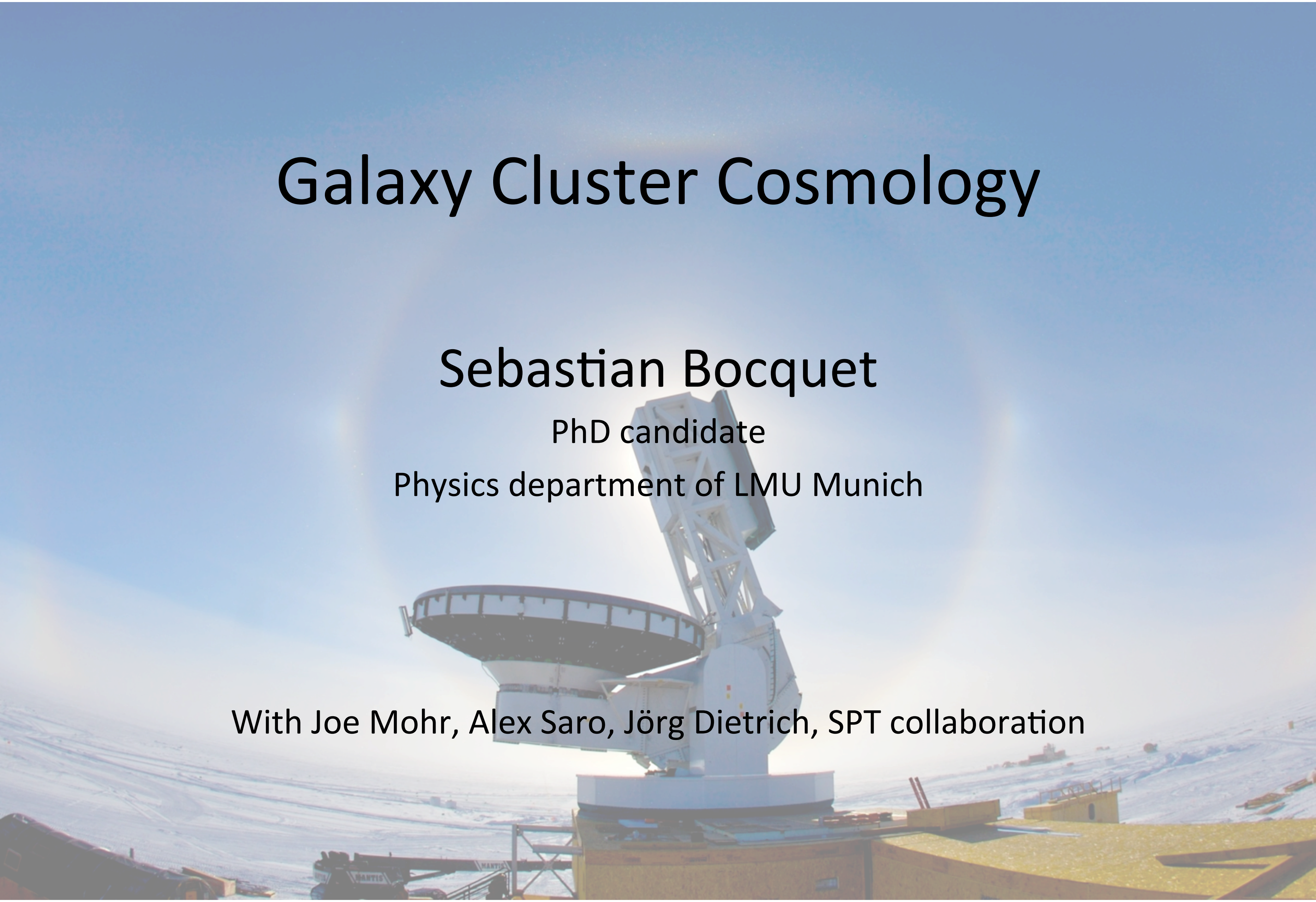


Galaxy Cluster Cosmology

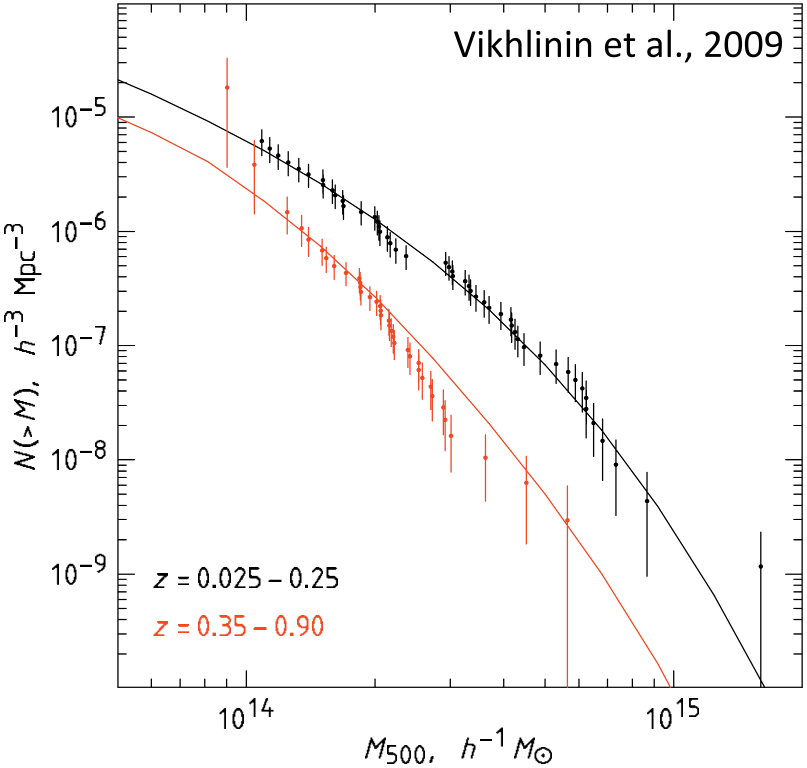
Sebastian Bocquet

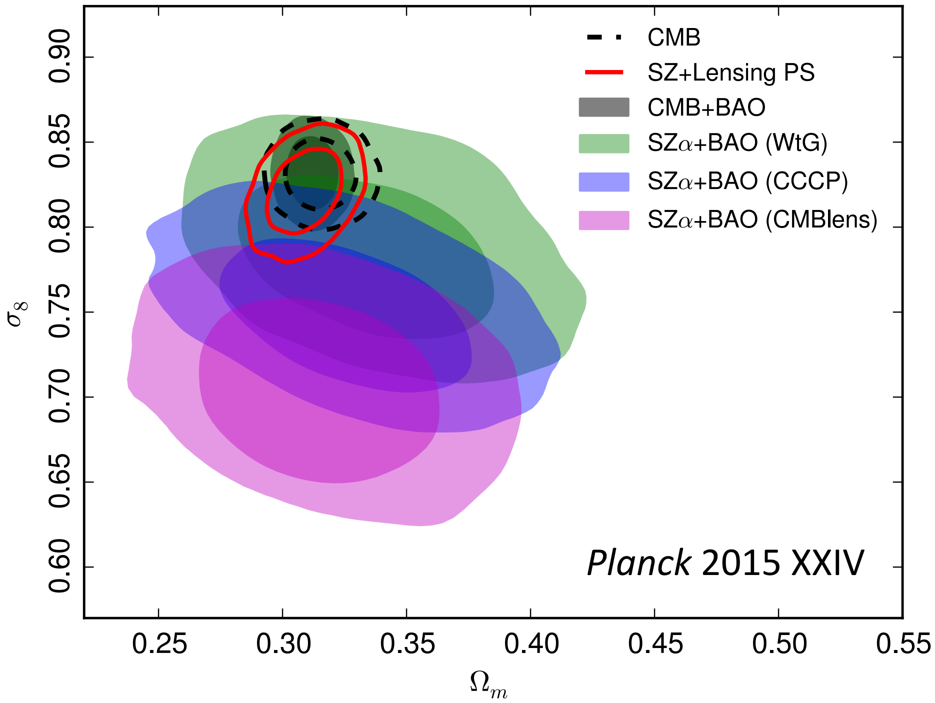
PhD candidate

Physics department of LMU Munich

With Joe Mohr, Alex Saro, Jörg Dietrich, SPT collaboration

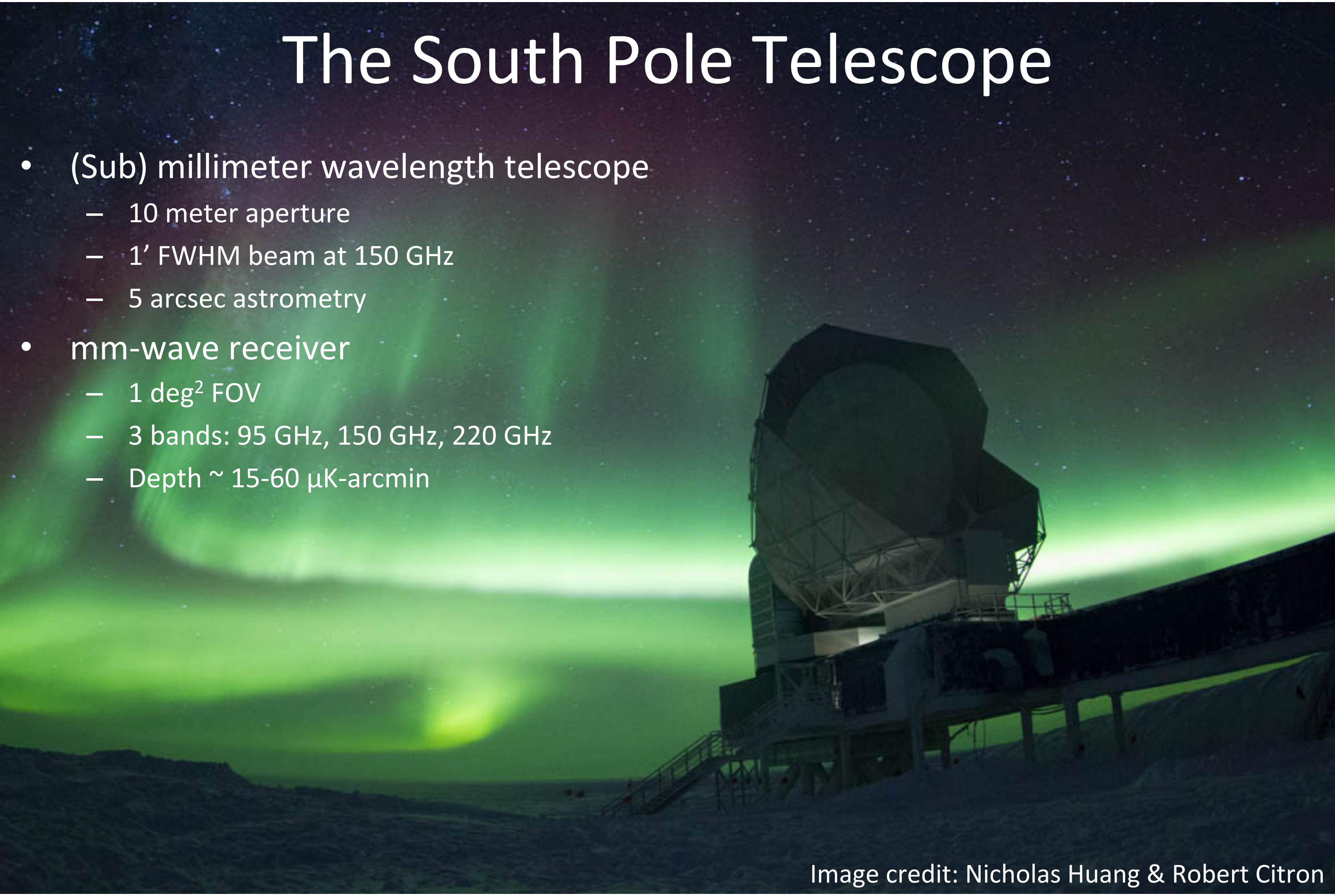
Galaxy Cluster Cosmology





- Expected cluster abundance (as function of mass and redshift) is linked to the linear matter power spectrum
