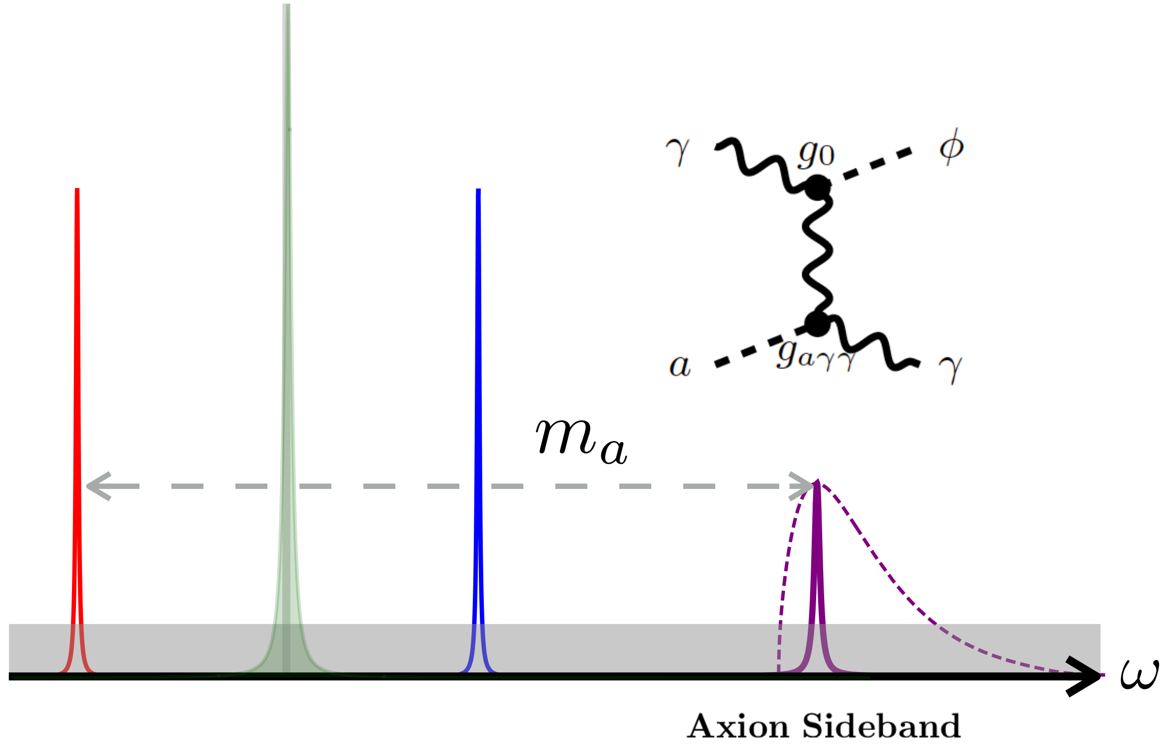


Axion Detection with Optomechanical Cavities

Yikun Wang

yikunw@caltech.edu

Joint IQ Initiative & PITT PACC Workshop: Axions, Fundamental and Synthetic

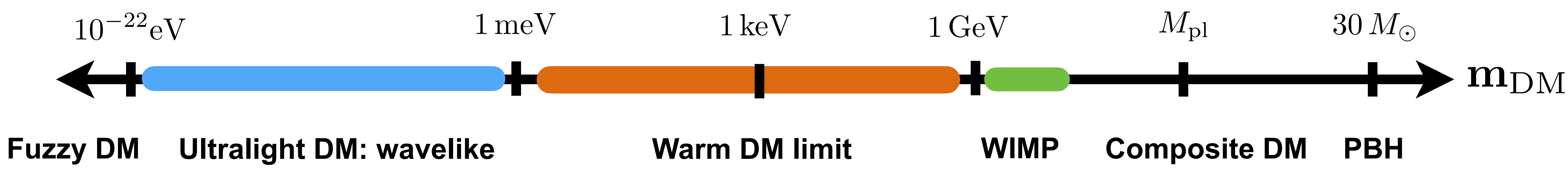
April 8th, 2023, Pittsburgh

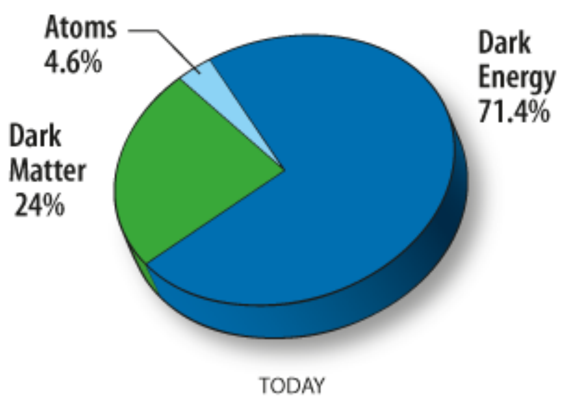
arXiv: 2211.08432

In Collaboration with: Clara Murgui, Kathryn Zurek

Upcoming: Experimental proposal with Jack Harris group at Yale

Dark Matter Direct Detection

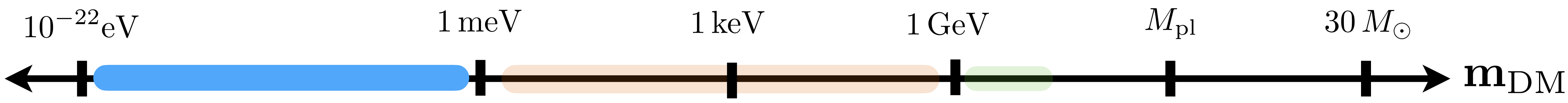




$v_{\rm DM} \sim 200\,{\rm km/s}$

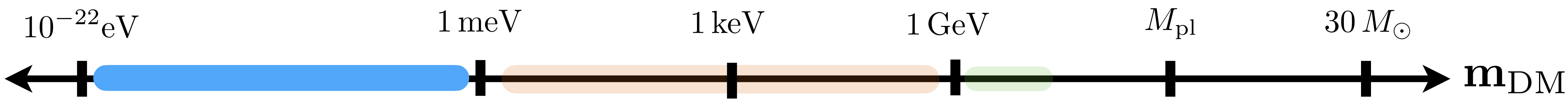
$\rho_{\rm DM} \sim 0.3\,{\rm GeV/cm^3}$

Axion Dark Matter



Ultralight DM: wavelike

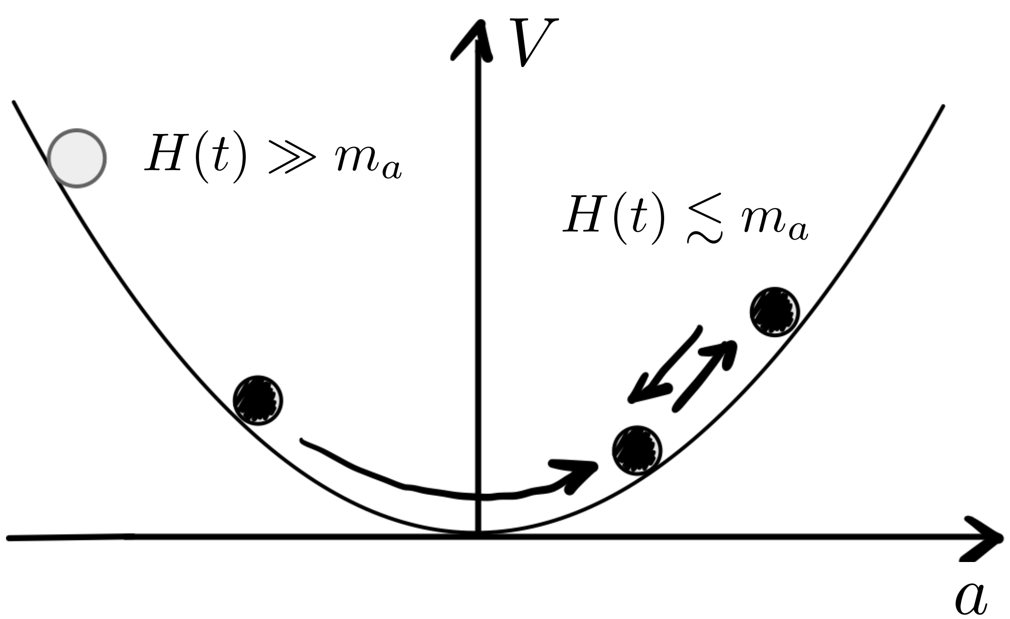
Axion Dark Matter



Ultralight DM: wavelike

Ultralight oscillating bosonic field

Misalignment mechanism



[Preskill, Wise, Wilczek 1977]

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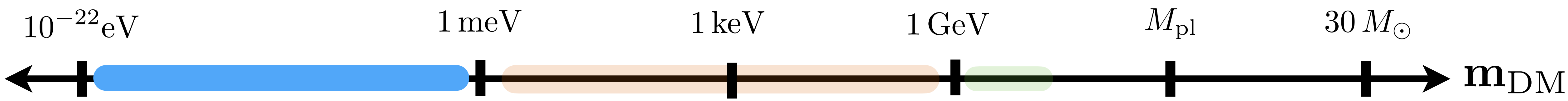

Ultralight DM: wavelike

Ultralight oscillating bosonic field , that weakly couples to the SM

$$\mathcal{L}_{\rm int} \sim \frac{\partial_\mu a}{f_a}\bar{f}\gamma^\mu\gamma^5 f + \frac{a}{f_a}G\tilde{G} + \frac{a}{f_a}F\tilde{F}$$

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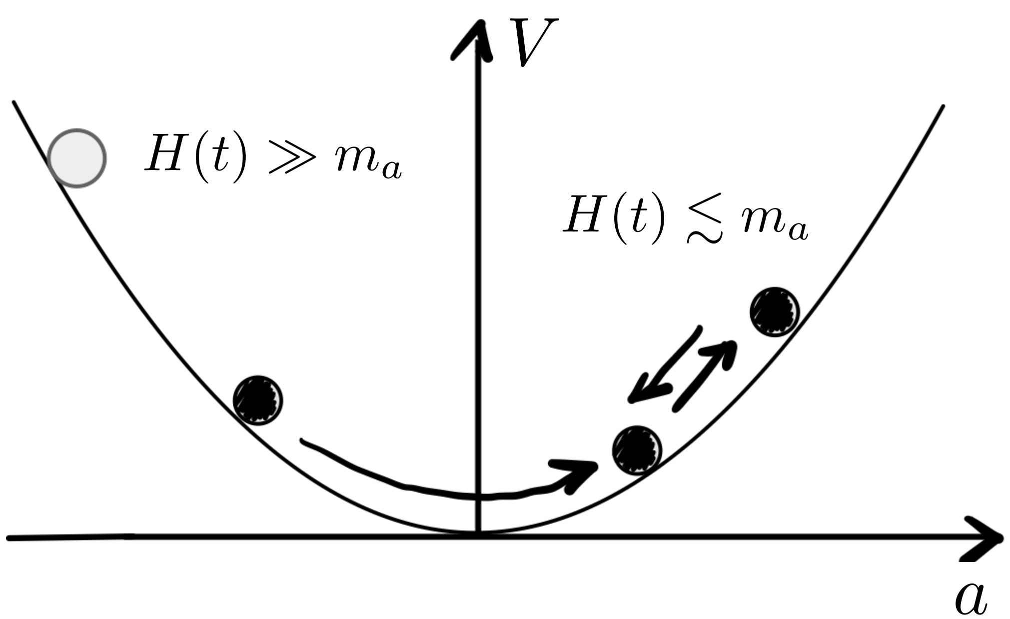

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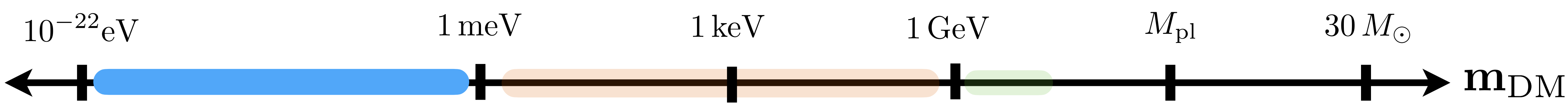

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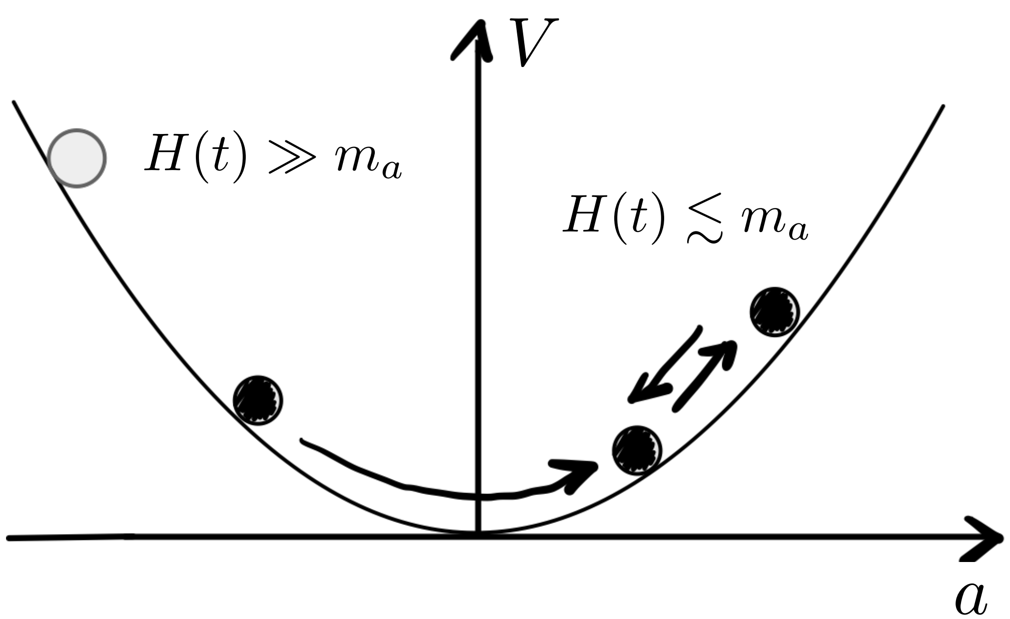

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QCD axion and axion like particles

Pseudo-Nambu-Goldstone bosons from the spontaneous breaking of global symmetries

QCD axion:
a solution to the strong CP problem

$$m_a \sim \frac{\Lambda^2_{\rm QCD}}{f_a}$$

[Peccei, Quinn 1977] [Wilzeck, 1978] [Weinberg, 1978]

Axion like particles

[Chikashige et al. 78; Gelmini,Roncadelli 80]
[Wilczek 82; Berezhiani,Khlopov 90]
[Witten 84; ….]

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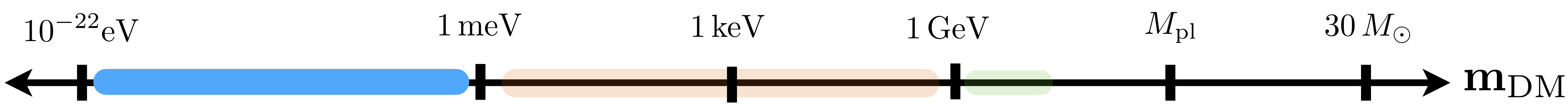

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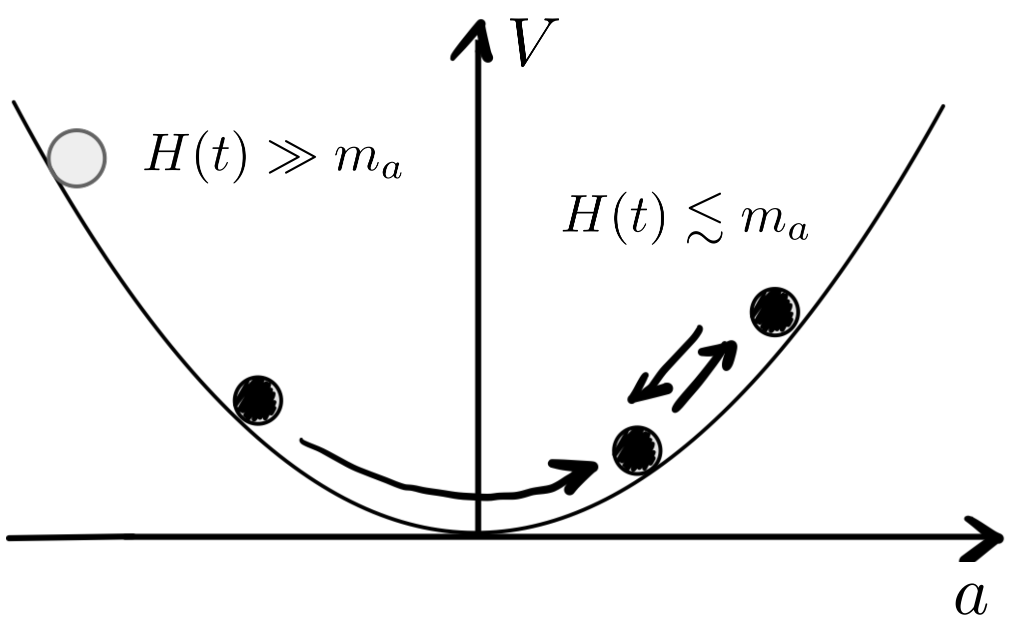

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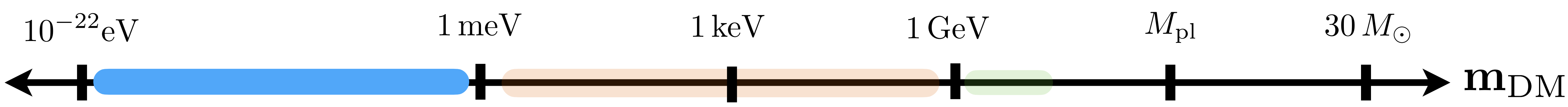
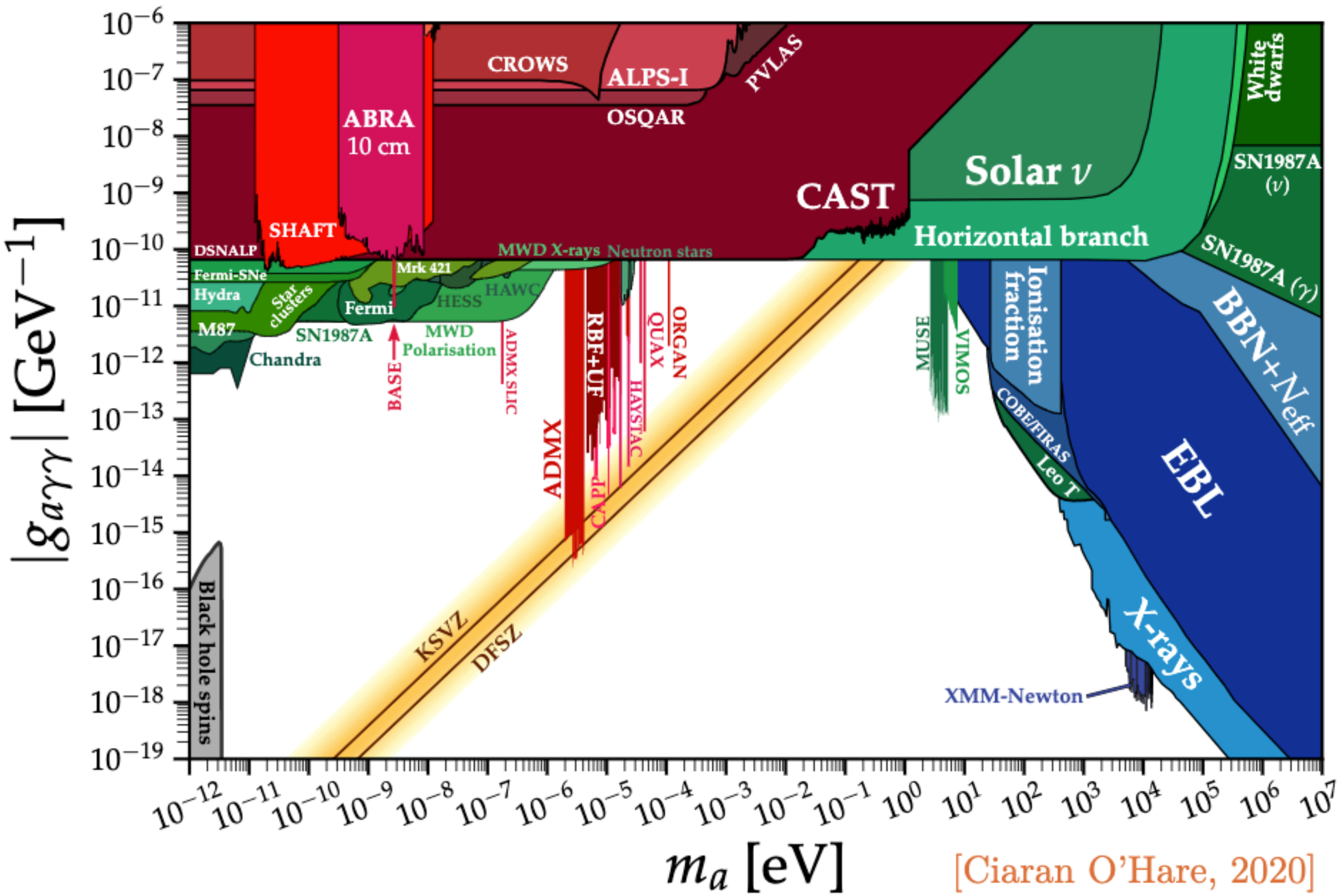


Axion searches

$$\mathcal{L} \sim g_{a\gamma\gamma} a F \tilde{F}$$



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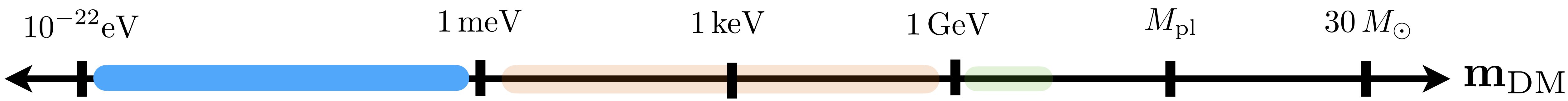
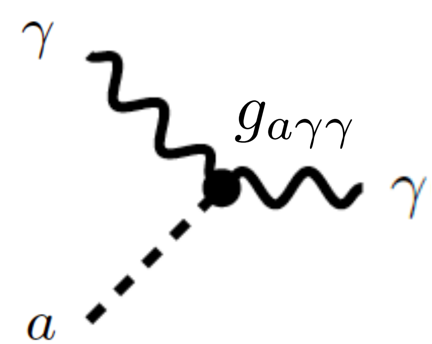


Axion searches

- Astrophysical bounds
- Solar axions
- Lab axions
- Axion section as DM
  - Axion electromagnetism (E.g. Axion Haloscope) [Sikivie 1983]
  - Non-EM couplings

Static field/initial photon



Signal photon: resonance enhancement

$$\omega_\gamma \sim m_a \sim \omega_{\rm res} \propto L^{-1}$$

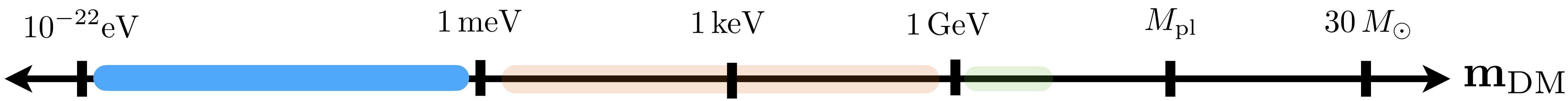
E.g. ADMAX, HYSTAC, etc

How to break the scaling?

