GALAXY CLUSTER COSMOLOGY

http://chandra.harvard.edu/photo/2006/1e0657/

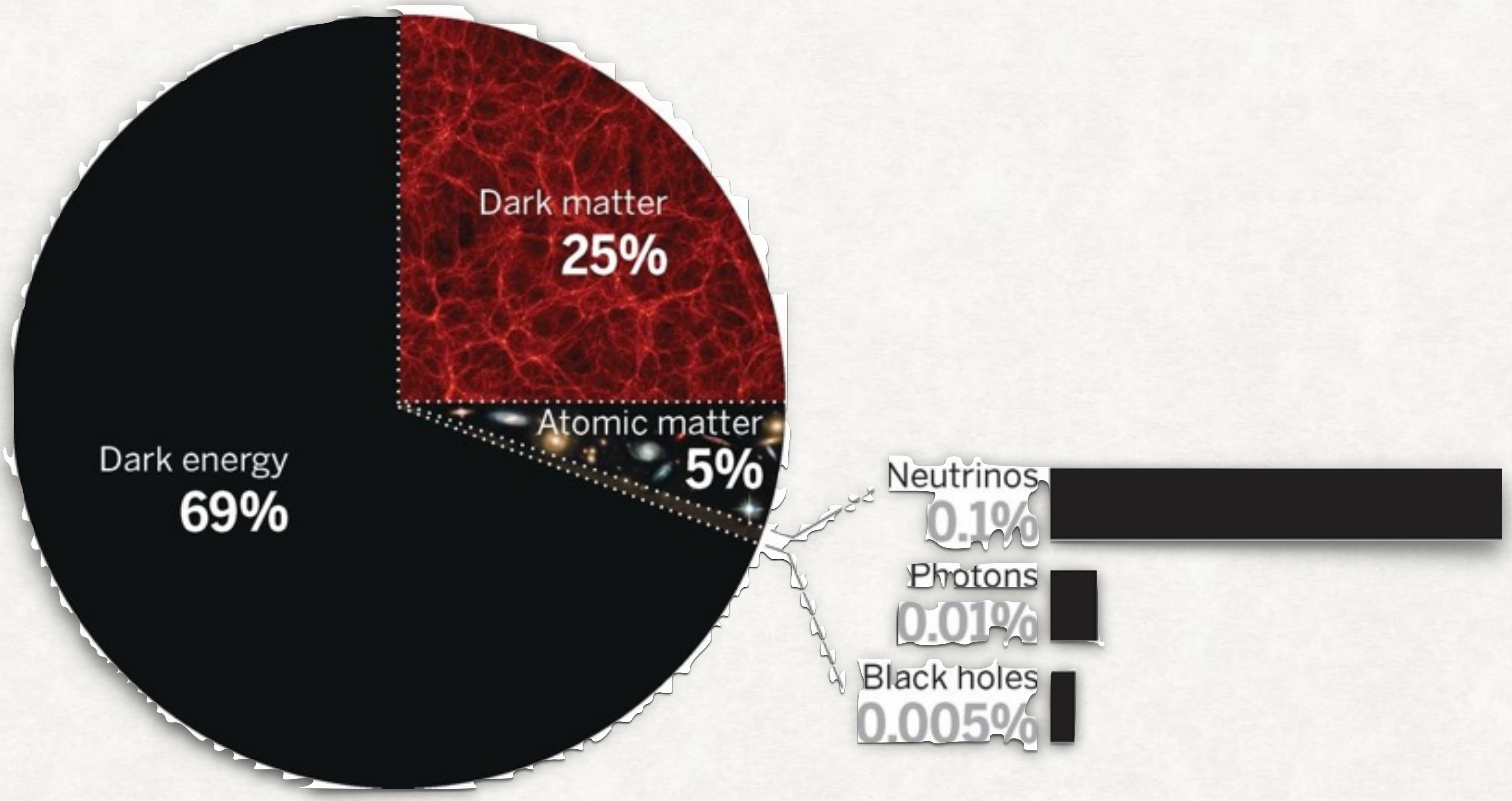
SEBASTIAN BOCQUET
ARGONNE NATIONAL LABORATORY / KICP

OVERVIEW

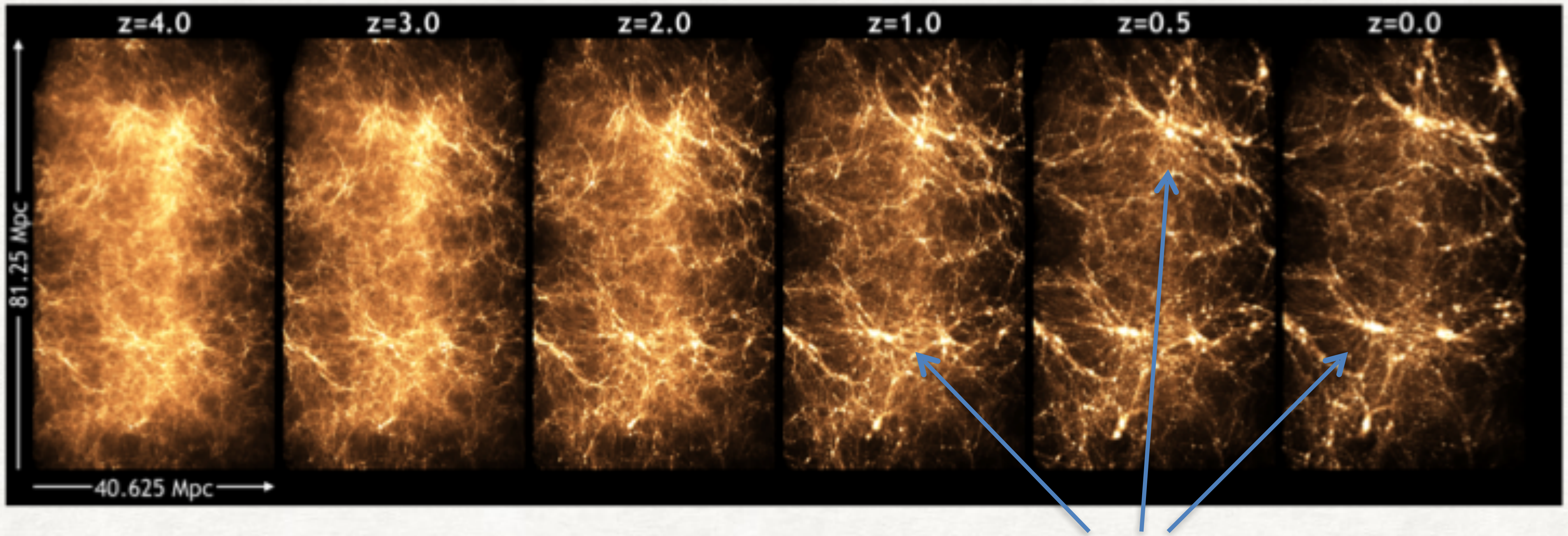
- Cluster Cosmology in a Nutshell
- The Halo Mass Function
- How do we Measure Cluster Properties?
- Scaling Relations
- Recent results (with a focus on SPT)

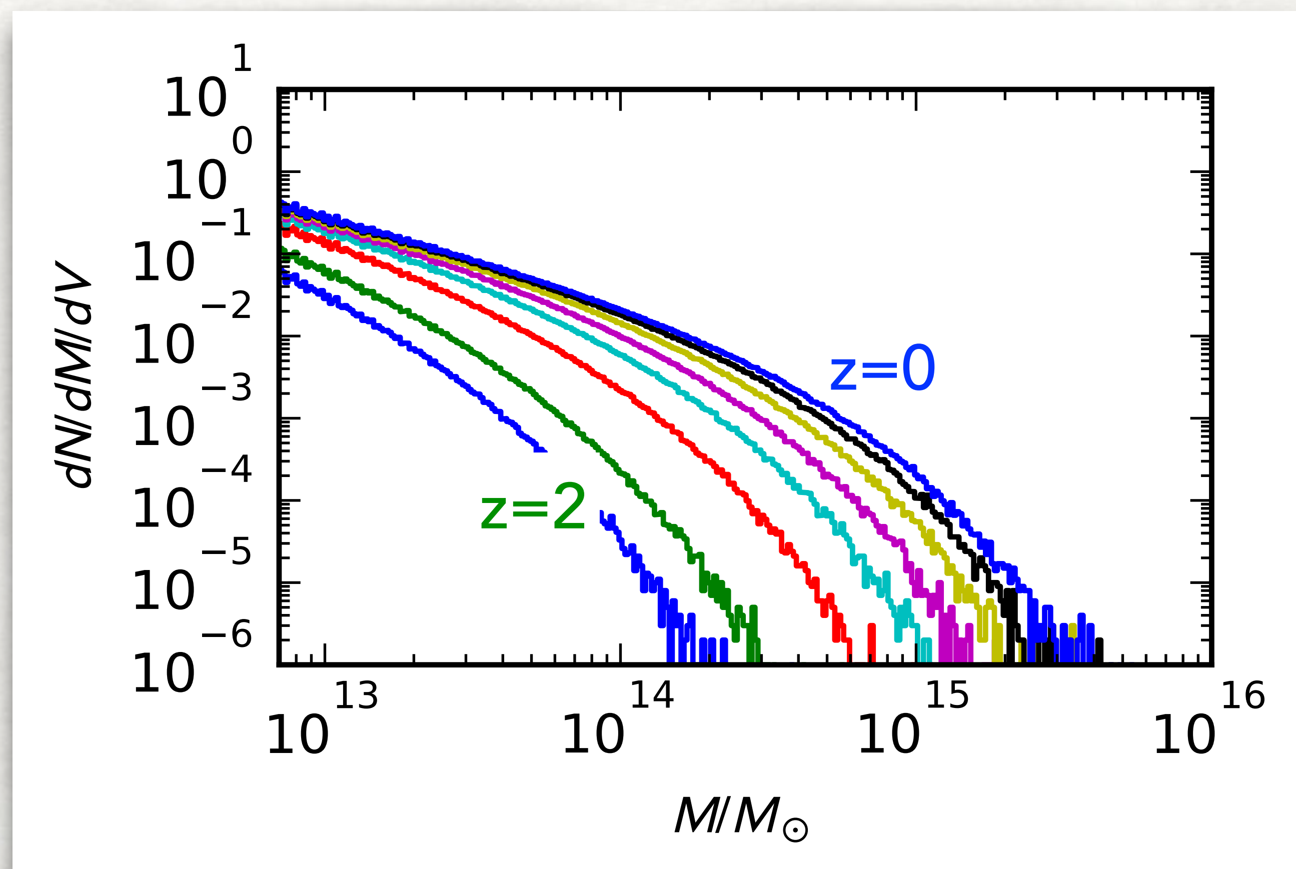
THE UNIVERSE

CONTENT



The Q Continuum Simulation: Heitmann et al., 2015 (arXiv:1411.3396)





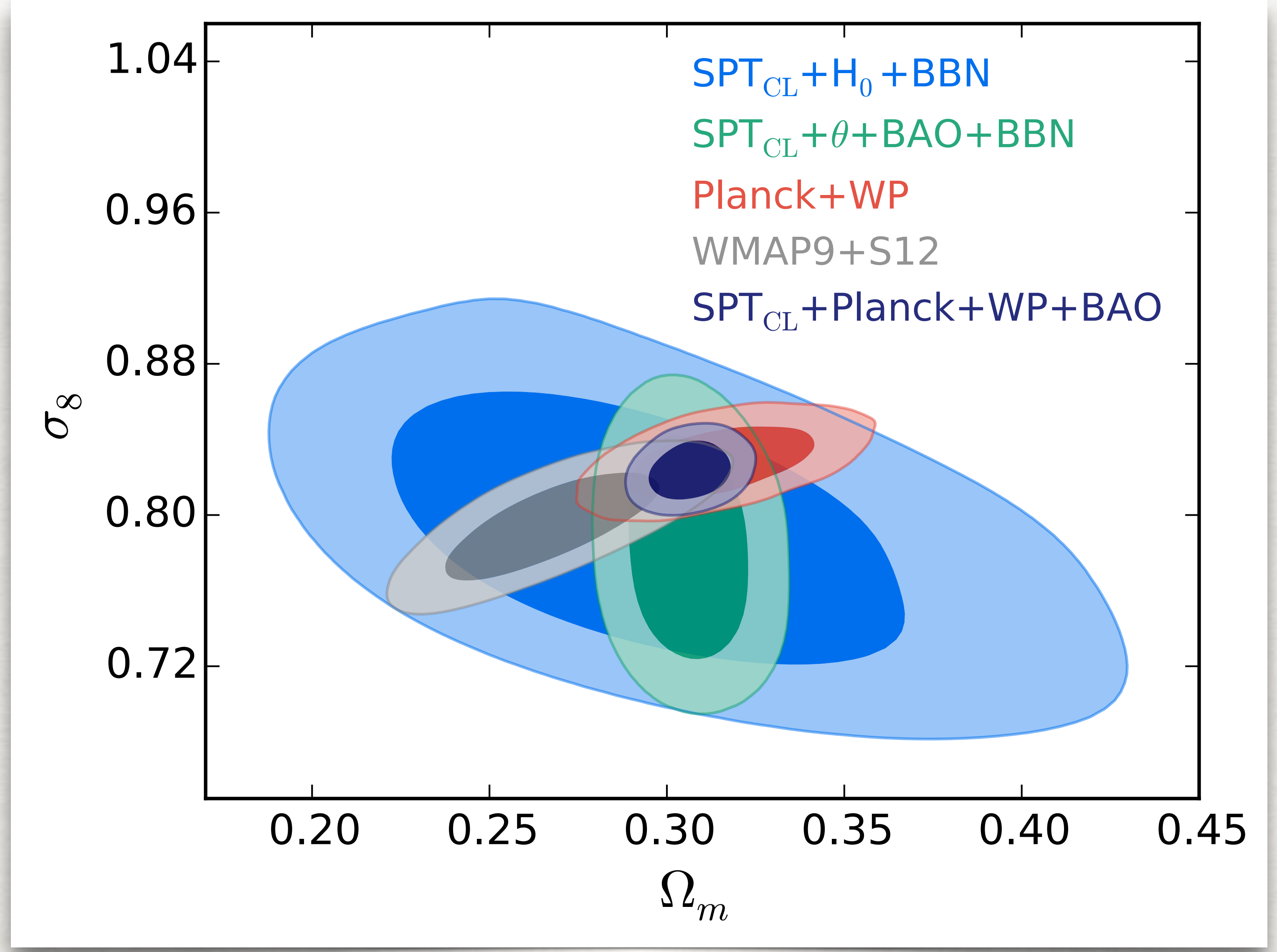
1. Predict abundance of halos as a function of cosmology using numerical simulations
2. Measure number of galaxy clusters in a given survey as a function of ***mass*** and ***redshift***
3. Learn about cosmology

CLUSTER MASS DEFINITIONS

- Cluster masses usually defined as M_Δ, which is mass enclosed within a sphere of radius r_Δ, whose average density is $\Delta * \boldsymbol{\rho}$
- defined with respect to $\boldsymbol{\rho}_{mean}$ or $\boldsymbol{\rho}_{critical}$
- Δ = 500c used for X-ray because only inner part is bright
- Δ = 200c used for weak grav. lensing and velocity dispersions
- In simulations, also consider friend-of-friend (FoF) masses with linking length $b \sim 0.2$

CONSTRAINTS ON FLAT LCDM MODEL

DE HAAN ET AL. 2016 (SPT COLLABORATION)



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Structure formation in numerical simulations

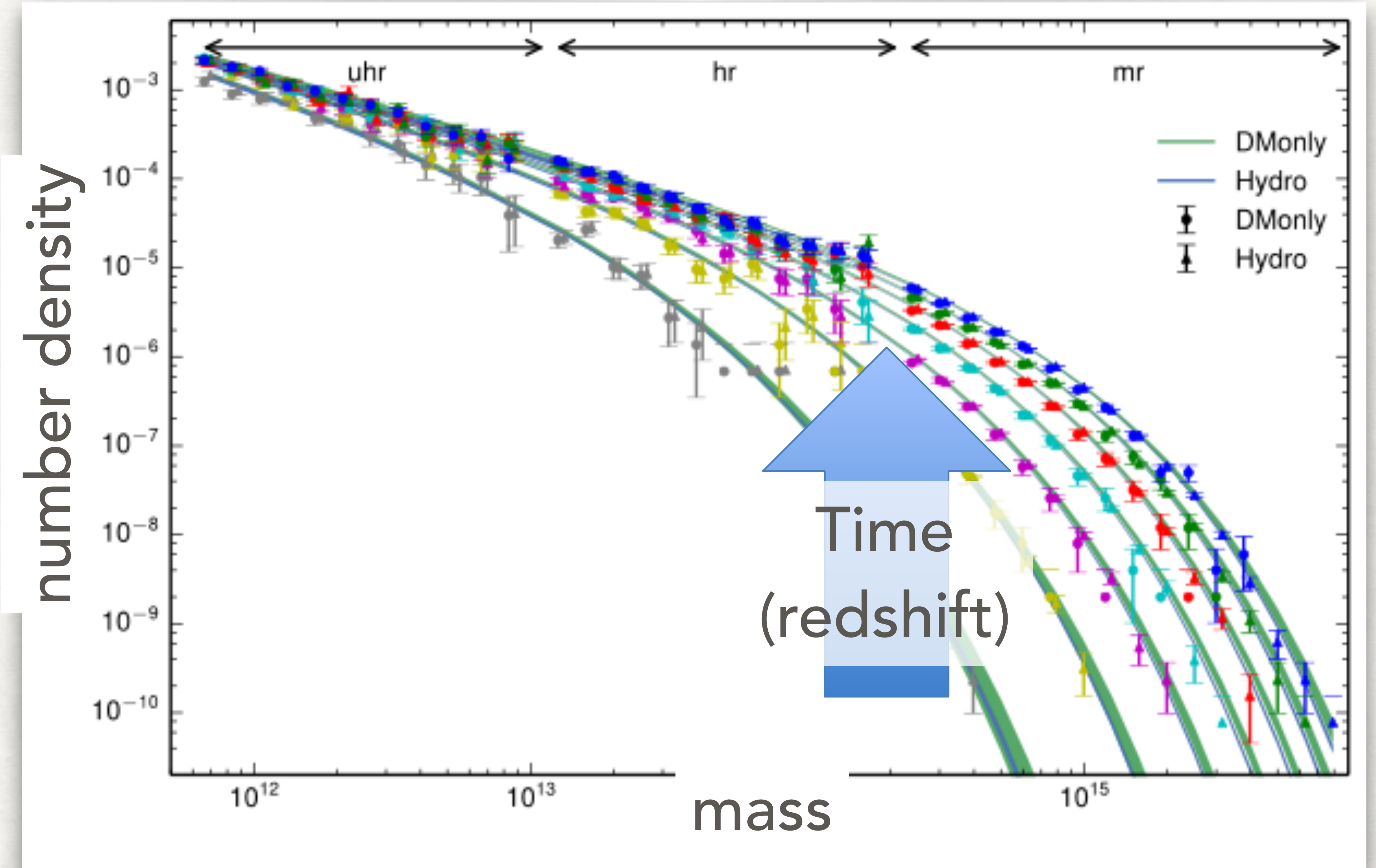
N-BODY VS. HYDRODYNAMIC SIMULATIONS

- gravity-only
- (relatively) cheap
- no free parameters

- gravity & gas
- more expensive
- complicated sub-grid physics such as star formation, feedback from active galactic nuclei