- through the mass function, calibrated against numerical simulations
- Challenge: Estimate cluster masses
- Mass proxies: X-ray, SZ, velocity dispersion, weak lensing, richness

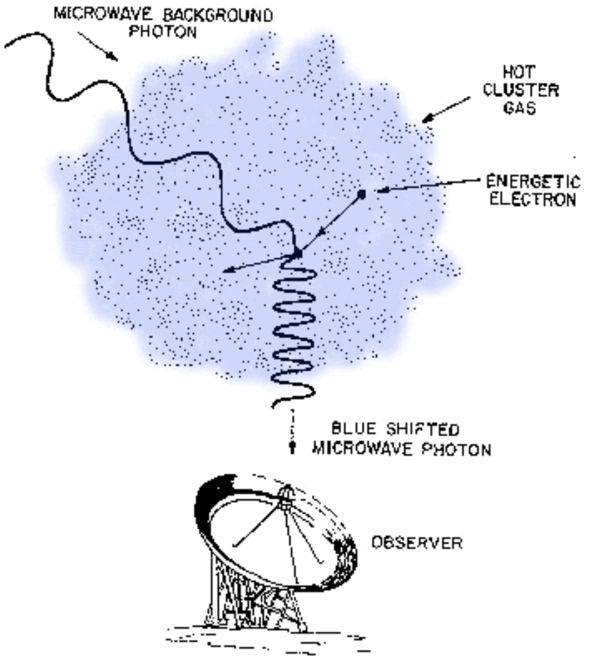
The South Pole Telescope



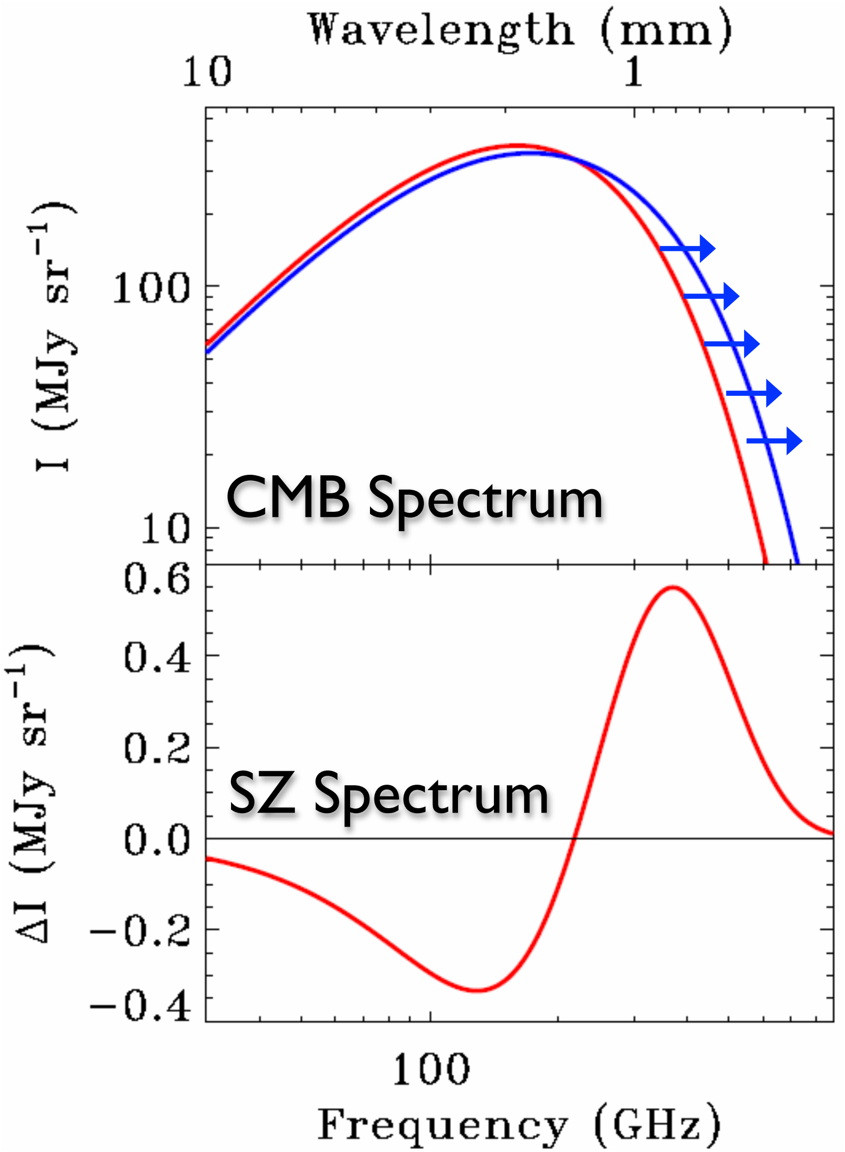
- (Sub) millimeter wavelength telescope
  - 10 meter aperture
  - 1’ FWHM beam at 150 GHz
  - 5 arcsec astrometry
- mm-wave receiver
  - 1 deg^2 FOV
  - 3 bands: 95 GHz, 150 GHz, 220 GHz
  - Depth ~ 15-60 μK-arcmin

