Title: Axion Dark Matter Detection with CMB Polarization

Speakers: Michael Fedderke

Series: Particle Physics

Date: April 30, 2019 - 1:00 PM

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Abstract: In this talk, I will detail two ways to search for low-mass axion dark matter using cosmic microwave background (CMB) polarization measurements. These appear, in particular, to be some of the most promising ways to directly detect fuzzy dark matter. Axion dark matter causes rotation of the polarization of light passing through it. This gives rise to two novel phenomena in the CMB. First, the late-time oscillations of the axion field today cause the CMB polarization to oscillate in phase across the entire sky. Second, the early-time oscillations of the axion field wash out the polarization produced at last-scattering, reducing the polarized fraction (TE and EE power spectra) compared to the standard prediction. Since the axion field is oscillating, the common (static) â€˜cosmic birefringenceâ€™ search is not appropriate for axion dark matter. These two phenomena can be used to search for axion dark matter at the lighter end of the mass range, with a reach several orders of magnitude beyond current constraints. I will present a limit from the washout effect using existing Planck results, and discuss the significant future discovery potential for CMB detectors searching in particular for the oscillating effect.

[1903.02666]

Axion Dark Matter Detection with CMB Polarization

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Perimeter Institute for Theoretical Physics
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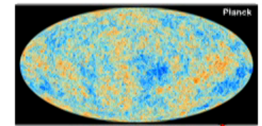
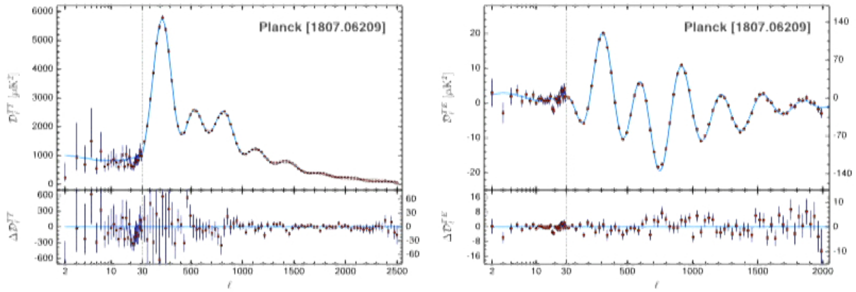
with
Peter W. Graham and Surjeet Rajendran

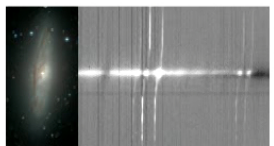
Outline

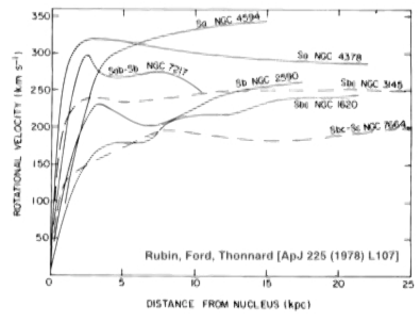
- Review and Motivations for Axions, and Axions as Dark Matter
- Effect of Axion-Photon on EM wave Propagation: Polarization Rotation
- Review of CMB Polarization
- Application of Rotation Effect to CMB: *New Effects for Dark Matter Axions*
- Experimental Limits and Discovery Potential

Dark Matter



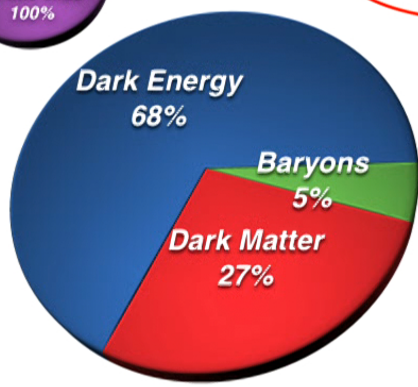






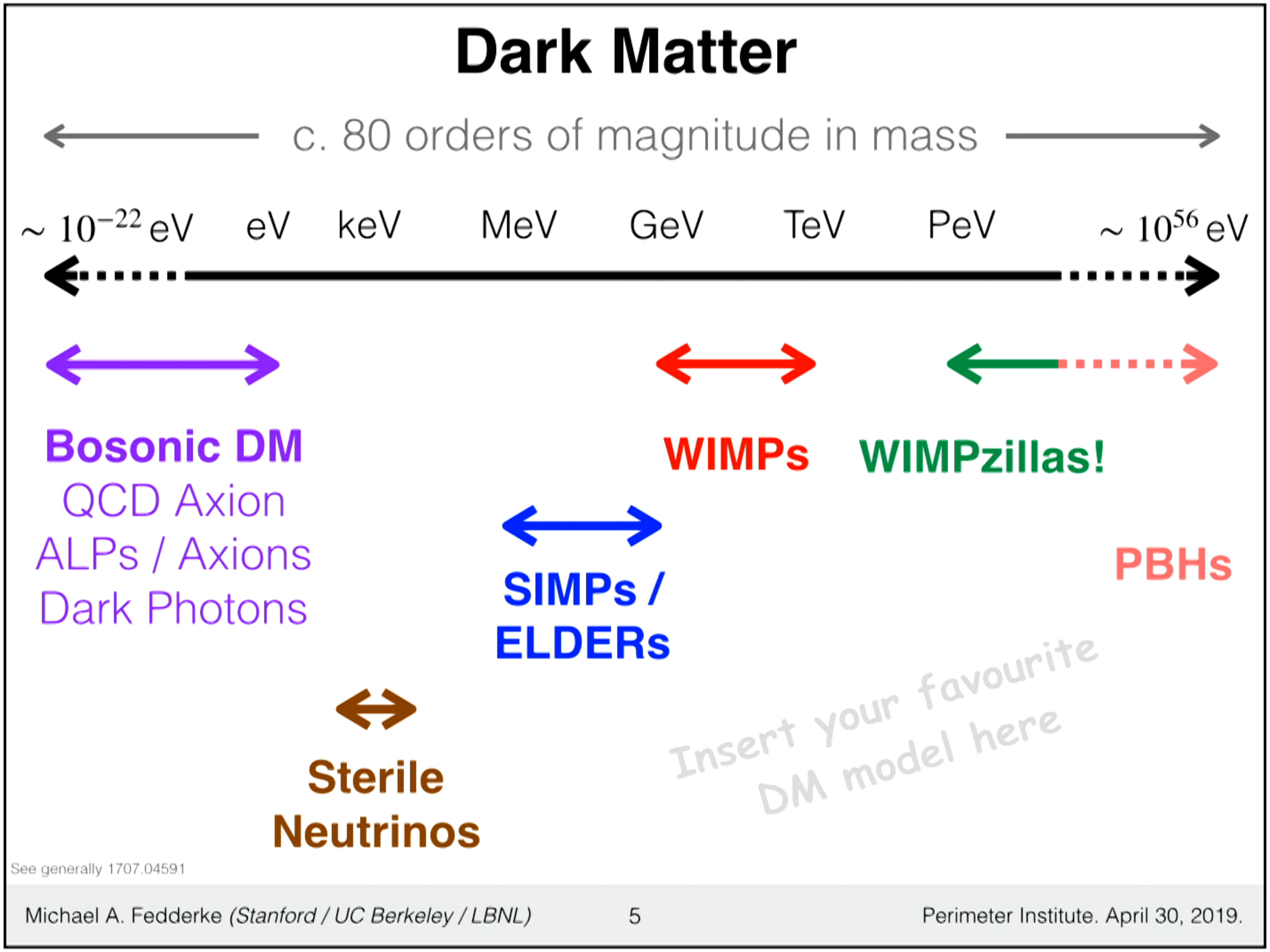
Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al. Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

Talks on DM containing some version of this slide 100%



- No alternative can explain observations on all scales.
- Existence determined gravitationally.
- No non-gravitational detection.

WHAT IS IT?



Dark Matter
c. 80 orders of magnitude in mass
~ 10^-22 eV
eV
keV
MeV
GeV
TeV
PeV
~ 10^56 eV
Bosonic DM
QCD Axion
ALPs / Axions
Dark Photons
WIMPs
WIMPzillas!
SIMPs /
ELDERs
PBHs
Insert your favourite
DM model here
Sterile
Neutrinos
See generally 1707.04591
Michael A. Fedderke (Stanford / UC Berkeley / LBNL)
5
Perimeter Institute. April 30, 2019.

Axions and ALPs

QCD axion mass-coupling relationship:

$$m_\phi \sim 6\,\mu\text{eV} \times \left(f/10^{12}\,\text{GeV}\right)^{-1}$$

… also generically other couplings; e.g.:

$$\mathcal{L} \supset -\frac{1}{4} g_{\phi\gamma} \phi F \tilde{F}, \qquad g_{\phi\gamma} = g_{\phi\gamma}(f) \;\; \text{[model-dependent]}$$

Beyond QCD: axion-like particles (ALPs).

Light pseudoscalars with axion-like couplings, but m_ϕ, $g_{\phi\gamma}$, etc. are independent parameters.

ALPs are generic degrees of freedom in low-energy effective descriptions of, e.g., string theory.

Conlon. JHEP **0605** (2006) 078.
Svrcek and Witten. JHEP **0606** (2006) 051.
Arvanitaki, et. al. Phys. Rev. **D81** (2010) 123520.
Arvanitaki, et. al. Phys. Rev. **D81** (2010) 075018.

Remainder of this talk: Axions ≡ ALPs.

Axions as Dark Matter

Excellent cold dark matter candidate.

Non-thermal production: misalignment, etc.

Preskill, Wise, Wilczek, Phys Lett. **B120**, 127 (1983).
Abbott and Sikivie. Phys. Lett. **B120**, 133 (1983).
Dine and Fishler. Phys. Lett. **B120**, 137 (1983)

$$\mathcal{N} \equiv \frac{\rho_{DM}}{m_\phi}\lambda_{dB}^3 \sim 10^6 \times \left(\frac{m_\phi}{\text{eV}}\right)^{-4} \sim 10^{94} \times \left(\frac{m_\phi}{10^{-22}\ \text{eV}}\right)^{-4}$$

Classical field limit of QFT

Coherent oscillations: $\phi(t) \approx \phi_0 \cos(m_\phi t + \alpha)$

Can be Fuzzy Dark Matter (FDM). Astrophysically large de Broglie wavelengths:

$$\lambda_{dB} \sim 0.5\,\text{kpc} \times (m_\phi/10^{-22}\ \text{eV})^{-1}$$

Hu, Burkina, and Gruzinov.
Phys. Rev. Lett. **85**, 1158 (2000).

