

Precision Platforms for Short Range and Time Dark Matter

**Surjeet Rajendran,
The Johns Hopkins University**

Light Weakly Coupled Bosons

Goal: Solve theoretical problems of the Standard Model
(Strong CP, flavor, hierarchy...)

Strategy: Propose global symmetry at some high scale, broken at low energy

Generic Prediction: Light weakly coupled Goldstone Boson
(Axion, axion-like-particle, familon, relaxion...)

Technically Natural Interactions

$$\frac{\phi}{f_a} F \tilde{F}, \frac{\phi}{f_a} G \tilde{G}, \frac{\partial_\mu \phi}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi, g \phi h^2$$

Vector Cousin

$$\frac{F'_{\mu\nu}}{\Lambda} \bar{\Psi} \sigma^{\mu\nu} \Psi, J^\mu A'_\mu, \epsilon F F'$$

Potentially Natural Interactions

$$g \phi \bar{\Psi} \Psi$$

Light Weakly Coupled Bosons

Goal: Solve theoretical problems of the Standard Model
(Strong CP, flavor, hierarchy...)

Strategy: Propose global symmetry at some high scale, broken at low energy

Generic Prediction: Light weakly coupled Goldstone Boson
(Axion, axion-like-particle, familon, relaxion...)

Technically Natural Interactions

$$\frac{\phi}{f_a} F \tilde{F}, \frac{\phi}{f_a} G \tilde{G}, \frac{\partial_\mu \phi}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi, g \phi h^2$$

Vector Cousin

$$\frac{F'_{\mu\nu}}{\Lambda} \bar{\Psi} \sigma^{\mu\nu} \Psi, J^\mu A'_\mu, \epsilon F F'$$

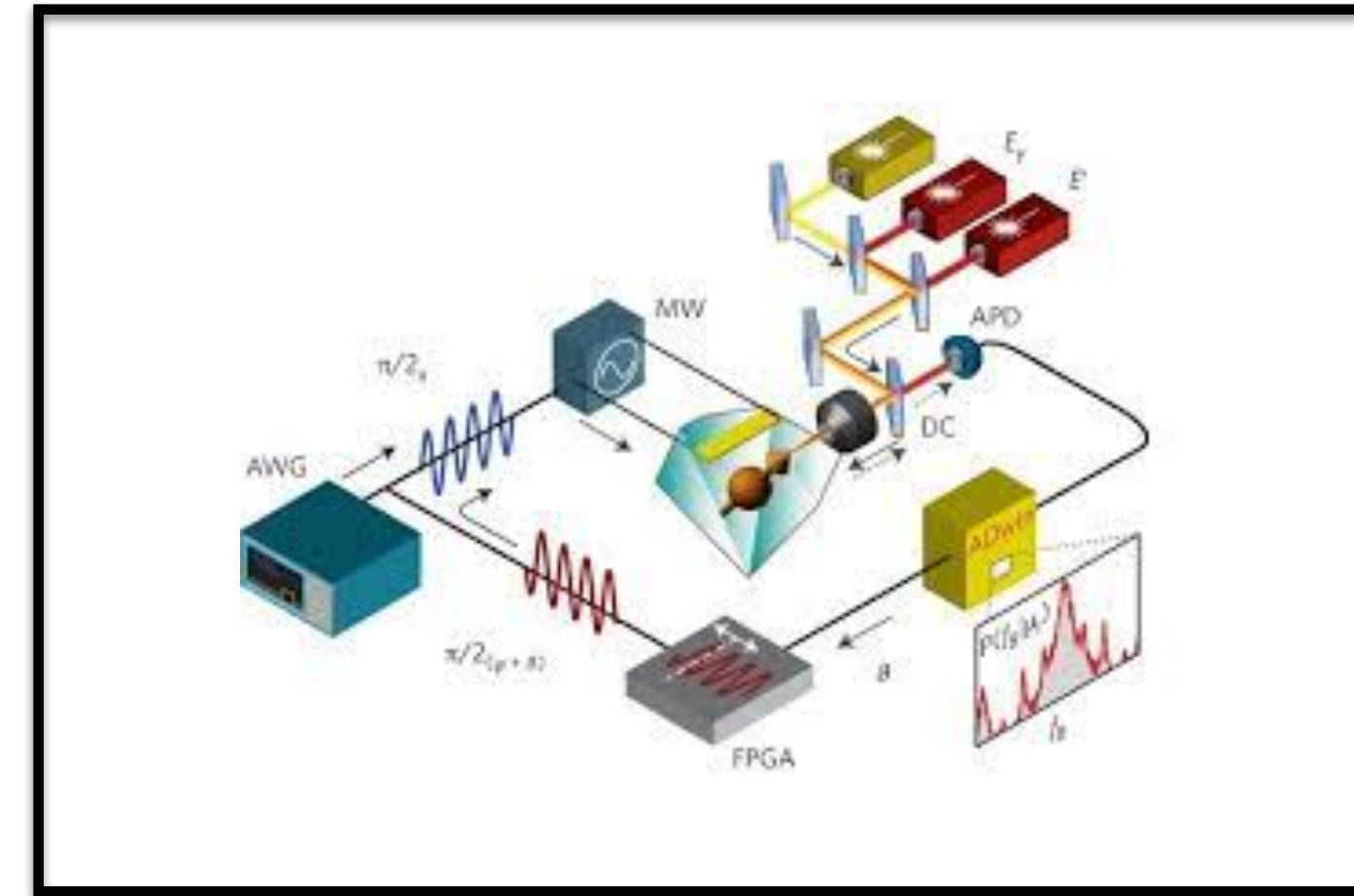
Potentially Natural Interactions

$$g \phi \bar{\Psi} \Psi$$

How do we find them?

Light Boson Detection

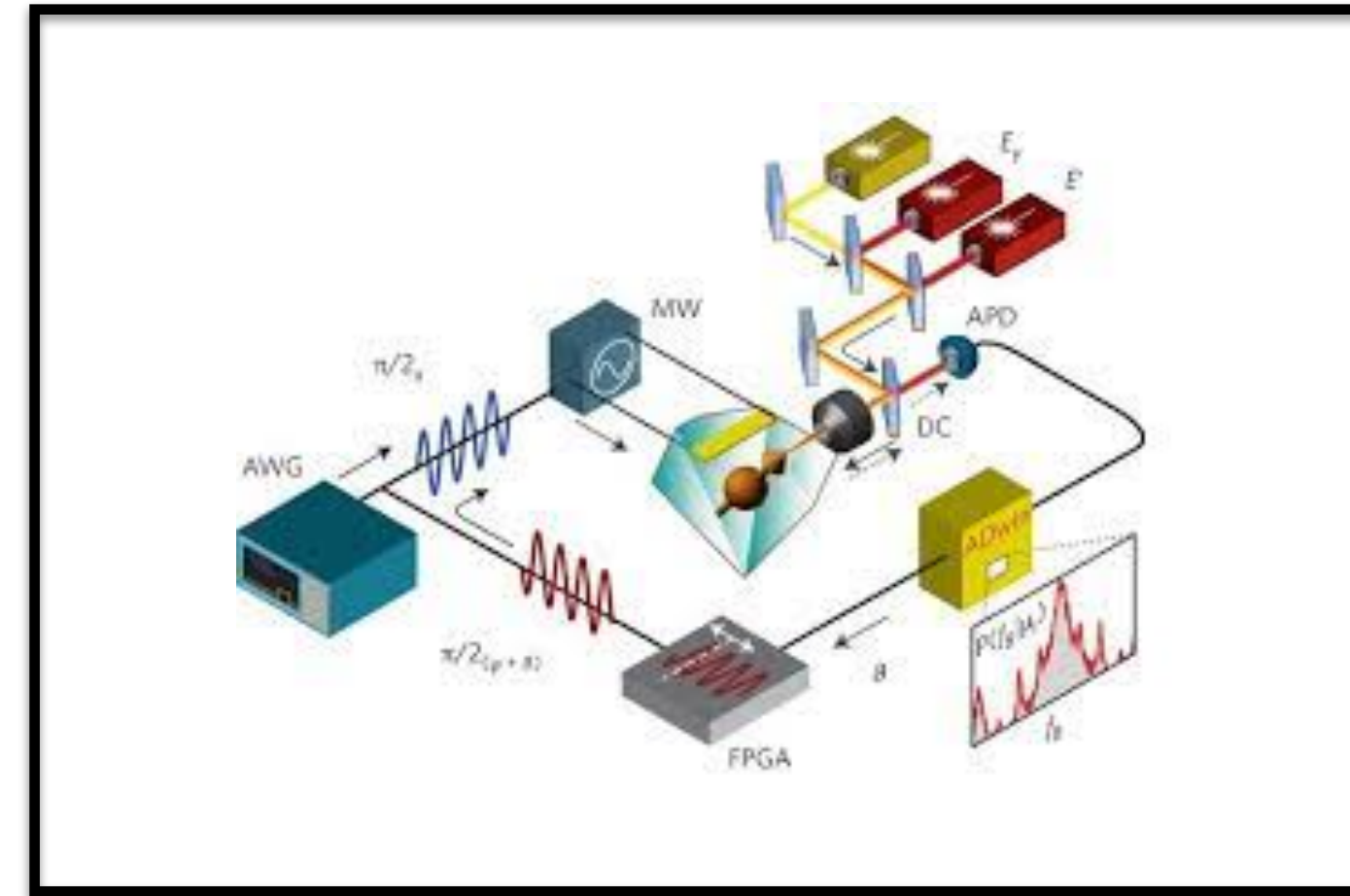
(I) Local Source



Null result directly relevant. Premium to produce and detect

Light Boson Detection

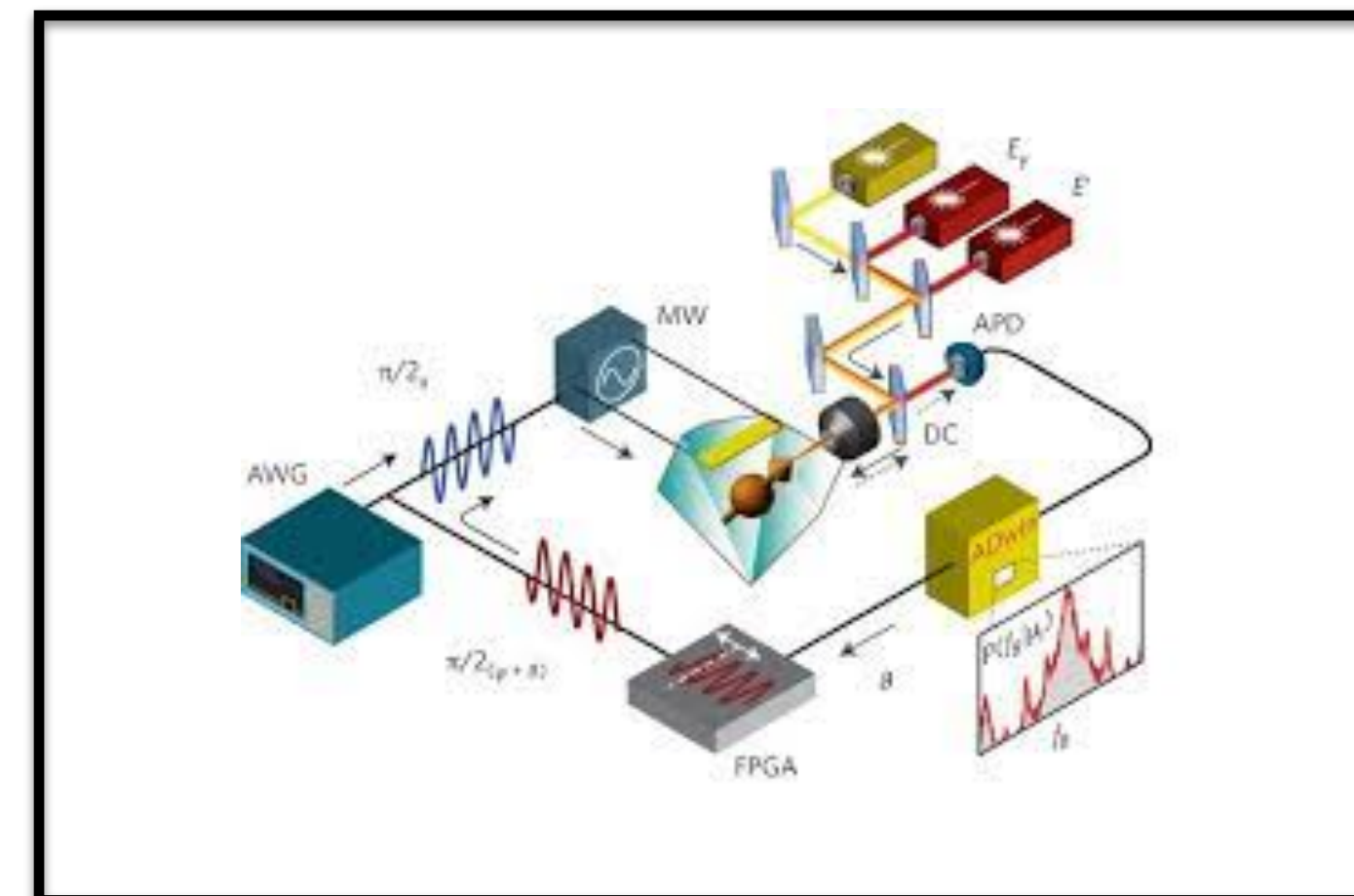
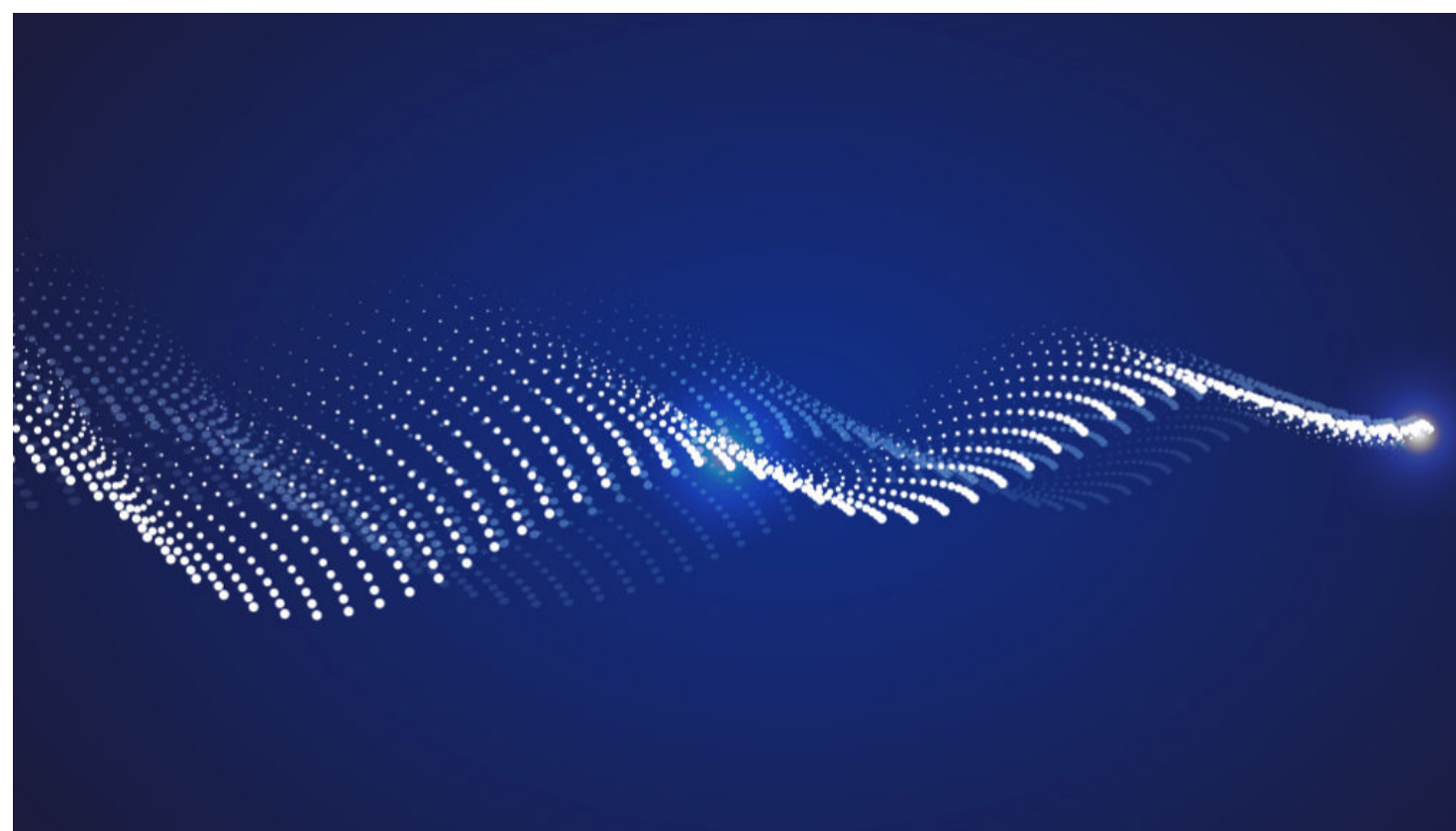
(I) Local Source



Null result directly relevant. Premium to produce and detect

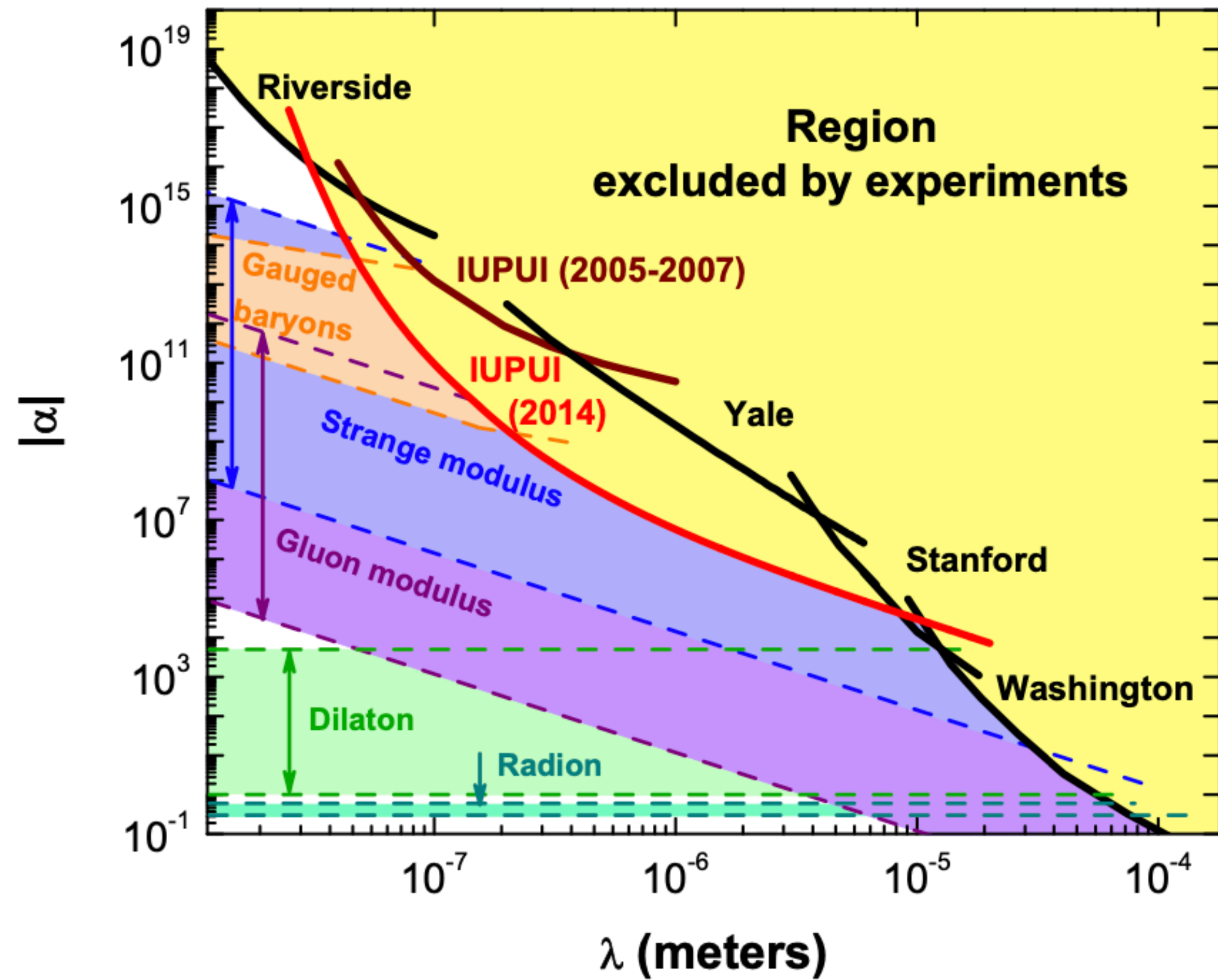
(2) Cosmic Source

Ultra-light dark matter ($\ll 1$ eV)



Where are we?

Short Distance Forces



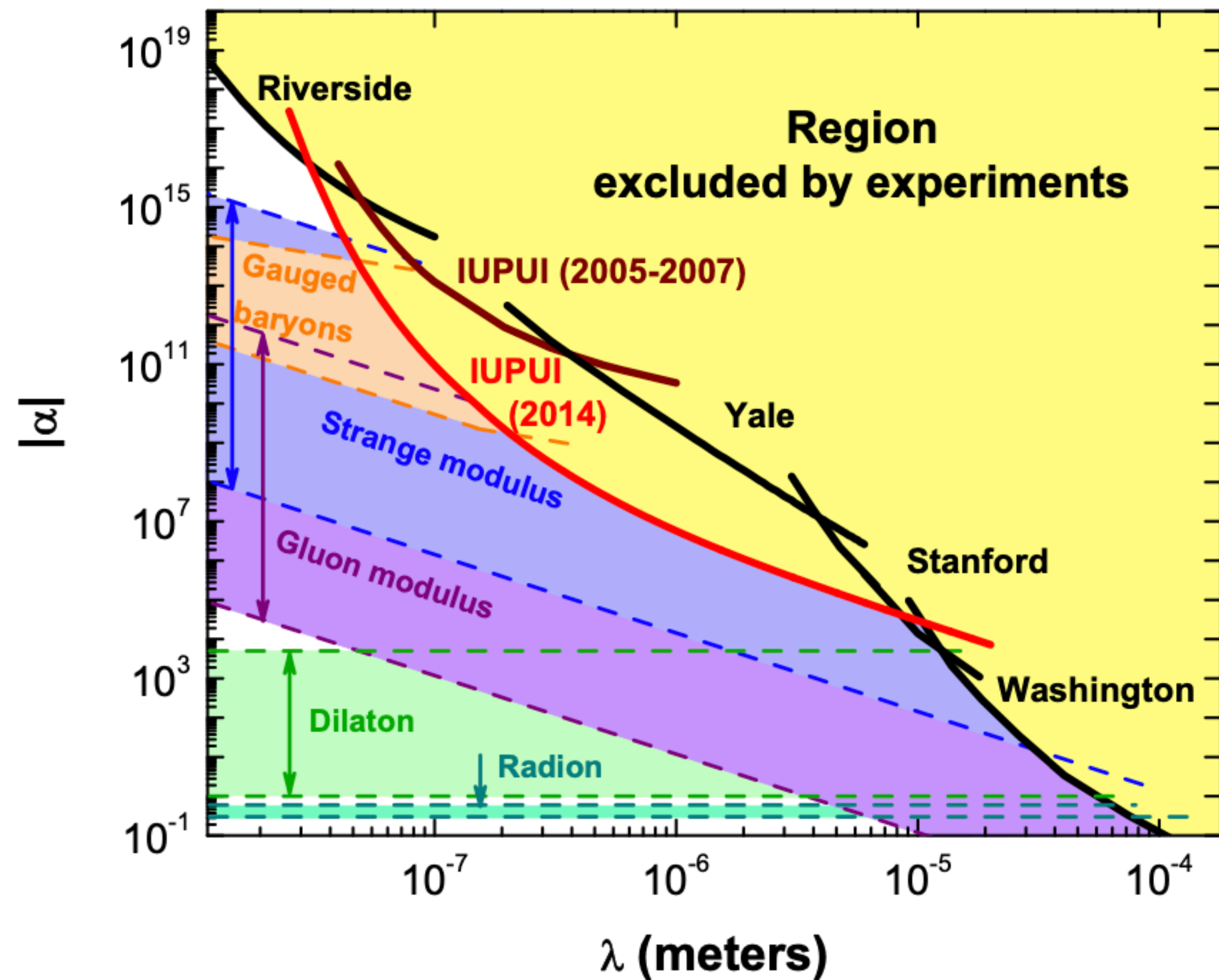
Very strong constraints at long ($> \mu\text{m}$) distances

Sensitivity rapidly drops at short ($< \mu\text{m}$) distances

$$F = \alpha \frac{G m_p^2}{r^2} e^{-\frac{r}{\lambda}}$$

Where are we?

Short Distance Forces



Very strong constraints at long ($> \mu\text{m}$) distances

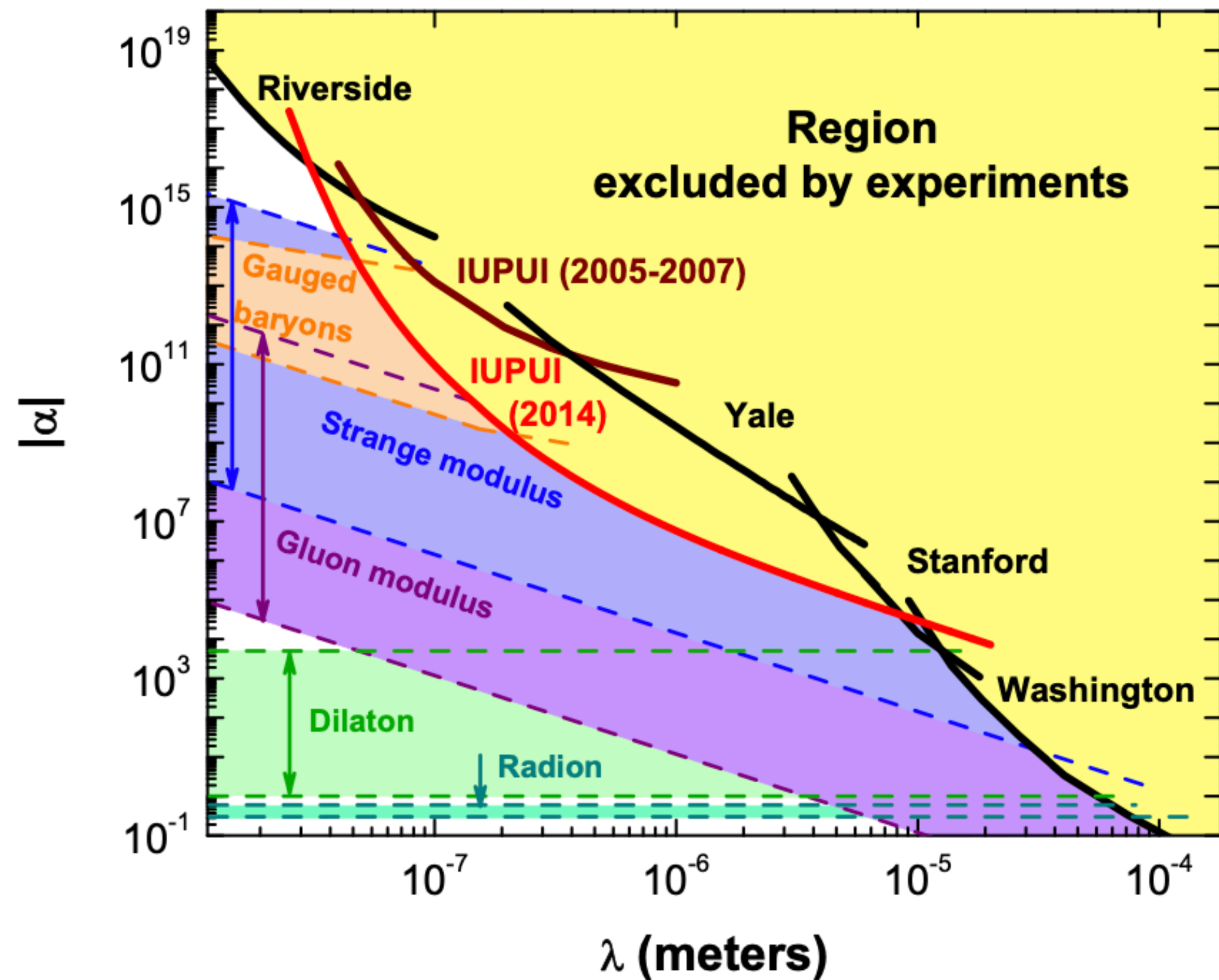
Sensitivity rapidly drops at short ($< \mu\text{m}$) distances

Why?

$$F = \alpha \frac{G m_p^2}{r^2} e^{-\frac{r}{\lambda}}$$

Where are we?

Short Distance Forces



Very strong constraints at long ($> \mu\text{m}$) distances

Sensitivity rapidly drops at short ($< \mu\text{m}$) distances

Why?

Short Range $\Rightarrow$ Objects need to be close

Electromagnetism $\gg$ New Physics

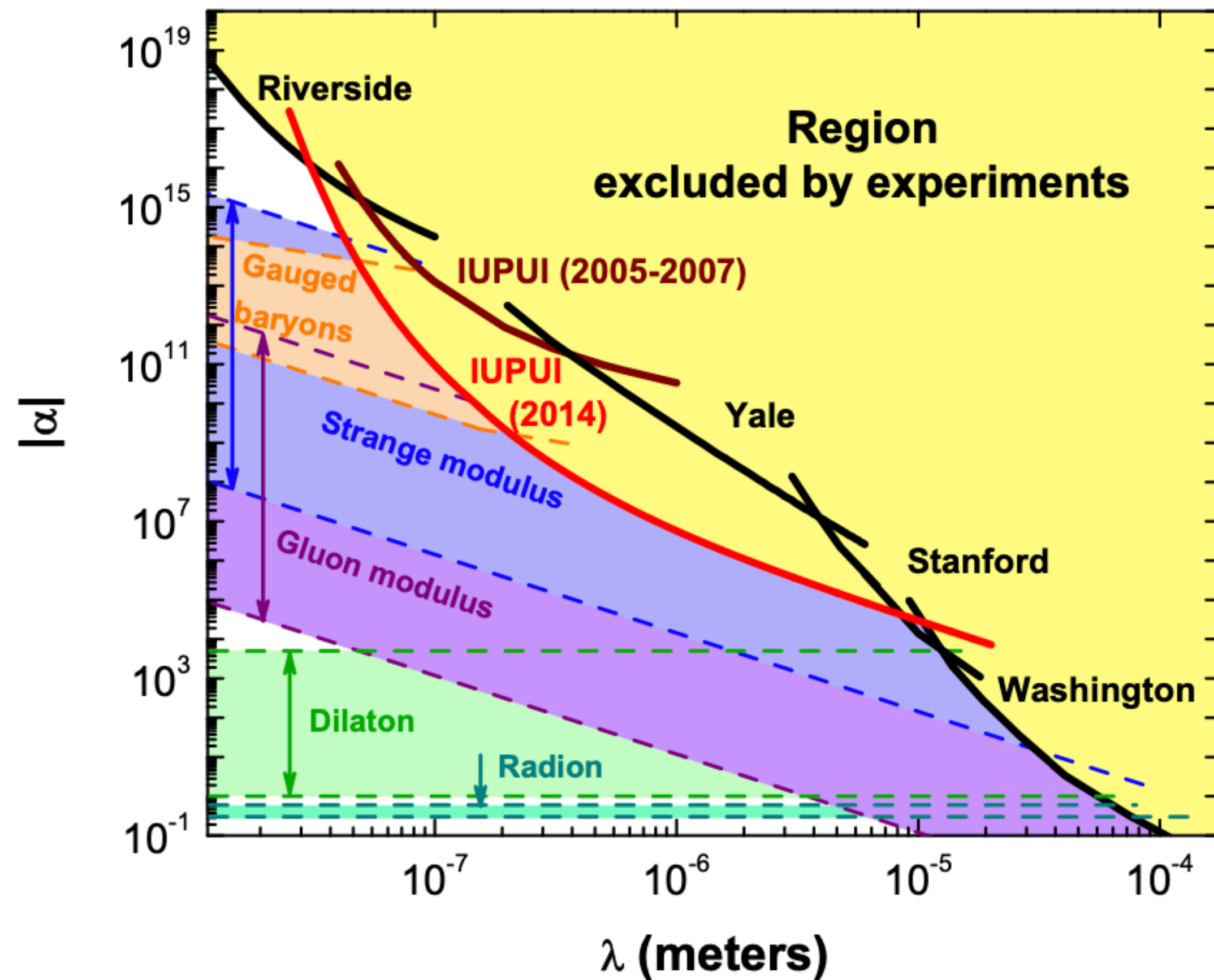
Short Range $\Rightarrow$ Only material within λ affected

Need to deal with thin objects with high precision

$$F = \alpha \frac{G m_p^2}{r^2} e^{-\frac{r}{\lambda}}$$

Where are we?

Short Distance Forces



Very strong constraints at long ($> \mu\text{m}$) distances

Sensitivity rapidly drops at short ($< \mu\text{m}$) distances

Why?

Short Range $\Rightarrow$ Objects need to be close

Electromagnetism $\gg$ New Physics

Short Range $\Rightarrow$ Only material within λ affected

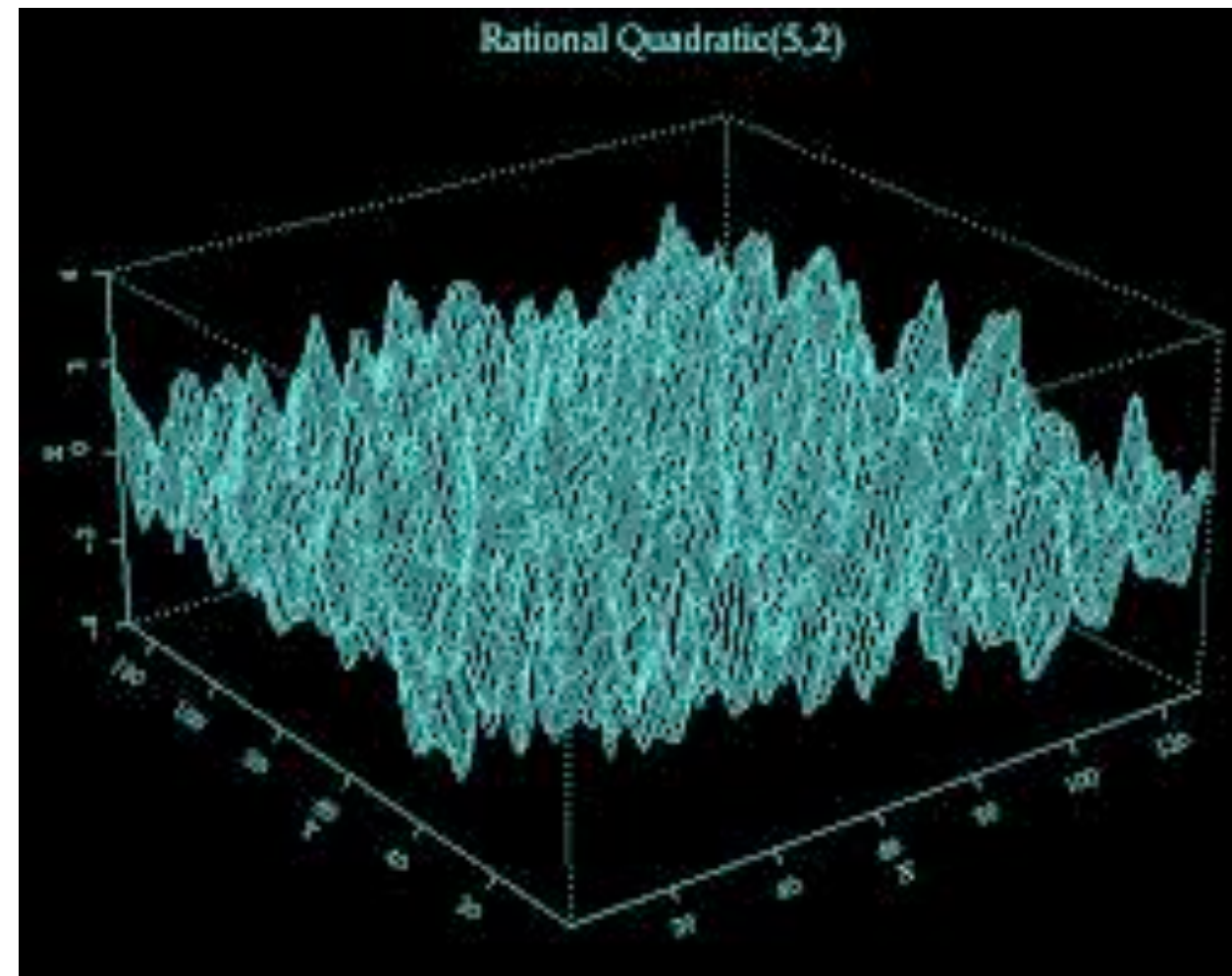
Need to deal with thin objects with high precision

$$F = \alpha \frac{G m_p^2}{r^2} e^{-\frac{r}{\lambda}}$$

Progress?

