Detection of early dark energy through CMB rotation spectrum

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The Hubble tension

- Local measurements of H_0 provide larger values than what is inferred from cosmological observables.
- Local measurements are dependent on the distance ladder. Parallax + Cepheid Variable + SNe 1a
- Calibration done in several independent manners.
- Cosmological measurement from CMB and BAO data.
- These can be considered independent and provide similar values

The Hubble tension

- Latest local measurement from Riess et al. Astrophys. J. 876, 85 (2019). SNe 1a at redshifts z~0.5
- Measurement of Cepheids in Large Magellanic Cloud (LMC).
- Cepheids have a known relationship of period vs luminosity.
- Calibration of the relationship is done by independently measuring the distance to the Cepheids. Several independent methods exist (Masers, DEBs, Parallax)
- SNE 1a are a standard candle. Cepheids are used to calibrate the SNe 1a

The Hubble tension

- Cosmological measurement from Baryon Acoustic Oscillations(BAO) and PLANCK CMB Data.
- Can be considered independent variables.
- Lower values of H_0 are inferred
- This suggests systematics in the data are not the cause.
- But inferences are dependent on ΛCDM.

The Hubble tension

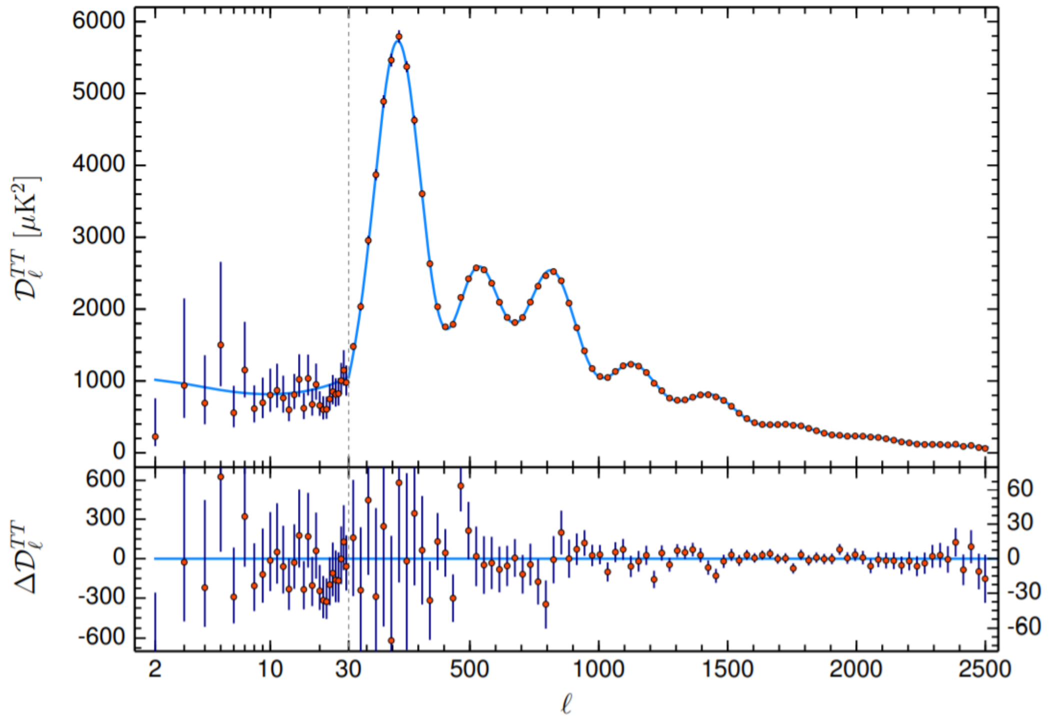
- Riess et al. Astrophys. J. 876, 85 (2019), local measurement

$$H_0 = (74.03 \pm 1.42) km/s/Mpc$$

- Planck Collaboration 2018

$$H_0 = (67.4 \pm 0.5) km/s/Mpc$$

CMB Power Spectrum



Planck2018

- Power spectrum determined by oscillations of primordial plasma.
- Two scales. Sound horizon at decoupling determines locations of peak. Damping scale at large L.
- Depend on H, or fluid content, before decoupling.
- Angular distance to LSS. Depends on H *today.*

$$r_s(\tau_{LSS}) = \int c_s \frac{da}{aH} \quad \frac{1}{k_D^2} = \int \frac{da}{2a^3 H n_e \sigma_T} \frac{R}{1+R}\left(\frac{8}{27} + \frac{c_s^2}{R^2}\right)$$

CMB Power Spectrum

- Peak positions of CMB TT spectrum well measured. Ratio of sound horizon to angular distance.
- Increasing H_0 leads to smaller angular distance -> larger subtended angles of peaks.
- If sound horizon decreased by the same amount, by some new physics, measured position of peaks would be the same.