E.g. ALPHA, MADMAX, ABRACADABRA, SRF etc

[Jaeckel1, Rybka, Winslow, and the Wave-like Dark Matter Community, 2022]

Axion Dark Matter



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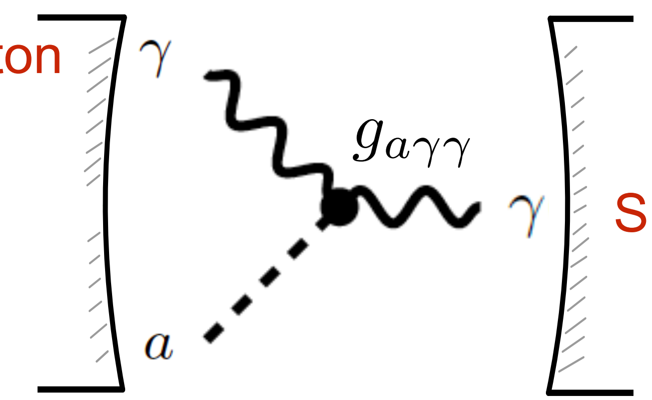

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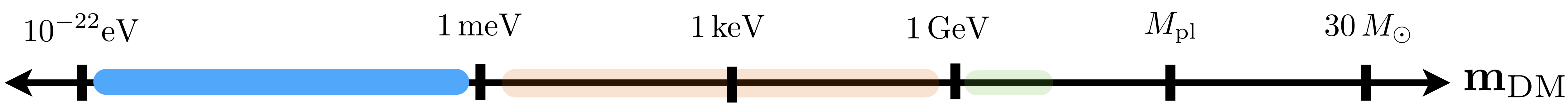
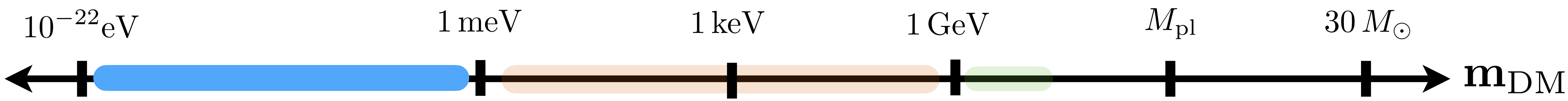


Axion direct detection with optomechanical cavities

Axion Dark Matter



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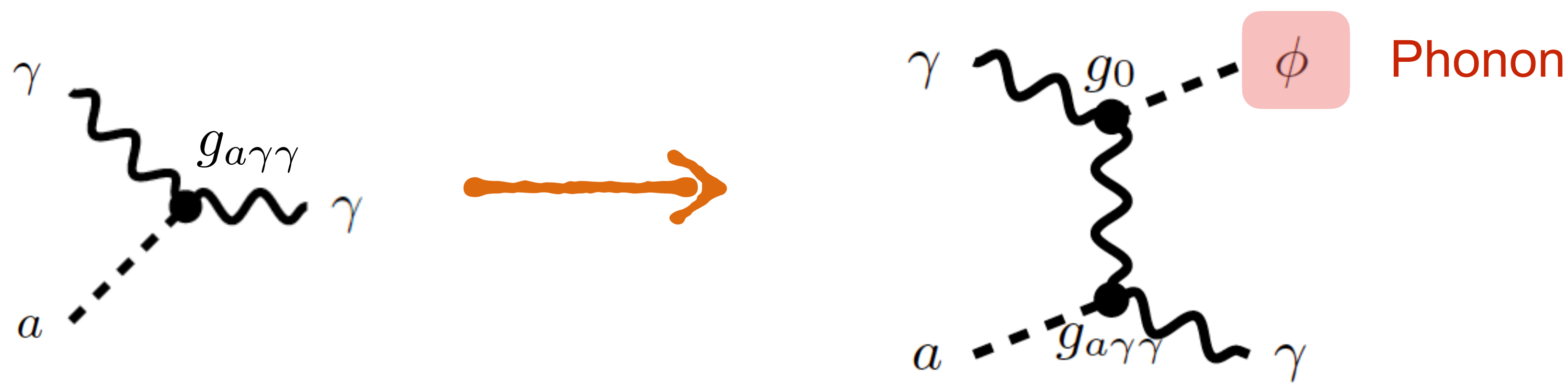

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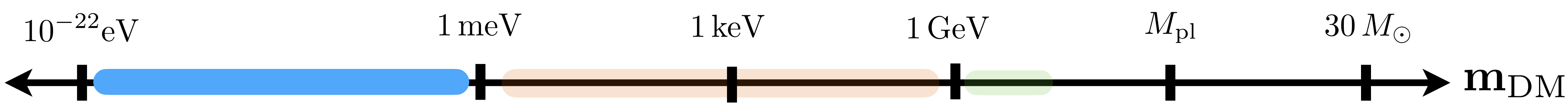

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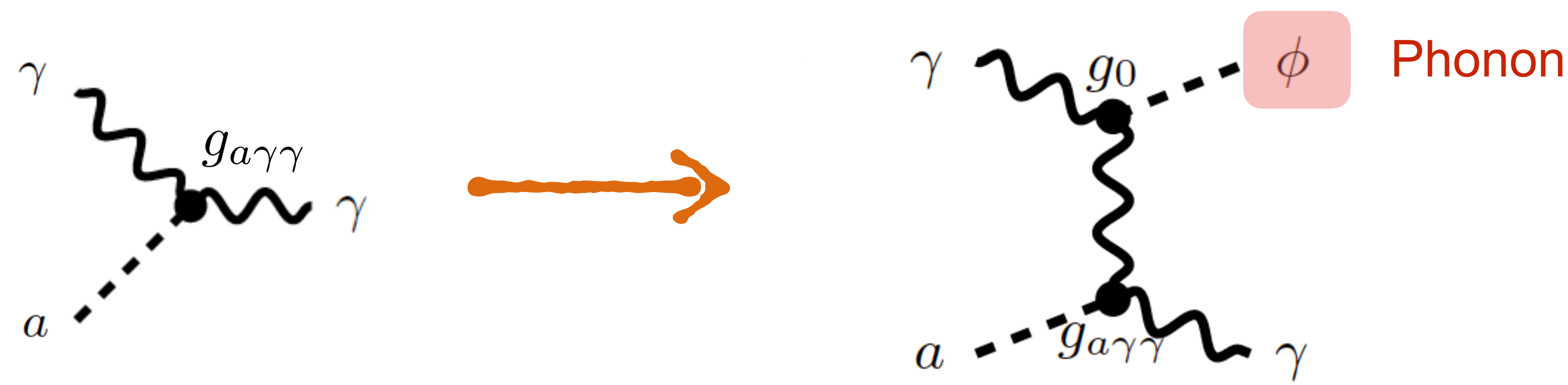
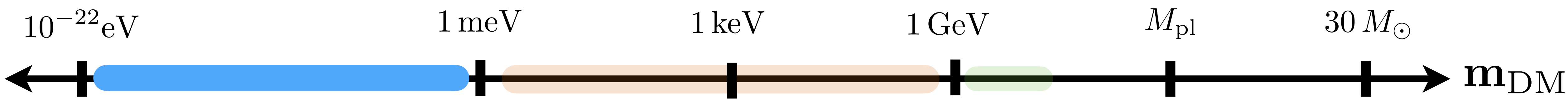


Phonons provide the **kinematic matching**: break the scaling between m_a and the cavity size;

Axion Dark Matter



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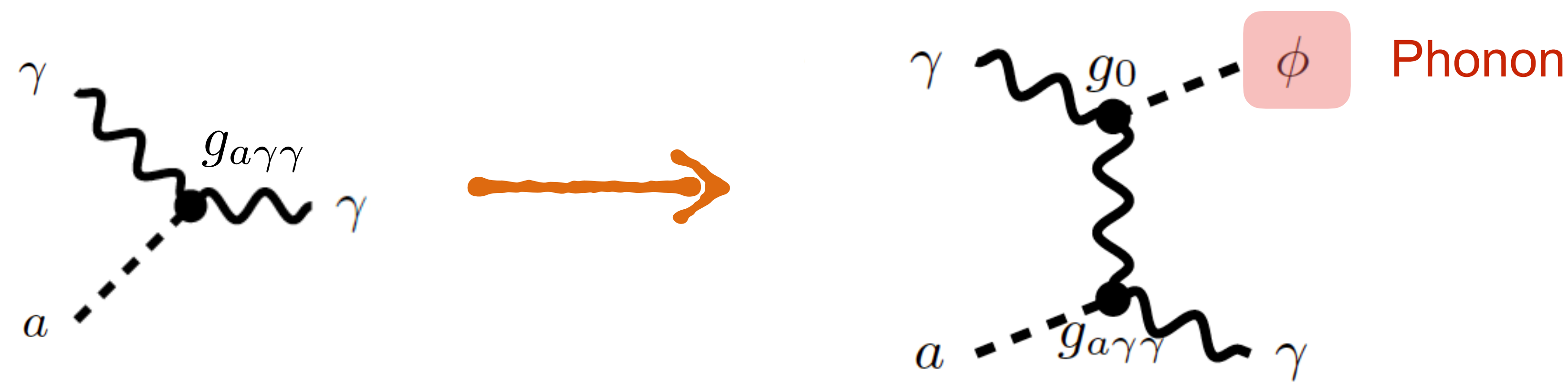
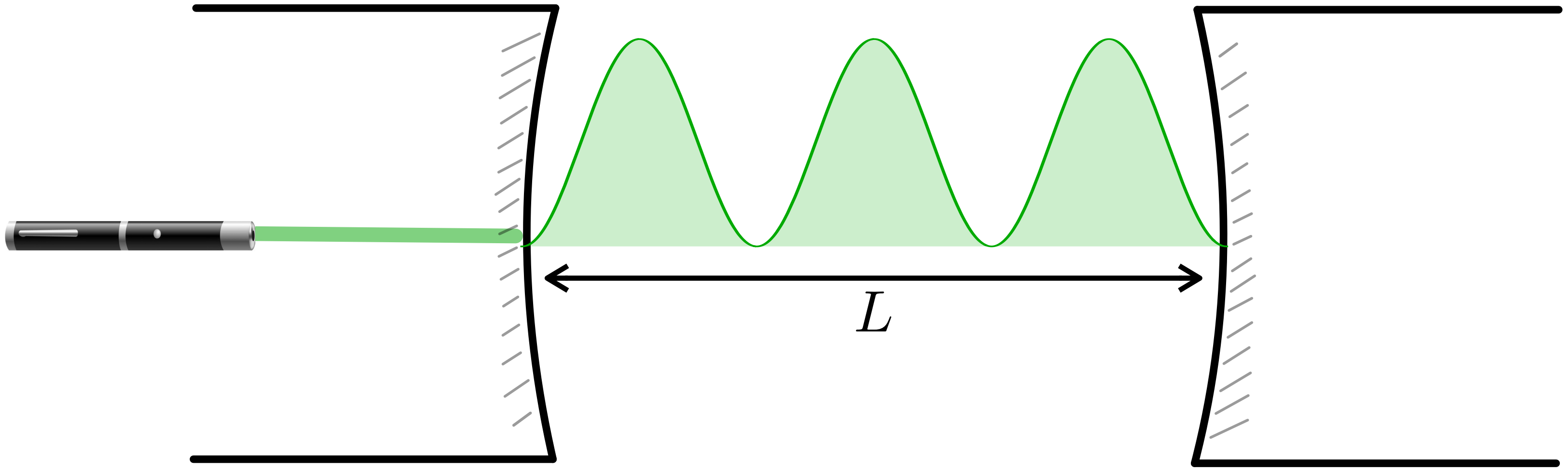


Phonons provide the **kinematic matching**: break the scaling between m_a and the cavity size;

Coherent enhancement from the large population of photons and/or phonons;

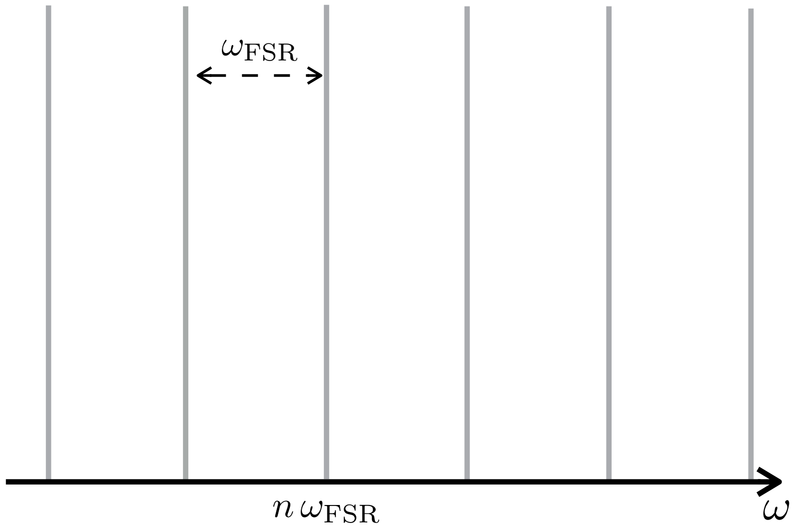
Cavity Optomechanics



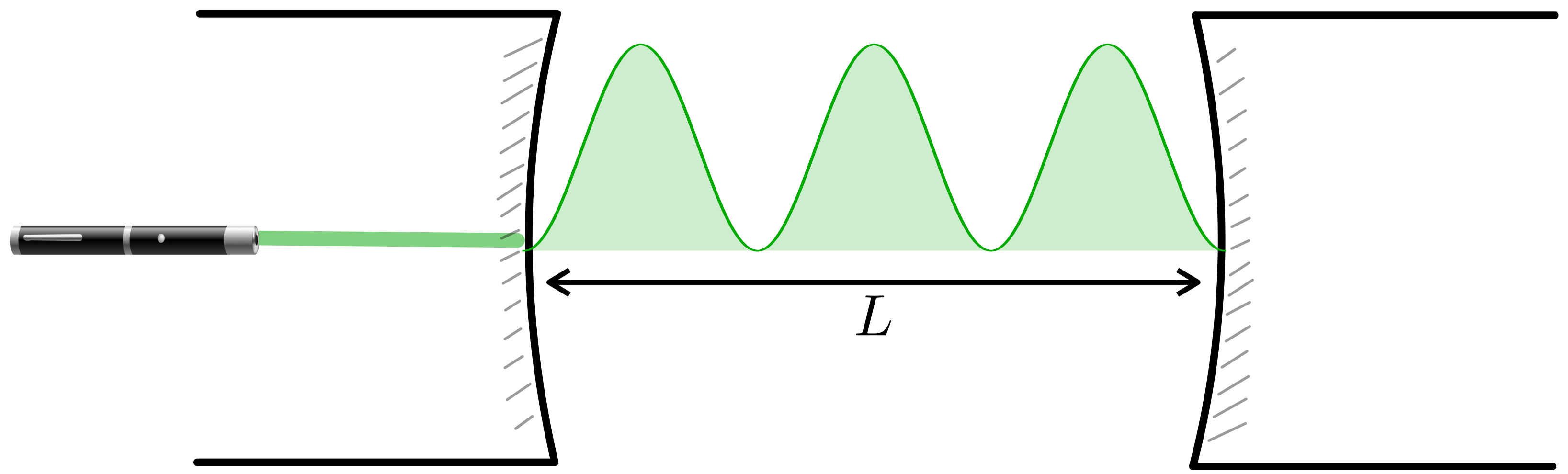
Mirrors confine light

Integer mode number

Optical resonance: $\lambda_{\text{opt}} = \frac{2L}{n}$ $\omega_{\text{opt}} = n\frac{\pi}{L}$ ω_{FSR}



Cavity Optomechanics



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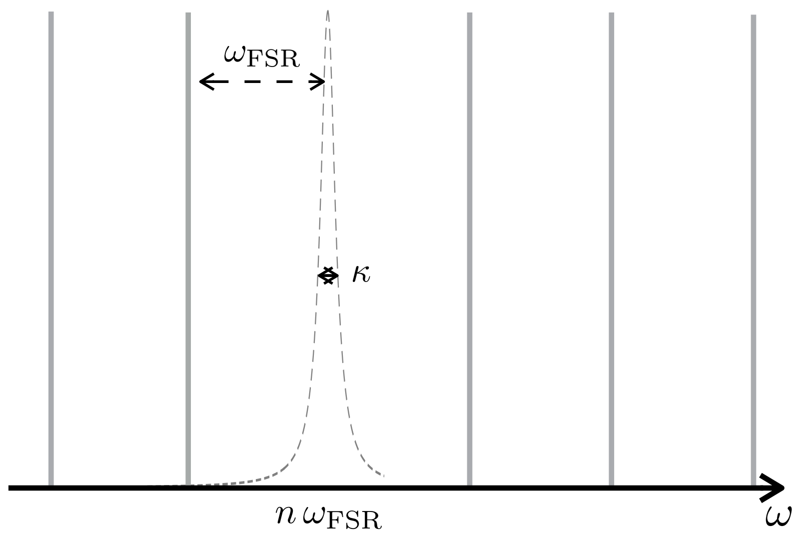

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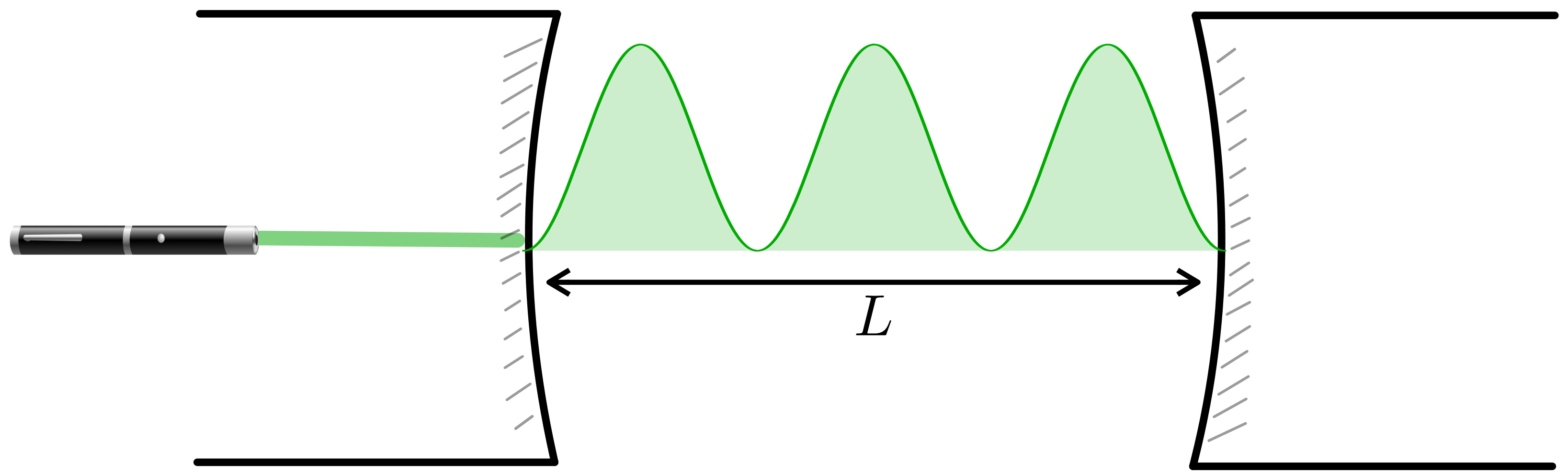

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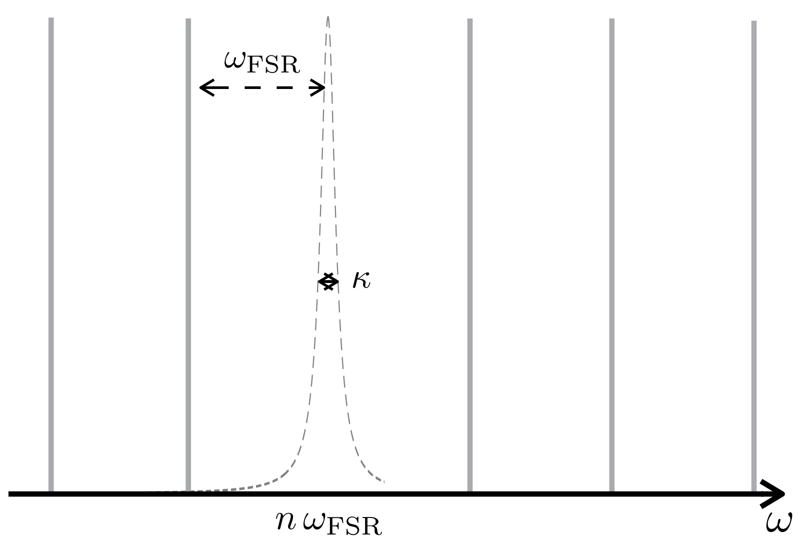
$$E \propto e^{-i\omega_{\mathrm{opt}} t} e^{-\kappa t}$$



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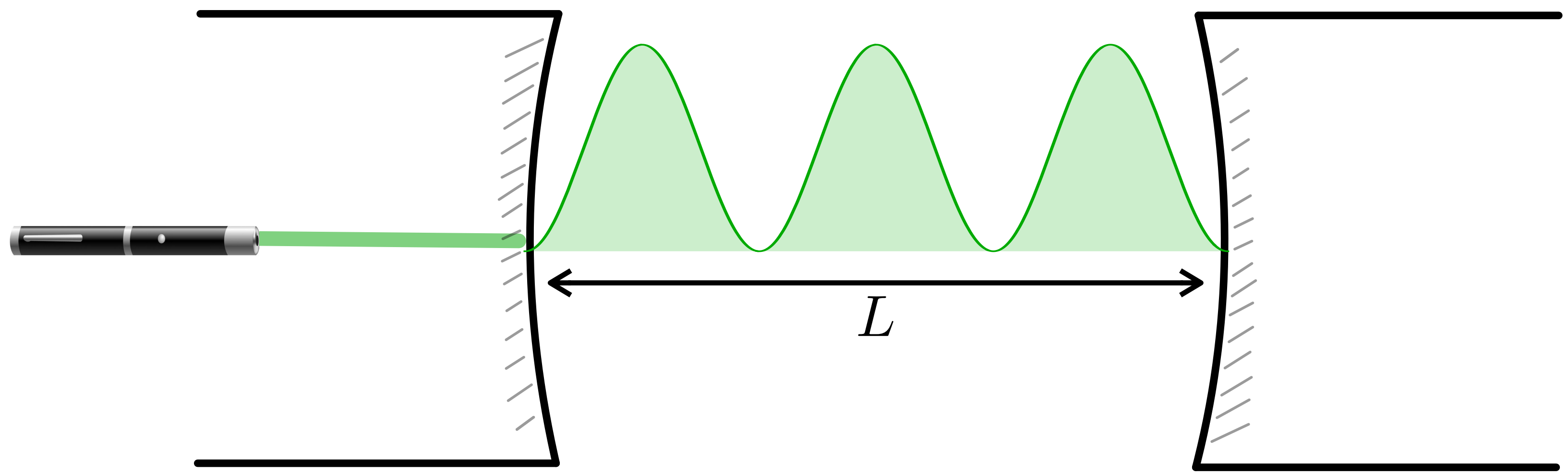

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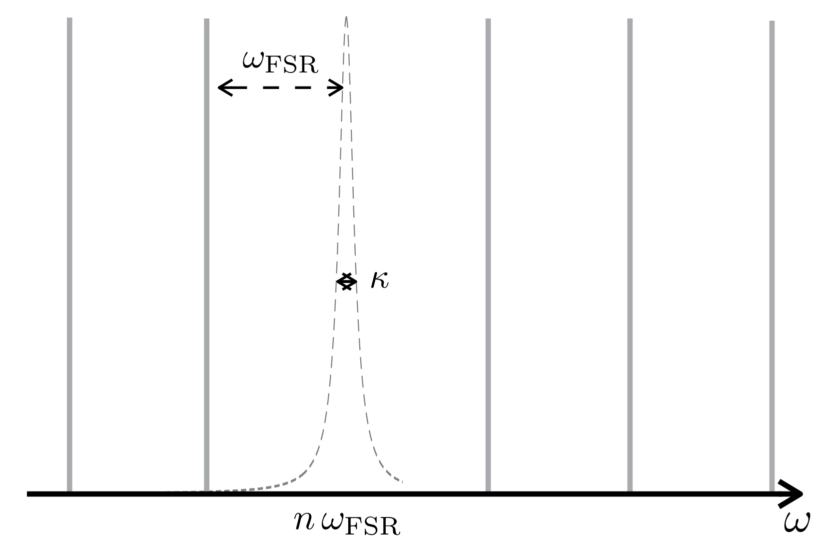
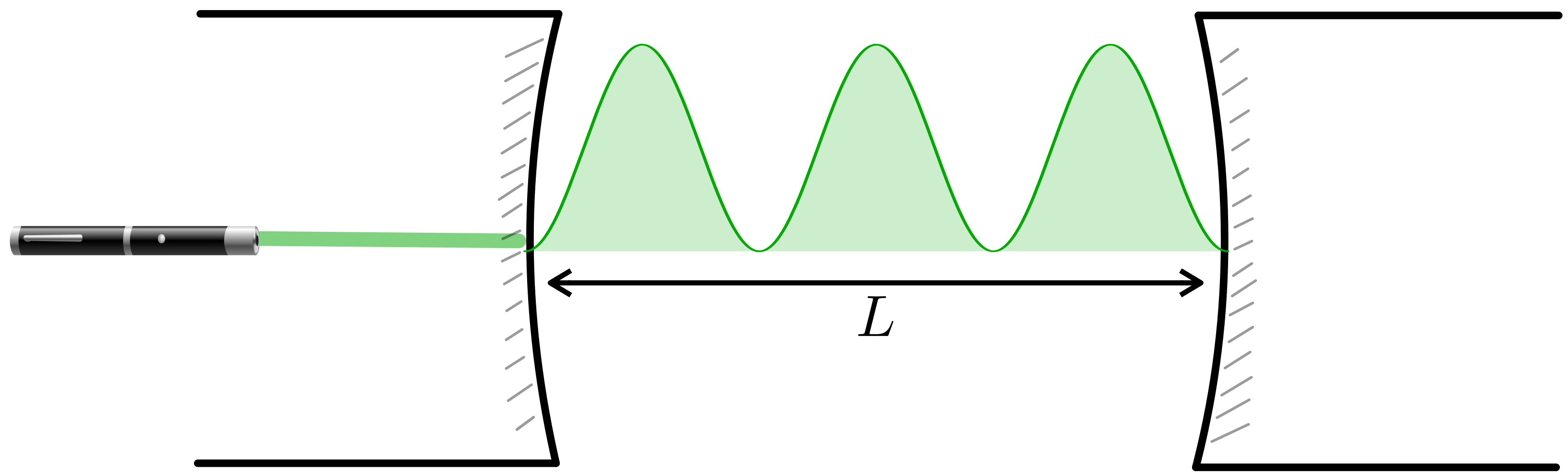


Quantization of light $\quad$ Photon population: $N_\gamma^{\text{circ}} = \frac{4P_{\text{laseer}}}{\omega_{\text{opt}}\kappa} \frac{(\kappa/2)^2}{(\omega_{\text{opt}} - \omega_{\text{laser}})^2 + (\kappa/2)^2}$

Cavity Optomechanics



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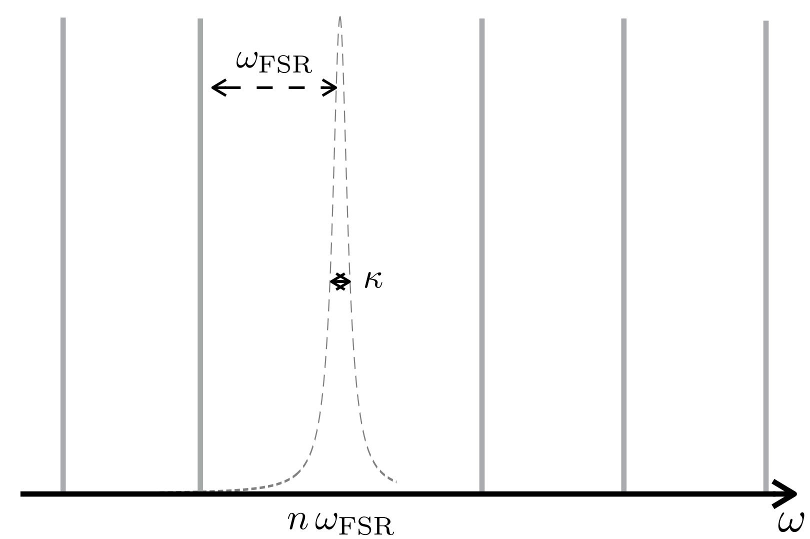

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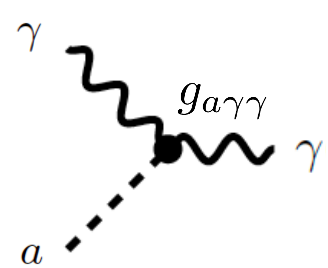
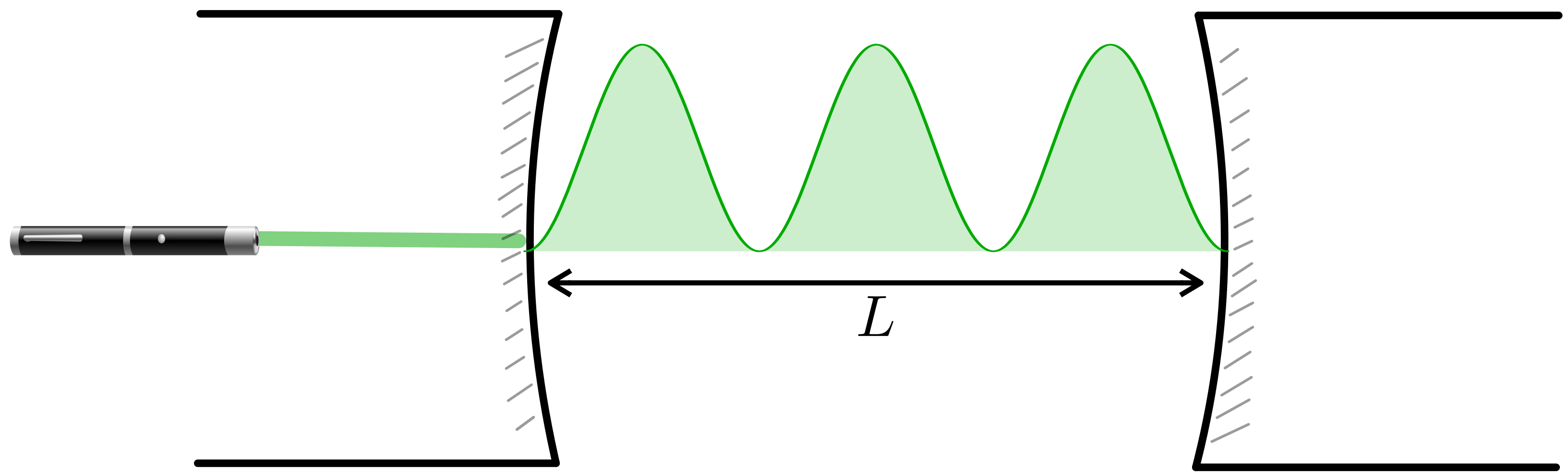


