Title: Testing dark matter with Stage-IV CMB experiments

Date: Sep 13, 2016 11:00 AM

URL: http://pirsa.org/16090046

Abstract: <p>In the coming decade, ground based CMB telescopes could face a substantial upgrade, to so-called CMB-S4. There are two main science drivers behind this initiative: B-modes, and neutrino mass, and I will focus on the latter. Thought of more generally, constraints on neutrinos can be thought of as generic tests of dark matter. I will discuss the prospects for CMB-S4 in the dark sector, with emphasis on searches for axions and neutrinos. It will be possible to detect percent level departures from standard cold dark matter at many sigma over a wide range of scales: a vast improvement over Planck (+ existing ground based). A large part of the improvement over Planck comes from precision lensing measurements at high multipole. I will briefly discuss some technical challenges in this measurement, based on modelling of dark matter clustering in the non-linear regime.</p>

Testing Dark Matter with Stage-IV CMB Experiments

David J. E. Marsh

CMB-S4 science book,

& 1607.08208

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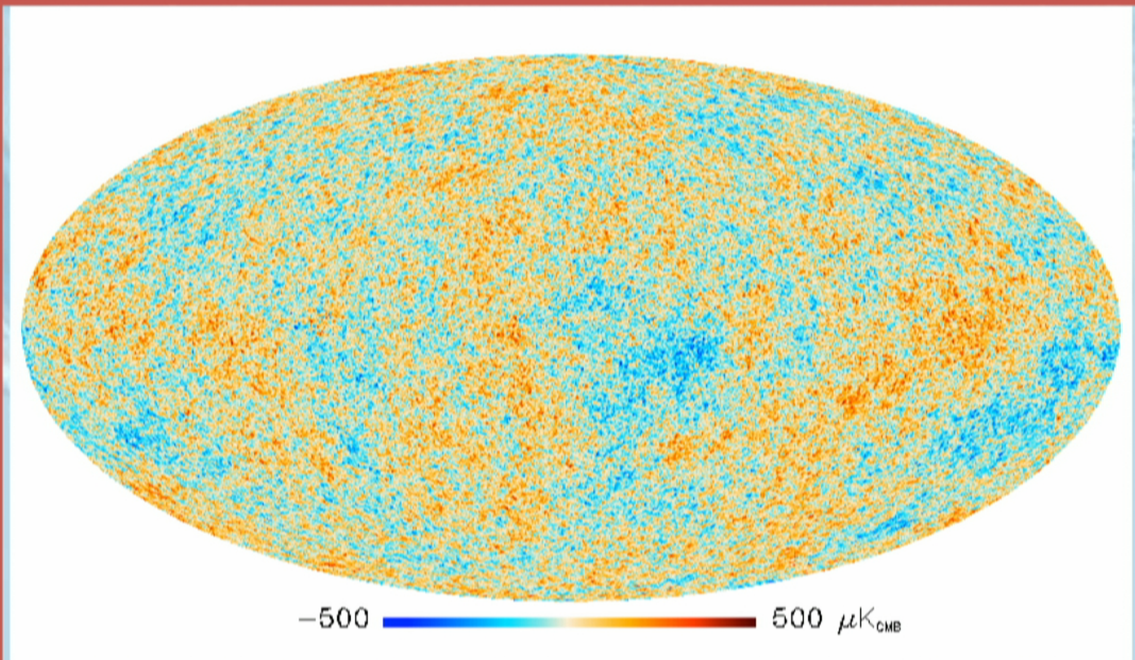
Cosmology and the CMB

Maps, power spectra, and parameter estimation!



(for a web widget with WMAP, see http://map.gsfc.nasa.gov/resources/camb_tool/index.html)

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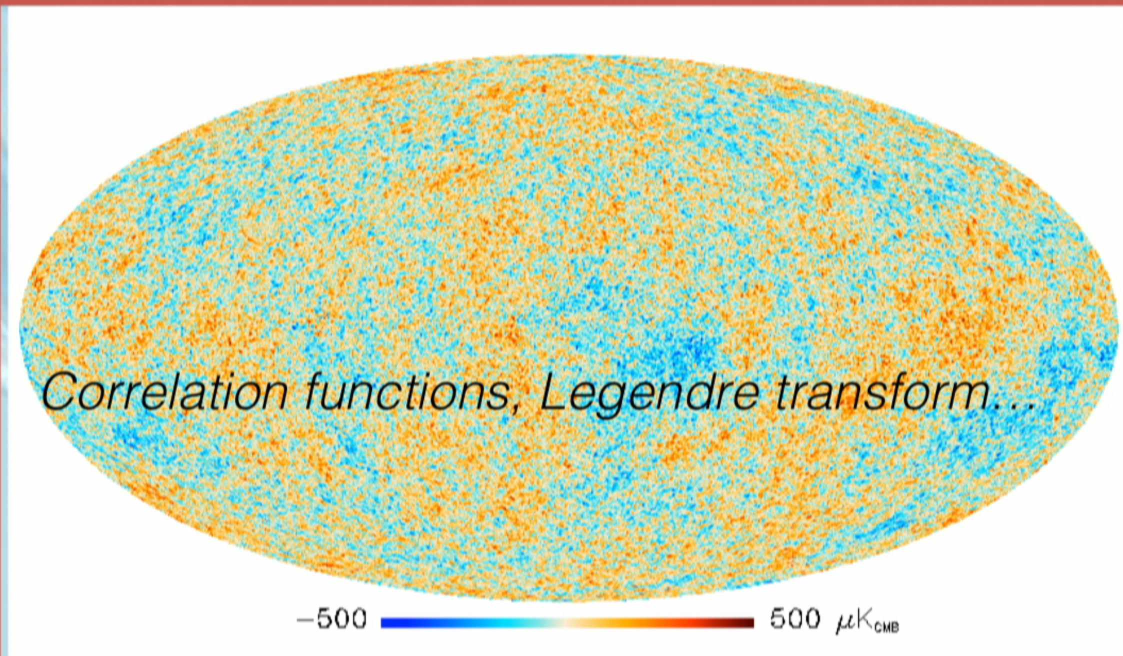

Correlation functions, Legendre transform...

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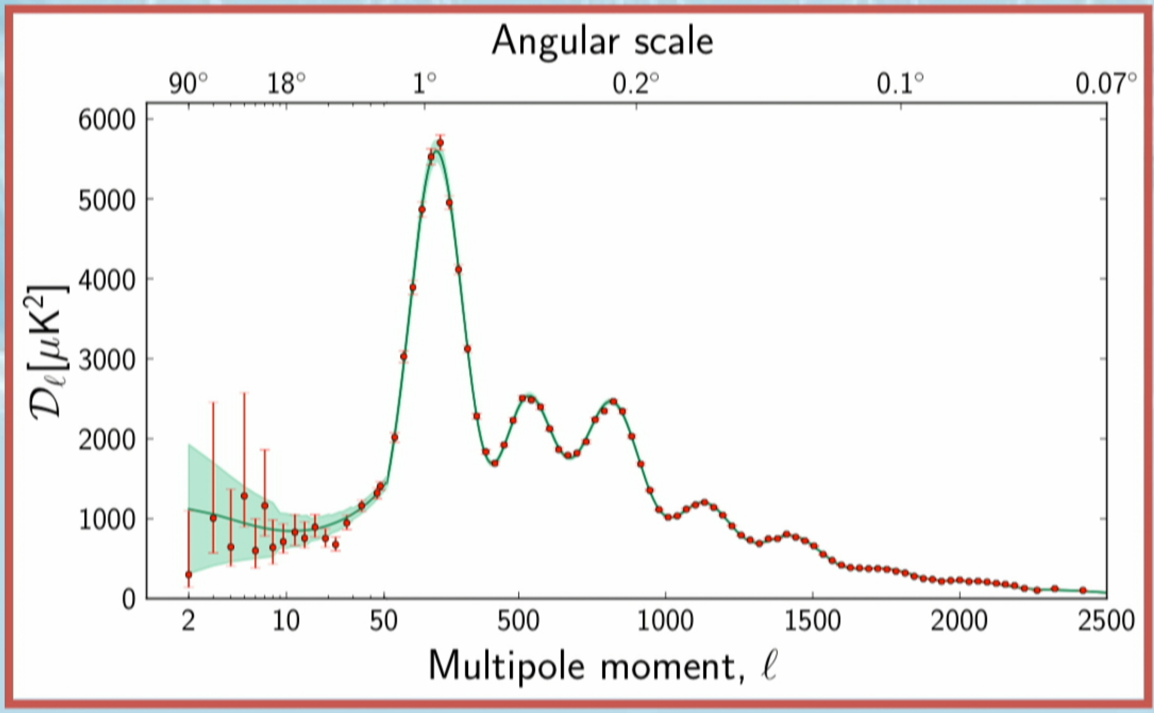

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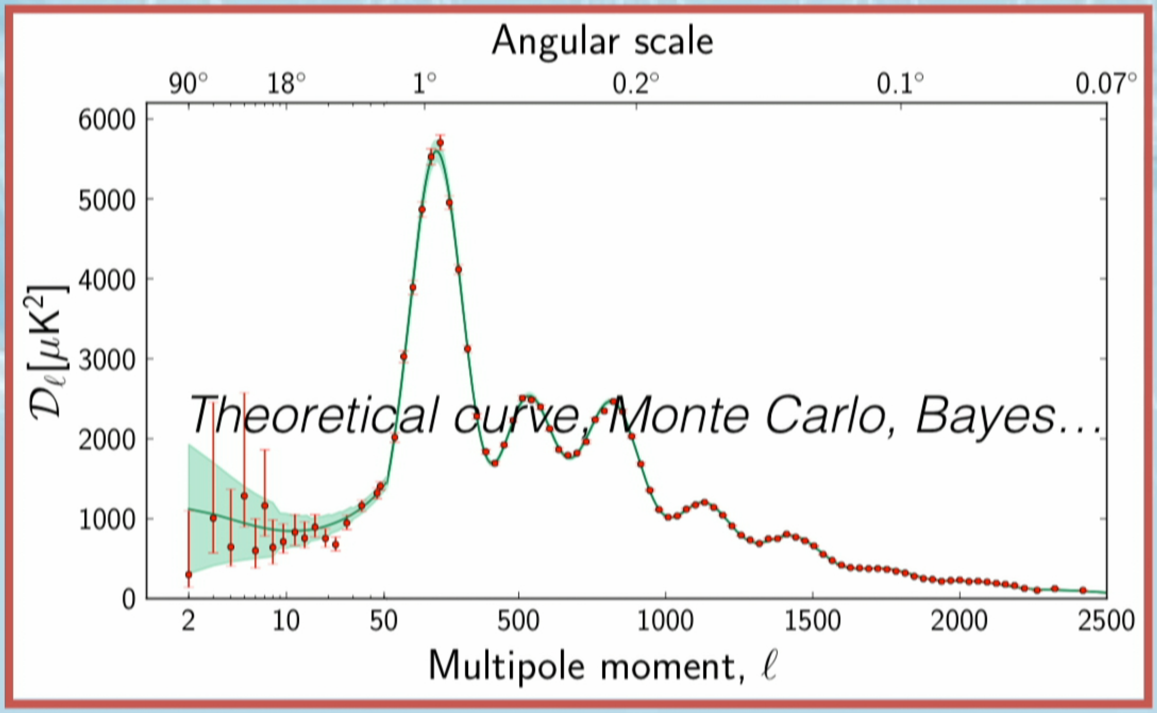

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Maps, power spectra, and parameter estimation!

