# Axion Interferometry

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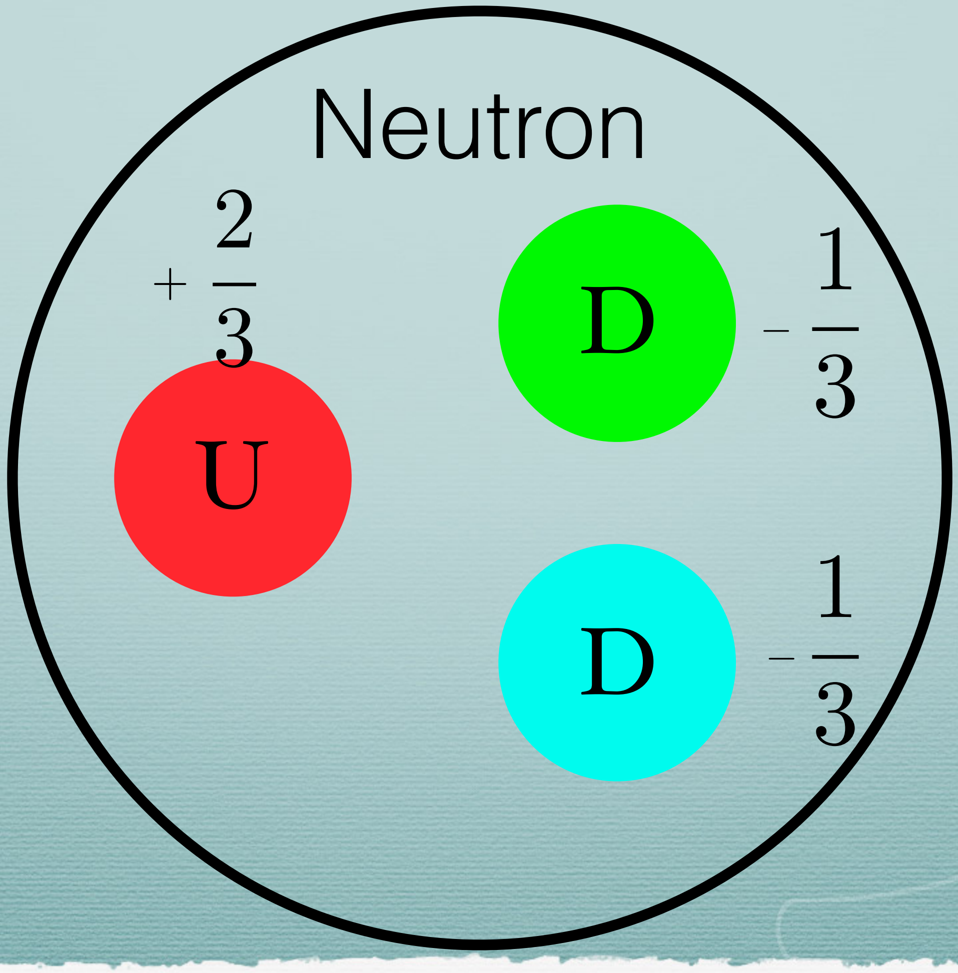
W. DeRocco, AH : 1802.10093

# Strong CP Problem

Axions are the simplest and most minimal solution to the Strong CP problem

# Classical Strong CP problem

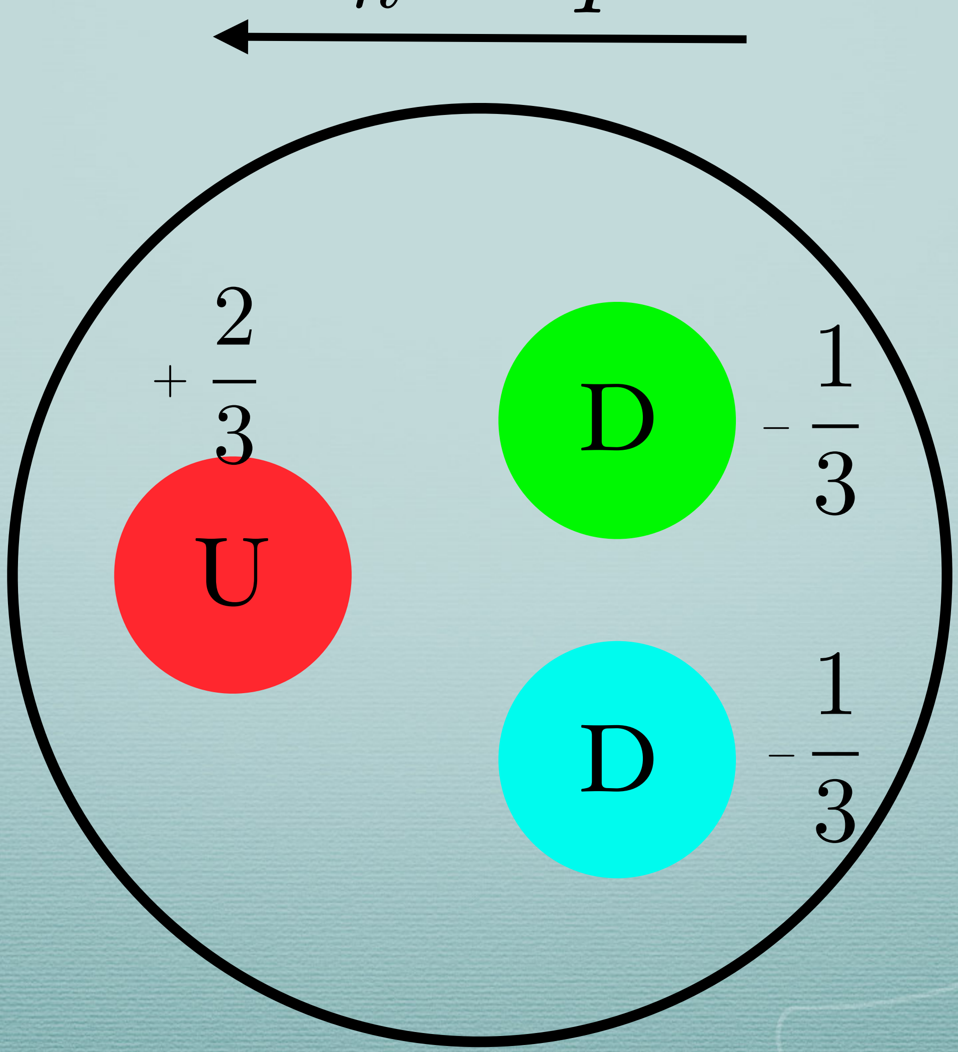
Neutron contains an up quark and two down quarks



