Title: Precision cosmology with the next generation of CMB and optical surveys

Speakers: Mathew Madhavacheril

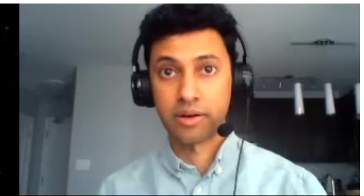
Series: Cosmology & Gravitation

Date: April 27, 2021 - 11:00 AM

URL: http://pirsa.org/21040032

Abstract: Ground-based cosmic microwave background (CMB) experiments are now pushing into discovery space where new insights on inflation, dark matter, dark energy and neutrino physics will be obtained by unraveling signatures buried beneath the primordial fluctuations. I will present new results from the Atacama Cosmology Telescope (ACT) that exemplify the power of high-resolution measurements of the microwave sky, including high-fidelity maps of dark matter through gravitational lensing. These maps set the stage for a robust measurement of the neutrino mass scale and hierarchy with upcoming ACT and Simons Observatory data. I will also discuss a new proposal for dramatically improving the sensitivity to primordial non-Gaussianity using measurements of the cosmic velocity field, and sketch a path towards using this technique to detect or rule out multi-field inflation using a combination of upcoming CMB data from the Simons Observatory and optical galaxy data from the Vera Rubin Observatory.

Precision cosmology with next generation CMB and optical surveys



Mathew Madhavacheril

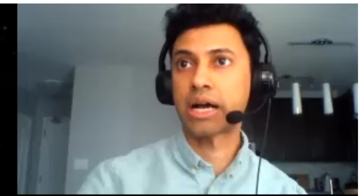
Peebles Fellow, Perimeter Institute

ACT

Perimeter Seminar, 27 April 2021

SIMONS OBSERVATORY

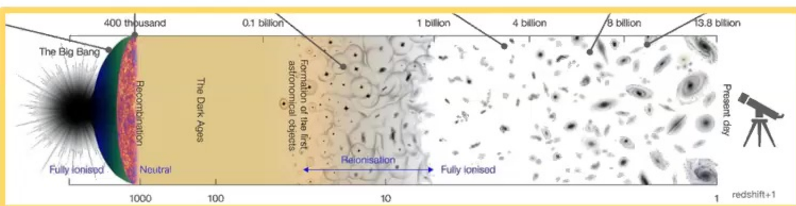
22°57'31" SOUTH, 67°47'15"WEST ELEVATION: 17,027.6' PARQUE ASTRONÓMICO ATACAMA, CHILE



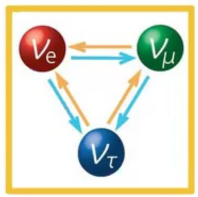
Precision cosmology with next generation CMB and optical surveys

Mathew Madhavacheril

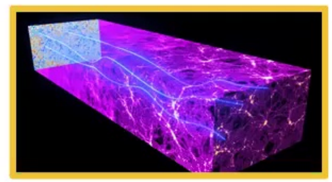
Peebles Fellow, Perimeter Institute



The CMB as a backlight

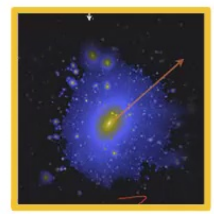


Neutrino mass

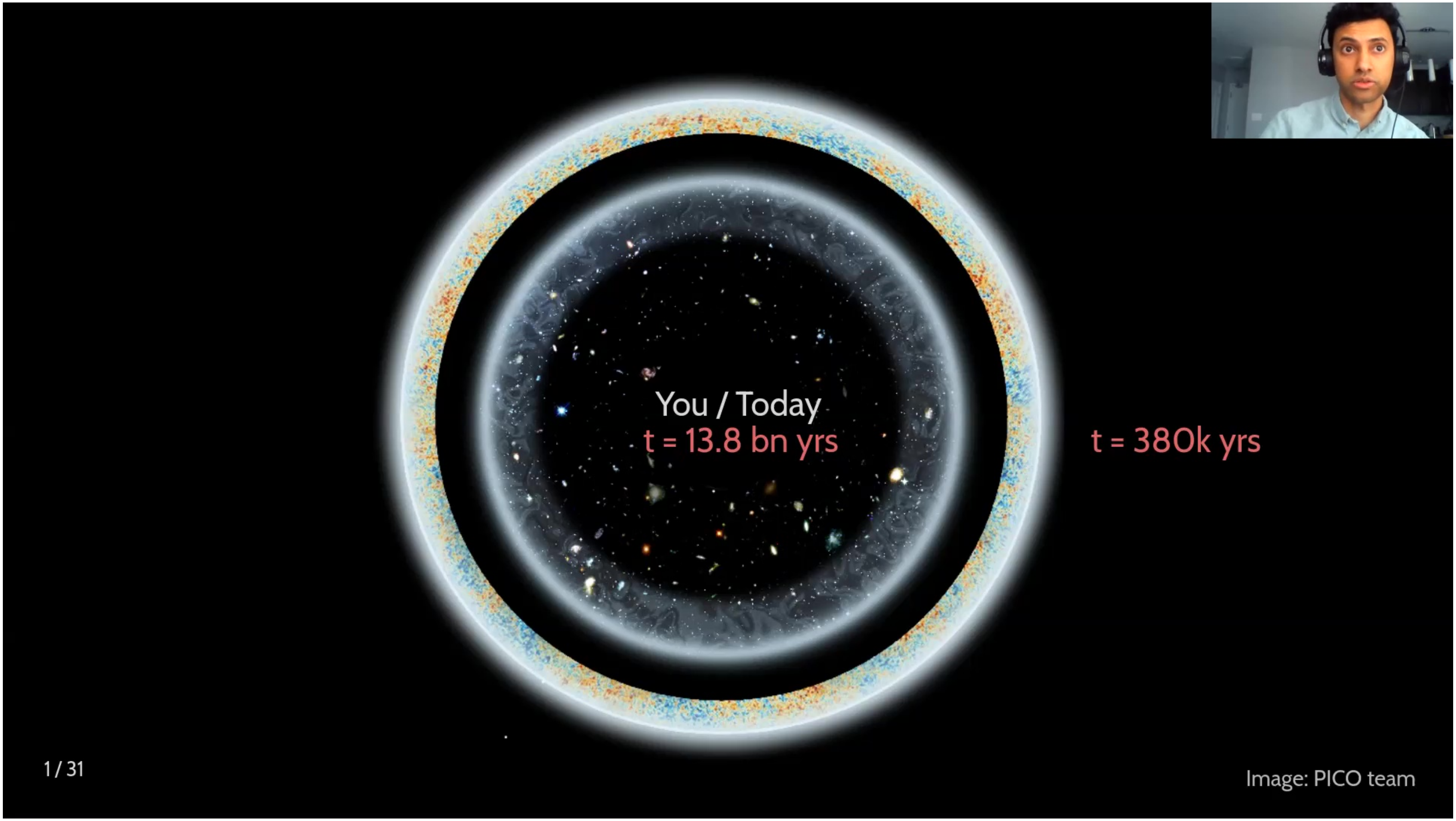


Mass mapping

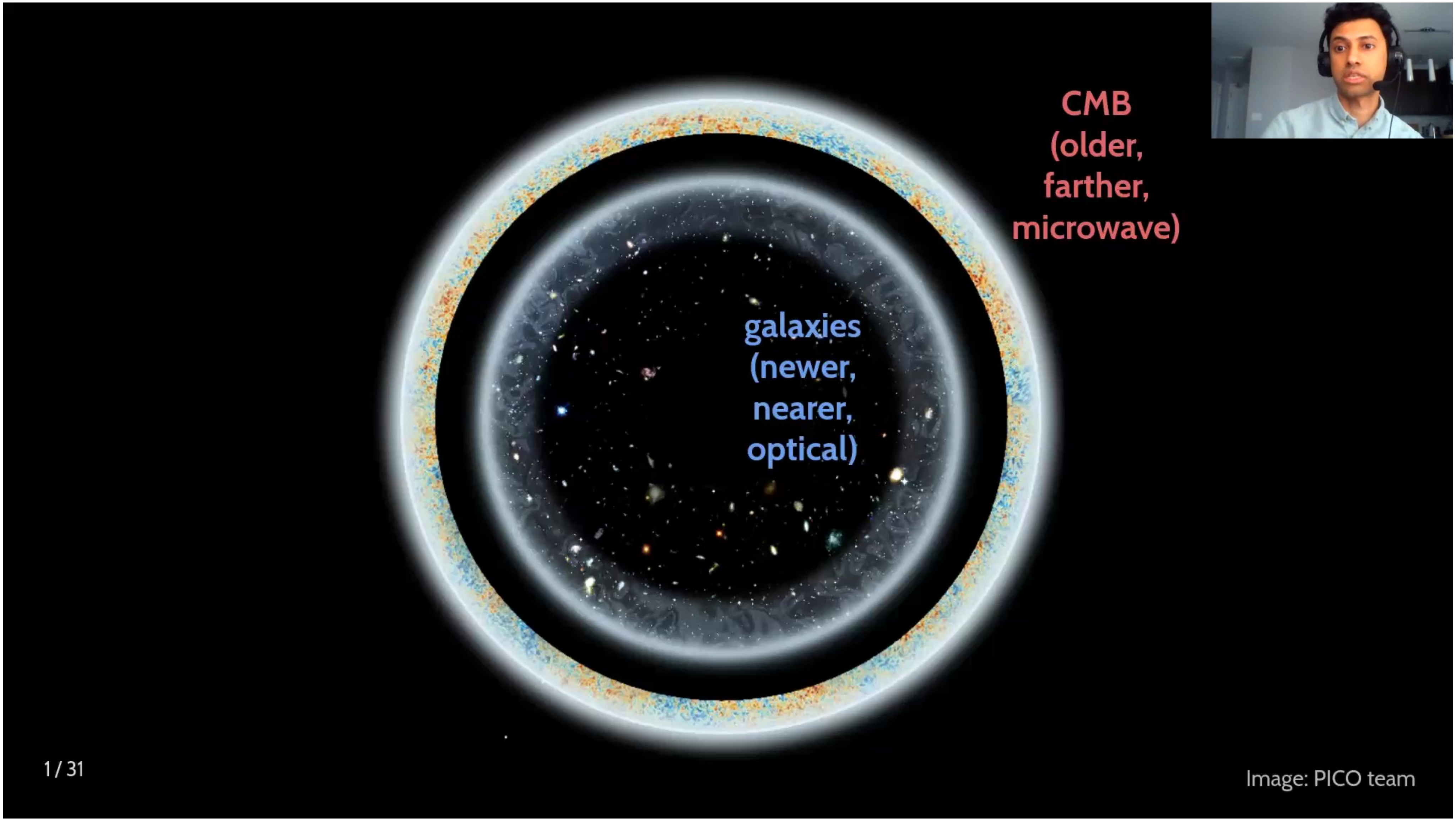
Cosmic inflation

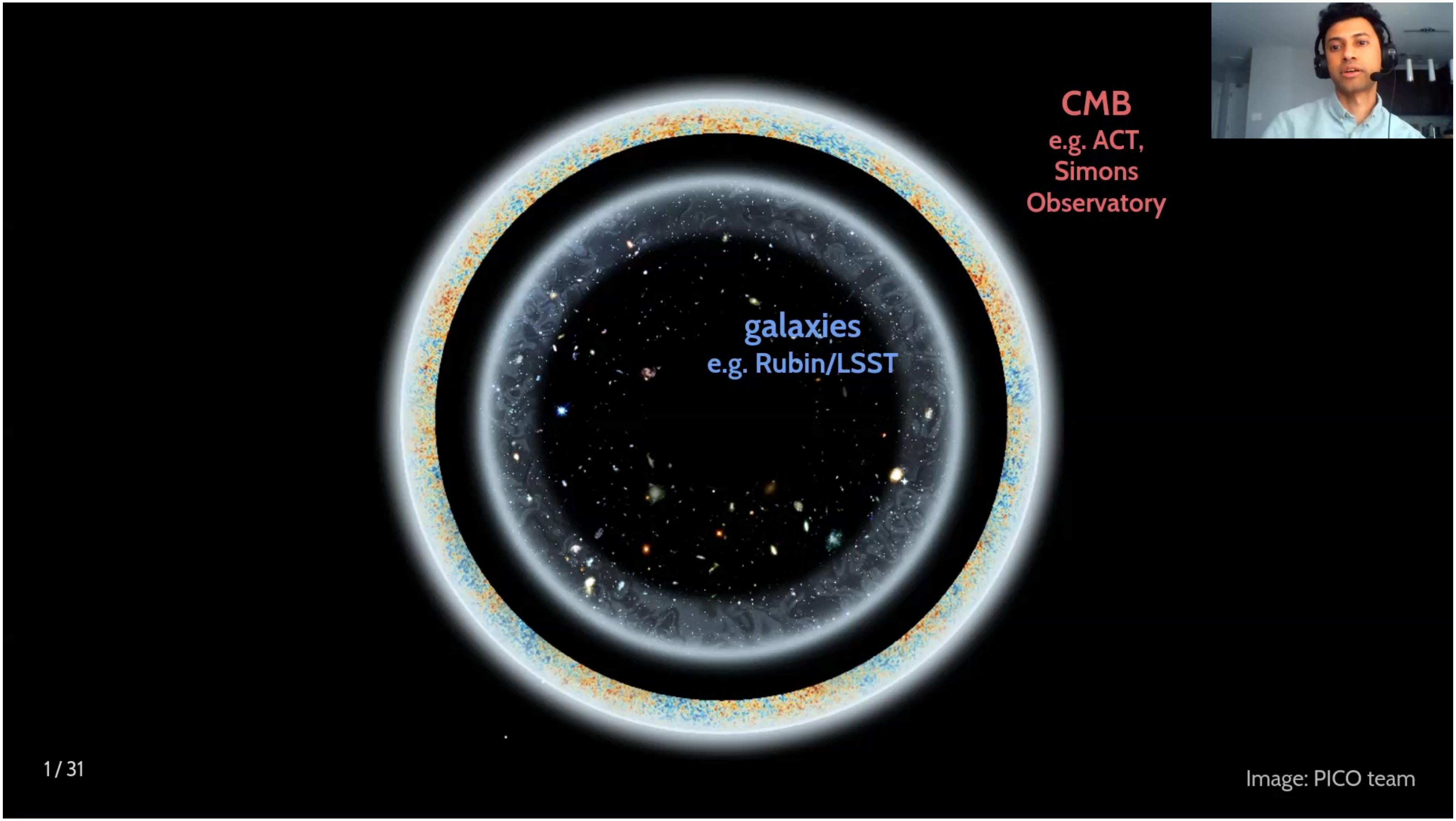


Velocity mapping



You / Today
t = 13.8 bn yrs
t = 380k yrs
1 / 31
Image: PICO team


CMB
(older,
farther,
microwave)
galaxies
(newer,
nearer,
optical)
1 / 31
Image: PICO team


CMB
e.g. ACT,
Simons
Observatory
galaxies
e.g. Rubin/LSST
1 / 31
Image: PICO team

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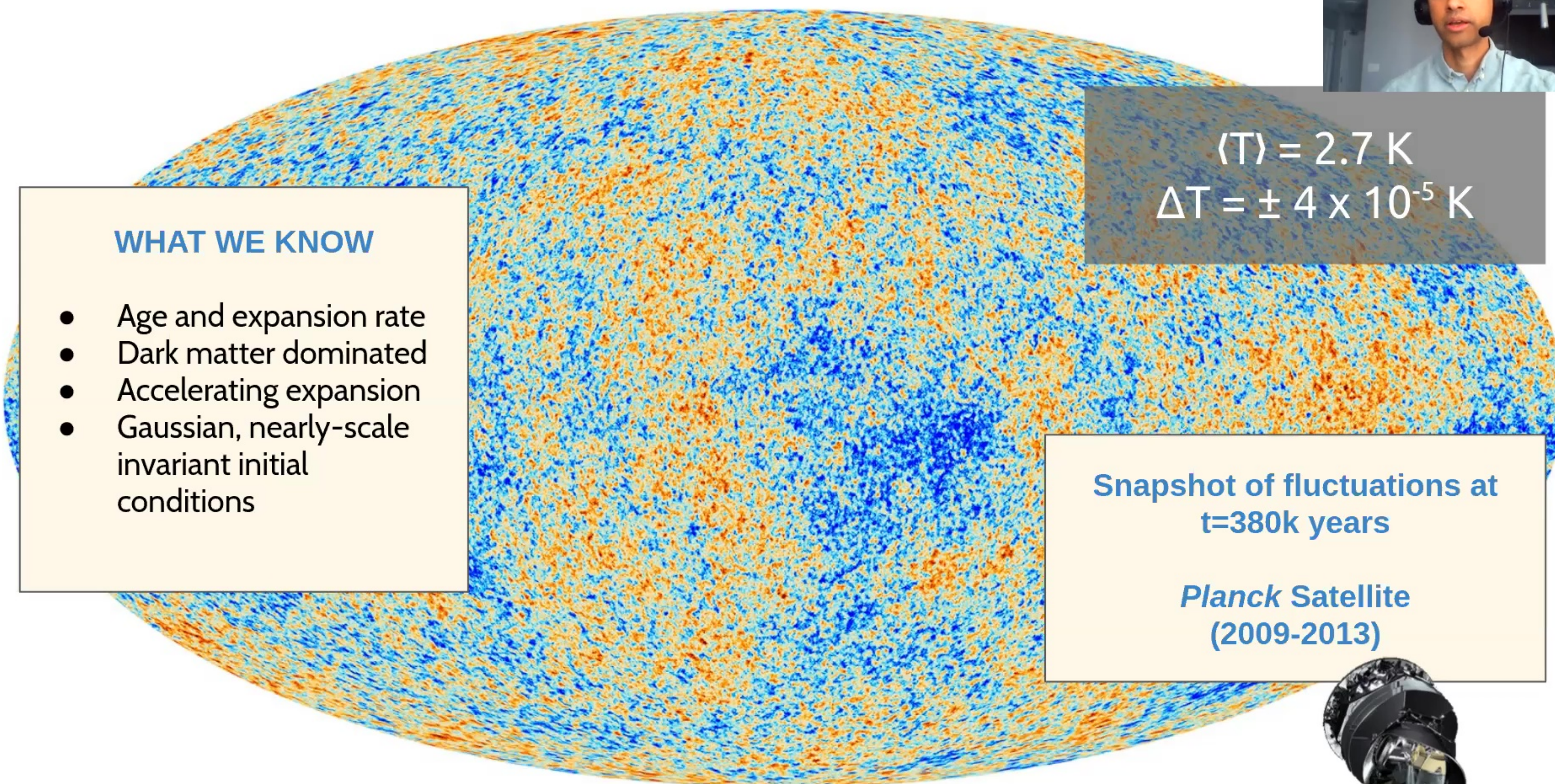


$\langle T \rangle = 2.7$ K
$\Delta T = \pm 4 \times 10^{-5}$ K

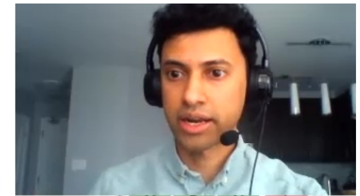
WHAT WE KNOW

- Age and expansion rate
- Dark matter dominated
- Accelerating expansion
- Gaussian, nearly-scale invariant initial conditions

Snapshot of fluctuations at t=380k years

***Planck* Satellite (2009-2013)**

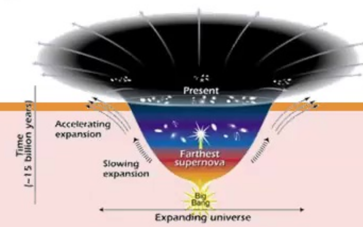
2 / 31



WHAT WE DON'T KNOW

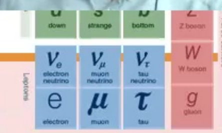
WHAT WE KNOW

- Age and expansion rate*
- Dark matter dominated
- Accelerating expansion
- Gaussian, nearly-scale invariant initial conditions



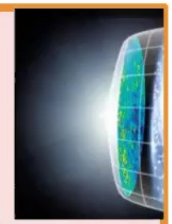
Dynamics

- Why is expansion accelerating?
  - Dark energy?
  - Modified gravity?



Fundamental particles

- Particle nature of dark matter?
- Additional light particles?
- Neutrino mass generation mechanism?



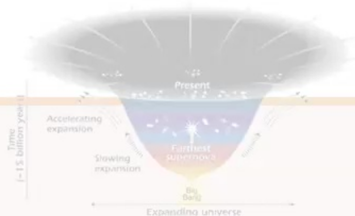
Initial conditions

- An inflationary phase?
  - Multi-field?
  - Gravitational waves?

Structure formation

- Missing baryons?
- Galaxy formation / evolution
- Reionization epoch
- Cosmic web structure

Science goals



Dynamics

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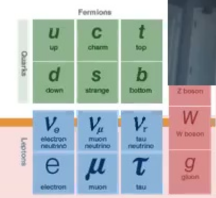

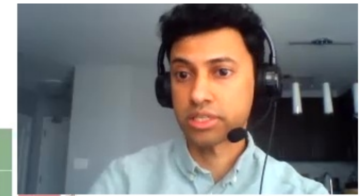

Fundamental particles

- Neutrino mass generation mechanism?

Constraining the Lagrangian for beyond-Standard Model physics

Initial conditions

- An inflationary phase?
  - Multi-field? Primordial non-Gaussianity?

