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

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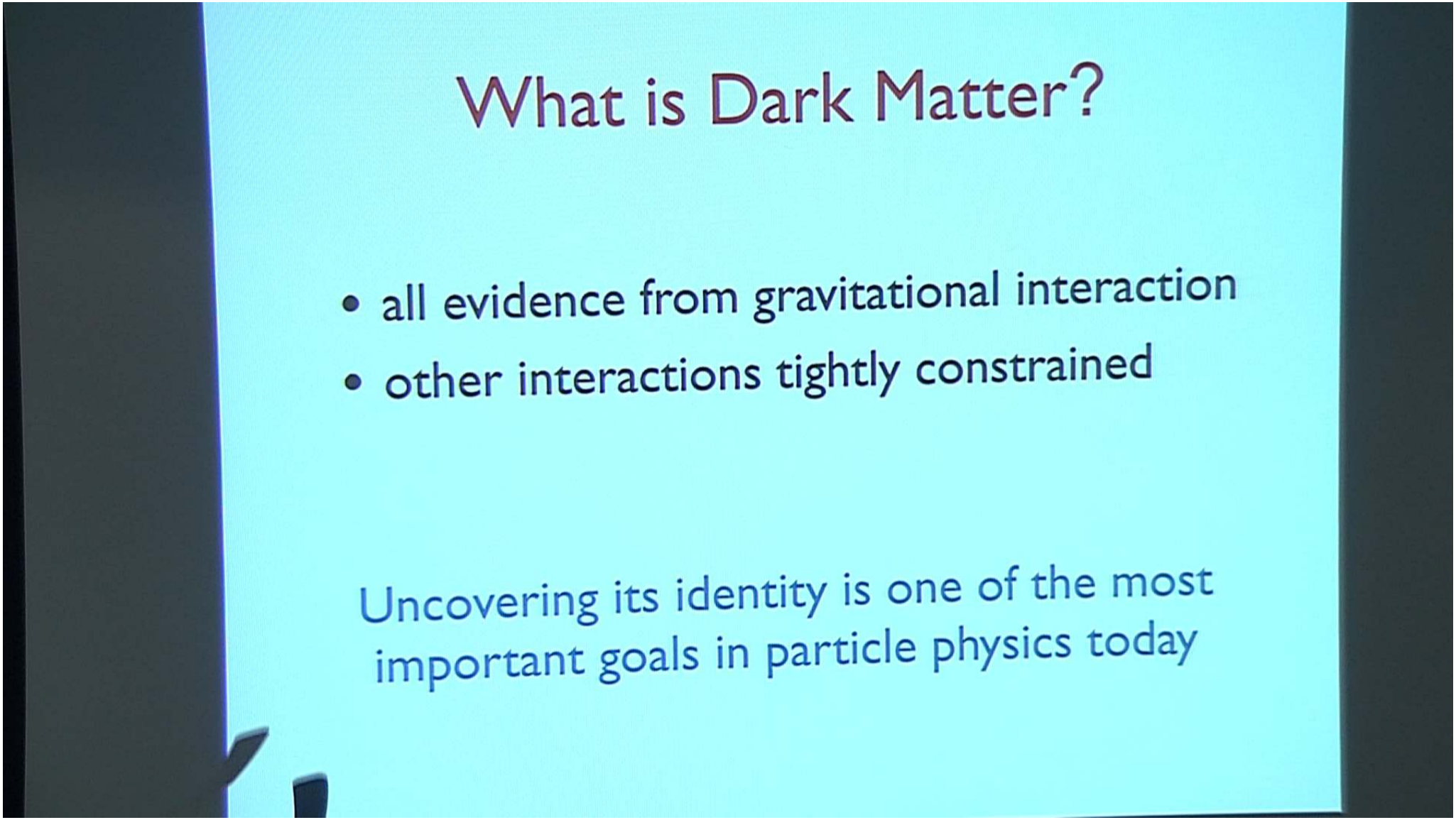
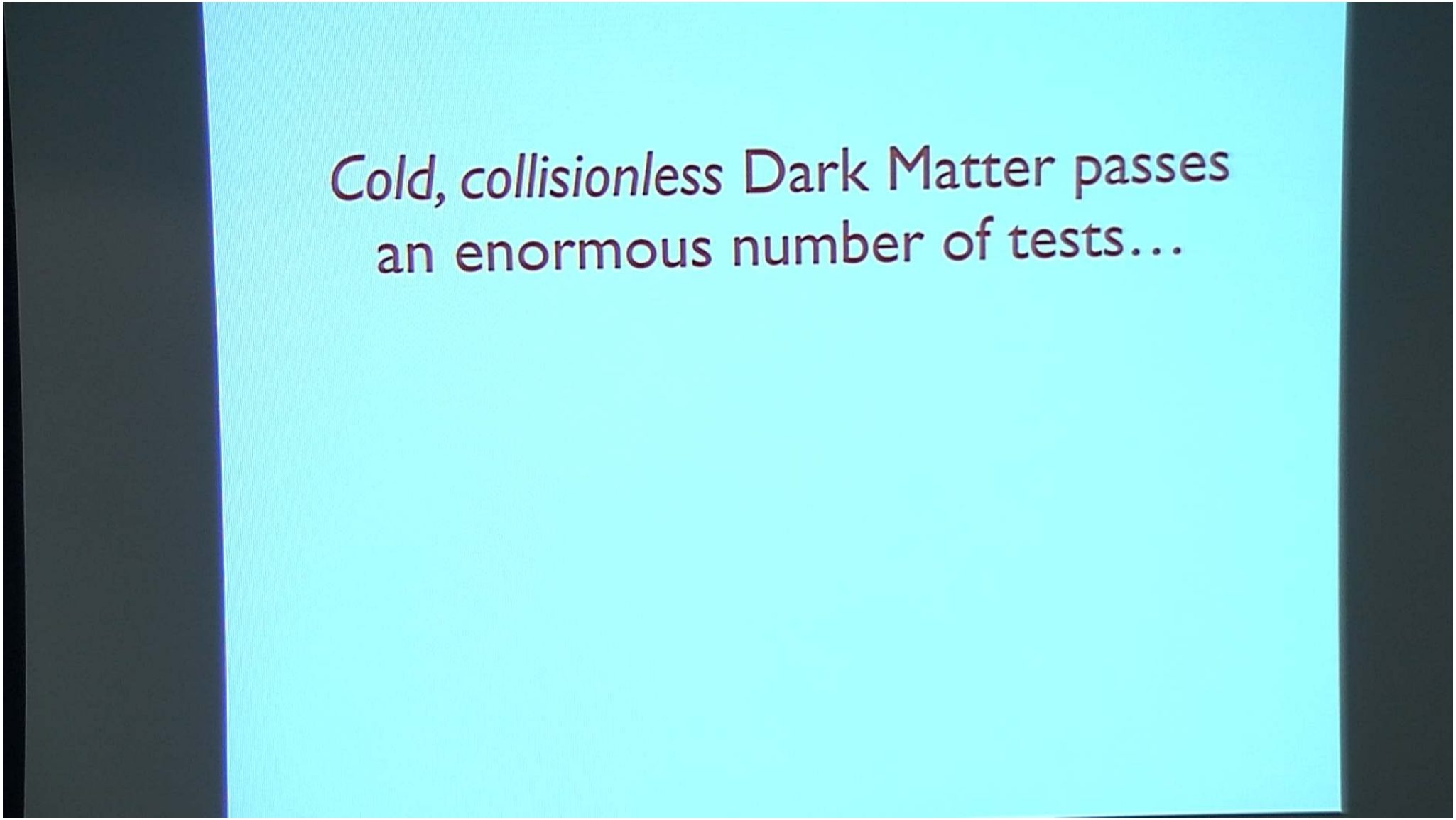
Abstract: I will discuss a novel and powerful way to probe dark matter particle properties using deep, high-resolution cosmic microwave background (CMB) gravitational lensing measurements. These measurements can distinguish between cold dark matter and alternative dark matter models that can explain observational puzzles of small-scale structure. I will also discuss a new experiment being developed, called CMB-HD, that can achieve this science and also open new windows on the early Universe, gas and galaxy evolution, planetary studies, and the transient sky.


