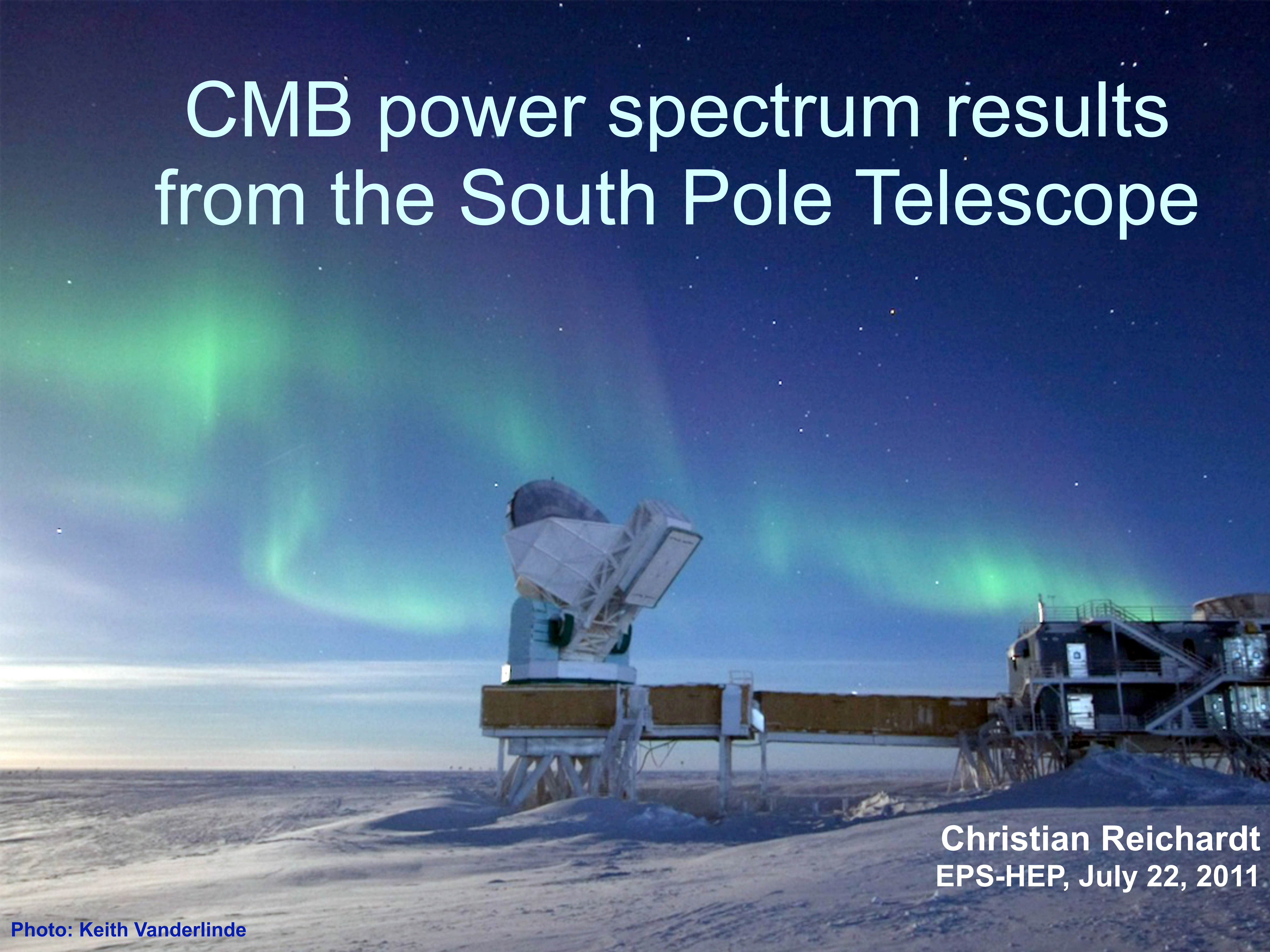
CMB power spectrum results from the South Pole Telescope



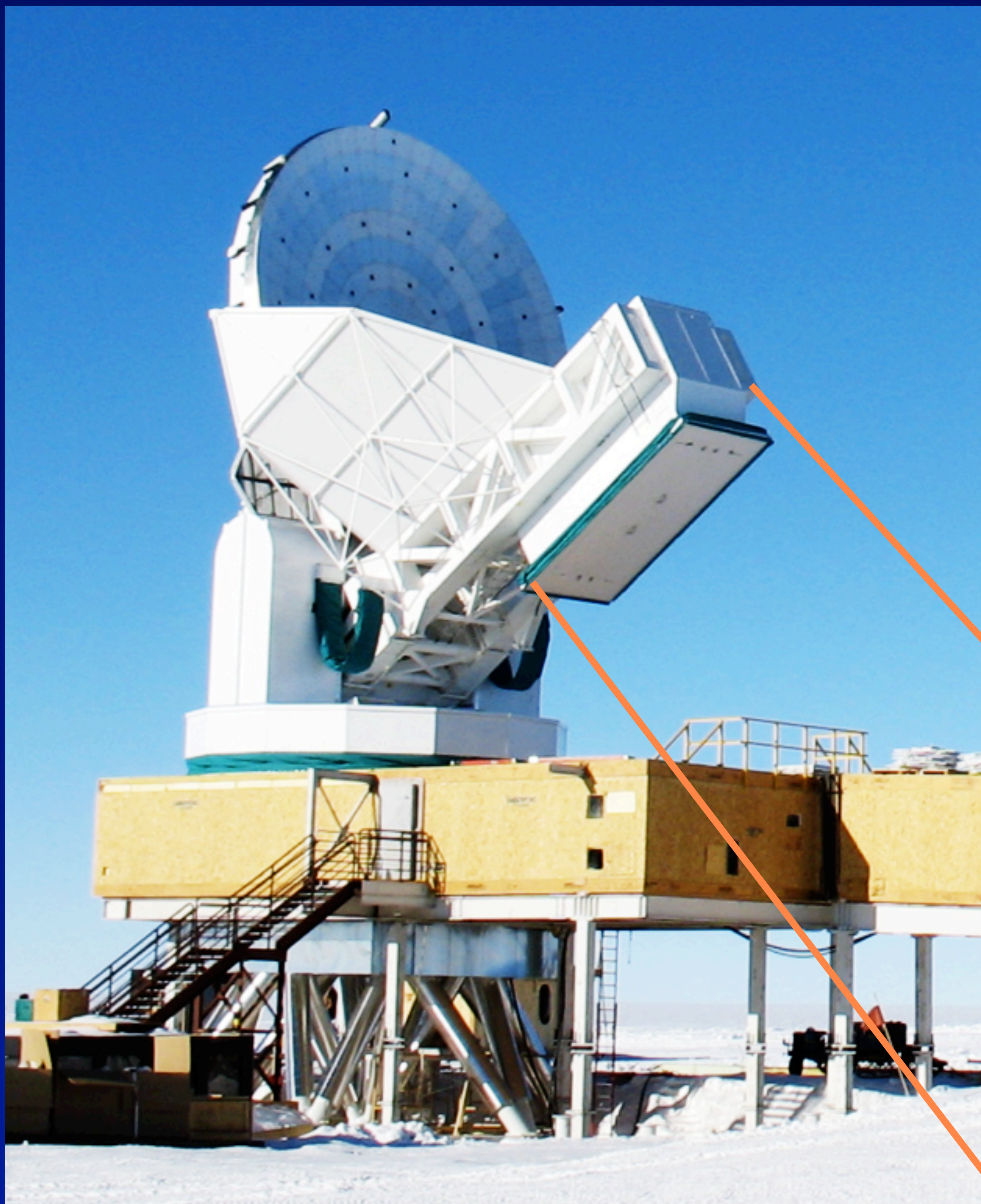
Christian Reichardt
EPS-HEP, July 22, 2011

Photo: Keith Vanderlinde

Outline

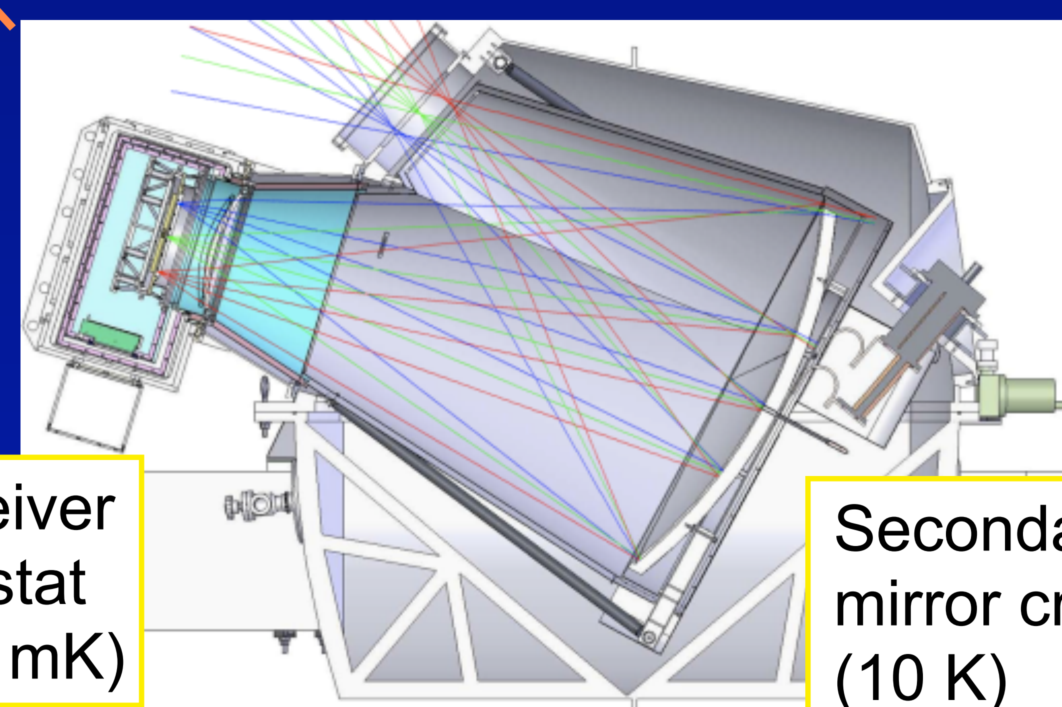
- The South Pole Telescope & survey
- Primary CMB results
- SPT cluster cosmology

Overview



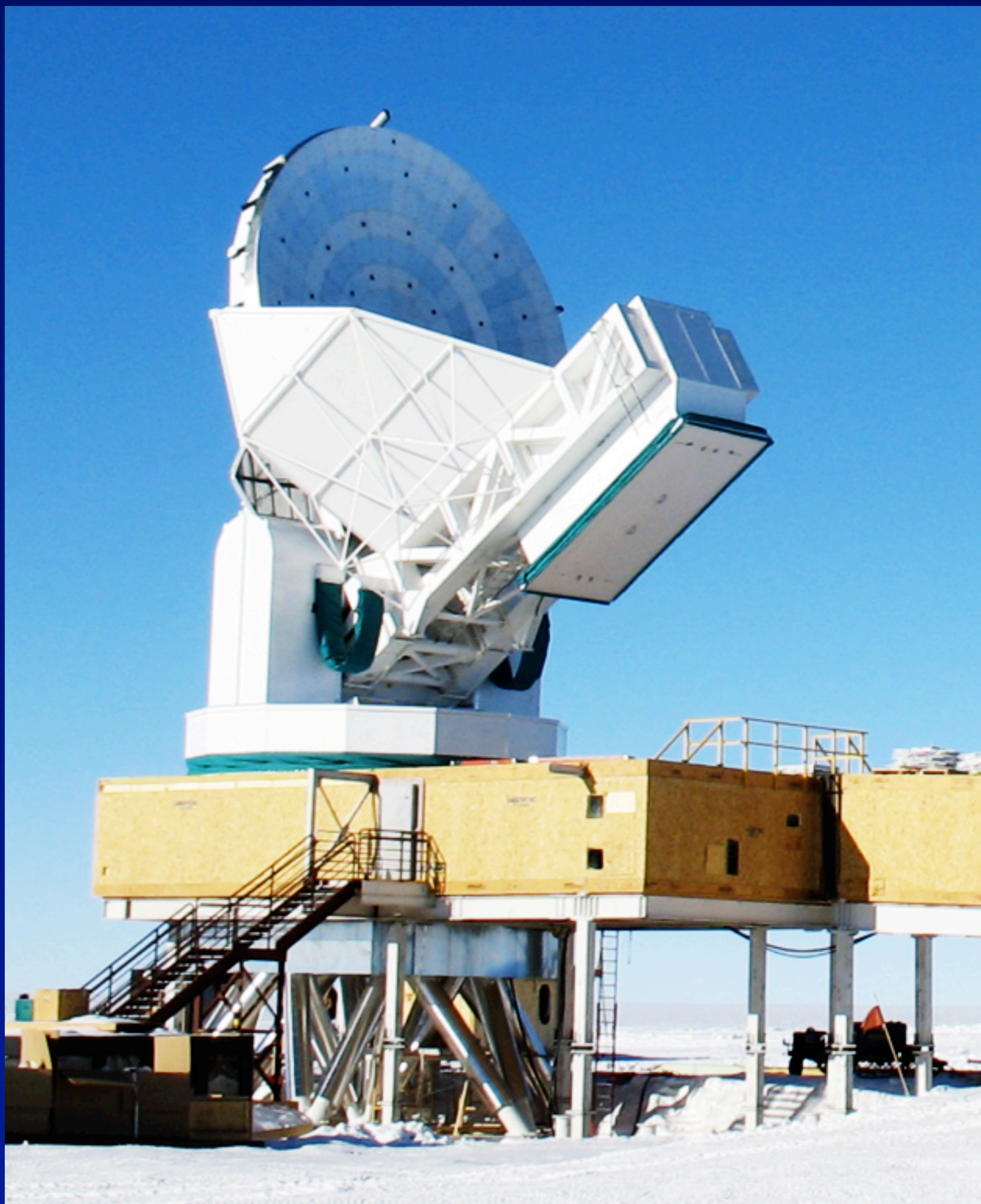
The South Pole Telescope (SPT):

- 10 meter telescope - 1 arcmin resolution at 150 GHz
- 1 deg FOV
- 960 feed-horn coupled, background-limited detectors
- Observe simultaneously in 3 bands - 95, 150, 220 GHz - with modular focal plane



Funded by NSF

Overview



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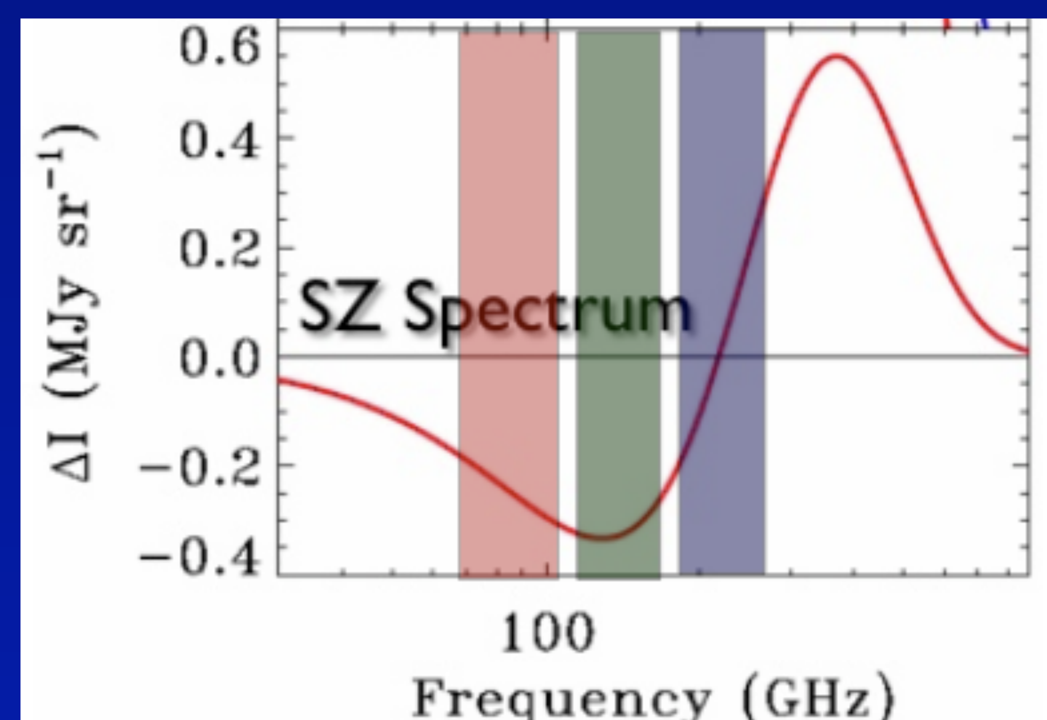
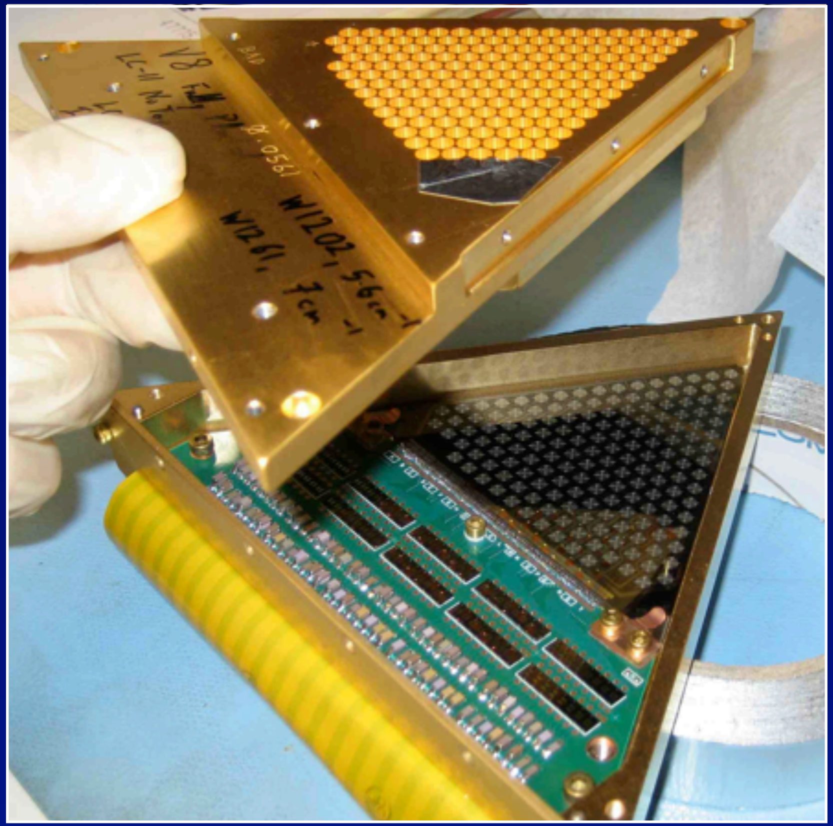
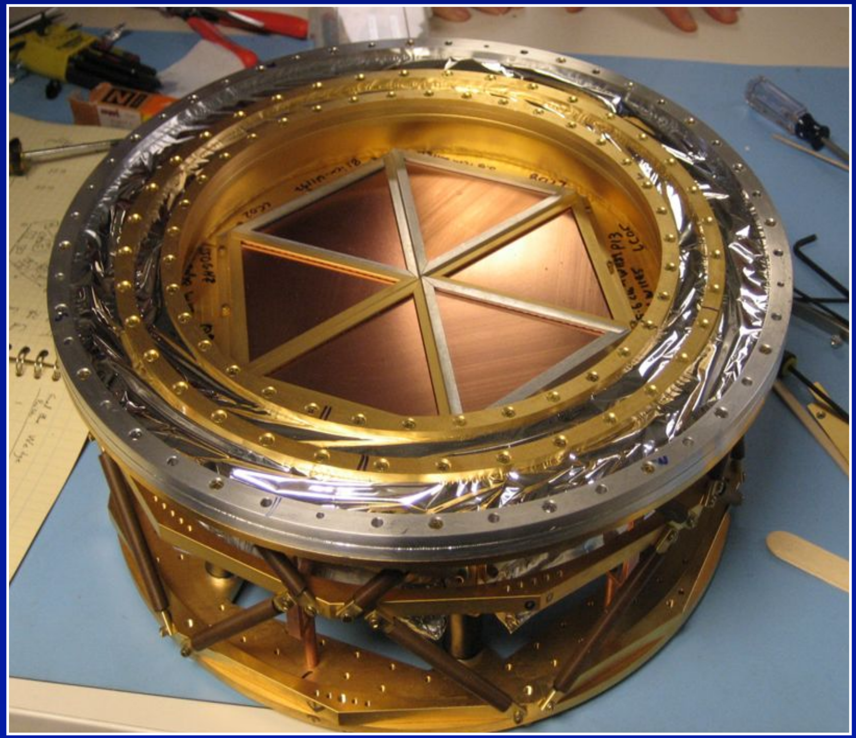


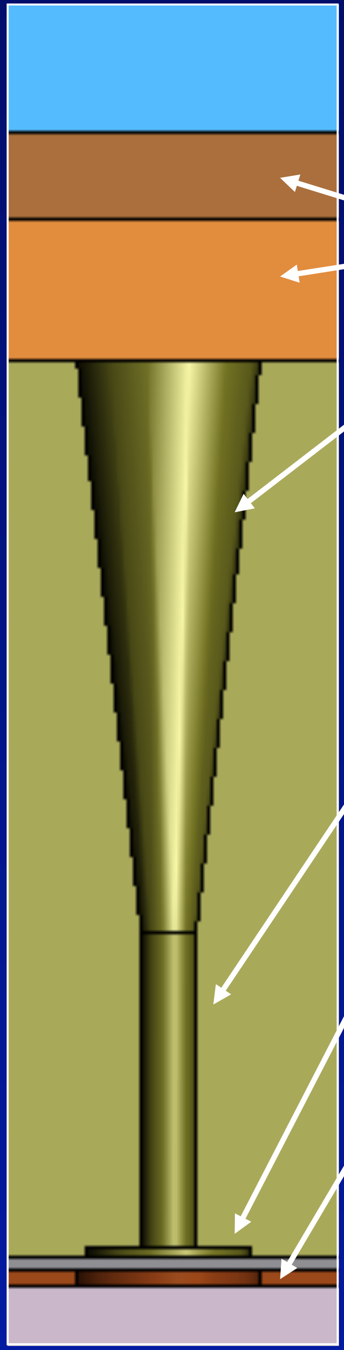
Funded by NSF

SPT Focal Plane





Modular design: 960 pixels fabricated on six silicon wafers



Incoming radiation is:

Low-pass filtered (capacitive mesh)

Coupled to waveguide via smooth-walled conical feedhorns

High-pass filtered by circular waveguide

Confined to an integrating cavity

Absorbed by detector

Why the South Pole?