HALO MASS FUNCTION

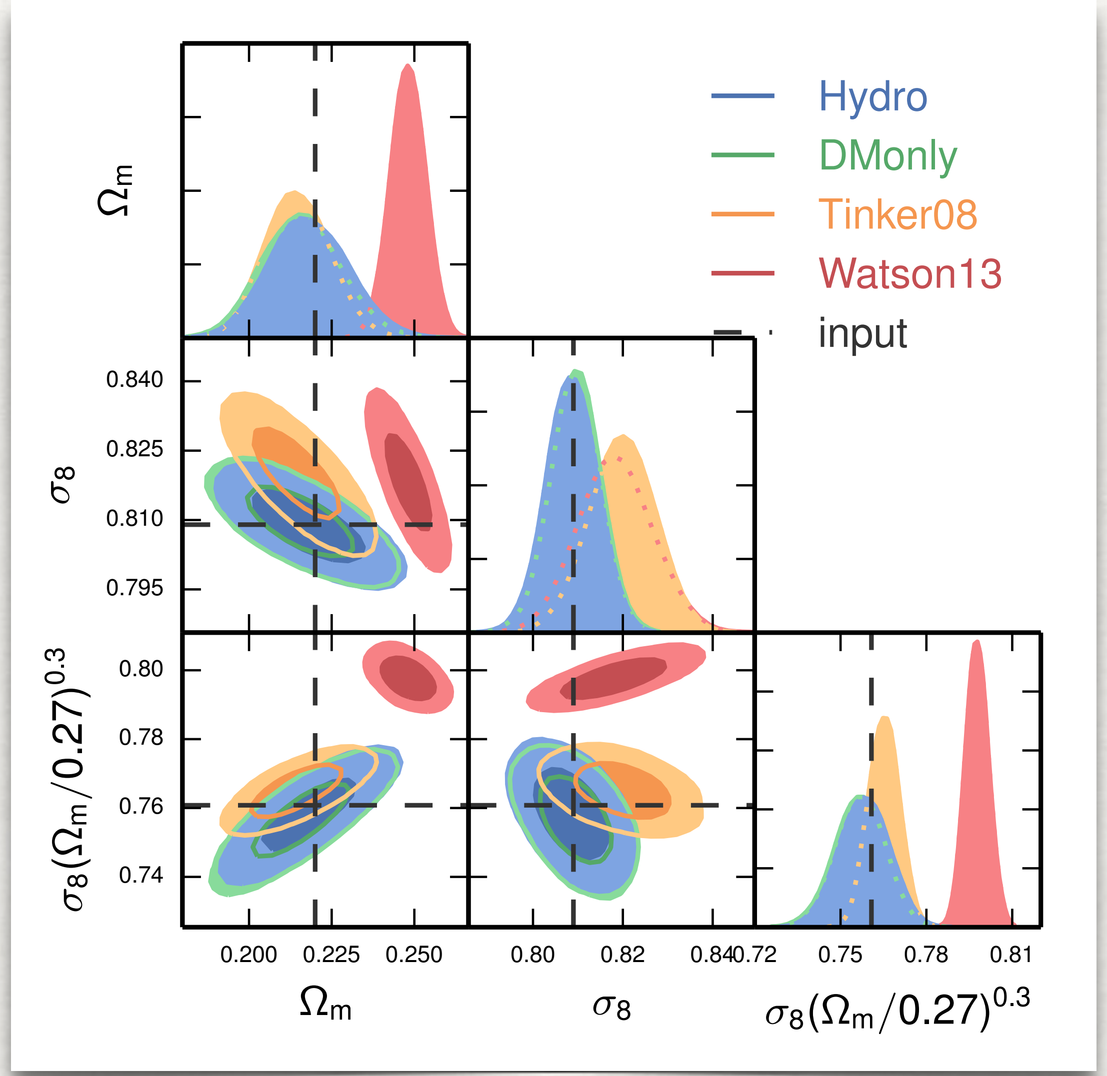
SB ET AL. 2016 (ARXIV:1502.07357)



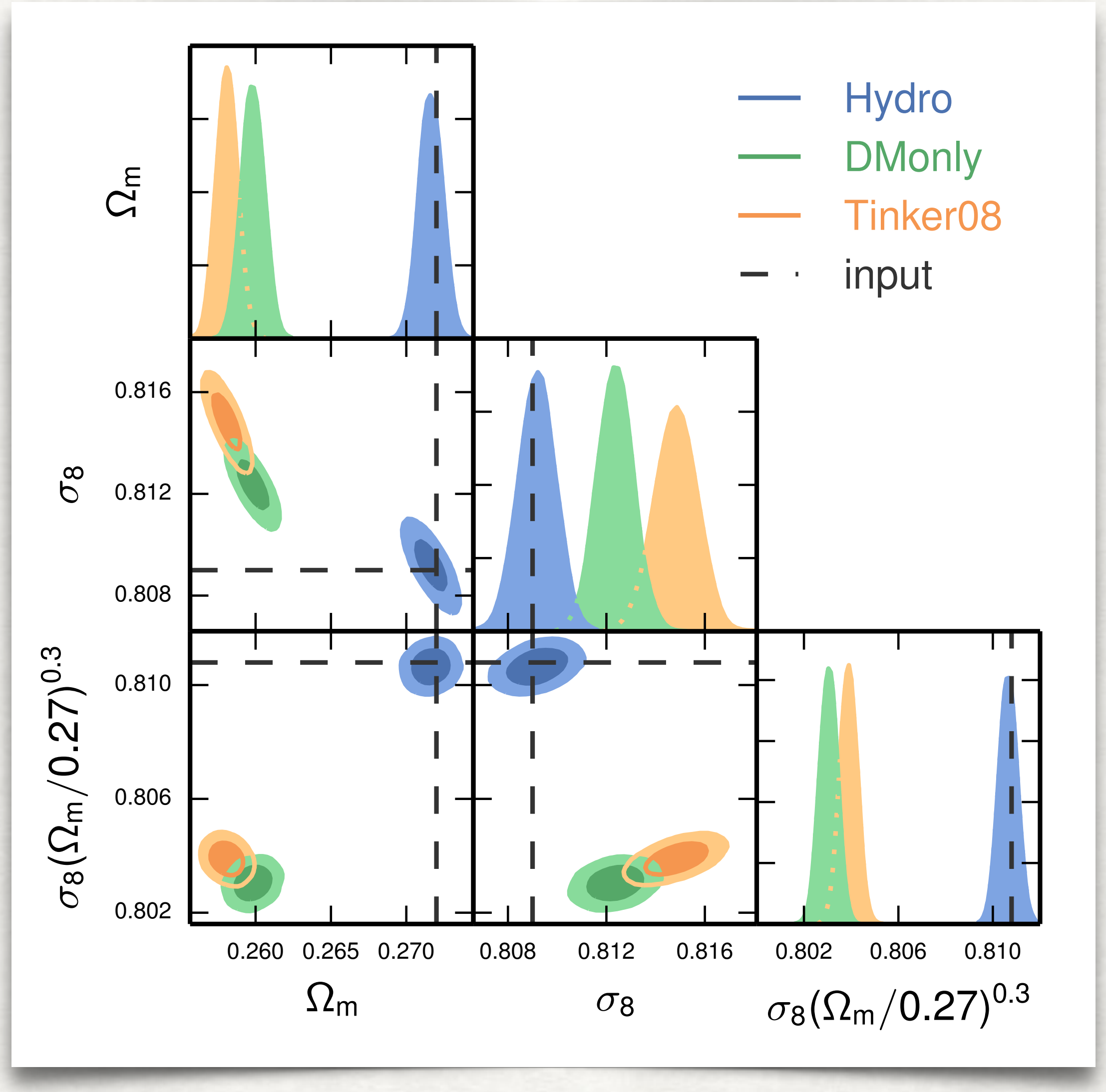
Impact of Baryons on the HMF

Magneticum Hydrodynamic Simulations: up to (3.8 Mpc)^3 (K. Dolag+)

SPT-like (high-mass > ~3e14 M_{sun})



eROSITA-like (all masses > ~5e13 M_{sun})



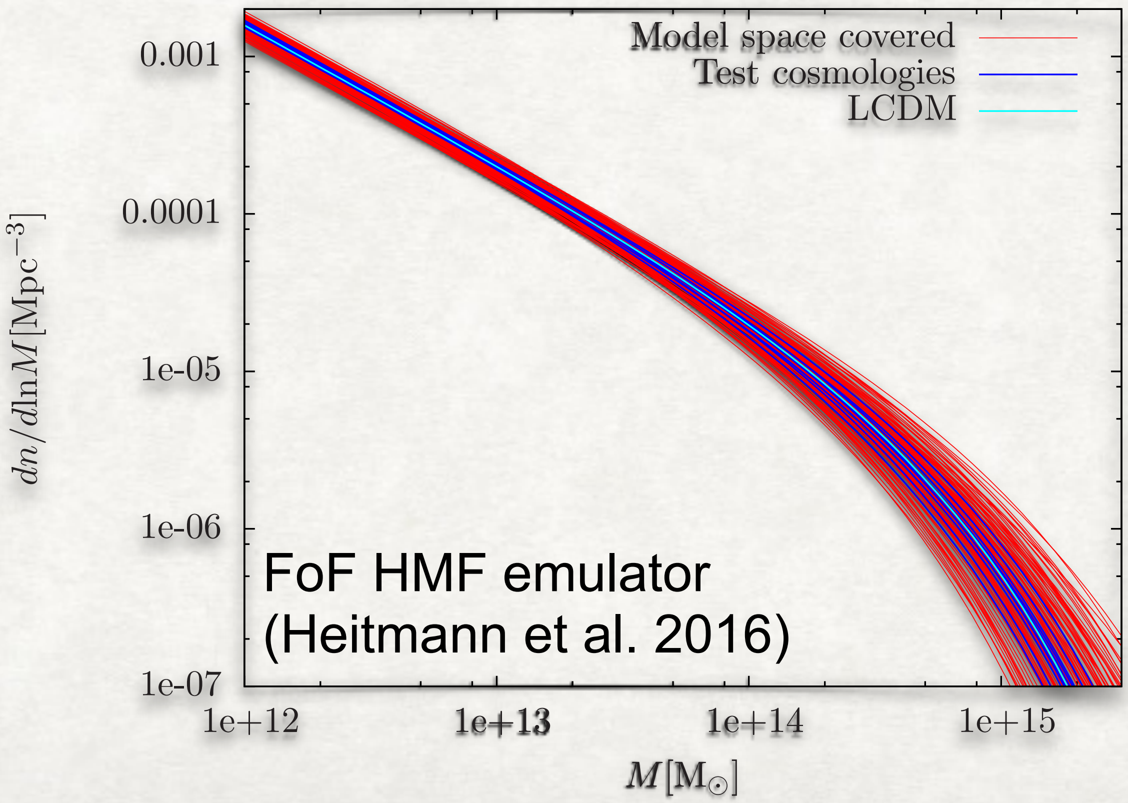
blue vs. green contours: impact of baryons on the HMF

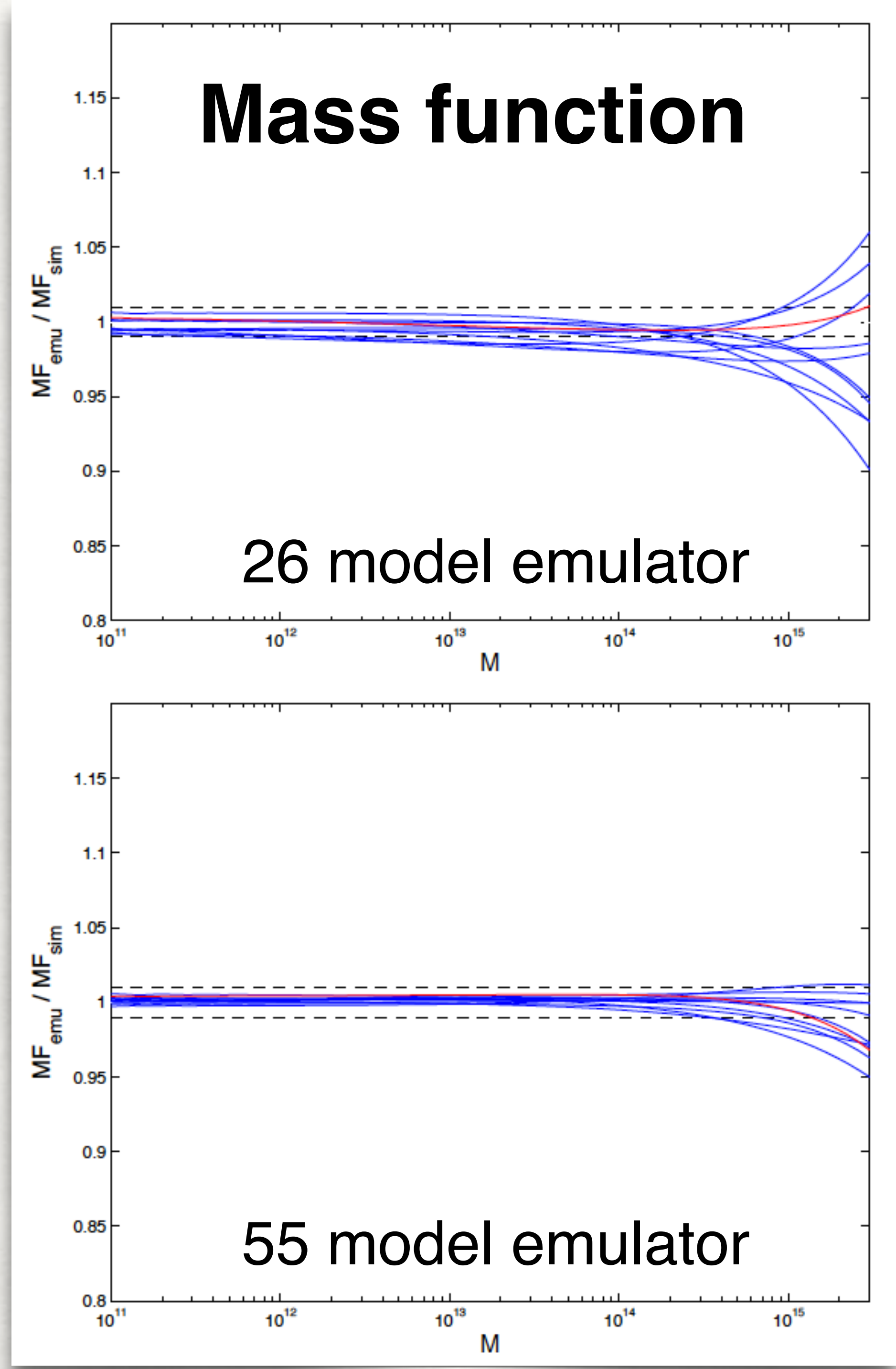
SB et al., MNRAS 2016 (arXiv: 1502.07357)

HMF - OUTLOOK

CALIBRATE THE COSMOLOGICAL DEPENDENCE

- Run simulations for a range of different cosmologies and mass definitions
- Use emulator to interpolate to desired cosmology





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http://spacetelescope.org/images/heic0916a/

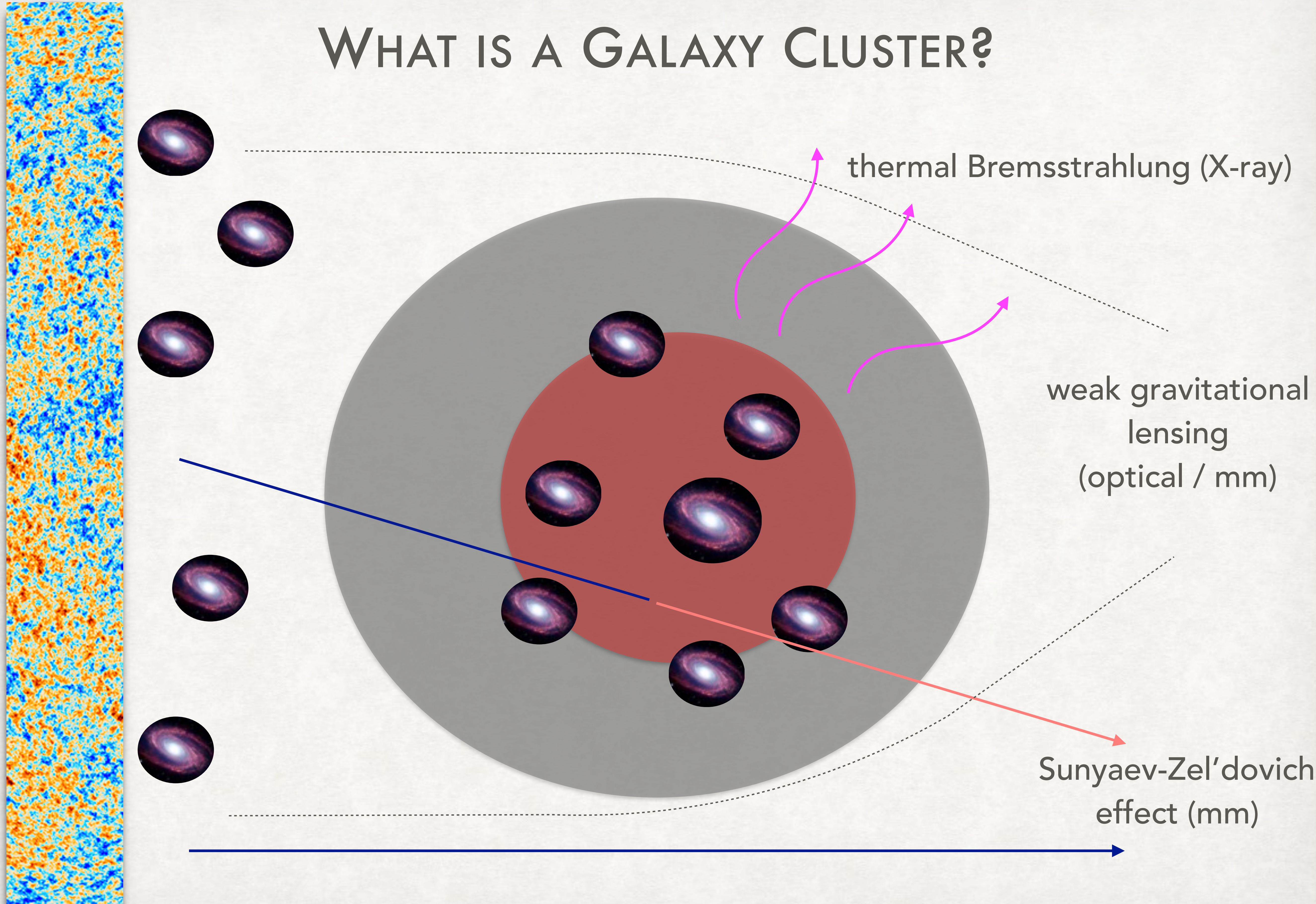
THESE ARE GALAXY CLUSTERS...

