First Data from Planck

Lloyd Knox
5th floor

First Data from Planck: Outline

- Why Planck?
- Instrument performance
- First data -- focus on galaxy cluster results
  - Galaxy clusters as dark energy probes
  - Detecting clusters by their imprint on the CMB
  - Results from Planck
  - Results from the South Pole Telescope
- A few words on upcoming future CMB power spectrum measurements

Planck in February 2009

CMB Accomplishments

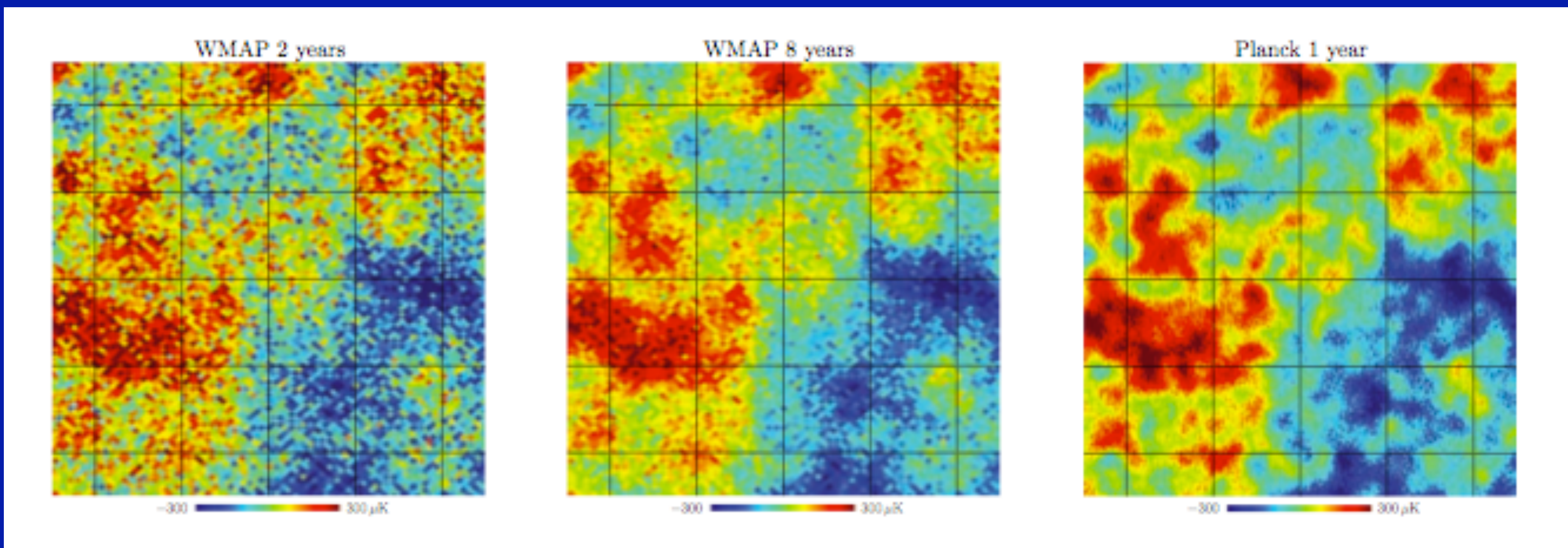
25,973

- CMB is a powerful cosmological probe
  - Applicability of linear theory → highly precise theoretical calculations
  - Richness of angular power spectrum phenomenology (all those bumps and wiggles… not just a power law) → lots of information
- CMB is a proven technique with many ***important*** accomplishments
  - Confirming our basic picture of structure formation (gravitational instability)
  - Confirming dark energy (acceleration inferred from SN data not widely accepted until confirmed by CMB)
  - Verifying prediction #1 of inflation (Ω_{tot} = 1 c.f. ~0.2)
  - Ruling out defect model for structure formation in favor of inflation
  - Verifying prediction #2 of inflation: correlations on super-horizon scales
  - Verifying prediction #3 of inflation: nearly scale-invariant spectrum of primordial perturbations
  - Best constraints on key cosmological parameters: baryon density, matter density, amplitude of primordial perturbations, temperature of the CMB
  - WMAP1 cosmological interpretation paper (Spergel et al. 2003) has ~~3207~~ 3239 citations to date! This has been the default paper to cite for 'cosmology'.

(Slide from my 2006 presentation to our external advisory board)

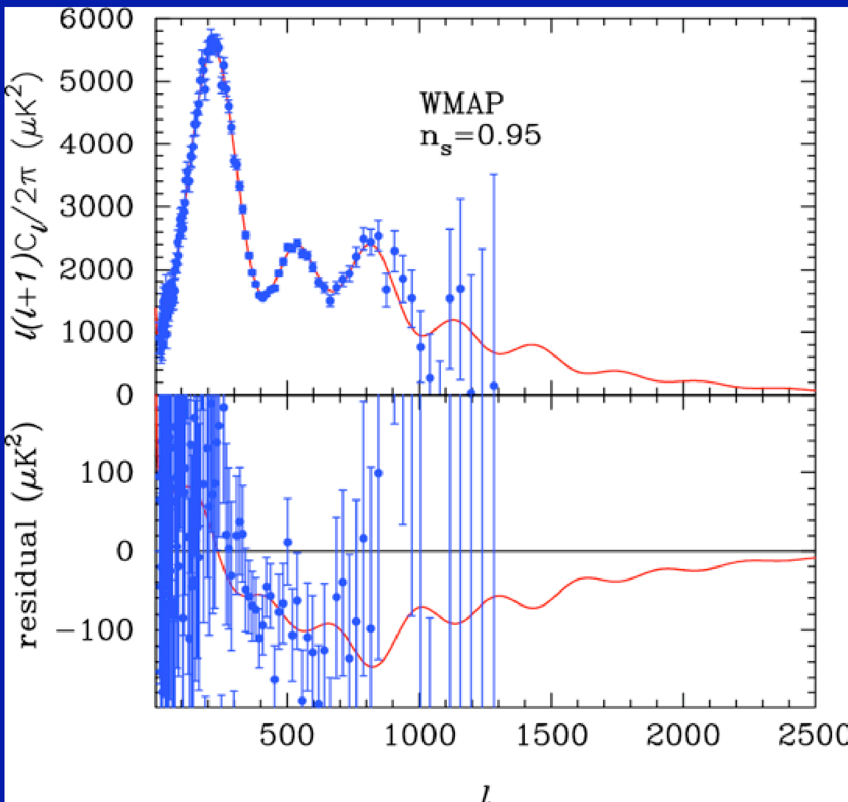
Planck Bluebook

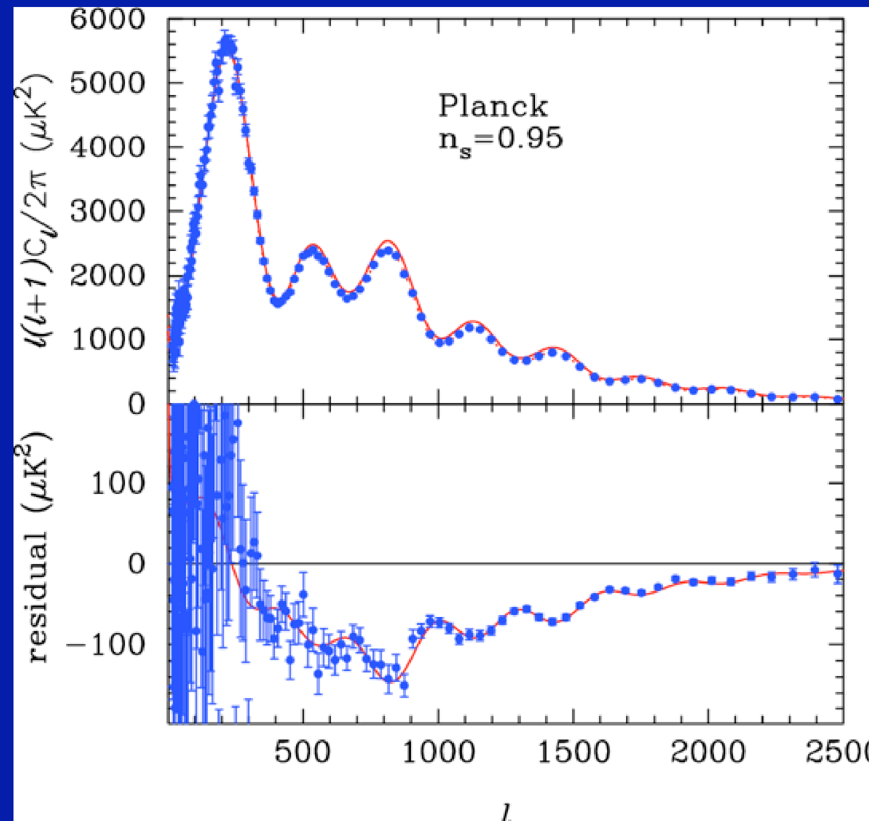
Temperature Maps



WMAP 2 years WMAP 8 years Planck 1 year

Great Opportunities Remain: Forecasted TT Power Spectrum Errors

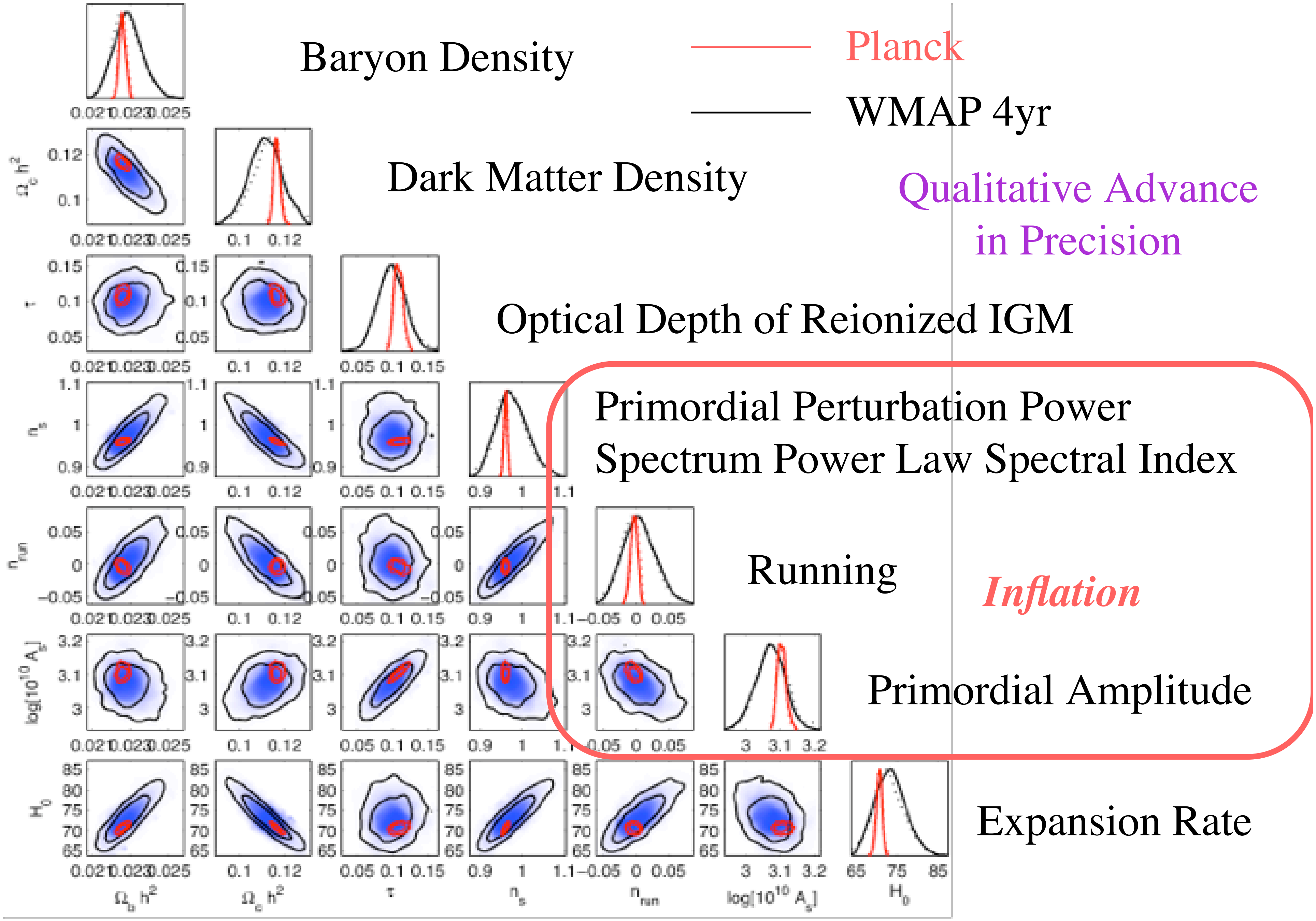




WMAP has revealed 4% of the information content* of the CMB temperature anisotropies.

Planck will reveal 64%. *(Percentage of a_{lm}'s at $l < 2000$ with $s/n > 1$)

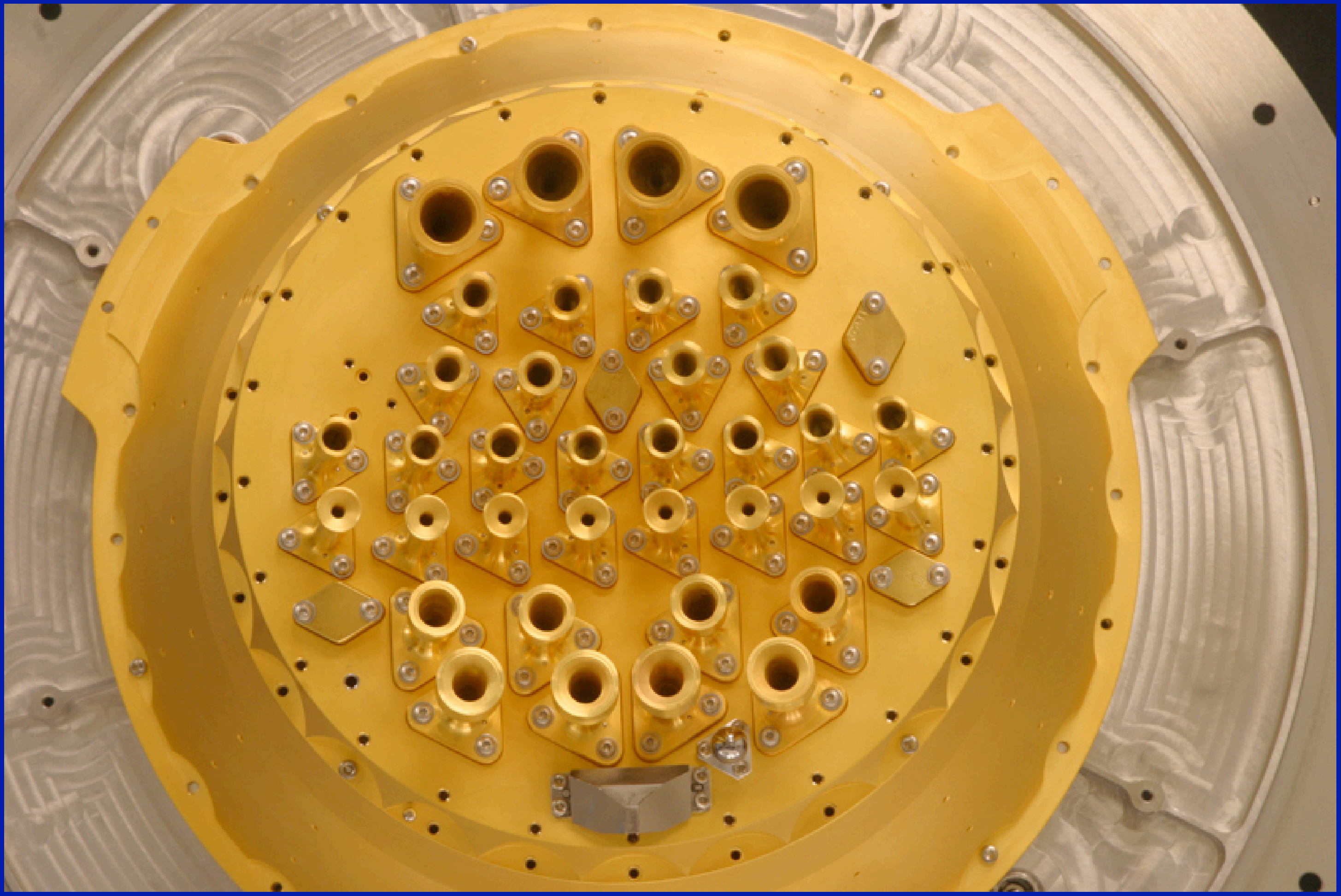
Enabled by Planck's greater sensitivity, angular resolution and frequency coverage



Planck Bluebook

Planck in February 2009

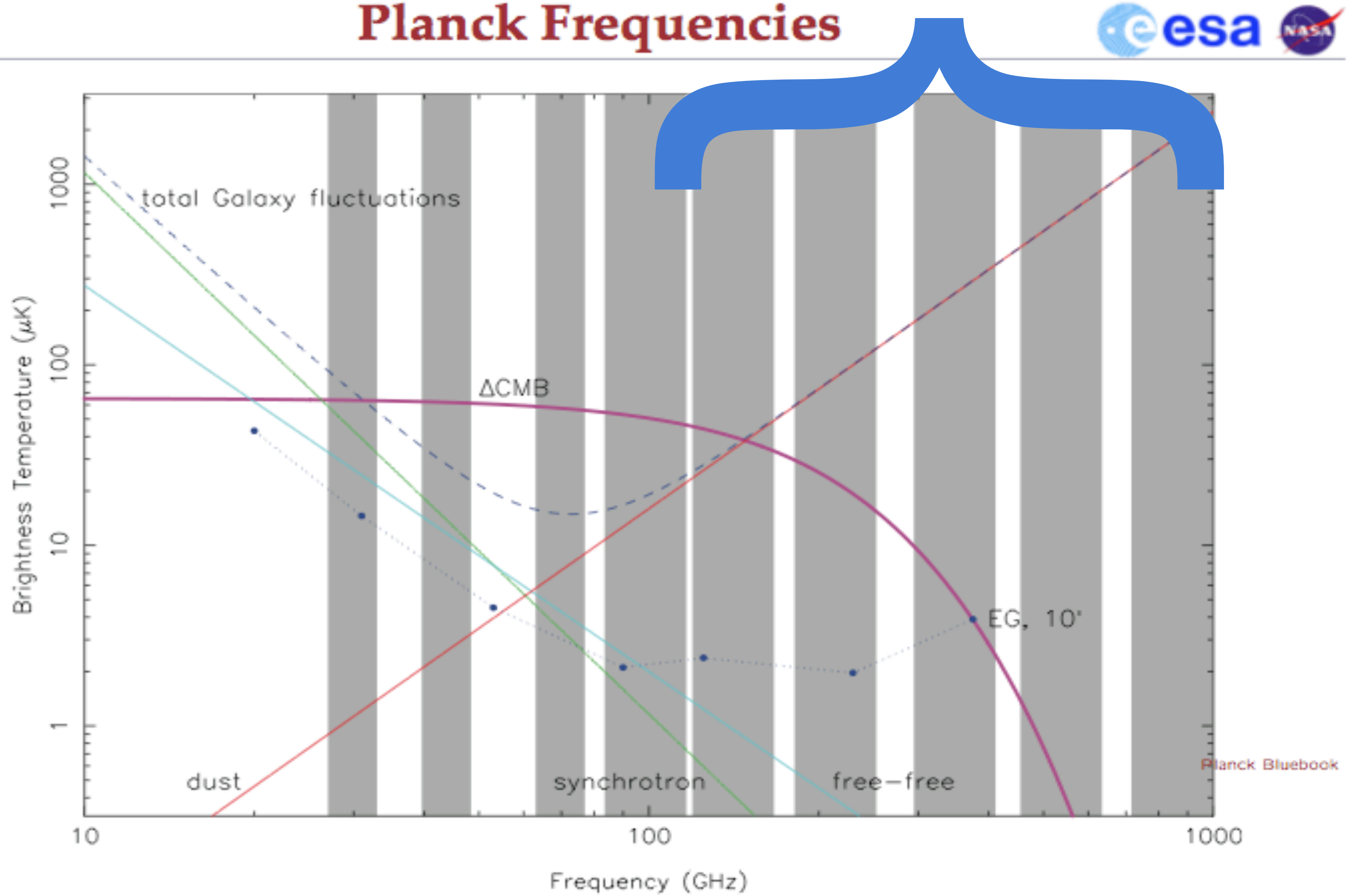
HFI: 100, 143, 217, 350, 540, 850 GHz



LFI: 30, 44, 70 GHz

Very new territory for an all-sky survey

Planck Frequencies



- Temperature measurement at nine frequencies: 30, 44, 70, 100, 143, 217, 353, 545, 857 GHz
- Polarization measurements at seven frequencies: 30, 44, 70, 100, 143, 217, 353 GHz

