

Title: Signatures of Cosmic Structure Formation in the Microwave Background

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URL: <http://pirsa.org/11030069>

Abstract: On small scales the cosmic microwave background (CMB) is perturbed by large scale structure in the universe, primarily through Compton scattering and gravitational lensing. The current generation of CMB experiments is measuring these signals, allowing new measurements of the build-up of cosmic structure. I will discuss two such measurements being made with the South Pole Telescope: 1) through Compton scattering (the Sunyaev-Zeldovich effect) we have compiled a large catalog of very massive galaxy clusters extending to  $z > 1$ , allowing a measure of the growth of structure from  $z=1$  to today; 2) we are currently measuring the gravitational lensing of the CMB, providing an accurate measure of the integrated structure between  $z=0$  and  $z=1100$ .

Both of these are powerful new tests of our cosmological understanding.

# Outline

- Background:
  - Life of a cosmic microwave background photon
  - Structure formation in the universe
- the South Pole Telescope:
  - Massive clusters of galaxies out to  $z > 1$ 
    - many shockingly massive clusters at  $z \sim 1$
    - turns out “shocking” is subjective (LCDM is fine)
  - Gravitational lensing of the CMB
    - mapping the matter distribution at  $z \sim 2-3$
    - power spectrum measurements allowing first probes of large scale structure at these redshifts

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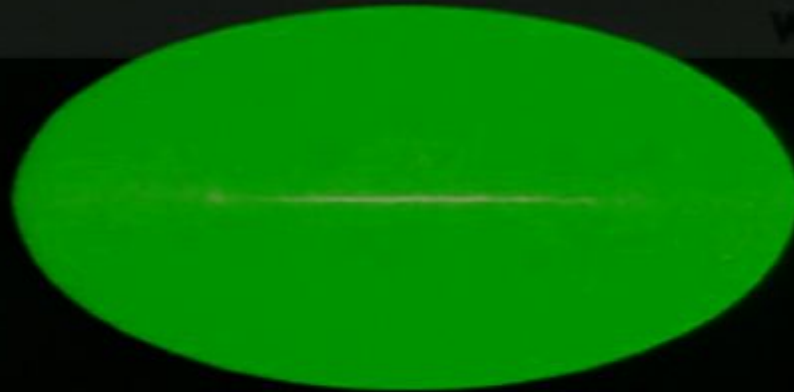
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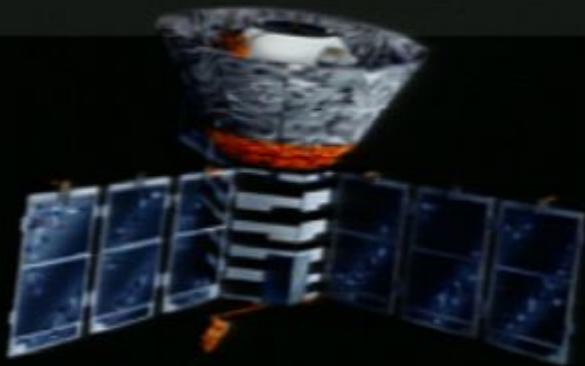
1965



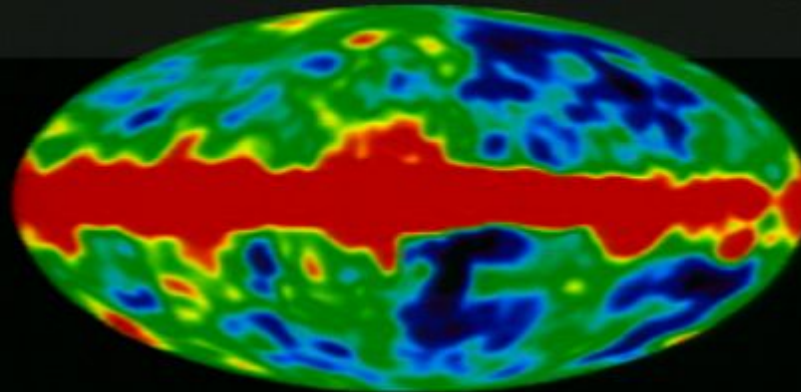
Penzias and Wilson



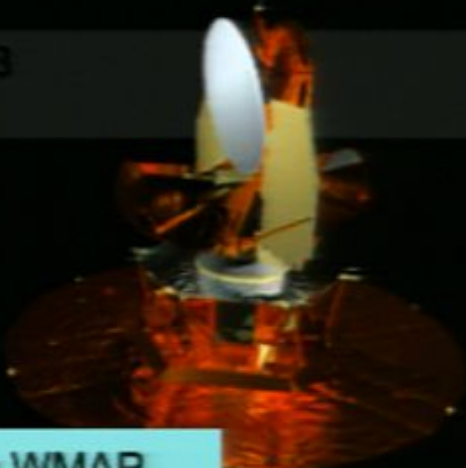
1992



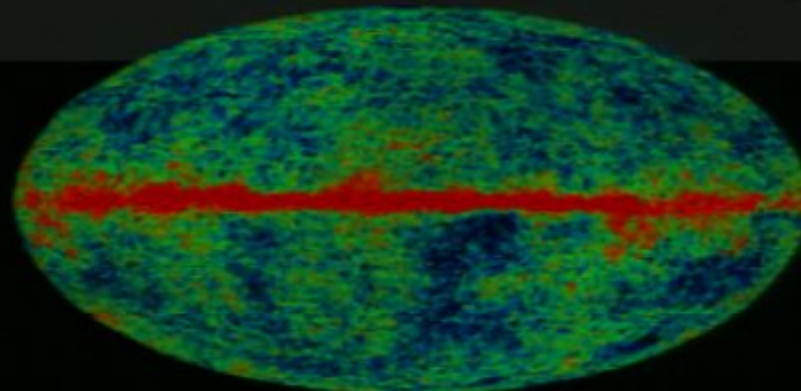
COBE



2003

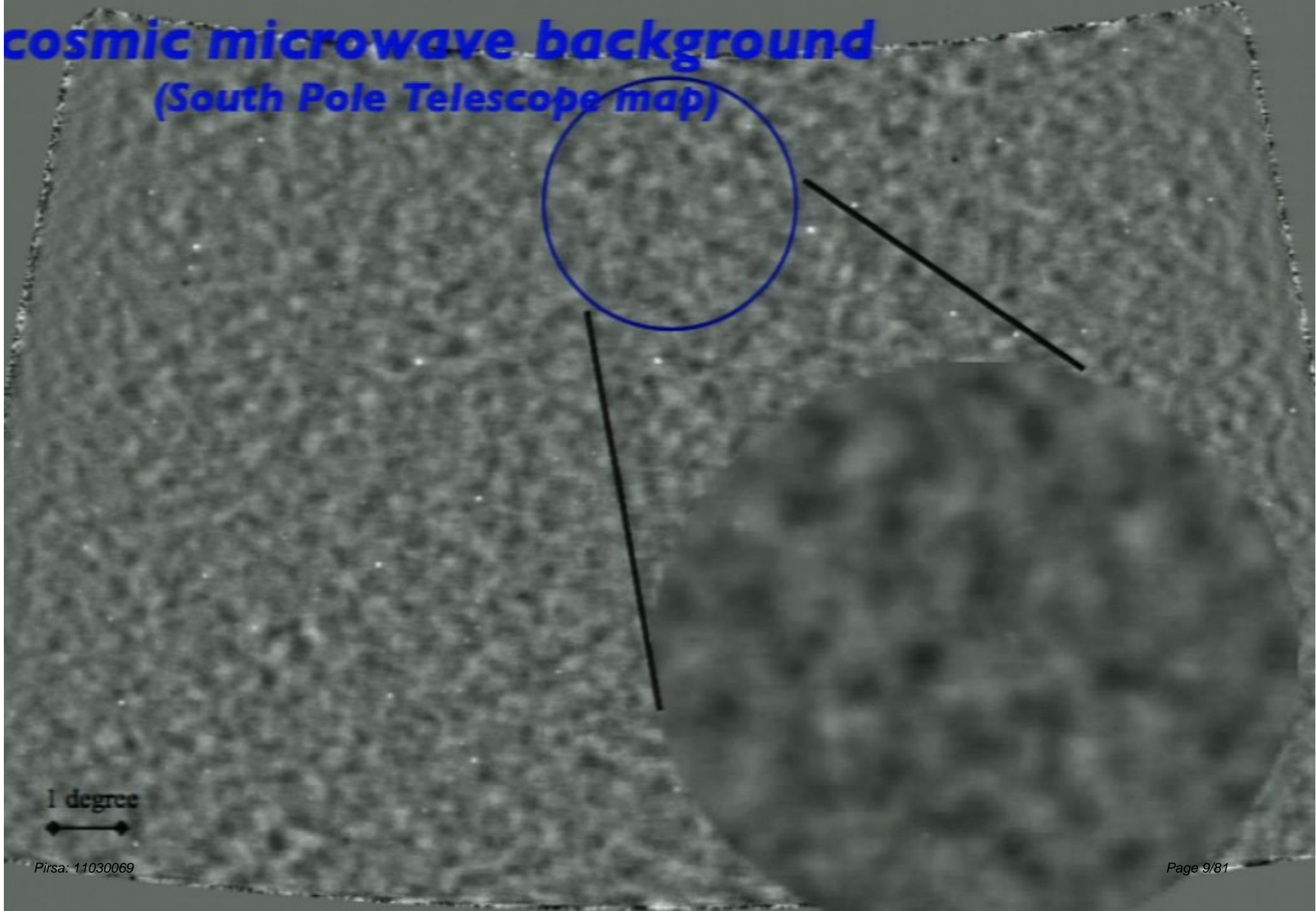


WMAP

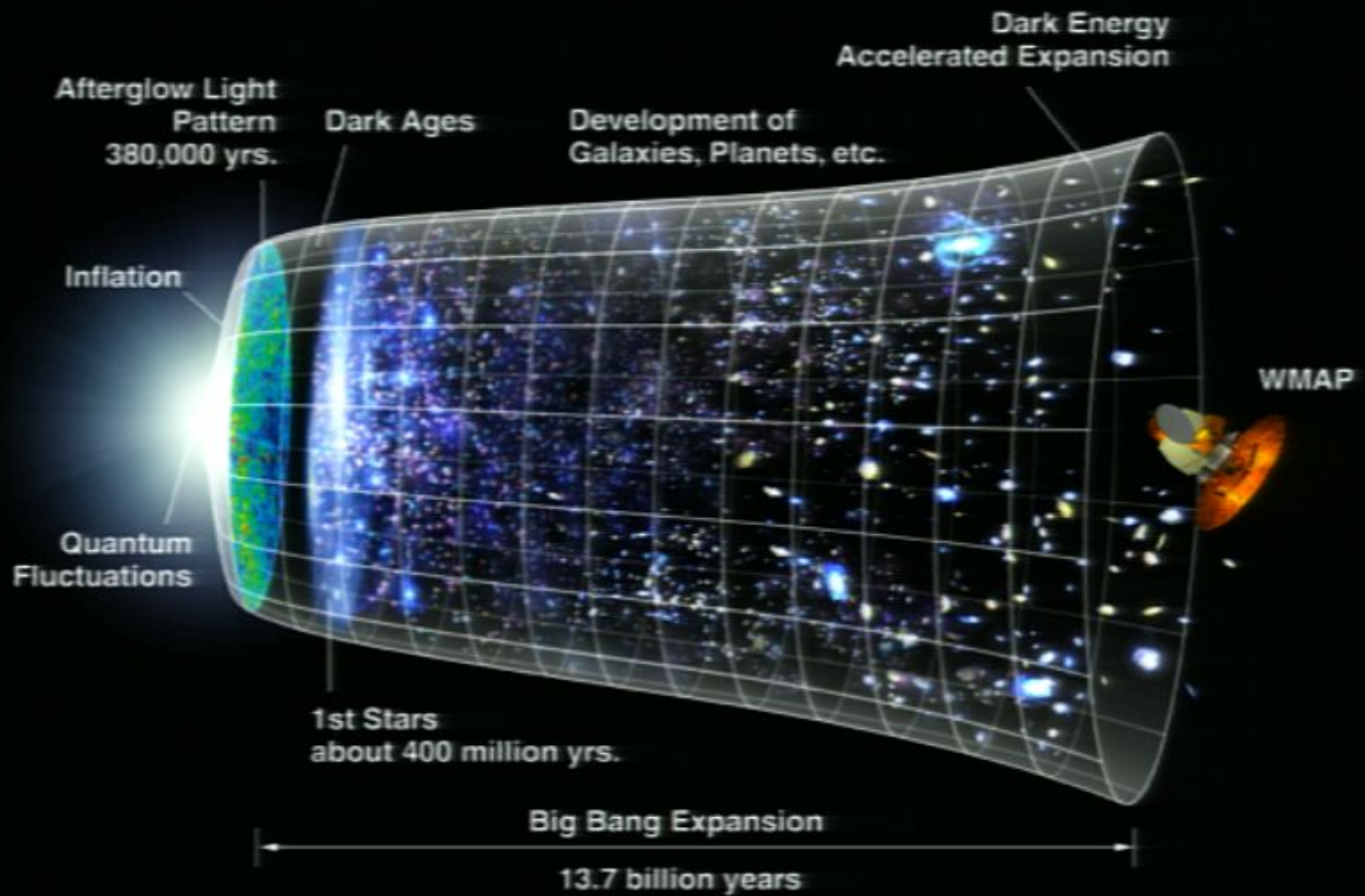


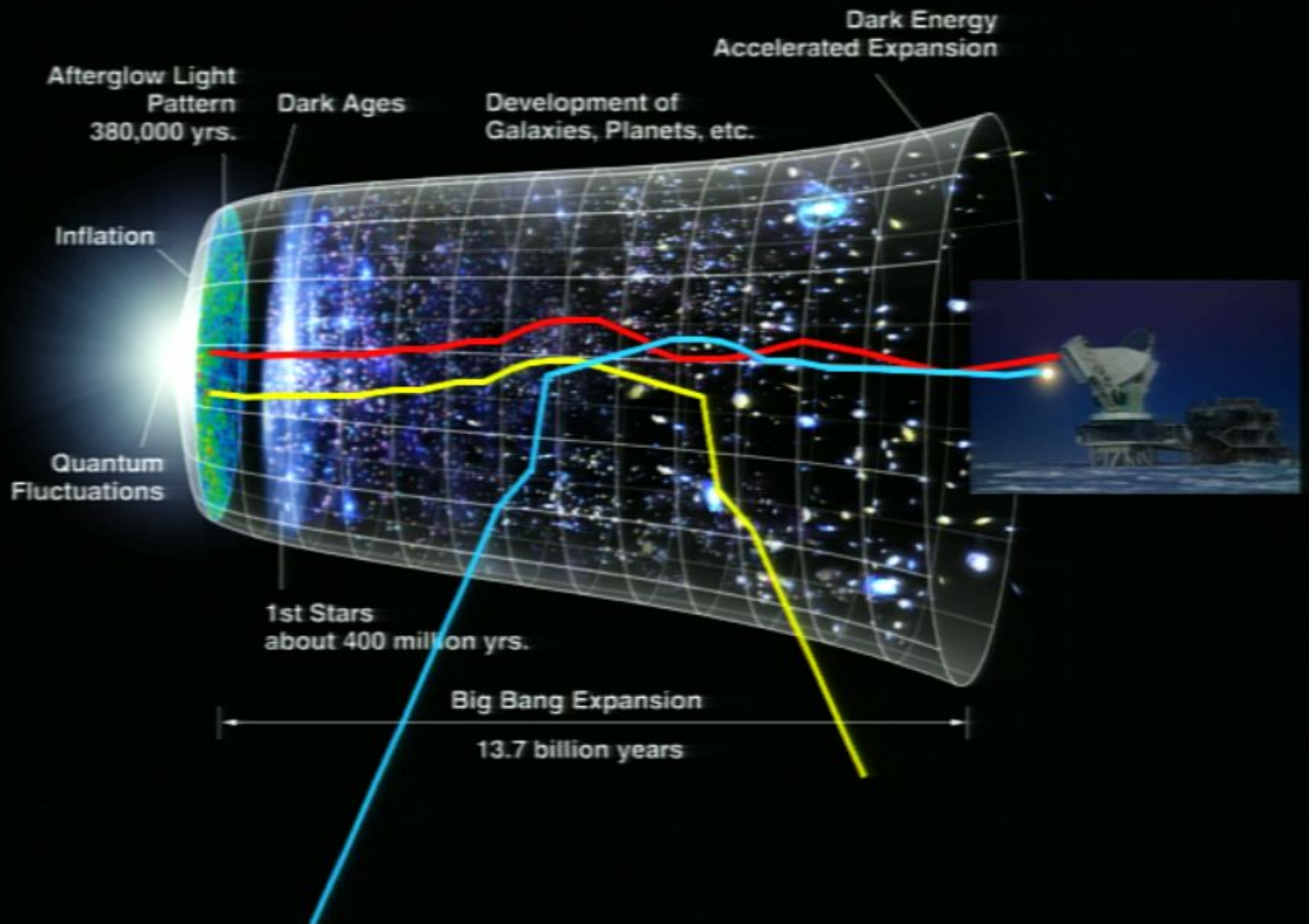


# cosmic microwave background (South Pole Telescope map)



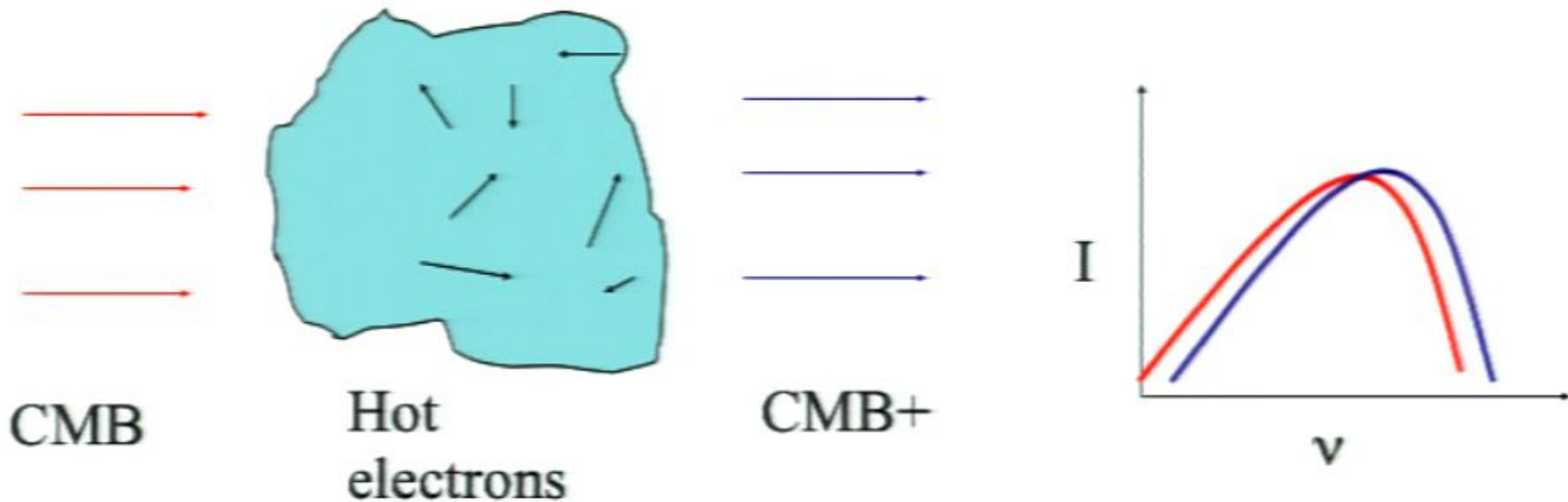
1 degree  
↔







# Thermal Sunyaev-Zel'dovich Effect



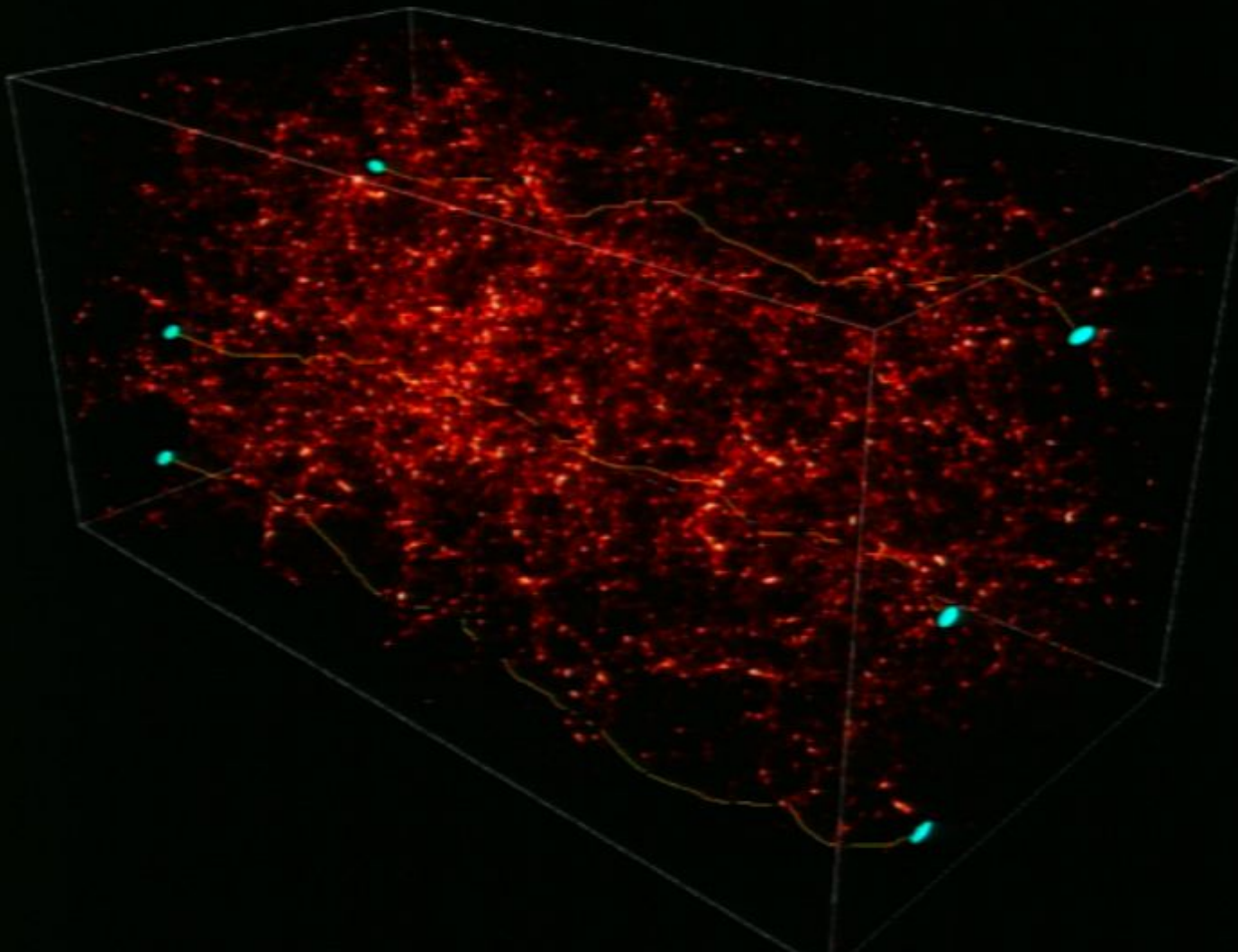
Optical depth:  $\tau \sim 0.01$

Fractional energy gain per scatter:  $\frac{kT}{m_e c^2} \sim 0.01$

*Typical cluster signal:  $\sim 500 \mu\text{K}$*

# Gravitational deflection

DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES



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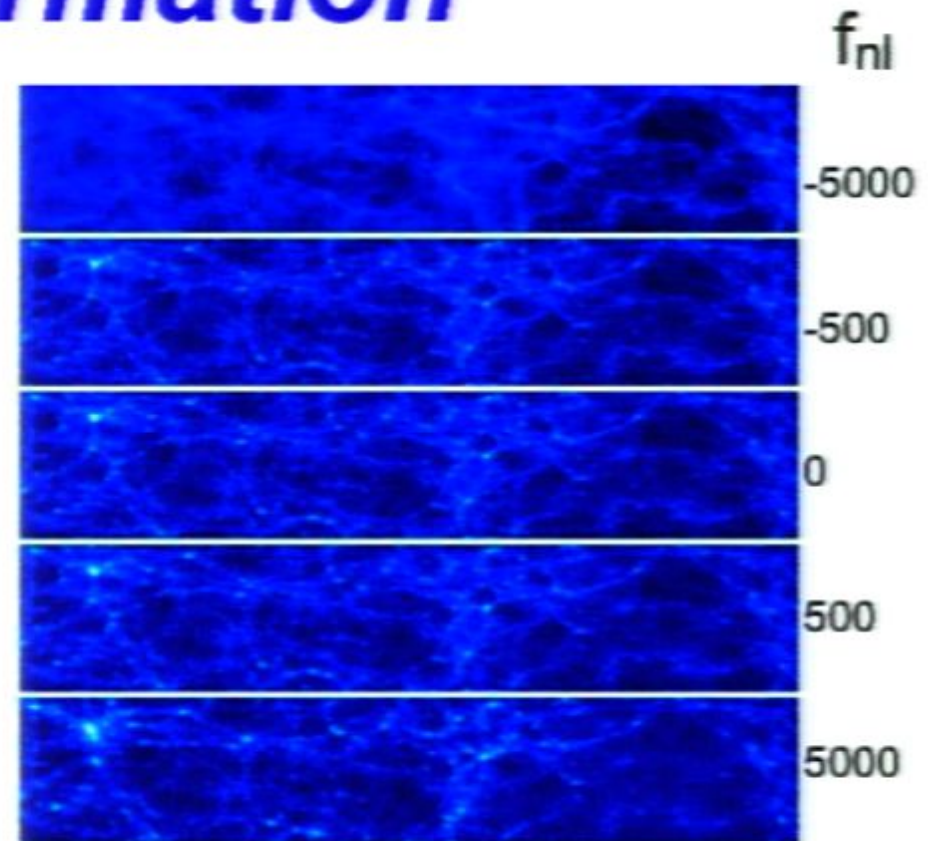
# ***Open questions in cosmology***

- how Gaussian are the density fluctuations?
- how much do neutrinos weigh?
- what is dark energy?
- is GR right?



# *Non-Gaussianity and structure formation*

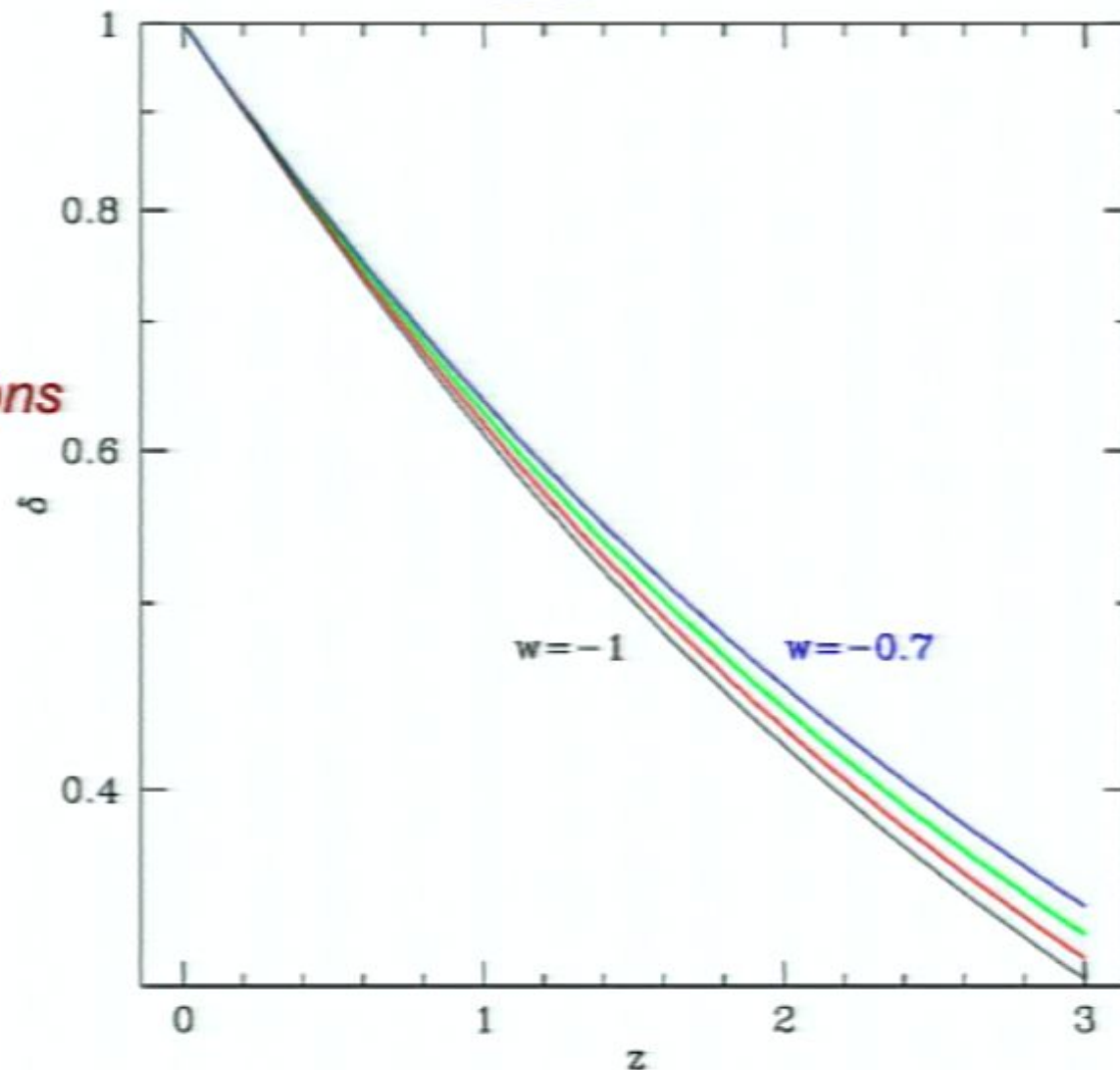
- large non-Gaussianity in initial conditions visible in large scale structure
- CMB (e.g., WMAP) probes larger scales than most large scale structure studies



Dalal et al 2008

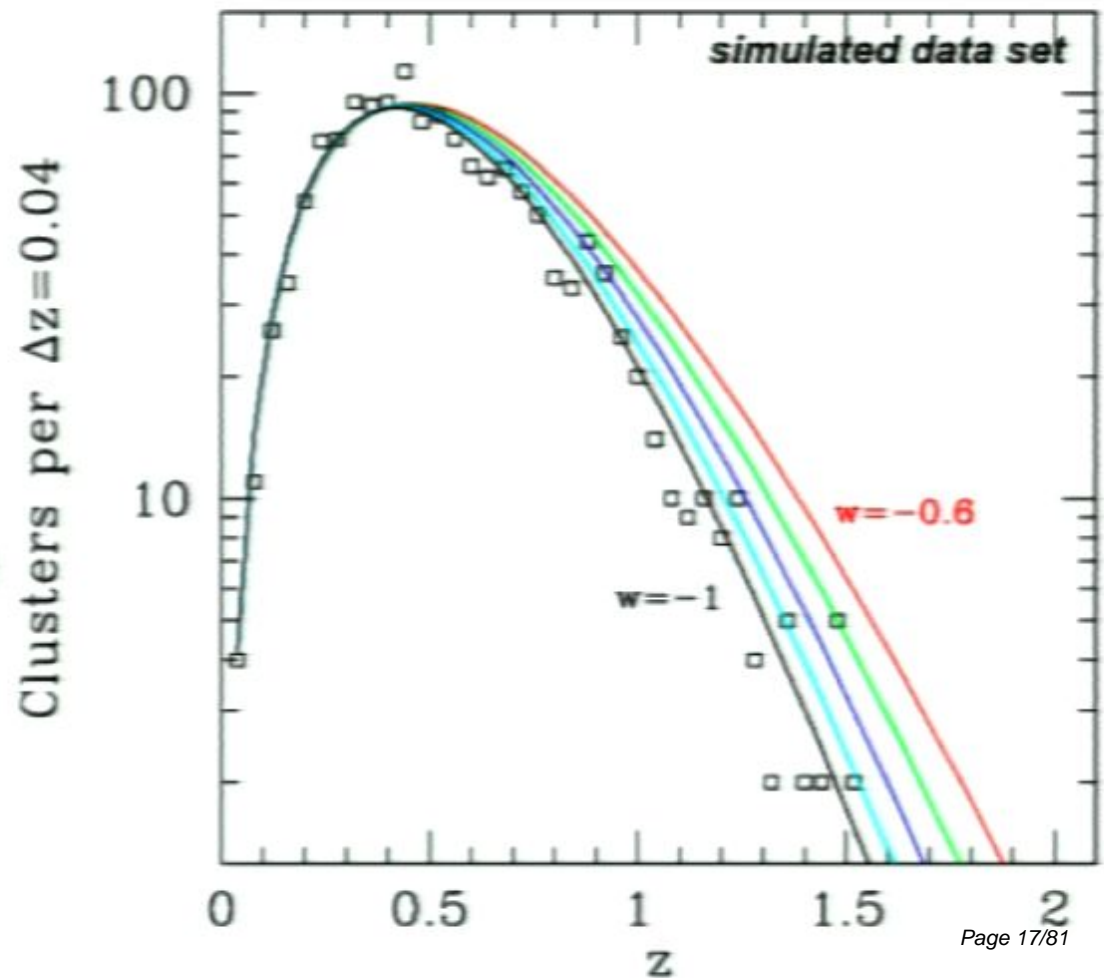
# Growth as a function of dark energy

*Amplitude of density fluctuations in linear theory*



# Dark Energy with Cluster Surveys

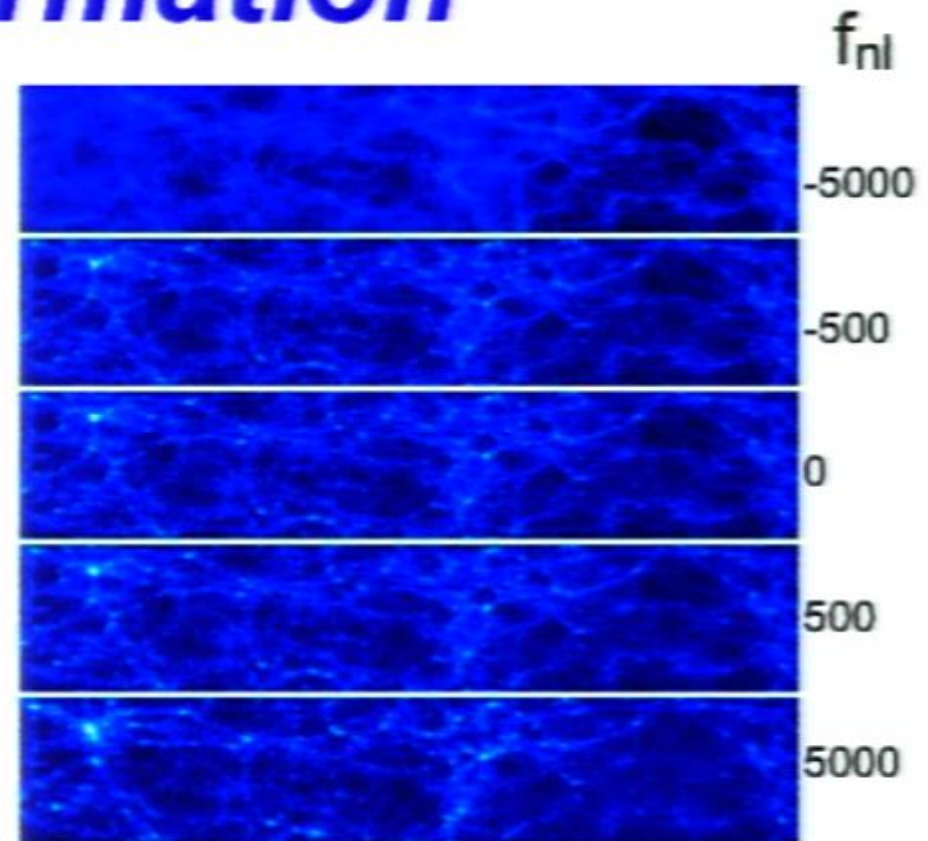
- Growth-based dark energy test (possible to differentiate between unknown particle physics and unknown gravity)





