Measurement of Axion Gradients with Photon Interferometry (MAGPI)

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Axions

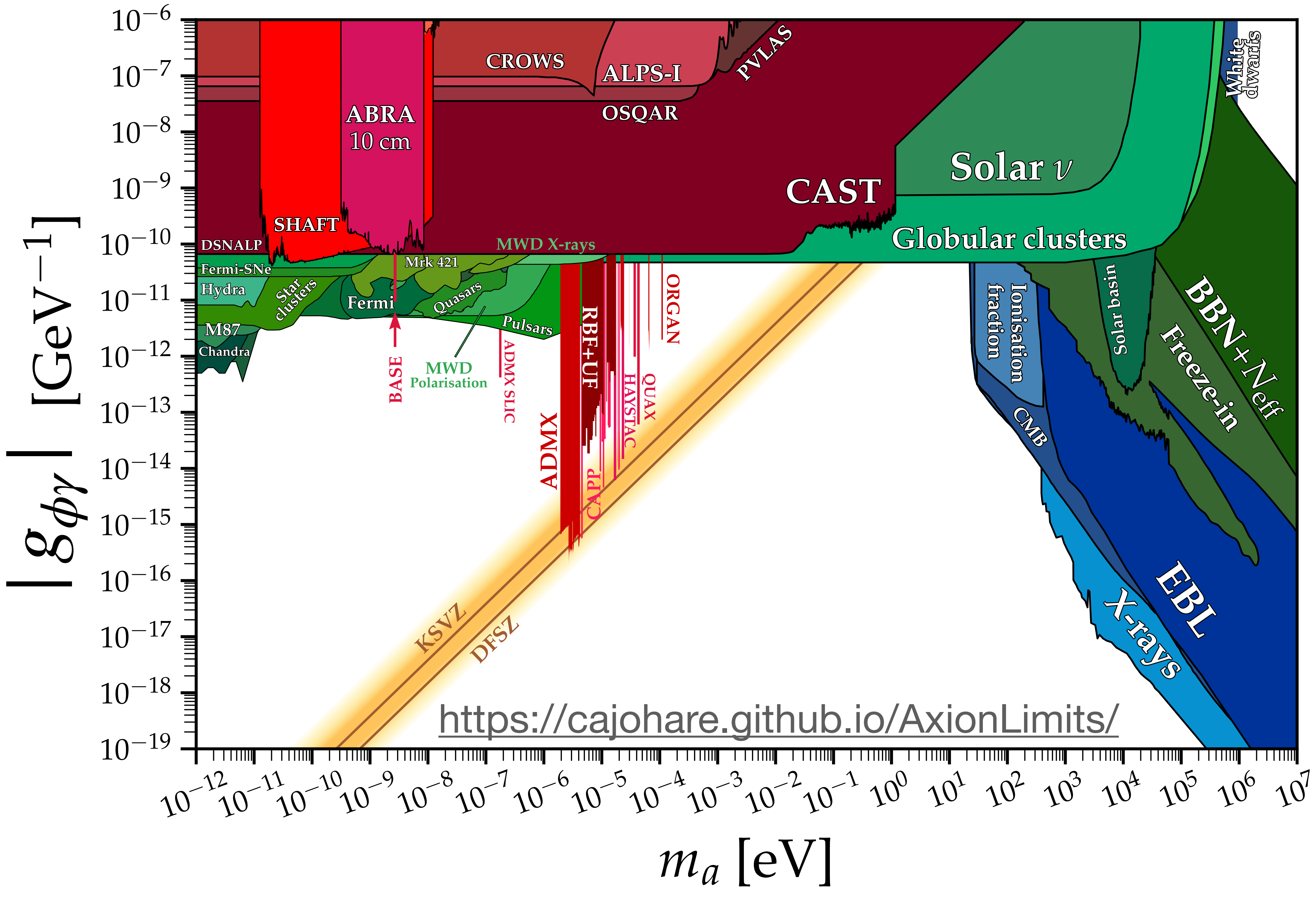
- Light pseudoscalar degrees of freedom (P, CP odd)
- Existence generically expected from UV theory
- Usually, pseudo-Nambu—Goldstone bosons of high-scale f spontaneous symmetry breaking
- Usually, derivatively coupled to the SM: $f^{-1}\partial_\mu\phi\,\bar{\psi}\gamma_\mu\gamma_5\psi, \quad f^{-1}\phi G\tilde{G}, \quad f^{-1}\phi F\tilde{F}$
- QCD axion originally introduced as a consequence of dynamical resolution of the QCD strong CP problem; mass and couplings linked Peccei, Quinn (1977); Weinberg (1978); Wilczek (1978)
- More generally, axion-like particles (ALPs); mass and couplings are free parameters
- Popular ultralight bosonic dark-matter candidate [not this talk]
- Can also act as dark-energy-like quintessence field [also not this talk]

Axion-photon coupling

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

- Lots of really interesting phenomenology

- Astrophysical axion production, effects on photon propagation, terrestrial detection, etc.
    - Helioscopes (CAST, IAXO, …)
    - LSW experiments (ALPS, …)
    - DM haloscopes (ADMX, ORGAN, QUAX, CAPP, HAYSTAC, MADMAX, ABRA, SHAFT,…)
    - Astrophysical production/conversion (green)
    - **Polarization rotation / photon birefringence**



https://cajohare.github.io/AxionLimits/

Photon birefringence

Carroll, Field, Jackiw (**1990**); Harari, Sikivie (**1992**)

