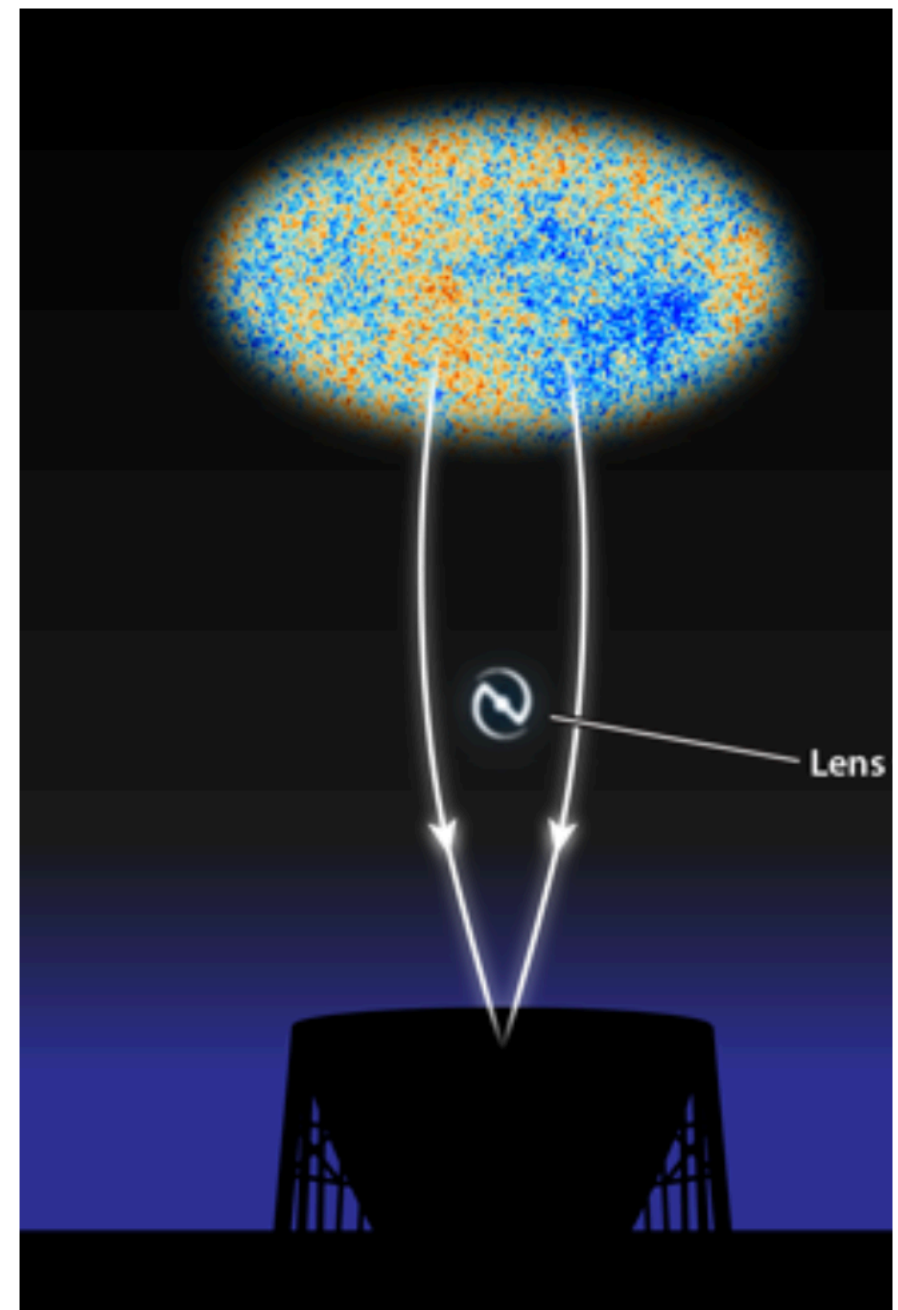
CMB-HD: Probing Dark Matter Particle Properties with Ultra-High-Resolution CMB Lensing

Neelima Sehgal

July 27, 2020; Snowmass2021

(Also see https://cmb-hd.org)



Ho Nam Nguyen, NS, Mathew Madhavacheril, PRD, 2019, (arXiv:1710.03747)

NS et al. 2019, Science White Paper for Astro2020 Decadal (arXiv:1903.03263)

NS et al. 2019, CMB-HD APC White Paper for Astro2020 Decadal (arXiv:1906.10134)

NS et al 2019, CMB-HD RFI for Astro2020 Decadal (arXiv: 2002.12714)

Motivation of CMB-HD

Rich Science from CMB-HD:

Dark Matter
- Dark Matter Properties from Small-Scale Matter Power Spectrum
- Number of Relativistic Species

Inflation
- Delensing for Primordial Gravitational Waves
- Primordial Non-Gausianity