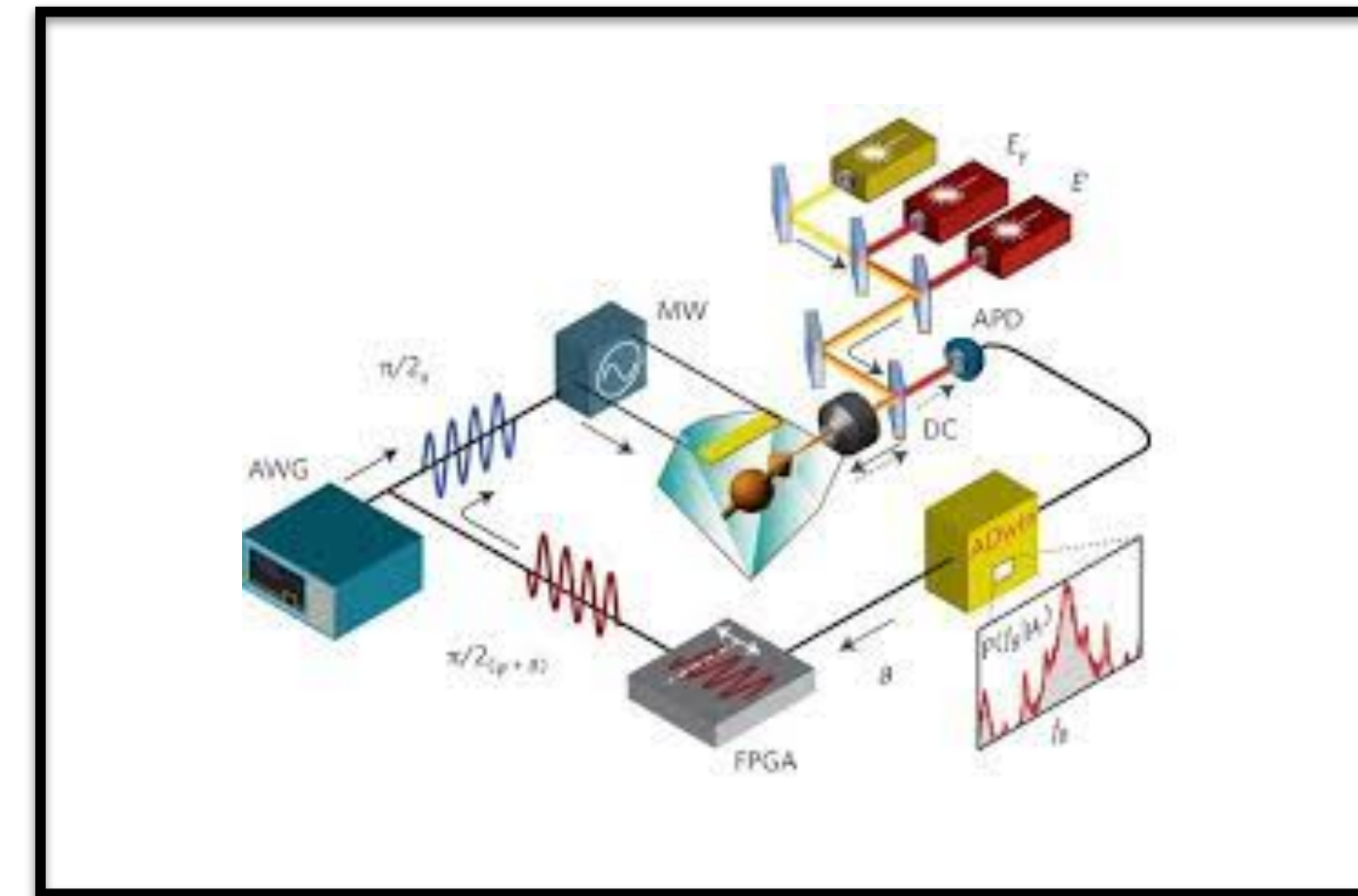
Where are we?

Cosmological Source



Axion Dark Matter

Oscillating signal, narrow band
($Q \sim 10^6$)



Detect Using suitable Resonator



nHz

kHz

MHz

GHz

10 GHz

CASPEr

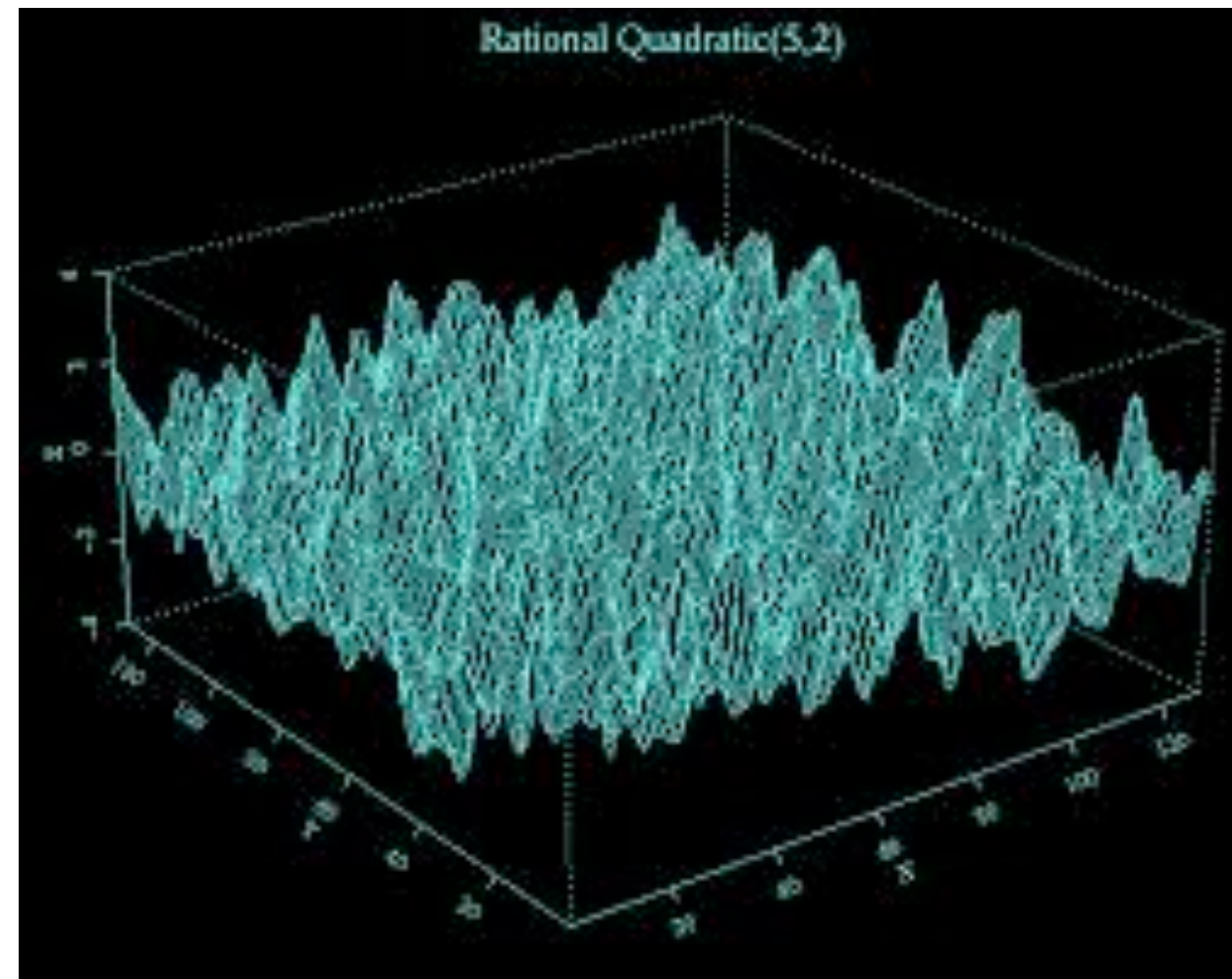
DMRadio

ADMX

HAYSTAC

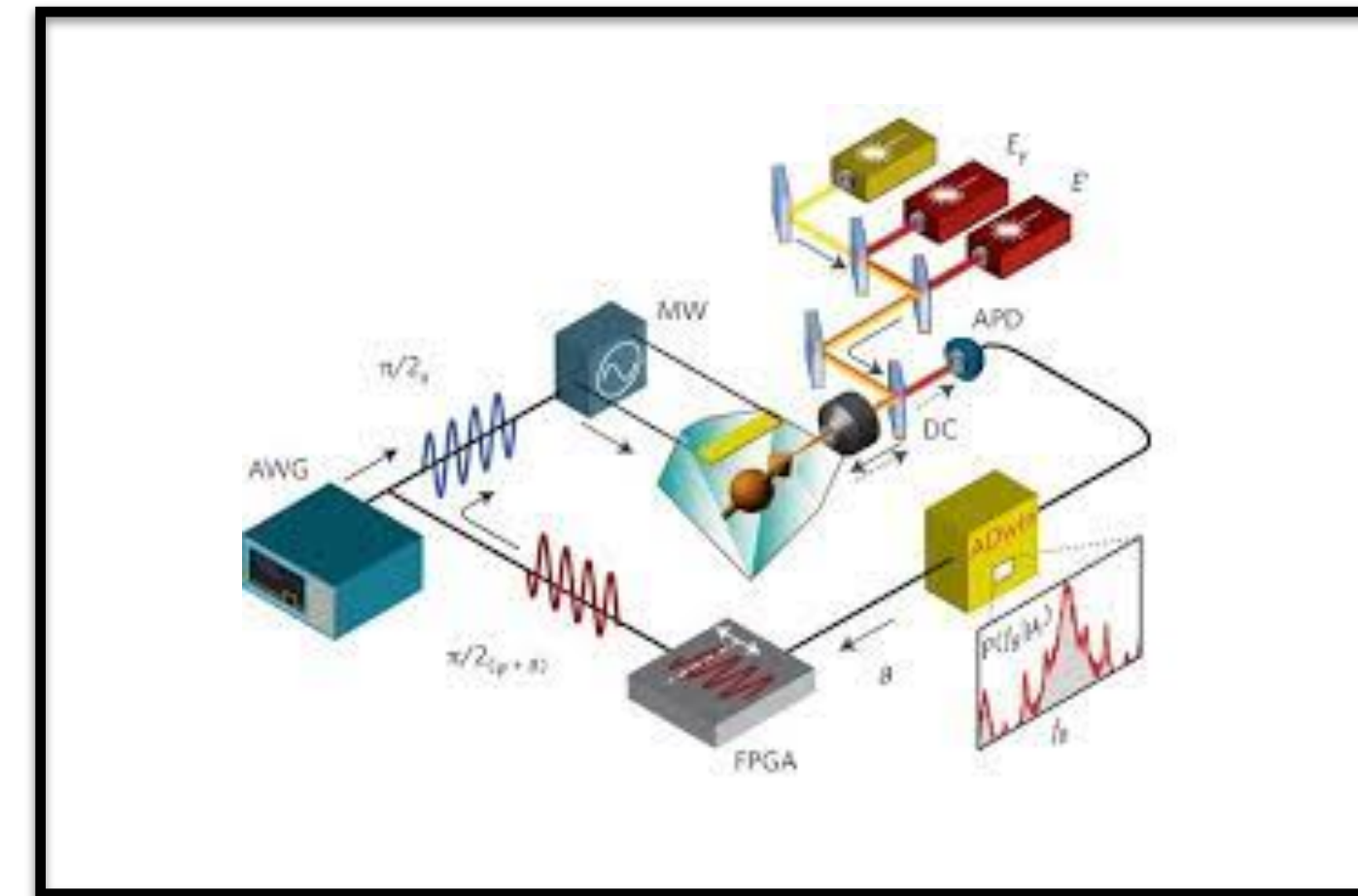
Where are we?

Cosmological Source



Axion Dark Matter

Oscillating signal, narrow band
($Q \sim 10^6$)



Detect Using suitable Resonator



Outline

1. Mossbauer Effect

2. High Frequency Axion Dark Matter
Detection

3. Conclusions

Mossbauer Effect

(Giorgio Gratta)

Outline

1. Mossbauer Effect

2. Setup

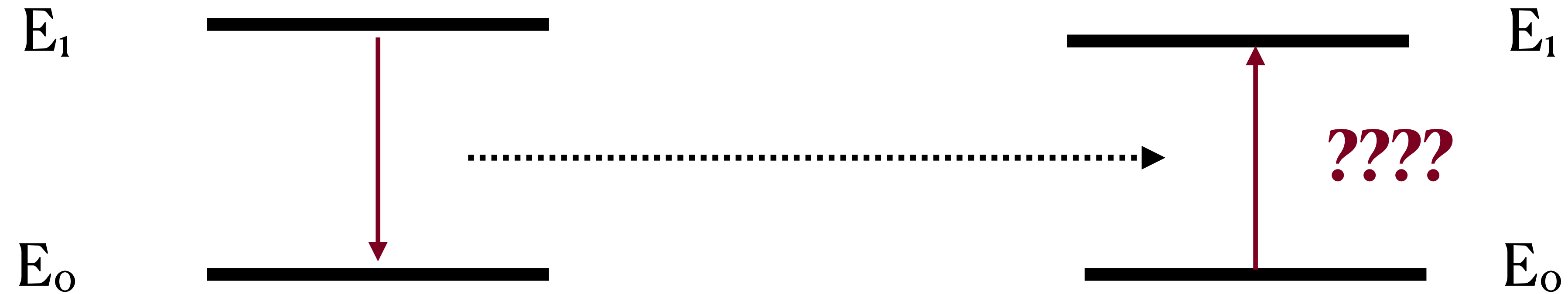
3. Backgrounds

4. Sensitivity

5. Synchrotron Light Sources?

6. Conclusions

Mossbauer Effect



Excited nuclear state decays via γ emission

Can the γ be reabsorbed?

Mossbauer Effect



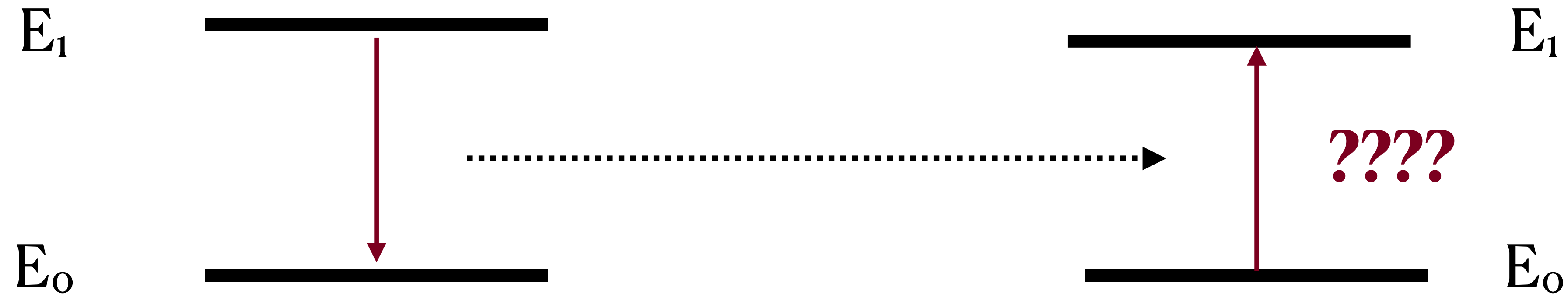
Excited nuclear state decays via γ emission

Can the γ be reabsorbed?

Issue: Small nuclear cross-sections

Efficient reabsorption only possible on resonance

Mossbauer Effect



Excited nuclear state decays via γ emission

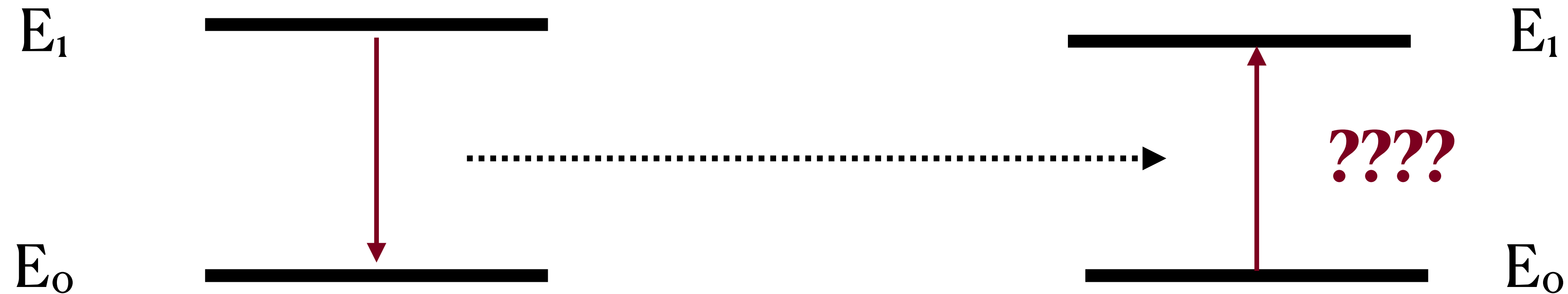
Can the γ be reabsorbed?

Issue: Small nuclear cross-sections

Efficient reabsorption only possible on resonance

Isn't emitted γ at transition energy? Automatically Resonant?

Mossbauer Effect



Excited nuclear state decays via γ emission

Can the γ be reabsorbed?

Issue: Small nuclear cross-sections

Efficient reabsorption only possible on resonance

Isn't emitted γ at transition energy? Automatically Resonant?

No : Recoiling nucleus takes energy, γ outside narrow width

Mossbauer Effect



Small enough E_γ , entire lattice recoils!

Negligible lattice kinetic energy - monochromatic E_γ

Resonant Reabsorption possible!

Mossbauer Effect



Small enough E_γ , entire lattice recoils!

Negligible lattice kinetic energy - monochromatic E_γ

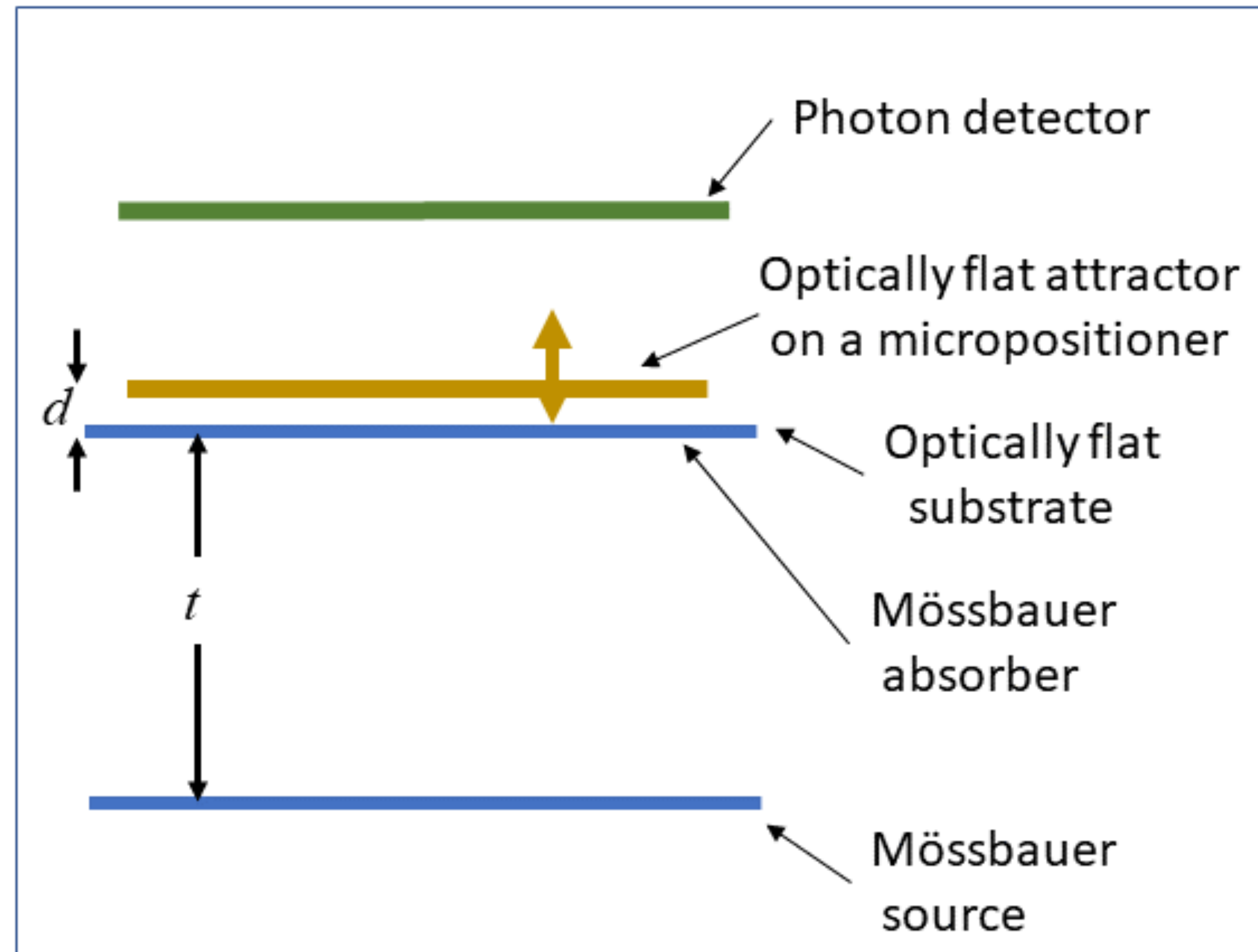
Resonant Reabsorption possible!

Narrow Nuclear Lines $\Rightarrow$ High Sensitivity to energy shifts

Setup

$$\mathcal{L} \supset y_q \phi \bar{q} q + \frac{\phi}{f_\gamma} F_{\mu\nu}^2 + \frac{\phi}{f_g} G_{\mu\nu}^2 + \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma} + g\phi h^2 + \frac{m_\phi^2}{2} \phi^2$$

**New interaction
shifts nuclear energy**

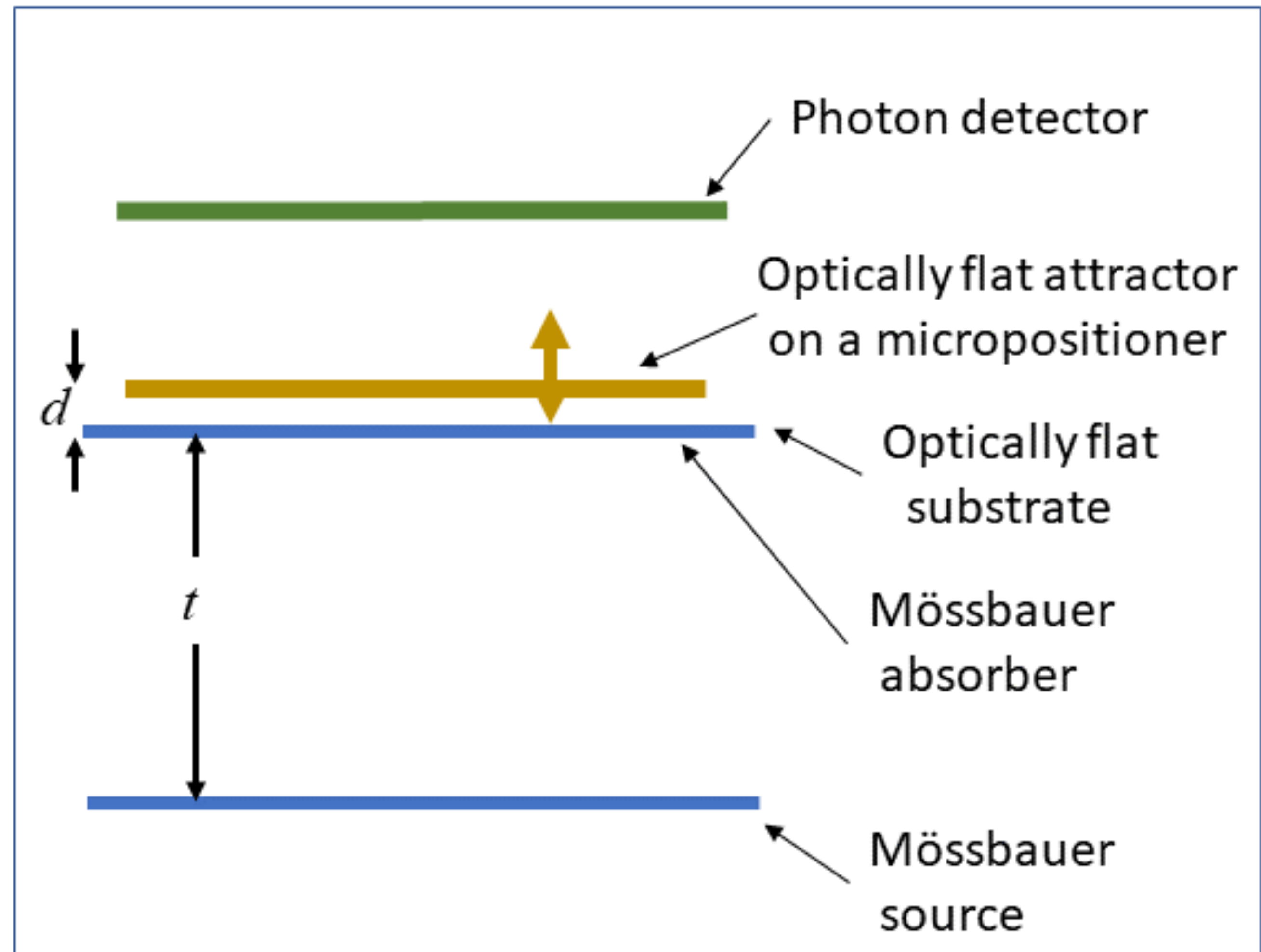


Setup

$$\mathcal{L} \supset y_q \phi \bar{q} q + \frac{\phi}{f_\gamma} F_{\mu\nu}^2 + \frac{\phi}{f_g} G_{\mu\nu}^2 + \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma} + g\phi h^2 + \frac{m_\phi^2}{2} \phi^2$$

**New interaction
shifts nuclear energy**

**Resonant
Reabsorption as a
function of d**



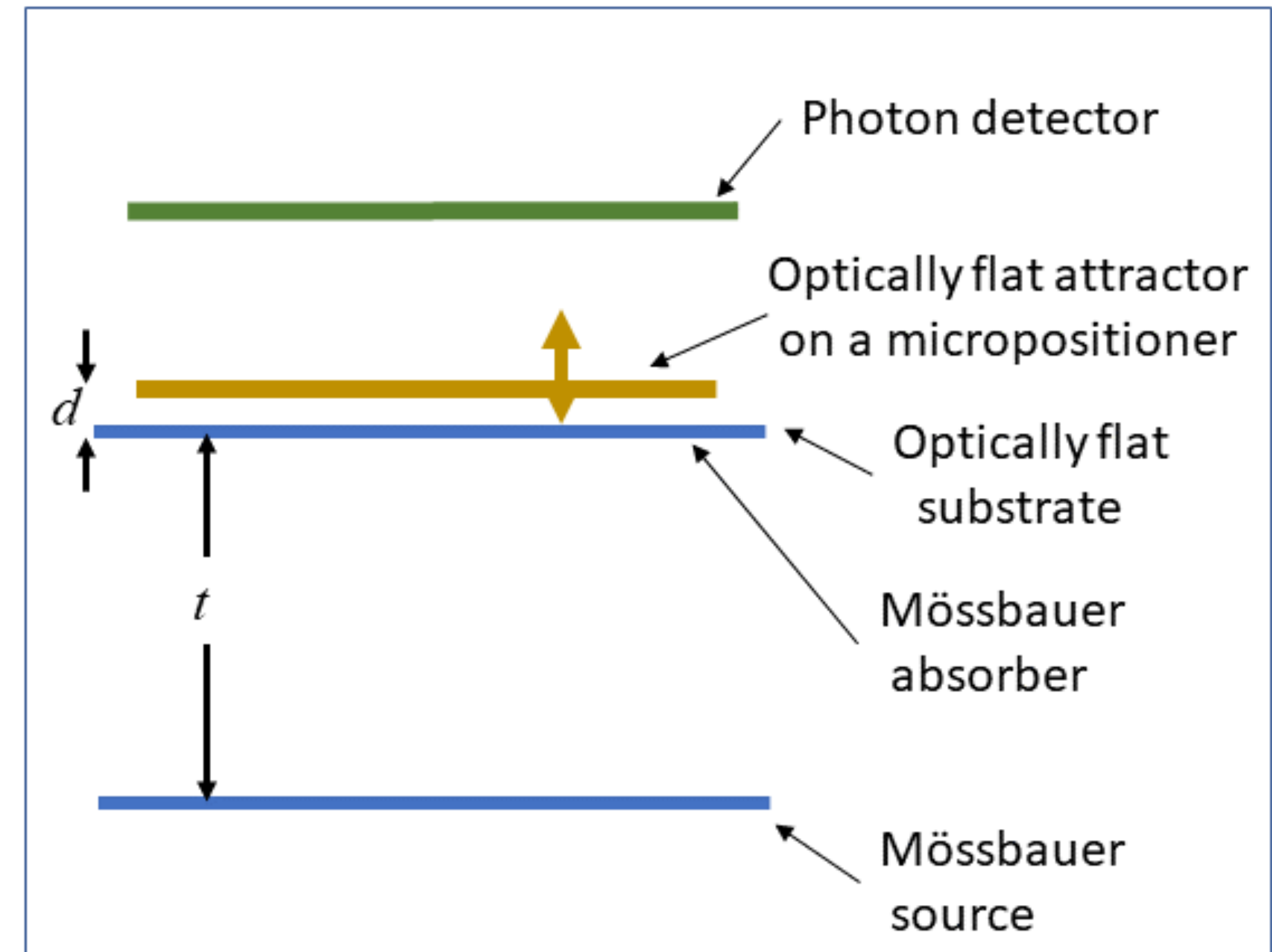
Backgrounds

$$\mathcal{L} \supset y_q \phi \bar{q} q + \frac{\phi}{f_\gamma} F_{\mu\nu}^2 + \frac{\phi}{f_g} G_{\mu\nu}^2 + \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma} + g\phi h^2 + \frac{m_\phi^2}{2} \phi^2$$

Electromagnetism?

Needs to change nuclear transition energies

Suppressed by small nuclear moments,
electron shielding



Backgrounds

$$\mathcal{L} \supset y_q \phi \bar{q} q + \frac{\phi}{f_\gamma} F_{\mu\nu}^2 + \frac{\phi}{f_g} G_{\mu\nu}^2 + \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma} + g\phi h^2 + \frac{m_\phi^2}{2} \phi^2$$

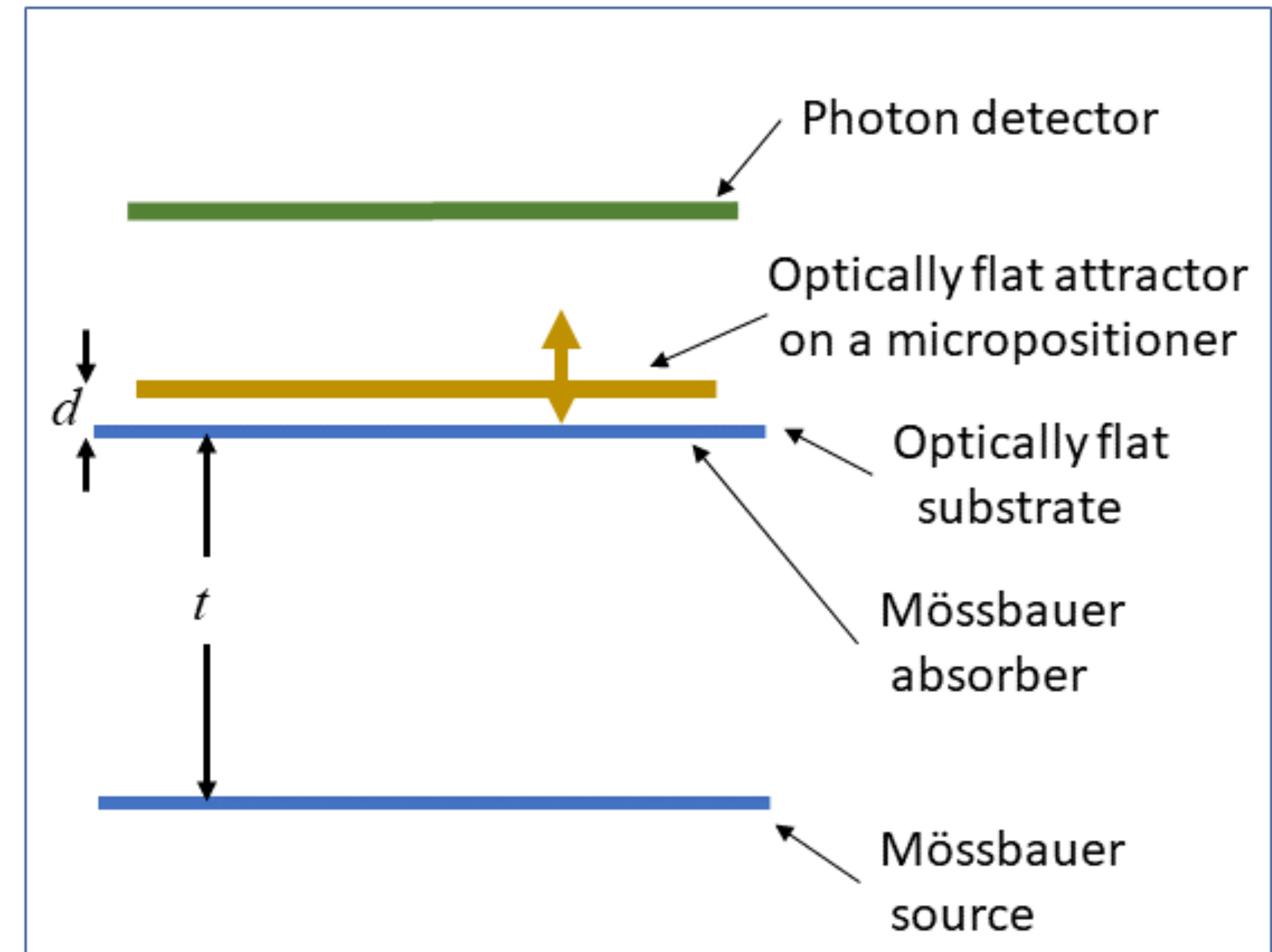
Electromagnetism?

Needs to change nuclear transition energies

Suppressed by small nuclear moments,
electron shielding

Unpolarized nuclear spin => effects average
down

Signal from new scalar and tensor
interactions are not suppressed!