# *Non-Gaussianity and structure formation*

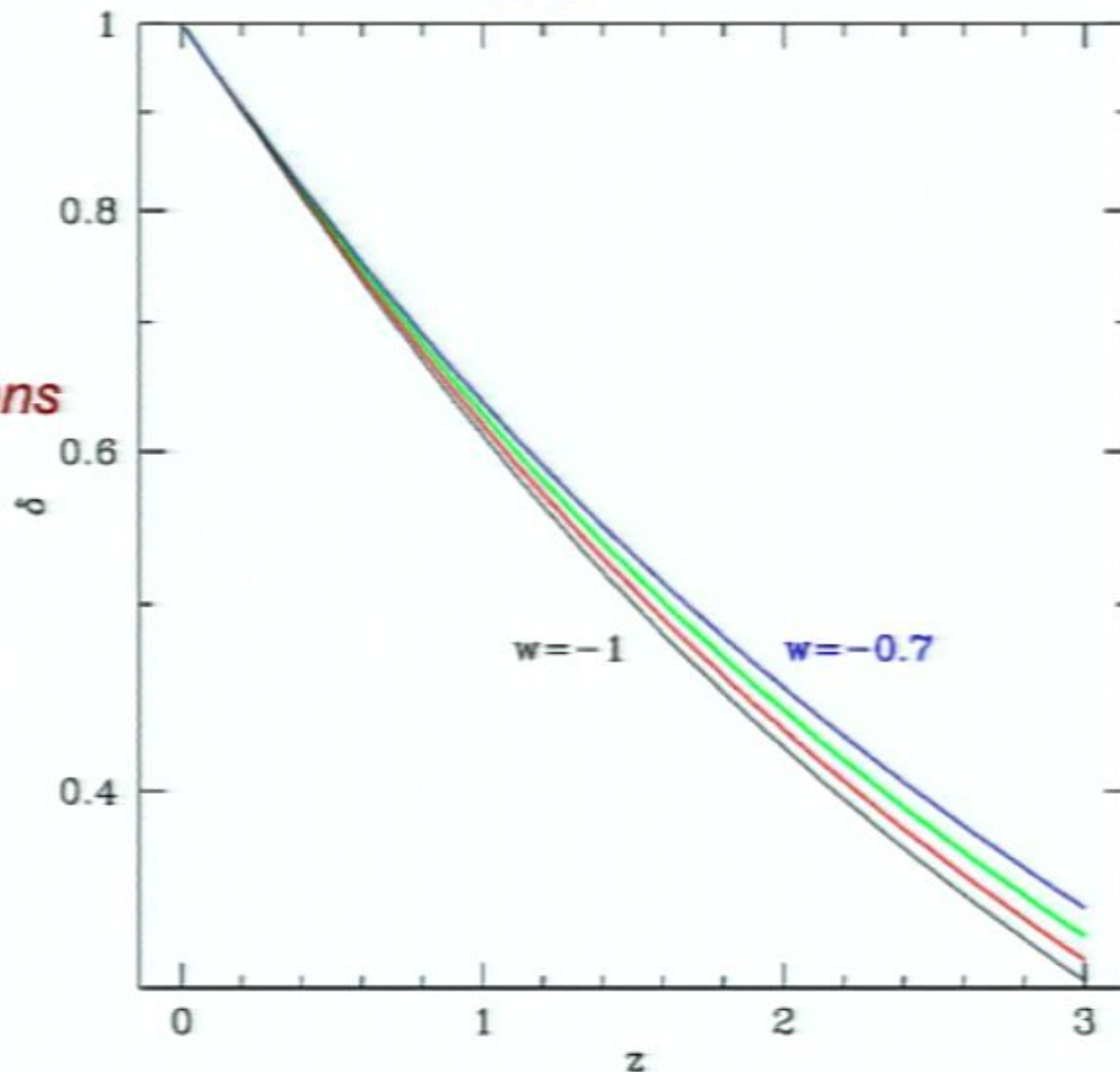
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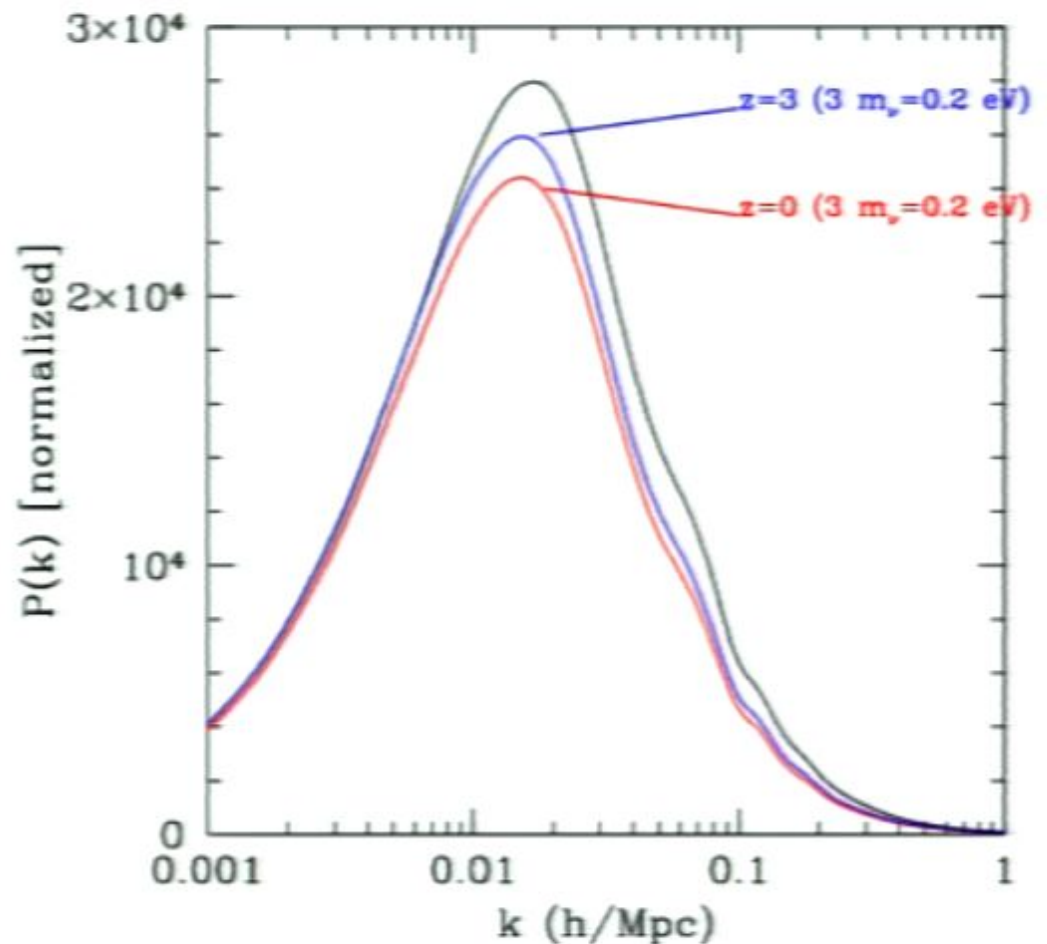
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# Massive Neutrinos in Cosmology

- Free streaming of neutrinos on small scales leads to time-dependent suppression of power
- CMB only sensitive to matter-radiation equality epoch (not affected by  $m < 0.3$  eV)
- Free-streaming scale roughly  $(m/1 \text{ eV}) 0.1 \text{ h/Mpc}$





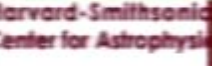
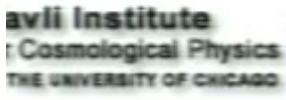
# South Pole Telescope

10 m mm-wave (3 different wavelengths) telescope at the south pole

- extremely dry
- very stable
- good support



Chicago Colorado  
UC Berkeley Case Western  
McGill Harvard

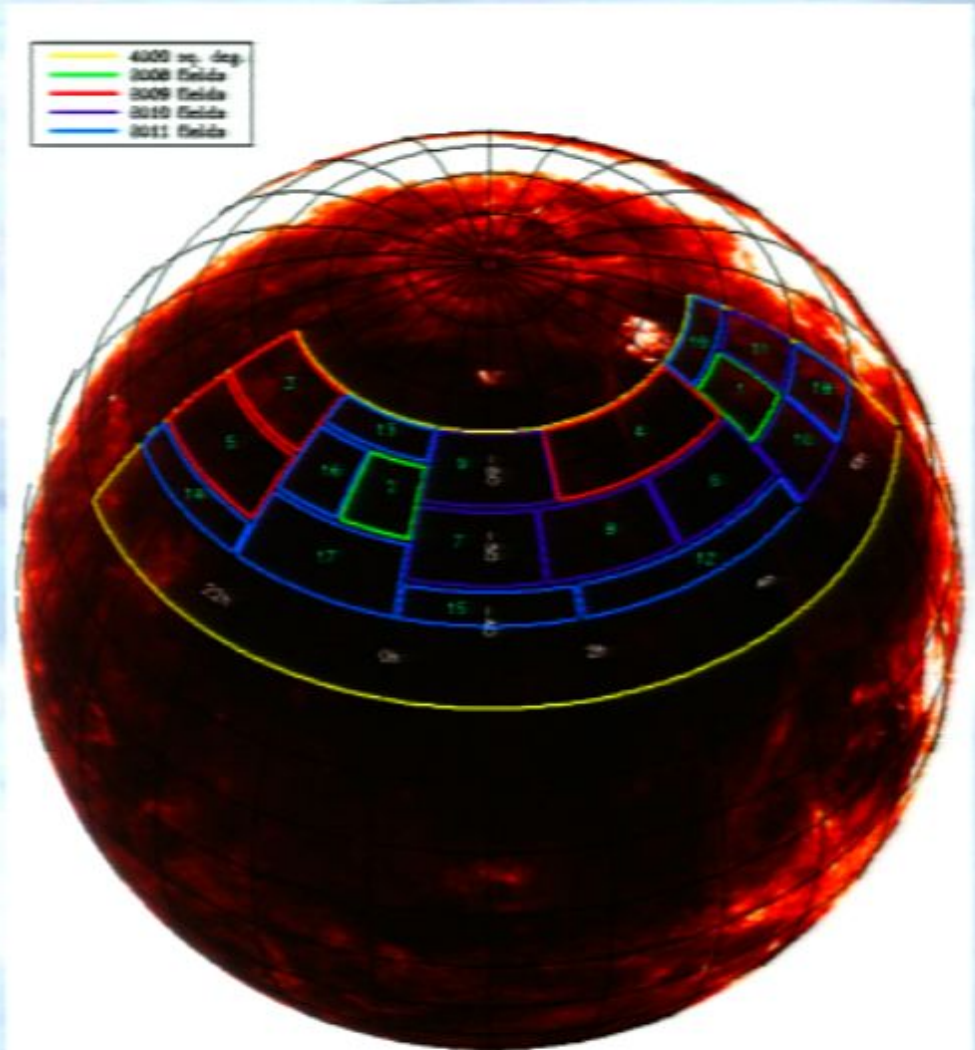


# SPT Collaboration

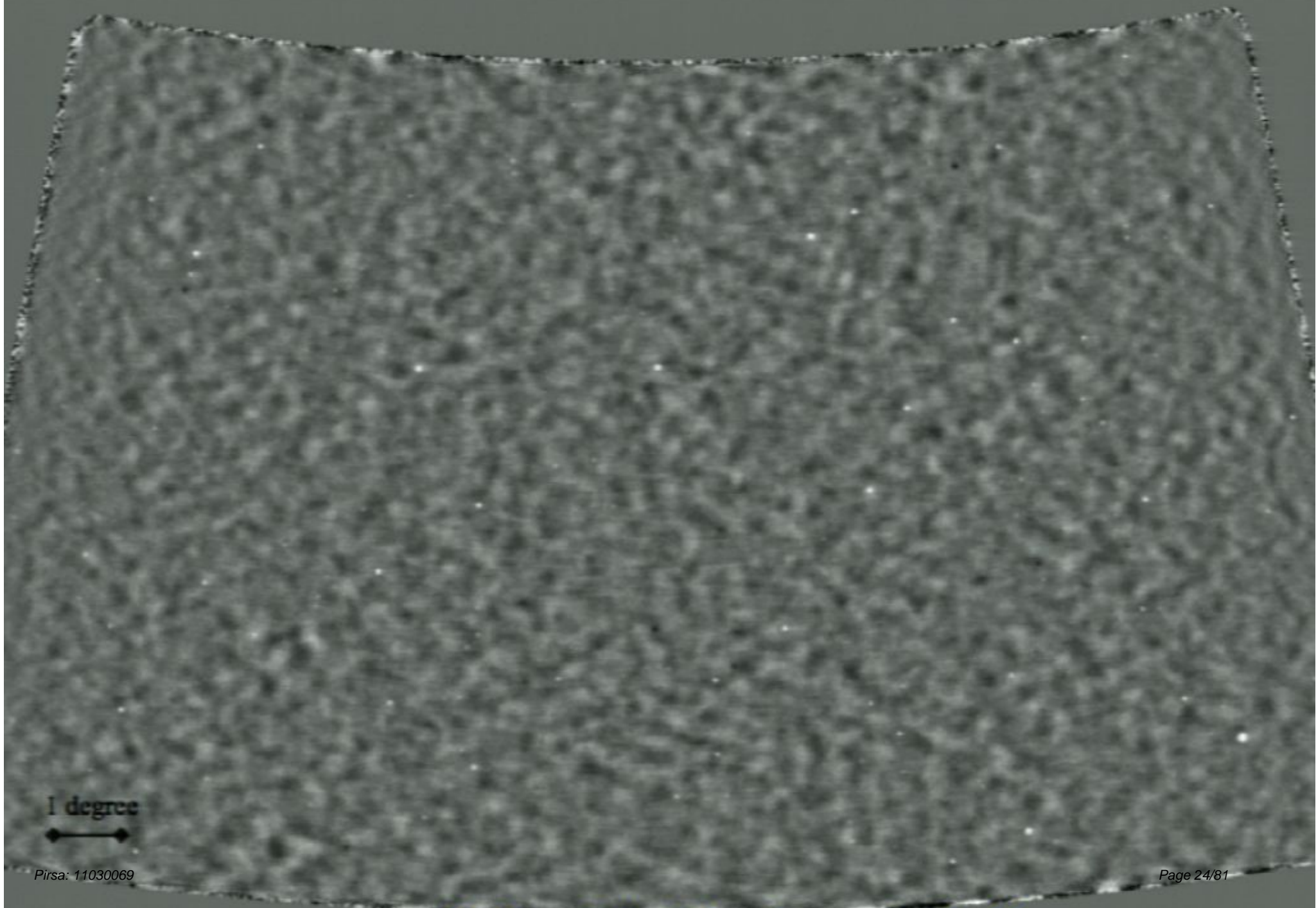


# The Survey

- So far have mapped ~1400 square degrees to survey depth (18 uK at 150 GHz)
- Full survey will be ~2500 square degrees.  
(concentrate on higher-latitude / more-negative-dec regions)

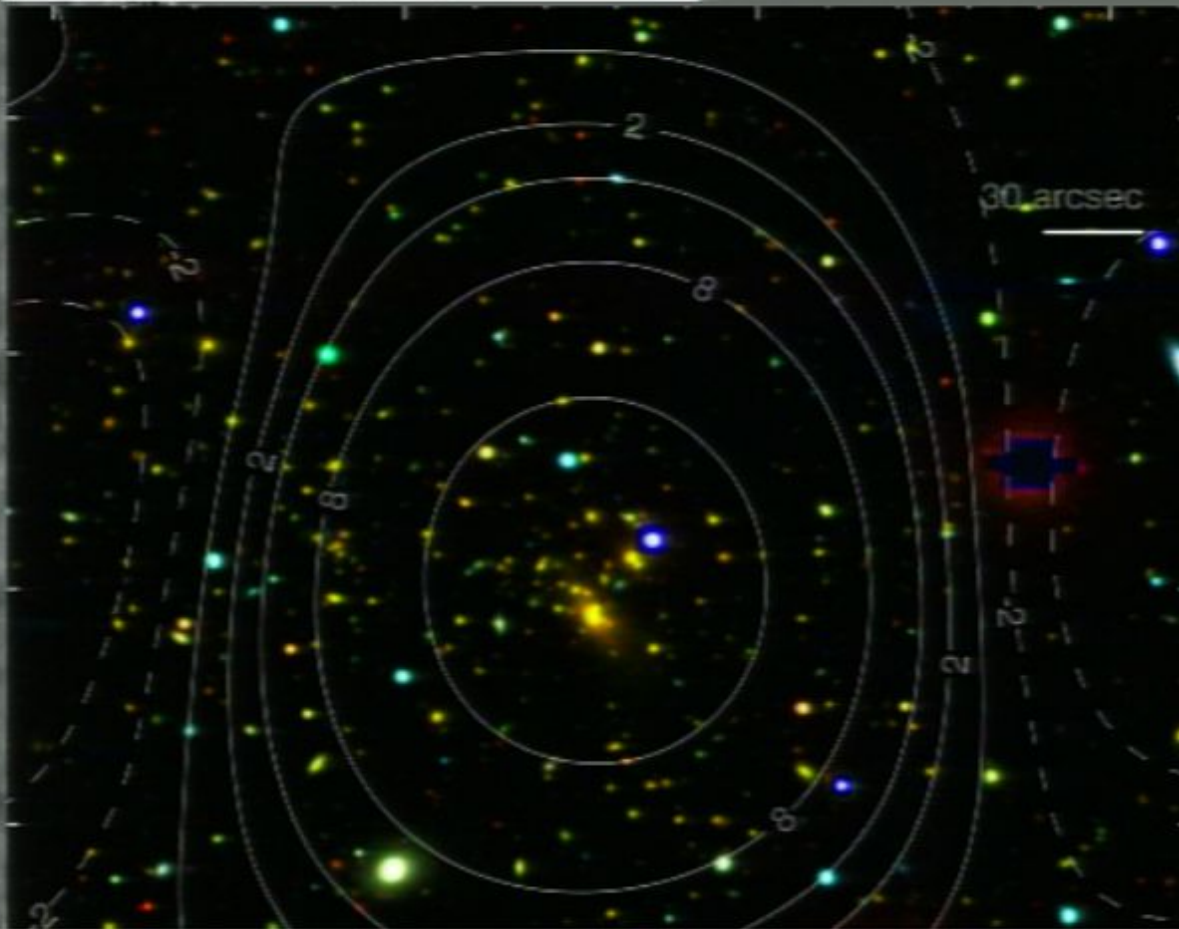






1 degree  
↔

Image by Will High in recent paper by Williamson et al



One of the heaviest objects in the universe  
 $> 10^{15}$  solar masses

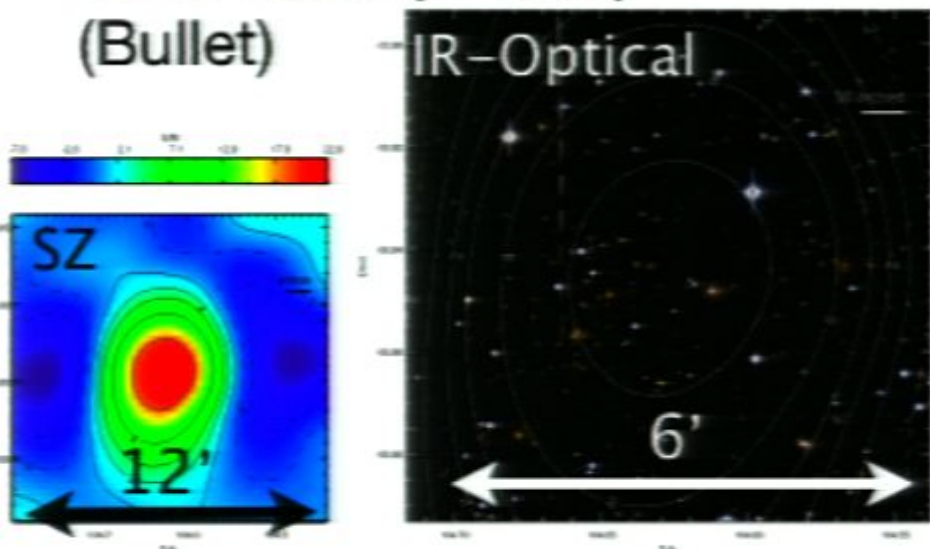
1 degree  
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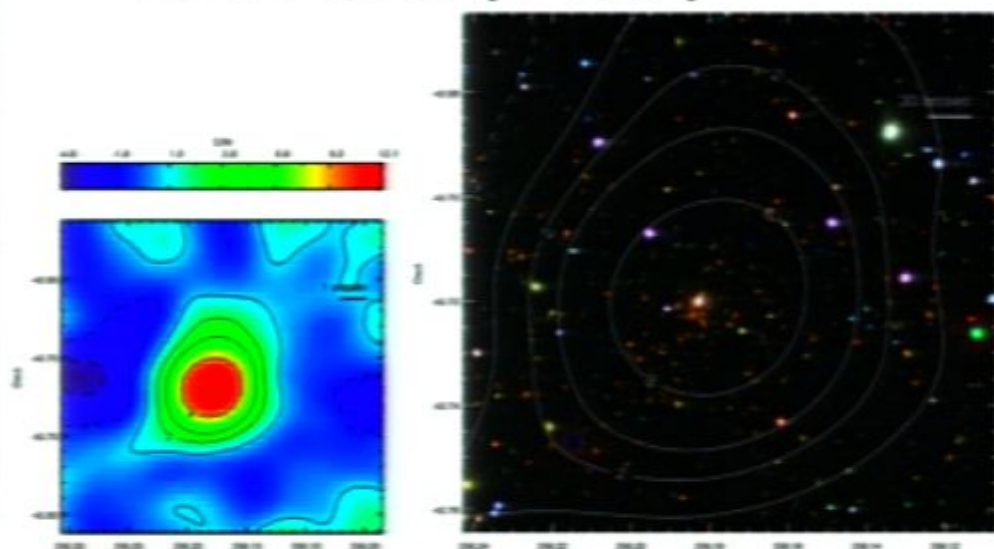
# SPT Cluster Images

0658-5556 ( $z=0.30$ )

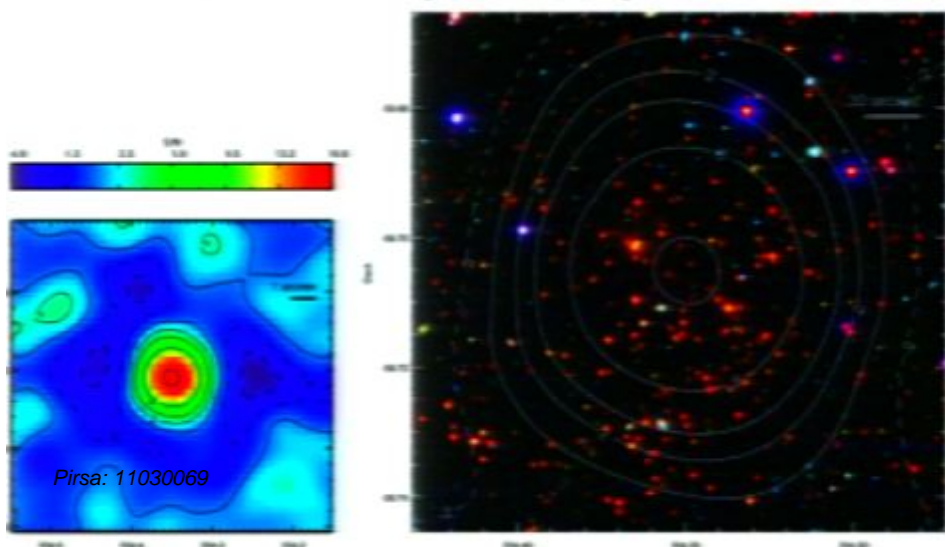
(Bullet)



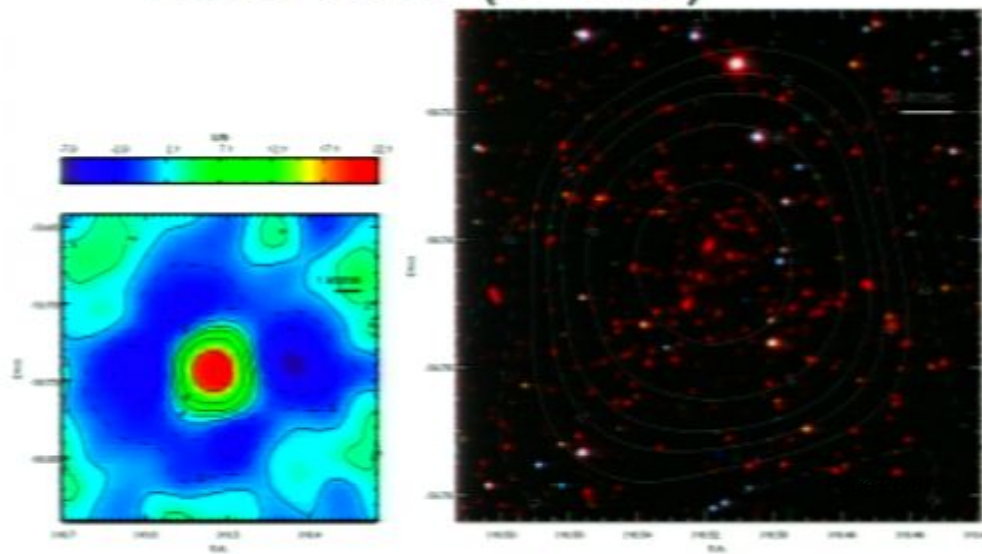
2344-4243 ( $z=0.62$ )



2337-5942 ( $z=0.78$ )



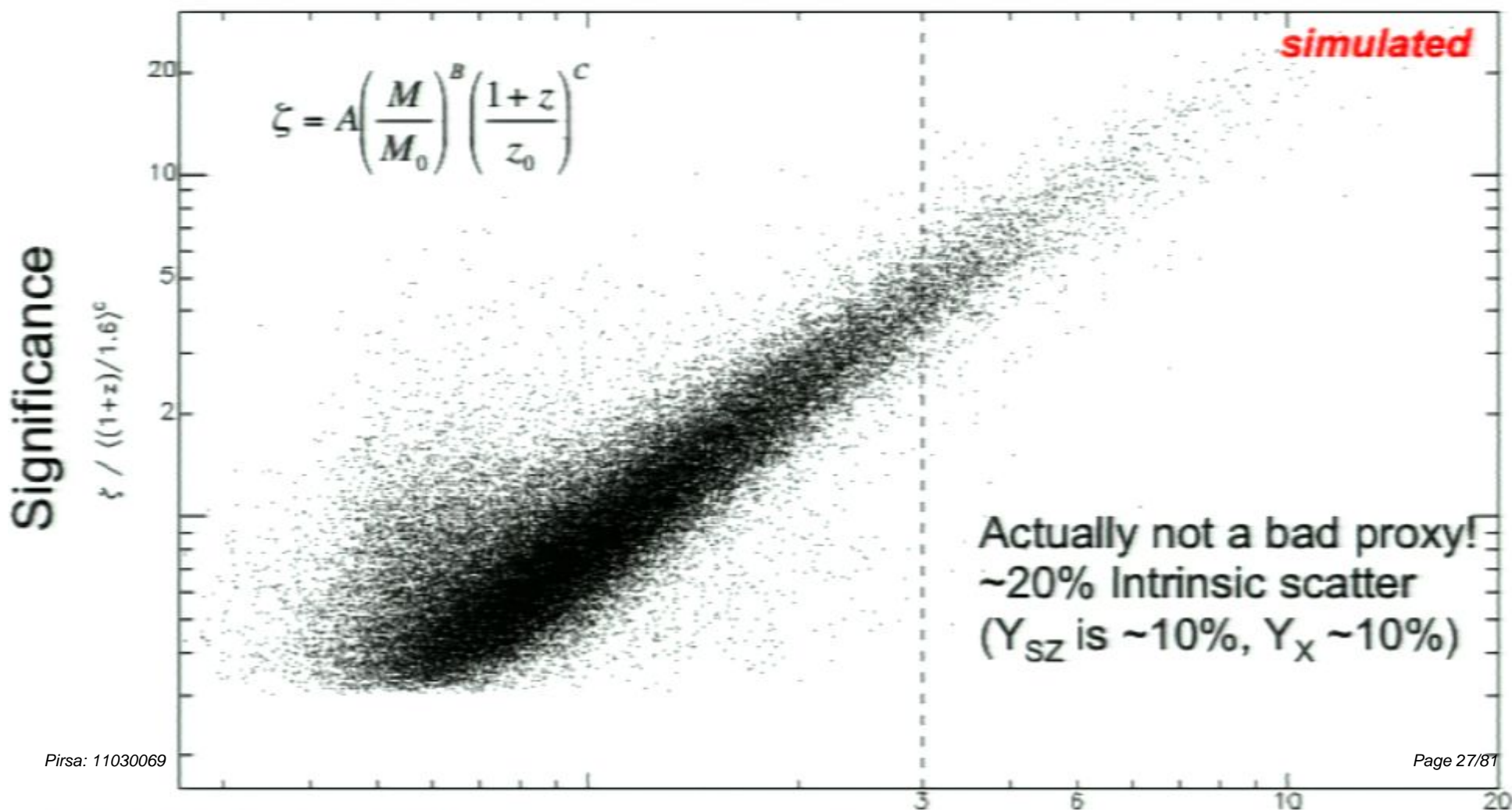
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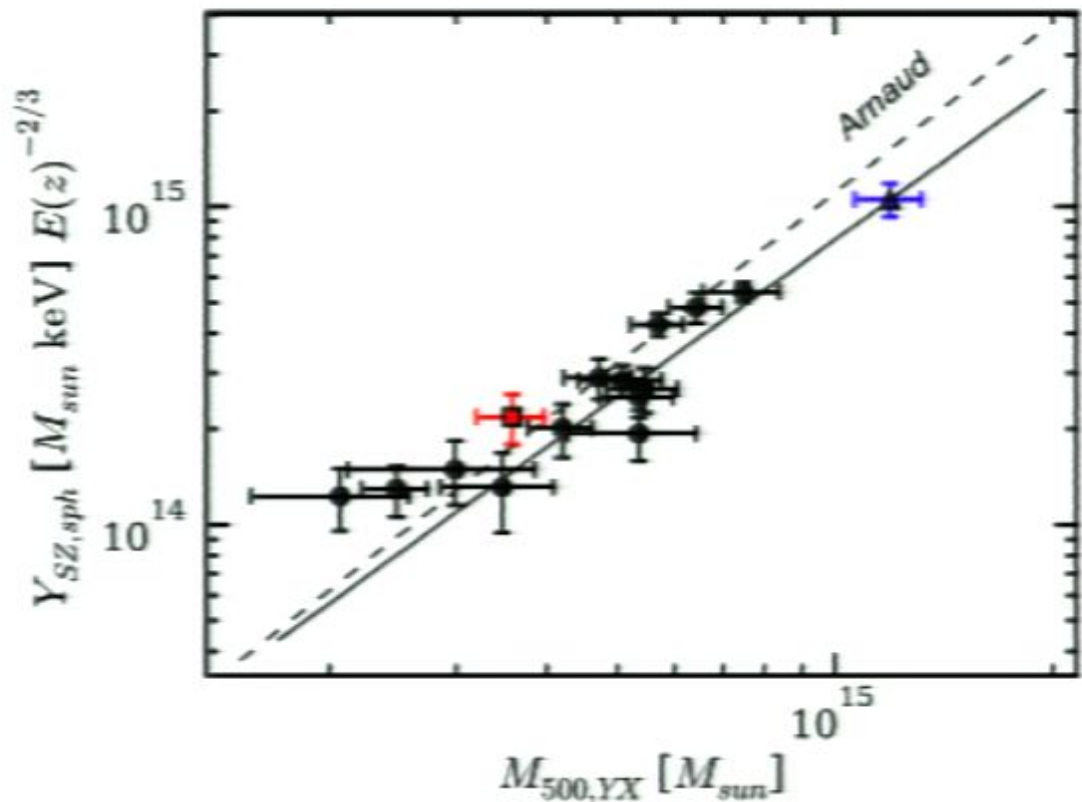
# Mass Proxy?