Image credit: Nicholas Huang & Robert Citron

Sunyaev-Zel'dovich (SZ) Effect



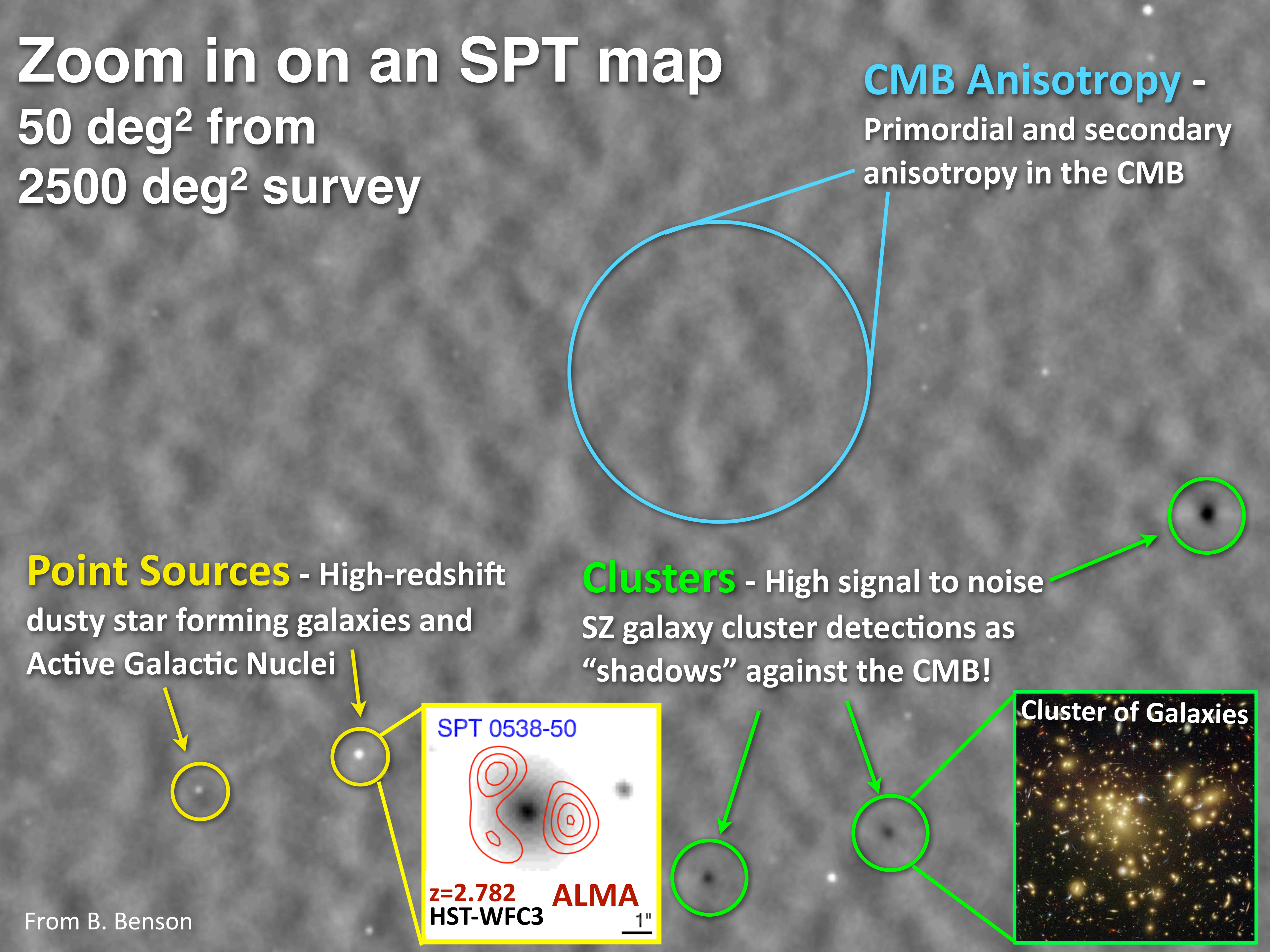
from L. Van Speybroeck



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

Zoom in on an SPT map

50 deg² from 2500 deg² survey



CMB Anisotropy - Primordial and secondary anisotropy in the CMB

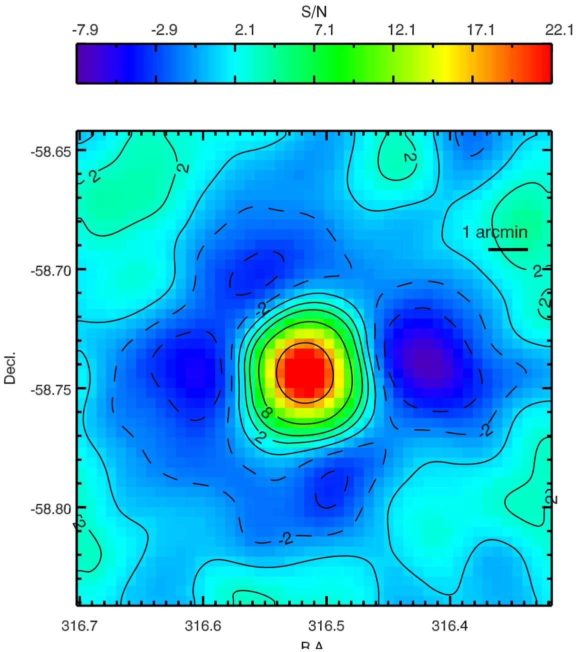
Point Sources - High-redshift dusty star forming galaxies and Active Galactic Nuclei

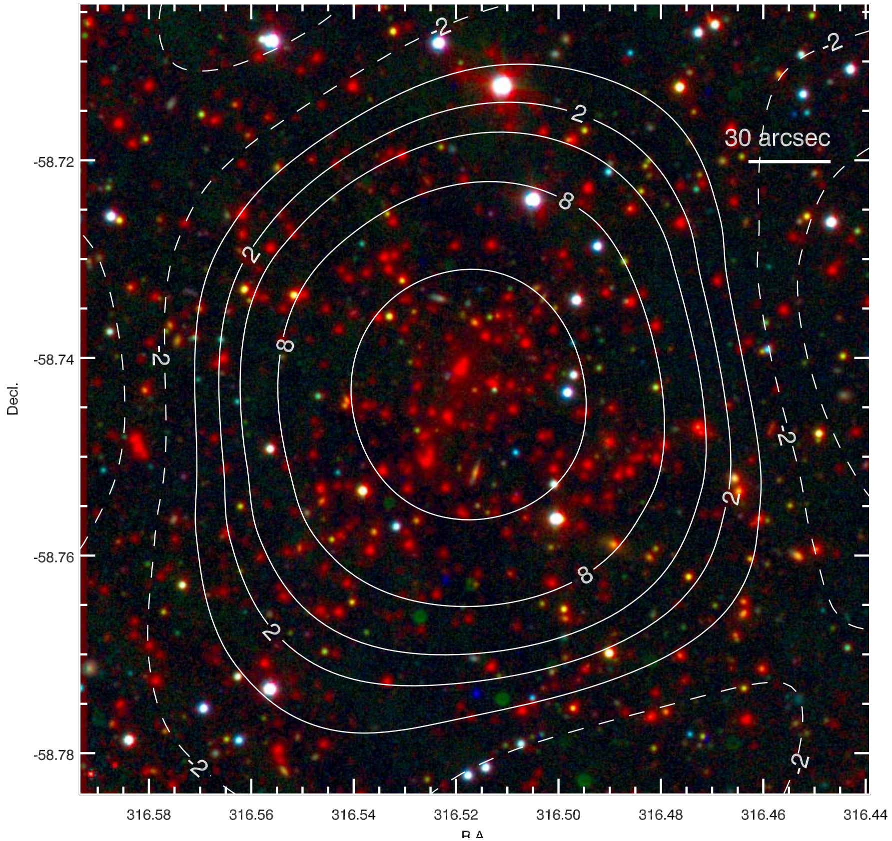
Clusters - High signal to noise SZ galaxy cluster detections as “shadows” against the CMB!