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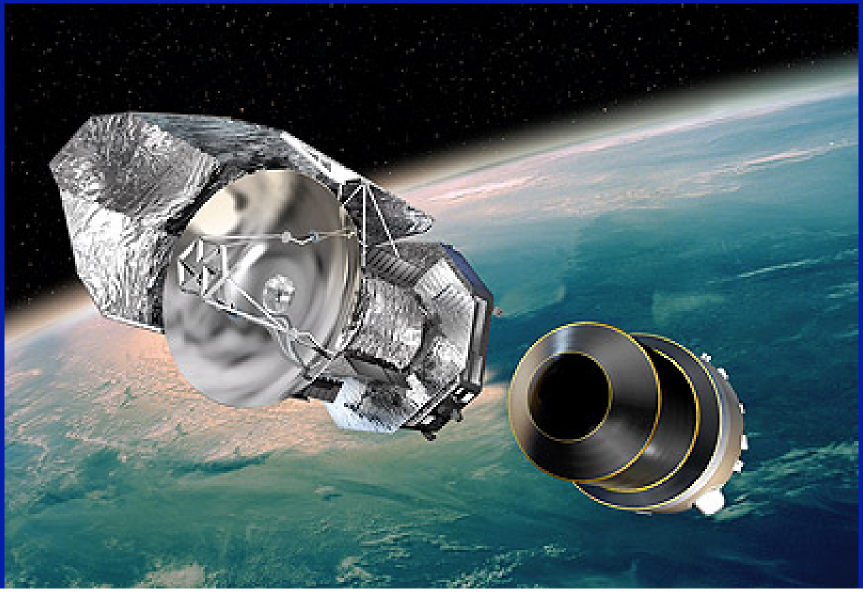
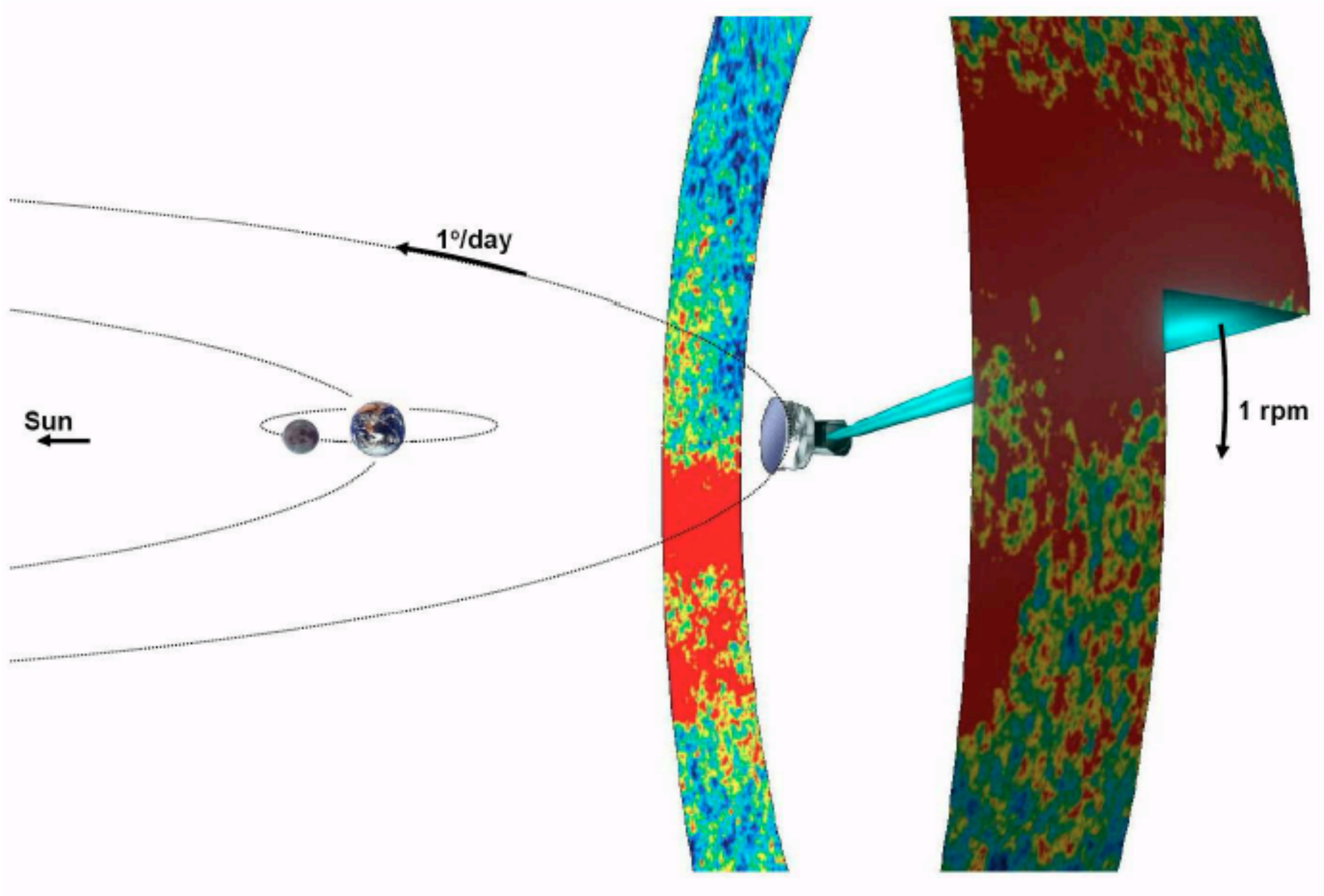
Planck (and Herschel) Launch

May 14th, 2009

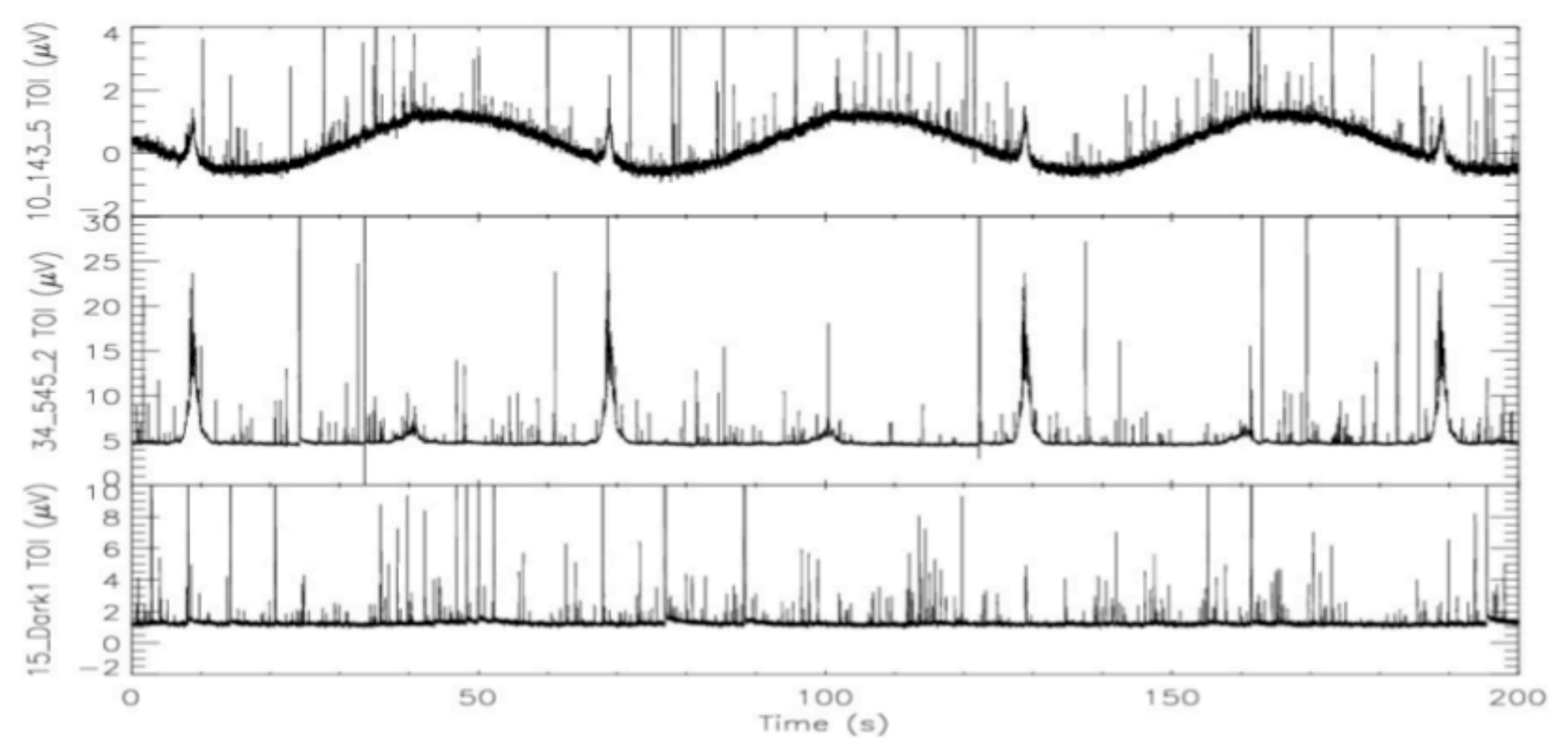


Planck scan strategy

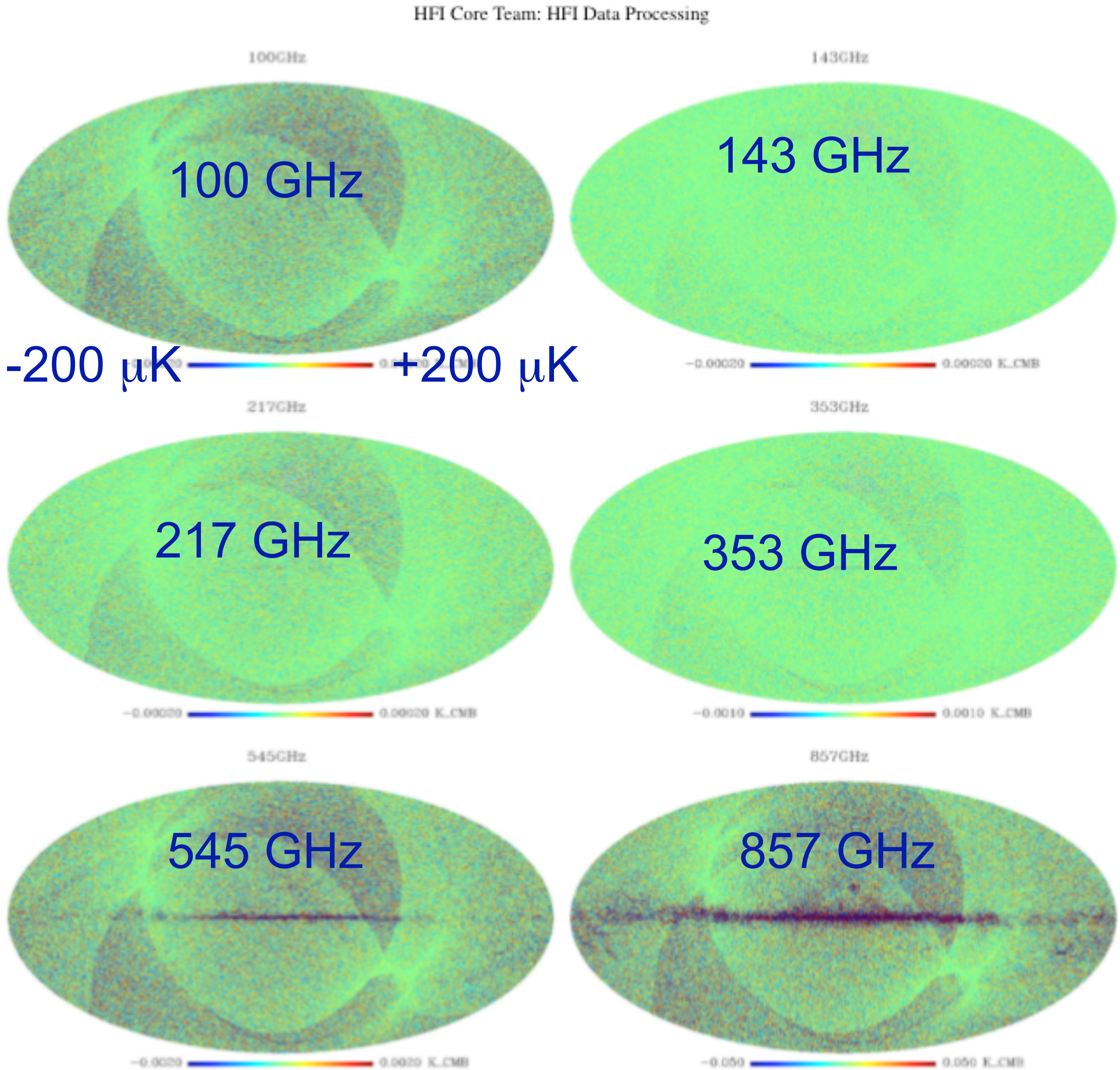


Planck scan strategy

Raw Data



Each map here is a difference between HFI maps made from two different sky scans.



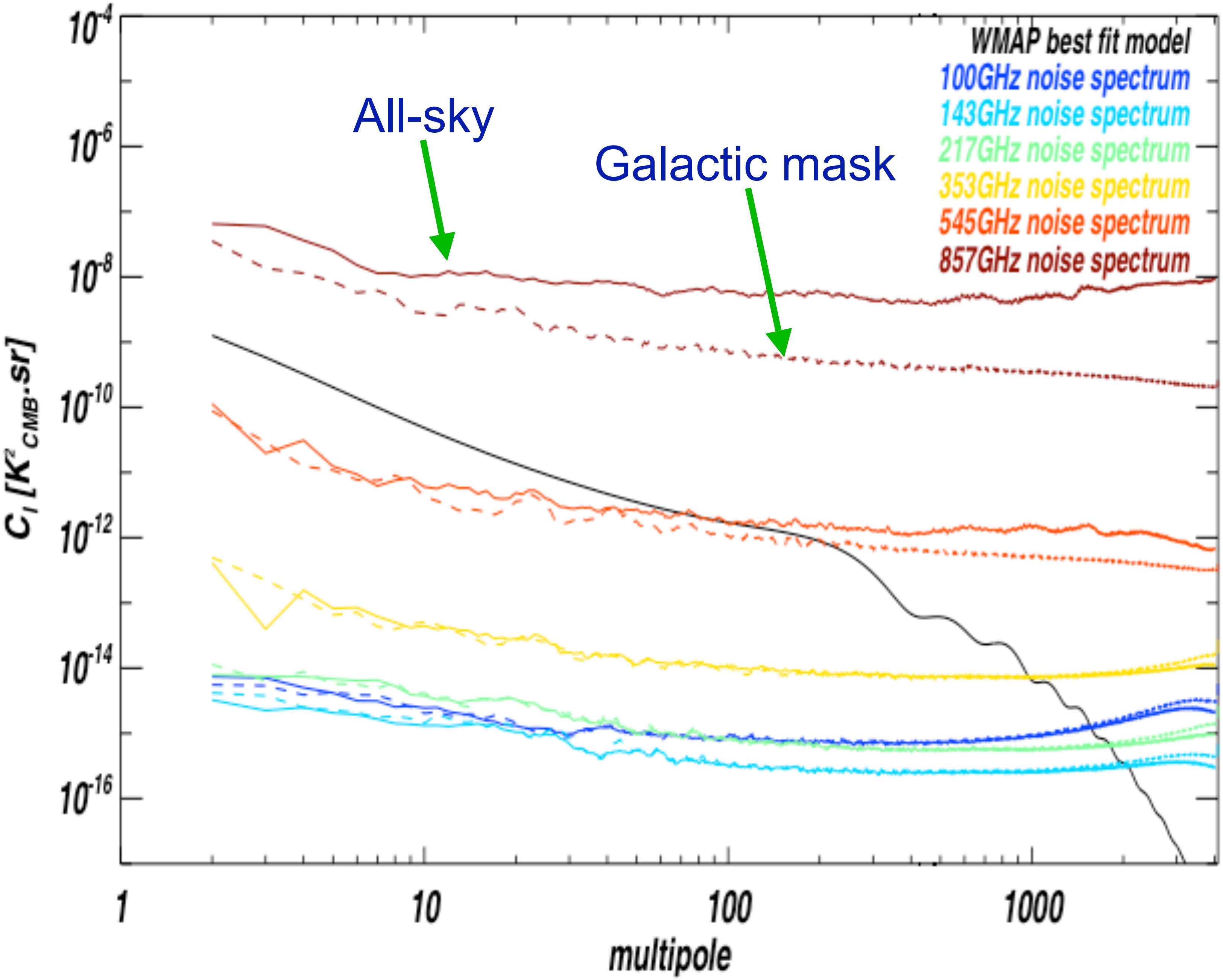


Figure 35. Power spectra from the difference maps shown on

Comparison with WMAP

WMAP

- 22-90 GHz
- 13’
- 300 uK-arcmin (@ 94 GHz)
- 420 uK-arcmin (polarization @ 94 GHz)

Planck

- 30-850 GHz
- 5’ (@>=217 GHz)
- 40 uK-arcmin (@143 GHz)
- 80 uK-arcmin (polarization @143 GHz)

Achieved 54 uK-arcmin already.

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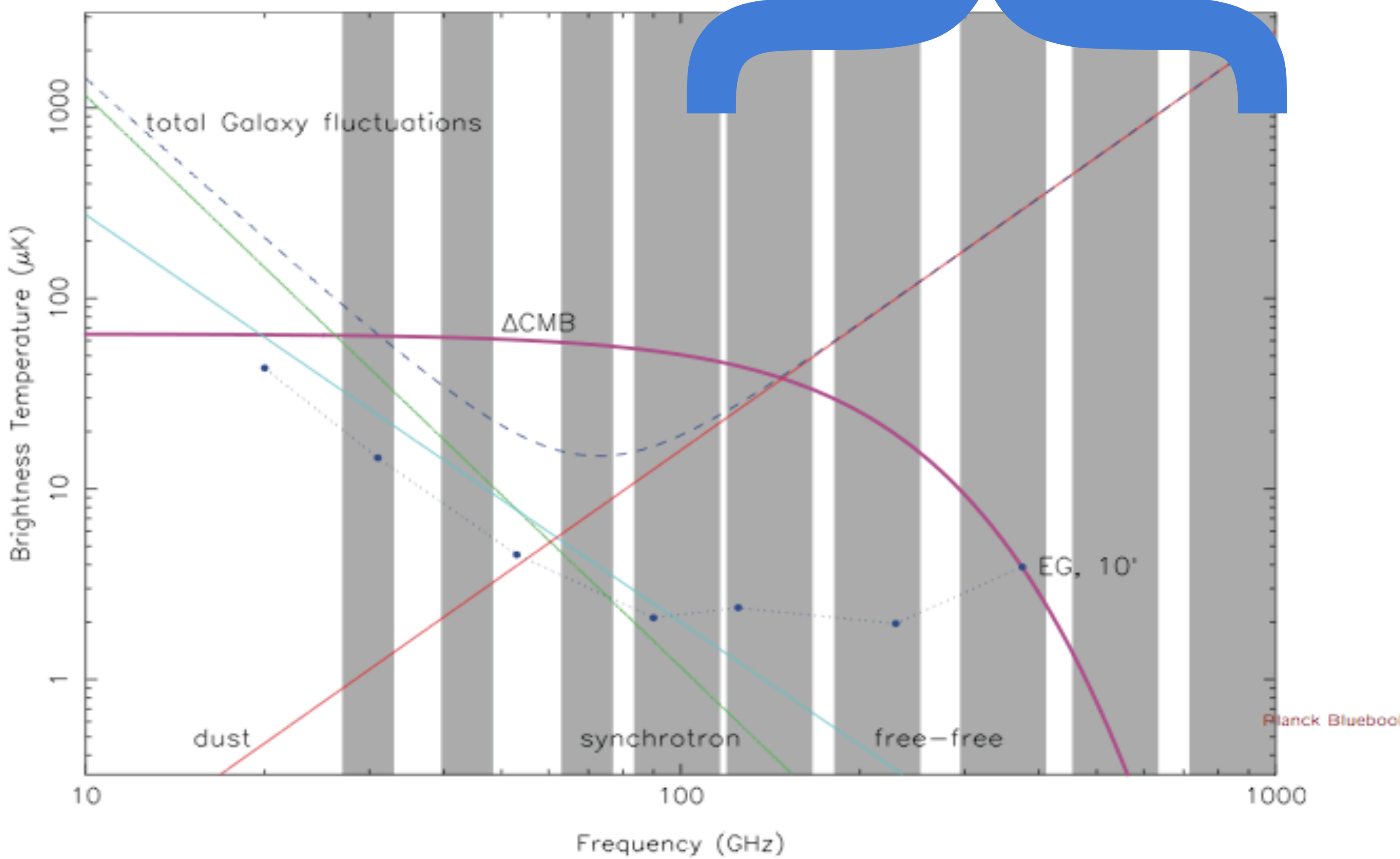
Very new territory for an all-sky survey

Planck Frequencies



- Temperature measurement at nine frequencies: 30, 44, 70, 100, 143, 217, 353, 545, 857 GHz
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1/11/11: 25 papers submitted + one explanatory supplement

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2/10/11: LK UCD cosmology seminar on this topic overview

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ERCSC

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galaxies

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The one area of Planck early science results I'll talk about today.

