Probing Dark Matter with CMB-S4 (and beyond)

David J. E. Marsh

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GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

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Changing the Expansion Rate

Different DM components affect the expansion rate at different times:

Sterile neutrinos: $w = 1/3 \to 0 \ (T \sim m)$

Relativistic at early times → free-streaming, radiation era.

Complex scalar: $w = 1 \to 1/3 \to 0 \ (H \sim m)$

Conserved charge → stiff phase, amplify GWs, early dominance.
Conformal phase → relativistic species, radiation era.

Real scalar: $w = -1 \to 0 \ (H \sim m)$

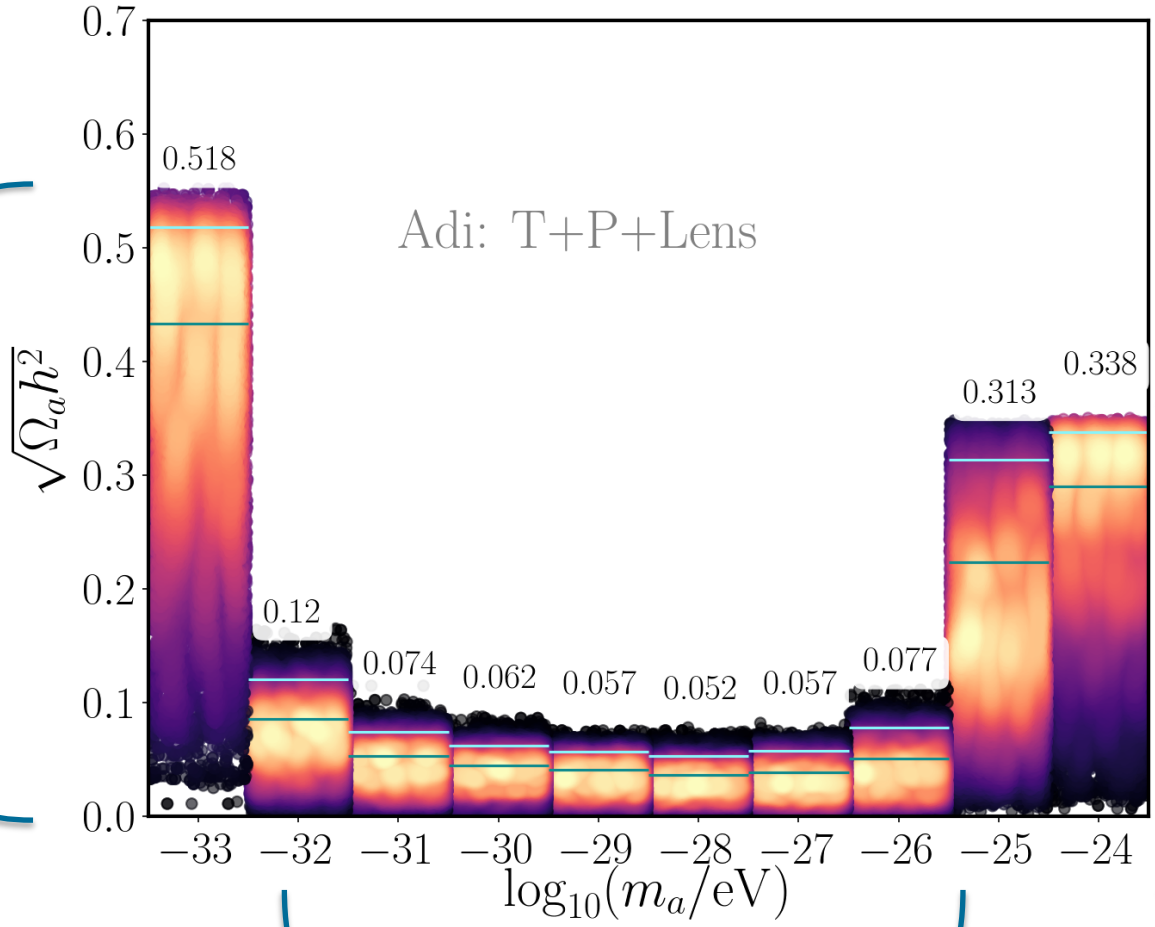
Friction → slow roll → DE-like, sub-dominant (early) or dominant (late). C.f. inflation and reheating.

All these effects alter the CMB. First two: peaks. Last: peaks and SW.

State of the Art: Planck ULAs

Hlozek et al (2017)
Uses CAMB, COSMOSIS

Dark Energy



Absolute lower bound on DM particle mass:

$m > 10^{-24}$ eV

(linear, well understood physics)

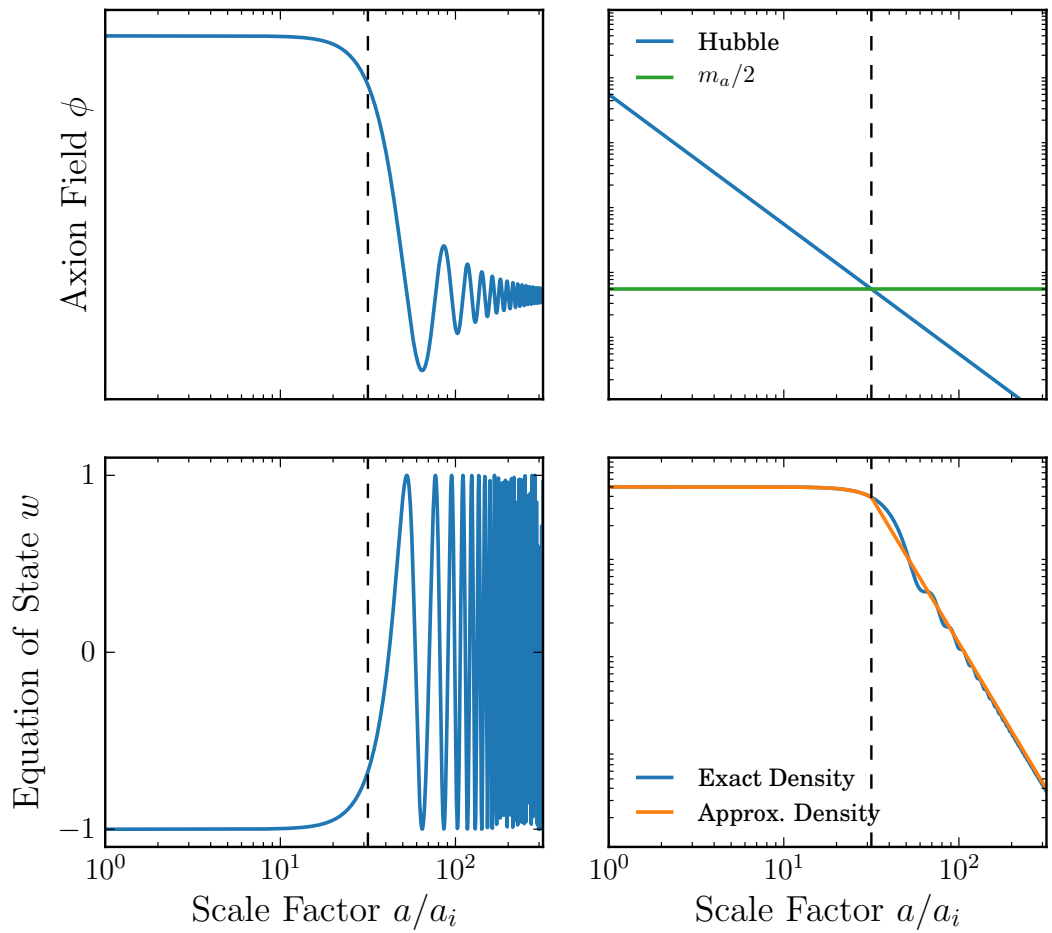
Precision constraints cover orders of magnitude: $\Omega_a h^2 < 0.003$

