

Mass mapping and precision cosmology with CMB lensing

mm universe 2025

Frank J Qu

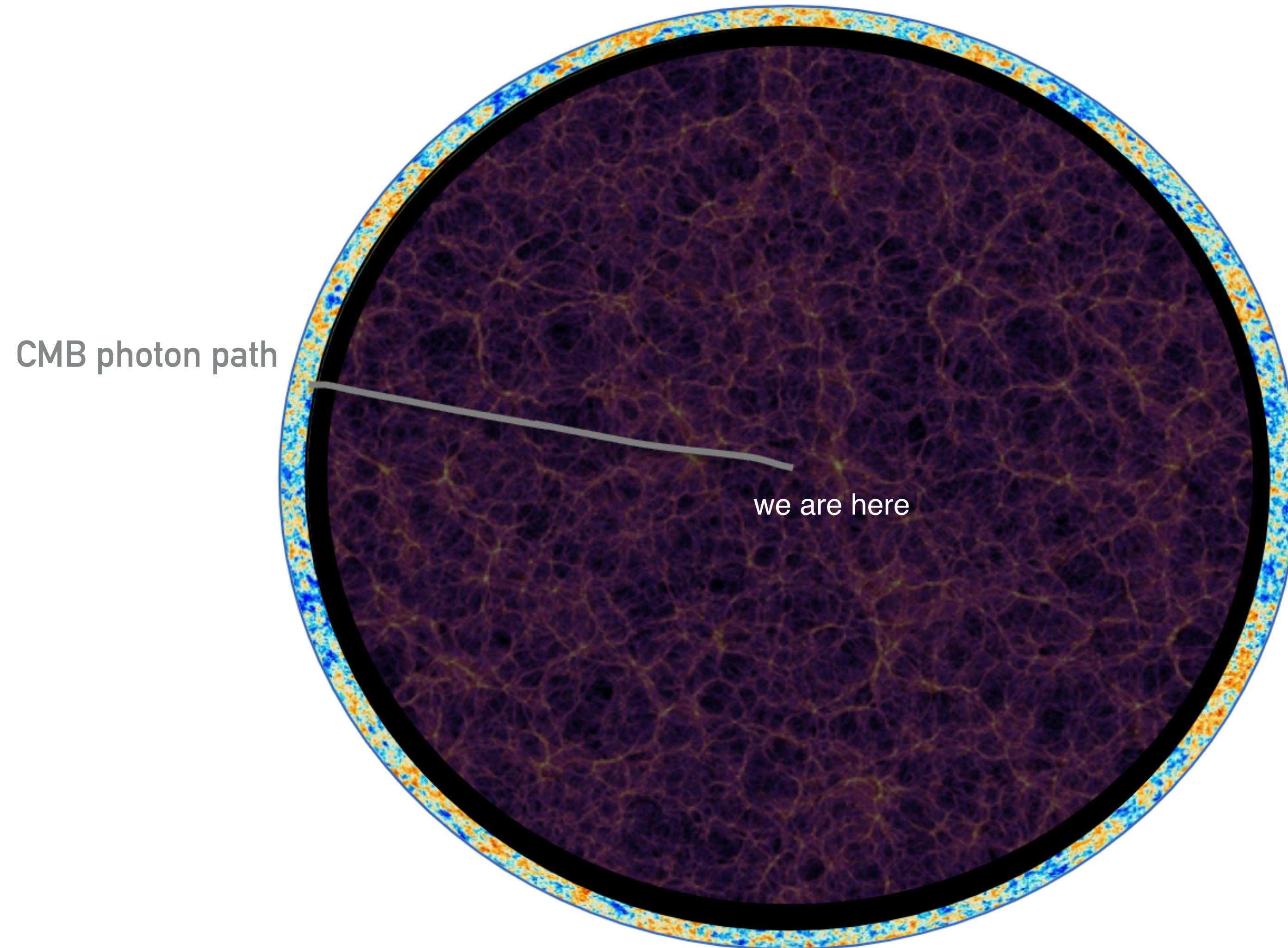
jq247@cantab.ac.uk [qujia7.github.io](https://github.com/qujia7)



Outline

- Introduction
- Current state of the art CMB lensing constraints
- New to come: DR6+ lensing
- Further ahead: CMB lensing with Simons Observatory

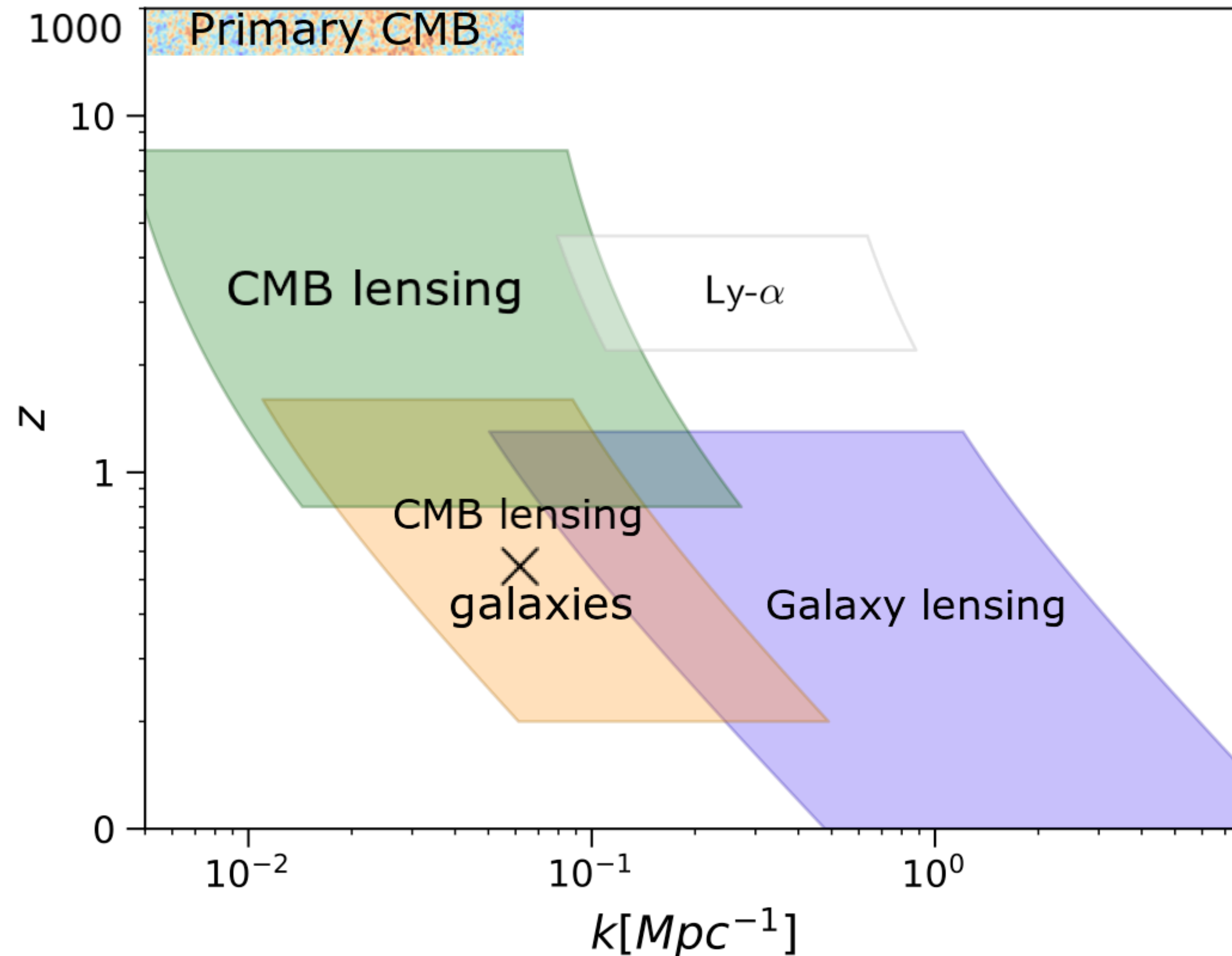
The CMB as a source for gravitational lensing



Ideal Source for lensing

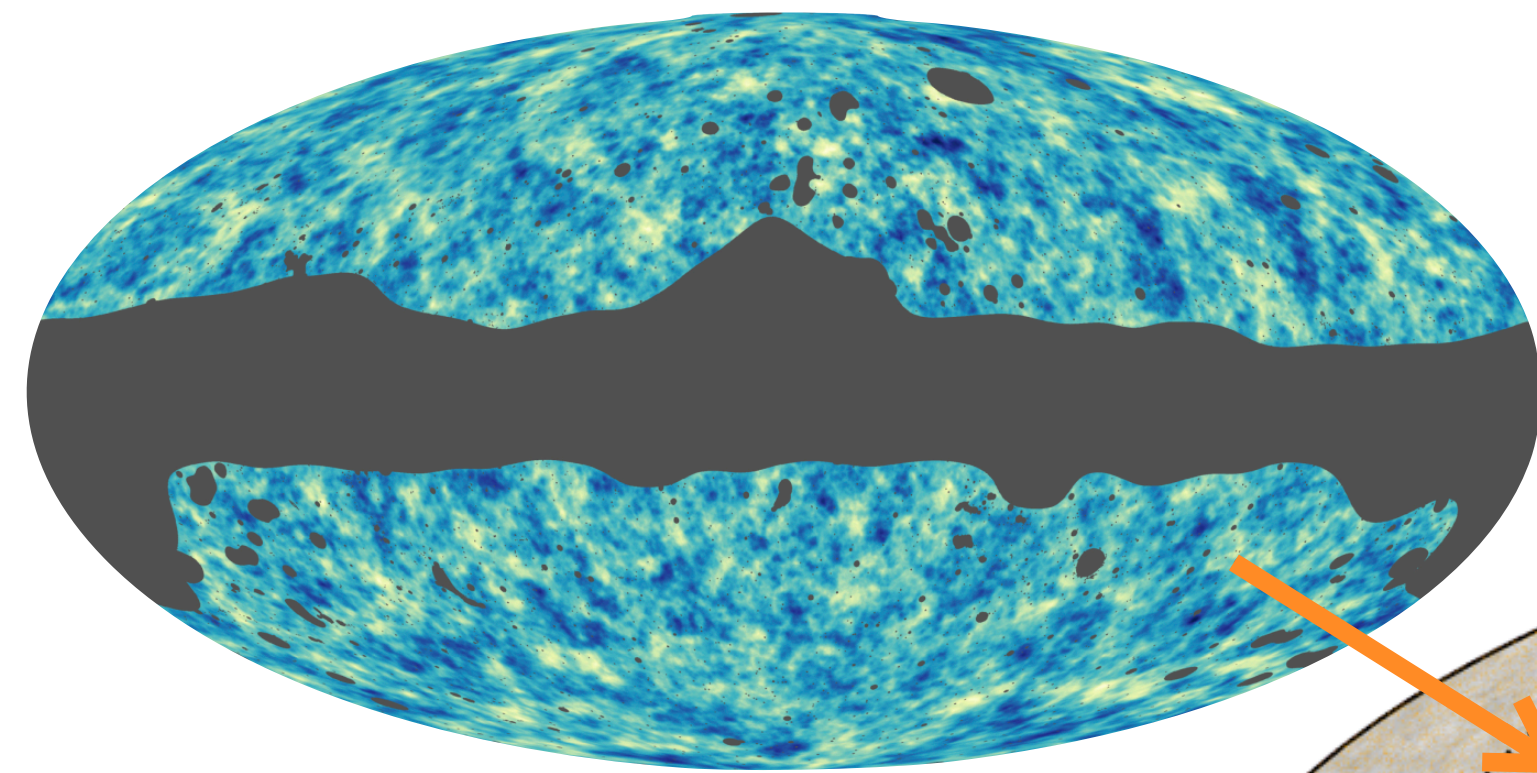
- Known redshift origin
- Known the statistics of CMB very well
- Probing all the mass (dark matter) distribution