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The Dream of Galaxy Cluster Precision Cosmology

Dark energy affects

1) the history of the expansion rate:

$$H^2(z) = 8\pi G/3\ [\rho_m(z) + \rho_X(z)+\rho_{rad}(z)]$$

Dark energy density

And

2) the rate of growth of structure (at fixed expansion rate, the spatially smooth dark energy suppresses growth)

Number densities of galaxy clusters, as a function of mass, are sensitive to both these effects.

Supernovae

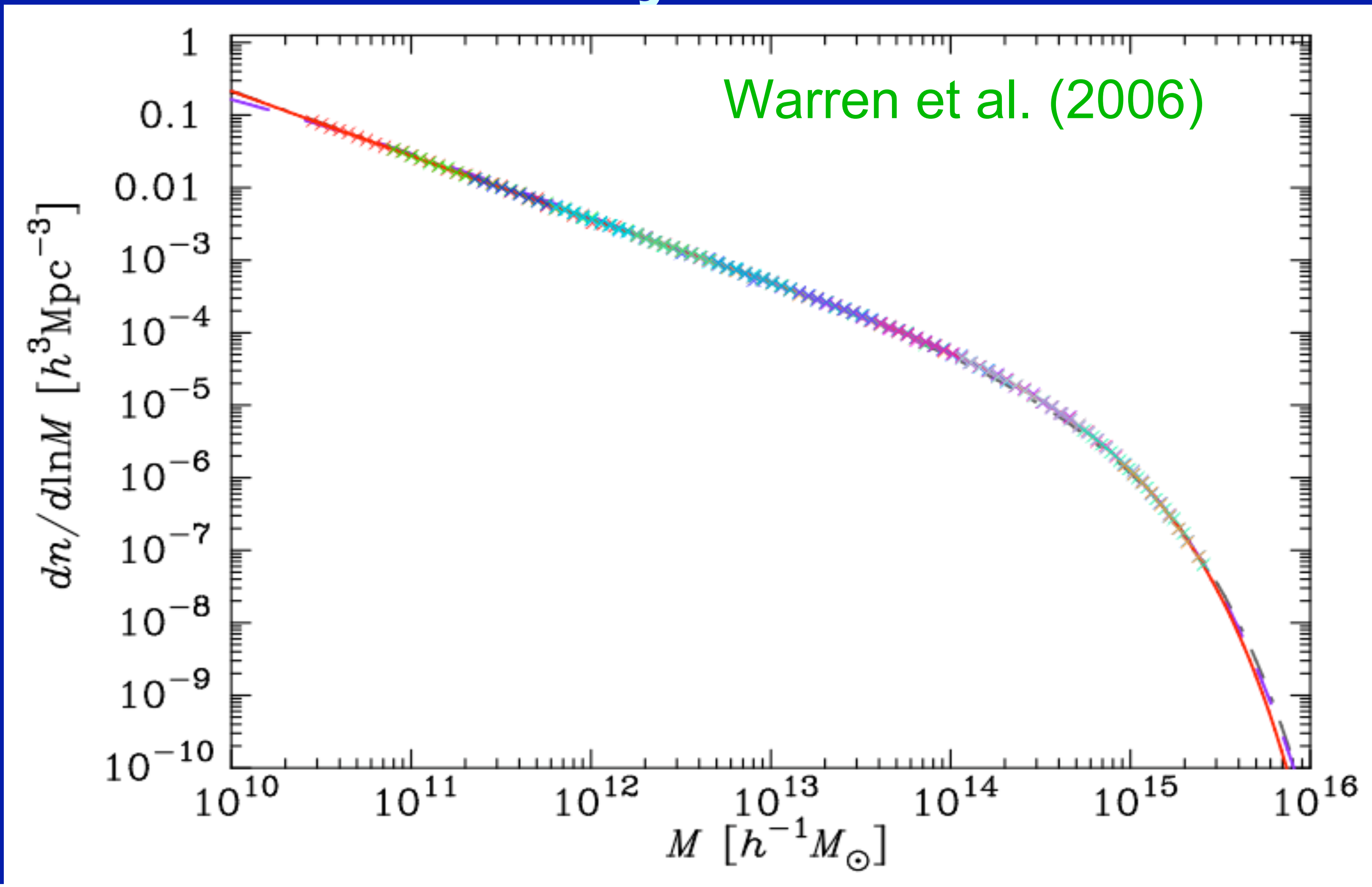
- Standardizable candles (exploit empirical relationship to infer luminosity from decay time)
- Measure flux
- Infer distance
- Map out distance as a function of redshift, which depends on history of expansion rate (and therefore D. E.)

Galaxy Clusters

- Standard population (can calculate spatial number density*)
- Measure number in a given solid angle and redshift range
- Infer corresponding volume, which also depends on history of expansion rate

*The calculated number densities are also sensitive to D.E.

We can calculate number density of dark matter haloes from N-body simulations



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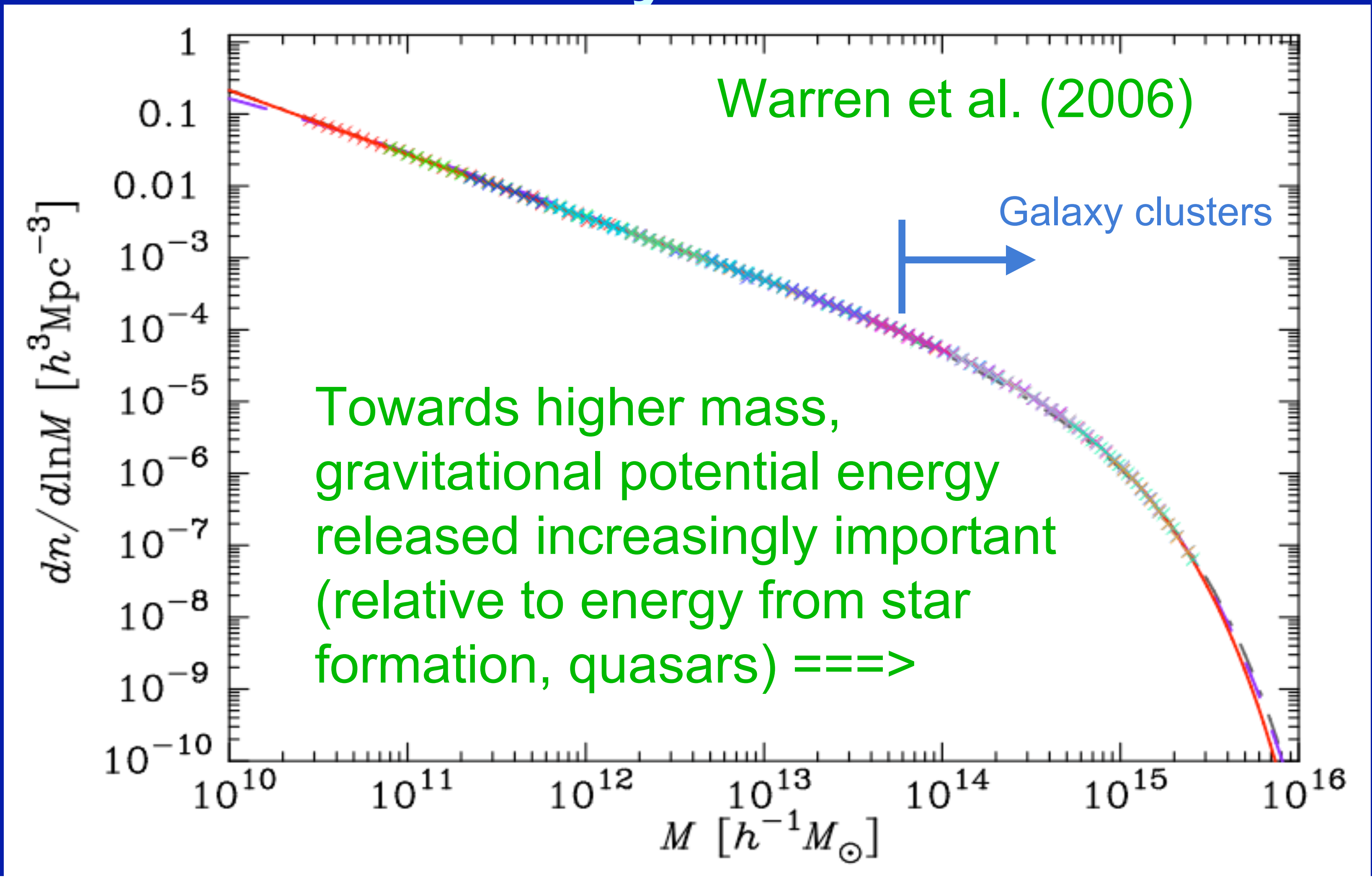
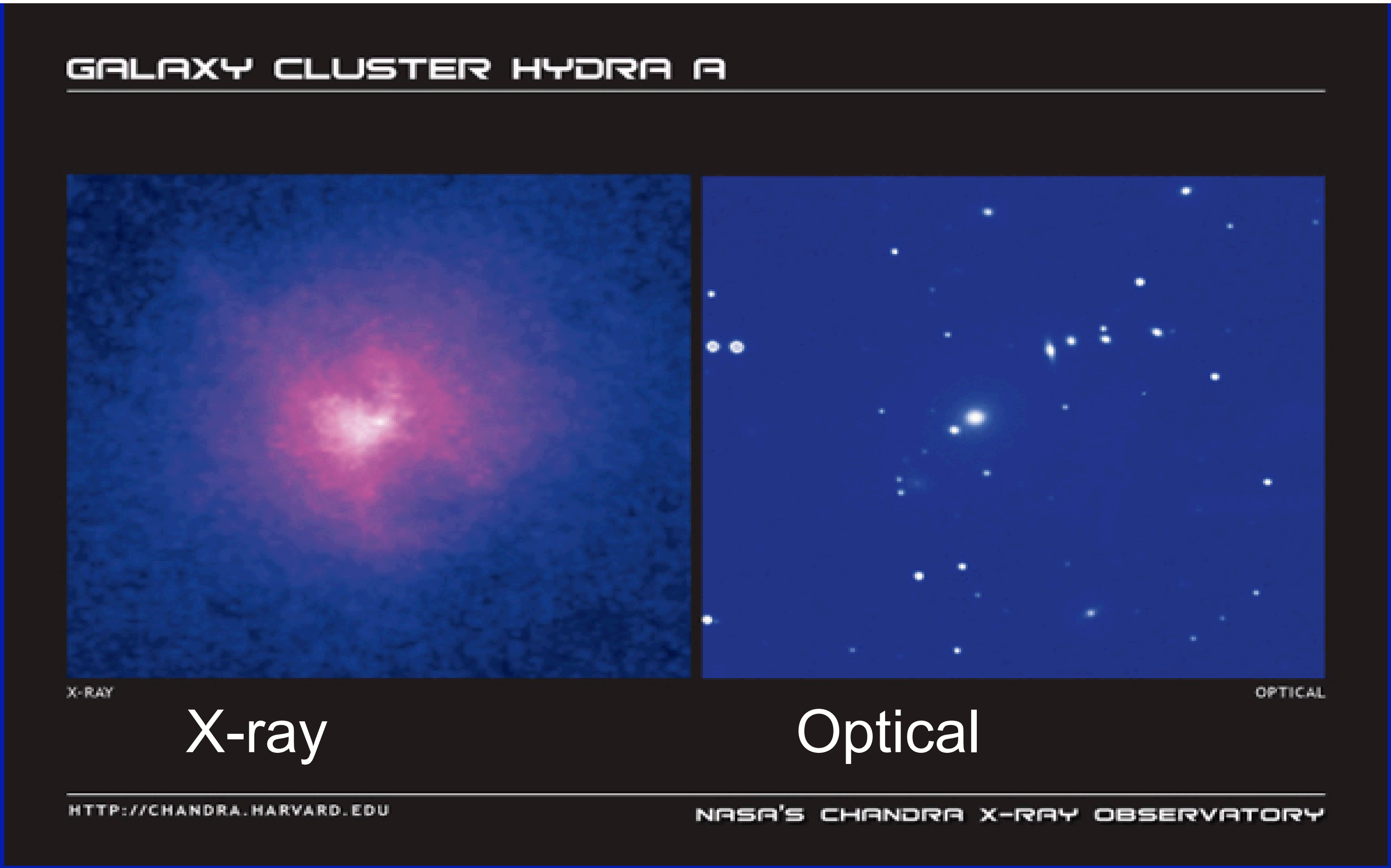


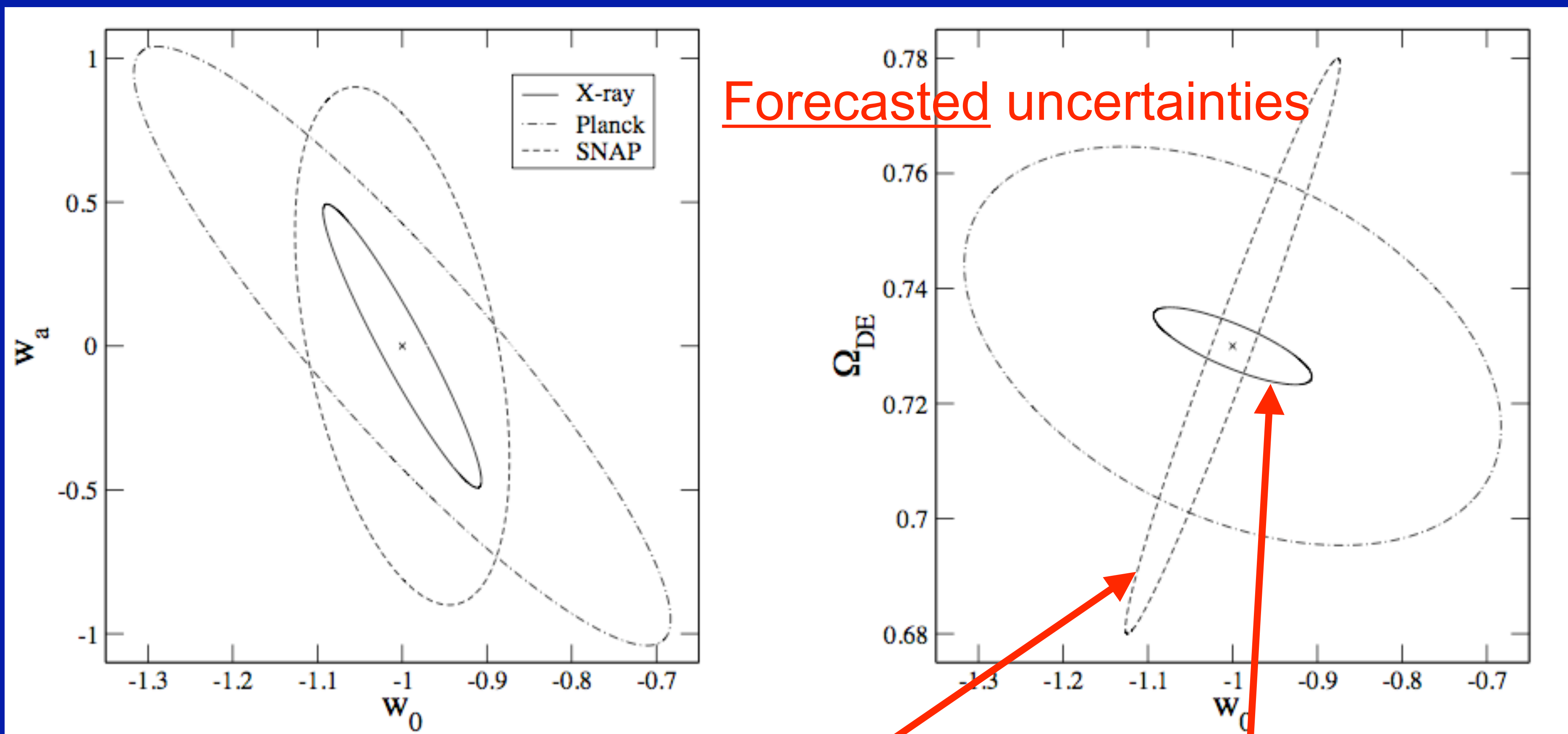


Galaxy clusters are composed of dark matter, gas and galaxies

Most of the kinetic energy of the gas is from gravitational potential energy.

We can see Bremstrahlung from the gas (plasma) in the X-ray image.

Complementary Constraints on Dark Energy Parameters



Forecasted uncertainties

Haiman et al. 2005 Dark Energy Task Force white paper on an X-ray survey

supernovae

clusters

The Mass-Observable Relation

- Key to the cluster cosmology program is being able to relate mass and observables.
- These relationships are being studied via
  - X-ray brightness and temperature measurements
  - Weak lensing measurements
  - Sunyaev-Zel'dovich Effect measurements
  - Numerical simulations

One way to understand Planck galaxy cluster results: one step in this program to make galaxy clusters safe for cosmological use.

Dark Energy Task Force Finding 4

4. The techniques are at different levels of maturity:
   a. The **BAO** technique has only recently been established. It is less affected by astrophysical uncertainties than other techniques.
   b. The **CL*** technique has the statistical potential to exceed the BAO and SN techniques but at present has the largest systematic errors. Its eventual accuracy is currently very difficult to predict and its ultimate utility as a dark energy technique can only be determined through the development of techniques that control systematics due to non-linear astrophysical processes.

*Clusters

Cosmology seminar this week: Shirley Ho talking about BAO constraints on dark energy (Thursday, Jan 27, 12:10 pm).

Dark Energy Task Force Finding 12

12. Our inability to forecast systematic error levels reliably is the biggest impediment to judging the future capabilities of the techniques. Assessments of effectiveness could be made more reliably with:
    a. For **BAO**– Theoretical investigations of how far into the non-linear regime the data can be modeled with sufficient reliability and further understanding of galaxy bias on the galaxy power spectrum.
    b. For **CL**– Combined lensing, Sunyaev-Zeldovich, and x-ray observations of large numbers of galaxy clusters to constrain the relationship between galaxy cluster mass and observables.