Axion Dark Matter

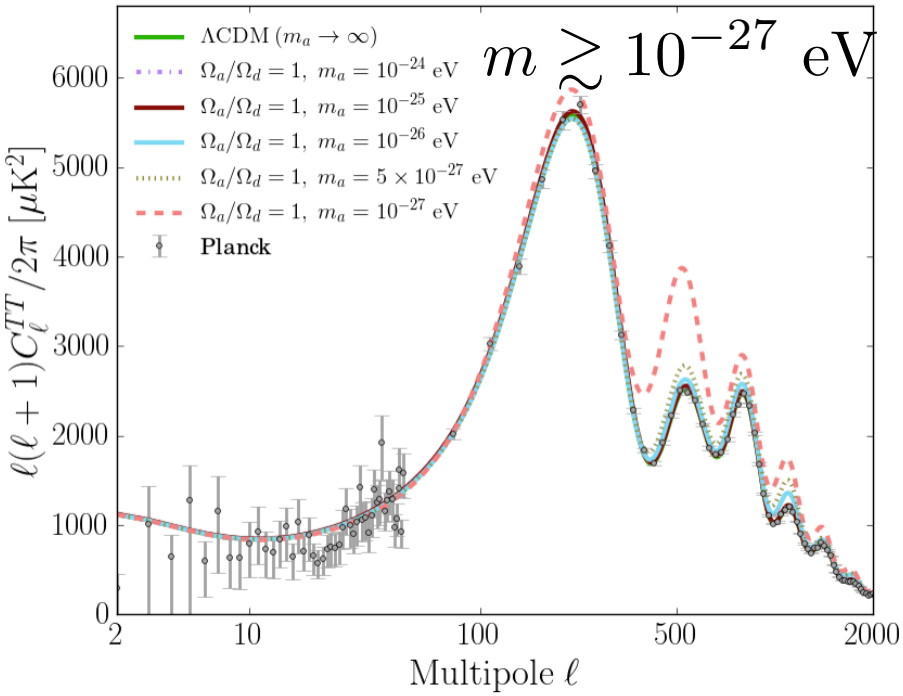
Review: DJEM Phys. Rep. (2016)

Non-thermal classical field. DM in coherent oscillations.

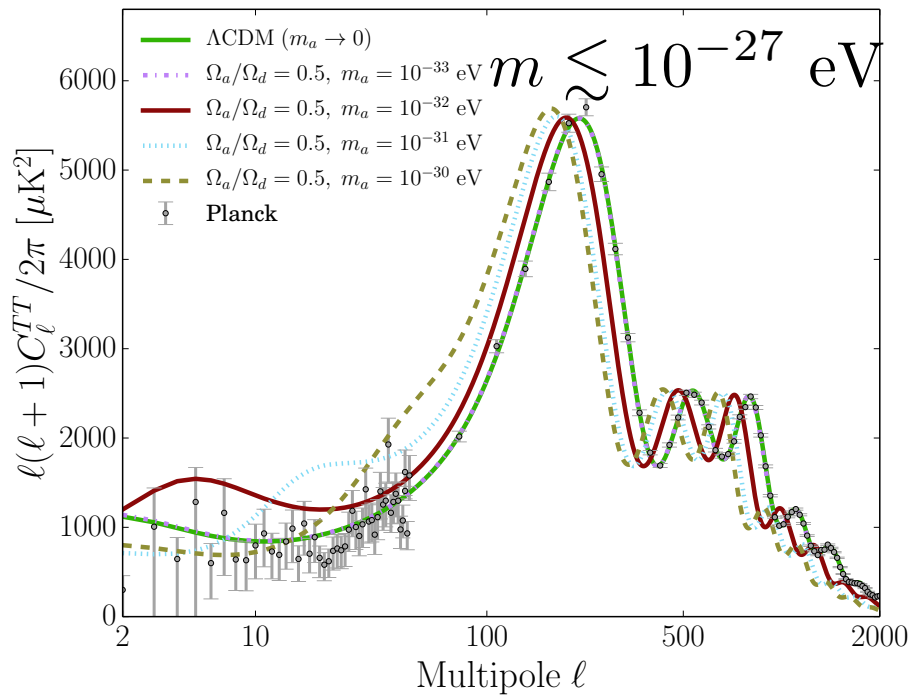
Dynamics governed by the Klein-Gordon equation.
Background field → relic density. Physics: Hubble "friction".
Perturbations → clustering. Physics: field gradient "pressure".



Hlozek et al (2015,2017)



DE-like axions affect angular size + ISW by expansion rate in matter dom. era.
Effects vanish for small m → mimic cosmological constant.



DM-like axions affect acoustic peaks by expansion rate in rad. dom. era.
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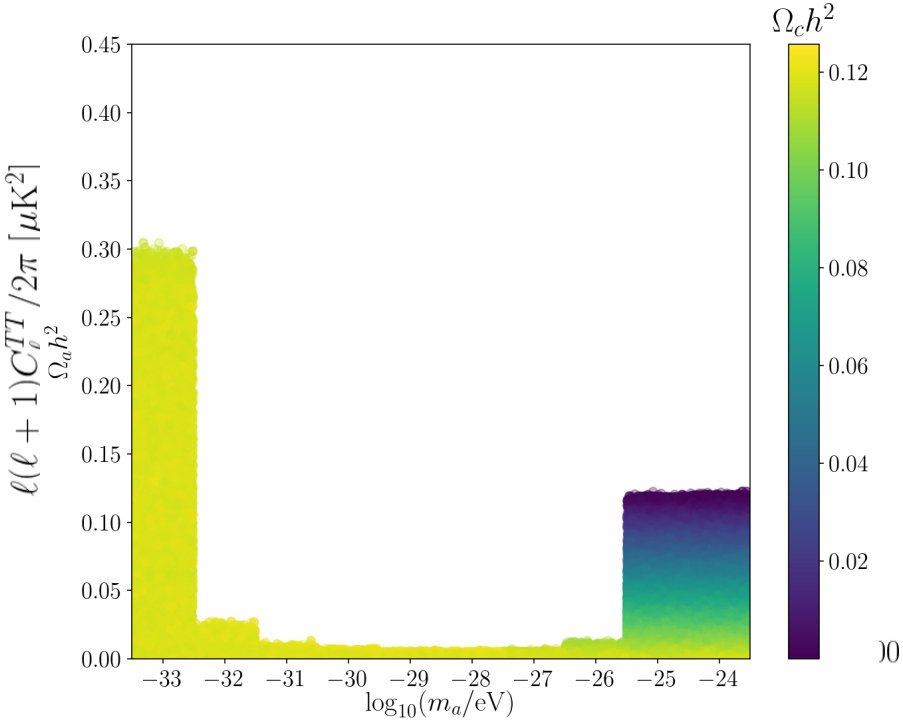