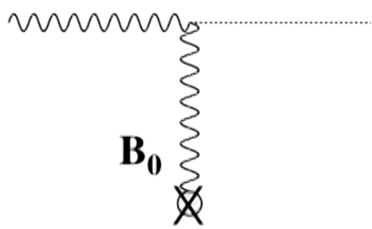
Small-scale galactic structure anomalies (“Too Big to Fail”, “Missing Satellites”, “Core-vs-Cusp”)? Constrained by Lyman-α.

Search strategies distinct from canonical WIMP approaches…

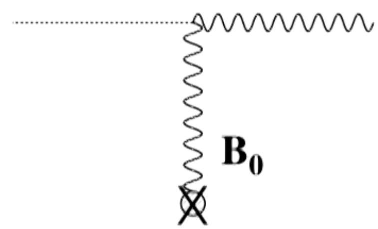
Axion-Photon Coupling

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

In the presence of a **external magnetic field**:



Convert axions to photons and vice versa



Primakoff Process

Production in the sun

HB cooling Axion-electron couplings dominate in higher-density stellar environments.

…

Inverse Primakoff Process

Helioscopes [CAST, IAXO, …]

Haloscopes [ADMX, ABRA, MADMAX, HAYSTAC, DM Radio, Dielectric stacks, …]

…

Light-shining-through-walls [ALPS, etc.], …

What if there's an axion background **without an external B field**?

Generically get other couplings too: CASPEr, etc.

Axion Electrodynamics

$$\nabla_\mu F^{\mu\nu} = J^\nu - g_{\phi\gamma}(\nabla_\mu \phi)\tilde{F}^{\mu\nu}$$

Wilczek. Phys. Rev. Lett. **58**, 1799 (1987).

$$\Box A_\nu + R^\mu{}_\nu A_\mu = g_{\phi\gamma}\,(\partial_\mu \phi)\,\epsilon_\nu{}^{\mu\lambda\rho}\,(\partial_\lambda A_\rho)$$

Lorenz Gauge

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

FLRW spacetime. Scale factor $a(\eta)$. Conformal-comoving coordinates.
Seek solutions in background $\phi(\eta, x^3 = z)$ that vary as $A_\mu(\eta, z)$: z is not redshift on this slide!

$$A_0 = A_3 = 0$$

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

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

If $|\partial_\eta\phi| \ll \omega|\phi|$, $|\partial_z\phi| \ll k|\phi|$, then an approximate solution ($\sim$ WKB) exists:

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

$$\Delta\phi(\eta, z; \eta', z') \equiv \phi(\eta, z) - \phi(\eta', z') \qquad \omega = k$$

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).

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

Polarization Rotation

What is the observable?

Linear polarization rotates!

$$E^i_\perp(\eta, z) = \left(\frac{a(\eta')}{a(\eta)}\right)^2 \exp\left[-i\omega(\eta-\eta') + ik(z-z')\right] R^{ij}\left[\frac{g_{\phi\gamma}}{2}\Delta\phi(\eta, z; \eta', z')\right] E^j_\perp(\eta', z')$$

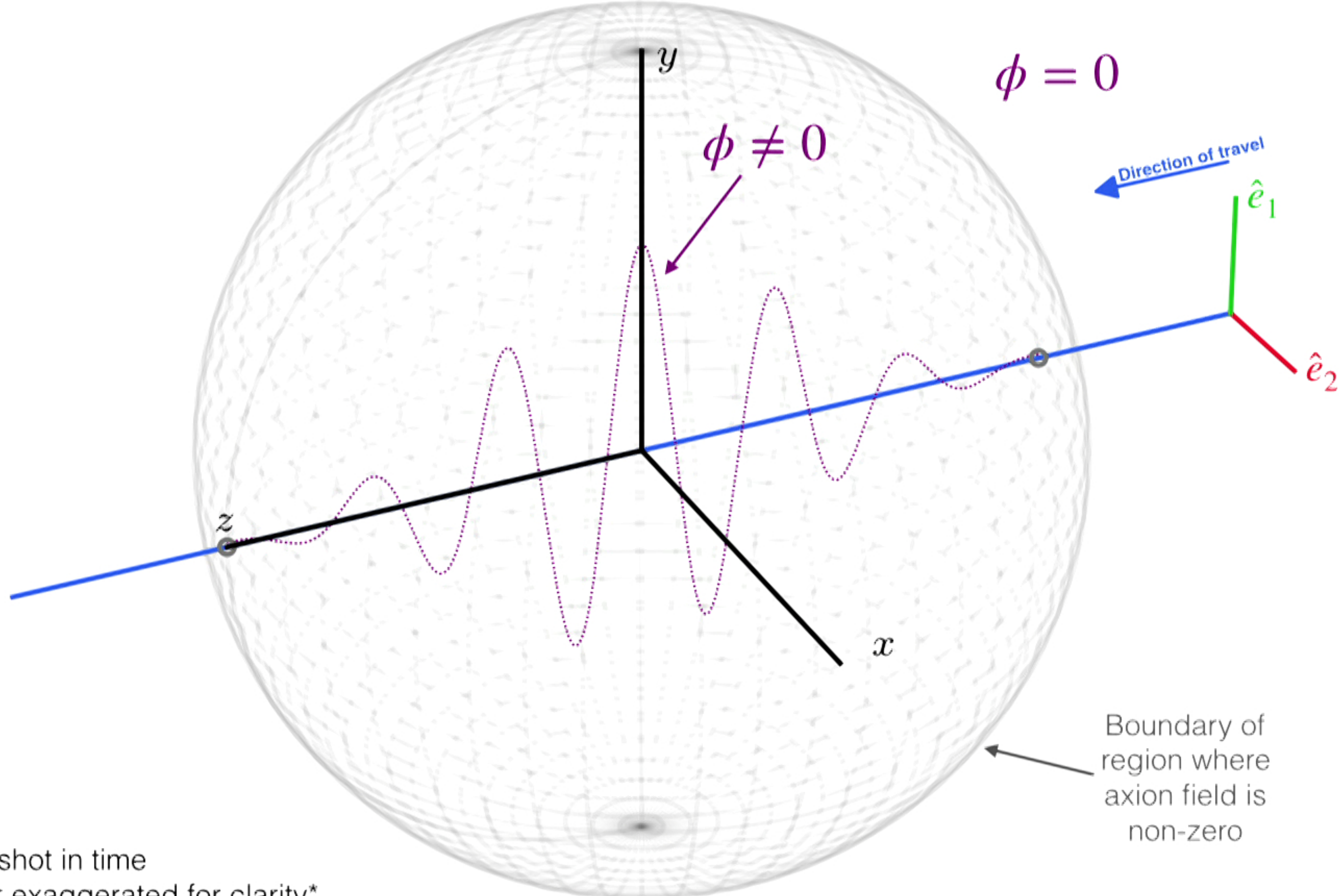
$$R[\Delta\theta] \equiv \begin{pmatrix} \cos\Delta\theta & \sin\Delta\theta \\ -\sin\Delta\theta & \cos\Delta\theta \end{pmatrix} \qquad \left(g_{\phi\gamma}\partial_\eta\phi/\omega \ll 1\right) \qquad \omega = k$$

NOTE: Rotation by angle $\propto$ difference in the axion field value at photon emission and photon absorption.

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

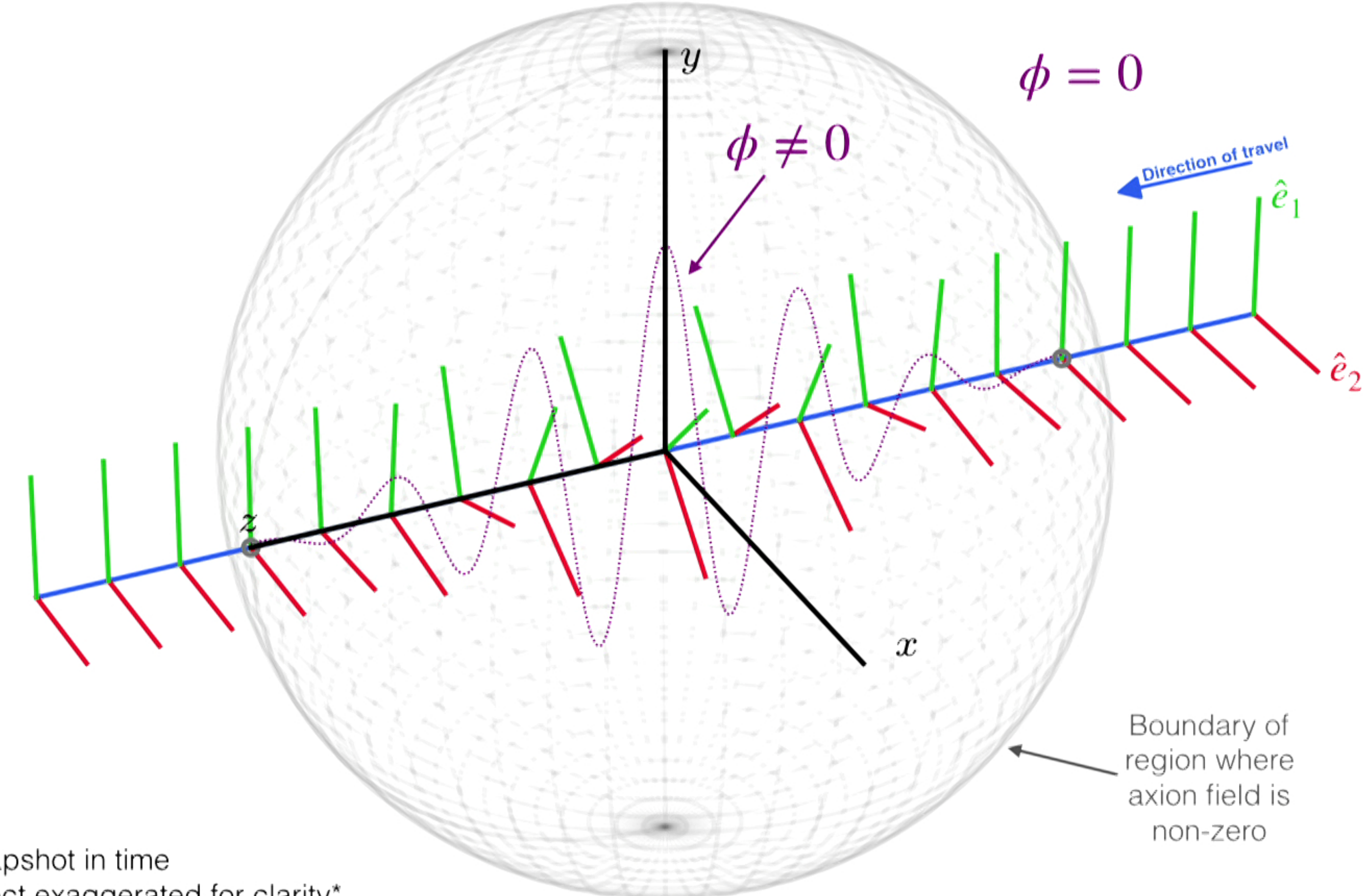
Independent of details of the axion field evolution between these points!

