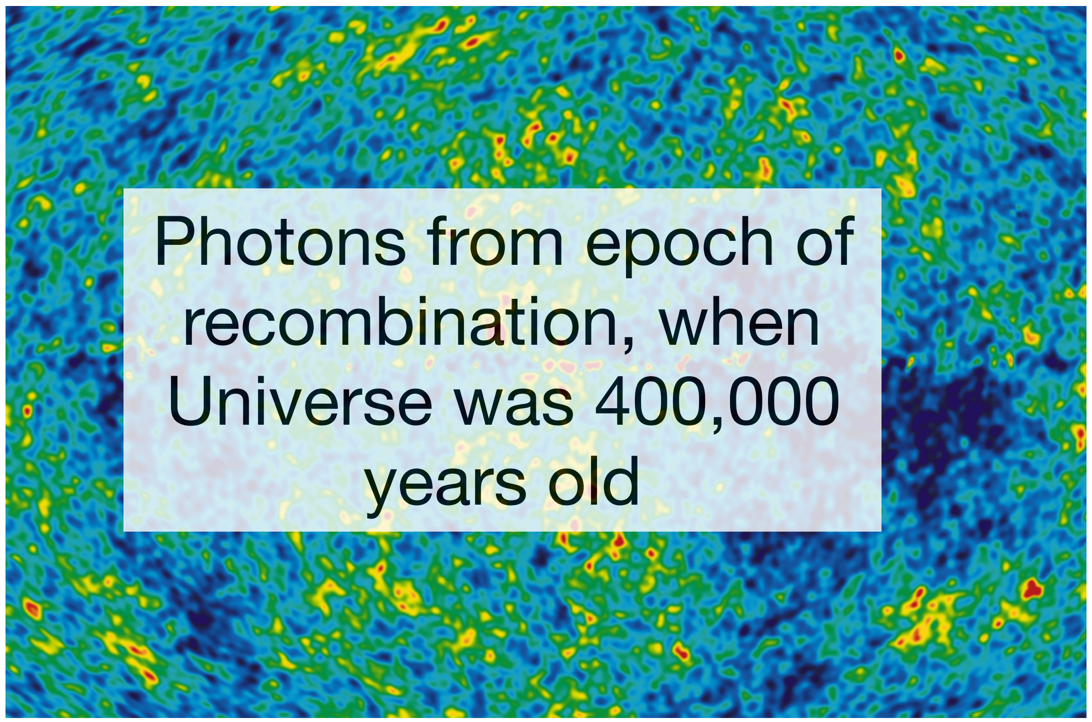
Cross-correlations at all scales:

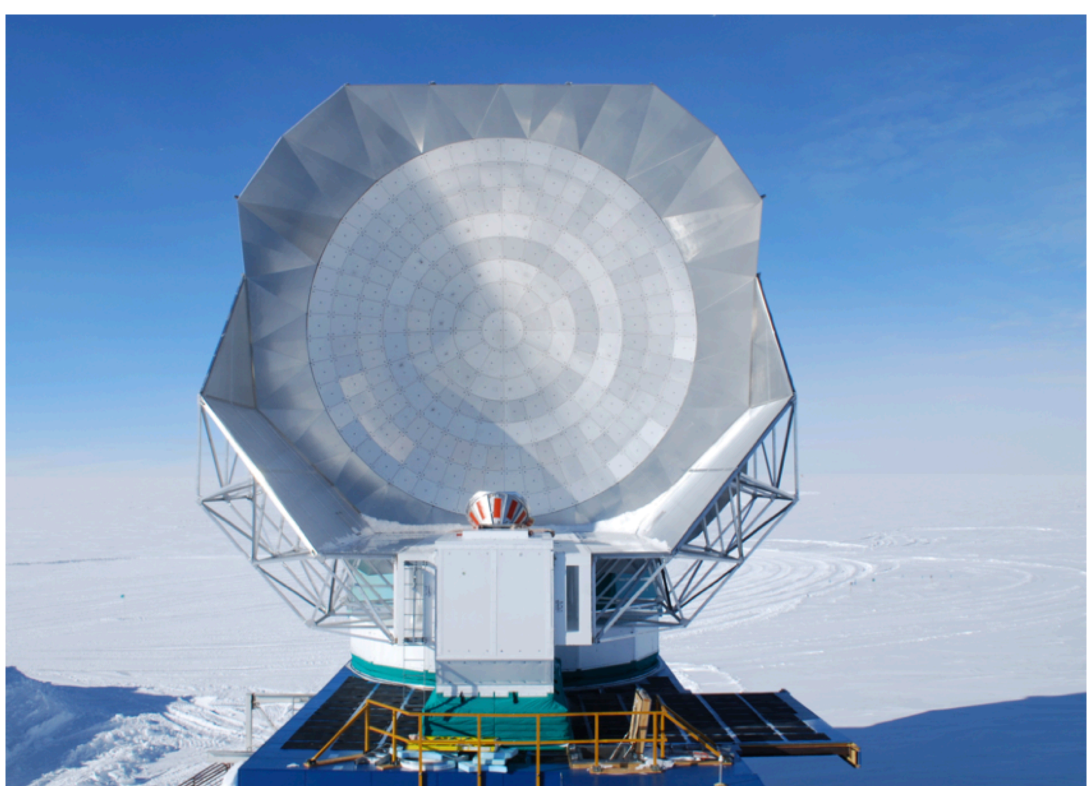
Correlating optical and CMB surveys to probe physics across a wide range of scales

Eric Baxter, University of Pennsylvania

with Yuuki Omori, Chihway Chang, Bhuvnesh Jain, Srini Raghunathan, Judit Prat, Lucas Secco, Shivam Pandey, Scott Dodelson, Tom Crawford, and many others in the **Dark Energy Survey**, and **South Pole Telescope** collaborations

Cosmic microwave background (CMB) and optical galaxy surveys





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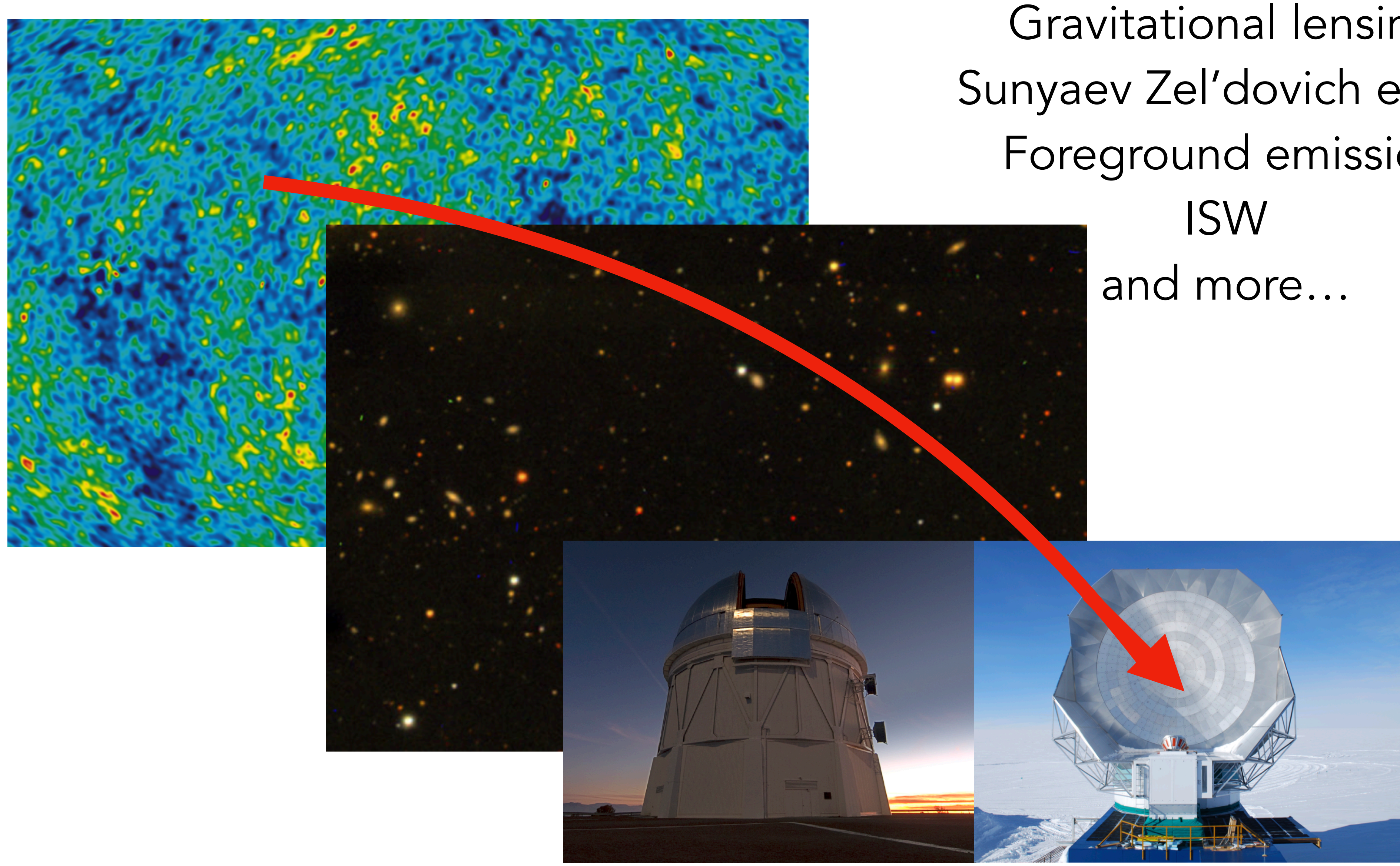
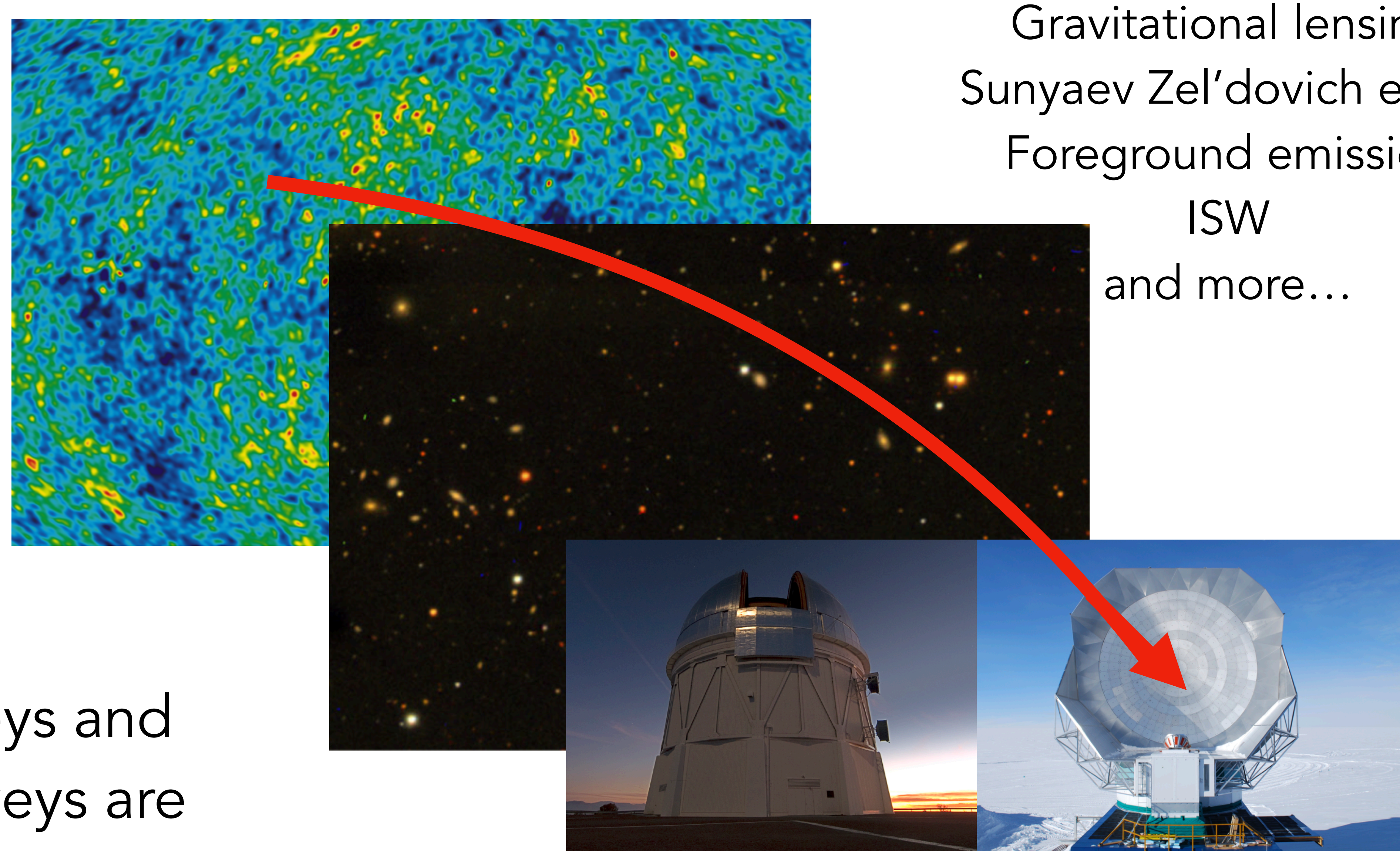


Gravitational lensing
Sunyaev Zel'dovich effect
Foreground emission
ISW
and more…

Cosmic microwave background (CMB) and optical galaxy surveys



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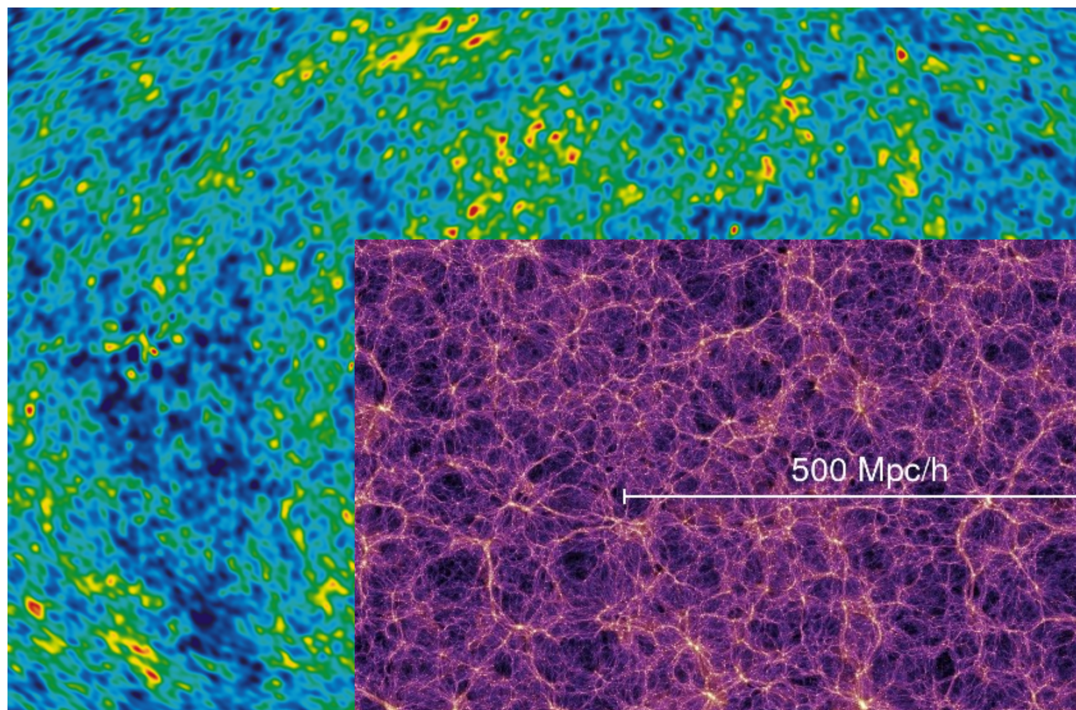
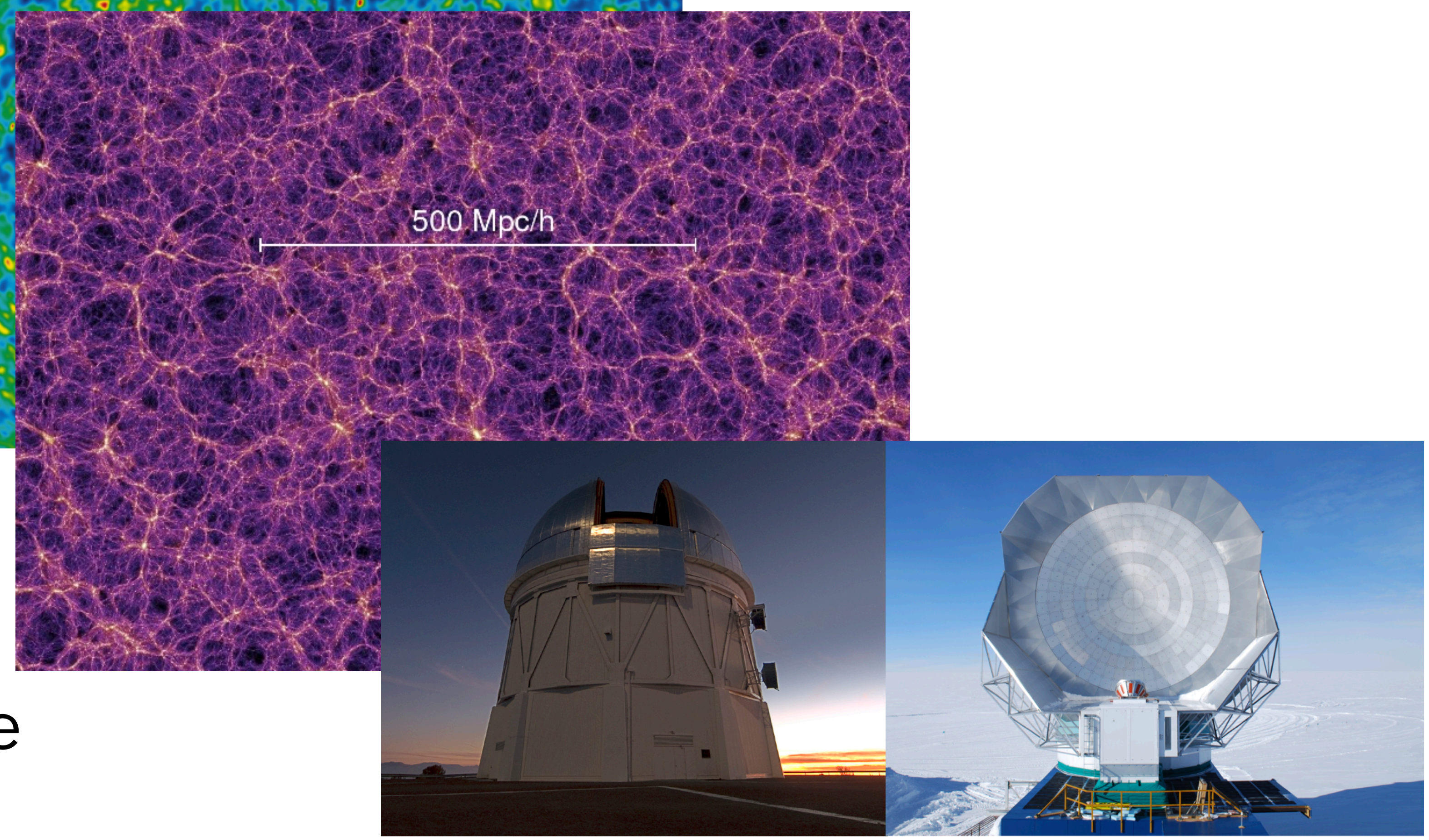
and more…

CMB surveys and optical surveys are correlated!

