Title: New Constraints on the Amplitude of Cosmic Density Fluctuations and Intracluster Gas from the Thermal SZ Signal Measured by Planck and ACT

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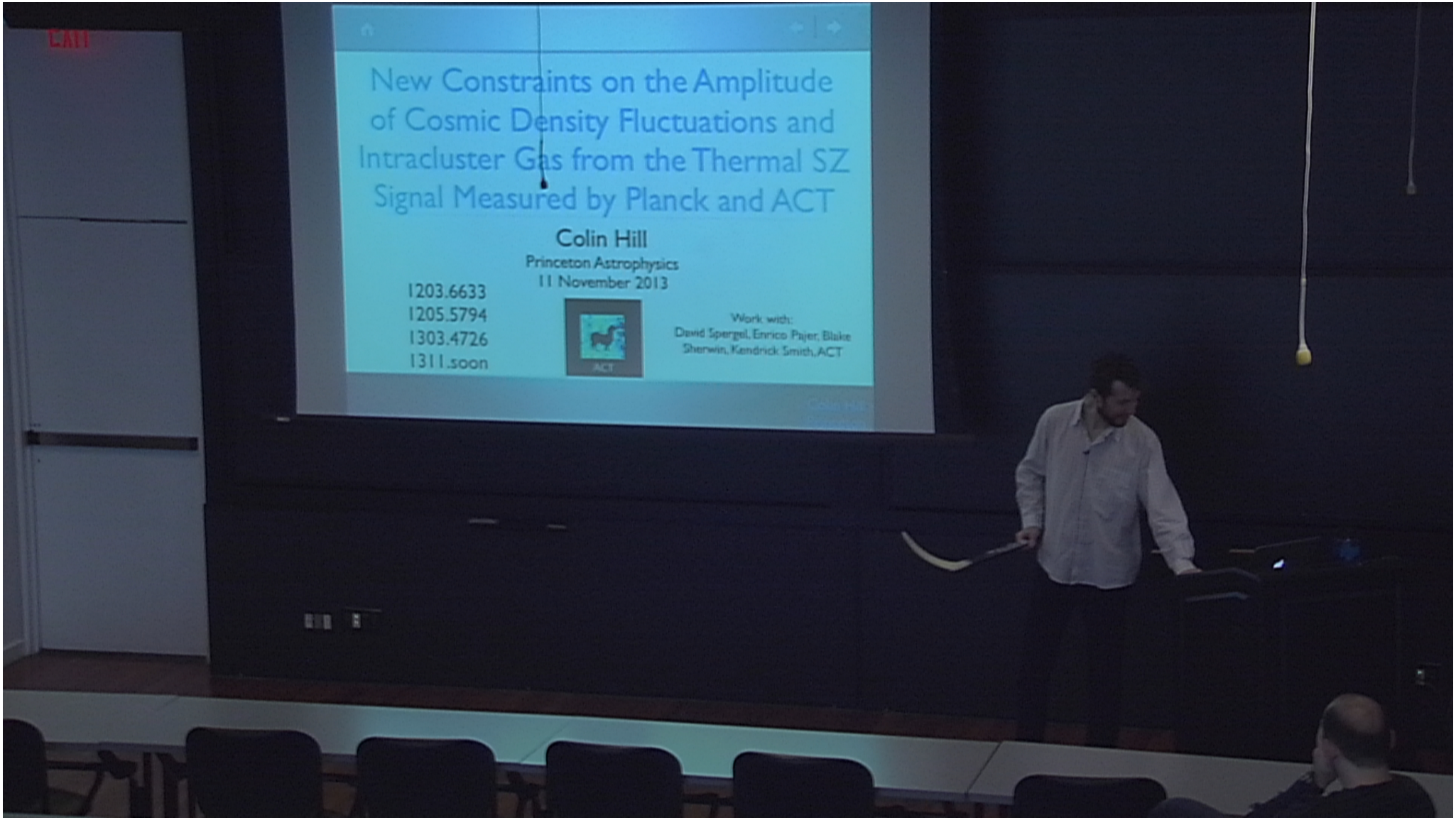
Abstract: Galaxy clusters form from the rarest peaks in the initial matter distribution, and hence are a sensitive probe of the amplitude of density fluctuations (sigma_8), the amount of matter in the universe, and the growth rate of structure. Galaxy clusters have the potential to constrain dark energy and neutrino masses. However, cluster cosmology is currently limited by systematic uncertainties due to poorly understood intracluster gas physics. I will present new statistical approaches to understand clusters and improve their cosmological constraining power through the thermal Sunyaev-Zel'dovich (tSZ) effect. First, I will describe a forthcoming first detection of the cross-correlation of the tSZ signal reconstructed from Planck data with the large-scale matter distribution traced by the Planck CMB lensing potential. This statistic measures the amount of hot gas found in moderately massive groups and clusters (M ~ 10^13-10^14.5 M_sun), a mass scale below that probed by direct cluster detections. Second, I will describe the first measurement of the PDF of the tSZ field using ACT 148 GHz maps. This measurement contains information from all (zero-lag) moments of the tSZ field, beyond simply the 2- or 3-point functions. It is a very sensitive probe of sigma_8 and may also provide a method with which to break the degeneracy between sigma_8 and uncertainties in the physics of the intracluster gas.

New Constraints on the Amplitude of Cosmic Density Fluctuations and Intracluster Gas from the Thermal SZ Signal Measured by Planck and ACT

Colin Hill
Princeton Astrophysics
11 November 2013

1203.6633
1205.5794
1303.4726
1311.soon

Work with:
David Spergel, Enrico Pajer, Blake Sherwin, Kendrick Smith, ACT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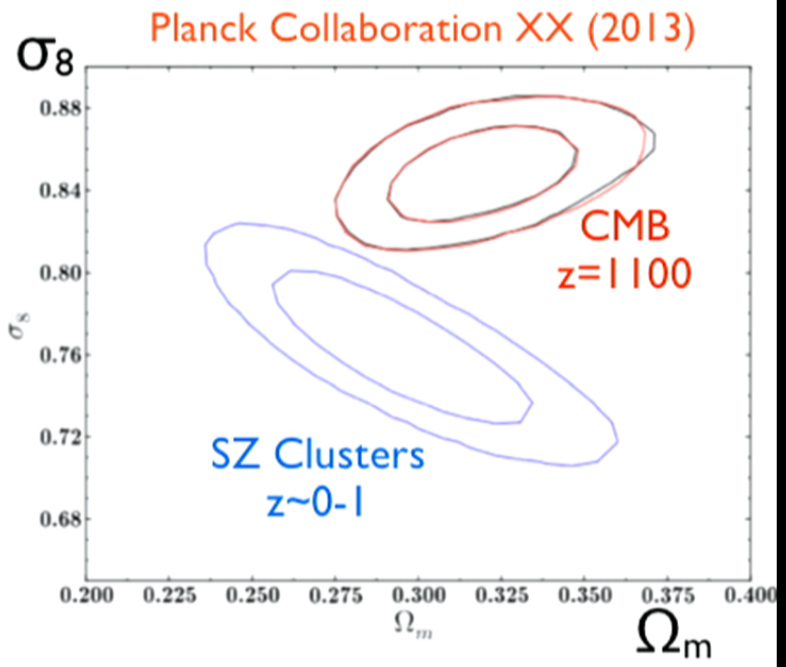
Outline


Planck Collaboration XX (2013)
σ8
0.88
0.84
0.80
0.76
0.72
0.68
σ8
0.200
0.225
0.250
0.275
0.300
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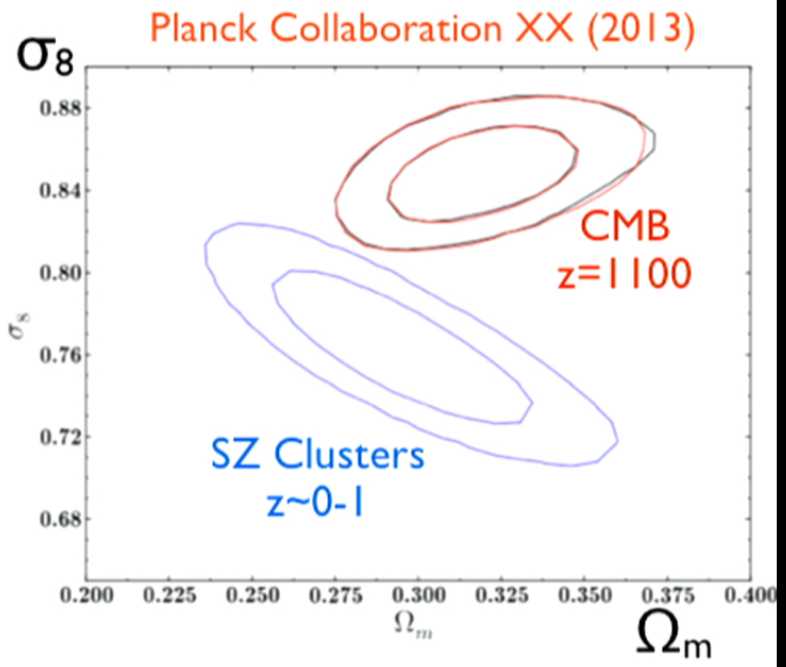
Ωm
Ωm
CMB
z=1100
SZ Clusters
z~0-1

Outline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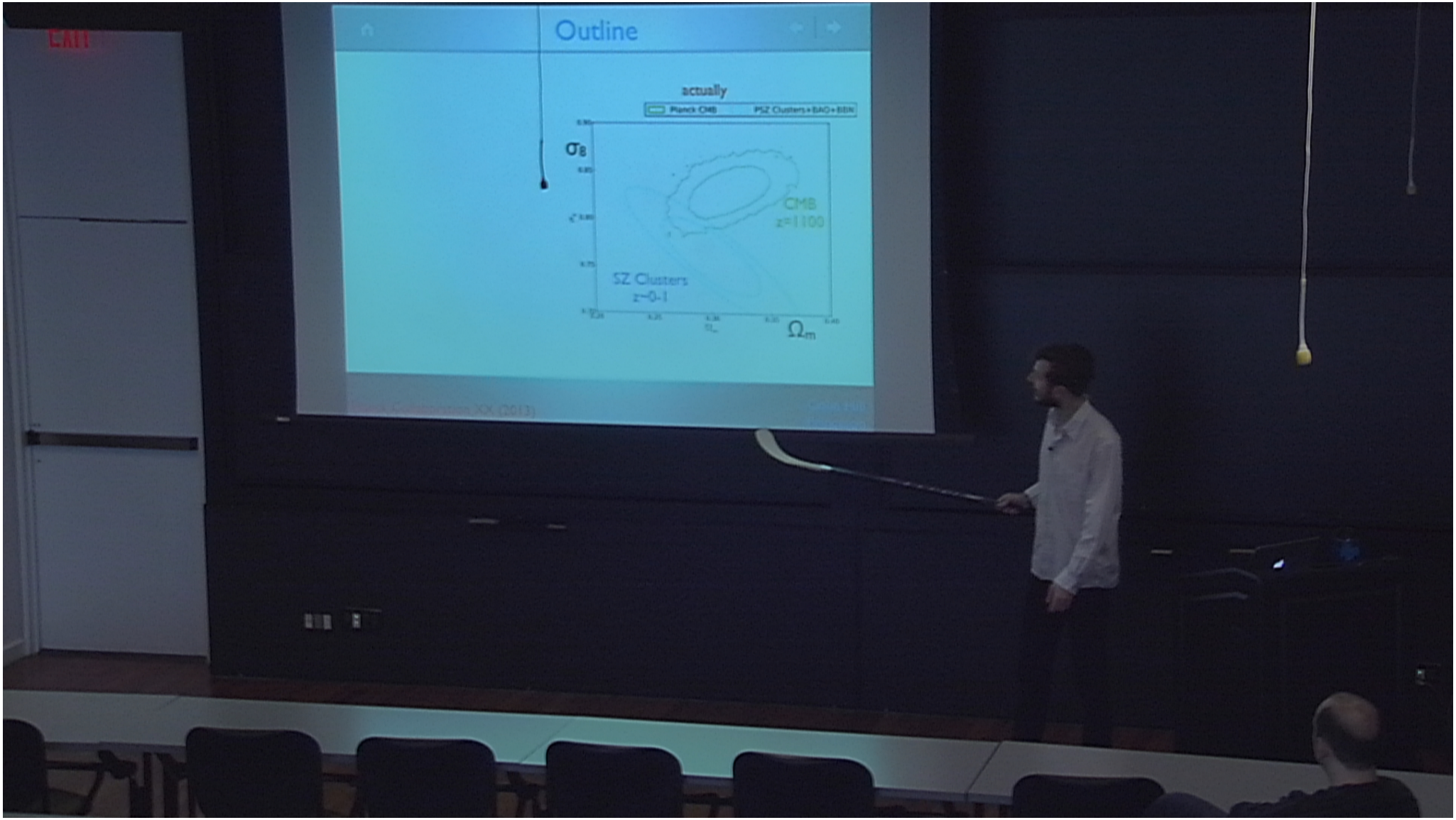
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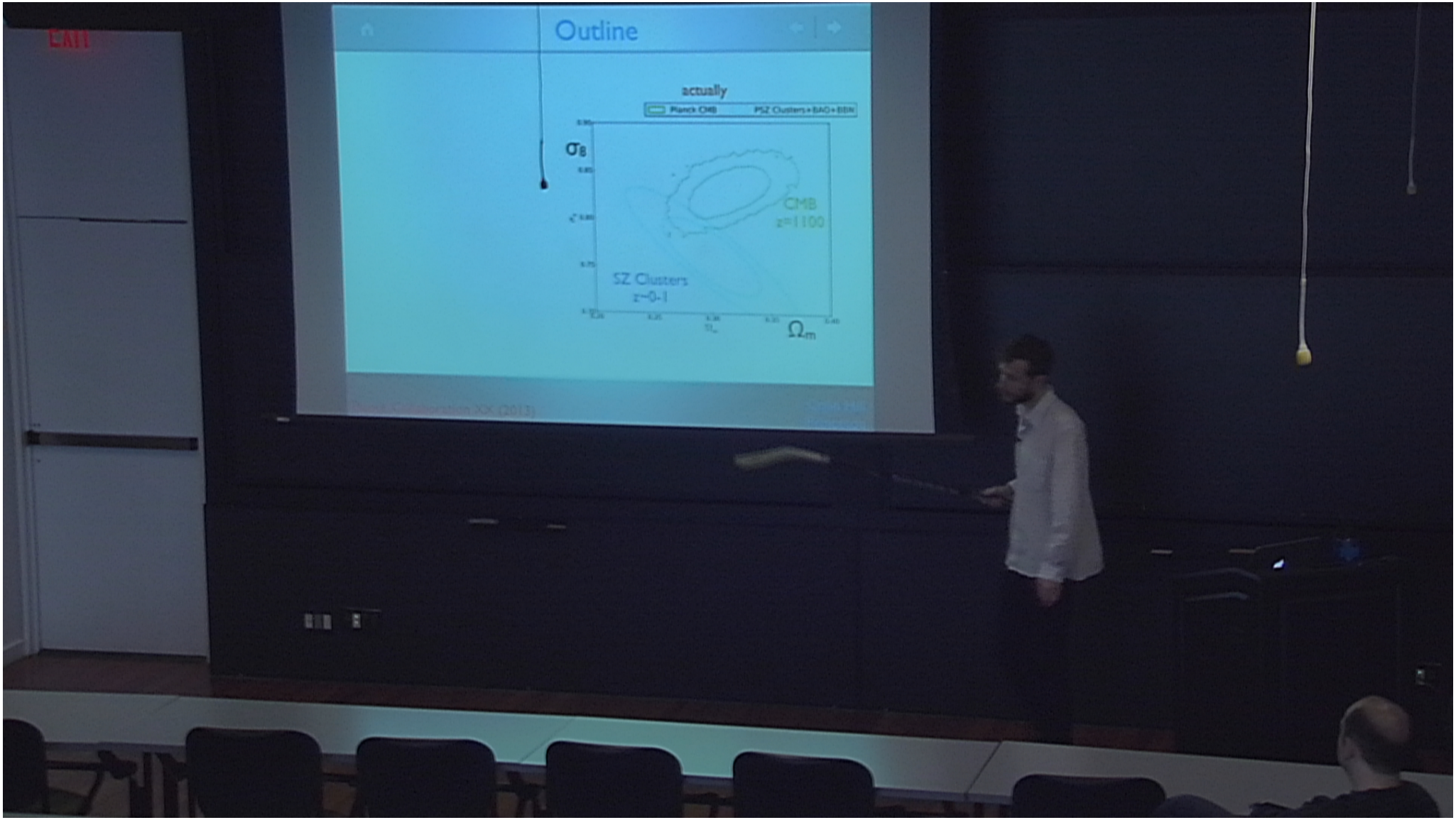
Ω_m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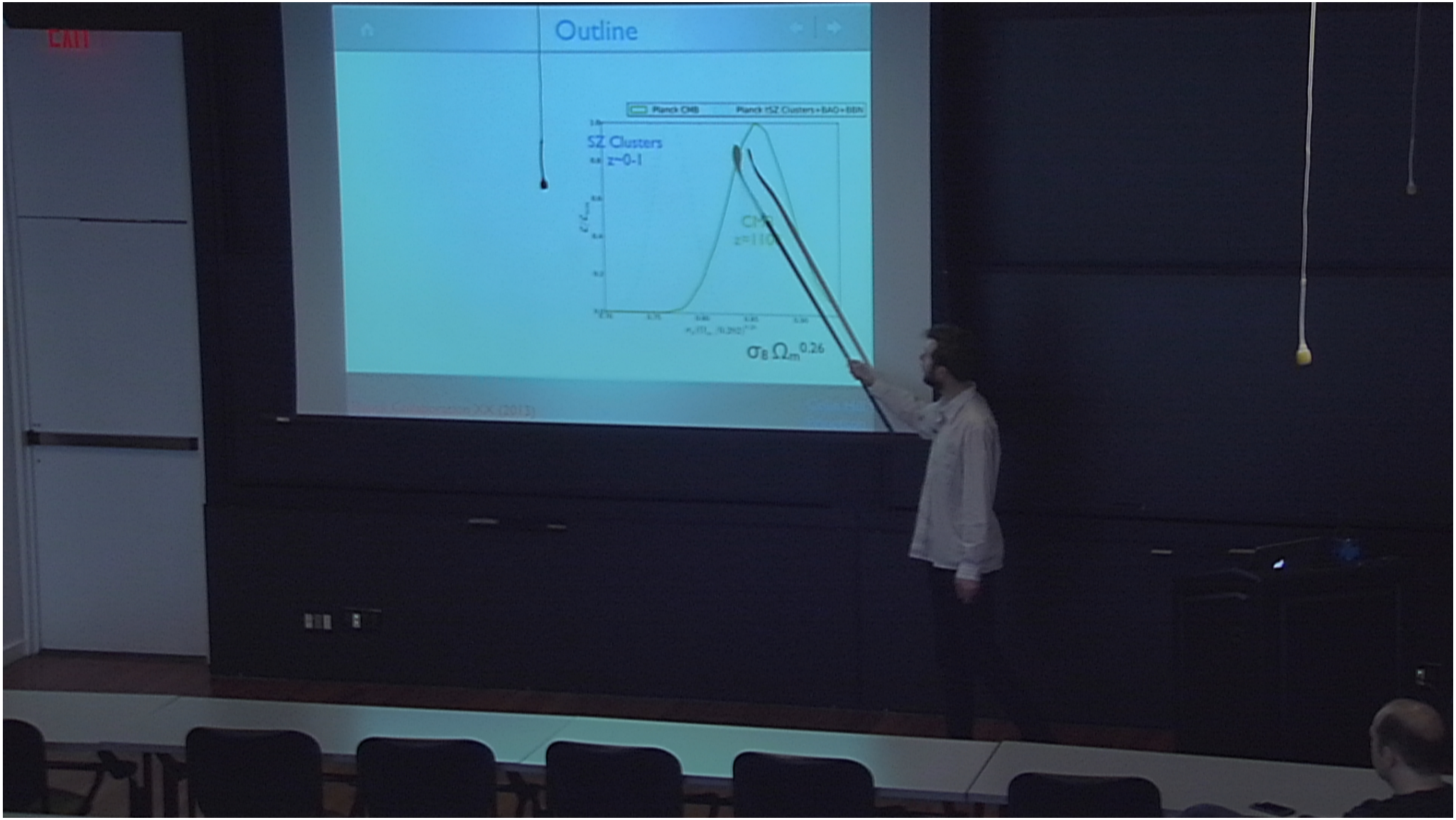
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Outline
Planck CMB
Planck tSZ Clusters+BAO+BBN
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z~0-1
CMB
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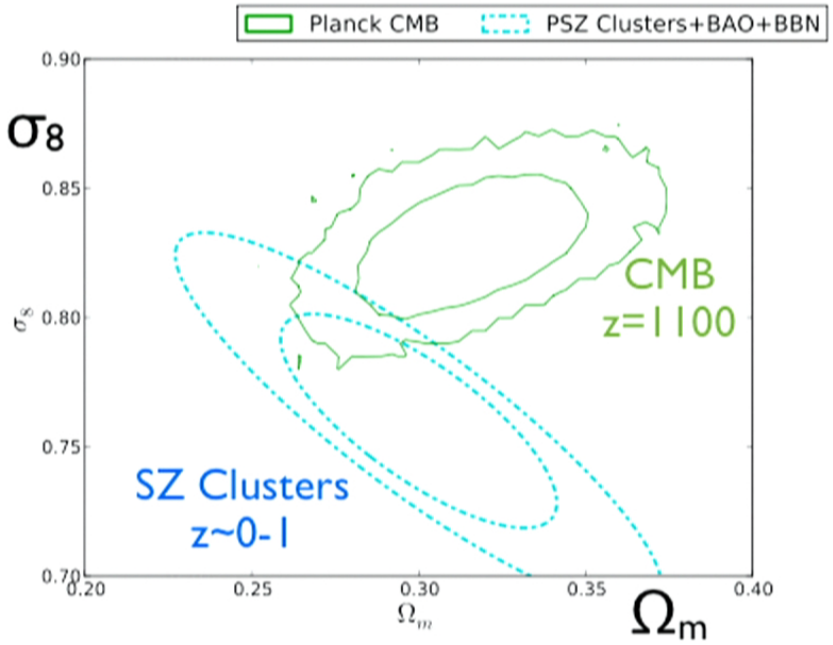
$\sigma_8 \Omega_m^{0.26}$

Outline

Wrong modeling of cluster gas physics?

Error in CMB analysis (e.g., foregrounds)?

New physics (e.g., massive neutrinos)?
$\Sigma m_\nu \sim 0.2\text{-}0.3$ eV



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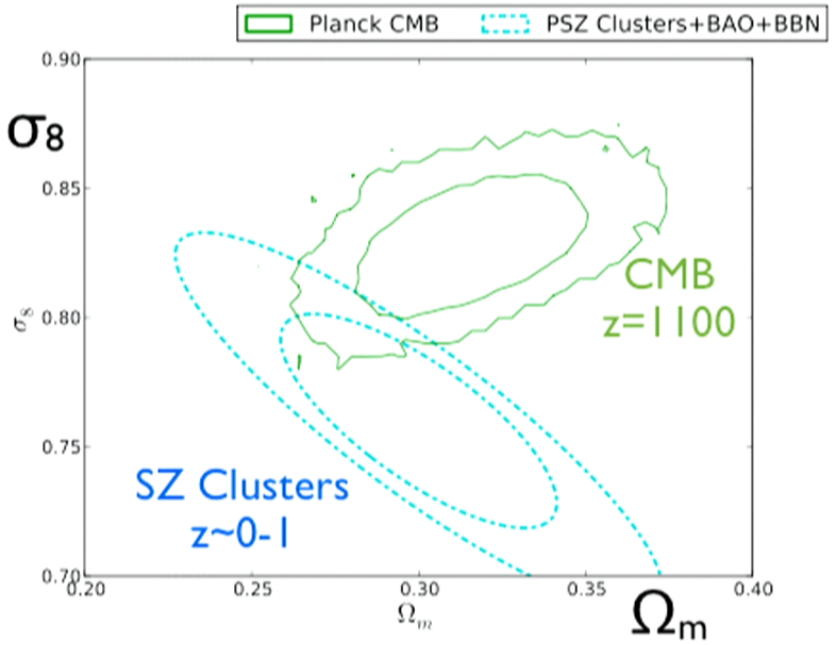

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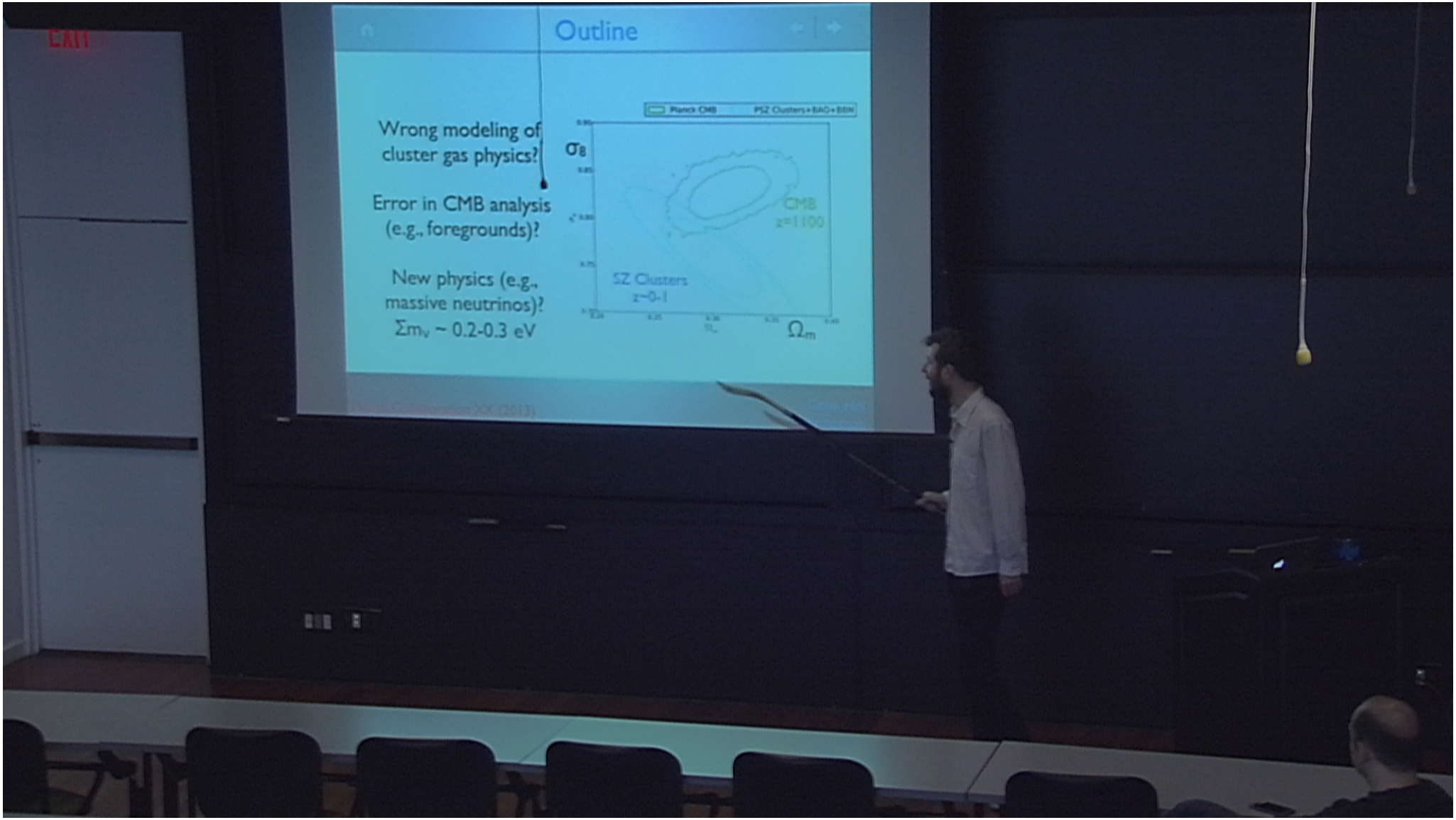
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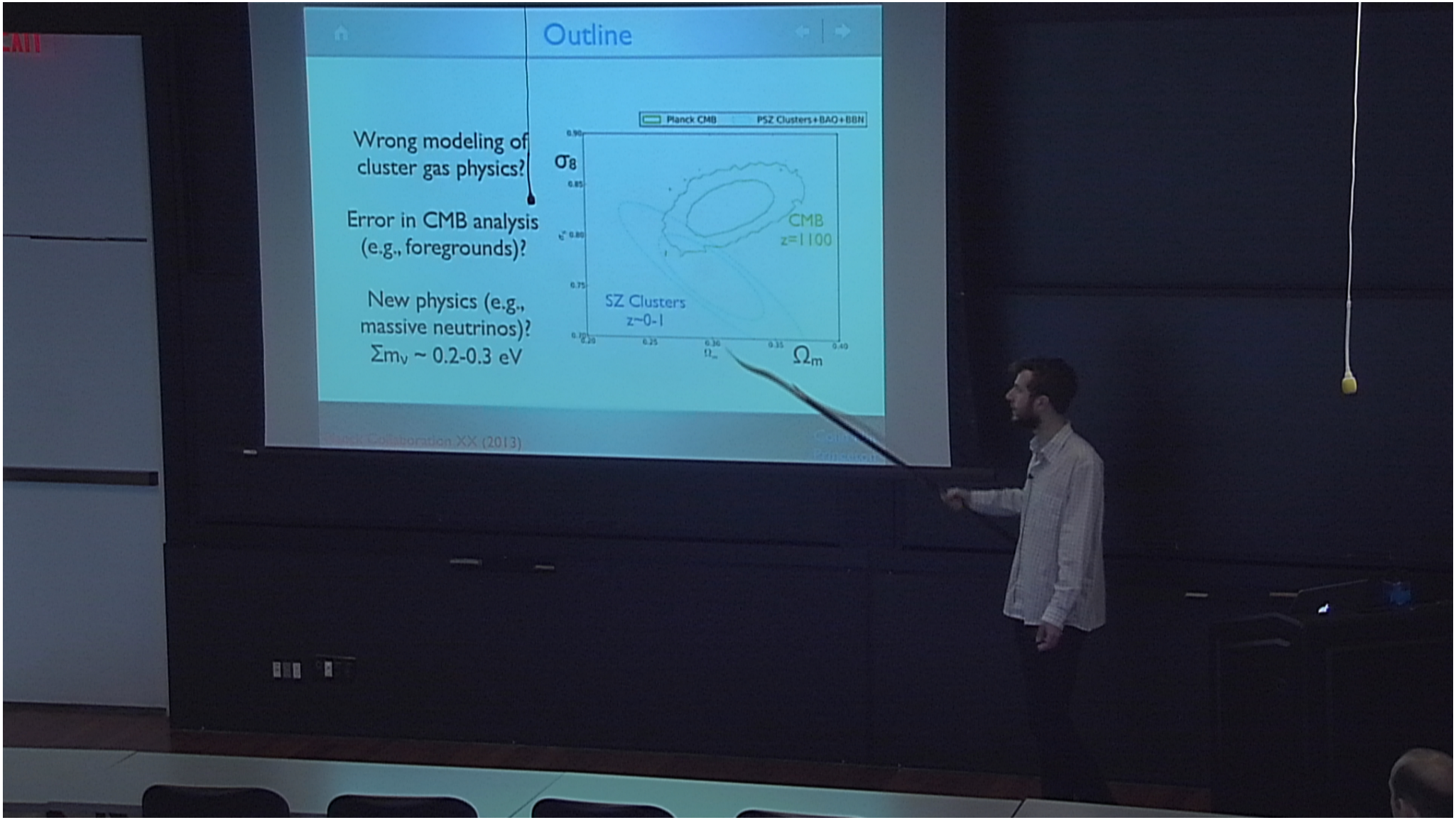
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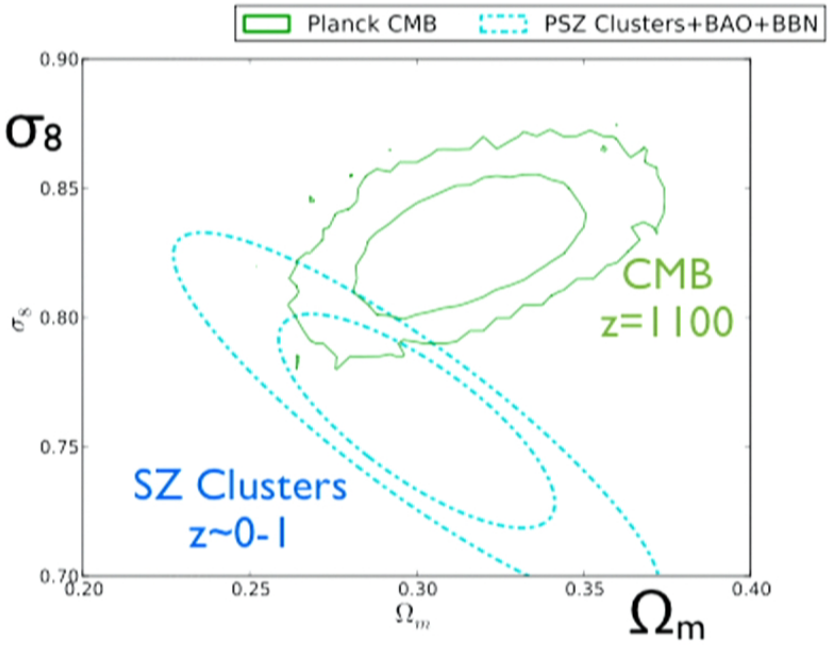

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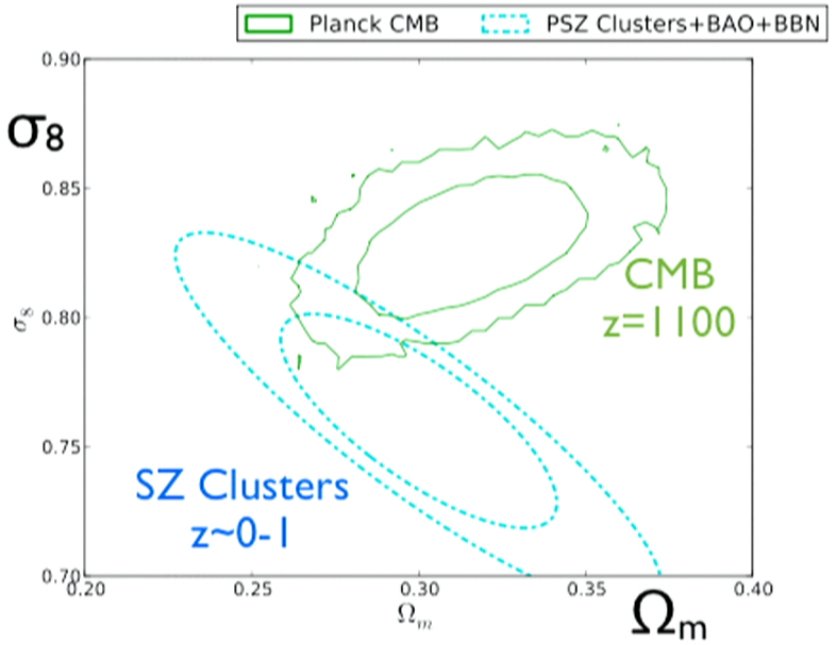

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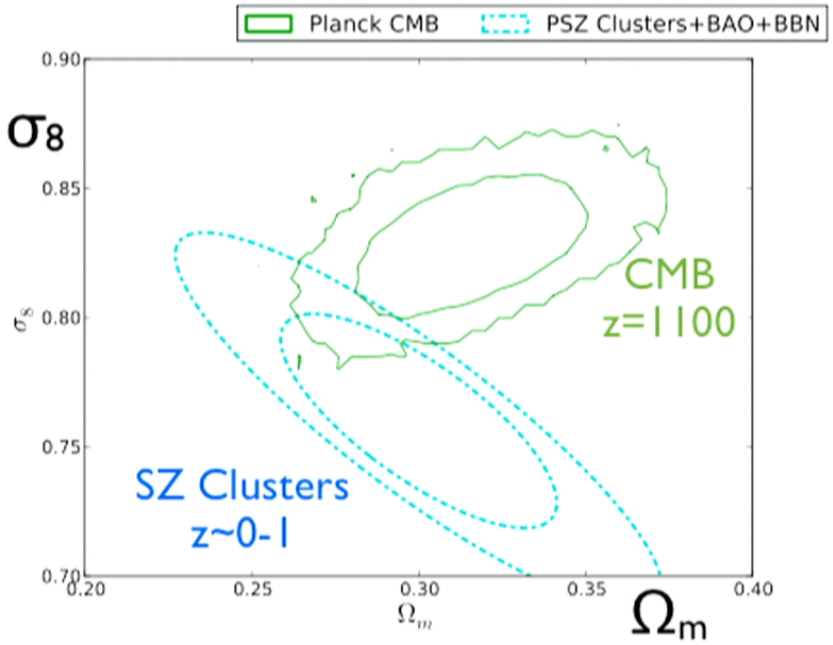
Outline

The Sunyaev-Zel'dovich (SZ) Effect

Planck:
- Thermal SZ Power Spectrum
- Thermal SZ x CMB Lensing

ACT:
- Thermal SZ 1-pt PDF



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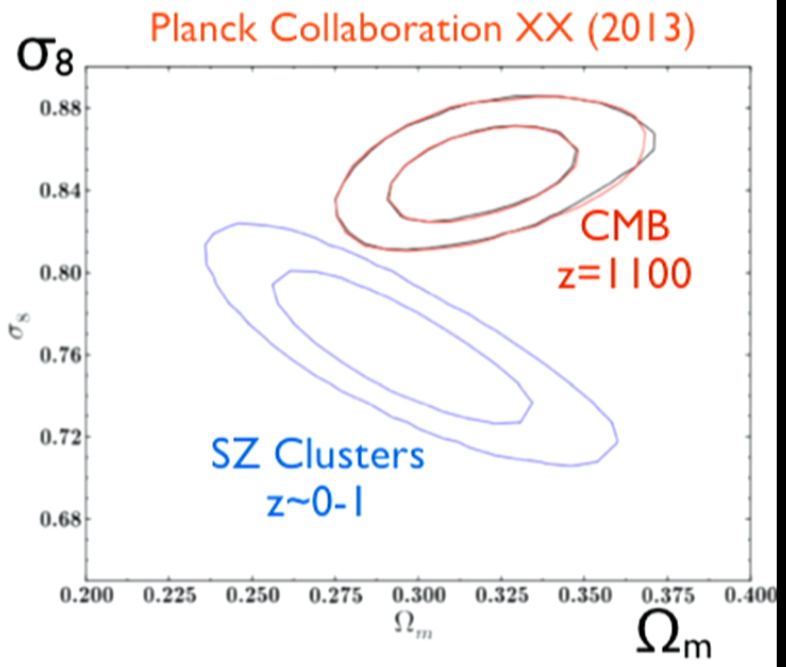
Outline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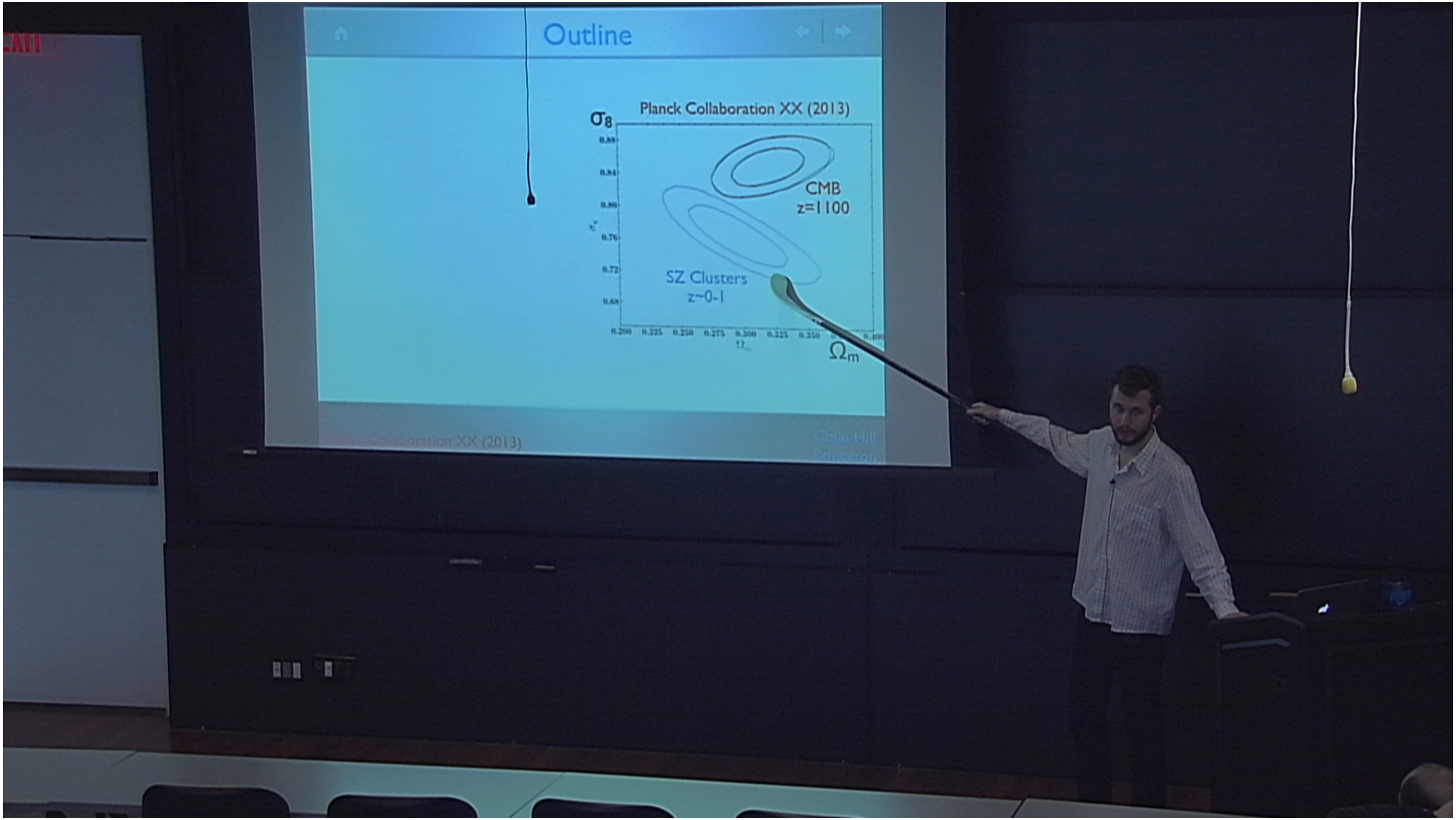
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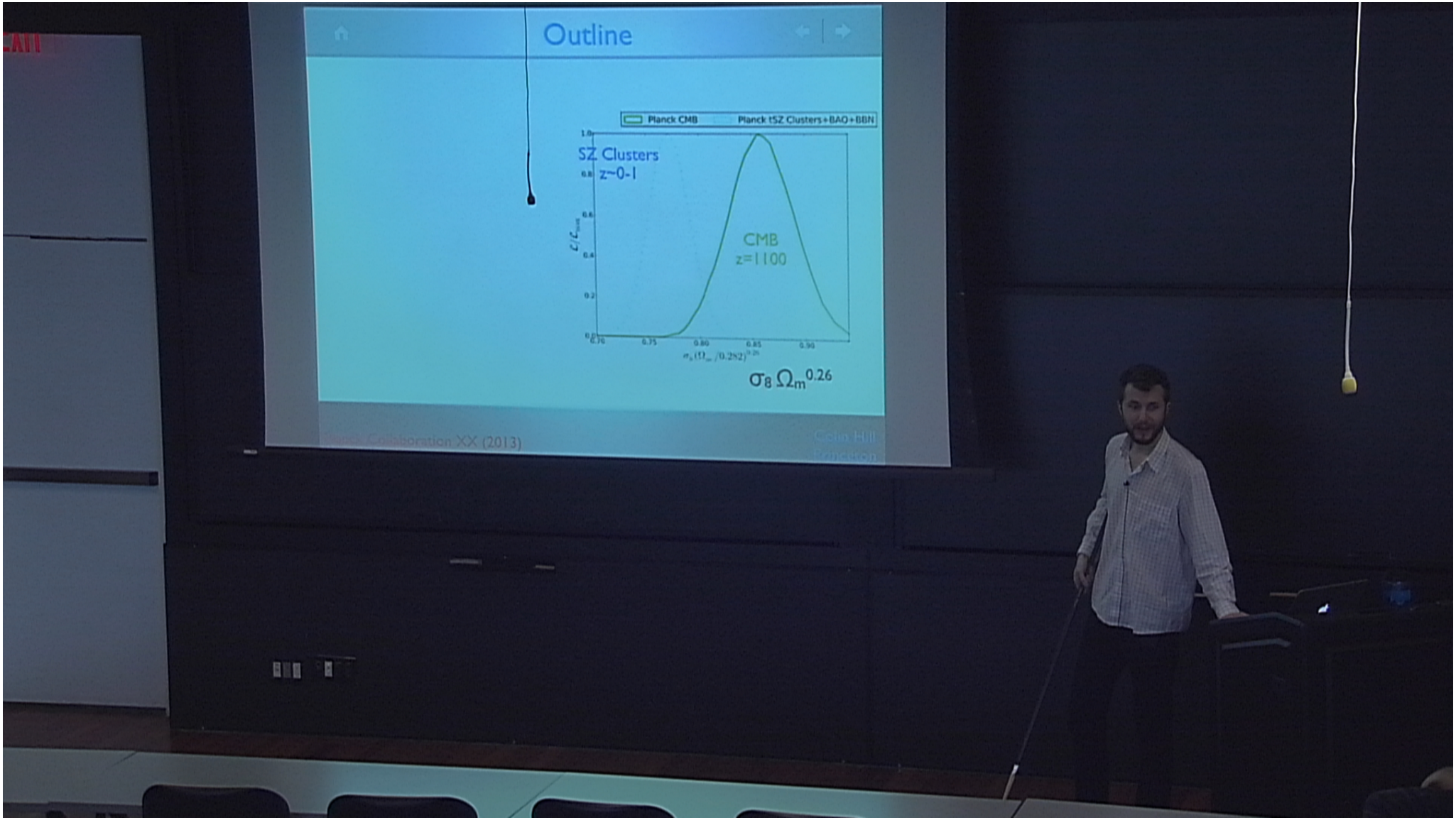
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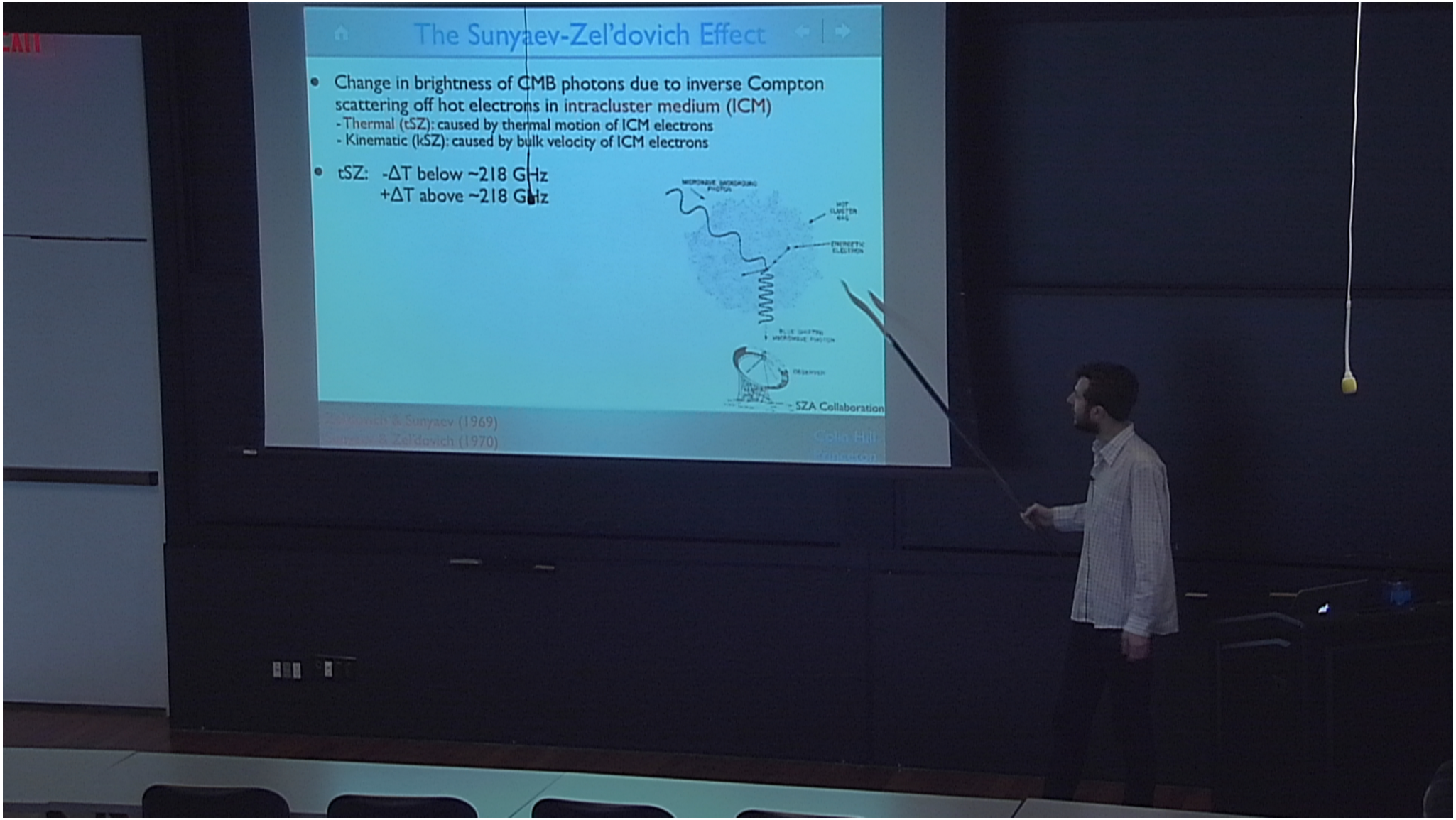
The Sunyaev-Zel'dovich Effect
Change in brightness of CMB photons due to inverse Compton scattering off hot electrons in intracluster medium (ICM)
- Thermal (tSZ): caused by thermal motion of ICM electrons
- Kinematic (kSZ): caused by bulk velocity of ICM electrons
tSZ: -ΔT below ~218 GHz
+ΔT above ~218 GHz
SZA Collaboration

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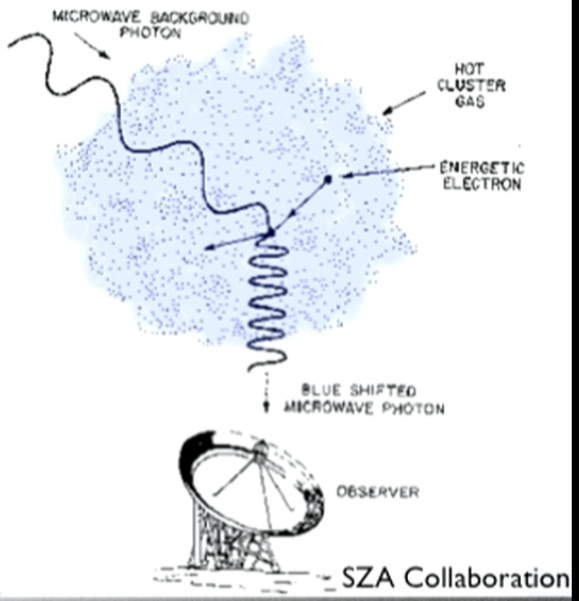

Zel'dovich & Sunyaev (1969)
Sunyaev & Zel'dovich (1970)

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Princeton

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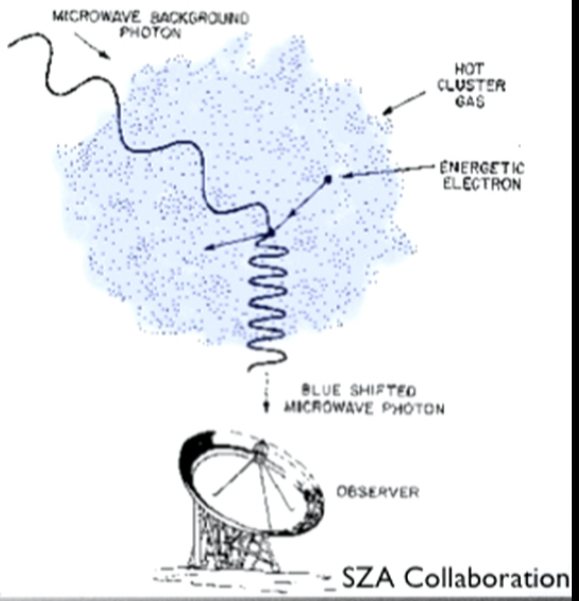

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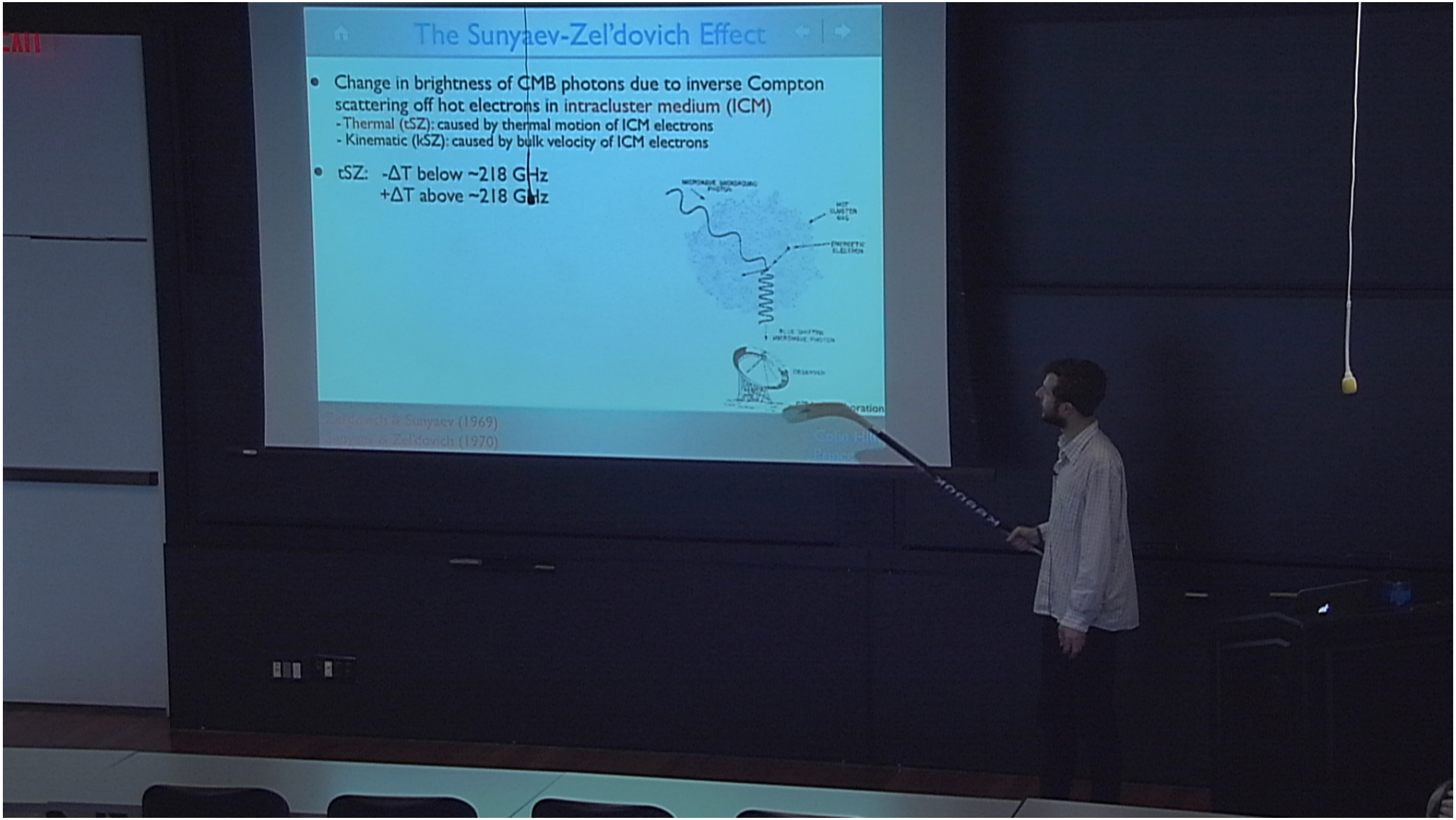
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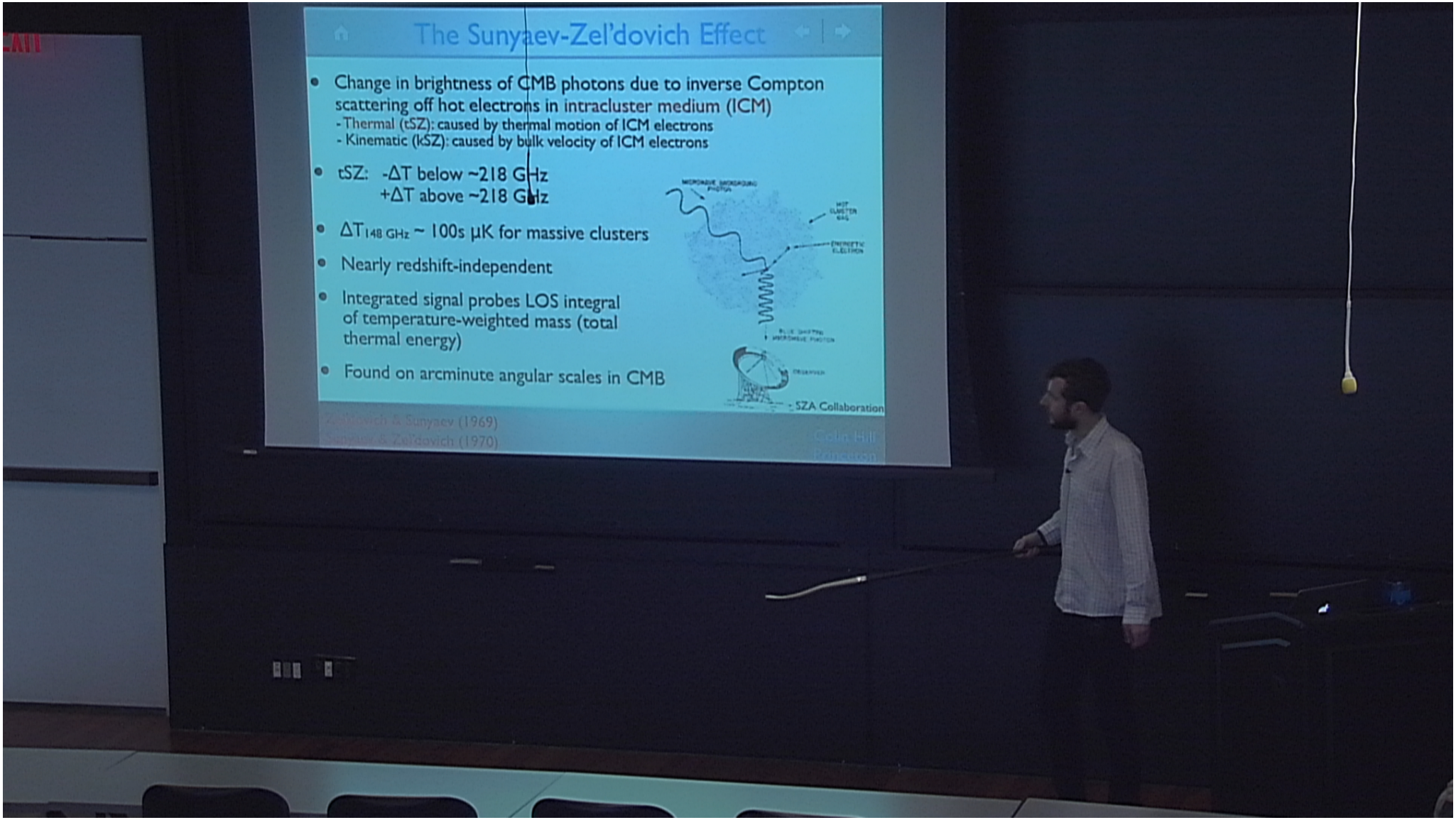
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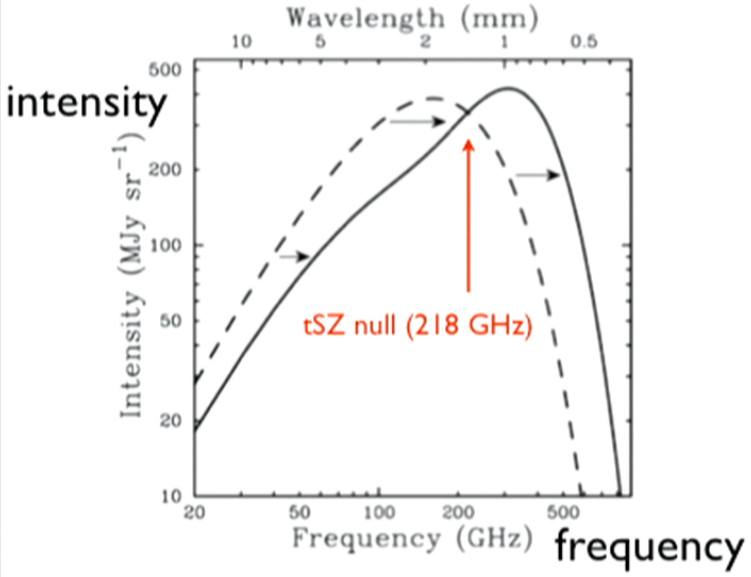
ΔT148 GHz ~ 100s μK for massive clusters
Nearly redshift-independent
Integrated signal probes LOS integral of temperature-weighted mass (total thermal energy)
Found on arcminute angular scales in CMB
- SZA Collaboration

