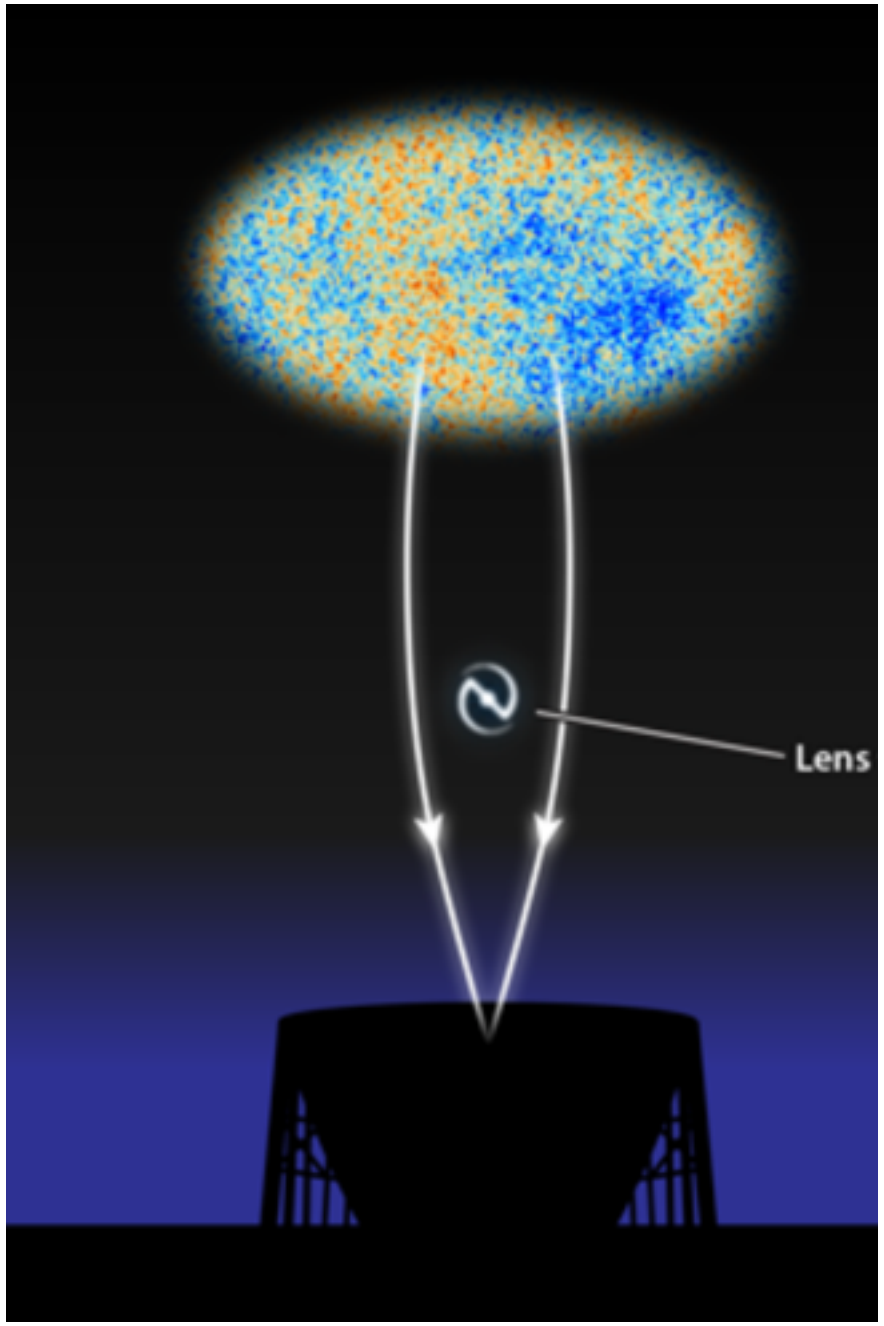
# Measuring the Small-Scale Matter Power Spectrum with High-Resolution CMB Lensing




Neelima Sehgal

KITP Conference - Dark Matter Detection and Detectability: Paradigm Confirmation or Shift?

May 1st, 2018

Ho Nam Nguyen, NS, Mathew Madhavacheril, 2017, arXiv:1710.03747

# 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 dark matter fluctuations look like on small-scales?**

# Measurements of Small-Scale Structure

- Identifying dwarf galaxies by their stars - star formation may be quenched, masses of dwarfs require expensive spectroscopy

- Measure abundance of ultra-faint, high-z galaxies in Hubble Frontier fields - photo-z, survey volume, survey selection uncertainties