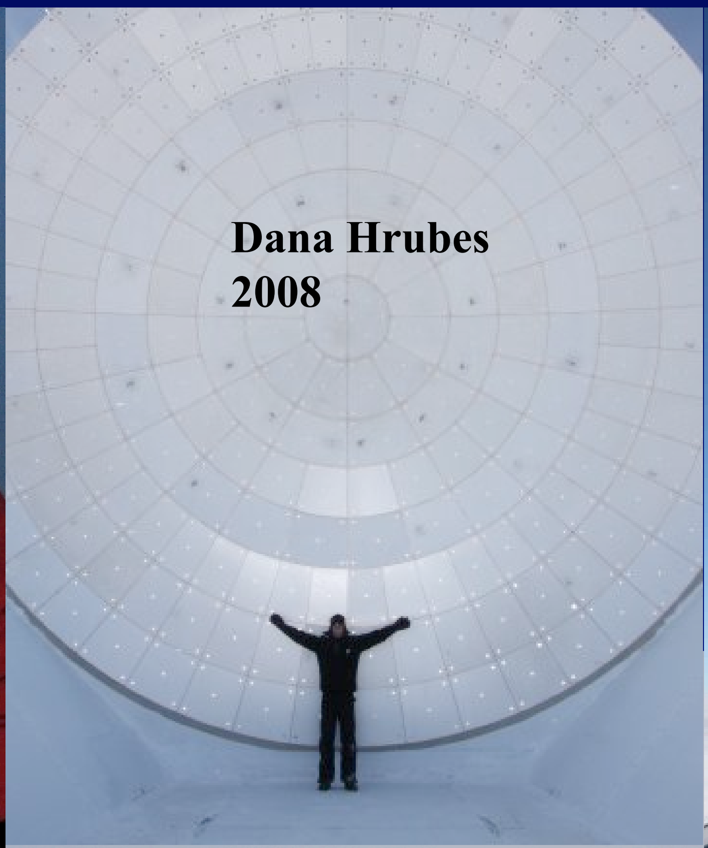
- Atmospheric transparency and stability:
  - Extremely dry and cold (average winter temperature below -60 C).
  - High altitude ~ 10,500 feet.
  - Sun below horizon for 6 months.
- Unique geographical location:
  - Observe the clearest views through the Galaxy 24/7/52 "relentless observing"
  - Clean horizon.
- Excellent support from existing research station.

KICP
Kavli Institute for Cosmological Physics at the University of Chicago
Berkeley University of California
Case Western Reserve University
The University of Chicago
UC Davis University of California
Astronomy University of Illinois at Urbana-Champaign
McGill
Harvard-Smithsonian Center for Astrophysics
Cardiff University Prifysgol Caerdydd
Colorado University of Colorado at Boulder
Berkeley Lab

SPT Collaboration

SPT Heroes Gallery

Dana Hrubes and Daniel Luong-Van 2010 AND 2011!!



Dana Hrubes 2008

Keith Vanderlinde 2008

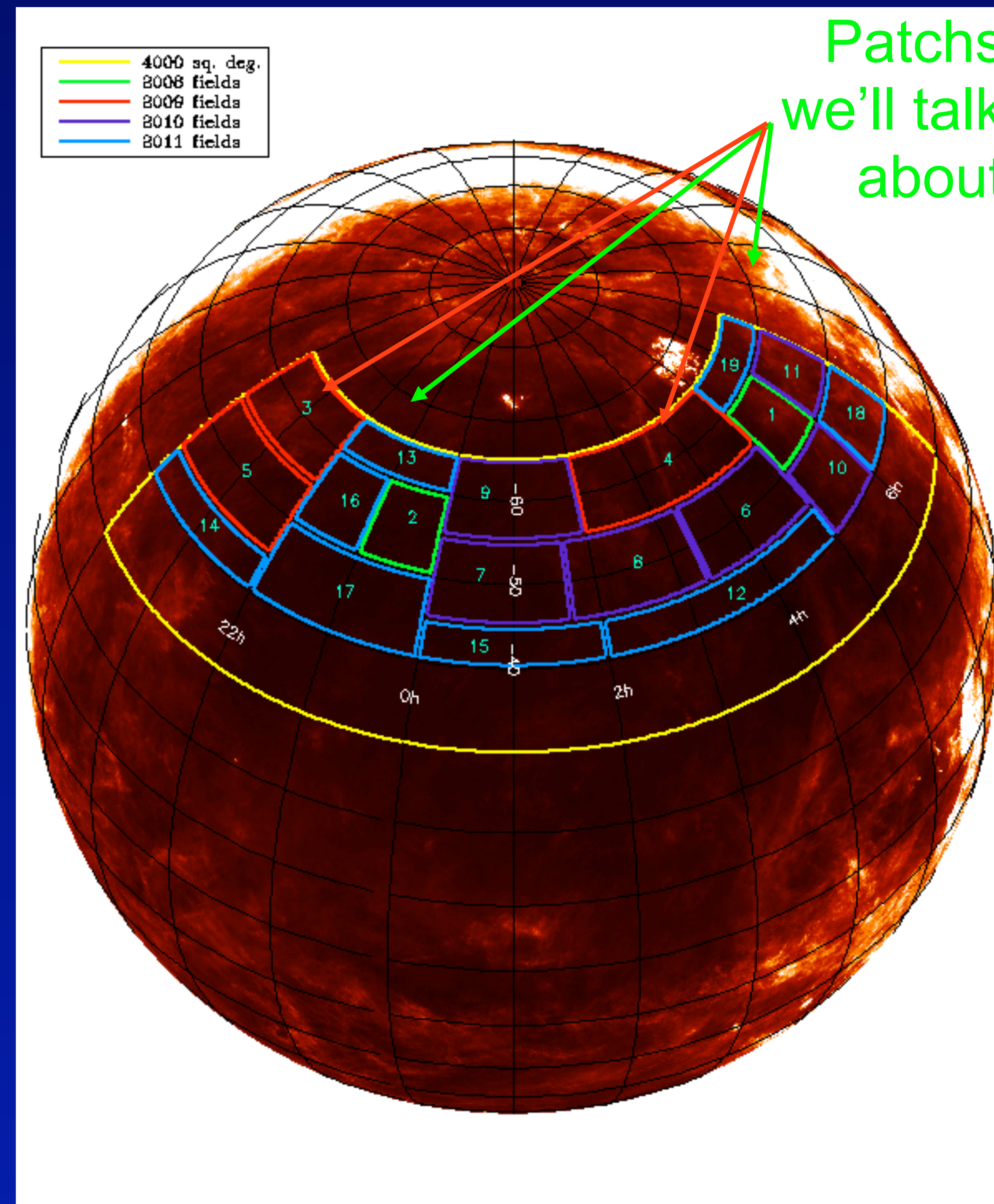
Steve Padin 2007

Zak Staniszewski 2007

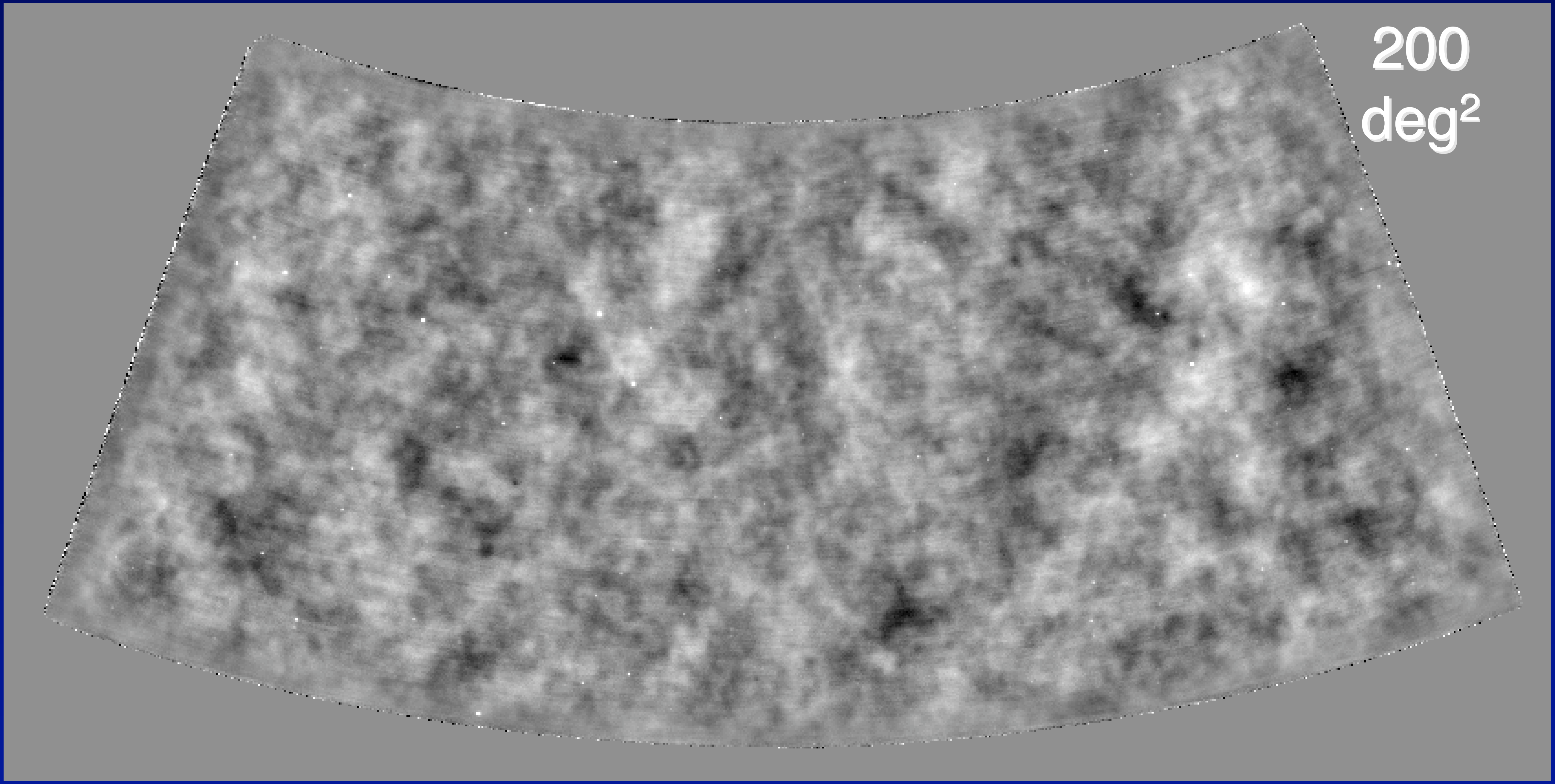
Ross Williamson and Erik Shirokoff 2009

The SPT Survey

- Finish 3-frequency survey of 6% of the sky this November
- Area chosen based on galactic dust and observable elevations
- Active optical & X-ray followup program
- Full DES coverage

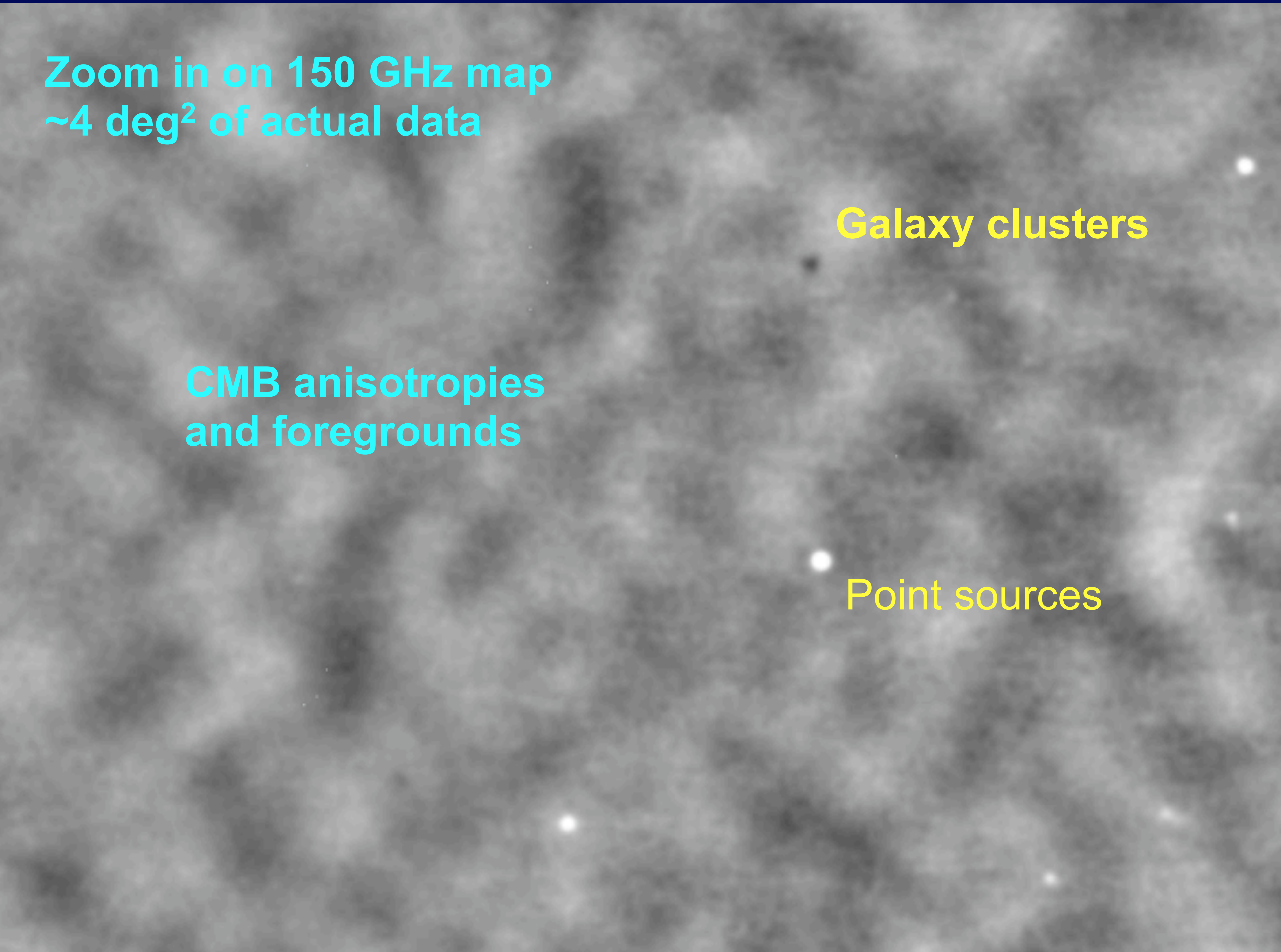


What a map looks like

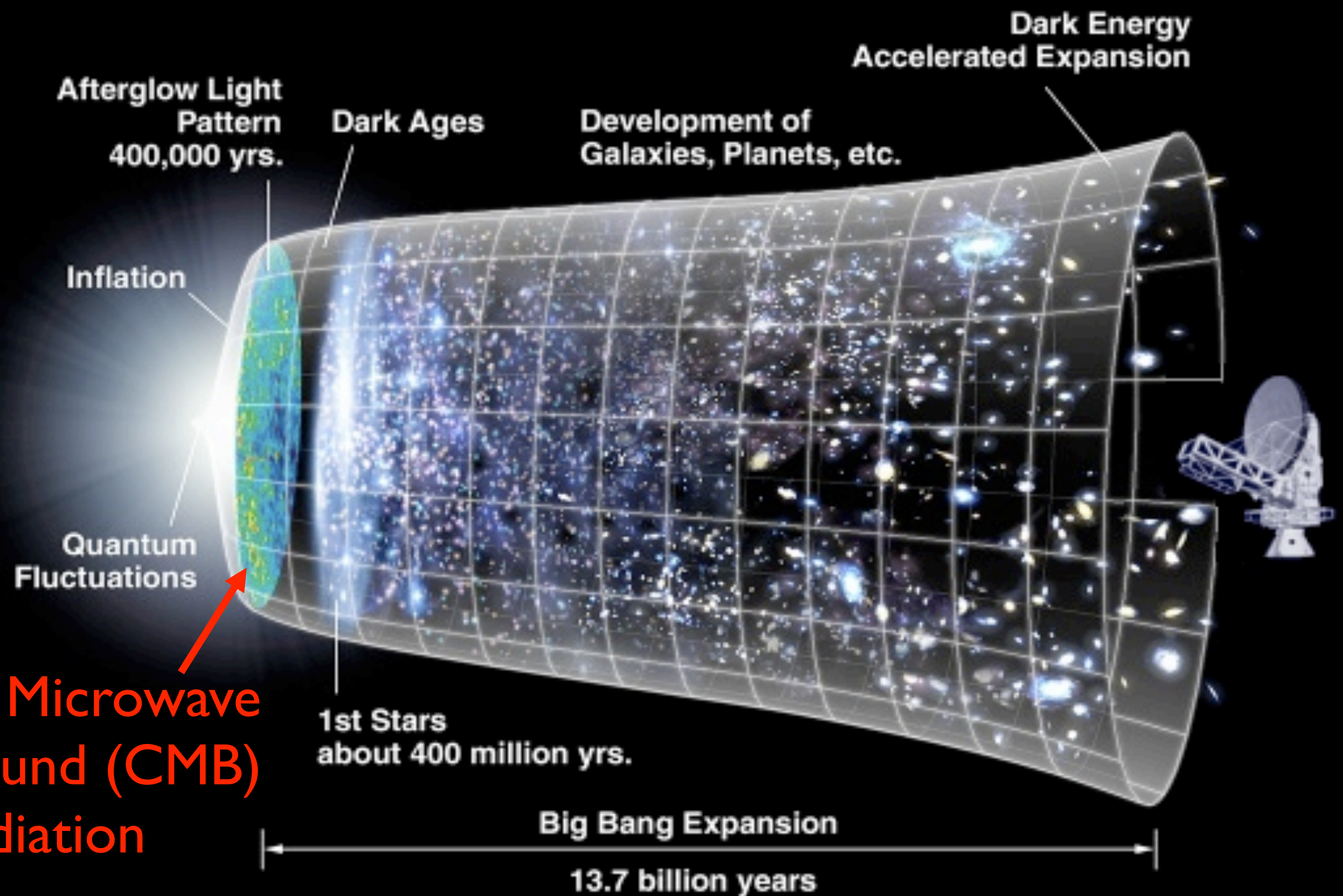


Full survey: 2500 deg^2

Noise: 40, 18, 65 μK-arcmin at 95, 150, 220 GHz


Zoom in on 150 GHz map
~4 deg^2 of actual data
Galaxy clusters
CMB anisotropies
and foregrounds
Point sources

A Brief History of the Universe

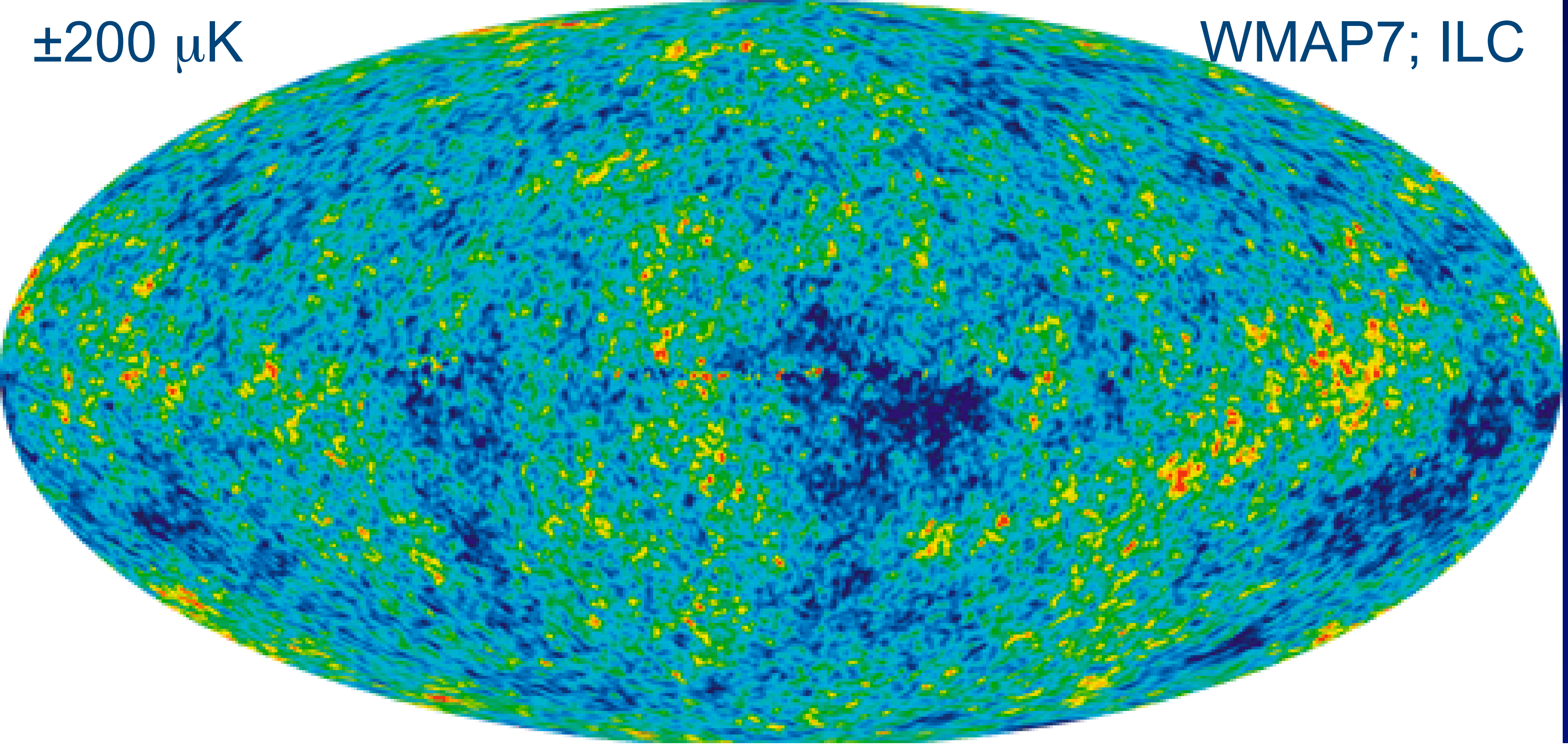


Cosmic Microwave Background (CMB) Radiation

~90% photons straight from (easy to model) early universe

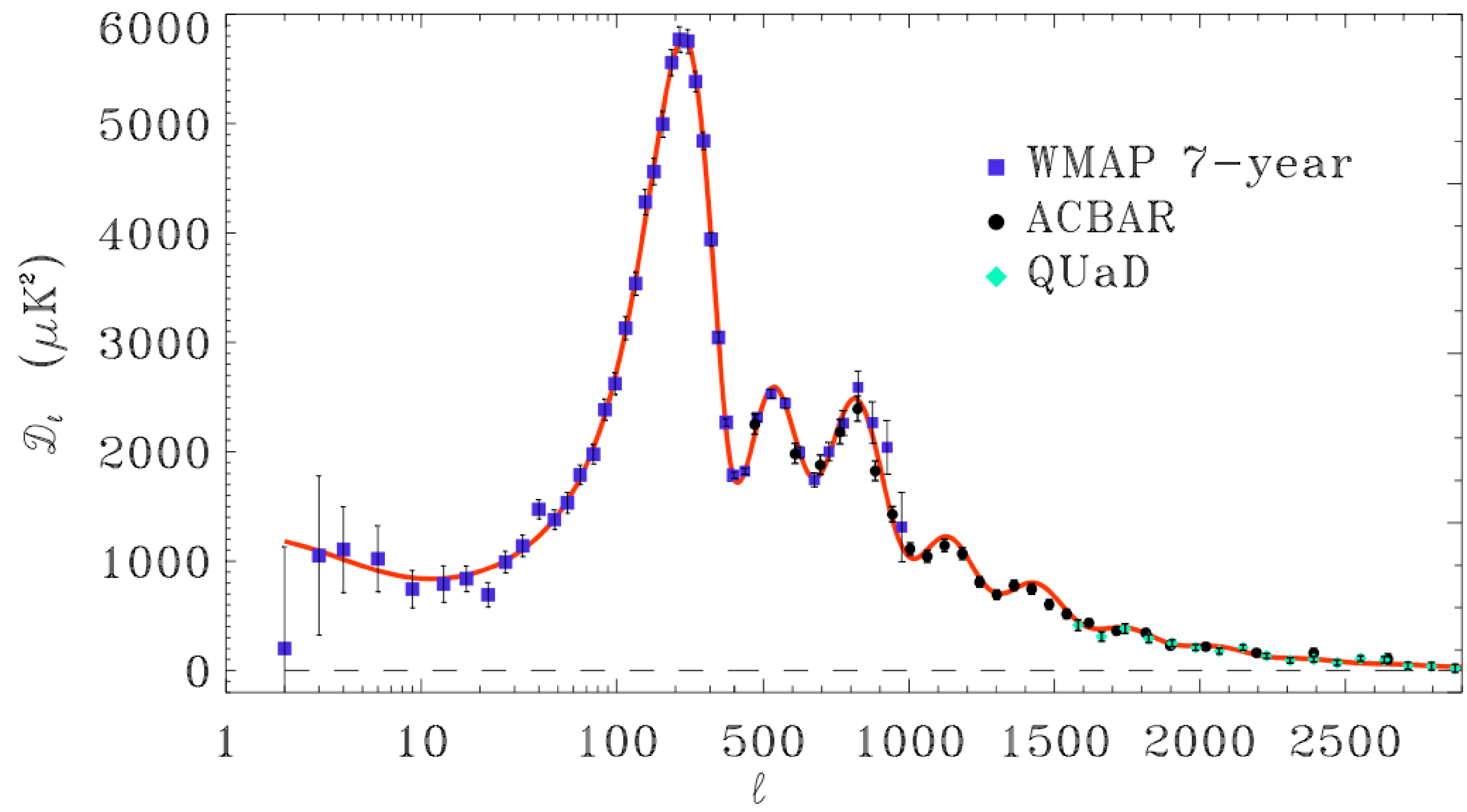
Lever arm on geometry

(image modified from NASA/WMAP)



