Title: CMB-HD as a Probe of Dark Matter on Sub-Galactic Scales

Speakers: Neelima Sehgal

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

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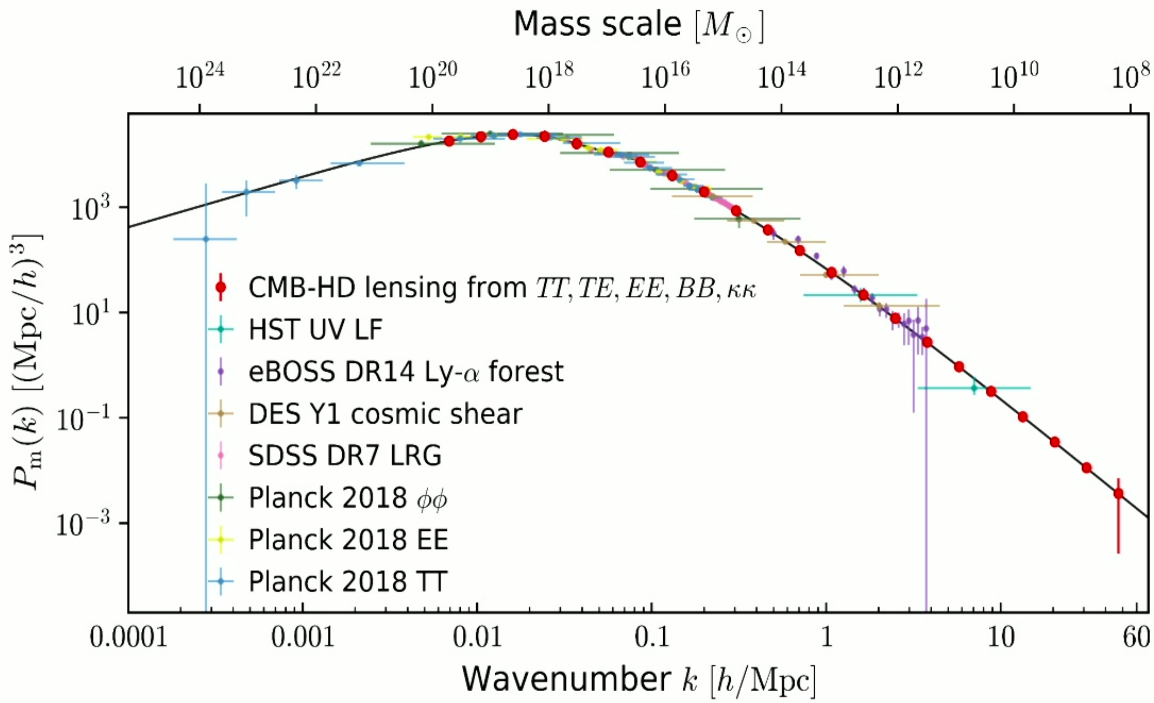
Abstract:

In this talk I will discuss the potential of future high-resolution CMB observations to probe structure on sub-galactic scales. In particular, I will discuss how a CMB-HD experiment can measure lensing over the range 0.005 h/Mpc < k < 55 h/Mpc, spanning four orders of magnitude, with a total lensing signal-to-noise ratio from the temperature, polarization, and lensing power spectra greater than 1900. These lensing measurements would allow CMB-HD to distinguish between cold dark matter (CDM) and non-CDM models that can resolve apparent small-scale tensions with CDM. In addition, CMB-HD can distinguish between baryonic feedback effects and non-CDM models due to the different way each impacts the lensing signal. The kinetic Sunyaev-Zel'dovich power spectrum measured by CMB-HD further constrains non-CDM models that deviate from CDM. In sum, future CMB experiments will not only measure traditional cosmological parameters with unprecedented precision, but will also simultaneously constrain baryonic physics and dark matter properties that impact sub-galactic scales.



CMB-HD as a Probe of Dark Matter on Sub-Galactic Scales

Based on MacInnis, NS, (2024), arxiv:2405.12220

(Slides from Amanda MacInnis's talk at Cambridge)

Stony Brook University

Neelima Sehgal

Perimeter Institute Dec. 17th 2024

Outline

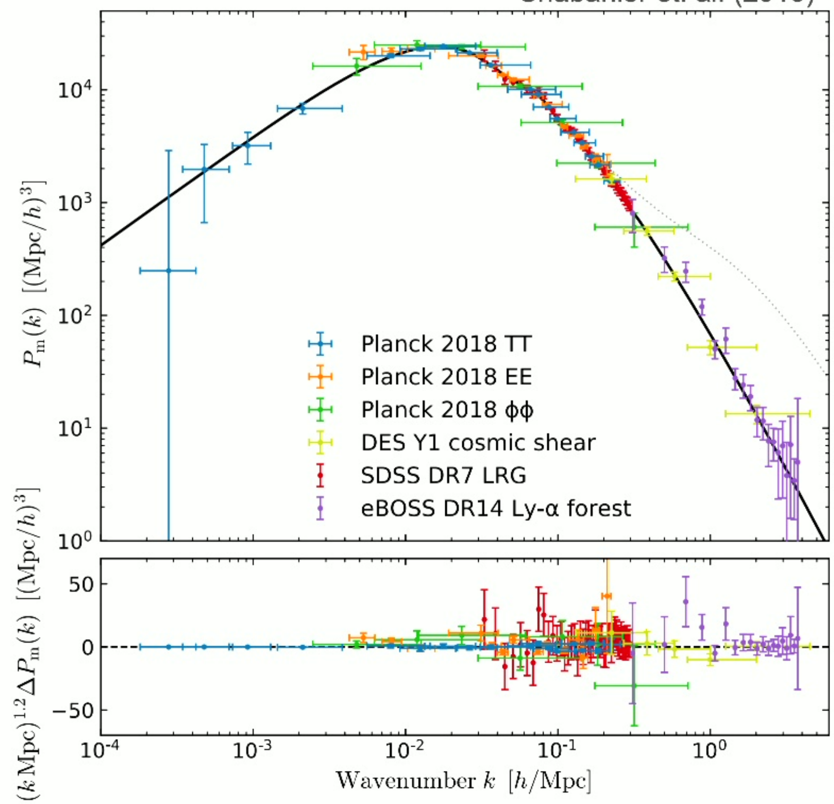
1. Motivation
2. CMB-HD
3. Probing Non-CDM Models and Baryonic Feedback