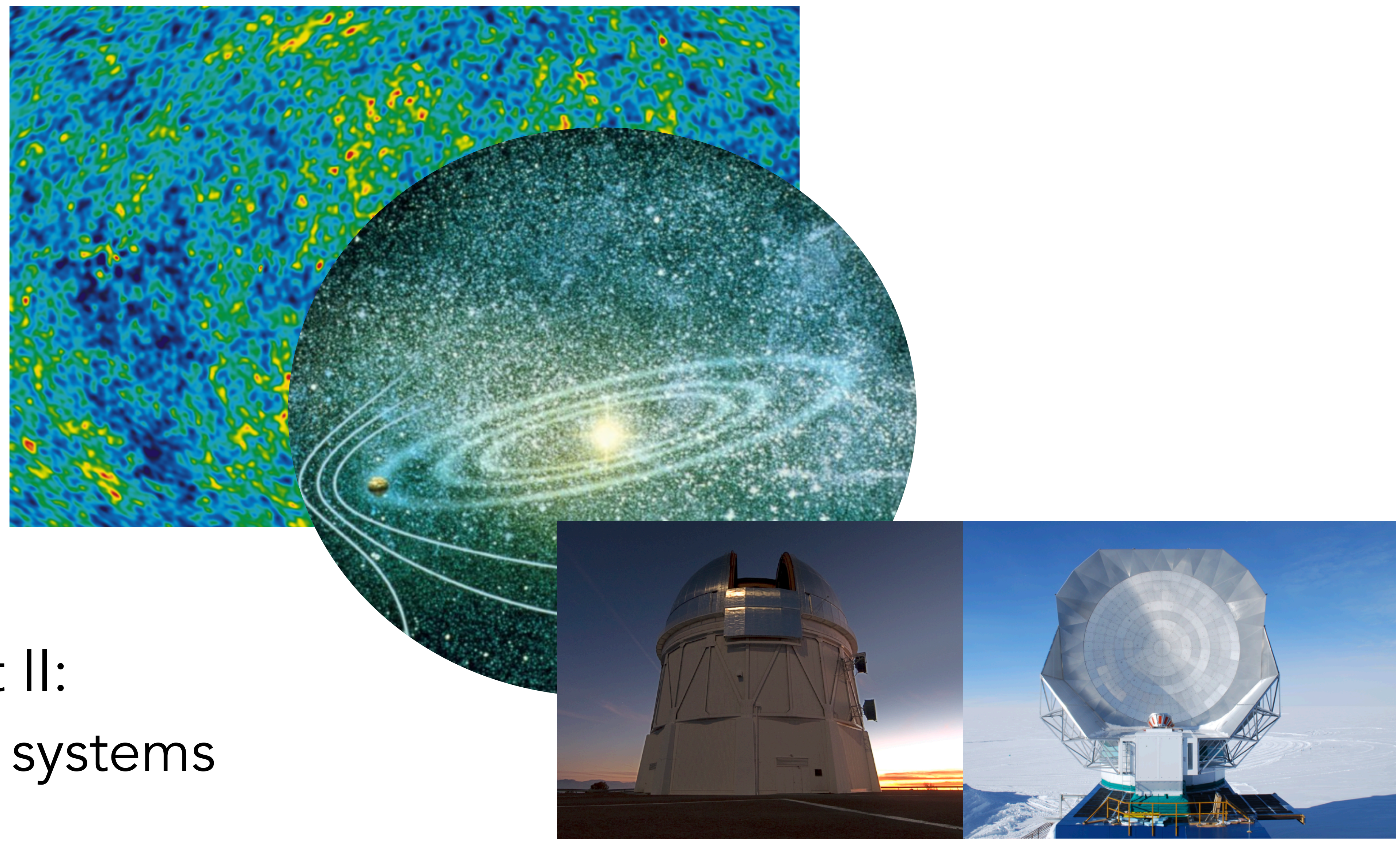
Cosmic microwave background (CMB) and optical galaxy surveys





Part I:
Large Scale Structure

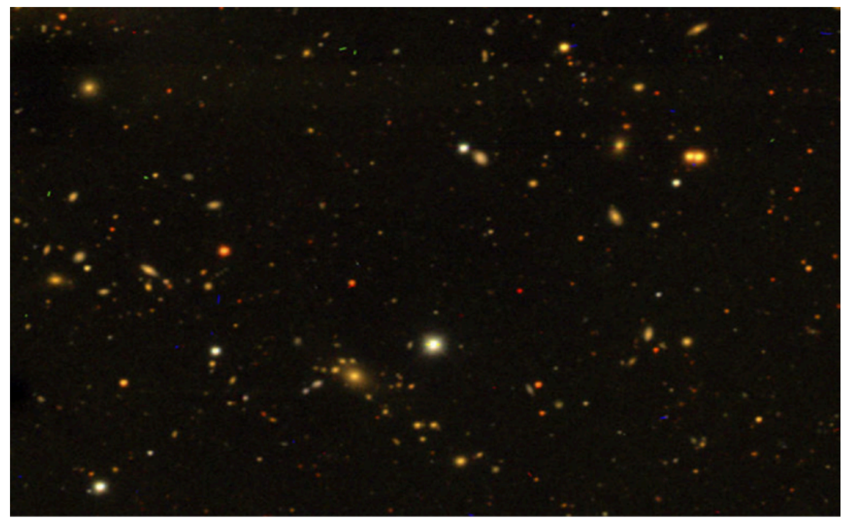
Cosmic microwave background (CMB) and optical galaxy surveys



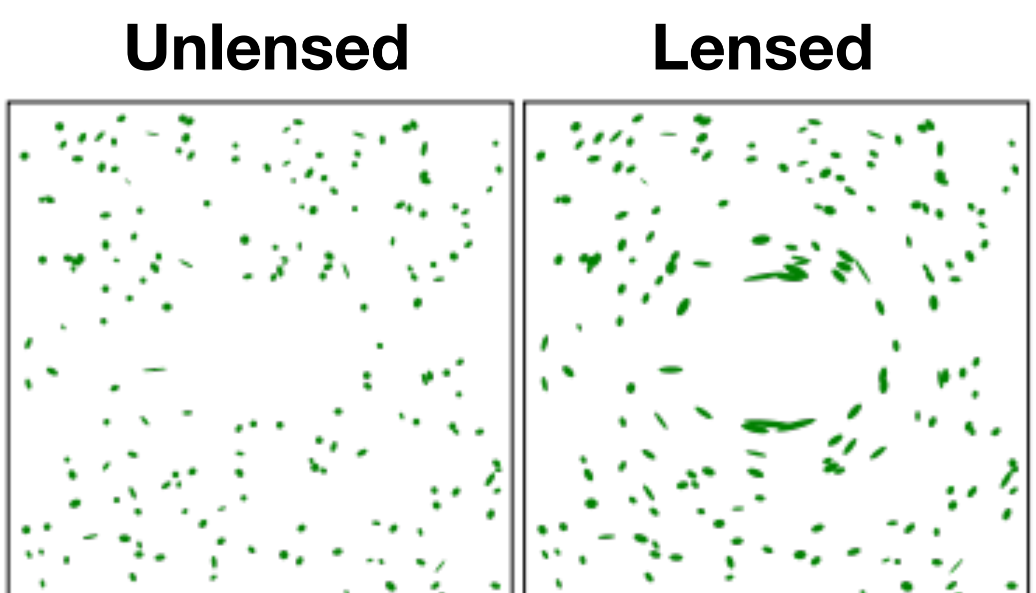
Part II:
Planetary systems

Part I:
Cosmology with correlations of large scale structure and CMB lensing

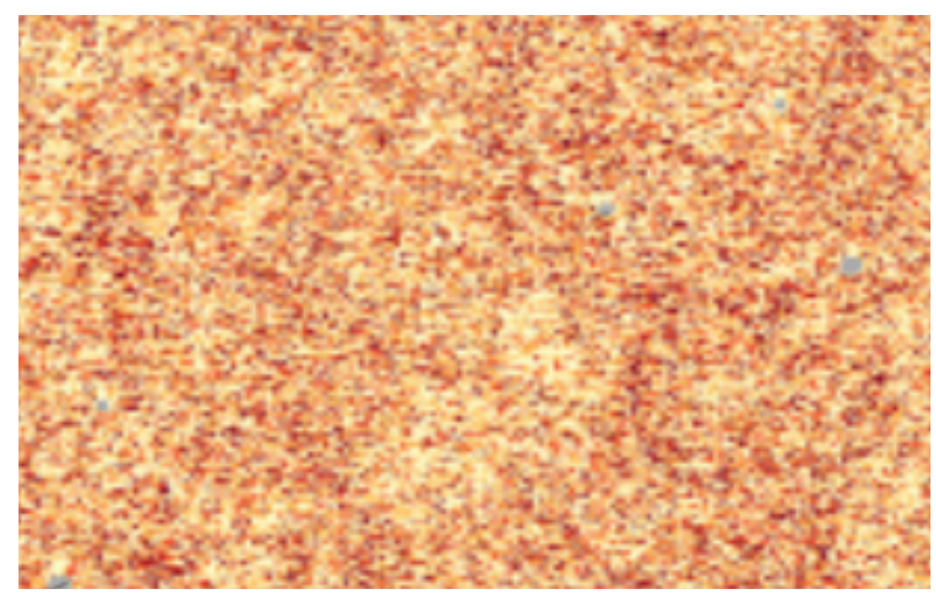
Probing large scale structure with a galaxy survey



Light from galaxies

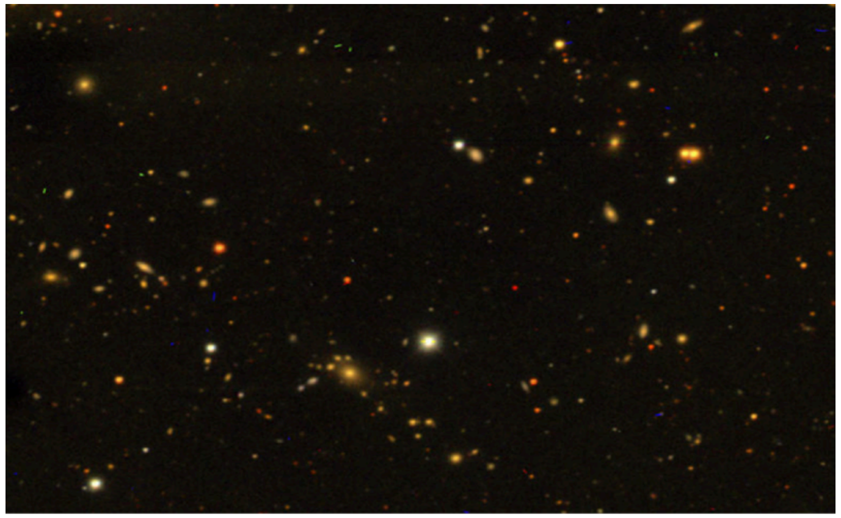


Galaxy lensing measures (weighted) projected mass

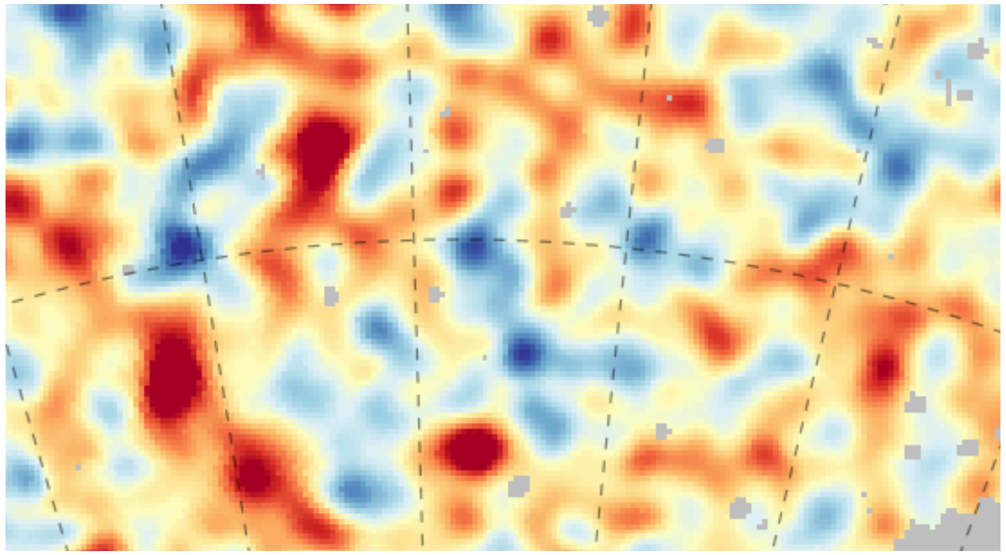


Galaxy positions trace large scale structure

Probing large scale structure with a galaxy survey



Light from galaxies



Galaxy lensing measures (weighted) projected mass

Galaxy positions trace large scale structure

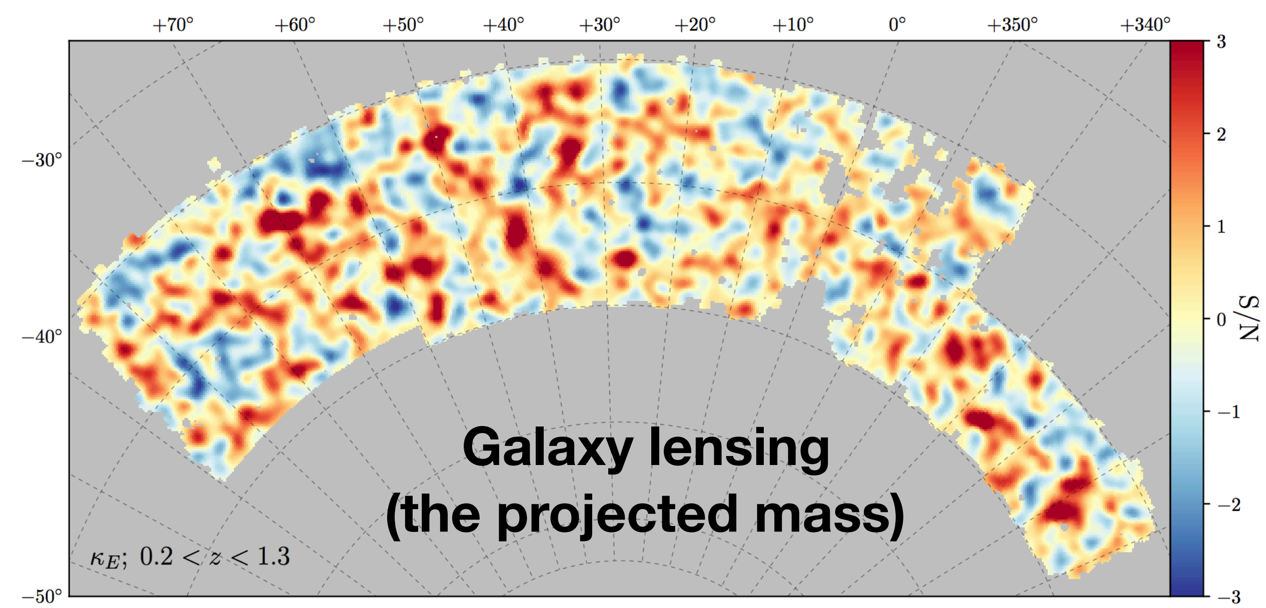
Two-point correlations between lensing and galaxy positions

The two-point correlation:

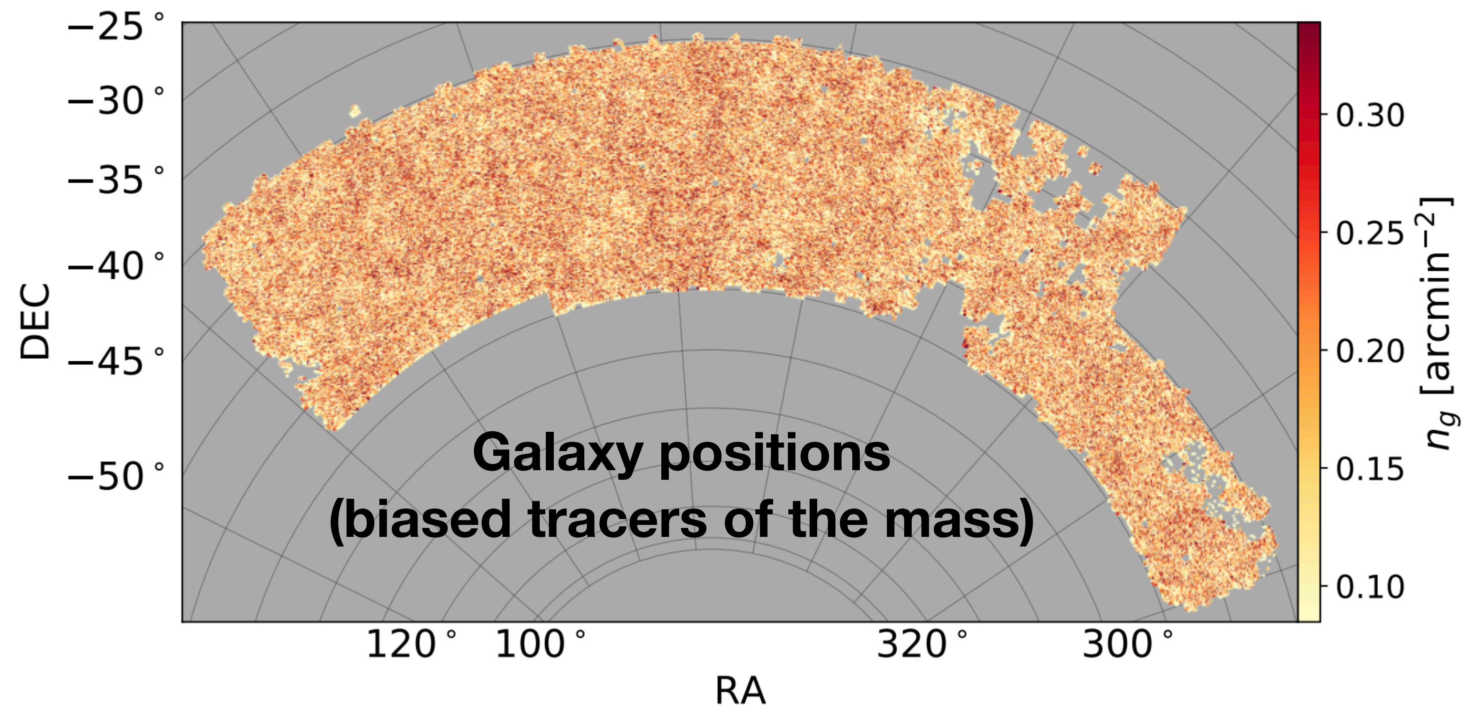
$$\langle f_1(\hat{n}) f_2(\hat{n} + \theta) \rangle$$

For a Gaussian random field, two-point functions contain all information*

*But…large scale structure is not Gaussian



Chang et al. 2017



Elvin-Poole et al. 2017

Cosmology with lensing correlations

The Limber approximation relates correlations between these fields to an integral along the line of sight of the matter power spectrum:

Correlation between fields ~ $\int d(\mathrm{distance})$ weight function x power spectrum

Cosmology with lensing correlations

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Correlation between fields ~ $\int d(\text{distance})$ weight function x power spectrum

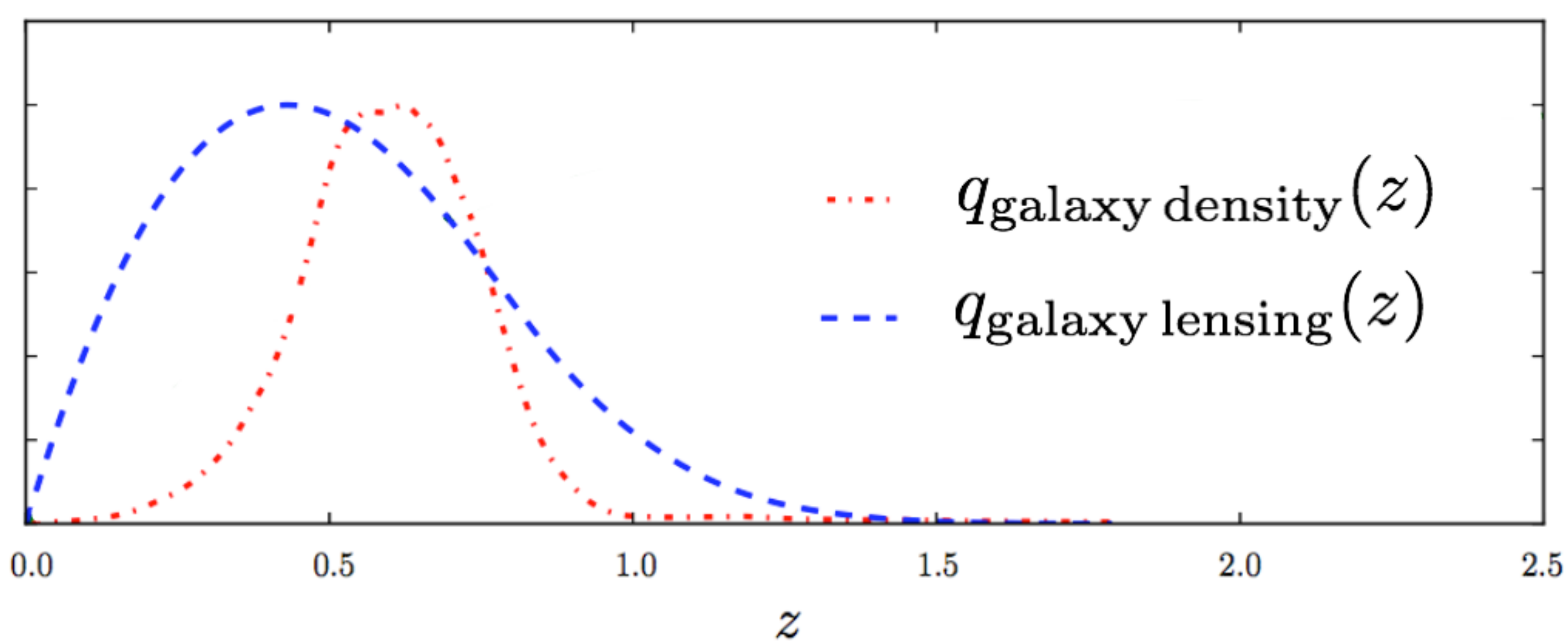
Cross-spectrum of fields X and Y

Geometry

Growth and geometry

$$C^{XY}(\ell) \approx \int d\chi \frac{q_X(\chi) q_Y(\chi)}{\chi^2} P\left(k = \frac{\ell + 1/2}{\chi}, z(\chi)\right)$$

Weight function, q(z)

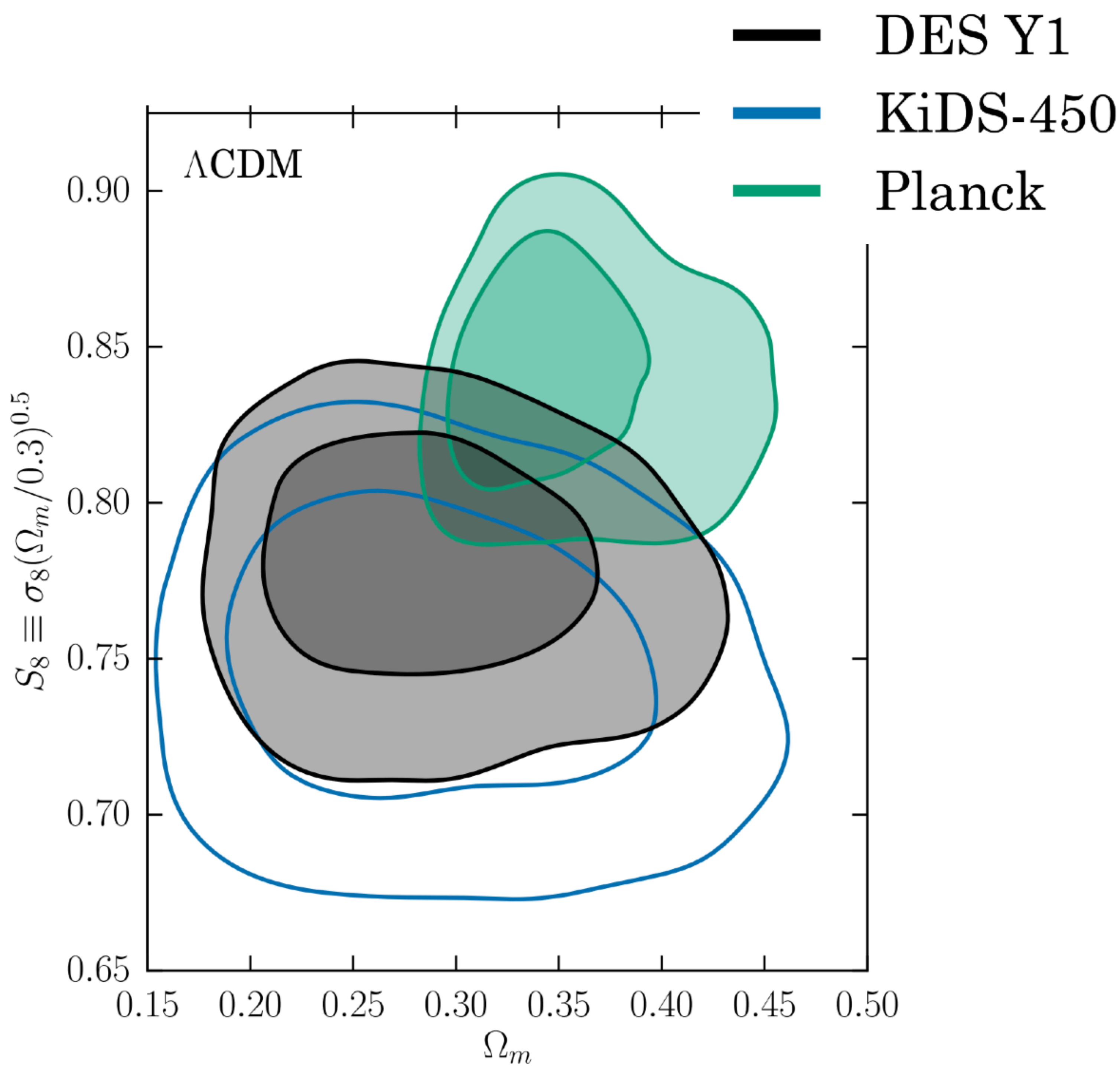


ℓ = multipole
z = redshift
k = wavenumber
χ = comoving distance
P(k,z) = matter power spectrum

