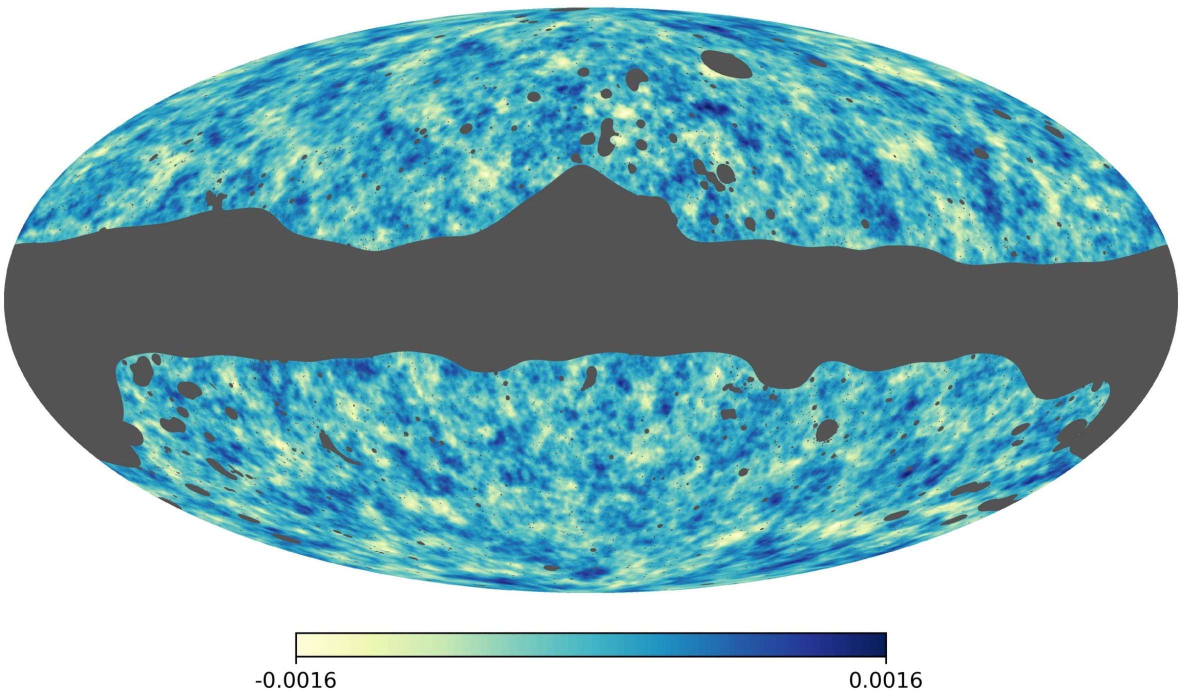
# Large-scale structure and neutrino properties from the CMB

*Anthony Challinor*




*KICC/IoA/DAMTP*
*University of Cambridge*

# *Science goals*

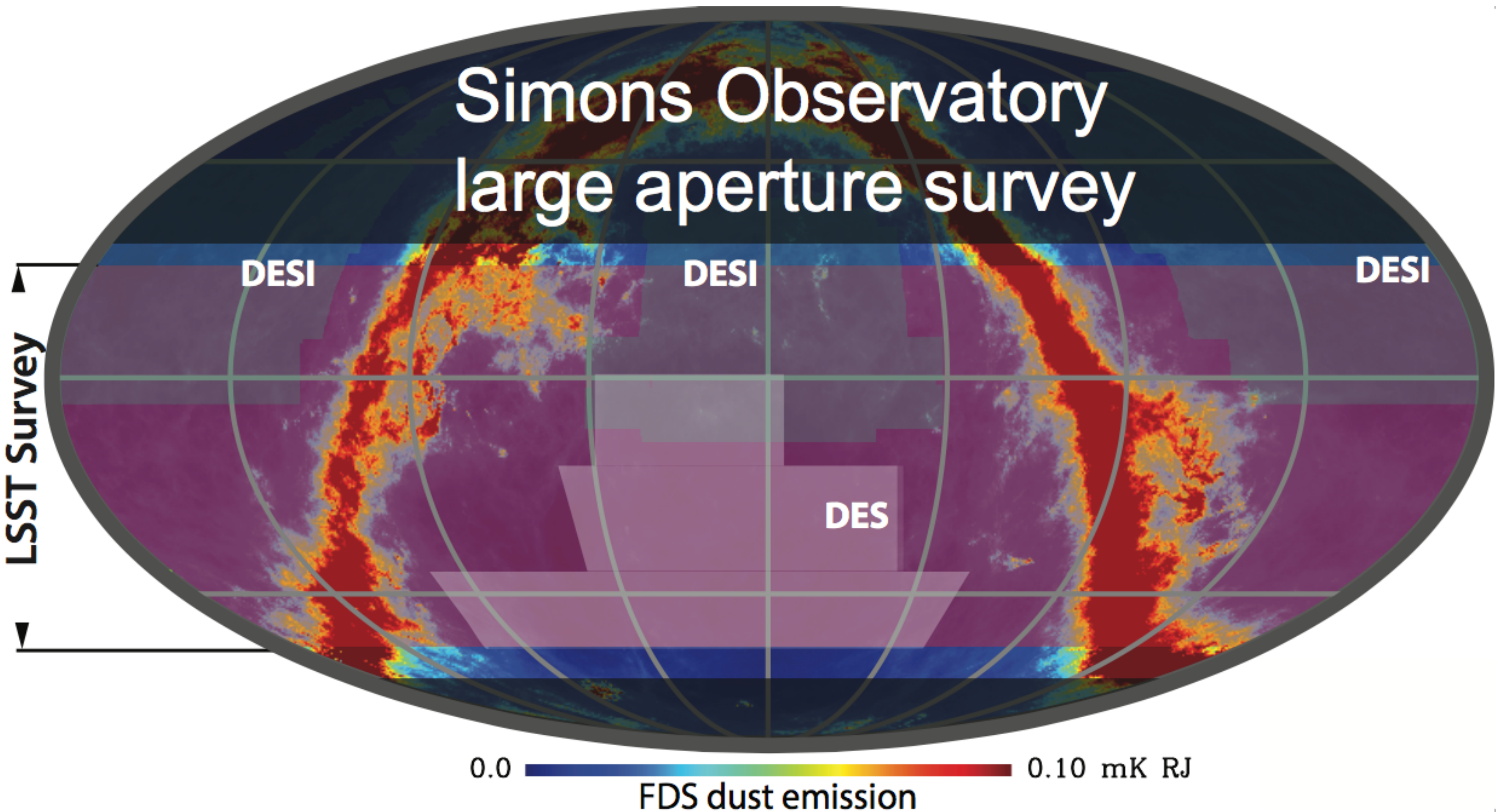
- Neutrino properties (mass, hierachy, number)
- Dark energy/non-GR
- Reionization (history, morphology)
- Astrophysics (e.g., baryons in galaxy and cluster outskirts)

*See Jim Bartlett's talk at Florence 2017*

# *CMB observations required*

- Temperature and polarization anisotropies
- 10s–100s GHz frequency coverage
- Few arcmin resolution
- O(1) μK-arcmin sensitivity to CMB
- Large sky coverage (sample variance and good overlap with other surveys)

