Axion Dark Matter Detection with CMB Polarization

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w/ Peter W. Graham & Surjeet Rajendran

Axion-Photon Coupling

$$\mathscr{L} \supset -\frac{1}{4} g_{\phi\gamma} \phi F \tilde{F} = + g_{\phi\gamma} \phi \mathbf{E} \cdot \mathbf{B}$$

External **B** field $\longrightarrow$ helioscopes, haloscopes, astrophysical cooling / emission, LSW, etc. [CAST, IAXO, ADMX, ABRA, MADMAX, HAYSTAC, DM Radio, Dielectric stacks, Dish/FUNK, ALPs, HB cooling, Solar production, etc.]

This talk: ultra-light axion DM background <u>without an external **B** field</u>.

Modified EM wave propagation in axion electrodynamics.

L/R-handed helicity transverse photon fields:

$$A_\sigma \equiv (A_1 - i\sigma A_2)/\sqrt{2} \qquad (\sigma \equiv \pm 1)$$

Modified wave equation:

$$\Box A_\sigma = i\sigma g_{\phi\gamma} \left[\partial_z \phi \partial_\eta A_\sigma - \partial_\eta \phi \partial_z A_\sigma \right]$$

Carroll, Field, and Jackiw. Phys. Rev. **D41**, 1231 (1990).
Carroll and Field. Phys. Rev. **D43**, 3789 (1991).
Harari and Sikivie. Phys. Lett. **B289**, 67 (1992).
Carroll. Phys. Rev. Lett. **81**, 3067 (1998).

$$\nabla^\mu A_\mu = 0$$

Polarization Rotation

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Ultra-light / fuzzy DM axions $m_\phi \sim 10^{-22}\,\text{eV} - 10^{-19}\,\text{eV}$

WKB-like approximate solution ($m_\phi \ll \omega_{\text{CMB}}$):

$$A_\sigma(\eta, z) = A_\sigma(\eta', z') \exp\left[-i\omega(\eta - \eta') + ik(z - z')\right] \exp\left[i\,\sigma\, g_{\phi\gamma}\,\Delta\phi(\eta, z; \eta', z')\,/\,2\right]$$

$$\Delta\phi(\eta, z; \eta', z') \equiv \phi(\eta, z) - \phi(\eta', z') \qquad (\sigma \equiv \pm 1)$$

Linear polarization of EM wave rotates ("birefringence"):

$$|\,x\rangle = \frac{1}{\sqrt{2}}\Big(\,|+\rangle + |-\rangle\Big) \quad \Rightarrow \quad |\,\Delta\theta\,\rangle = \frac{1}{\sqrt{2}}\Big(e^{i\Delta\theta}|+\rangle + e^{-i\Delta\theta}|-\rangle\Big)$$

$$\Delta\theta = \frac{g_{\phi\gamma}}{2}\Delta\phi(\eta, z; \eta', z') = \frac{g_{\phi\gamma}}{2}\left[\phi_{\text{obs.}} - \phi_{\text{emit}}\right] = \frac{g_{\phi\gamma}}{2}\int_C ds\, n^\mu \partial_\mu \phi$$

NOTE: Independent of details of axion field evolution between photon emission and observation.

How to study?

Required: polarized source; sufficient $\Delta\phi$ over light-travel time.

Many (recent) studies. Talks of I. Obata [next] and P. Trivedi [Thurs. PM].

Rotation of CMB polarization ("Cosmic birefringence").

Well-studied when axion field evolves slowly cosmologically (i.e., dark energy/quintessence).

DM axions oscillate faster: $T_\phi \sim 1\text{yr} \times (m_\phi/10^{-22}\,\text{eV})^{-1}$

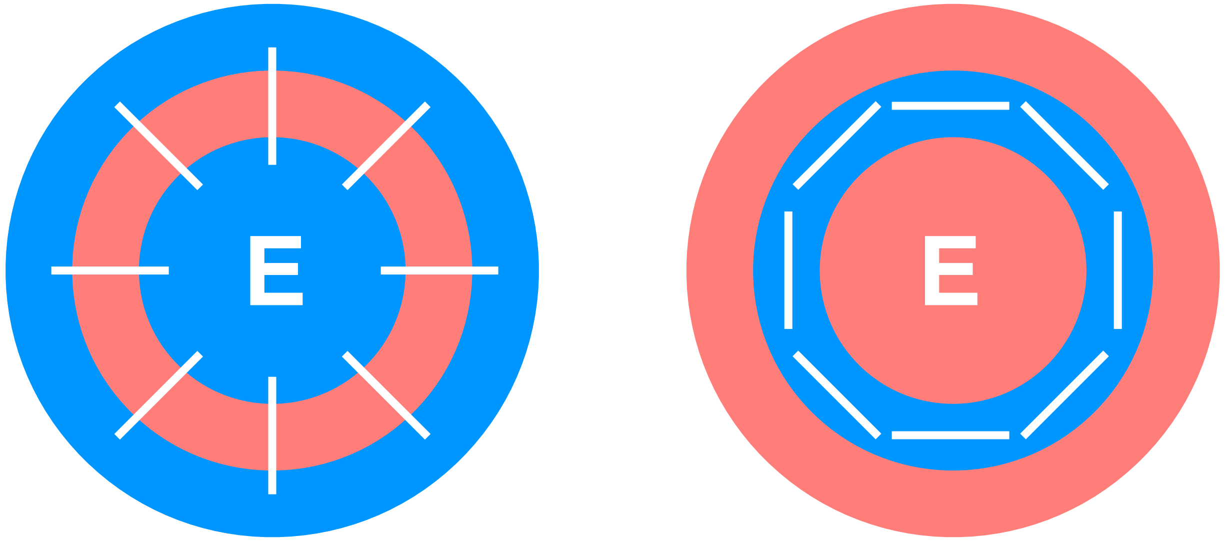
NOVEL CMB EFFECTS

Complementary studies of axion impact on CMB via modified cosmology exist. Not axion-photon coupling & consider different mass range.

See, e.g., Hlozek, Marsh, and Grin. MNRAS **476**, 3063 (2018), and references therein.