CMB lensing as a high redshift and large scale probe of structure

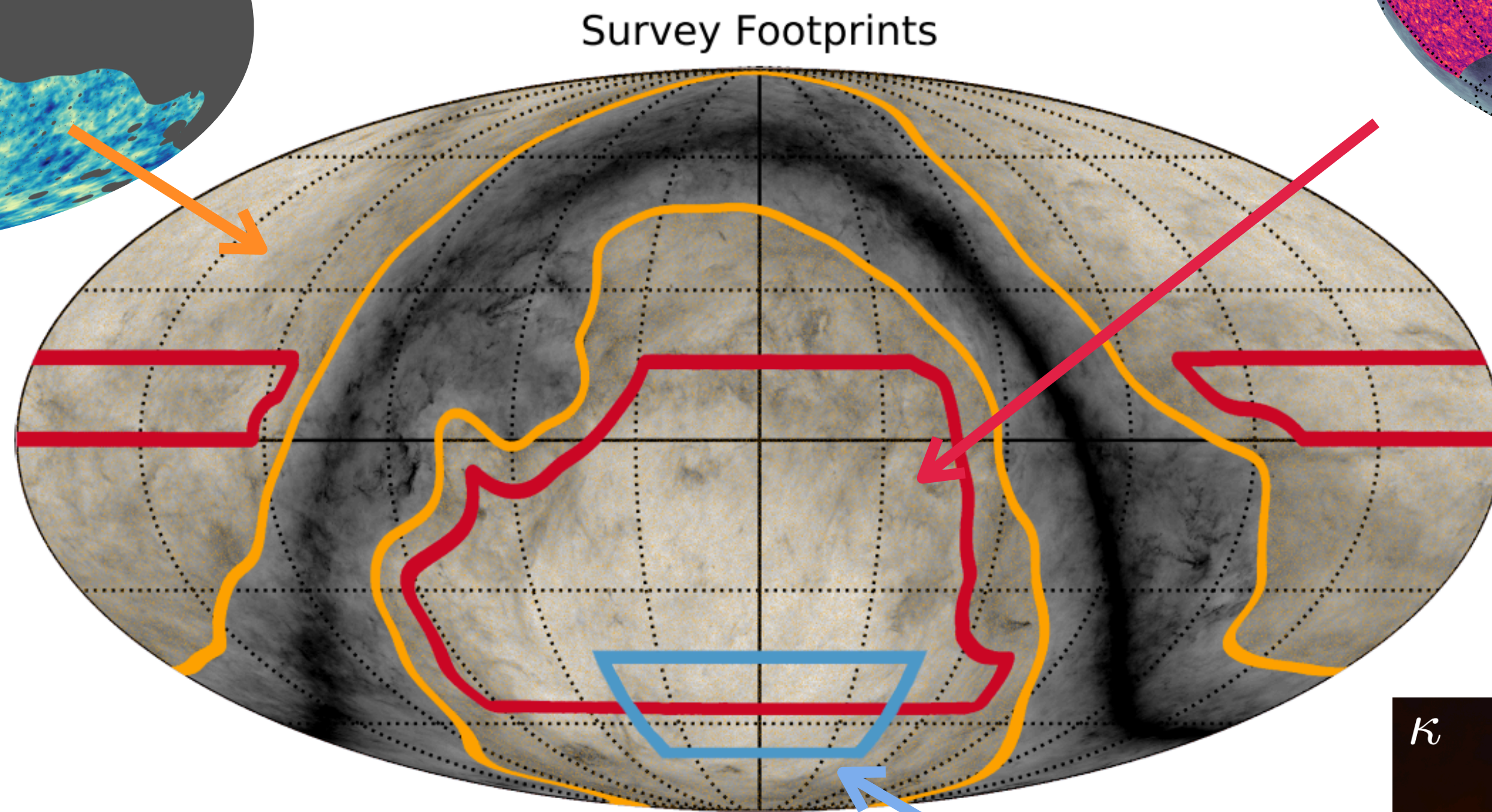


Can give insight into systematics and test z/k dependence of any new physics.