# *Survey overlap from Chile*



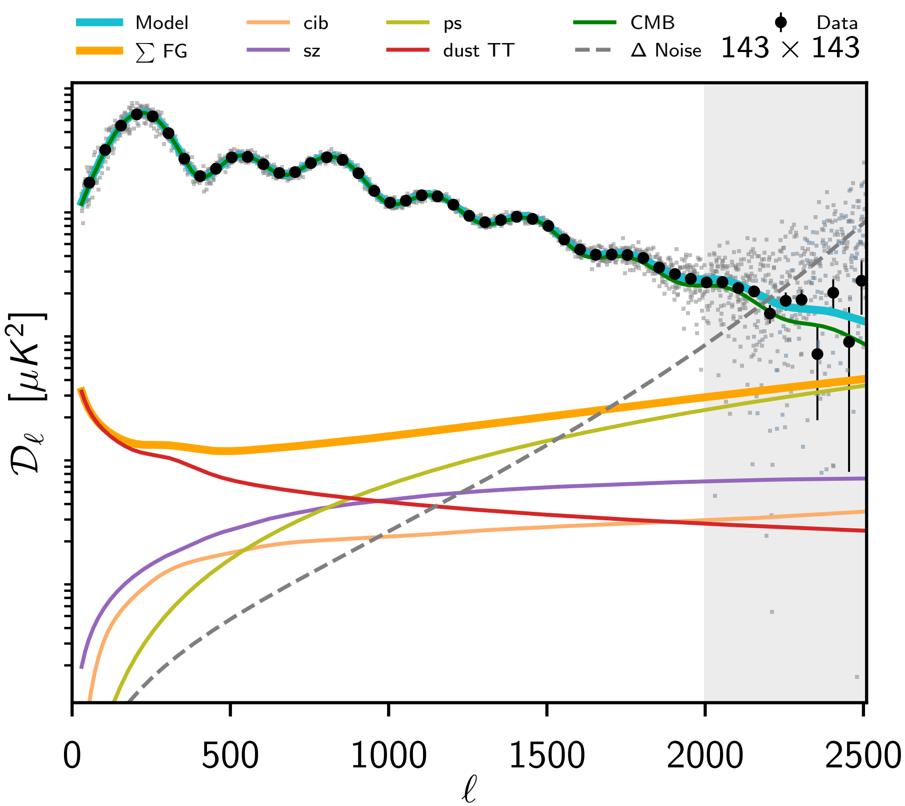

SO Collaboration 2018

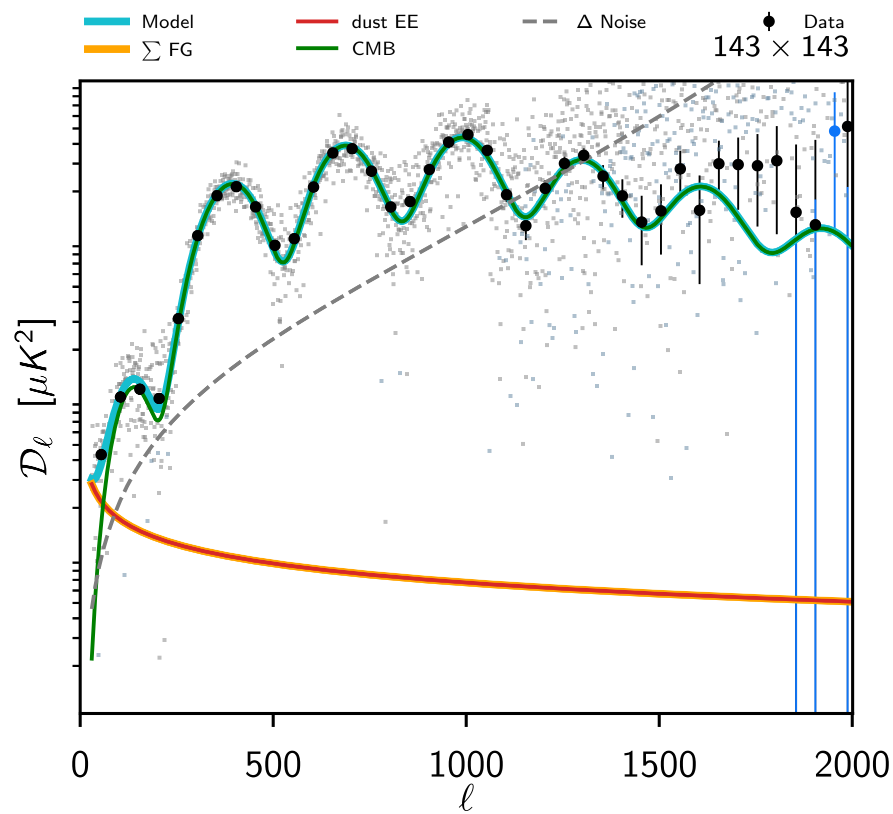
# *CMB probes*

- Small-scale *T* and, particularly, *P* anisotropy power
- Lensing of the CMB by LSS and individual halos
- Thermal Sunyaev-Zel'dovich (tSZ) effect in clusters
- Kinematic SZ (kSZ) effect from reionization and later

+ cross-correlation with galaxies, cosmic shear etc.

# Small-scale CMB anisotropy power

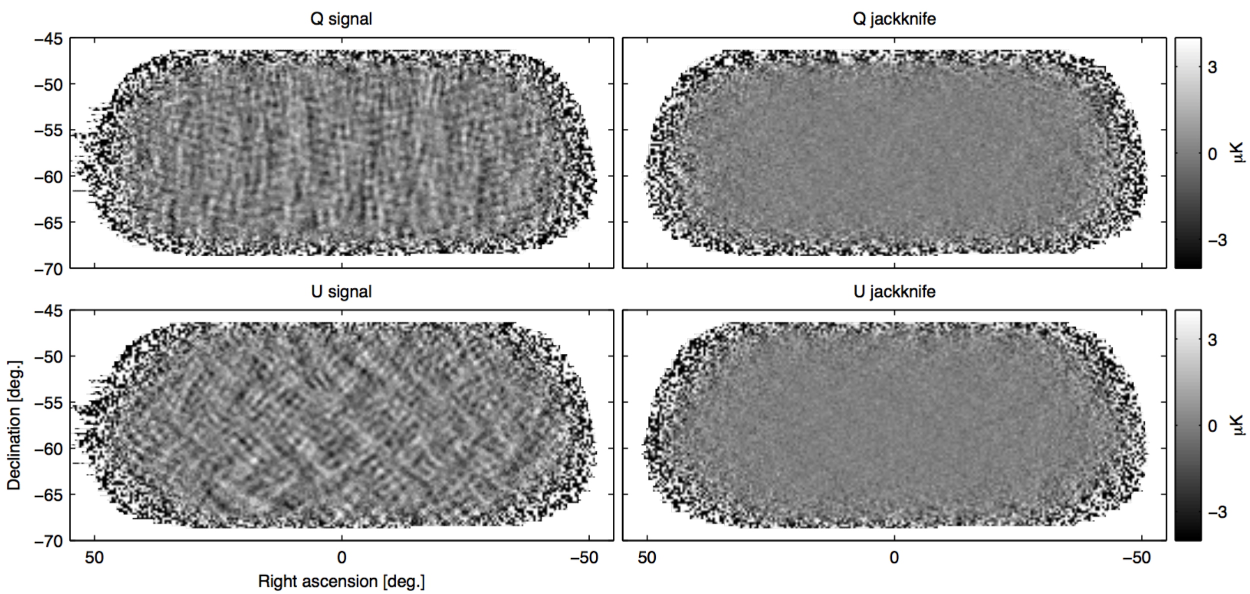



Many new, clean, well-understood modes accessible in pol.

Planck Collaboration 2018

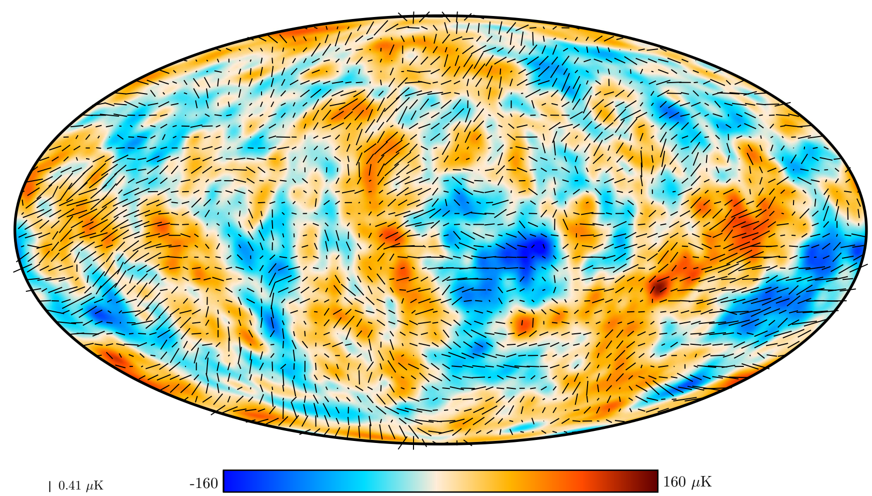
# *Mapping CMB pol. anisotropies*




*3 μK-arcmin sensitivity over 400 deg² at 0.5 deg resolution*

Keck Array + BICEP2 2015

*O(50) μK-arcmin sensitivity over full sky at 5 arcmin resolution*

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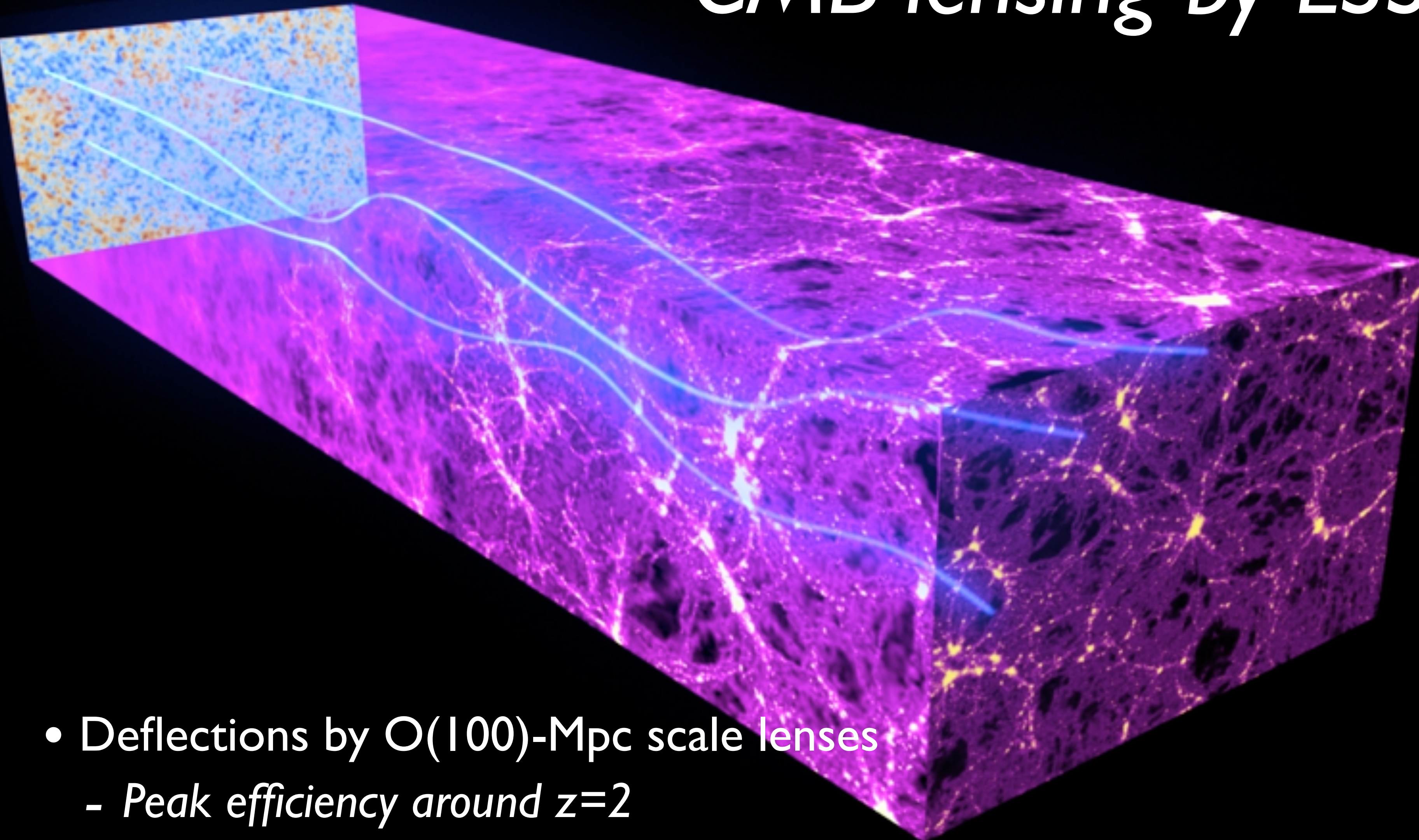
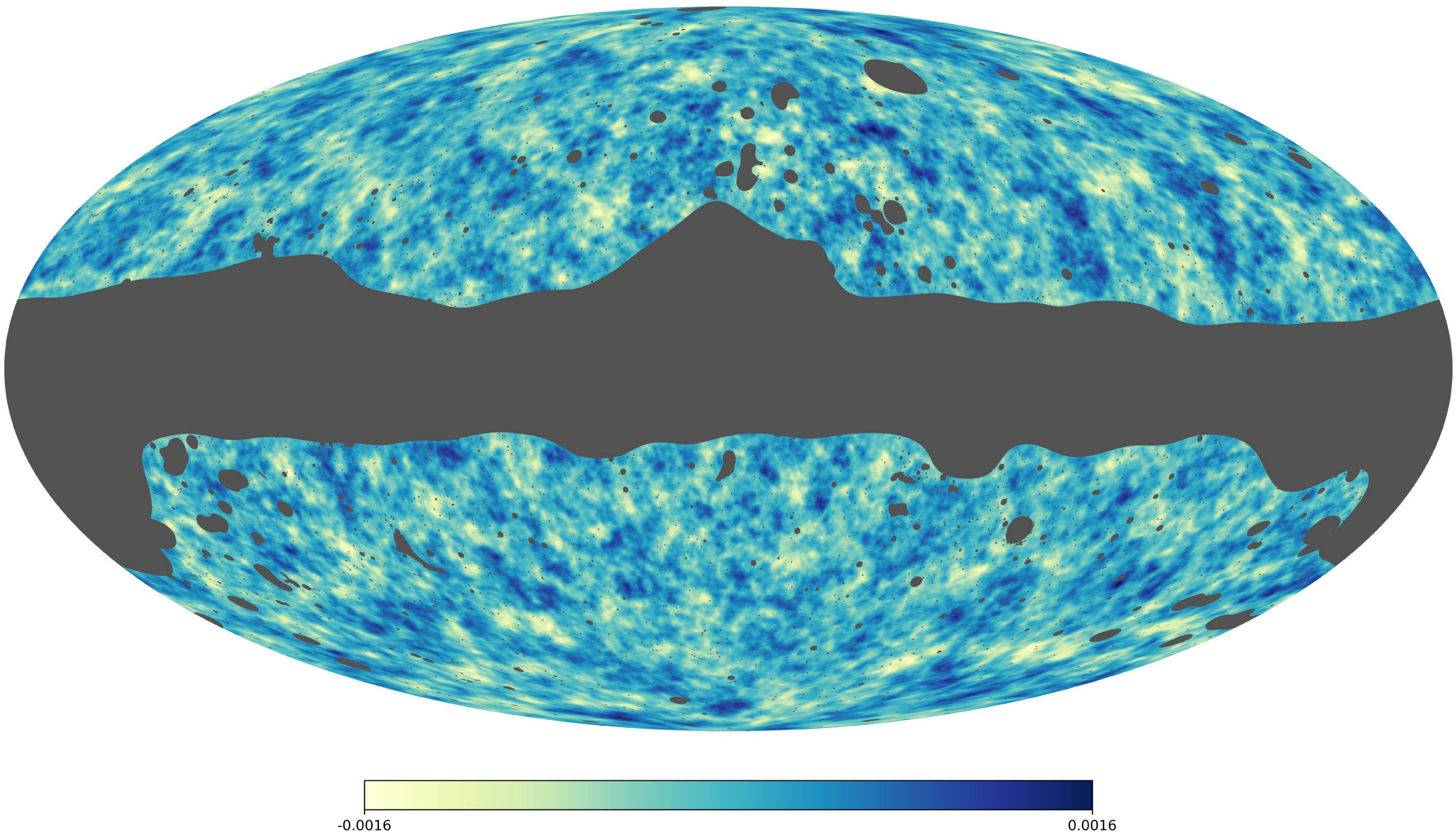
# *CMB lensing by LSS*



