Cosmology with CMB Lensing

ACT, SO and beyond

Mathew Madhavacheril

Perimeter Institute

From Planck to the Future of CMB

Ferrara

May 26, 2022

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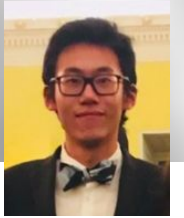


Frank Qu,
grad student at
Cambridge

Omar Darwish, grad
student at Cambridge

Eunseong Lee, grad
student at
Manchester

Zach Atkins, grad
student at
Princeton

Boryana Hadzhiyska,
grad student at
Harvard

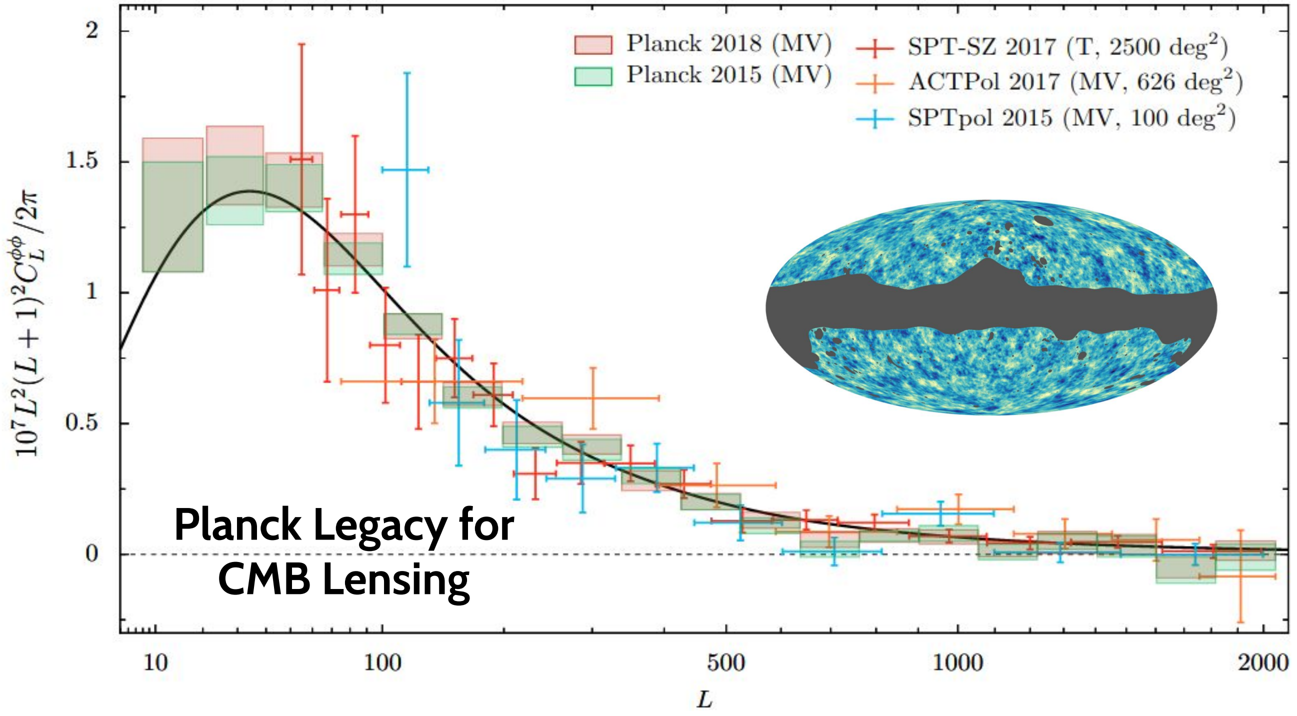
Nam Nguyen, grad
student at Berkeley

NSF

ACT

SIMONS OBSERVATORY

CMB-S4



See also
Wu et al SPT 2019
and measurements from PolarBear and BICEP

Planck 2013 XVII A&A, 380+ citations
Planck 2015 XV, A&A, 520+ citations
Planck 2018 VIII, A&A, 400+ citations

- Mostly linear scales; therefore robust probe of (dark) matter distribution
- 2.5% measurement
- Map with S/N per mode ~1 over 65% of the sky

The CMB lensing inferred matter field is a particle physics laboratory

- Neutrino mass (absolute mass scale; in combination with lab experiments: hierarchy, Majorana phases) *e.g. Allison, Caucal, Calabrese, Dunkley, Louis PRD 2015*
- Dark-matter baryon scattering *e.g. Zack Li, Gluscevic, Boddy, Madhavacheril PRD 2018*
- Axion dark matter *e.g. Nguyen, Sehgal, Madhavacheril PRD 2017*
- Dark matter decay *e.g. Alvi, Brinckmann, Gerbino, Lattanzi, Pagano 2022*
- + more (see talks by Jo Dunkley and Massimiliano Lattanzi)

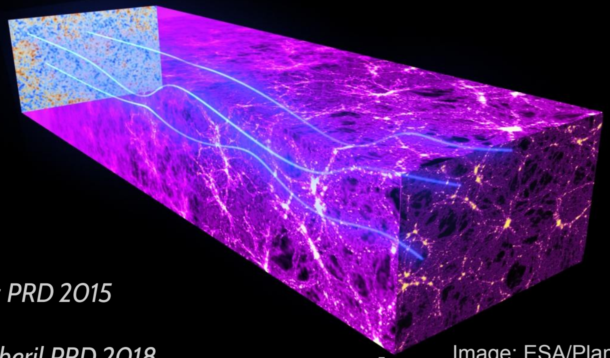


Image: ESA/Planck

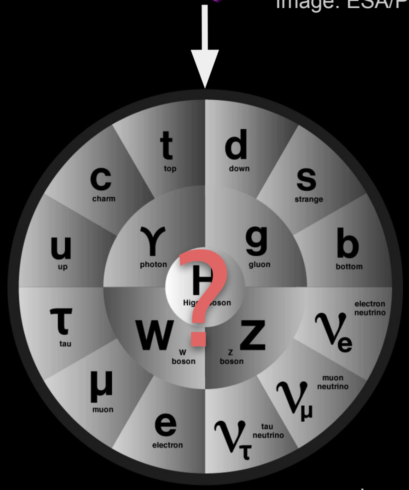


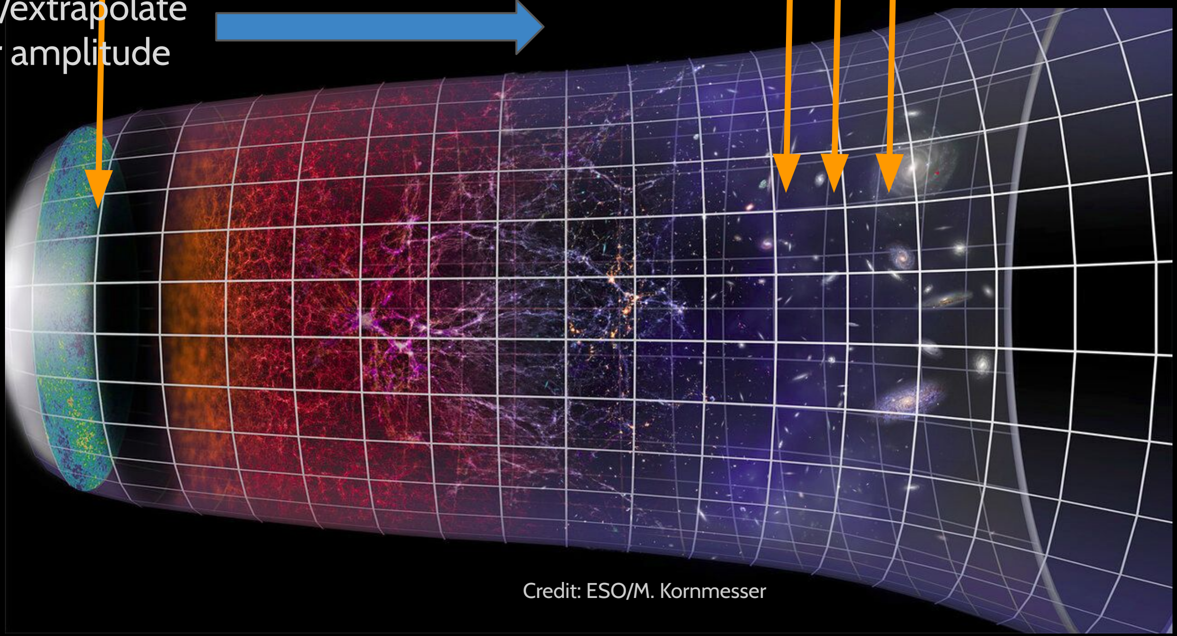
Image: CERN

"Indirect sigma8"