$$r_s(\tau_{LSS}) = \int c_s \frac{da}{aH}$$

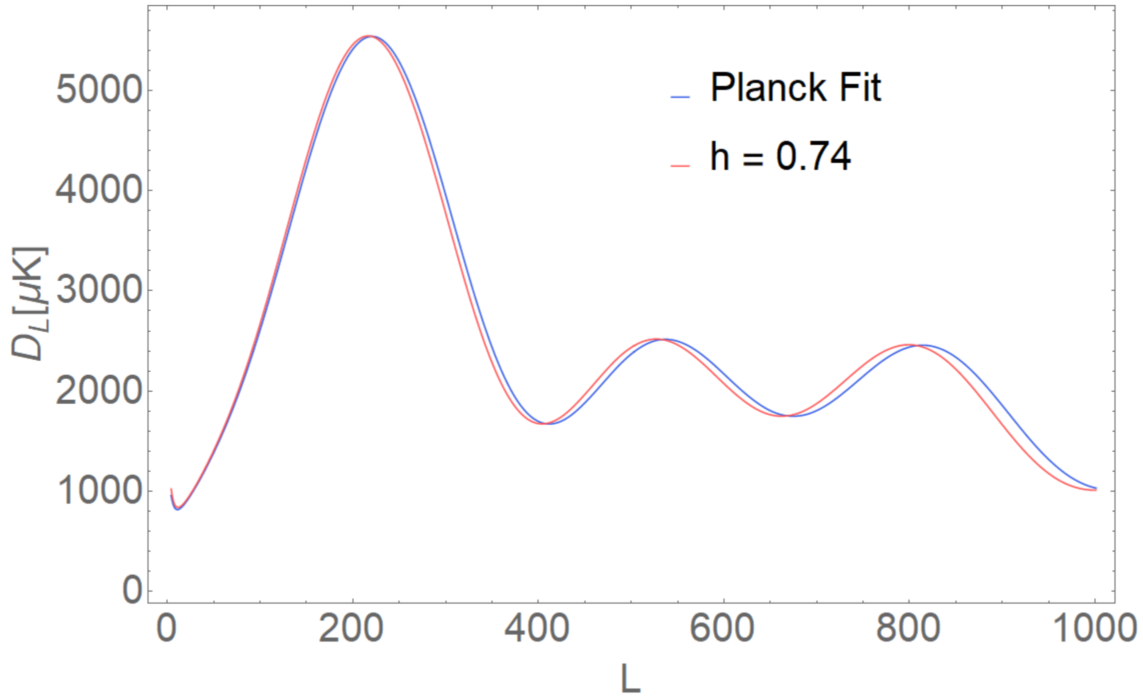
Probing the dark sector?

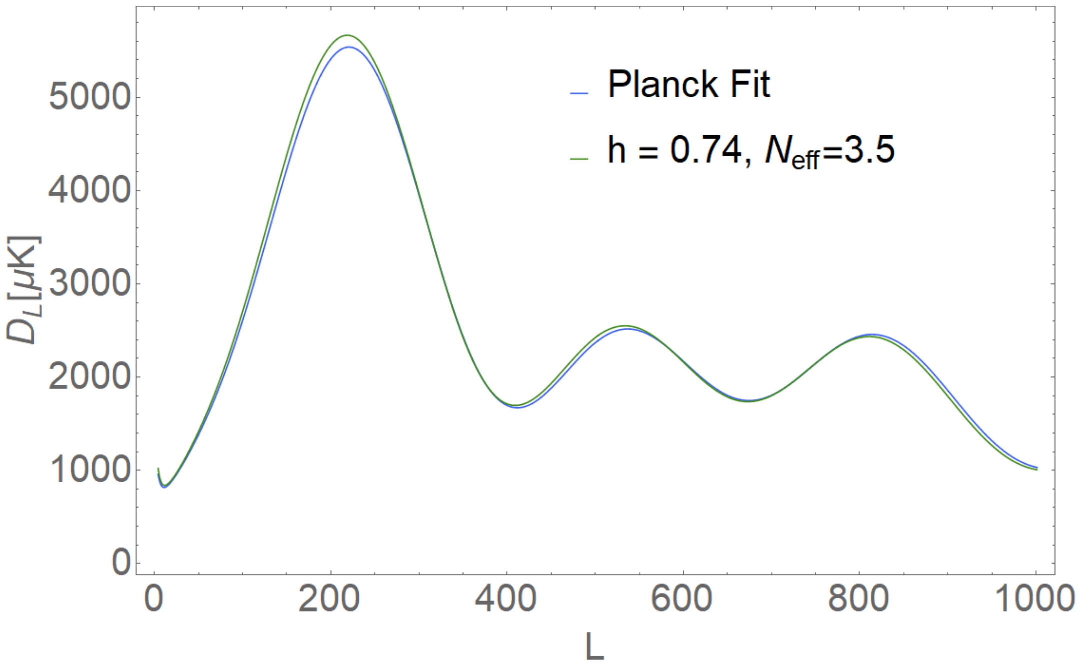
- Idea. Could an extra non-interacting ultra-relativistic component in the early universe solve the tension?
- Increasing H before decoupling decreases sound horizon.

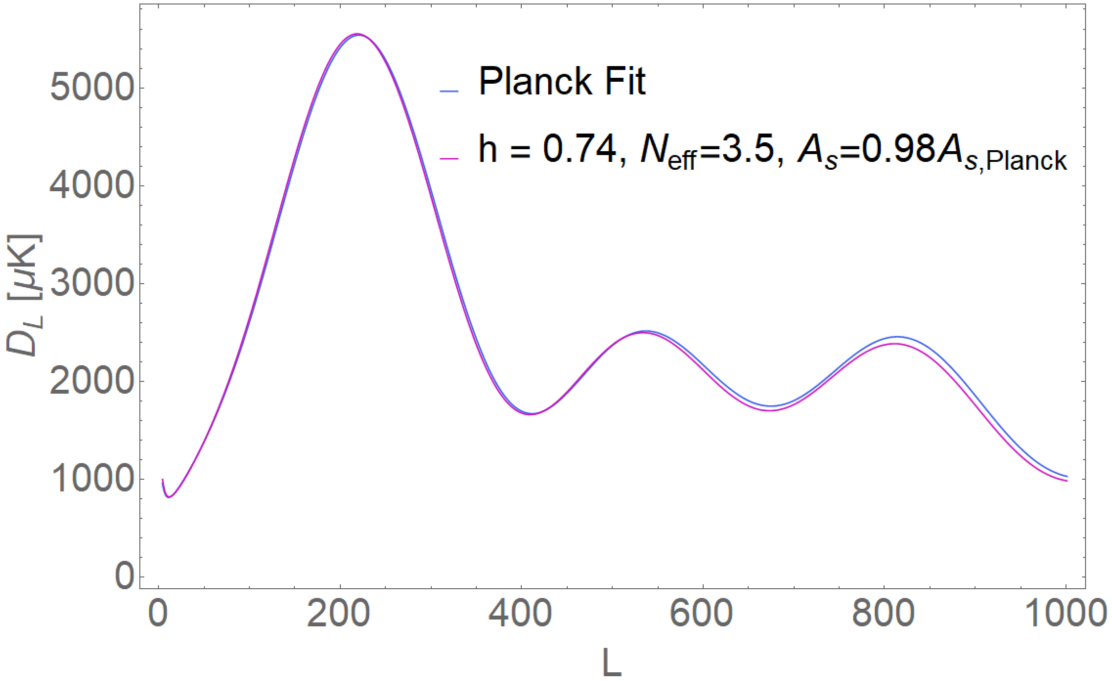
$$\rho_{ur} = (N_{eff} + \Delta N_{eff})\rho_\nu \qquad r_s(\tau_{LSS}) = \int c_s \frac{da}{aH}$$