# Classical Strong CP problem

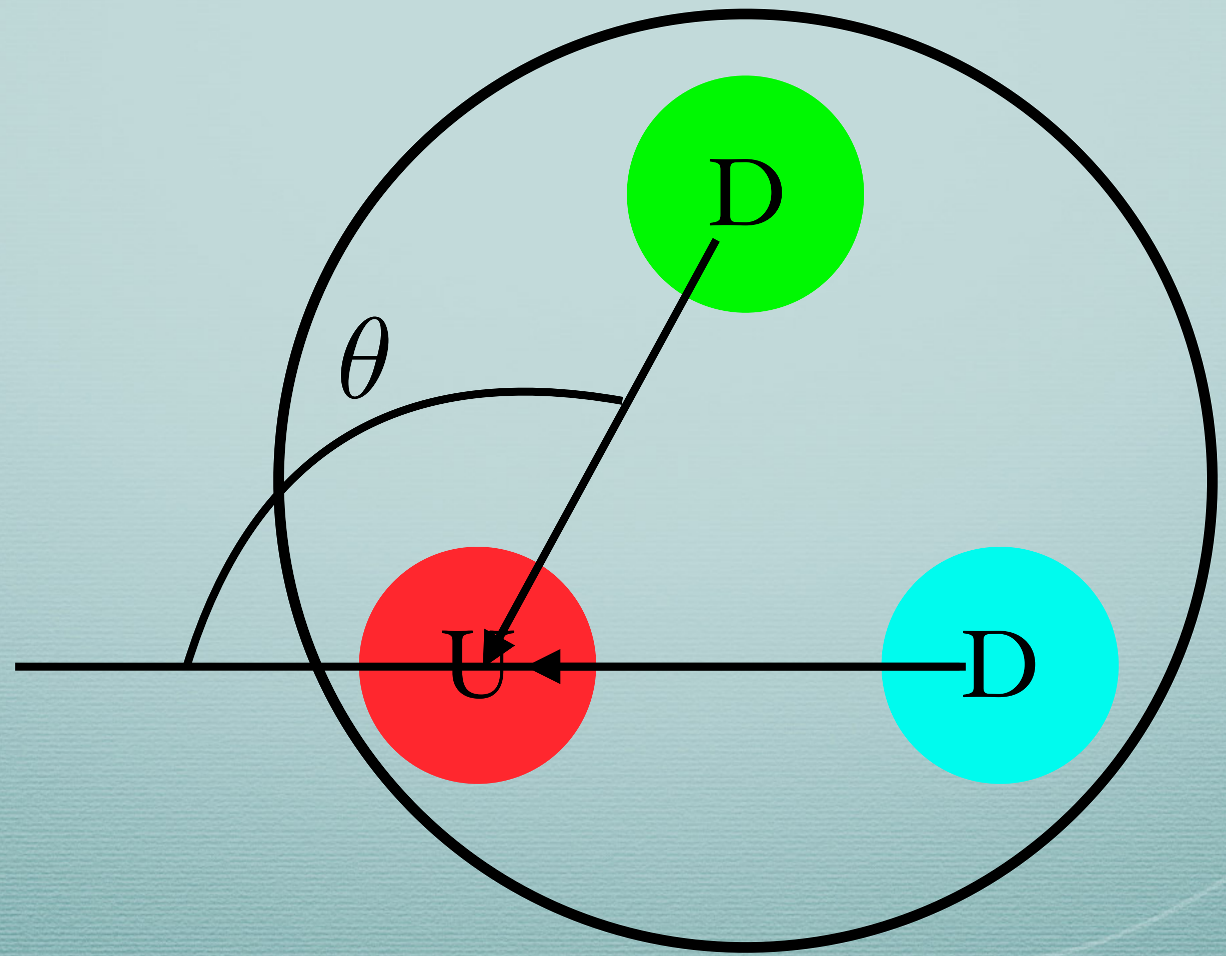
Electric Dipole moment

$$d_n = qx$$



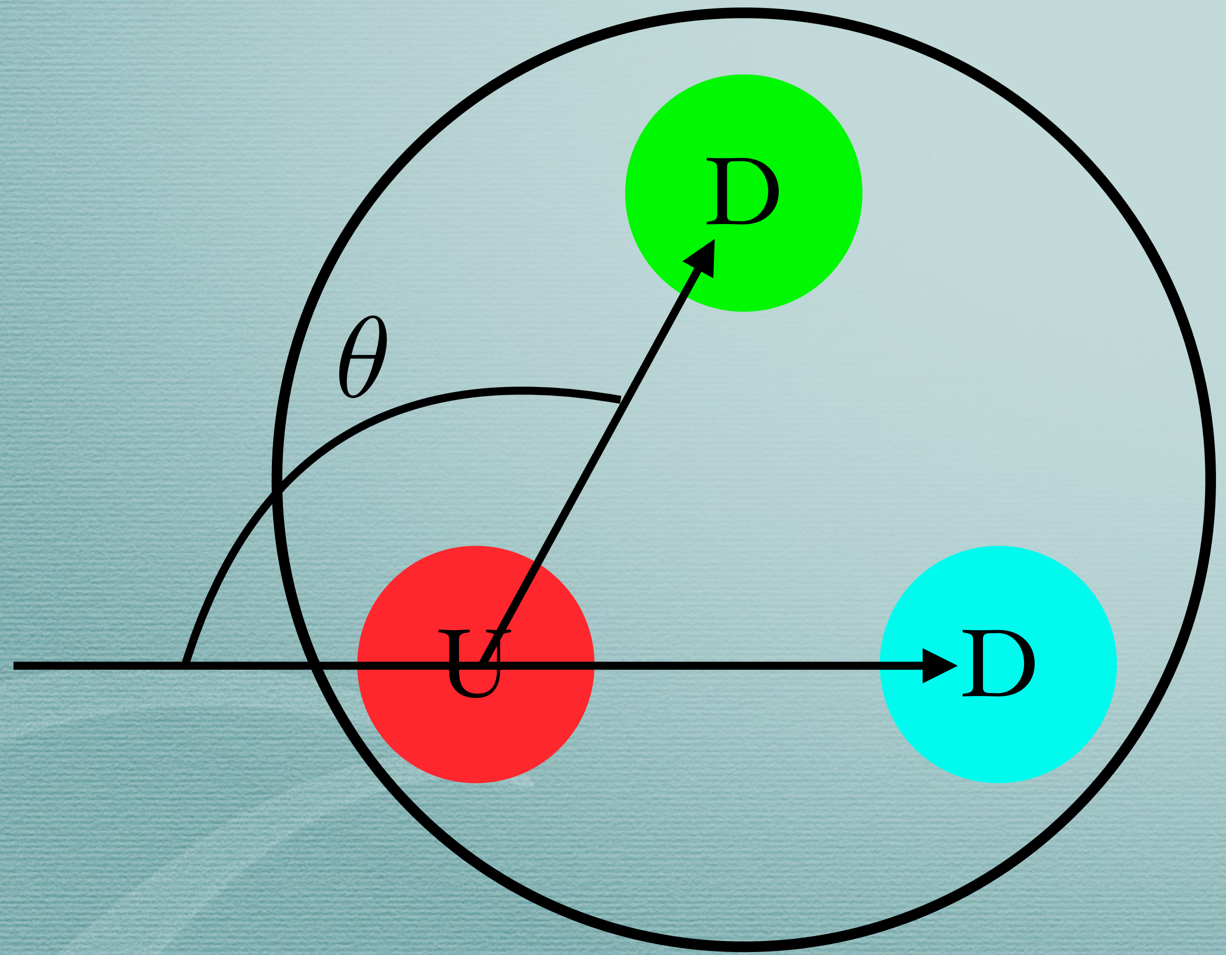
# Expected Dipole moment

$$|d_n| \approx ex\sqrt{1-\cos\theta}$$
$$\approx 10^{-14}\, e\, \sqrt{1-\cos\theta}\ \mathrm{cm}$$



# Measured EDM

$$|d_n| \approx ex\sqrt{1-\cos\theta}$$
$$\approx 10^{-14}\, e\sqrt{1-\cos\theta}\ \text{cm}$$