Current status of CMB lensing



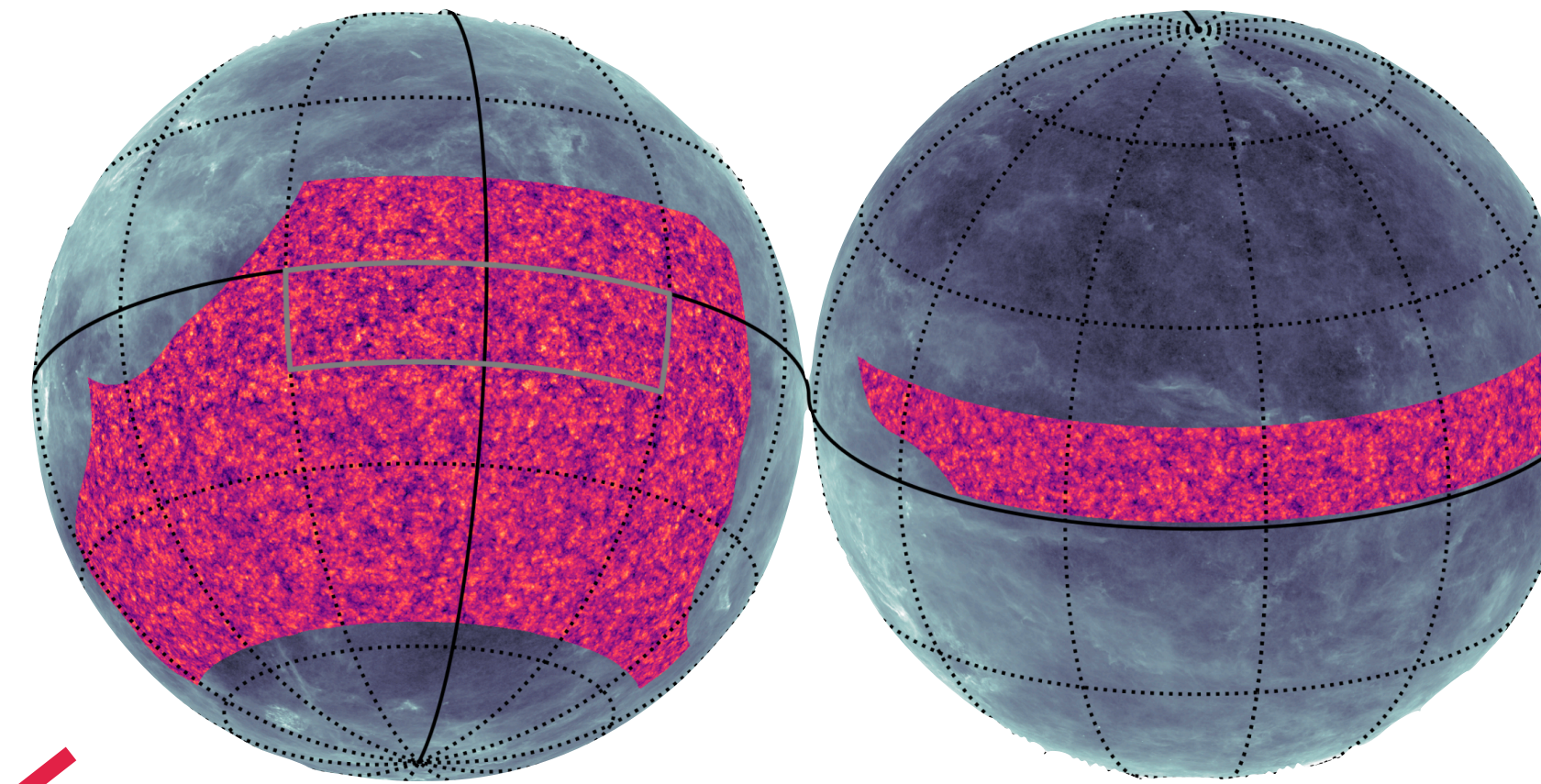
Planck 2018 Carron++



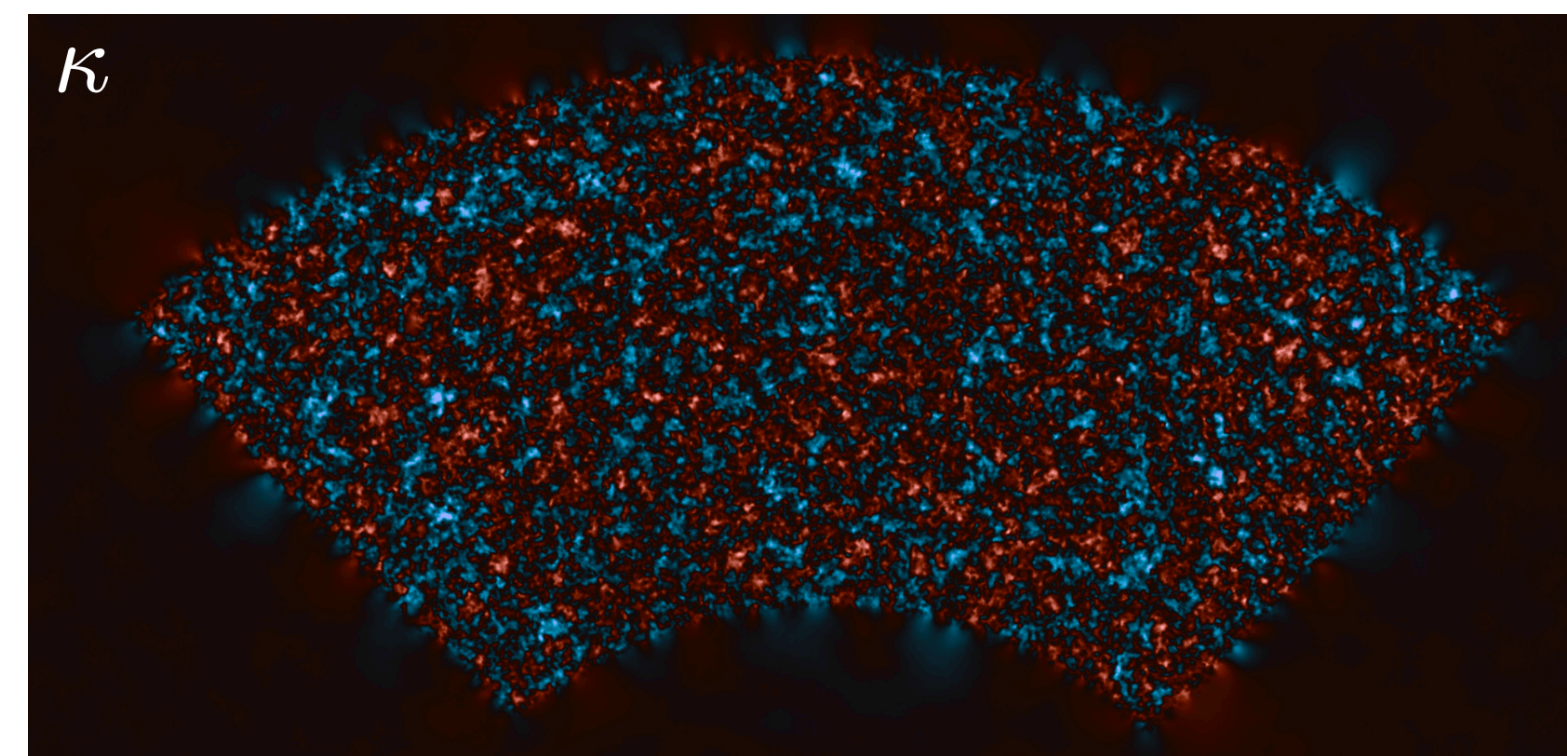
Planck

ACT

SPT-3G



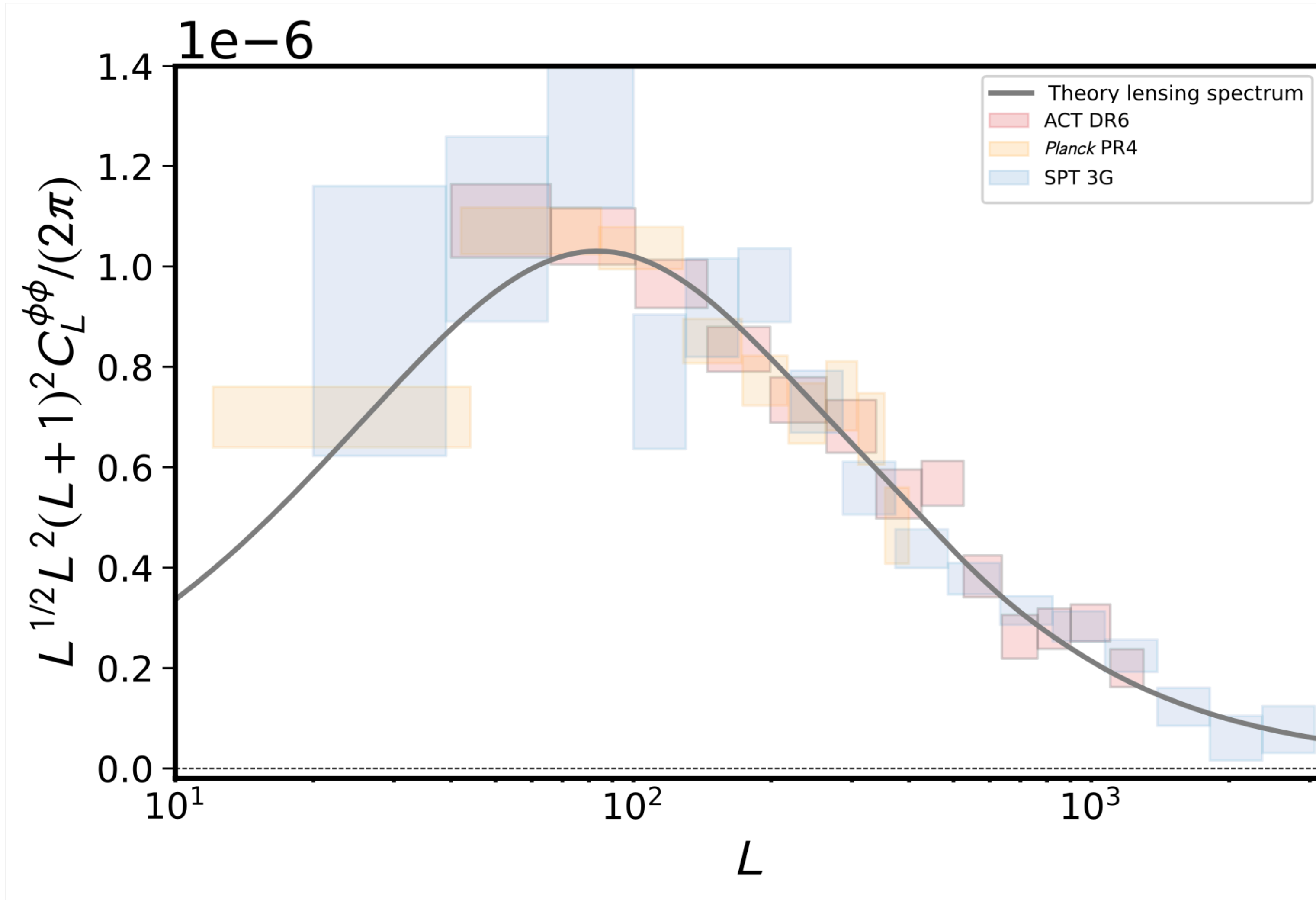
ACT DR6 Madhavacheril++
Qu++
MacCrann++



SPT-3G Ge++

See Fei Ge's talk

Current status of CMB lensing



- **ACT DR6 (Qu++):**

- SNR=43
- 23% of the sky
- TT+POL
- Quadratic estimator

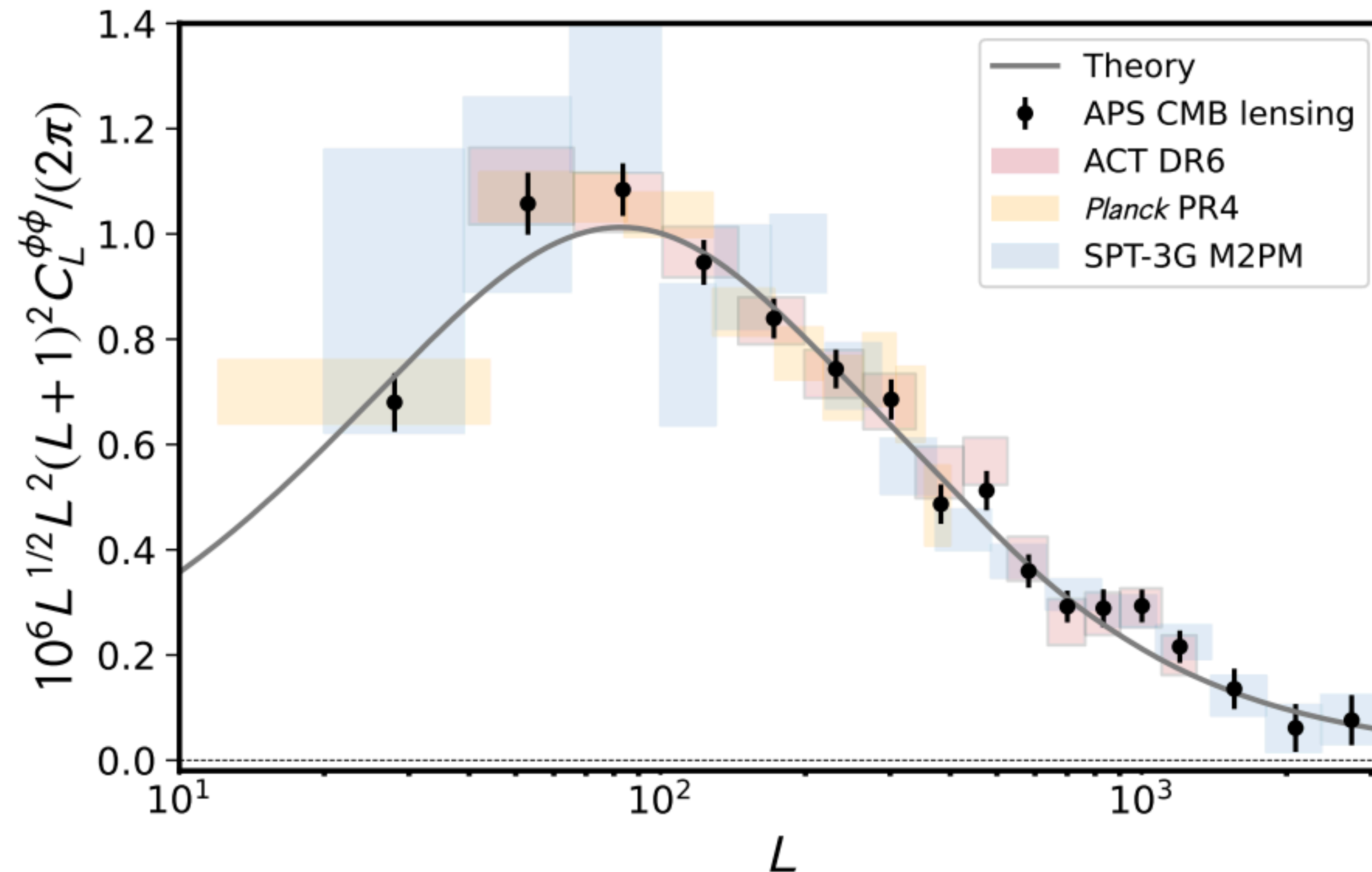
- **SPT-3G (Ge++):**

- SNR=38
- Polarization only.
- 3.5% of the sky
- Fully bayesian framework MUSE

- **Planck NPIPE (Carron++):**

- SNR=42
- 70% of the sky
- TT+POL
- Quadratic estimator.

One lensing to rule them all



- Bandpower combination of the three lensing likelihoods
- SNR=61
- $A_{\text{lens}} = 1.025 \pm 0.016$
- Excellent fit to CMB predictions based on LCDM fit PTE=16%



Fei Ge KIPAC

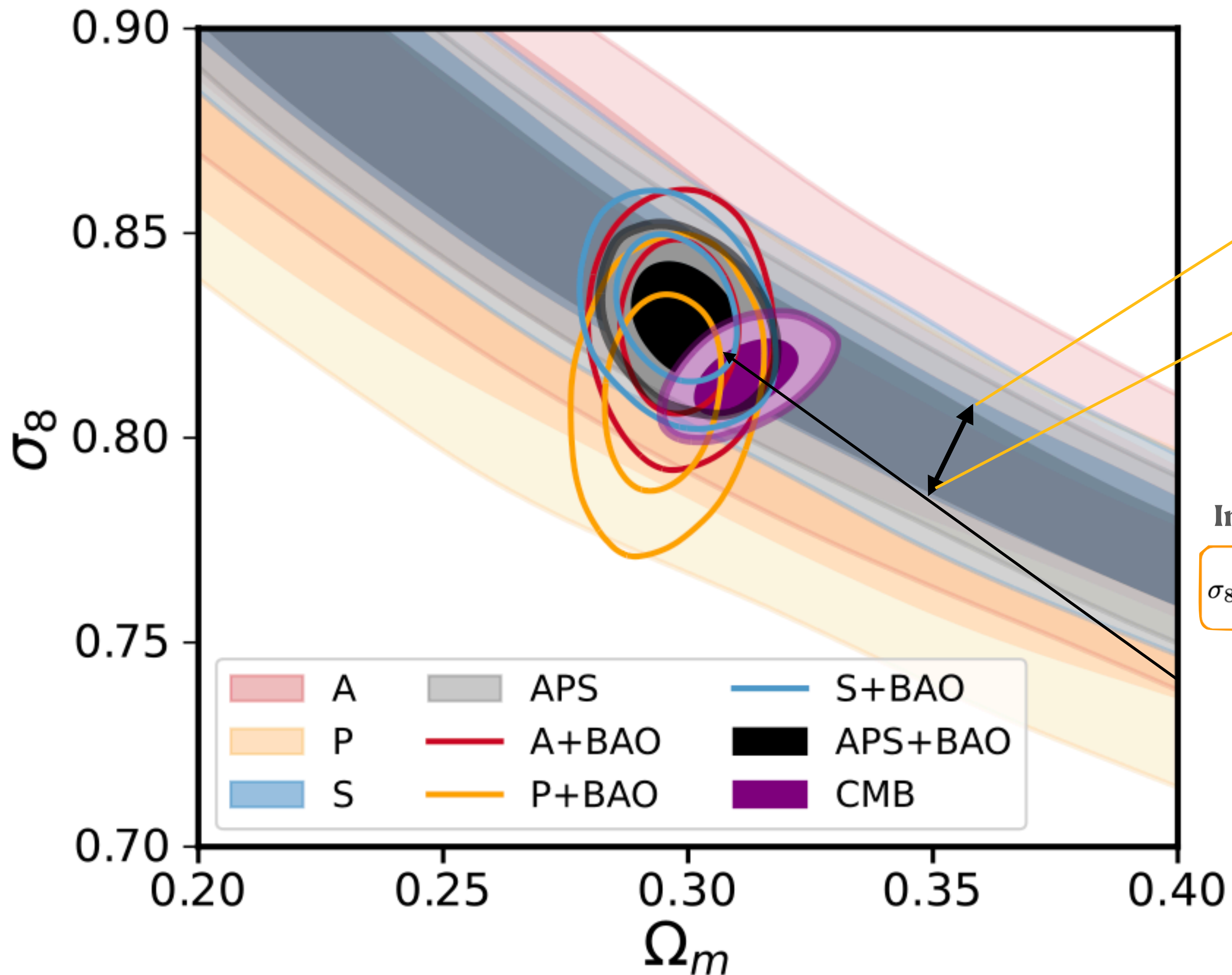


Kimmy Wu KIPAC

Full likelihood available publicly at [qujia7/spt_act_likelihoood](https://github.com/qujia7/spt_act_likelihoood)