- N_{eff} = 3.046 in the SM. Planck measurement: $N_{eff} = 3.0 \pm 0.5$

Probing the dark sector?







Doesn't work, even when adjusting other parameters.
Too much damping at large scales.

Computed with CLASS Boltzmann code
D. Blas, J. Lesgourgues, T. Tram, JCAP 1107 (2011) 034
http://class-code.net/

Probing the dark sector?

- Fixing the horizon scale affects the damping scale. Different dependencies on primordial H.
- Also problems in BAO spectra.
- Cosmic scalar field, or early dark energy (EDE) may work. Poulin, Smith, Karwal, Kamionkowski, Phys. Rev. Lett. **122**
- Diffusion scale depends on H before matter-radiation equality, as modes enter the horizon sooner.
- Sound horizon on H until decoupling.
- Add a component which decays at ~ matter-radiation equality

$$\frac{1}{k_D^2} = \int \frac{da}{2a^3 H n_e \sigma_T} \frac{R}{1+R}\left(\frac{8}{27} + \frac{c_s^2}{R^2}\right)$$

Cosmic scalar field

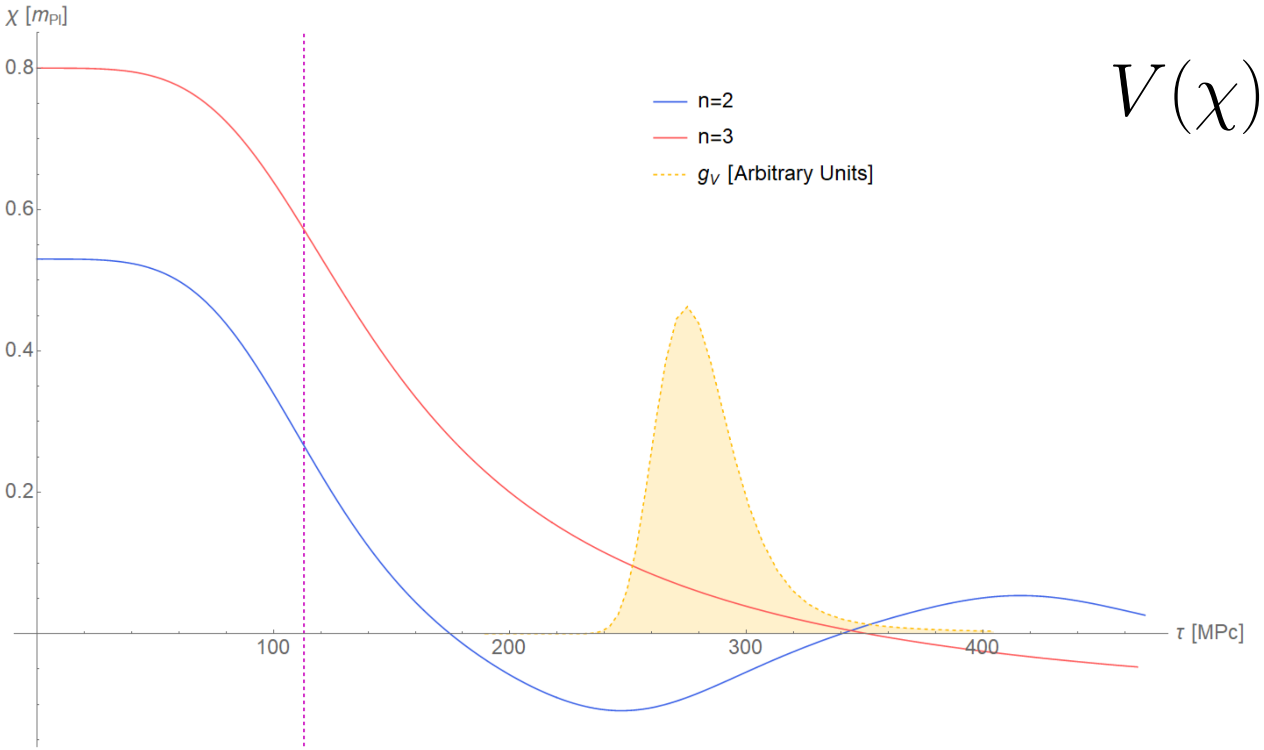
- Evolution frozen at early times. Dark energy component w≈-1. Then coherent oscillations.
- At late times dilutes as matter, radiation, or faster, according to form of potential.

$$\ddot{\bar{\chi}} + 2\mathcal{H}\dot{\bar{\chi}} + a^2\frac{dV}{d\chi} = 0 \qquad \chi(\tau,\vec{x}) = \bar{\chi}(\tau) + \delta\chi(\tau,\vec{x})$$

$$\delta\ddot{\chi} + 2\mathcal{H}\delta\dot{\chi} + k^2\delta\chi + a^2V''(\bar{\chi})\delta\chi = \dot{\bar{\chi}}(\dot{\psi} + 3\dot{\phi}) - 2a^2\psi V'(\bar{\chi})$$