- Axion—photon coupling in the presence of an **axion background** causes circular photon birefringence:

$$k_\pm \sim \omega \pm \frac{1}{2} g_{\phi\gamma} \left(\dot{\phi} + \hat{\mathbf{k}} \cdot \nabla \phi \right) \quad \Rightarrow \quad A_\pm \sim A_\pm^{(0)} e^{-ik_\mu x^\mu \pm i g_{\phi\gamma} \Delta\phi/2}$$

- Opposite-sign phase shifts $\alpha_\pm$ for right- and left-handed photons (≡ rotation of plane of linear polarization)
- Effect depends only on axion field at endpoints of photon path: $\alpha_\pm = \pm\, g_{\phi\gamma} \Delta\phi/2$

Lu Yin's talk yesterday

- **Lots** of work on phenomenology of this effect with axion DM or quintessence fields O(100+) papers
  - CMB observables ("cosmic birefringence" [TB, EB power, …]; polarization oscillation; …)
  - Astrophysical polarization rotations Ivanov, et al. (2018), …

    Fedderke, Graham, Rajendran (2019) +BICEP/Keck, SPT-3G, and POLARBEAR searches

    Jacob Spisak's talk yesterday
  - Lab-based searches for $\Delta\phi \sim \int \dot{\phi} dt$ Melissinos (2009); DeRocco, Hook (2018); Obata, Fujita, Michimura (2018); Liu, Elwood, Evans, Thaler (2018); Nagano, Fujita, Michimura, Obata (2019); Martynov, Miao (2020); Oshima et al. [DANCE experiment] (2023)
- **This talk: AXION GRADIENTS: $\Delta\phi \sim \int d\mathbf{l} \cdot \nabla \phi$**

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AS SEEN ON TV

- **This talk: AXION GRADIENTS:** $\Delta\phi \sim \int d\mathbf{l} \cdot \nabla \phi$

Axion monopole couplings

- How do you get an axion gradient?
- DM axion? Yes, but $|\nabla\phi|_{\text{DM}} \sim 10^{-3}|\dot{\phi}|_{\text{DM}}$. Much smaller effects.
- Consider axions with an explicitly broken shift symmetry (also, CP broken)
- Monopole couplings to bulk SM charges (B, L, $B-L$, etc.): e.g., $\mathscr{L} \supset -\tilde{g}_B\phi\bar{N}N$
- Occurs naturally in presence of non-zero strong CP angle for QCD axion, and can also consider generally for ALPs Moody, Wilczek (1984); Pospelov (1997)
- **SM matter will source axion field profiles $\phi(\mathbf{r})$ that have gradients**
- Mass tuning for light axions? Yes, but depends on a lot of additional assumptions

Sourced axion gradients

- Sources? Earth, or a small lab mass

Yohei Ema's talk today

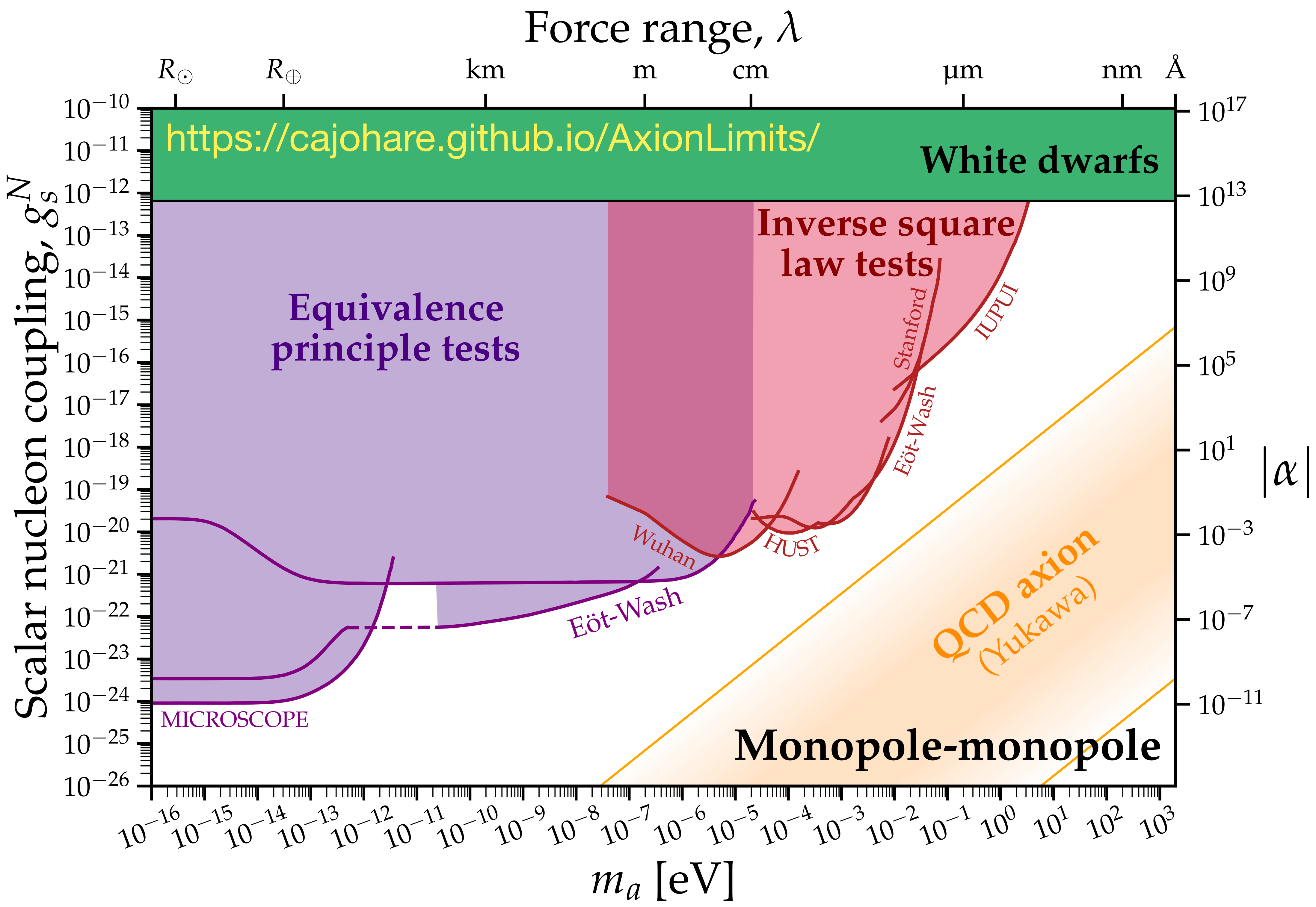
- Recently invoked as a possible environmental explanation of the $(g-2)_\mu$ anomaly: $\nabla\phi \sim \mathbf{B}_{\text{pseudo}}$ if coupled to muon spins, so extra precession