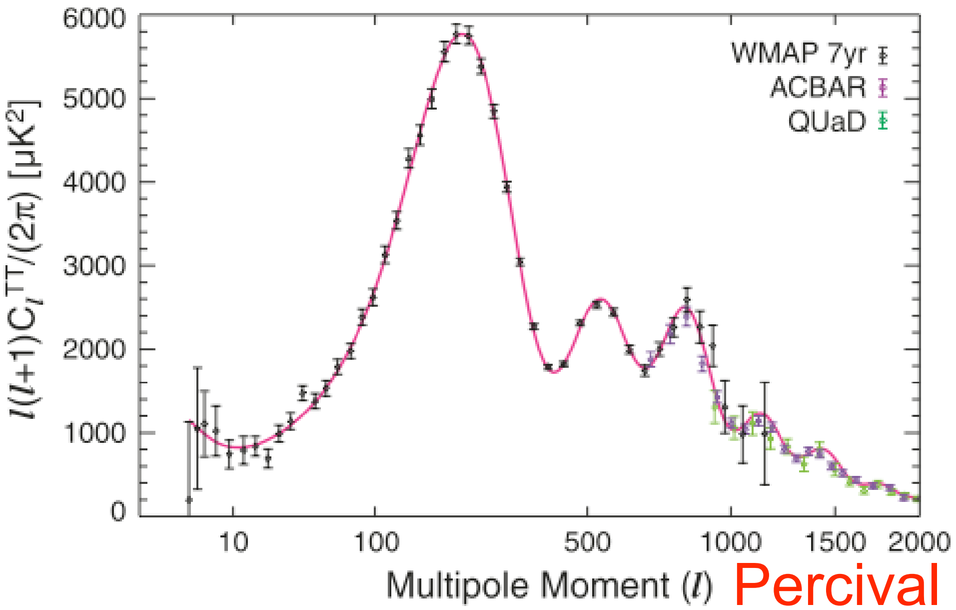
CMB and cosmology

(primary anisotropy)

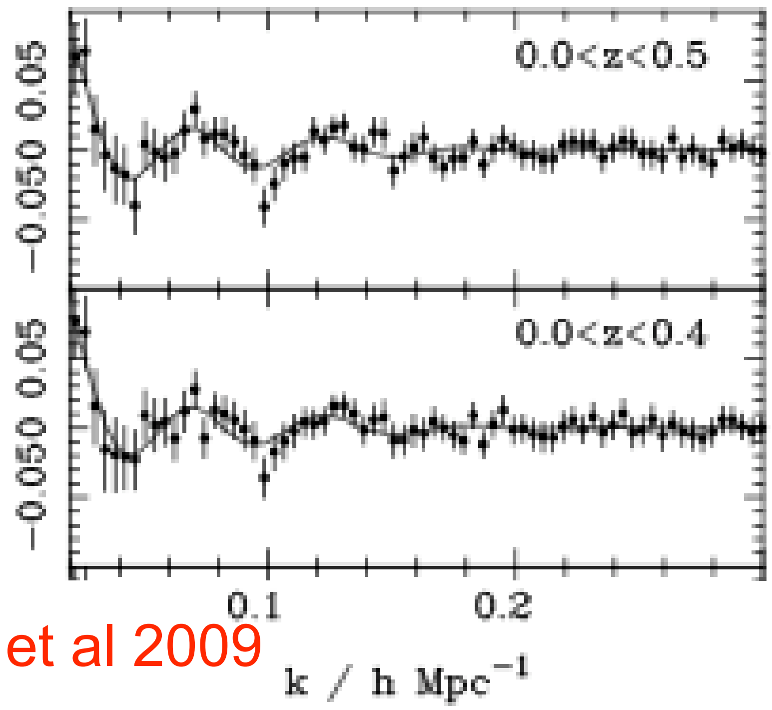


A dark energy dominated Universe

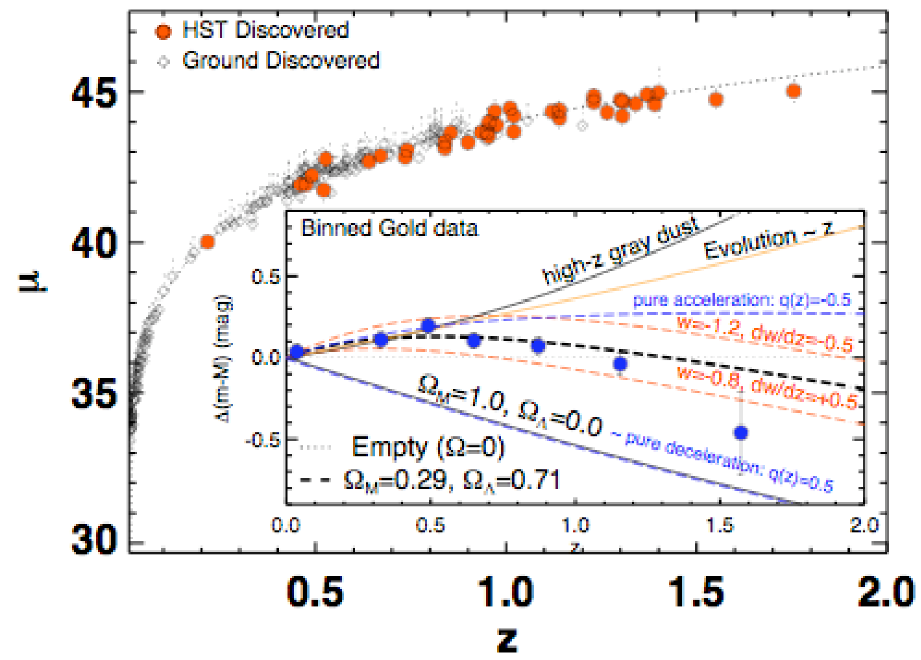
Komatsu et al 2010



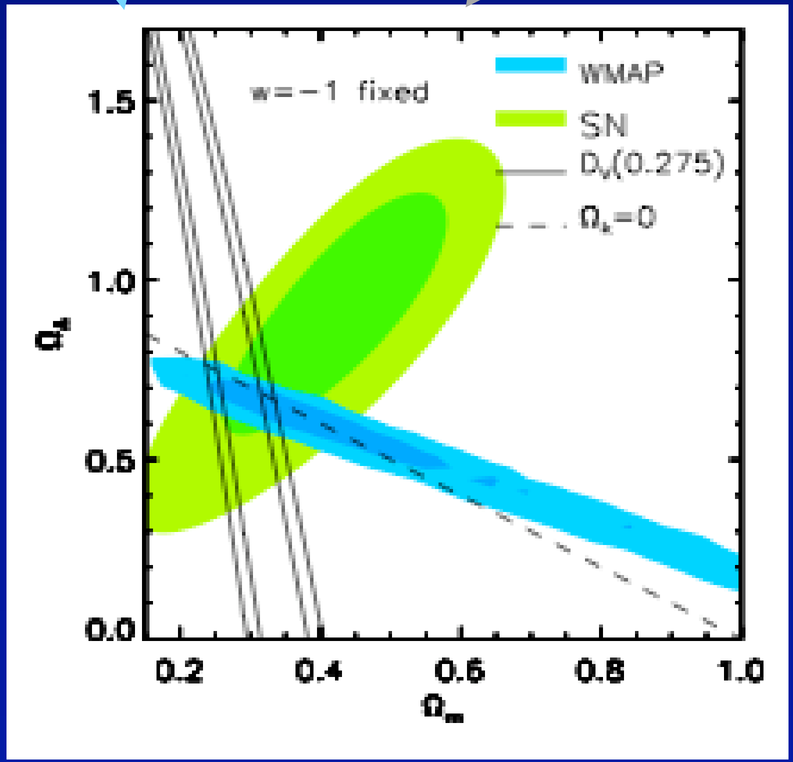
Percival et al 2009

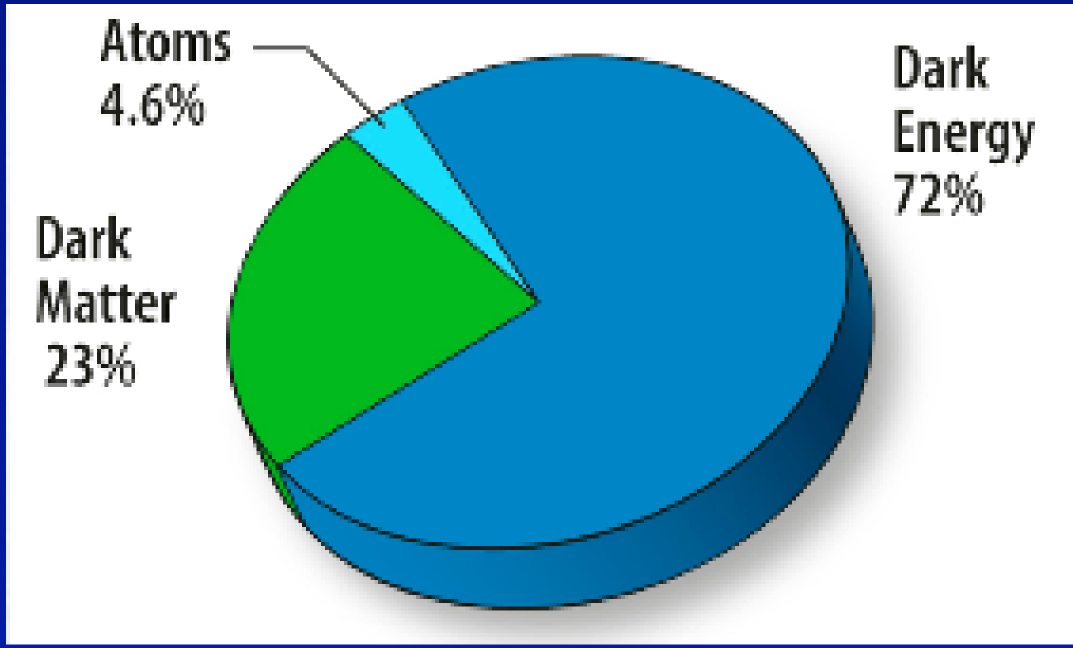


Riess et al 2007



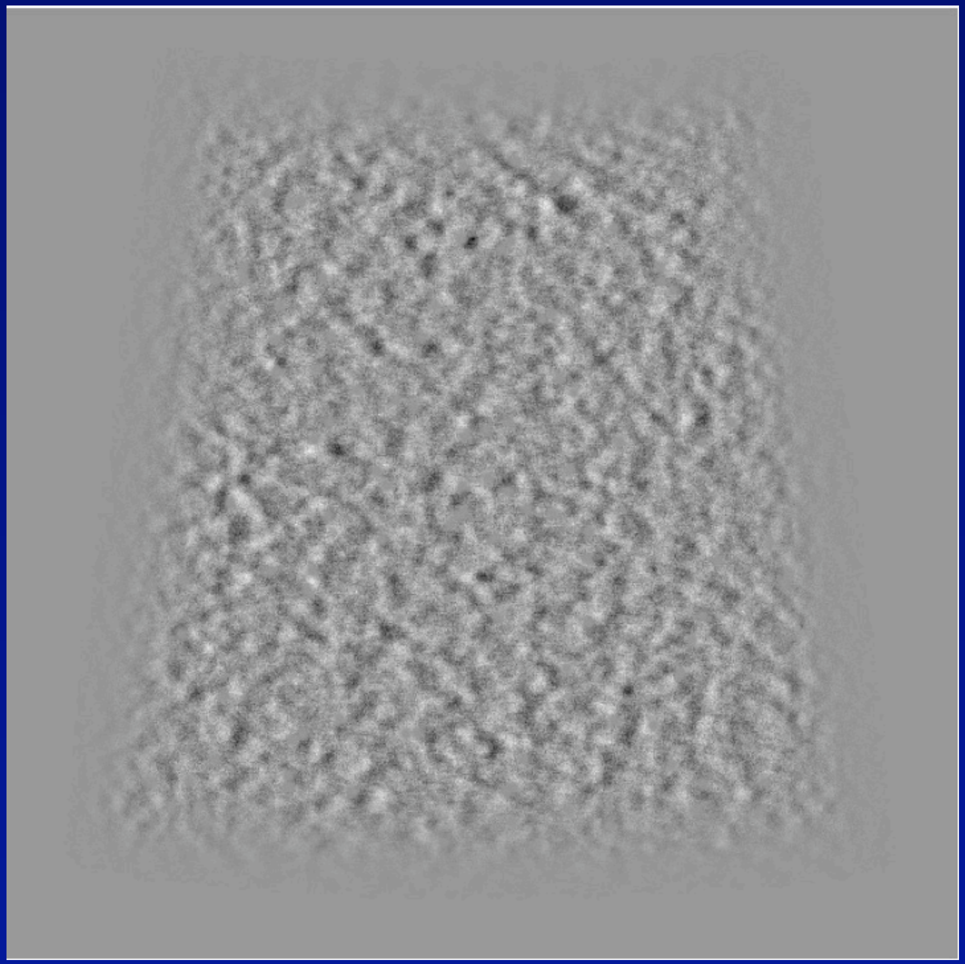
CMB BAO SN





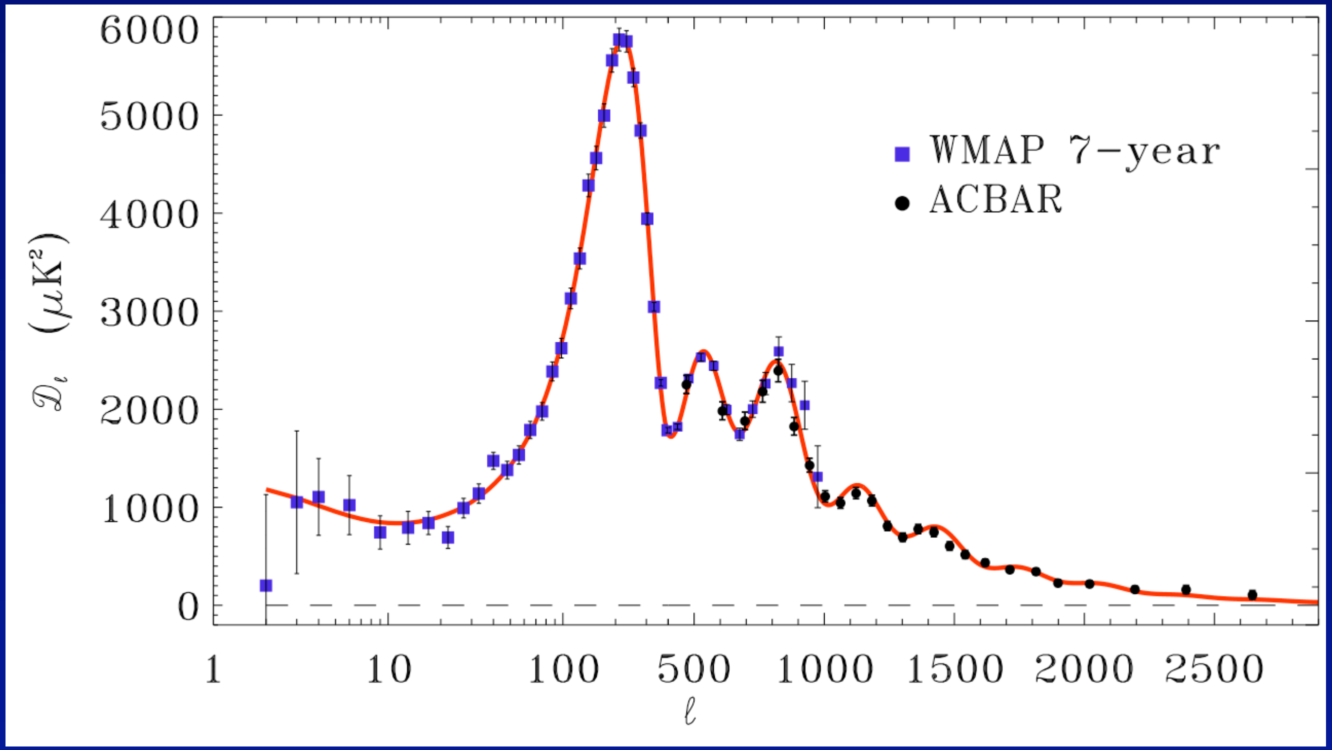
Maps to bandpowers

Beam + Calibration
+ 800 deg^2 Map



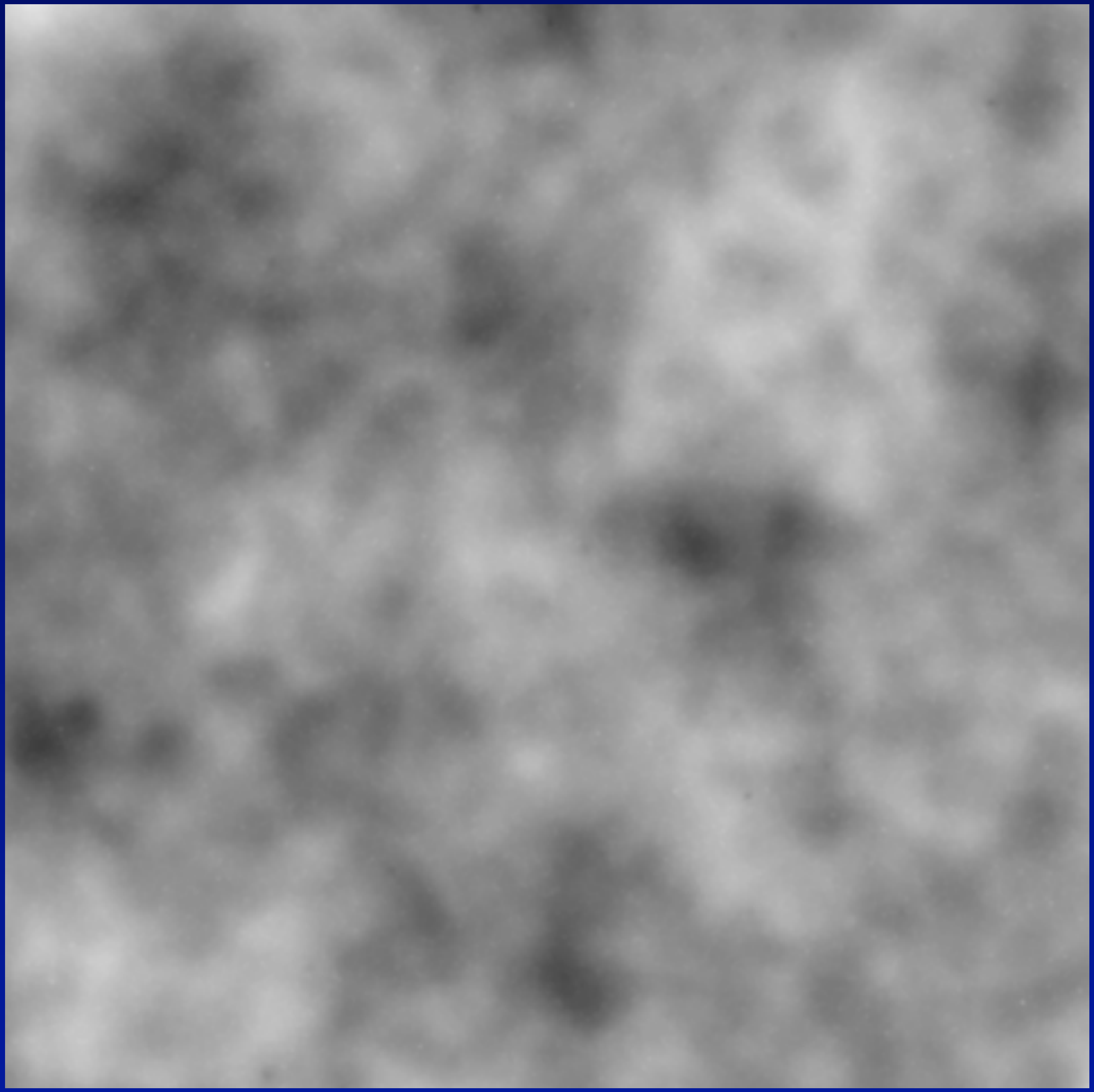
?