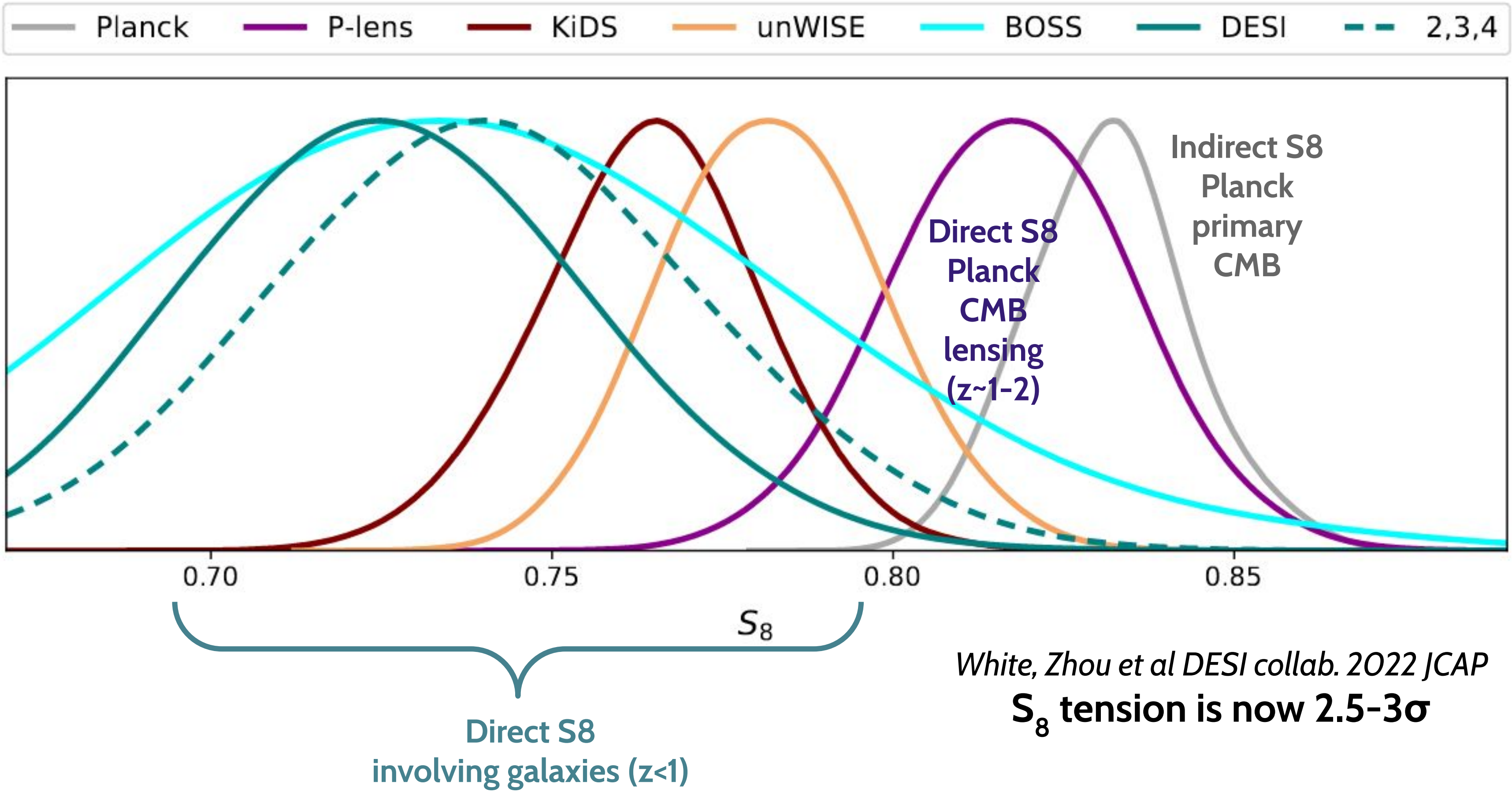
1. Measure parameters from primary CMB
2. Derive/extrapolate matter amplitude

"Direct sigma8"

1. Measure matter amplitude directly
2. Tomographic!



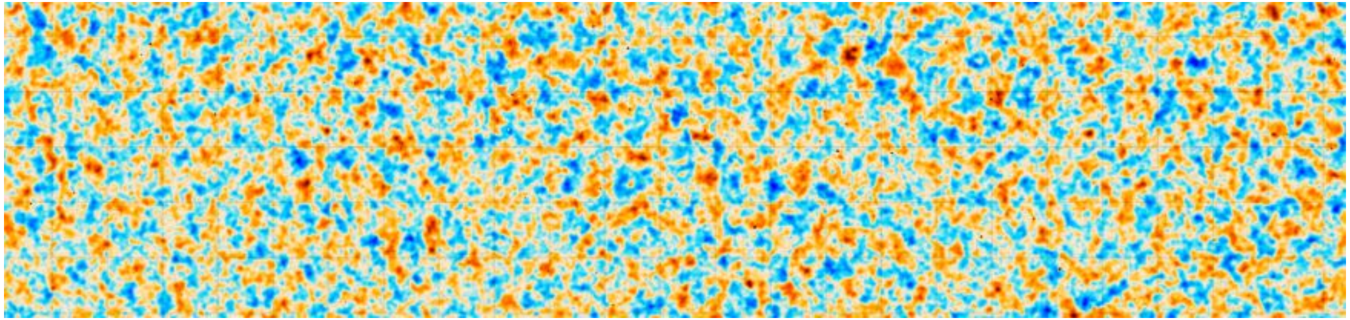
Credit: ESO/M. Kornmesser

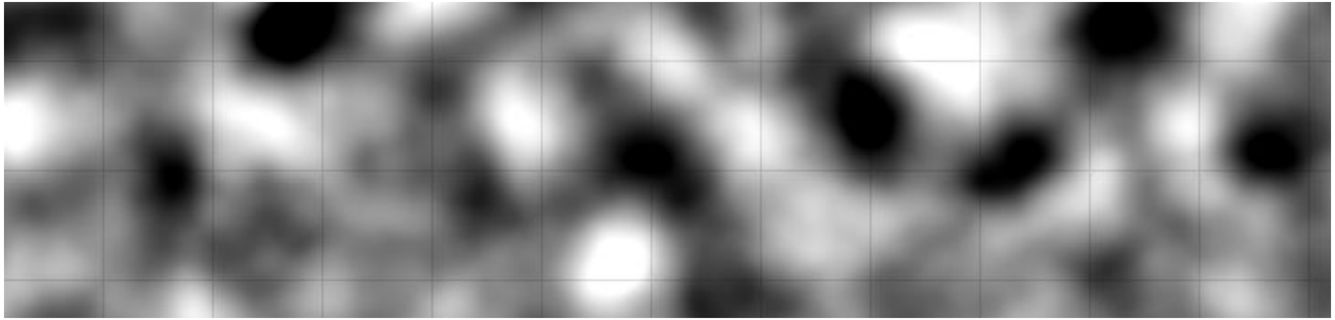


White, Zhou et al DESI collab. 2022 JCAP

S_8 tension is now 2.5-3σ

OBSERVED CMB (MICROWAVE LIGHT)





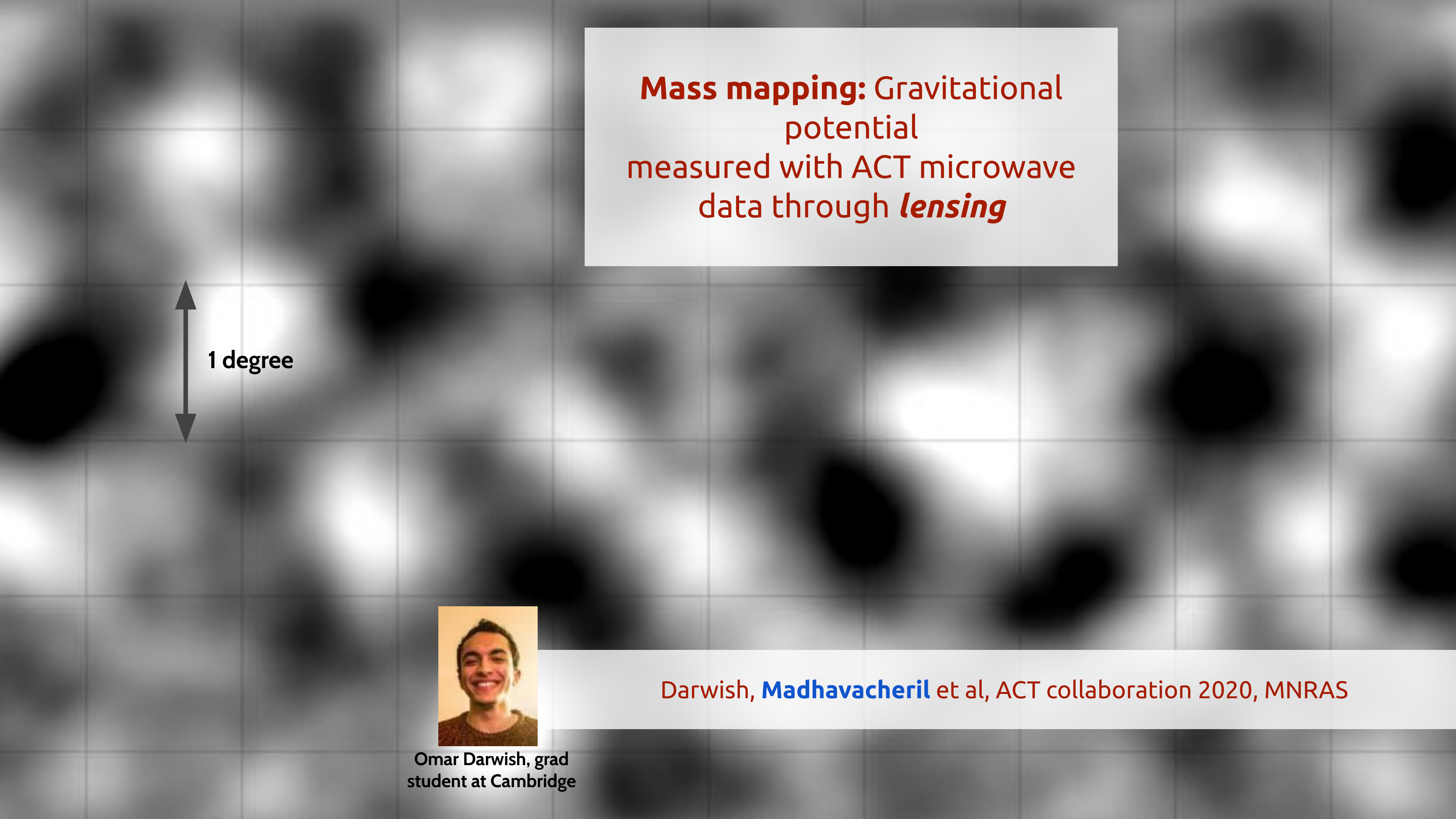
RECONSTRUCTED LENSING (DARK) MATTER DISTRIBUTION

Key point: Large-scale lenses change **small-scale** CMB features

Need **high-resolution** to measure this!