- Neutrino Mass
- Dark Energy

Galaxy Evolution
- Galaxy Cluster Astrophysics
- Galaxy Formation

- Reionization

Planets
- Solar and Extrasolar Planetary Studies

- Synergy with Optical Lensing Surveys

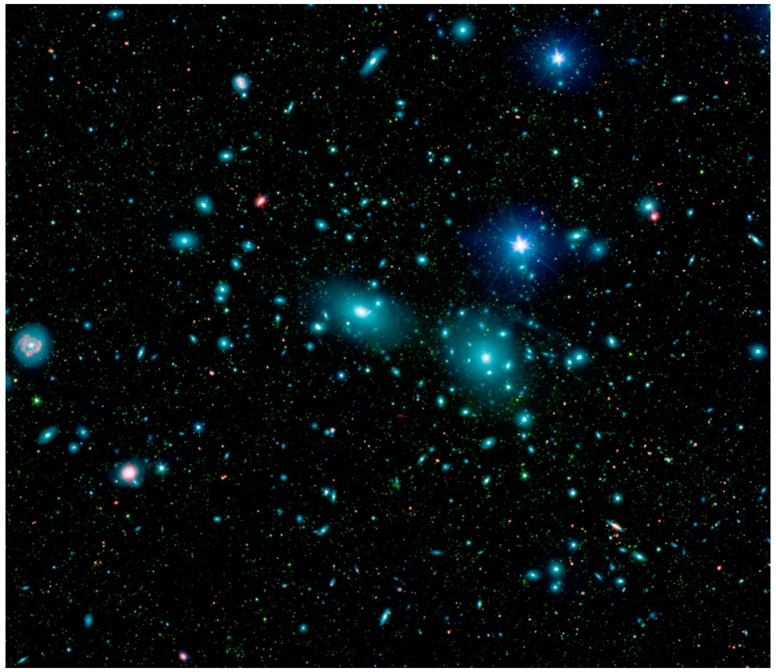
Transients
- Mapping the Transient Sky

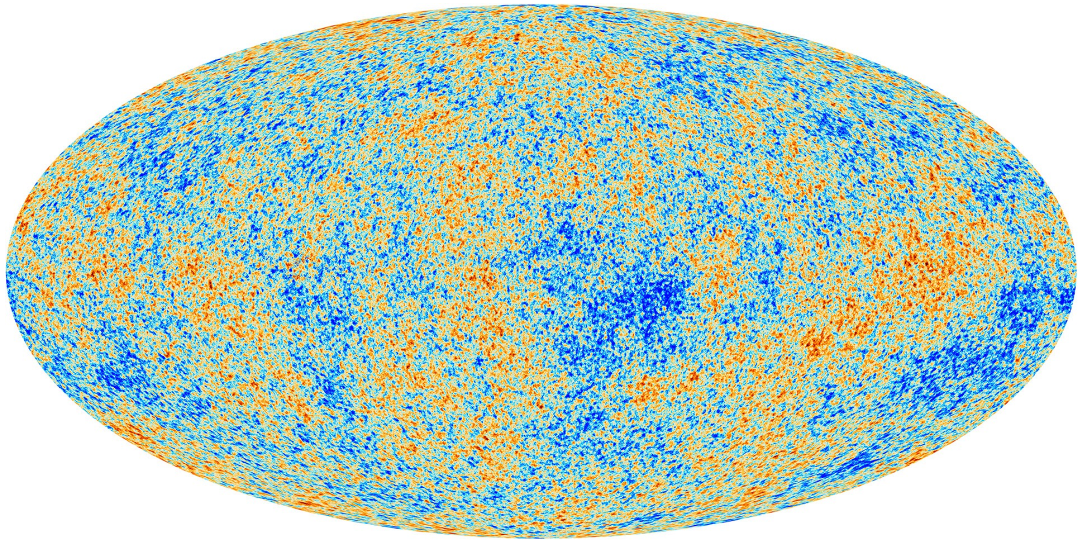
- Novel Ideas and Searches for New Physics

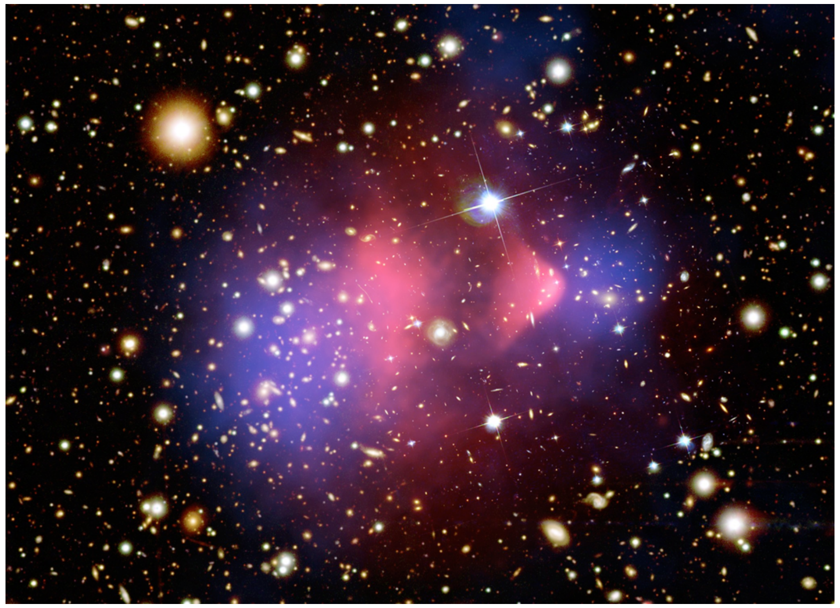
For more info see 1903.03263, 1906.10134, 2002.12714