From B. Benson

Optical / NIR follow-up

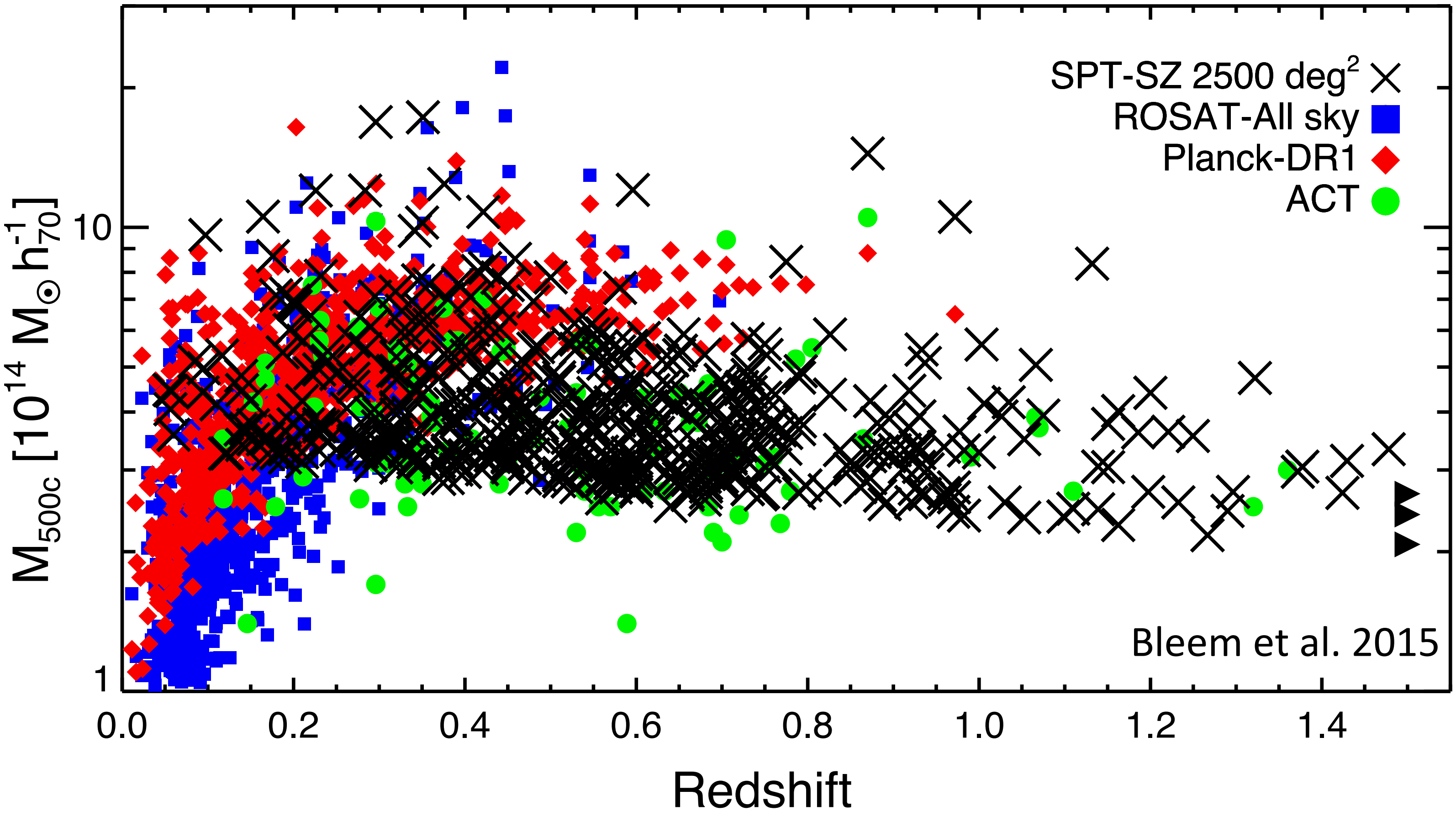
SPT-CL J2106-5844 at z = 1.133





Most massive cluster known at z > 1, Foley et al. 2013

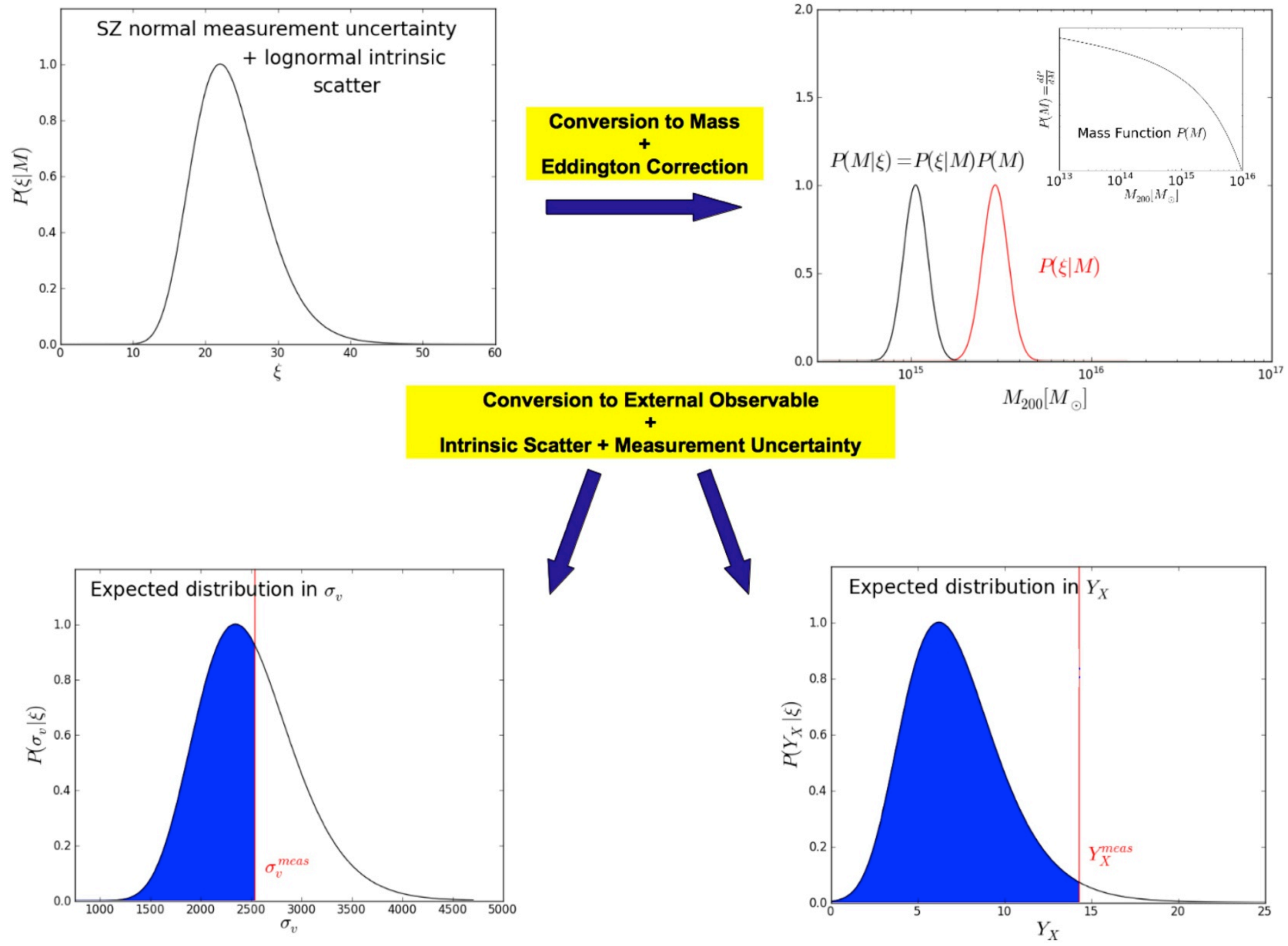
SPT-SZ sample from 2500 deg^2 survey



Cluster Cosmology and Mass Calibration with the SPT

Bocquet et al., 2015, ApJ, 799, 214, arXiv: 1407.2942

- Starting point:
  - Cluster survey selected in SZ observable
  - (Incomplete) follow-up in further observables
- Data:
  - SPT 720deg^2 sample: 96 clusters selected with SZ effect
  - 16 X-ray Y_X measurements (Andersson et al. 2011, Foley et al. 2011)
  - 63 velocity dispersions (Barrena et al. 2002, Buckley-Geer et al. 2011, Sifón et al. 2013, Ruel et al. 2014)
- Mass-observable relations
  - Each observable is linked to the true cluster mass
  - There is some intrinsic scatter associated to this relation!

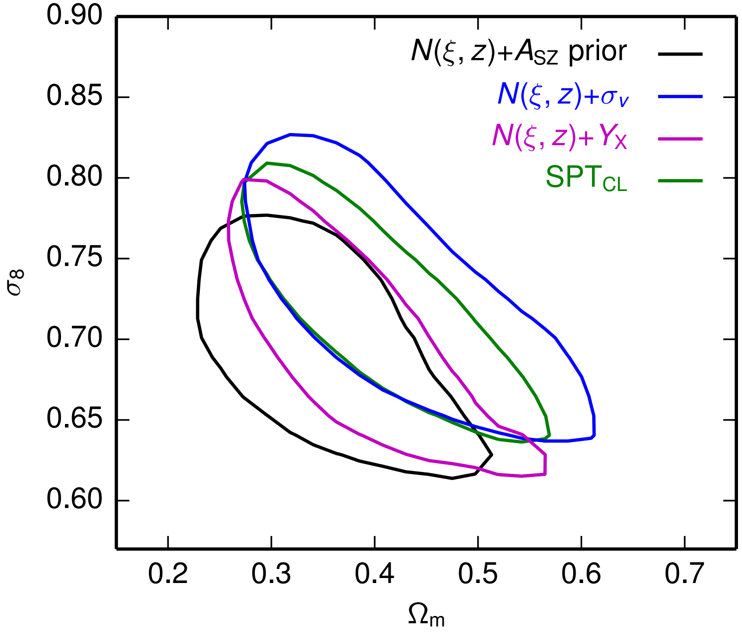


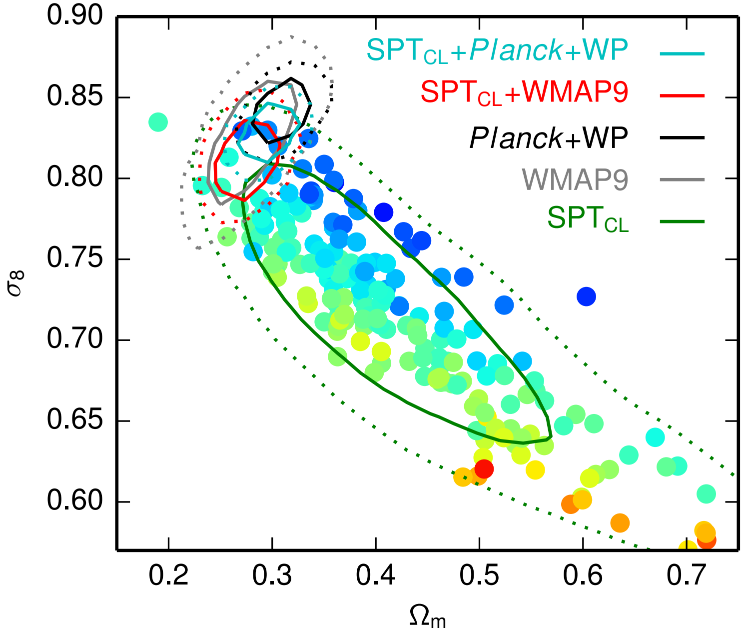
Conversion to Mass
+
Eddington Correction

Conversion to External Observable
+
Intrinsic Scatter + Measurement Uncertainty

- Calibrate the survey observable-mass relation through follow-up measurements
- Account for the selection!
- Compare the observables with their predicted values

Cluster Cosmology with SPT

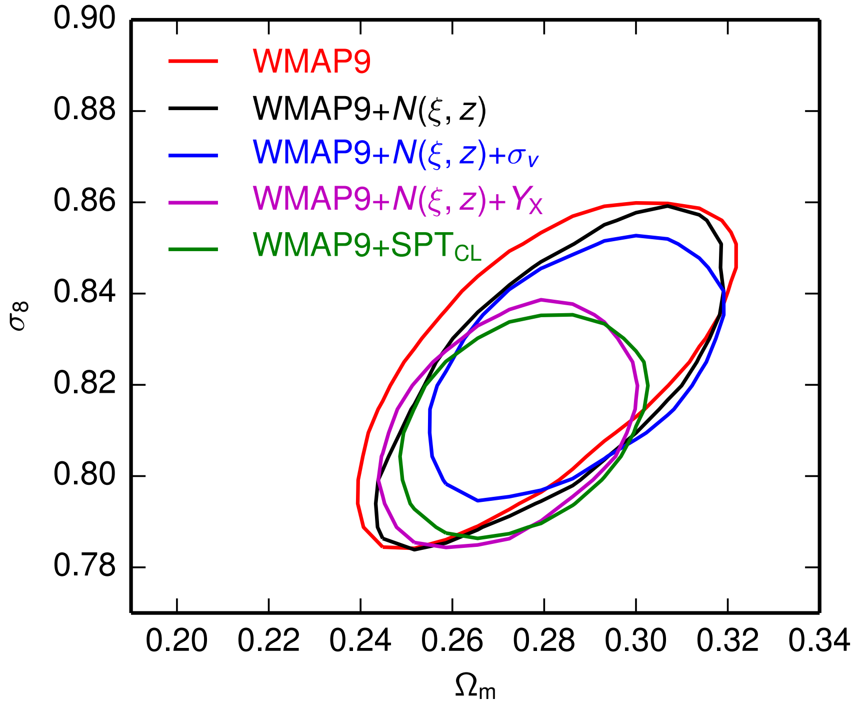




From simulation prior to Y_X+σ_v:
Improve constraints on
$\sigma_8 (\Omega_m/0.27)^{0.3}$ by 44%