As a first crack, just use detection significance! (Well... almost.)



# SZ-Mass Scaling

- SZ properties of SPT-selected cluster sample tightly correlated with X-ray mass estimates  
(Chandra & XMM)

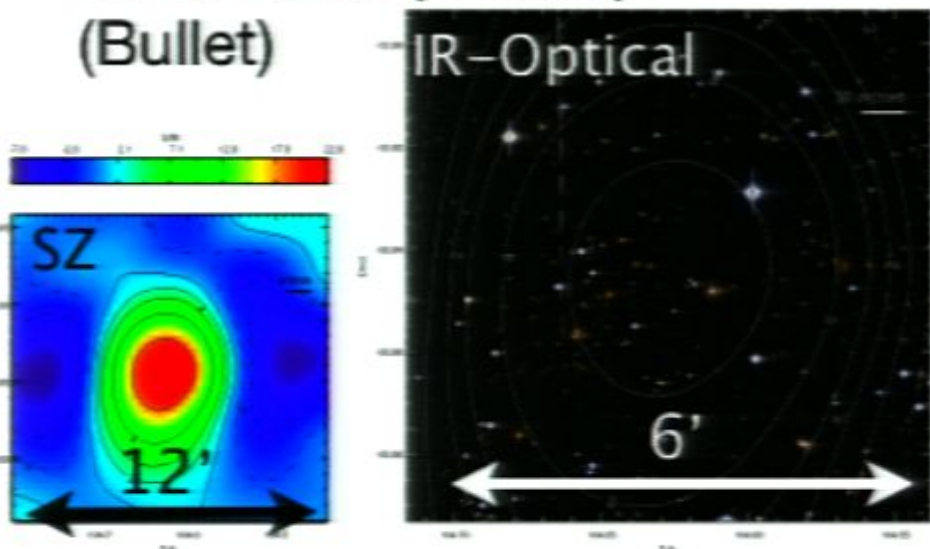


Andersson et al 2010

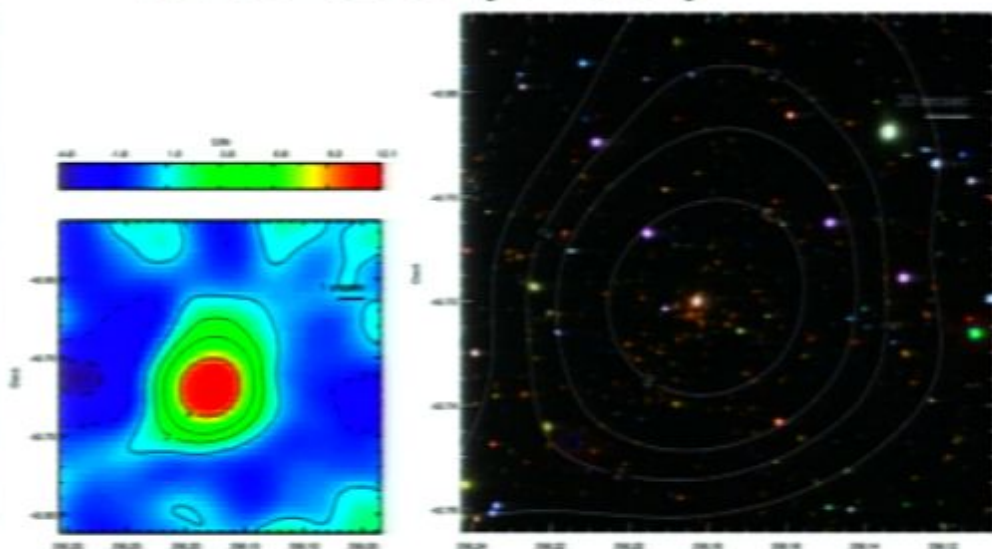
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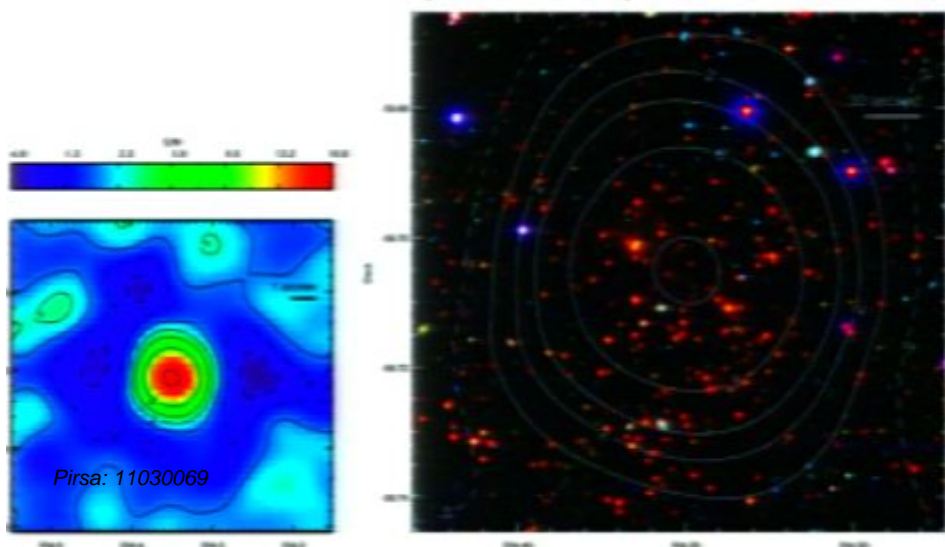
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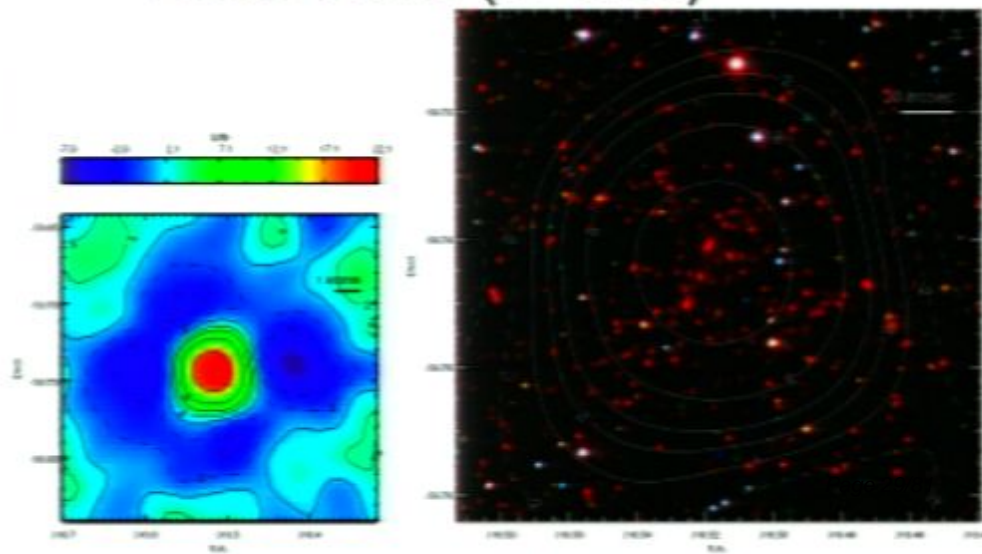
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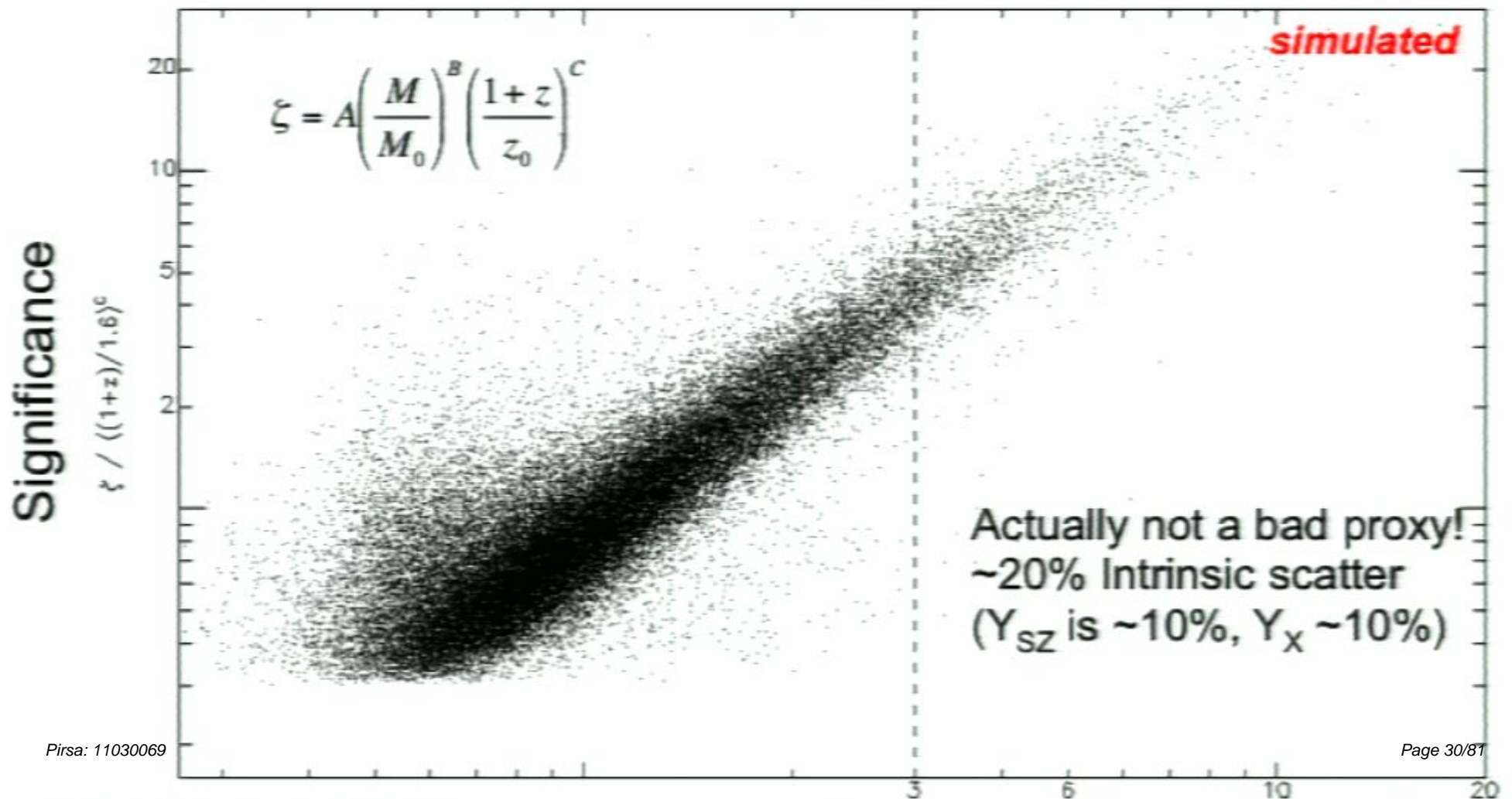
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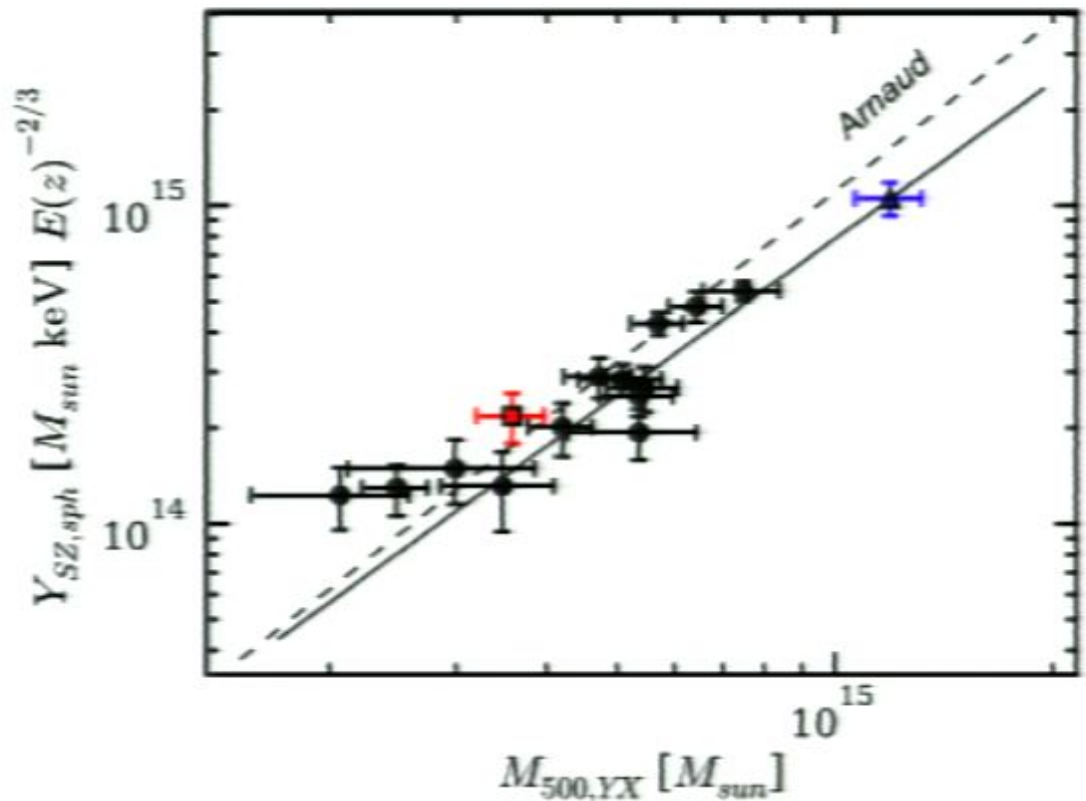
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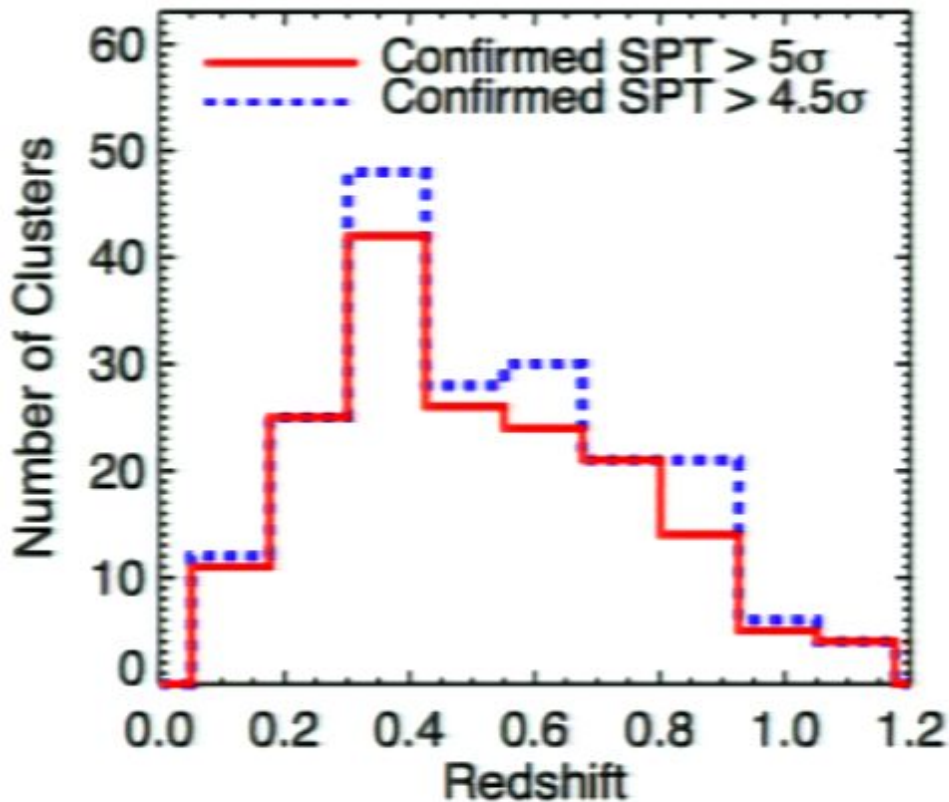
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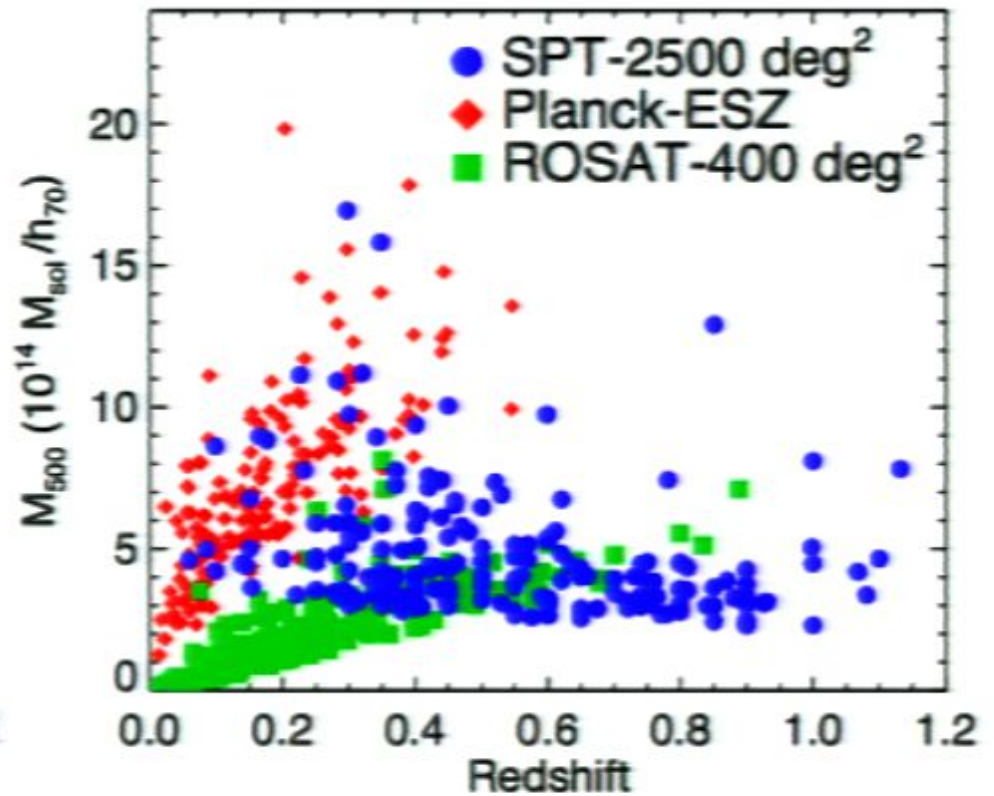
Andersson et al 2010

# SPT Cluster Sample Properties

## Redshift Histogram



## SZ Mass vs Redshift

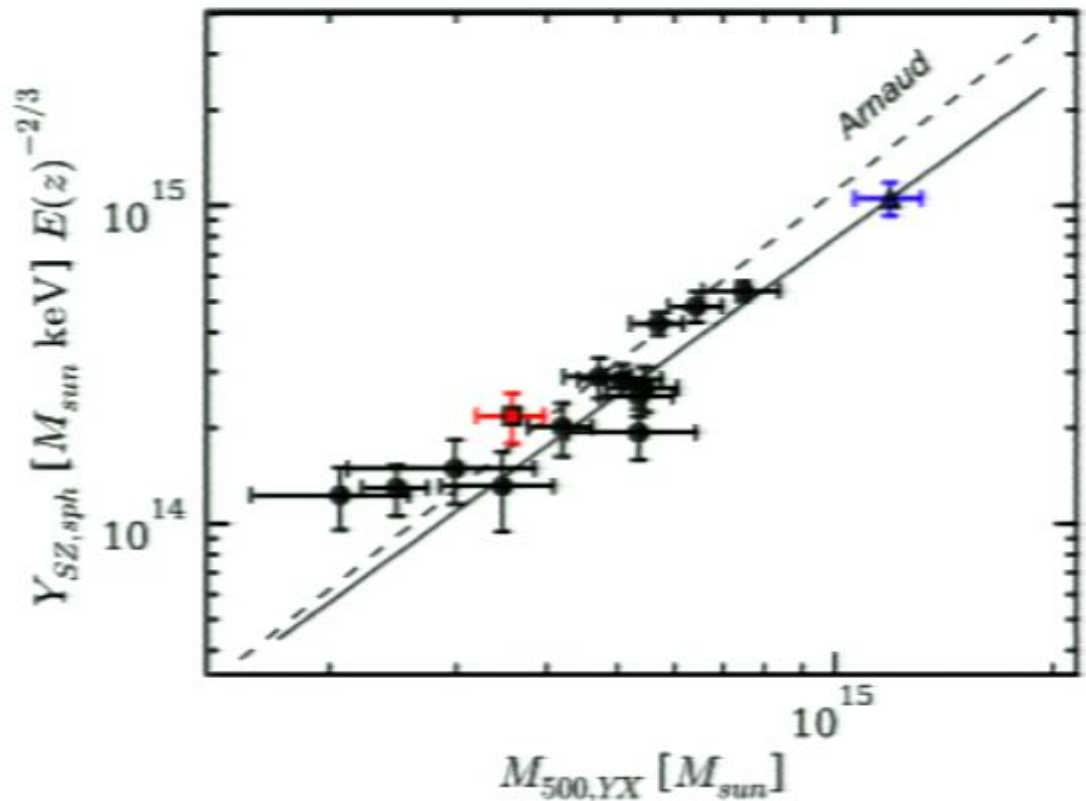


- Optically confirmed ~300 clusters, ~80% newly discovered
- High redshift:  $\langle z \rangle = 0.55$  and ~20-25% of clusters at  $z > 0.8$
- Optical measurements also confirm ~95% purity at S/N = 5
- Mass threshold flat/falling w/ redshift:  $M_{500}(z=0.6) > \sim 3 \times 10^{14} M_{\text{sol}}/h_{70}$



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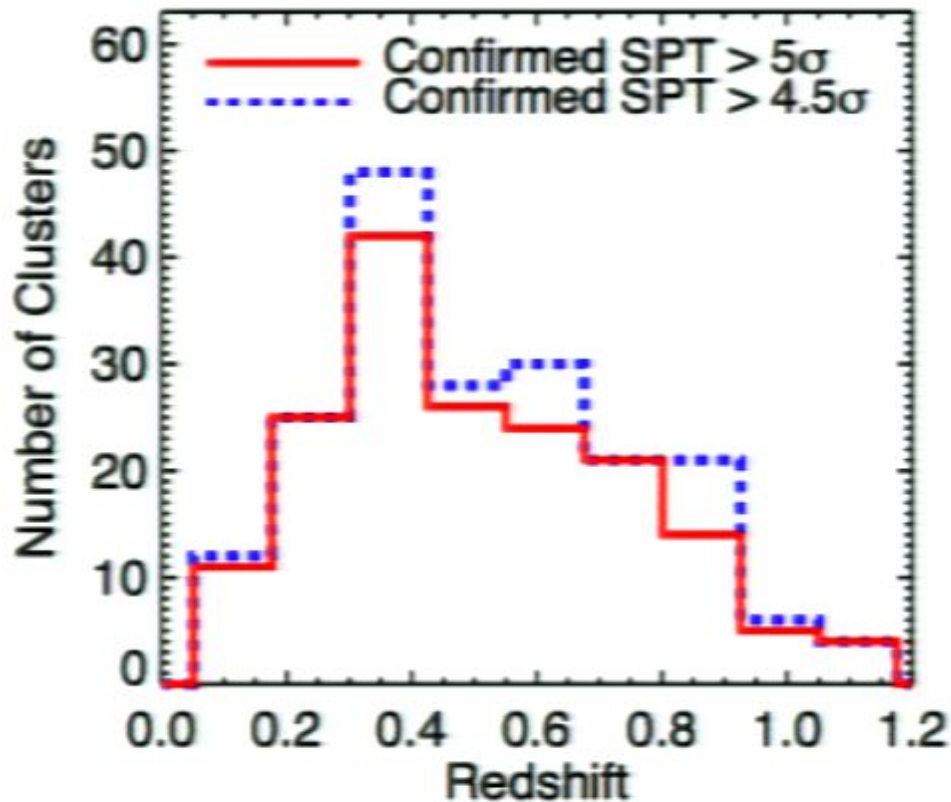
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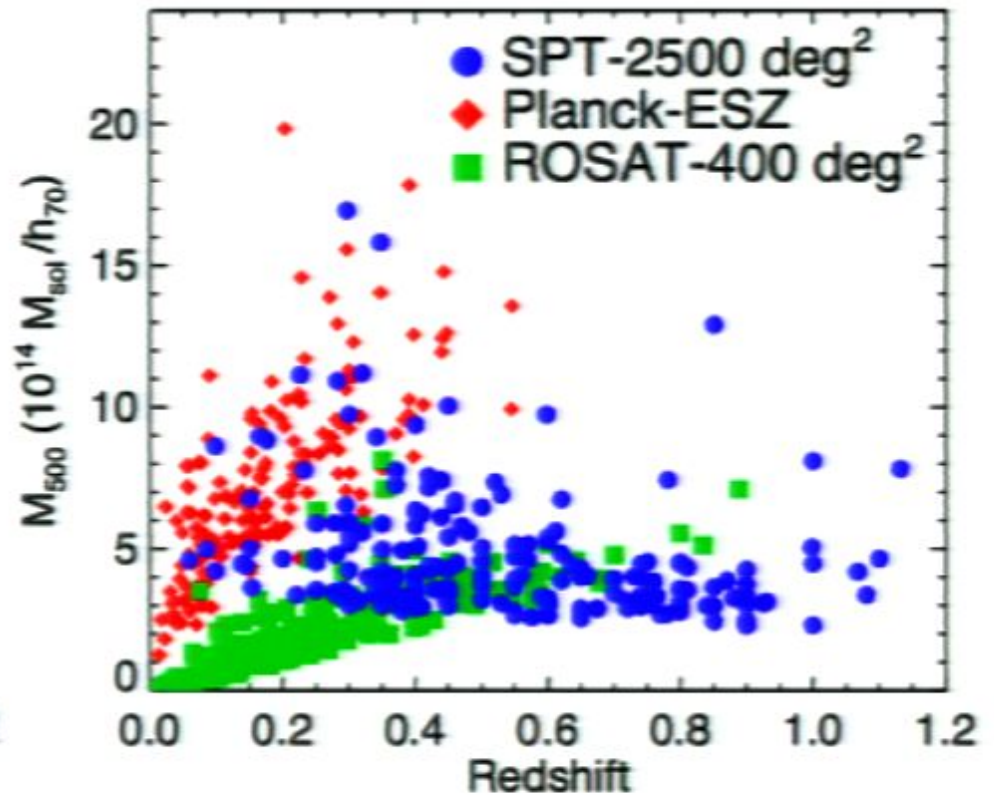
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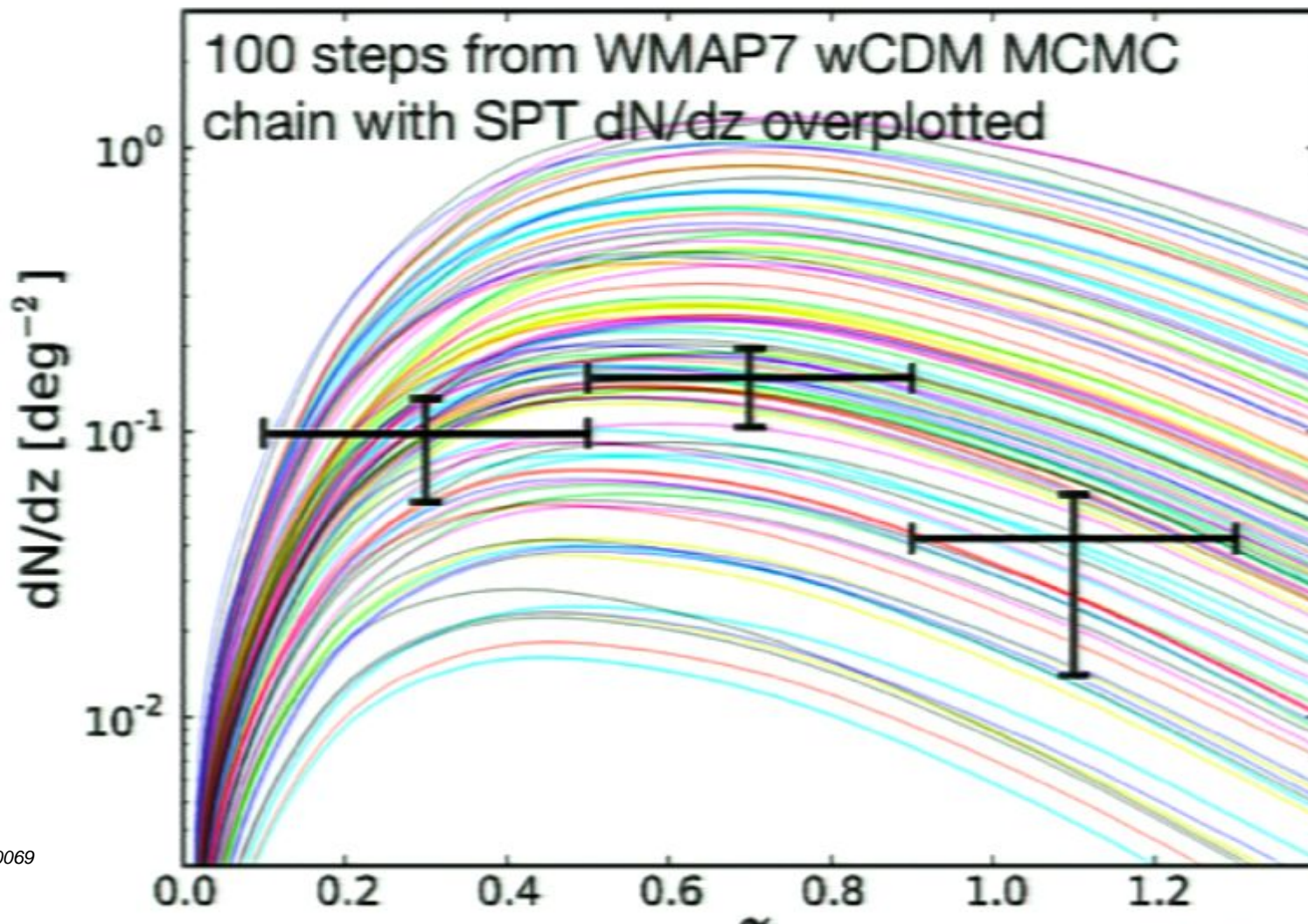


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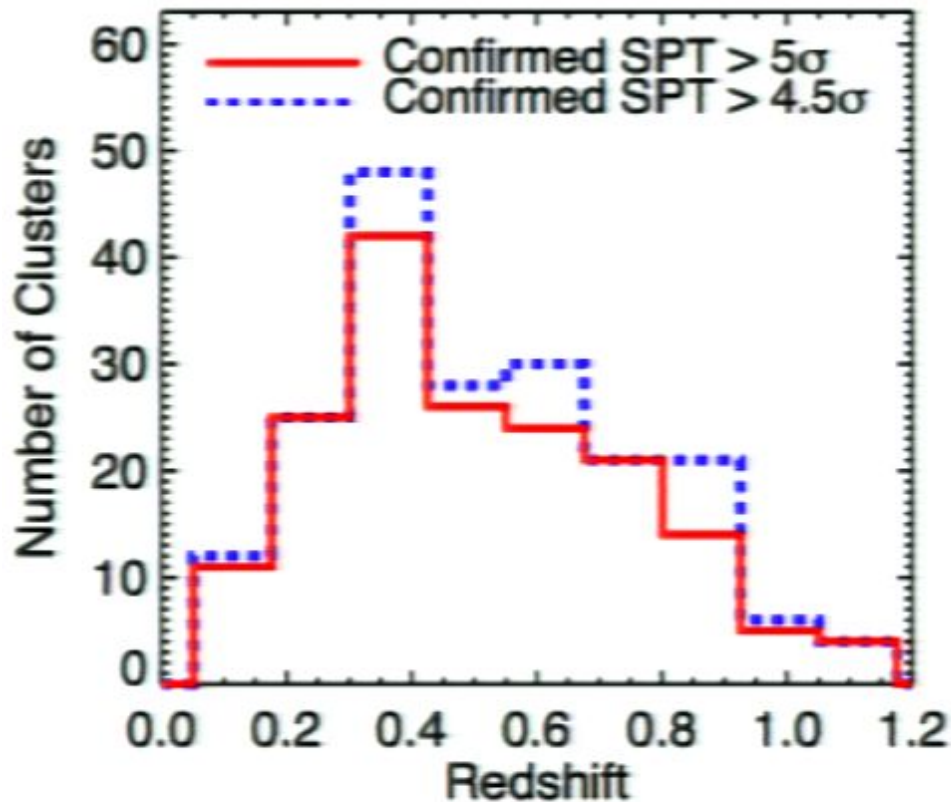
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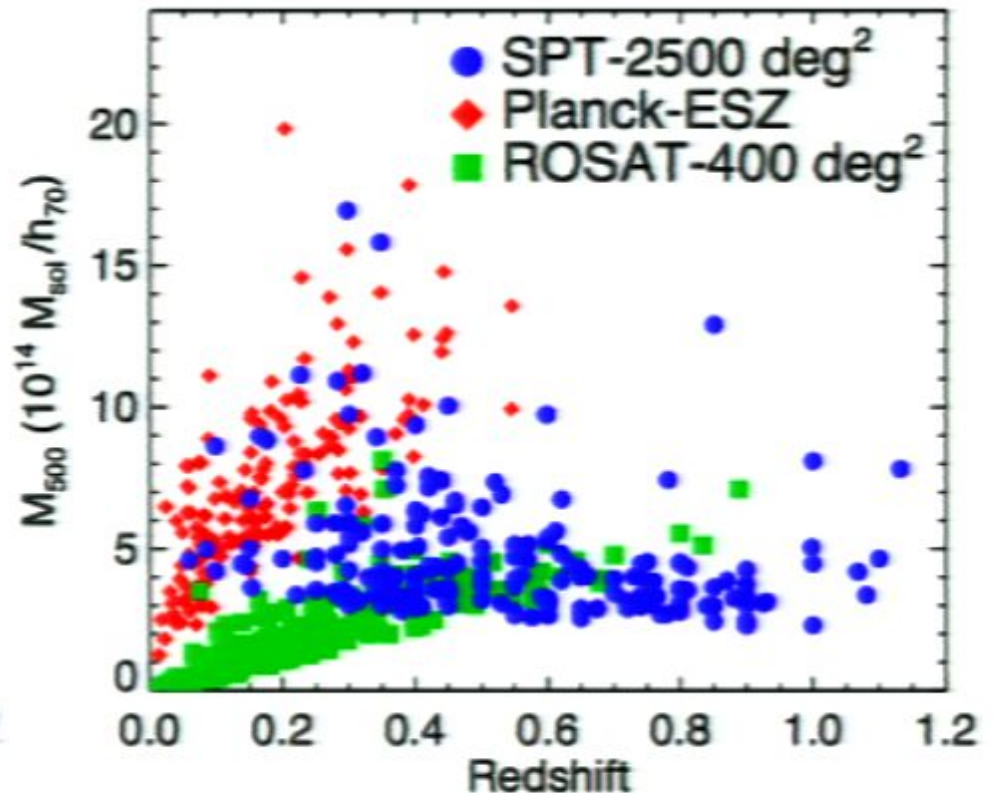