Physics colloqium today on LSST by TT will certainly mention weak lensing observations of clusters

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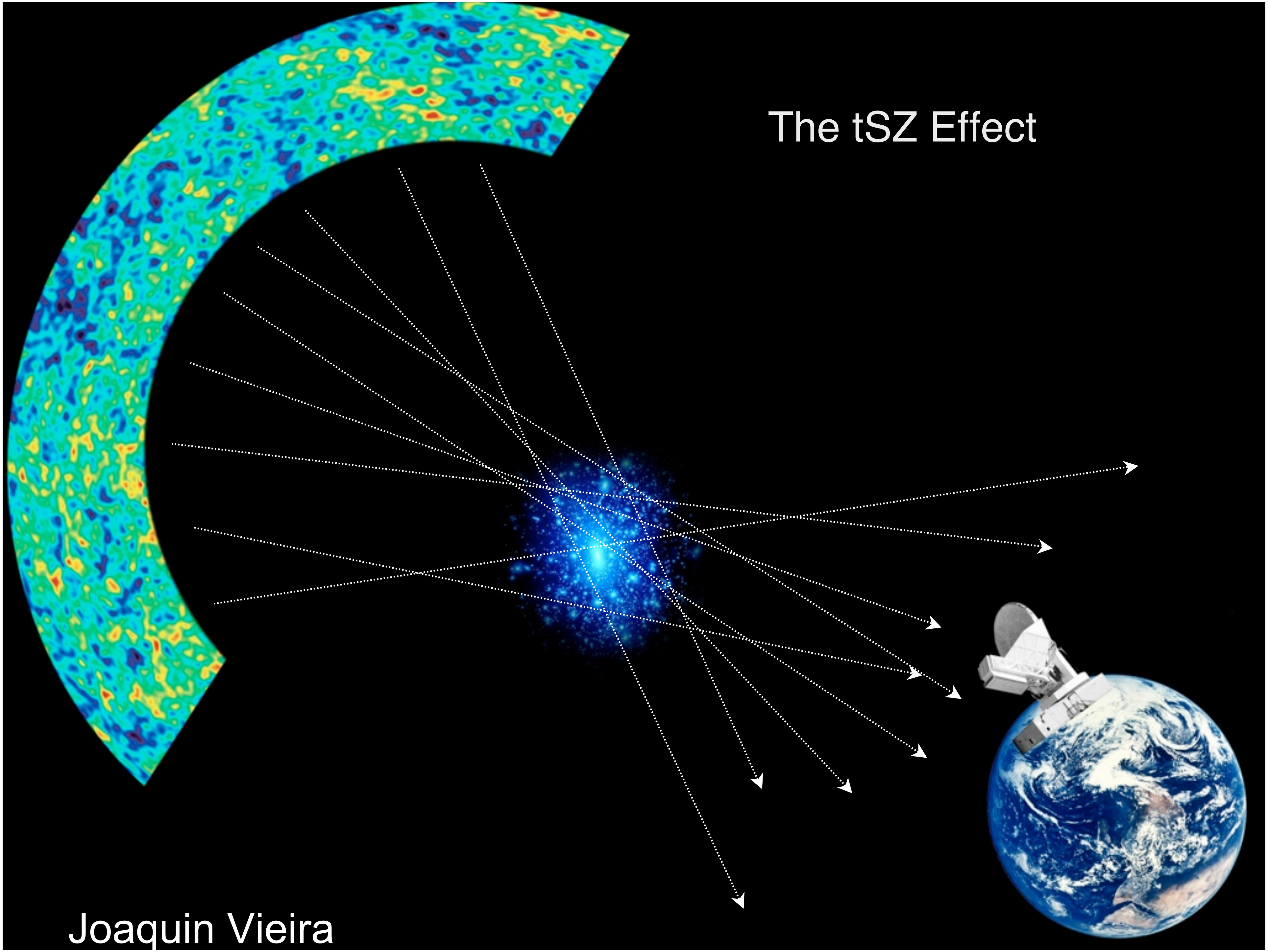
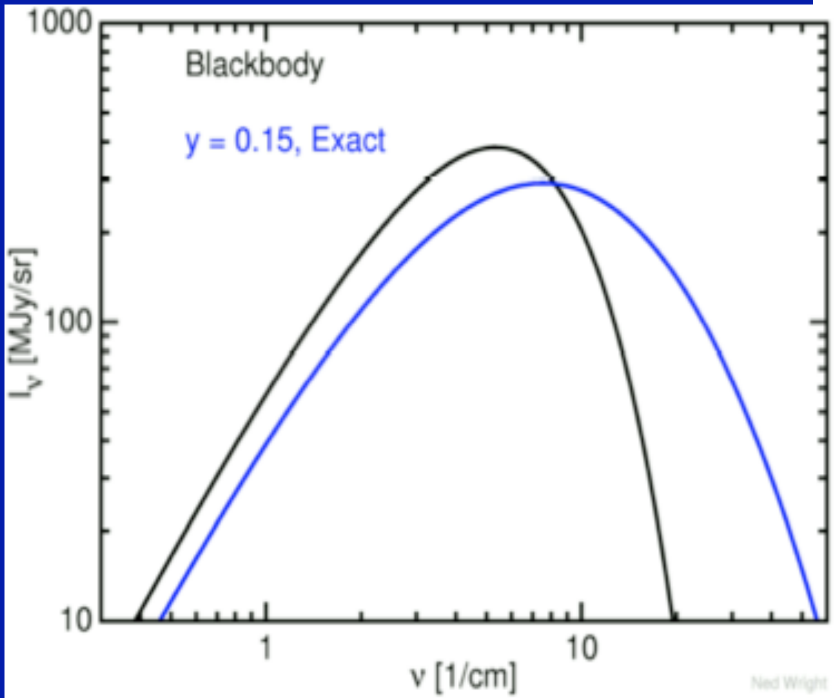
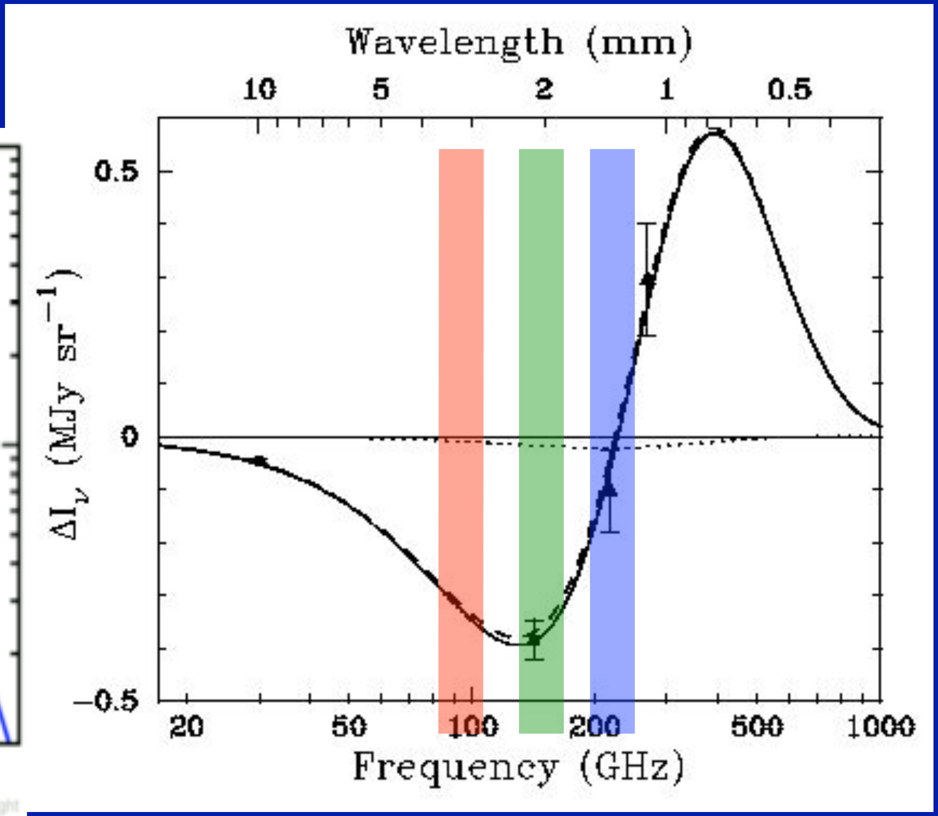

The tSZ Effect
Joaquin Vieira

Sunyaev-Zel'dovich Effect



from Ned Wright



From Joaquin Vieira

SPT Bands

Effect of hot electrons on CMB photons

$$\left[\frac{\partial}{\partial t} - \frac{\dot{R}}{R} k \frac{\partial}{\partial k}\right] f(k,t) = C_I(k) + \frac{1}{k}\int \frac{d^3k'}{(2\pi)^3}\frac{1}{2k'}\int \frac{d^3p}{(2\pi)^3}\frac{1}{2E(p)}\int \frac{d^3p'}{(2\pi)^3}\frac{1}{2E(p')}|M|^2(2\pi)^4\delta^4(k+p-k'-p')$$
$$\times\{f(k',t)g_e(p',t)[1+f(k,t)] - f(k,t)g_e(p,t)[1+f(k',t)]\} \;. \qquad (2.3)$$

Bernstein and Dodelson (1990)

$f(k,t)$ is the photon phase-space distribution function (k = momentum)

$g_e(p,t)$ is the electron phase-space distribution function

Amplitude of spectral distortion proportional to $y = \sigma_T \int dl\, n_e (kT_e/m_e)$ is proportional to pressure integrated along line of sight

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Planck ESZ

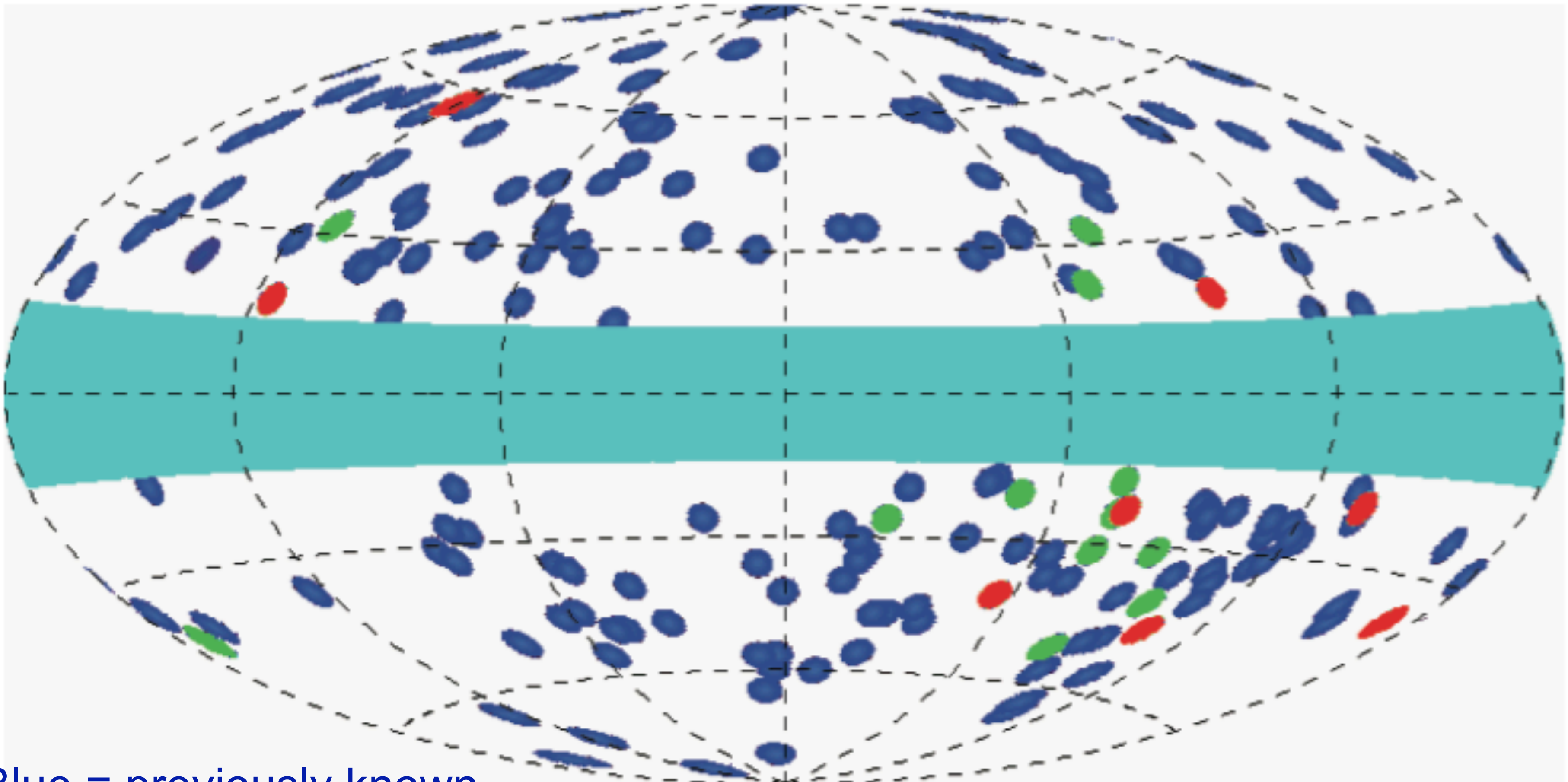
ESZ = Early-release SZ catalog

- The Planck SZ survey
  - Is the first all-sky cluster survey since ROSAT (1992)
  - Finds massive clusters, good for cosmology
  - Is easy to follow-up (e.g., X-ray) once you know where to point!
- ESZ “firsts”
  - All sky SZ
  - Multiple frequency detections (6 bands around null)
- 189 clusters
  - 169 previously known (blue on next figure)
  - 20 of them not previously known

    12 confirmed: 11 by XMM; 1 by AMI/WISE (green on next figure)

    8 to be confirmed (red on next figure)

SZ Clusters — ESZ



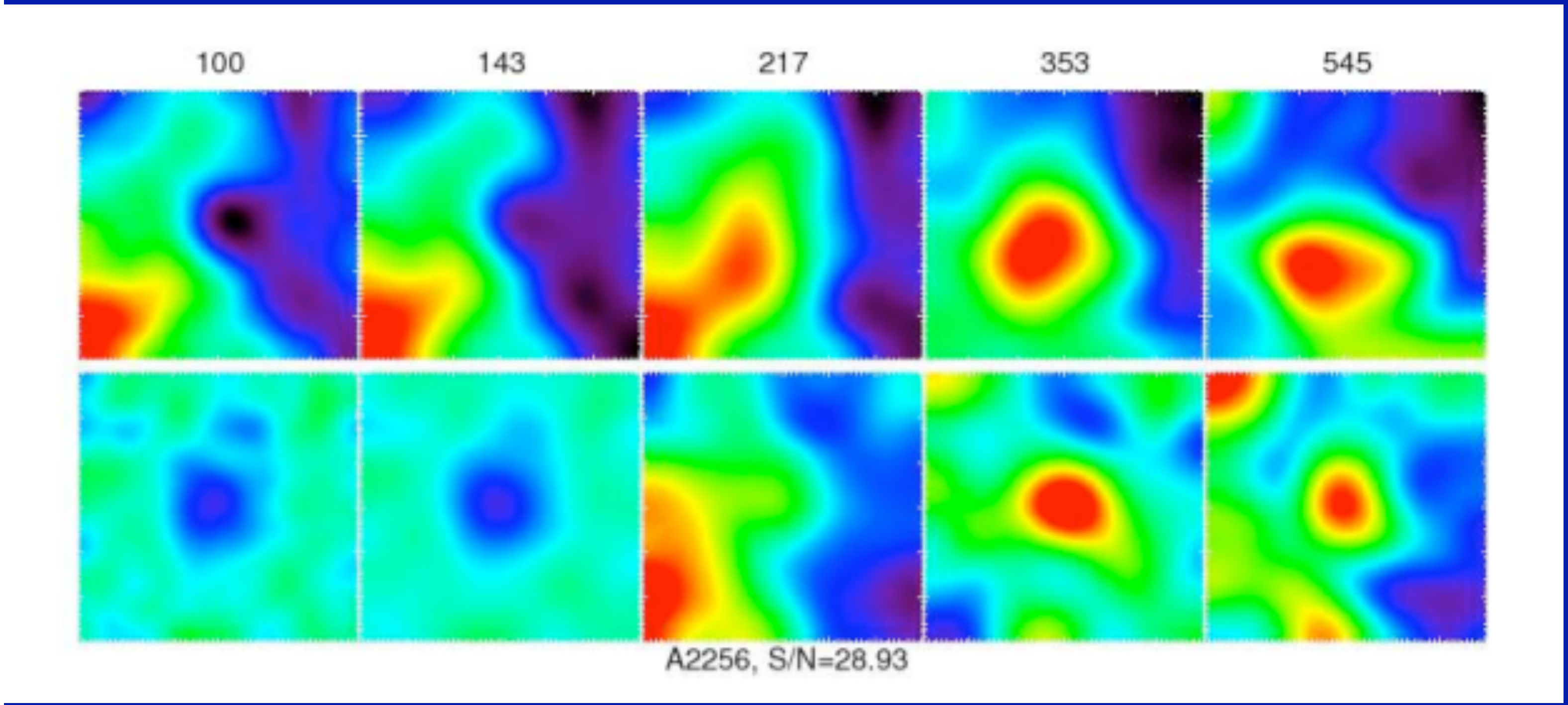
Blue = previously known

Green = confirmed by XMM follow-up (11) or AMI/WISE (1)

Red = unconfirmed

Highest S/N SZ Effect in Planck maps

Planck Collaboration 2011d



Raw maps

`cleaned' maps

Abell 2256

Planck Collaboration 2011d

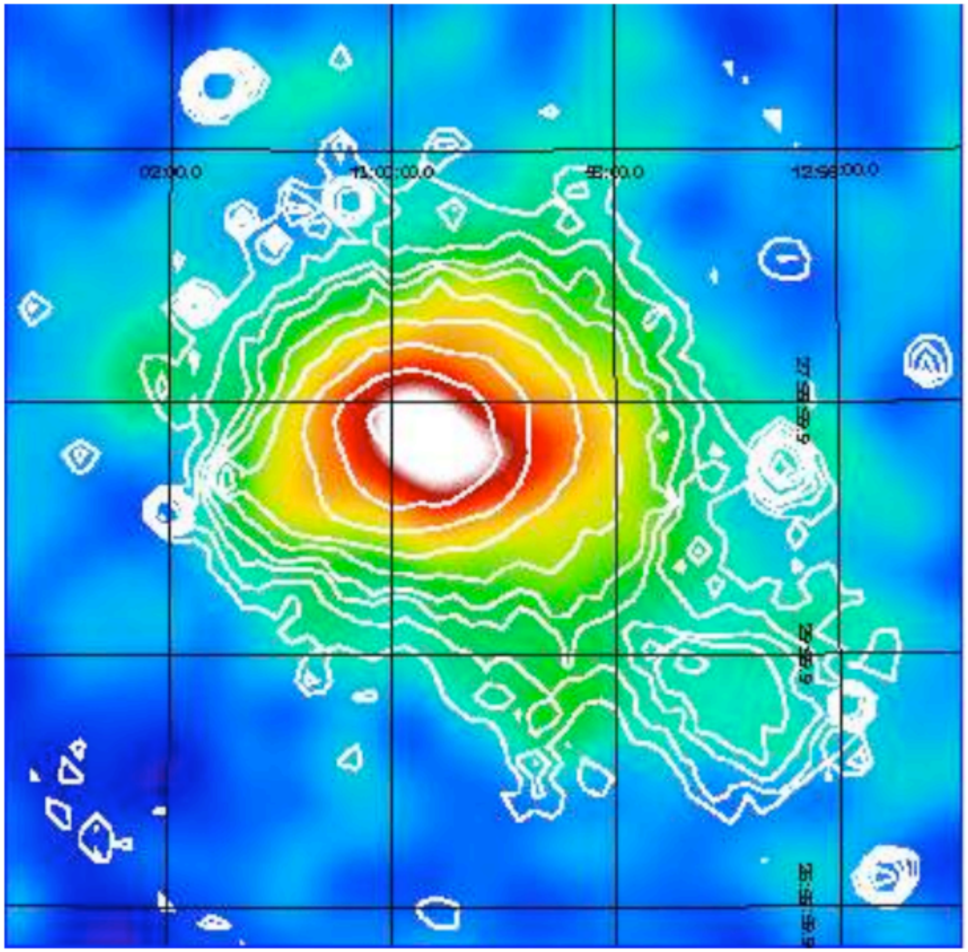
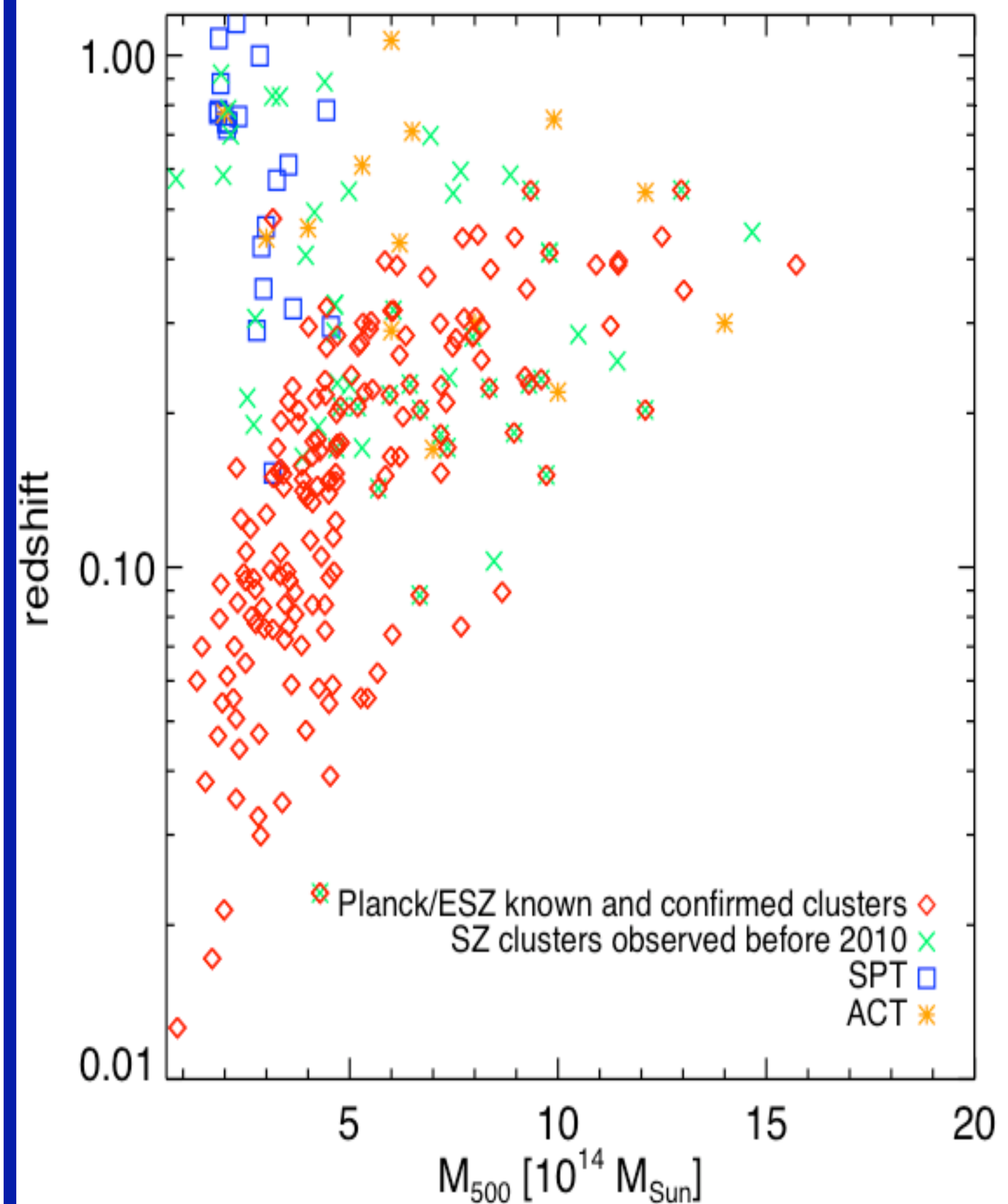


Fig. 1. *Planck* *y*-map of Coma on a ~ 3° × 3° patch with the *ROSAT-PSPC* iso-luminosity contours overlaid.

