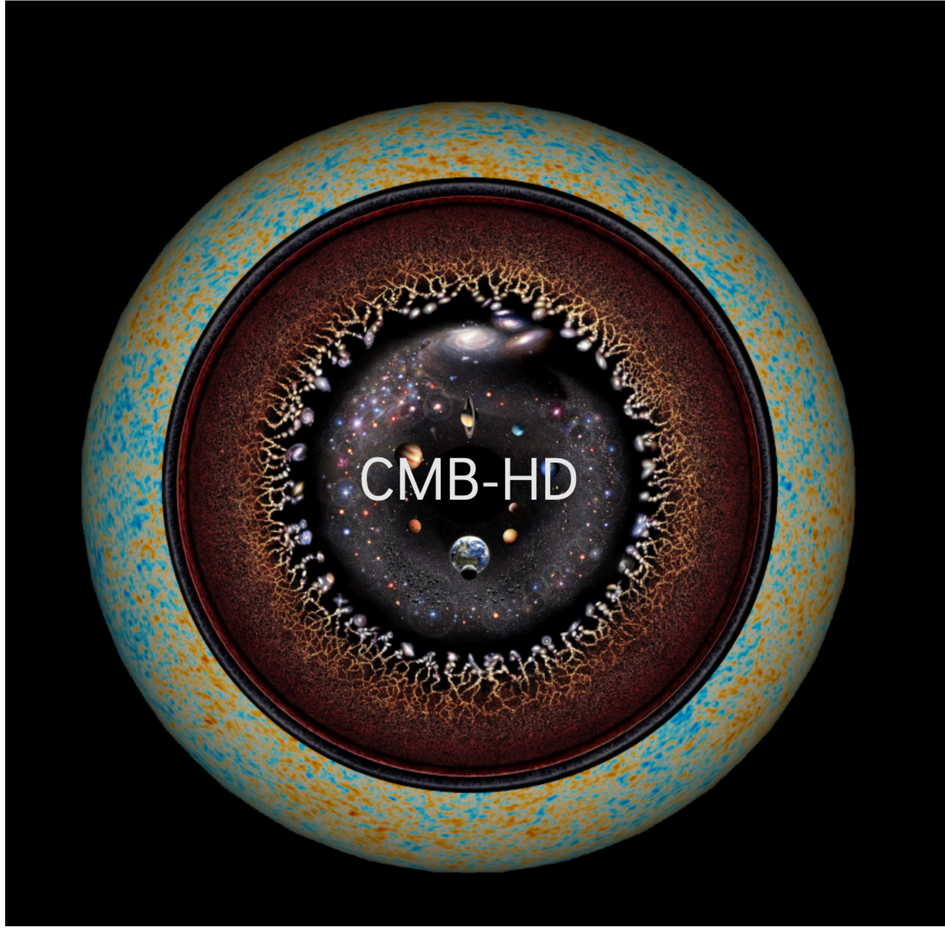
CMB-HD: Constraining Wave-Like Dark Matter

Neelima Sehgal, Oct 20, 2021, CF02 Snowmass2021



CMB-HD: Next-generation, ground-based, CMB experiment

Rich Science from CMB-HD:

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

Inflation
- Primordial Gravitational Waves
- Primordial Non-Gausianity
- Primordial Magnetic Fields

- Neutrino Mass
- Dark Energy

Galaxy Evolution
- Galaxy Cluster Astrophysics
- Galaxy Formation

- Reionization

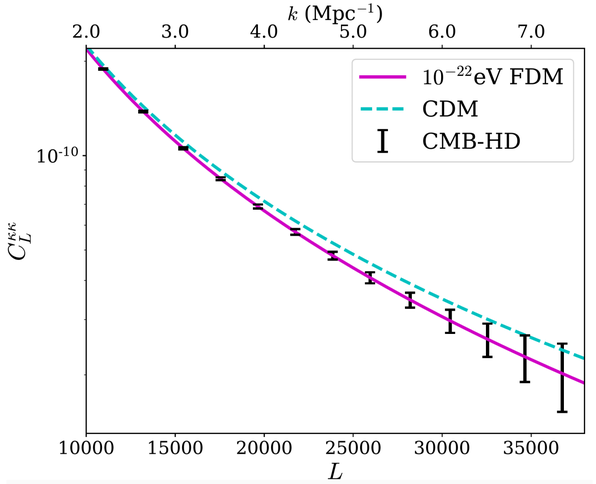
Planets
- Solar and Extrasolar Planetary Studies

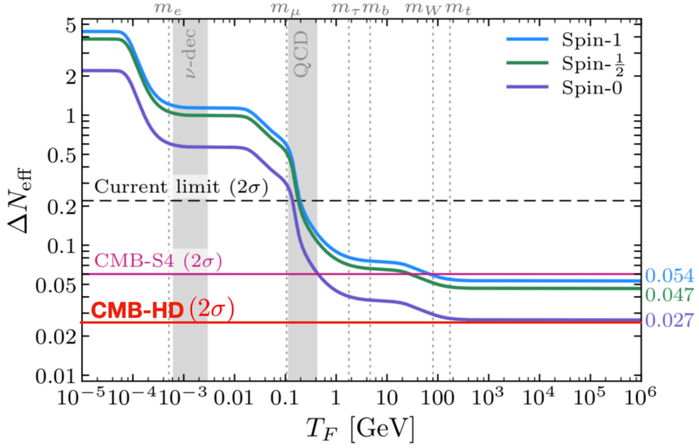
- Synergy with Optical Lensing Surveys

Transients
- Mapping the Transient Sky

- Novel Ideas and Searches for New Physics

Three times more sensitive and six times higher resolution than CMB-S4



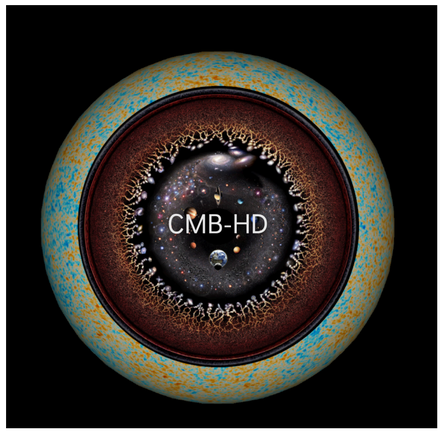


Dark Matter Properties (not accessible to any other CMB experiment)

New Particles in the Early Universe (no other CMB experiment hits the critical target)

Collaboration has 57 members

See also: https://cmb-hd.org



Astro2020 Decadal white papers: 1903.03263, 1906.10134, 2002.12714

(also being submitted to Snowmass2021)

Neelima Sehgal

Snowmass LOI: SNOWMASS21-CF5_CF3-NF2_NF0-TF9_TF11_Neelima_Sehgal-016.pdf

CMB-HD

Instrument and Survey

- Two 30-meter off-axis crossed Dragone telescopes
- Each with 800,000 detectors (200,000 pixels)
- Location: Cerro Toco in the Atacama Desert
- Survey: 50% of sky, 7.5 years, 0.5 uK-arcmin noise in temp, 15 arcsecond resolution (5 times better resolution and 3 times deeper than the CMB-S4 wide survey)

CMB-HD Collaboration

- 55 people currently; open collaboration roughly following model of Rubin Observatory

