Probing Dark Matter and Galaxy Evolution with Ultra-Deep, High-Resolution CMB Lensing

Neelima Sehgal

BCCP Lensing 2019

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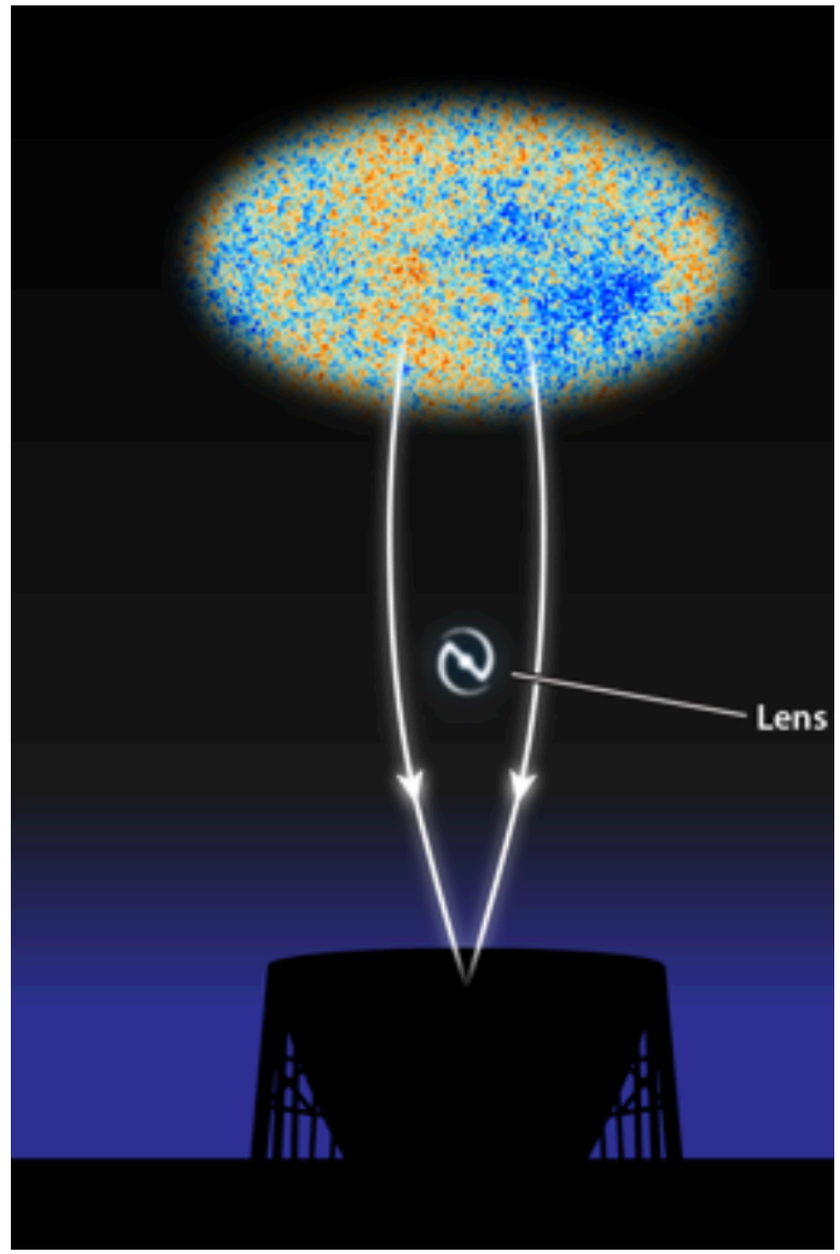


Ho Nam Nguyen, NS, Mathew Madhavacheril,
PRD, 2019, (arXiv:1710.03747)

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 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

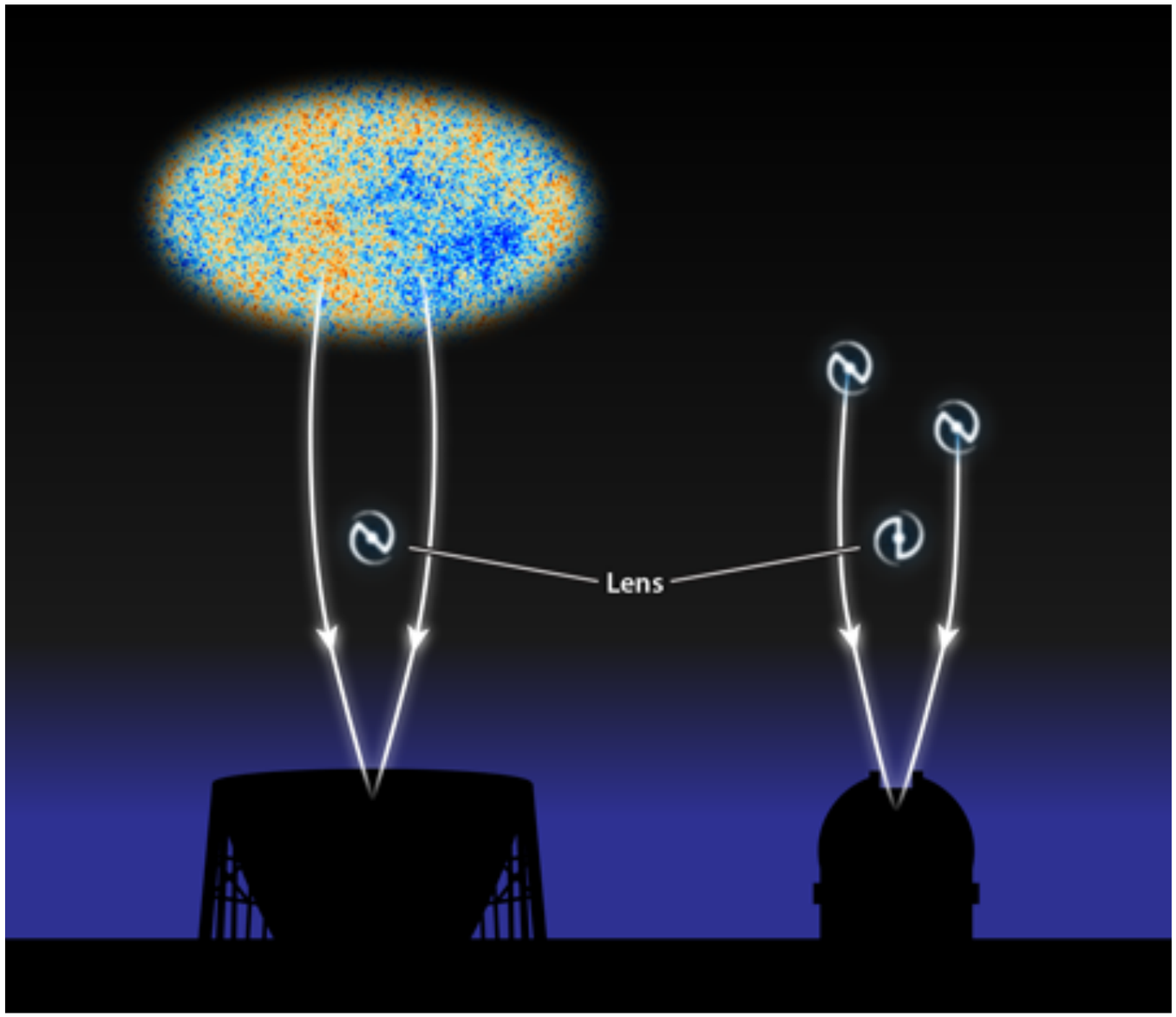
- Galaxy-galaxy strong lensing in optical and mm-wavelegths - need to model lensing halo, need many (~100) expensive strong lensing systems, need to assume sub-halo density profile to obtain sub-halo mass