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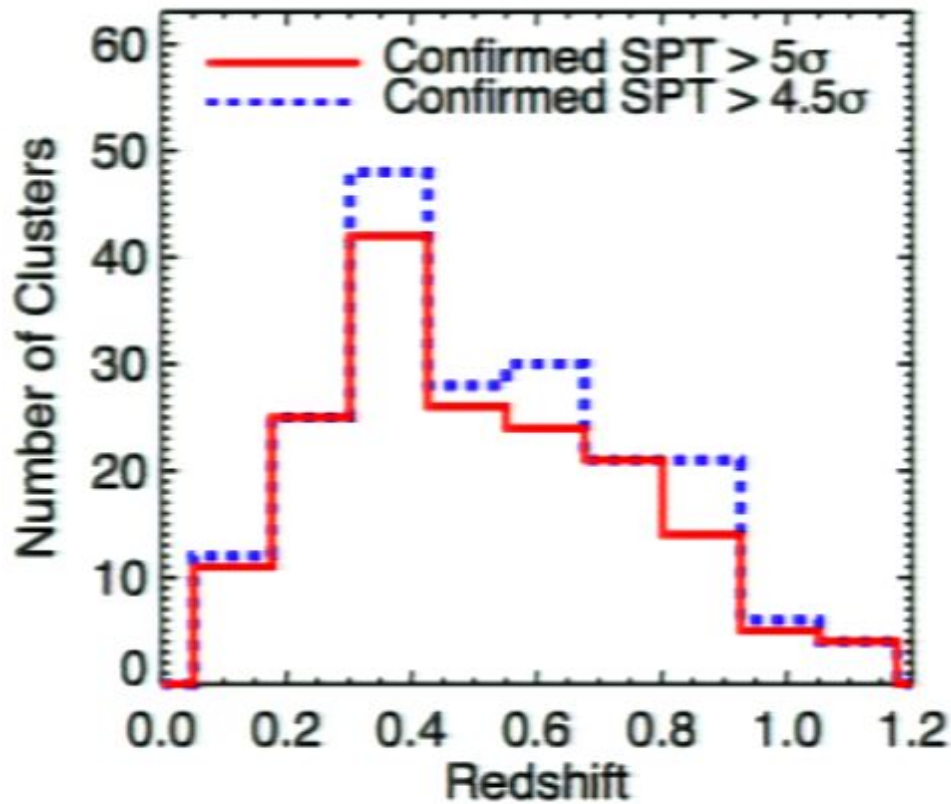
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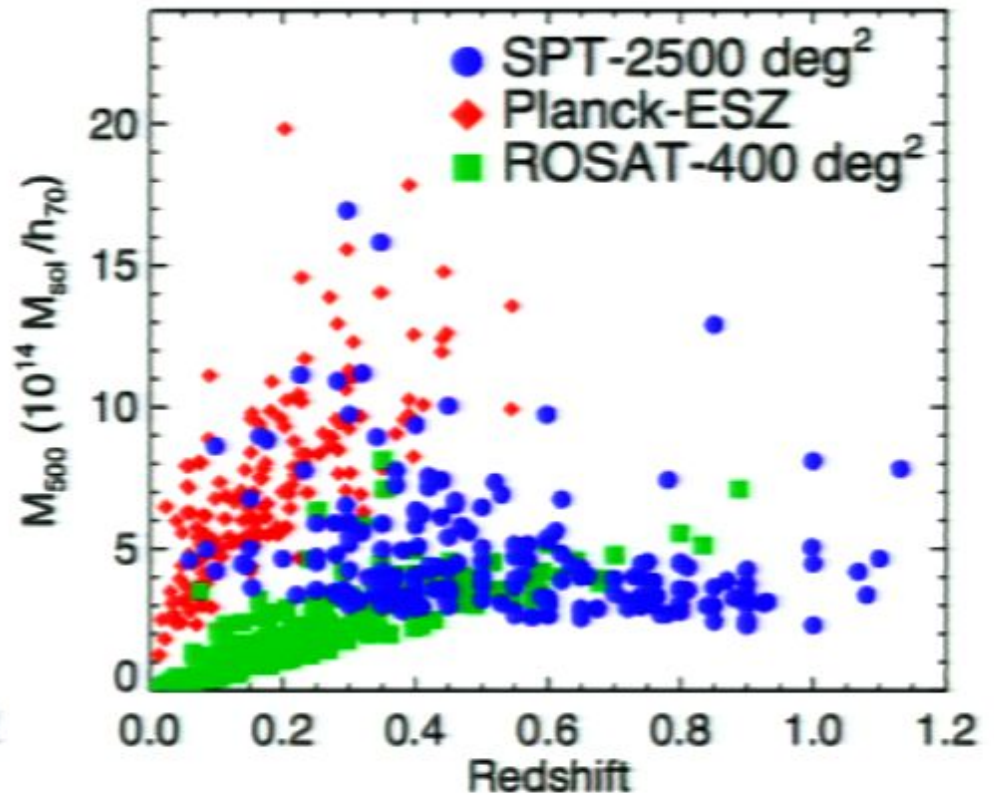
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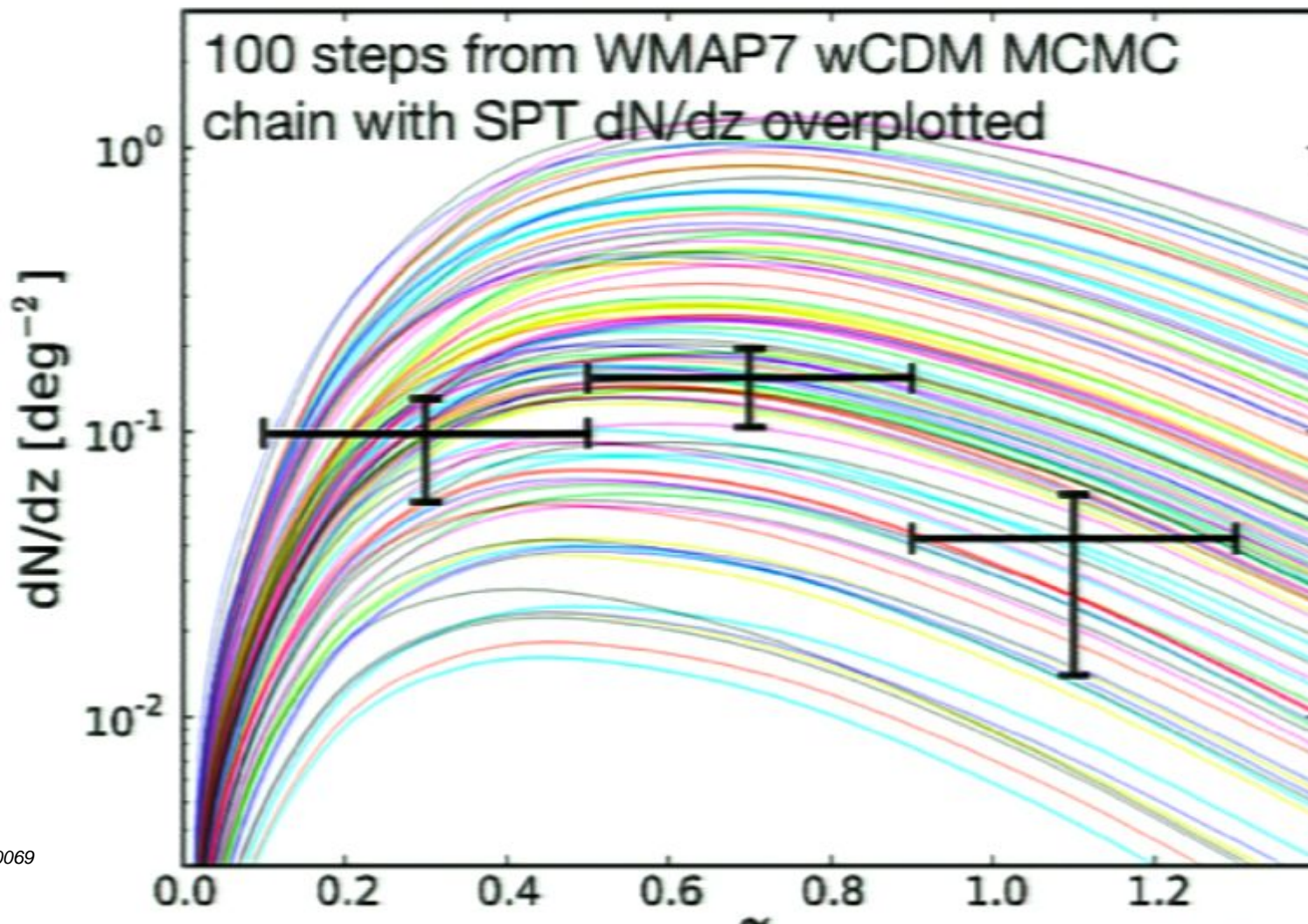


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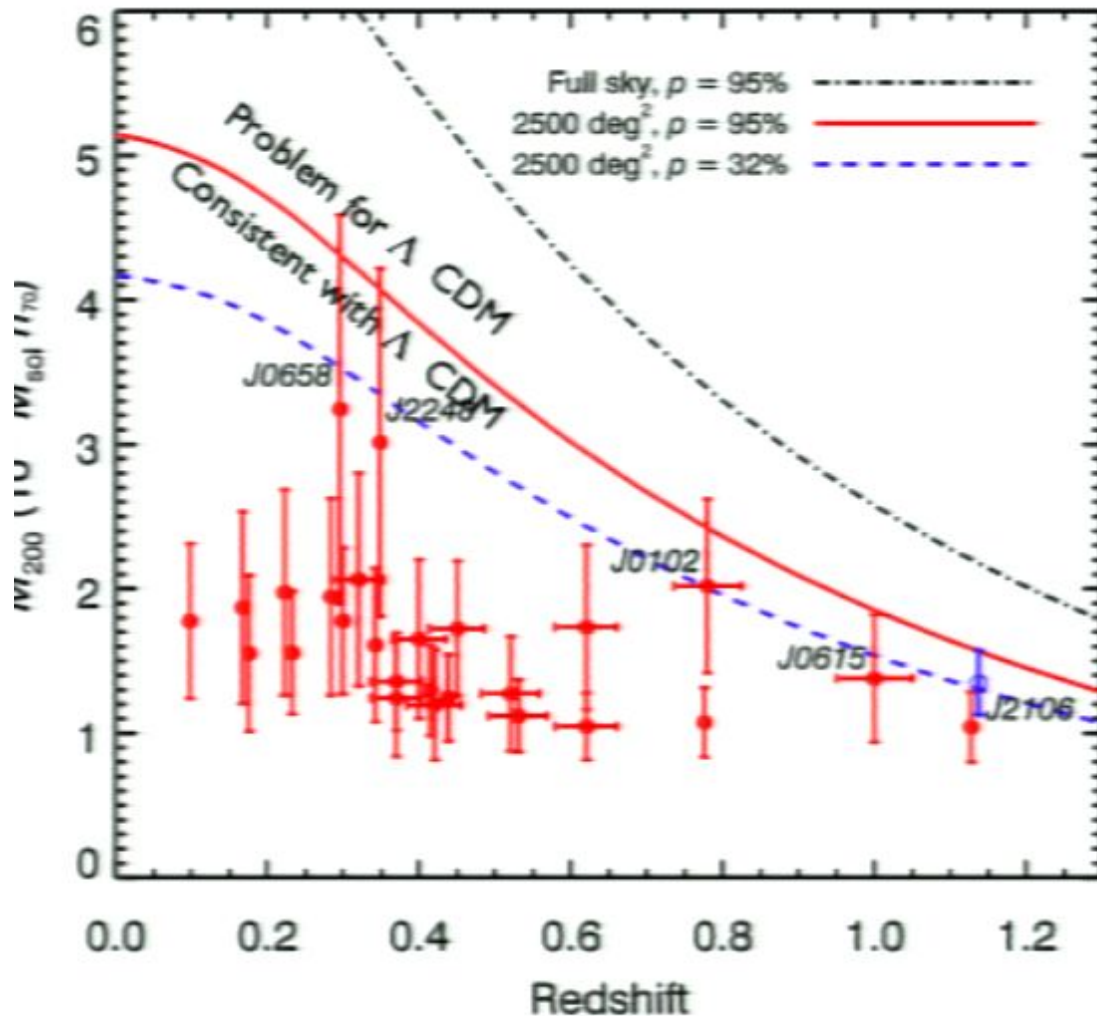
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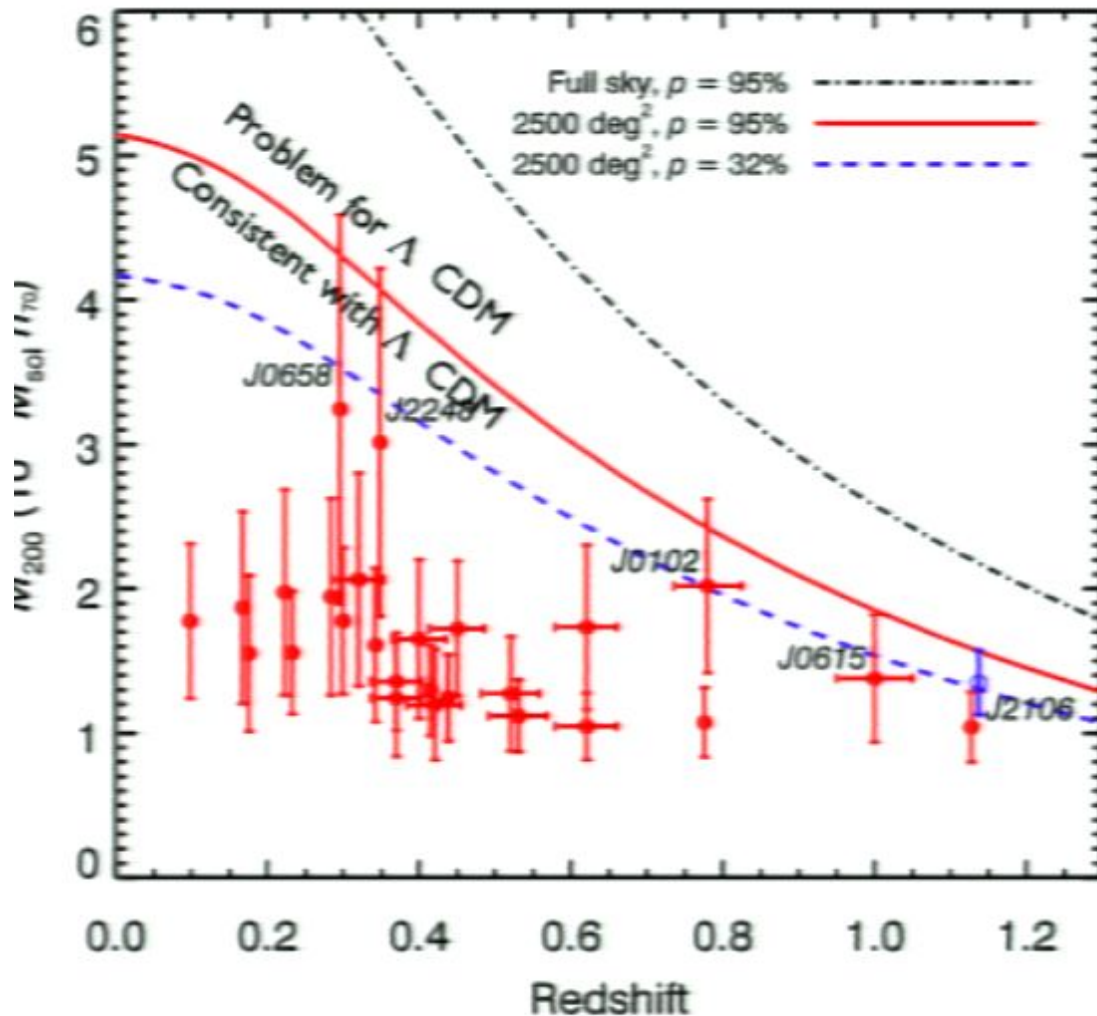


# Tests of $\Lambda$ CDM and Non-Gaussianity



- SPT provides a clean uniform nearly redshift independent selection over a large area
- Catalog of 26 most significant clusters from full 2500 deg<sup>2</sup> survey
- Even a single massive cluster could indicate tension with  $\Lambda$ CDM (Mortonson, Hu, Huterer 2010), however:
  - consistent with  $\Lambda$ CDM
  - consistent with Gaussian density fluctuations ( $f_{NL}=20 \pm 450$ )

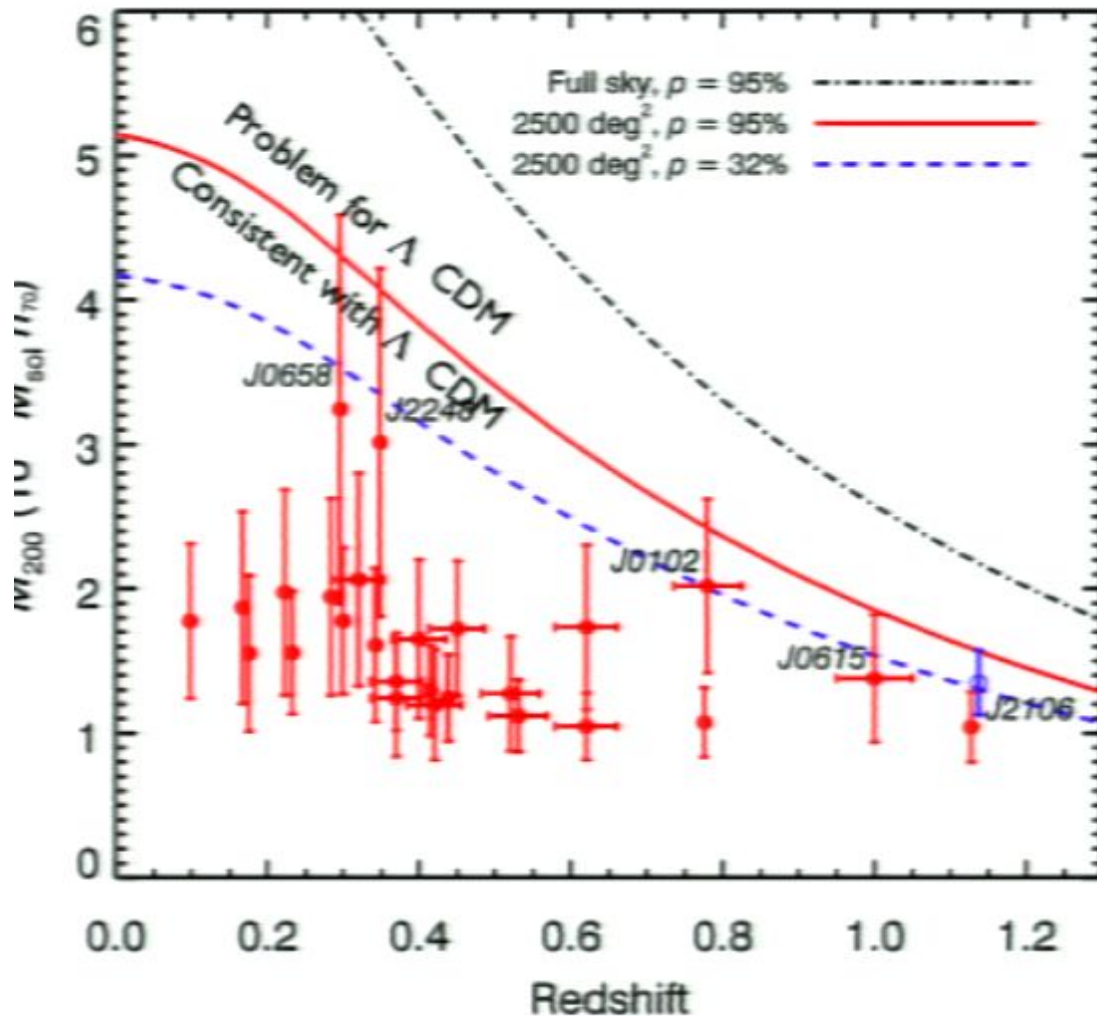
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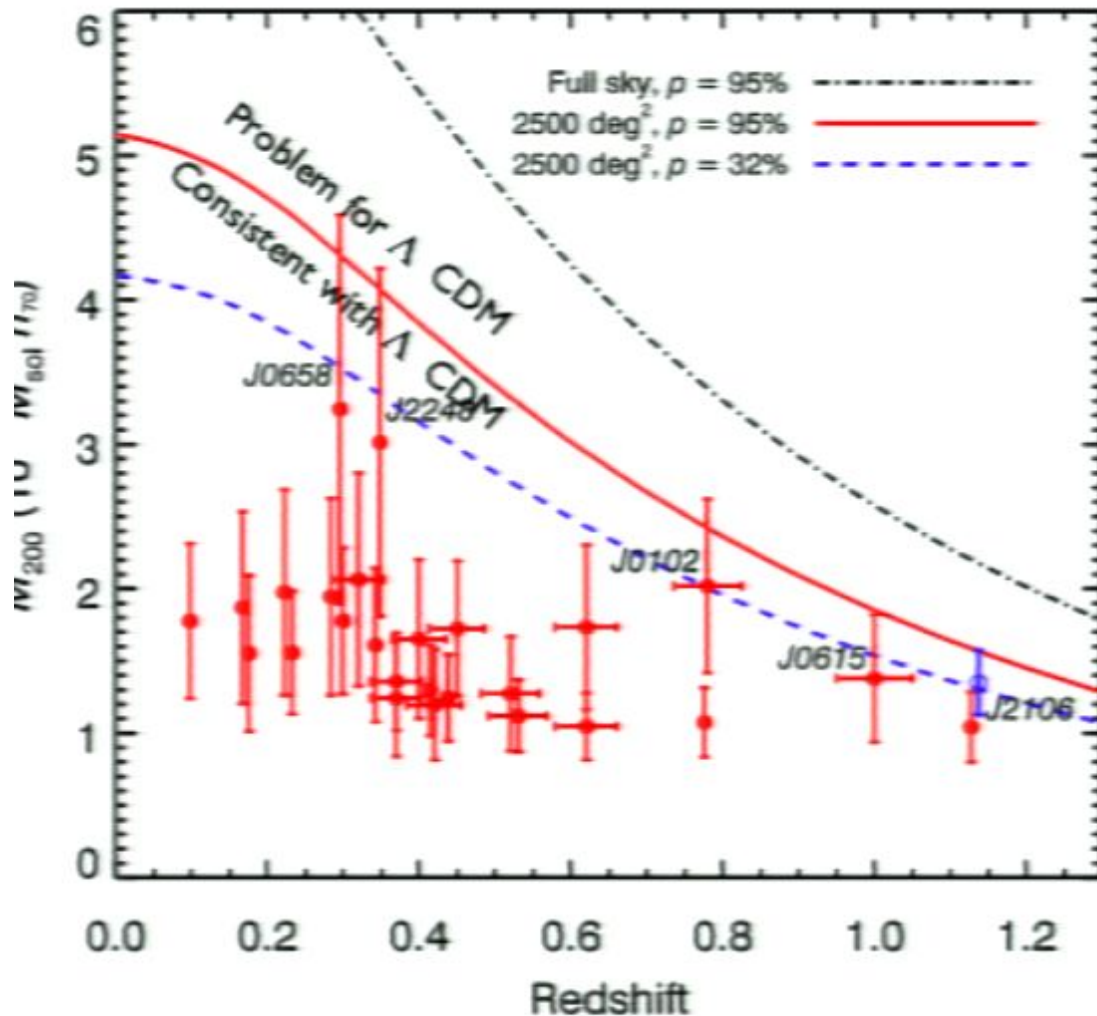
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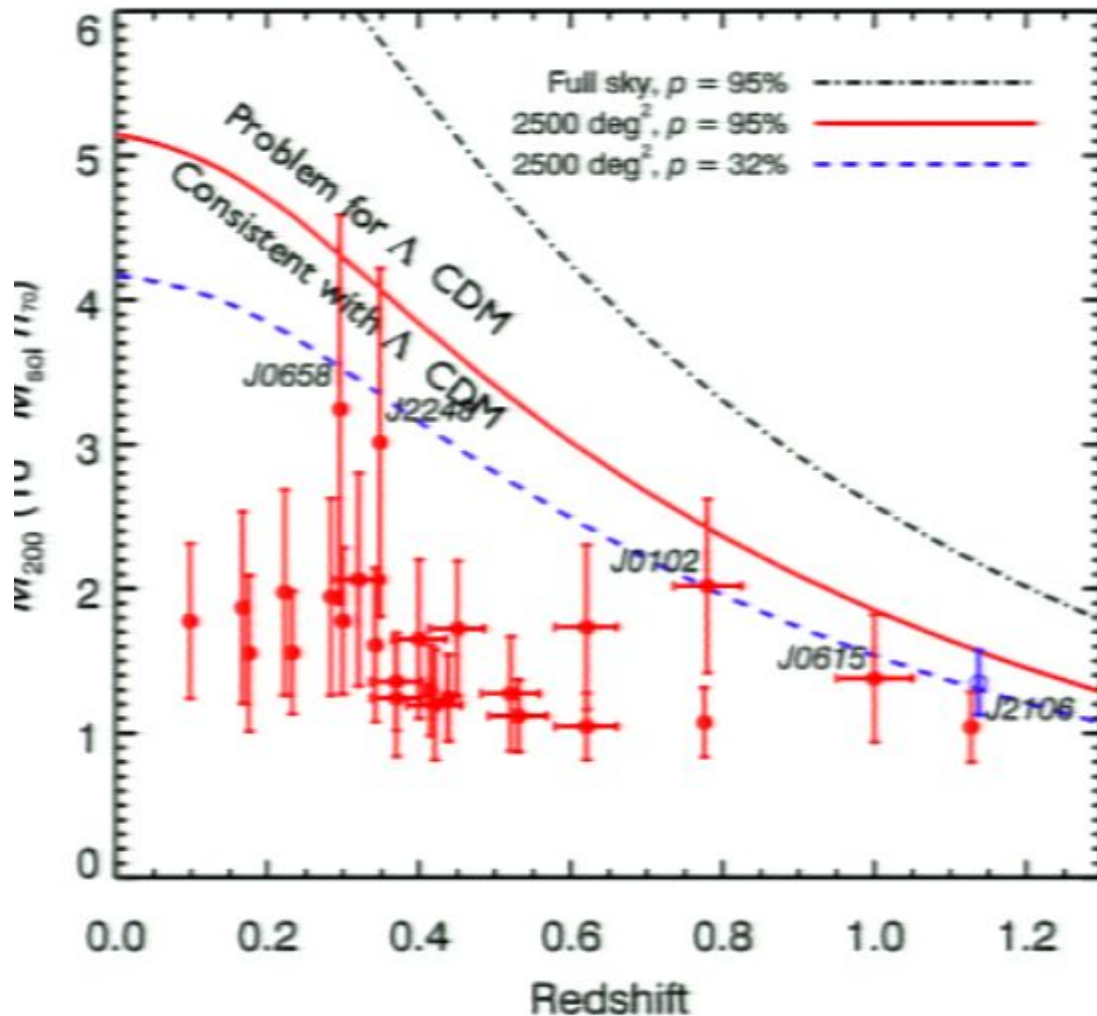