Scale of Investment

- 1 billion dollar project; joint NSF and DOE investment needed

DOE laboratory system instrumental for detector and instrumentation delivery

Timescale

- 2 years design + 2 years construction; 7.5 years of survey operations

R+D Plan

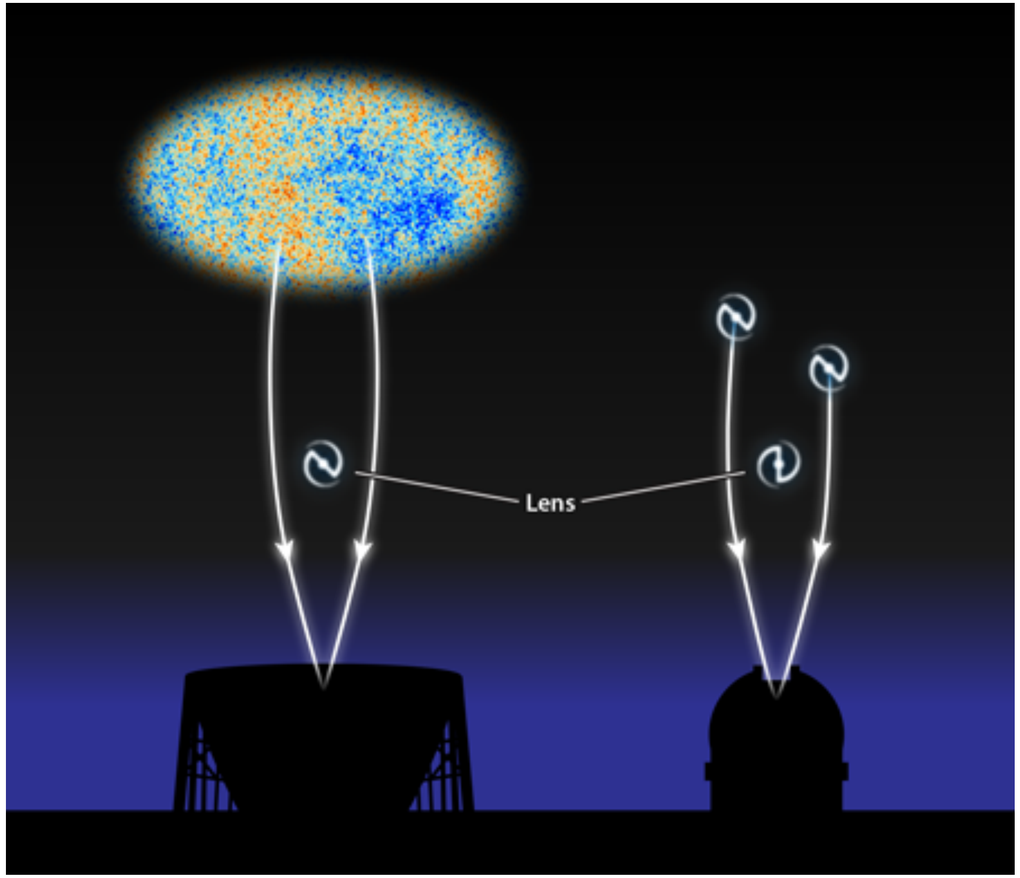
- Several enabling technologies being developed and advanced by current experiments (e.g. GBT, SO, CCAT-prime, BLAST-TNG, TolTEC -- see 2002.12714 for details)

Neelima Sehgal, Stony Brook University

Techniques to Probe Axion-like Dark Matter

- Ultra-high Resolution CMB Lensing to Probe Small-scale Structure
- A Time-Varying Axion Dark Matter Signal in the Polarized CMB
- Measuring Photon-ALPs Conversion using CMB as a Backlight

Ultra-High Resolution CMB Lensing to Probe Small-Scale Structure



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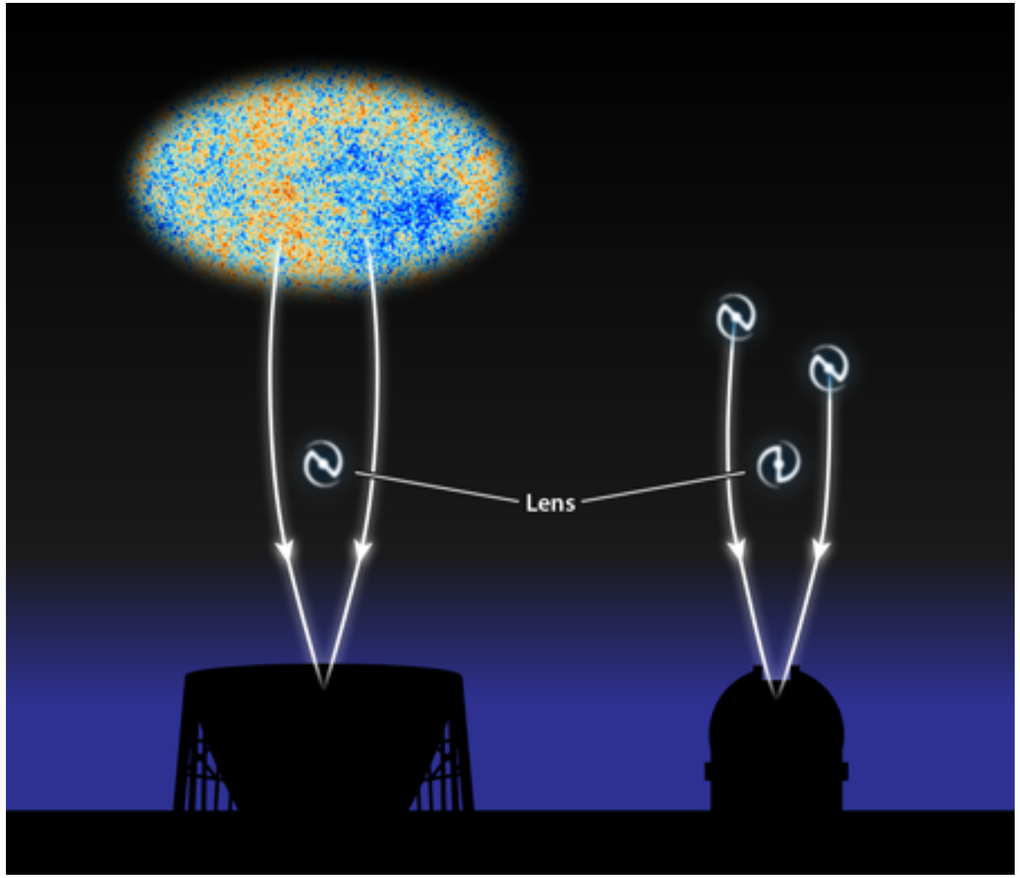
- CMB Lensing is when light from the primordial CMB is bent by intervening matter



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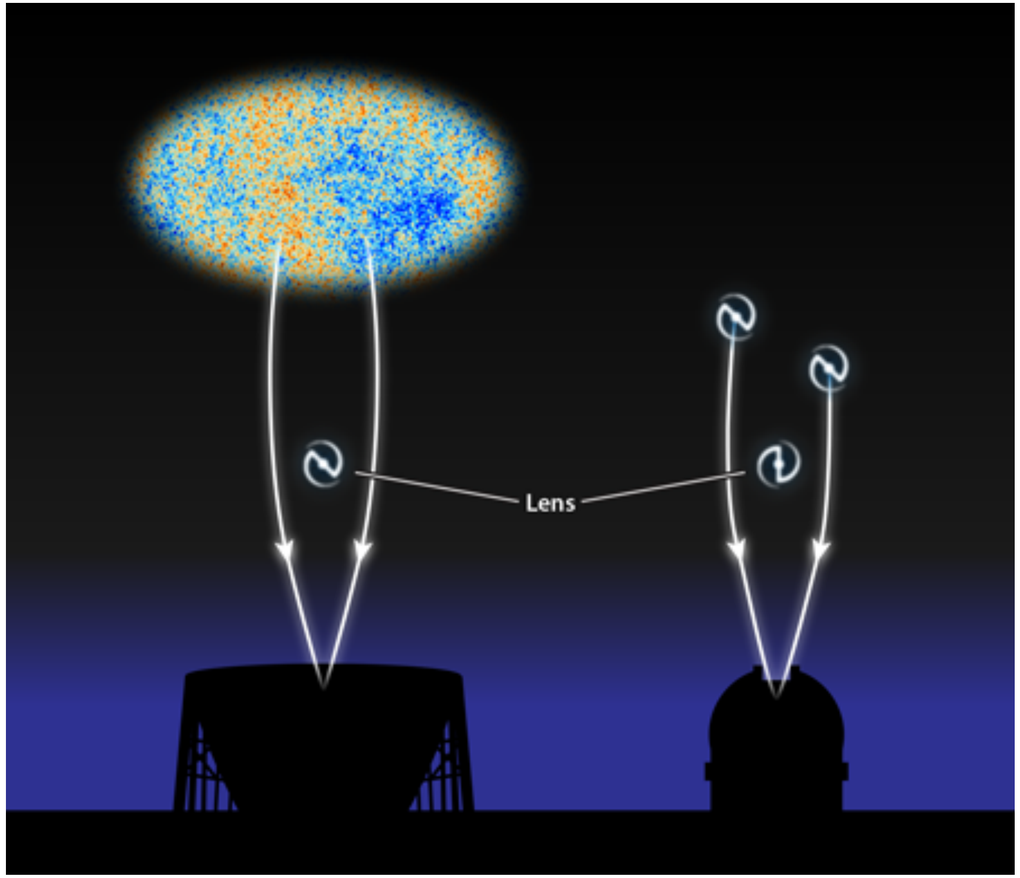