... SO WHAT ARE THEIR MASSES?

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

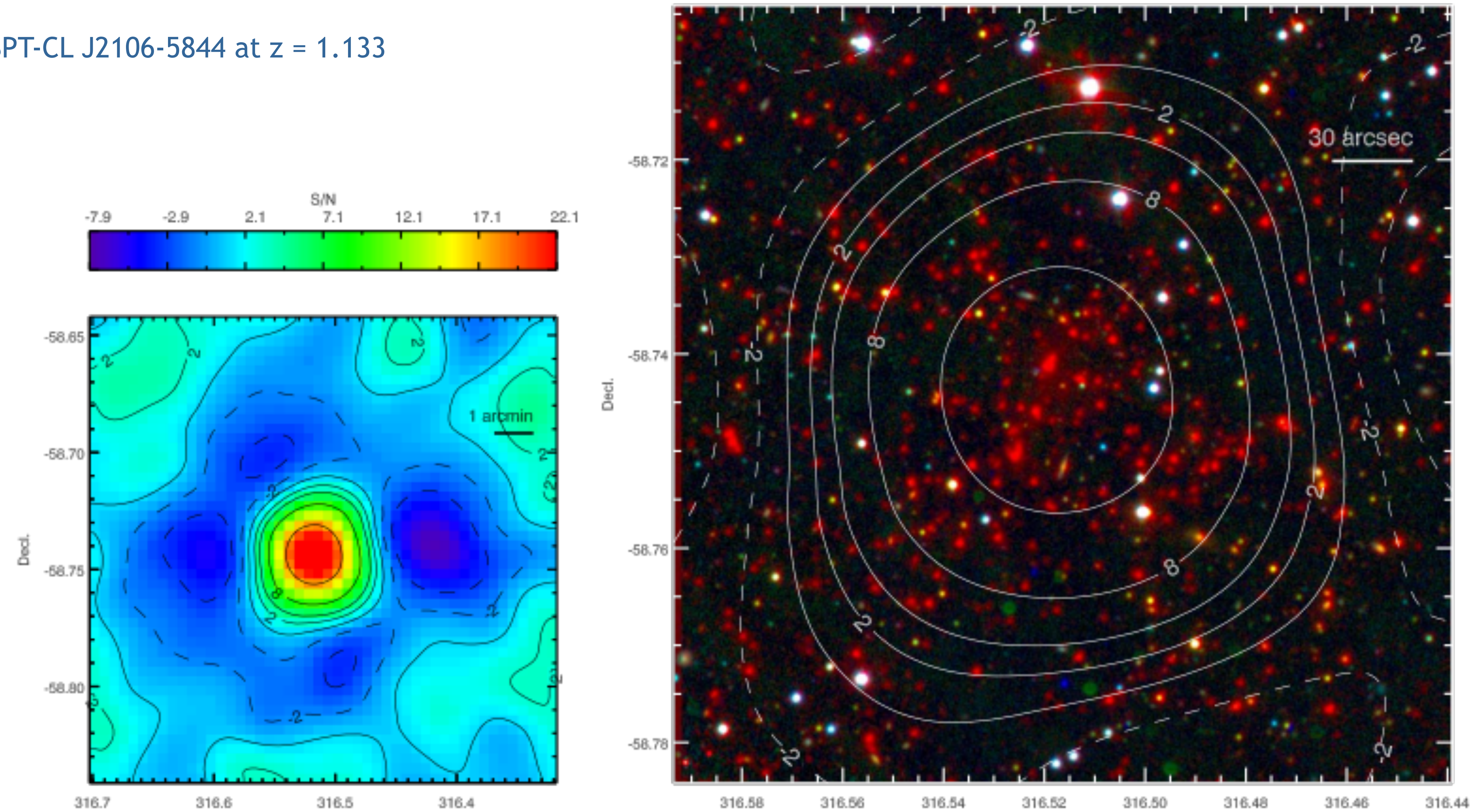
What is a Galaxy Cluster?



SZ / NIR OBSERVATIONS

MOST MASSIVE CLUSTER KNOWN AT Z > 1, FOLEY ET AL. 2013

SPT-CL J2106-5844 at z = 1.133



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
- Observed the CMB over >2500 deg^2

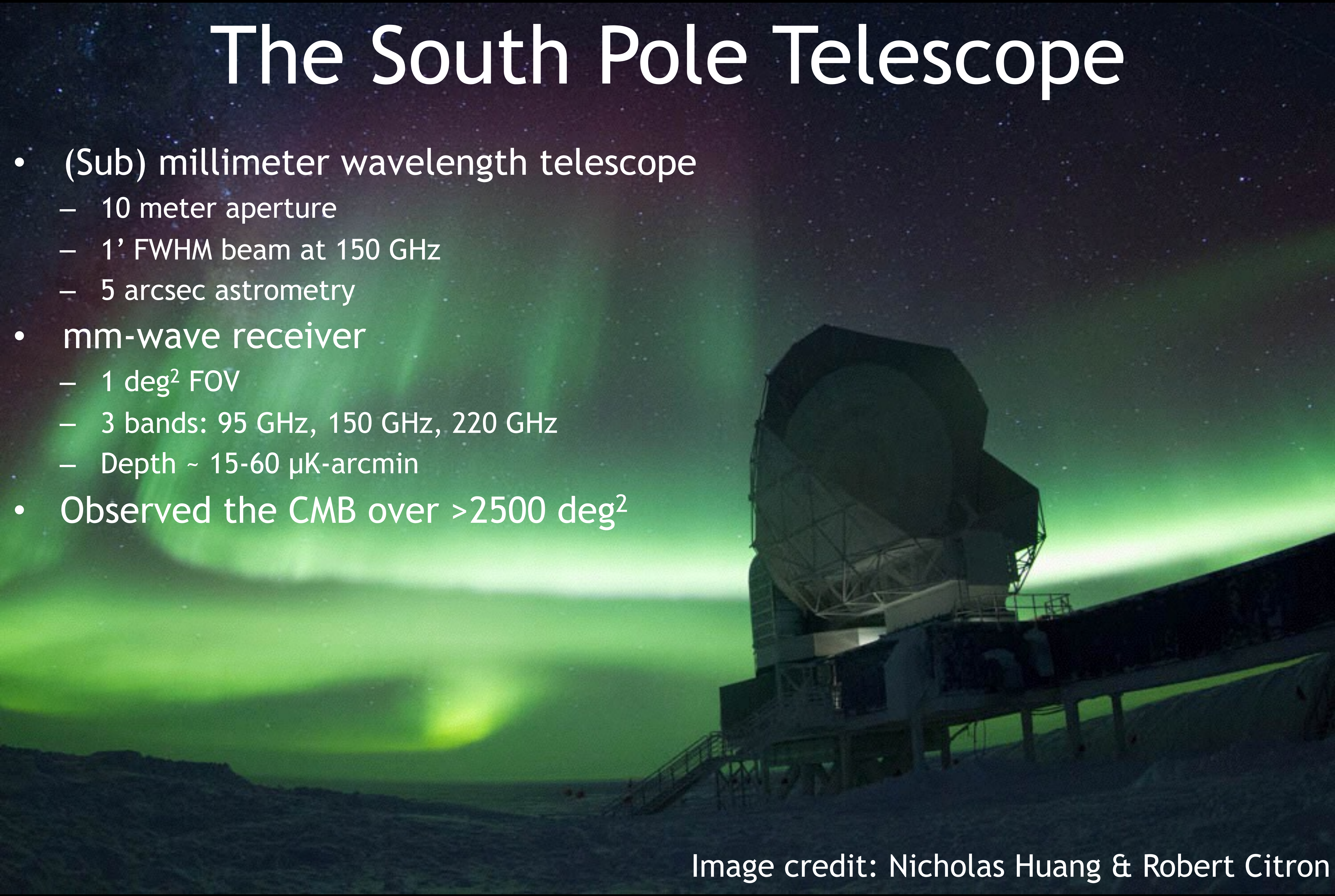
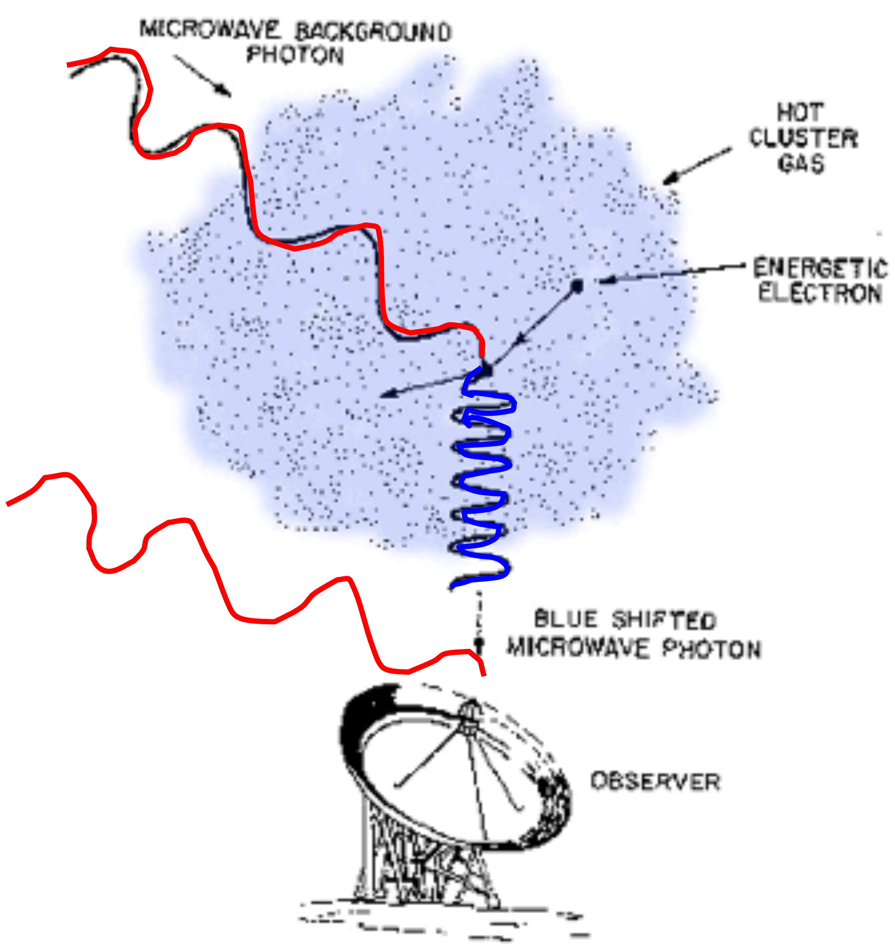
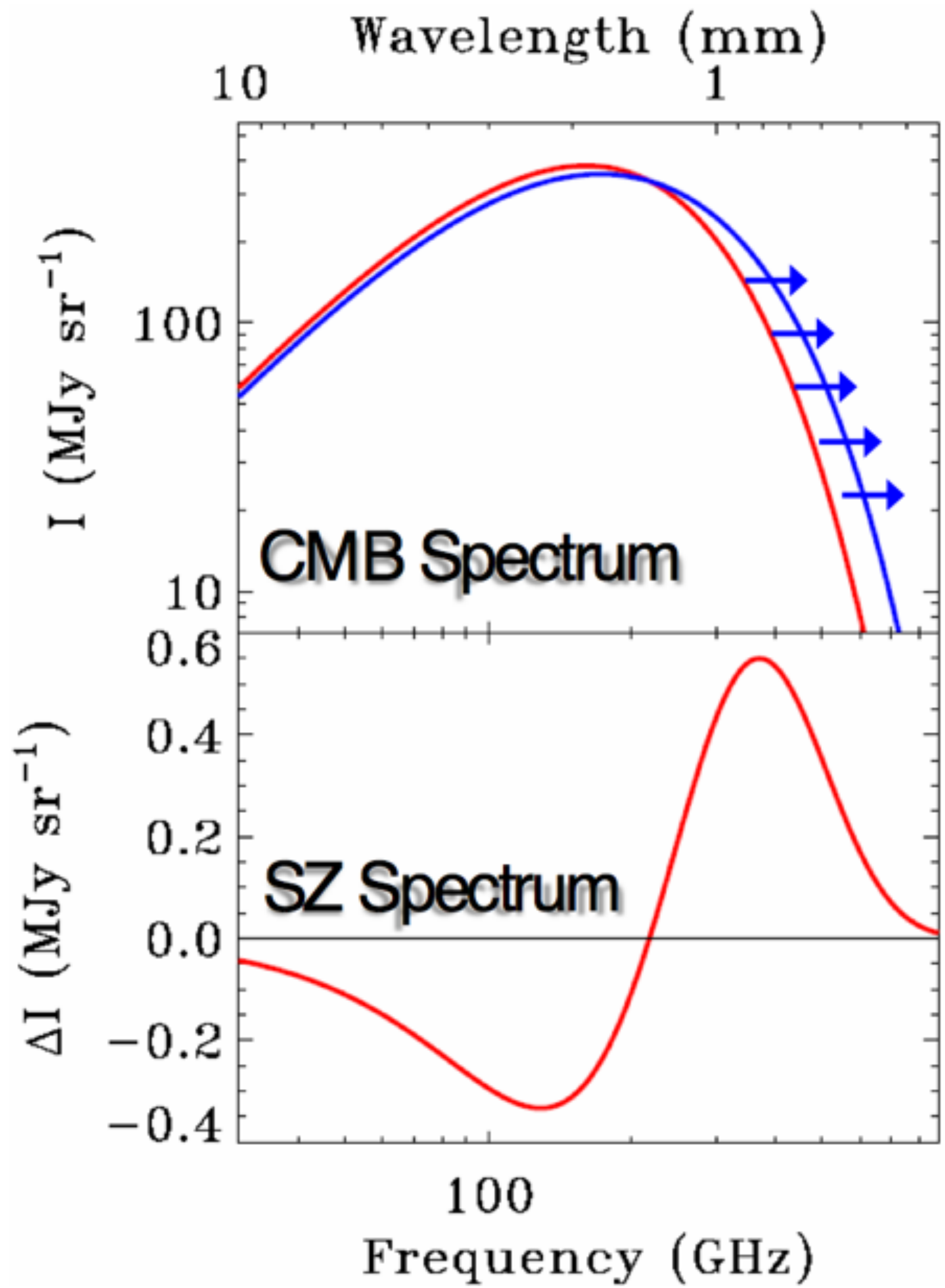