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

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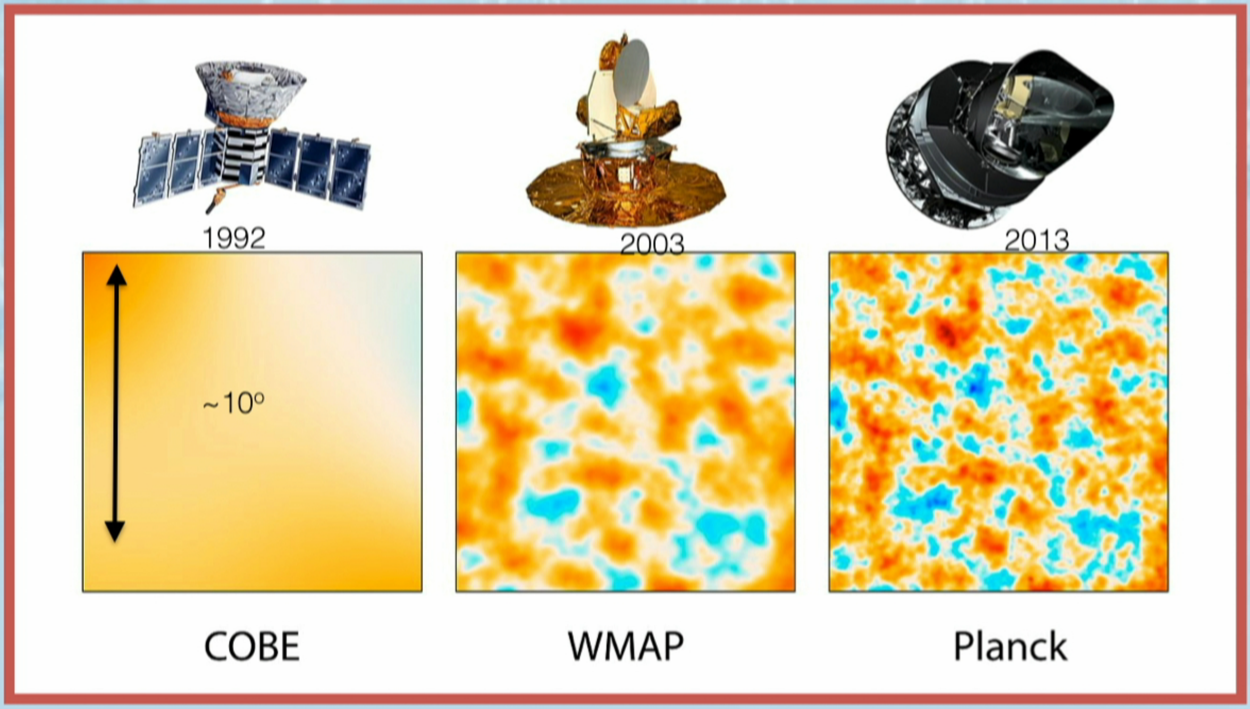

Image modified from NASA

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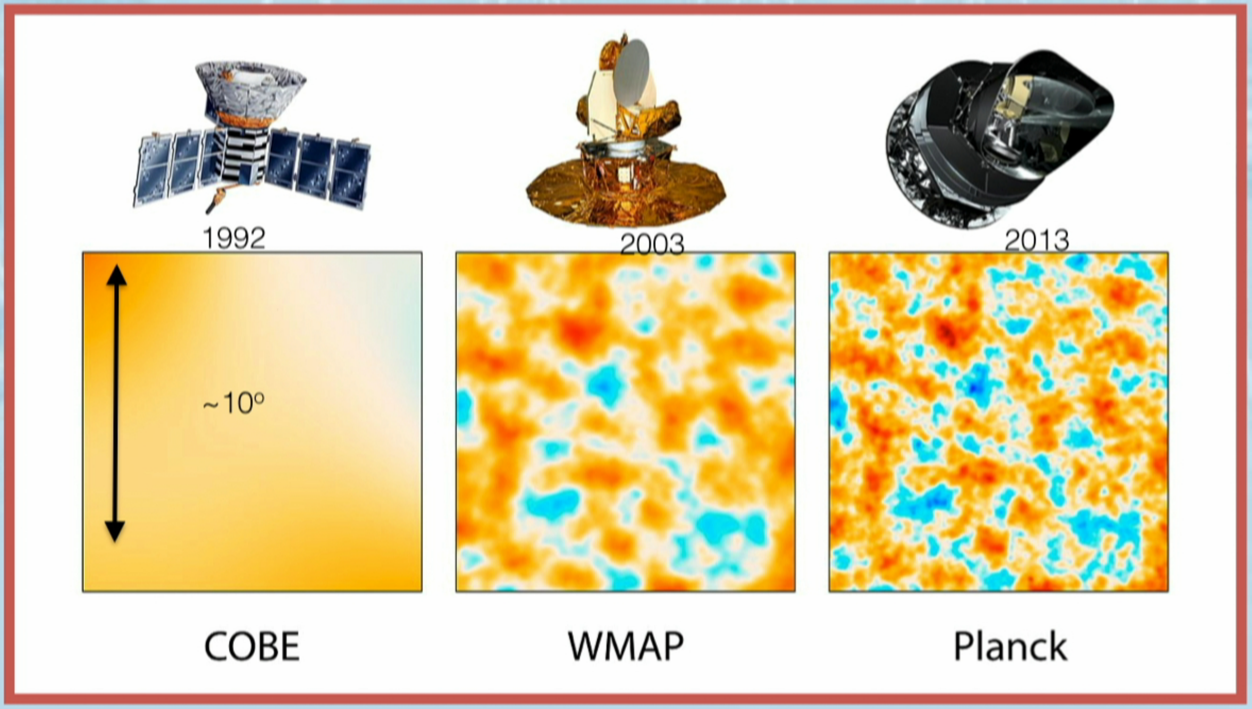

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DISCOVERY: 1965 (Penzias and Wilson)

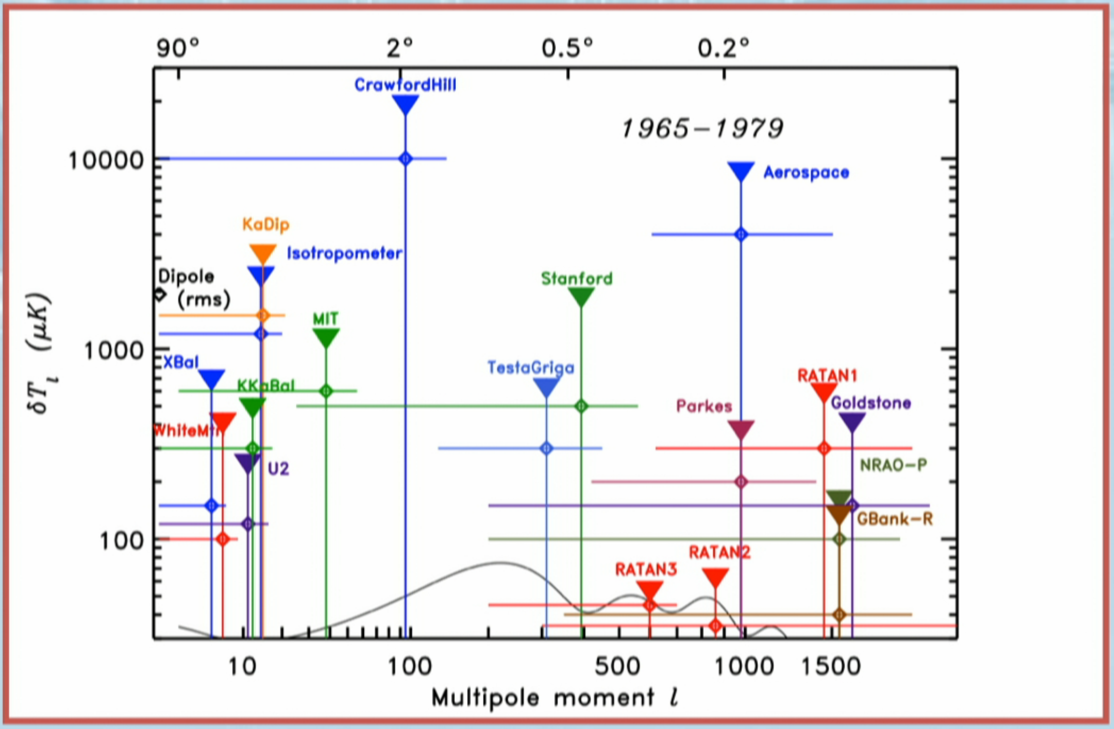

Image: Lyman Page

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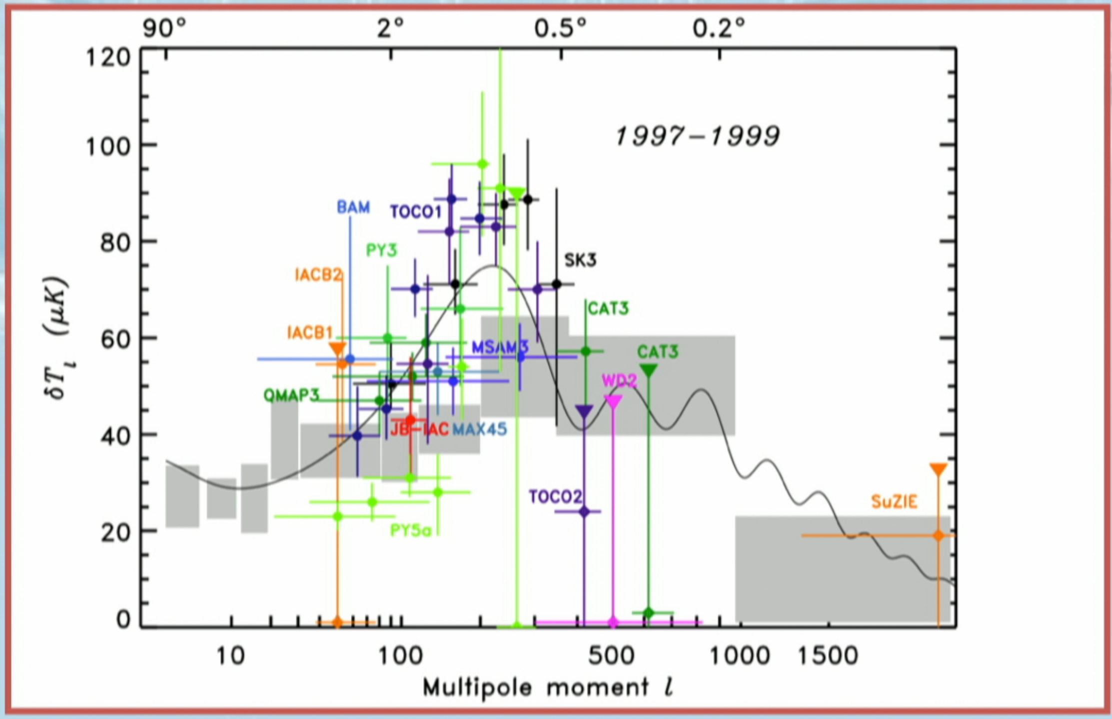
FIRST ACOUSTIC PEAK: Saskatoon (~1997)