Conformal-Newtonian Gauge

PNGB Cosmic scalar field

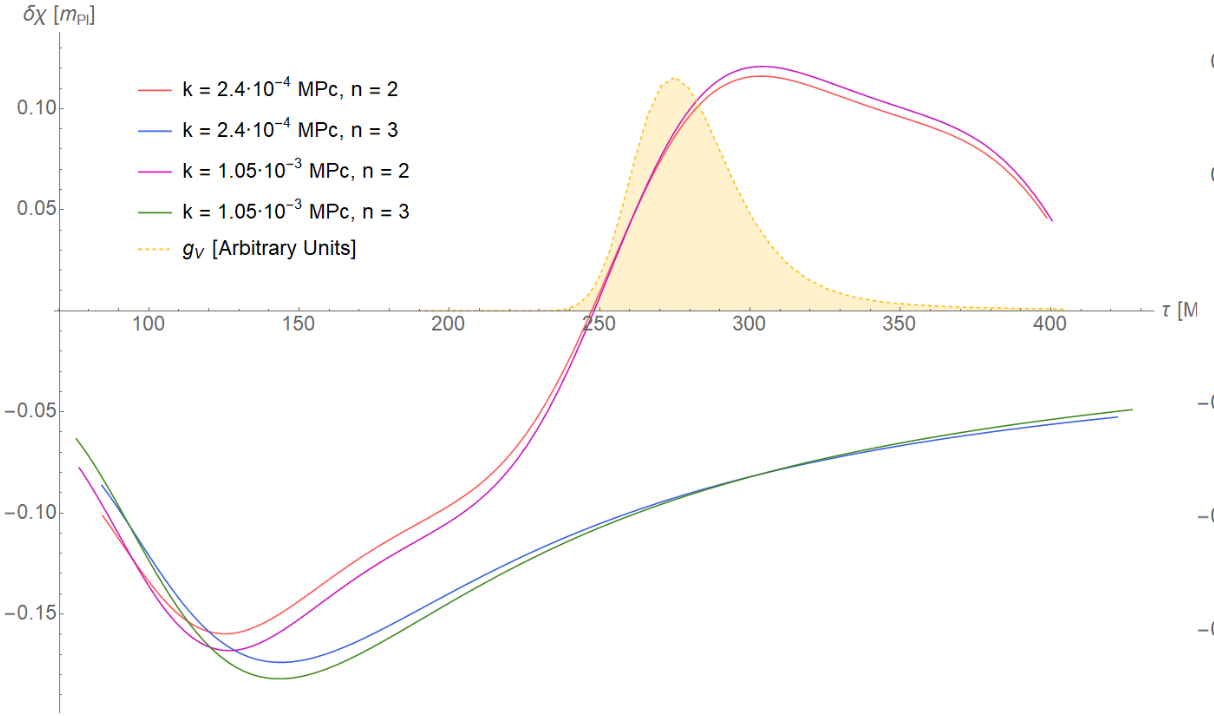


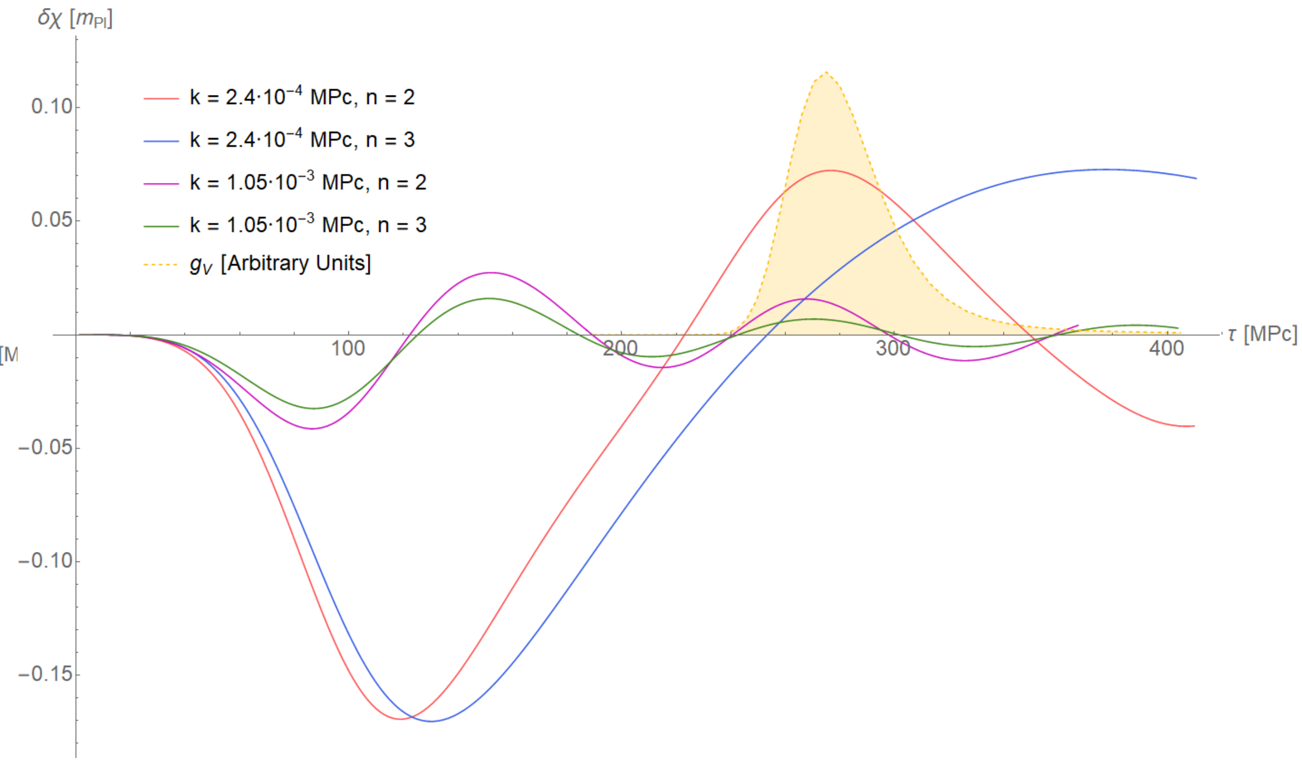
$$V(\chi) = \Lambda^4 (1 - \cos\frac{\chi}{f})^n$$

- PNGB potential. n=1 cannot solve Hubble tension
- "Thawing" depends on parameters.
- Anomalous expansion only in radiation dominated era, less so in matter dominated one.

