ACT DR6: Testing structure growth with new CMB lensing measurements

Blake D. Sherwin
DAMTP and
Kavli Institute for Cosmology,
University of Cambridge

European Research Council
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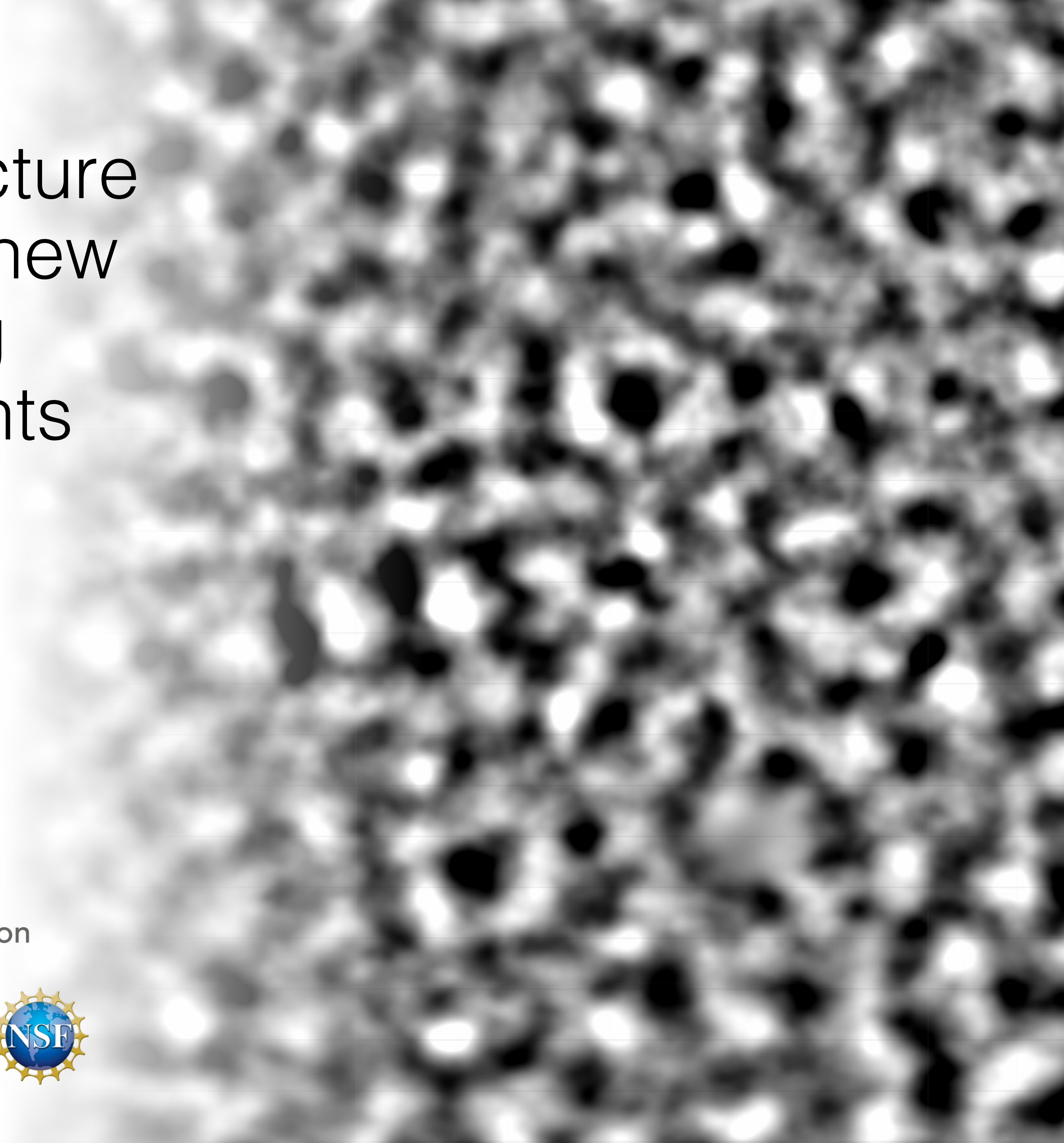
for the Atacama Cosmology Telescope Collaboration



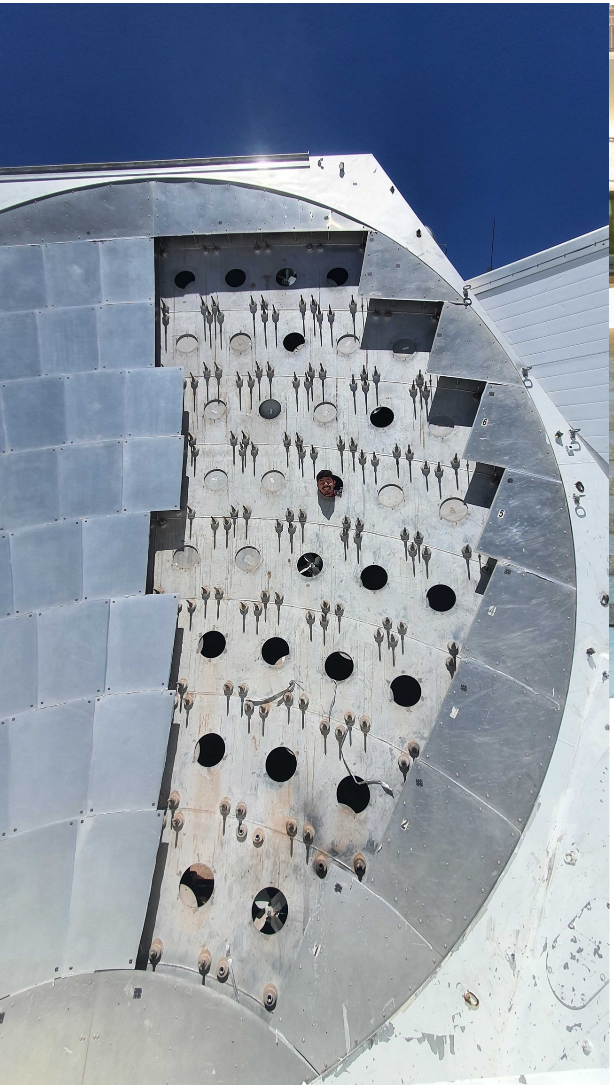
Outline

- ACT Data Release 6: Data and Science Overview
- Progress on new CMB lensing spectra from AdvACT DR6 and implications for structure growth
- Tracking structure growth across redshifts with lensing cross-correlations

Atacama Cosmology Telescope (ACT)

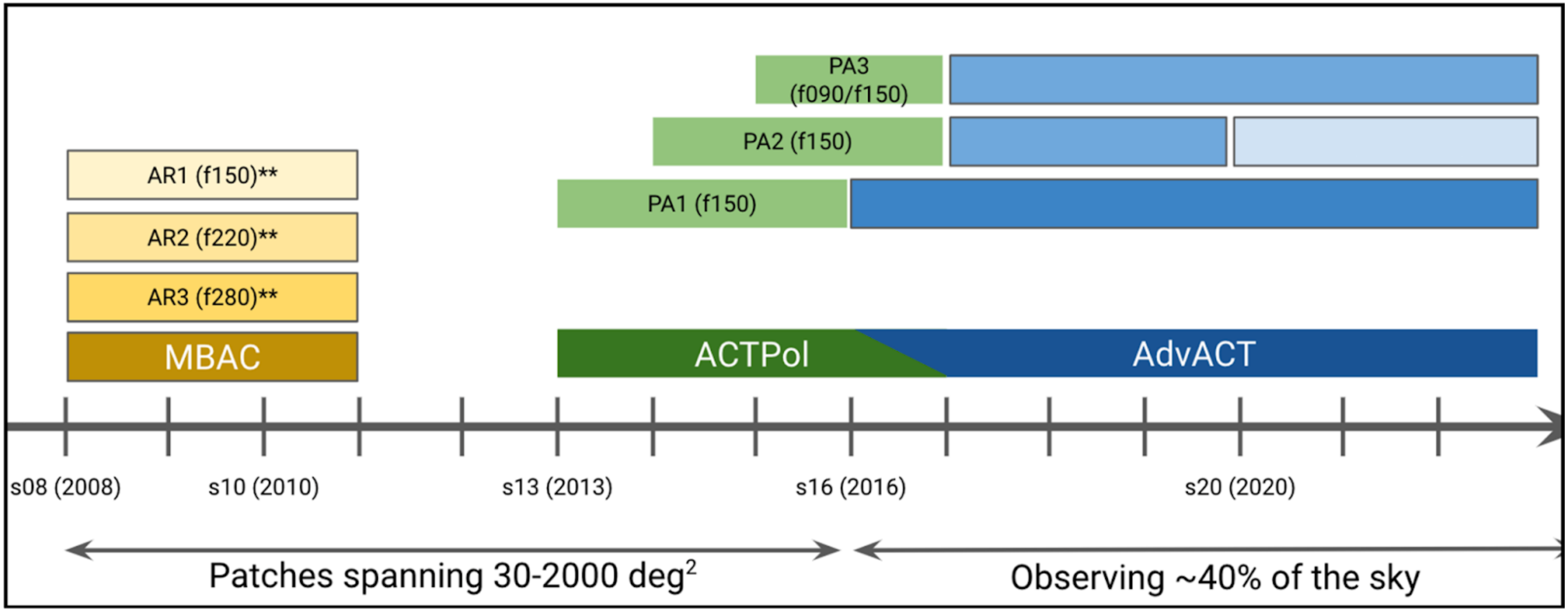
- Arcminute resolution CMB telescope at 5200m in the Chilean Atacama desert, with arrays of sensitive (TES bolometer) detectors

RIP – Atacama Cosmology Telescope (ACT)



- Telescope being dismantled. ACT is now just collaboration, but two more powerful data releases to go!

Atacama Cosmology Telescope Observations: Overview



Atacama Cosmology Telescope: DR4

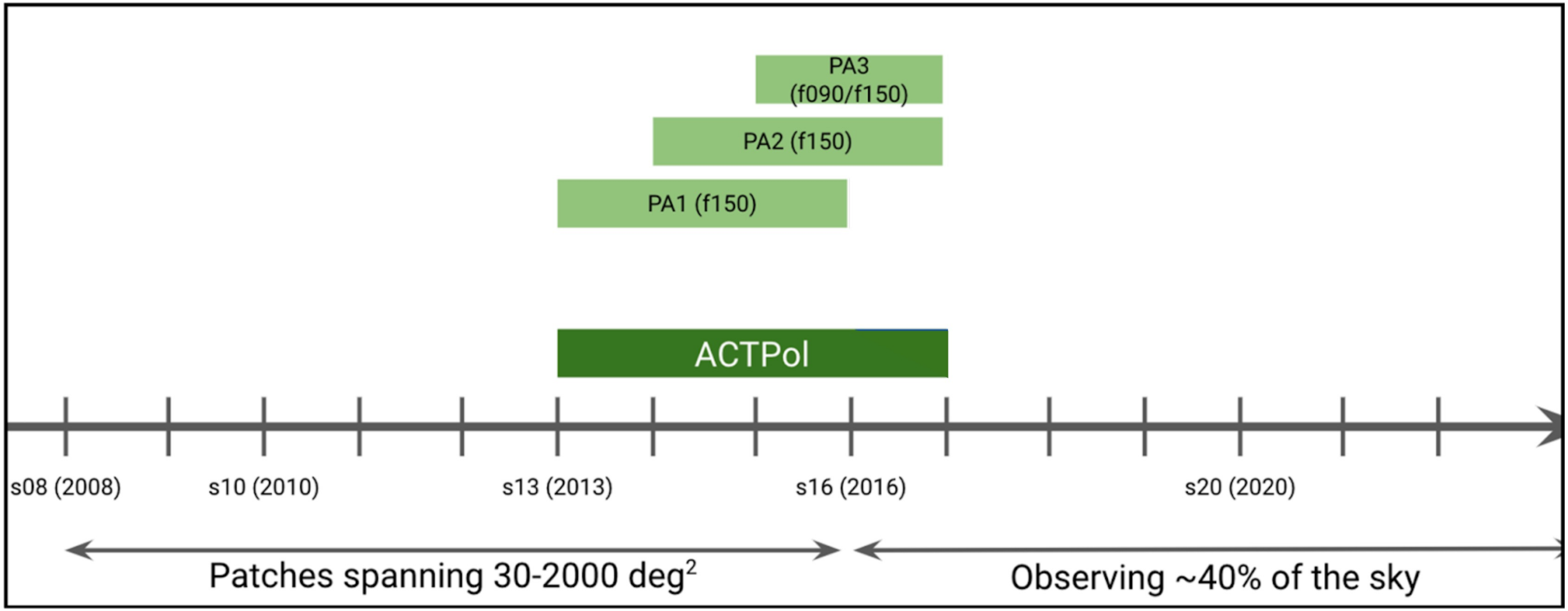
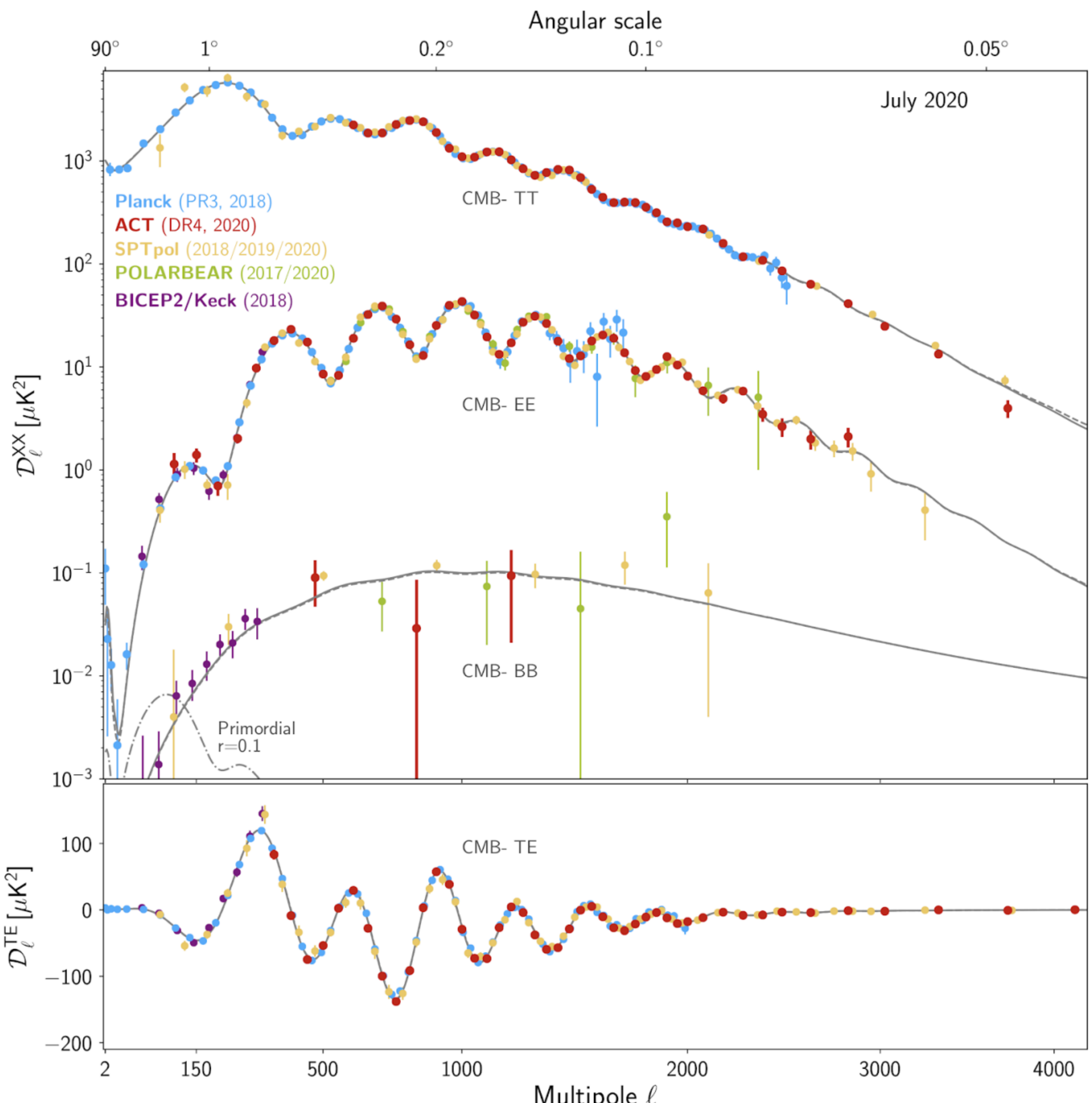


Image credit: Adri Duivenvoorden

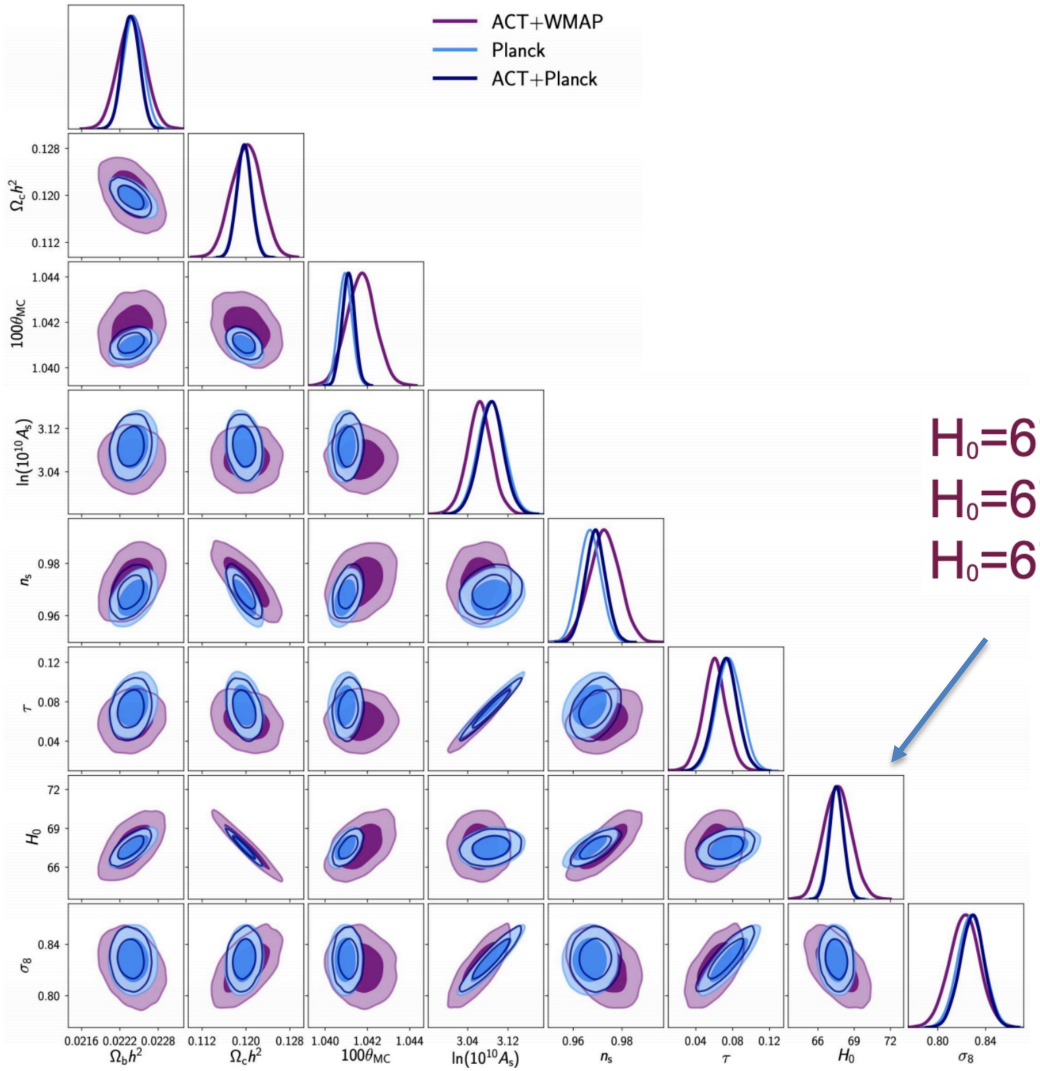
Previous Cosmology Release: ACT DR4 Spectra



Choi++, Aiola++ 2020

Previous Cosmology Release: ACT DR4 Spectra

- ACT+WMAP: good agreement with Planck in LCDM. Indep. test of params, e.g. H0! Tension not from Planck systematics



