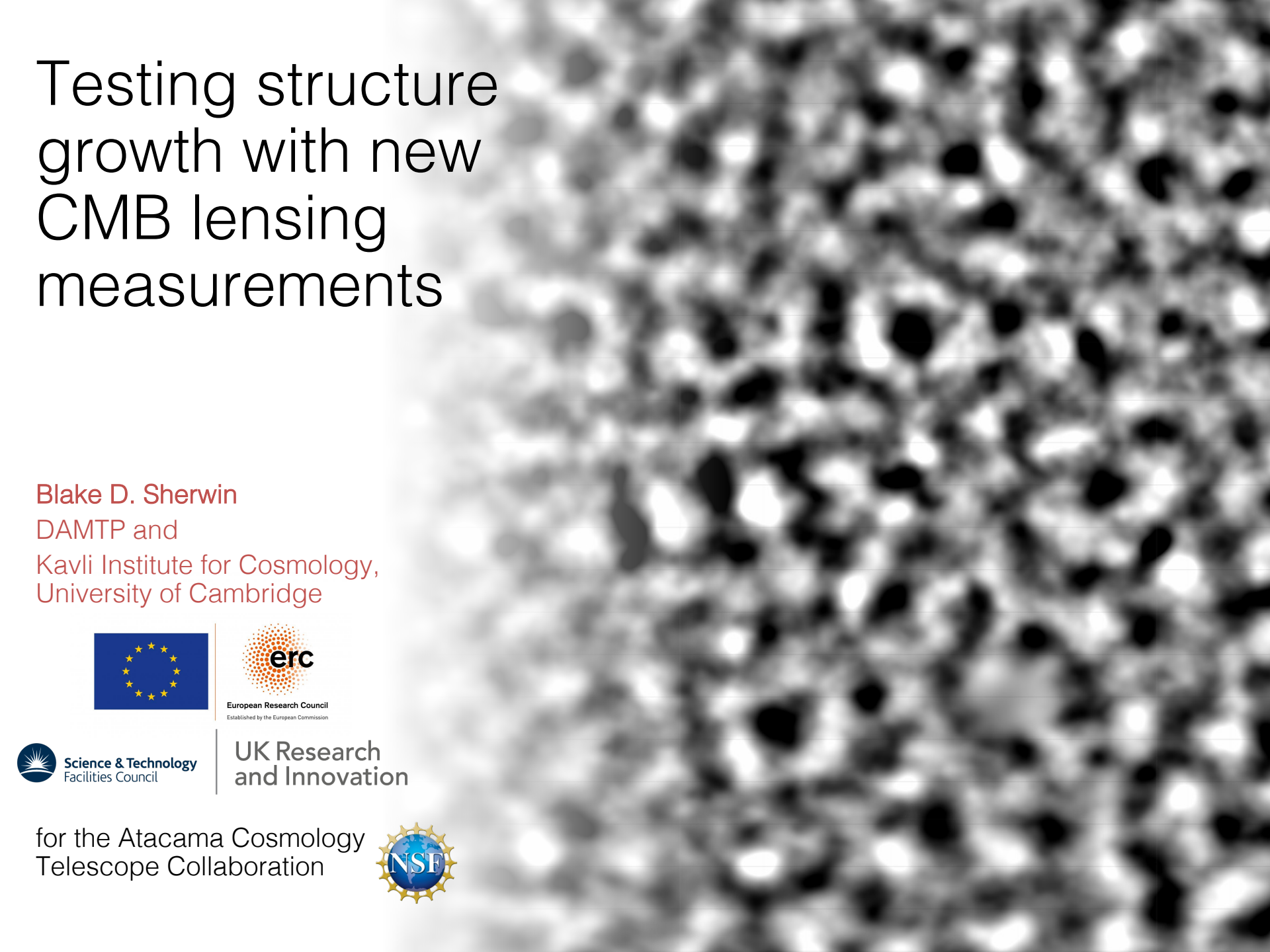
Testing structure growth with new CMB lensing measurements



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

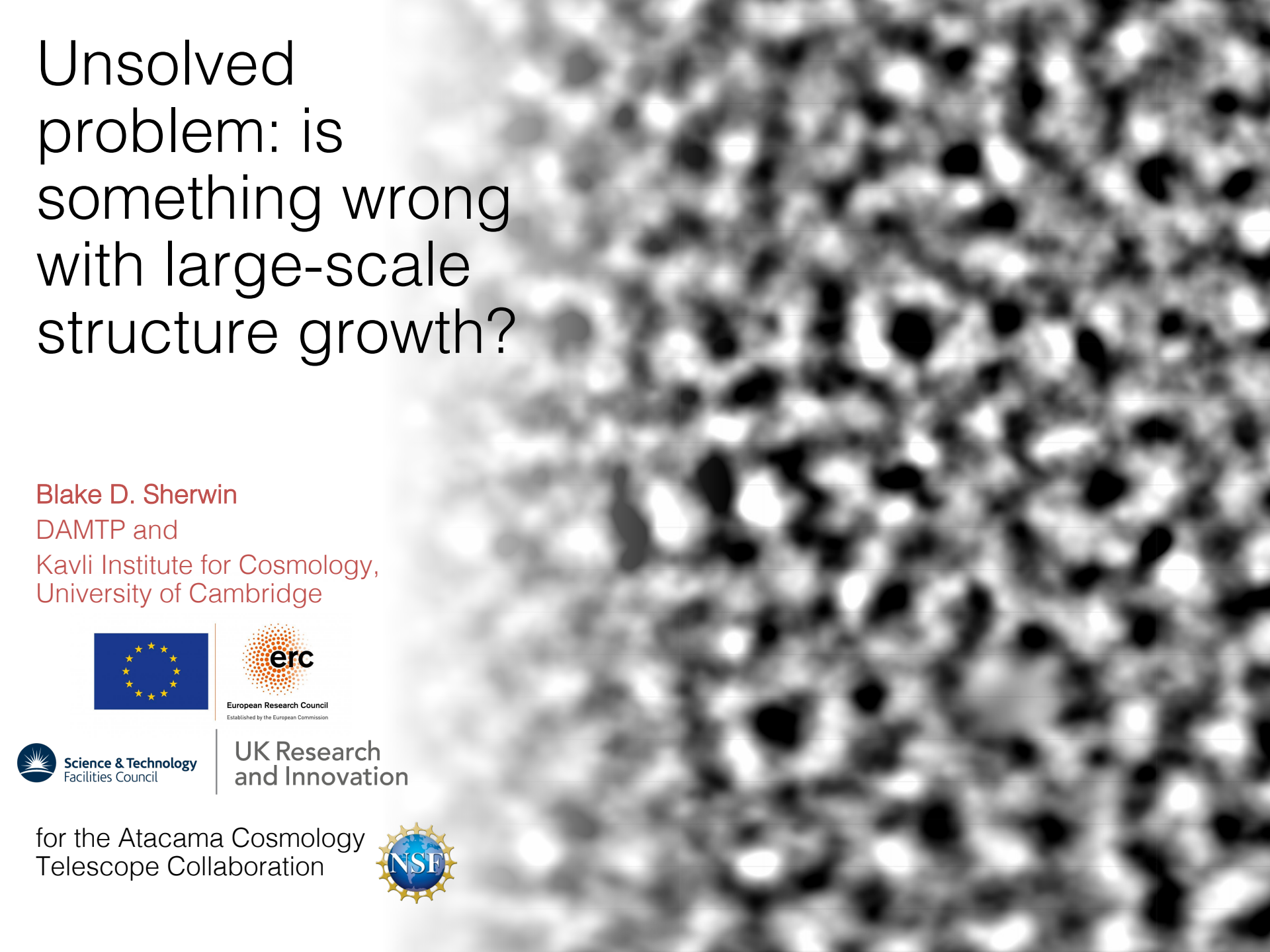
European Research Council
Established by the European Commission

Science & Technology Facilities Council

UK Research and Innovation

for the Atacama Cosmology Telescope Collaboration

Unsolved problem: is something wrong with large-scale structure growth?



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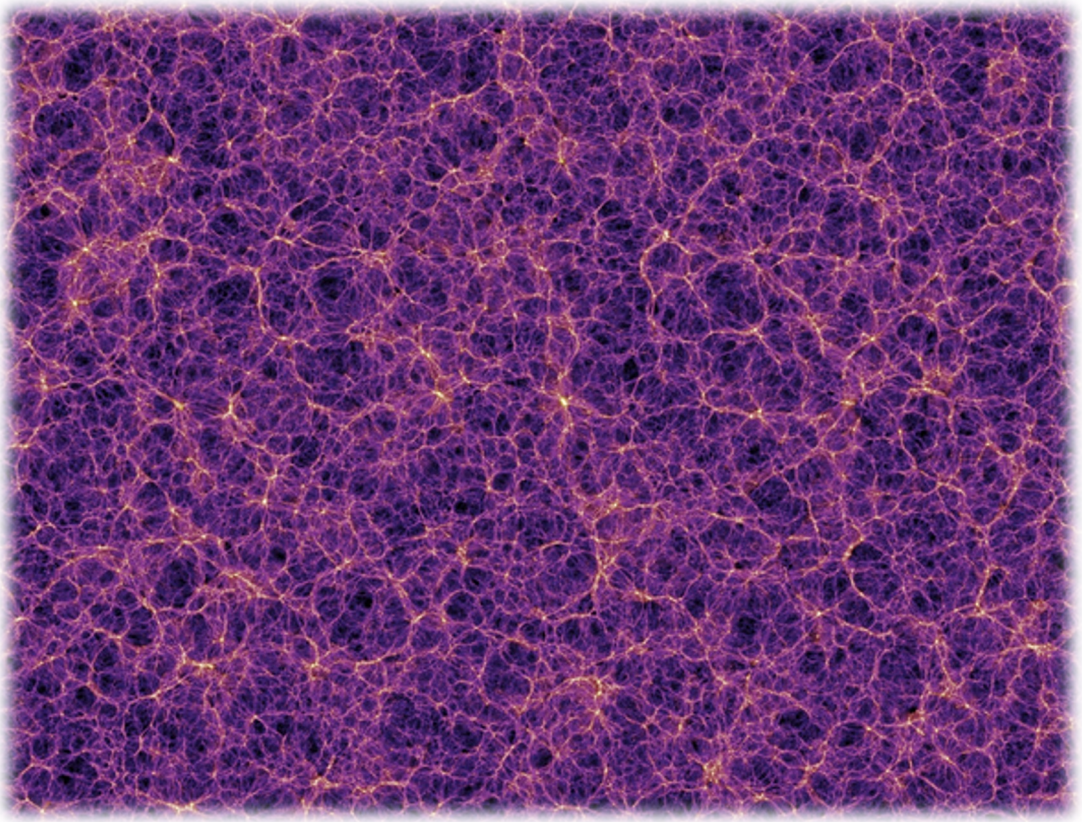
NSF

Cosmic mass maps: a powerful observable

- Want to probe mass distribution in detail, as contains clean information on open questions in cosmology and physics:

1. Is standard structure growth correct?

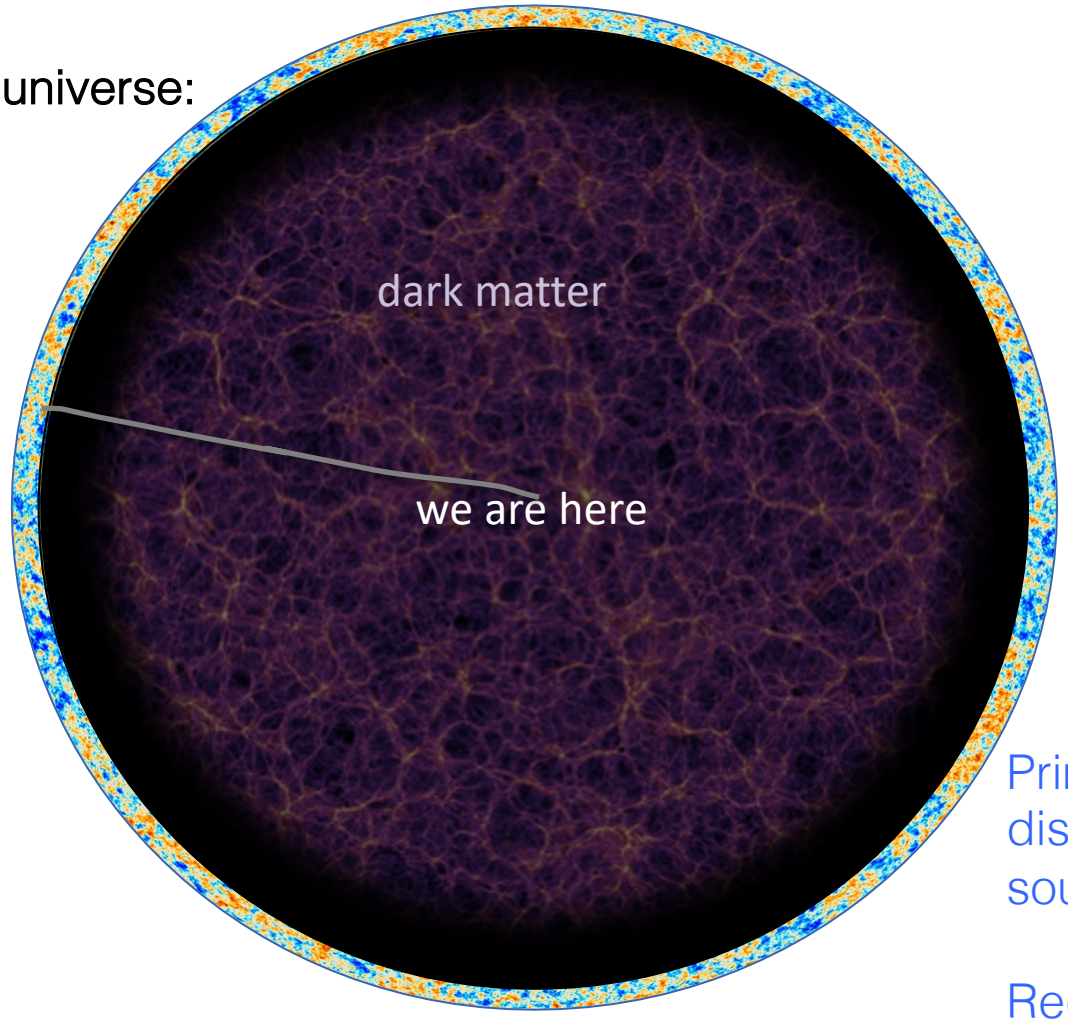
E.g., dark matter, dark energy = cosmological constant, GR