Polarization Rotation



Snapshot in time
Effect exaggerated for clarity*

Polarization Rotation



Snapshot in time
Effect exaggerated for clarity*

How to study this effect?

Topic of $\mathcal{O}(100)$ studies over past 30 years.

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).
etc. …

Require:
- polarized source
- sufficient axion phase evolution in experimental light-travel time

Interferometric laboratory searches for higher-mass axions.

DeRocco and Hook. Phys. Rev. **D98**, 035031 (2018).
Obata, Fujita, and Michimura. Phys. Rev. Lett. **121**, 161301 (2018).
Liu, Elwood, Evans, and Thaler. 1809.01656.
Nagano, Fujita, Michimura, and Obata. 1903.02017.

To address FDM region (or lighter), have to go
- astrophysical: pulsars, AGNs, protoplanetary disks, etc.
- cosmological: CMB polarized fraction

di Serego Aligheri, et al. Astrophys. J. **715**, 33 (2010).
Fujita, Tazaki, and Toma. 1811.03525.
Ivanov, et al. 1811.10997.
Liu, Smoot, Zhao. 1901.10981*v2*.
Caputo, et al. 1902.02695*v2*.

We focus on CMB. Not a new idea per se, but we find **NEW EFFECTS**.

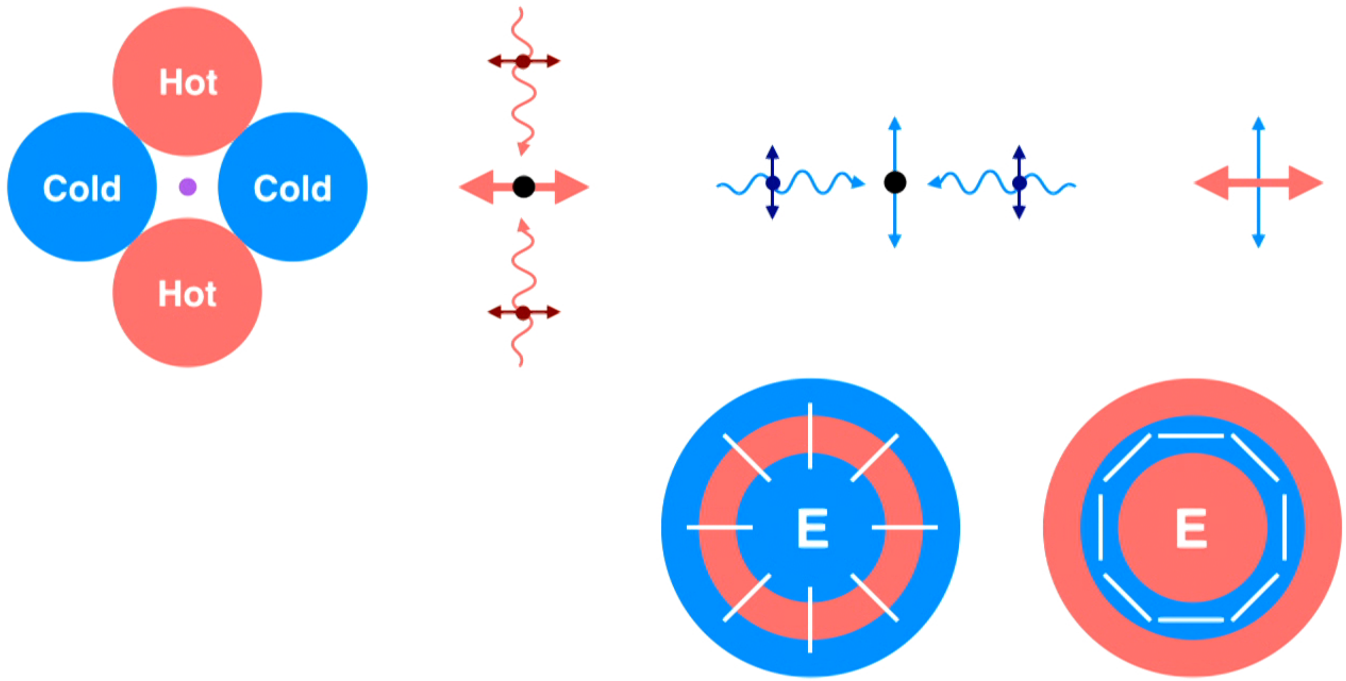
Gravitational effects of axions on CMB anisotropy observables considered before. Complementary. Our effects from axion-photon coupling, and at larger axion masses.

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

cf. Wayne Hu's excellent CMB tutorials

CMB Polarization: How?

Local temperature quadrupole $\Delta_{T2}^{(S)}$ at decoupling epoch gives rise to polarized fraction of CMB light via Thompson scattering



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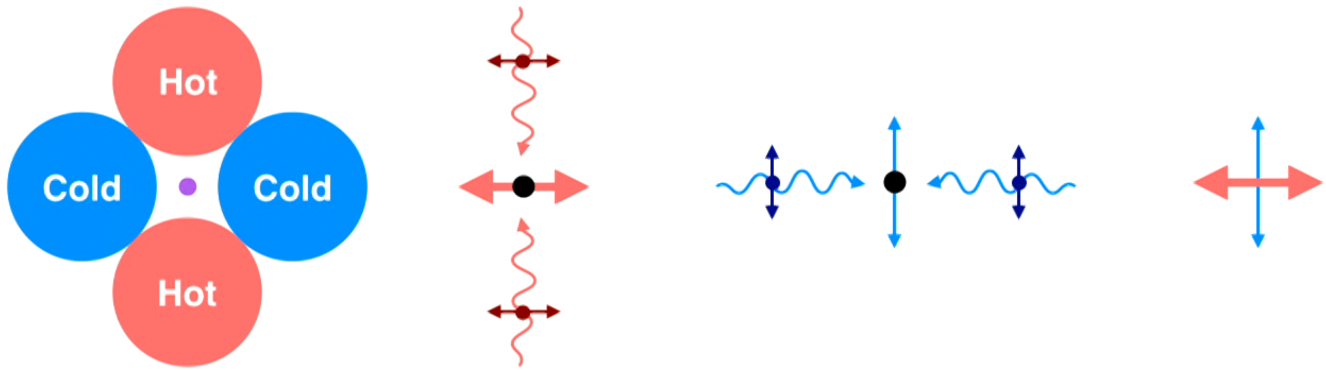
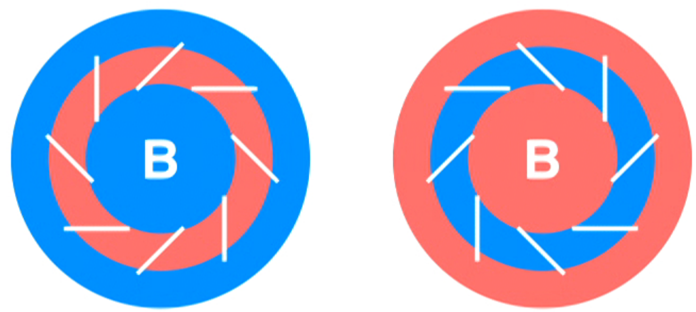


<u>USUAL SEARCHES FOR ROTATION</u>

DC Cosmic Birefringence

STATIC E-to-B rotation

WMAP, BICEP1, POLARBEAR, Planck, KECK/BICEP2
Gluscevic, Kamionkowski, and Cooray. Phys. Rev. **D80**, 023510 (2009)
Gluscevic, Hanson, Kamionkowski, and Hirata. Phys. Rev. **D86**, 103529 (2012)



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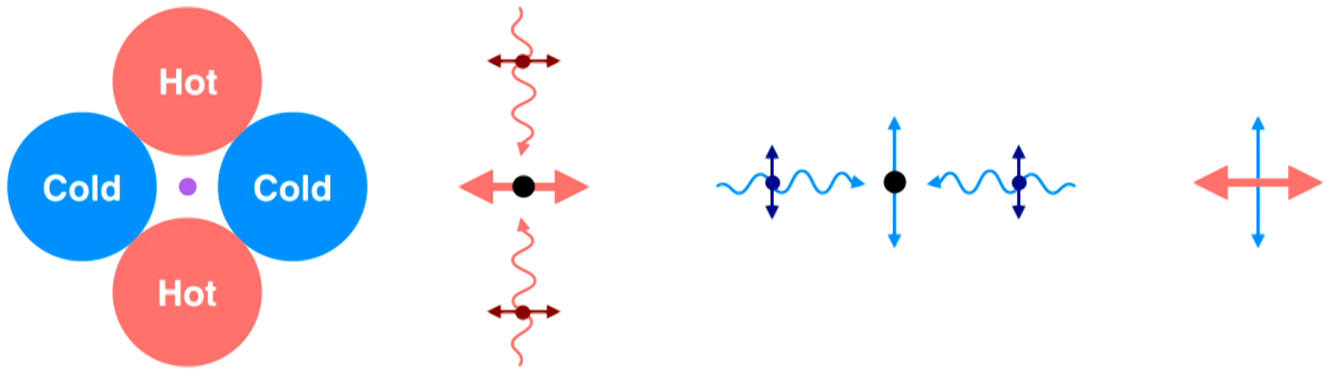

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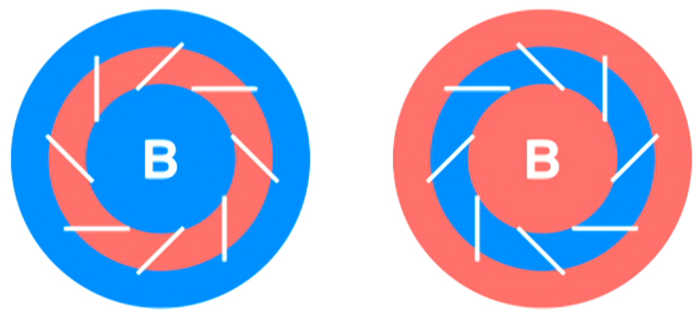


NOT FOR FDM AXIONS!
WE FIND NEW EFFECTS!