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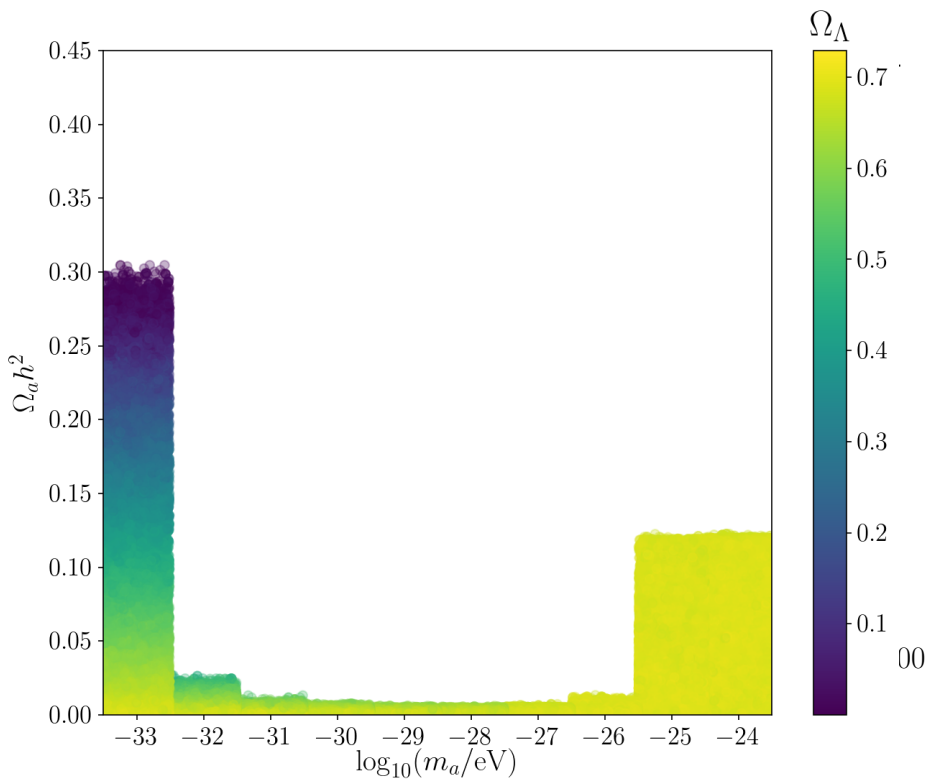

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The Axion Jeans Scale

In the non-relativistic limit the Einstein-Klein-Gordon equations reduce to the (non-linear) Schrodinger-Poisson equations.

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi + \frac{k^2}{a^2}\phi = \dot{\phi}\left[-3\dot{H}_L - \frac{\partial_i B^i}{a} + \dot{A}\right] - Am^2\phi$$

Ignore expansion, non-relativistic limit, and WKB approximation:

$$i\dot{\psi} + \frac{k^2}{2m}\psi - mV\psi = 0 \qquad \nabla^2 V = 4\pi G|\psi|^2$$

Polar co-ordinates (Madeulng form) → equivalent fluid w. pressure:

$$\psi = \sqrt{\rho}e^{iS} \quad F = -\nabla(V + Q) \quad Q = \frac{\nabla^2\sqrt{\rho}}{2m^2\sqrt{\rho}}$$

The Axion Jeans Scale

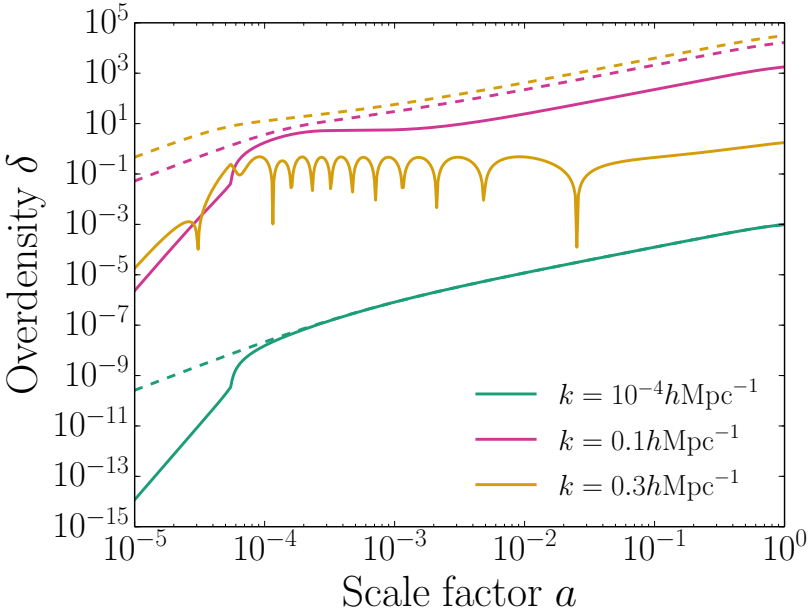
Linear theory:

$$\ddot{\delta} + 2H\dot{\delta} + \left[\frac{k^4}{4m^2a^2} - 4\pi G\rho\right]\delta = 0$$

→ Transfer function to CDM with steep cut-off and oscillations.

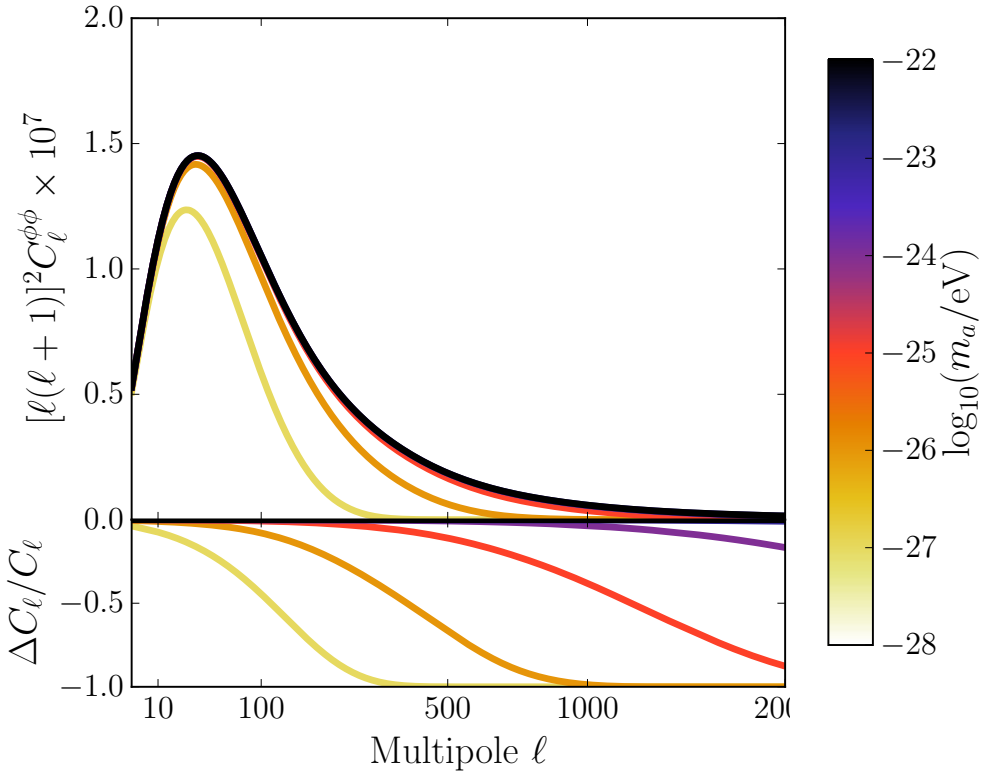
Non-linear theory: solve the Schrodinger-Poisson equations.
→ Requires physics beyond collisionless N-body. More later…

The Jeans scale suppresses growth of perturbations, similarly to free streaming of relativistic particles.