Axion haloscope etc

Cavity Optomechanics



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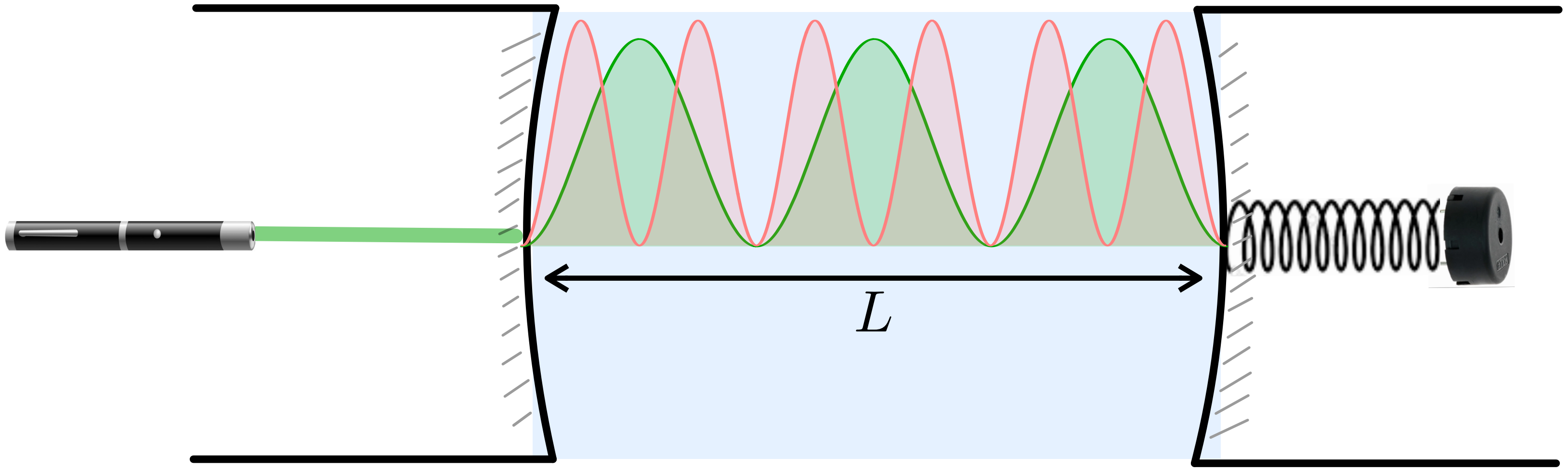

Mirrors confine light & sound

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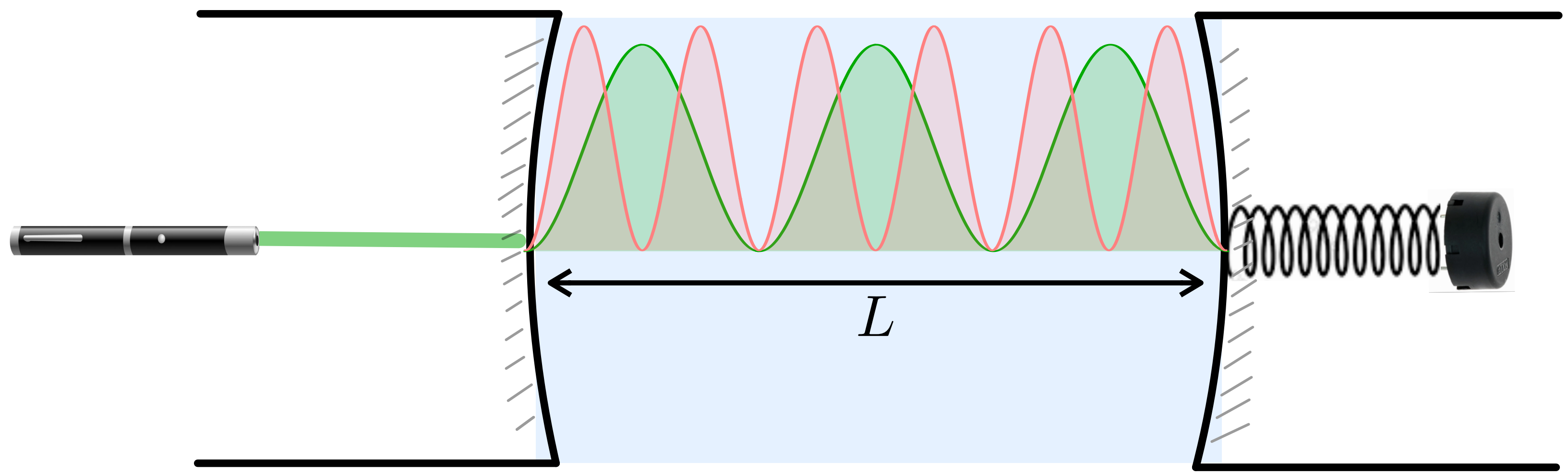

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Integer mechanical mode number

Mechanical resonance: $\Omega_{\text{m}} = n_{\text{m}}\, c_s\, \frac{\pi}{L}$ Mechanical width: $\Gamma_{\text{m}} = \tau_{\text{ac}}^{-1} = c_s\frac{\pi}{L\mathcal{F}_{\text{ac}}}$

Acoustic finesse

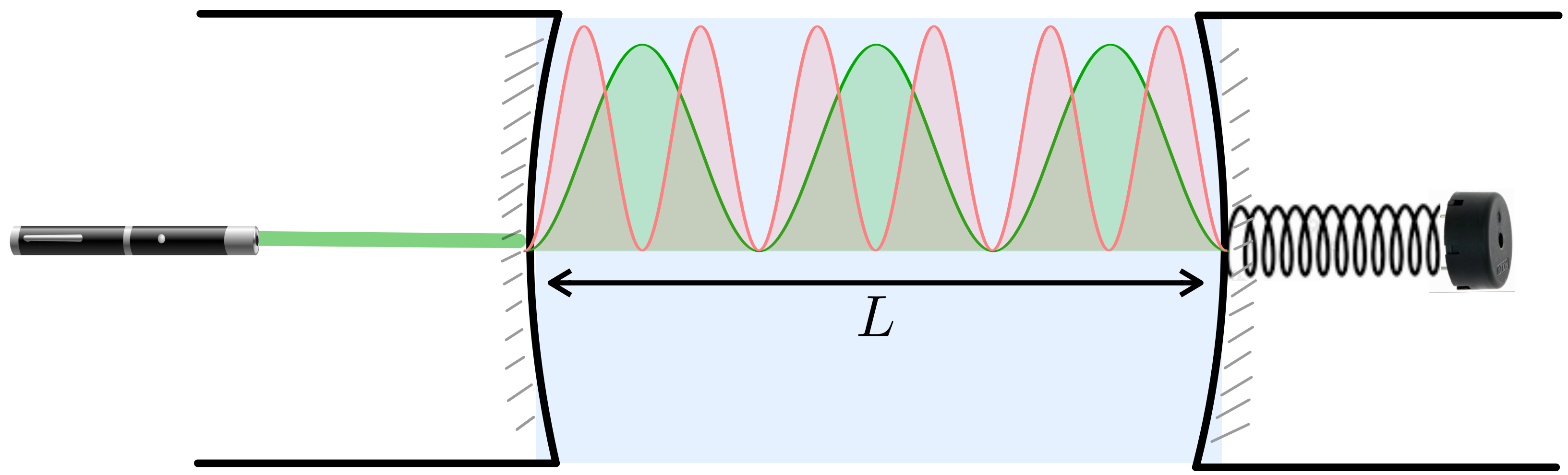
$$\mathcal{F}_{\text{ac}} = \left[\frac{1 - r_1^{\text{ac}} r_2^{\text{ac}}}{\pi\, r_1^{\text{ac}} r_2^{\text{ac}}}\right]^{-1}$$

speed of sound

Quantization of sound

Phonon population: $N_\phi^{\text{circ}} = N_{\text{phi}}\frac{(\Gamma_{\text{m}}/2)^2}{(\Omega_{\text{m}} - \Omega_{\text{m.d.}})^2 + (\Gamma_{\text{m}}/2)^2}$

Cavity Optomechanics



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Optomecanical interaction

$$H_{\text{OM}} = -\frac{1}{2}\alpha \int d^3\,\mathbf{r} n(\mathbf{r})\mathbf{E}(\mathbf{r})\cdot\mathbf{E}(\mathbf{r}) \longrightarrow H_{\text{OM}} = \sum_{i,j,k} g_0\, a_i\, a_j^\dagger\, \left(b_k + b_k^\dagger\right)$$

'mech' 'opts'

Cavity Optomechanics

[Aspelmeyer et al., 2013]
[Kashkanova et al., 2017]
[Reningner et al., 2017]

$$H_{\mathrm{OM}} \ni g_0\, a_{n_1}\, a^\dagger_{n_2}\, \left(b_{n_\mathrm{m}} + b^\dagger_{n_\mathrm{m}}\right)$$

$$g_0 = \omega_{\mathrm{opt}} \frac{3}{2} \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \frac{1}{\varepsilon_r} \sqrt{\frac{|\mathbf{k}_\mathrm{m}|}{2 c_s \rho V_{\mathrm{mode}}}} a_{\mathrm{ovl}} \quad \text{with} \quad a_{\mathrm{ovl}} = \mathrm{sinc}\left(\frac{\pi}{2}(n_1 + n_2 \pm n_\mathrm{m})\right)$$

Mode overlap factor. $a_{\mathrm{ovl}} = 1$ indicates momentum conservation in free space

Cavity Optomechanics

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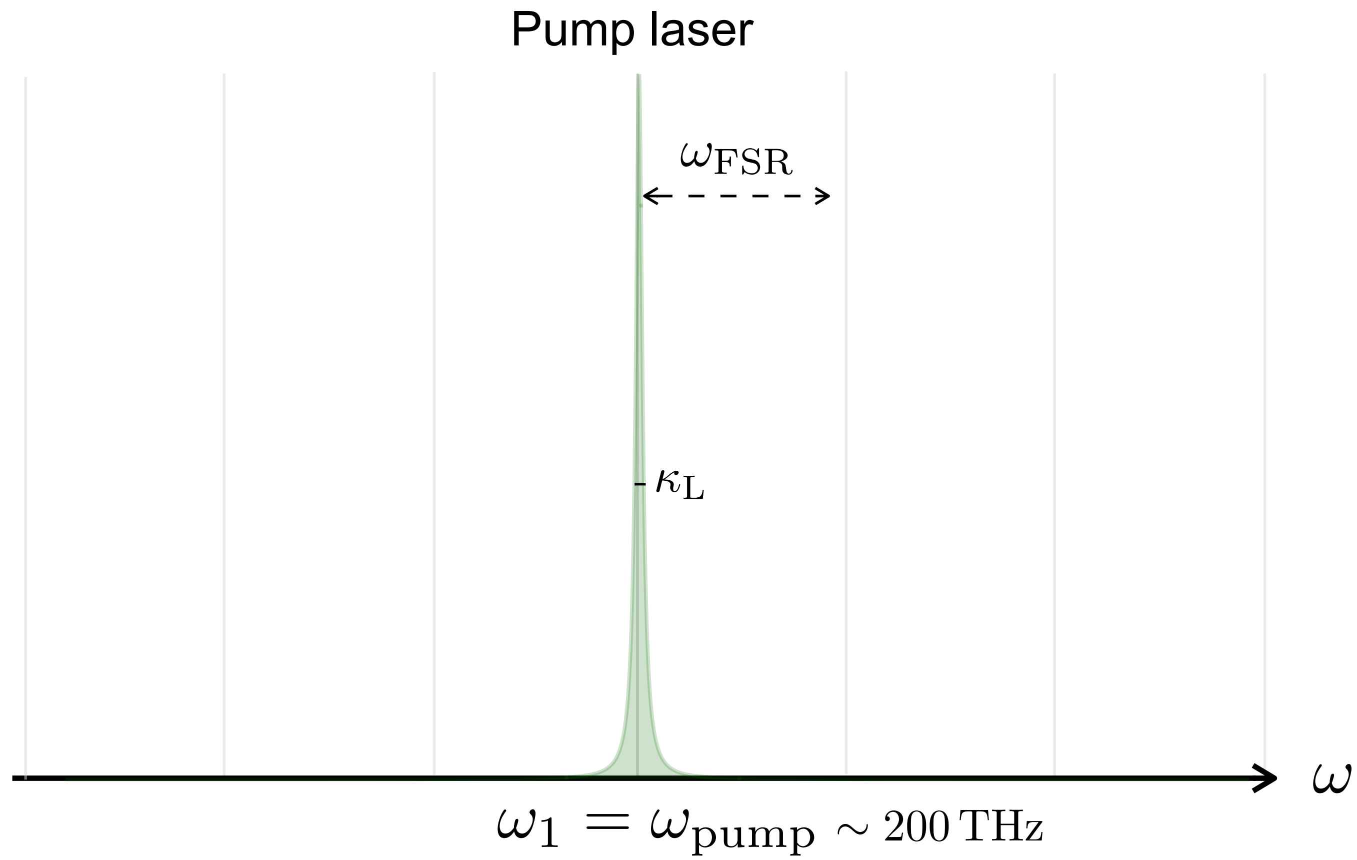


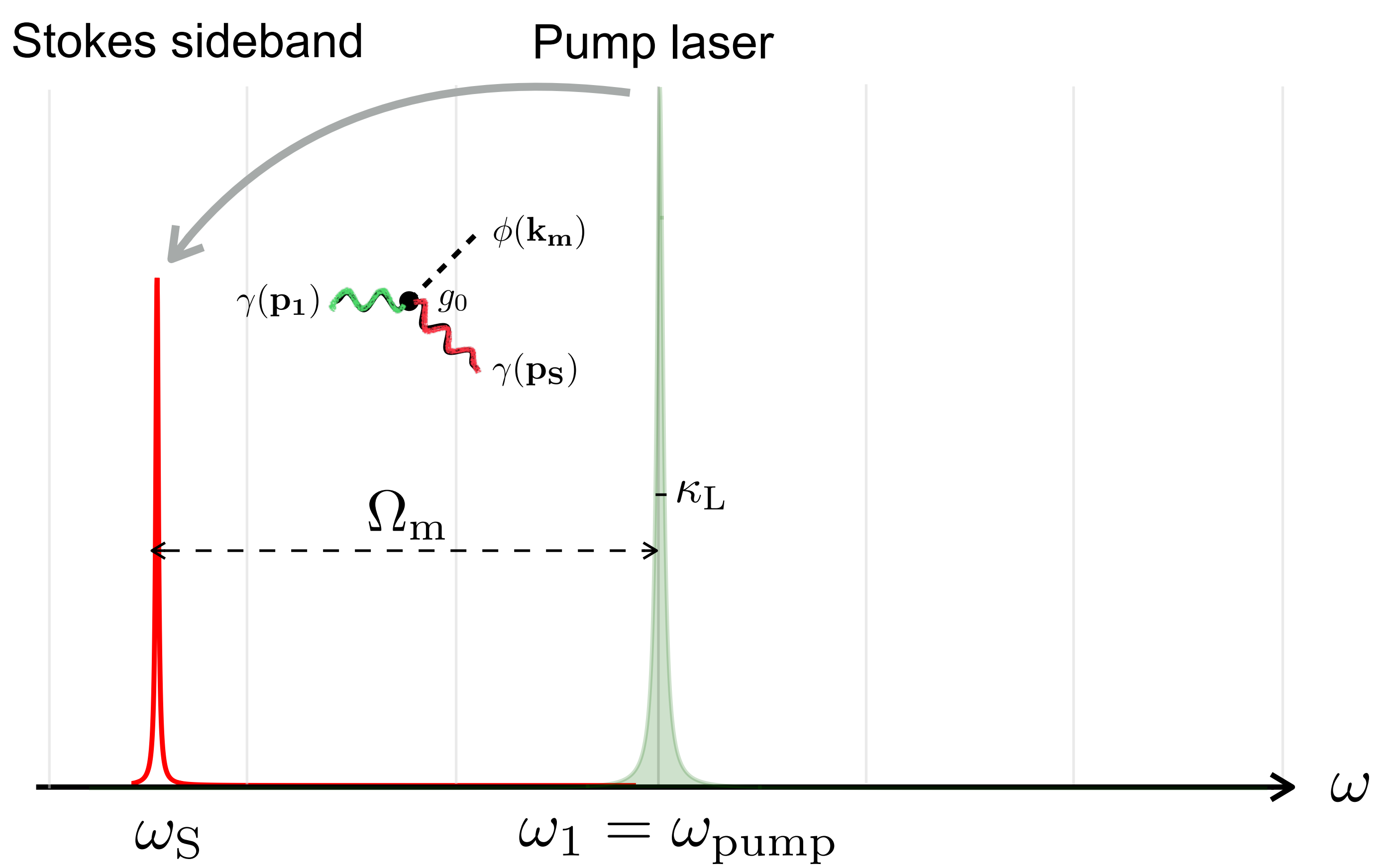
Density of states $\rho(\omega) = \frac{1}{\pi} \frac{\kappa_\mathrm{L}/2}{(\omega - \omega_1)^2 + (\kappa_\mathrm{L}/2)^2}$

Cavity Optomechanics

$$H_{\rm OM} \ni g_0\, a_{n_1}\, a^\dagger_{n_2}\, (b_{n_{\rm m}} + b^\dagger_{n_{\rm m}})$$

$$g_0 = \omega_{\rm opt} \frac{3}{2} \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \frac{1}{\varepsilon_r} \sqrt{\frac{|\mathbf{k}_{\rm m}|}{2 c_s \rho V_{\rm mode}}}\, a_{\rm ovl} \quad \text{with} \quad a_{\rm ovl} = \text{sinc}\left(\frac{\pi}{2}(n_1 + n_2 \pm n_{\rm m})\right)$$

Mode overlap factor. $a_{\rm ovl} = 1$ indicates momentum conservation in free space



Energy conservation: $\omega_2 = \omega_1 - \Omega_{\rm m}$

Momentum conservation (mode overlap): $\mathbf{p}_2 = \mathbf{p}_1 - \mathbf{k}_{\rm m}$

$$\omega_{1,2} = |\mathbf{p}_{1,2}|, \quad \Omega_{\rm m} = c_s |\mathbf{k}_{\rm m}|$$

$$c_s \ll 1 \quad \rightarrow \quad \mathbf{k}_{\rm m} \approx 2\mathbf{p}_1 \approx -2\mathbf{p}_2$$

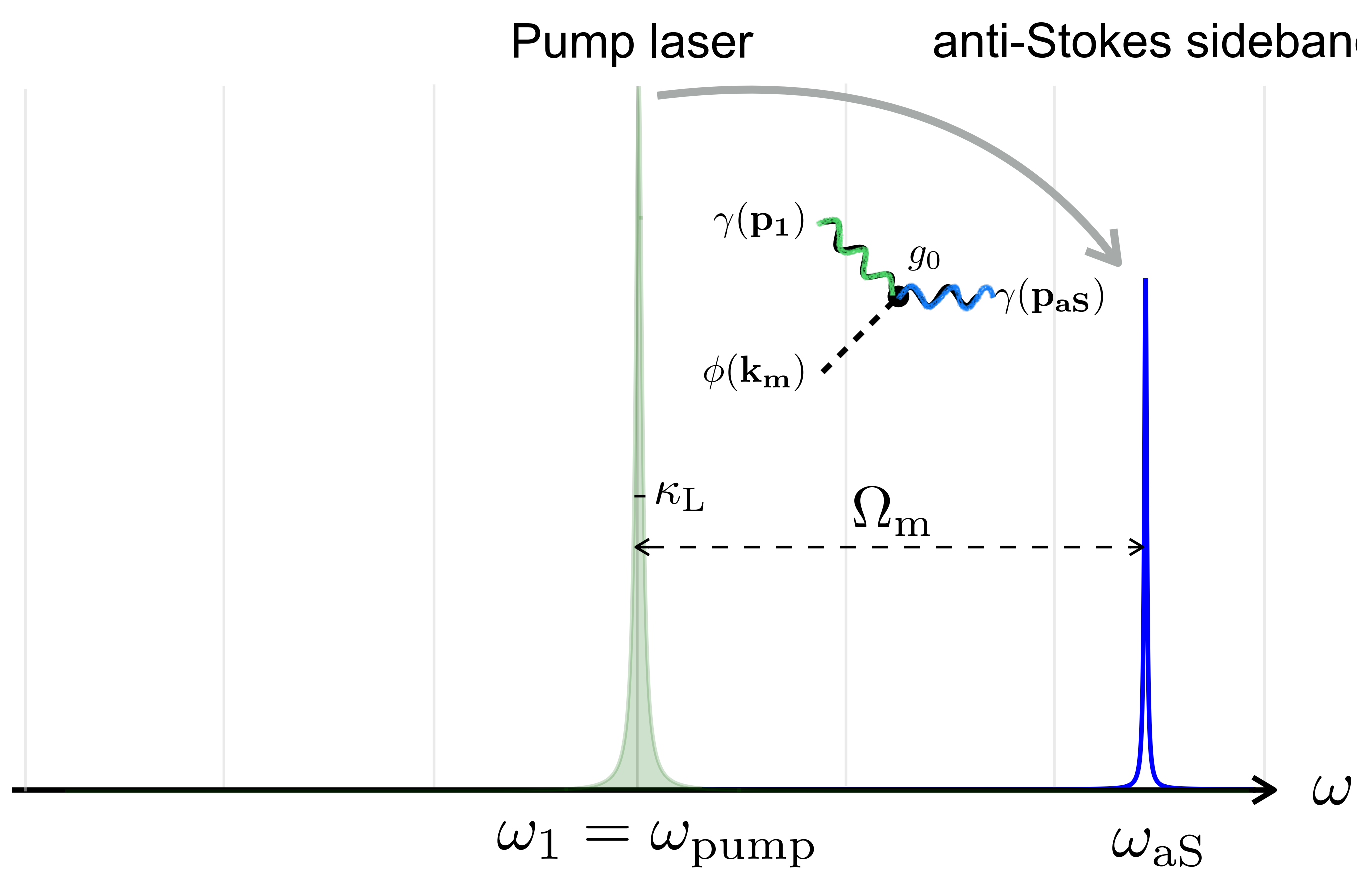
$$\Omega_{\rm m} \approx 2 c_s \omega_1$$

Cavity Optomechanics

$$H_{\rm OM} \ni g_0\, a_{n_1}\, a^\dagger_{n_2}\, \left(b_{n_{\rm m}} + b^\dagger_{n_{\rm m}}\right)$$

$$g_0 = \omega_{\rm opt} \frac{3}{2}\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\frac{1}{\varepsilon_r}\sqrt{\frac{|\mathbf{k}_{\rm m}|}{2 c_s \rho V_{\rm mode}}}\, a_{\rm ovl} \quad \text{with} \quad a_{\rm ovl} = \text{sinc}\left(\frac{\pi}{2}(n_1 + n_2 \pm n_{\rm m})\right)$$

Mode overlap factor. $a_{\rm ovl} = 1$ indicates momentum conservation in free space



Energy conservation: $\omega_2 = \omega_1 + \Omega_{\rm m}$

Momentum conservation (mode overlap): $\mathbf{p}_2 = \mathbf{p}_1 + \mathbf{k}_{\rm m}$

$$\omega_{1,2} = |\mathbf{p}_{1,2}|, \quad \Omega_{\rm m} = c_s |\mathbf{k}_{\rm m}|$$

$$c_s \ll 1 \quad \rightarrow \quad \mathbf{k}_{\rm m} \approx -2\mathbf{p}_1 \approx 2\mathbf{p}_2$$

$$\Omega_{\rm m} \approx 2 c_s \omega_1$$

Cavity Optomechanics

$$H_{\rm OM} \ni g_0\, a_{n_1}\, a^\dagger_{n_2}\, \left(b_{n_{\rm m}} + b^\dagger_{n_{\rm m}}\right)$$