Backgrounds

$$\mathcal{L} \supset y_q \phi \bar{q} q + \frac{\phi}{f_\gamma} F_{\mu\nu}^2 + \frac{\phi}{f_g} G_{\mu\nu}^2 + \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma} + g\phi h^2 + \frac{m_\phi^2}{2} \phi^2$$

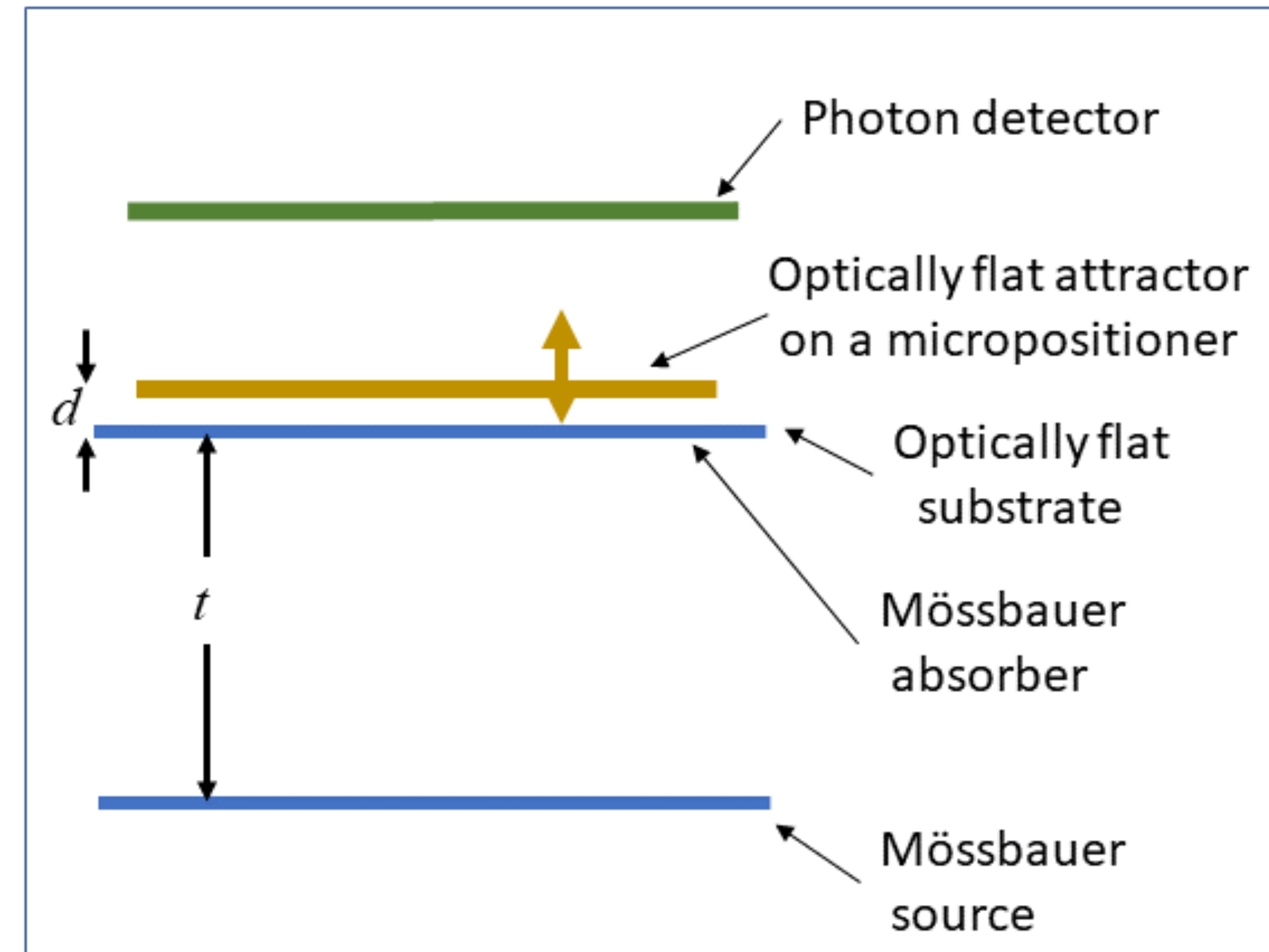
Electromagnetism?

Needs to change nuclear transition energies

Suppressed by small nuclear moments,
electron shielding

Unpolarized nuclear spin => effects average
down

Signal from new scalar and tensor
interactions are not suppressed!



First order effects irrelevant

Leading Background: Chemical Shift from Casimir

Sensitivity

$$\mathcal{L} \supset y_q \phi \bar{q} q + \frac{\phi}{f_\gamma} F_{\mu\nu}^2 + \frac{\phi}{f_g} G_{\mu\nu}^2 + \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma} + g \phi h^2 + \frac{m_\phi^2}{2} \phi^2$$

For given coupling, compute energy shift ΔE

Sensitivity

$$\mathcal{L} \supset y_q \phi \bar{q} q + \frac{\phi}{f_\gamma} F_{\mu\nu}^2 + \frac{\phi}{f_g} G_{\mu\nu}^2 + \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma} + g \phi h^2 + \frac{m_\phi^2}{2} \phi^2$$

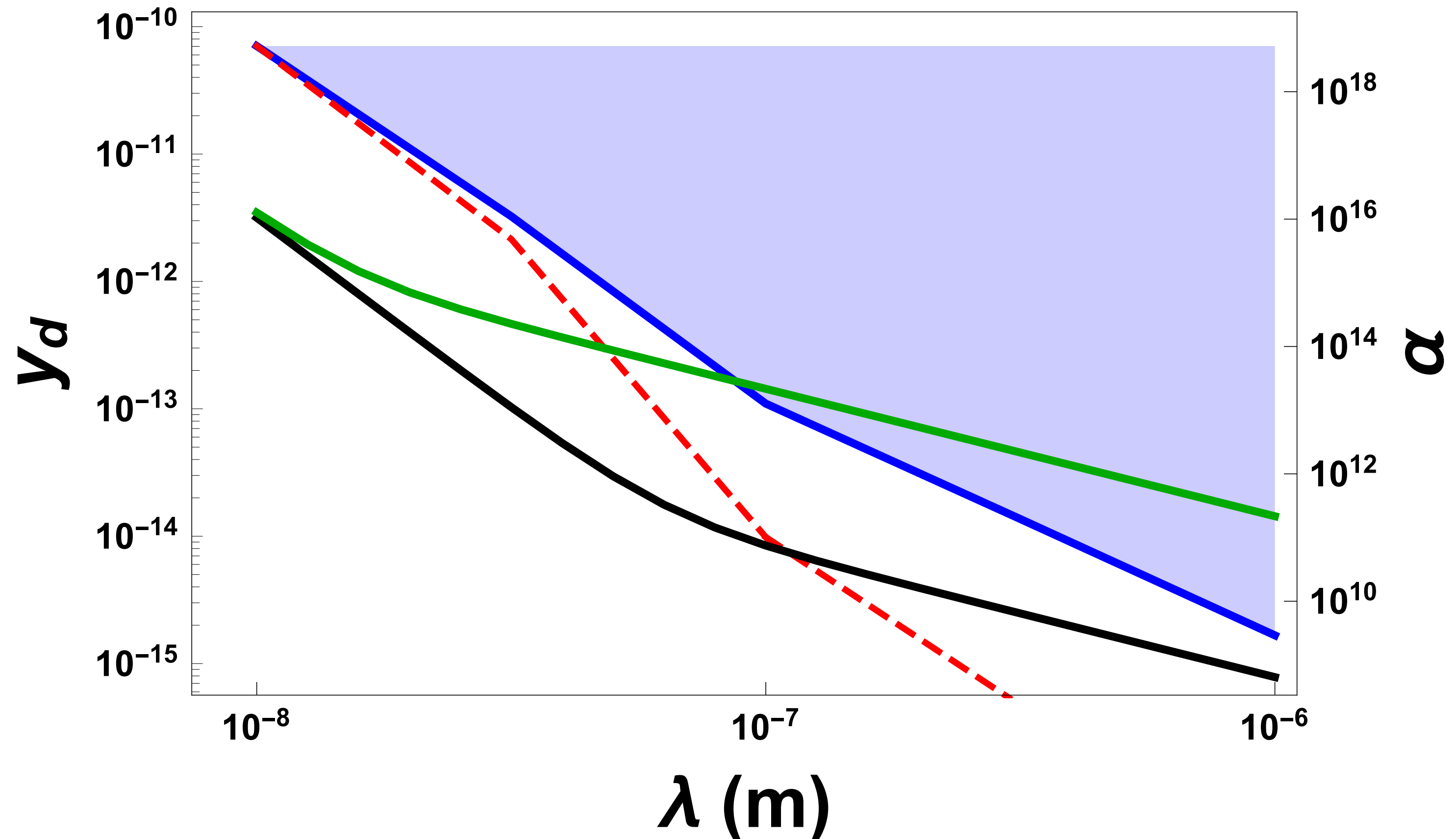
For given coupling, compute energy shift ΔE

$$\Delta E = \frac{\Gamma}{\sqrt{N_\gamma}}$$

$$^{57}\text{Fe} \quad \Delta E = 10^{-15} \text{ eV}$$

$$^{181}\text{Tl} \quad \Delta E = 10^{-17} \text{ eV}$$

$$N_\gamma = 3 \times 10^{14}$$



Sensitivity

$$\mathcal{L} \supset y_q \phi \bar{q} q + \frac{\phi}{f_\gamma} F_{\mu\nu}^2 + \frac{\phi}{f_g} G_{\mu\nu}^2 + \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma} + g \phi h^2 + \frac{m_\phi^2}{2} \phi^2$$

For given coupling, compute energy shift ΔE

$$\Delta E = \frac{\Gamma}{\sqrt{N_\gamma}}$$

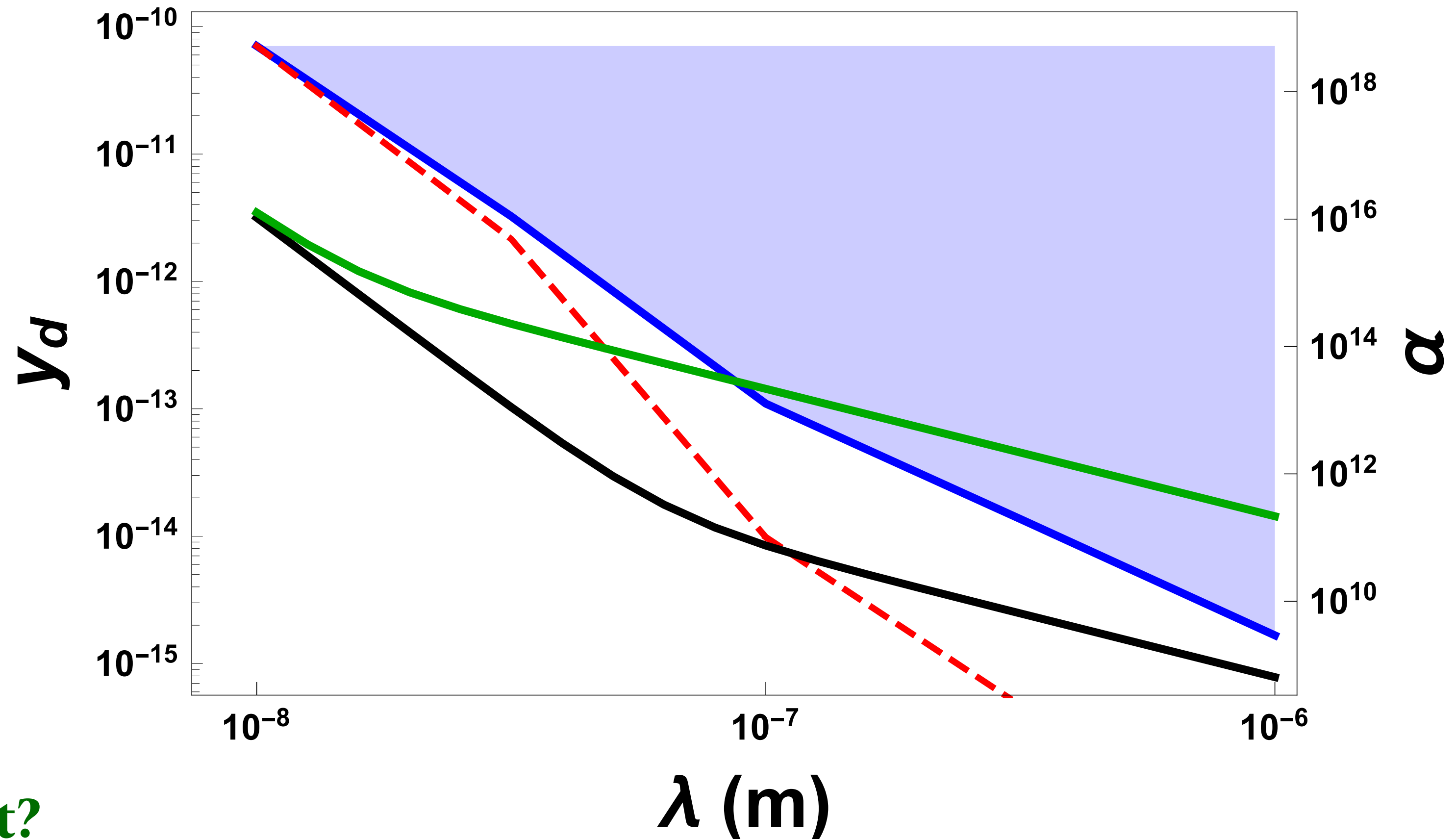
$$^{57}\text{Fe} \quad \Delta E = 10^{-15} \text{ eV}$$

$$^{181}\text{Tl} \quad \Delta E = 10^{-17} \text{ eV}$$

$$N_\gamma = 3 \times 10^{14}$$

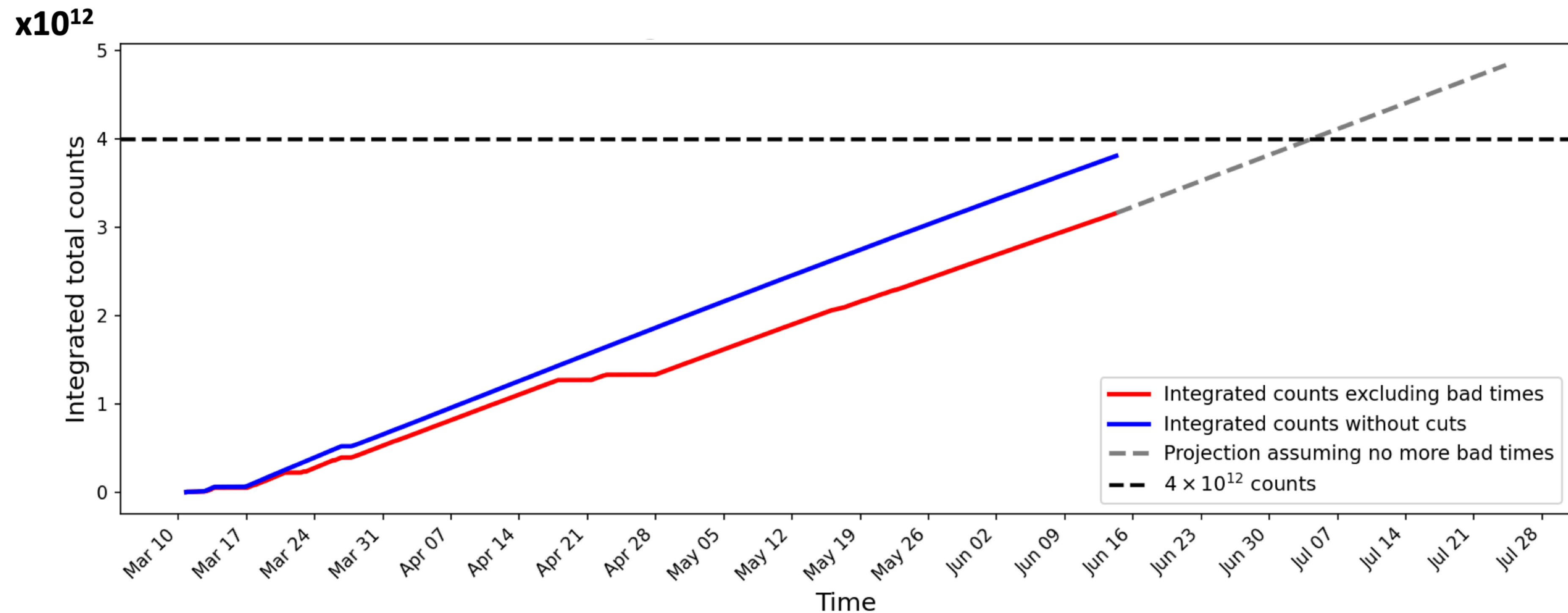
Second Order Casimir Background at
shortest distances

Mitigate using differential measurement?



Experimental Progress

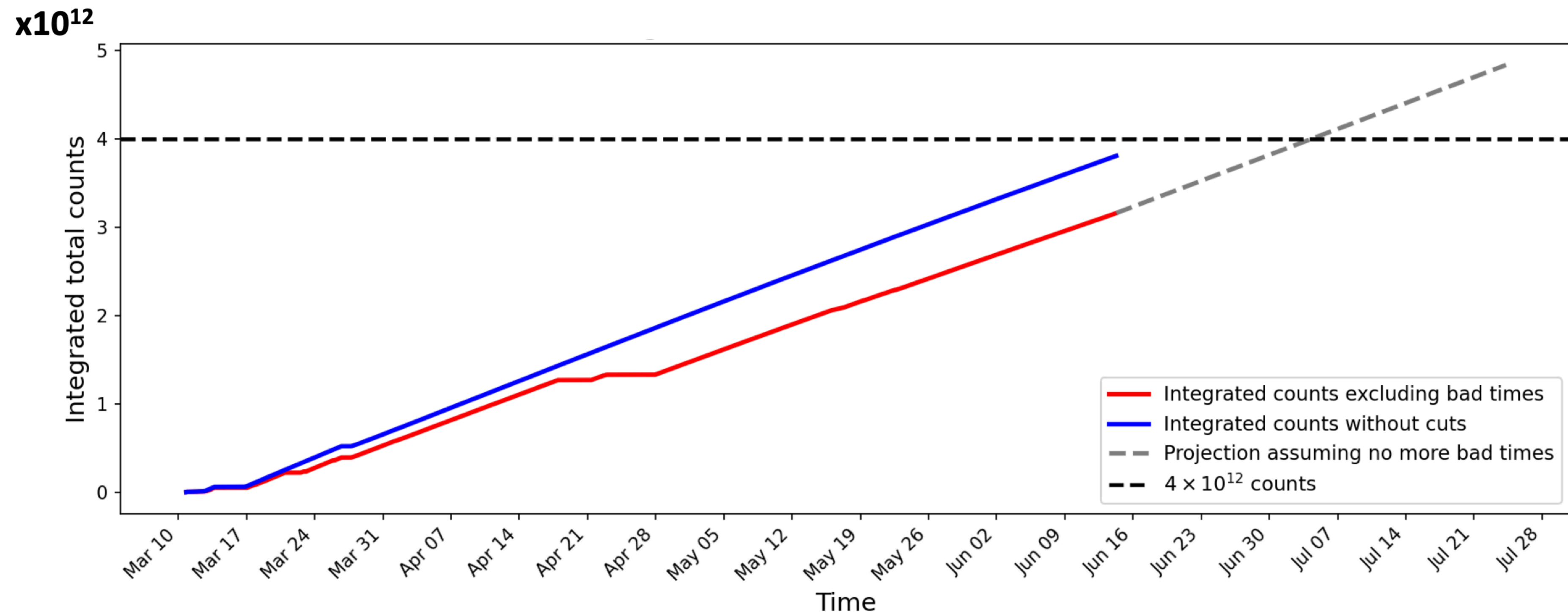
We already have ~100 days of data on disk, using a ~30mCi ^{57}Co source.



$$\Delta E \approx 10^{-14} \text{ eV}$$

Experimental Progress

We already have ~100 days of data on disk, using a ~30mCi ^{57}Co source.

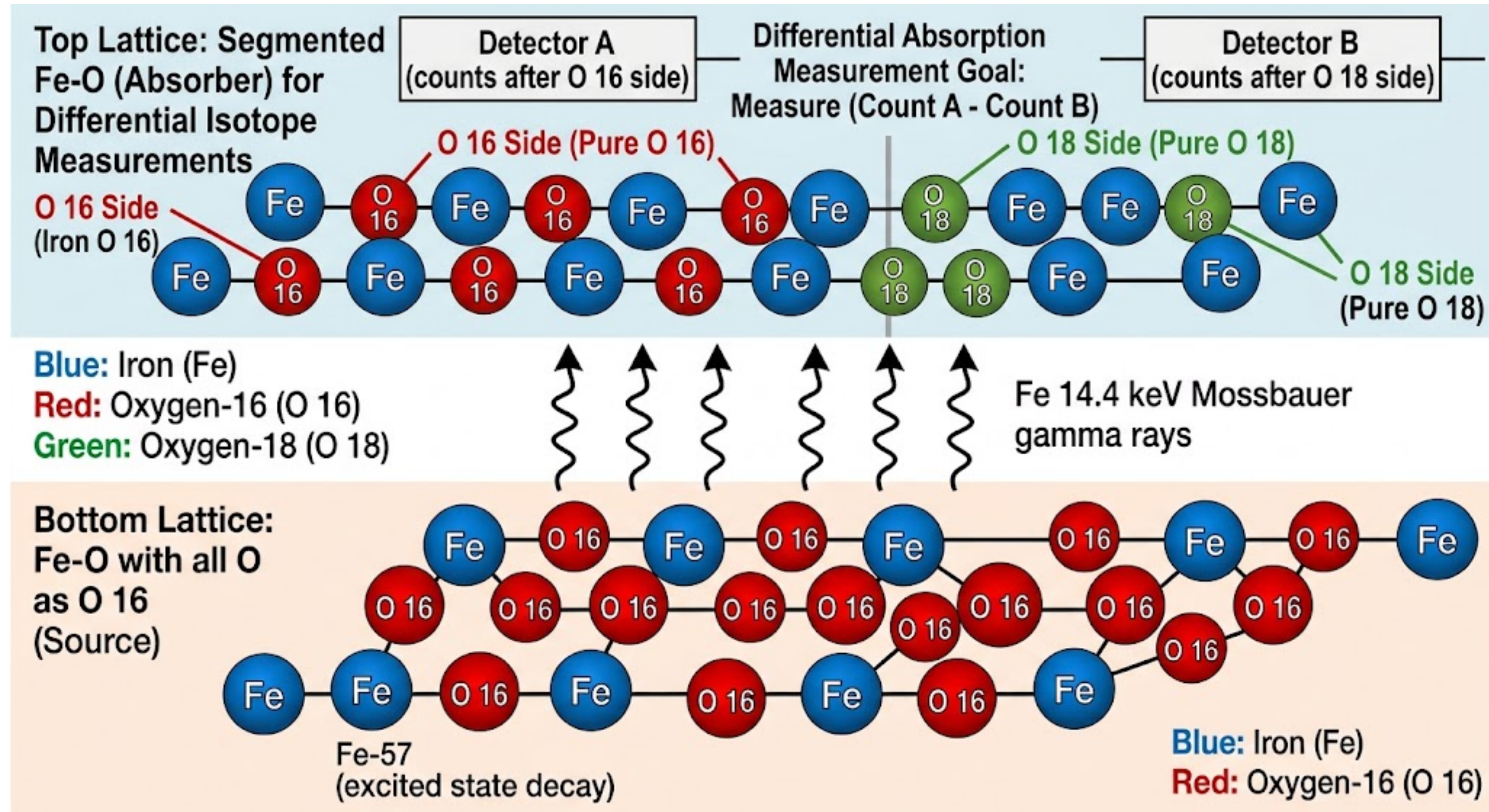


$$\Delta E \approx 10^{-14} \text{ eV}$$

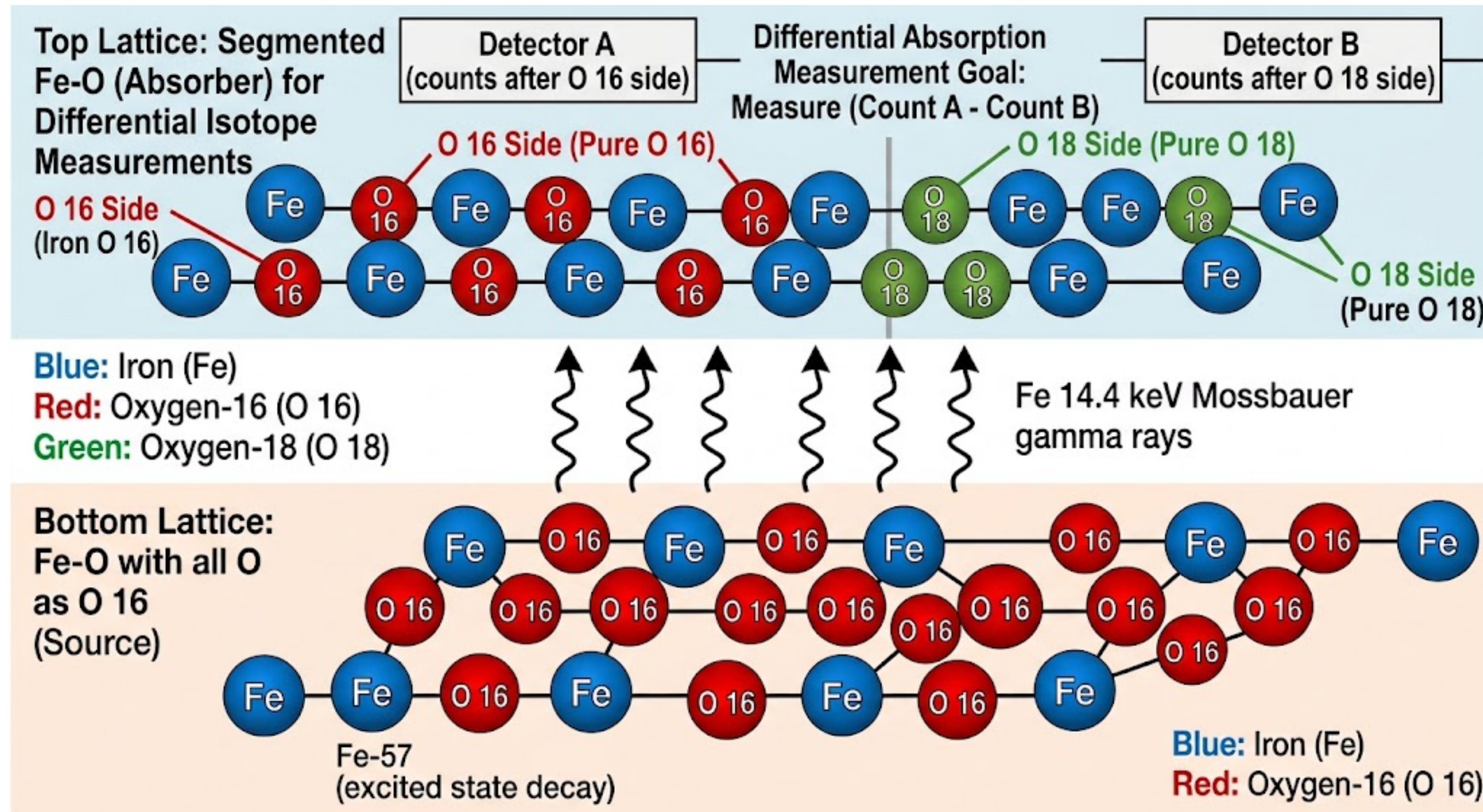
**Next Steps: Higher Flux Iron Source
Natural Line width in Tantalum**

Gratta Lab @ Stanford

Angstrom Scale Forces

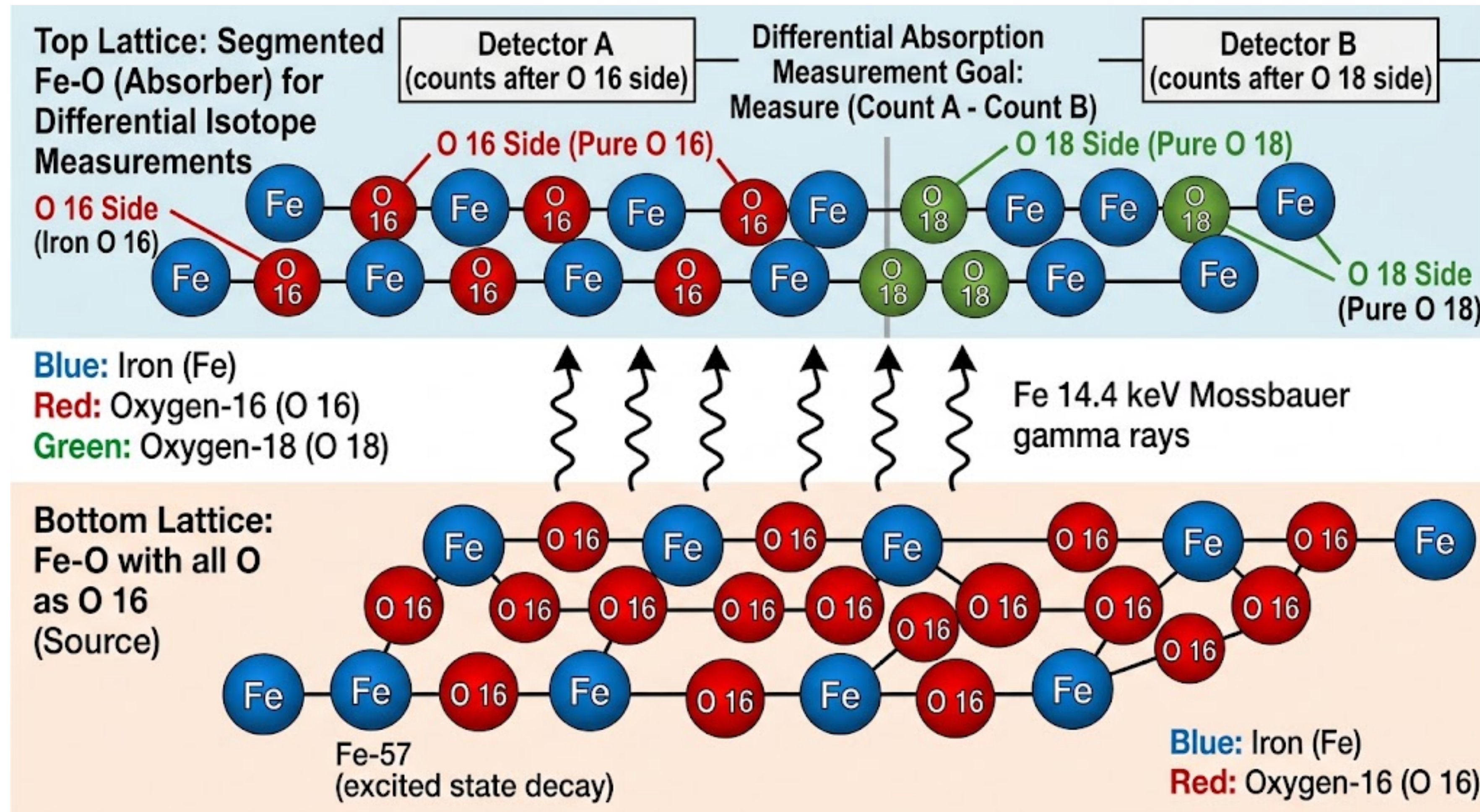


Angstrom Scale Forces



Standard Model Estimate $\sim 10^{-13}$ eV
(Dipole shift from Isotope Change x Chemical Shift)

Angstrom Scale Forces

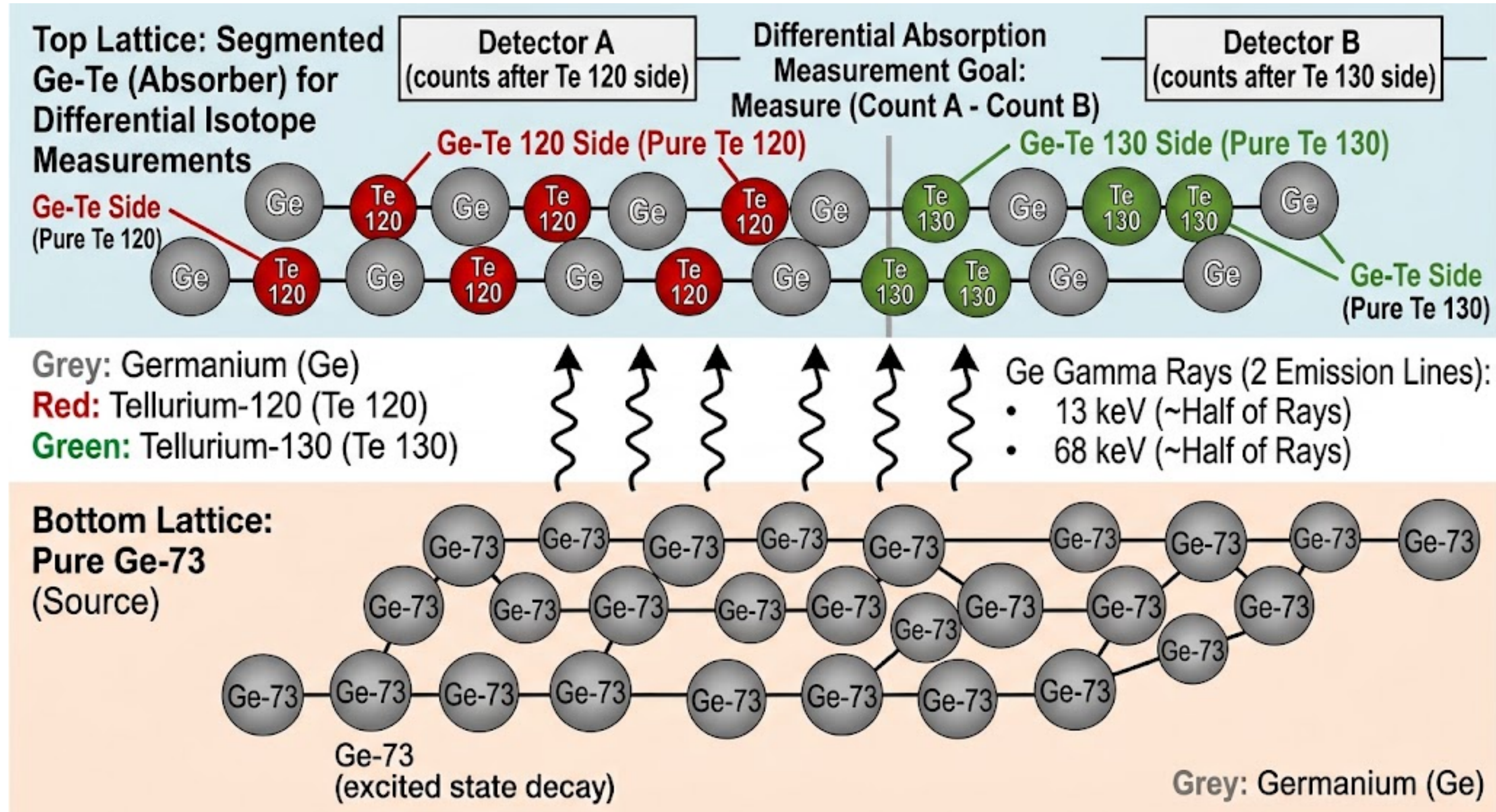


Standard Model Estimate $\sim 10^{-13}$ eV

(Dipole shift from Isotope Change x Chemical Shift)

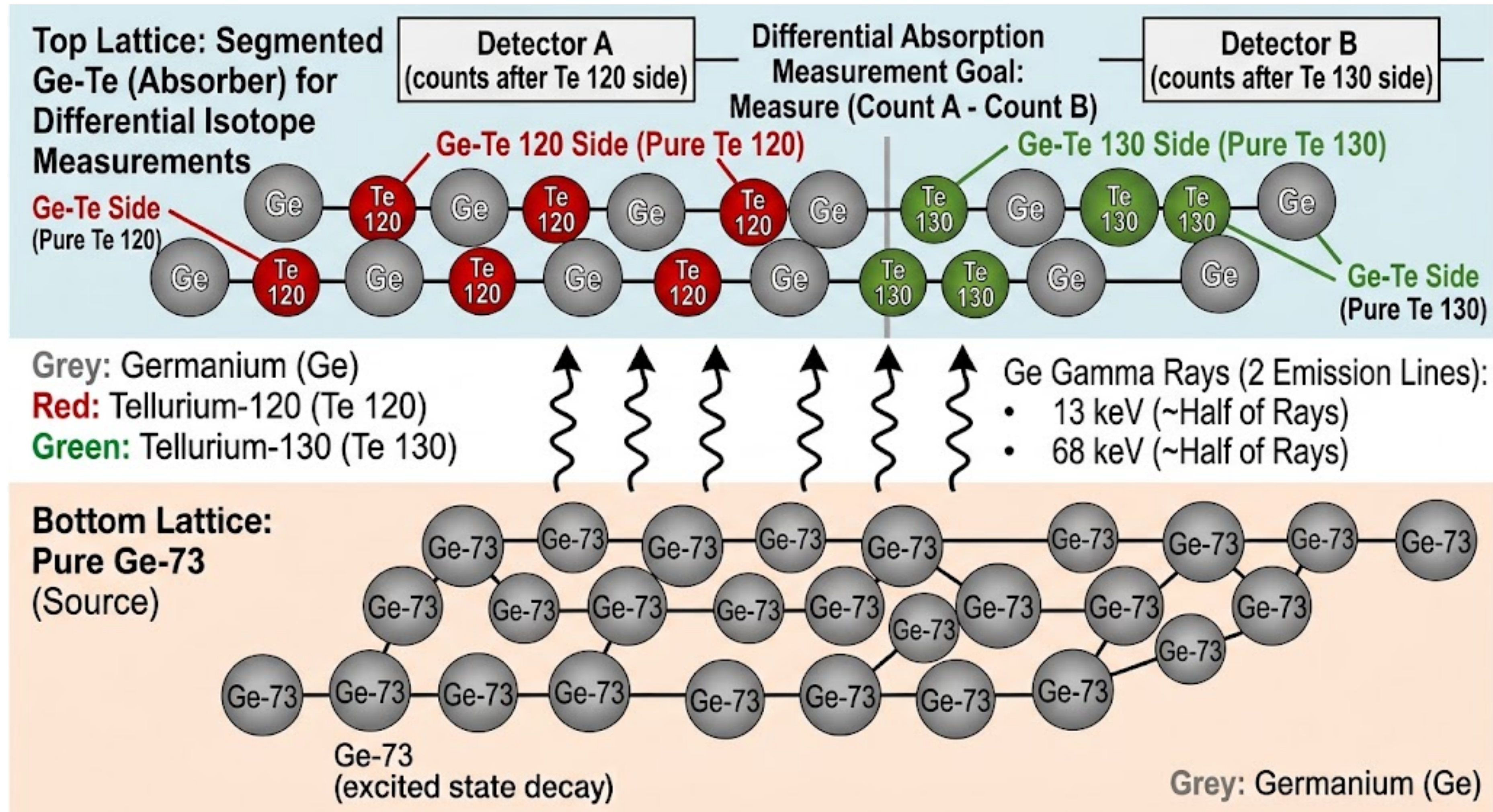
Can we do better?