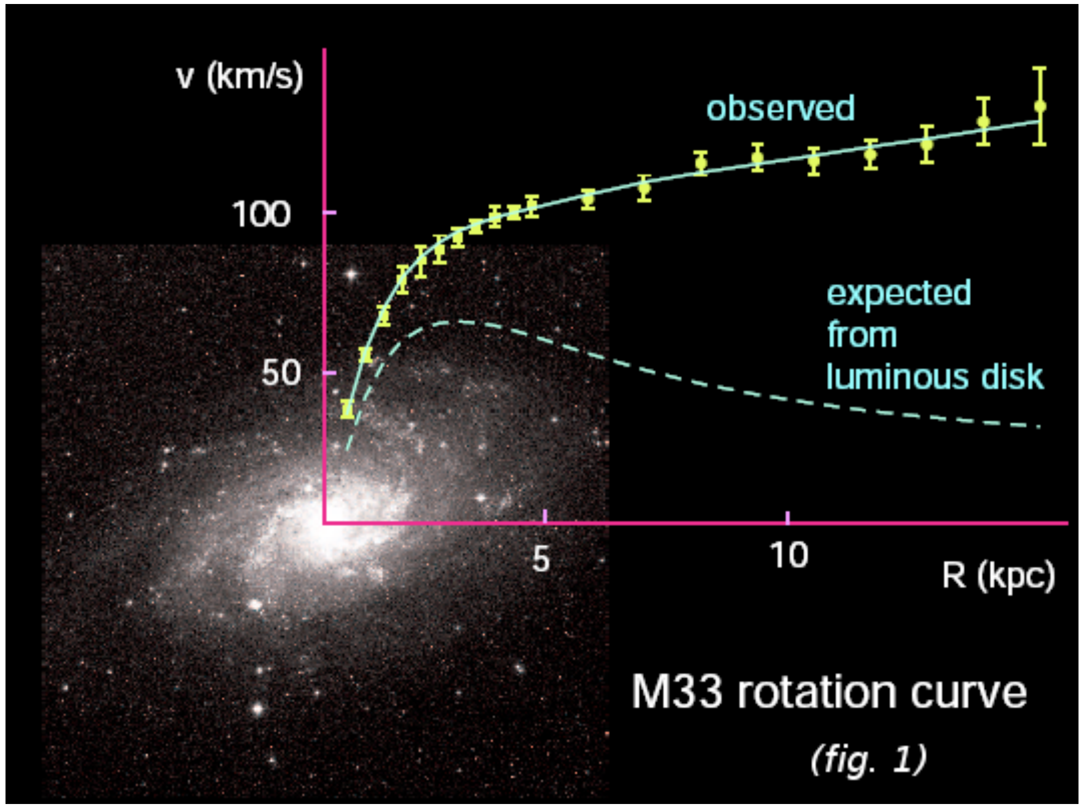
Neelima Sehgal, Stony Brook

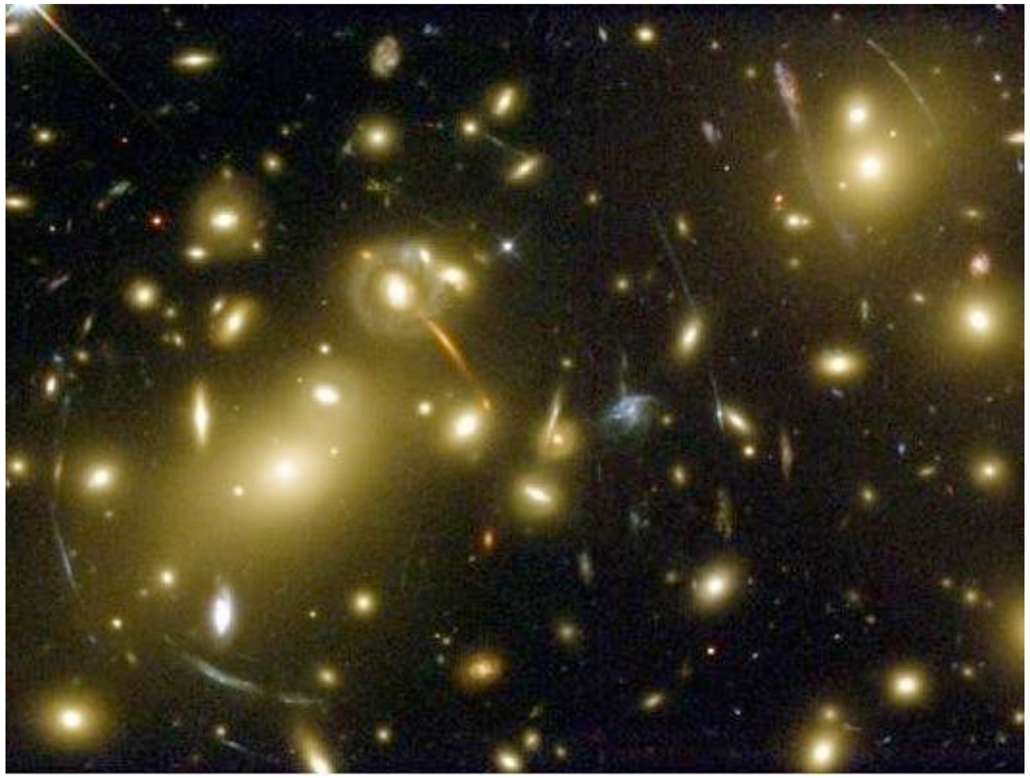
Overwhelming Evidence for Dark Matter











Small-Scale CDM Problems?

- CDM works well on scales larger than 10 kpc, but seems to fail on smaller scales (maybe):
  - Missing Dark Matter Satellites?
  - Cores vs cusps?
  - Too-big to fail?
  - Too much diversity?
- Data on the properties of structure on scales below 10 kpc is not conclusive

Key Question: What do matter fluctuations look like on small-scales?

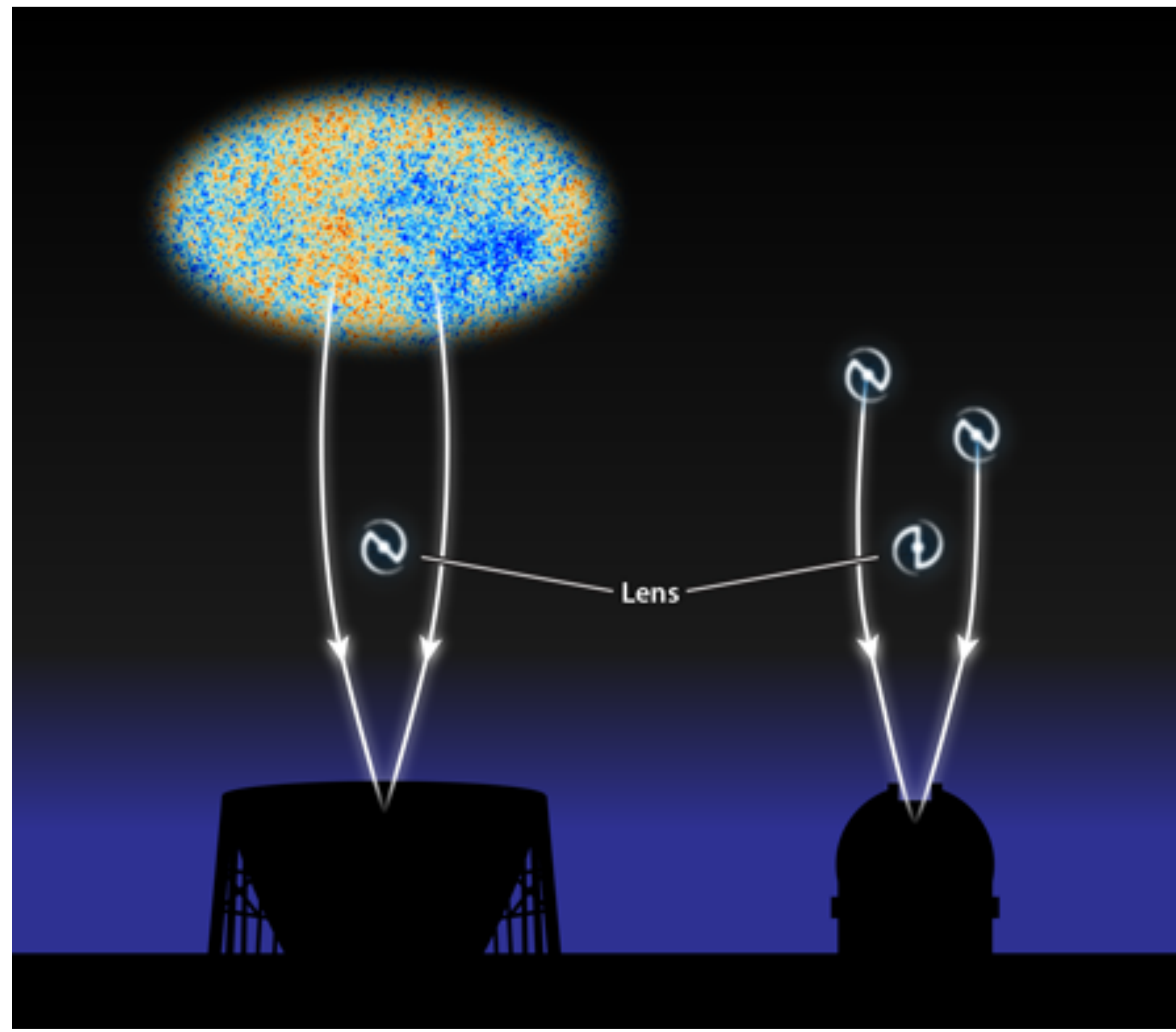
Neelima Sehgal, Stony Brook

Gravitational Lensing of the Cosmic Microwave Background

- CMB Lensing is when light from the primordial CMB is bent by intervening matter