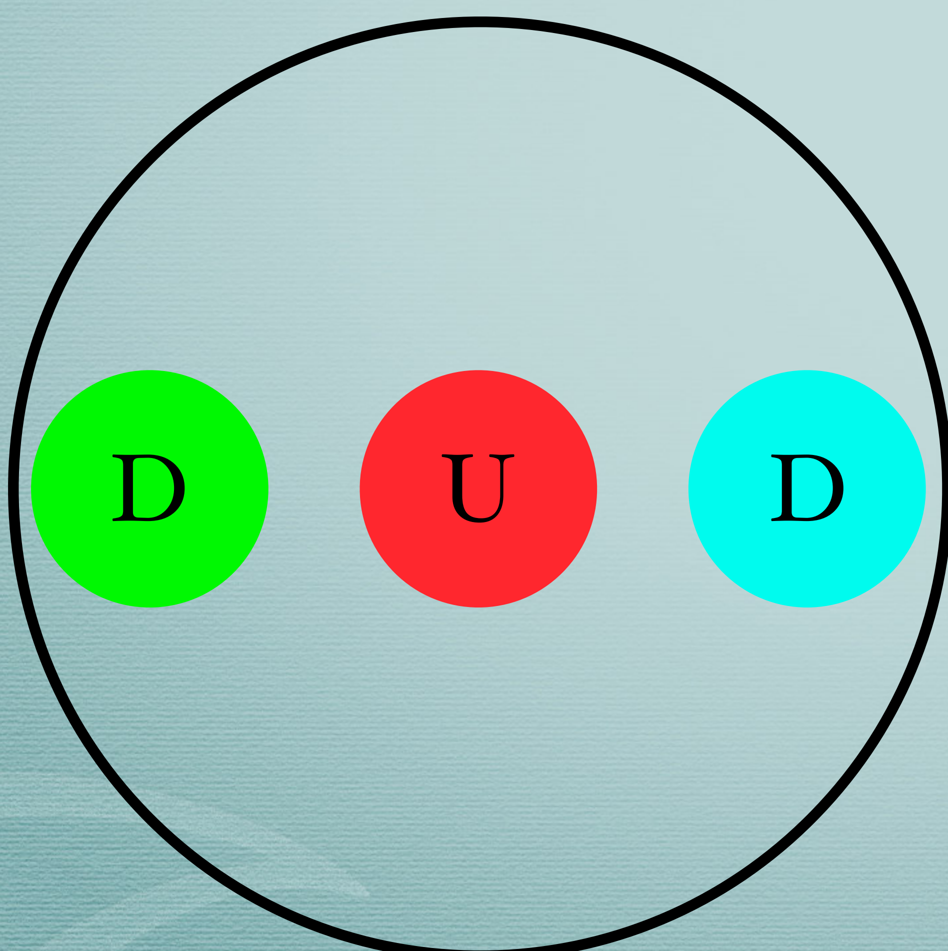



$$|d_n| < 2.9 \times 10^{-26}\, e\,\text{cm}$$

Baker et. al. hep-ex/0602020 :
Institut Laue-Langevin, Grenoble

# Classical Strong CP problem

Measurement indicates a small theta



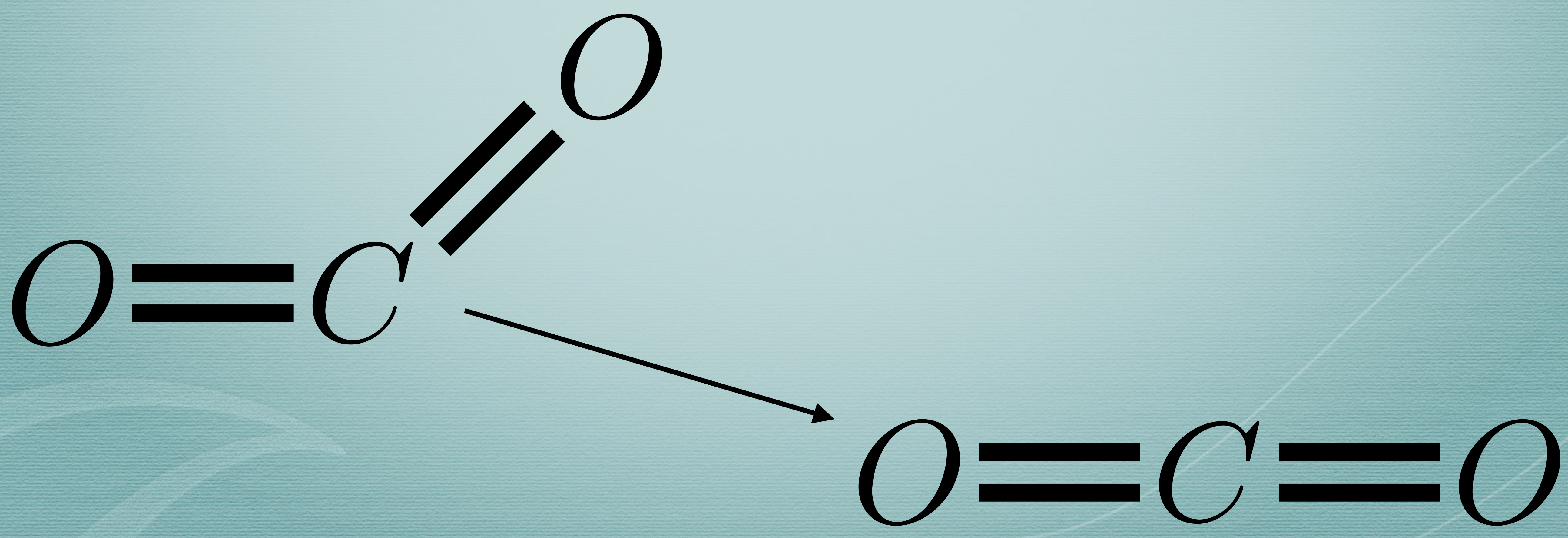

$$\theta < 10^{-12}$$

Must be a reason!

# Strong CP Problem

Axion solution is the same solution as why carbon dioxide lives on a line

Angle is dynamical and relaxes to minimum



# Strong CP Problem

- Axions are the simplest and most minimal solution to the Strong CP problem
- Solves a problem and can be dark matter
- Axion dark matter obtains its number abundance through the misalignment mechanism
    - Produces cold dark matter regardless how light the axion is

# Axion dark matter

- If it is dark matter, how can we look for it?
- The axion is a classical field due to large number abundance
    - If mass is less than eV, then many particles per Compton wavelength

# Axion dark matter

$$\phi(x,t) = \sum \frac{1}{l^{3/2}} \frac{1}{\sqrt{2\omega_n}} (a_n e^{ip\cdot x} + a_n^\dagger e^{-ip\cdot x})$$

- First treat dark matter as a particle in a box
- Take velocity profile of dark matter from simulation and find the quantum state that reproduces it
    - Isothermal Profile

# Axion dark matter

$$\rho = \int d^3v f(v)\omega_v \overline{n}$$

Just like how a laser has Poisson statistics for number of photons, Axion state also has Poisson statistics for number of axions

$$N_n = (\frac{2\pi}{m})^3 f(v_n)\overline{n} \qquad \mid N\rangle = \alpha e^{\sqrt{N_n}a_n^\dagger} \mid 0\rangle$$

# Axion dark matter

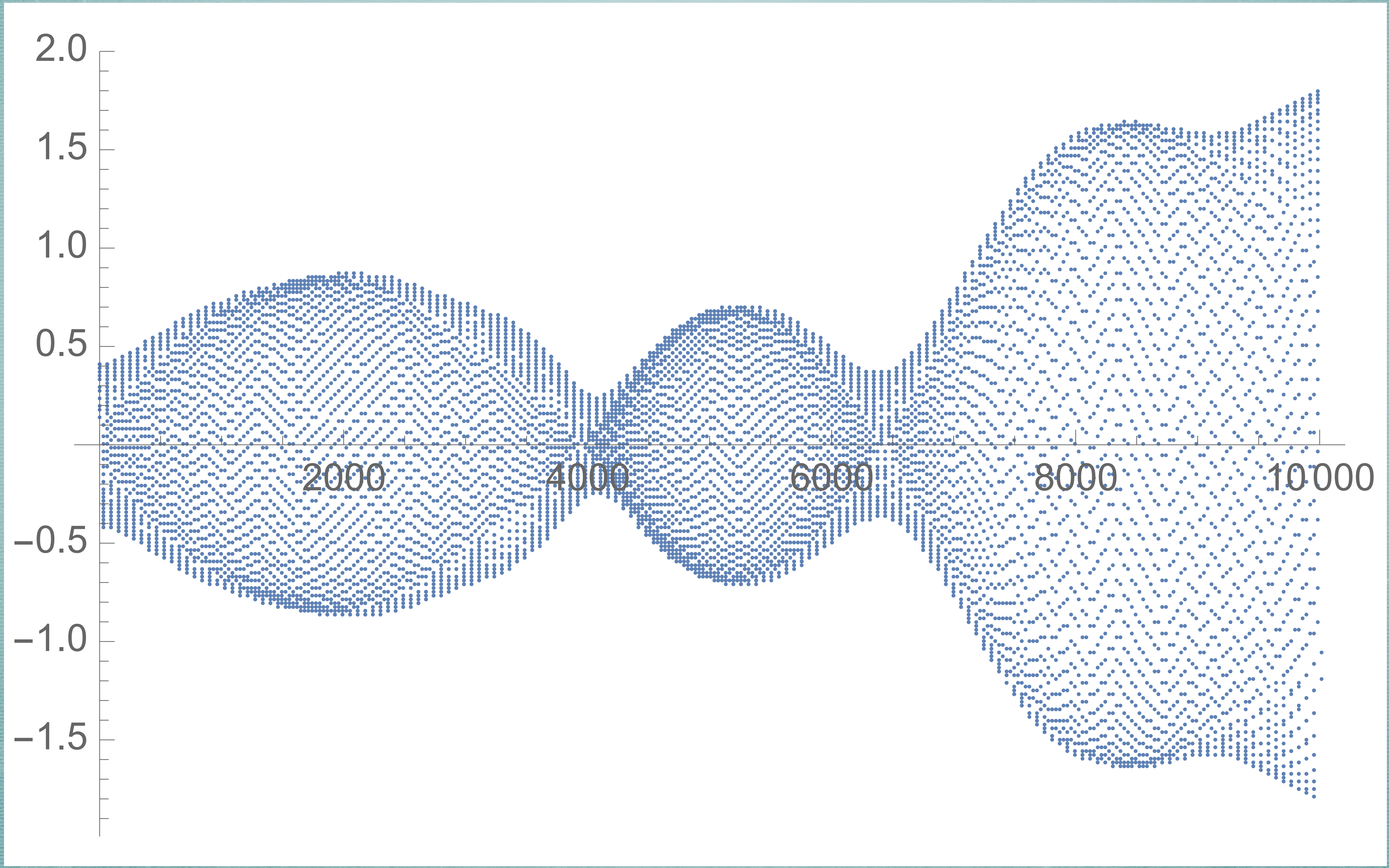
$$\phi(t) = \frac{\sqrt{\rho}}{m} \sum_{i_r} \alpha_r \sqrt{f_r 4\pi v^2 \Delta v} \cos\left(\omega_r t + \phi_r\right)$$

Crank through and calculate a(t) in this background

Sum of many sines with random phases

Basically the square root of an integral

# Axion dark matter



# Qualitative Features

- Axion acts like a cosine function over distance scales

$$L \sim \frac{1}{m_a v}$$

Afterwards amplitude and phase randomly scrambled

- Coherence length of order de Broglie wavelength

# Qualitative Features

- Axion acts like a cosine function over time scales

$$\tau \sim \frac{1}{m_a v^2}$$

Afterwards amplitude and phase randomly scrambled

- Coherence time is large

# Qualitative Features

- Frequency of the axion sine wave

$$\omega \sim m_a \pm 10^{-6} m_a$$

- Thus the quality factor of axion dark matter is very large

$$Q = \frac{1}{\omega\tau} \sim 10^6$$

# Looking for the axion

$$\mathcal{L} \supset \frac{a}{4f} F\tilde{F}$$

- Looking for the axion through the coupling to gluons is HARD
    - Very few experiments can reach the QCD axion line
- Instead look for the axion through its coupling with the photon

# DISCLAIMER

- QCD Axion
  - Solves the Strong CP problem
  - Couples to photons and gluons and fermion spin
- ALP (Axion like particles)
  - Does NOT solve the Strong CP problem
  - Couples to photons and/or fermion spin
- Axions
  - Can be either
  - Figure it out from context