Mathew Madhavacheril, Perimeter Institute

Mass mapping: Gravitational potential
measured with ACT microwave data through ***lensing***

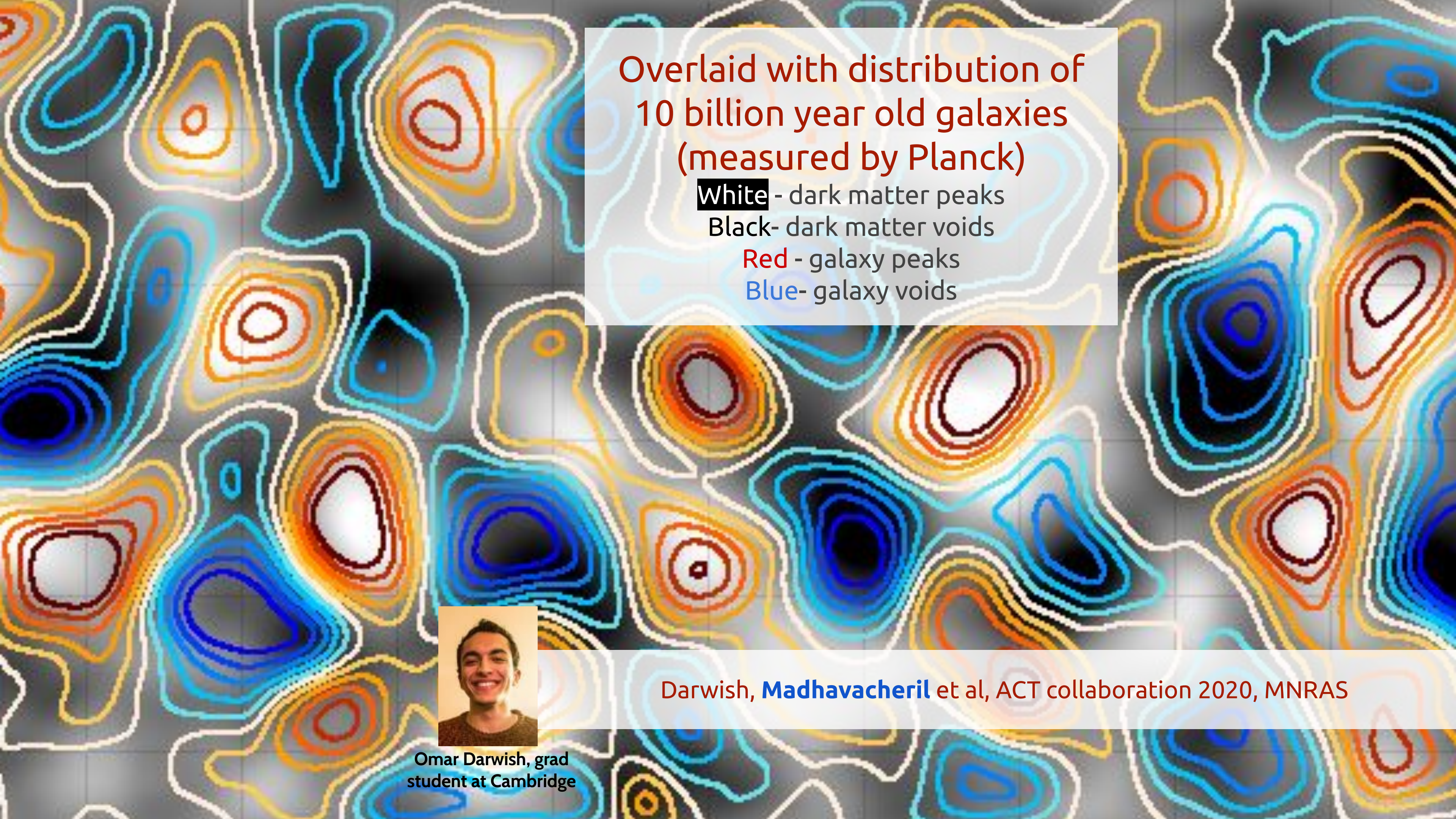


Omar Darwish, grad student at Cambridge

Darwish, **Madhavacheril** et al, ACT collaboration 2020, MNRAS

Overlaid with distribution of 10 billion year old galaxies (measured by Planck)

White - dark matter peaks
Black- dark matter voids
Red - galaxy peaks
Blue- galaxy voids



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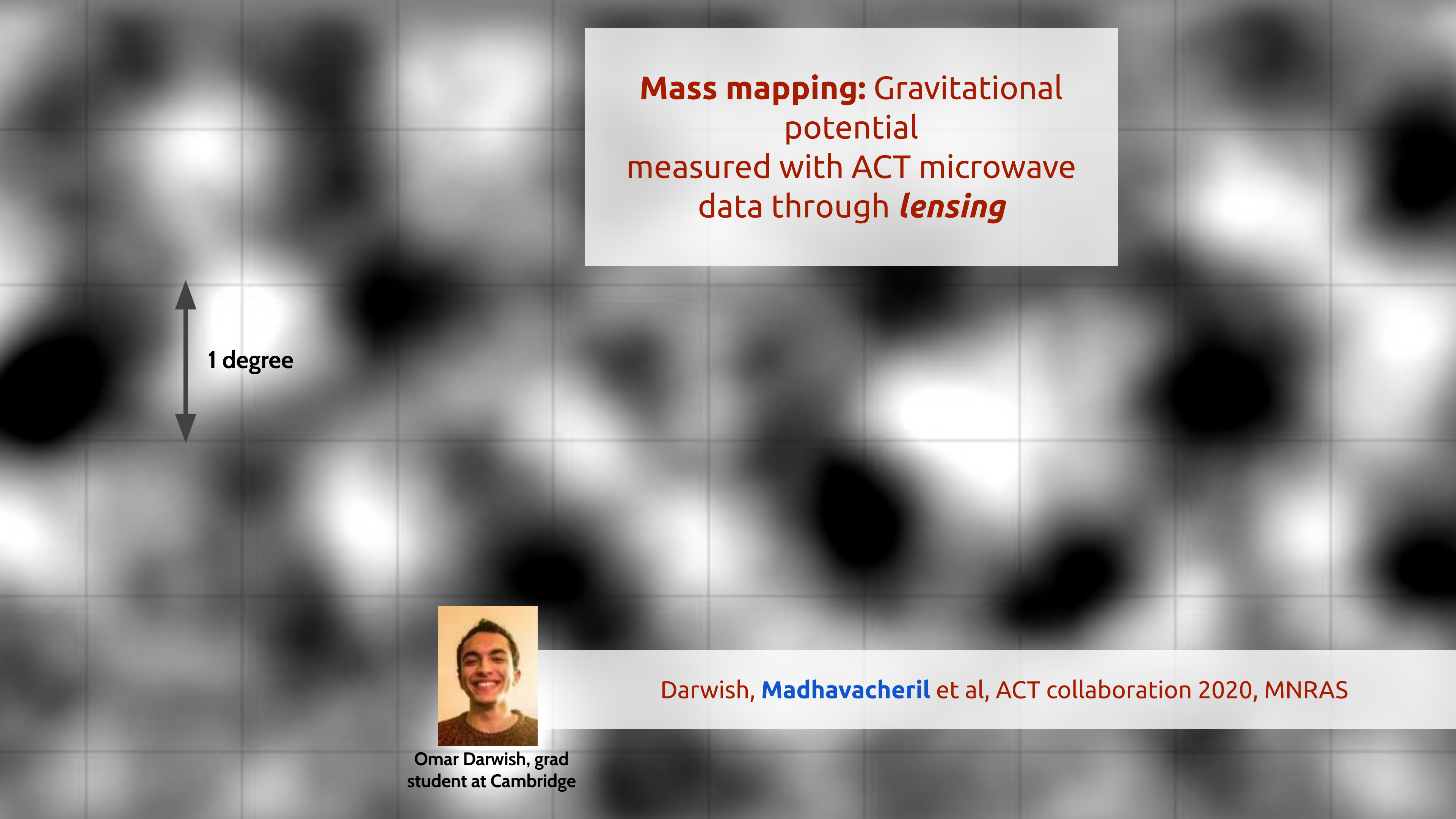

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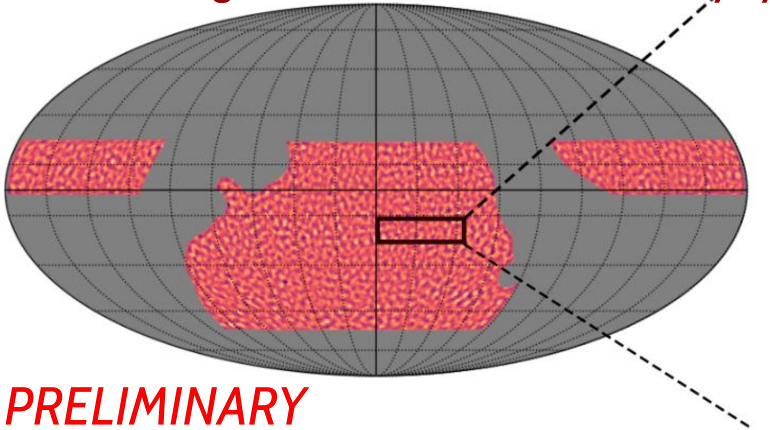
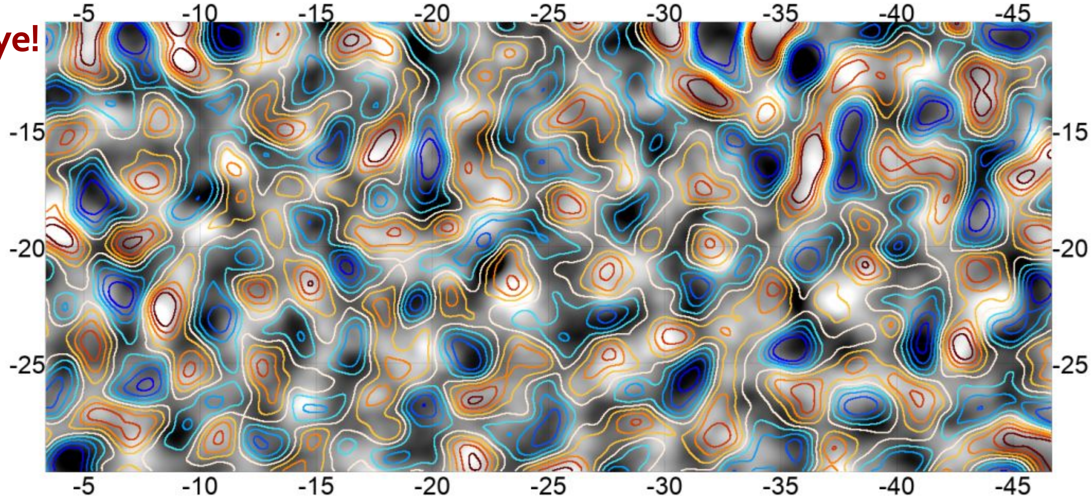
Upcoming ACT release: High-fidelity dark matter mapping over wide area

ACT 30% sky - 6x more than previously shown

You are seeing the dark matter distribution by eye!