Power Spectrum



Pseudo-C_l methods

“Pseudo-Cl” Analysis



$$< \tilde{C}^{ii}_{\ell} >= B^2_{\ell} < C_{\ell'} >$$

Direct Fourier transform:

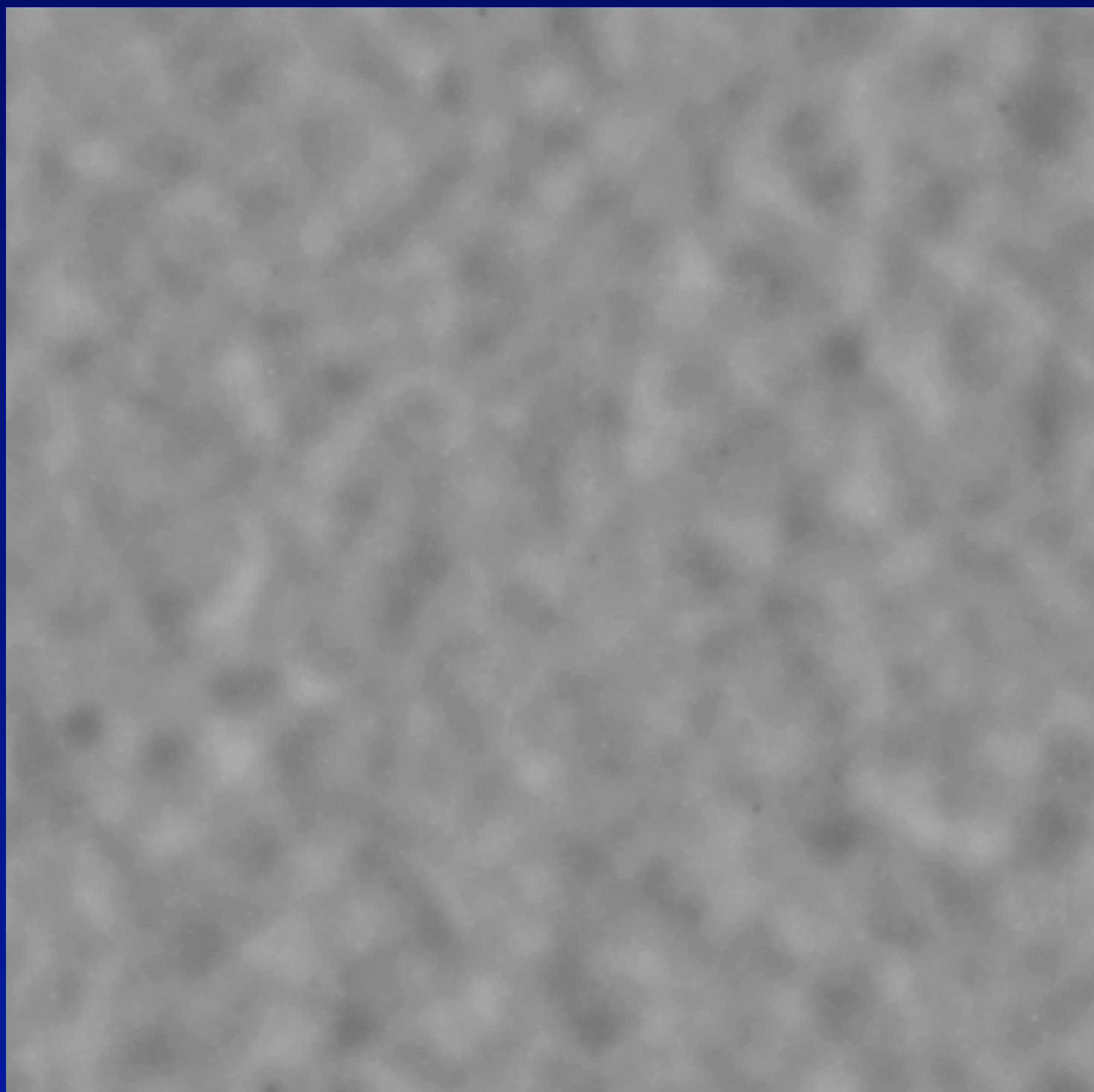
$$\tilde{a}^i_{\ell m} = \int d\hat{n} \left[\Delta T^i(\hat{n}) W(\hat{n})\right] Y_{\ell m}(\hat{n})$$

$$\tilde{C}^{ii}_{\ell} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\tilde{a}^i_{\ell m}|^2$$

Need to explicitly account for:

- Experimental beam shape

"Pseudo-Cl" Analysis



$$< \tilde{C}_\ell^{ii} > = F_\ell B_\ell^2 < C_{\ell'} >$$

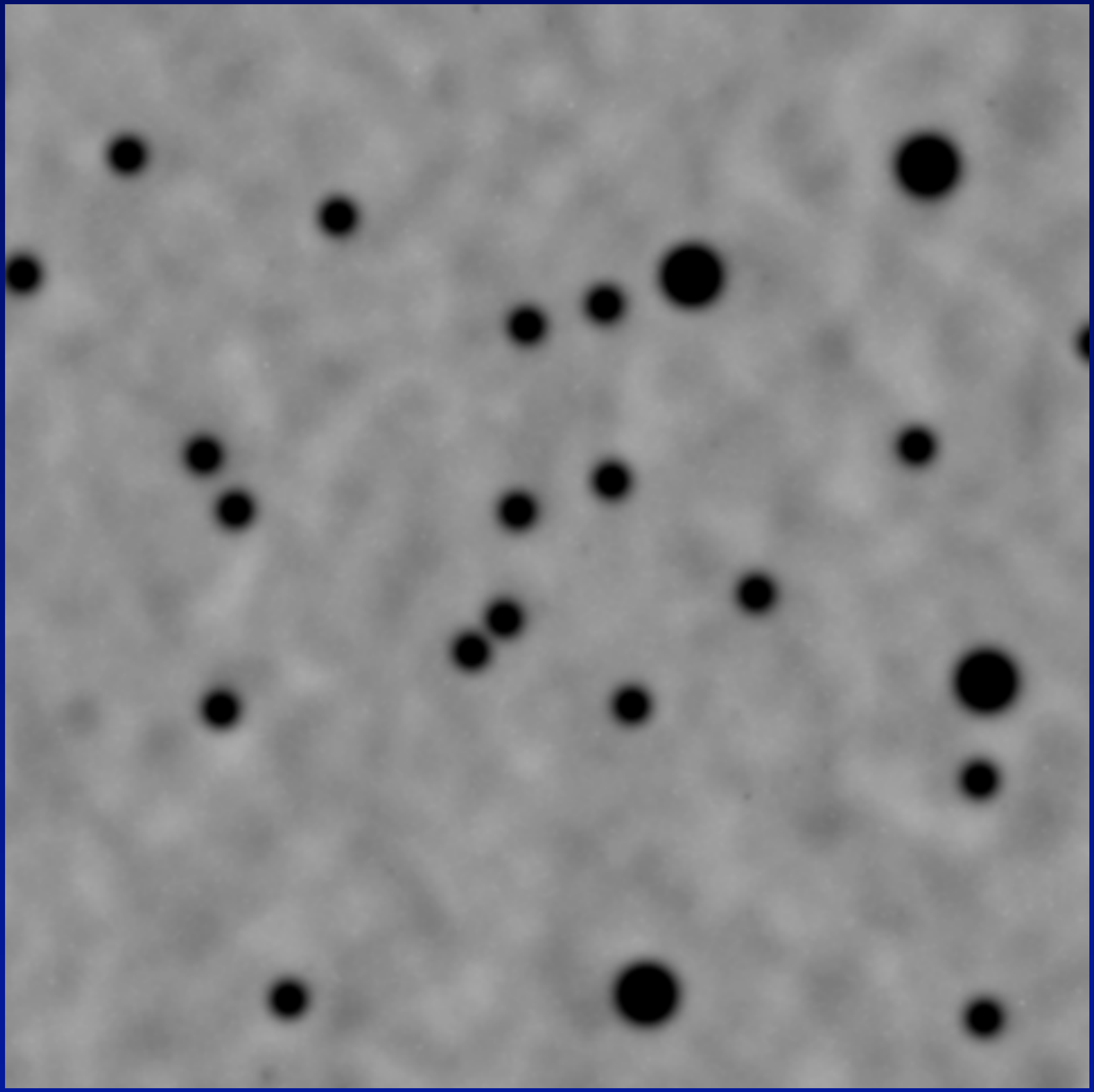
Direct Fourier transform:

$$\tilde{a}^i_{\ell m} = \int d\hat{n} \left[\Delta T^i(\hat{n}) W(\hat{n}) \right] Y_{\ell m}(\hat{n})$$

$$\tilde{C}_\ell^{ii} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\tilde{a}^i_{\ell m}|^2$$

Need to explicitly account for:
- Experimental beam shape
- Filtering of timestream data

“Pseudo-Cl” Analysis



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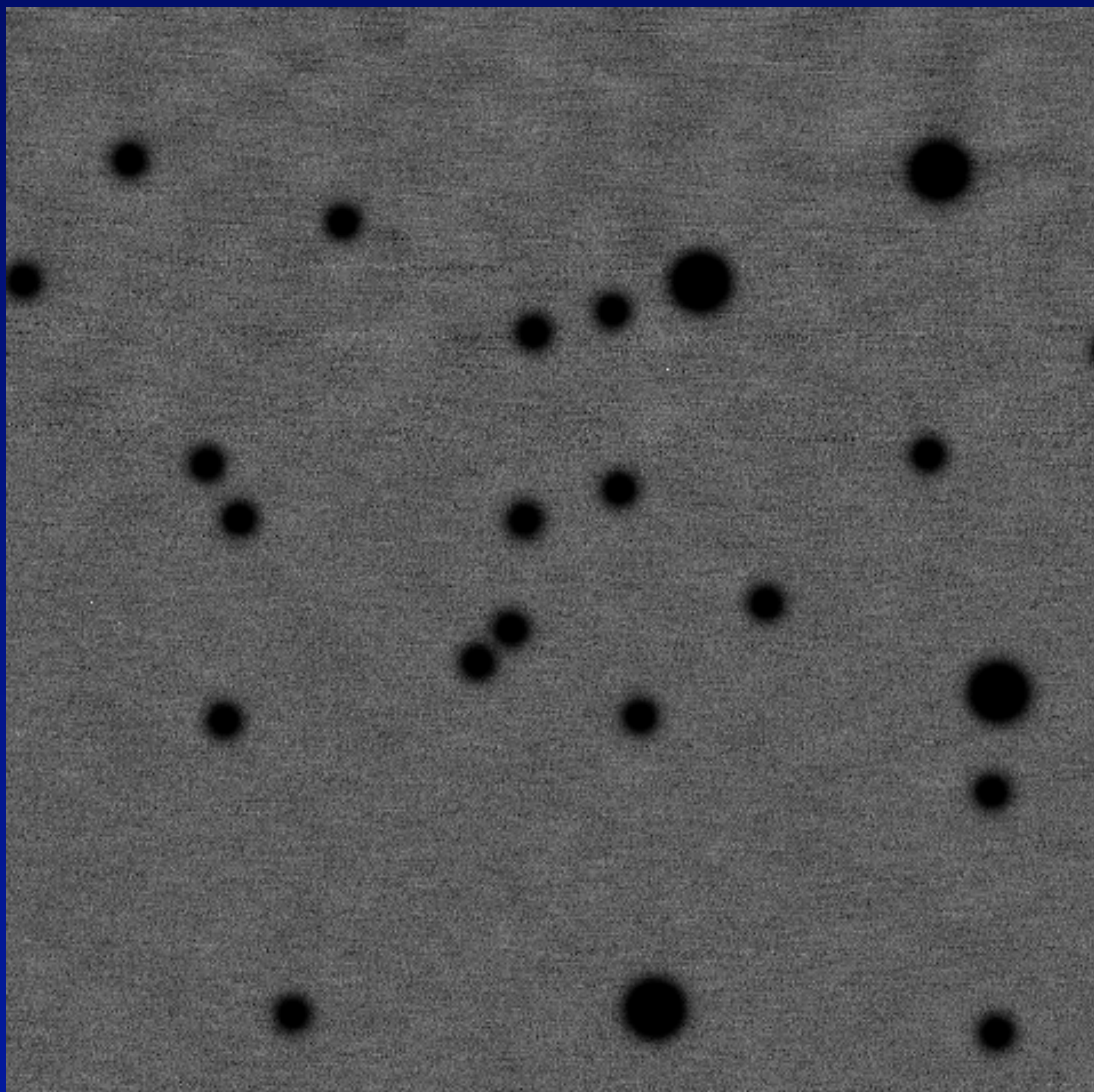
Need to explicitly account for:

- Experimental beam shape
- Filtering of timestream data
- Masking for unwanted sources

$$< \tilde{C}^{ii}_\ell > = \sum_{\ell'} M_{\ell\ell'}[W] F_{\ell'} B^2_{\ell'} < C_{\ell'} >$$

“Pseudo-Cl” Analysis



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$$\tilde{a}^i_{\ell m} = \int d\hat{n}\,\left[\Delta T^i(\hat{n}) W(\hat{n})\right] Y_{\ell m}(\hat{n})$$

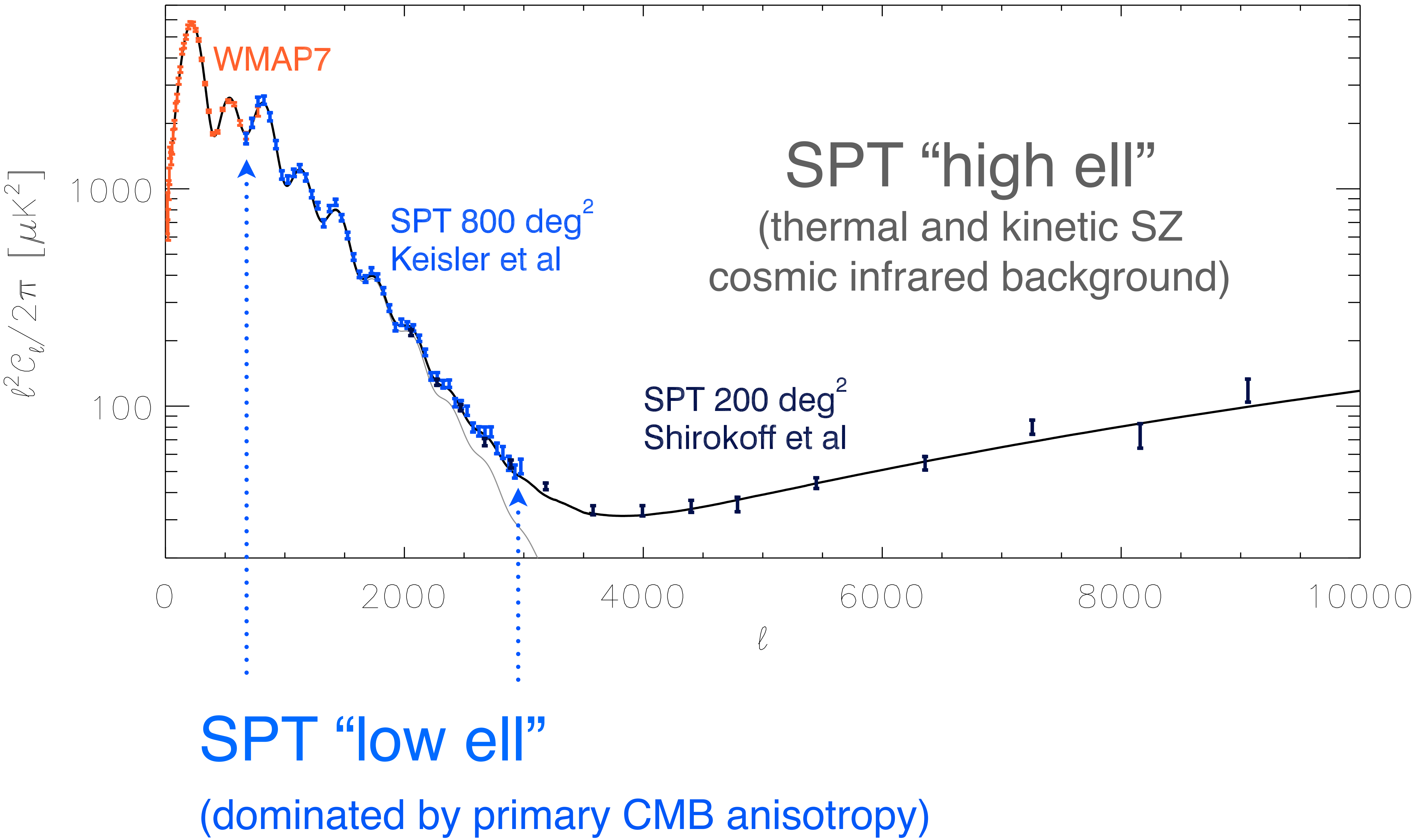
$$\tilde{C}^{ii}_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |\tilde{a}^i_{\ell m}|^2$$

Need to explicitly account for:

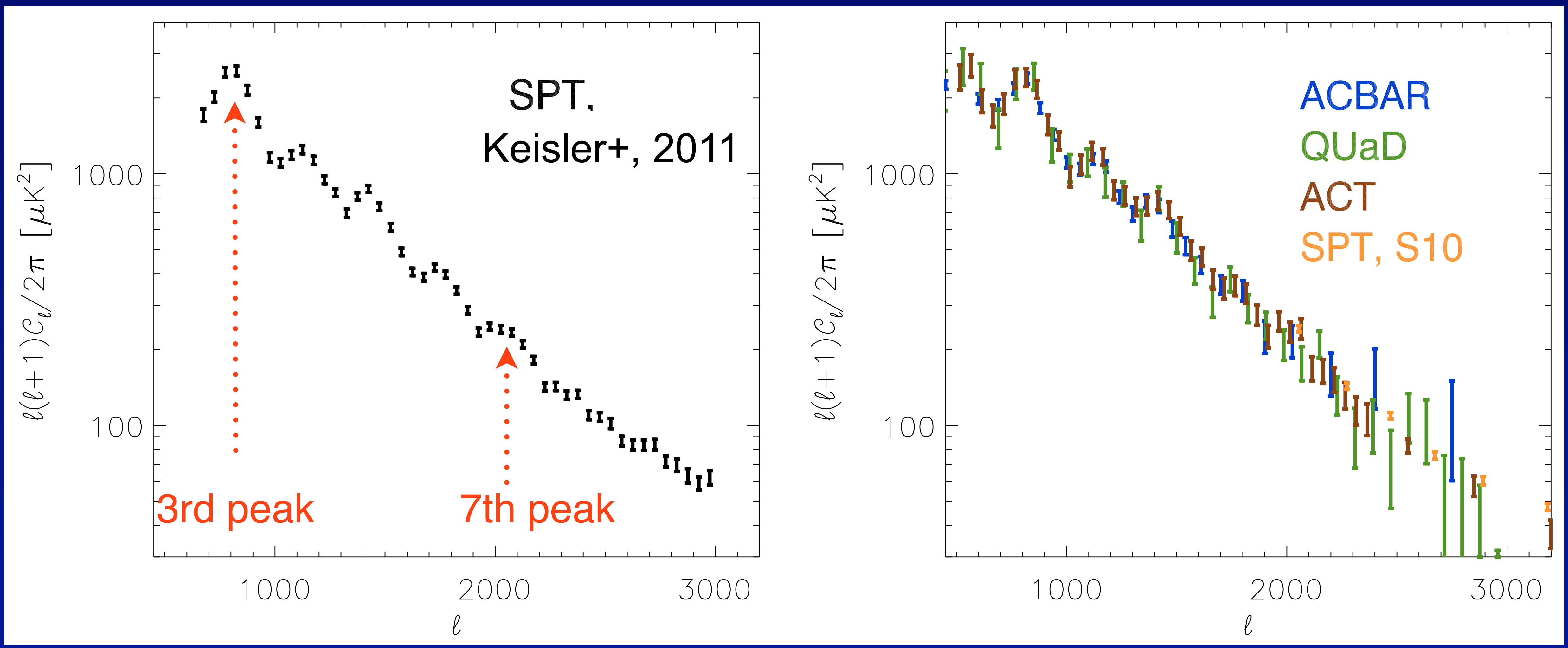
- Experimental beam shape
- Filtering of timestream data
- Masking for unwanted sources
- Biases introduced by noise

$$< \tilde{C}^{ii}_\ell > = \sum_{\ell'} M_{\ell\ell'}[W] F_{\ell'} B^2_{\ell'} < C_{\ell'} > + < N_\ell >$$

SPT - both primary & secondary CMB

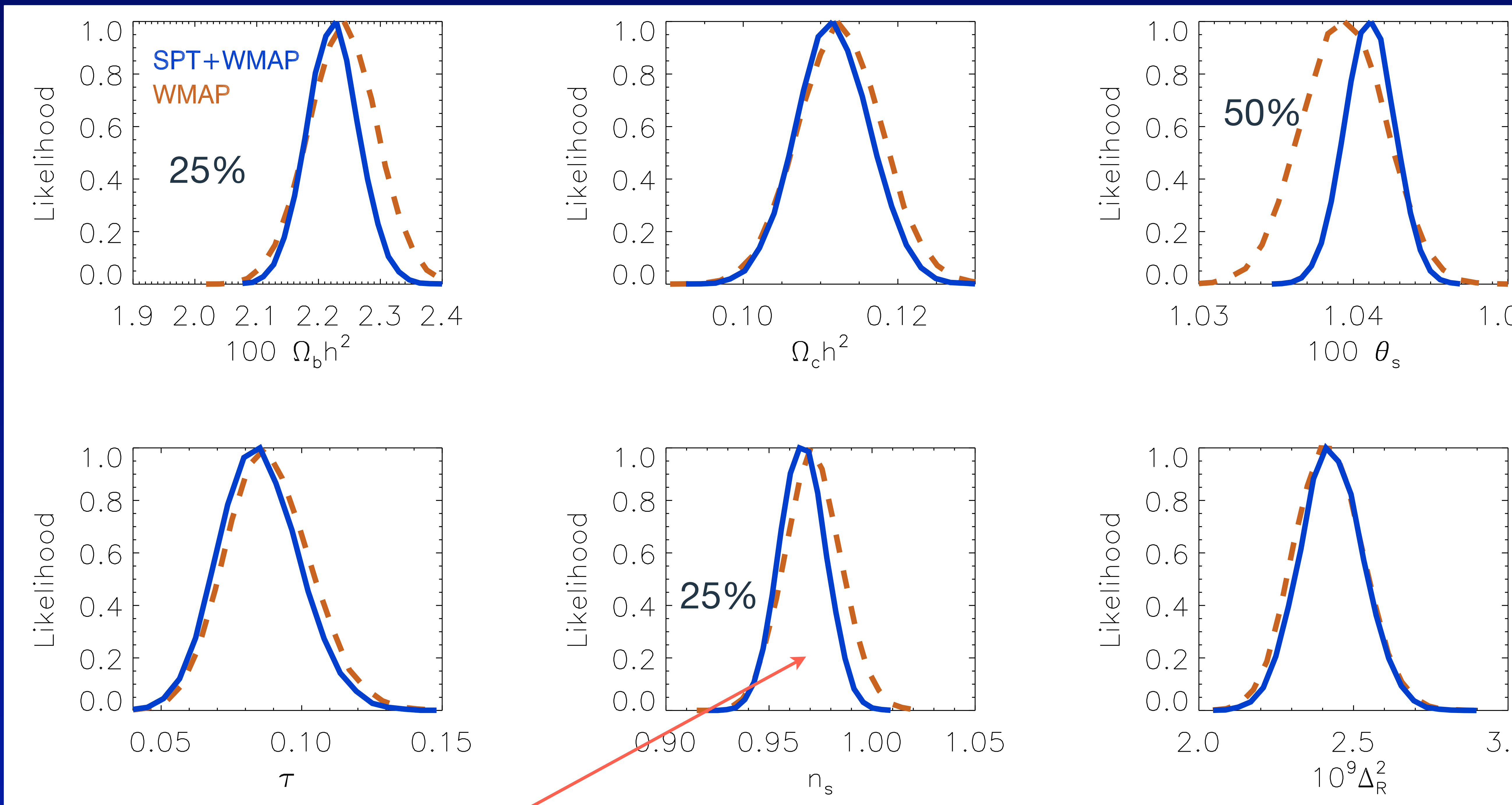


Primary CMB



- Reduces uncertainties by >2 across damping tail

SPT modestly improves 6 “vanilla” cosmo parameters



ns = 0.9663 +/- 0.0112 (3.0-sigma from 1.0)