# Effect of photon coupling

$$\mathcal{L} \supset \frac{a}{4f} F\tilde{F}$$

- For circularly polarized light

$$-\omega^2 + k^2 \mp \frac{da}{dt}\frac{k}{f} = 0$$

$$v_{\rm phase} \approx 1 \pm \frac{\dot{a}}{2kf}$$

# Effect of photon coupling

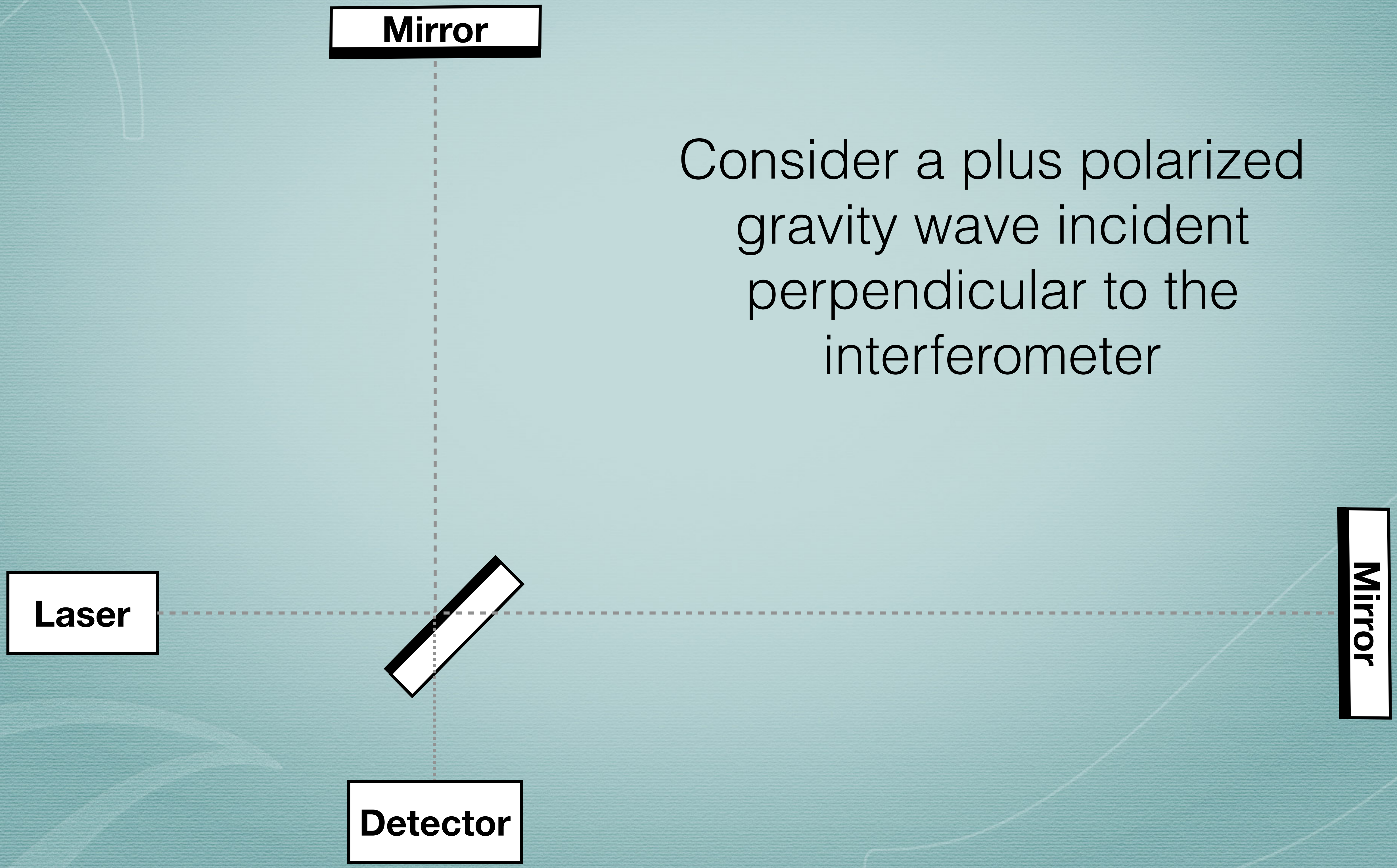
$$v_{\text{phase}} \approx 1 \pm \frac{\dot{a}}{2kf}$$

- Phase velocity of circularly polarized light is different depending on which polarization it is
- Device most sensitive to differences in phase velocities is an interferometer

# Axion interferometry

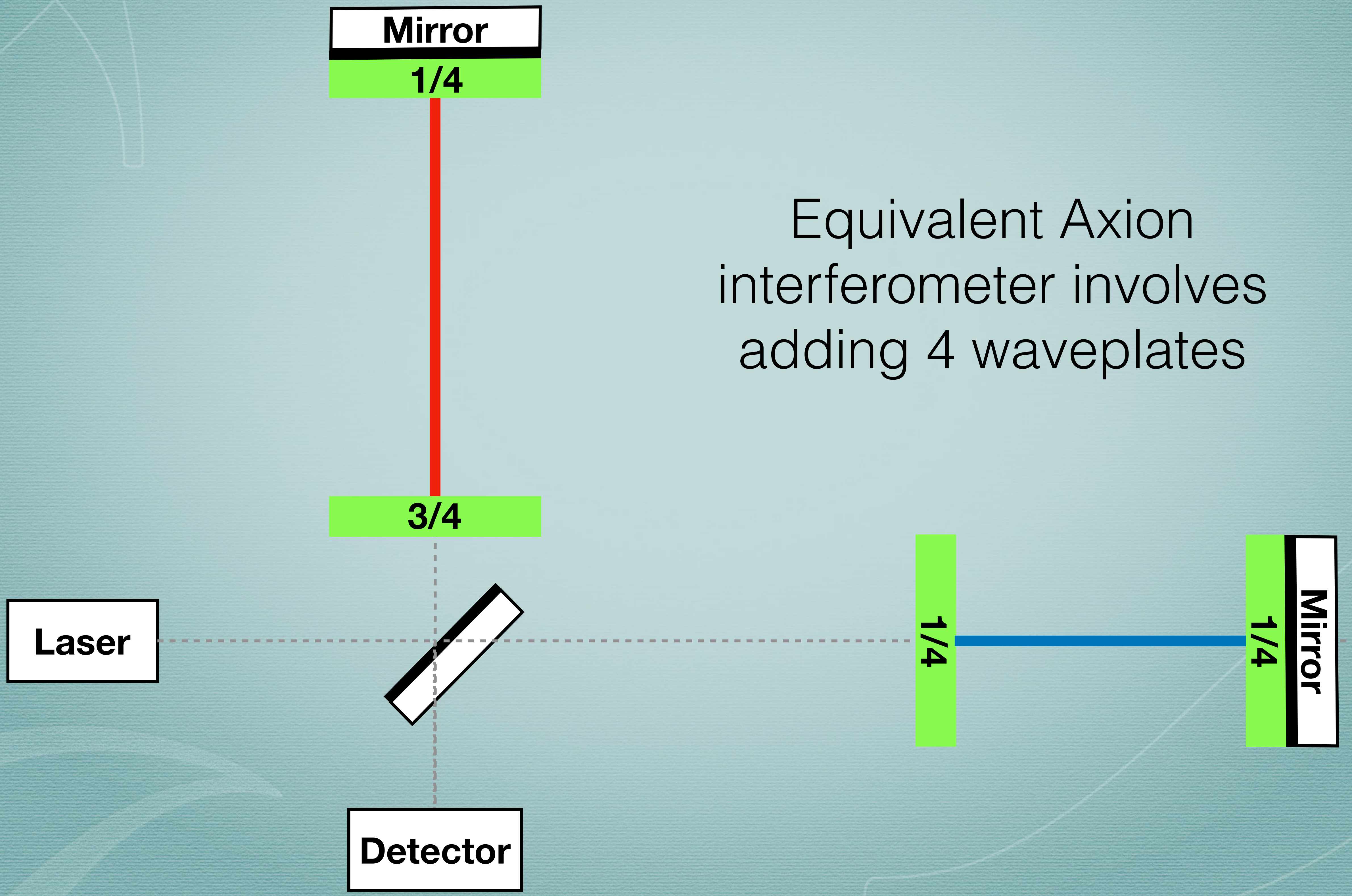
- One-to-one mapping between axion interferometry and gravity wave interferometry
- An axion interferometer can double as a gravity wave detector
- Axion dark matter appears in the same manner as a continuous gravity wave signal with a quality factor of $10^6$