CMB Polarization

Local temperature quadrupole anisotropy at decoupling ⇒ polarization of CMB via Thompson scattering off free electrons

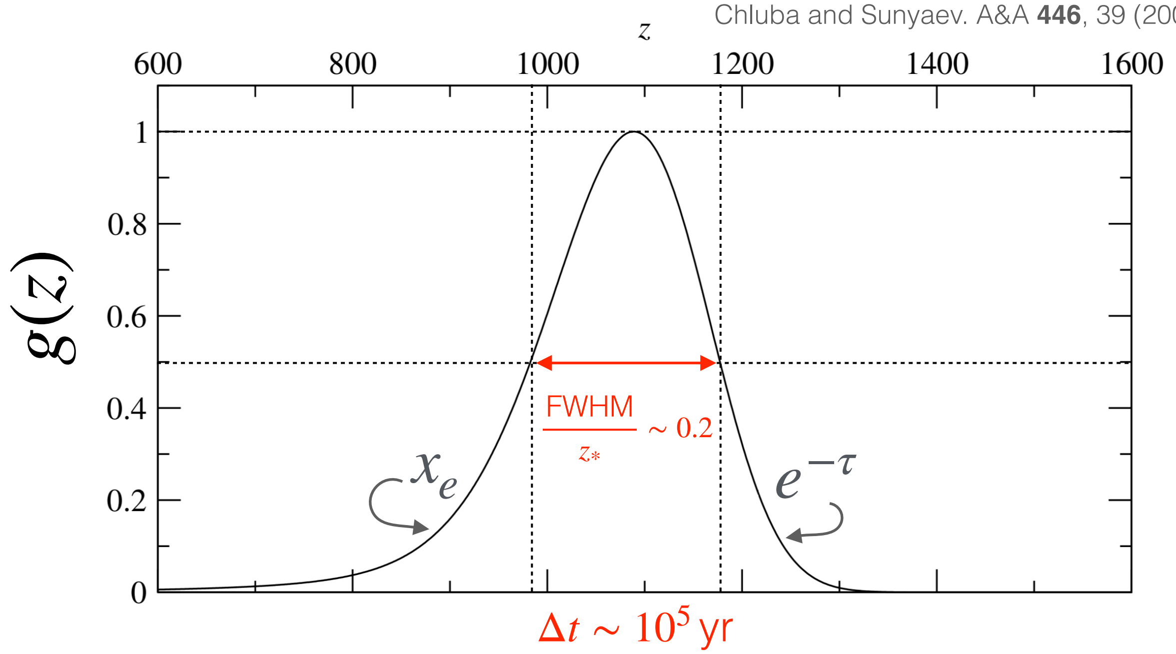


Imprinted over range of redshifts

PDF for last-scattering redshift:
visibility function $g(z)$.

Peaked, but broad:

Chluba and Sunyaev. A&A **446**, 39 (2006).



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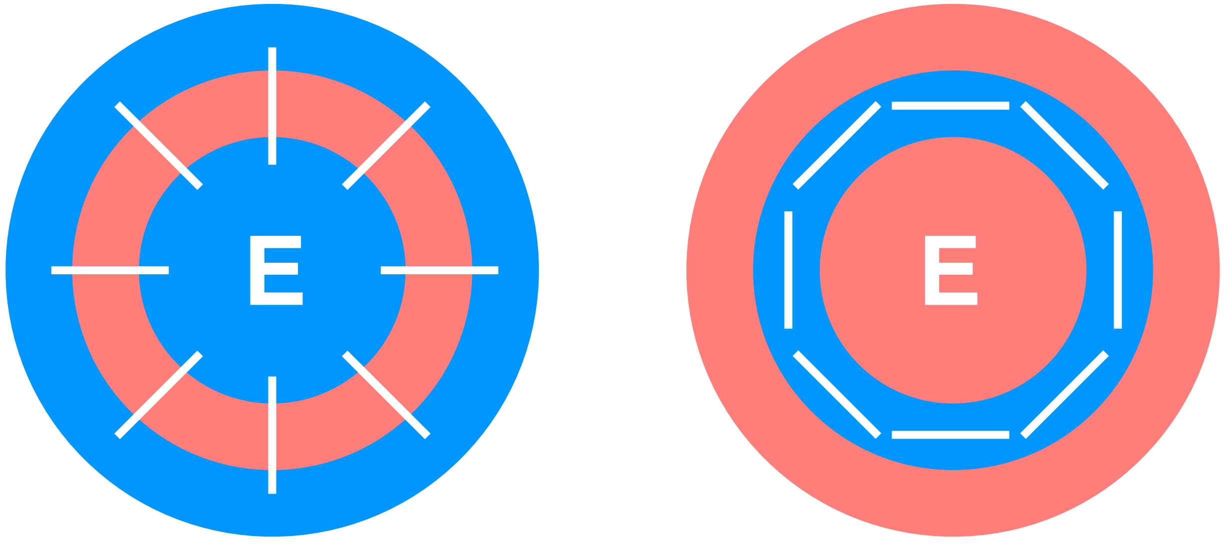

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Cosmic Birefringence

Static (DC) E-to-B rotation

WMAP, BICEP1, POLARBEAR, Planck, KECK/BICEP2
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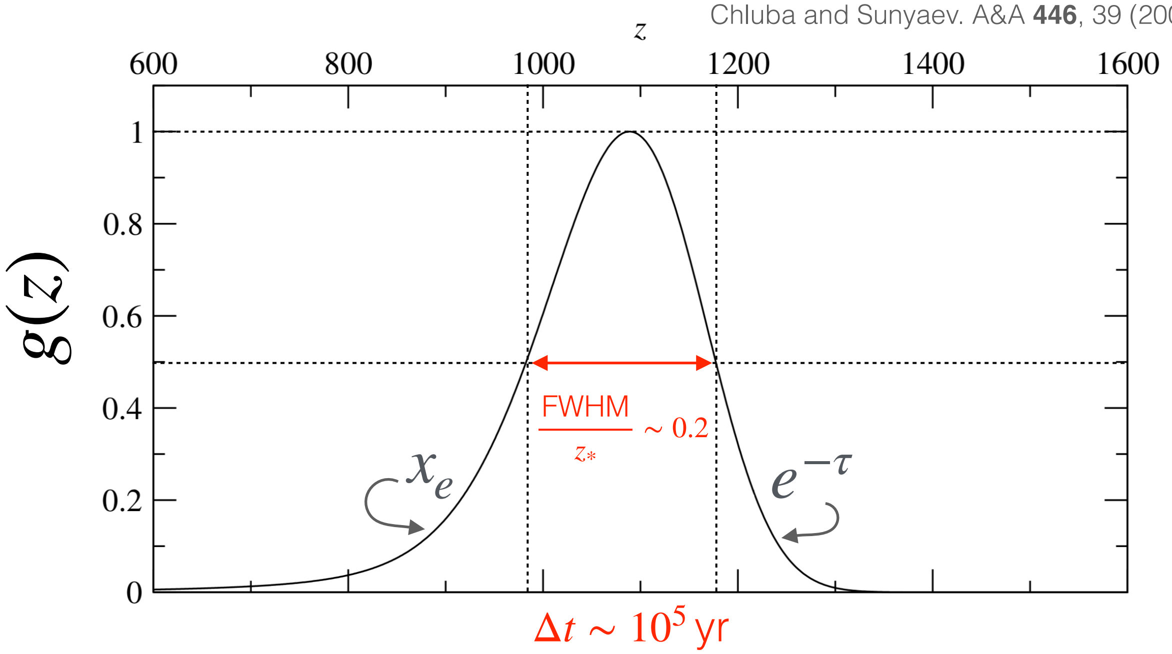