- Abundance of high-z gamma-ray bursts - uncertainty in mass of host halo

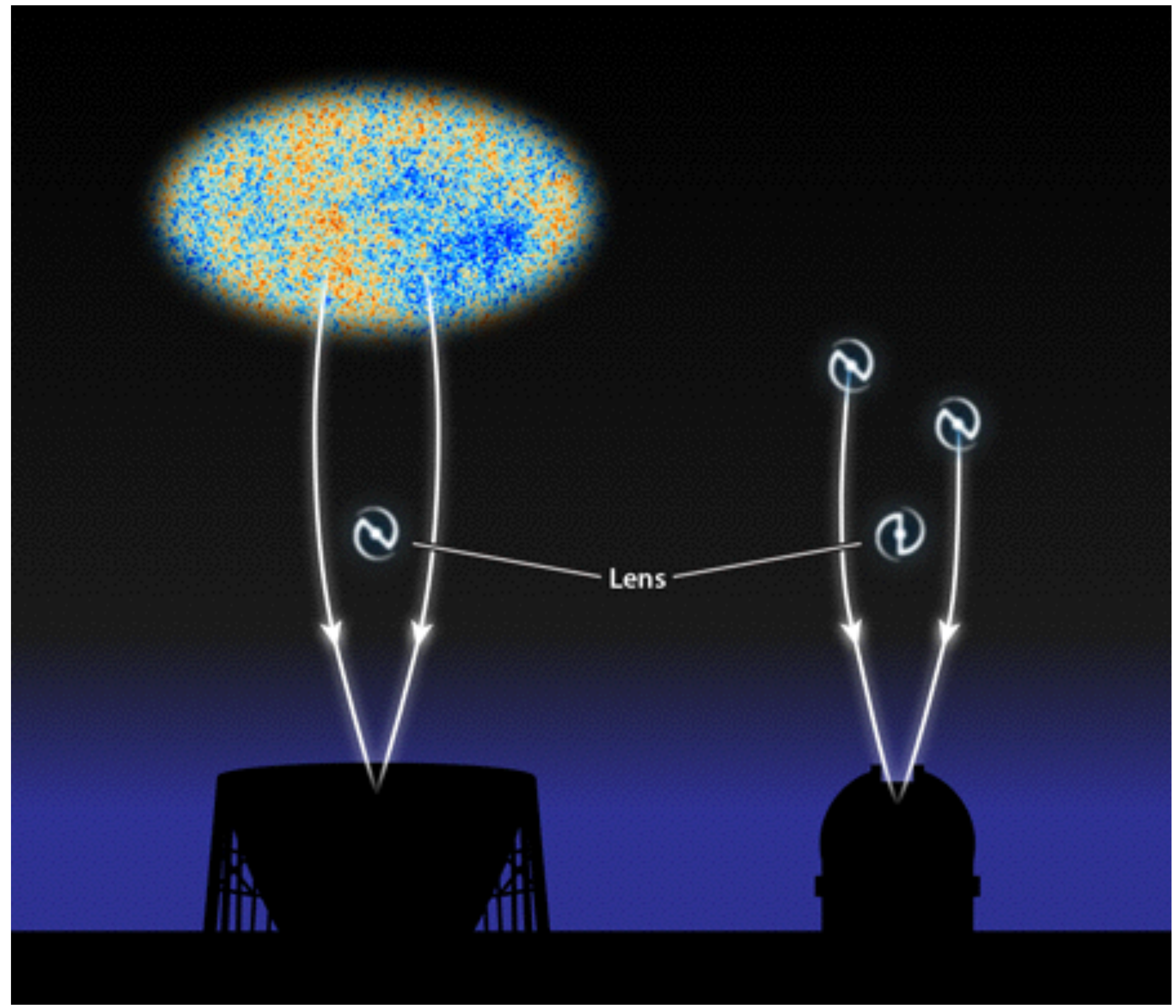
- Tidal debris streams from disrupted MW satellites - uncertainties in progenitor of streams and impact of passing through baryonic disk

- Lyman-alpha forest - baryons may have power on small scales not traced by dark matter

- Galaxy-galaxy strong lensing in optical and mm-wavelegths - need to model lensing halo, need many (~100) expensive strong lensing systems

# Gravitational Lensing of the Cosmic Microwave Background (CMB)

- CMB Lensing is when light from the primordial CMB is bent by intervening matter
- Traditionally measured to probe large-scale structure
- 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