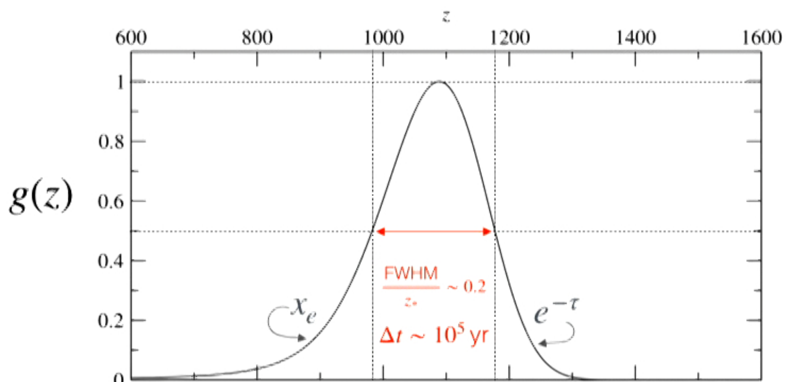
Some hints:
Finelli and Galaverni. Phys. Rev. **D79**, 063002 (2009).
Galaverni and Finelli. Nucl. Phys. Proc. Suppl. **194**, 51 (2009).

(Requires an extended period of decoupling to arise as $\Delta_{T2}^{(S)}$ is highly suppressed during tight-coupling epoch…)

CMB Polarization: When?

Polarization imprinted over some finite range of redshifts during decoupling.

Encoded by the ***visibility function***.
Probability that a photon last scattered between conformal time η and $\eta + d\eta$ is given by $g(\eta)d\eta$ where $g(\eta) \equiv -\tau' e^{-\tau}$ and $\tau = \int_{\eta}^{\eta_0} d\eta' \sigma_T a n_e x_e$



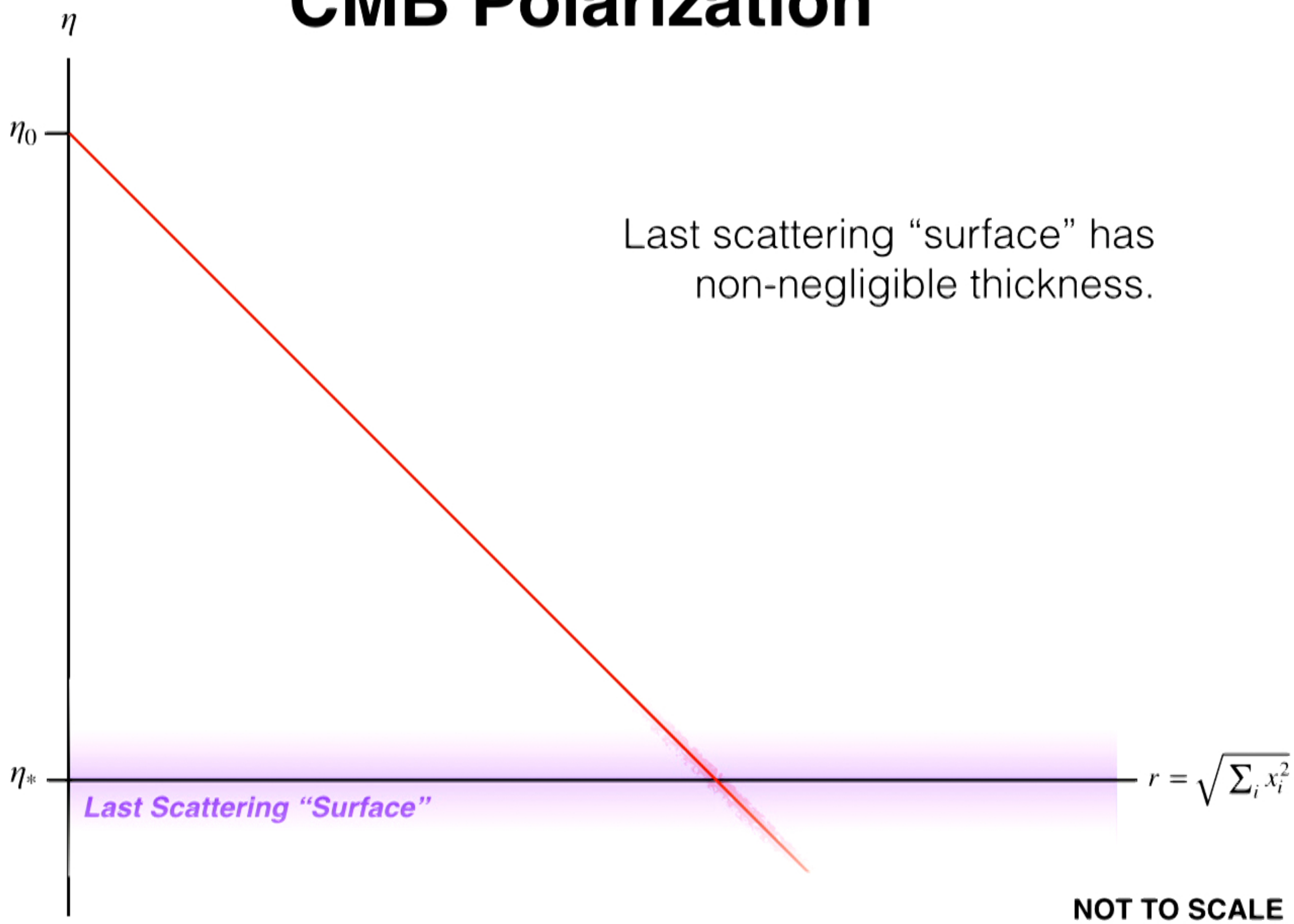
Chluba and Sunyaev. A&A **446**, 39 (2006).

Polarization perturbation (scalar): Seljak and Zaldarriaga. Astrophys. J. **469**, 437 (1996).

EVOLVES MUCH SLOWER THAN VISIBILITY FUNCTION

$$\Delta_P^{(S)} = \frac{1}{2}\int_0^{\eta_0} d\eta' e^{ik\mu(\eta-\eta_0)} g(\eta')[1 - P_2(\mu)]\Pi(\eta'), \qquad \Pi = \Delta_{T2}^{(S)} + \Delta_{P0}^{(S)} + \Delta_{P2}^{(S)}$$

CMB Polarization



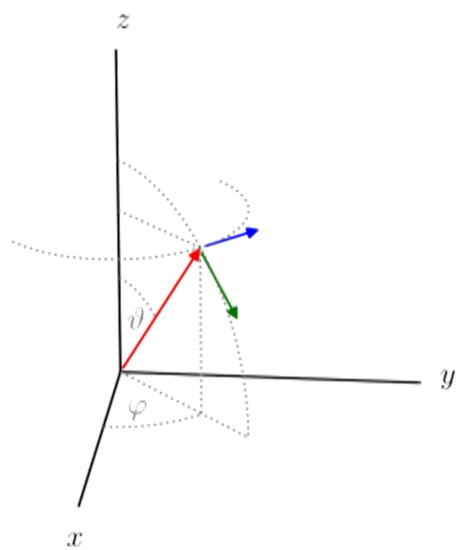
Notational Review: Stokes Parameters

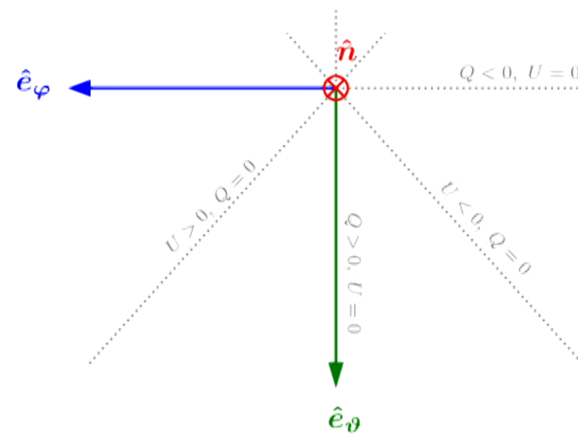
Common way to characterise CMB polarization is via the Stokes parameters:

I : intensity

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

Q, U : linear polarization on two axes at 45-degree separation





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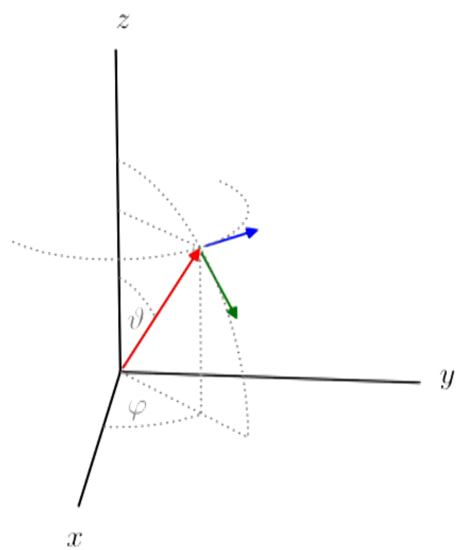
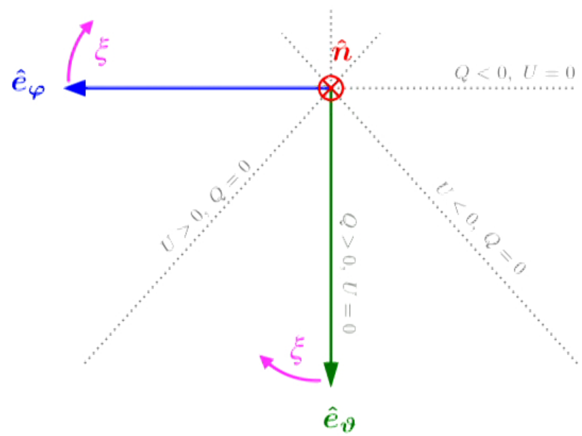