Gas pressure map of the Coma cluster

Amplitude of spectral distortion proportional to
$y = \sigma_T \int dl\, n_e\, (kT_e/m_e)$ which is
proportional to pressure integrated along line of sight.



Planck Collaboration 2011d

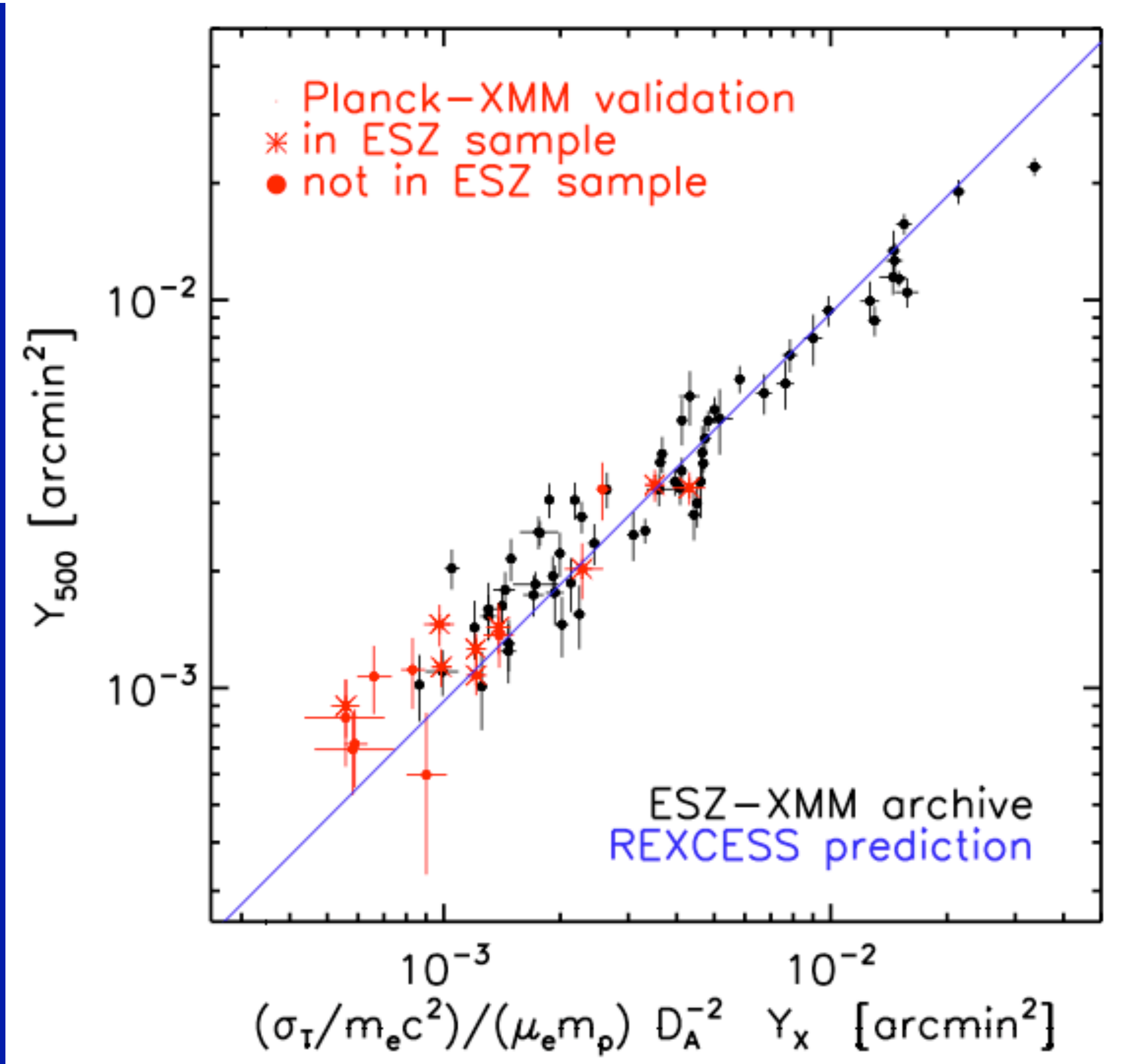
189 new SZ measurements

80% had no previous SZ measurement.

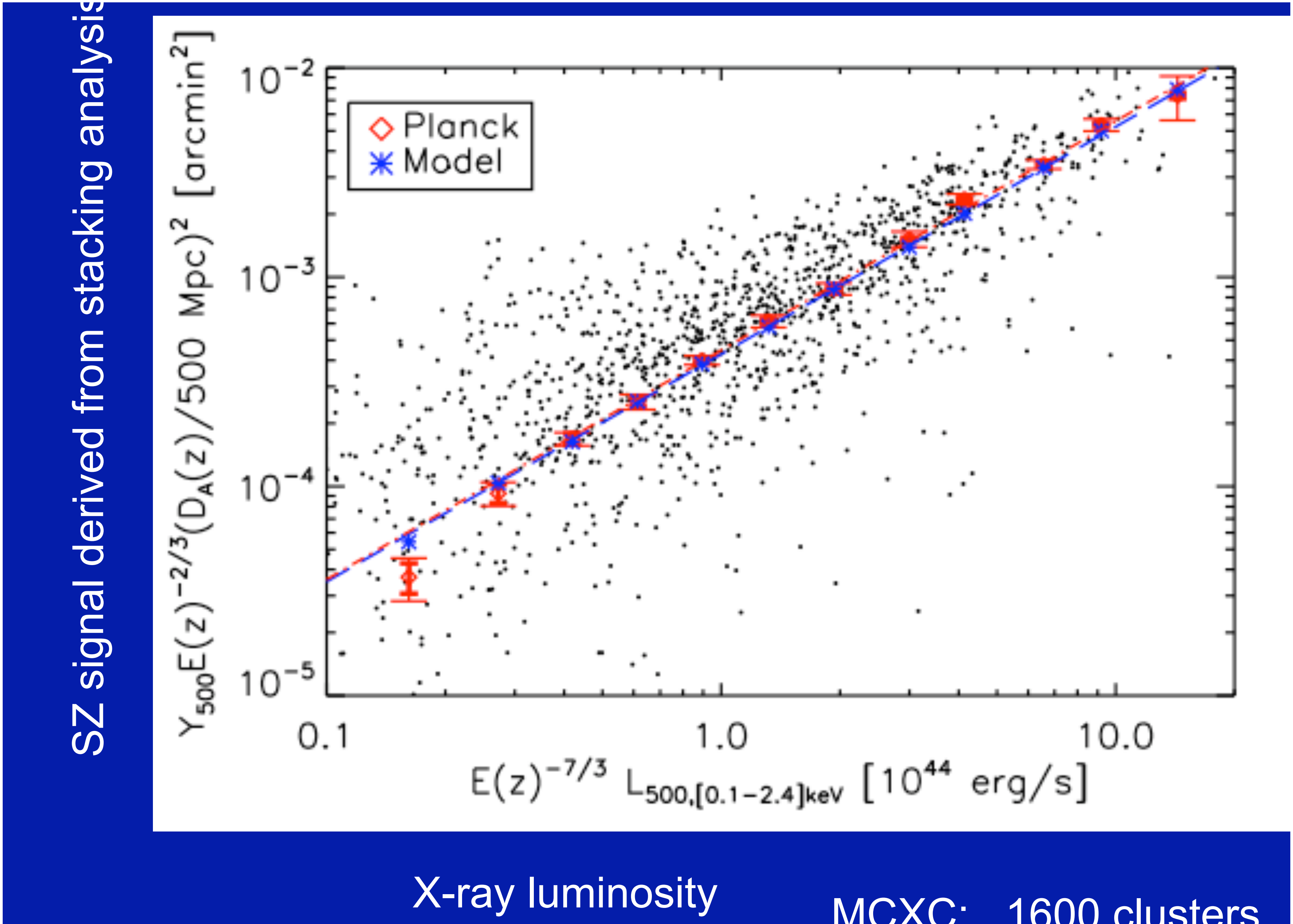
All but 20 were previously known galaxy clusters.

SPT and ACT are higher-resolution ground-based instruments.

Planck measurement of SZ signal



X-ray-based prediction of SZ signal



MCXC: 1600 clusters

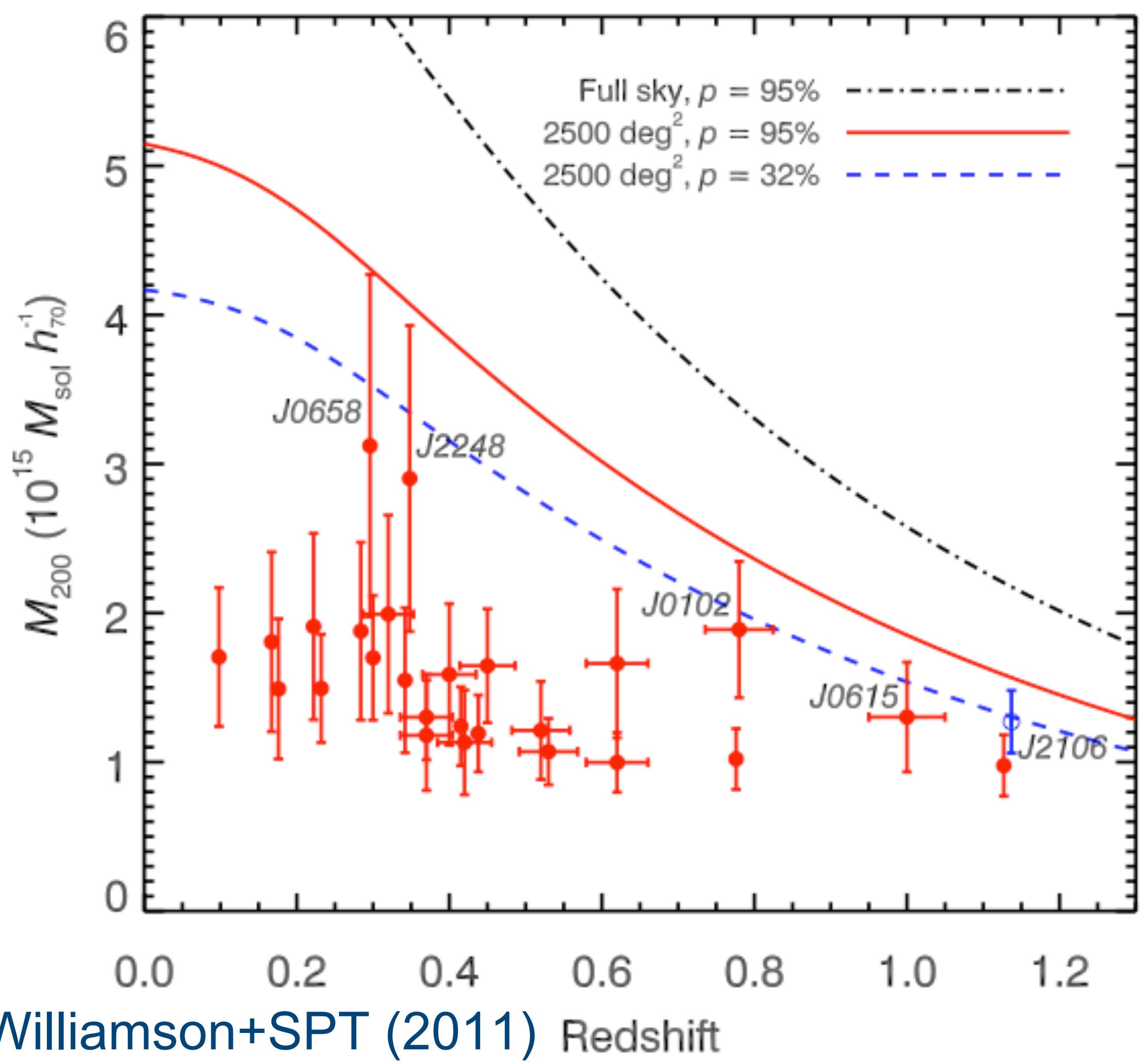
Conclusion on Clusters

- Largest sample of SZ-selected galaxy clusters to date. Uniform selection important for cluster cosmology.
- Further work needed on mass-observable relation before one can extract cosmological implications.
- Initial results show very good agreement between X-ray-based predictions for SZ, and observation of SZ ==> no surprises from the intra-cluster medium, or confusing millimeter wavelength signals: synchrotron, thermal dust emission.
- Field is evolving rapidly.

First Data from Planck: Outline

- Why Planck?
- Instrument performance
- First data -- focus on galaxy cluster results
  - Galaxy clusters as dark energy probes
  - Detecting clusters by their imprint on the CMB
  - Results from Planck
  - Results from the South Pole Telescope
- A few words on upcoming future CMB power spectrum measurements

SPT catalog of 26 SZ galaxy clusters submitted first week in January.



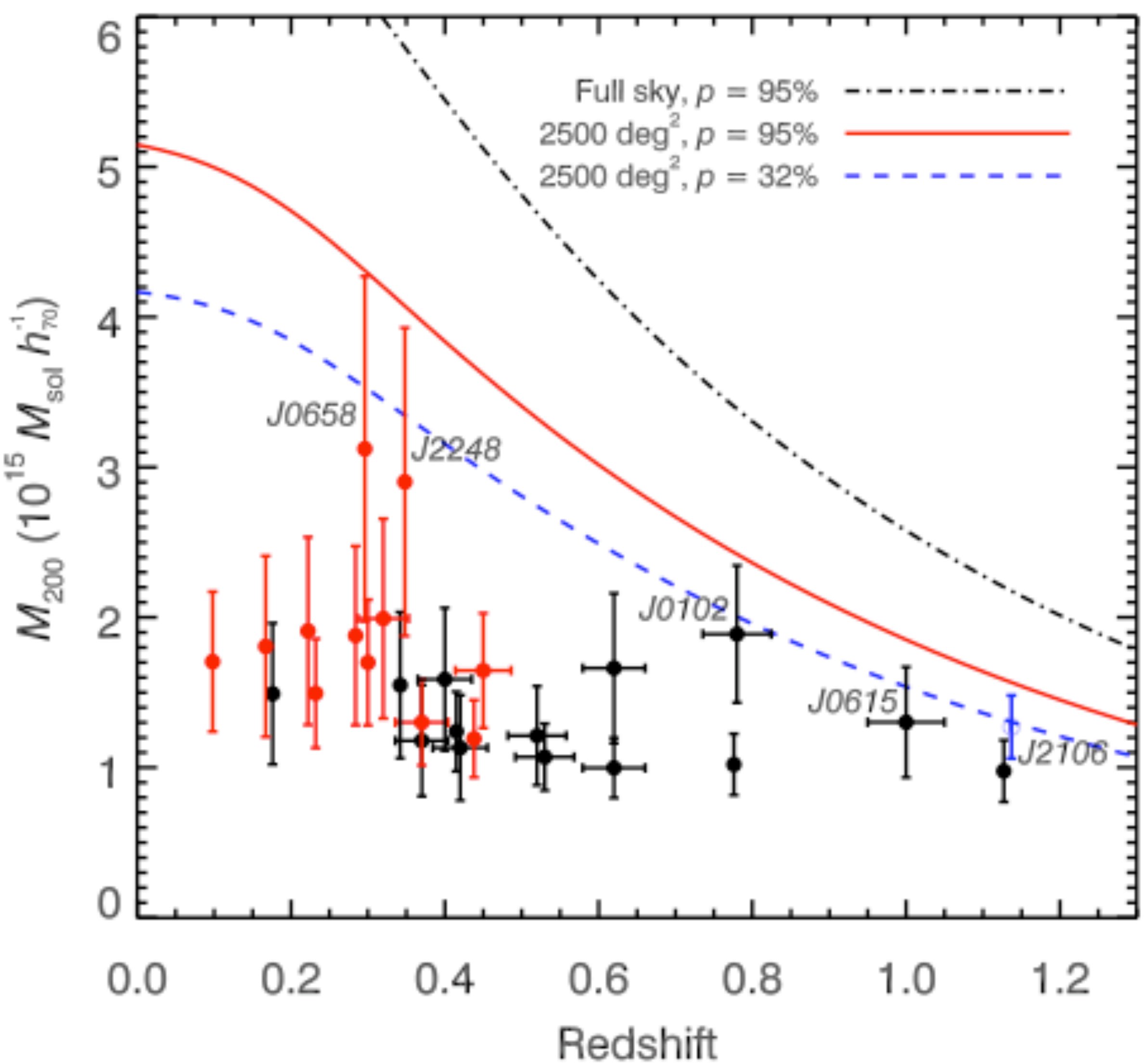
Williamson+SPT (2011)

Higher resolution of SPT ==> can detect clusters to higher redshift.

(But SPT only surveys one sixteenth of the sky.)

SPT catalog of 26 SZ galaxy clusters submitted first week in January.