Small-scale Matter Distribution

- CDM works well to explain data on large scales (although some tensions may exist, e.g. S8)
- Measurements may indicate problems with CDM on small scales
- Lack of knowledge of baryonic physics limits constraints on both cosmological parameters and dark matter properties
- Measurements of small-scale matter distribution may be only handle we have on dark matter properties

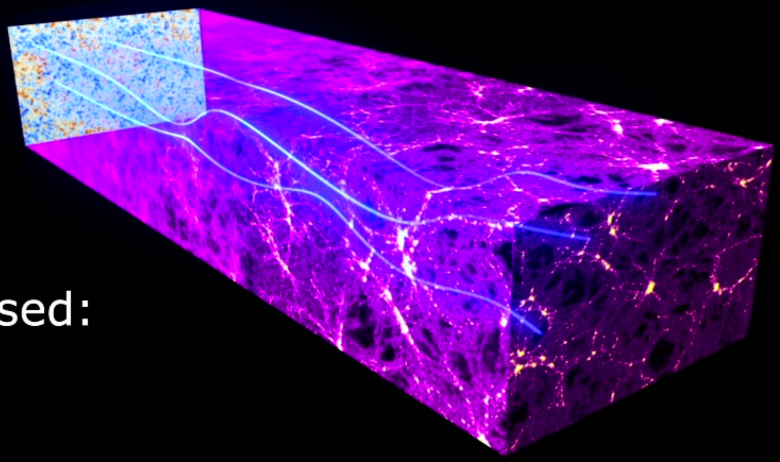
We need better measurements and theoretical modelling of **small scales**

Chabanier et. al. (2019)



4

Image: ESA and the Planck Collaboration



Small-scale CMB Lensing

Use CMB lensing measurements:

- CMB is the background light source being lensed:
  - Originates from a known redshift $z \approx 1100$
  - Behind all structure in the Universe
  - Physics of unlensed CMB is well understood
  - Unlensed CMB is a smooth gradient on **small scales**

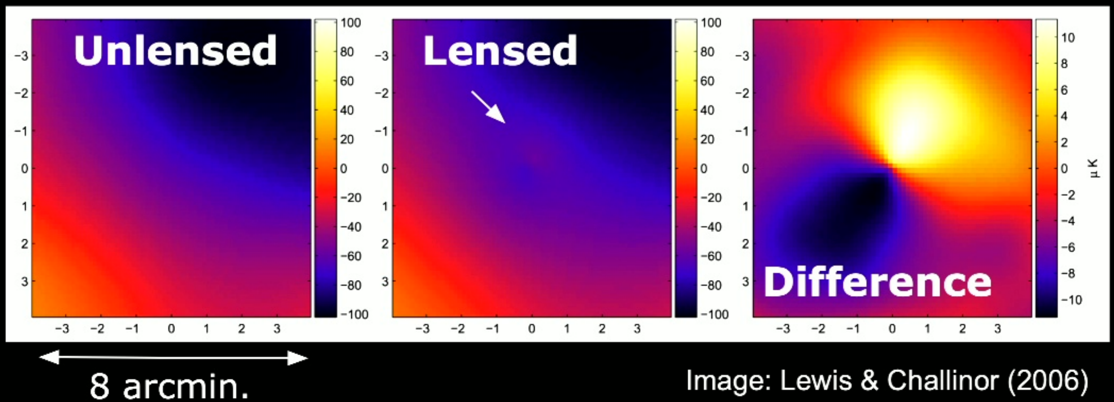


Image: Lewis & Challinor (2006)

Image: ESA and the Planck Collaboration

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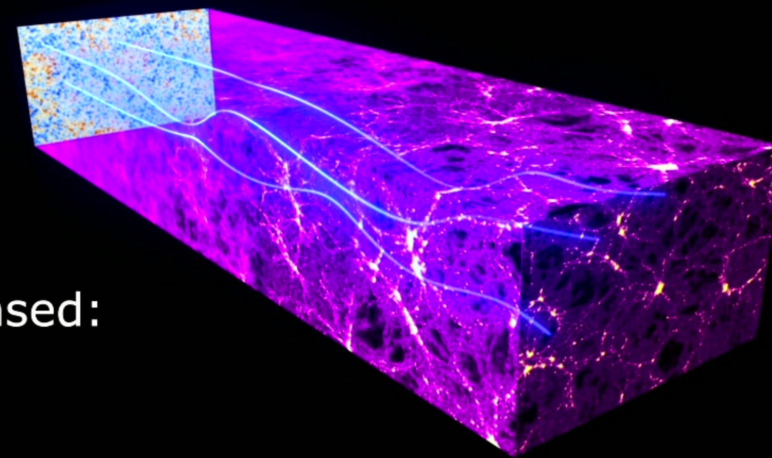

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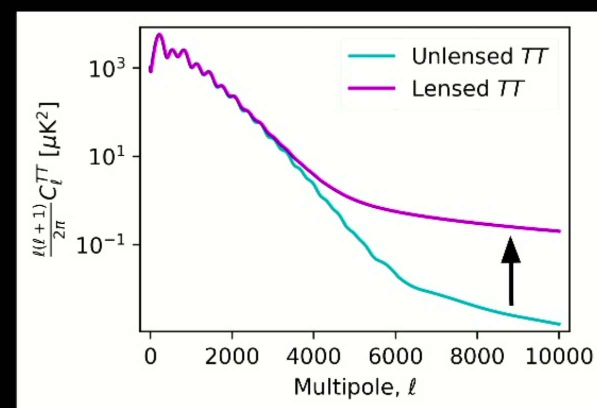
- Directly probes total matter distribution without relying on baryonic tracers
- Lensing increases power on **small scales**



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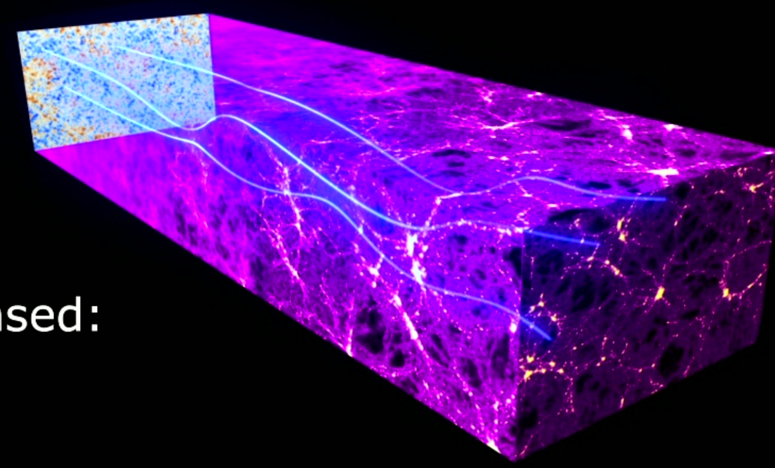