- Traditionally measured to probe large-scale structure

- More recently, it has been used to measure halo-sized objects

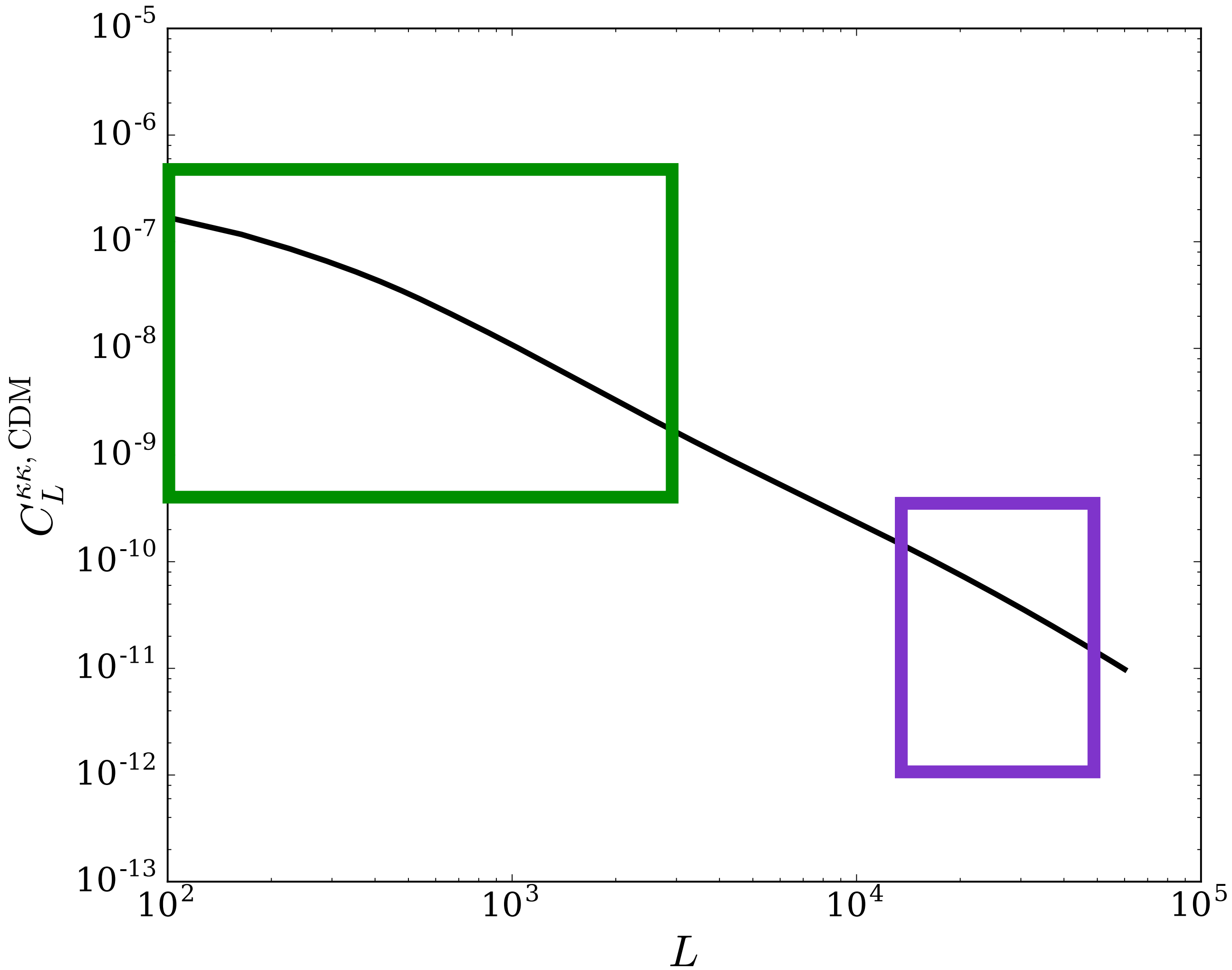


First Measurement of CMB Lensing on Halo Scales
Madhavacheril, NS, for the ACT Collaboration
PRL, 114, 2015

Advantage of CMB Lensing to Probe Small-Scale Structure

1. Directly sensitive to dark matter via gravitational lensing
2. Source light is at well-defined redshift
3. Properties of primordial CMB are well understood
4. Sensitive to structure at higher redshifts than other gravitational lensing probes; this makes it more sensitive to FDM/WDM-type models

CMB Lensing Power Spectrum



CMB Lensing Power Spectrum is matter power spectrum convolved with window

$$C_L^{\phi\phi} = \frac{9\Omega_{m0}^2 H_0^4}{c^4} \int_0^{\chi_s} d\chi \left(\frac{\chi_s - \chi}{\chi^2 \chi_s}\right)^2 \frac{(1+z)^2 P_m(k, z(\chi))}{k^4}$$

$$C_L^{\kappa\kappa} = \frac{[L(L+1)]^2 C_L^{\phi\phi}}{4}$$

Measured on scales L < 3000 so far (k < 1 Mpc^-1)

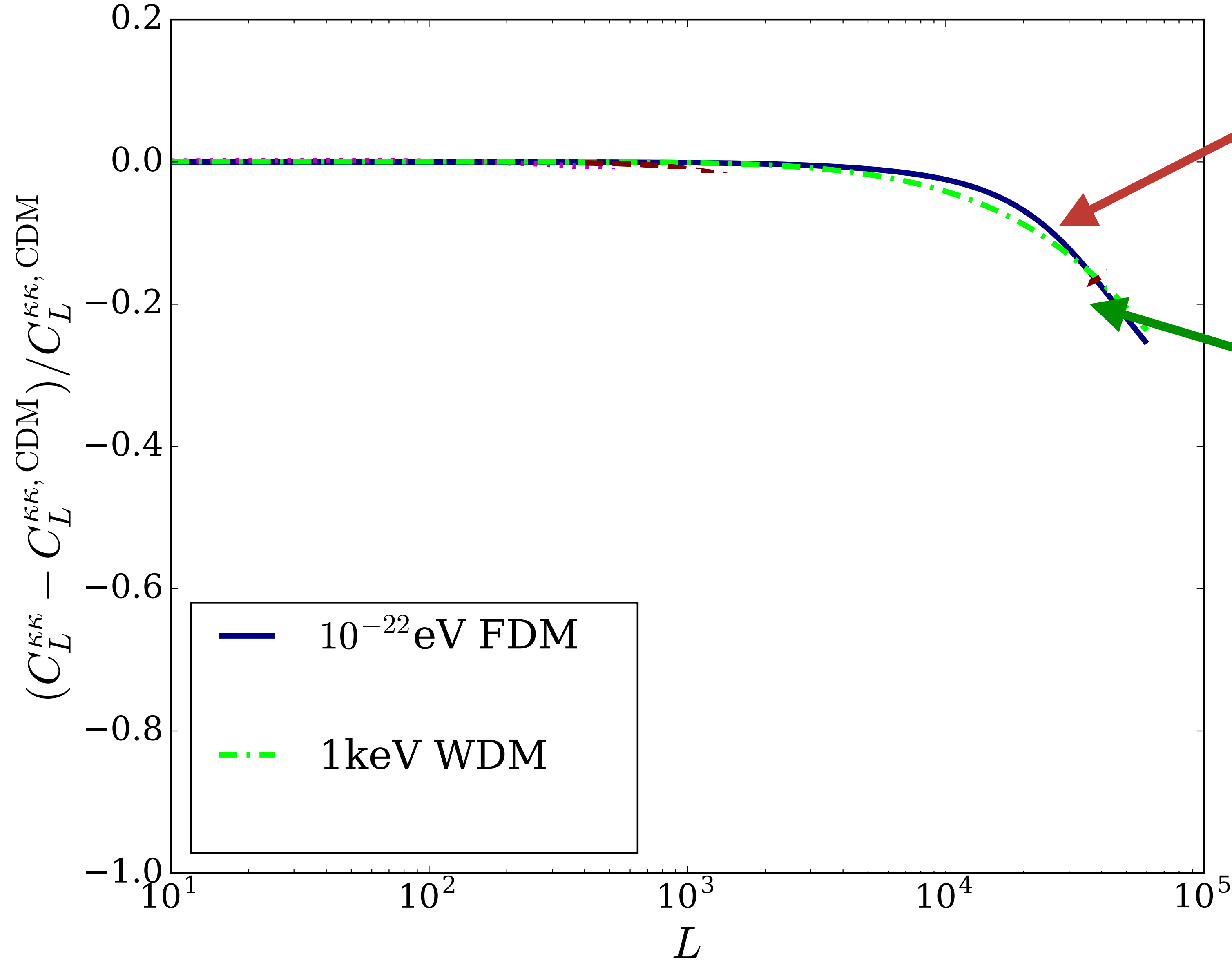
at these scales sensitive to structure at z~1-3