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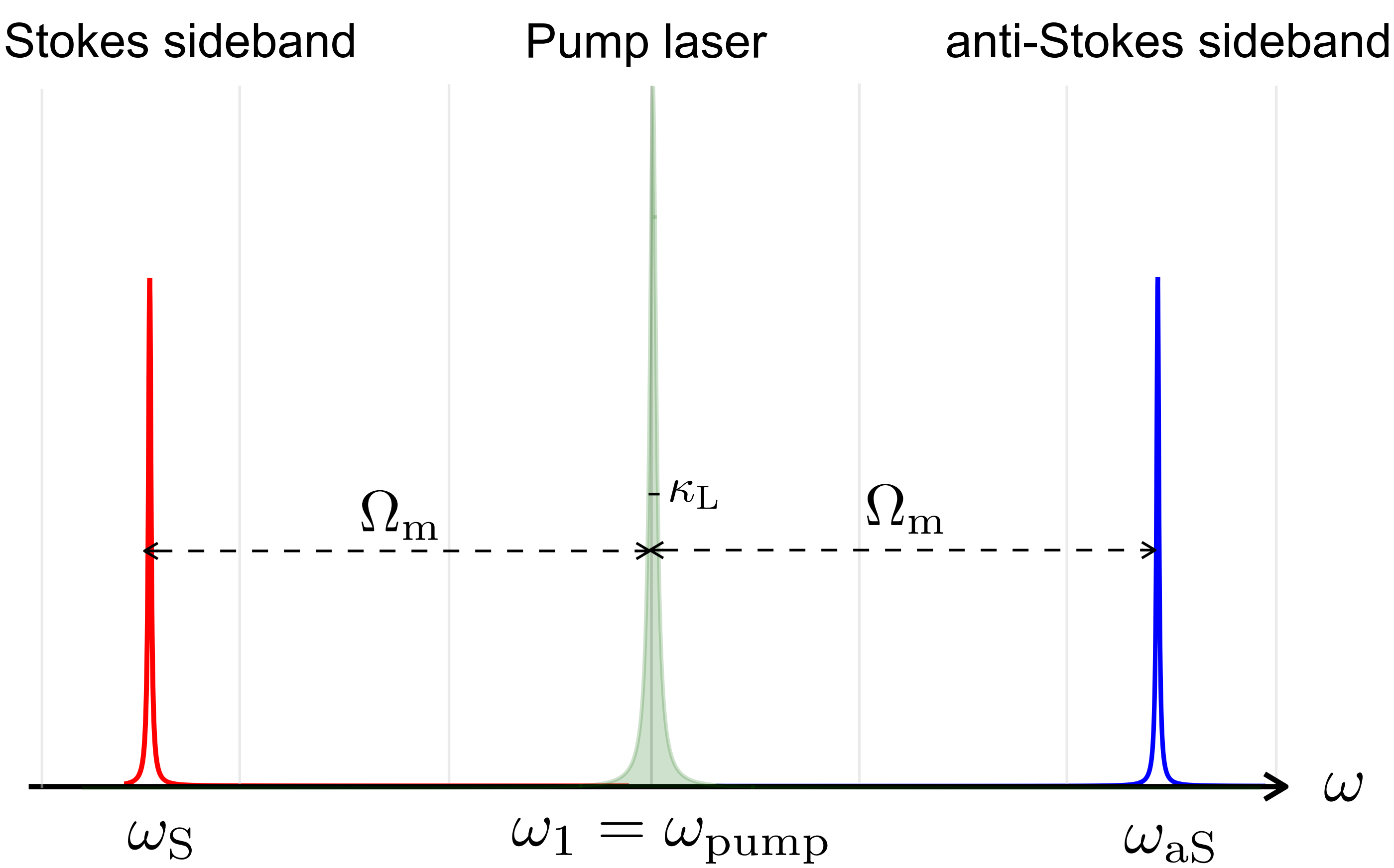
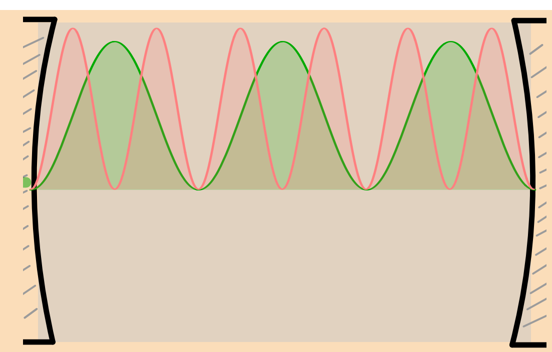


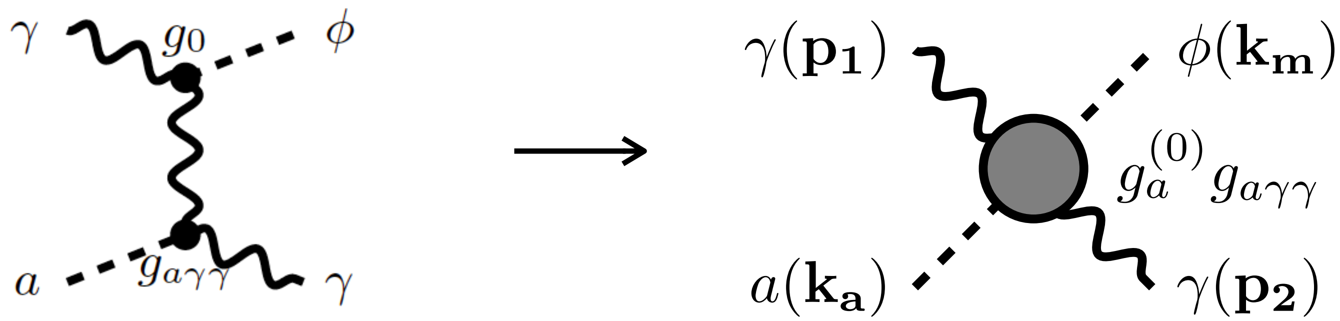
Cavity optomecanical kinematics

$$\pm\mathbf{k}_{\rm m} = 2\mathbf{p}_1 \approx -2\mathbf{p}_2 \quad (n_{\rm m} = 2n_1 = 2n_2)$$

$$\Omega_{\rm m} \approx 2c_s\omega_1$$



Axioptomechanics - kinematics



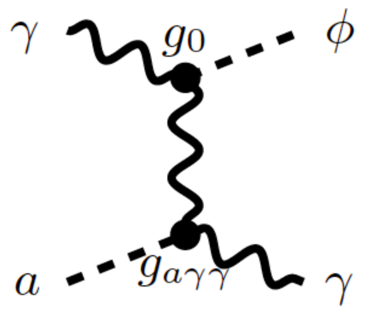
$$g_a^{(0)} \propto a_{\rm ovl} = {\rm sinc}\left(\frac{\pi}{2}(n_1 + n_2 - n_{\rm m} + \frac{k_a}{\pi/L})\right)$$

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

$$H_{\rm eff} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma} \int d^3\mathbf{r}\, a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$$

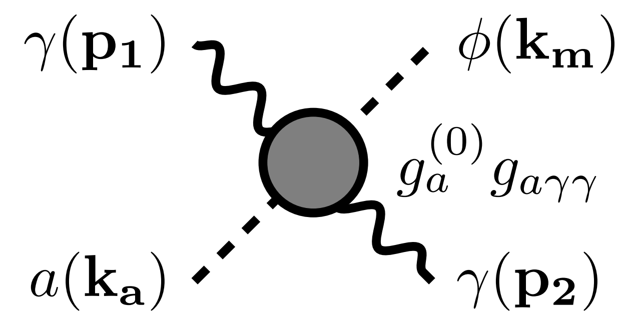
$$H_{\rm eff} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a^\dagger_{n_2}\, b^\dagger_{n_{\rm m}}$$

Axioptomechanics - kinematics



$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$

$\longrightarrow$



$g_a^{(0)} \propto a_{\mathrm{ovl}} = \mathrm{sinc}\left(\frac{\pi}{2}(n_1 + n_2 - n_{\mathrm{m}} + \frac{k_a}{\pi/L})\right)$

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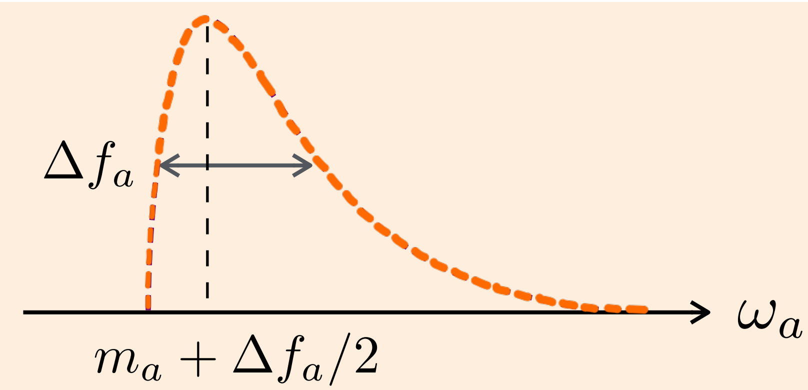
$$H_{\mathrm{eff}} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a_{n_2}^\dagger\, b_{n_{\mathrm{m}}}^\dagger$$

Axion dark matter $|a(\omega_a)|^2 = \frac{2\rho_a}{m_a^2} B(\omega_a)$

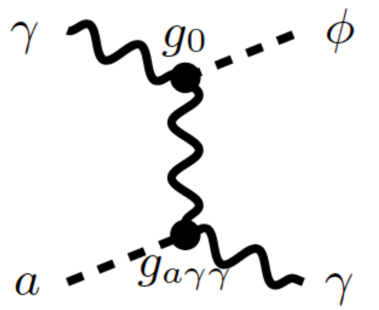
$$k_a \sim v_a m_a \sim v_a \omega_a$$

$(\mathrm{recall}\ k_{\mathrm{m}} \sim c_s^{-1}\Omega_{\mathrm{m}},\ p_{1,2} \sim \omega_{1,2})$



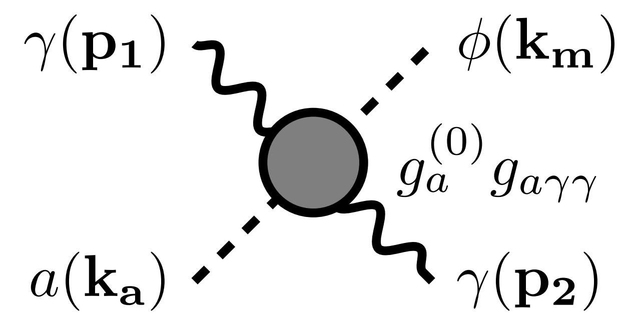
Axion width $\Delta f_a = \tau_a^{-1} = m_a v_a^2/(2\pi) \sim 10^{-7} m_a$

Axioptomechanics - kinematics



$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$

$\longrightarrow$



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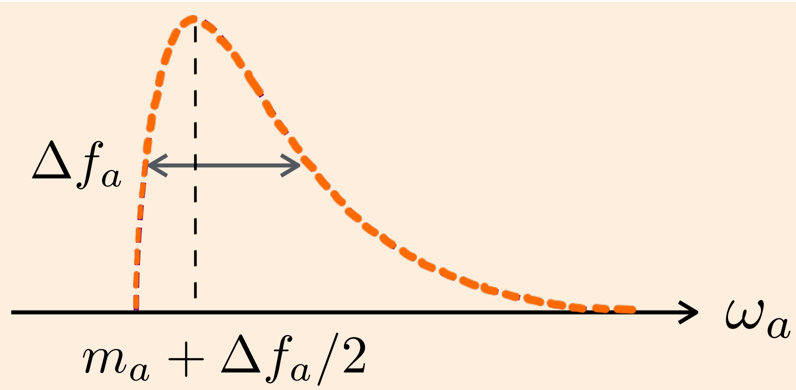


Axion width $\Delta f_a = \tau_a^{-1} = m_a v_a^2/(2\pi) \sim 10^{-7} m_a$

Energy conservation: $\omega_1 + m_a \simeq \omega_2 + \Omega_{\rm m}$

Momentum conservation ($a_{\rm ovl} = 1$): $\mathbf{p}_1 + \mathbf{k}_a = \mathbf{p}_2 + \mathbf{k}_{\rm m}$

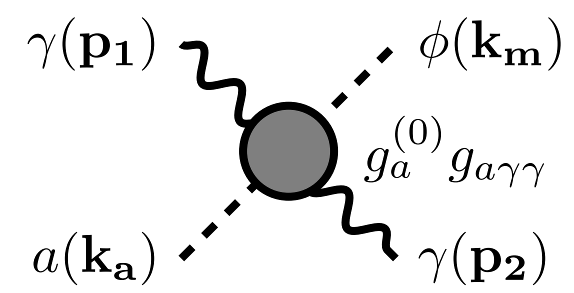
Axioptomechanics kinematics:

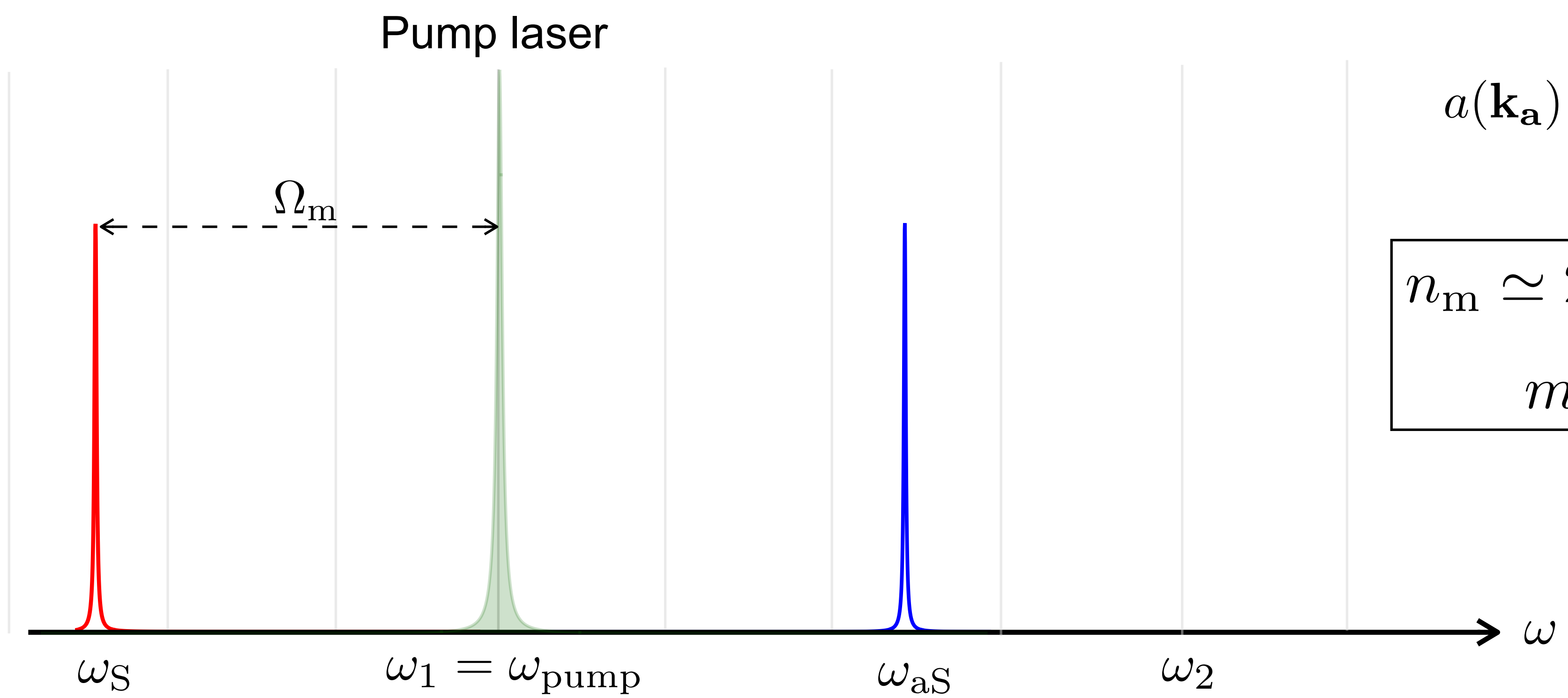
$$n_{\rm m} \simeq 2\,n_1 + [m_a/\omega_{\rm FSR}]$$
$$m_a \simeq \Delta + \Omega_{\rm m}$$

Axion mass decouples from $\omega_{\rm FSR}$, thus the cavity length, because of the phonon mode.

Axioptomechanics - rates

$$H_{\rm eff} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a^\dagger_{n_2}\, b^\dagger_{n_{\rm m}}$$



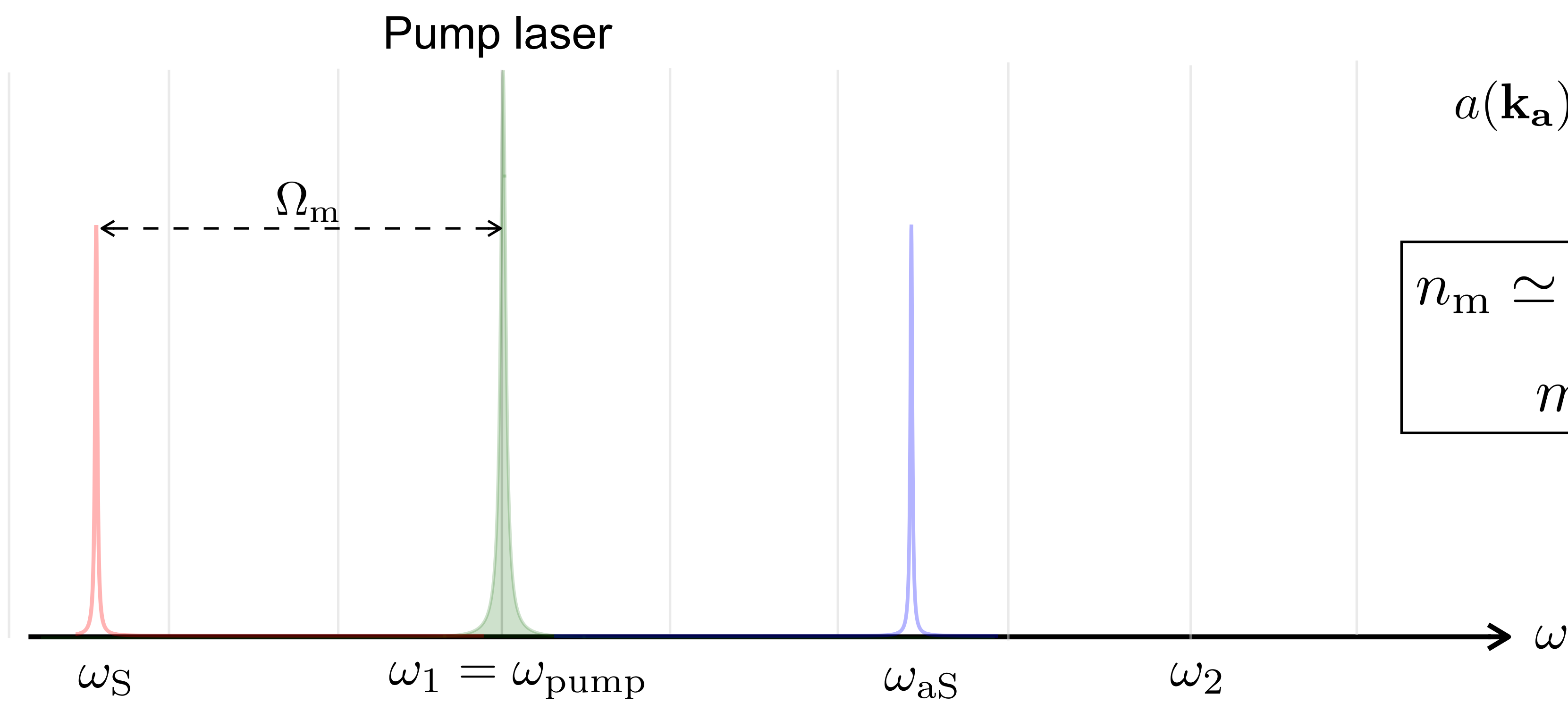


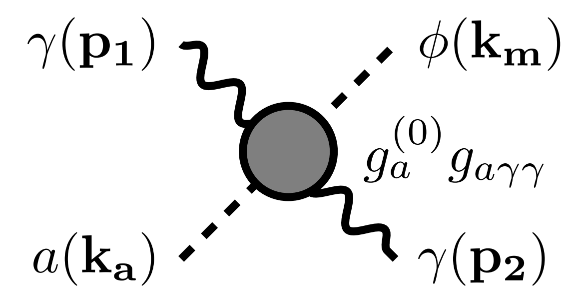
$$n_{\rm m} \simeq 2\, n_1 + [m_a/\omega_{\rm FSR}]$$

$$m_a \simeq \Delta + \Omega_{\rm m}$$

Axioptomechanics - rates

$$H_{\text{eff}} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a_{n_2}^\dagger\, b_{n_{\text{m}}}^\dagger$$





$$n_{\text{m}} \simeq 2\, n_1 + [m_a/\omega_{\text{FSR}}]$$
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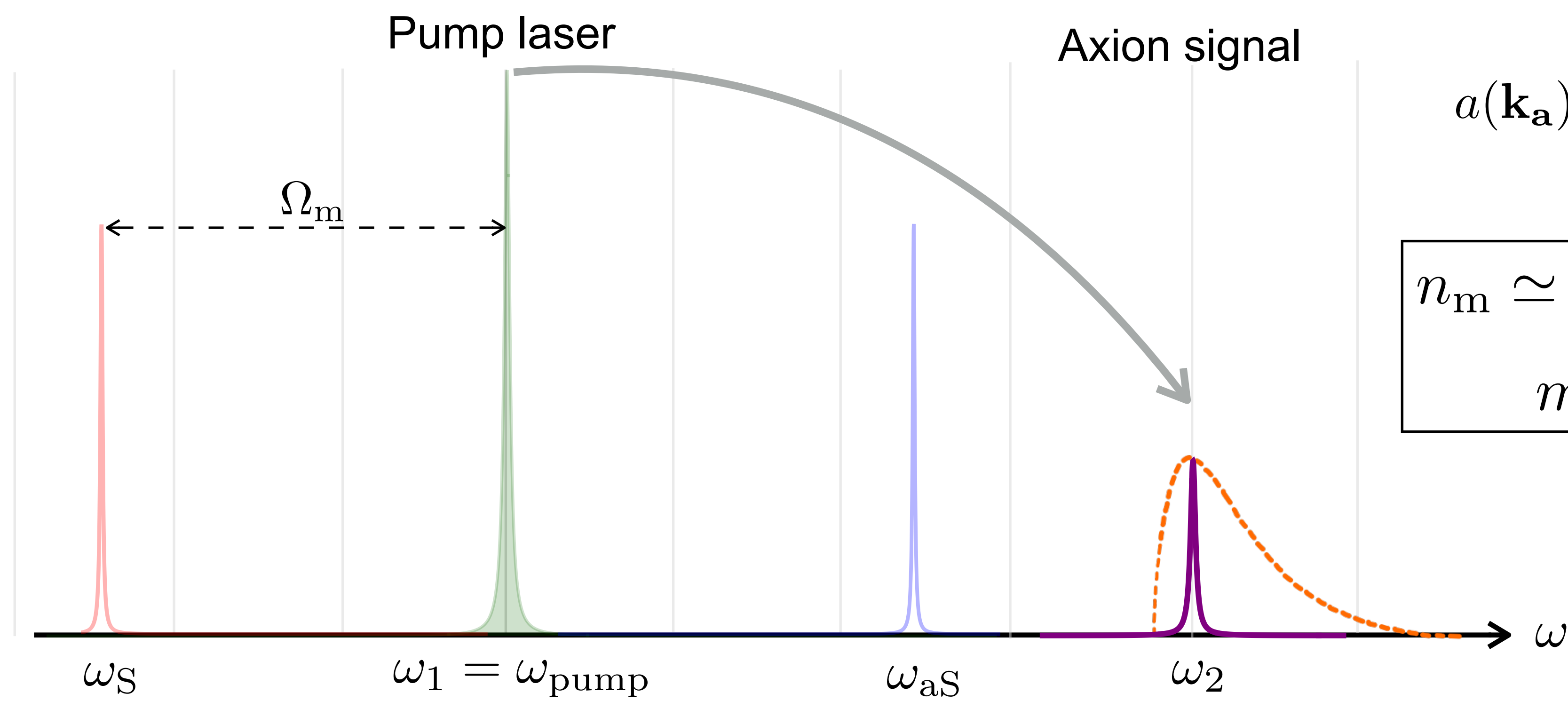
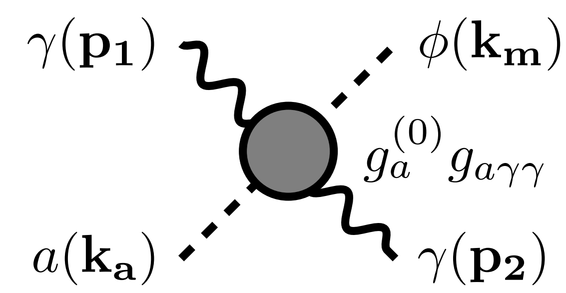
Axioptomechanics - rates

$$H_{\text{eff}} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a_{n_2}^\dagger\, b_{n_\text{m}}^\dagger$$





$$n_\text{m} \simeq 2\, n_1 + [m_a/\omega_\text{FSR}]$$

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Axioptomechanics - rates

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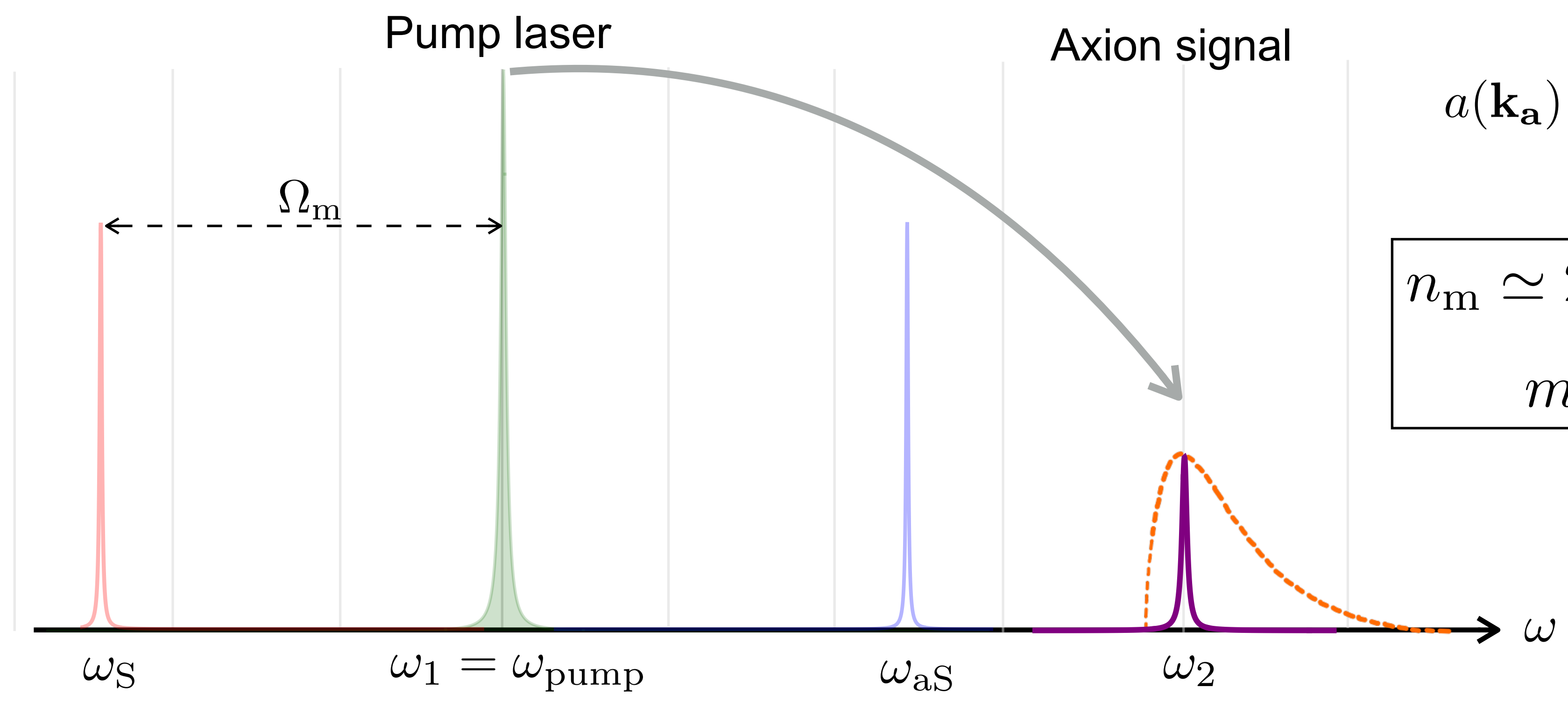