Scalar field perturbations

- Must be studied consistently with other primordial perturbations (photons, neutrinos, baryons and dark matter).





At small ks, potential is important in determining evolution. At larger ks, less so

Cosmic Birefringence

- EDE fits data within error and alleviates Hubble tension. Can we discern EDE?
- Cosmic birefringence. Rotation of CMB polarization on the sky with scalar field.

$$\mathcal{L}_{\chi\gamma\gamma} = \frac{G_{\chi\gamma\gamma}}{4}\chi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Causes rotation of E modes into B modes.
- Can be cast into *rotation power spectrum, and cross correlation with temperature*

$$C_\ell^{EB} \neq 0, C_\ell^{TB} \neq 0 \qquad C_\ell^{\alpha\alpha}, C_\ell^{\alpha T}$$

- Rotation angle given by difference of field at emission and

detection.

$$\alpha = \frac{G_{\chi\gamma\gamma}}{2}\Delta\chi$$

Cosmic Birefringence

- Uniform rotation angle accounts for probability distribution of photon emission at decoupling. The visibility function.

$$\bar{\alpha}(\tau) = -\frac{G_{\chi\gamma\gamma}}{2}\int_0^{\tau} d\tau' g(\tau')\bar{\chi}(\tau')$$

- Perturbations to the scalar field cause a non-uniform rotation across the sky: rotation power spectrum.
- Also perturbations to the time of emission. Perturbed visibility function through perturbed electron density.
- Usually electron perturbation not tracked by Boltzmann codes. Assume $\delta n_e \simeq \delta_b n_e$; tight coupling!

Cosmic Birefringence

- Perturb the integral and find the rotation transfer function today

$$\Delta_{\alpha,\ell}(k) = \int_0^{\tau_0} d\tau S(\vec{k},\tau) j_\ell(k(\tau_0-\tau))$$

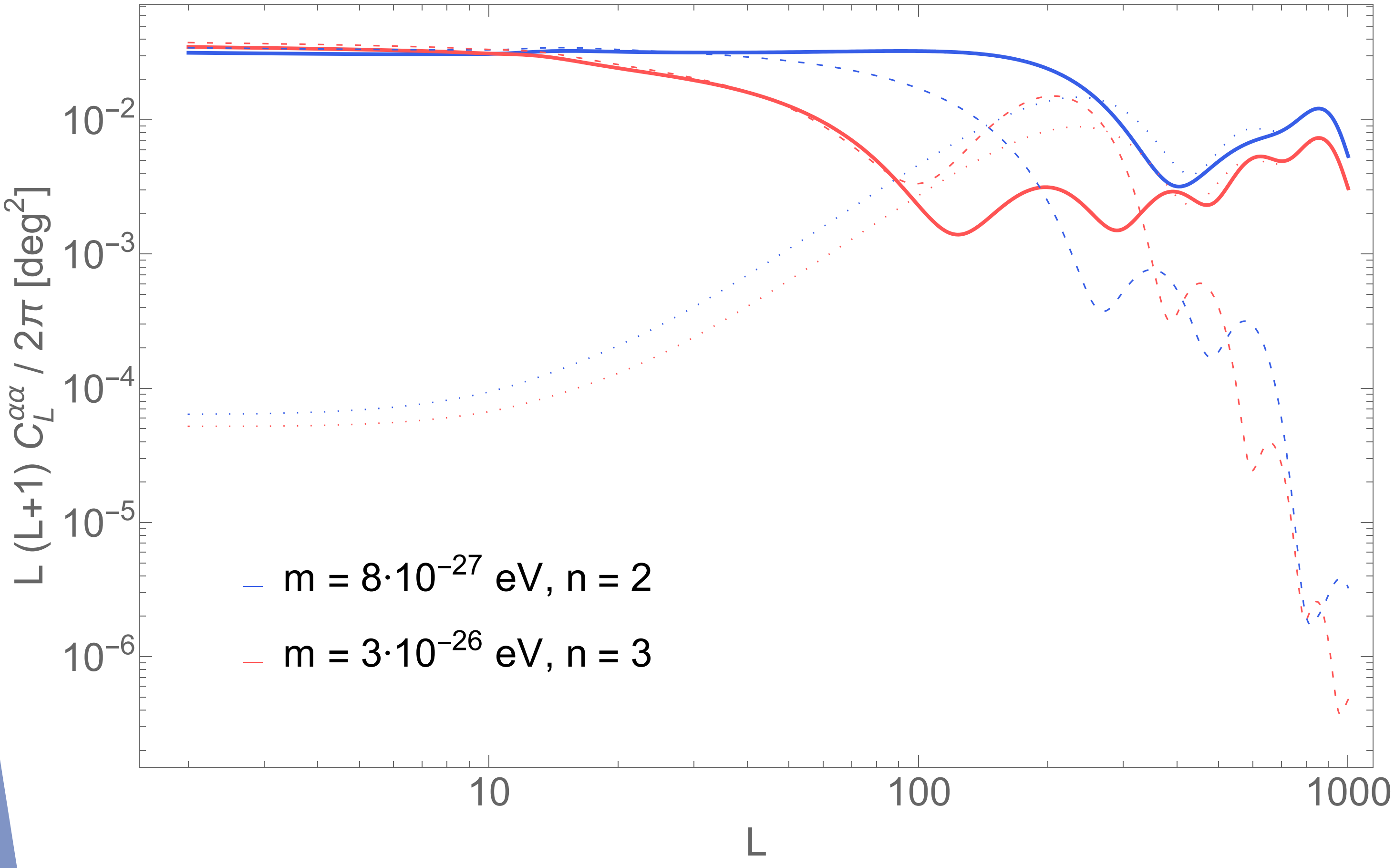
- The source is also due to matter and metric perturbations.

$$S(\tau,\vec{k}) = -g(\tau)\left(\frac{1}{2}G_{\chi\gamma\gamma}\delta\chi + (\bar{\alpha} + \frac{1}{2}G_{\chi\gamma\gamma}\bar{\chi})(2\psi+\delta_b)\right)$$

- Rotation spectrum and cross correlation

$$C_\ell^{\alpha X} = \frac{2}{\pi}\int k^2 dk P_\psi(k)\Delta_{\alpha,\ell}(k)\Delta_{X,\ell}(k)$$

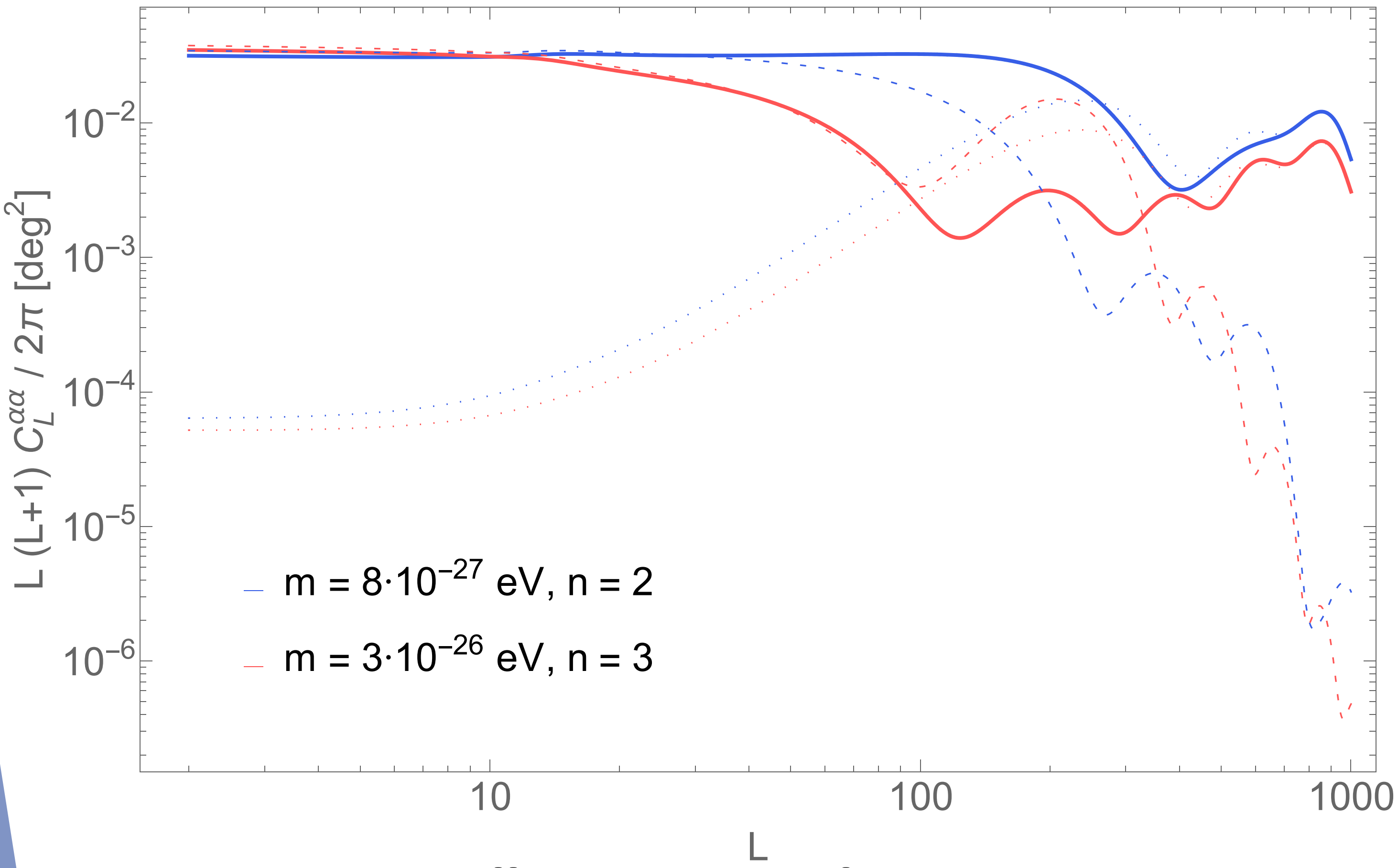
Rotation spectra



Solid: total.
Dashed: field perturbations.
Dotted: matter perturbation

Acoustic oscillations contribute