Want to measure scales L ~ 30,000 (k ~ 10 Mpc^-1 and M < 10^9 Msun)

Contrast between CDM and models that wash out small-scale structure is larger at higher redshifts

Neelima Sehgal, Stony Brook

CMB Lensing Power Spectrum for CDM Versus FDM/WDM



Fractional difference between FDM/WDM and CDM for the CMB lensing power spectrum

While we directly measure structure with lensing, as opposed to using a baryonic tracer, baryons may still suppress matter power

But shape is different

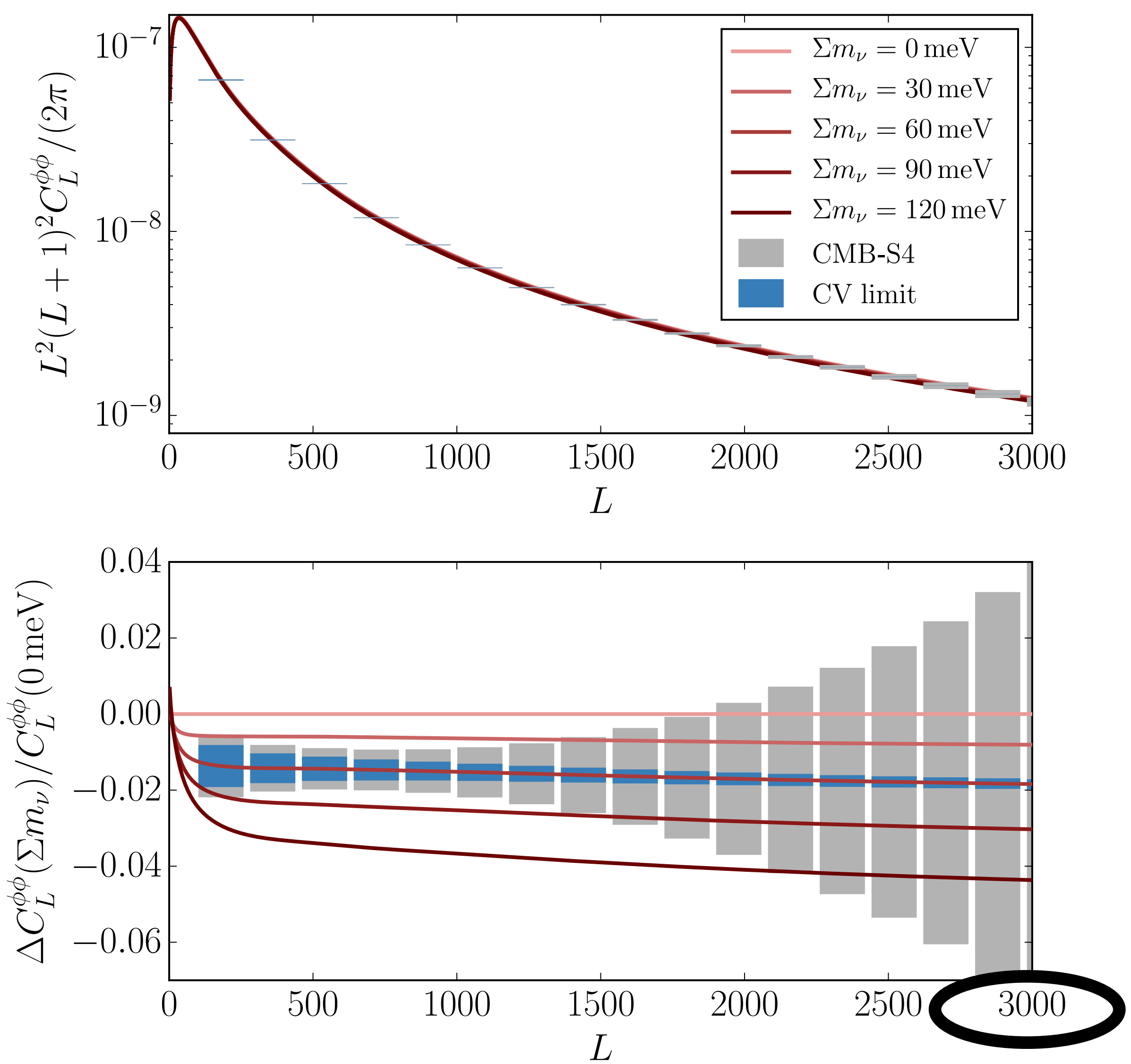
1.) If see little deviation from pure CDM curve, then constrain both baryons and alternate DM models