[FJQ, Ge, Wu++ \(ACT+SPT\)](#)

Structure growth



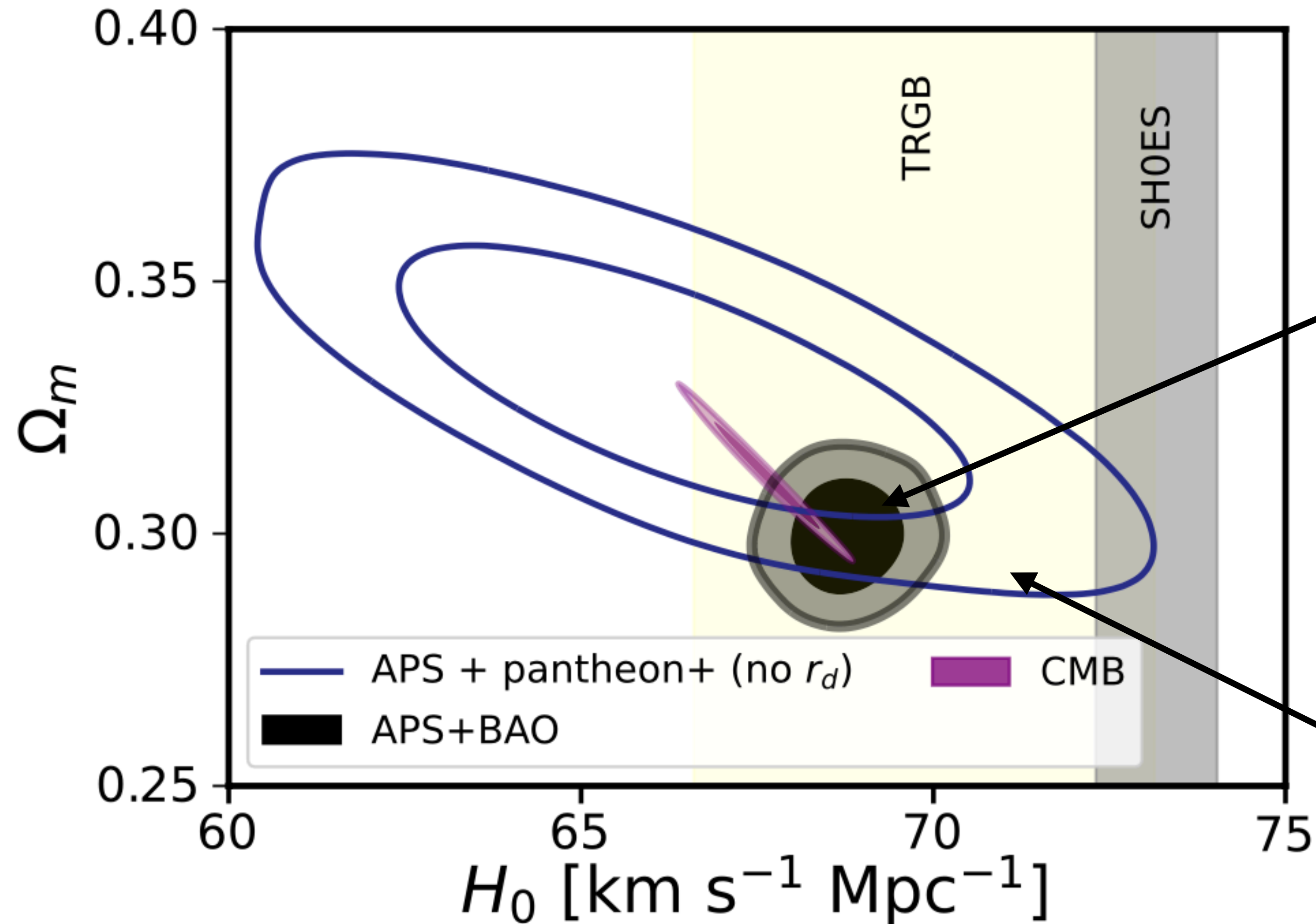
$$S_8^{\text{CMBL}} = 0.825^{+0.015}_{-0.013} \text{ (68\% C.L., APS)}$$

Inclusion of DESI DR2 BAO

$$\sigma_8 = 0.829 \pm 0.009 \text{ (68\% C.L., APS + BAO)}$$

Consistent within 1.2sigma
with ab initio predictions
using **P-A CMB**

Measuring Hubble with lensing



- Hubble constant measurements that depend on the sound horizon (combination with DESI DR2 BAO)

$$H_0 = 68.77 \pm 0.53 \text{ km s}^{-1} \text{Mpc}^{-1}$$

- Independent of BAO and sound horizon, using, as a ruler, the matter-radiation equality scale imprinted in the matter distribution

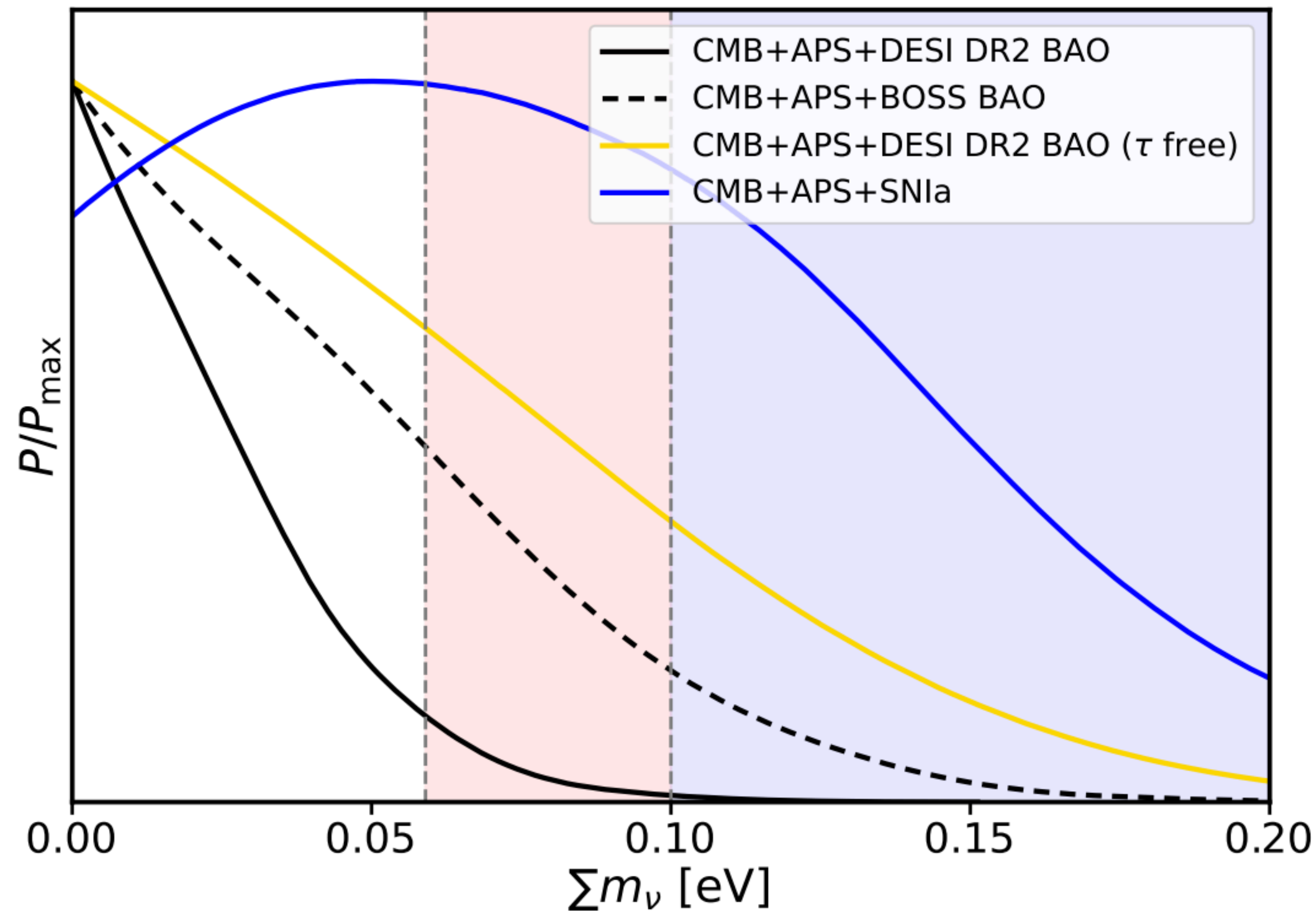
Based on Baxter and Sherwin 2007.04007

$$H_0 = 66.4^{+2.5}_{-2.8} \text{ km s}^{-1} \text{Mpc}^{-1}$$

(68% C.L., APS + Pantheon+).

- Both consistent, and both low w.r.t to Cepheids

Neutrino mass with CMB lensing



- Combined with DR2 BAO, APS lensing places one of the tightest bounds on neutrino mass sum.

$$\Sigma m_\nu < 0.062 \text{ eV (95\% C.L., CMB + APS + BAO)}$$

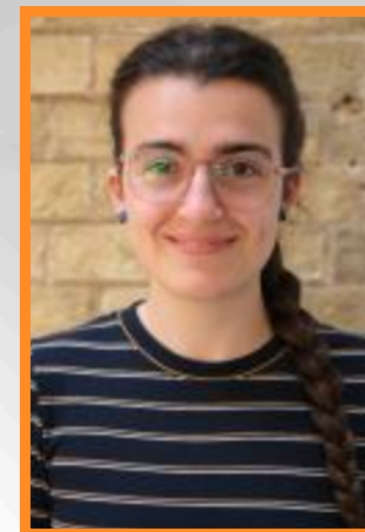
Using different alternative datasets can relax the constraints

$$\Sigma m_\nu < 0.112 \text{ eV (95\% C.L., CMB + APS + BOSS BAO)}$$

$$\Sigma m_\nu < 0.193 \text{ eV (95\% C.L., CMB + APS + Pantheon+)}$$

$$\Sigma m_\nu < 0.150 \text{ eV (95\% C.L., CMB + APS + BAO, } \tau \text{ free)}$$

- Introduction
- Current state of the art CMB lensing
- **New to come: DR6+ lensing**
- Further ahead: CMB lensing with the Simons Observatory