Davoudiasl, Szafron (2022)
Agrawal, Kaplan, Kim, Rajendran, Reig (2022)

- Constraints on the monopole coupling from EP tests / fifth-force experiments
- How big is the gradient still allowed to be?
- Big, for Earth!

$$|\nabla\phi|_\oplus \sim 0.2\,\text{eV}^2 \times \left(\tilde{g}_B/6\times10^{-25}\right)$$

- Compare: $|\dot{\phi}|_{\text{DM}} \sim 2\times10^{-3}\,\text{eV}^2$
- Birefringence effects up to $\sim 10^2$ larger!

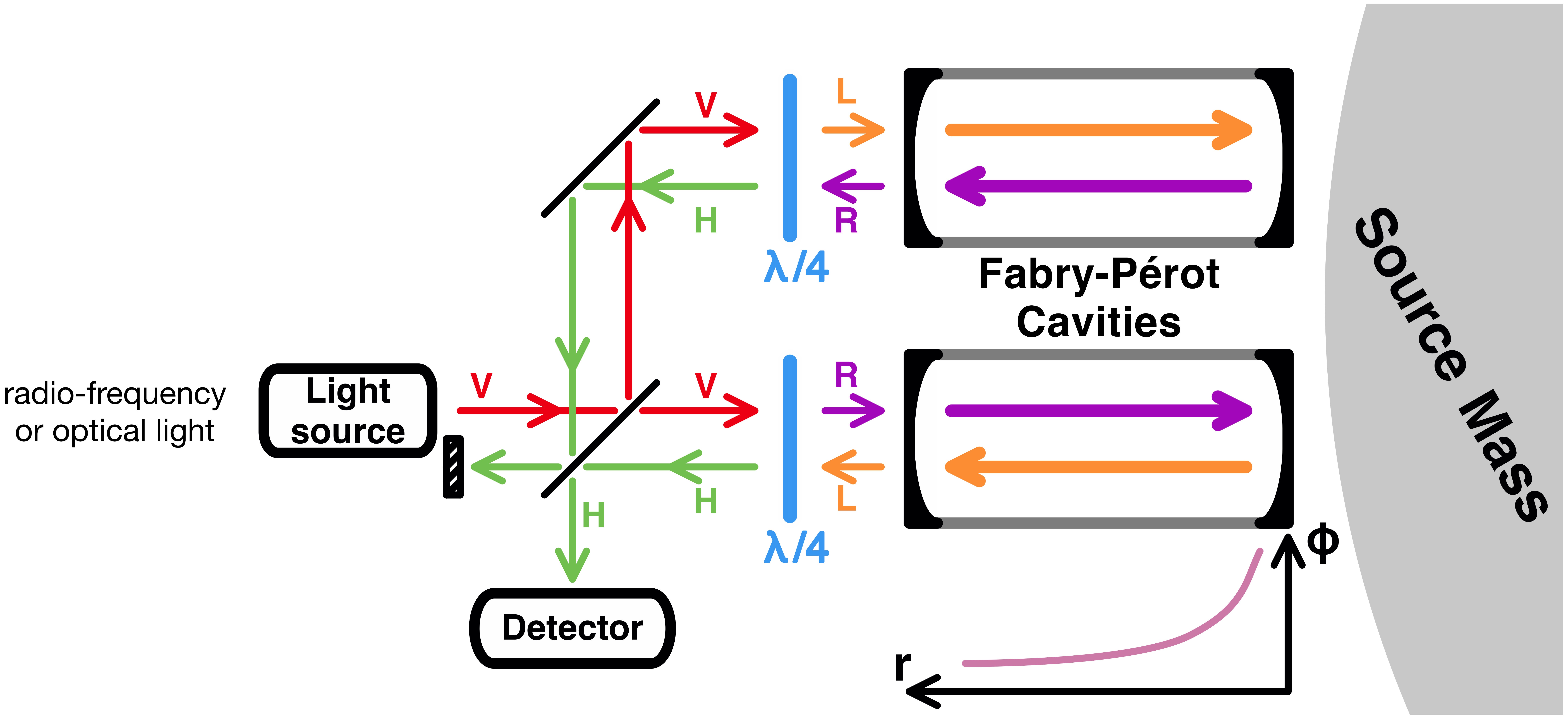


Monopole-dipole scenario: a new signal

- Monopole $\tilde{g}_Q$: a large mass / axion source causes a field gradient
- "Dipole" $g_{\phi\gamma}$: gradient causes circular photon birefringence (achromatic phase shift for L/R)
- Detect differential L/R phase shift in the lab using interferometers
- Boost signal with Fabry-Pérot (FP) cavities in the interferometer arms (cf. LIGO)**

** For experts: I'll come back to why this signal does not cancel out

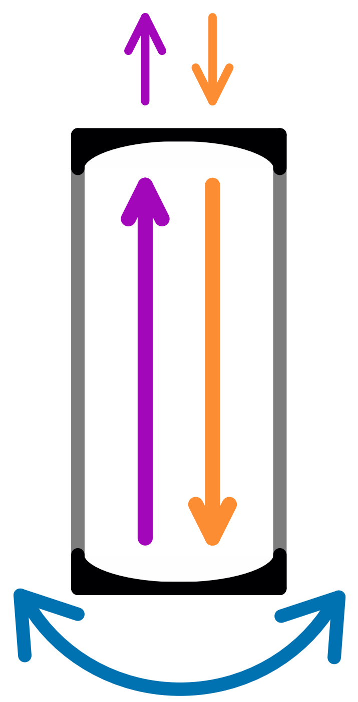
Experimental architecture