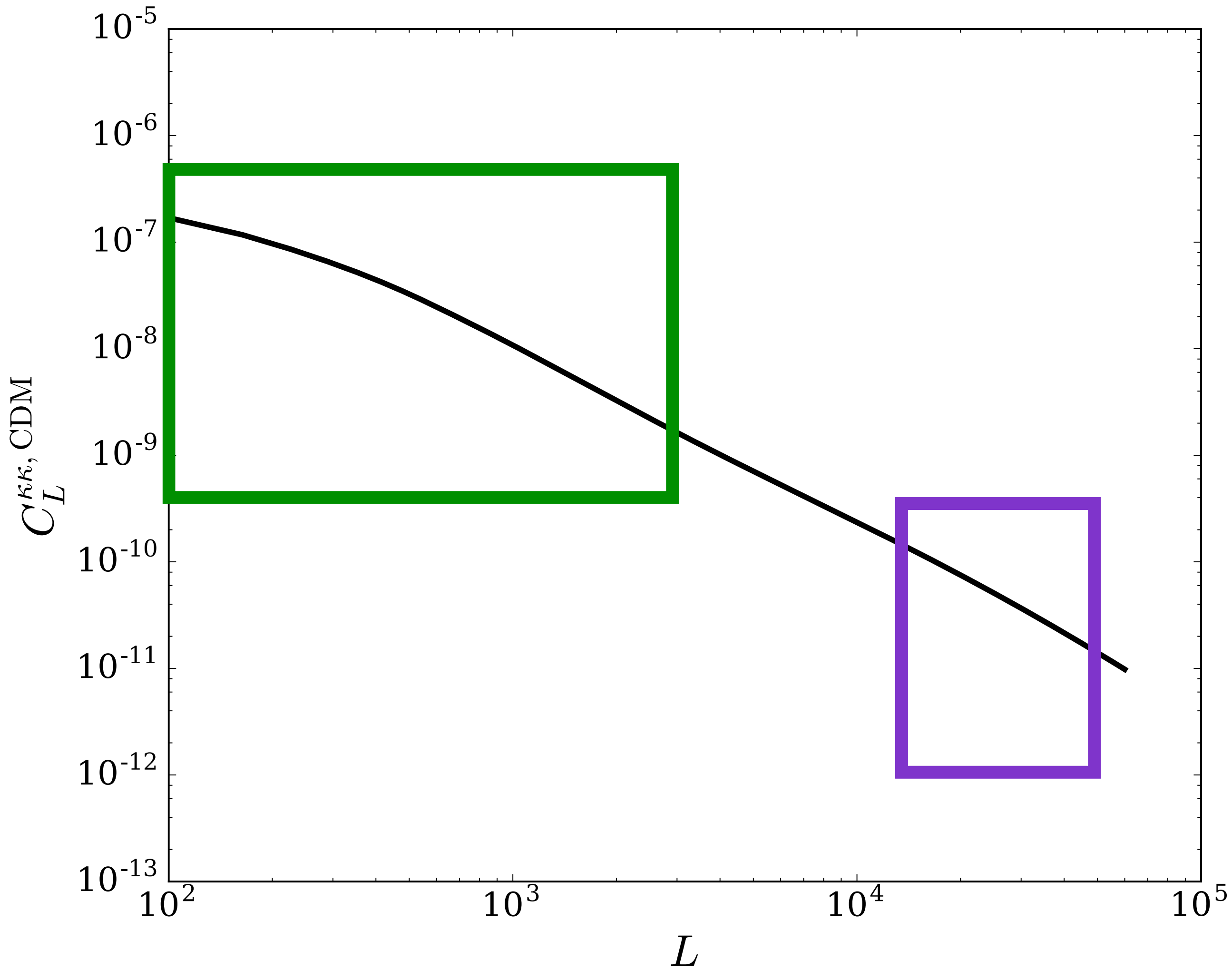
1. Directly sensitive to dark matter via gravitational lensing

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**

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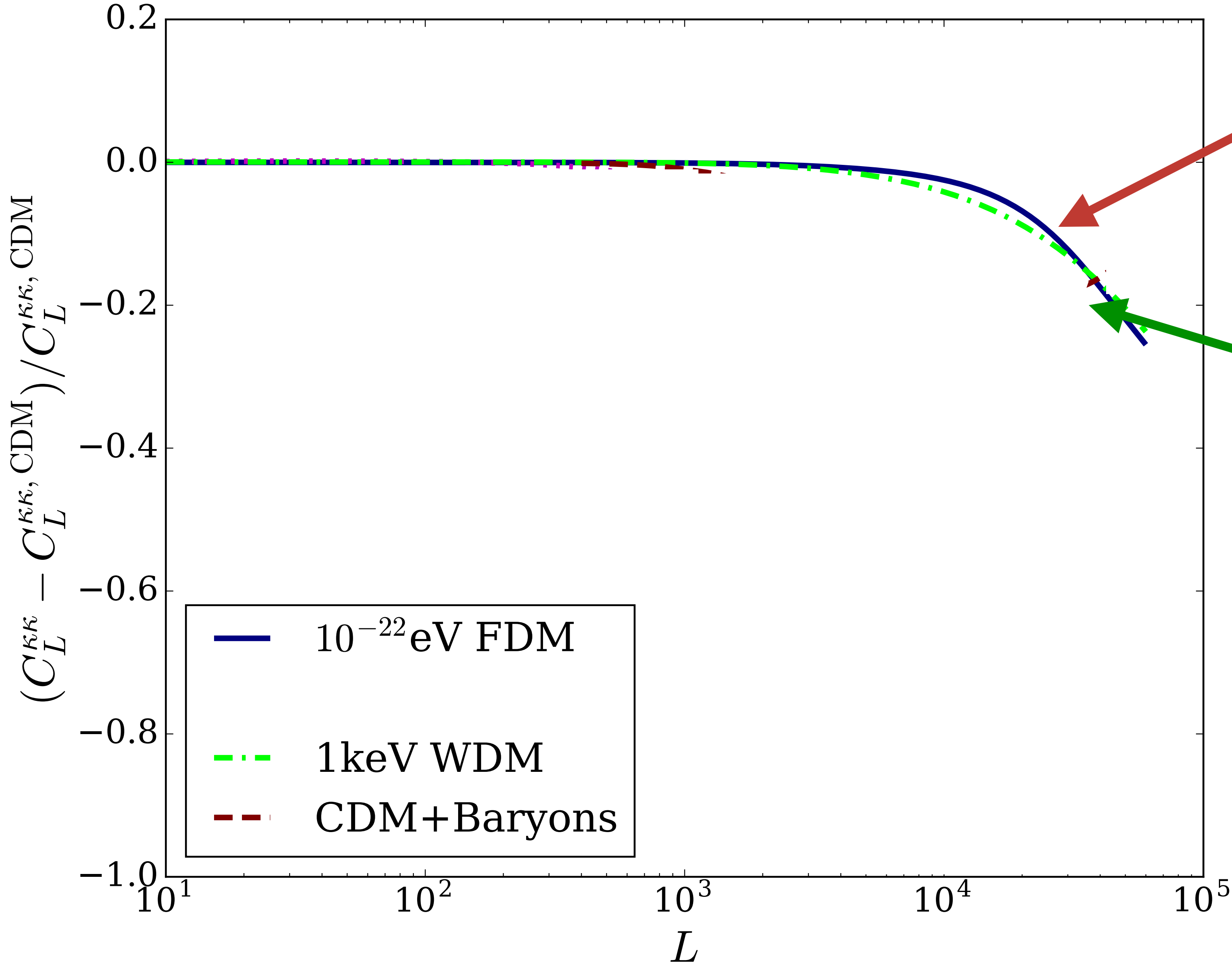
# CMB Lensing Power Spectrum for CDM Versus FDM/WDM