PRELIMINARY



Madhavacheril, Qu et al ACT in prep (data up to mid-2021)

Forecast: constrain **neutrino mass to ~70 meV,** close to ruling out inverted hierarchy (>100 meV), 35-40 meV with DESI BAO

~few % constraint on amplitude of fluctuations (significant improvement over *Planck*)

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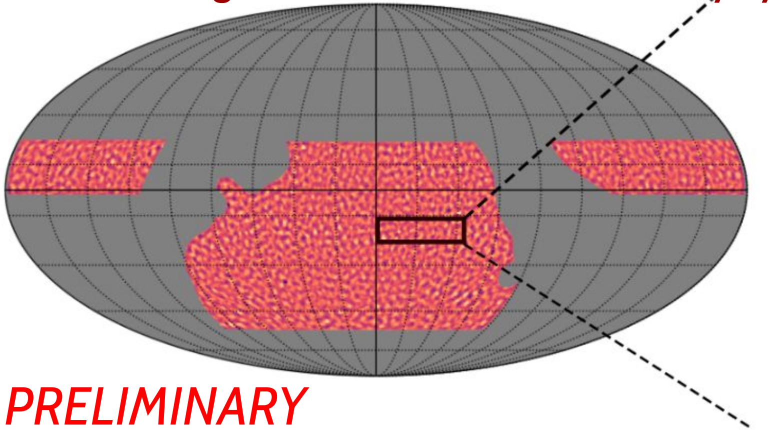

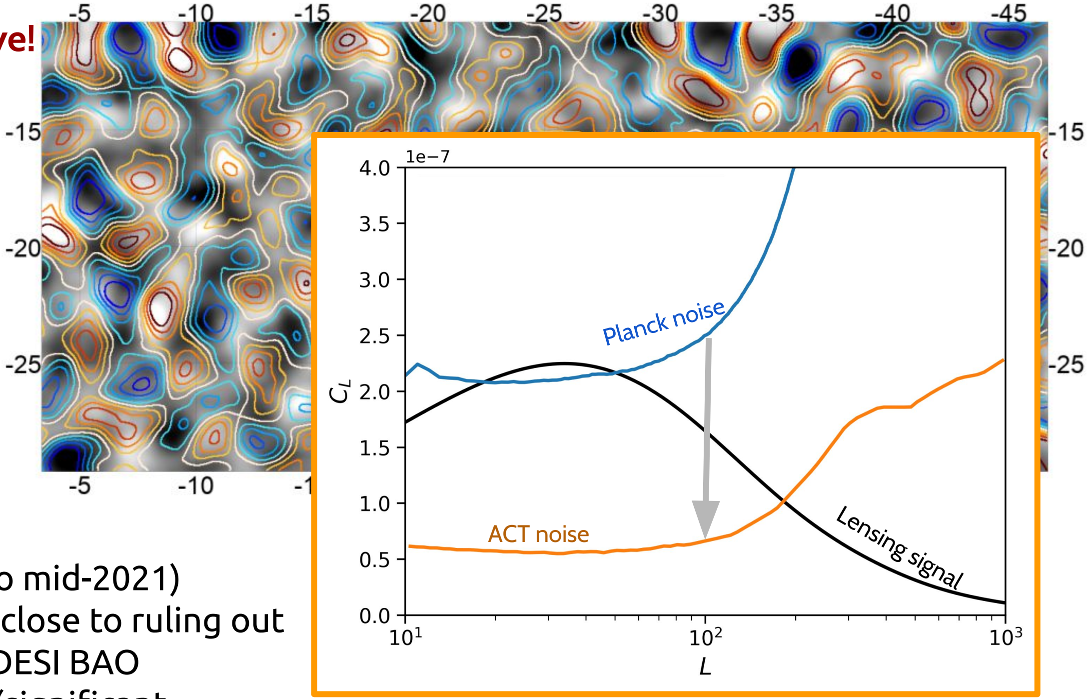

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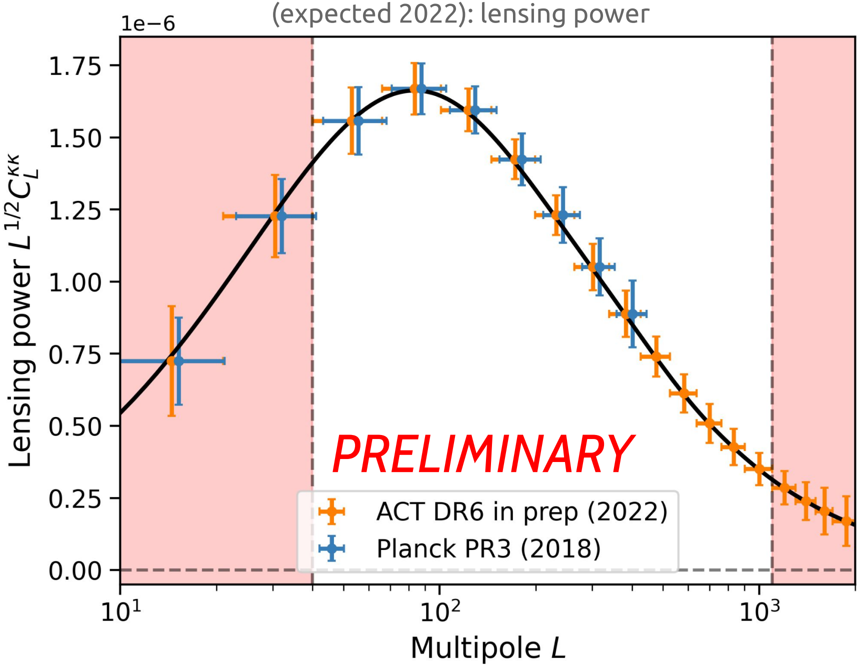
High-precision lensing power spectrum with ACT

Frank Qu, Sherwin, Madhavacheril et al ACT in prep (expected 2022): lensing power



Frank Qu, grad student at Cambridge

See poster!

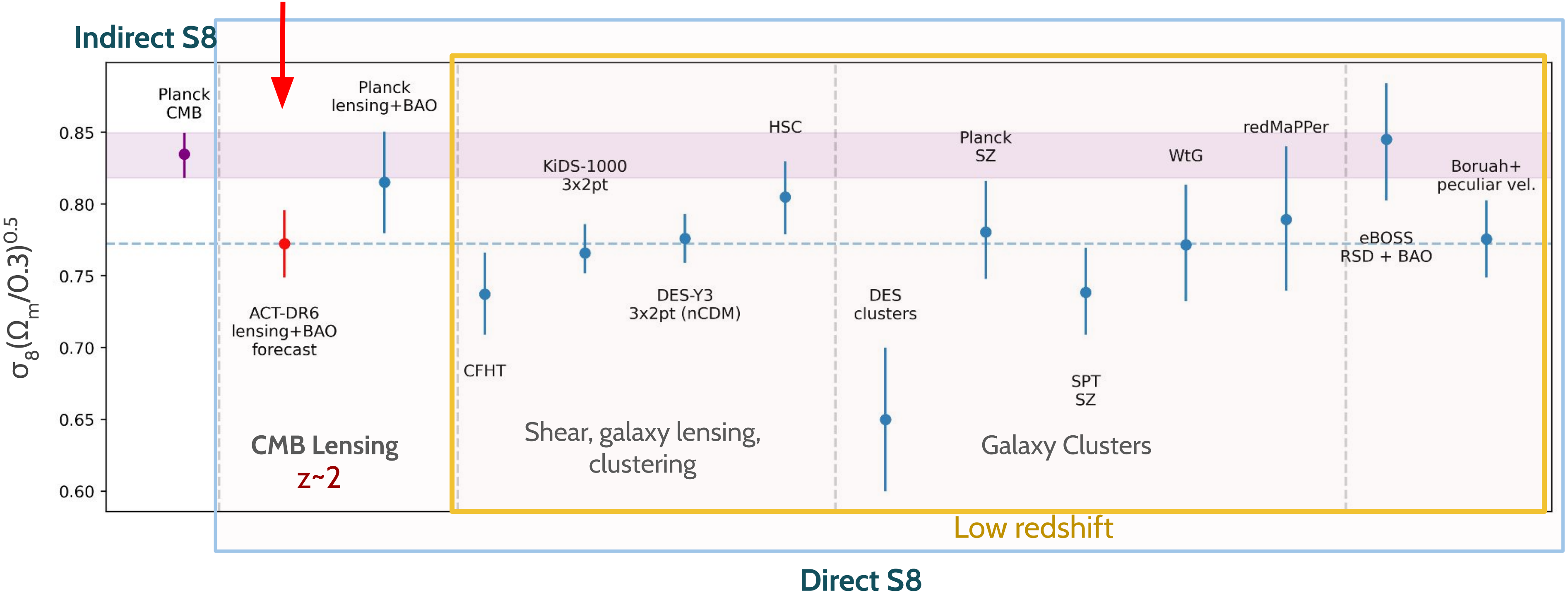
- 2% measurement
- We do **~200 null tests** ; **blinded** until complete
- Lots of lessons learnt for future CMB science readiness (e.g. informing data quality iteration, scan strategy)

Also

- Madhavacheril, Qu et al ACT in prep (expected 2022): lensing map and cosmology
- MacCrann et al ACT (incl. MM) in prep (expected 2022): foreground bias mitigation

Important input to S_8 tension soon with ACT CMB lensing

PRELIMINARY FORECAST



Challenges

- Calibration (gain, beams and more); see talk by Giulio Fabbian
  e.g. Mirmelstein, Fabbian, Lewis, Peloton PRD 2021
- Foregrounds
- Noise bias
- Optimality in the low noise and/or small-scale regime