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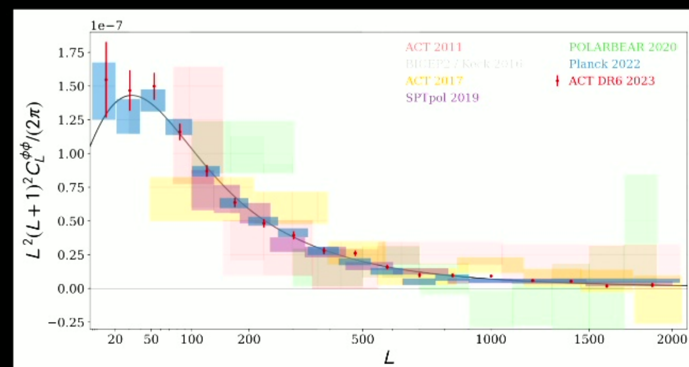
- Measure lensing in CMB power spectra & CMB lensing power spectrum



ACT collaboration (Qu et. al., 2023)

Lewis & Challinor (2006)

Image credit: Debra Kellner

CMB-HD

CMB-HD is a proposed low-noise, high-resolution millimeter-wave survey over half the sky.

- 6x higher resolution & 3x lower noise than CMB-S4 wide-area survey
- Will measure angular scales $30 < \ell < 40{,}000$
- 7 frequencies from 30 to 350 GHz
- Will be located in the Atacama desert in Chile

Frequency (GHz)	30	40	90	150	220	280	350
Resolution (arcmin)	1.25	0.94	0.42	0.25	0.17	0.13	0.11
White noise level (μK-arcmin)[a]	6.5	3.4	0.7	0.8	2.0	2.7	100.0

[a] Sensitivity is for temperature maps. For polarization maps, the noise is $\sqrt{2}$ higher.

CMB HD

(Snowmass 2021 CMB-HD White Paper; **arXiv:2203.05728**)

cmb-hd.org

CMB-HD Data

Signal: CMB-HD lensed temperature & polarization + CMB lensing spectra

(MV lensing estimator)

Okamoto & Hu (2003), Hu et. al. (2007)

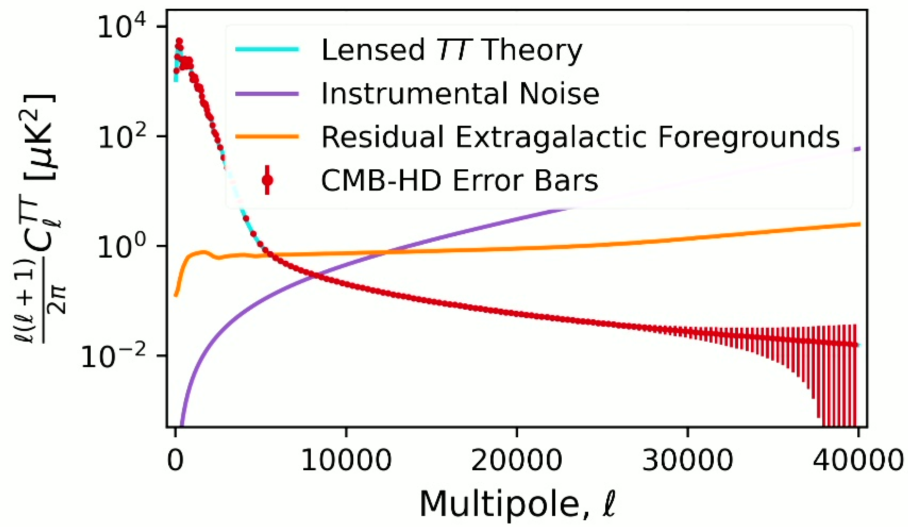
Noise:

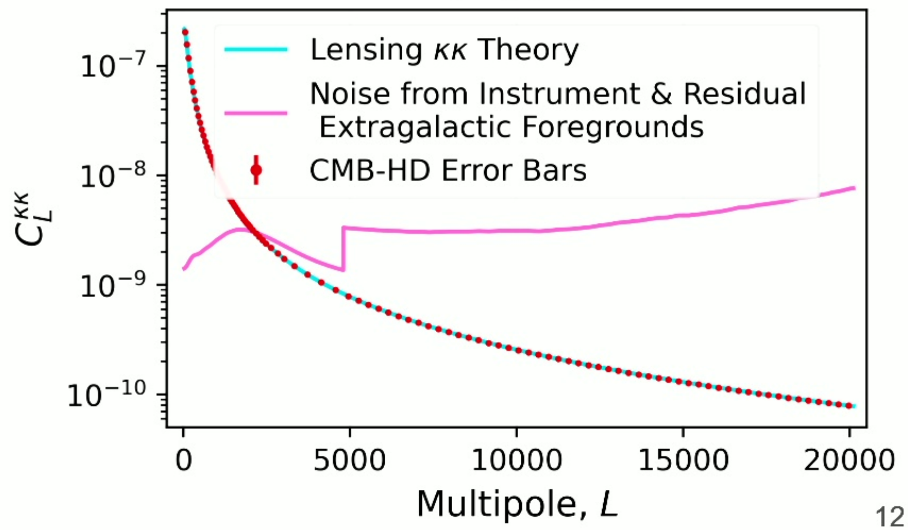
- Instrumental noise + residual extragalactic FG in 90 & 150 GHz

  Han & Sehgal (2022)

- Joint covariance of all spectra

  Hotinli et. al. (2022), Benoit-Levy et. al. (2012)