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

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

But shape may be different

1.) If see little deviation from pure CDM curve, that constrains 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

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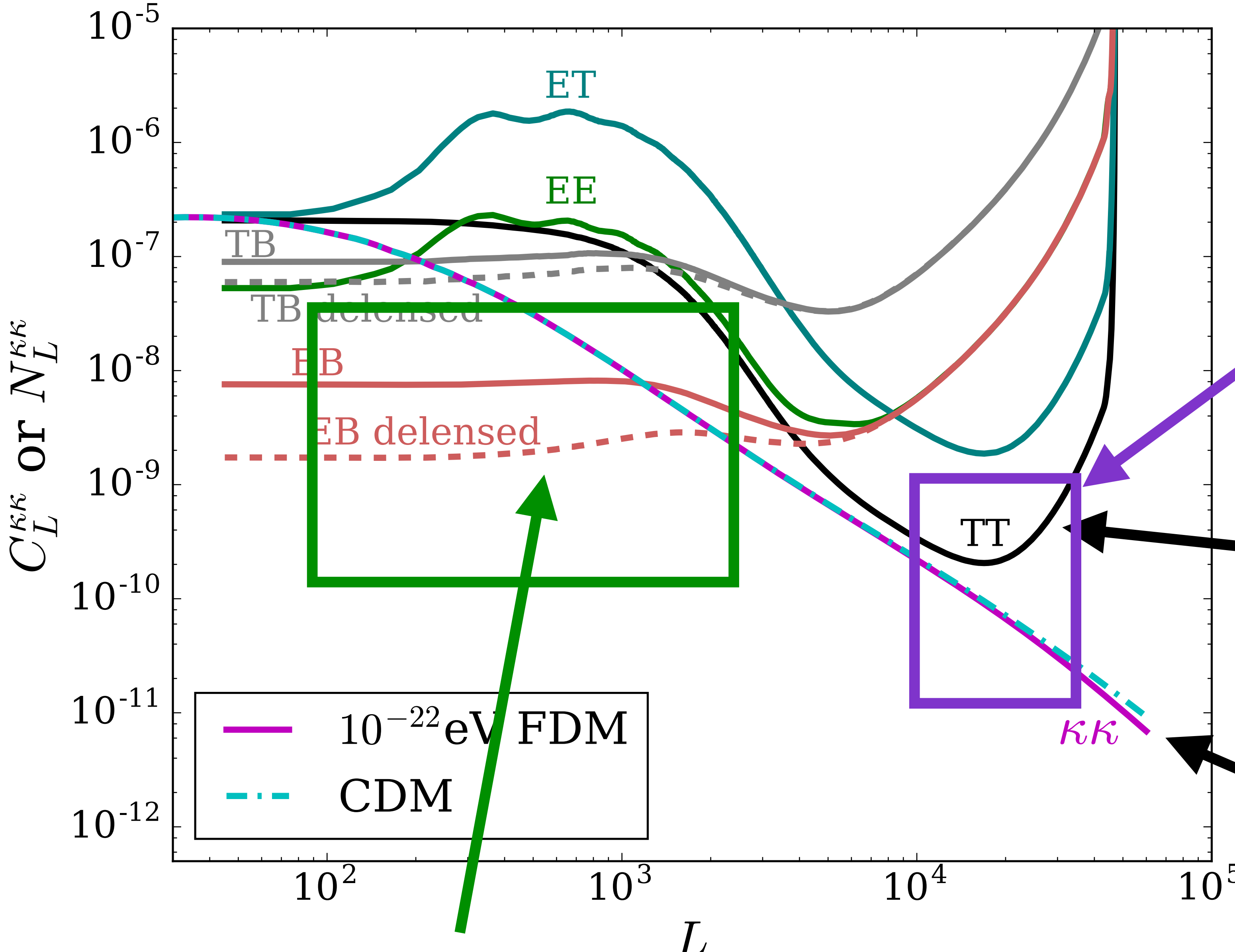
# CMB Lensing Noise Curves to Estimate Sensitivity




**Lensing from CMB temperature maps yield lower noise than from polarization maps in this small-scale regime**

**Noise curves per L-mode for lensing measured using different combinations of CMB maps**

**Signal Curves**

**In large-scale regime, polarization yields lowest noise**

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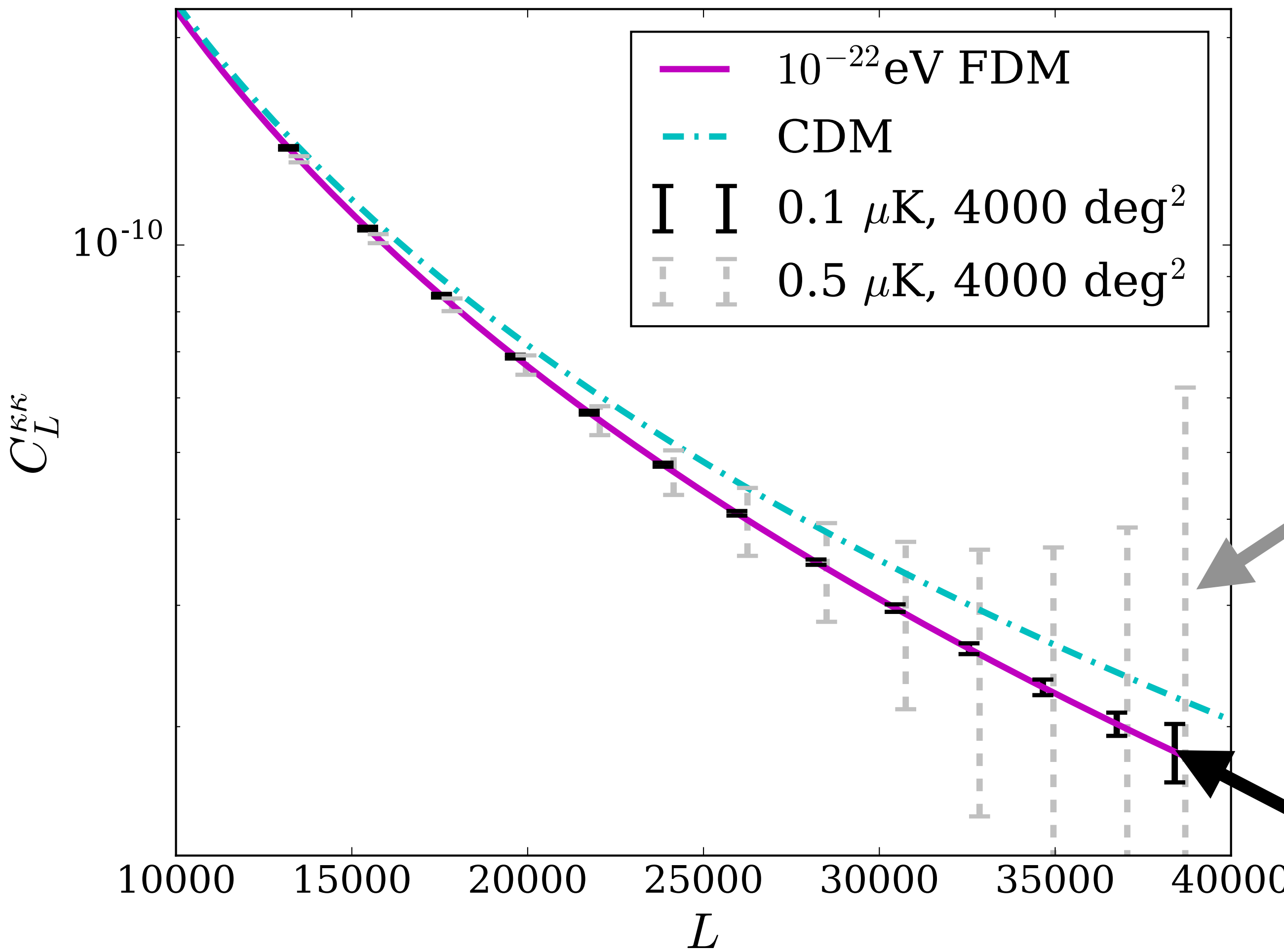
# Potential Ability to Distinguish Between Dark Matter Models




**Grey:** S/N ~ 5 for distinguishing between CDM and FDM/WDM

**Requires:** CMB-S4-type camera on existing 50-meter dish

**Black:** S/N ~ 30 for distinguishing between CDM and FDM/WDM

**Requires:** Camera few times more sensitive than CMB-S4 on existing 50-meter dish

| Sky fraction ($f_{sky}$) | Noise ($\mu$K-arcmin) | Signal-to-noise ratio 18″ Resolution | Signal-to-noise ratio 9.5″ Resolution |
|---|---|---|---|
| 0.1 | 0.5 | 3.9 | 5.2 |
| 0.025 | 0.1 | 10.1 | 15.9 |
| 0.1 | 0.1 | 20.2 | 31.9 |

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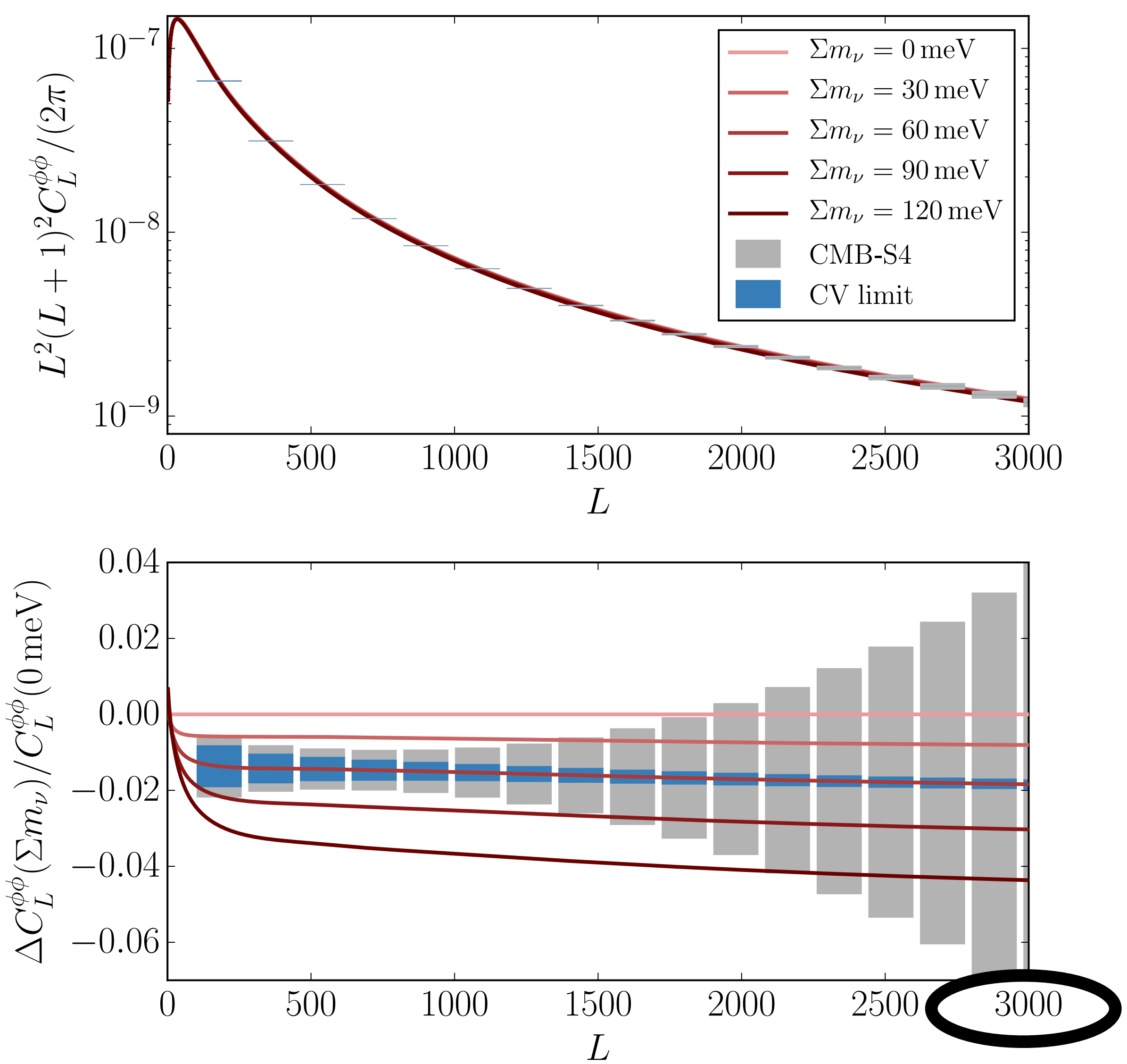
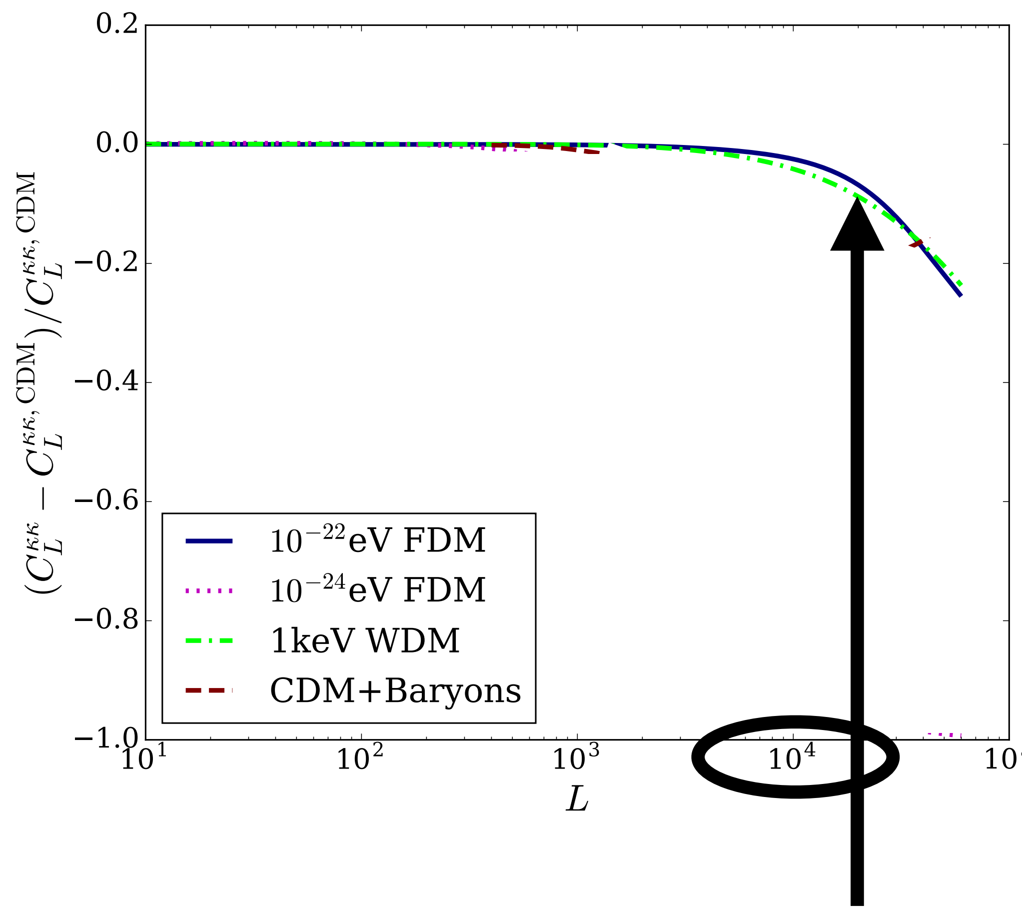
# Dark Matter Constraints Not Degenerate with Neutrino Mass

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**

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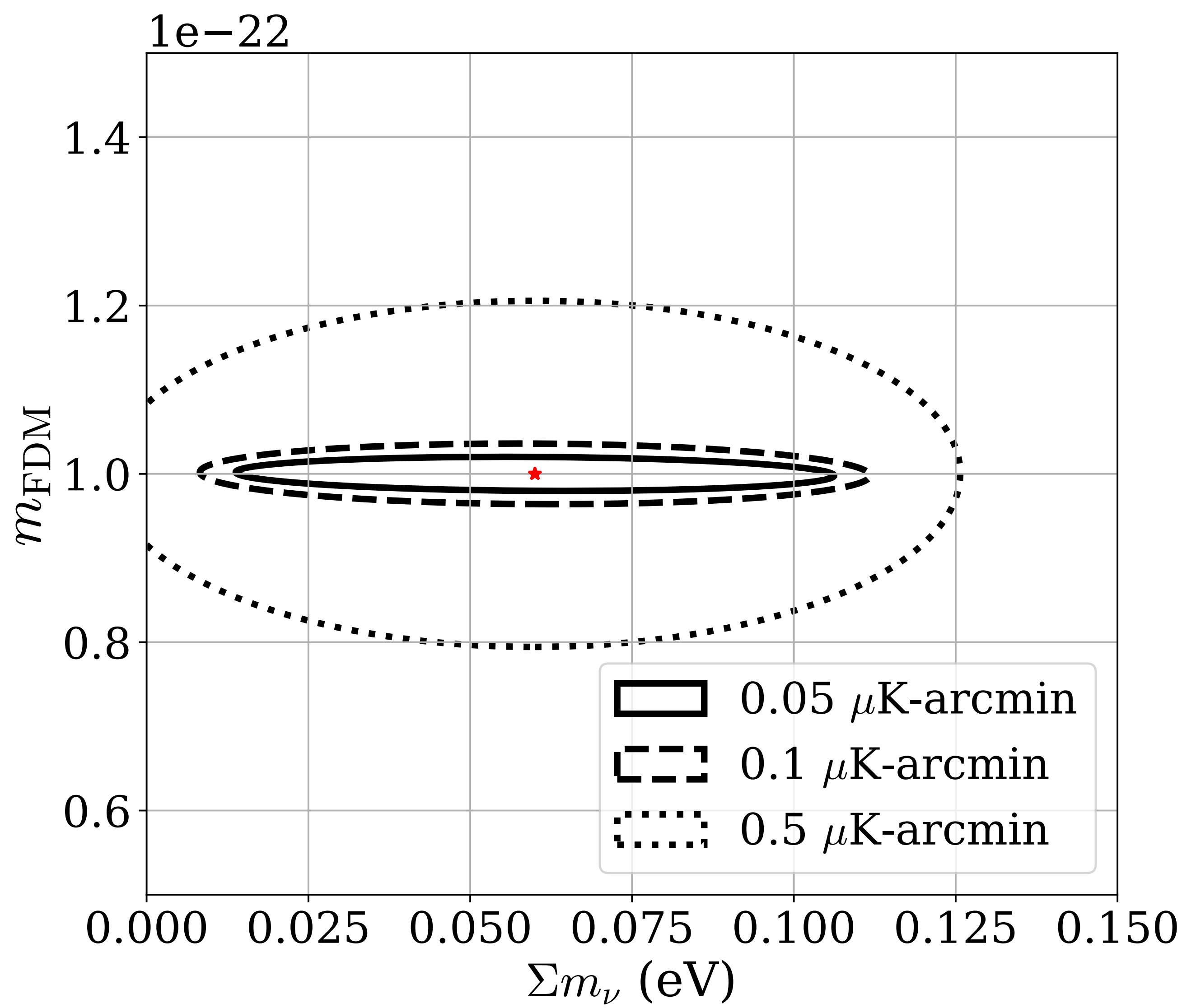
# Dark Matter Constraints Not Degenerate with Neutrino Mass

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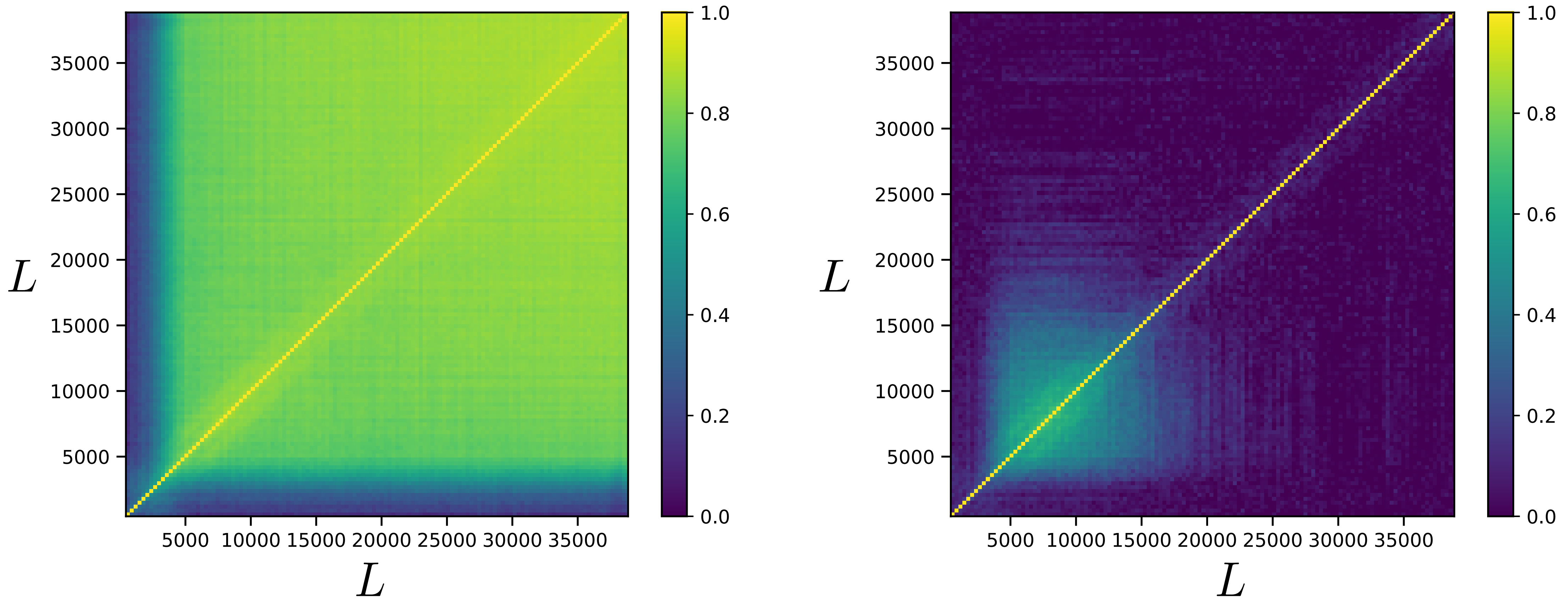
# Potential Advantage/Complementarity of CMB vs Optical Weak Lensing

**Small-scale matter power spectrum may also be measured by galaxy shear from optical surveys**

**Some advantages of CMB:**

- **Well defined redshift of background light source**
- **Properties of background light source well understood**
- **Easier to remove correlated modes on small scales?**

# Potential Advantage/Complementarity of CMB vs Optical Weak Lensing




**Possible optical complication is correlated modes on small scales from, e.g., point spread function uncertainties**

**For CMB lensing, realization-dependent subtraction of Gaussian component minimizes correlation between modes**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# Potential Paths to Make High-Res CMB Lensing Measurement

**The Large Millimeter Telescope - 50 meters (~10 arcsec resolution)**


Location of Large Millimeter Telescope

**The Green Bank Telescope - 60 meters (~10 arcsec resolution)**


Location of Green Bank Telescope

**Need CMB-S4-type camera or better on one of these dishes**

**Traditional CMB science also gains from better camera and higher resolution (e.g. r and $N_{eff}$)**

# Summary

- Key question: what do dark 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 high-resolution CMB lensing to measure the matter power spectrum
- Requires CMB-S4-type telescope on a 50-ish meter dish
- Traditional CMB science would also gain from this (r and $N_{eff}$)
- Potentially good motivation for next stage ground-based CMB experiment