Challenges

- Calibration (gain, beams and more); see talk by Giulio Fabbian
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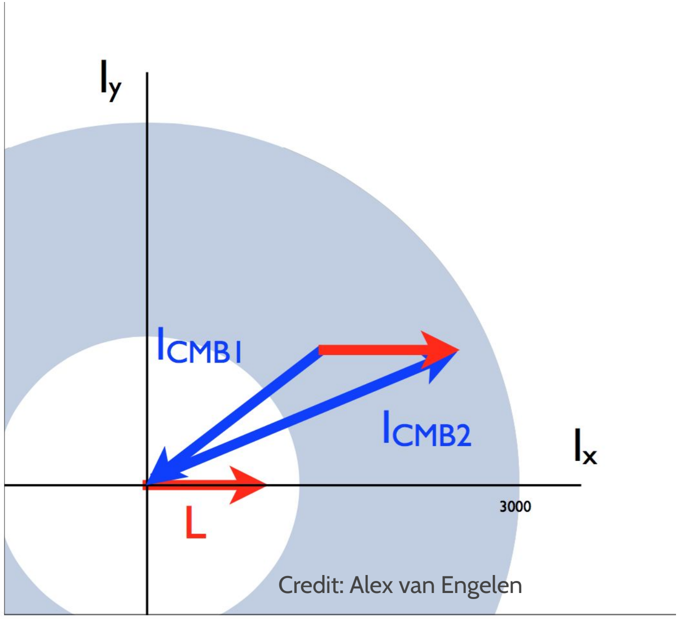
- Foregrounds
- **Noise bias**
- **Optimality in the low noise and/or small-scale regime**

Lensing introduces mode coupling: quadratic estimators



Given an underlying gravitational potential

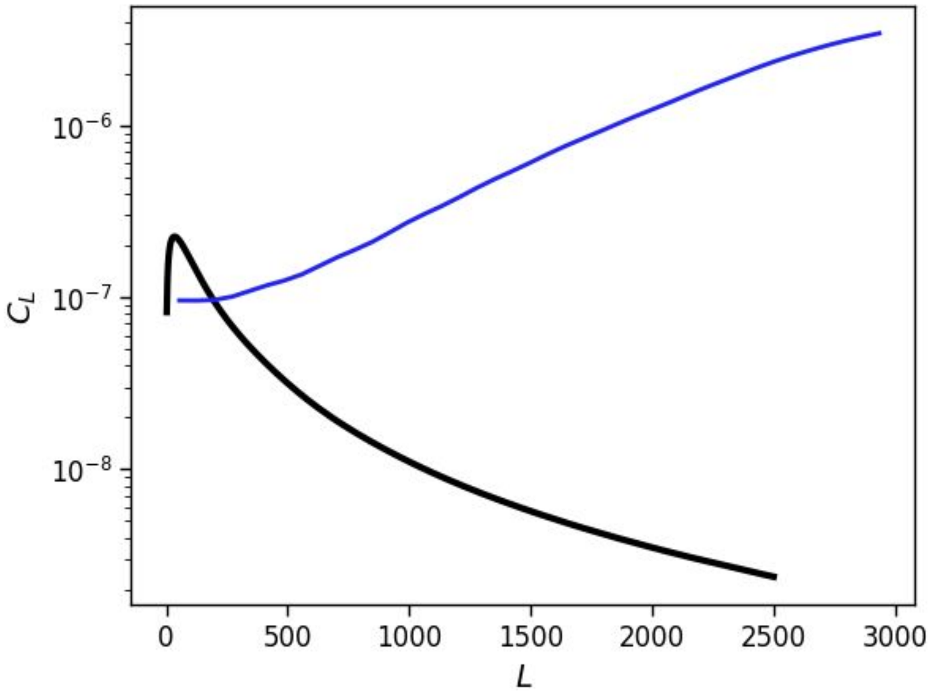
- Real space: lensing remaps points conserving surface brightness
- Fourier space: mode-coupling

$$\langle X(\mathbf{l}_1) X'(\mathbf{l}_2) \rangle_{\rm CMB} = f^{\mathcal{D}}_{XX'}(\mathbf{l}_1, \mathbf{l}_2)\, \phi(\mathbf{l}_1 + \mathbf{l}_2)$$

This triangle configuration allows one to use a quadratic estimator for the underlying potential

$$\hat{\phi}(\mathbf{L}) \sim \sum_{l} X(\mathbf{l}) X'(\mathbf{L} - \mathbf{l})$$

We subtract a large noise bias



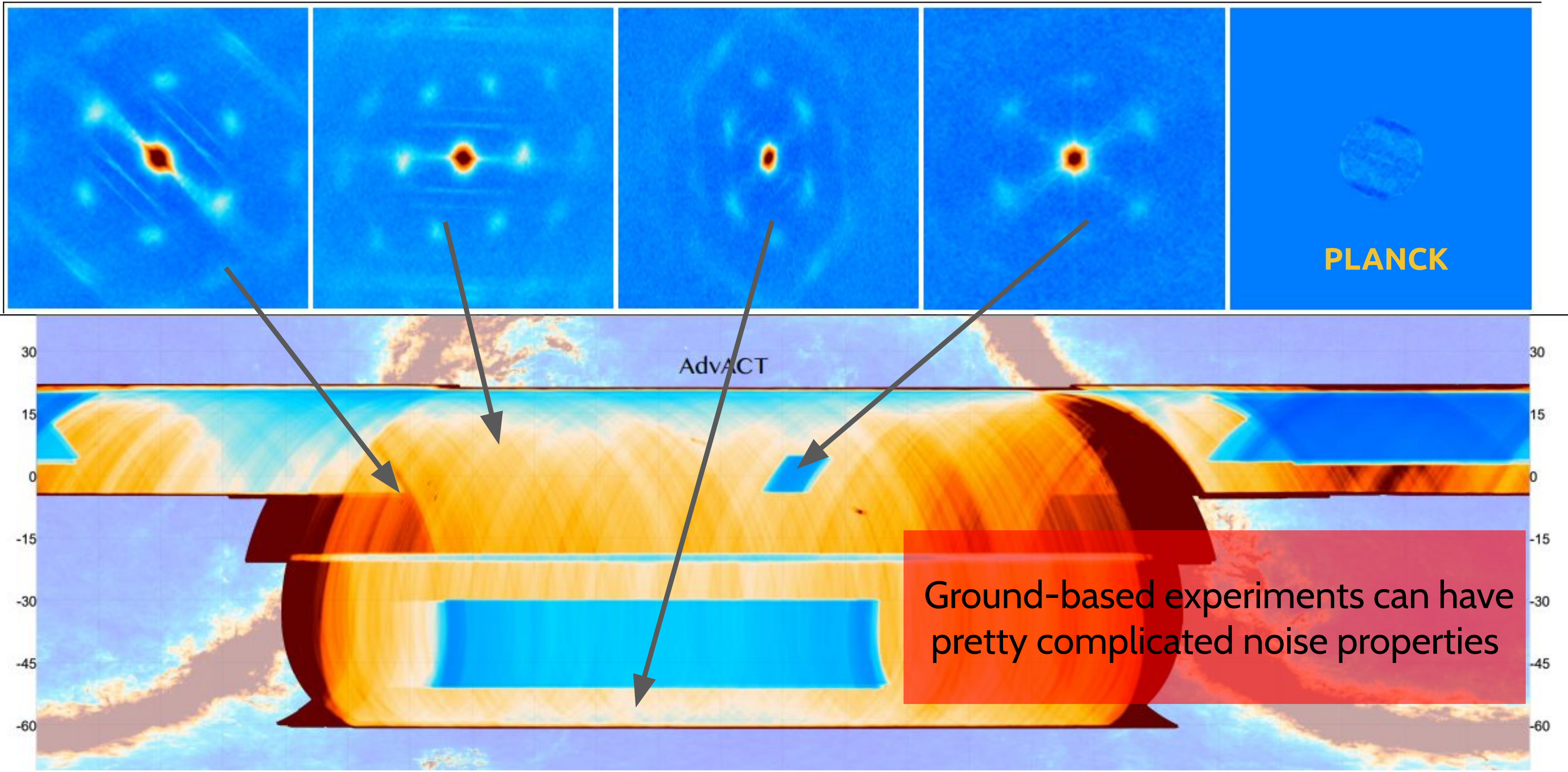
$$\langle TTTT \rangle \sim \langle \phi\phi \rangle \sim C_L^{\phi\phi}$$

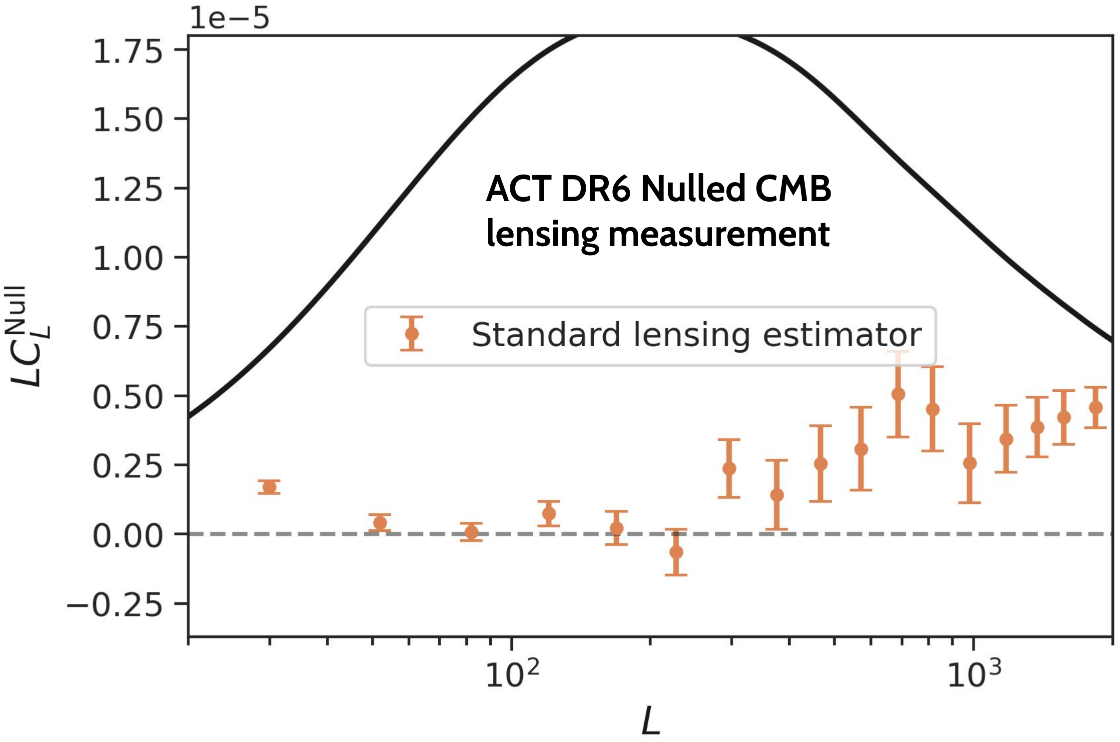
Large noise biases appear from chance CMB correlations and instrument noise correlated between each of 4 legs (Gaussian / disconnected part of 4-point function)

Subtracted off using simulations (but in a realization dependent way -- which adds robustness)

However...