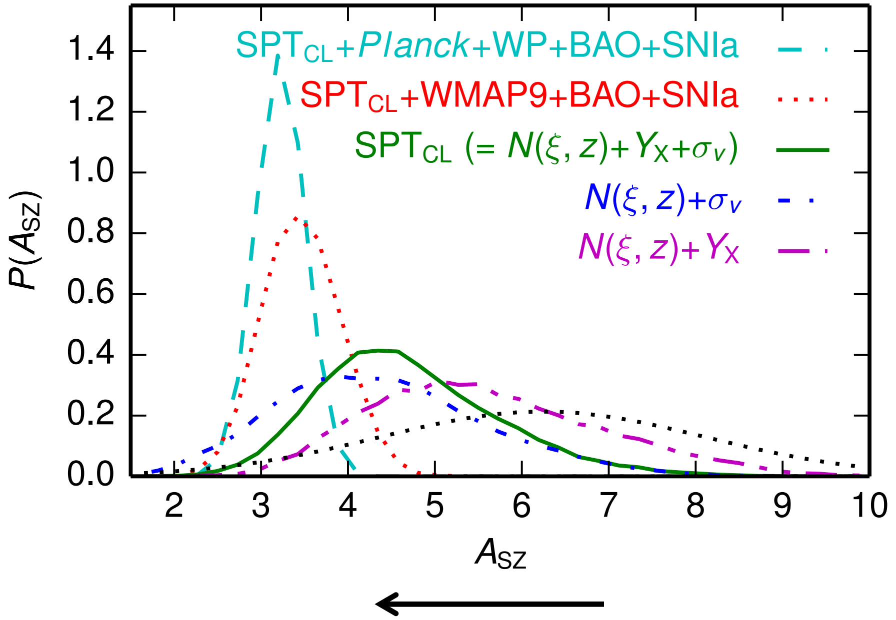
Adding SPT$_{CL}$ to *Planck*+WP:
Improve constraints on Ω_m, σ_8, and
$\sigma_8 (\Omega_m/0.27)^{0.3}$ by ~15%

Impact of Mass Calibration



- When combining with CMB data, the latter dominates the constraints
- The mass calibration from $Y_X+\sigma_v$ helps in further tightening constraints by
  - Ω_m: 36%
  - σ_8: 37%
  - $\sigma_8 (\Omega_m/0.27)^{0.3}$: 47%
- In this case, X-ray Y_X has more impact than velocity dispersions

SPT Mass Scale



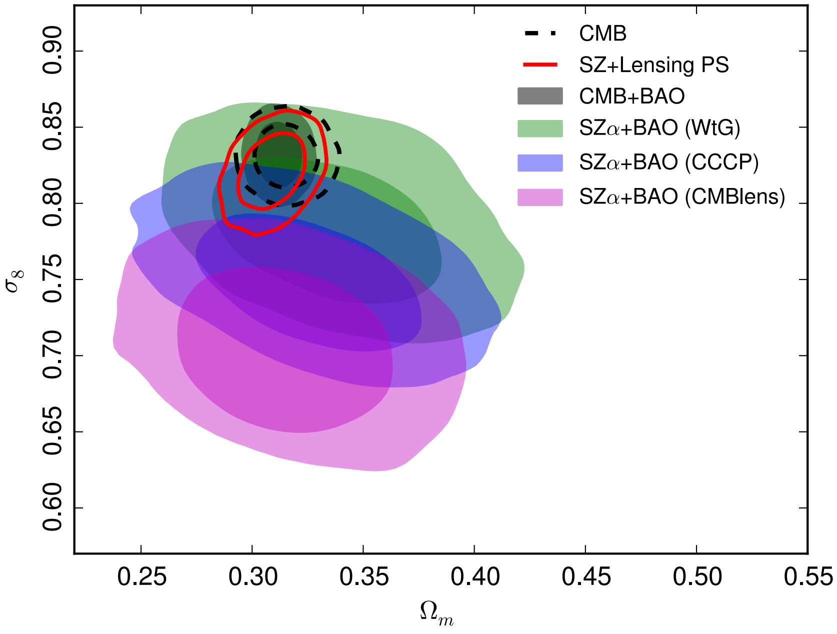
cluster mass

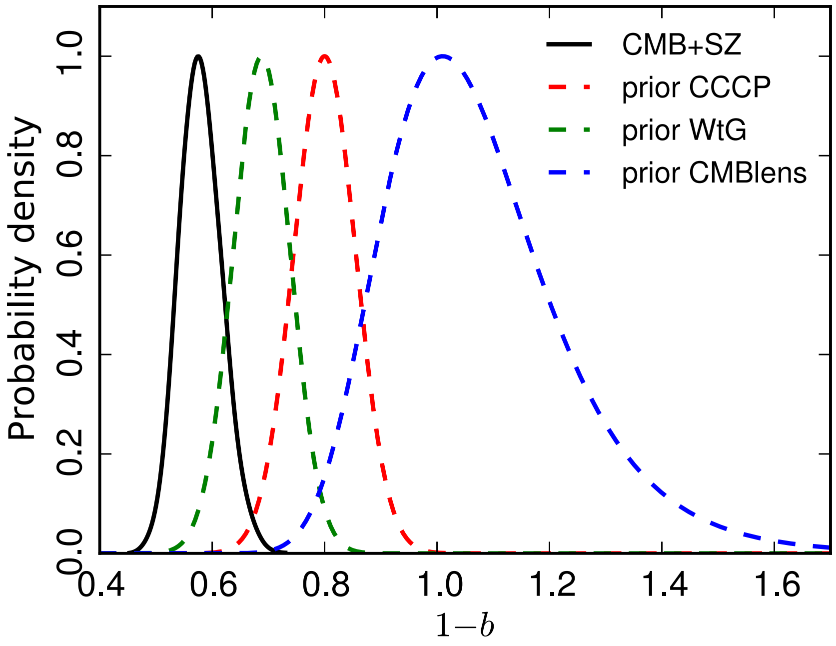
- Cluster mass estimates depend on SZ normalization A_{SZ}

$$\zeta = A_{SZ}\left(\frac{M_{500}}{3\times10^{14}h^{-1}M_\circ}\right)^{B_{SZ}}\left(\frac{E(z)}{E(0.6)}\right)^{C_{SZ}}$$

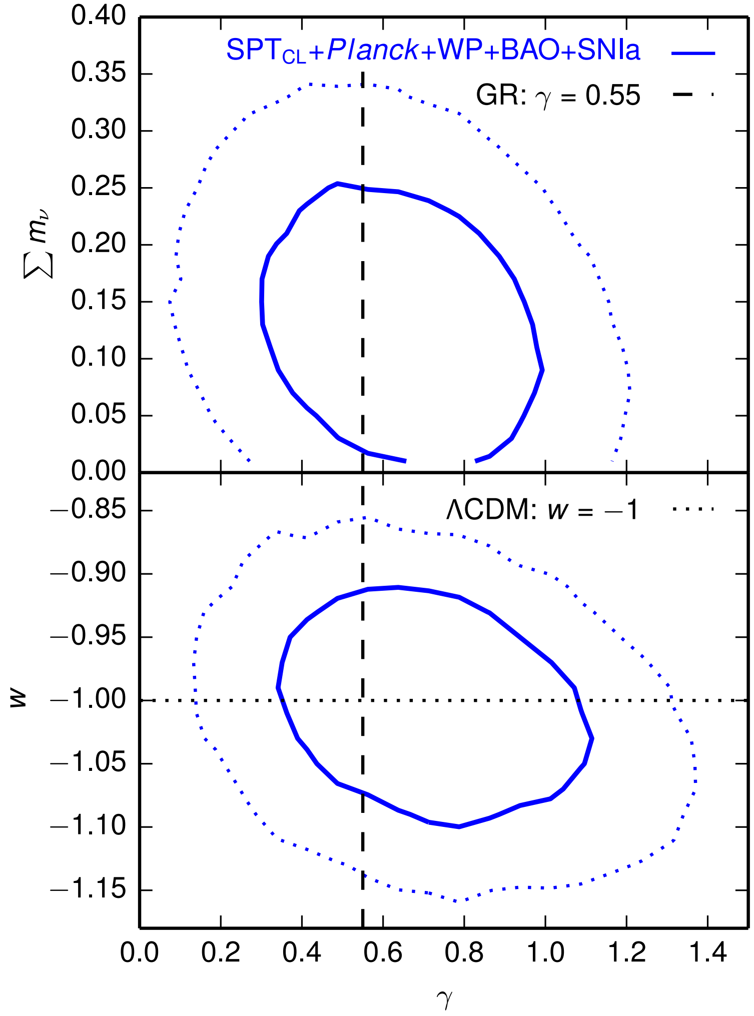
- Cluster masses increase by
  - 16% from X-ray calibration (purple) to dispersion calibration (blue)
  - 44% from X-ray calibration to combined analysis including *Planck* +WP (cyan)