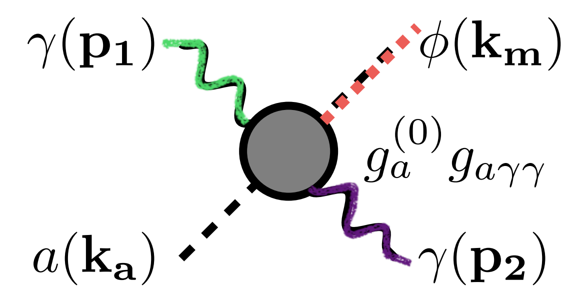

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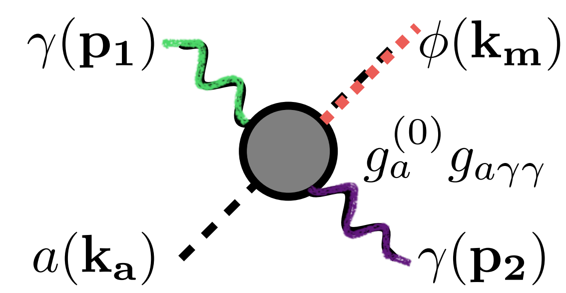

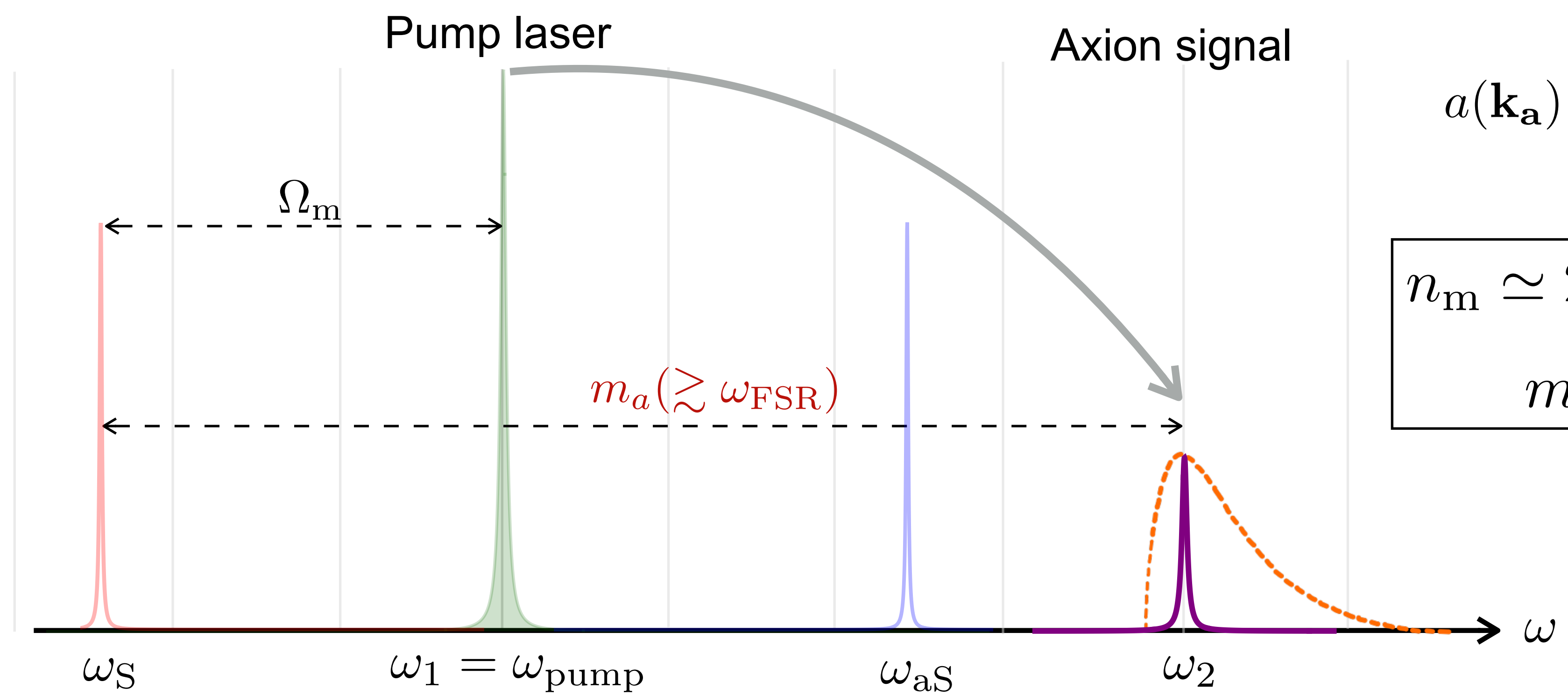

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Axioptomechanics - rates

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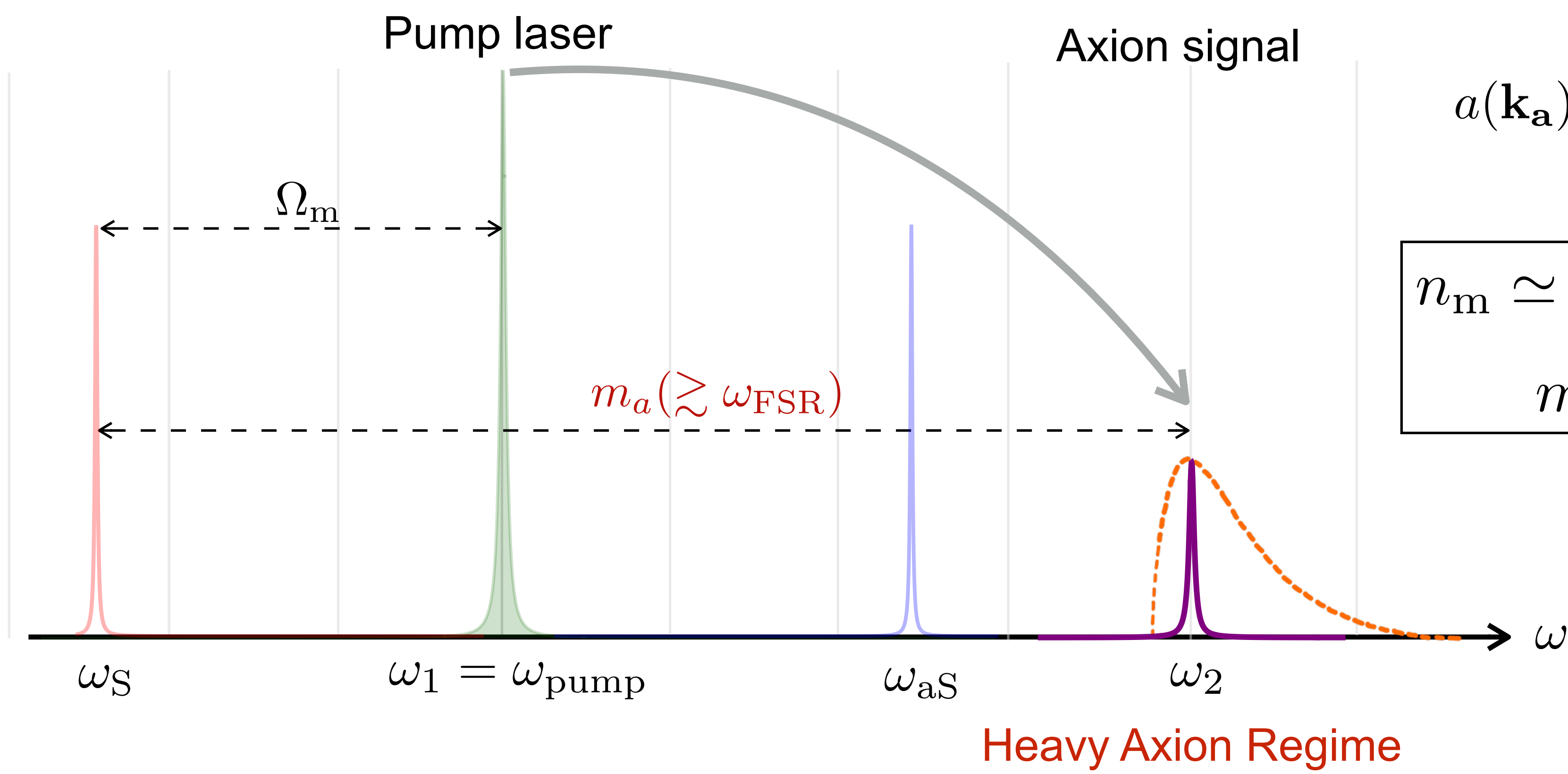

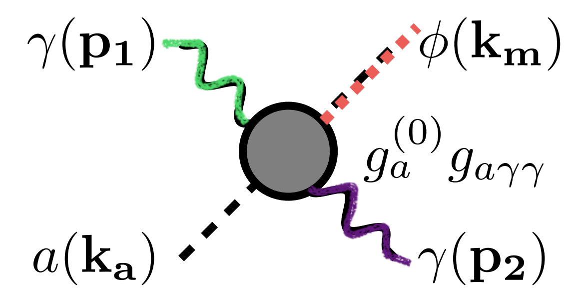

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Axioptomechanics - rates

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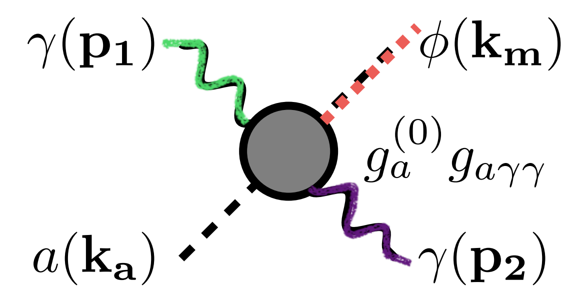

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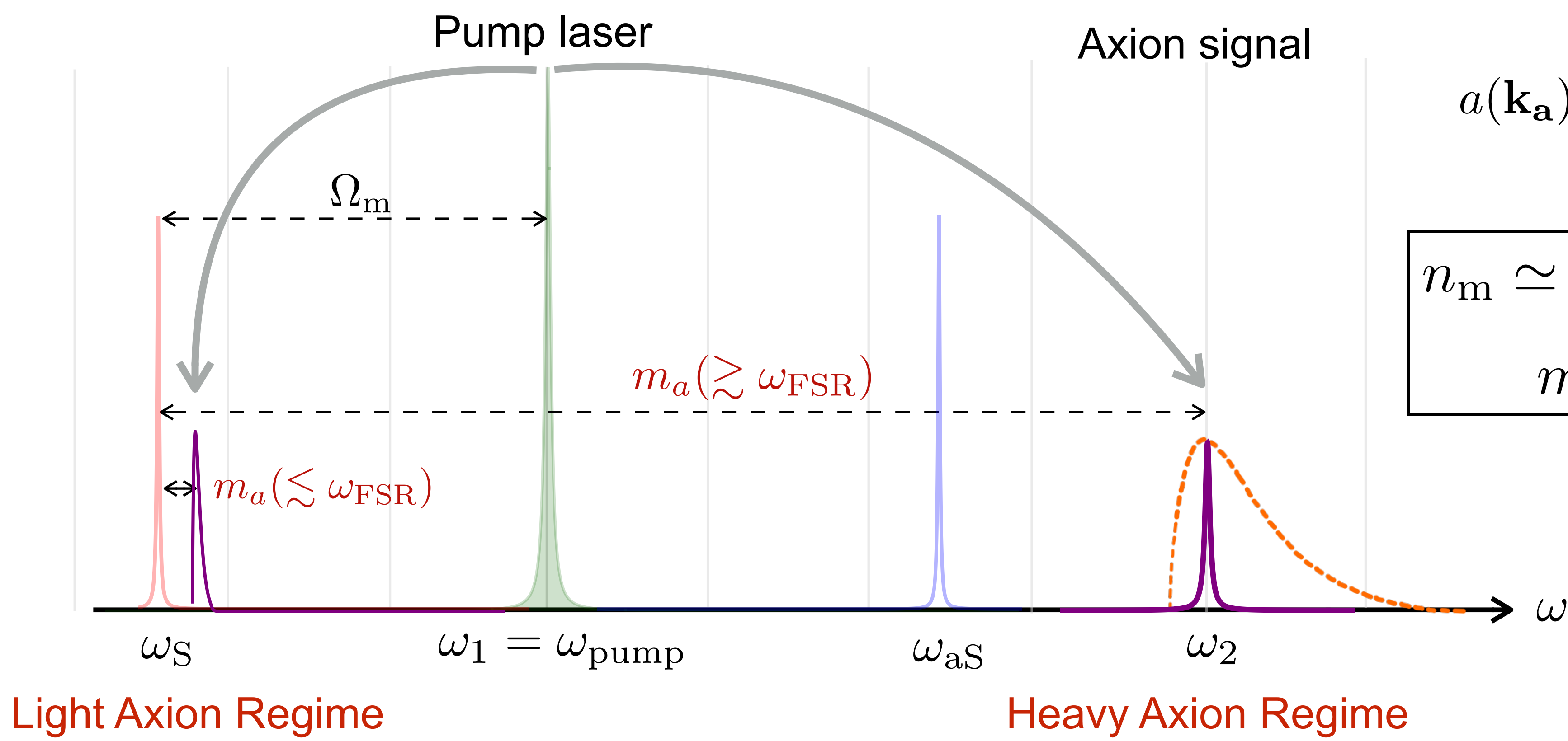

Axioptomechanics - rates

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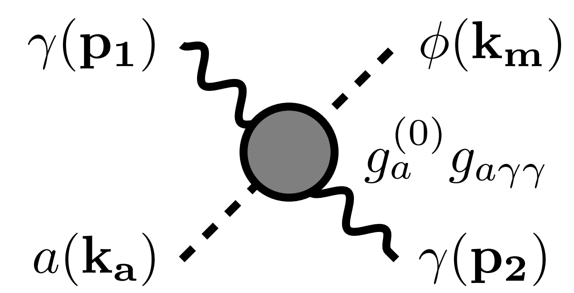

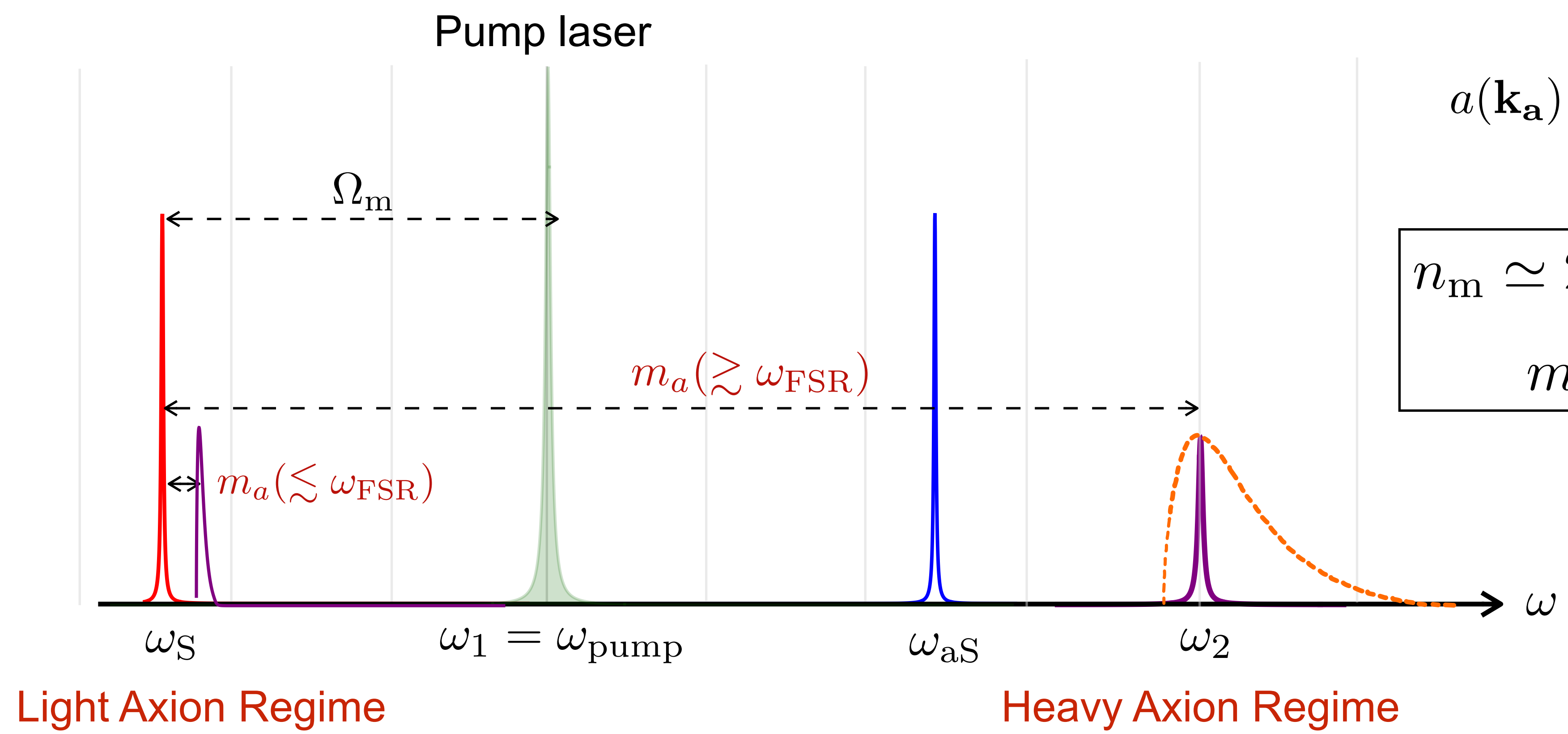

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Axioptomechanics - rates

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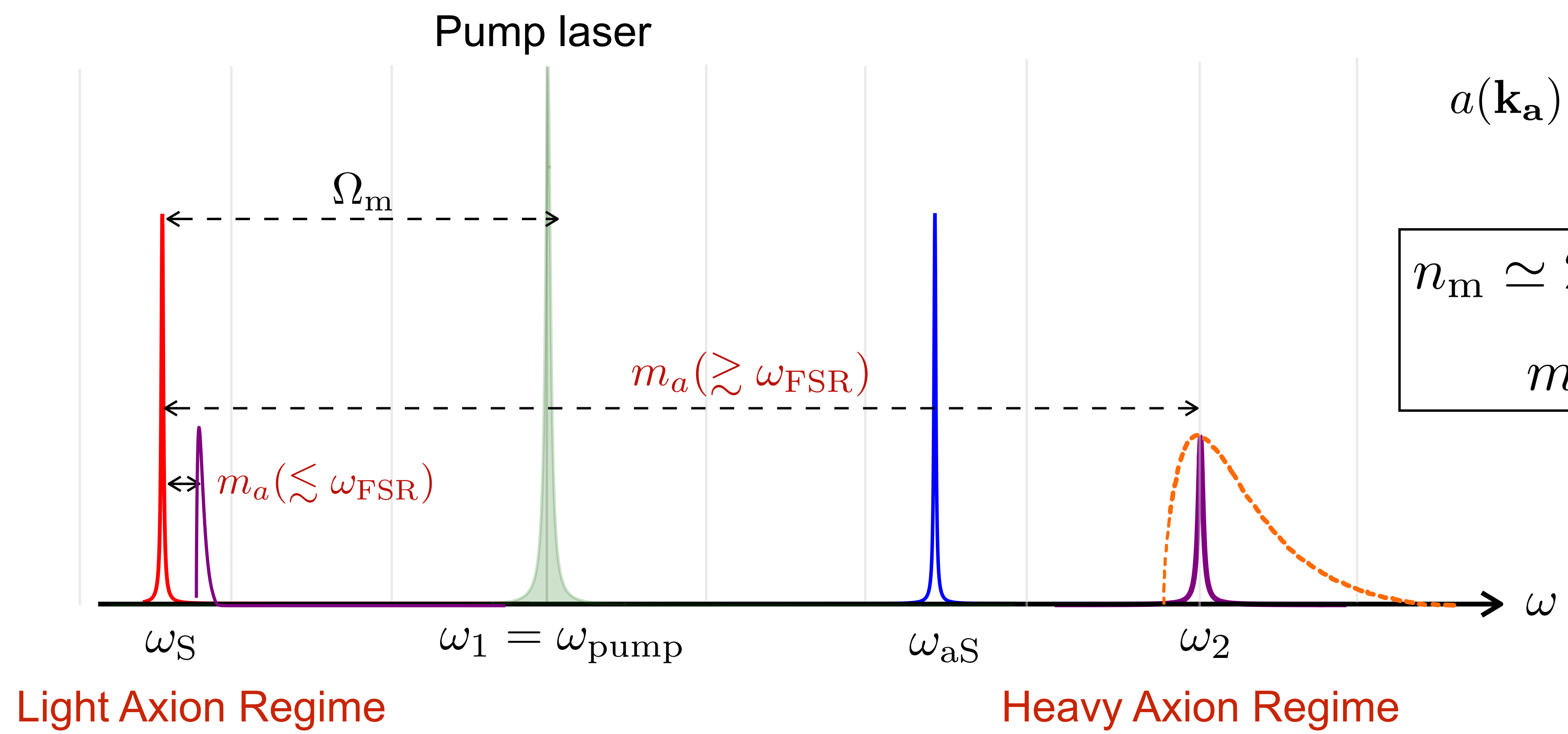
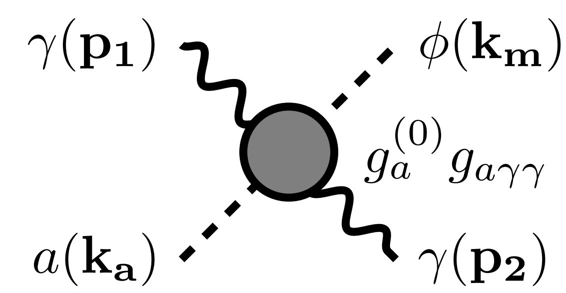




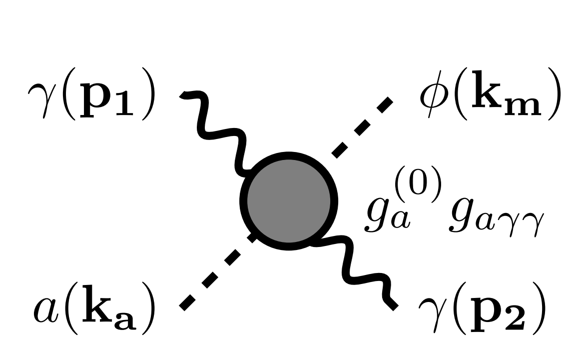
$$n_\text{m} \simeq 2\,n_1 + [m_a/\omega_\text{FSR}]$$
$$m_a \simeq \Delta + \Omega_\text{m}$$

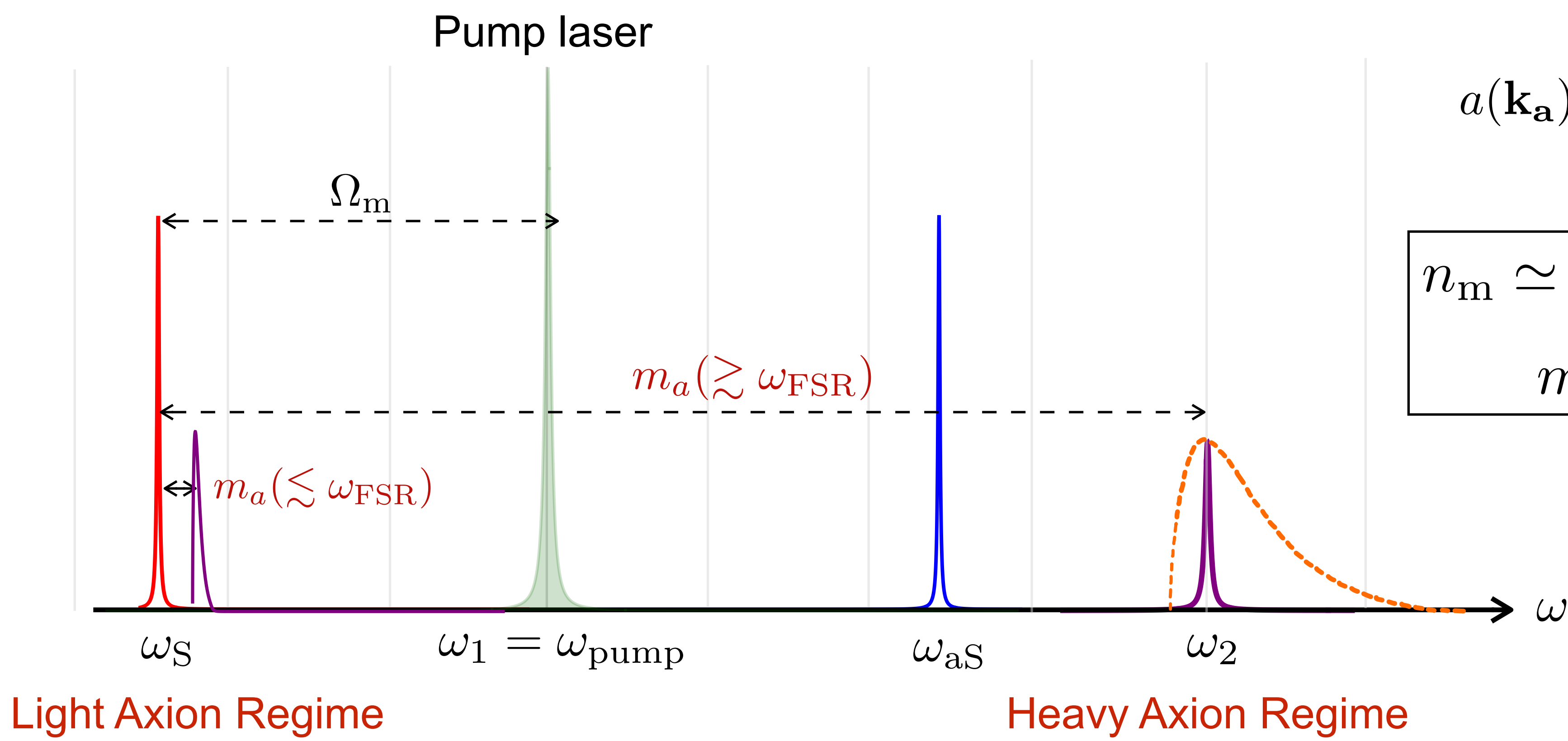
The rate $\Gamma \sim (2\pi)|g_a^{(0)}|^2 \left(\frac{2\rho_a}{m_a^2}\, g^2_{a\gamma\gamma}\right)$