What is Dark Matter?
• all evidence from gravitational interaction
• other interactions tightly constrained
Uncovering its identity is one of the most important goals in particle physics today


*Cold, collisionless* Dark Matter passes
an enormous number of tests…

# A simulated Milky-Way CDM Halo

[Diemand et.al.]

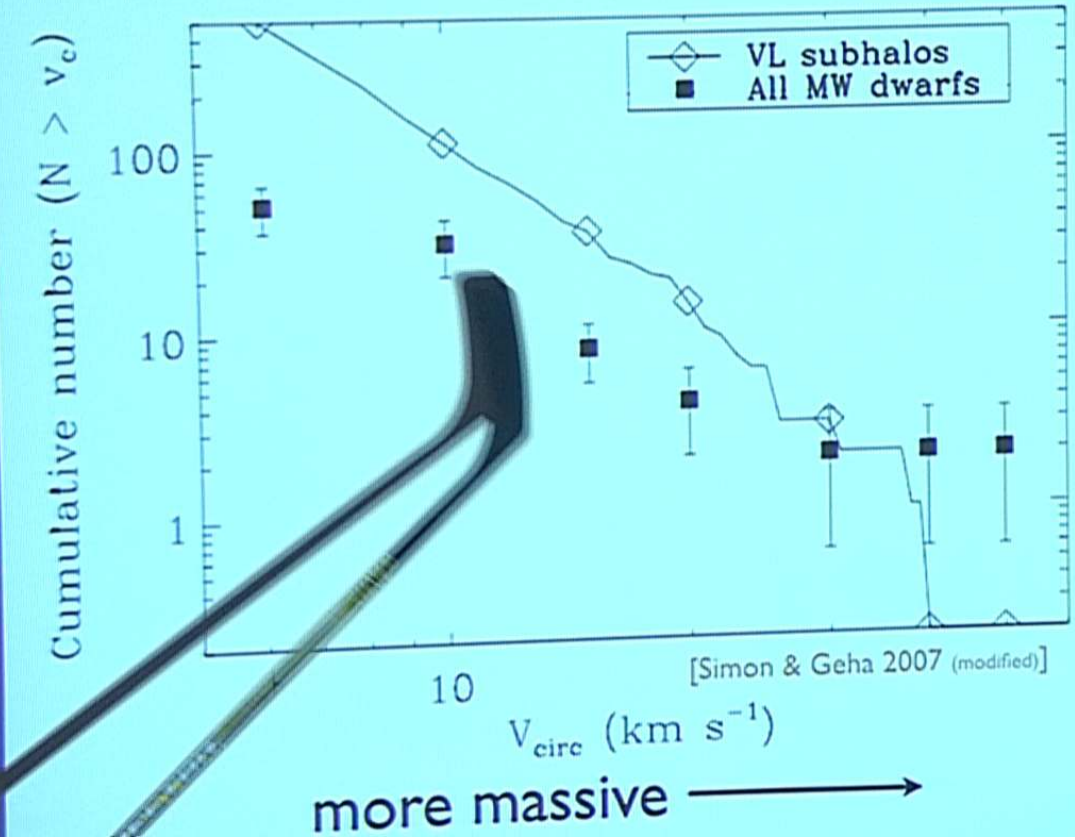
Via Lactea II
Simulation

(only DM, no baryons)

.6 Mega-light-yrs cube

# Missing Satellites Problem

e.g. Klypin et al. 1999; Moore et.al. 1999




many subhalos ("dwarfs") predicted…

not enough are observed!

# Small-Scale CDM Problems?

- CDM works well on scales larger than 10 kpc, but seems to fail on smaller scales (maybe):

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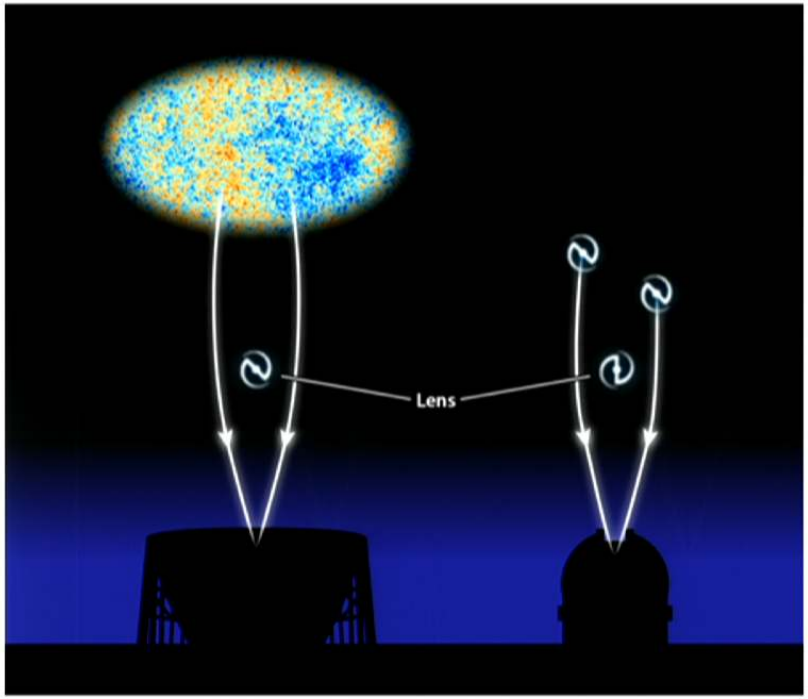
# Gravitational Lensing of the Cosmic Microwave Background