Constraining (possibly) string phenomenology

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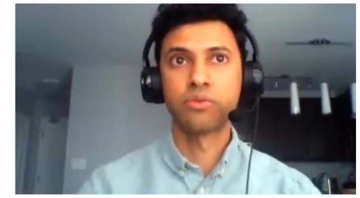
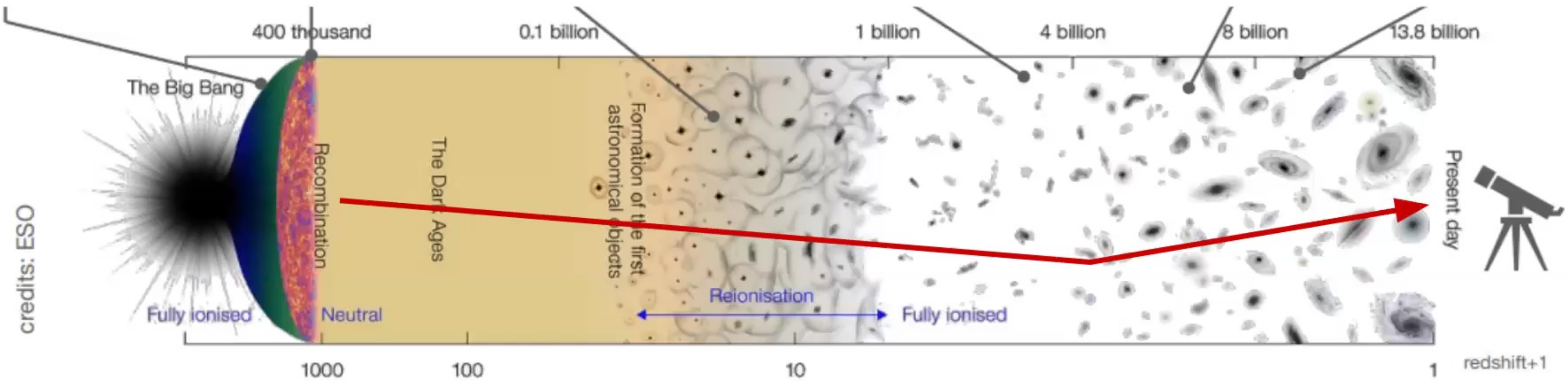


The CMB as a backlight

Interactions with matter as it evolves and structure forms

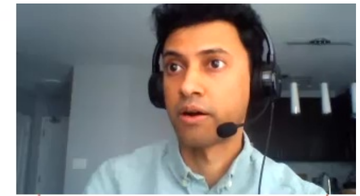


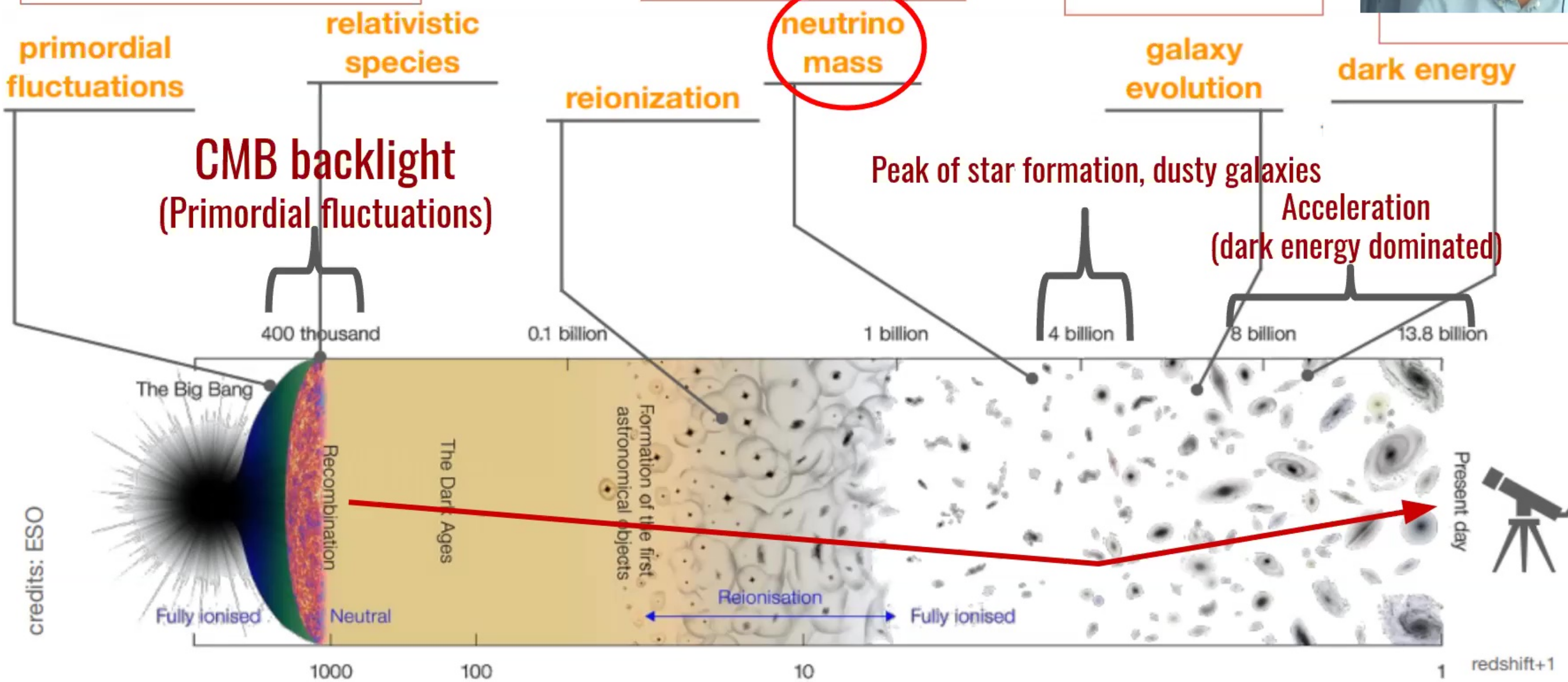
4 / 31

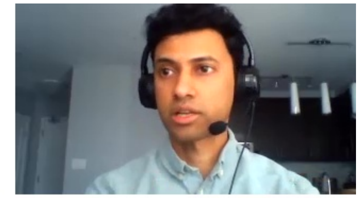
MM, Sehgal+, 2014
Sehgal, MM+, 2016
Li, Gluscevic, Boddy, MM, 2018
Munchmeyer, MM+, 2018

[redacted]
Liu, MM, 2019
Coulton, Liu, MM+, 2019
Darwish, MM+ 2020

Smith, MM+ 2018
McCarthy, MM 2020
MM+, 2020



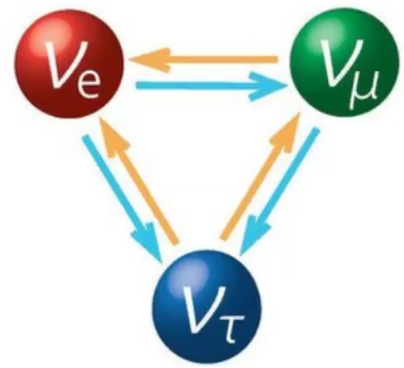




Neutrino physics open questions

- Flavor oscillations seen -> have mass (quantum oscillation of superpositions of mass eigenstates)
- What is the absolute mass scale?

  This is tied to physics beyond the Standard Model; sensible ways to add mass require extensions



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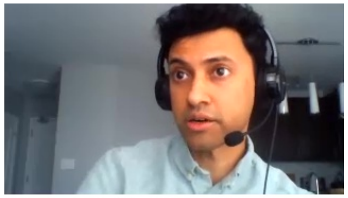
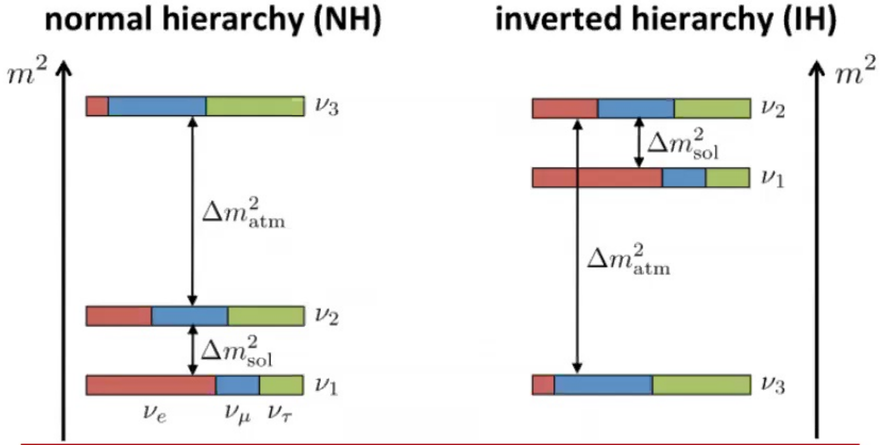


Neutrino physics open questions

- Flavor oscillations seen -> have mass
- What is the absolute mass scale?
- What is the hierarchy or ordering of mass states?

Oscillation experiments only tell us about the difference of mass squared



sum > 60 meV | **sum > 100 meV**

6-10 **orders of magnitude lighter** than all the other Standard Model particles. Why?

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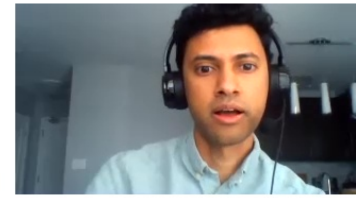
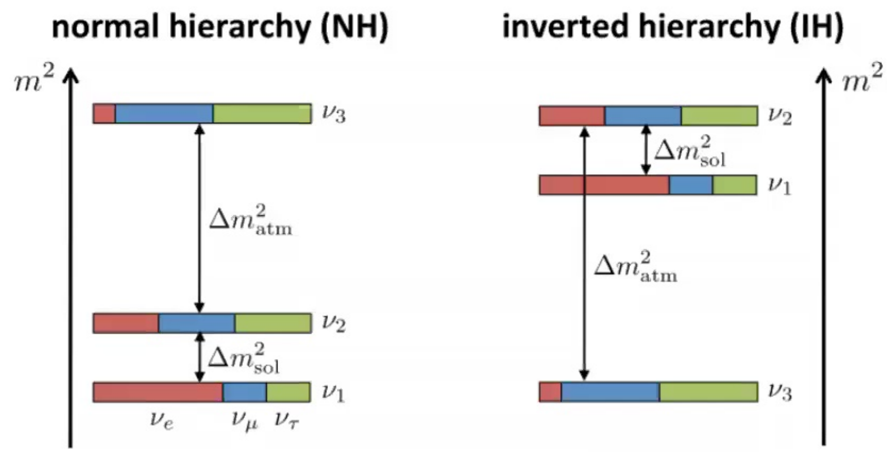


Neutrino physics open questions

- Flavor oscillations seen -> have mass
- What is the absolute mass scale?
- What is the hierarchy or ordering of mass states?
- Need to extend Standard Model Lagrangian by adding **new particles** to generate mass for ordinary neutrinos



sum > 60 meV **sum > 100 meV**

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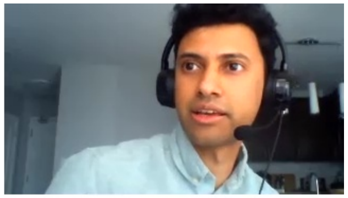
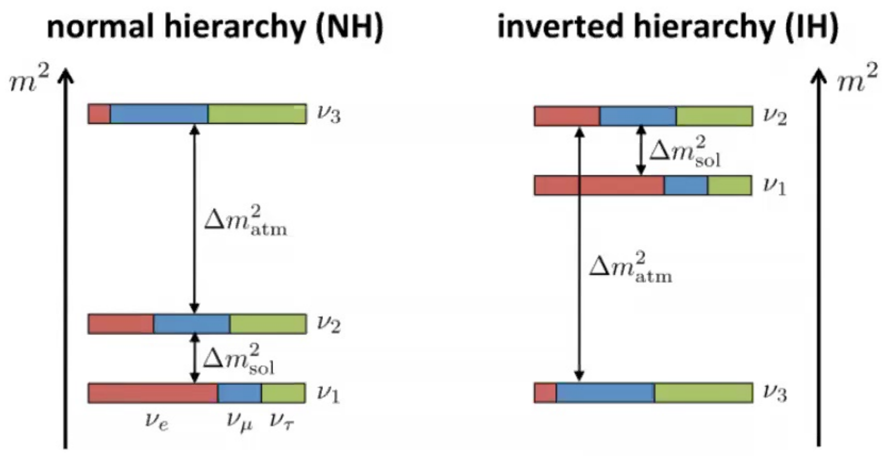
Neutrino physics open questions



- Flavor oscillations seen -> have mass
- What is the absolute mass scale?
- What is the hierarchy or ordering of mass states?
- Are there additional sterile neutrino species?
- Laboratory measurements (e.g. KATRIN) in the next decade < 200 meV

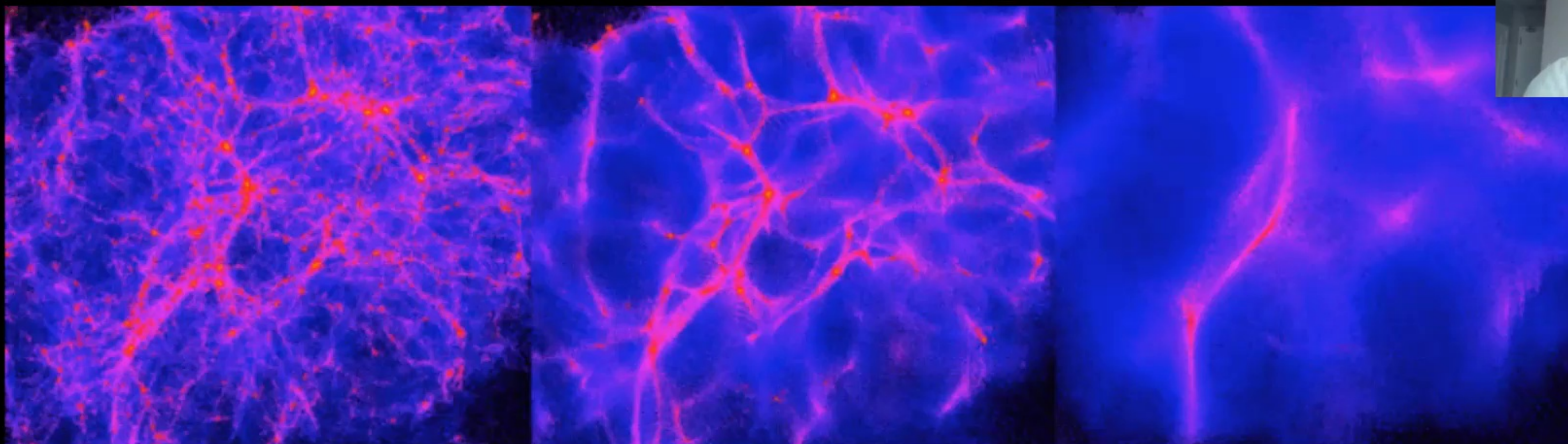
Cosmological measurements tell us the absolute mass scale and hierarchy. Projected 1σ uncertainty: 10-30 meV

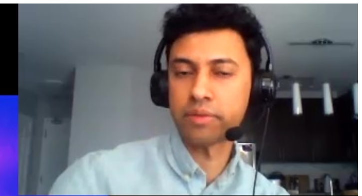


sum > 60 meV **sum > 100 meV**

Constraining the Lagrangian for beyond-Standard Model physics

Massless neutrinos | Intermediate mass | High mass





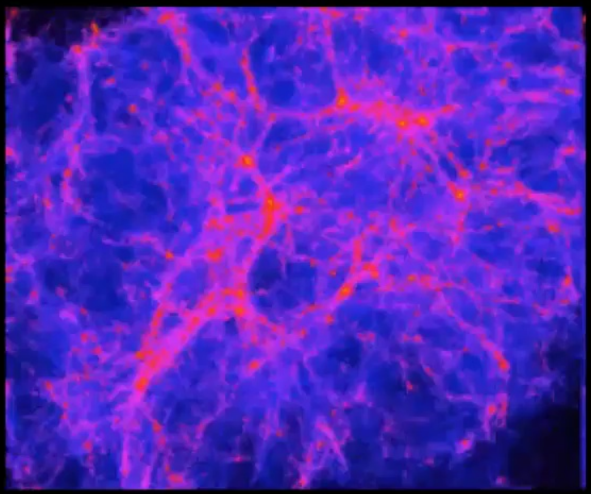
Cosmic density
smoothed by massive neutrinos

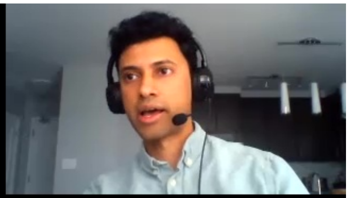
We need to measure the total matter distribution, but most of it is dark matter!

Simulations from **Ben Moore (Zurich)**

Massive neutrinos smooth the matter distribution
(few percent level)

80% of the matter is invisible (dark matter)



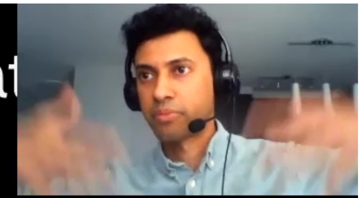


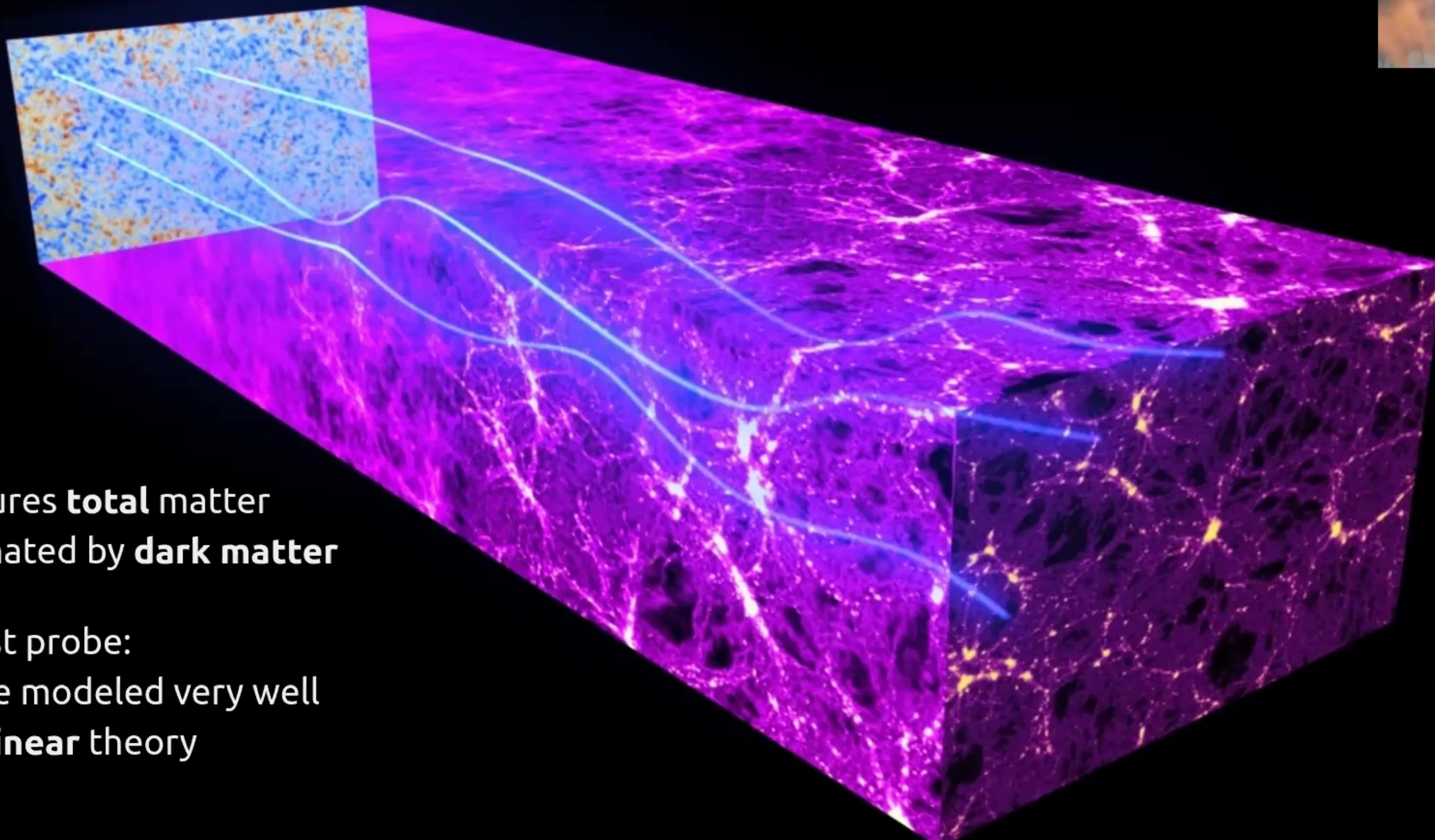
Massive neutrinos smooth the matter distribution
(few percent level)

80% of the matter is invisible (dark matter)

How do we measure the matter distribution?
With gravitational lensing of the microwave sky.

Gravitational lensing: the CMB acts as a backlight for mat



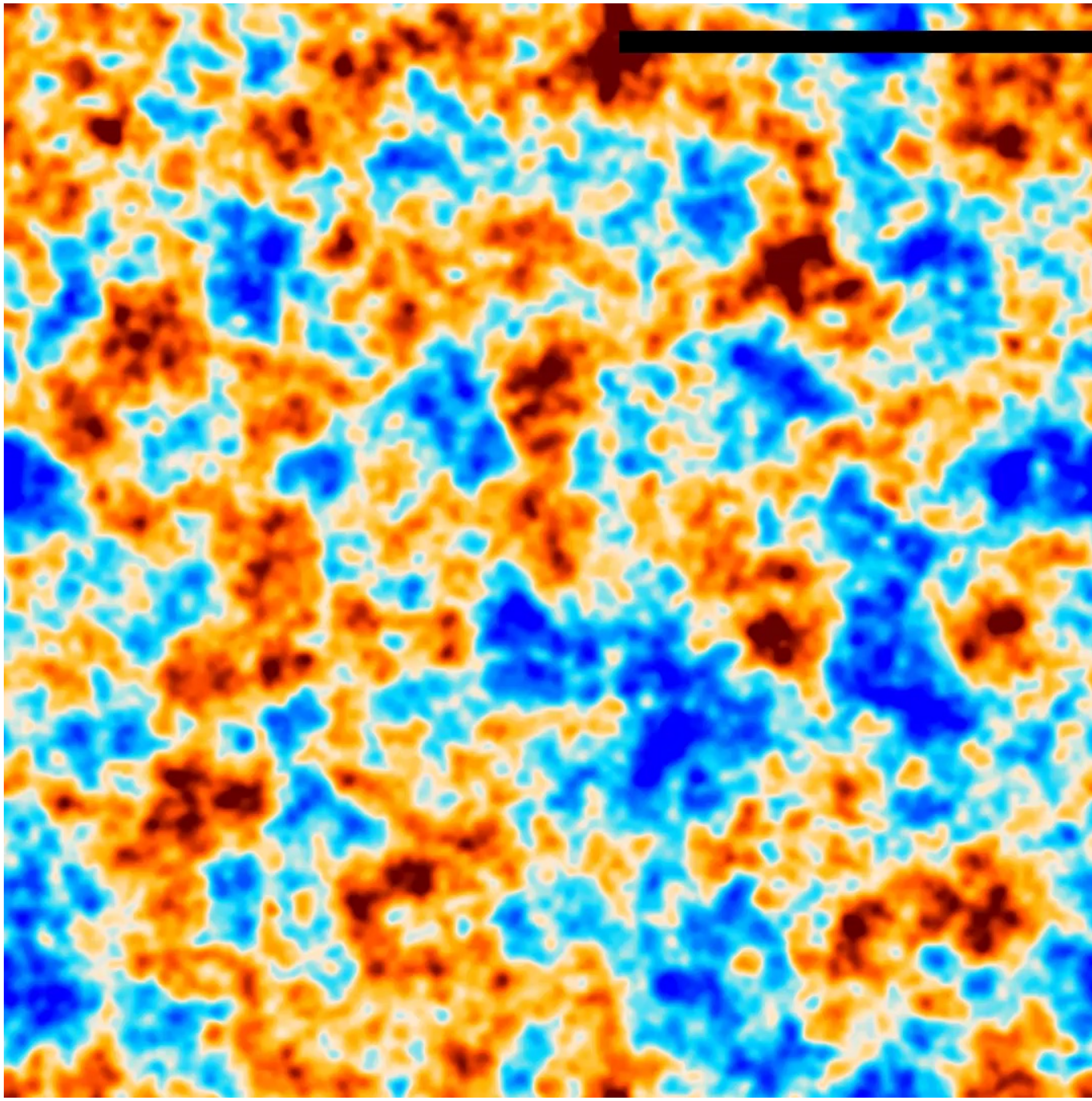


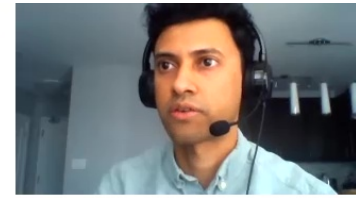
Measures **total** matter
dominated by **dark matter**