DES Year 1 lensing-lensing correlation

Cosmological constraints from lensing-lensing correlations in first year **Dark Energy Survey** data

- Roughly 1300 sq. deg.
- 4 source galaxy redshift bins

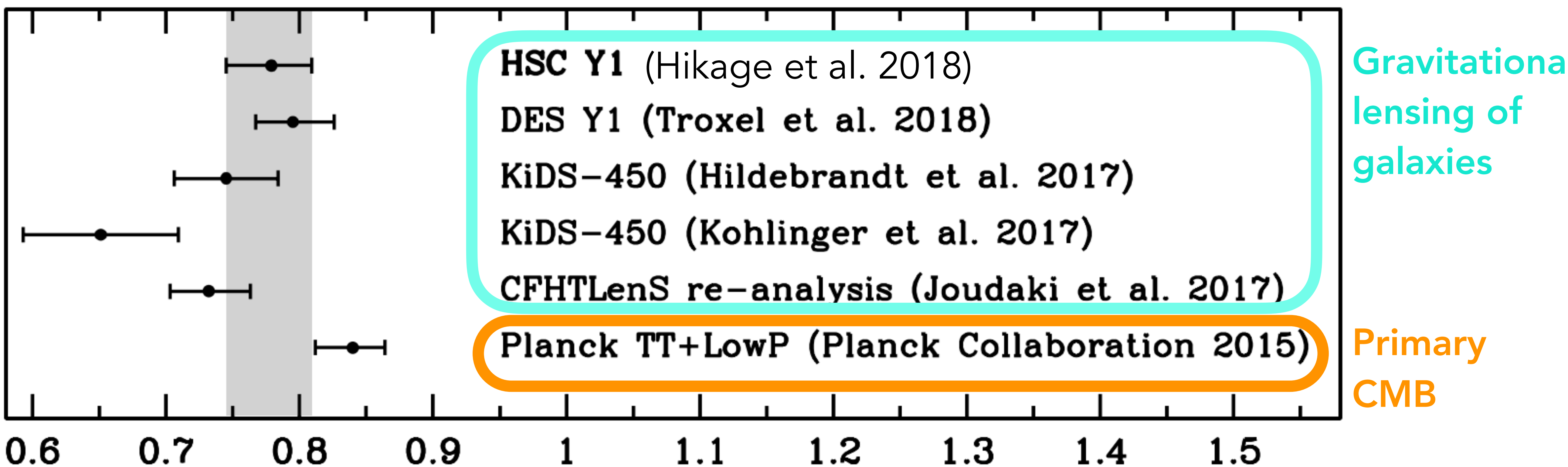


Troxel et al. 2018

Is LCDM beginning to break?

galaxy lensing vs. primary CMB fluctuations

Hikage et al. 2018



$$S_8 \equiv \sigma_8 \left(\Omega_{\rm m}/0.3\right)^{0.5}$$

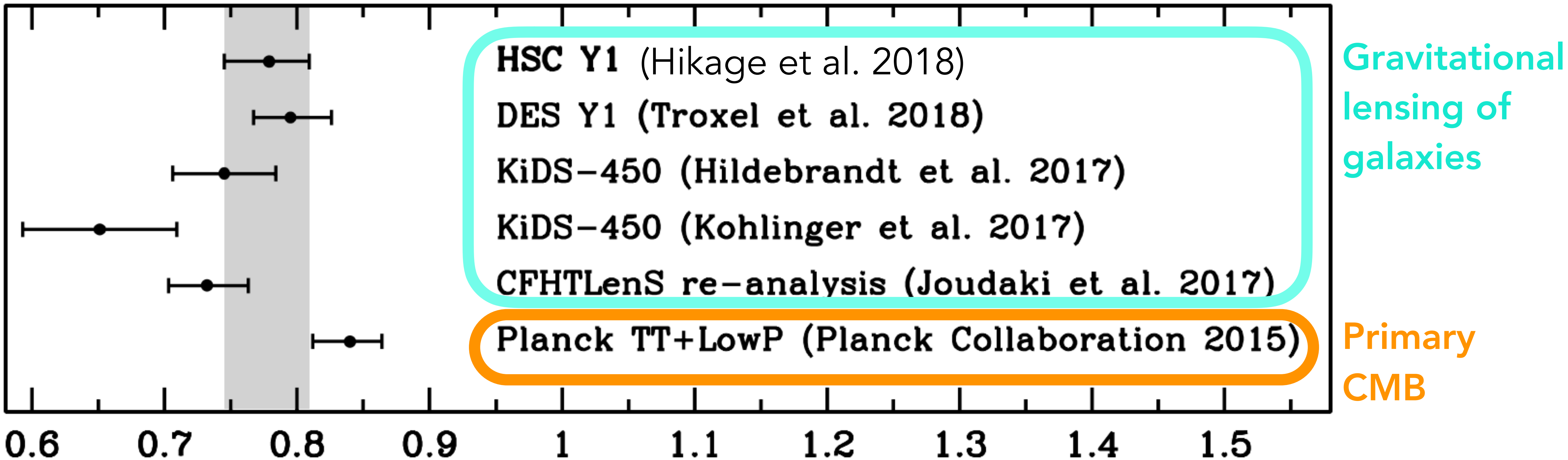
σ_8 = amplitude of matter fluctuations

$\Omega_{\rm m}$ = matter density

Or are there systematic errors?

galaxy lensing vs. primary CMB fluctuations

Hikage et al. 2018



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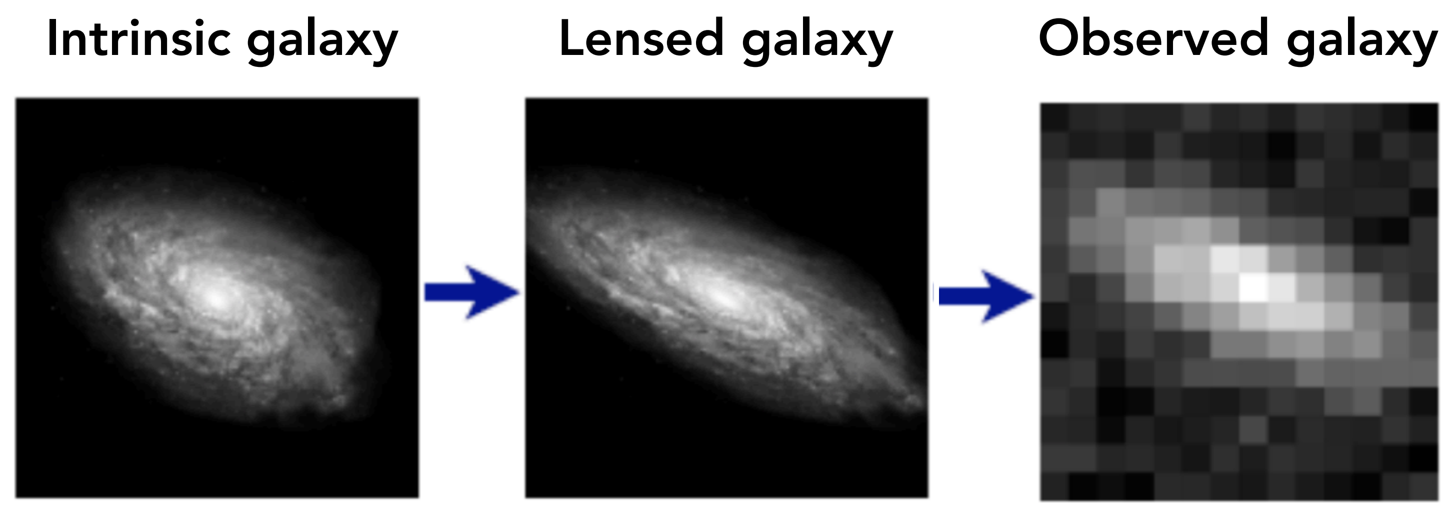
Challenges of galaxy lensing

Difficulties associated with galaxy lensing:

- **Point spread function**
- **Source blending**
- **Intrinsic alignments**
- Photometric redshifts of source galaxies



As **statistical uncertainties** get smaller, **systematic errors** become increasingly important

Challenges of galaxy lensing

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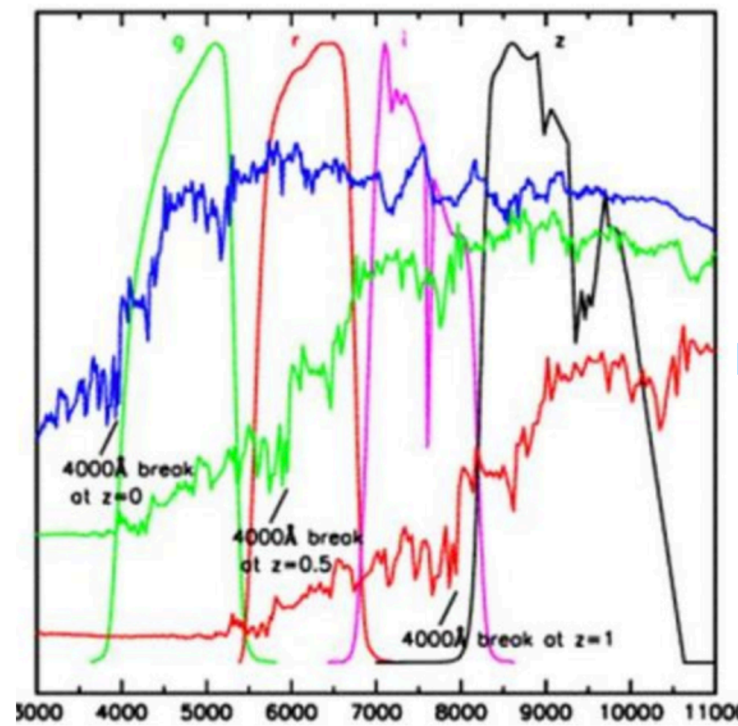
- Point spread function
- Source blending
- Intrinsic alignments
- **Photometric redshifts of source galaxies**

Flux



Wavelength (angstroms)

Redshifts of source galaxies

As **statistical uncertainties** get smaller, **systematic errors** become increasingly important

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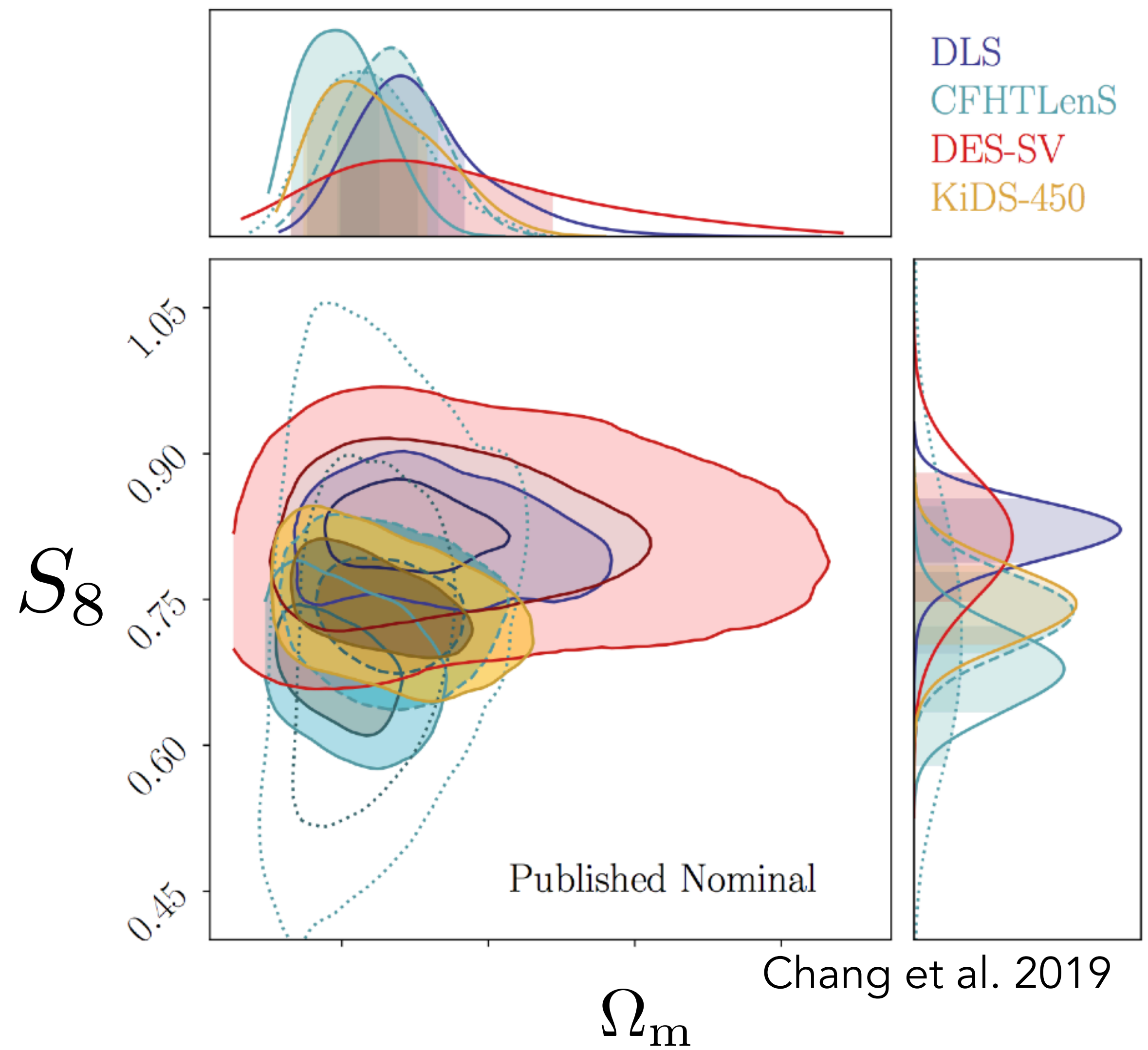

Chang et al. 2019

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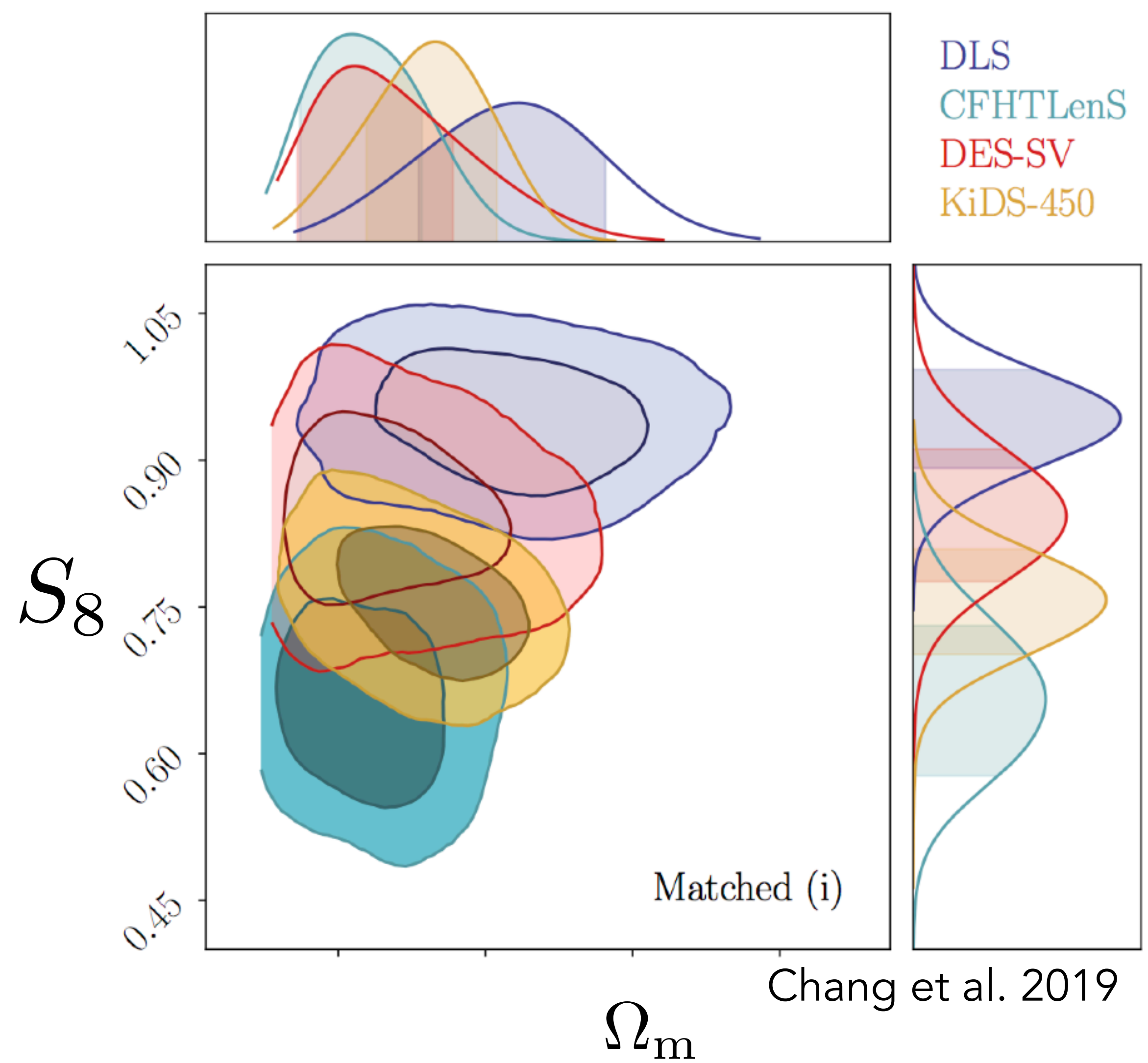

Chang et al. 2019

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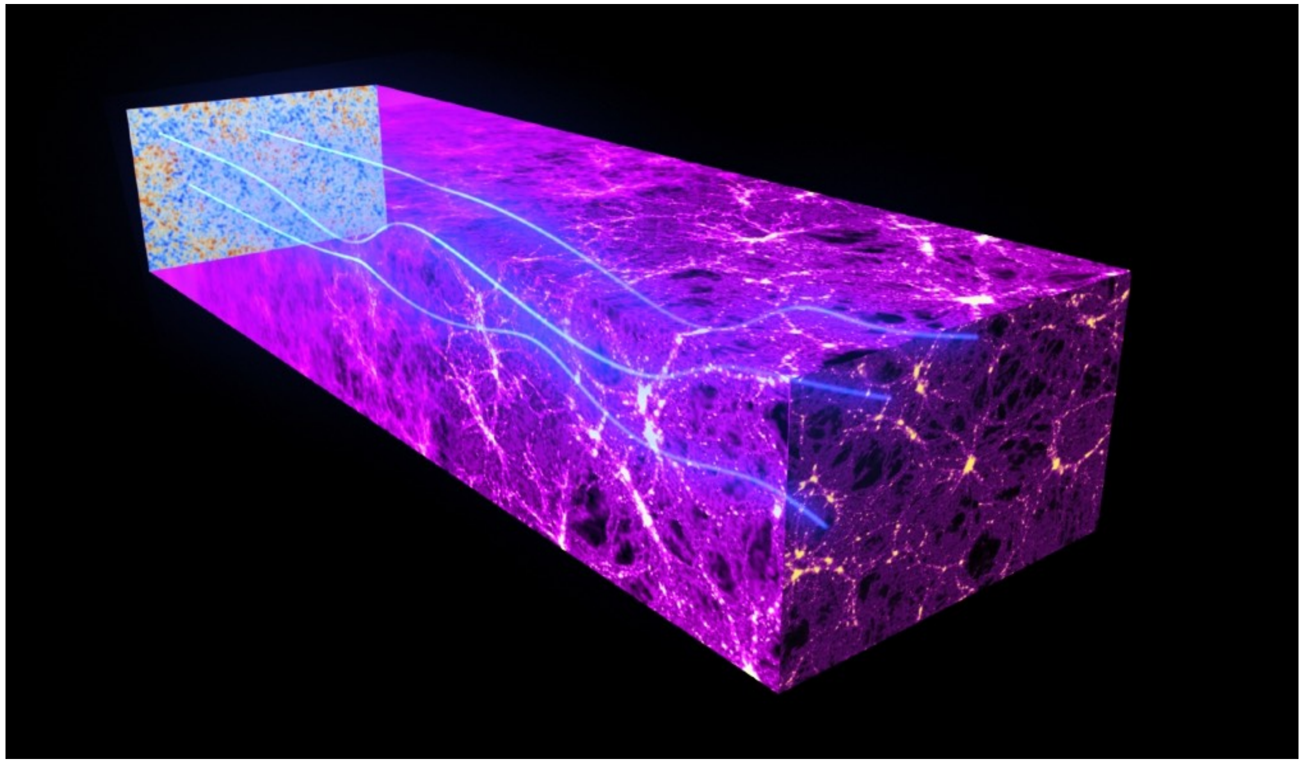
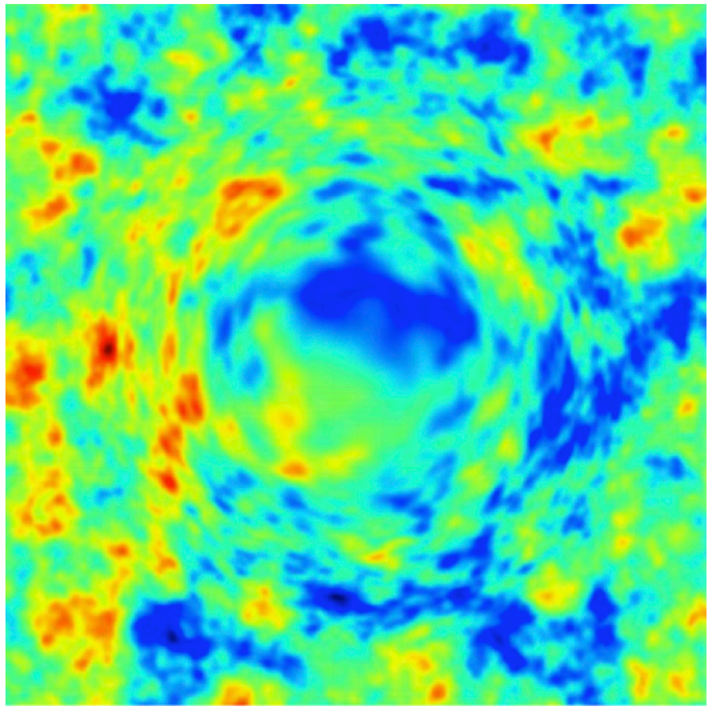
CMB lensing to the rescue



The cosmic microwave background (CMB) is also gravitationally lensed by large scale structure

How can CMB lensing help?