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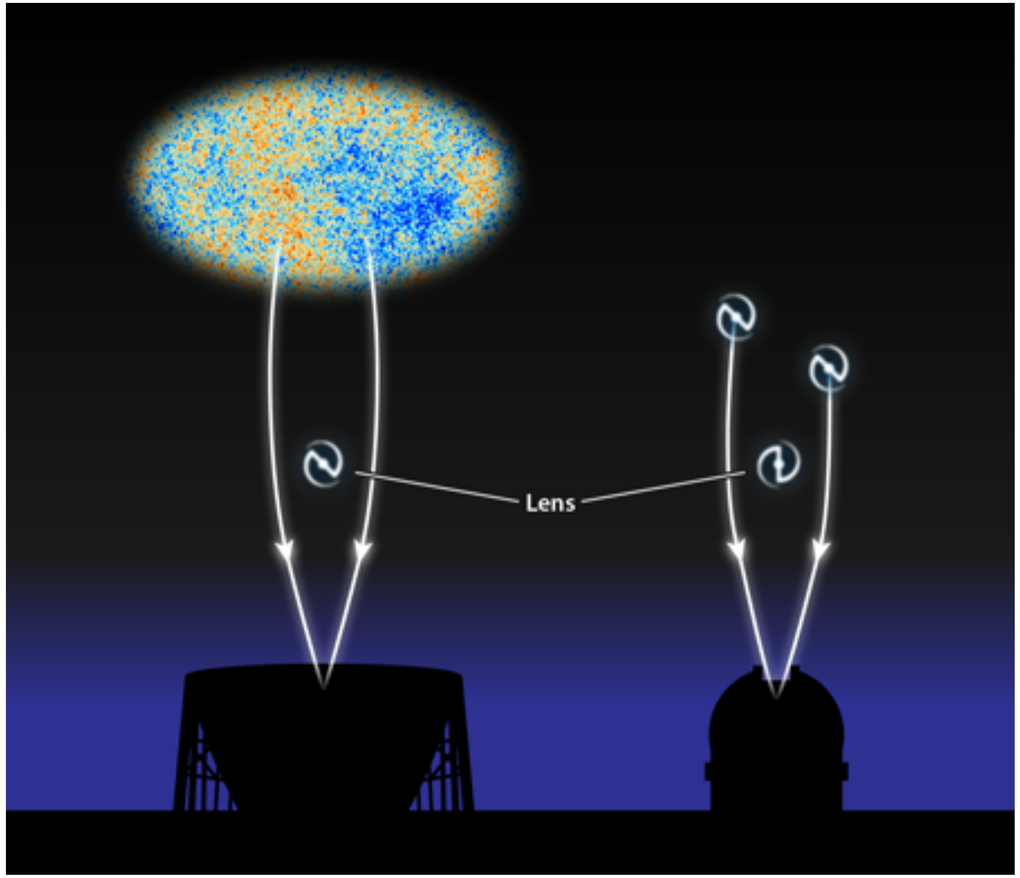

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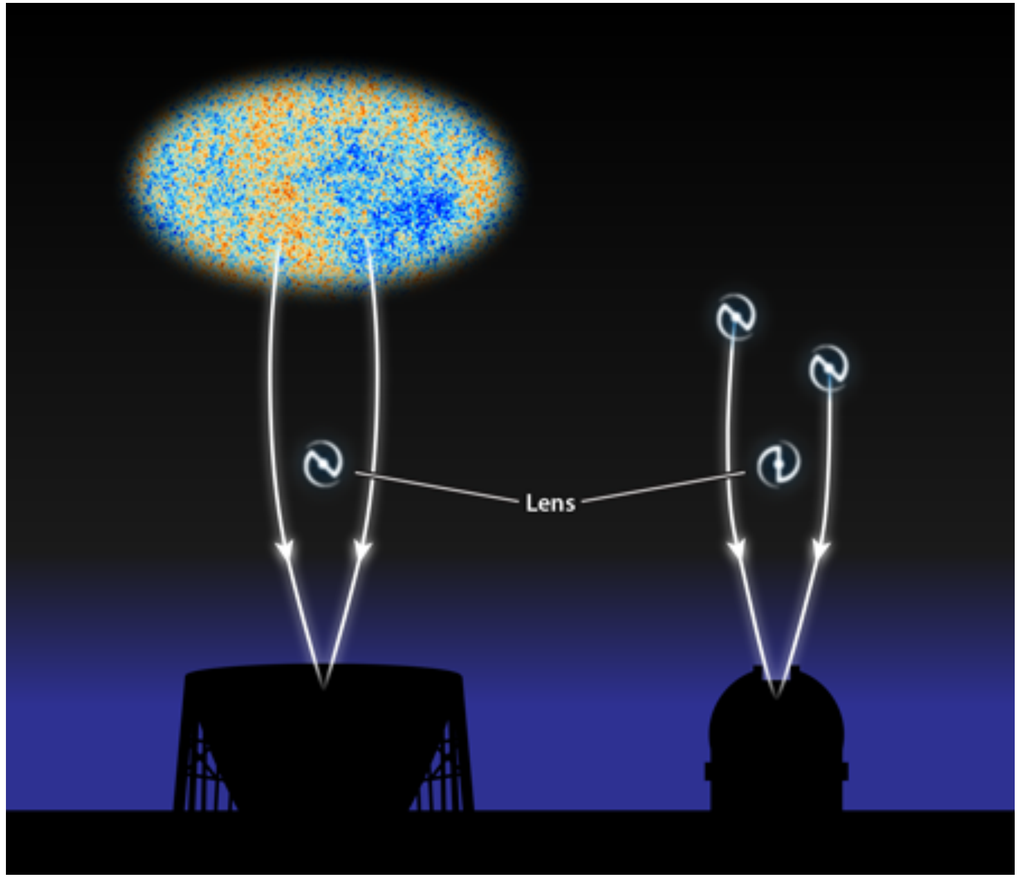

First Measurement of CMB Lensing on Halo Scales
Madhavacheril, NS, for the ACT Collaboration
PRL, 114, 2015