# Gravity wave interferometry



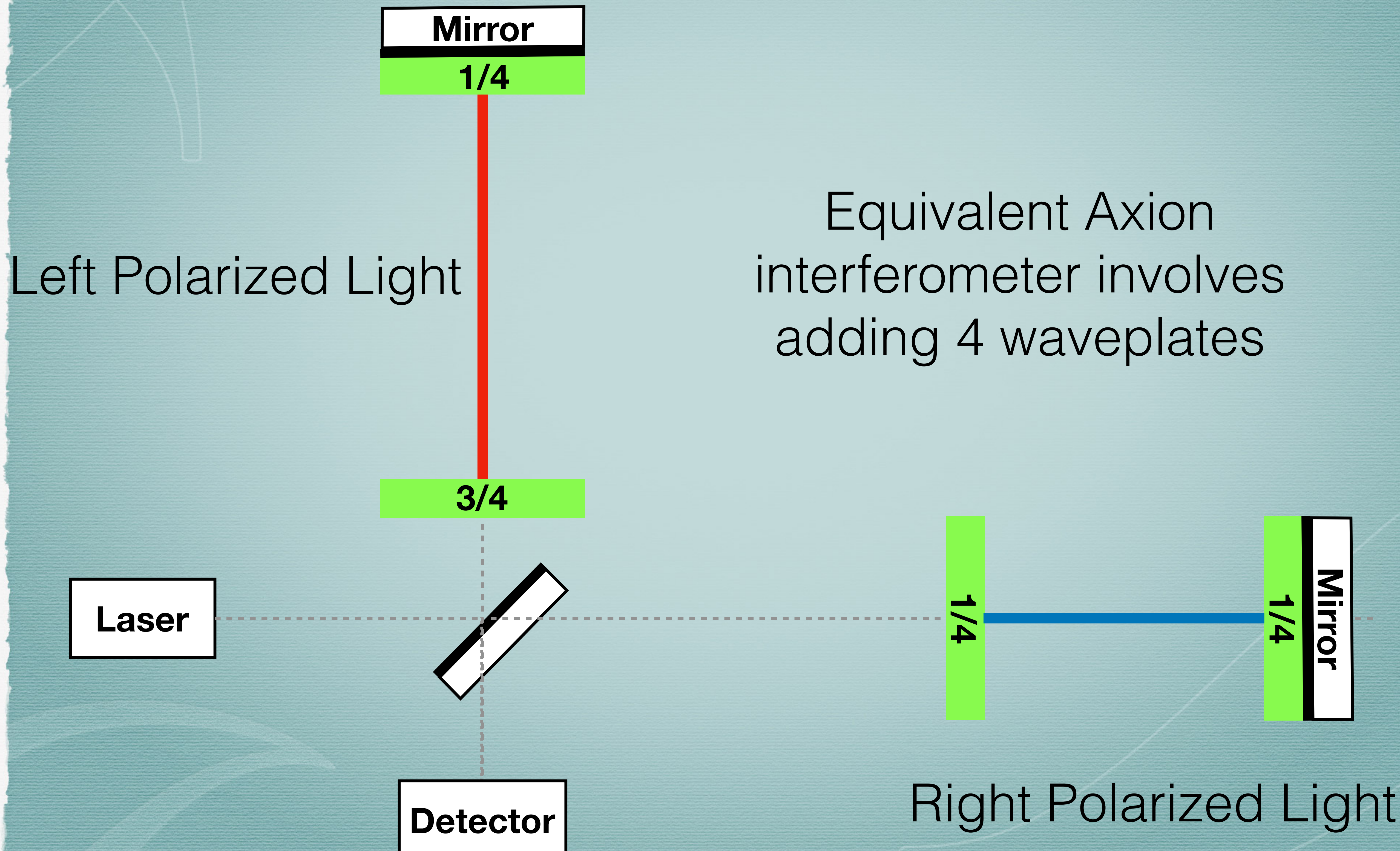

Consider a plus polarized gravity wave incident perpendicular to the interferometer

# Axion interferometry




Equivalent Axion interferometer involves adding 4 waveplates

# Axion interferometry

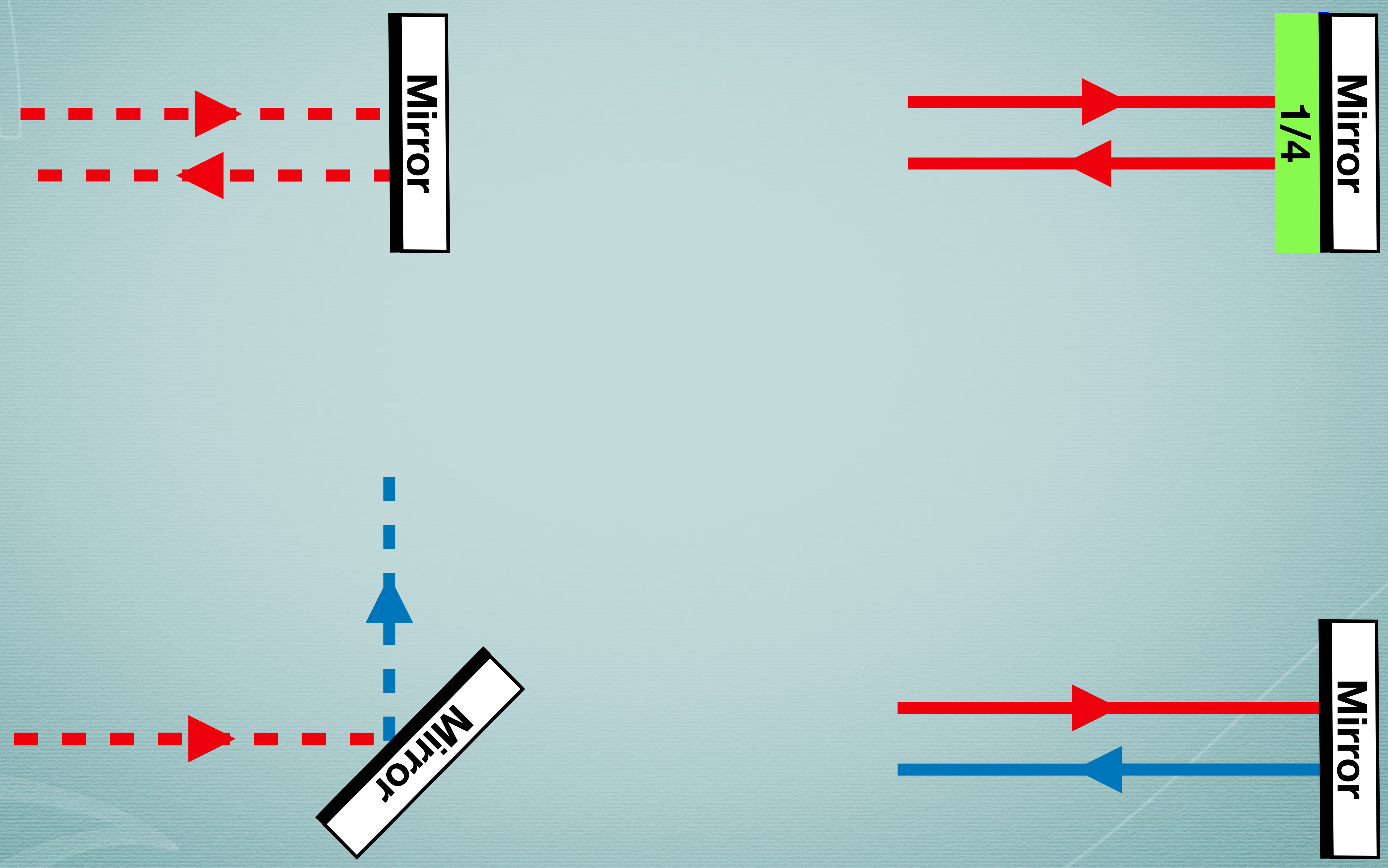



Equivalent Axion interferometer involves adding 4 waveplates

# Axion wave

- Only difference is the presence of wave plates
- Needed to maintain polarization