2. What are the masses of neutrinos?

CMB: A Unique Source for Gravitational Lensing

The observable universe:

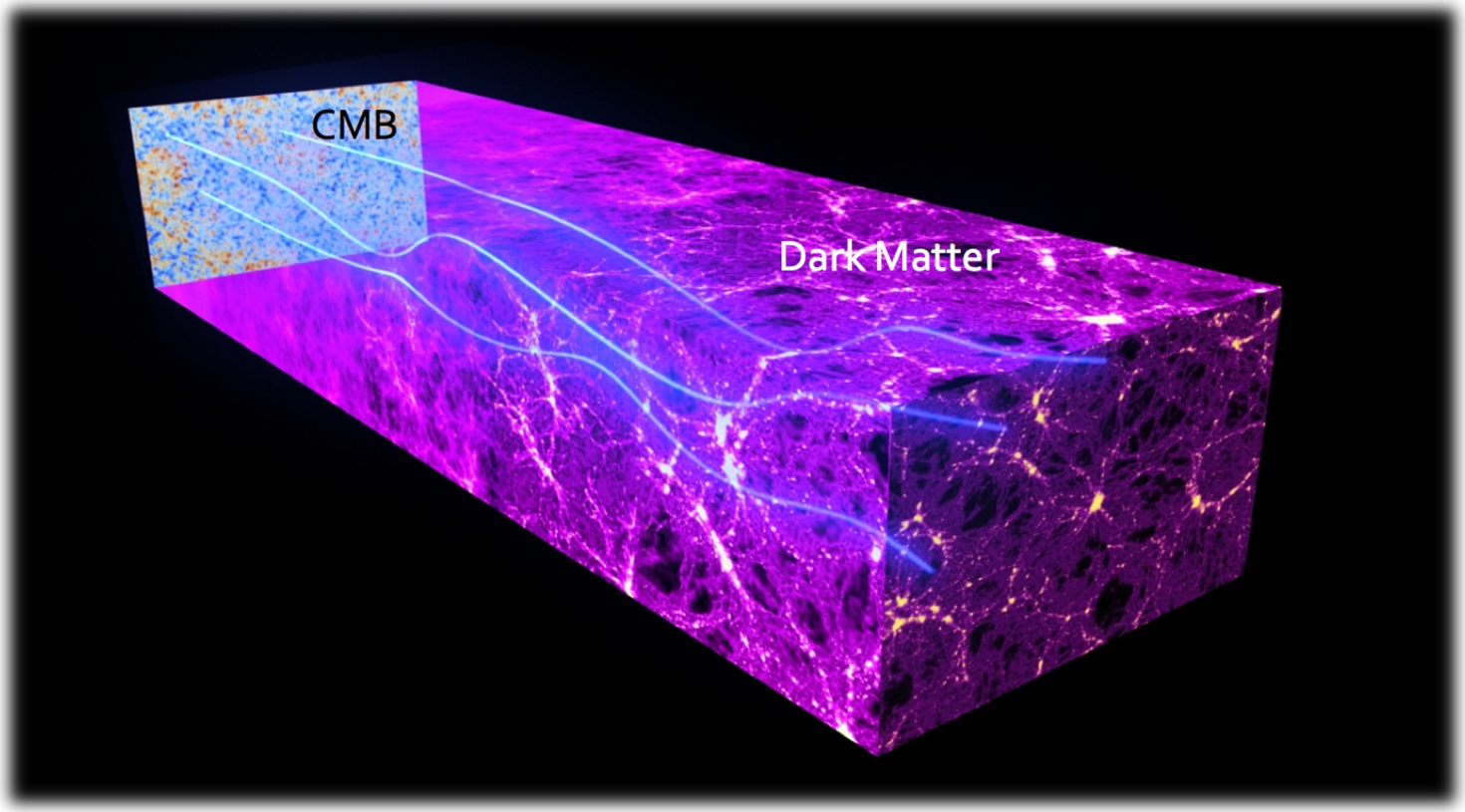


Primordial CMB (most distant and oldest source of radiation)

Redshift and CMB source well known, matter mildly nonlinear

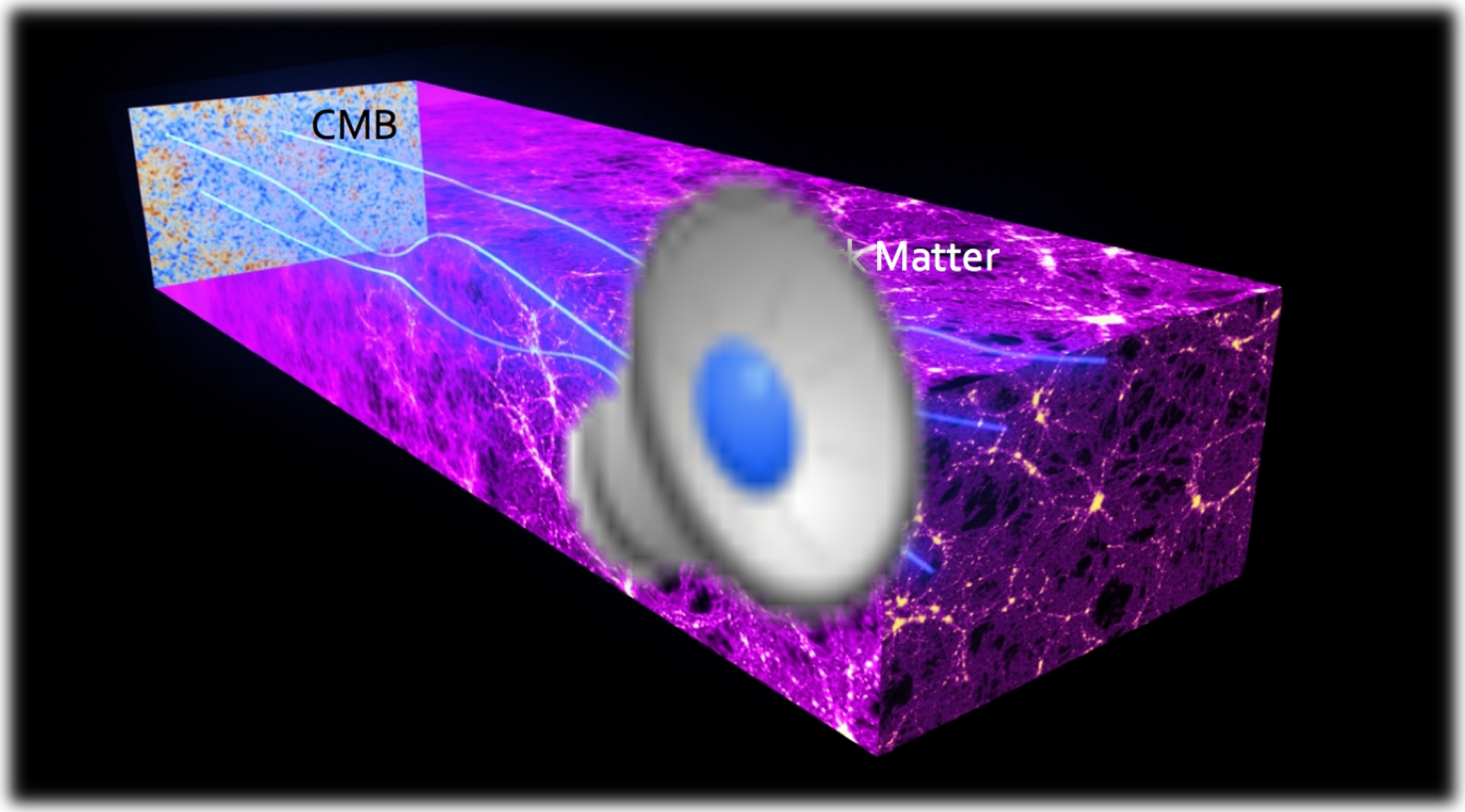
CMB Gravitational Lensing

- Distribution of dark matter deflects CMB light that passes through

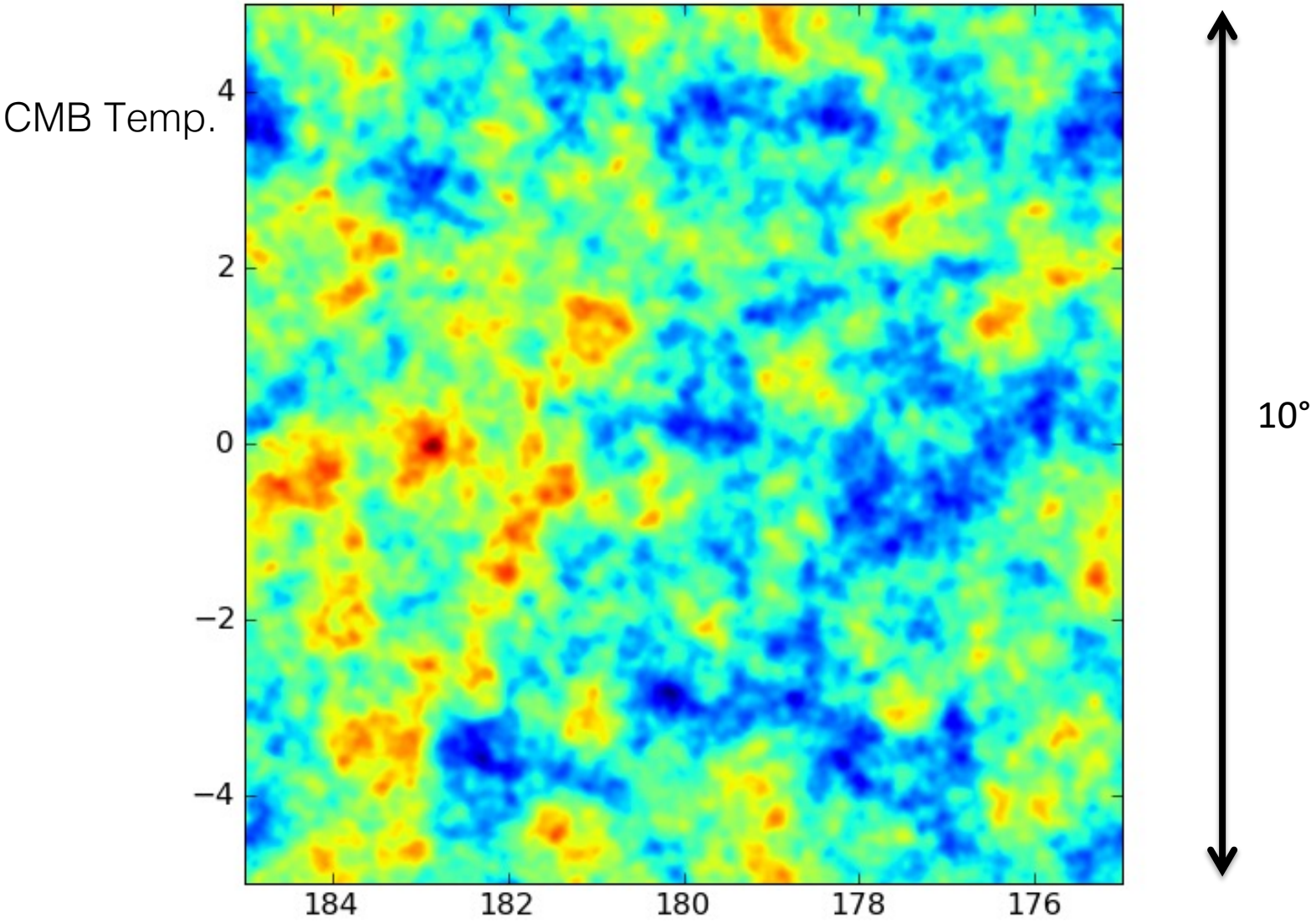


“Light” Source for Lensing: The Cosmic Microwave Background (CMB)