Irene Abril Cabezas
Cambridge



Joshua Kim
Penn



Blake
Sherwin
Cambridge



Mathew
Madhavacheril
Penn



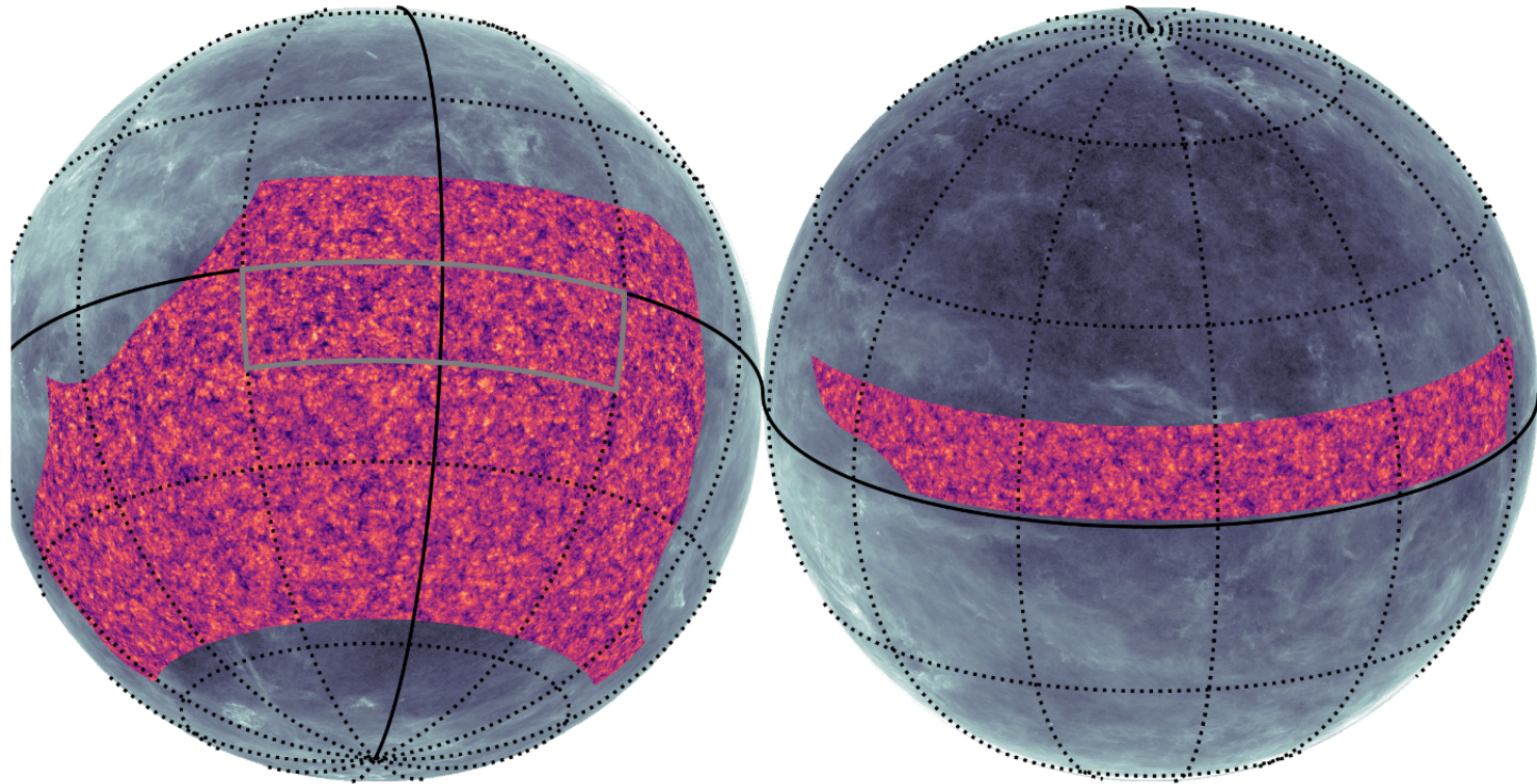
Karen Perez
Penn

DR6 high fidelity lensing maps

Gravitational Lensing
Convergence

$\kappa \propto$ mass density

- 2017-2021 Advanced ACT DR6 observations
- Covers 9400 sq deg, ~25% of the sky
- Detection at 43σ
- 2x SNR per mode compared with *Planck*



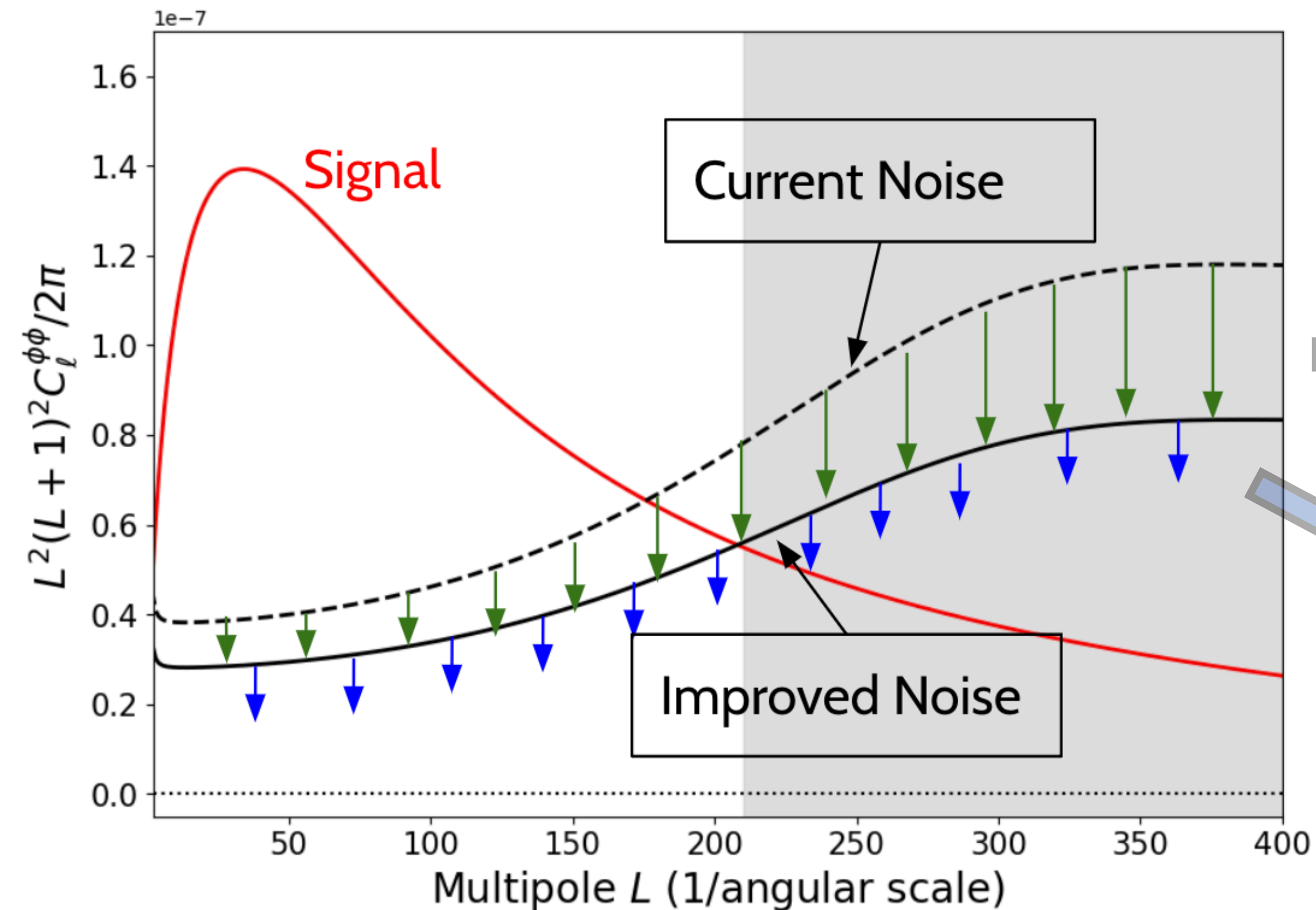
Qu, Sherwin++2023, Madhavacheril+
+2023, MacCrann++2023

AAS featured image



Signal dominated mass map covering a quarter of the sky.

New to come: Further Improvements in mass mapping



Expected Improvements for the next set of analyses

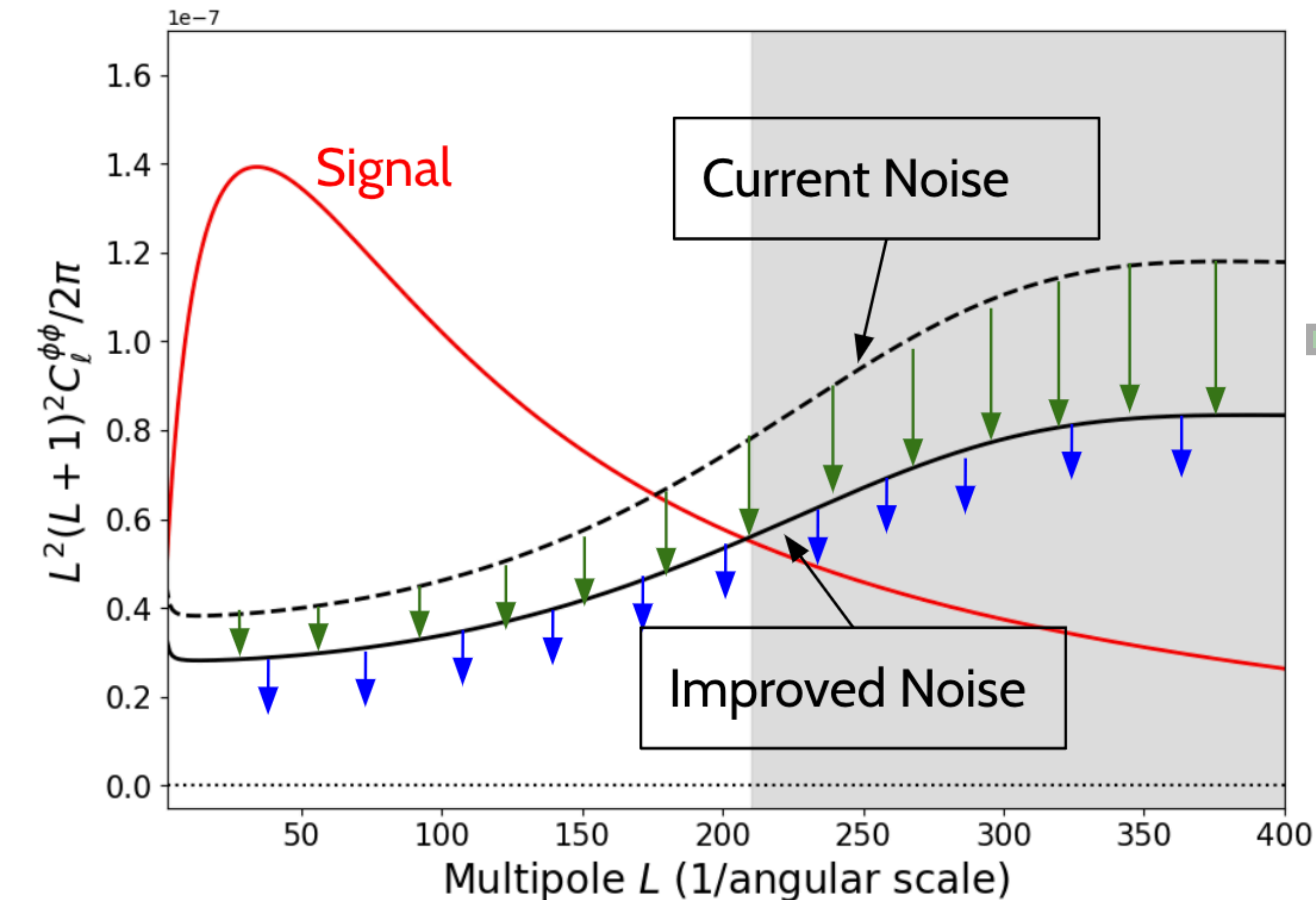
- Inclusion of the daytime data: ~ 1.7x amount of the data
- Additional Seasons (Season 2021-2022)

- Optimal Filtering (10-15% improvement)
- Improve sky-cuts (~10% improvement)
- Map-level combination with Planck