- **No source photo-z**
- No intrinsic alignments
- No source blending
- High redshift sensitivity
- Offers independent test of galaxy lensing measurements



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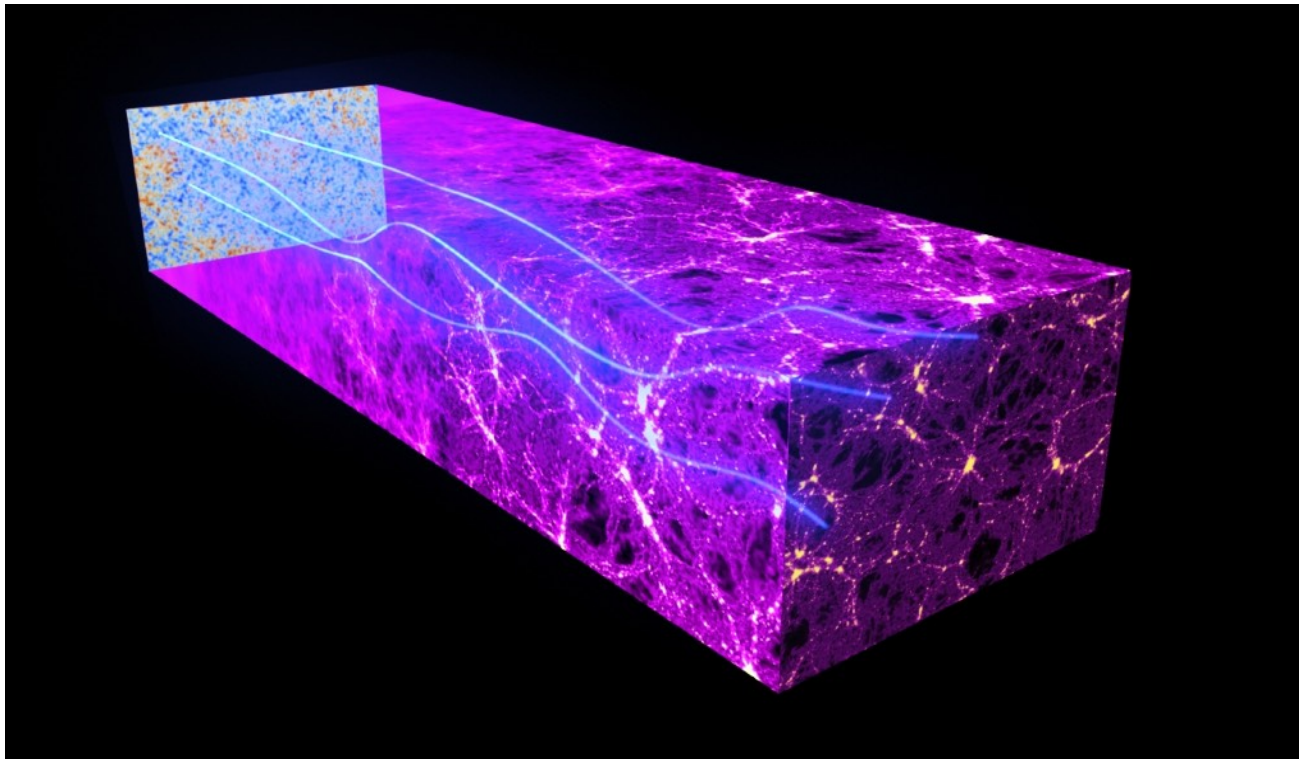

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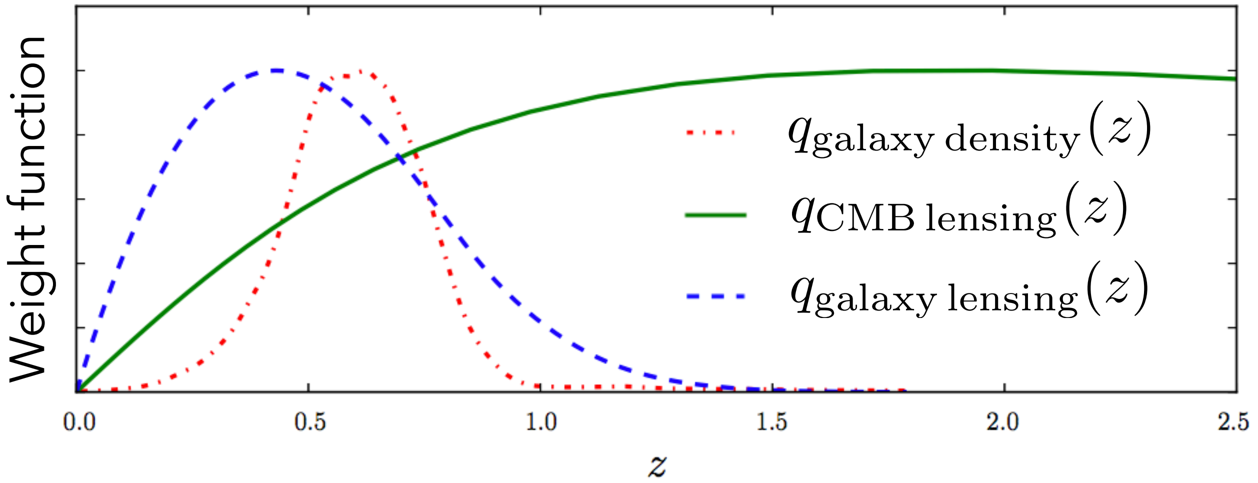


The Dark Energy Survey Year 1
6x2pt analysis

CMB lensing measurements from the **South Pole Telescope** and **Planck**

Joint measurement of six two-point functions:

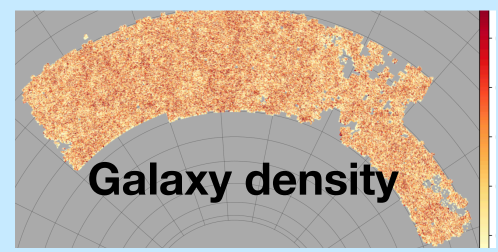
< galaxy lensing x galaxy lensing >
< galaxies x galaxies >
< galaxies x galaxy lensing >

< galaxies x CMB lensing >
< galaxy lensing x CMB lensing >
< CMB lensing x CMB lensing >

The 6x2pt papers:

Methodology + tSZ bias: Baxter et al. 2018

Omori et al. 2018



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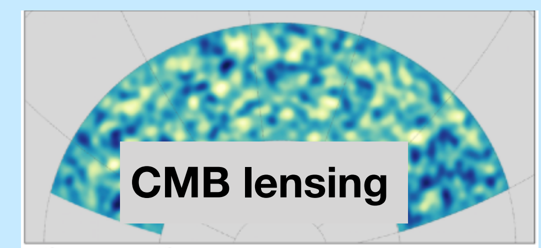
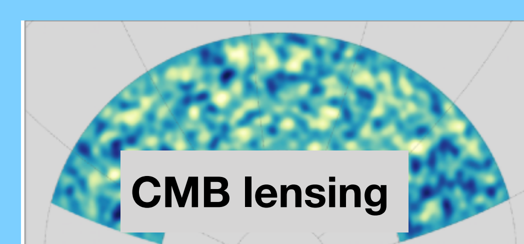


Omori, Baxter, 2018



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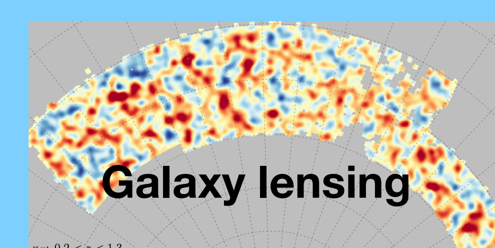

Cosmological results: DES+ SPT, 2018

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DES-only “3x2pt” analysis

< galaxy lensing x galaxy lensing >
< galaxies x galaxies >
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< CMB lensing x CMB lensing >

CMB lensing cross-correlations

The 6x2pt papers:

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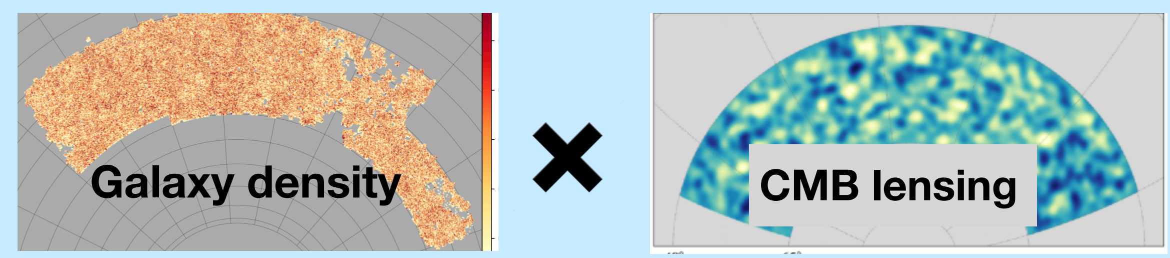
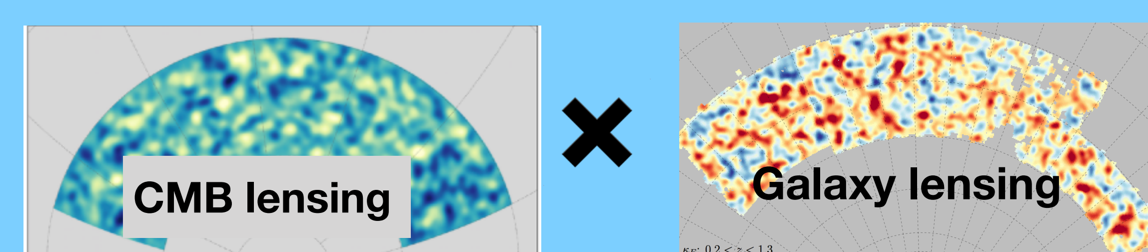


Omori, Baxter, 2018



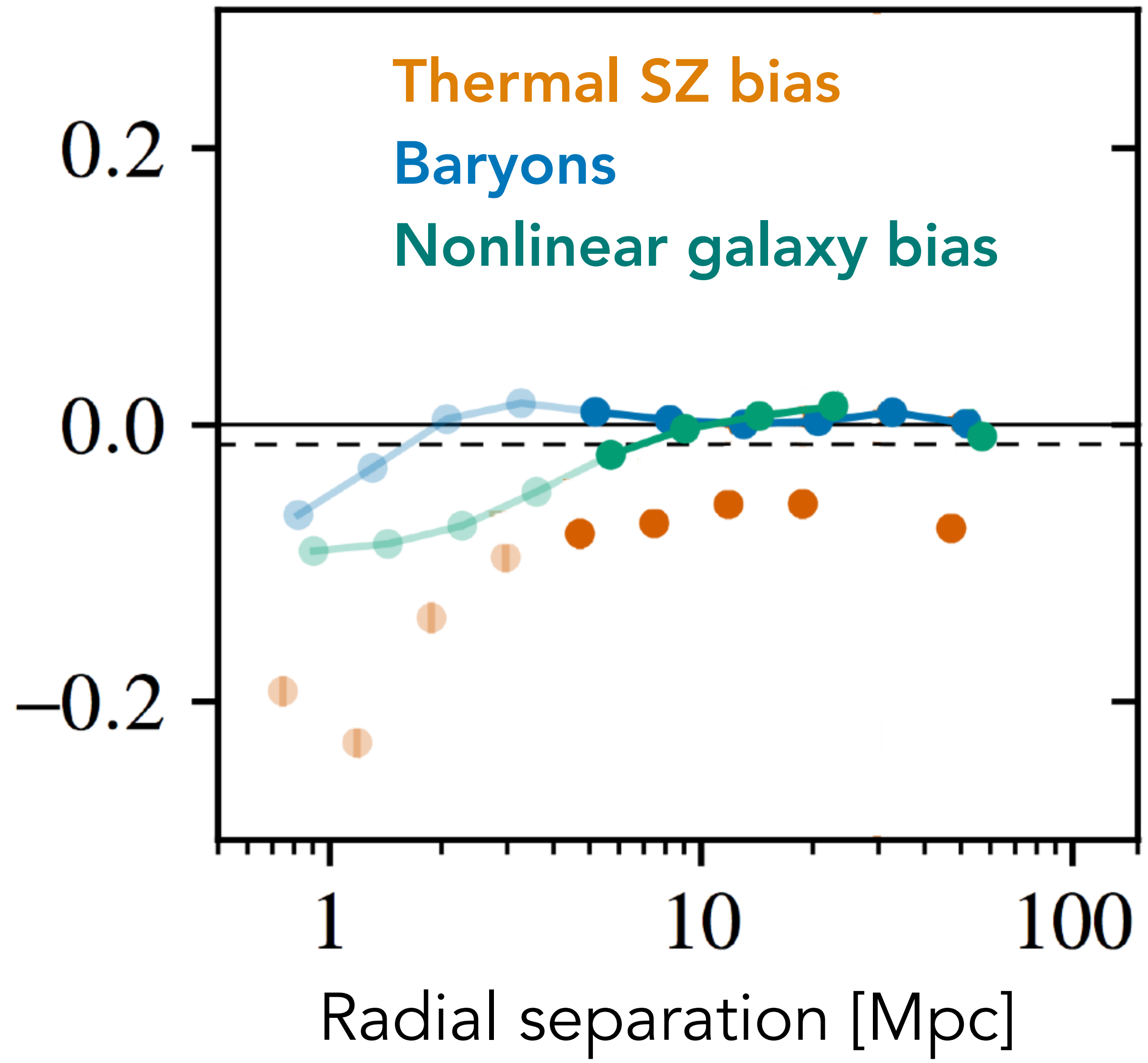
Cosmological results: DES+ SPT, 2018

6x2pt:
Validating the model

Thermal Sunyaev-Zel'dovich effect results from inverse Compton scattering of CMB photons with hot electrons

Identified thermal SZ effect contaminates CMB lensing cross-correlations, but bias can be controlled

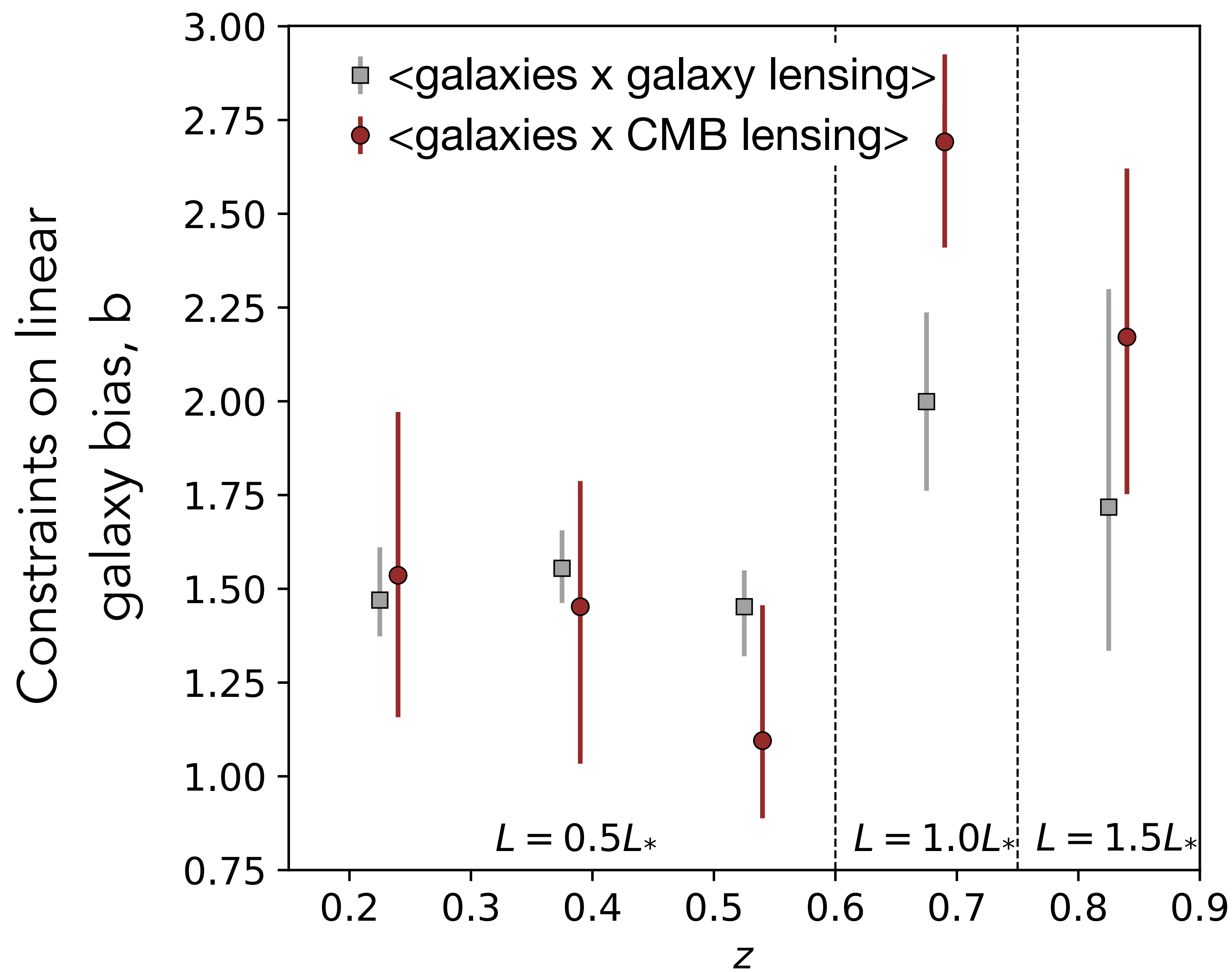
Fractional bias in
<galaxy x CMB lensing>



Baxter et al. 2018

6x2pt results:
high-redshift sensitivity of CMB lensing

Beyond z > 0.7, signal-to-noise of galaxies x CMB lensing is about the same as galaxies x galaxy lensing



Omori, …, Baxter, et al. 2018

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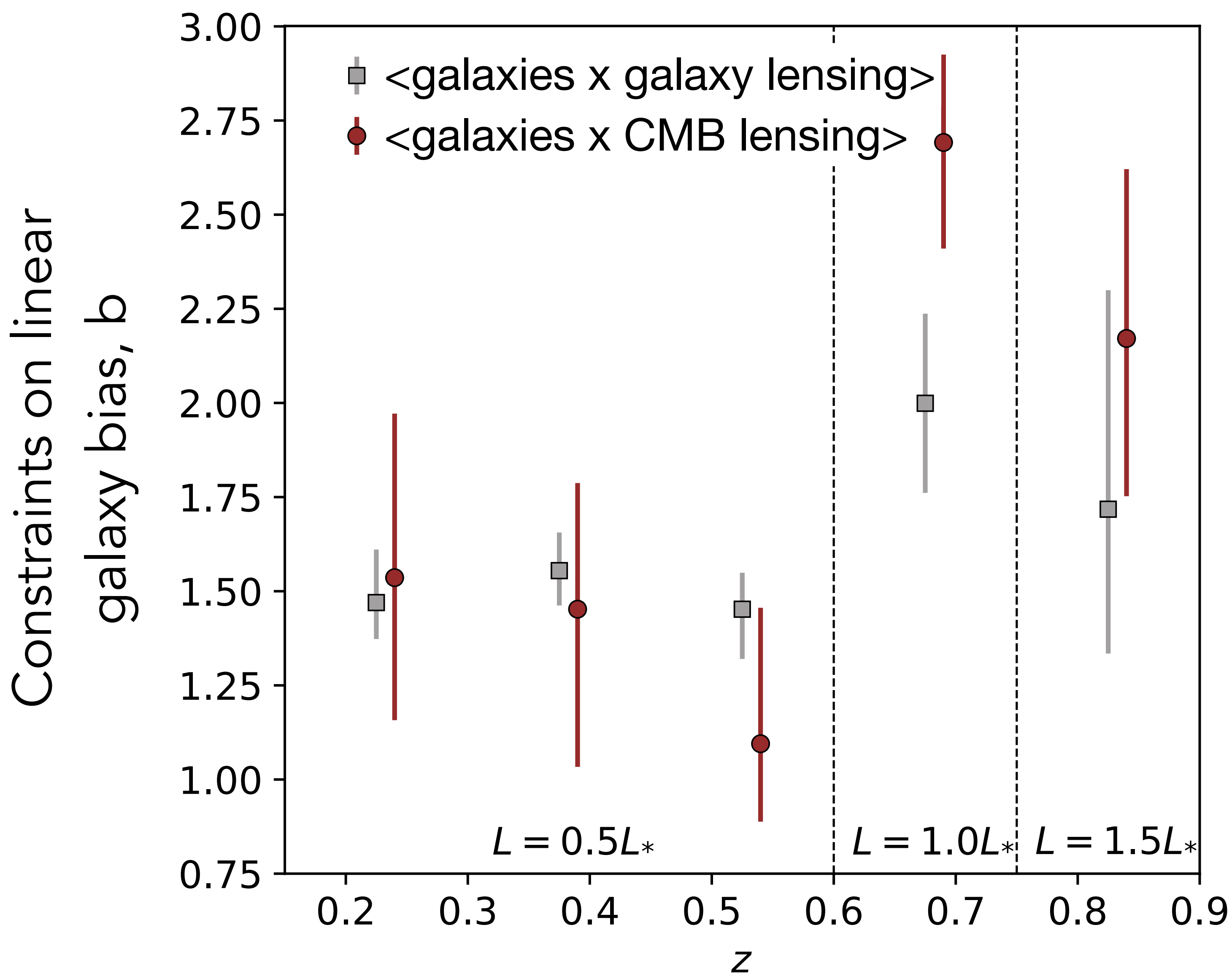


The high redshift regime of future surveys, like LSST and WFIRST

Omori, …, Baxter, et al. 2018

6x2pt results:
consistency of 3x2pt and CMB-lensing cross-correlations

Two approaches: **posterior predictive distribution** (PPD) and **evidence ratio**

Is D_2 consistent with D_1?
PPD: are data D_2 a reasonable realization, given a model posterior from analysis of D_1?