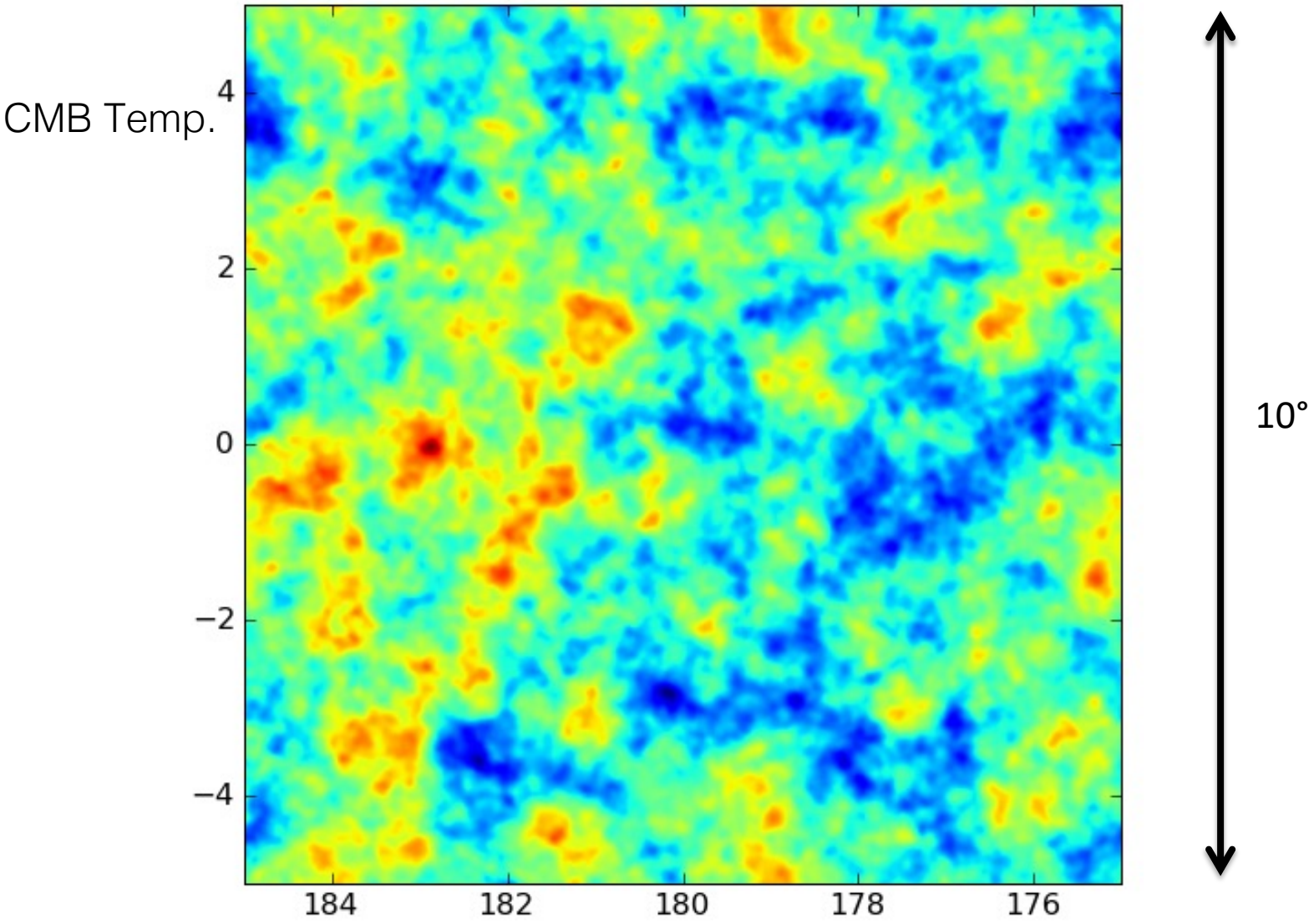
- Distribution of dark matter deflects light that passes through



Unlensed CMB

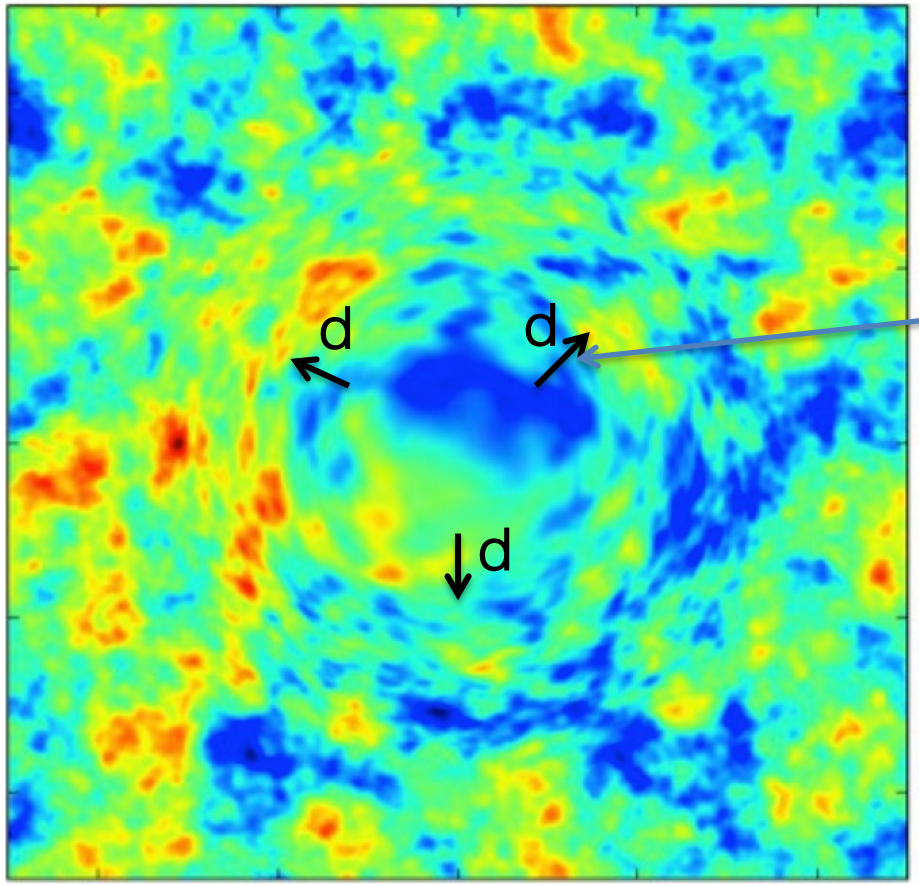


Lensed CMB



CMB Lensing: An Approximate Picture

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

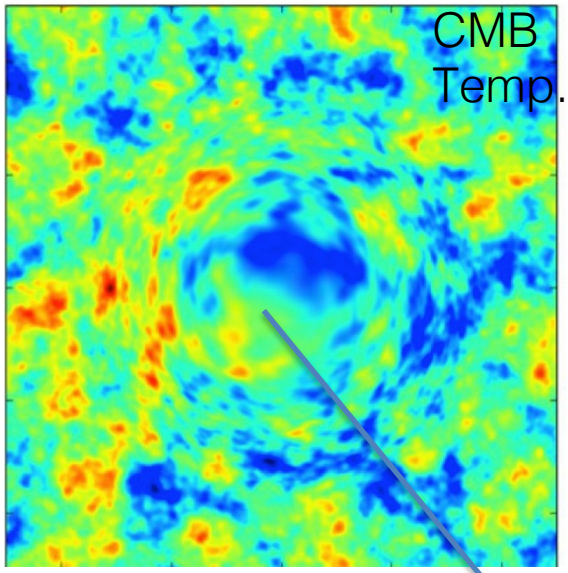


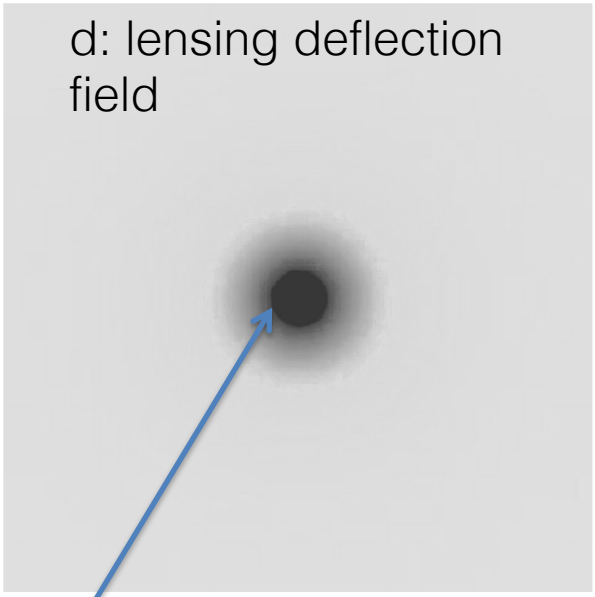
described by **lensing deflection field: d**

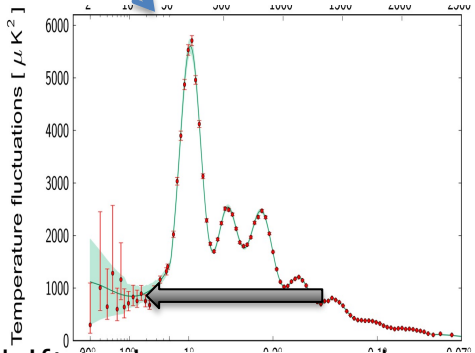
(very small: here exaggerated by x ~100, actually a few arcmins)

- Dark matter causes lensing magnification feature in the CMB

CMB Lensing Measurement: An Approximate Picture







shift to larger angular scales

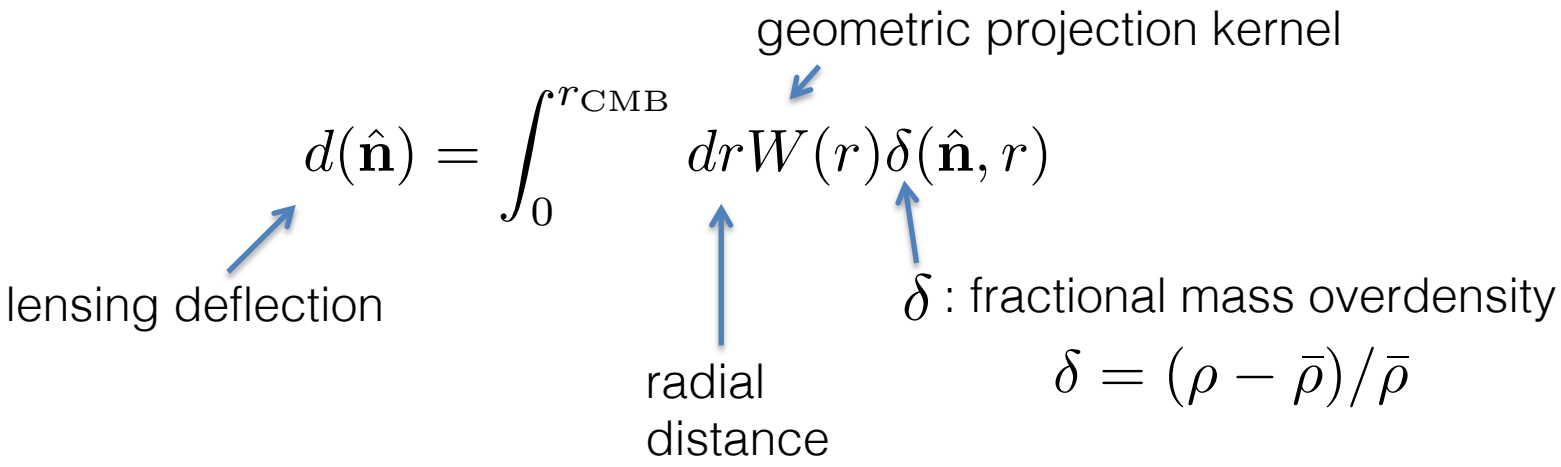
Infer lensing from stretching/shearing of the local CMB two-point function

Full version: quadratic estimator

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

What Does CMB Lensing Tell Us?

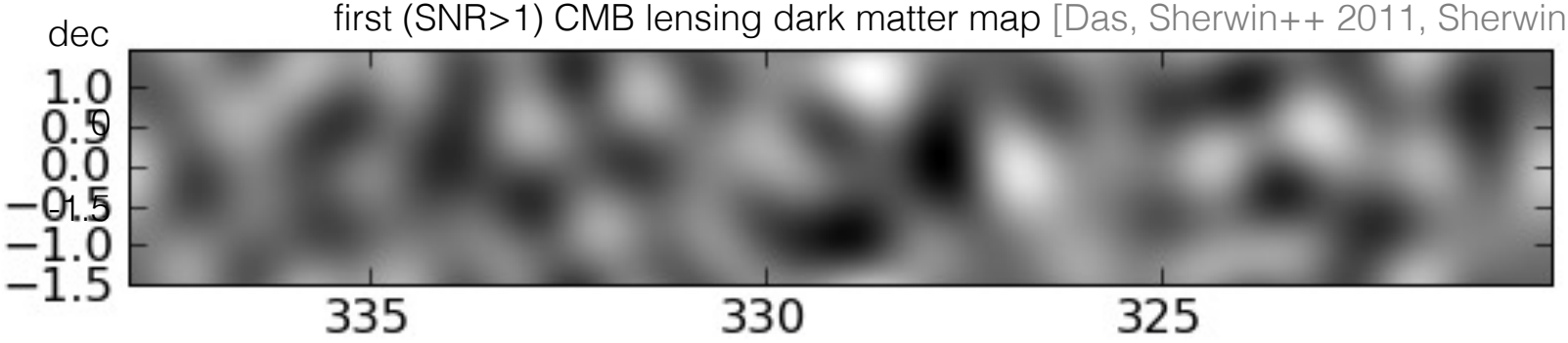
- Lensing probes projected total mass density (of which most is dark matter)



- Sensitivity to z~0.5-6, peak at z~2

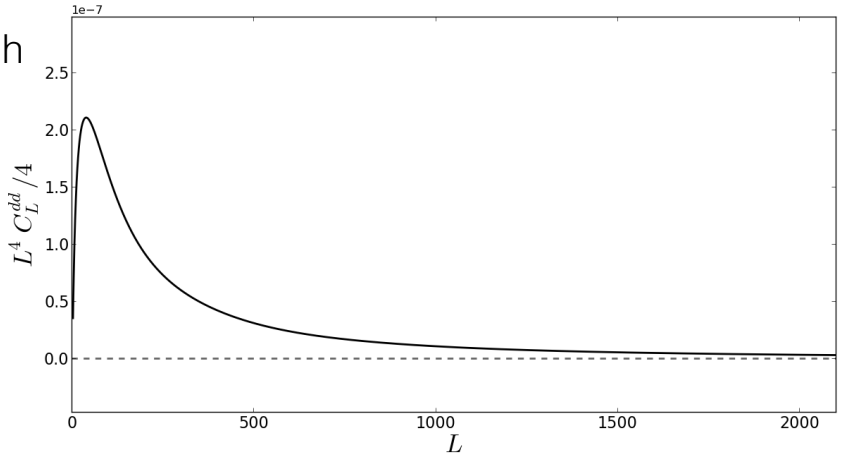
Key Observable: CMB Lensing Power Spectrum C_L^{dd}

first (SNR>1) CMB lensing dark matter map [Das, Sherwin++ 2011, Sherwin++ 2011]



white = higher density

Y axis: “How much lensing ….”