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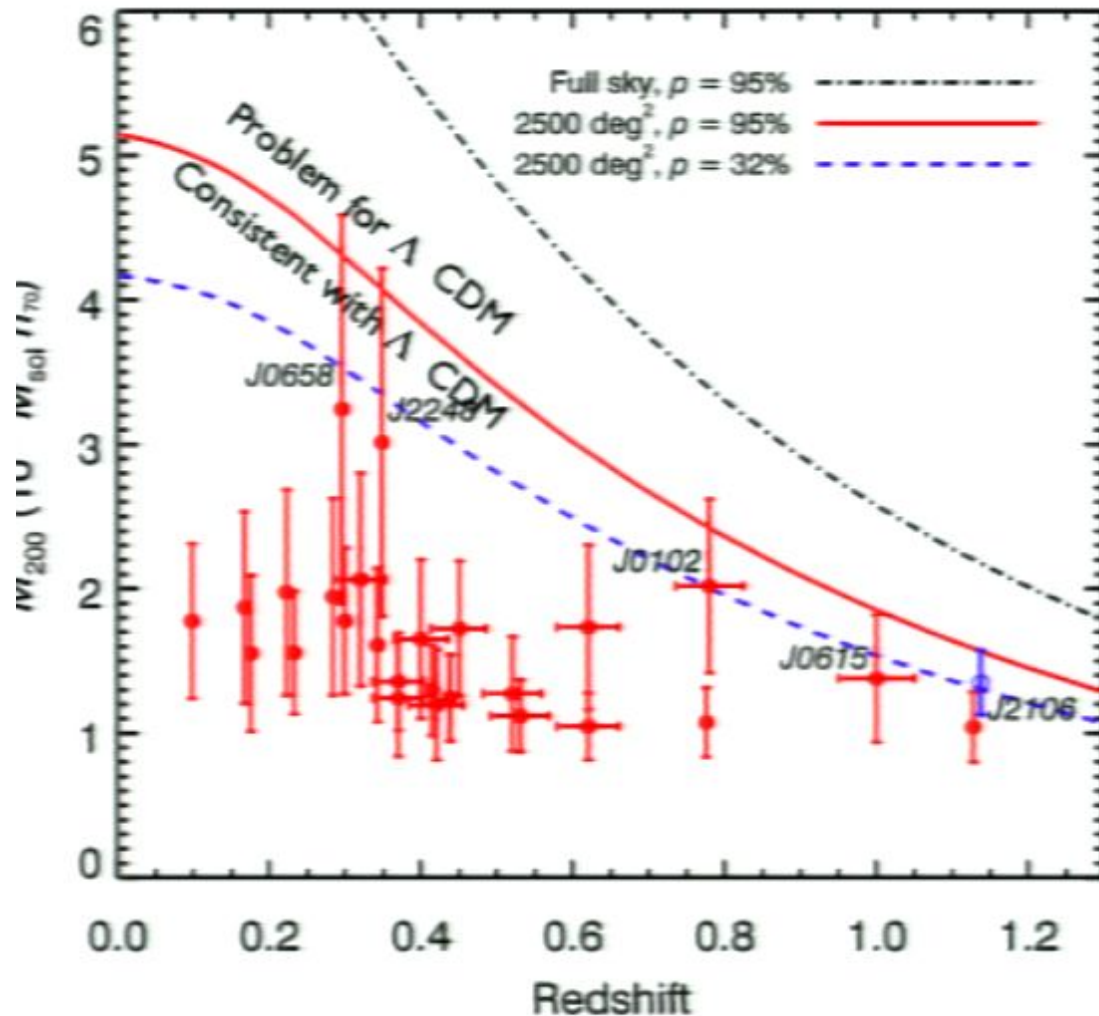
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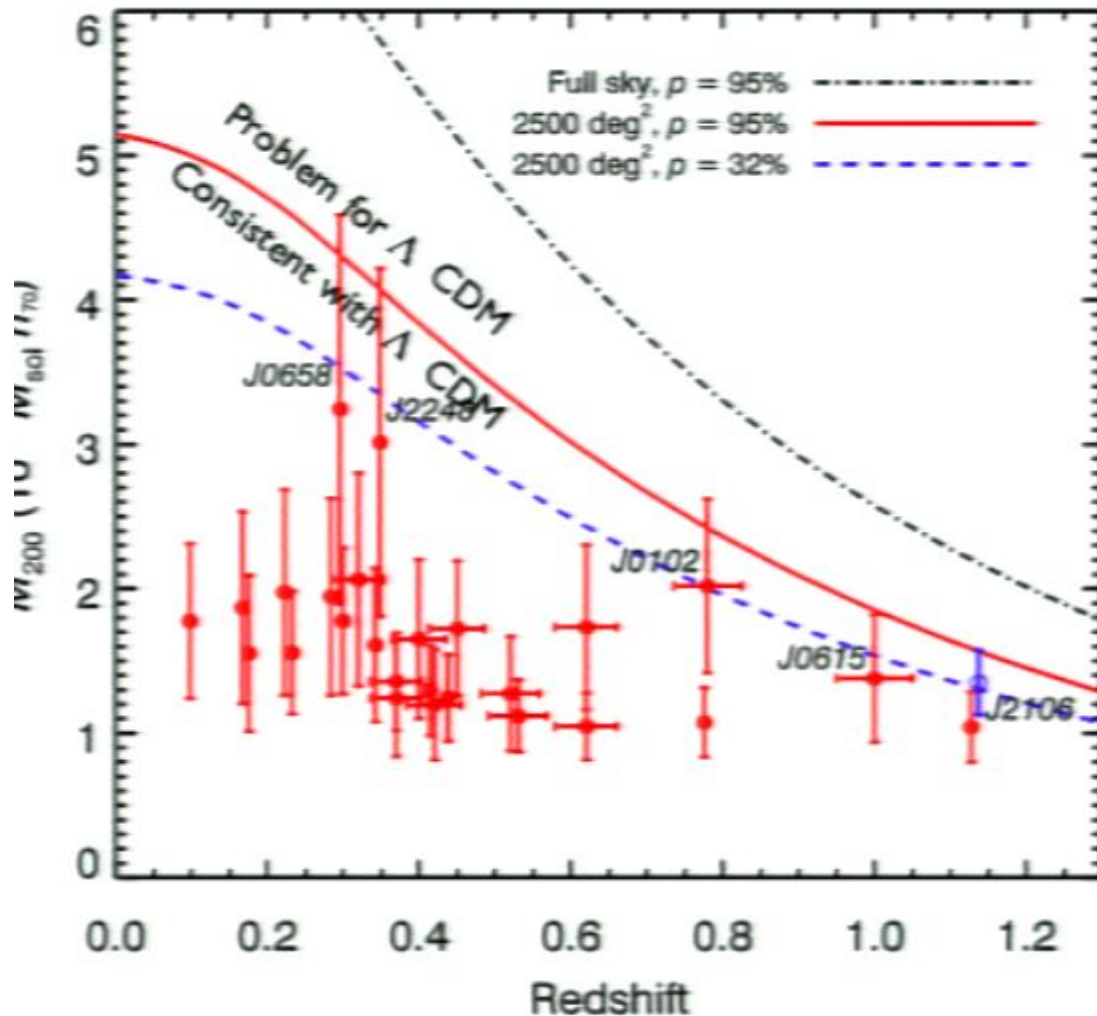
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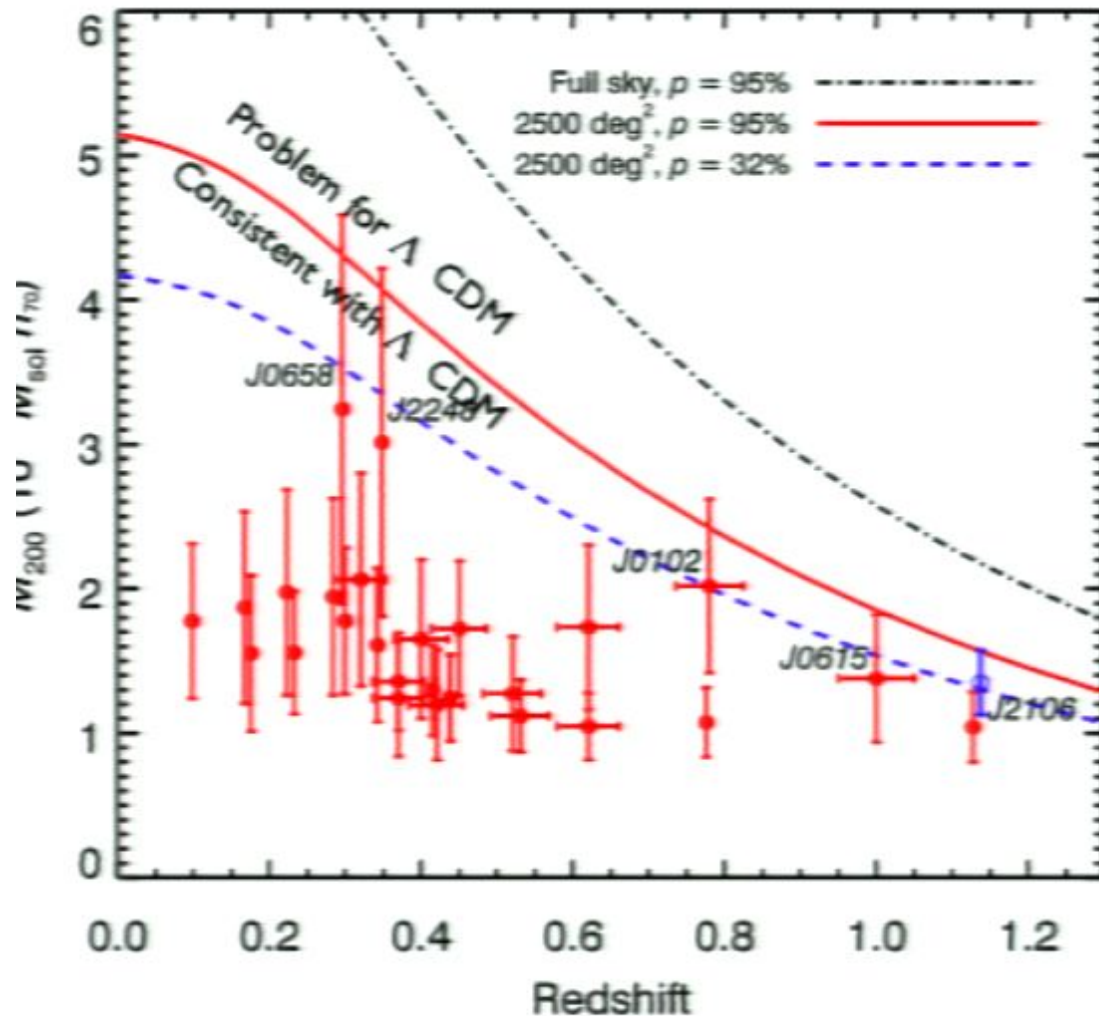


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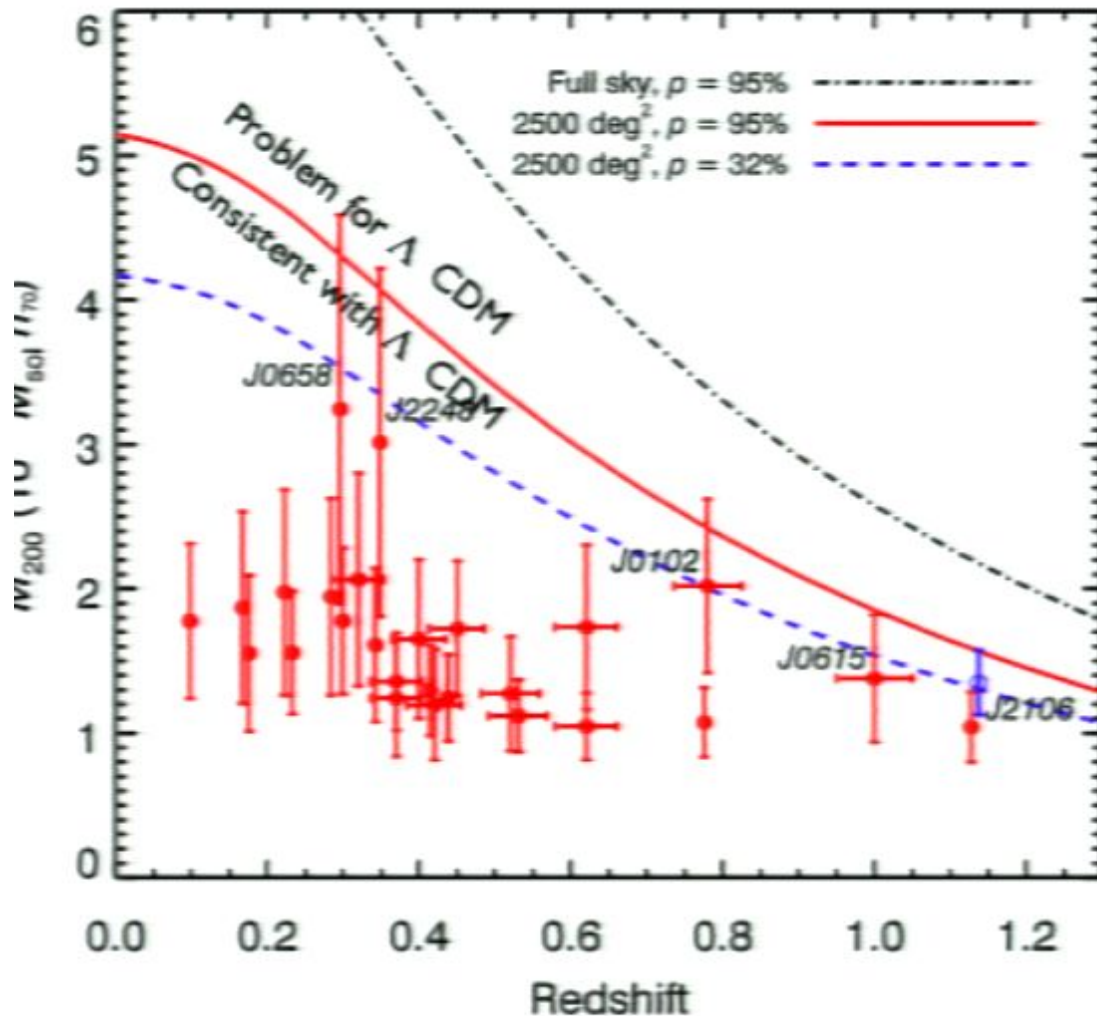
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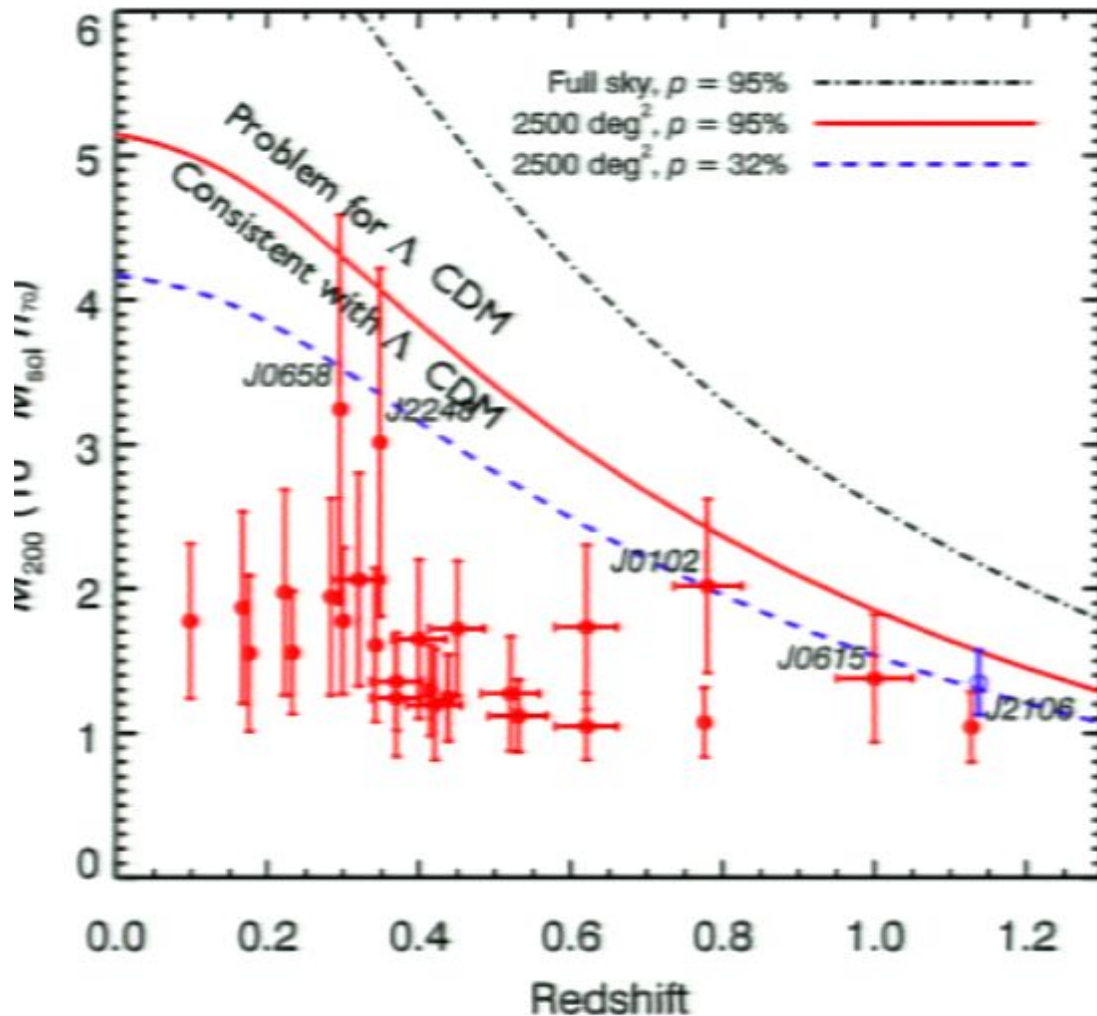
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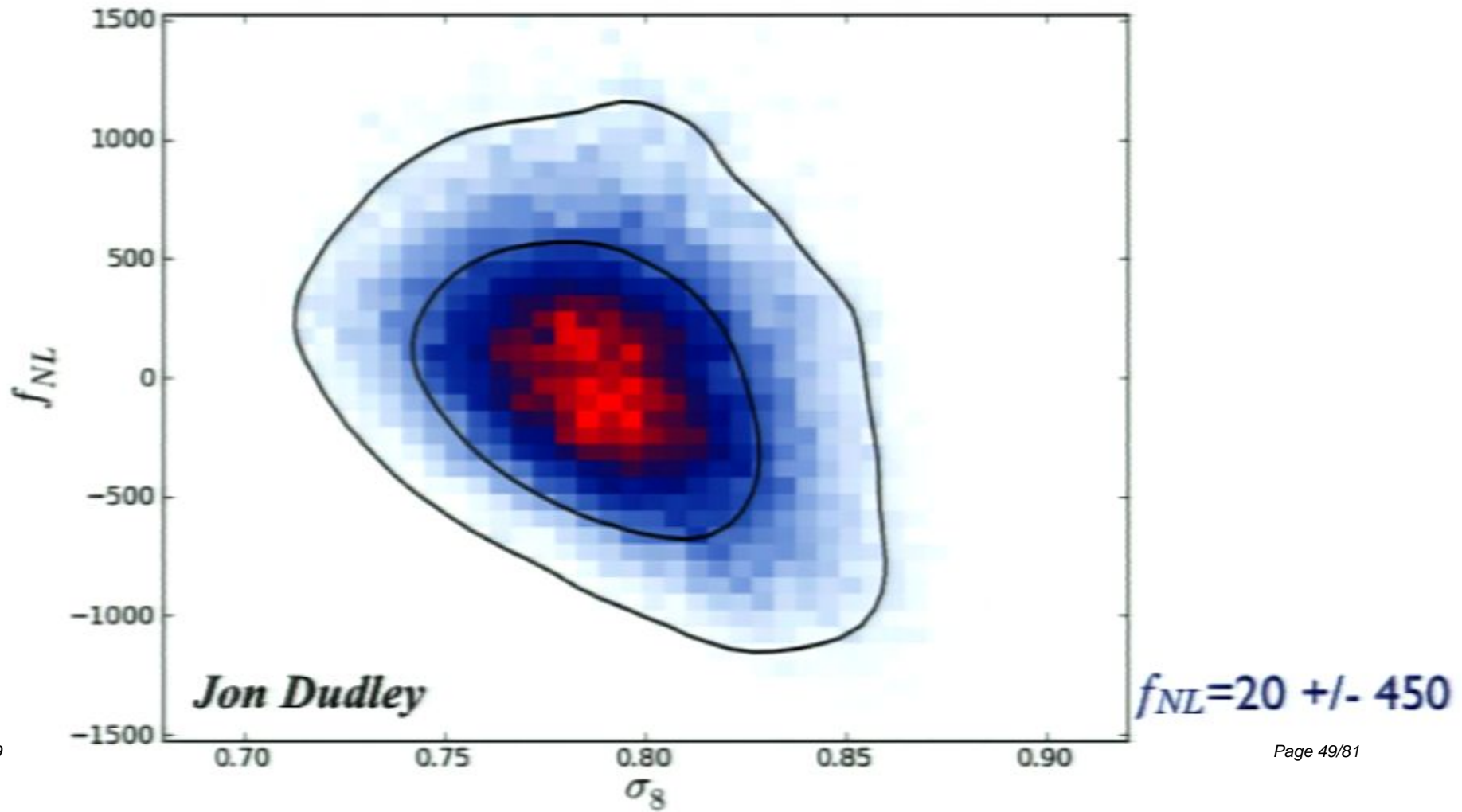
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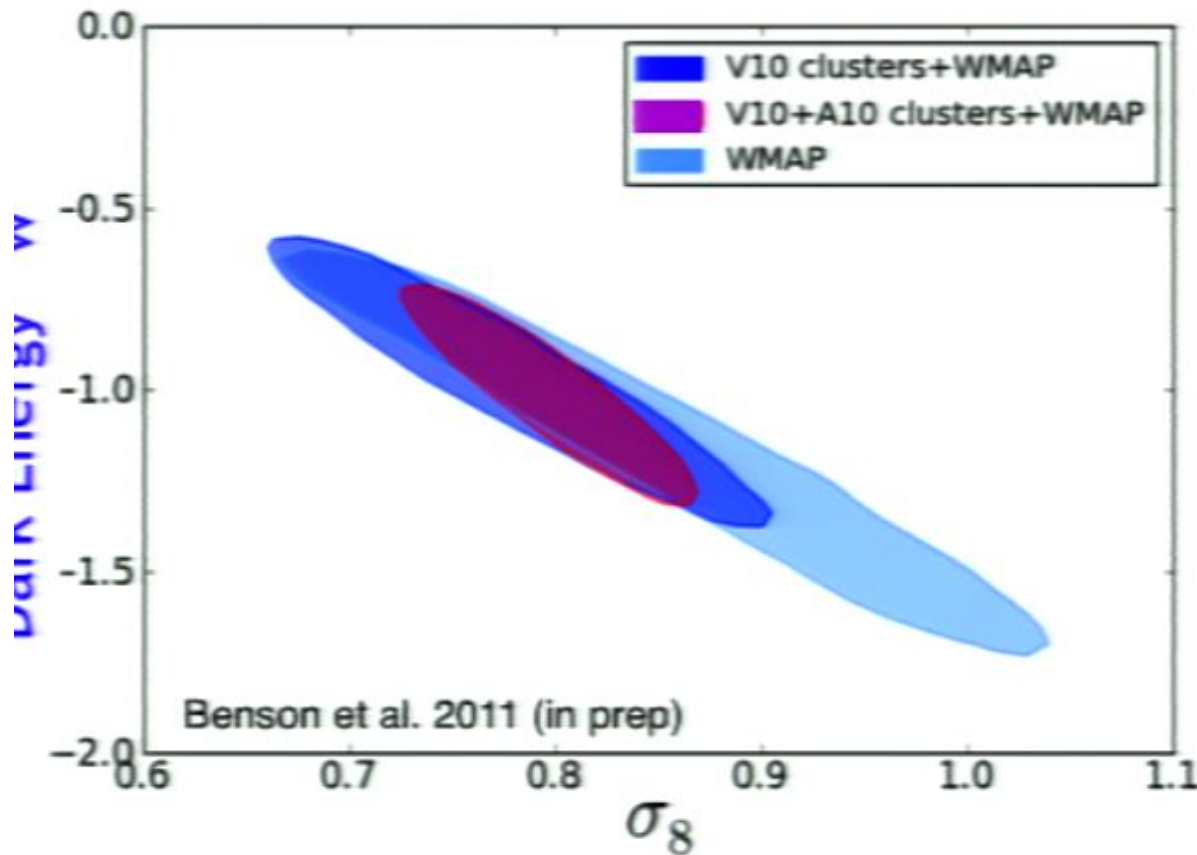
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- huge clusters at  $z \sim 1$  turn out to be expected in LCDM, this is just the first time anyone has seriously looked



# SPT Cosmological Constraints with X-rays



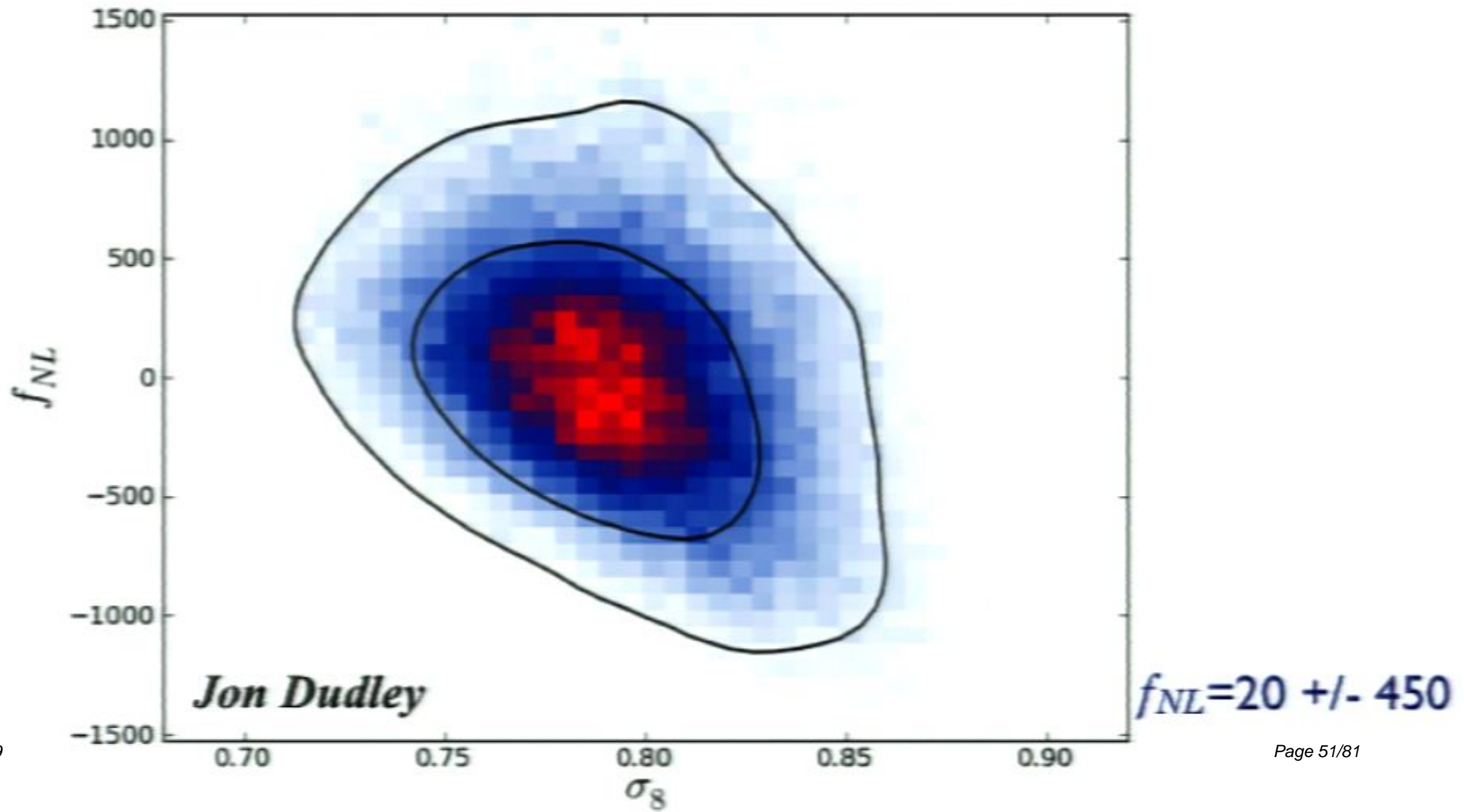
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- X-ray measurements reduce mass uncertainty from 25% to 10%
- Improves 2l cluster cosmological constraints on  $\sigma_8$  by  $\sim 50\%$  and  $w$  by  $\sim 30\%$

*using just 2008 data (one night!)*

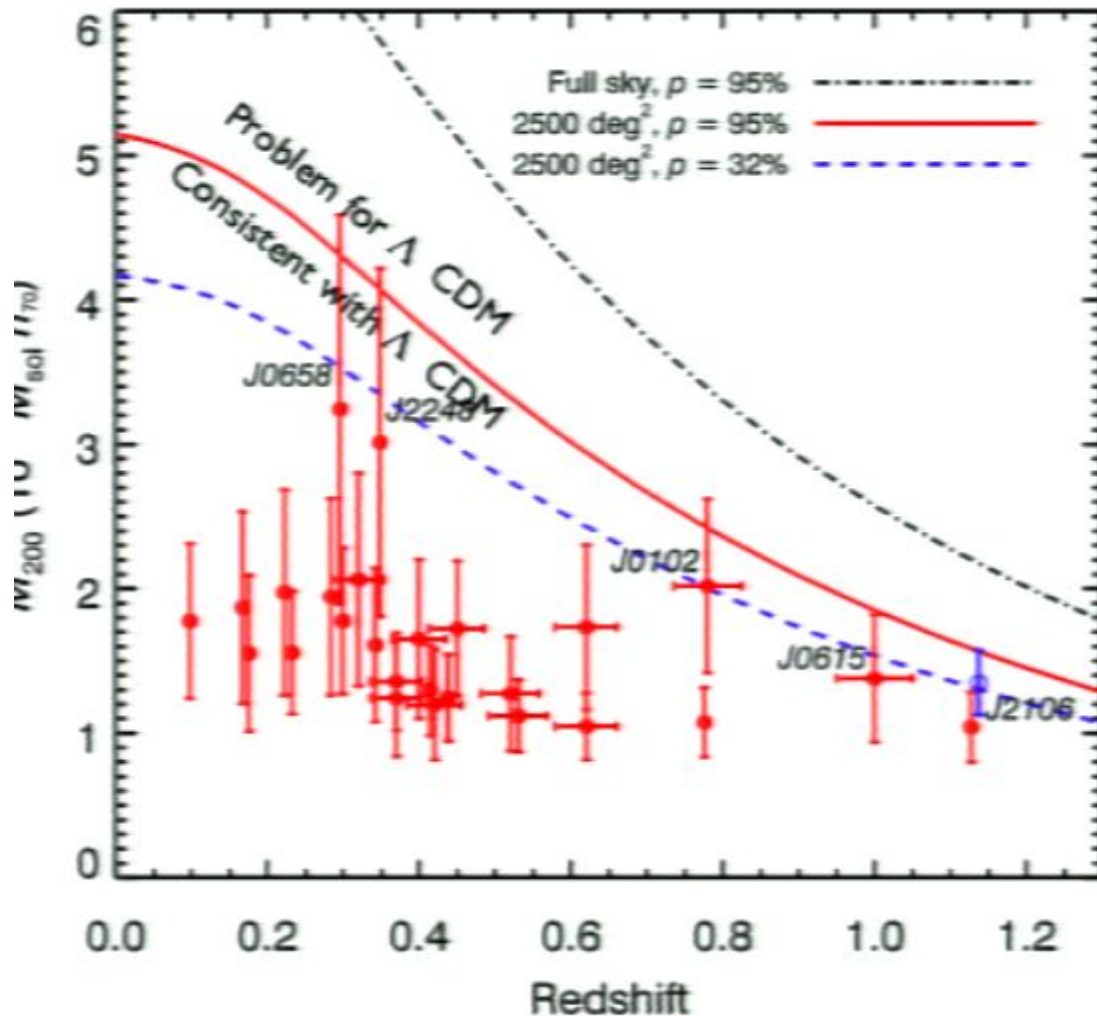


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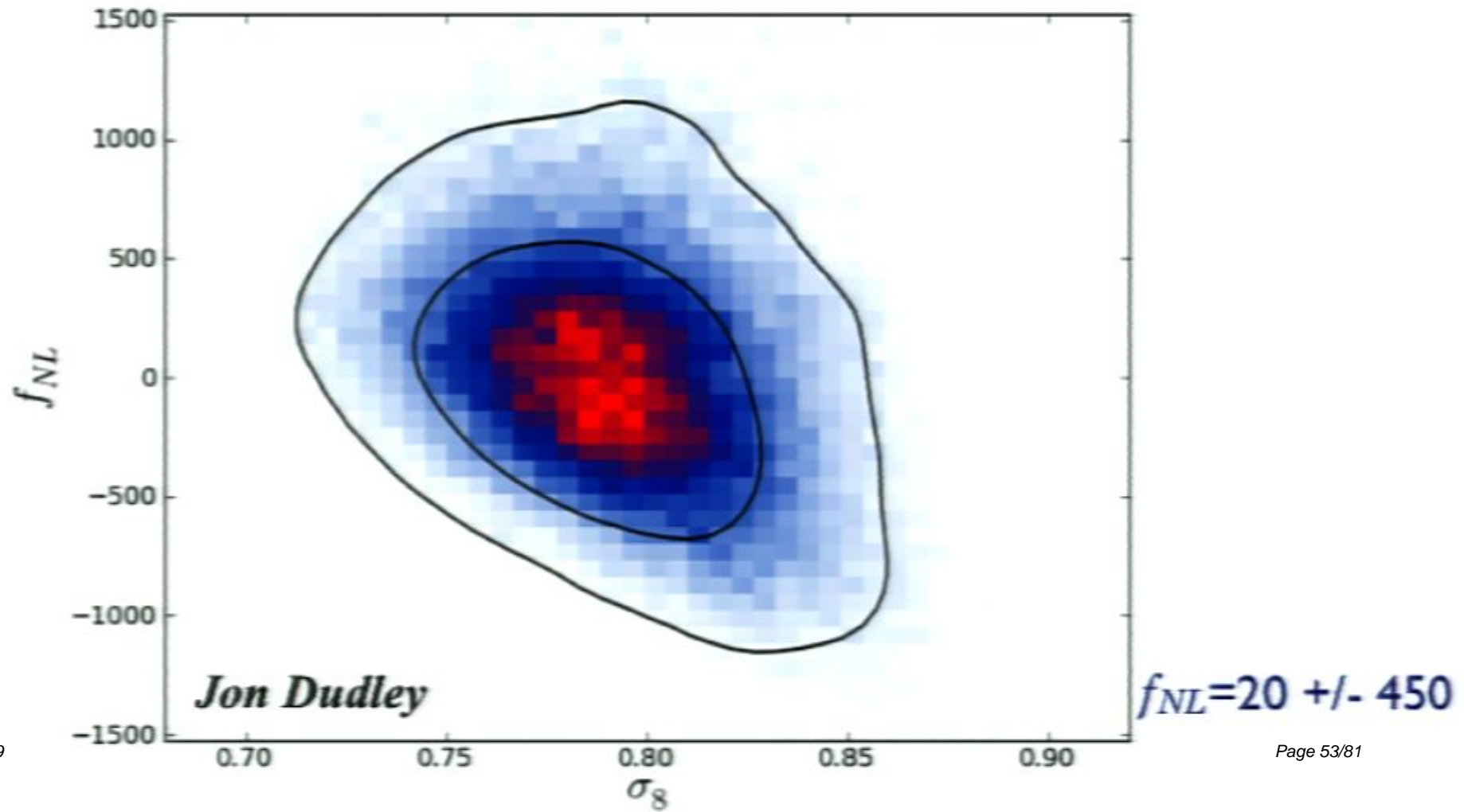
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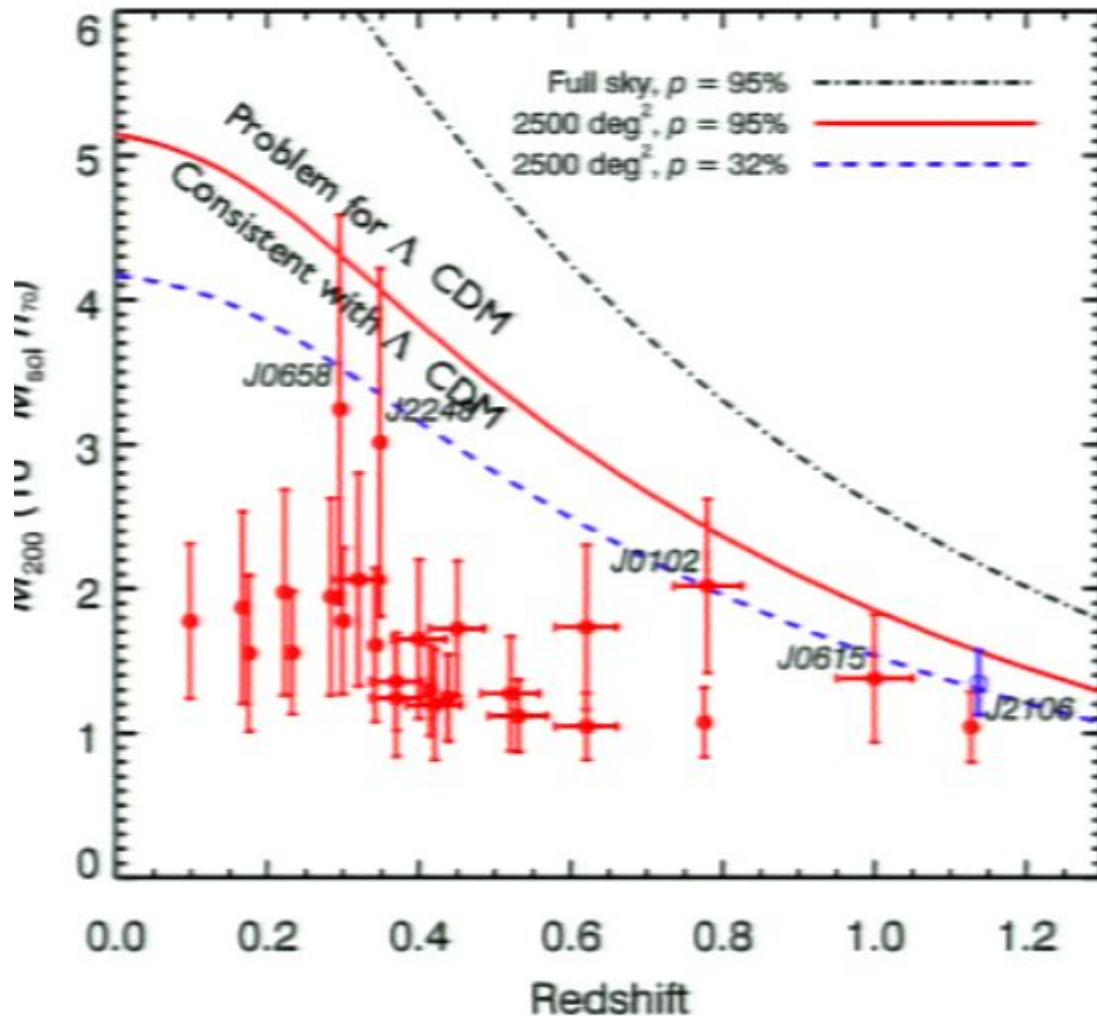
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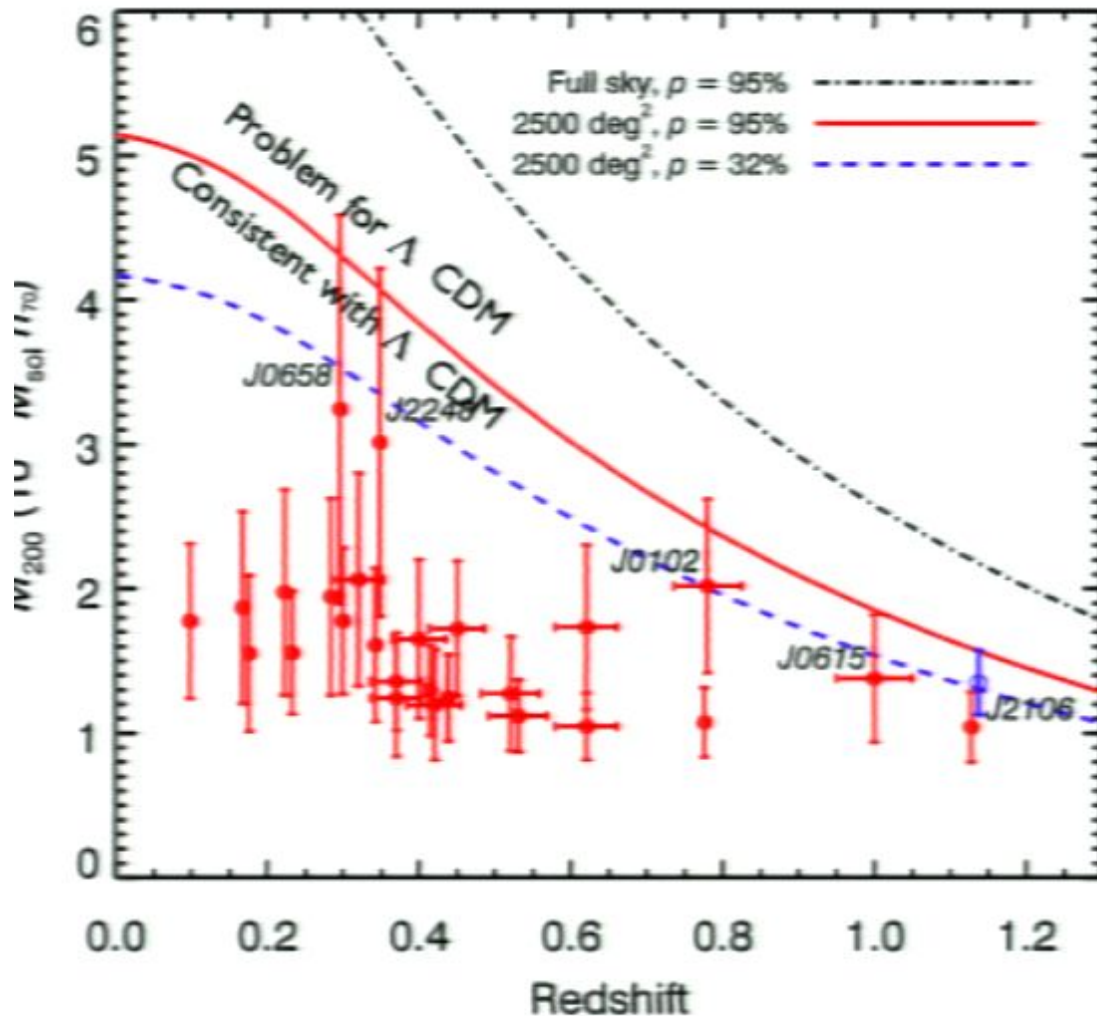