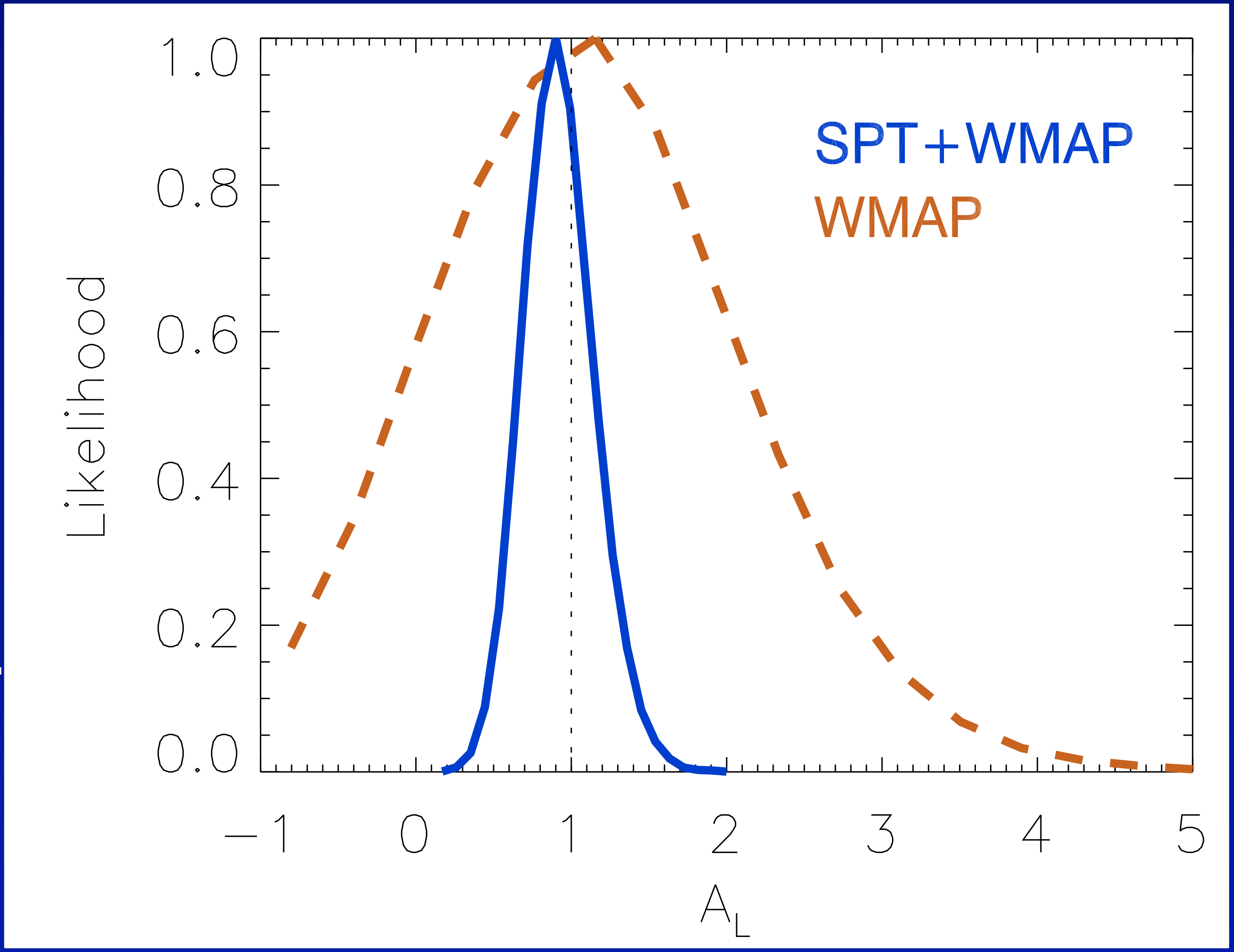
CMB Lensing

Introduce **A_lens** which smoothly scales lensing potential power spectrum:

$$C_\ell^\psi \rightarrow A_{\mathrm{lens}} C_\ell^\psi$$

(lensing smooths out acoustic peaks)

- (A_{lens})^0.65 = 0.94 +/- 0.15
- Consistent with $A_{\mathrm{lens}} = 1$.
- 5-6σ rejection of $A_{\mathrm{lens}} = 0$.
- Predict 30 σ detection for full spt survey & lensing analysis. Constrain neutrino mass, early dark energy, modified gravity

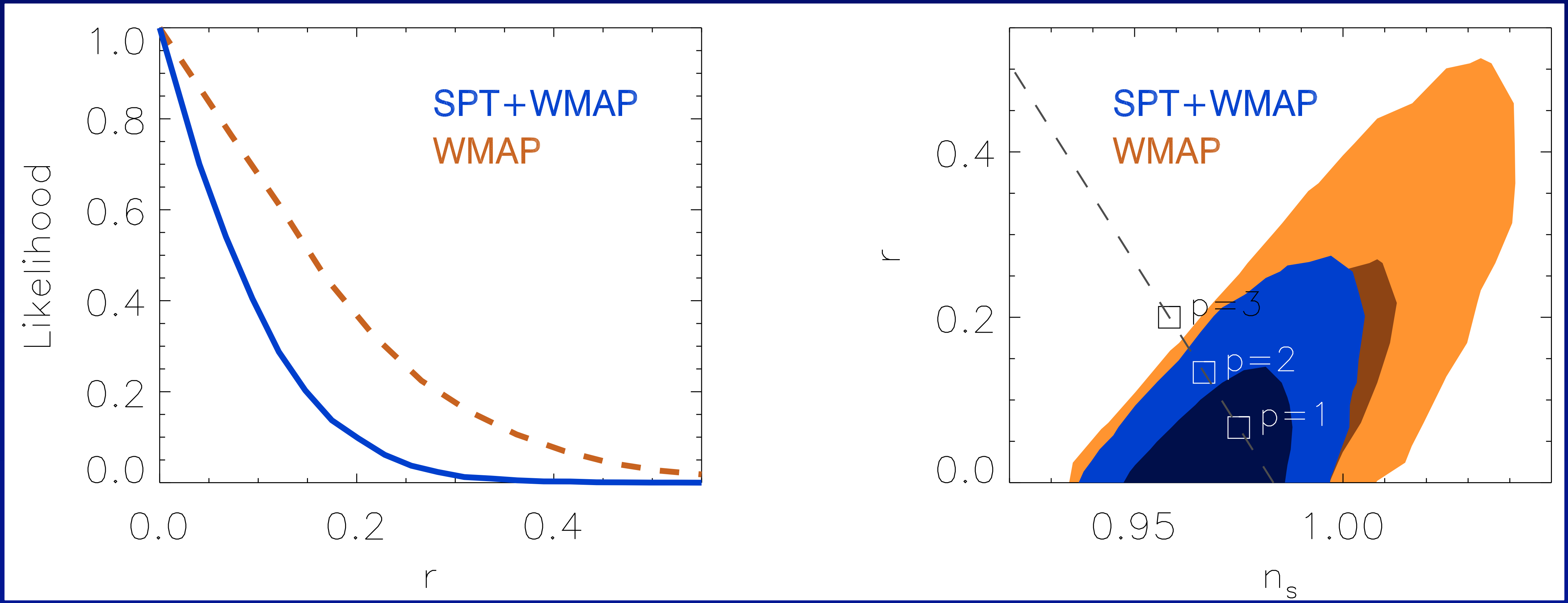


Extensions beyond LCDM

- Inflation - **Running** and **Tensor** modes (normally=0, allow to be free)
- **Primordial Helium** (normally determined by BBN, a tight function of $\Omega_b h^2$. Allow to be free).
- **Number of relativistic species** (think neutrinos) (normally 3.046, allow to be free)

Initial conditions

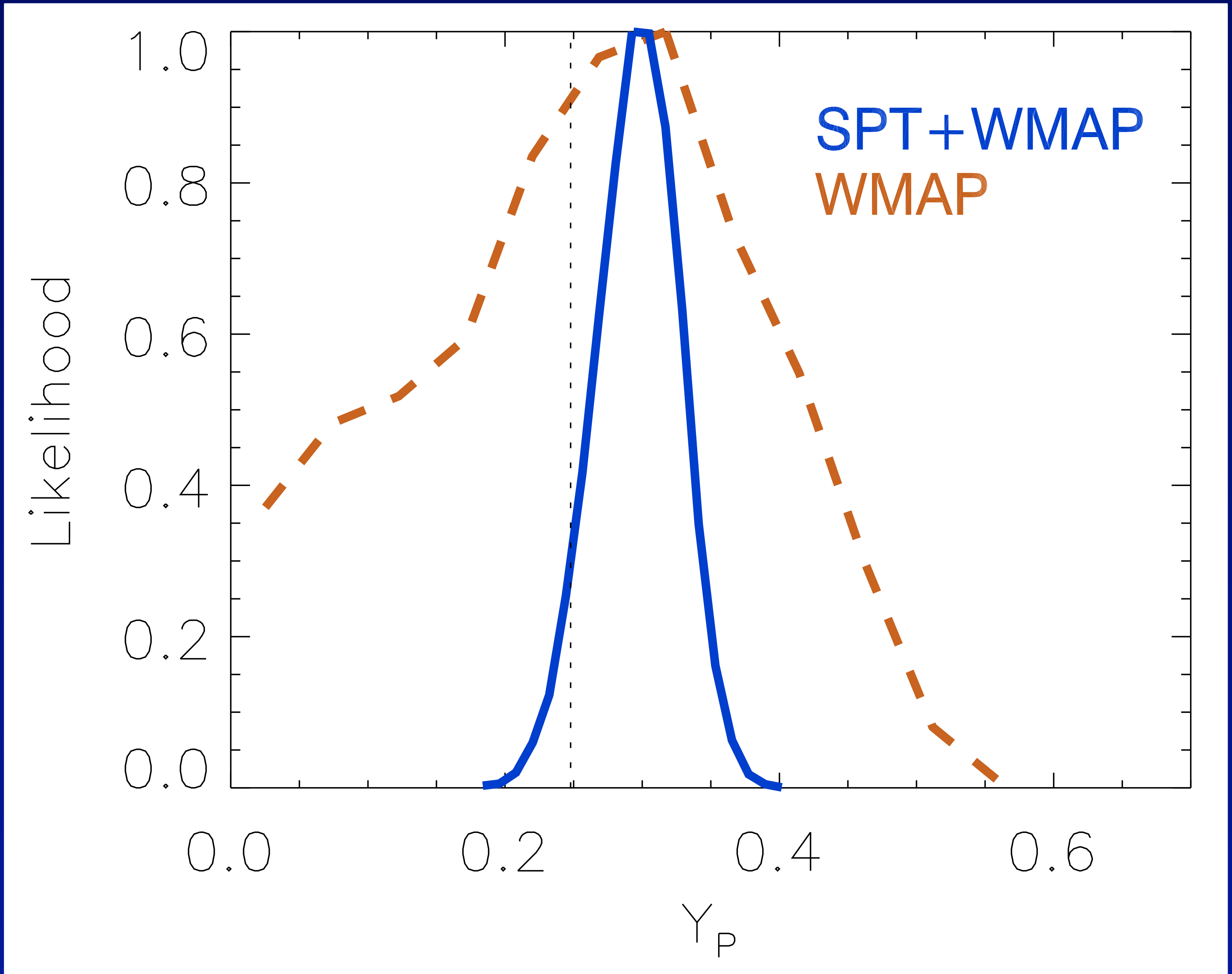
Chaotic inflationary models - $V(\Phi) = \Phi^p$



- Tightest constraints on tensor-scalar ratio (r), running and n_s
- r<0.21 (95%), SPT+WMAP7
- r<0.17 (95%), SPT+WMAP7+H0+BAO

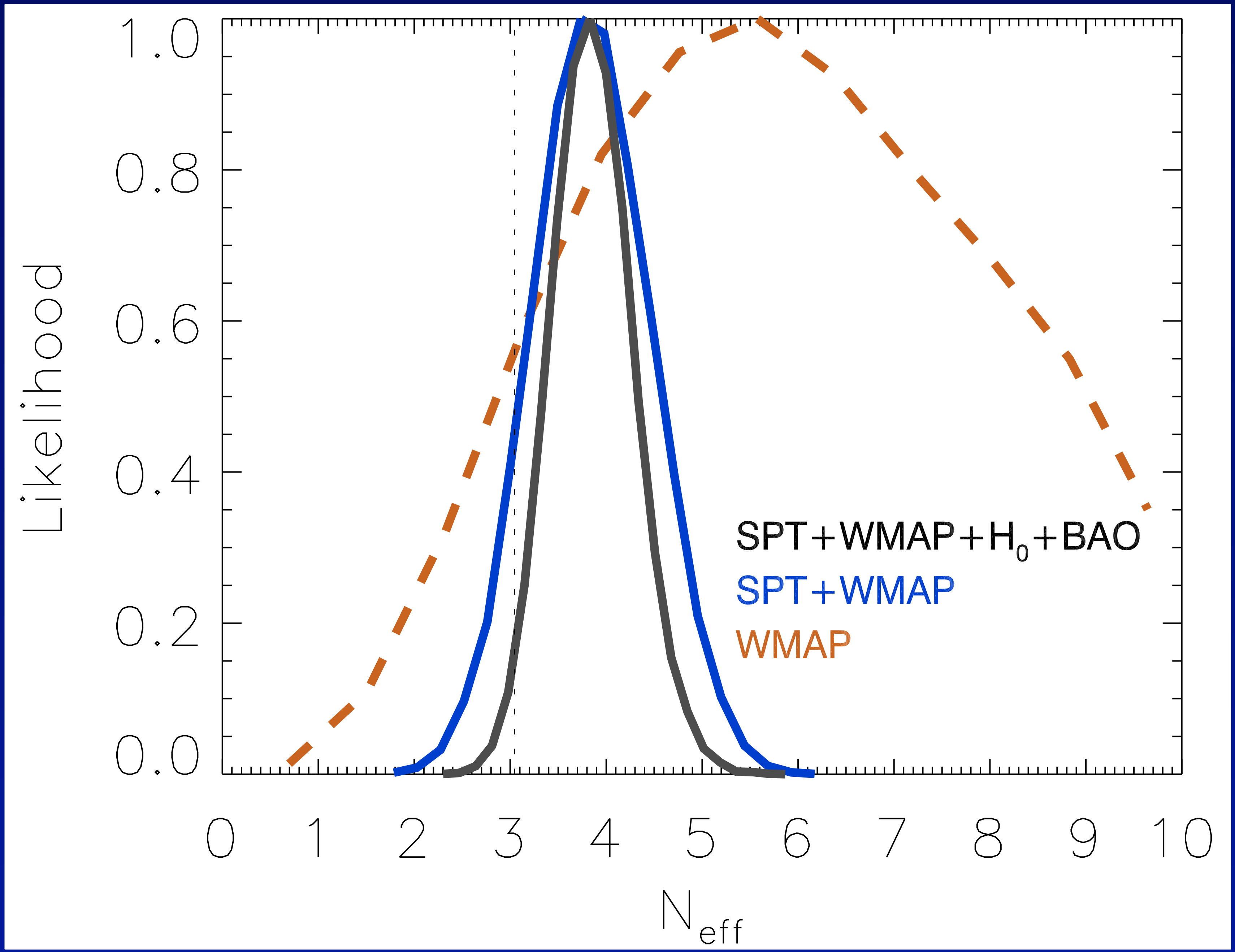
Primordial Helium

7.7σ rejection of Yp=0.



- Yp = 0.296 +/- 0.030 (SPT+WMAP7)

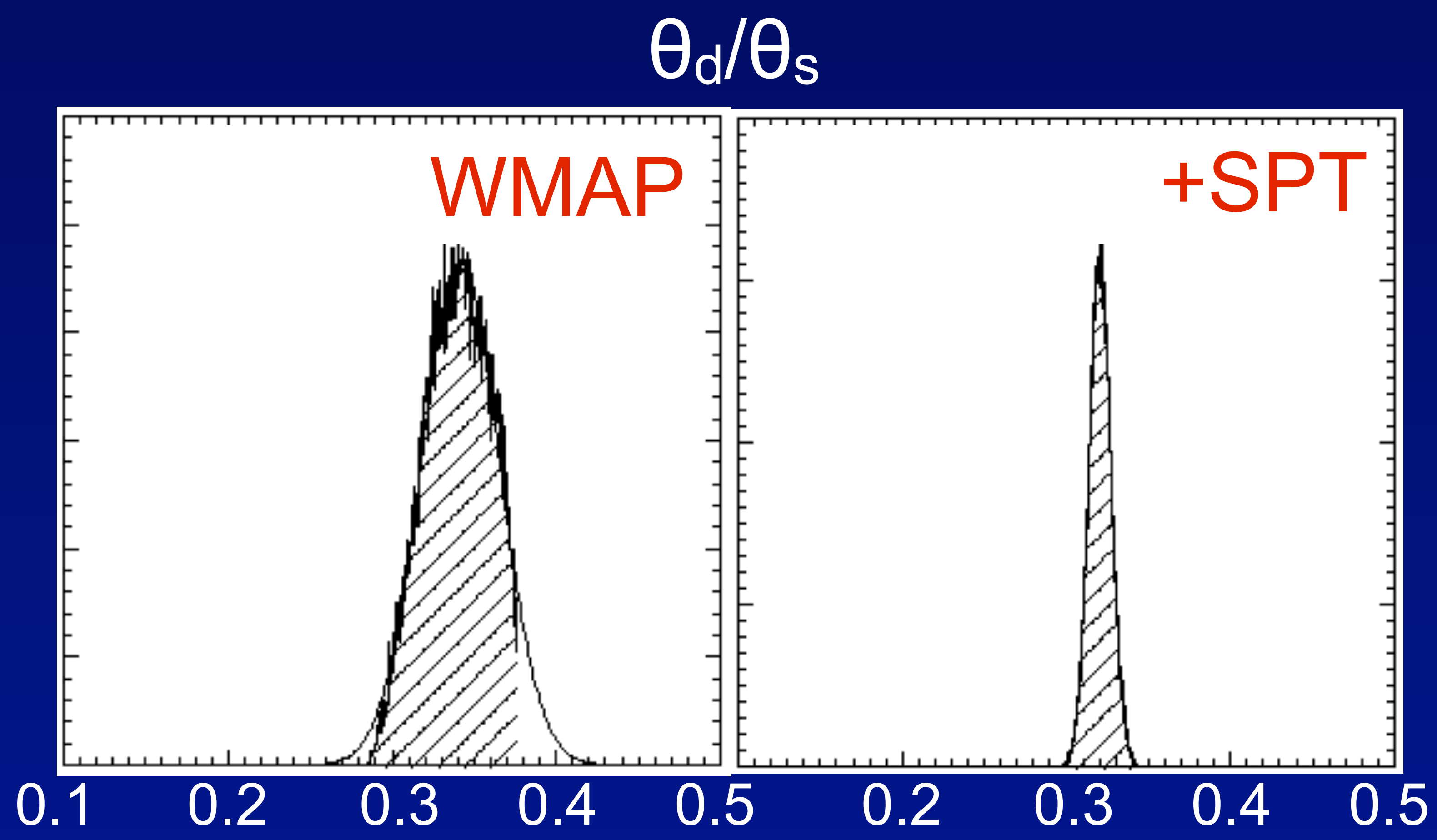
Number of Relativistic Species



7.5σ rejection of N_{eff}=0.

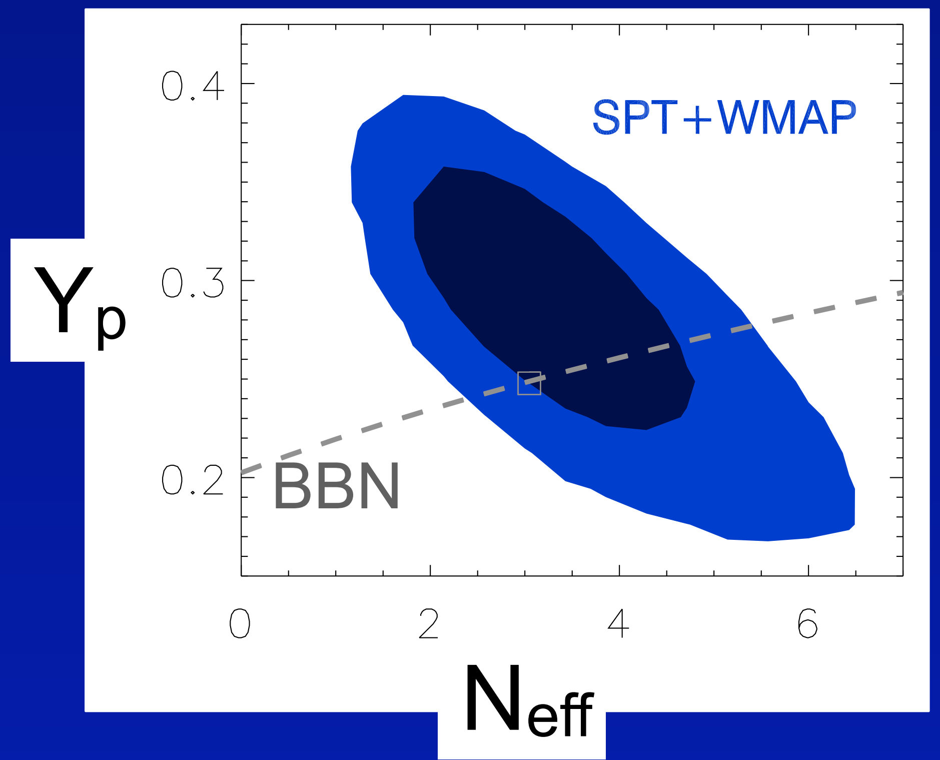
- Neff = 3.85 +/- 0.62 (SPT+WMAP7)
- Neff = 3.86 +/- 0.42 (SPT+WMAP7+H0+BAO)

Damping scale

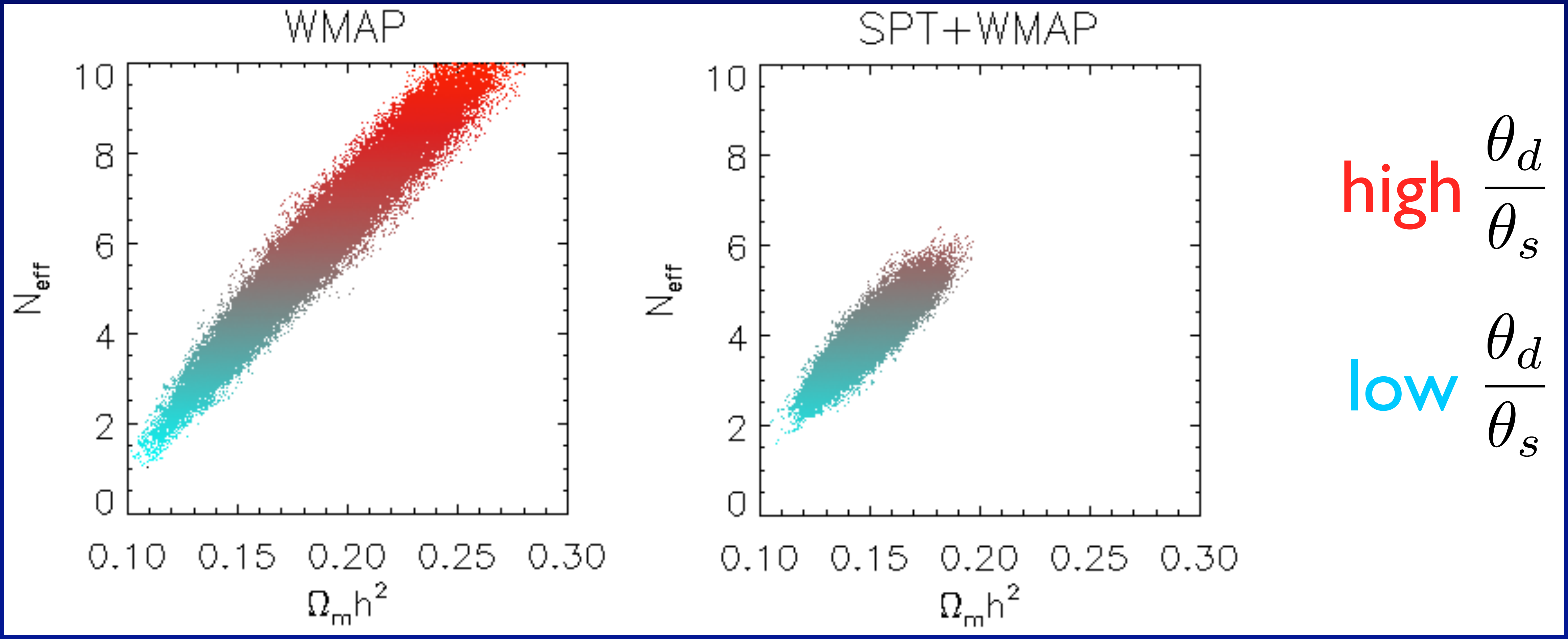


$$\frac{\theta_d}{\theta_s} \simeq \frac{0.24(1+0.227\ \mathrm{N_{eff}})^{0.22}}{\sqrt{1-Y_p}}$$