Rotation spectra

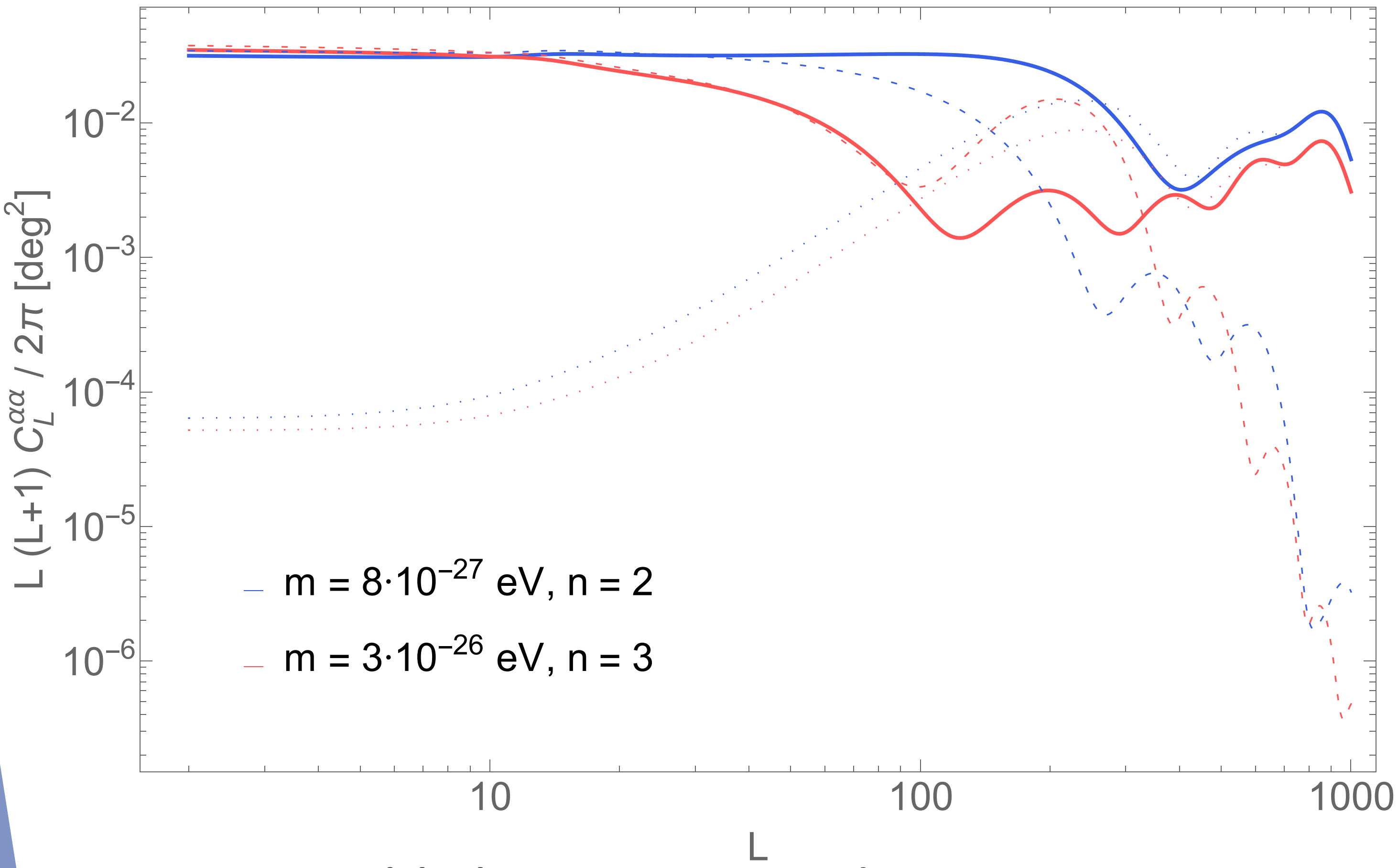


Solid: total.
Dashed: field perturbations.
Dotted: matter perturbation

$$G_{\chi\gamma\gamma} = 10^{-15} GeV$$

- **Acoustic oscillations contribute**
- With this coupling, slightly below experimental limits ~1deg^2

Rotation spectra



Solid: total.
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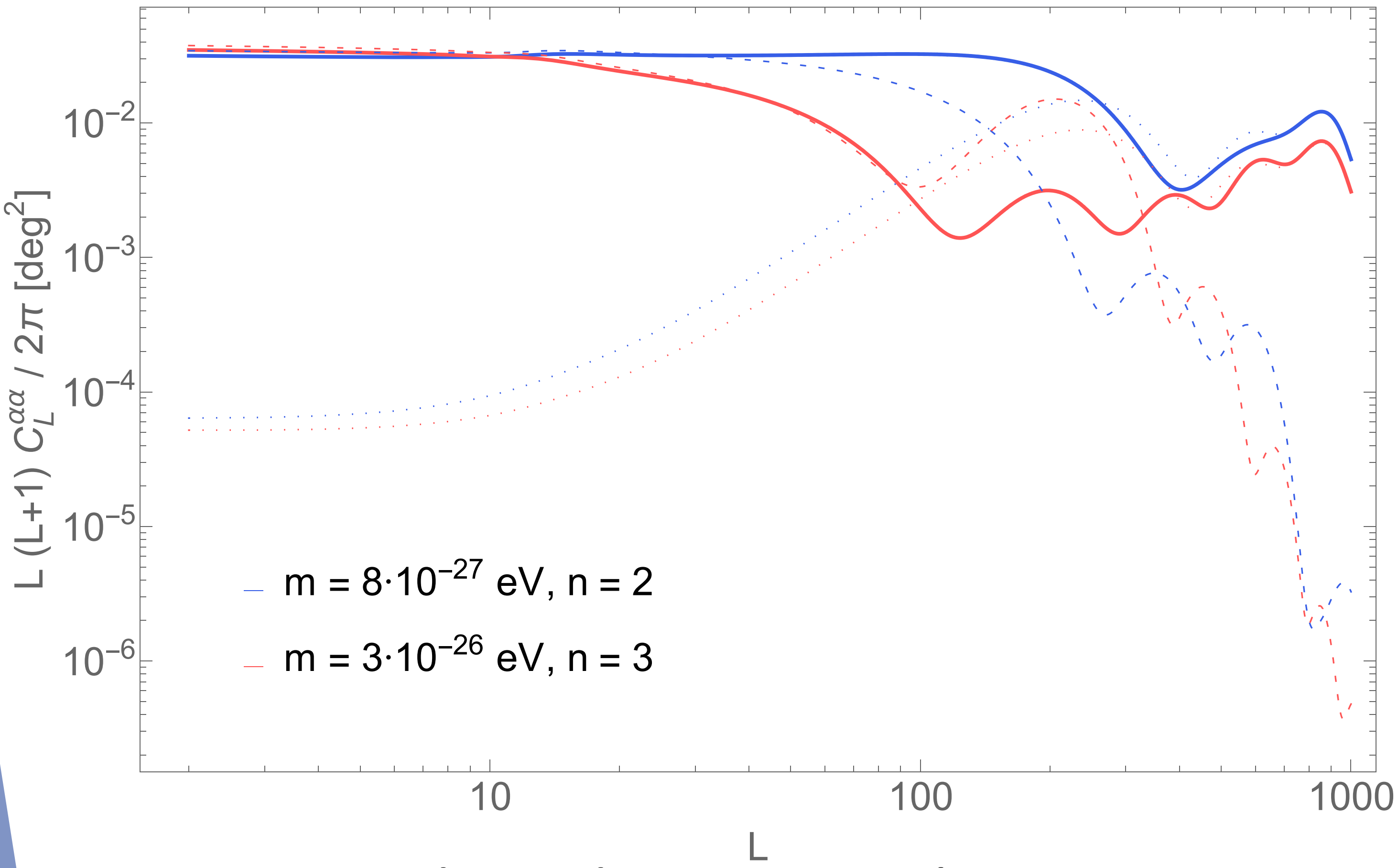
$$G_{\chi\gamma\gamma} = 10^{-15} GeV$$