# 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

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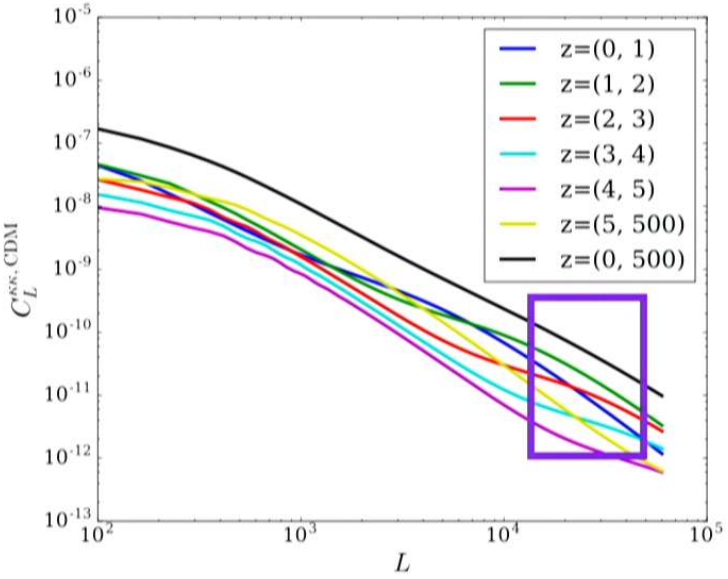
# CMB Lensing Power Spectrum




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

**CMB Lensing Power Spectrum is matter power spectrum convolved with window**

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

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

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

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

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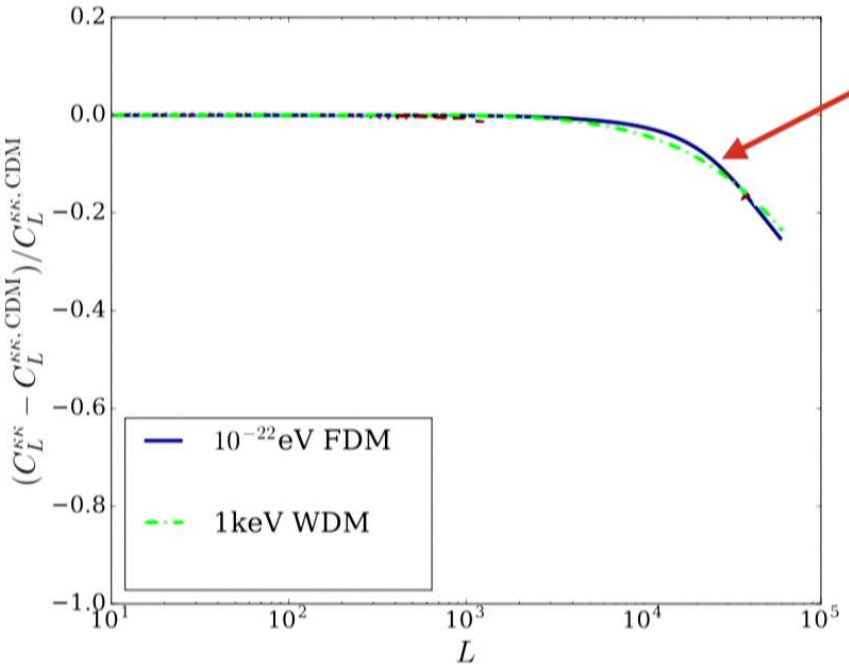
# CMB Lensing Power Spectrum for CDM Versus FDM/WDM




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

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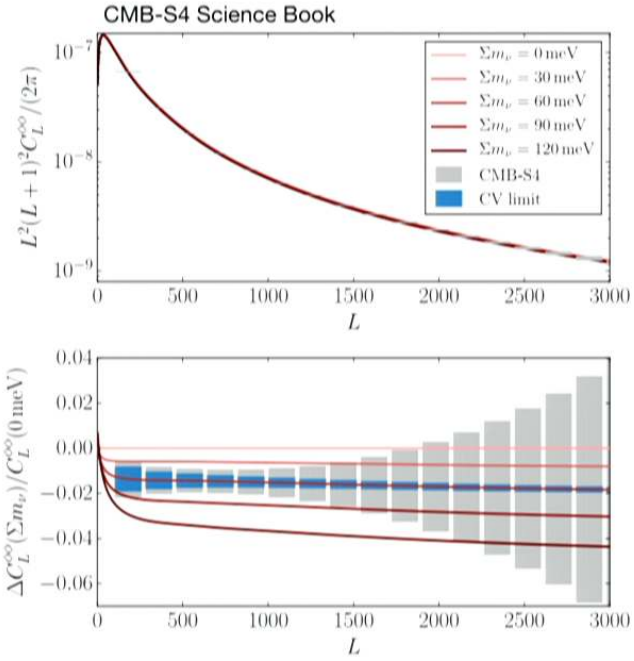
# Dark Matter Constraints Not Degenerate with Neutrino Mass

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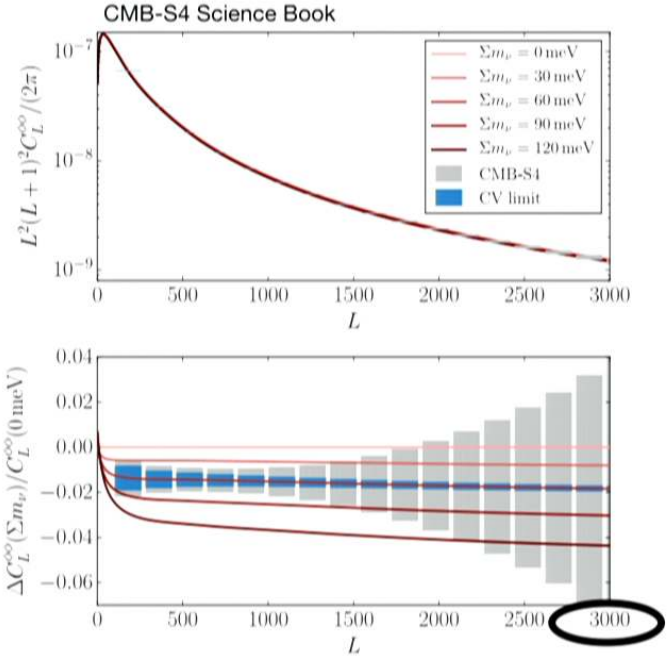
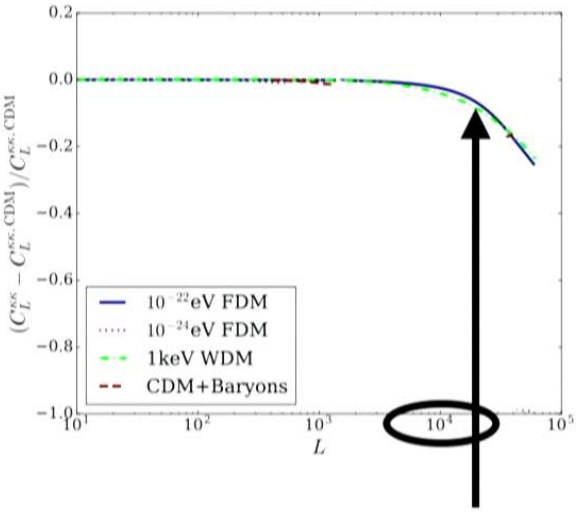



**CMB lensing is known for its potential to constrain the sum of the neutrino masses**




**Alternative DM models of interest suppress power on much smaller scales**

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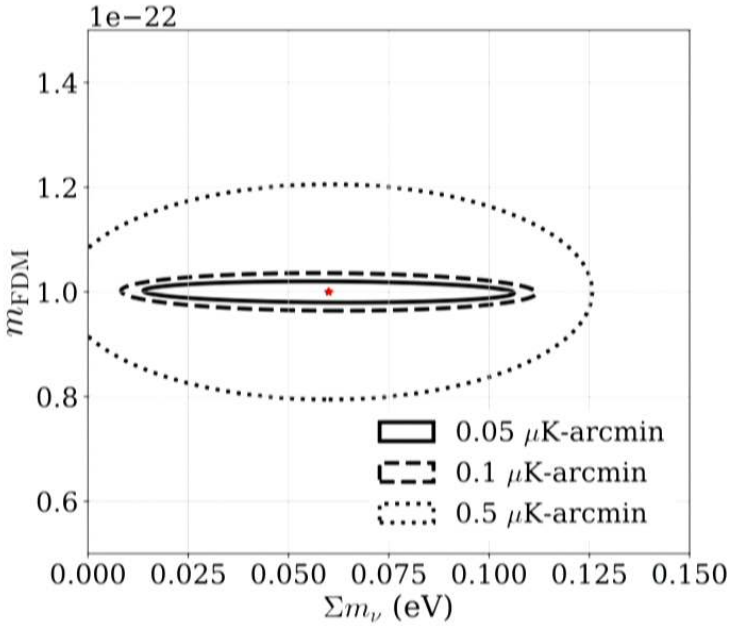


Ho Nam Nguyen, NS, Mathew Madhavacheril, 2019, PRD

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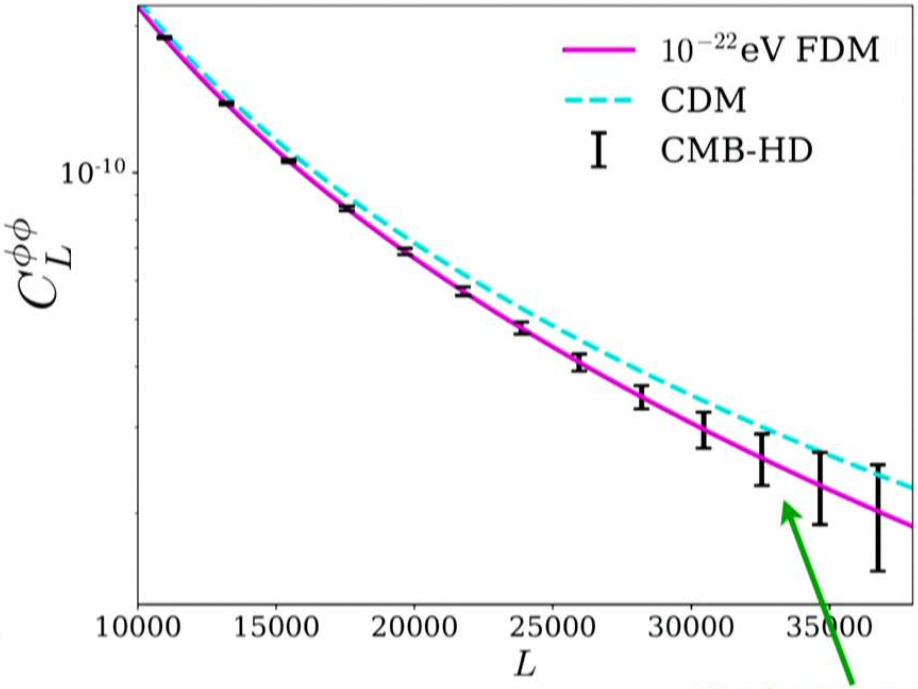
# Dark Matter Forecasts Using Ultra-Small-Scale CMB Lensing




8-sigma preference for FDM over CDM

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

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# Instrument Path

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

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# 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)