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

- 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

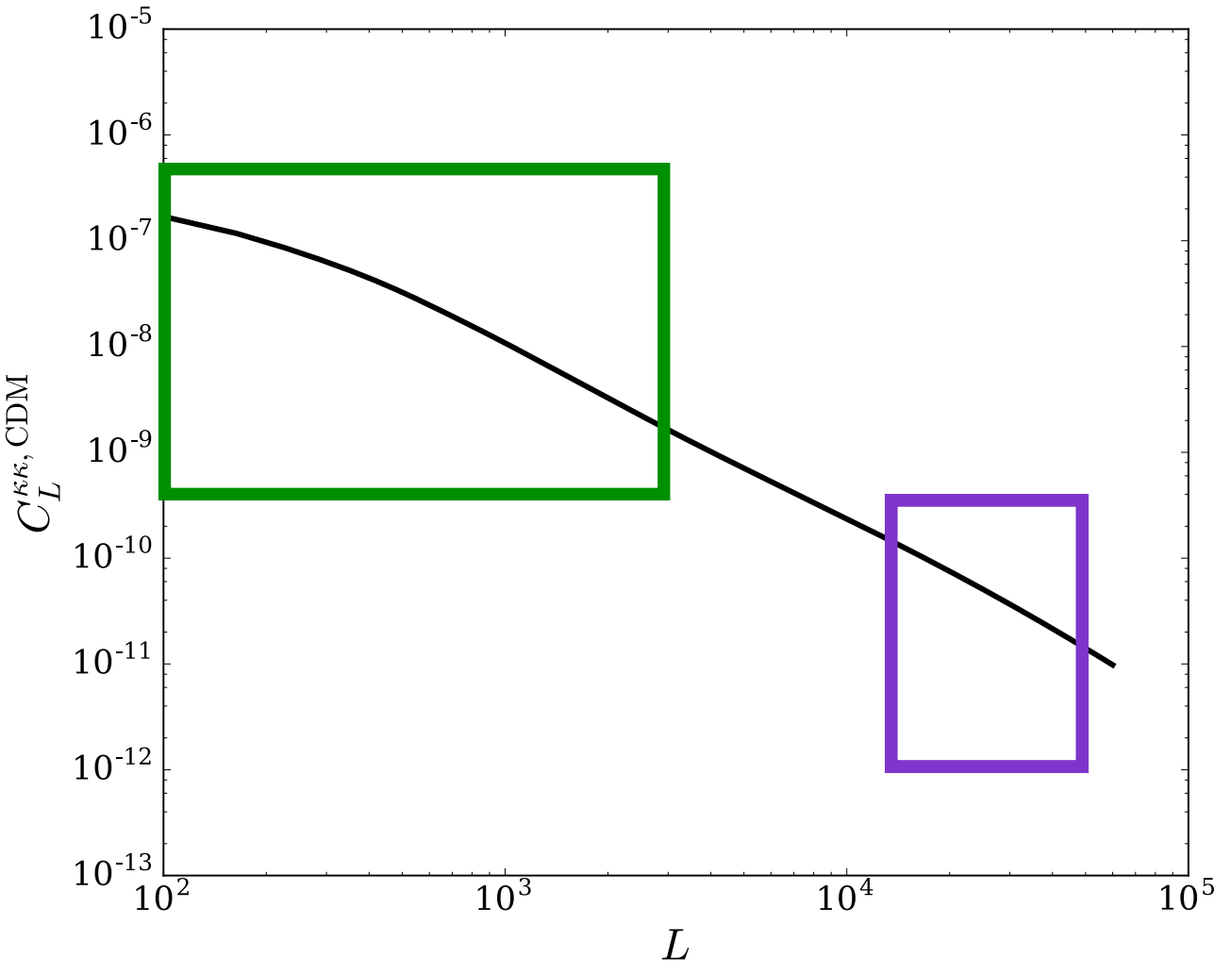
1. Directly sensitive to dark matter via gravitational lensing