Q, U are spin-2 objects: $(Q \pm iU) \rightarrow e^{\mp 2i\xi}(Q \pm iU)$

Toy Model 1

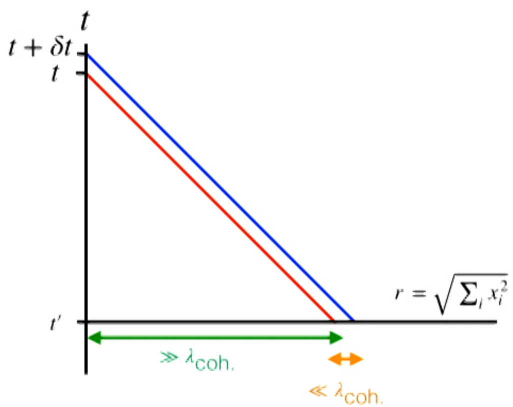
Build up to CMB results by way of some simplified toy models.

Minkowski spacetime with $a \equiv 1 \Rightarrow \eta \equiv t$.

No "smearing" at the source; i.e., visibility function $g(t) = \delta(t - t')$.

Axion field near-homogeneous: $\phi_{\text{abs.}}(t) = \phi_0 \cos(m_\phi t + \alpha)$

$$\phi_{\text{emit}}(t') = \phi_0 \cos(m_\phi t' + \beta(t, t'))$$



Source and observer separated by more than a coherence length $\lambda_{\text{coh.}} \sim 2\pi(m_\phi v_0)^{-1}$

$$|\beta(t, t') - \alpha| \sim \mathcal{O}(\pi)$$

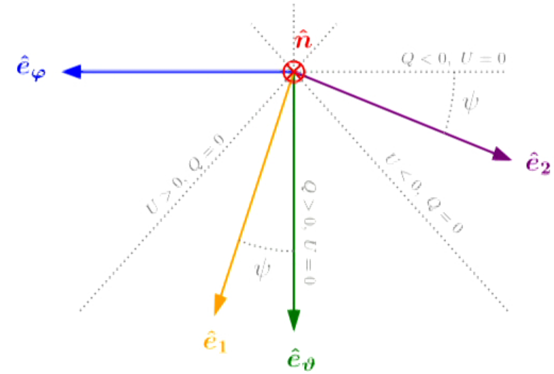
Near-homogeneity: $v_0 \lesssim 10^{-3}$

$$|\beta(t + T_\phi, t') - \beta(t, t')| \ll \pi$$

Toy Model 1

N photons polarized along $\hat{e}_1$ *at the source.*
M photons polarized along $\hat{e}_2$ *at the source.*

BUT! Rotation between source and observer.



At the observer:

$$I(\hat{\boldsymbol{n}}) = E_0^2(N+M)$$
$$V(\hat{\boldsymbol{n}}) = 0$$
$$(Q \pm iU)(\hat{\boldsymbol{n}}) = \epsilon I \exp\left[\pm 2i\left(\psi + \frac{g_{\phi\gamma}}{2}\Delta\phi\right)\right] \qquad \epsilon = \frac{N-M}{N+M}$$

$$\Delta\phi \equiv \phi_0 \left[\cos\left(m_\phi t + \alpha\right) - \cos\left(m_\phi t' + \beta(t,t')\right)\right]$$

$$(Q \pm iU)(\hat{\boldsymbol{n}}) = \exp\left[\pm 2i\left(\frac{g_{\phi\gamma}}{2}\Delta\phi\right)\right](Q \pm iU)_0(\hat{\boldsymbol{n}})$$

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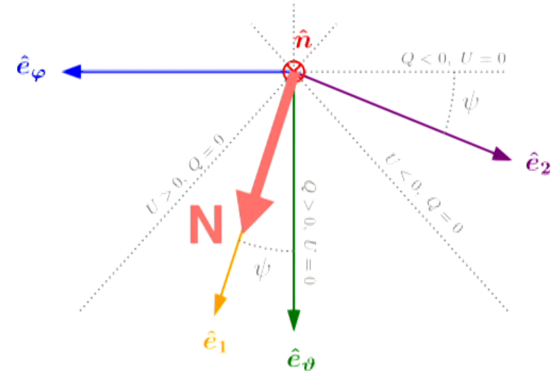

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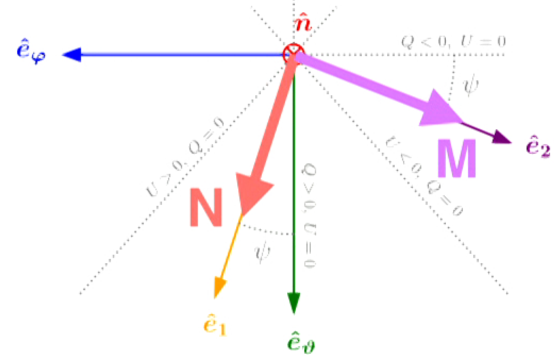

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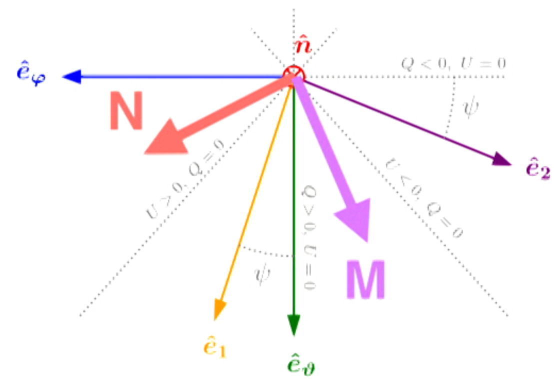

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Toy Model 1

Make two observations separated in time $t_2 - t_1 \sim$ (a few) $\times\, T_\phi$:

$$(Q \pm iU)(\hat{n}, t_2) = \exp\left[\pm 2i\left(\frac{g_{\phi\gamma}}{2}\left(\Delta\phi_2 - \Delta\phi_1\right)\right)\right](Q \pm iU)(\hat{n}, t_1)$$

$$\Delta\phi_i \equiv \phi_0\left[\cos\left(m_\phi t_i + \alpha\right) - \cos\left(m_\phi t' + \beta(t_i, t')\right)\right]$$

$$\Delta\phi_2 - \Delta\phi_1 \approx \phi_0\left[\cos(m_\phi t_2 + \alpha) - \cos(m_\phi t_1 + \alpha)\right]$$

NEW EFFECT 1

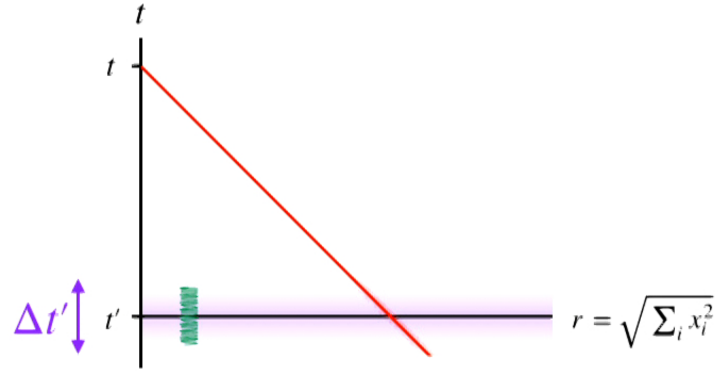
ON-THE-SKY AC OSCILLATION OF THE CMB POLARIZATION ANGLE AT THE AXION PERIOD

$T_\phi \sim 0.1$ yrs $\times\, (m_\phi/10^{-21}\,\text{eV})^{-1}$

See also recent work on AC effects in astrophysical context: Fujita, Tazaki, and Toma. 1811.03525. Ivanov, et al. 1811.10997. Liu, Smoot, Zhao. 1901.10981v2.

Toy Model 2

Same as Toy Model 1, but put back the smearing of the source:



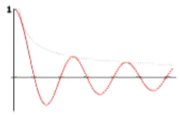
N+M photons emitted randomly during period $\Delta t'$, weighted by $g(t')$.

MANY axion oscillations during emission period:

$$\left(\Delta t' \sim 10^{4-5}\,\text{yrs}\right) \gg \left(T_\phi \sim 0.1\text{yrs} \times (m_\phi/10^{-21}\,\text{eV})^{-1}\right)$$

In the limit of large photon statistics, the Stokes parameters are given by

$$(Q \pm iU)(\hat{\boldsymbol{n}}) = \epsilon I \int d\tilde{t}'\, g(\tilde{t}') \exp\left[\pm 2i \left(\psi + \frac{g_{\phi\gamma}}{2} \Delta\phi(t, \tilde{t}')\right)\right]$$



Toy Model 2

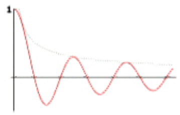
$$(Q \pm iU)(\hat{\boldsymbol{n}}) \approx J_0\left(g_{\phi\gamma}\phi_0\right) \exp\left[\pm 2i\left(\frac{g_{\phi\gamma}}{2}\phi_0 \cos(m_\phi t + \alpha)\right)\right](Q \pm iU)_0(\hat{\boldsymbol{n}})$$

NEW EFFECT 1

ON-THE-SKY AC OSCILLATION OF THE CMB POLARIZATION ANGLE AT THE AXION PERIOD

NEW EFFECT 2

WASHOUT OF POLARIZATION COMPARED TO ΛCDM PREDICTION



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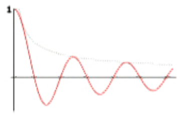