The Sunyaev-Zel'dovich Effect



Unique Spectral Signature

Carlstrom et al. (2002)

Colin Hill
Princeton


The Sunyaev-Zel'dovich Effect
Wavelength (mm)
intensity
tSZ null (218 GHz)
Frequency (GHz)
frequency
Unique Spectral Signature
intensity change
Kinetic SZE
Thermal SZE
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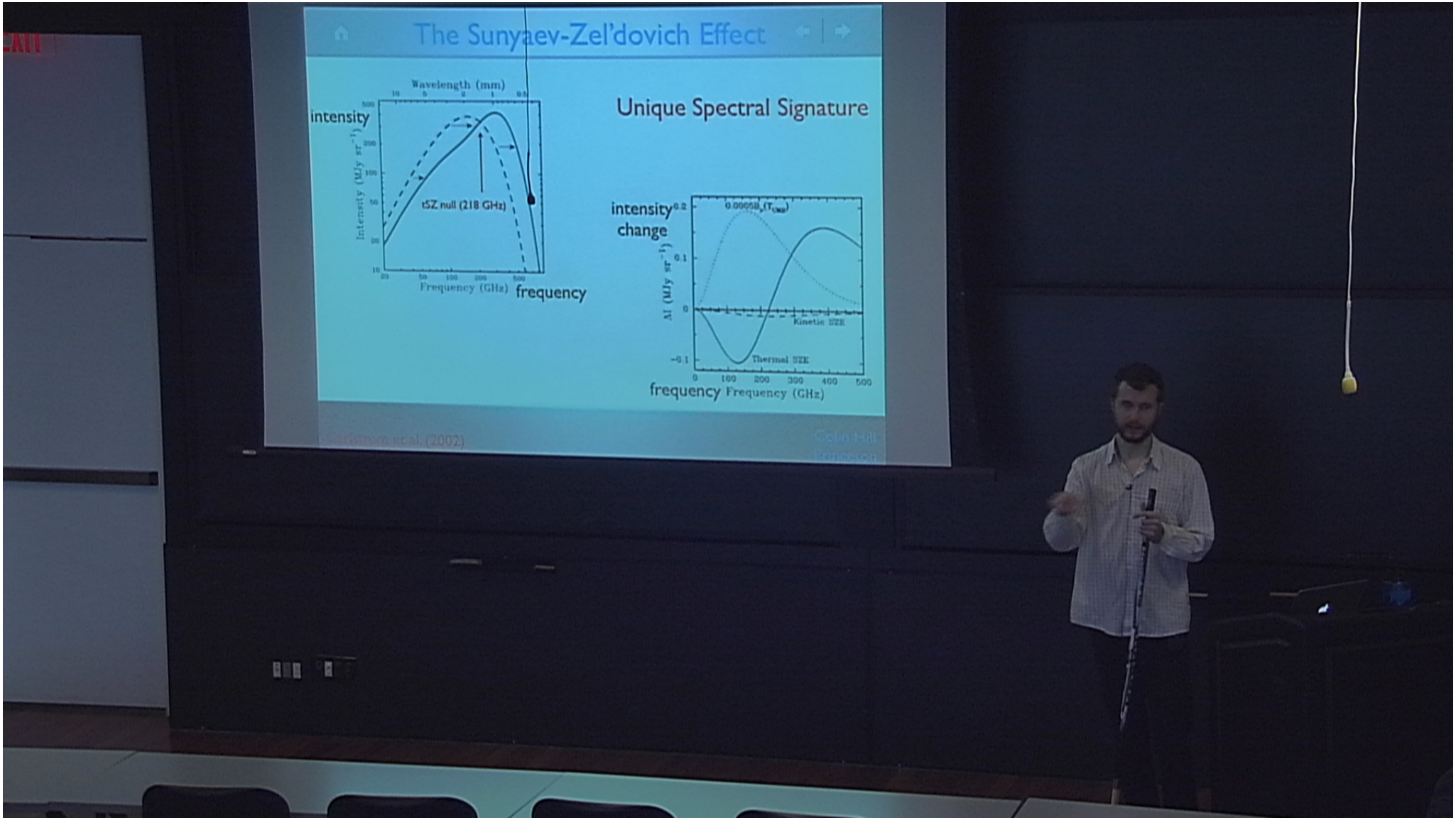
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The Sunyaev-Zel'dovich Effect

- Thermal SZ temperature shift at position $\vec{\theta}$ on the sky with respect to the center of a cluster of mass *M* at redshift *z*:

"Compton-y"

$$\frac{\Delta T(\vec{\theta}; M, z)}{T_{\rm CMB}} = g(\nu) y(\vec{\theta}; M, z)$$

tSZ spectral function

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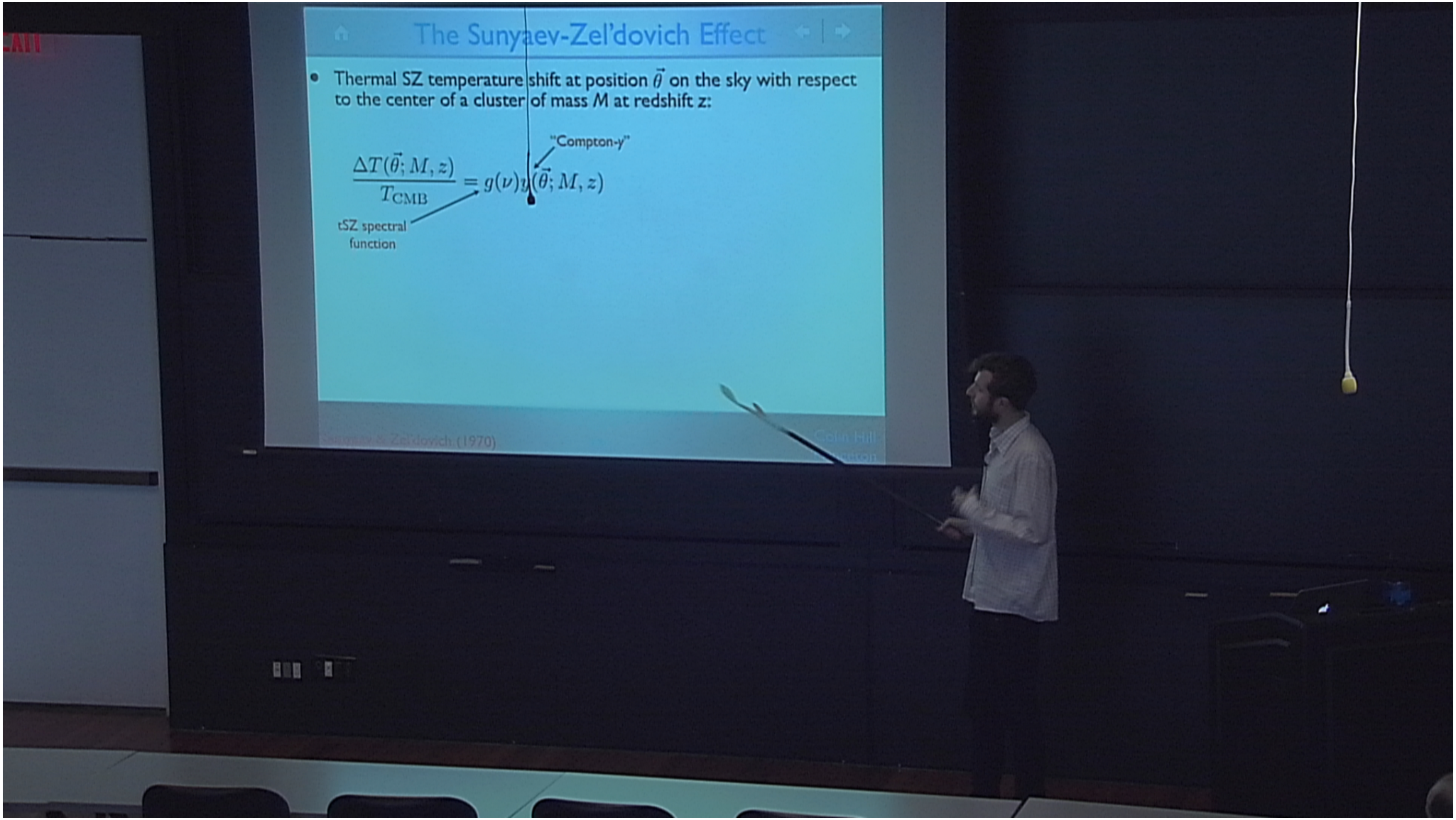
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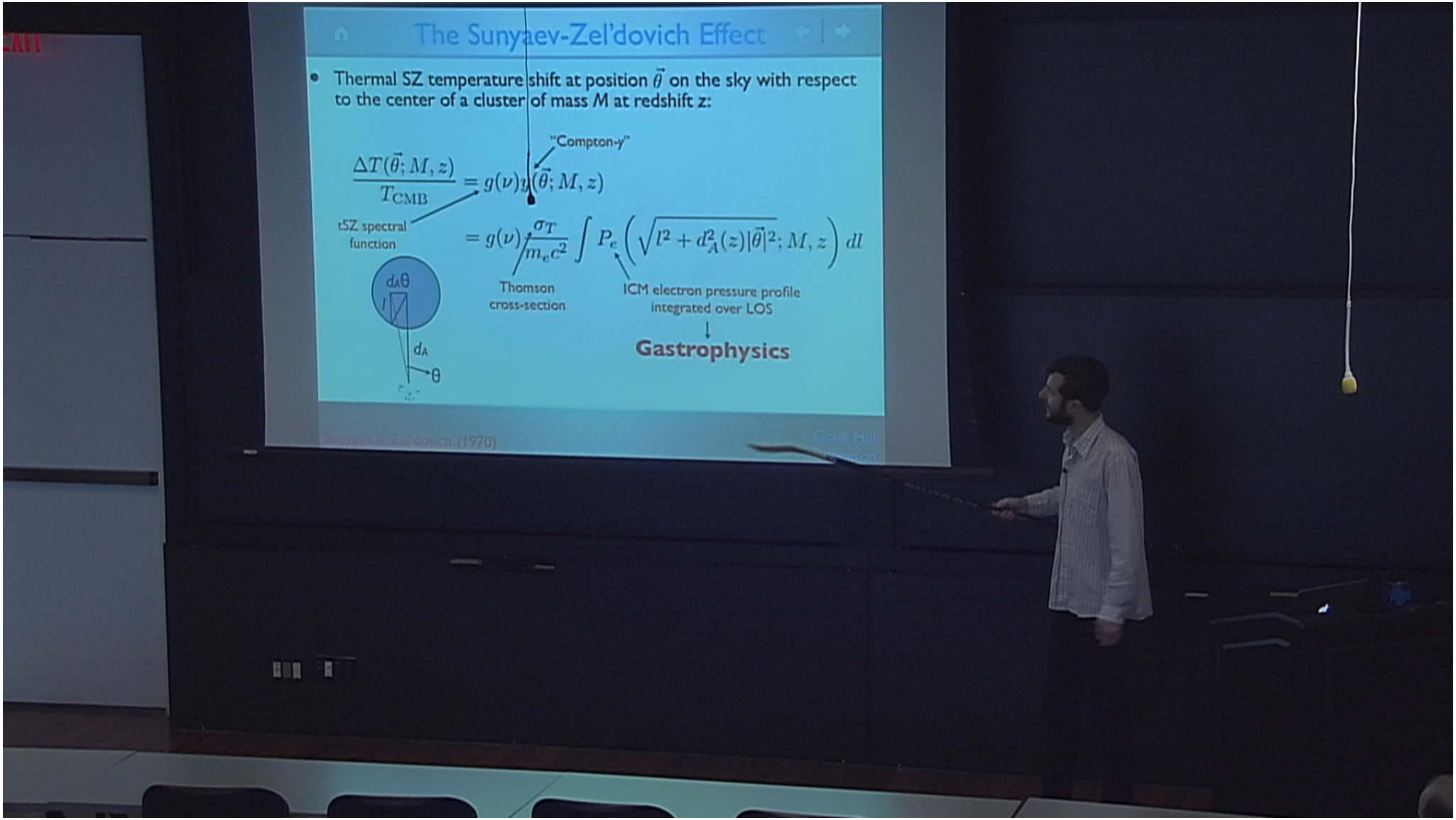
tSZ spectral function
Sunyaev & Zel'dovich (1970)
Colin Hill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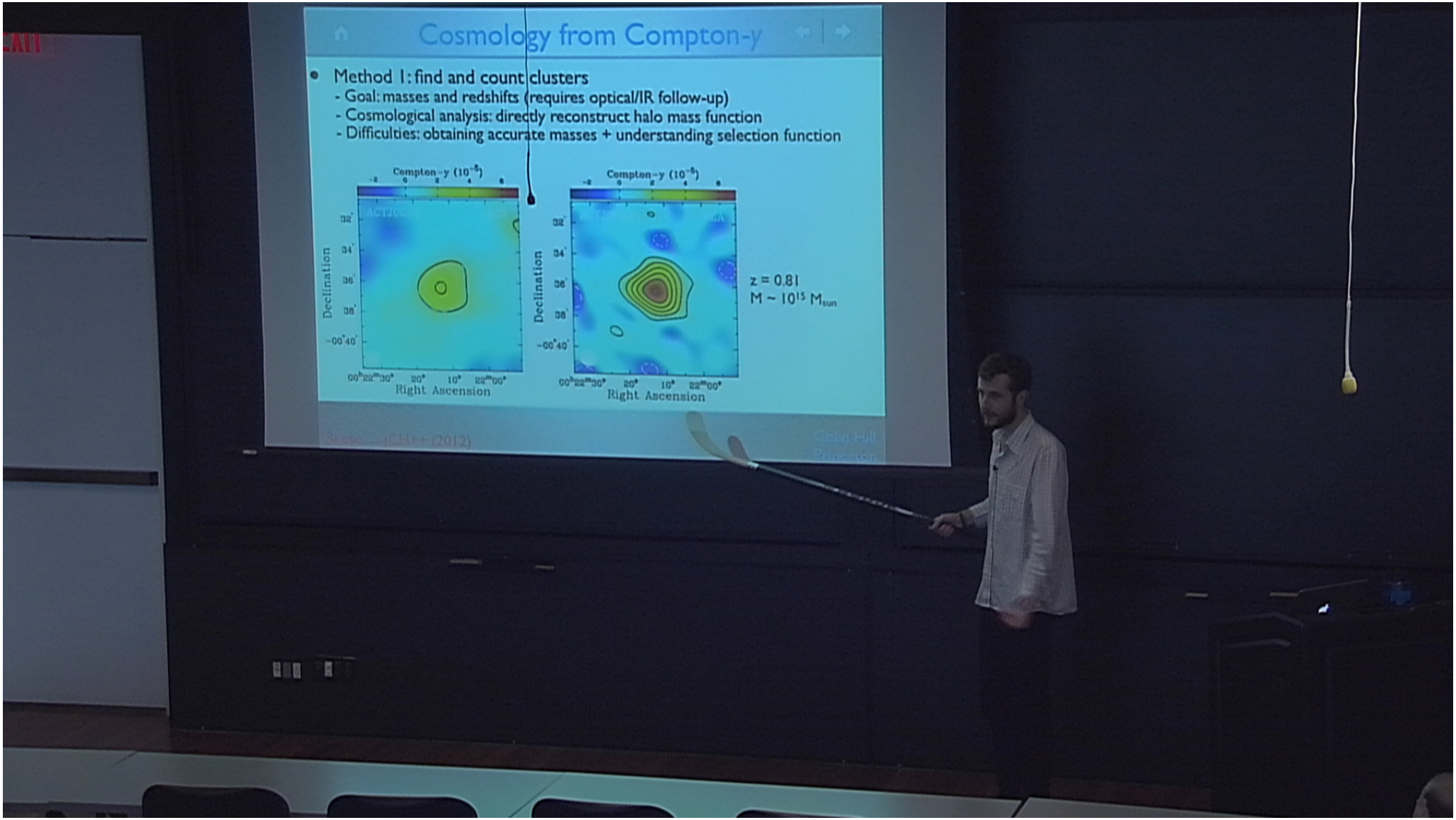
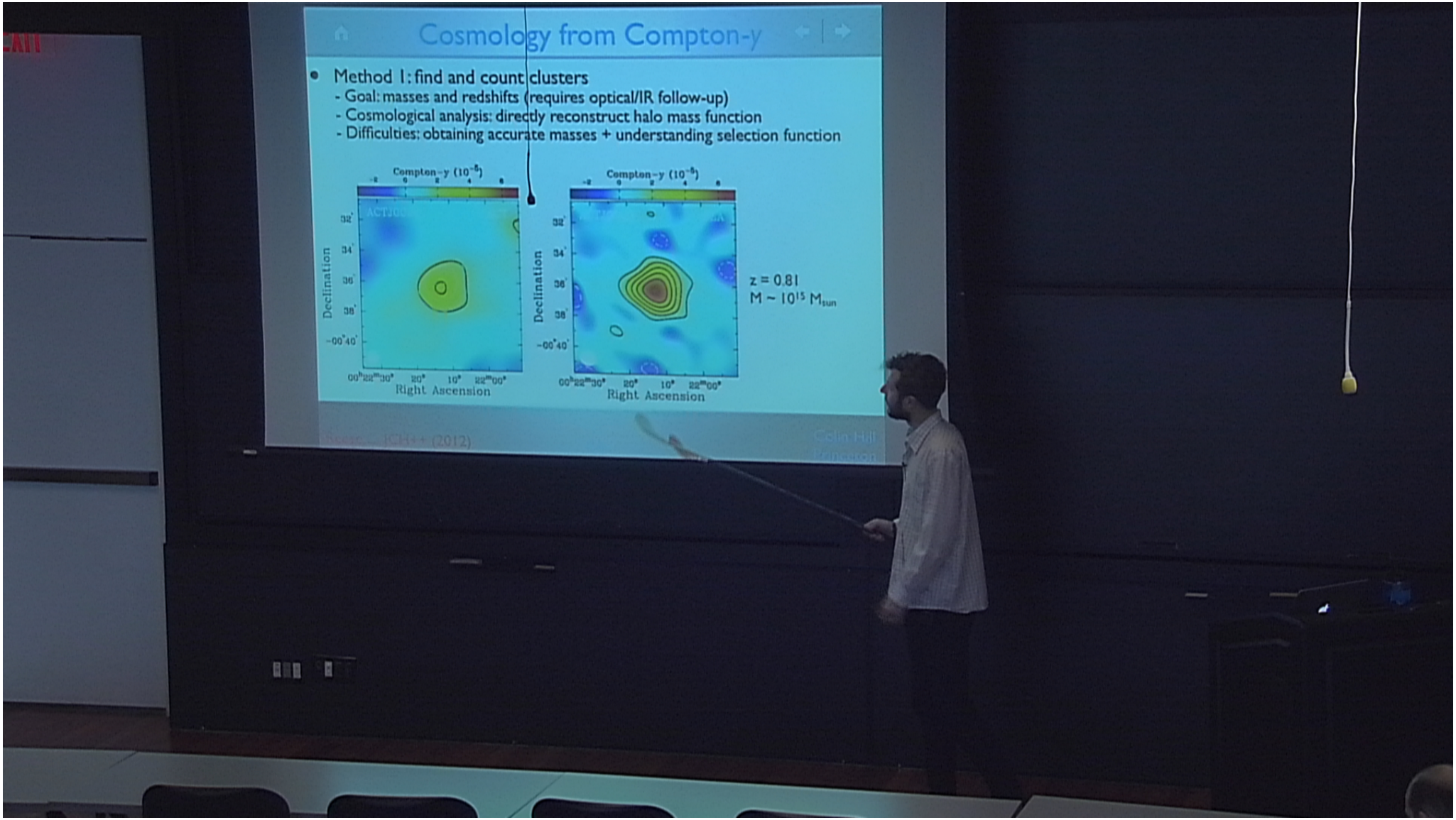
tSZ spectral function
$= g(\nu) \frac{\sigma_T}{m_e c^2} \int P_e \left(\sqrt{l^2 + d_A^2(z) |\vec{\theta}|^2}; M, z \right) dl$
Thomson cross-section
ICM electron pressure profile integrated over LOS
Gastrophysics
$d_A\theta$
l
d_A
θ
Sunyaev-Zel'dovich (1970)
Colin Hill


Cosmology from Compton-y
Method 1: find and count clusters
- Goal: masses and redshifts (requires optical/IR follow-up)
- Cosmological analysis: directly reconstruct halo mass function
- Difficulties: obtaining accurate masses + understanding selection function
Compton-y (10^{-5})
Declination
Right Ascension
z = 0.81
M ~ 10^{15} M_{sun}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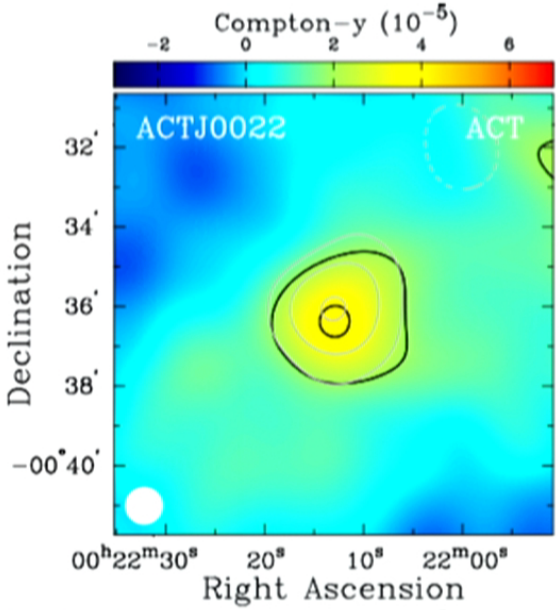

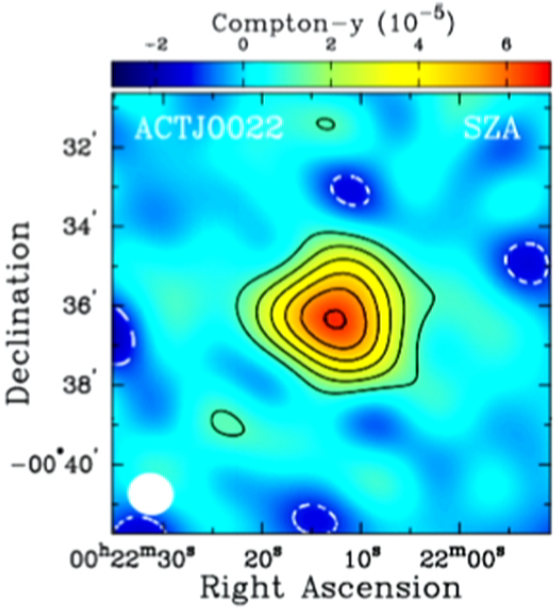

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Reese, ..., JCH++ (2012)

Colin Hill
Princeton

Cosmology from Compton-y

- Method II: statistical approaches (power spectrum, bispectrum, ...)
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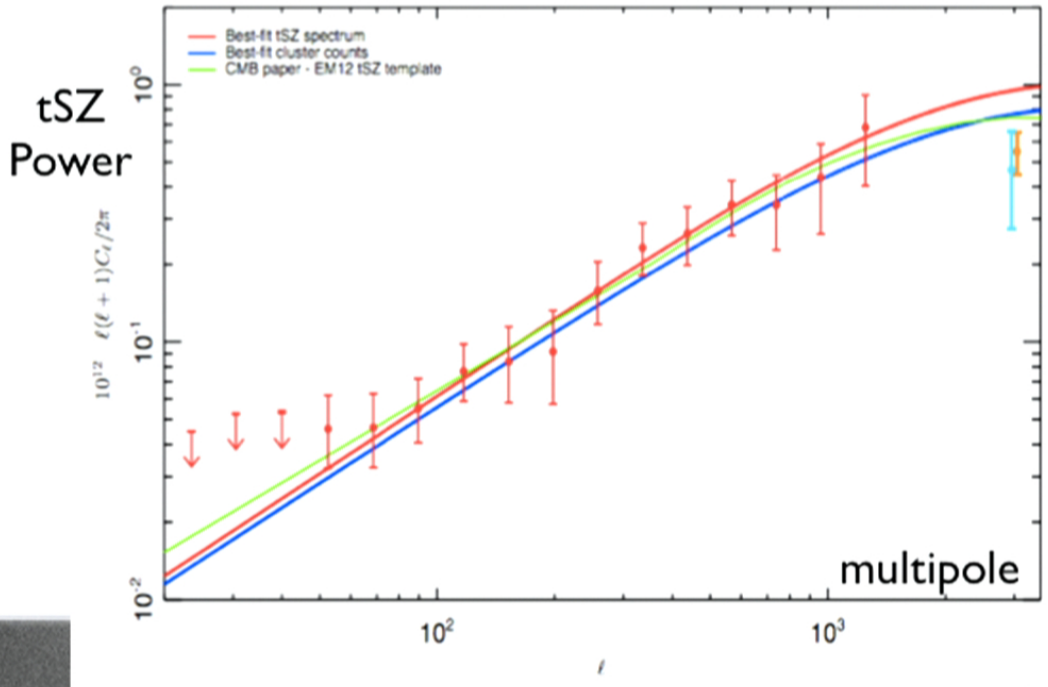

Planck Collaboration XXI (2013)

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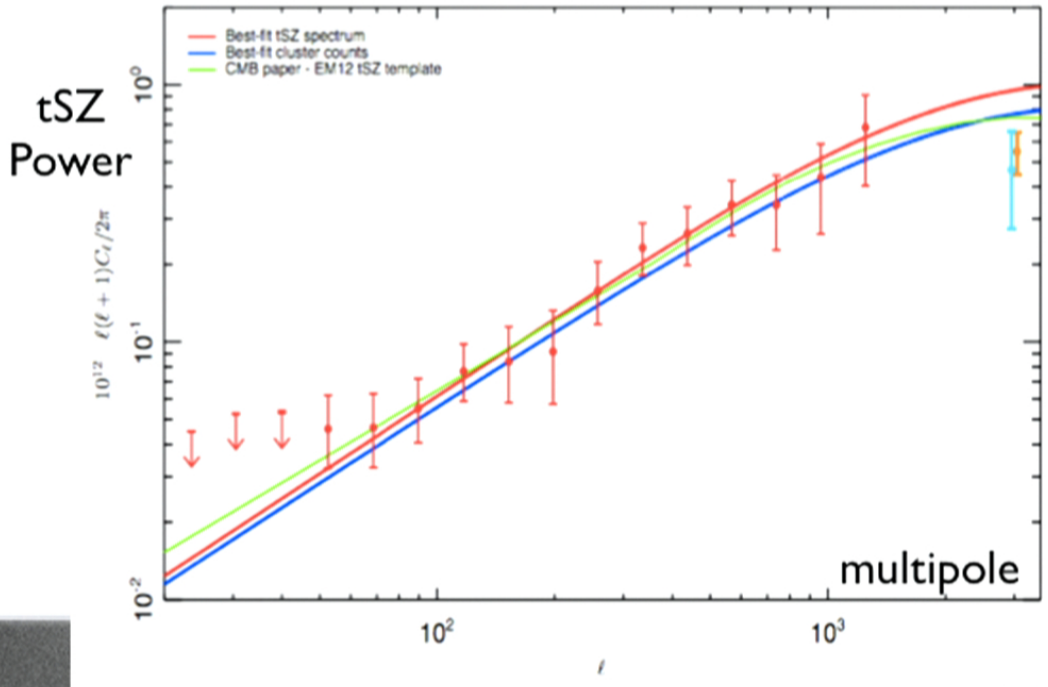

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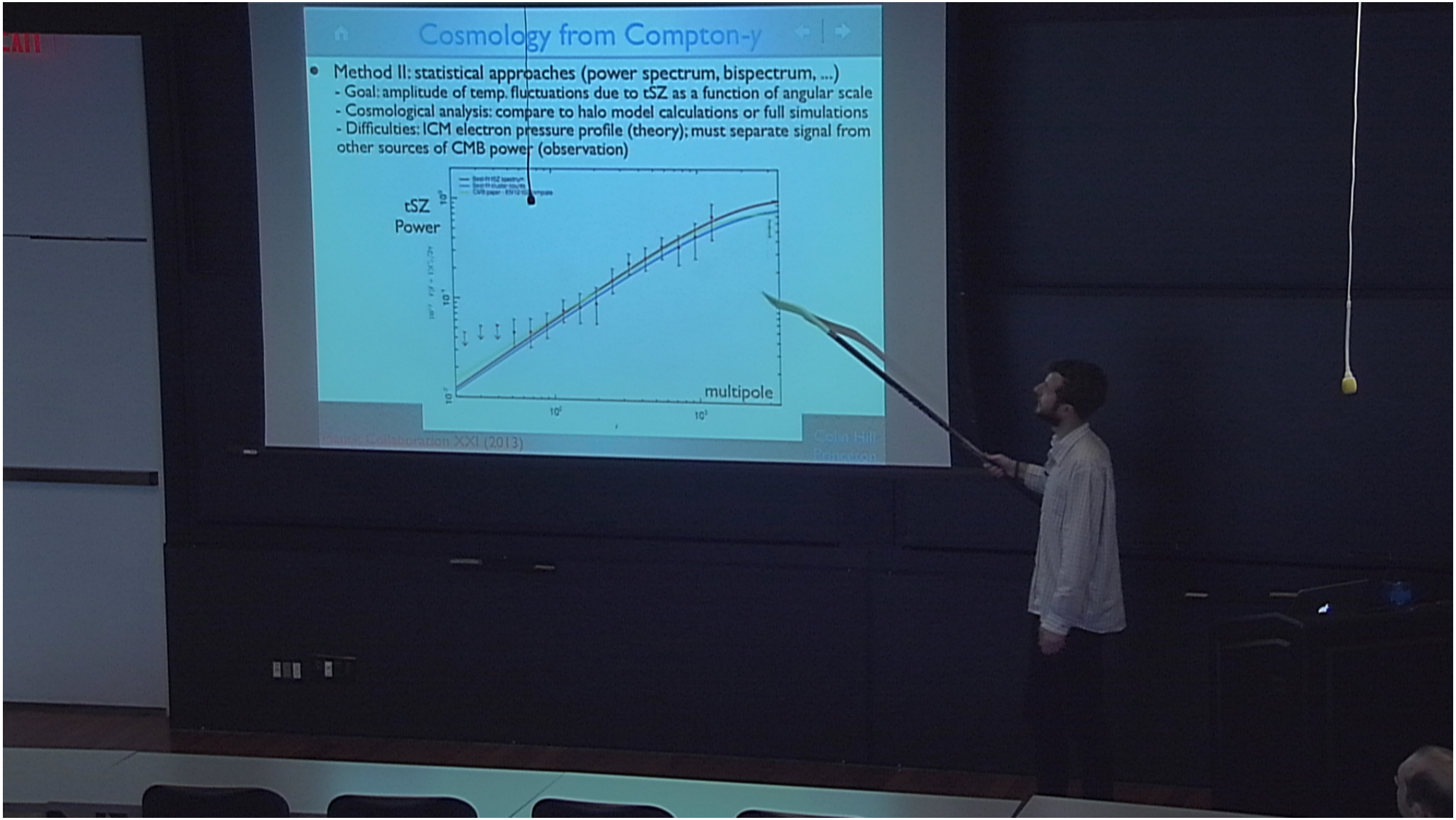
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tSZ Power
multipole
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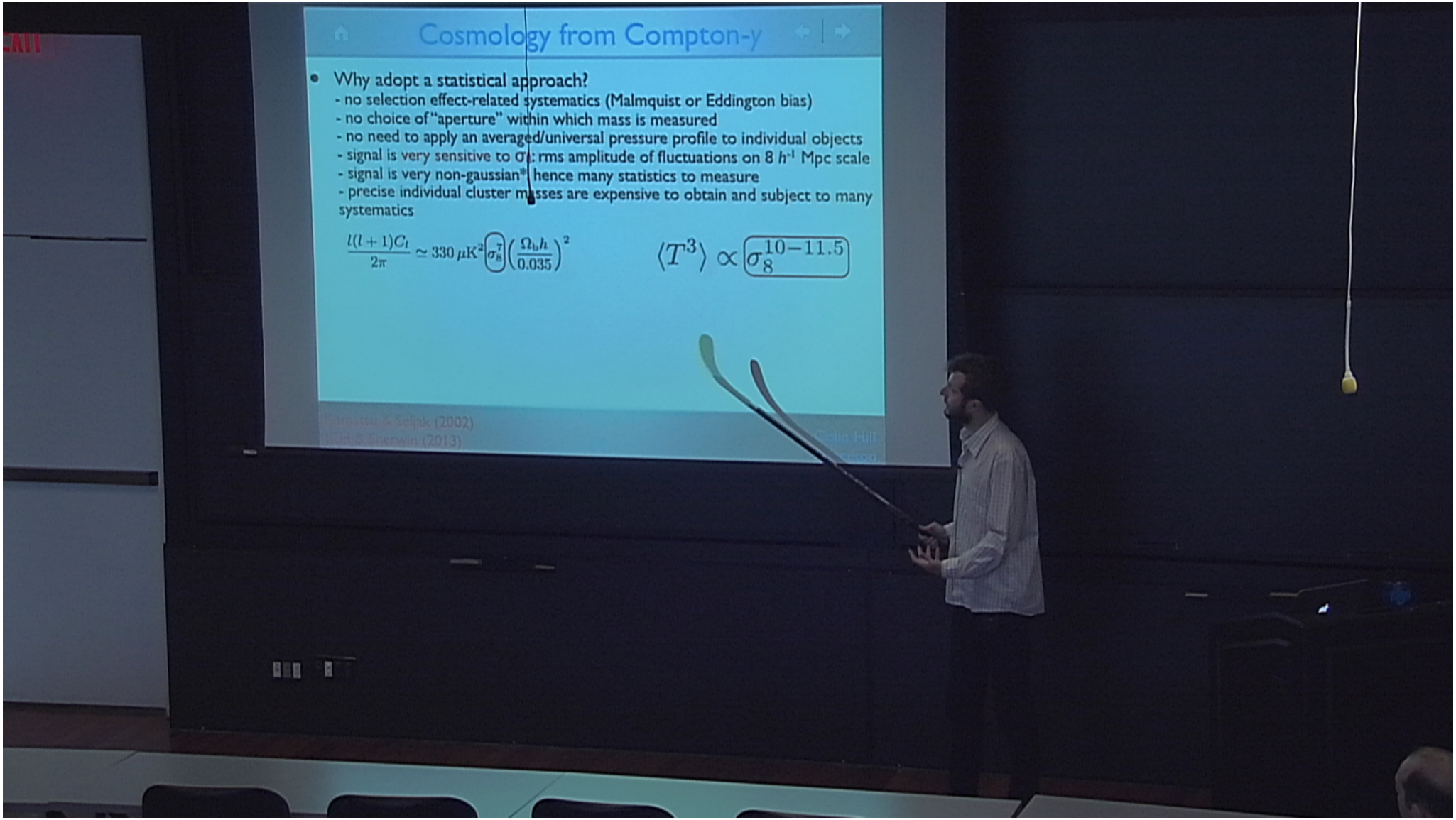
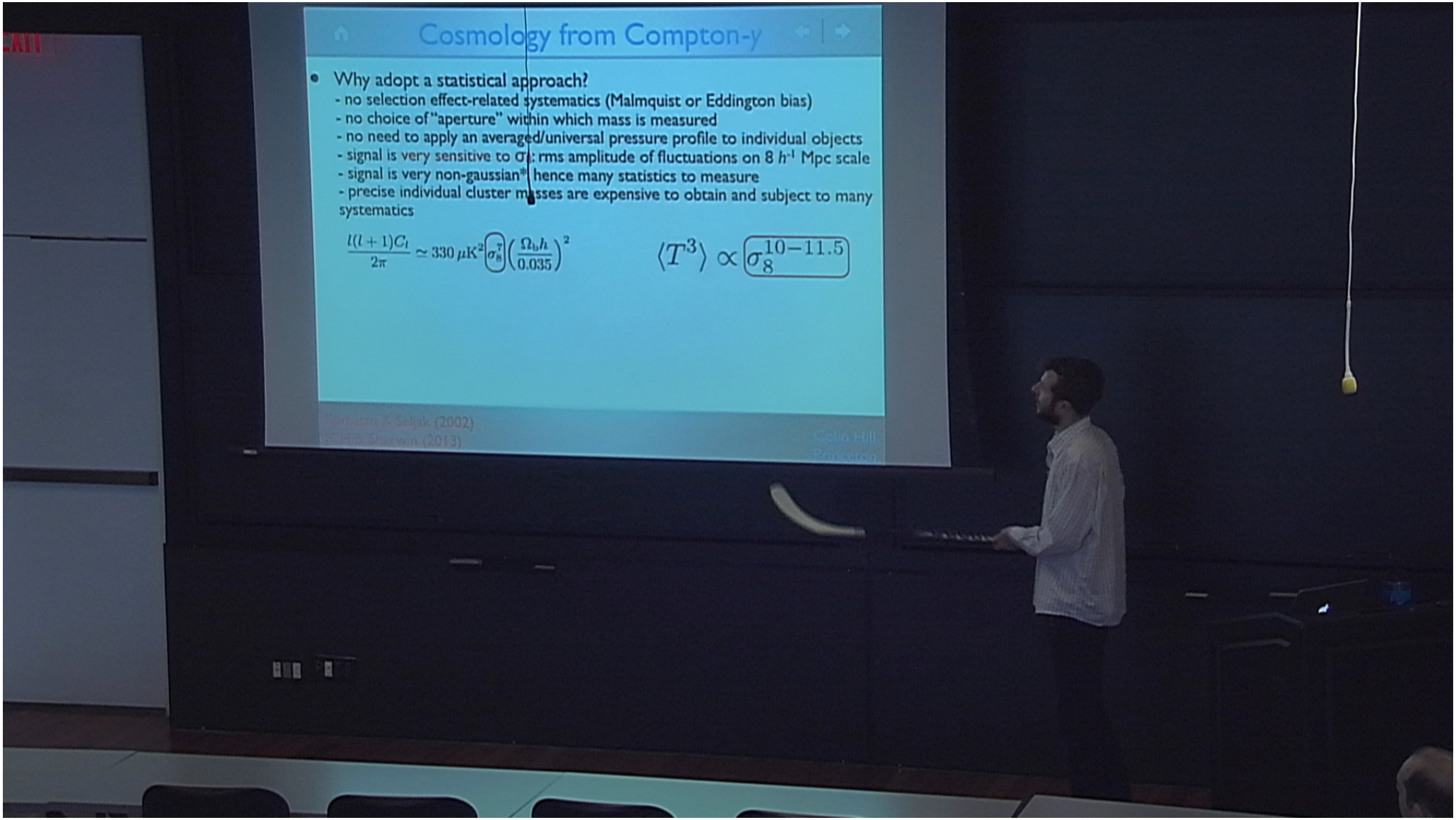

Cosmology from Compton-y
Why adopt a statistical approach?
- no selection effect-related systematics (Malmquist or Eddington bias)
- no choice of "aperture" within which mass is measured
- no need to apply an averaged/universal pressure profile to individual objects
- signal is very sensitive to σ8: rms amplitude of fluctuations on 8 h-1 Mpc scale
- signal is very non-gaussian* hence many statistics to measure
- precise individual cluster masses are expensive to obtain and subject to many systematics
$\frac{l(l+1)C_l}{2\pi} \simeq 330\,\mu\mathrm{K}^2 \sigma_8^7 \left(\frac{\Omega_b h}{0.035}\right)^2$
$\langle T^3 \rangle \propto \sigma_8^{10-11.5}$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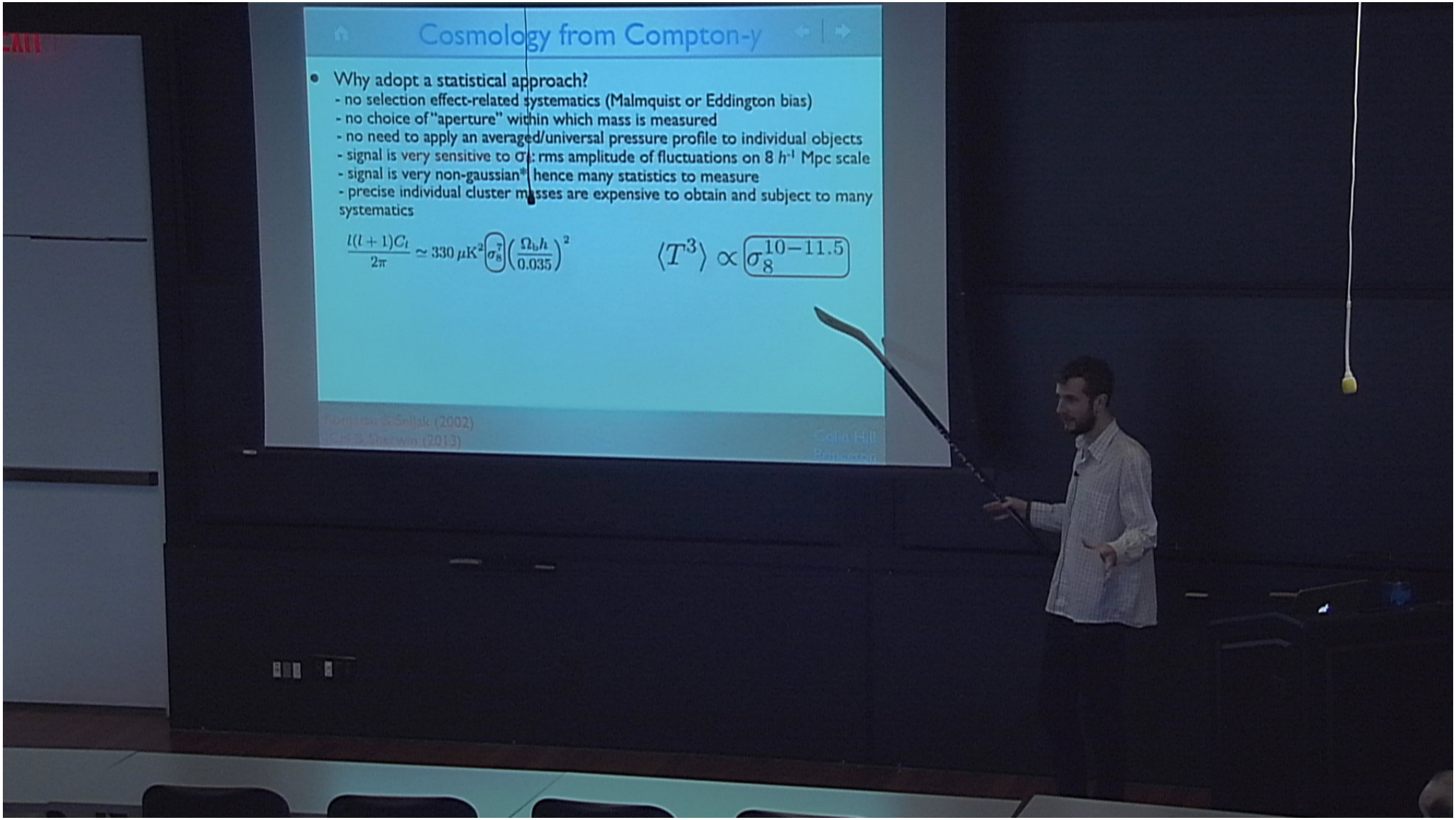
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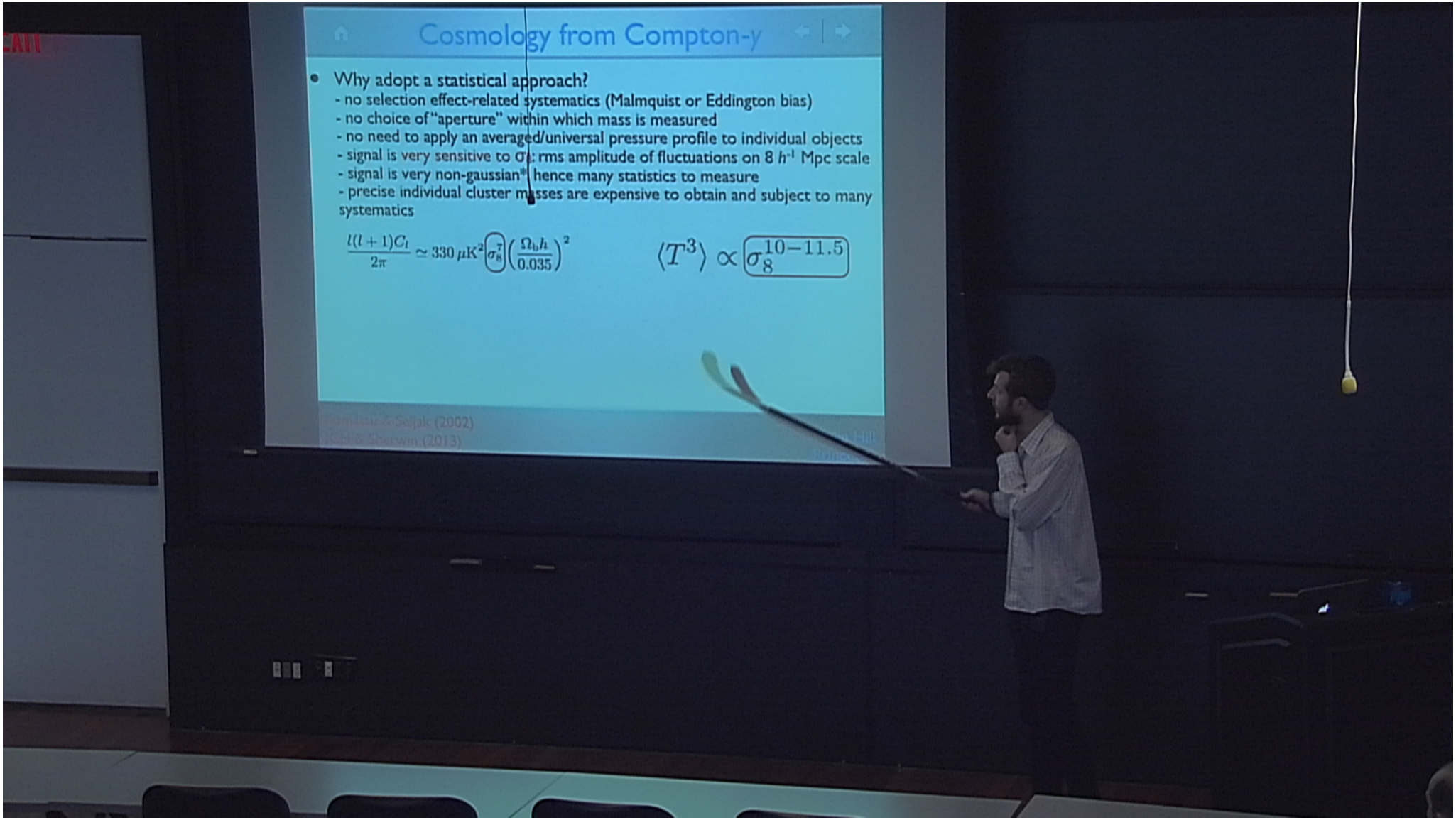
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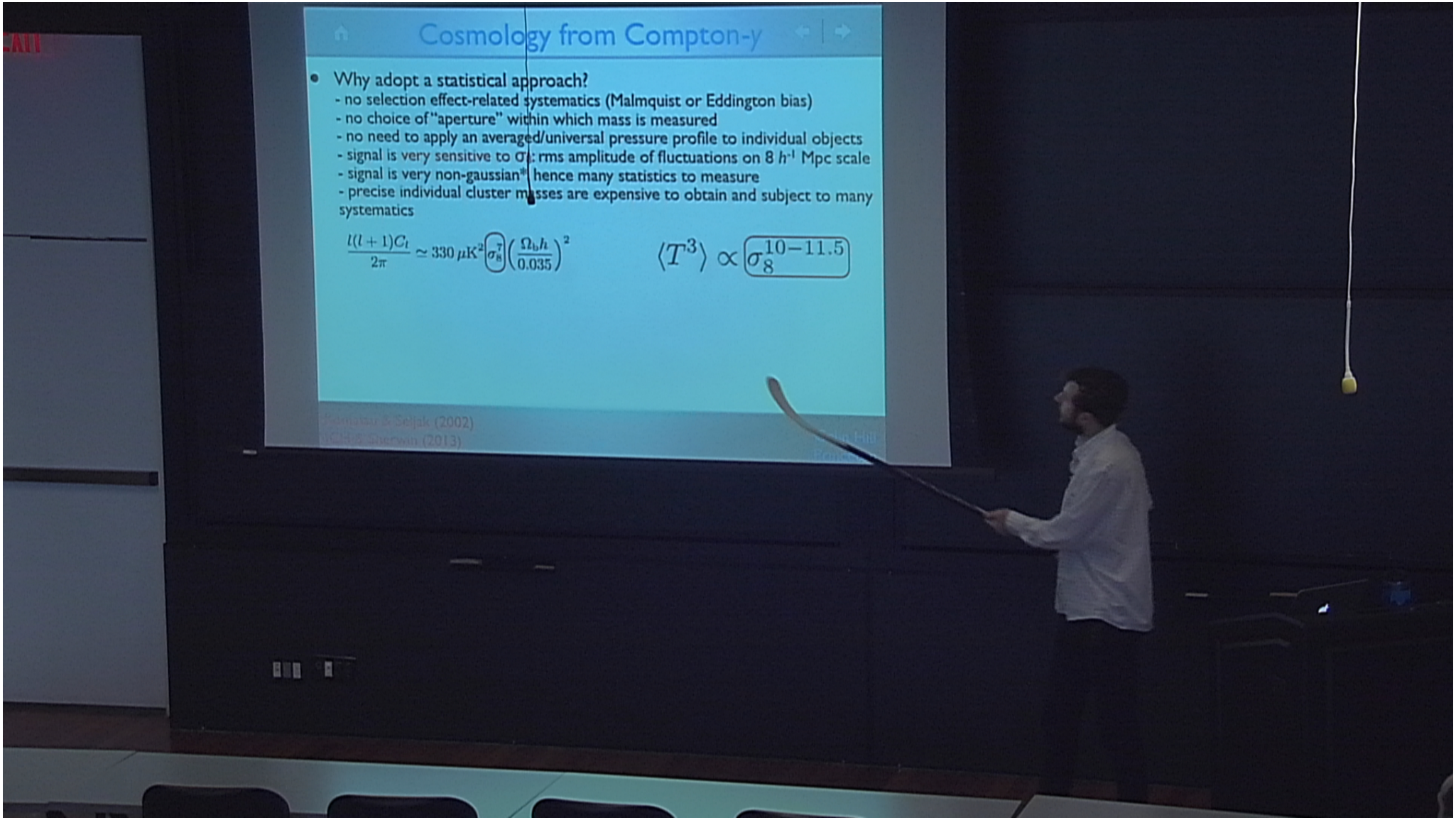
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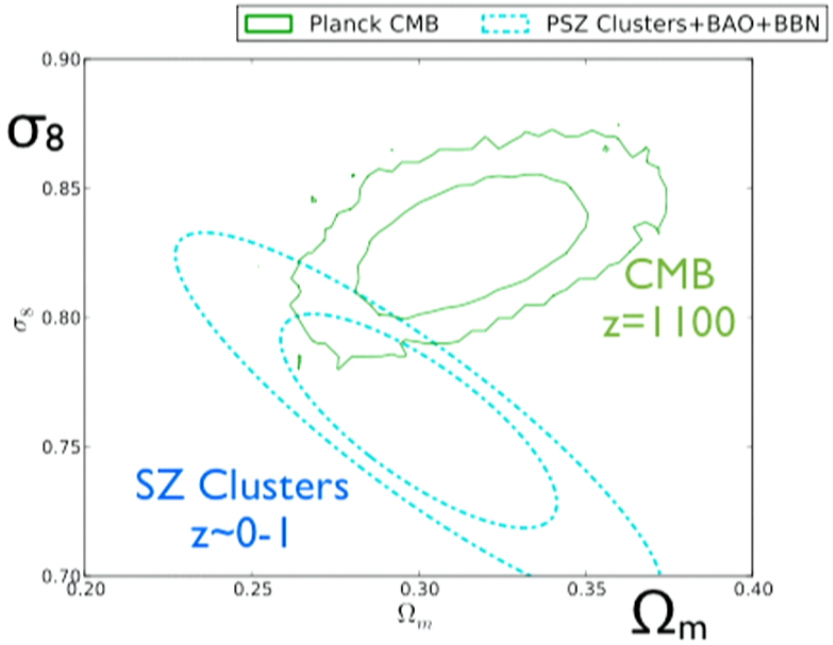
Planck: Thermal SZ Power Spectrum



Planck Collaboration XX (2013)

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Thermal SZ Power Spectrum

- First: compute the Fourier transform of the *y*-profile of each cluster

Gastrophysics

$$y(\vec{\theta}; M, z) \xrightarrow{\text{F.T.}} \tilde{y}_\ell(M, z)$$

- Then: add up the contributions from all clusters in the universe

$$C_\ell^{y,1h} = \int dz \frac{d^2V}{dz d\Omega} \int dM \frac{dn}{dM} |\tilde{y}_\ell(M, z)|^2$$

("one-halo" term)

comoving volume per steradian

halo mass function

Cosmology

("two-halo" term also included in results)

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ICM Gastrophysics

- ICM to lowest order: hydrostatic equilbrium between gas pressure and DM potential; gas traces DM; polytropic EOS (Komatsu-Seljak)

$$\frac{dP_{gas}(r)}{dr} = -\rho_{gas}(r)\frac{d\Phi_{DM}(r)}{dr}$$

- Problems: central cooling catastrophe, non-convergent profile at edge

Komatsu & Seljak (2001,02)
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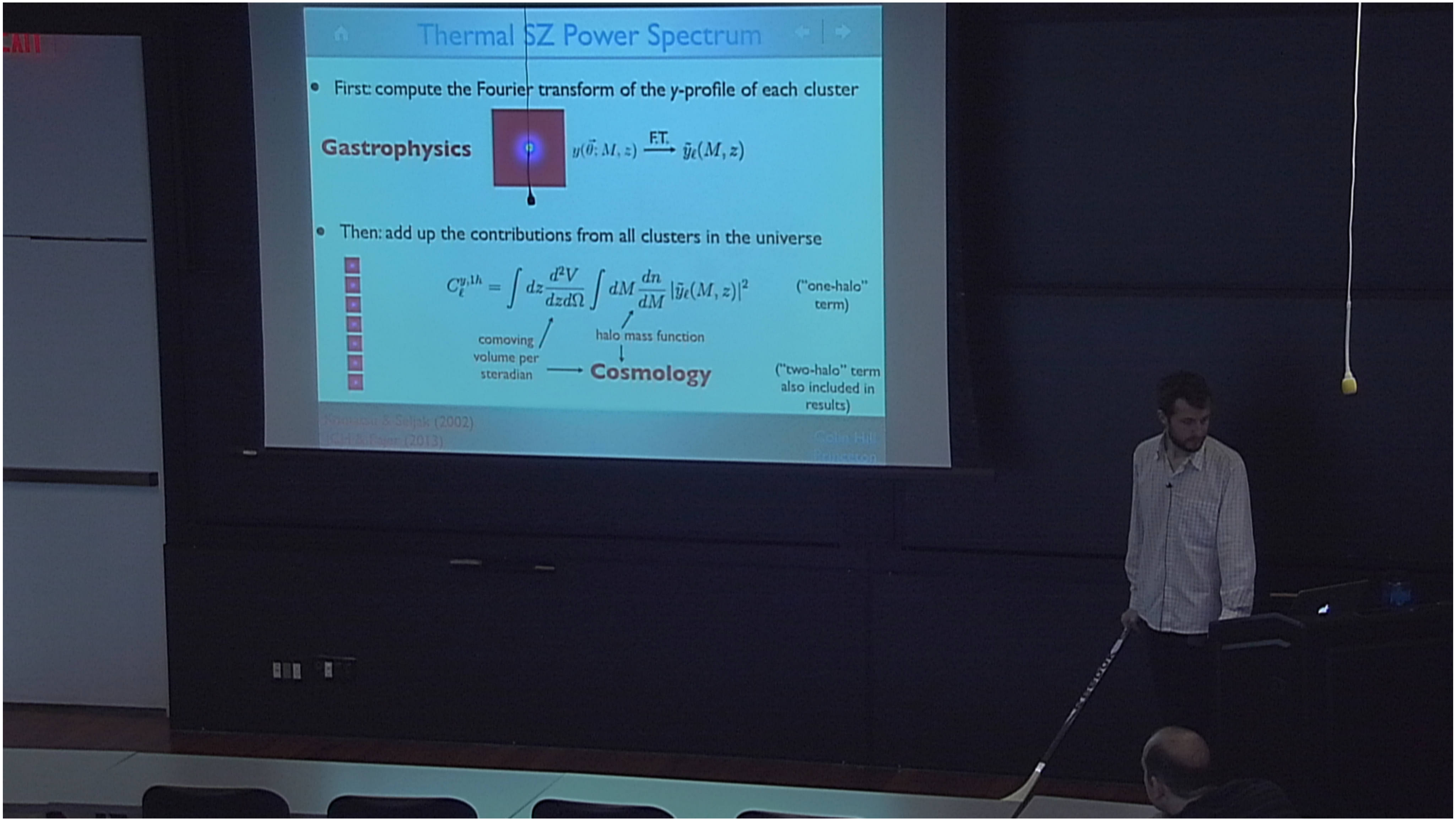