Hou et al. 2011



Number of neutrinos

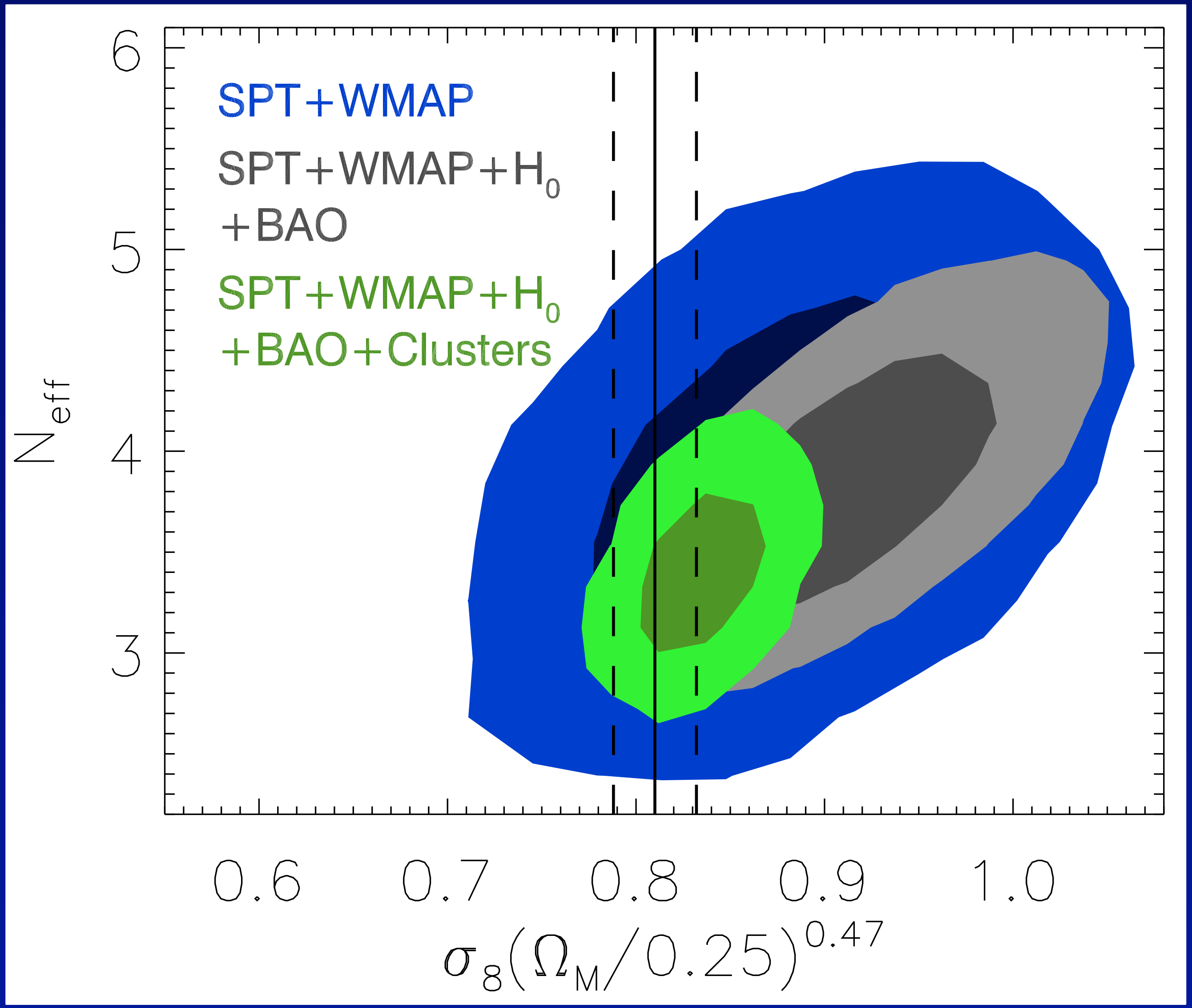


- N_{eff}: > 2.7 (WMAP)
  3.85 ± 0.62 (WMAP+SPT)

Tension with measures of structure

Data prefers N_{eff} > 3 (1.8-sigma)

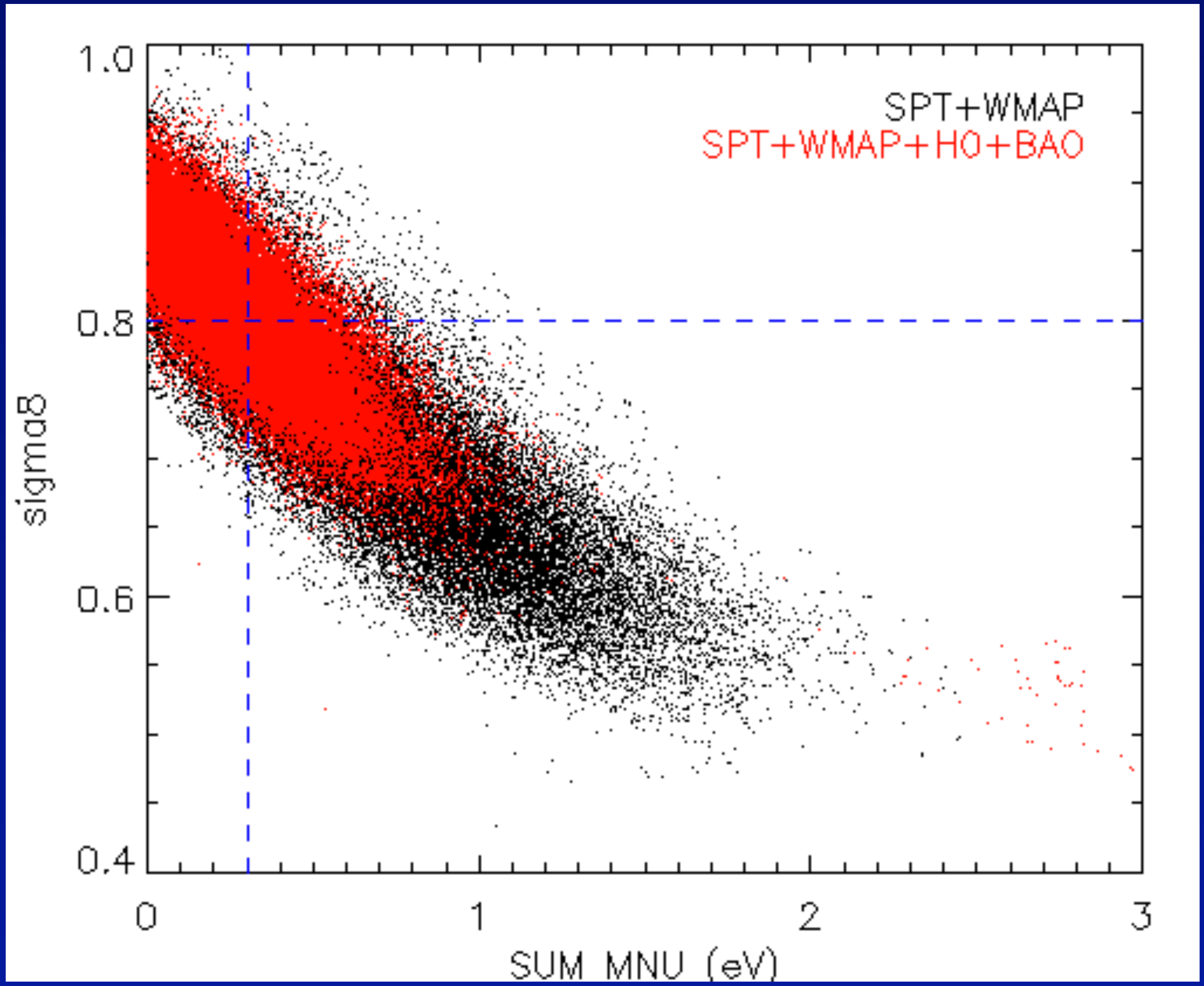
Such models need high σ_8

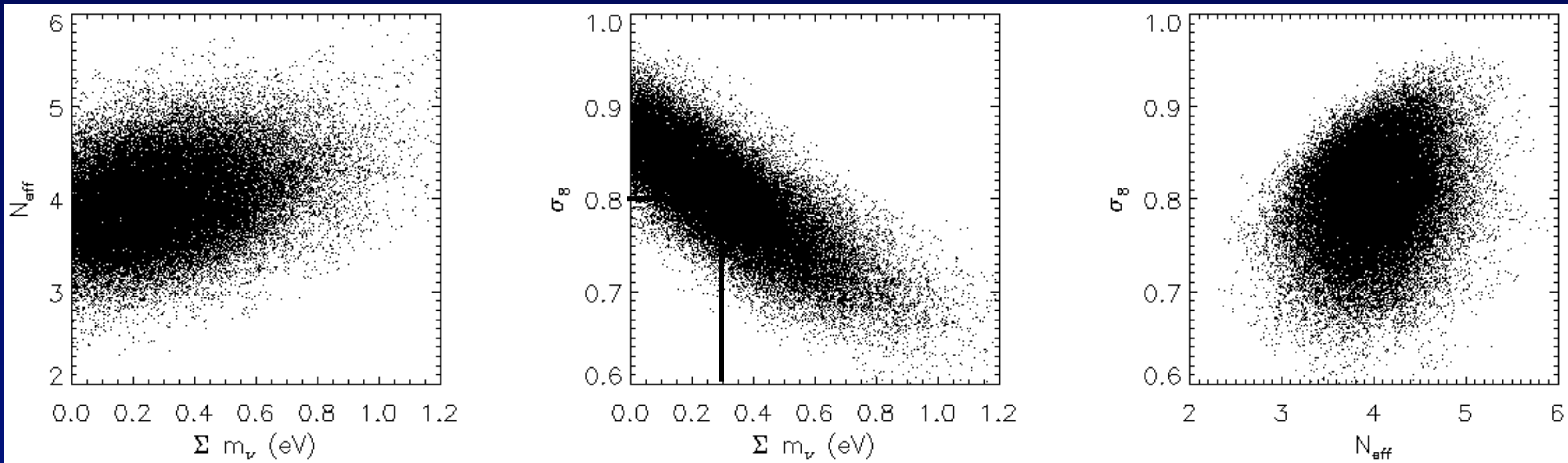


- N_{eff}: 3.42 ± 0.34 (WMAP+SPT+BAO+Clusters)

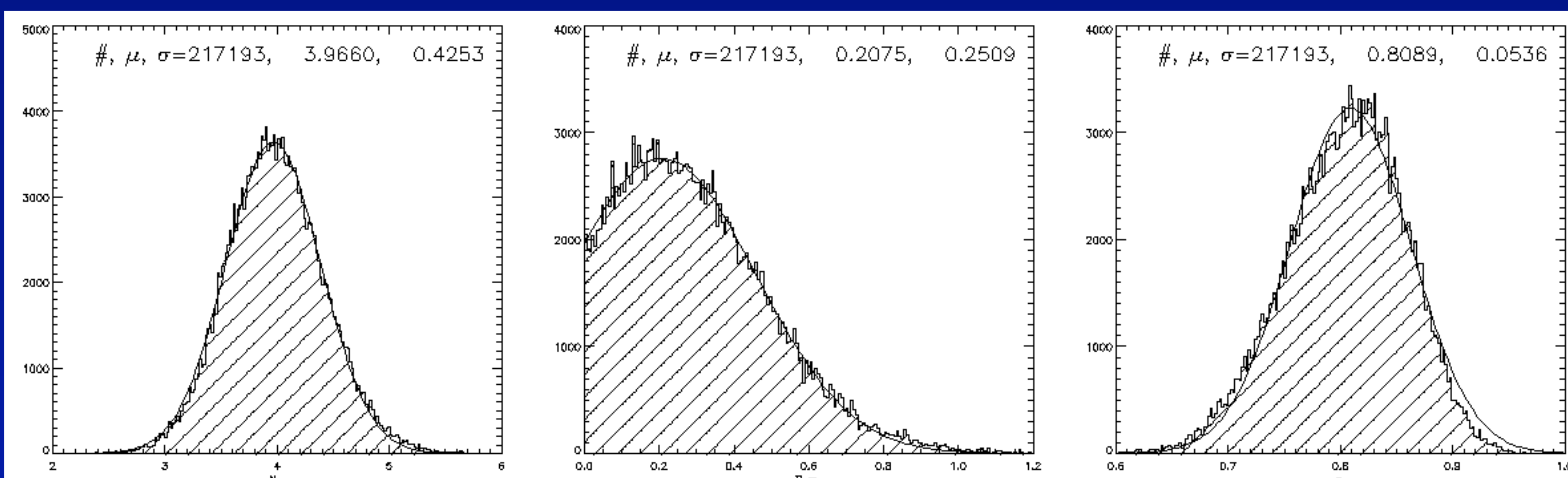
Hold on - massive neutrino's

- Can have a lower and "more reasonable" σ_8, like 0.8, if you allow for Sum of m_{nu} ~ 0.3 eV.





Allowing for (not very) massive neutrinos decorrelates N_{eff} and σ_8, at no expense to N_{eff} constraint.



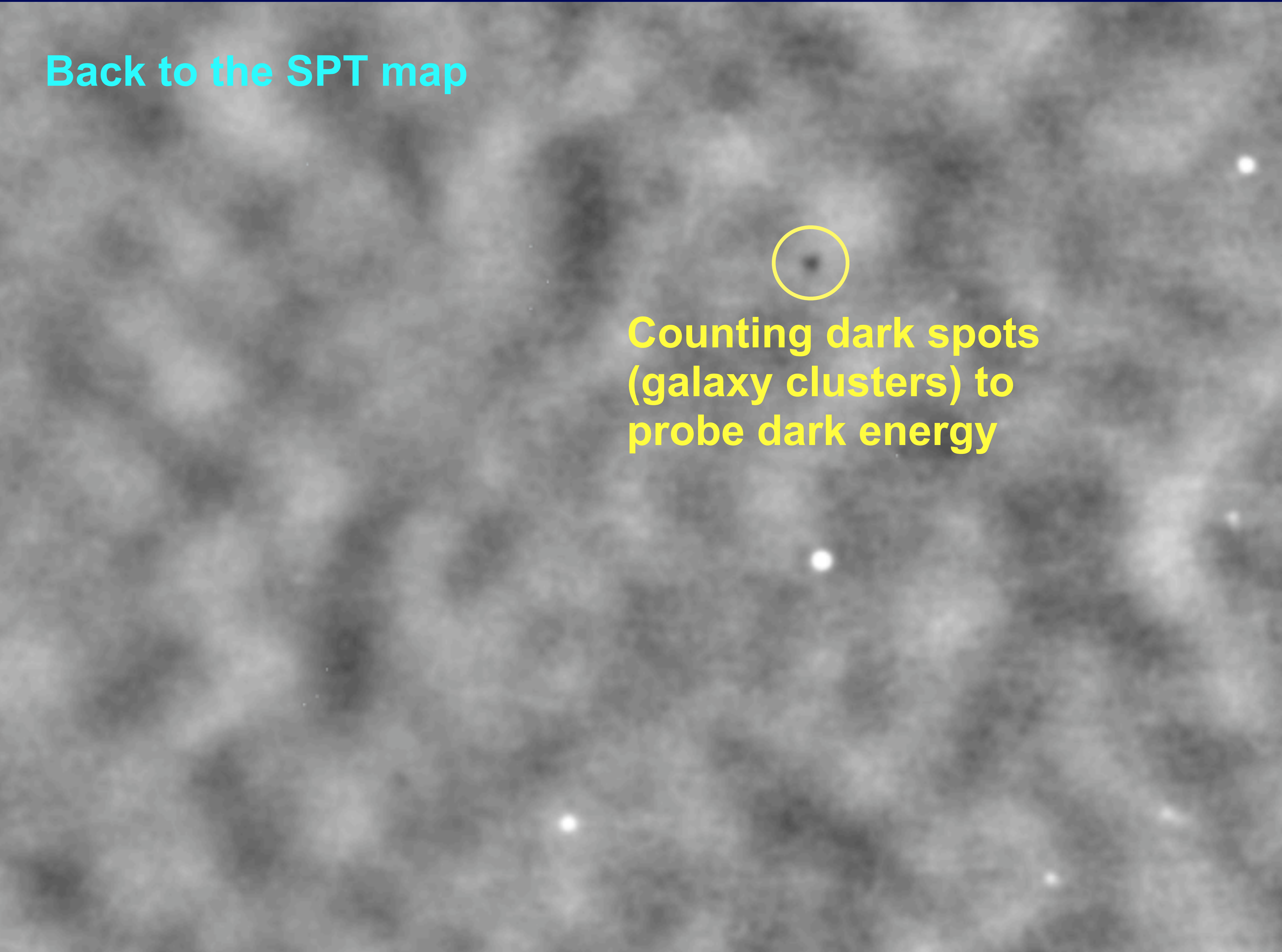
N_{eff} $\sum m_\upsilon$ (eV) σ_8

Take Away #1

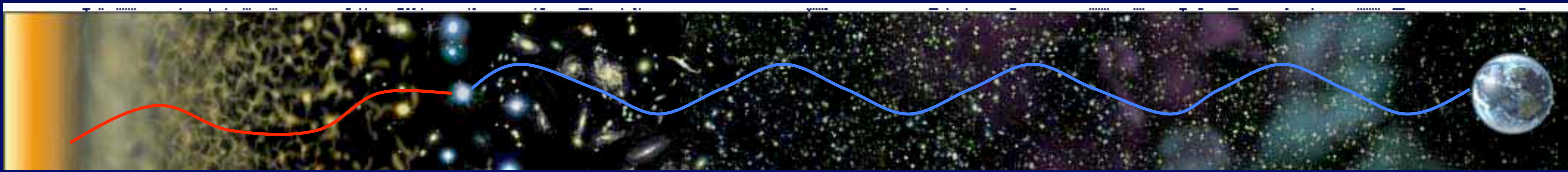
- SPT has mapped out the CMB damping tail, in order to detect gravitational lensing, and measure the number of relativistic species (among other things).

Read more in astro-ph/1105.3182

Back to the SPT map



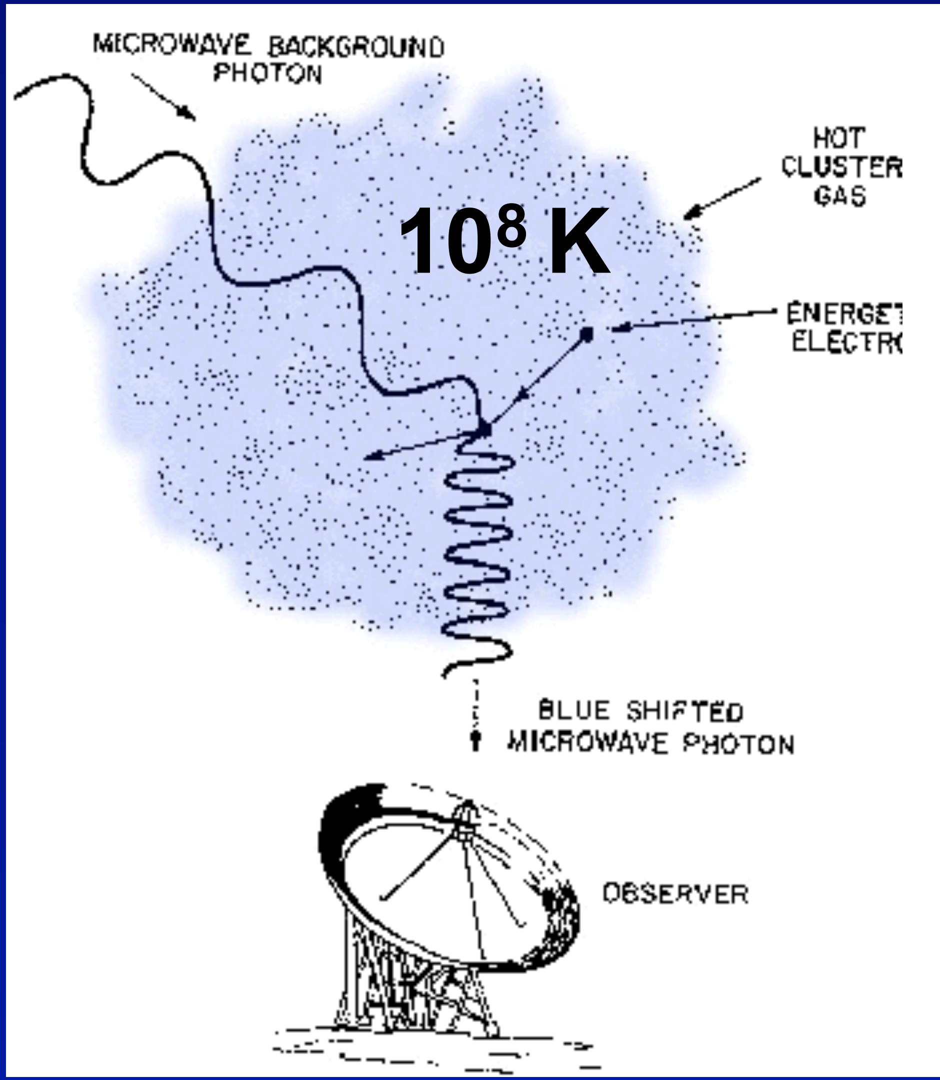
Structure as viewed by the CMB

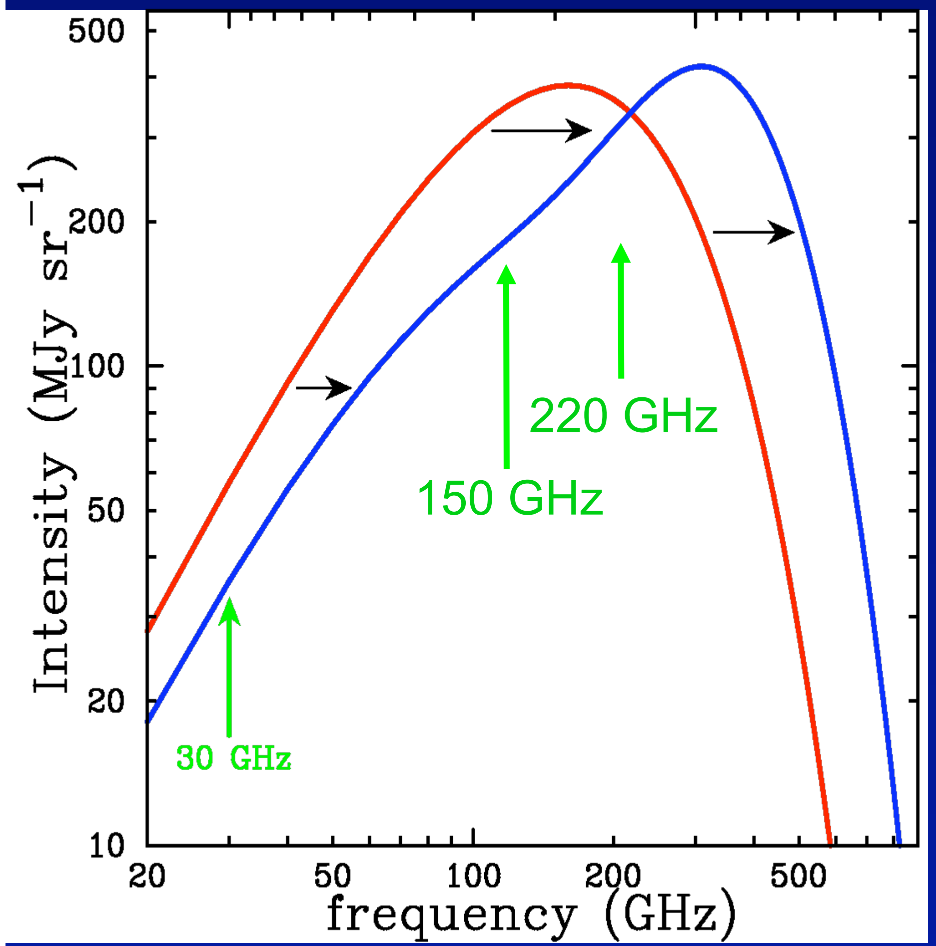


Sunyaev-Zel'dovich Effect:

CMB photons provide a backlight for structure in the universe.