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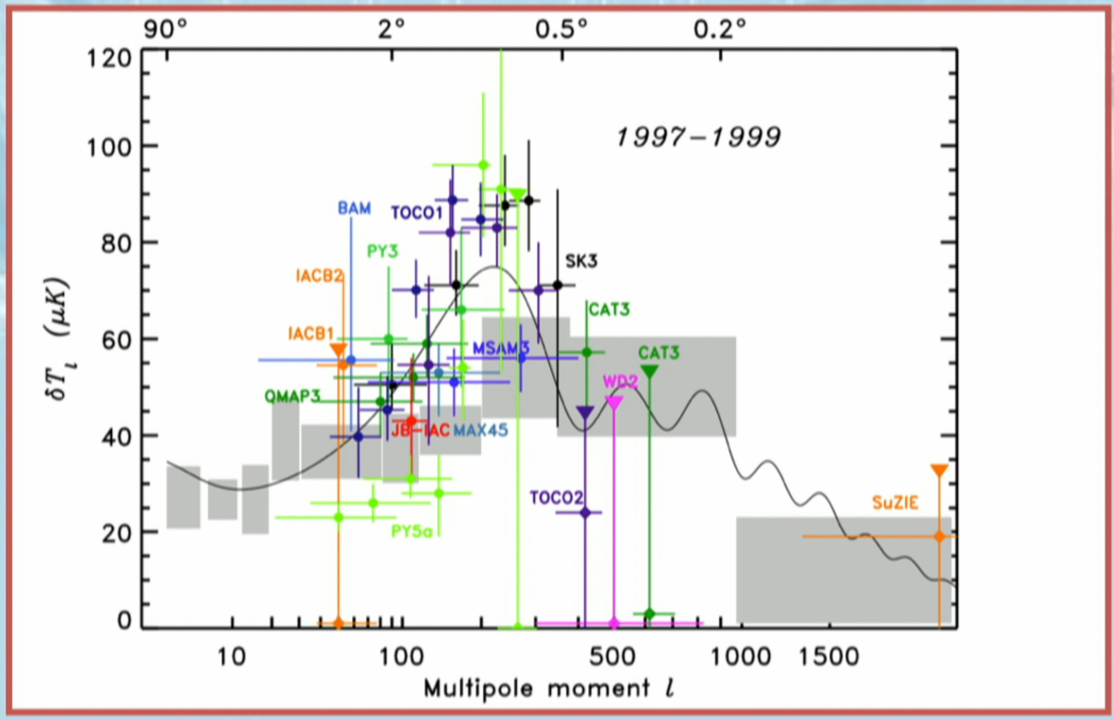

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LENSING DETECTION: ACT (2011)

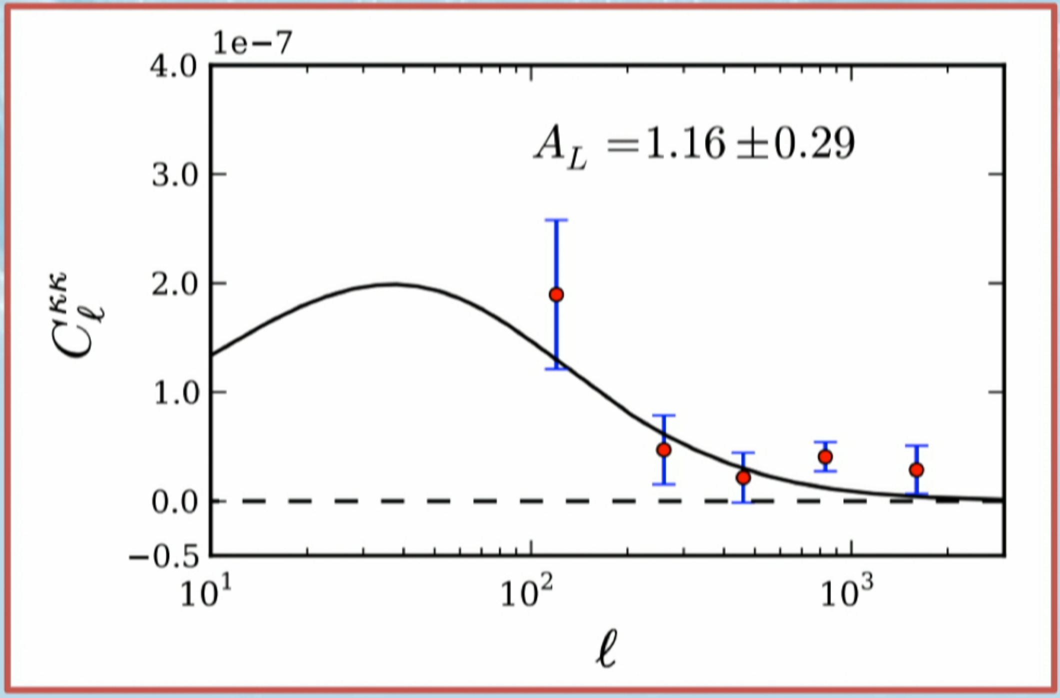
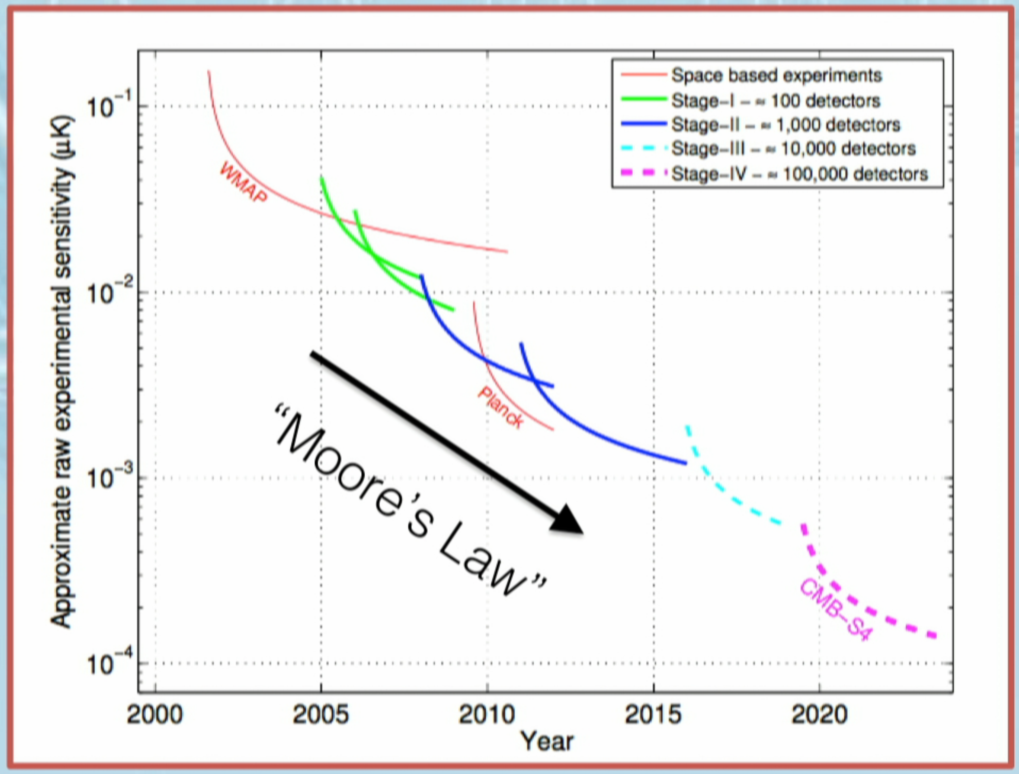


Image: Das et al (2011)

CMB Stage-IV

Planned upgrade of existing ground-based telescopes: SPT, ACT, BICEP, Polarbear +possible northern hemisphere.

Image: SNOWMASS CF5 Neutrino planning & CMB-S4 Science Book



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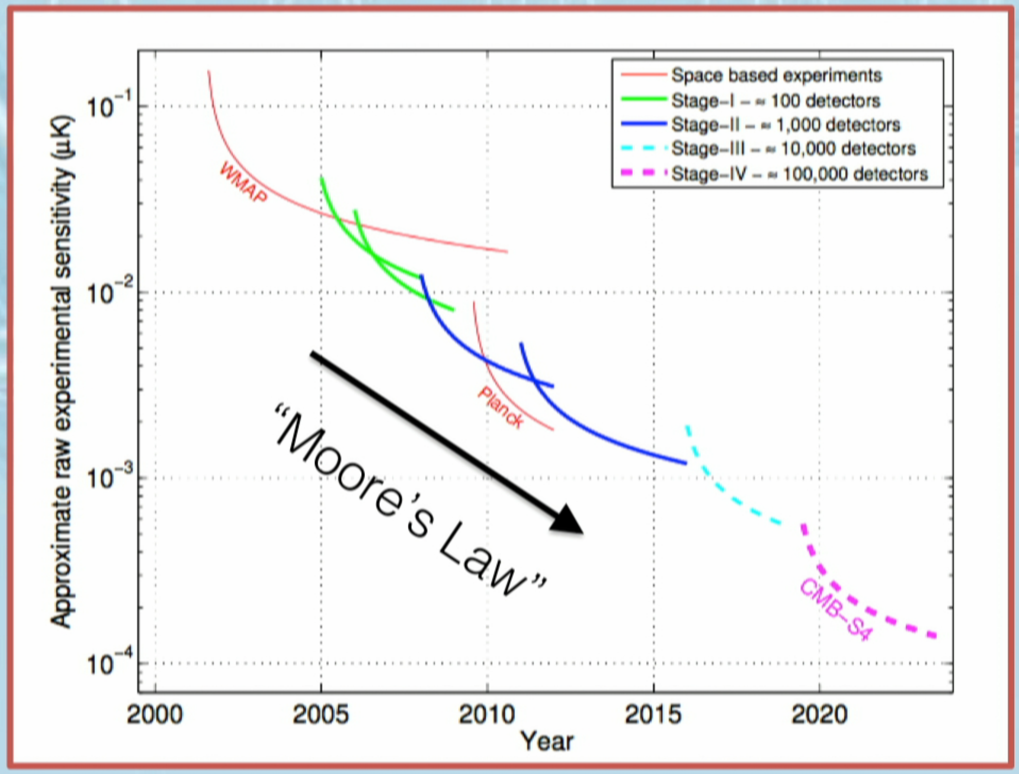

CMB Stage-IV

At a glance:

- Run for 4 years beginning 2020 (if funded).
- Temperature, polarization and lensing spectra to l~4000.

(c.f. Planck l-max~2000 in T,E. l-max~500 lensing).

- Fiducial 1μk-arcmin noise, 1 arcmin beam, f_{sky}=0.4

(c.f. WMAP 12 arcmin, Planck 5 arcmin).

- 8 frequency bands form 30 to 270 GHz (dust etc.)
- Superconducting cameras: existing tech scales up.
- B-modes with $\sigma(r)$ ~ 0.001 (c.f. BICEP2 r<0.12, 95% C.L.).
- Dark energy "Figure of merit" up by factor of 2 (clusters).
- Neutrino mass with $\sigma(m_\nu)$~15 meV (c.f. m_{min}~ 60 meV).
- Relativistic species with $\sigma(N_{eff})$~0.02 (c.f. Planck ~0.2).
- Improve axion DM fraction by factor of 10 from Planck.

More Details: Abazajian et al, 1309.5383; Science Book (soon)

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Dark Matter and Neutrinos from the CMB: Current Status

Neutrino mass from Planck

Planck 2015 Paper XIII

Oscillation experiments: neutrino's have mass: $\sum m_\nu \gtrsim 0.06\ \mathrm{eV}$

e.g. PDG

Neutrino energy density:

$$\Omega_\nu = \frac{\sum m_\nu}{93.14\ \mathrm{eV}}$$

Hot DM "free streams":
does not cluster on all
scales like cold DM does.