Advantages of CMB Lensing to Probe Small-Scale Structure

Neelima Sehgal, Stony Brook

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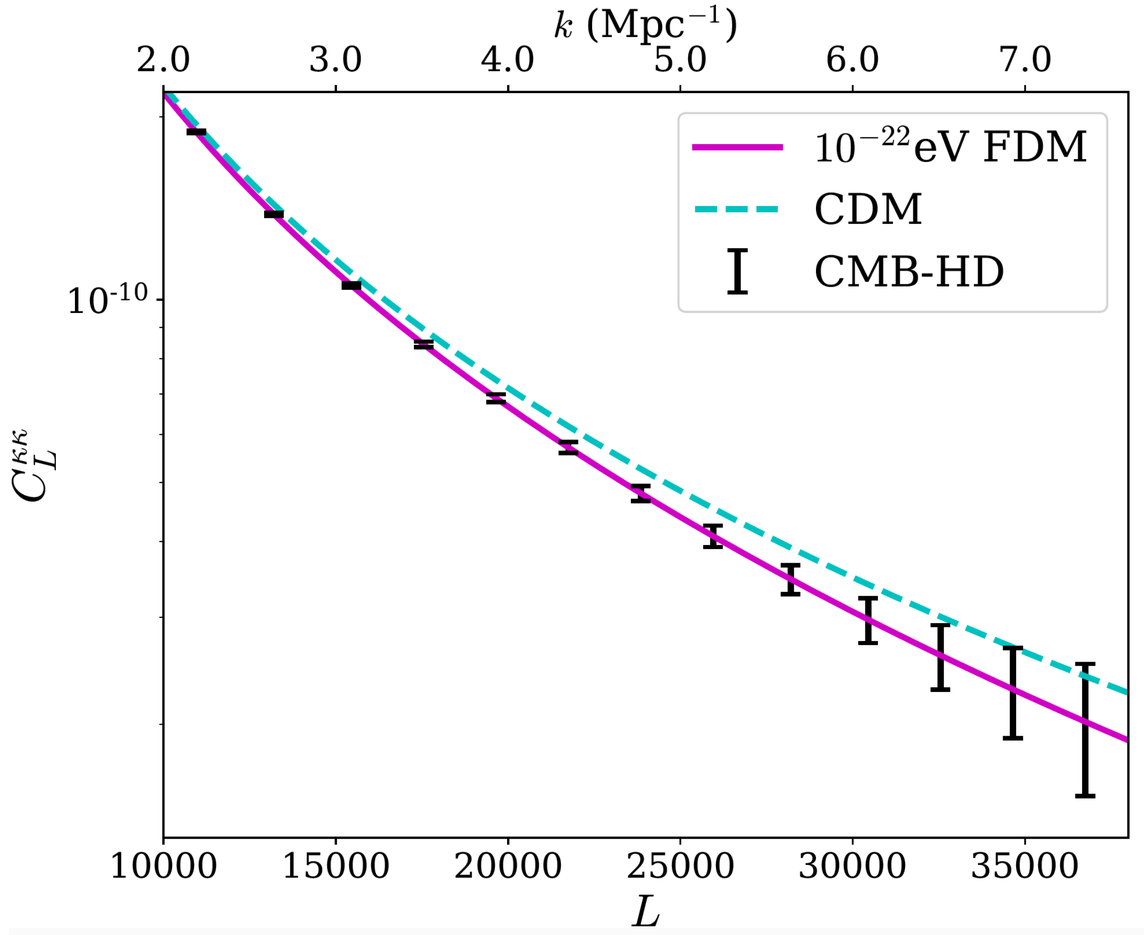
2. Source light is at well-defined redshift

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-HD Dark Matter Forecasts Using Small-Scale CMB Lensing



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

NS et al., 2019, arXiv:1903.03263

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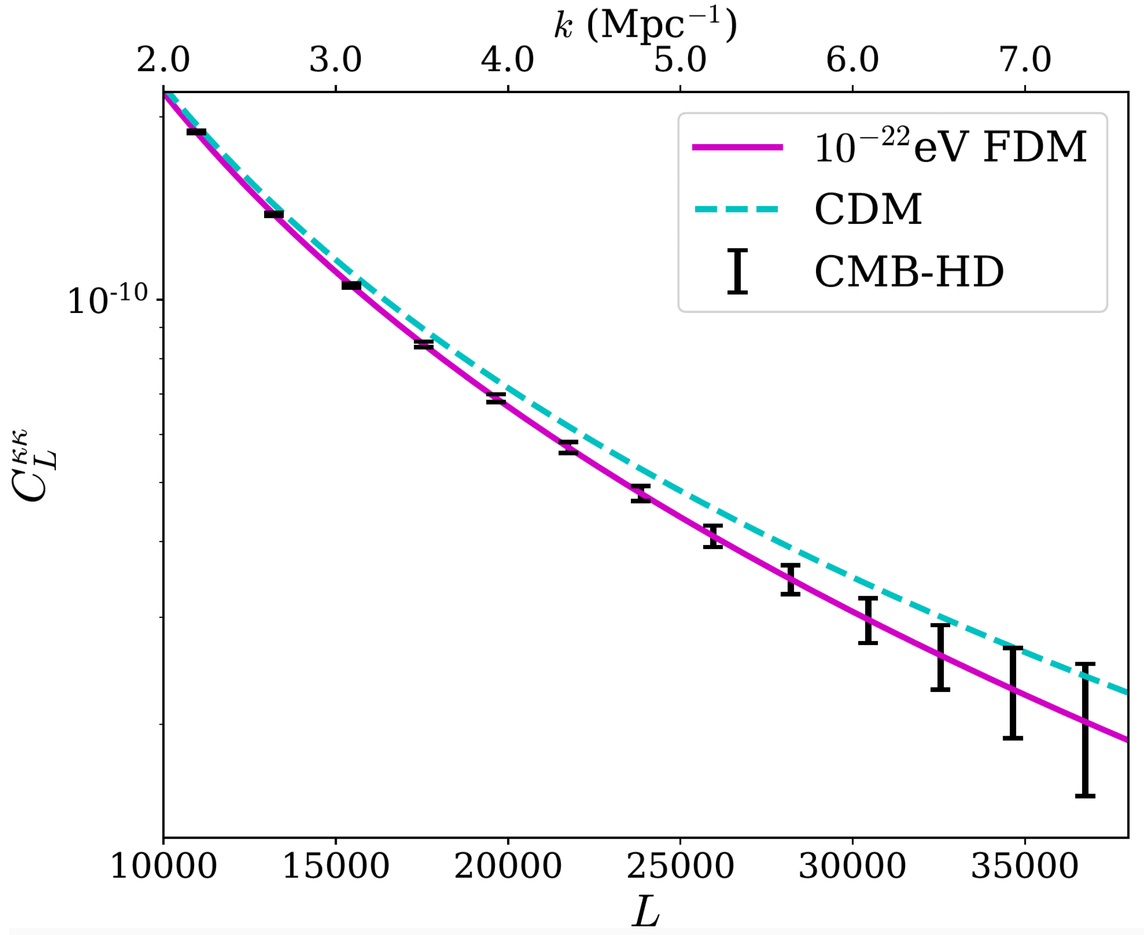