Robust probe:
Can be modeled very well
with **linear** theory

7 / 31

Image: ESA/Planck





Unlensed CMB

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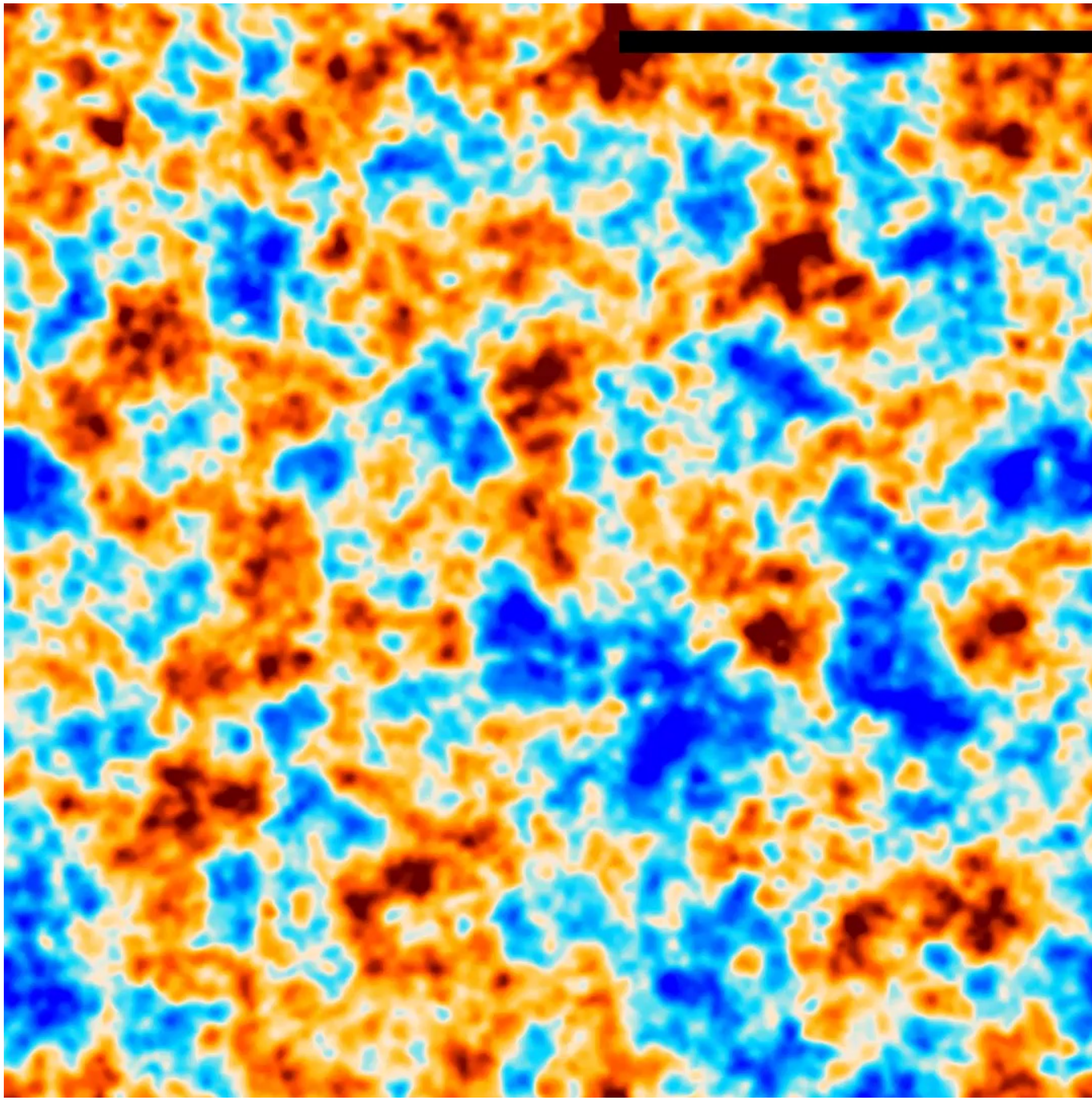

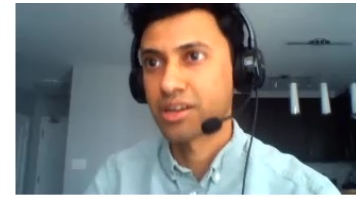

Lensed CMB

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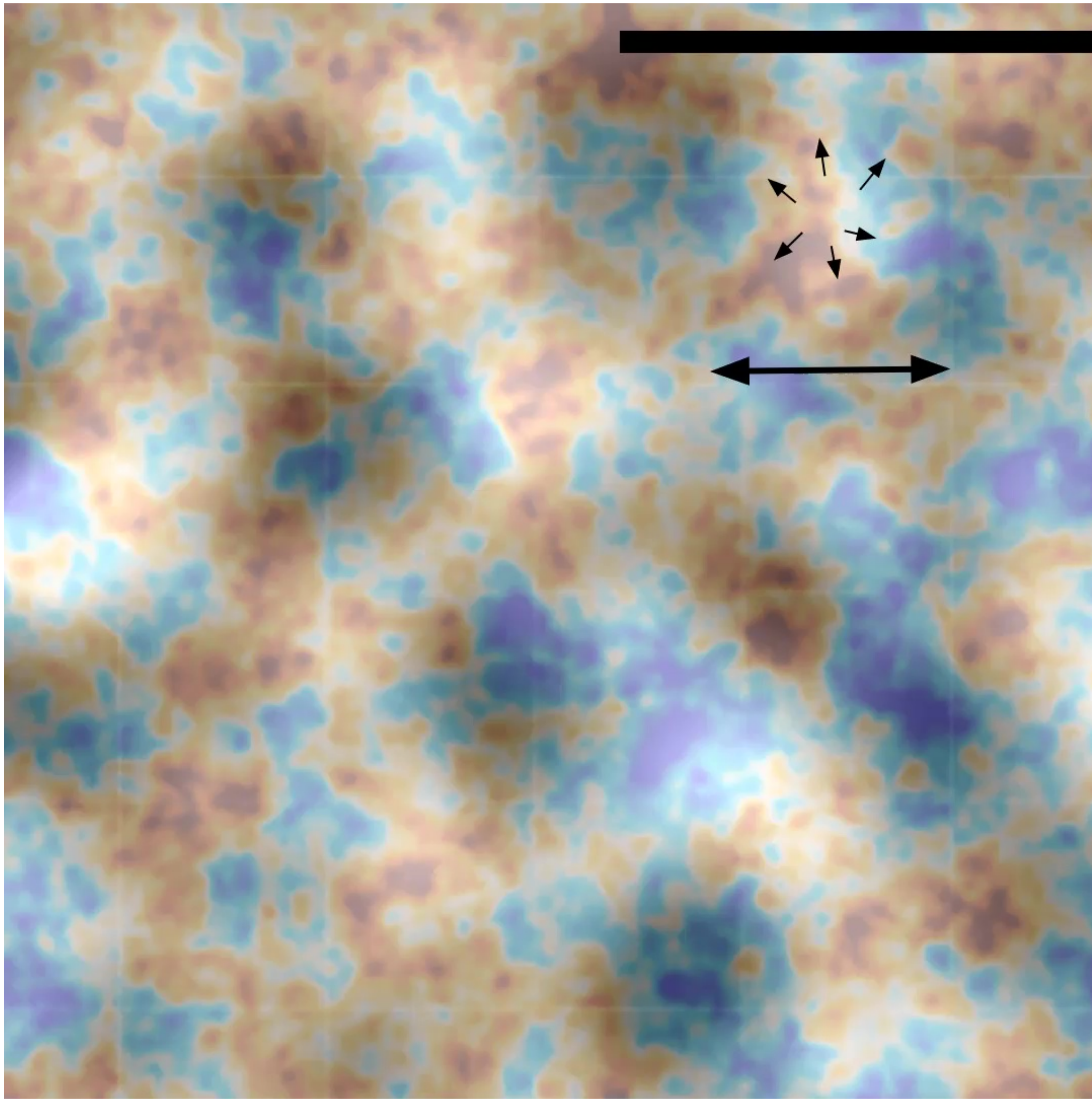

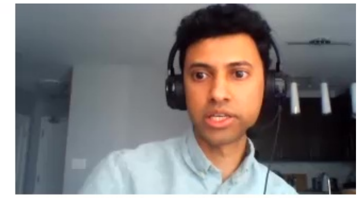

small-scale deflections

coherent over large (degree) scales

$$\langle T(\boldsymbol{\ell_1})T(\boldsymbol{\ell_2})\rangle_{\rm CMB} = f(\boldsymbol{\ell_1},\boldsymbol{\ell_2})\phi(\boldsymbol{\ell_1}+\boldsymbol{\ell_2})$$

Lensed CMB

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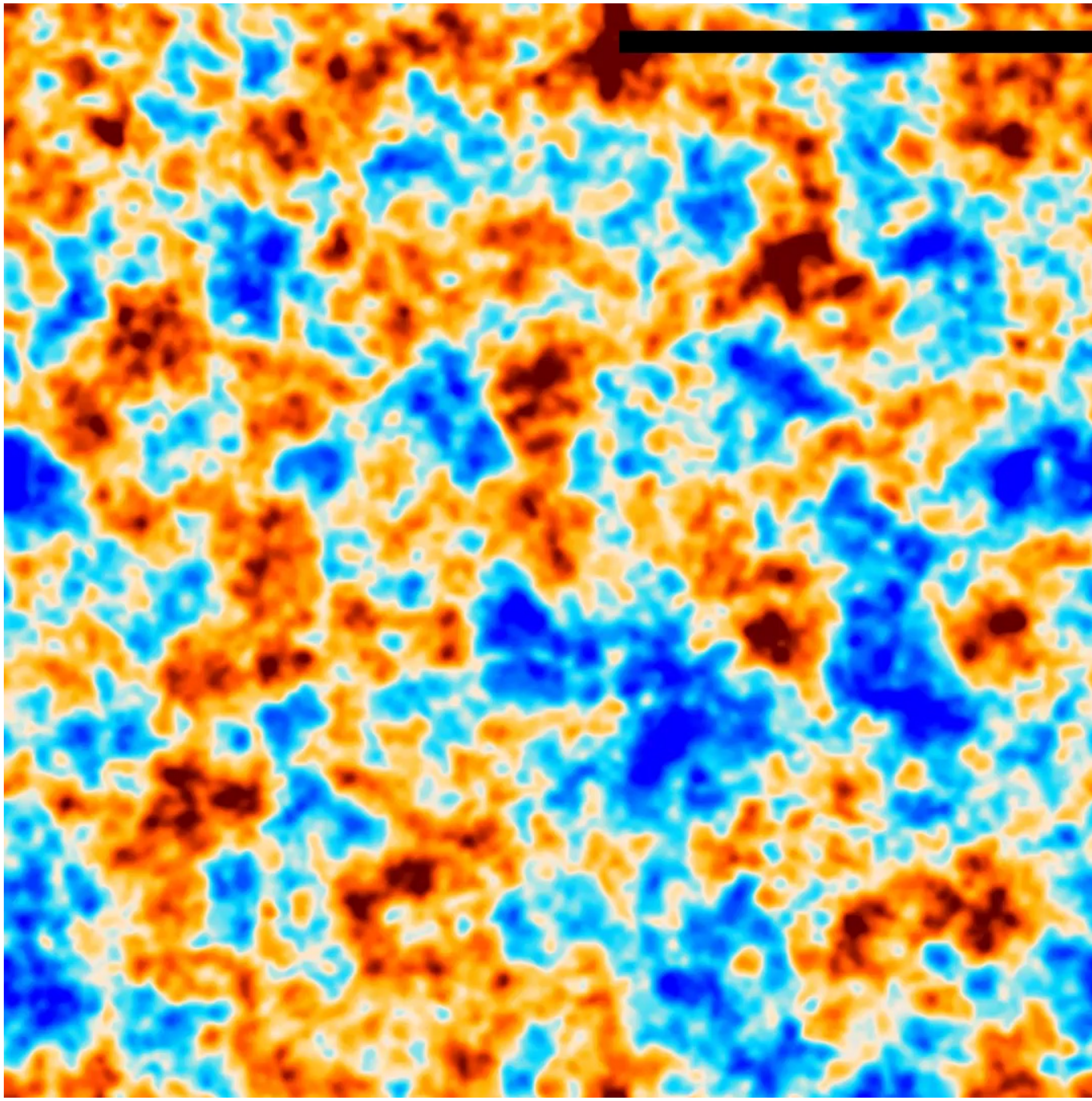

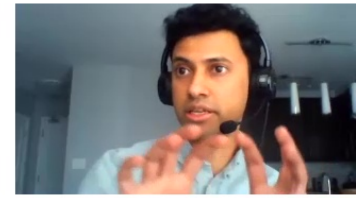

Lensed CMB

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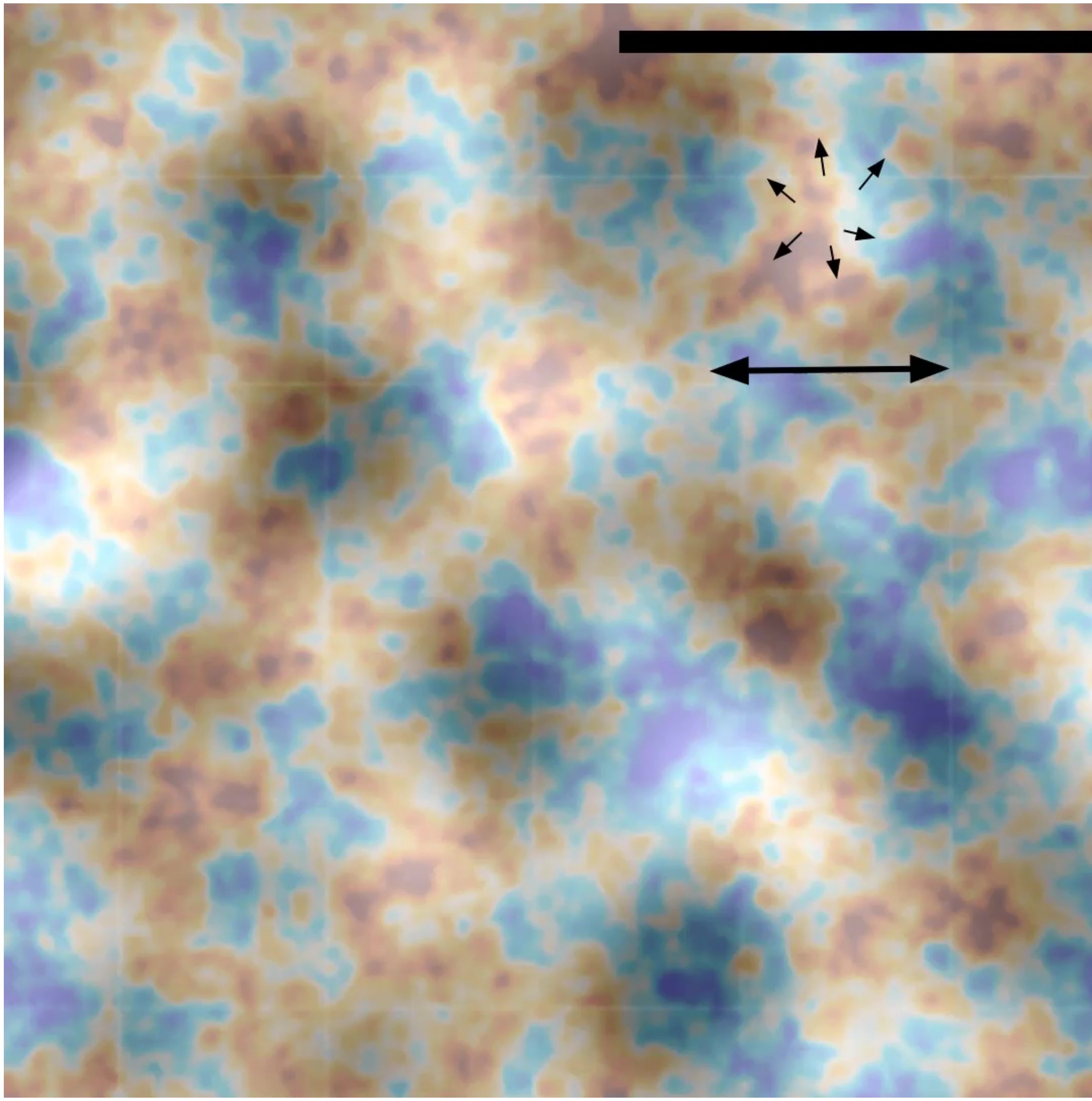

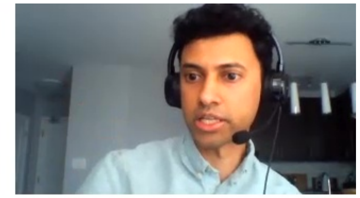

small-scale deflections

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Lensed CMB

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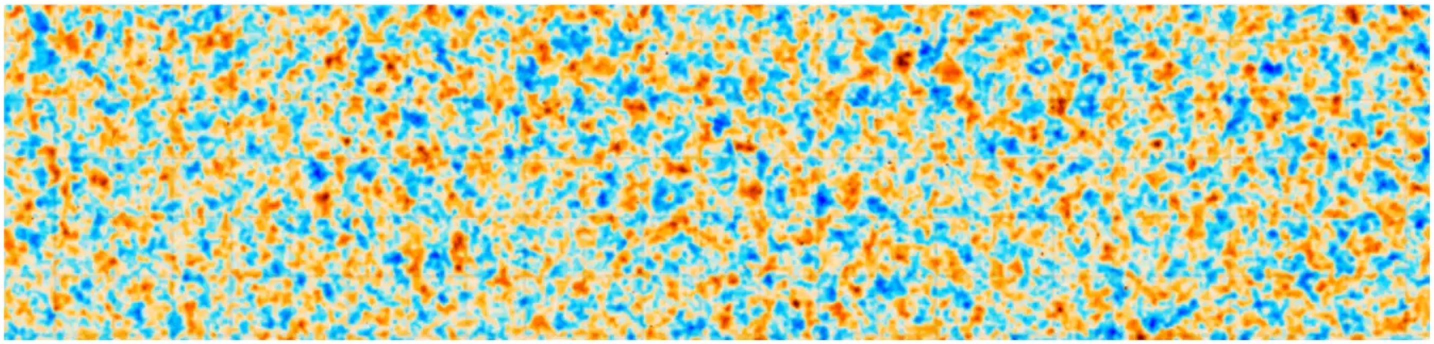
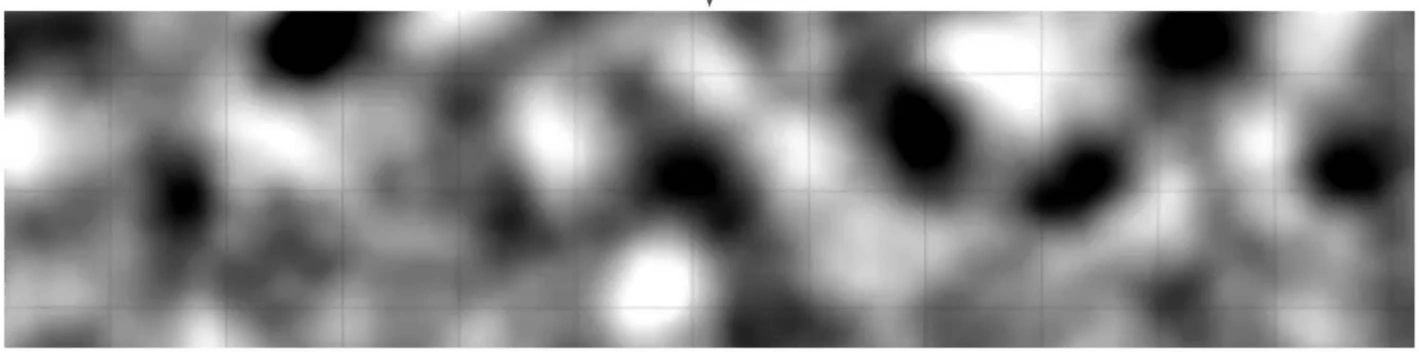
OBSERVED CMB (MICROWAVE LIGHT)



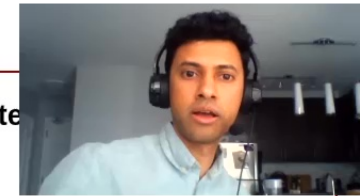
$$\langle T(\boldsymbol{\ell}_1)T(\boldsymbol{\ell}_2)\rangle_{\rm CMB} = f(\boldsymbol{\ell}_1,\boldsymbol{\ell}_2)\phi(\boldsymbol{\ell}_1+\boldsymbol{\ell}_2)$$



RECONSTRUCTED LENSING (DARK) MATTER DISTRIBUTION

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

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

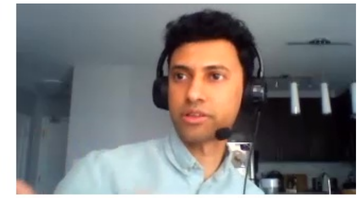


Subtleties, te

MM+ 2020
(noise-simulation robustness)
MM+ 2018
(foreground robustness)
Sehgal, MM+ 2017
(robust delensing)
Hadzhiyska, Sherwin, MM+ 2019
(ultra-small-scale lensing)

Novel applications

MM+ 2020 (high-z clusters)
MM+ 2017 (neutrinos, dark energy)
MM+ 2015 (halo lensing)
McCarthy, MM 2020 (star formation)
Darwish, MM+ 2020
(foreground-robust maps)
Miyatake, MM+ 2016 (cosmography)
Nguyen, Sehgal, MM 2017
(axion dark matter)
Li, Gluscevic, Boddy, MM 2018
(dark matter-baryon scattering)



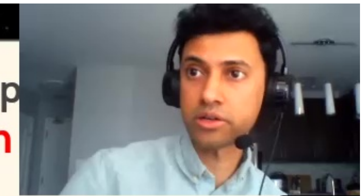
Massive neutrinos smooth the matter distribution

We need high-resolution measurements of the microwave sky to map the matter distribution

How do we measure the high-resolution microwave sky?