95% limits:

$$\sum m_\nu < 0.59\ \mathrm{eV}$$

(lensing)

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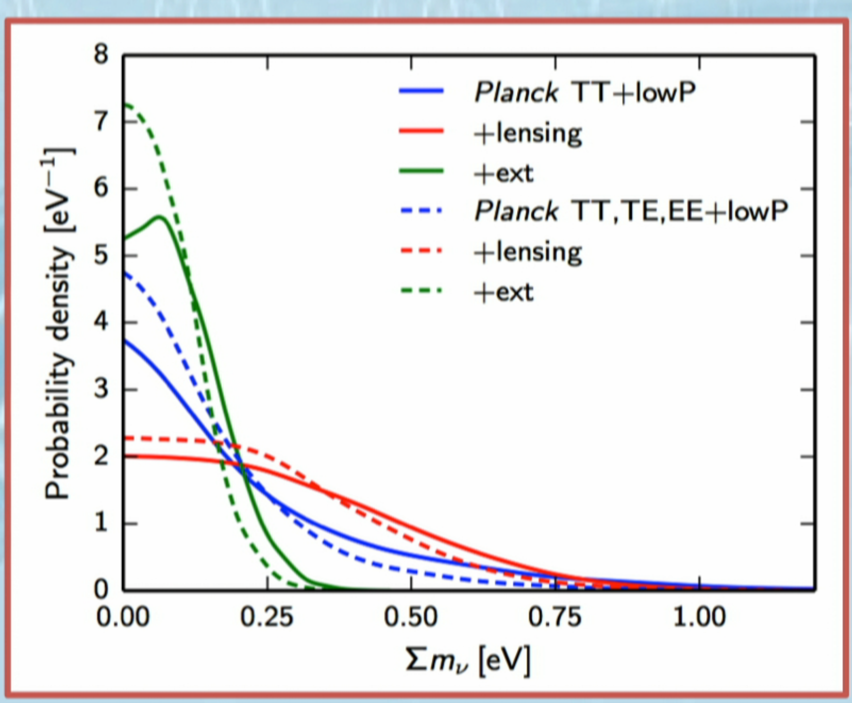

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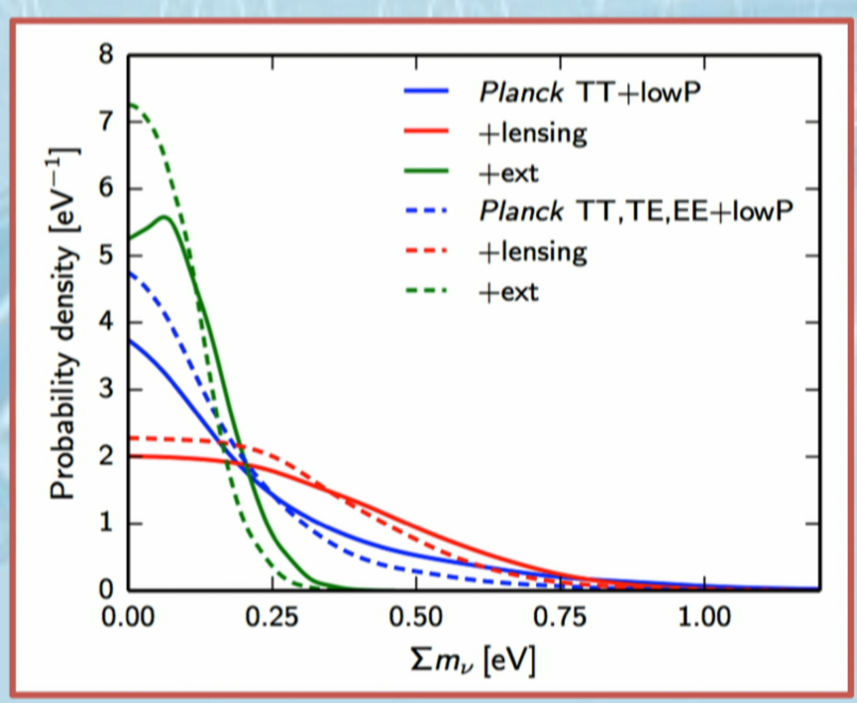

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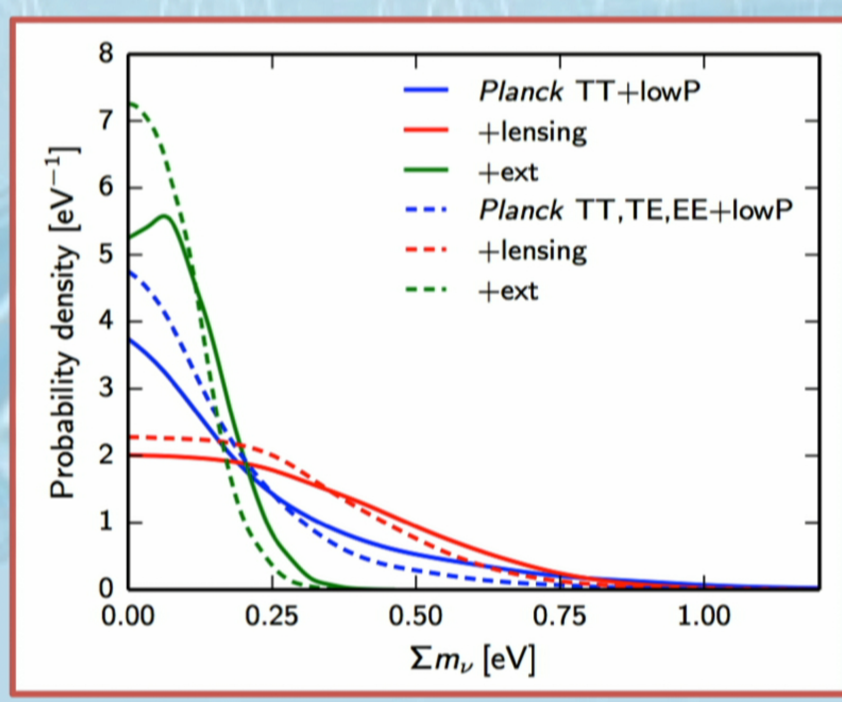

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Parameterised as "additional neutrino species".

$$\rho = N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$$

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Planck + BAO 68%:

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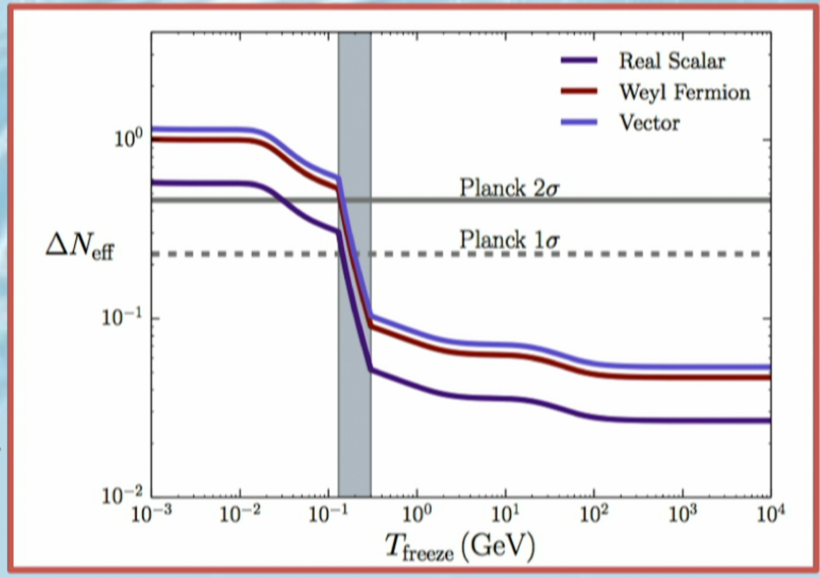
$$\Delta N_{\rm eff} = 0.027, 0.047, 0.054$$



CMB-S4 Science Book

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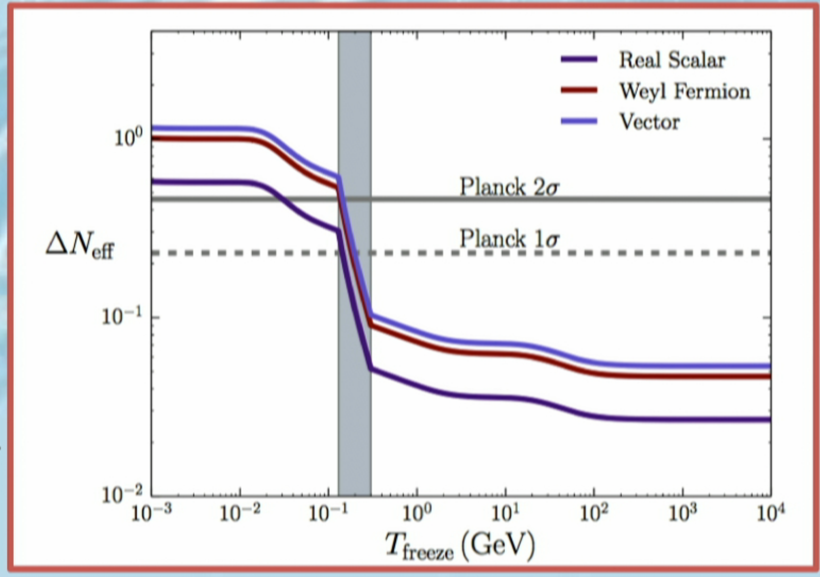

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Neutrino combinations

Planck 2015 Paper XIII

Are they really neutrinos? Test with perts.: $c^2_{\rm eff} = c^2_{\rm vis} = 1/3$

$$c^2_{\rm eff} = 0.3242 \pm 0.0059\,,\;\; c^2_{\rm vis} = 0.331 \pm 0.037$$

Sterile neutrinos:

$$N_{\rm eff} < 3.7$$

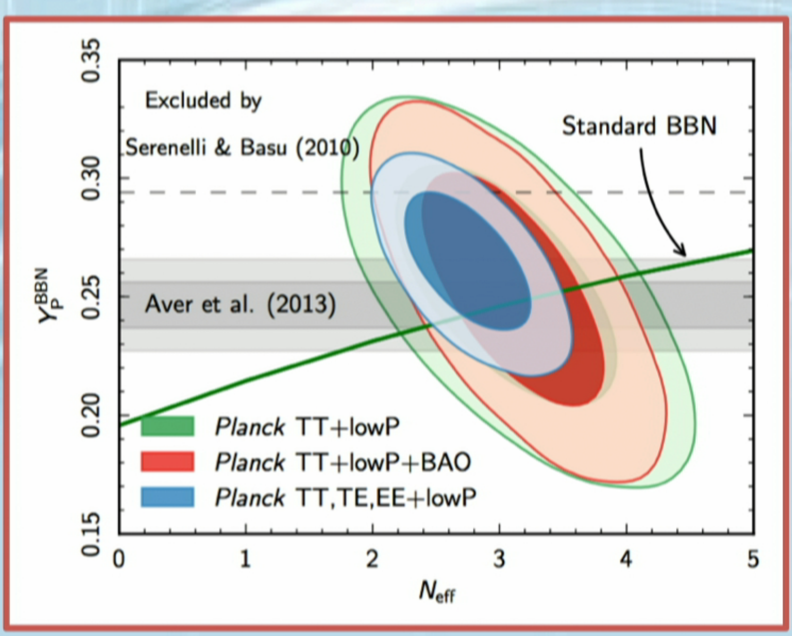
$$m^{\rm eff}_{\nu,\rm sterile} < 0.38 \text{ eV}$$

Massive standard + DR:

$$N_{\rm eff} = 3.2 \pm 0.5$$

$$\sum m_\nu < 0.32 \text{ eV}$$

Consistency with BBN:



Ultralight Axions (ULAs)

Hlozek et al (2015)

Cold, vacuum realignment axions change expansion rate and clustering relative to CDM if H<m on some scale of interest.