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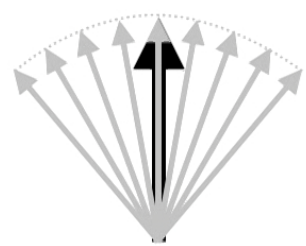

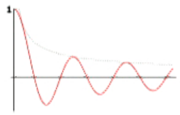

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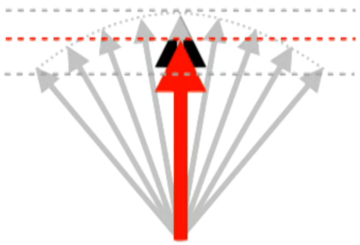

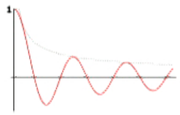

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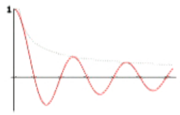

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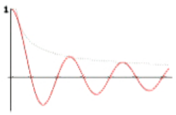

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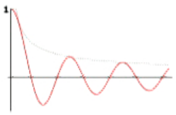

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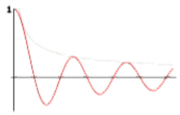

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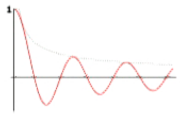

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NEW EFFECT 2

WASHOUT OF POLARIZATION COMPARED TO ΛCDM PREDICTION

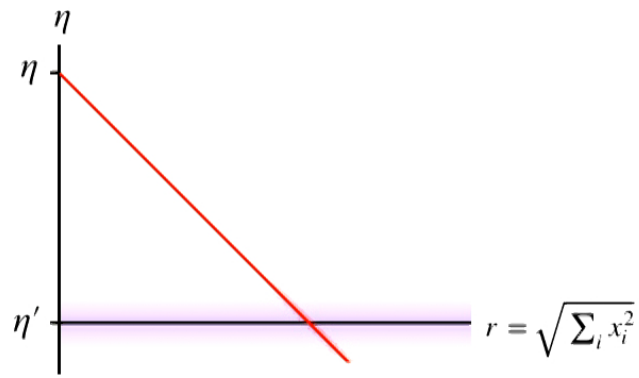
Washout only because the DM axion oscillates many times during decoupling!

Distinct phenomenology from when axion evolves slowly cosmologically: **no* DC rotation!** Static E-to-B conversion is not the correct search.

*unsuppressed

Realistic (Toy) Model 3

Same as Toy Model 2, but now in FLRW, and using axion field with real-universe evolution



Effect operates the same way in FLRW and Minkowski.

In the limit of large photon statistics,

$$(Q \pm iU)(\hat{\boldsymbol{n}}) = \epsilon I \int d\tilde{t}' \, g(\tilde{t}') \exp\left[\pm 2i \left(\psi + \frac{g_{\phi\gamma}}{2} \Delta\phi(t, \tilde{t}')\right)\right]$$

But must now change the expression for $\Delta\phi$

Realistic (Toy) Model 3

Early-Universe axion field $\phi(t', \hat{\boldsymbol{n}}) \approx \phi_*(\hat{\boldsymbol{n}}) \left[\frac{1+z'}{1+z_*}\right]^{3/2} \cos\left(m_\phi t' + \beta\right)$

$$\frac{1}{2} m_\phi^2 \phi_*^2 = \rho_c \Omega_c^0 (1+z_*)^3$$

$$\phi_* \approx 1.6 \times 10^{11}\,\text{GeV} \times \left(\frac{m_\phi}{10^{-21}\,\text{eV}}\right)^{-1} \times \left(\frac{\Omega_c^0 h^2}{0.11933}\right)$$

Local axion field $\phi(t) \approx \phi_0 \cos(m_\phi t + \alpha(t))$

$$\frac{1}{2} m_\phi^2 \phi_0^2 = \rho_0$$

$$\phi_0 \approx 2.1 \times 10^{9}\,\text{GeV} \times \left(\frac{m_\phi}{10^{-21}\,\text{eV}}\right)^{-1} \times \left(\frac{\rho_0}{0.3\,\text{GeV}\,\text{cm}^{-3}}\right)$$

Realistic (Toy) Model 3

$$(Q \pm iU)(\hat{\boldsymbol{n}}) = \epsilon I \int d\tilde{t}'\, g(\tilde{t}') \exp\left[\pm 2i \left(\psi + \frac{g_{\phi\gamma}}{2} \Delta\phi(t, \tilde{t}')\right)\right]$$

$$\vdots$$

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

$$\begin{aligned} &J_0 \left[g_{\phi\gamma} \langle \phi_* \rangle (\hat{\boldsymbol{n}})\right] \\ &\equiv \int d\tilde{z}\, g(\tilde{z})\, J_0 \left(g_{\phi\gamma} \phi_*(\hat{\boldsymbol{n}}) \left[\frac{1+\tilde{z}}{1+z_*}\right]^{3/2} \right) \\ &\approx J_0 \left[g_{\phi\gamma} \phi_*(\hat{\boldsymbol{n}})\right] \end{aligned}$$

WASHOUT CONTROLLED BY EARLY-UNIVERSE AXION FIELD AMPLITUDE

OSCILLATION CONTROLLED BY LOCAL AXION FIELD AMPLITUDE AND PERIOD

NO UNSUPPRESSED NET STATIC DC ROTATION

Realistic (Toy) Model 3

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

(Holds point-by-point)

AC OSCILLATION

$$\Delta\theta \sim g_{\phi\gamma}\phi_0/2$$

Linear in axion-photon coupling times (smaller) present day axion field.

WASHOUT

$$1 - J_0(g_{\phi\gamma}\phi_*) \sim (g_{\phi\gamma}\phi_*/2)^2$$

Quadratic in axion-photon coupling times (larger) early-universe axion field.

Possibly need to consider both effects; not a priori *clear which is more important*

Washout Effect on CMB

Ignore AC effect for now.

What does the washout do to CMB observables?

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

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

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

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

Specific pattern of reductions compared to ΛCDM predictions.

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

Approximate analysis

Consider only high multipoles ($50 \leq l \leq 1996$) in Planck 2018 data. [1807.06209]

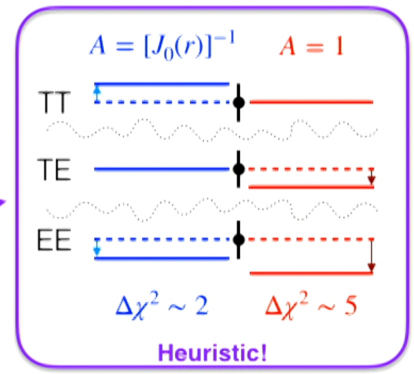
Likelihood function to perform one-parameter profile likelihood ratio test on $r \equiv g_{\phi\gamma}\langle\phi_*\rangle$ against null hypothesis $r = 0$:

$$-2\ln\mathcal{L}(r \equiv g_{\phi\gamma}\langle\phi_*(m_\phi)\rangle; A) \equiv \sum_{XY\in\{TT,TE,EE\}} \sum_{l=50}^{l=l_{\max}} \left(\frac{C^{\text{observed}}_{XY,l} - A \times f_{XY}(r) \times C^{\text{theory}}_{XY,l}}{u(C^{\text{observed}}_{XY,l})} \right)^2$$

ΛCDM

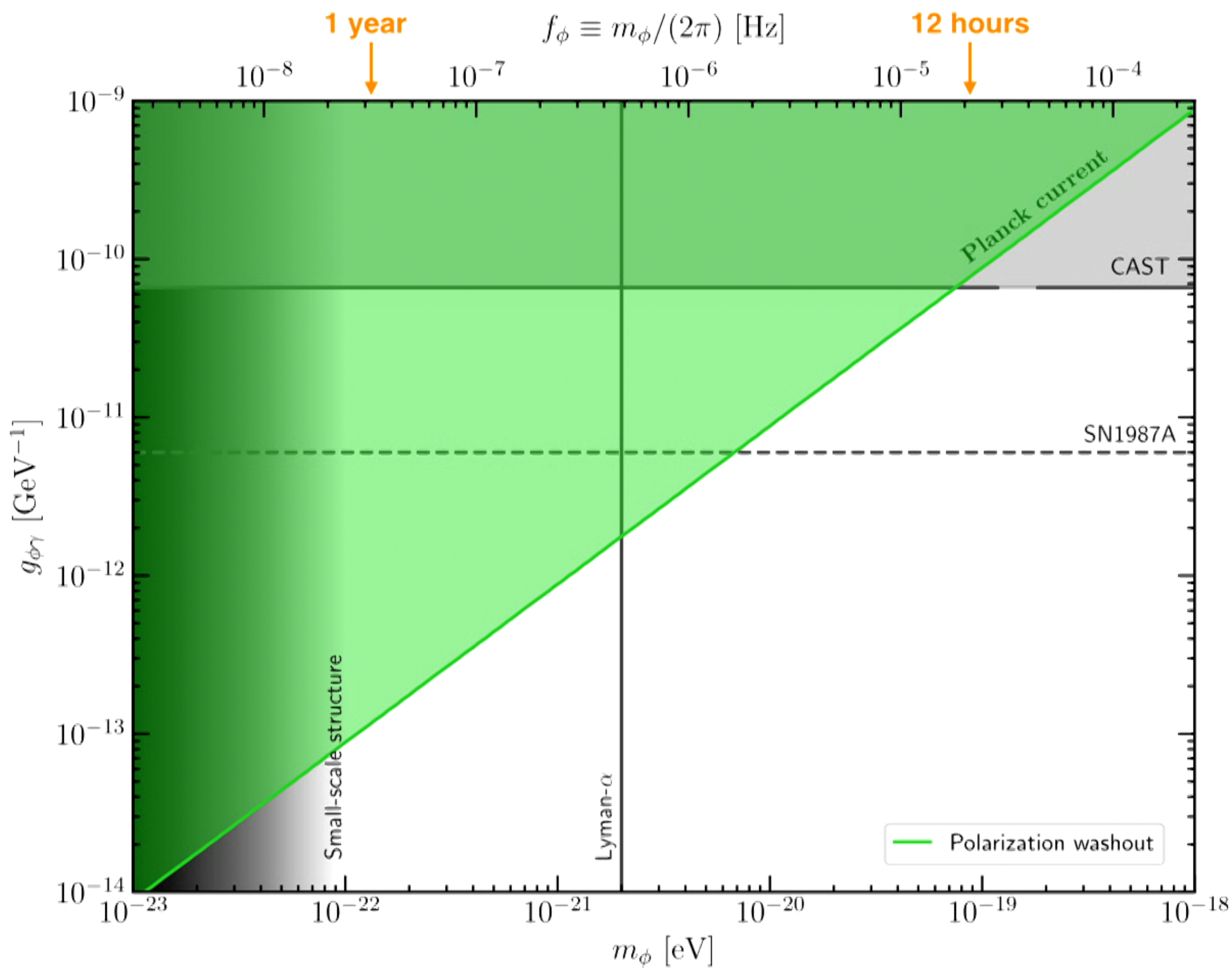
$$f_{XY}(r) \equiv \begin{cases} 1 & XY = TT \\ J_0(r) & XY = TE \\ [J_0(r)]^2 & XY = EE \end{cases}$$

Partial compensation of our effect by adjusting overall common amplitude A of spectra.