- Deflections by O(100)-Mpc scale lenses
  - *Peak efficiency around z=2*
  - *2.5 arcmin deflections coherent over several degrees*

# *Lensing reconstruction from CMB*

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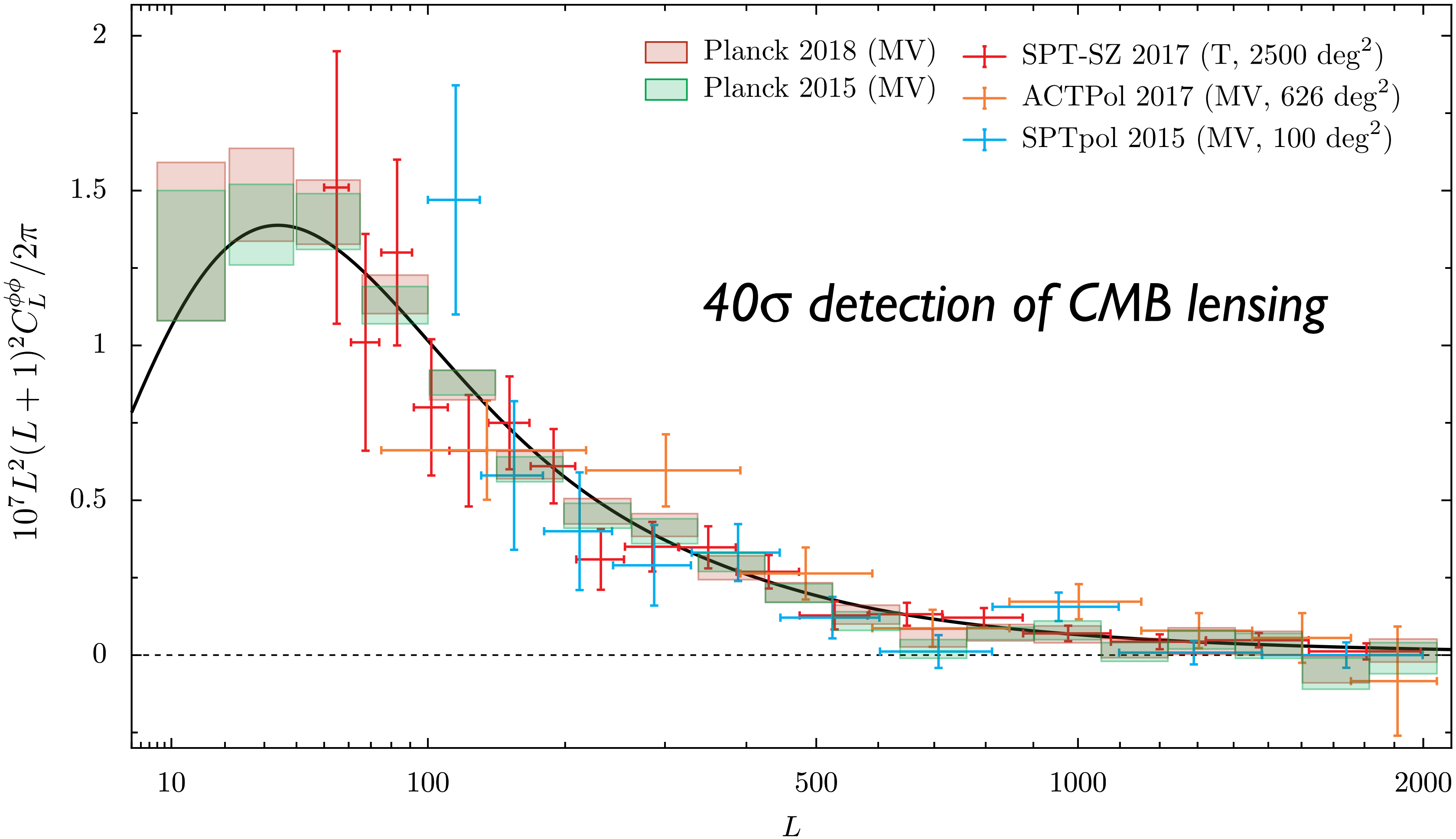
# Measured lensing power spectrum

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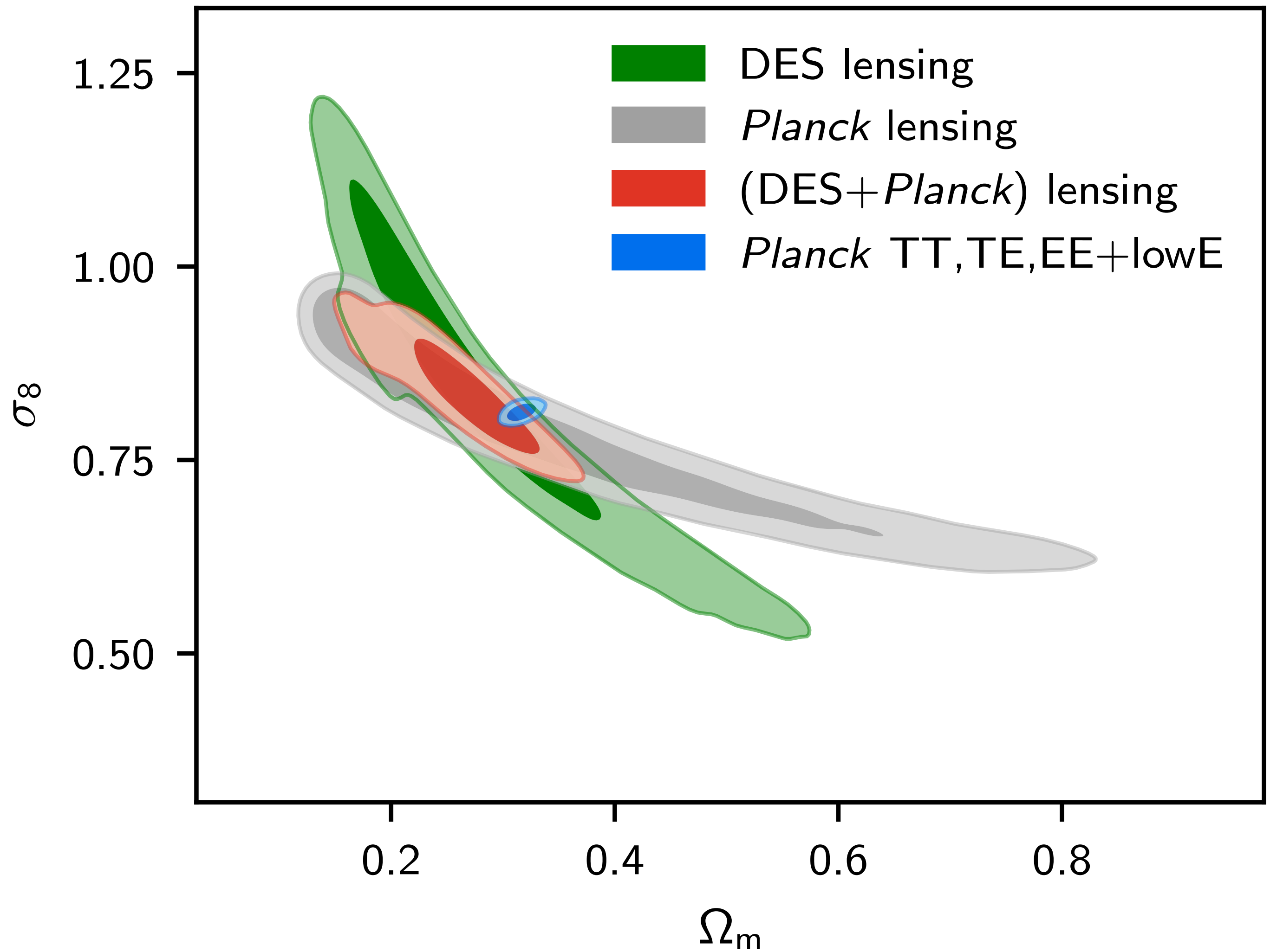
# Comparison with galaxy lensing