If ULAs are DM:

$$m_a \gtrsim 10^{-24} \text{ eV}$$

Constrained region:

$$\Omega_a h^2 < 0.006$$

Decay constant:

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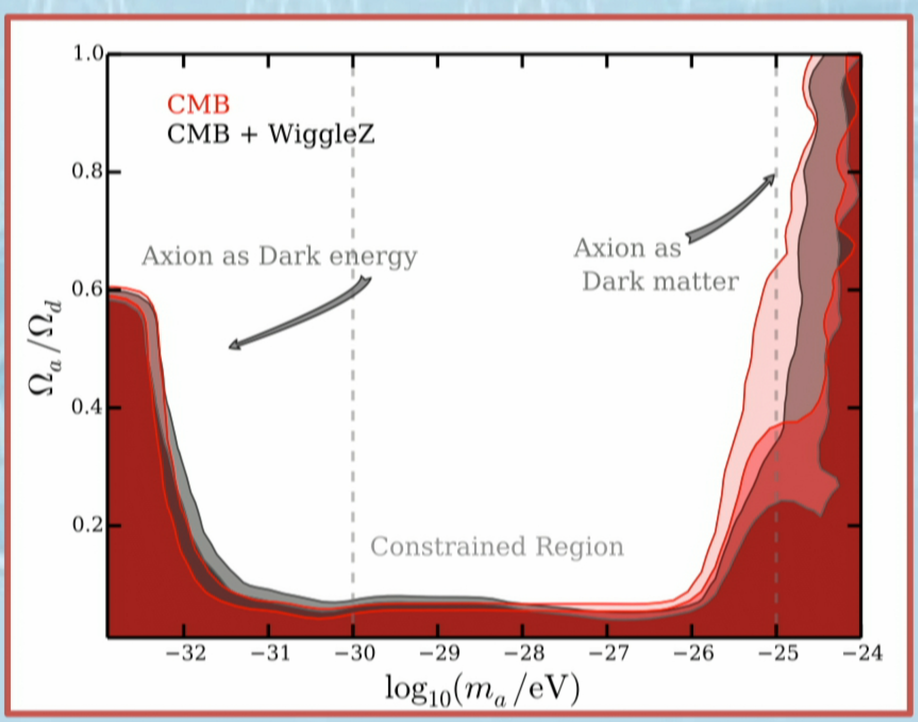

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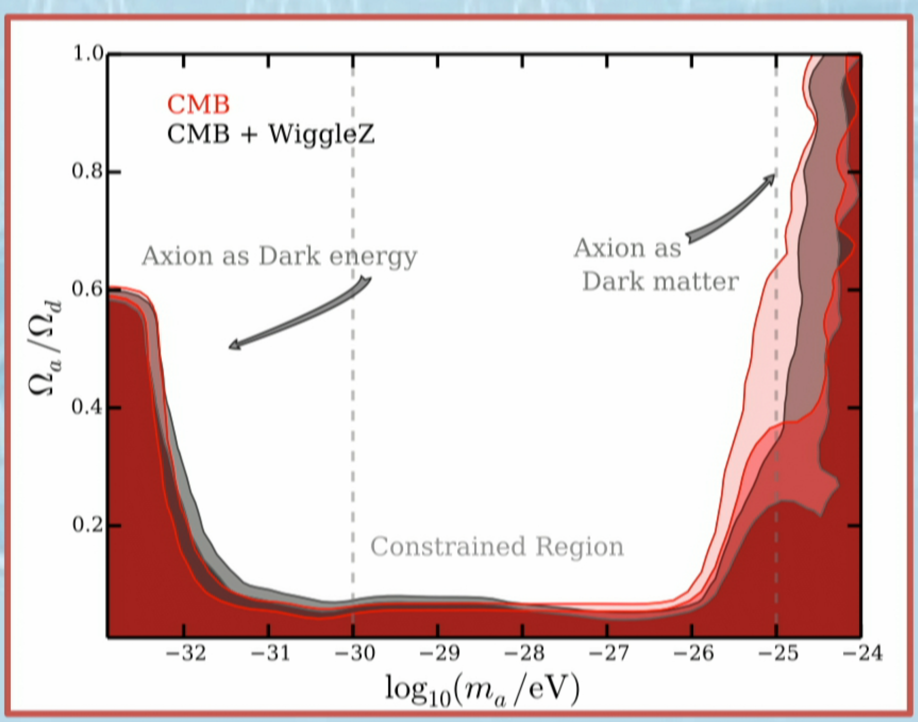

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Prospects from CMB-S4 (S4 Science Book; Allison et al, 2015; Hlozek et al, 2016)

Fisher Matrix Forecasts

Intro: e.g. Bassett et al (2011)

Approximate covariance matrix as inverse of Likelihood derivs

$$\mathcal{F}_{ij} = -\left\langle \frac{\partial^2 \ln P(\mathbf{D}|\Xi)}{\partial \Xi_i \partial \Xi_j} \right\rangle,$$

Assumes covariances are Gaussian: good for T, E, κ, not B.
White noise power spectrum, foreground-cleaned to l_{max}=3000 (TT, kk), 4000; (TE, EE), pol is cleaner.

$$N_\ell^{\alpha\alpha} = (\Delta\alpha)^2 \exp\left(\frac{\ell(\ell+1)\theta^2_{\mathrm{FWHM}}}{8\ln 2}\right), \quad (\alpha = \mathrm{T,E,}\kappa)$$

$f_{\rm sky}$	Beam size (arcmin)	ΔT (μK-arcmin)	$\Delta E, B$ (μK-arcmin)
0.4	1	1	1.4

lowP Planck, and τ prior.
LSS (e.g. DESI) with H_0 prior.

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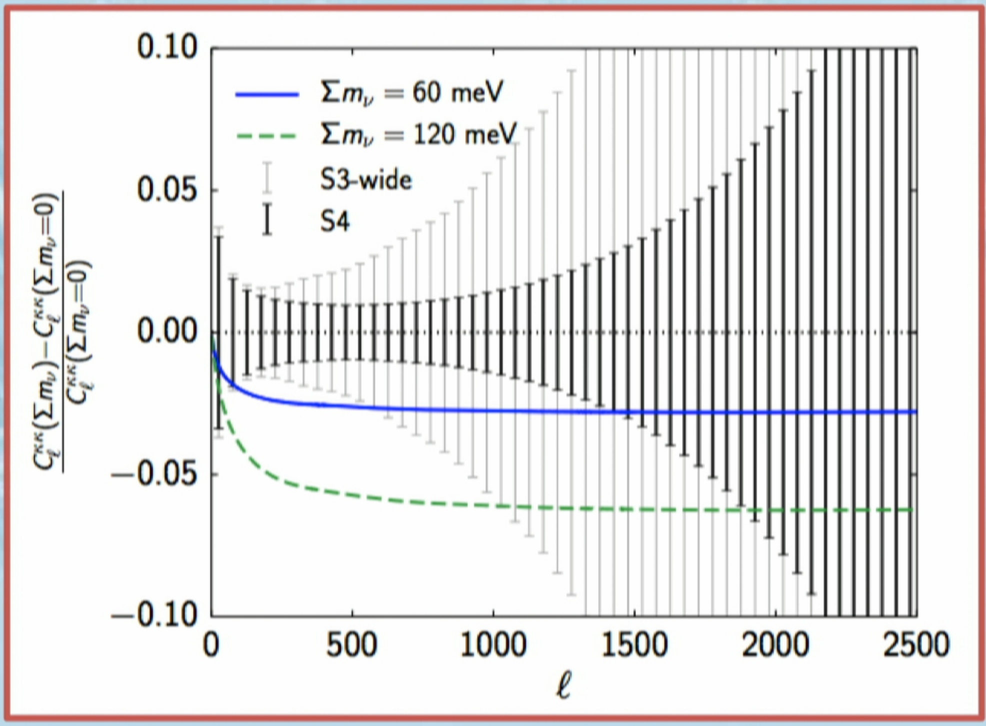
Detecting Neutrino Mass

Allison et al (2015)
CMB-S4 Science Book

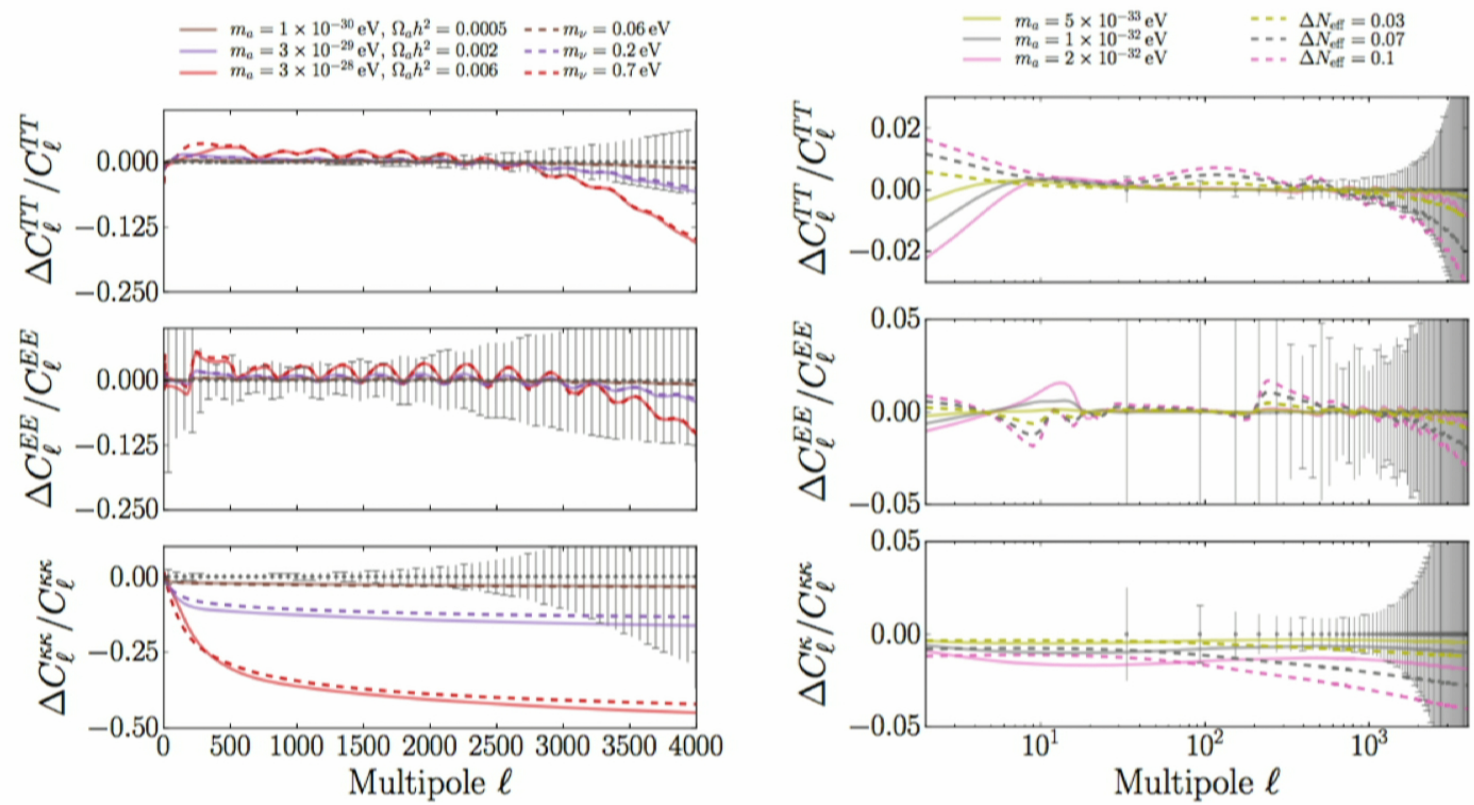
Neutrino mass seen by suppression of lensing power:



Need τ prior (low-l P) and BAO for Ω_m to break degeneracies
$\sigma(m_\nu)$ = 15 meV → 4σ detection in minimal (normal hierarchy)

ULA and Neutrino CMB Spectra

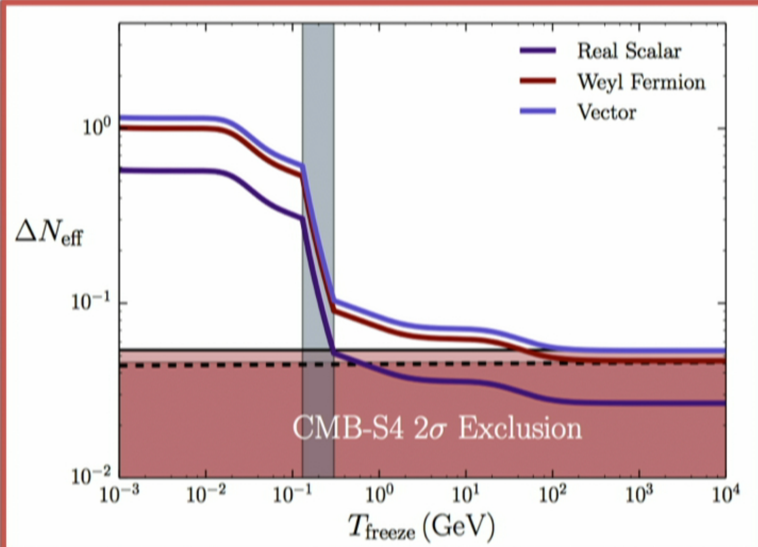
Choose axion models to try and mimic neutrinos.
Free streaming degenerate, DR versus DE background not.