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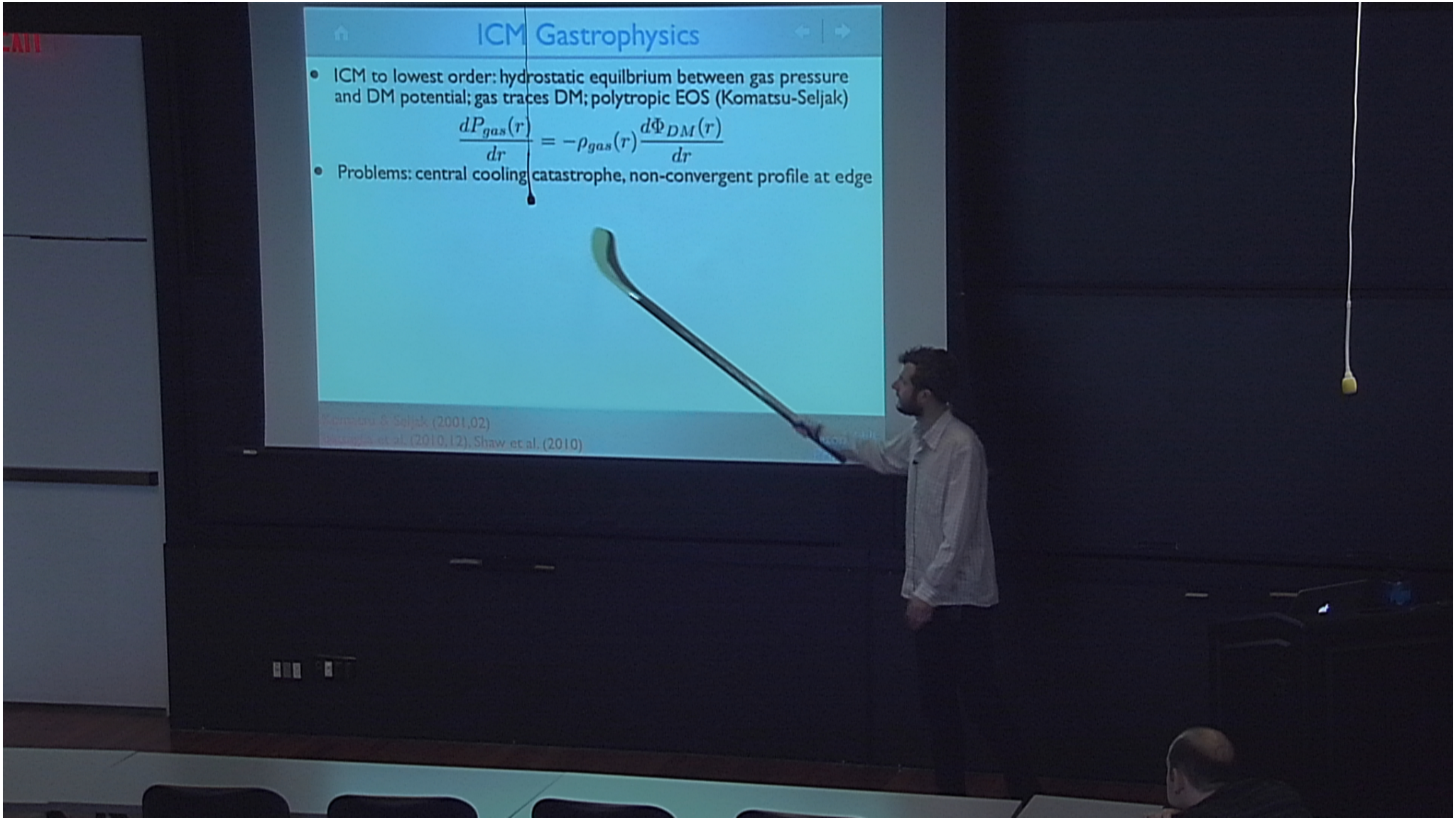
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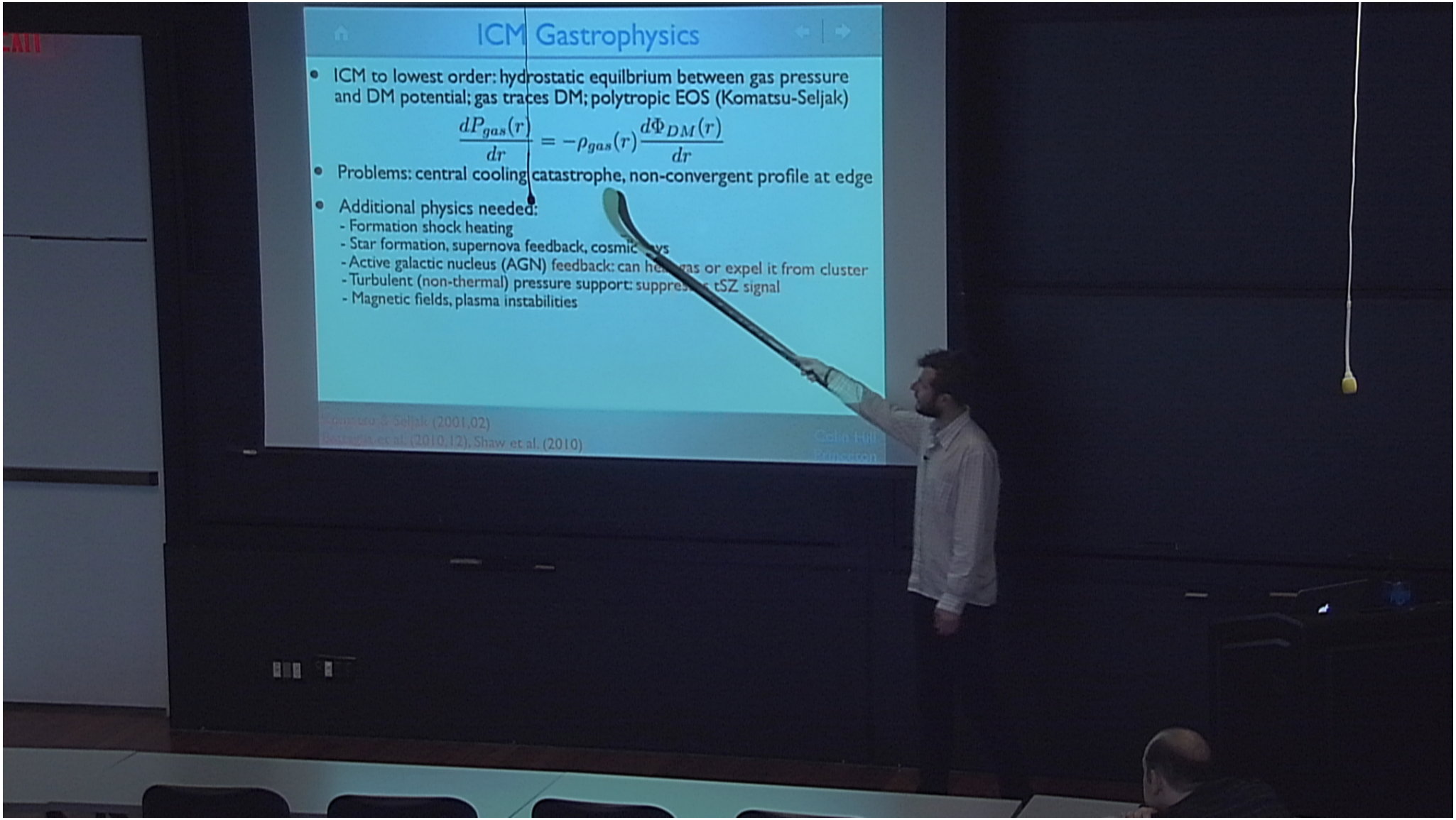
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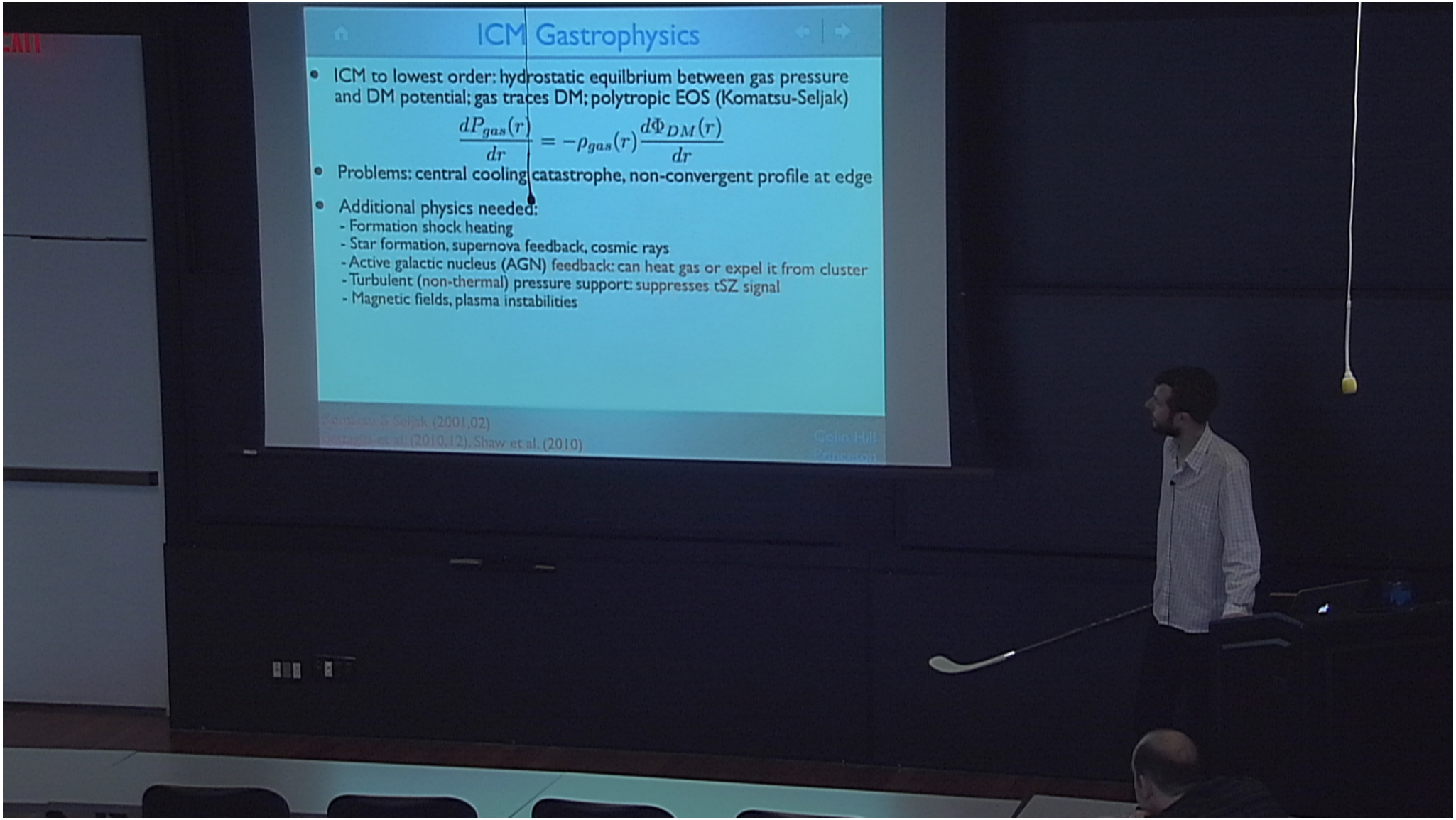
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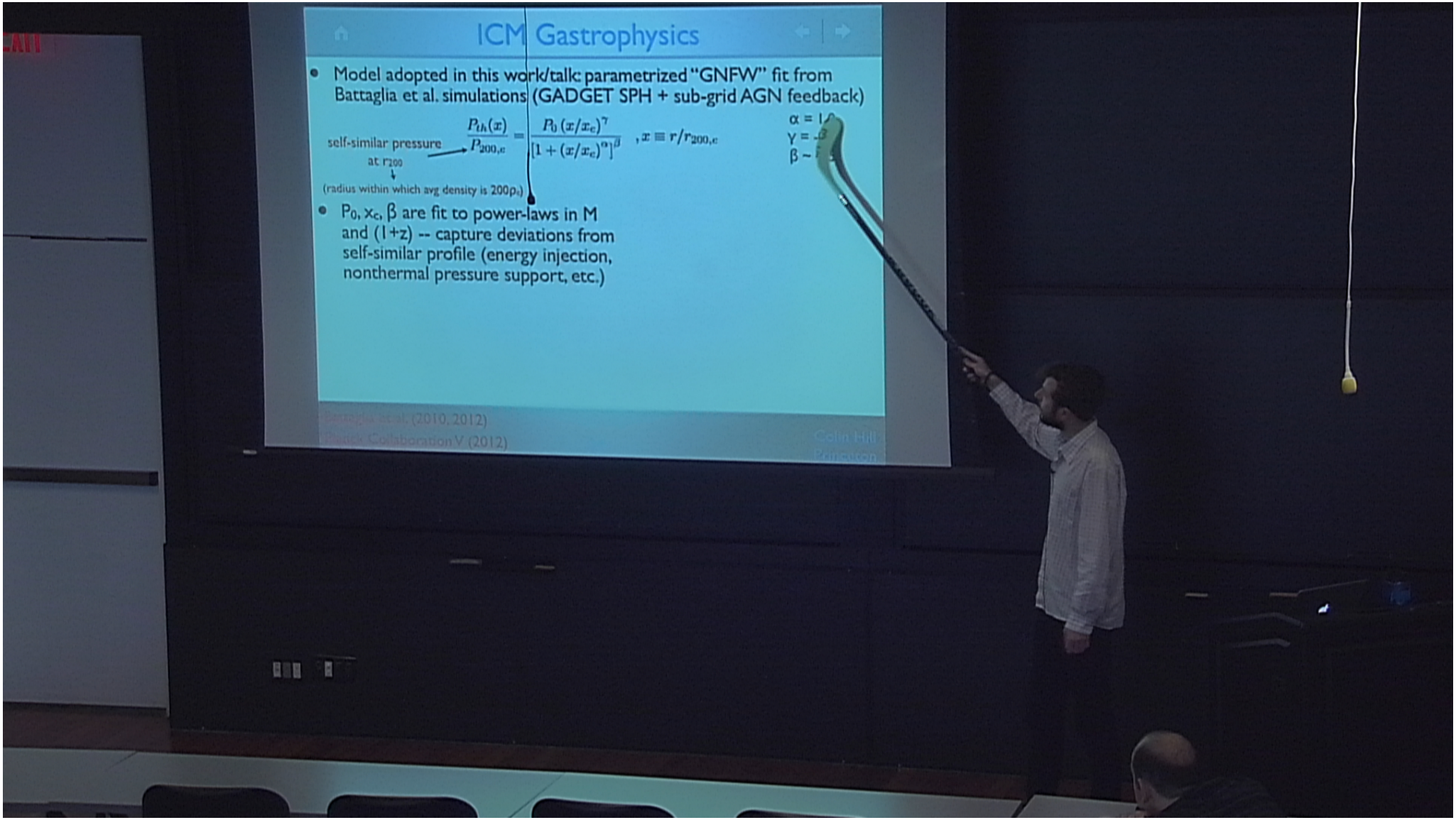
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α = 1.0
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P0, xc, β are fit to power-laws in M and (1+z) -- capture deviations from self-similar profile (energy injection, nonthermal pressure support, etc.)
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Planck Collaboration V (2012)
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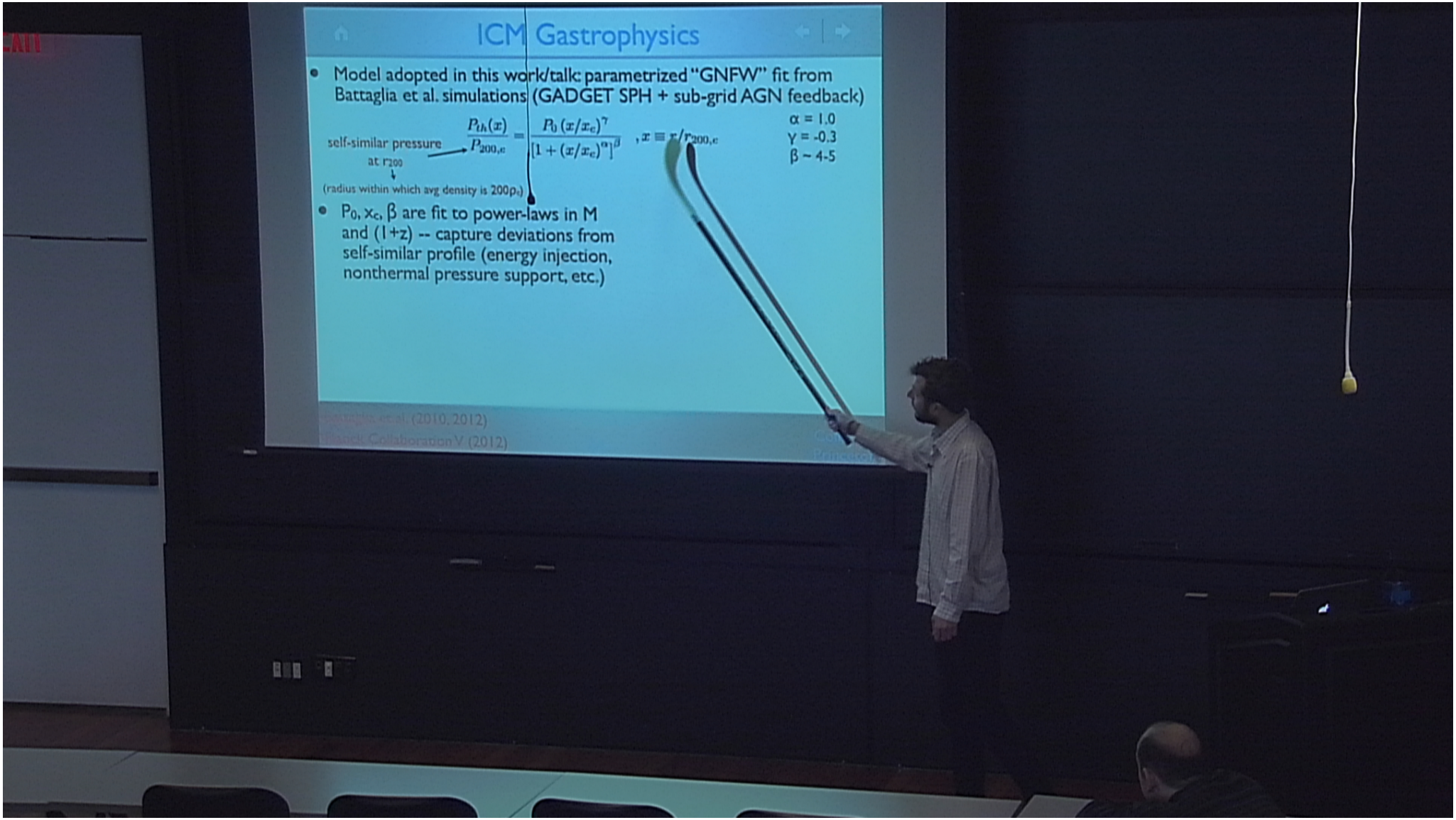
Princeton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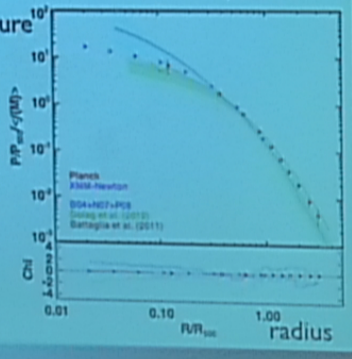

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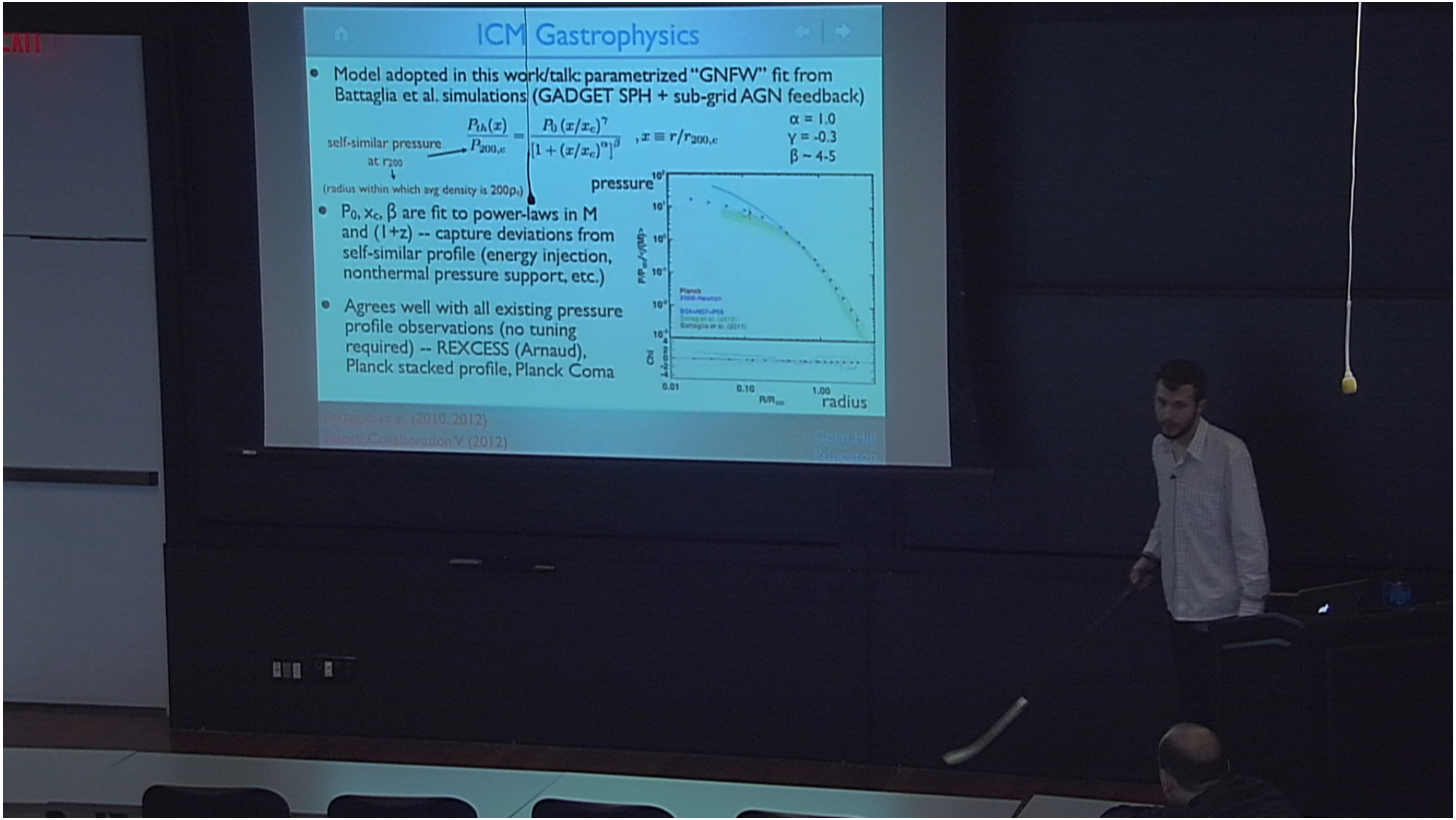
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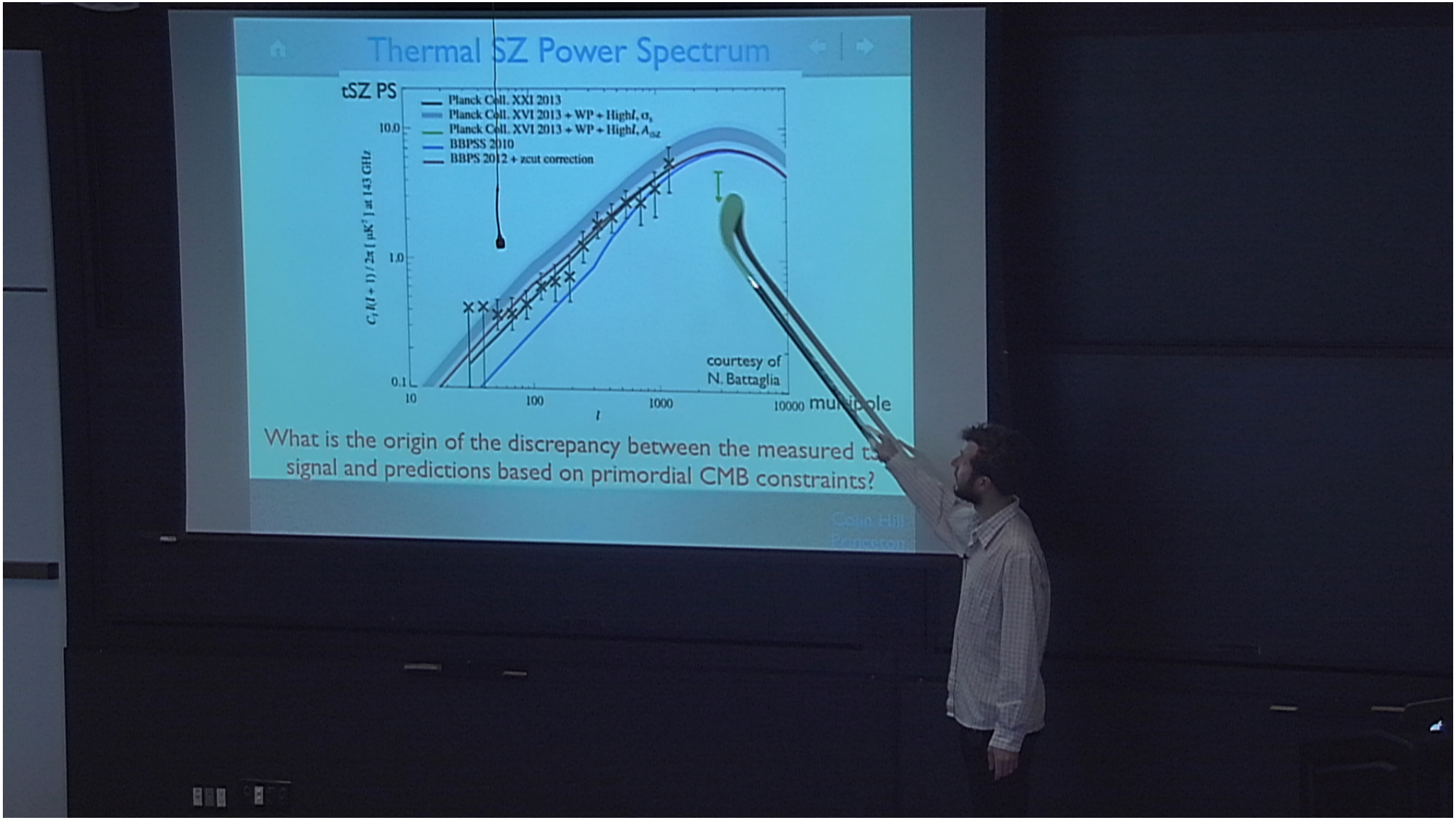
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$C_l\,l(l+1)/2\pi$ [μK^2] at 143 GHz
10.0
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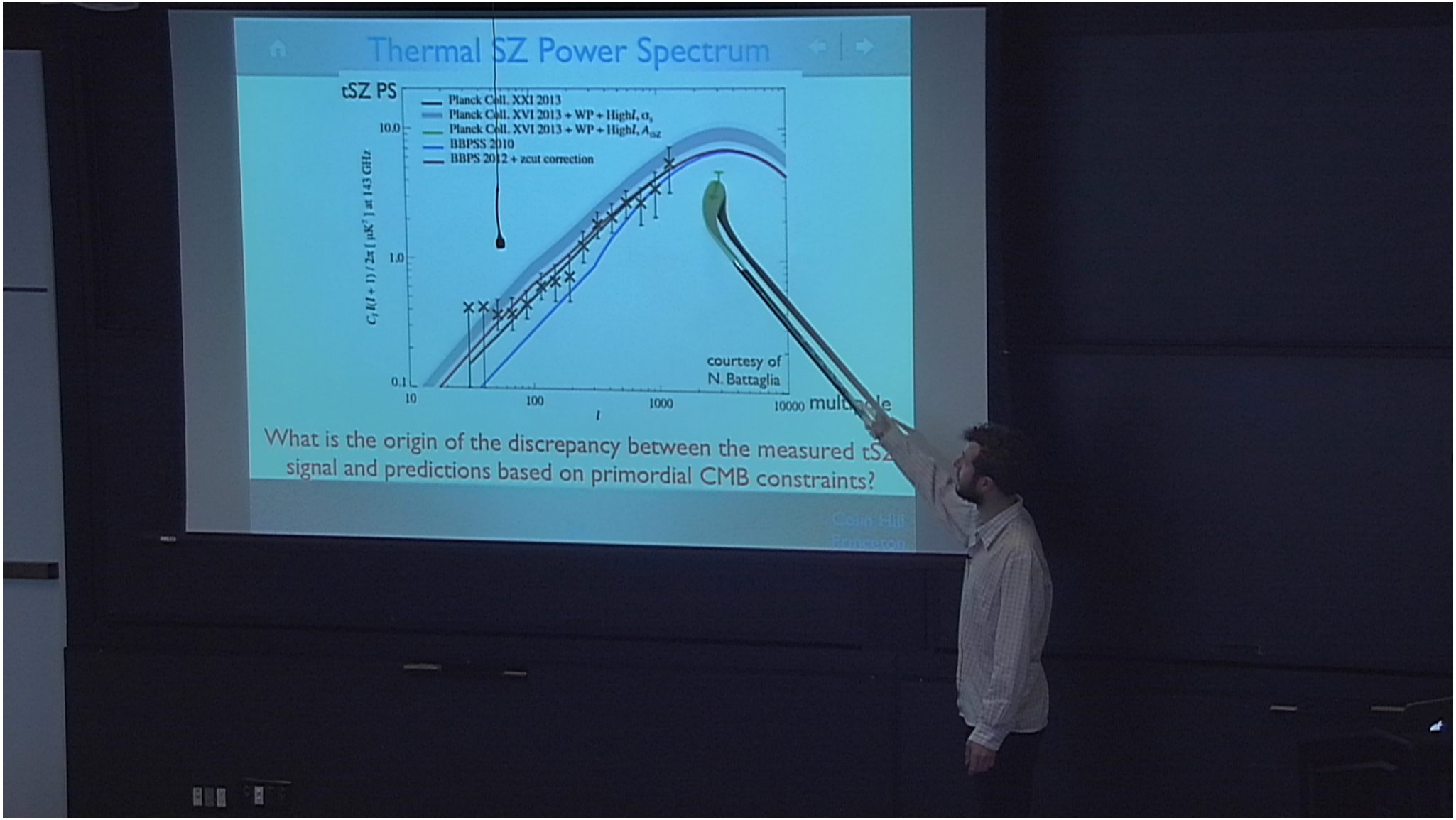
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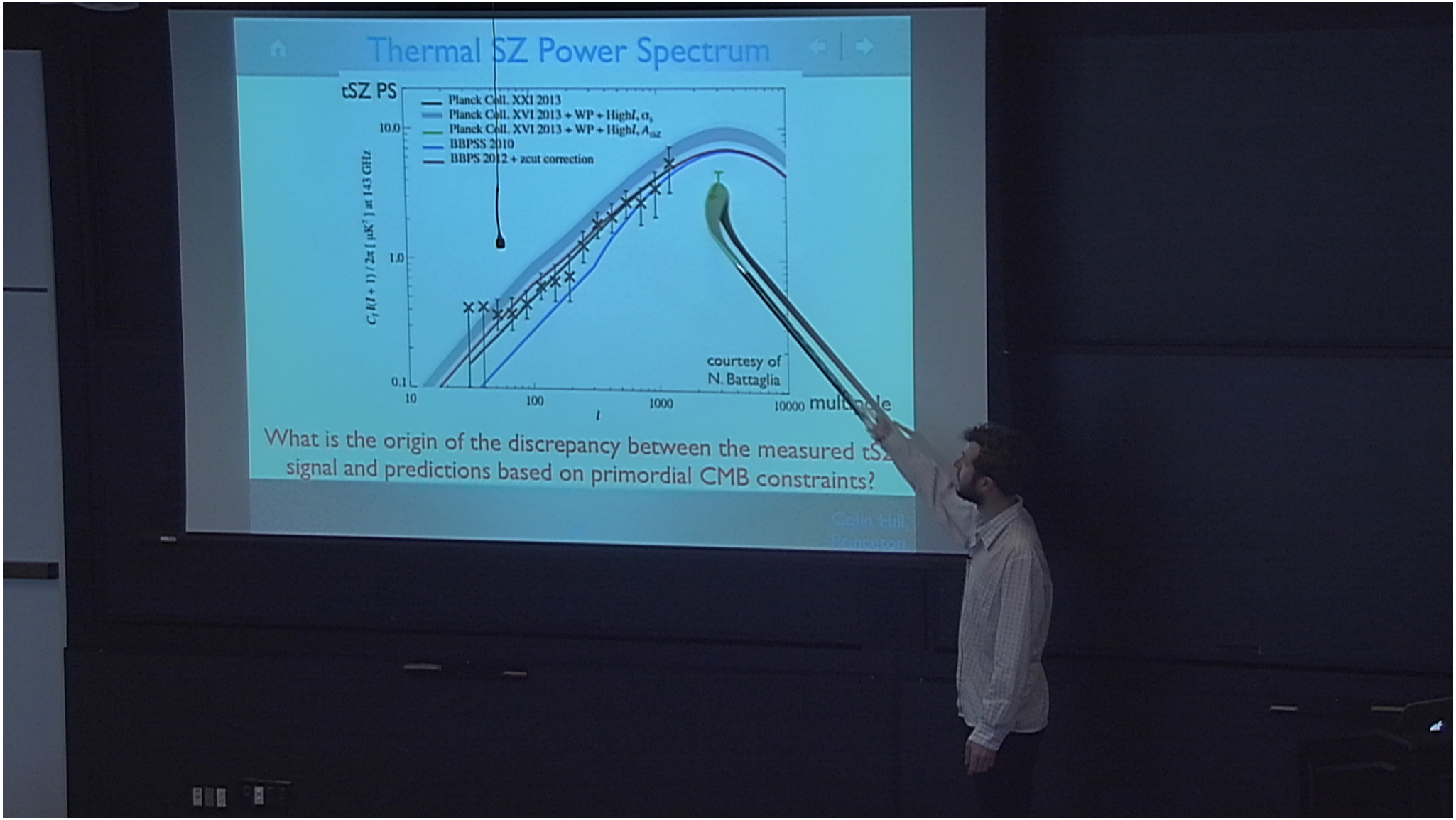
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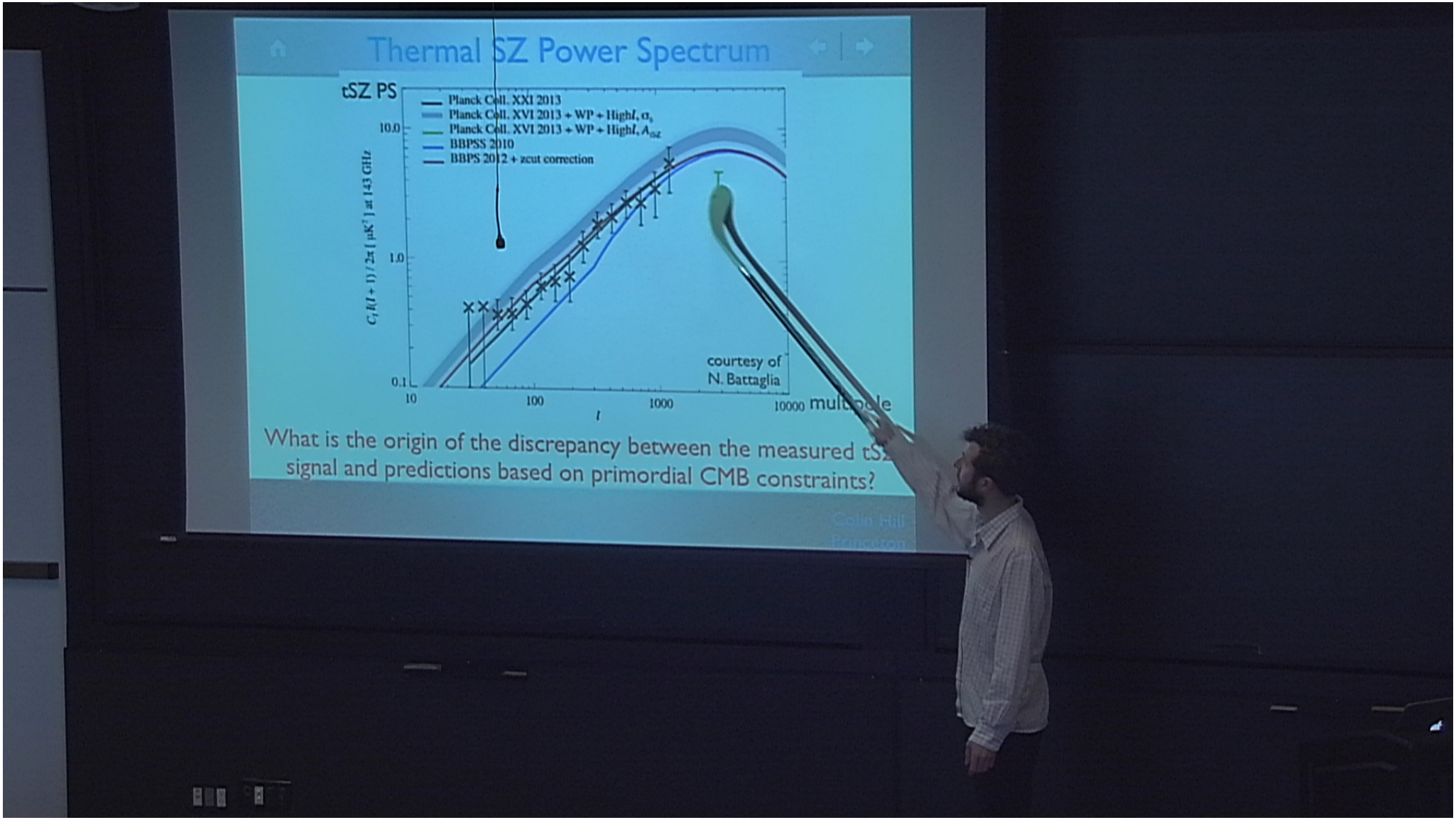
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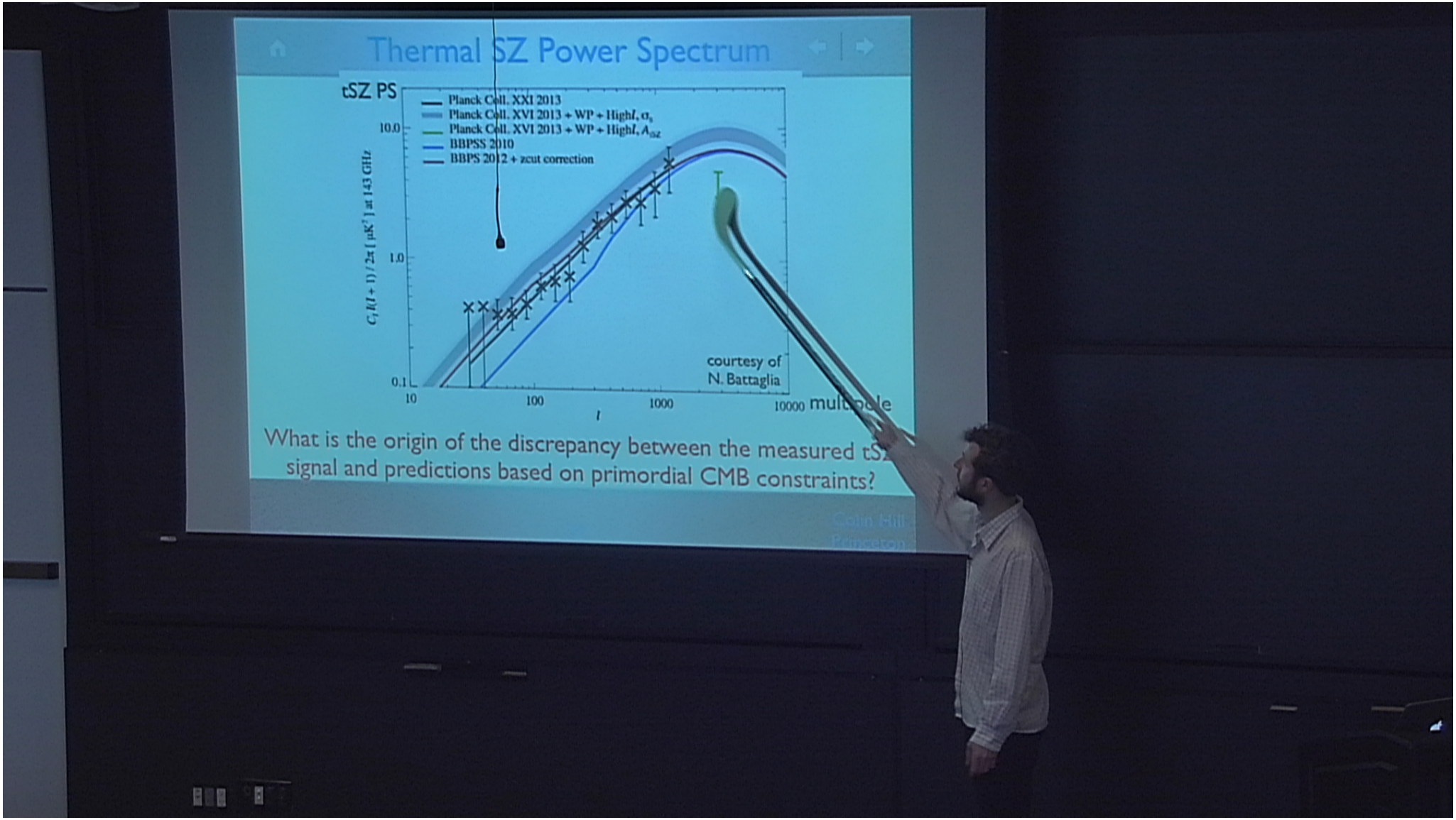
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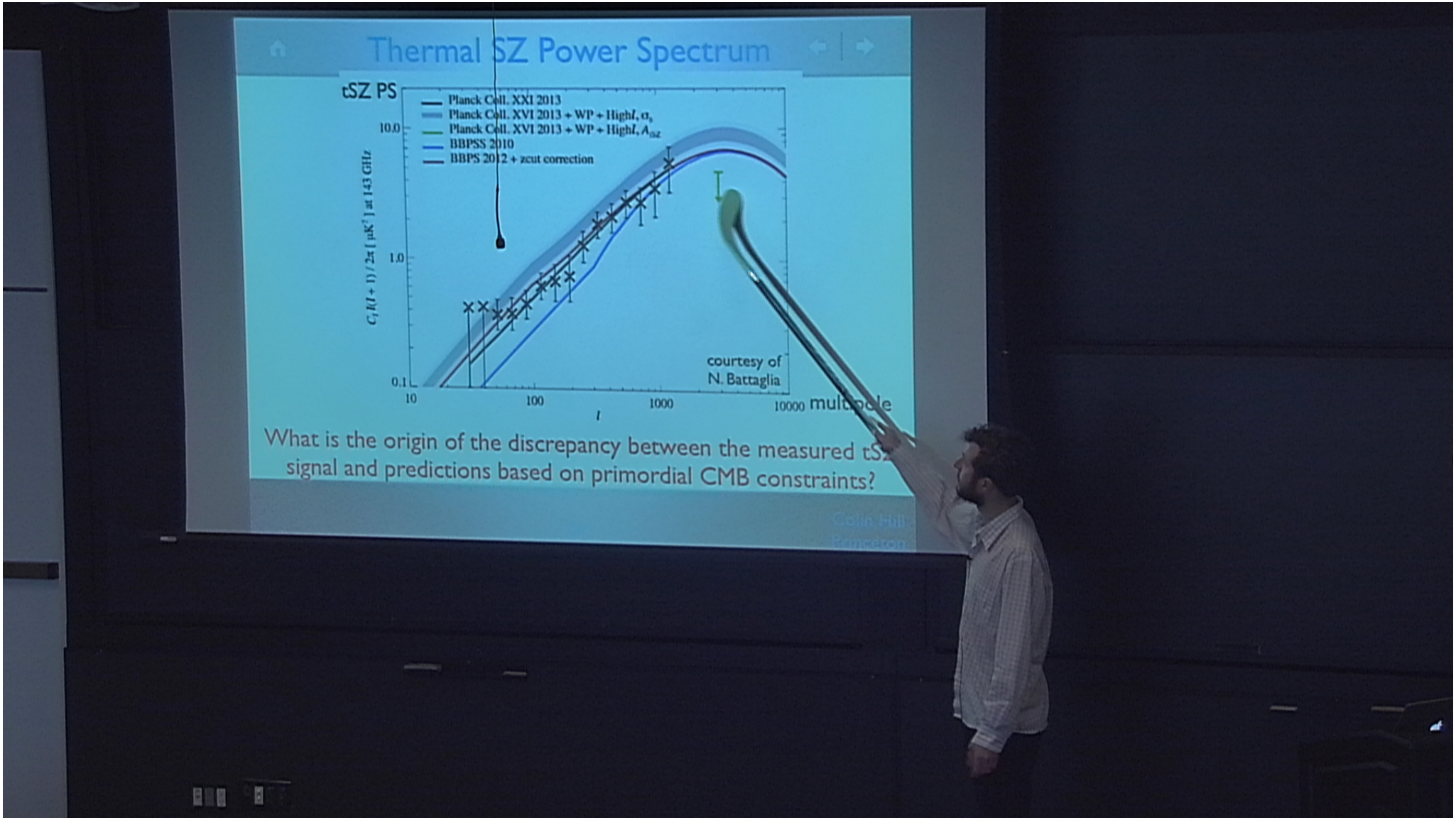
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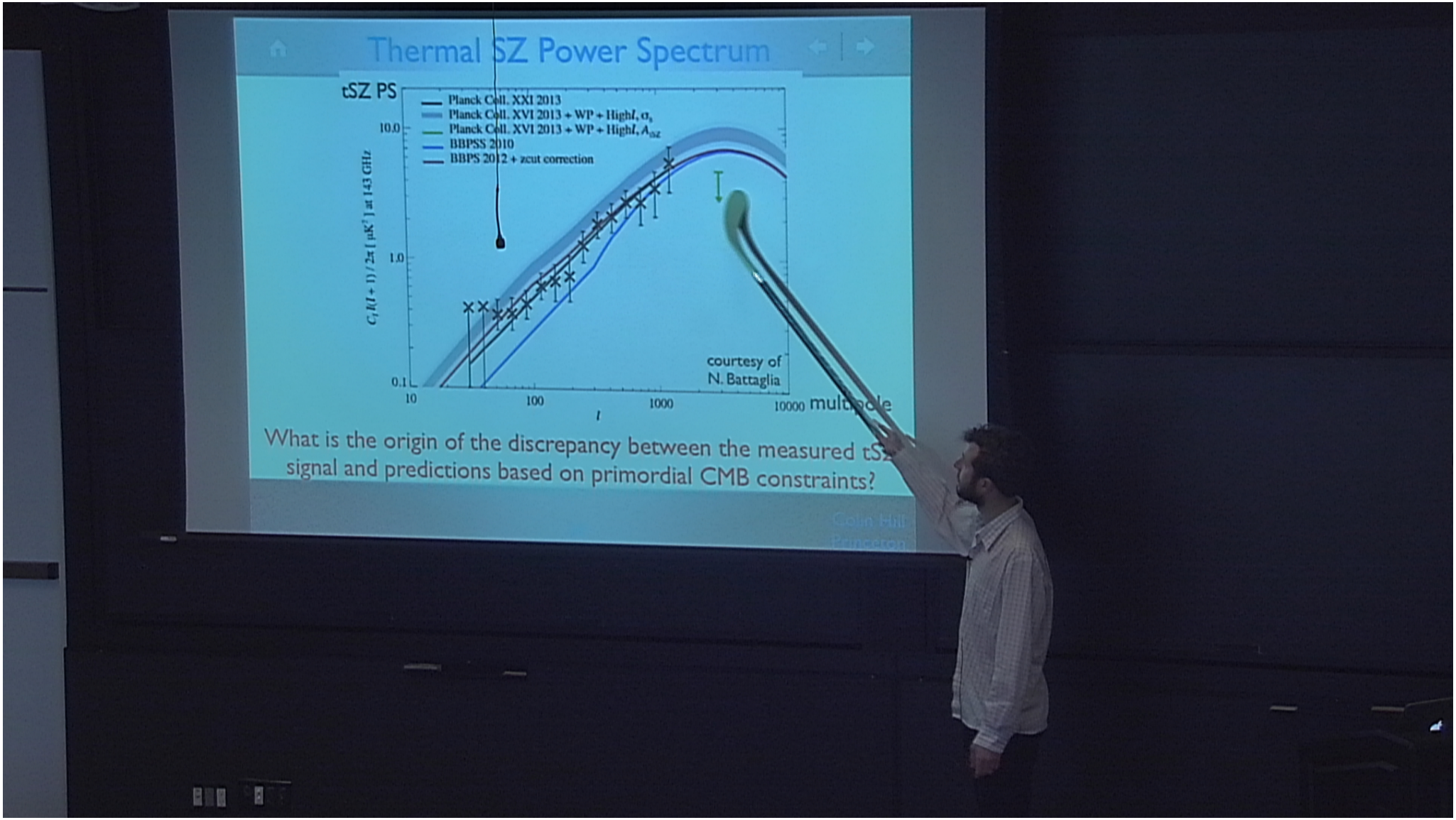
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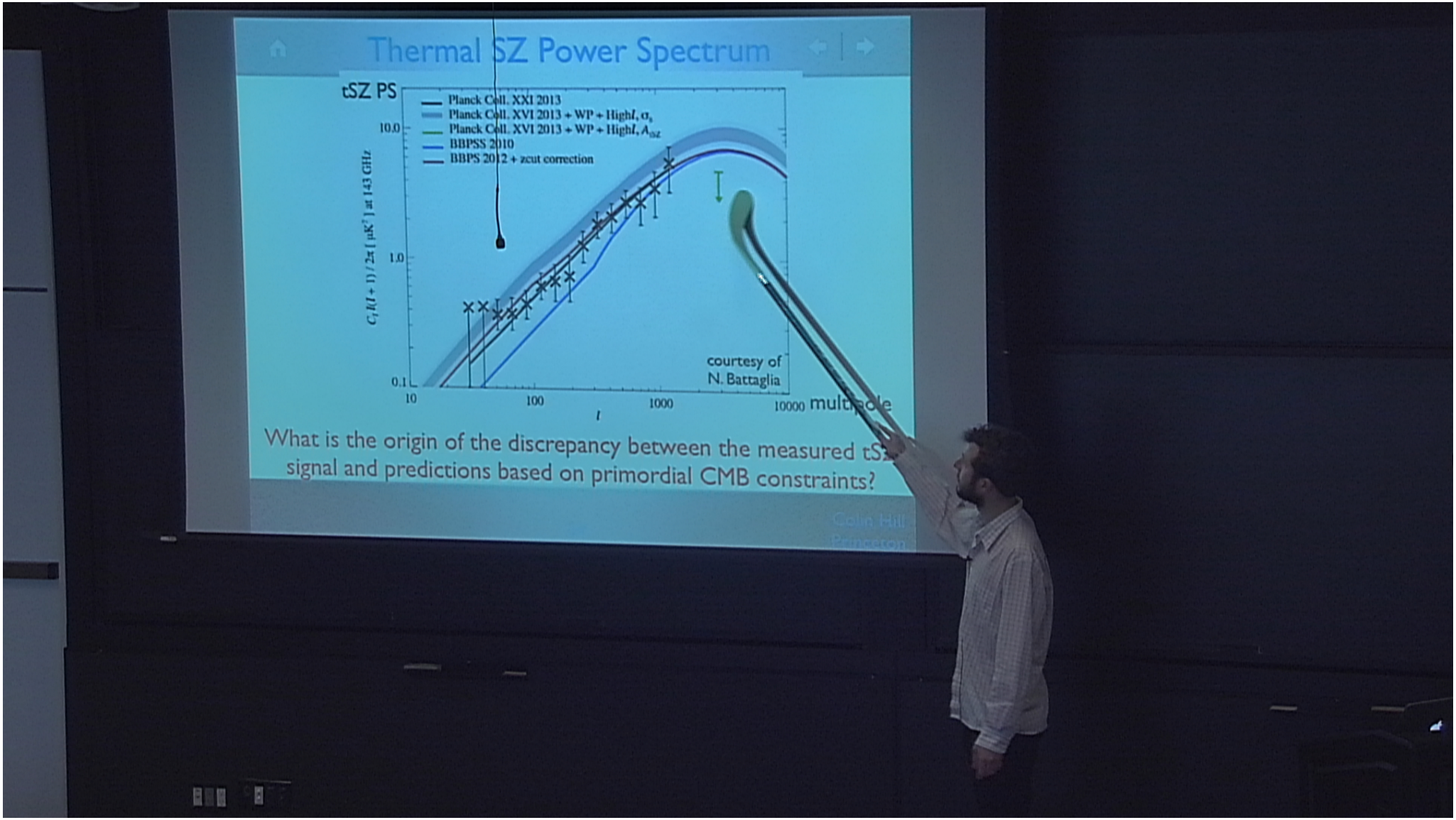
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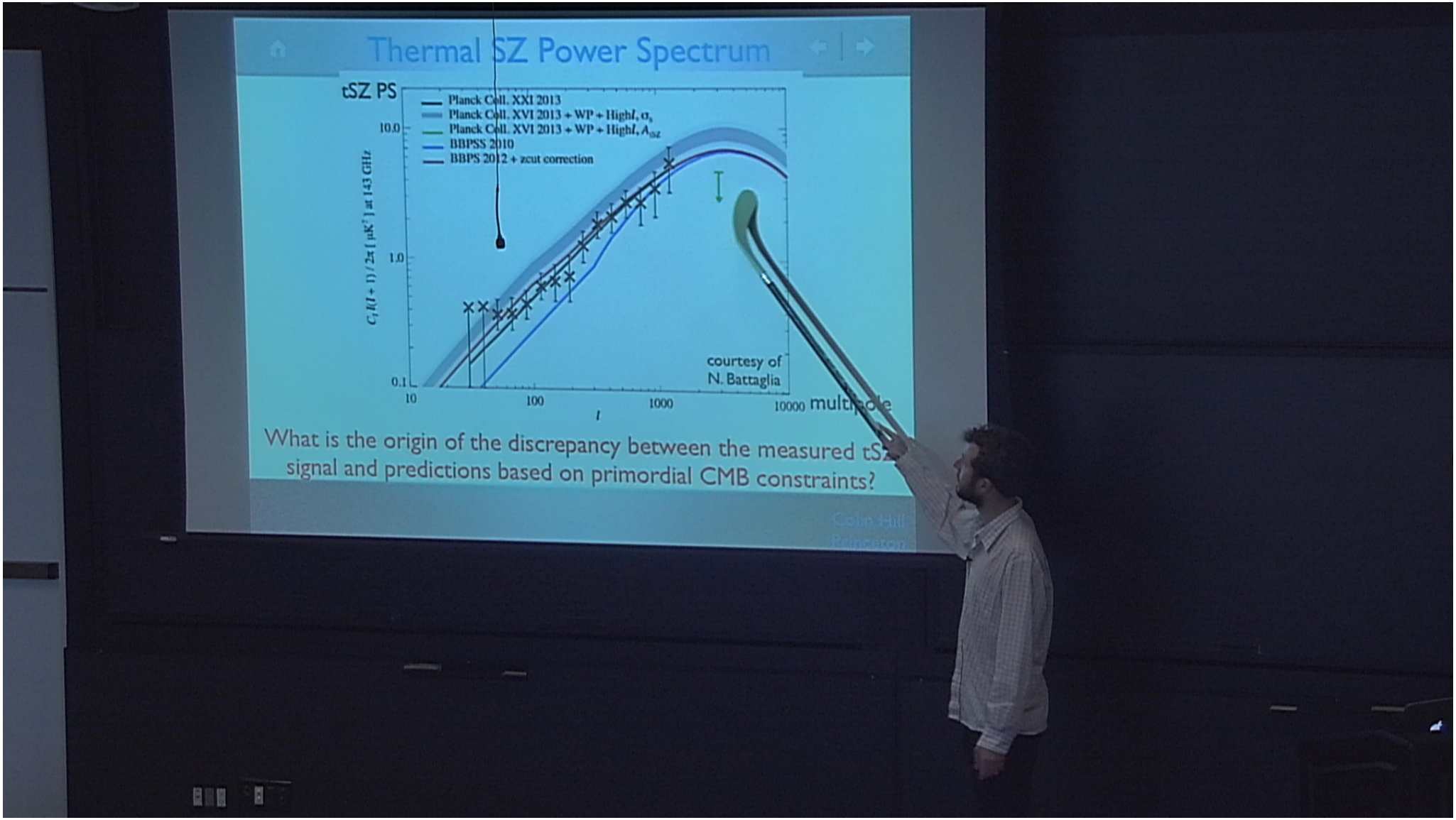
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10.0
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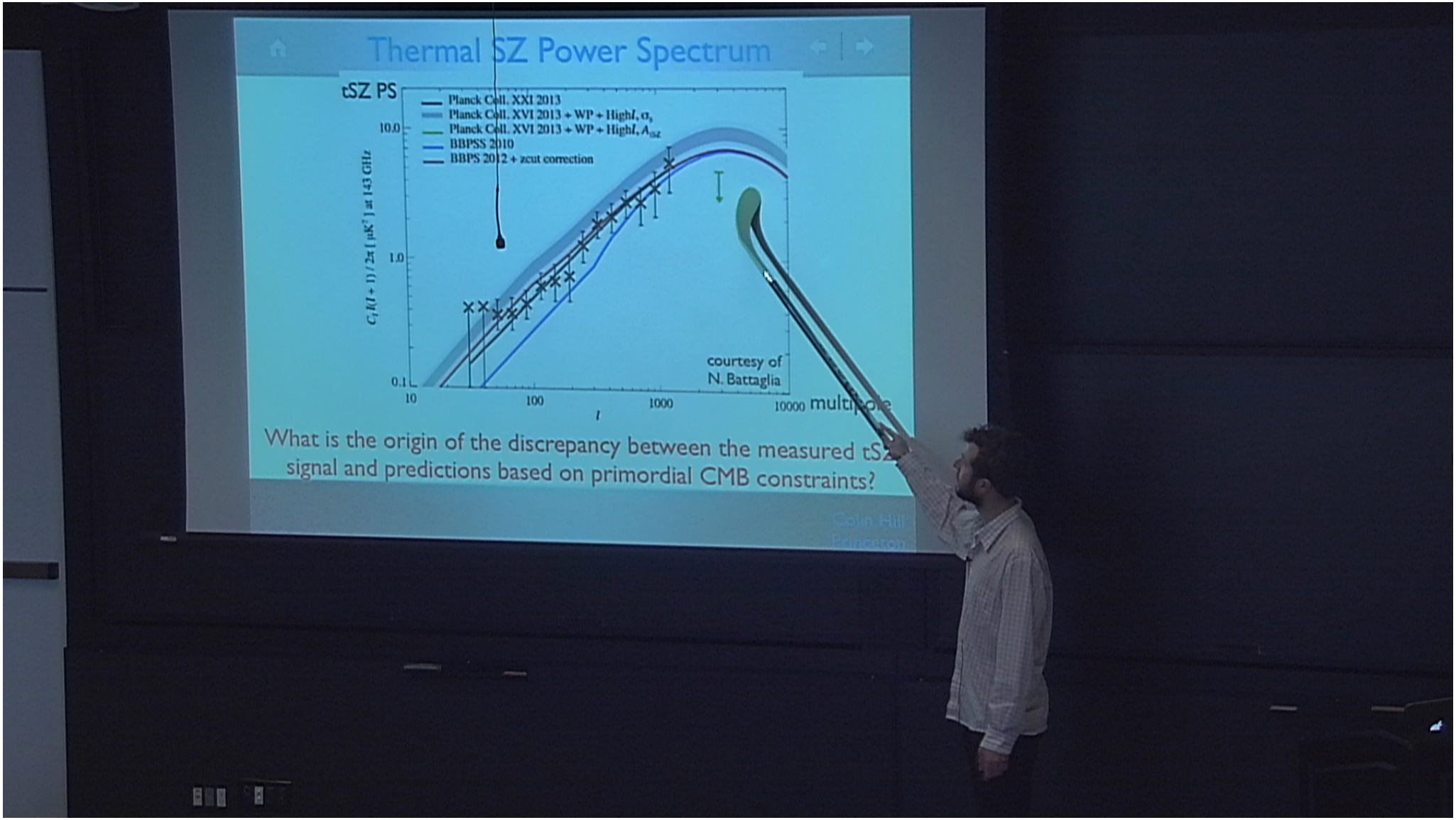
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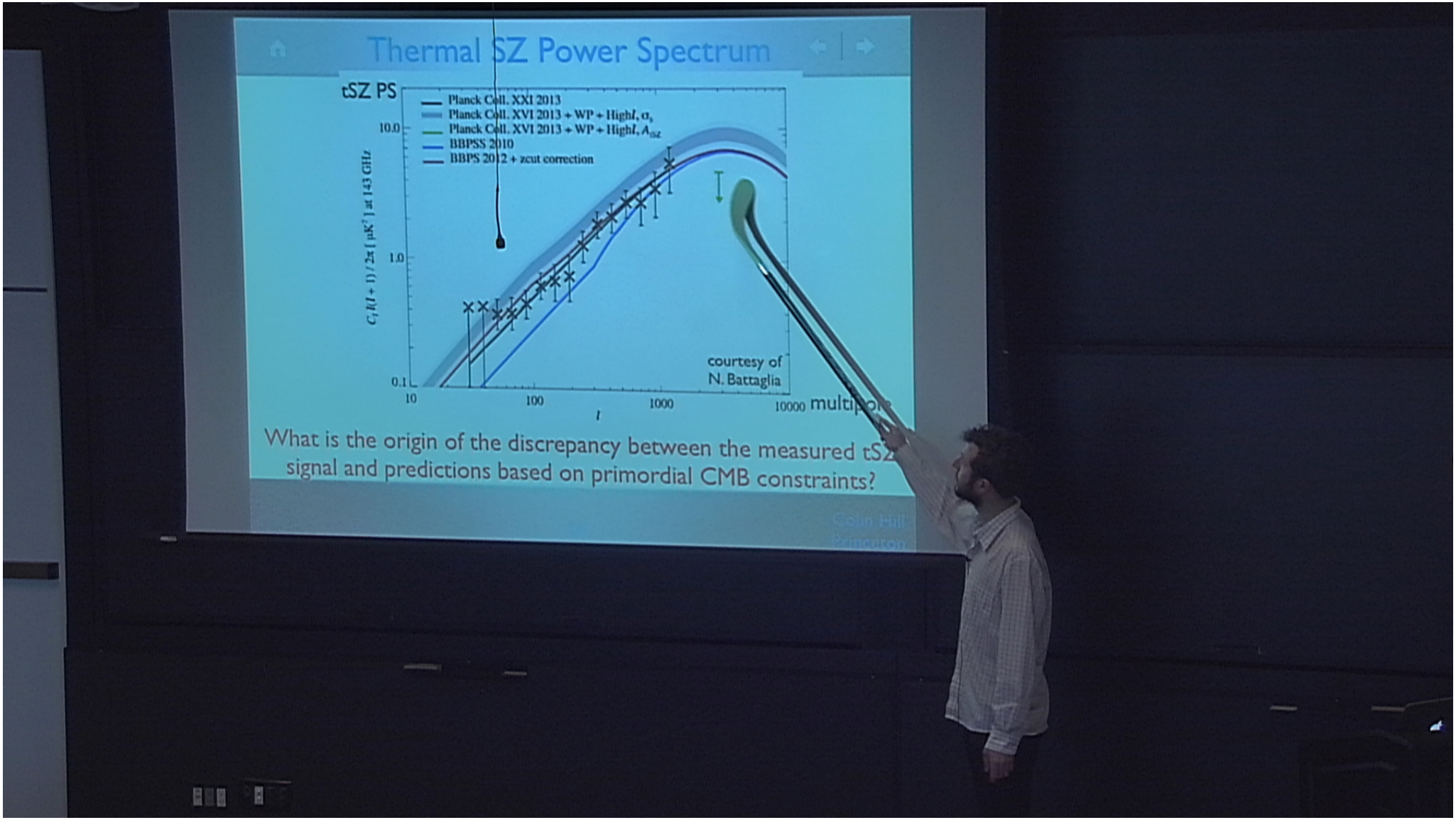
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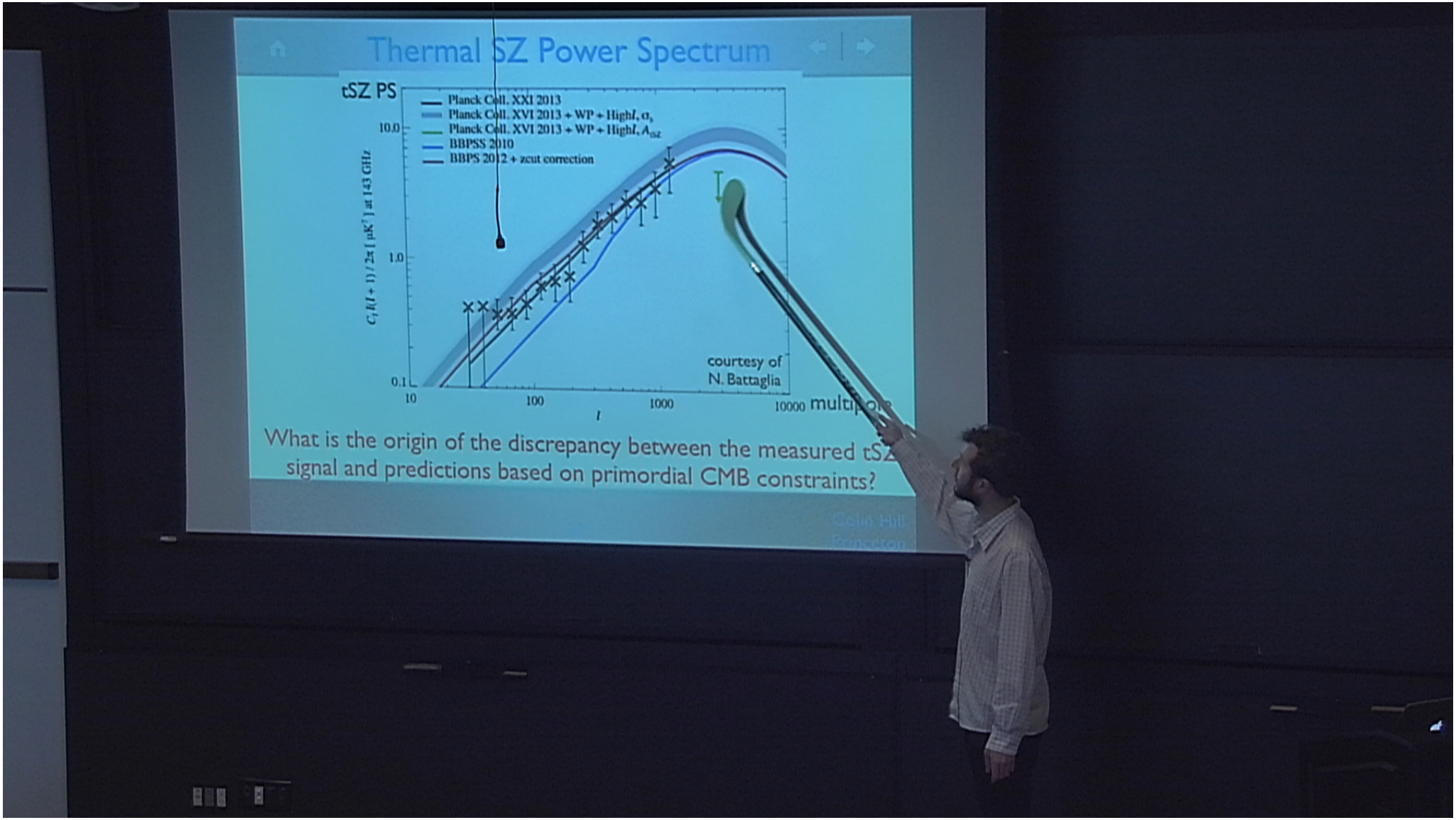
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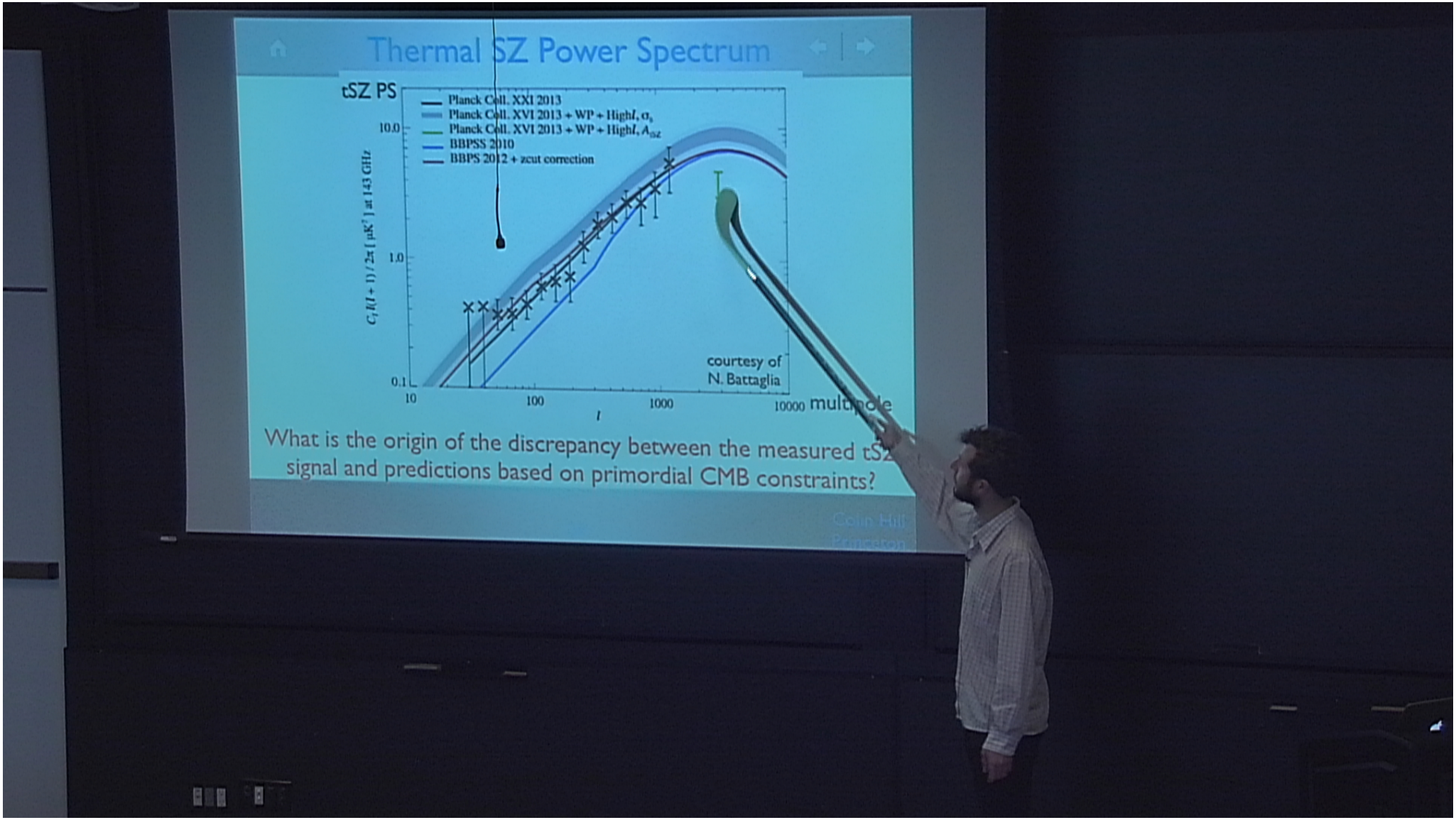
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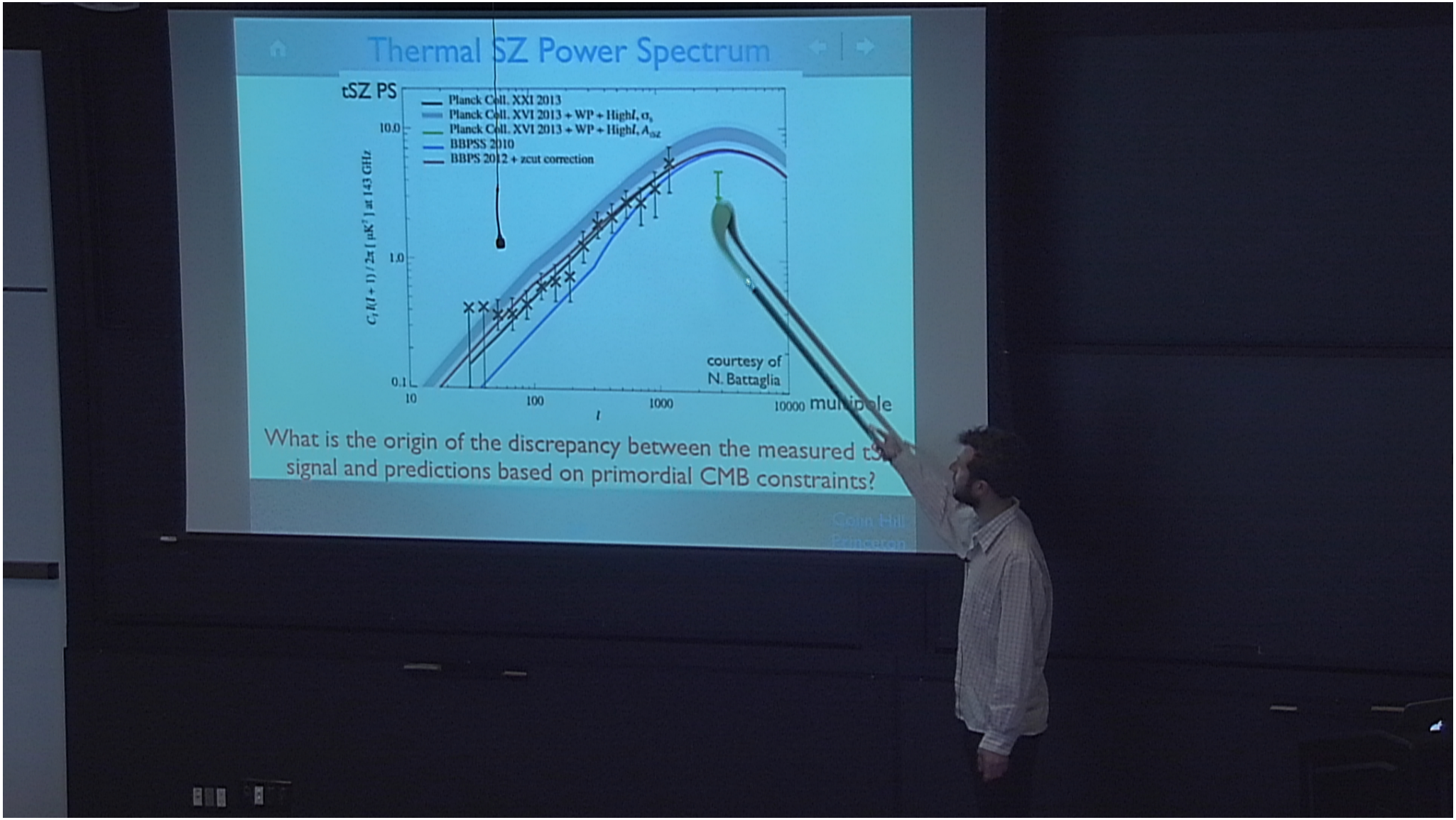
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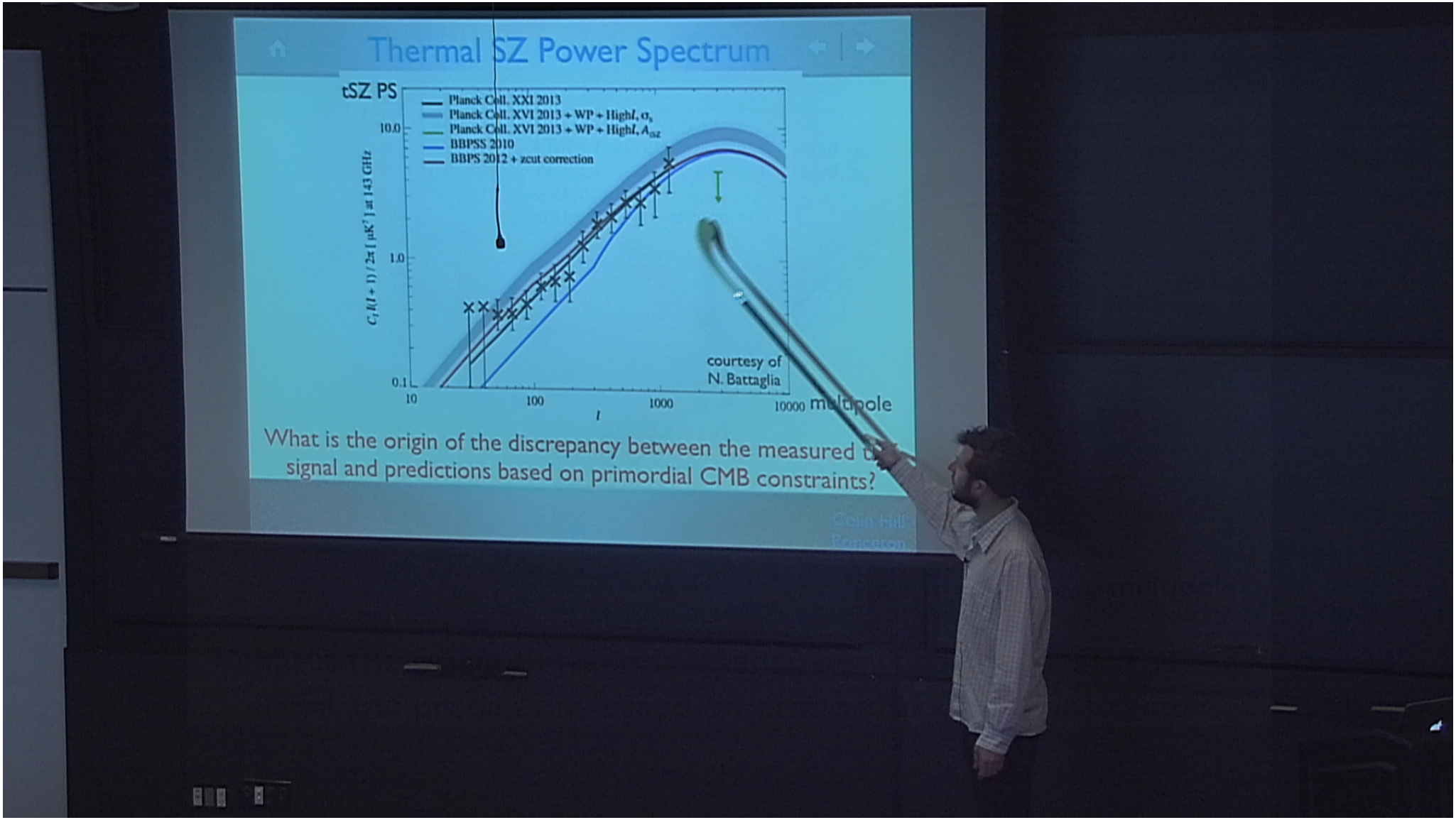
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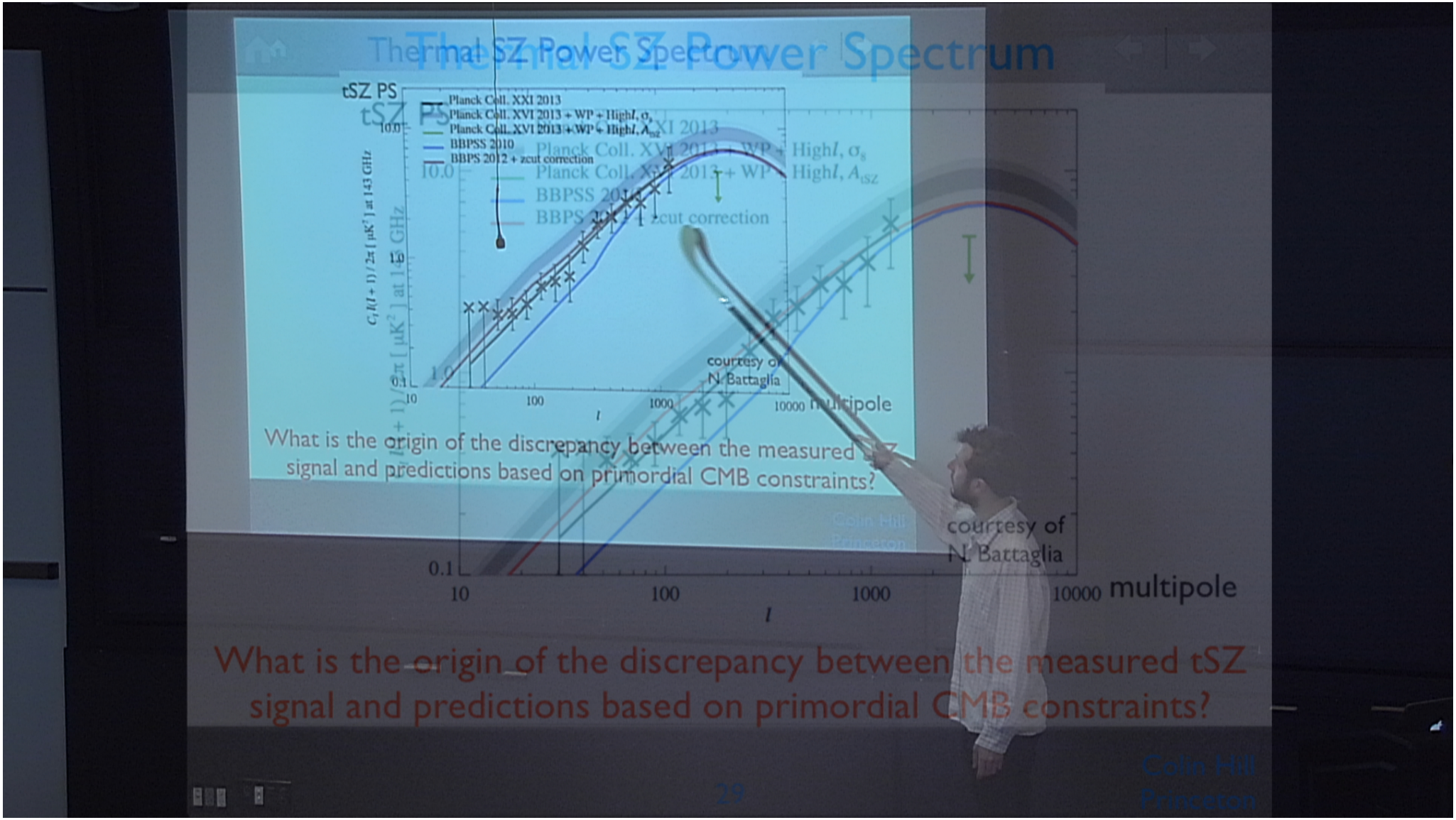
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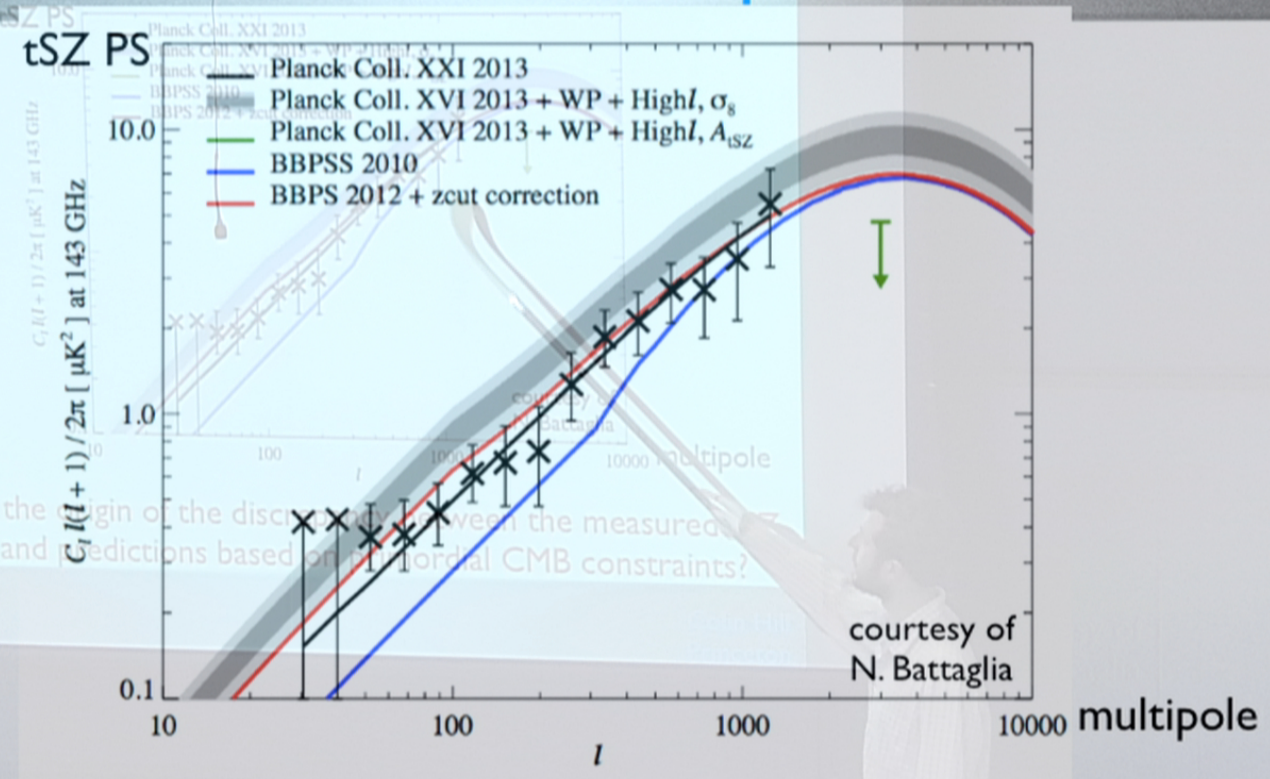
29