Image credit: Nicholas Huang & Robert Citron

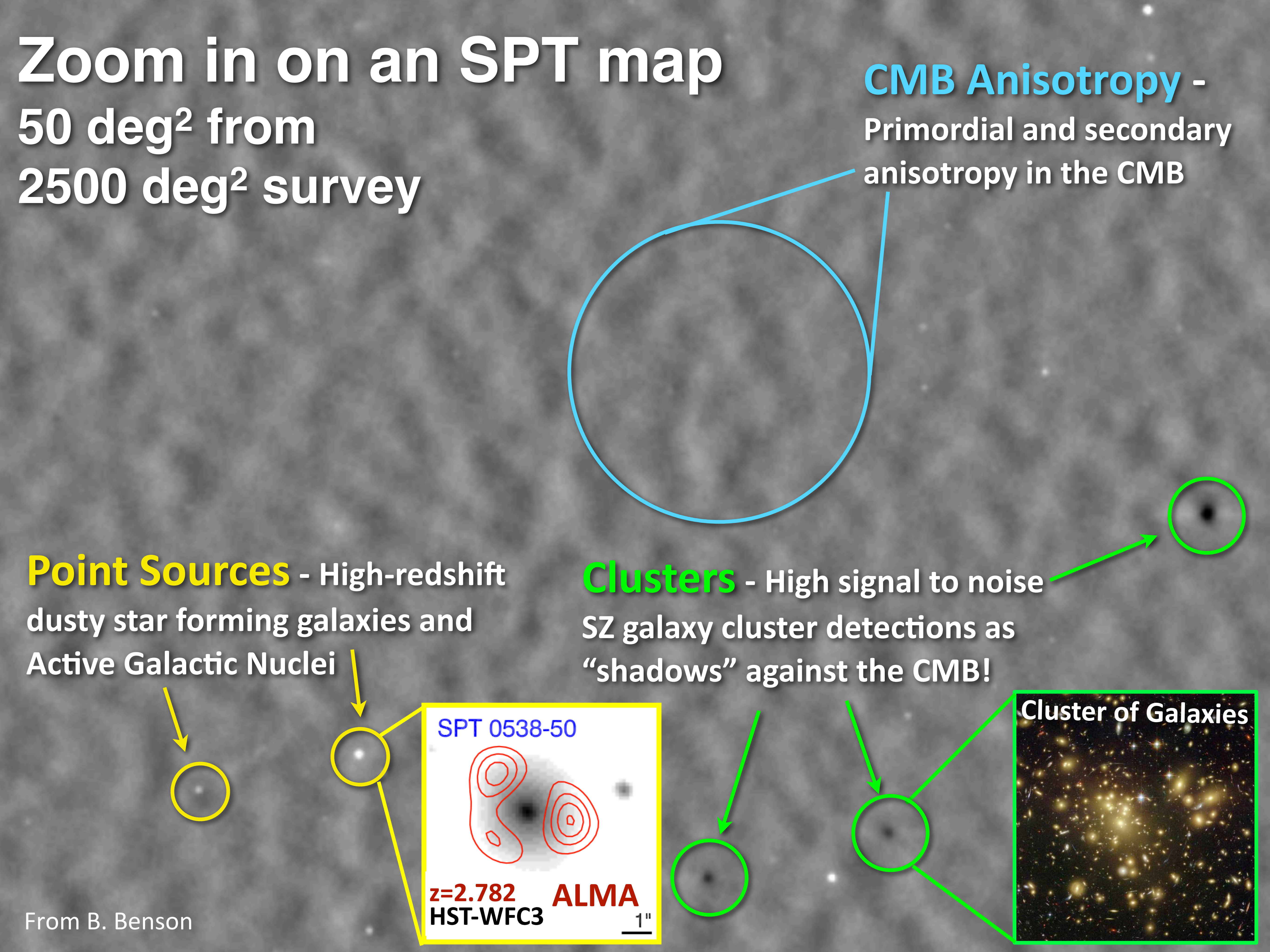
Sunyaev-Zel'dovich Effect (SZE)



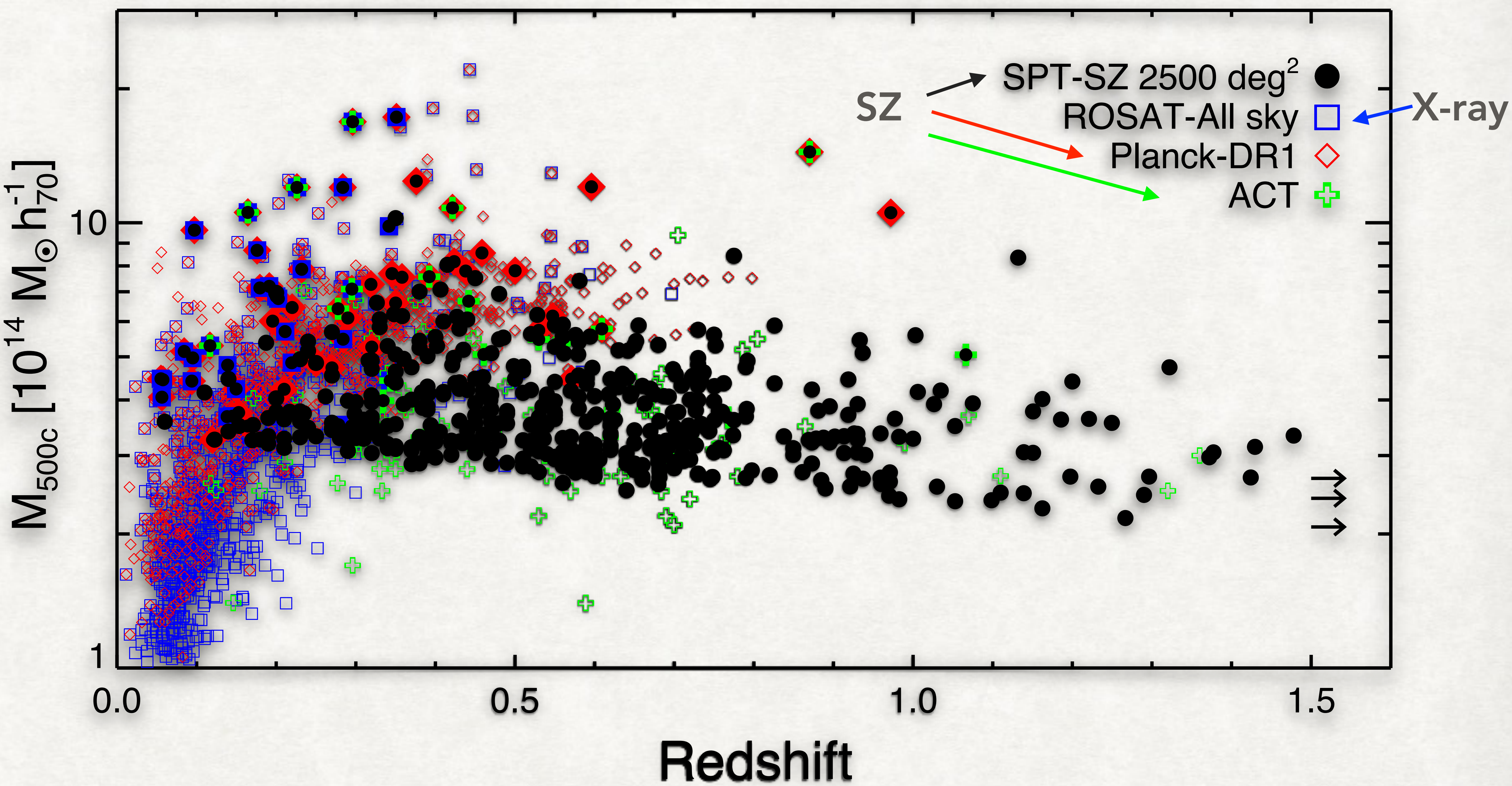
from L. Van Speybroeck



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

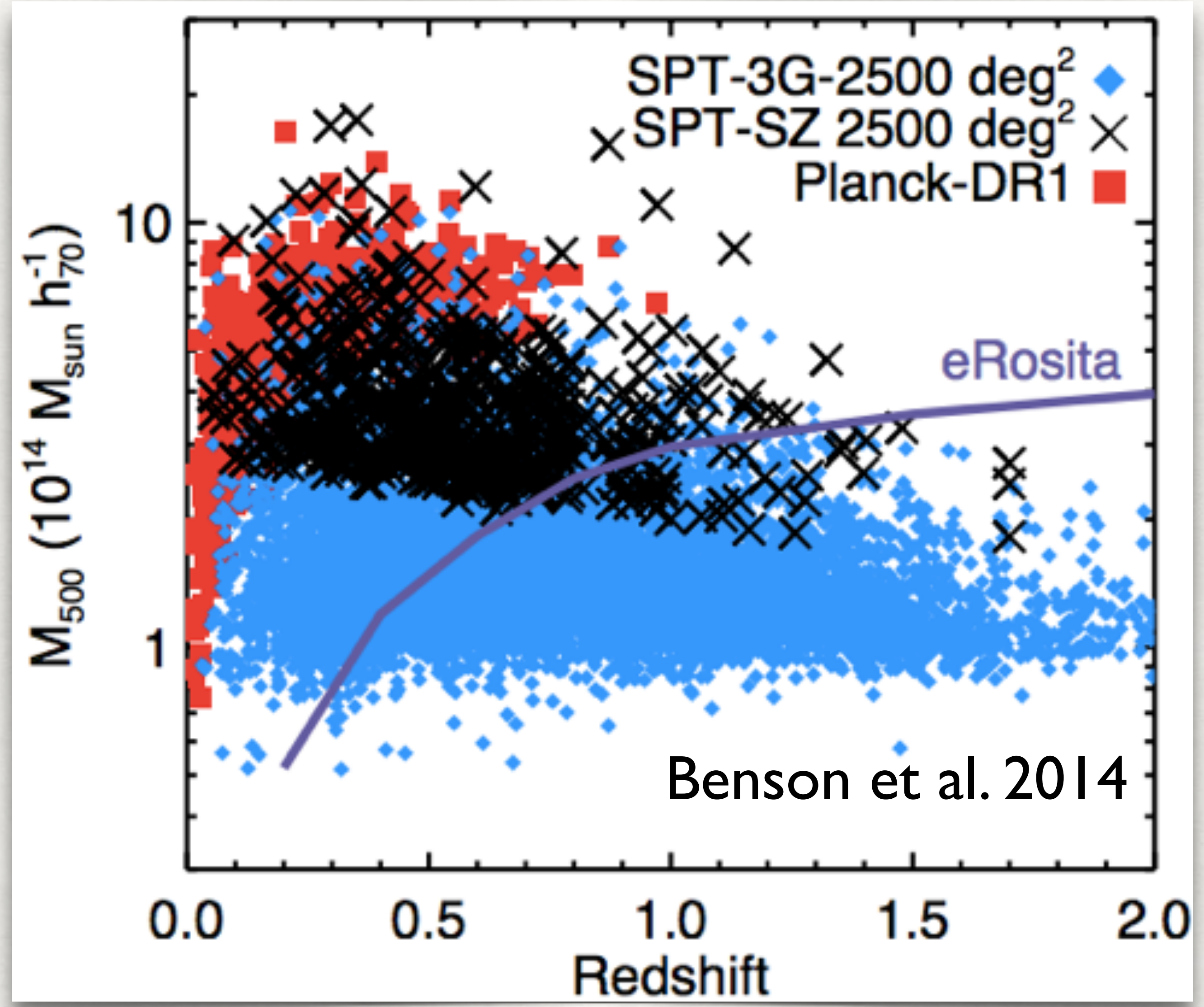

Zoom in on an SPT map
50 deg^2 from
2500 deg^2 survey
CMB Anisotropy - Primordial and secondary anisotropy in the CMB
Point Sources - High-redshift dusty star forming galaxies and Active Galactic Nuclei
SPT 0538-50
z=2.782
HST-WFC3
ALMA
1"
Clusters - High signal to noise SZ galaxy cluster detections as "shadows" against the CMB!
Cluster of Galaxies
From B. Benson

SZ AND X-RAY SURVEYS



(SOME OF THE) UPCOMING SURVEYS

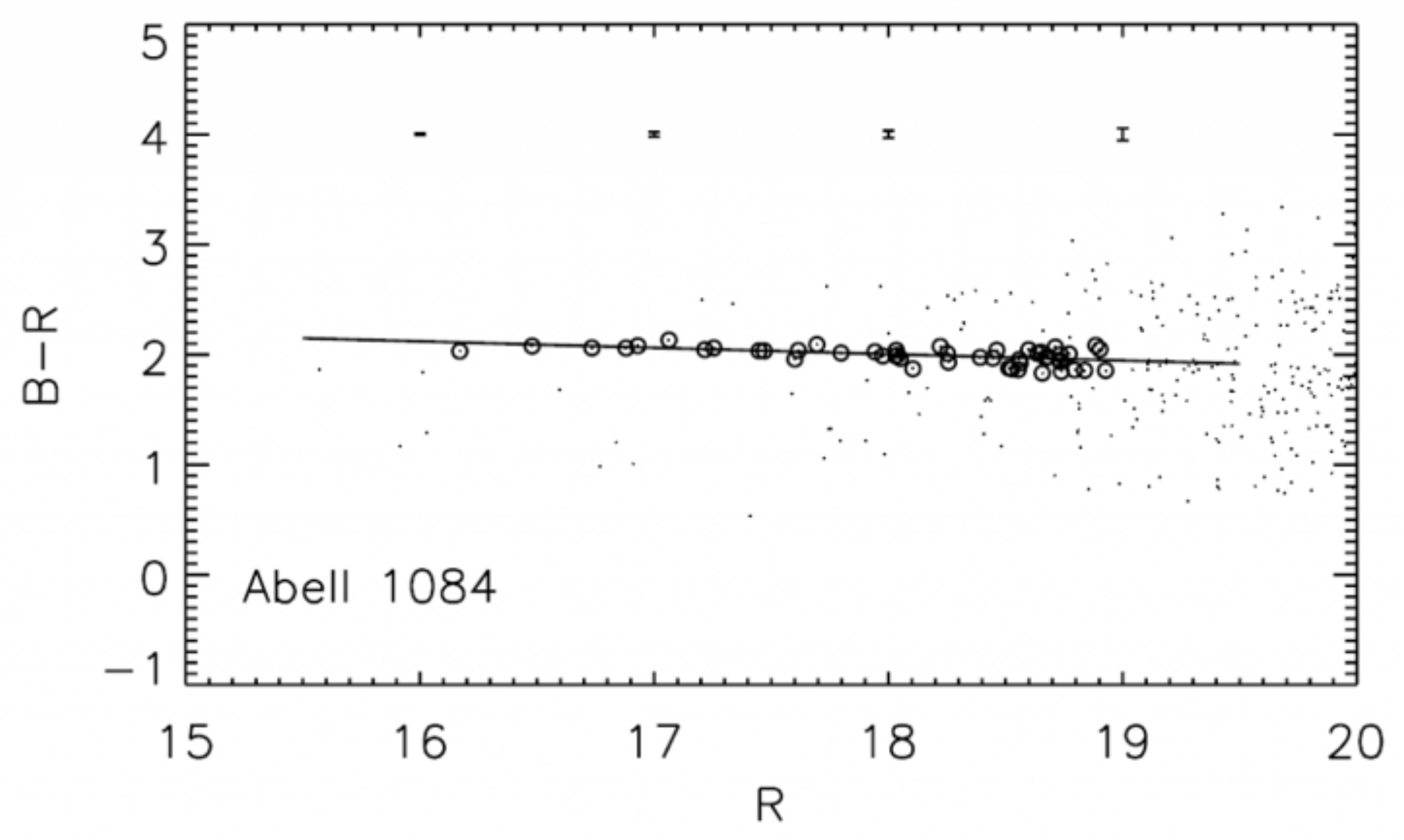
SPT-3G, EROSITA



CLUSTER RED SEQUENCE

USEFUL FEATURE IN COLOR-MAGNITUDE SPACE

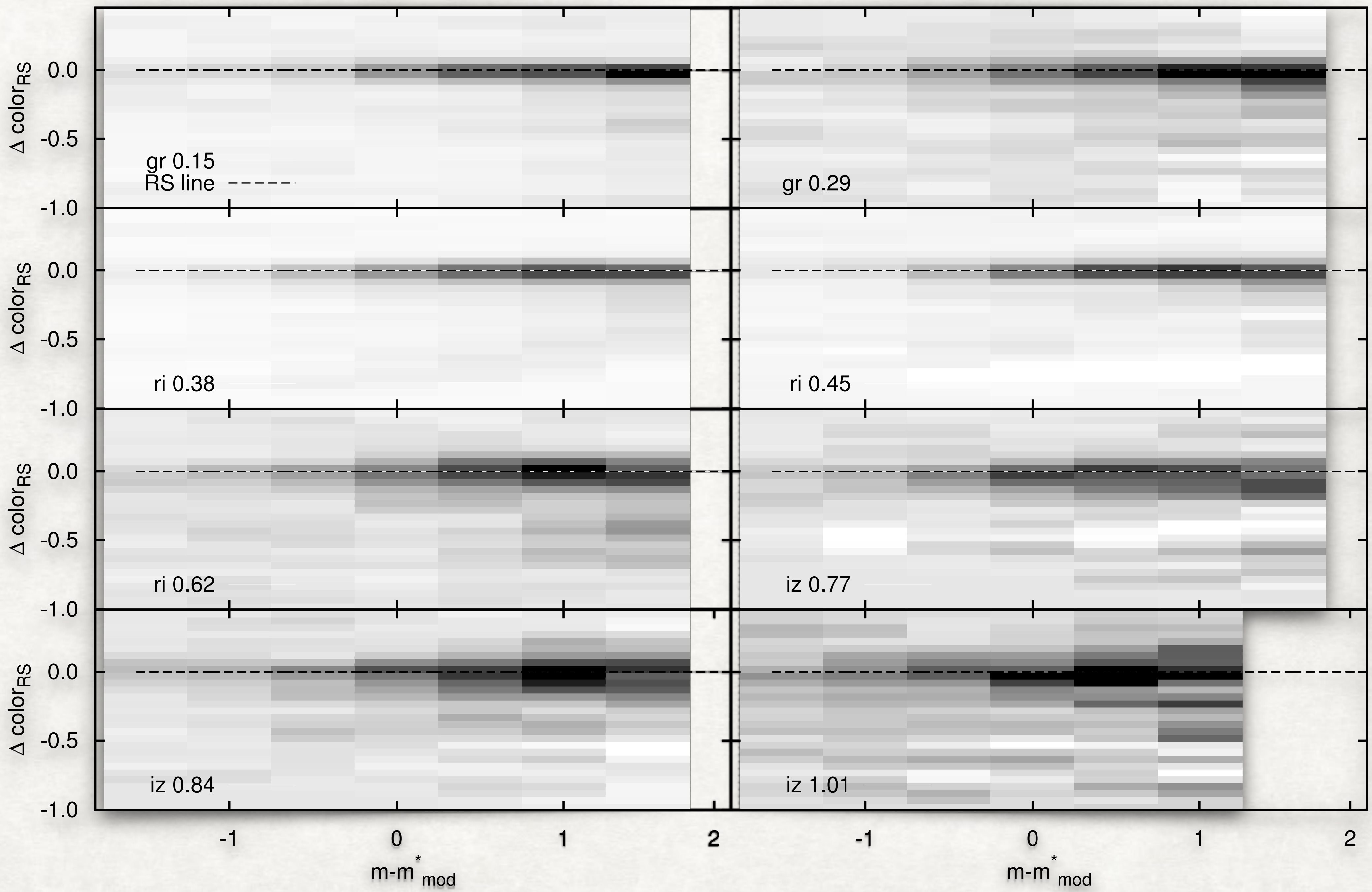
RED-SEQUENCE MATCHED-FILTER PROBABILISTIC PERCOLATION CLUSTER FINDER (REDMAPPER, RYKOFF ET AL.)