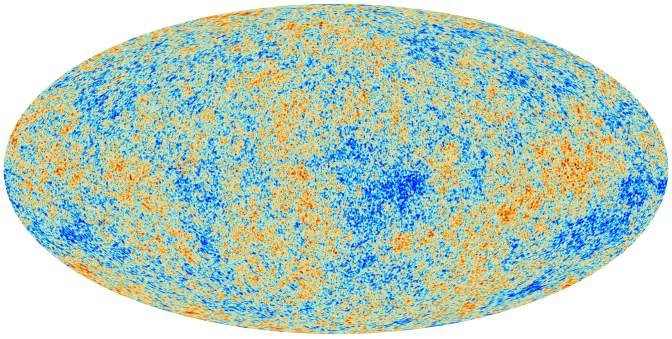


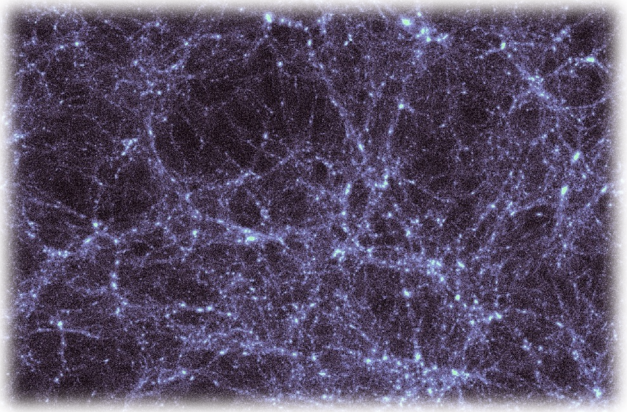
X axis: “for a lens of this angular scale?”

Describe lensing maps statistically with lensing power spectrum.
Probes “clumpiness”
~σ_8

Motivation 1: is something wrong with large-scale structure growth?

- Do observations match predictions of standard-model structure growth? Particularly powerful test:



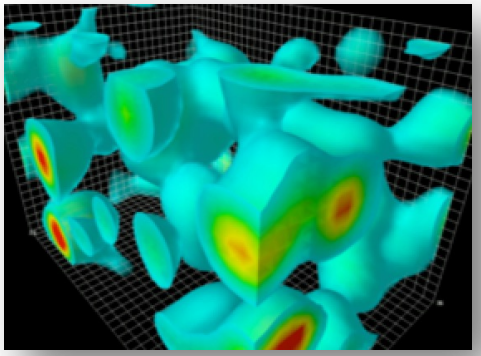


Fit model to CMB at early times

Predict structure at late times + compare with lensing observations

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

Motivation 1: is something wrong with large-scale structure growth?

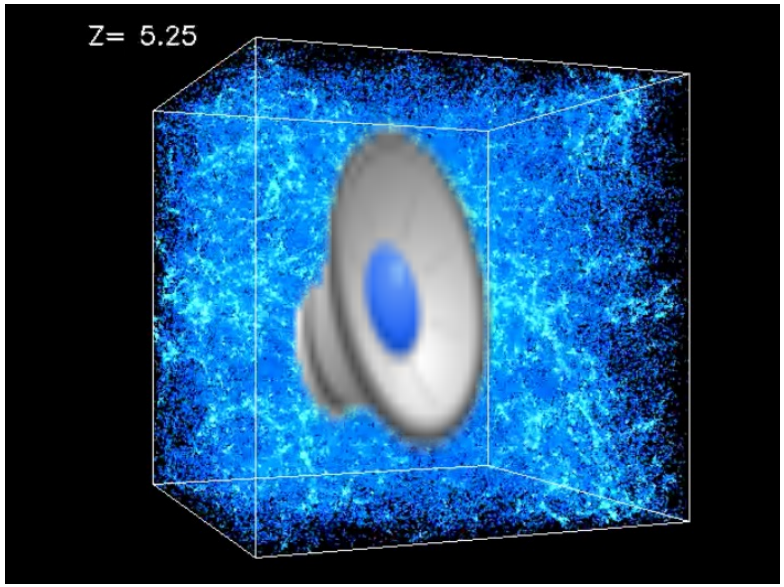


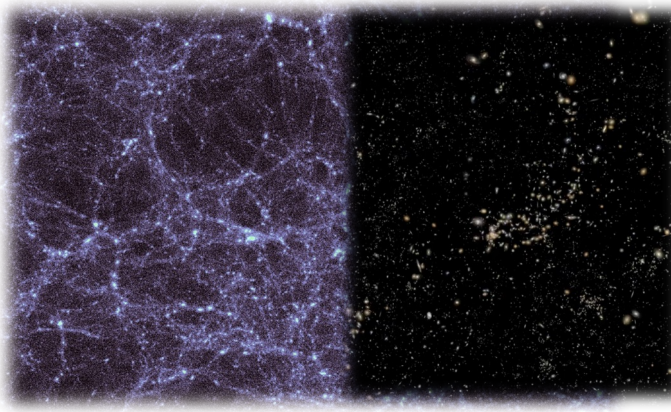
Primordial fluctuations

Growth due to gravity.
Assumptions:

- Standard GR
- Dominated by Cold Dark Matter
- Constant Dark Energy

Sensitive to new physics!

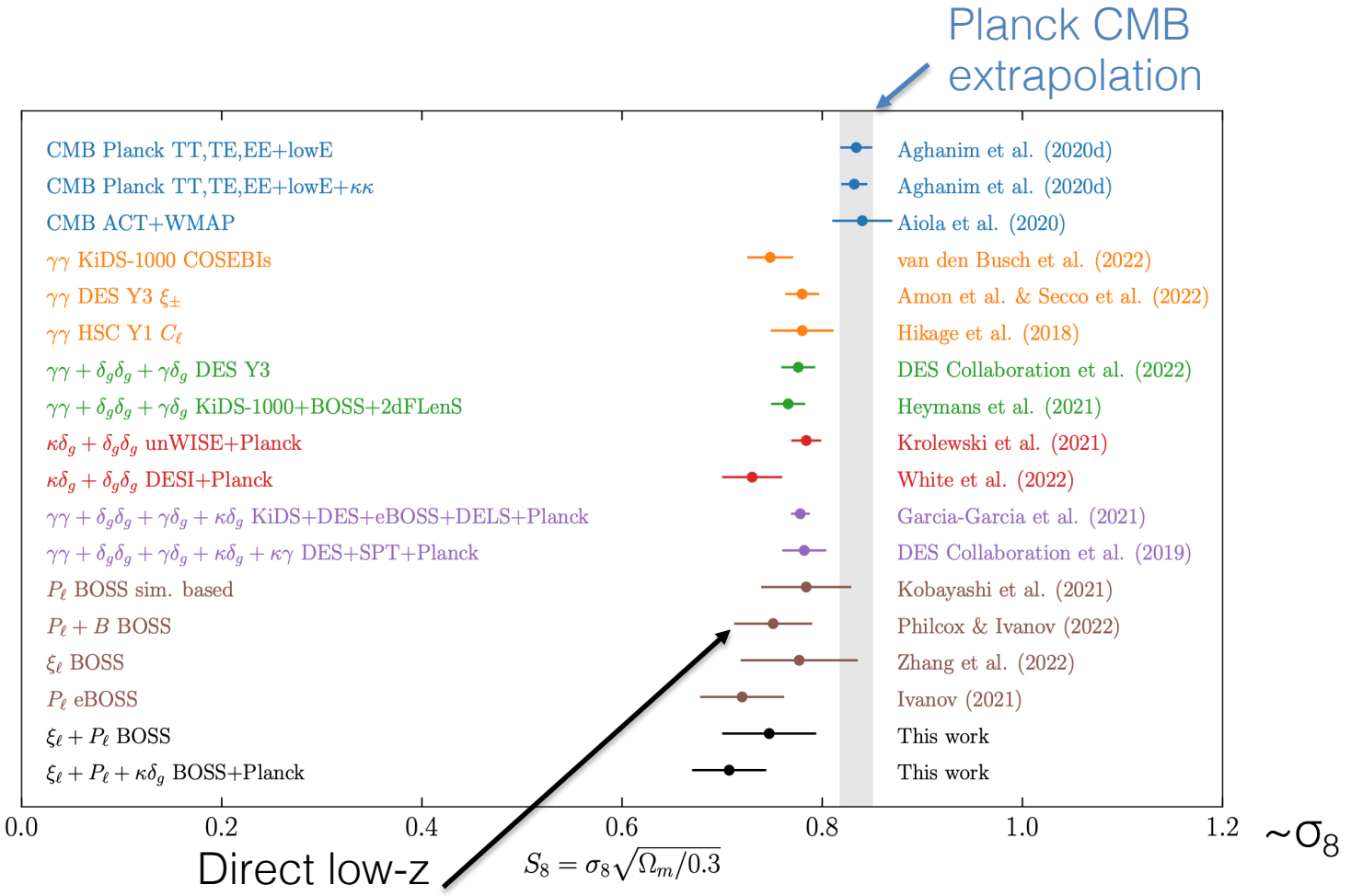




Cosmic structure today

[Video: A. Kravtsov++]

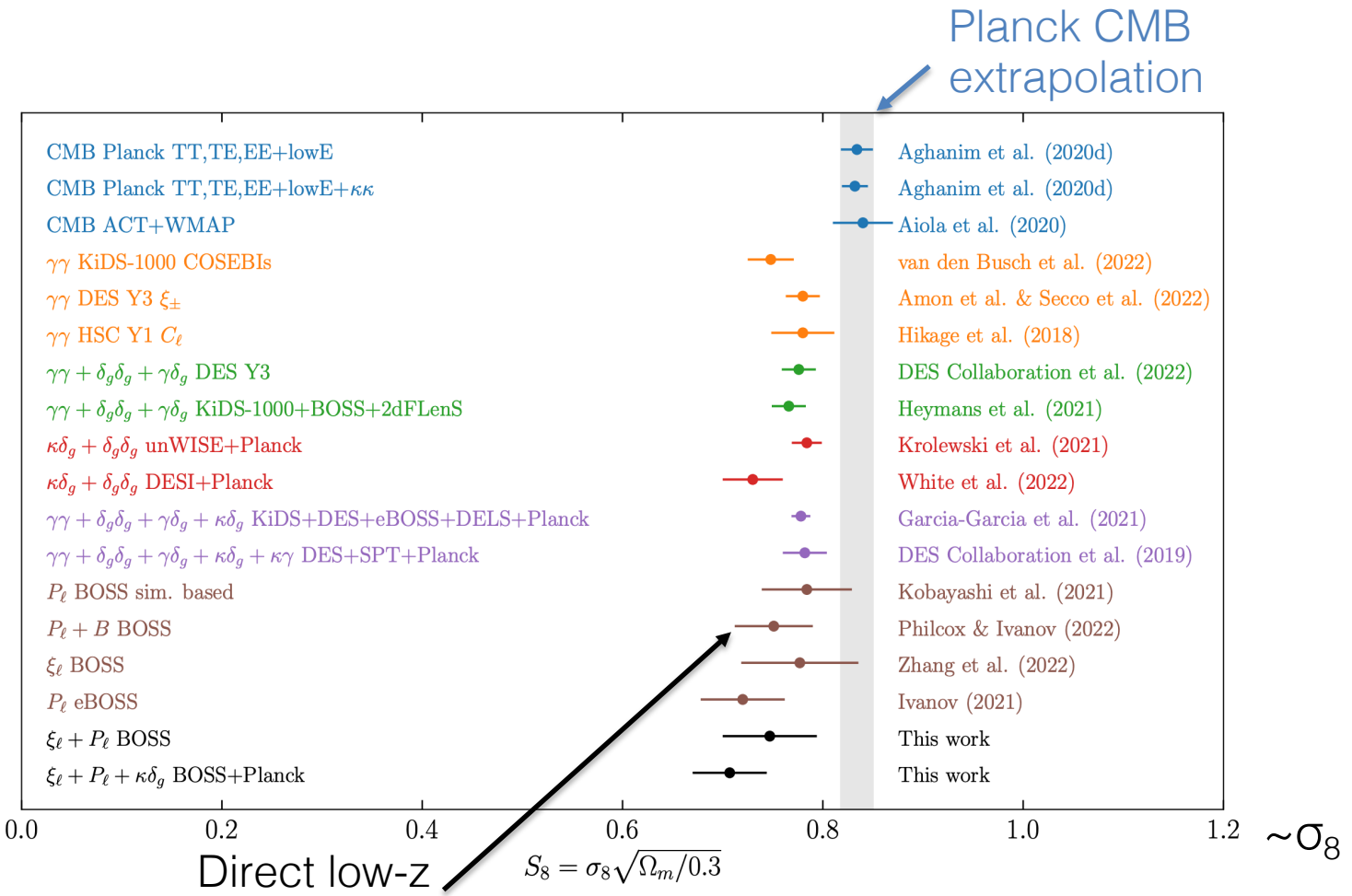
Motivation 1: is something wrong with large-scale structure growth? "σ_8 tension"



Direct low-z measurements from galaxy surveys: 2-3 sigma low in several channels

[Chen++ 2022]

Motivation 1: is something wrong with large-scale structure growth? "σ_8 tension"



Direct low-z measurements from galaxy surveys: 2-3 sigma low in several channels

New, independent measurements needed!