Thermal SZ Power Spectrum



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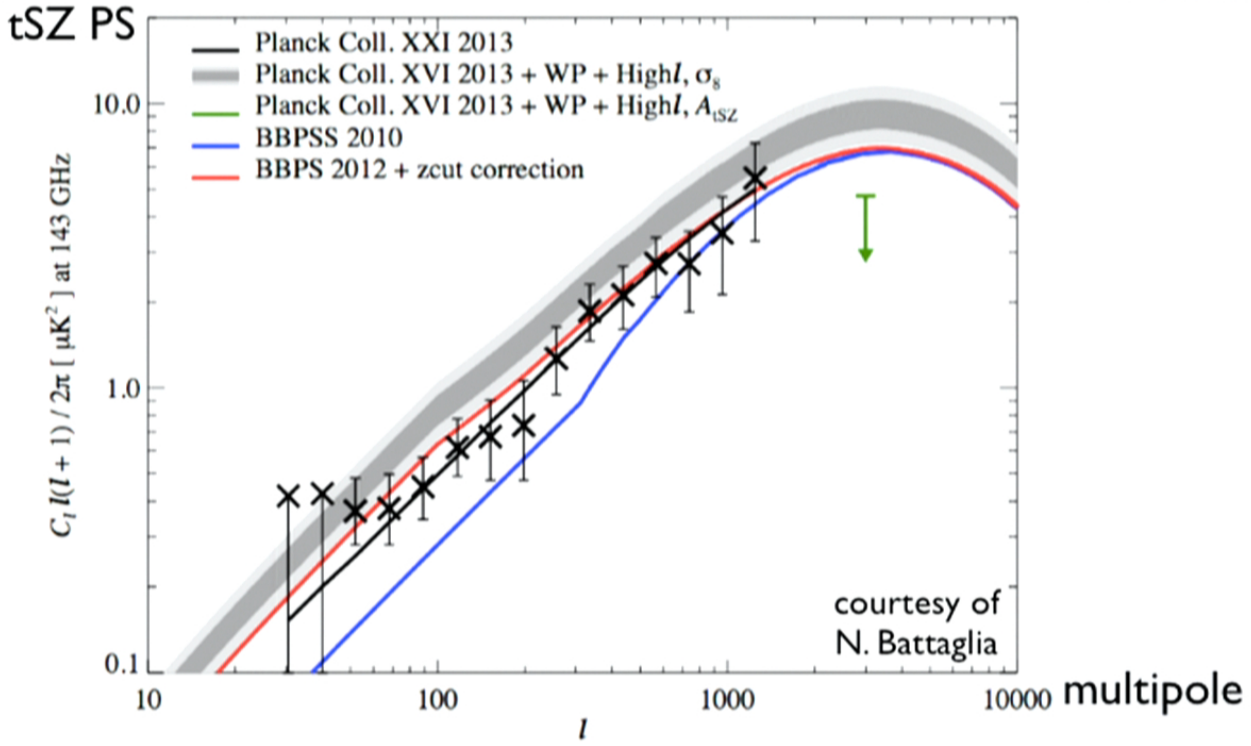

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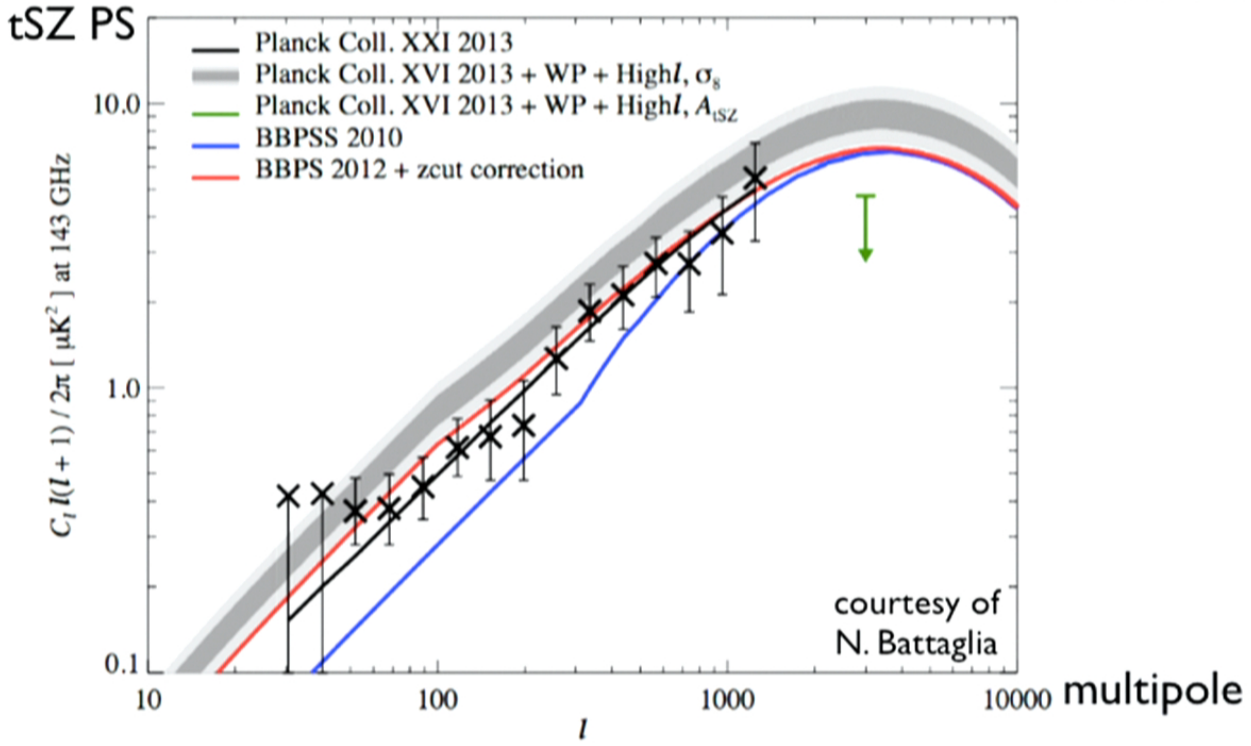

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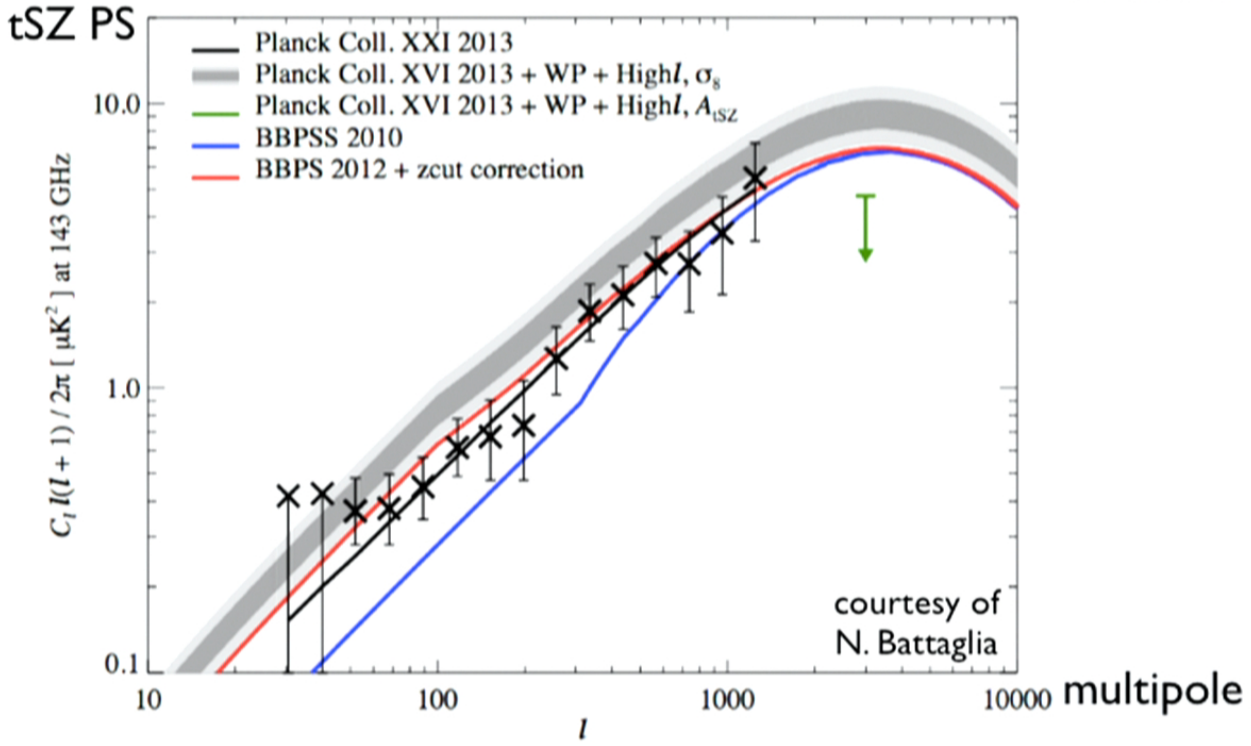

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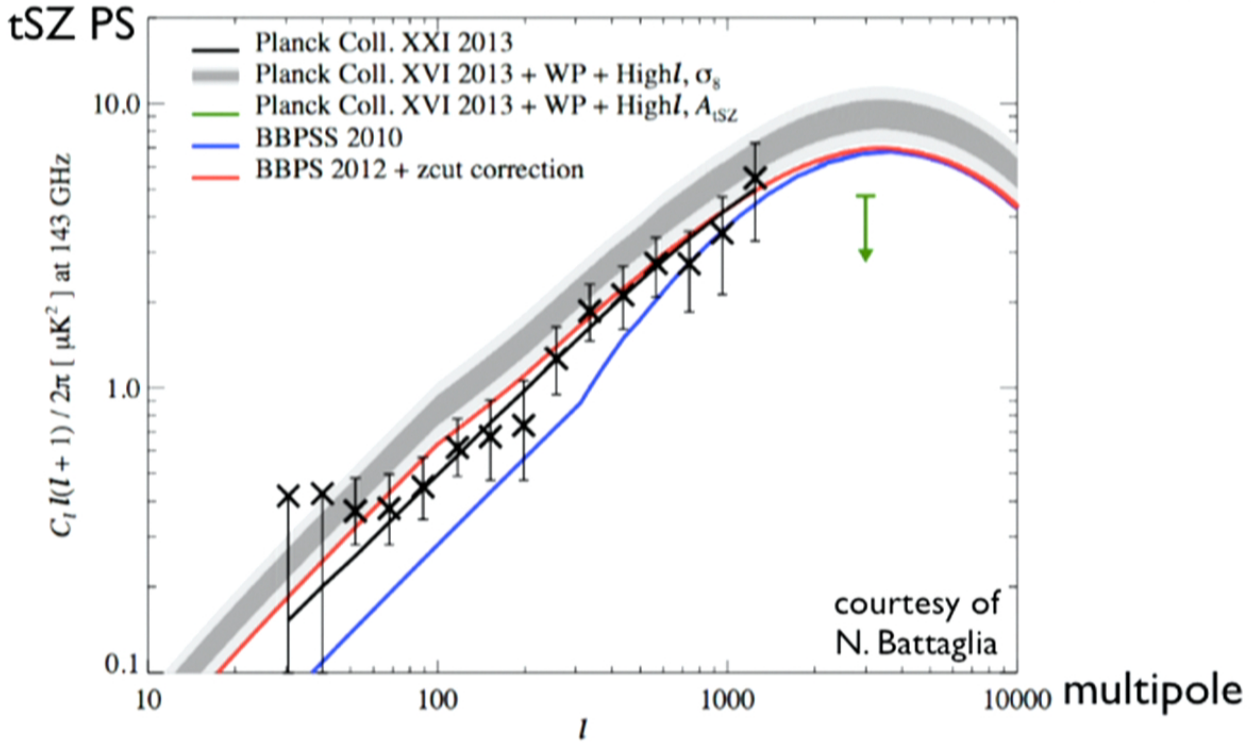

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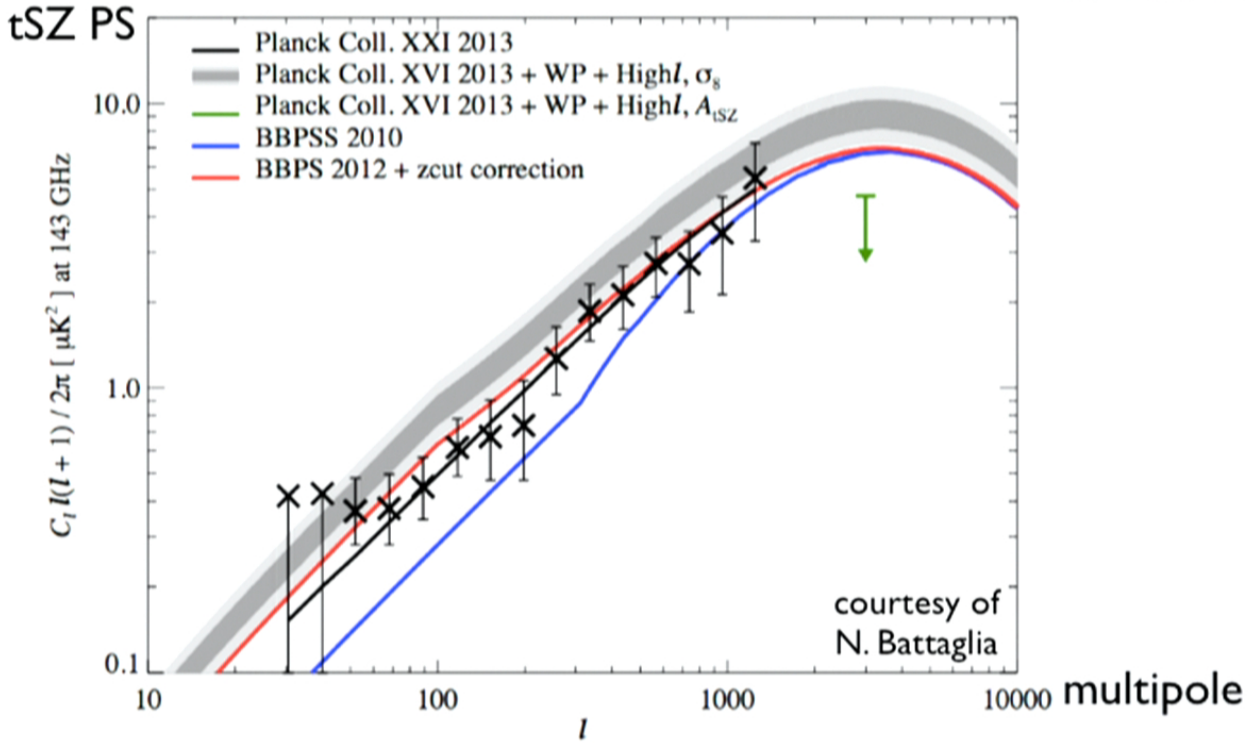

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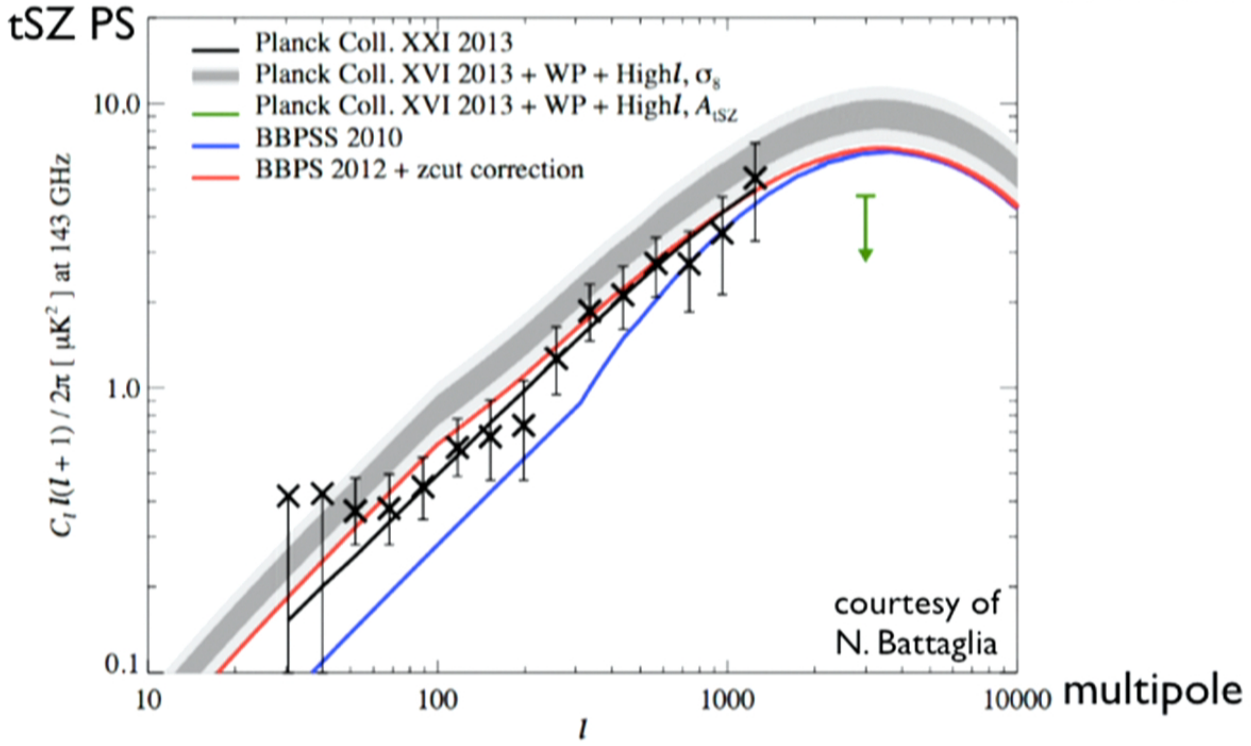

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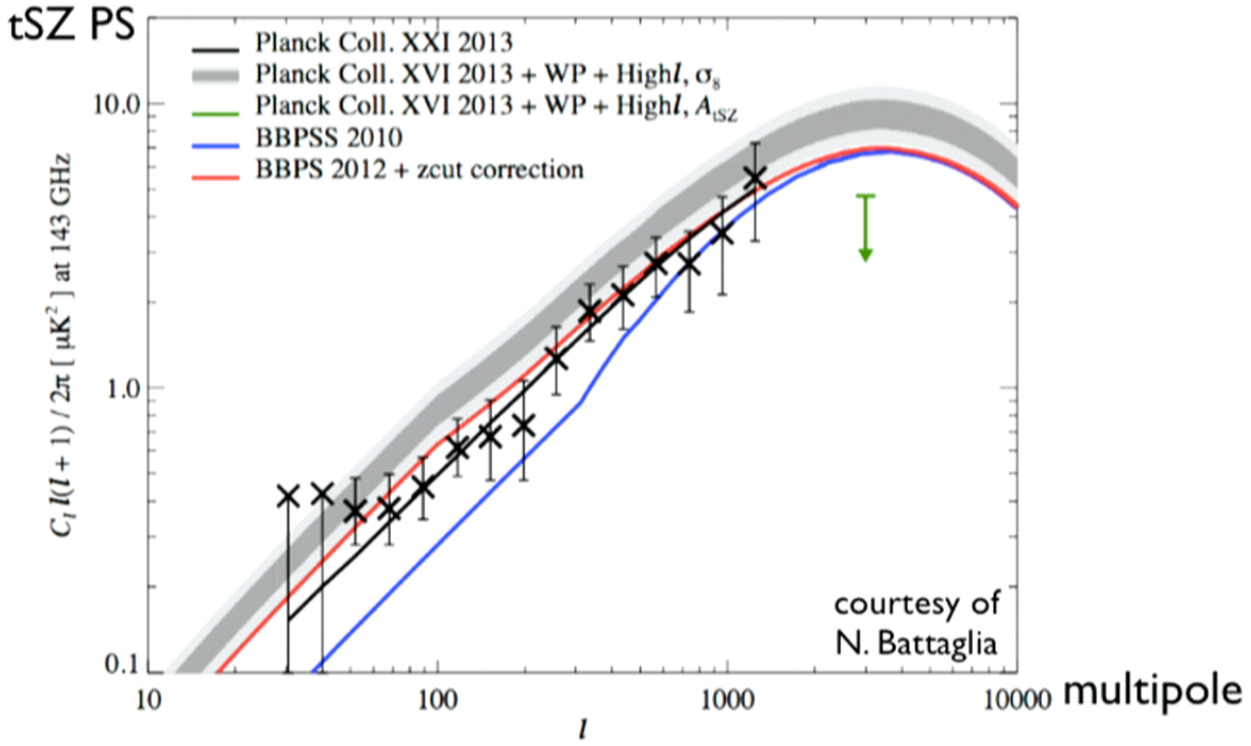

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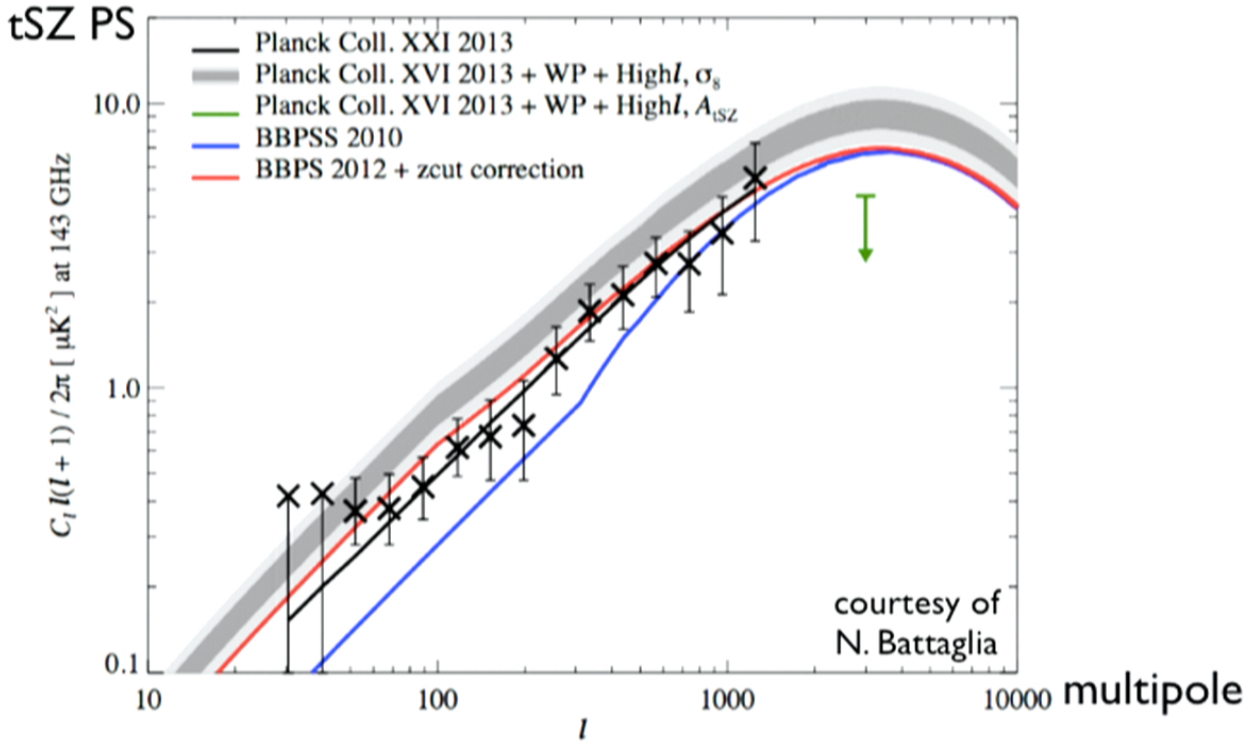

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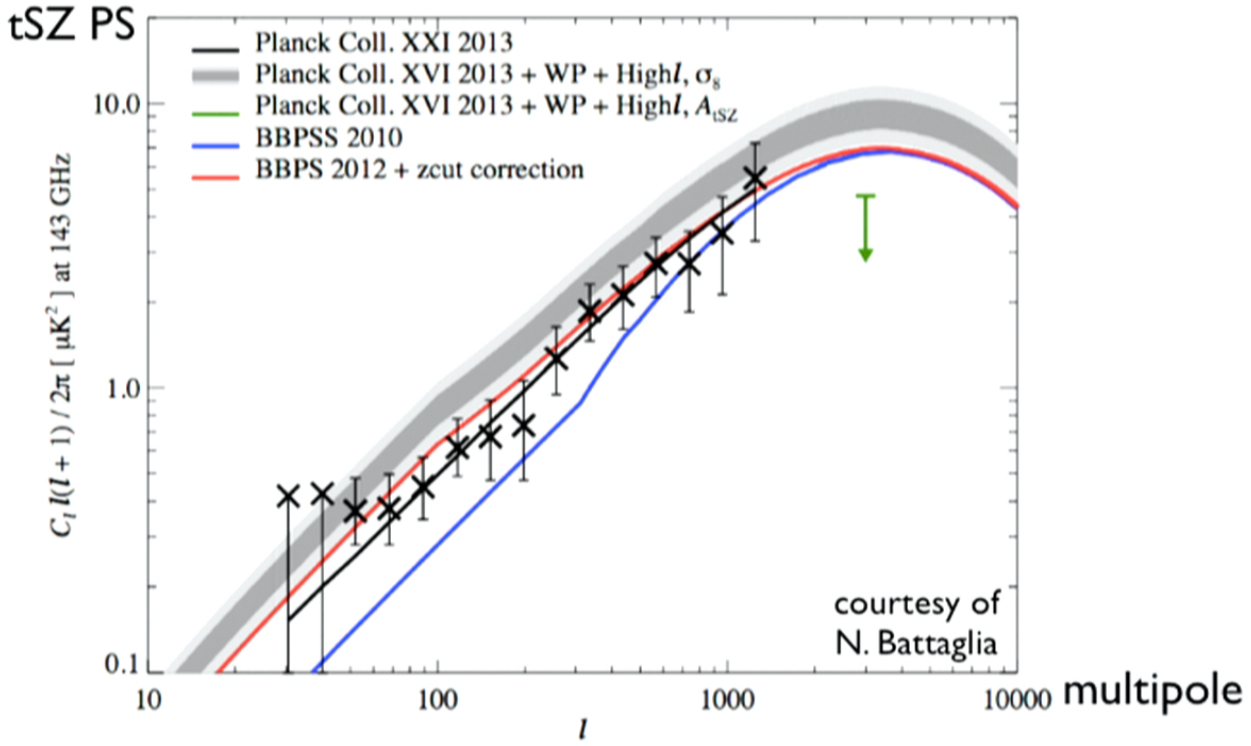

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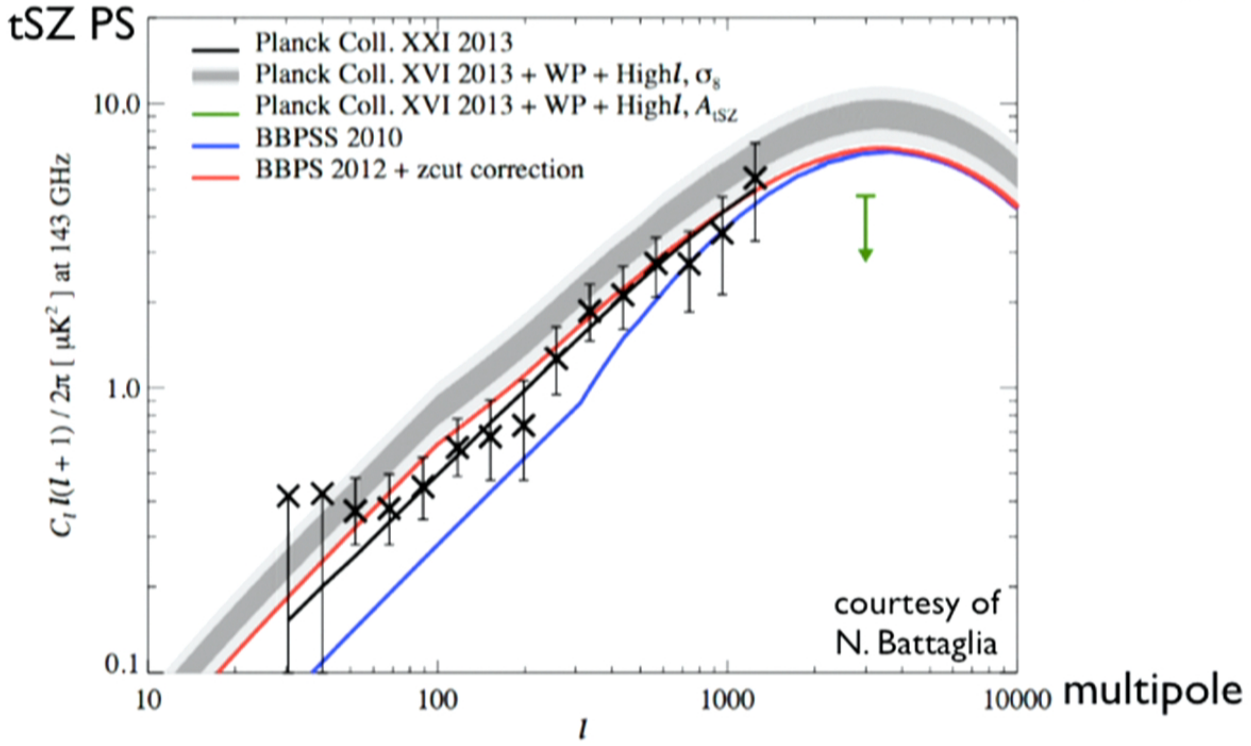

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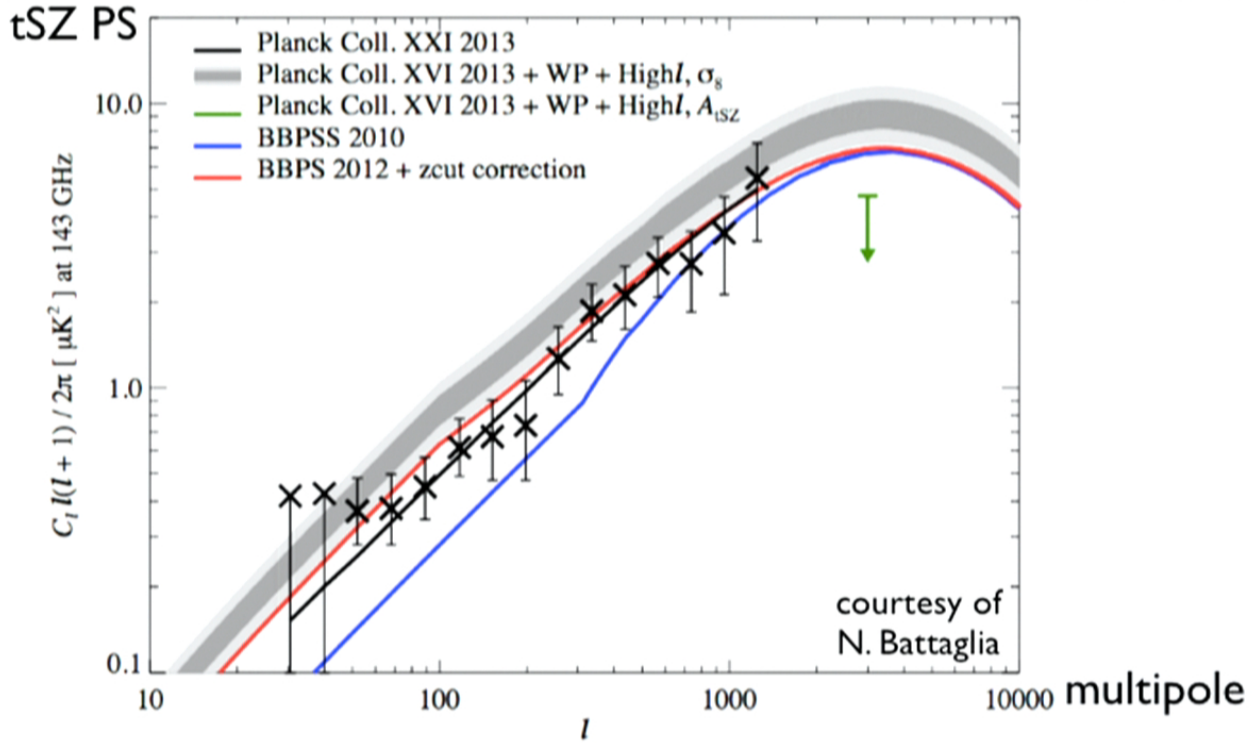

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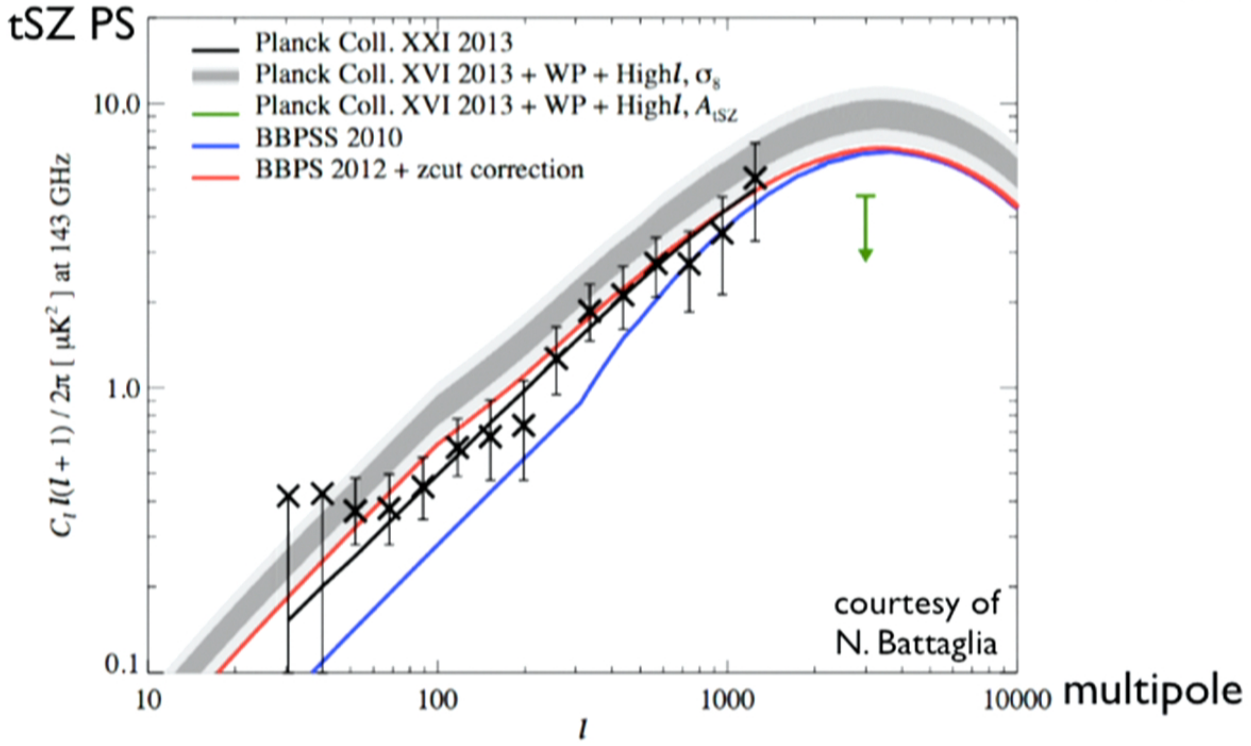