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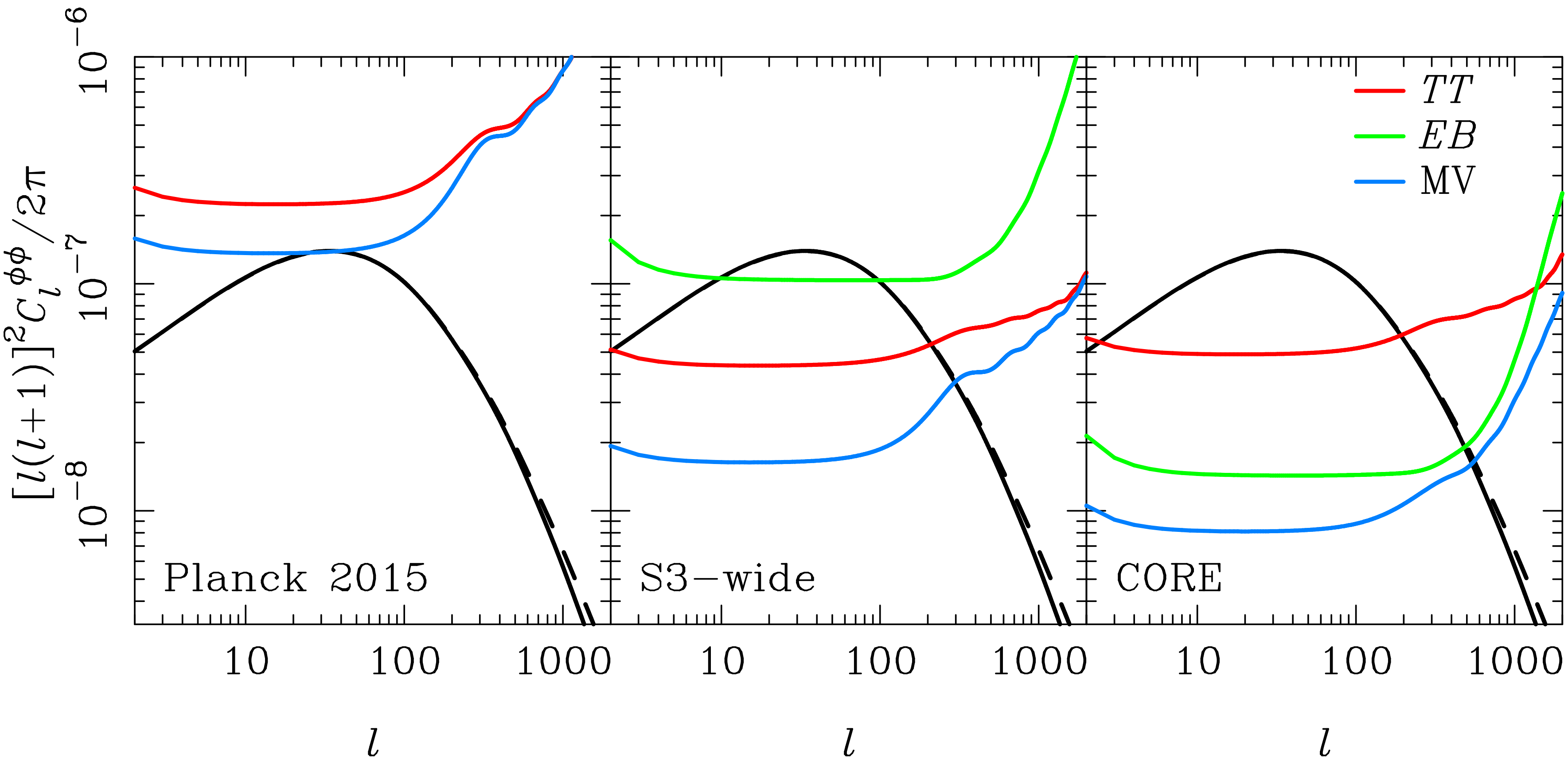
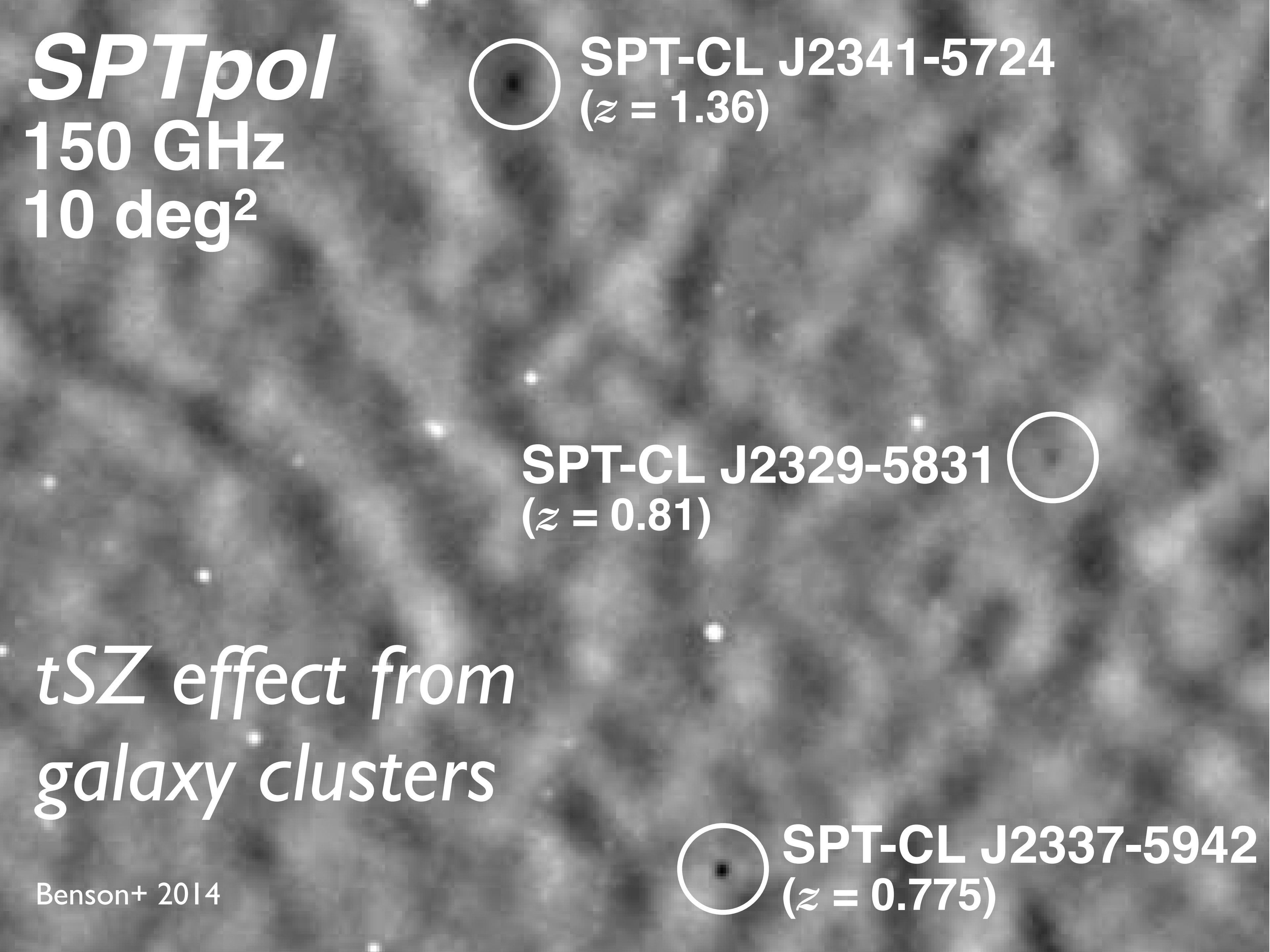
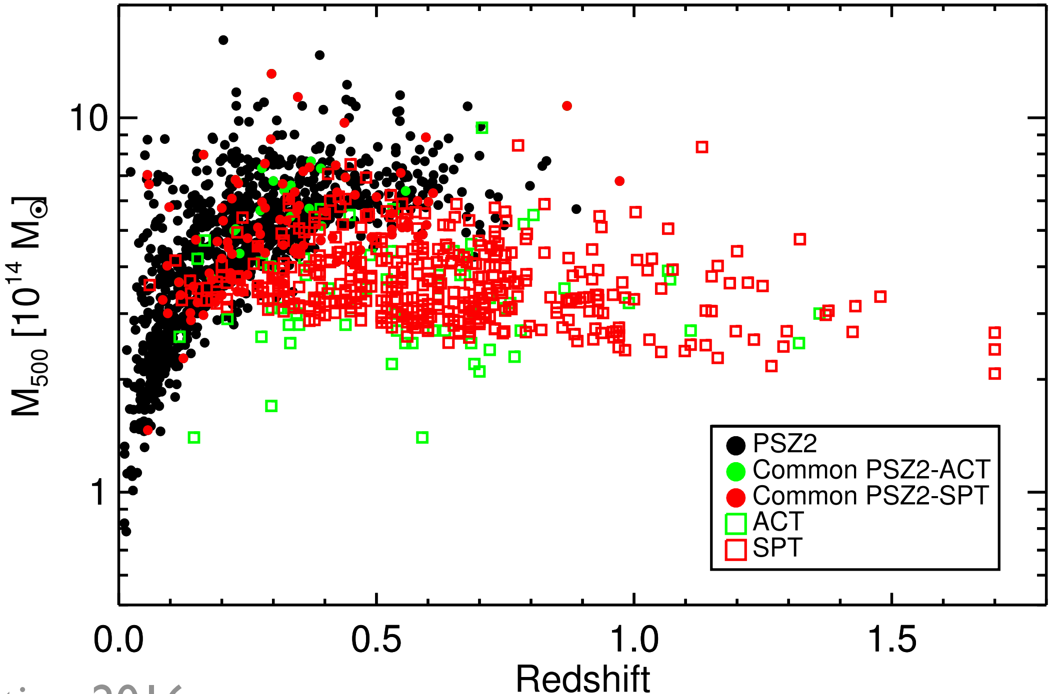
# The future: towards EB dominance