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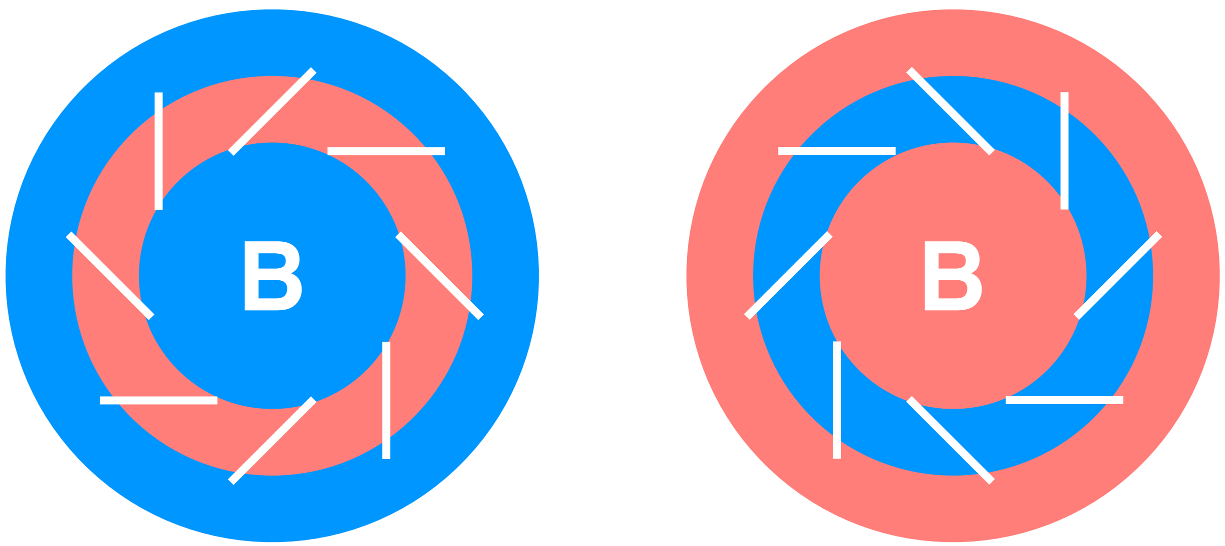

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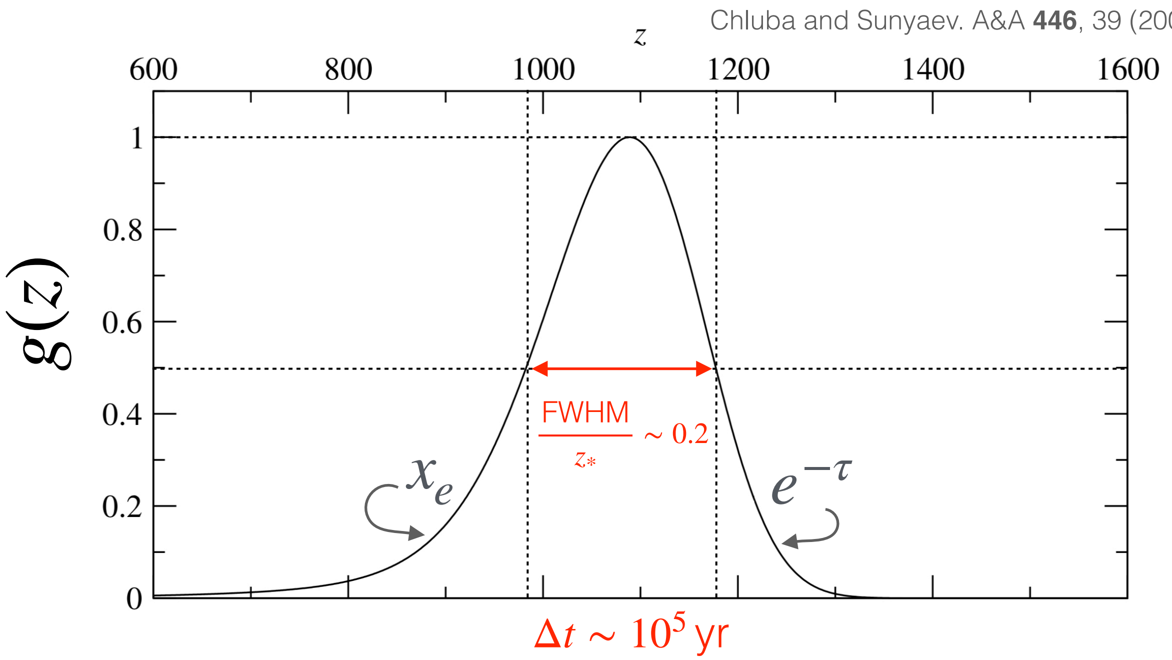

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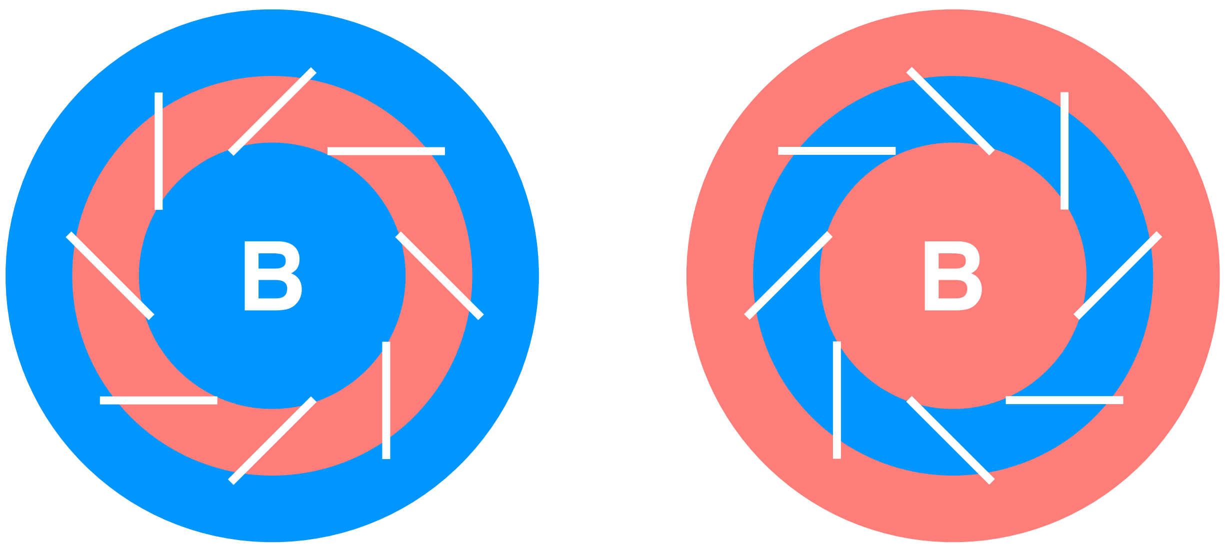