Similar to DeRocco, Hook (2018), but with important differences

Signal Properties

- Signal is static (DC); change cavity orientation wrt the field gradient to give AC signal
  - For Earth as source: vertical cavities, rotate in vertical plane
  - For lab source: horizontal cavities, rotate in horizontal plane *or* move the mass



- Search is non-resonant: probes all (sufficiently low) axions masses with single run
- Achromatic signal not completely degenerate with differential length fluctuation of the FP cavities (those give a chromatic phase shift)

Cancellation? No!

- Key point: photon helicity flips on reflection from a mirror $\left(\mathbf{j} \to +\mathbf{j}; \quad \mathbf{k} \to -\mathbf{k} \right)$

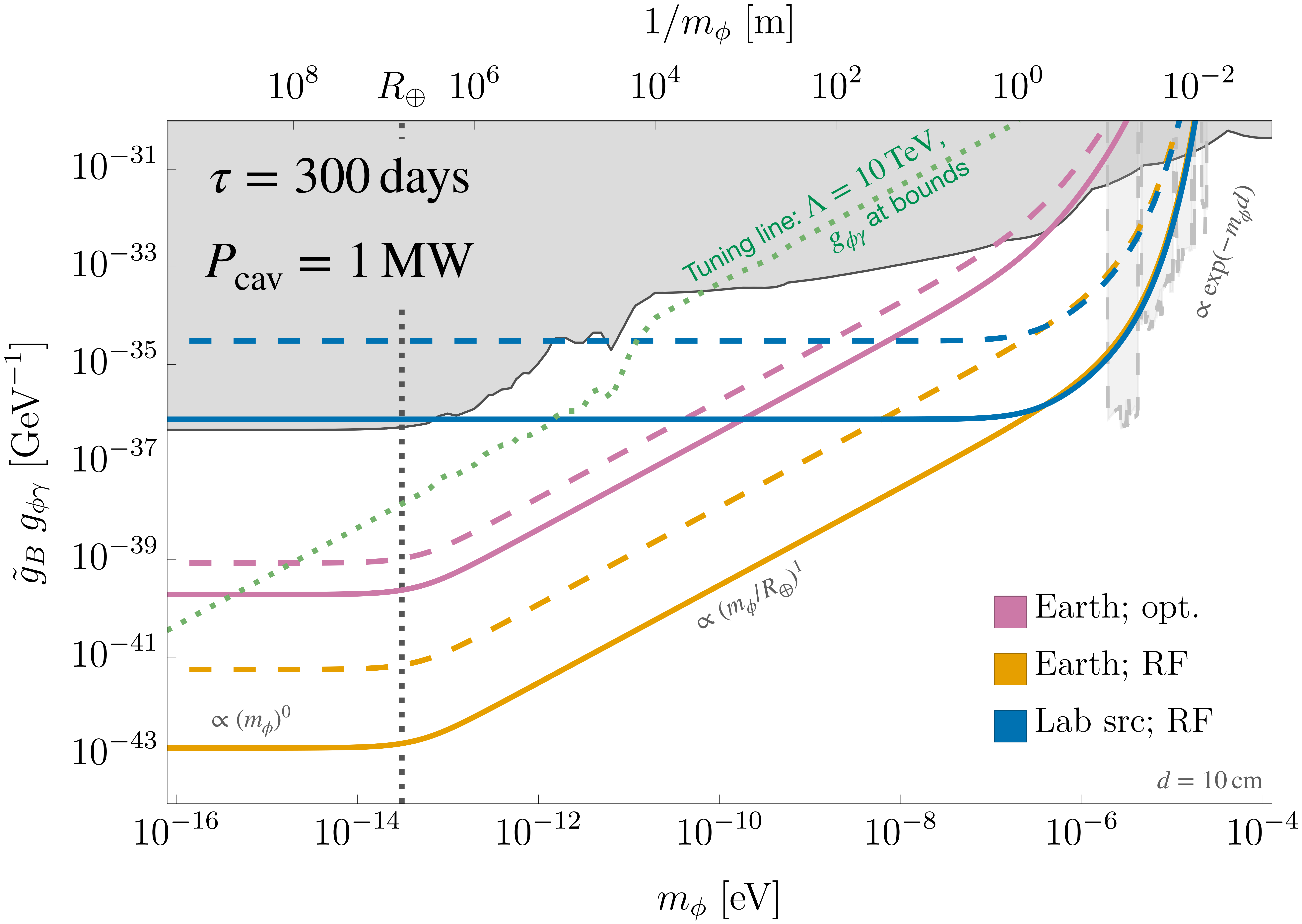
- For a DM axion experiment with the same architecture, this causes a signal cancellation when $m_\phi L \ll 1$: DeRocco, Hook (2018)
  - Phase shift: $\sim \pm g_{\phi\gamma}\dot{\phi}L$ on outbound leg, but $\sim \mp g_{\phi\gamma}\dot{\phi}L$ on inbound leg.