Red = also in Planck catalog



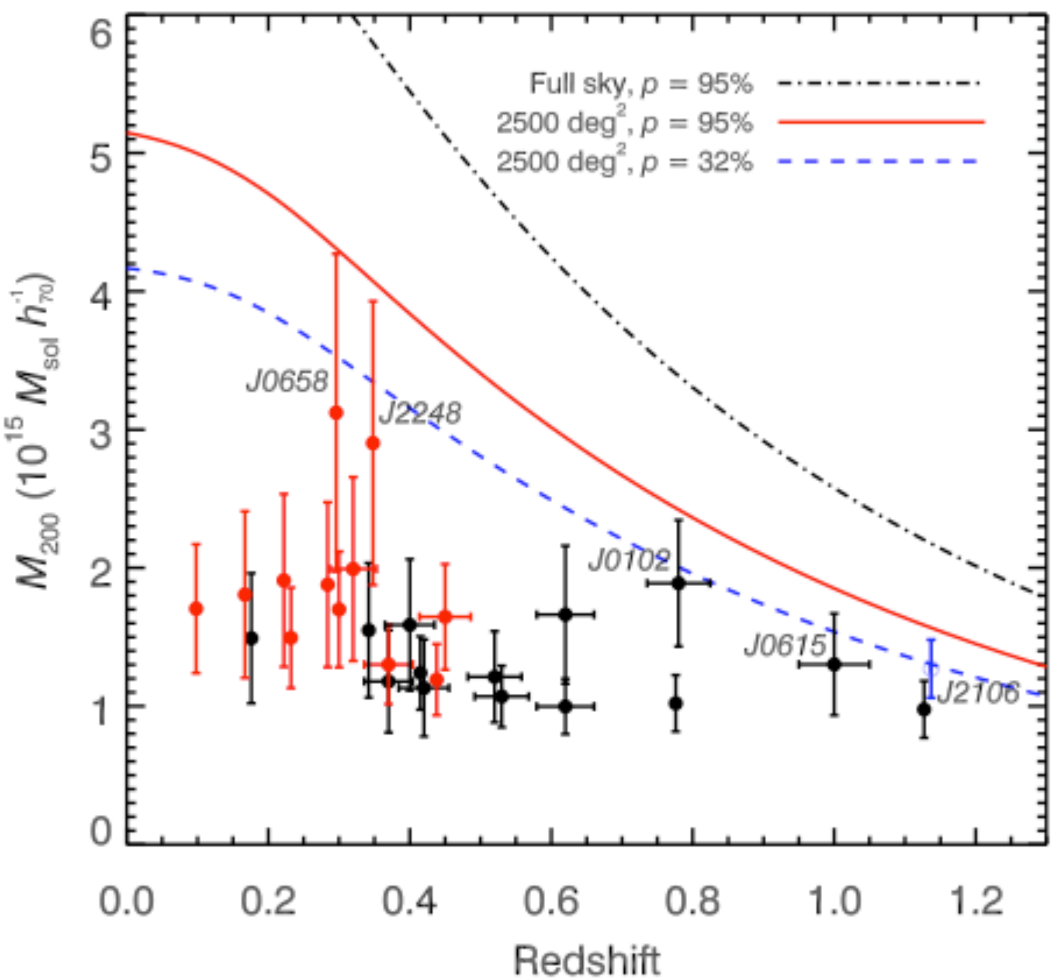
Higher resolution of SPT ==> can detect clusters to higher redshift.

SPT: greater redshift reach

Planck: full sky (sixteen times SPT survey area)

Planck clusters detected by SPT

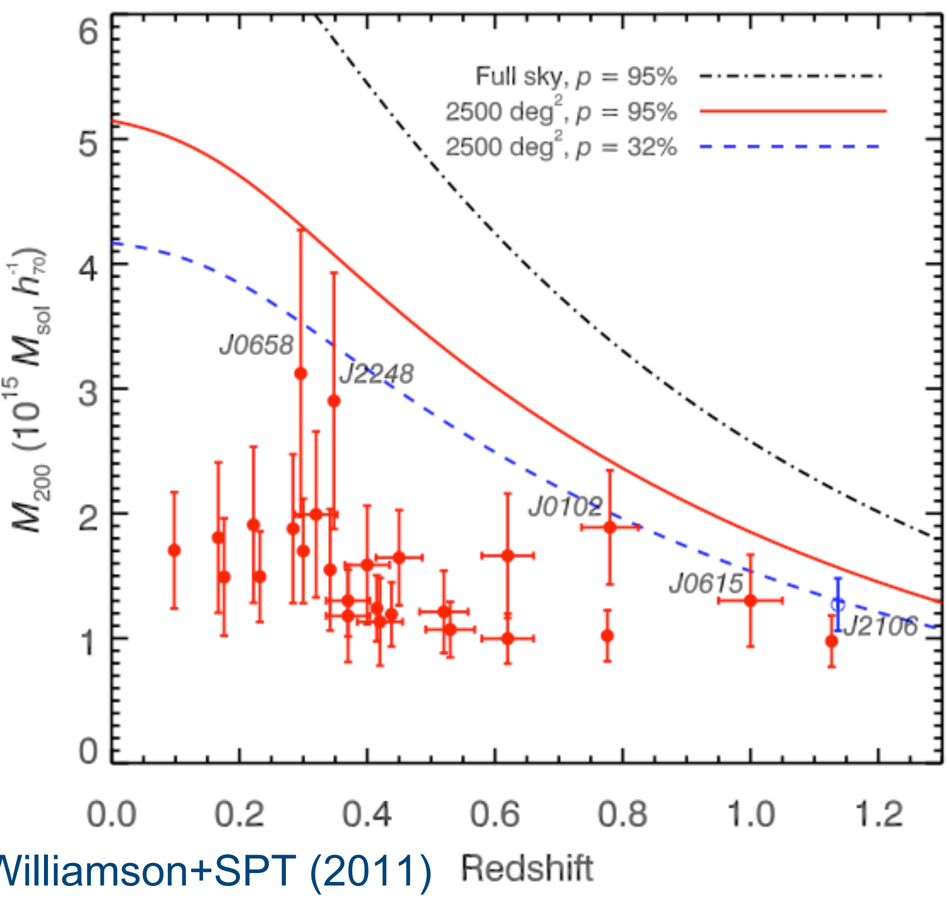
Red = also in Planck catalog



One of these was an unconfirmed Planck cluster (now confirmed by SPT)

Four more unconfirmed Planck clusters are in southern sky, and have been targeted by SPT.

Clusters and Primordial non-Gaussianity



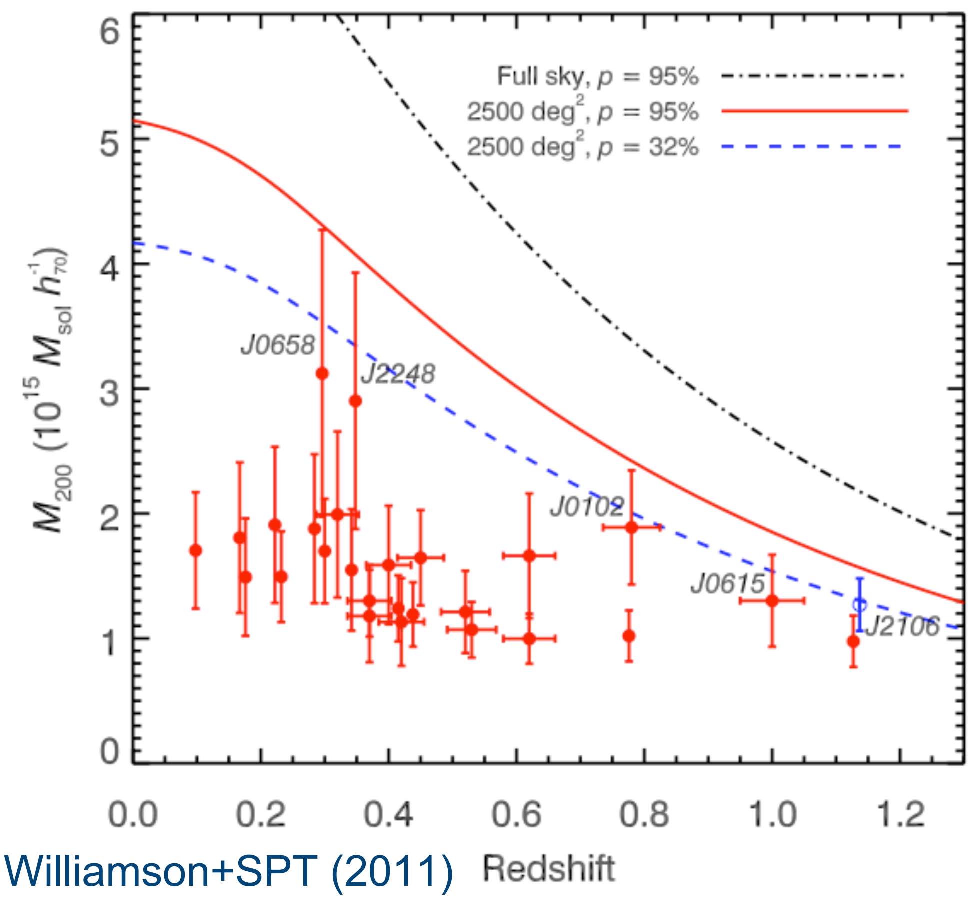
Williamson+SPT (2011)

Massive clusters form regions with unusually large, positive, density fluctuations.

==> Sensitive to assumption of Gaussianity of the primordial density field

Claims of NG from galaxy cluster surveys by several recent papers [Cayon et al., Hoyle et al., Enqvist et al. (2010)]

Clusters and Primordial non-Gaussianity



Williamson+SPT (2011)

We find no evidence of NG in SPT cluster data

For rarest object: ΛCDM gives 7% chance we would see something of greater mass, at greater redshift (Foley et al. 2011)

Whole SPT catalog used to constrain

$f_{NL} = 20 \pm 450$

[using method of Dalal et al. (2008)]

Other Cluster Work at UCD

THE ORIGIN OF [OII] IN POST-STARBURST AND RED-SEQUENCE GALAXIES IN HIGH-REDSHIFT CLUSTERS

Lemaux, B.C., Lubin, L.M., Shapley, A.[1], Kocevski, D., Gal, R.R.[2], & Squires, G. K.[3]
Department of Physics, University of California, Davis, 1 Shields Avenue, Davis, CA 95616, USA

Aimed at understanding galaxy evolution (e.g., star-formation histories) in the process of assembly of massive clusters

FOCUSING COSMIC TELESCOPES: EXPLORING REDSHIFT $Z \sim 5-6$ GALAXIES WITH THE BULLET CLUSTER 1E0657−56*

Maruša Bradač[1,2,x], Tommaso Treu[1,y], Douglas Applegate[3], Anthony H. Gonzalez[4], Douglas Clowe[5], William Forman[6], Christine Jones[6], Phil Marshall[1], Peter Schneider[7], Dennis Zaritsky[8]

Using galaxy clusters as cosmic telescopes to study very distant galaxies

Lots of lensing work too: see the colloquium today

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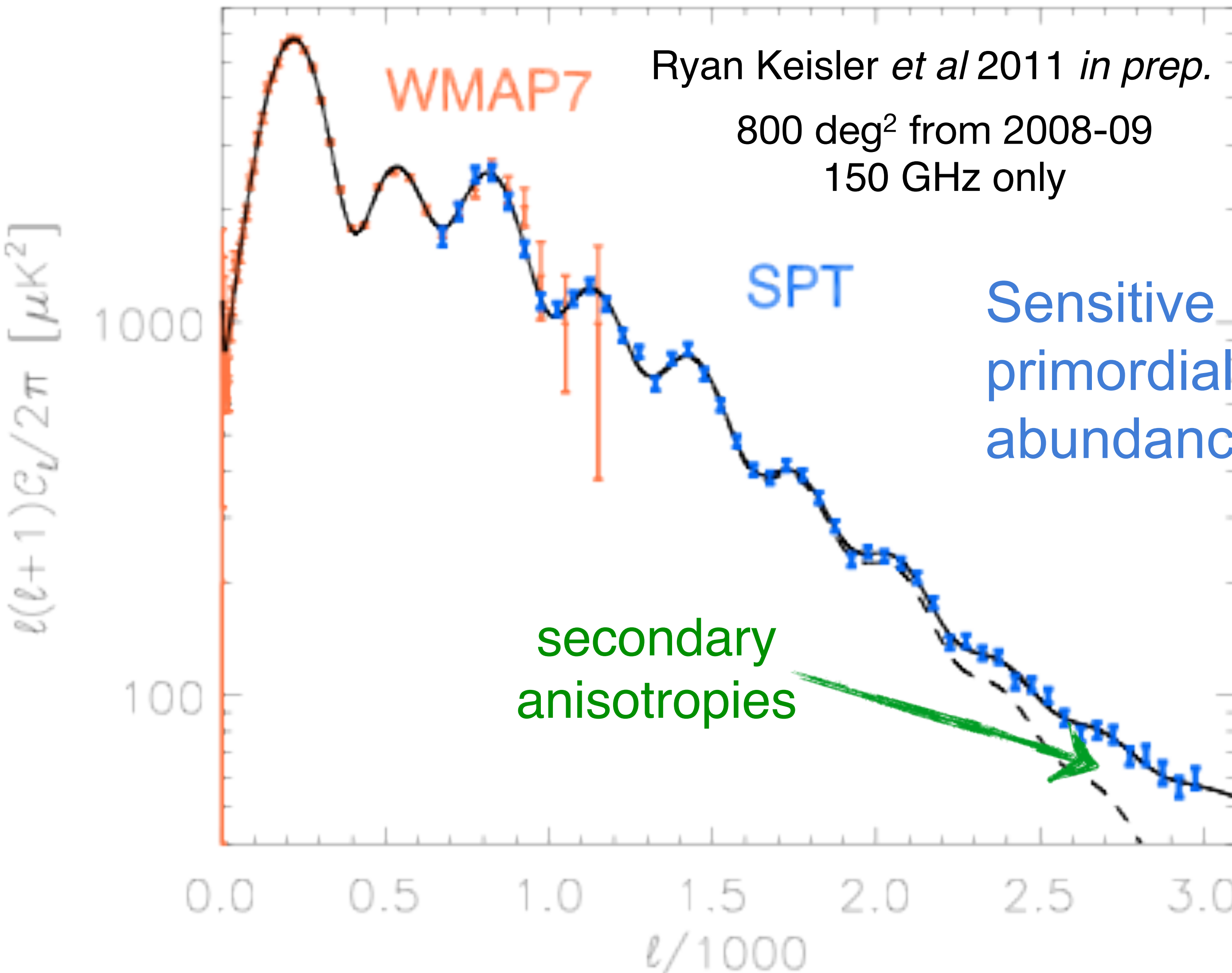
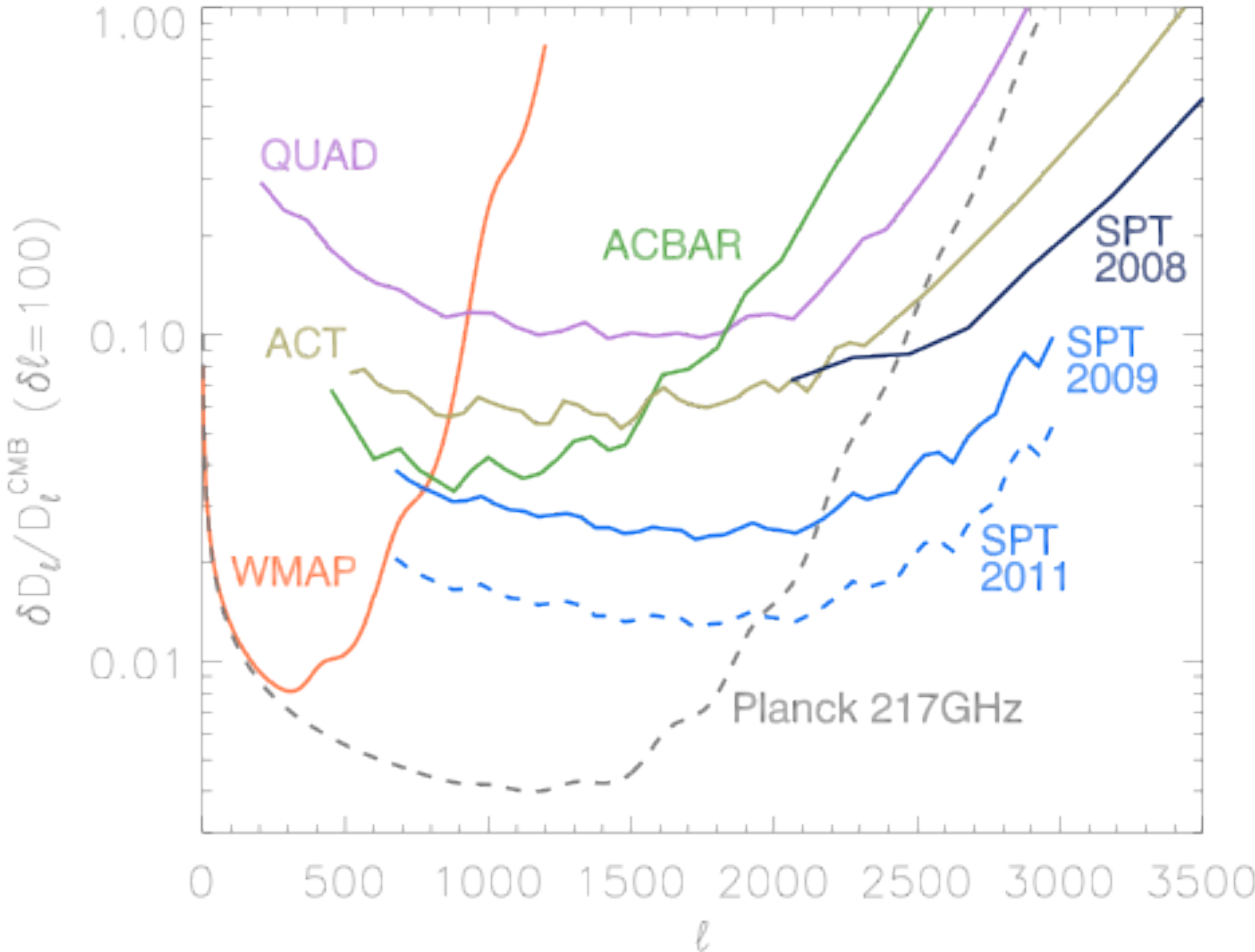
state-of-the-art TT measurements