CMB-HD Lensing

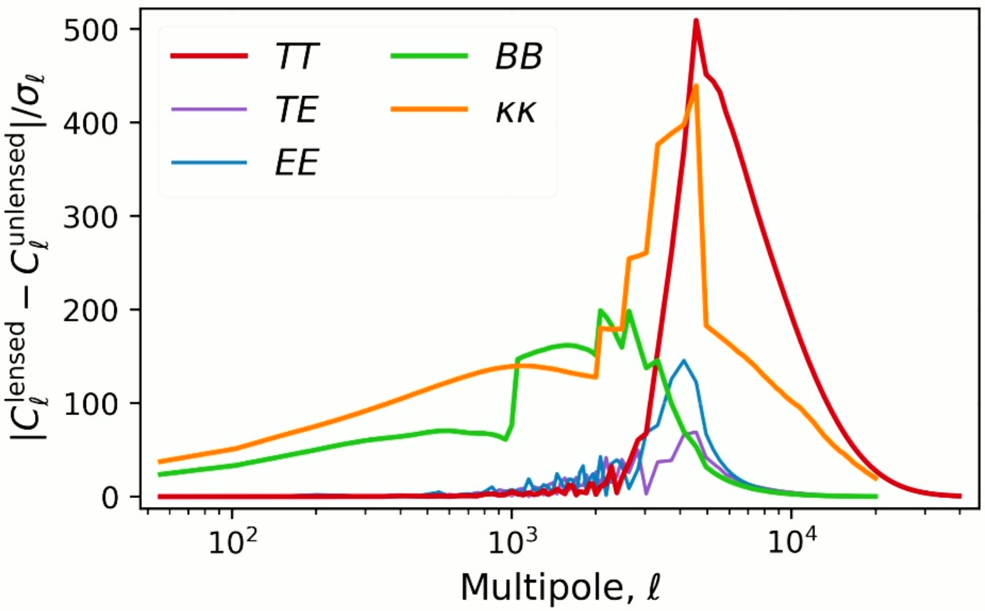
$$\frac{S}{N} = \sqrt{\sum_{ij} (\Delta C_\ell)_i (\mathbb{C}^{-1})_{ij} (\Delta C_\ell)_j}$$

Sum over bins

Lensed - unlensed spectra

Full covariance

Contribution to lensing SNR from the different spectra:



Spectra	SNR
TT	1573
TE	161
EE	276
BB	493
$\kappa\kappa$	1287
All	**1947**

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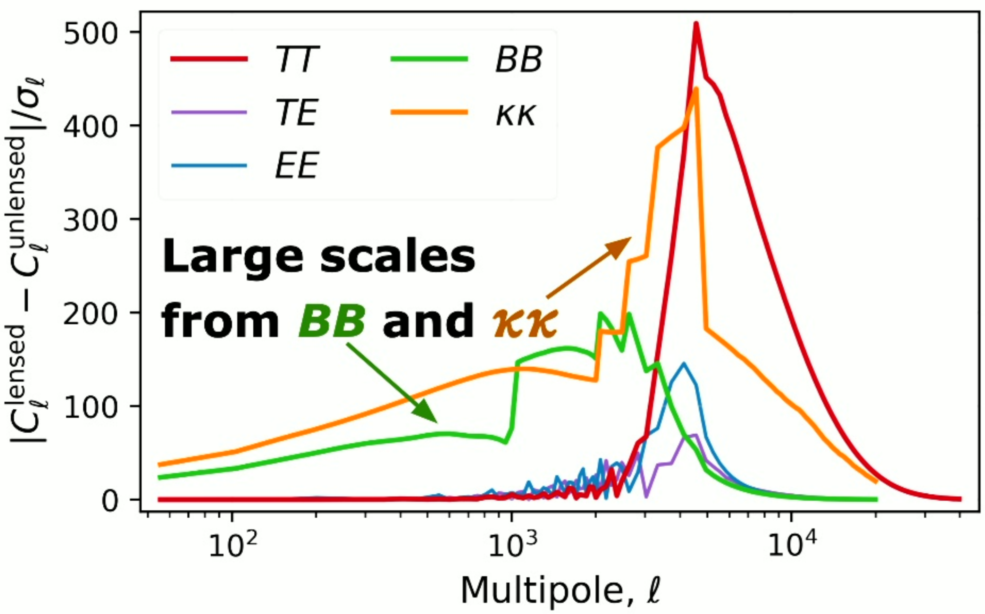

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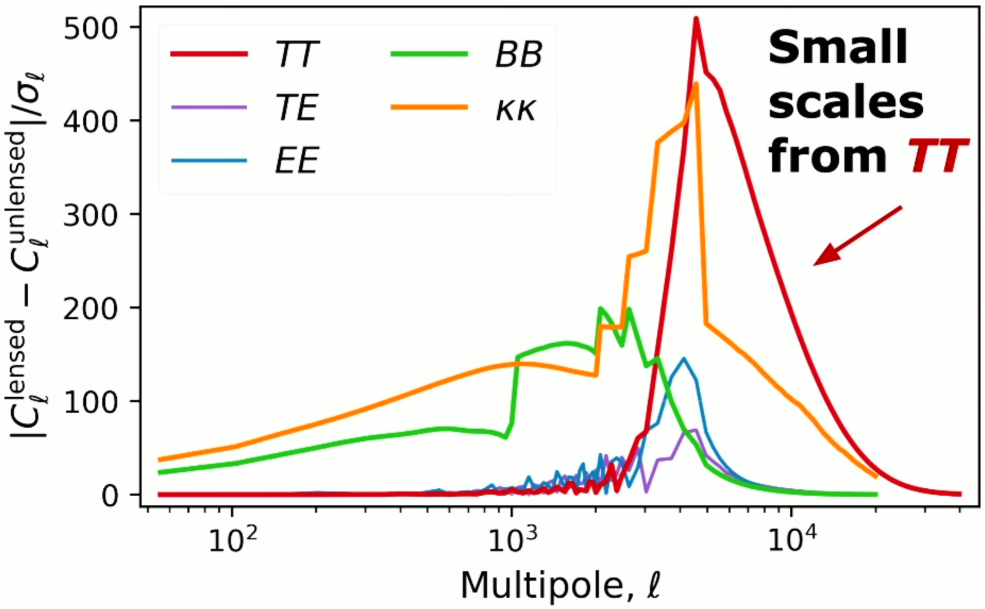