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



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

CMB Lensing Power Spectrum is matter power spectrum convolved with window

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

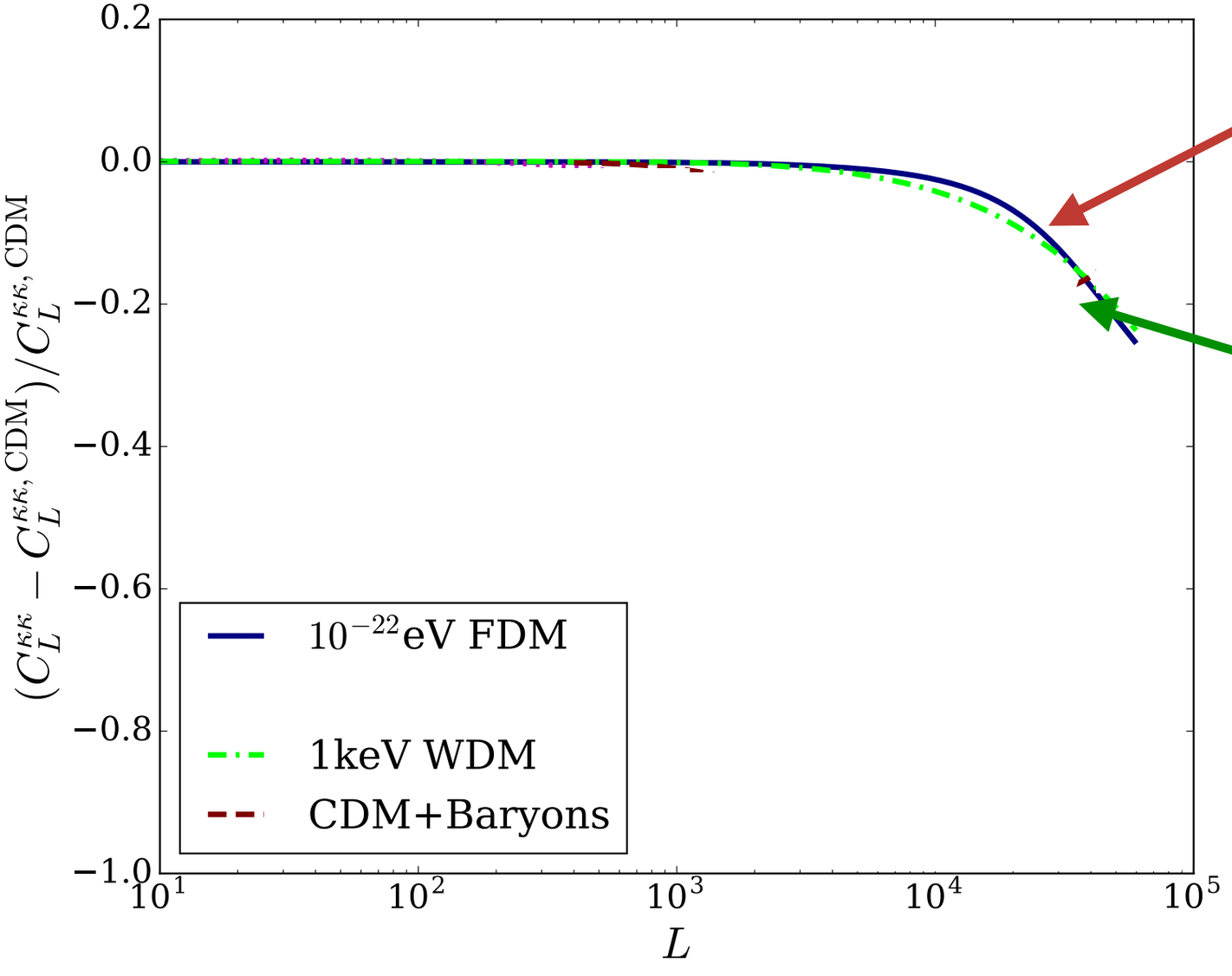
$$C_L^{\kappa\kappa} = \frac{[L(L+1)]^2 C_L^{\phi\phi}}{4}$$

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)

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

CMB Lensing Power Spectrum for CDM Versus FDM/WDM



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

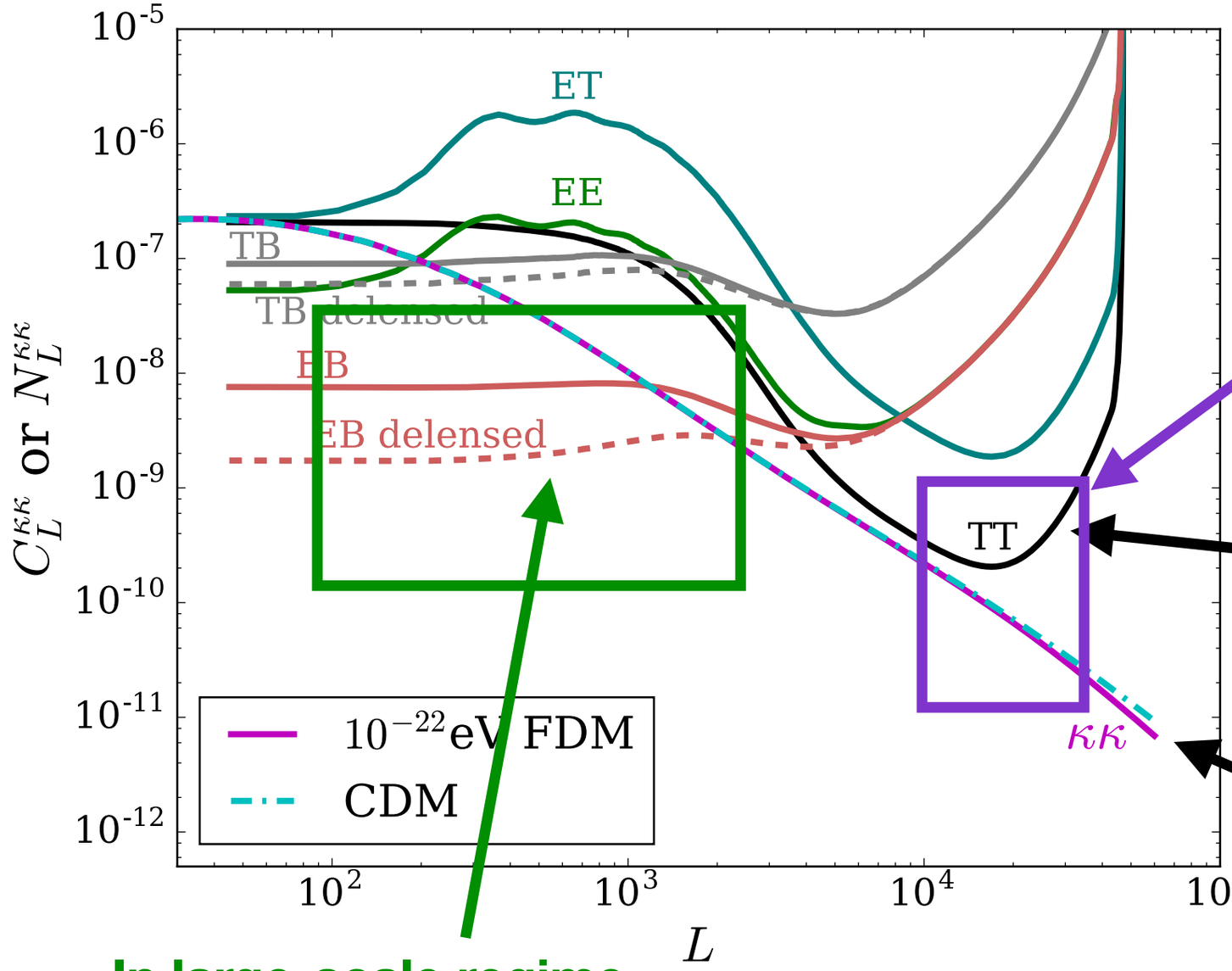
While we directly measure structure with lensing, as opposed to using a baryonic tracer, baryons may still suppress matter power