- For DM axions: requires extra optical elements *inside the FP cavity*, DeRocco, Hook (2018)
  OR other architectures / resonant approaches (e.g., bowtie cavities)
  Melissinos (2009); Obata, Fujita, Michimura (2018); Liu, Elwood, Evans, Thaler (2018); Martynov, Miao (2020); Oshima et al. [DANCE] (2023)

- **BUT HERE IT'S DIFFERENT!**
  $\hat{\mathbf{k}} \cdot \nabla\phi$ also changes sign for trips in opposite directions! **Two sign changes compensate.**
  - Phase shift: $\sim \pm g_{\phi\gamma}(+\mathbf{z} \cdot \nabla\phi)L$ on outbound leg; $\sim \mp g_{\phi\gamma}(-\mathbf{z} \cdot \nabla\phi)L$ on inbound leg.

- Signal builds up to number of bounces in cavity ($\sim$ finesse $\mathscr{F} \gg 1$), without need for extra optical elements in the FP cavity!

Reach



$\delta m_\phi^2 \sim \tilde{g}_B^2\Lambda^2/(8\pi^2)$

Noise sources

Shot noise [solid]

Vibrational noise @ 4K [dashed]

Radiation pressure noise
(subdominant; rigid cavity)

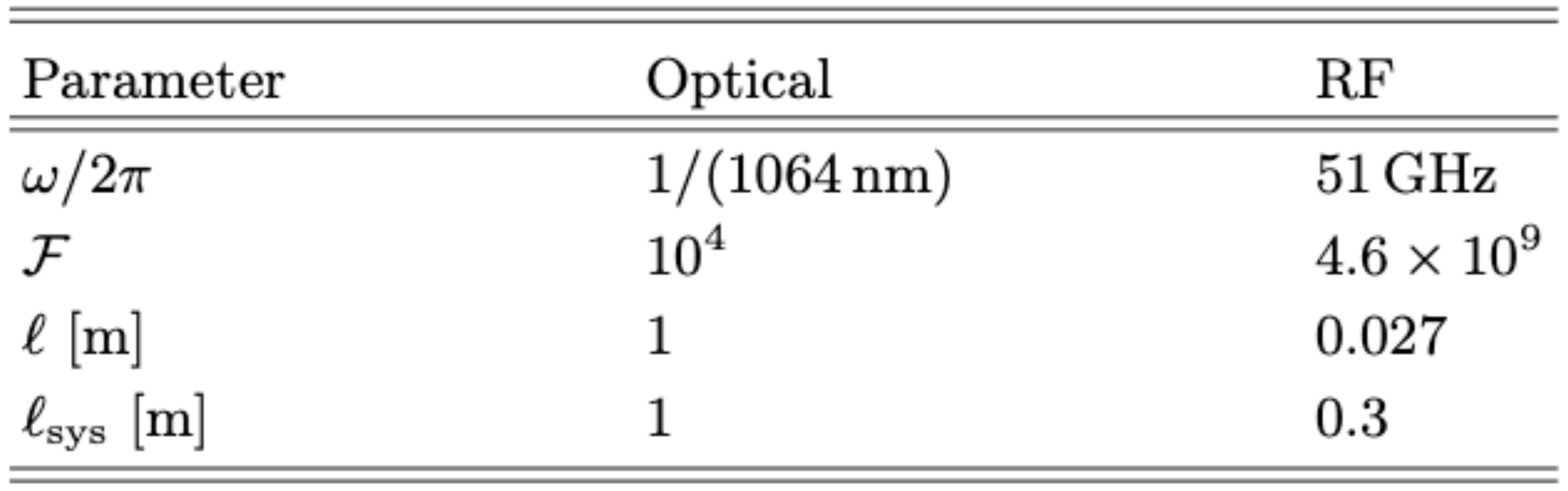
NOT ESTIMATED QUANTITATIVELY:
THERMAL EXPANSION NOISE
(Depends on detailed experimental design)