$$m = \frac{\Lambda^2}{f}$$

- Measurable by programmed experiments: LiteBIRD, Simons Obs., CMB S-3, CMB S-4

Rotation spectra



Solid: total.
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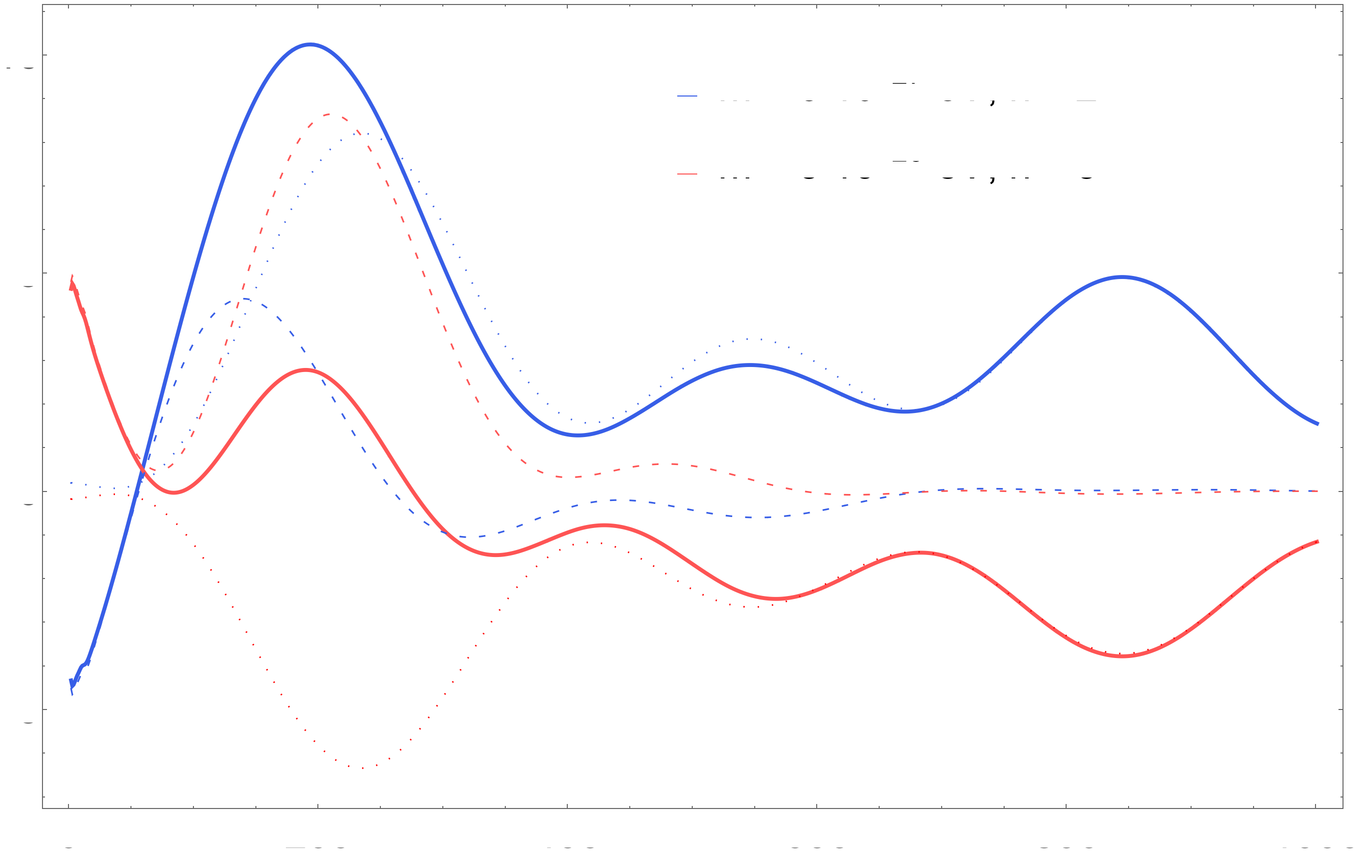
$$G_{\chi\gamma\gamma} = 10^{-15} GeV$$

$$m = \frac{\Lambda^2}{f}$$

- Spectrum depends on potential.

Rotation-Temperature cross-correlation



Solid: total.
Dashed: field perturbations.
Dotted: matter perturbation

$$G_{\chi\gamma\gamma} = 10^{-15} GeV$$

$$m = \frac{\Lambda^2}{f}$$

- Relative contributions of matter and field perturbations alter form drastically. Strong dependence on potential.
- Note: overall sign is not fixed.

Conclusions

- Hubble tension needs explanation. PNGB Early dark energy?
- Rotation power spectrum and temperature cross-correlation important experimental signal to confirm hypothesis.
- Dependence on potential in the power spectrum.
- Rotation spectra is not featureless. Acoustic oscillations appear.
- Capparelli, Caldwell, Melchiorri, Submitted to PRL, [1909.04621]

Thank you!