At each point in parameter chain from analysis of D_1, $\boldsymbol{\theta}_i$:

- generate simulated D_2, conditioned on observed D1: $d_{2,\mathrm{sim}} \sim P(d_2|d_1,\theta_i)$
- Compute χ^2 for this **simulated** data vector relative to the model at that point in parameter space: $(d_{2,\mathrm{sim}} - m(\theta_i))^T \, \mathbf{C}^{-1} \, (d_{2,\mathrm{sim}} - m(\theta_i))$
- Compute χ^2 for **true** data vector relative to the model at that point in parameter space:
$$(d_2 - m(\theta_i))^T \, \mathbf{C}^{-1} \, (d_2 - m(\theta_i))$$

Define p = fraction of points for which simulated χ^2 is bigger than data χ^2
Small p-value (say $p < 0.01$): χ^2 of D_2 is larger than you'd expect given D_1
Large p-value (say $p > 0.99$): you got a suspiciously low value of χ^2 for D_2

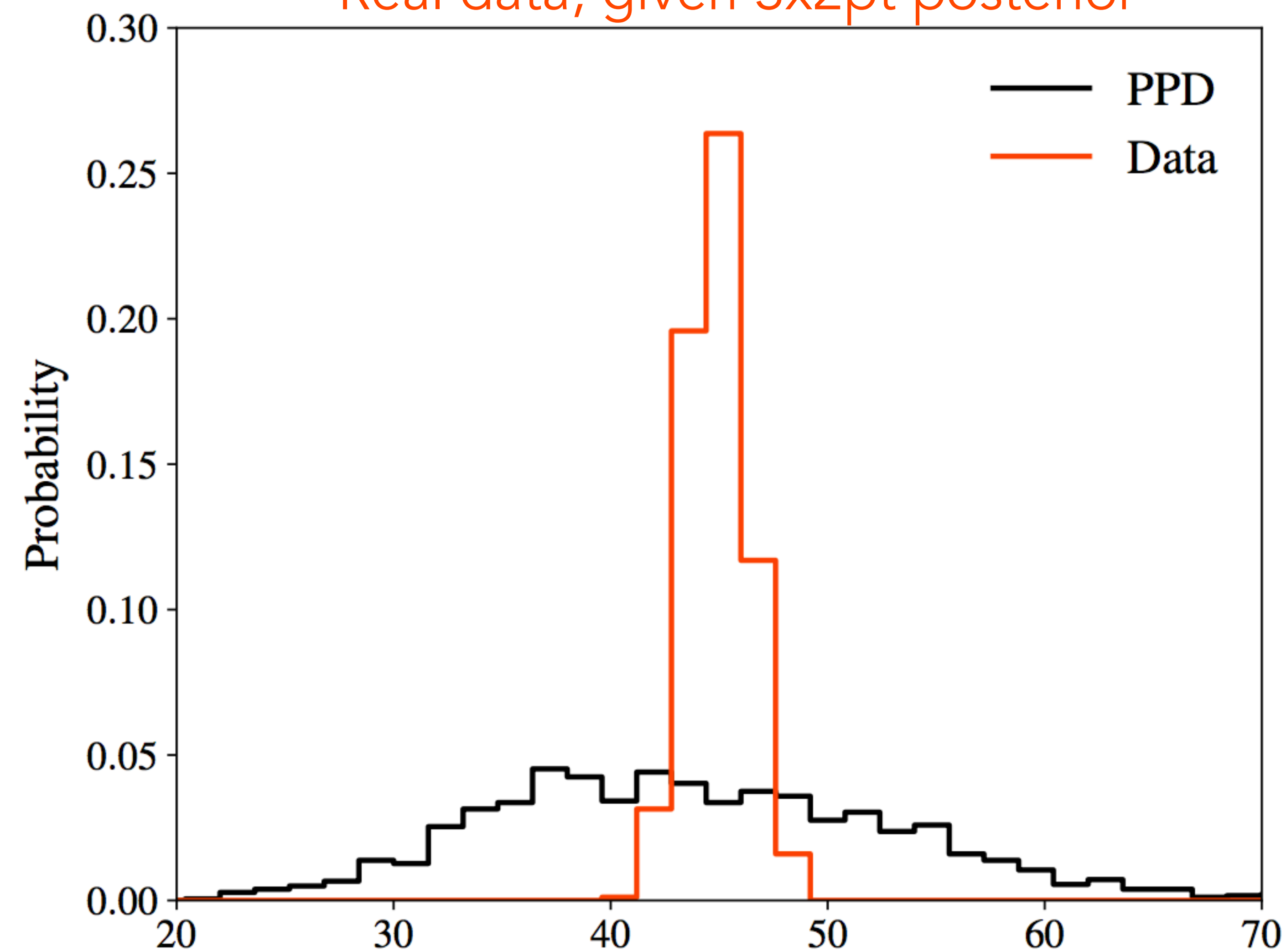
6x2pt results:
consistency with 3x2pt (DES-only correlations)

Both PPD and evidence ratio approaches confirm that **CMB lensing cross-correlations are consistent with galaxy lensing and clustering**

PPD p-value = 0.48

Simulated data, given 3x2pt posterior

Real data, given 3x2pt posterior



χ^2 for CMB lensing cross-correlations **given** galaxy lensing measurements

DES+SPT et al. 2018

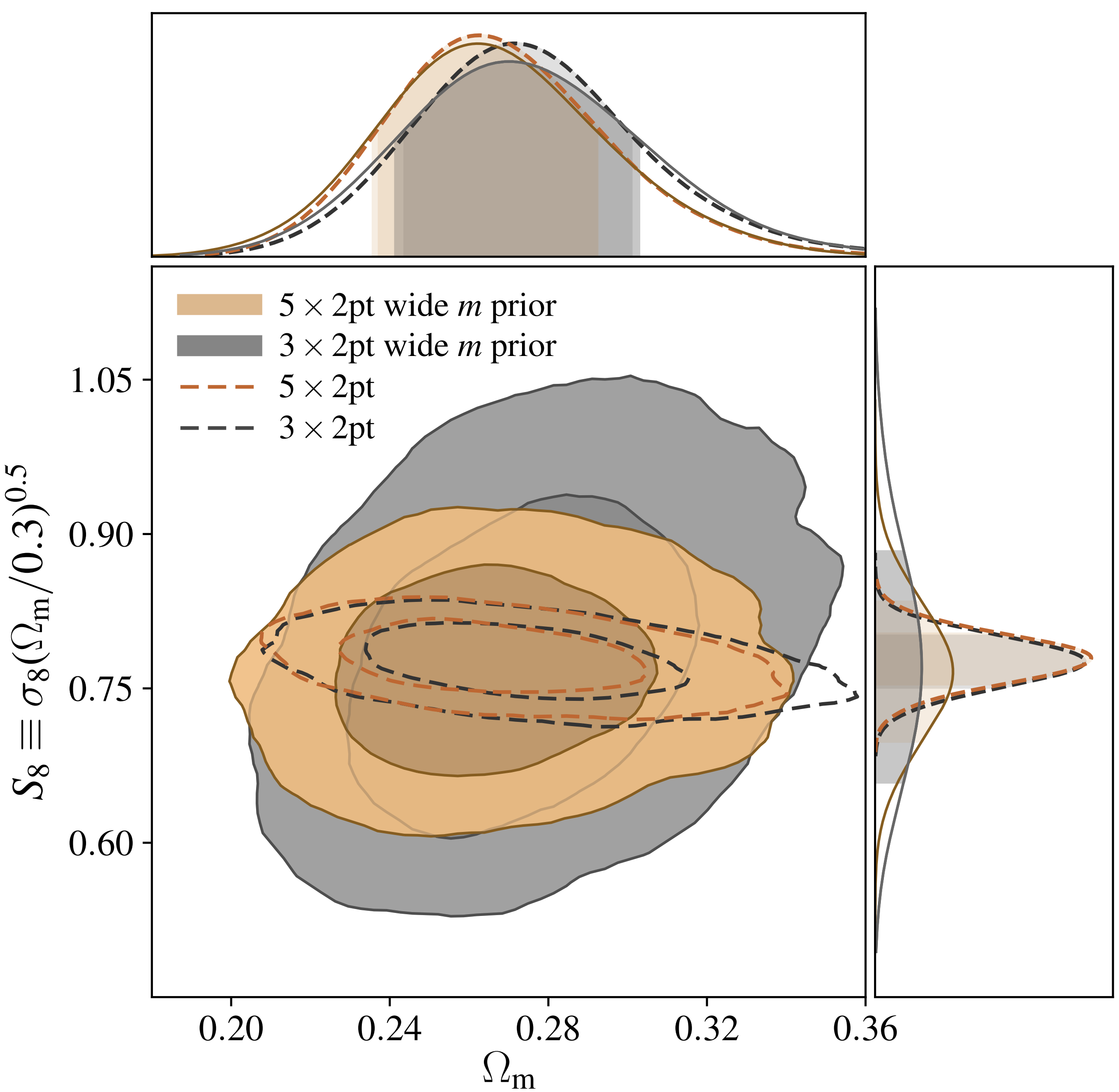
6x2pt results:
robustness to systematics

Large source of systematic uncertainty for DES 2pt analysis:
multiplicative shear bias

$$\gamma_{\rm obs} = (1+m)\gamma_{\rm true}$$

DES-only 2pt analysis needs strong priors on multiplicative shear bias from simulations

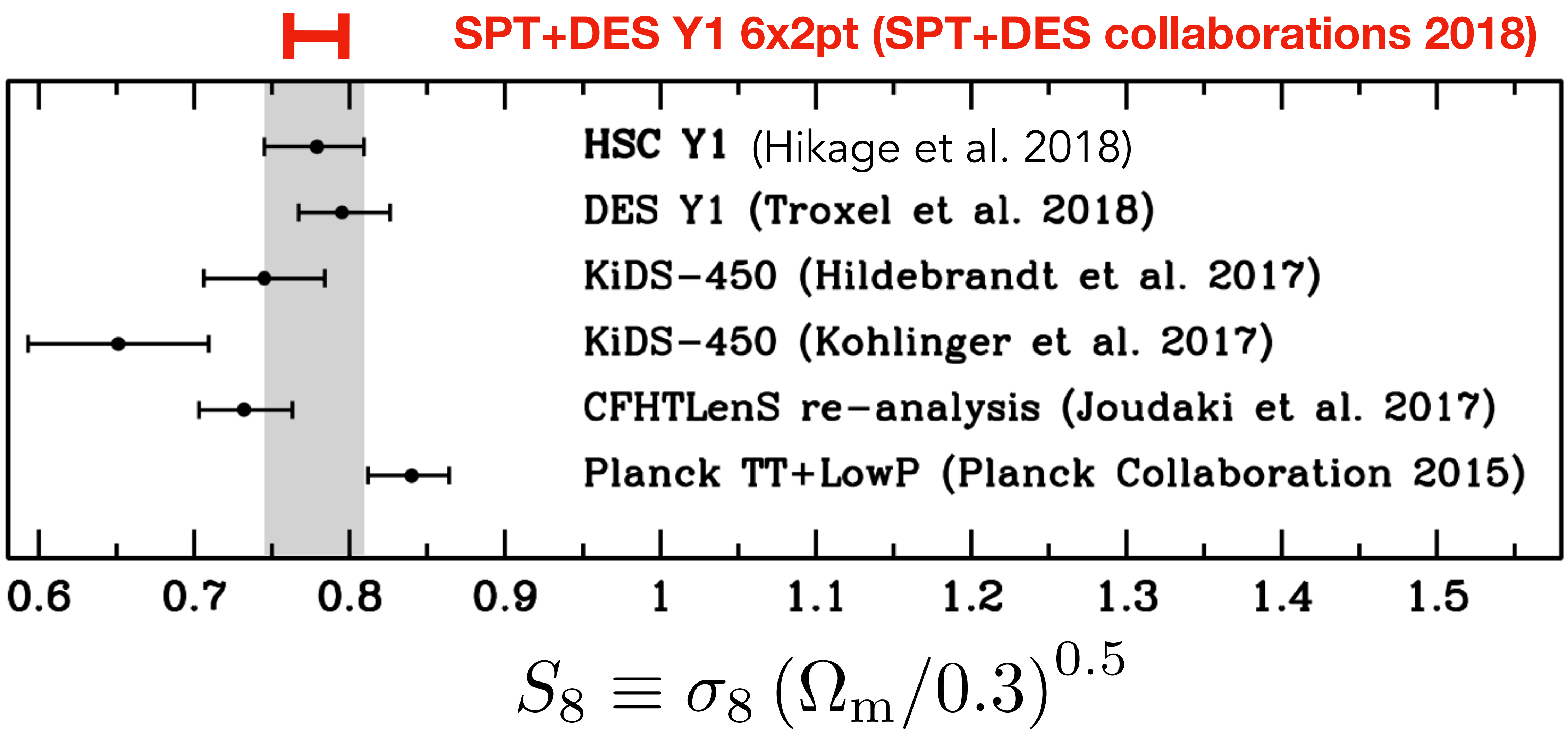
With CMB lensing cross-correlations, **data** calibrates multiplicative shear bias



DES+SPT et al. 2018 (see also Schaan et al. 2016)

6x2pt results:

cosmological constraints with CMB lensing autospectrum



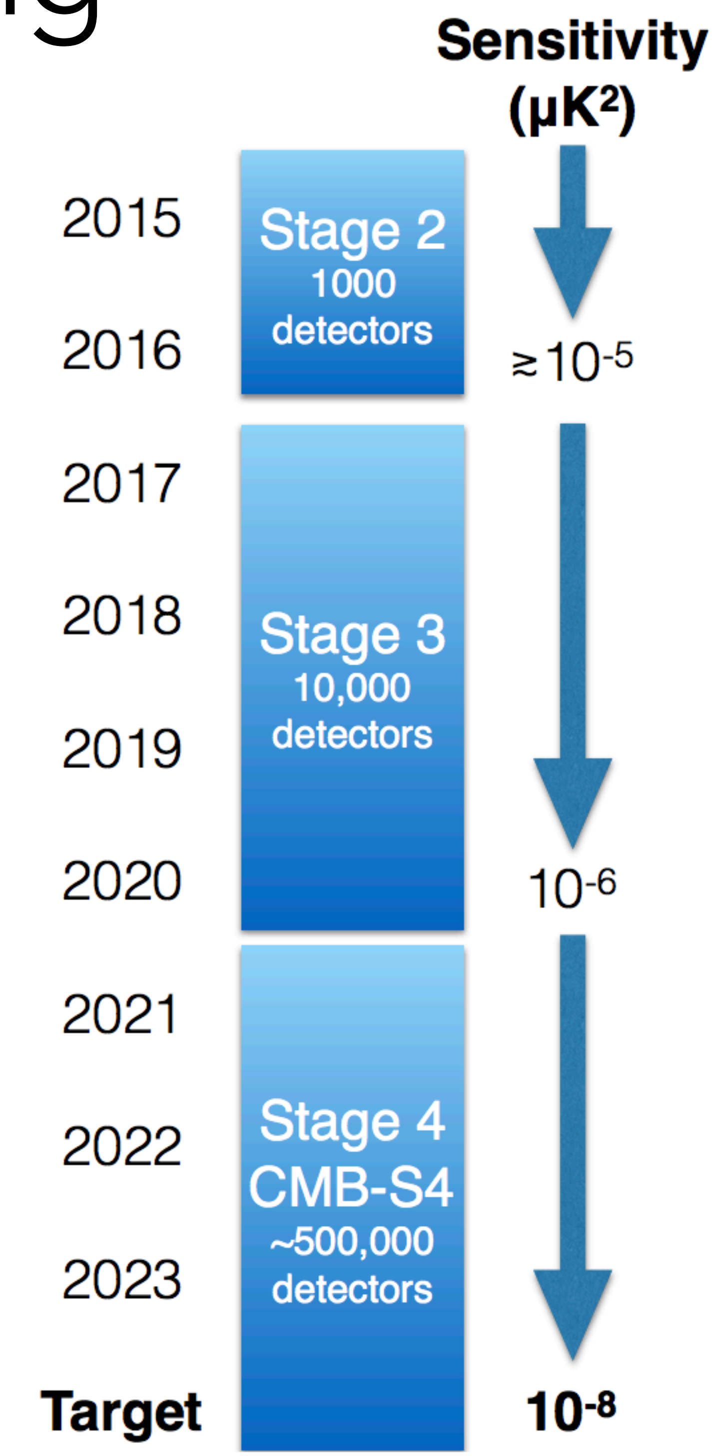
Future prospects with large scale structure x CMB lensing

Improvements on multiple fronts:

- CMB data: larger areas, lower noise
- Galaxy survey data: wider area, higher redshift
- Methodology - eliminating thermal SZ bias

(e.g. Hill & Madhavacheril 2018, Schaan & Ferraro 2018)

Should know fairly soon whether S8 tension is real or not

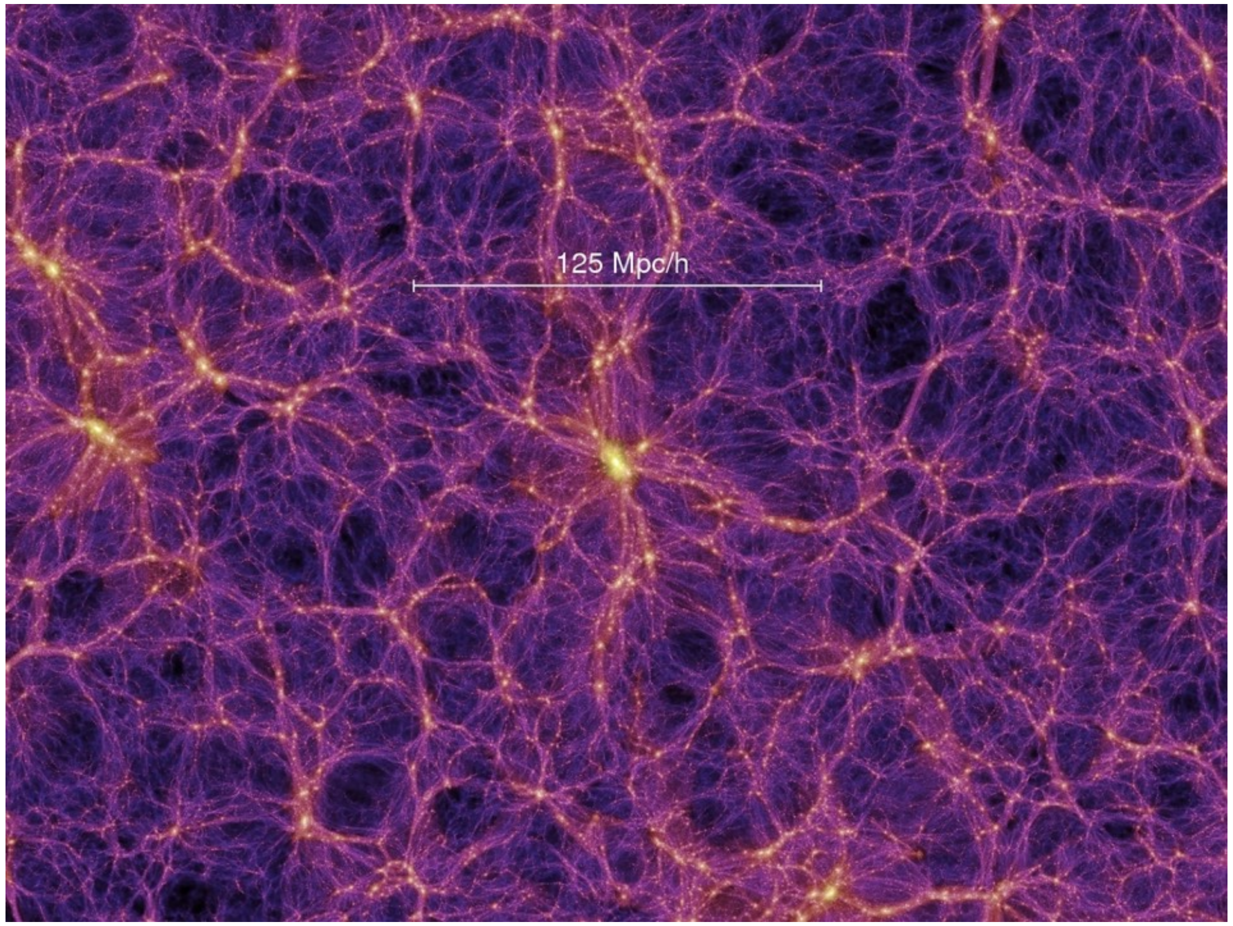


CMB S4 Science Book

Beyond two-point functions…

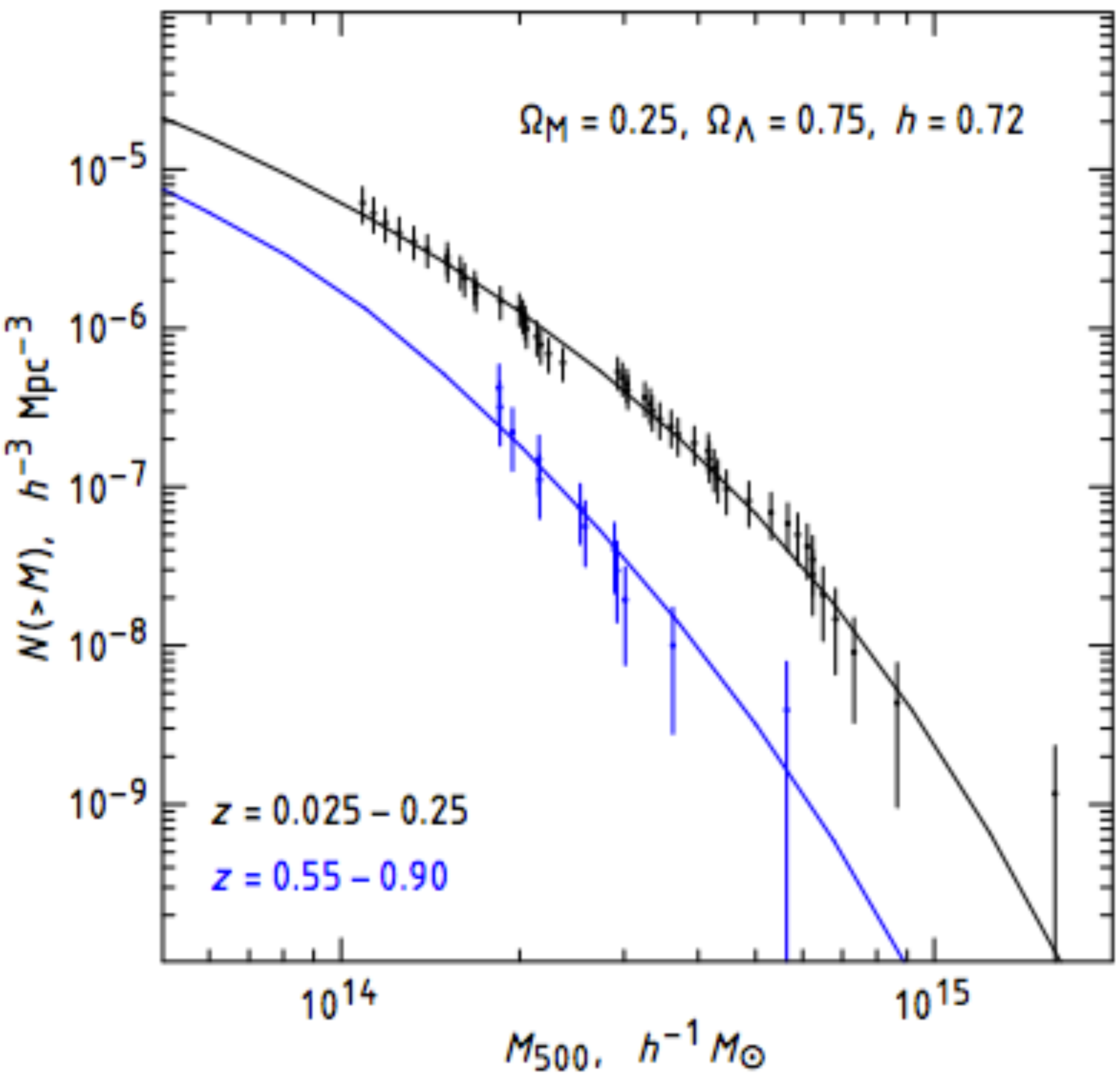
As most massive bound objects in the Universe, galaxy clusters form in rare non-Gaussian peaks