$\sim \mathcal{O}(10^{-44})$ for QCD axion

Axioptomechanics - rates

$$H_{\text{eff}} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a_{n_2}^\dagger\, b_{n_\text{m}}^\dagger$$





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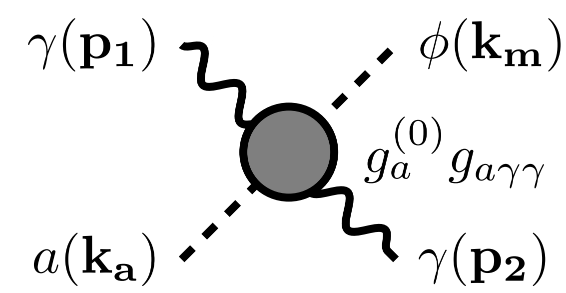
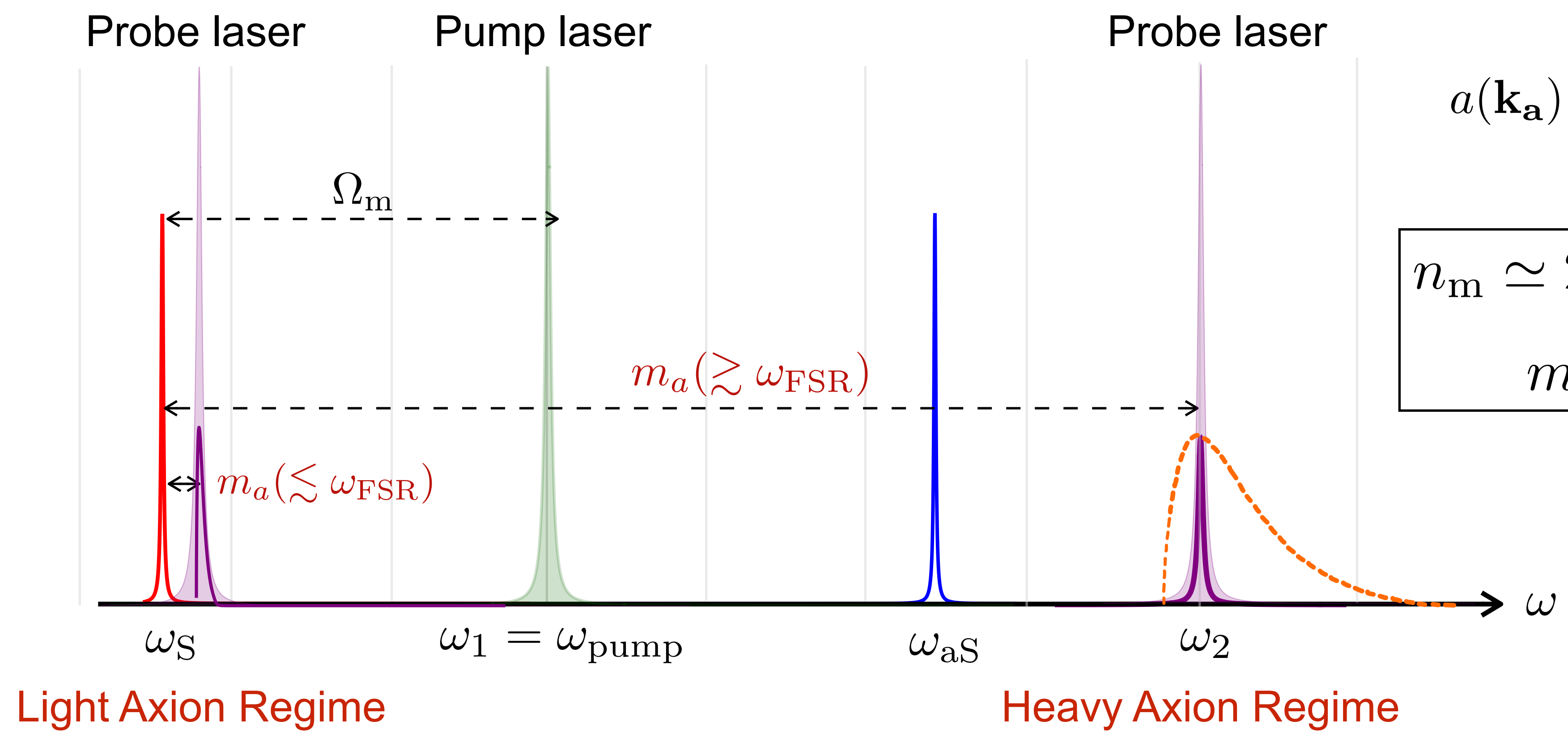
Axioptomechanics - rates

$$H_{\text{eff}} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a_{n_2}^\dagger\, b_{n_m}^\dagger$$





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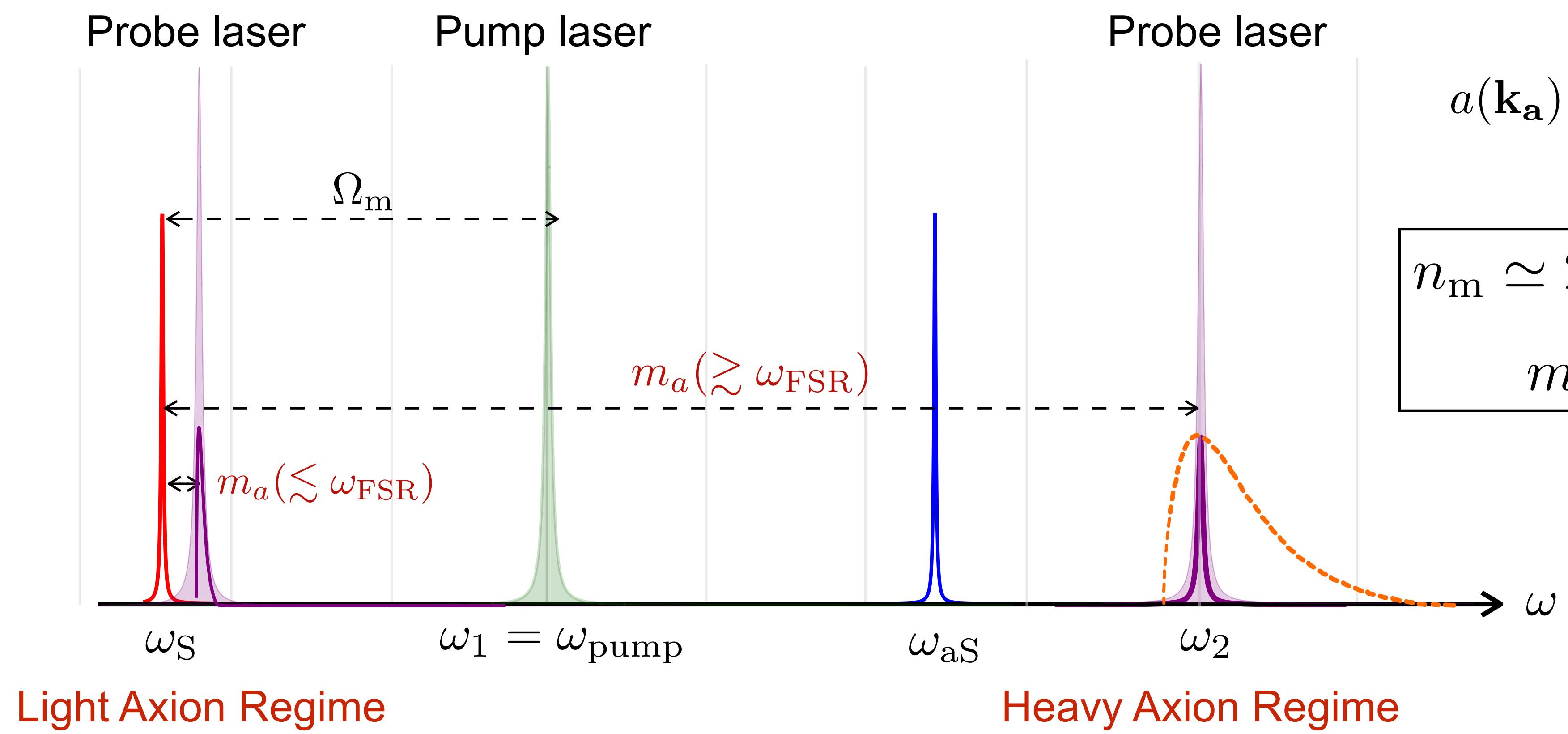
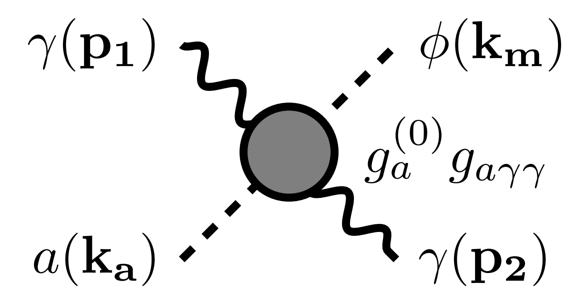
$\sim \mathcal{O}(10^{-44})$ for QCD axion

Axioptomechanics - rates

$$H_{\text{eff}} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a_{n_2}^\dagger\, b_{n_\text{m}}^\dagger$$





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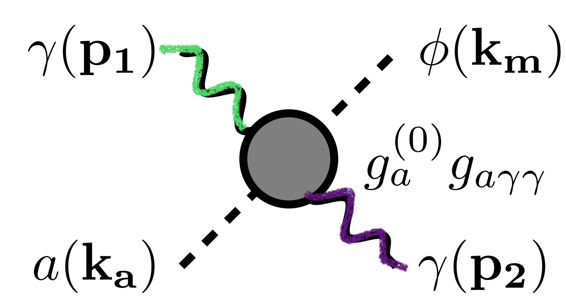
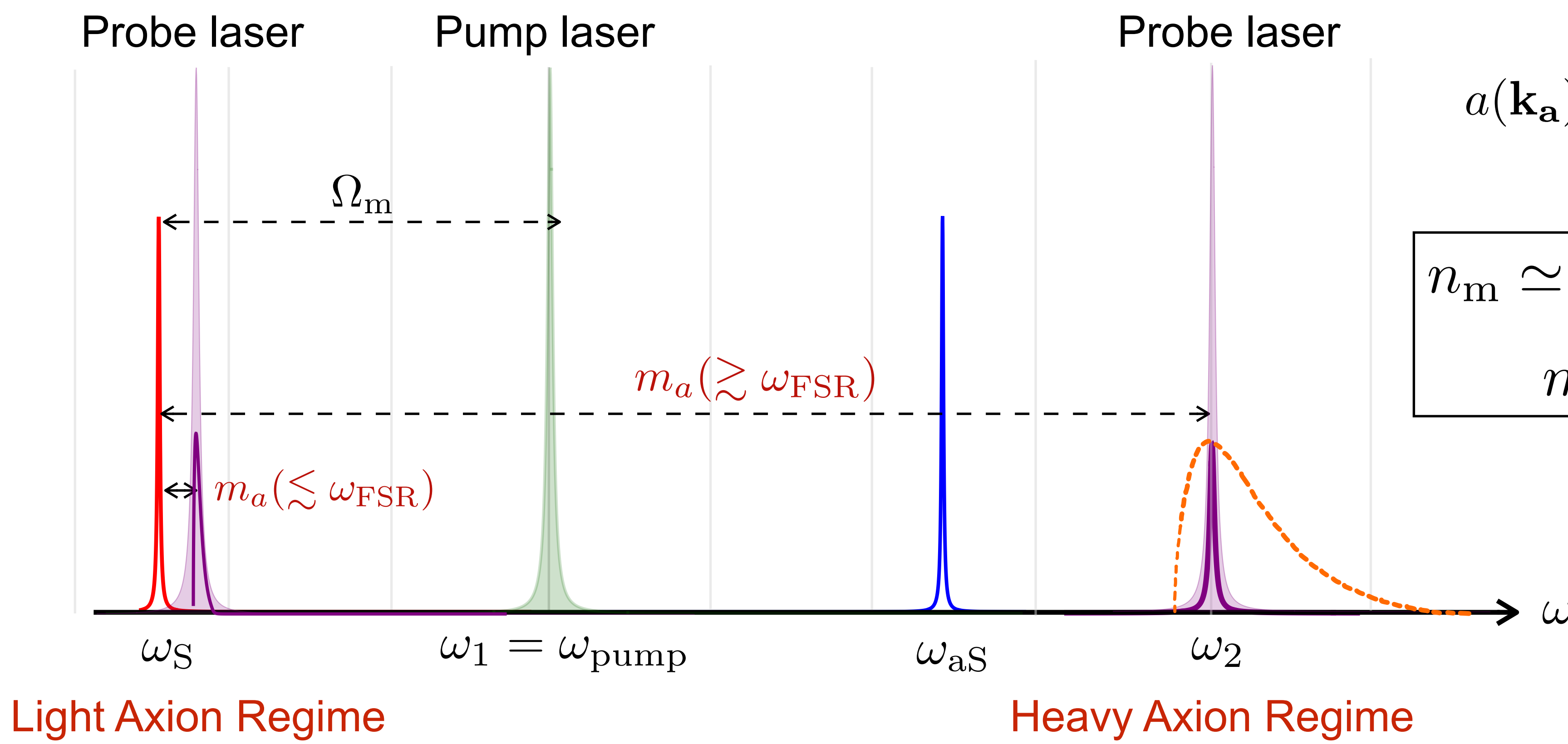
$\sim \mathcal{O}(10^{-44})$ for QCD axion

'coherent enhancement'

Axioptomechanics - rates

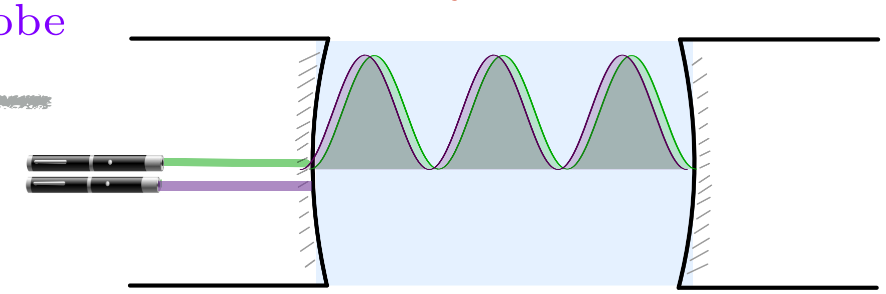
$$H_{\rm eff} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a^\dagger_{n_2}\, b^\dagger_{n_{\rm m}}$$





$$n_{\rm m} \simeq 2\, n_1 + [m_a/\omega_{\rm FSR}]$$
$$m_a \simeq \Delta + \Omega_{\rm m}$$

‘photon-pop’
Heterodyne detection



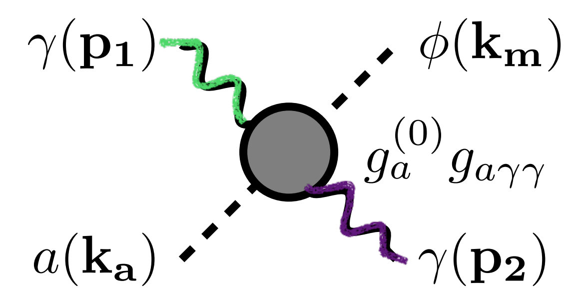
The rate $\Gamma \sim (2\pi)|g_a^{(0)}|^2 \left(\frac{2\rho_a}{m_a^2}\, g_{a\gamma\gamma}^2\right) N^{\rm circ}_{\gamma,\rm pump}\, N^{\rm circ}_{\gamma,\rm probe}$

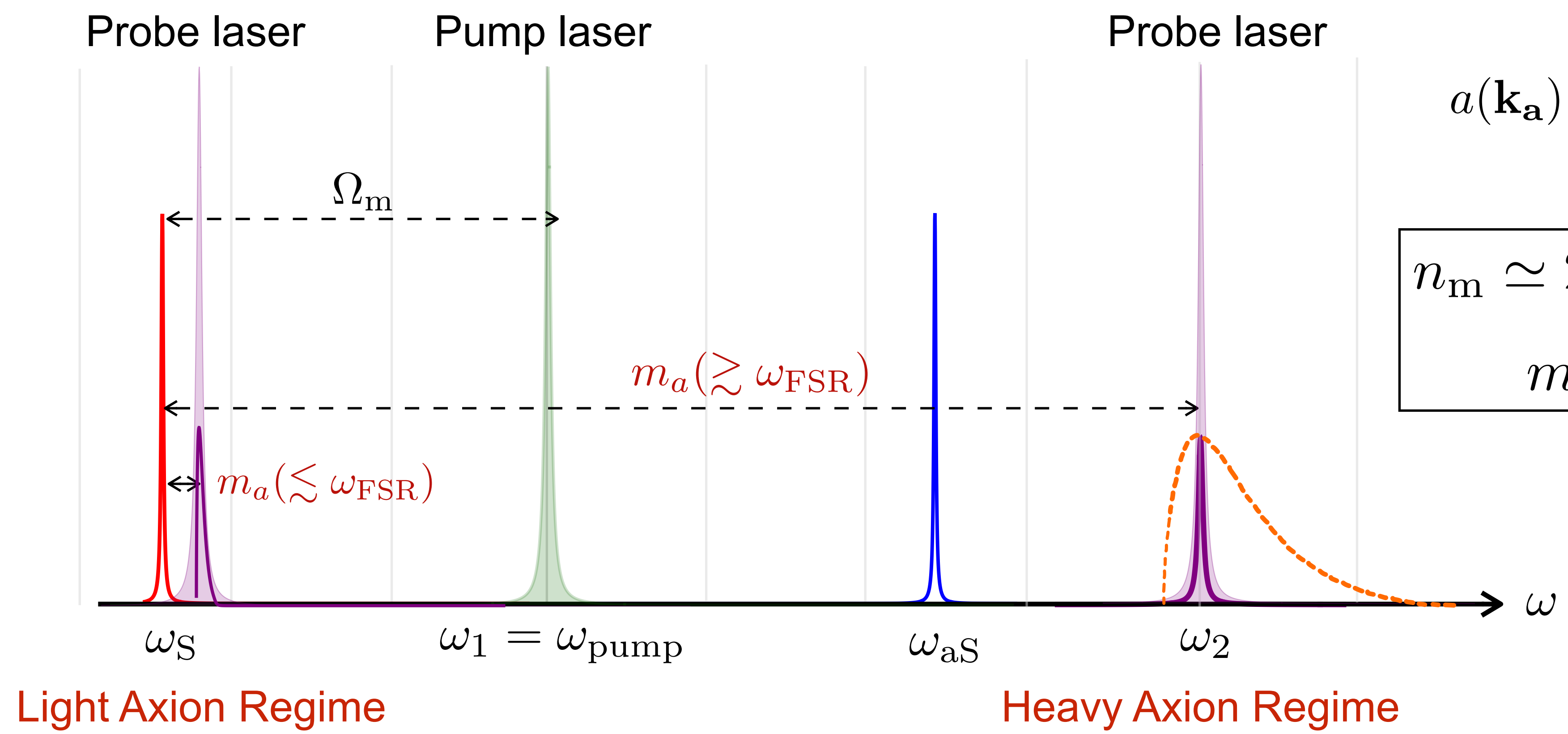
$\sim \mathcal{O}(10^{-44})$ for QCD axion

‘coherent enhancement ’

Axioptomechanics - rates

$$H_{\text{eff}} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a^\dagger_{n_2}\, b^\dagger_{n_m}$$





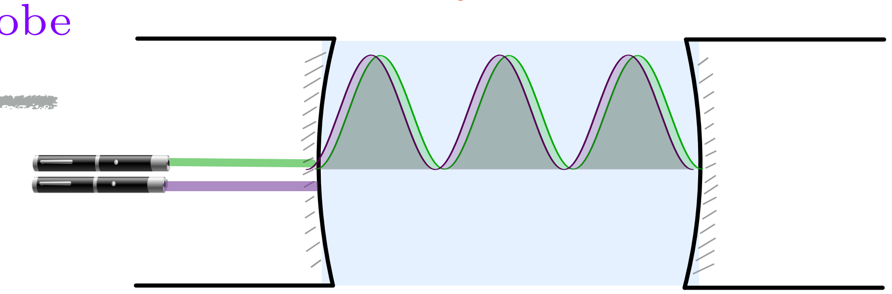
$$n_\text{m} \simeq 2\, n_1 + [m_a/\omega_\text{FSR}]$$
$$m_a \simeq \Delta + \Omega_\text{m}$$

The rate $\Gamma \sim (2\pi)|g_a^{(0)}|^2 \left(\frac{2\rho_a}{m_a^2}\, g_{a\gamma\gamma}^2\right) N_{\gamma,\text{pump}}^{\text{circ}}\, N_{\gamma,\text{probe}}^{\text{circ}}$

$\sim \mathcal{O}(10^{-44})$ for QCD axion

‘coherent enhancement ’

‘photon-pop’
Heterodyne detection



Phonon emission is spontaneous; photon emission is stimulated.

Axioptomechanics - rates

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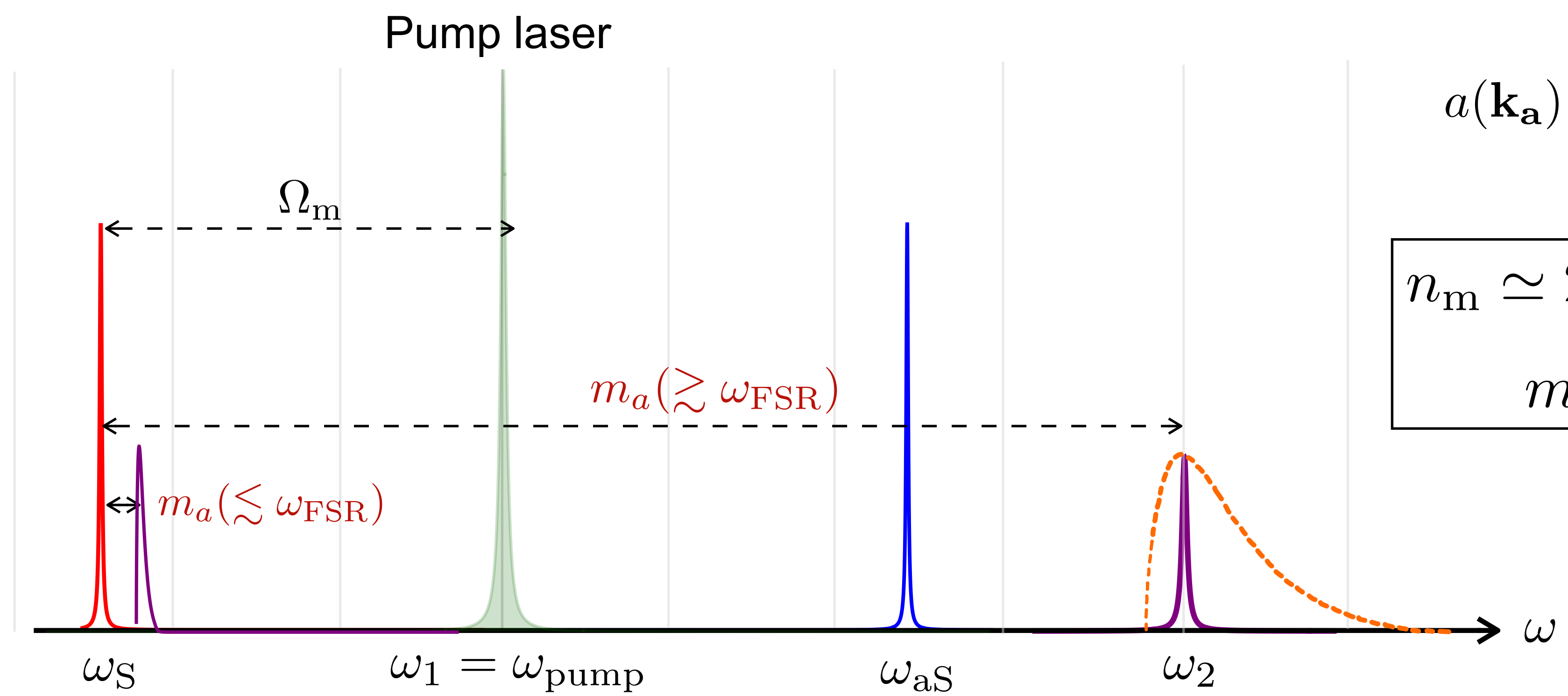

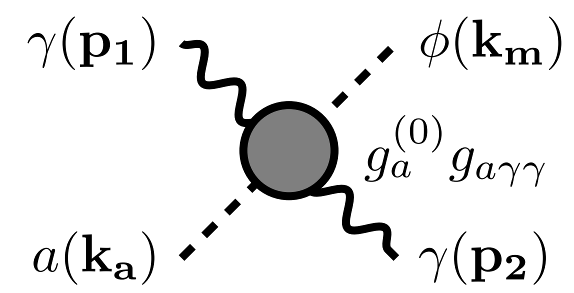

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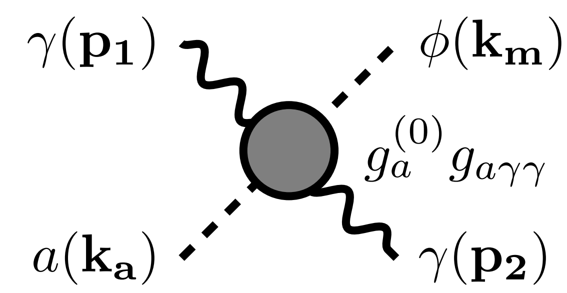