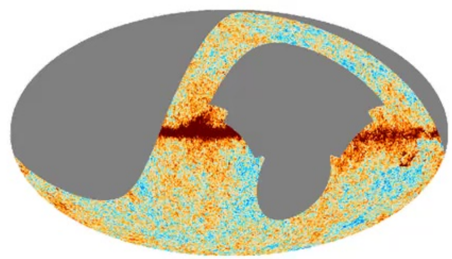
ACT

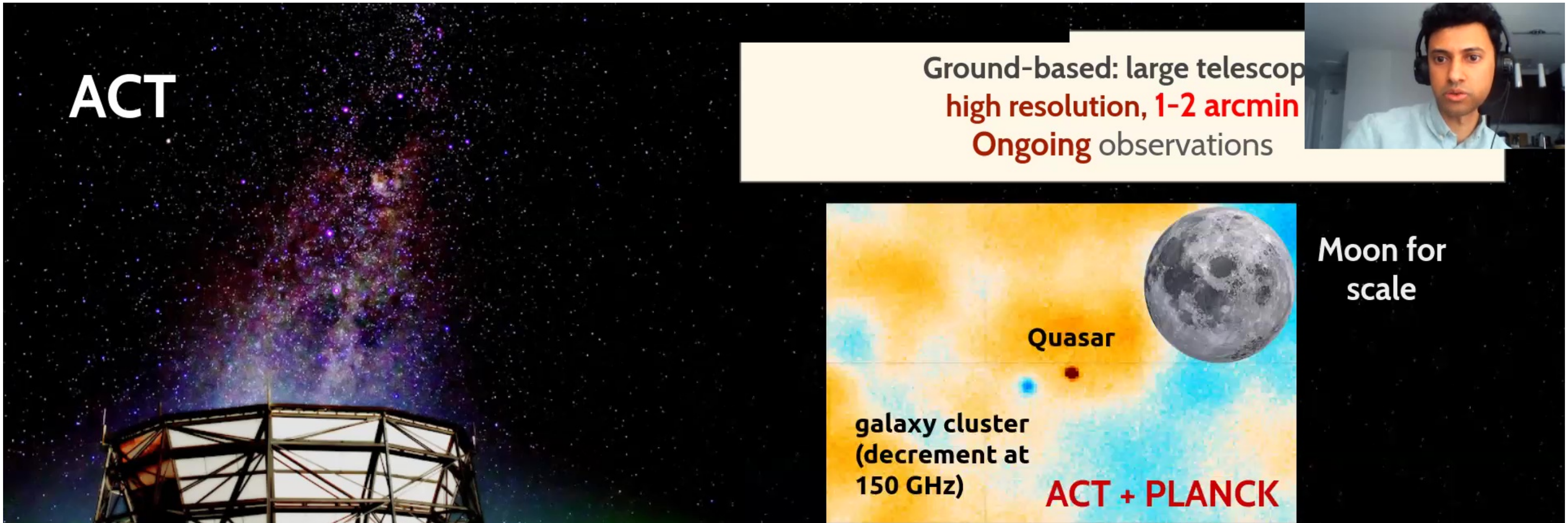
Ground-based: large telescop
high resolution, 1-2 arcmin
Ongoing observations

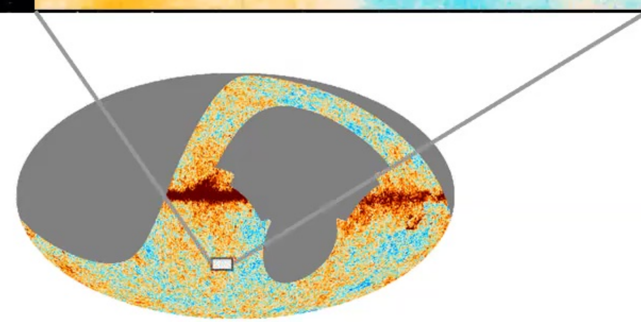


Wide area 30% sky for science
Noise 3-6x lower than Planck

We can build big / high-resolution
experiments on the ground







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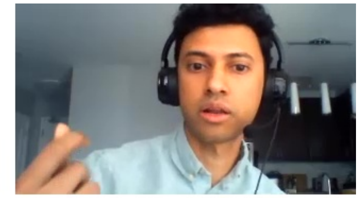
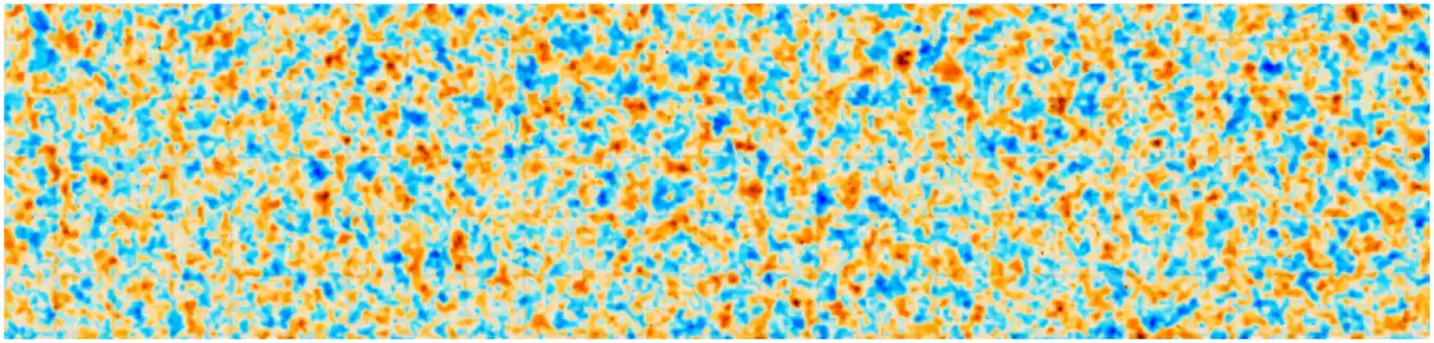
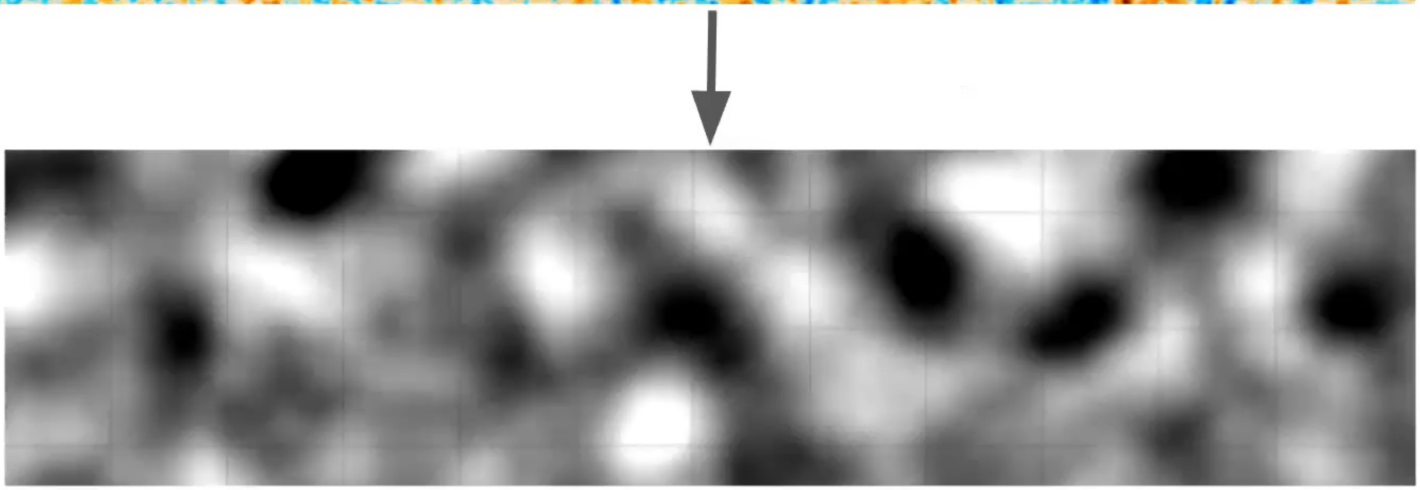


High-resolution ACT CMB data
(great for lensing!)
->
New dark matter maps from ACT

OBSERVED CMB (MICROWAVE LIGHT)



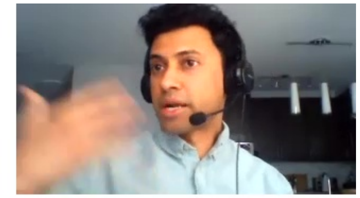


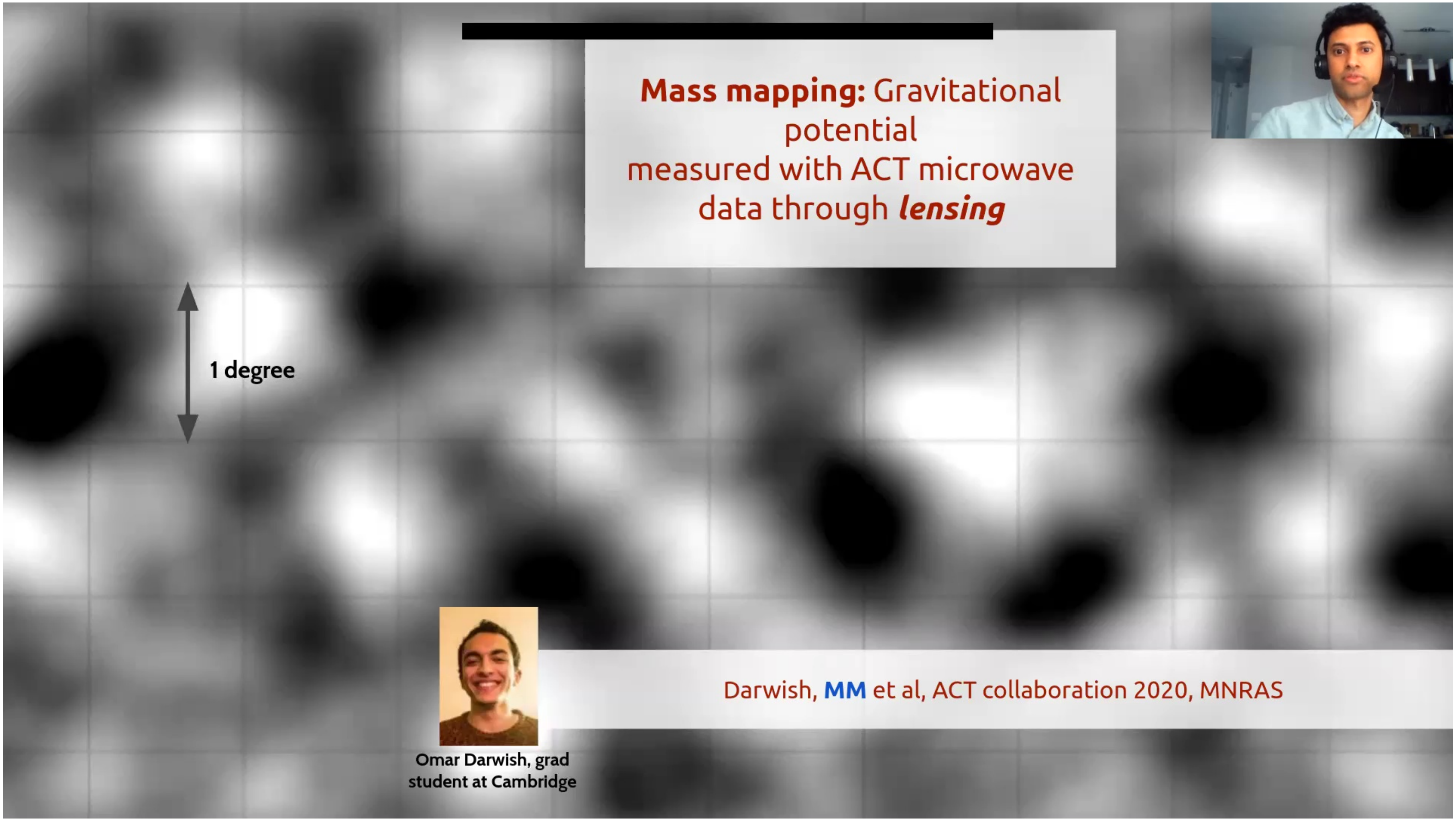
RECONSTRUCTED LENSING MATTER DISTRIBUTION

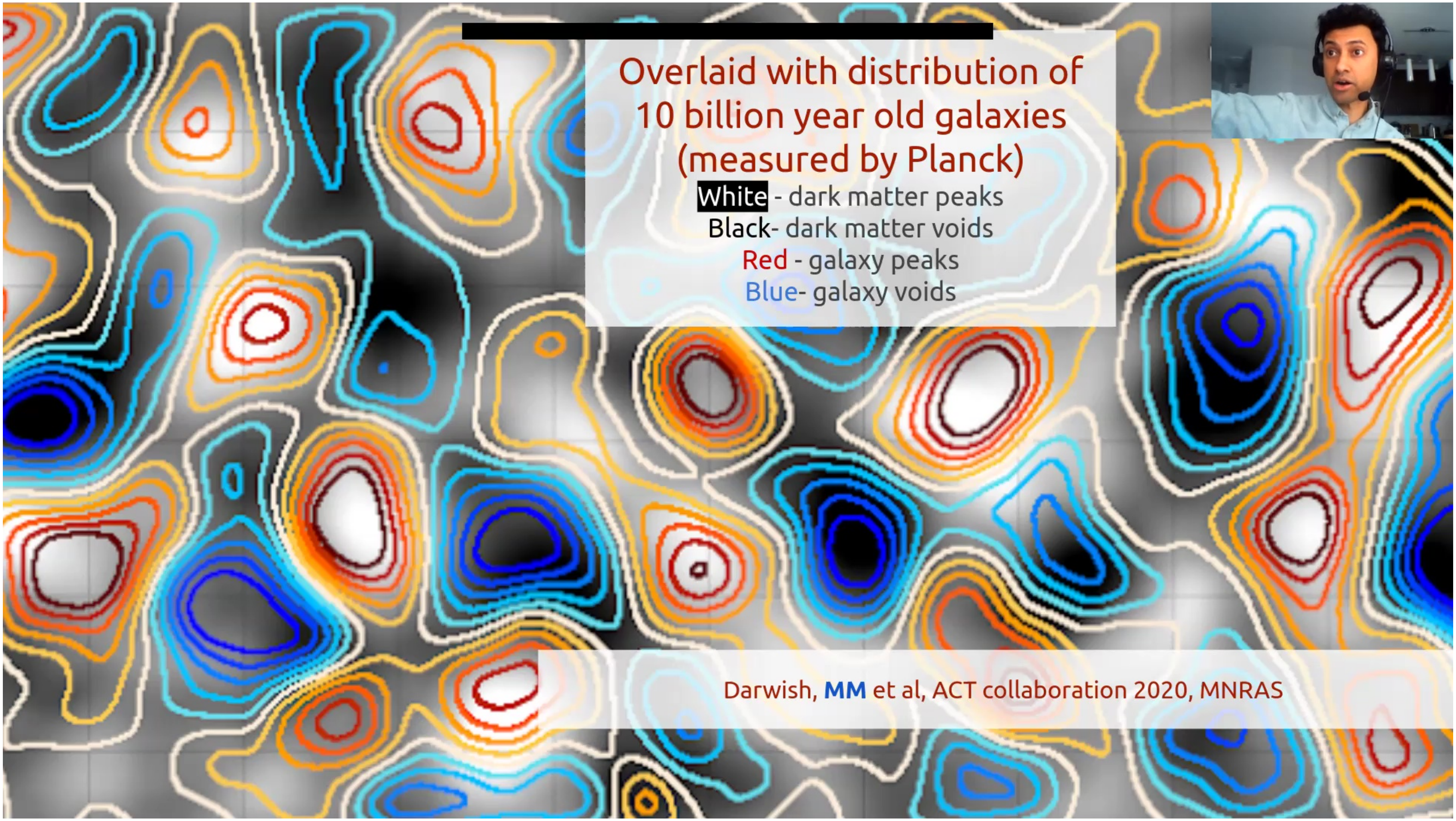
Key point: Large-scale lenses change **small-scale** CMB statistics

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

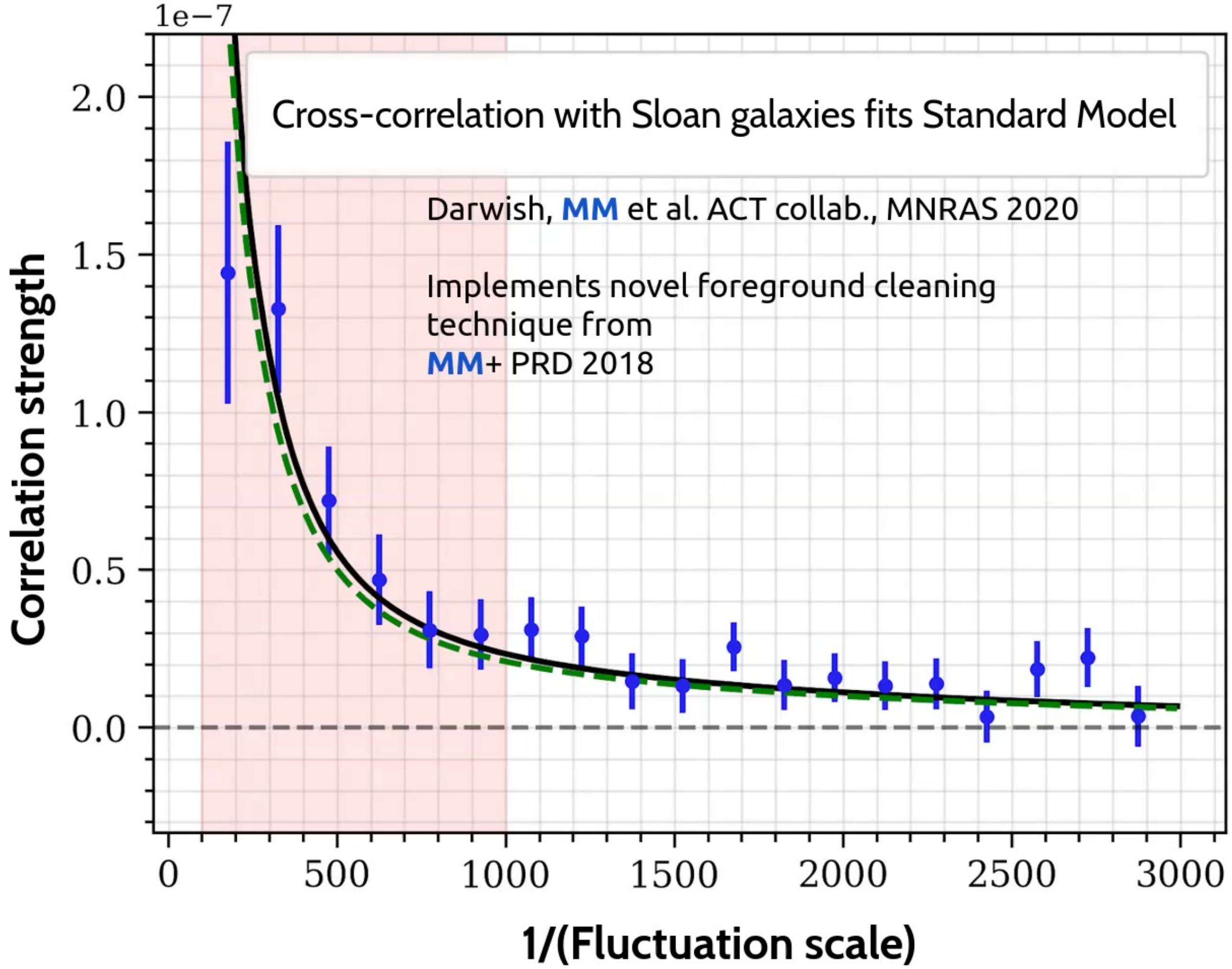
14 / 31

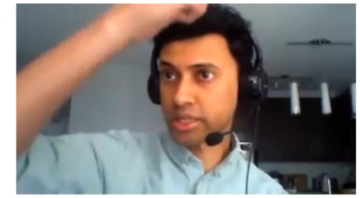



Mass mapping: Gravitational potential
measured with ACT microwave data through ***lensing***
1 degree
Darwish, **MM** et al, ACT collaboration 2020, MNRAS
Omar Darwish, grad student at Cambridge


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
Darwish, MM et al, ACT collaboration 2020, MNRAS

[redacted]



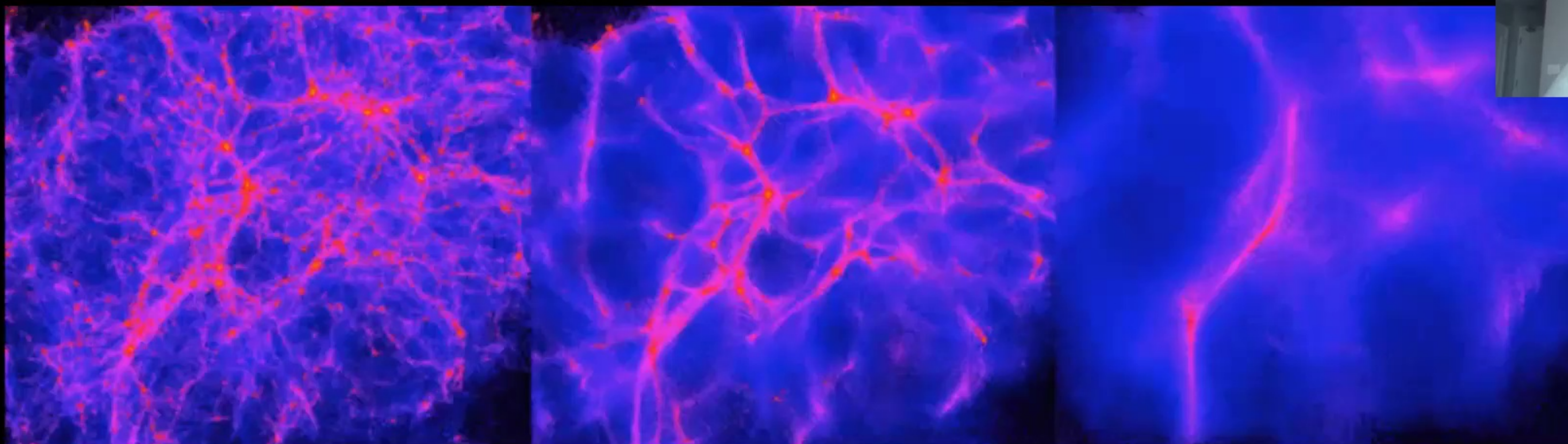


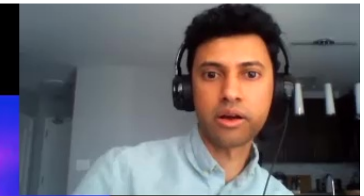
Important step towards improved neutrino mass measurements

e.g. Sherwin, van Engelen, Sehgal, **MM** et al ACT 2016

17 / 31

Massless neutrinos | Intermediate mass | High mass





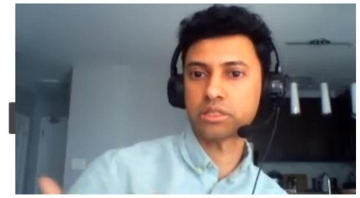
Cosmic density
smoothed by massive neutrinos

Simulations from **Ben Moore (Zurich)**

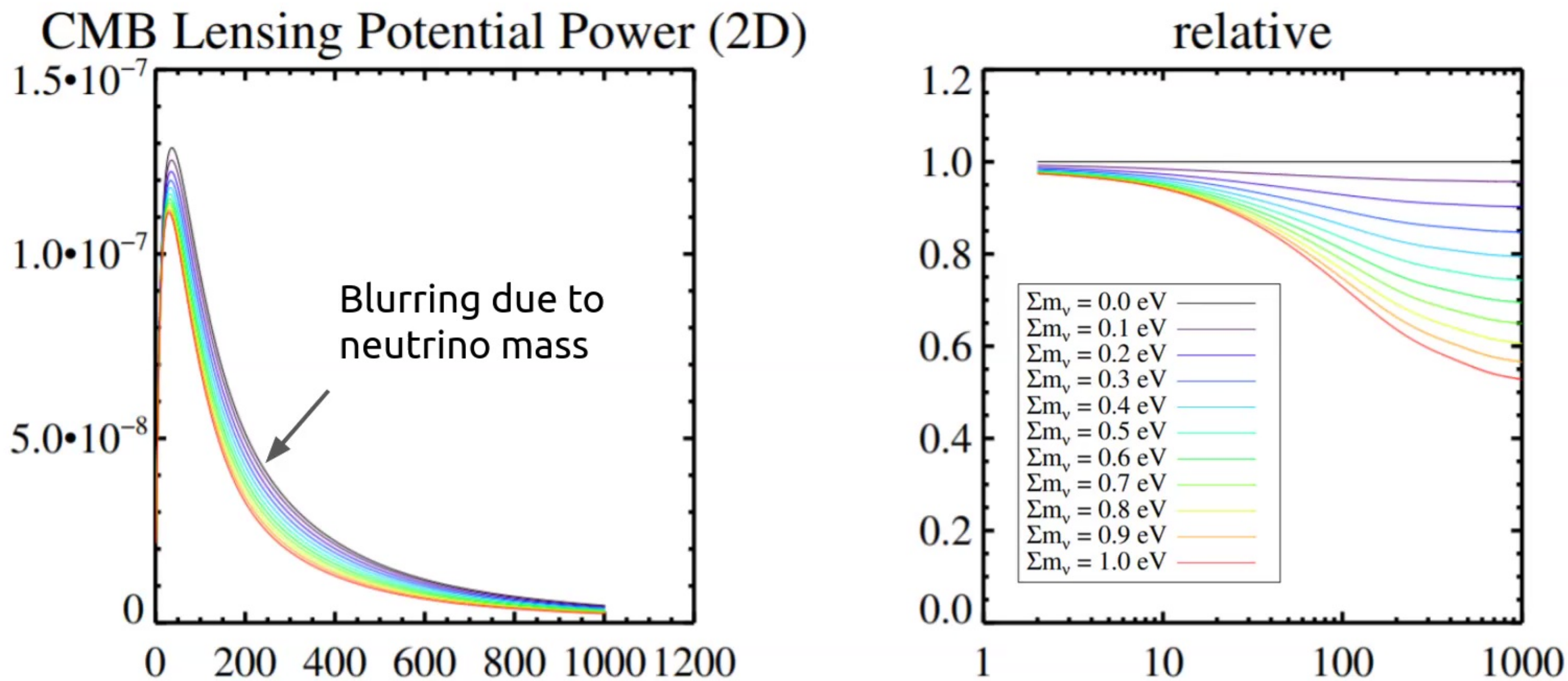
18 / 31

[redacted]

Measure statistics of lensing map to constrain neutrino

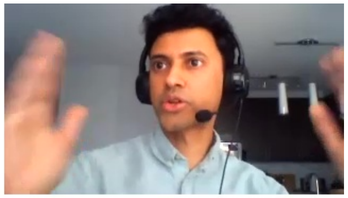


Y-axis:
How
much
lensing

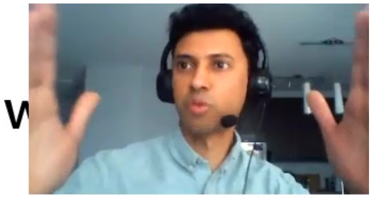


X-axis:
For a lens of this (1/angle) scale

Abazajian et al. (incl. **MM**) 2016, CMB-S4 science book



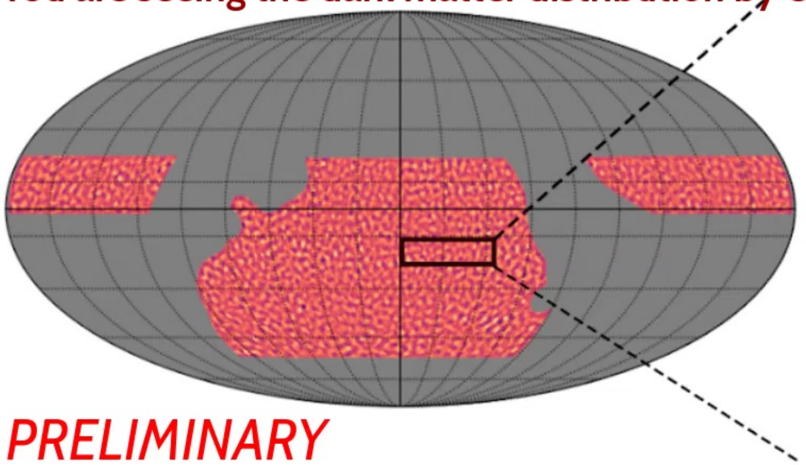
We need more data...
So we went wide.