Angstrom Scale Forces



Two Ge-73 Mossbauer Lines: 13 keV and 68 keV

Angstrom Scale Forces



Two Ge-73 Mossbauer Lines: 13 keV and 68 keV

Differential Measurement with Ge-Te (120) and Ge-Te(130)

Angstrom Scale Forces

Leading Order Standard Model Background: Shift in Electron Cloud x Nuclear Transition

$$\delta (120)_{13} = \text{Ge} (120) \Delta_{13} + 120\gamma_{13}$$

$$\delta (130)_{13} = \text{Ge} (130) \Delta_{13} + 130\gamma_{13}$$

$$\delta (120)_{68} = \text{Ge} (120) \Delta_{68} + 120\gamma_{68}$$

$$\delta (130)_{68} = \text{Ge} (130) \Delta_{68} + 130\gamma_{68}$$

Angstrom Scale Forces

Leading Order Standard Model Background: Shift in Electron Cloud x Nuclear Transition

$$\delta (120)_{13} = \text{Ge} (120) \Delta_{13} + 120\gamma_{13}$$

$$\delta (130)_{13} = \text{Ge} (130) \Delta_{13} + 130\gamma_{13}$$

$$\delta (120)_{68} = \text{Ge} (120) \Delta_{68} + 120\gamma_{68}$$

$$\delta (130)_{68} = \text{Ge} (130) \Delta_{68} + 130\gamma_{68}$$

$$\frac{\delta (120)_{13}}{\delta (120)_{68}} - \frac{\delta (130)_{13}}{\delta (130)_{68}} \propto (13 \text{ Ge} (120) - 12 \text{ Ge} (130)) (\gamma_{68} \Delta_{13} - \gamma_{13} \Delta_{68})$$

Angstrom Scale Forces

Leading Order Standard Model Background: Shift in Electron Cloud x Nuclear Transition

$$\delta (120)_{13} = \text{Ge} (120) \Delta_{13} + 120\gamma_{13}$$

$$\delta (130)_{13} = \text{Ge} (130) \Delta_{13} + 130\gamma_{13}$$

$$\delta (120)_{68} = \text{Ge} (120) \Delta_{68} + 120\gamma_{68}$$

$$\delta (130)_{68} = \text{Ge} (130) \Delta_{68} + 130\gamma_{68}$$

$$\frac{\delta (120)_{13}}{\delta (120)_{68}} - \frac{\delta (130)_{13}}{\delta (130)_{68}} \propto (13 \text{ Ge} (120) - 12 \text{ Ge} (130)) (\gamma_{68} \Delta_{13} - \gamma_{13} \Delta_{68})$$



$$\text{Ge} (120) + \left(\mathcal{O} \left(\frac{m_e}{m_N} \right) \right)^2$$

Angstrom Scale Forces

Leading Order Standard Model Background: Shift in Electron Cloud x Nuclear Transition

$$\delta (120)_{13} = \text{Ge} (120) \Delta_{13} + 120\gamma_{13}$$

$$\delta (130)_{13} = \text{Ge} (130) \Delta_{13} + 130\gamma_{13}$$

$$\delta (120)_{68} = \text{Ge} (120) \Delta_{68} + 120\gamma_{68}$$

$$\delta (130)_{68} = \text{Ge} (130) \Delta_{68} + 130\gamma_{68}$$

$$\frac{\delta (120)_{13}}{\delta (120)_{68}} - \frac{\delta (130)_{13}}{\delta (130)_{68}} \propto (13 \text{ Ge} (120) - 12 \text{ Ge} (130)) (\gamma_{68} \Delta_{13} - \gamma_{13} \Delta_{68})$$



$$\text{Ge} (120) + \left(\mathcal{O} \left(\frac{m_e}{m_N} \right) \right)^2$$

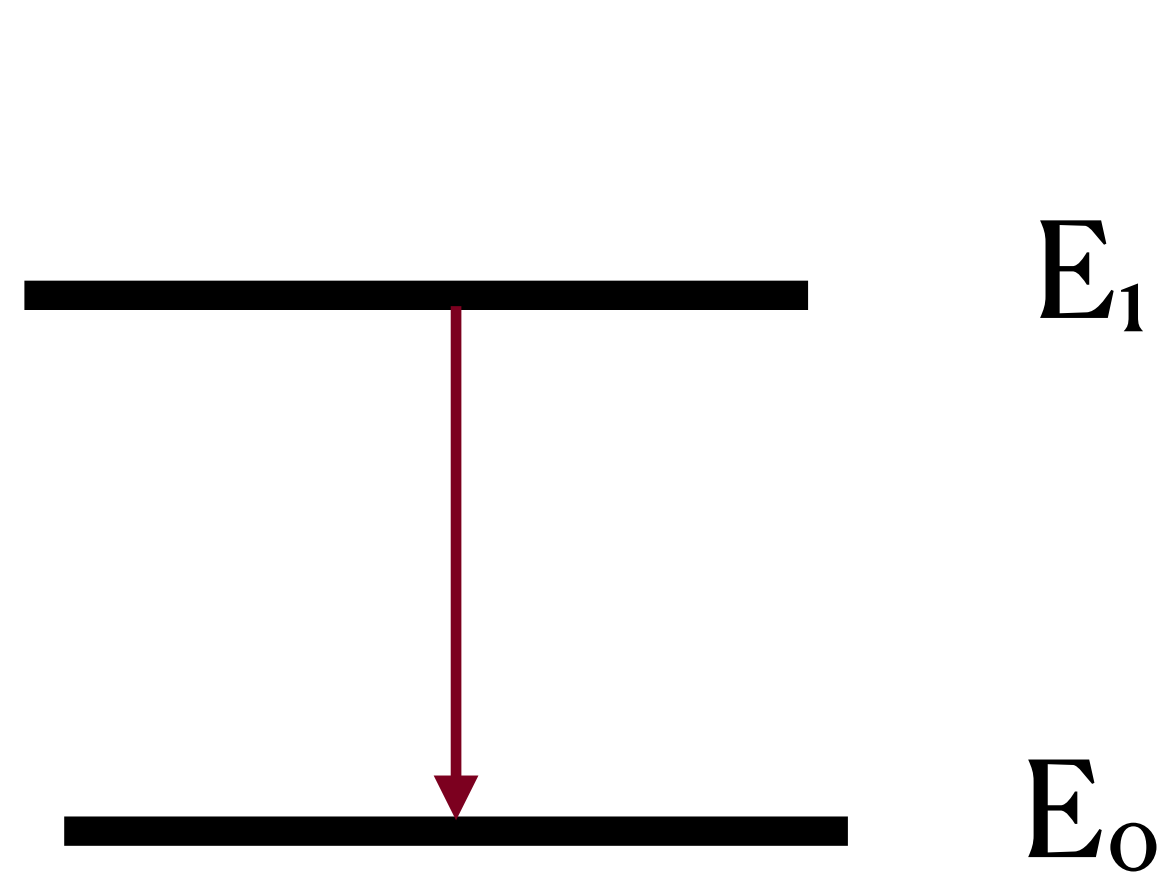
Differential Measurement sensitive to new force - suppressed standard model background

Mossbauer at Synchrotron Source

Well after pulse, state starts to decay

Coherent initial excitation $\Rightarrow$ decays in phase

Decay along forward direction amplified by in phase addition



In phase decay

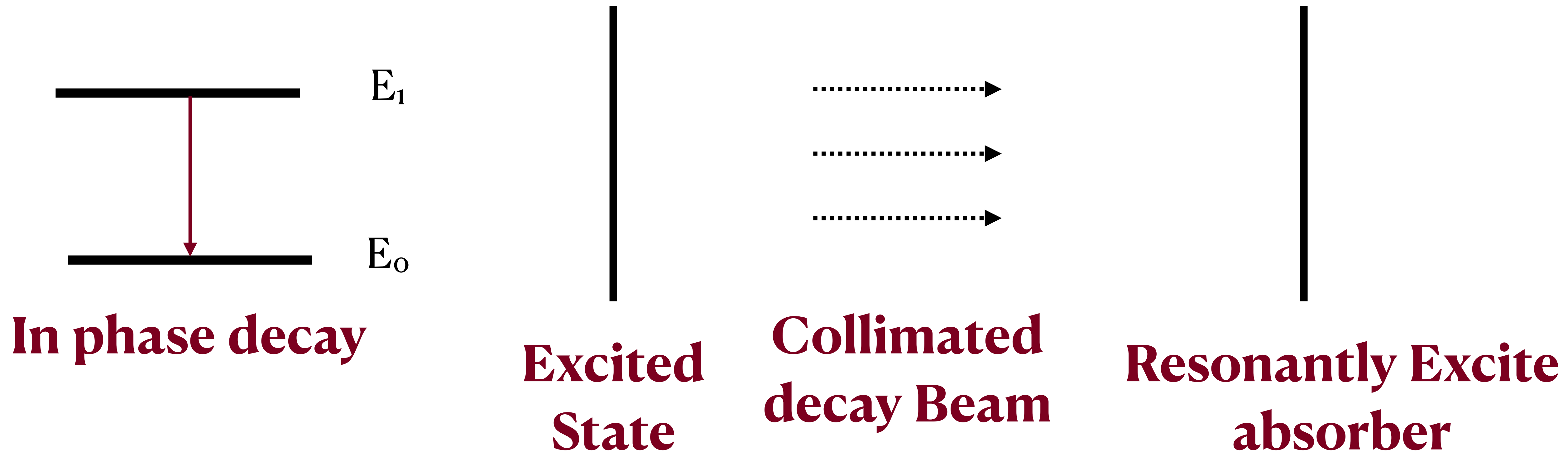
Excited
State

Mossbauer at Synchrotron Source

Well after pulse, state starts to decay

Coherent initial excitation => decays in phase

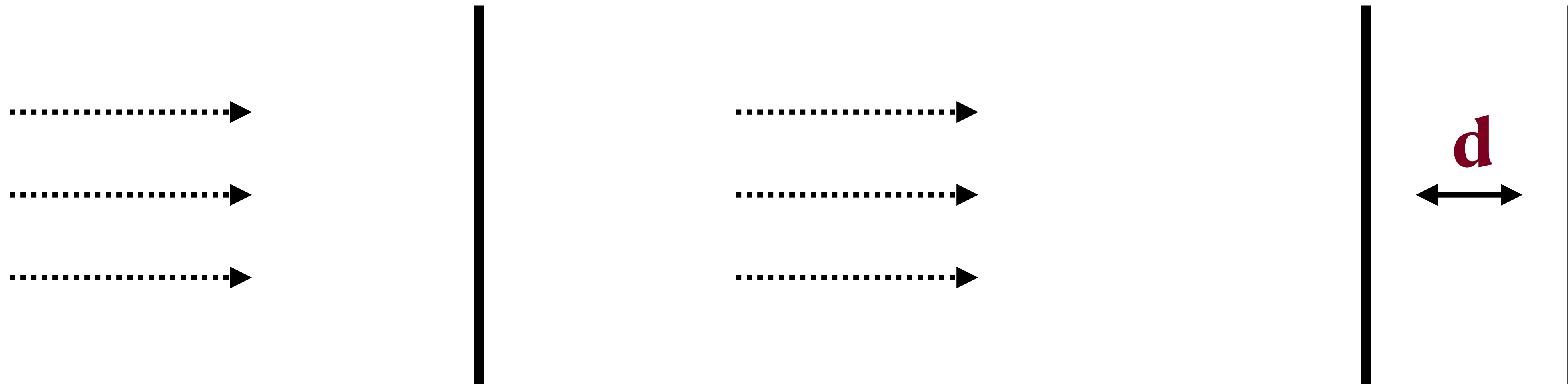
Decay along forward direction amplified by in phase addition



Mossbauer at Synchrotron Source



Mossbauer at Synchrotron Source

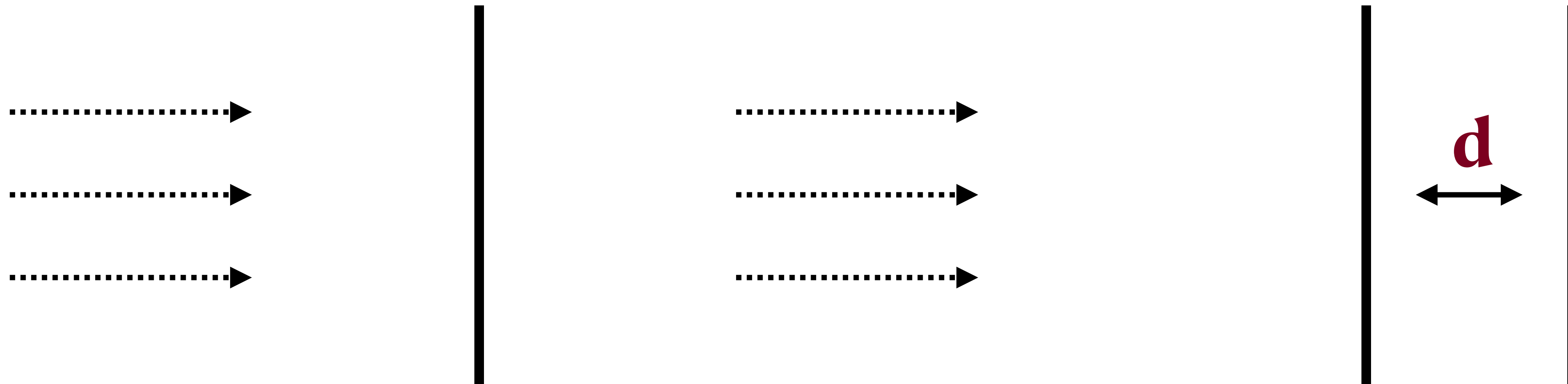


Send Synchrotron Pulse

Well after pulse, collimated emission

Measure resonant reabsorption as a function of d

Mossbauer at Synchrotron Source



Send Synchrotron Pulse

Well after pulse, collimated emission

Measure resonant reabsorption as a function of d

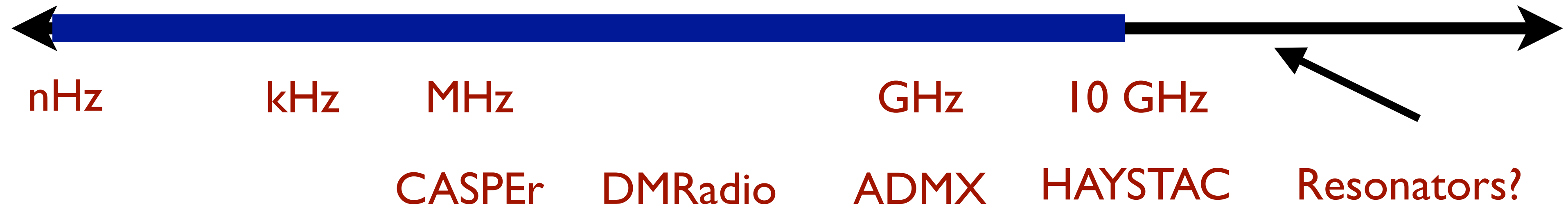
Why?

Clean excitation unlike radioactive decay

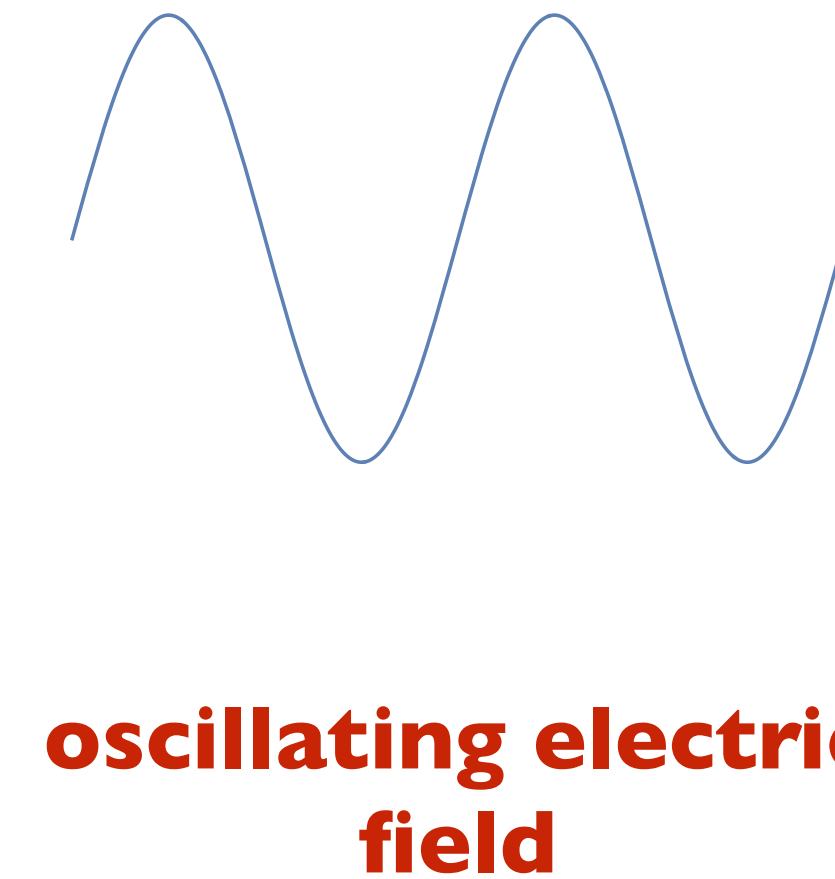
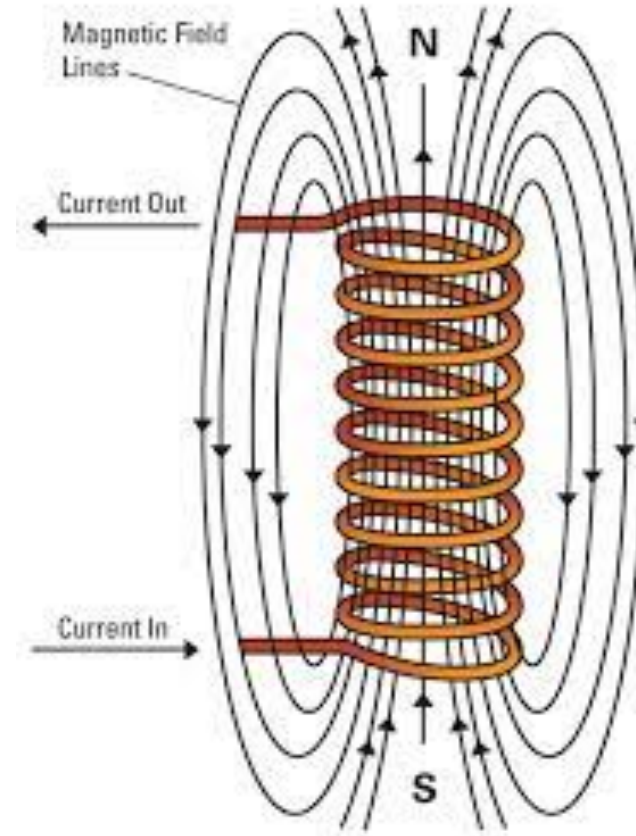
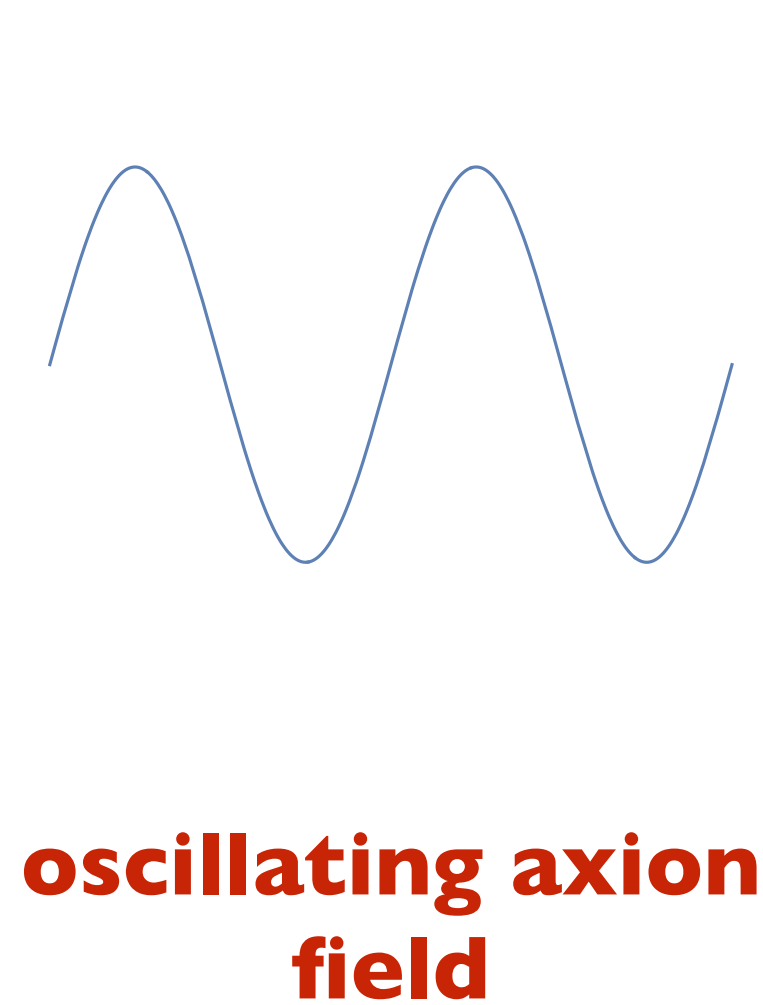
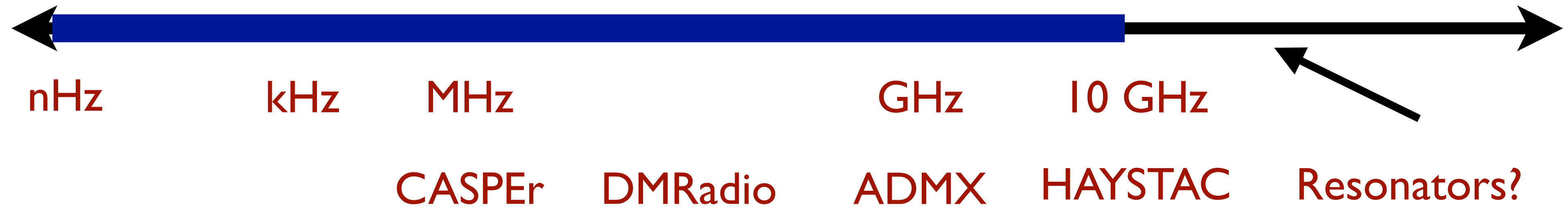
May enable new class of ultra narrow Mossbauer

High Frequency Axion Dark Matter Detection (GALILEO)

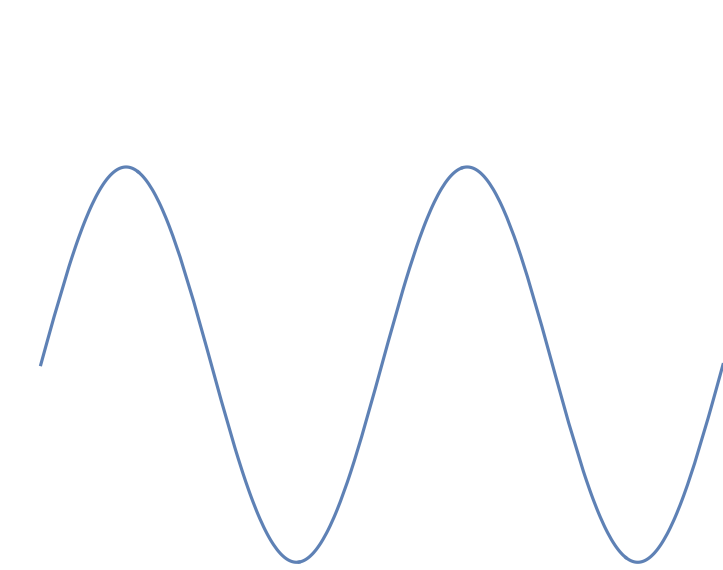
High Frequency Resonators



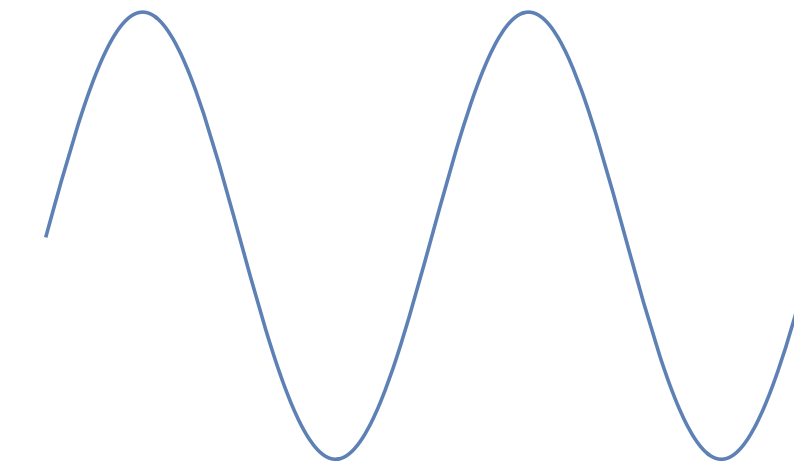
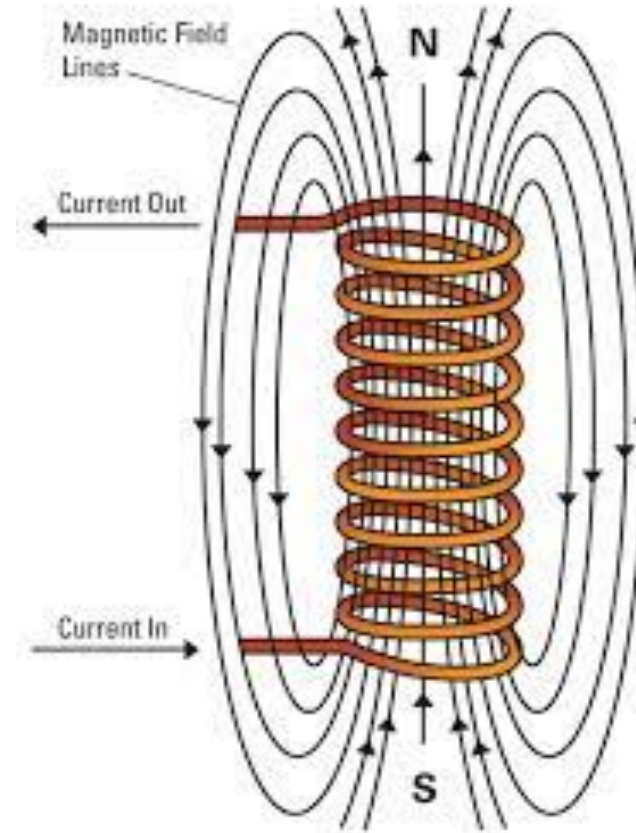
High Frequency Resonators



High Frequency Resonators



**oscillating axion
field**

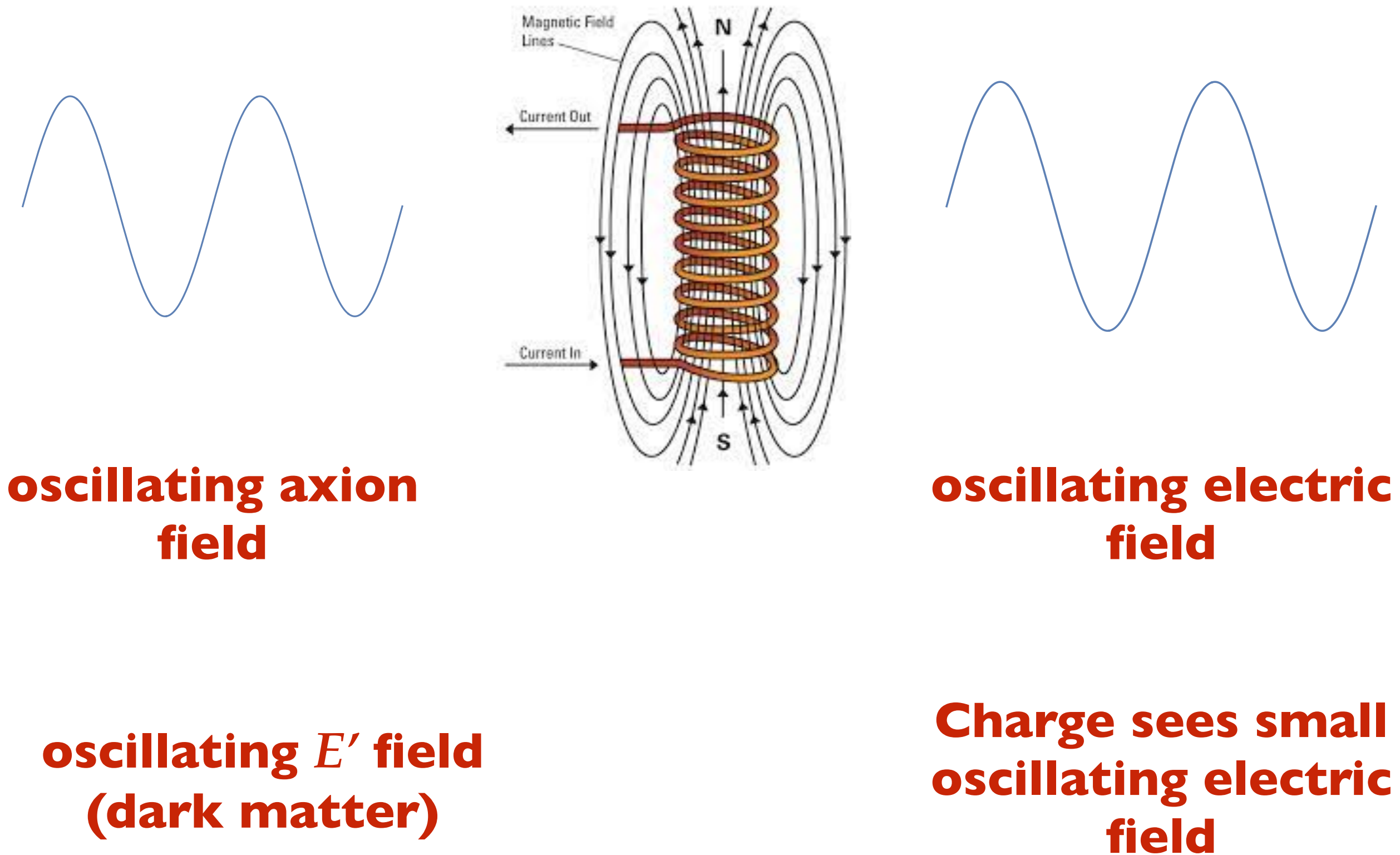


**oscillating electric
field**

**oscillating E' field
(dark matter)**

**Charge sees small
oscillating electric
field**

High Frequency Resonators



Detect high frequency oscillating electric field

Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift

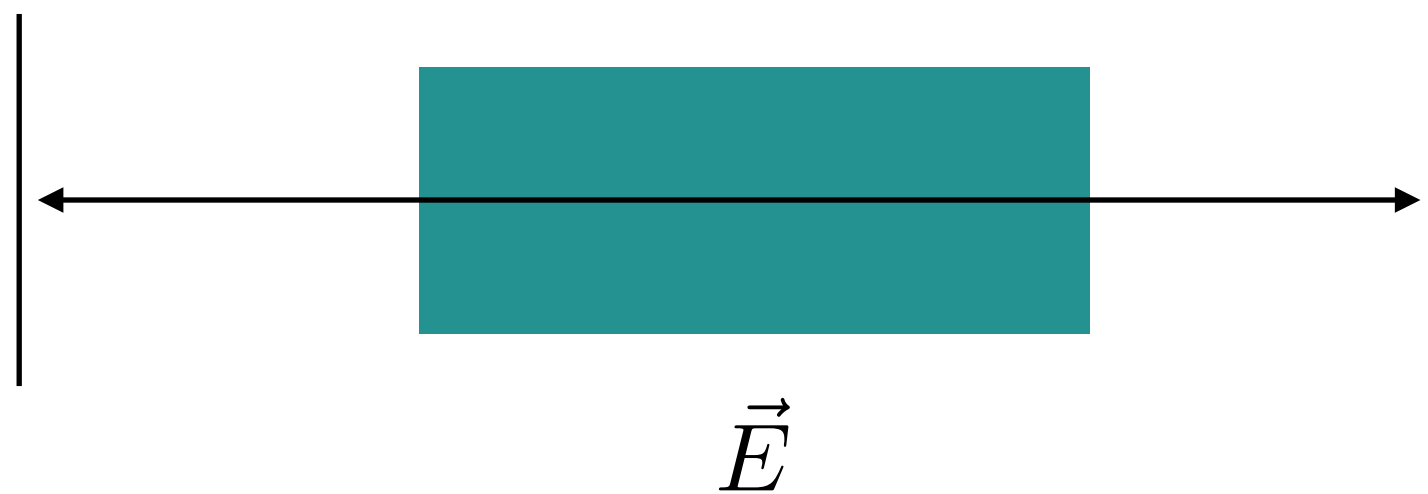
Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift



Phase shift depends on index of refraction -
measures time varying electric field

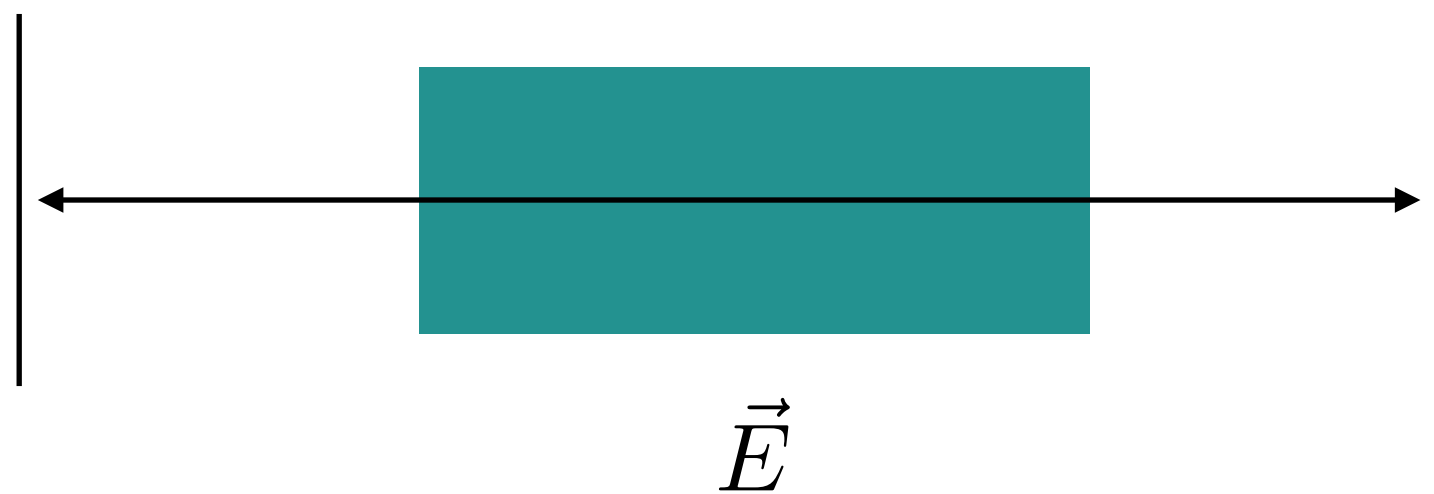
Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift



Phase shift depends on index of refraction -
measures time varying electric field

Lowest frequency set by absorption length of light ($\sim$ km)

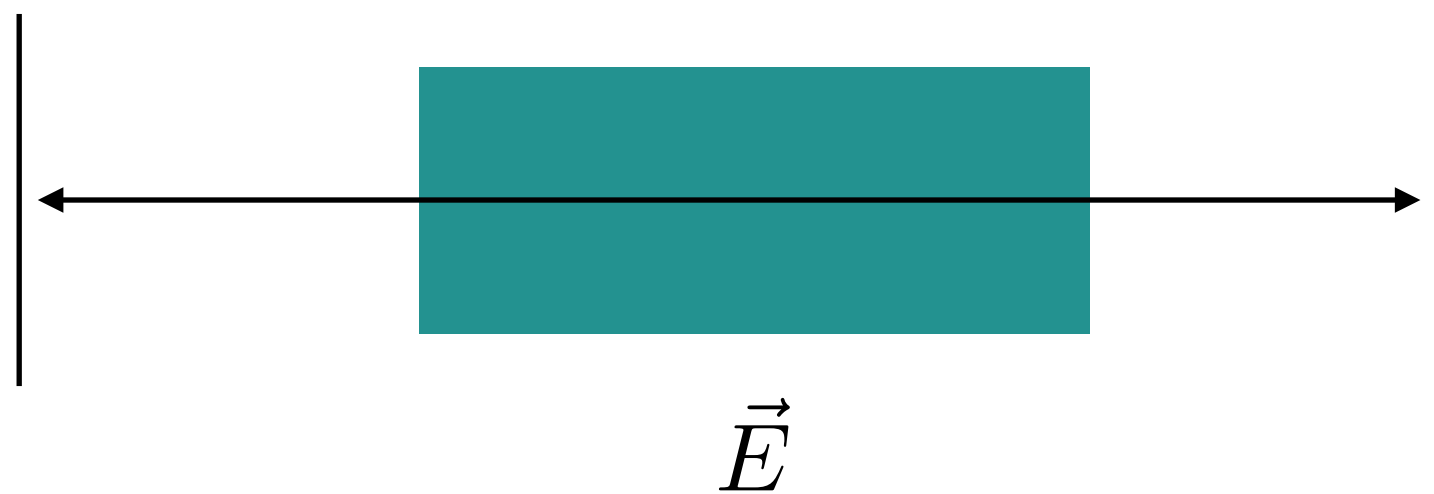
Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift

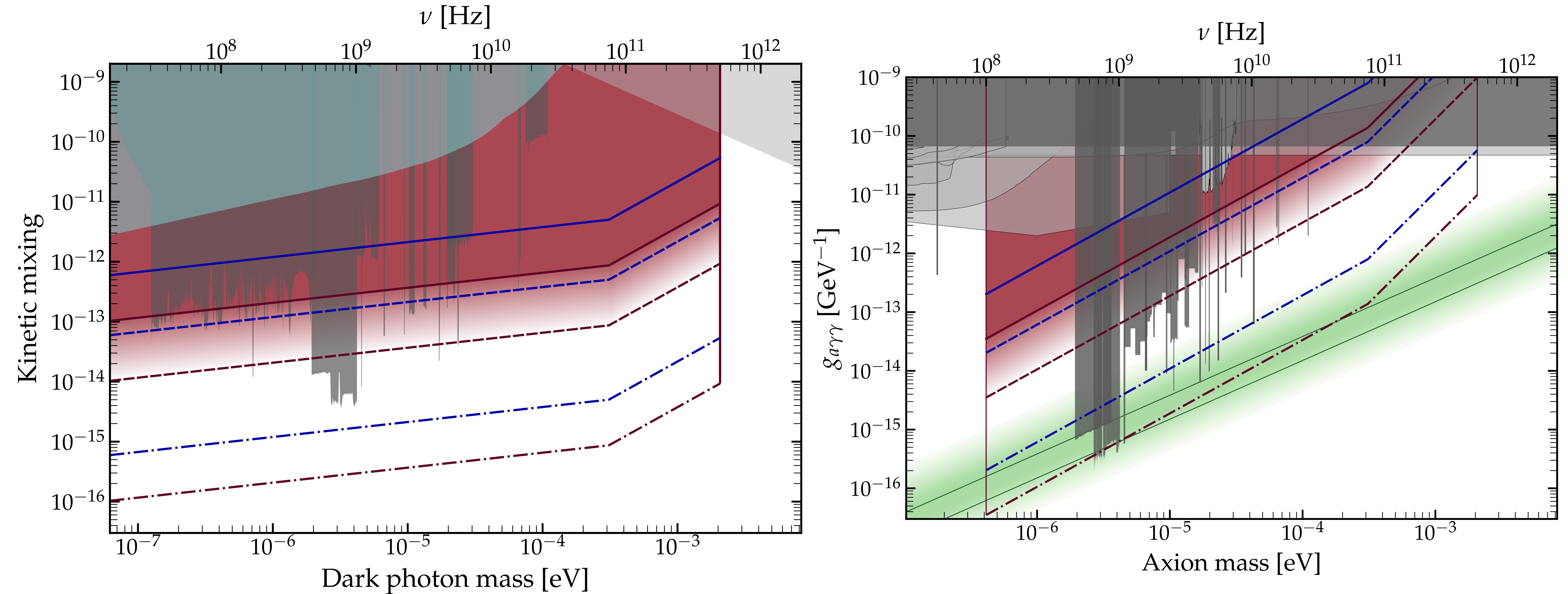


Phase shift depends on index of refraction -
measures time varying electric field

Lowest frequency set by absorption length of light ($\sim$ km)

High frequency cut-off: Nyquist limit, response time of
crystal ($>$ THz)

Projected Sensitivity



Conservative Solid Lines: 1 s averaging
Super aggressive dot dashed: ~ 1 yr
averaging, 10 db Squeezing, 10 W

Conclusions

Conclusions

1. Important to search broad range of couplings and frequencies
2. Exciting opportunities combining nuclear physics + optics

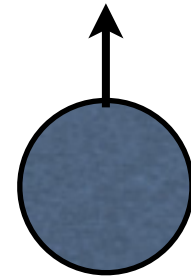
Where are we?

Local Source



$$g\phi\bar{\Psi}\Psi$$

Monopole Source



$$\frac{\partial_\mu \phi}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi$$

Spin Sensor

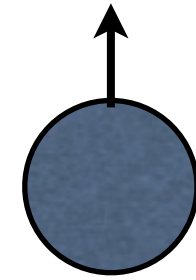
Where are we?

Local Source



$$g\phi\bar{\Psi}\Psi$$

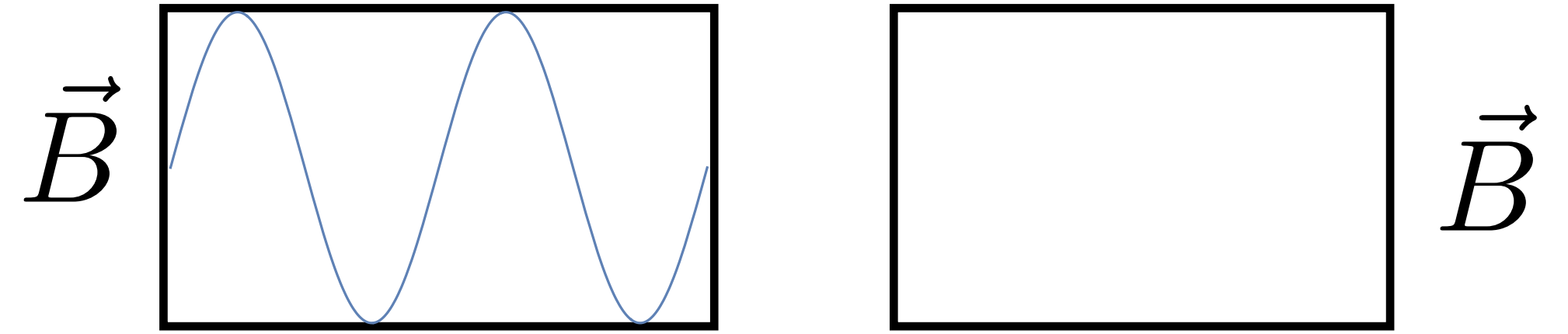
Monopole Source



$$\frac{\partial_\mu \phi}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi$$

Spin Sensor

$$\frac{\phi}{f_a} F \tilde{F}$$



Light Shining Through a Wall

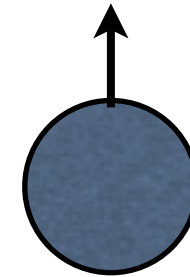
Where are we?

Local Source



$$g\phi\bar{\Psi}\Psi$$

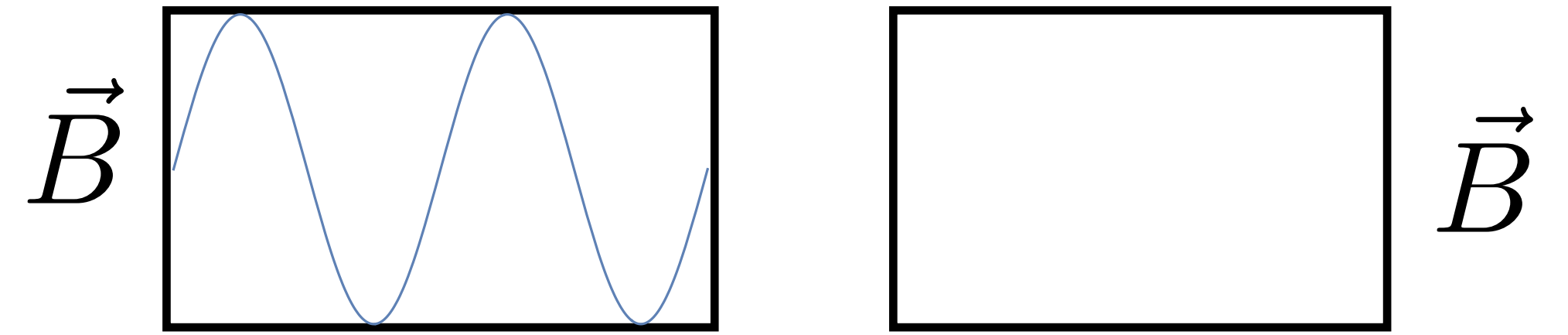
Monopole Source



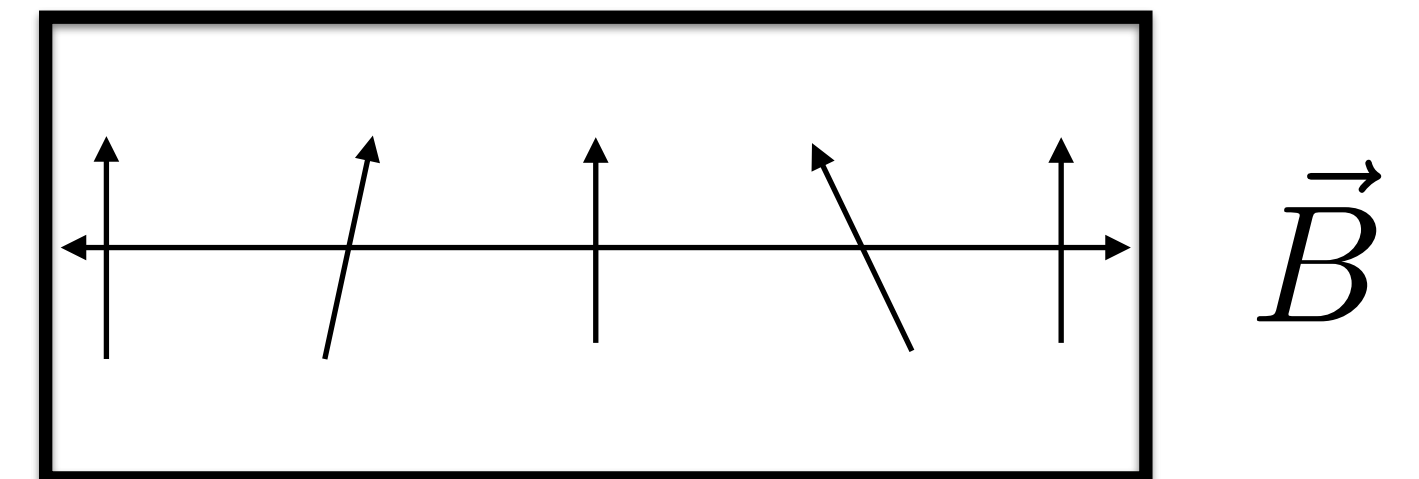
$$\frac{\partial_\mu \phi}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi$$

Spin Sensor

$$\frac{\phi}{f_a} F \tilde{F}$$



Light Shining Through a Wall



Polarization Rotation
(Spin Sensor)

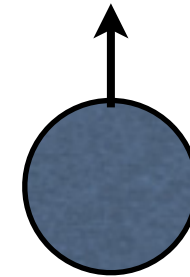
Where are we?

Local Source



$$g\phi\bar{\Psi}\Psi$$

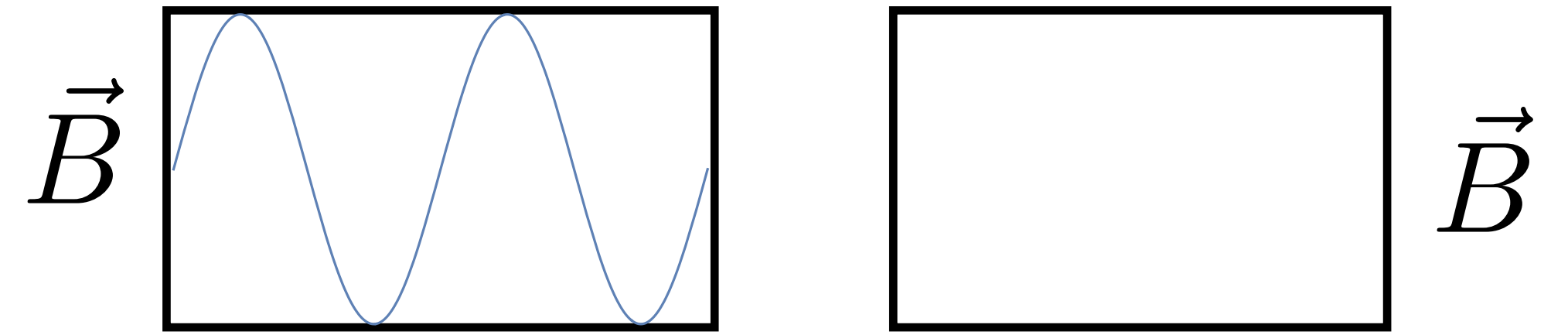
Monopole Source



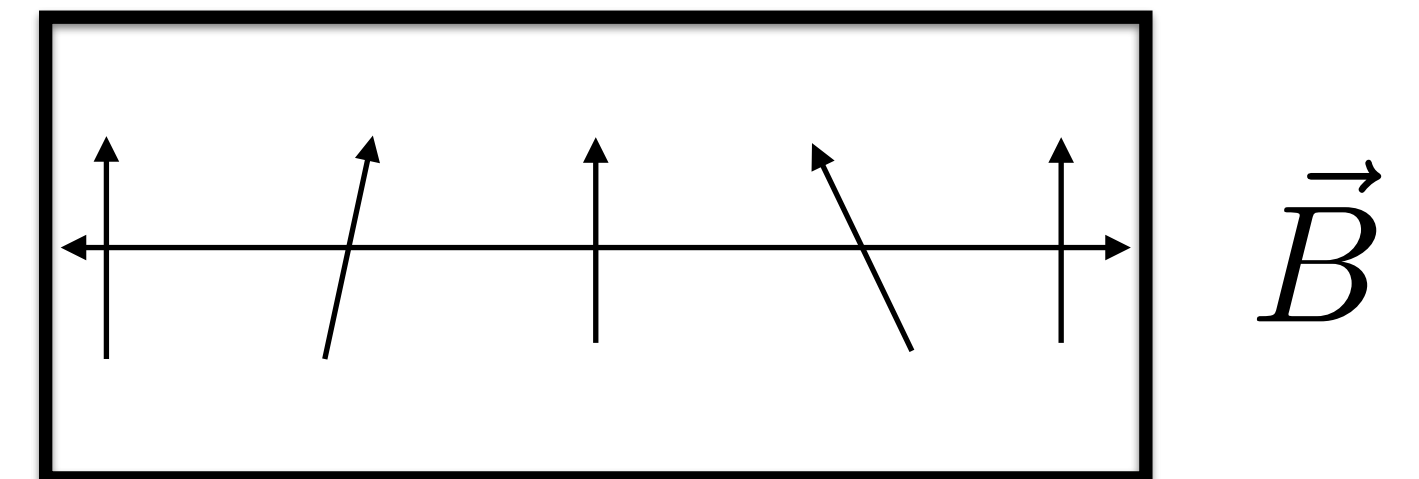
$$\frac{\partial_\mu \phi}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi$$

Spin Sensor

$$\frac{\phi}{f_a} F \tilde{F}$$



Light Shining Through a Wall



Polarization Rotation
(Spin Sensor)

New opportunities?

Acceleration Search using Atom Interferometers (MAGIS)

New Opportunities

Local Source

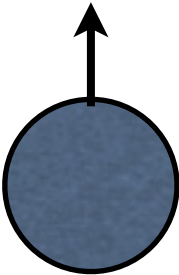


ϕ

ϕ

$$g\phi\bar{\Psi}\Psi$$

Monopole Source



$$\frac{\partial_\mu \phi}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi$$

Spin Sensor

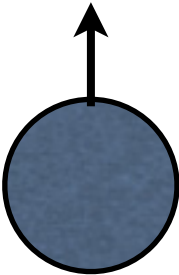
New Opportunities

Local Source



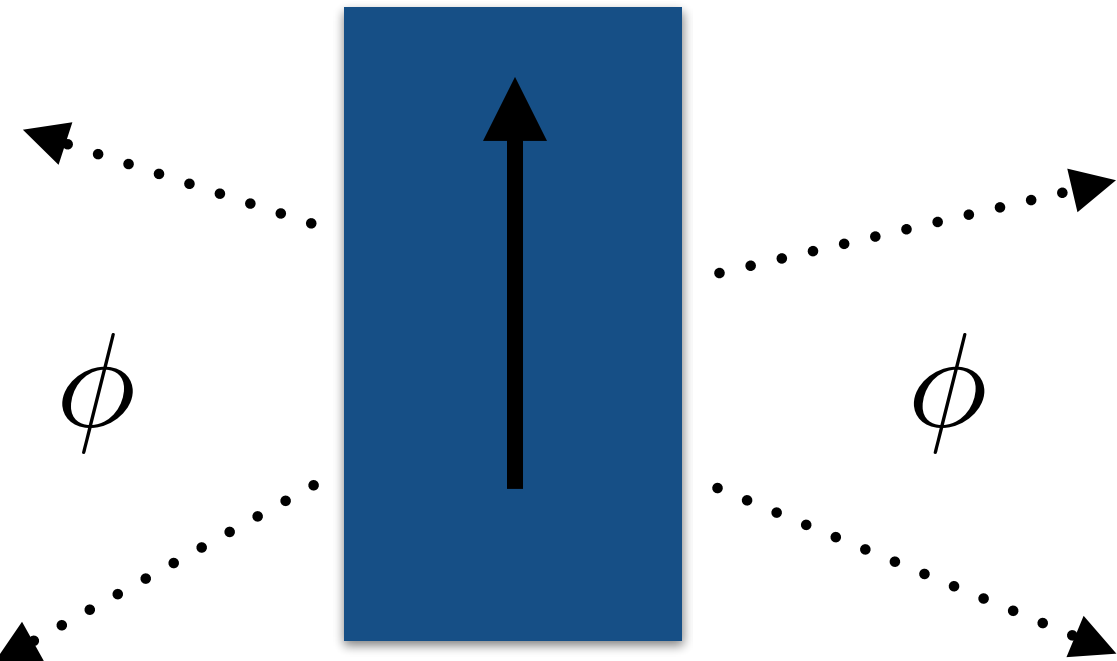
$$g\phi\bar{\Psi}\Psi$$

Monopole Source

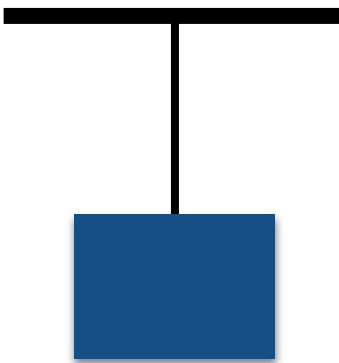


$$\frac{\partial_\mu \phi}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi$$

Spin Sensor



Dipole Source

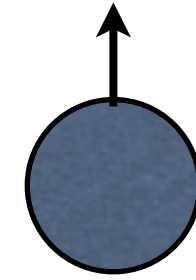


Monopole Sensor

Monopole Dipole Forces

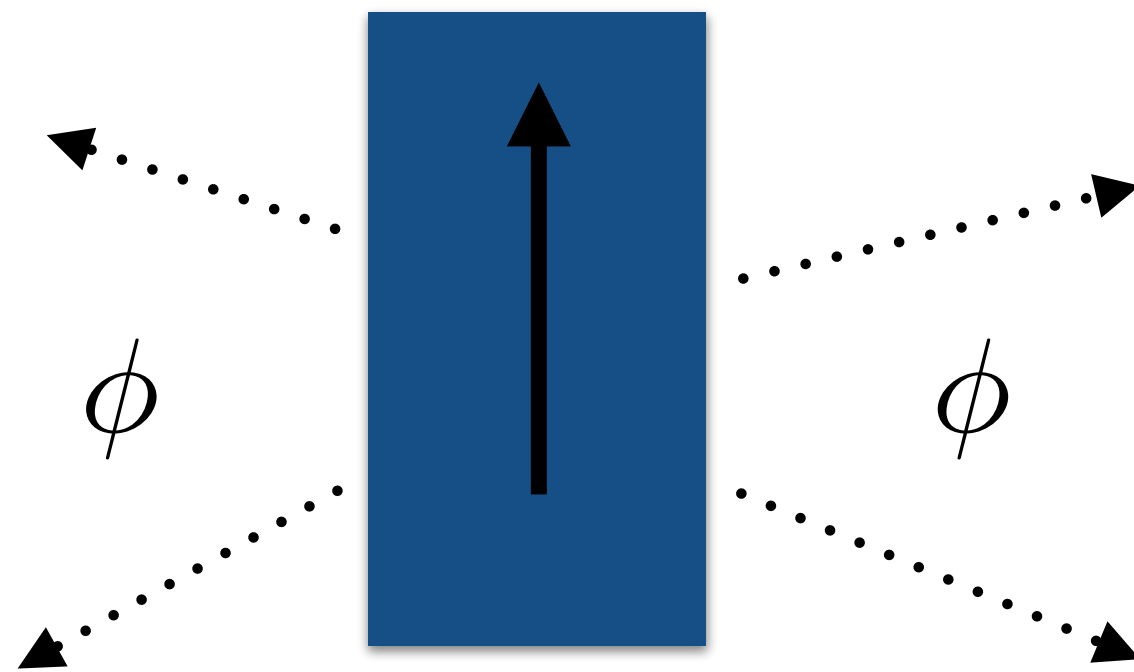


Monopole Source

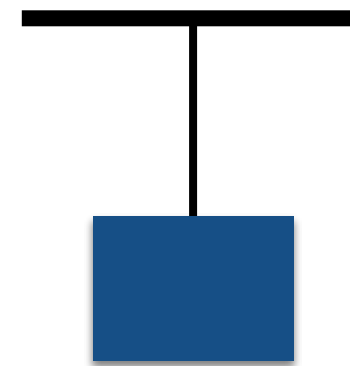


Spin Sensor

$$\delta\phi = \Delta ET$$



Dipole Source



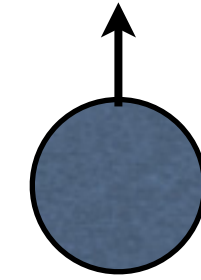
Monopole Sensor

$$\delta\phi = kaT^2$$

Monopole Dipole Forces

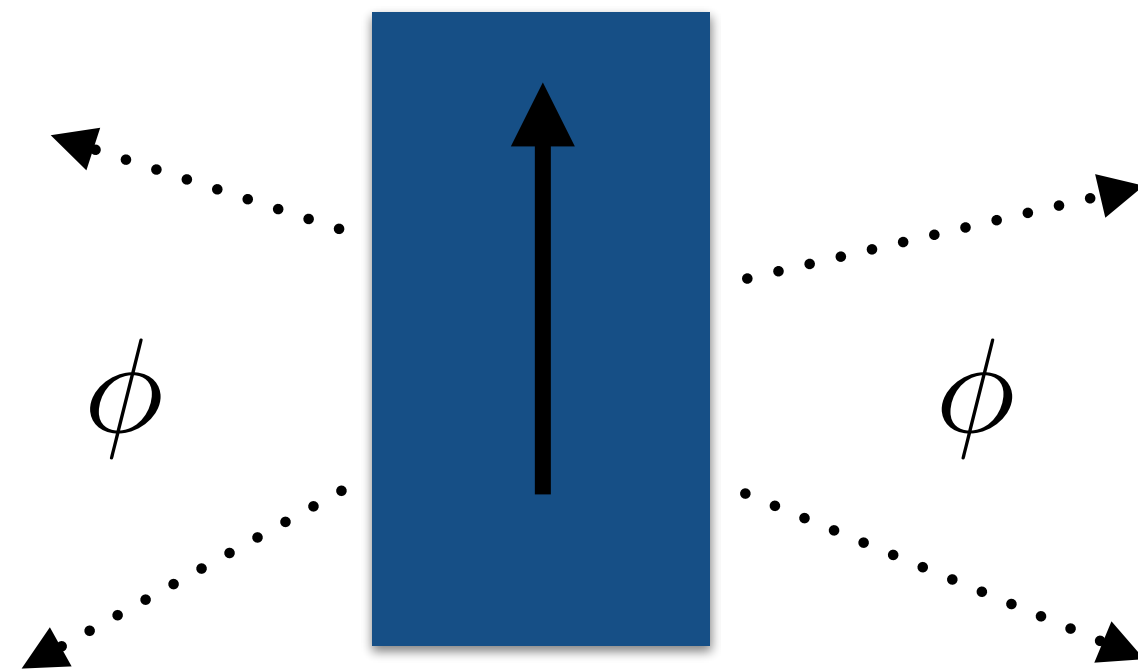


Monopole Source

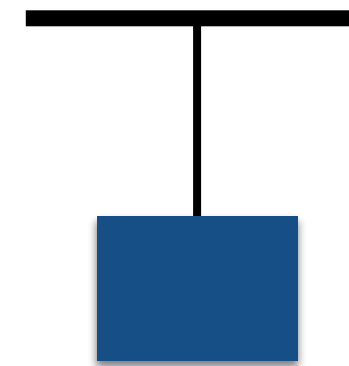


Spin Sensor

$$\delta\phi = \Delta ET$$



Dipole Source



Monopole Sensor

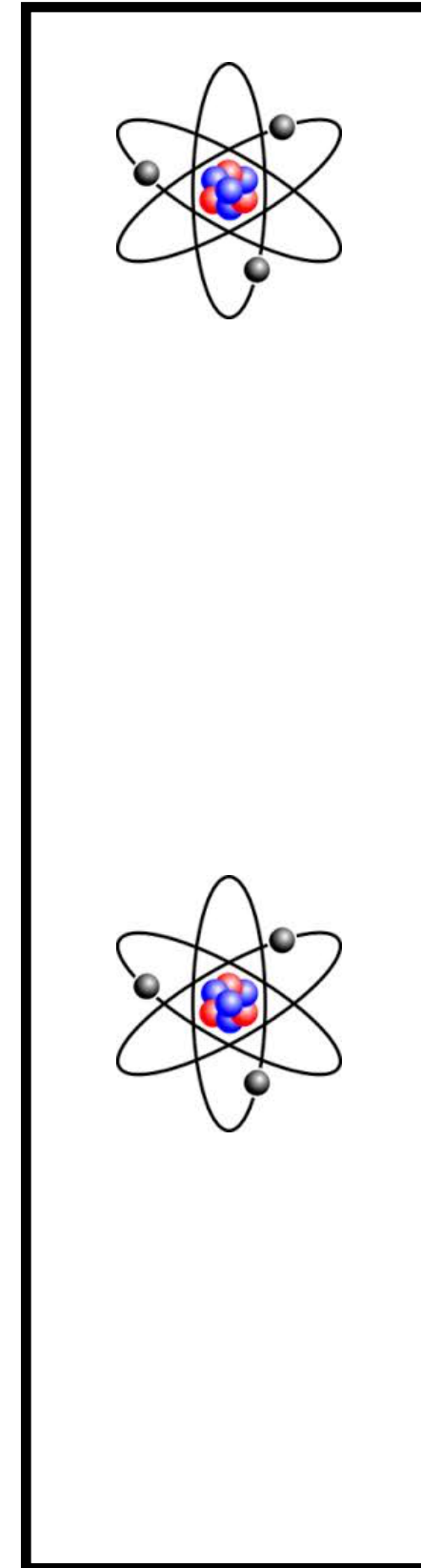
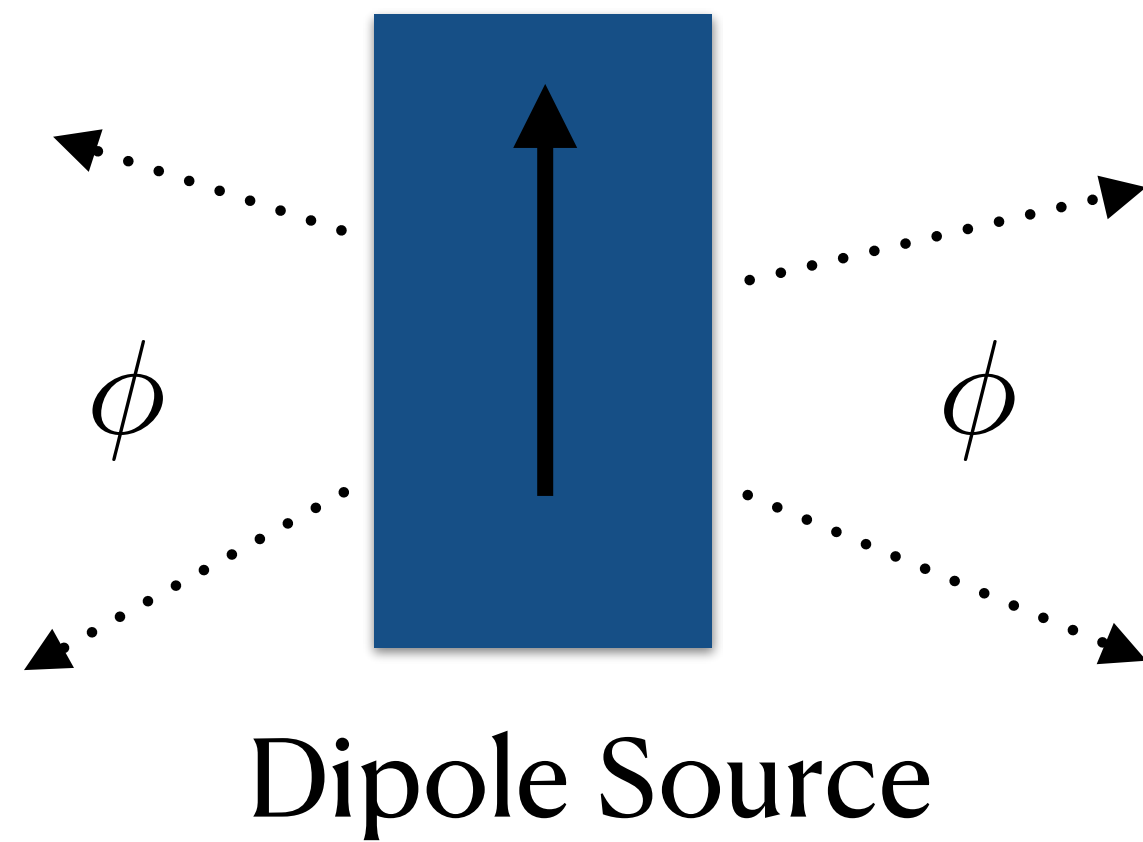
$$\delta\phi = kaT^2$$

Accelerometers gain with T

For macroscopic masses, limited by vibration and thermal noise

Use free falling atoms!