Stott et al. 2009

RED SEQUENCE OF SPT CLUSTERS IN DES

0.07 < z < 1.12 (Hennig et al. 2016)



EXAMPLE OPTICAL SURVEYS

- Sloan Digital Sky Survey (SDSS): 14,000 deg^2, 26,311 clusters with richness **λ** > 20, 0.08 < z < 0.6
- Dark Energy Survey (DES): 5,000 deg^2; currently: 150 deg^2 Science Verification Data, 786 clusters with **λ** > 20, 0.2 < z < 0.9
- Large Synoptic Survey Telescope (LSST, ~2020): 18,000 deg^2

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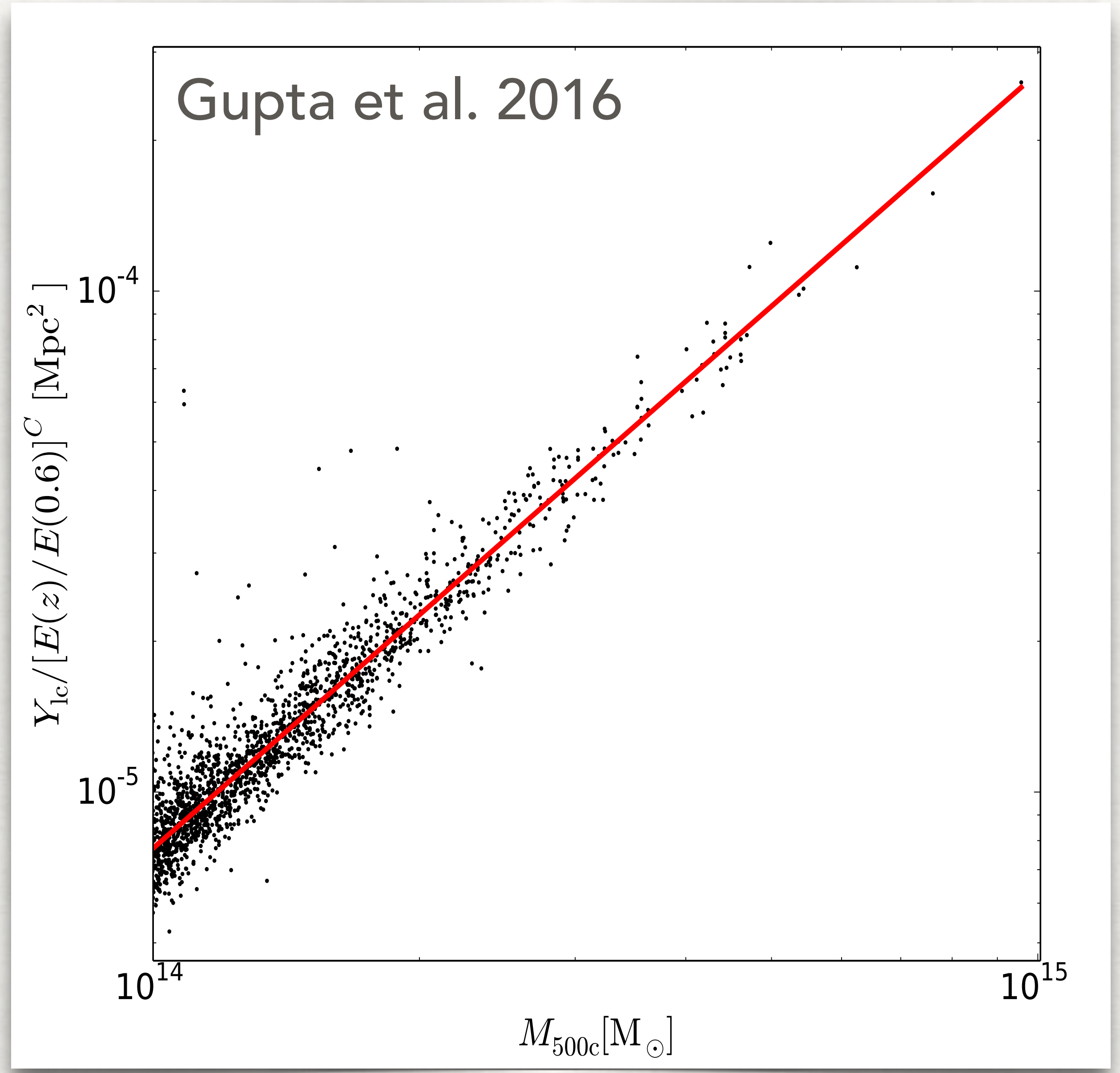
SCALING RELATIONS

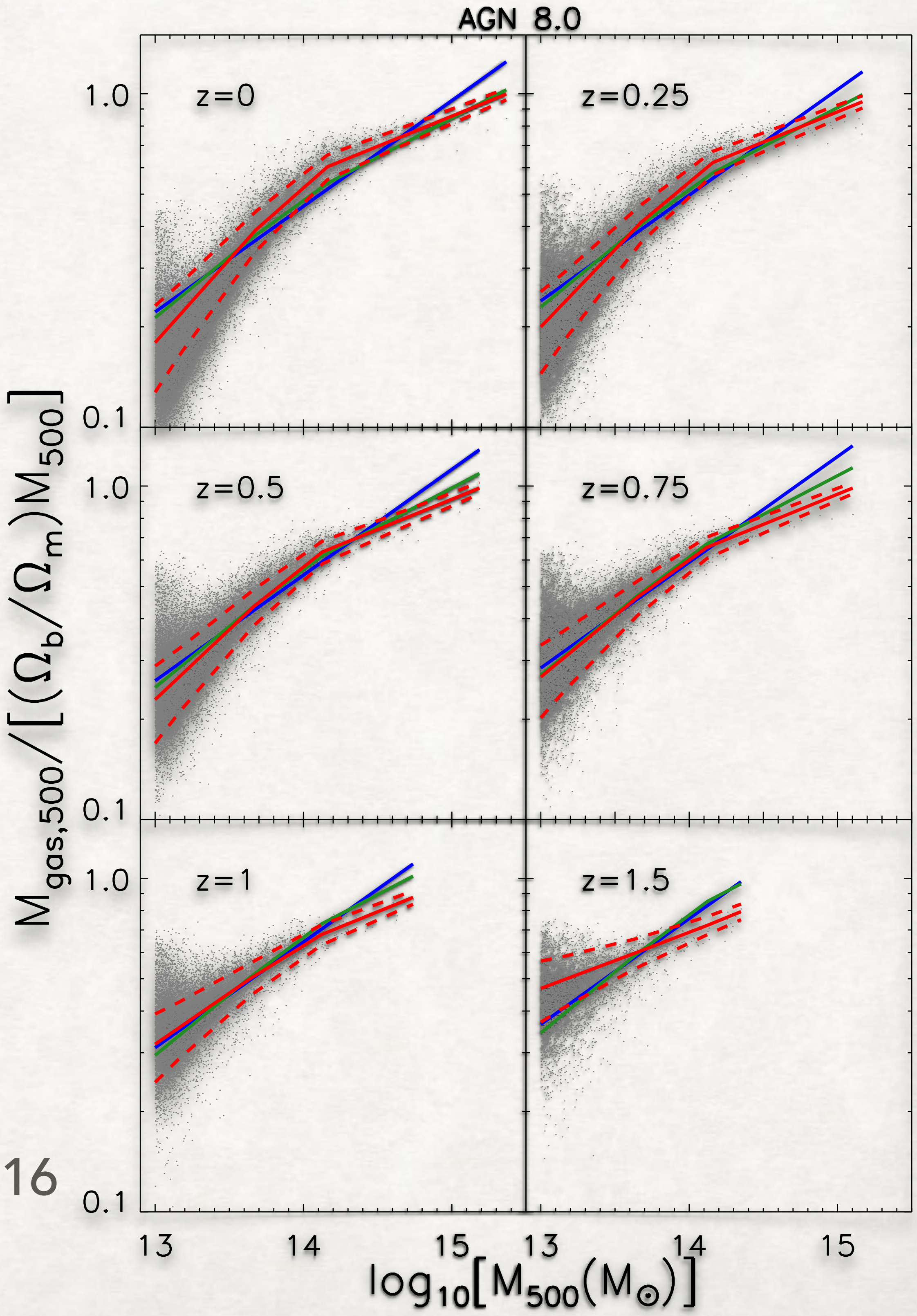
RELATE OBSERVABLES TO MASS

- Assume there is a mean relation $<Obs> = f(Mass)$ with scatter
- self-similar model for virialized objects (Kaiser 1986)
  - $Mgas = C_{gas}\ M_{\Delta c}$
  - $T^{3/2} = C_T\ E(z)\ M_{\Delta c}$
  - $Ysz^{3/5} = C_{SZ}\ E(z)^{2/5}\ M_{\Delta c}$
  - $E(z) = H(z)/H_0$
- In practice, allow for more freedom $<Obs> = A\ M^B\ E(z)^C$

SCALING RELATIONS IN SIMULATIONS

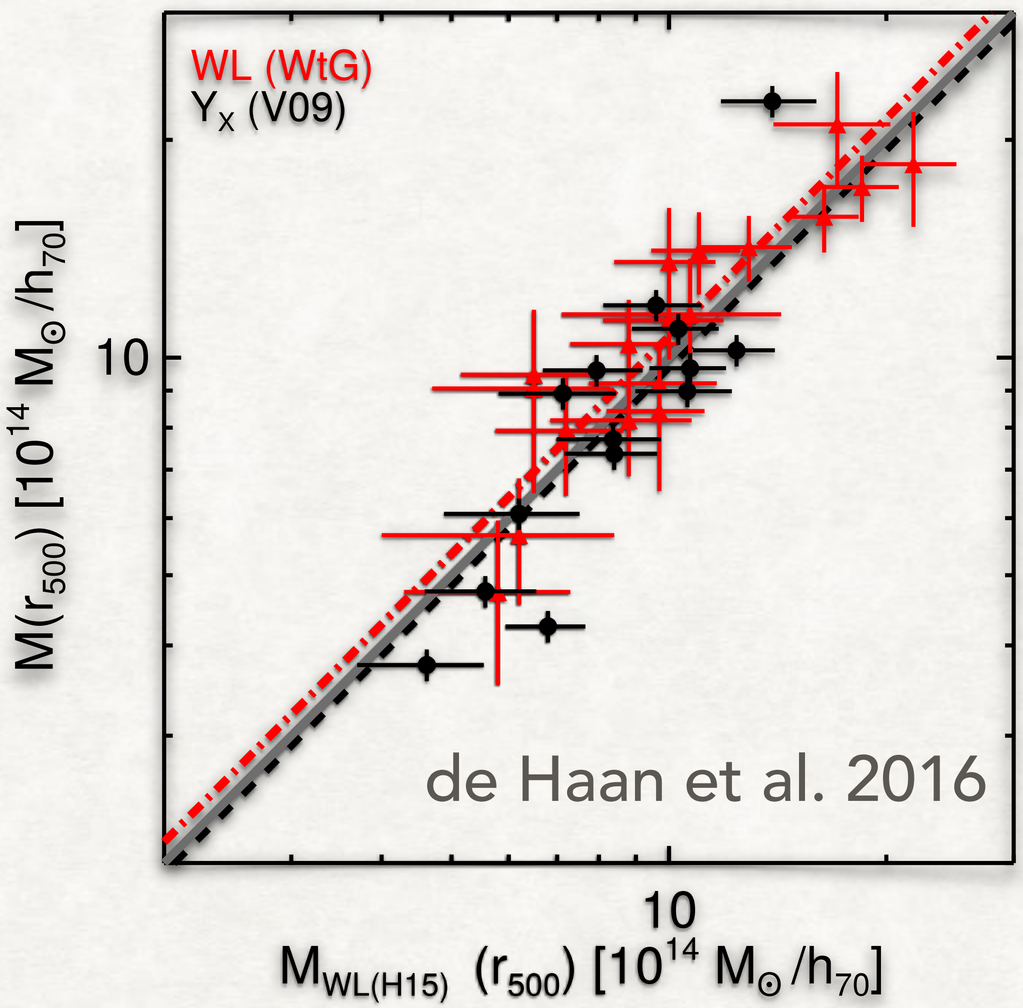


Le Brun et al. 2016

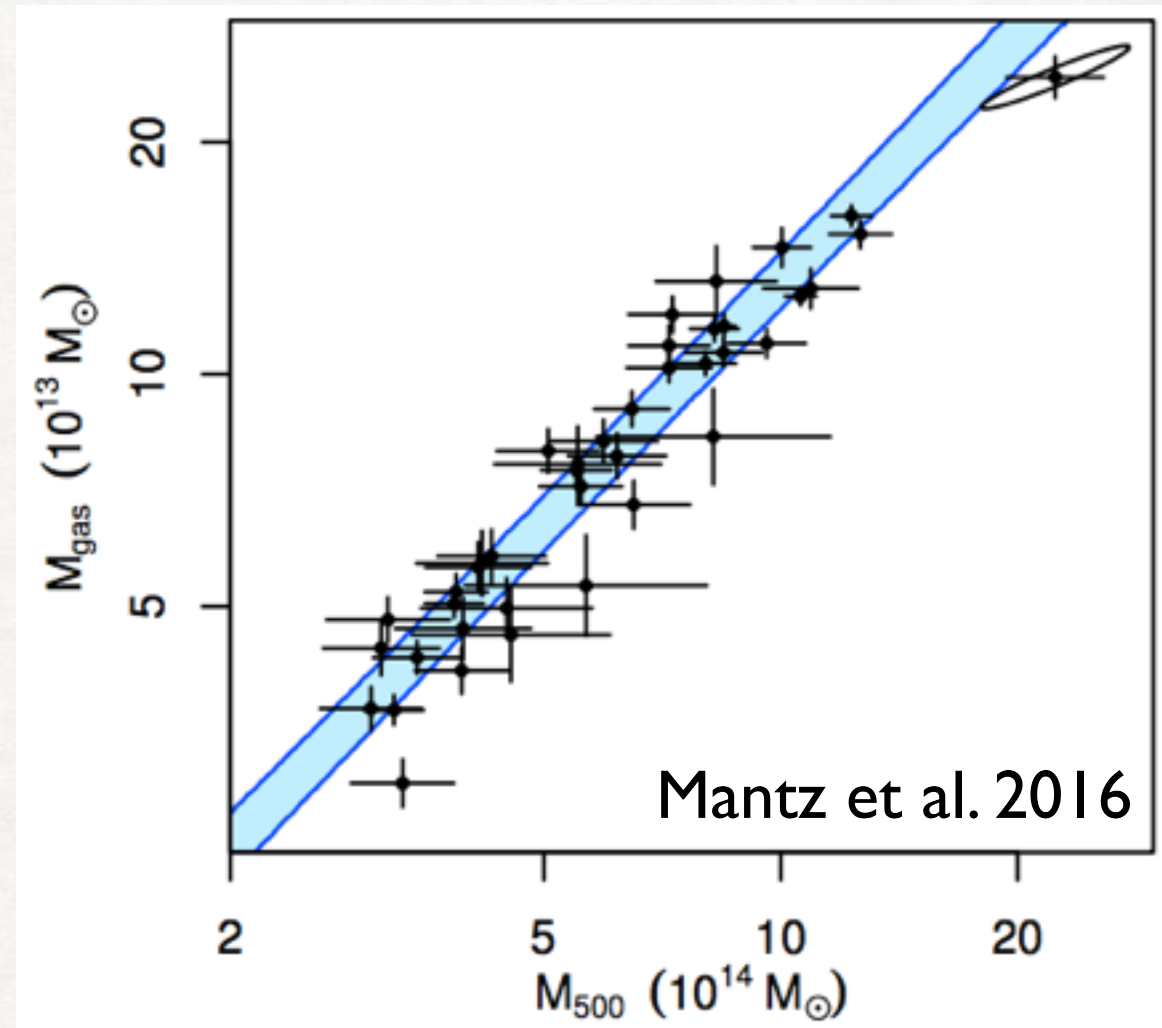


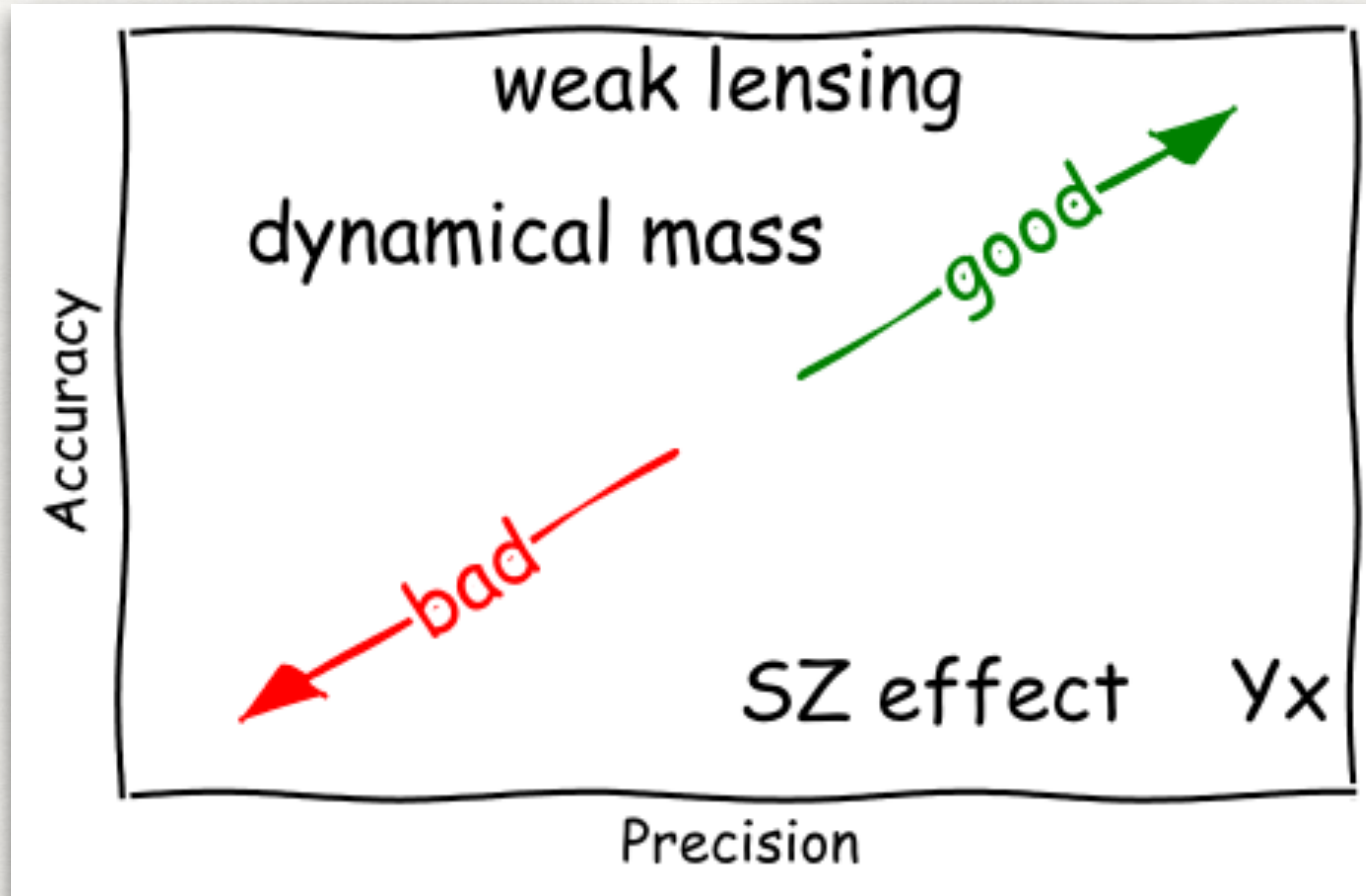
X-RAY - WL CALIBRATION

X-ray



weak lensing mass




weak lensing
dynamical mass
good
bad
SZ effect
Yx
Accuracy
Precision

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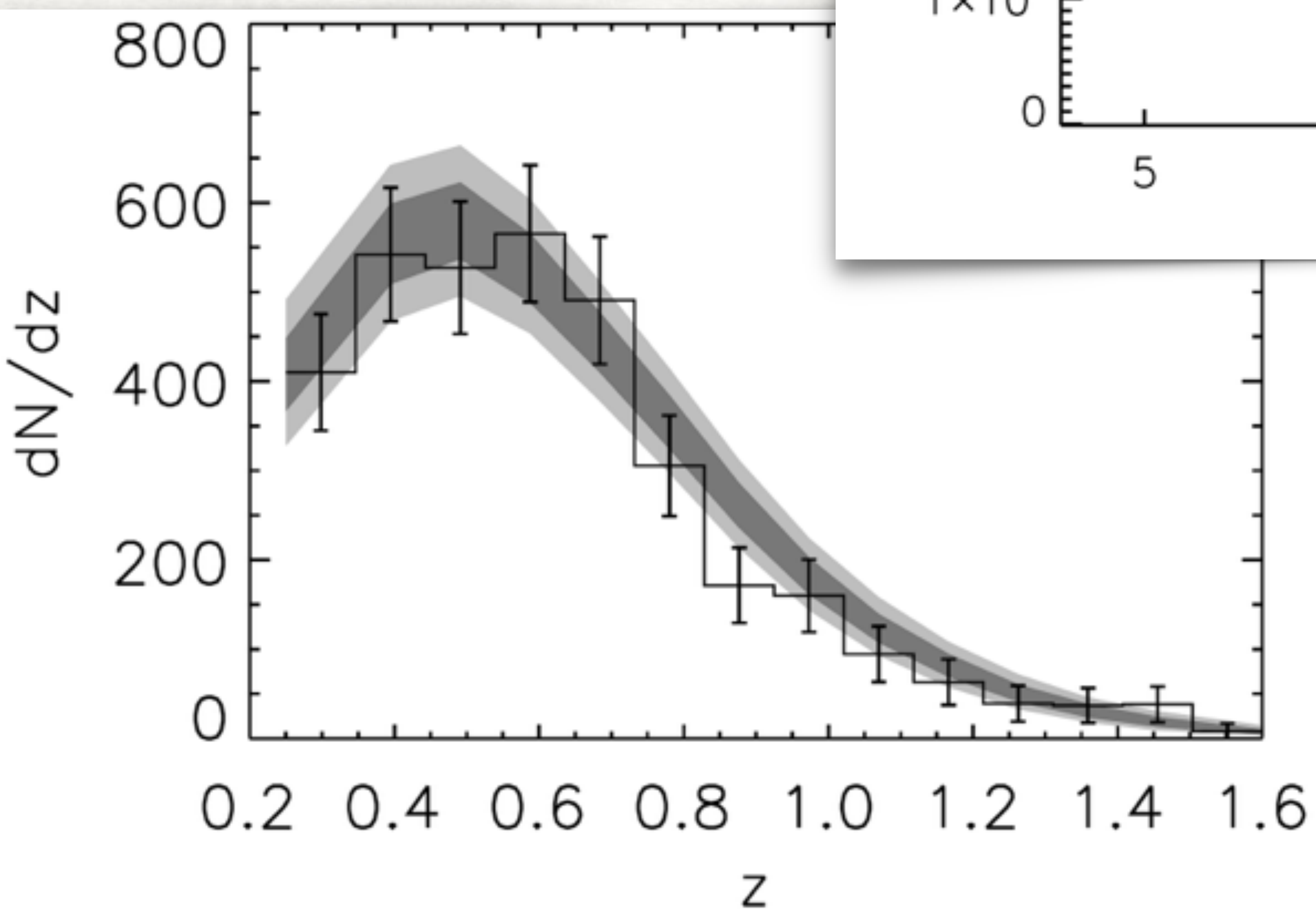
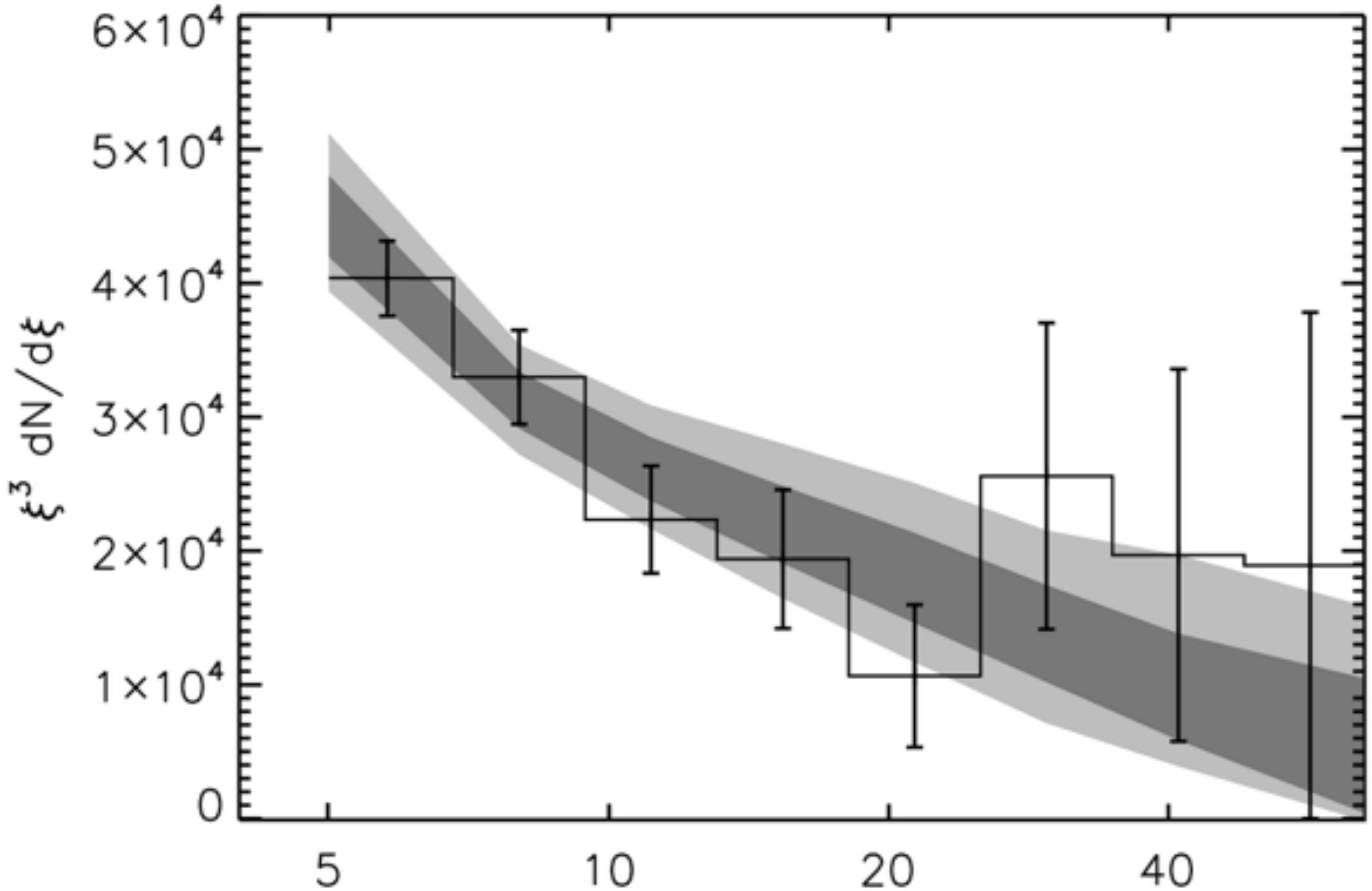
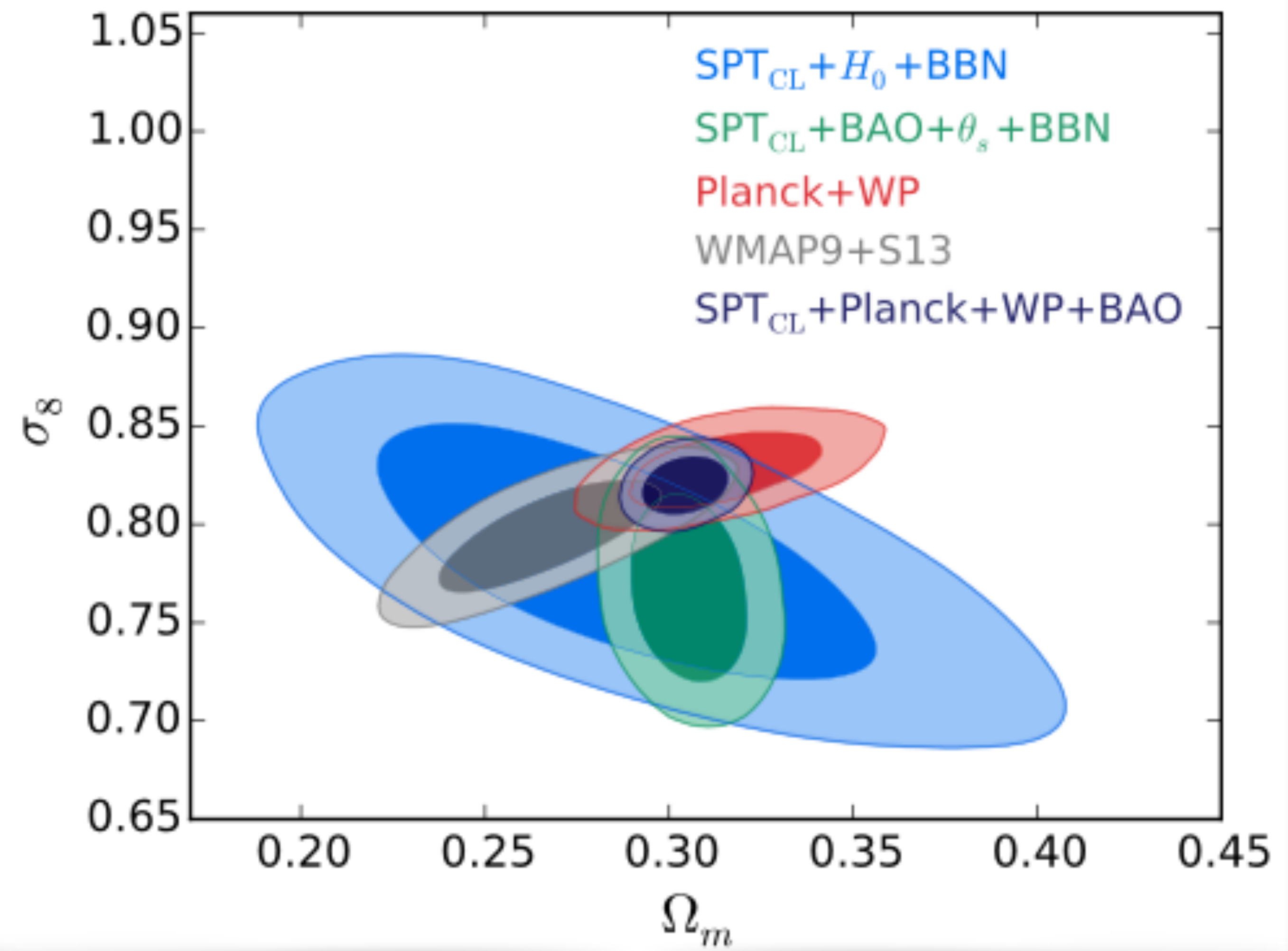
Observed Cluster Mass Function