# Axion wave



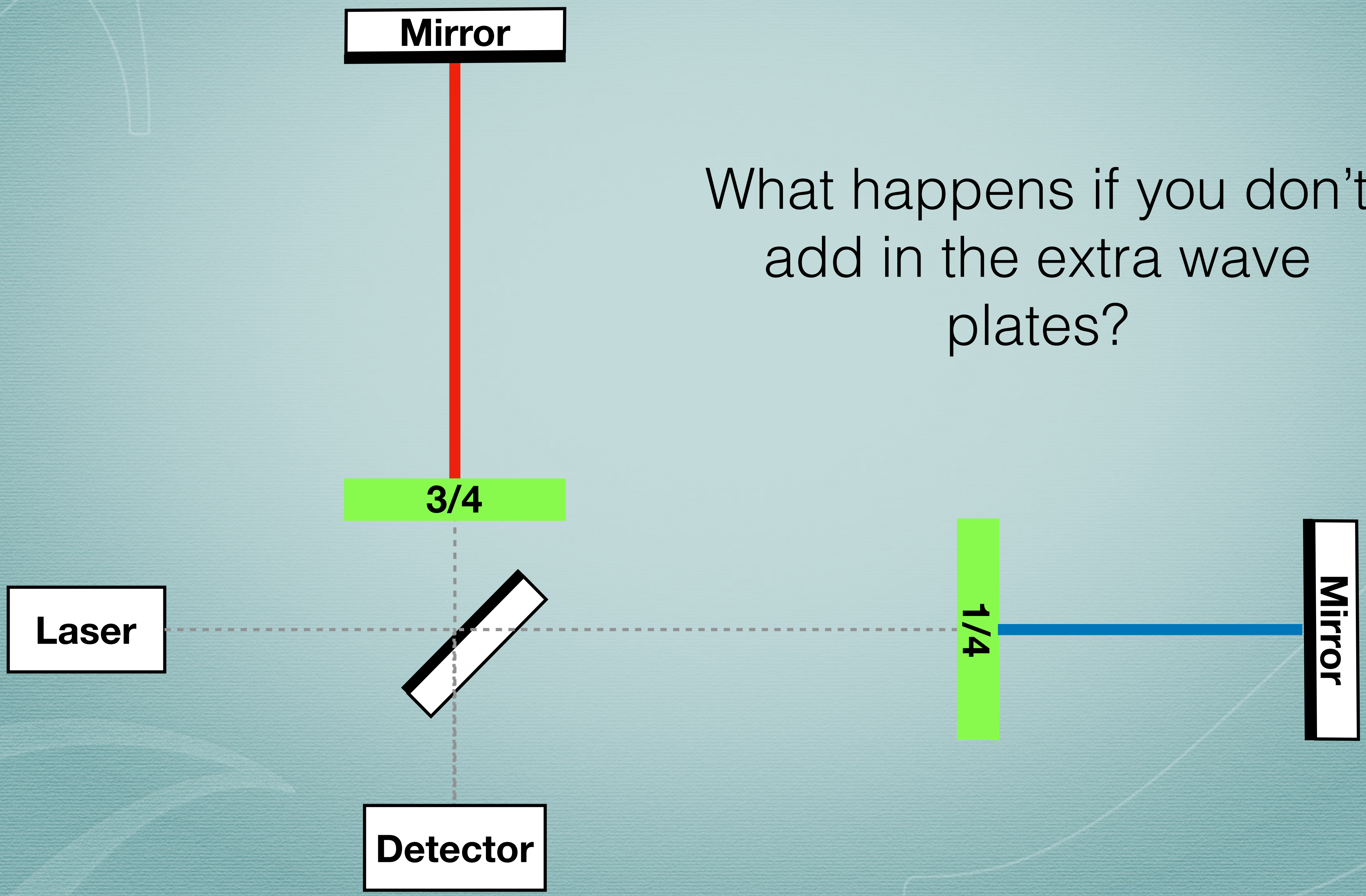
# No Axion DM

Exactly the same as a gravity wave interferometer

Experiment doubles as a gravity wave detector

No need to send the legs in different directions otherwise

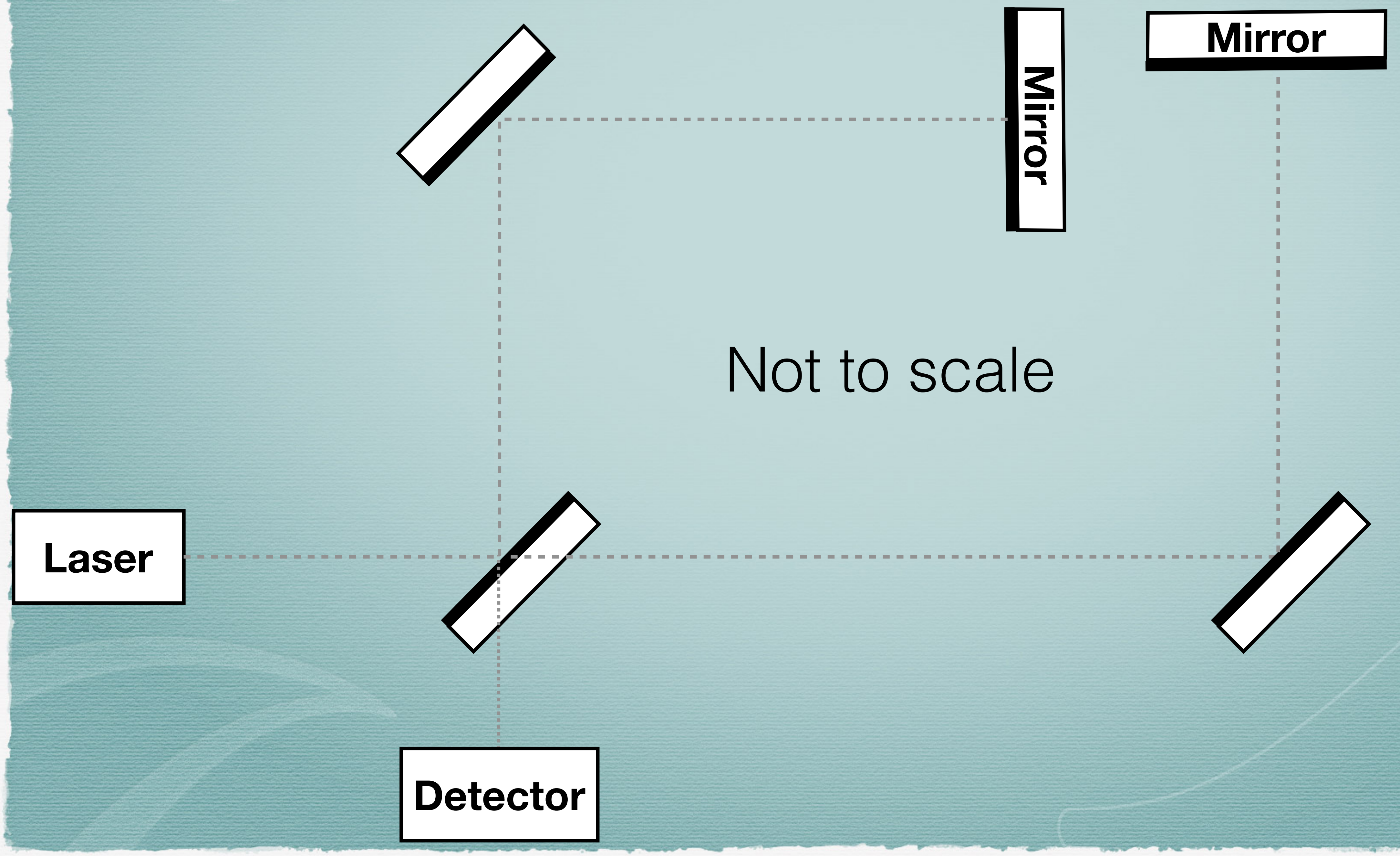
# Resonant interferometry




What happens if you don't add in the extra wave plates?

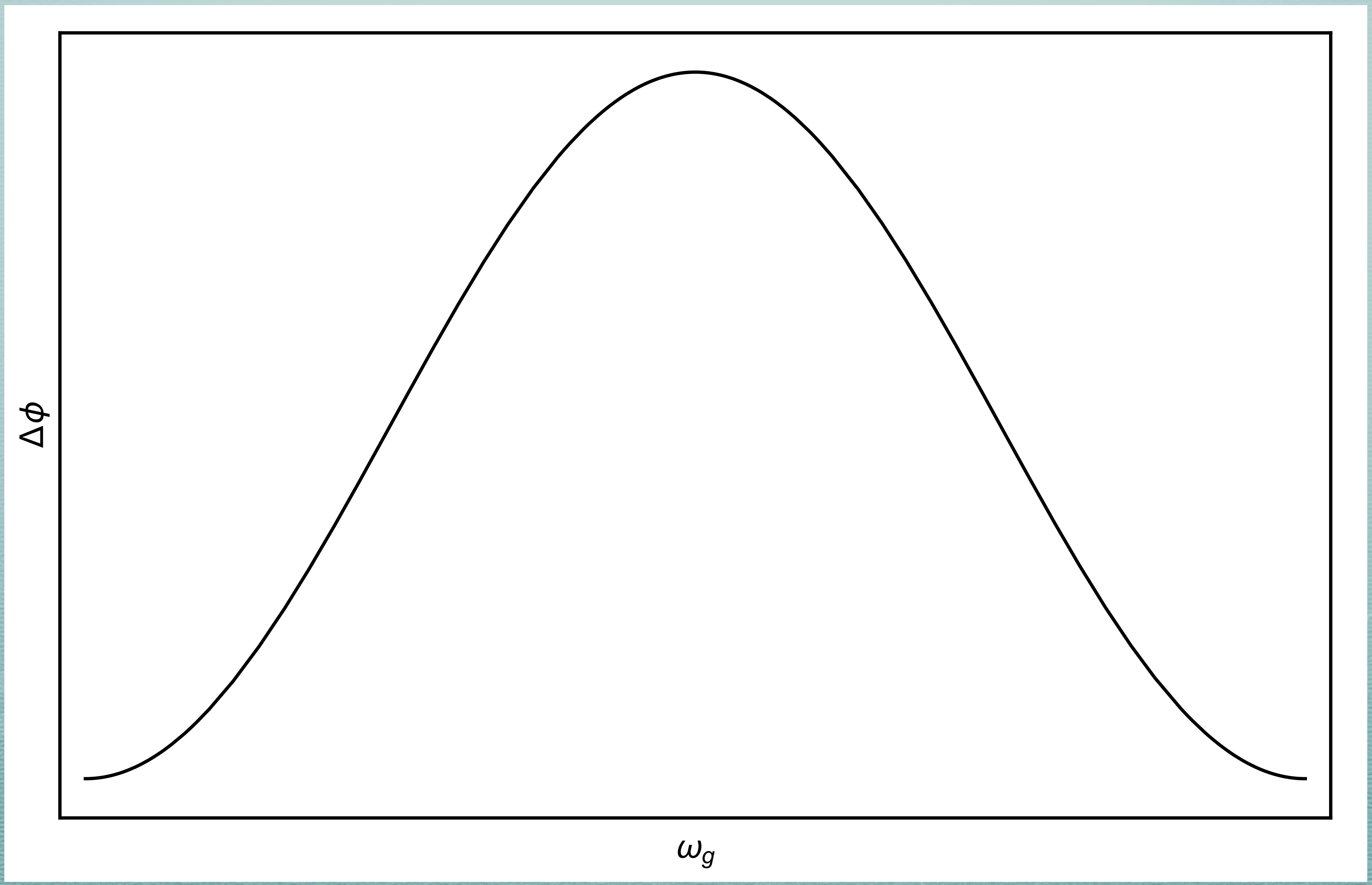
# Resonant interferometry

Resonant Detector instead!