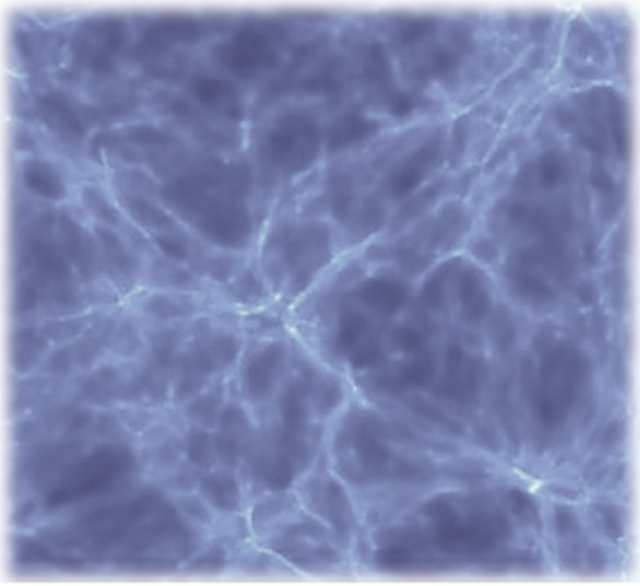
[Chen++ 2022]

Motivation 2:
What is the Mass of Neutrinos?

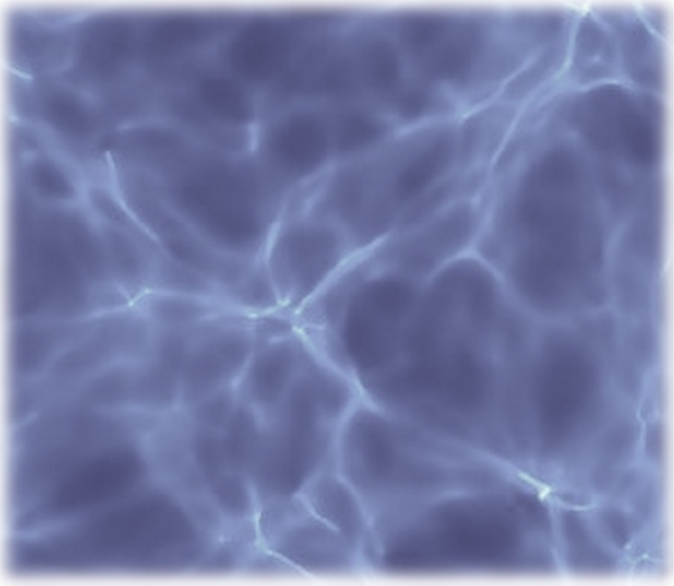
- The more massive neutrinos are, the more small-scale structure growth is suppressed.

Large-scale mass distribution:

Image: Viel++ 2013



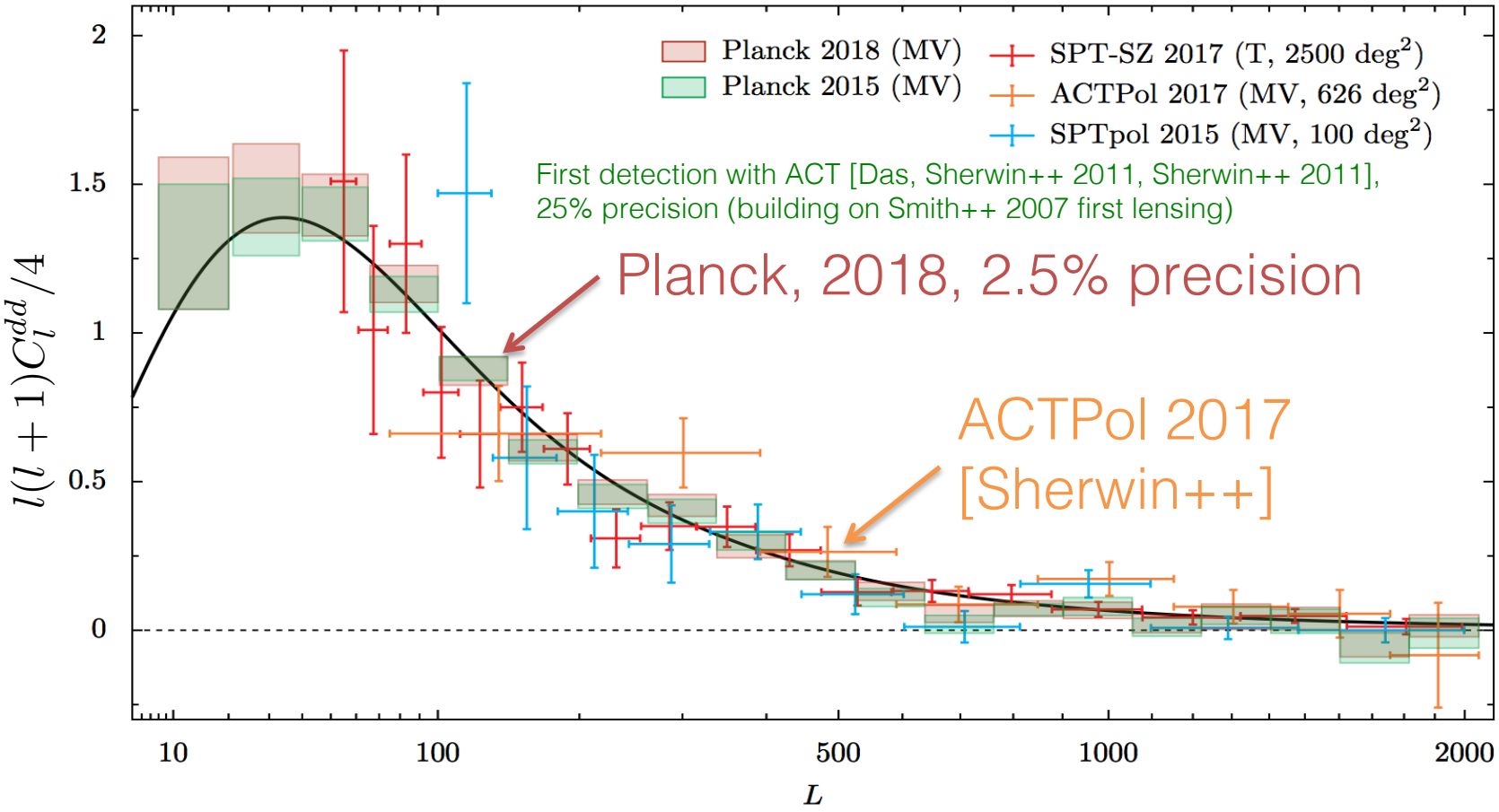
No neutrinos



Massive neutrinos

- Probes approaching detection limit!

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



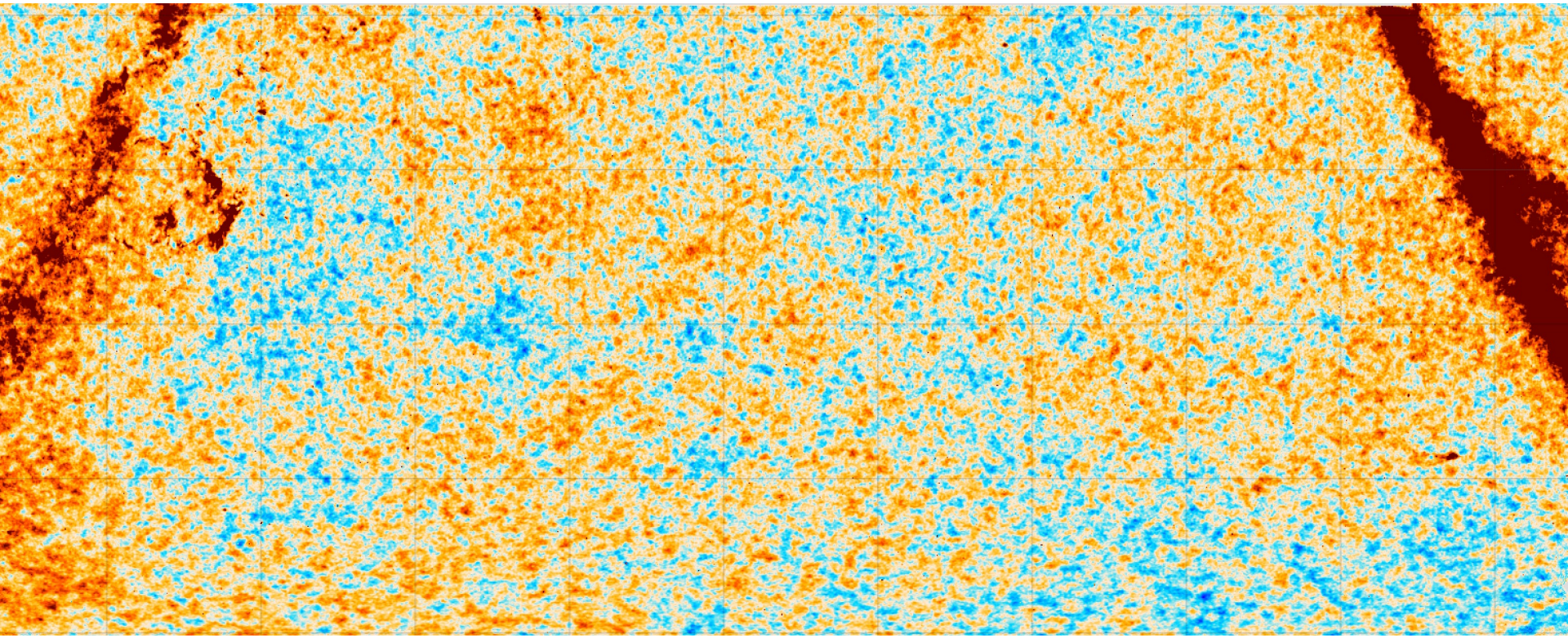
- Rapid progress – but only just beginning. New ground-based experiments such as AdvACT, Simons Observatory!

Atacama Cosmology Telescope (ACT) – RIP ☹

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

ACT Data Release (DR) 6:
new, state of the art CMB and lensing maps!

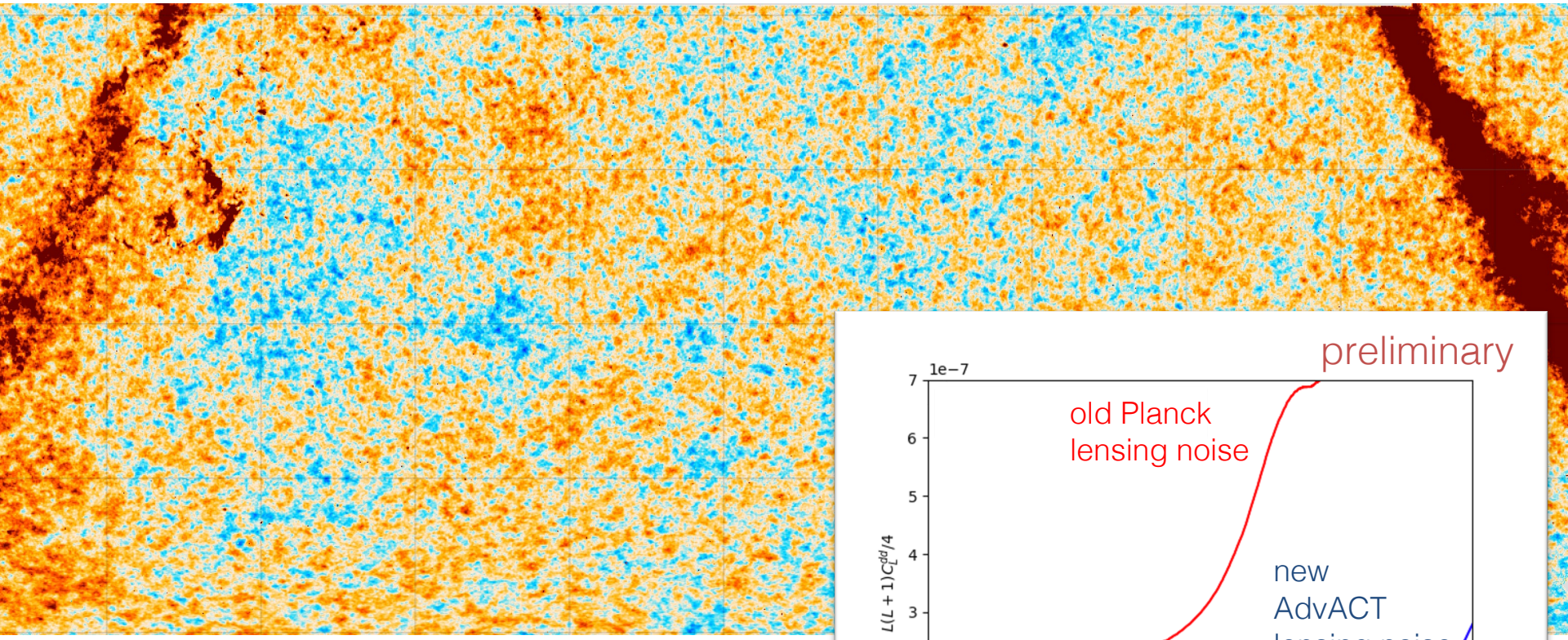
ACT DR6 CMB map



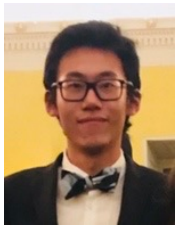
- New ACT polarized data through 2020 (DR6):16000 deg^2 at high resolution
  ~10 x more data volume than previous release!

ACT DR6: new, state of the art CMB and lensing maps!