H_0=67.6±1.1 km/s/Mpc *ACT+WMAP*

H_0=67.9±1.5 km/s/Mpc *ACT*

H_0=67.5±0.6 km/s/Mpc *Planck*

Choi++, Aiola++ 2020

Next Cosmology Release:
Atacama Cosmology Telescope DR6

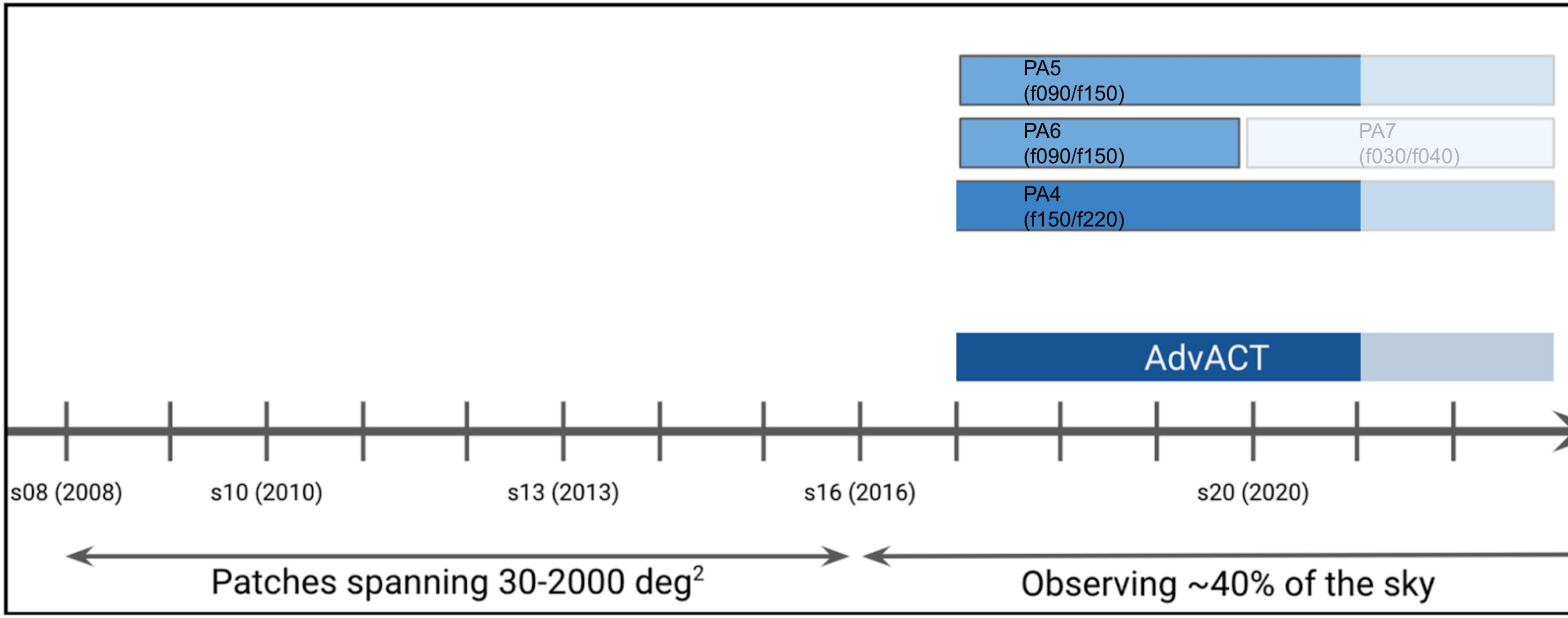
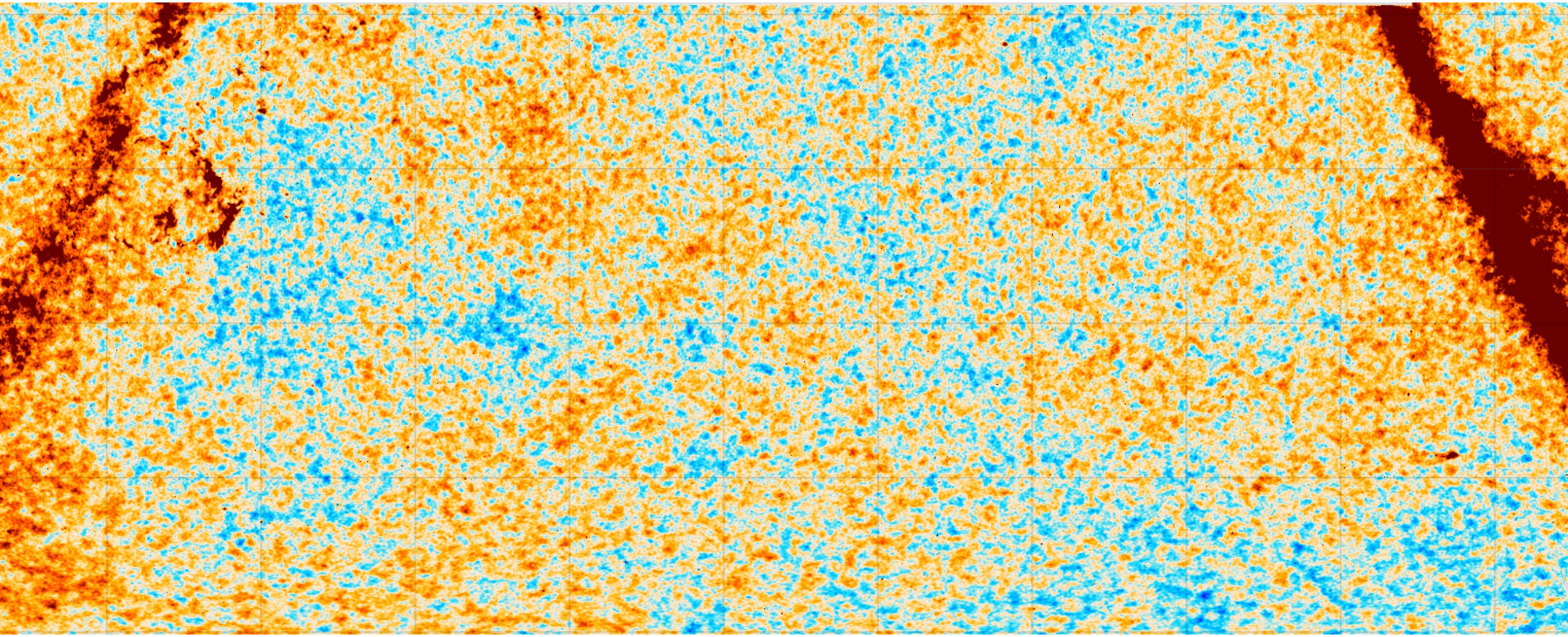


Image credit: Adri Duivenvoorden

- Observations on 40% sky at 90, 150, 220 GHz from 2017-2021
- ~10 x more data volume than DR4!

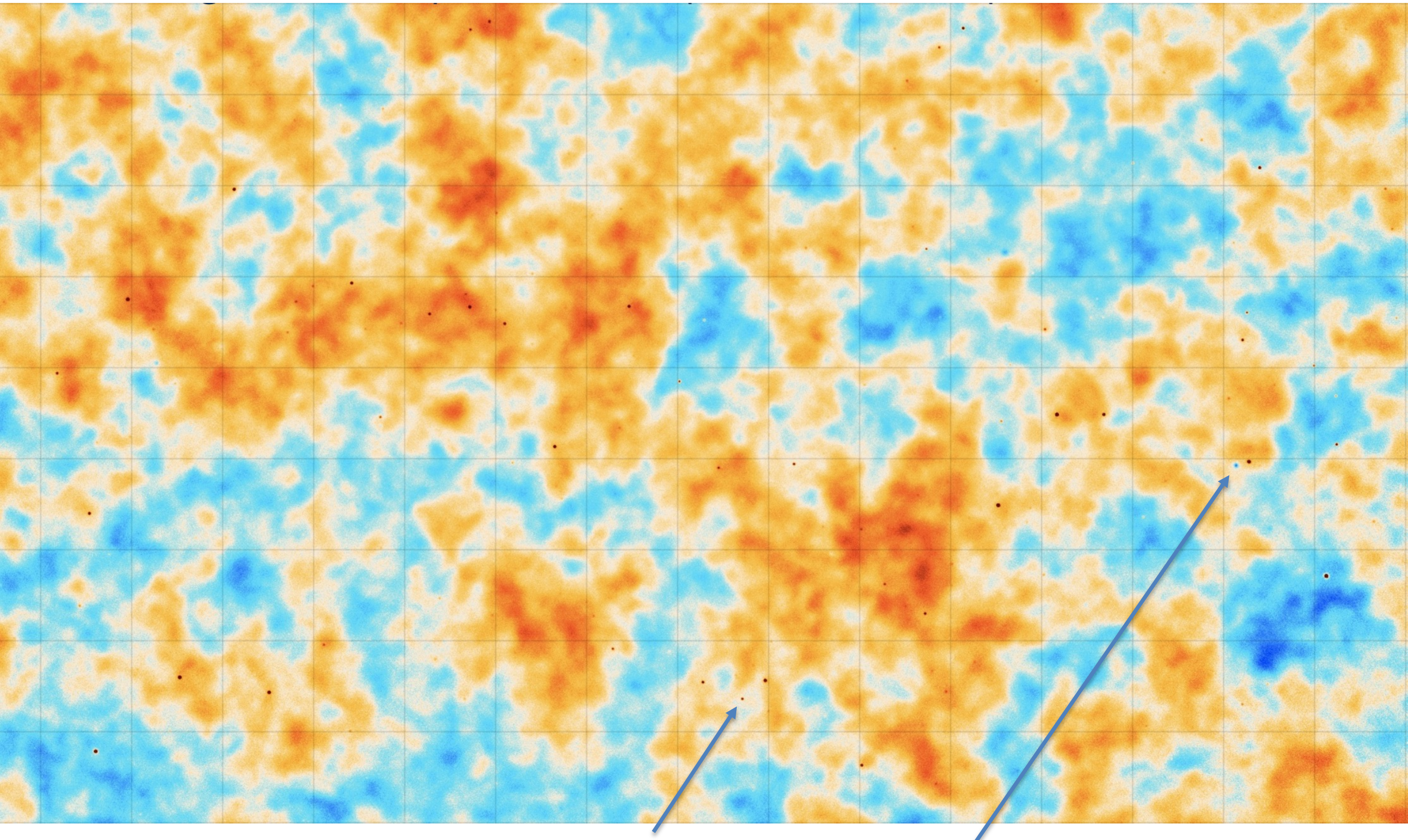
ACT DR6: new, state of the art CMB maps

AdvACT CMB map



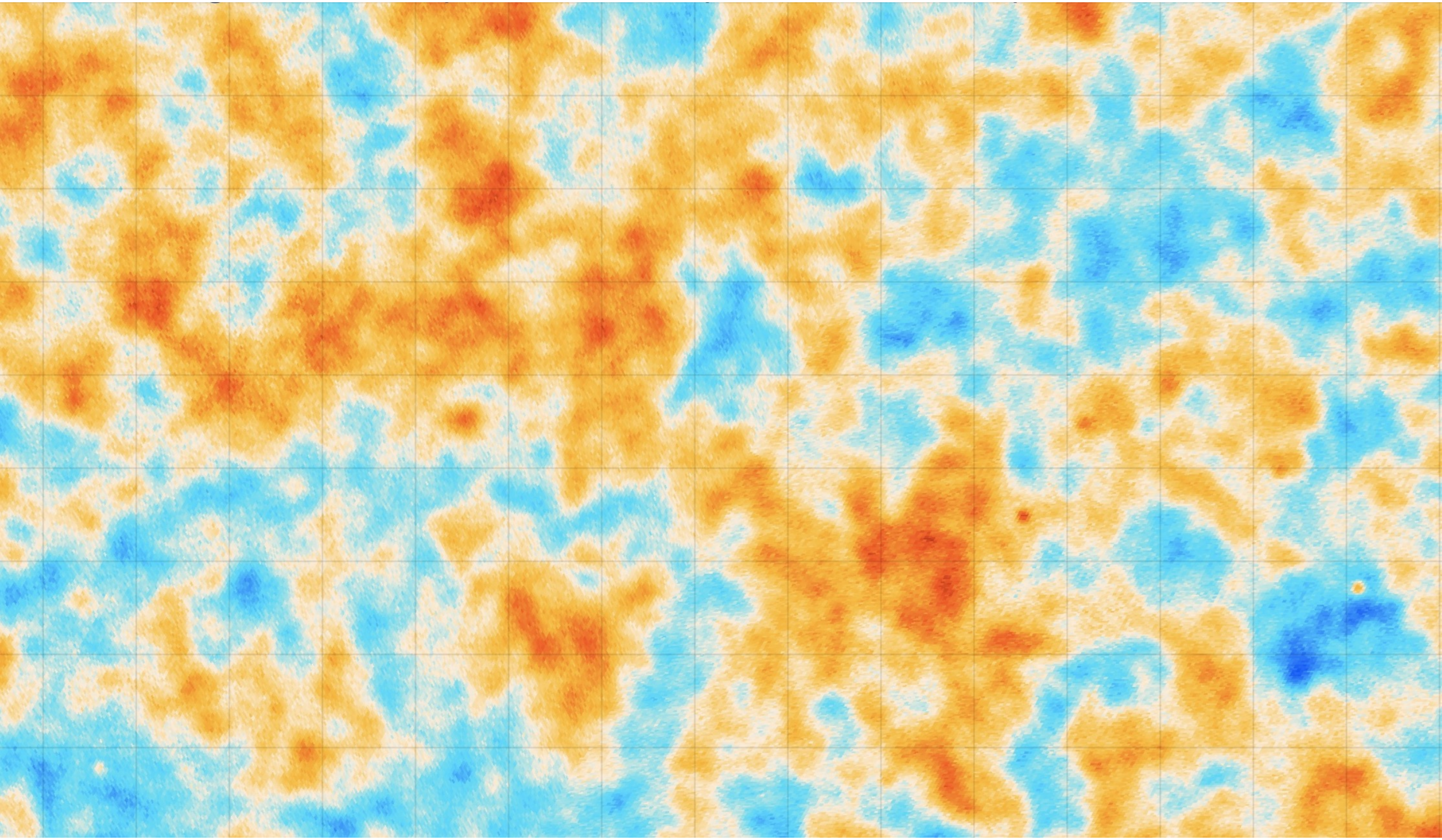
- New AdvACT polarized data through 2021: low noise (<15uK') CMB maps (link) on 16000 deg^2 at high resolution.

ACT DR6: new, state of the art CMB maps



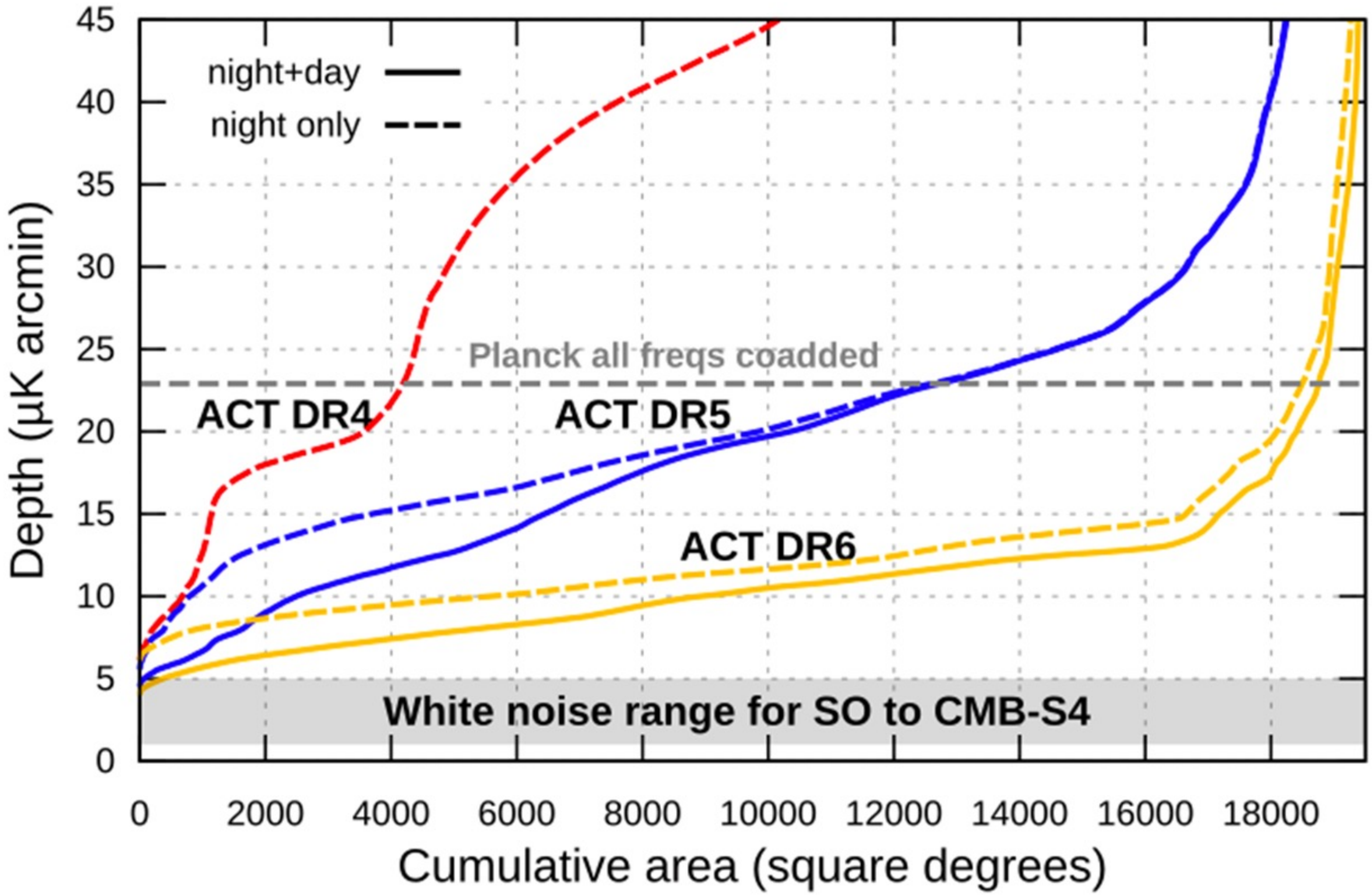
- High resolution, low noise (Radio/IR sources and SZ clusters visible by eye)

Compare with Planck maps:



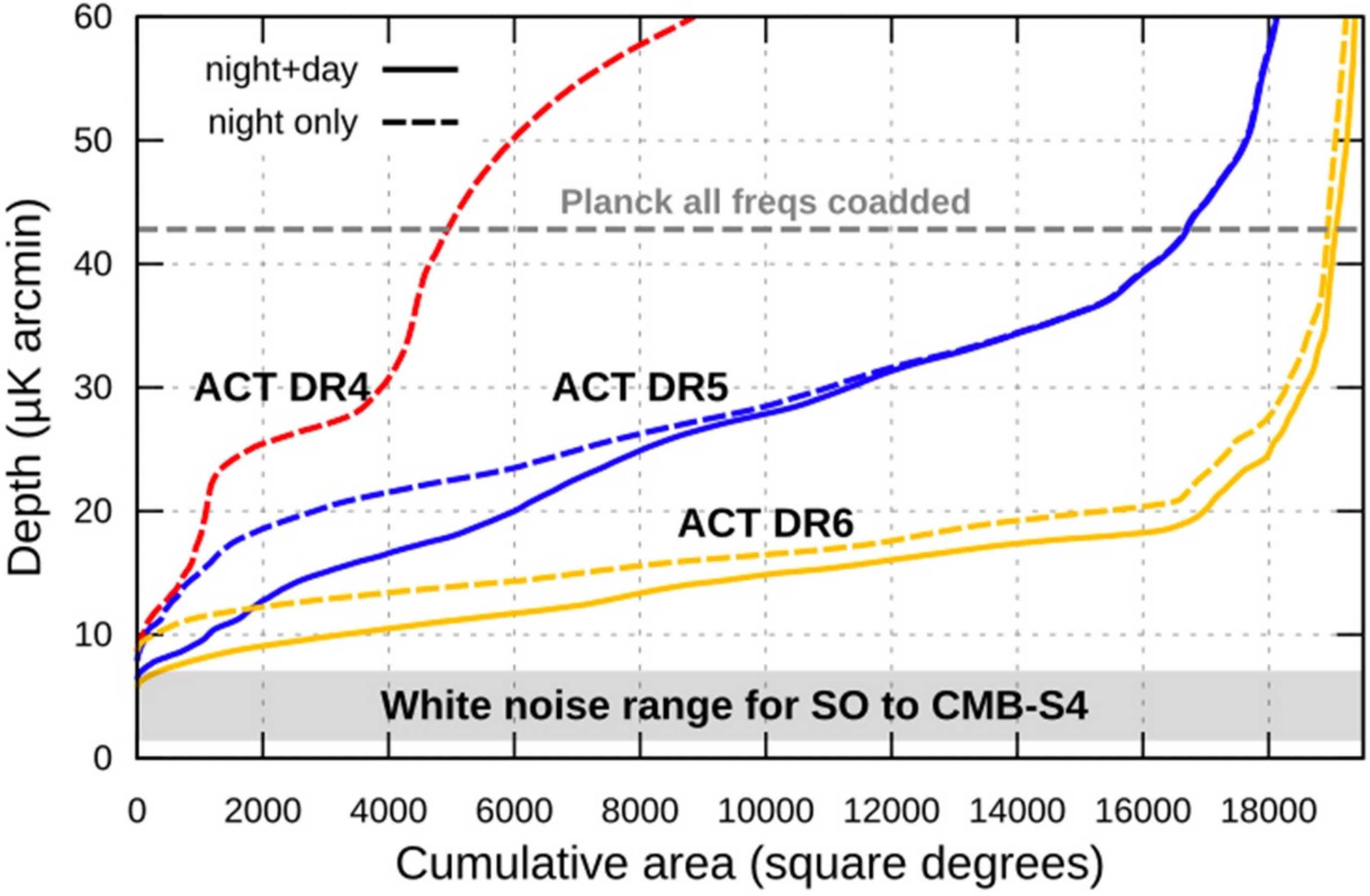
AdvACT DR6: map noise levels

Temperature depth [figures: S. Naess]



AdvACT DR6: map noise levels

Polarization depth

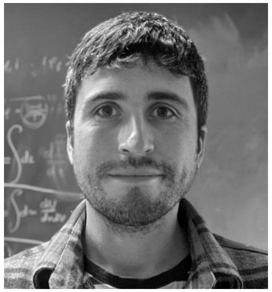


Main Science Cases

- CMB power spectra
- SZ science
- Lensing science
- Transients +…

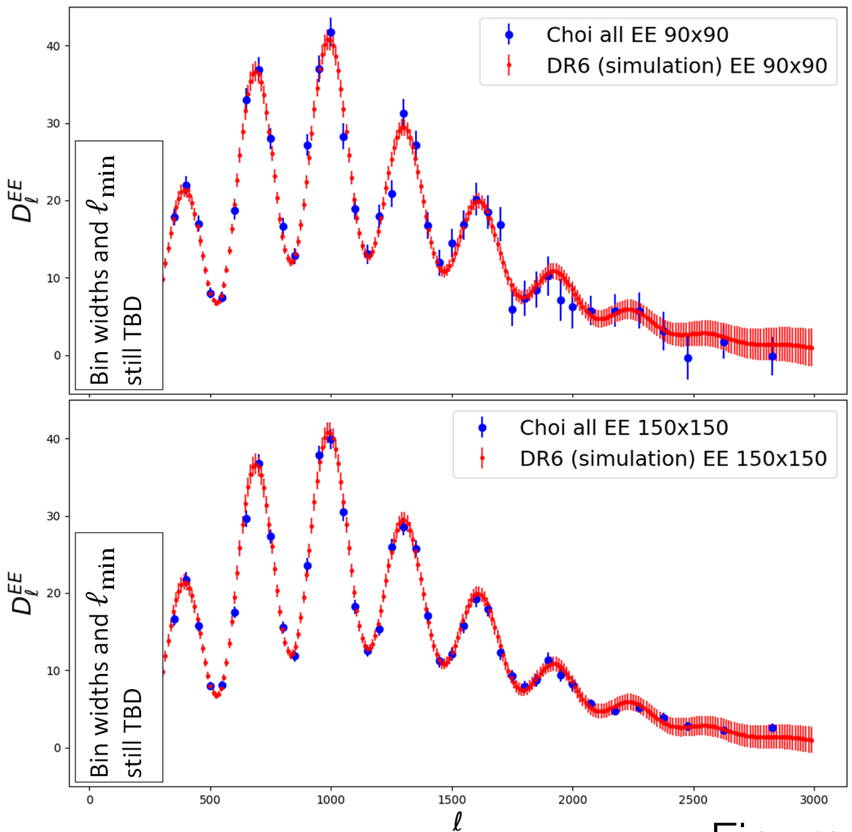
Thibaut Louis

Adrien La Posta



Boris Bolliet

Science Case 1: ACT DR6 Spectra + Parameters



	ACT DR4	ACT DR4 + WMAP	Planck	Planck + ACT DR6
$\sigma(H_0)$	1.5	1.1	0.5	0.4
$\sigma(n_s)$	0.015	0.006	0.004	0.003
$\sigma(N_{eff})$	0.4	0.3	0.2	0.1

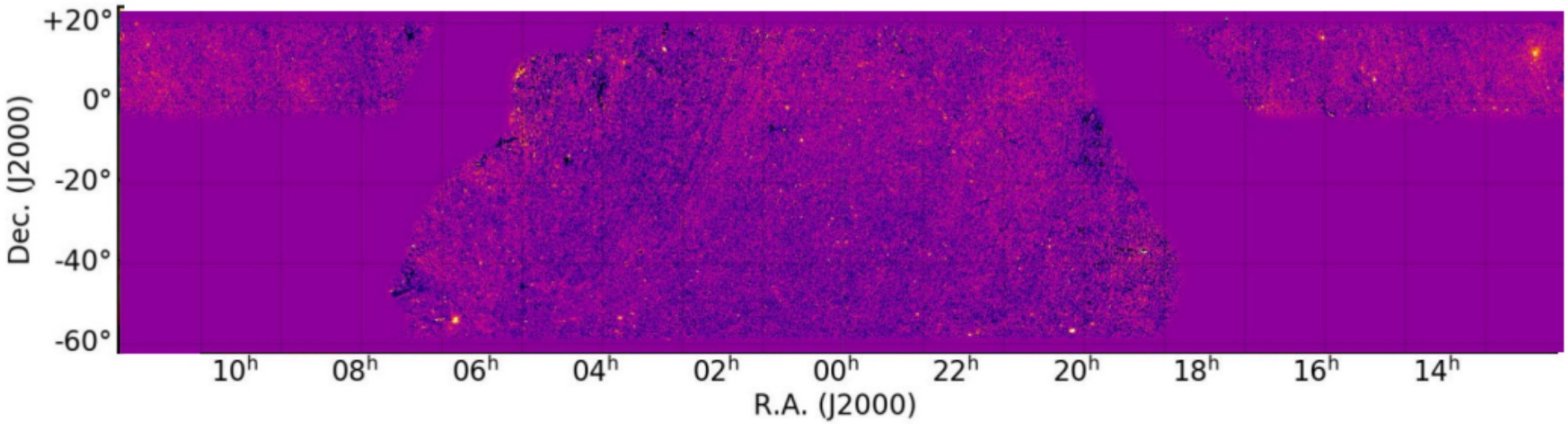
Forecast

Figure: Thibaut Louis

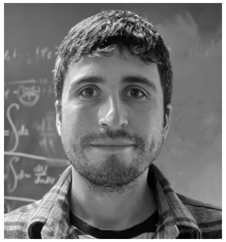
- High-precision polarized spectra will lead to significant improvements to N_{eff} and Hubble

Science Case 2: SZ Science

Preliminary new ACT y-map



- Wealth of information about both cosmology and baryonic physics from tSZ and kSZ
- See Boris Bolliet's talk!