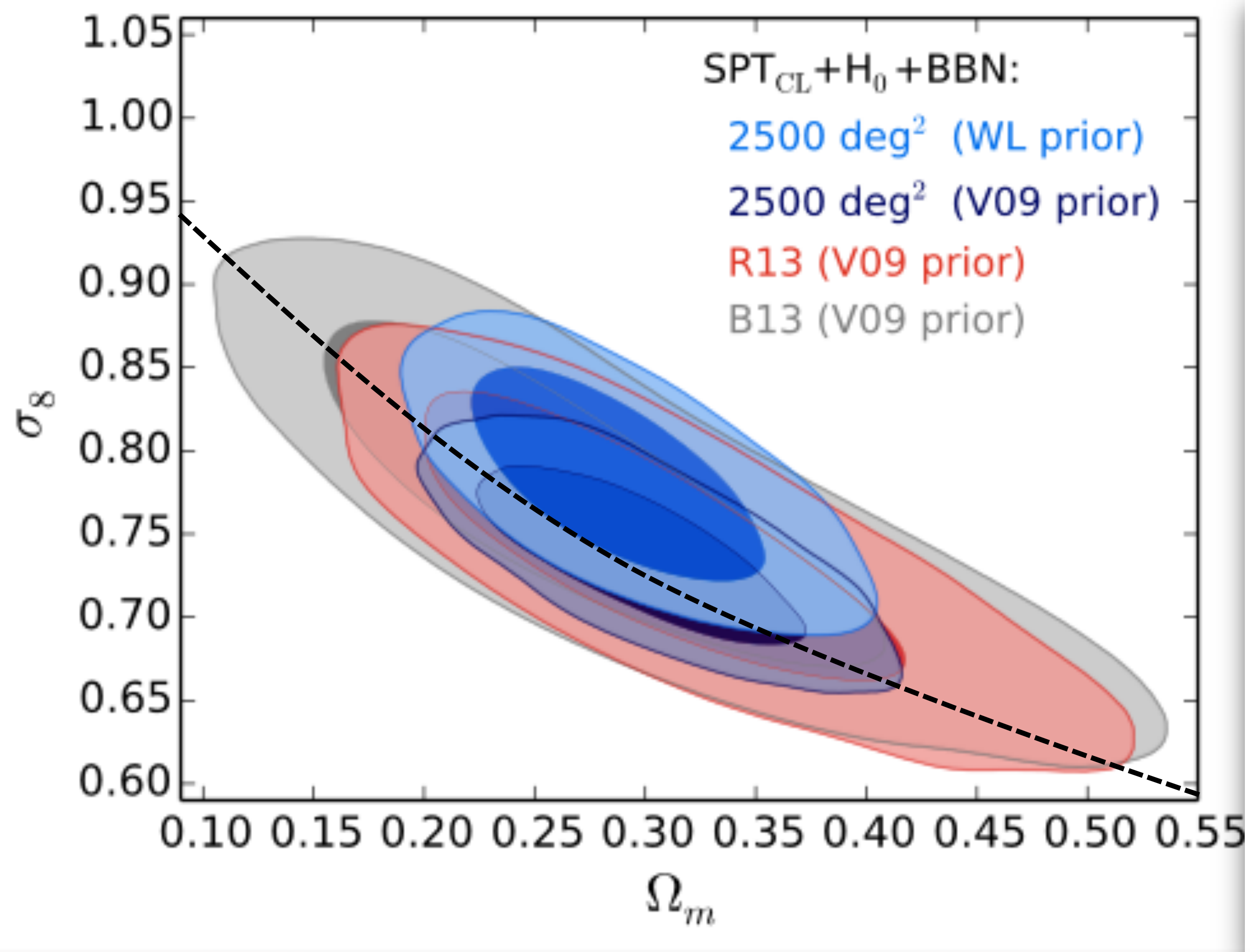


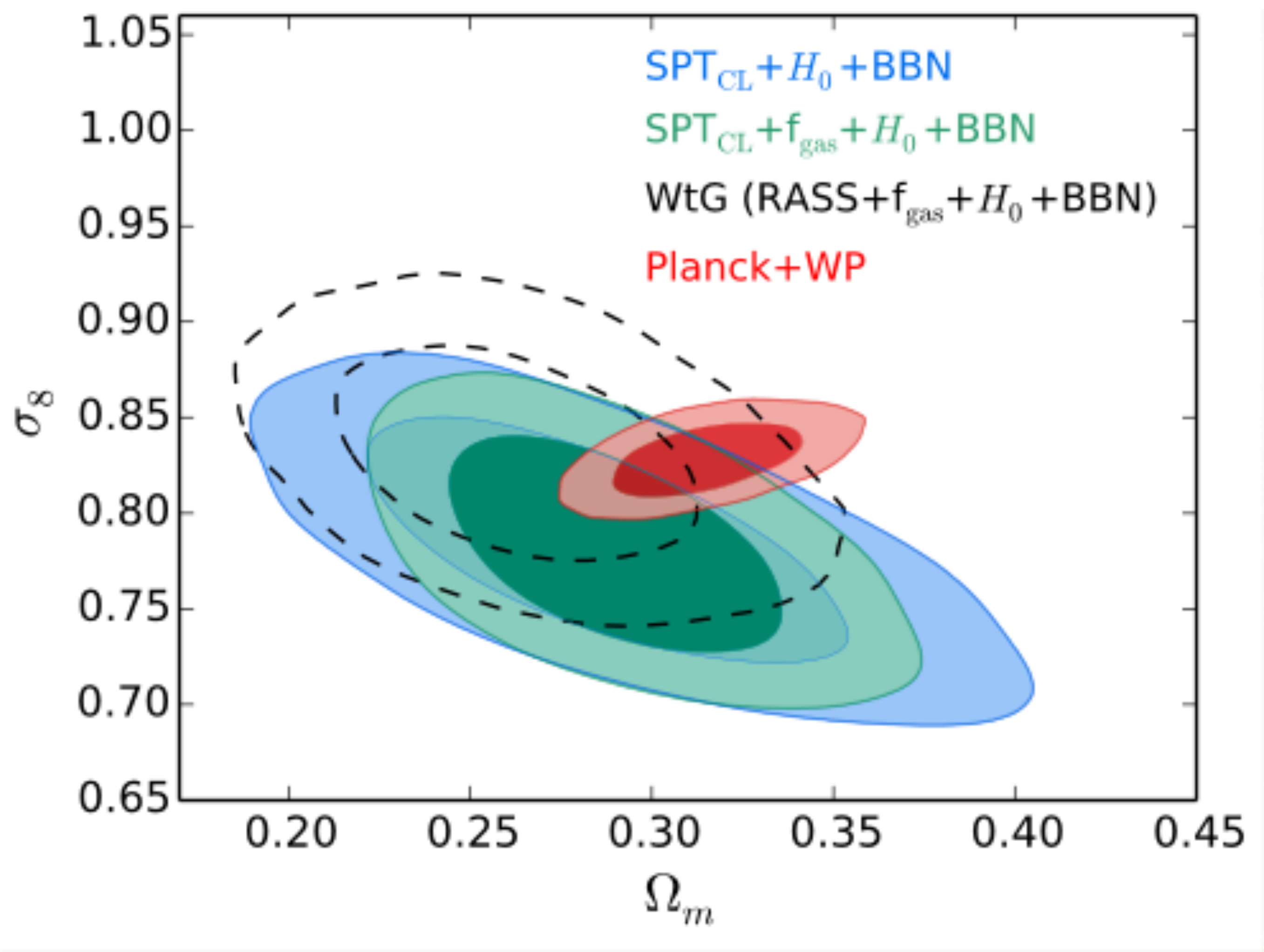


ξ: SPT-SZ mass proxy

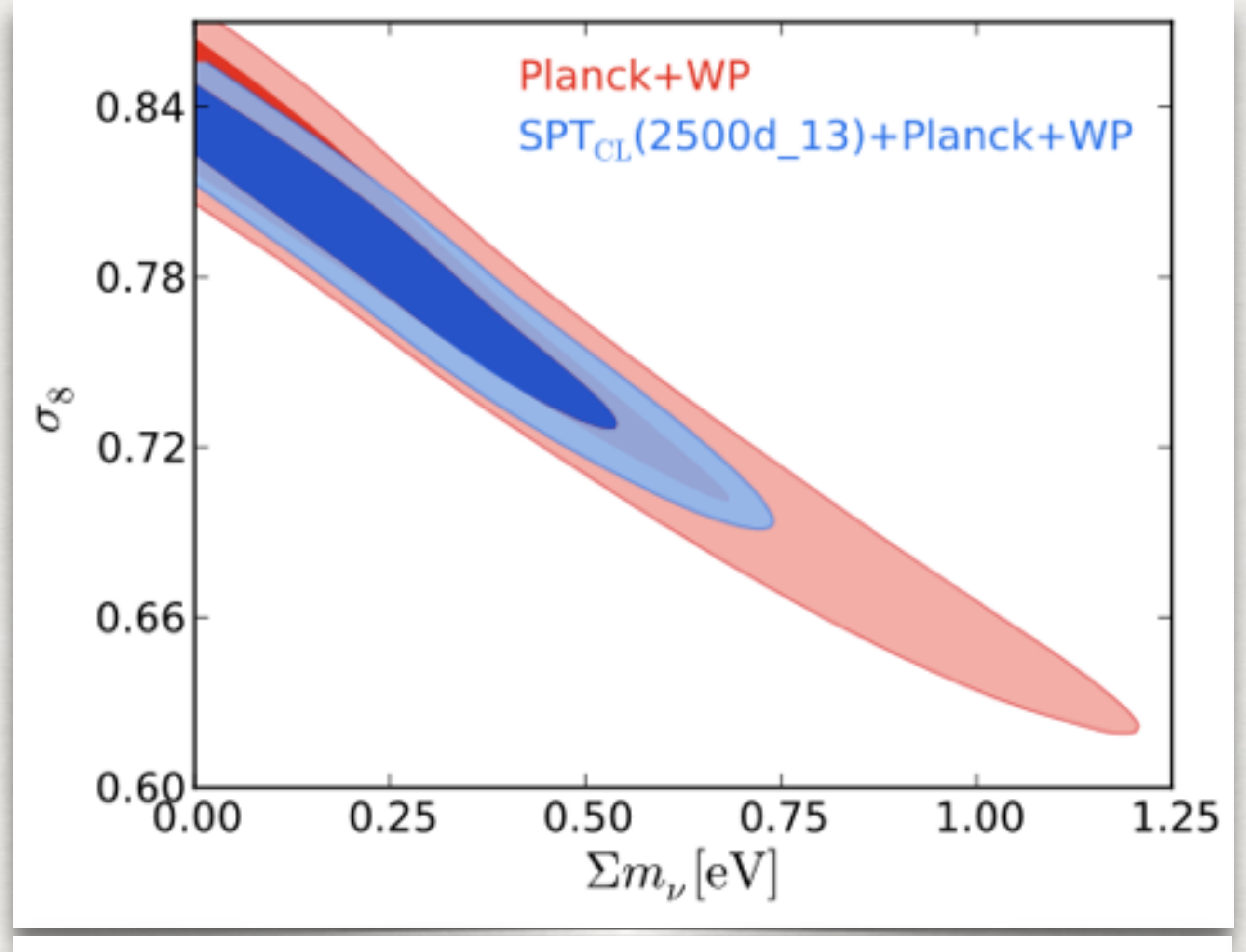
Flat LCDM Cosmology

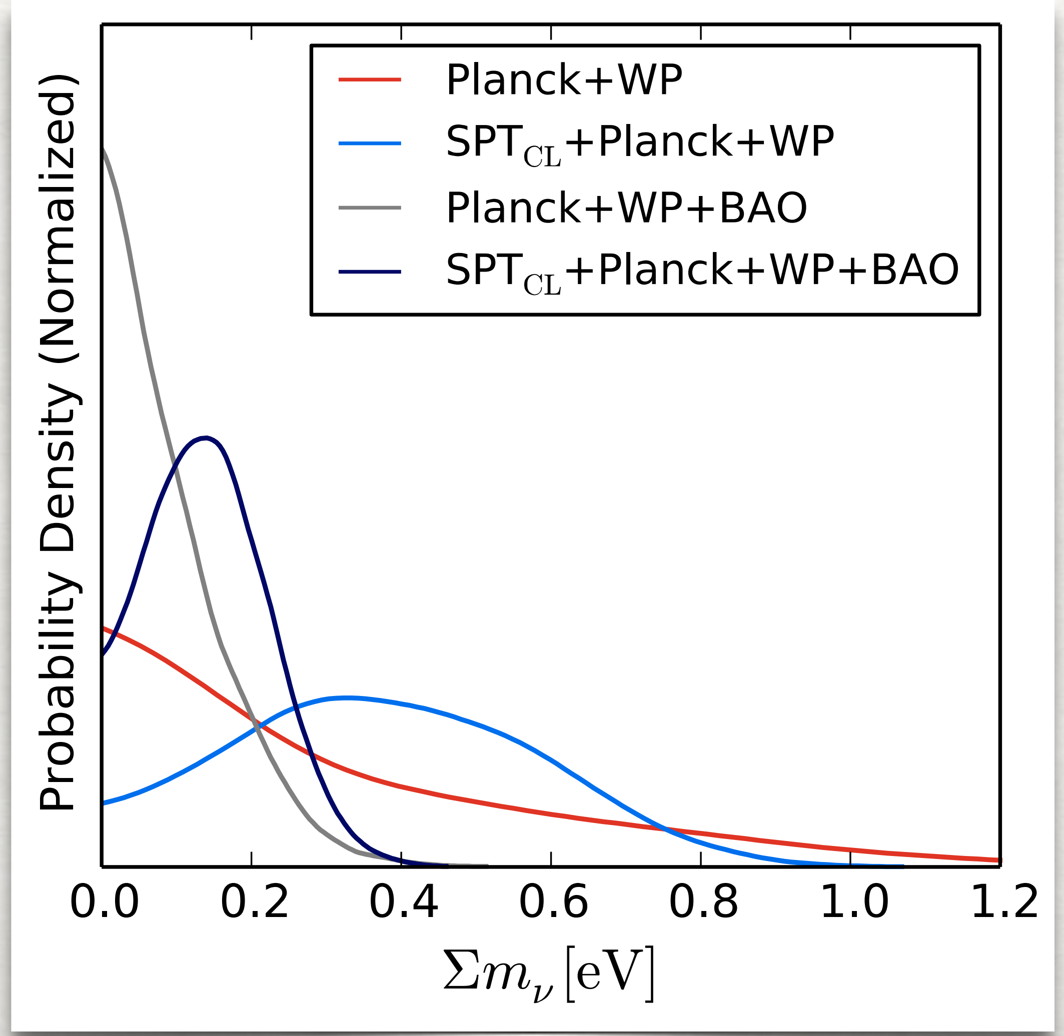


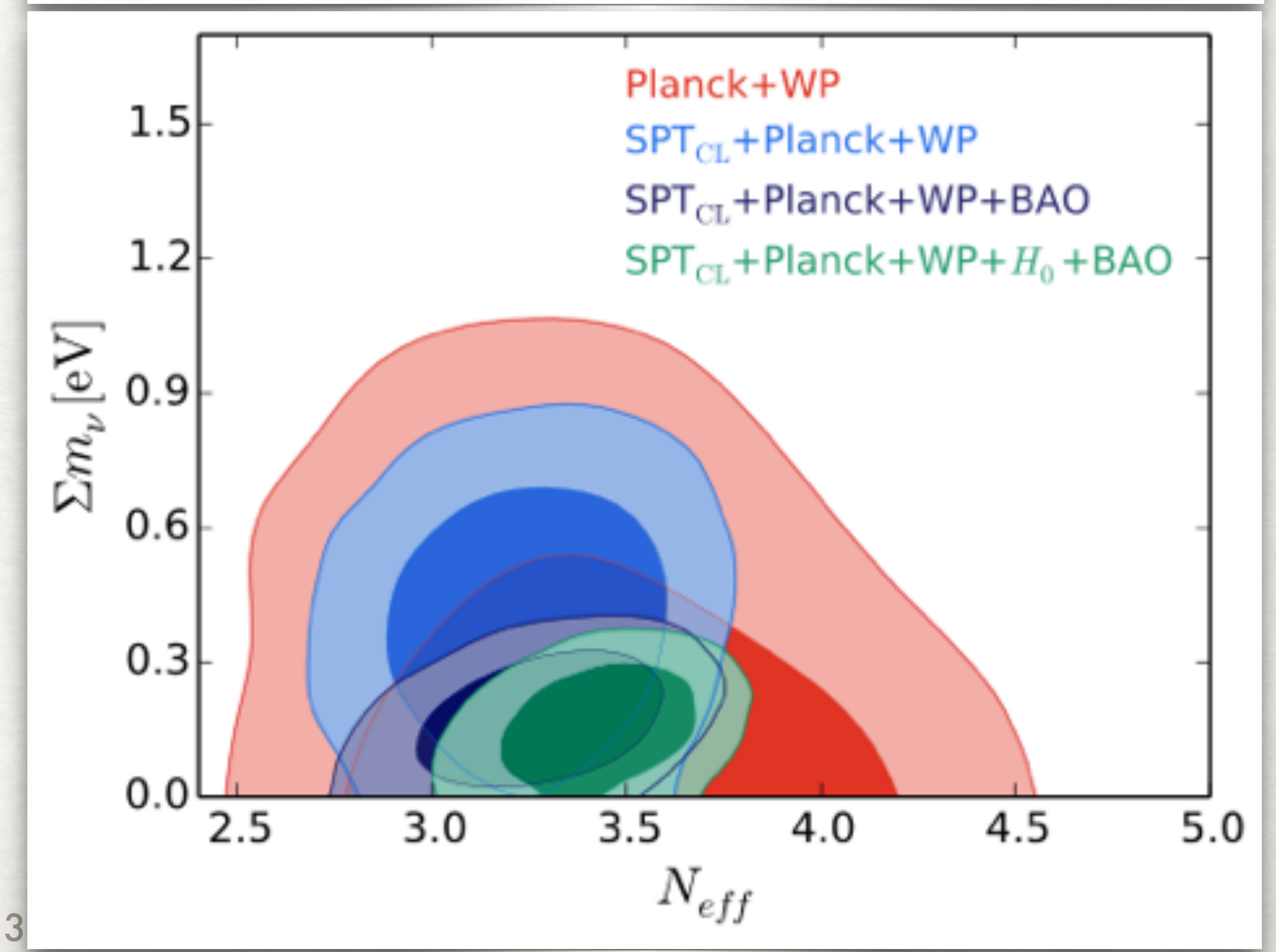




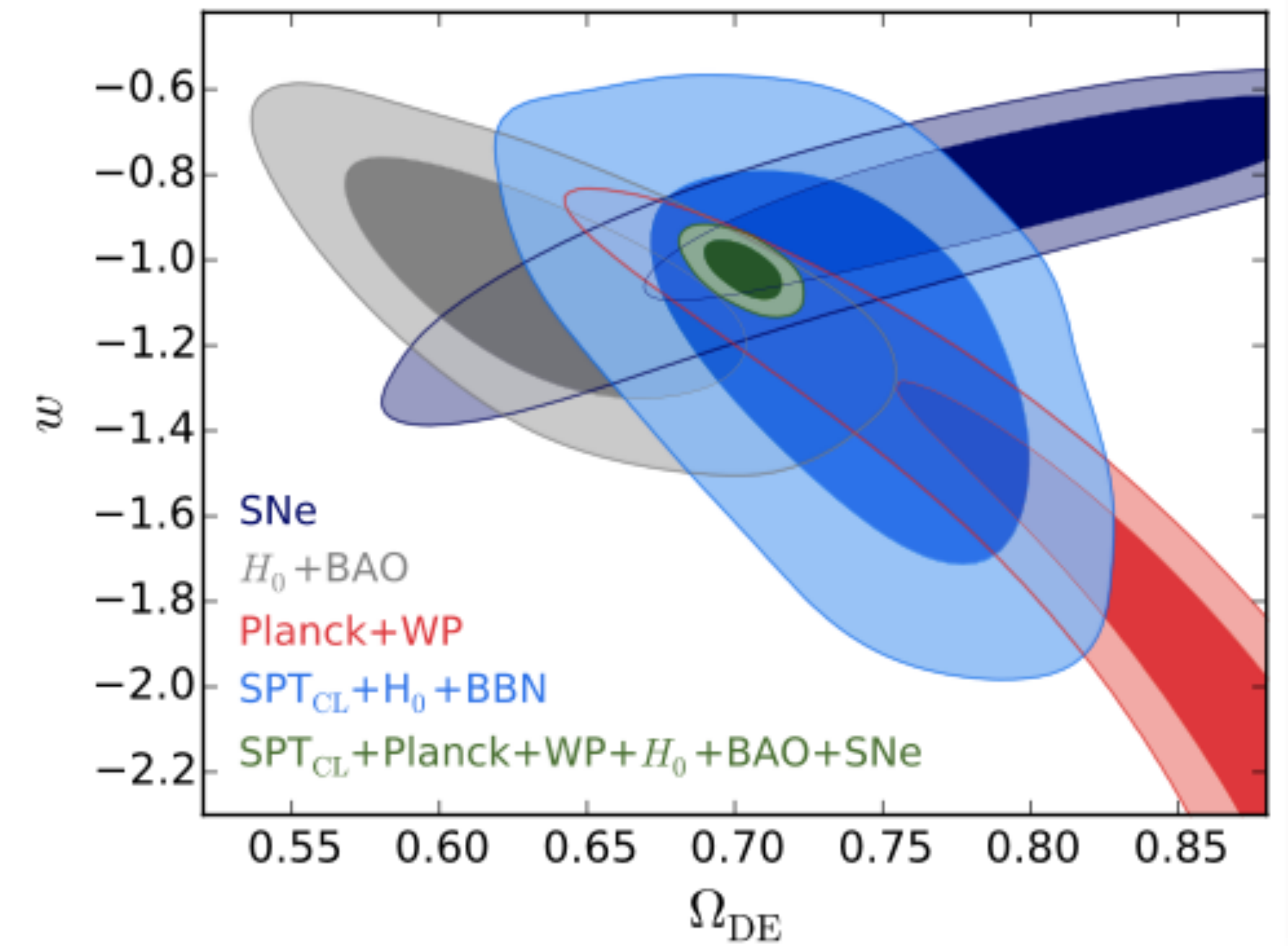
Neutrino Sector

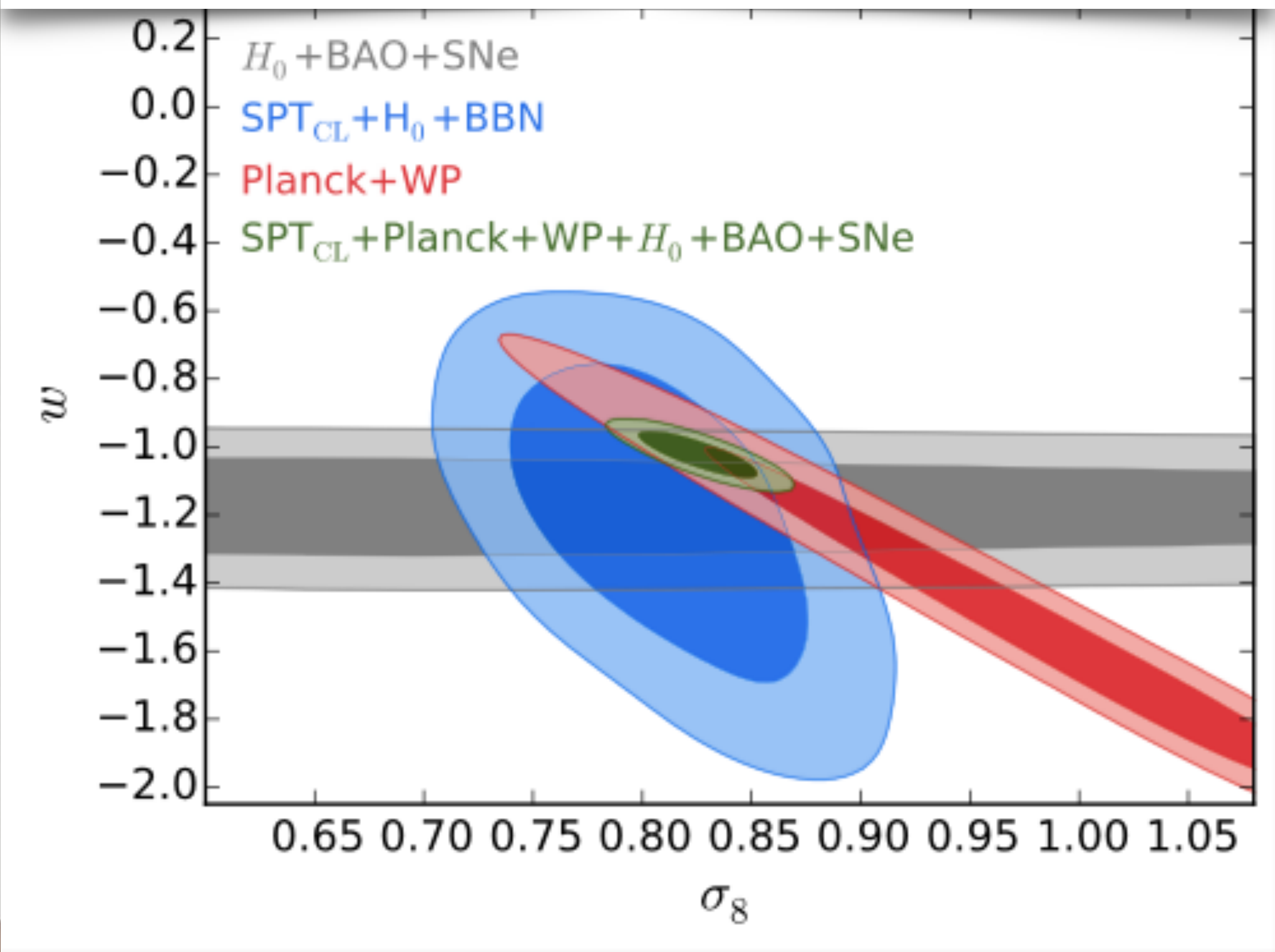






Dark Energy Equation of State





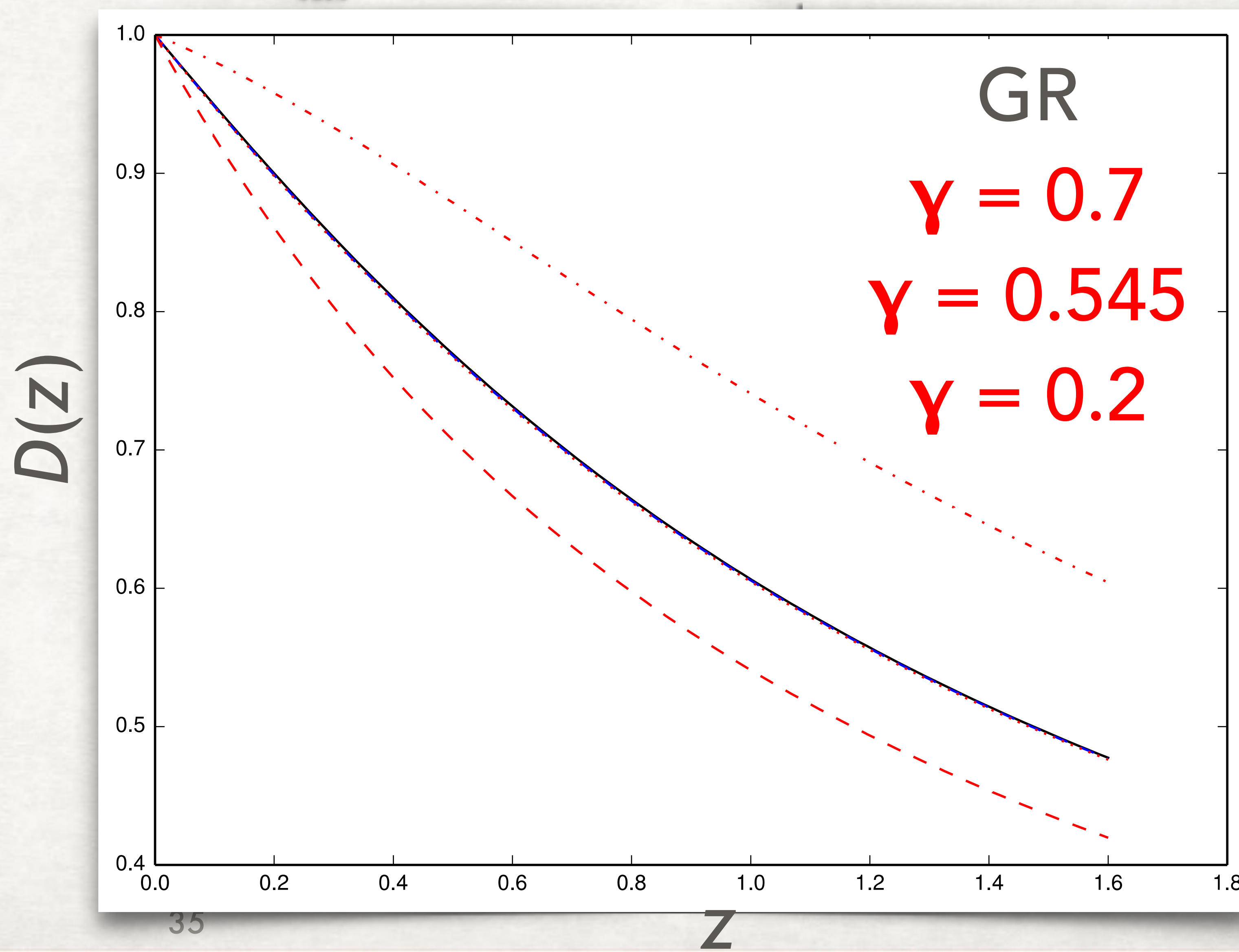
PARAMETRIZED GROWTH OF STRUCTURE

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