AdvACT CMB map



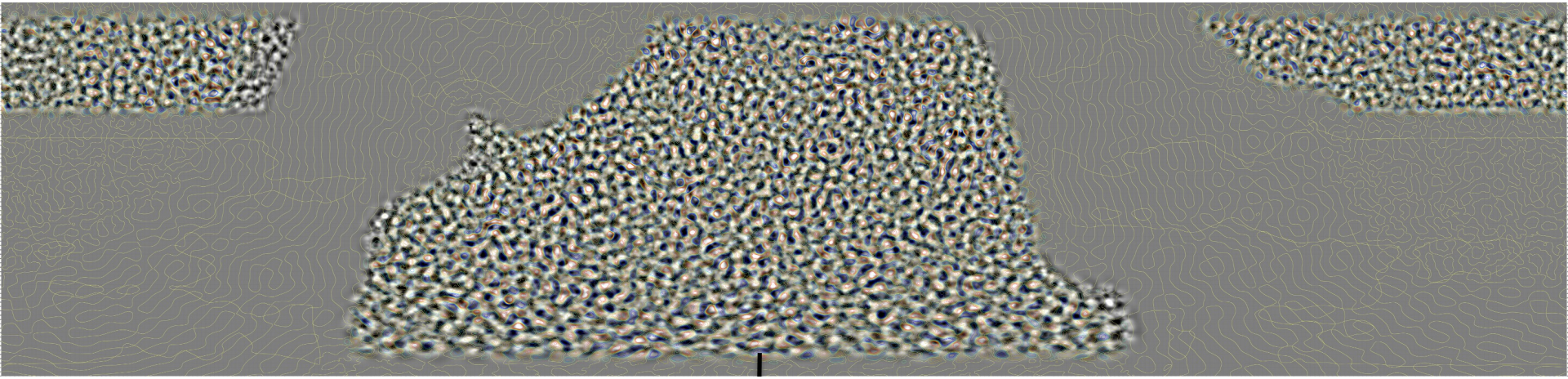
- Gives powerful lensing map! (link)

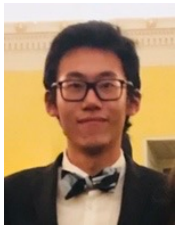


Frank Qu

ACT DR6: new, state of the art lensing mass maps!

AdvACT CMB lensing map: 10000 deg^2 total





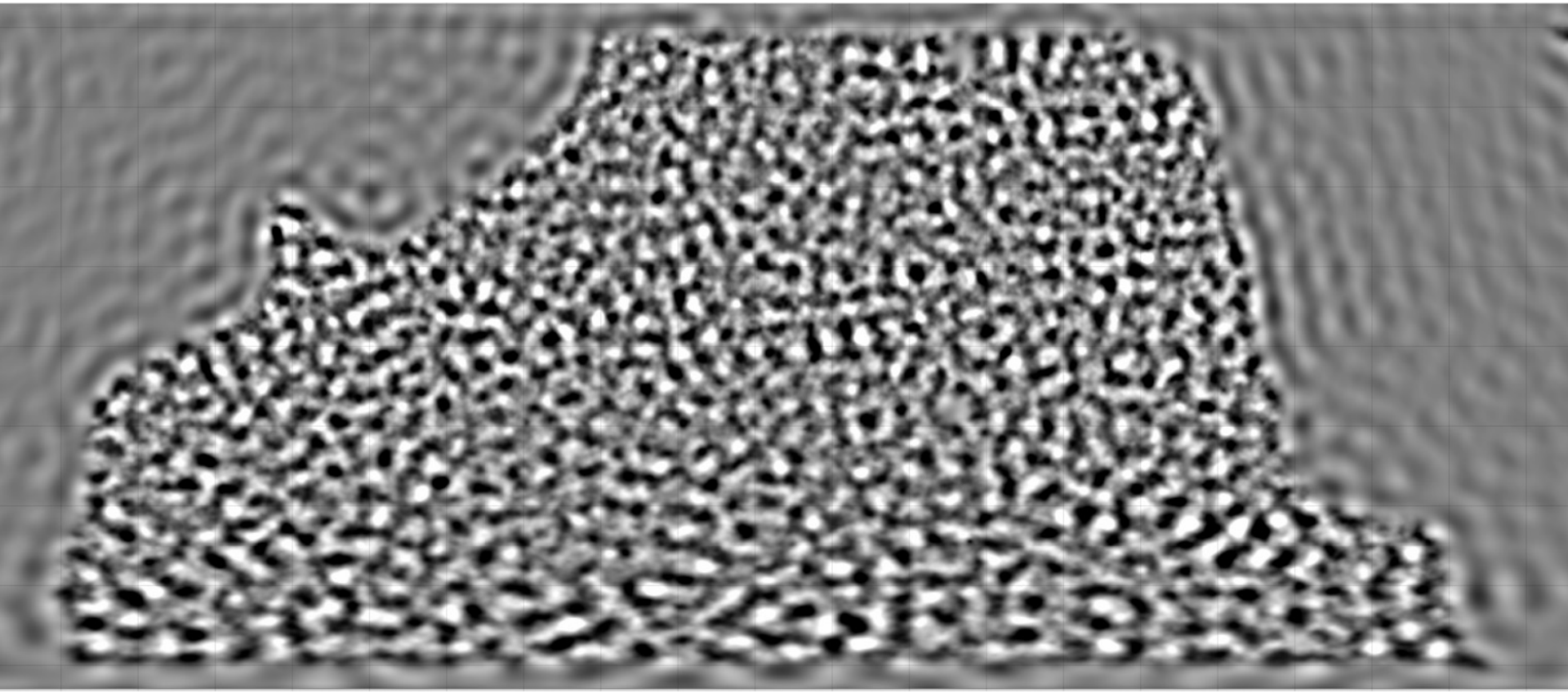
Frank Qu

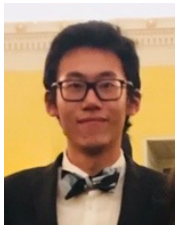
- Gives powerful lensing map! (link)

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

ACT DR6: new, state of the art lensing mass maps!

AdvACT CMB lensing map: 10000 deg^2 total



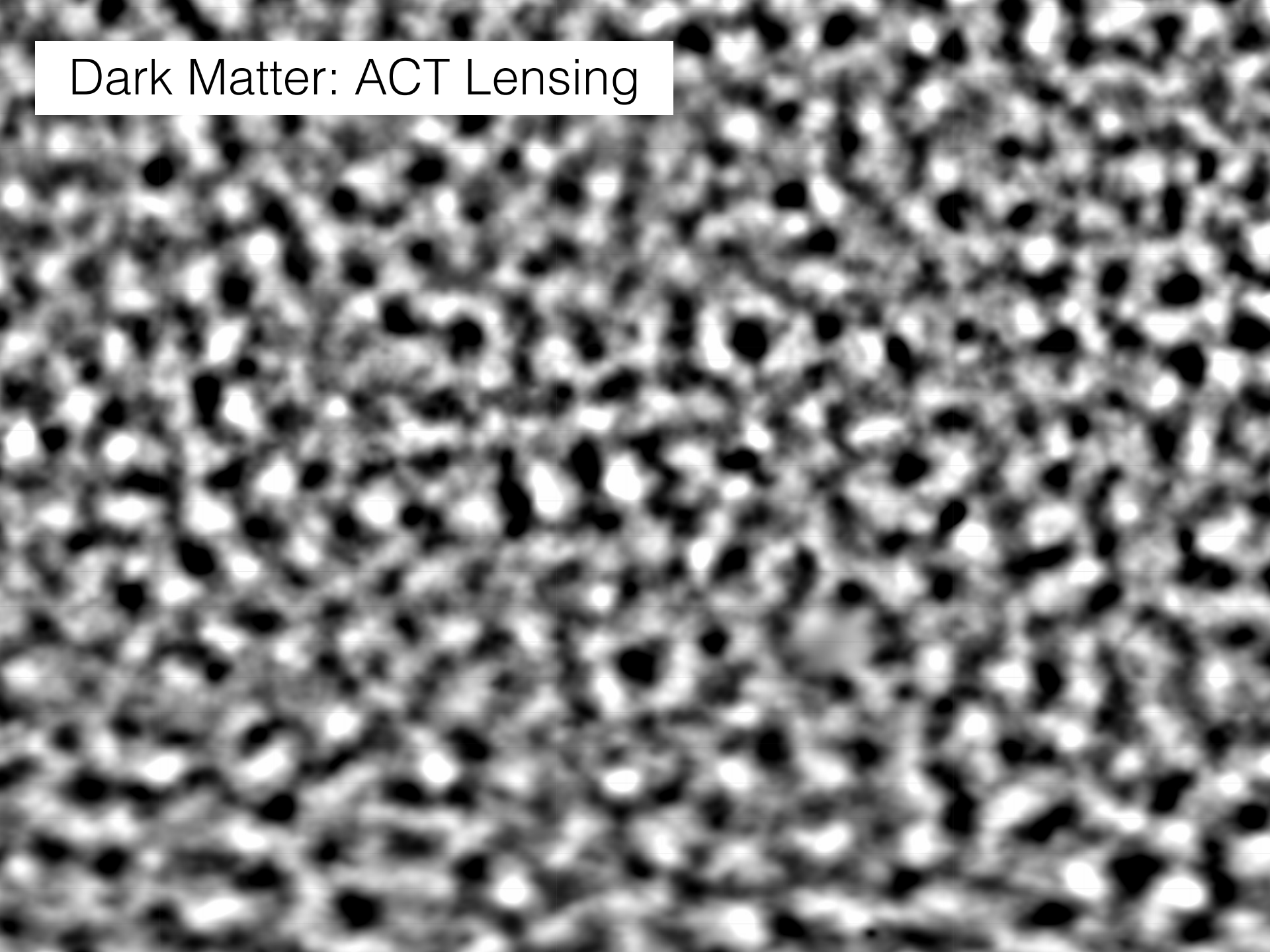


Frank Qu

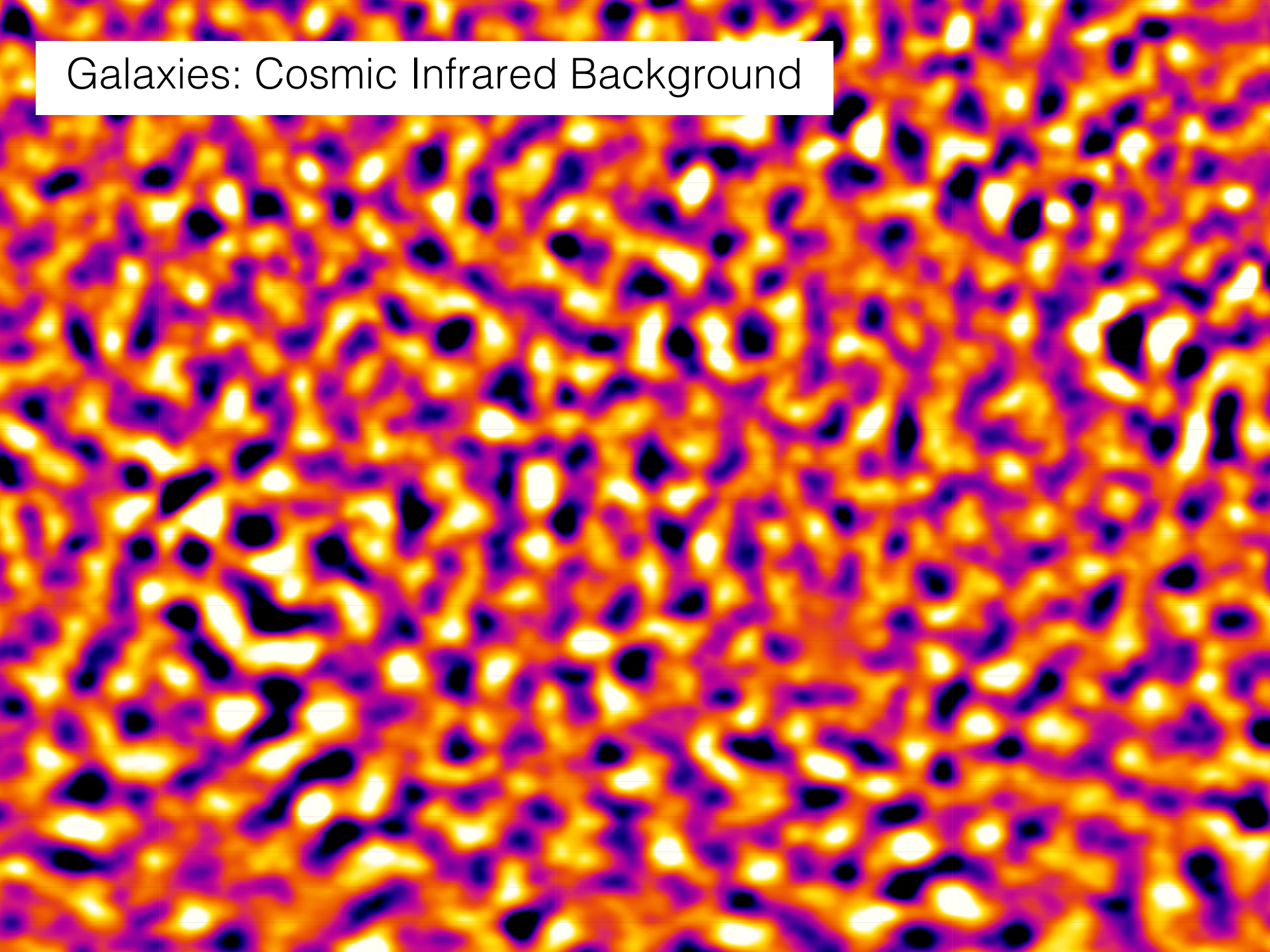
- Gives powerful lensing map! (link)