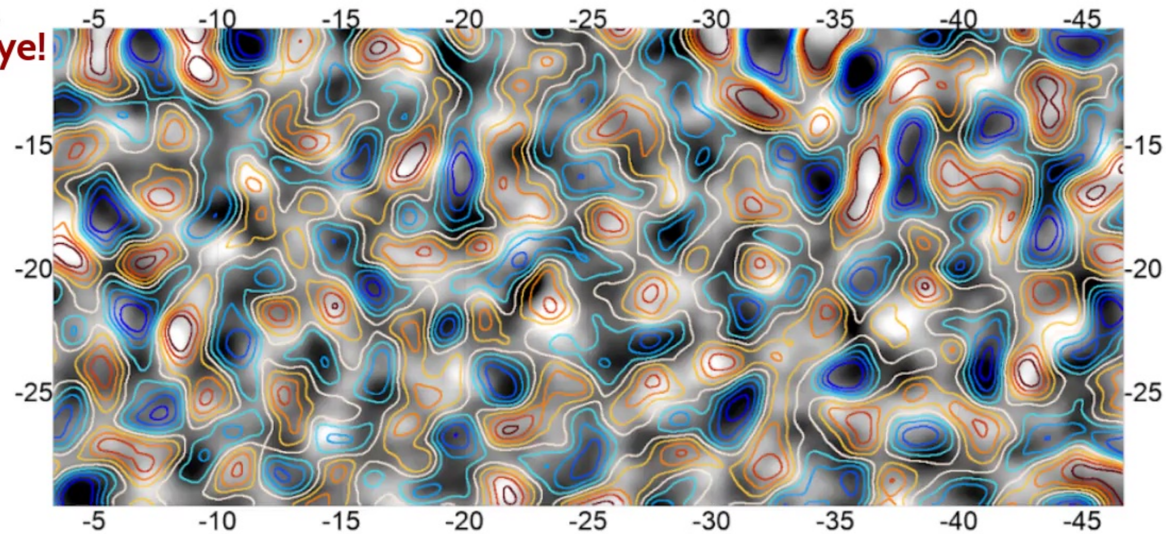


Upcoming ACT release: High-fidelity dark matter mapping over w

ACT 30% sky - 6x more than previously shown

You are seeing the dark matter distribution by eye!





PRELIMINARY

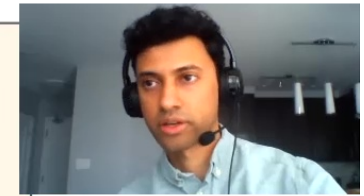
MM et al, in prep (data up to 2019)
Forecast: constrain **neutrino mass to ~60 meV,** close to ruling out inverted hierarchy (>100 meV)
~1% constraint on amplitude of fluctuations (~4x improvement over Planck)

Worked hard for sub-percent precision lensing!

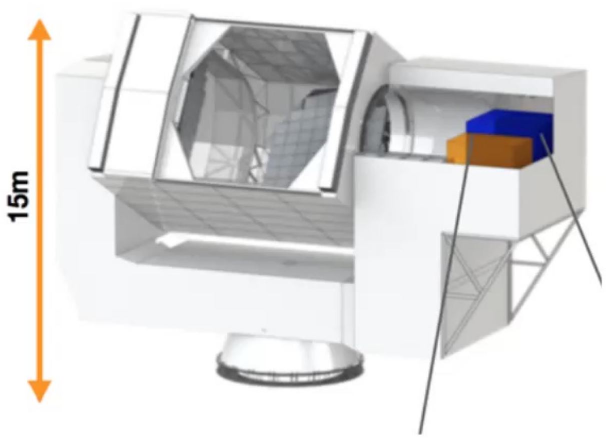
MM+ 2020 (noise-simulation robustness)
MM+ 2018 (foreground robustness)

[redacted]

Ground-based: large telescopes, high resolution
FUNDED and UNDER CONSTRUCTION
Observing from 2023 onwards



Simons Observatory



~ 300 members
(including Perimeter)
~$80 million in funding in place

40% sky for science
Noise 2-3 times < ACT
1-2 arcmin resolution
30, 40, 98, 150, 220, 270 GHz

21 / 31

[redacted]

Ground-based: large telescopes, high resolution
FUNDED and UNDER CONSTRUCTION
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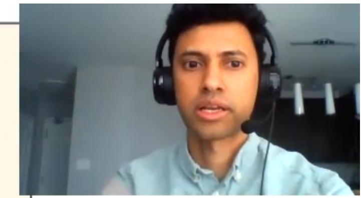

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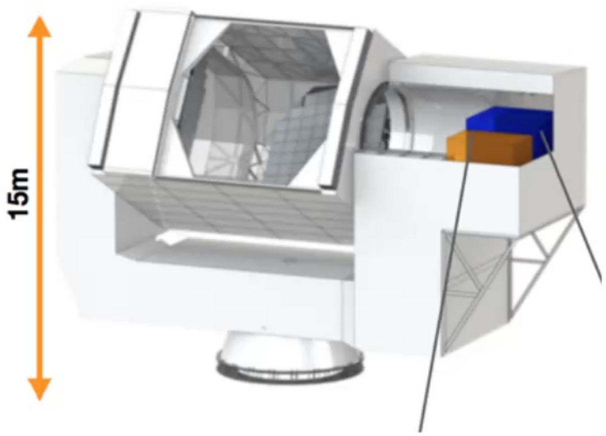

40% sky for science
Noise 2-3 times < ACT
1-2 arcmin resolution
30, 40, 98, 150, 220, 270 GHz

~ 300 members
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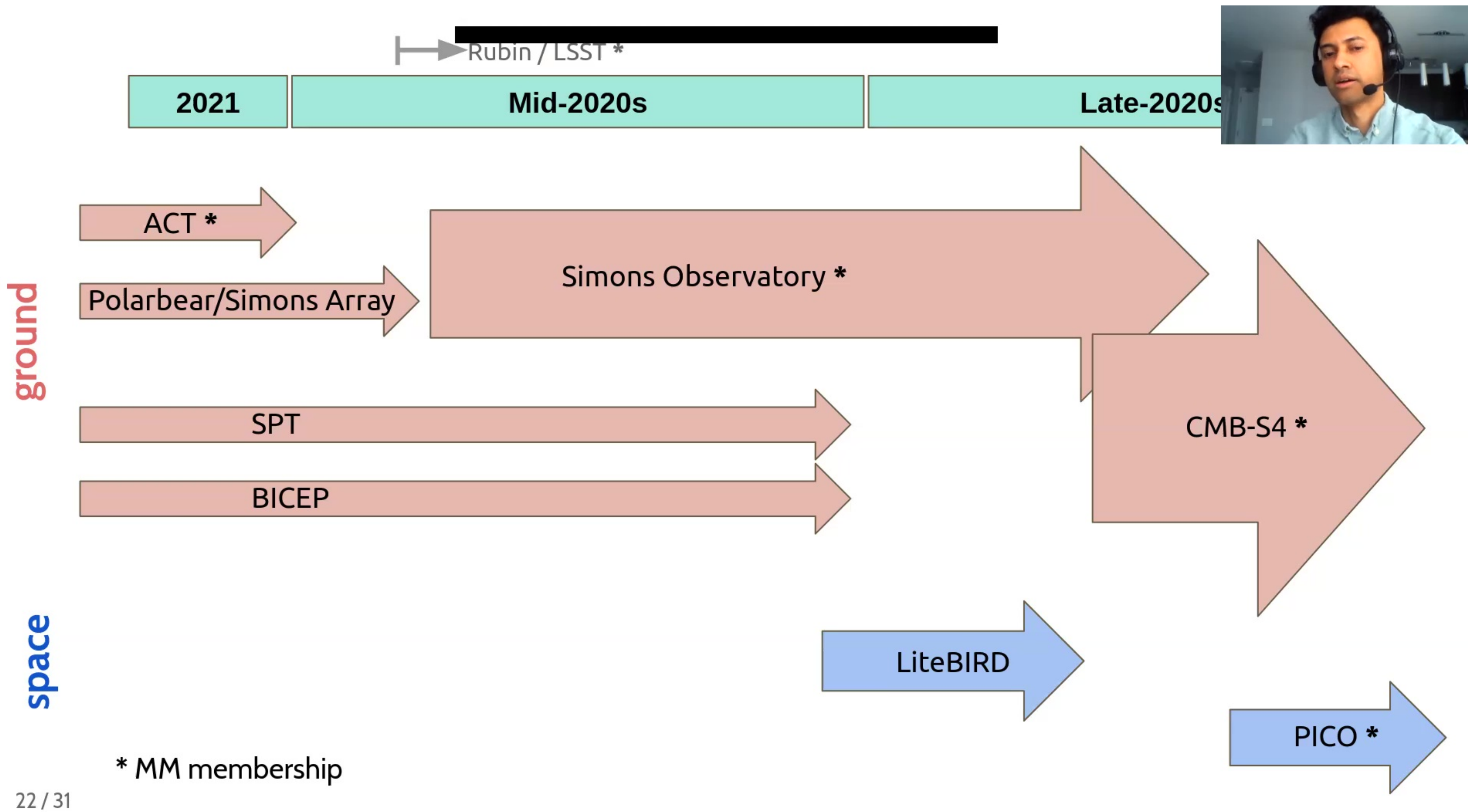
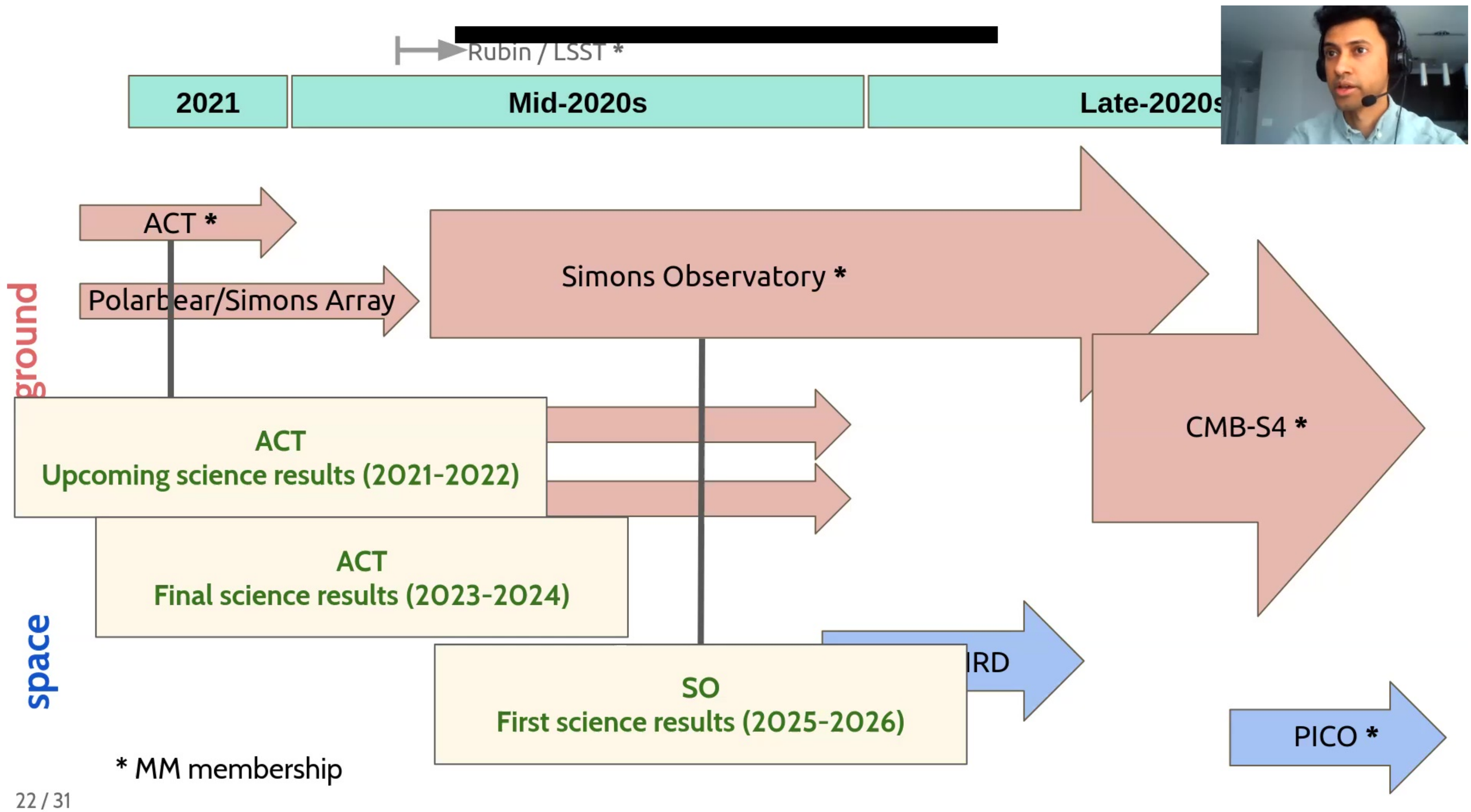
~$80 million in funding in place

My roles:

- **Lead:** Gravitational lensing reconstruction
- **Lead:** Systematics and science interfaces
- **Member:** Theory and Analysis Committee


[redacted]
Rubin / LSST *
2021
Mid-2020s
Late-2020s
ground
ACT *
Polarbear/Simons Array
Simons Observatory *
SPT
BICEP
CMB-S4 *
space
LiteBIRD
PICO *
* MM membership
22 / 31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Rubin / LSST *
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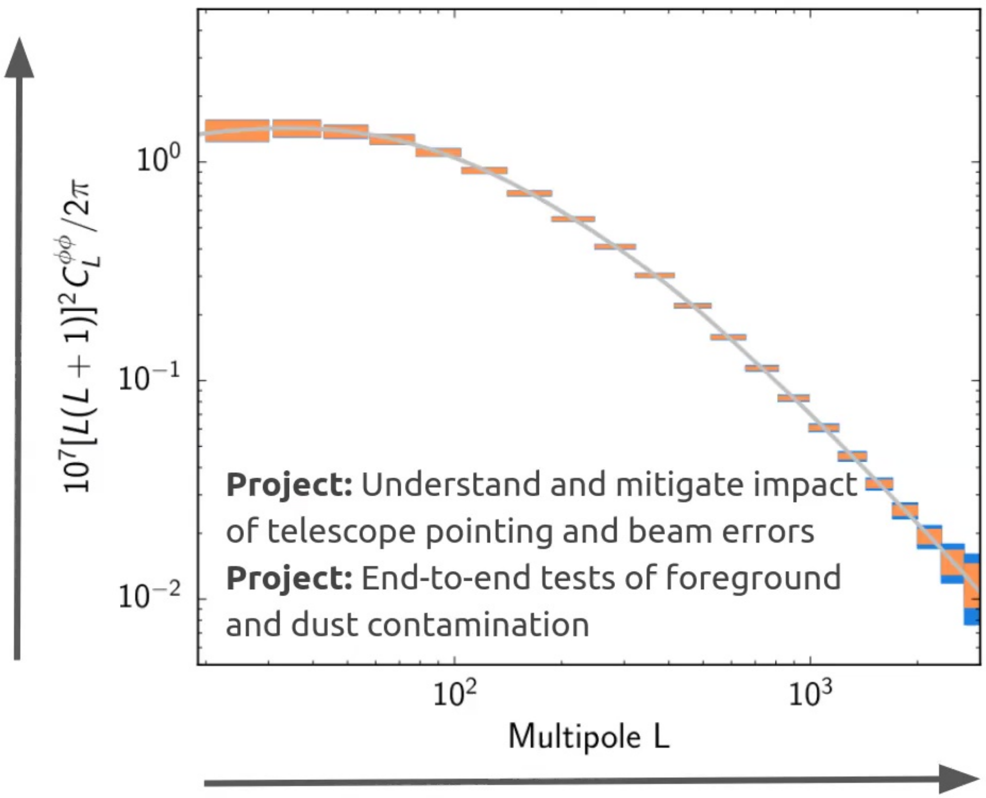
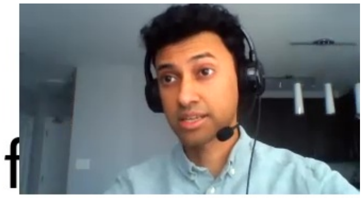
ACT
Upcoming science results (2021-2022)
ACT
Final science results (2023-2024)
space
IRD
SO
First science results (2025-2026)
PICO *
* MM membership
22 / 31

[redacted]

Y-axis:
How
much
lensing



X-axis:
For a lens of this (1/angle)
scale

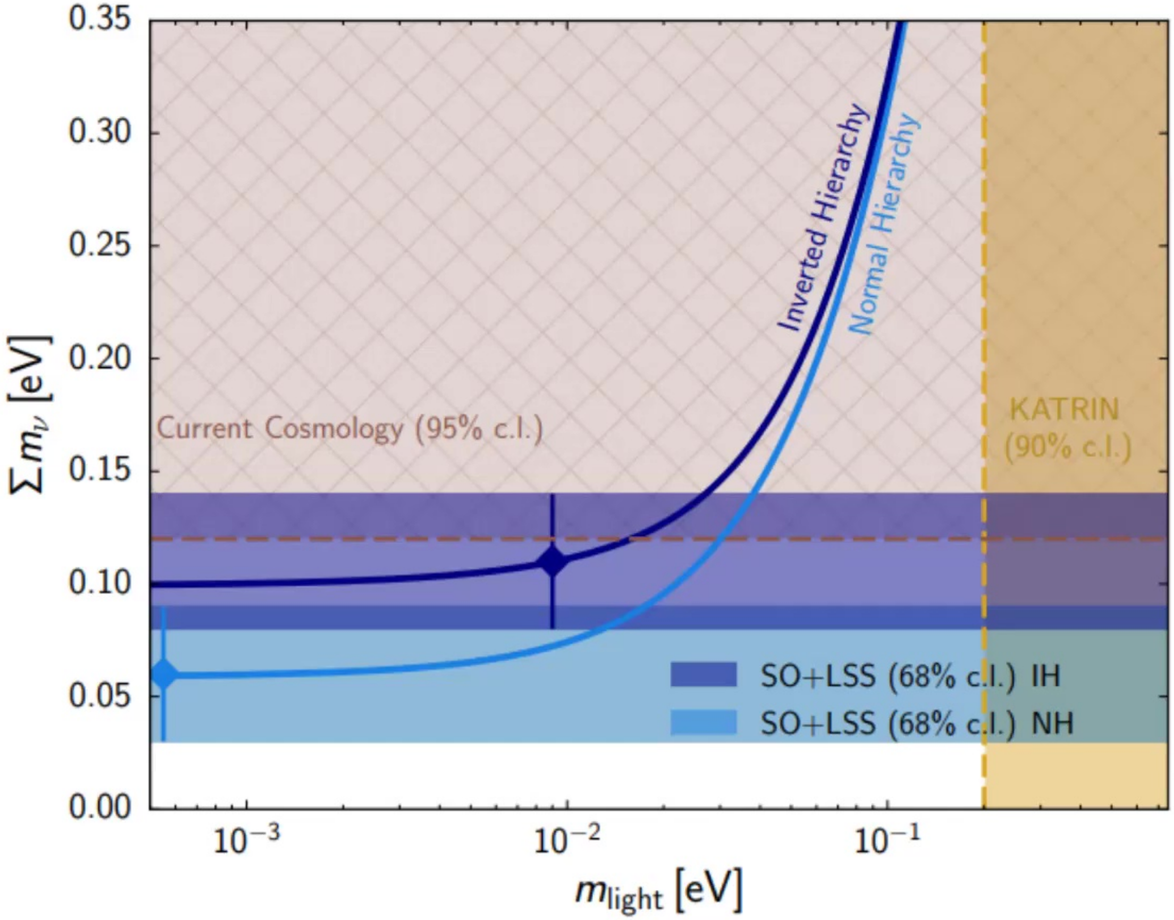


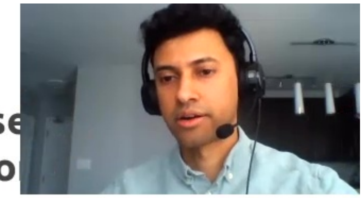
~0.7% f measurement of lensing with Simons Observatory

Simons Observatory collaboration
(incl. **MM**)
arXiv:1808.07445

My role:
Leading the group that reconstructs this signal

[redacted]





Simons Obse
collaboratio
(incl. **MM**)
arXiv:1808.07445

- Exclude inverted hierarchy with Simons Obs.
- Possible measurement of minimal mass with Simons Obs. (<2029)
- Proposed CMB-S4 experiment (starting 2027+) will measure the minimal mass
- Set target for direct detection