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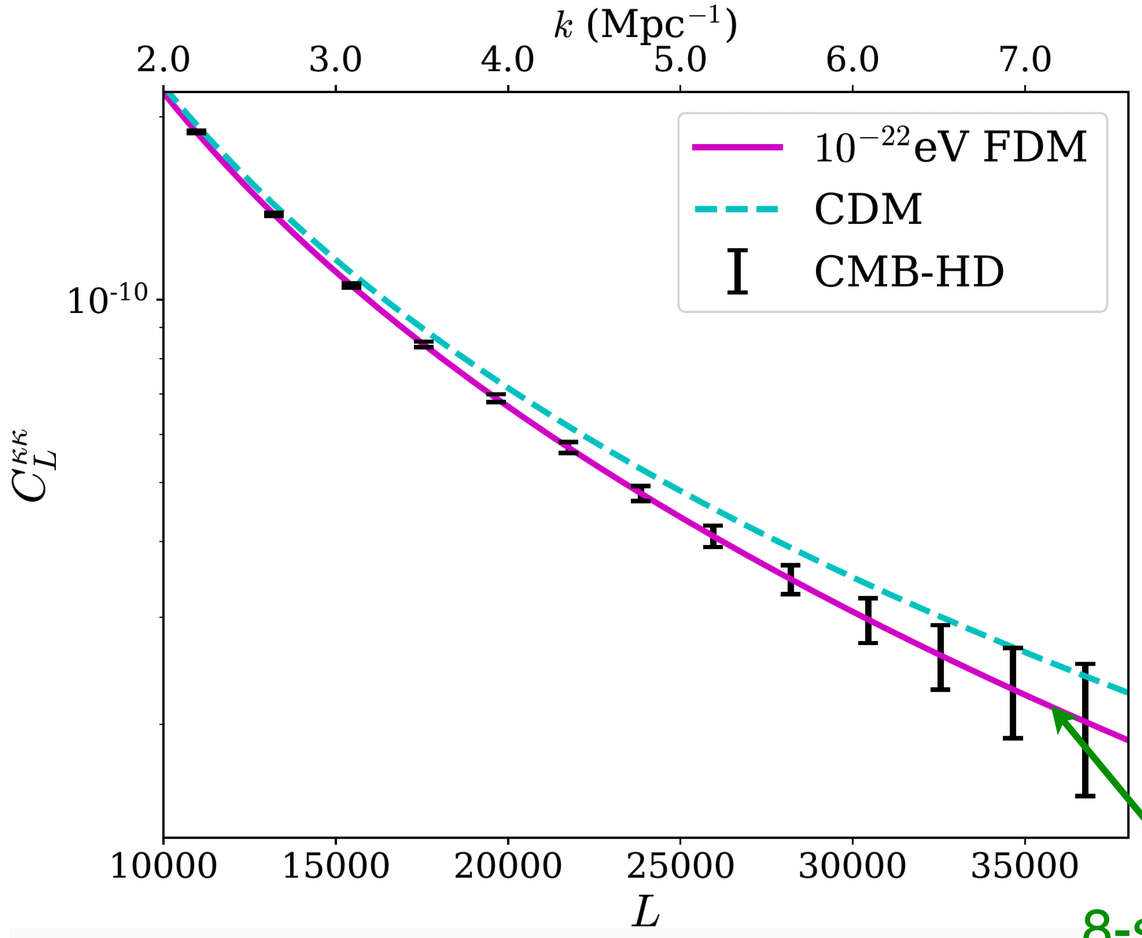

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CMB-HD is new proposed experiment

8-sigma preference for FDM over CDM

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

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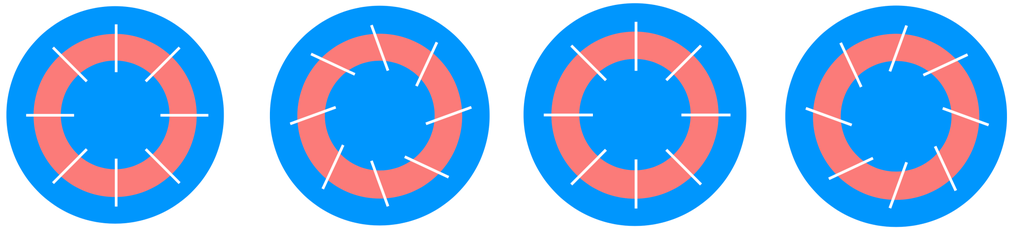
A Time-Varying Axion Dark Matter Signal in the Polarized CMB

A varying axion background field causes cosmic birefringence.
CMB polarization rotates:

$$\Delta\theta = (g_{\phi\gamma}/2)\,\Delta\phi(t_0, t_*) = (g_{\phi\gamma}/2)\left[\phi_0 - \phi_*\right]$$

FDM **axions oscillate "rapidly"** (on cosmological timescales): **distinct CMB phenomenology.**



Text and Figure credit: Michael A. Fedderke

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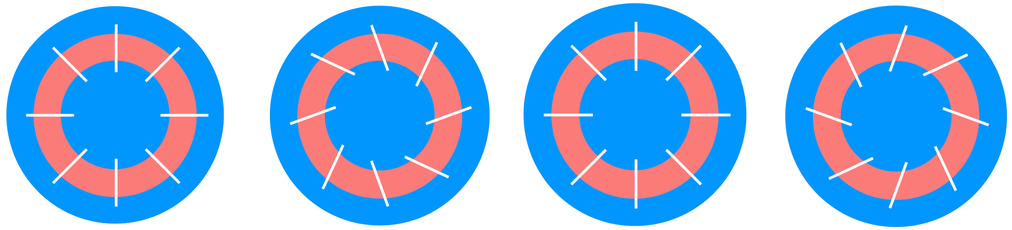


Important Properties of the Signal

On-the-sky oscillation of the CMB polarization angle at every point.

Period of ~ a year to ~ a few hours. *Set by axion mass.*

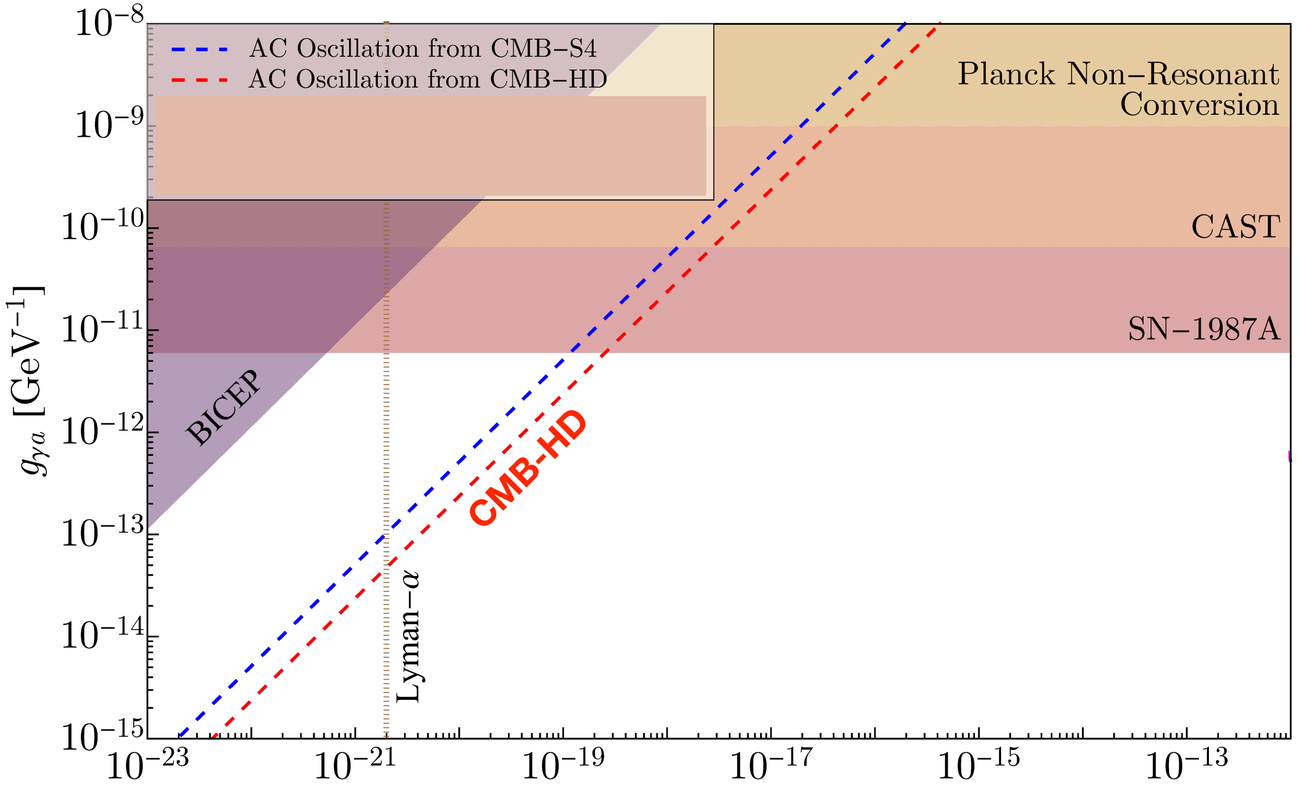
Phase-coherent in time: $T_{\text{coh.}} \sim 10^6 \times T_\phi \gtrsim 10^3\,\text{yrs}$

In-phase across the whole sky. *Depends on local axion field only.*

Not subject to cosmic variance. *Time variation of the realized sky.*

Depends only on polarization, not temperature.