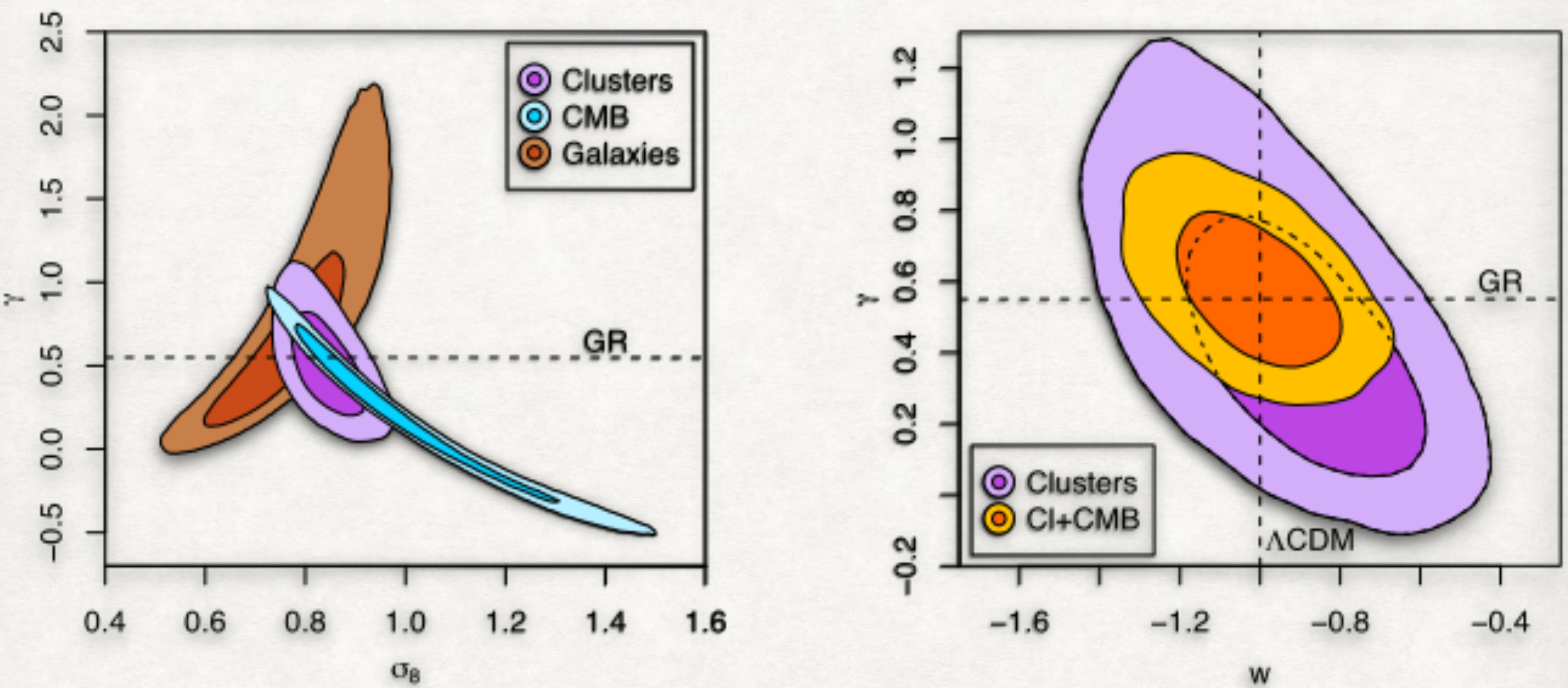
$$D_{\rm ini}(z) \equiv \frac{\delta(z)}{\delta(z_{\rm ini})} = \delta(z_{\rm ini})^{-1} \exp\left(\int_{a_{\rm ini}}^{a} d\ln a'\, \Omega_m^\gamma(a')\right)$$

$$\mathrm{P}(k,z) = P(k, z_{\rm ini})\, D_{\rm ini}^2(z)$$

GR predicts γ = 0.55

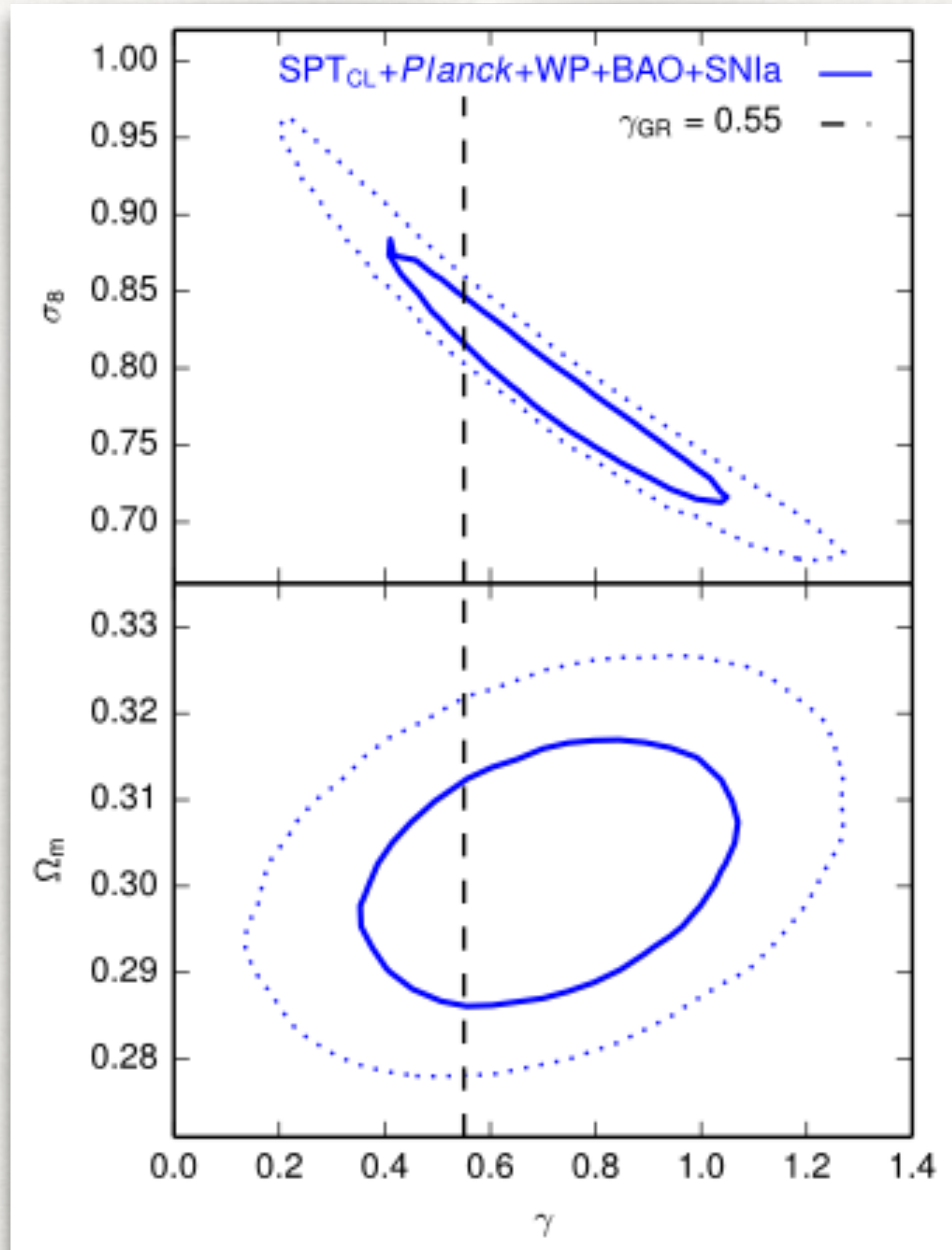


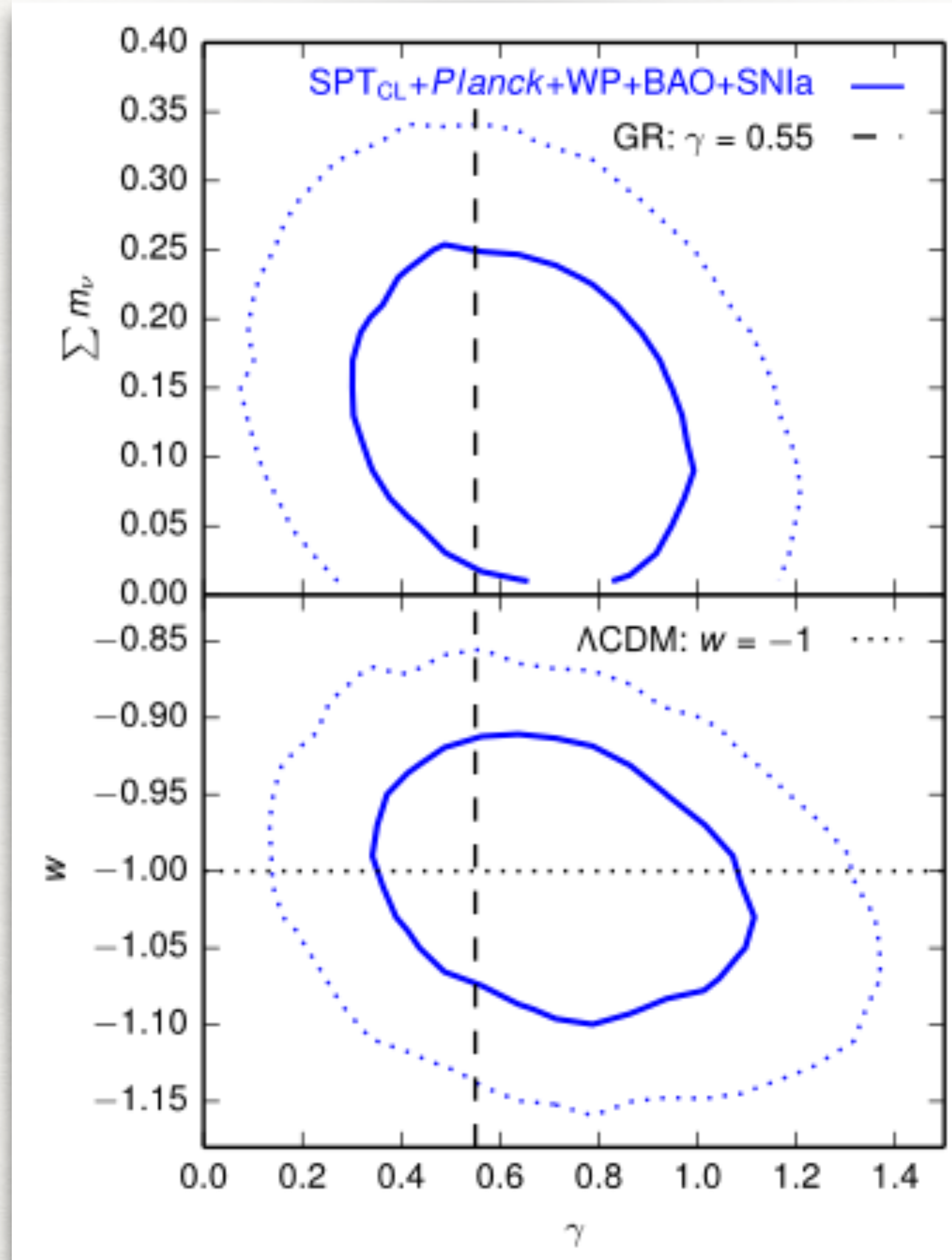
RESULTS FROM CLUSTERS TO DATE



Weighing the Giants IV: Mantz et al. 2015
Also: Rapetti et al. 2009, 2010, 2013

RESULTS FROM CLUSTERS TO DATE





SPT-SZ 720 deg^2: SB et al. 2015