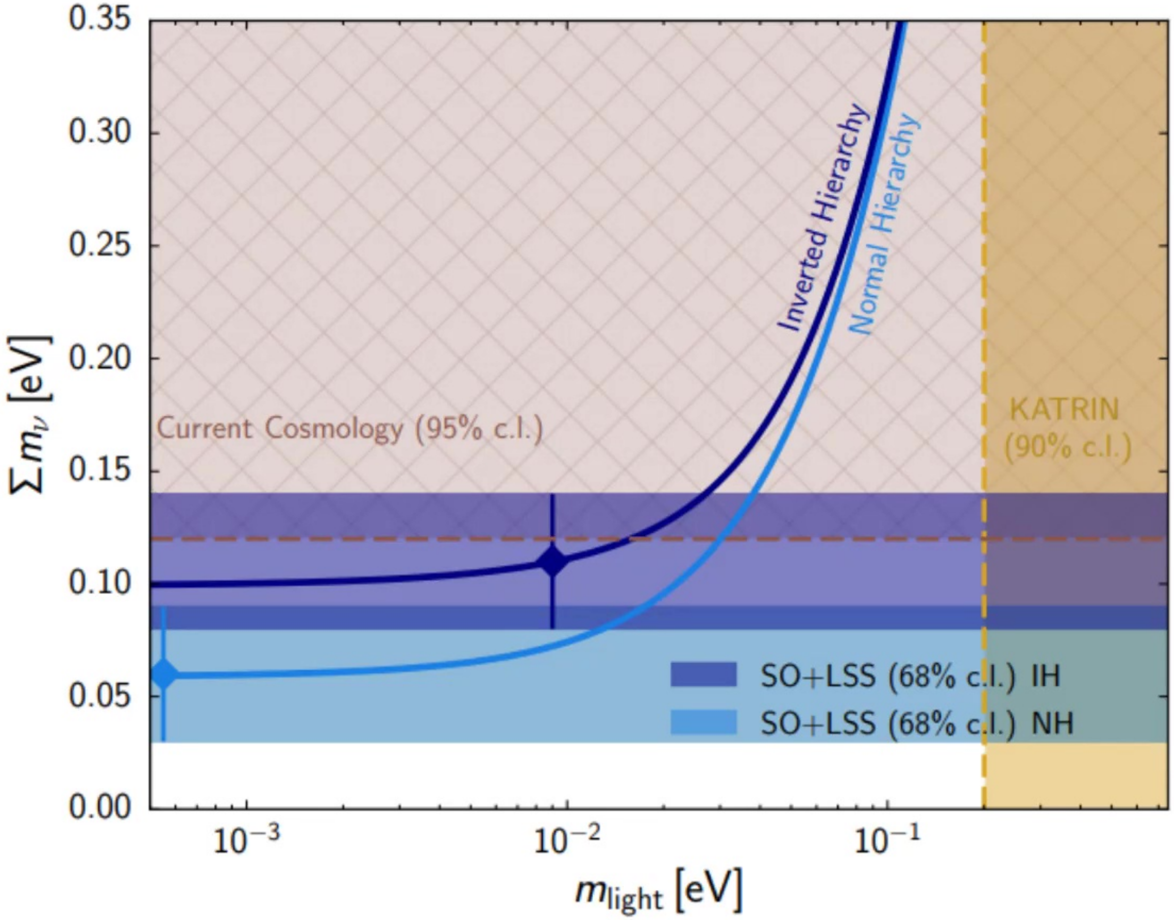
Mathew Madhavacheril, Perimeter Institute

Neutrinos smooth the matter distribution

We measure the matter distribution from the microwave sky using **gravitational lensing**

Can also learn about the **very early universe** using relics buried in the CMB and galaxy distribution

[redacted]



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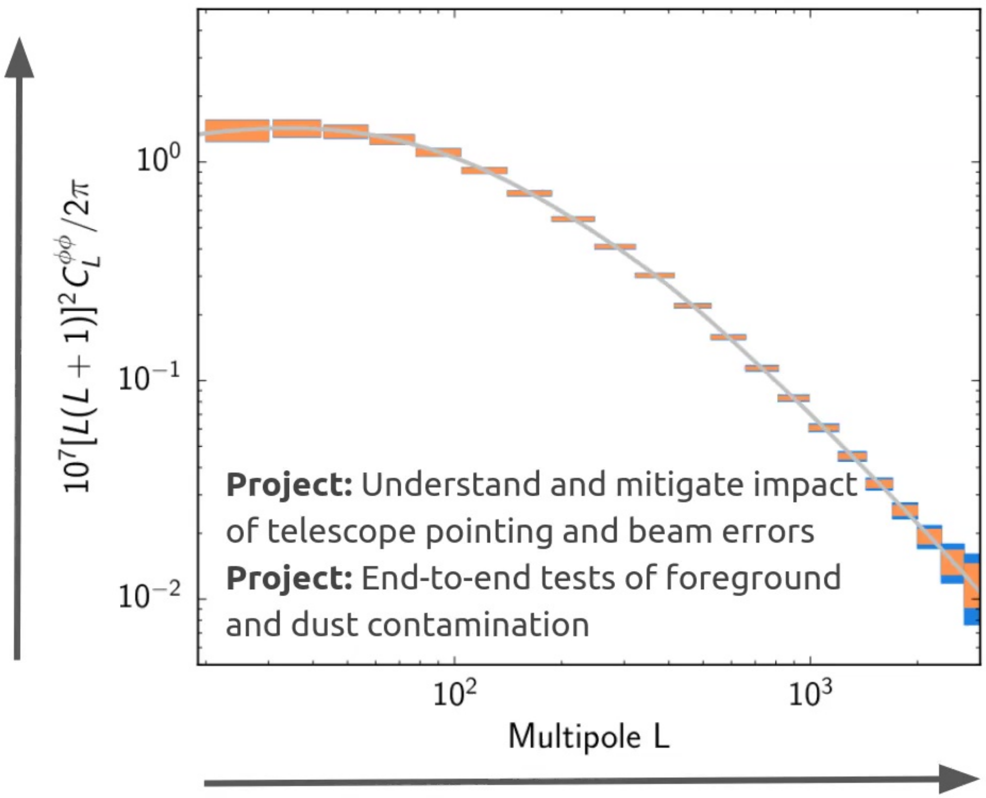

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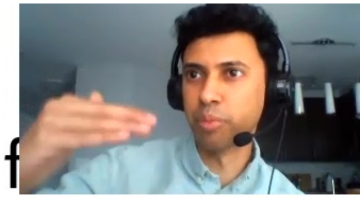

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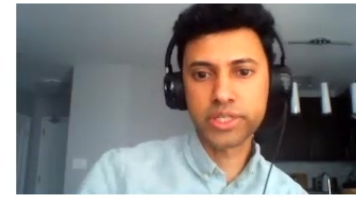

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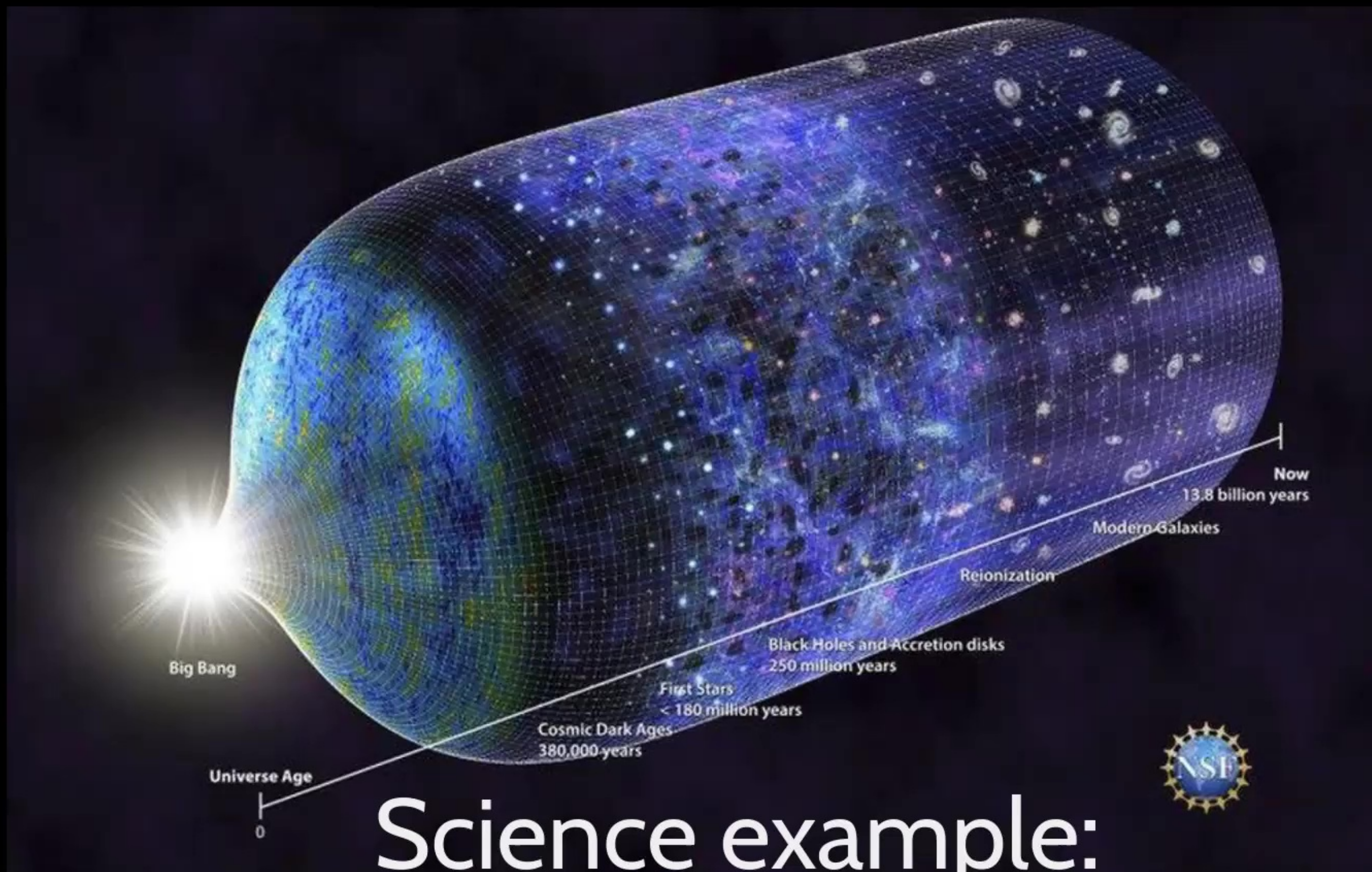
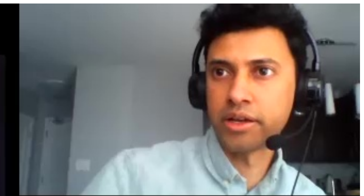
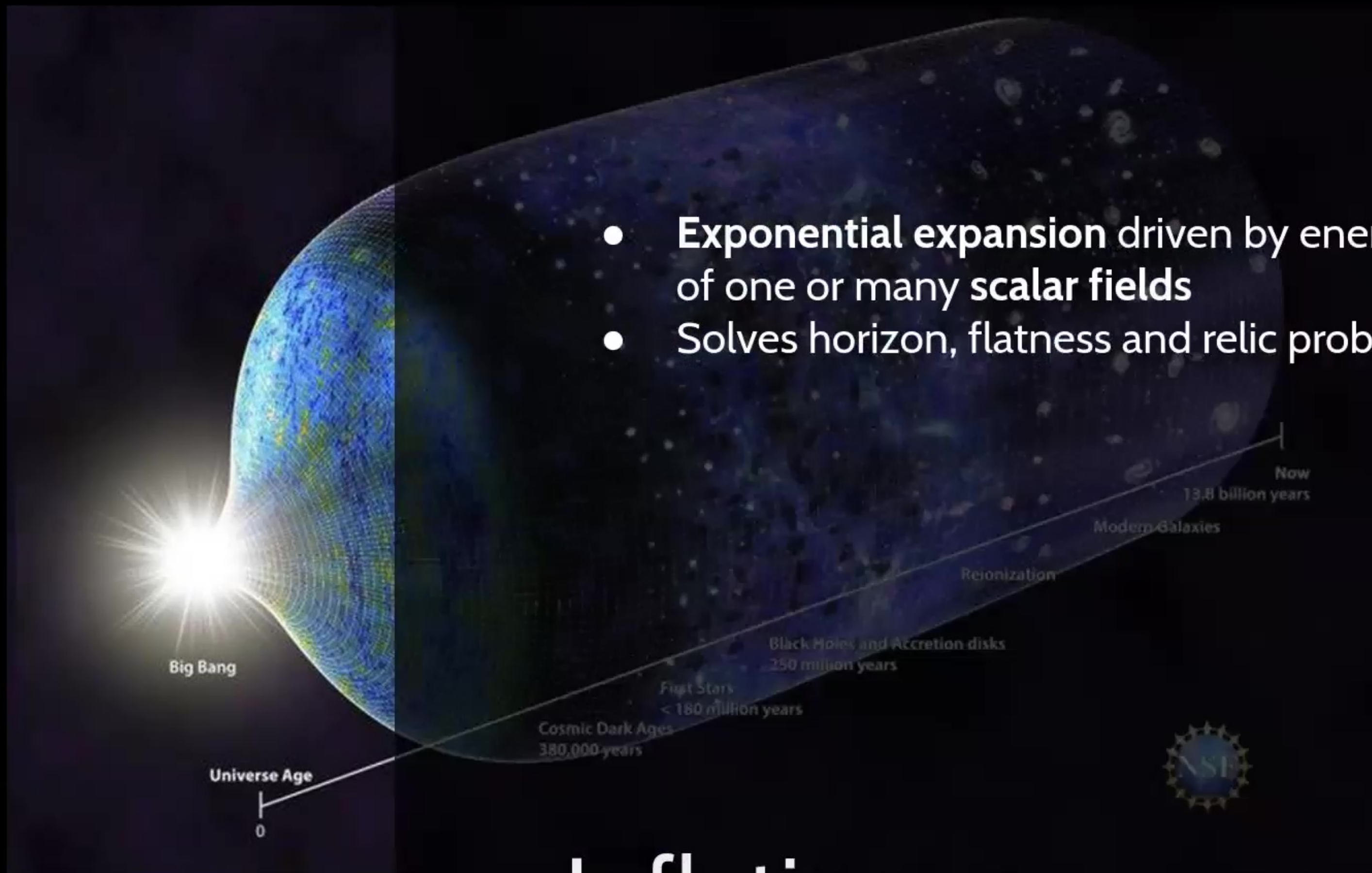


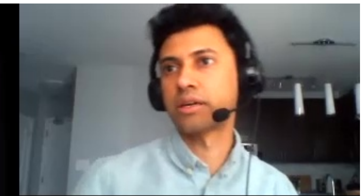
Science example: Multi-field inflation

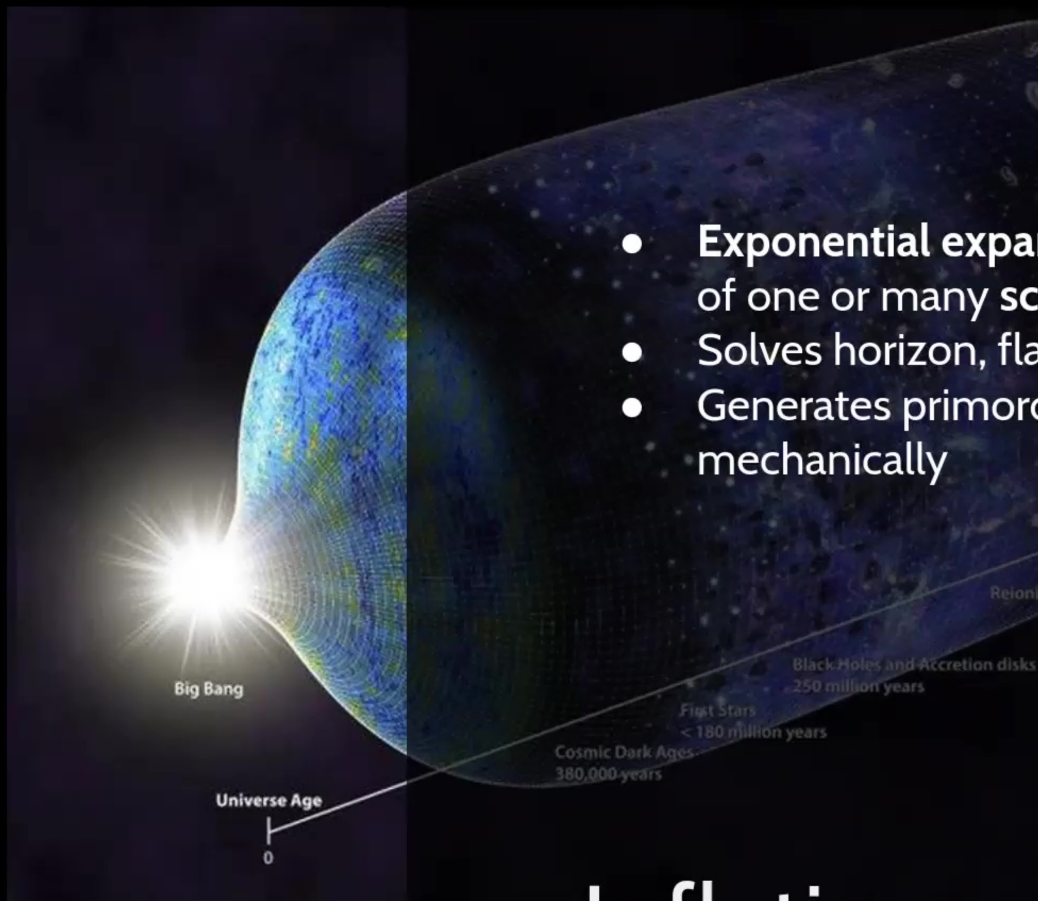




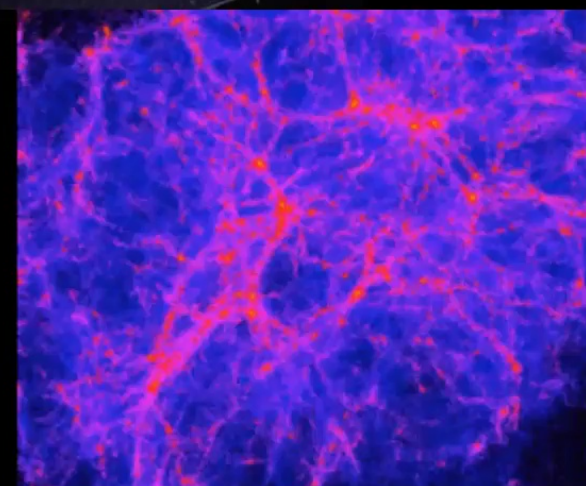
- **Exponential expansion** driven by energy density of one or many **scalar fields**
- Solves horizon, flatness and relic problems

Inflation

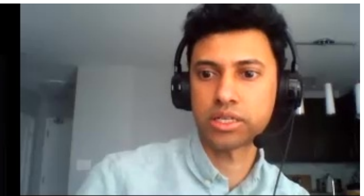


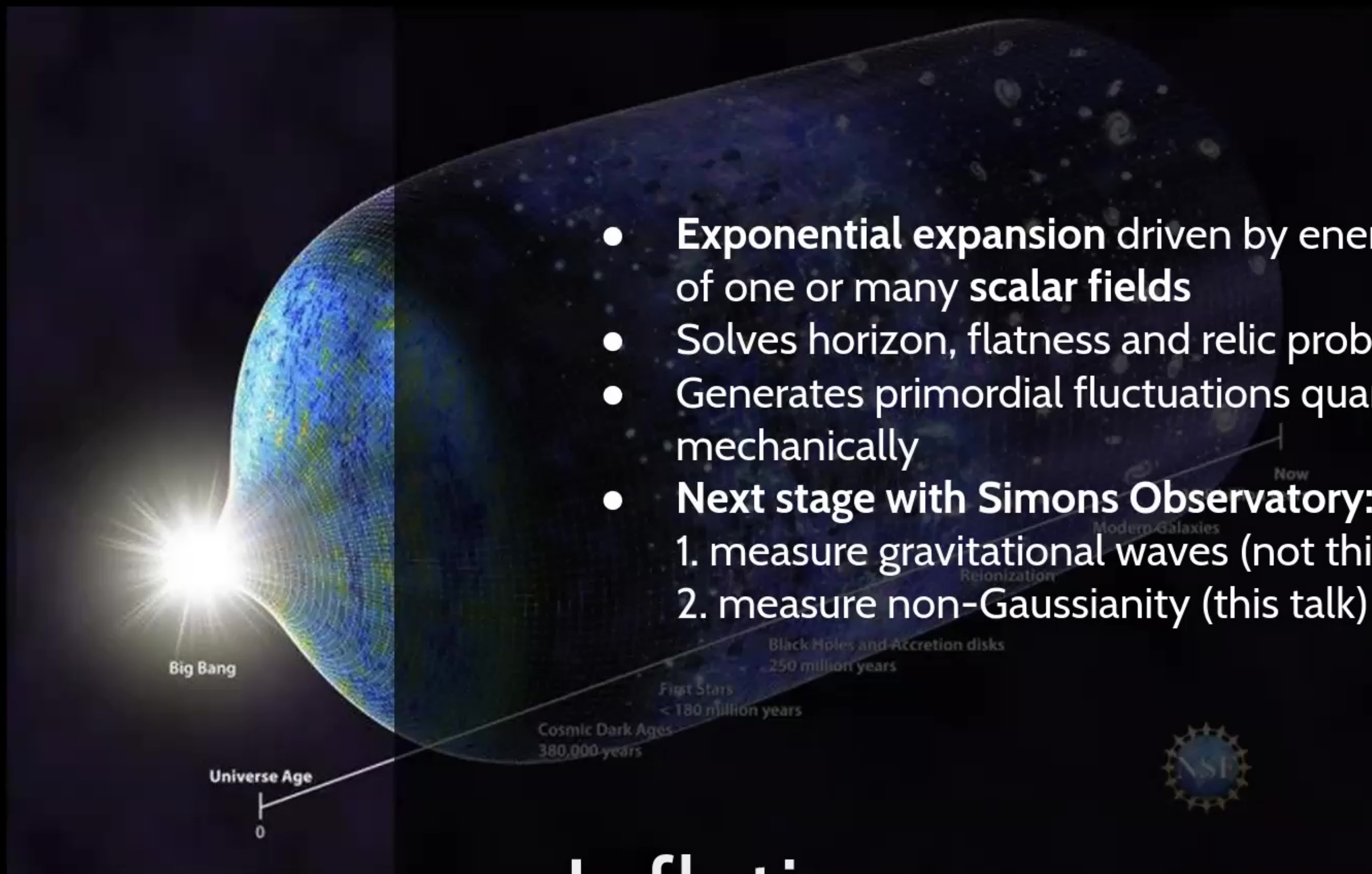


- **Exponential expansion** driven by energy density of one or many **scalar fields**
- Solves horizon, flatness and relic problems
- Generates primordial fluctuations quantum mechanically



Inflation

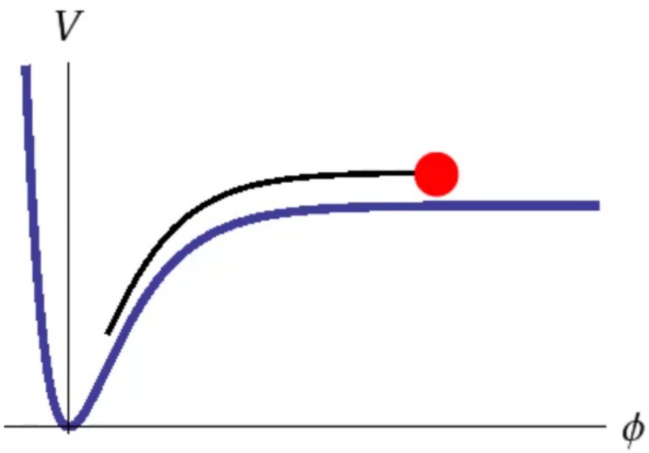


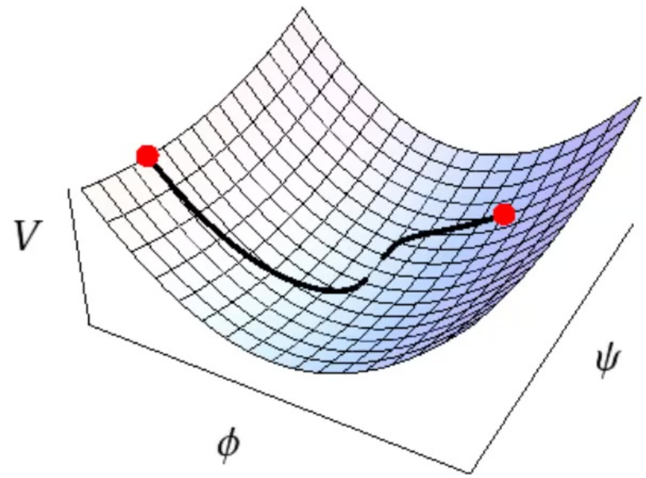


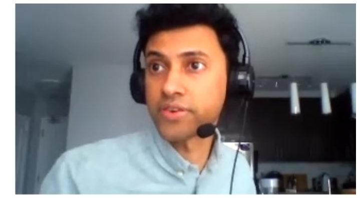
- **Exponential expansion** driven by energy density of one or many **scalar fields**
- Solves horizon, flatness and relic problems
- Generates primordial fluctuations quantum mechanically
- **Next stage with Simons Observatory:**
  1. measure gravitational waves (not this talk!)
  2. measure non-Gaussianity (this talk)