Non-trivial cross-checks on signal; distinct from many non-instrumental backgrounds.



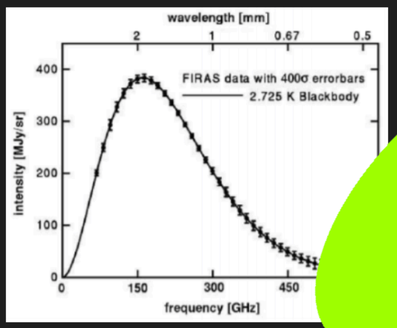
SIGNIFICANT DISCOVERY POTENTIAL!

Text and Figure credit: Michael A. Fedderke

Measuring Photon-ALPs Conversion using CMB as a Backlight

A simplistic description of the phenomenon: photon to ALPs conversion

Signature: Polarized spectral distortions of CMB black body



Mukherjee, Khatri, Wandelt, JCAP 04 (2018) 045

Mukherjee, Spergel, Khatri, Wandelt, JCAP 02 (2020) 032

Magnetic field

and

Unpolarized CMB photons

Loss of CMB photons

ALPs

Text and Figure credit: Suvodip Mukherjee

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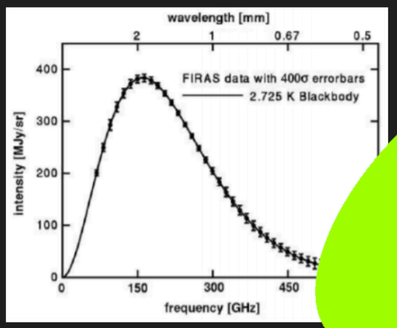

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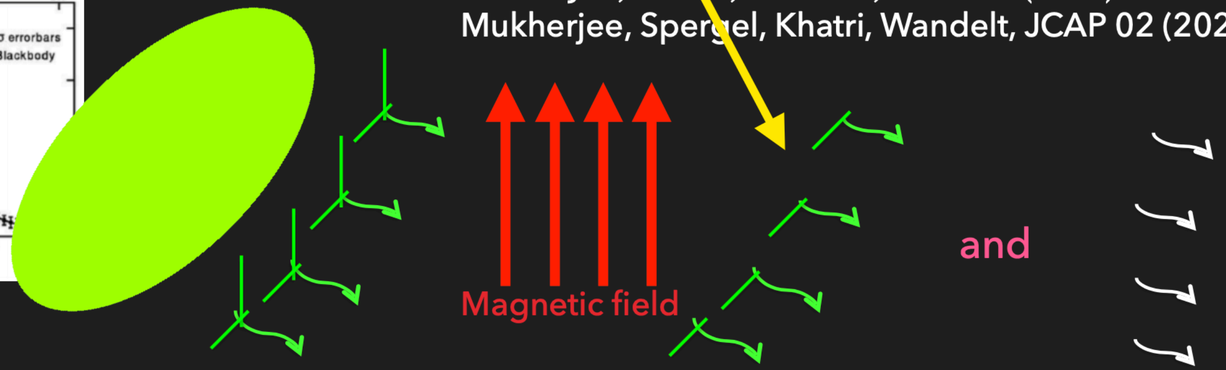

Unpolarized CMB photons

Loss of CMB photons

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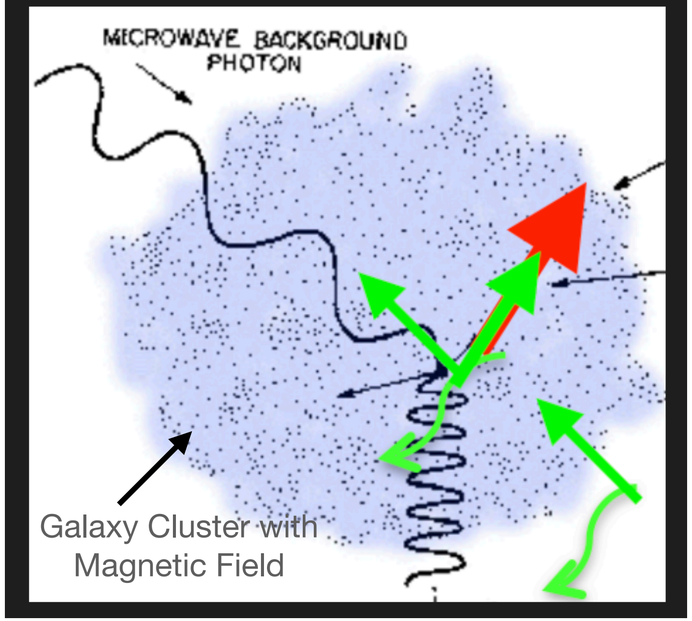
Resonant conversion

Happen at places where ALPs mass equals photon mass in the plasma



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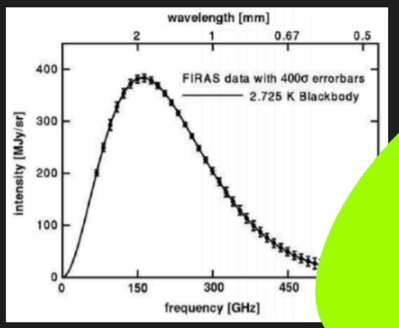

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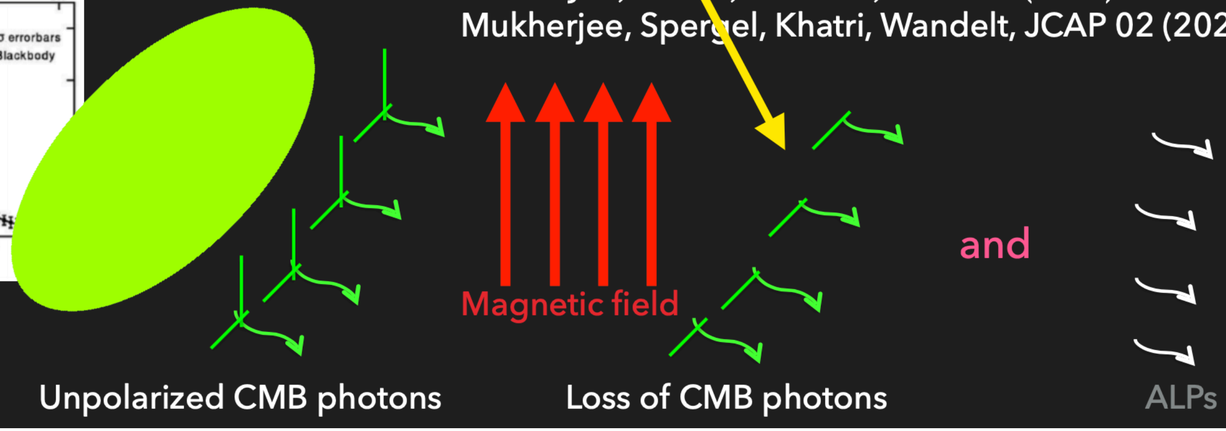