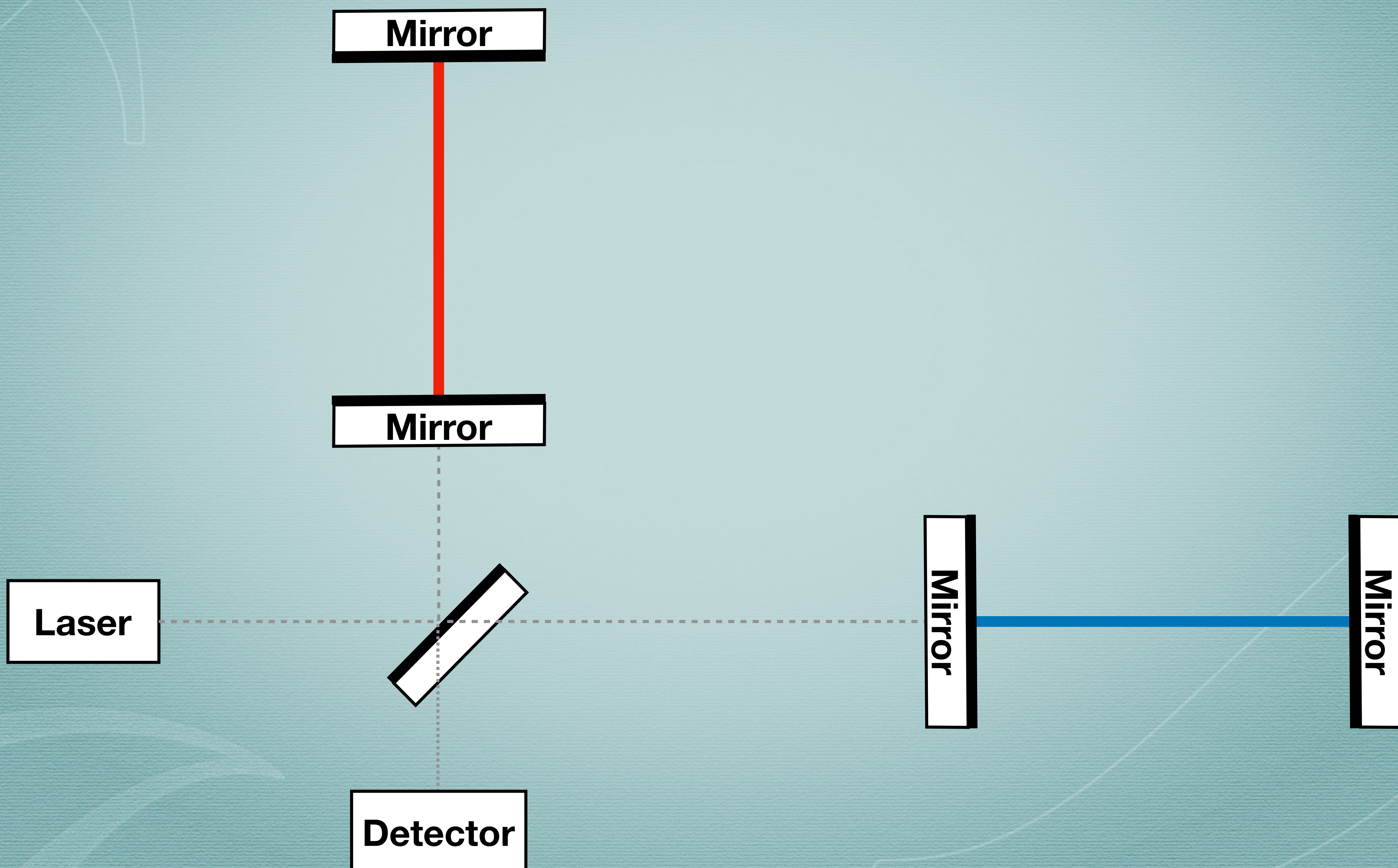


# Resonant interferometry

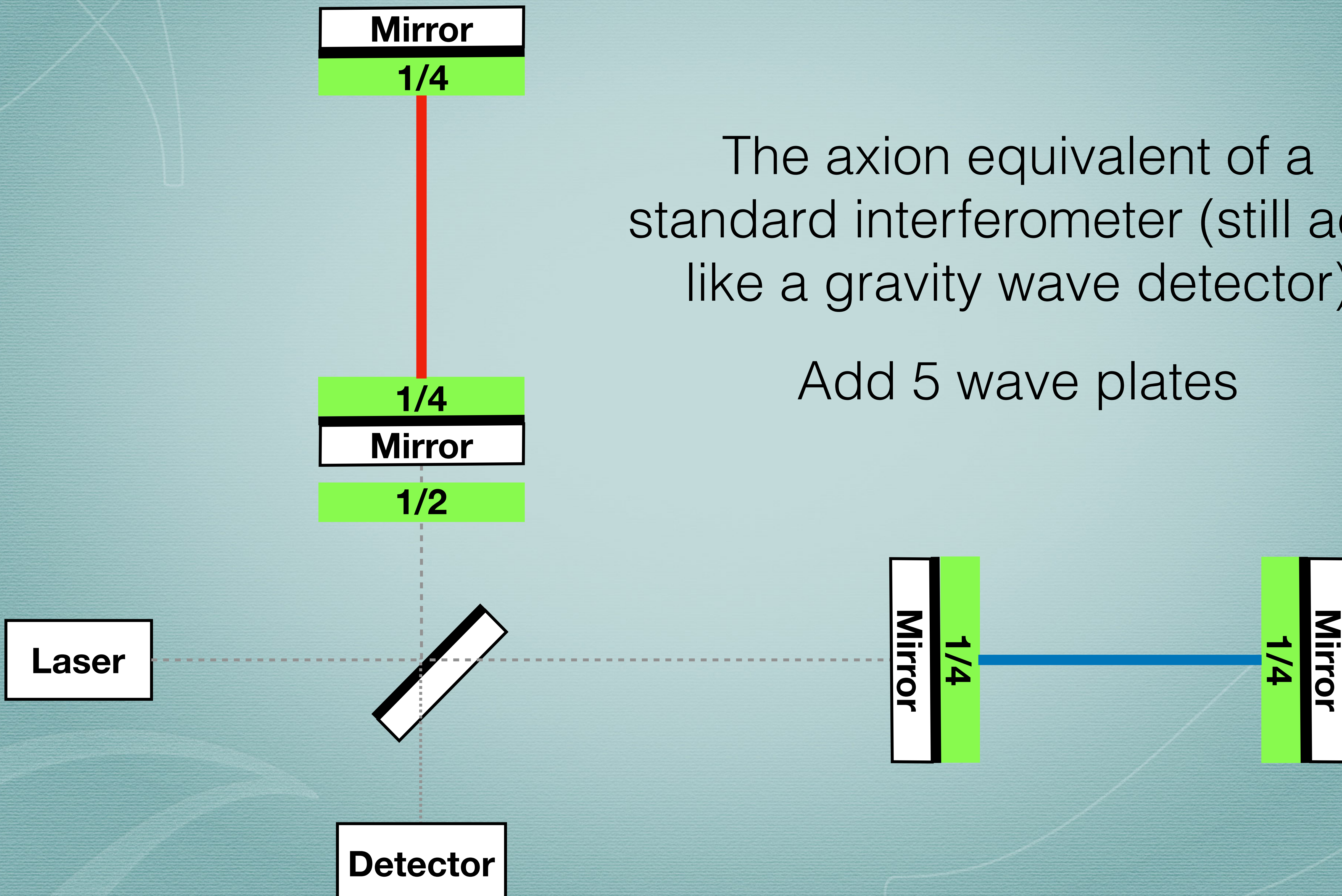
1. Optimal Length is as expected $L = \lambda_g/2$
2. Resonant detector



# Fabry-Perot



# Axion Interferometer




The axion equivalent of a standard interferometer (still acts like a gravity wave detector)

Add 5 wave plates

# Axion Interferometer

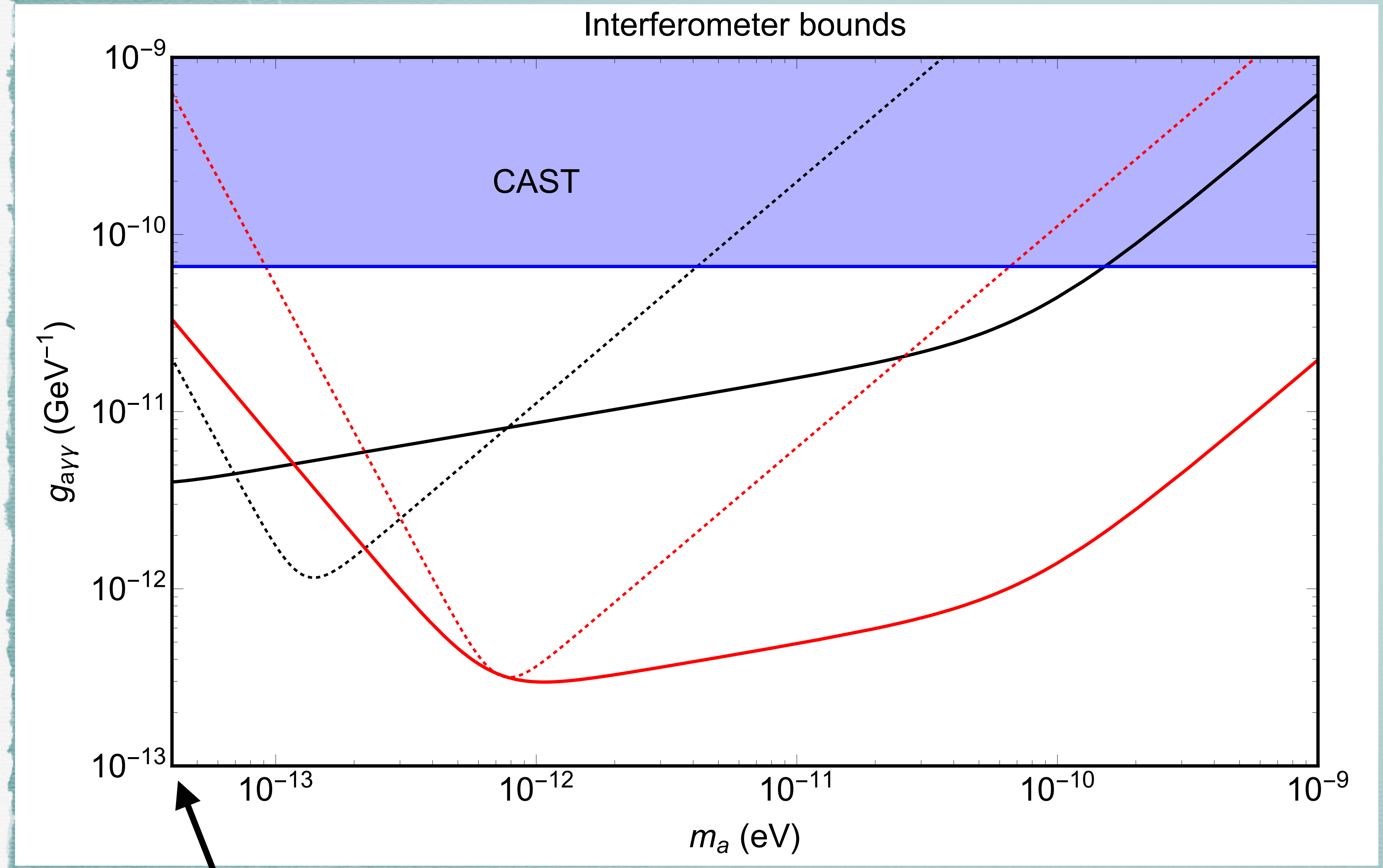
Same Mapping as before

Otherwise identical to Gravity wave detector

# Parameters

- What are reasonable parameters?
  - Similar to gravity wave interferometers : Maybe do as part of setting up and testing a gravity wave interferometer
  - Cost is all in man power
- Assumption : Shot noise and radiation noise limit until 10 Hz where seismic noise becomes an issue
  - 40 m arm length
  - 10 kg mirror
  - 30 days run time : factor of 3 worse limits if you run for 6 hours