Compare with *Planck* 2015 XXIV





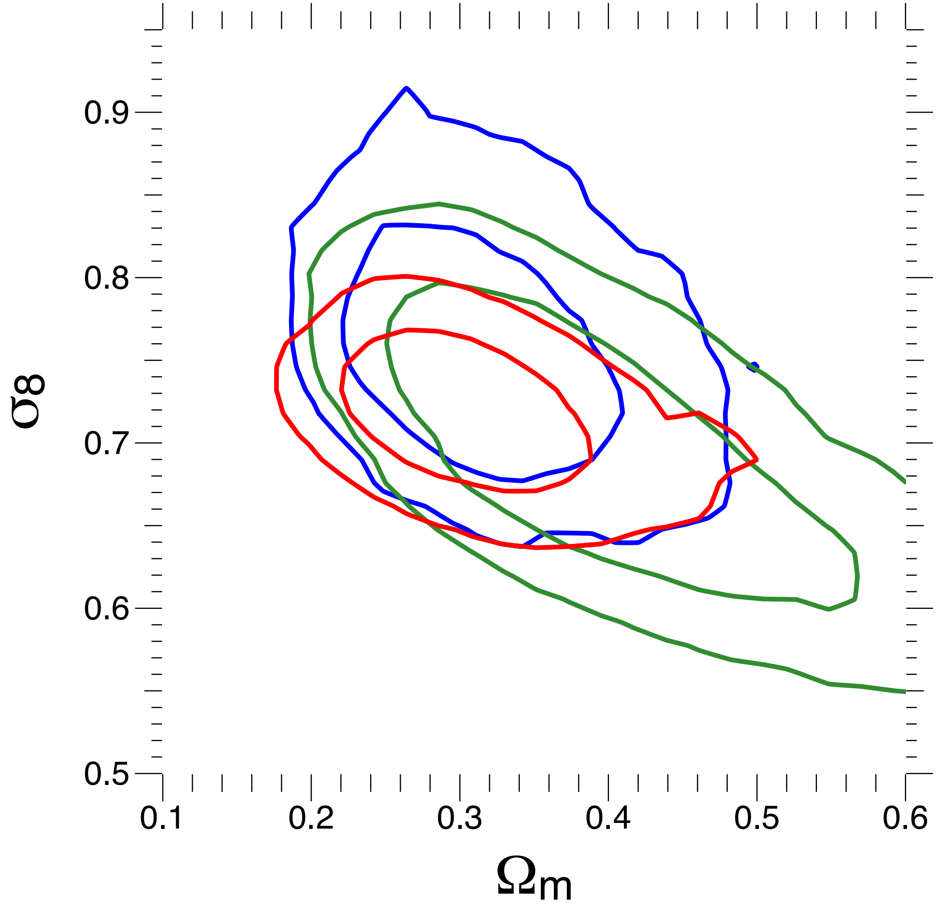
Growth of Structure



- Parametrized structure growth
- $d\ln\delta / d\ln a = \Omega_m(a)^\gamma$
- γ = 0.55 predicted by GR
- Simultaneously probe:
  - Growth and sum of neutrino masses
    - $\Sigma m_\nu < 0.277$ eV (95% CL)
    - $\gamma = 0.63 \pm 0.25$
  - Growth and expansion histories
    - $w = -1.007 \pm 0.065$
    - $\gamma = 0.73 \pm 0.28$

Summary / Outlook

- Use multi-wavelength mass calibration for accuracy and precision
- Velocity dispersions are closer to the CMB preferred mass scale than Y_X



Work in progress:

- Cluster cosmology from full SPT survey with Y_X calibration from ~80 clusters
- Extended velocity dispersion sample with ~100 clusters
- WL shear profiles are measured for 32 clusters (MegaCam and HST)
- Calibration of Y_X scaling relations from WL for SPT selected clusters
- Comparison of SZ signal and optical richness (with DES)

Baryon impact on the halo mass function: Fitting formulae and implications for cluster cosmology

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[3]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany*
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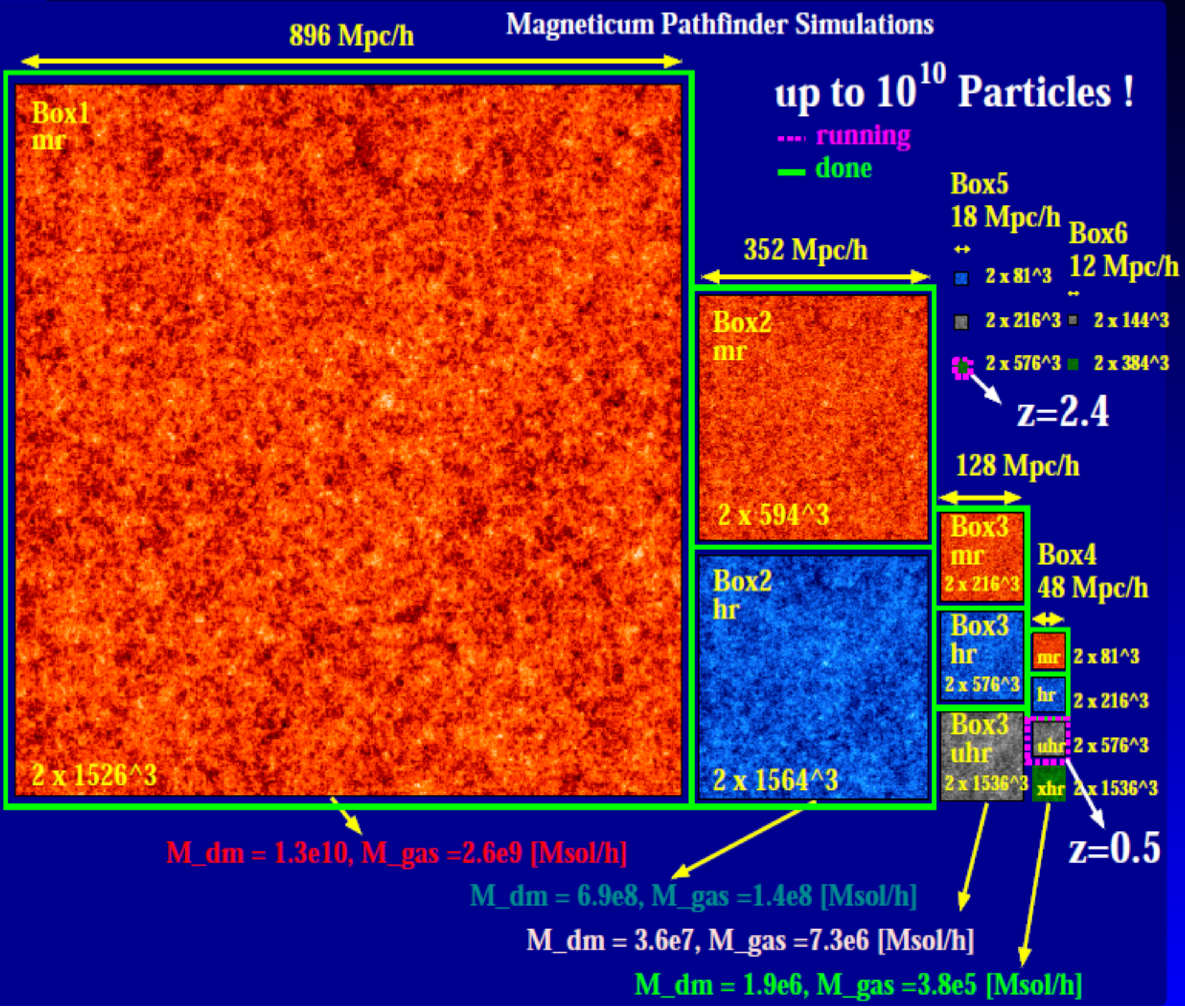
Using hydrodynamical *Magneticum* simulations (Dolag, in preparation)
see e.g. Hirschmann et al. 2014, McDonald et al. 2014, Saro et al. 2014

LSS Simulations



Magneticum Pathfinder Simulations

up to 10^{10} Particles !

┅ running

▬ done

896 Mpc/h

Box1
mr
2 x 1526^3

352 Mpc/h

Box2
mr
2 x 594^3

Box2
hr
2 x 1564^3

128 Mpc/h

Box3
mr
2 x 216^3

Box3
hr
2 x 576^3

Box3
uhr
2 x 1536^3

Box4
48 Mpc/h

mr 2 x 81^3

hr 2 x 216^3

uhr 2 x 576^3

xhr 2 x 1536^3

z=0.5

Box5
18 Mpc/h

2 x 81^3

2 x 216^3

2 x 576^3

Box6
12 Mpc/h

2 x 144^3

2 x 384^3

z=2.4

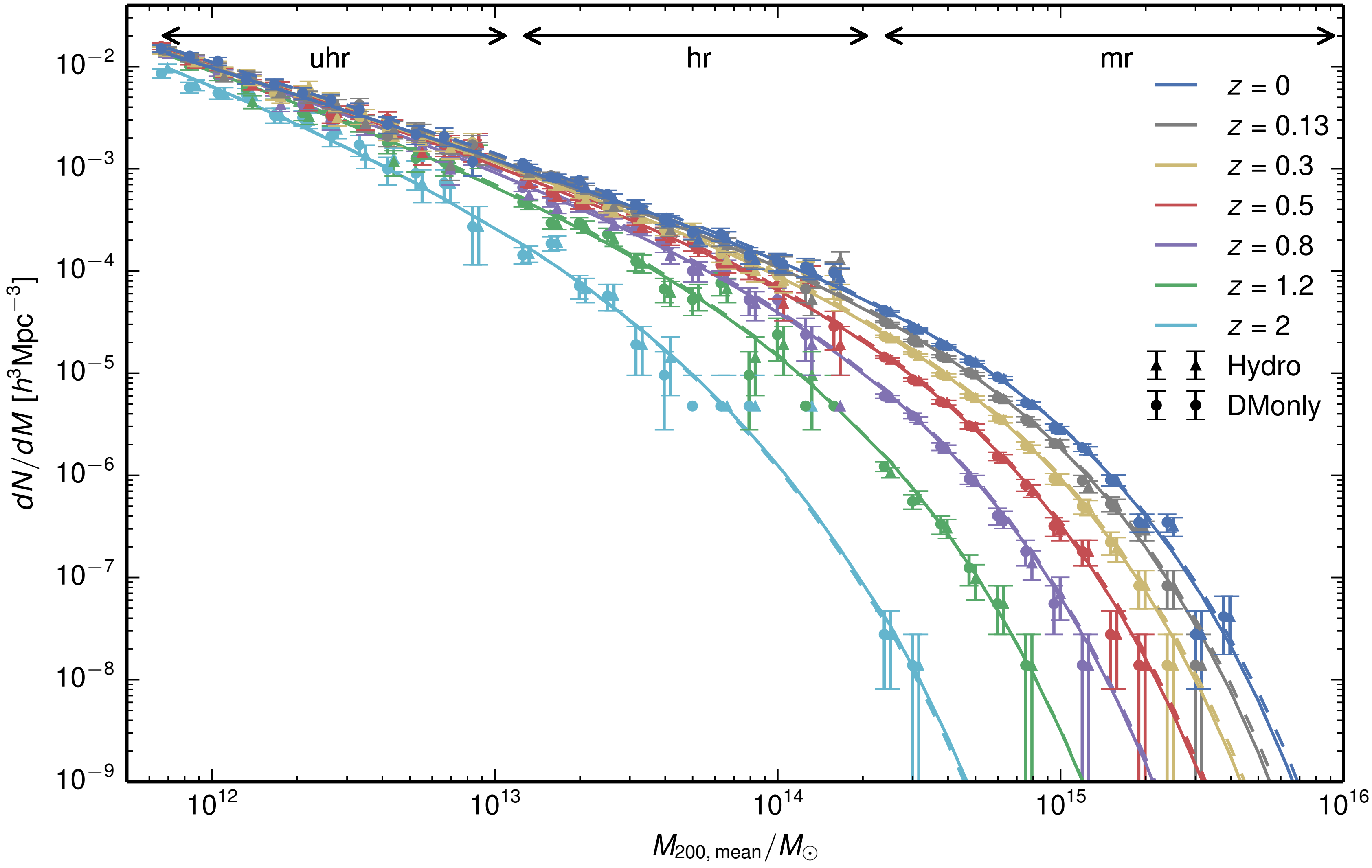
M_dm = 1.3e10, M_gas =2.6e9 [Msol/h]