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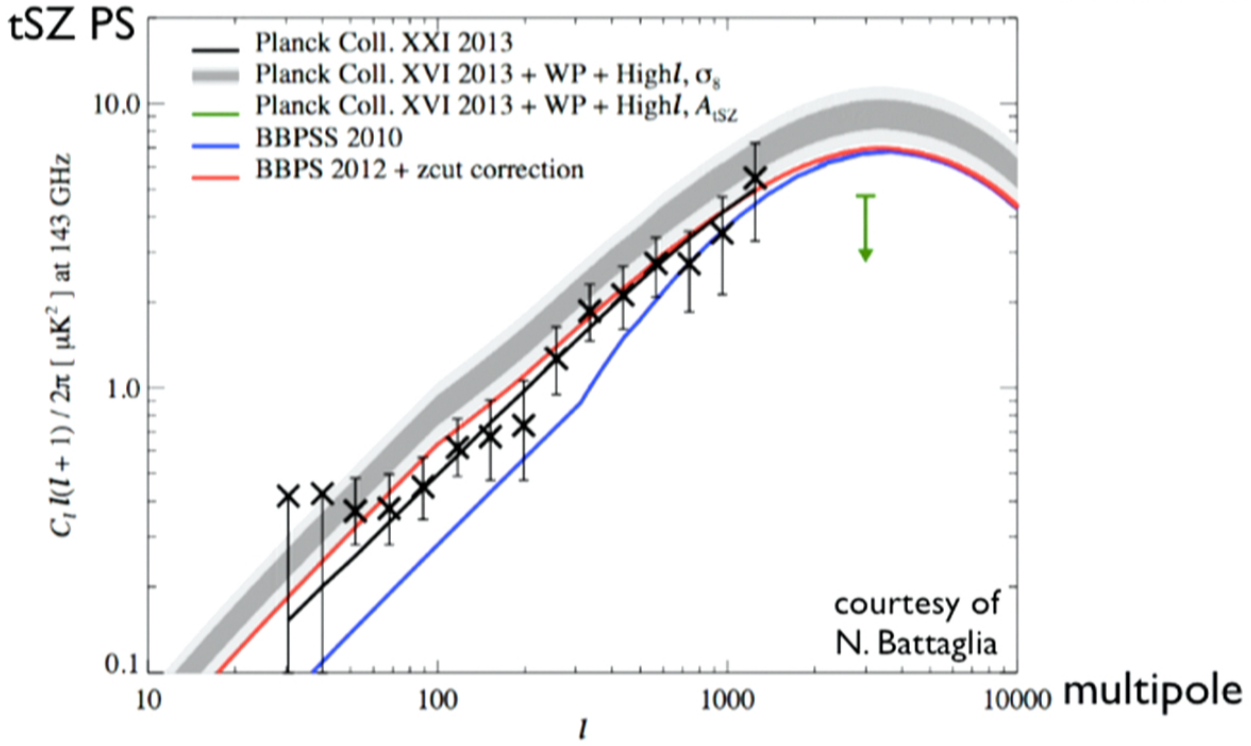

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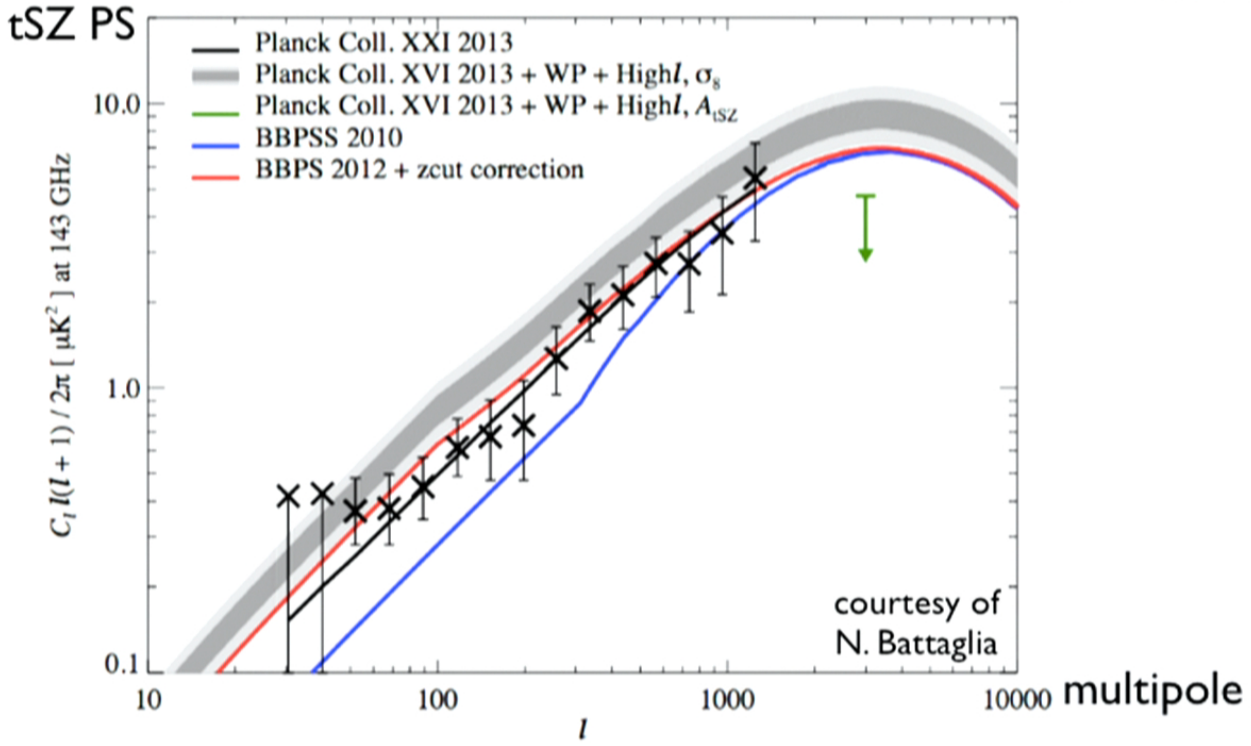

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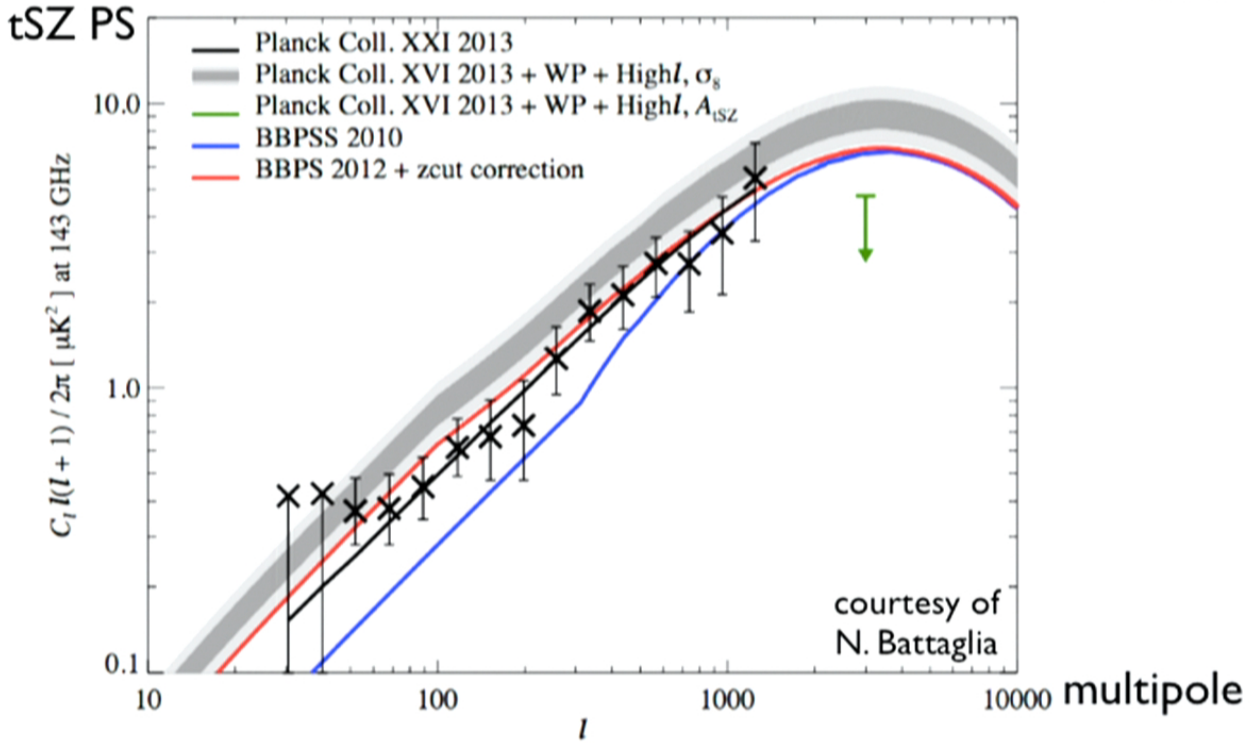

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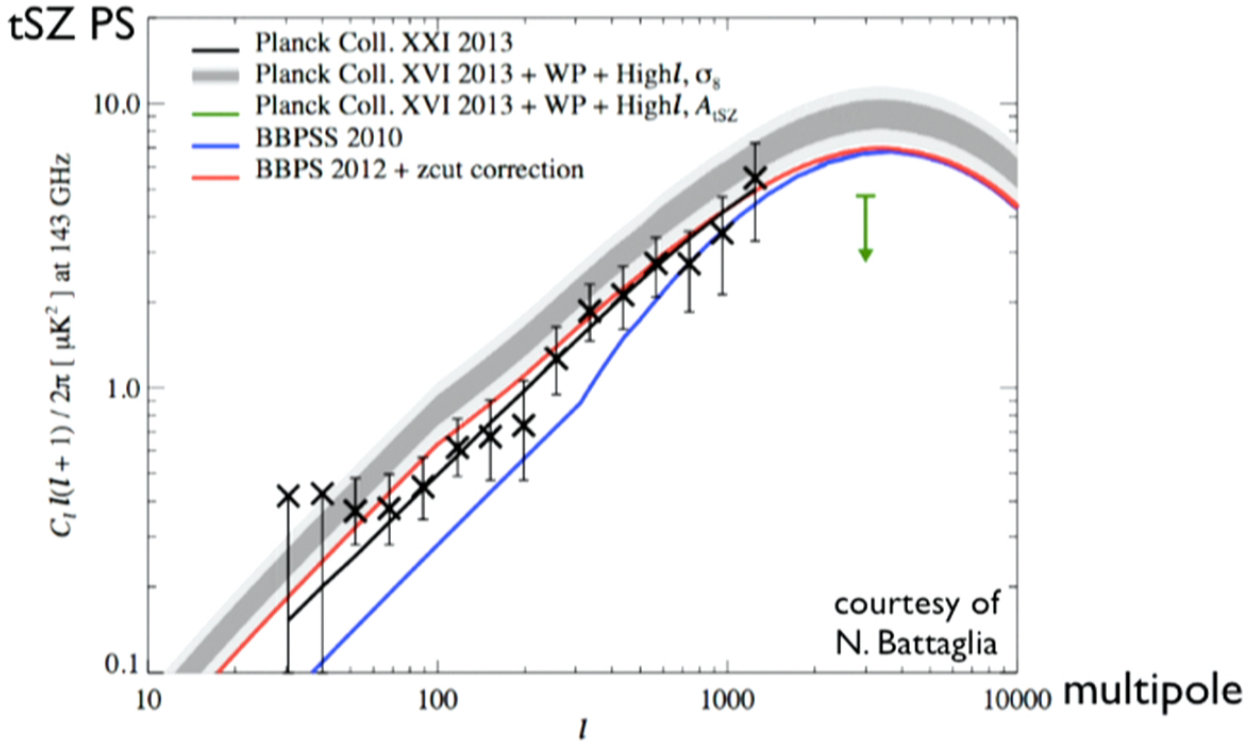

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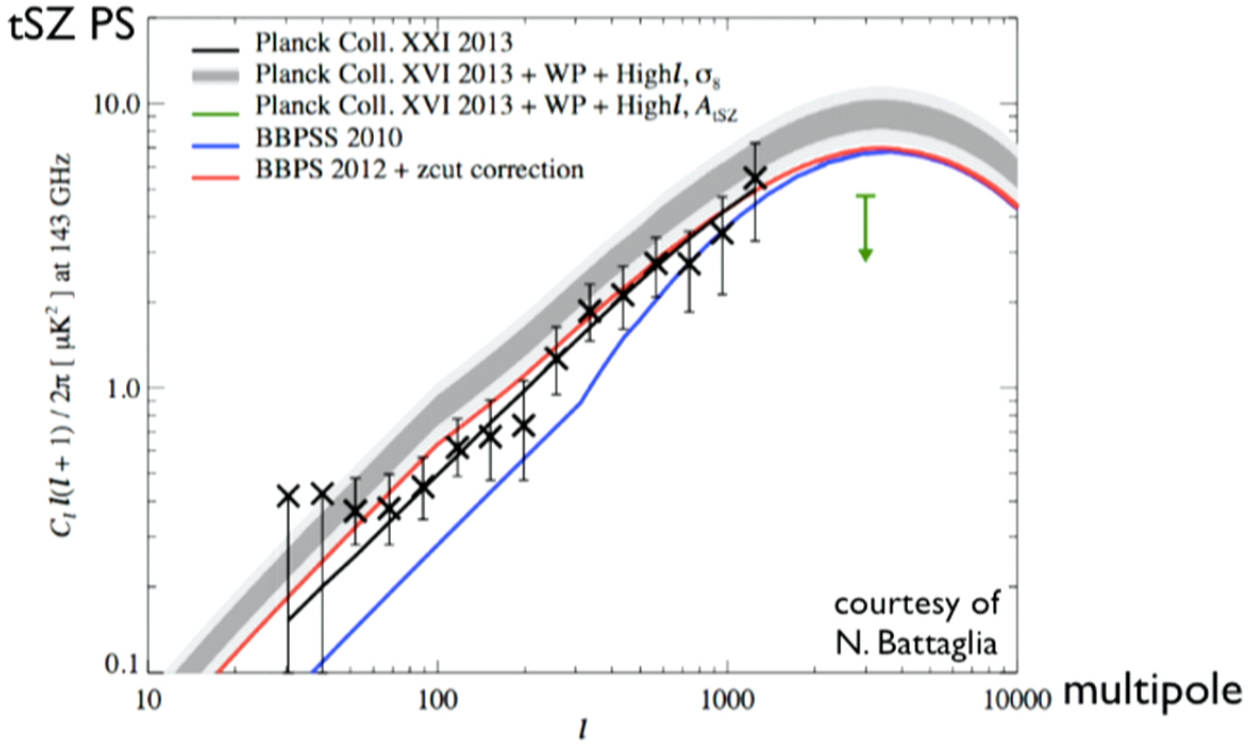

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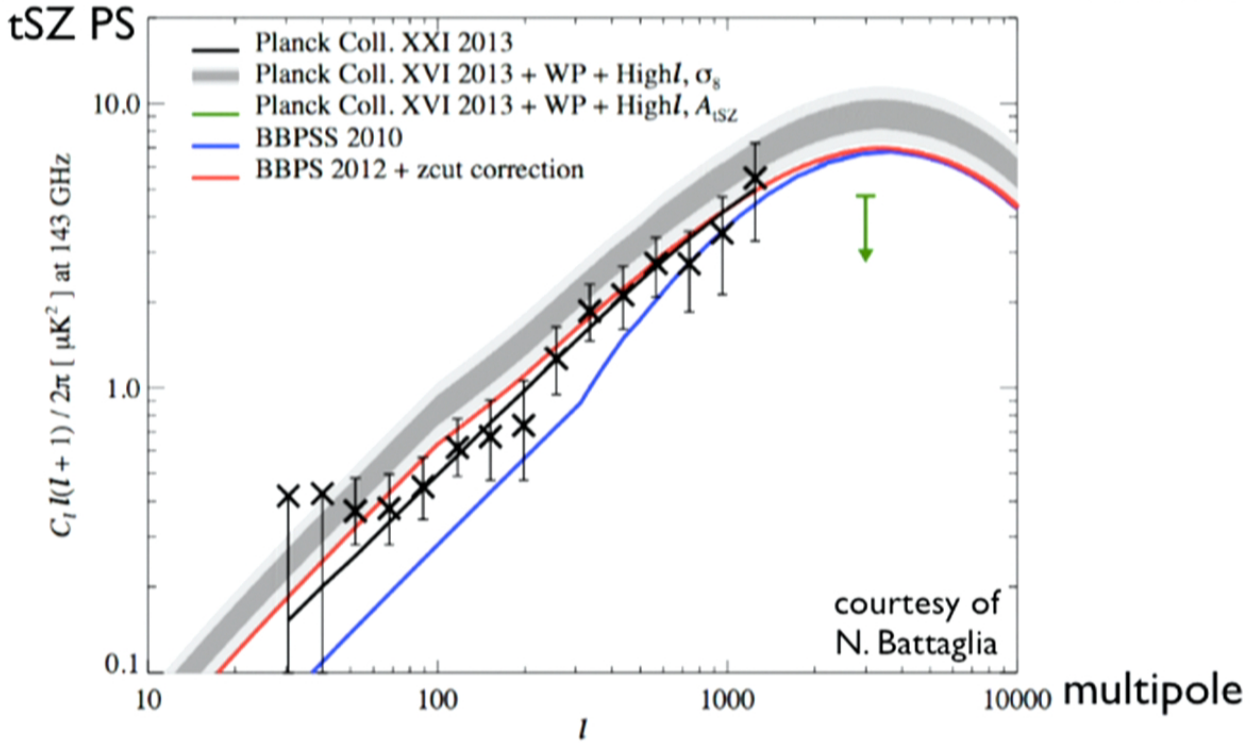

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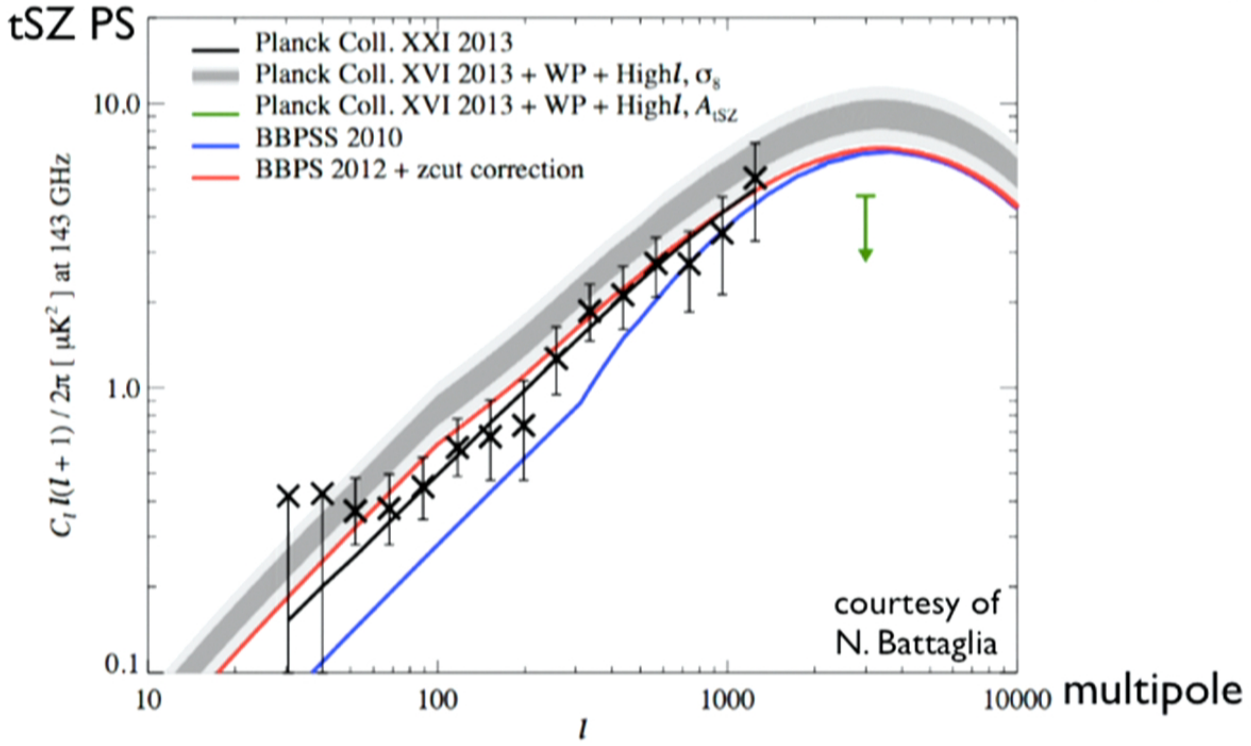

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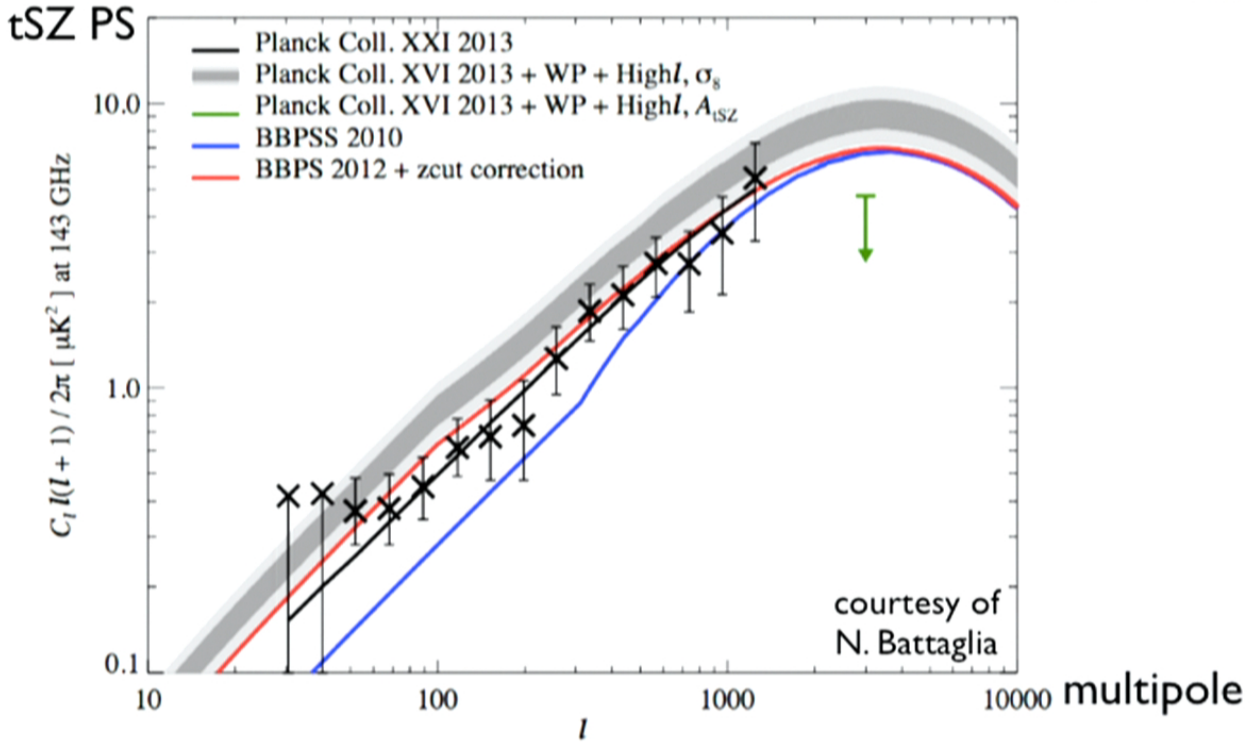

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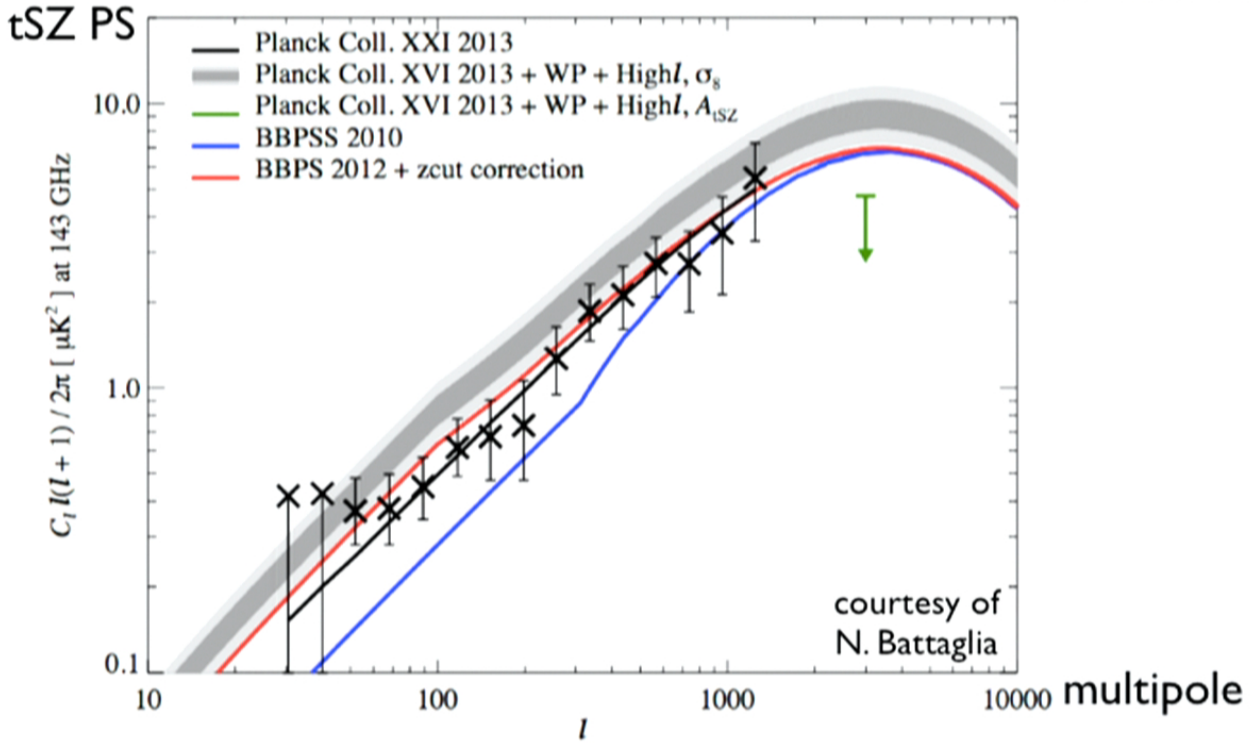

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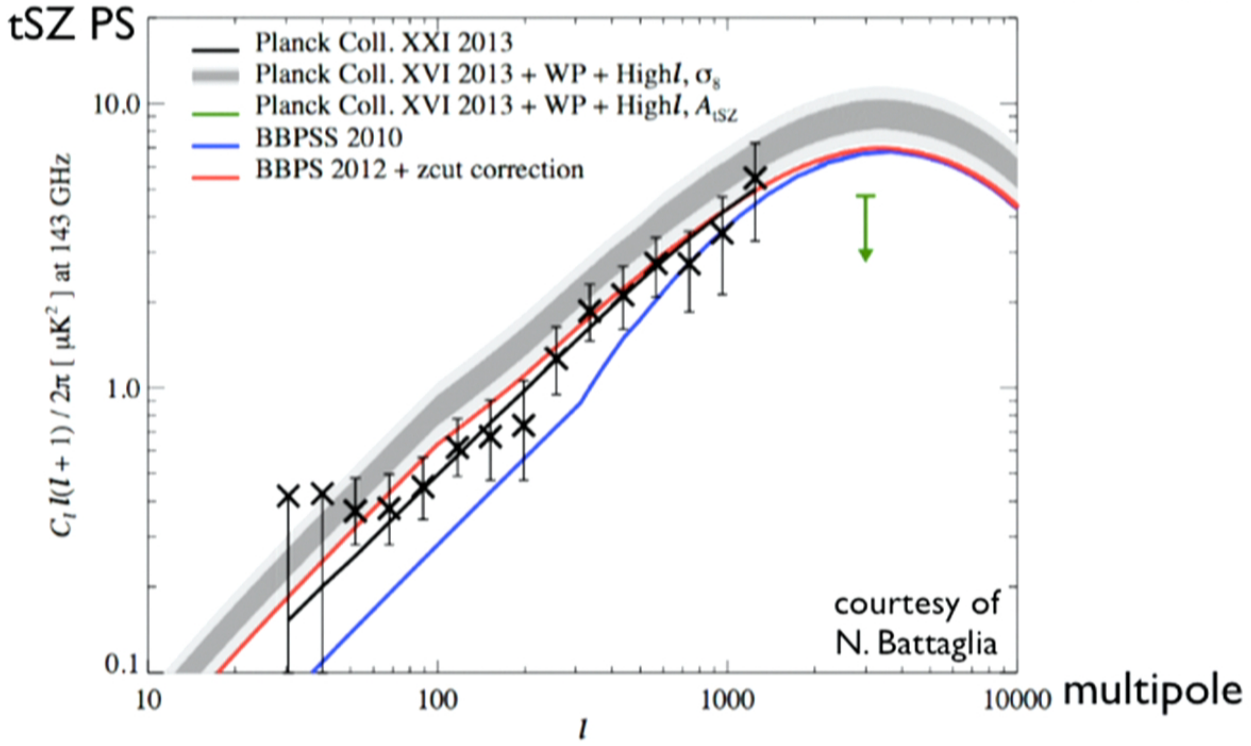

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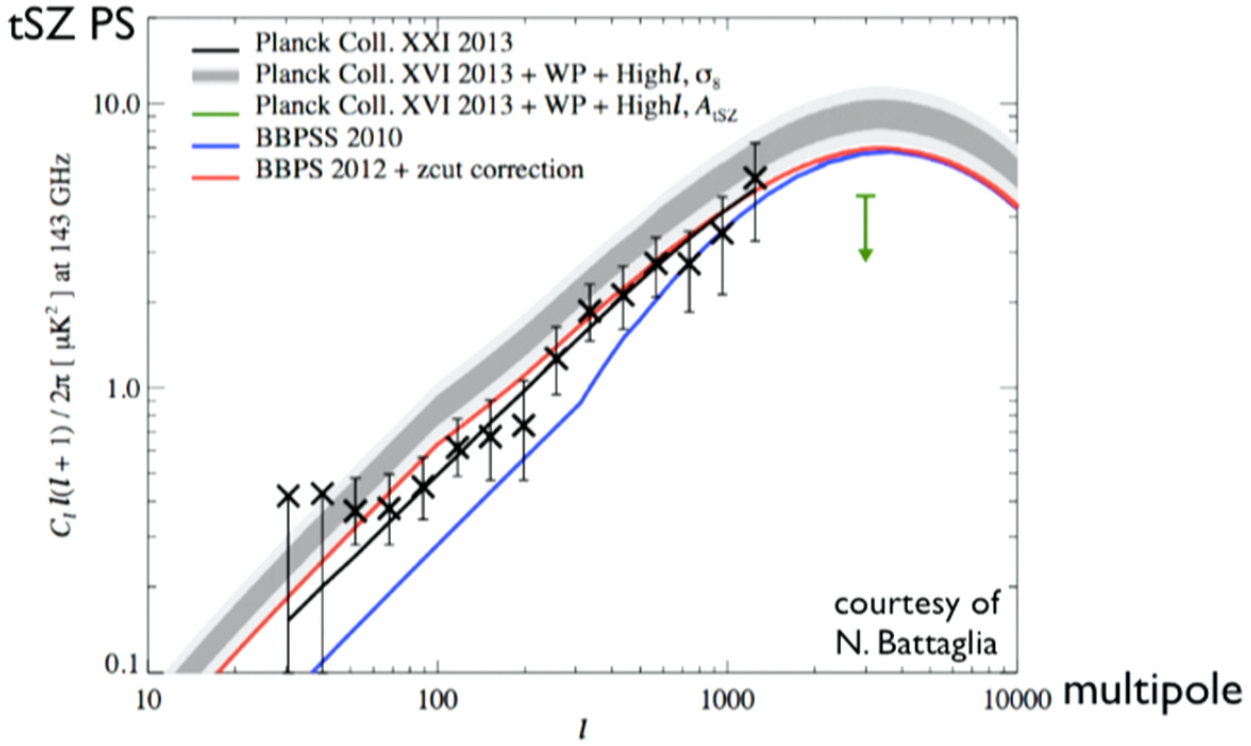

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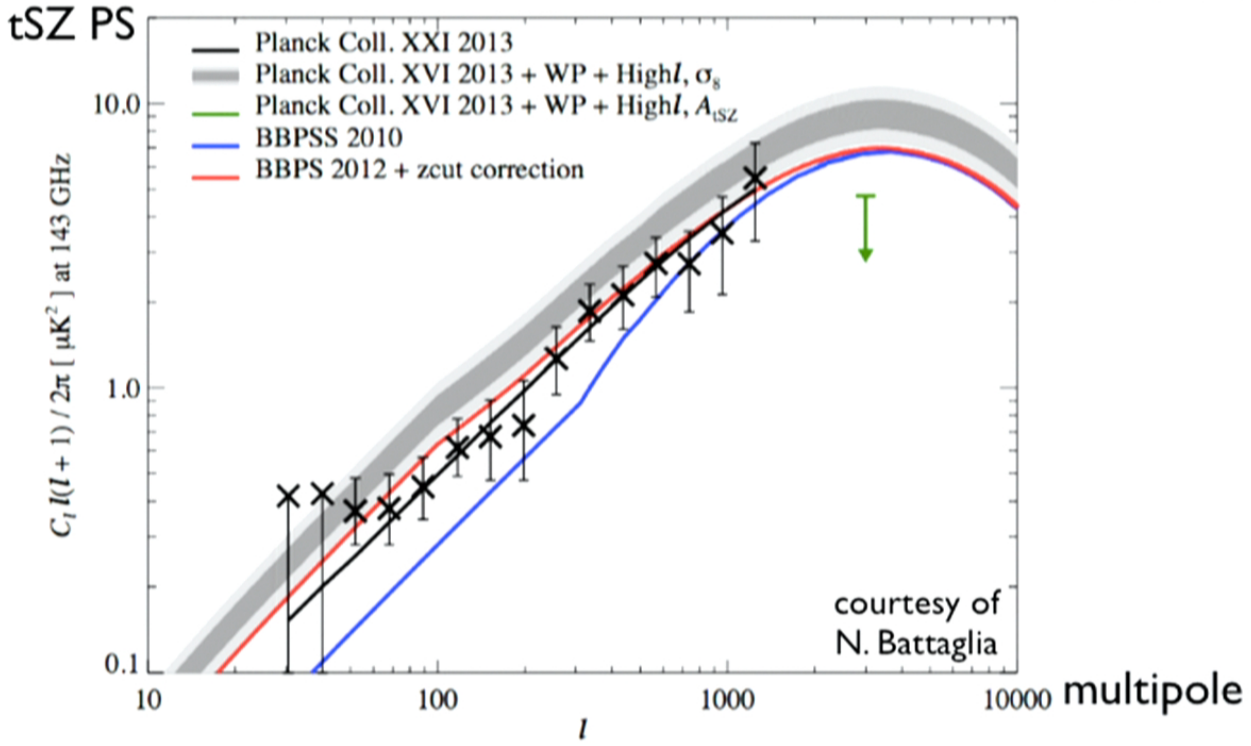

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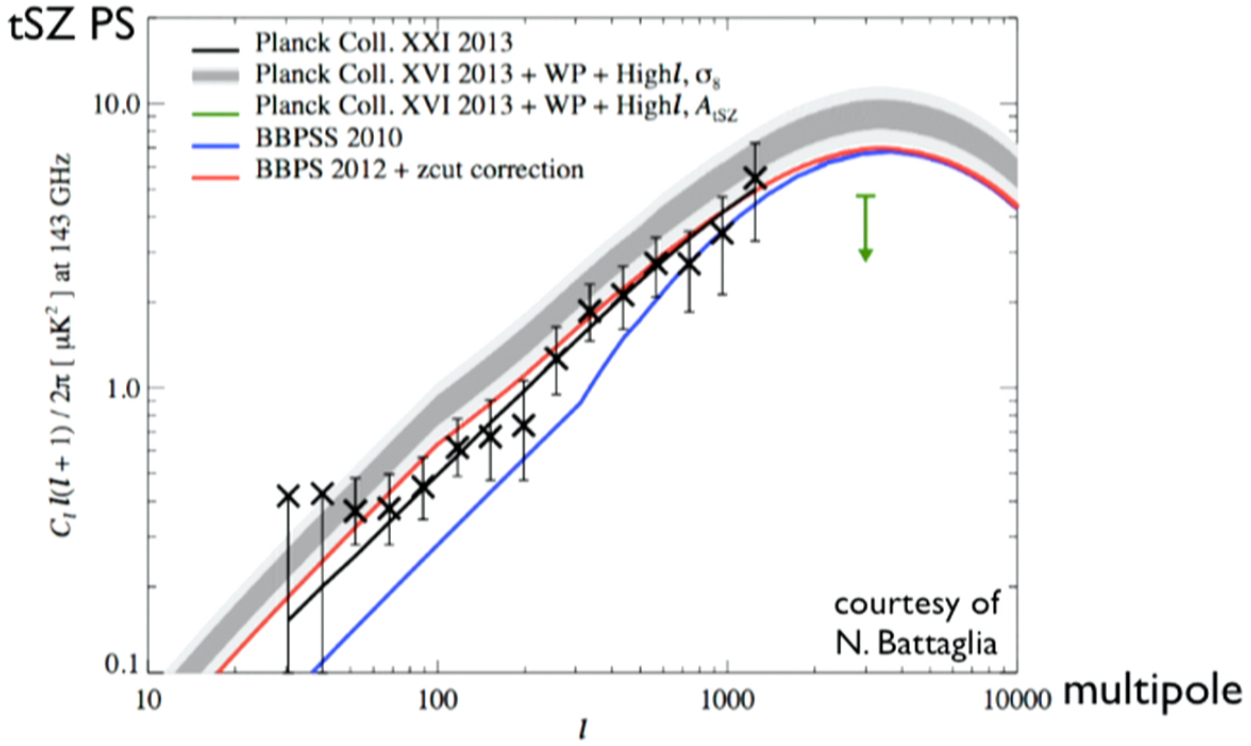

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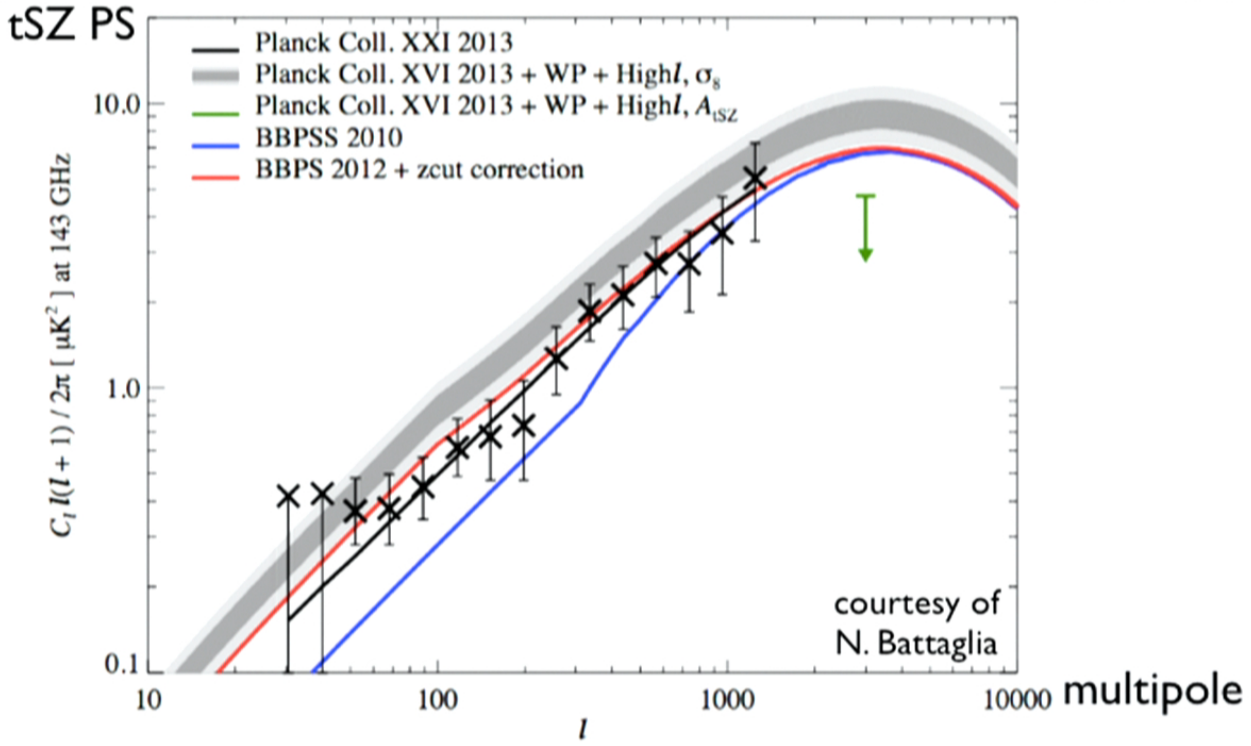

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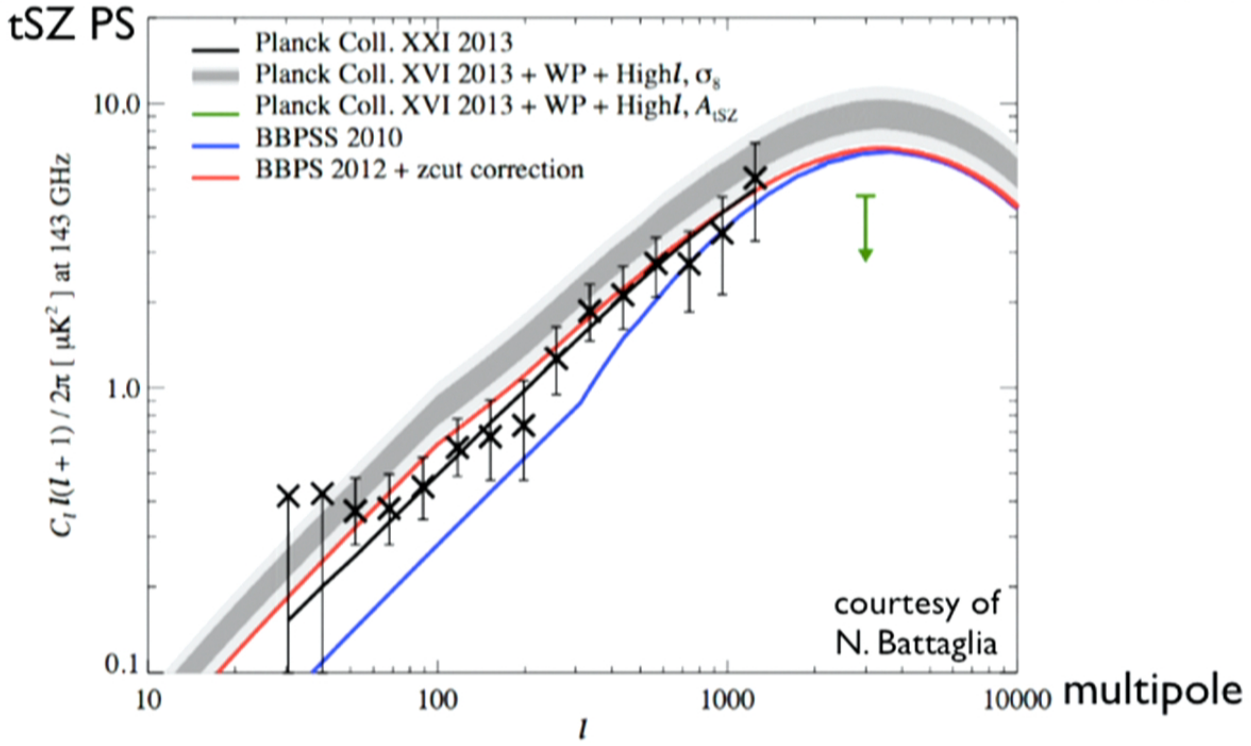

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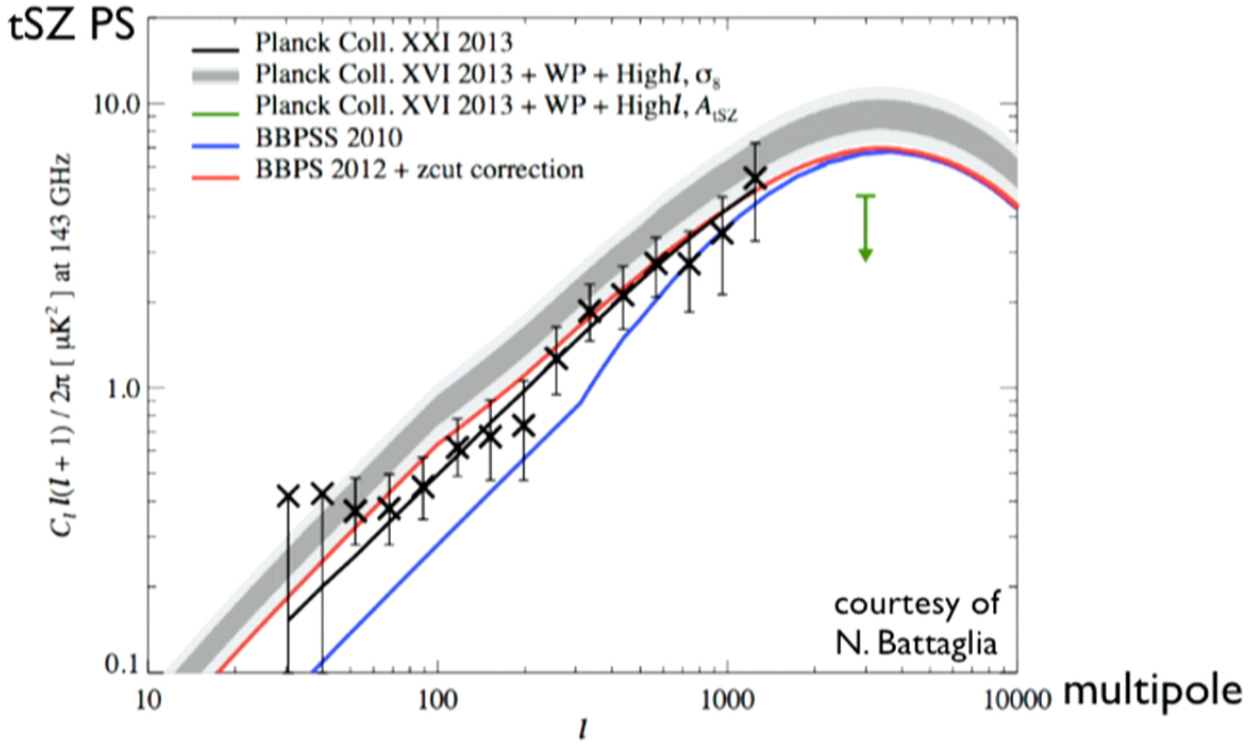

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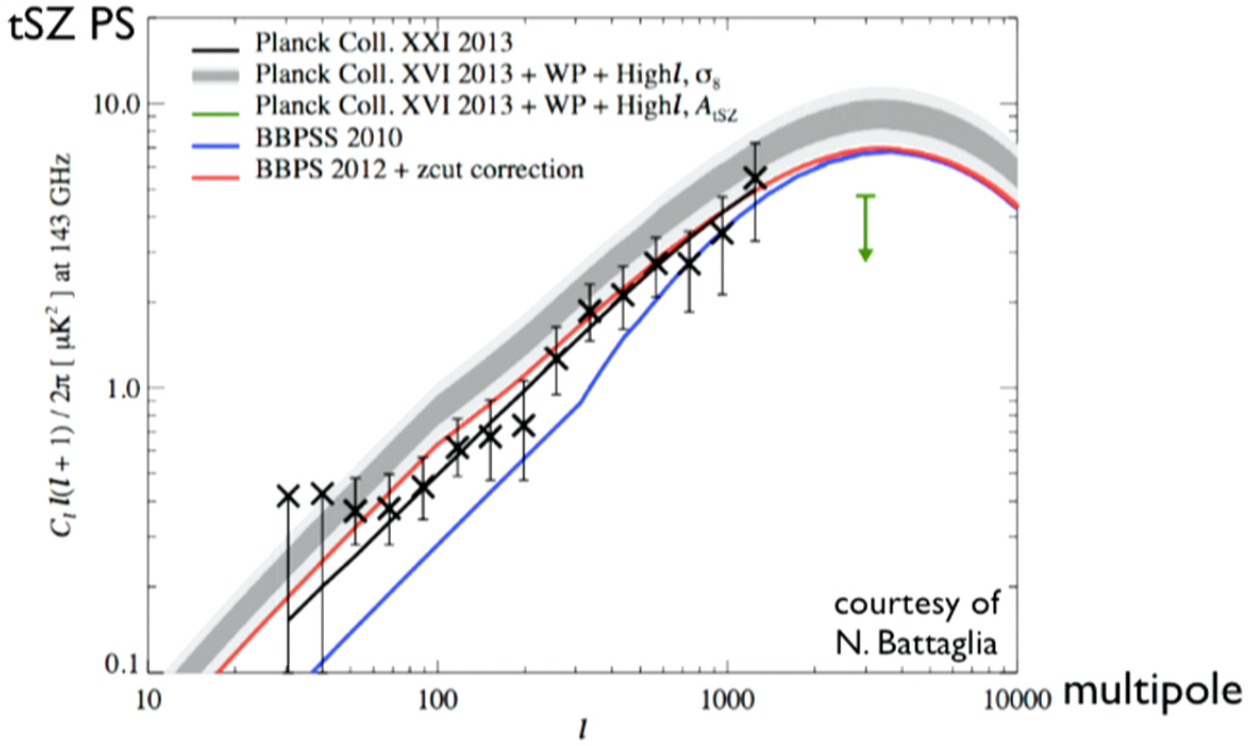

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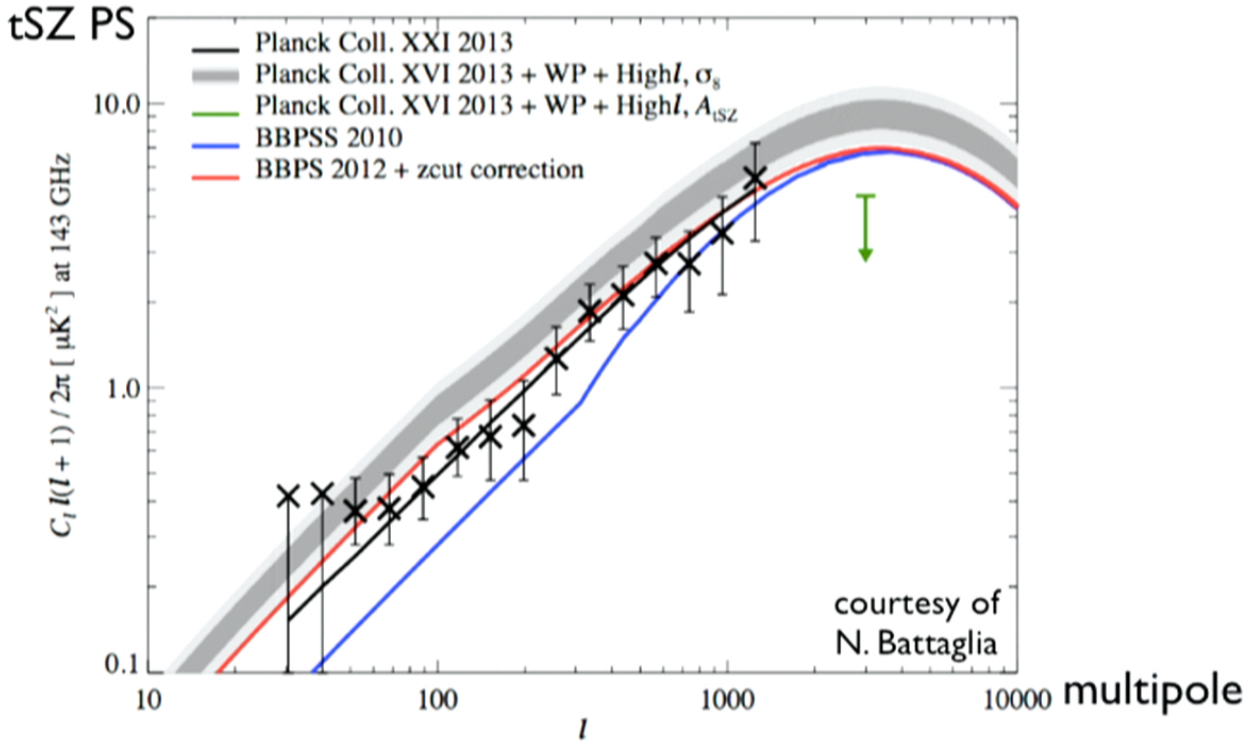

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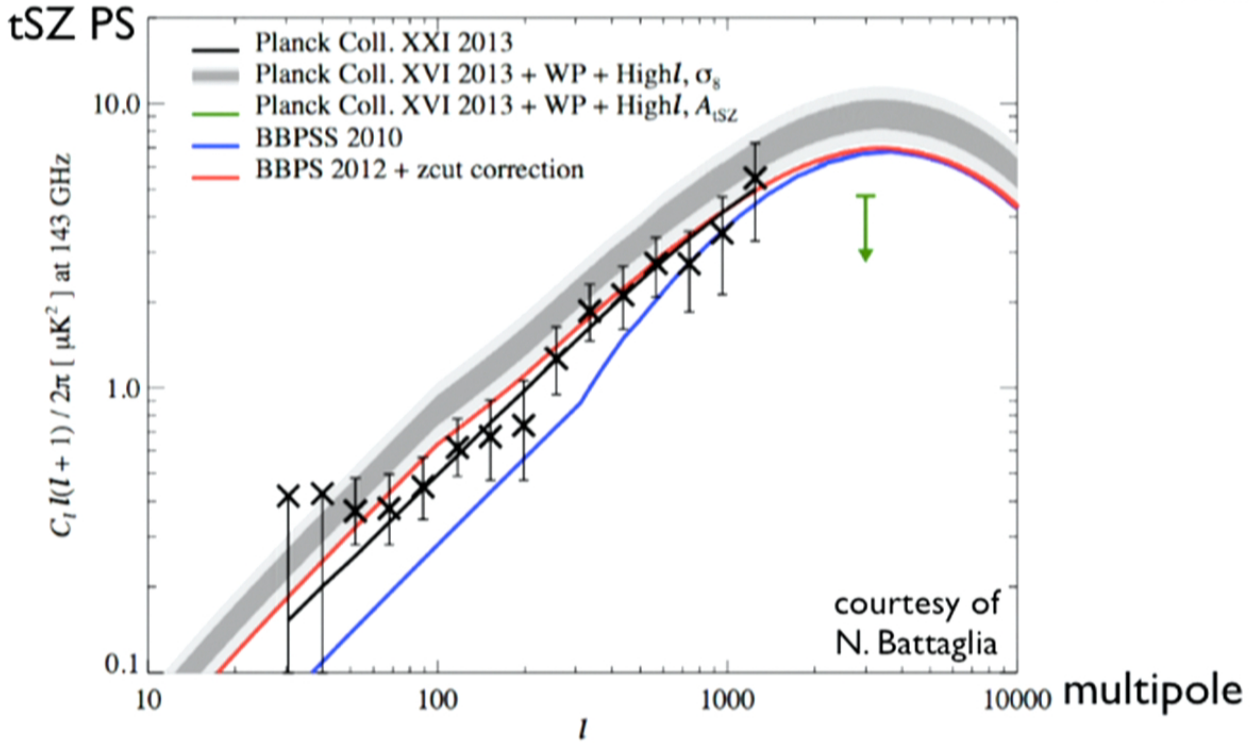

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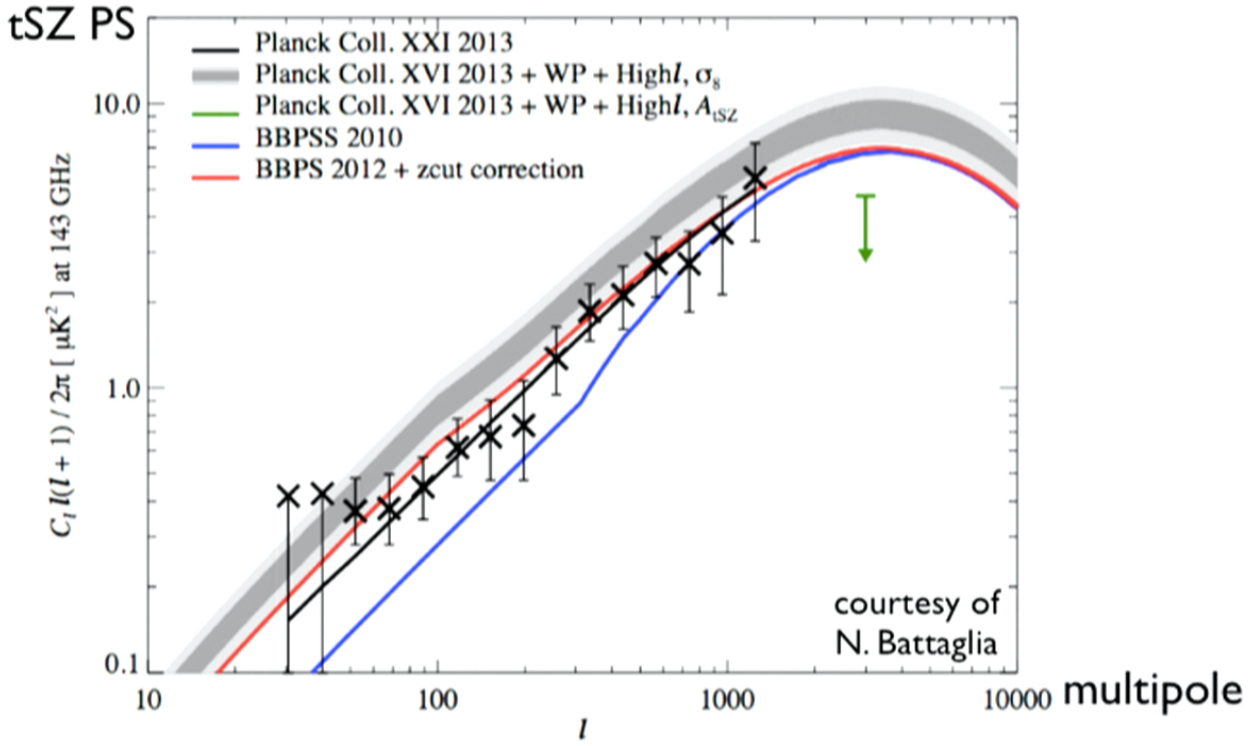