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

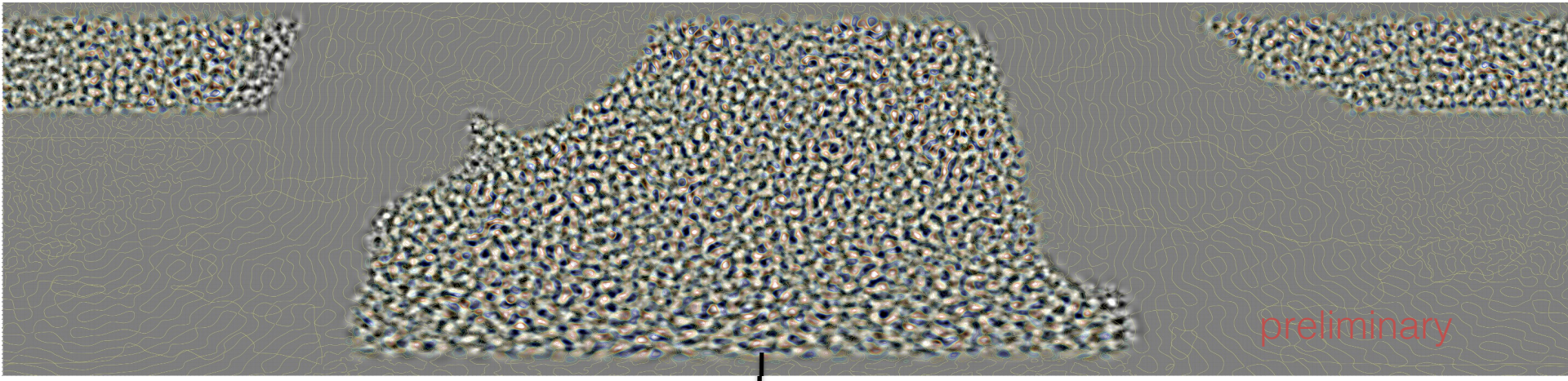
Dark Matter: ACT Lensing



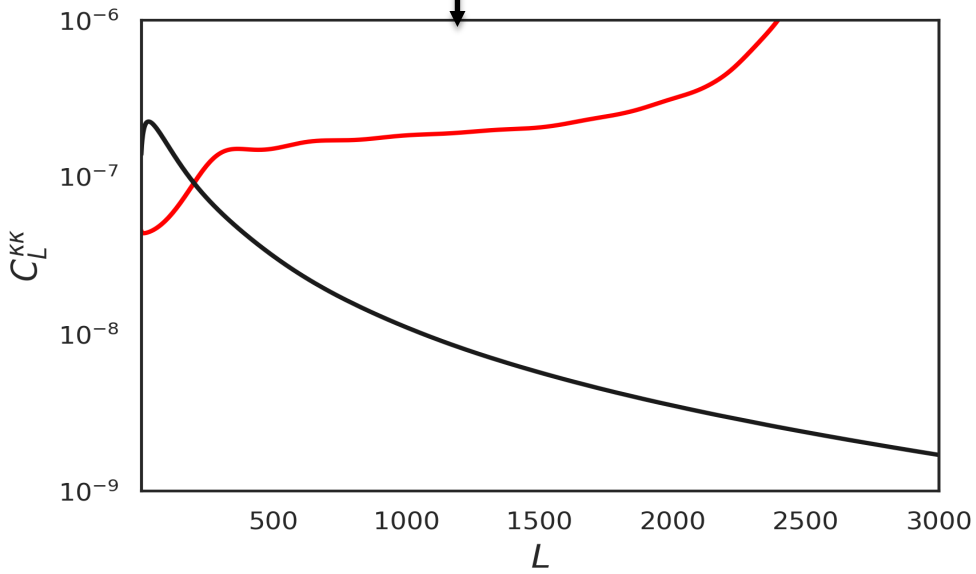
Galaxies: Cosmic Infrared Background



Measuring the CMB Lensing Power Spectrum



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

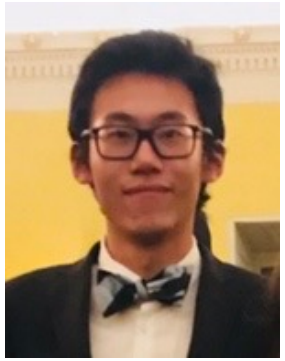


[Qu++ in prep.]

Null and systematic test suite

200+ tests!

Array difference	Temperature vs polarization
Frequency difference	Curl deflection
Sky region difference	Noise only map

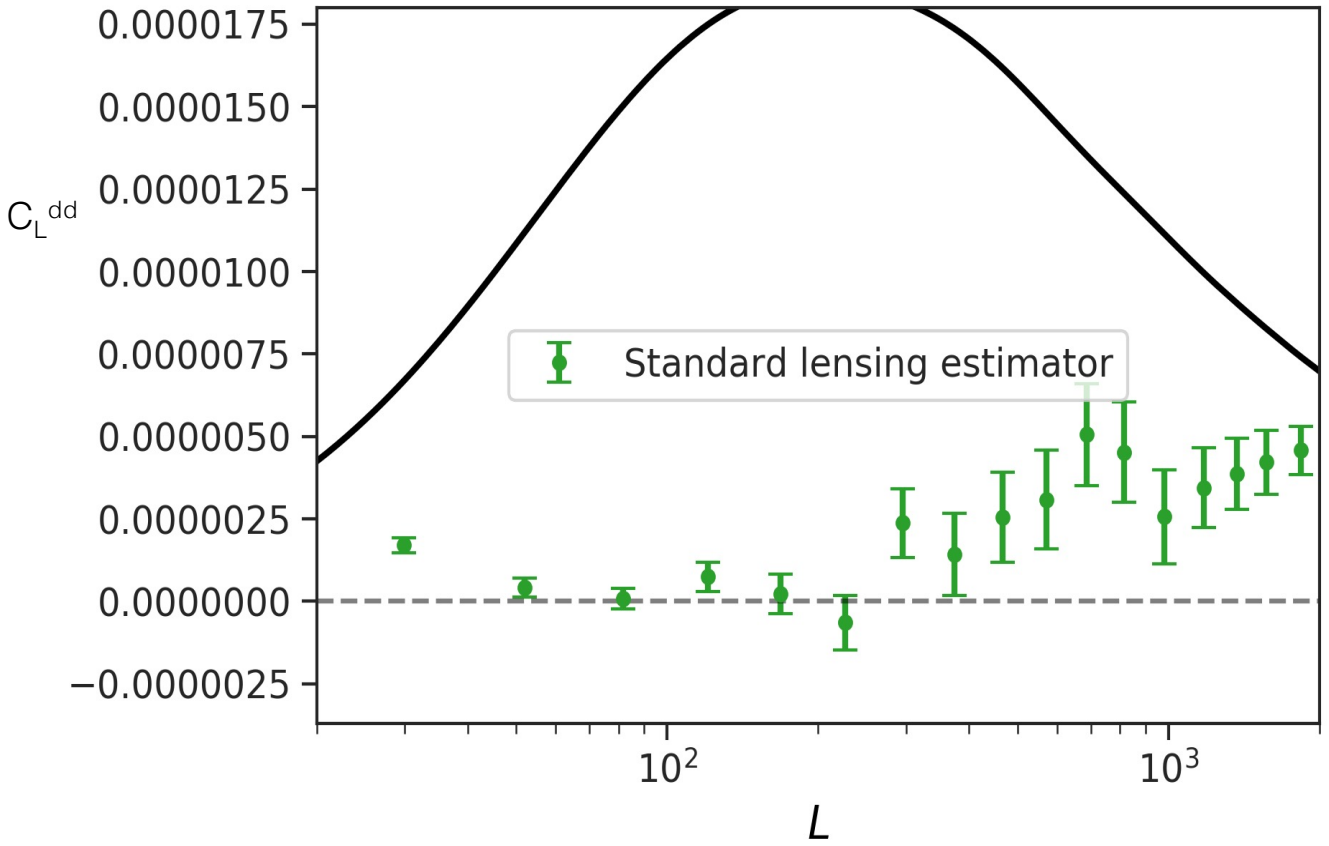


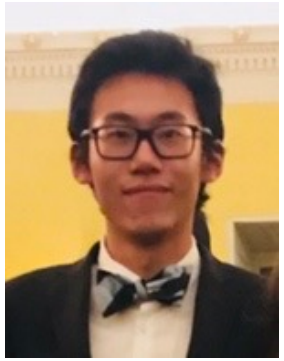
Frank Qu

[Qu, Sherwin++ in prep.]

Null test problems…

- Problem: getting biased results from even basic null with data noise??



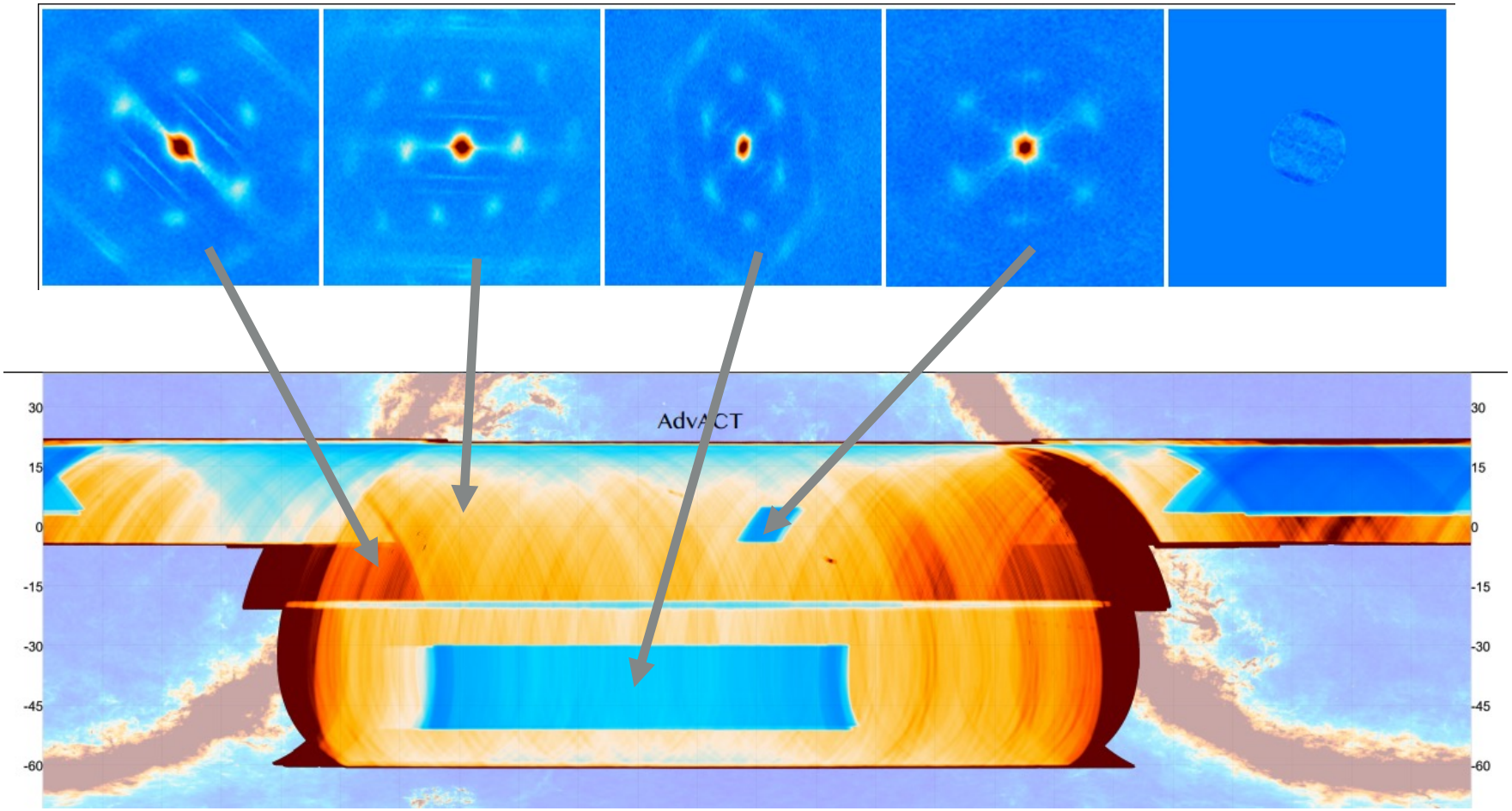


Frank Qu

[Qu, Sherwin++ in prep.]