M_dm = 6.9e8, M_gas =1.4e8 [Msol/h]

M_dm = 3.6e7, M_gas =7.3e6 [Msol/h]

M_dm = 1.9e6, M_gas =3.8e5 [Msol/h]

Mass functions



The fitting function

The comoving number density of clusters of mass *M* is

$$\frac{dn}{dM} = f(\sigma)\frac{\bar{\rho}_{\rm m}}{M}\frac{d\ln\sigma^{-1}}{dM}$$

and depends on:

- variance of the matter density field

$$\sigma^2(M,z) \equiv \frac{1}{2\pi^2}\int P(k,z)\hat{W}^2(kR)k^2dk$$

- mean matter density

$$\bar{\rho}_{\rm m}$$

- Fitting function (8 fit parameters)

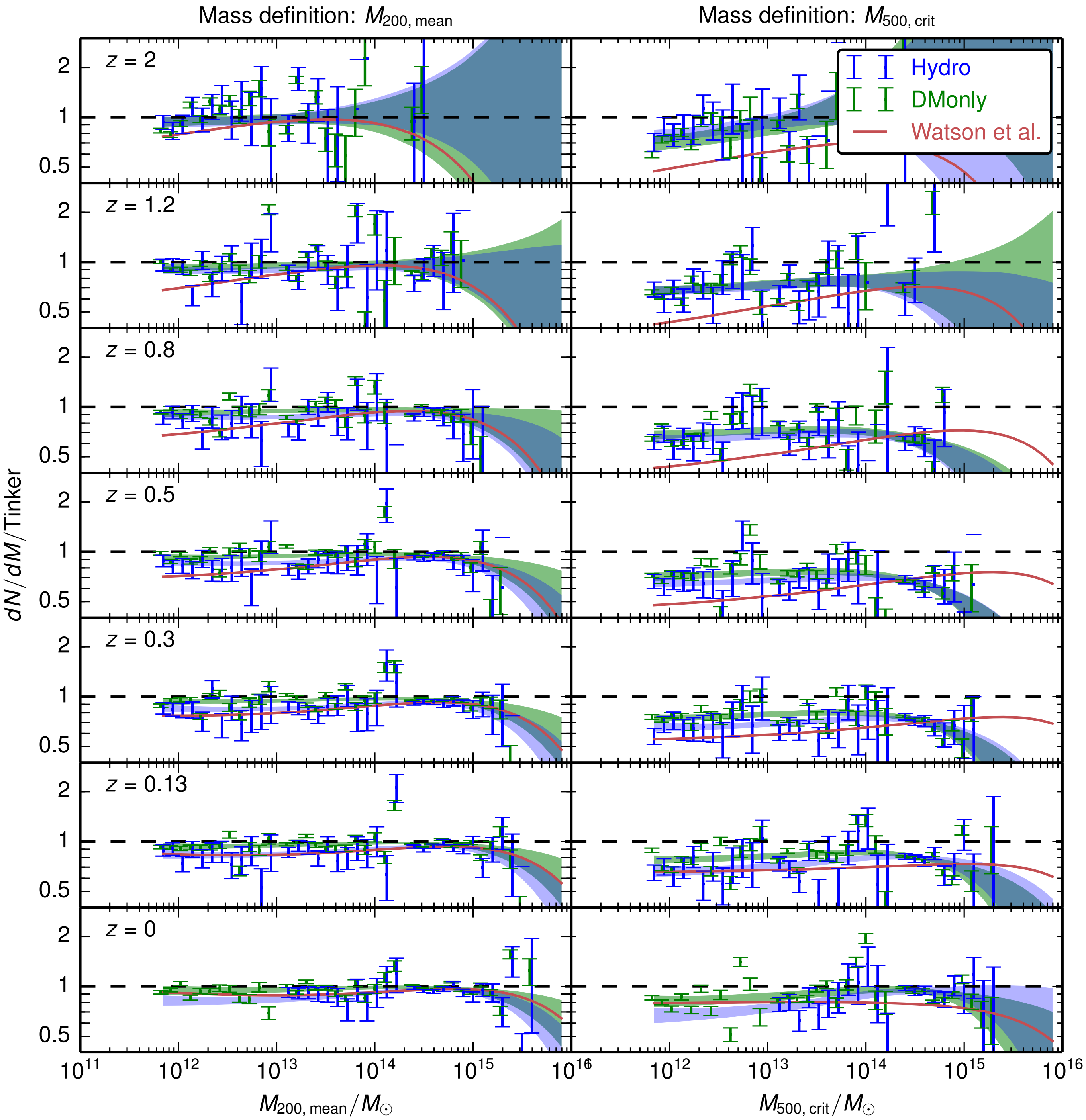
$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right]\exp\left(-\frac{c}{\sigma^2}\right)$$

$$A(z) = A_0(1+z)^{A_z}$$

$$a(z) = a_0(1+z)^{a_z}$$

$$b(z) = b_0(1+z)^{b_z}$$

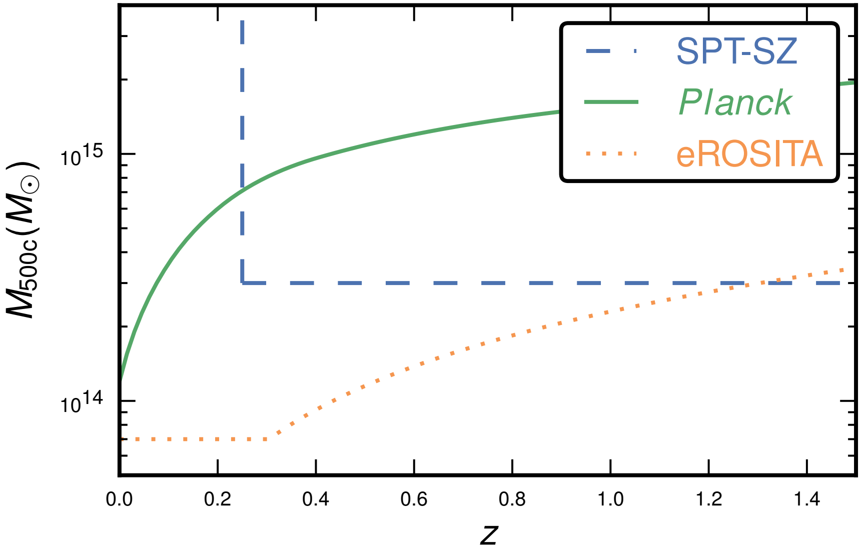
$$c(z) = c_0(1+z)^{c_z}$$

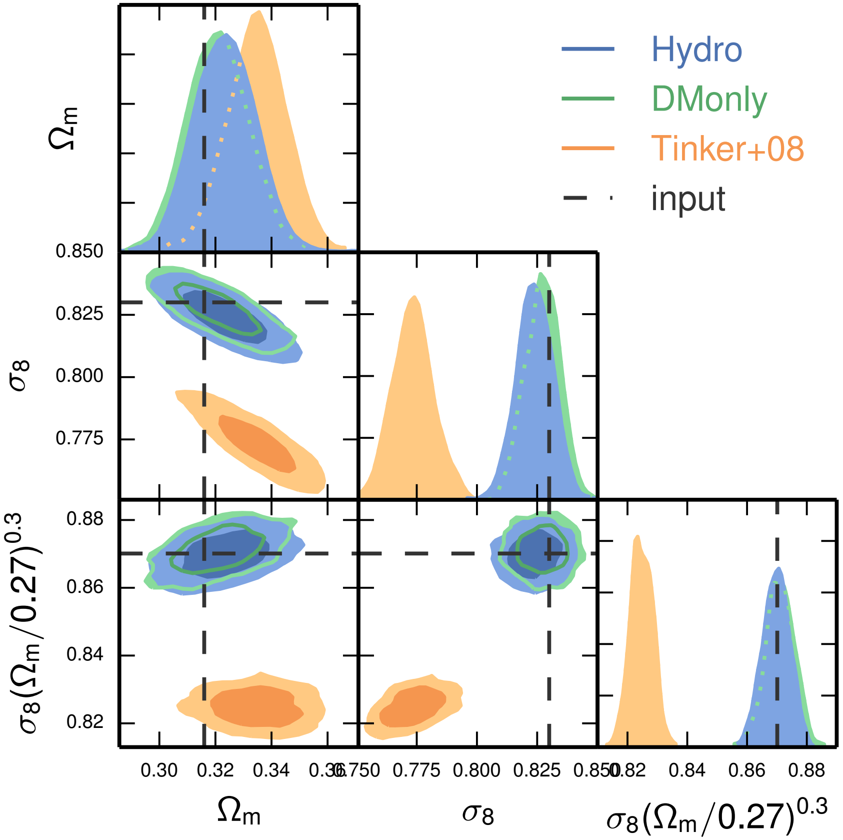


Mass definition: $M_{200,\mathrm{mean}}$
Mass definition: $M_{500,\mathrm{crit}}$
Hydro
DMonly
Watson et al.
$z = 2$
$z = 1.2$
$z = 0.8$
$z = 0.5$
$z = 0.3$
$z = 0.13$
$z = 0$
2
1
0.5
$dN/dM/\mathrm{Tinker}$
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
$M_{200,\mathrm{mean}}/M_\odot$
$M_{500,\mathrm{crit}}/M_\odot$