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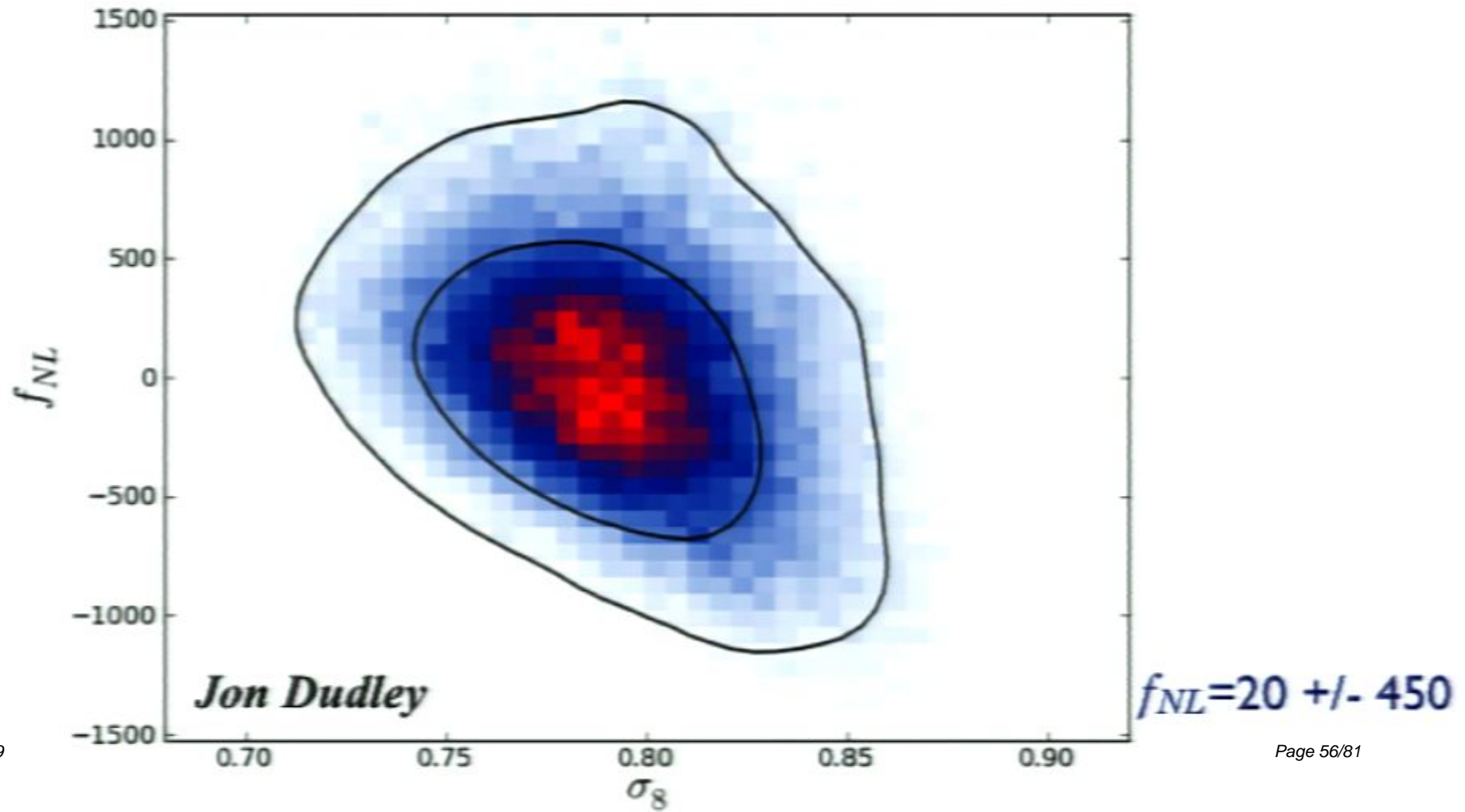
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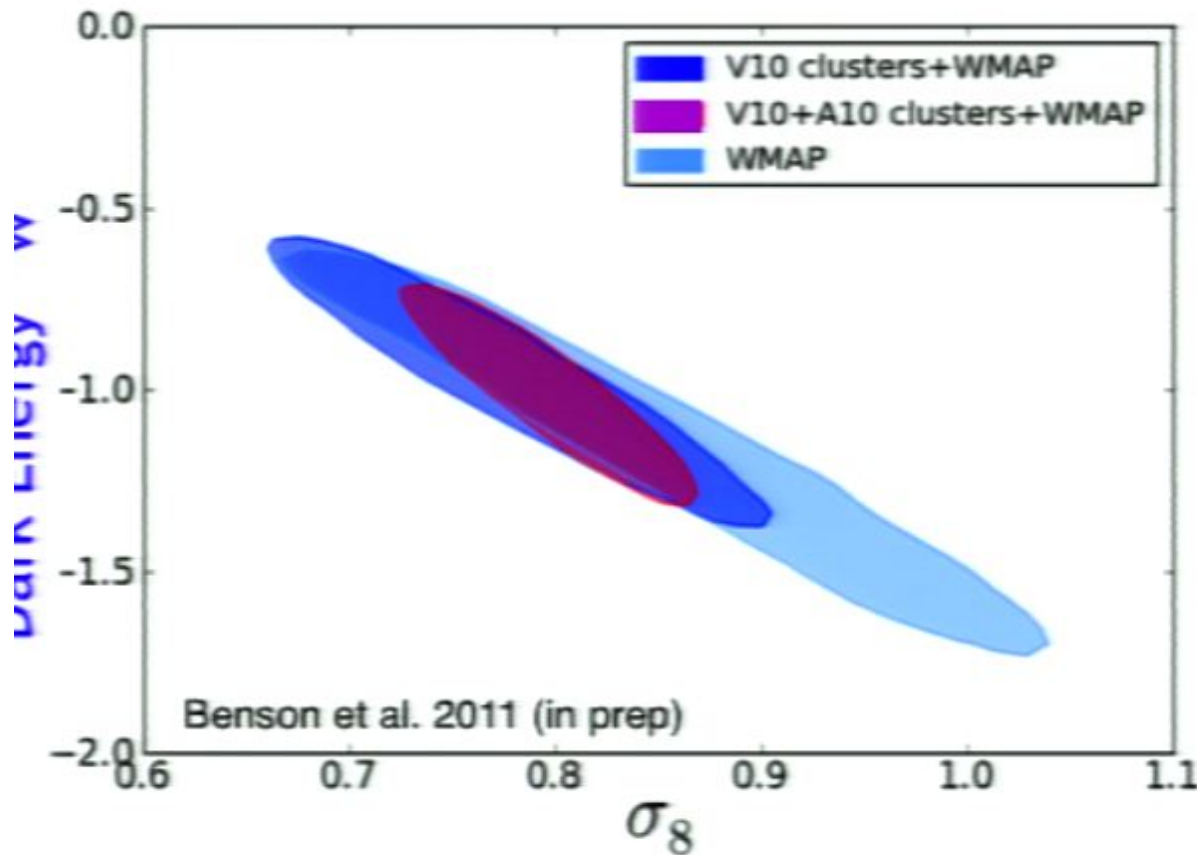
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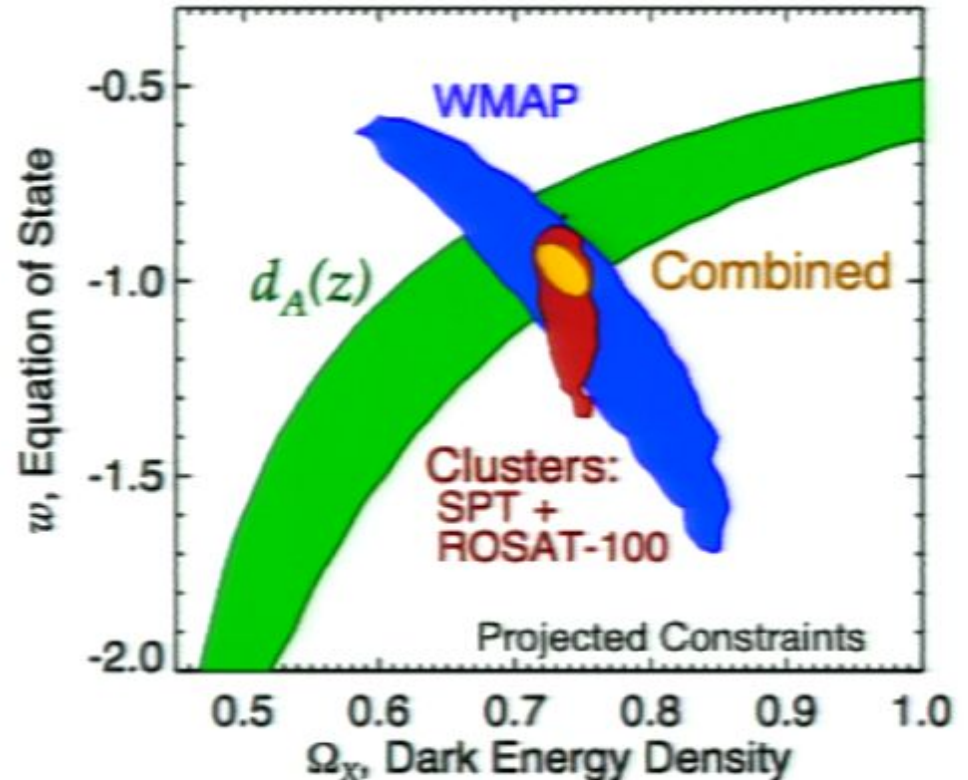
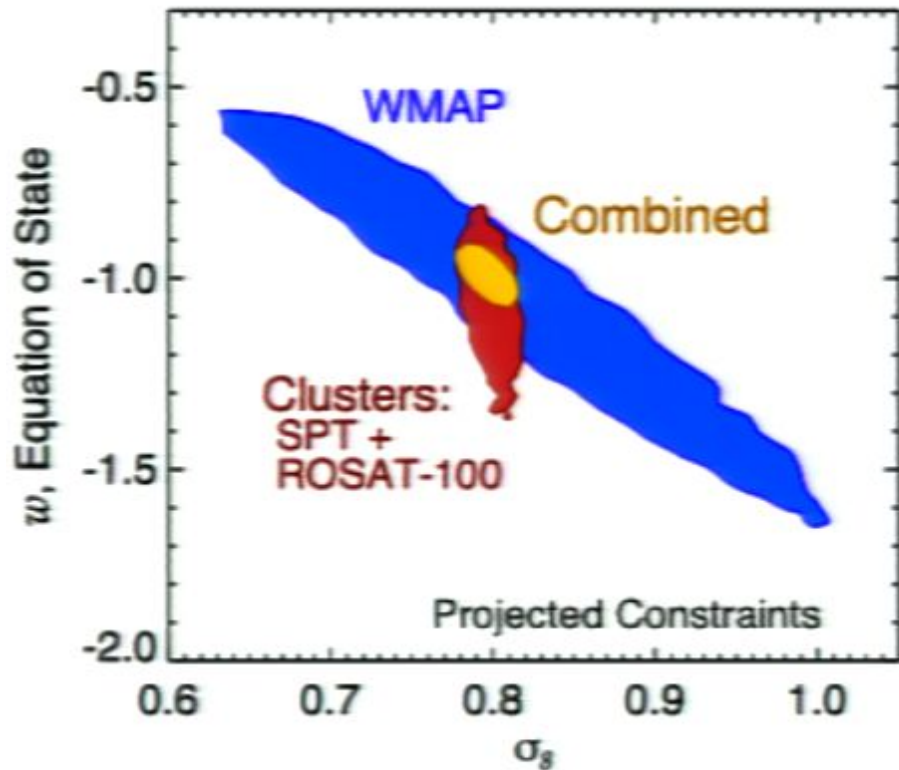
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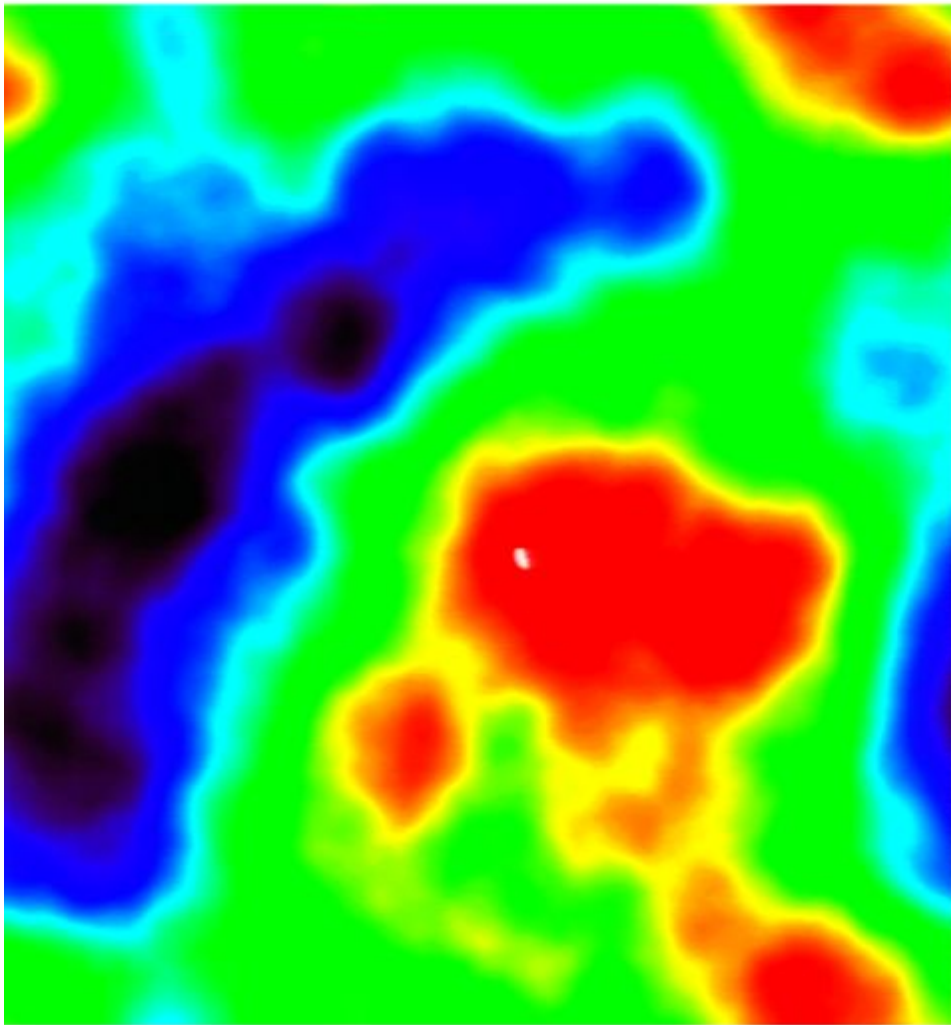
SPT 2500 deg<sup>2</sup> survey will detect  $\sim 440$  clusters at  $S/N > 5$ . With mass calibration uncertainty of 5% mean and 10% evolution ( $z=0.0$ -to- $1.0$ ), will constrain  $\sigma_8$  to  $\pm 1.2\%$  and  $w$  to  $\pm 4.6\%$

- independent of geometric cosmological constraints (SN, BAO)
- 3.3% systematic uncertainty in  $w$  from mass calibration

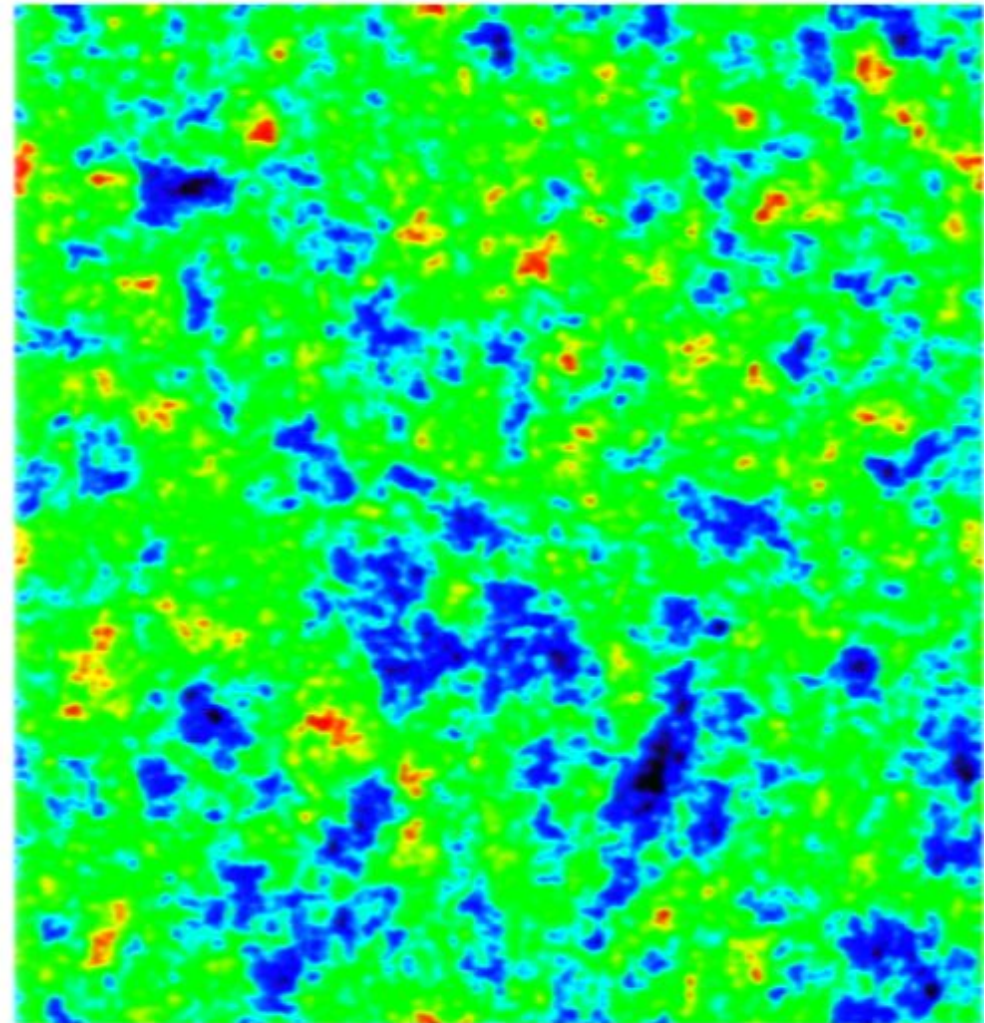


# Lensing of the CMB

17°x17°



lensing potential

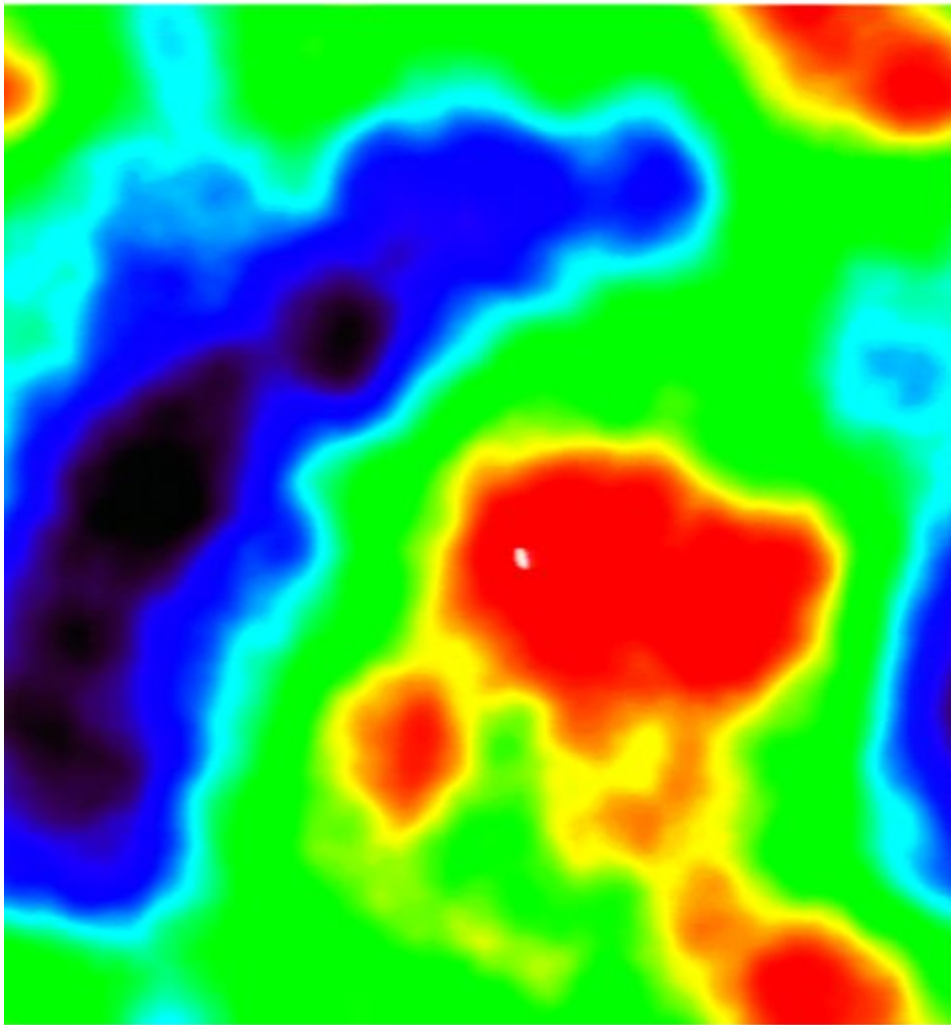


unlensed cmb

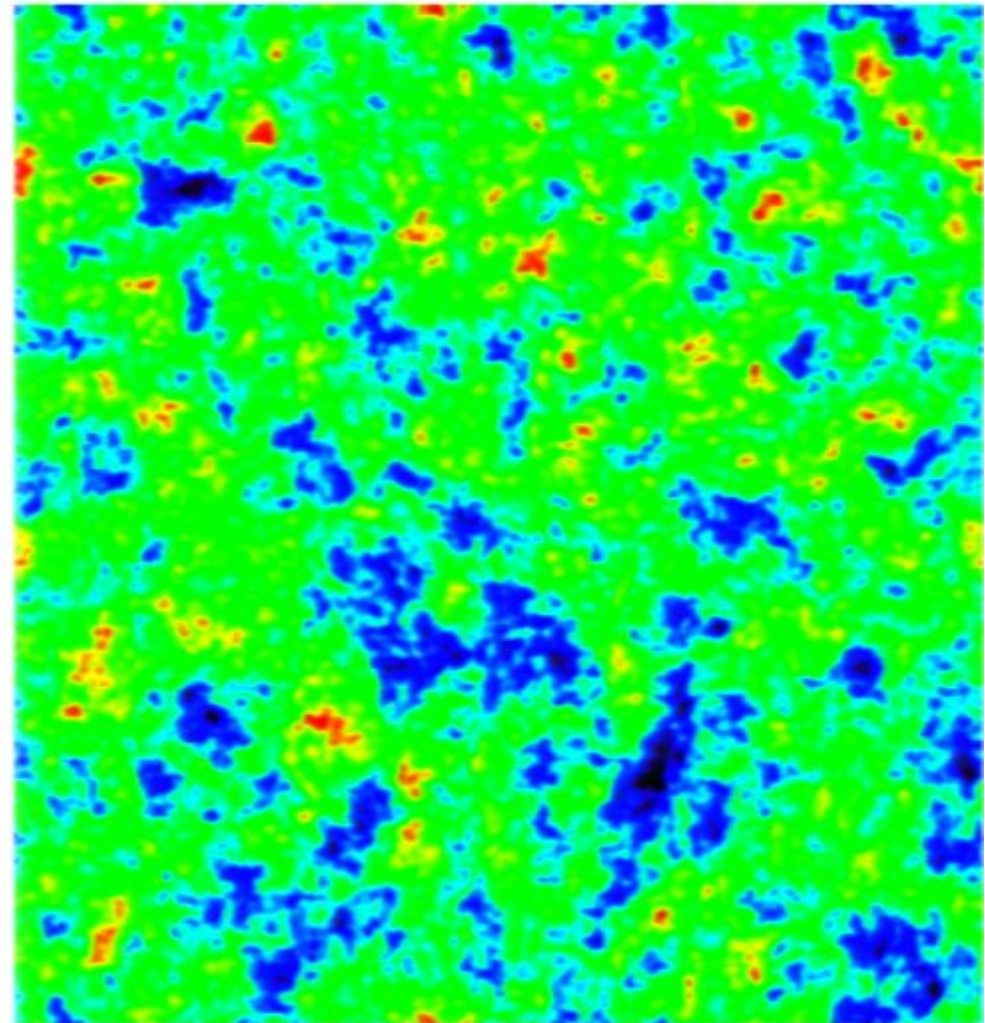


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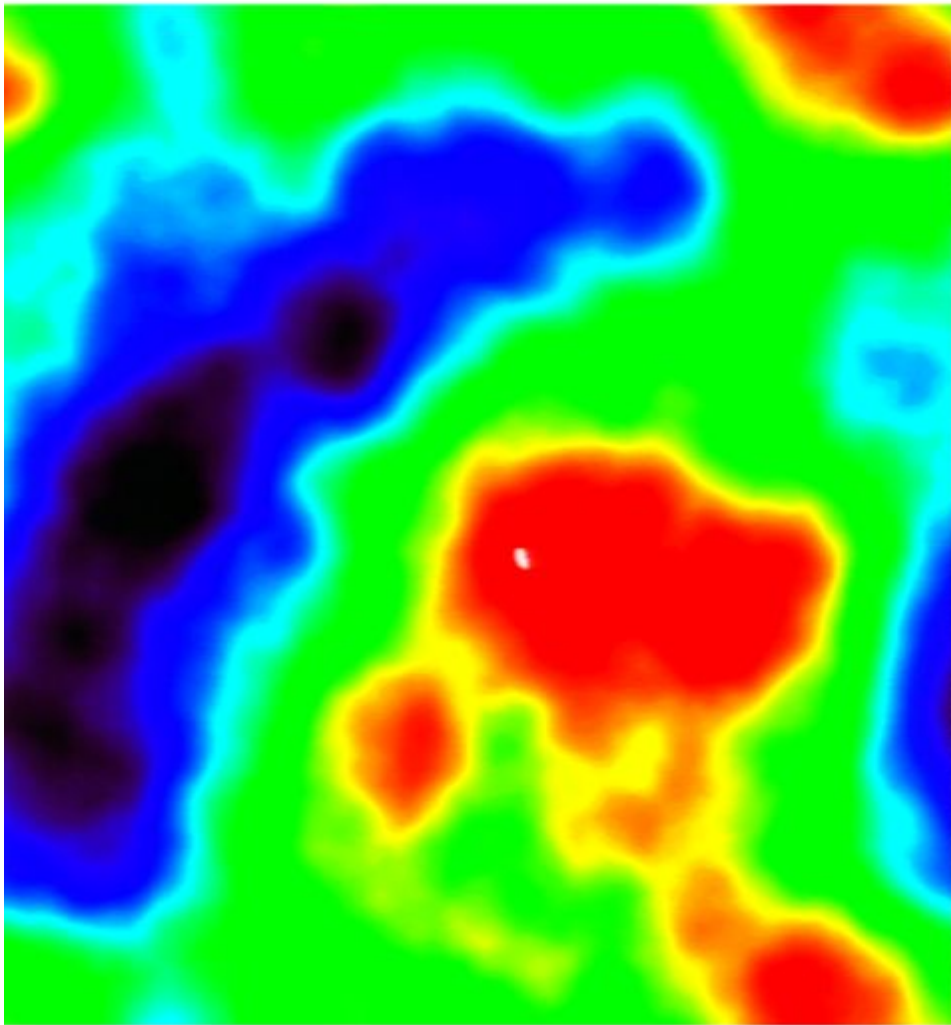
lensing potential