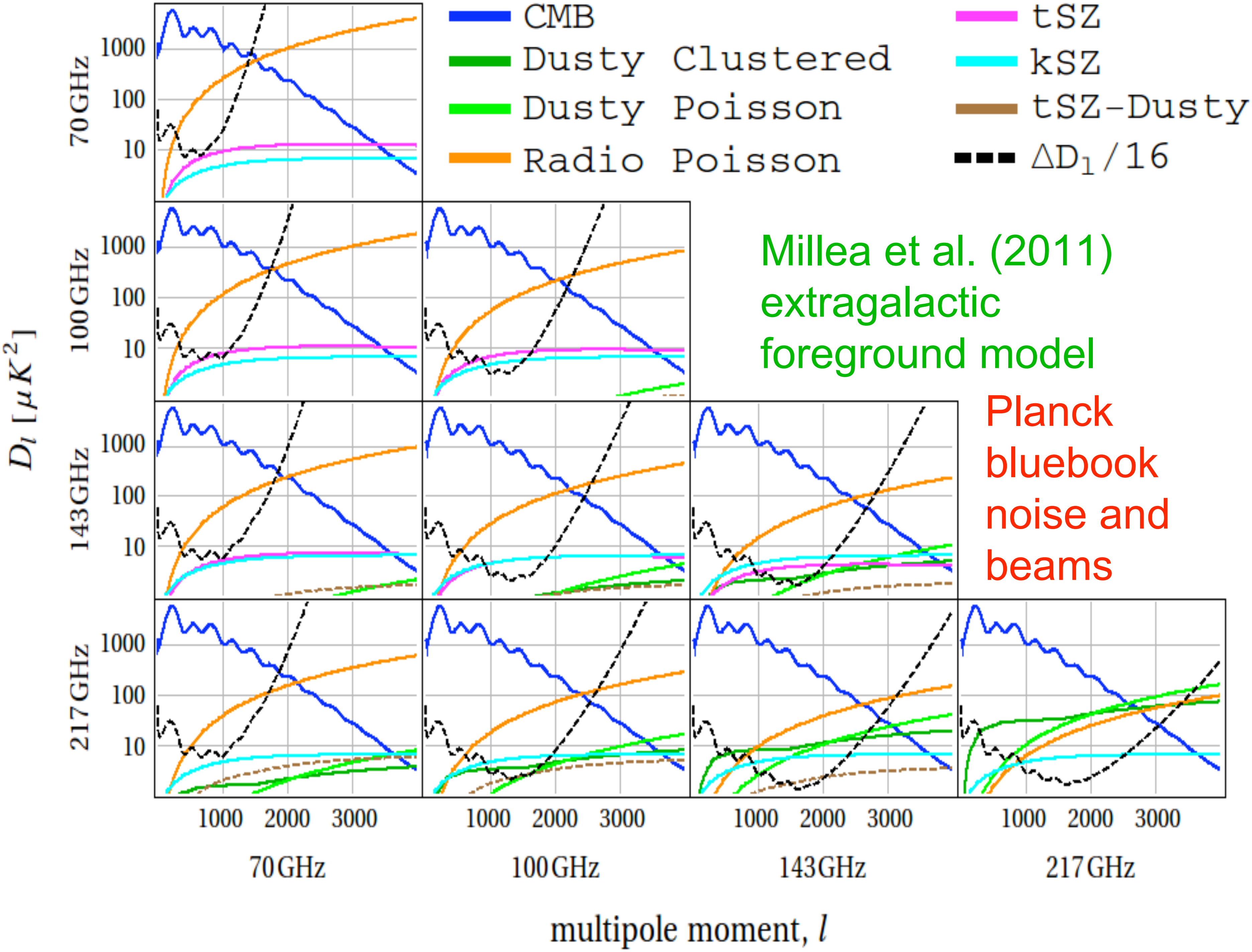


Sensitive to, e.g., primordial Helium abundance and N_ν

state-of-the-art TT measurements

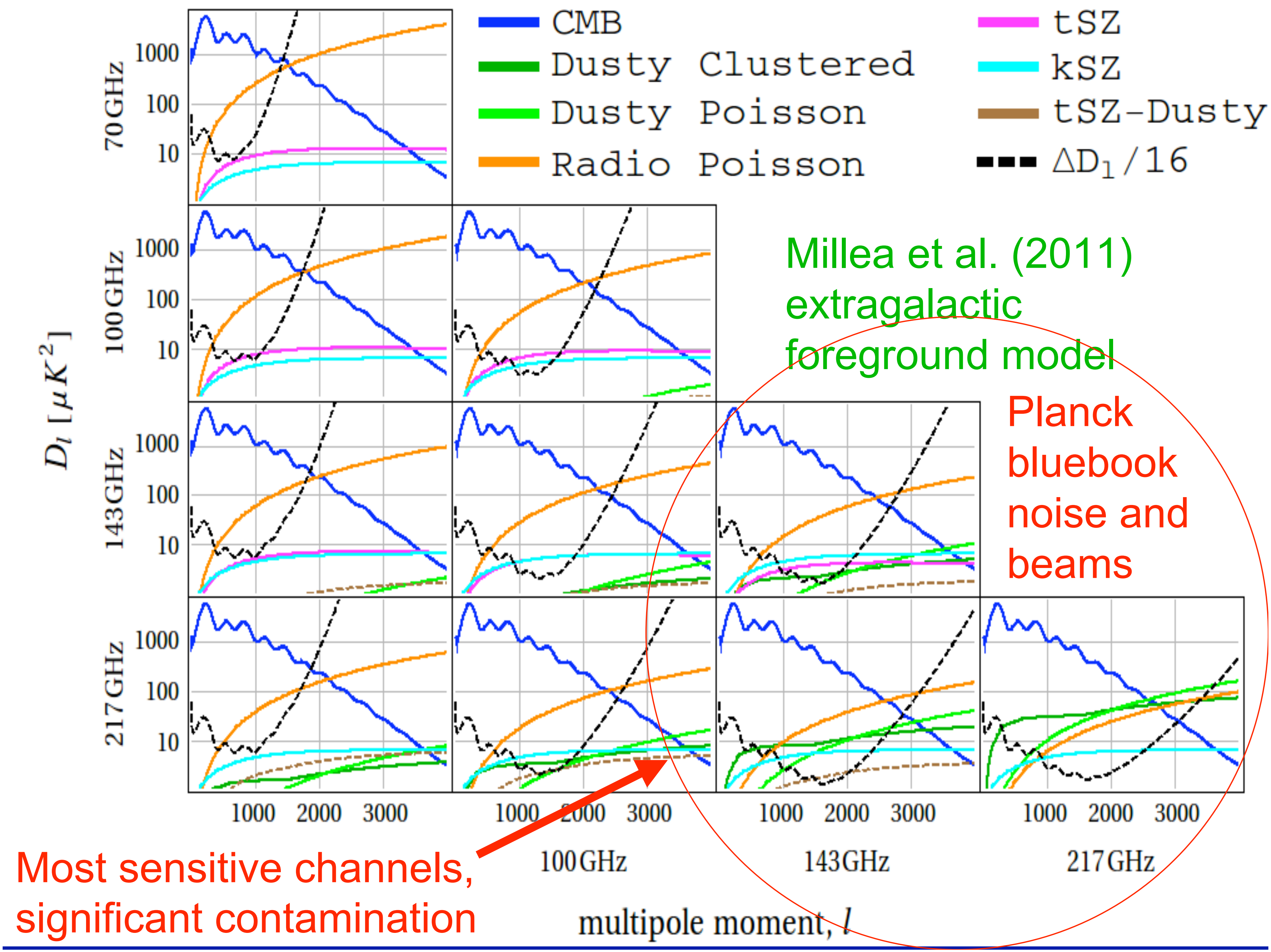
Fractional power spectrum uncertainty



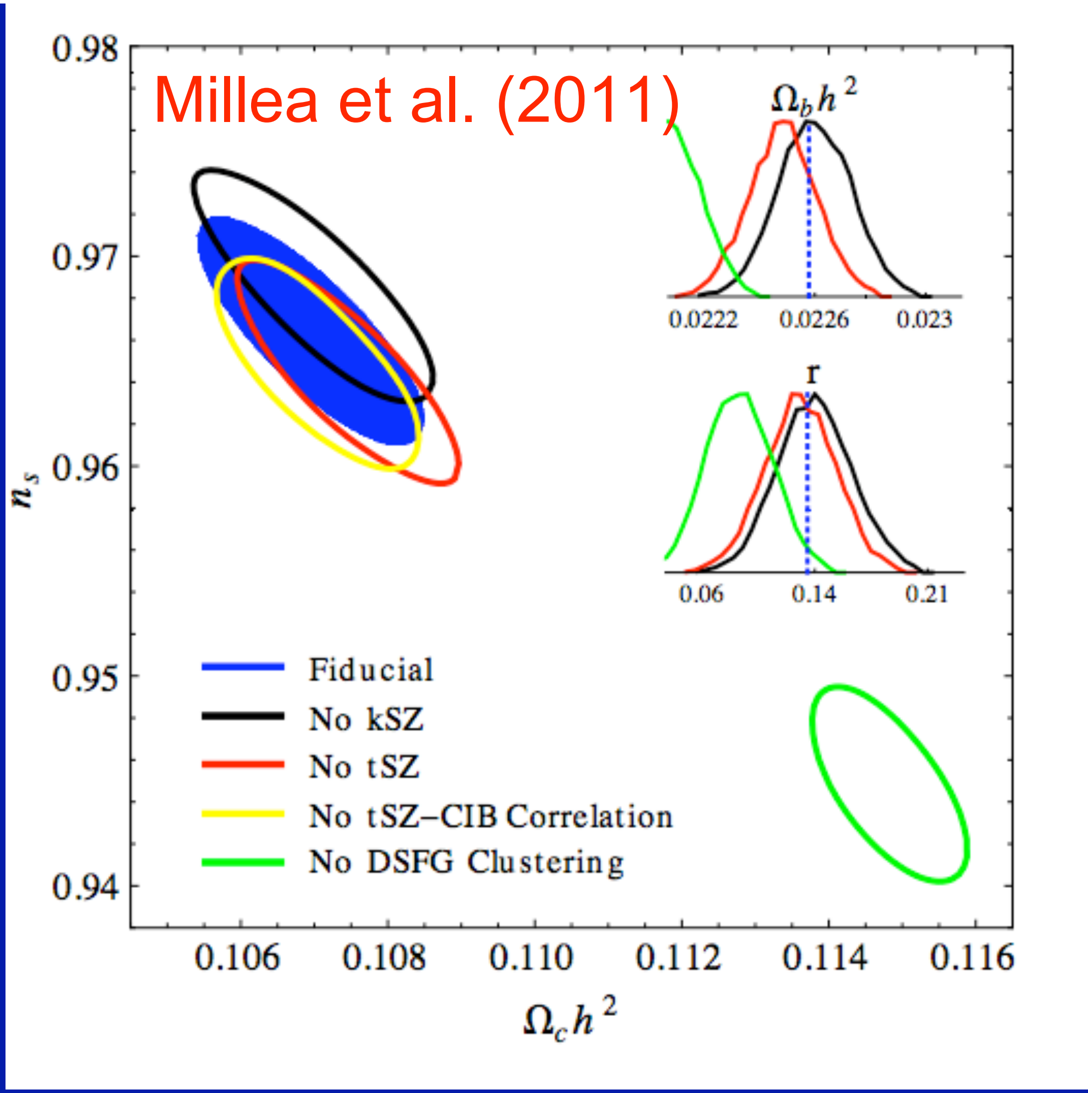


Millea et al. (2011) extragalactic foreground model

Planck bluebook noise and beams


CMB
Dusty Clustered
Dusty Poisson
Radio Poisson
tSZ
kSZ
tSZ-Dusty
ΔD1/16
70GHz
100GHz
143GHz
217GHz
$D_l\ [\mu K^2]$
1000
100
10
1000 2000 3000
multipole moment, l
Millea et al. (2011) extragalactic foreground model
Planck bluebook noise and beams
Most sensitive channels, significant contamination

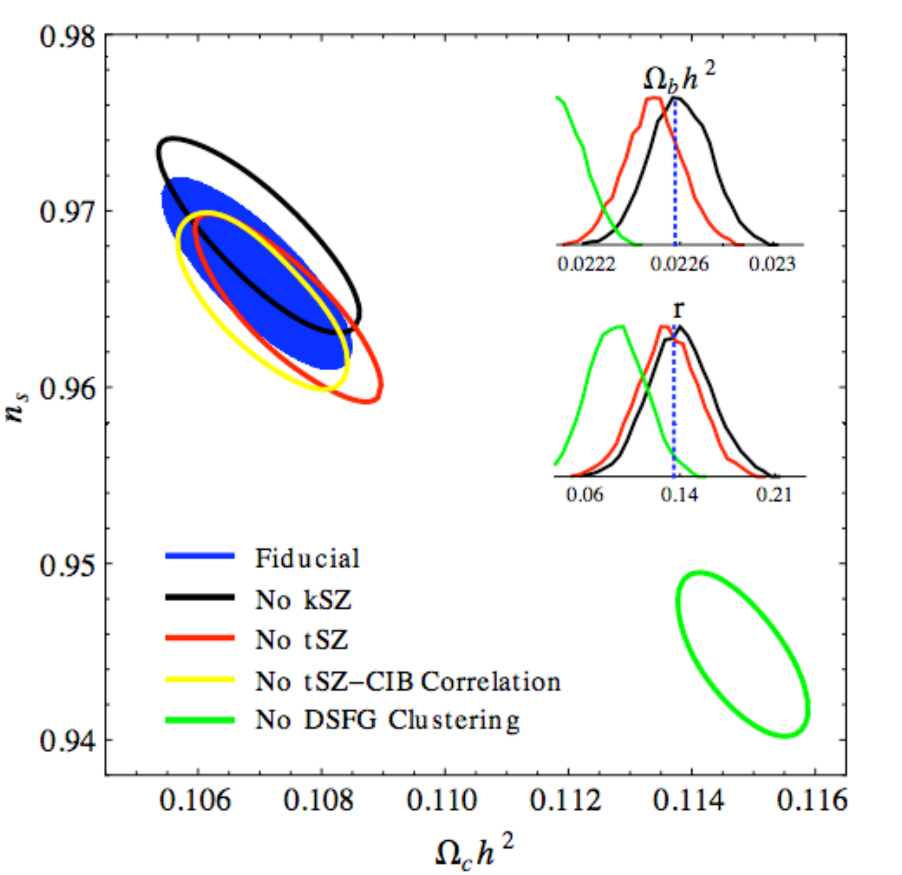
n_s

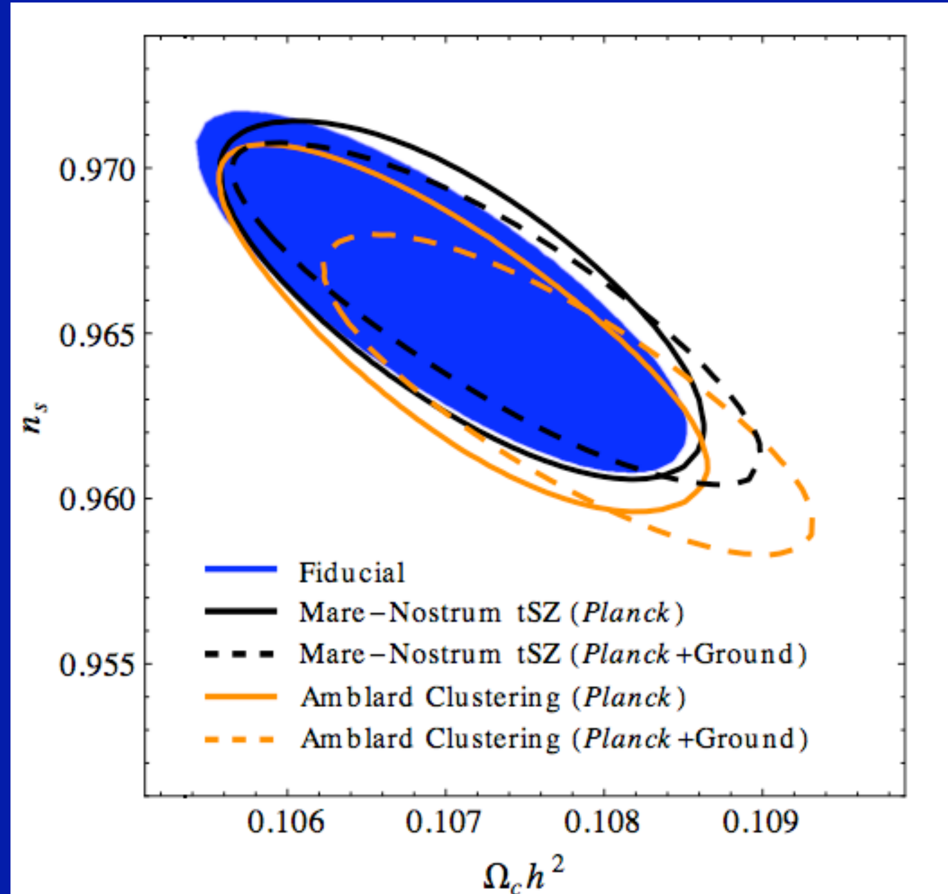


Dark matter density

Cosmological parameter biases that would result from neglecting various extragalactic components

Millea et al. (2011): A model for cleaning out extragalactic foregrounds





Biases are reduced to an insignificant level by our modeling (at least for Planck only case)

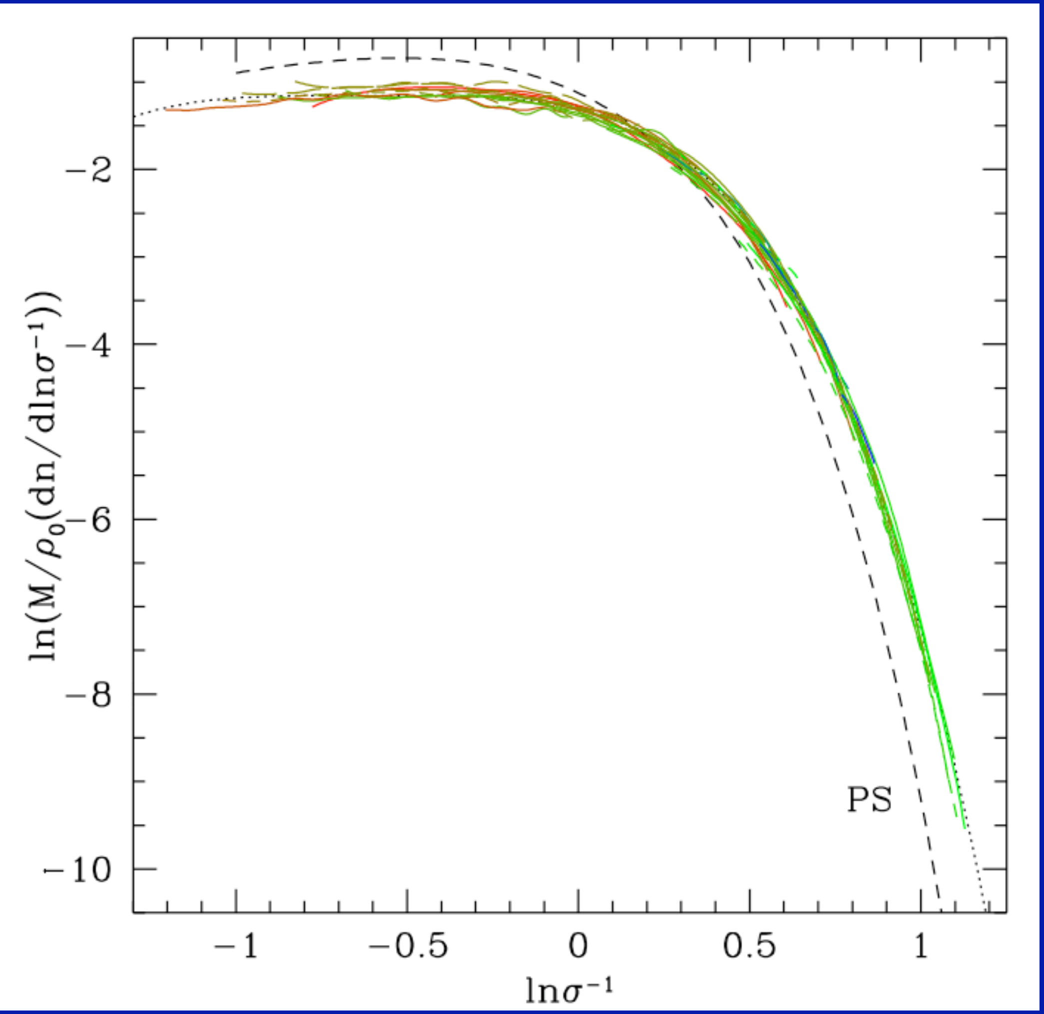
Summary

- Planck was successfully launched, instruments are working well. One can anticipate exciting cosmological results.
- Planck has created the first all-sky surveys capable of detecting individual objects from 100 to 1000 GHz ==> lots of astrophysics being done.
- SZ cluster measurements represent a significant milestone in the effort to tame clusters for precision cosmology. Field is developing rapidly.
- New CMB results out soon from SPT. Much better ones from Planck by end of 2012.