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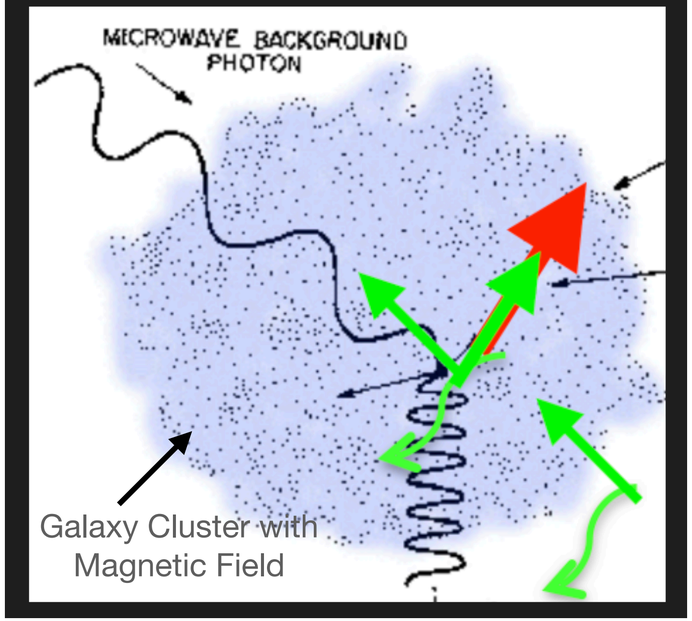
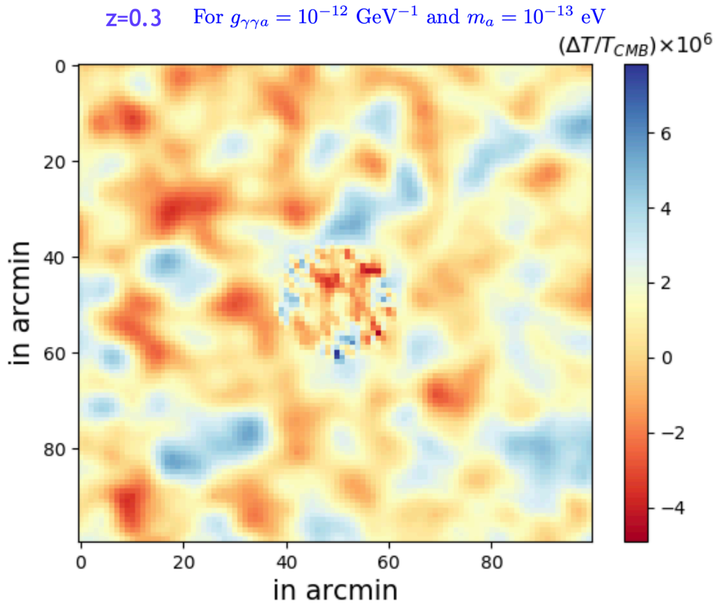


Q- polarization map Mukherjee, Spergel, Khatri, Wandelt (2020



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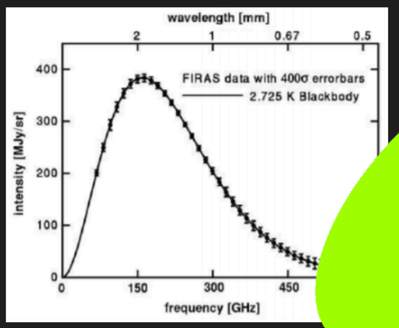

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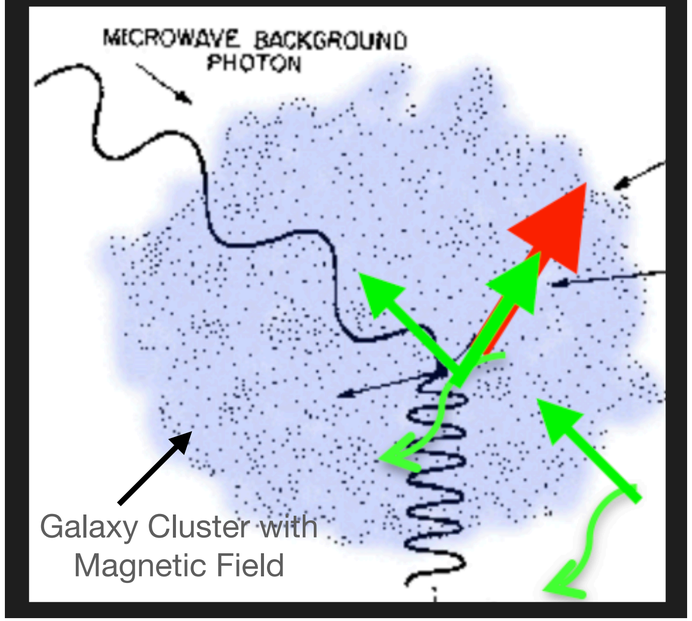

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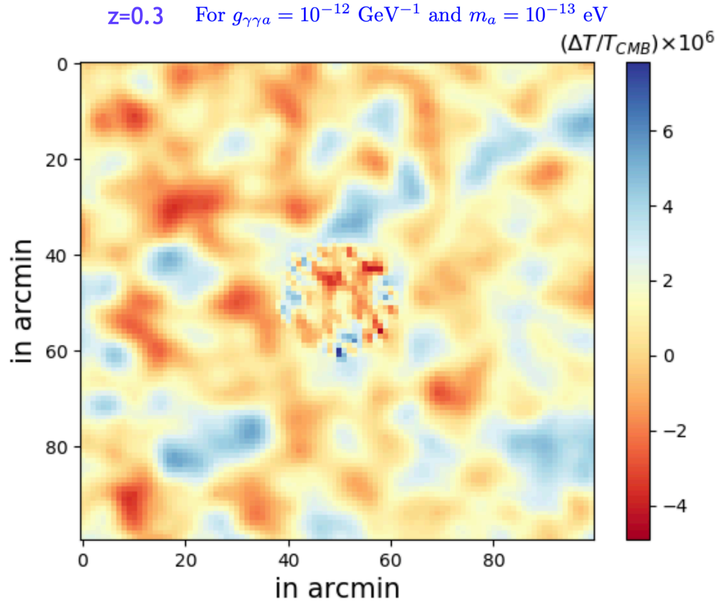

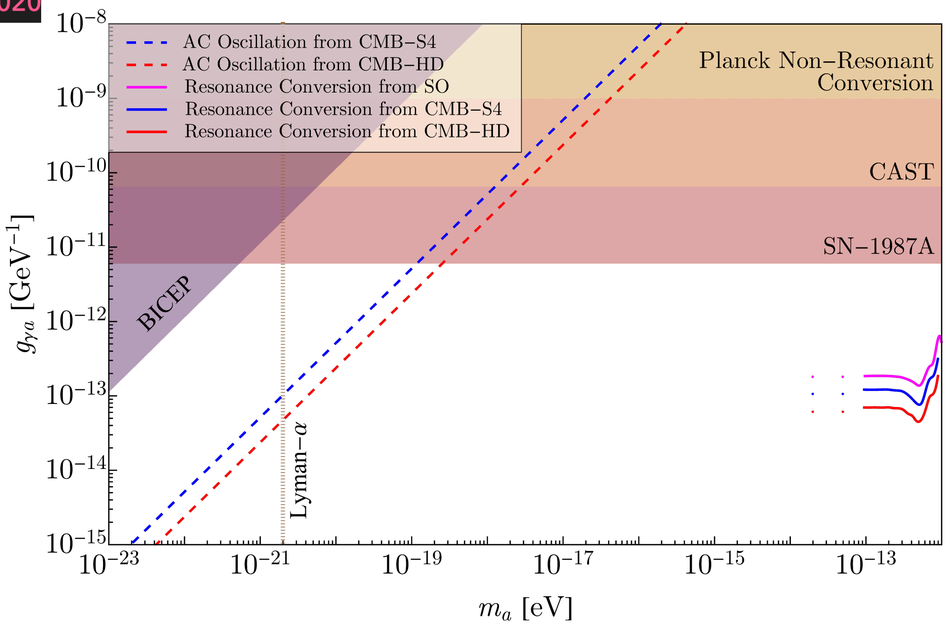

Conversion of CMB photons to ALPs will produce a new CMB polarization distortion at the location of galaxy clusters

Upcoming CMB experiments will probe a new parameter space of photon-axion coupling and axion mass not explored by other probes