Naess et al ACT 2020





1. Make noise-only maps from differences of splits (remove CMB signal)
2. Run full lensing pipeline including sim-based noise bias subtraction
3. Hope you get zero

We don't; failing null test!

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

↑

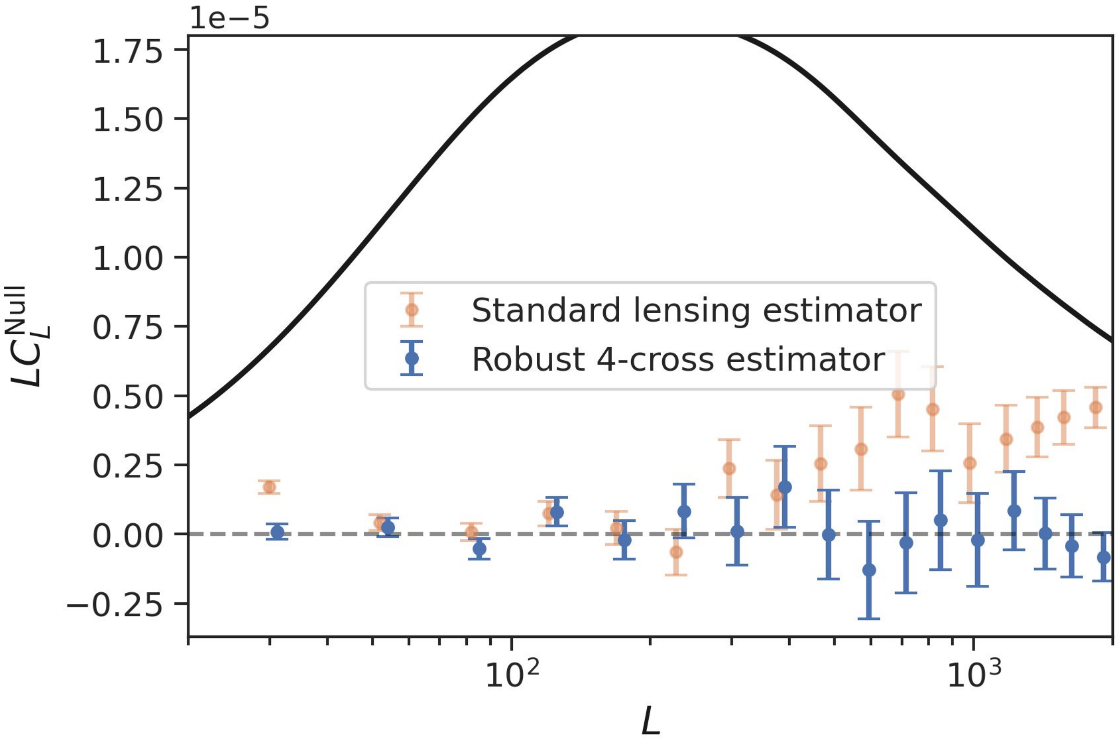
Madhavacheril, Smith, Sherwin, Naess JCAP 2021

Solution: Only use 4-point combinations that do not repeat a split (need at least m=4 splits).
SNR penalty should go to zero as m goes to infinity.

This is not trivial for a 4-point estimator! We show:

1. Possible to perform analysis with $O(m^2)$ complexity instead of $O(m^4)$
2. Almost no SNR penalty even for m=4 splits! (large number of signal dominated modes)

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



1. Make noise-only maps from differences of splits (remove CMB signal)
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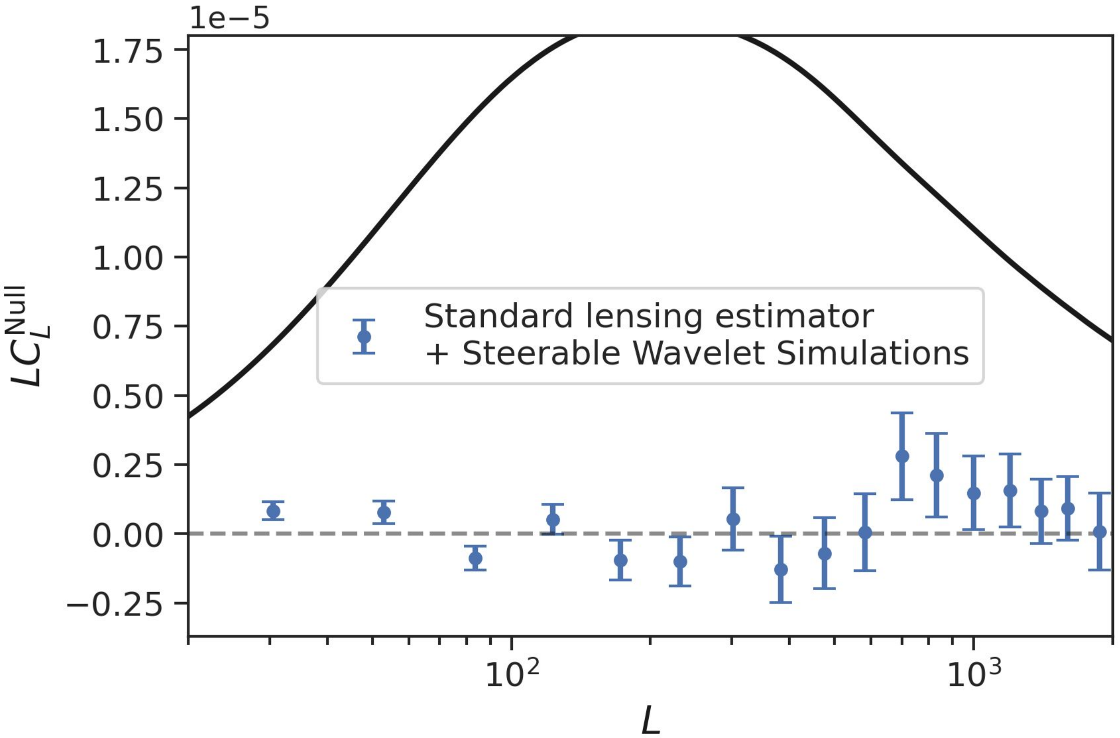
3. Hope you get zero

We pass with the new robust estimator.

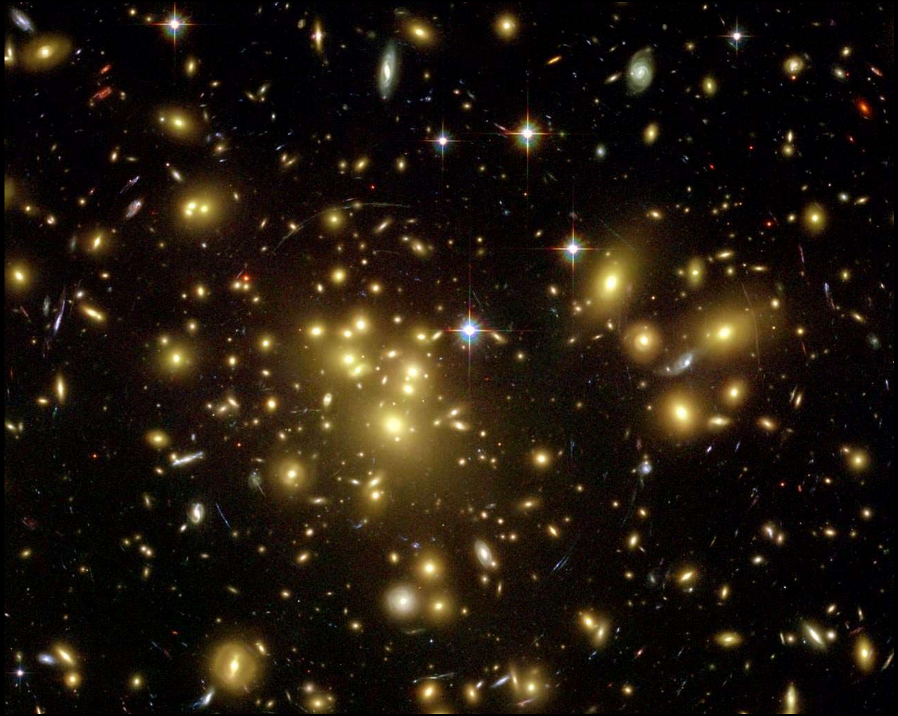


Zach Atkins,
grad student at Princeton

Adri Duivenvoorden

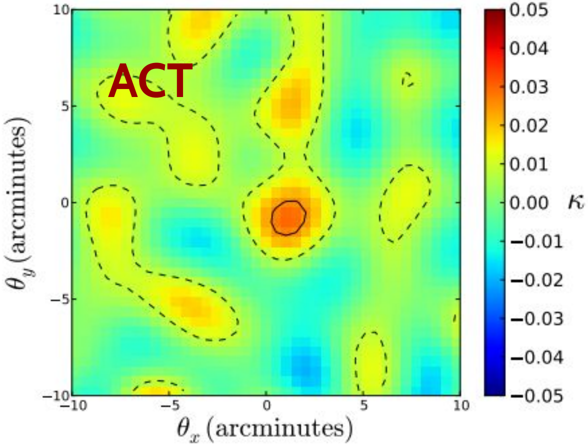
- However, very recent developments in map-based sims (directional wavelets) show we are learning better how to simulate our noise.
- Could avoid small SNR penalty and increased data analysis complexity in the future.