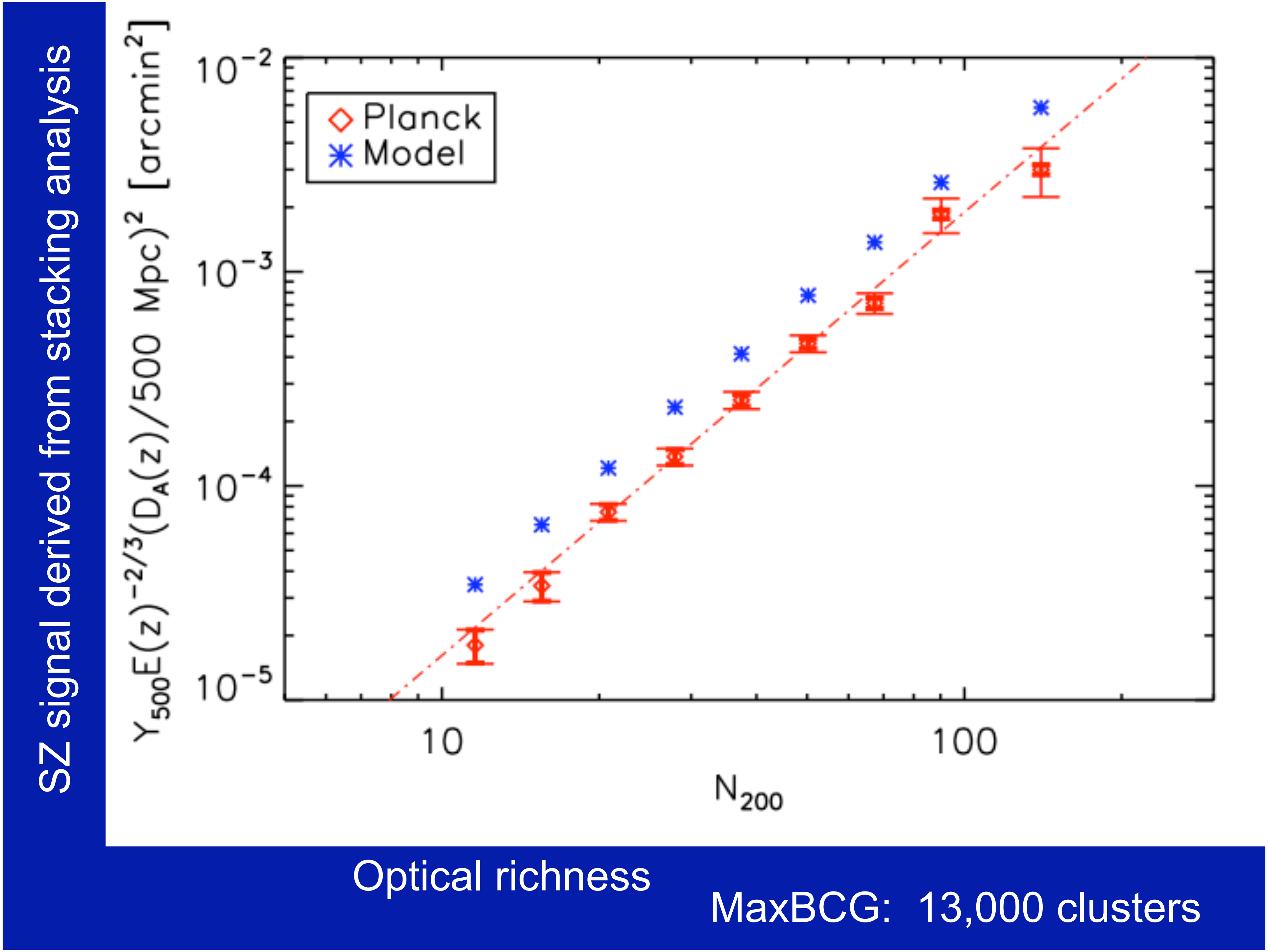
The highest mass objects are the result of rare fluctuations ==>

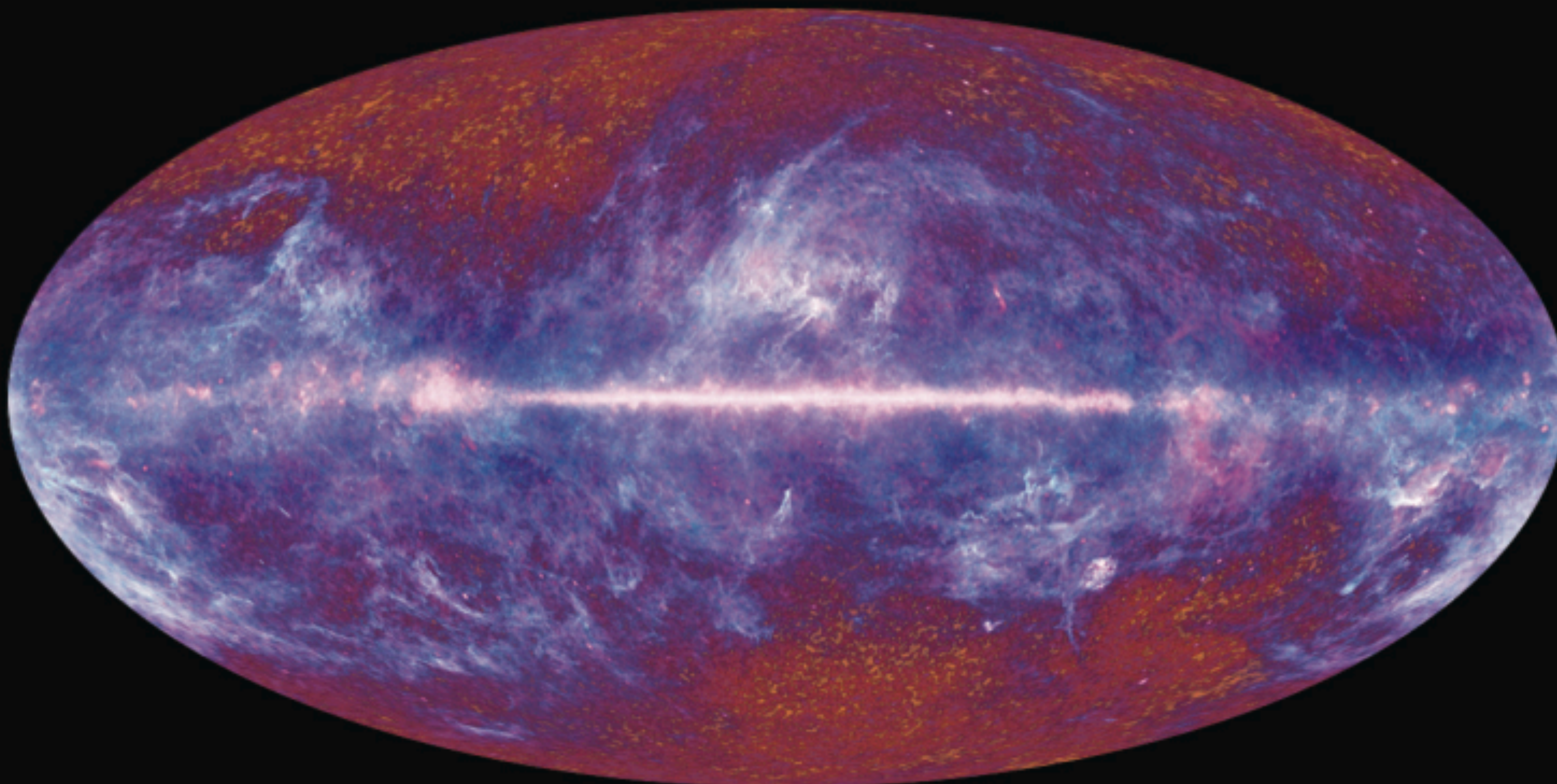
Number densities are highly sensitive to

1) Variance of matter density fluctuations, smoothed on the length scale, R.
2) The assumption of Gaussianity.



$\sigma^2(M) = \langle(\delta\rho/\rho)^2\rangle$ in linear perturbation theory, smoothed on the length scale corresponding to $M = 4/3\ \pi R^3 \rho$.


SZ signal derived from stacking analysis
$Y_{500}E(z)^{-2/3}(D_A(z)/500\ \mathrm{Mpc})^2$ [arcmin^2]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Planck
Model
10
100
N_{200}
Optical richness
MaxBCG: 13,000 clusters



The Planck one-year all-sky survey

esa

Planck

- Planck's primary design goal is to

  MEASURE THE TEMPERATURE ANISOTROPIES OF THE CMB TO FUNDAMENTAL LIMITS DOWN TO 5 ARCMINUTES

  - Also to

    MEASURE THE POLARIZATION OF THE CMB

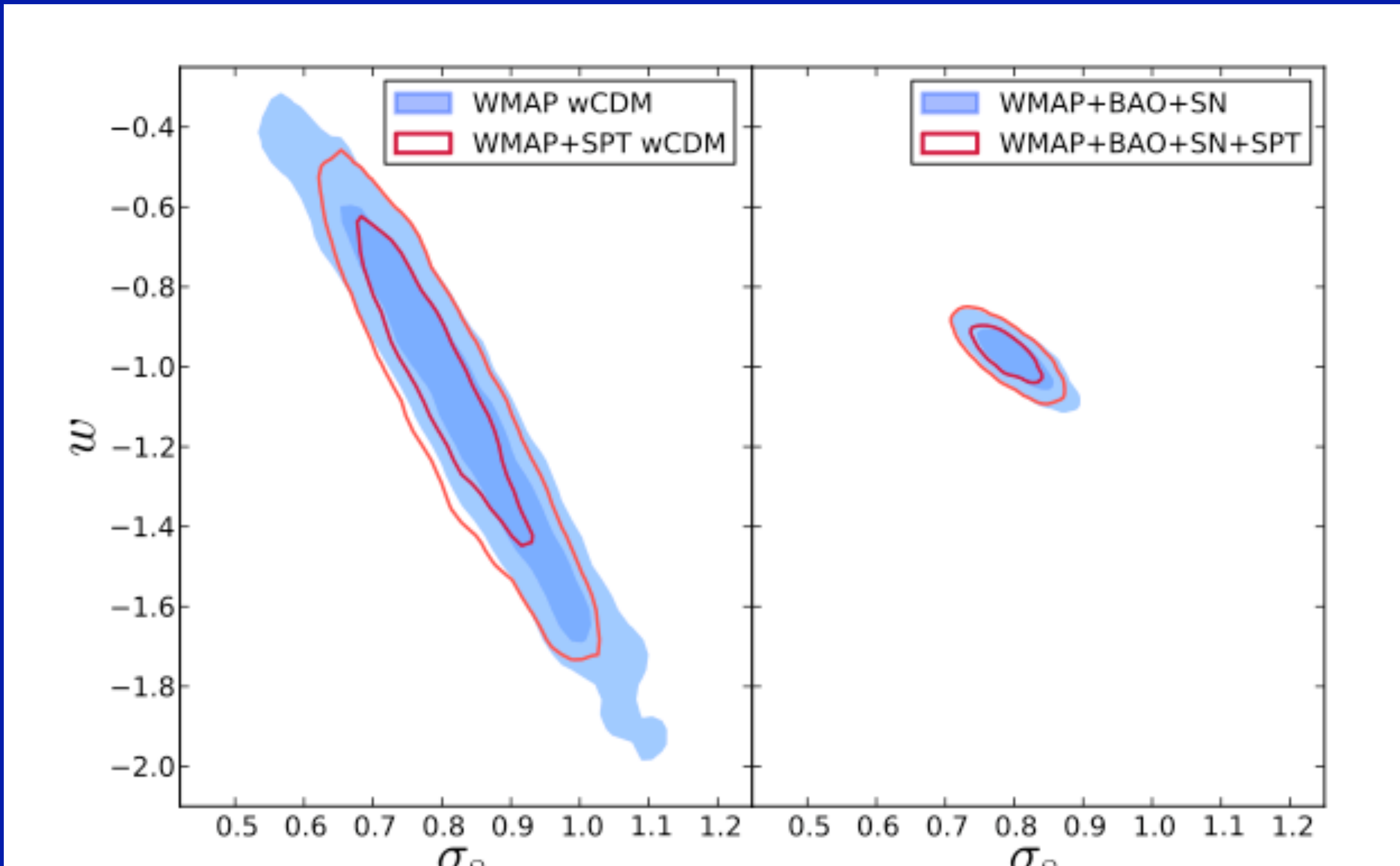
- To do these, we must be able to separate the CMB from foreground radiation

- To do that, we must measure over a wide frequency range

- Of necessity, we measure the foregrounds very well

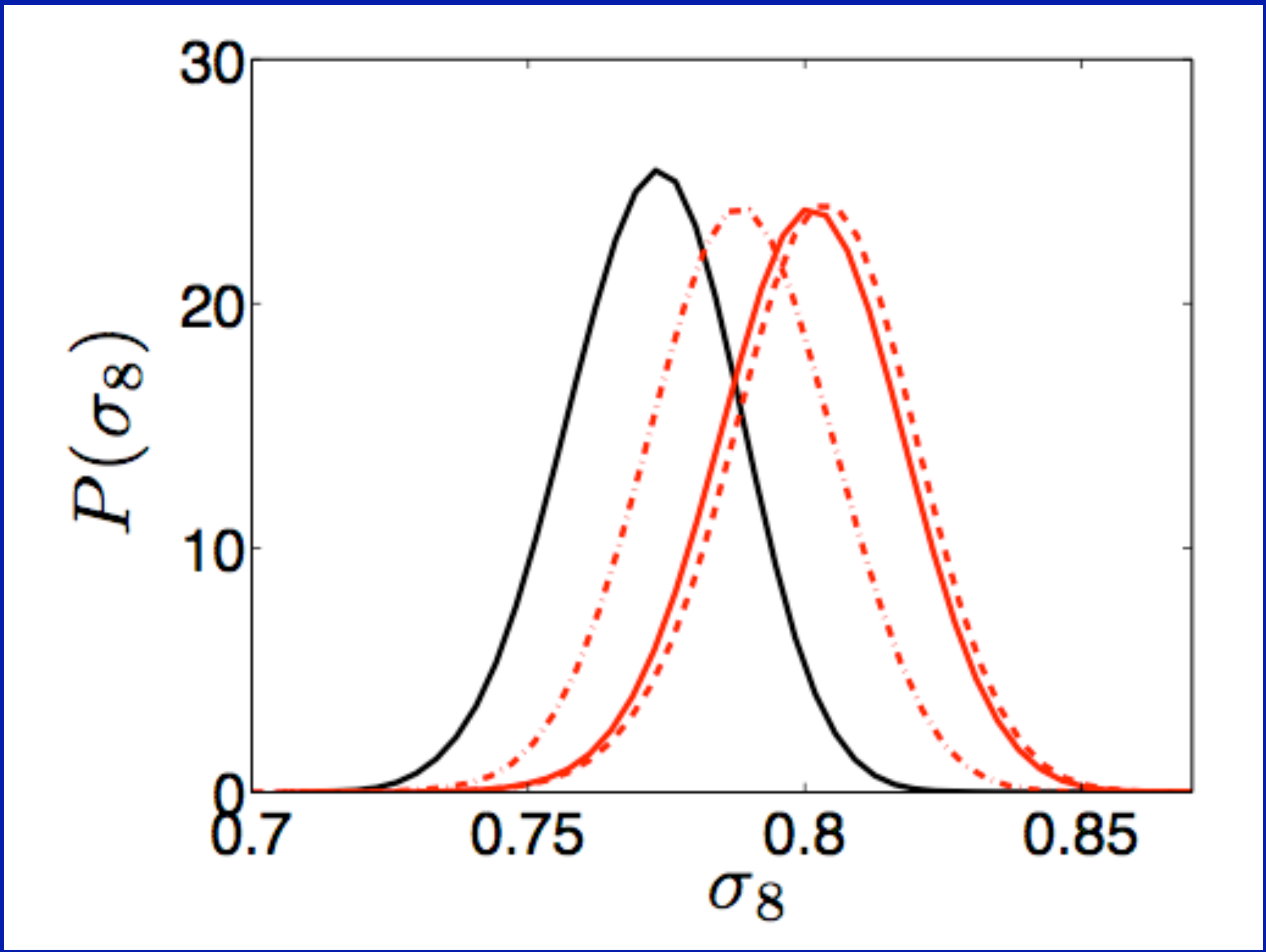
  ⇒ LOTS OF ASTROPHYSICS

Current SZ cluster cosmology constraints



Vanderlinde+SPT (2010)

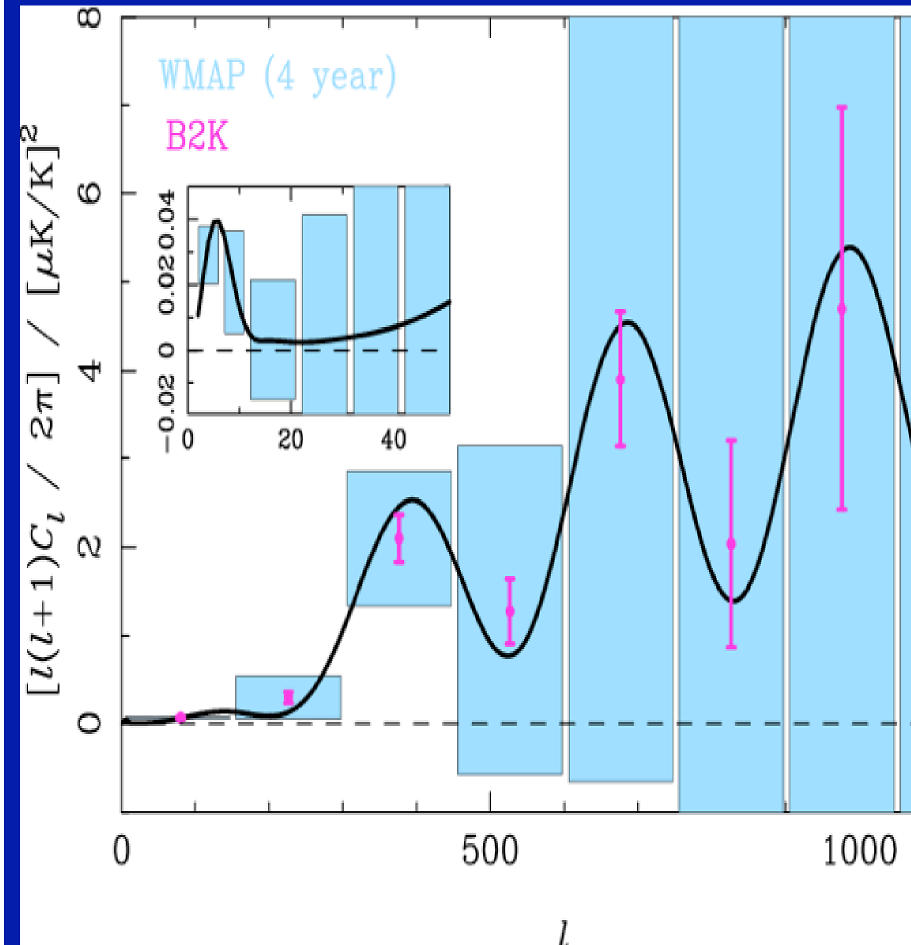
Current SZ cluster cosmology constraints

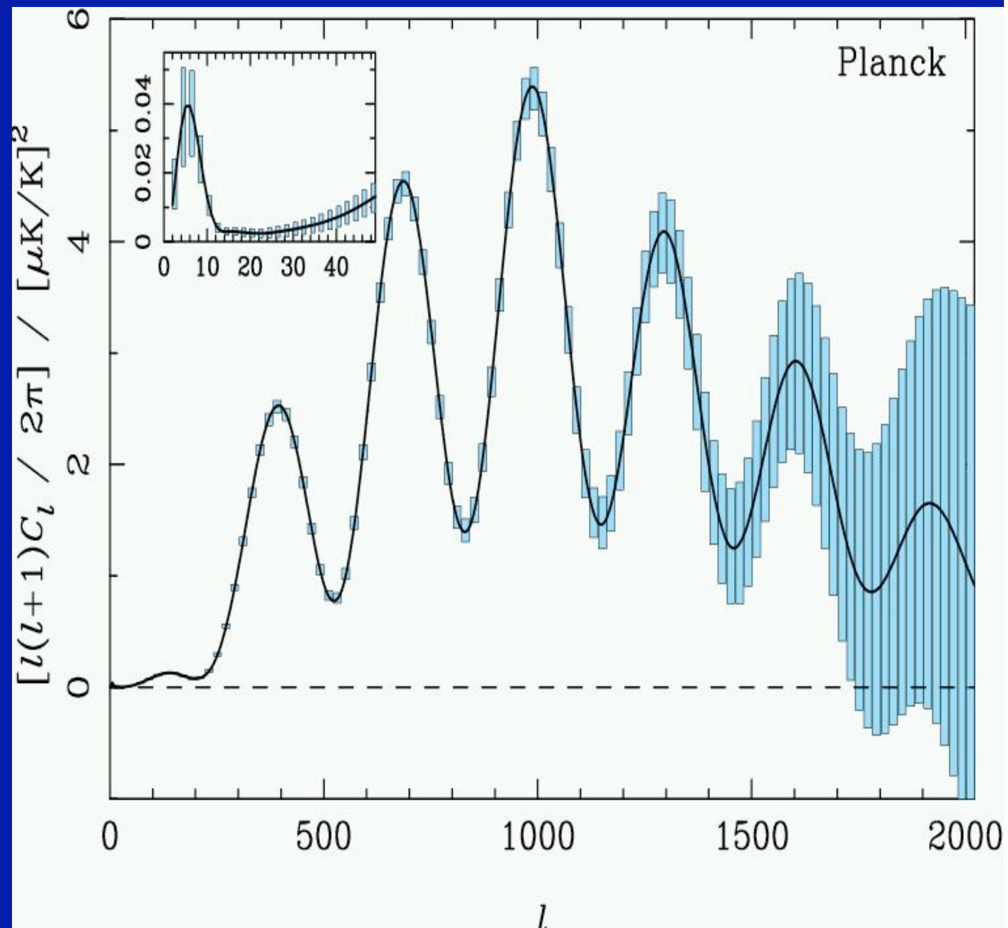


Different curves for different cluster modeling assumptions

Shirokoff+SPT (2010)

Great Opportunities Remain: Forecasted EE Power Spectrum Errors





Enabled by Planck's greater sensitivity, angular resolution and frequency coverage