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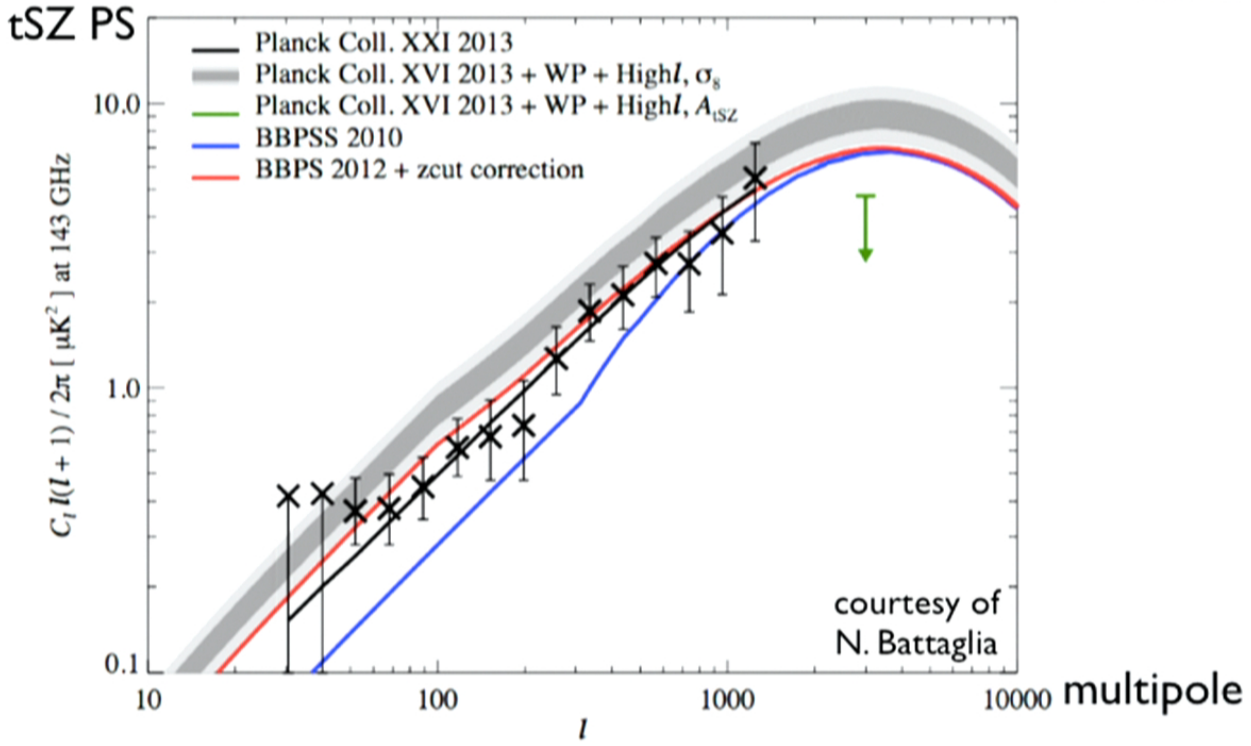

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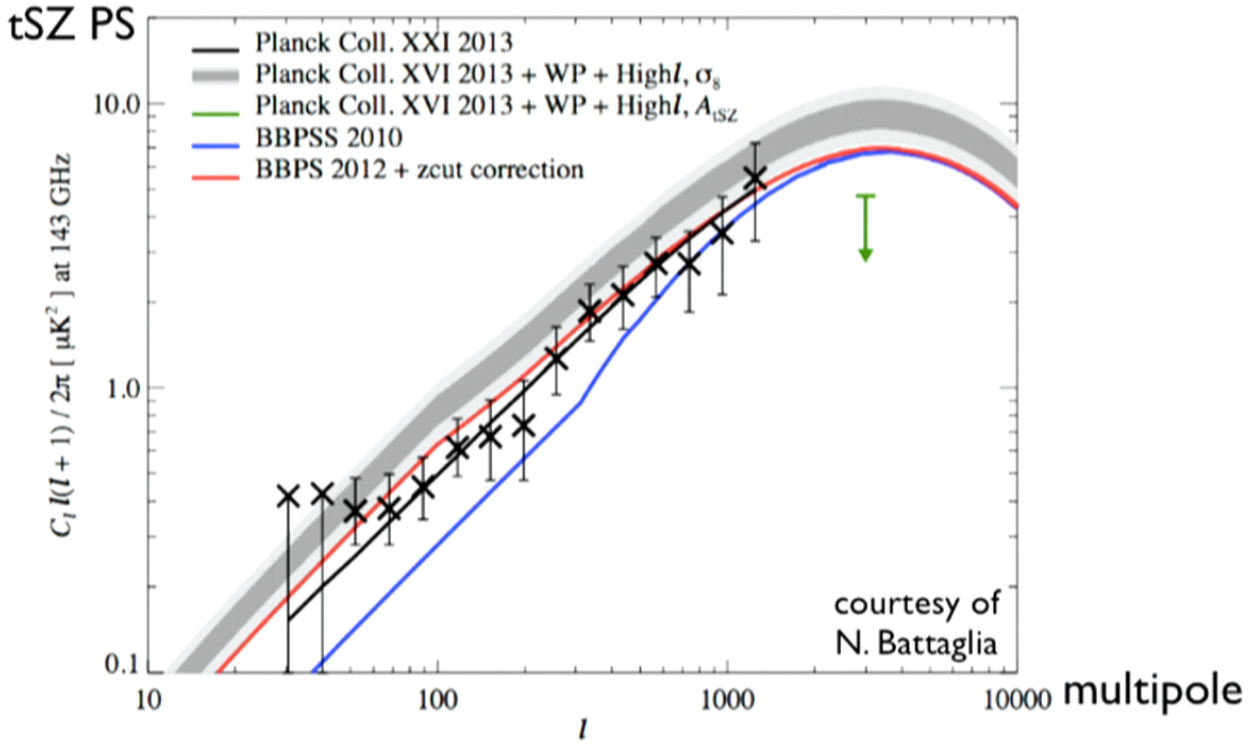

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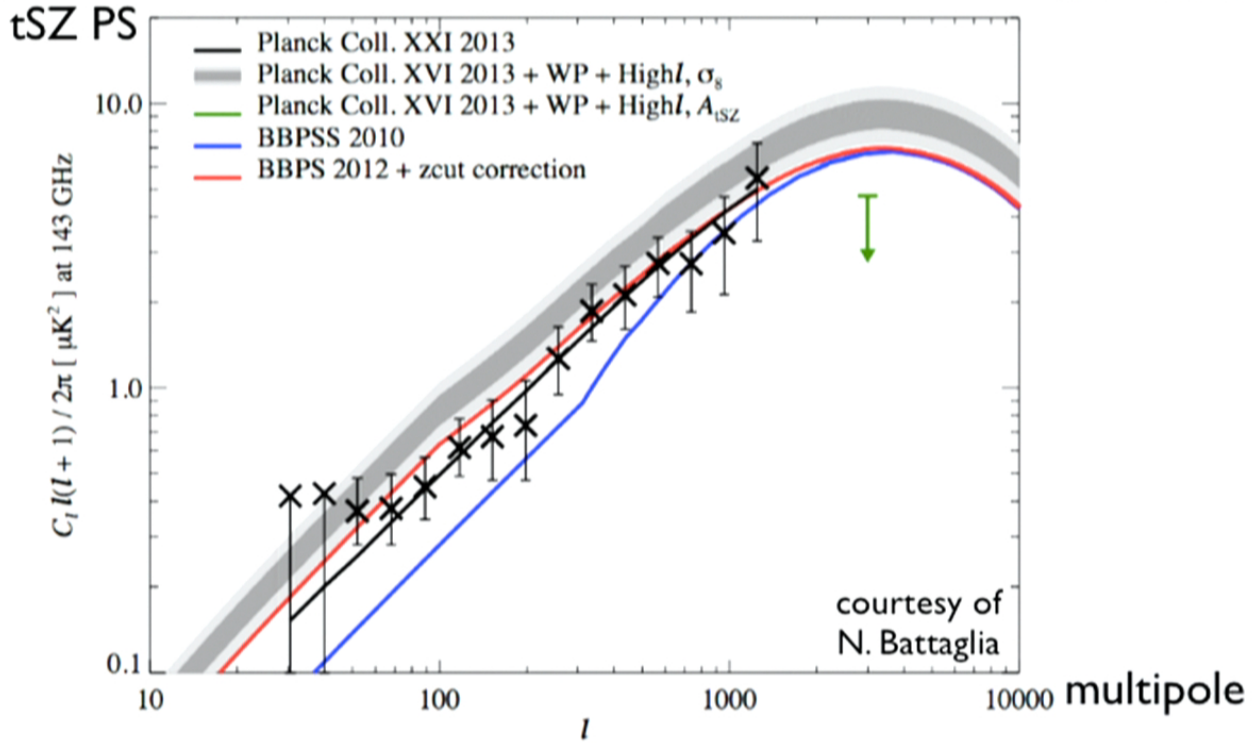

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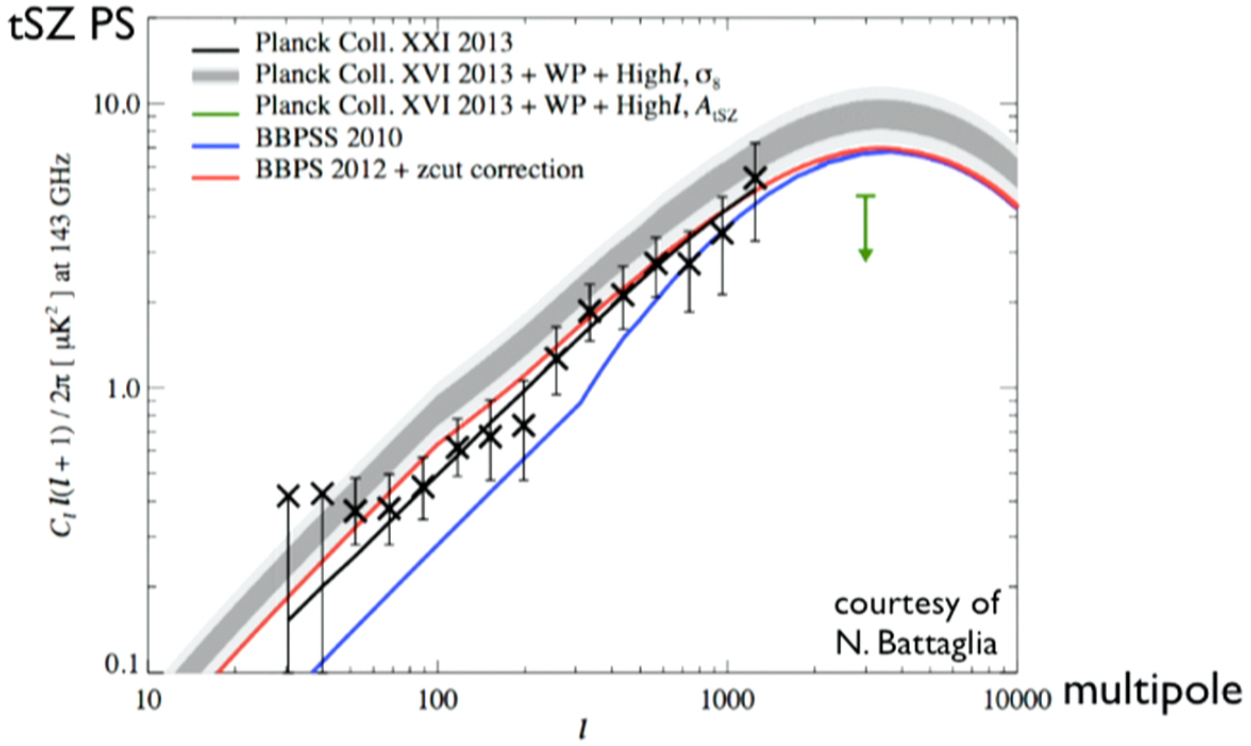
Thermal SZ Power Spectrum



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Colin Hill
Princeton

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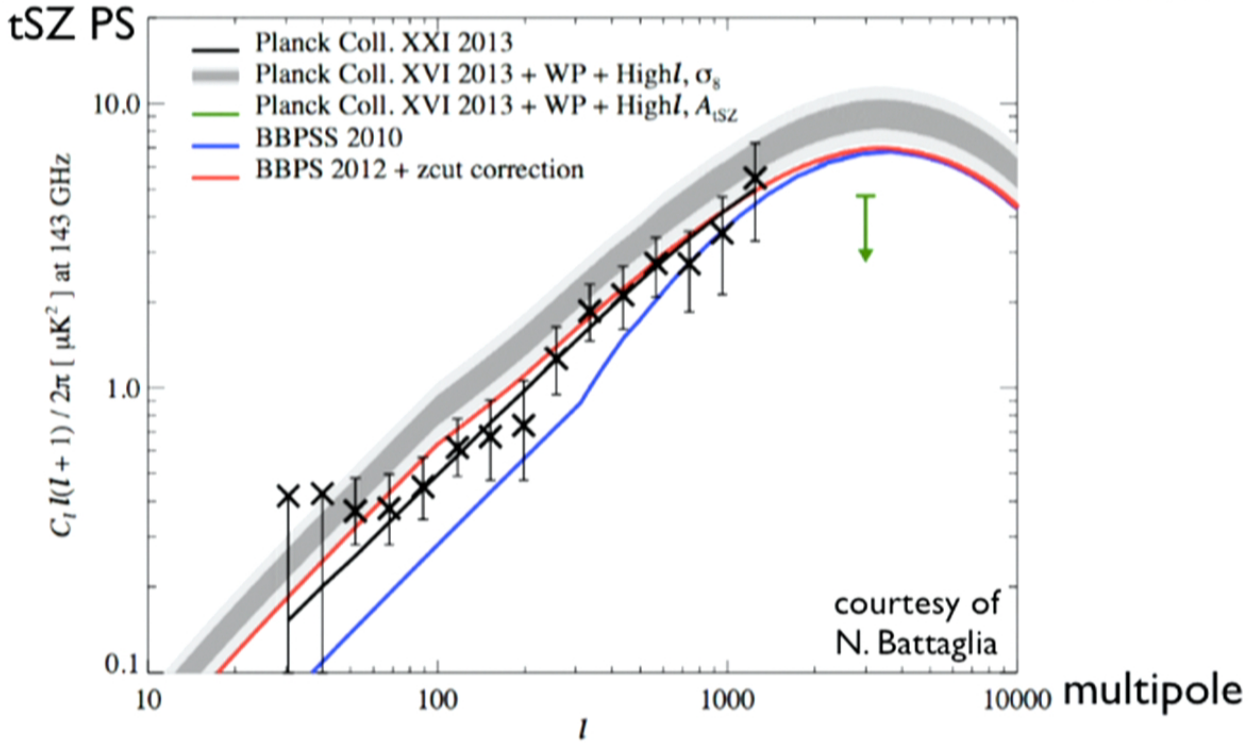

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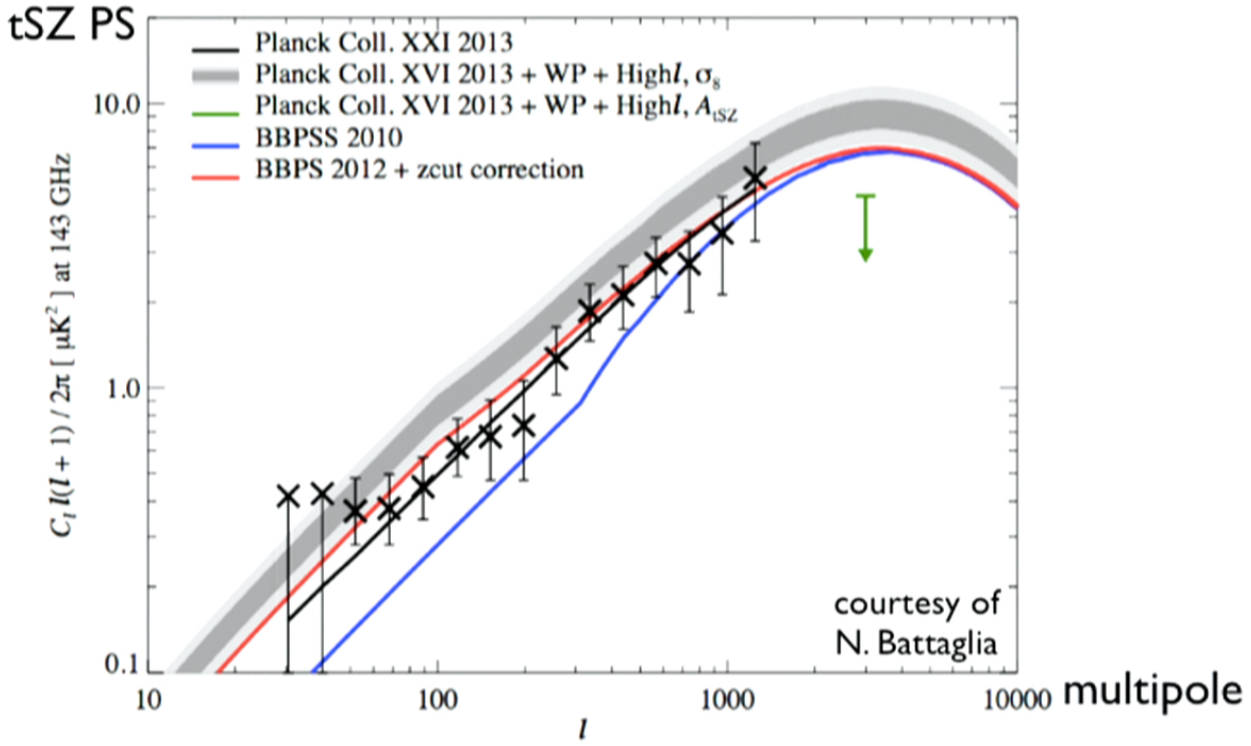

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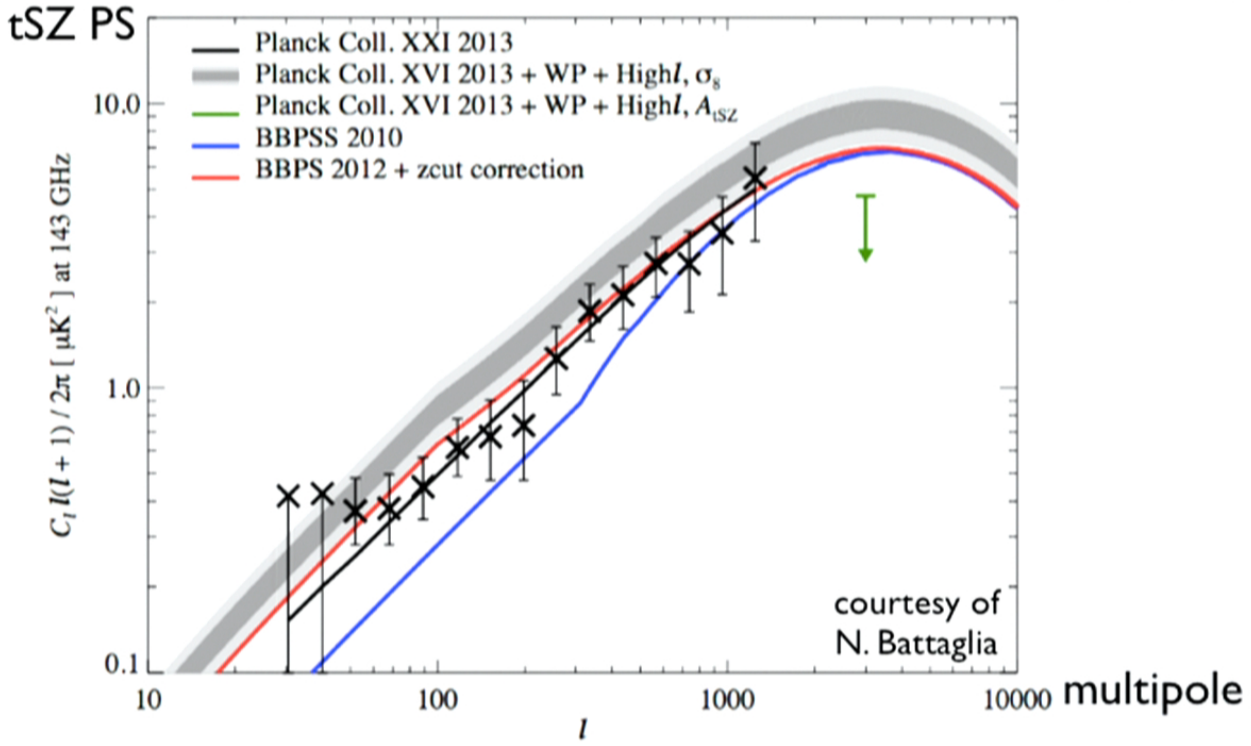

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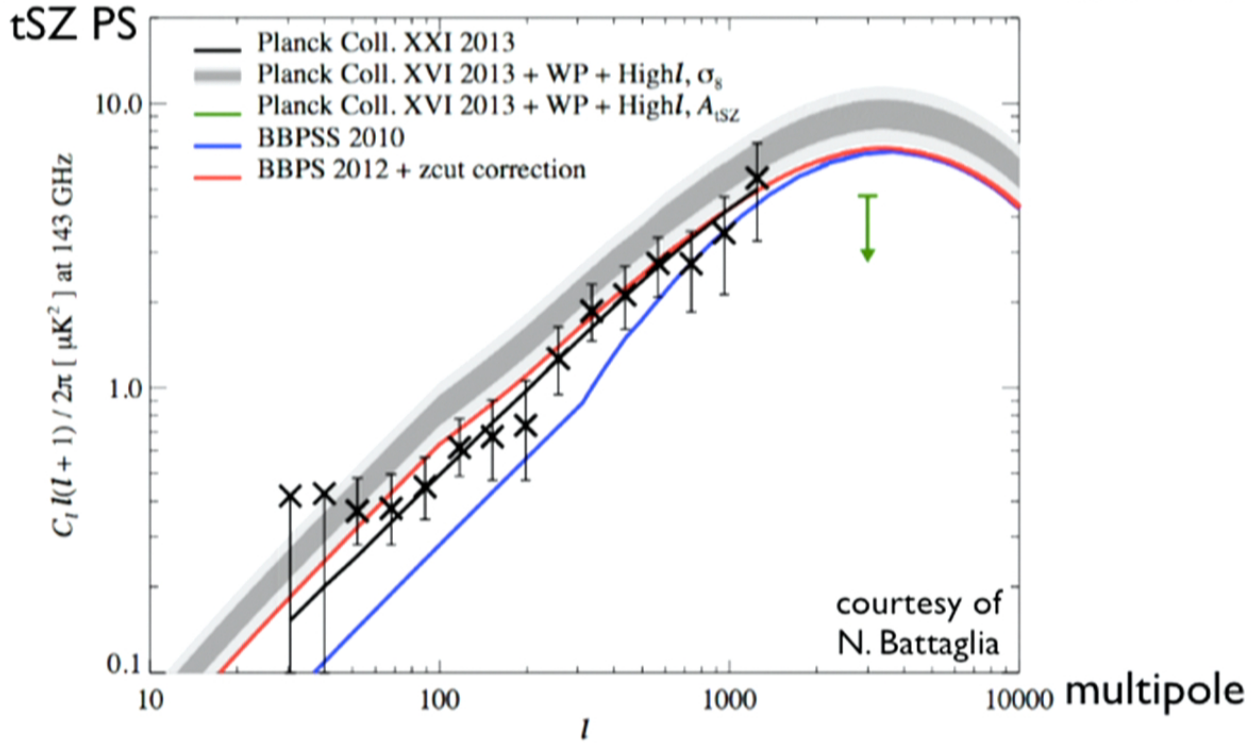

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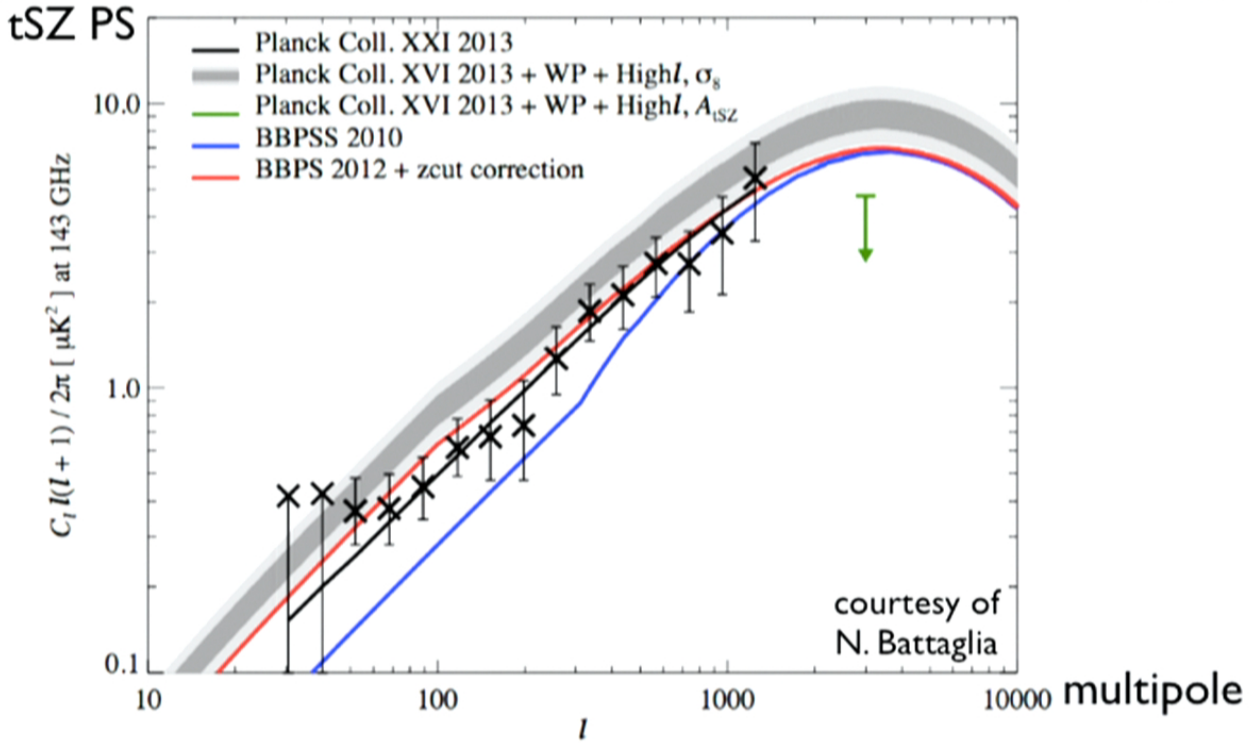

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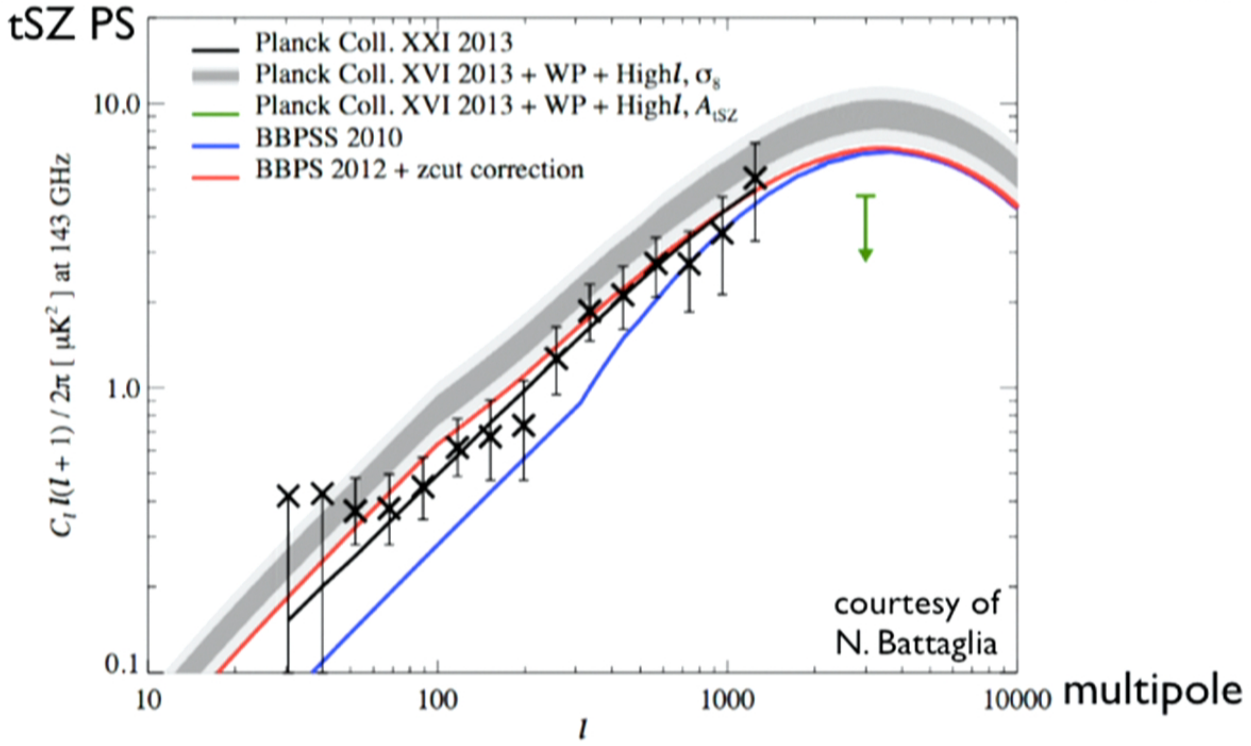

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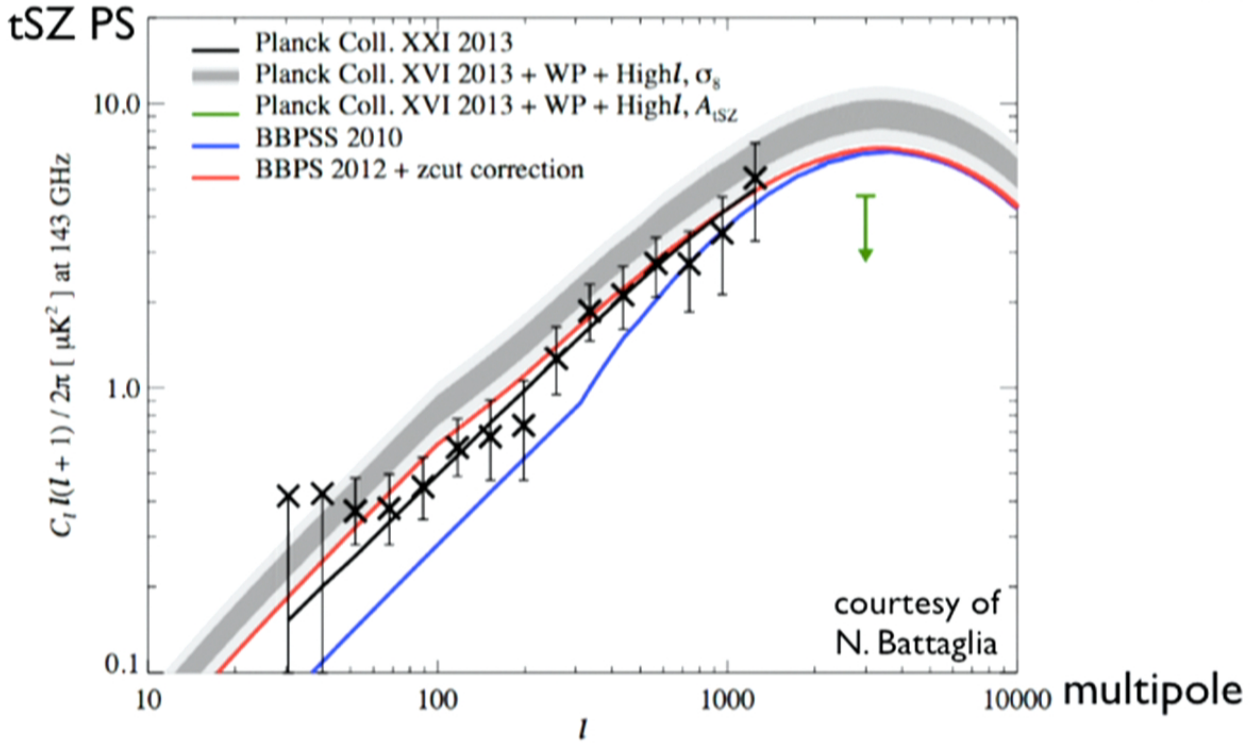

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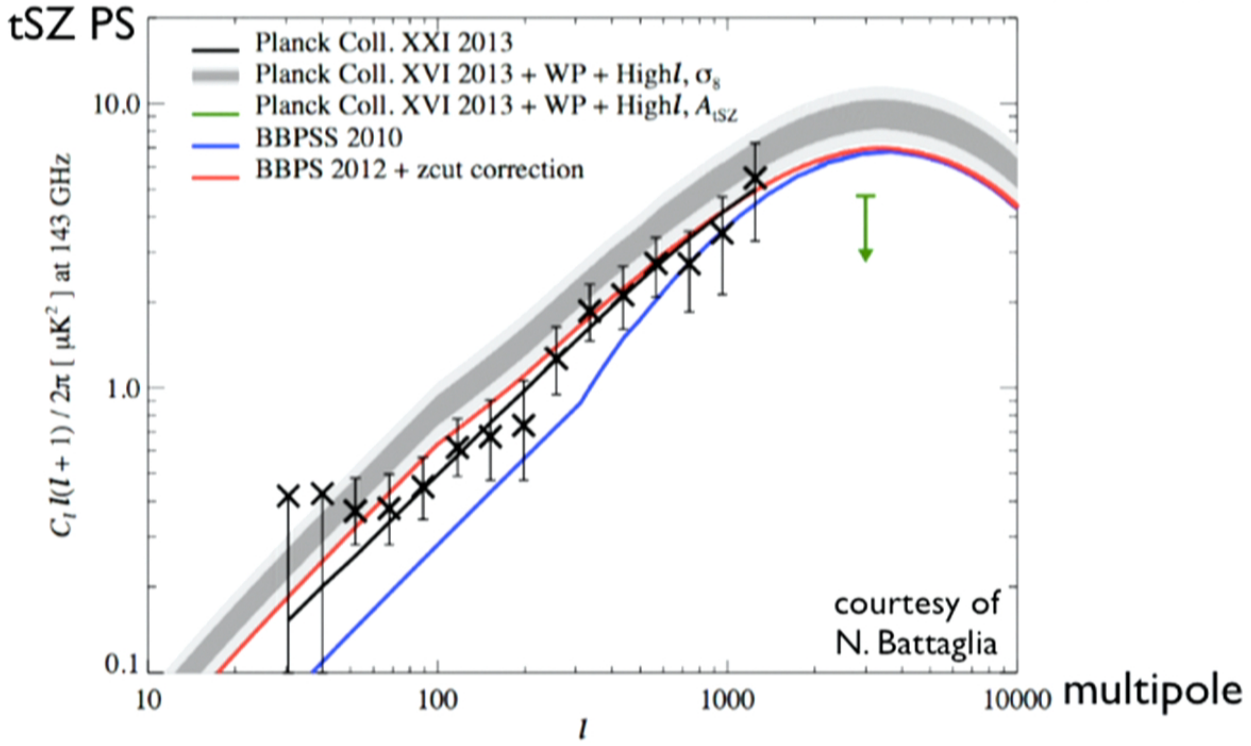

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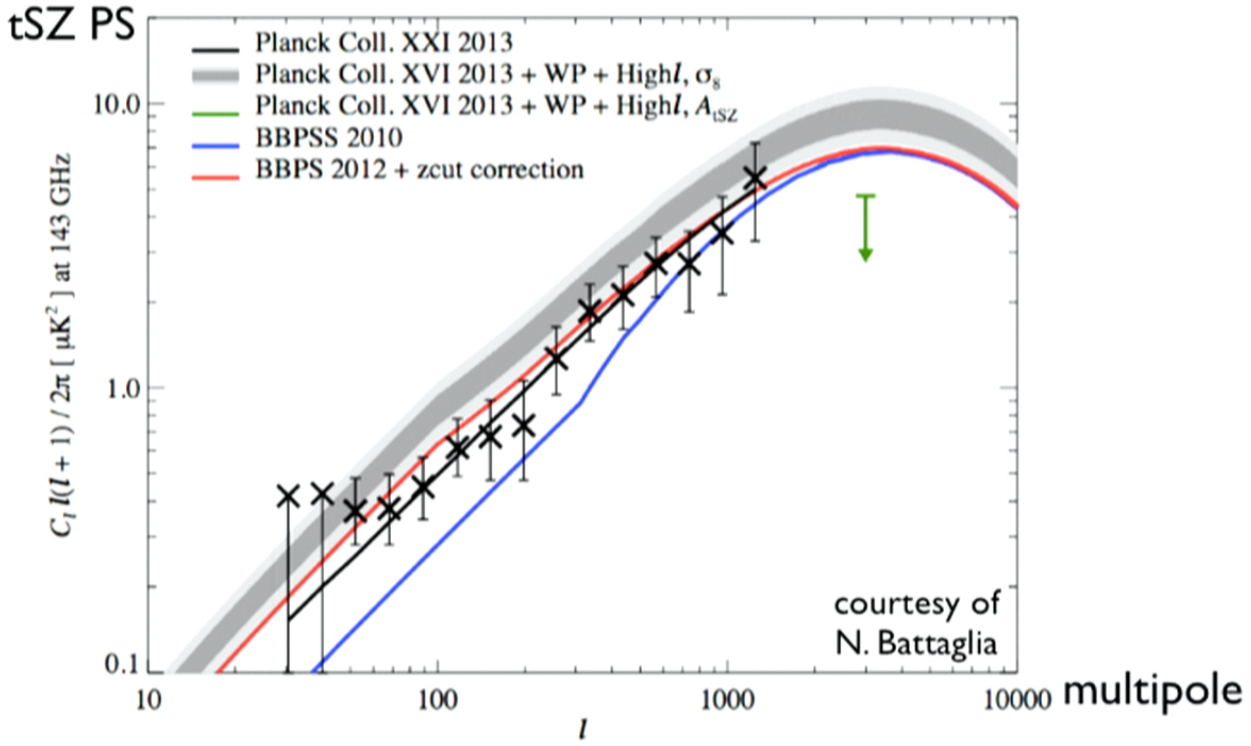

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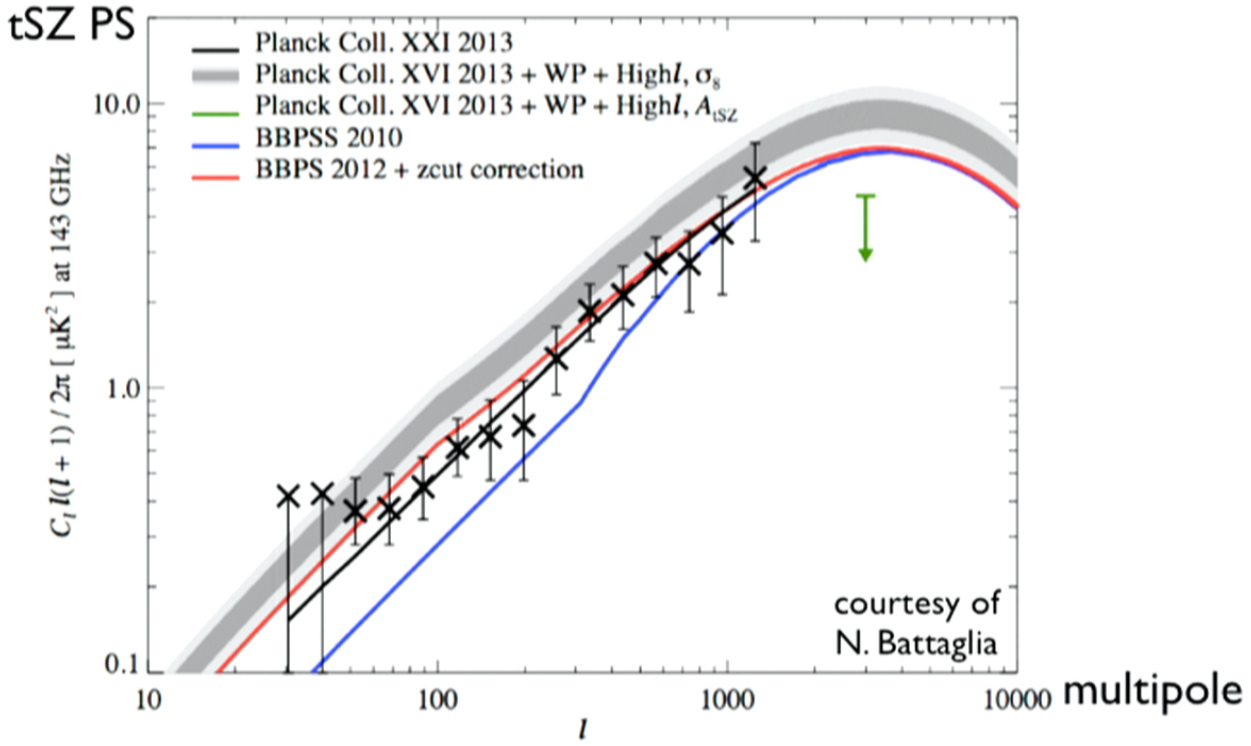

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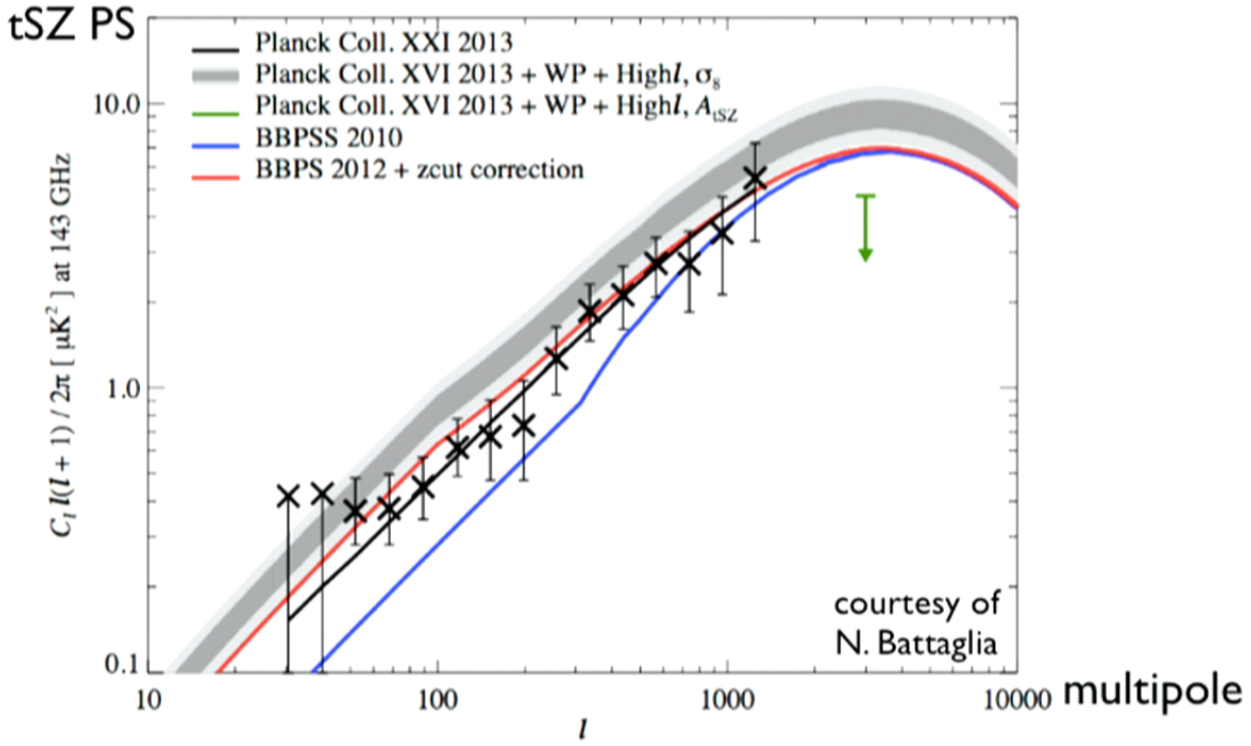

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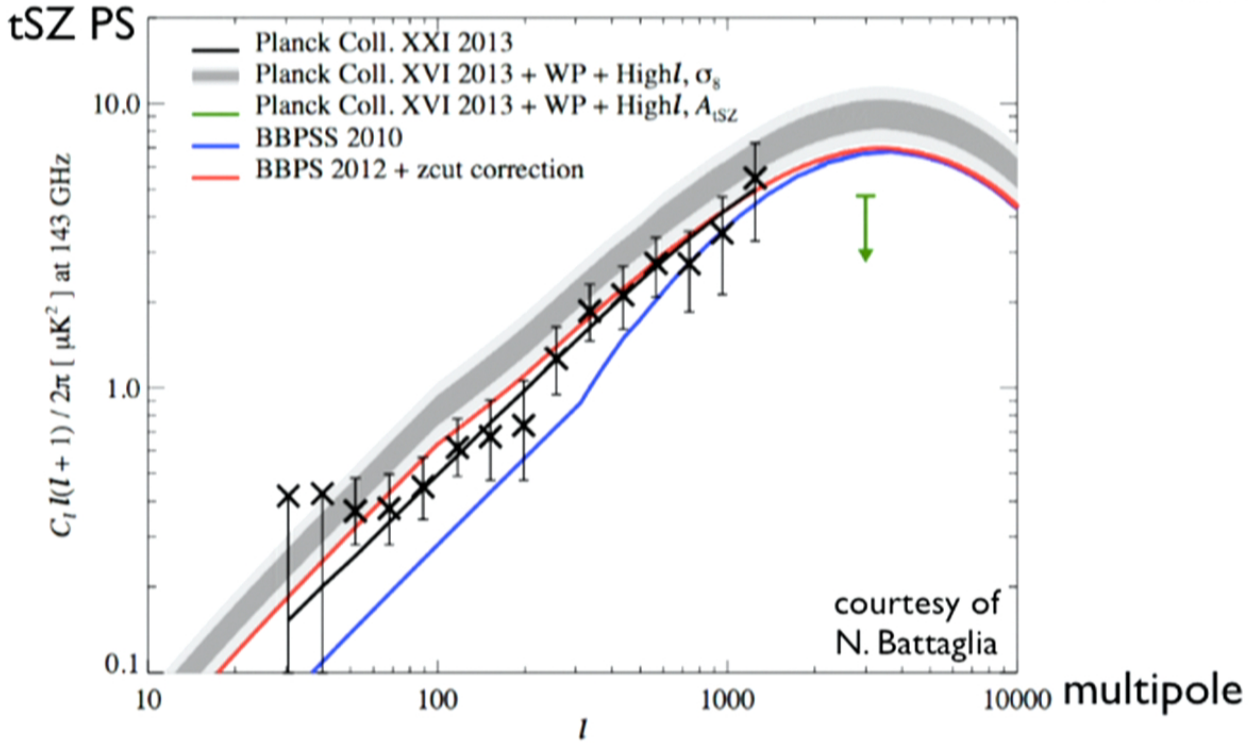

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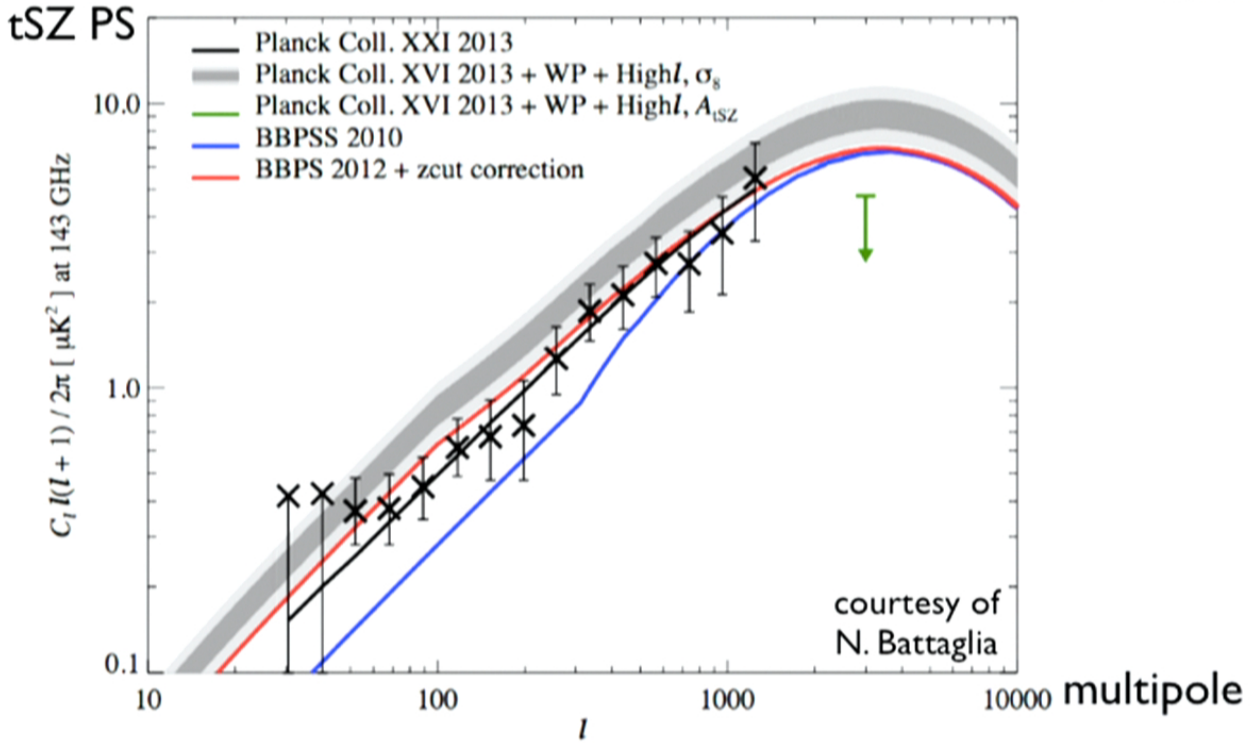

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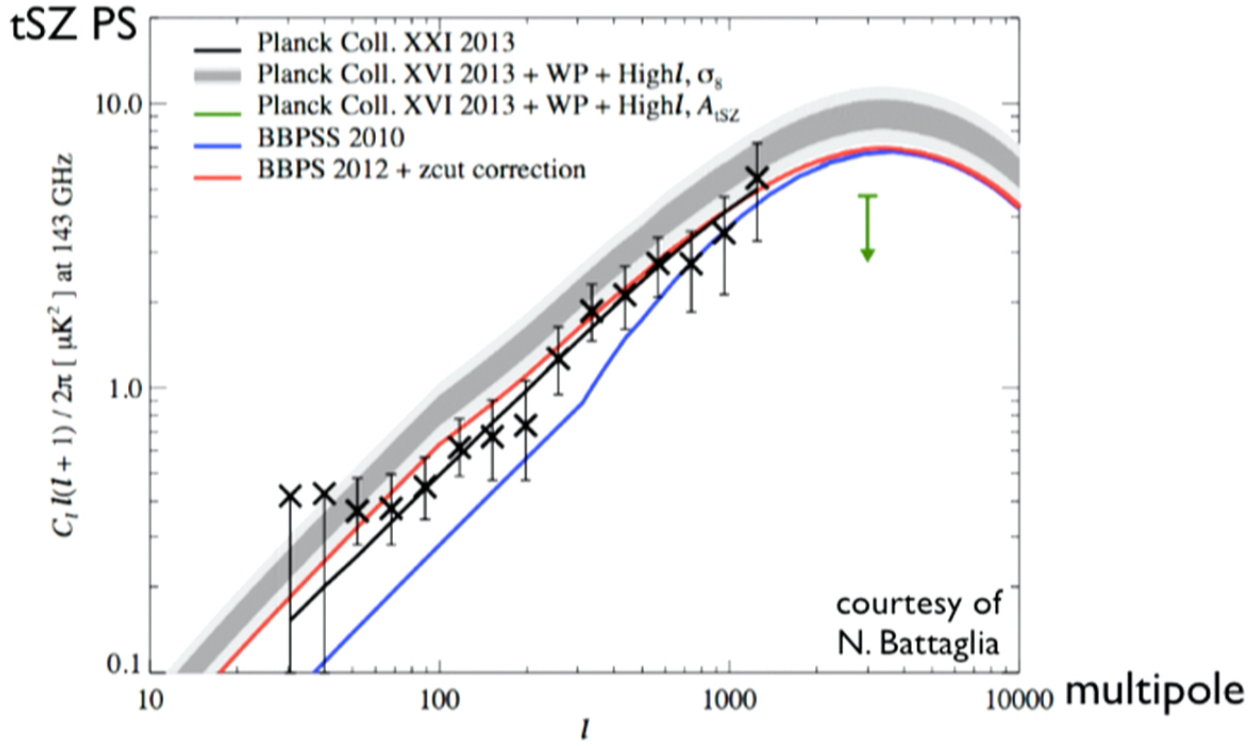

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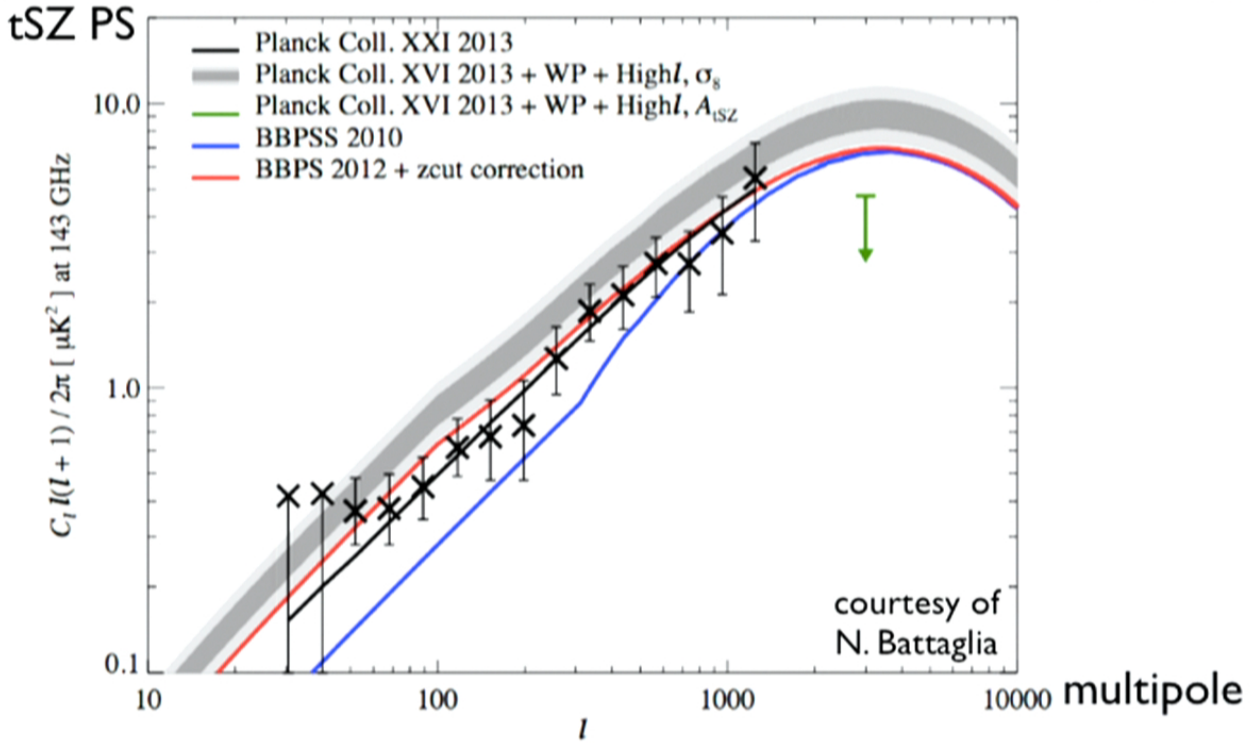

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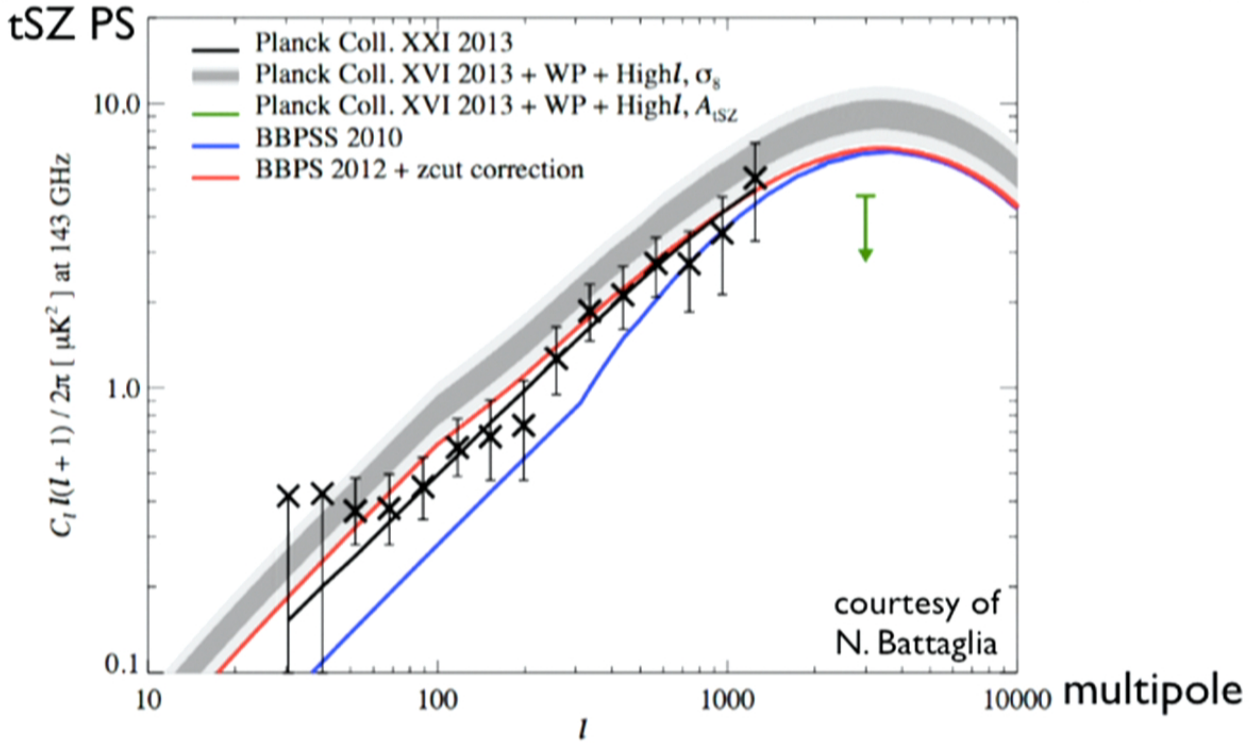

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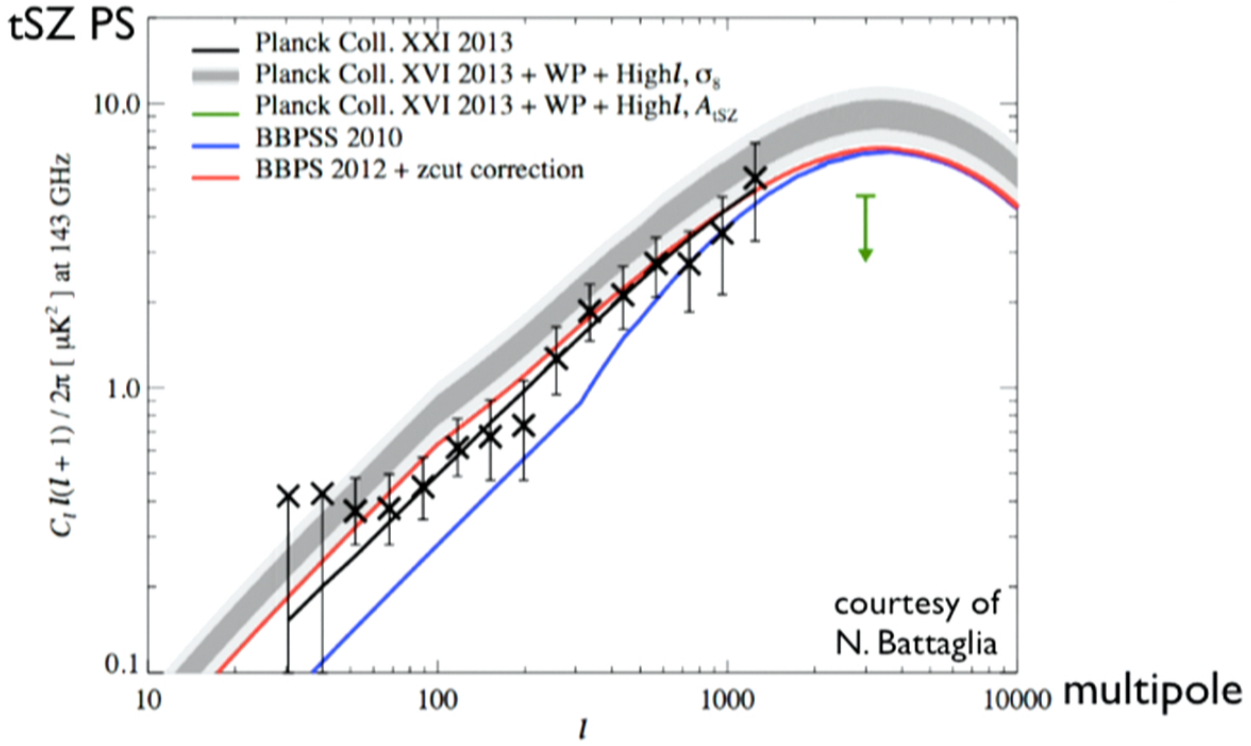