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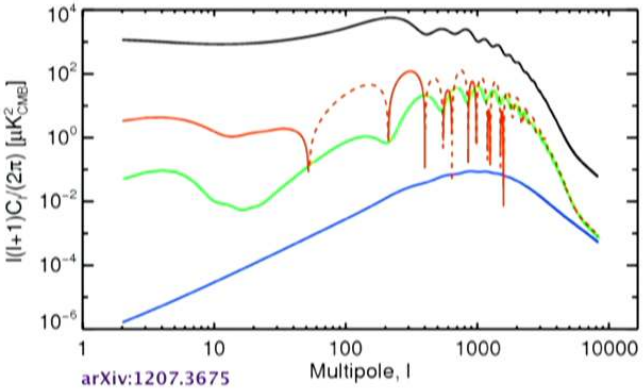
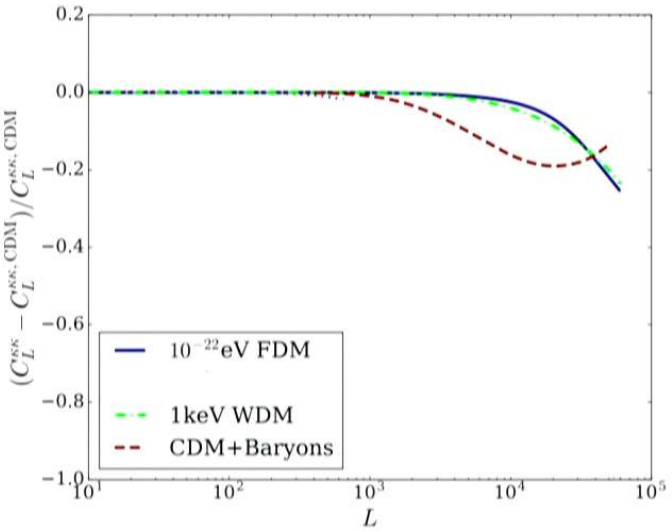


# Theory Questions

Degeneracy between baryons impacting matter and alternatives to CDM

Use difference in shape



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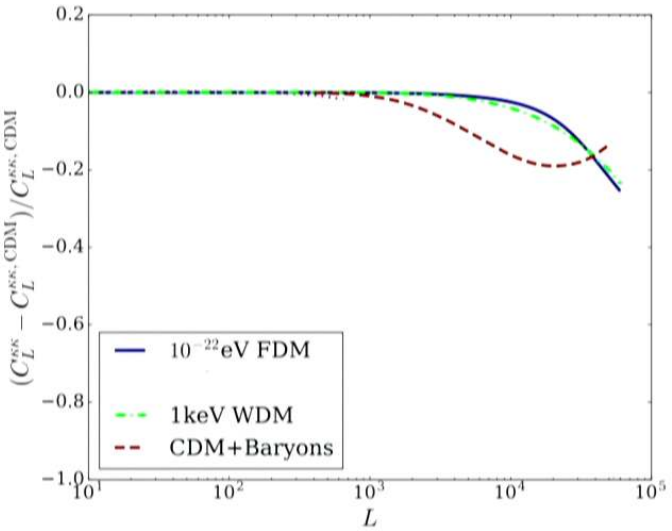


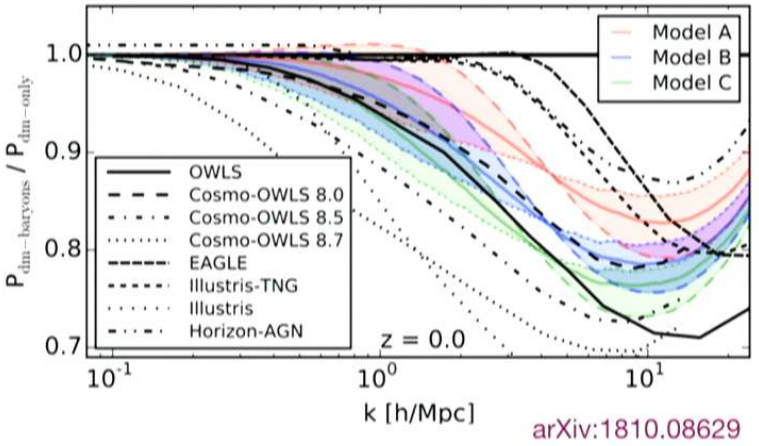


arXiv:1810.08629

**Quantifying baryon effects on the matter power spectrum and the weak lensing shear correlation**

Aurel Schneider, Romain Teyssier, Joachim Stadel, Nora Elisa Chisari, Amandine M. C. Le Brun, Adam Amara, Alexandre Refregier

# Summary

- Key question: what do matter fluctuations look like on small scales?
- Multiple techniques to measure this are 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