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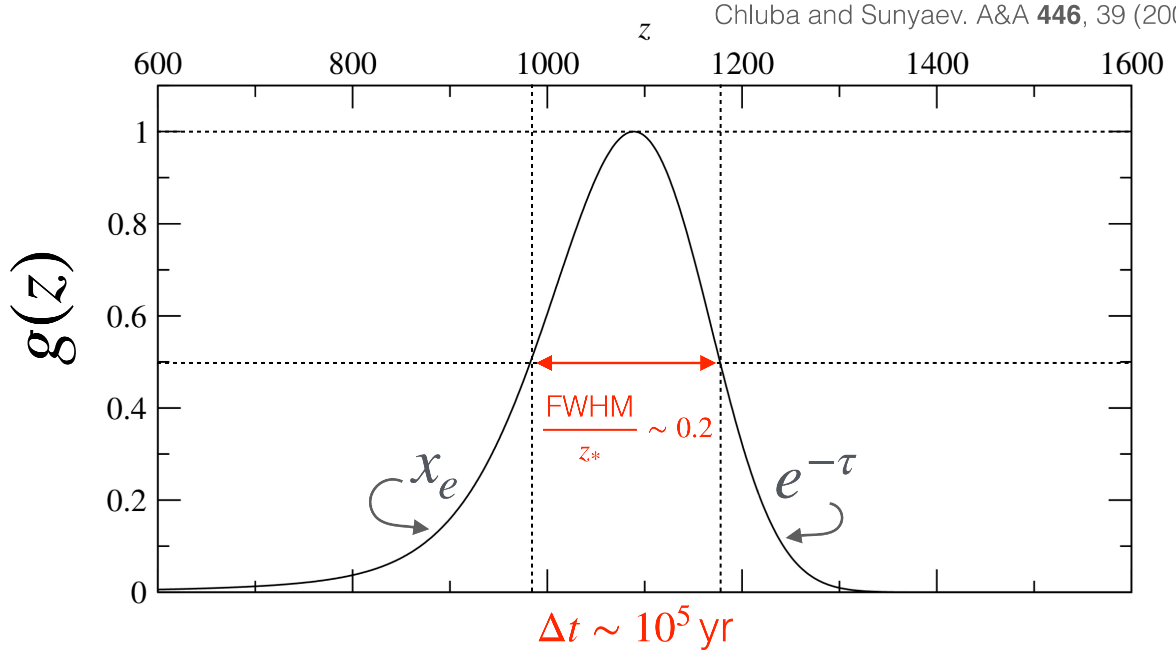
TWO NOVEL EFFECTS FOR (F)DM AXIONS

See also:
Finelli and Galaverni. Phys. Rev. **D79**, 063002 (2009).
Galaverni and Finelli. Nucl. Phys. Proc. Suppl. **194**, 51 (2009).

Chluba and Sunyaev. A&A **446**, 39 (2006).



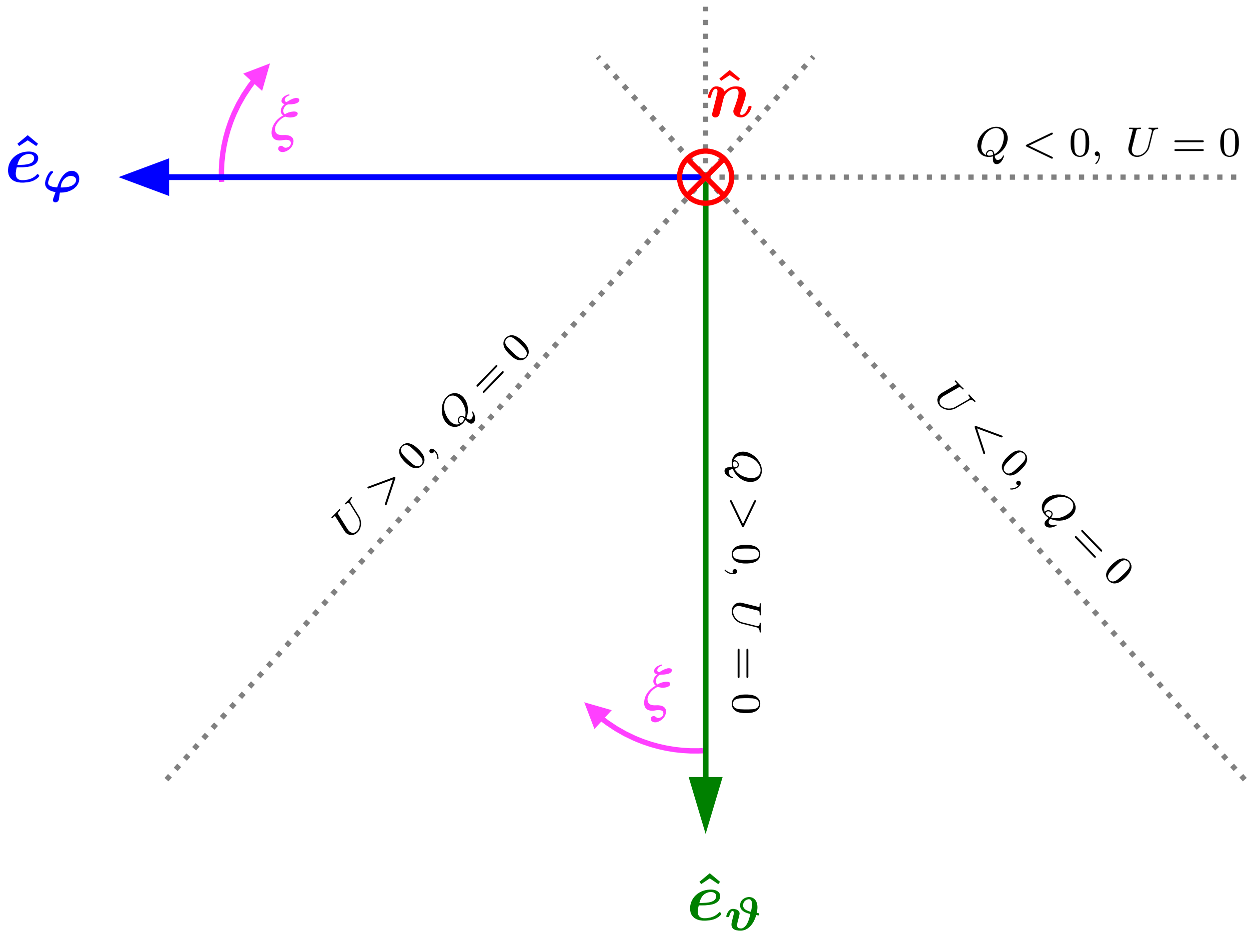
Stokes Parameters

Characterise radiation field by:

I : intensity

Q, U : linear polarization on 45°-separated axes

~~V : elliptical polarization (zero for CMB)~~



Q, U are spin-2: $(Q \pm iU) \to e^{\mp 2i\xi}(Q \pm iU)$

Rotation of CMB Polarization

Pretend: CMB visibility function is $g(t) = \delta(t - t')$.

Polarization rotation: $\Delta\theta = g_{\phi\gamma}\Delta\phi(t, t')/2$

ΛCDM prediction

$$(Q \pm iU)(\hat{\boldsymbol{n}}) = \exp\left[\pm 2i\left(\frac{g_{\phi\gamma}}{2}\Delta\phi(t,t')\right)\right](Q \pm iU)_0(\hat{\boldsymbol{n}})$$

Observed

$$\Delta\phi(t,t') \equiv \phi_{\text{today}} - \phi_{\text{dec.}} = \phi_0 \cos(m_\phi t + \alpha) - \phi_* \left(a_*/a(t')\right)^{3/2} \cos(m_\phi t' + \beta)$$

Actually: CMB photons emitted weighted by $g(t) \neq \delta(t - t')$ …

… and many axion oscillations during decoupling:

$$\left(\Delta t_{\text{dec.}} \sim 10^5\,\text{yrs}\right) \gg \left(T_\phi \sim 1\text{yr} \times (m_\phi/10^{-22}\,\text{eV})^{-1}\right)$$

Integrate "single-slice" result over visibility function:

$$(Q \pm iU)(\hat{\boldsymbol{n}}) \approx (Q \pm iU)_0(\hat{\boldsymbol{n}}) \int dt'\, g(t') \exp\left[\pm 2i\left(\frac{g_{\phi\gamma}}{2}\Delta\phi(t,t')\right)\right].$$

see paper for a more careful treatment

$$(Q \pm iU)(\hat{\boldsymbol{n}}) \approx J_0\left[g_{\phi\gamma}\langle\phi_*\rangle(\hat{\boldsymbol{n}})\right] \exp\left[\pm 2i\left(\frac{g_{\phi\gamma}}{2}\phi_0\cos(m_\phi t + \alpha)\right)\right](Q \pm iU)_0(\hat{\boldsymbol{n}})$$

Observed

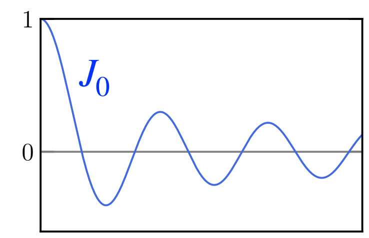
Axion field at decoupling
(suitably averaged)

Axion field at Earth

ΛCDM prediction

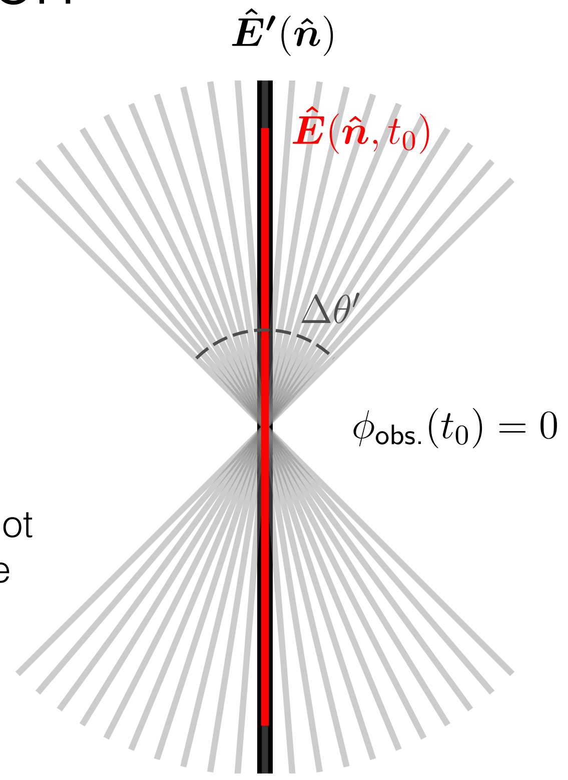
WASHOUT EFFECT

Reduction of polarization compared to the ΛCDM prediction

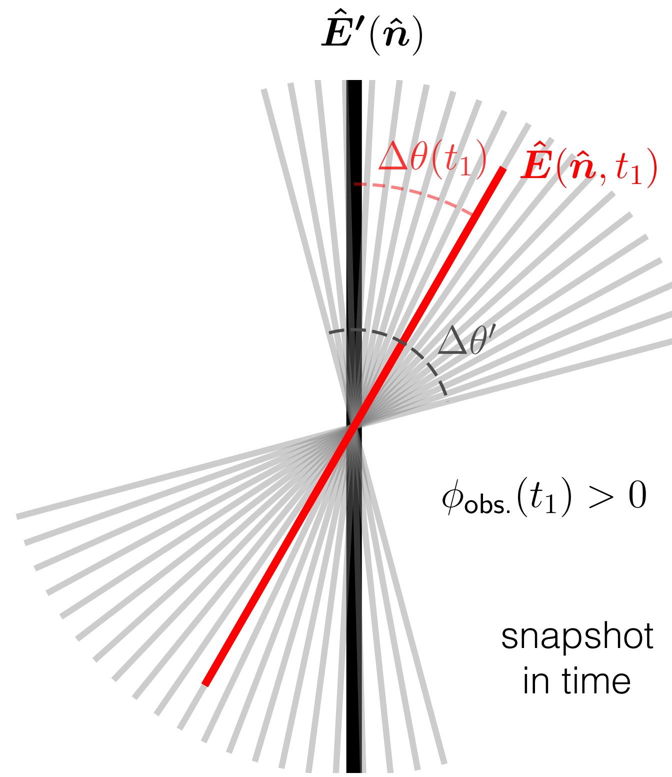


AC OSCILLATION

Oscillation of the CMB polarization angle at $\omega = m_\phi$



$$\Delta\theta = \frac{g_{\phi\gamma}}{2}\left[\phi_{\text{obs.}} - \phi_{\text{emit}}\right]$$



See also: F. Finelli and M. Galaverni. Phys. Rev. **D79**, 063002 (2009) for earlier work

Washout Effect: Current Limits

Ignore AC effect for now.

CMB observables? $(Q \pm iU)(\hat{\boldsymbol{n}}) \to J_0\left(g_{\phi\gamma}\langle\phi_*\rangle\right)(Q \pm iU)(\hat{\boldsymbol{n}})$

$$C_{TT,l} \to C_{TT,l}$$

$$C_{TE,l} \to J_0\big[g_{\phi\gamma}\langle\phi_*\rangle\big] \times C_{TE,l}$$

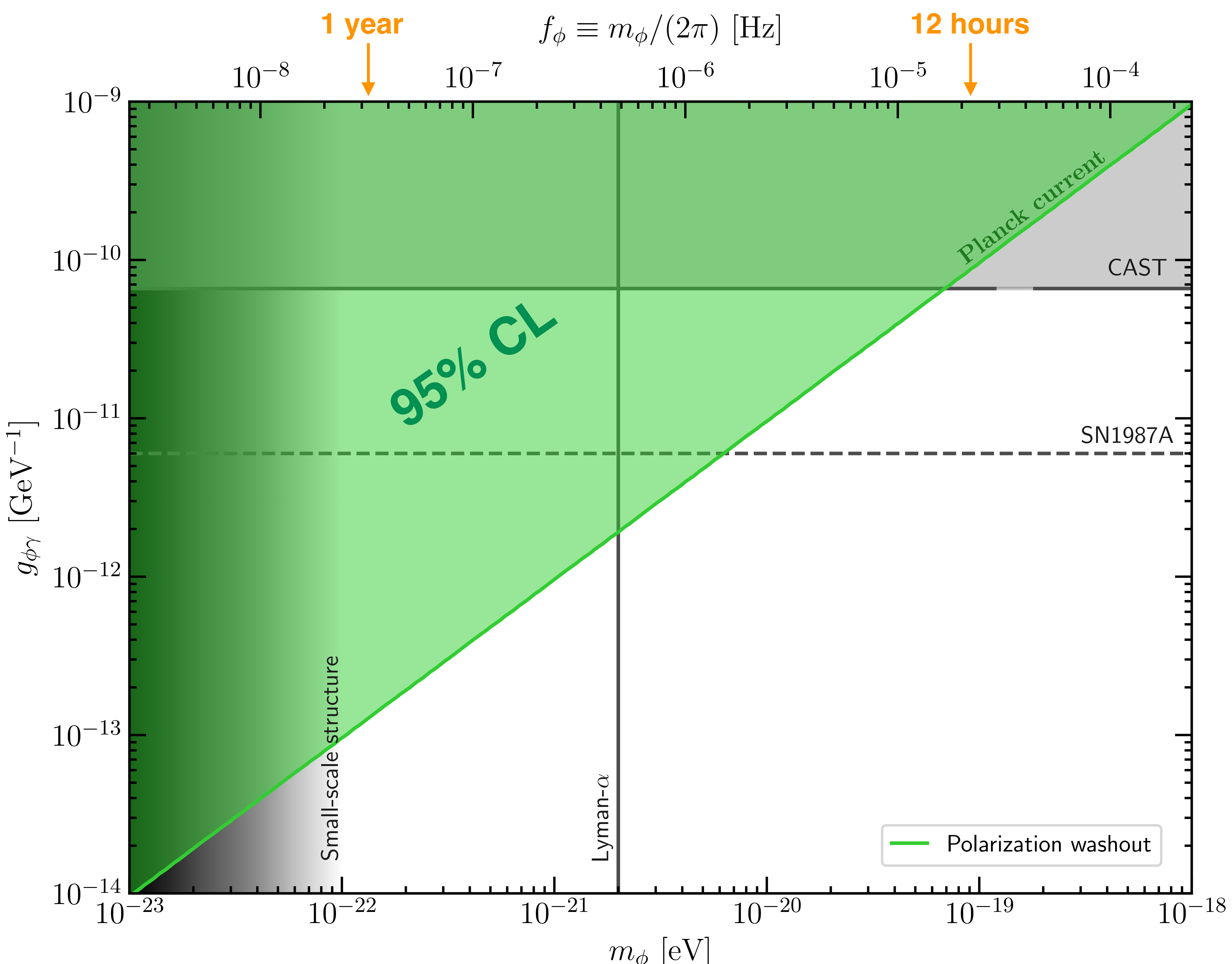
$$C_{EE,l} \to \Big(J_0\big[g_{\phi\gamma}\langle\phi_*\rangle\big]\Big)^2 \times C_{EE,l}$$

Uniform reduction on all (pristine) scales: $l \gtrsim 20$.

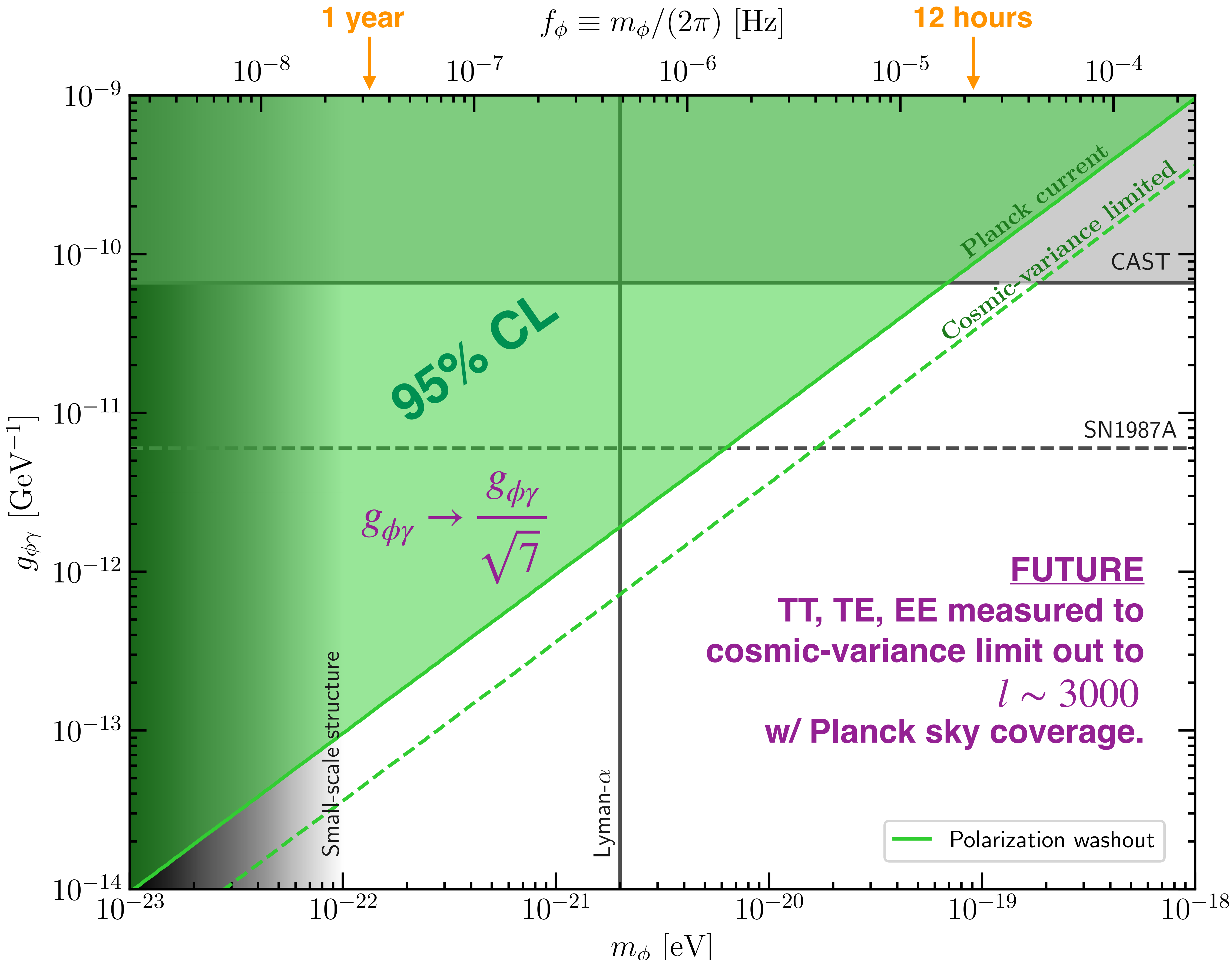
Specific pattern of reductions compared to ΛCDM predictions.

Look for effects in **existing** public Planck (2018) data.
See paper for details.

Verified these effects are “beyond ΛCDM”.



Assuming axions are 100% of DM



Assuming axions are 100% of DM

AC Effect

Distinct from any other cosmological signature:

- Point-by-point, on-the-sky oscillation of the local polarization angle.
- Period of ~ a year to ~ a few hours. *Set by axion mass.*
- Phase-coherent in time: $T_{\text{coh.}} \sim 10^6 T_\phi \gtrsim 10^3$ yrs
- In-phase across the whole sky. *Depends on local axion field only.*

Non-trivial cross-checks on signal (compare experiments, patches of sky, observation times).

SIGNIFICANT DISCOVERY POTENTIAL!

AC Effect: Benchmarks

CMB time-series data required! Not publicly available.

CMB experimental colleagues interested in performing analysis.
(does double-duty as an AC systematics check)

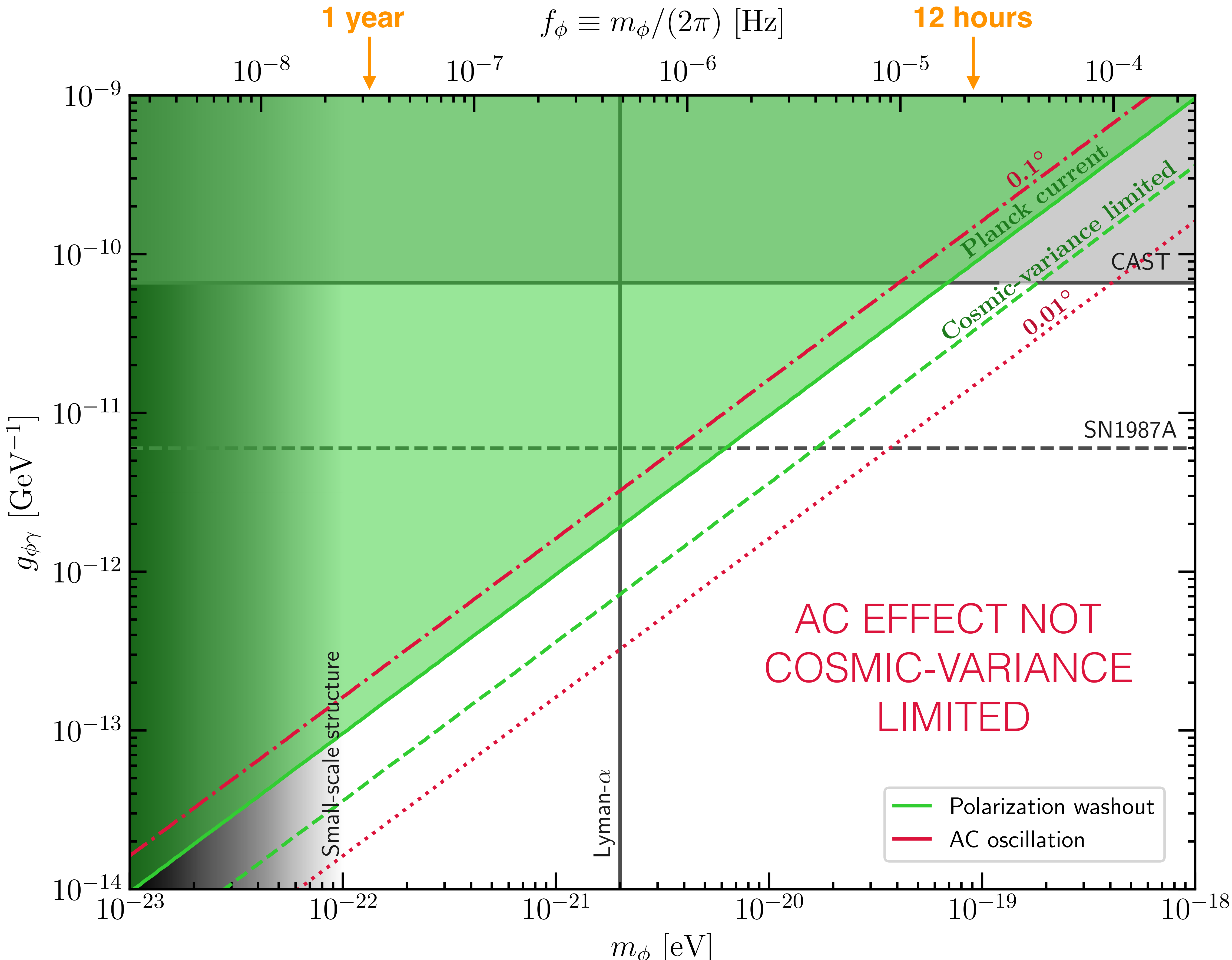
We provide benchmarks on reach for this search.