Null test problems…

- Ground-based noise is very complicated to model

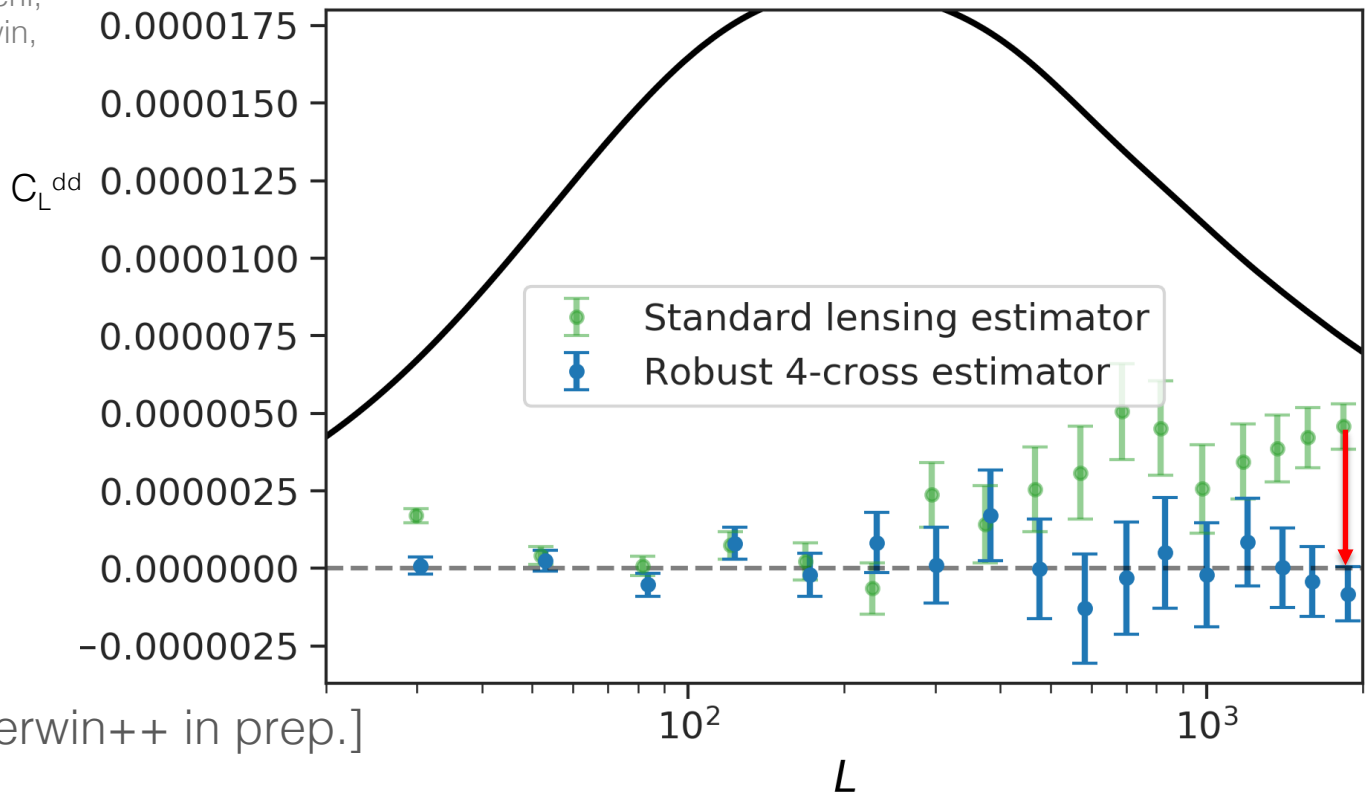


and solutions

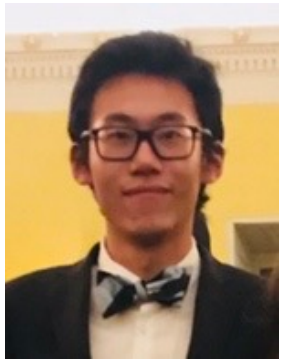
- New solution: divide data into many independent splits, perform 4-field equivalent of a cross-correlation

$$C_L^{dd} \sim \langle T_1 T_2 T_3 T_4 \rangle$$

[Madhavacheril, Smith, Sherwin, Naess 20]



[Qu, Sherwin++ in prep.]

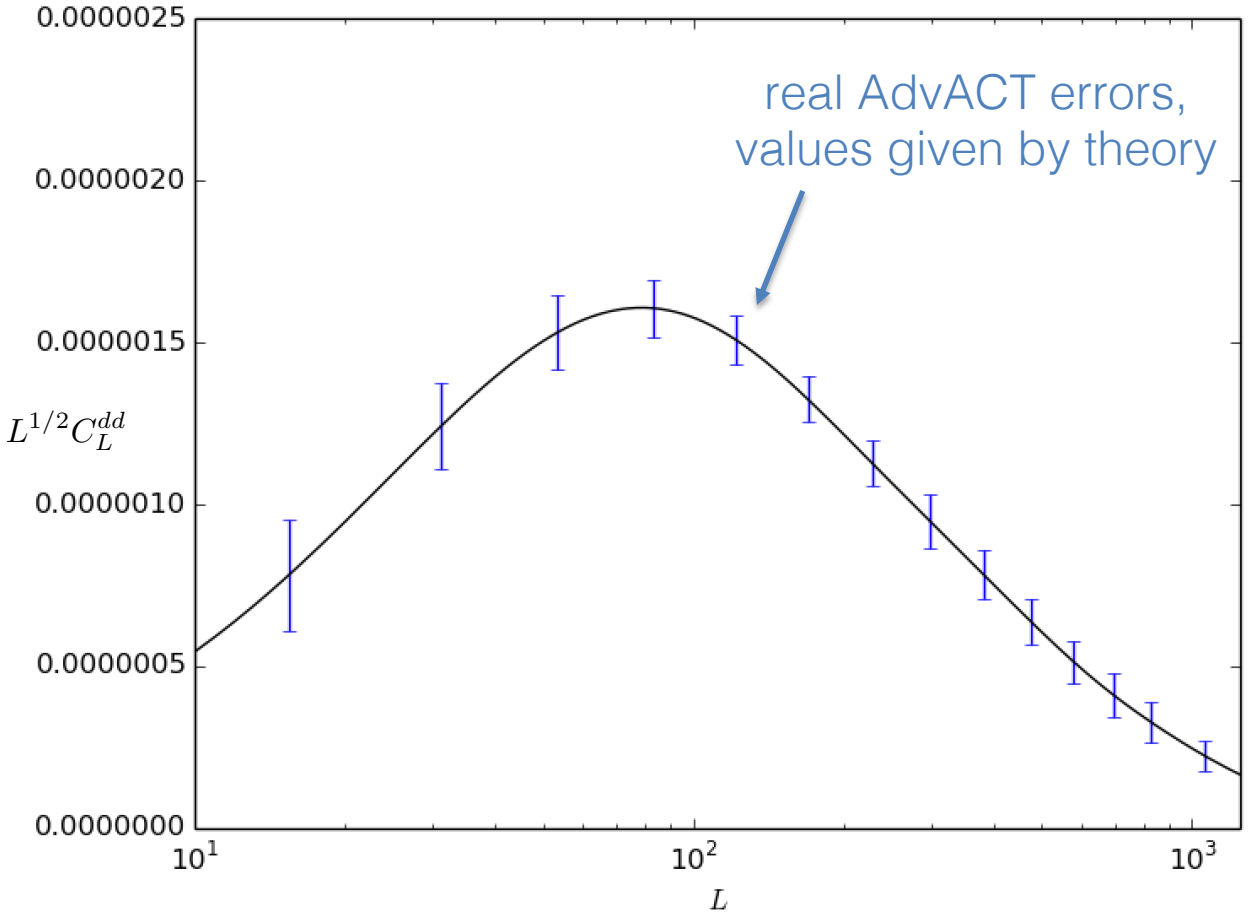


Frank Qu

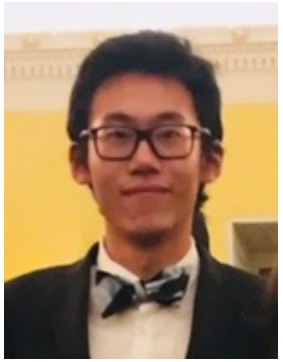
Split-estimator fixes null failure

- Suite of 200+ null tests look good – unblinded!

New ACT DR6 lensing power spectrum errors



Frank
Qu



+ Mat Madhavacheril,
Niall MacCrann

preliminary

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

[Qu, Sherwin++ in prep.]

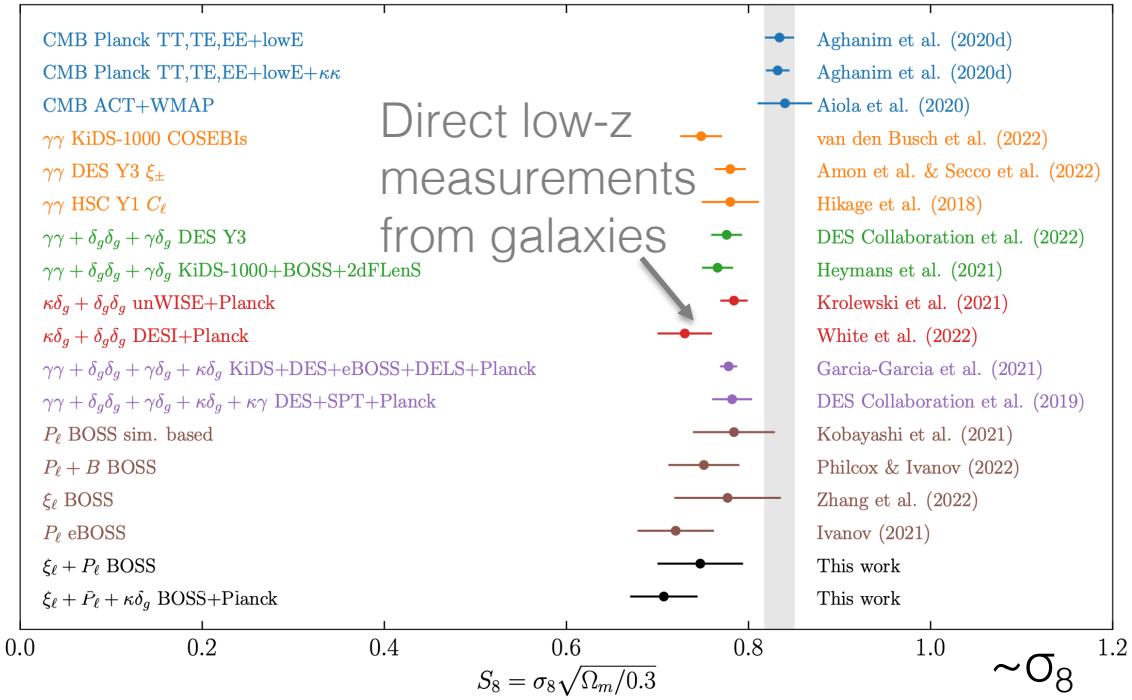
Exciting applications: test σ_8 tension, neutrino mass…

- Competitive but independent constraints on σ_8

  Expect new insights into σ_8 tension!

Planck CMB extrapolation

[Chen++ 2022]



Our approx. error bar size

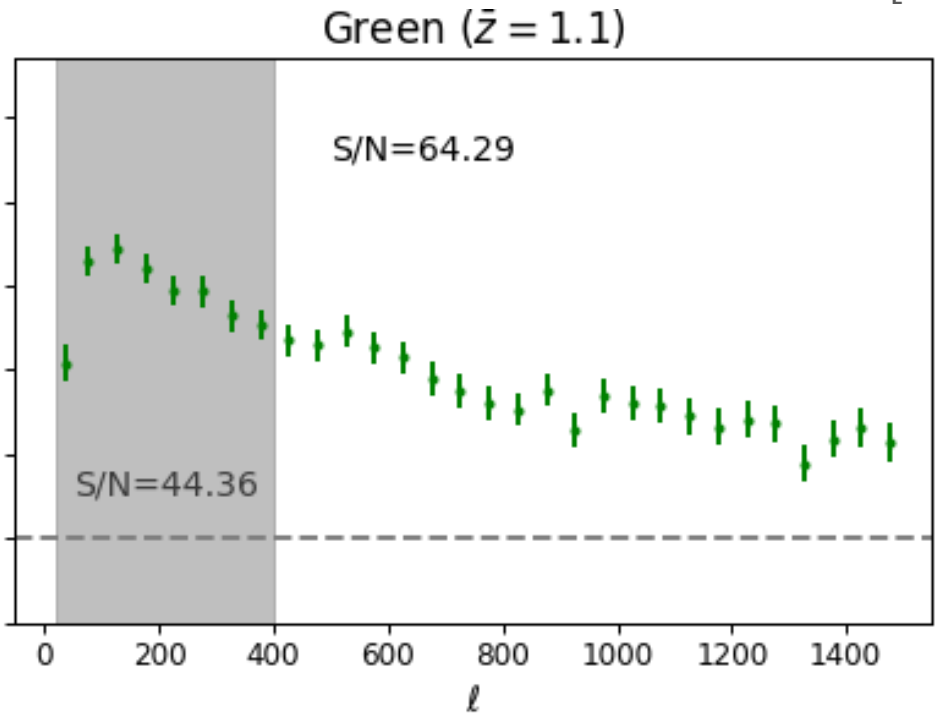
- And: new, tightest (?) constraints on neutrino mass approaching minimum 60 meV

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

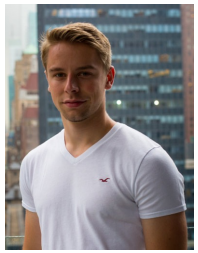
Low-redshift structure growth from cross-correlations

- Not just projection: use cross-correlations with galaxies to restore z-dependence

[Farren++ in prep.]



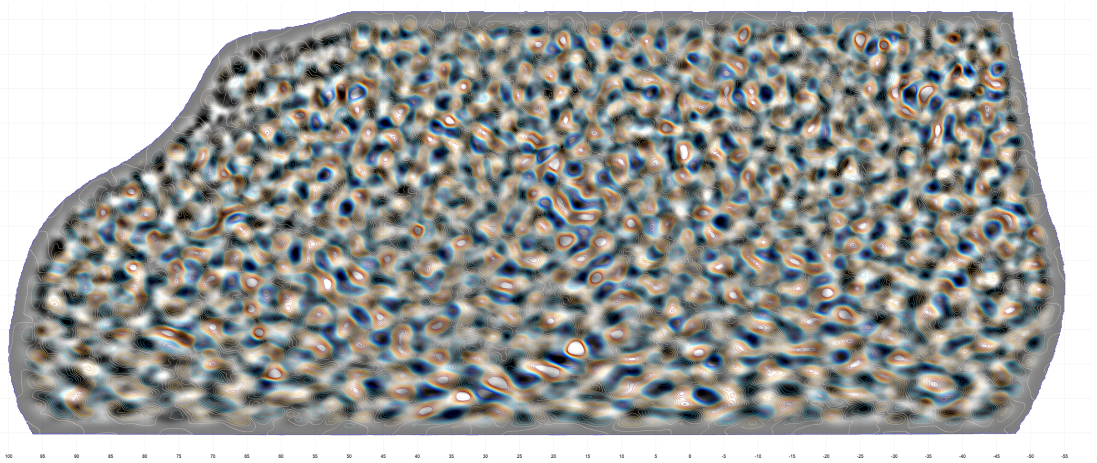
- UnWISE x ACT: comparable tests of structure growth but at lower redshift z~0.6-1. Soon! (Future, z>4).



Gerrit Farren

Summary

- AdvACT: new CMB lensing mass maps and spectra measured
- Provide tests of cosmic structure growth + neutrino masses
- Aim to clarify unsolved problems: is something wrong with large-scale structure growth? What is neutrino mass?



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!