Suppressed matter power → suppressed lensing below the Jeans scale. Large effect for high axion mass where density can be large. High-L >10^3.

Small k modes grow and "lock" to CDM adiabatic mode. Large k modes oscillate and have reduced clustering.



CMB Targets for DM

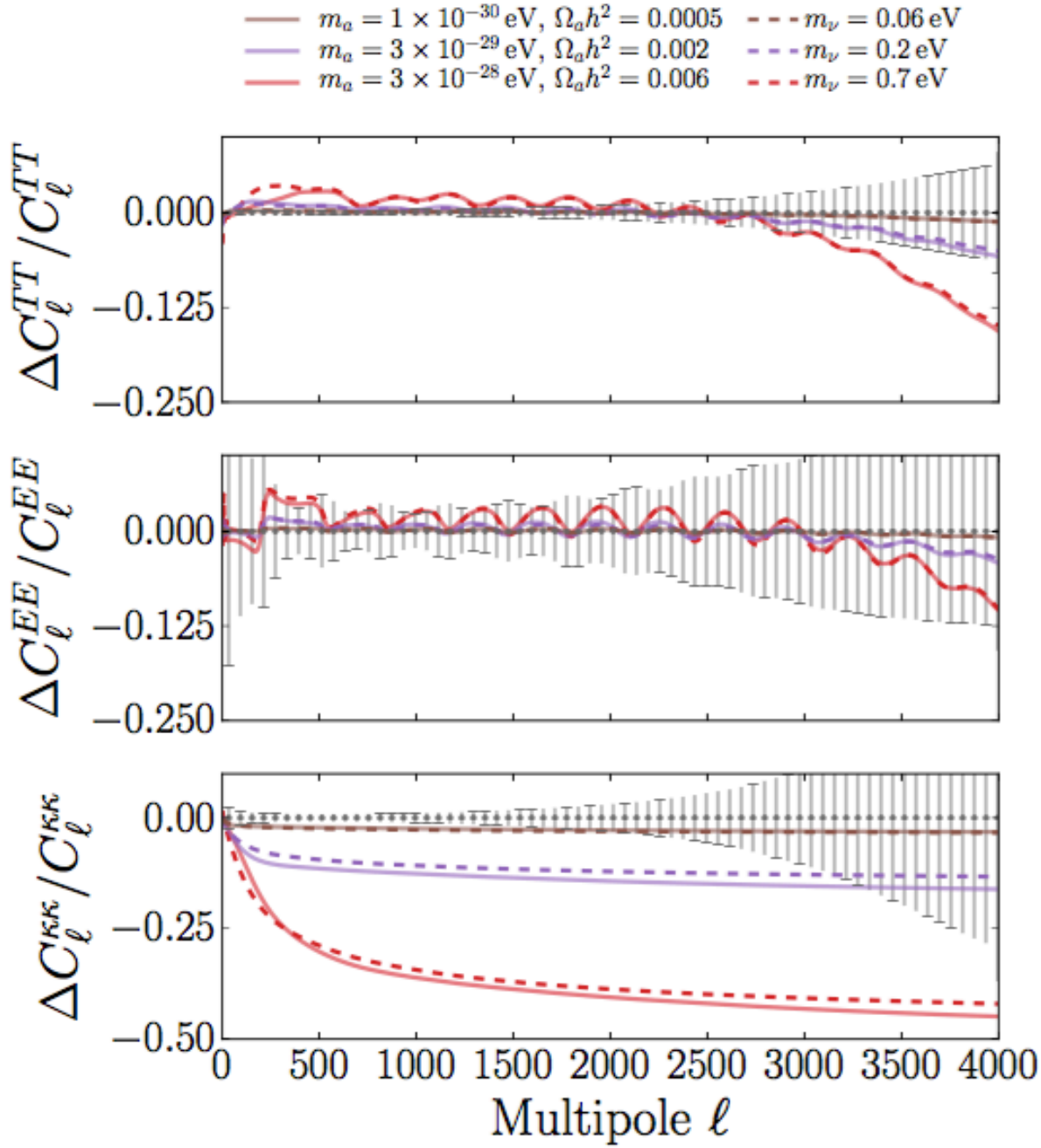
Expansion rate effects remove some DM at early times. Drive precision constraints at low axion mass in primary anisotropies. Improve high L acoustic peaks to get better precision DM constraints. Axion, massive ν, N_{eff}.

Clustering effects dominate constraints for the dominant component, i.e. high axion mass. In the CMB, this is seen in secondary lensing anisotropies. Measure lensing to extremely high L to improve DM lower bound. Axions, massive ν, WDM.

Some effects are degenerate between models.

Here, thermal neutrino free streaming is mimicked by non-thermal scalar gradient pressure.