# Axion Interferometer




Red : 1 MW power

Black : 1 kW power

Dotted : F = $10^6$

Solid : F = $10^2$

Seismic Noise becomes an issue

# Axion Interferometer

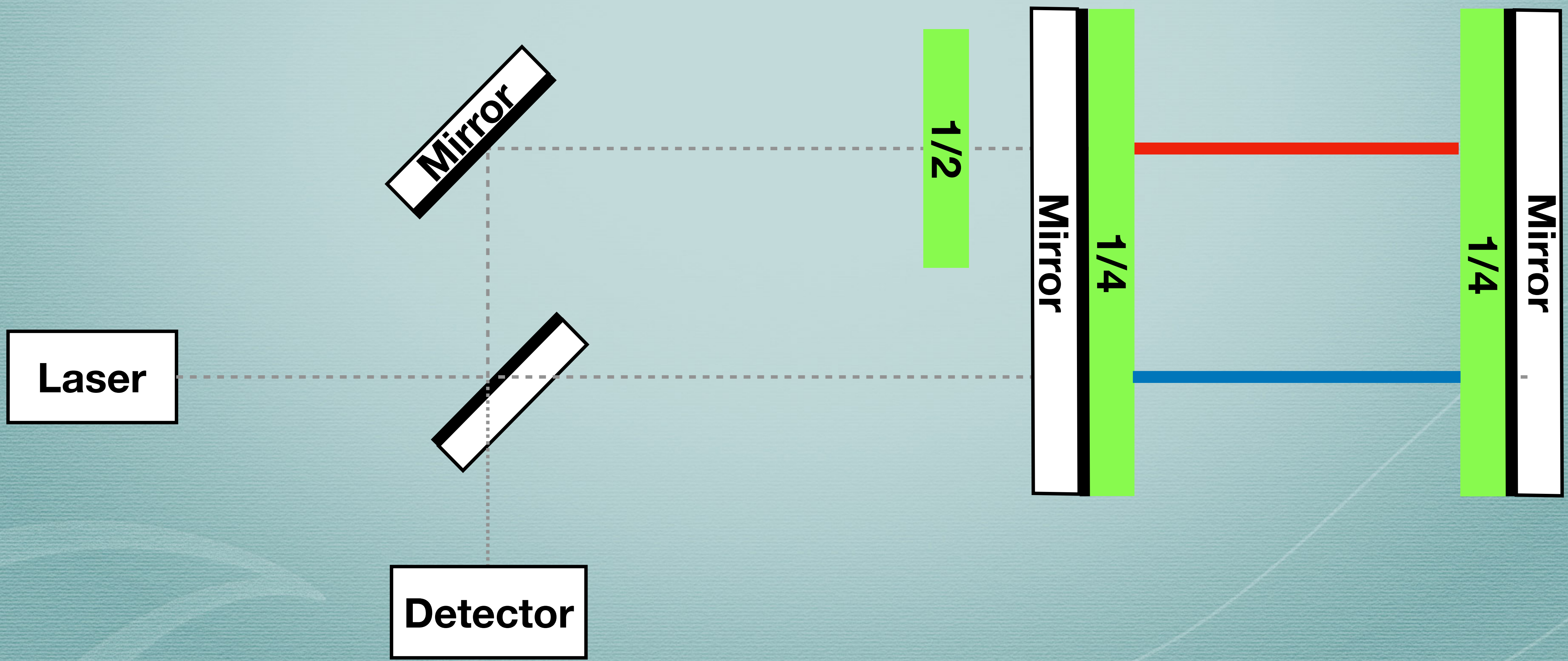
- Large Finesse/power not needed to probe new regions of parameter space!

# Axion Interferometer

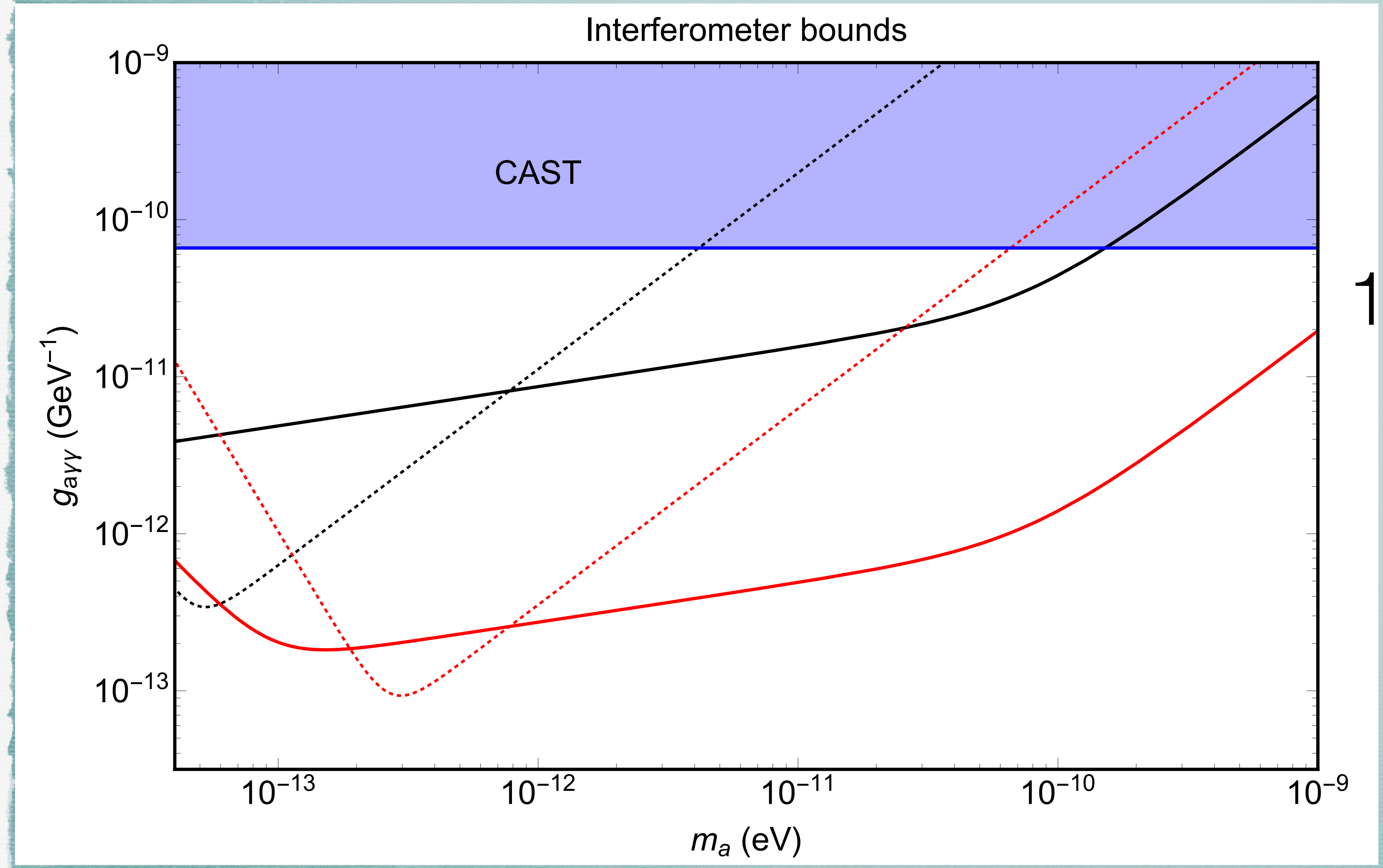
- If detector is dedicated to an axion search and not gravity wave search, can do better!
- Radiation pressure can be mitigated if same mirror is used for both arms!

# Axion Interferometer

Radiation Pressure replaced by Radiation Torque



# Axion Interferometer




10 kg mirror

10 cm diameter

1 cm between beams

Red : 1 MW power

Black : 1 kW power

Dotted : F = $10^6$

Solid : F = $10^2$

# Conclusion

- Axion dark matter changes the phase velocity of circularly polarized light
- Can look for this effect in an interferometer
- Can extend bounds by up to 2-3 orders of magnitude over some range of parameters
- Do not need the newest fanciest technology
    - Need to make sure that birefringent backgrounds are under control!