Abundance of clusters is exponentially sensitive to growth of structure



Accurate cluster masses are essential to cluster abundance cosmology

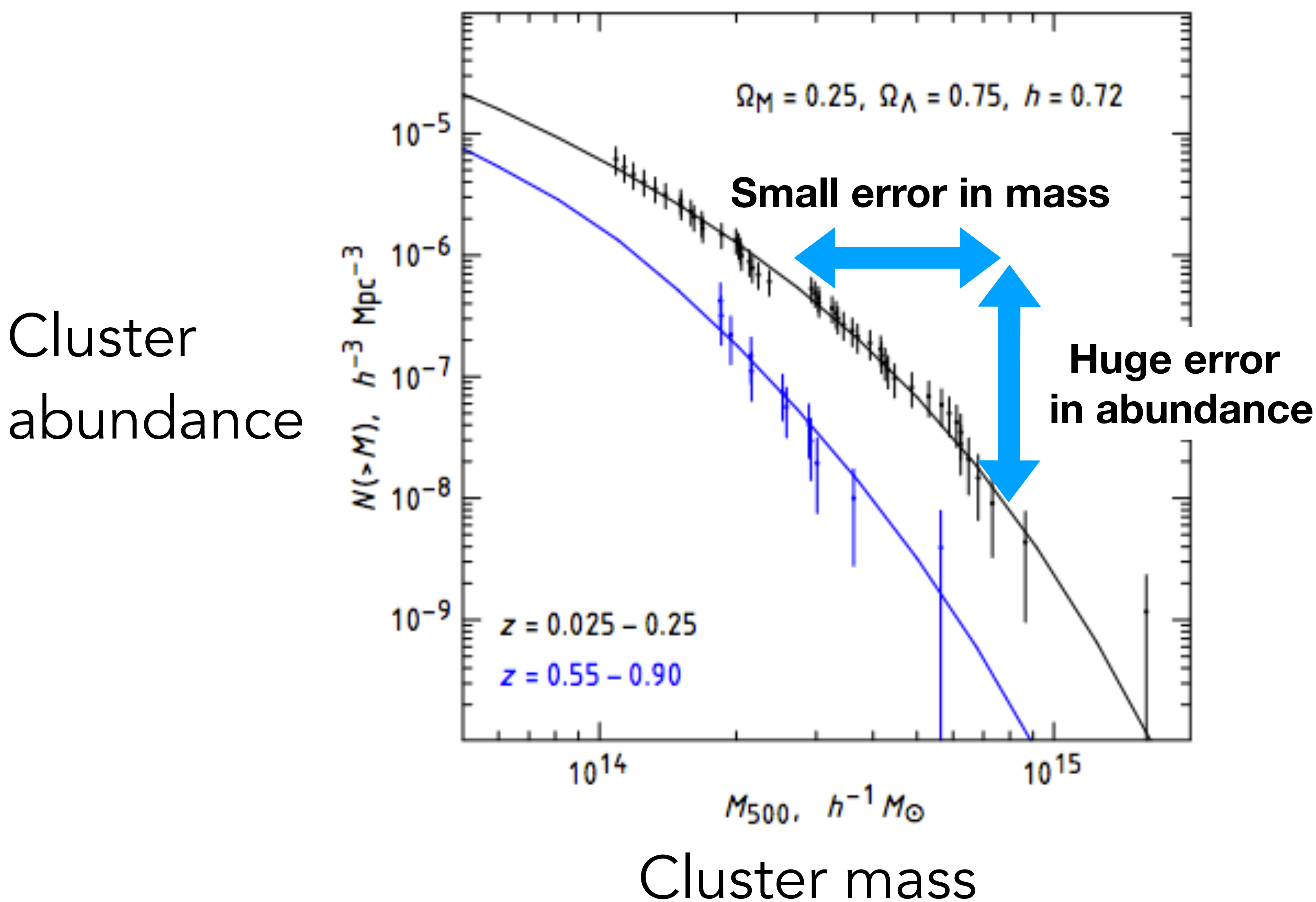
Cluster abundance



Cluster mass

Vikhlinin+ 2008

Accurate cluster masses are essential to cluster abundance cosmology

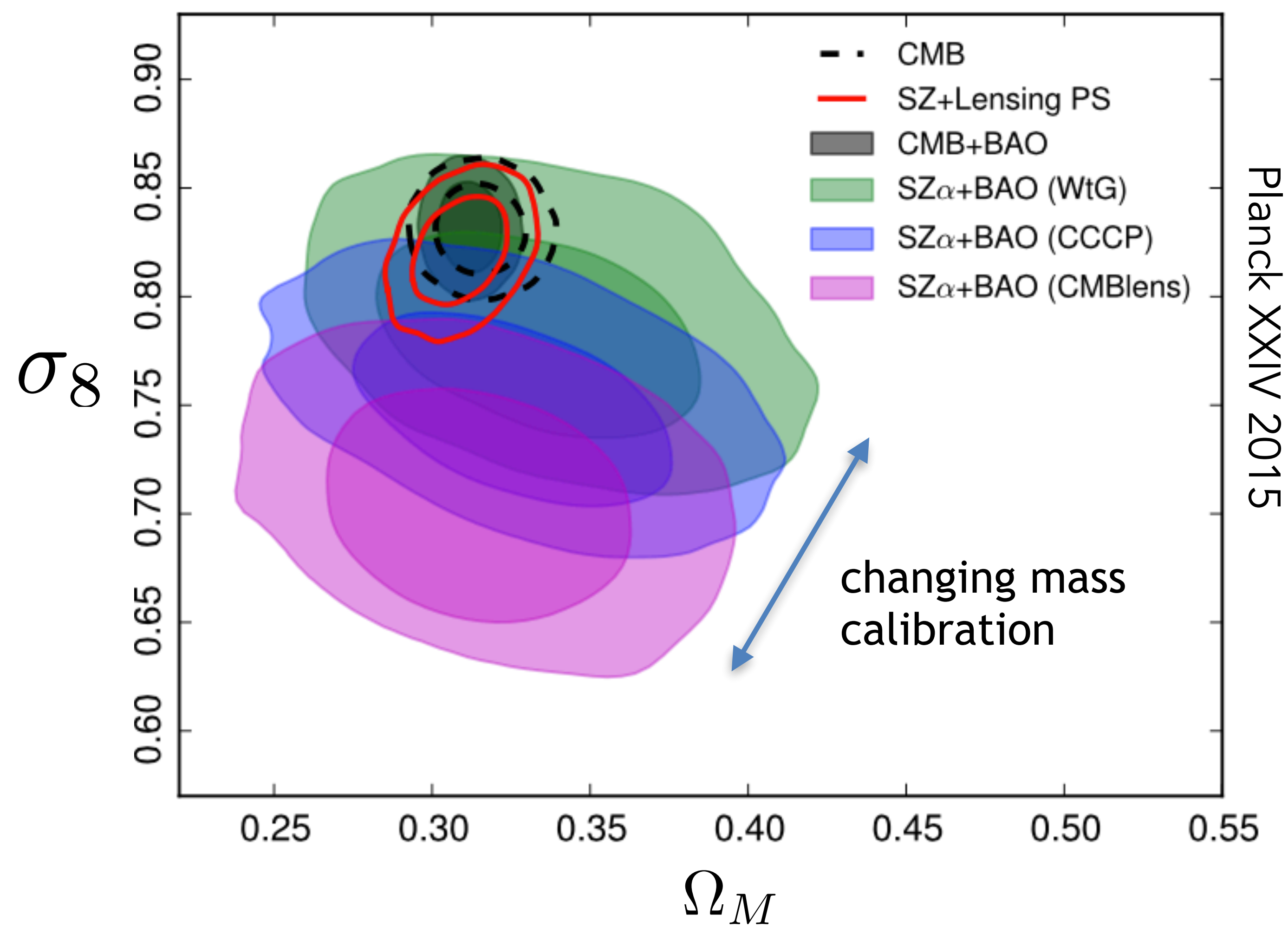


Vikhlinin+ 2008

More hints of tension?
Cluster abundance vs. Primary CMB

Like lensing, cluster abundance measurements prefer lower S_8 than primary CMB

Resolving this tension will require better cluster mass calibration



CMB lensing to the rescue again!

No **photometric redshift uncertainty**

Dominant systematic for year one DES cluster mass calibration (McClintock et al. 2018)

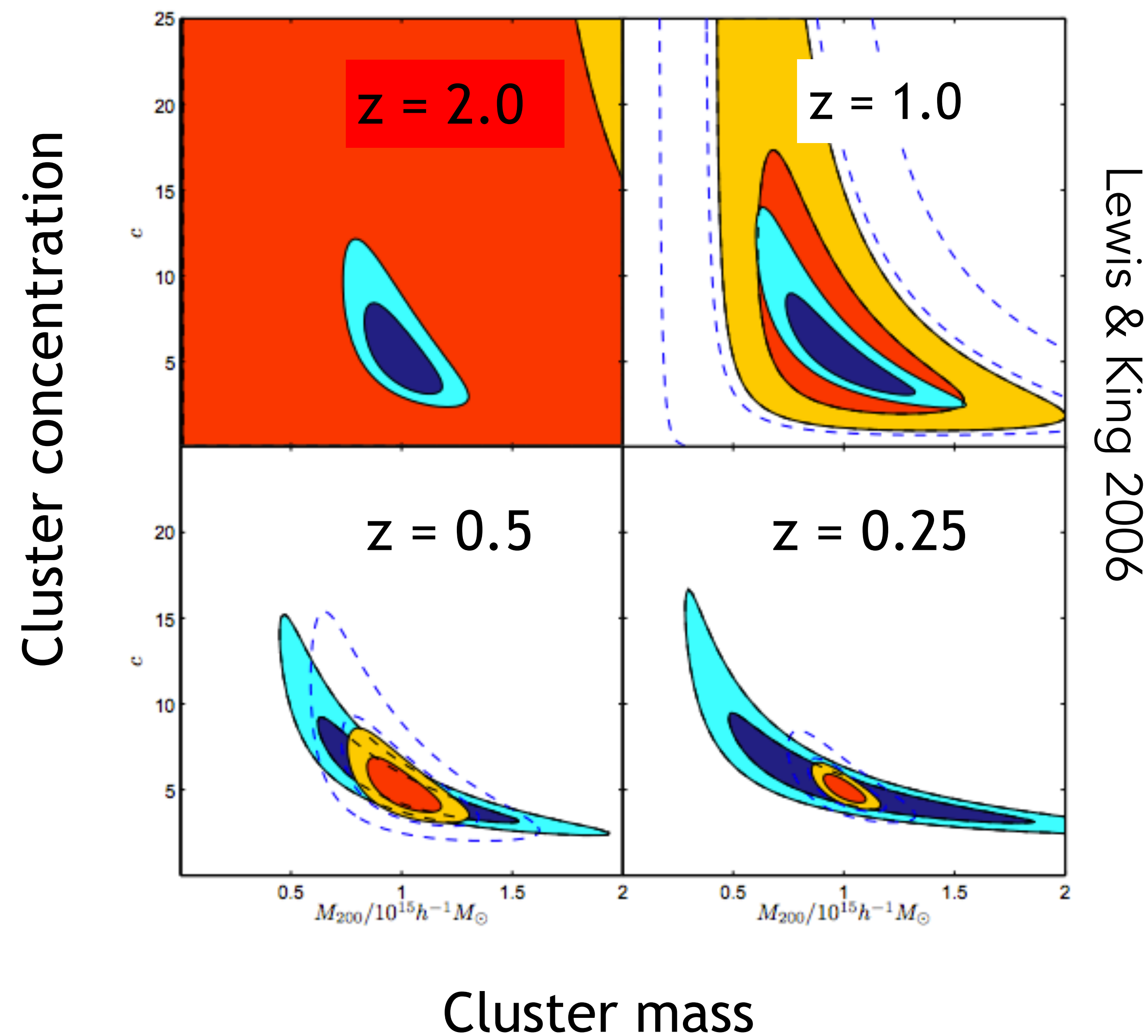
No **boost factors**

Dilution of lensing signal due to contamination of source galaxy sample by cluster members

High redshift sensitivity

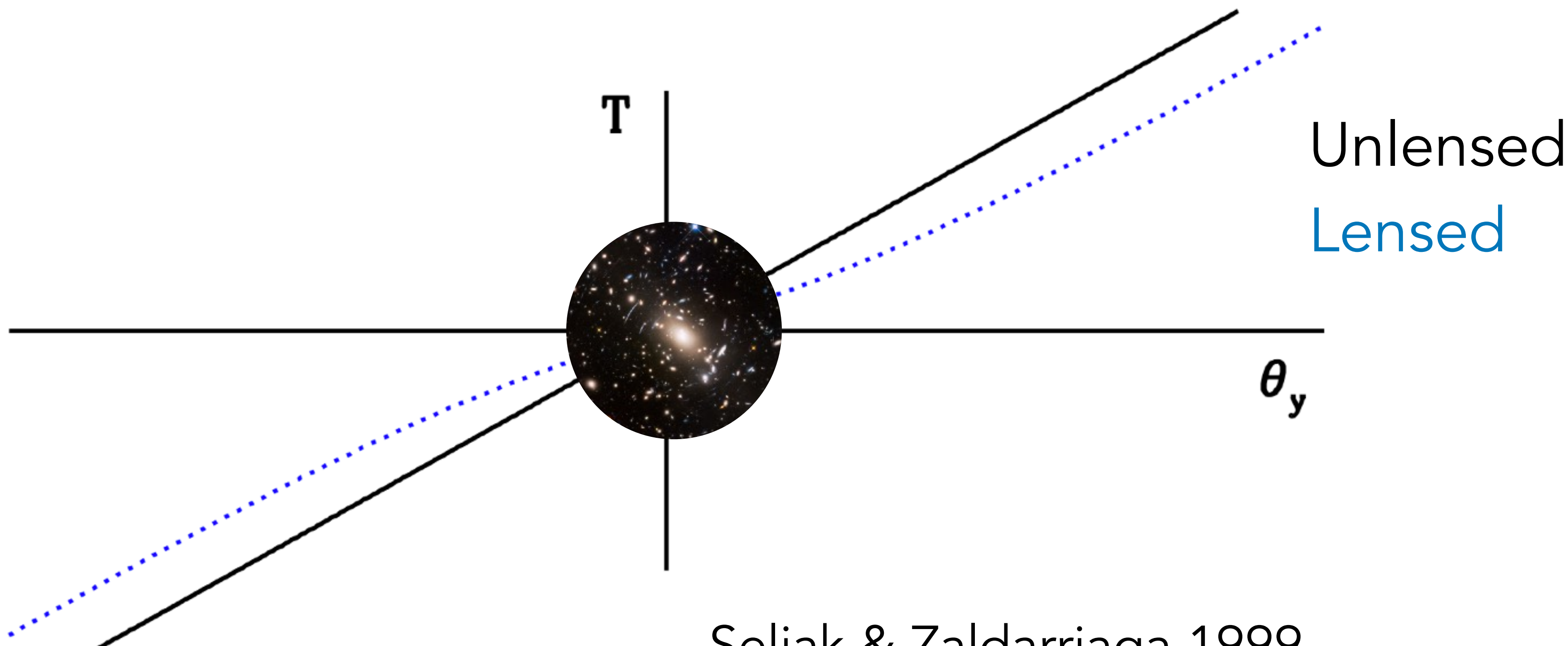
CMB lensing one of the only ways to get lensing-calibrated masses for high redshift clusters from future SZ surveys

Red = space-based galaxy lensing
Blue = CMB S4–like experiment



The small scale CMB lensing signal

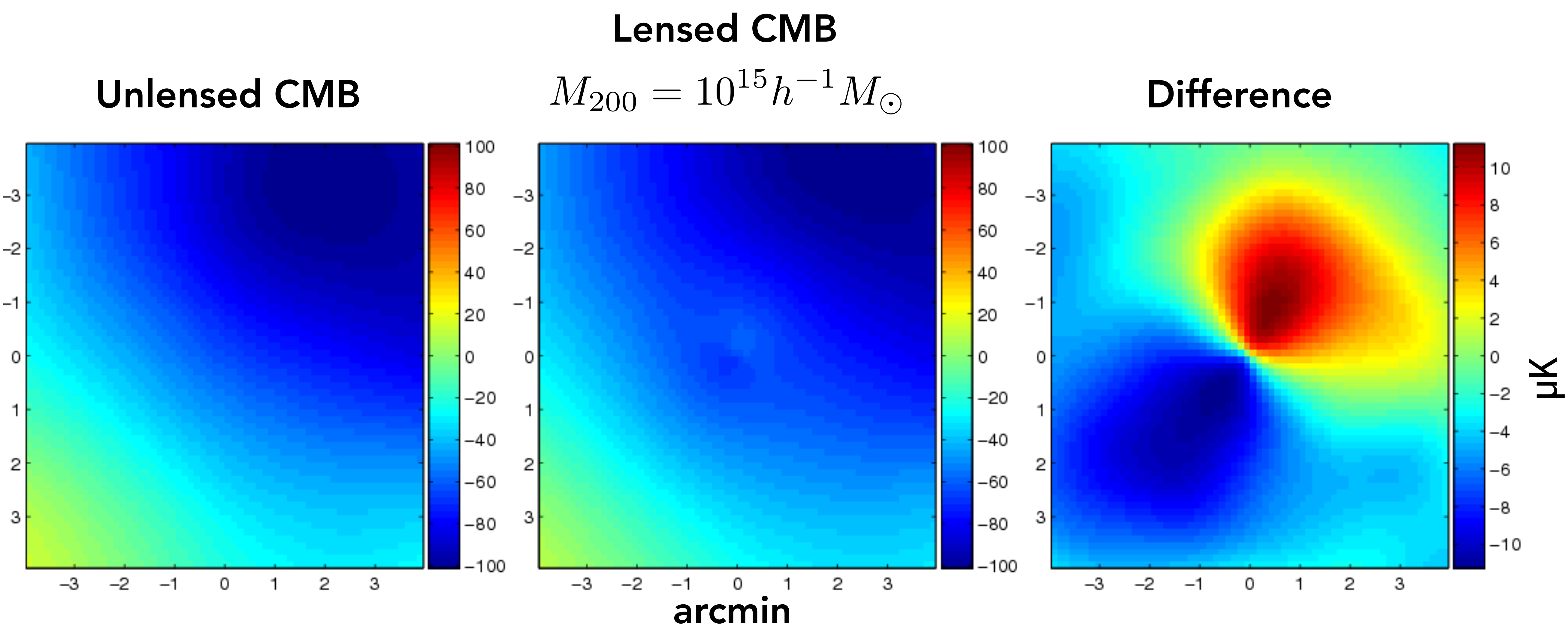
At small scales, unlensed CMB is approximately a pure gradient (typical fluctuations of order ~1 deg)