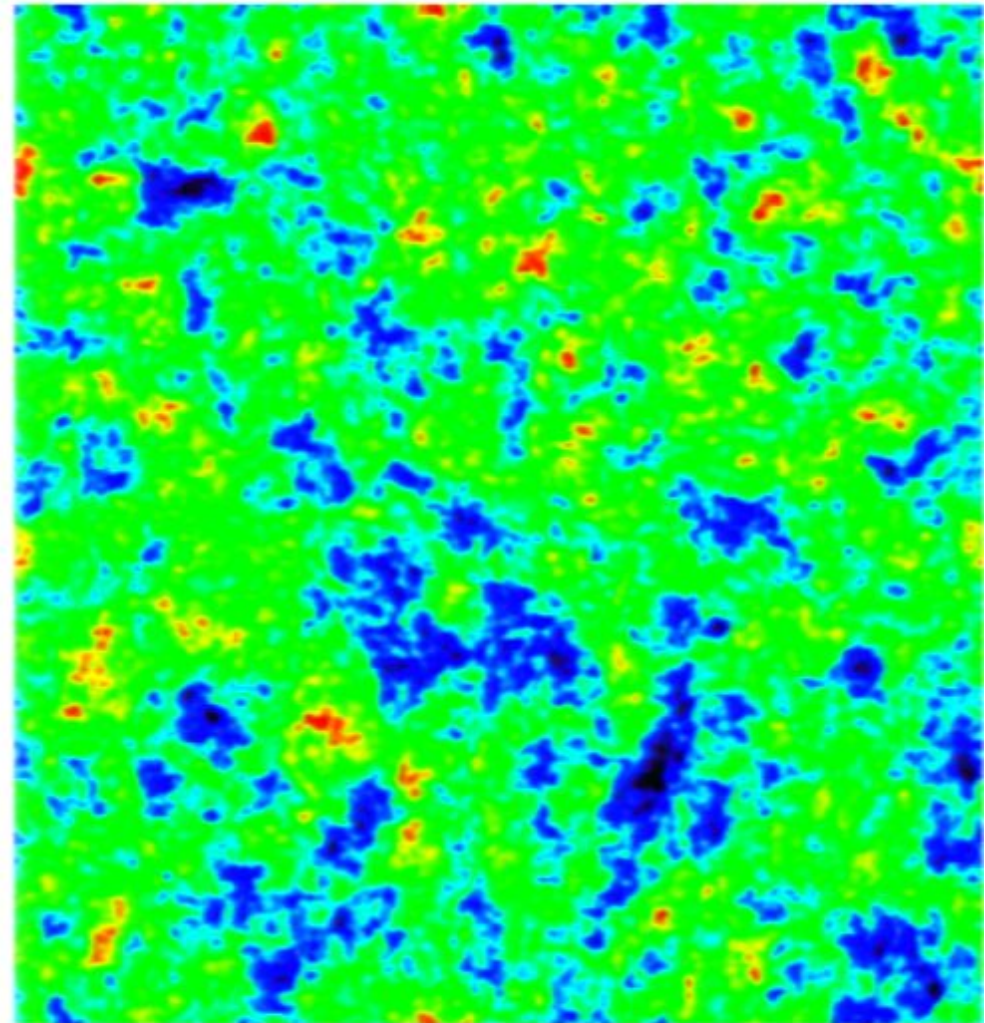
lensed cmb

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lensing potential

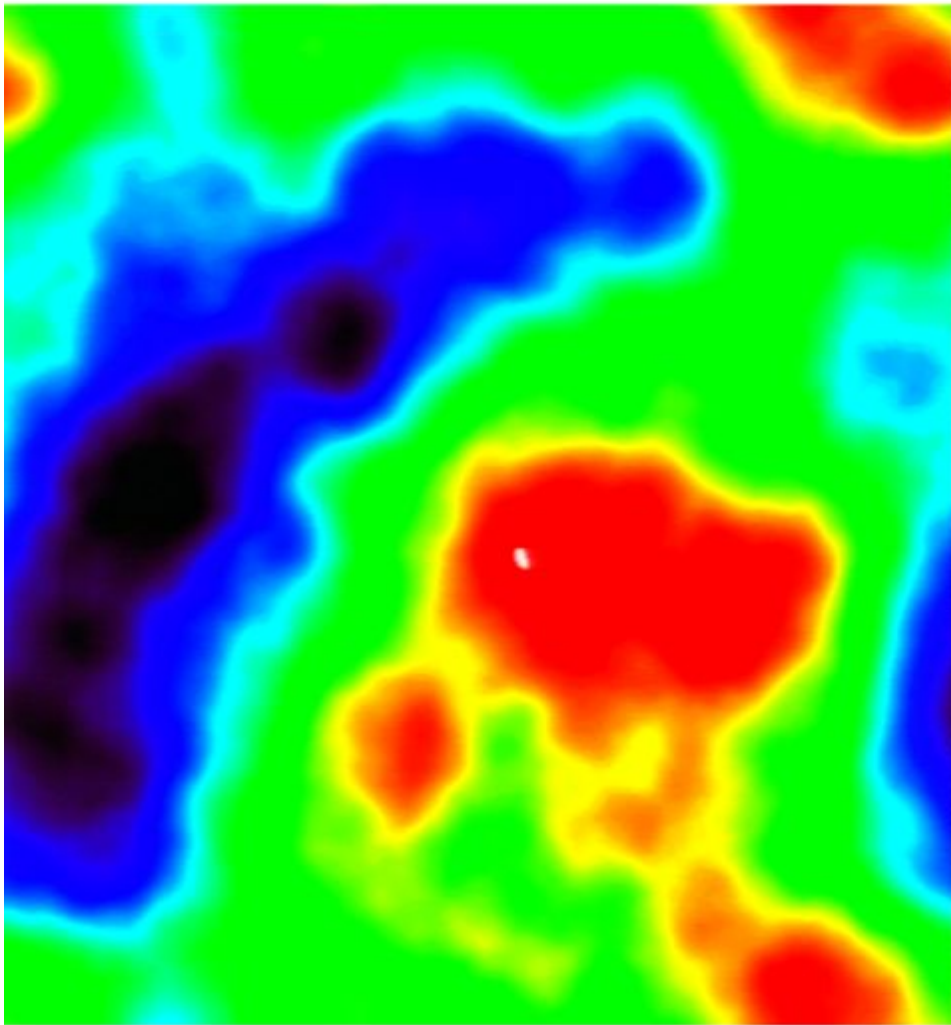


lensed cmb

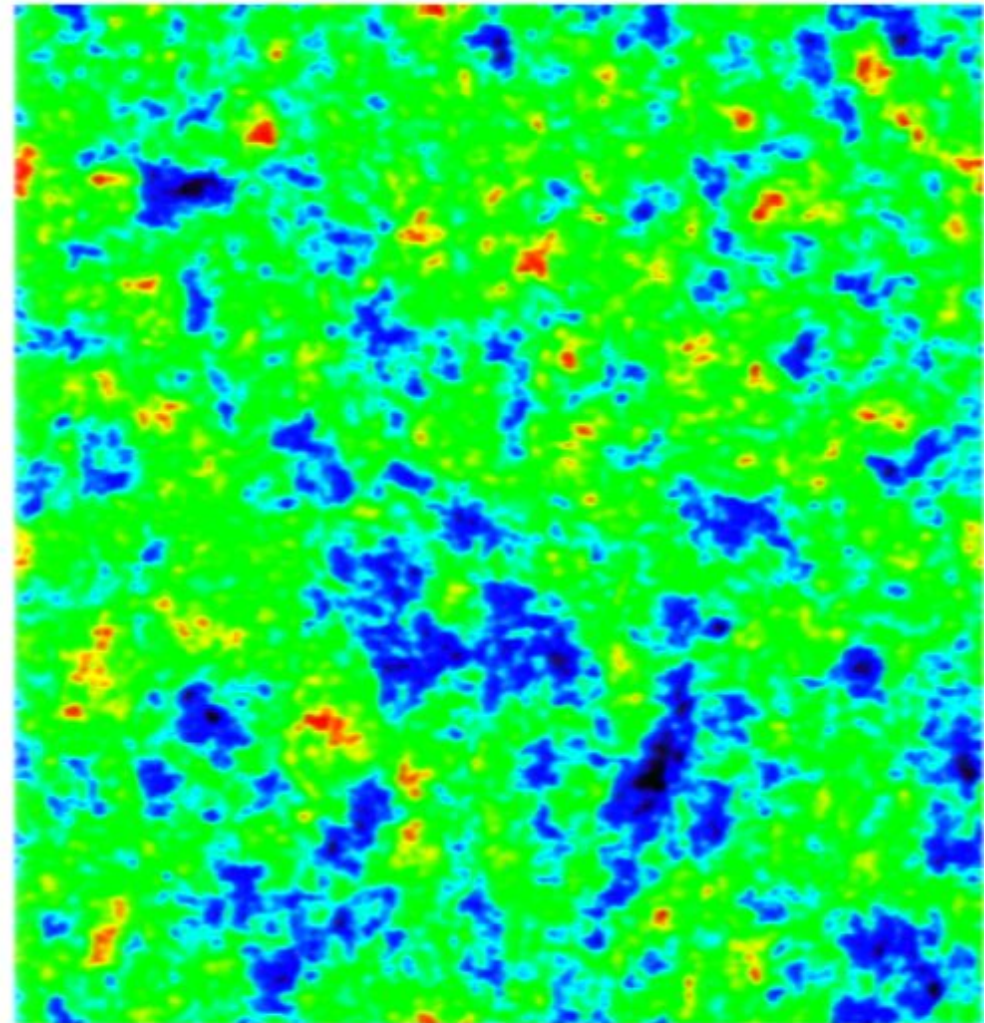


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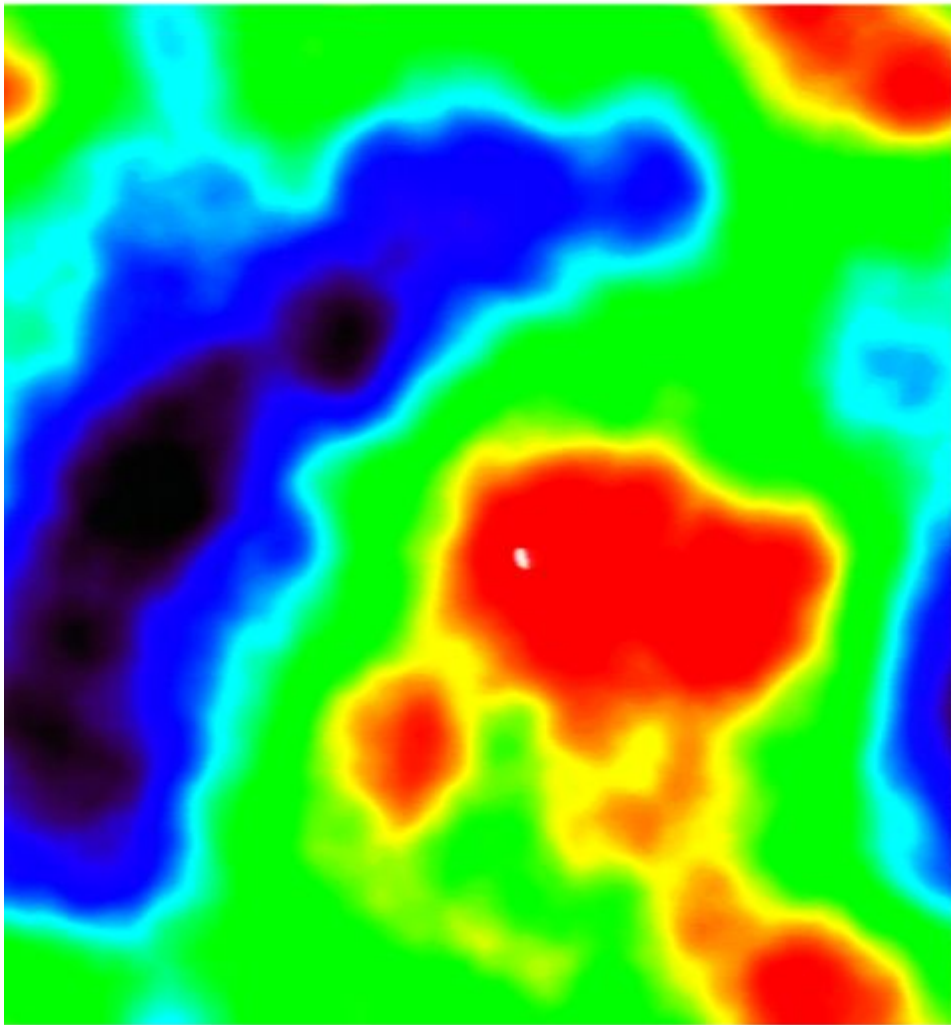


lensed cmb

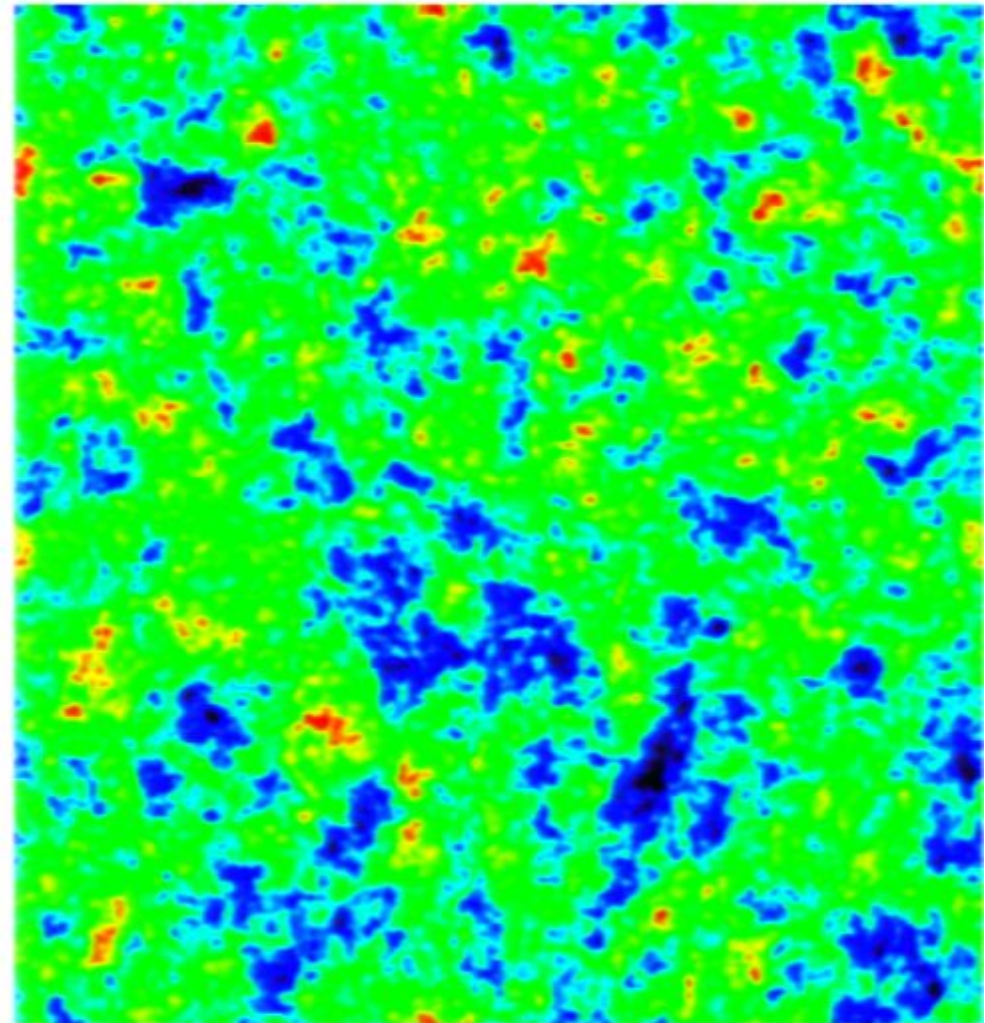


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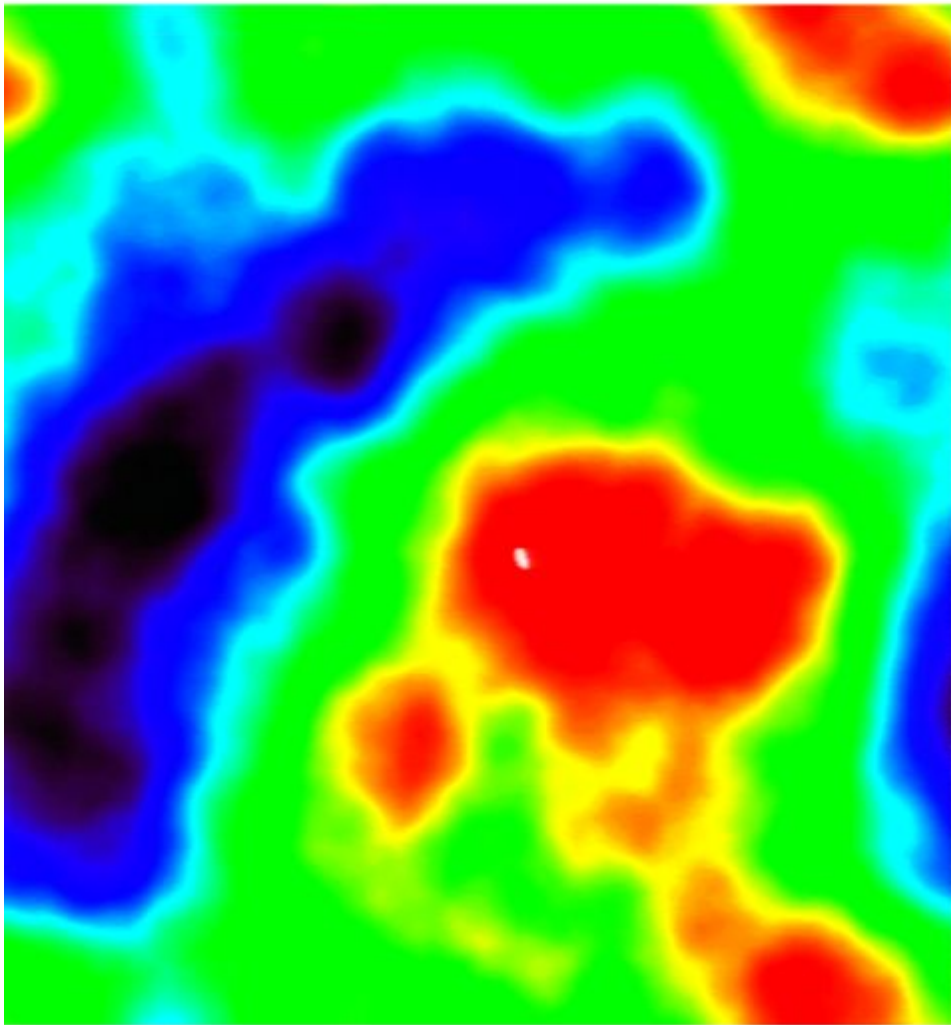
lensing potential



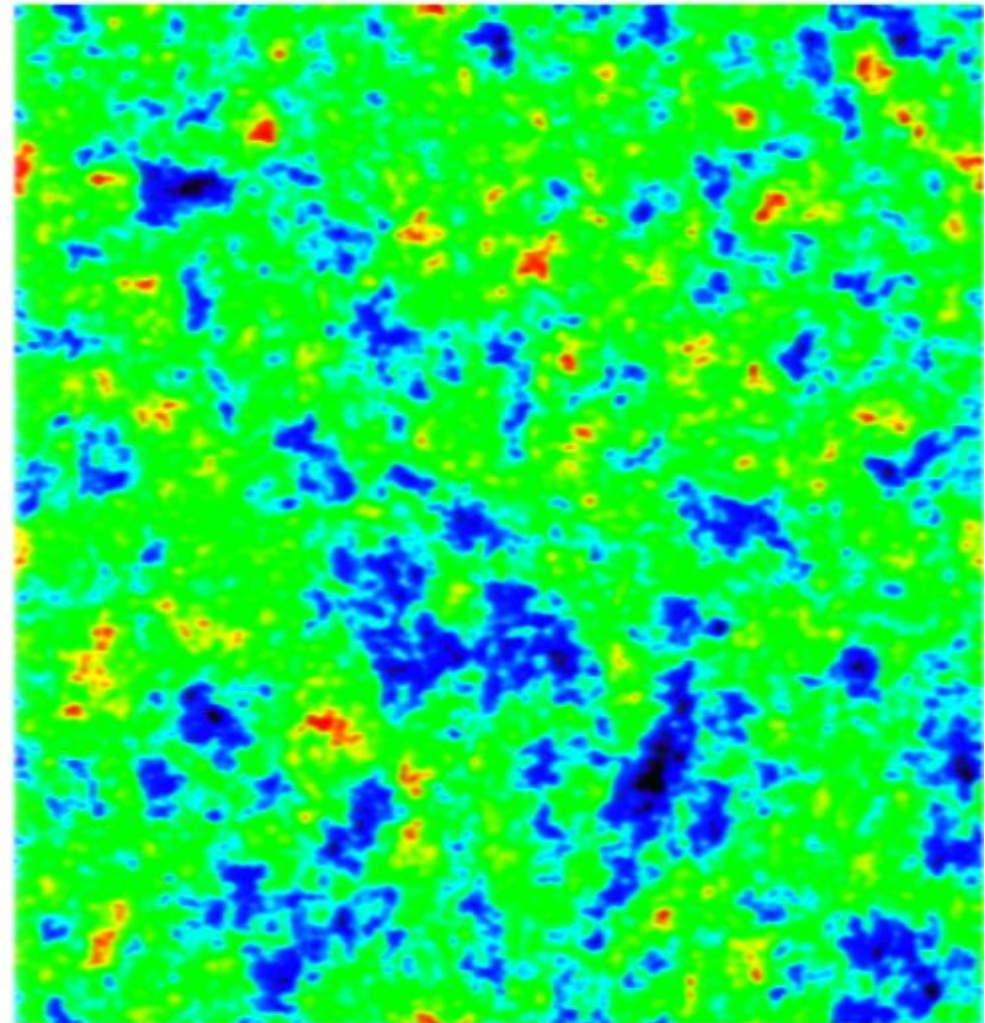
lensed cmb

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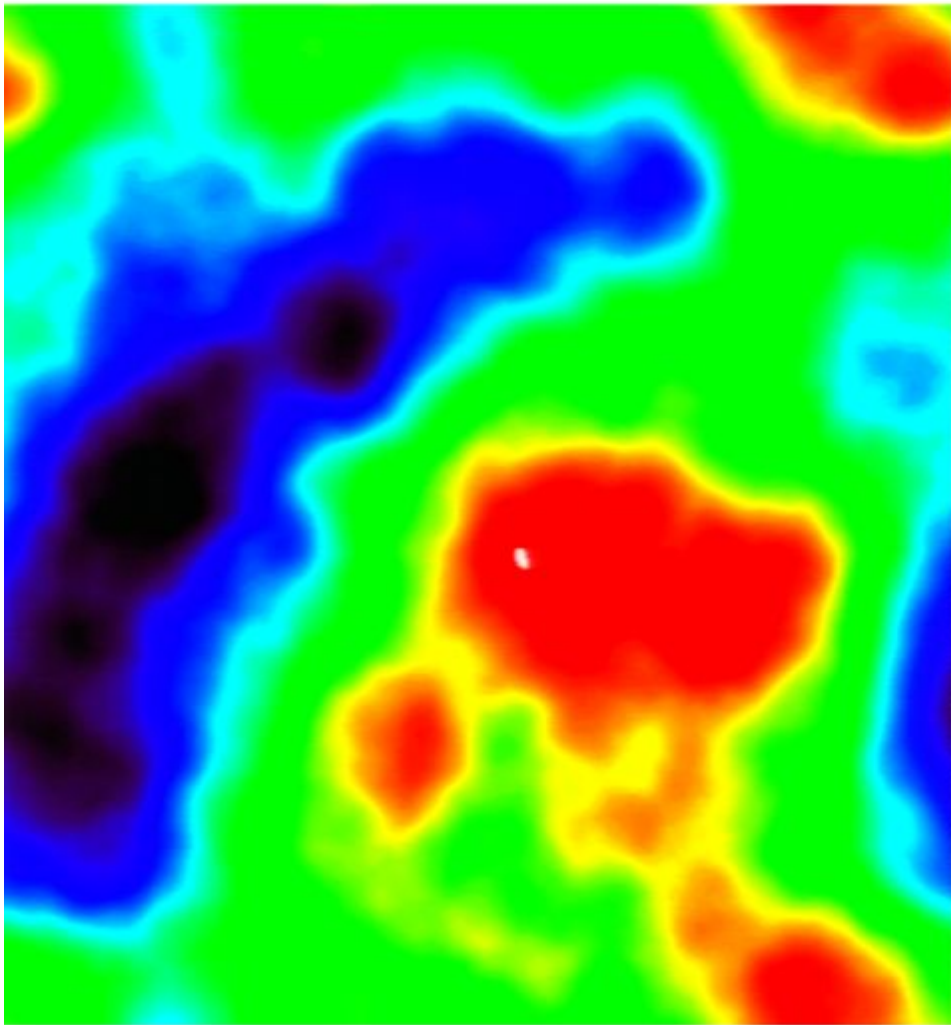


unlensed cmb

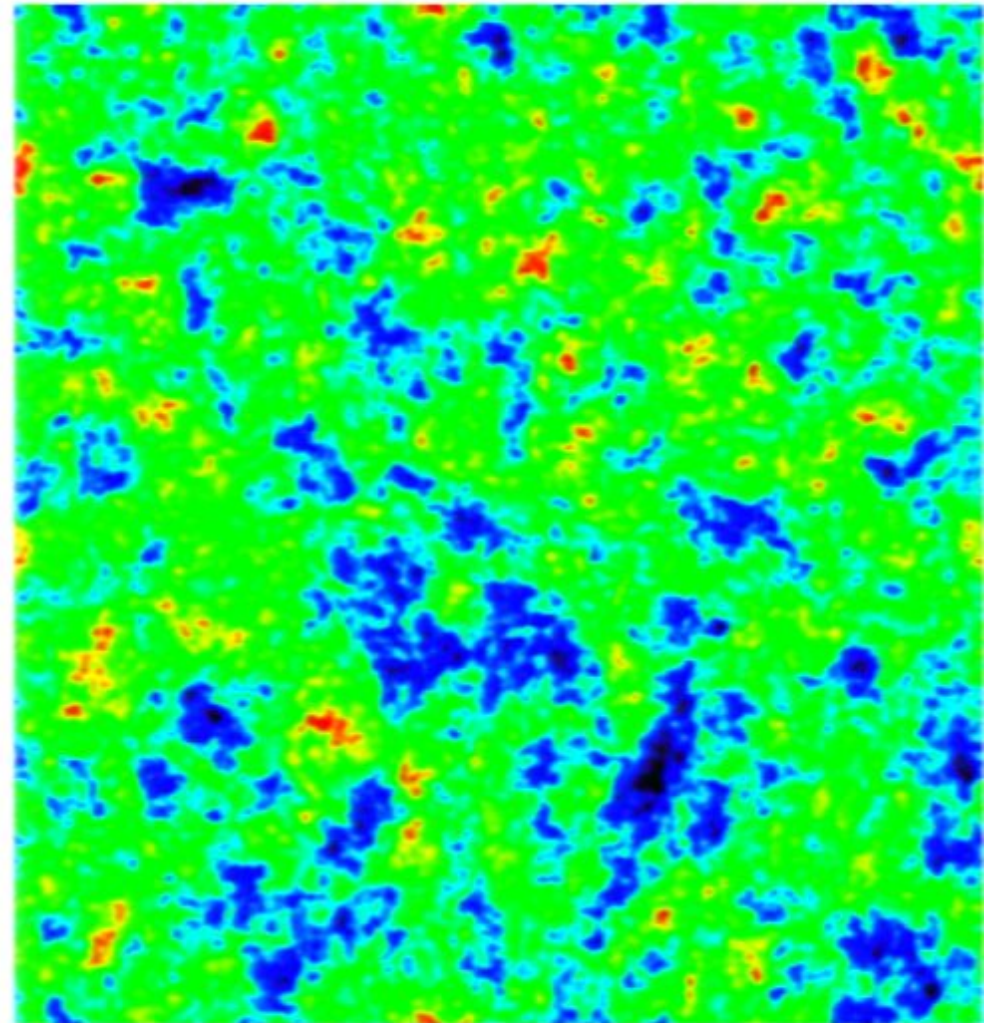


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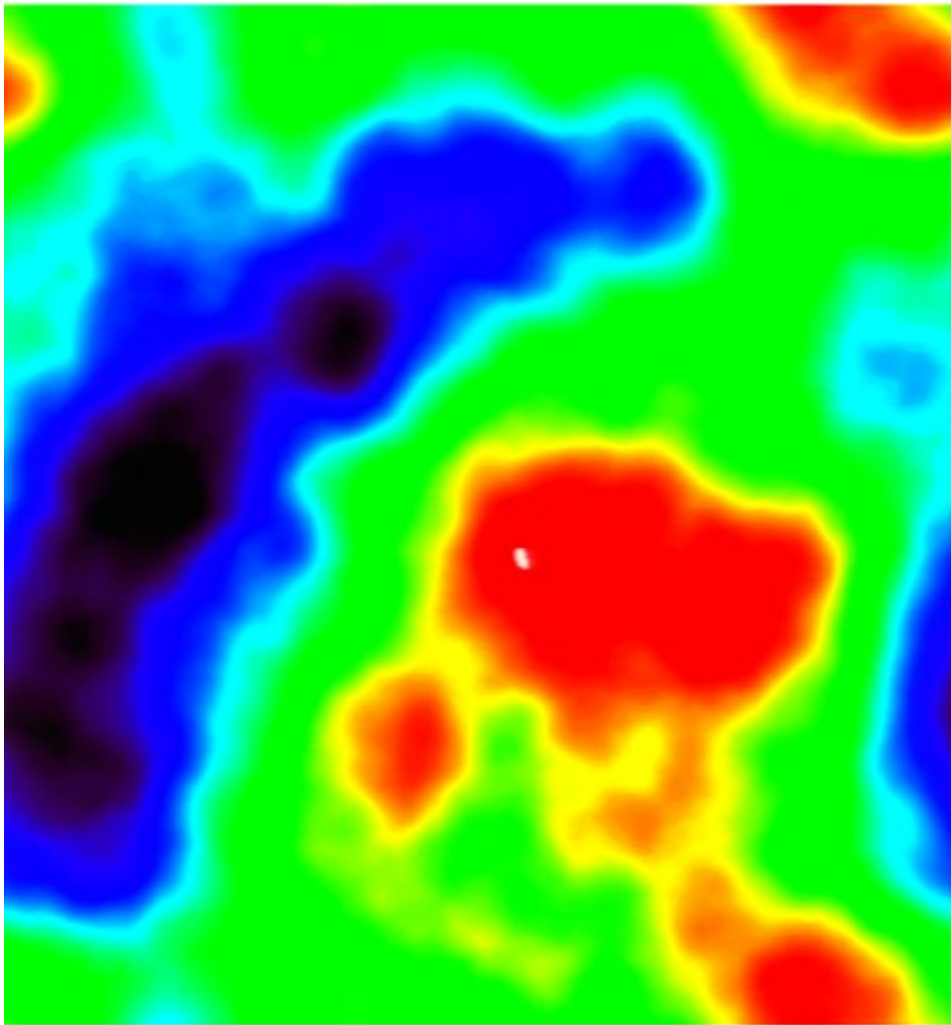


unlensed cmb

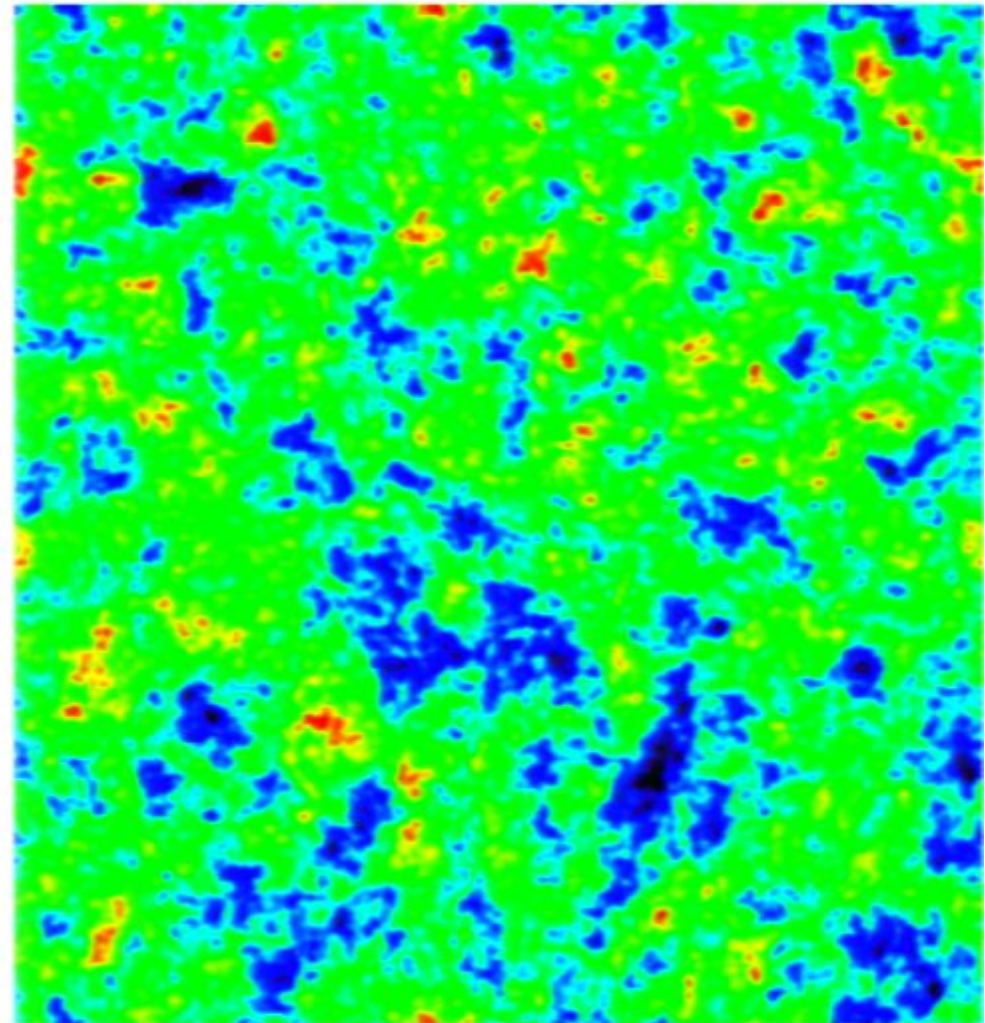


# Lensing of the CMB

$17^\circ \times 17^\circ$



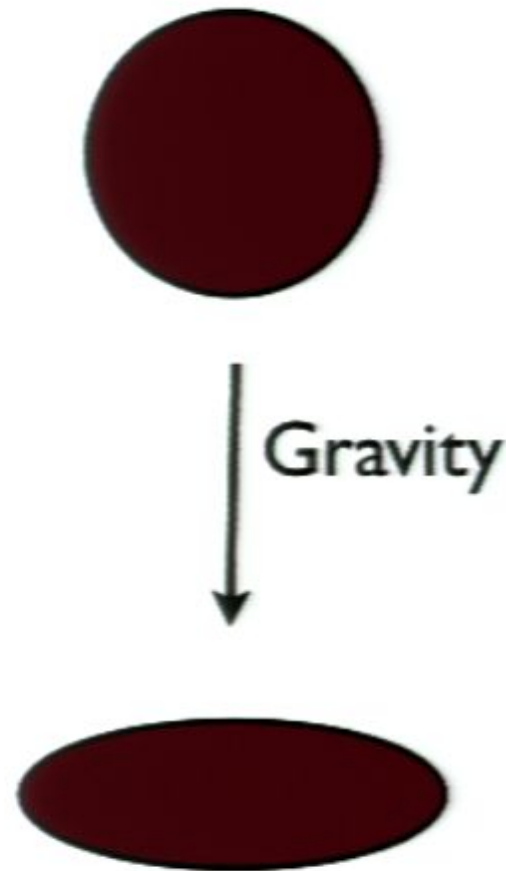
lensing potential



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# *Lensing simplified*

- gravitational potentials distort shapes by stretching, squeezing, shearing





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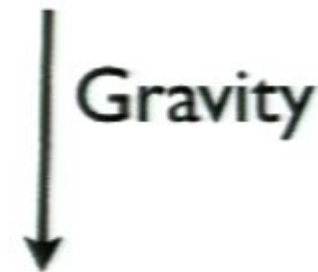