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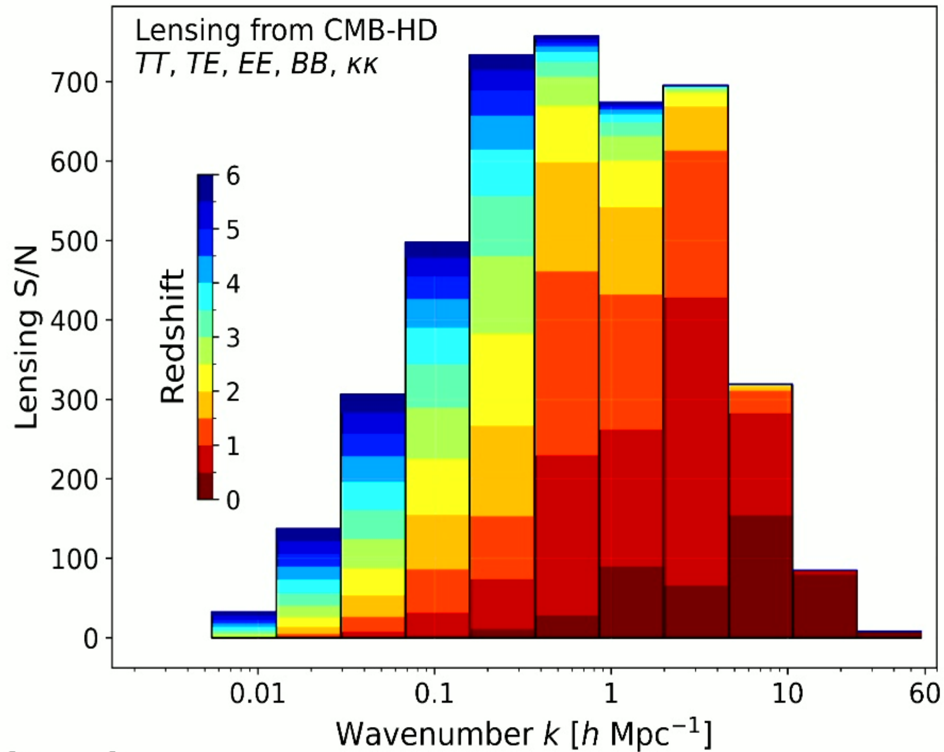
15

CMB-HD Lensing

Contribution to lensing SNR from different scales and redshifts:

$$C_\ell^{\kappa\kappa} = \int_{z_{\rm min}=0}^{z_{\rm max}=1100} dz\ P_{\rm m}\left(k \approx \frac{\ell+1/2}{\chi(z)},\ z\right) \times \begin{bmatrix}\text{other}\\ \text{stuff}\end{bmatrix}$$

Lewis & Challinor (2006)



- Integrate over each redshift bin → SNR(ℓ, z_i)
- Relate k to (ℓ, z_i) → SNR(k) $k \approx \frac{\ell+1/2}{\chi(z)}$
- Sum over the SNR(k) values for each k in a given wavenumber bin

16

Matter Power Spectrum

CMB-HD lensing can probe the matter power spectrum out to scales of k ~ 55 *h*/Mpc
→ halo masses ~ $10^8\ M_\odot$ today

$$\left(\frac{S}{N}\right)_{k_j} = \frac{P_{\rm m}^{\rm non-lin}(k_j)}{\sigma\left(P_{\rm m}^{\rm non-lin}(k_j)\right)} = \frac{P_{\rm m}^{\rm lin}(k_j)}{\sigma\left(P_{\rm m}^{\rm lin}(k_j)\right)}$$

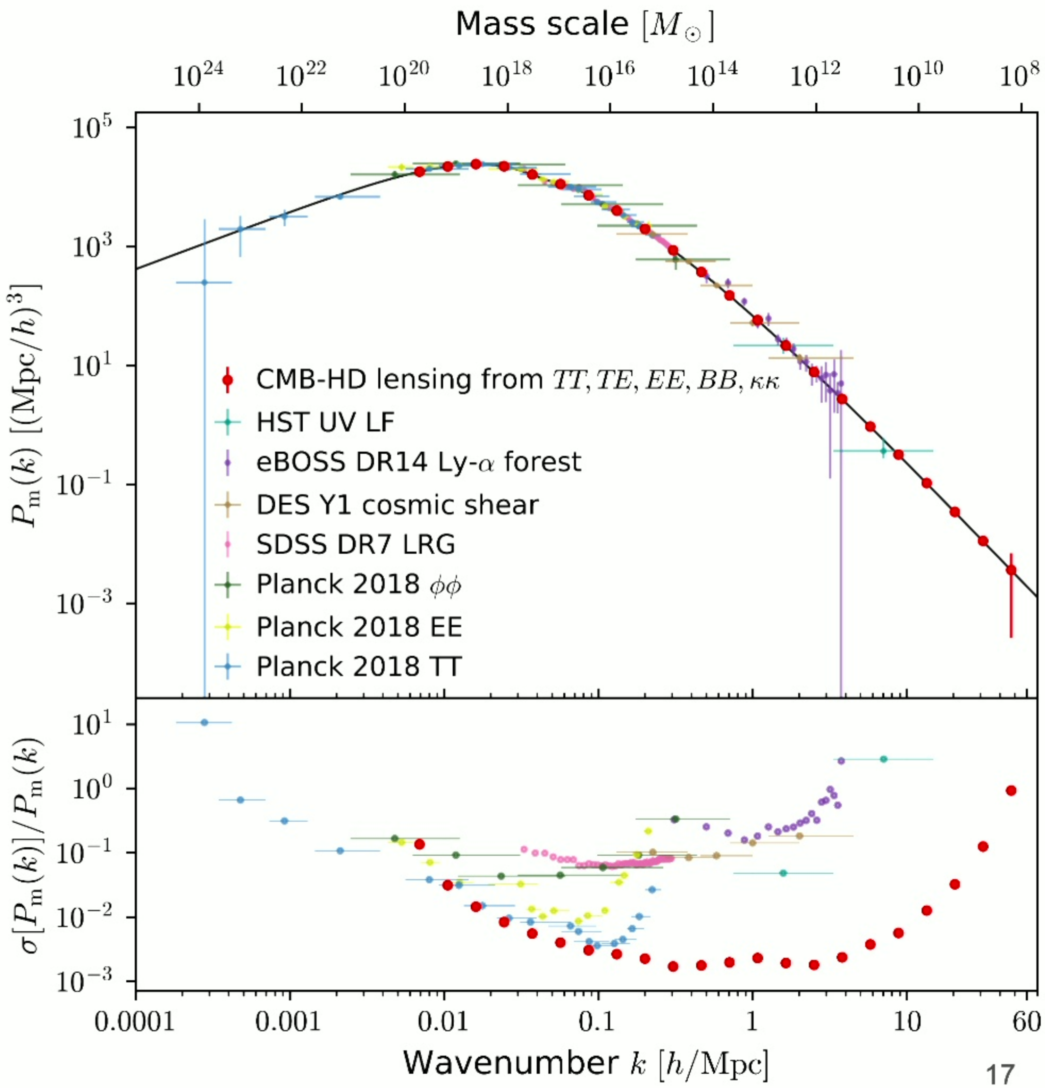


Figure adapted from Chabanier et. al. (2019)