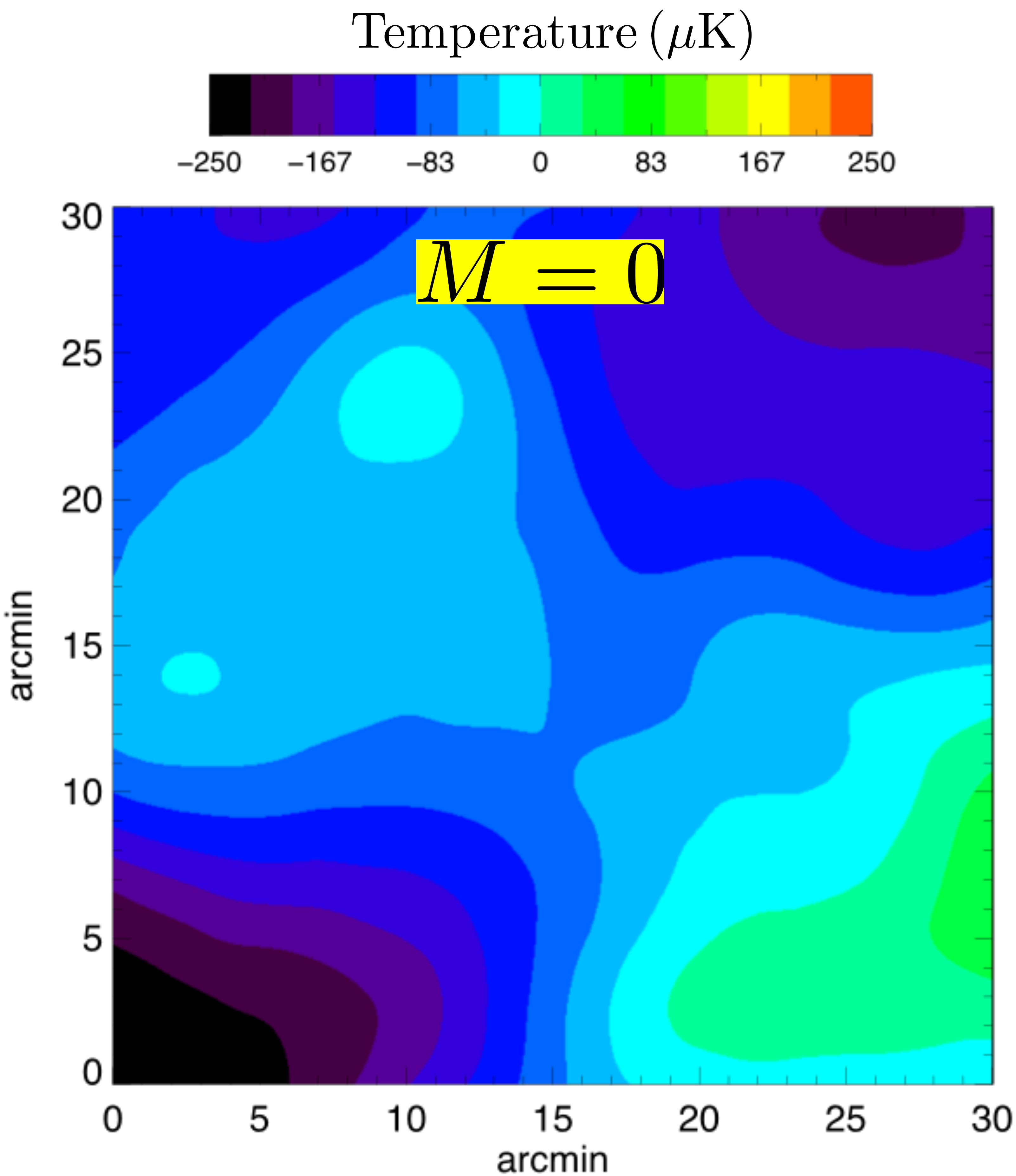
Seljak & Zaldarriaga 1999

Lensing by a cluster induces a “dimple” on top of a gradient

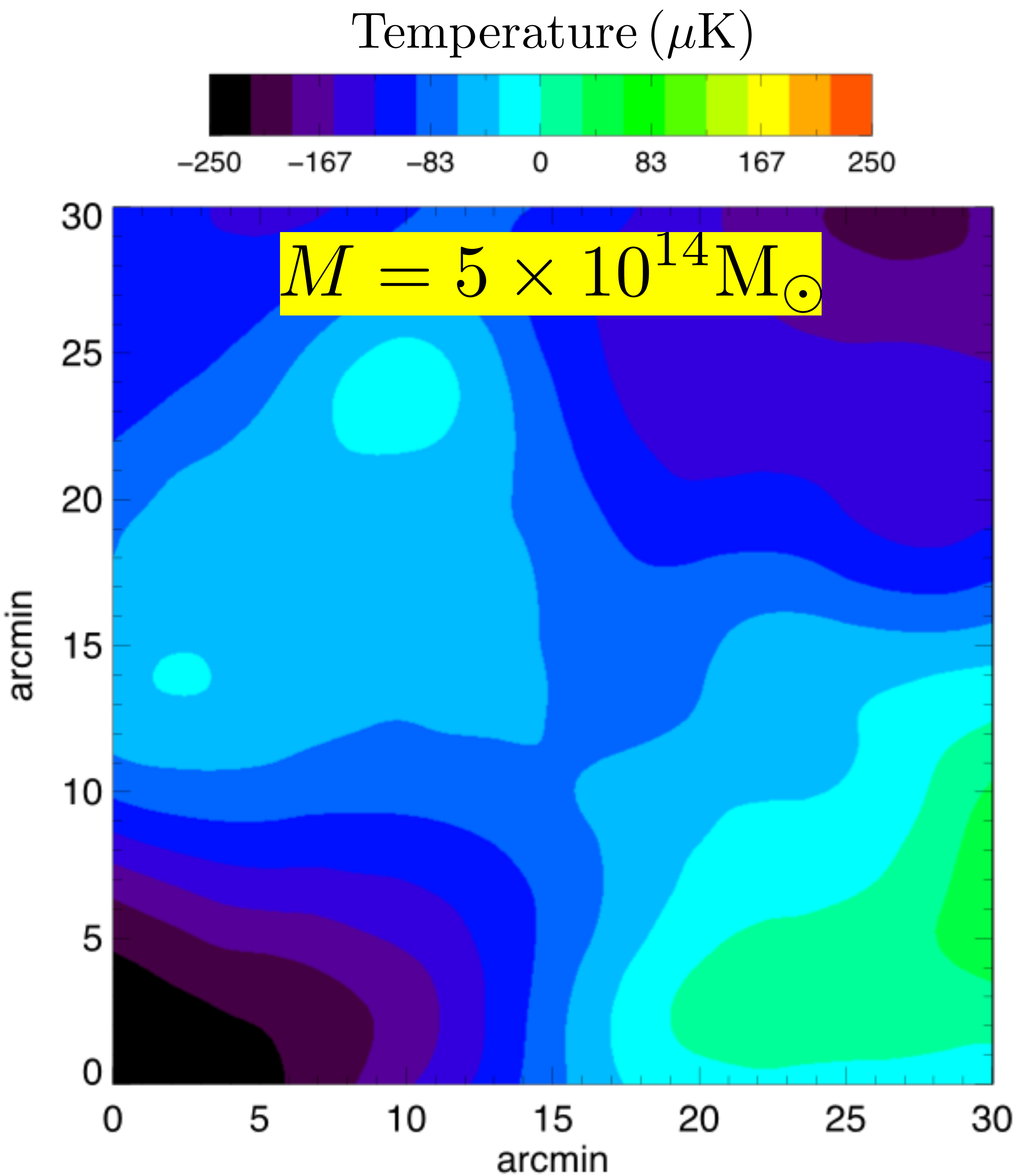
The CMB cluster lensing signal



Lewis and Challinor, 2006



Temperature (μK)
−250
−167
−83
0
83
167
250
M = 0
arcmin
arcmin
0
5
10
15
20
25
30



Temperature (μK)
−250
−167
−83
0
83
167
250
$M = 5 \times 10^{14} \mathrm{M}_{\odot}$
arcmin
arcmin
0
5
10
15
20
25
30

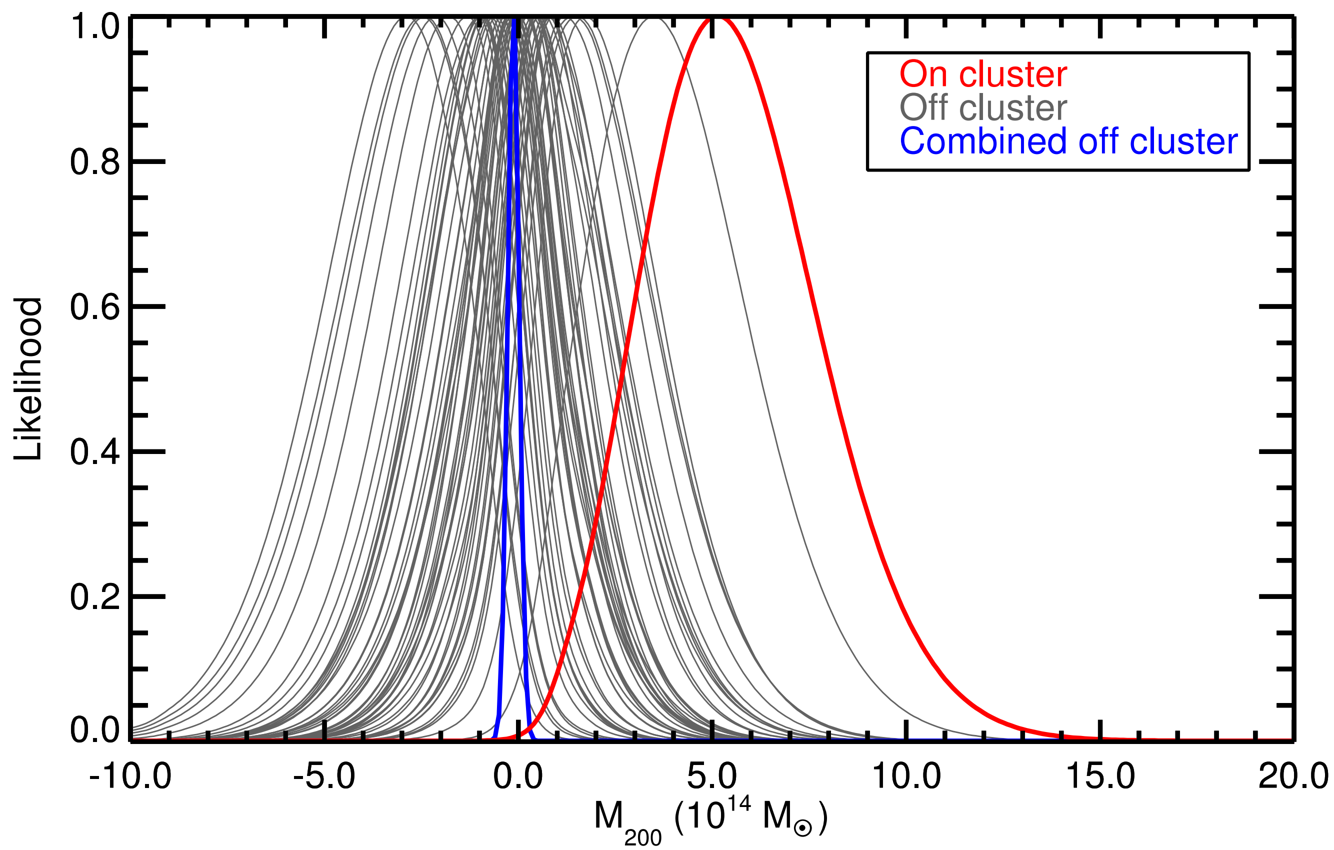
CMB cluster lensing is a rapidly evolving field…

First detection of CMB cluster lensing in 2015 with South Pole Telescope-selected clusters

Recent measurements using optically selected clusters (Geach & Peacock 2017, Baxter et al. 2018)

Now provides useful constraints on cluster mass-observable relations

3.1σ first detection!



Baxter et al. 2016

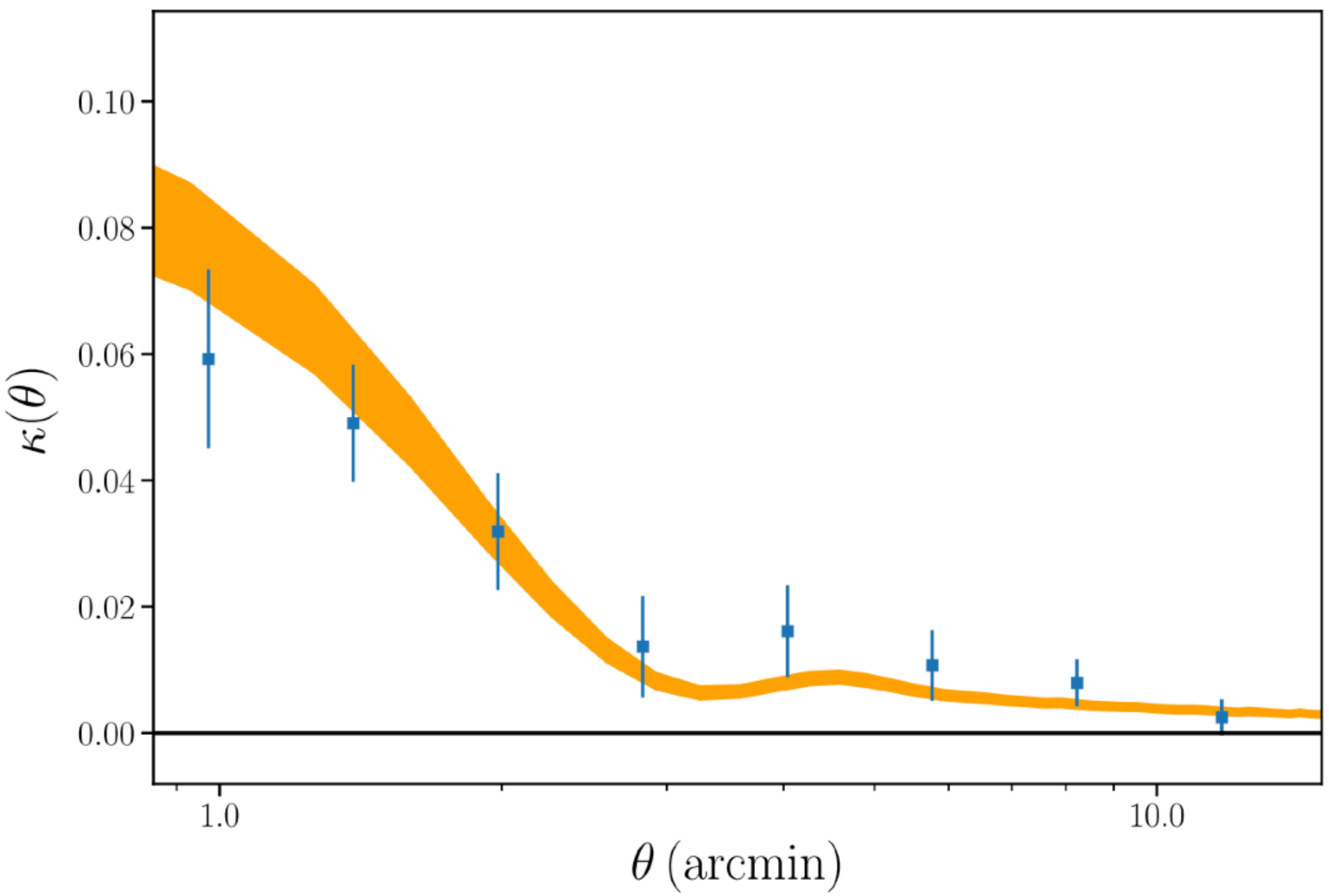
CMB cluster lensing is a rapidly evolving field…

First detection of CMB cluster lensing in 2015 with South Pole Telescope-selected clusters

Recent measurements using optically selected clusters (Geach & Peacock 2017, Baxter et al. 2018)

Now provides useful constraints on cluster mass-observable relations

8.1σ detection!



Baxter et al. 2018

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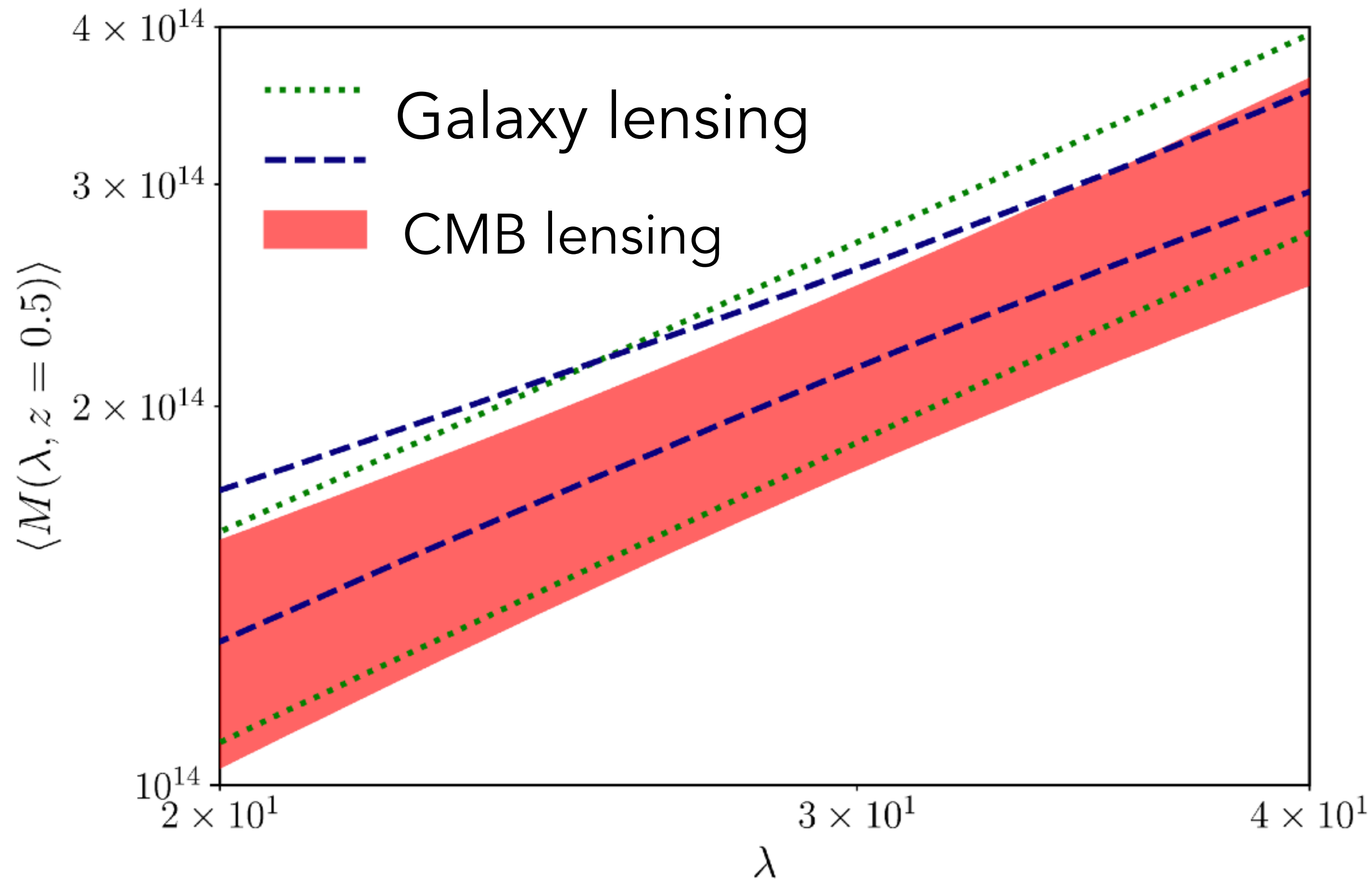


Baxter et al. 2018

Raghunathan, Patil, Baxter et al. 2019

Future of CMB cluster lensing

Larger cluster samples from CMB and galaxy surveys
(including high-z clusters from future SZ surveys)

Low noise, high resolution CMB surveys

Improved methodology: less SZ contamination

Experiment	ΔT [μK−arcmin]			f_{sky}	Effective beam [$\theta_{\rm FWHM}$]	# of clusters (N_{clus})	$T_{\rm ML}$ (ILC)	$QU_{\rm ML}$ (ILC)
	90	150	220					
CMB - S4	1.0	1.0	1.0	0.50	1.0′	100,000	0.87%	0.83%
					2.0′		0.95%	0.98%
					3.5′		1.20%	1.60%
SPT-3G	4.5	2.5	4.5	0.06	1.2′	10,000	3.28%	6.12%
AdvACT	8.0	7.0	25.0	0.50	1.4′		4.35%	>15%
Simons Array - Deep	1.5	1.5	4.7	0.05	3.5′		4.41%	8.45%
Simons Array - Wide	5.5	5.5	20.0	0.40			5.86%	>15%

Raghunathan, Patil, Baxter et al. 2017

Part II:

Planetary science with correlations between CMB and optical surveys

Why consider planetary science with CMB surveys?

Thermal emission of outer solar system objects fairly well matched to CMB bands

- Small objects: stellar heating
- Large objects (e.g. planets): internal heating

Wide area

- Useful for detecting rare objects (like a Planet 9)
- Useful for measuring statistics of large populations

Time domain information

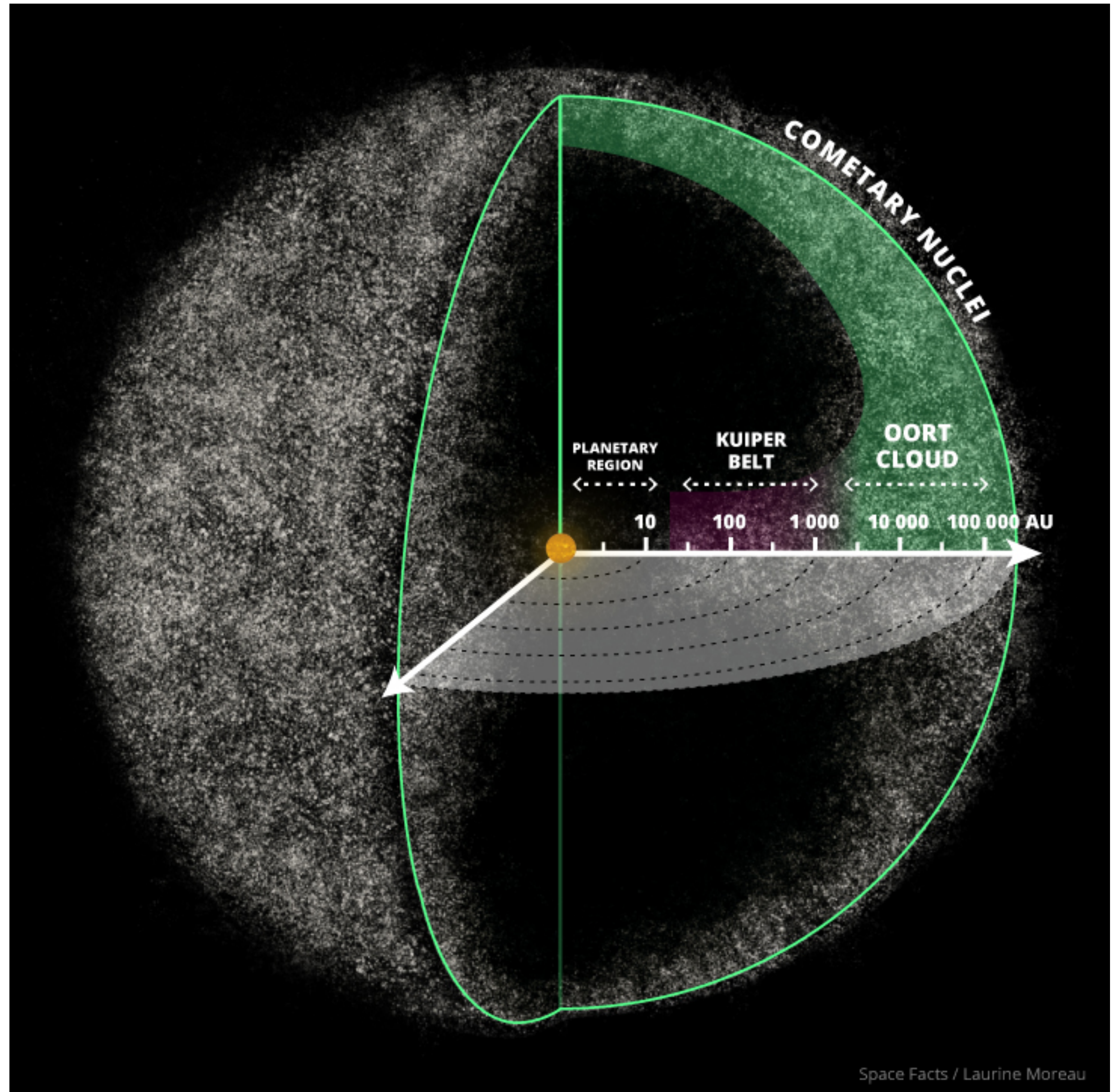
- CMB surveys typically scan the sky frequently, useful for detecting moving objects in our own solar system