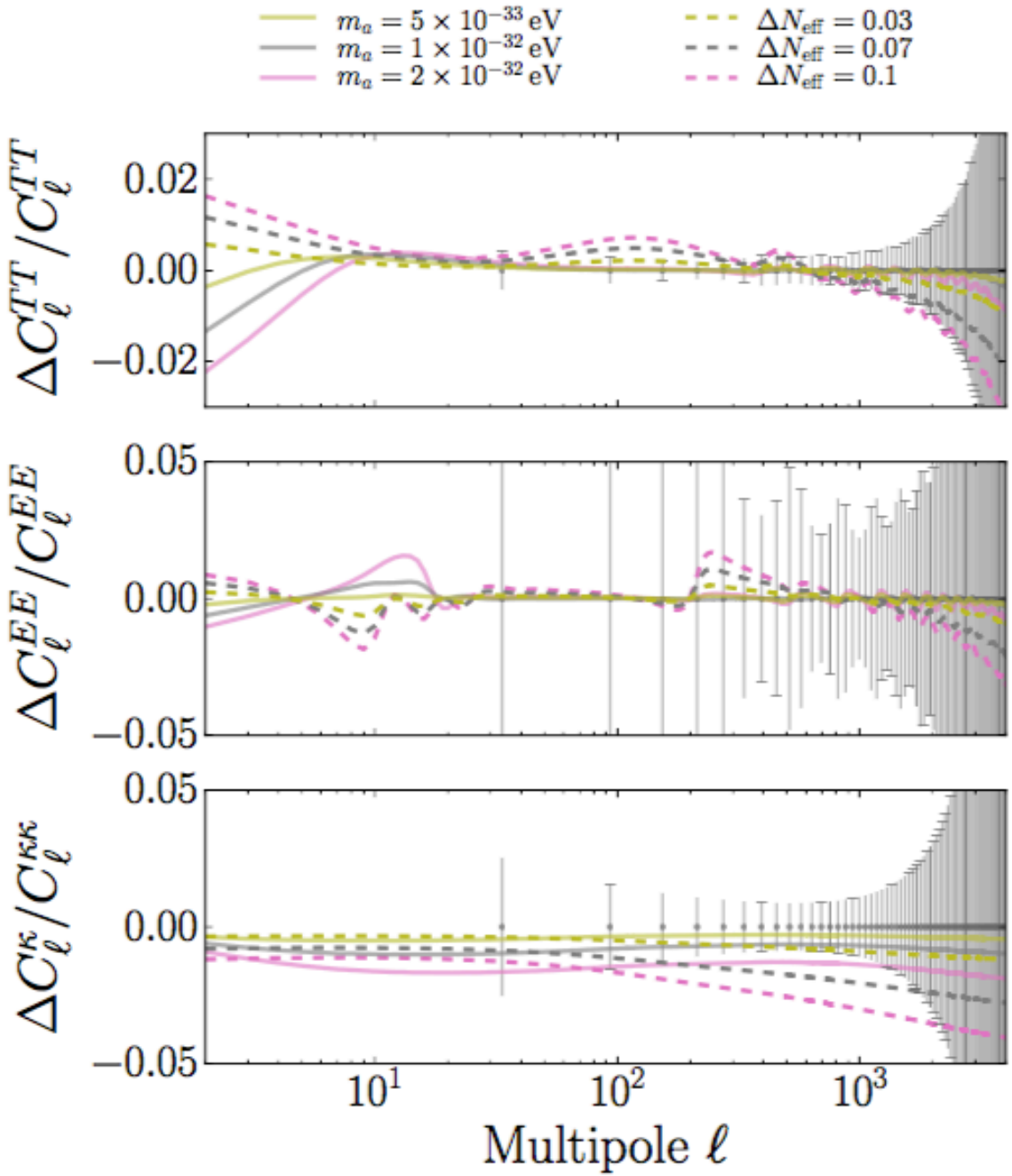
Non-thermal axions are NOT degenerate with N_{eff}.



Other effects break apparent degeneracies.

Here, relativistic species suppress power in the damping tails, while DE-like light scalars have a distinct ISW shape.

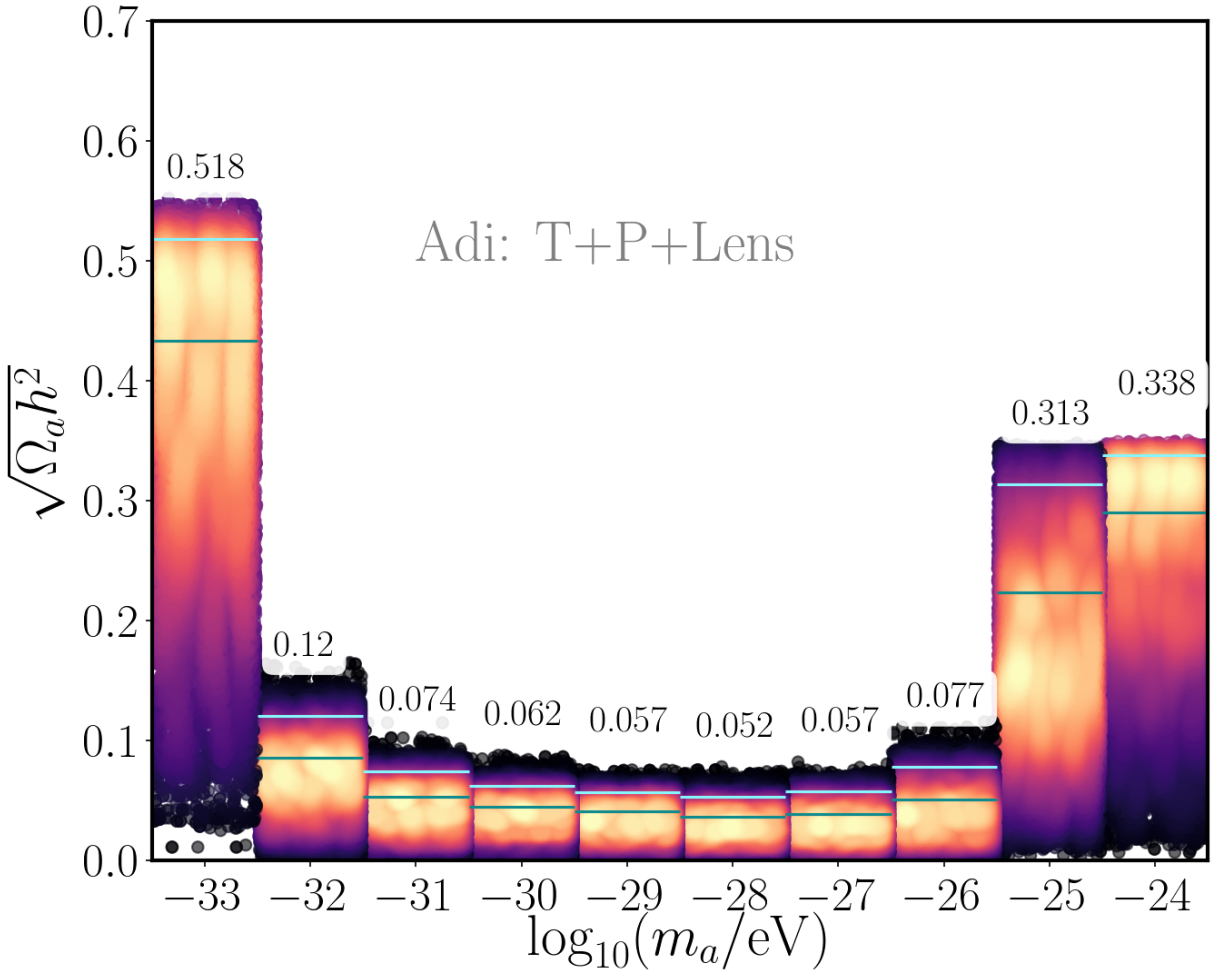
All these N_{eff} values allowed by Planck.



S4 versus Planck for ULAs

Hlozek et al (2016)

Recall Planck MCMC result:



S4 versus Planck for ULAs

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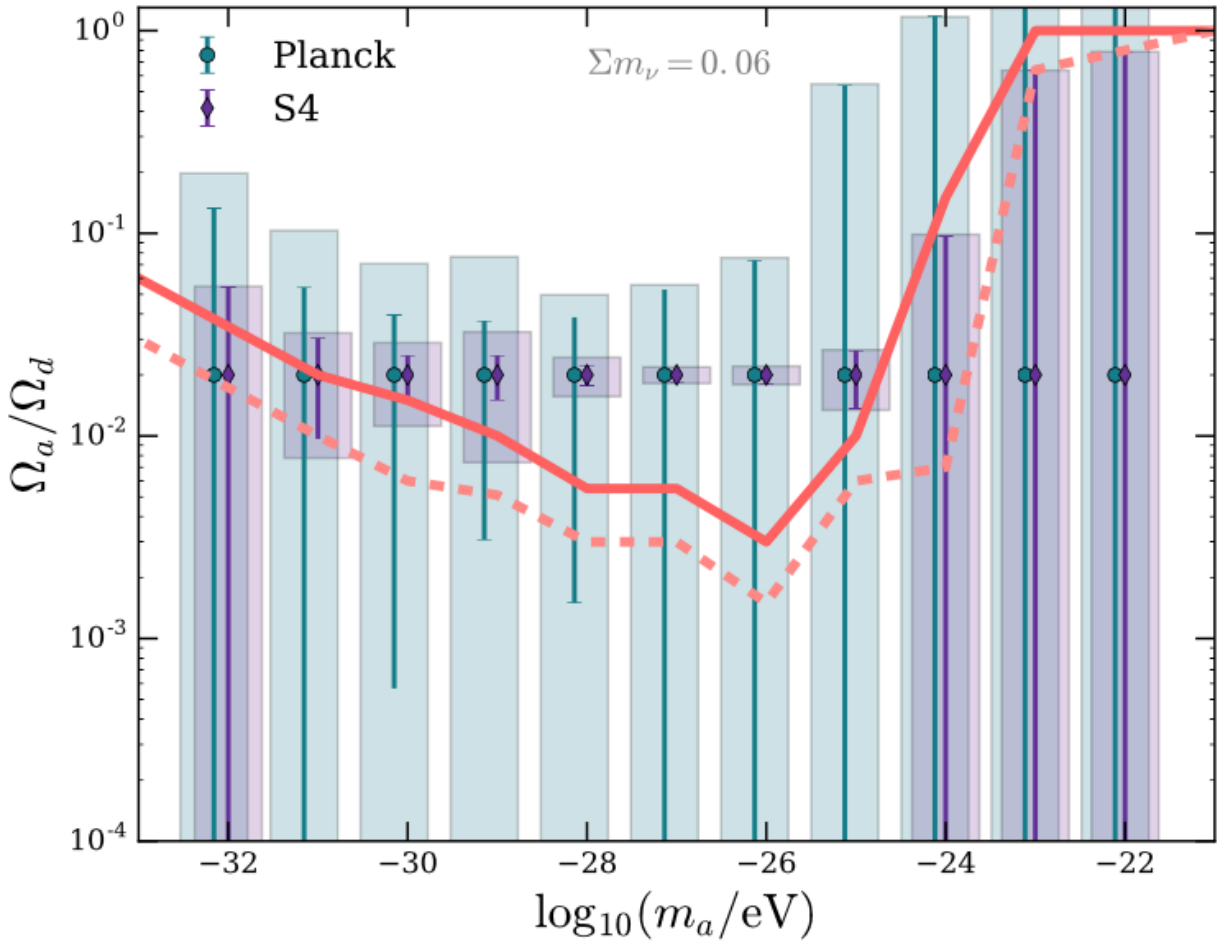
Replace MCMC constraints with Fisher forecasts to compare.



S4 versus Planck for ULAs

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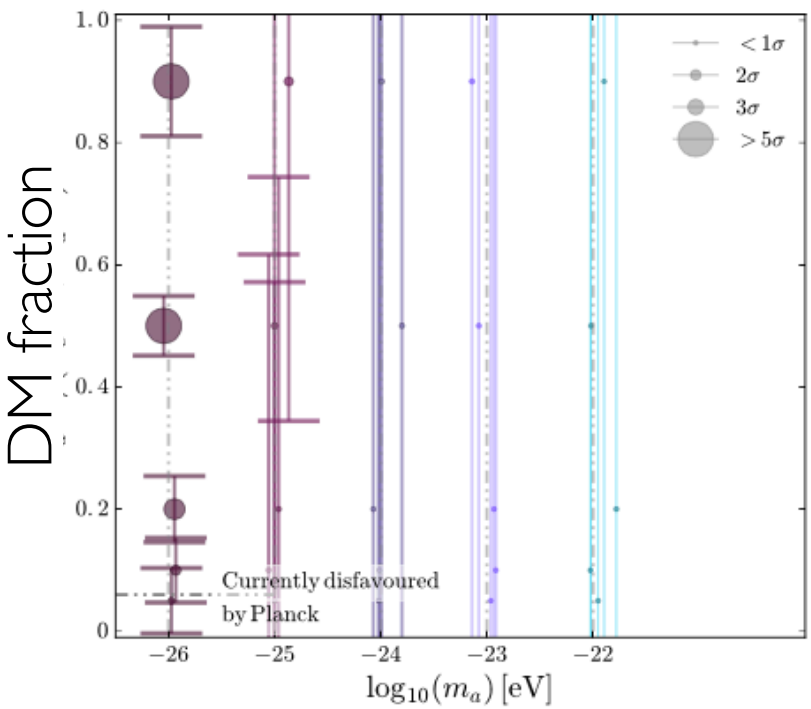
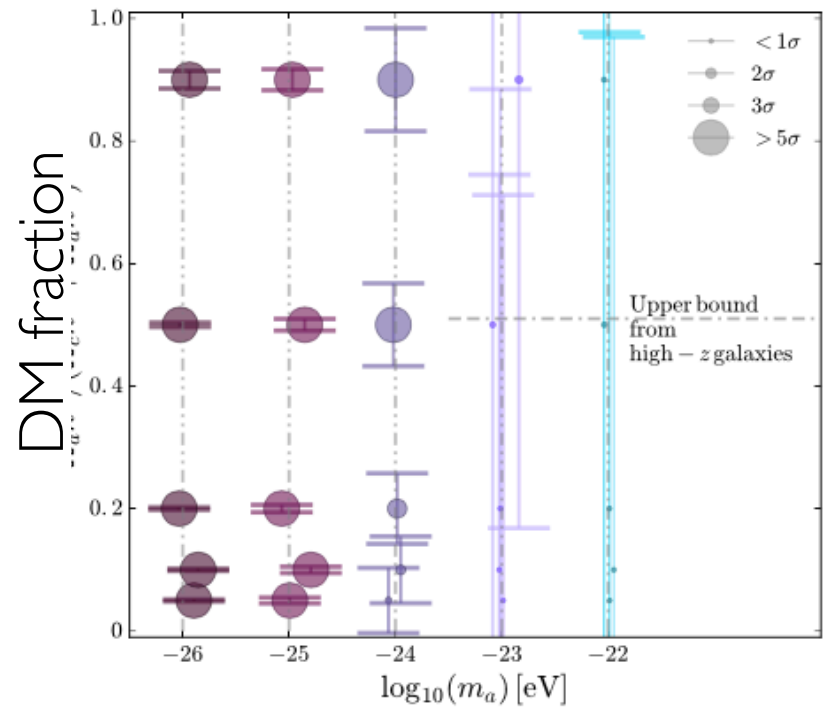
High mass only. Vary fiducial models. Ball size → σ detection.