Text and Figure credit: Suvodip Mukherjee

Back up slide

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]	$\sigma(f_{\rm NL}) = 0.26$
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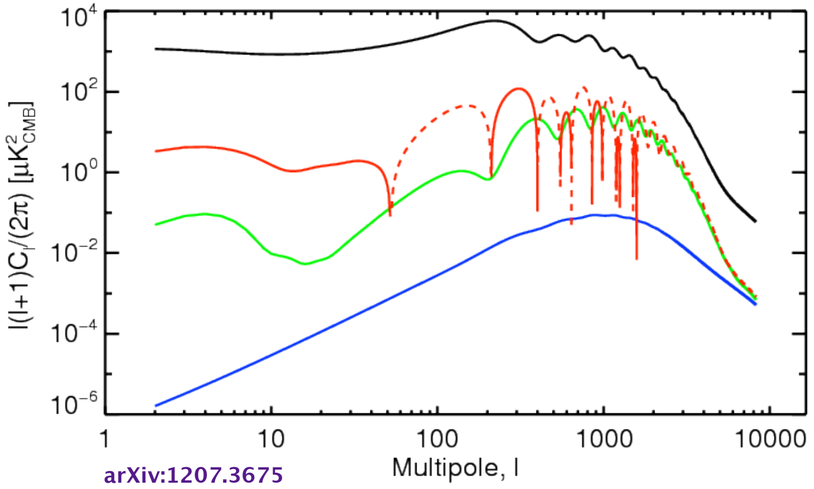

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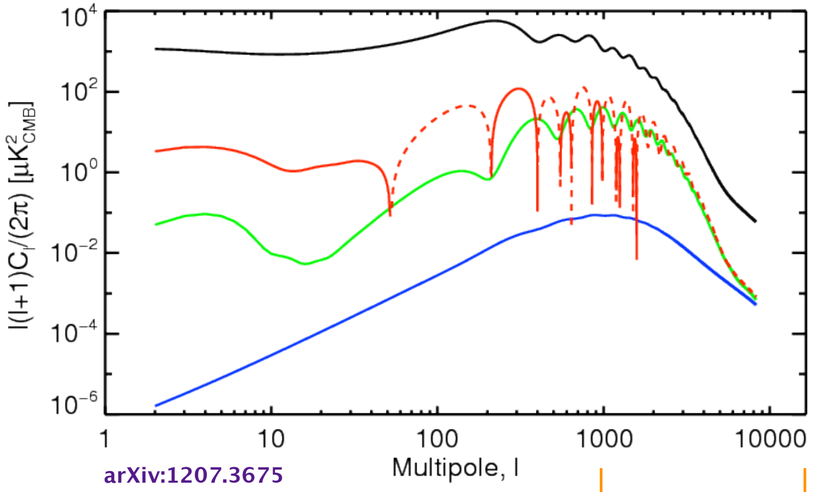

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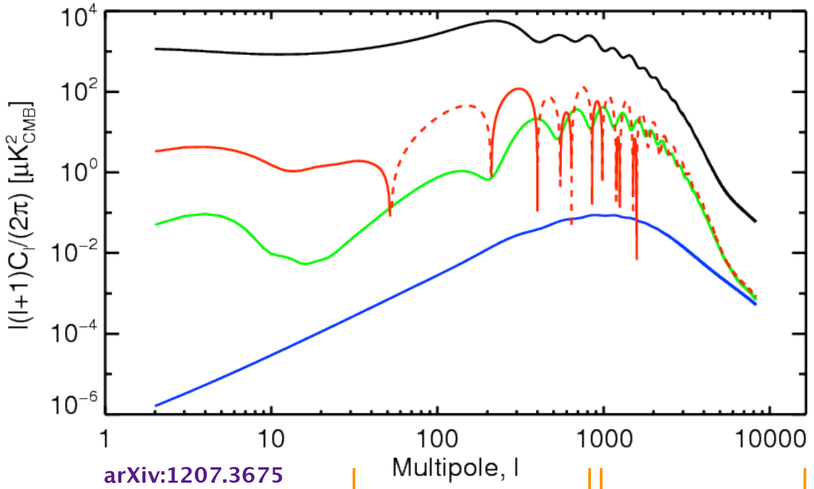

SO measures this; TT, TE, EE to the cosmic variance limit

CMB-HD measures this

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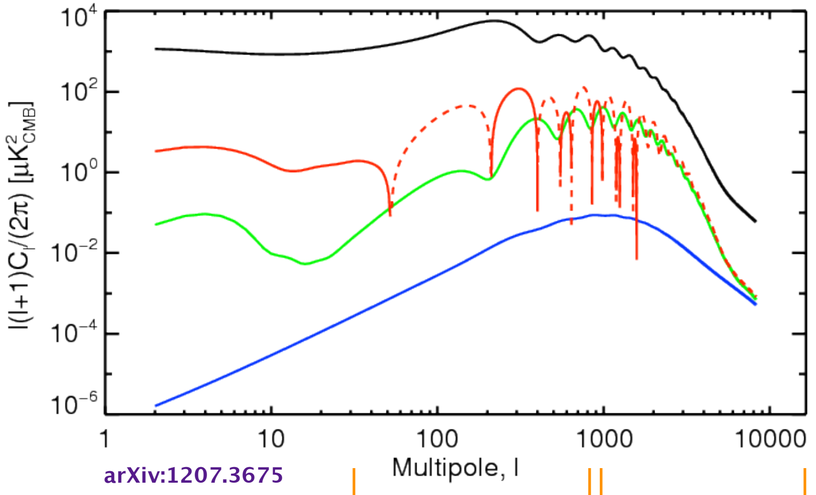

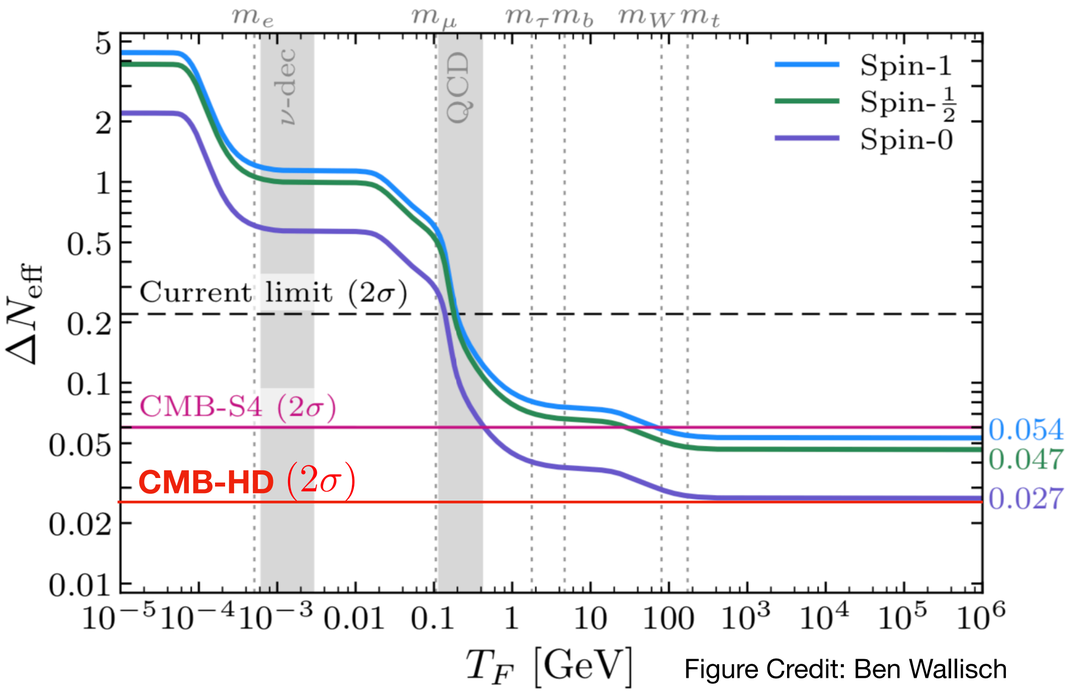

Figure Credit: Ben Wallisch