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

CMB Lensing Noise Curves to Estimate Sensitivity



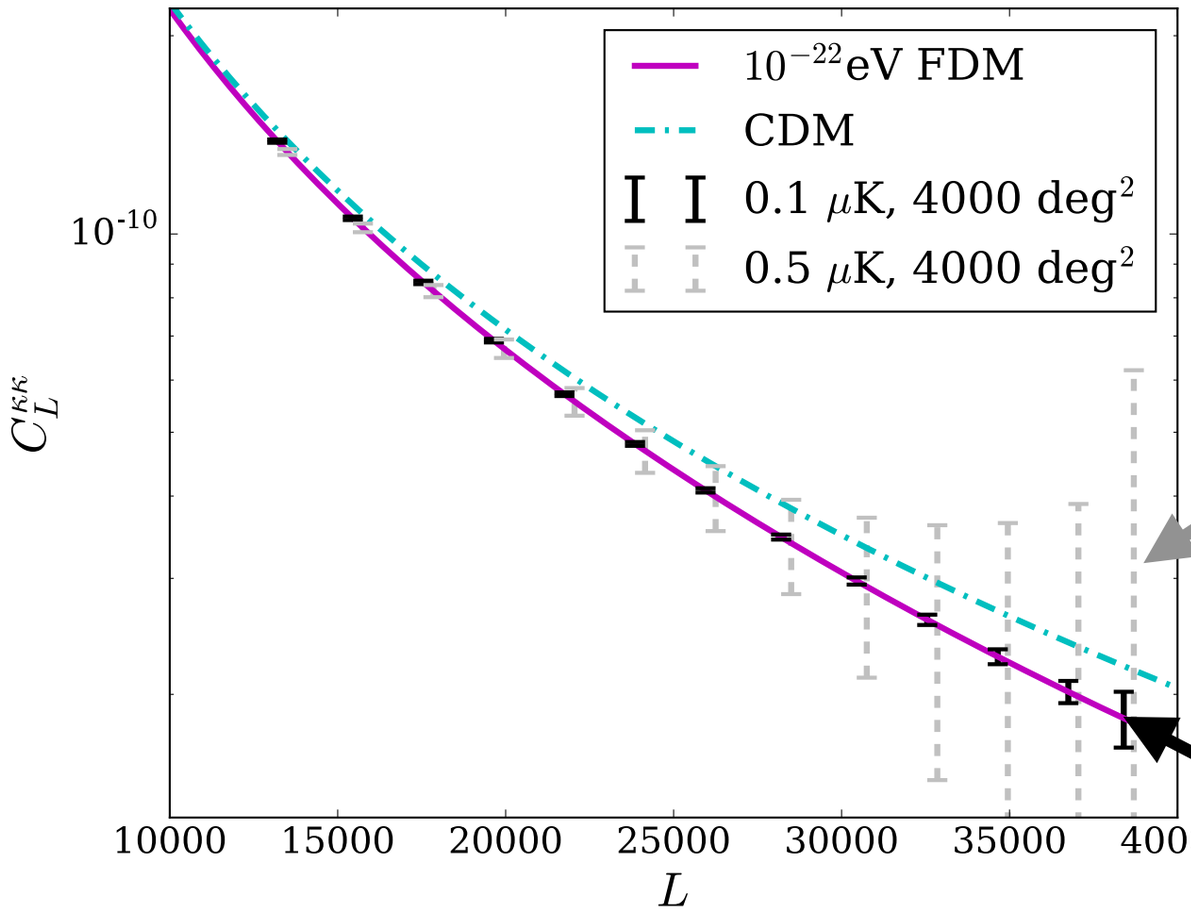
Lensing from CMB temperature maps yield lower noise than from polarization maps in this small-scale regime