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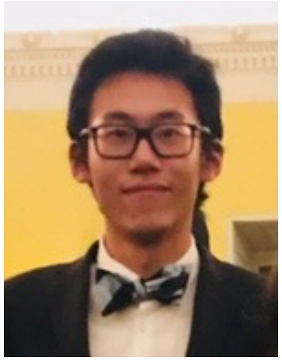
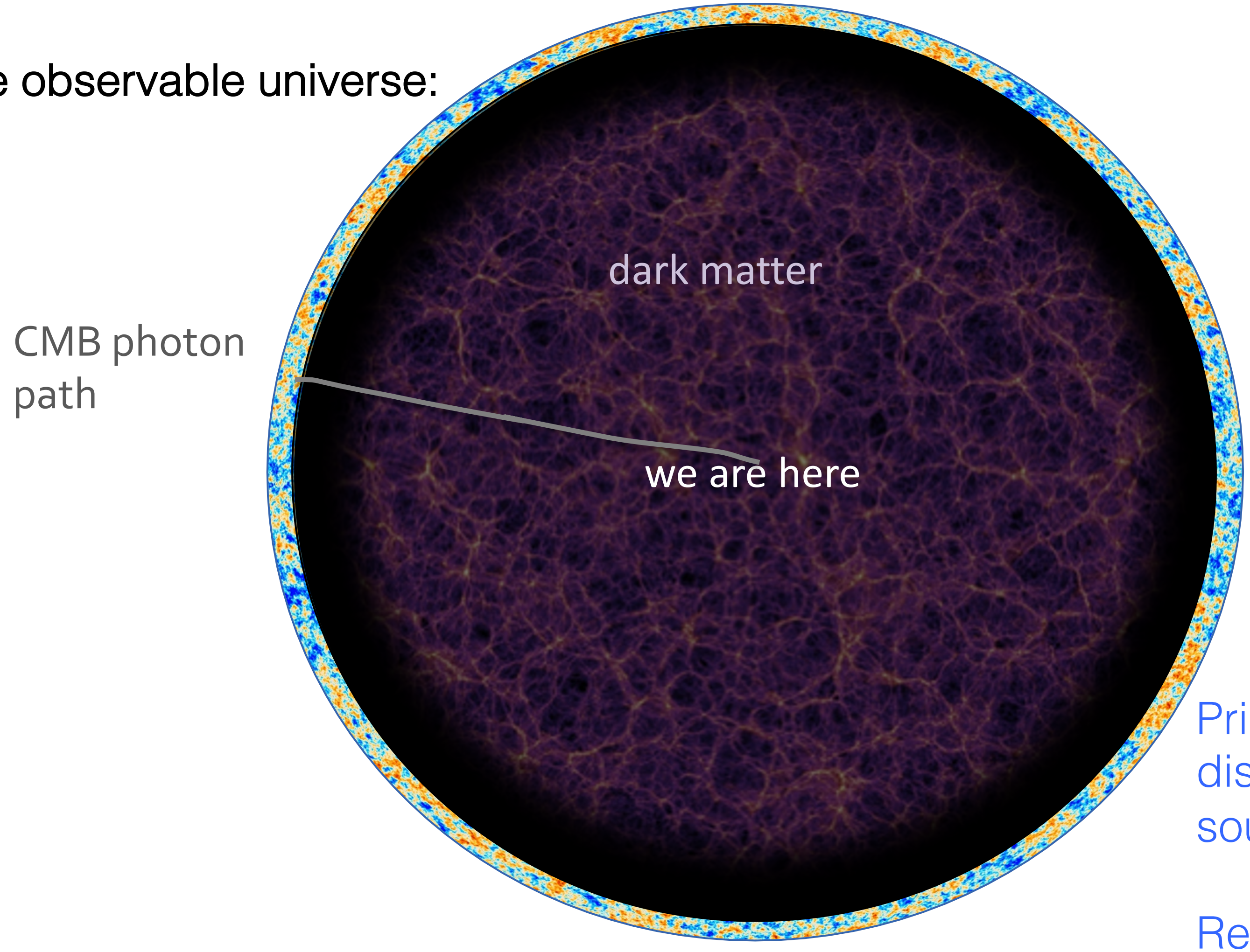


With Frank Qu,
+ Niall MacCrann, Mat Madhavacheril, Dongwon Han

[Qu, Sherwin++ in prep., MacCrann, Sherwin++ in prep. Madhavacheril, Qu, Sherwin in prep.]

CMB: A Unique Source for Gravitational Lensing

The observable universe:

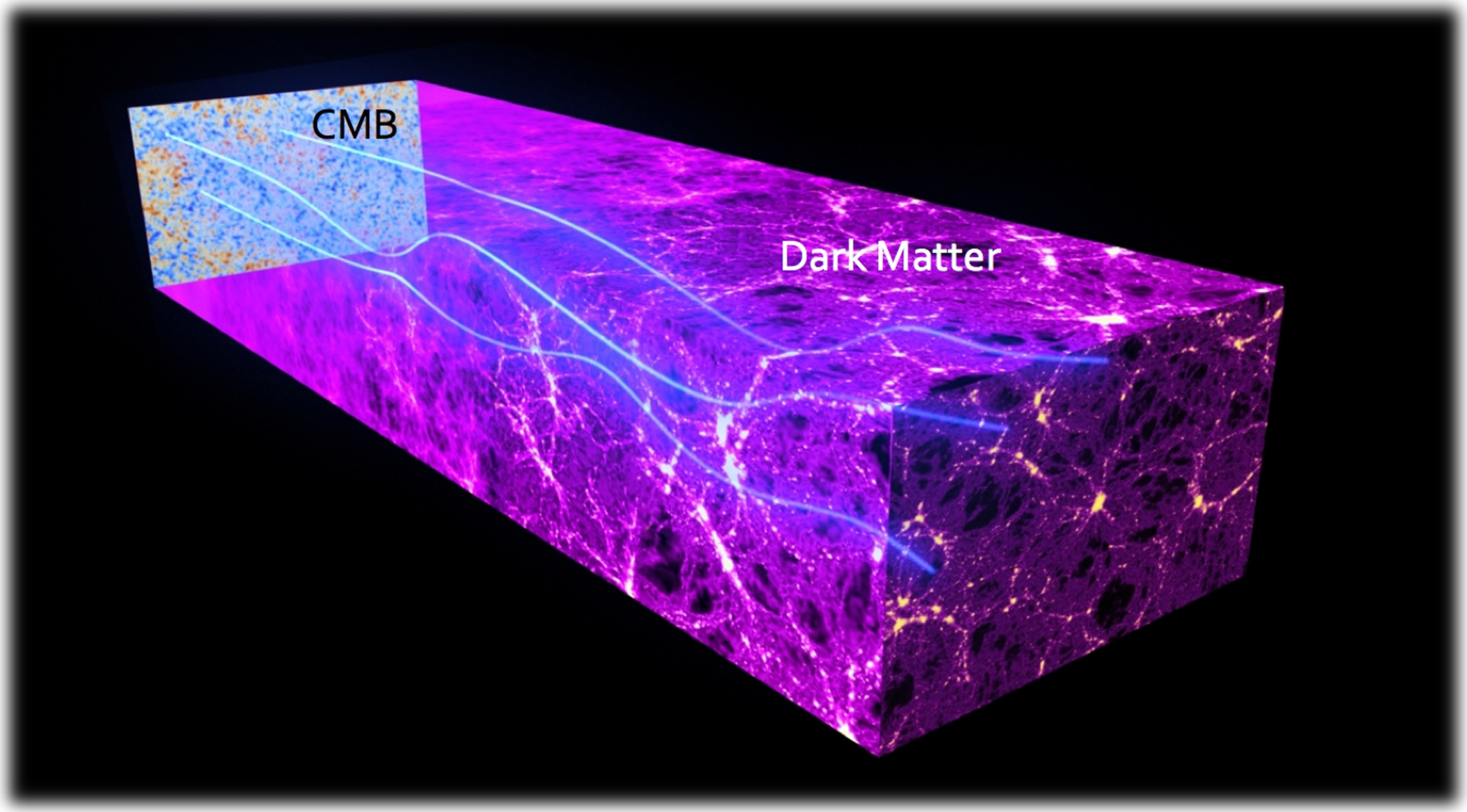


Primordial CMB (most distant and oldest source of radiation)

Redshift and CMB source well known, matter mildly nonlinear

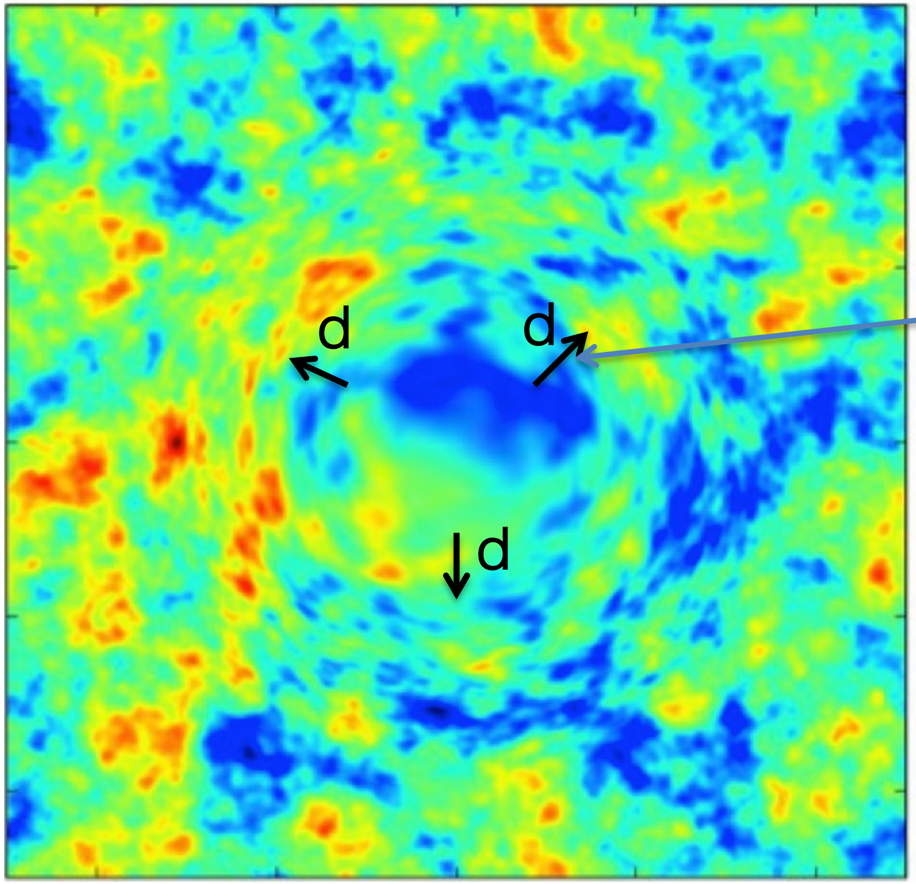
CMB Gravitational Lensing

- Distribution of dark matter deflects CMB light that passes through



CMB Lensing: An Approximate Picture

$$T^{lensed}(\hat{\mathbf{n}}) = T^0(\hat{\mathbf{n}} + \mathbf{d})$$



described by **lensing deflection field: d**

(very small: here exaggerated by x ~100, actually a few arcmins)

- Dark matter causes lensing magnification feature in the CMB

Aside: Lensing Reconstruction Details

- From translation invariance (of 2-point correlation function),

$$\langle T^0(\mathbf{l})T^{0*}(\mathbf{l}-\mathbf{L})\rangle = 0$$

T: temperature (Fourier mode)
l: wavenumber

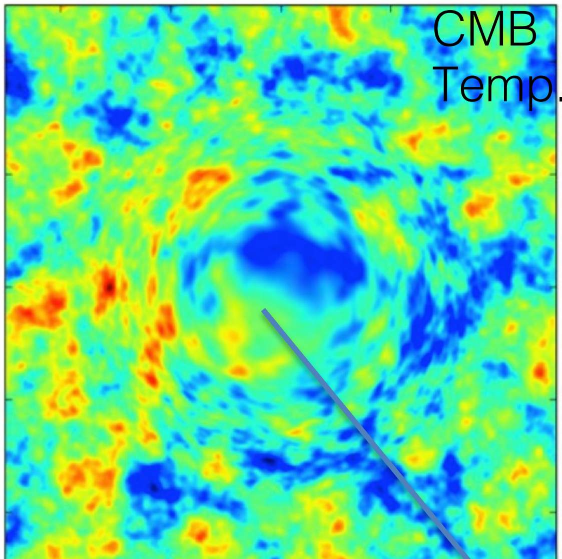
- **Lensing breaks translation invariance** => new correlations

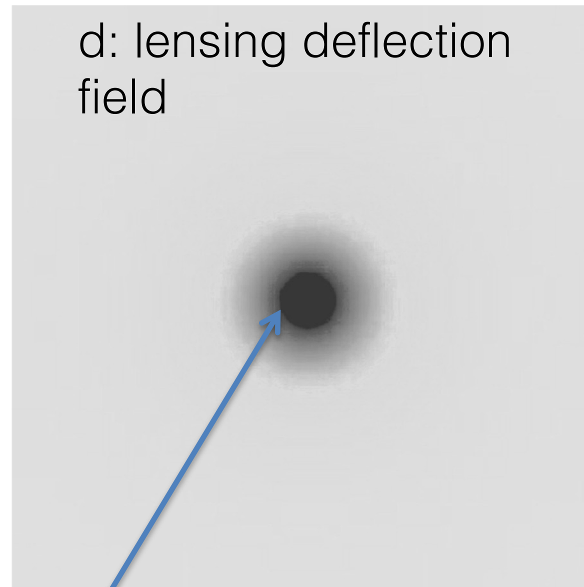
$$\langle T(\mathbf{l})T^{*}(\mathbf{l}-\mathbf{L})\rangle \sim d(\mathbf{L})$$

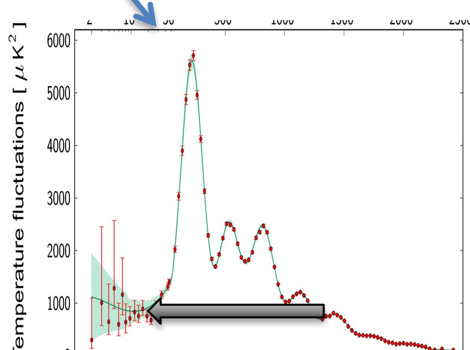
- So: measure lensing by looking for these new correlations in the CMB two-point function

$$\hat{d}(\mathbf{L}) \sim \int d^2\mathbf{l}\, T(\mathbf{l})T^{*}(\mathbf{l}-\mathbf{L})$$

CMB Lensing Measurement: An Approximate Picture







shift to larger angular scales

Infer lensing from stretching/shearing of the local CMB power spectrum

Key Observable: CMB Lensing Power Spectrum C_ℓ^{dd}

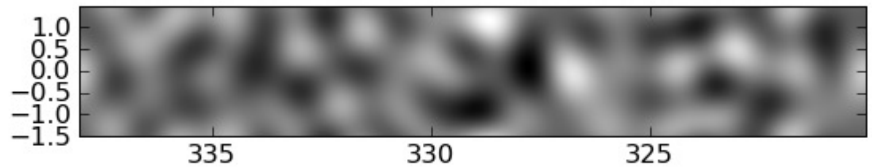
- Lensing probes projected matter

$$\kappa(\hat{\mathbf{n}}) \sim \nabla \cdot d(\hat{\mathbf{n}}) = \int_0^{r_{\rm CMB}} dr W(r) \delta(\hat{\mathbf{n}}, r)$$

- Lensing power spectrum: projection over matter power spectrum

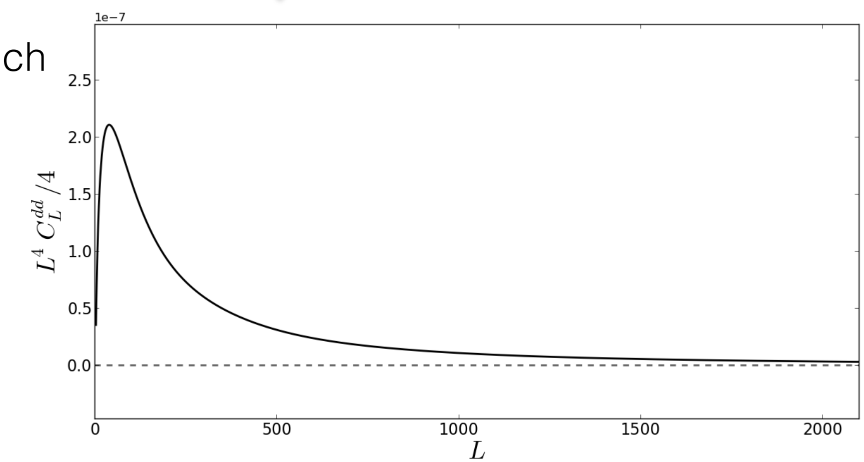
- Constrains parameter combination $\sim \sigma_8 \, \Omega_m^{0.25}$

[Das, Sherwin++ 2011, Sherwin++ 2011]



brightness ~ density

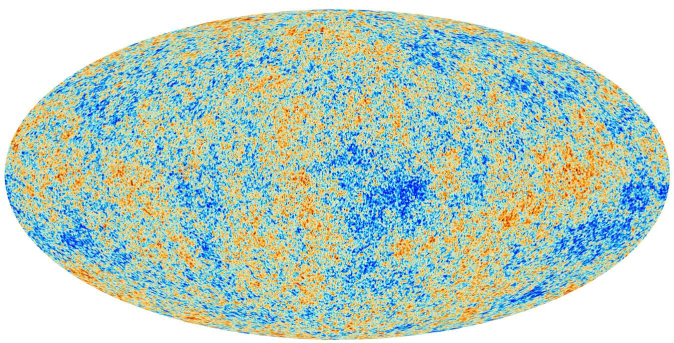
Y axis: "How much lensing …."



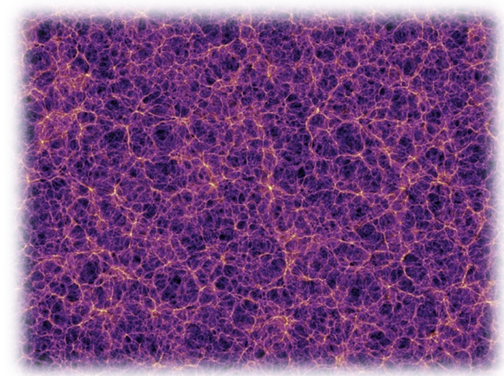
X axis: "for a lens of this angular scale?"

Motivation 1: lensing spectra as tests of structure growth

- Do observations match predictions of standard structure growth (dark matter, w=-1 dark energy, GR)? One test:



Fit standard cosmological model to CMB at early times, t=0.004 Gyr



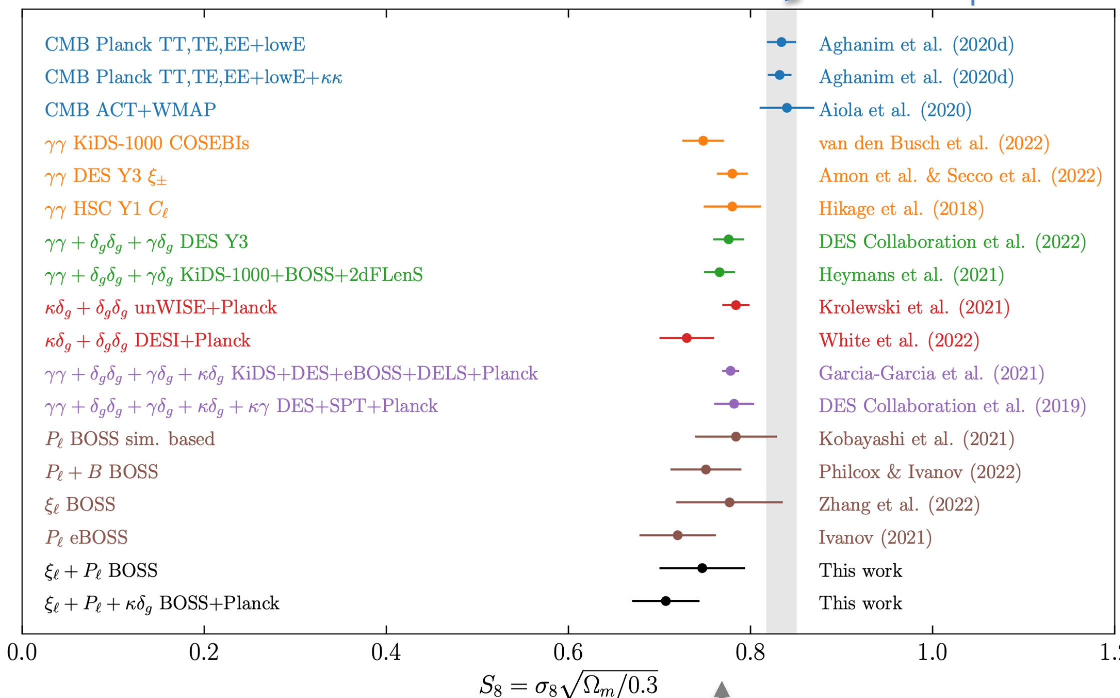
Predict amplitude of structure formed at late times (t>1 Gyr) + compare with observations

- Parametrize structure size today with σ_8 , RMS matter density fluctuation smoothed on scale of 8 Mpc/h

Motivation 1: S8 tension

- S8 ~ $\sigma_8\ \Omega_m^{0.5}$ at low-z appears low in several probes vs. prediction from early-time CMB

CMB extrapolation



[Chen++ 2022]

~σ_8

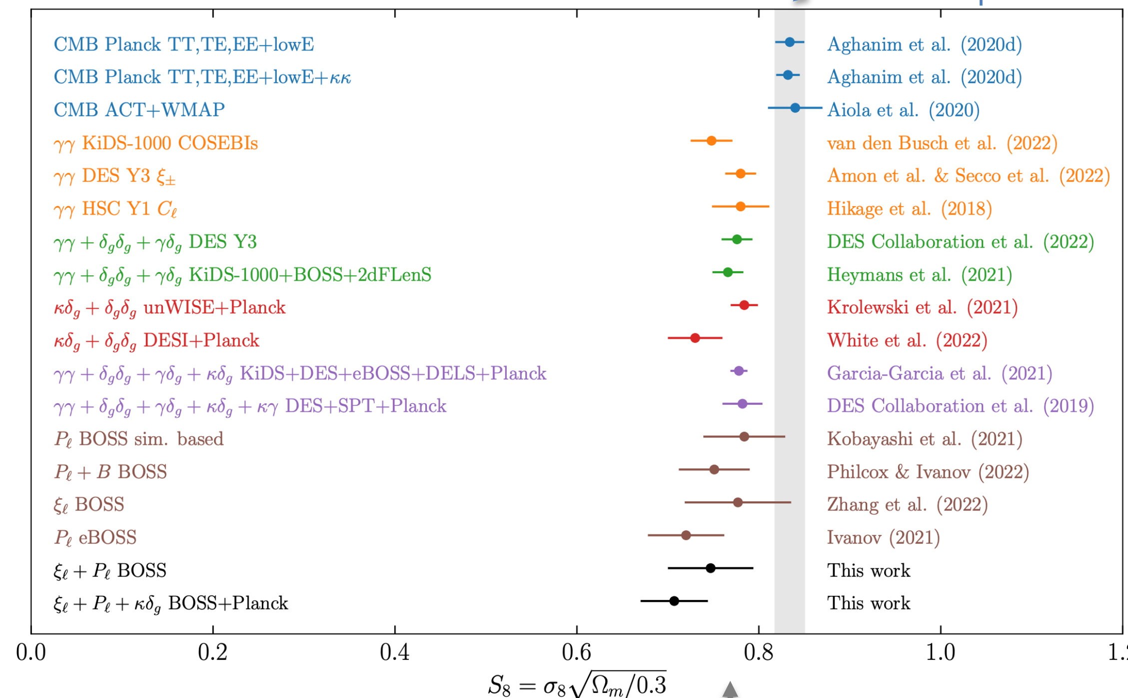
Direct low-z measurements (from lensing and/or galaxies)

Motivation 1: S8 tension

- $S8 \sim \sigma_8\ \Omega_m^{0.5}$ at low-z appears low in several probes vs. prediction from early-time CMB

- New measurements with different systematics crucial: Do we also find a low S8?

CMB extrapolation



[Chen++ 2022]

$\sim\sigma_8$

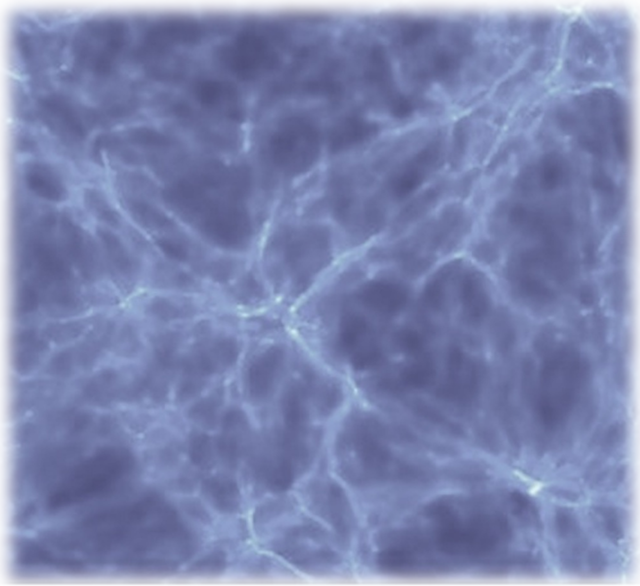
Direct low-z measurements (from lensing and/or galaxies)

Motivation 2: Measuring Neutrino Mass w. Lensing

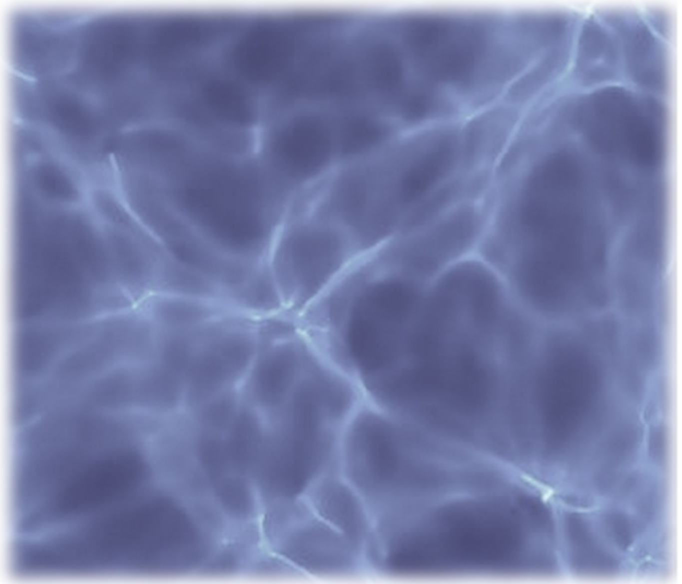
- Neutrino mass affects structure growth: the more massive neutrinos are, the more small-scale growth is suppressed.

Large-scale mass distribution:

Image: Viel++ 2013



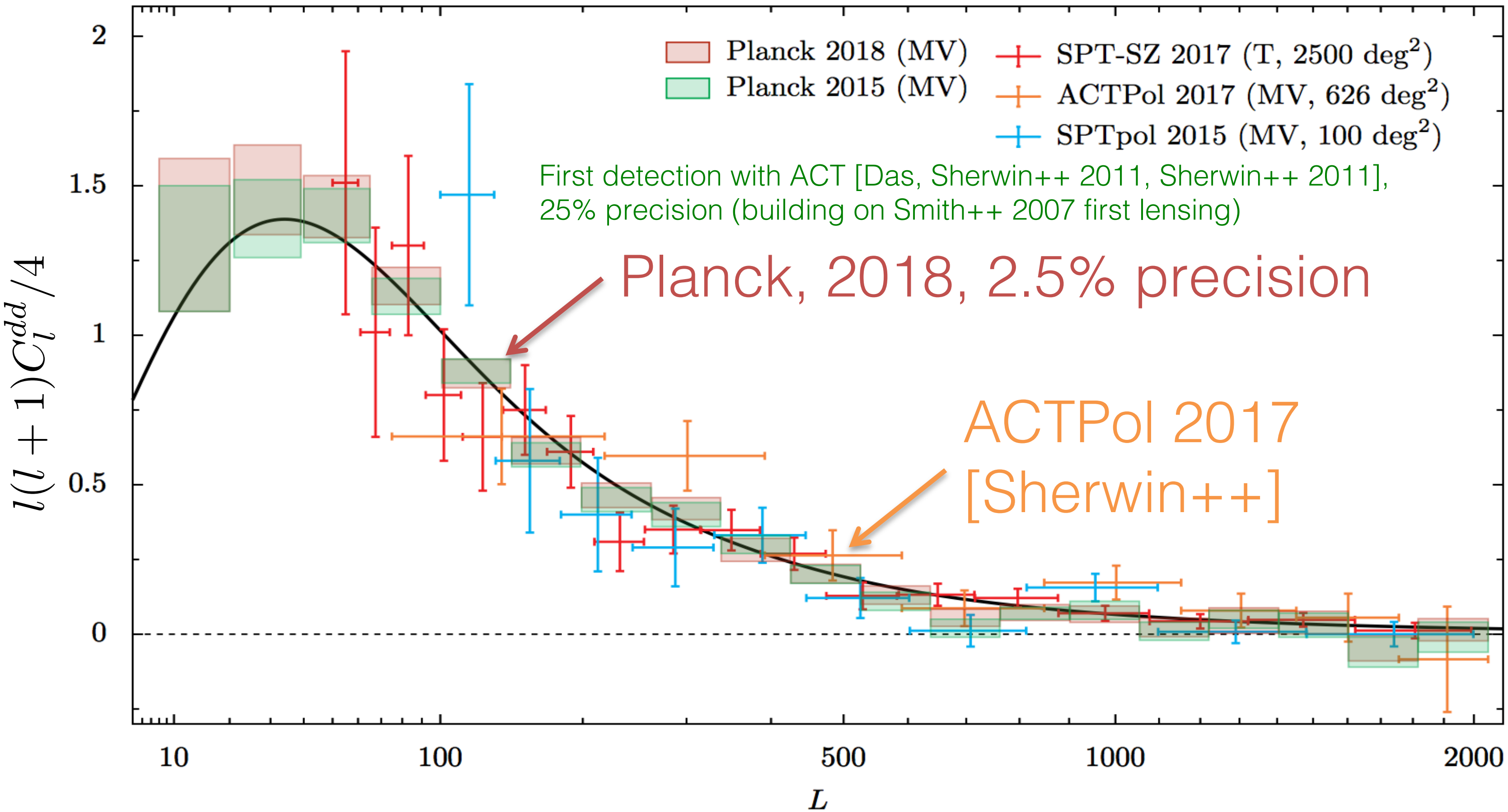
Neutrino Mass Negligible



Neutrino Mass Really Large (qualitative)

- Probes approaching 60meV lower limit. Measurement would be significant contribution to neutrino physics program.

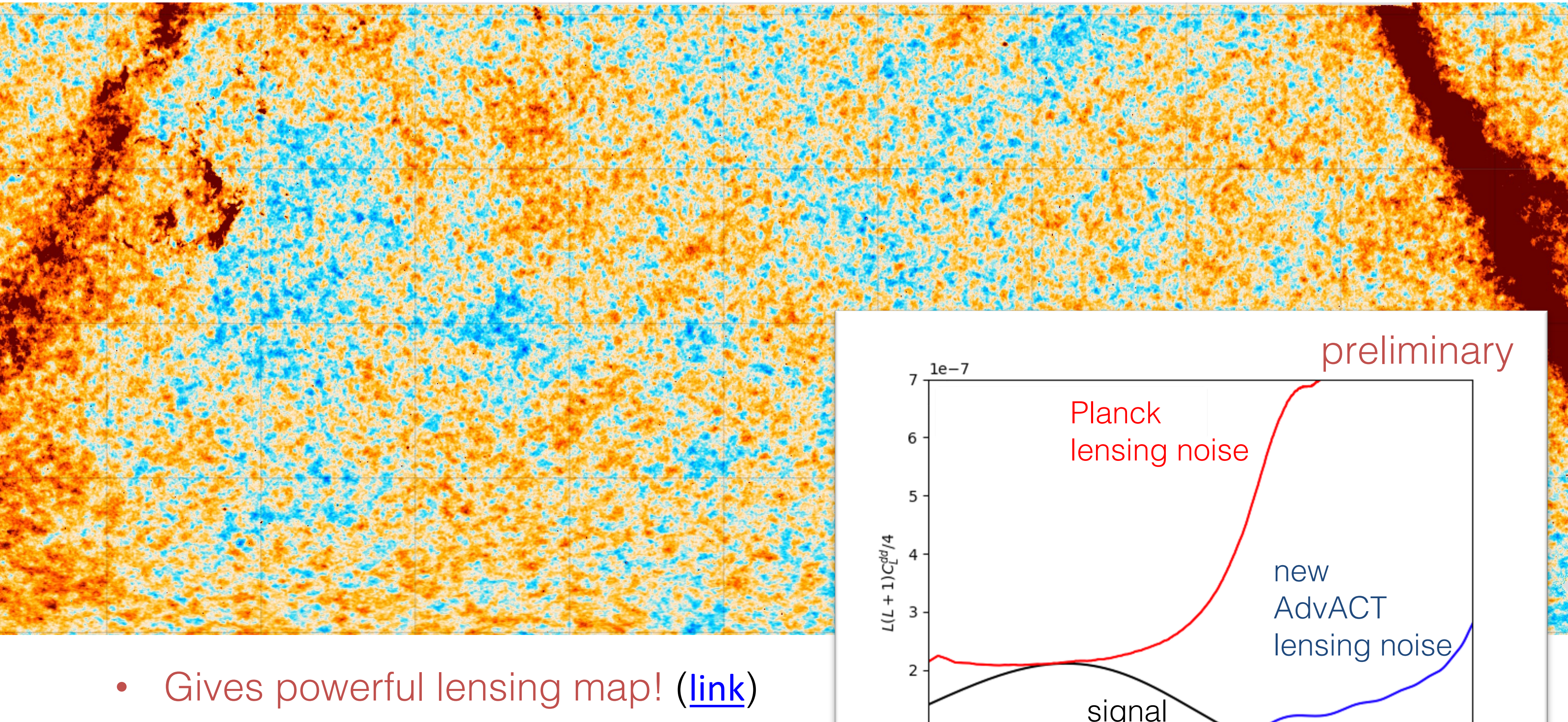
CMB Lensing Power Spectra: From First Measurements…to a Precise Probe



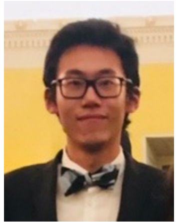
- Rapid progress – but only just beginning. New ground-based experiments such as AdvACT!

AdvACT: new, state of the art CMB and lensing maps!

AdvACT CMB map



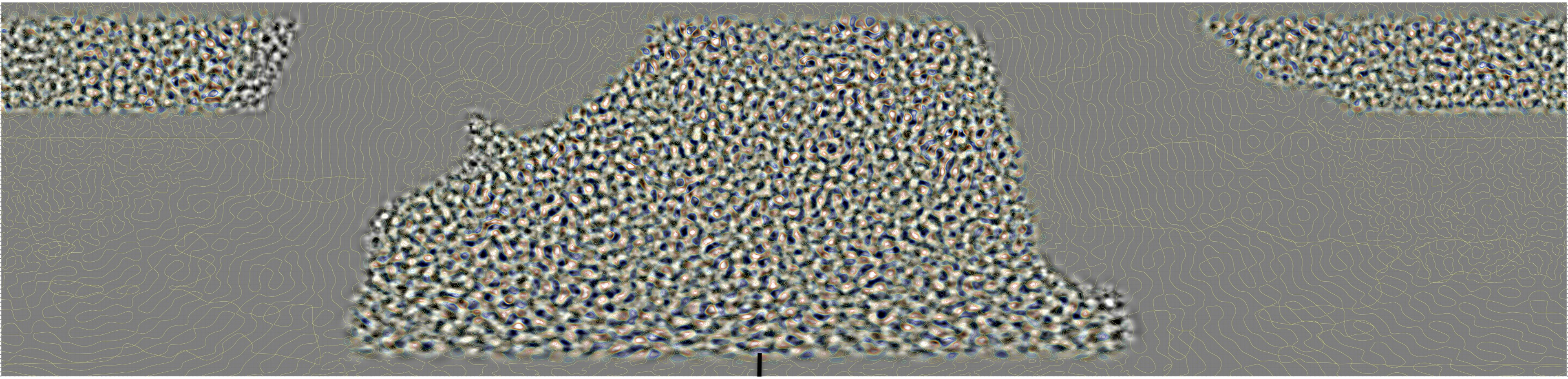
- Gives powerful lensing map! (link)

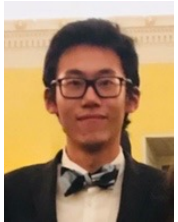


Frank Qu

AdvACT: new, state of the art CMB and lensing maps!

AdvACT CMB lensing map: 10000 deg^2 total





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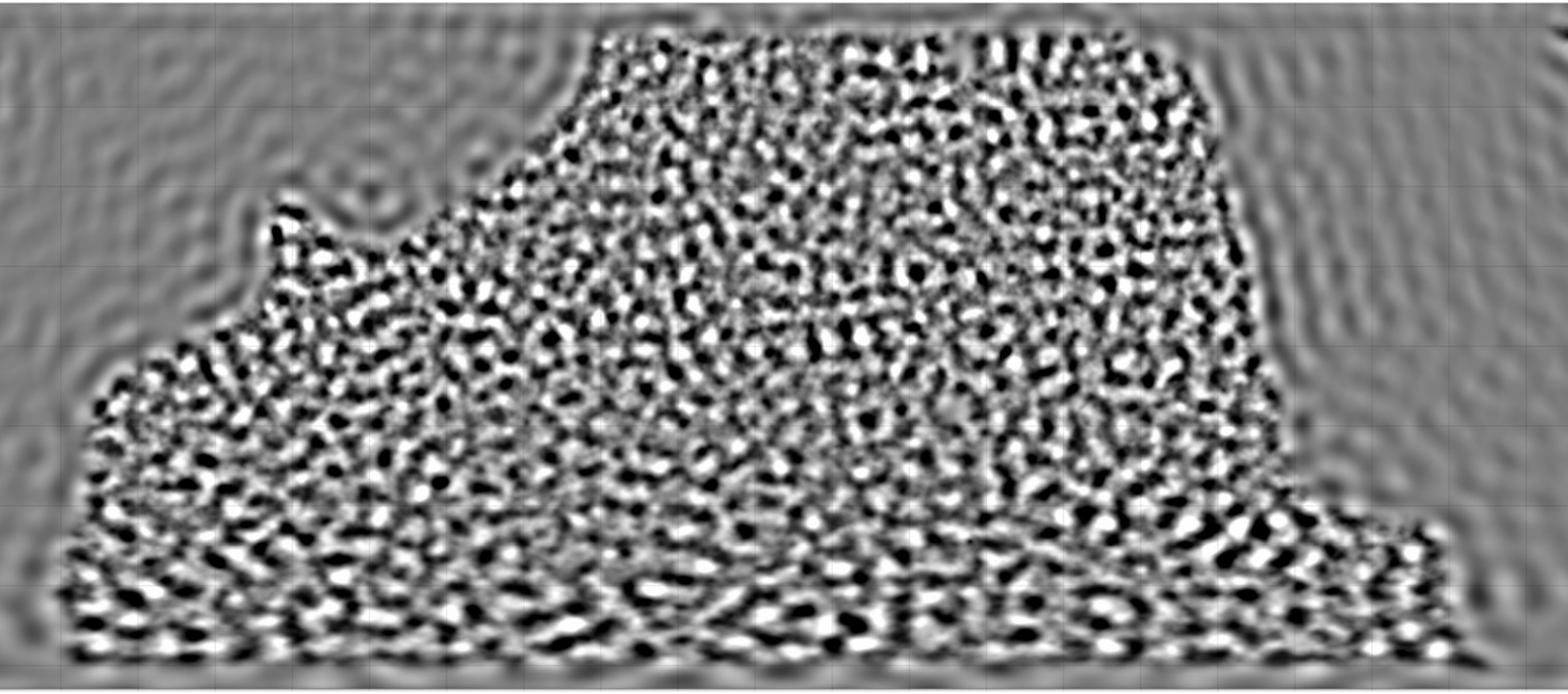

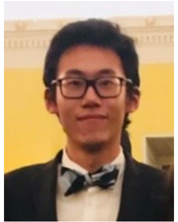

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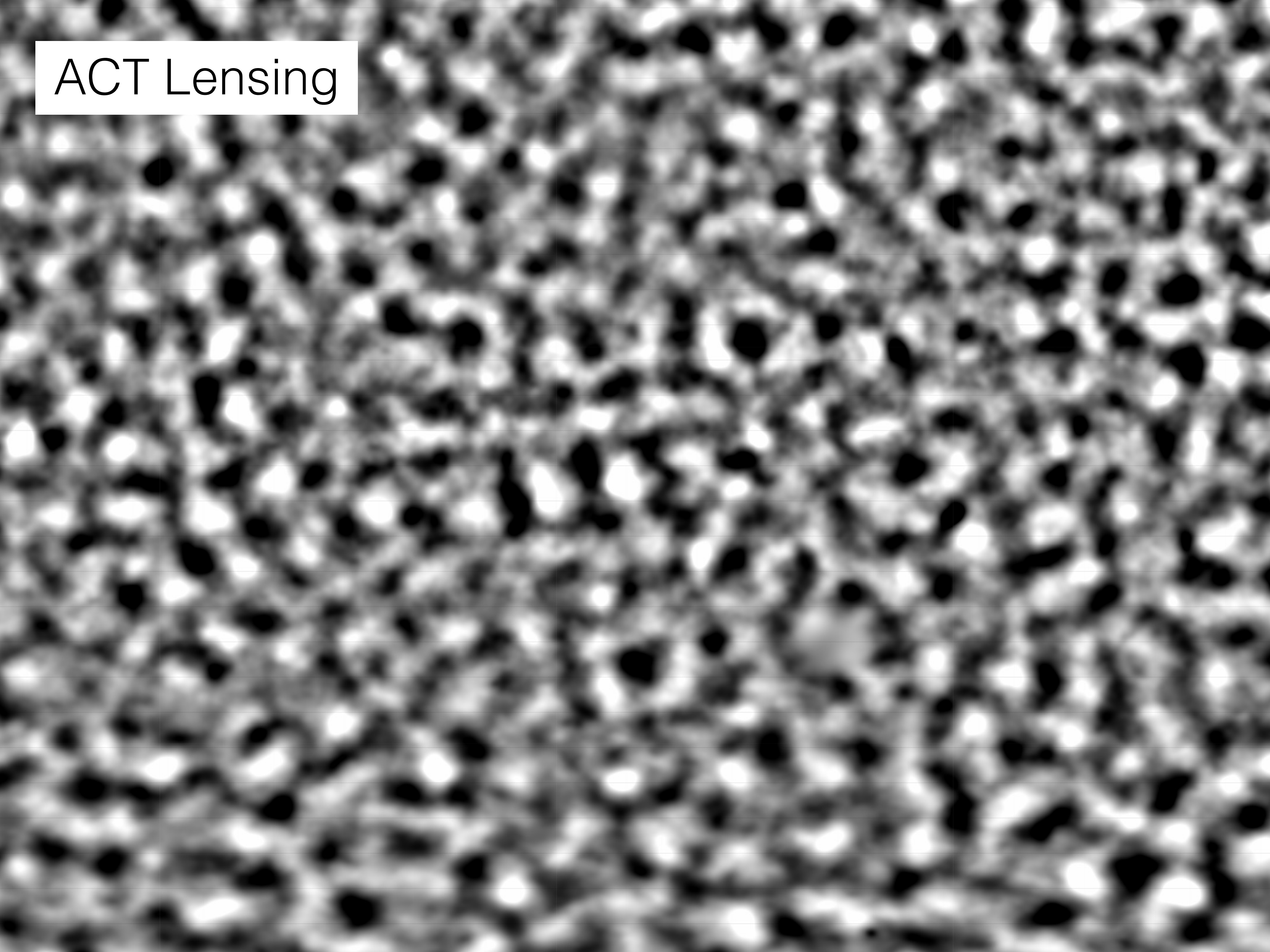
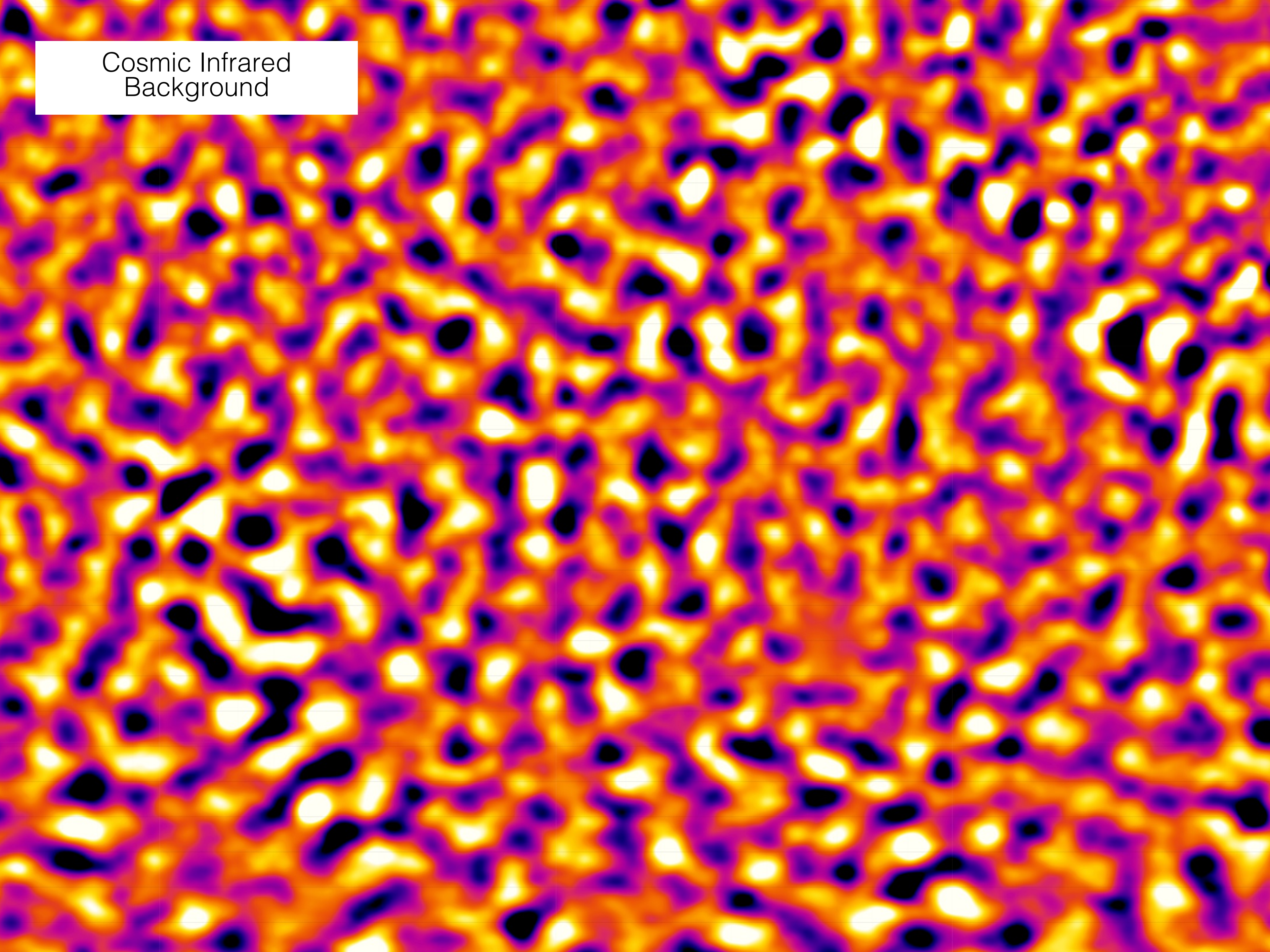
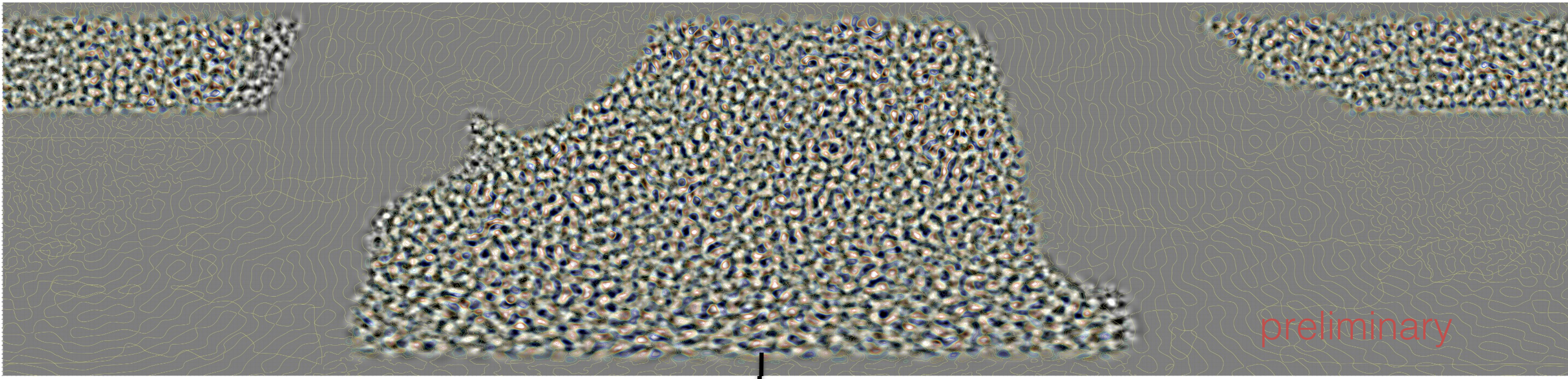
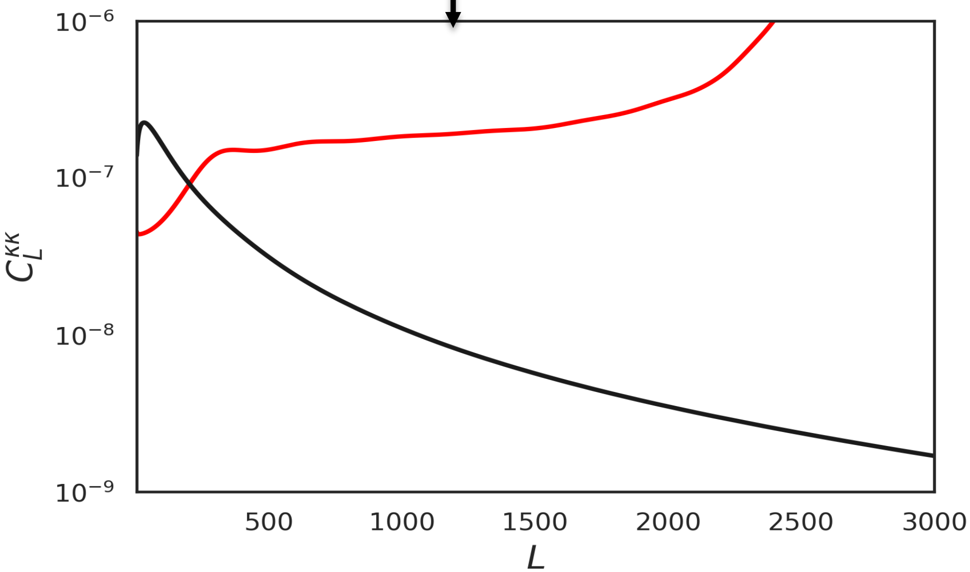

ACT Lensing


Cosmic Infrared
Background

Measuring the CMB Lensing Power Spectrum



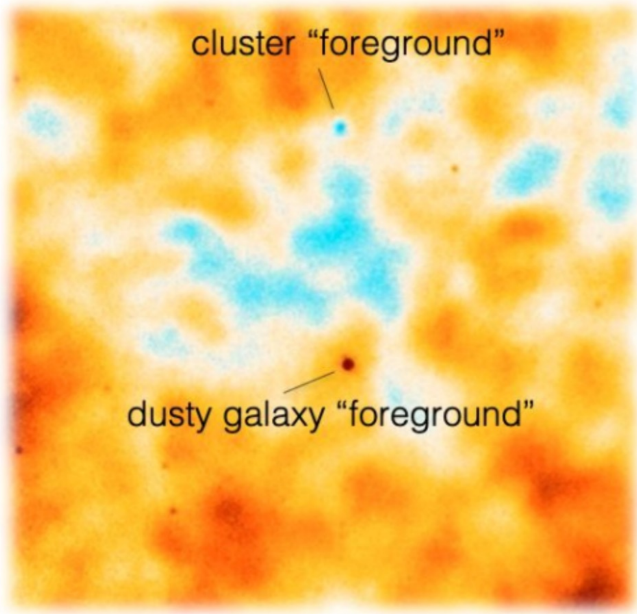
$$C_L^{dd} \sim \langle \hat{d}_L^* \hat{d}_L \rangle - \text{biases} \sim \langle TTTT \rangle - \langle TT \rangle \langle TT \rangle_{gauss} - \cdots$$



[Qu++ in prep.]

Key challenge: foreground mitigation

- Lensing power estimated via trispectrum, but foregrounds also contribute: biases! [N.B. our l_{max}=3000]



CMB map cutout (3°x3°)

- Foregrounds F include: CIB, SZ, radio sources…, correlated with lensing.

$$T(\hat{\mathbf{n}}) = T^{CMB}(\hat{\mathbf{n}}) + F(\hat{\mathbf{n}})$$

- How to mitigate?

$$\hat{C}_L^{dd} \sim \langle Q[TT]Q[TT]\rangle$$

$$\sim C_L^{dd} + \langle Q[FF]Q[FF]\rangle + 2\langle Q[FF]\ d\rangle + \cdots$$

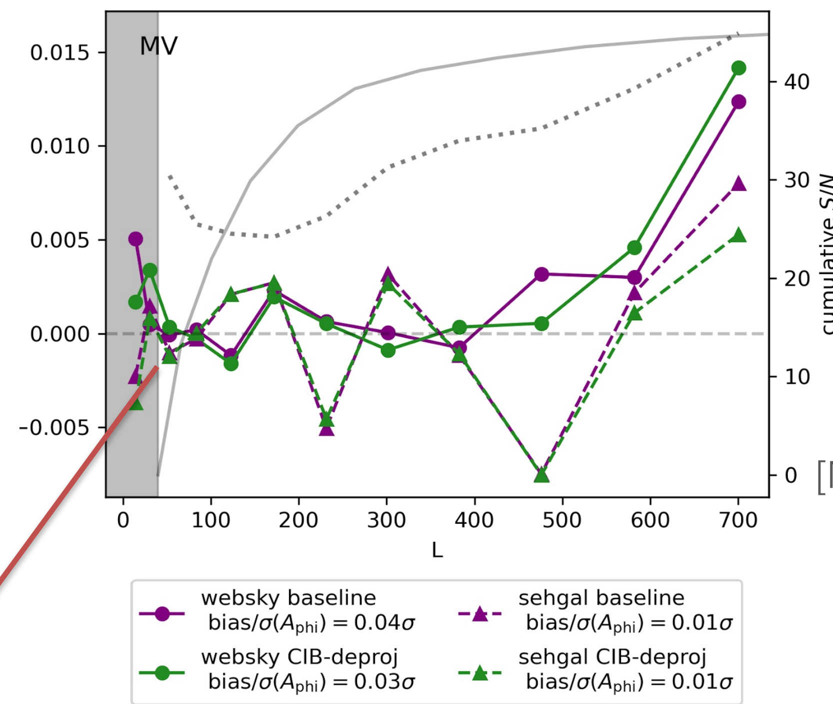
[MacCrann, Sherwin++ in prep.]

Mitigation I: Simulate Bias Estimates

- AdvACT lensing: two primary mitigation methods
  - Geometric method: profile-bias-hardening
  - Multifrequency: CIB deprojection + above

[Namikawa++2011, Osborne++2012, Sailor++2022; Darwish, Madhavacheril, Sherwin++2021, Darwish, Sherwin++2022…]

fractional bias to C_L^{dd}



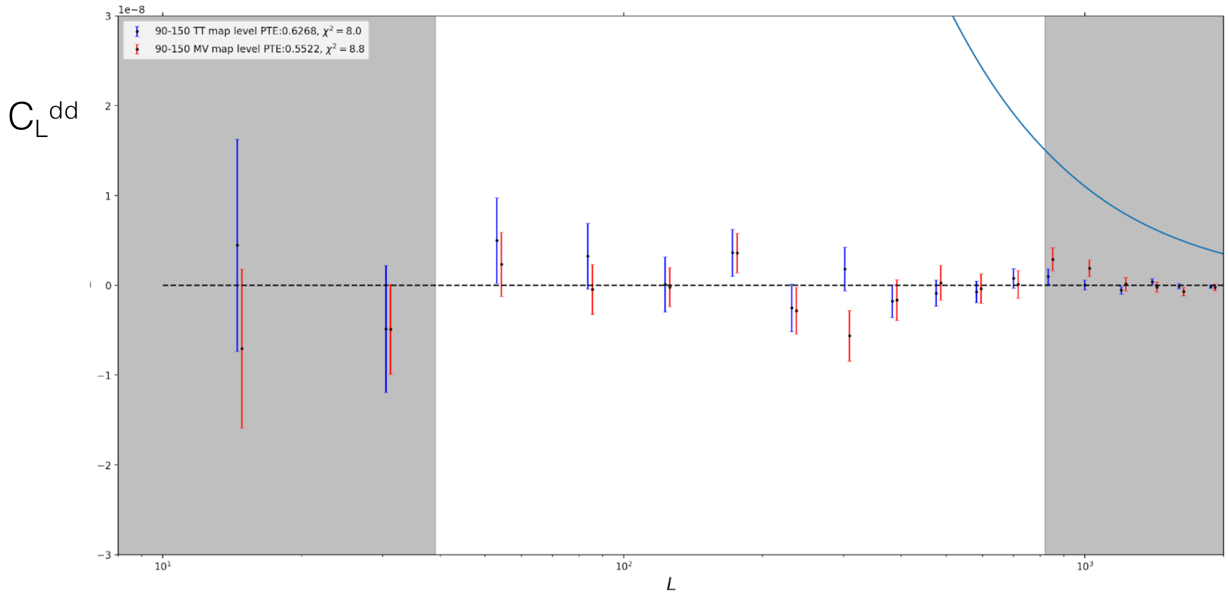
[MacCrann, Sherwin++ in prep.]

→ Simulated biases negligible in both methods (2 different sims)

Mitigation II: Tests in Data

- Cross-check lensing spectrum between methods
- Check consistency of lensing in 90 and 150 GHz maps

90 GHz – 150 GHz null test in Temperature and Temp.+Pol.



[MacCrann, Sherwin++ in prep.]

→ Consistent power spectra for all mitigation methods and frequencies

Null and systematic test suite

High precision so need to be careful. Null tests and systematics checks needed!

Main worries: beams, noise sim issues, foregrounds.

Array difference

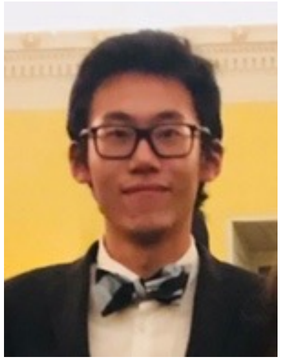
Temperature vs polarization

Frequency difference

Curl deflection

Sky region difference

Noise only map

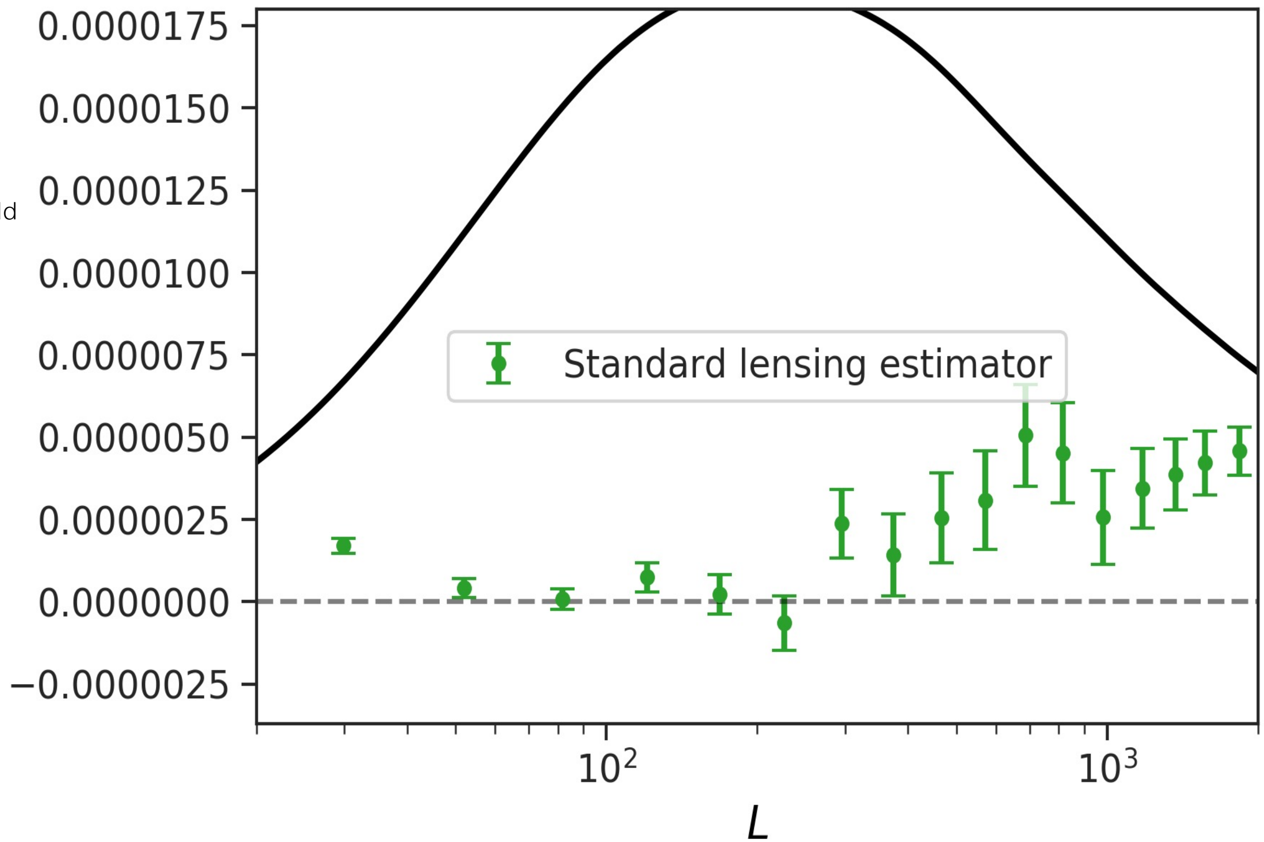


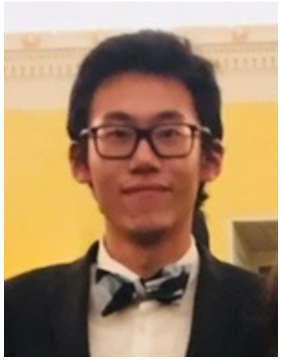
Frank Qu

… (200+ tests)

Null test problems…

- Problem: getting biased results from even basic null with data noise, despite advanced methods??





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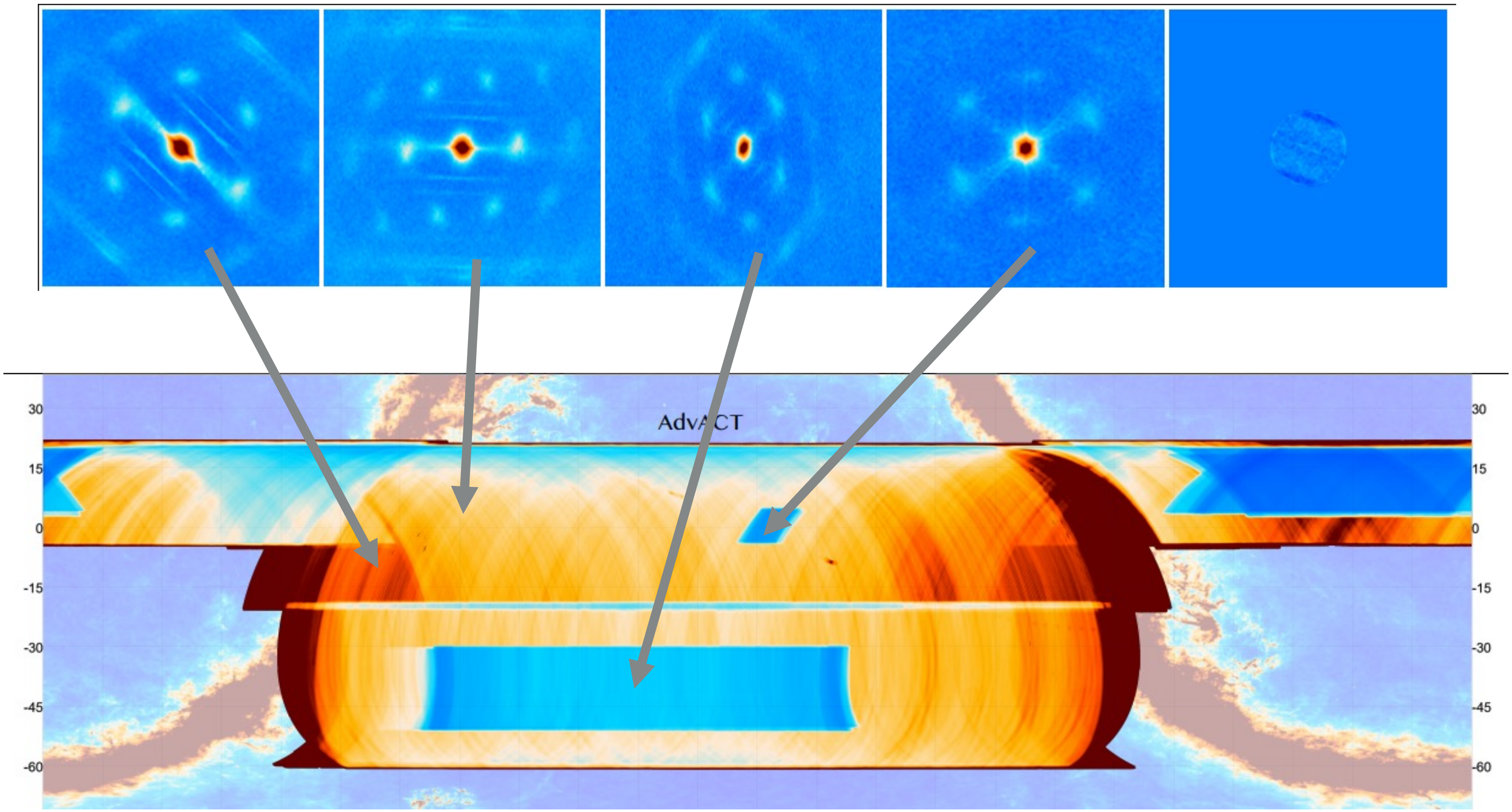
[Qu, Sherwin++ in prep.]

Null test problems…

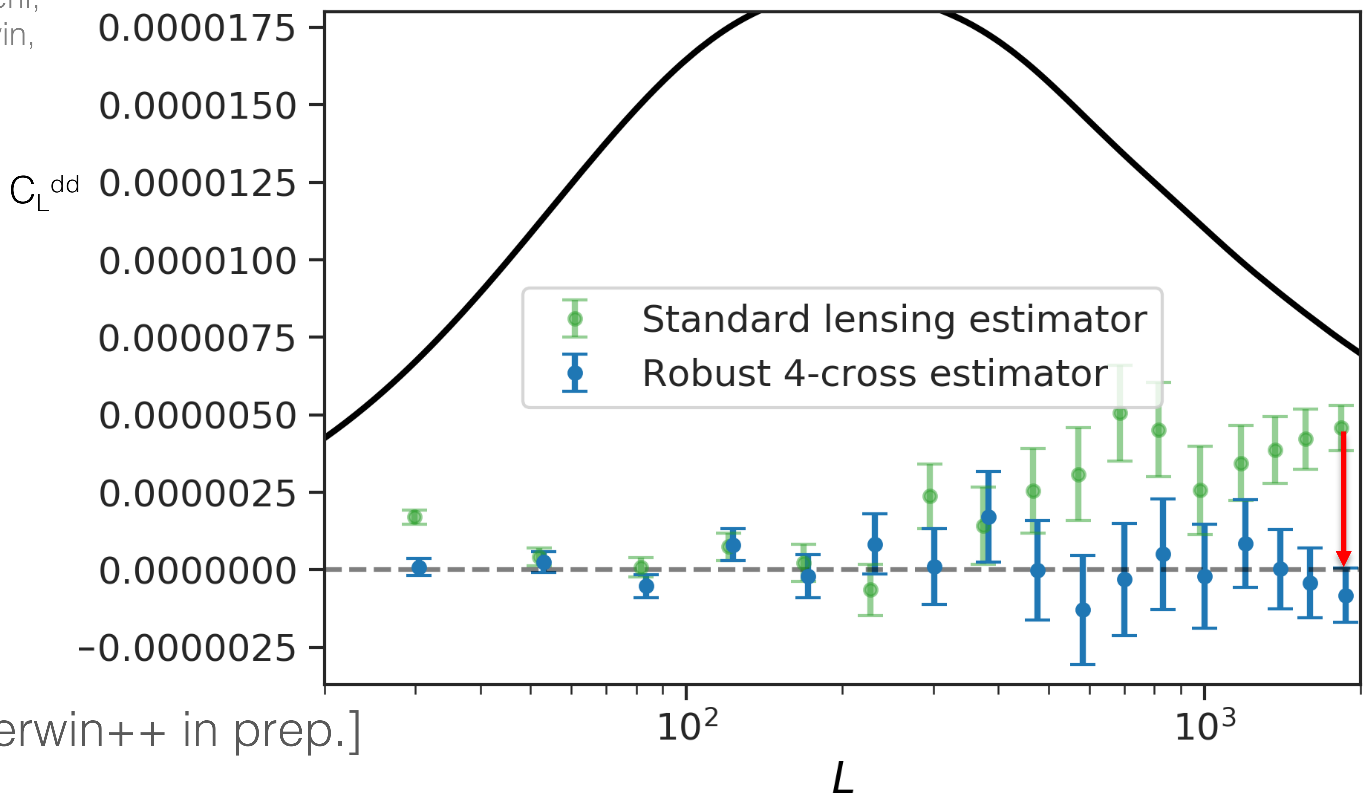
- Ground-based noise is very complicated to model



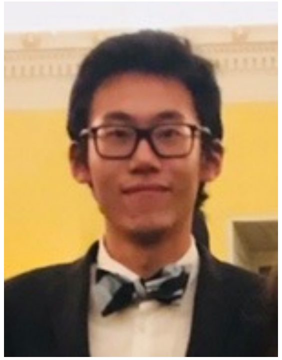
and solutions

- Solution: new cross-estimator method. Divide data into independent splits, use only different crosses (combinatorics non-trivial). $C_L^{dd} \sim \langle T_1 T_2 T_3 T_4 \rangle$

[Madhavacheril, Smith, Sherwin, Naess 20]



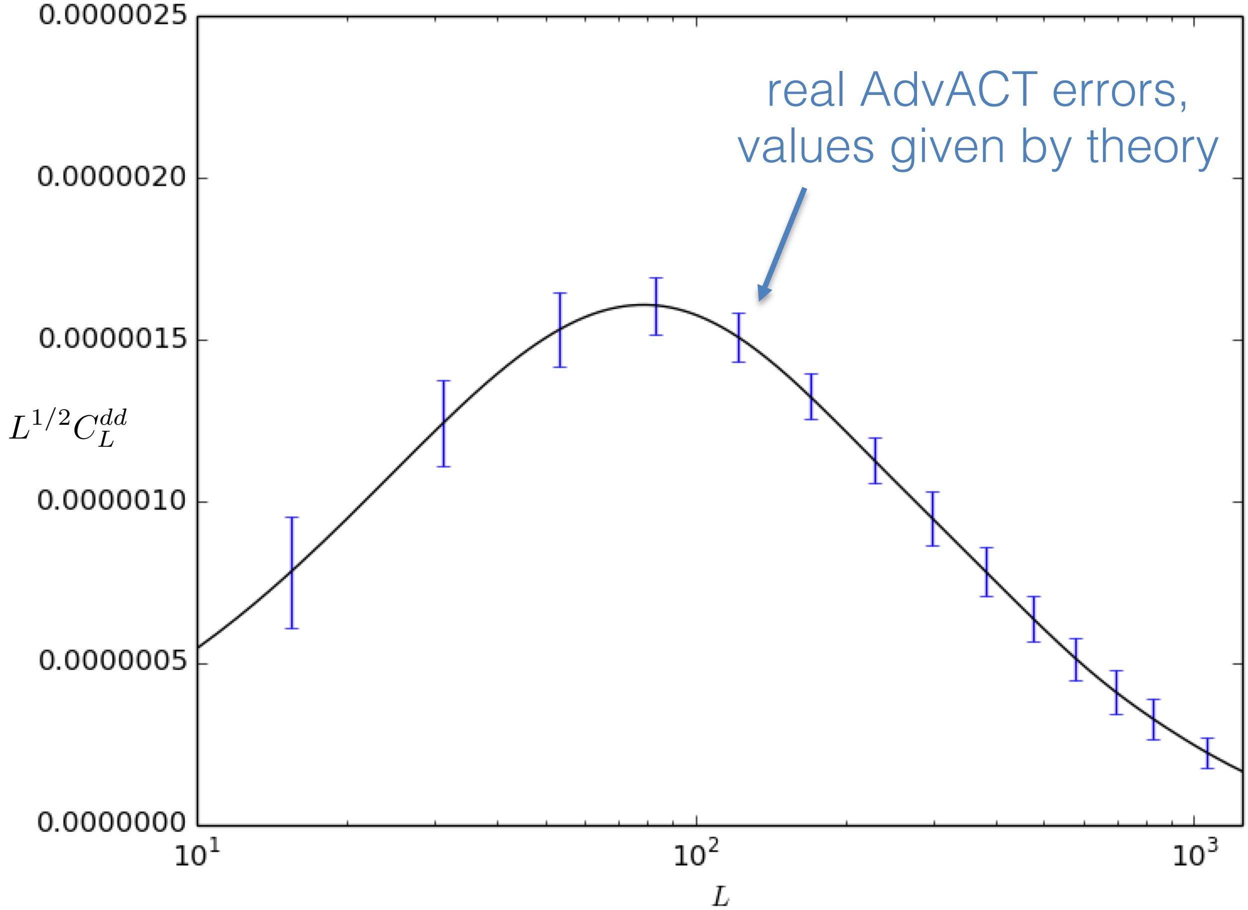
[Qu, Sherwin++ in prep.]



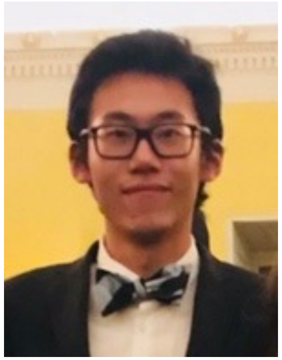
Frank Qu

- Suite of 200+ null tests now (finally) all looking good!

New AdvACT lensing power spectrum errors



Frank
Qu



+ Mat Madhavacheril, Niall MacCrann

preliminary

- SNR ~42-44 (state of the art)

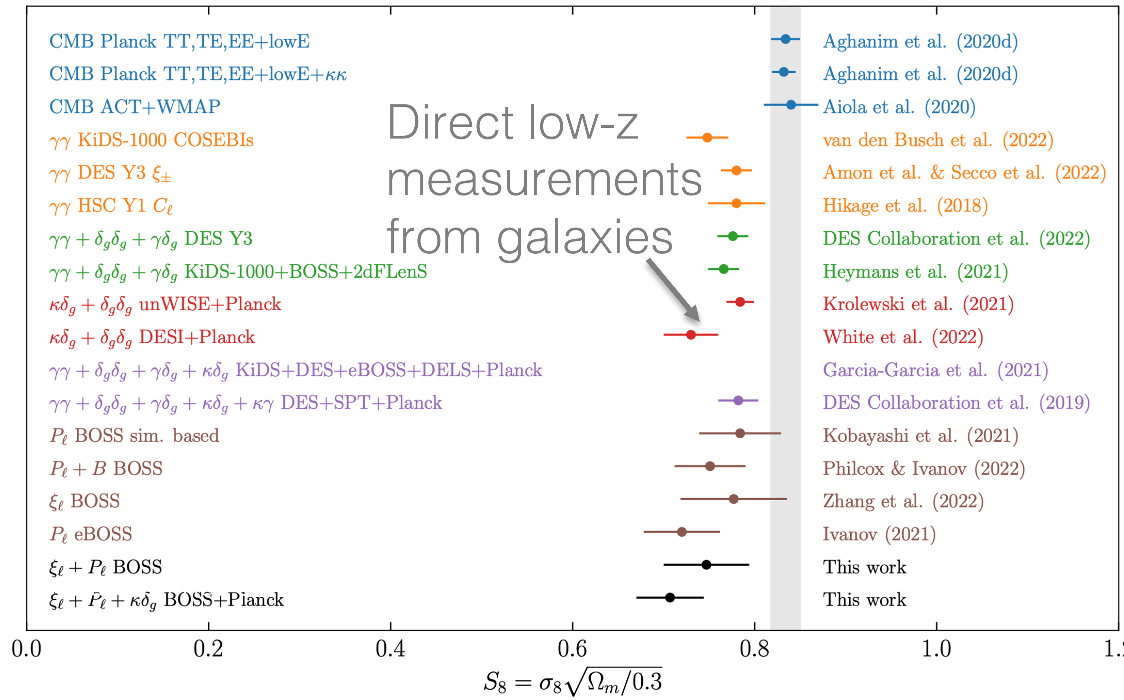
[Qu, Sherwin++ in prep.]

Exciting applications: test S_8 tension, neutrino mass…

- Constraints: $\sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.25}$ to ~
  ACT+BAO σ_8 to ~

CMB extrapolation

[Chen++ 2022]



Our error bar size

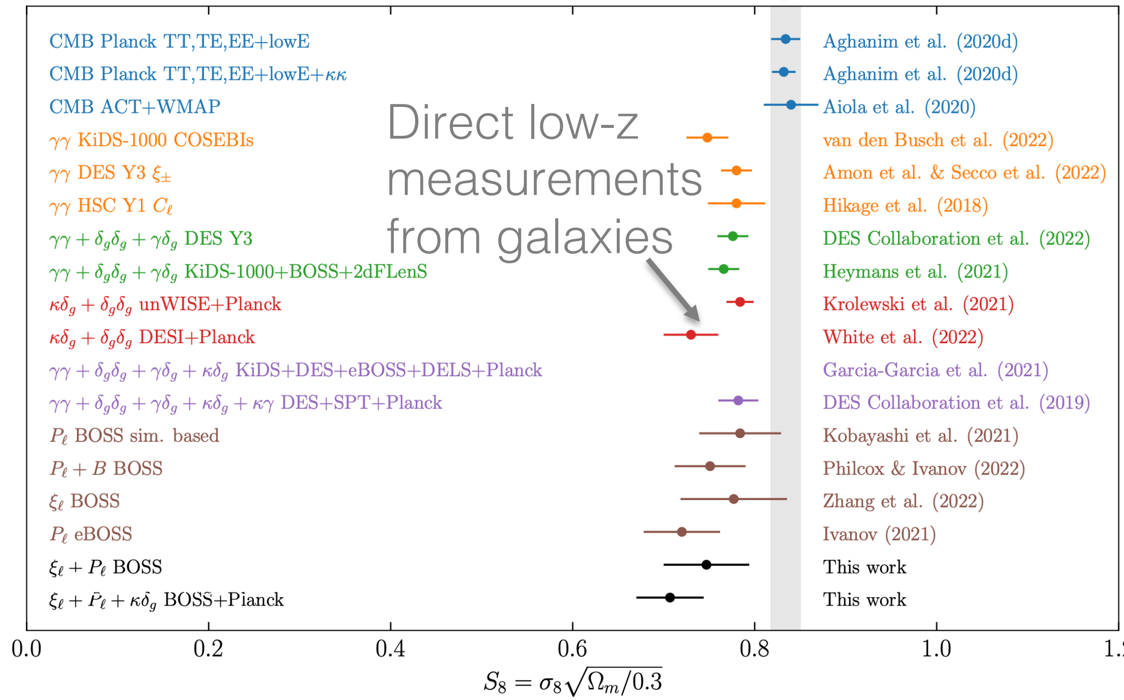
- Further insight into σ_8 tension very soon with new ACT results!

Exciting applications: test S_8 tension, neutrino mass…

- Constraints: $\sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.25}$ to ~
  ACT+BAO σ_8 to ~

CMB extrapolation

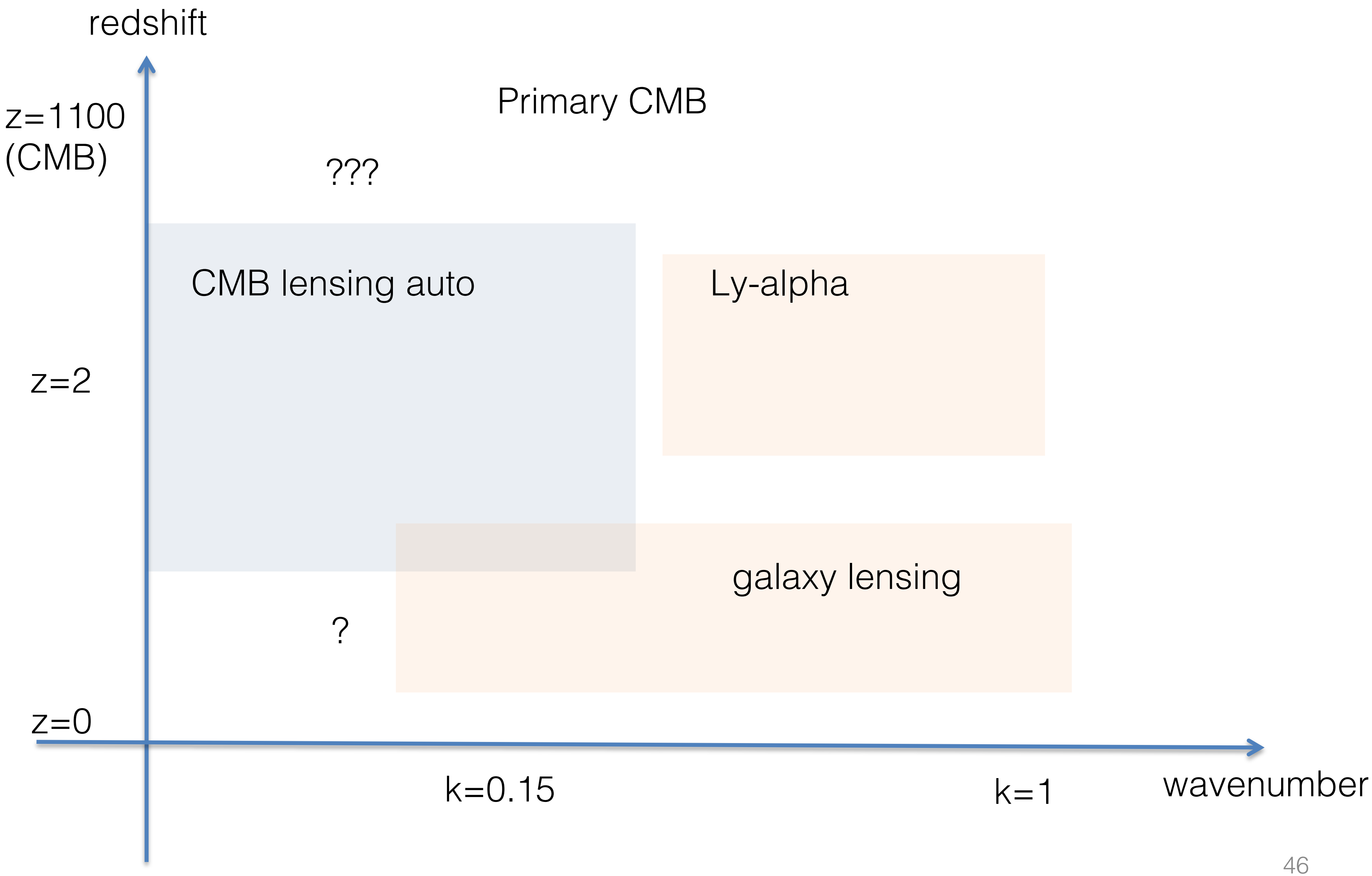
[Chen++ 2022]



Our error bar size

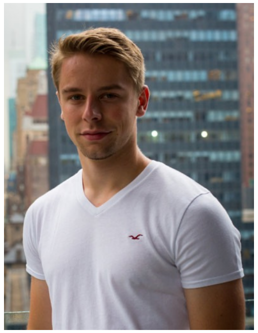
- And: new, tightest (?) constraints on neutrino mass of 70 meV (with BOSS BAO) or 40 meV (with DESI BAO.) C.f. minimum 60 meV

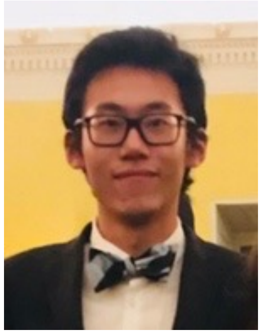
Probing structure growth vs. redshift and scale



Outline

- ACT DR6 Status and Overview
- Progress on new CMB lensing spectra from AdvACT DR6 and implications for structure growth
- Tracking structure growth across redshifts with new cross-correlations and new methods

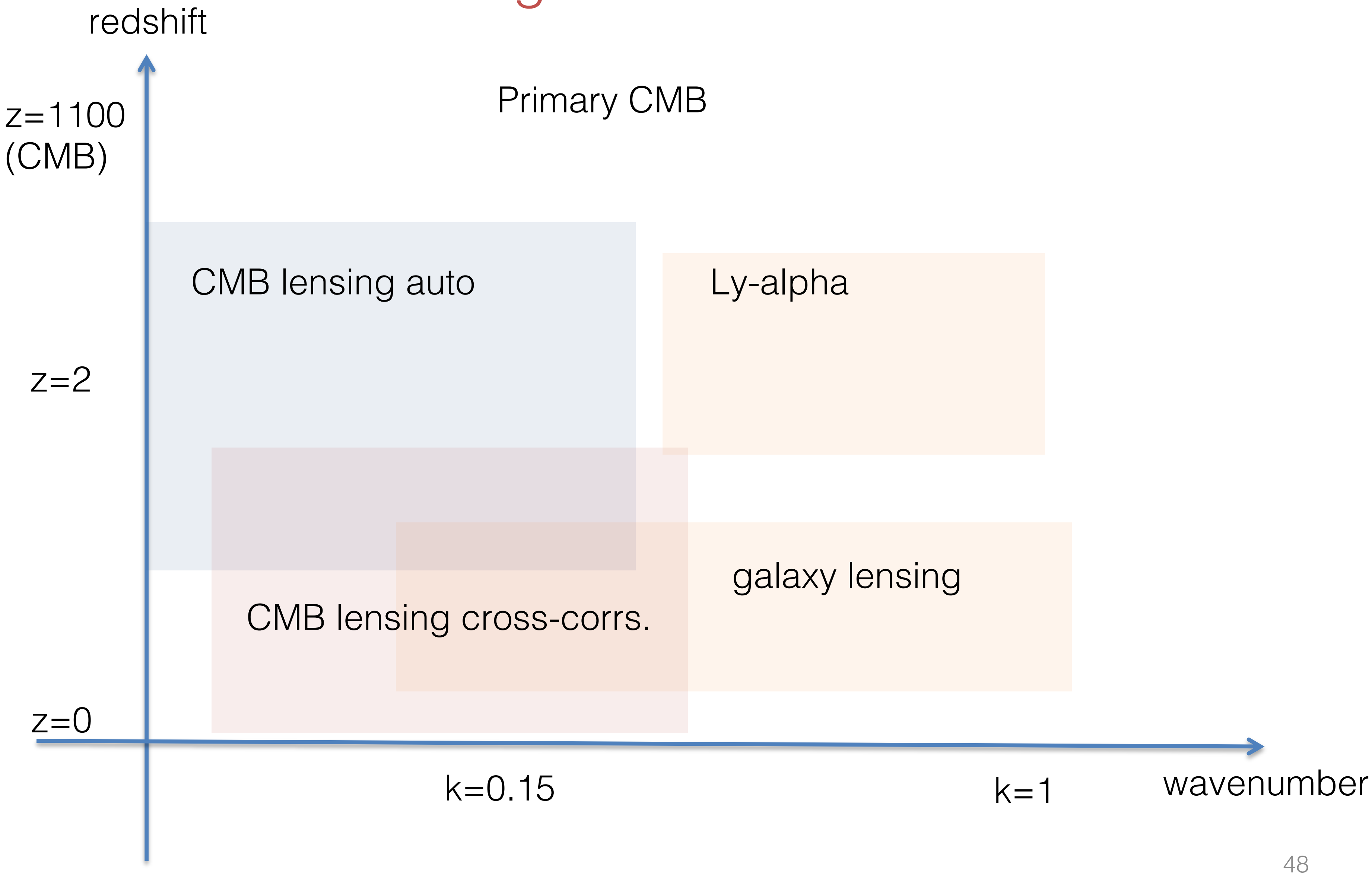




With Gerrit Farren, Frank Qu, Alex Krolewski, Simone Ferraro++

[Farren++ in prep., Qu++ 2022]

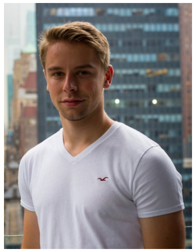
Testing for new physics in structure formation at both high and low redshifts



Low-redshift structure growth with cross-correlations

- Lensing tomography: $C_L^{dg} \propto b\sigma_8(z)^2; \quad C_L^{gg} \propto b^2\sigma_8(z)^2; \quad \to \sigma_8(z)$

  [Farren++ in prep.]