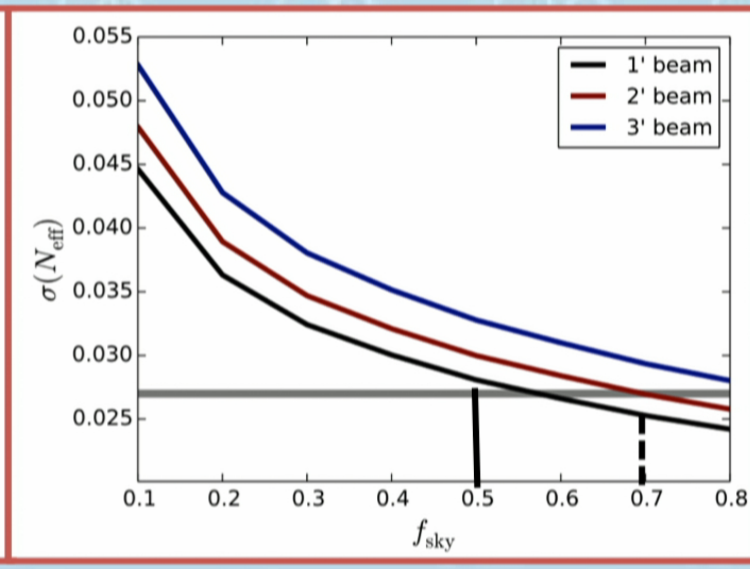


Relativistic Species

CMB-S4 Science Book

Factor O(10) improvement over Planck in $\sigma(N_{eff})$!



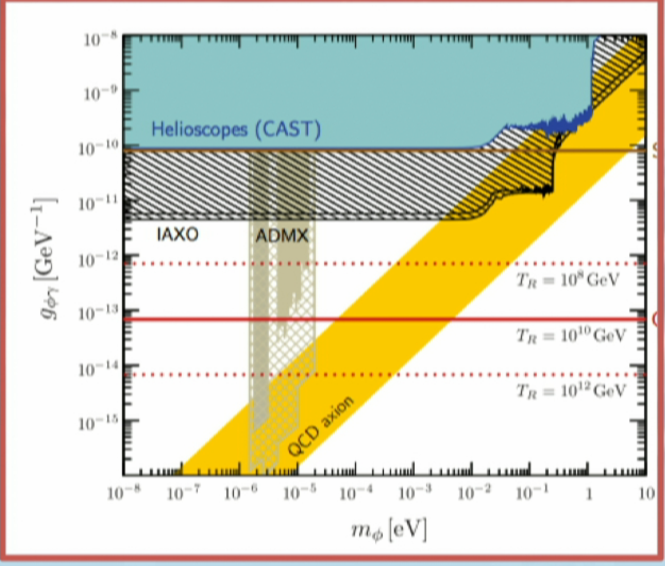


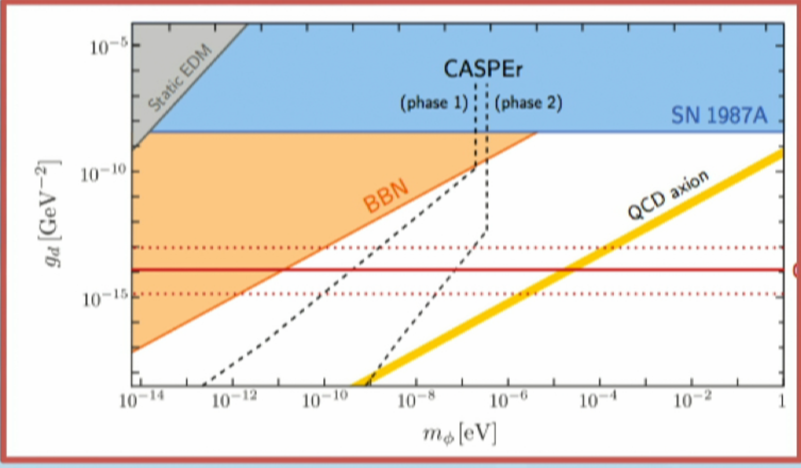
Reach 2σ exclusions for fermion and vector (1σ for scalar).
Survey design for narrow beam and wide survey
→ Possible conflict with science goals for B-modes?

Dark Radiation and Axions

Baumann et al (2016)
CMB-S4 Science Book

Thermal axions produced by photon or gluon couplings.
Contribution to N_{eff} depends on $T_F > T_{reh}$. Take $\Delta N_{eff}=0.027$.





Beat existing bounds, and assume nothing about axions as DM.

Isocurvature and Direct Detection

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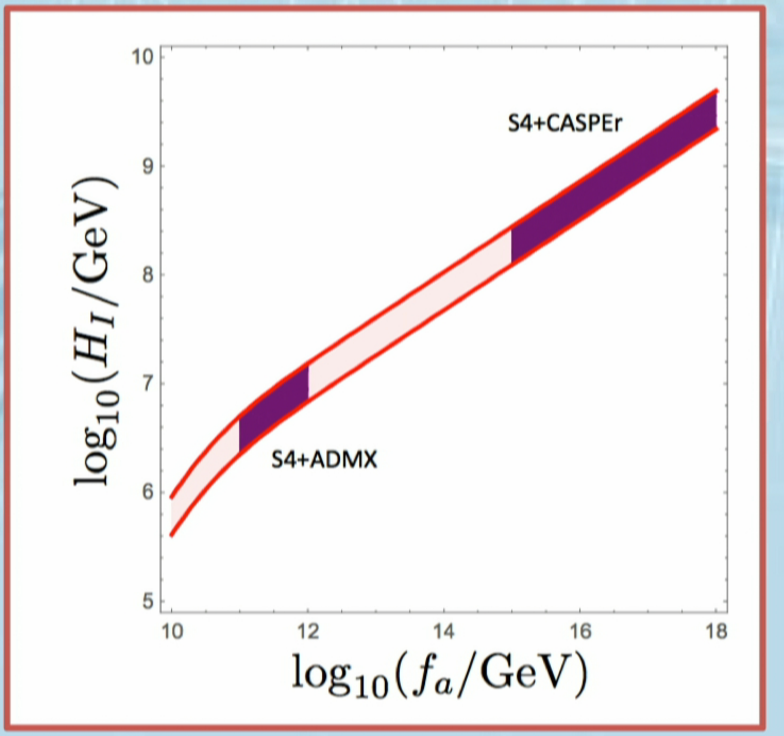
$$10^{6}\ \mathrm{GeV} \lesssim H_I \lesssim 10^{10}\ \mathrm{GeV}$$

Probe totally different range of inflationary models!

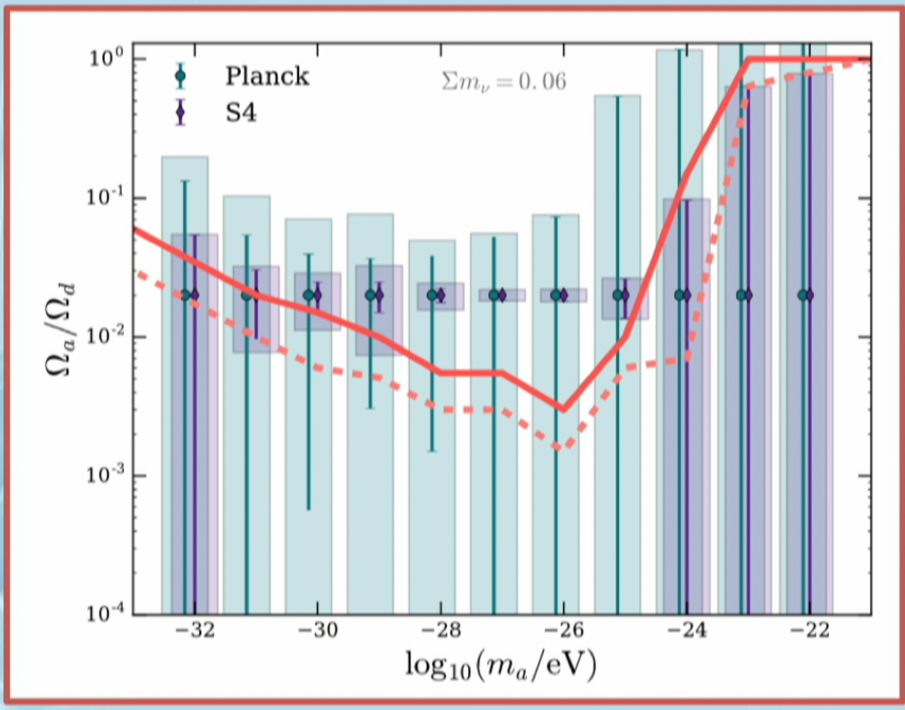


DJEM et al & CMB-S4 Science Book

ULAs and Tests of CDM

Hlozek et al (2016)

- Bin by mass, include neutrinos, ULA fraction consistent with Planck.
- Error bars: with/w-out marginalise over mν.
- Fiducial 2% ULAs detectable at > 13σ!
- Lines: 1 and 2σ exclusions.



CMB-S4 will test the “one component CDM paradigm” at the sub-percent level. Probes decay constants at < GUT scale.

ULAs and Tests of CDM

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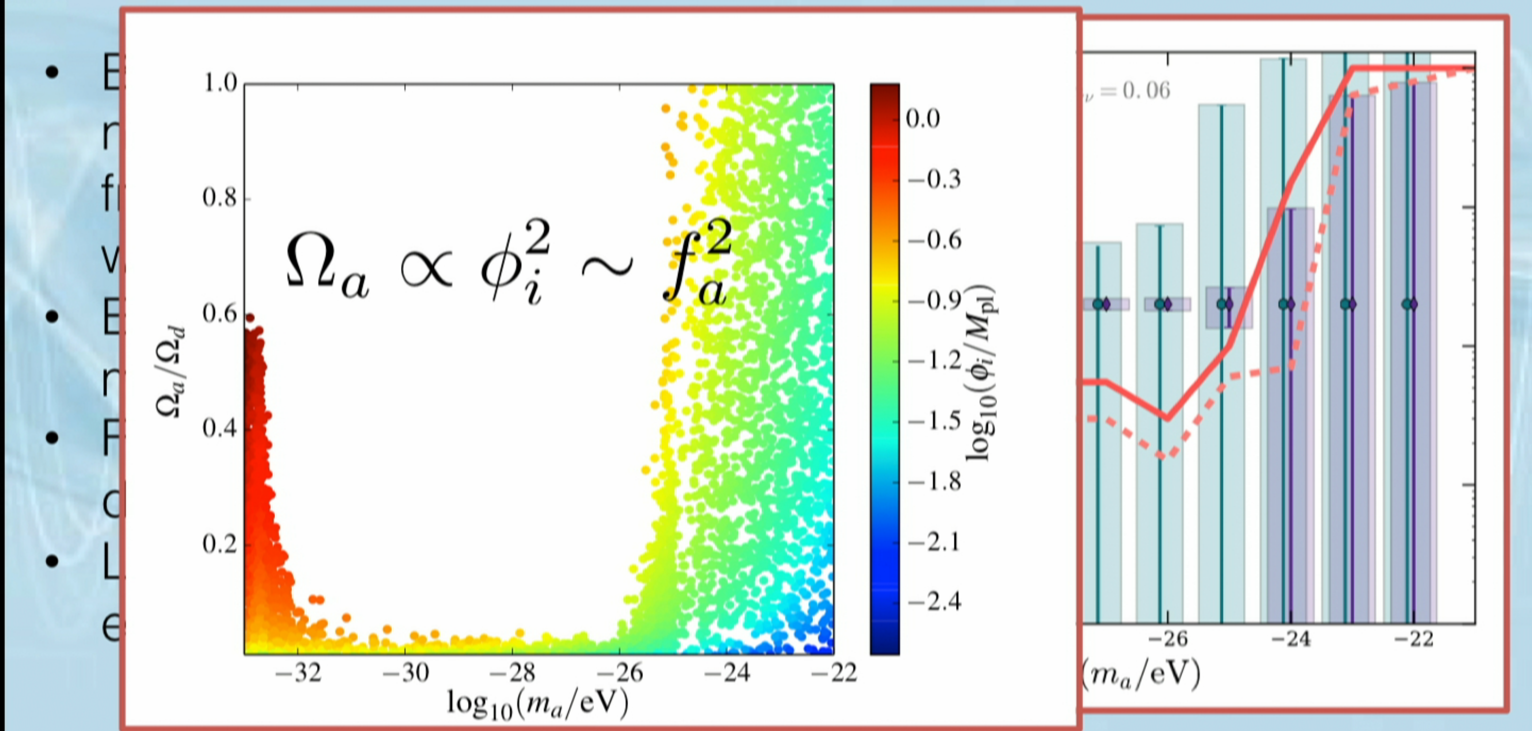