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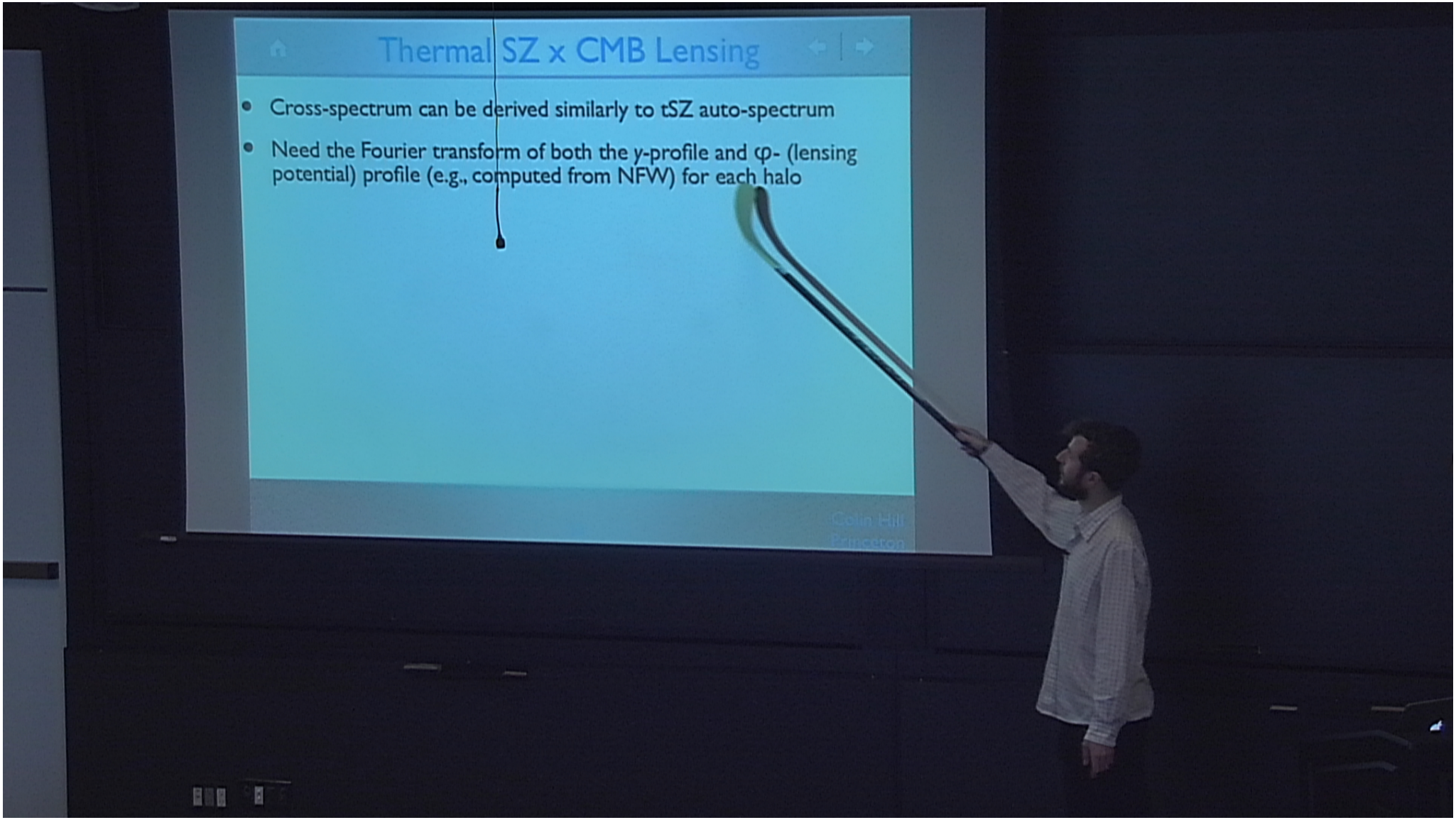
Thermal SZ x CMB Lensing
Cross-spectrum can be derived similarly to tSZ auto-spectrum
Need the Fourier transform of both the y-profile and φ- (lensing potential) profile (e.g., computed from NFW) for each halo

Thermal SZ x CMB Lensing

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Princeton

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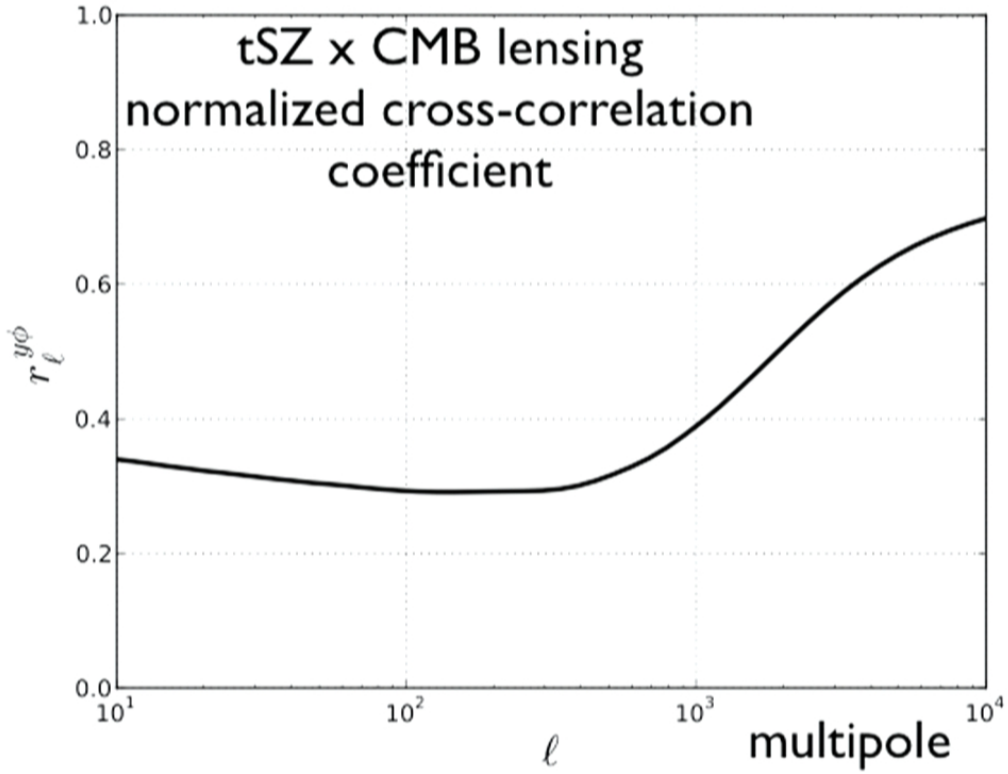
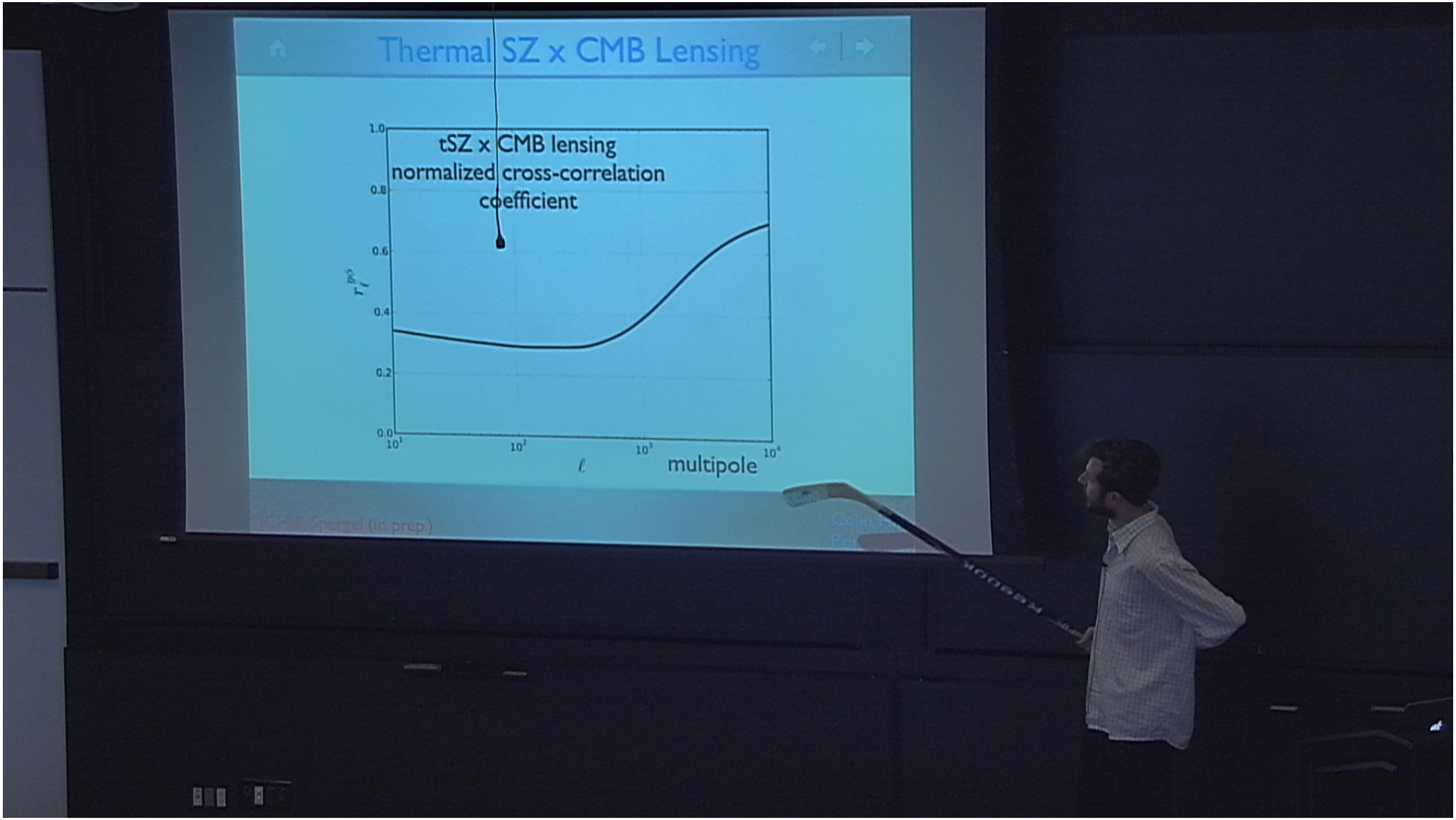
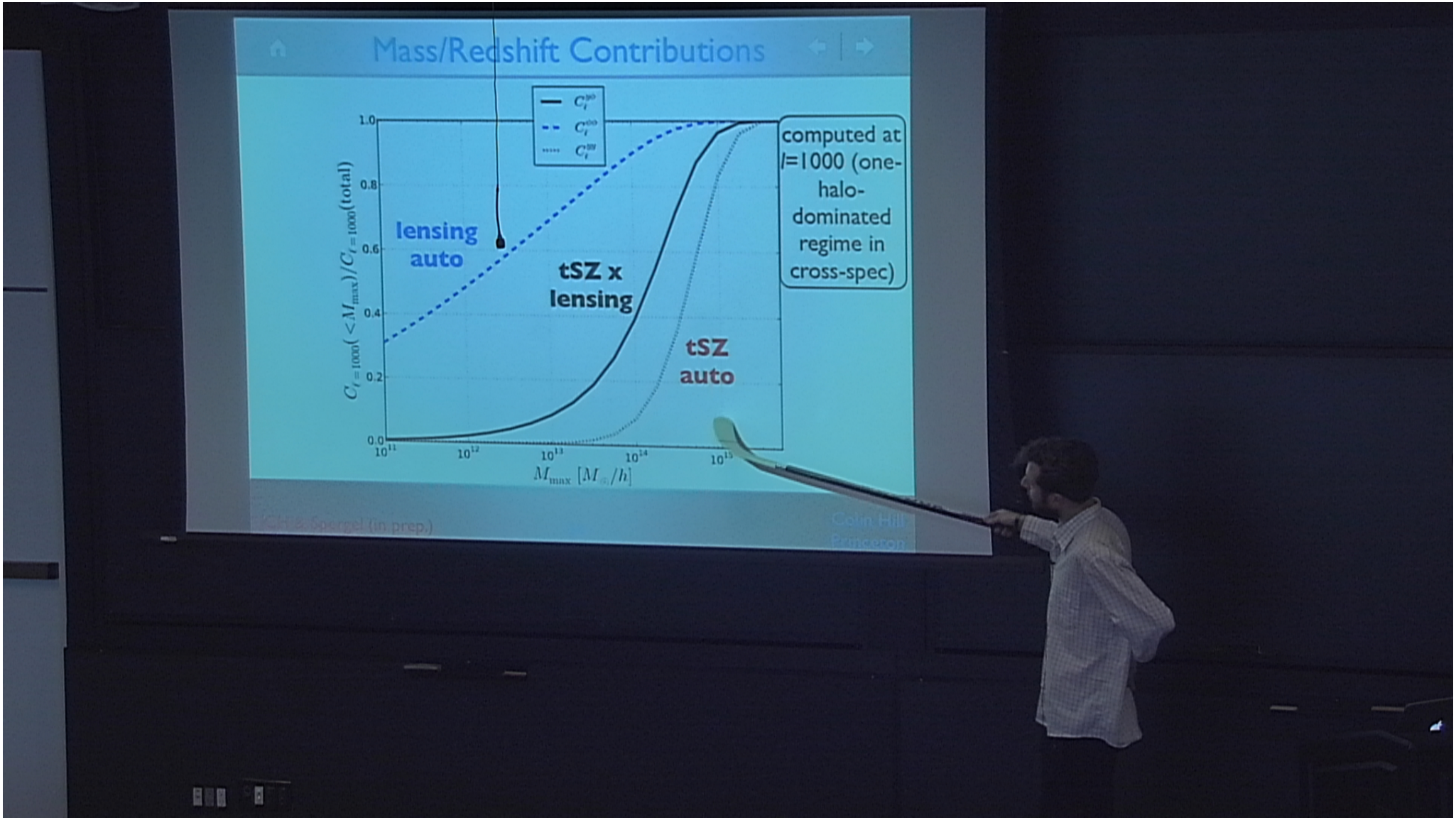
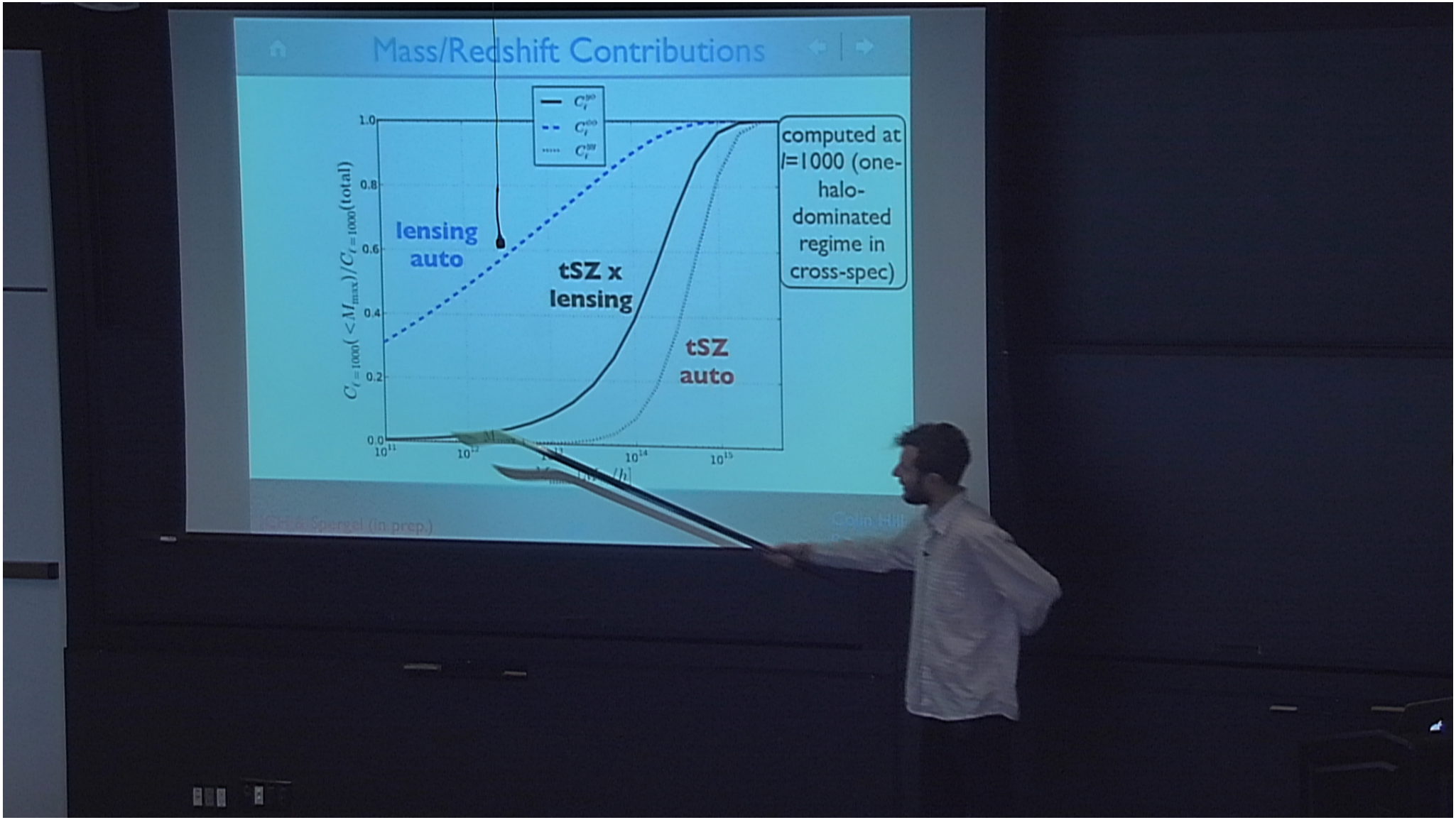


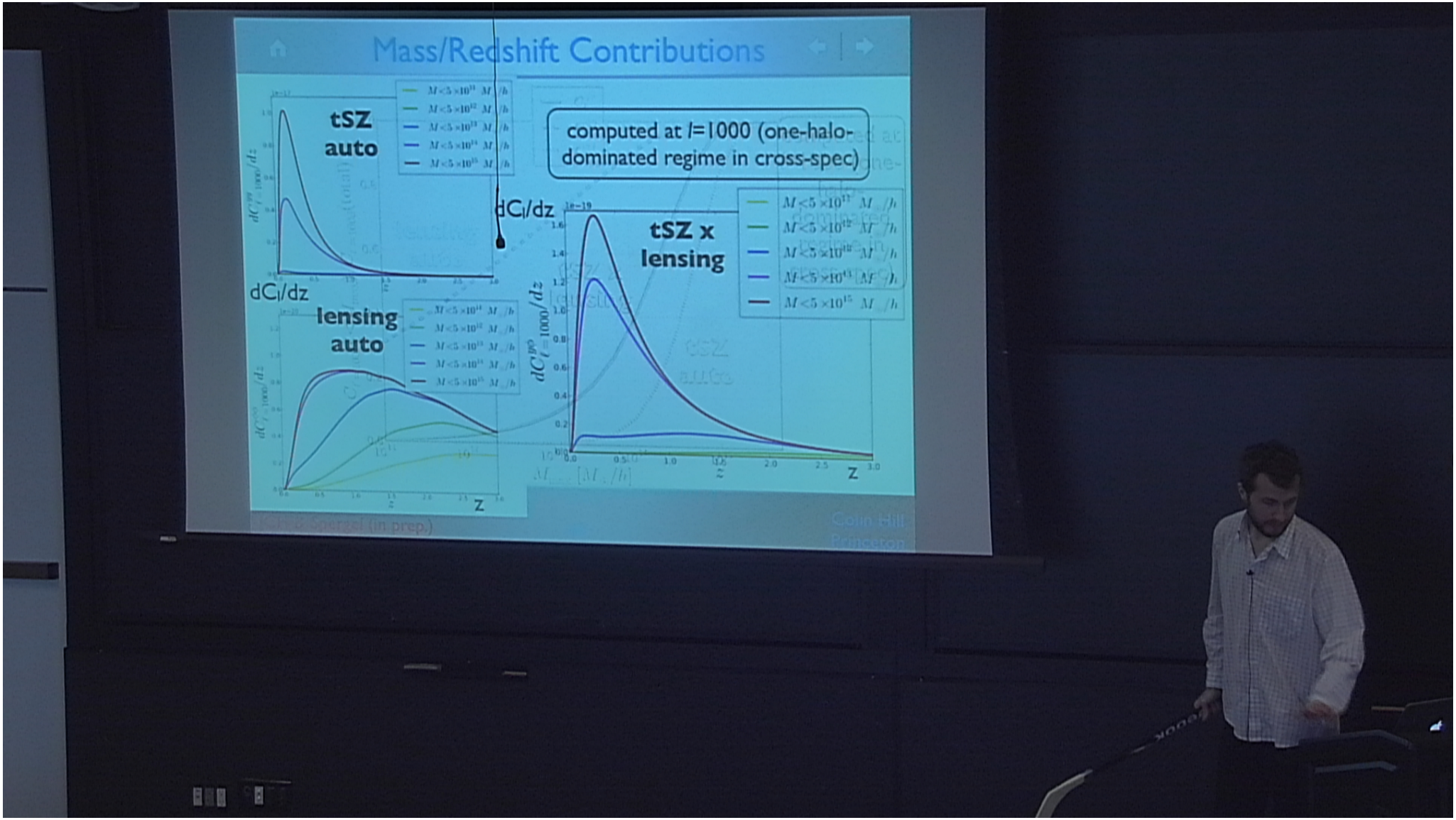
JCH & Spergel (in prep.)

Colin Hill
Princeton

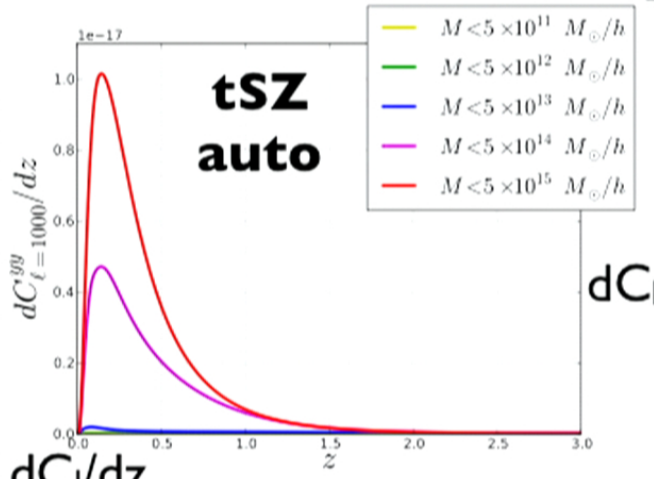

Thermal SZ x CMB Lensing
tSZ x CMB lensing
normalized cross-correlation
coefficient
1.0
0.8
0.6
0.4
0.2
0.0
r_ℓ^{gg}
10^1
10^2
10^3
10^4
ℓ
multipole


Mass/Redshift Contributions
lensing auto
tSZ x lensing
tSZ auto
computed at l=1000 (one-halo-dominated regime in cross-spec)
$C_{\ell=1000}(<M_{\rm max})/C_{\ell=1000}({\rm total})$
$M_{\rm max}\ [M_\odot/h]$
Colin Hill
Princeton

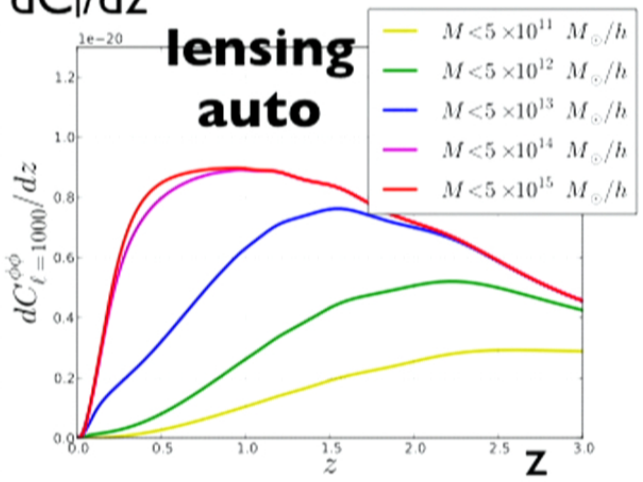

Mass/Redshift Contributions
lensing auto
tSZ x lensing
tSZ auto
computed at l=1000 (one-halo-dominated regime in cross-spec)
1.0
0.8
0.6
0.4
0.2
0.0
10^{11}
10^{14}
10^{15}
$C_{l=1000}(<M_{max})/C_{l=1000}(total)$
(Sehgal, Spergel (in prep.)


Mass/Redshift Contributions
tSZ auto
computed at l=1000 (one-halo-dominated regime in cross-spec)
dCl/dz
tSZ x lensing
dCl/dz
lensing auto
z
z
Colin Hill
Princeton

Mass/Redshift Contributions

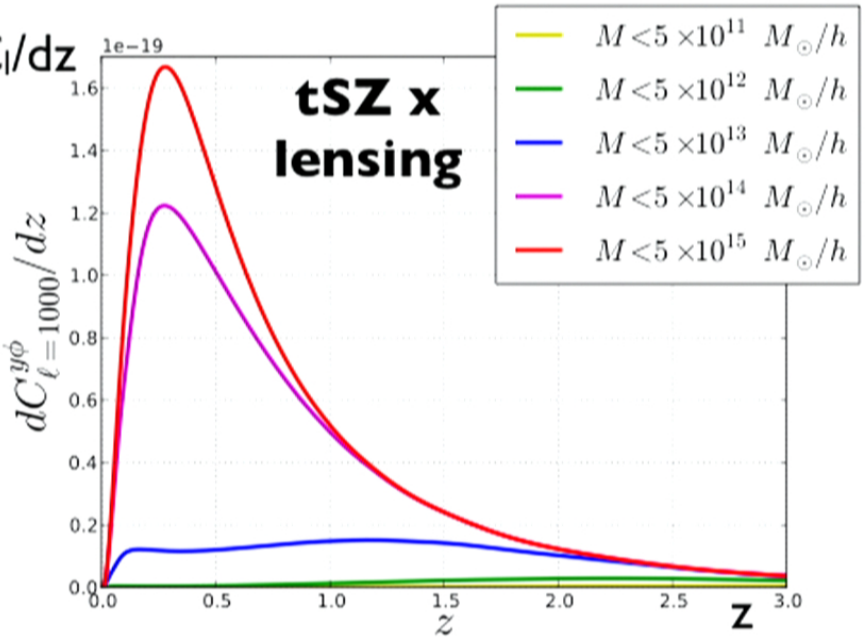


dC$_l$/dz



computed at *l*=1000 (one-halo-dominated regime in cross-spec)

dC$_l$/dz



JCH & Spergel (in prep.)

Colin Hill
Princeton

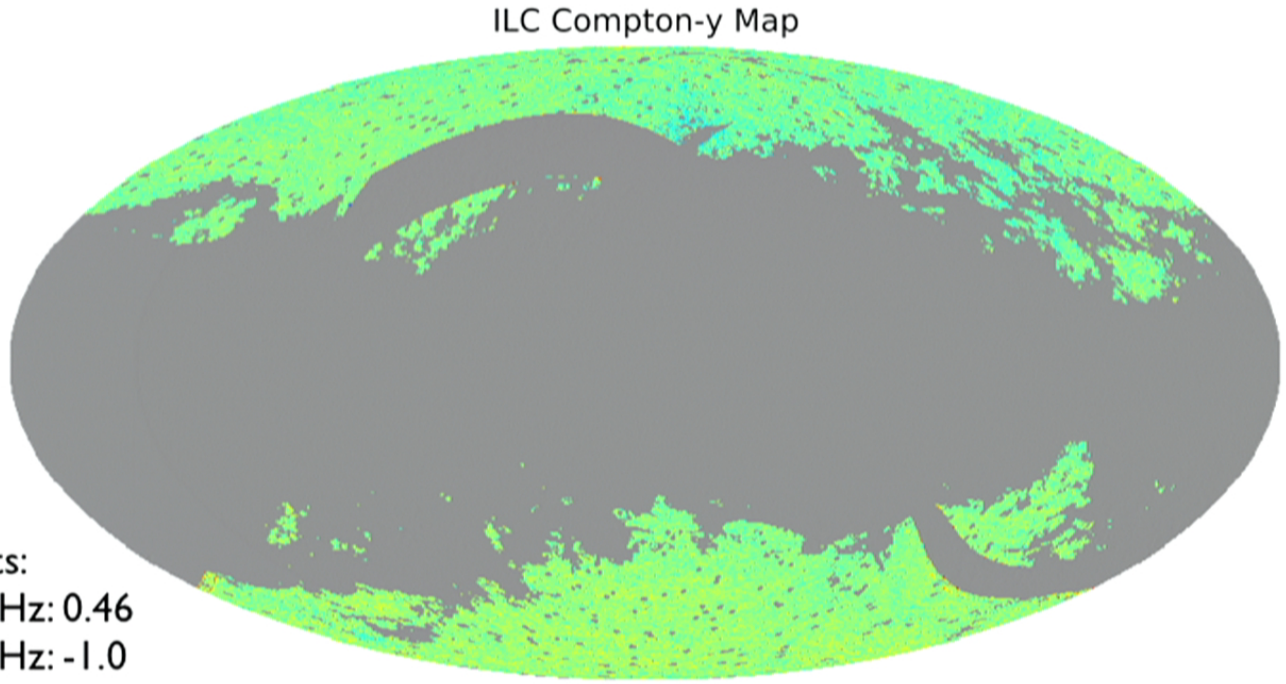
Measurement

Cross-correlate a Compton-y map with a CMB lensing potential map.

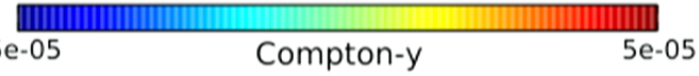
Measurement

Cross-correlate a Compton-y map with a CMB lensing potential map.

D.I.*y*-Map



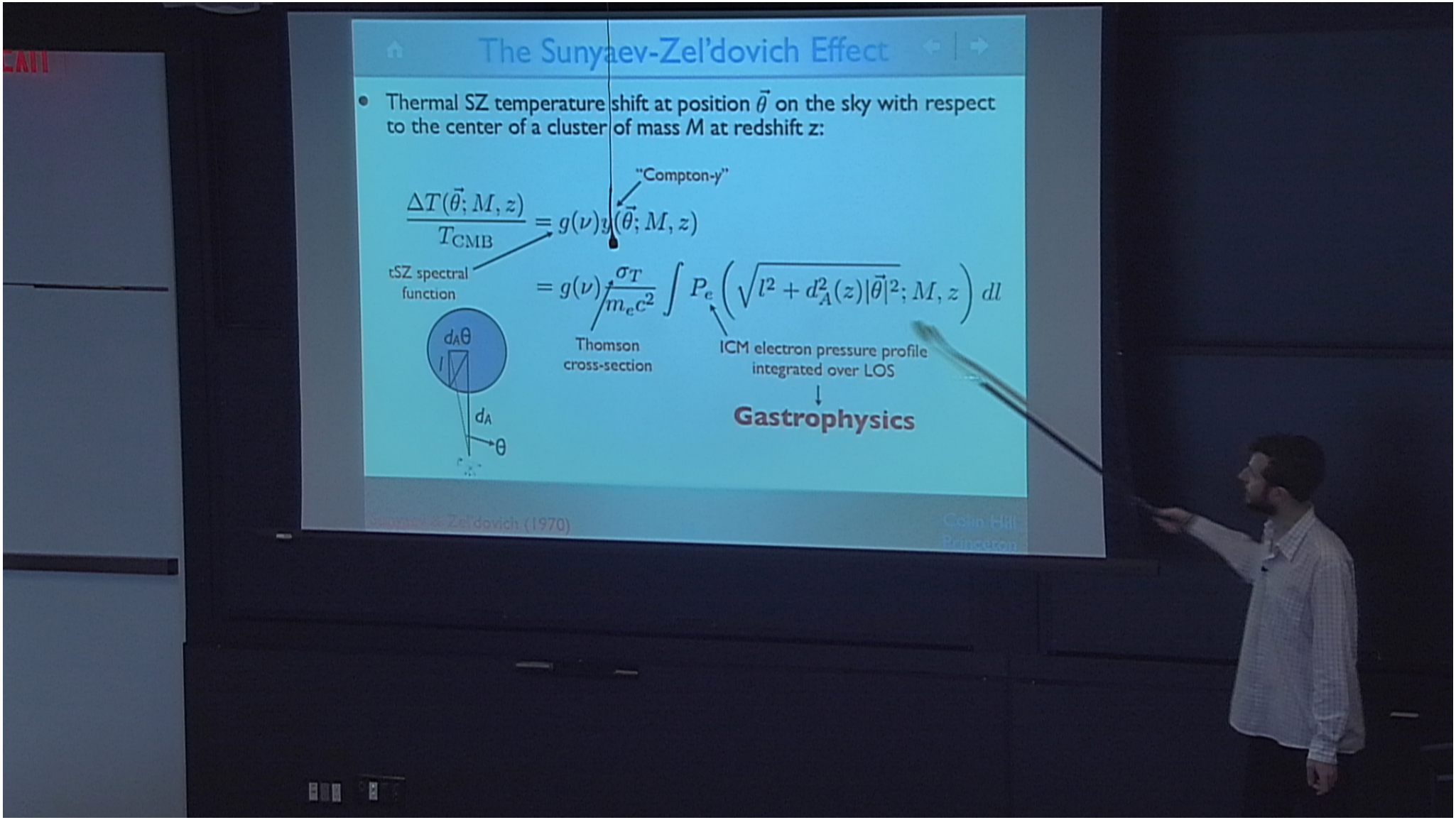
weights:
100 GHz: 0.46
143 GHz: -1.0
217 GHz: 0.54
353 GHz: 0.00032
545 GHz: -0.0028

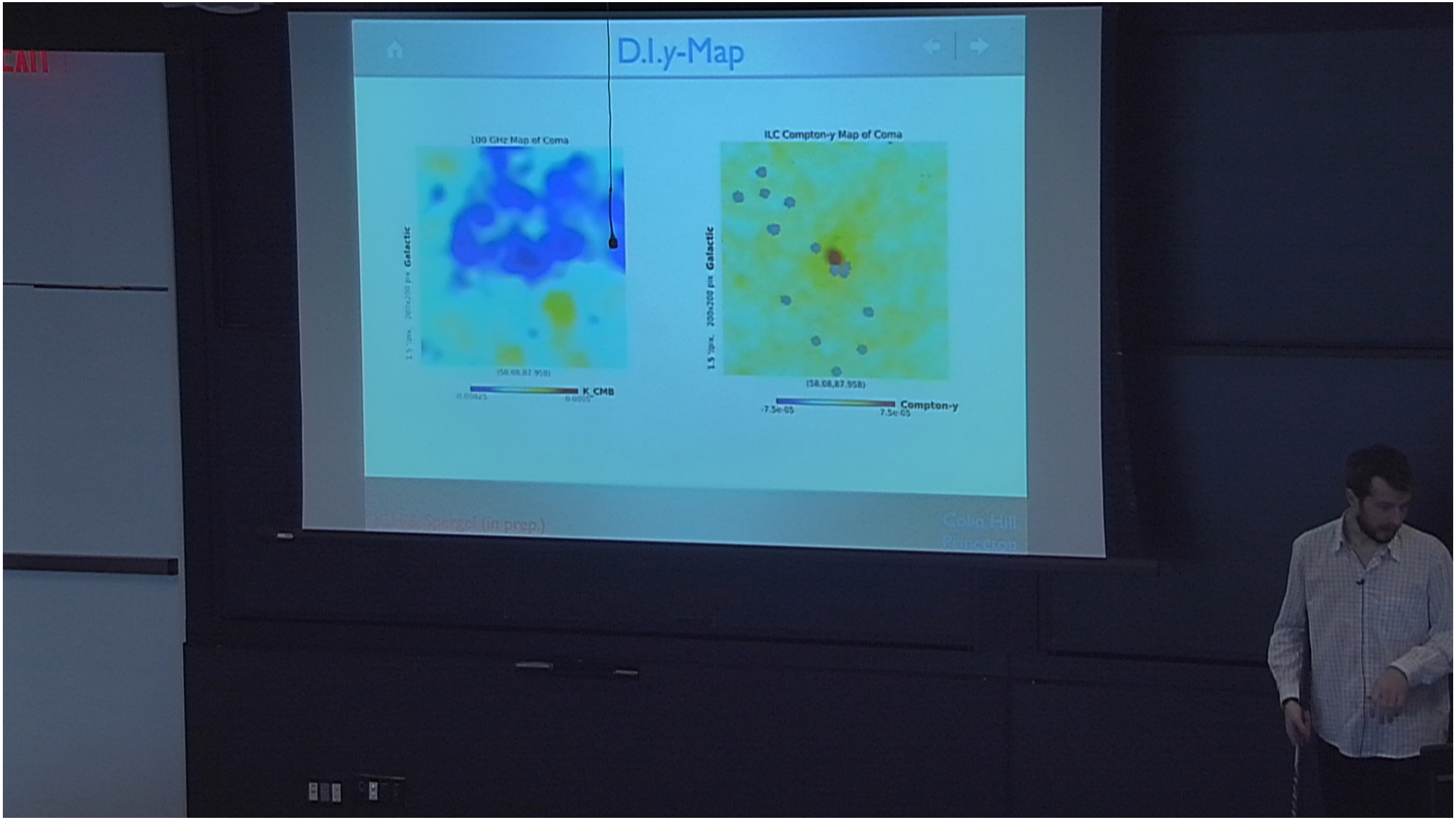


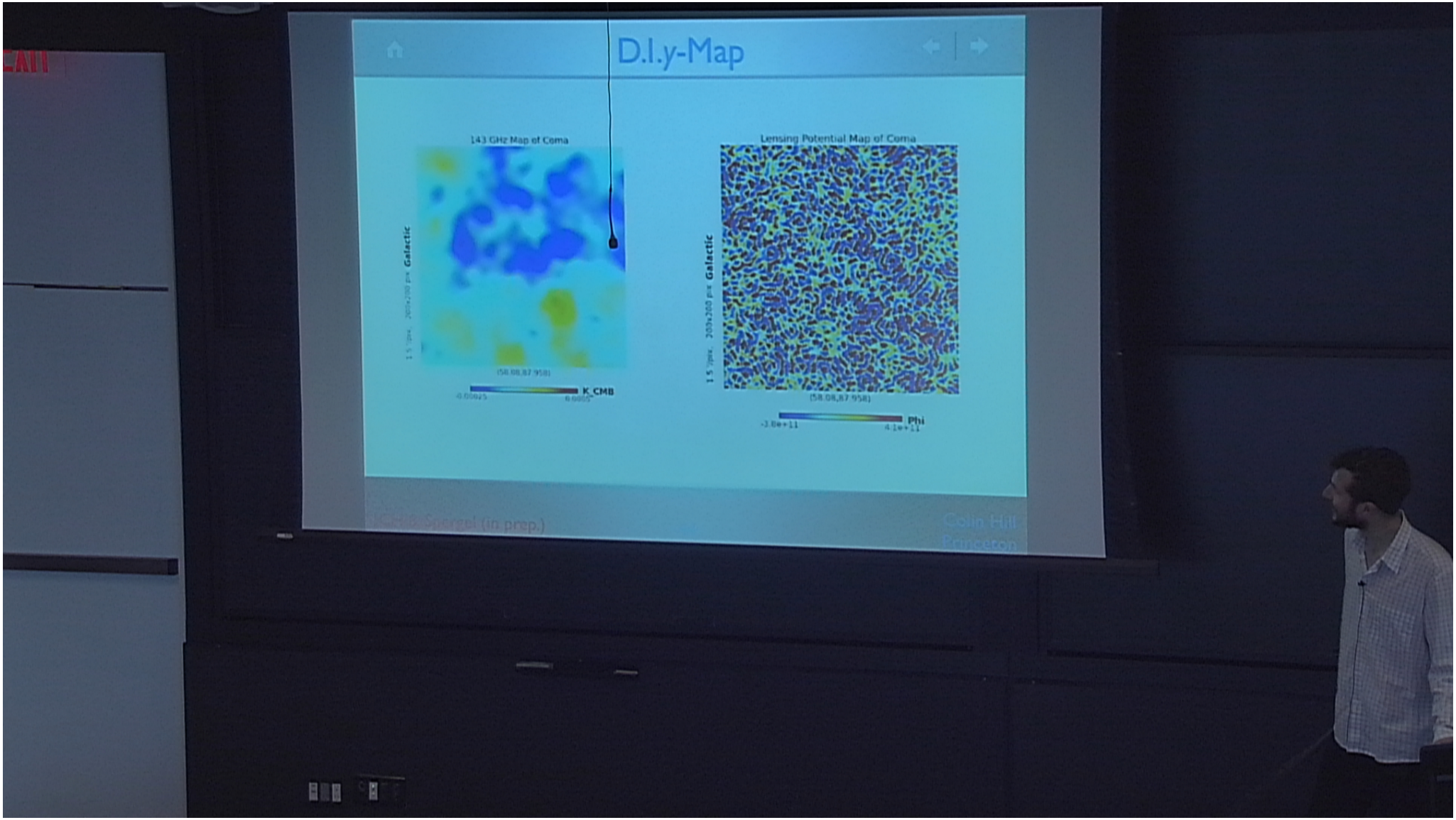
$f_{sky} \sim 0.25$

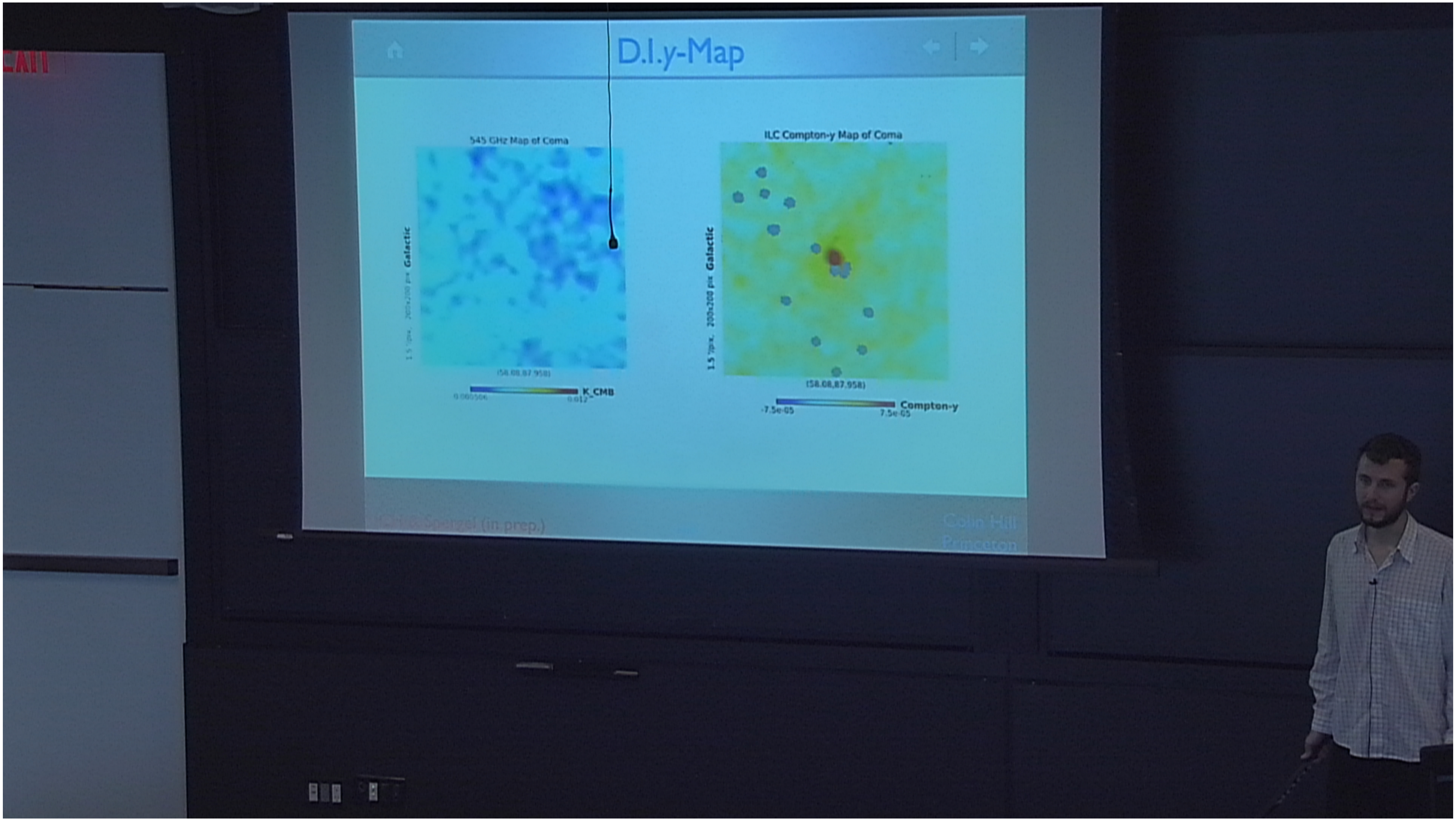
JCH & Spergel (in prep.)

Colin Hill
Princeton


The Sunyaev-Zel'dovich Effect
Thermal SZ temperature shift at position $\vec{\theta}$ on the sky with respect to the center of a cluster of mass M at redshift z:
"Compton-y"
$\frac{\Delta T(\vec{\theta}; M, z)}{T_{\rm CMB}} = g(\nu) y(\vec{\theta}; M, z)$
tSZ spectral function
$= g(\nu) \frac{\sigma_T}{m_e c^2} \int P_e \left(\sqrt{l^2 + d_A^2(z) |\vec{\theta}|^2}; M, z \right) dl$
Thomson cross-section
ICM electron pressure profile integrated over LOS
Gastrophysics
$d_A\theta$
d_A
θ
Sunyaev & Zel'dovich (1970)
Colin Hill
Princeton

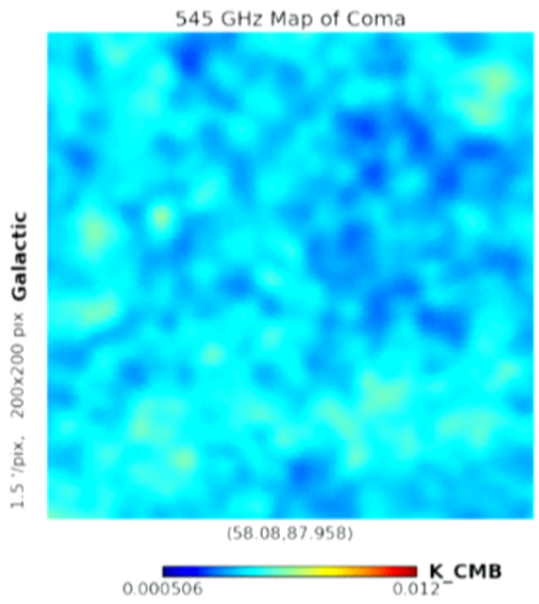

D.I.y-Map
100 GHz Map of Coma
ILC Compton-y Map of Coma
Galactic
K_CMB
Compton-y
-7.5e-05
7.5e-05
Colin Hill

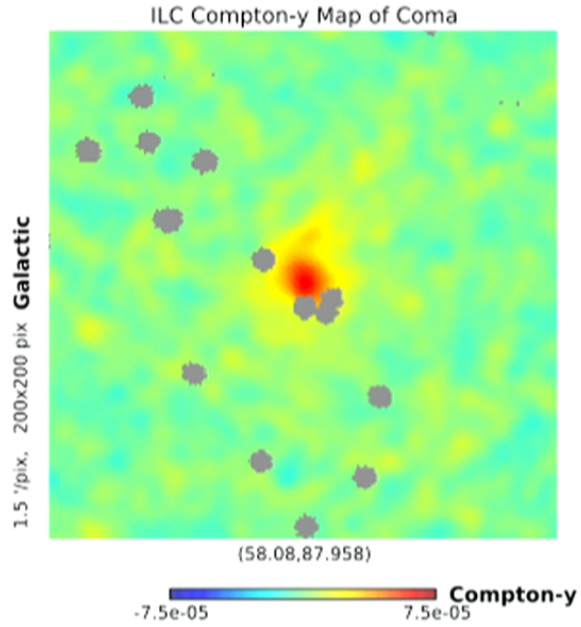

D.I.y-Map
143 GHz Map of Coma
Galactic
K_CMB
Lensing Potential Map of Coma
Galactic
Phi
Colin Hill
Princeton



D.I.y-Map
545 GHz Map of Coma
K_CMB
ILC Compton-y Map of Coma
Galactic
(58.08,87.958)
-7.5e-05
7.5e-05
Compton-y
Spergel (in prep.)
Colin Hill
Princeton

D.I.y-Map



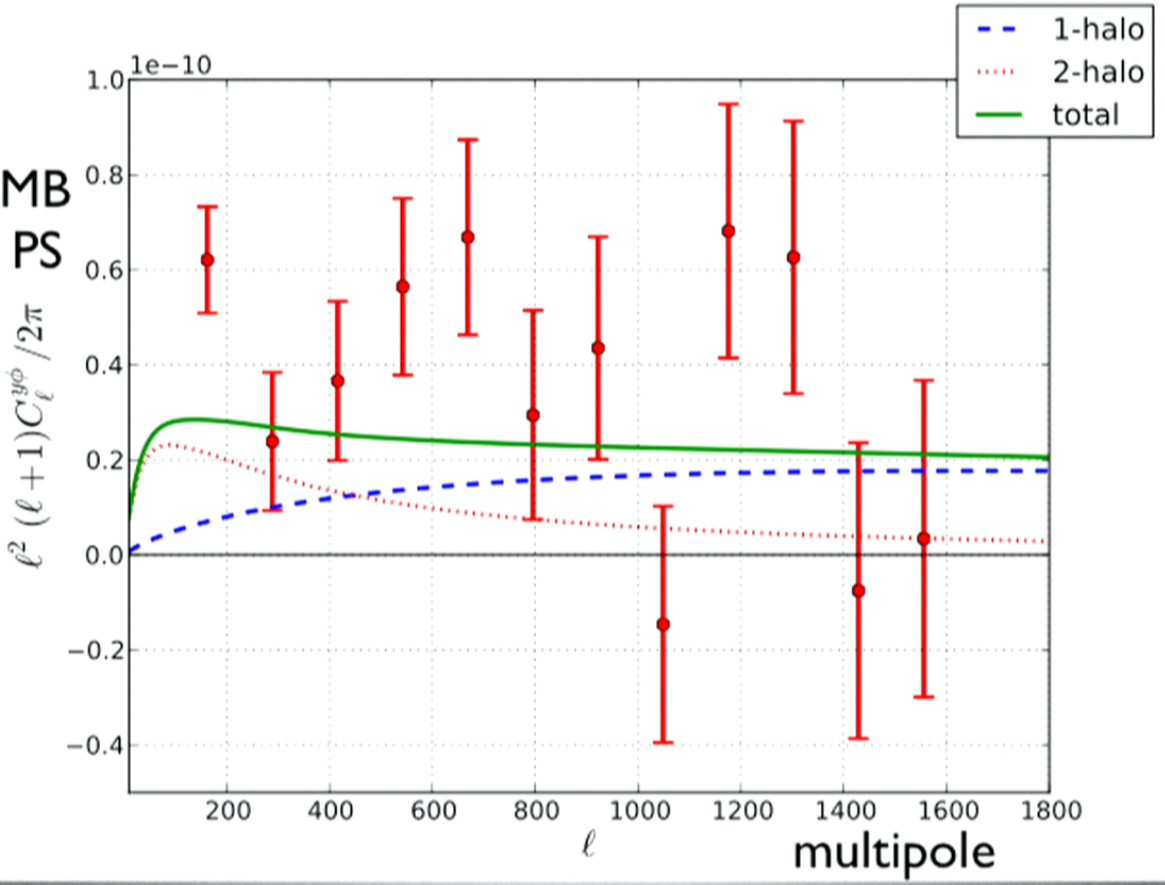


JCH & Spergel (in prep.)

Colin Hill
Princeton

D.I.y x CMB Lensing

tSZ x CMB Lensing PS



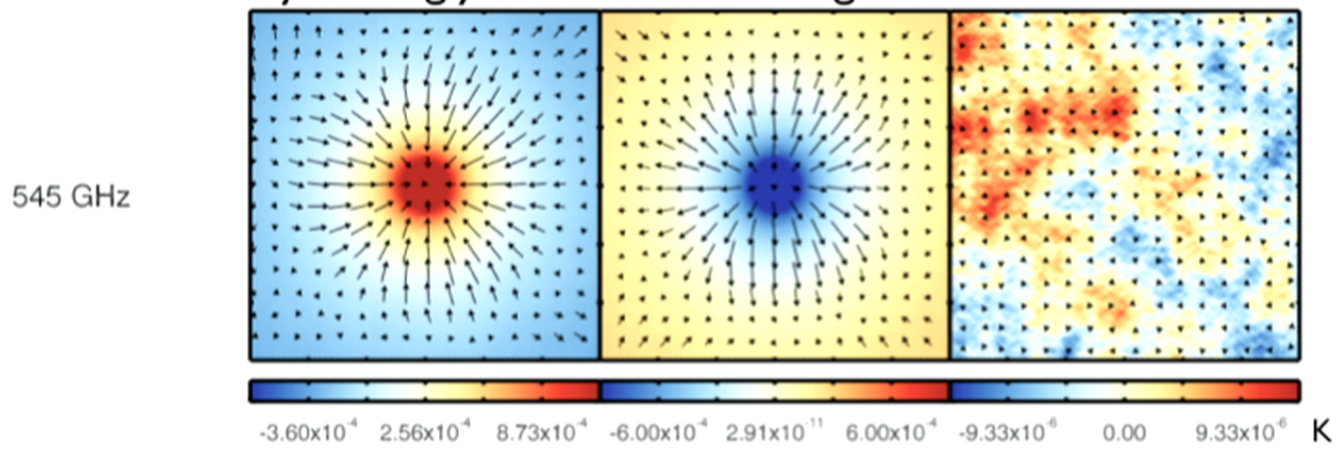
8.7σ

JCH & Spergel (in prep.)

Colin Hill
Princeton

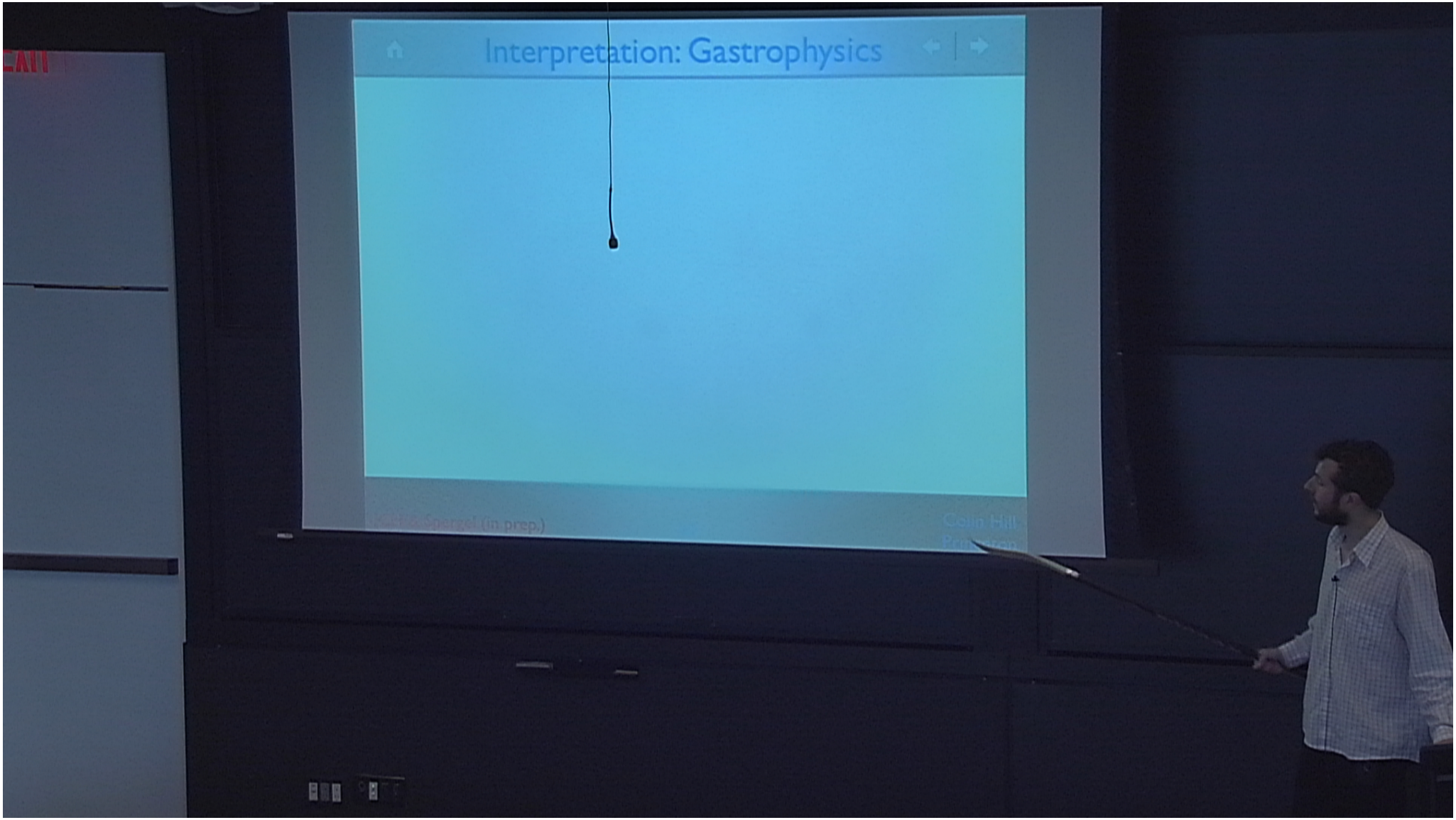
D.I.y x CMB Lensing

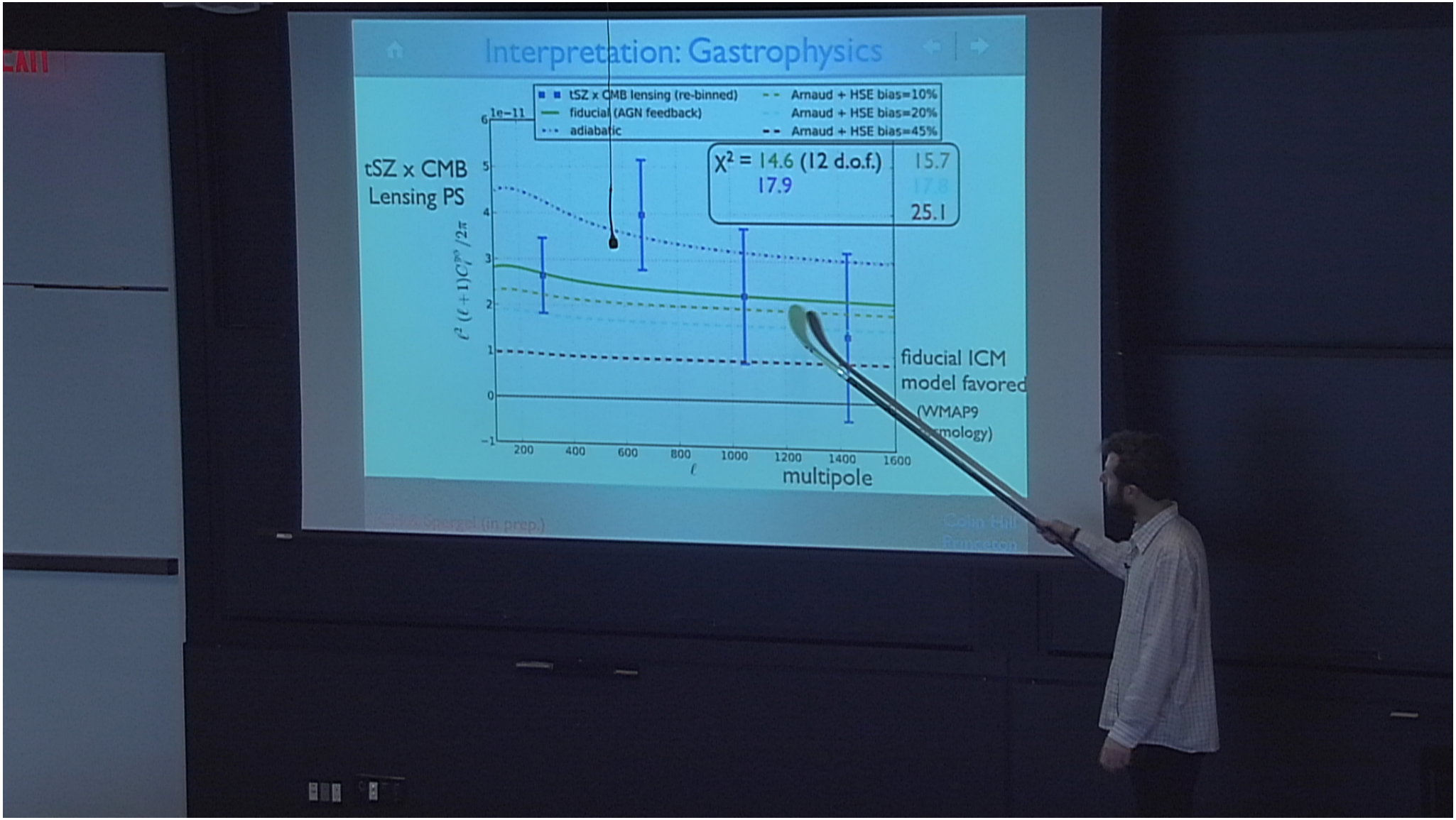
- Main contamination worry: cosmic infrared background (CIB)
- Correlates very strongly with CMB lensing



Planck Collaboration XVIII (2013)

Colin Hill
Princeton


Interpretation: Gastrophysics


Interpretation: Gastrophysics
tSZ x CMB lensing (re-binned)
fiducial (AGN feedback)
adiabatic
Arnaud + HSE bias=10%
Arnaud + HSE bias=20%
Arnaud + HSE bias=45%
tSZ x CMB
Lensing PS
χ^2 = 14.6 (12 d.o.f.)
17.9
15.7
25.1
fiducial ICM
model favored
(WMAP9
mology)
multipole
Sherwin & Spergel (in prep.)