Another frontier for CMB lensing: galaxy clusters


Credit: Hubble

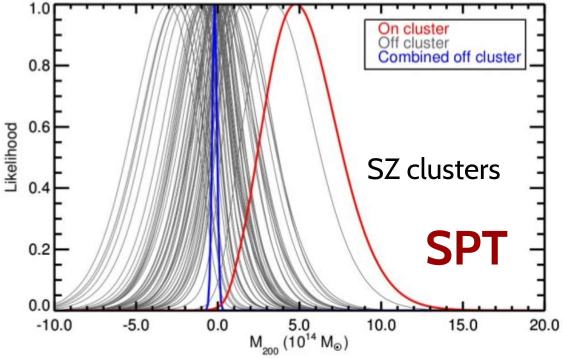
Stacked CMB lensing Measurement status

Madhavacheril, Sehgal + ACT *(PRL 2015)*
3.2 sigma

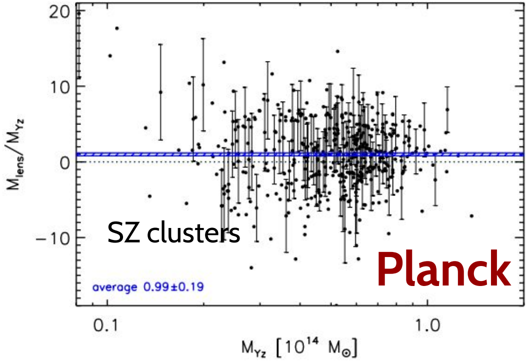


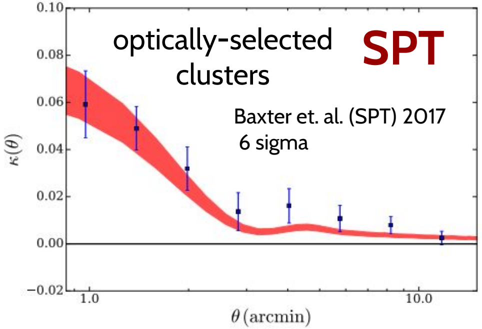
spectroscopic galaxy groups

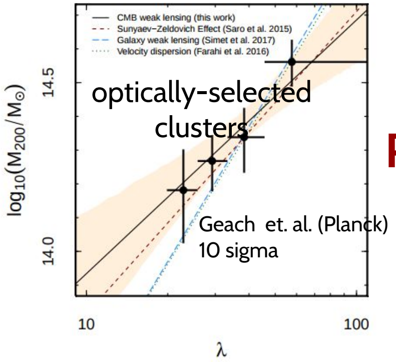
Baxter et. al (SPT) 2015
3 sigma



Planck 2015
5 sigma







Planck

Up to 10% measurements -- we're leaving few sigma regime for precision measurements

New ACT data allows us to push to a new frontier:

weighing **super-distant** galaxy clusters

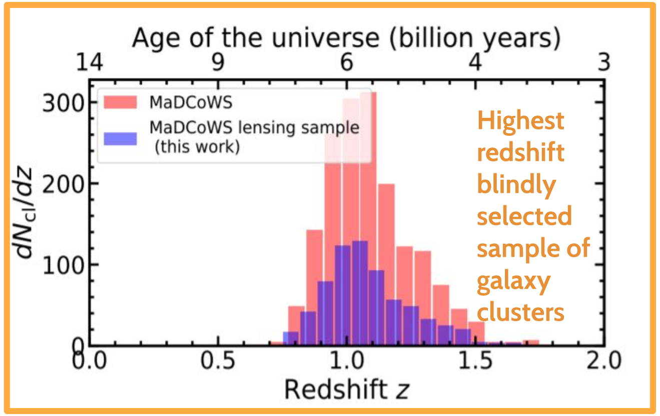
Detail: We now implement and develop important techniques to mitigate contamination from astrophysical foregrounds (SZ signal overwhelms lensing!)

- *Madhavacheril, Hill 2018 PRD*
- *Raghunathan et al 2020 JCAP*
- *Patil et al 2020 ApJ*

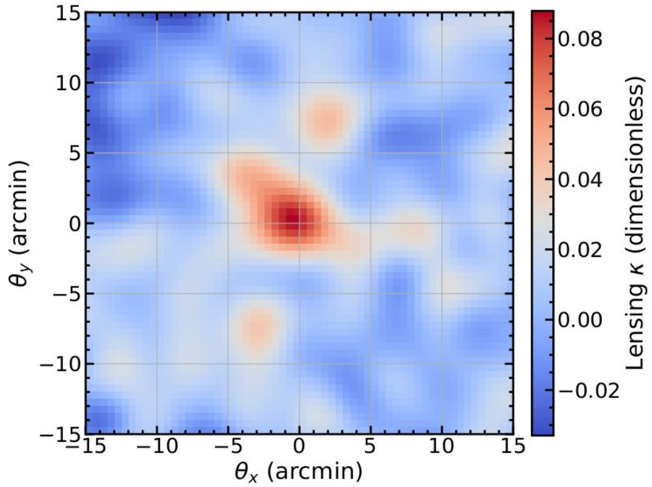
Representative galaxy cluster lensing at the highest redshift to date
Using ACT CMB lensing

Reconstruct the CMB lensing signal around each of ~700 MaDCoWS clusters

Stack/average these;
detect lensing at 4.2 sigma



Madhavacheril, Sifon, Battaglia et al 2020, ApJ Letters



Representative galaxy cluster lensing at the highest redshift to date

Using ACT CMB lensing

Reconstruct the CMB lensing signal around each of ~700 MaDCoWS clusters

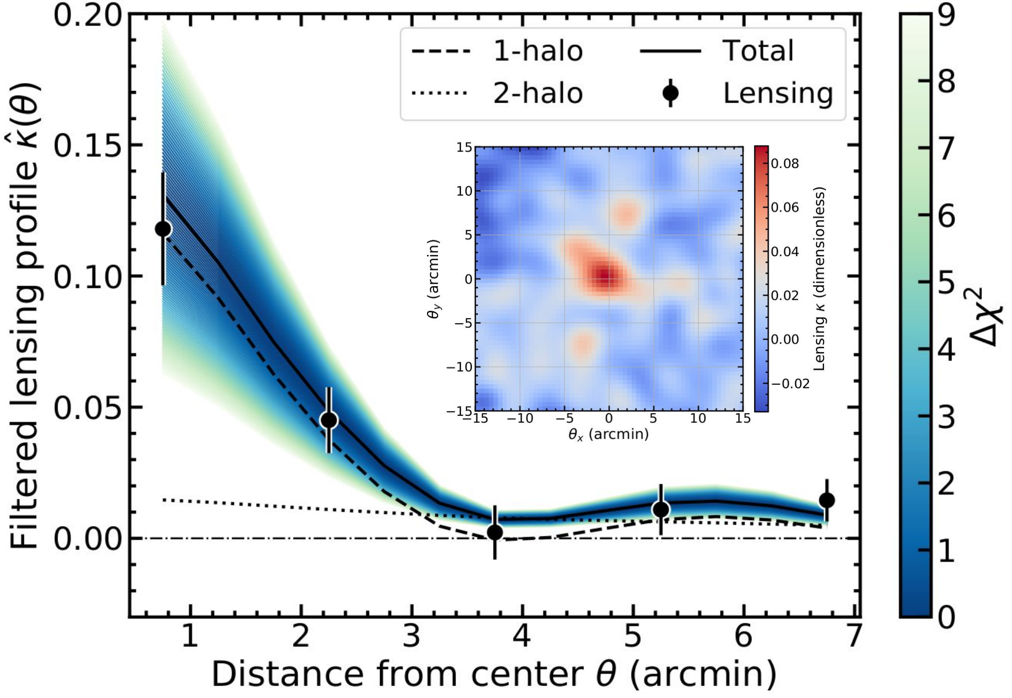
Stack/average these

Detect lensing at 4.2 sigma

Fit to NFW profile, mass constraint of 1.7±0.4 x 10^{14} Msolar

Highlights power of CMB for distant clusters

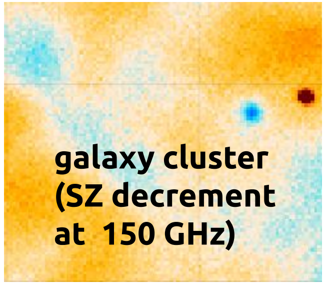
Madhavacheril, Sifon, Battaglia et al 2020, ApJ Letters