Inflation

[redacted]





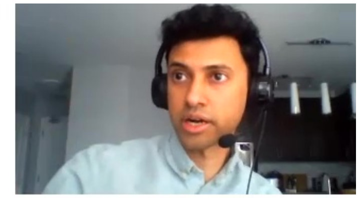


- Inflation driven by energy density of one or many **scalar fields**
- Current measurements (Planck CMB) consistent with single field
- Multiple fields naturally motivated by e.g. string theory
  - Predicts possibly detectable amounts of departure from Gaussianity
  - This shows up as **excess clustering of galaxies** on the largest scales *Dalal et al 2007*

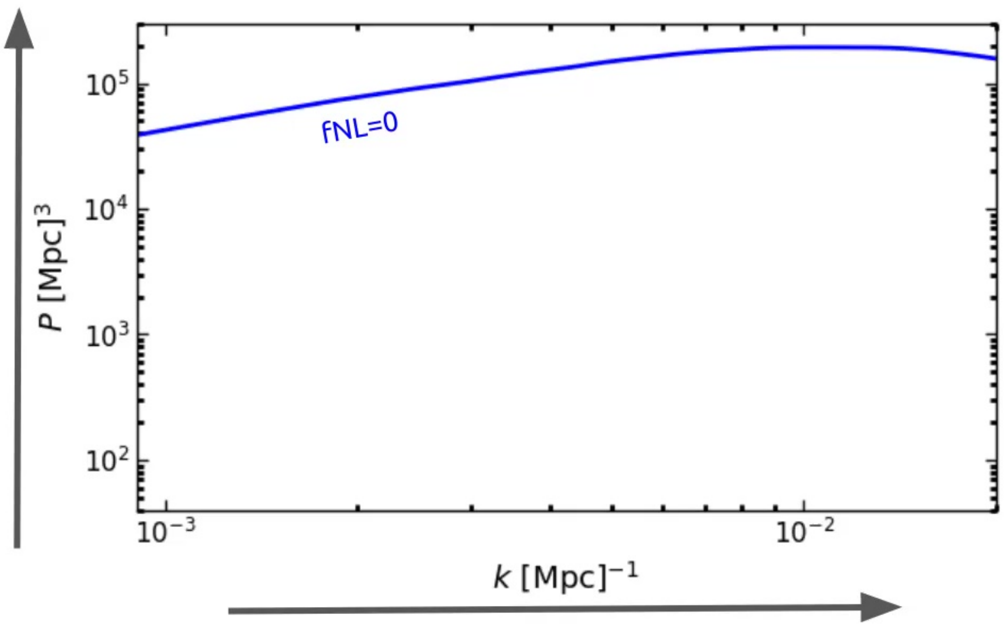
$$\Phi_{\rm NG} = \Phi_{\rm L} + f_{\rm NL}\Phi_{\rm L}^2$$

26 / 31

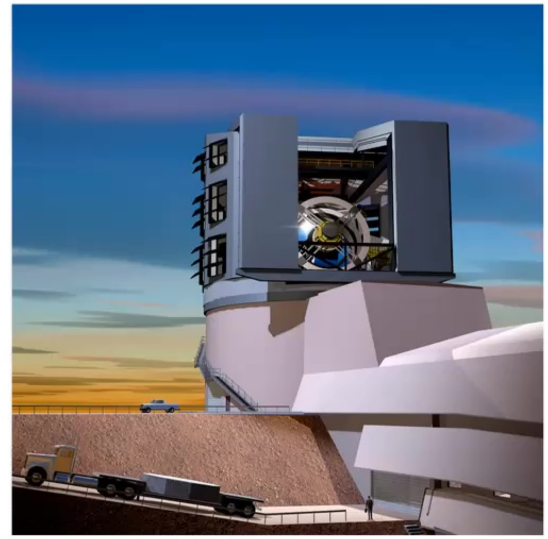
Galaxy surveys like Rubin/LSST measure clustering



Y-axis:
How
much
clustering



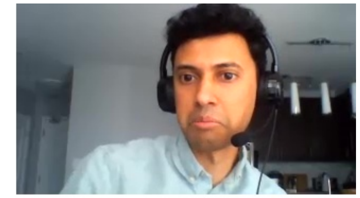
X-axis:
(1/length) scale



Vera Rubin Observatory
LSST survey
Beginning in a couple of years
Several billion galaxies
Galaxies cluster with dark matter

Mathew Madhavacheril, Perimeter Institute

Galaxy surveys like Rubin/LSST measure clustering



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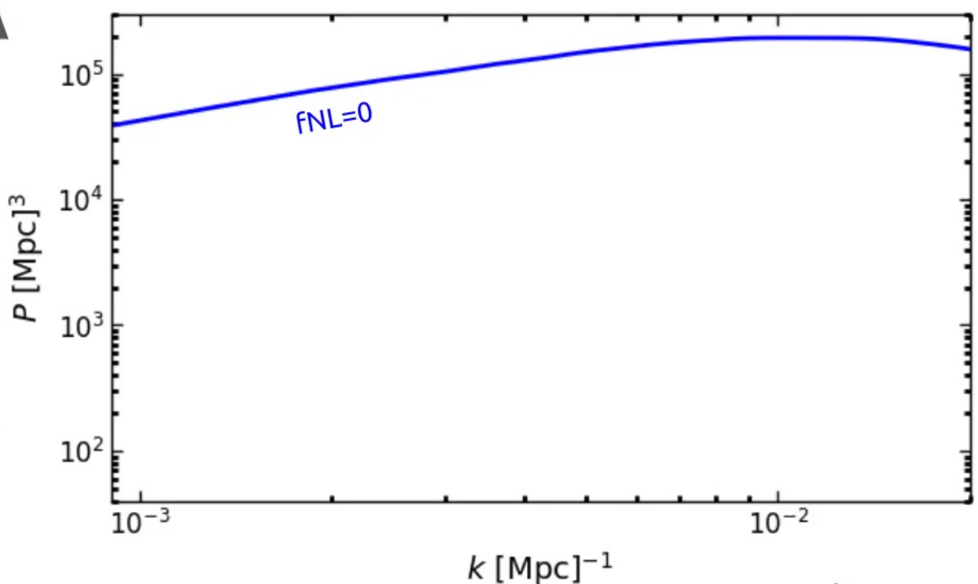

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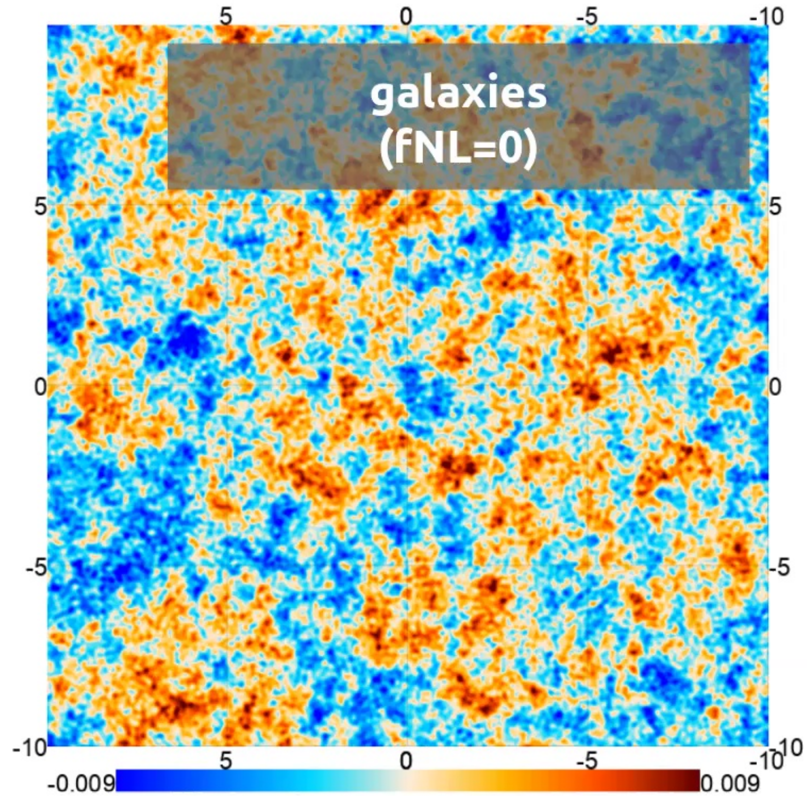
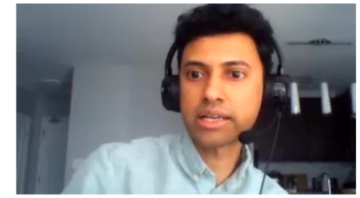


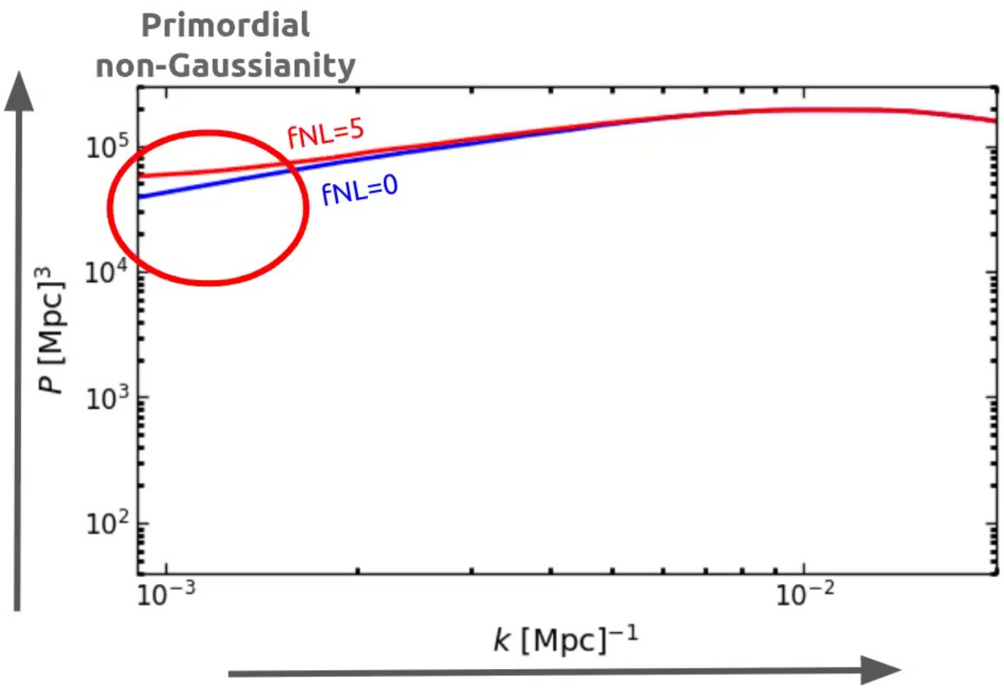
Mathew Madhavacheril, Perimeter Institute

[redacted]

Multi-field inflation predicts excess clustering



Y-axis: How much clustering



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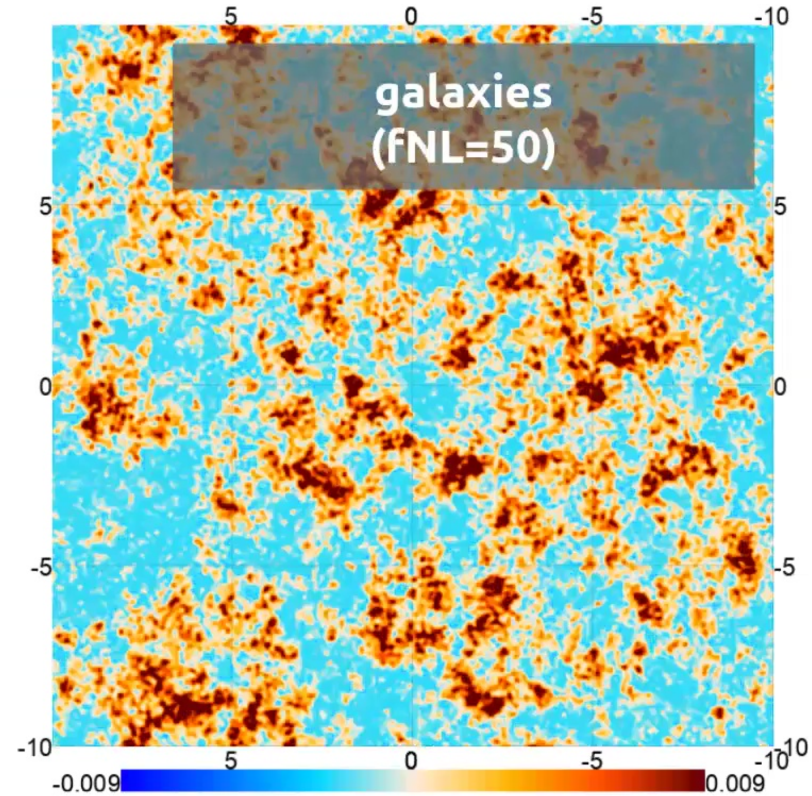

Mathew Madhavacheril, Perimeter Institute

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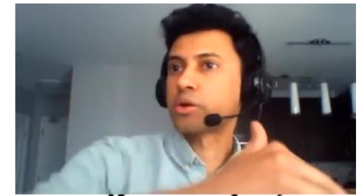
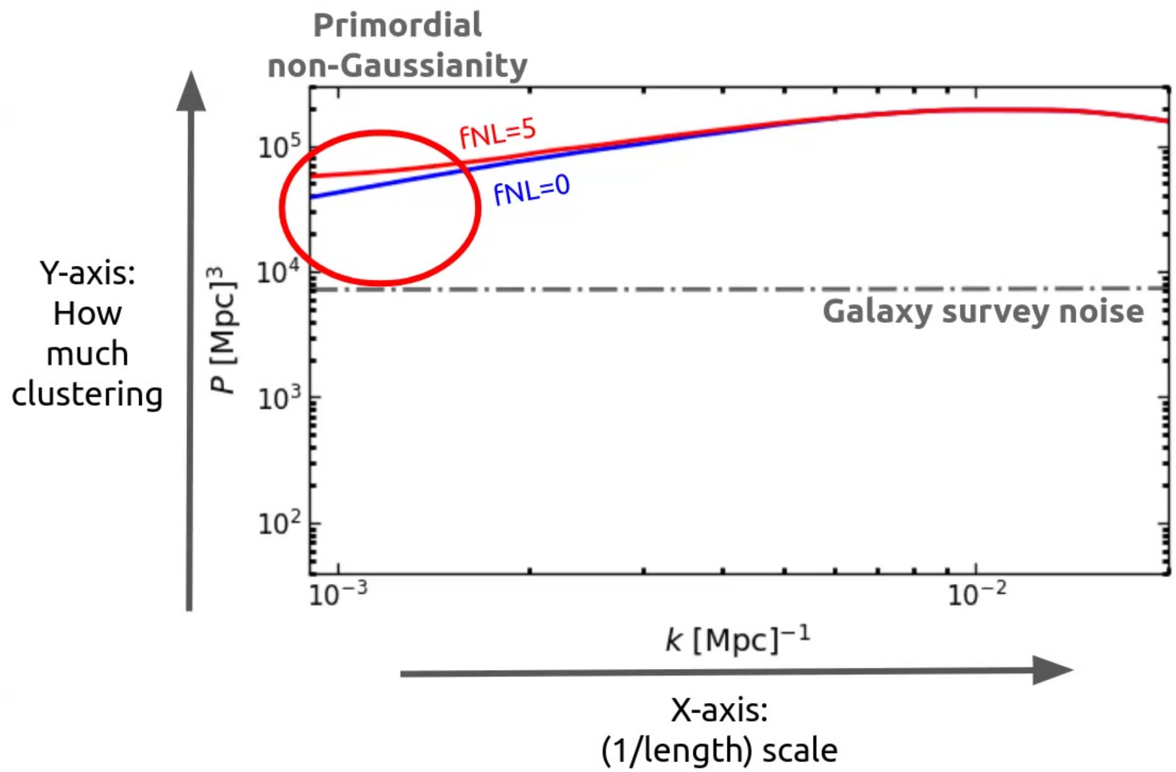
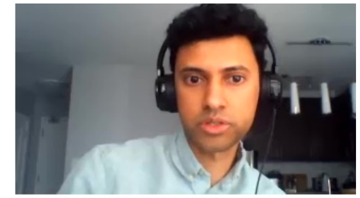




$$\Phi_{\mathrm{NG}} = \Phi_{\mathrm{L}} + f_{\mathrm{NL}}\Phi_{\mathrm{L}}^2$$

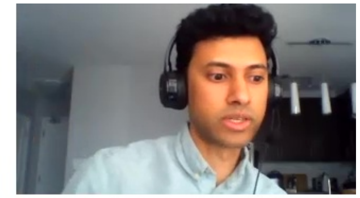
- Current constraint from Planck CMB sigma(fNL) ~ 5
- Rubin/LSST sigma(fNL) ~ 2
- MFI generically predicts fNL ~ 1

Mathew Madhavacheril, Perimeter Institute



Can we improve large-scale clustering measurements beyond what galaxy surveys can measure?

[redacted]

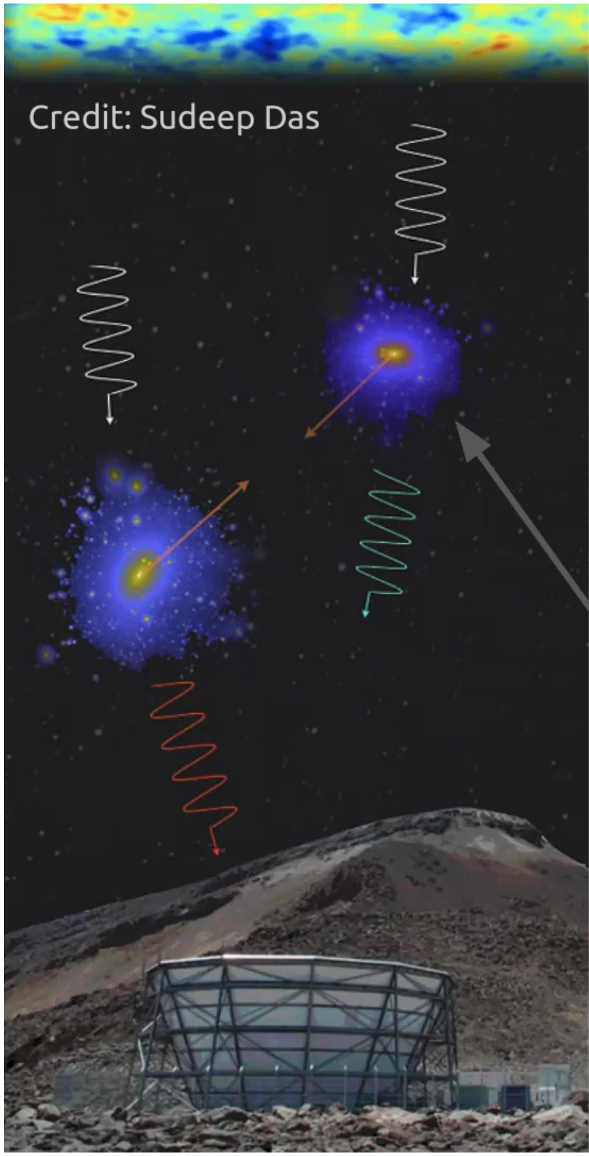


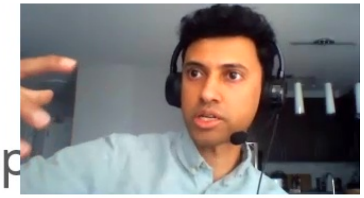
Can we improve large-scale clustering measurements beyond what galaxy surveys can measure?

Yes, by a lot!