Monopole Dipole Forces



Freely Falling Atom Gradiometer

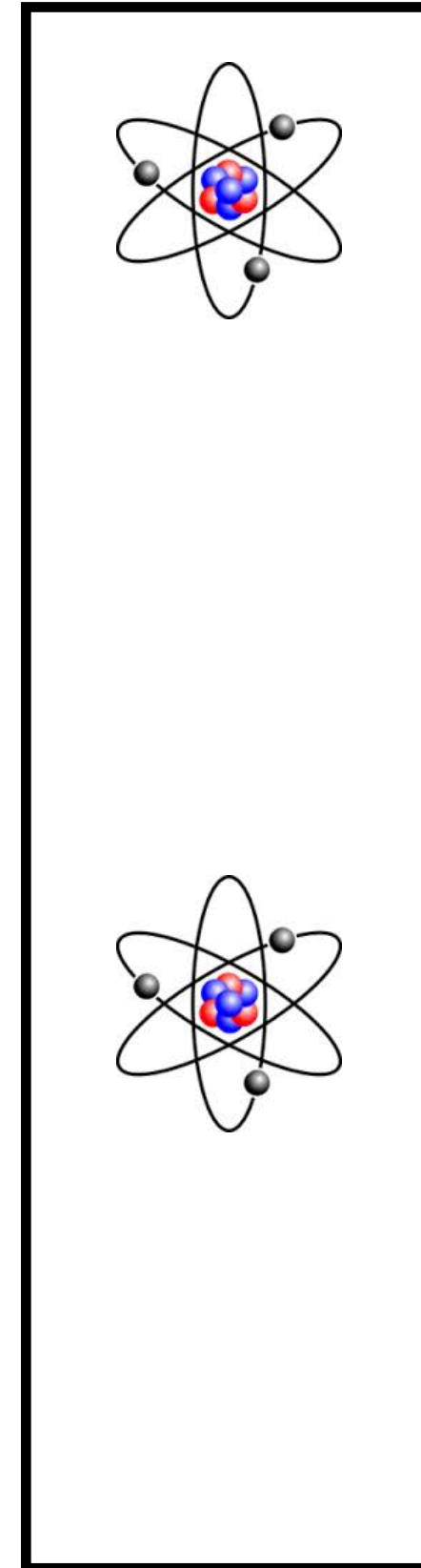
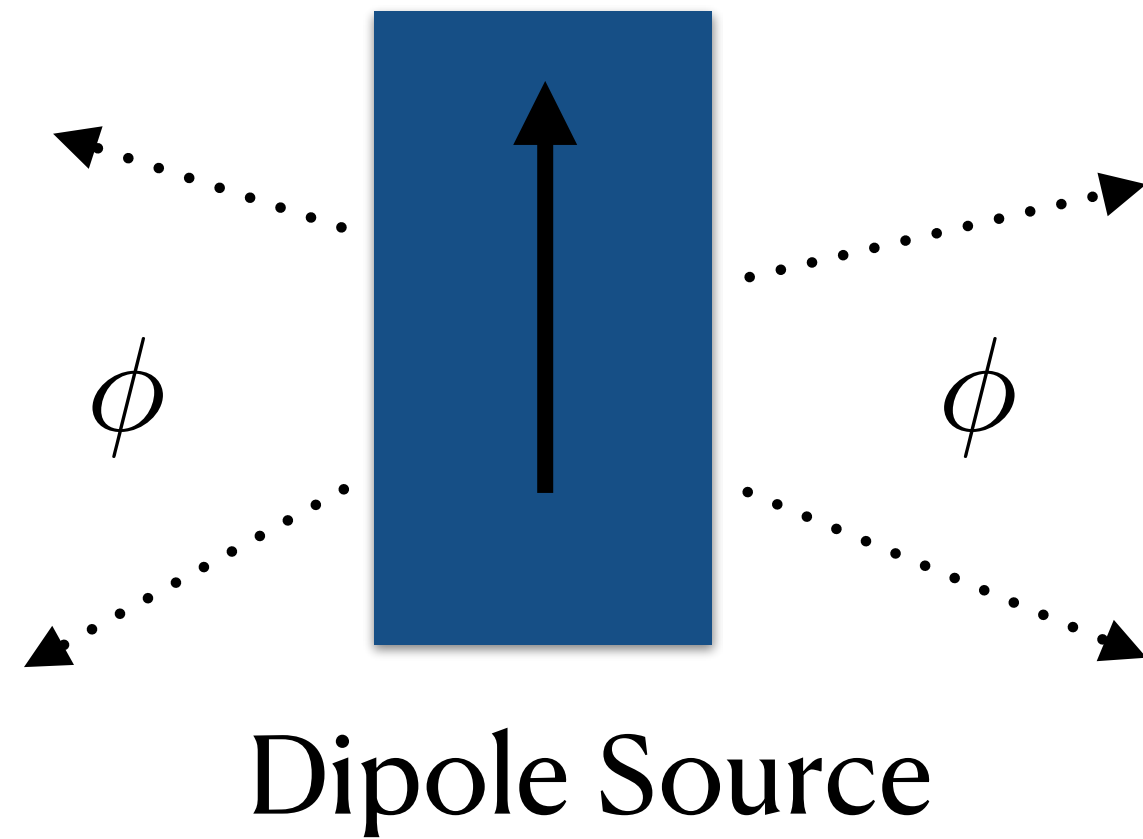
Atoms are vibrationally decoupled
Operate using magnetically
insensitive states or atomic
comagnetometer

Using modern atom optics, can get
atoms to bounce

Can obtain $T \sim 1$ s (or more)

Axion range ~ 10 cm - set by size of atom cloud

Monopole Dipole Forces



Freely Falling Atom Gradiometer

Atoms are vibrationally decoupled
Operate using magnetically
insensitive states or atomic
comagnetometer

Using modern atom optics, can get
atoms to bounce

Can obtain $T \sim 1$ s (or more)

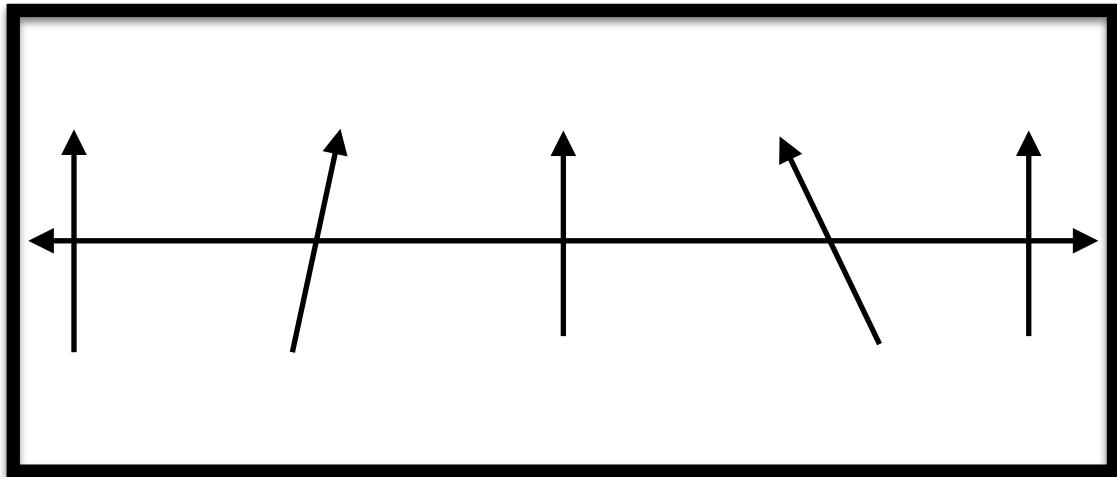
Axion range ~ 10 cm - set by size of atom cloud

$$g_e g_N \sim 10^{-28} - 10^{-32}$$

Photon Polarization Search (MAGPI)

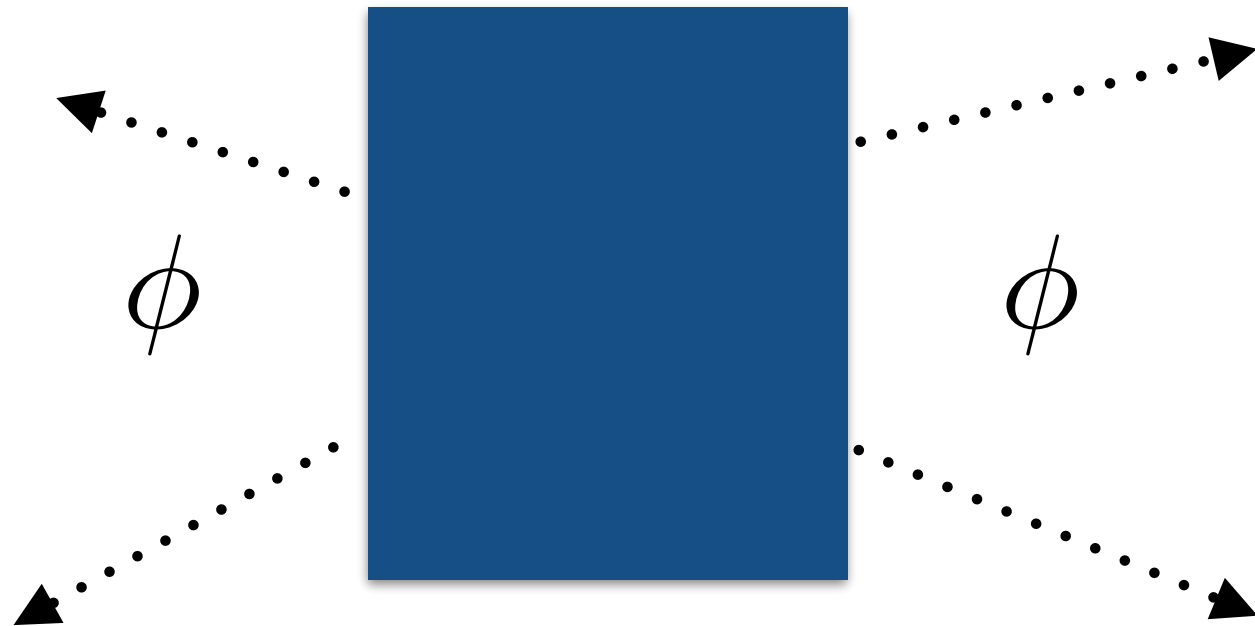
New Opportunities

Local Source



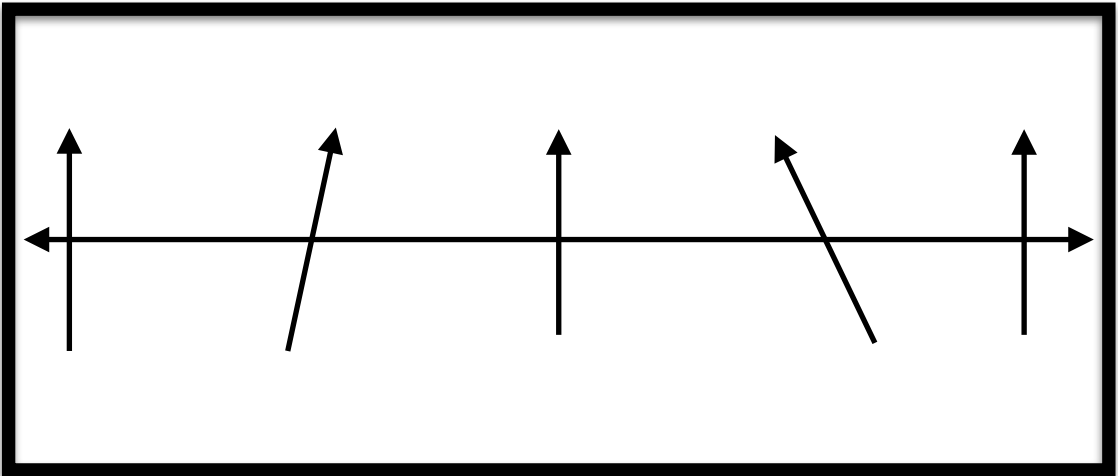
$$\vec{B}$$

Polarization Rotation
(Spin Sensor)



$$g\phi\bar{\Psi}\Psi$$

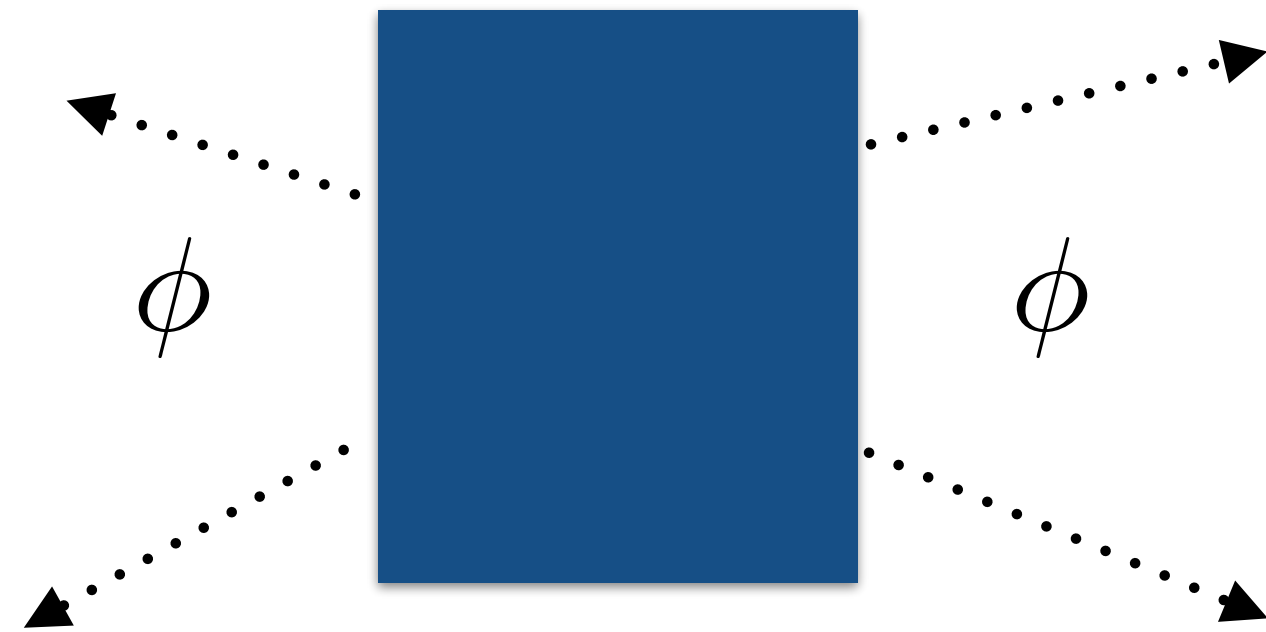
Monopole Source



$$\frac{\phi}{f_a} F \tilde{F}$$

Polarization Rotation
(Spin Sensor)

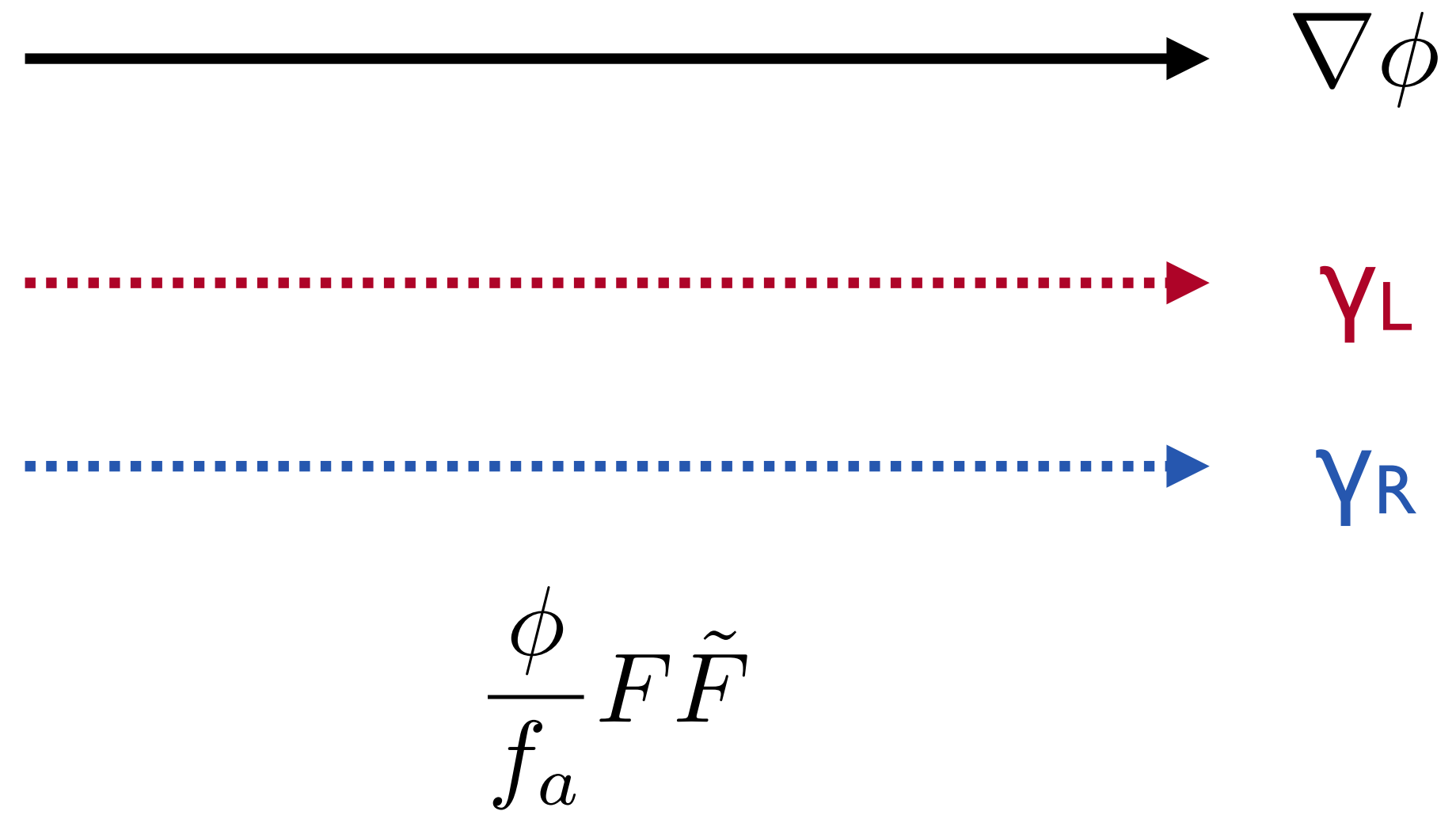
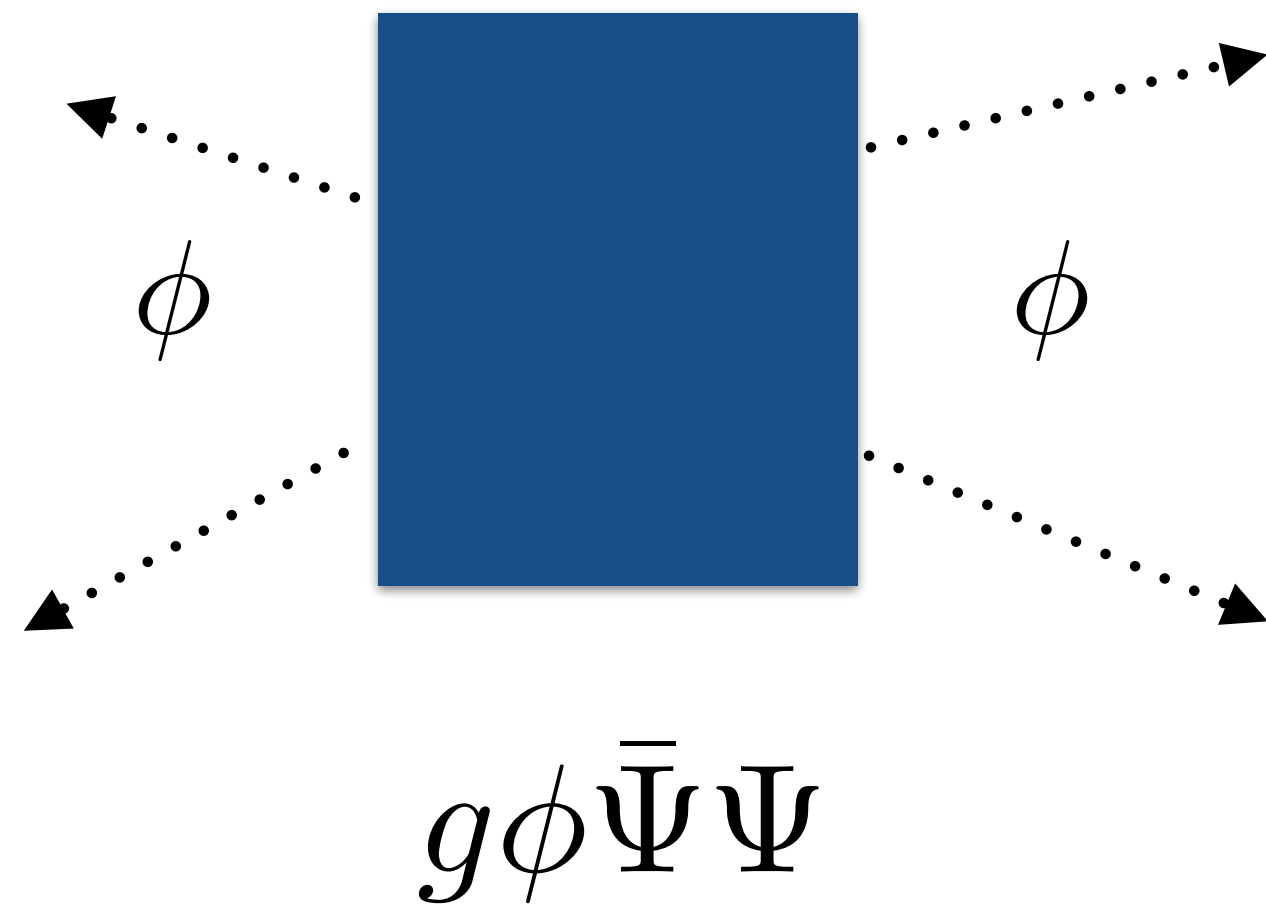
Photon Polarization Search



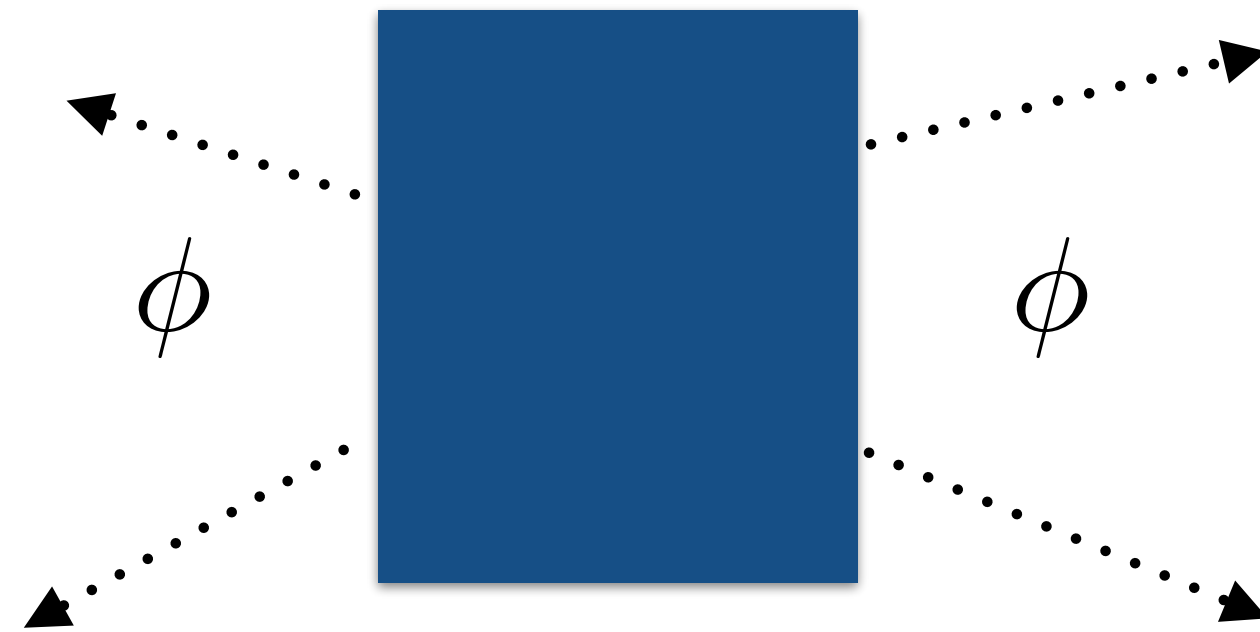
$$g\phi\bar{\Psi}\Psi$$

A diagram showing a scalar particle ϕ (dashed line with arrows) interacting with a gradient $\nabla\phi$ (solid line with an arrow).

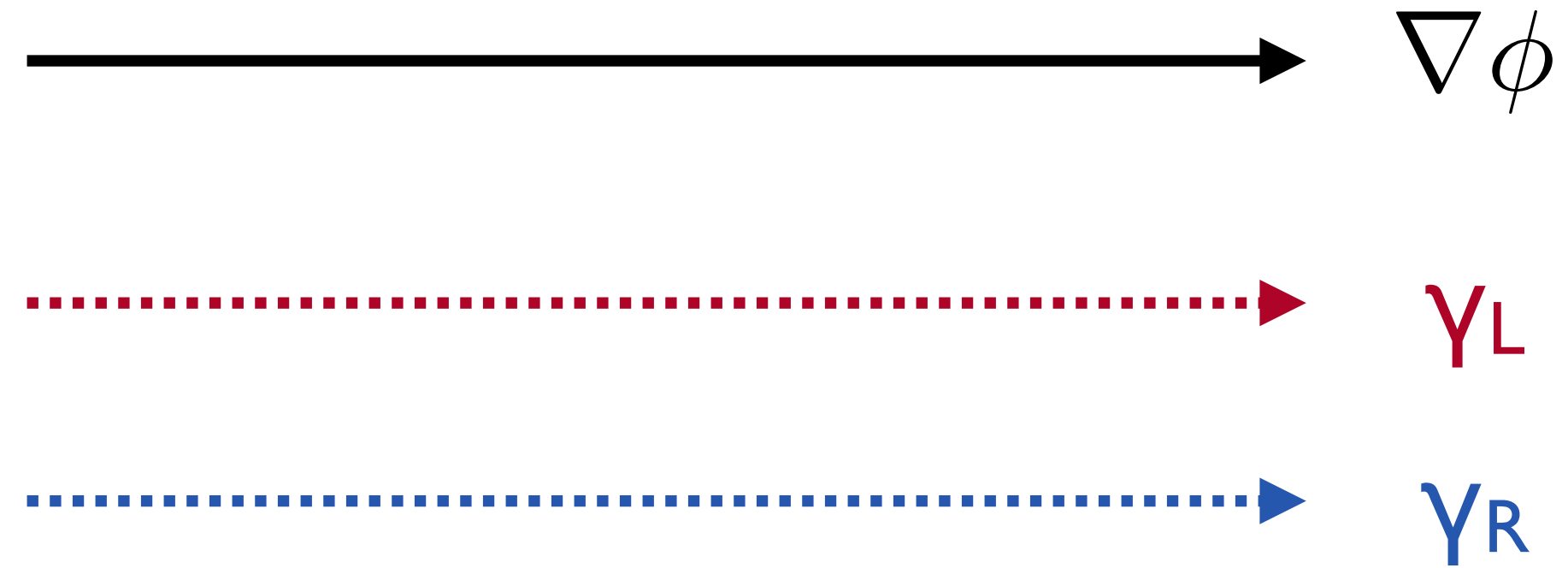
Photon Polarization Search



Photon Polarization Search



$$g\phi\bar{\Psi}\Psi$$

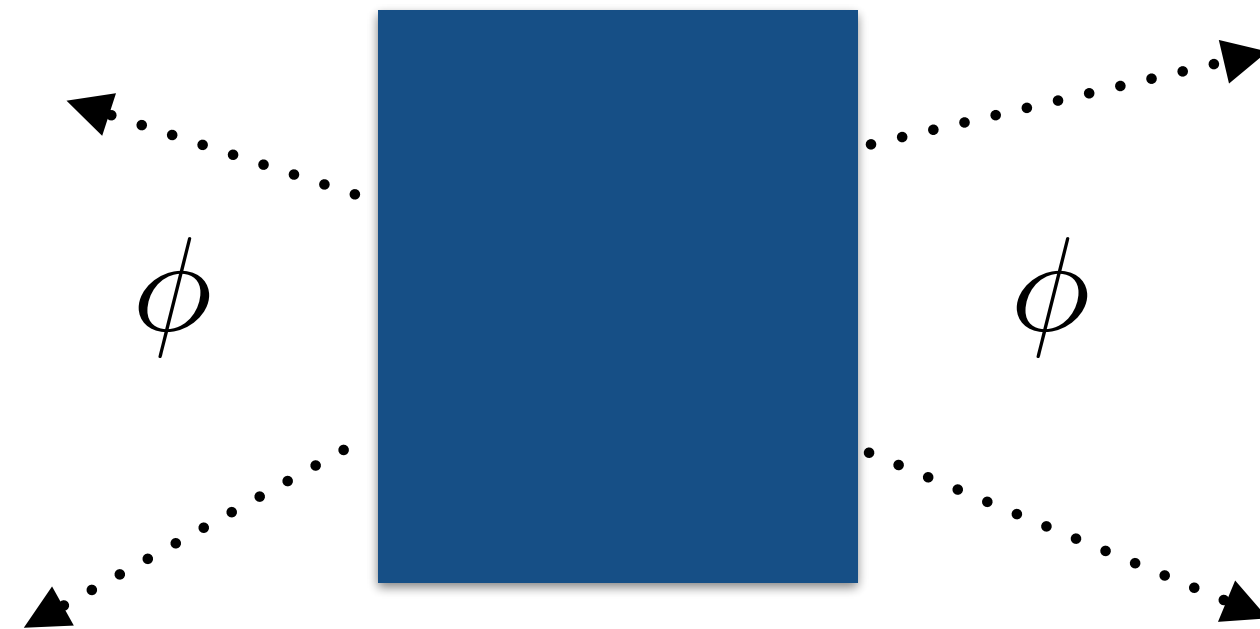


$$\frac{\phi}{f_a} F \tilde{F}$$

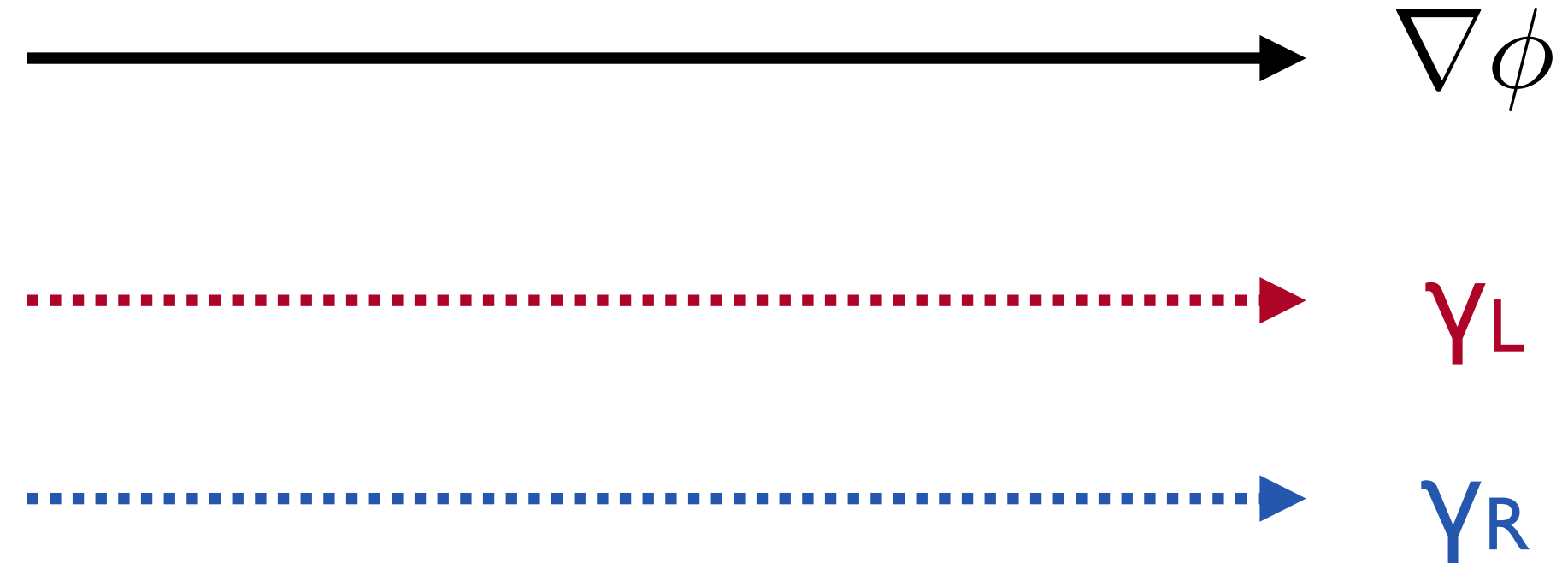
$$\delta k = k_L - k_R = \frac{\nabla\phi}{f_a}$$