See Joshua Kim's talk

New to come: Further Improvements in mass mapping

Expected Improvements for the flagship DR6+ analysis

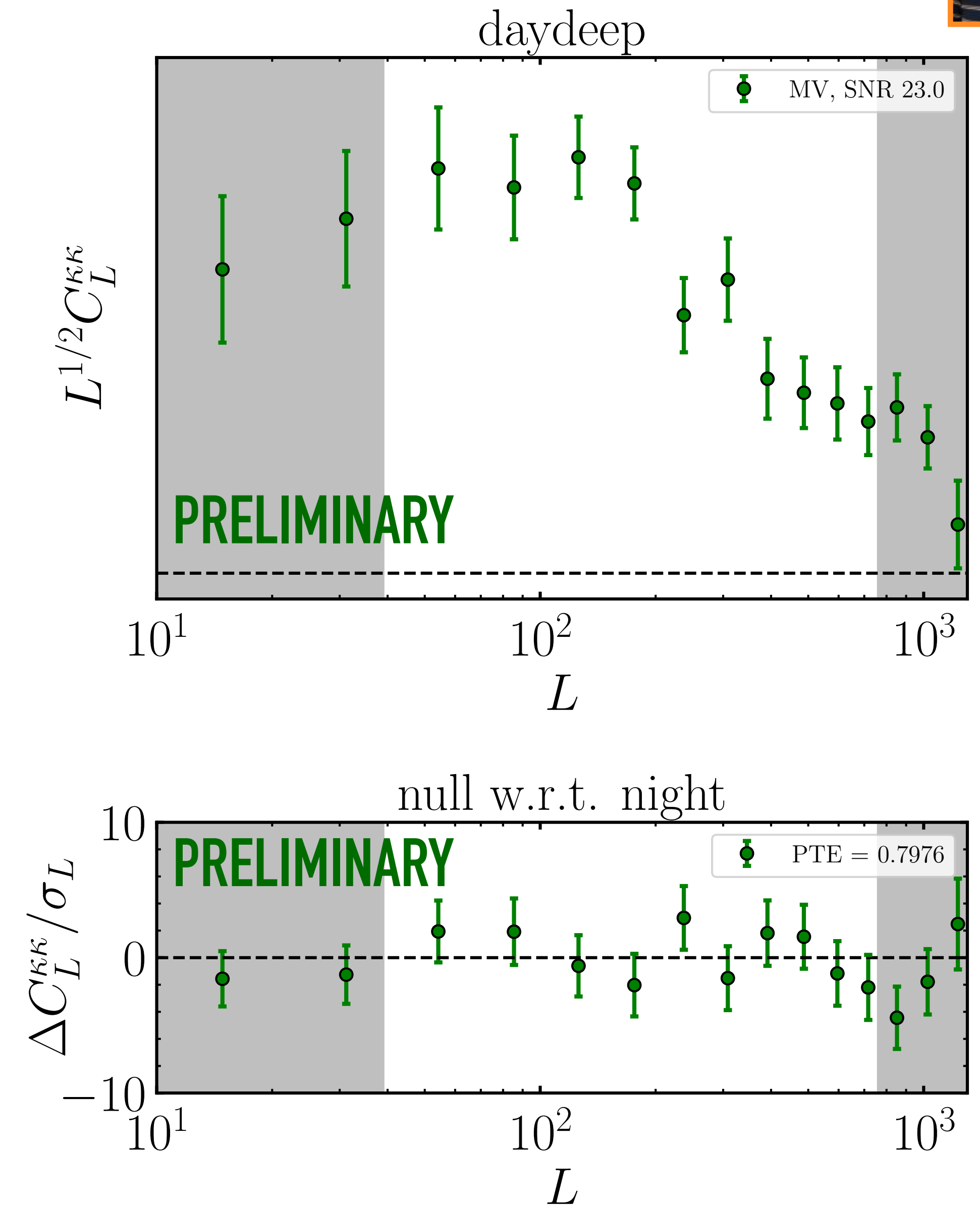
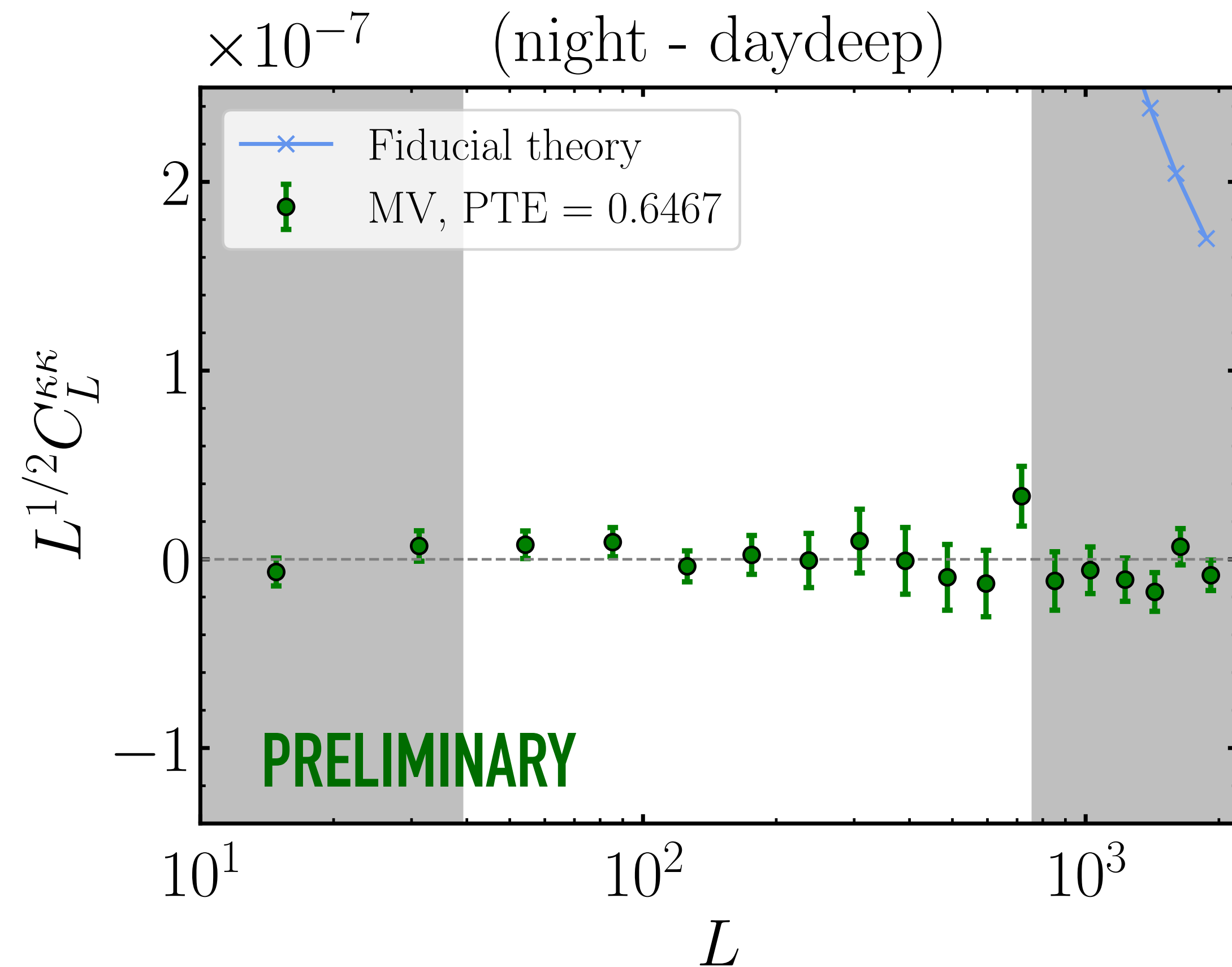


Inclusion of more data

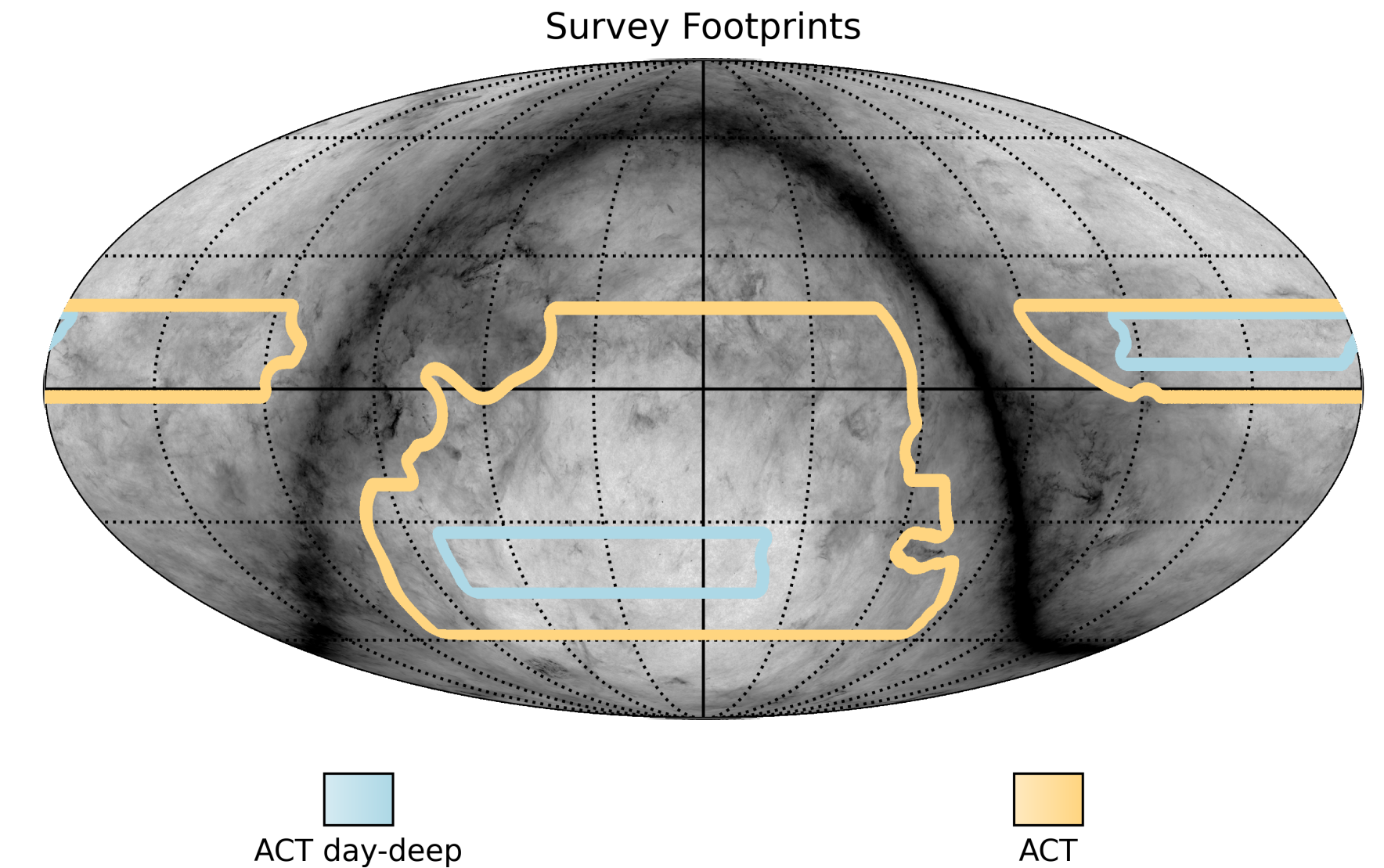
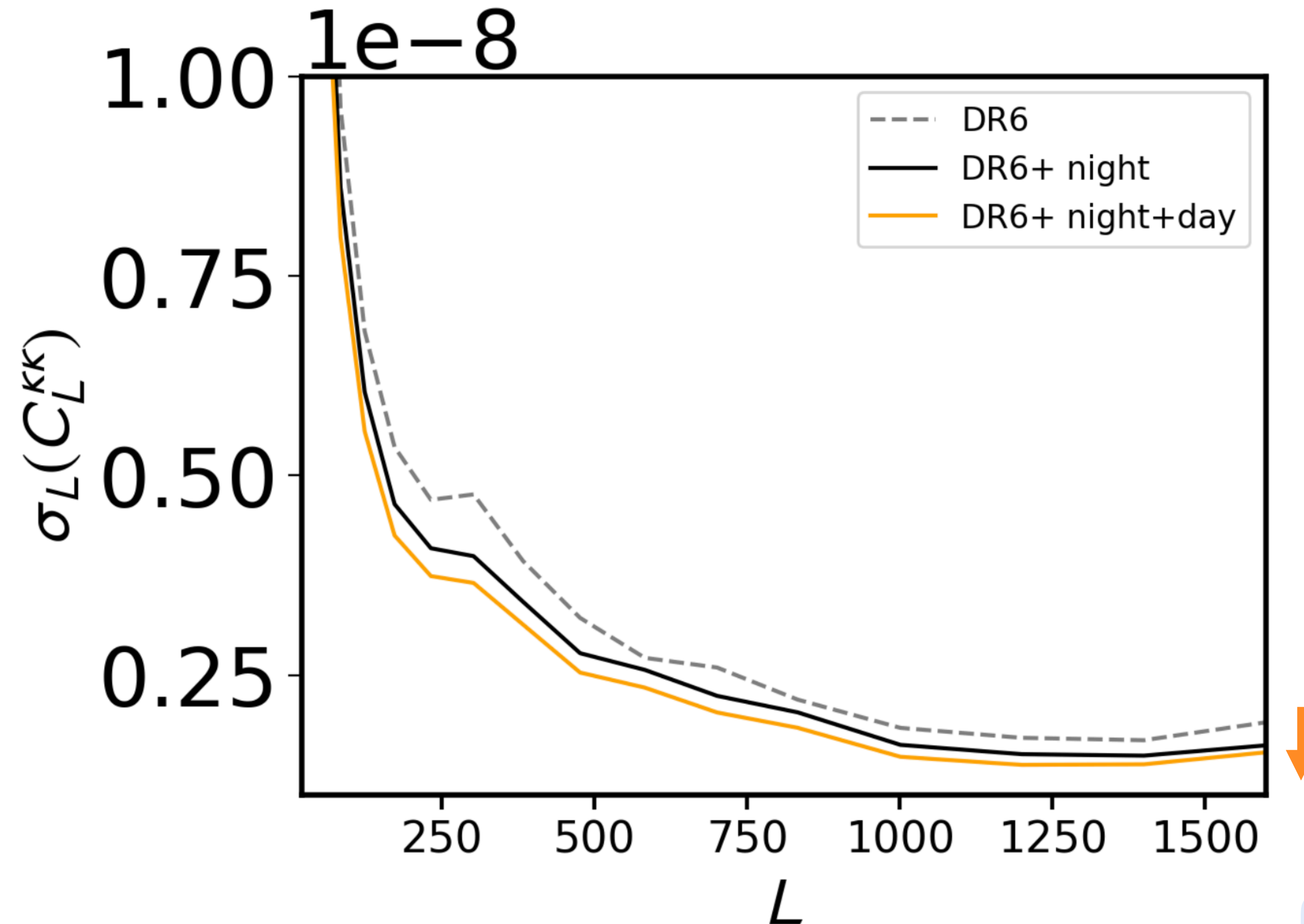
- **Extra nighttime season (2022 nighttime data)** ~12% gain of lensing SNR
- **Inclusion of the daytime data: ~1.7x amount of the data** ~30% gain of lensing SNR