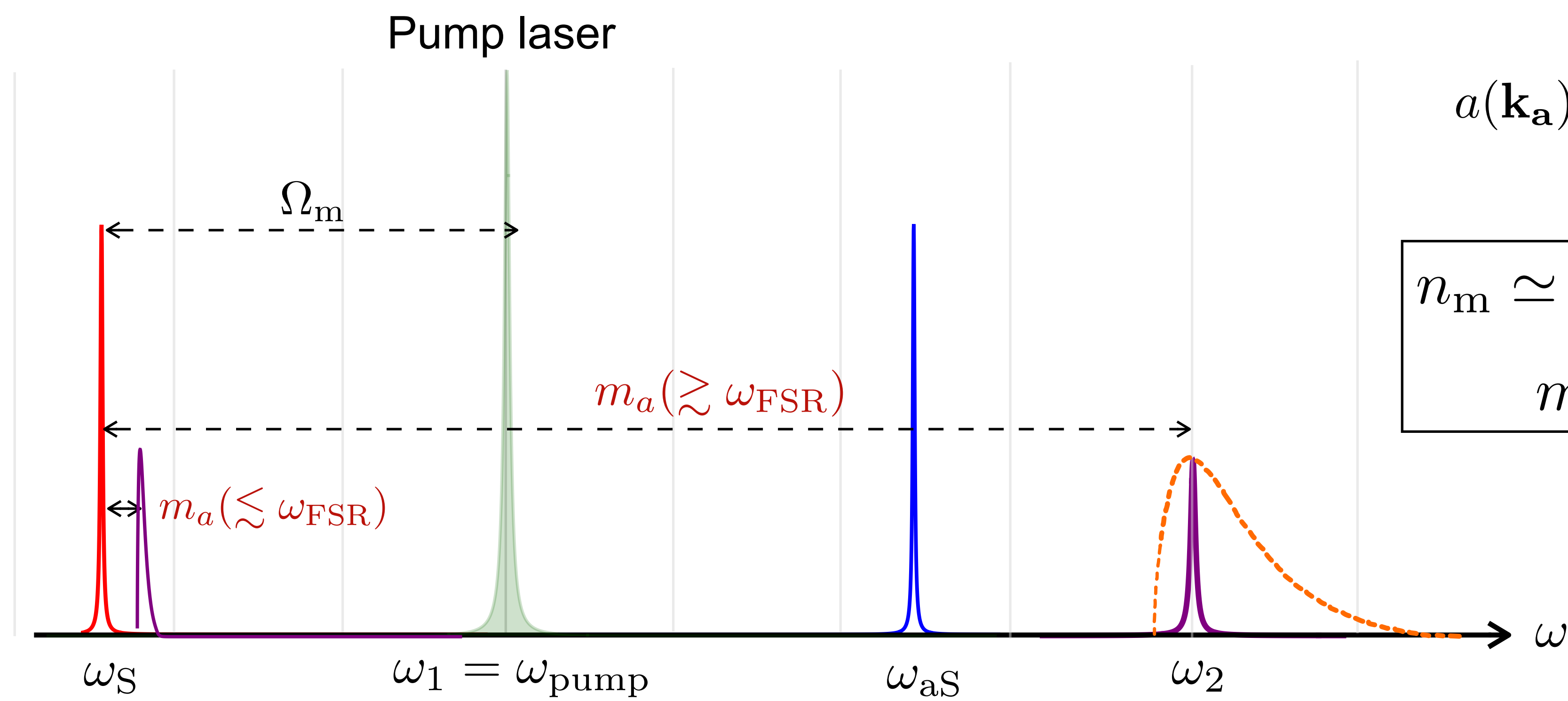

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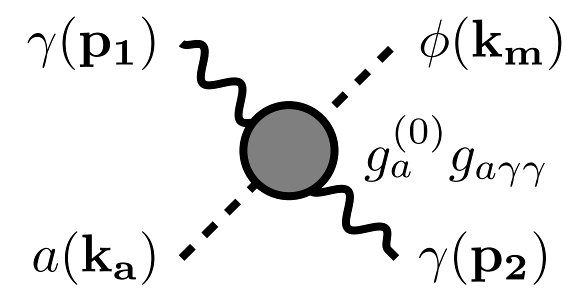

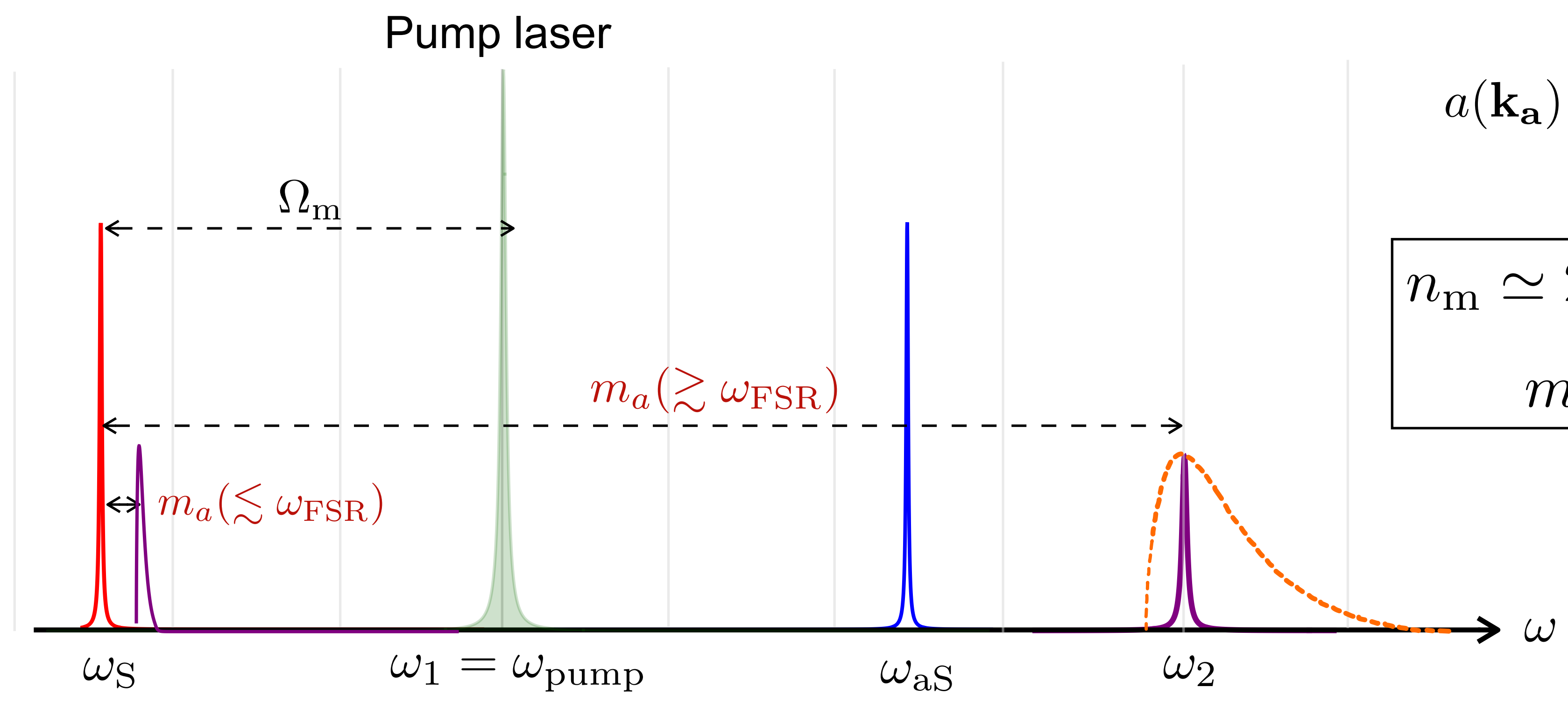

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‘coherent enhancement ’

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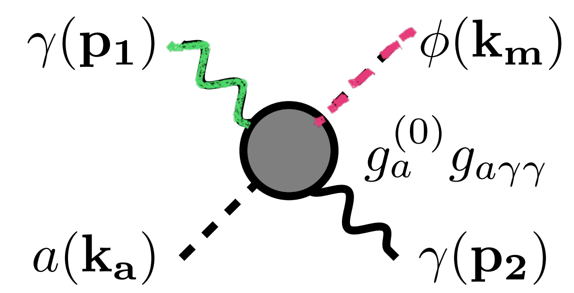

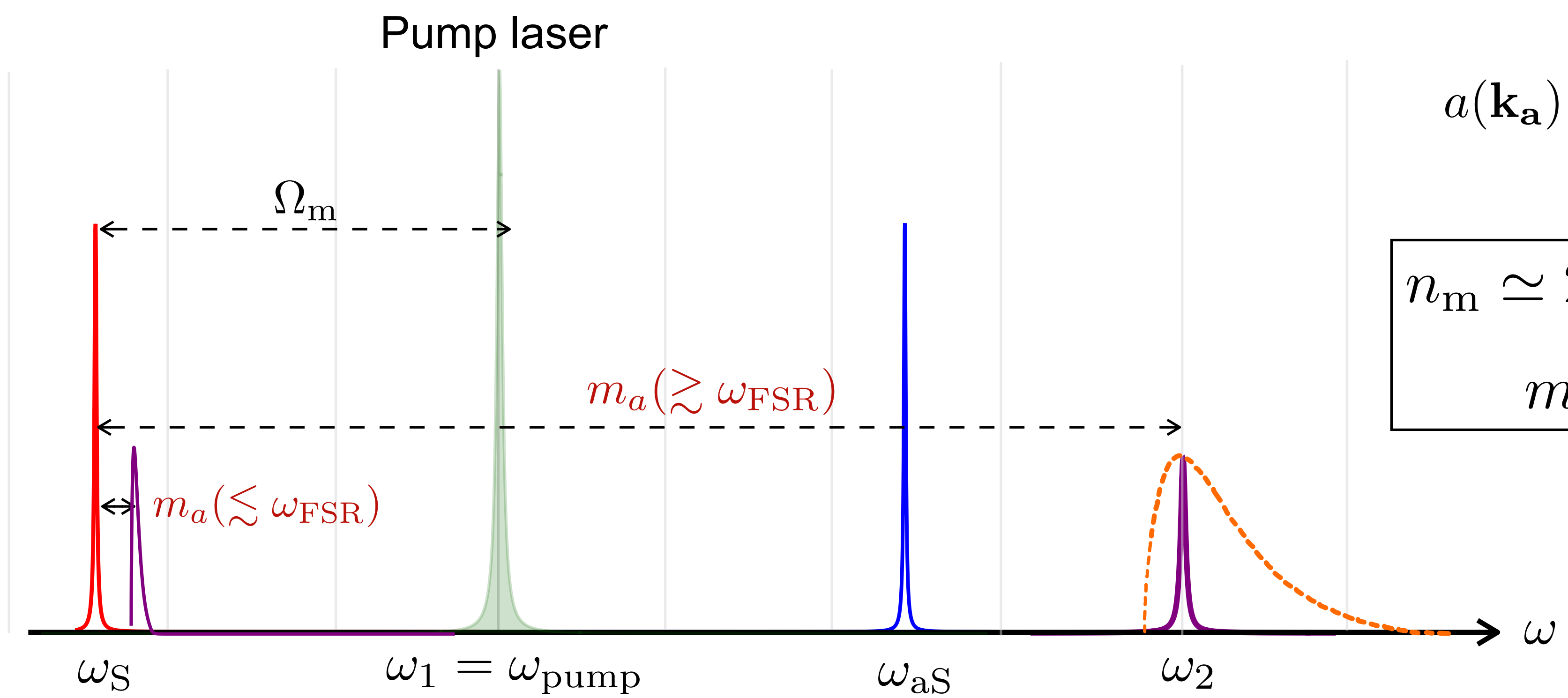

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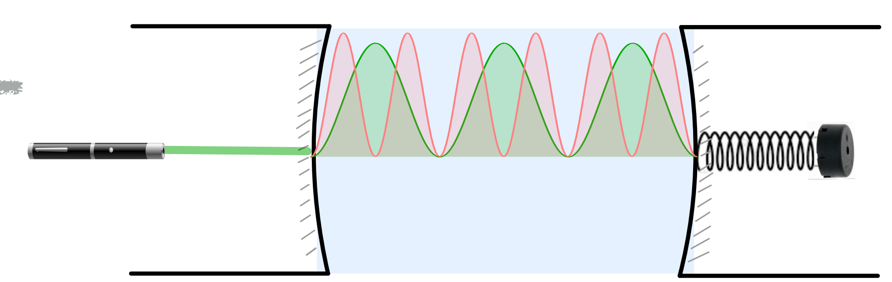
'coherent enhancement '

'phonon-pop'

Single photon detection



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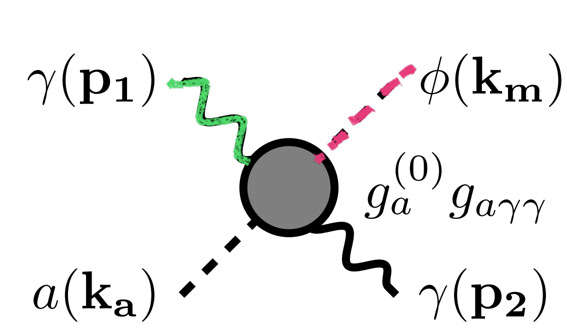

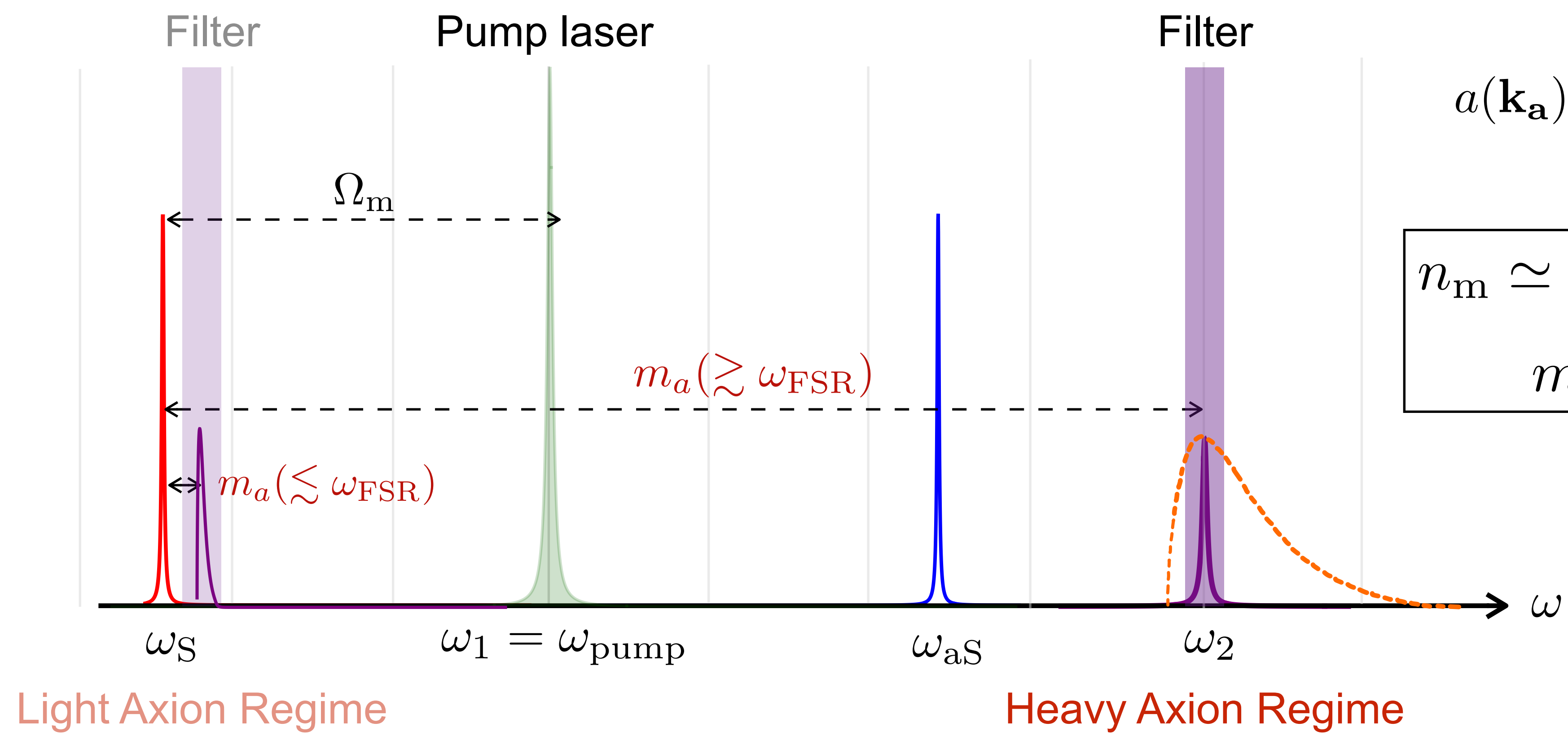

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'phonon-pop'
Single photon detection

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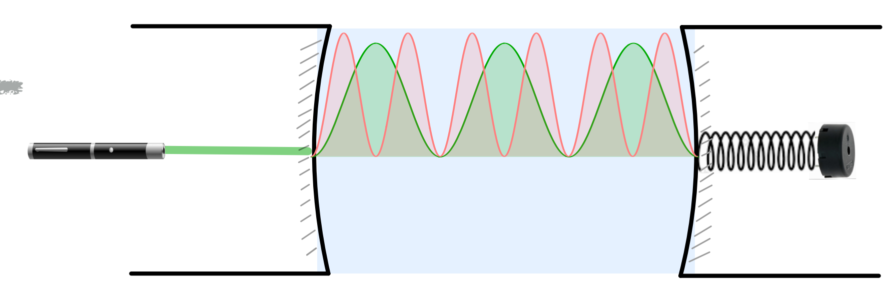

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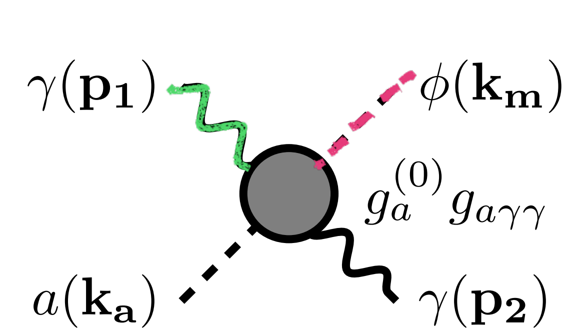

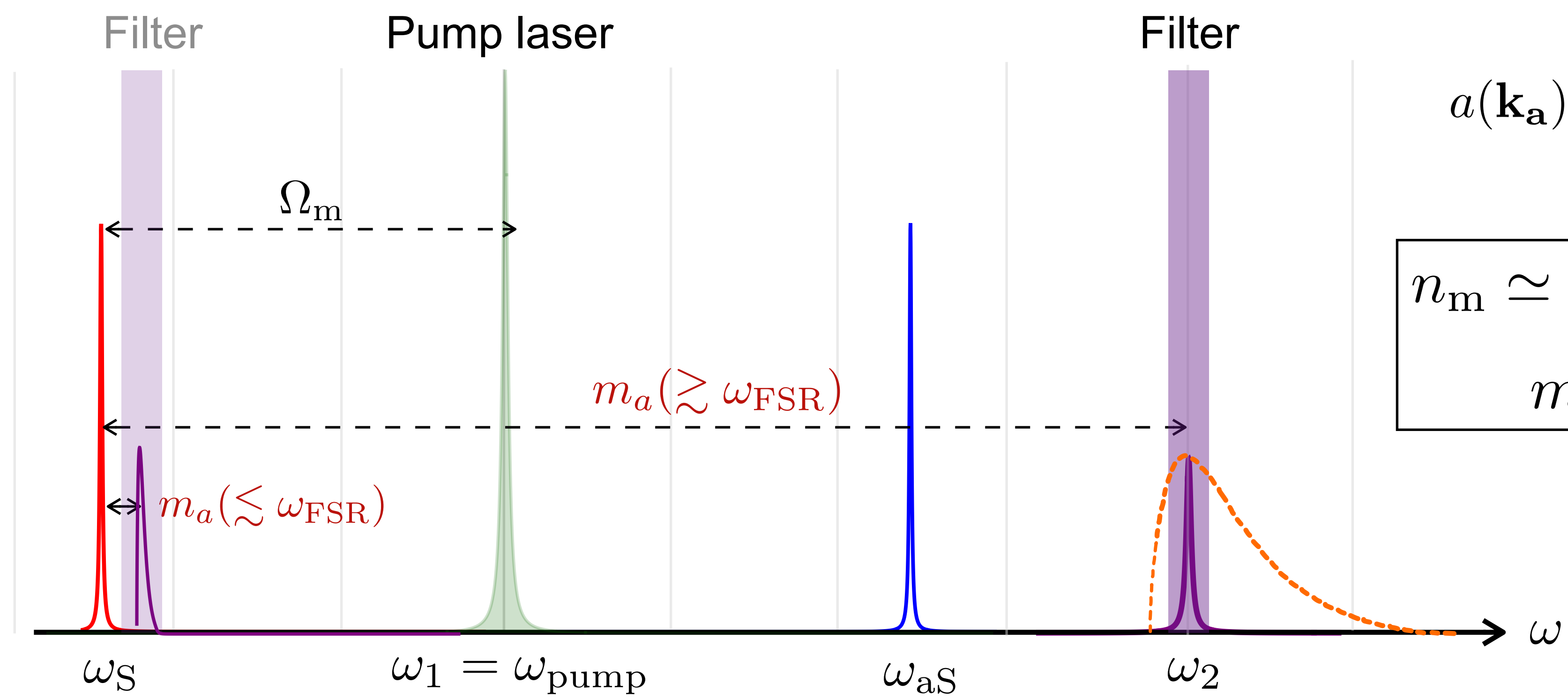

Light Axion Regime

Heavy Axion Regime

$$n_\text{m} \simeq 2\, n_1 + [m_a/\omega_{\text{FSR}}]$$
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'phonon-pop'

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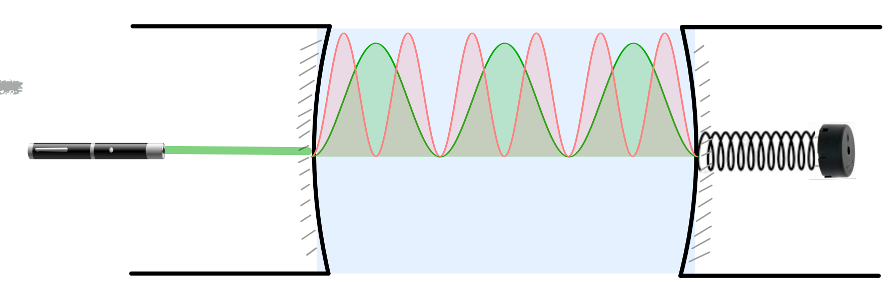

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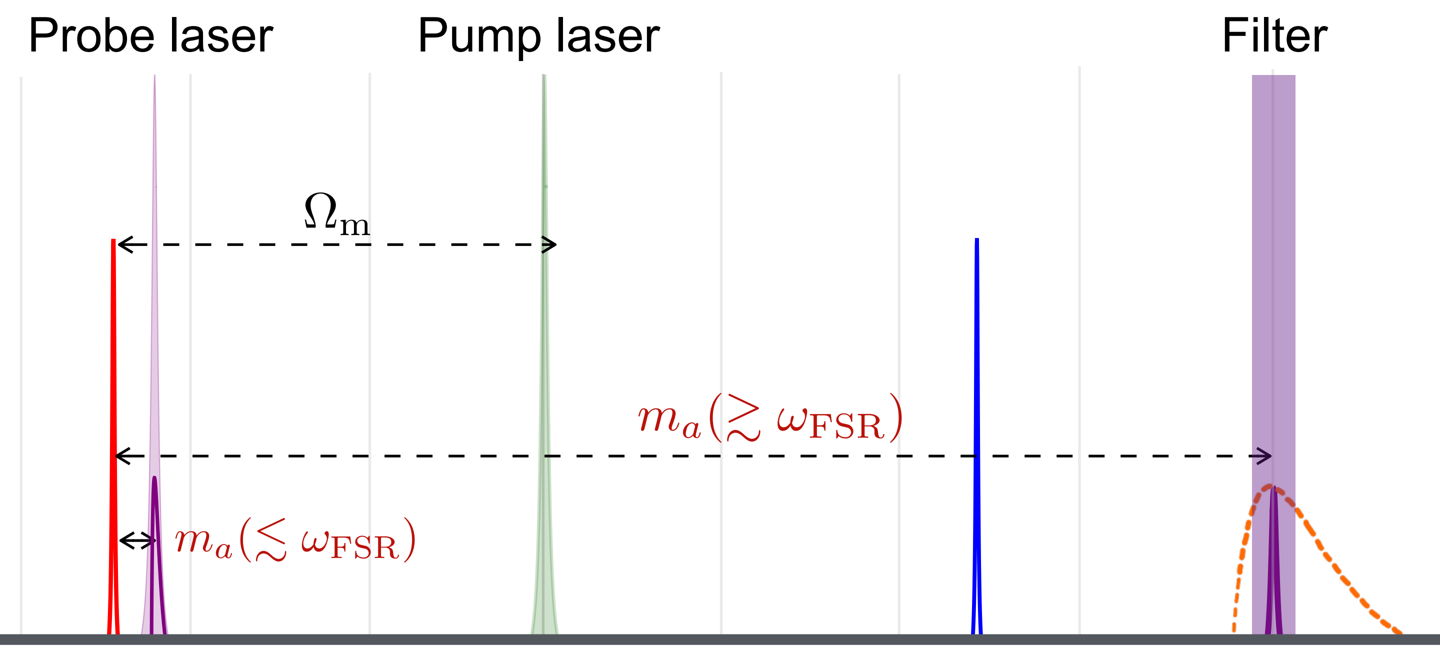

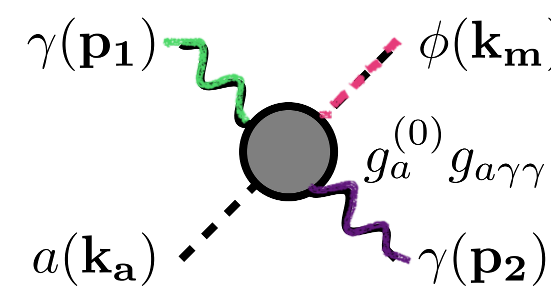

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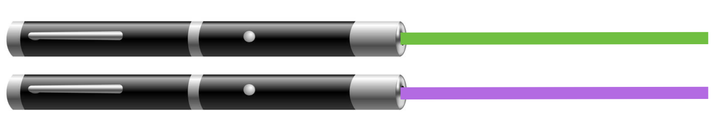
Photon-pop

$$\Gamma \sim (2\pi)|g_a^{(0)}|^2 \left(\frac{2\rho_a}{m_a^2}\, g_{a\gamma\gamma}^2\right) N_{\gamma,\text{pump}}^{\text{circ}}\, N_{\gamma,\text{probe}}^{\text{circ}}(\Delta_\text{probe}) \int d\omega_2\, B_{m_a}(\omega_2 + \Omega_{n_\text{m}} - \omega_\text{pump}) L(\omega_2 - \omega_\text{probe}, 2\kappa_\text{L})$$



Phonon-pop

$$\Gamma \sim (2\pi)|g_a^{(0)}|^2 \left(\frac{2\rho_a}{m_a^2}\, g_{a\gamma\gamma}^2\right) N_{\gamma,\text{pump}}^{\text{circ}}\, N_{\phi}^{\text{circ}}(\Delta_\text{m}) \int d\omega_2\, B_{m_a}(\omega_2 + \Omega_\text{m} - \omega_\text{pump}) L(\omega_2 - \omega_{n_2}, \kappa)$$

Sensitivity and scanning

Narrowband detection

For a specific m_a:

1. Photon pop: probe laser need to be turned to a specific frequency;
2. Phonon pop: final-state phonons need to be populated at a specific frequency, as well as the filter;
3. Importantly, the cavity length need to be **turned** such that photons and phonons are on-resonance:

   $\omega_{1,2} = n_{1,2}\omega_{\mathrm{FSR}}$, $\Omega_{\mathrm{m}} = c_s n_{\mathrm{m}} \omega_{\mathrm{FSR}}$

$$\boxed{\mathrm{SNR} = \Gamma_{\mathrm{sig}} \,/\, \Gamma_{\mathrm{back}}}$$

$$\Gamma_{\mathrm{sig}} \sim \begin{cases} t_{\mathrm{int}}/\tau_a & \text{if } t_{\mathrm{int}} \ll \tau_a, \\ 1 & \text{if } t_{\mathrm{int}} \gtrsim \tau_a, \end{cases}$$

Photon-pop

$$\Gamma_{\mathrm{back}} = \begin{cases} \kappa\sqrt{N_{\gamma,\mathrm{bkg}}}/4 & \text{if } t_{\mathrm{int}} < \tau_a \\ \kappa\sqrt{N_{\gamma,\mathrm{bkg}}}/(4\sqrt{t_{\mathrm{int}}\kappa_{\mathrm{sig}}}) & \text{if } t_{\mathrm{int}} > \tau_a \end{cases} \Rightarrow \mathrm{SNR} \propto N_\gamma \sqrt{N_\gamma}$$

Phonon-pop

$$\Gamma_{\mathrm{back}} = \Gamma_{\mathrm{DCR}} \Rightarrow \mathrm{SNR} \propto N_\gamma N_\phi$$

Reducible background photons:

- Tails of the pump laser, and the Stokes, anti-Stokes sidebands
- Filtering - experiment capability

  Frequency based filtering: $\mathcal{O}(200\mathrm{dB})$

  Polarization based filtering: $\mathcal{O}(60\mathrm{dB})$ commonly used

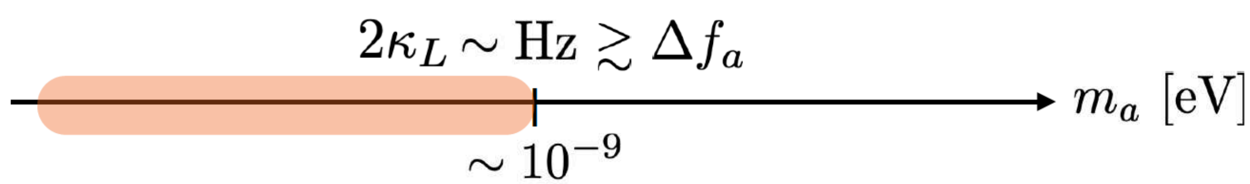
Other noise sources: thermal noise, mechanical noise, etc

Sensitivity and scanning

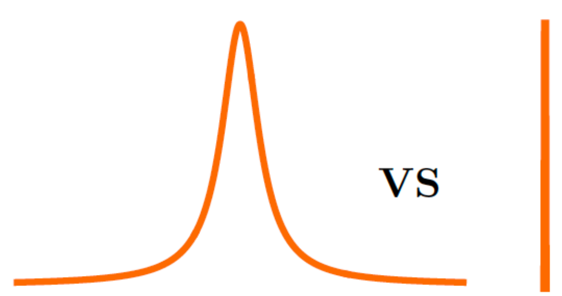
$$\text{SNR} \geq 3 \quad \rightarrow \quad g_{a\gamma\gamma} > f(m_a, \text{cavity}, \text{lasers}, \text{material})$$

Scanning: covering an extended mass range

E.g. $\Gamma_{\text{sig}} \propto \int d\omega_2 \, B_{m_a}(\omega_2 + \Omega_{n_\text{m}} - \omega_\text{pump}) L(\omega_2 - \omega_\text{probe}, 2\kappa_\text{L})$



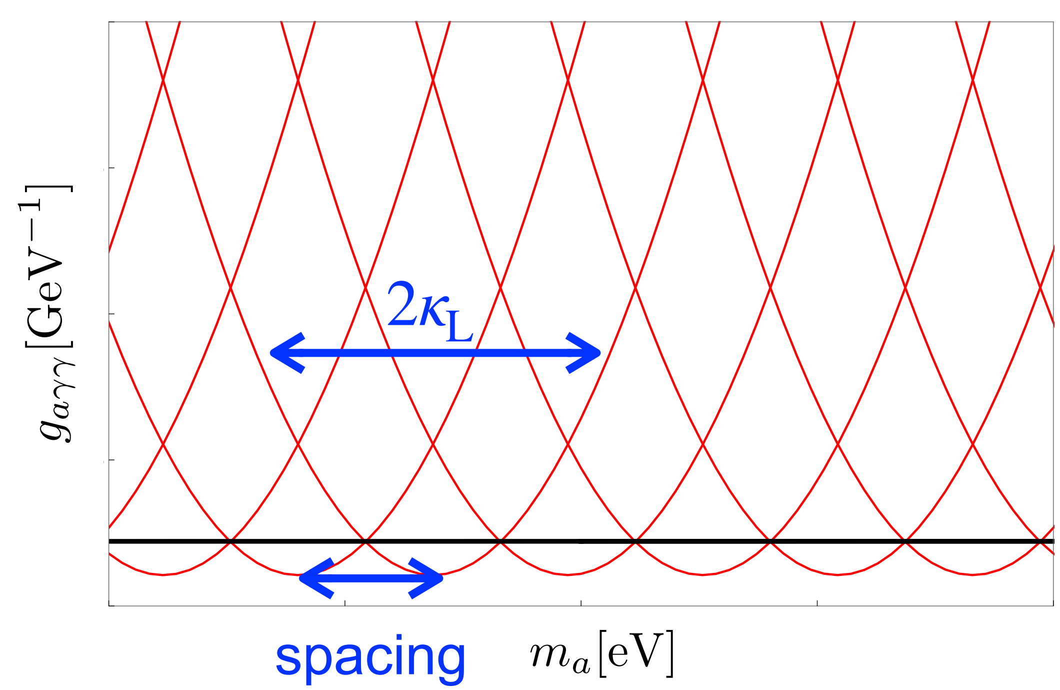
Lorenzian regime



$$\Gamma \propto \frac{\kappa_L}{\kappa_L^2 + (\Delta + \Omega_\text{m} - m_a)^2}$$

$$\text{spacing} = \epsilon \, \kappa_L$$

$t_\text{int} = 1\,\text{s} \Rightarrow$ ~10 neV/year



Sensitivity and scanning

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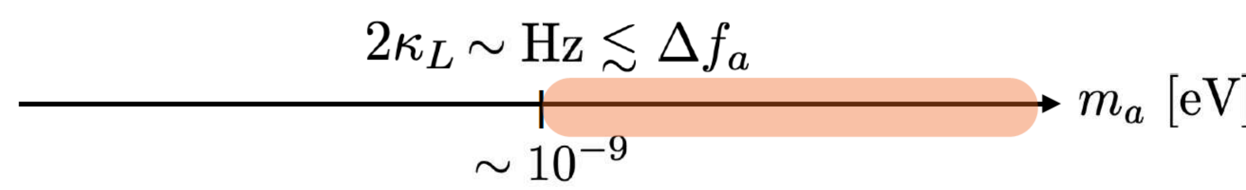
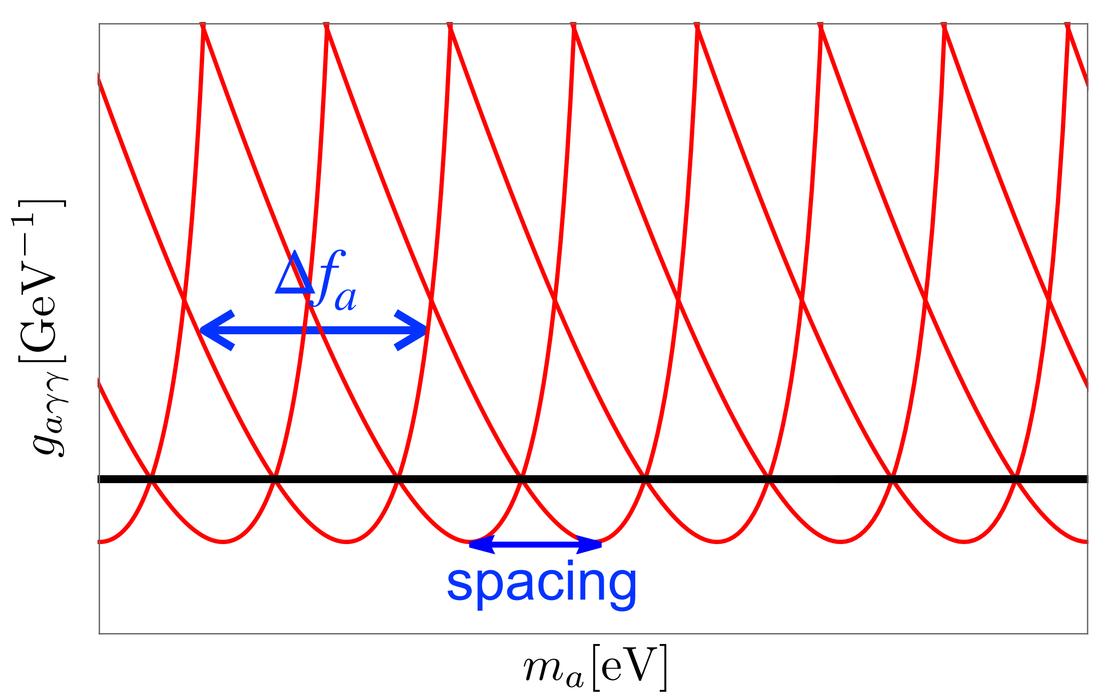
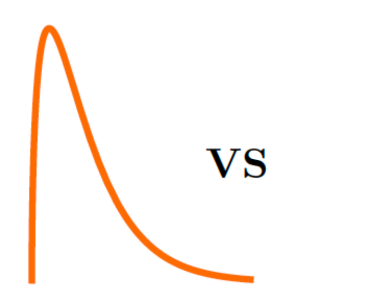




Boltzmann regime



$$\Gamma \propto B_{m_a}(\Delta + \Omega_{\text{m}})$$

$$\text{spacing} = \epsilon \left(\frac{\Delta f_a}{2}\right) = \epsilon \frac{m_a}{4\pi} v^2$$

$$t_{\text{int}} = 1\,\text{s} \Rightarrow \sim 1.6 \text{ oom/year}$$

Sensitivity and scanning

Optical frequency	$\omega_{\rm opt}$	$\simeq 2\pi \times 200\,{\rm THz}$ $(0.8\,{\rm eV})$
Mechanical frequency	$\Omega_{\rm m}$	$\simeq 2\pi \times 318\,{\rm MHz}$ $(1.4\,\mu{\rm eV})$
Free spectral range	$\omega_{\rm FSR} = \dfrac{\pi}{L}$	$2\pi \times 150\,{\rm MHz}\,^*$ $(0.6\,\mu{\rm eV}\,^*)$
Optical loss rate	$\kappa = \dfrac{\pi}{L\mathcal{F}_{\rm opt}}$	$300\,{\rm Hz}\,^*$ $(2\times 10^{-13}\,{\rm eV}\,^*)$
Laser width	$\kappa_{\rm L}$	$1\,{\rm Hz}\,^*$ $(6.6\times 10^{-16}\,{\rm eV}\,^*)$
Mechanical loss rate	$\Gamma_{\rm m} = \dfrac{\pi c_s}{L\mathcal{F}_{\rm ac}}$	$24\,{\rm mHz}\,^*$ $(1.6\times 10^{-17}\,{\rm eV}\,^*)$
Optical finesse	$\mathcal{F}_{\rm opt}$	$\pi \times 10^6\,^*$
Acoustic finesse	$\mathcal{F}_{\rm ac}$	$\pi \times 10^4\,^*$
Axion bandwidth	$\Delta f_a = \frac{v^2}{2\pi} m_a$	$2.7\times 10^{-7}\,m_a$

Scales with a one meter cavity

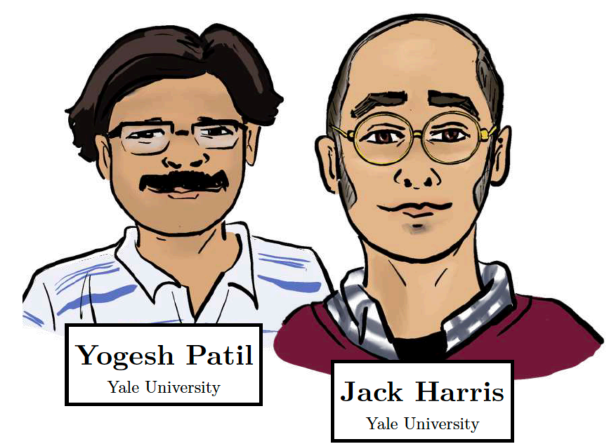
$$\Gamma \sim (2\pi)|g_a^{(0)}|^2 \left(\frac{2\rho_a}{m_a^2}\, g_{a\gamma\gamma}^2\right) N_{\gamma,\rm pump}^{\rm circ}\{N_{\gamma,\rm probe}^{\rm circ}, N_\phi^{\rm circ}\}$$

$$N_\gamma^{\rm circ} \sim \frac{4P_{\rm laseer}}{\omega_{\rm opt}\kappa} \qquad N_\phi^{\rm circ} = \frac{U_{\rm m}}{\Omega_{\rm m}} \lesssim \frac{1}{2\Omega_{\rm m}}\rho_{\rm He}\, c_s^2 \left(\frac{\delta\rho_{\rm He}}{\rho_{\rm He}}\right)^2 V_{\rm mode}$$

1 For usual experiments in their lab:

- $N_{\rm pump} \simeq 10^6$ — $P_{\rm pump} \sim 1\,\mu{\rm W}$
- $N_{\rm probe} \simeq 10^6$ — $L \sim 100\,\mu{\rm m}$
- $N_\phi = 1$ — $\mathcal{F}_{\rm opt}/\pi \sim 10^5$

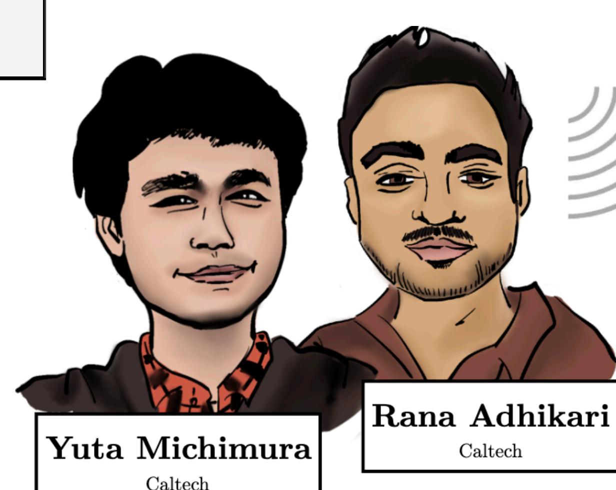
Yale University
Jack Harris Lab



(by Clara Murgui)

2 What could be feasible to achieve:

- $N_{\rm pump} \simeq 10^{17}$ — $P_{\rm pump} \sim 1$ W
- $N_{\rm probe} \simeq 10^{17}$ — $P_{\rm probe} \sim 1$ W
- $N_\phi \simeq 10^{14}$ — $L \sim 1$ m
- $\mathcal{F}_{\rm opt}/\pi \sim 10^6$



LIGO

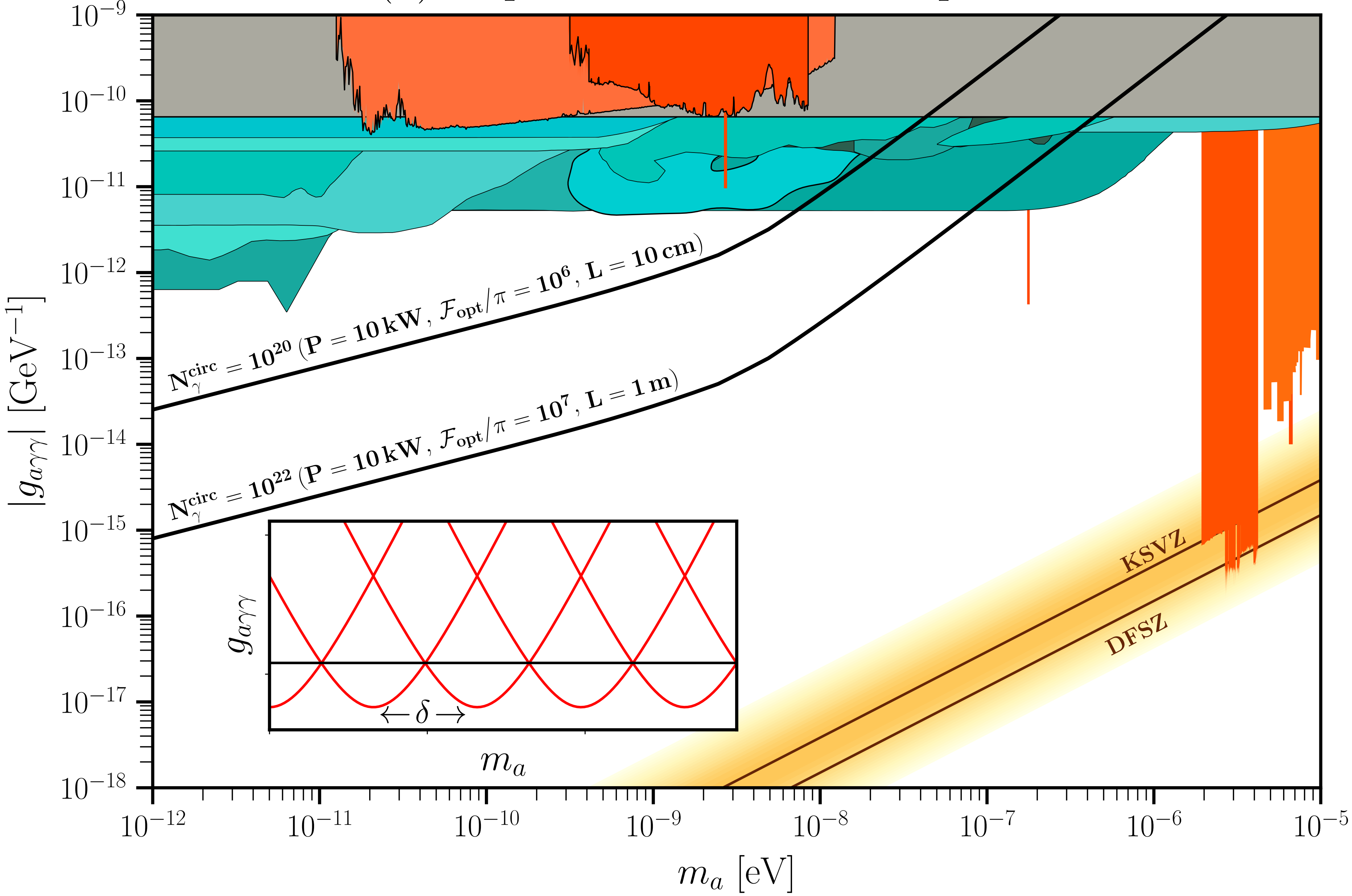
3 What other experiments are aiming for:

- $N_{\rm pump} \simeq 10^{22}$ — $P_{\rm pump} \sim 10$ kW
- $L \sim 5$ m
- $\mathcal{F}_{\rm opt}/\pi \sim 10^6$

GQuEST

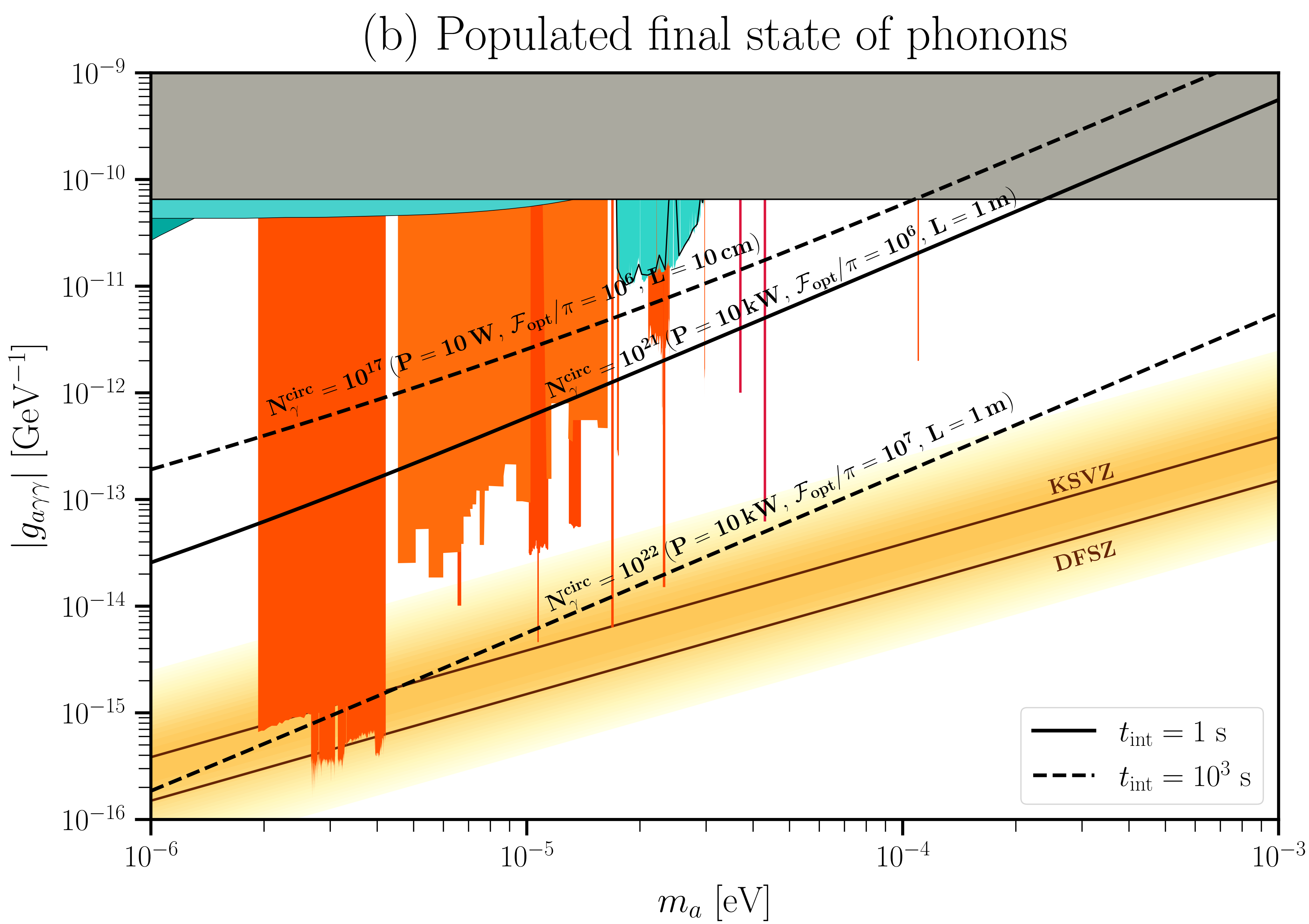
The reach

(a) Populated final state of photons



$$g_{a\gamma\gamma}^{\gamma-\mathrm{pop}} \propto \left(\rho^{1/2} c_s^{1/2} \frac{\epsilon_r + 2}{\epsilon_r - 1} \epsilon_r^{3/4}\right)\left(\frac{1}{\mathcal{F}_{\mathrm{opt}}^{5/4}} \frac{1}{L^{1/4}}\right)\left(\frac{1}{\omega_{\mathrm{opt}}^{5/4}} \frac{1}{P_{\mathrm{pump}}^{1/2}} \frac{1}{P_{\mathrm{probe}}^{1/4}}\right)\frac{m_a}{\rho_a^{1/2}} \times \begin{cases} m_a^{\frac{1}{2}} \left(\frac{e^{\epsilon}-1}{e^{\frac{\epsilon}{1-e^{\epsilon}}}\epsilon}\right)^{\frac{1}{4}} \left(\frac{1}{t_{\mathrm{int}}\kappa_L}\right)^{\frac{1}{4}}, & t_{\mathrm{int}} > (2 \\ \kappa_L^{\frac{1}{2}} (1+\epsilon^2/4)^{\frac{1}{2}} \left(\frac{1}{t_{\mathrm{int}} m_a}\right)^{\frac{1}{4}}, & t_{\mathrm{int}} > \tau_a \\ \kappa_L^{\frac{1}{2}} (1+\epsilon^2/4)^{\frac{1}{2}} \left(\frac{1}{t_{\mathrm{int}} m_a}\right)^{\frac{1}{2}}, & t_{\mathrm{int}} < \tau_a \end{cases}$$

The reach



$$g_{a\gamma\gamma}^{\phi-\mathrm{pop}} \propto \left(\rho^{1/2} c_s^{1/2} \frac{\epsilon_r+2}{\epsilon_r-1}\epsilon_r^{3/4}\right)\left(\frac{L^{1/2}}{\mathcal{F}_{\mathrm{opt}}^{1/2}}\right)\left(\frac{1}{\omega_{\mathrm{opt}}^{3/2}}\frac{1}{P_{\mathrm{pump}}^{1/2}}\frac{1}{N_\phi^{1/2}}\right)\frac{m_a}{\rho_a^{1/2}} \times \begin{cases} m_a^{\frac{1}{2}}\left(\frac{e^{\epsilon}-1}{e^{\frac{\epsilon}{1-e^{\epsilon}}}\epsilon}\right)^{\frac{1}{4}}, & t_{\mathrm{int}} > \kappa \\ (\mathcal{F}_{\mathrm{opt}}L)^{-\frac{1}{2}}(1+\epsilon^2/4)^{\frac{1}{2}}, & t_{\mathrm{int}} > \tau \\ (\mathcal{F}_{\mathrm{opt}}L)^{-\frac{1}{2}}(1+\epsilon^2/4)^{\frac{1}{2}}\left(\frac{1}{t_{\mathrm{int}}m_a}\right)^{\frac{1}{2}}, & t_{\mathrm{int}} < \tau \end{cases}$$

Summary and outlook

Thank you!

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- **Axioptomechical coupling** allows the decoupling of the axion mass from the resonance frequency of the system, thus the system size, for resonance searches of the axion dark matter;
- **Highly coherent acoustic modes** that can be hosted in well developed optomechanical systems can coherently enhance the axion absorption rate on top of the coherent enhancement from optical modes;
- Theory prediction shows promising observational prospects of QCD axion and axion like particles with laboratory constructible **optomechanical cavities**.

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- Theory prediction shows promising observational prospects of QCD axion and axion like particles with laboratory constructible **optomechanical cavities**.

Ongoing:

- **Gravitational wave?**
- **Filtering** of reducible backgrounds for single photon detection;
- **Thermal model** that will limit the injecting laser power and acoustic mode coherence;
- **Strong coupling regime** $g_0 \tilde{N}_\phi \geq 1$;
- **A concrete experimental proposal.**

Thank you!