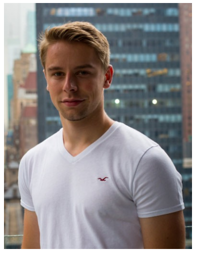
Gerrit Farren

Low-redshift structure growth with cross-correlations

- E.g., UnWISE x AdvACT lensing cross-correlation data:

[Farren++ in prep.]

- Comparable constraints but from z~0.6-1, S8 to ~± . Soon!



Gerrit Farren

Low-redshift structure growth with cross-correlations

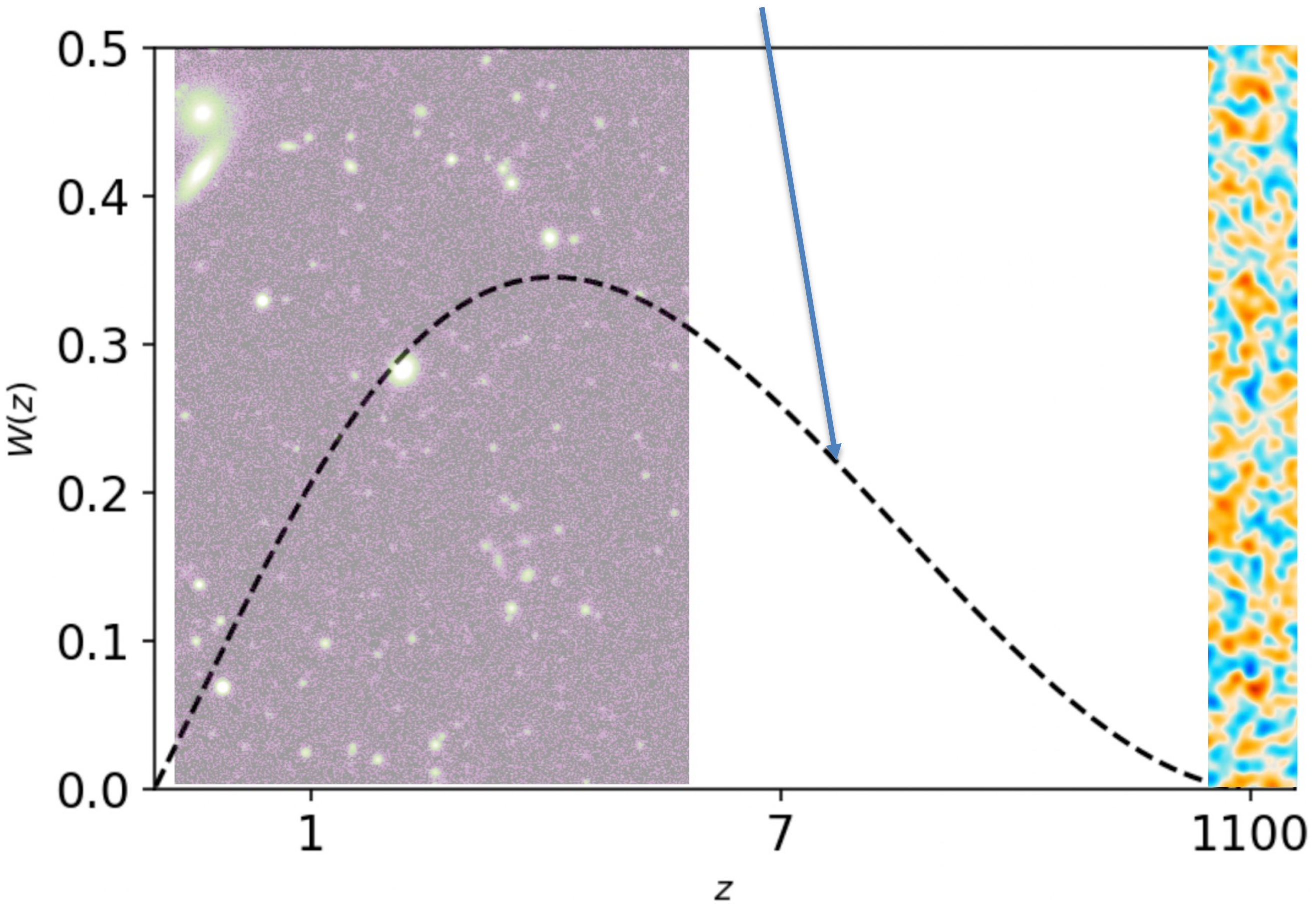
- E.g., UnWISE x AdvACT lensing cross-correlation data:

  [Farren++ in prep.]

- Since we observe 40% sky, wealth of ACT DR6 correlations with optical surveys (DESI gals/QSOs/Ly-a, DES/KiDS/HSC gals/lensing, soon LSST and Euclid)

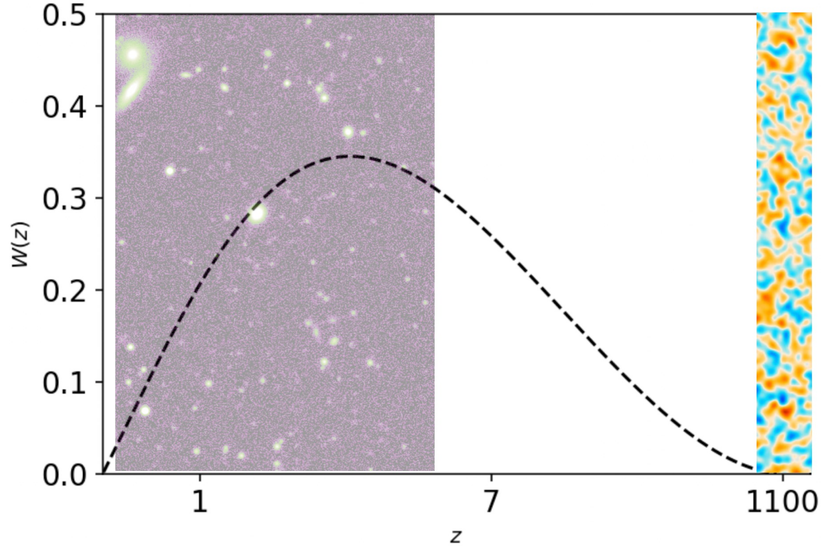
Forecasting opportunities at high-z

- Lensing maps probe matter density, projected over a wide redshift range peaking at z~2. Unique z>5 reach!
- How can I probe only the high-z structure?



Towards high-z only mass maps

- Galaxy surveys will span a broad redshift range
- Idea: subtract suitably scaled low-z galaxy maps to remove low-z contribution to lensing



$$c(\mathbf{L}) = \frac{C_L^{\kappa X}}{C_L^{XX}}$$

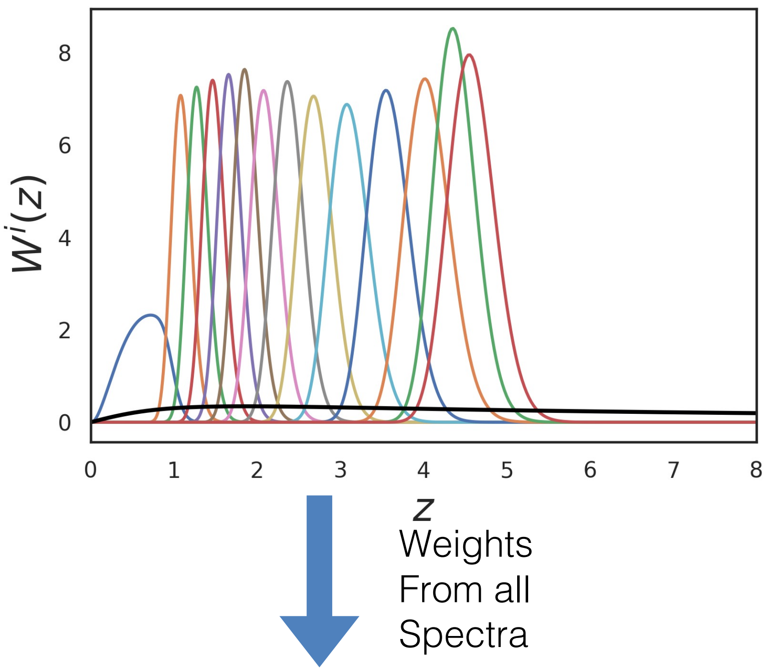
$$\hat{\kappa}_{\mathbf{L}}^{clean} = \hat{\kappa}_{\mathbf{L}} - c(\mathbf{L})\hat{X}_{\mathbf{L}}$$

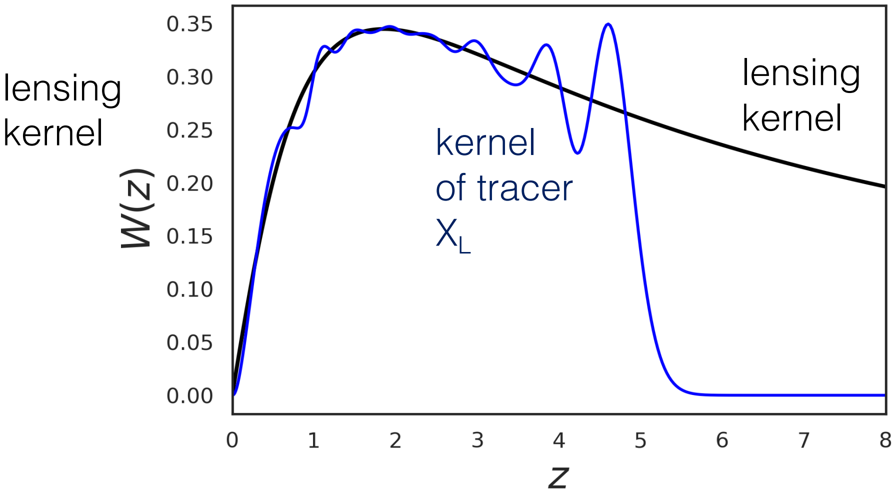
Filter Galaxy tracer

$$\kappa(\hat{\mathbf{n}}) \sim \nabla \cdot \mathbf{d}(\hat{\mathbf{n}})$$

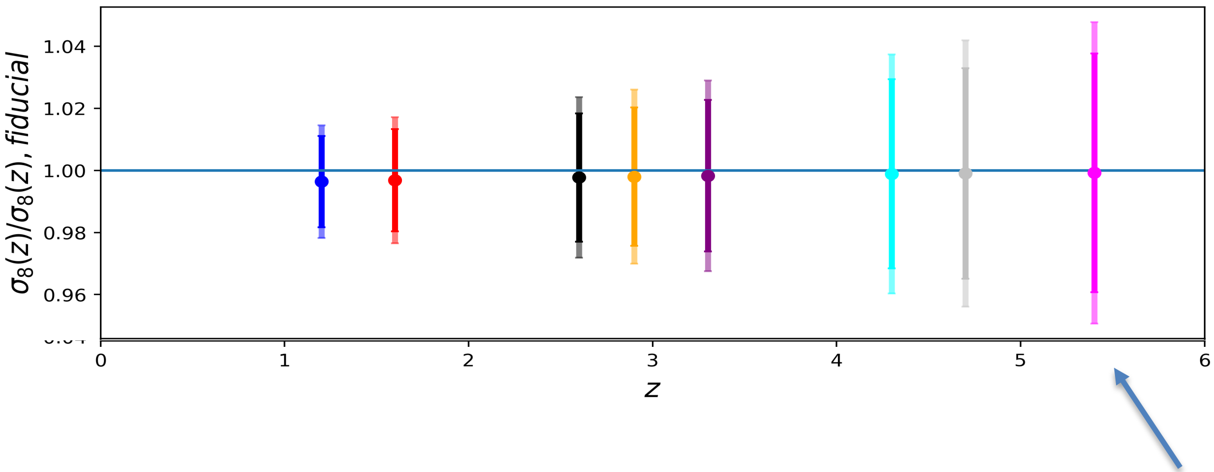
Towards high-z only mass maps

- Construct tracer field by combining LSS tracers in narrow z bins
- Weights to match low-z lensing can be obtained empirically from spectra





Tracking structure growth from high to low z with CMB lensing (forecast)

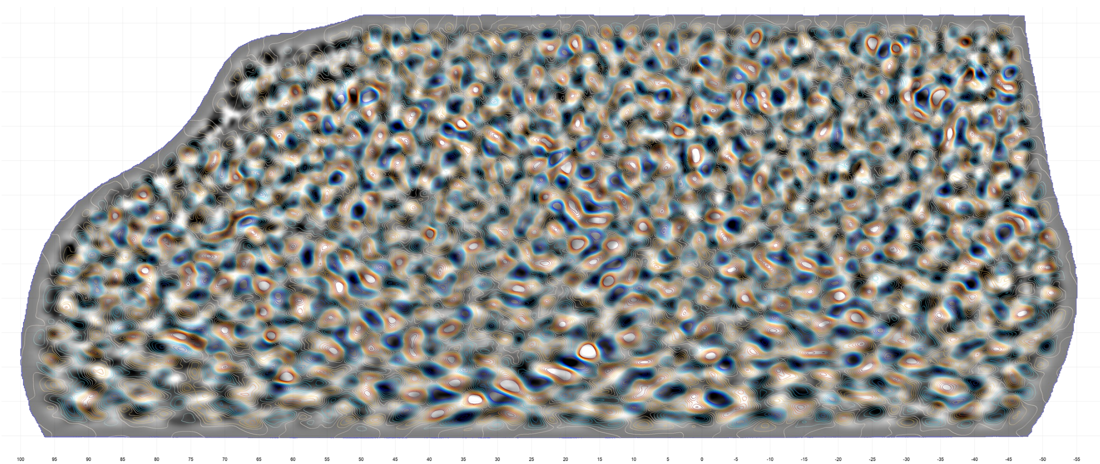


- Cleaned lensing kernels have negligible support at low-z. Can measure direct high-z lensing spectrum

- Demonstration planned with ACT. Forecast 4% measurement of S8 at z~5 with CMB-S4 and LSST

Summary

- ACT DR6 will be an exciting release with 10x more data than DR4
- From DR6 we have new lensing maps and spectra, powerful probes of structure growth in auto- and cross-correlation
- Stay tuned for state-of-the-art S8(z) + neutrino masses in next months!

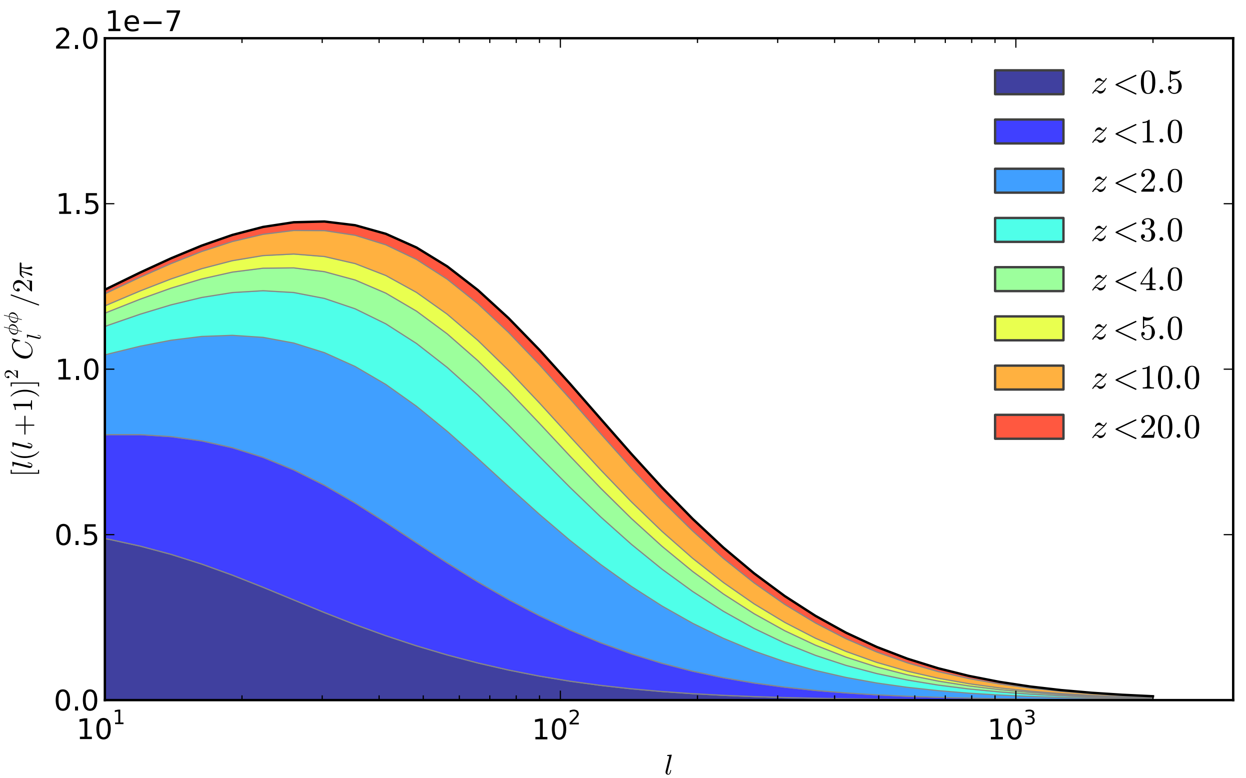


Also happy to discuss:

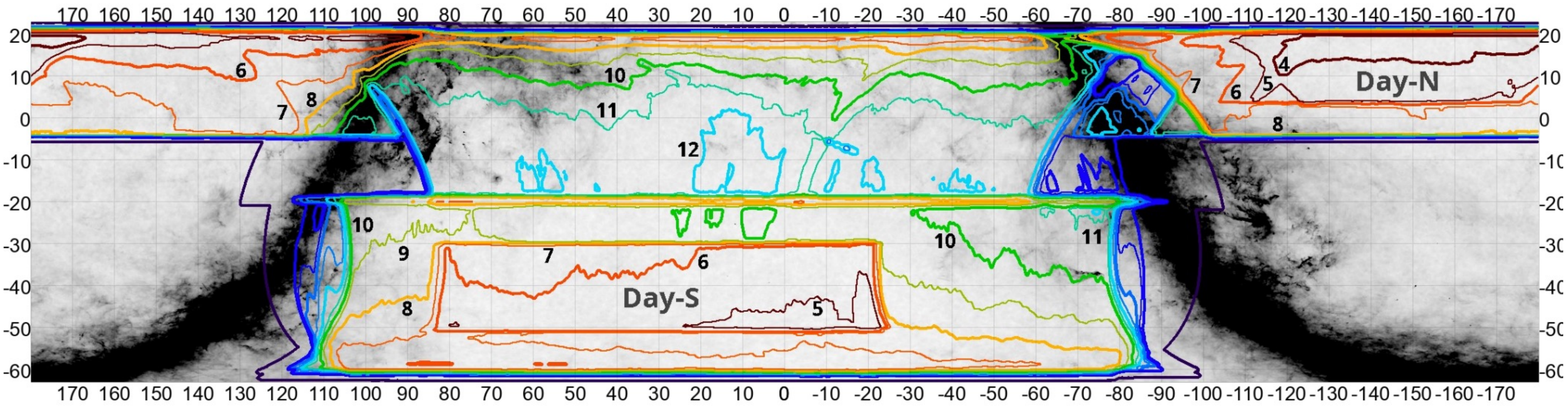
- Galaxy surveys and lensing surveys can measure Hubble constant without relying on sound horizon: a consistency test for new physics. New measurement $H_0 = 64.8^{+2.2}_{-2.5}\,\mathrm{km\,s^{-1}Mpc^{-1}}$ with BOSS/Planck (via new method to marginalize over BAO info.)

Redshift Distribution

- Lensing maps probe matter density, projected over a wide redshift range peaking at z~2.
- Some tomography vs. scale possible!