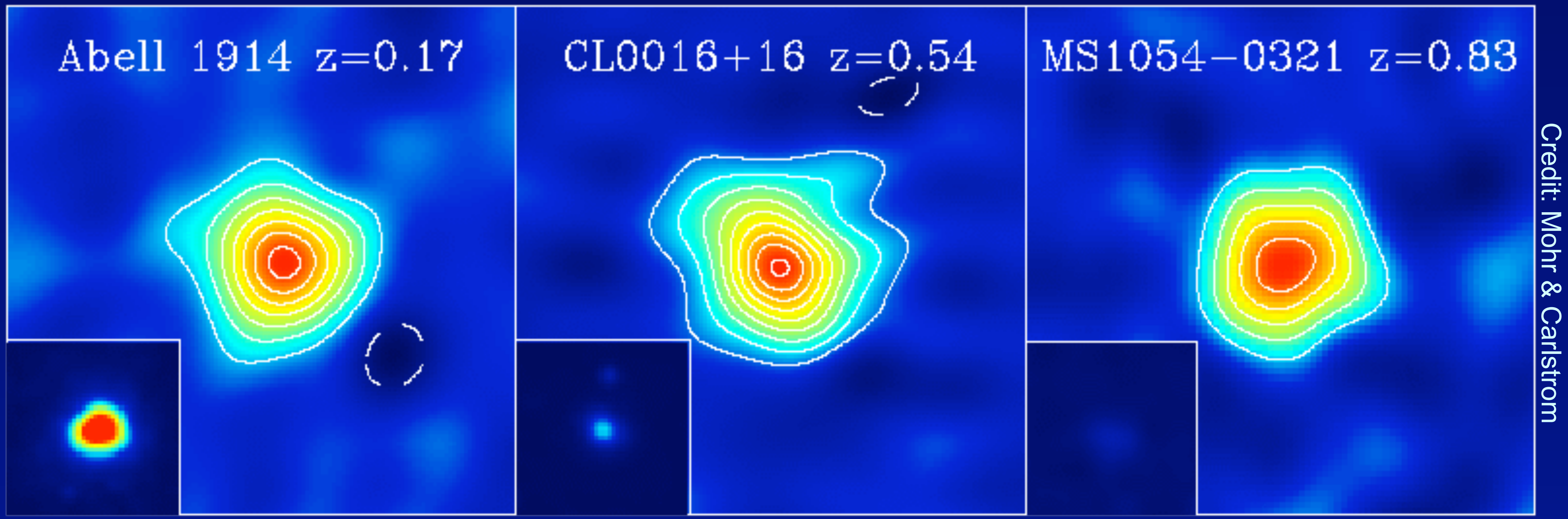
- **Thermal**: 1-2% of CMB photons traversing galaxy clusters are inverse Compton scattered to higher energy
- **Kinetic**: Doppler shift from motion of cluster





SZE Surveys

Use SZE as a Probe of Structure Formation
and to provide nearly unbiased cluster sample



Same range of X-ray surface brightness and SZ decrement in all three insets.

$$\text{SZE Flux}: \; S \propto \frac{1}{d_A(z)^2} \int n_e T_e \, dV$$

- Surface brightness independent of redshift
- Total flux proportional to the total thermal energy of cluster (expected to be good mass proxy)

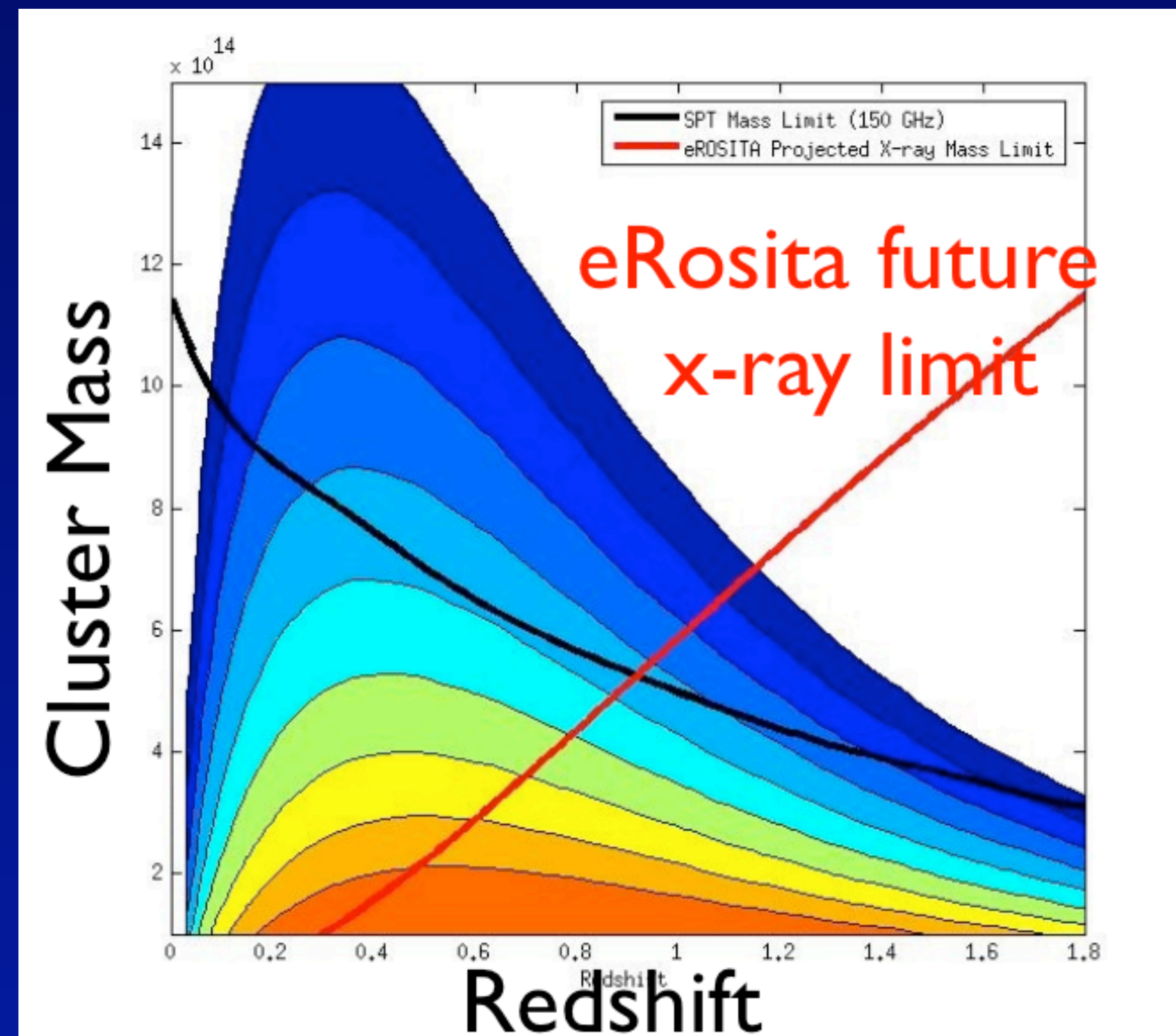
Cosmology with Galaxy clusters

Cluster Abundance, dN/dz

$$\frac{dN}{d\Omega dz} = n(z)\frac{dV}{d\Omega dz}$$

Growth

Volume



Cluster dN/dZ with Mass > M

Chris Greer

Cosmology with Galaxy clusters

Cluster Abundance, dN/dz

$$\frac{dN}{d\Omega dz} = n(z)\frac{dV}{d\Omega dz}$$

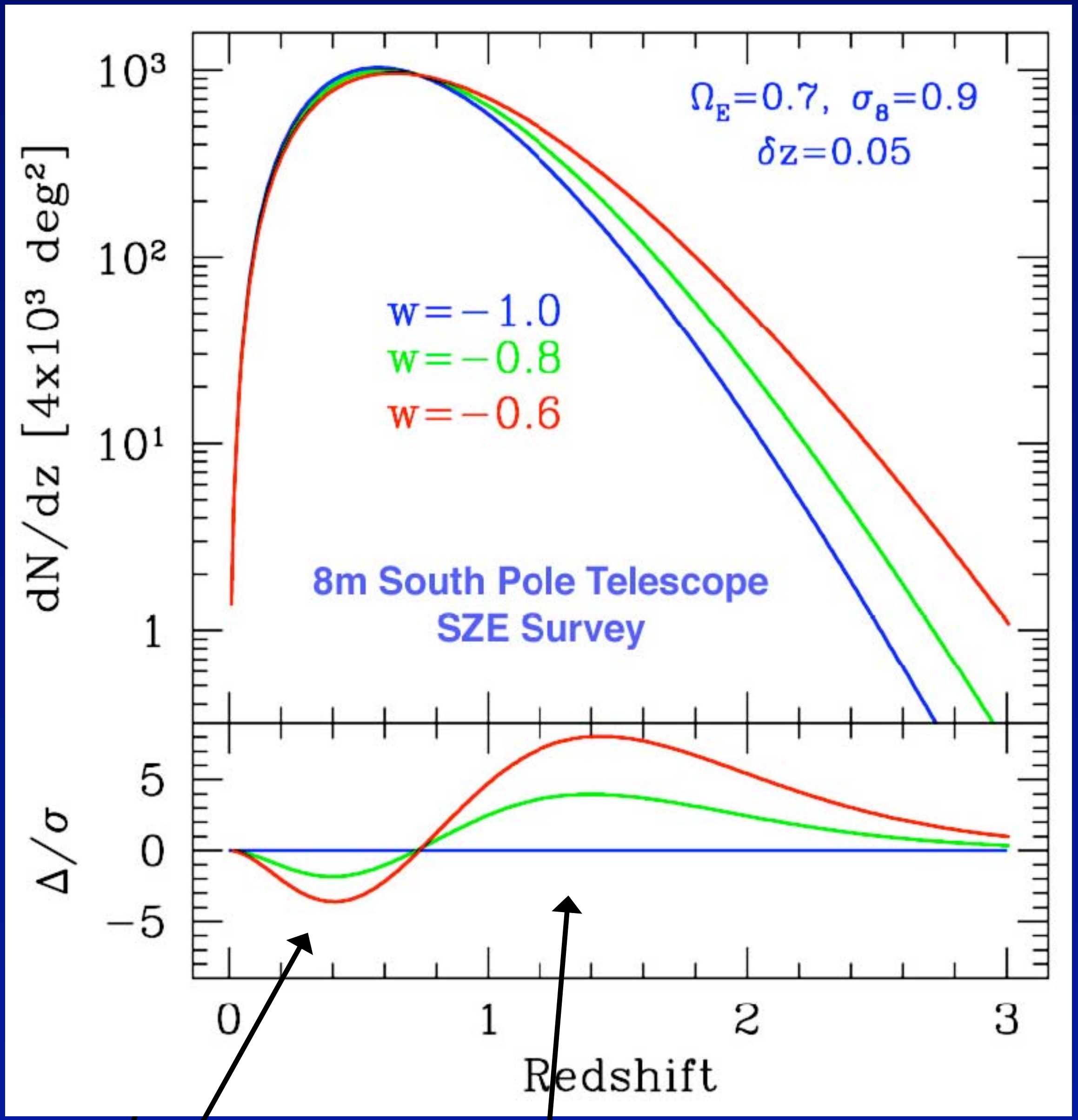
Growth

Depends on:
Matter Power Spectrum, *P(k)*
Growth Rate of Structure, *D(z)*

Volume

Depends on:
Rate of Expansion, *H(z)*

$\rho(z) = \rho_0(1+z)^{3(1+w)}$
where w = ρ/p is eqn. of state

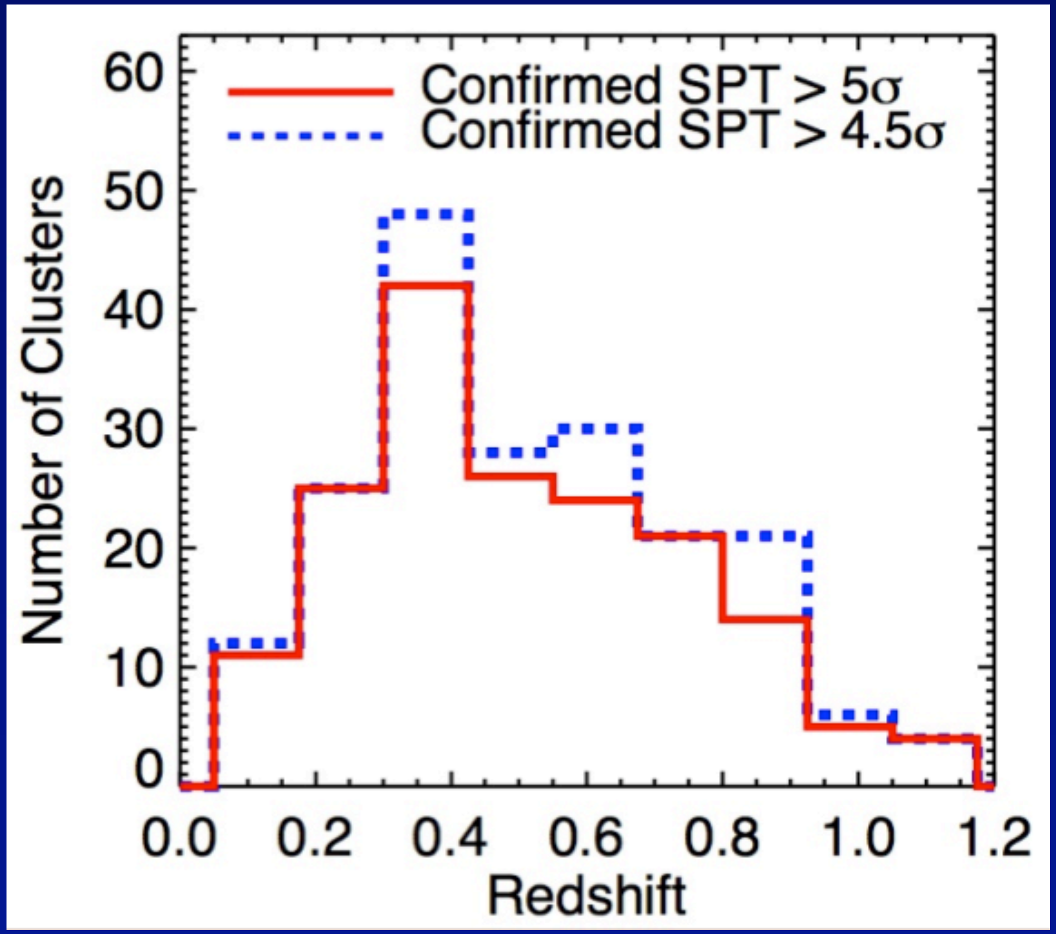


Volume Effect **Growth Effect**

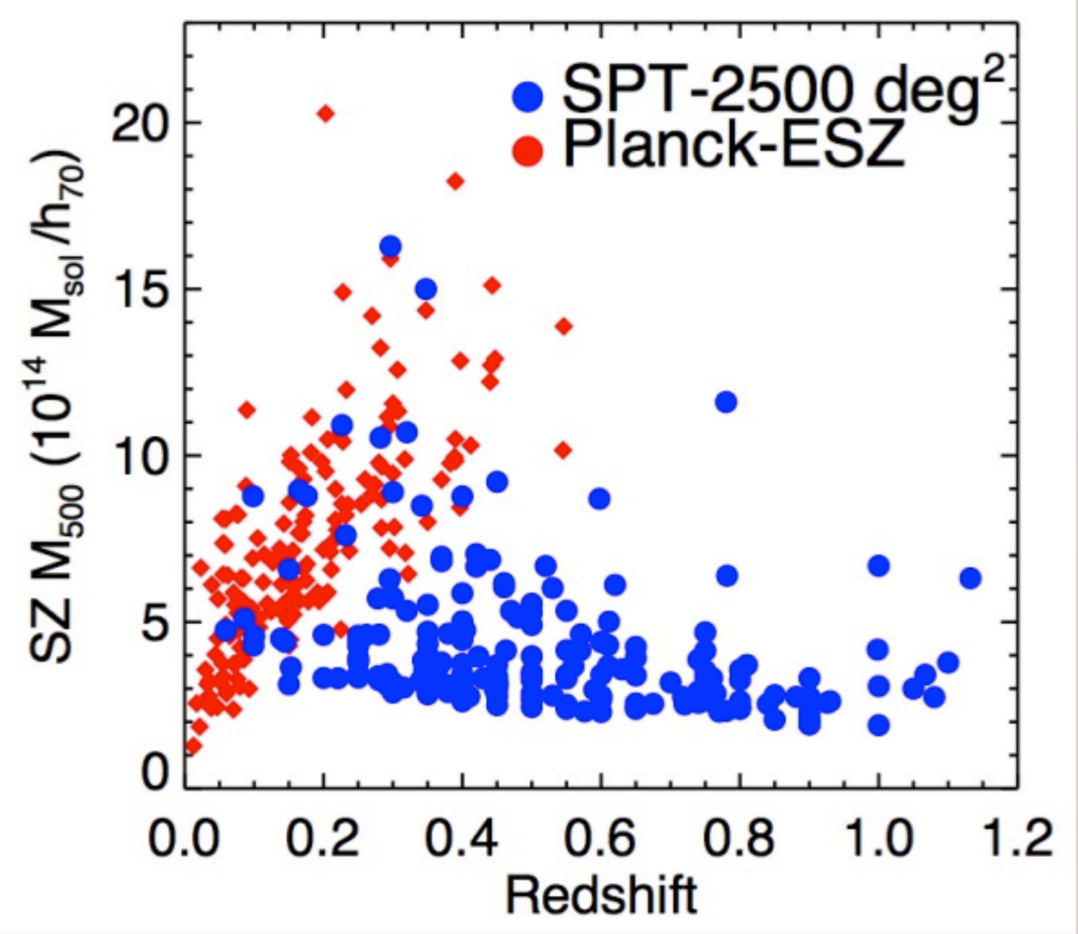
Credit: Joe Mohr

SPT cluster sample

Redshifts



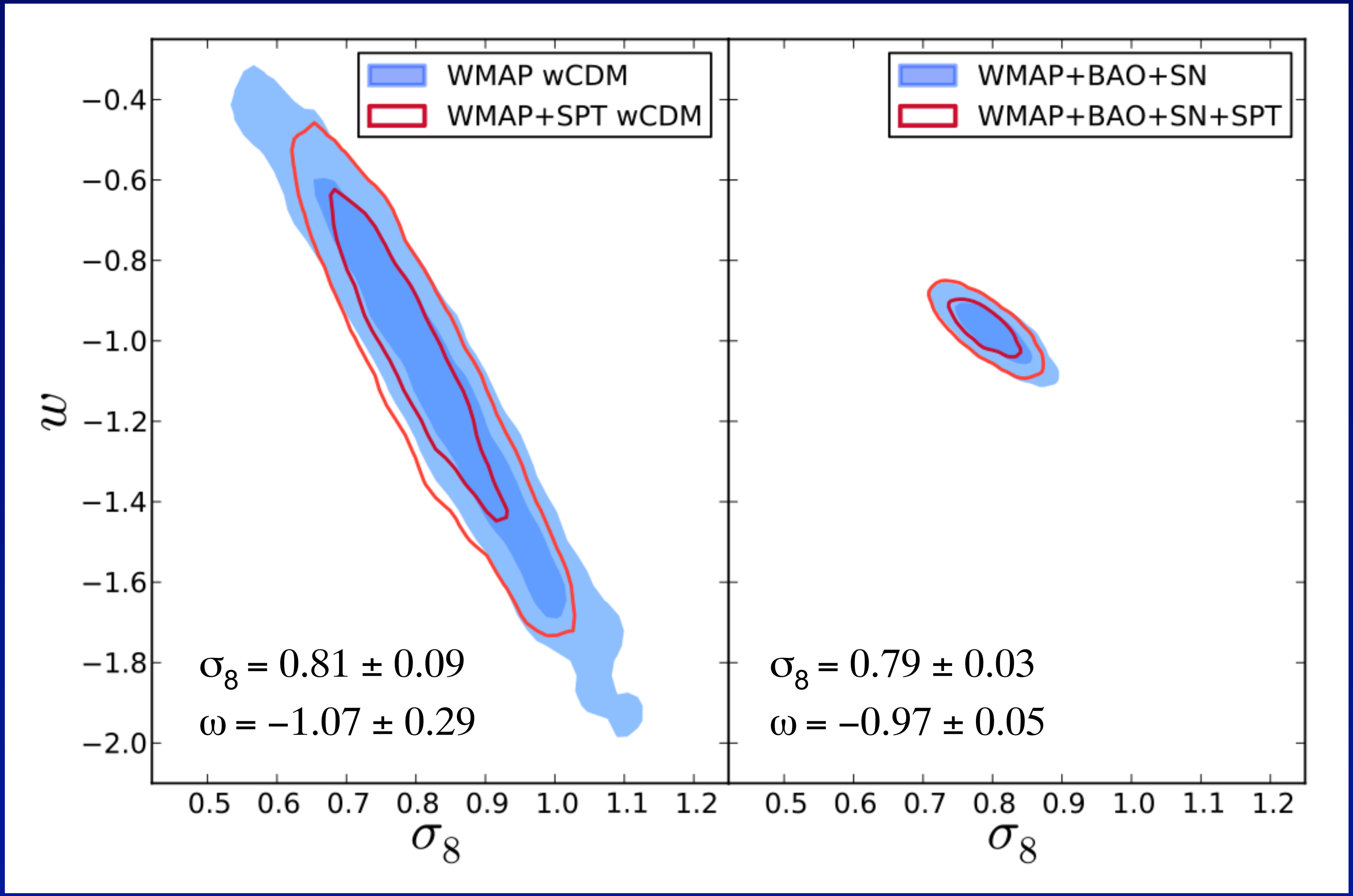
Mass vs. Redshift



- Over 300 optically confirmed candidates
  - ~80% new discoveries
  - Confirmed 95% purity at >5 sigma
- High redshift, <z> ~0.5 - 0.6
- $M_{500}(z=0.6)$ = > 3e14 $M_{\odot}$ / h_{70} (lower at higher z)