17

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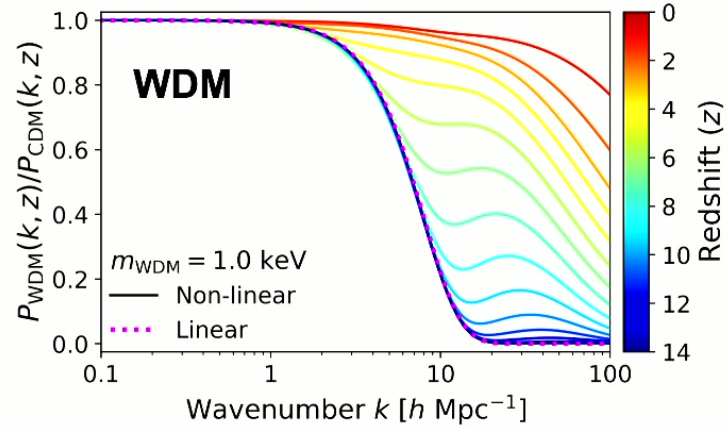
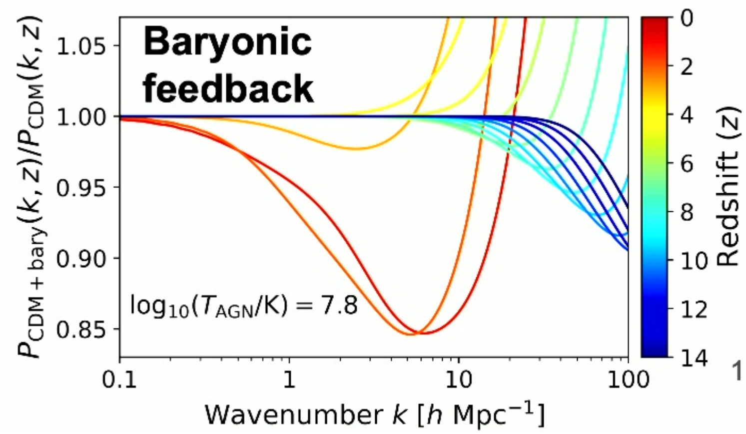
Alternate Dark Matter Models and Baryonic Feedback Affect Different Scales



We include models that suppress small-scale structure by applying a transfer function to P(k)

Models: CDM or WDM, each with or without baryonic feedback

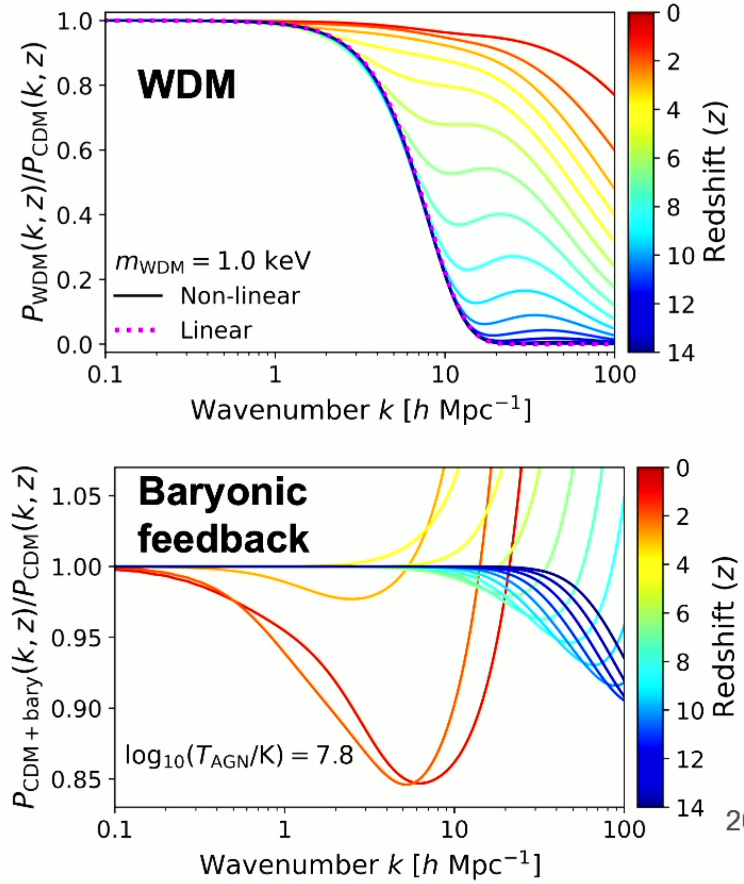
- WDM: transfer function from Marsh (2016)
- Baryonic feedback: single-parameter model from Mead et. al. (2020)



19

Alternate Dark Matter Models and Baryonic Feedback Affect Different Scales

Both baryonic feedback and WDM leads to a suppression in power relative to CDM-only, but change the spectra in different ways