Frequency Independent

Photon Polarization Search



$$g\phi\bar{\Psi}\Psi$$



$$\frac{\phi}{f_a} F \tilde{F}$$

$$\delta k = k_L - k_R = \frac{\nabla \phi}{f_a}$$

Frequency Independent

Measure Interferometrically

$$\delta \phi = \delta k L$$

Setup

$$\delta k = k_L - k_R = \frac{\nabla \phi}{f_a}$$

$$\delta \phi = \delta k L$$

Want large L

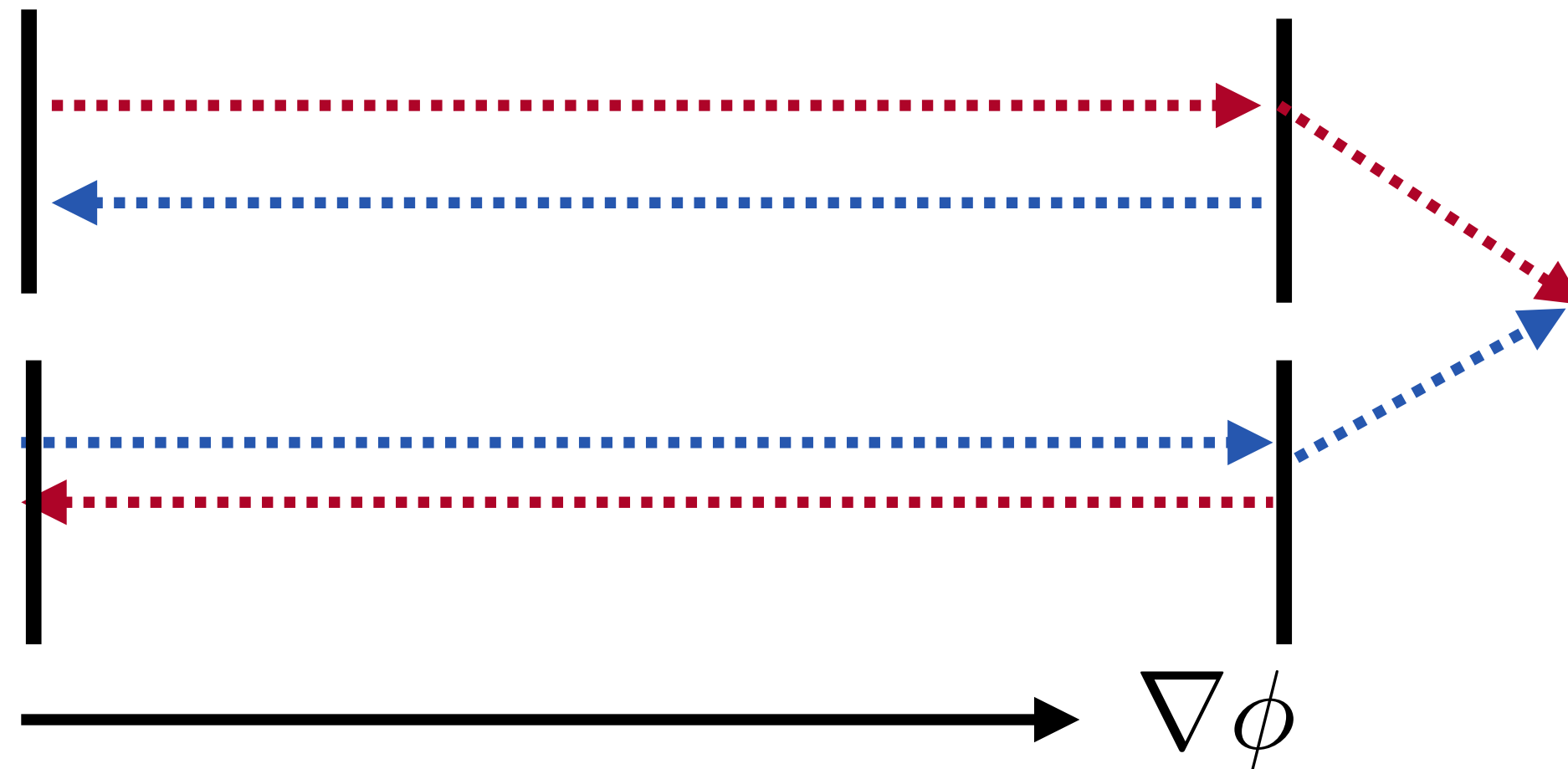
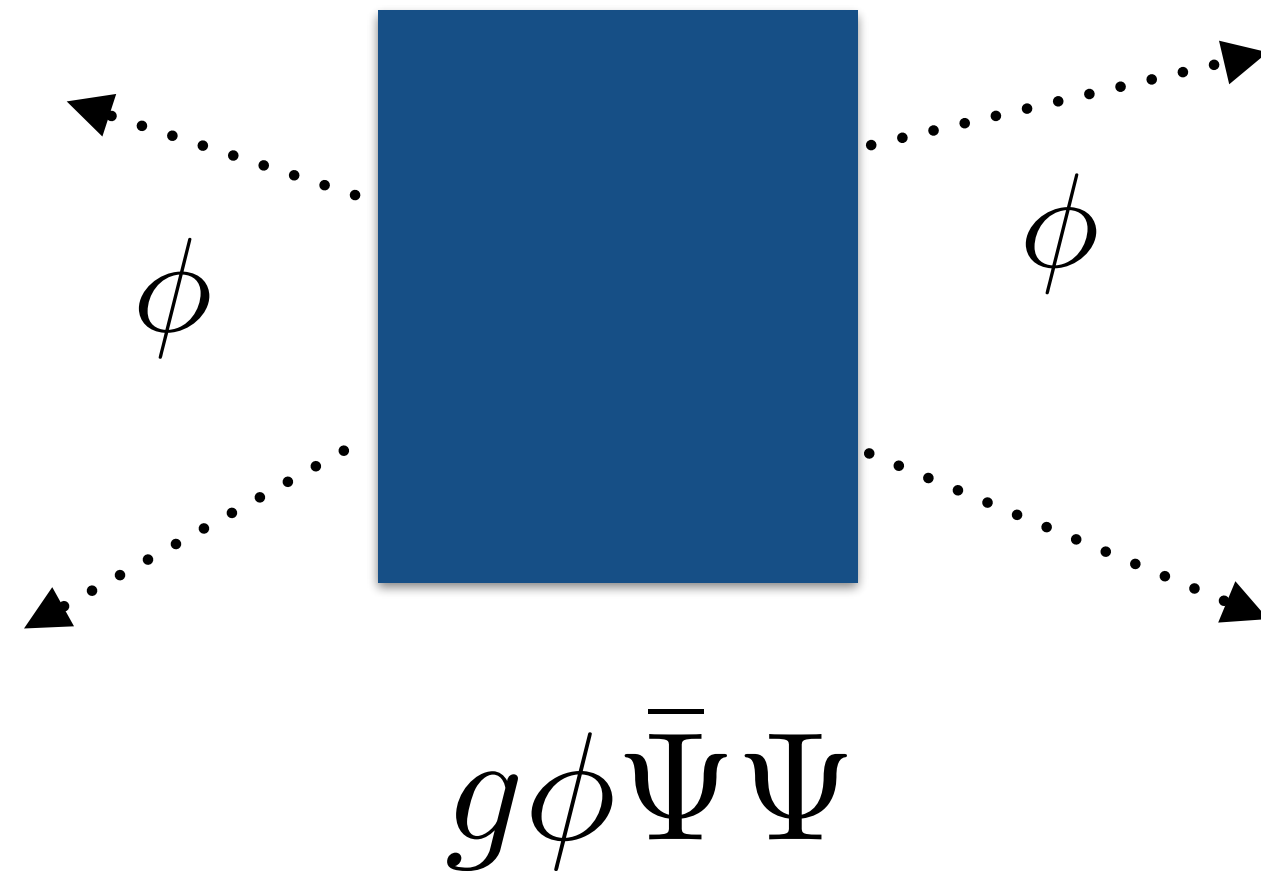
Setup

$$\delta k = k_L - k_R = \frac{\nabla \phi}{f_a}$$

$$\delta \phi = \delta k L$$

Want large L

Trap light in Fabry Perot cavity, compare phase shift
between left and right circularly polarized light



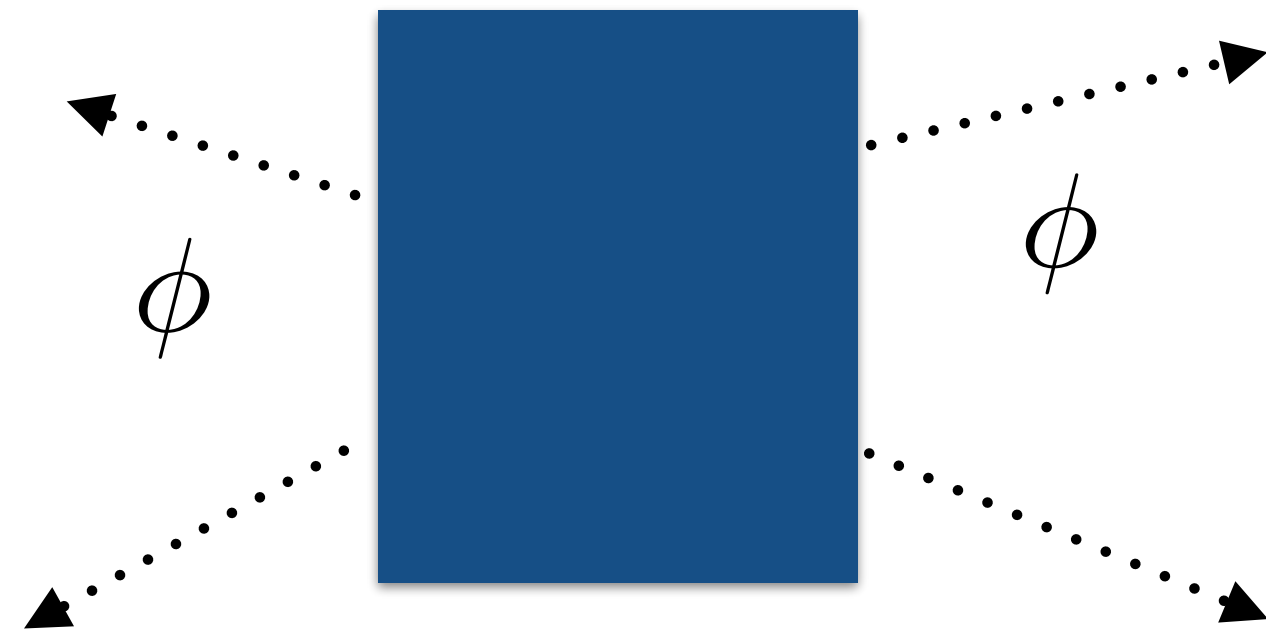
Setup

$$\delta k = k_L - k_R = \frac{\nabla \phi}{f_a}$$

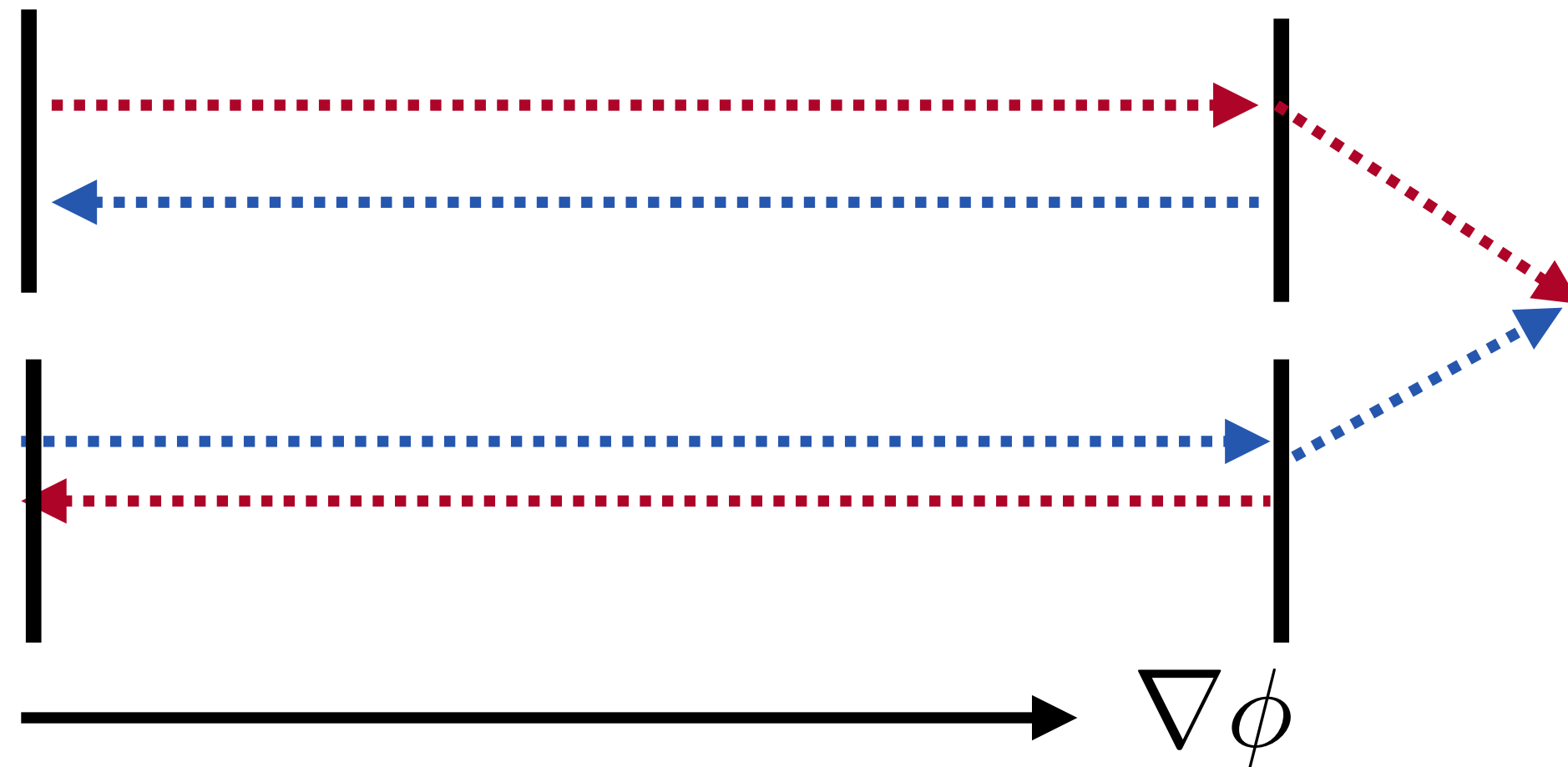
$$\delta \phi = \delta k L$$

Want large L

Trap light in Fabry Perot cavity, compare phase shift
between left and right circularly polarized light

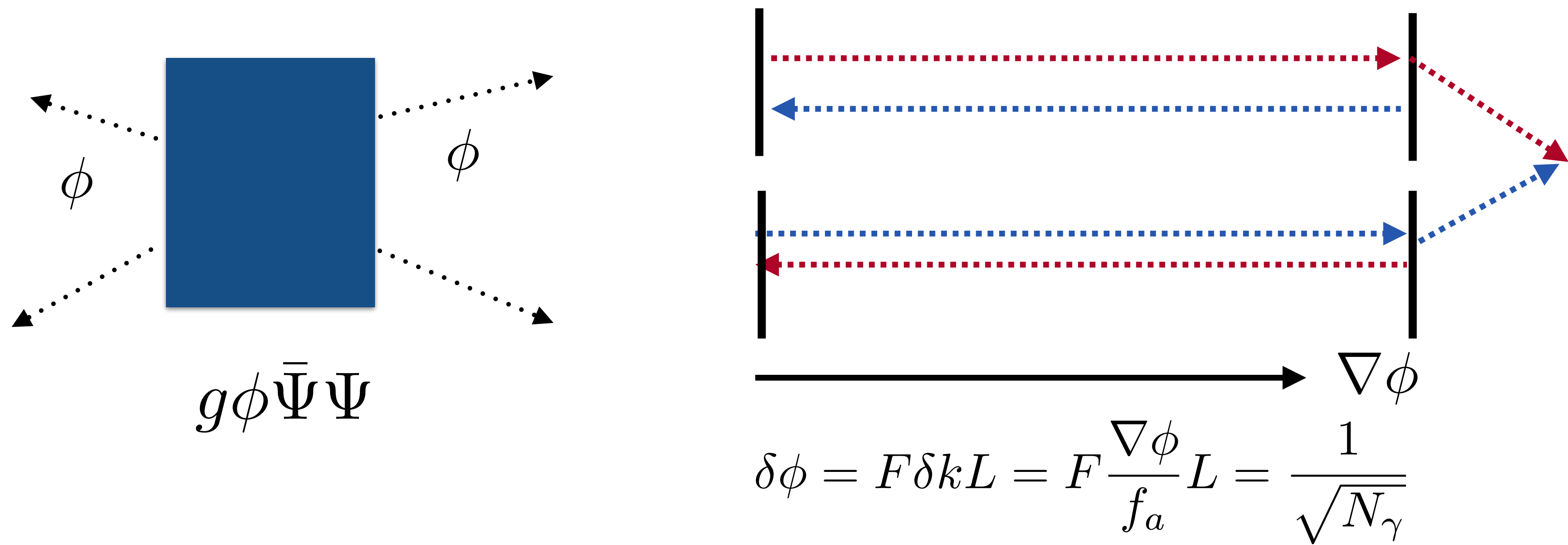


$$g\phi\bar{\Psi}\Psi$$



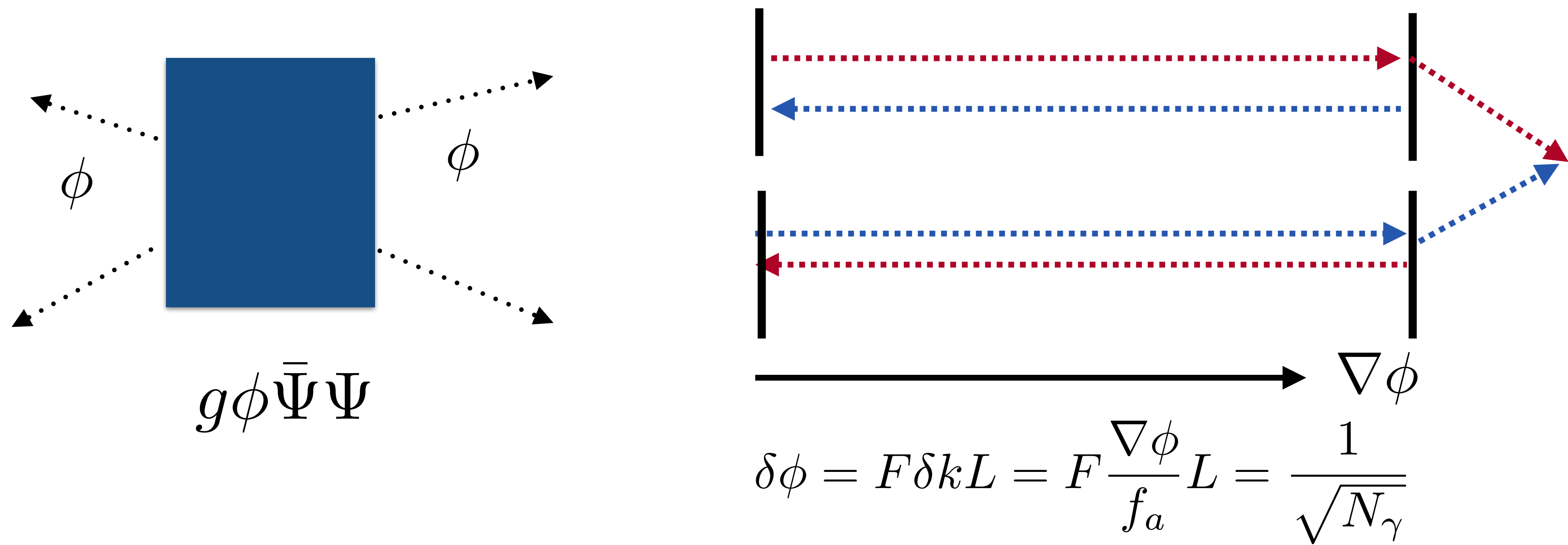
$$\delta \phi = F \delta k L = F \frac{\nabla \phi}{f_a} L = \frac{1}{\sqrt{N_\gamma}}$$

Experimental Realization



Independent of frequency - can realize in optical or superconducting RF

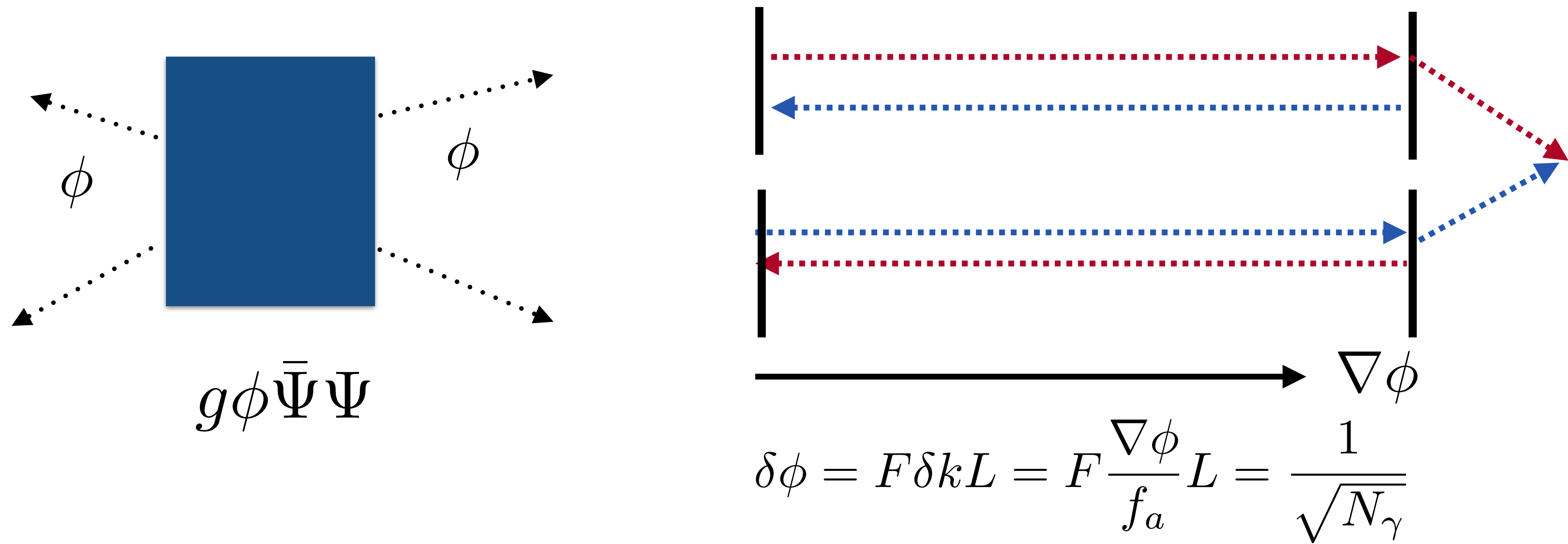
Experimental Realization



Independent of frequency - can realize in optical or superconducting RF

Optical: Smaller mirrors, lower F

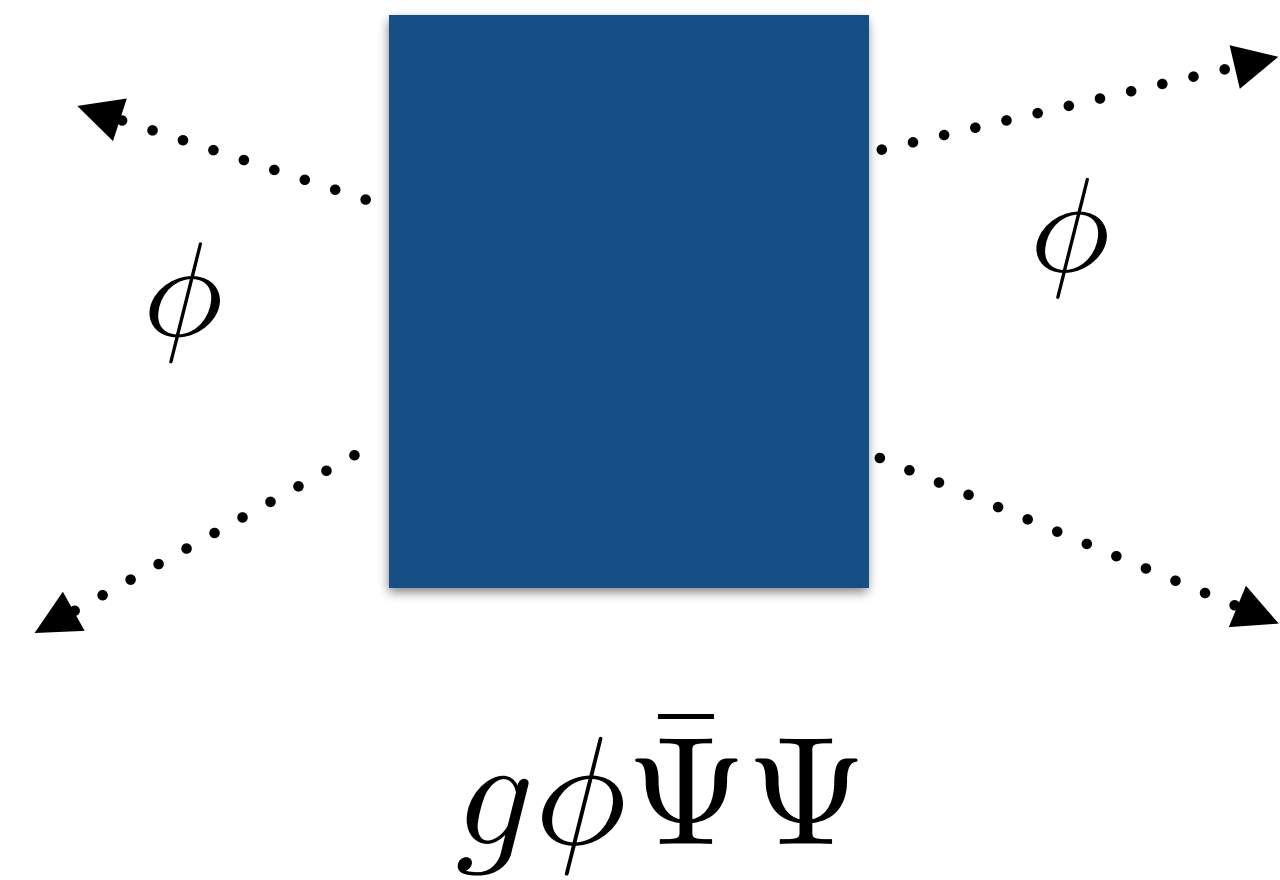
Experimental Realization



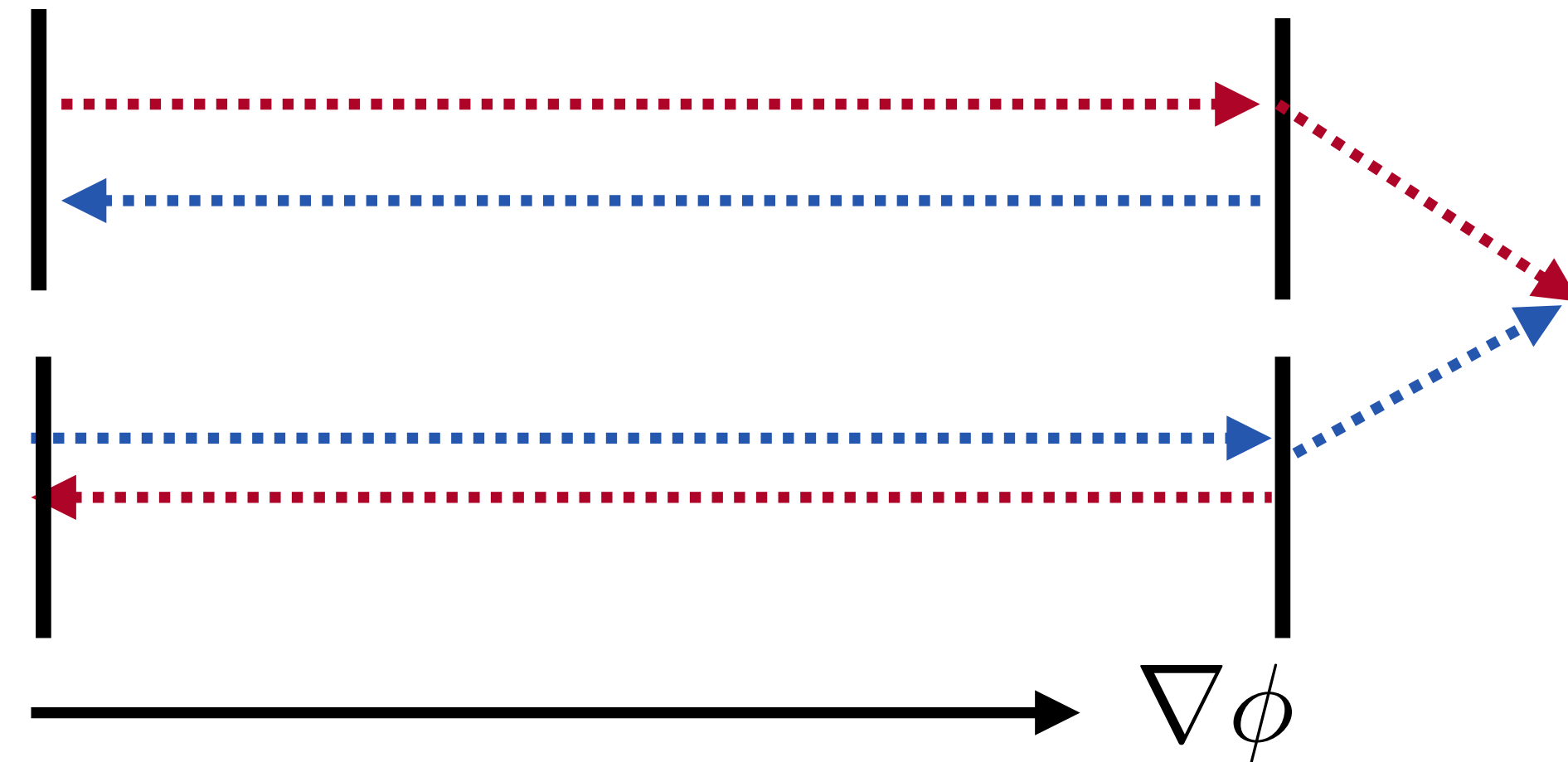
Independent of frequency - can realize in optical or superconducting RF

Optical: Smaller mirrors, lower F

RF: Large mirrors, high F



Systematics

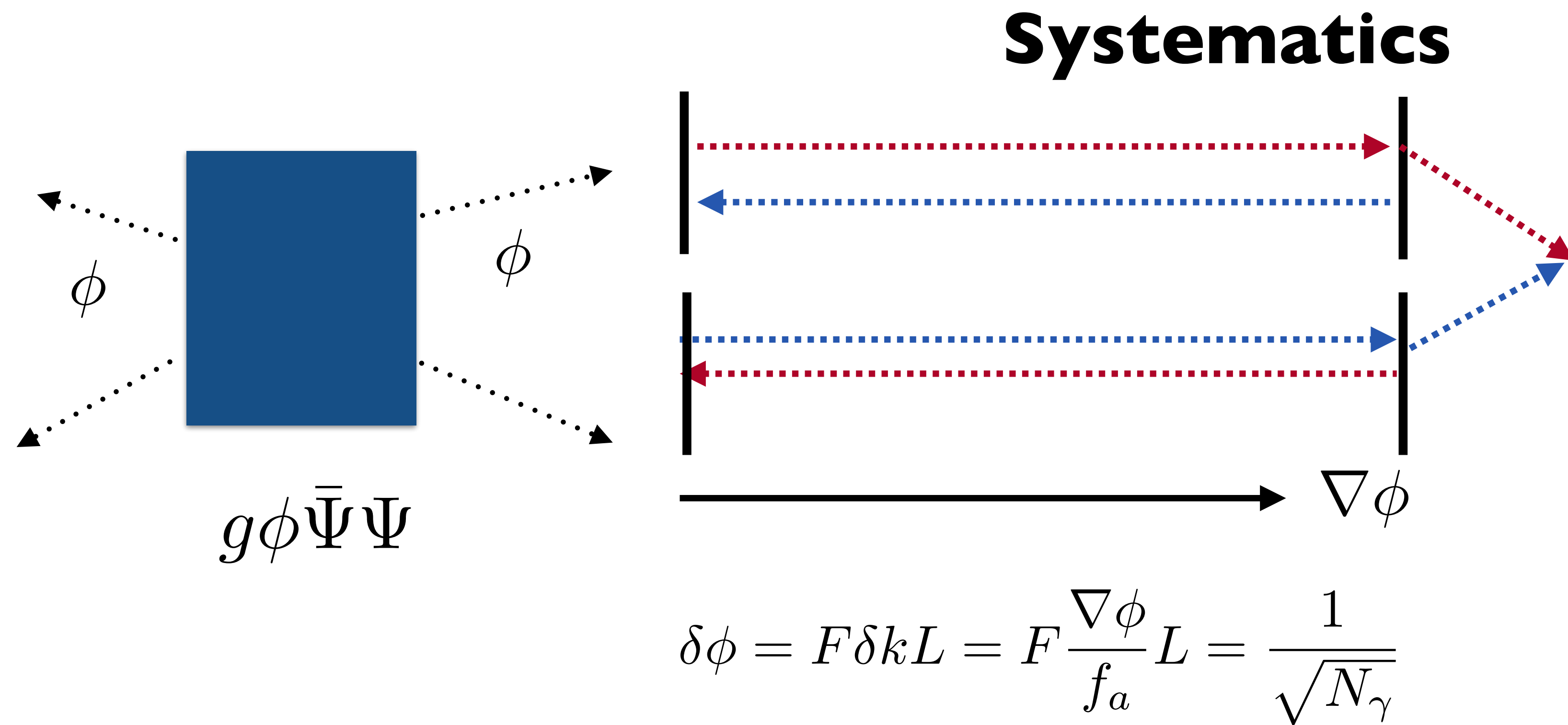


$$\delta\phi = F\delta kL = F\frac{\nabla\phi}{f_a}L = \frac{1}{\sqrt{N_\gamma}}$$

Issues

Cavity Length Fluctuations -
phase shift depends on
frequency

Strain in mirror induces phase -
scales with F but not L



Issues

Cavity Length Fluctuations -
phase shift depends on
frequency

Strain in mirror induces phase -
scales with F but not L

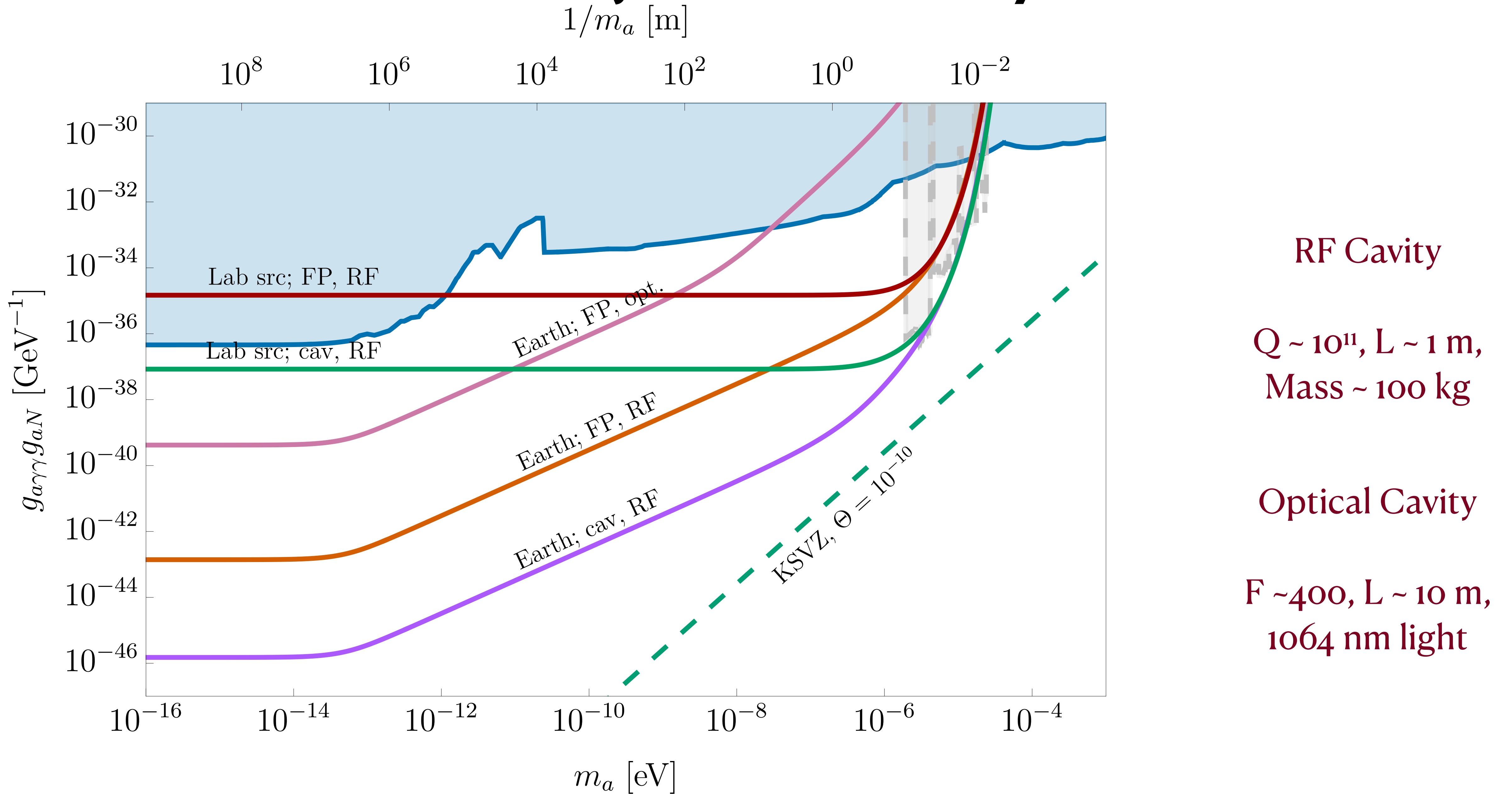
Handles

Use two different frequencies - differential measurement retains signal

Modulate L, but fix F - mirror strain remains same, signal changes

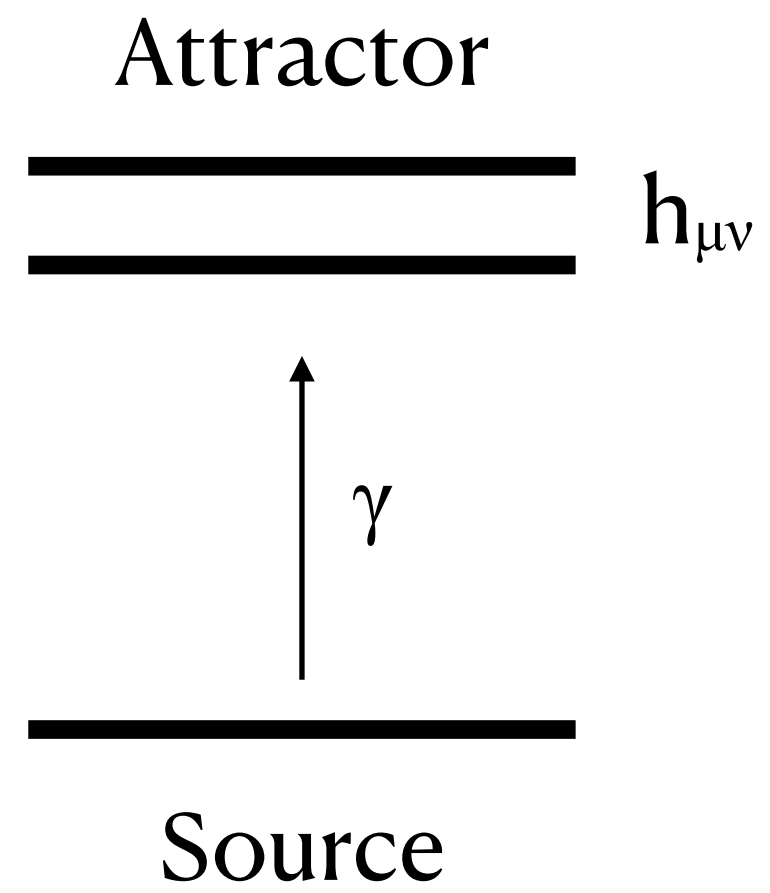
Modulate orientation relative to source or distance