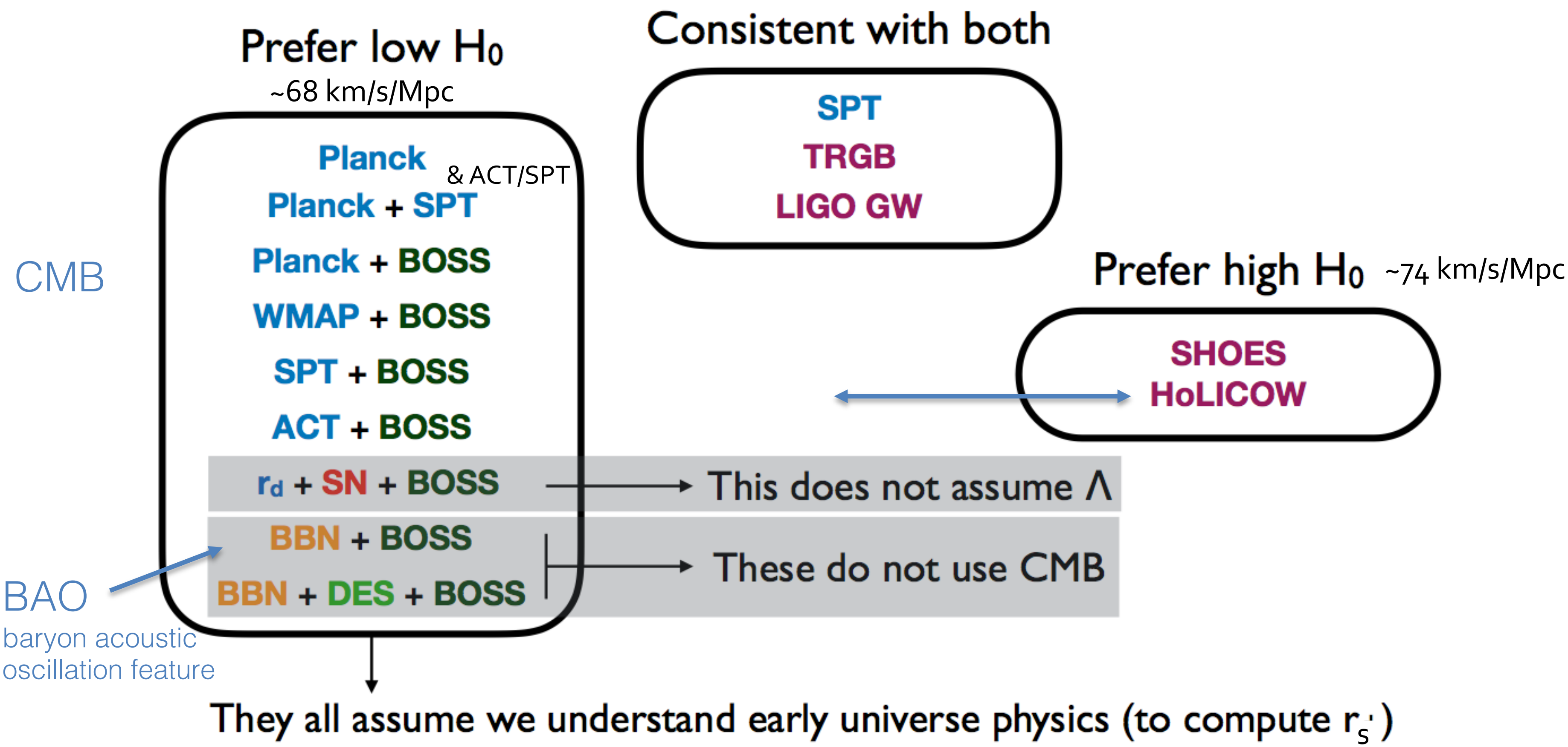
Redshift Distribution



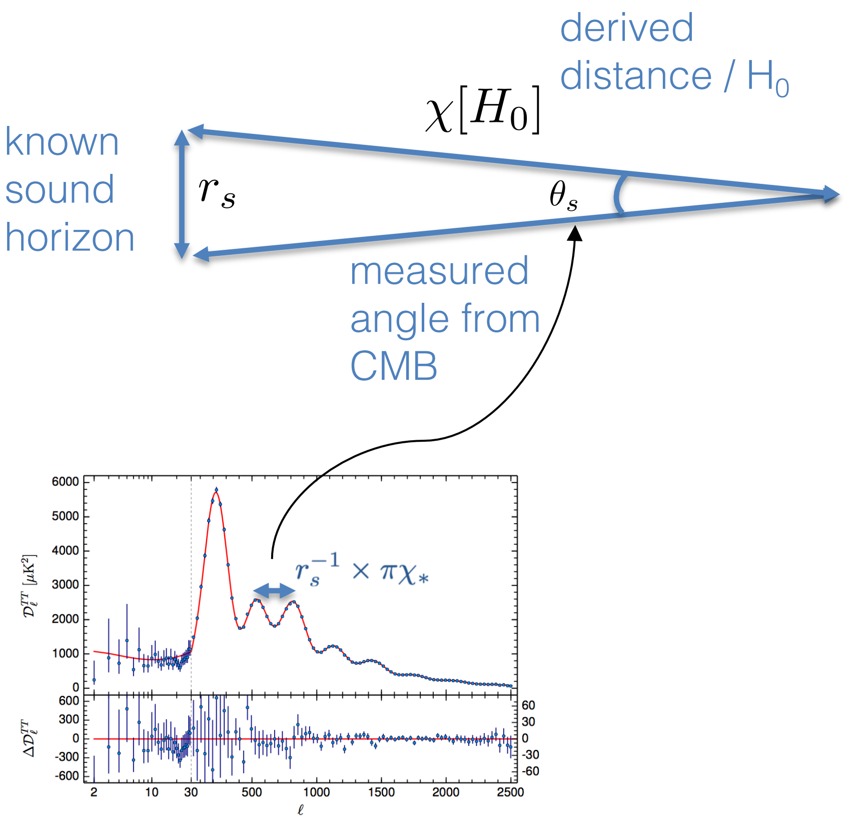
T, night+day, frequency-combined

Hubble tension: not just one probe (?)

Figure credit: A. Font-Ribera



Measuring Hubble with CMB: Sound Horizon Importance



$\mathcal{D}_l \equiv l(l+1)C_l/2\pi$

- Compute (calibr.) sound horizon r_s

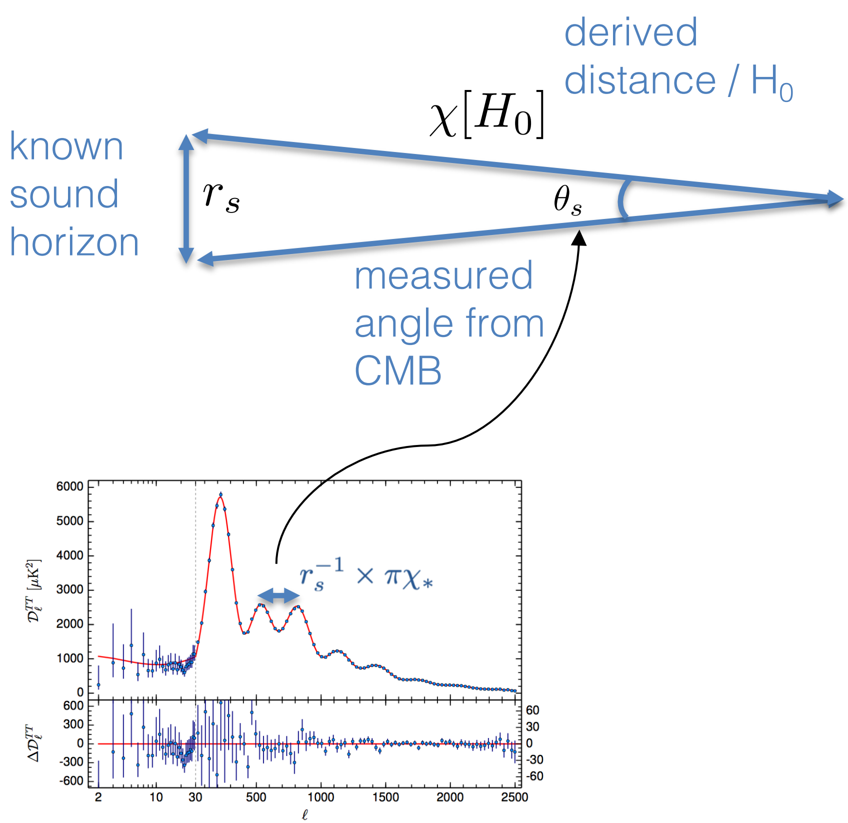
sound speed

$$r_s = \int_{z_r}^{\infty} \frac{c_s}{H(z)} dz$$

expansion rate

- Measure angle θ_s and infer distance $\chi[H_0] \sim r_s/\theta_s$
- Distance[H_0]
  => H_0 !
- Same for BAO in galaxy clustering

Measuring Hubble with CMB: Sound Horizon Importance



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sound speed (c_s), expansion rate ($H(z)$)

- Measure angle θ_s and infer distance $\chi[H_0] \sim r_s/\theta_s$
- Distance[H_0]
  => H_0 !
- Same for BAO in galaxy clustering

Idea for resolving tension: is new physics changing r_s ?

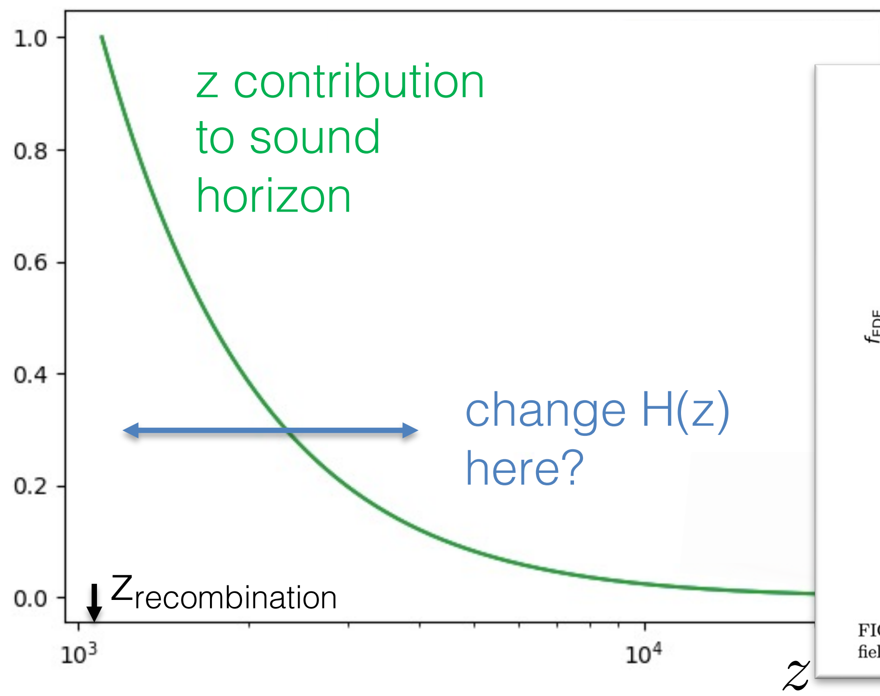
Possible explanation for tension: Changing sound horizon via early expansion

The final category is the set of solutions that introduces new components to increase $H(z)$ in the decade of scale factor evolution prior to recombination. We see these as the most likely category of solutions. They are also

[Knox + Millea 2019]

$$r_s = \int_{z_r}^{\infty} \frac{c}{H(z)} dz$$

$$\frac{d \ln r_s}{d \ln H(z)}$$



e.g. early dark energy…

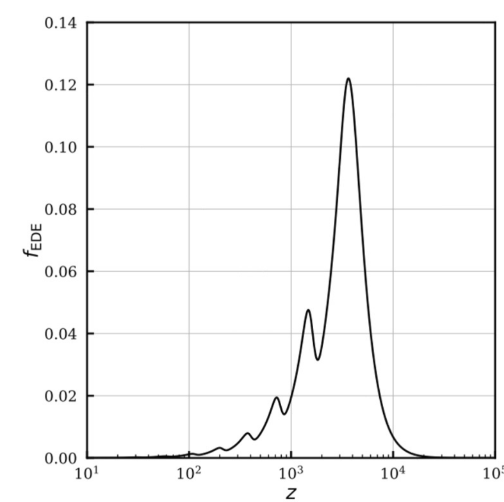


FIG. 2: Fraction of the cosmic energy density in the EDE field ϕ as a function of redshift, for the parameters in Eq. (7).

Possible explanation for tension: Changing sound horizon via early expansion

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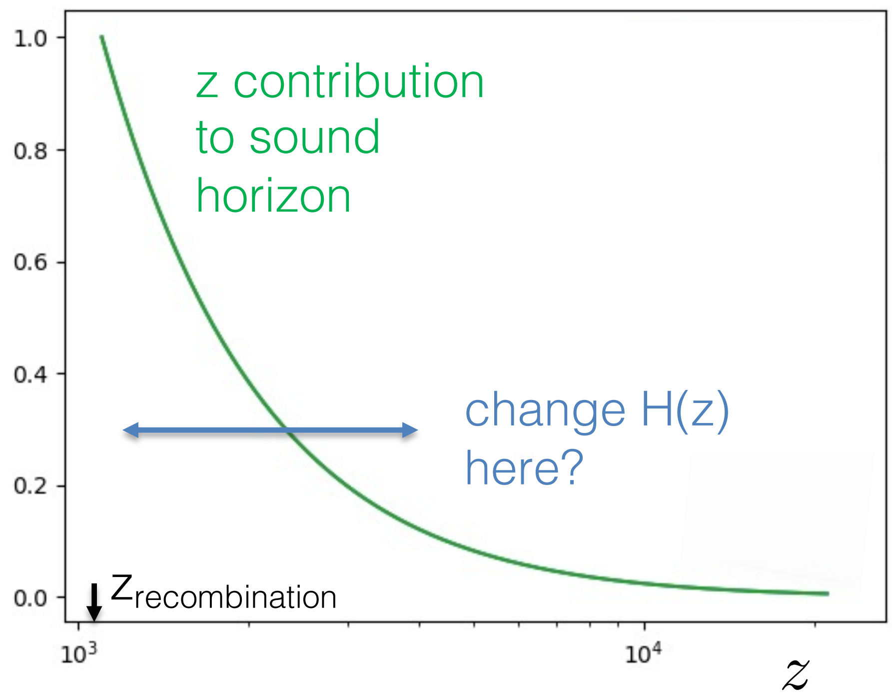
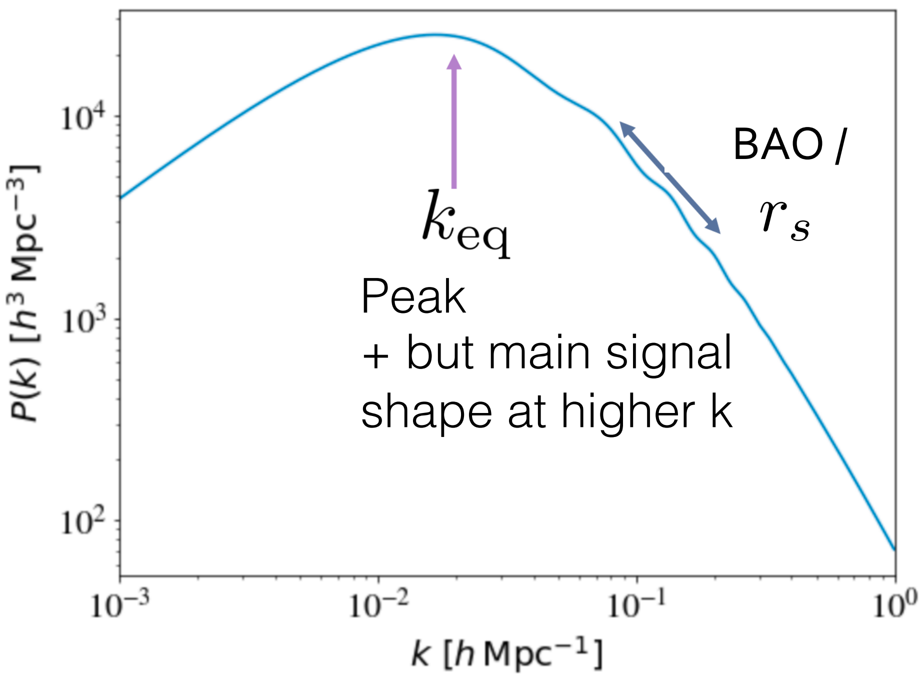


e.g. early dark energy…
problem: many models

Q: how to test these kinds of modifications generically?

Idea: Use k_{eq} to get H_0 without the sound horizon

- Matter radiation equality scale k_{eq}: alternate standard ruler to get H_0. Different redshift/new physics sensitivity!
- Details: get k_{eq} / $H_0 \sim \Omega_m H_0$. Then just need a probe of Ω_m and solve for H_0. Different z + sensitivity to new physics?

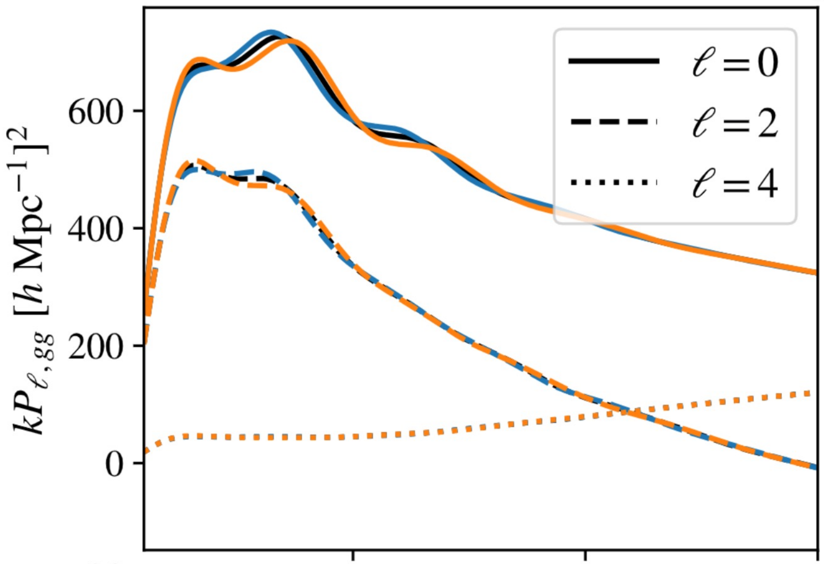


Galaxy power, marginalizing over r_s

- How to avoid r_s information? Idea: marginalize sound horizon value to isolate k_{eq} information.
- Can only be approximate (r_s not fundamental) but new way of measuring H_0 + consistency test. Marginalization procedure:

$$P^{\rm lin}(k) \to P^{\rm lin}(k, \alpha_{r_s}) \equiv P^{\rm lin}_{\rm nw}(k) + P^{\rm lin}_{\rm w}(\alpha_{r_s} k).$$

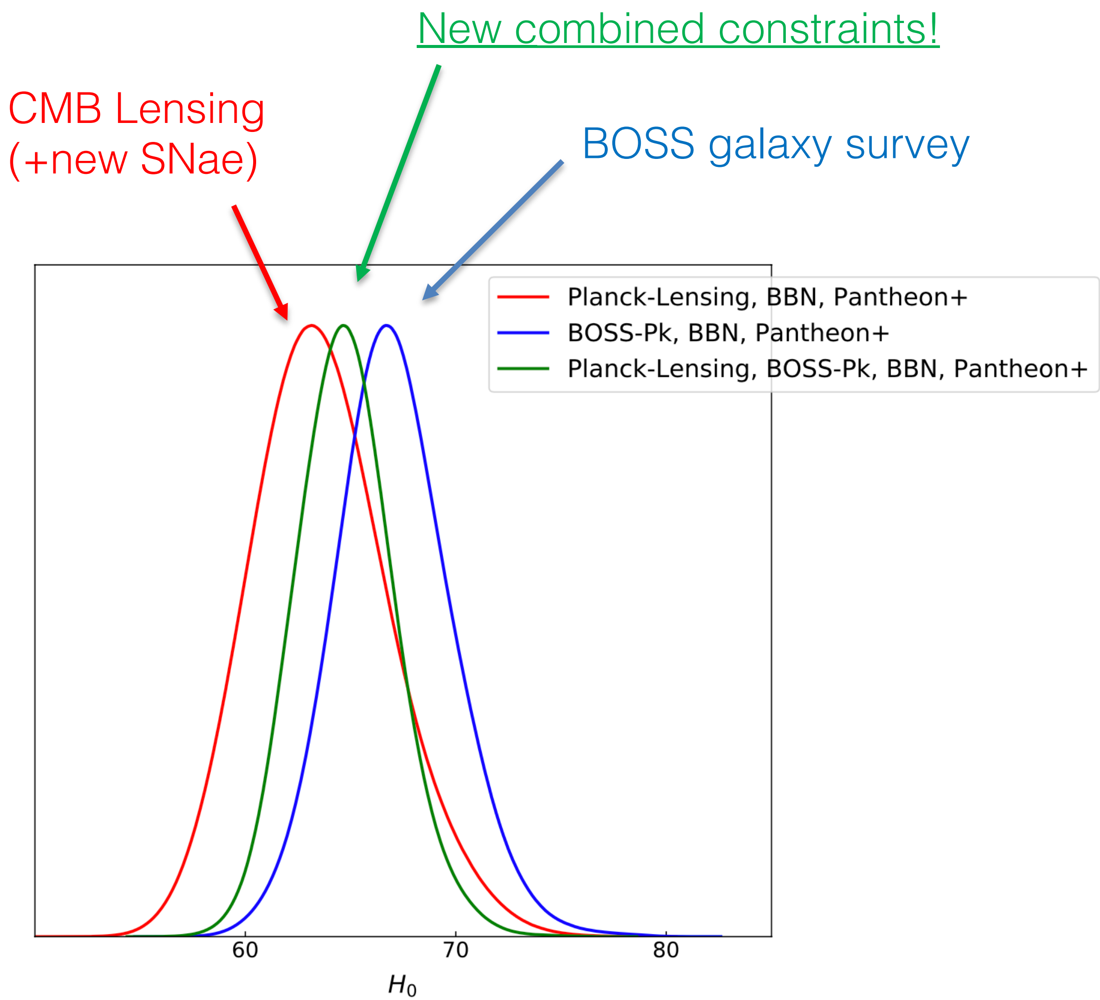
Rescale "wiggle" part of power spectrum by α_{rs}



- + broadband r_s marginalization; + lots of tests that r_s info killed!

[Farren, Philcox, Sherwin 2021]

New results – BOSS galaxy power with r_s marginalization + CMB lensing



[Philcox, Farren, Sherwin++ 2022]

- New measurement without sound horizon info! (Prelim.)

$$H_0 = 64.8^{+2.2}_{-2.5}\,\mathrm{km\,s^{-1}Mpc^{-1}}$$

- Now in 3 sigma tension with SH0ES distance ladder H_0.
- Any new physics must give same “wrong answer” for both scales – difficult? Differences in early tests.
- For future surveys, great performance: Euclid H_0 within +/- 0.72 km/s/Mpc!

Summary

- With AdvACT we have powerful new lensing maps, giving state-of-the-art S8 + neutrino masses this year!
- Lensing and galaxy surveys can measure Hubble constant without relying on sound horizon: a consistency test for new physics. New measurement $H_0 = 64.8^{+2.2}_{-2.5}\,\mathrm{km\,s^{-1}Mpc^{-1}}$ with BOSS/Planck!