Profile over A: $\Delta\chi^2(r) \equiv -2\ln\left(\frac{\mathcal{L}(r;\hat{\hat{A}}(r))}{\mathcal{L}(r=0;\hat{A}(r=0))}\right)$

95% confidence limit: $1 - J_0(g_{\phi\gamma}\phi_*(m_\phi)) \leq 4.9 \times 10^{-3}$ [approximate]



1 year
$f_\phi \equiv m_\phi/(2\pi)$ [Hz]
12 hours
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$g_{\phi\gamma}$ [GeV^{-1}]
Planck current
CAST
SN1987A
Small-scale structure
Lyman-α
Polarization washout
10^{-23}
10^{-22}
10^{-21}
10^{-20}
10^{-19}
10^{-18}
m_ϕ [eV]

Rigorous analysis

Ad hoc? Combinations of CMB parameters degenerate with our effect?

Profile over full ΛCDM parameter set $\boldsymbol{\Theta} \equiv (\Omega_b h^2,\, \Omega_c h^2,\, 100\,\theta_{\mathrm{MC}},\, \tau,\, \ln(10^{10} A_s),\, n_s)$

Use CAMB + MC techniques to sample / profile.

[Lewis, Challinor, and Lasenby. Astrophys. J **538**, 473 (2000).]

$$\Delta\chi^2(r) \equiv -2\ln\left(\frac{\mathcal{L}(r;\hat{\hat{\boldsymbol{\Theta}}}(r))}{\mathcal{L}(r=0;\hat{\boldsymbol{\Theta}}(r=0))}\right)$$

Must extend likelihood to lift $\ln A_s - 2\tau$ degeneracy. $\left(A_{l\gtrsim 20} \sim A_s e^{-2\tau}\right)$

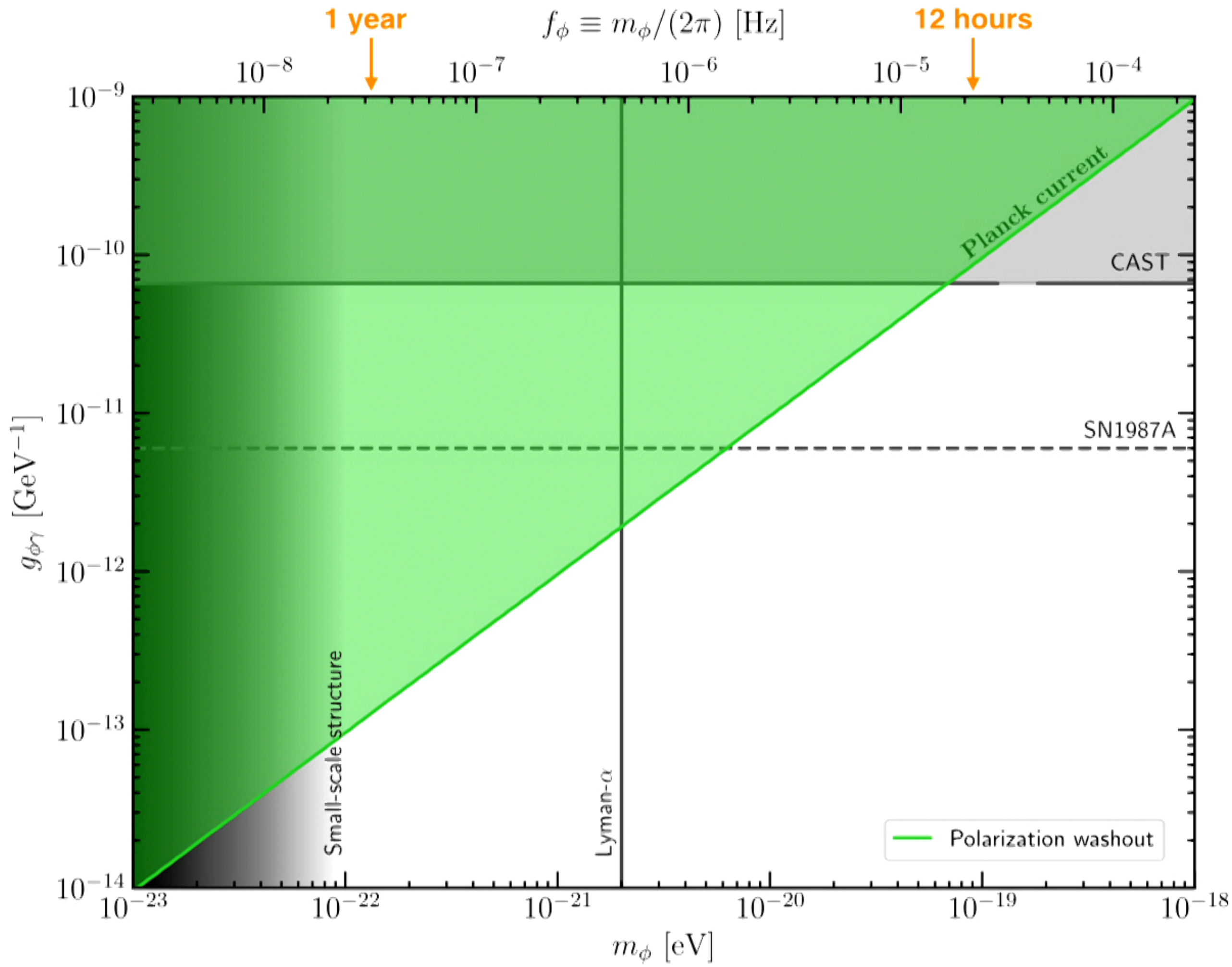
Turn effect off for low-l: $f_{XY}(r) \;\to\; (1 - h(l)) + f_{XY}(r)h(l)$

$$h(l) \;\equiv\; \tfrac{1}{2}\left[1+\tanh((l-l_0)/\delta l)\right] \text{ with } l_0 = 20 \text{ and } \delta l = 5$$

(Approximate, but most statistical power not from low-l. To get fully correct, run Boltzmann codes… computationally challenging.)

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

Only 9% weaker than approx.; no degeneracies with effect in ΛCDM.



Michael A. Fedderke *(Stanford / UC Berkeley / LBNL)* 32 Perimeter Institute. April 30, 2019.

Future Projection

Use approximate analysis technique since good to ~10%.

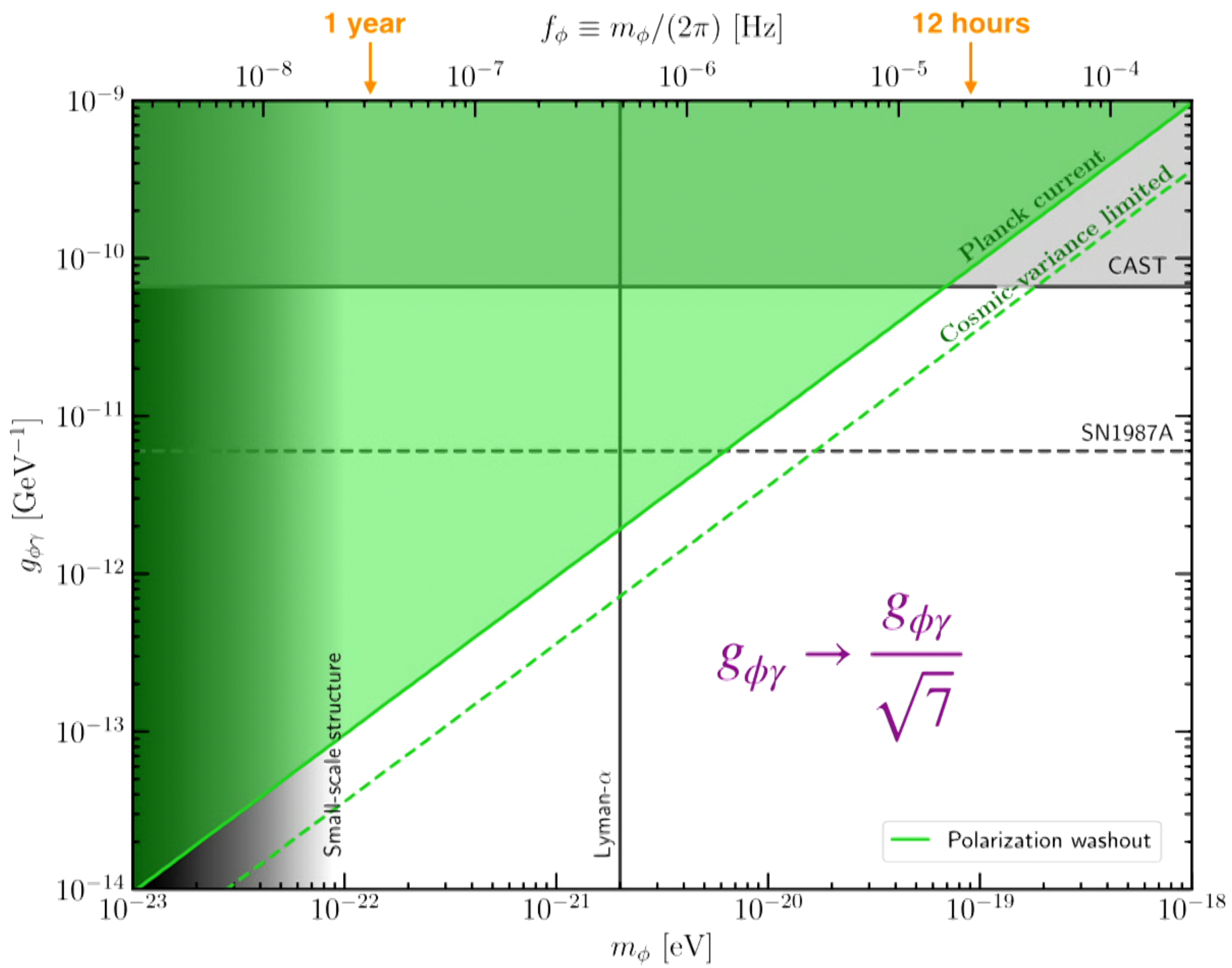
TT, TE, EE measured to cosmic-variance limit out to $l = 3000$
(above, TT has significant foregrounds).