Three architectures

Earth as source; optical

Earth as source; RF

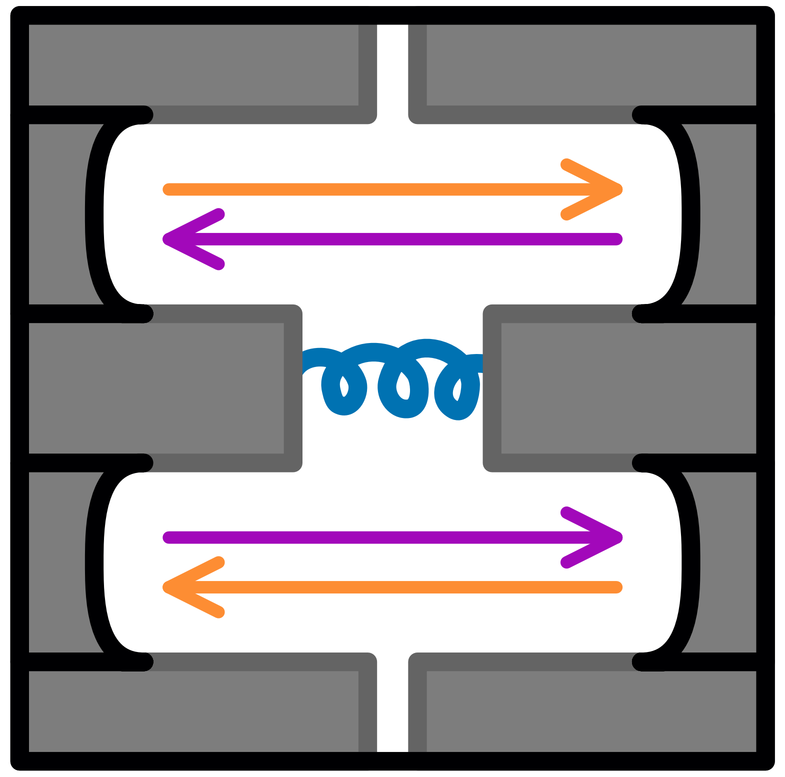
Lab source (1m ball of ~steel); RF



Parameter	Optical	RF
$\omega/2\pi$	$1/(1064\,\mathrm{nm})$	51 GHz
$\mathcal{F}$	10^4	4.6×10^9
ℓ [m]	1	0.027
$\ell_{\rm sys}$ [m]	1	0.3

Noise mitigation & systematics

- Cavity “co-metrology” (multiple cavity-resonant frequencies) to exploit achromatic signal vs chromatic noise
  - Differential length-fluctuation noises (chromatic) can be measured out and subtracted. **May be required to mitigate thermal expansion noise!** Work needed to see if viable.
- Common support structure might cancel common length-fluctuation noise
- Intrinsic cavity birefringence (stress-induced in mirror coatings, imperfections, …)
  - Signal modulation (only in-band noise is an issue)
- Multiple cavity lengths to break length-independent systematics (e.g., mirror coatings): signal ∝ length



Conclusions

- New experimental proposal to look for the axion monopole-dipole scenario
- Earth sources an axion gradient
- Vertical FP cavities experience phase shifts for L/R polarized light
- Phase shift builds up to cavity finesse and does not cancel
- Read out interferometrically
- Co-metrology may be necessary distinguish ahrcomatic signal from chromatic backgrounds
- If shot-nose limited sensitivity can be reached, many orders of magnitude improvement past current bounds seems possible