By analogy: Planck result looking for all-sky DC rotation finds

$$\Delta\theta_{\mathrm{DC}} = 0.31^\circ \pm 0.28^\circ \text{ (sys.)} \pm 0.05^\circ \text{ (stat.)}$$

Look at **statistical** power of all-sky DC analysis. Different systematics for AC… to be understood.

Benchmark: amplitude of AC effect (95% CL) with current statistical power: 0.1°. Optimistic future: 0.01°. Ultimate: ? (new type of search?)



Assuming axions are 100% of DM

Conclusions

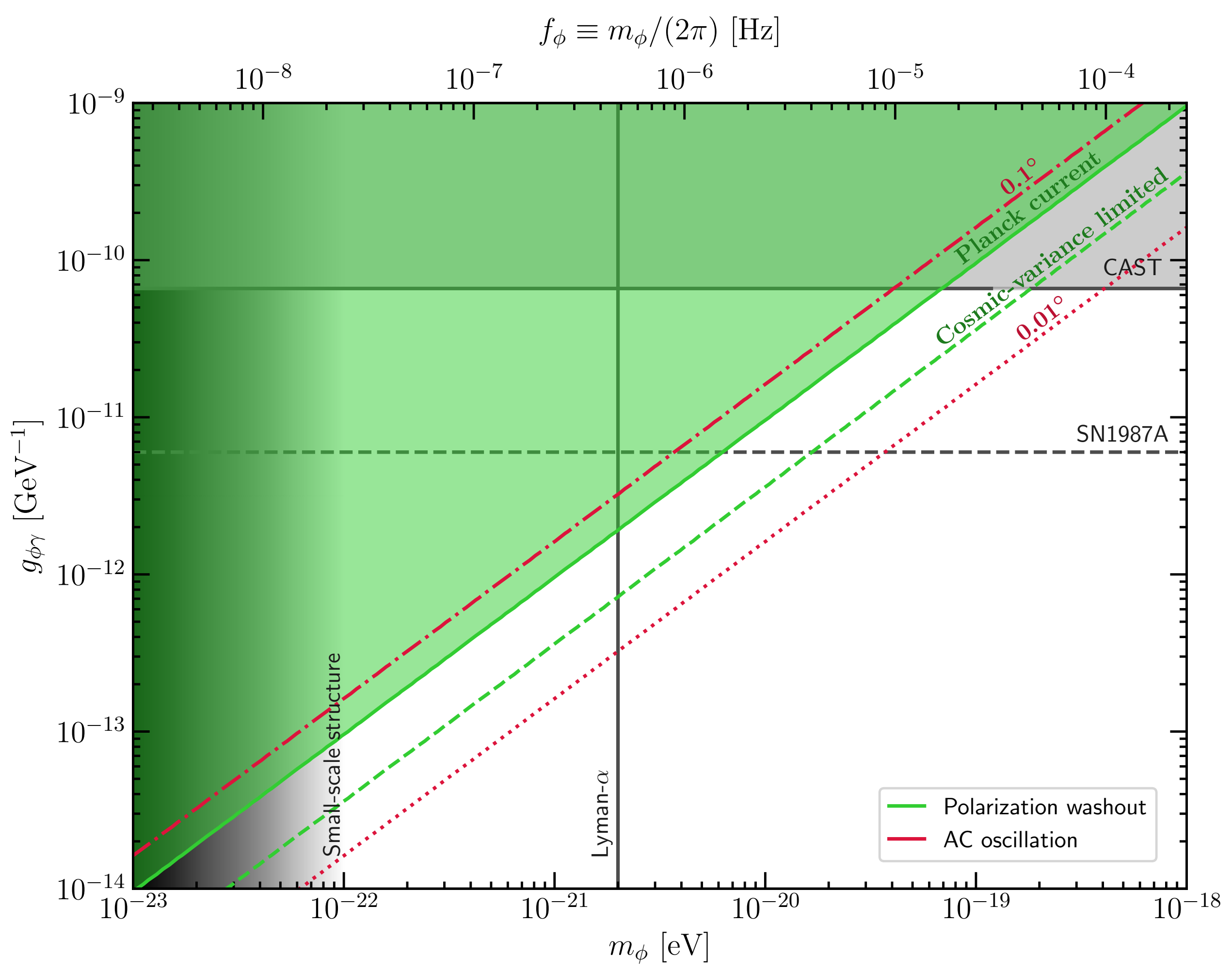
Novel CMB effects of (fuzzy) dark matter axion-induced linear polarization rotation.

Polarization washout

Existing limits some orders of magnitude better than previous bounds.
Eventually cosmic-variance limited.

AC oscillation

Limits require dedicated analyses.
Encouraging projected reach.
Not cosmic-variance limited.
Discovery potential significant.



CMB polarization is an exciting avenue to constrain or detect ultra-light / fuzzy axion dark matter.

BACKUP

Current exclusion bounds

assuming axions are 100% of DM

Use **existing** public Planck (2018) data.

One-parameter profile likelihood ratio test on $r \equiv g_{\phi\gamma}\langle\phi_*\rangle$ against null hypothesis $r = 0$.

Profile over full ΛCDM parameter set (CAMB + MC) [Lewis, Challinor, and Lasenby. Astrophys. J **538**, 473 (2000).]

$$\boldsymbol{\Theta} \equiv (\Omega_b h^2,\, \Omega_c h^2,\, 100\,\theta_{\rm MC},\, \tau,\, \ln(10^{10} A_s),\, n_s)$$

Approximate low-l treatment. Negligible impact; large cosmic variance.

See paper for the further details.

Bound (95% CL): $1 - J_0\left(g_{\phi\gamma}\phi_*(m_\phi)\right) \leq 5.8 \times 10^{-3}$

No unconstrained degeneracy with washout within ΛCDM.