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

Signal Curves

In large-scale regime, polarization yields lowest noise

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 (μK-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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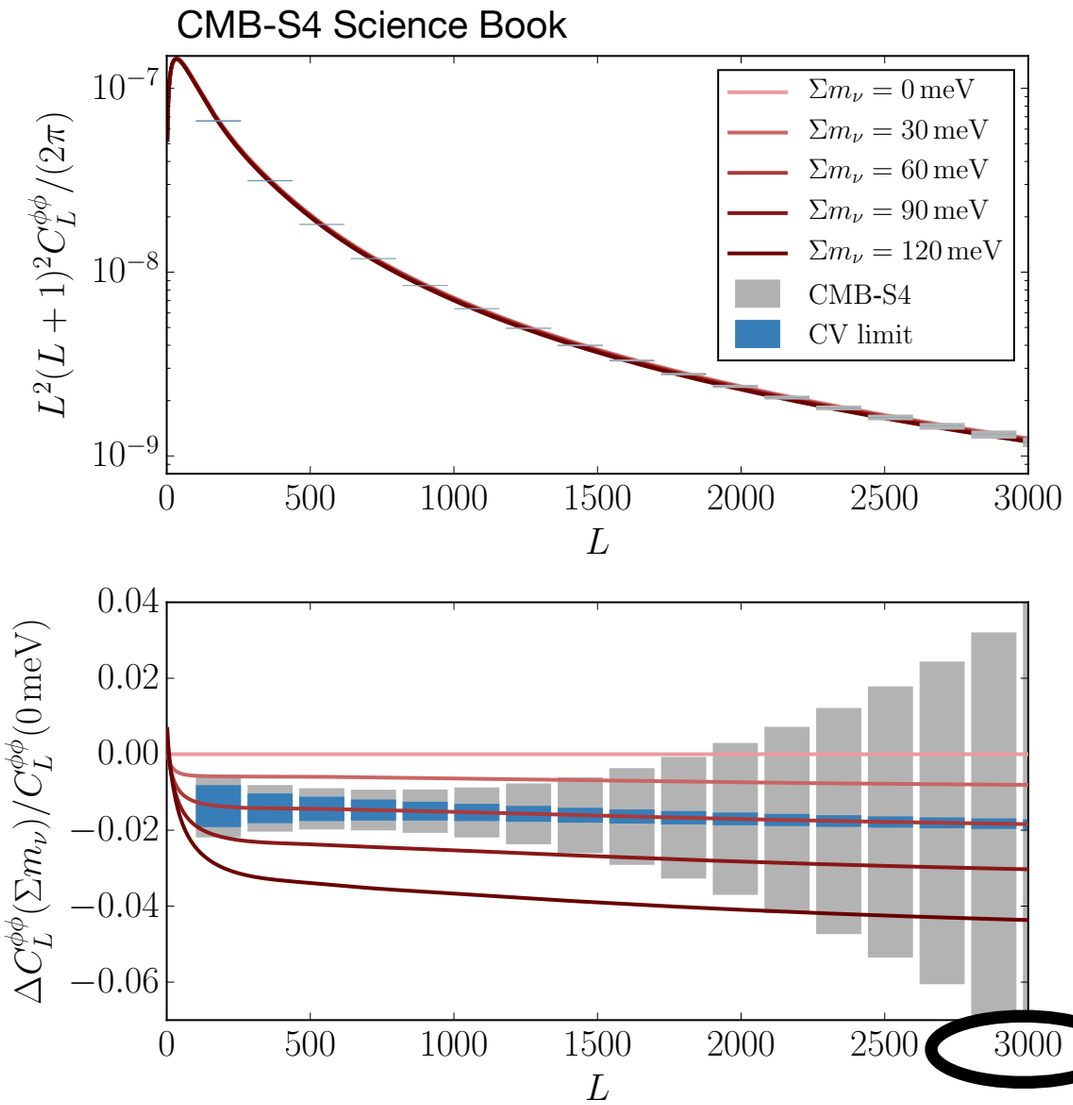
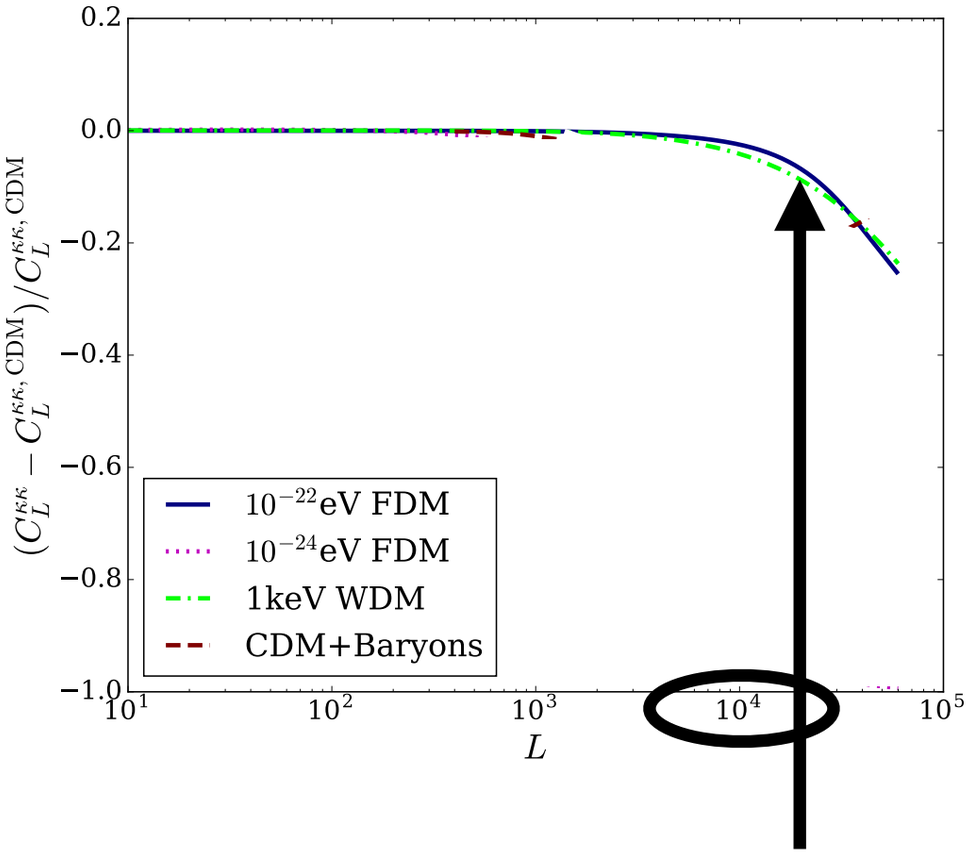
Dark Matter Constraints Not Degenerate with Neutrino Mass

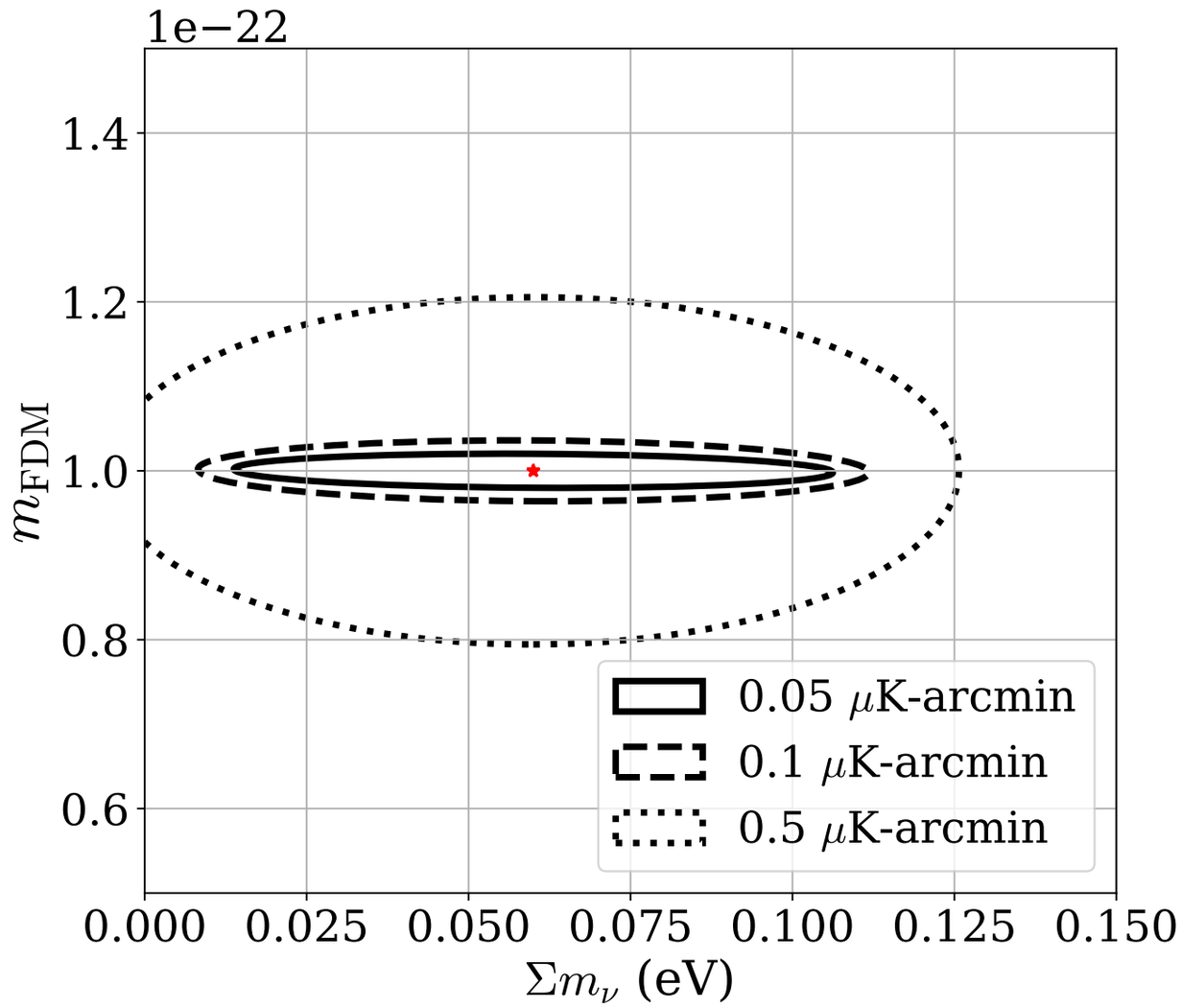


CMB lensing is known for its potential to constrain the sum of the neutrino masses



Alternative DM models of interest suppress power on much smaller scales

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

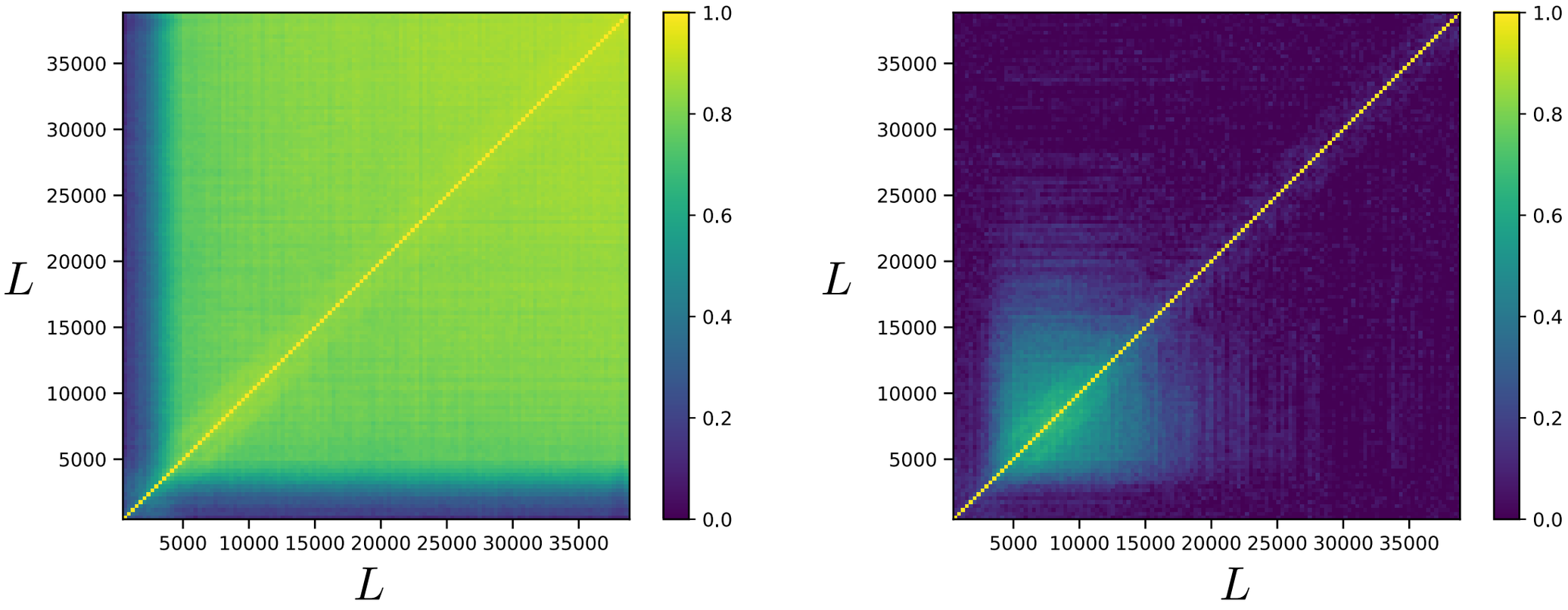
Some advantages of CMB:

- **Well defined redshift of background light source**
- **Properties of background light source well understood**

(Cyr-Racine, Keeton, Moustakas, 2018 -1806.07897)

- **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

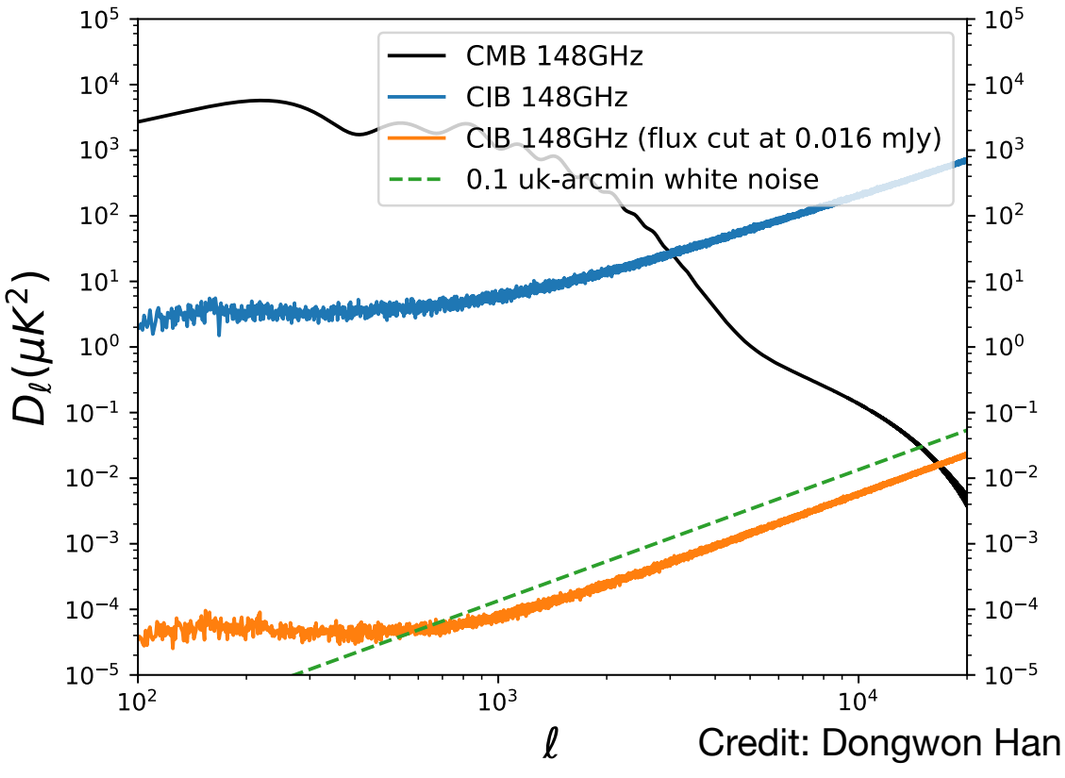
Theory Questions

Remove frequency-dependent astrophysical foregrounds
(extragalactic radio and infrared galaxies, thermal SZ from galaxy clusters, Galactic dust and synchrotron)

- Deproject foreground in the large-scale map (l < 2000)
- Filter out scales with l<5000 in the small-scale map
- Remove Poisson sources by template subtraction in small-scale map

Slide from Guilaine Lagache AtLAST talk

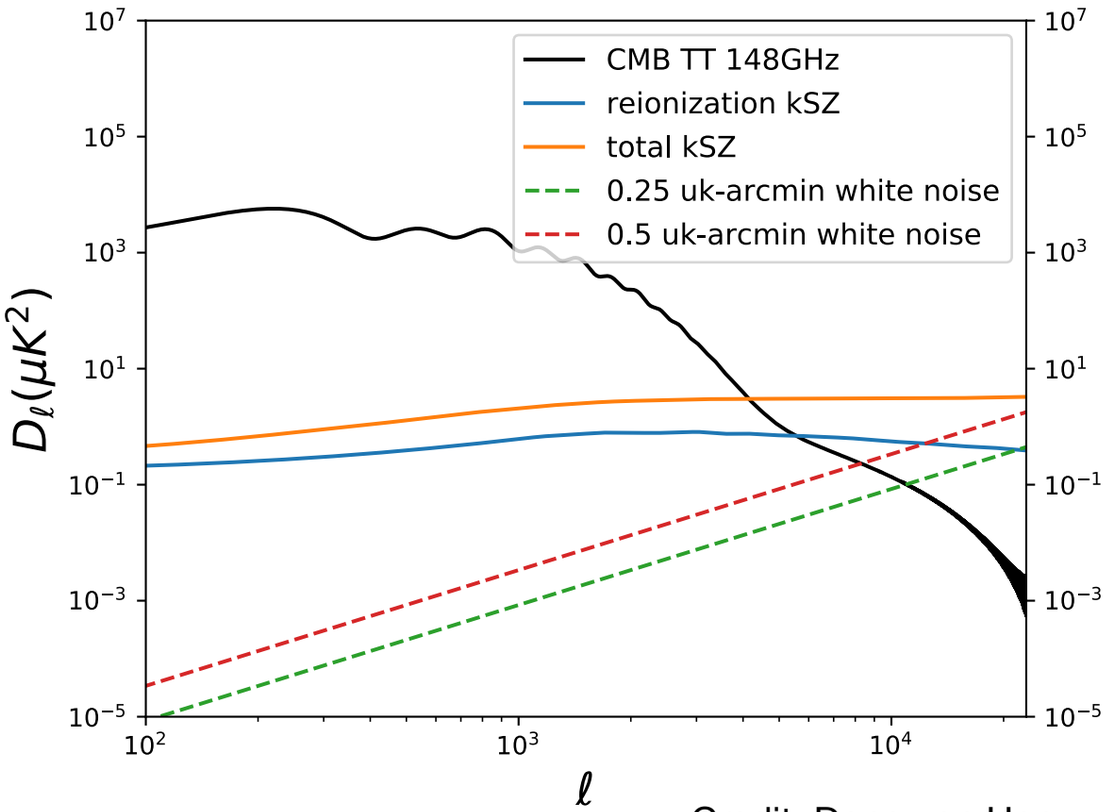
	25 m	30 m	40 m	50m
1σ confusion μJy/beam	152	107	57	32



Theory Questions

Remove frequency-independent astrophysical foregrounds (kinetic SZ)

- Exploit fact that kSZ is not aligned with background CMB gradient, whereas lensing is (removes bias from kSZ)
- De-kSZ late-time kSZ with overlapping galaxy survey
- Reionization kSZ will add noise to small-scale map — exploring gain of going wider with larger noise