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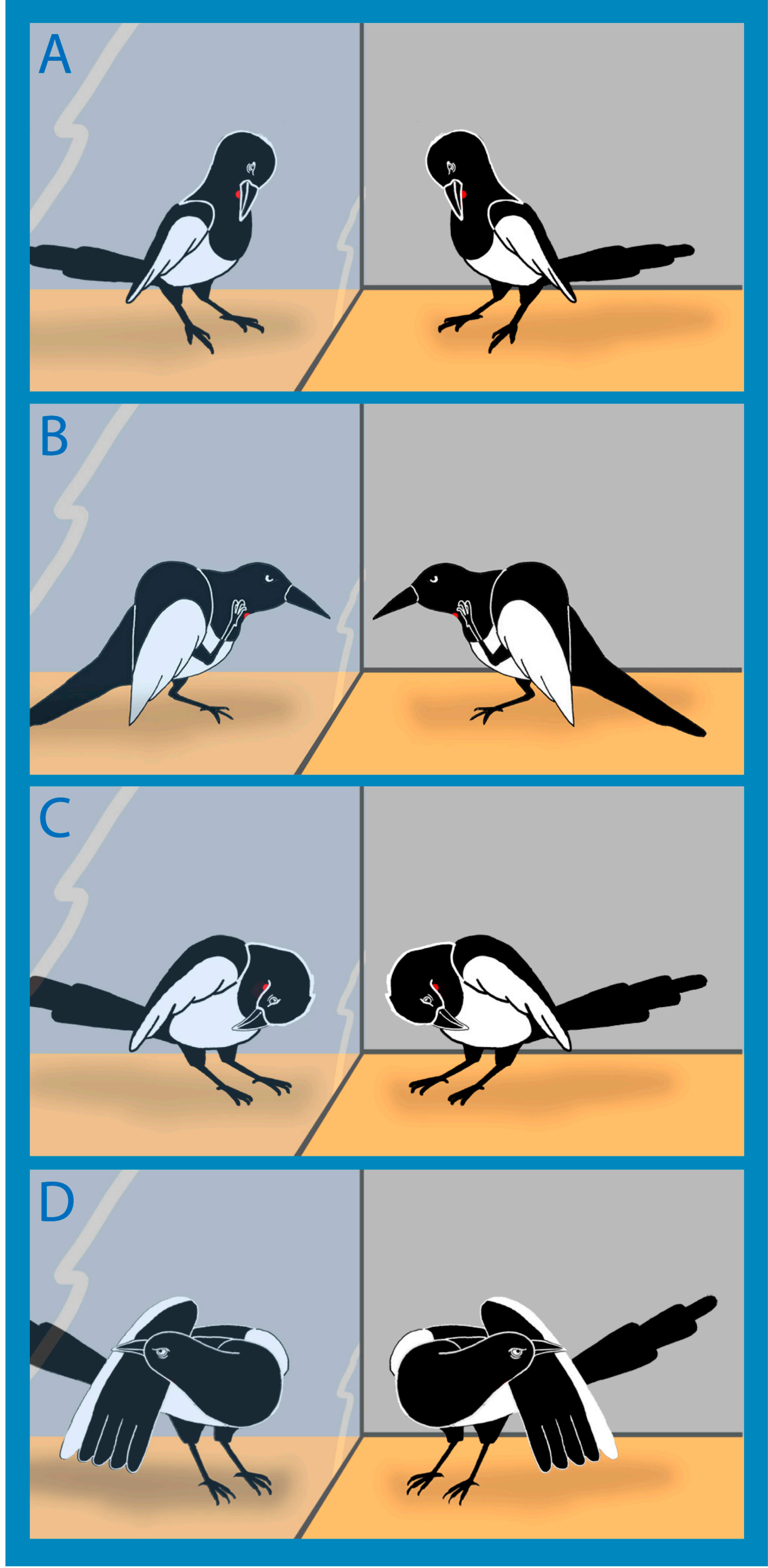
BACKUP

Why "MAGPI"?

Axion backgrounds break parity / "mirror symmetry"

Magpies can recognise themselves in mirrors.

> Prior, Schwarz, Güntürkün (2008). Mirror-Induced Behavior in the Magpie (Pica pica): Evidence of Self-Recognition. PLoS Biol 6(8): e202.
>
> https://doi.org/10.1371/journal.pbio.0060202



Signal

SIGNAL

ACHROMATIC

NOISE

CHROMATIC

$k = 2\pi/\lambda$

$$\Delta\alpha \equiv \alpha_+ - \alpha_- = \Delta\alpha_\phi + \Delta\alpha_\ell; \qquad \Delta\alpha_\phi \equiv \frac{4\mathscr{F}}{\pi}\cdot g_{\phi\gamma}\Delta\phi; \qquad \Delta\alpha_\ell \equiv \frac{4\mathscr{F}}{\pi}\cdot k\left(\Delta\ell_+ - \Delta\ell_-\right)$$

$$\Delta\alpha_\phi = \tilde{g}_\oplus g_{\phi\gamma}\frac{\mathscr{F}}{\pi^2}\frac{M_\oplus}{\mu_a}\frac{\ell\, e^{-m_\phi d}}{(R_\oplus + d)^2}\Psi(m_\phi\ell, m_\phi R_\oplus, m_\phi d)$$

$\tilde{g}_\oplus \approx \tilde{g}_B + \frac{1}{2}\left(\tilde{g}_L + \tilde{g}_{B-L}\right)$

Finite source size vs finite axion-field range

Non-linear r-dependence of $\phi(r)$

$$\Psi(x,y,z) \equiv -\boxed{\frac{3e^{-y}}{y^3}\left(y\cosh y - \sinh y\right)} \times \boxed{\frac{y+z}{x}\left[1 - \frac{e^{-x}}{1 + x/(y+z)}\right]}$$

Modulate:

$$\Delta\alpha_\phi \to \Delta\alpha_\phi \cdot f(t); \qquad f(t) \approx \frac{\sinh\left[\frac{m_\phi\ell}{2}\cos(\Omega t)\right]}{\sinh\left(\frac{m_\phi\ell}{2}\right)} \longrightarrow \cos(\Omega t) \qquad \left[m_\phi\ell \ll 1\right]$$