Assume Planck sky coverage of 57.7%
(may be aggressive, but trying to see ultimate reach).

Future median projected 95% confidence bound:

$$1 - J_0\left(g_{\phi\gamma}\phi_*(m_\phi)\right) \leq 8.2 \times 10^{-4}$$

About a factor of 7 better… and then no further on this effect.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Planck current
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Small-scale structure
Lyman-α
$g_{\phi\gamma} \rightarrow \frac{g_{\phi\gamma}}{\sqrt{7}}$
Polarization washout
10^{-23}
10^{-22}
10^{-21}
10^{-20}
10^{-19}
10^{-18}
m_ϕ [eV]

AC Effect

Distinct from any other cosmological signature:

- On-the-sky, point-by-point oscillation of the local polarization angle.
- Period of ~ a year to ~ a few hours, set by axion mass.
- Single frequency: $\Delta\omega/\omega \sim 10^{-6}$
- 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.

SIGNIFICANT DISCOVERY POTENTIAL!

Highly non-trivial cross-checks on any putative signal between different experiments, different patches of sky, different observation times.

AC Effect

CMB time-series data required! Not publicly available.

In discussions with a number of CMB experimental colleagues; interested in performing this analysis (does double-duty as an AC systematics check).

We can provide estimates / projections on reach for this search.

Cf. recent Planck result looking for all-sky DC rotation finds:

$$\alpha = 0.31^\circ \pm 0.28^\circ \text{ (sys.)} \pm 0.05^\circ \text{ (stat.)}$$

$$\alpha = 0.35^\circ \pm 0.28^\circ \text{ (sys.)} \pm 0.05^\circ \text{ (stat.)}$$

Different analysis techniques

These systematics are from DC-calibration-related.

"Irrelevant" for AC search: noise PSD at zero frequency $\neq$ noise PSD at finite frequency.

AC Effect

Statistical uncertainty gives indication of power of search, but..

DC search uses TB, EB cross-correlation: cosmic-variance limited!

Our effect **NOT** limited by cosmic variance! "Fix a region of the sky with known high polarization; watch it varying in time."

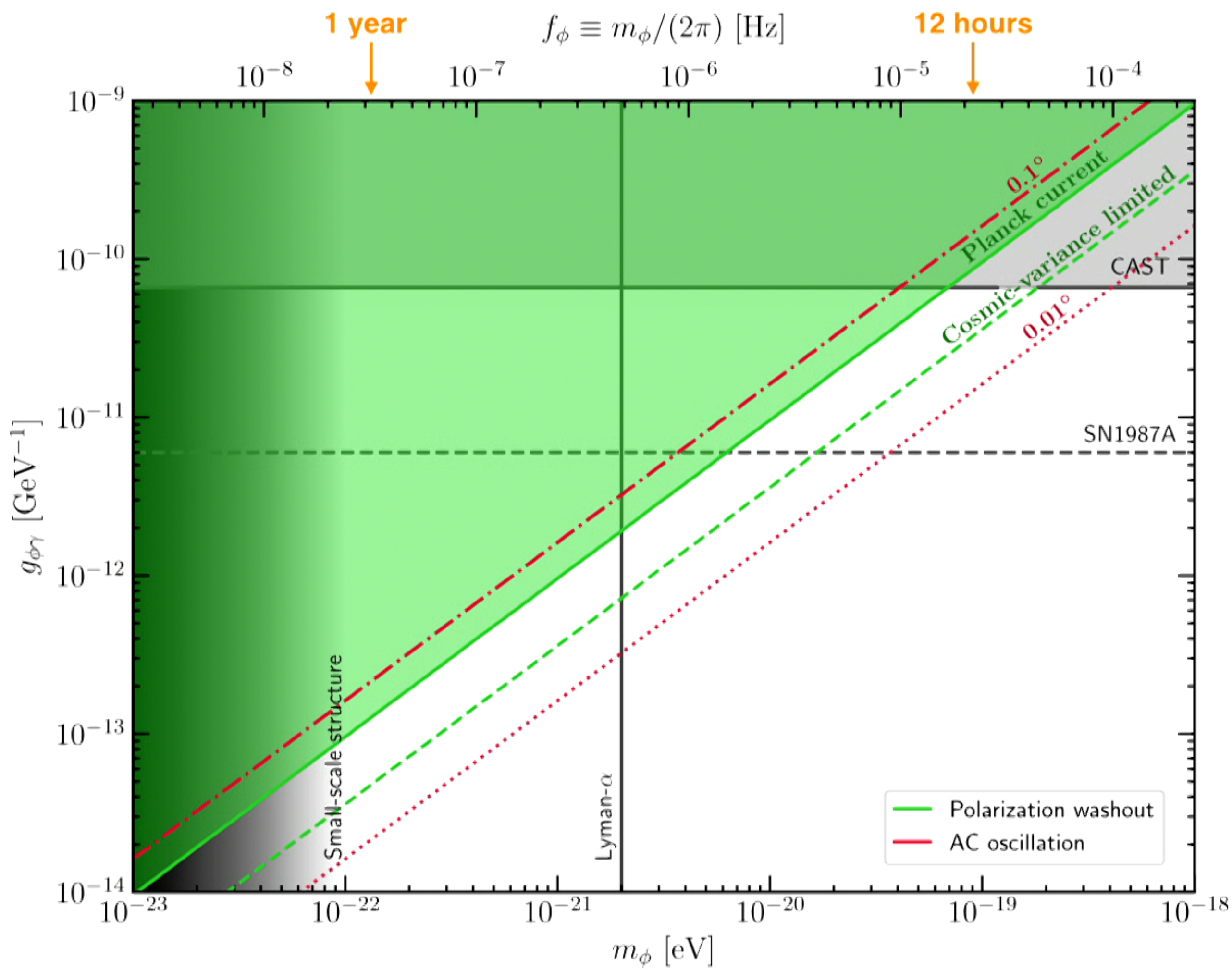
We argue: AC search should do *at least* as well as the statistical uncertainty on the all-sky DC search.

Systematics / calibration need to be understood! Best addressed by experimental collaborations.

Benchmark: at 95% confidence, could reach at least $\Delta\theta \sim 0.1^\circ$

Future reach? Estimate a factor of 10 better: $\Delta\theta \sim 0.01^\circ$

Ultimate reach unknown… this is a new type of CMB analysis.



Michael A. Fedderke *(Stanford / UC Berkeley / LBNL)* 38 Perimeter Institute. April 30, 2019.

Conclusions

Re-examined effect of axion-photon coupling on CMB polarization when axion mass is in the fuzzy dark matter range.

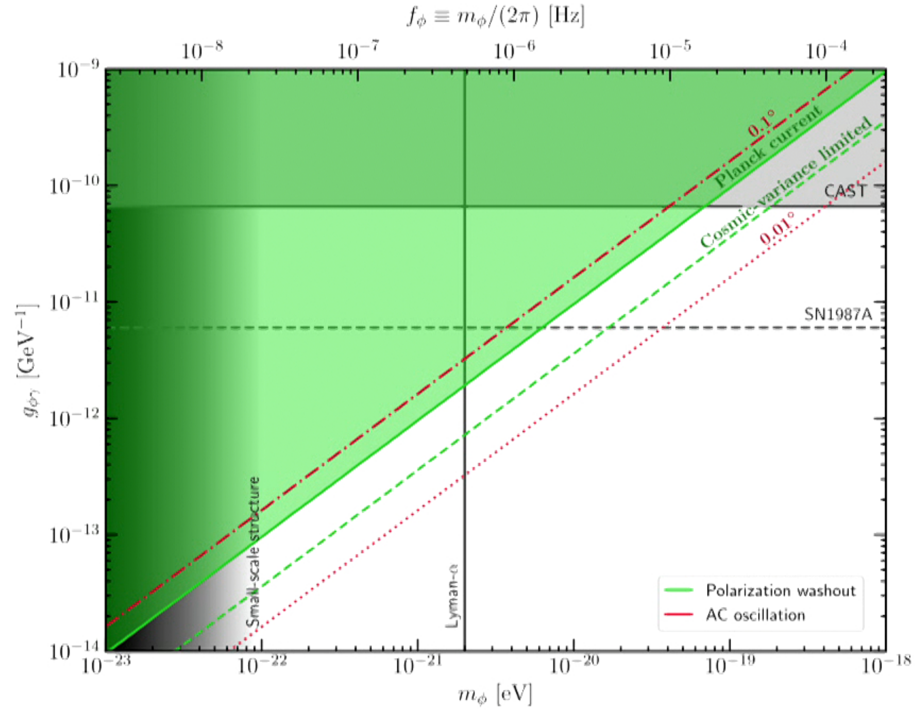
Found two **new** phenomenological effects arising from the photon linear polarization rotation induced by the axion field.

Polarization washout: reduction in polarization power on all pristine CMB scales (averaging over axion phases at emission).
Limits already some orders of magnitude better than previous bounds.
Eventually cosmic-variance limited.

AC oscillation: point-by-point, on-the-sky oscillation of the CMB polarization angle at axion period.
Limits require dedicated analyses. Estimates/projections indicate at least as good as washout.
Not cosmic-variance limited. Discovery potential is significant.

Exciting new avenue to constrain or detect axion fuzzy dark matter.

Thank you!



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