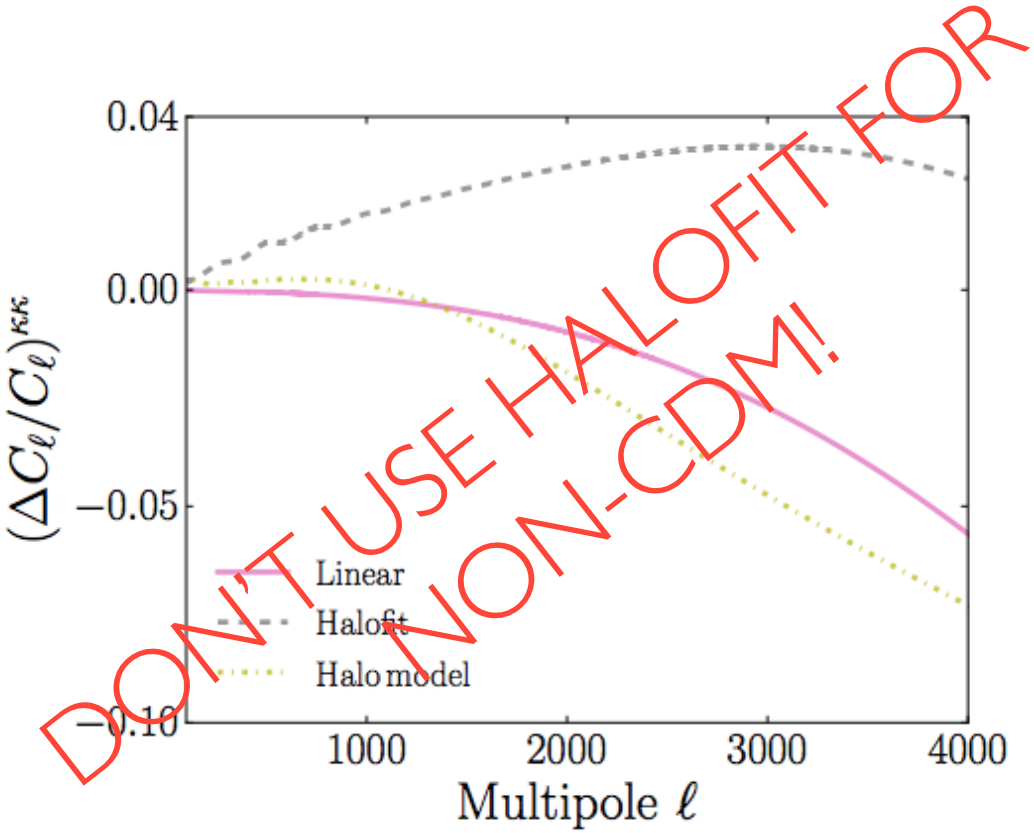
5σ detections of 1% departures from CDM.

Lower bound increases by two orders of magnitude.

The Limits of Lensing

DJEM (2016)
Hlozek et al (2016)
Nguyen et al (2017)

S4 can probe the popular ``fuzzy DM'' model, $m \approx 10^{-22}$ eV
Lensing at high-L requires the non-linear DM power.



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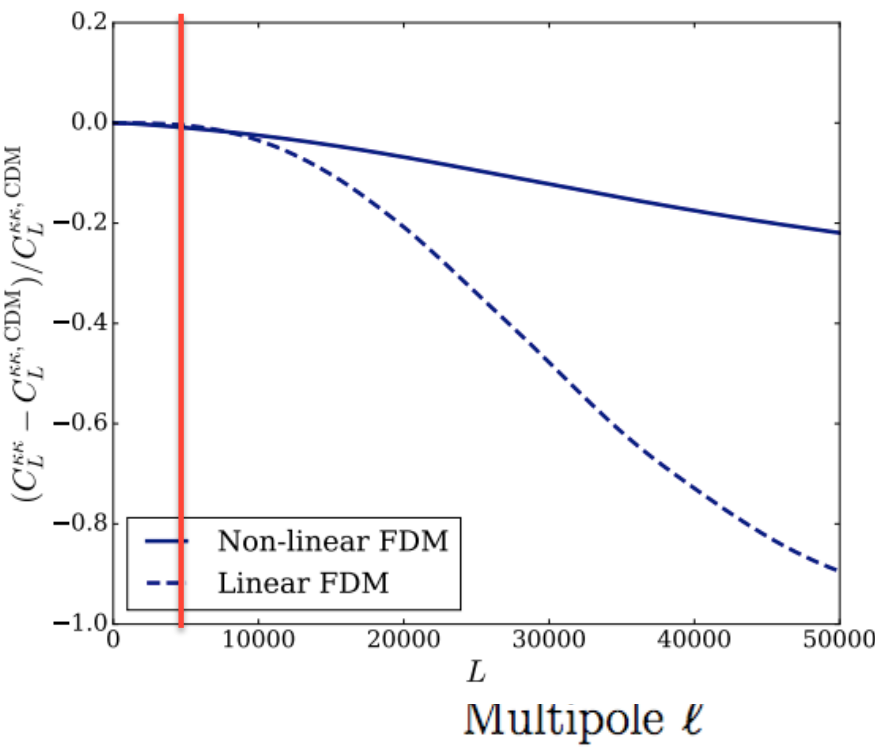
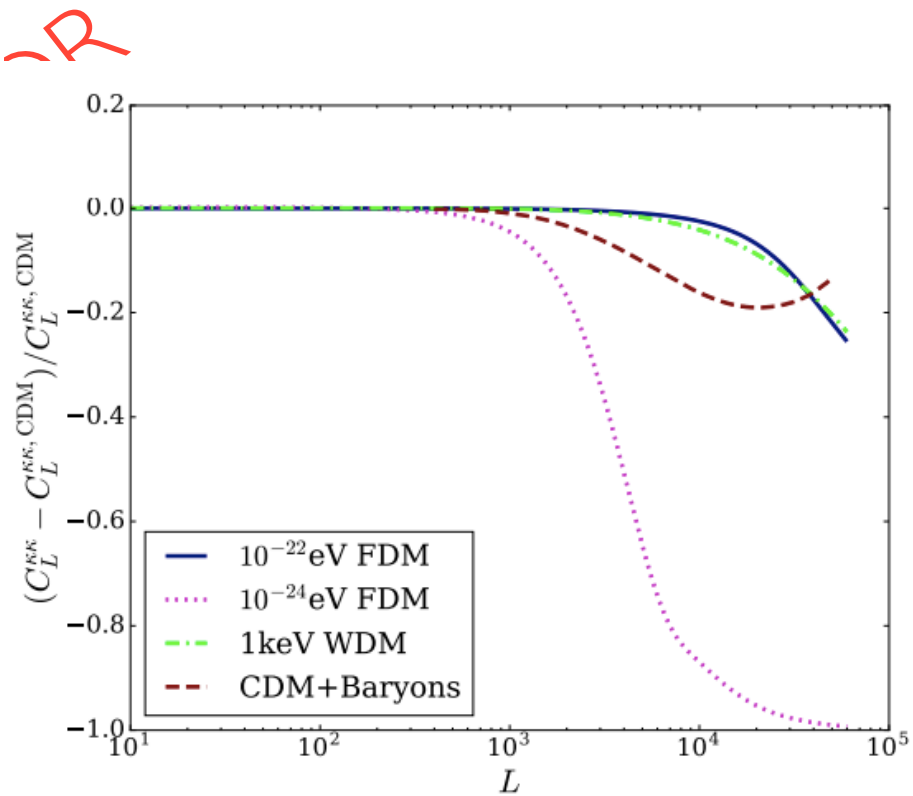
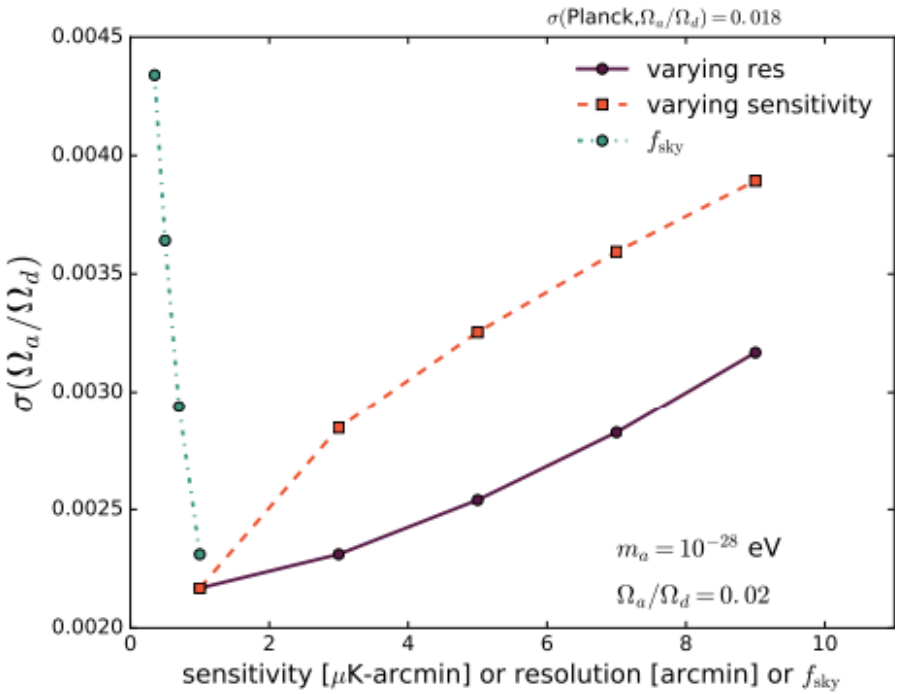