Projected Sensitivity



Sensitivity

$$\mathcal{L} \supset \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma}$$

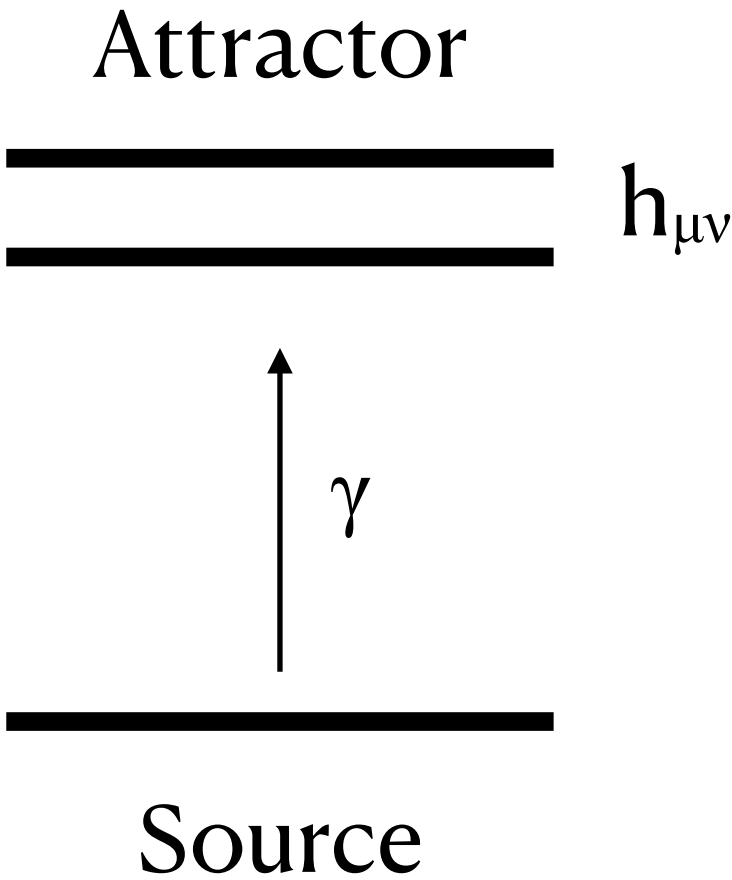


Sensitivity

$$\mathcal{L} \supset \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma}$$

Electromagnetic Contribution to the Mass of
a nucleus of charge Z - assuming this is a
uniform ball of charge Z

$$m_N^{em} = \frac{3}{5} \frac{Z^2 \alpha}{A^{\frac{1}{3}} r_p}$$



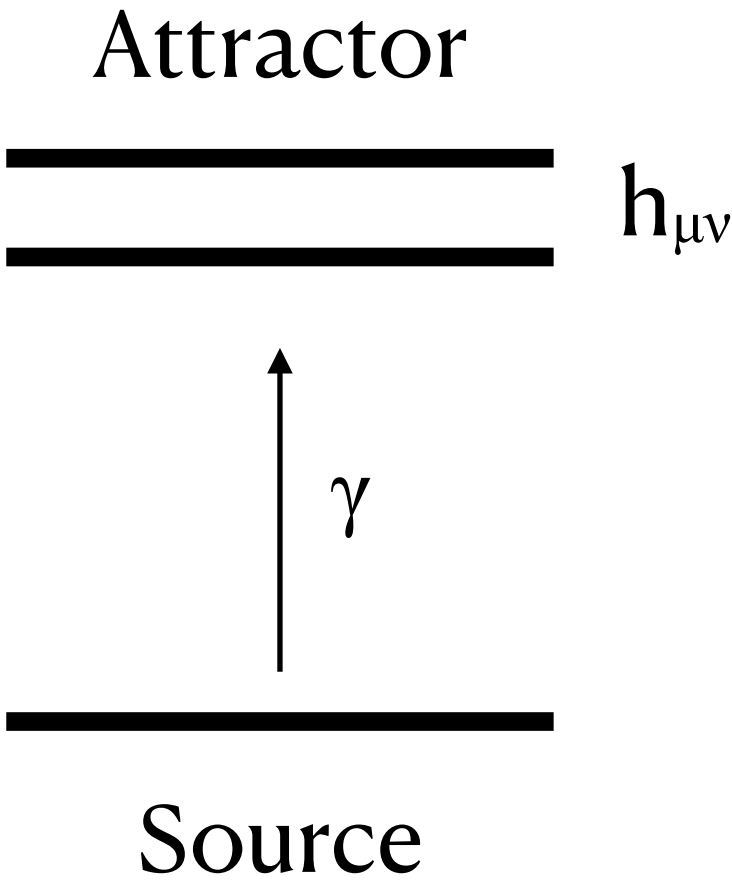
Sensitivity

$$\mathcal{L} \supset \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma}$$

Electromagnetic Contribution to the Mass of
a nucleus of charge Z - assuming this is a
uniform ball of charge Z

$$m_N^{em} = \frac{3}{5} \frac{Z^2 \alpha}{A^{\frac{1}{3}} r_p}$$

$$m_p^{em} = \frac{m_N^{em}}{A} = \frac{3}{5} \frac{Z^2 \alpha}{A^{\frac{4}{3}} r_p}$$



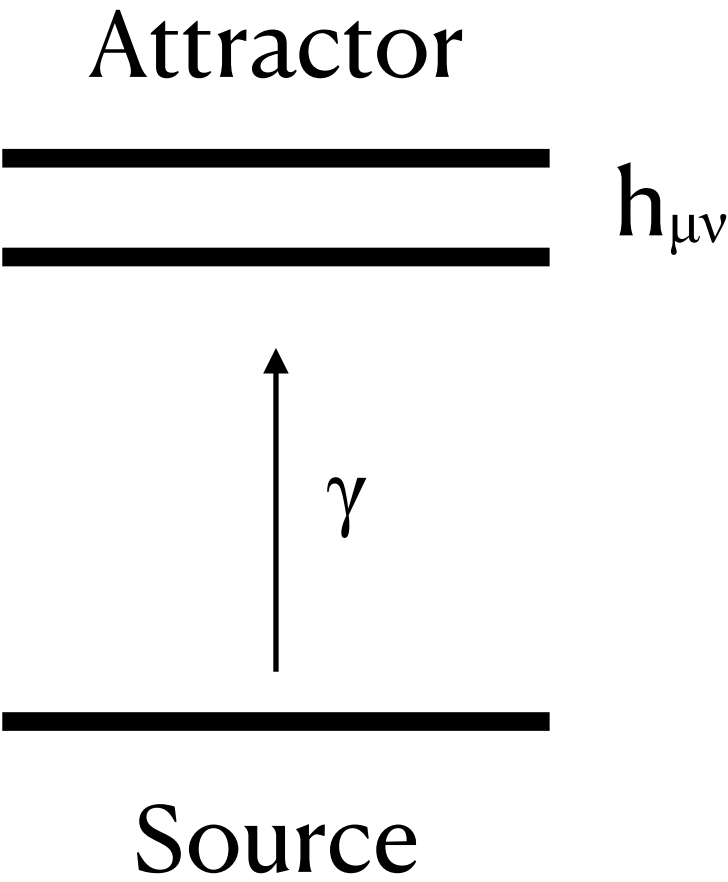
From this, find the effective contribution
per proton/nucleon

Sensitivity

$$\mathcal{L} \supset \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma}$$

Electromagnetic Contribution to the Mass of
a nucleus of charge Z - assuming this is a
uniform ball of charge Z

$$m_N^{em} = \frac{3}{5} \frac{Z^2 \alpha}{A^{\frac{1}{3}} r_p}$$



From this, find the effective contribution
per proton/nucleon

$$m_p^{em} = \frac{m_N^{em}}{A} = \frac{3}{5} \frac{Z^2 \alpha}{A^{\frac{4}{3}} r_p}$$

Dimensionless coupling to Nucleons

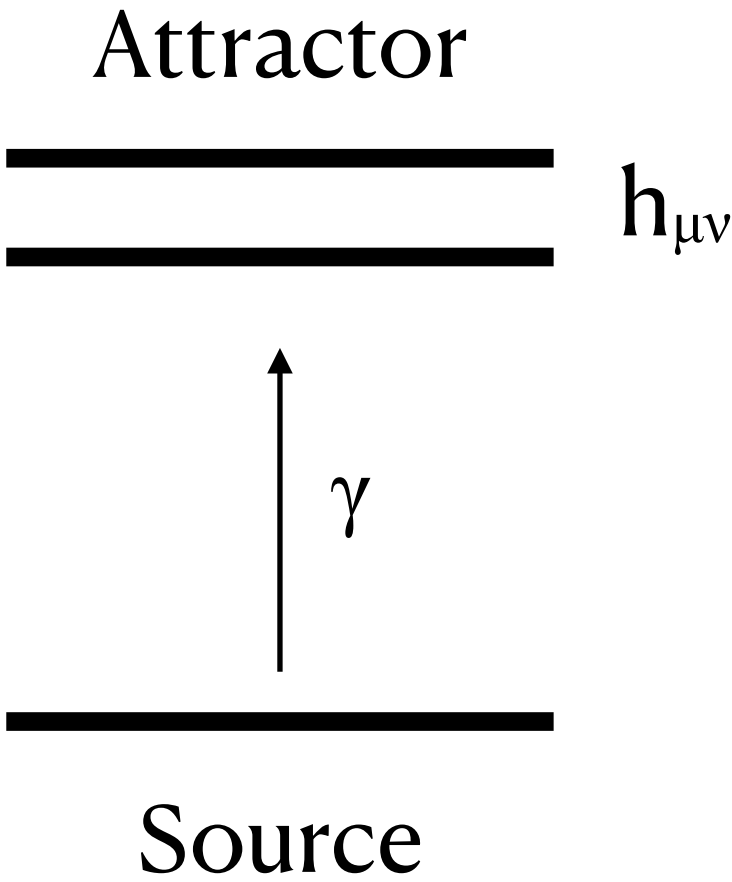
$$g = \frac{m_p^{em}}{f_T}$$

Sensitivity

$$\mathcal{L} \supset \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma}$$

Electromagnetic Contribution to the Mass of
a nucleus of charge Z - assuming this is a
uniform ball of charge Z

$$m_N^{em} = \frac{3}{5} \frac{Z^2 \alpha}{A^{\frac{1}{3}} r_p}$$



From this, find the effective contribution
per proton/nucleon

$$m_p^{em} = \frac{m_N^{em}}{A} = \frac{3}{5} \frac{Z^2 \alpha}{A^{\frac{4}{3}} r_p}$$

Dimensionless coupling to Nucleons

$$g = \frac{m_p^{em}}{f_T}$$

Field Created by Attractor

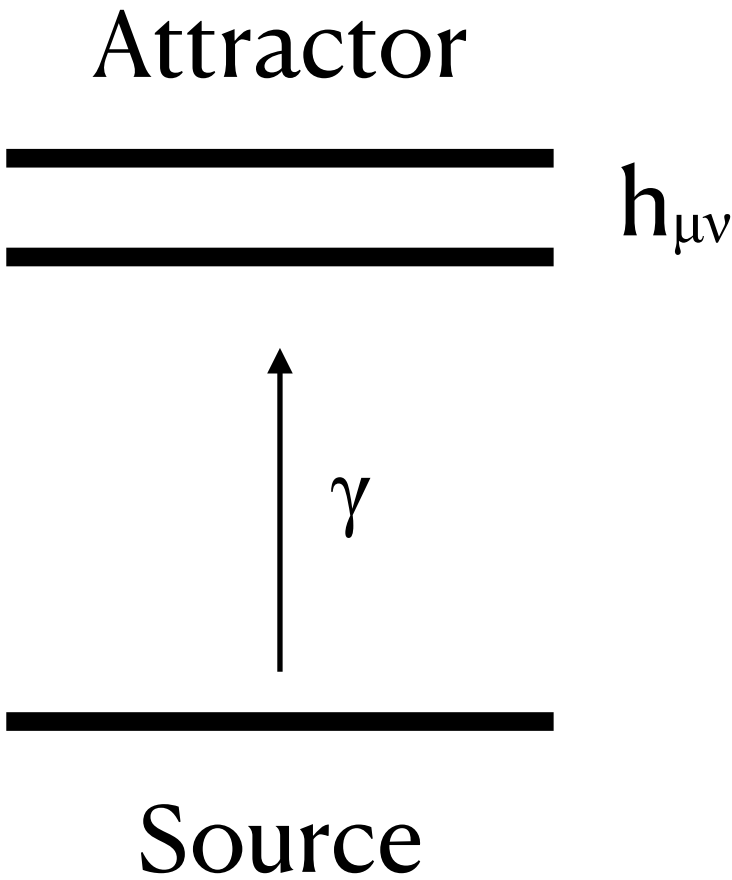
$$h = \frac{g n_0 \lambda^2}{2e}$$

Sensitivity

$$\mathcal{L} \supset \frac{\tilde{h}_{\mu\nu}}{f_T} F^\mu{}_\sigma F^{\nu\sigma}$$

Electromagnetic Contribution to the Mass of
a nucleus of charge Z - assuming this is a
uniform ball of charge Z

$$m_N^{em} = \frac{3}{5} \frac{Z^2 \alpha}{A^{\frac{1}{3}} r_p}$$



From this, find the effective contribution
per proton/nucleon

$$m_p^{em} = \frac{m_N^{em}}{A} = \frac{3}{5} \frac{Z^2 \alpha}{A^{\frac{4}{3}} r_p}$$

Dimensionless coupling to Nucleons

$$g = \frac{m_p^{em}}{f_T}$$

Field Created by Attractor

$$h = \frac{g n_0 \lambda^2}{2e_h}$$

Frequency Shift

$$\delta\omega = \omega \frac{h}{f_T}$$

Sensitivity

$$\delta\omega = \delta E$$

$$\Rightarrow f_T = \frac{1}{3} \frac{\sqrt{n_0} Z \sqrt{\alpha} \lambda \sqrt{\omega}}{A^{\frac{2}{3}} \sqrt{r_p} \sqrt{\delta E}}$$

Sensitivity

$$\delta\omega = \delta E$$

$$\Rightarrow f_T = \frac{1}{3} \frac{\sqrt{n_0} Z \sqrt{\alpha} \lambda \sqrt{\omega}}{A^{\frac{2}{3}} \sqrt{r_p} \sqrt{\delta E}}$$

Numbers - take Gold attractor

$$n_0 = \frac{10 \times 10^{24}}{\text{cm}^3} \quad Z = 79, A = 197$$

$$\alpha = \frac{1}{137}, r_p = 1 \text{ fm} \quad \lambda = 10^{-7} \text{ m}, \delta E = 10^{-15} \text{ eV}$$

$$\Rightarrow \frac{1}{f_T} \sim \frac{2 \times 10^{-9}}{\text{GeV}}$$

Sensitivity

Conversion to the alpha - lambda plot

$$g = \frac{m_p^{em}}{f_T}$$

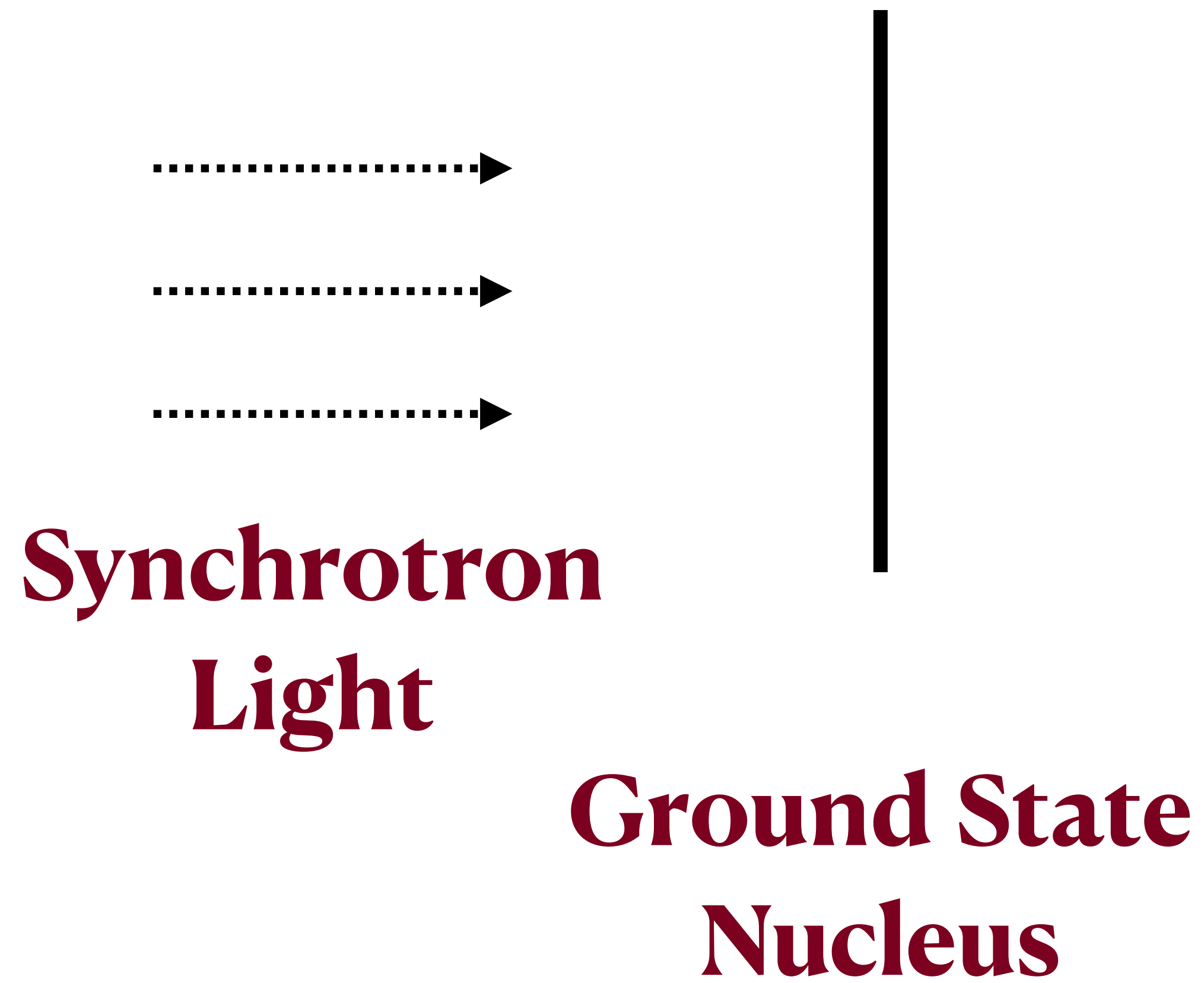
$$F_\lambda = \frac{\text{GeV}}{g}$$

$$\alpha_\lambda = \frac{\left(1.2 \times 10^{19} \text{ GeV}\right)^2}{4\pi F_\lambda^2}$$

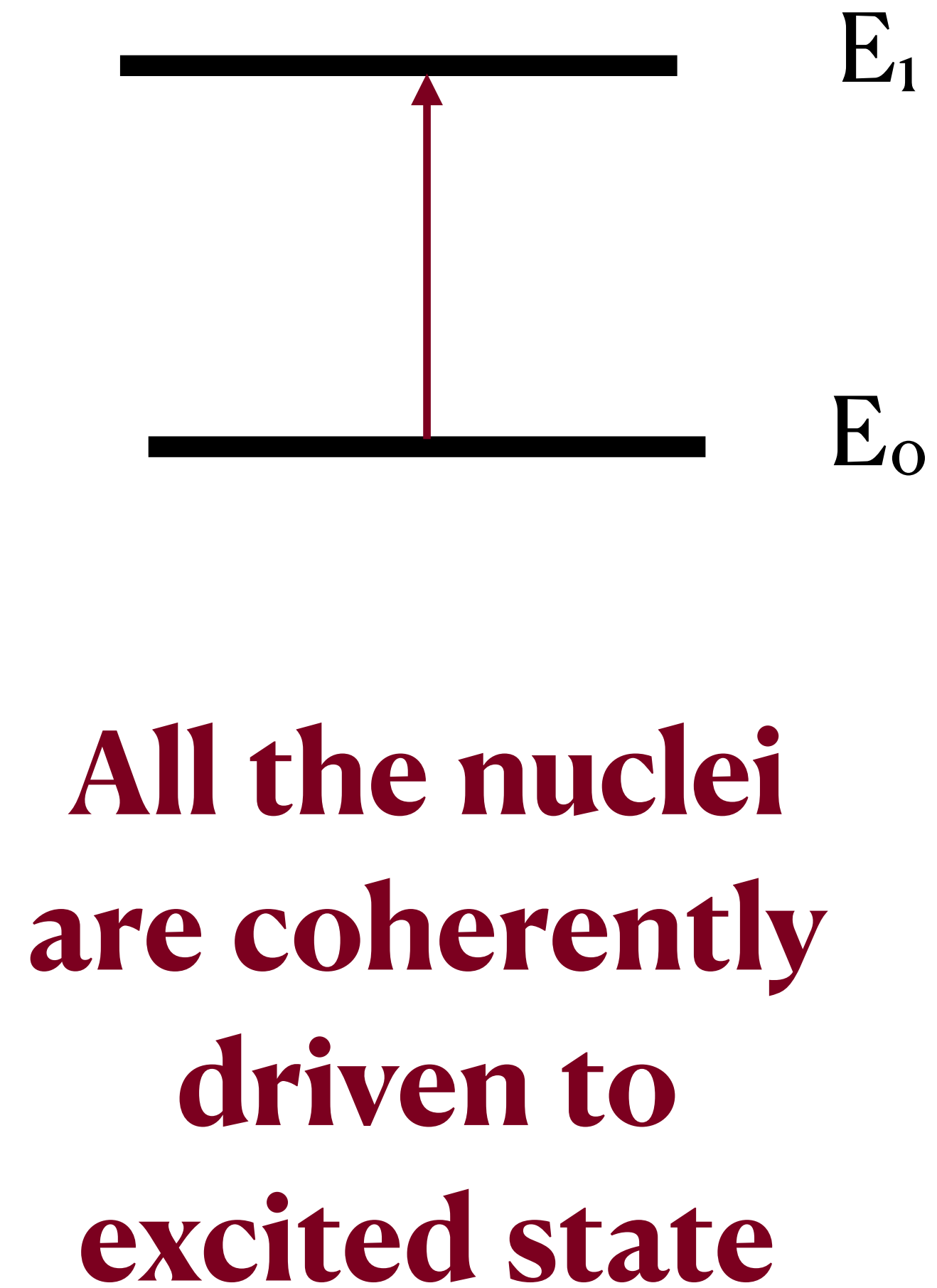
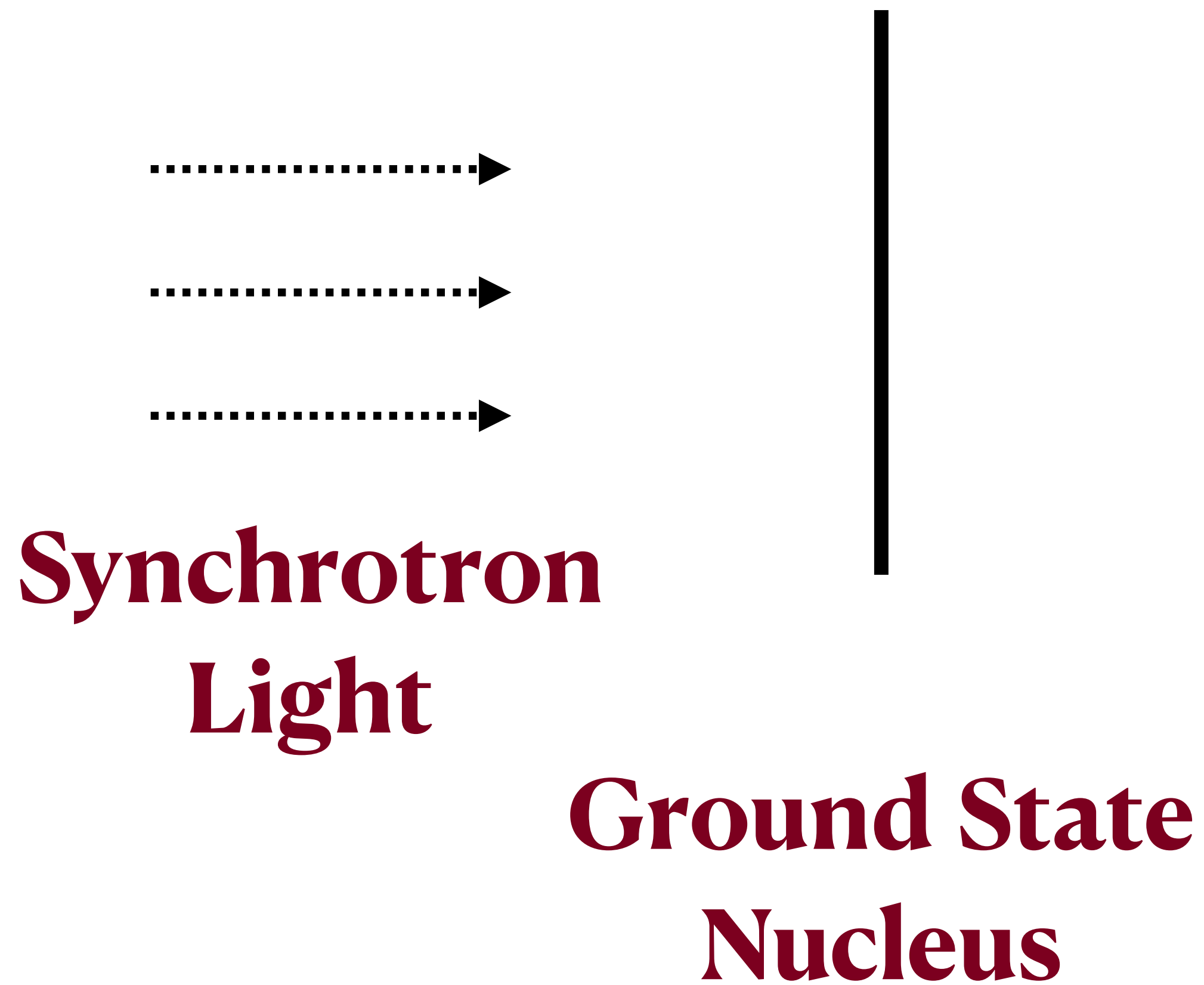
Plugging in with the values for Gold and f_T we found in the previous slide, we get

$$\alpha_\lambda \sim 2 \times 10^{15} \text{ at } 100 \text{ nm}$$

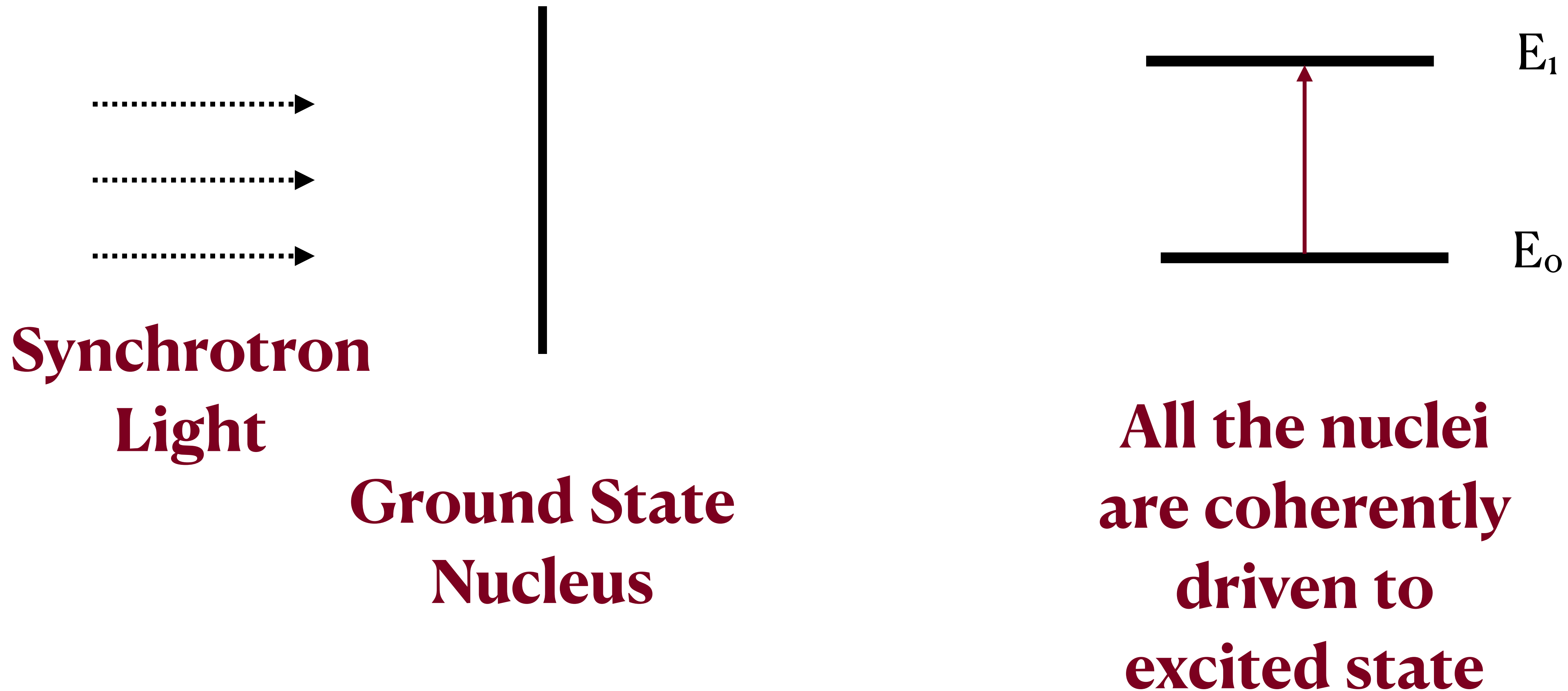
Mossbauer at Synchrotron Source



Mossbauer at Synchrotron Source



Mossbauer at Synchrotron Source



Short Pulse $\ll$ Lifetime of State

Bosonic Dark Matter

Photons

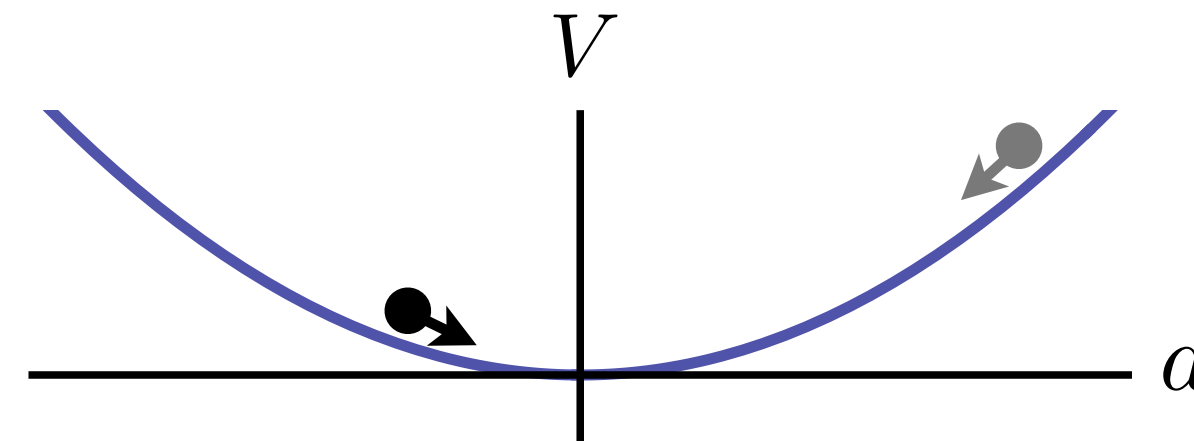


$$\vec{E} = E_0 \cos(\omega t - \omega x)$$

Detect Photon by
measuring time varying
field

Dark Bosons

Early Universe:
Misalignment Mechanism



$$a(t) \sim a_0 \cos(m_a t)$$

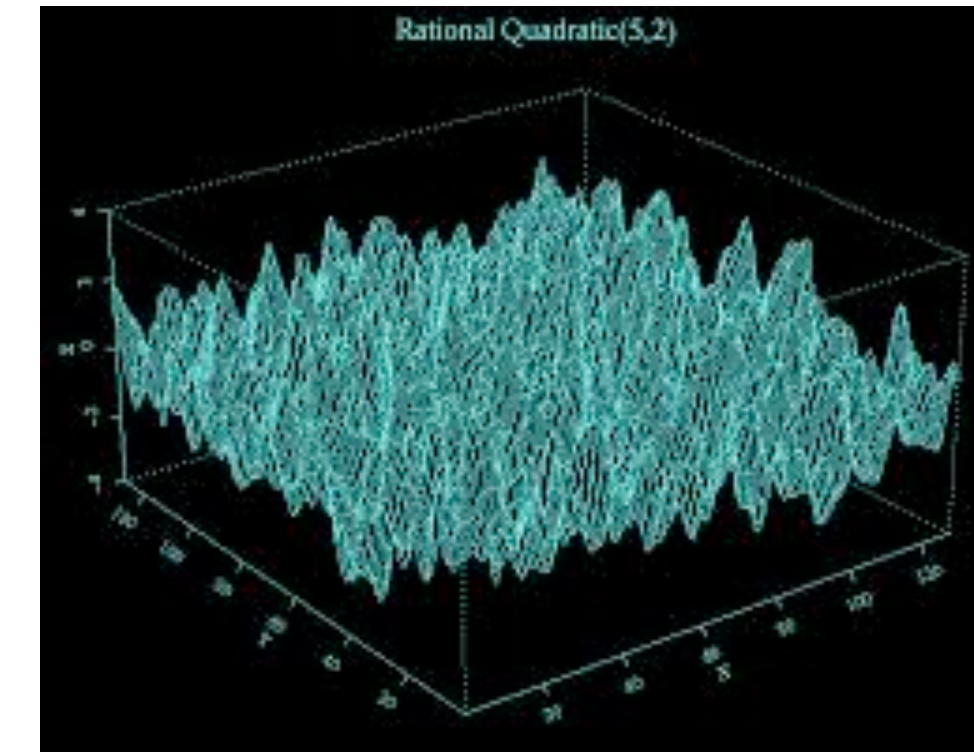
Spatially uniform, oscillating field

$$m_a^2 a_0^2 \sim \rho_{DM}$$

Detect effects of oscillating dark matter field

Resonance possible. $Q \sim 10^6$ (set by $v \sim 10^{-3}$)

Today:
Random Field



Correlation length
 $\sim 1/(m_a v)$

Coherence Time
 $\sim 1/(m_a v^2)$
 $\sim 1 \text{ s (MHz}/m_a)$