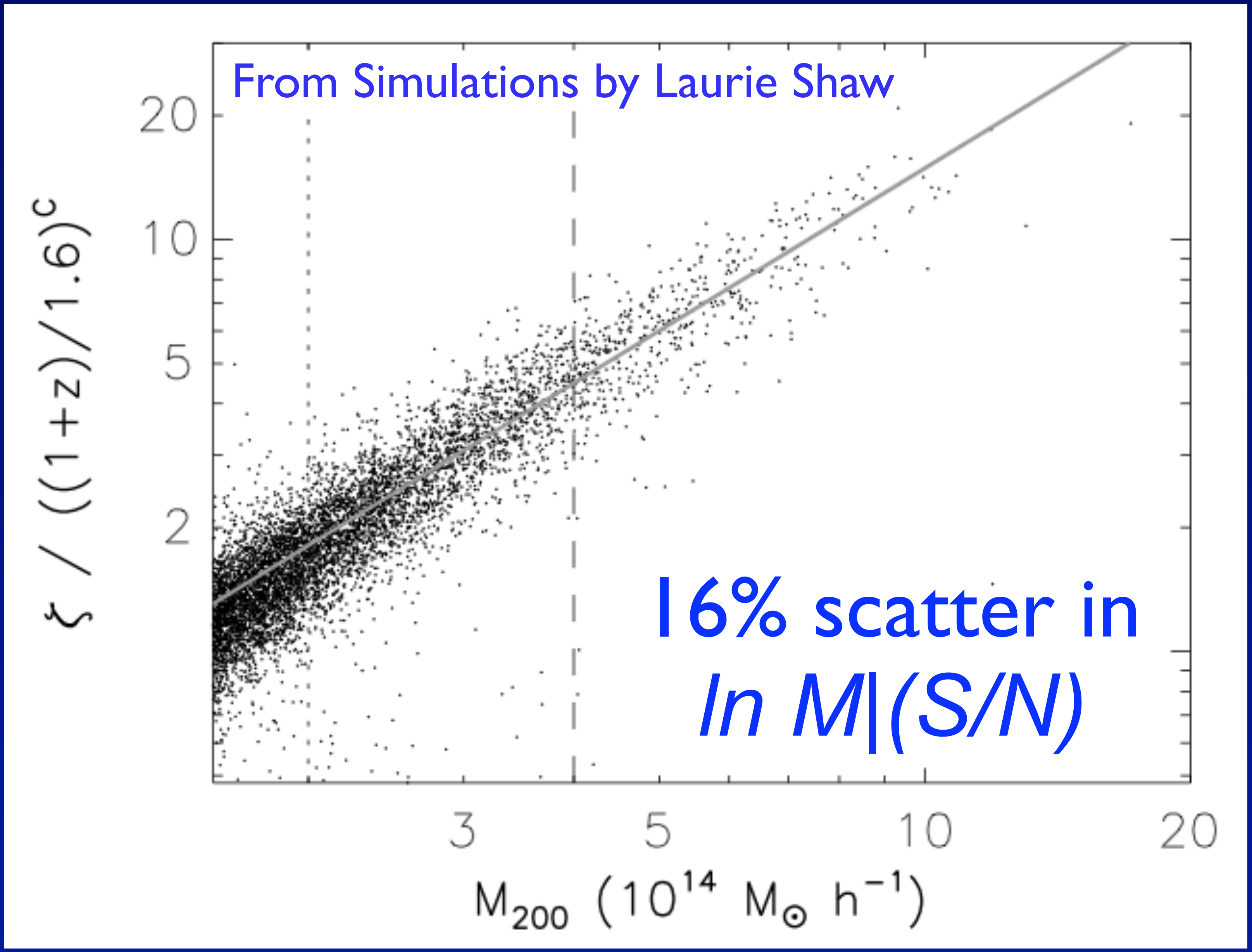
Early results from SPT

Vanderlinde+, 2010



- Only 21 clusters!
- Constraints limited by mass calibration (but early days)

SPT significance as a Mass Proxy



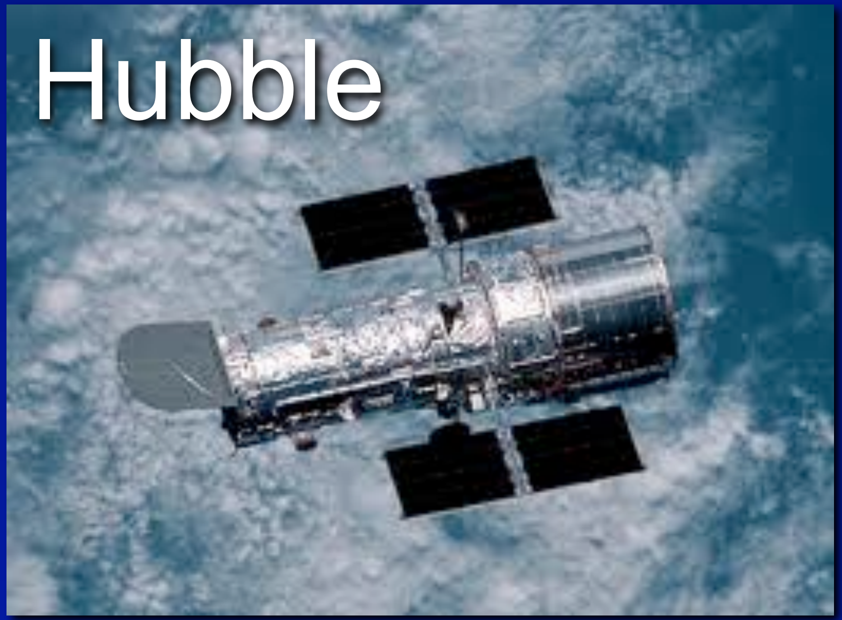
- Y_{sz} should have low (~7%) scatter with mass (Kravstov, Vikhlinin, Nagai 2006)
- However, poor constraints on cluster amplitude and angular size with low significance detections
- Signal-to-noise in spatial filtered map is mass proxy (Vanderlinde et al 2010)
- Use simulation based priors on this scaling relation (~25% one-sigma prior on mass calibration)

Multi-wavelength Observations: Mass Calibration

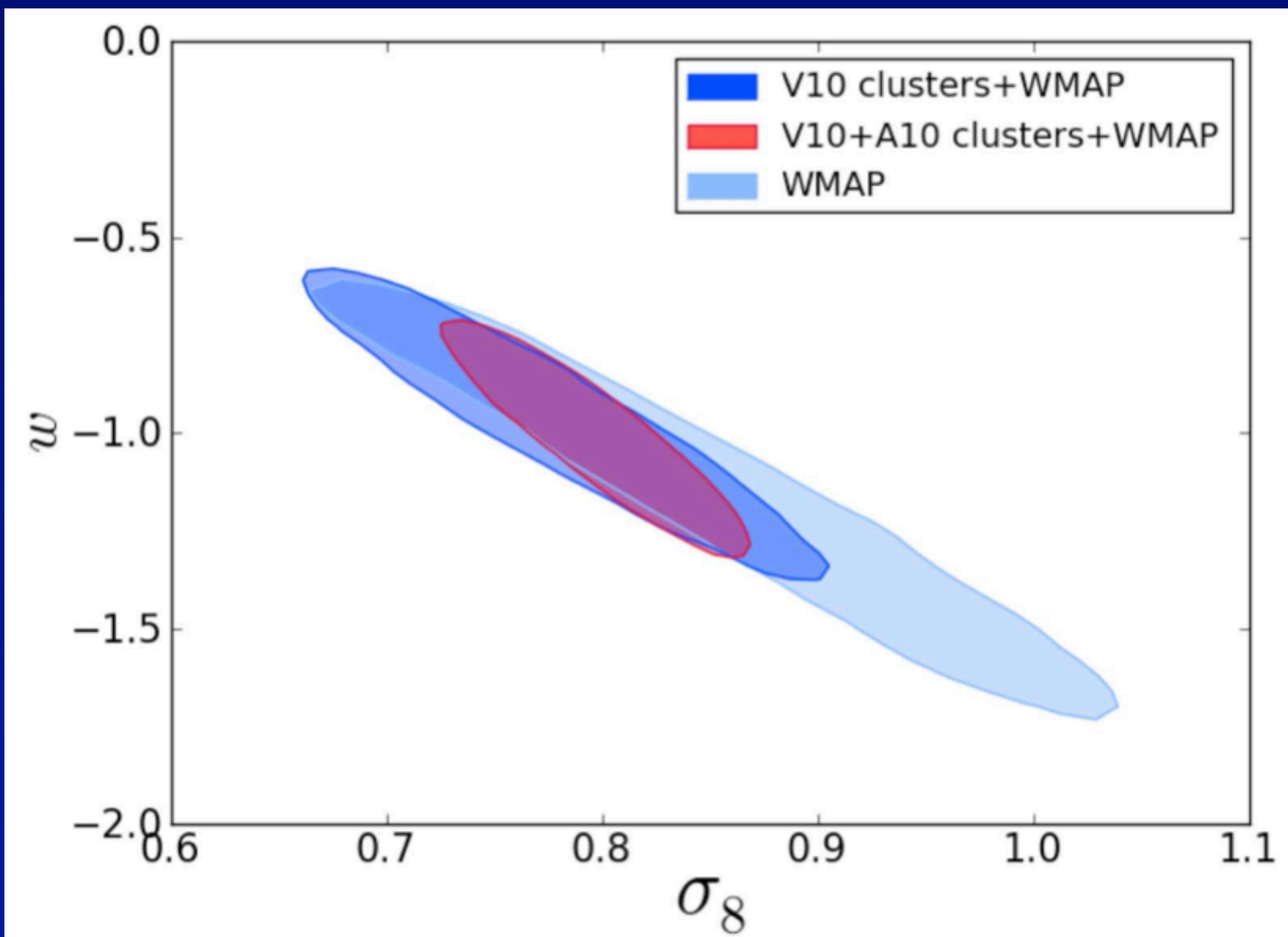
SZ-mass scaling relation needs precise and unbiased mass calibration ***AT ALL REDSHIFTS***.

Multi-wavelength mass calibration campaign, including:

- X-ray with Chandra and XMM (PI: Benson, Andersson, Vikhlinin)
- Weak lensing from Magellan (0.3 < z < 0.6) and HST (z > 0.6) (PI: Stubbs, High, Hoekstra)
- Dynamical masses from NOAO 3-year survey on Gemini (0.3<z< 0.8); VLT at z > 0.8

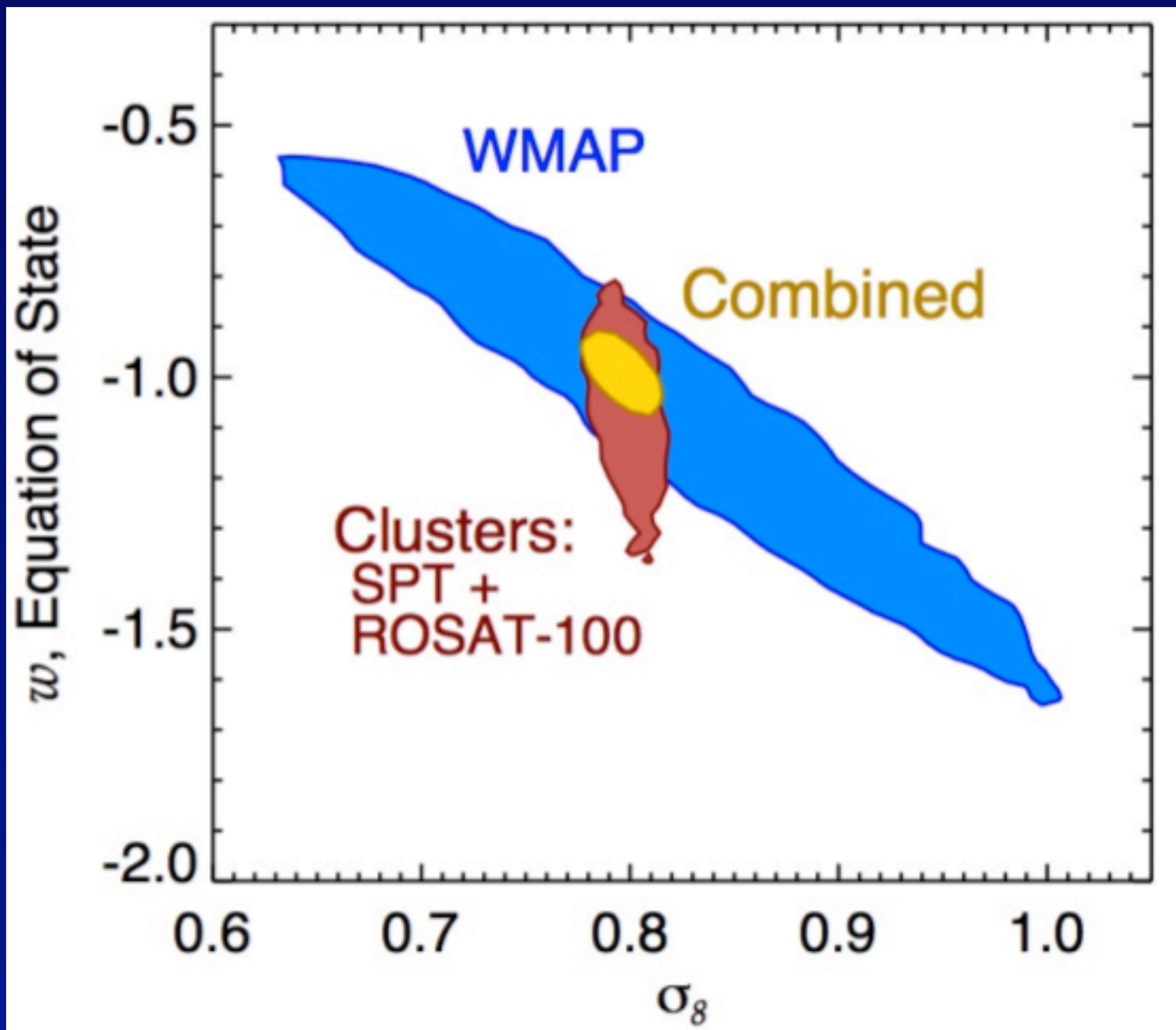


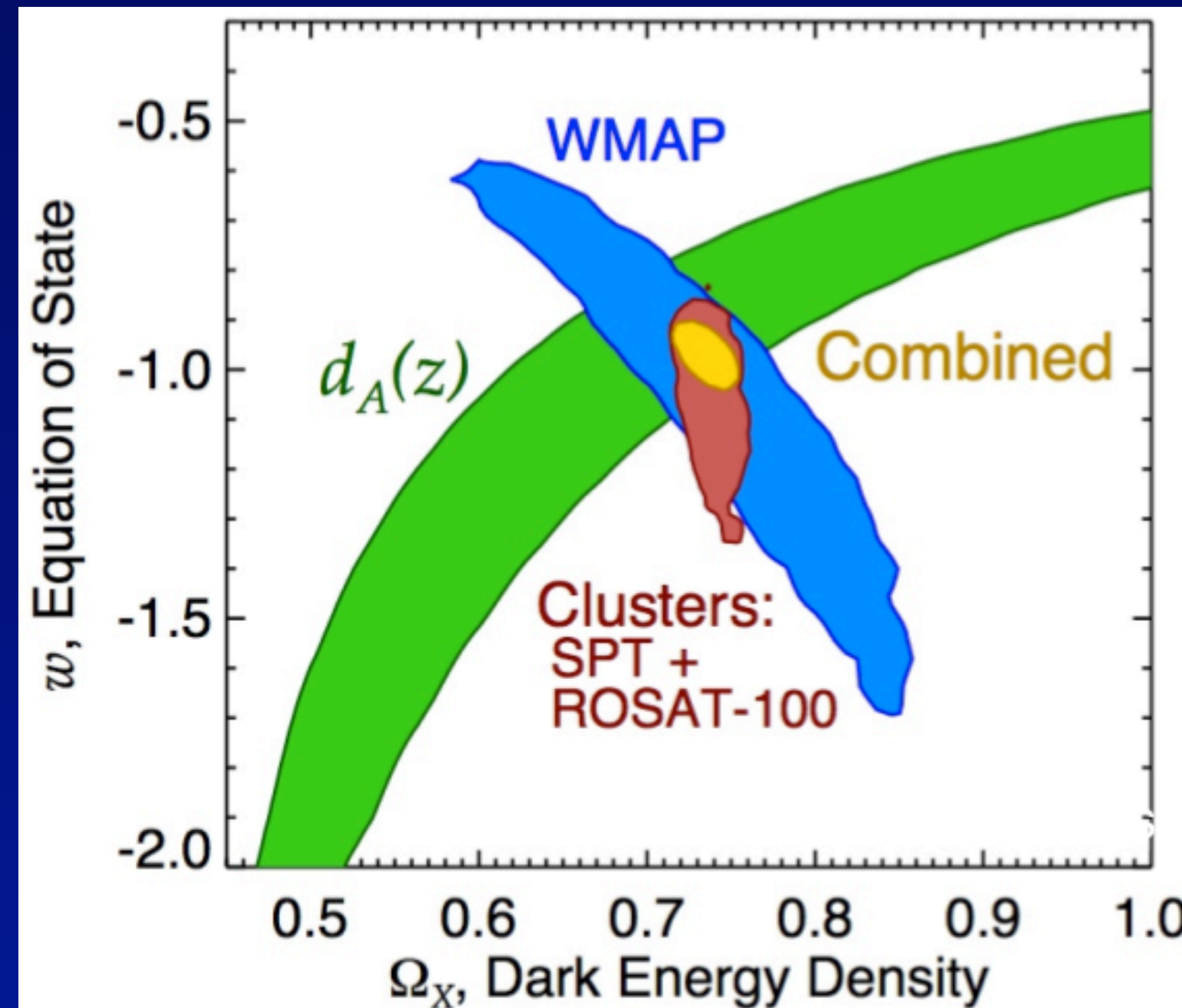
SPT Cosmological Constraints with X-ray



- Developing full cosmological MCMC to jointly fit cosmology, *Yx-M*, *ξ-M* relations, using priors from Vikhlinin et al (2009)
- X-ray measurements reduce mass uncertainty from 25% to 10%
- Improves 21 cluster cosmological constraints on σ_8 by ~50% and *w* by ~30%

Future constraints with SPT+Xray





SPT 2500 deg^2 survey with ~450 clusters at 5 sigma
X-ray based mass calibration with 5% mean from 80 clusters - Chandra XVP

Constrain σ_8 to 1.2%; w to 4.6%

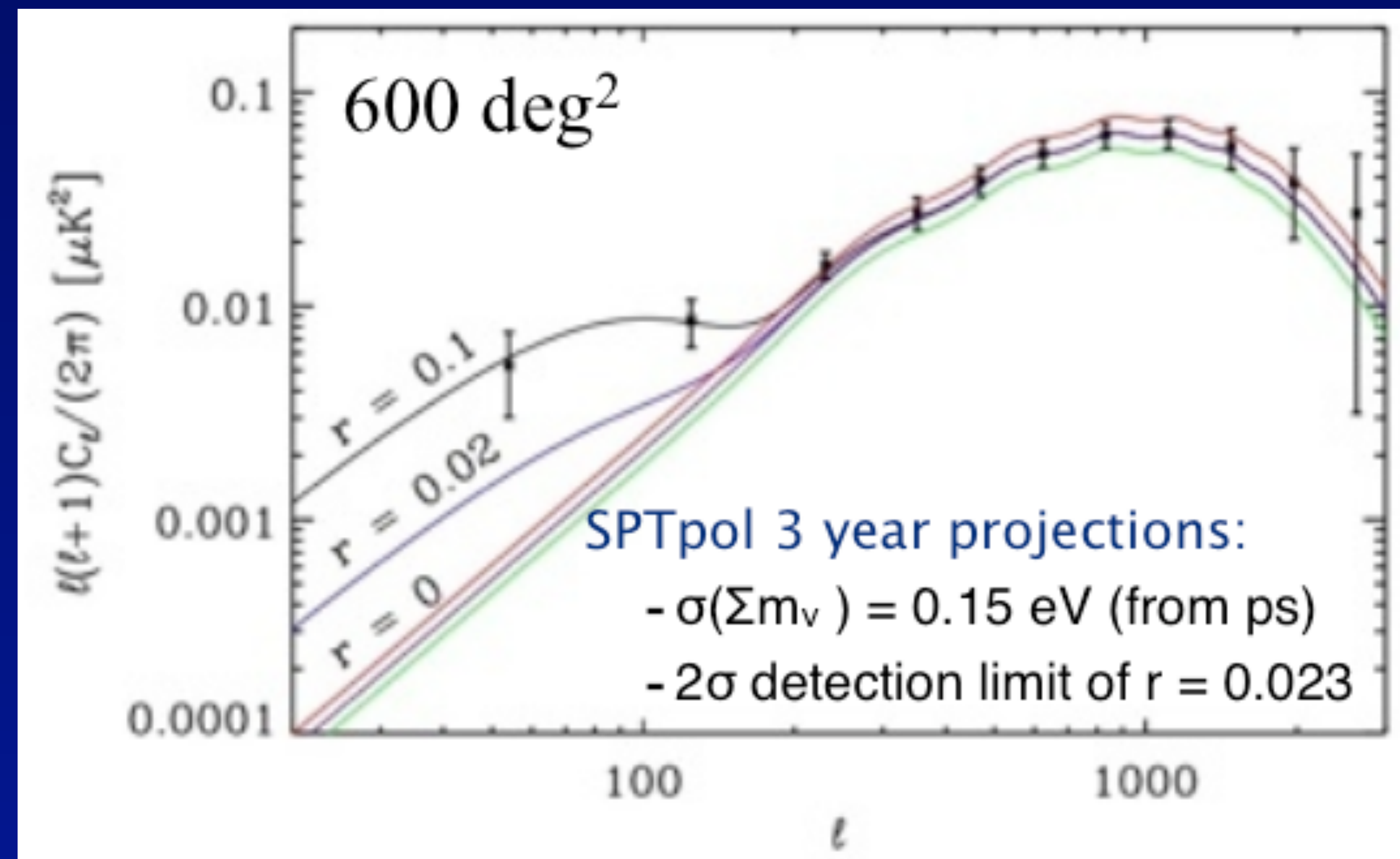
Independent of geometric constraints (SN/BAO)
Note: 3.3% systematic uncertainty in w due to mass calibration

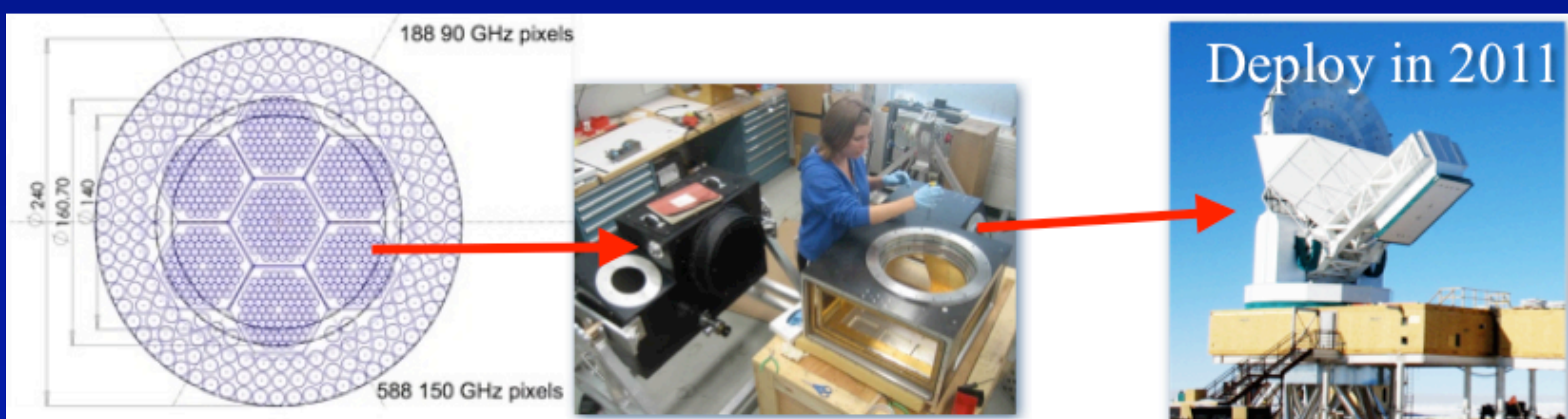
Take Away #2

- SPT has discovered hundreds of real, massive clusters. Observations underway will accurately determine the mass calibration at all redshifts, enabling strong constraints on dark energy.

SPTPol: CMB polarization

- Building 760 pixel polarimeter for SPT
- Scheduled to deploy this winter
- 3x mapping speed of current receiver





Abby Crites (U. Chicago)


Snow sculpture at the South Pole

The End