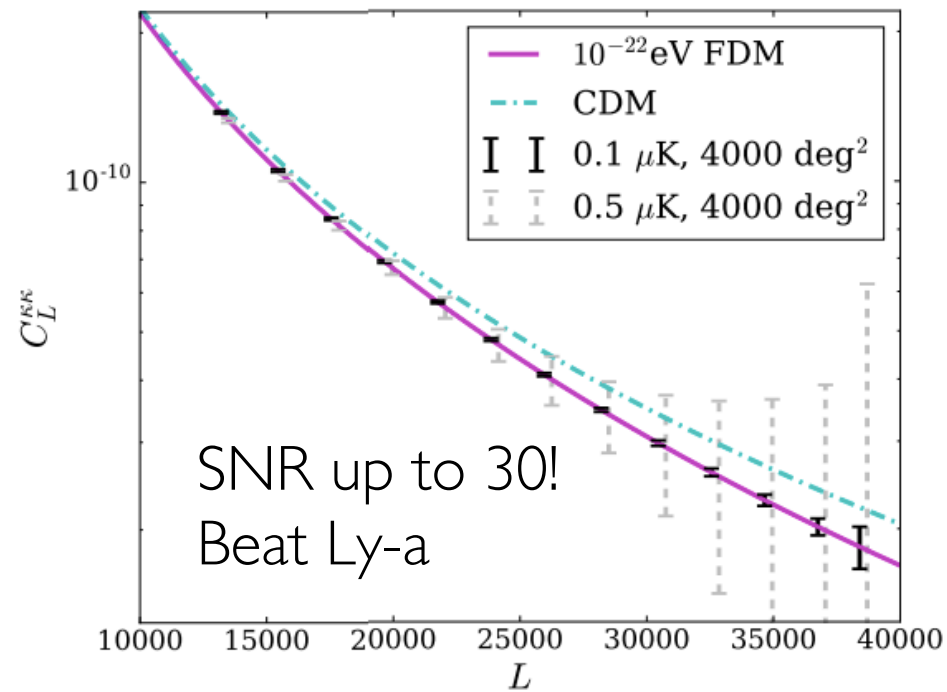


Sensitive to FDM/WDM. Distinguish DM models from baryonic effects.

Survey Design

Hlozek et al (2016)
Nguyen et al (2017)





An S4-like survey improves sensitivity to light DM fraction by almost factor of 10 compared to Planck.

Probing FDM will require 20 arcsecond resolution. CMB-S4 camera on Large Millimeter Telescope dish.

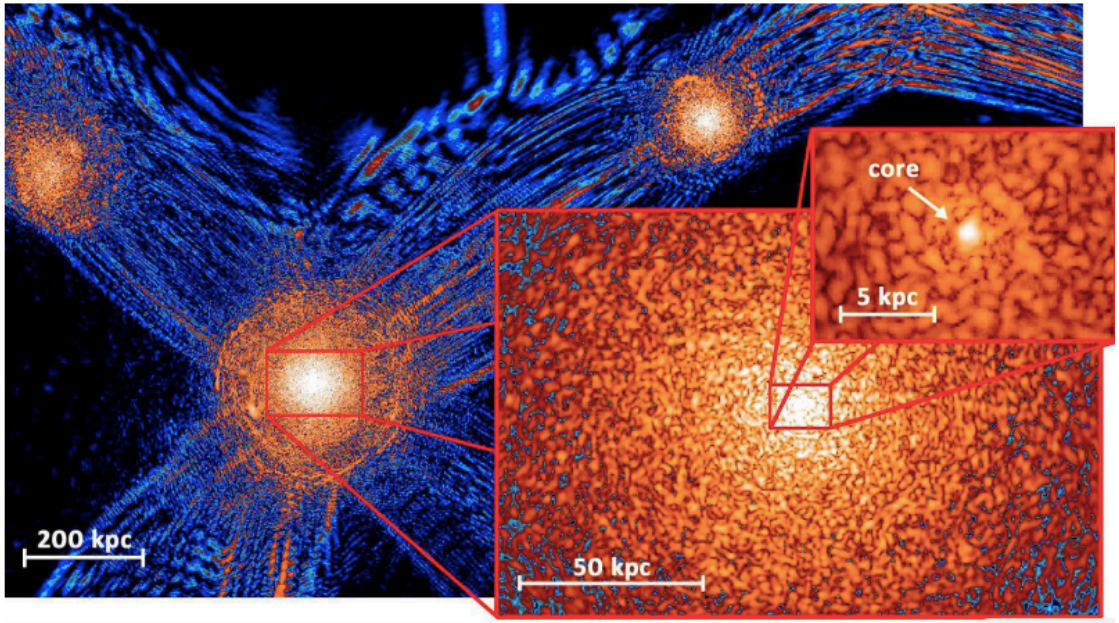
Fully Non-linear

Corasaniti et al (2016)
DJEM (2016)

Halo model tested for N-body sims with truncated power.
Distinguishing DM models requires "beyond N-body" sims.

Widrow & Kaiser (1993); Woo & Chiueh (2009); Schive et al (2014+); Mocz++; Niemeyer ++; Nori & Baldi (2018)

Cores and fringes key effects. New statistical tools?
Schrodinger expensive due to phase resolution in voids.
SPH requires large N to see interference.



Relativistic instabilities of the central "axion stars" must be simulated in full numerical GR, e.g. GRChombo.

Clough et al (2015); Helfer et al (2017)

Thank You

CMB-S4 =
Community Observations Mapping the Microwave UNIverse with Telescopes for cosmologY