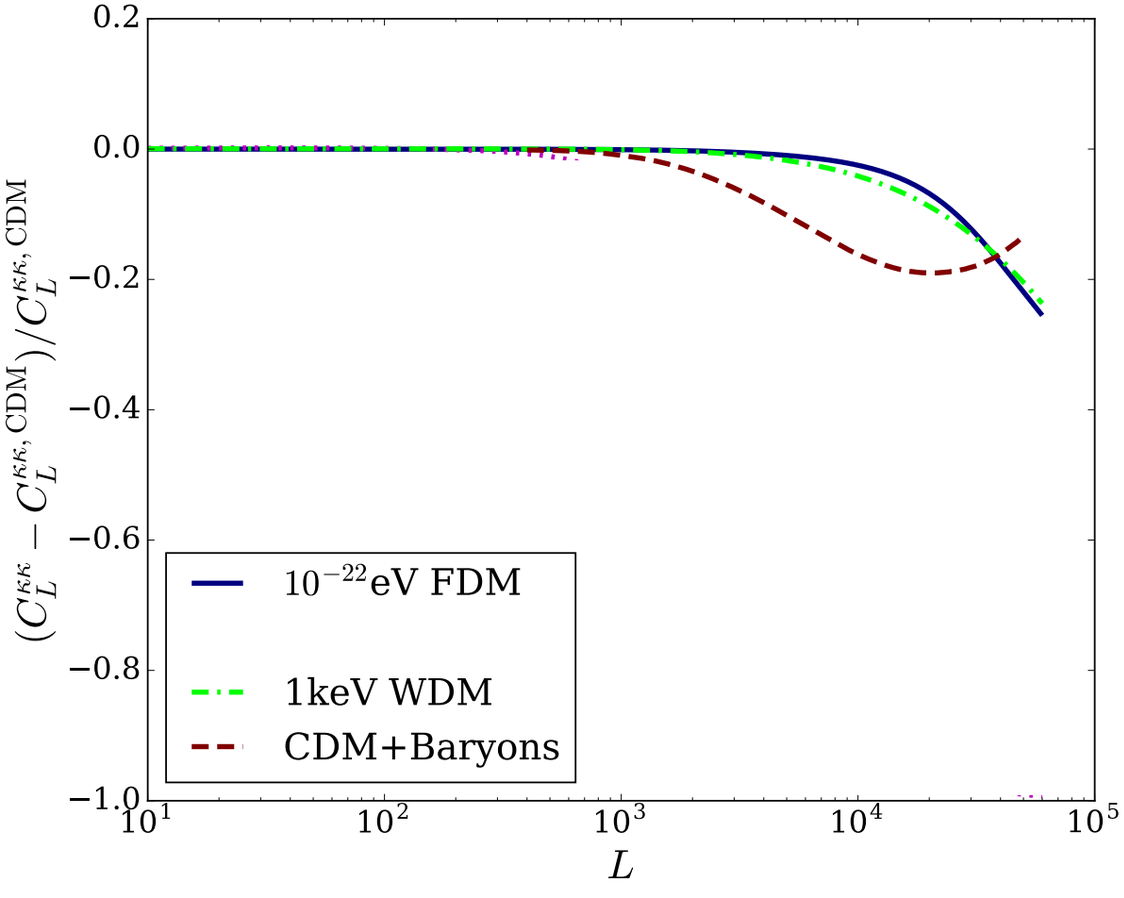


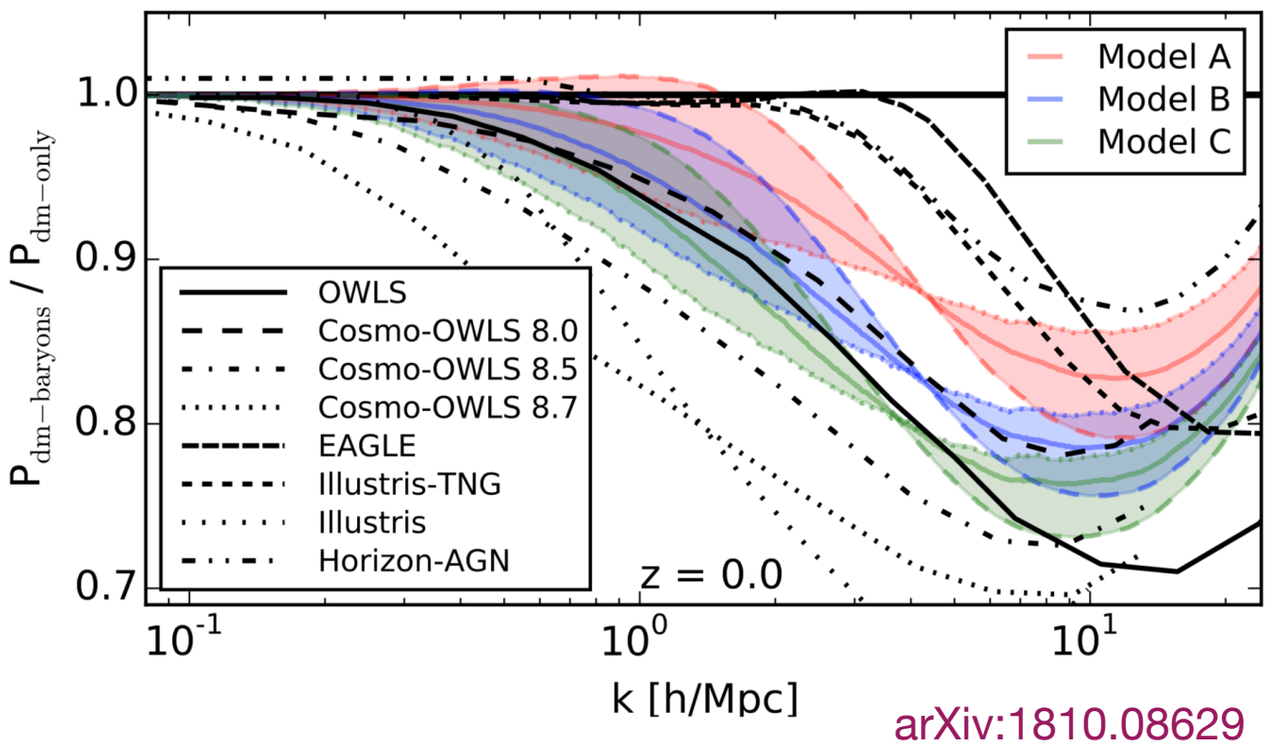
Credit: Dongwon Han

Theory Questions

Degeneracy between baryons impacting matter and alternatives to CDM

Use difference in shape





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 (important for dark matter properties and galaxy evolution)

- 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 enhanced 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, i.e. CMB in HD