- Many more well-understood (i.e., almost linear) modes available
- *EB* will be particularly helpful for pol. noise < 5 μK-arcmin
  - *Also, less extragalactic foreground contamination (e.g., tSZ)*


SPTpol
150 GHz
10 deg²
SPT-CL J2341-5724
(z = 1.36)
SPT-CL J2329-5831
(z = 0.81)
SPT-CL J2337-5942
(z = 0.775)
tSZ effect from galaxy clusters
Benson+ 2014

# SZ-selected clusters




Planck Collaboration 2016

- Abundance with mass and redshift a sensitive probe of growth of structure
- Well-understood selection and almost mass-limited to high *z*
- Limiting issue: relation of (observable) SZ flux to mass

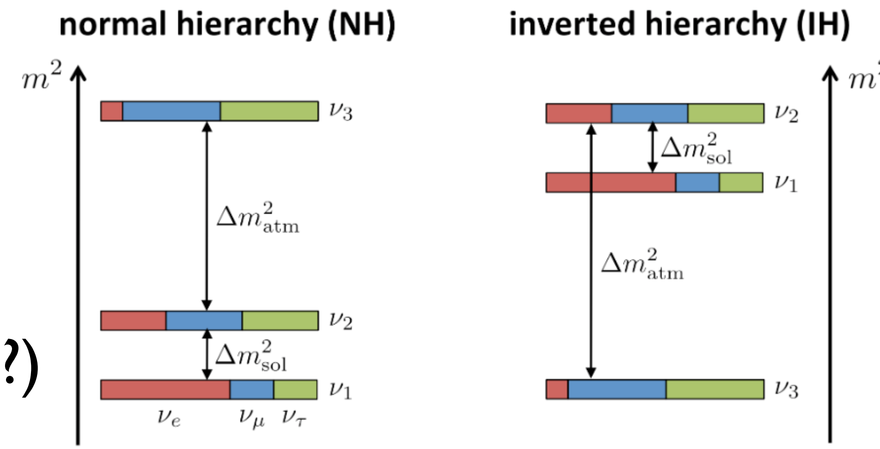
# *Case studies*

- Number of relativistic species
- Absolute neutrino mass scale from lensing
- Growth of structure from lensing x galaxies
- Growth of structure from cluster counts

# *Neutrino(-like) sector*

## Outstanding issues:

- Absolute mass scale?
- Mass ordering?
- (Dirac/Majorana and CP violation?)
- Additional (sterile) neutrinos or relativistic particles?



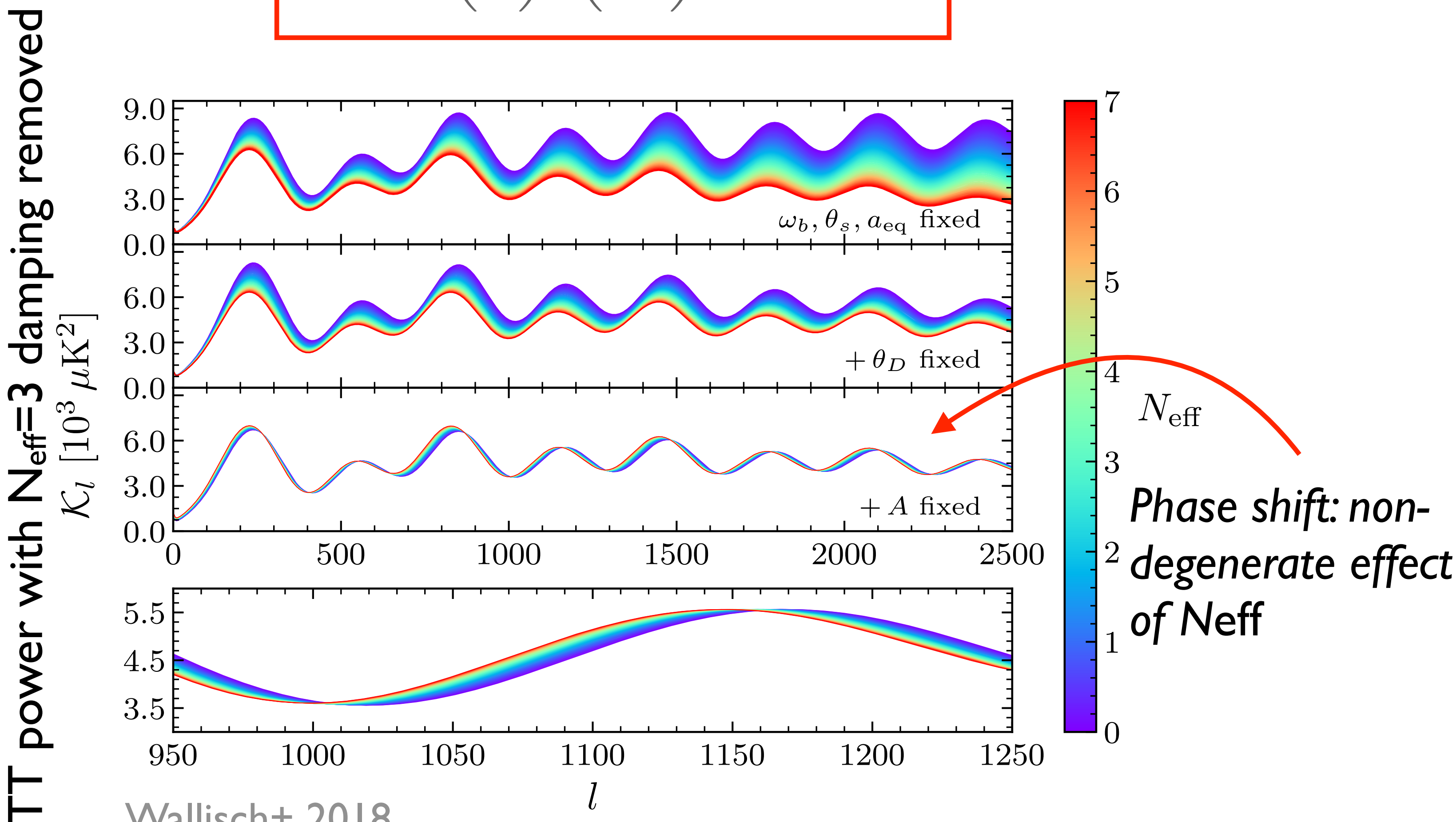

$\sum m_\nu > 58\,\mathrm{meV}$ $\sum m_\nu > 105\,\mathrm{meV}$

Cosmology → $\sum m_\nu$

Cosmology → $N_{\rm eff}$

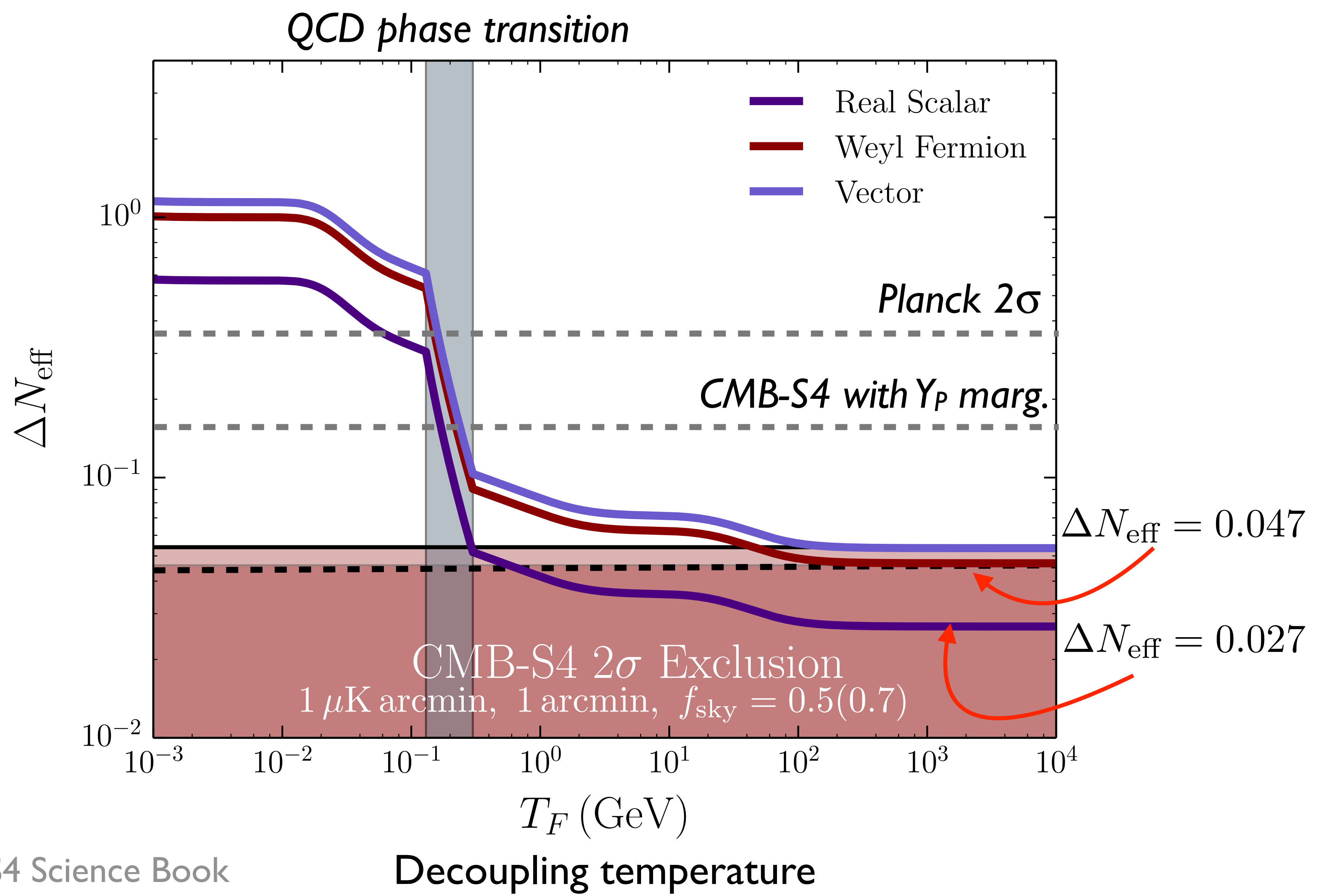
# *Number of relativistic species*

$$\bar{\rho}_{\rm rel} = \left(\frac{7}{8}\right)\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\,\bar{\rho}_\gamma$$