Cosmological impact

Simulated *Planck*-like survey

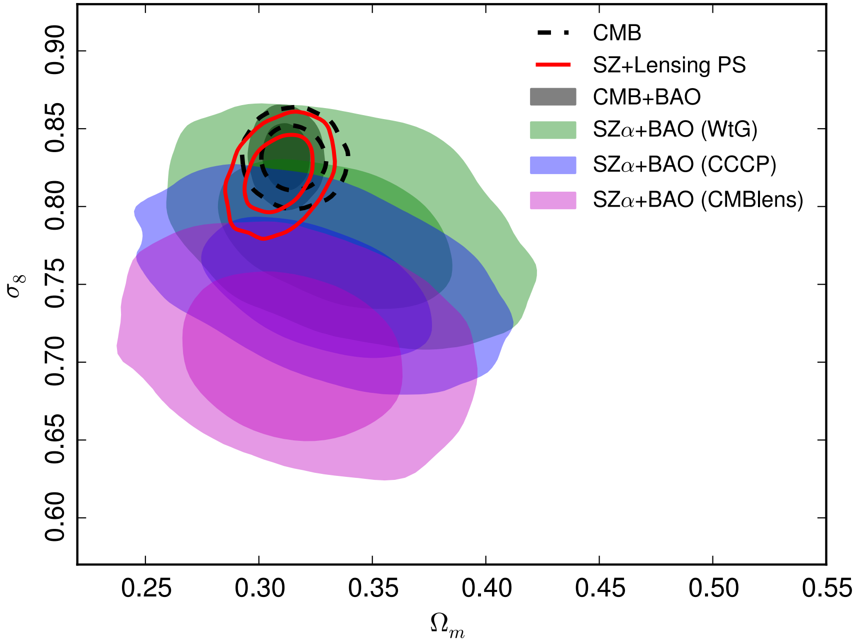


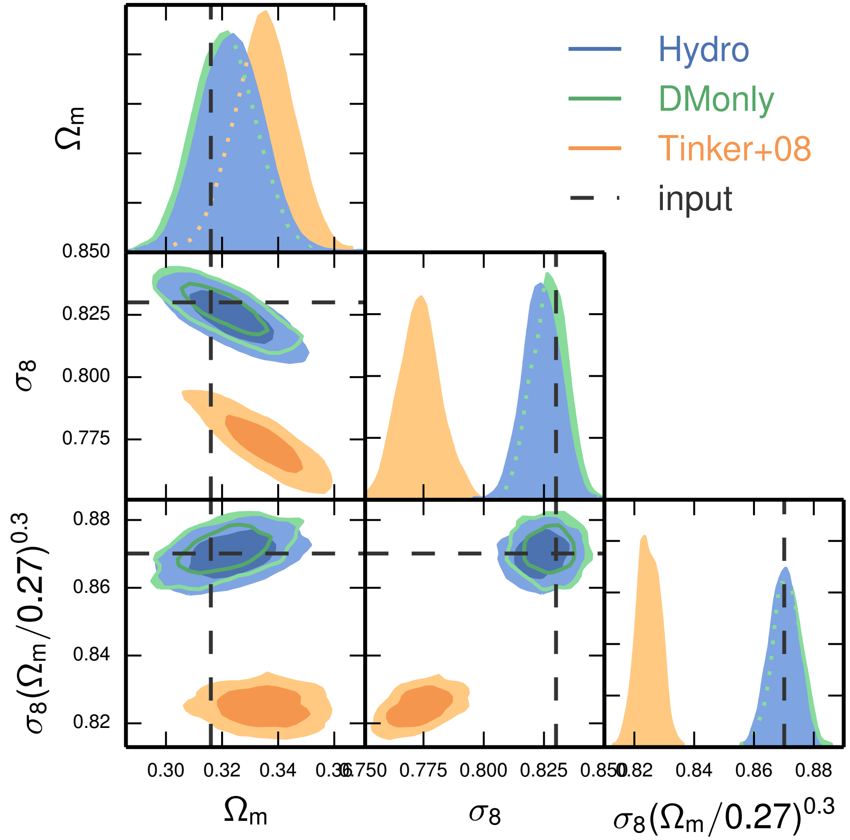


- High-mass sample
- Baryonic impact is negligible
- Systematic difference with Tinker et al. 2008
- Our mass function fully resolves any tension between clusters and CMB anisotropies

Cosmological impact

Simulated *Planck*-like survey

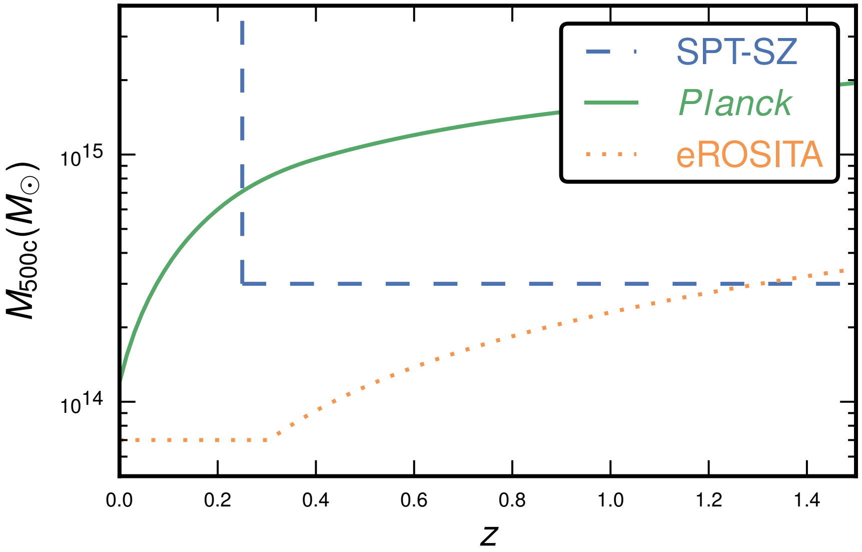


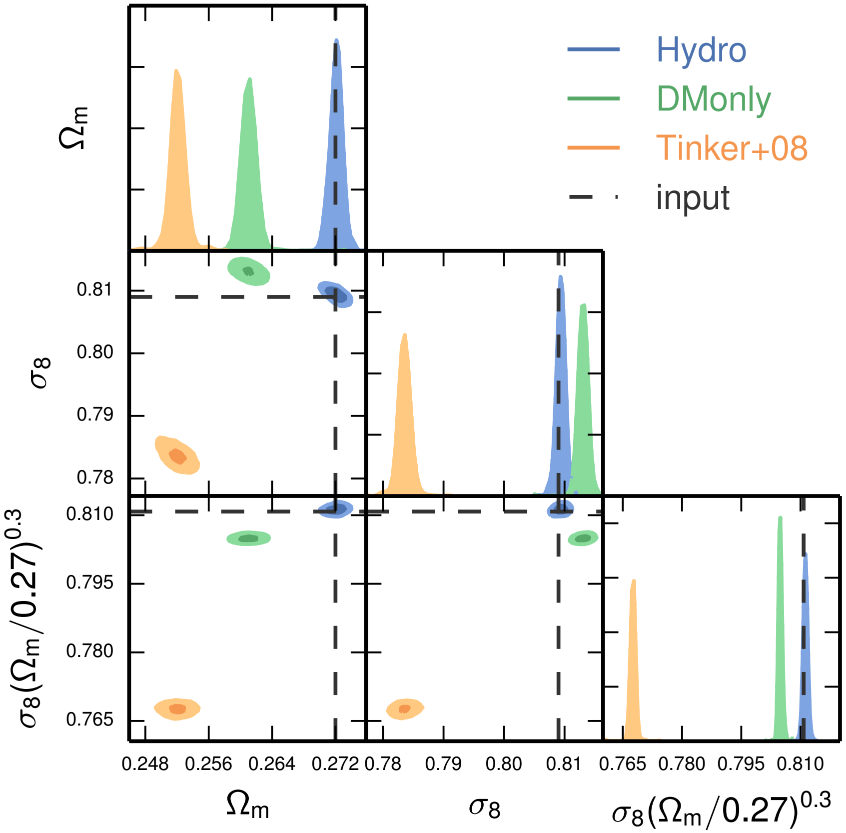


- High-mass sample
- Baryonic impact is negligible
- Systematic difference with Tinker et al. 2008
- Our mass function fully resolves any tension between clusters and CMB anisotropies

Cosmological impact

Simulated eROSITA-like survey





- Low-mass sample
- Baryonic impact is visible
- Neglecting baryonic effects leads to underestimate $\Delta\Omega_m$ = - 0.01
- This is the expected level of uncertainties from eROSITA (Pillepich et al. 2012)

Conclusions

- Baryonic effects on the mass function will be important for surveys like eROSITA
- There are systematic differences between different mass function fits that shift cosmological results
- The corresponding level of systematic uncertainty is already comparable to current constraints!
- Using our mass function instead of Tinker et al. would fully resolve the “tension” between *Planck* clusters and CMB
- Stay tuned!