20

Alternate Dark Matter Models and Baryonic Feedback Affect Different Scales

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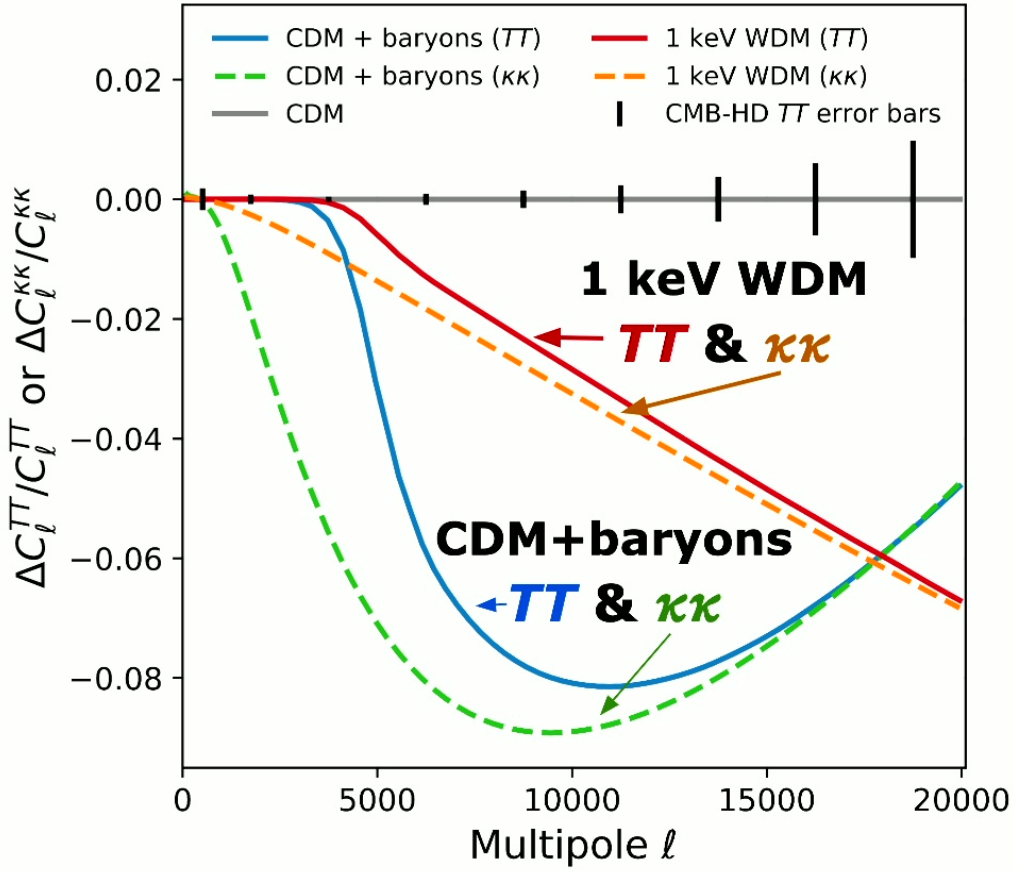
Compare TT & CMB lensing spectra to CDM-only prediction: difference in shape can be measured by HD



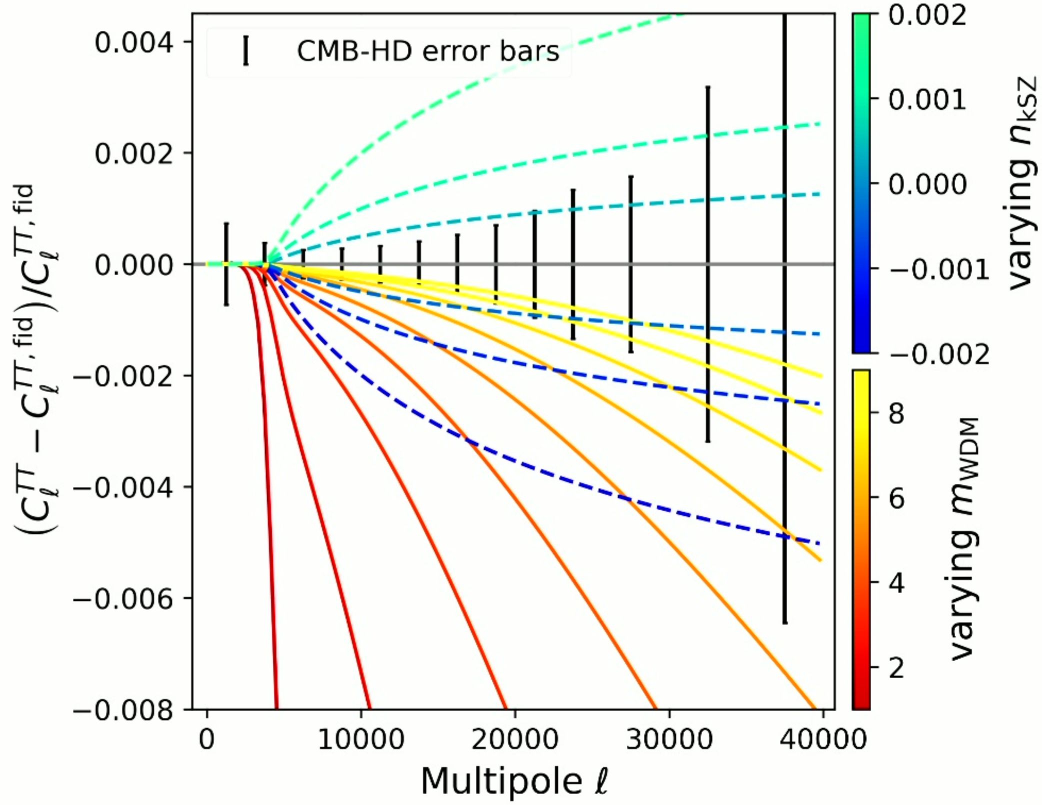
21

Parameter Forecasts with kSZ Power Spectrum

We include kSZ power spectrum in *TT*, with free parameters for amplitude & slope of kSZ spectrum

We also model the suppression due to WDM in both kSZ & CMB power spectrum

- We find varying kSZ slope does not produce the same suppression as WDM



$$C_\ell^{TT,\mathrm{fid}} = C_\ell^{TT,\mathrm{CDM}} + C_\ell^{\mathrm{kSZ}}\Big|_{n_{\mathrm{kSZ}}=0}$$

Parameter Forecasts

CMB-HD + DESI BAO Fisher matrix

→ Delensed TT, TE, EE, BB
CMB + CMB lensing + kSZ

Parameters:

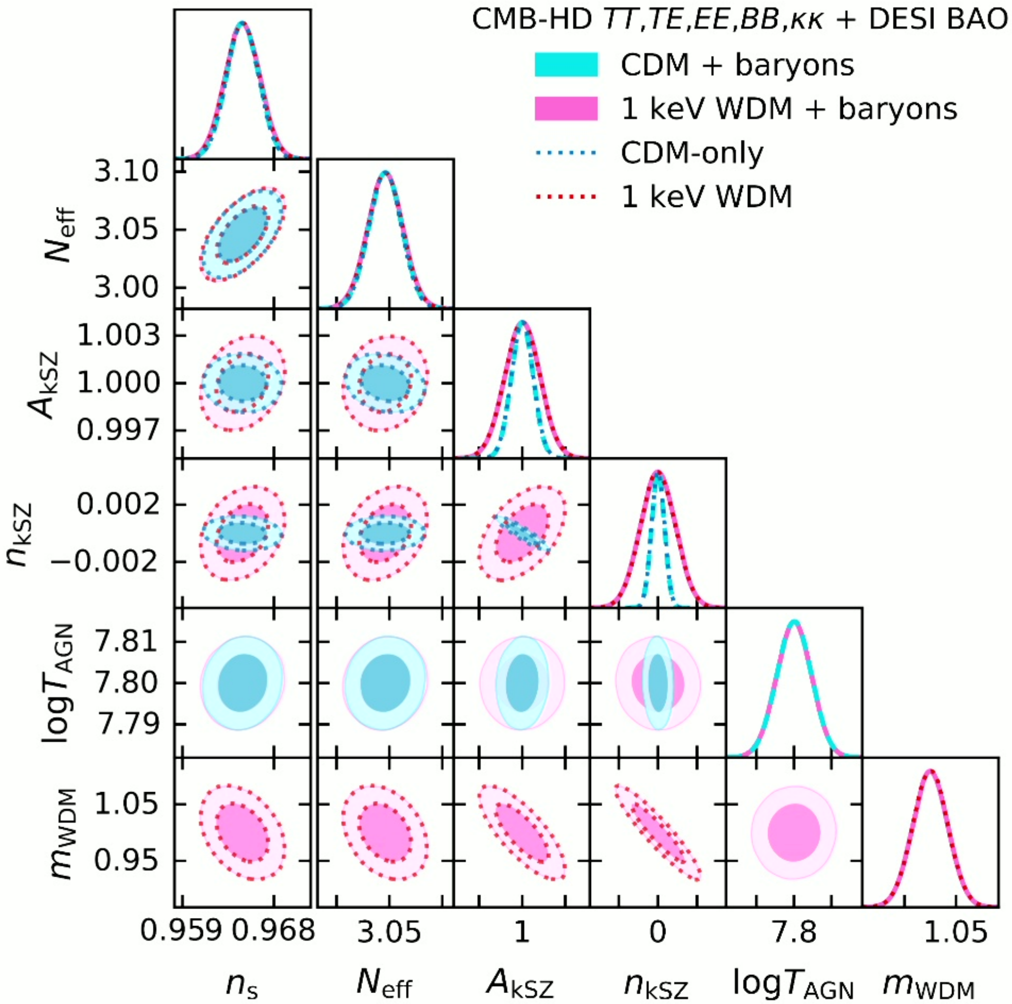
$\Lambda\mathrm{CDM}/\Lambda\mathrm{WDM}$ (+ τ prior from *Planck* (2018))

$+ N_{\mathrm{eff}} + \sum m_\nu$

$+ A_{\mathrm{kSZ}} + n_{\mathrm{kSZ}}$ (kSZ amplitude & slope)

$\left[+\log_{10}(T_{\mathrm{AGN}})\right]$ (baryonic feedback)
(+ HD SZ prior)

$\left[+m_{\mathrm{WDM}}\right]$ (WDM mass [keV])

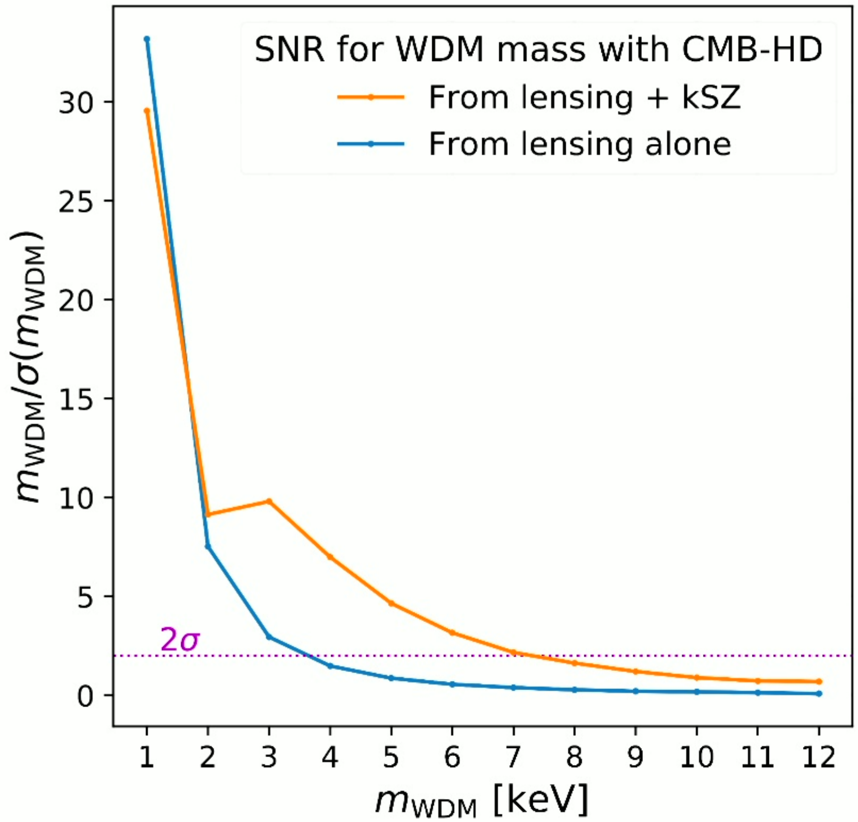


23

Parameter Forecasts: WDM Mass

After marginalizing over all other parameters (including baryonic feedback), CMB-HD can measure WDM mass at 95% C.L. of:

- 3.5 keV from lensing alone
- 7 keV from lensing + kSZ



Summary

- CMB-HD will measure lensing with SNR > 1900
  - On small scales, TT contributes more than $\kappa\kappa$
- Probes scales over 4 orders in magnitude, $0.005 < k < 55$ h/Mpc
- Measures lensing & kSZ on small scales and can distinguish between CDM-only and alternative models that change the small-scale matter distribution
  - Can detect or rule out ~ 7 keV WDM at 95% C.L.
  - Can marginalize over baryonic feedback without degrading other parameter errors
- Public forecasting code: **github.com/CMB-HD/hdPk**