The Oort Cloud

Long period comets believed to originate in Oort cloud

Formation likely connected to giant planets

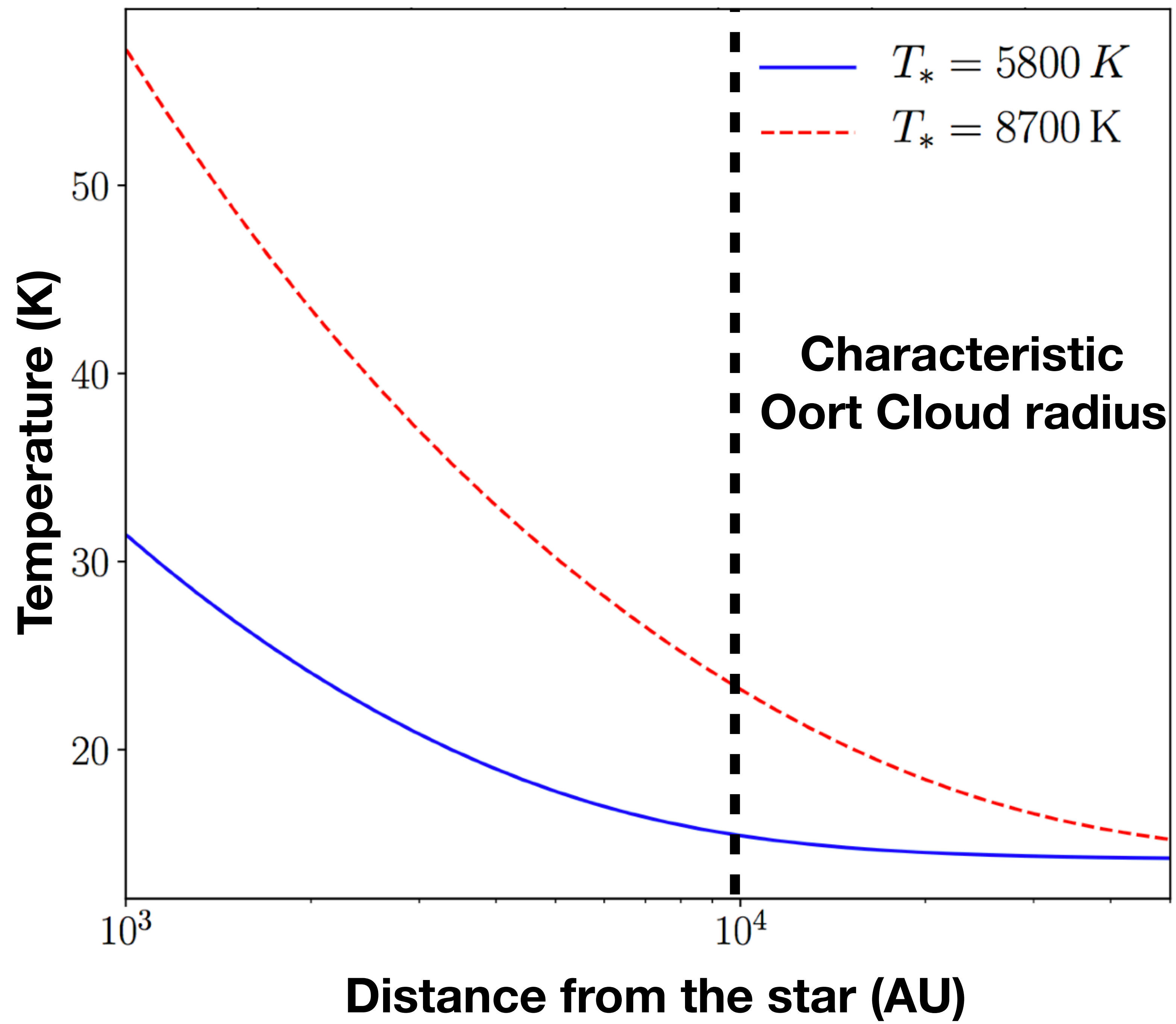
No direct detections of outer Oort cloud objects



Oort Cloud thermal emission

Oort cloud objects **warmer** than the Cosmic Microwave Background: depends on stellar flux, distance, grain emissivity

Expected temperatures: ~10-40 K



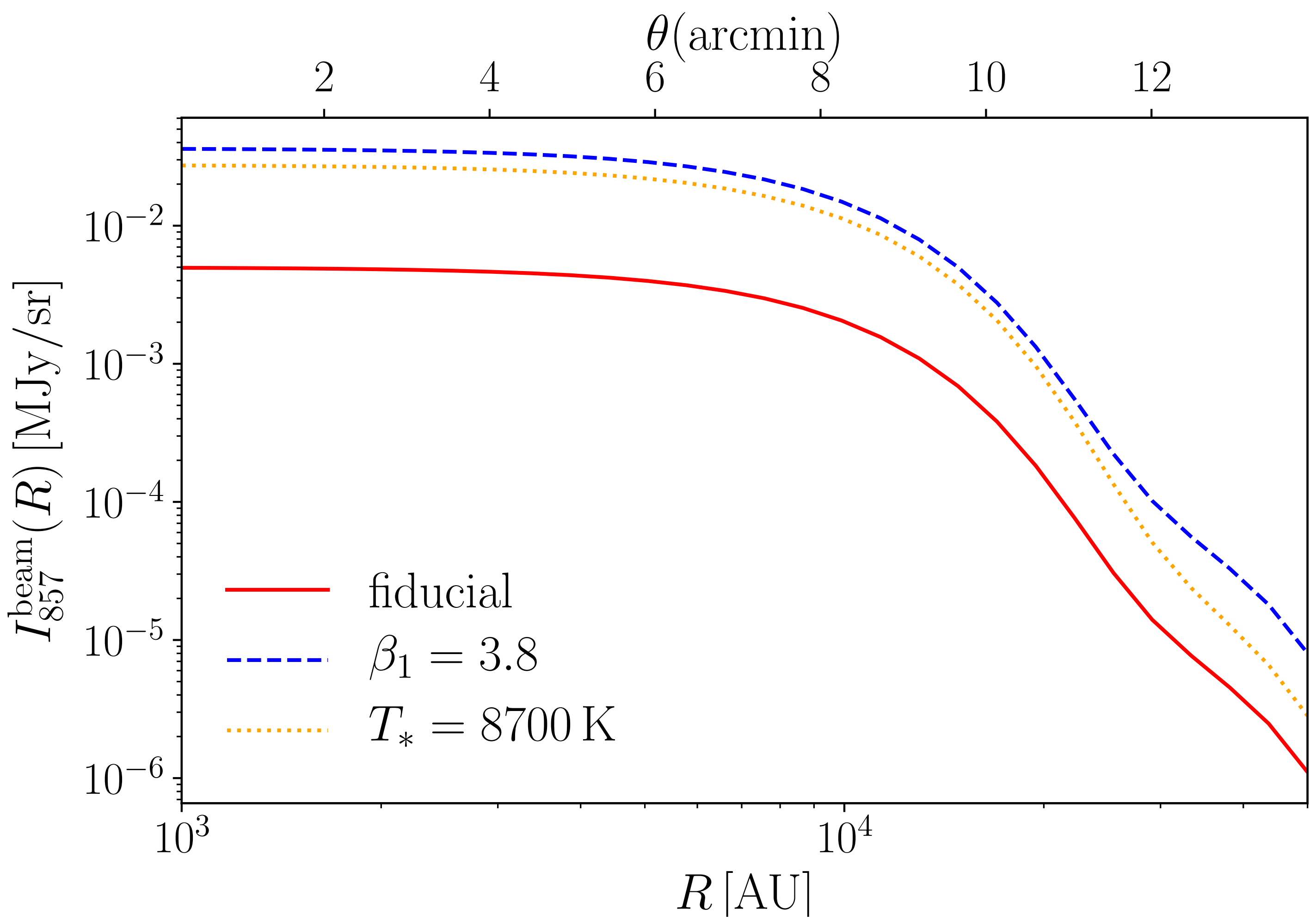
Baxter et al. 2018b

Exo-Oort clouds

Detecting thermal emission from **our** Oort cloud is challenging since signal will be close to uniform on the sky (see Babich et al. 2007)

Signal from **exo**-Oort clouds on the other hand will be correlated with host star

Signal expected in 857 GHz Planck maps



Baxter, Blake, Jain 2018

Exo-Oort clouds with *Planck* and *Gaia*

Correlated *Gaia*-detected stars with *Planck* sky maps

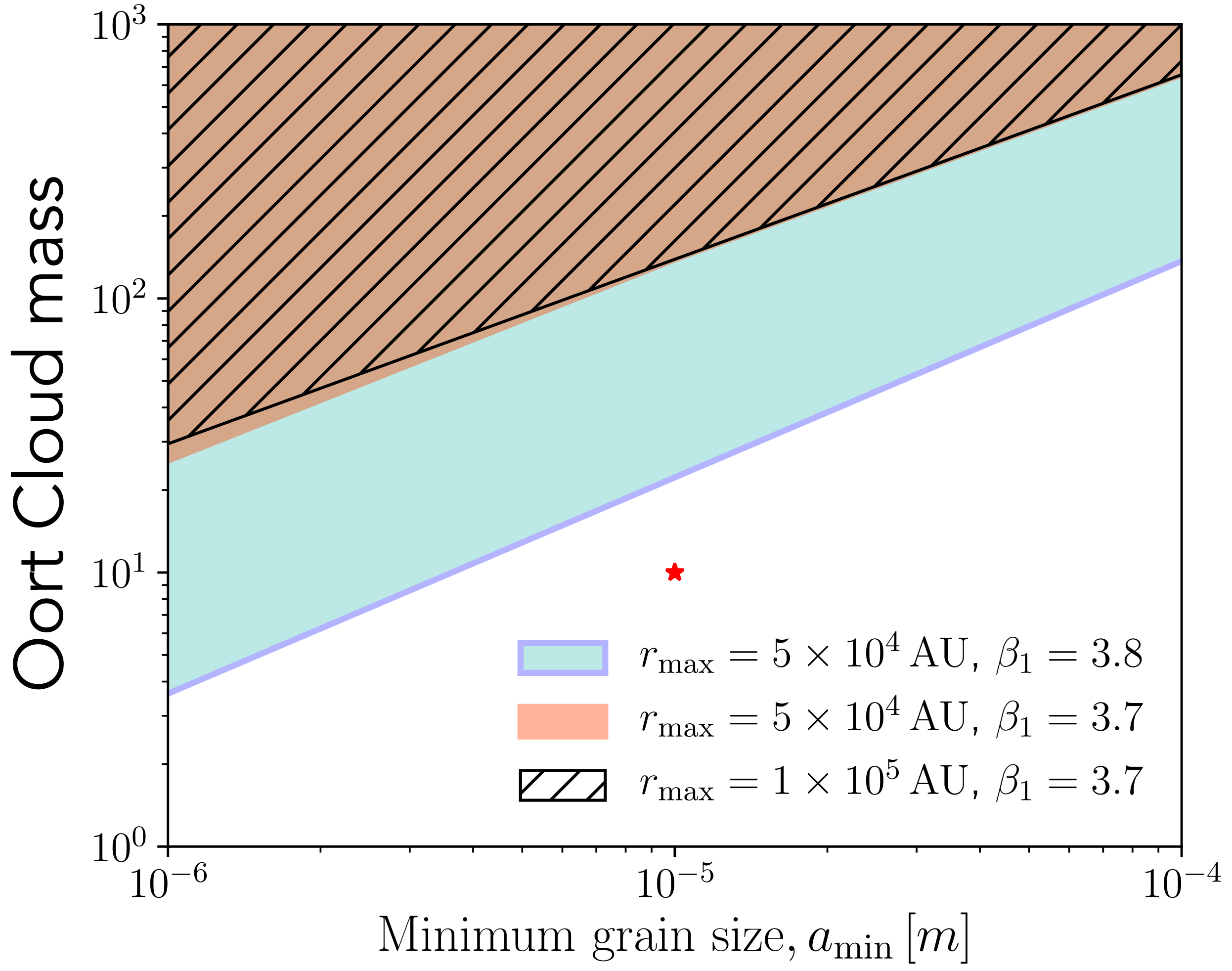
No excess emission found in fiducial analysis

Our measurements constrain Exo-Oort cloud parameter space

Signal most sensitive to:

- Mass of exo-Oort cloud
- Minimum grain size
- Power-law index of grain size distribution

Data: *Planck* maps, *Gaia* star catalogs



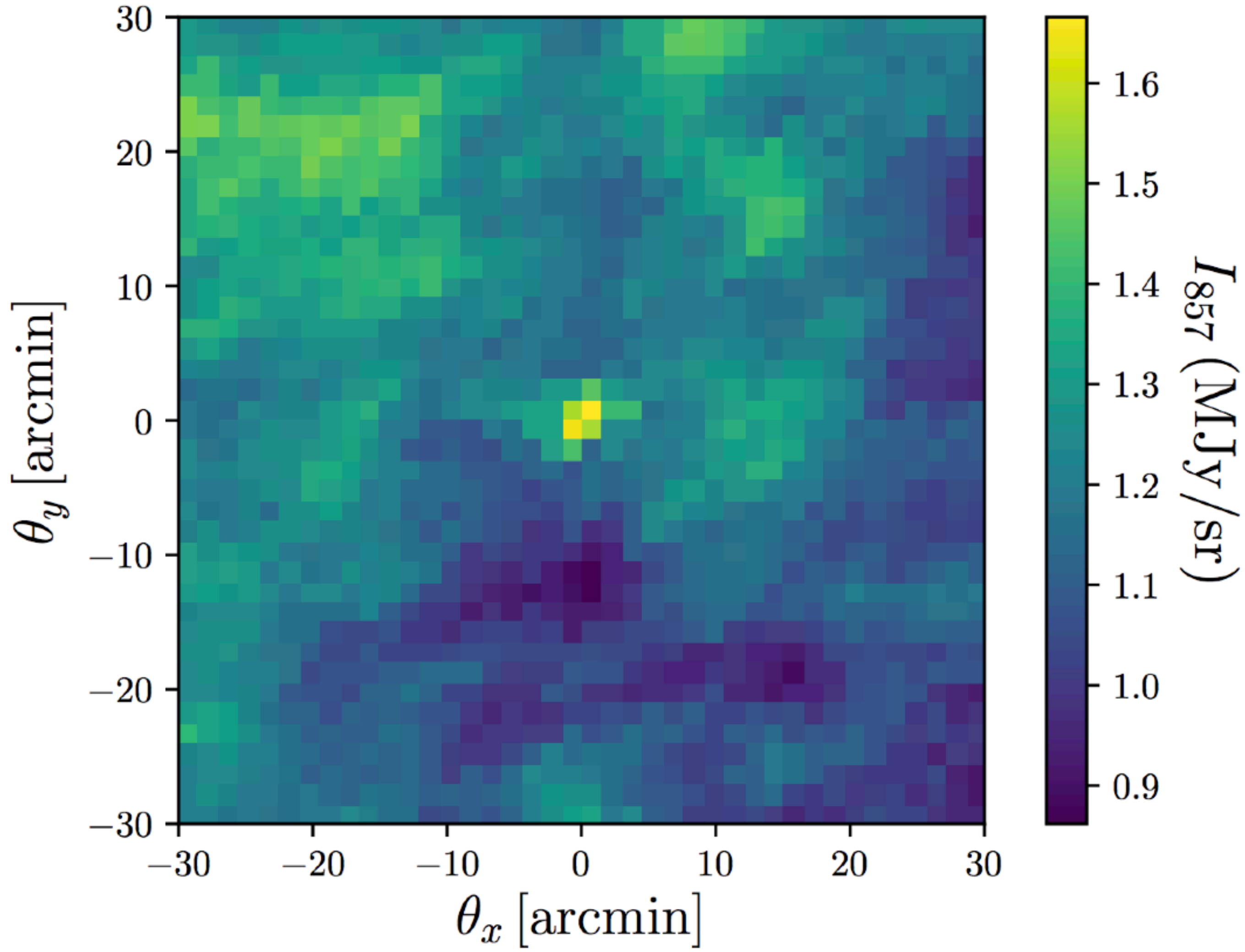
Baxter, Blake, Jain 2018

We detected some interesting signals around stars…

We detect emission from debris disks in Planck data!

Future high resolution CMB surveys can study statistics of debris disks

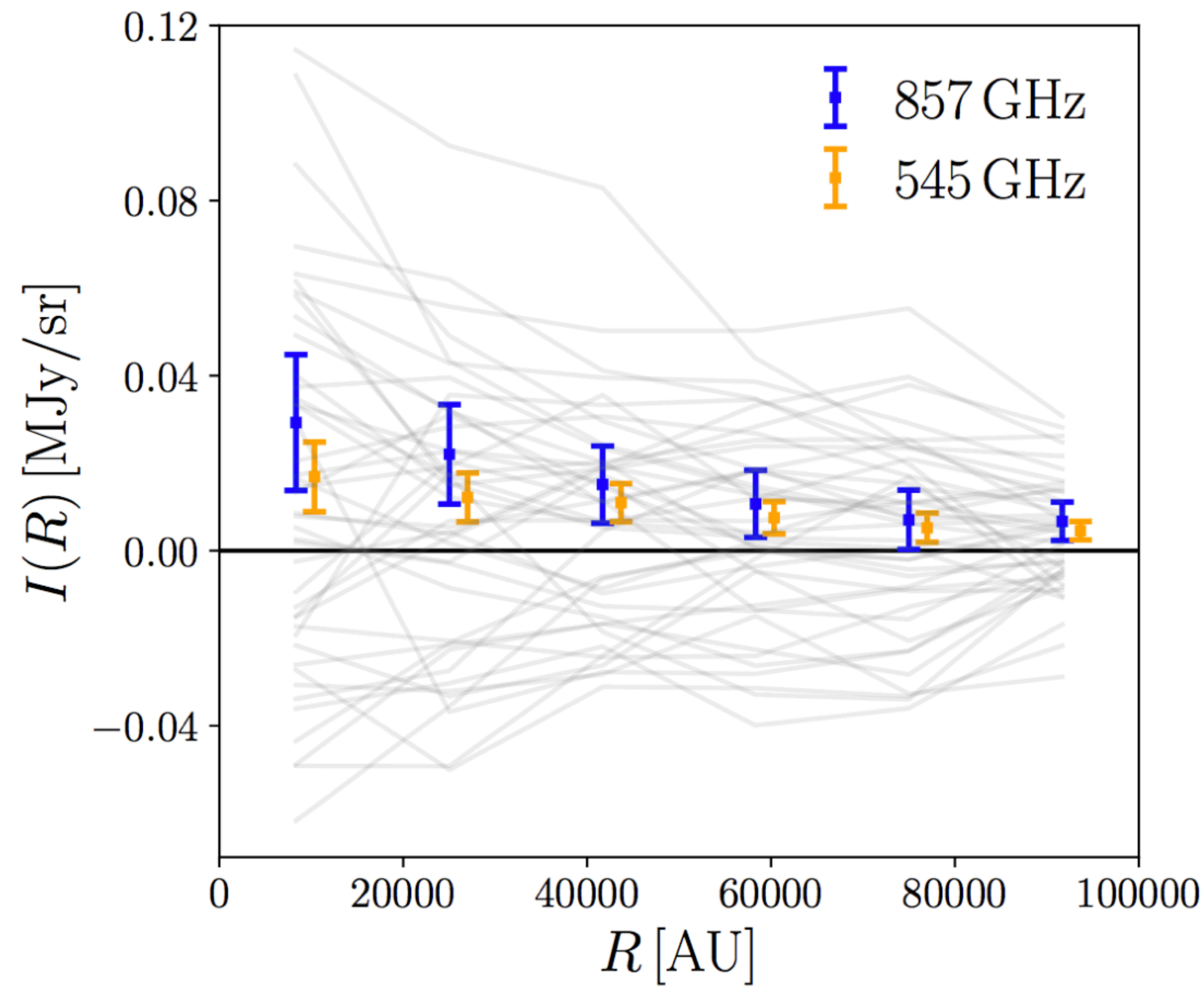
Fomalhaut, as seen by *Planck*



Baxter, Blake, Jain 2018

We detected some interesting signals around stars…

There is excess extended emission coming from the hottest and closest stars in *Gaia* sample



Baxter, Blake, Jain 2018

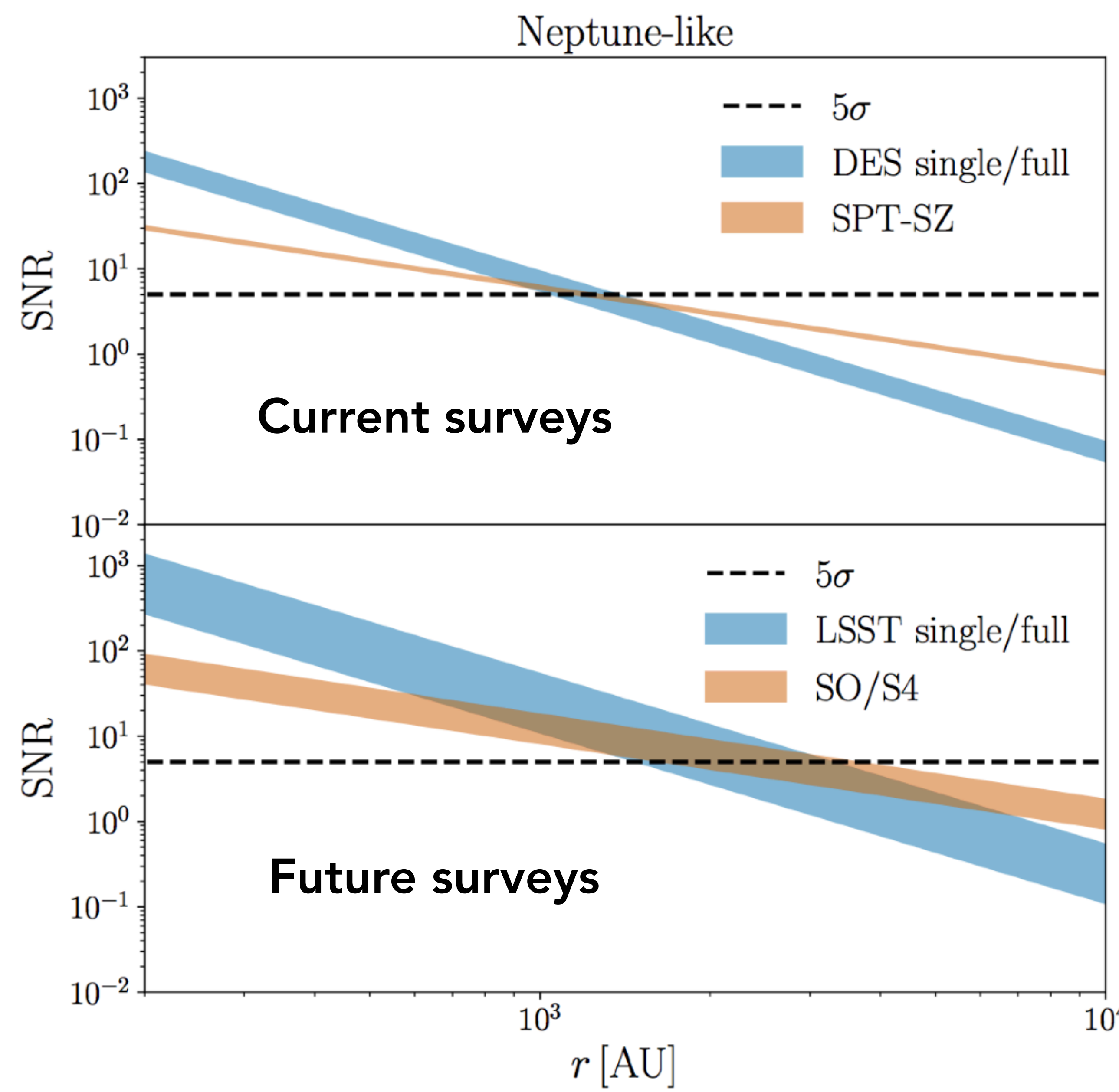
Can CMB surveys detect other objects in the outer solar system? Maybe: Planet 9

Internal heat sources ➔
temperature of Planet 9 is 30-50 K

CMB surveys have sensitivity to detect Planet 9!

The advantage of a CMB survey:
Flux from reflected emission falls as d^{-4}
Flux from thermal emission falls as d^{-2}

CMB searches are complementary to optical searches



Baxter et al. 2018b
Cowan, Holder, Kaib 2016

Summary

CMB and optical surveys are remarkably complementary

Cosmology: CMB lensing x galaxy survey

- CMB lensing has very different systematics from galaxy lensing
- CMB lensing has better high redshift sensitivity

Planetary science: submillimeter x optical

- Thermal emission of objects in outer solar system is fairly well matched to CMB surveys
- Wide area CMB surveys are great for finding rare objects or statistics of large populations

Progress will be rapid of the next few years as both CMB and galaxy surveys improve dramatically