Rotate about cavity midpoint
at angular frequency Ω

Noise / SNR

$$\text{SNR} \sim \frac{\Delta\alpha_\phi \sqrt{\tau}}{\sqrt{S_\alpha}}$$

$$\text{SNR}_{\text{shot}} \sim \sqrt{\frac{2\pi P_{\text{cav}}\tau}{\omega\mathscr{F}}}\Delta\alpha_\phi$$

$P_{\text{cav}} = 1\,\text{MW}$

$$\text{SNR}_{\text{rad}} \sim \frac{\pi}{2\sqrt{2}}\frac{M\omega_{\text{vib}}^2}{\mathscr{F}^{3/2}}\sqrt{\frac{\tau}{P_{\text{cav}}\omega^3}}\Delta\alpha_\phi$$

$\rho \sim 8\,\text{g/cm}^3$

$c_s \sim 6\,\text{km/s}$

$M \sim \rho\ell_{\text{sys}}^3$

$\omega_{\text{vib}} = \dfrac{\pi c_s}{\ell_{\text{sys}}}$

$$\text{SNR}_{\text{vib}} \sim \frac{\pi}{4}\sqrt{\frac{\tau M Q_{\text{vib}}\omega_{\text{vib}}^3}{T_{\text{sys}}}}\frac{\Delta\alpha_\phi}{\omega\mathscr{F}}$$

$Q_{\text{vib}} = 10^3$

$T_{\text{sys}} \sim 4\,\text{K}$

QCD Expectation

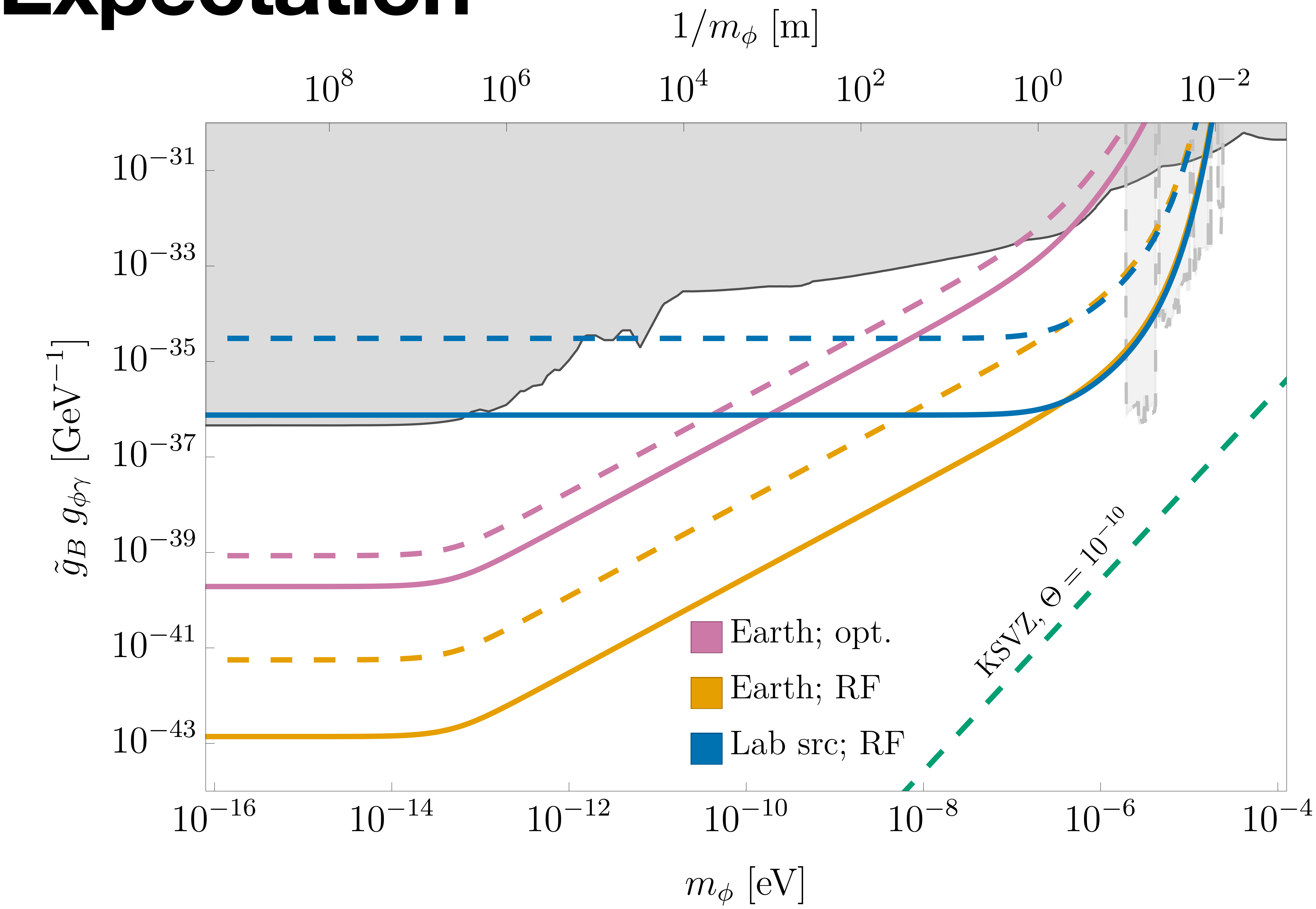


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Figure credits: Jed Thompson