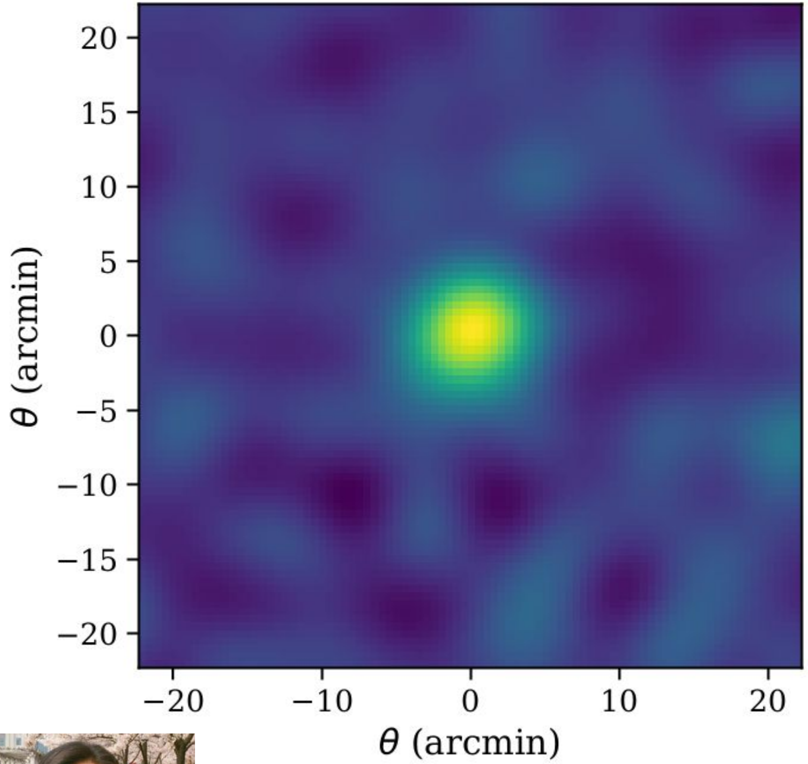


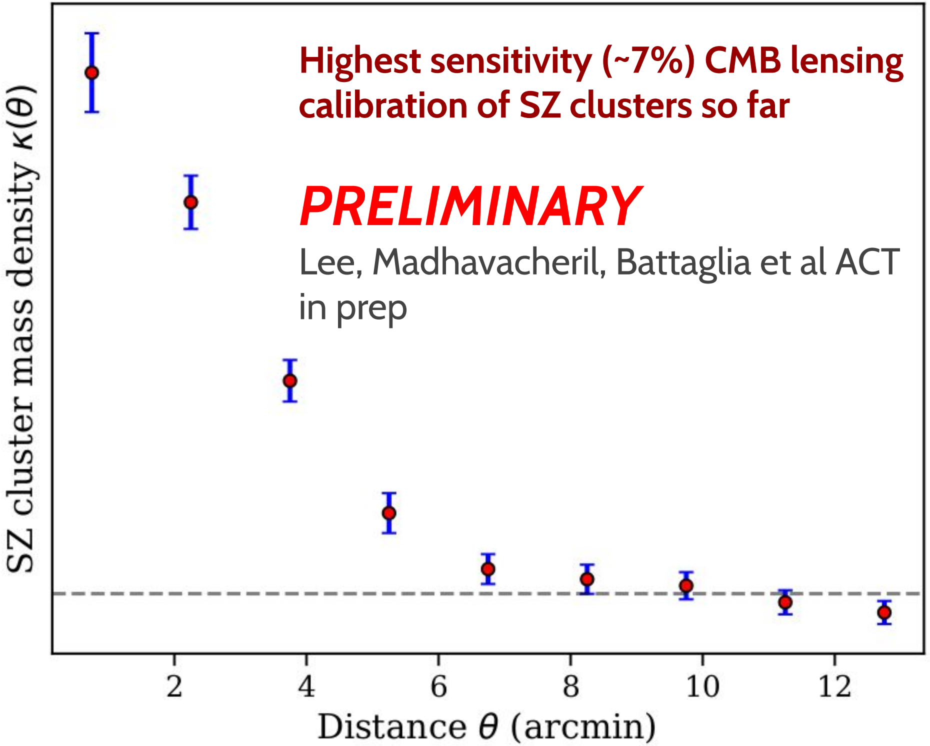
Next CMB lensing frontier:

Mass calibration for **cosmology** with galaxy clusters

Requires well-characterized SZ cluster sample







Eunseong Lee, grad student at Manchester

Mass calibration for ~4000 ACT SZ clusters with ACT CMB lensing

Future CMB lensing regimes

- Low-noise and polarization dominated (CMB-S4)
- Small-scale CMB lensing (proposed 20-50 meter CMB-HD telescope)

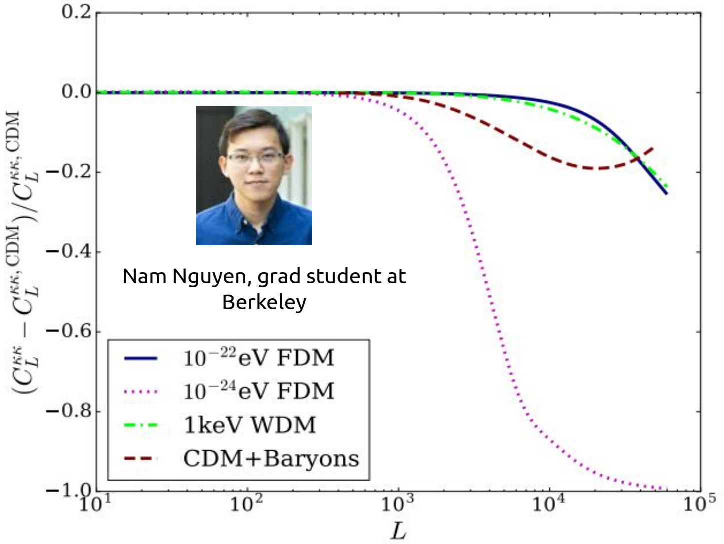
Standard quadratic estimators massively sub-optimal in both regimes

(See poster by Sebastian Belkner+ on iterative delensing)

Work needed to understand effect of foregrounds and noise modeling in Bayesian and iterative schemes (esp. for wide-area maps)

e.g. Millea et al SPT 2021

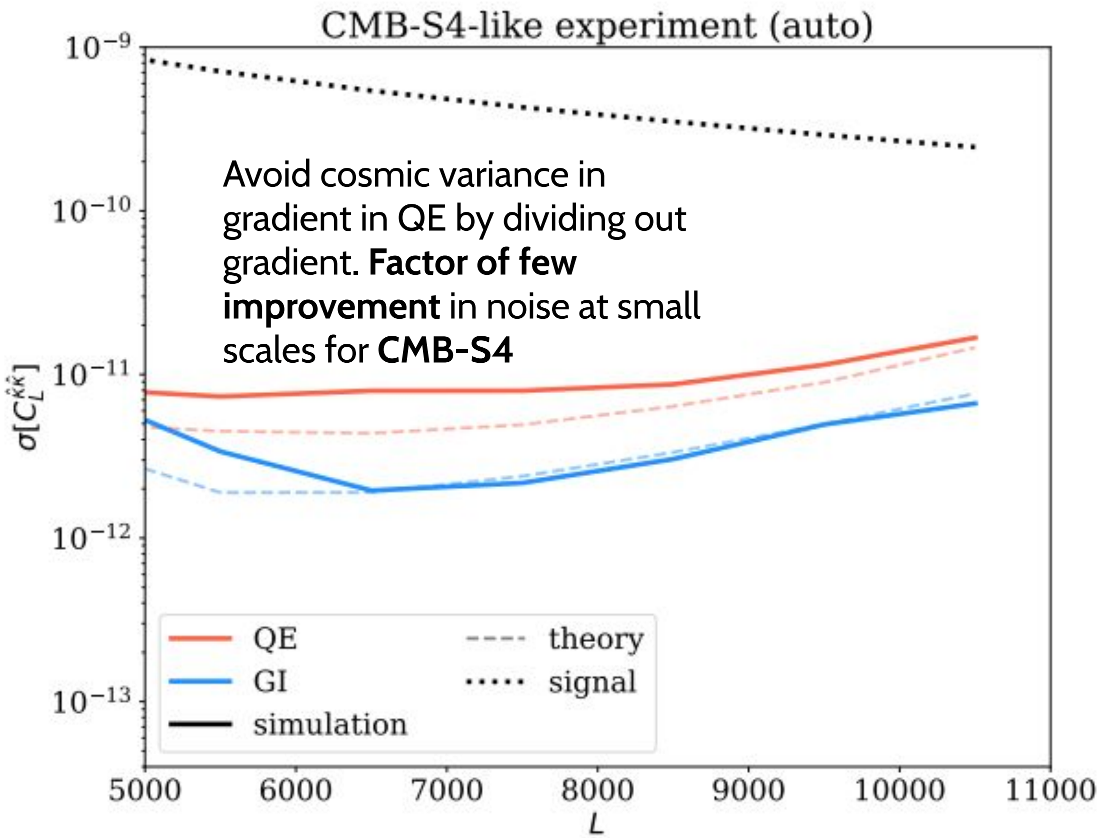
e.g. Carron et al 2017



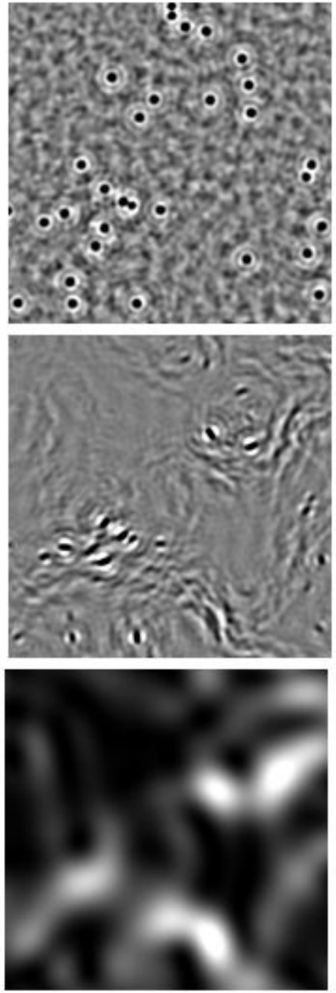
Nguyen, Sehgal, Madhavacheril 2017 PRD

Boryana Hadzhiyska, grad student at Harvard

Improving small-scale lensing reconstruction; divide maps instead of Bayesian sampling or iteration

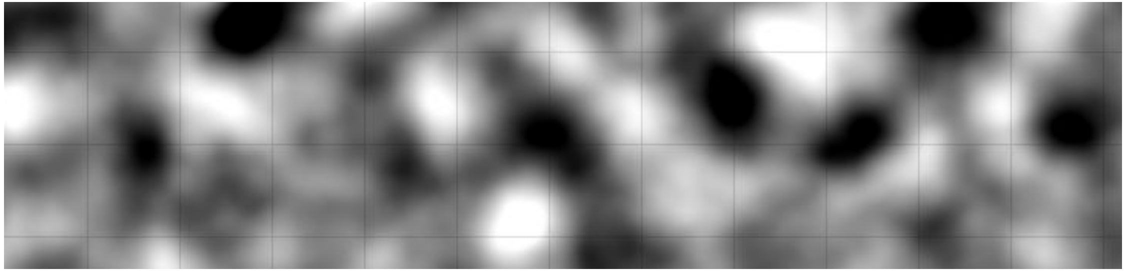


Avoid cosmic variance in gradient in QE by dividing out gradient. **Factor of few improvement** in noise at small scales for **CMB-S4**



Hadzhiyska, Sherwin, Madhavacheril, Ferraro PRD 2019
Enables e.g. **tighter axion dark matter constraints** from **CMB-HD** *(Nguyen, Sehgal, Madhavacheril, PRD 2017)*

Conclusions



- Lensing will drive many particle physics constraints; inform S8 tension
- Ground-based experiments like ACT and SPT are now measuring lensing at higher SNR than Planck
- New techniques were needed to handle (1) (extragalactic) foregrounds at ell>2000 and (2) complexity of ground-based instrument/atmospheric noise
- CMB lensing now competitive for **cluster mass calibration**
- More work is needed to build optimal estimators in the low noise (CMB-S4, CMB-HD) and/or small-scale regime (CMB-HD)