New idea: reconstruct large scale velocity field using CMB imprint of moving clouds of electrons

Munchmeyer, **MM** et al, PRD 2018



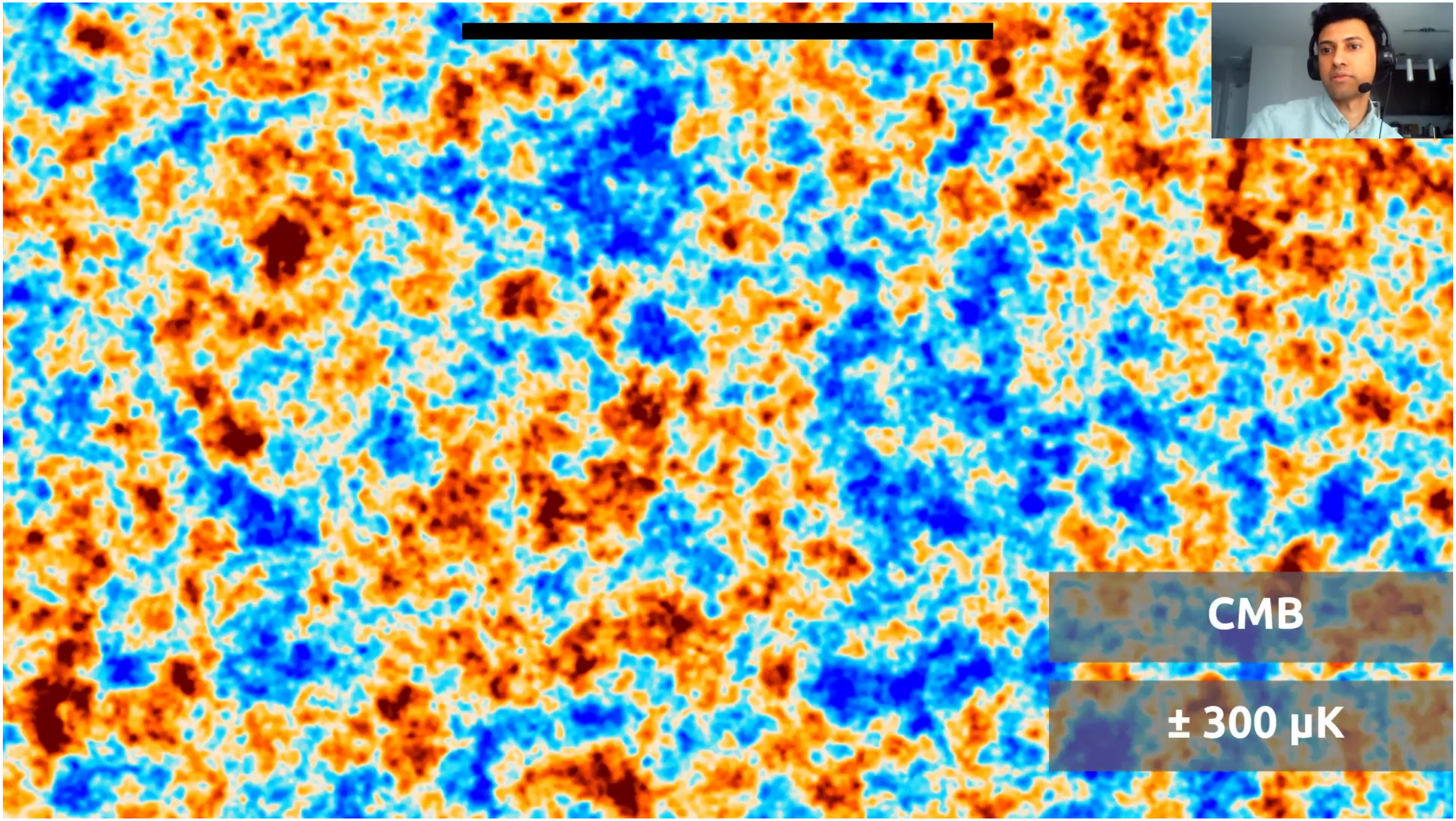


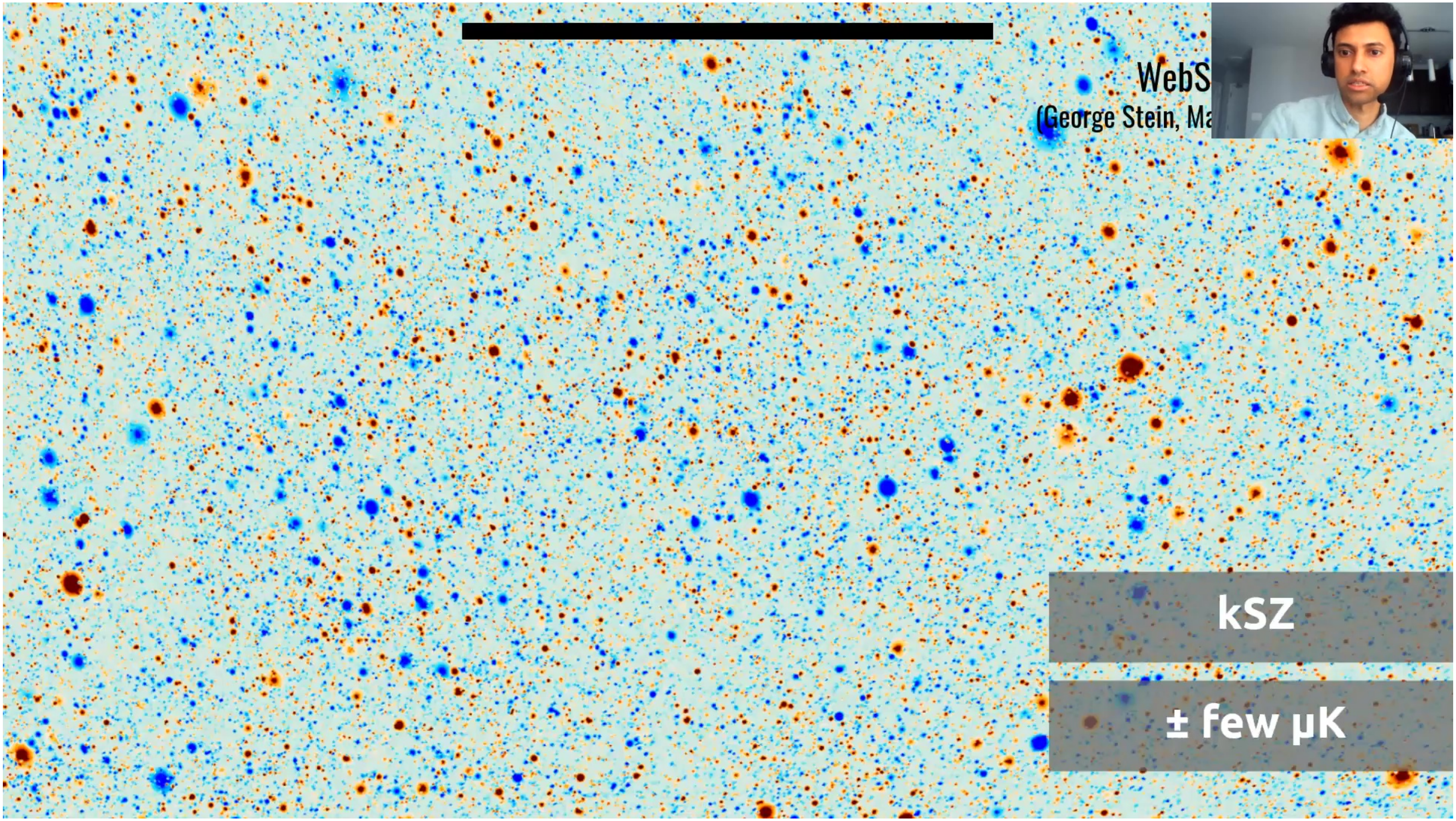
kSZ (kinetic Sunyaev Zeldovich) effect: Dopp
CMB photons scattering off electrons with bulk velocity

$$\frac{\Delta T_{\mathrm{kSZ}}(\vec{\mathbf{n}})}{T_{\mathrm{CMB}}} \sim \int d\chi e^{-\tau(z)} v_r \delta_e(\vec{\mathbf{n}}, \chi)$$

Ionized gas in and between galaxy clusters

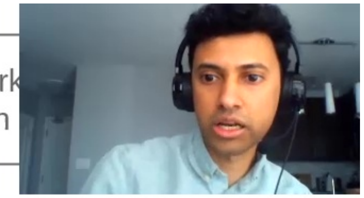
Currently detected only at the 4-8σ level
But expected to improve quickly with (deeper) CMB and larger galaxy volume.
SNR O(100-1000) expected!

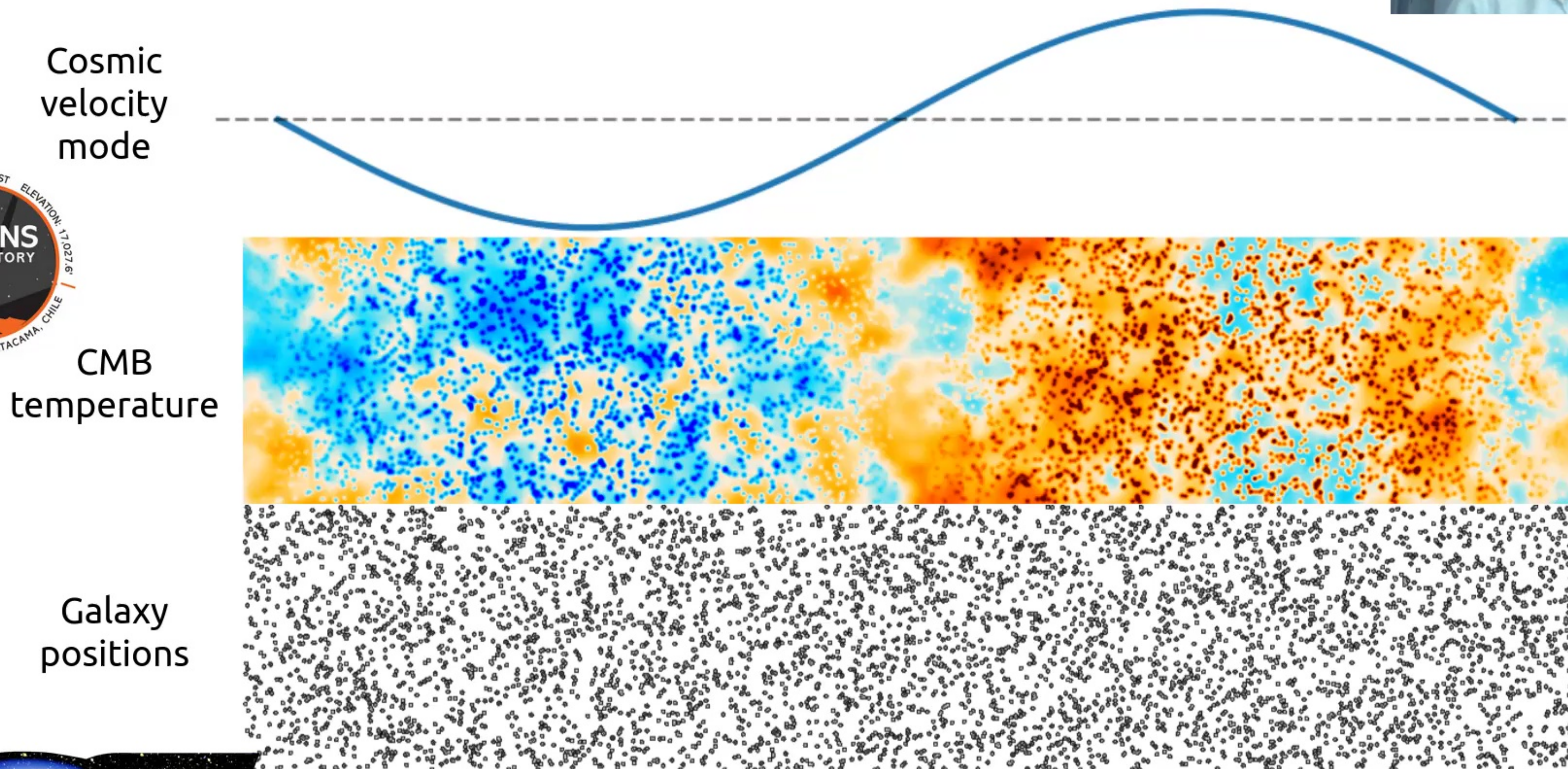

[redacted]
CMB
± 300 μK


kSZ
± few μK

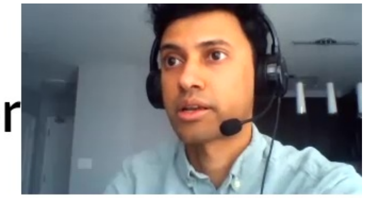
How might we measure kSZ?

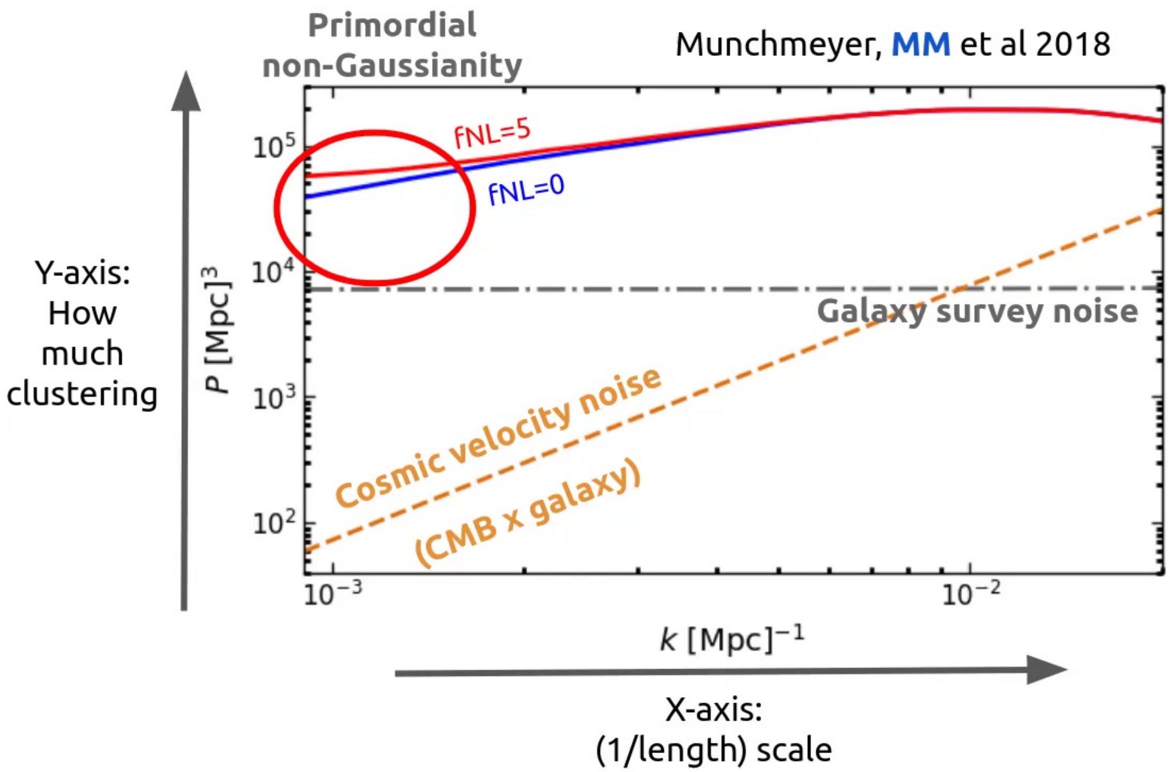
Smith, **MM**+ 2018 (unified framework
MM+ 2019 (combination with





Multi-field inflation from the cosmic velocity field: 1.5-3x impr





New application of the kinetic Sunyaev Zeldovich (kSZ) effect that probes cosmic velocities using **CMB x galaxy cross-correlation**

Rule out or detect MFI that predicts fNL ~ 1

Mathew Madhavacheril, Perimeter Institute

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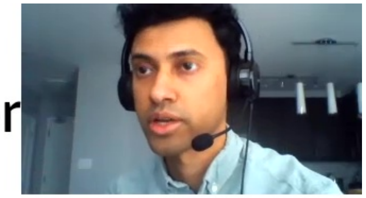

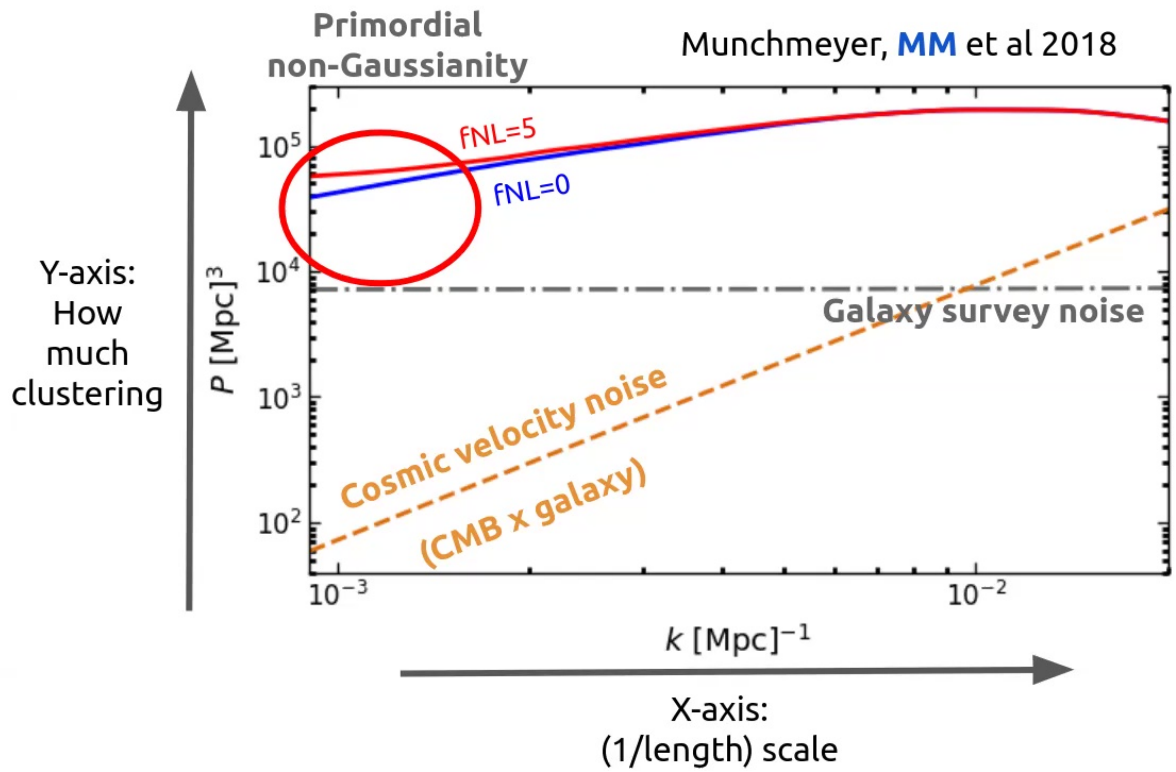

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Next: Apply similar technique as lensing for velocity reconstruction

ACT and DES data, first demo, sigma(fNL) ~ 10

SO and LSST 2-year data, sigma(fNL) ~ 5

Eventually:
SO and LSST 5-year data, sigma(fNL) ~ 2
SO and LSST 10-year data, sigma(fNL) ~ 1
S4 and LSST 10-year data, sigma(fNL) ~ 0.5

Rule out or detect MFI that predicts fNL ~ 1

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Well-motivated prediction of non-Gaussianity from cosmic inflation due to multiple scalar fields

Galaxy surveys (like Rubin/LSST) alone don't probe this

The combination of CMB data from Simons Observatory and galaxy data from Rubin/LSST does!

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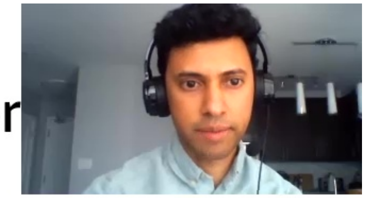

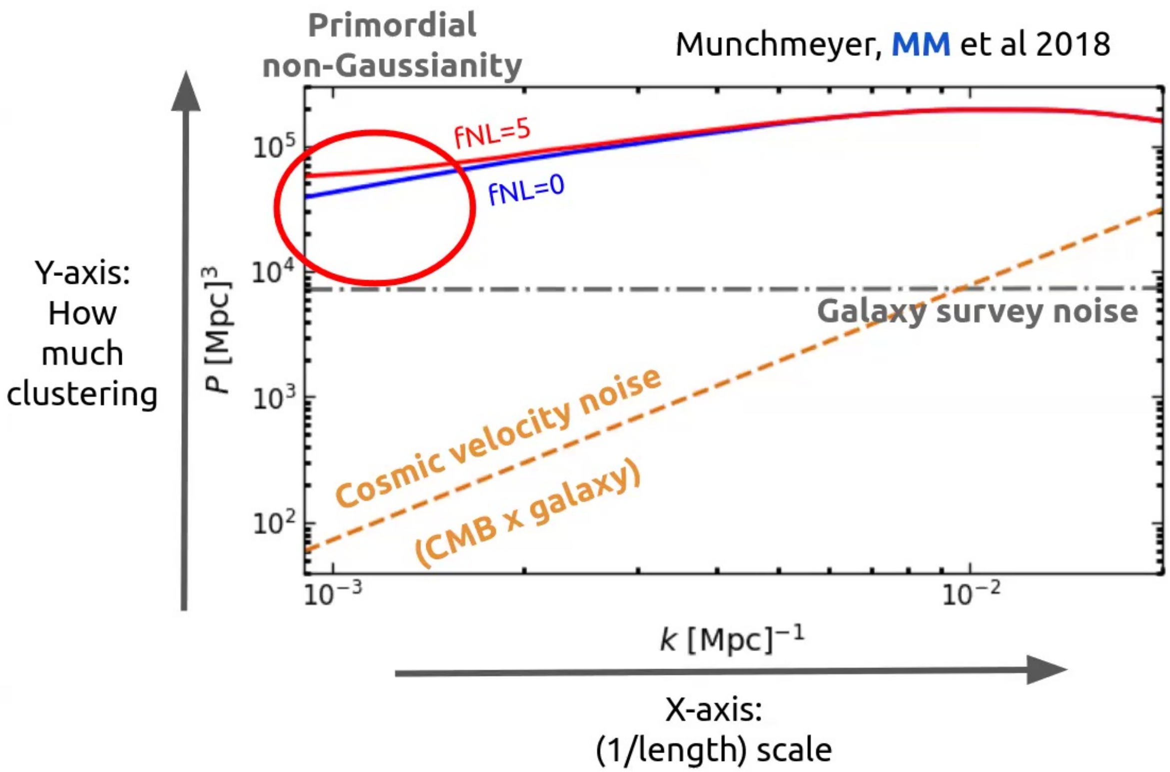

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[redacted]

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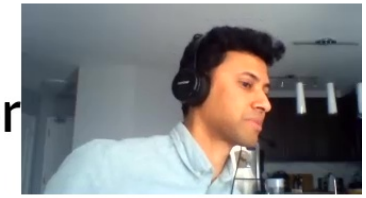

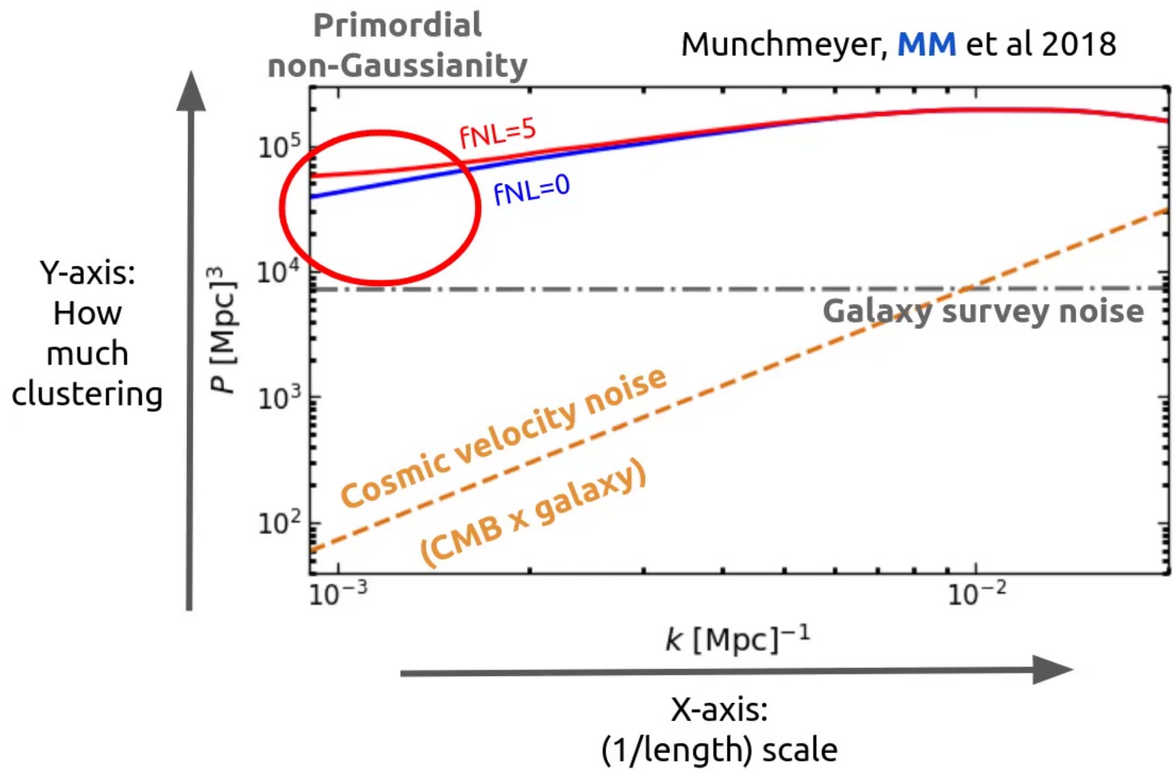

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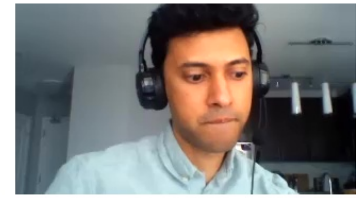

Conclusion

- The next decade of cosmology exploits **the CMB as a backlight**
- We reach sub-percent precision on gravitational lensing (challenge and opportunity)
  - Allowing us to understand massive neutrinos
- A new application of the CMB+galaxy inferred cosmic velocity field
  - Detect or rule out a smoking gun signal from inflation