Gravity  
↓



# *Lensing simplified*

- where gravity stretches, gradients become smaller
- where gravity compresses, gradients are smaller

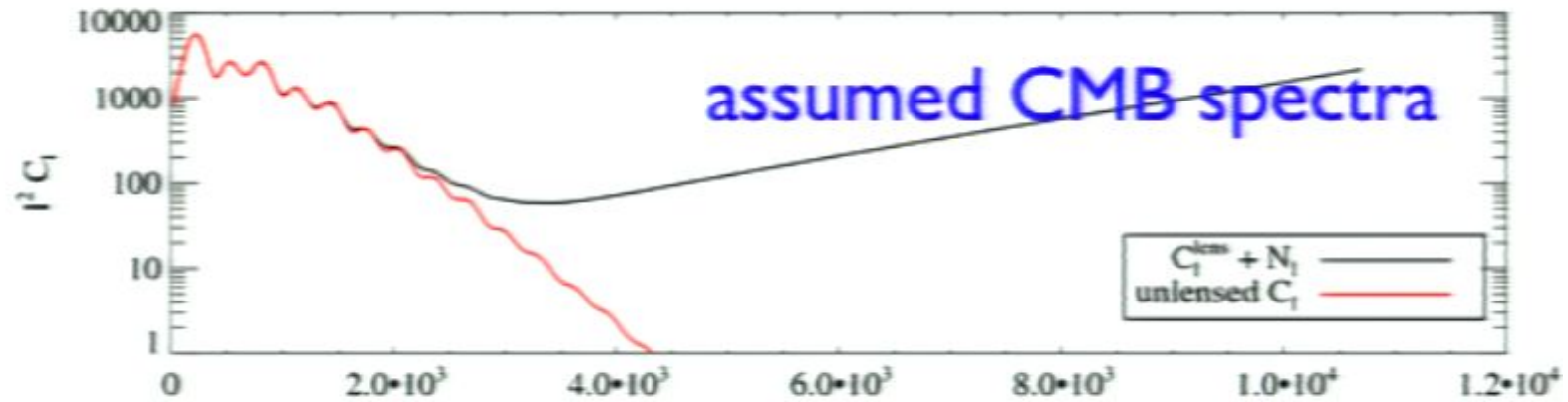




# Effect of lensing

- lensing disturbs the local CMB gradient that is seen on small scales
- correlation between the gradient and the new power induced on small scales
- Idea of estimator is to average over many small distortions around a large scale ( $l \leq \text{few hundred}$ ) density fluctuation, to constrain the fluctuation
- ... average over off-diagonal terms  
 $\langle \theta(l_1) \theta(l_2) \rangle$
- Zaldarriaga & Seljak 1999; optimal filters Hu 2001; discovery via cross-correlation of WMAP with radio number counts, Smith et al 2007 ( $3.4\sigma$ ), Hirata et al 2008 ( $2.5\sigma$ )

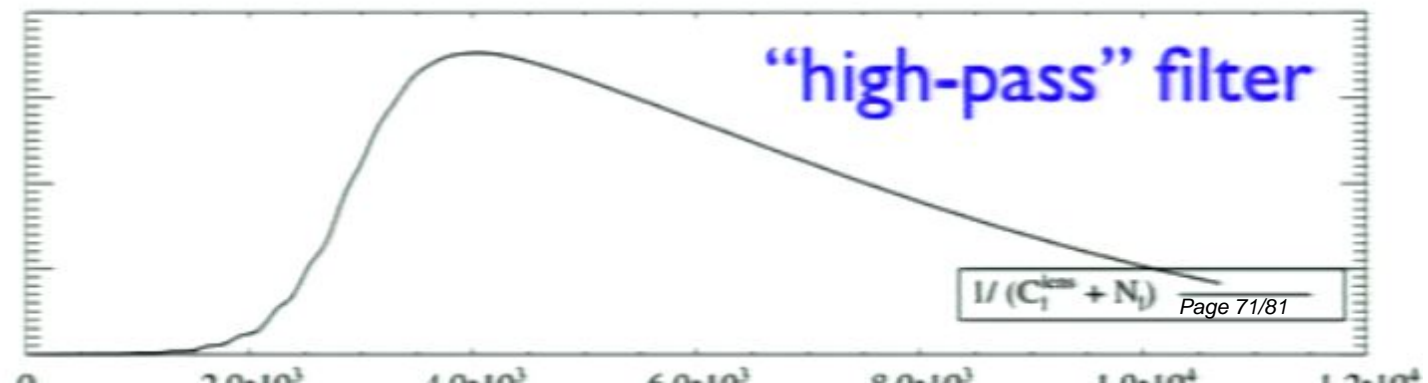
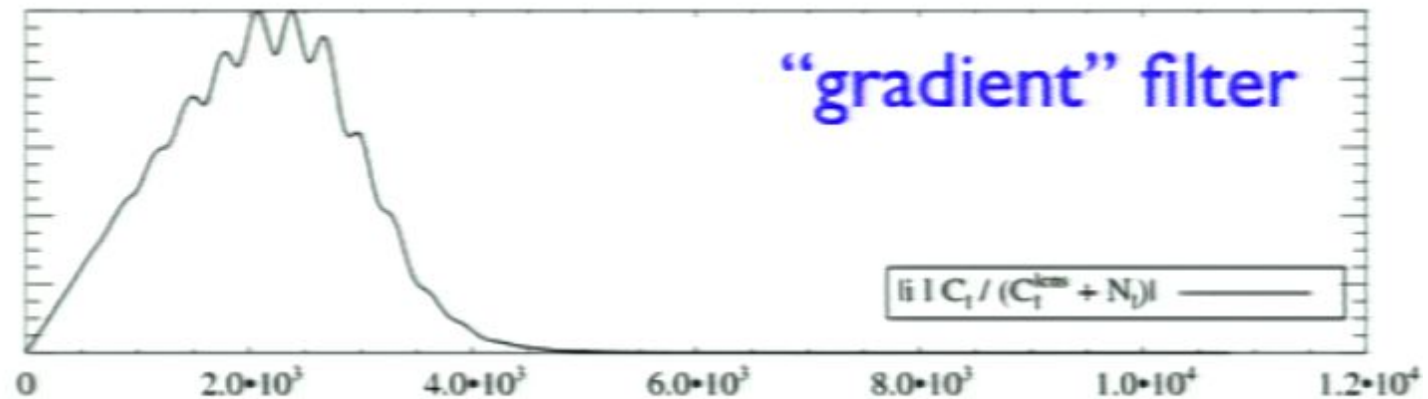
# Filters



Simplest version of estimator: simply multiply two filtered maps together

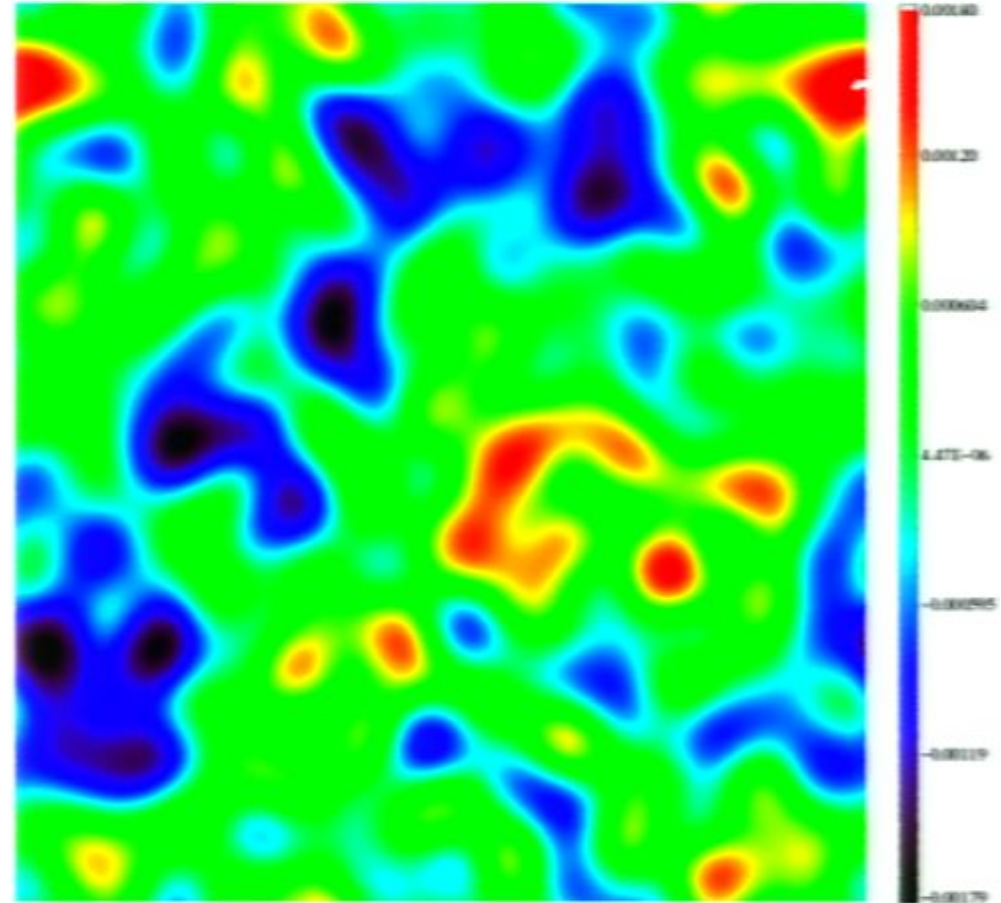
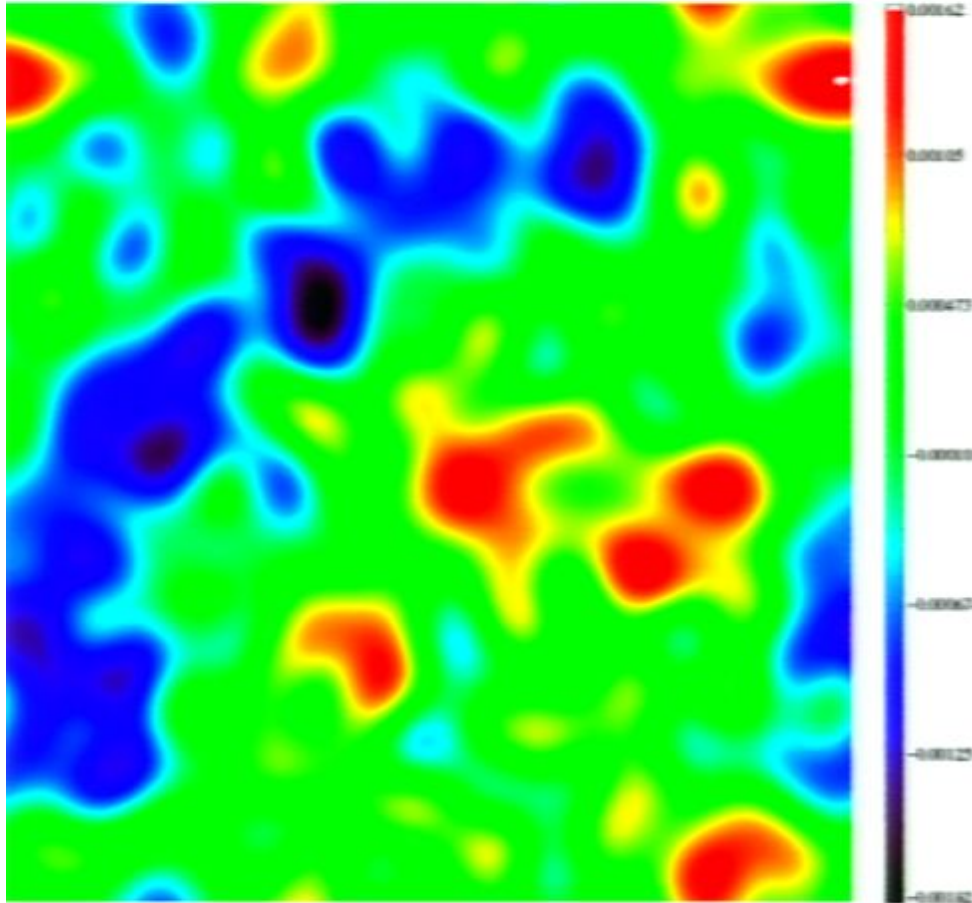
- ...and renormalize so that  $\langle \phi^{\text{est}}(L) \rangle_{\text{CMB}} = \phi(L)$ , to first order in  $\phi$

The filters shown optimize S/N in the reconstruction (Hu 2001)



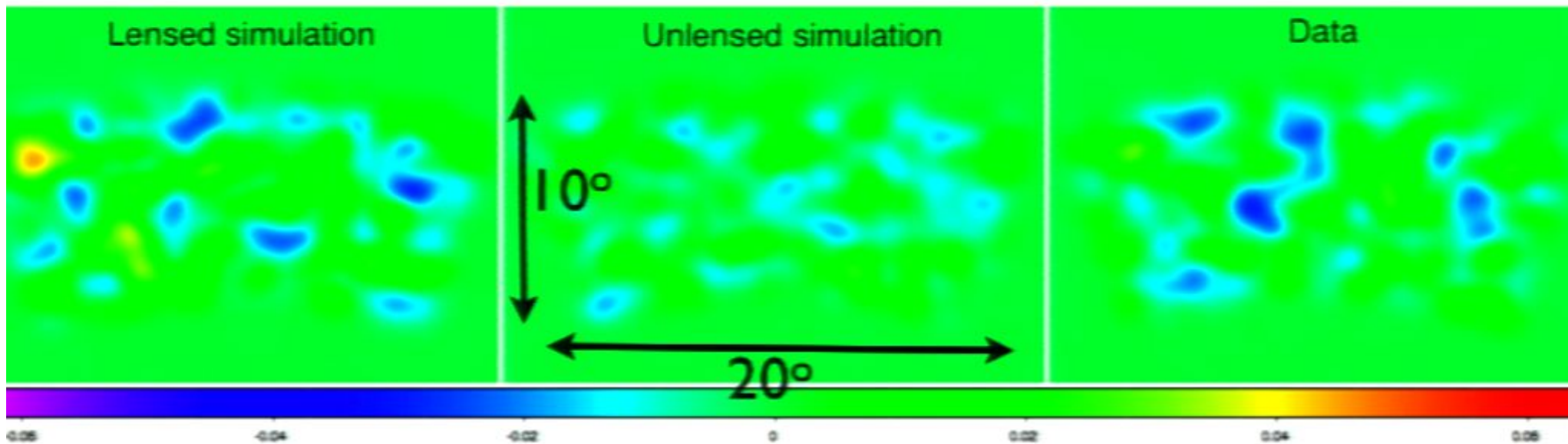
# Simulated reconstructions

- Input and recovered deflection angle maps,  $17^\circ \times 17^\circ$
- filtered for display at  $l < 200$





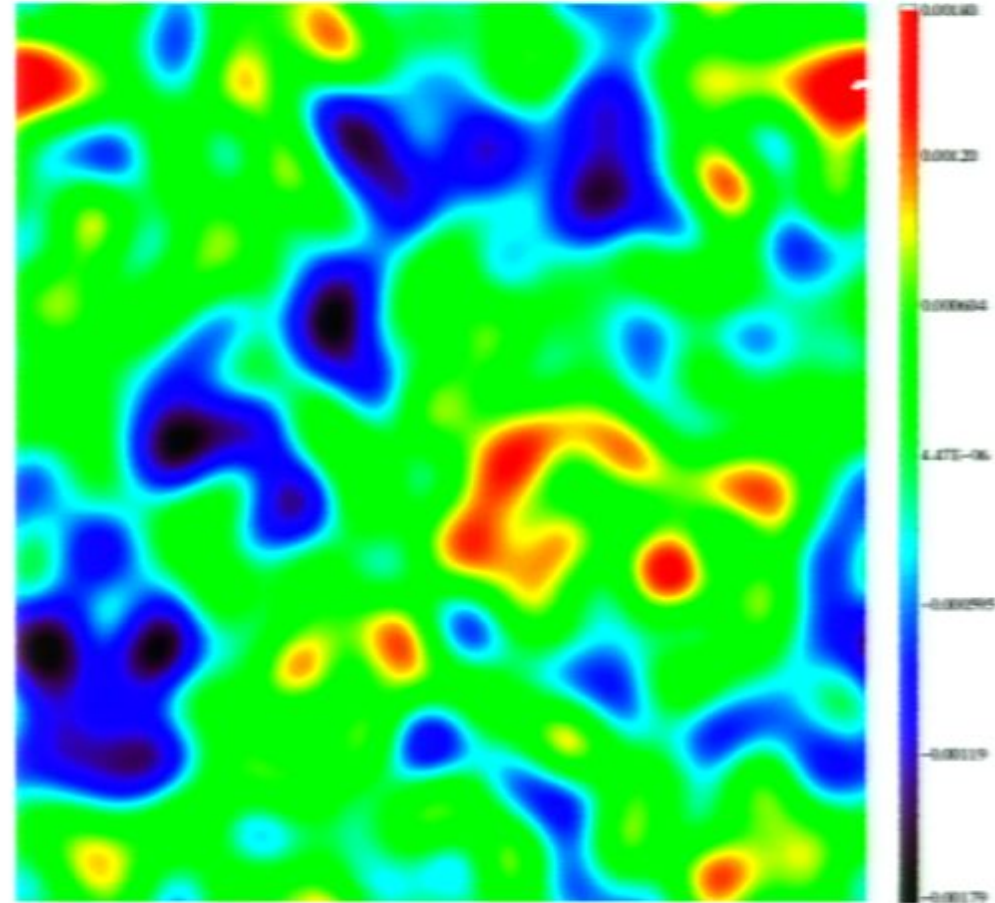
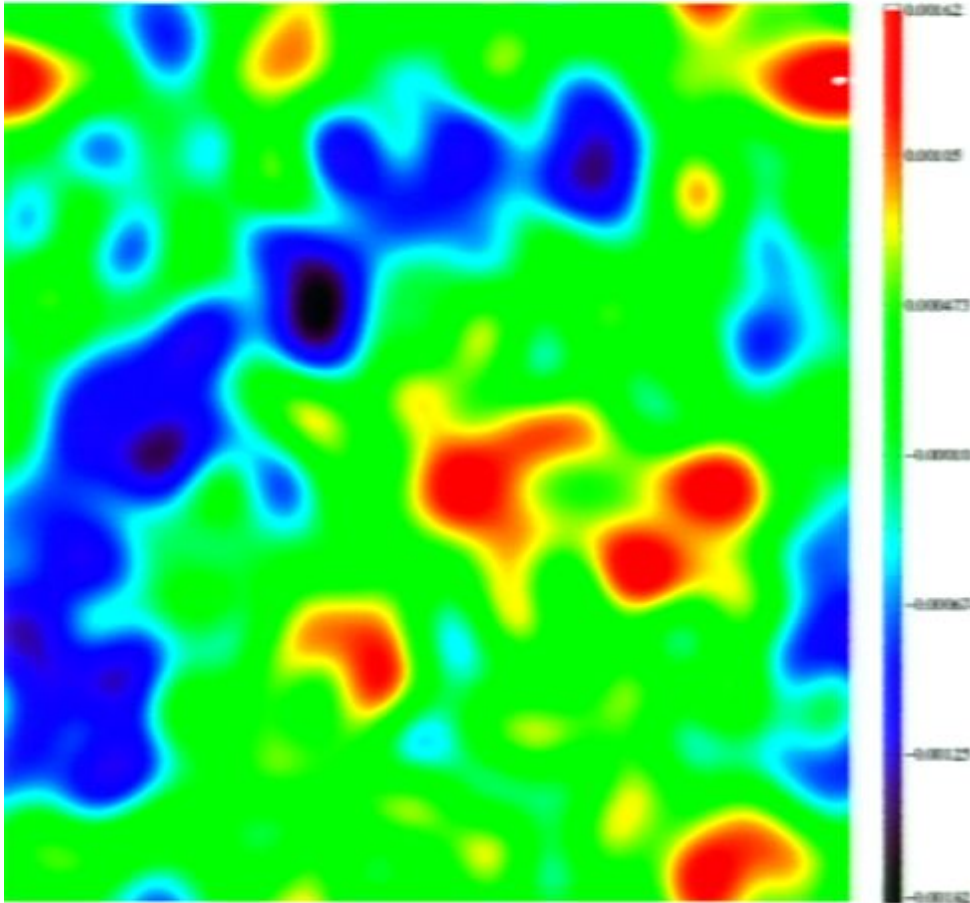
# Mapping the universe



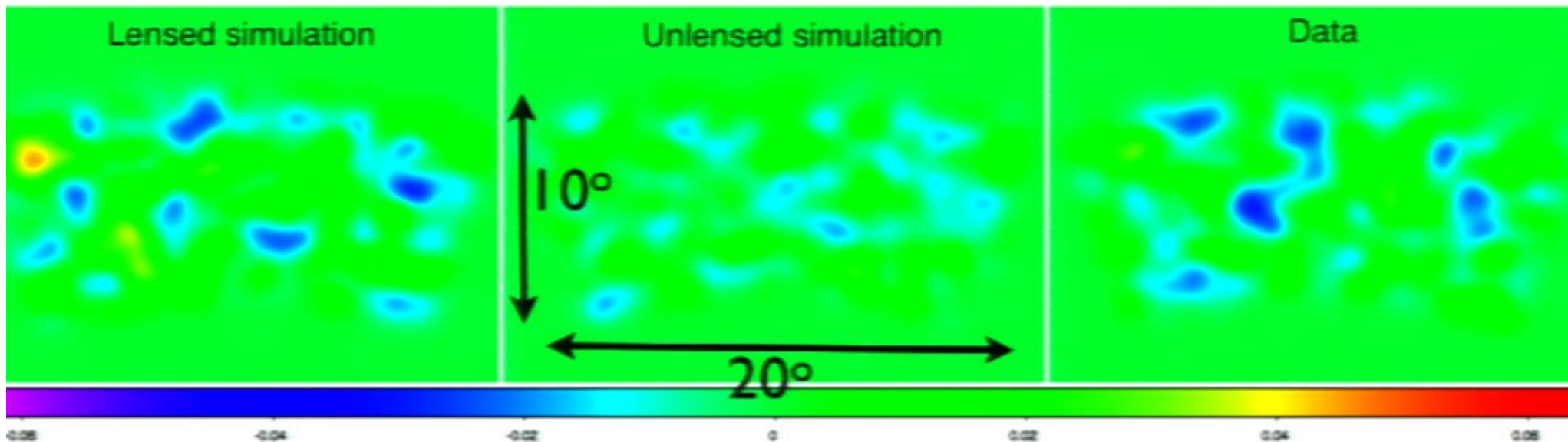
- SPT making maps of total matter (including dark matter) between  $z=0-1100$

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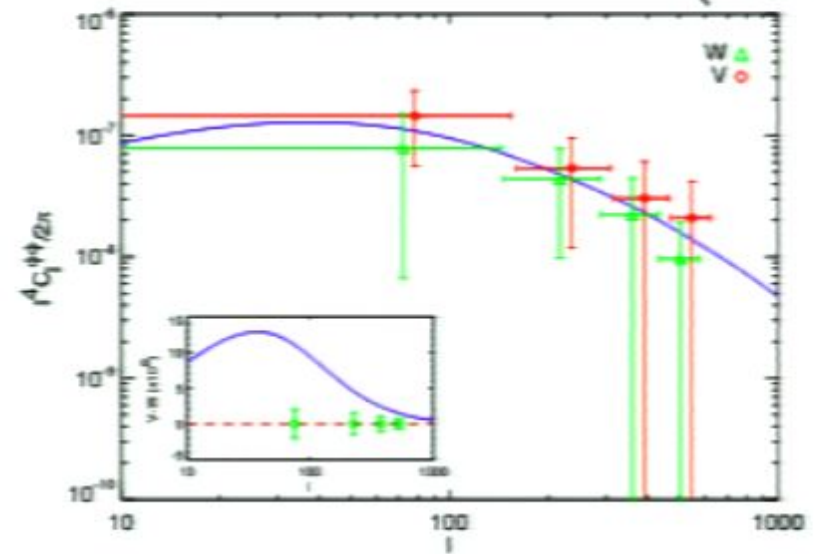
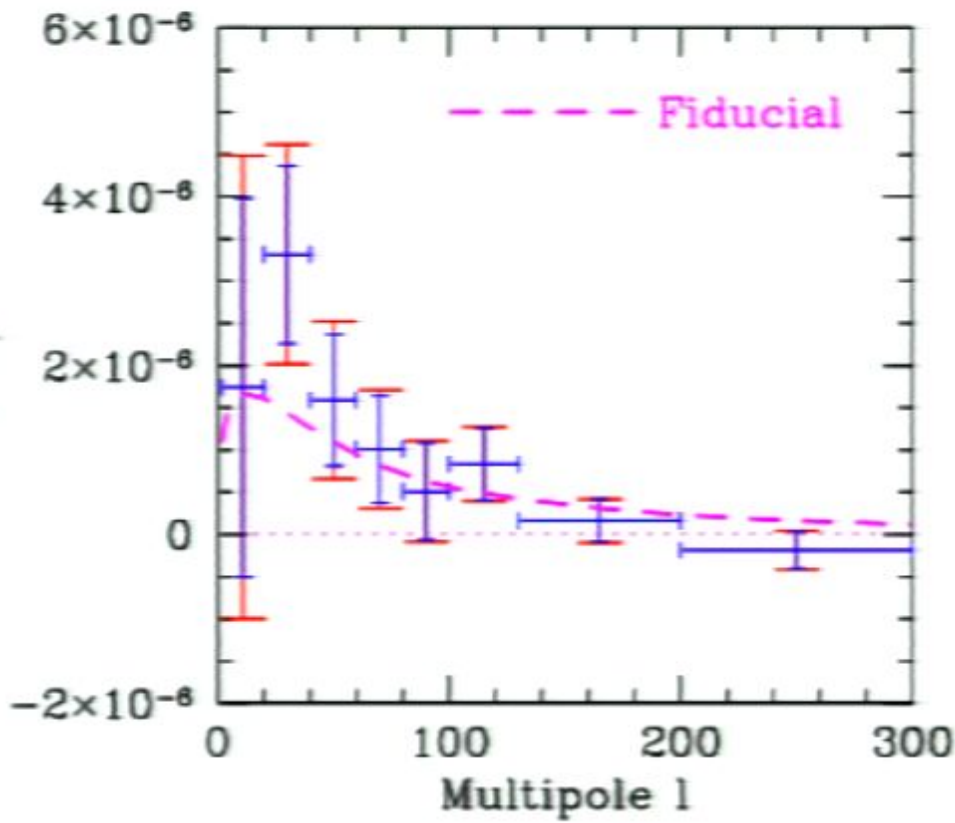


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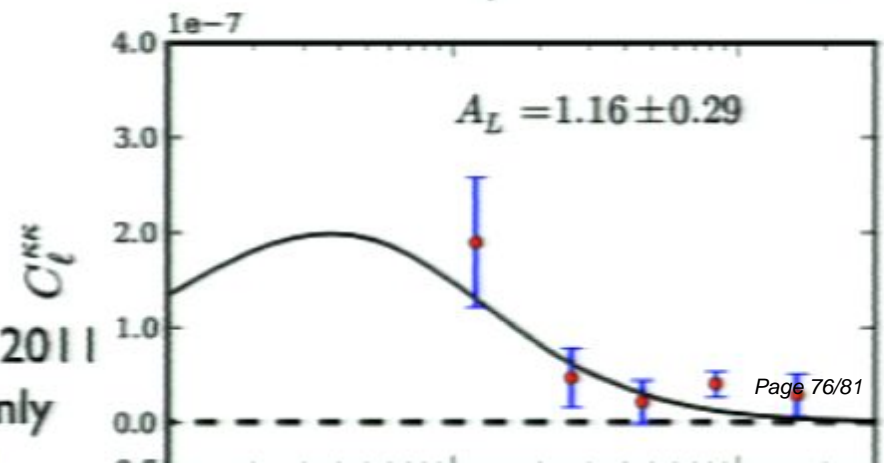


# CMB Lensing Detections

Smidt et al 2011  
WMAP only  
("1.9" $\sigma$ )

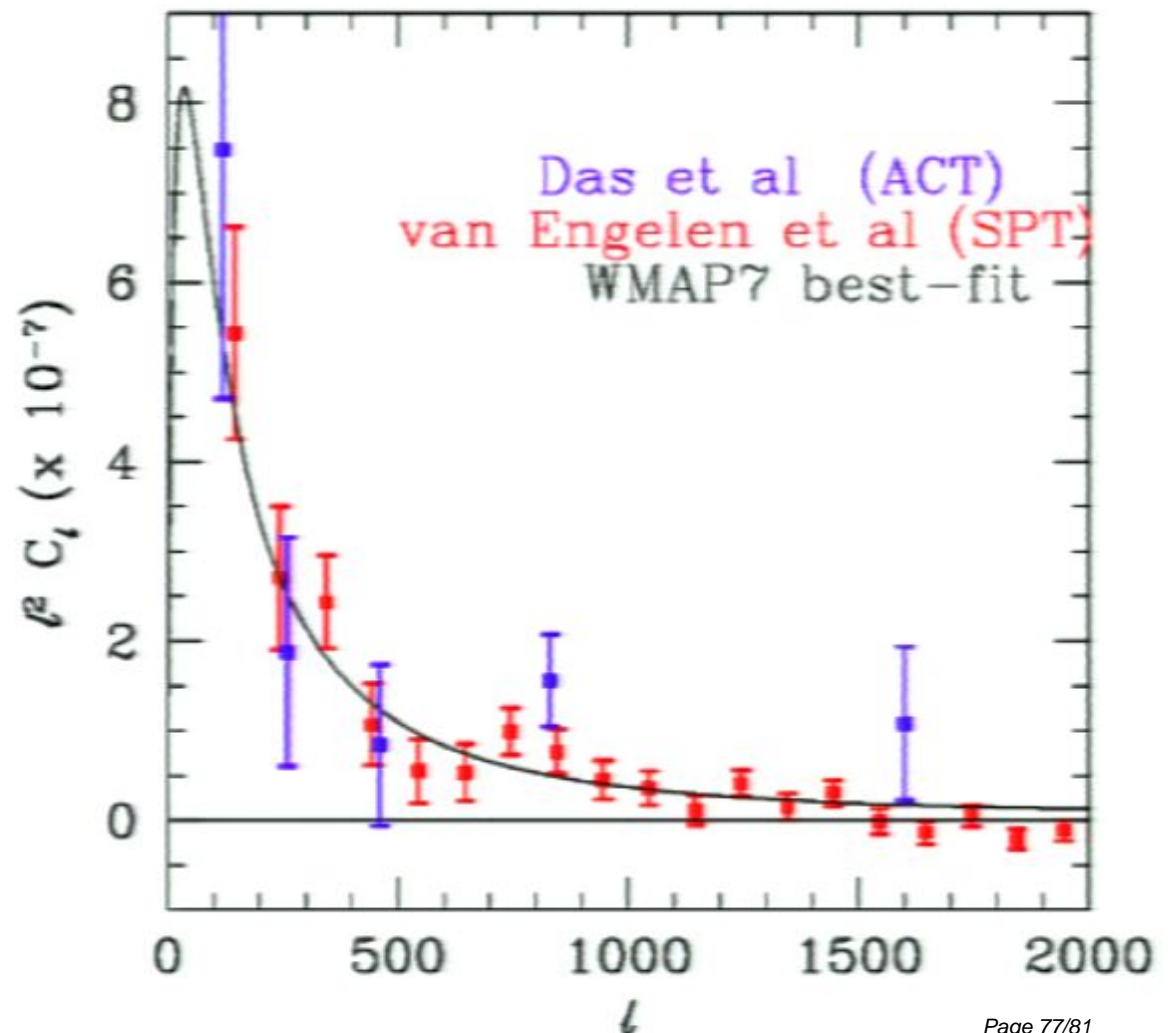


Das et al 2011  
ACT only  
(4 $\sigma$ )



# SPT Lensing Power Spectrum

- high significance detection of non-Gaussianity in the CMB induced by gravitational lensing
- based on  $\sim 1/5$  of SPT area, single-frequency only



## *E-modes/B-modes*

- E-modes vary spatially parallel or perpendicular to polarization direction
- B-modes vary spatially at 45 degrees
- CMB
  - scalar perturbations only generate \*only\* E
- ***Lensing of CMB is much more obvious in polarization!***



*Image of positive  $k_x$ /positive  $k_y$  Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]*



# Summary

- the story of structure formation is encoded in the cosmic microwave background
- Large cluster catalog for cosmological searches for physics beyond standard  $\Lambda$ CDM
  - Jon Dudley, Tijmen de Haan, Keith Vanderlinde
- detection of gravitational lensing through non-Gaussianity of CMB
  - Alex van Engelen