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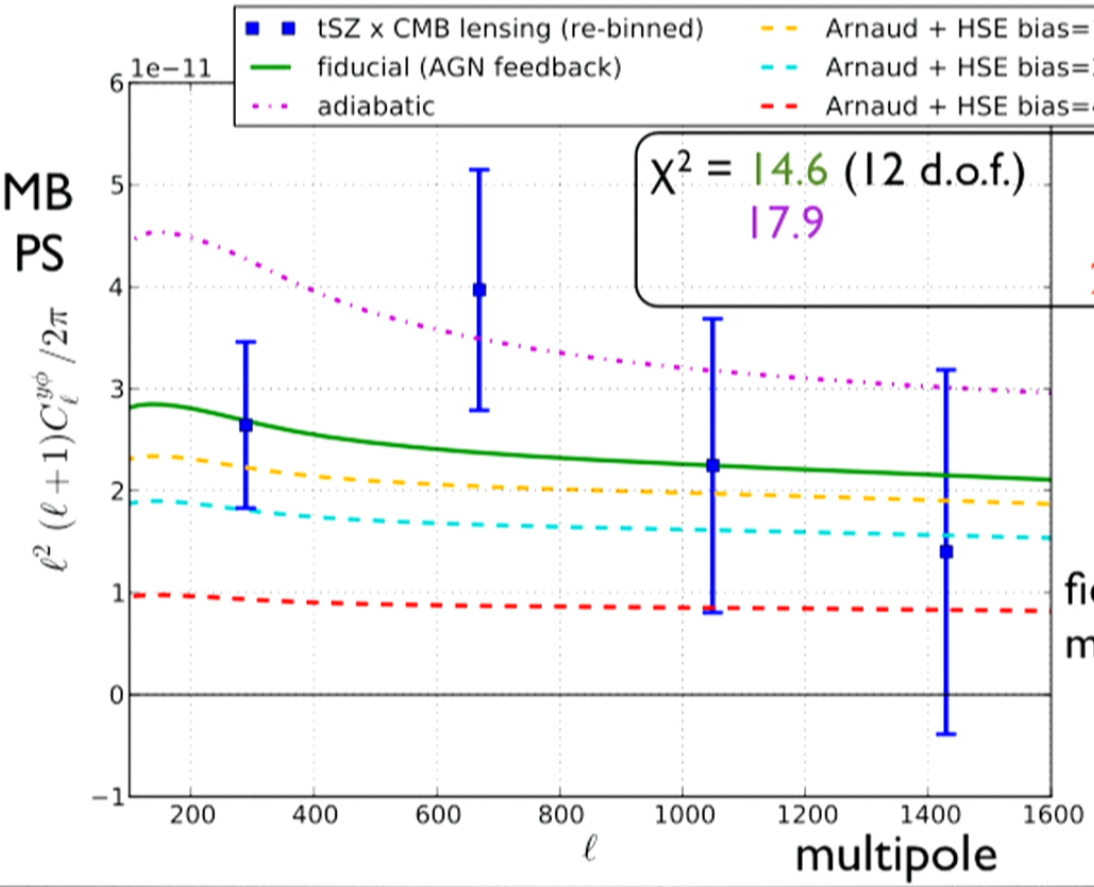

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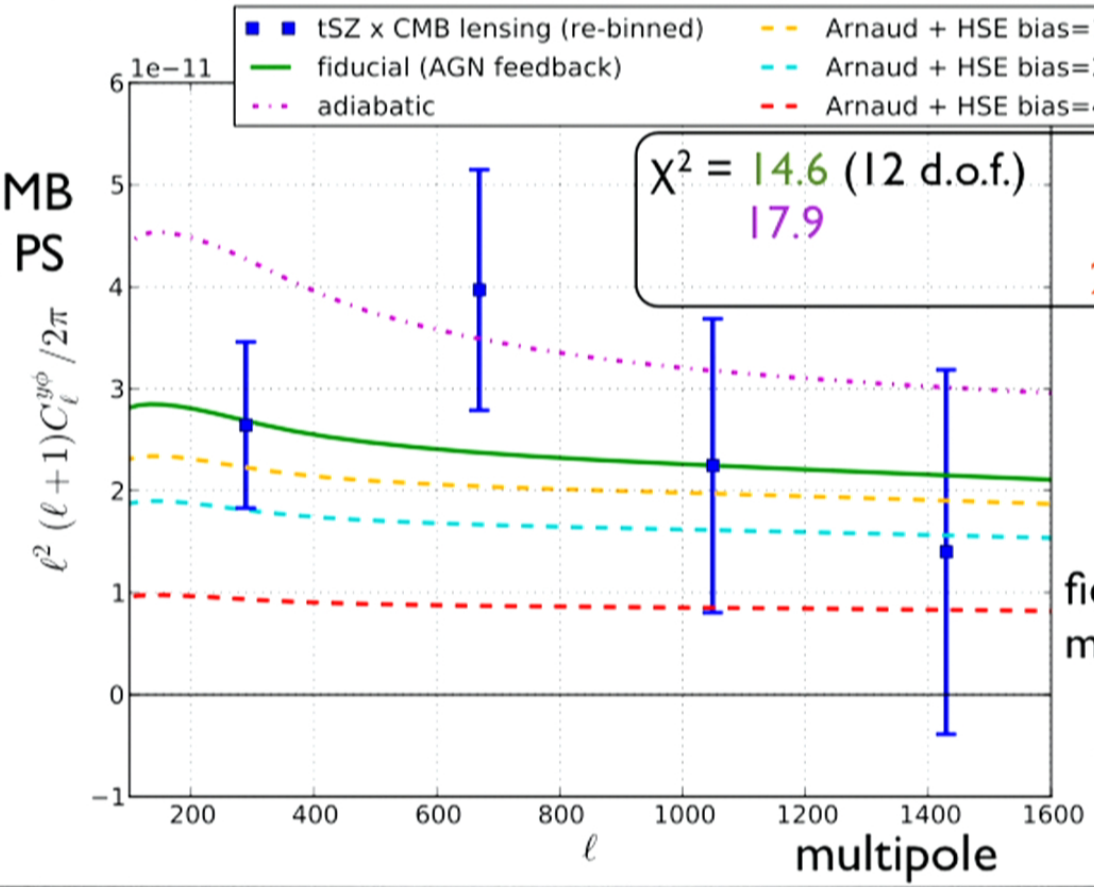

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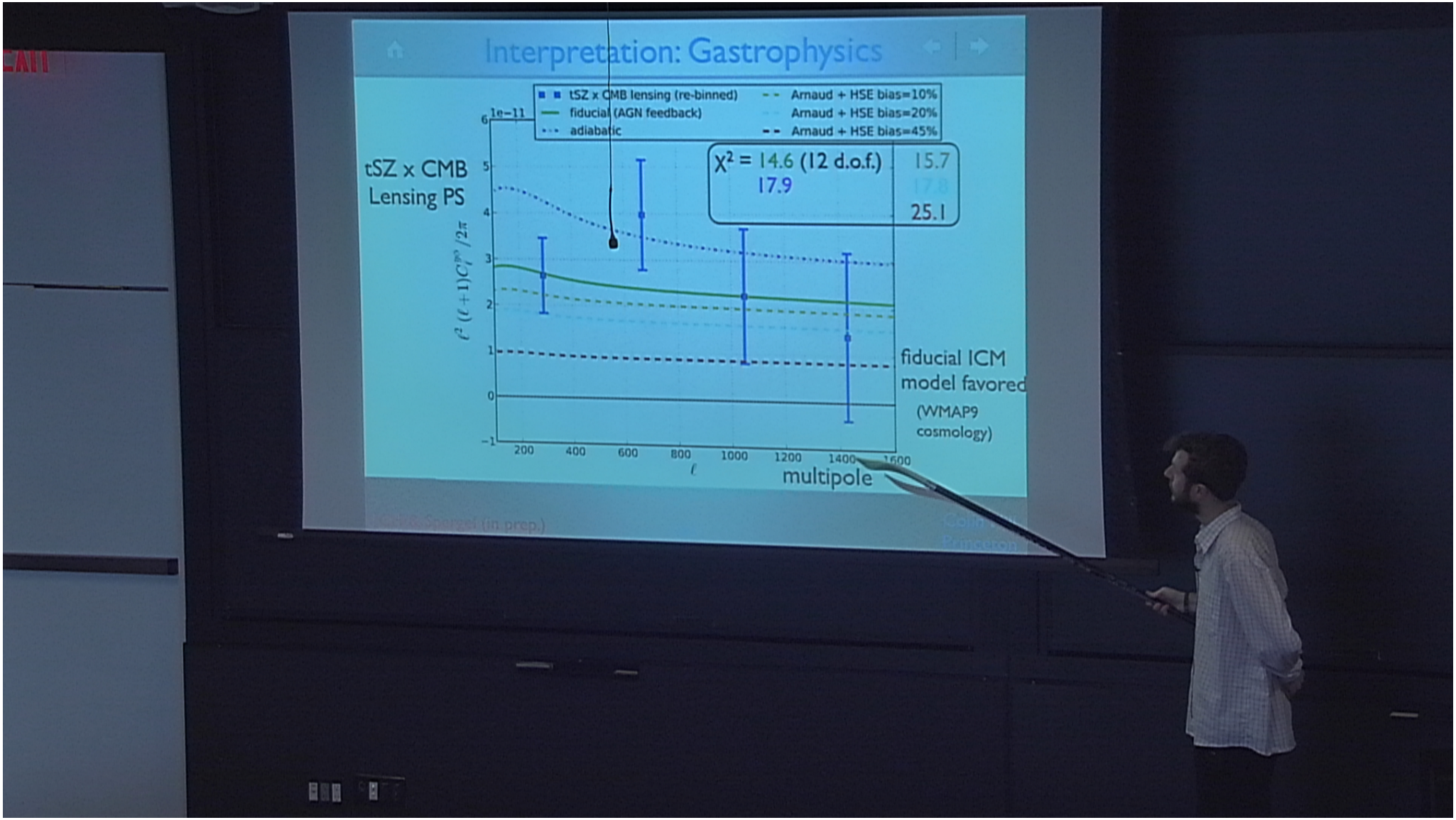
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Lensing PS
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25.1
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Sehgal (in prep.)

Interpretation: Gastrophysics

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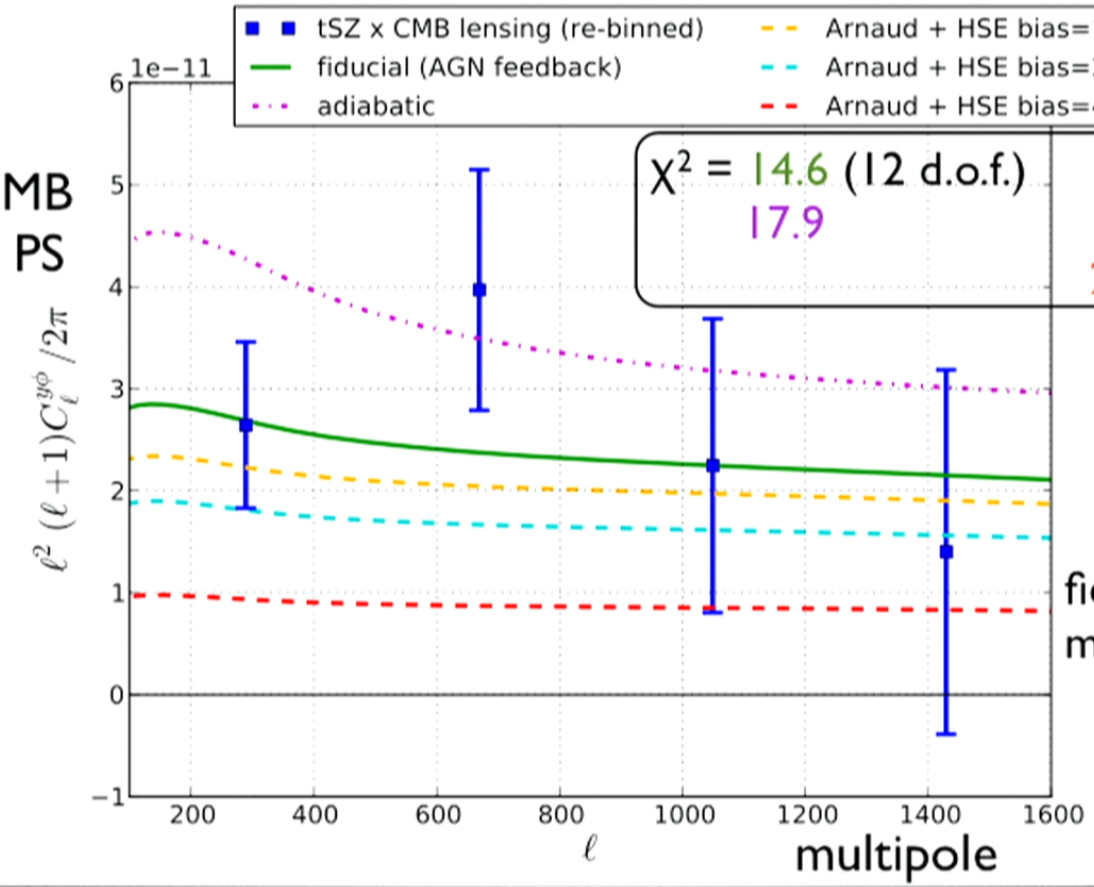

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17.9

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17.8
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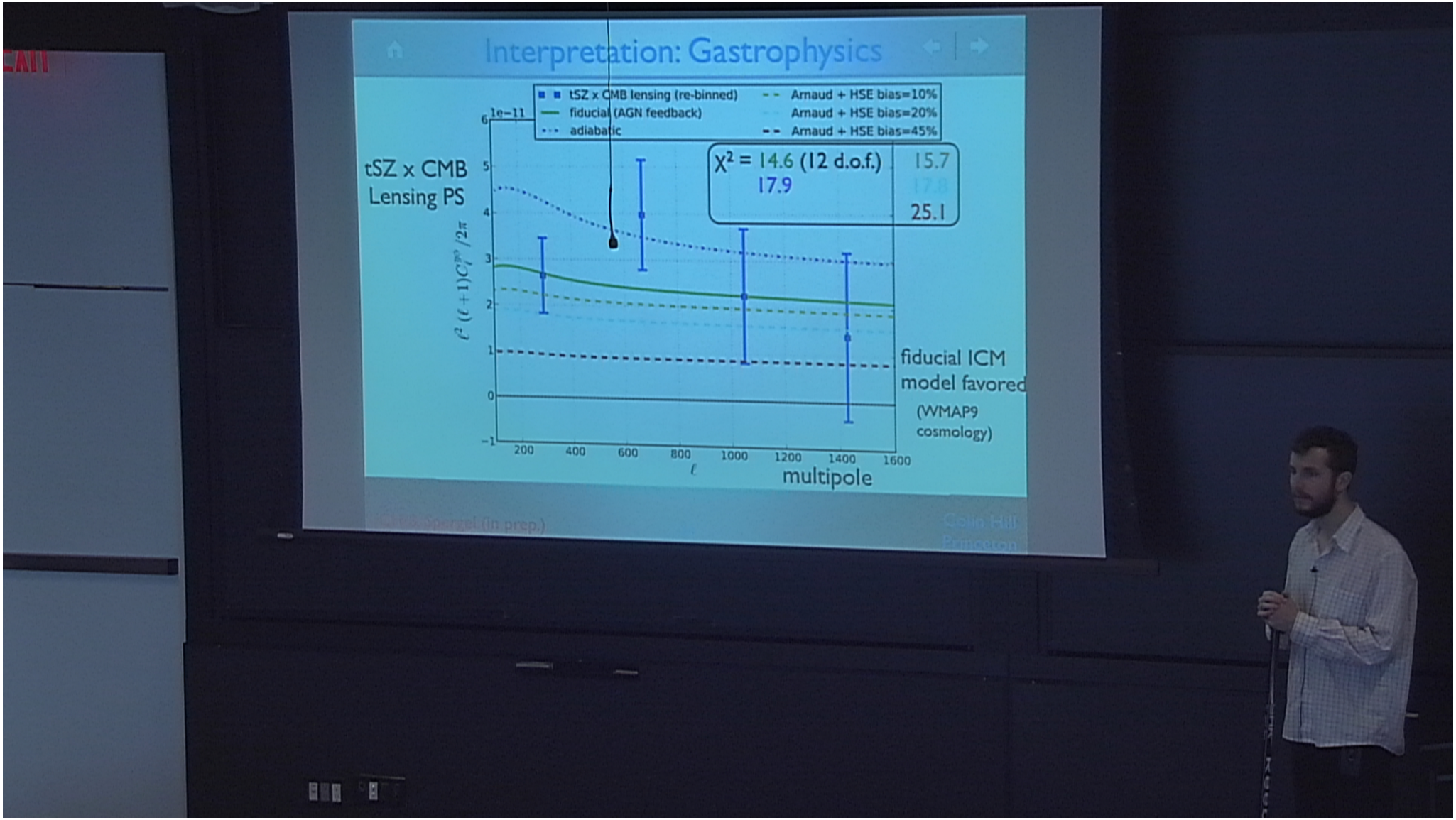
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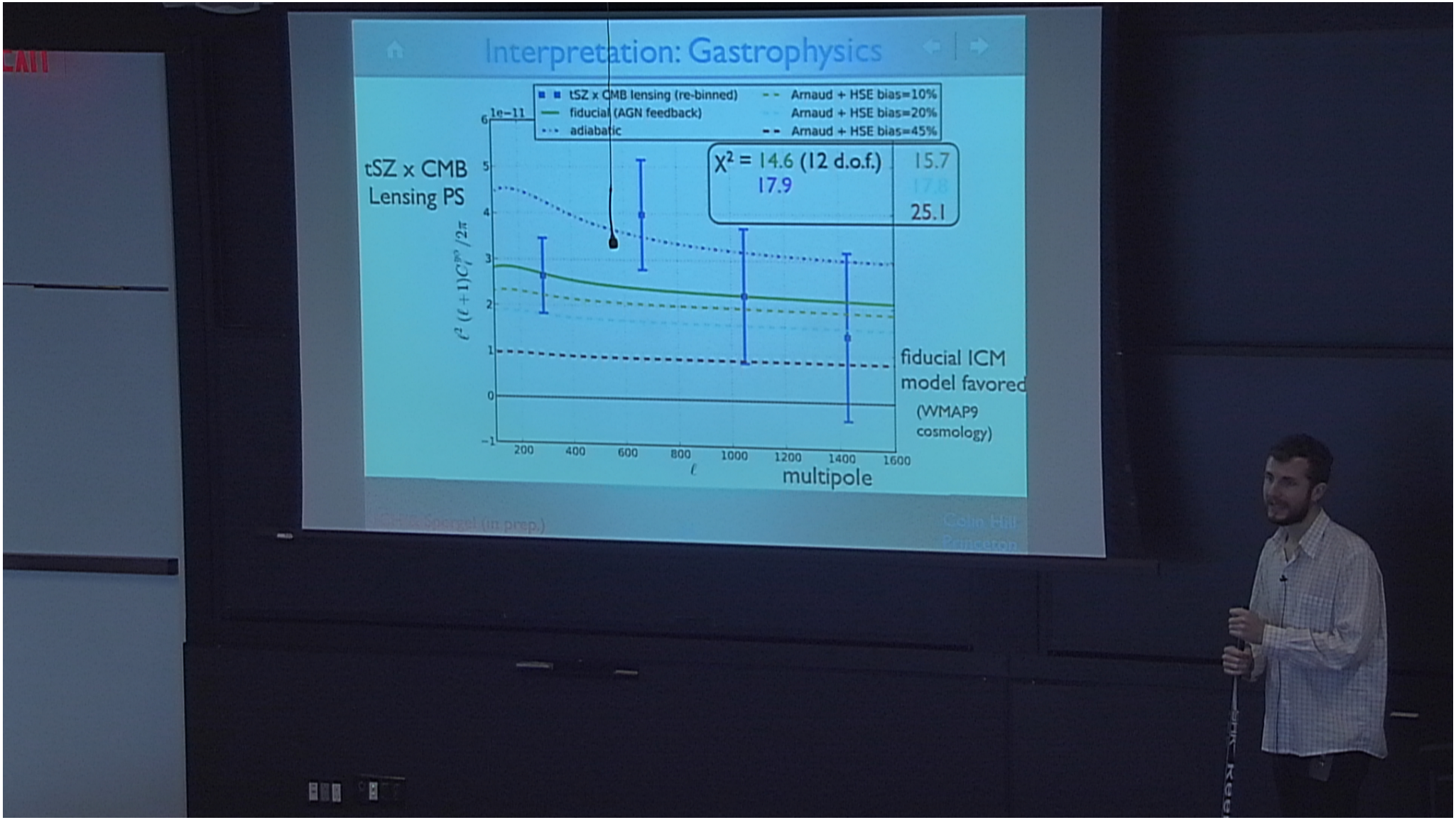
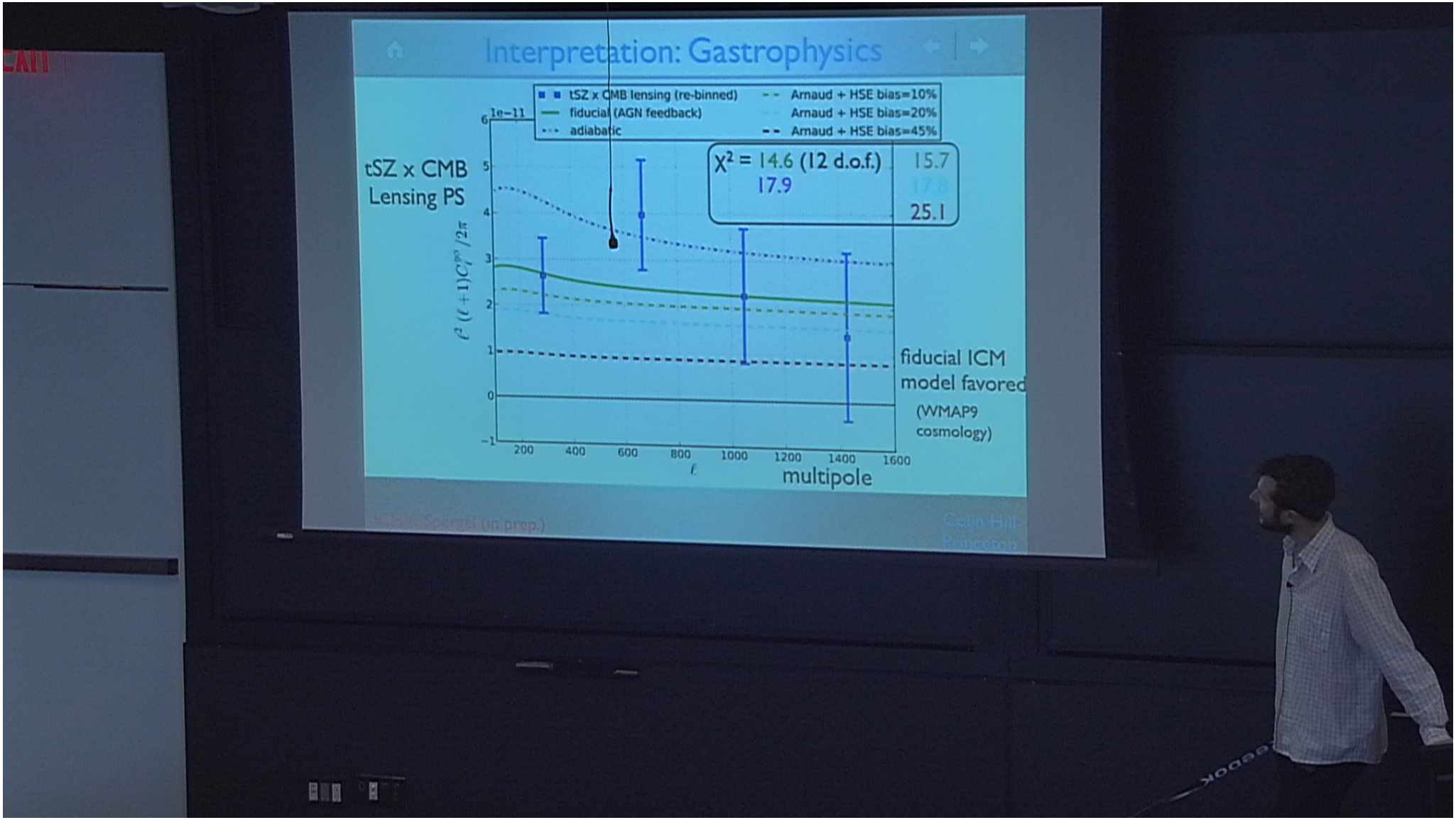
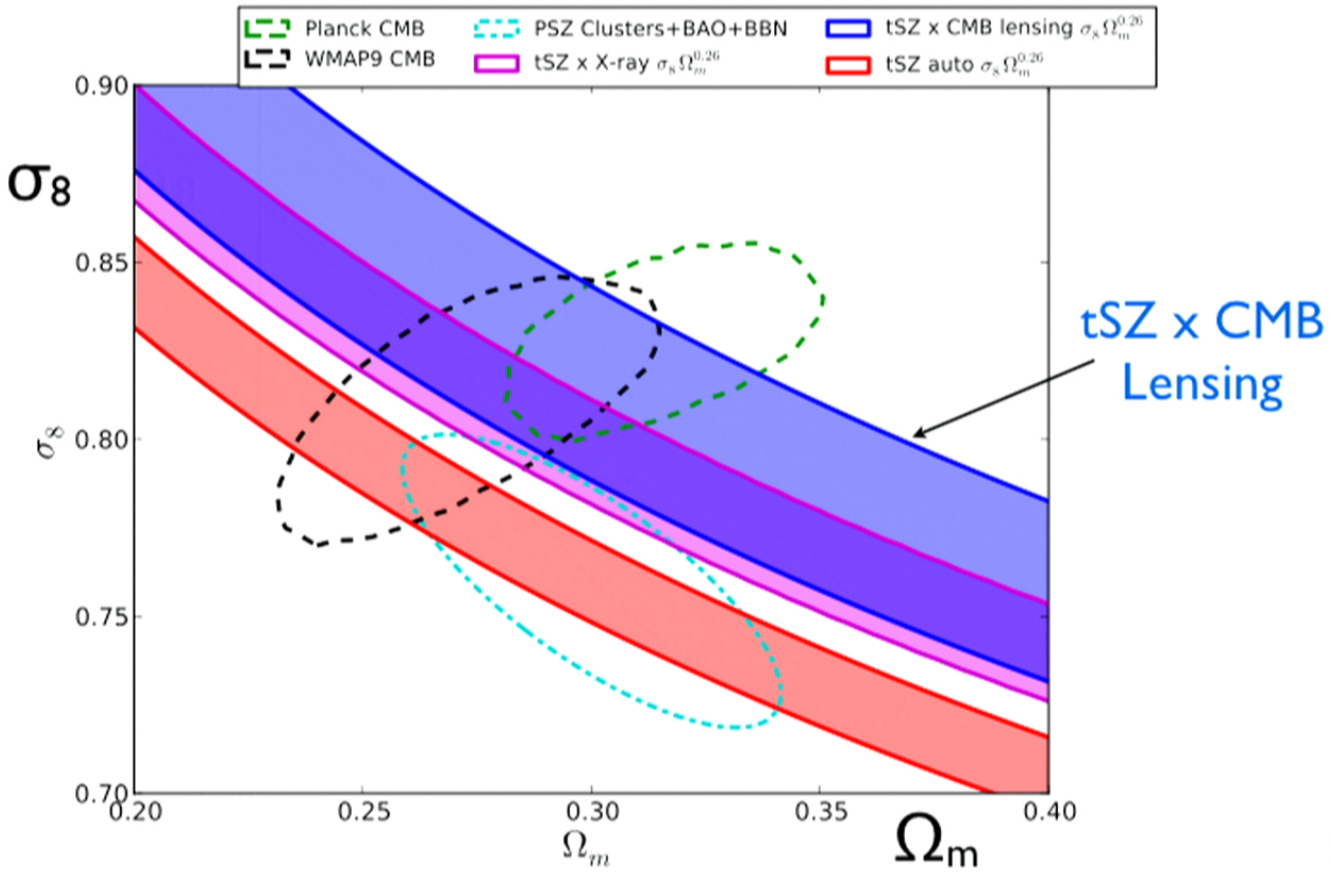
X^2 = 14.6 (12 d.o.f.)
17.9
15.7
25.1
fiducial ICM model favored
(WMAP9 cosmology)
multipole


Interpretation: Gastrophysics
tSZ x CMB lensing (re-binned)
fiducial (AGN feedback)
adiabatic
Arnaud + HSE bias=10%
Arnaud + HSE bias=20%
Arnaud + HSE bias=45%
tSZ x CMB
Lensing PS
χ^2 = 14.6 (12 d.o.f.)
17.9
15.7
25.1
fiducial ICM
model favored
(WMAP9
cosmology)
multipole


Interpretation: Gastrophysics
tSZ x CMB lensing (re-binned)
fiducial (AGN feedback)
adiabatic
Arnaud + HSE bias=10%
Arnaud + HSE bias=20%
Arnaud + HSE bias=45%
tSZ x CMB Lensing PS
χ^2 = 14.6 (12 d.o.f.)
17.9
15.7
25.1
1e−11
$\ell^2\,(\ell+1)C_\ell^{yy}/2\pi$
multipole
fiducial ICM model favored
(WMAP9 cosmology)
Sherwin, Spergel (in prep.)
Colin Hill
Princeton

Interpretation: Cosmology



JCH & Spergel (in prep.)
Hajian, Battaglia, et al. (2013)

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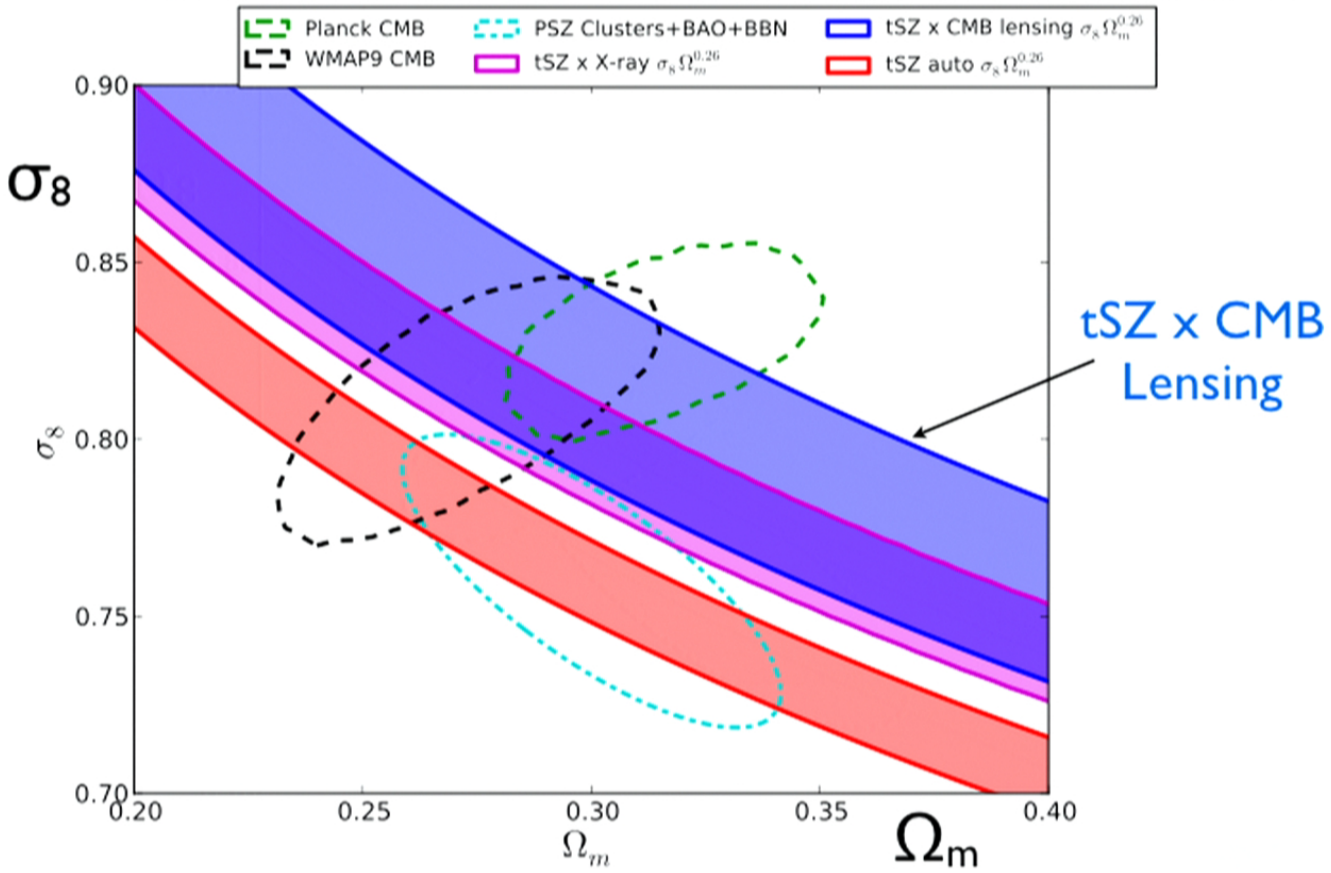
Princeton

Interpretation: Cosmology



JCH & Spergel (in prep.)
Hajian, Battaglia, et al. (2013)

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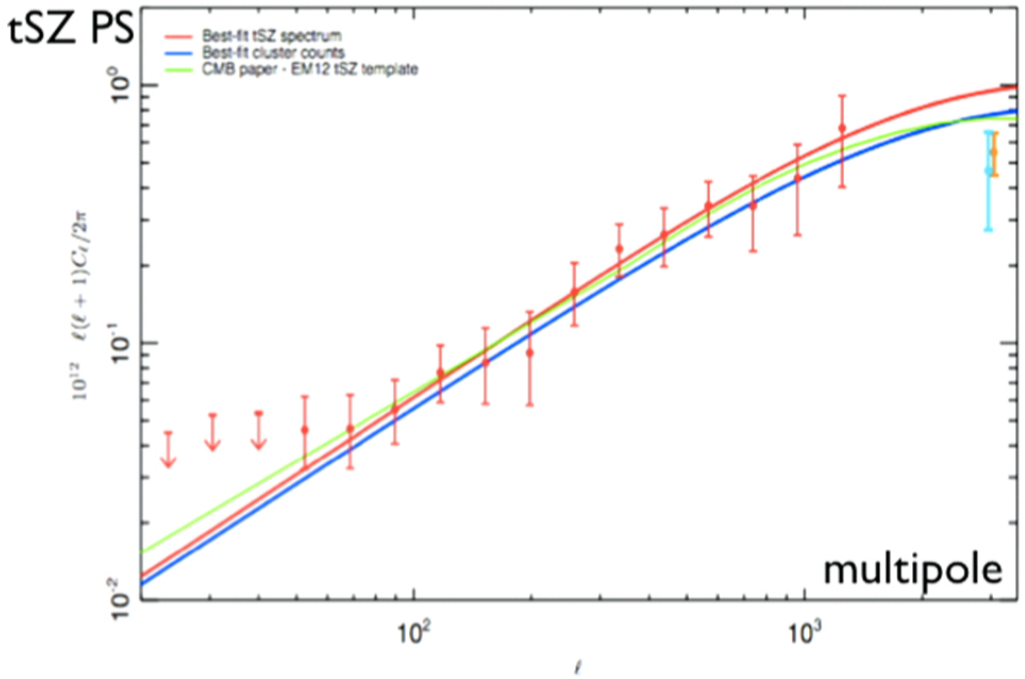
Thermal SZ Power Spectrum



gastrophysics model is fixed (Arnaud); no variations considered

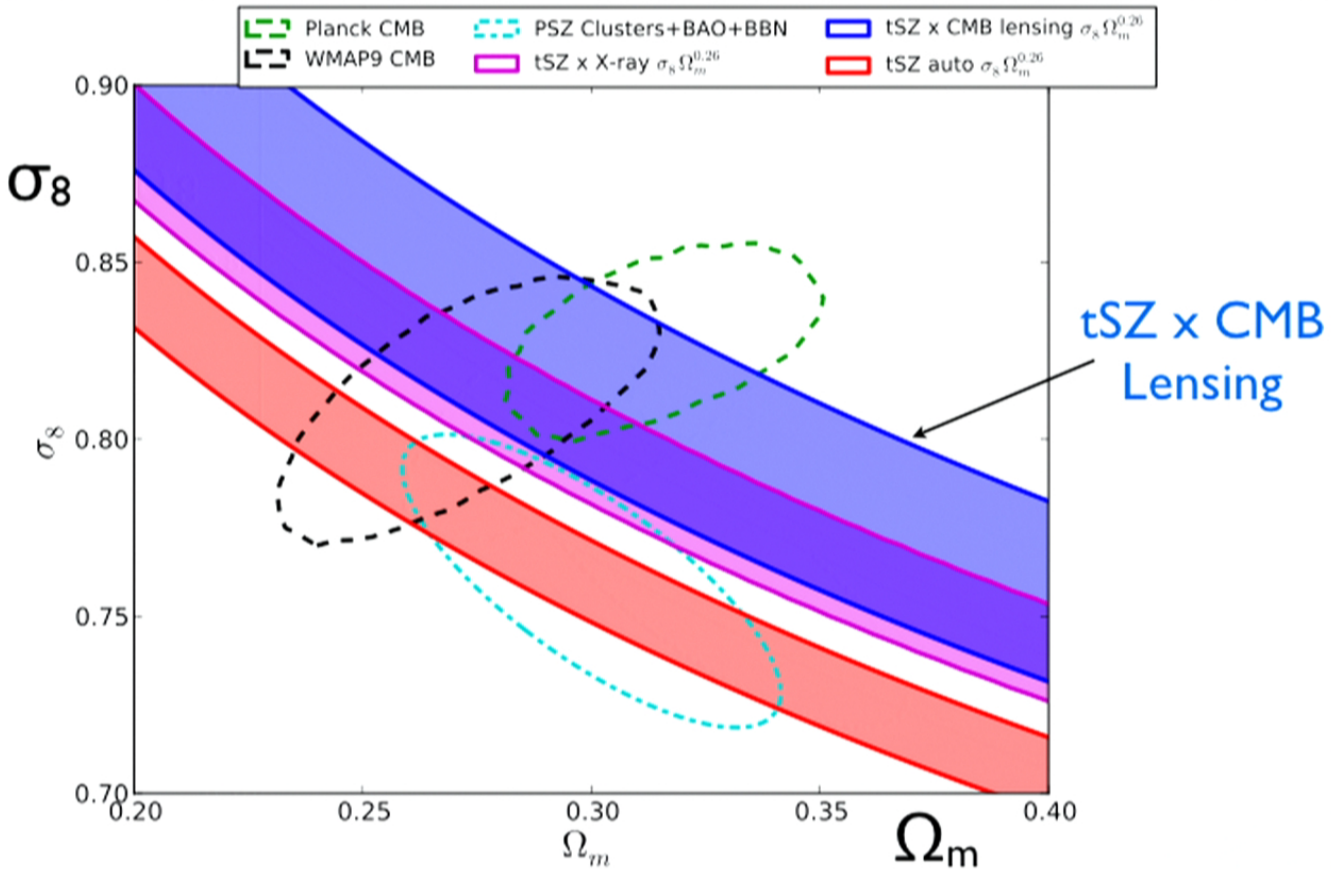
$$\sigma_8 \left(\Omega_m/0.28\right)^{3.2/8.1} = 0.784 \pm 0.016$$

12.3σ detection

foreground uncertainties dominate the errors

Planck+WP CMB: 0.868 ± 0.013

Interpretation: Cosmology



JCH & Spergel (in prep.)
Hajian, Battaglia, et al. (2013)

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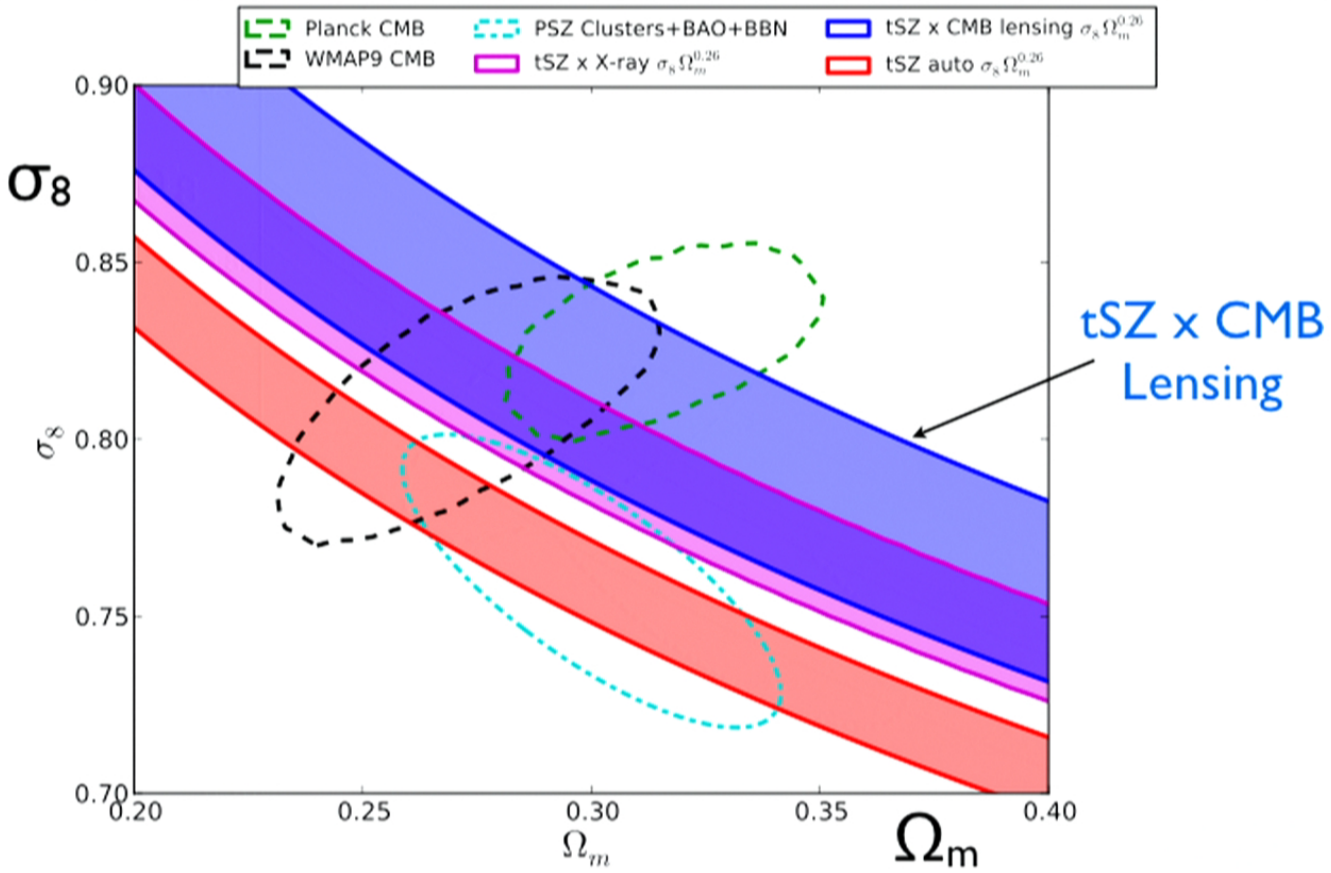
Interpretation: Cosmology



JCH & Spergel (in prep.)
Hajian, Battaglia, et al. (2013)

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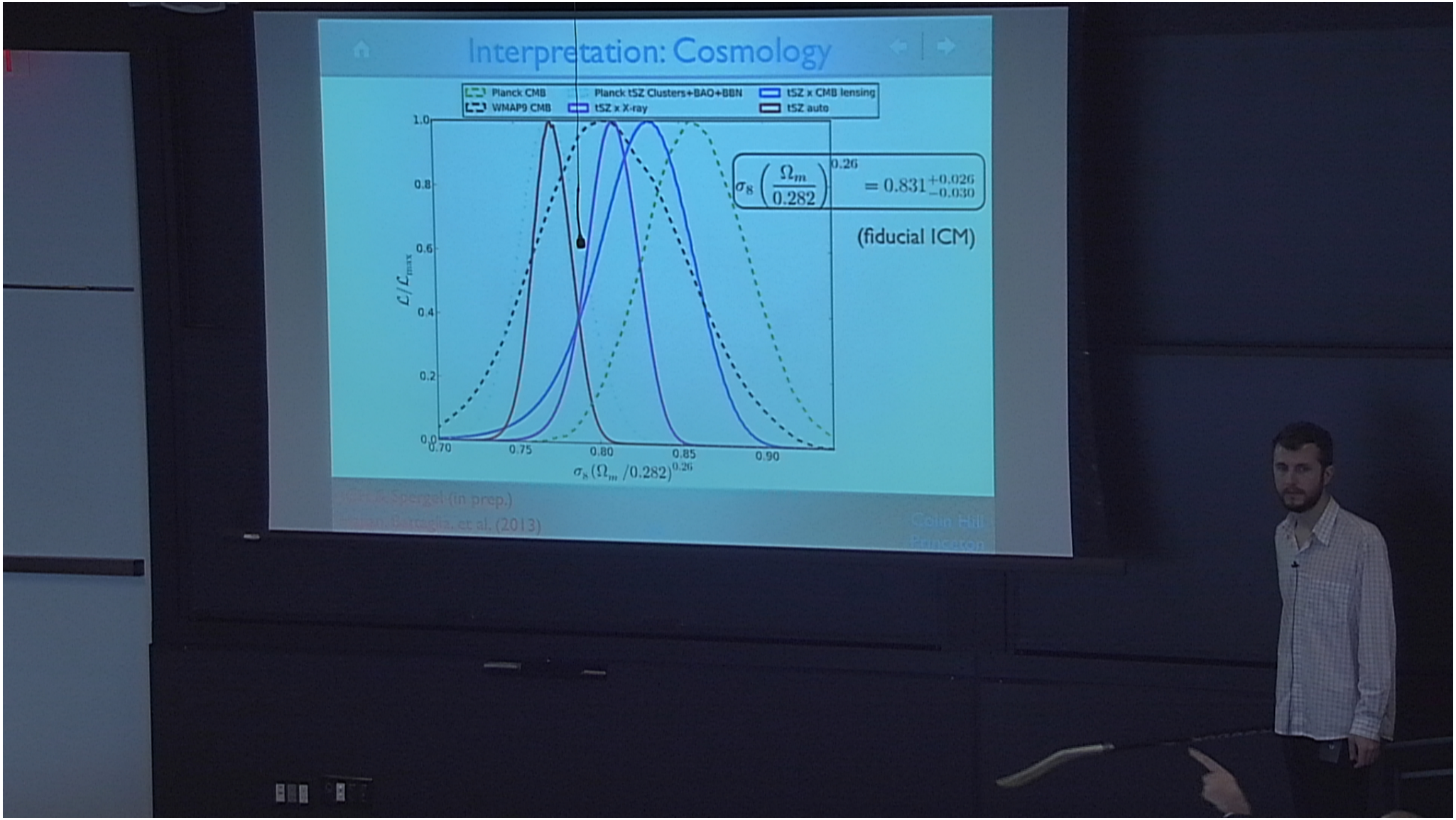
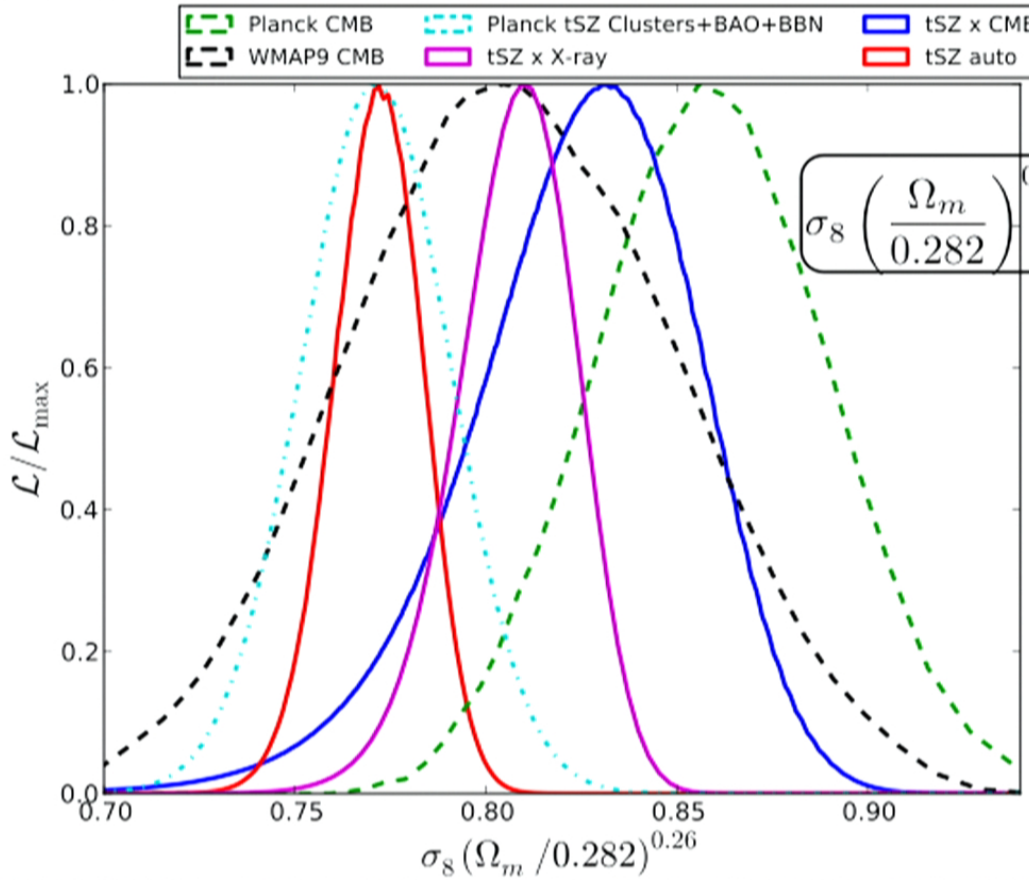

Interpretation: Cosmology
Planck CMB
WMAP9 CMB
Planck tSZ Clusters+BAO+BBN
tSZ x X-ray
tSZ x CMB lensing
tSZ auto
$\sigma_8 \left(\frac{\Omega_m}{0.282}\right)^{0.26} = 0.831^{+0.026}_{-0.030}$
(fiducial ICM)
$\mathcal{L}/\mathcal{L}_{\rm max}$
$\sigma_8 (\Omega_m/0.282)^{0.26}$
0.0
0.2
0.4
0.6
0.8
1.0
0.70
0.75
0.80
0.85
0.90
Spergel (in prep.)
Sartoglia, et al. (2013)
Colin Hill
Planck

Interpretation: Cosmology



$$\sigma_8\left(\frac{\Omega_m}{0.282}\right)^{0.26} = 0.831^{+0.026}_{-0.030}$$

(fiducial ICM)

JCH & Spergel (in prep.)
Hajian, Battaglia, et al. (2013)

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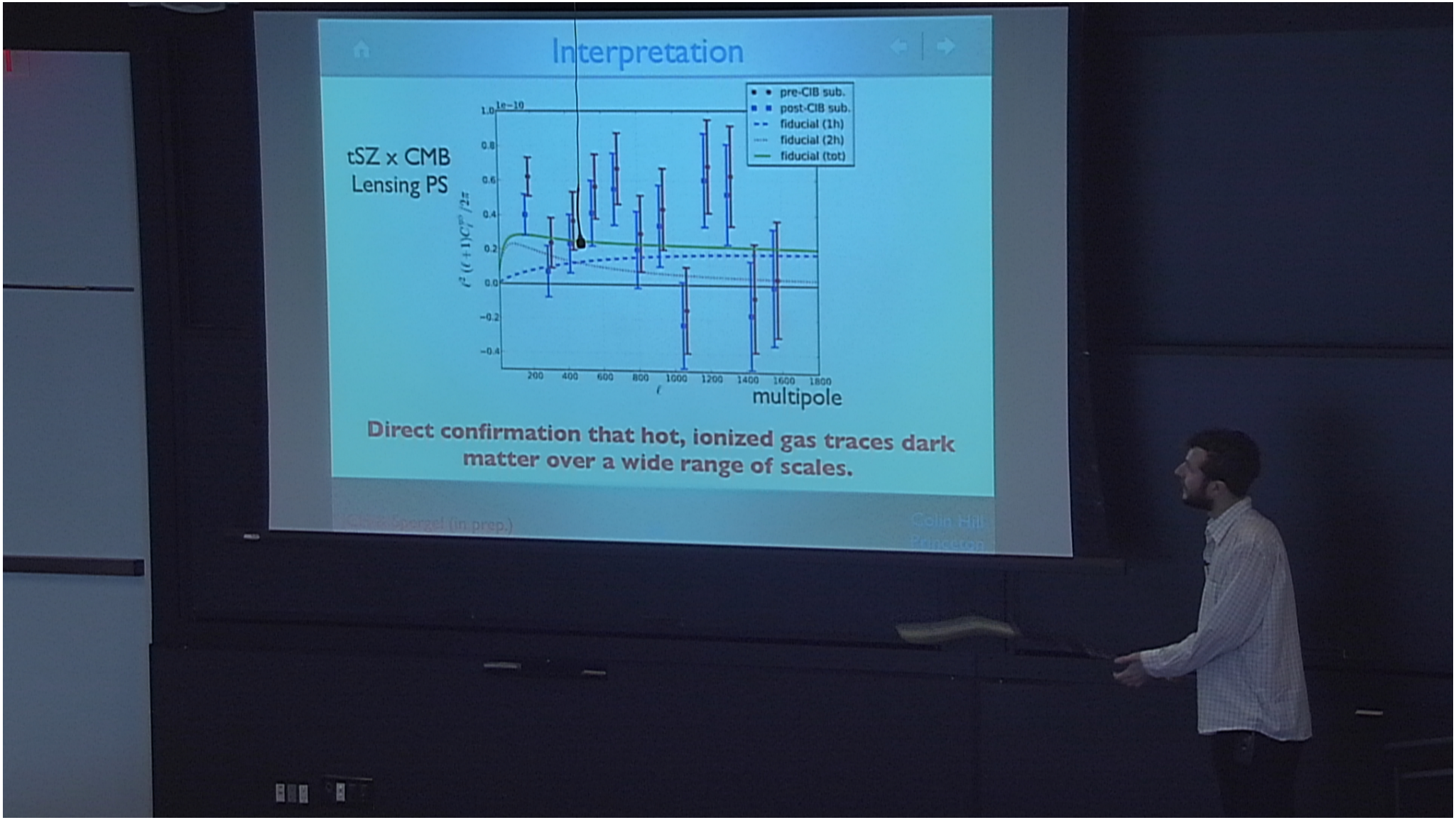
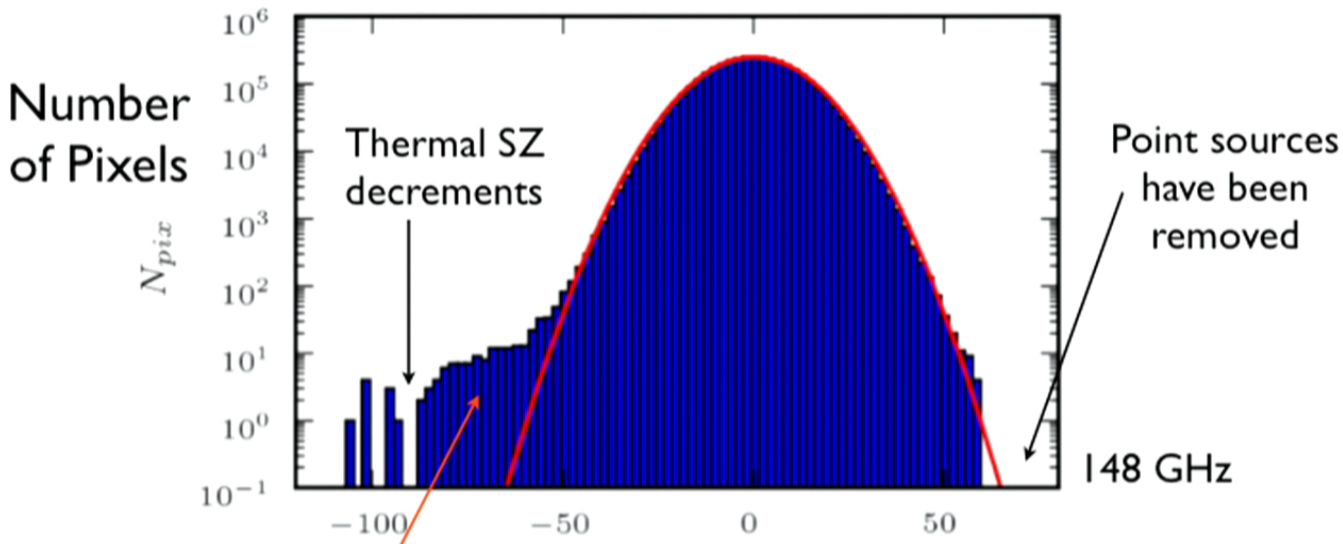

Interpretation
tSZ x CMB
Lensing PS
pre-CIB sub.
post-CIB sub.
fiducial (1h)
fiducial (2h)
fiducial (tot)
1e−10
multipole
Direct confirmation that hot, ionized gas traces dark matter over a wide range of scales.

Beyond the Skewness



Why not compute the PDF itself? Have we used all of the information?

Colin Hill
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