CMB lensing with daytime data

- More than 60 map and band power-level null tests **passing**
- **SNR ~30** with daytime only data



Forecasted performance

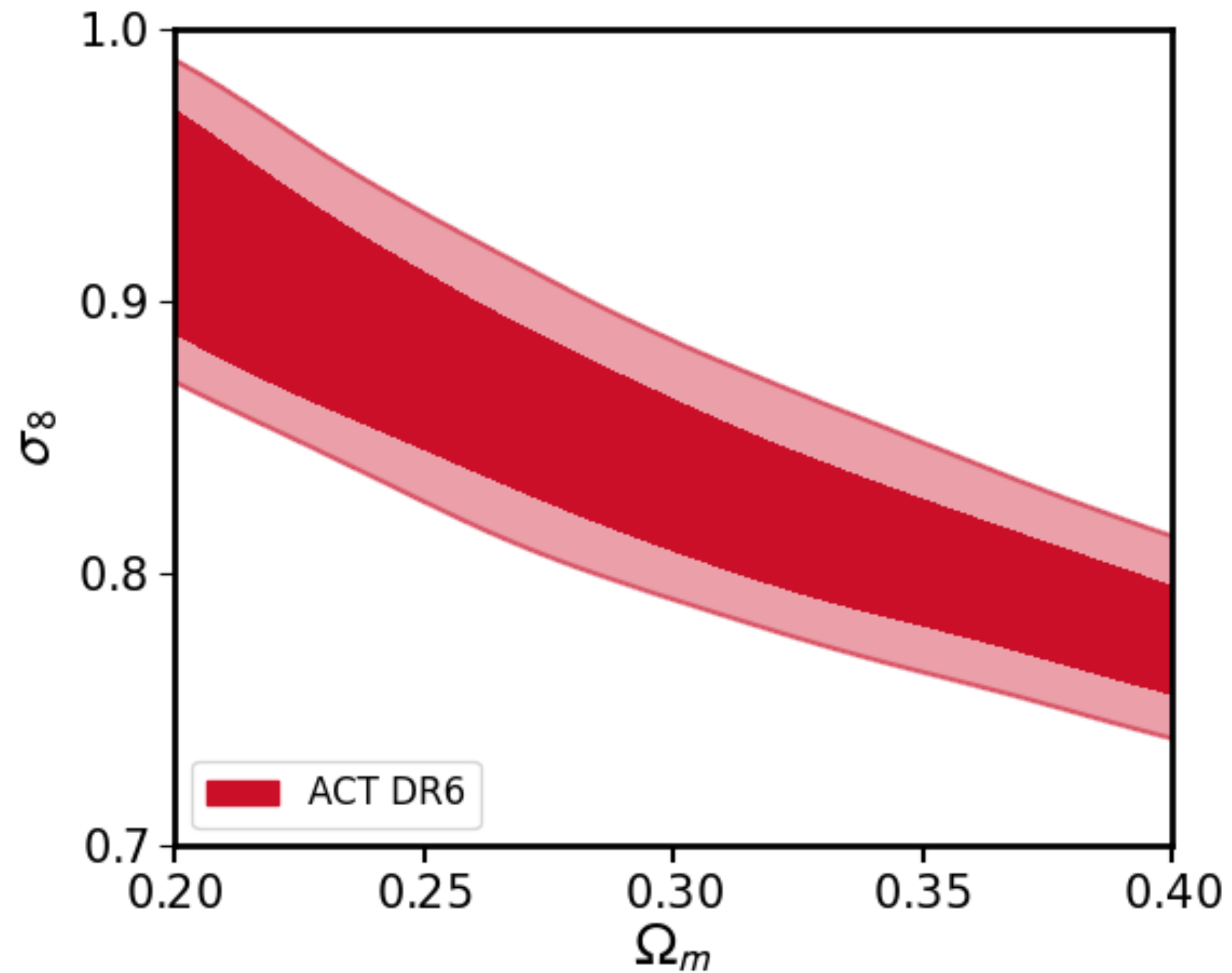


**>20% reduction in errorbars
compared to DR6 with
DR6+night+day**

SNR=60 For nighttime+ day-deep coadd

Forecasted performance

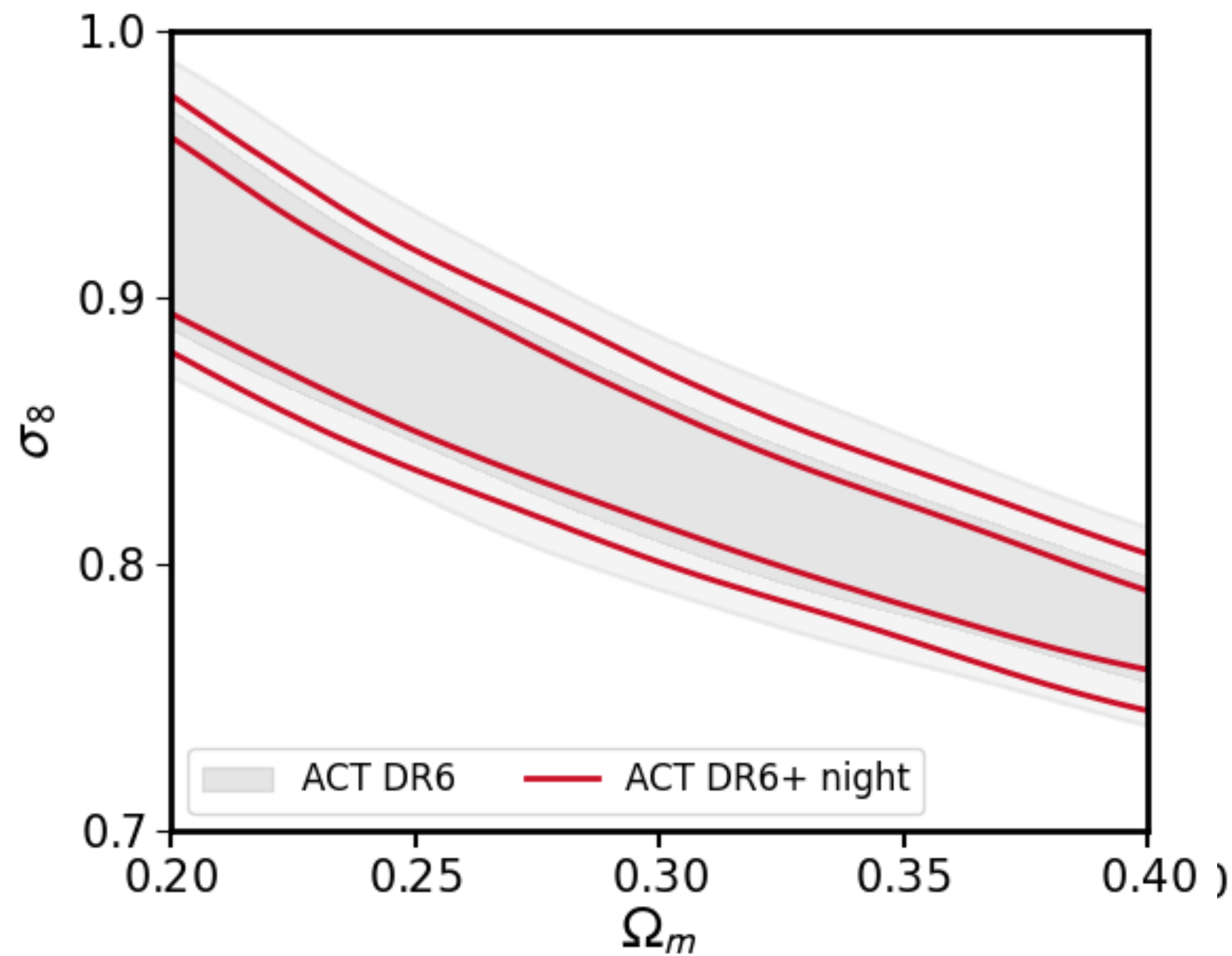
Chains run using **mock bandpowers** with realistic analysis errorbars