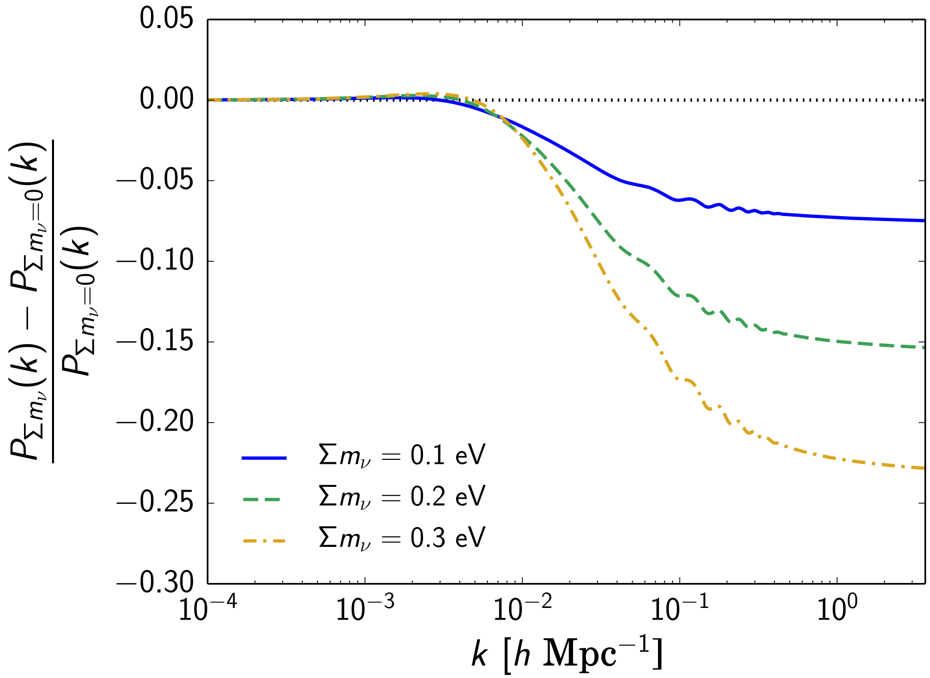

Wallisch+ 2018

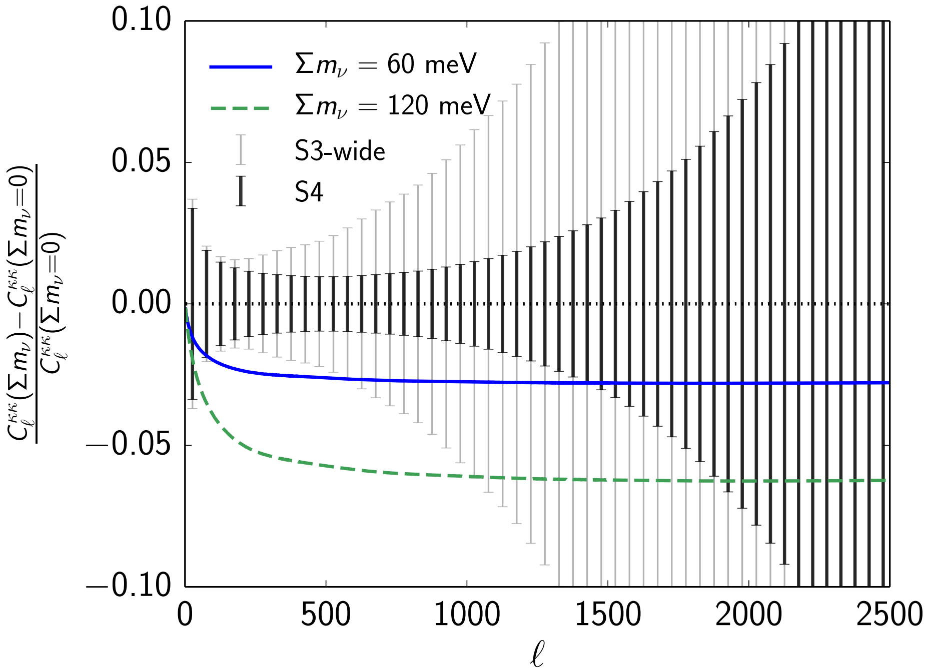
# Natural targets and CMB limits




CMB-S4 Science Book

# *Neutrino masses from CMB lensing*



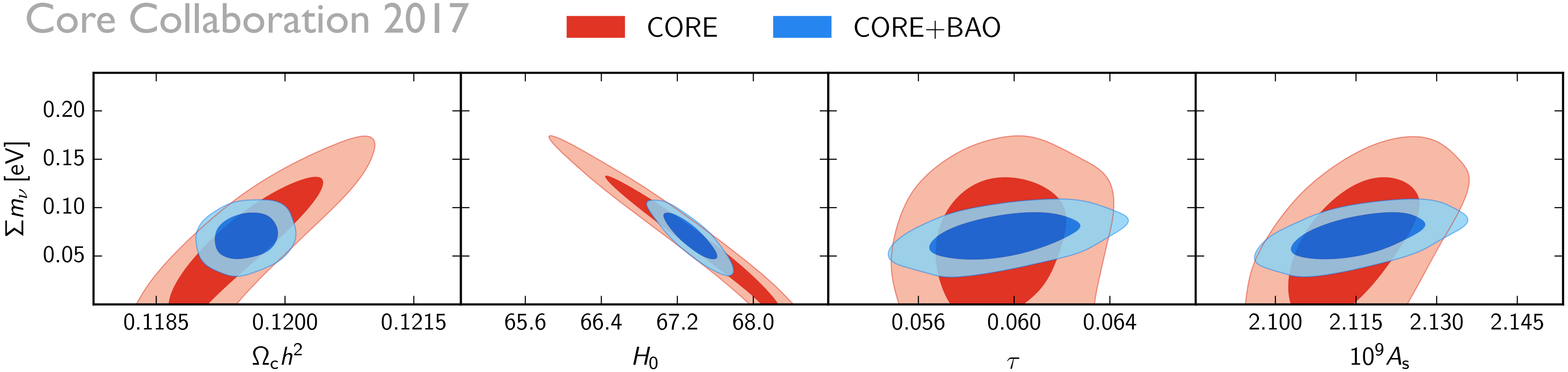




Allison+ 2015

- Complementary to optical weak lensing and galaxy clustering
  - *Higher-z, mostly linear regime, no intrinsic-alignment issues*
  - *Scale-dependent bias complicates broad-band galaxy P(k)*
- Sensitive to $\Sigma m_\nu$ not directly to mass splittings (i.e., ordering)
- $\Sigma m_\nu$ from SZ cluster counts also

# $\Sigma m_\nu$ *degeneracies and limits*

Core Collaboration 2017




$$\sigma\left(\sum m_\nu\right) = 73\,\mathrm{meV} \qquad \text{CMB-S4}$$

$$\sigma\left(\sum m_\nu\right) = 26\,\mathrm{meV} \qquad \text{CMB-S4+DESI BAO}$$

$$\sigma\left(\sum m_\nu\right) < 15\,\mathrm{meV} \qquad +\text{c.v. } \sigma(\tau) = 0.002$$

CMB-S4 Science Book

*Cf. Planck+BAO:*

$$\sum m_\nu < 120\,\mathrm{meV}$$

*4σ detection even for minimal-mass normal hierarchy*

C.V.-limited τ [σ(τ) = 0.002] becomes limiting for $N_{\mathrm{modes}} > 10^5$

# *Cosmic acceleration and the CMB*

- Limited sensitivity in primary CMB (too high z)
- Lensing, cluster abundance and peculiar velocities probe growth of structure over cosmic time

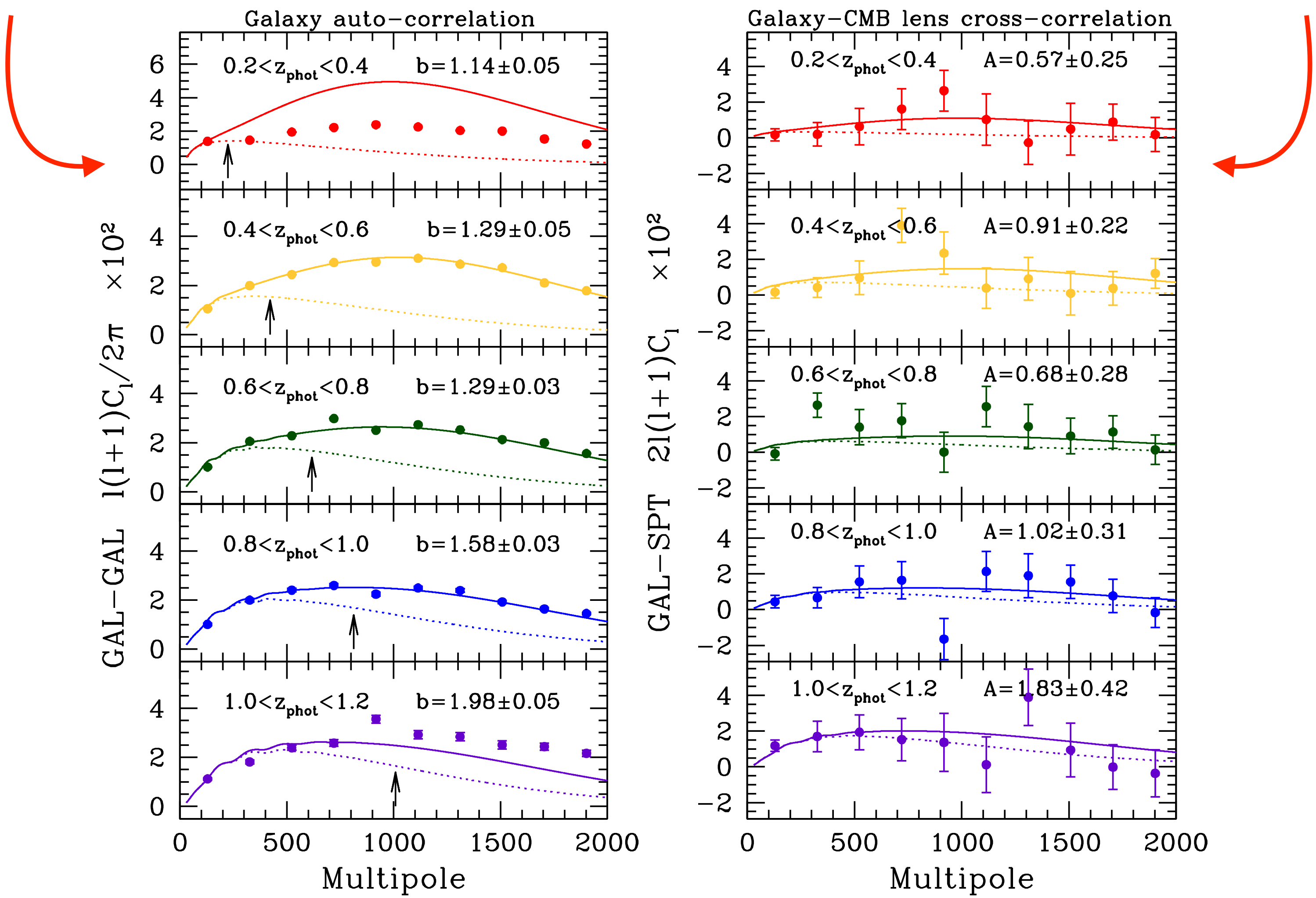
| | |
|---|---|
| Smooth dark energy | $H(z) \implies \sigma_8(z)$ |
| non-GR | $H(z) \not\Longrightarrow \sigma_8(z)$ |

- Synergies with galaxy and lensing surveys
  - *Extend redshift reach*
  - *Cross-calibration of astrophysics (e.g., bias) and systematics*

# Growth with lensing-galaxy x-corr.

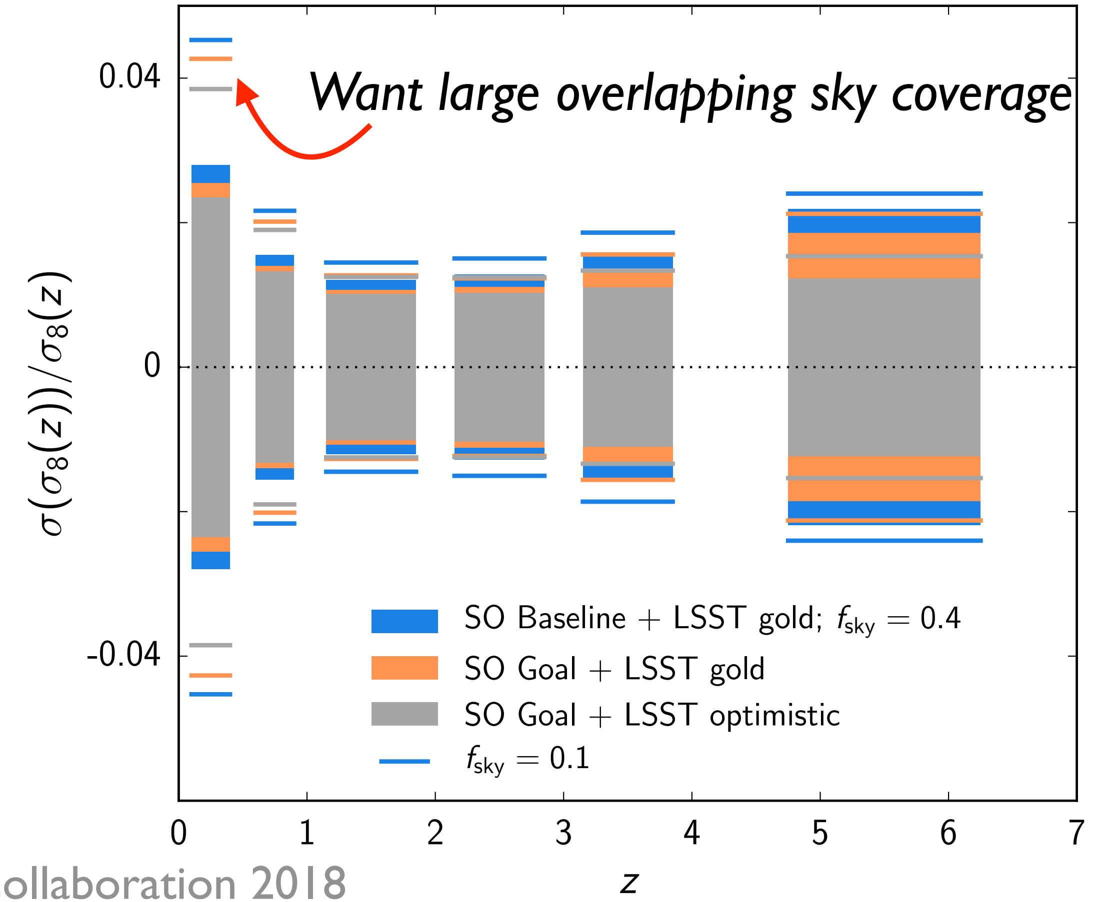
$\langle gg \rangle \propto b^2(z)\sigma_8^2(z)$

$\langle g\kappa_{\rm CMB} \rangle \propto b(z)\sigma_8^2(z)$




Giannantonio+ 2016

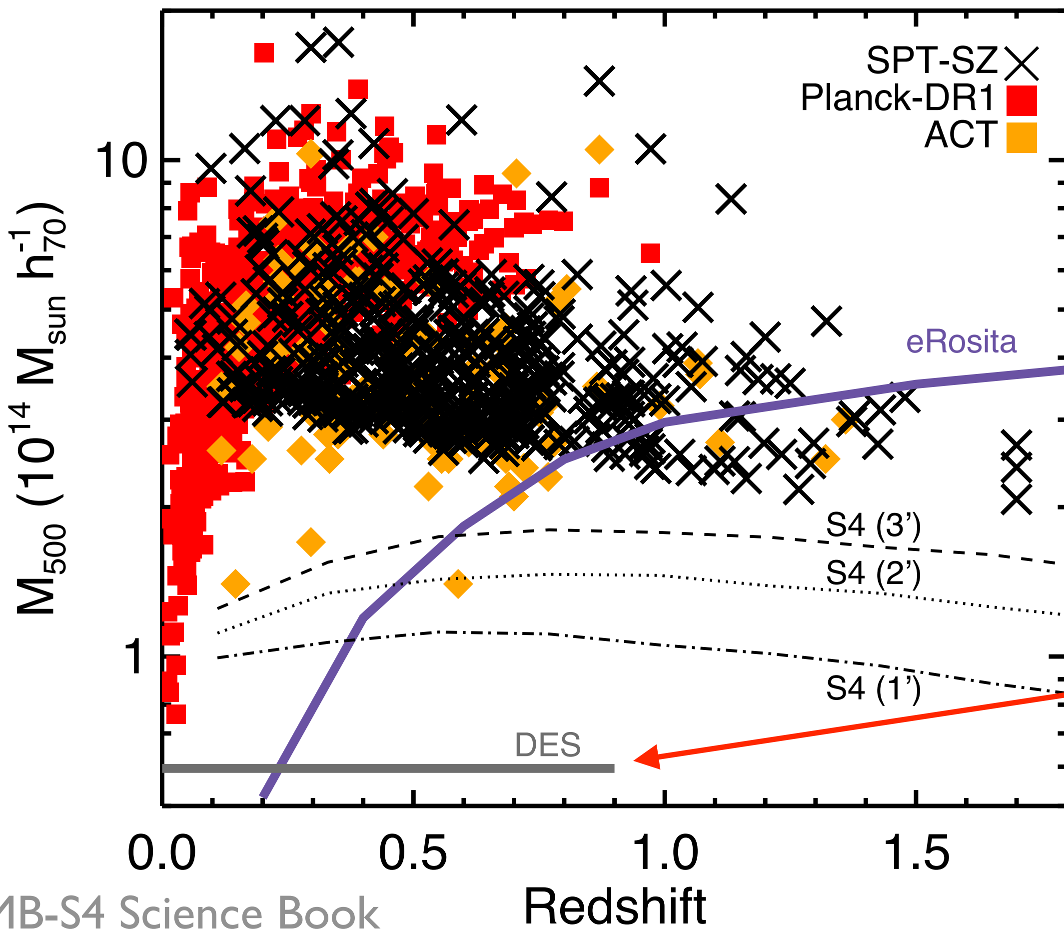
# *Expected performance*




SO Collaboration 2018

- Expect 1% constraints for CMB-S4 + LSST
  - *More than sum of parts due to cosmic variance cancellation*

# Future SZ cluster surveys

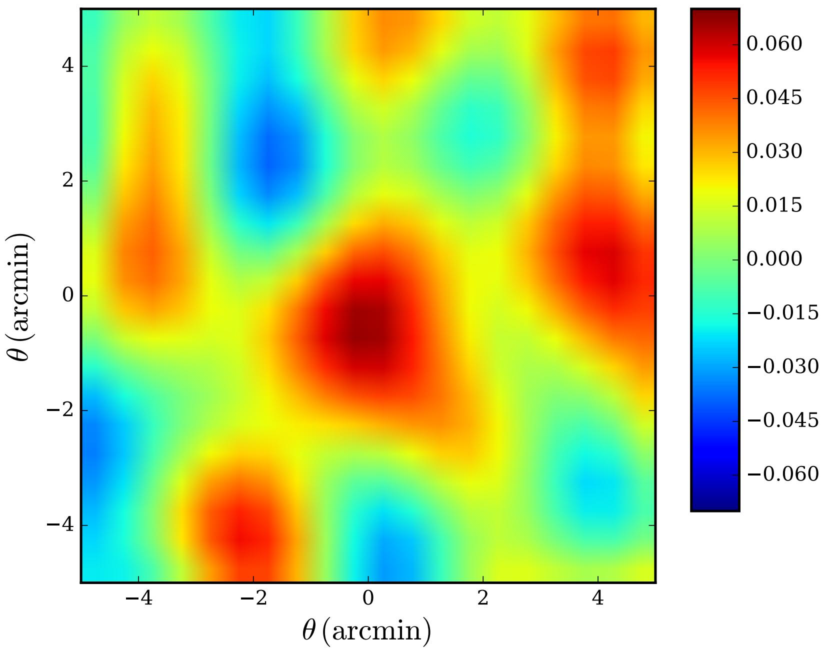


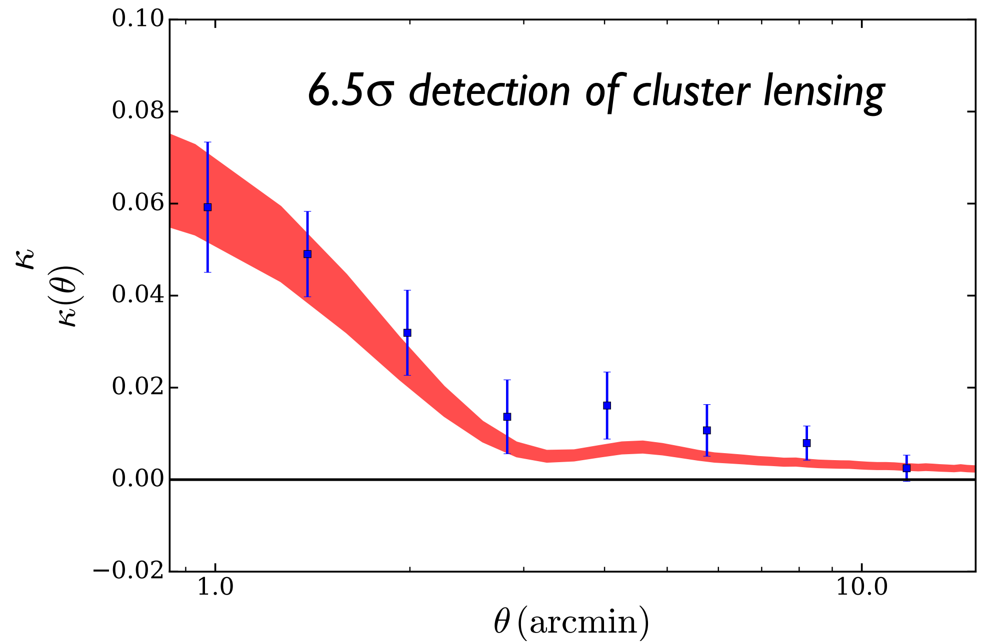

CMB-S4 Science Book

*Greatly extend redshift reach cf. optical surveys*

O($10^5$) cleanly-selected clusters extending to high redshift

# Cluster masses from CMB lensing



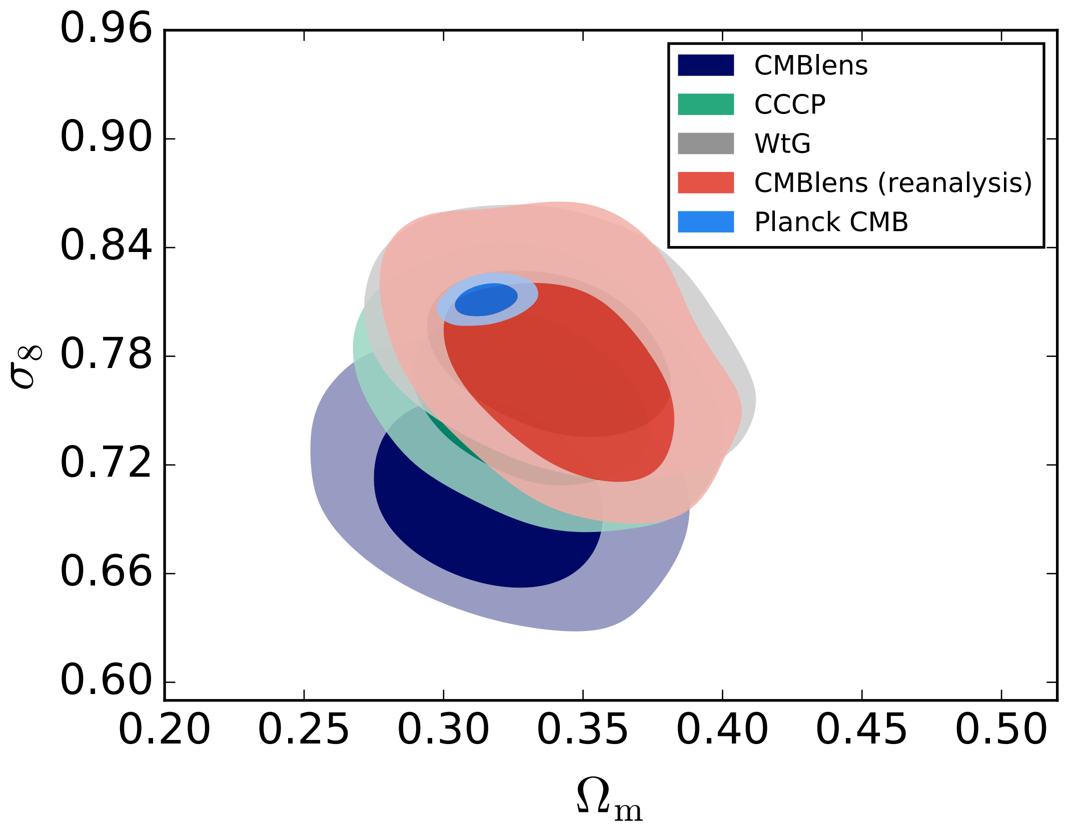




Baxter+ 2017

- Statistical mass calibration for large samples at high redshift
  - *Few-% precision on 1000-cluster stacks for CMB-S4*
  - *Complements galaxy shear for lower redshift clusters*

See also Baxter+ 2015; Planck Collaboration 2016; Madhavacheril+ 2015; Geach & Peacock 2017

# Cosmology from Planck clusters

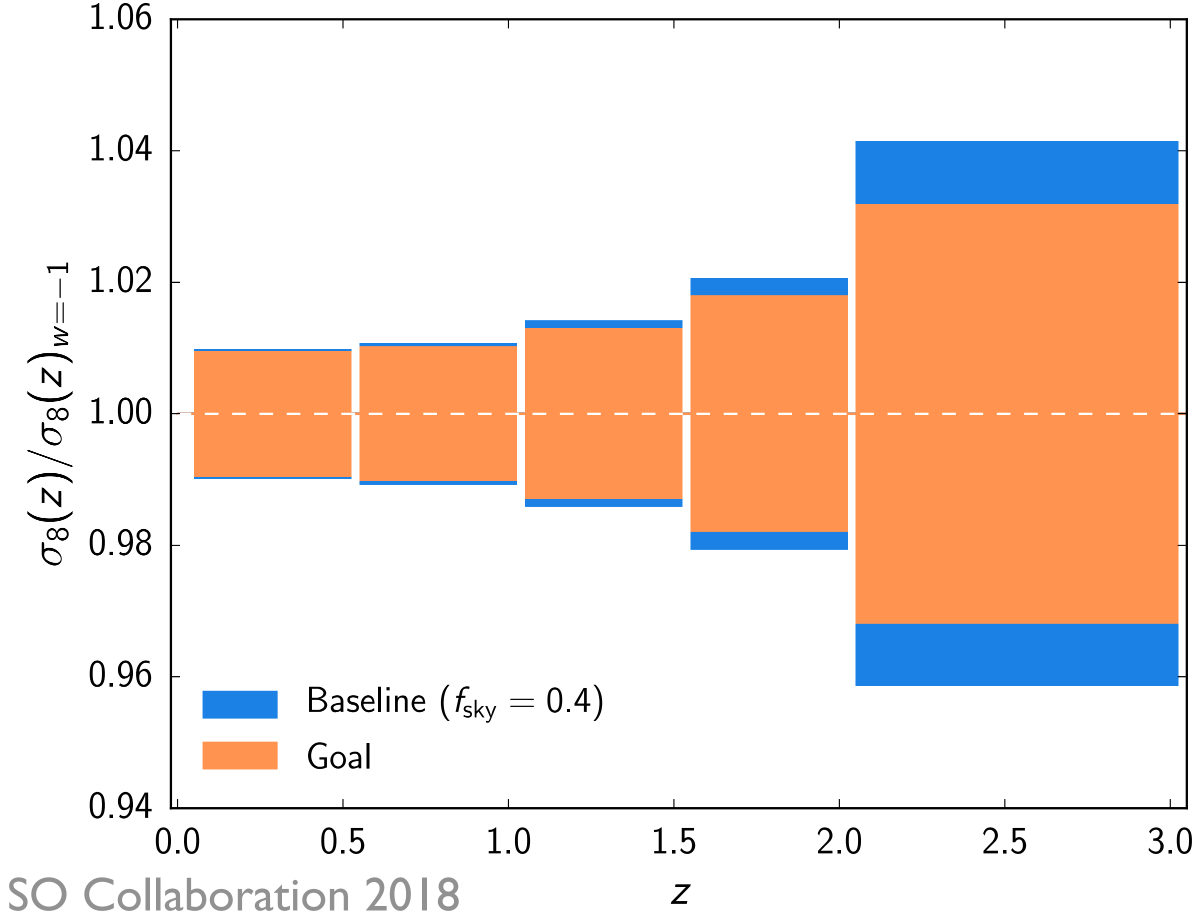



$$D_A^2(z)\bar{Y}_{500} \propto \left[(1-b_{\rm SZ})M_{500}\right]^{\alpha}$$

$$1-b_{\rm SZ} = 0.68 \pm 0.09$$

Zubeldia & AC (in prep.); Planck Collaboration 2016; Planck Collaboration 2018

# *Growth of structure from clusters*




Percent-level constraints on growth of structure from ~20000 SZ-selected clusters with CMB-lensing-calibrated masses

# *Summary*

- Few-σ guaranteed detection of summed neutrino mass with future CMB experiments
- Natural targets for additional relativistic degrees of freedom just within reach
- Strong synergies between CMB lensing and other LSS probes
  - *Degeneracy breaking (and c.v. cancellation) and systematics mitigation*
- Samples of $O(10^5)$ galaxy clusters to high redshift with well-understood selection and (CMB)-lensing-calibrated masses