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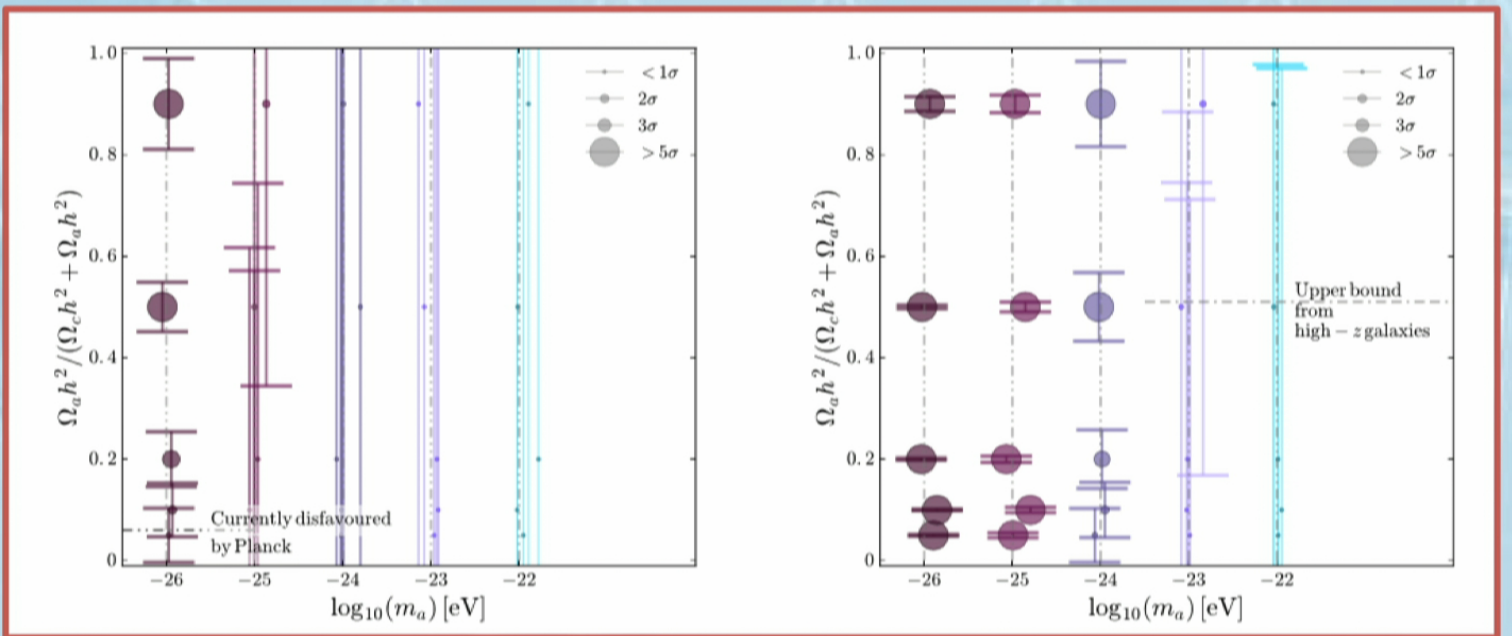
Lower limit on DM mass

Hlozek et al (2016)

Vary fiducial fraction. Ball-size → detection significance.



Improve precision region by 2 orders of magnitude over Planck. Exclude dominant DM at m~10^{-23} eV → contact to high-z galaxies and "Fuzzy DM" in small-scale-problems. e.g. DJEM & Silk (2013)

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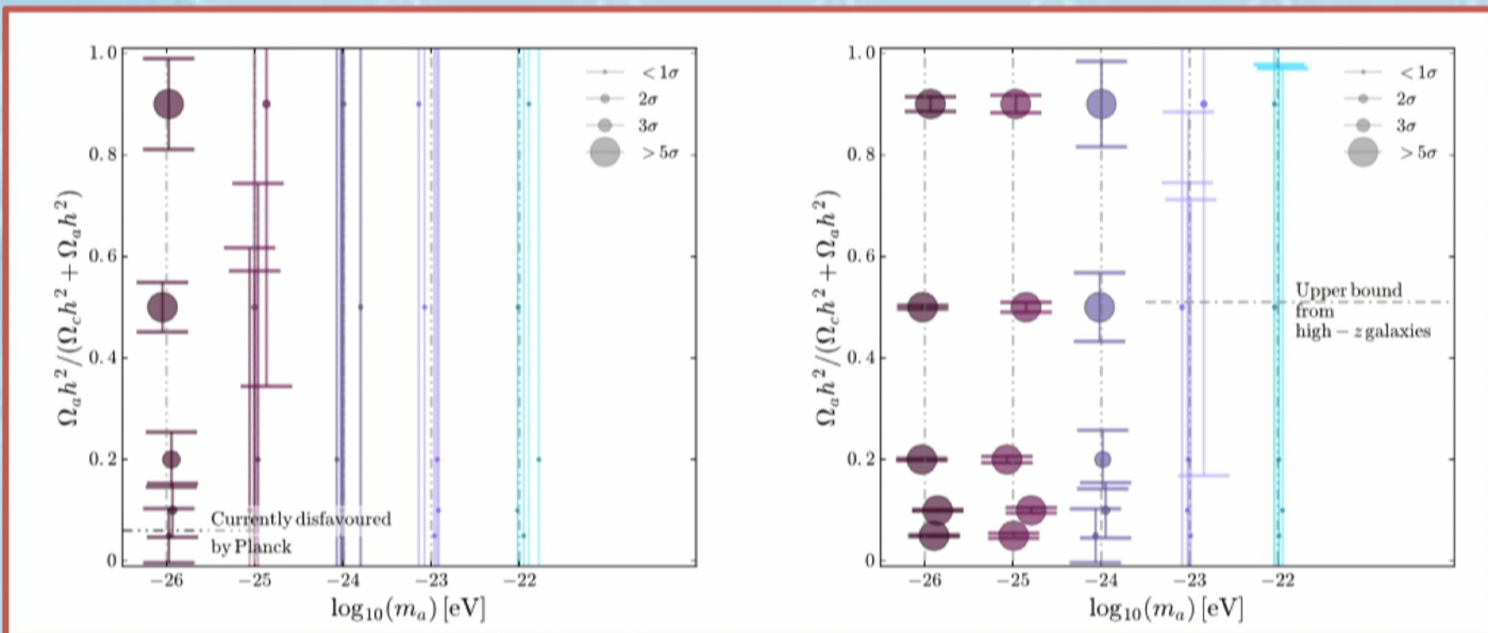

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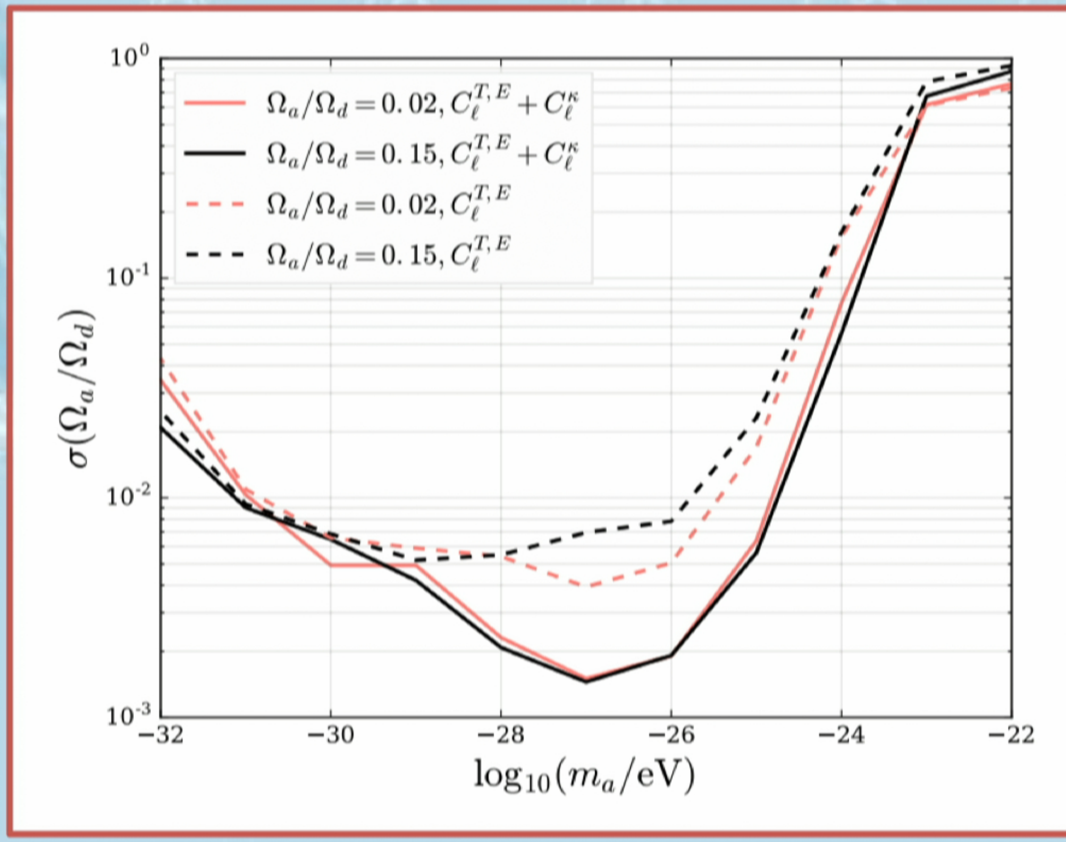
The Role of Lensing

Hlozek et al (2016)

Improvements by factor >2 for "DM-like". Important at high m.