ACT DR6 $\sigma(S_8^{\text{lens}}) \sim 2.7 \%$

Forecasted performance

Chains run using **mock bandpowers** with realistic analysis errorbars

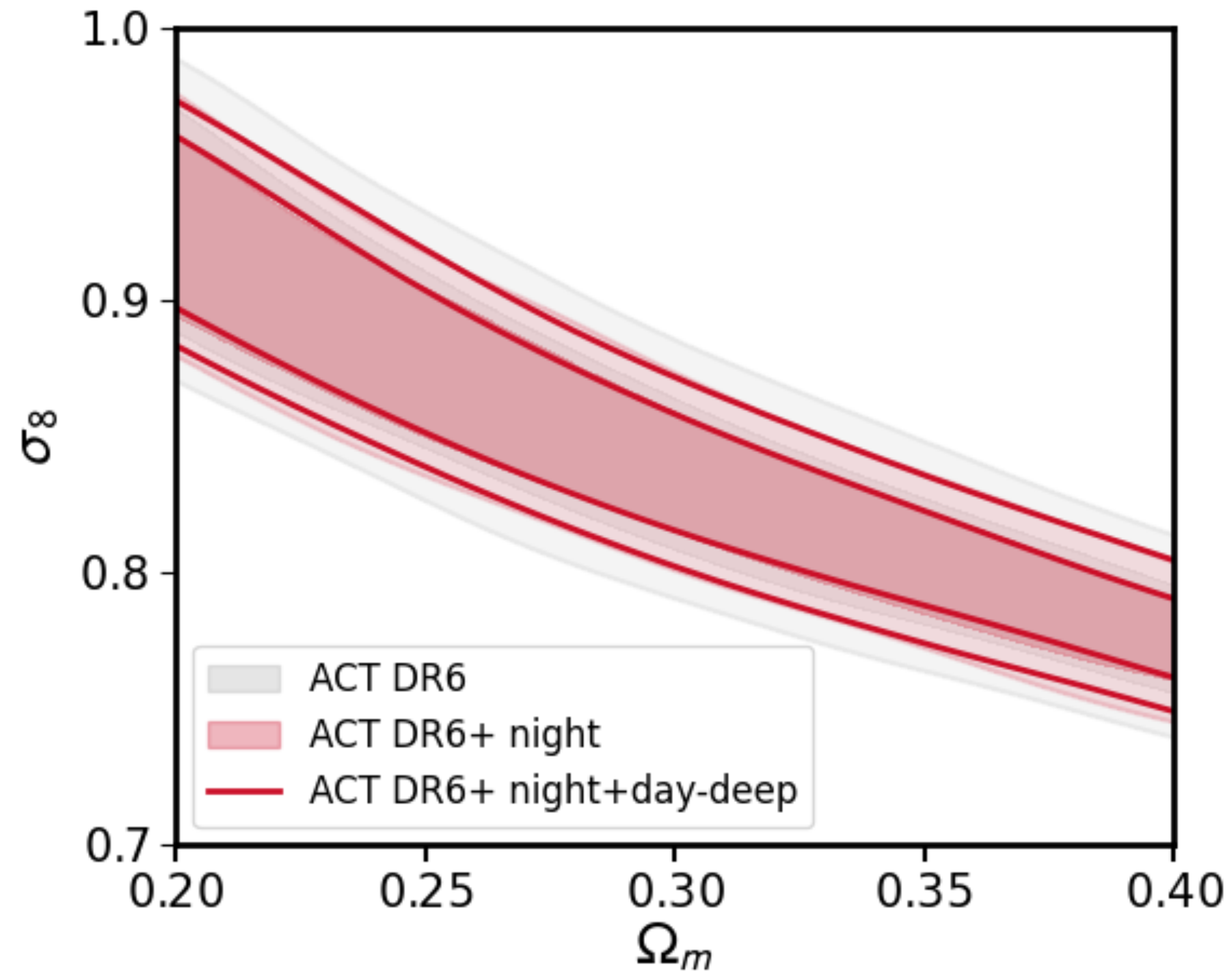


ACT DR6 $\sigma(S_8^{\text{lens}}) \sim 2.7 \%$

**ACT DR6+
nighttime** $\sigma(S_8^{\text{lens}}) \sim 2.1 \%$

Forecasted performance

Chains run using **mock bandpowers** with realistic analysis errorbars



ACT DR6 $\sigma(S_8^{\text{lens}}) \sim 2.7 \%$
**ACT DR6+
nighttime** $\sigma(S_8^{\text{lens}}) \sim 2.1 \%$
**ACT DR6+
nighttime+daydeep** $\sigma(S_8^{\text{lens}}) \sim 1.9 \%$

+Further improvements expected with:
- NILC coadd of daywide + Planck
- optimal filtering

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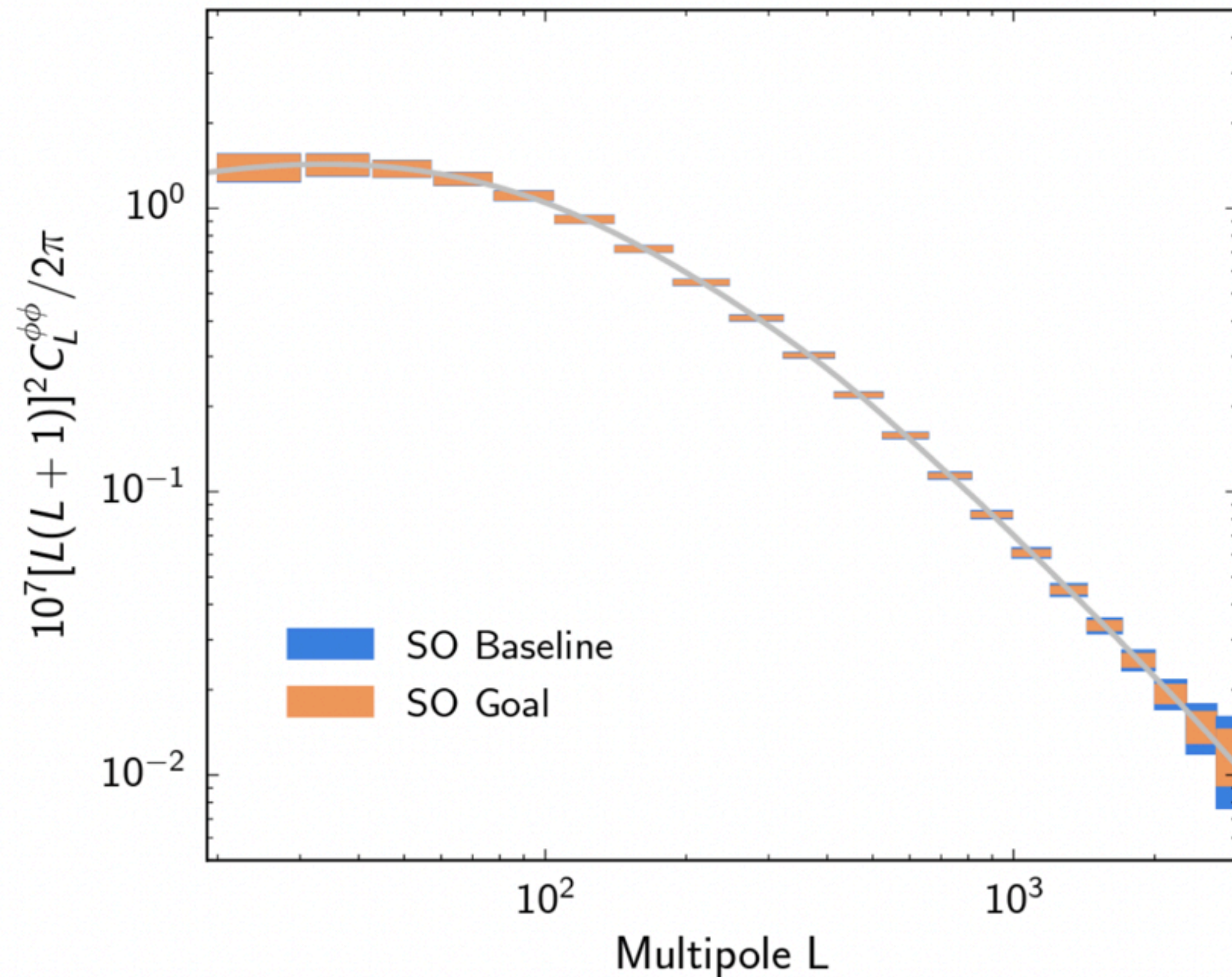
Towards sub-percent CMB lensing measurements



SO collaboration et al arXiv: 1808.07445

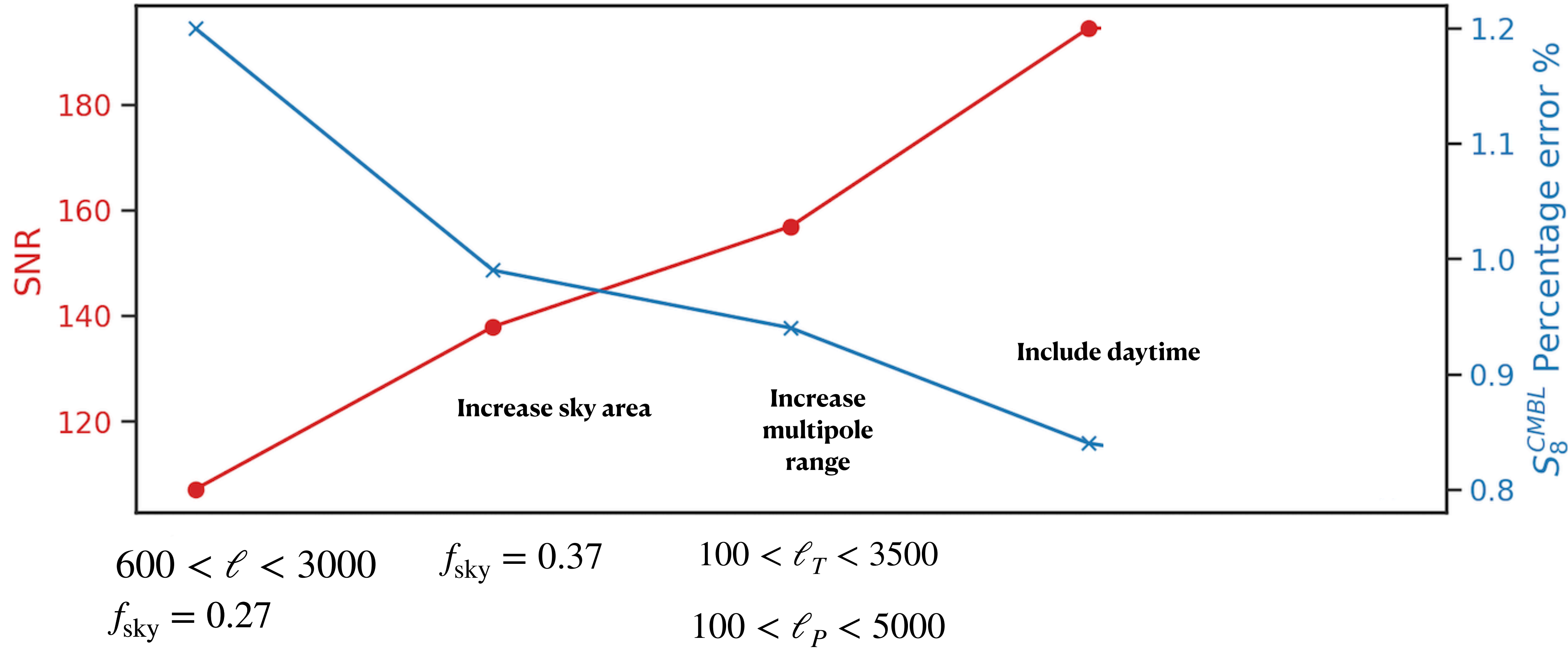
$S/N \sim 140$ with SO baseline

- Sub Percent level measurements of matter density fluctuations for consistency check of GR and LCDM.
- Constraints on neutrino mass sum and hierarchy



$$\sigma(\Sigma m_\nu) = 31 \text{ meV} \quad \text{SO Goal} + \text{DESI-BAO}$$

Current optimizations for ACT should translate to further improvements on SO lensing



Conclusions

- Structure growth measurements from three CMB lensing experiments fully consistent with Λ CDM ab initio expectations.

$$S_8^{\text{CMBL}} = 0.825^{+0.015}_{-0.013} \text{ (68\% C.L., APS)}$$

+BAO

$$\sigma_8 = 0.829 \pm 0.009 \text{ (68\% C.L., APS + BAO)}$$

- Working towards even more precise CMB lensing measurements:
 - ACT DR6+. Expecting SNR 60-70 lensing measurements.
 - Simons Observatory online and taking data. Towards sub-percentage CMB lensing.