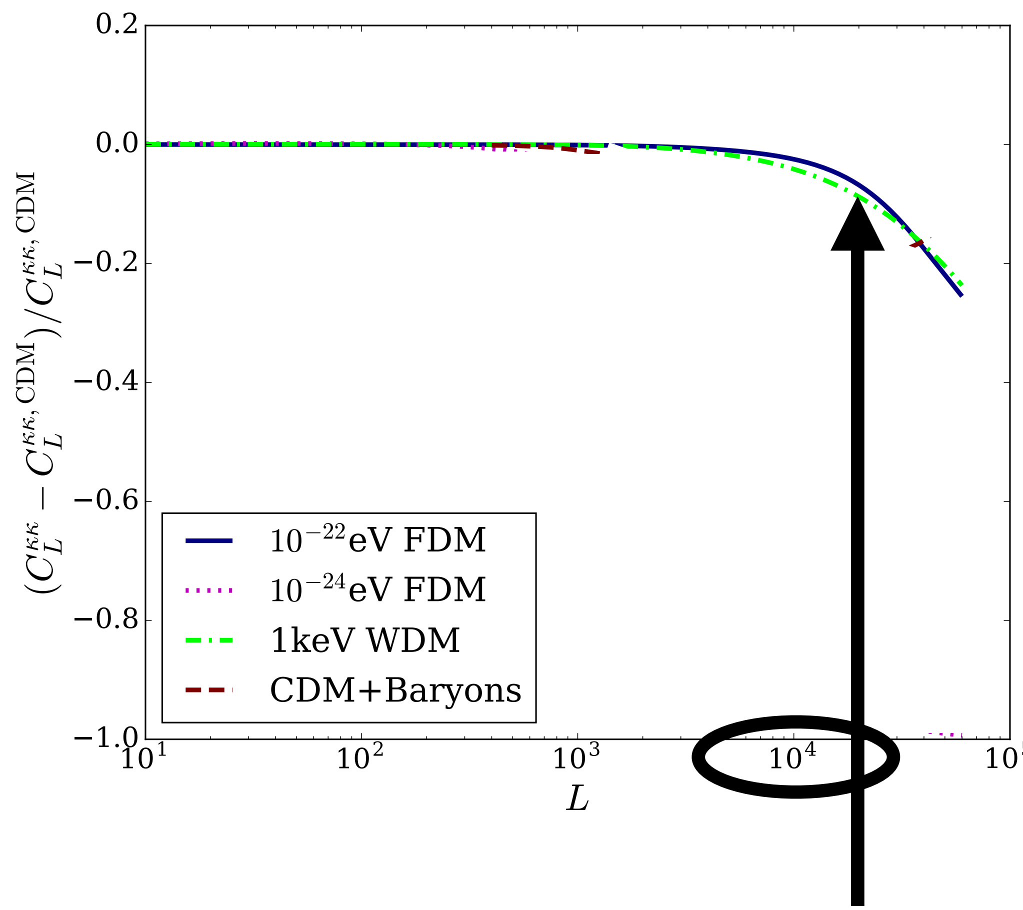
2.) If see significant deviation, then can potentially use shape of curve to determine whether it is due to baryons or alternative to CDM

Neelima Sehgal, Stony Brook

Dark Matter Constraints Not Degenerate with Neutrino Mass

CMB-S4 Science Book



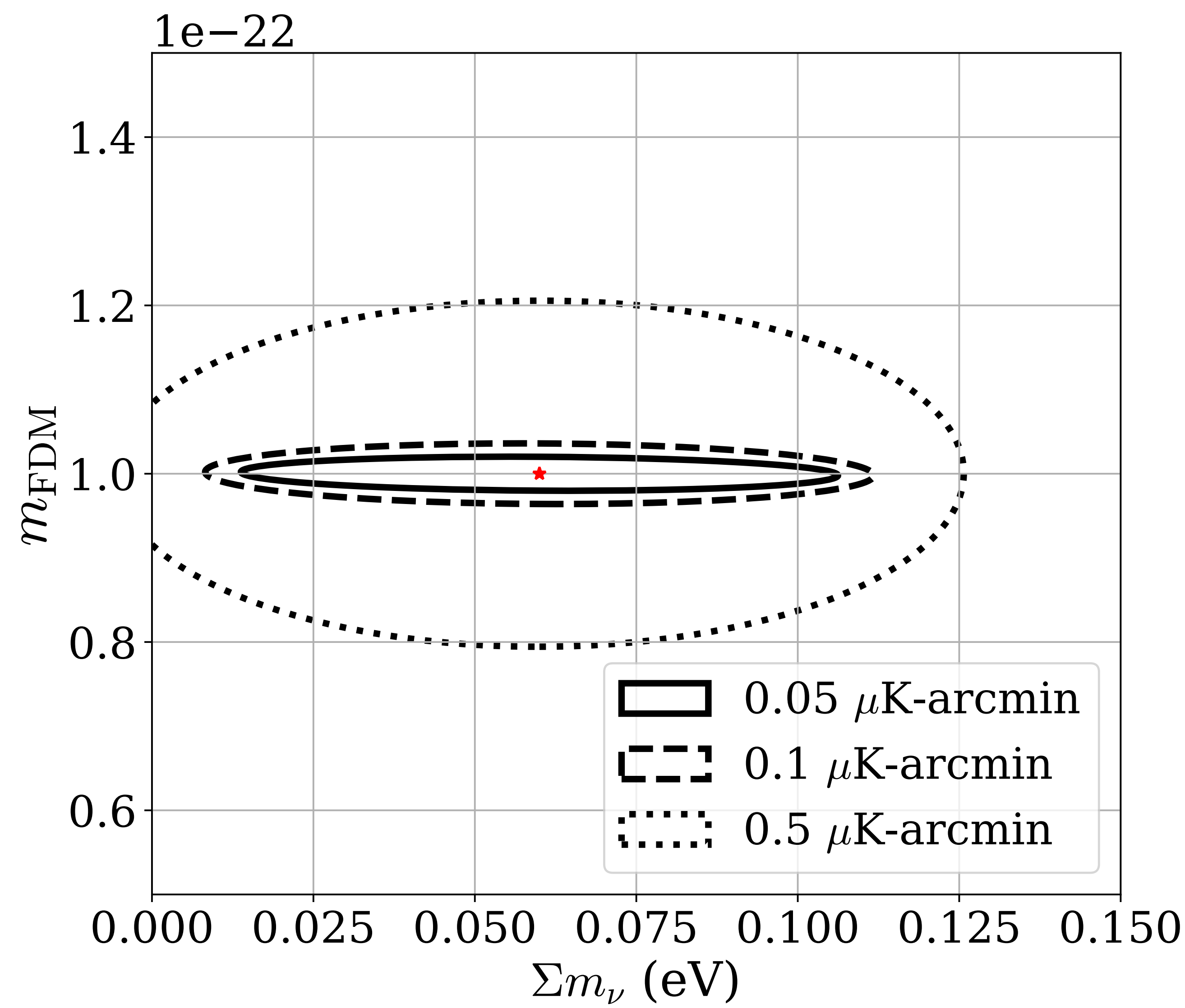


Alternative DM models of interest suppress power on much smaller scales

CMB lensing is known for its potential to constrain the sum of the neutrino masses

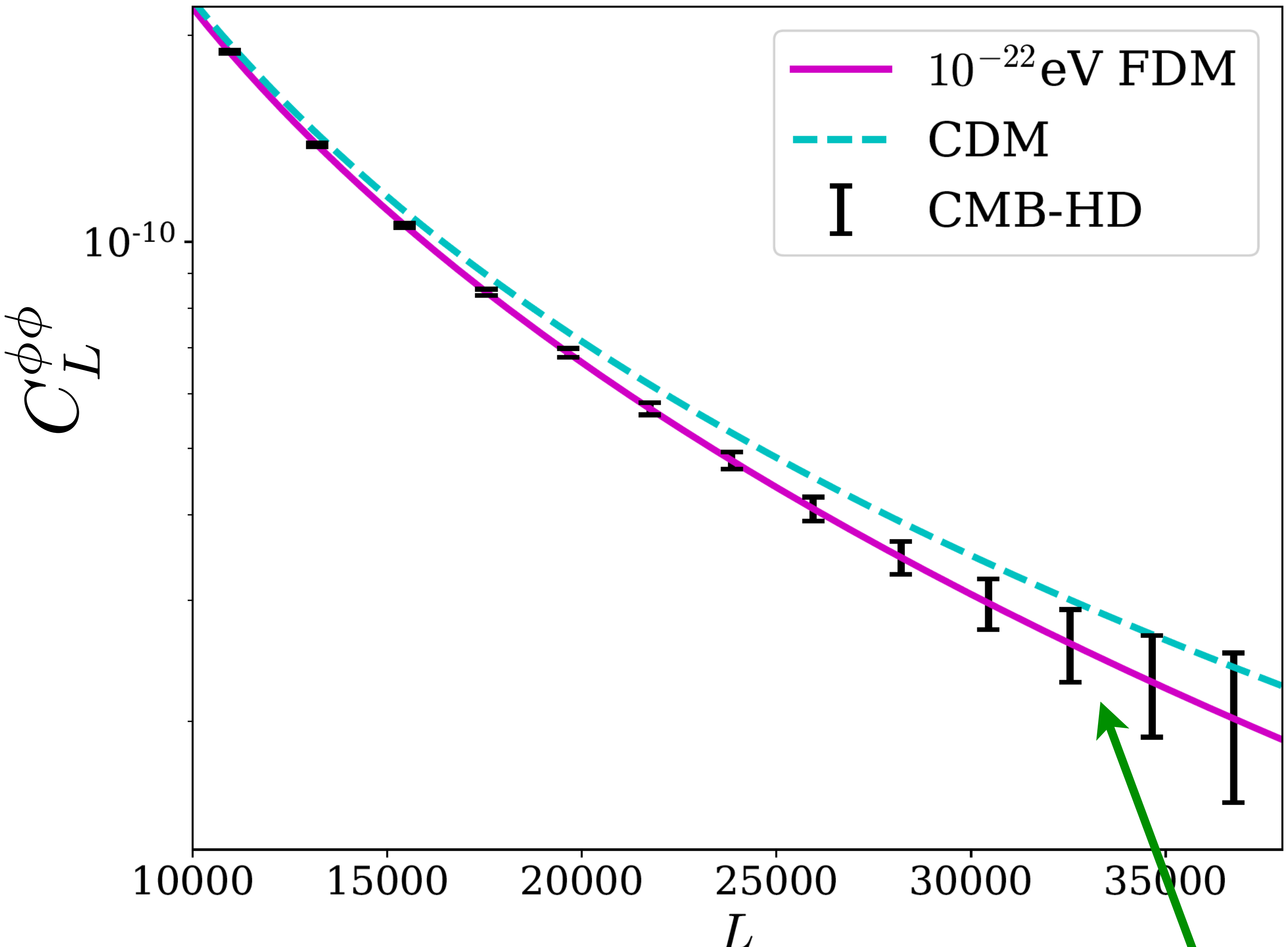
Neelima Sehgal, Stony Brook

Dark Matter Constraints Not Degenerate with Neutrino Mass



Ho Nam Nguyen, NS, Mathew Madhavacheril, 2019, PRD

Dark Matter Forecasts Using Ultra-Small-Scale CMB Lensing



Need camera 3 times more sensitive and with 5 times better resolution than CMB-S4

CMB-HD is new proposed experiment

8-sigma preference for FDM over CDM

Ho Nam Nguyen, NS, Mathew Madhavacheril, 2019, PRD
NS et al., 2019, arXiv:1903.03263

Instrument Path

Two new 30-meter mm-wave telescopes in Atacama Desert with total sensitivity 3 times deeper than CMB-S4 == CMB-HD

Each telescope holds 800,000 detectors (200,000 pixels); Survey duration = 7.5 years

Survey is over half the sky; Cost = 1 billion dollars

Neelima Sehgal, Stony Brook

Motivation of CMB-HD

Rich Science from CMB-HD:

Dark Matter
- Dark Matter Properties from Small-Scale Matter Power Spectrum
- Number of Relativistic Species

Inflation
- Delensing for Primordial Gravitational Waves
- Primordial Non-Gausianity

- Neutrino Mass
- Dark Energy

Galaxy Evolution
- Galaxy Cluster Astrophysics
- Galaxy Formation

- Reionization

Planets
- Solar and Extrasolar Planetary Studies

- Synergy with Optical Lensing Surveys

Transients
- Mapping the Transient Sky

- Novel Ideas and Searches for New Physics

For more info see 1903.03263, 1906.10134, 2002.12714

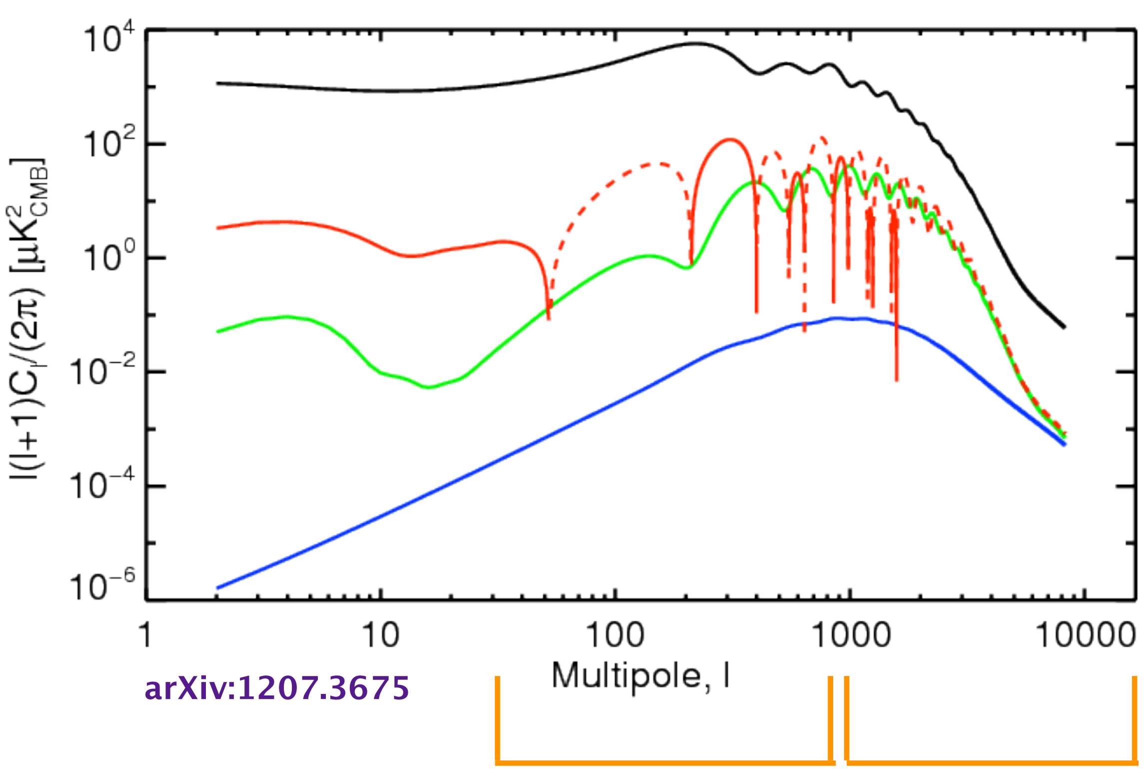
Neelima Sehgal, Stony Brook

CMB-HD Probe of Light Particles

Table 1: Summary of CMB-HD key science goals in fundamental physics

Science	Parameter	Sensitivity
Dark Matter	S/N: Significance in Differentiating FDM/WDM from CDM[a]	S/N = 8
New Light Species	$N_{\rm eff}$: Effective Number of Relativistic Species[b]	$\sigma(N_{\rm eff}) = 0.014$
Inflation	$f_{\rm NL}$: Primordial Non-Gaussianity[c]	$\sigma(f_{\rm NL}) = 0.26$
Inflation	$A_{\rm lens}$: Residual Lensing B-modes[d]	$A_{\rm lens} = 0.1$

NS et al. 2019, CMB-HD APC White Paper for Astro2020 Decadal (arXiv:1906.10134)



SO measures this; TT, TE, EE to the cosmic variance limit

CMB-HD measures this

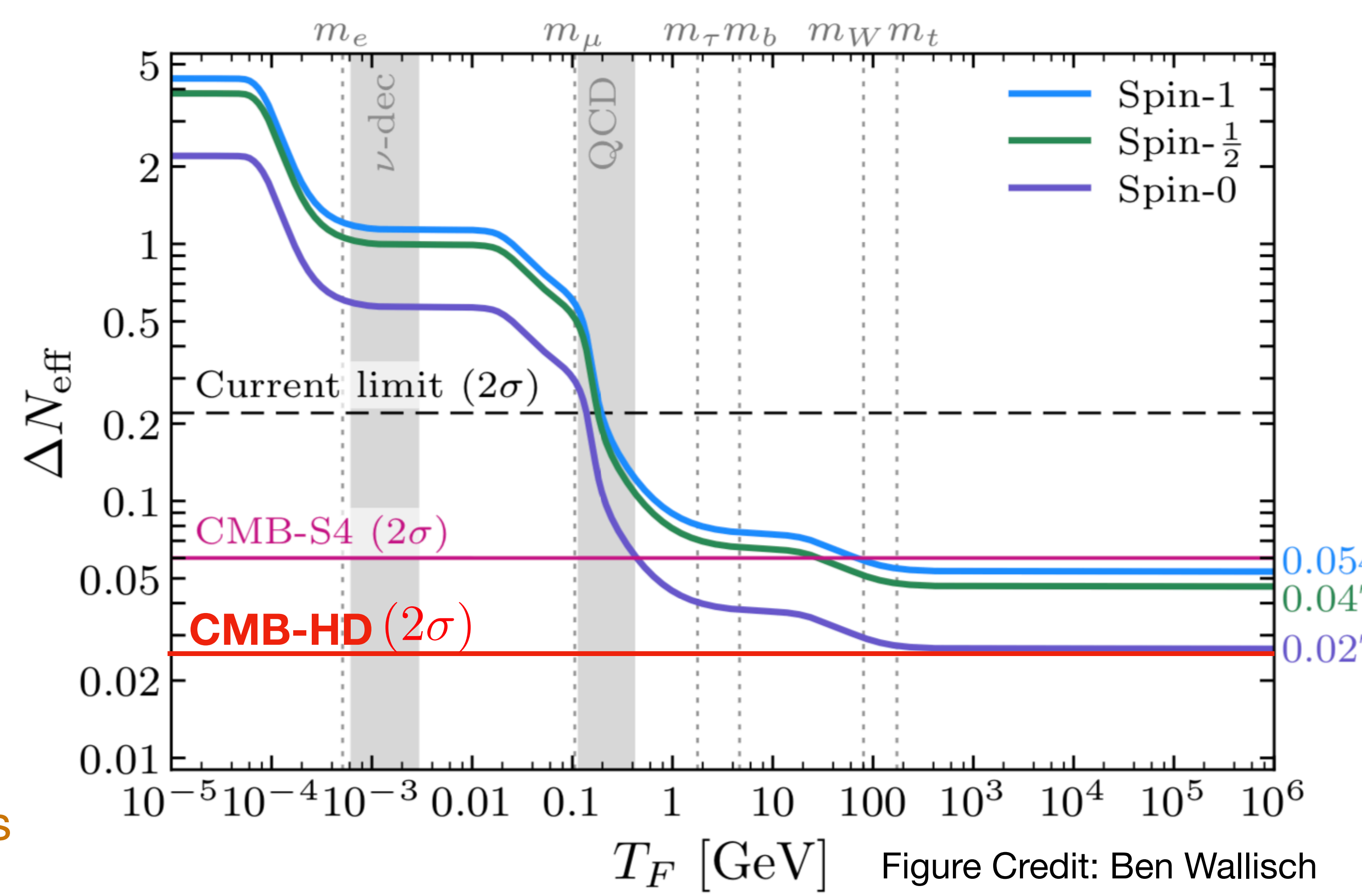


Figure Credit: Ben Wallisch

Summary

- Key question: what do matter fluctuations look like on small scales?
- Multiple techniques to measure this have been proposed, each with different challenges and systematics
- Another complementary, potentially powerful technique, with different systematics, is to use ultra-deep, high-resolution CMB lensing to measure the matter power spectrum
- Requires two 30-meter mm-wave telescopes with total sensitivity 3 times deeper than proposed CMB-S4
- Would open new frontier of mm-wave observations
- Good motivation for future ground-based CMB experiment, i.e. CMB-HD (see http://cmb-hd.org for more info)