Non-linear Axions and Lensing: A Cautionary Tale

DJEM: 1605.05973, Hlozek et al: 1607.08208

Lensing Power

Lensing is an intergral along the line of sight of the potential:

$$C_\ell^{\phi\phi} = \frac{8\pi^2}{\ell^3}\int_0^{z_{\rm rec}} dz \mathcal{P}_\Psi(\ell/x, z) x \frac{dx}{dz}\left(\frac{x_{\rm rec}-x}{x_{\rm rec}x}\right)^2 .$$

Potential related to matter dist. by Poisson equation. On small-scales/late times matter collapses into halos → non-lin.

$$\mathcal{P}_{\Psi,{\rm non-lin}}(k,z) = \frac{P_{m,{\rm non-lin}}(k,z)}{P_{m,{\rm lin}(k,z)}}\mathcal{P}_{\Psi,{\rm lin}}(k,z)$$

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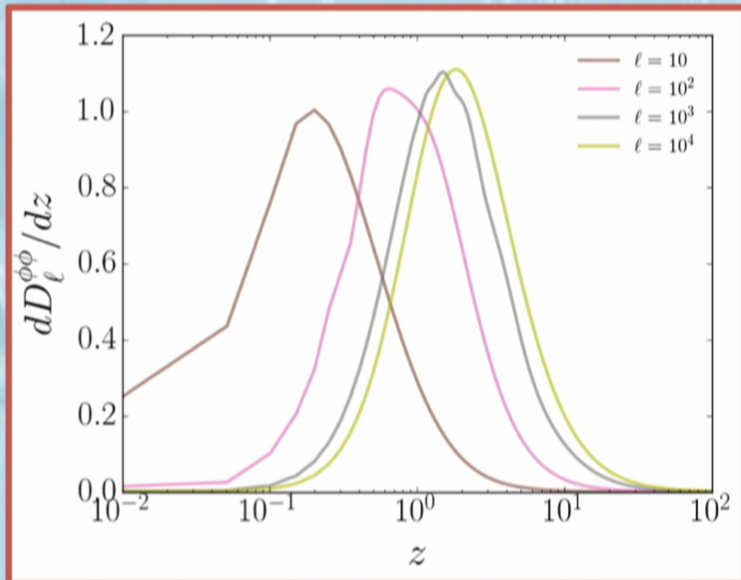
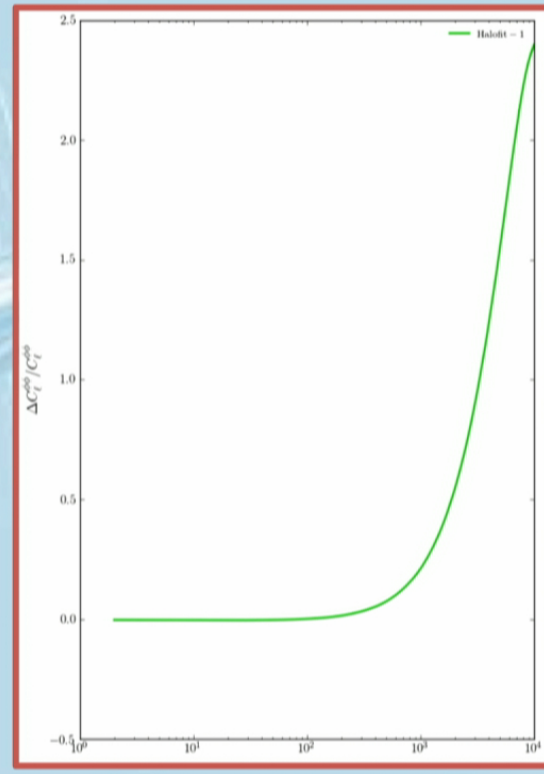
Need to approximate non-lin for integral. But how?
CAMB: uses "halofit" formula, from CDM(+ν) simulations.

Smith et al (2003), Bird et al (2012)

Lensing Power

When are non-linearities important?

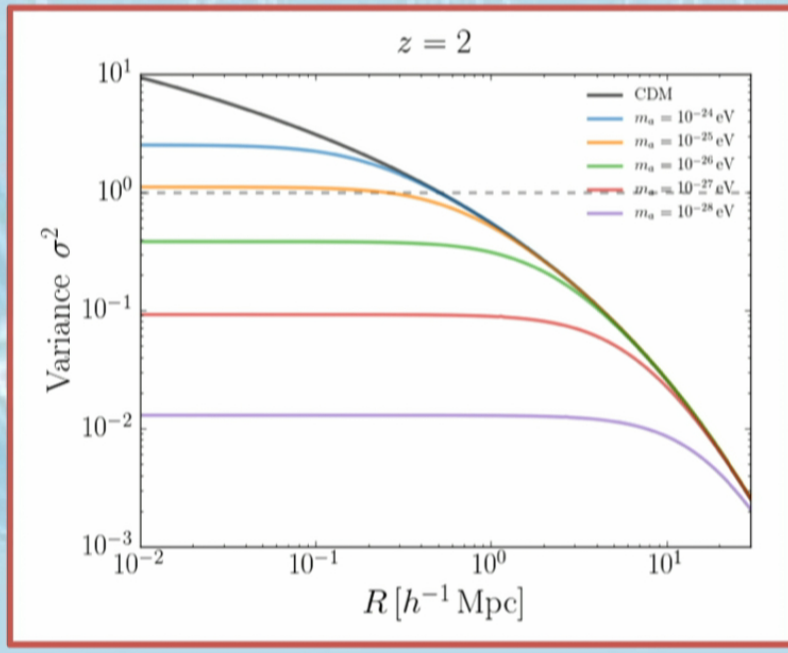




In lensing, >10% by l=1000, coming from collapse at z~2.

What do we treat as "collapsed"?

$\delta \sim 1$: Halofit defines non-linear scale from $\sigma_m^2(R_{nl})=1$.
Ideally, test this on a component basis. But let's cheat…



→ Only $m>10^{-25}$ eV non-lin on scales relevant to lensing.
(+sub-dominant and large Jeans → no effect on forecasts)

The Halo Model

e.g. Cooray and Sheth (2002)

For heavy axions as all DM, must use something better.
Halo model code “WarmAndFuzzy” for P(k). Mead et al (2015); DJEM (2016)

Image: Hlozek et al (2016)

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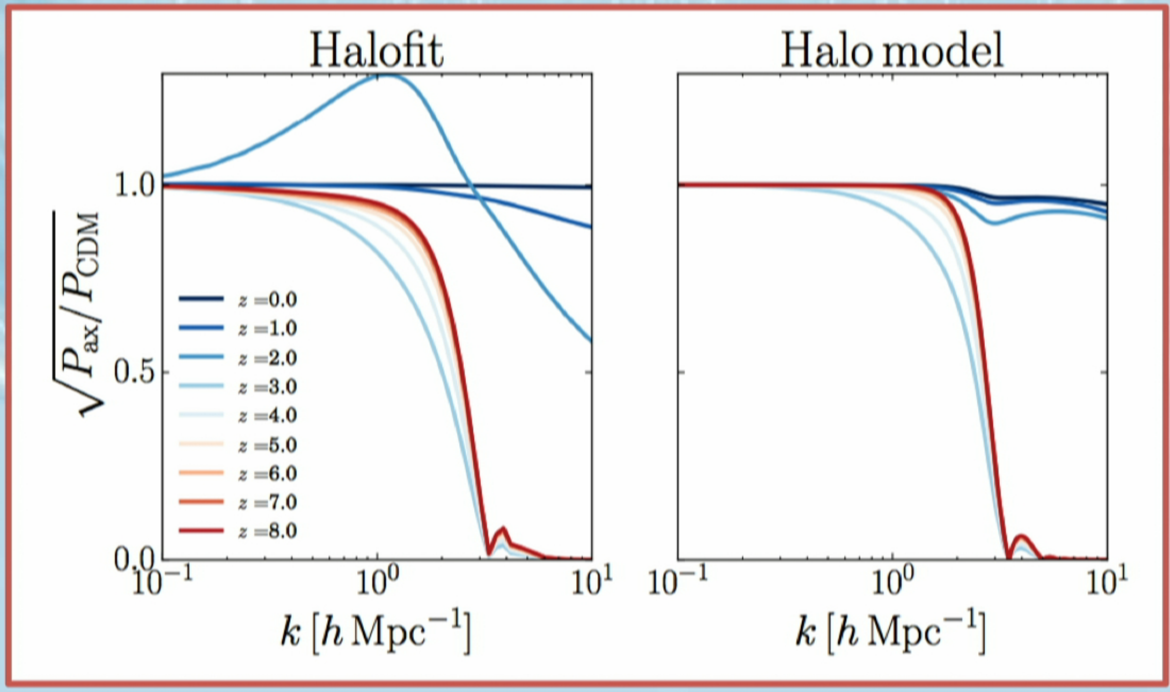
Image: Hlozek et al (2016)

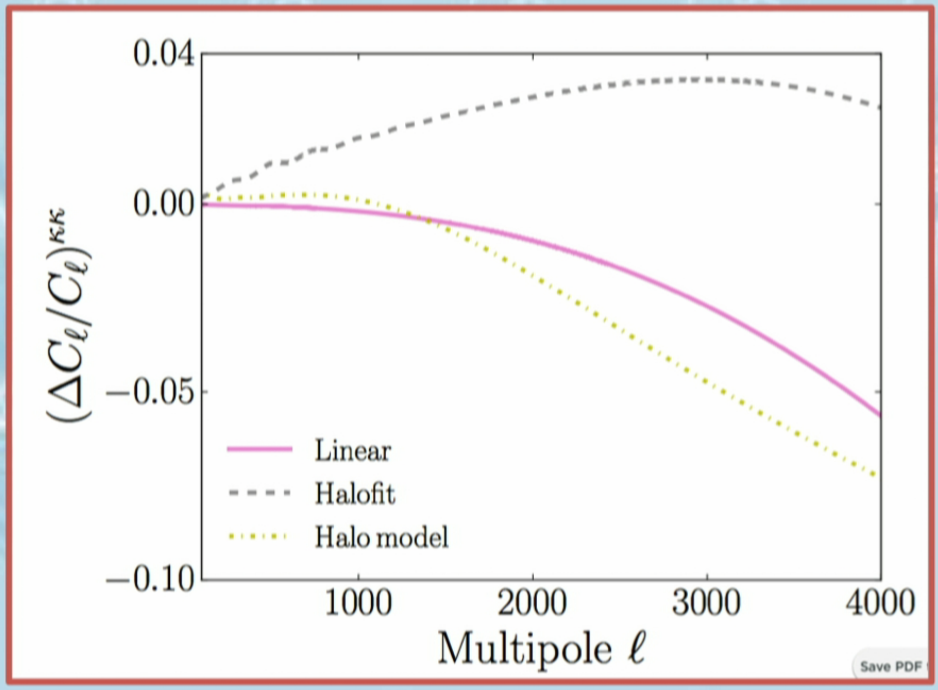


For most interesting masses m~10^{-23} eV Halofit goes v. wrong!

Halo Models and Lensing

Hlozek et al (2016)

Halo model NOT integrated into CAMB: need a quick fix.



Linear theory captures sign and magnitude of halo model.

→ Can use linear theory for forecasts, BUT NOT DATA!

Conclusions

- CMB-S4: proposed upgrades for 2020.
- Science goals: $\sigma(r)$~0.001, $\sigma(m_\nu)$~15 meV, $\sigma(N_{eff})$~0.027
- Extra DM science: neutrinos degeneracies, new light species, isocurvature and axion detection.
- Axions: detect ~1% fractions at many σ → test CDM paradigm over a vast range of scales!
- Lower limit on DM mass improved by ~2 orders of magnitude. Requires new understanding of non-lin effects.

Things I have left out: DM annihilations and ionization, sterile neutrinos, neutrino hierarchy, DE/Modified Gravity, B-modes, de-lensing, foregrounds …

Contributing yourself, via github: fork us!
axionCAMB: github.com/dgrin1/axionCAMB
WarmAndFuzzy: github.com/DoddyPhysics/HMcode

Black hole formation from axion stars

Thomas Helfer,[1] David J. E. Marsh,[1] Katy Clough,[1] Malcolm Fairbairn,[1] Eugene A. Lim,[1] and Ricardo Becerril[2]
[1] *King's College London, Strand, London, WC2R 2LS, United Kingdom*
[2] *Instituto de Física y Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Ciudad Universitaria, CP 58040 Morelia, Michoacn, Mexico.*
(Dated: September 11, 2016)

The classical equations of motion for an axion with potential $V(\phi) = m_a^2 f_a^2[1 - \cos(\phi/f_a)]$ possess quasi-stable, localized, oscillating solutions, which we refer to as "axion stars". We study, for the first time, collapse of axion stars numerically using the full non-linear Einstein equations of general relativity and the full non-perturbative cosine potential. We map regions on an "axion star stability diagram", parameterized by the initial ADM mass, $M_{\rm ADM}$, and axion decay constant, f_a. We

Unbiased constraint on ultralight axions from dwarf spheroidal galaxies

Alma X. Gonzalez-Morales[1,2*], David J. E. Marsh[3], Jorge Peñarrubia[4], and Luis Ureña-Lopez[2]
[1] *Division de Ciencias e ingenierias, Universidad de Guanajuato, Leon, Guanajuato, Mexico*
[2] *CONACYT*
[3] *Department of Physics, King's College London, Strand, London, WC2R 2LS, UK*
[4] *Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK*