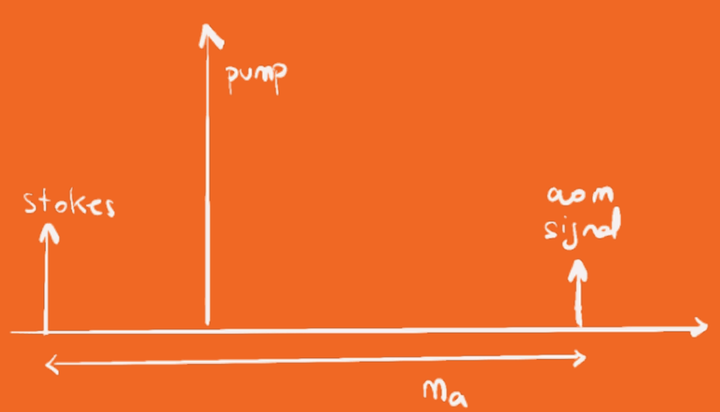
Axion (DM) Detection with Optomechanical Cavities

Clara Murgui

in collaboration with Yikun Wang and Kathryn M. Zurek

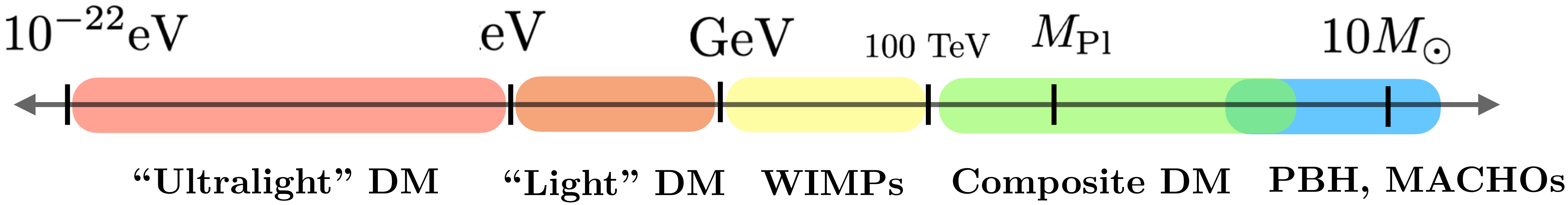
2211.08432



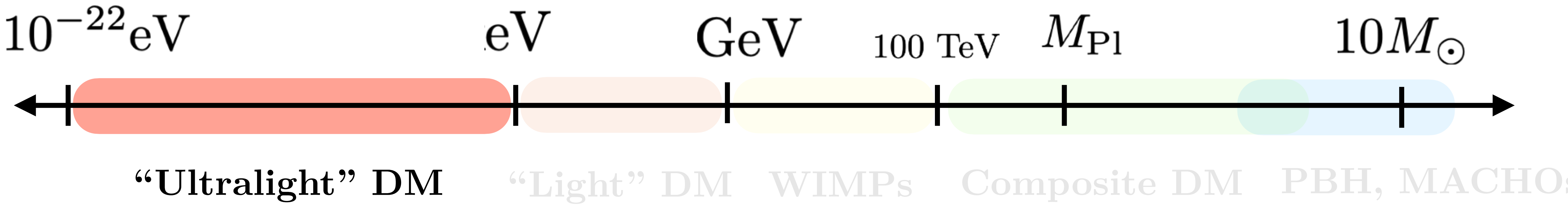
UCLA DM Conference

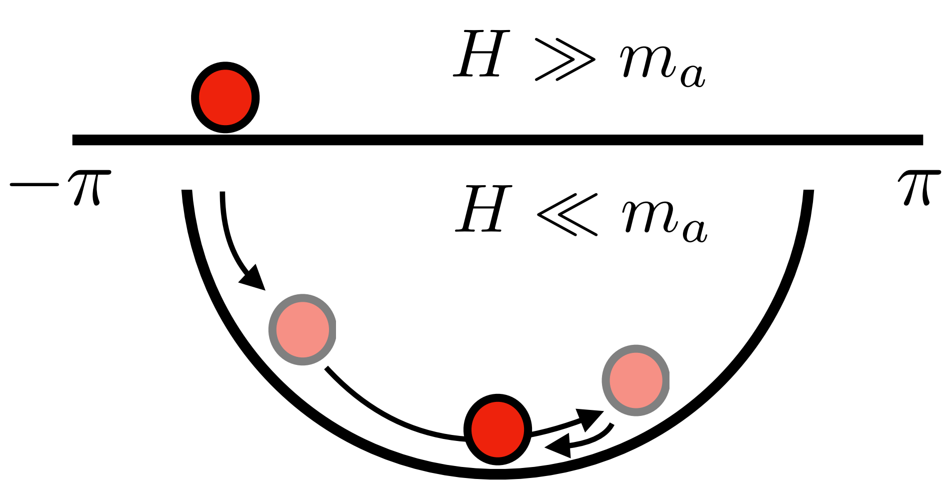
30th March 2023

Dark Matter: where to look?



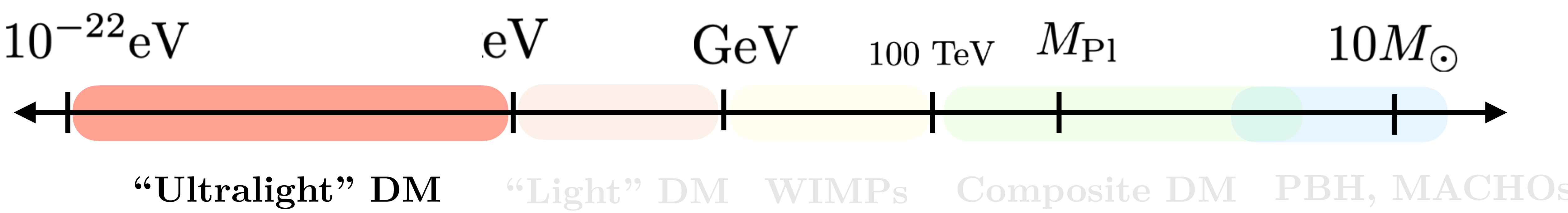
Dark Matter: where to look?

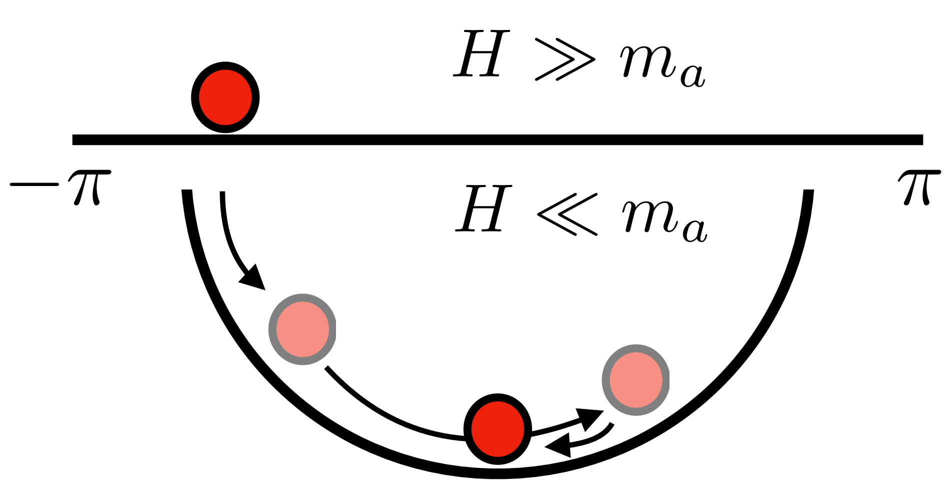




[Preskill, Wise, Wilczek, 1983]
[Abbott, Sikivie, 1983]
[Dine, Fischler, 1983]

Axion Dark Matter





[Preskill, Wise, Wilczek, 1983]
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[Peccei, Quinn, 1977] [Wilzeck, 1978] [Weinberg, 1978]
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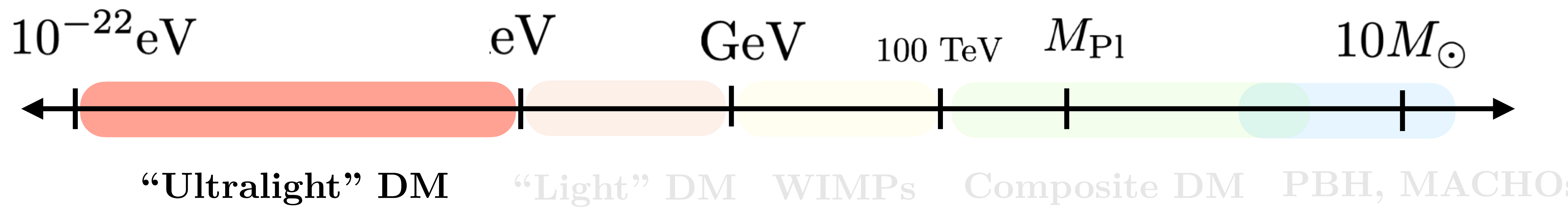
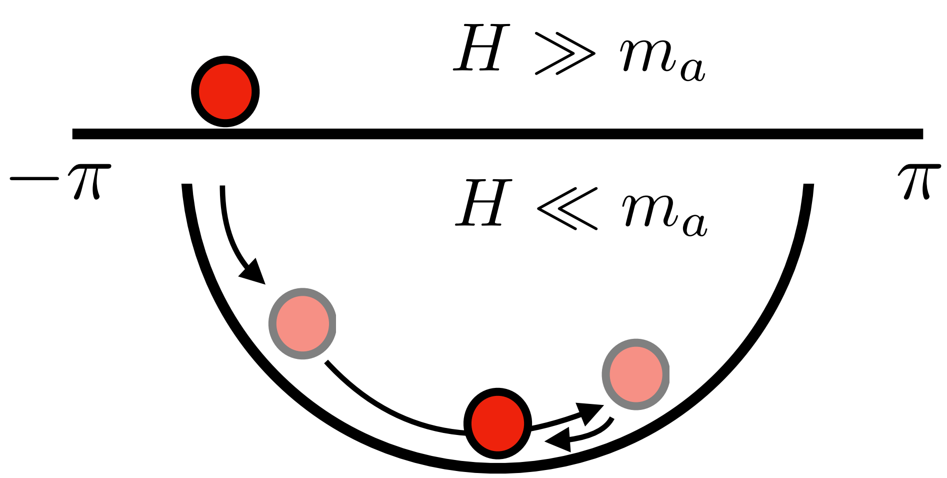
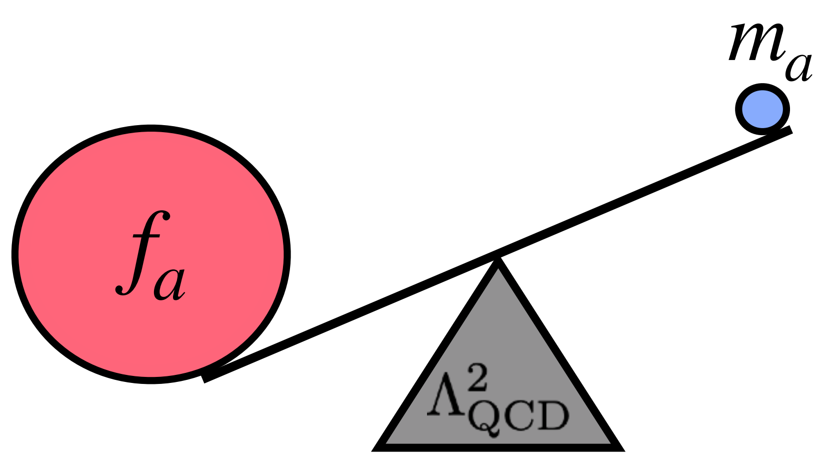
Axion Dark Matter







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

[Preskill, Wise, Wilczek, 1983]
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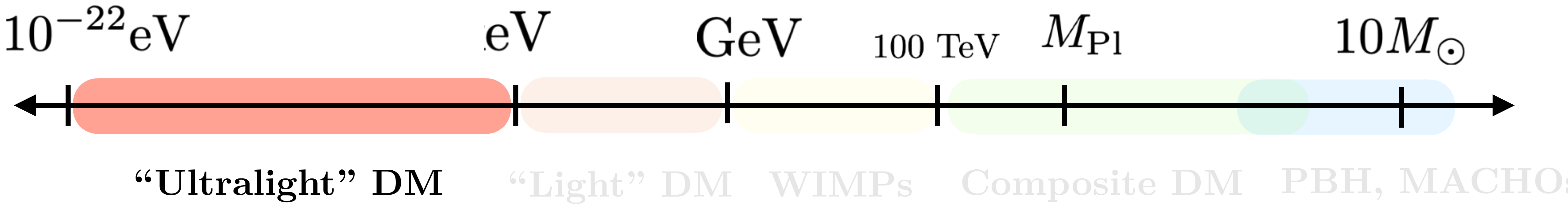
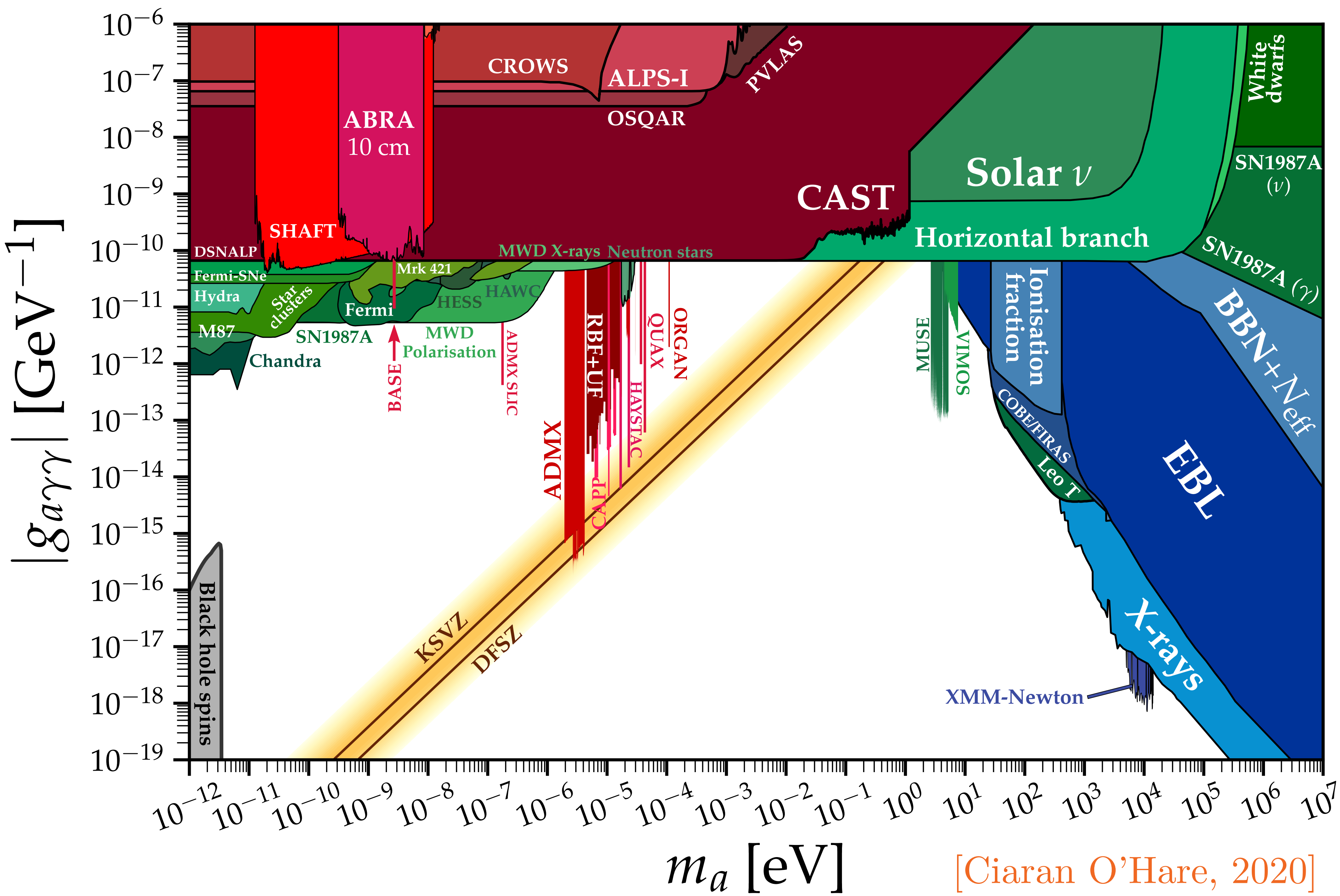
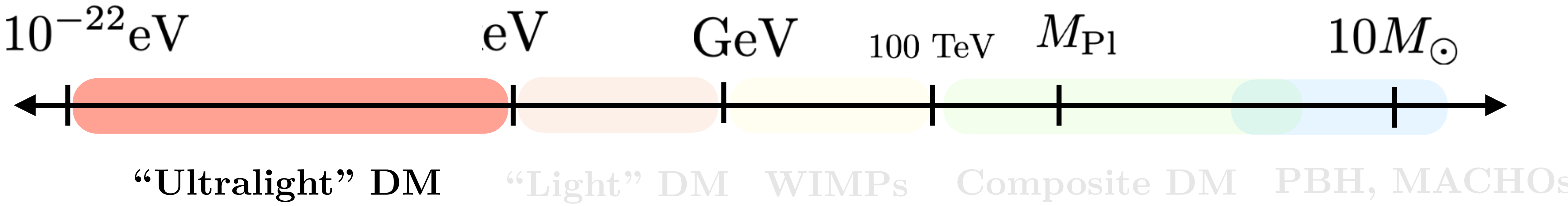
Axion Dark Matter

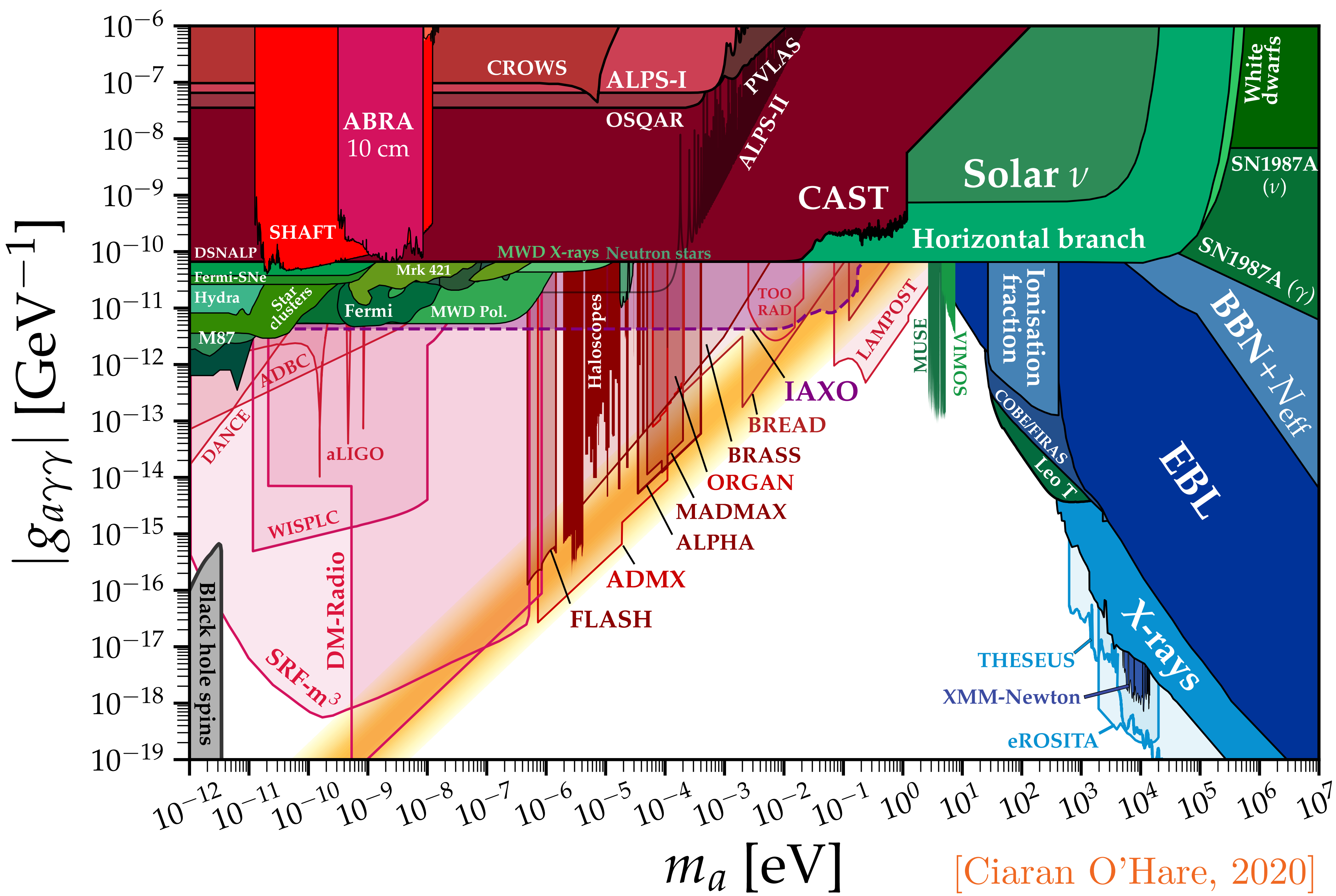




[Ciaran O'Hare, 2020]

Axion Dark Matter





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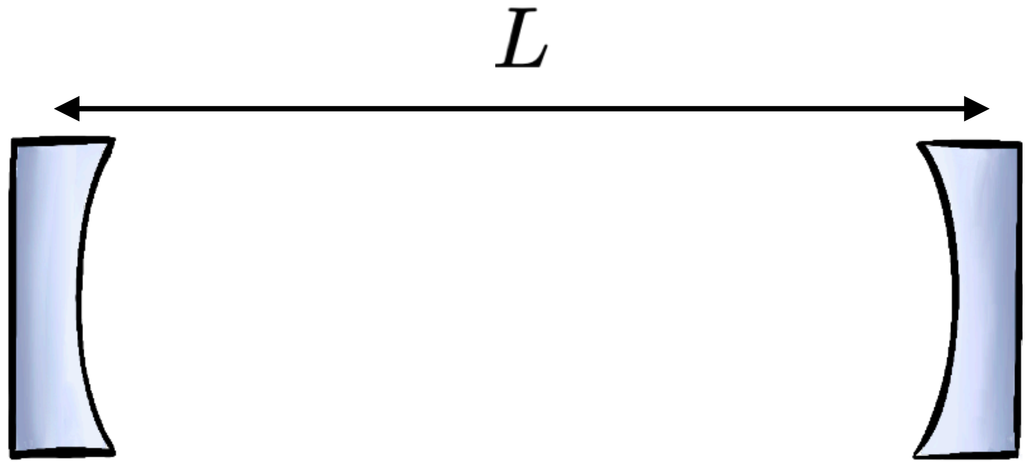
Standard Optomechanics



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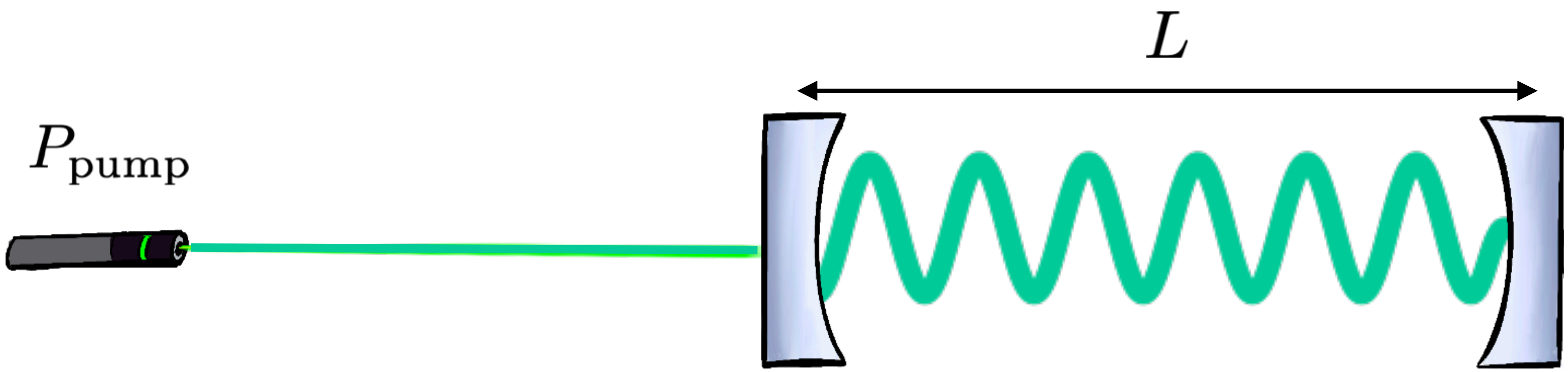
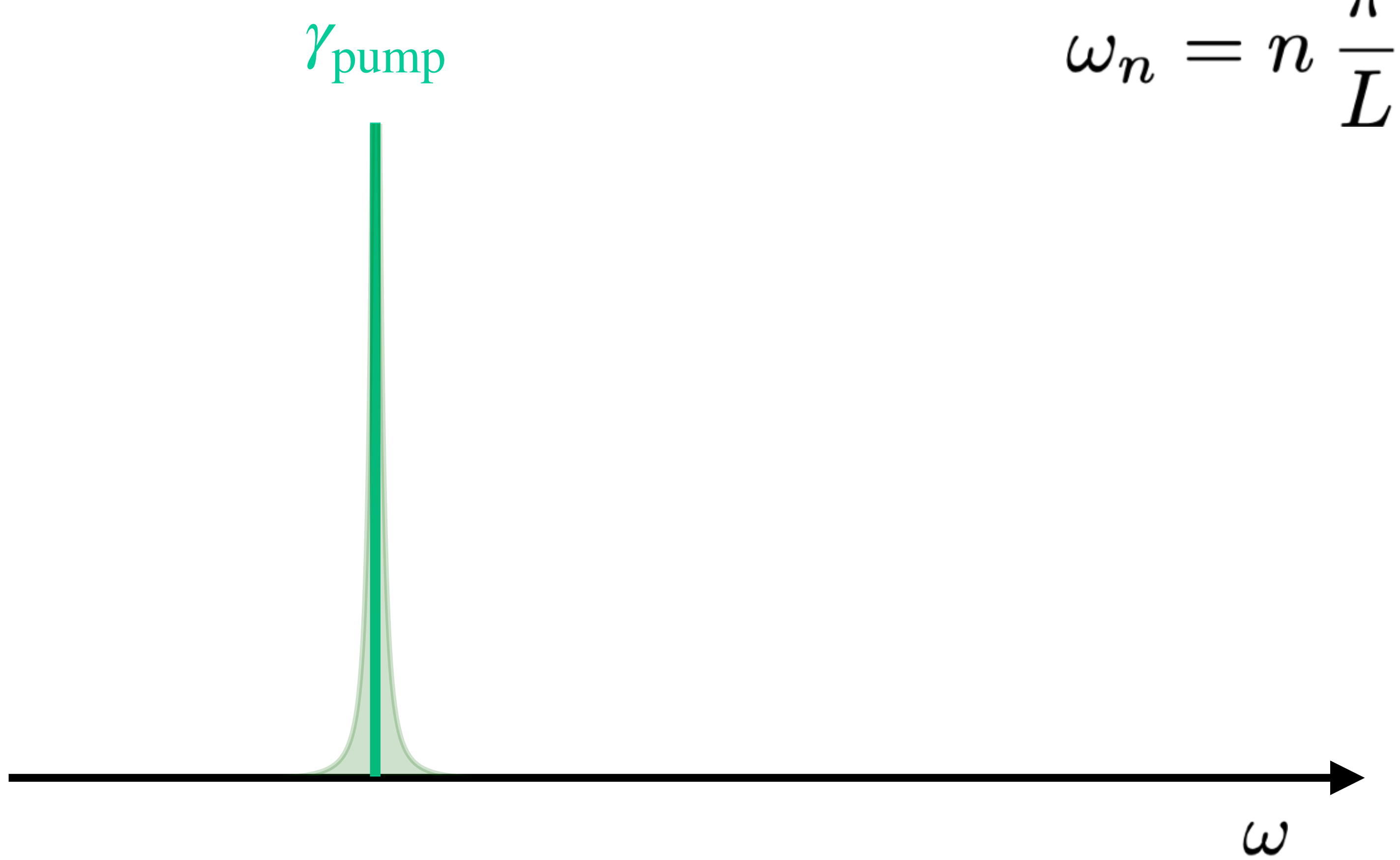


$$\omega_n = n\,\frac{\pi}{L}, \qquad n \subset \mathbb{Z}$$



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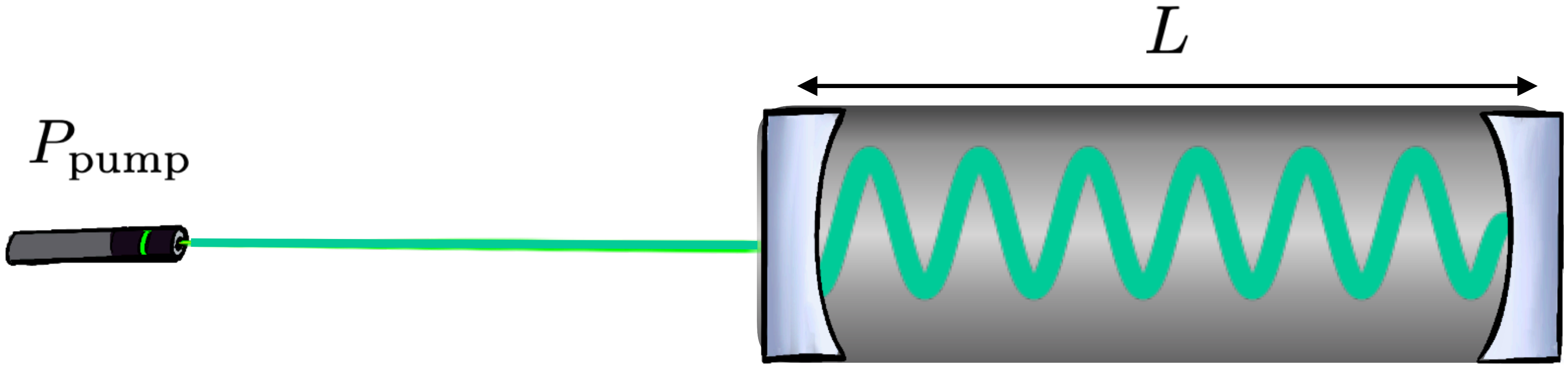

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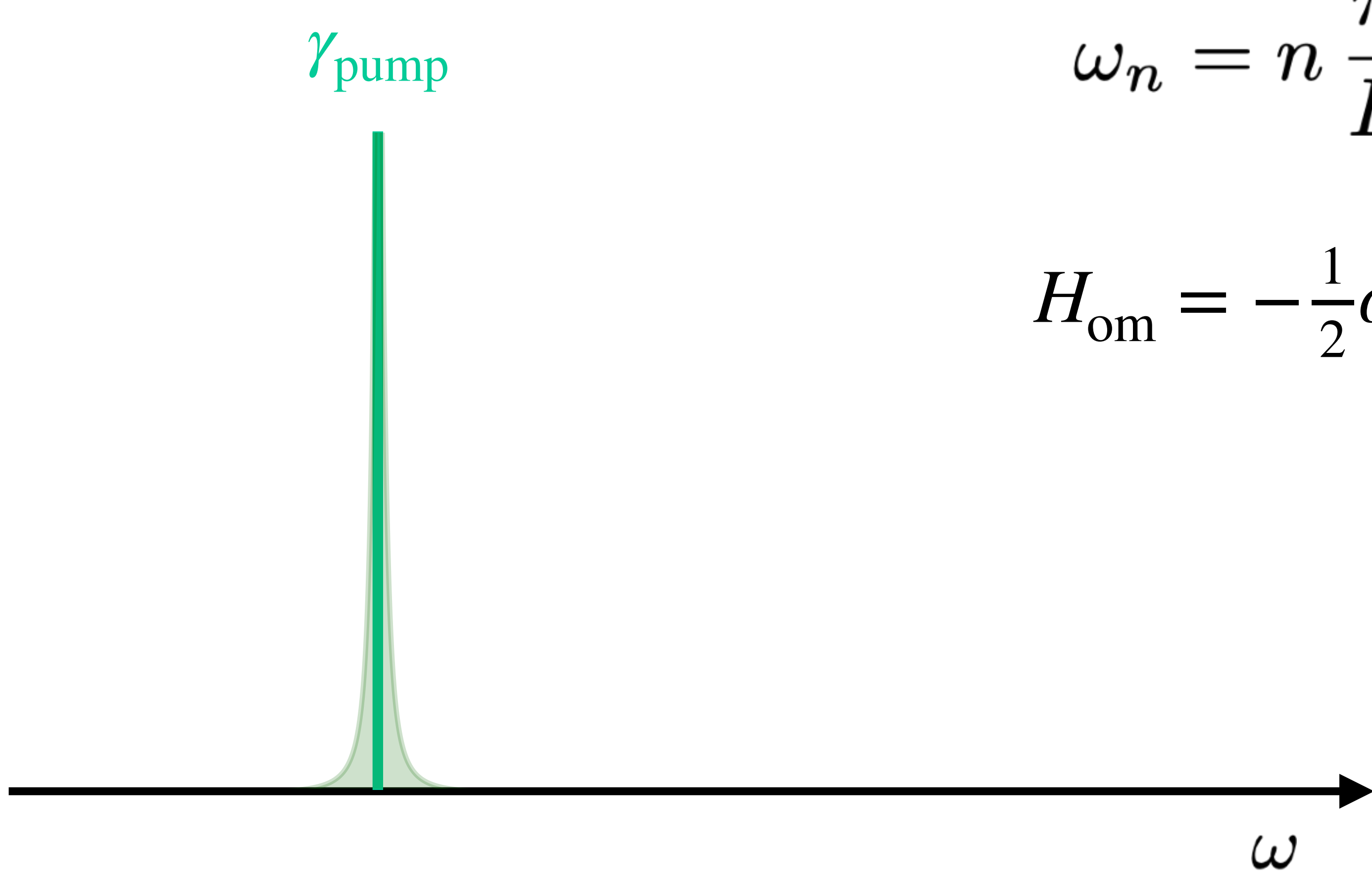
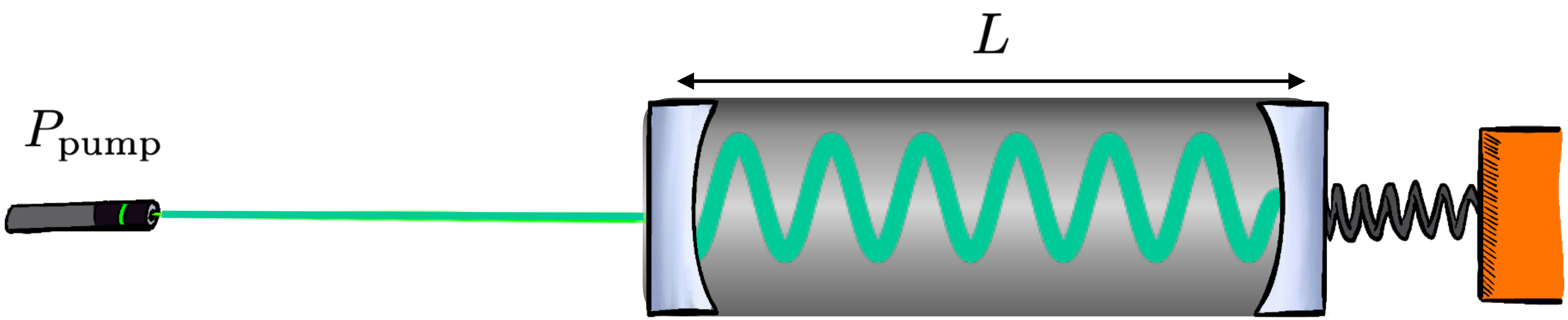


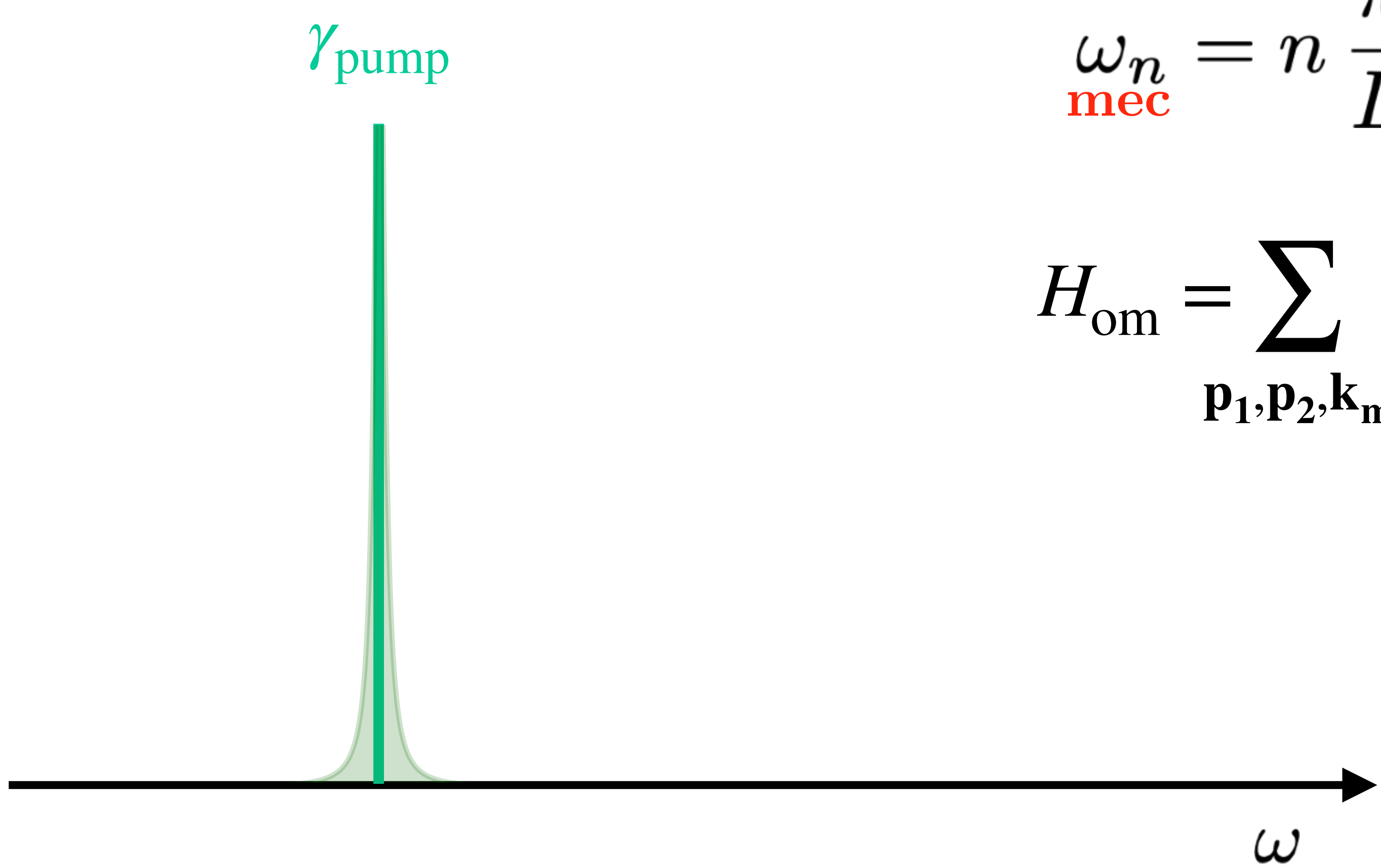
$$H_{\text{om}} = -\frac{1}{2}\alpha \int d^3\mathbf{r}\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{E}(\mathbf{r})$$

Standard Optomechanics



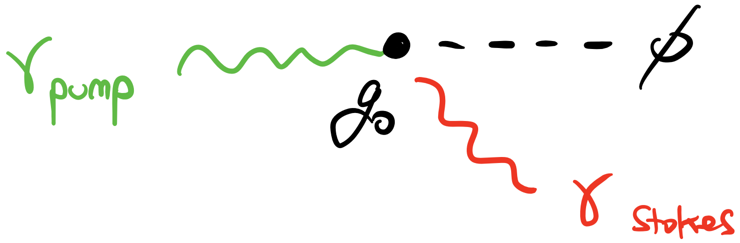
$$\underset{\text{mec}}{\omega_n} = n \frac{\pi}{L} c_s, \quad n \subset \mathbb{Z}$$

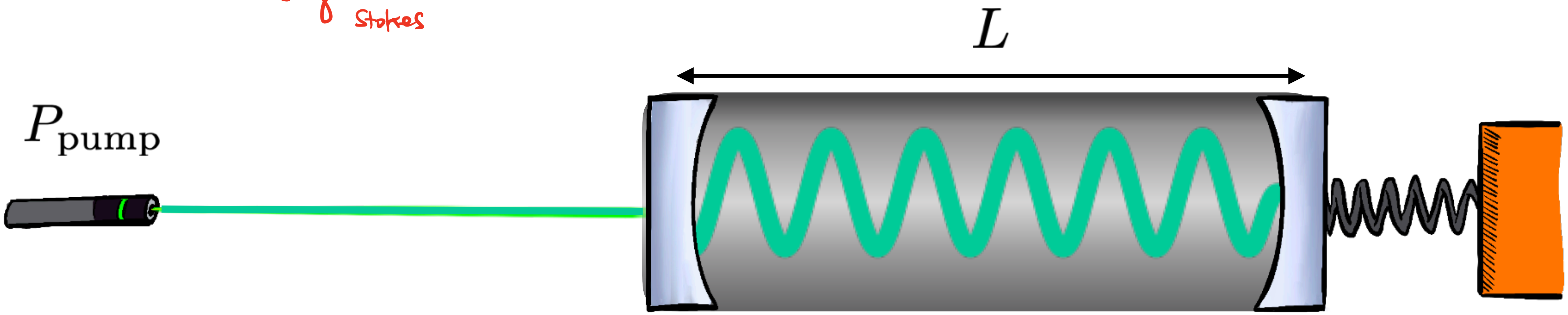
$$H_{\text{om}} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} + \cdots \right.$$



Standard Optomechanics

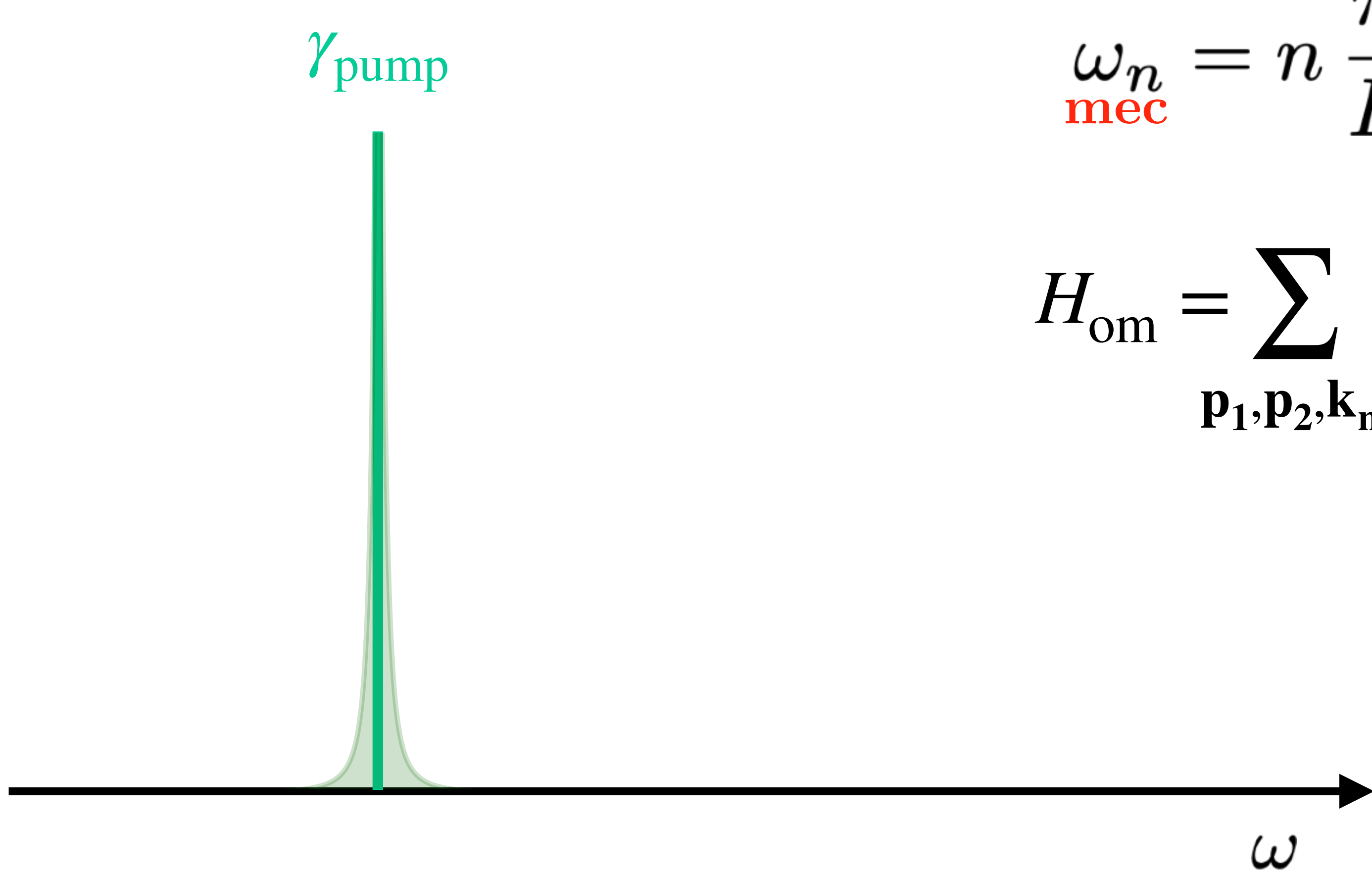
$$\vec{p}_{\gamma 1} = \vec{p}_{\phi} + \vec{p}_{\gamma 2}$$
$$\omega_{\gamma 1} = \omega_{\mathrm{m}} + \omega_{\gamma 2}$$





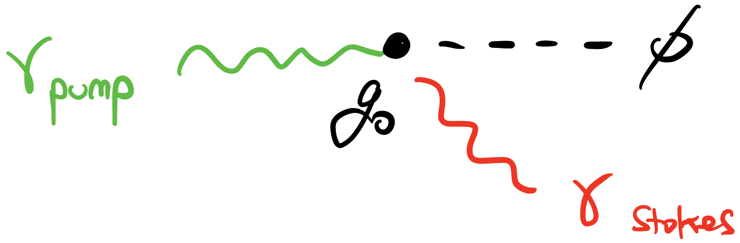
$$\omega_{n}^{\mathbf{mec}} = n \frac{\pi}{L} c_s, \quad n \subset \mathbb{Z}$$

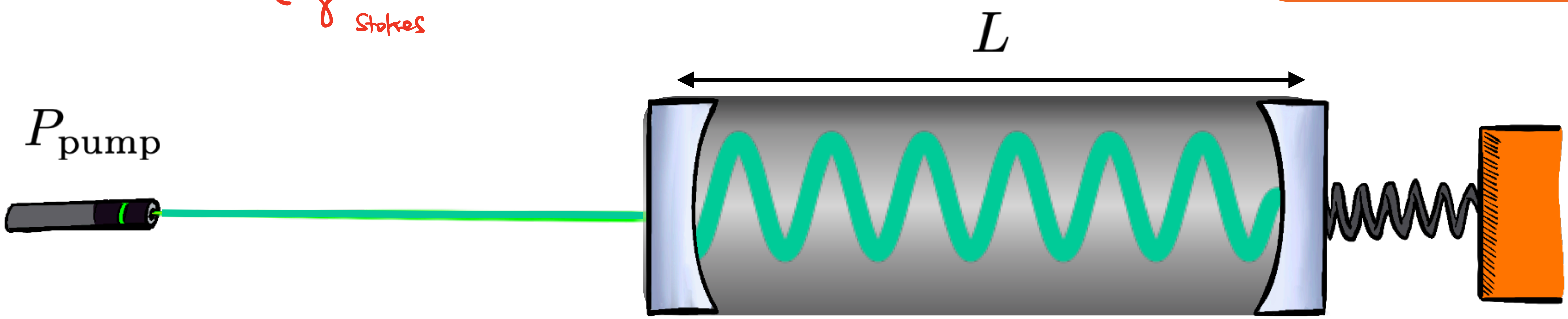
$$H_{\mathrm{om}} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left(a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b^{\dagger}_{\mathbf{k_m}} + \cdots \right.$$



Standard Optomechanics

$$p_\phi = 2p_\gamma$$
$$\Omega_\mathrm{m} = 2c_s\omega_\mathrm{opt}$$





$$\underset{\mathbf{mec}}{\omega_n} = n\,\frac{\pi}{L}\,c_s\,, \qquad n \subset \mathbb{Z}$$

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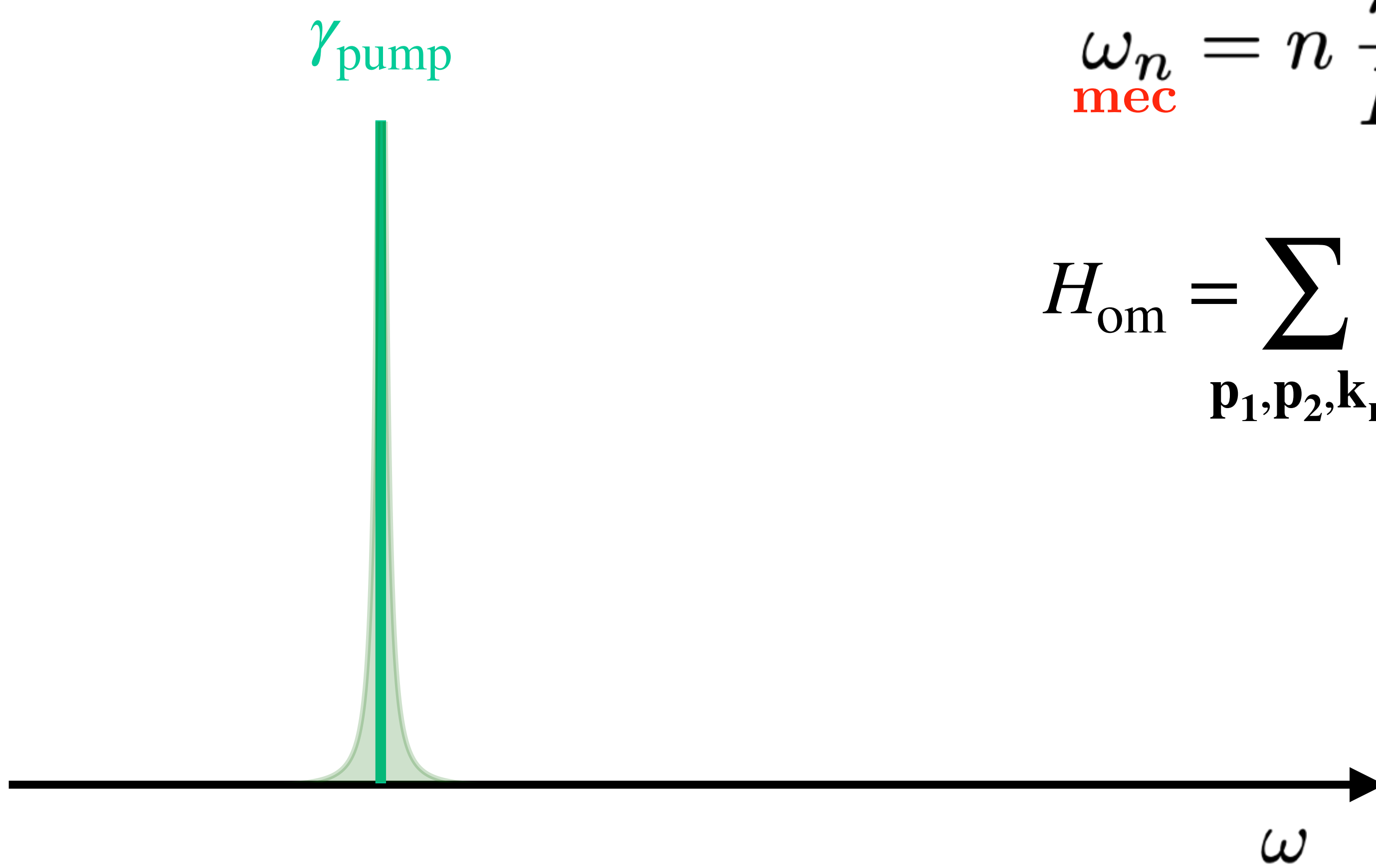

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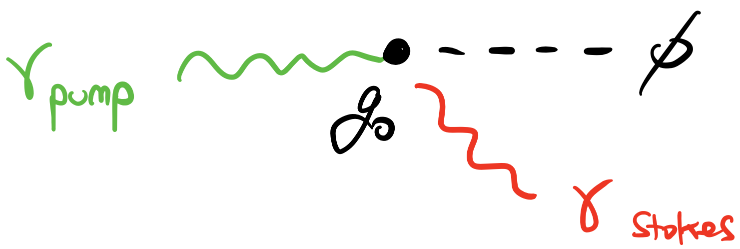
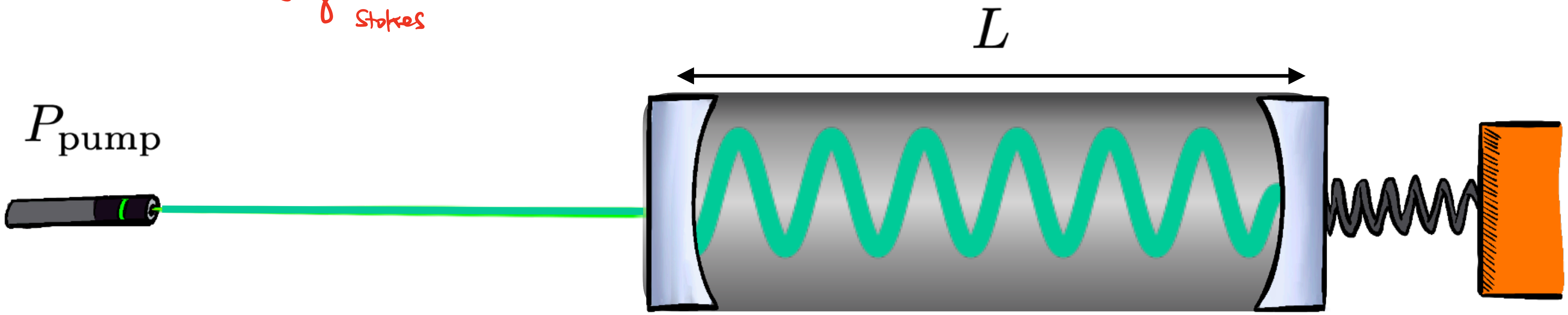
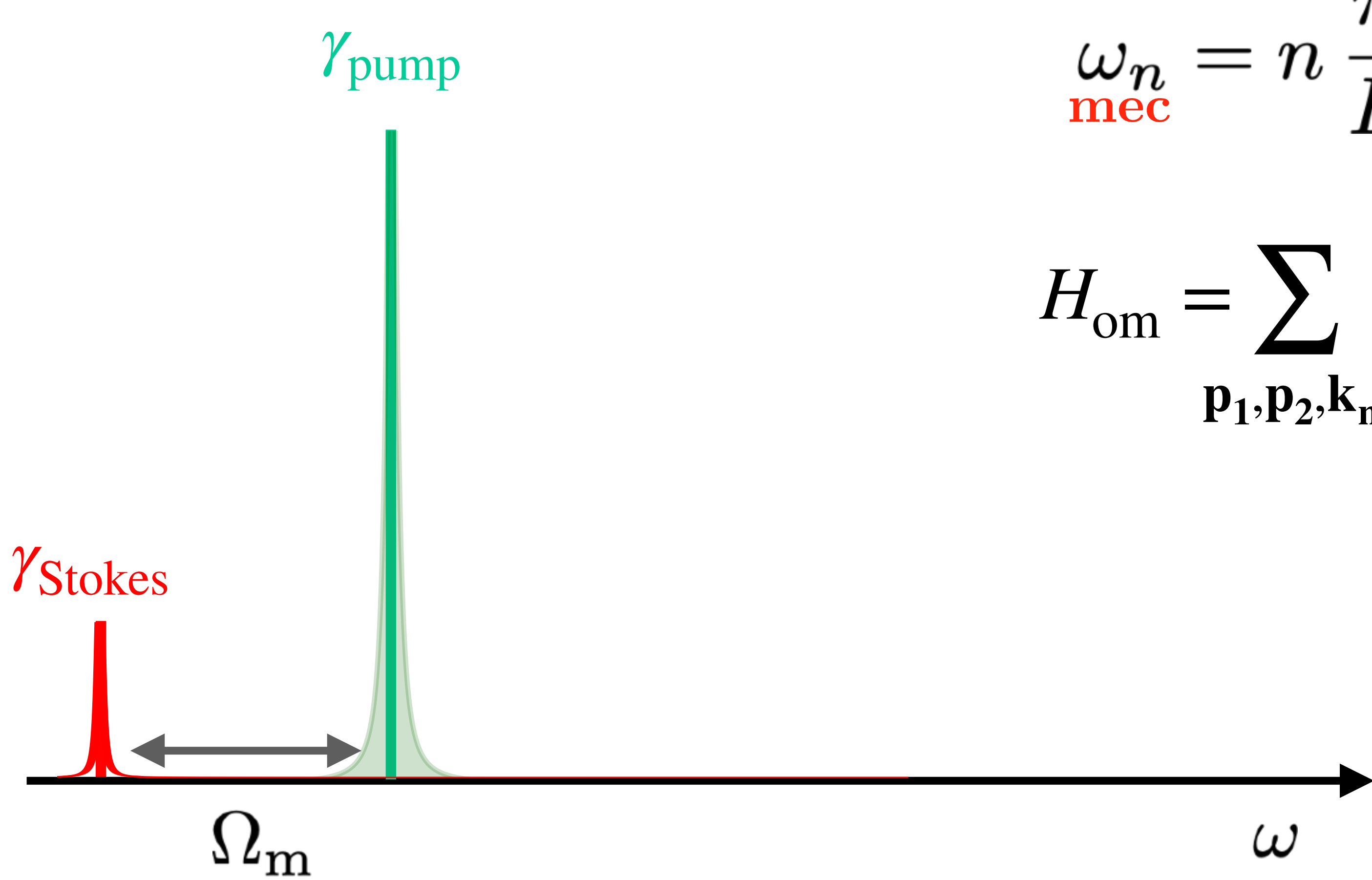




$$\omega_{n_{\rm mec}} = n\frac{\pi}{L}c_s, \quad n \subset \mathbb{Z}$$

$$H_{\rm om} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0\left(a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b^\dagger_{\mathbf{k_m}} + \cdots\right.$$



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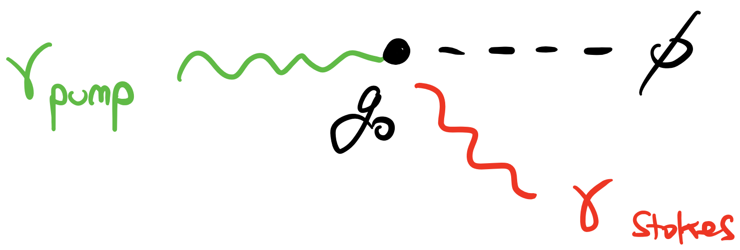
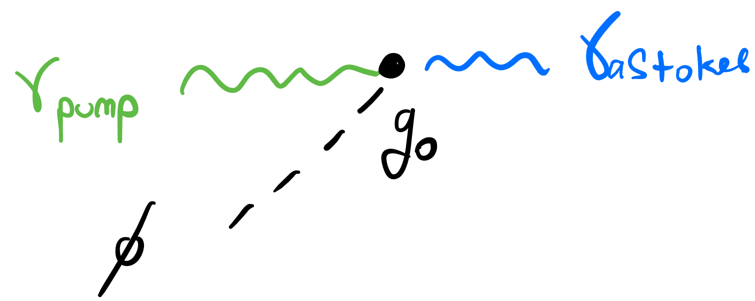


and/or



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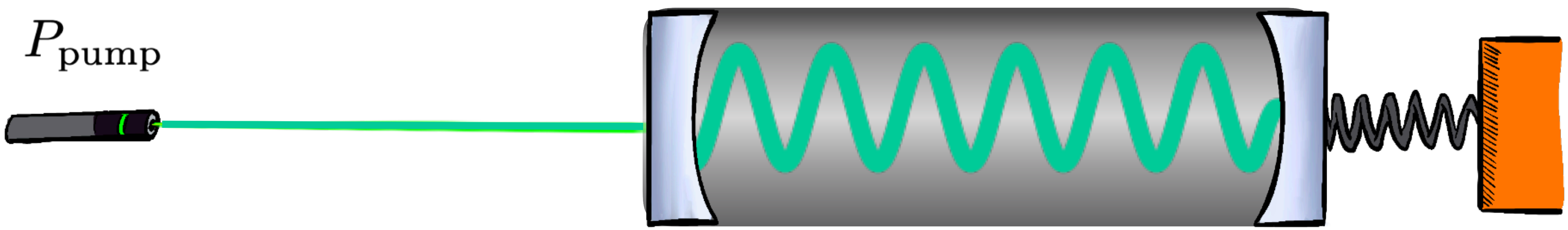

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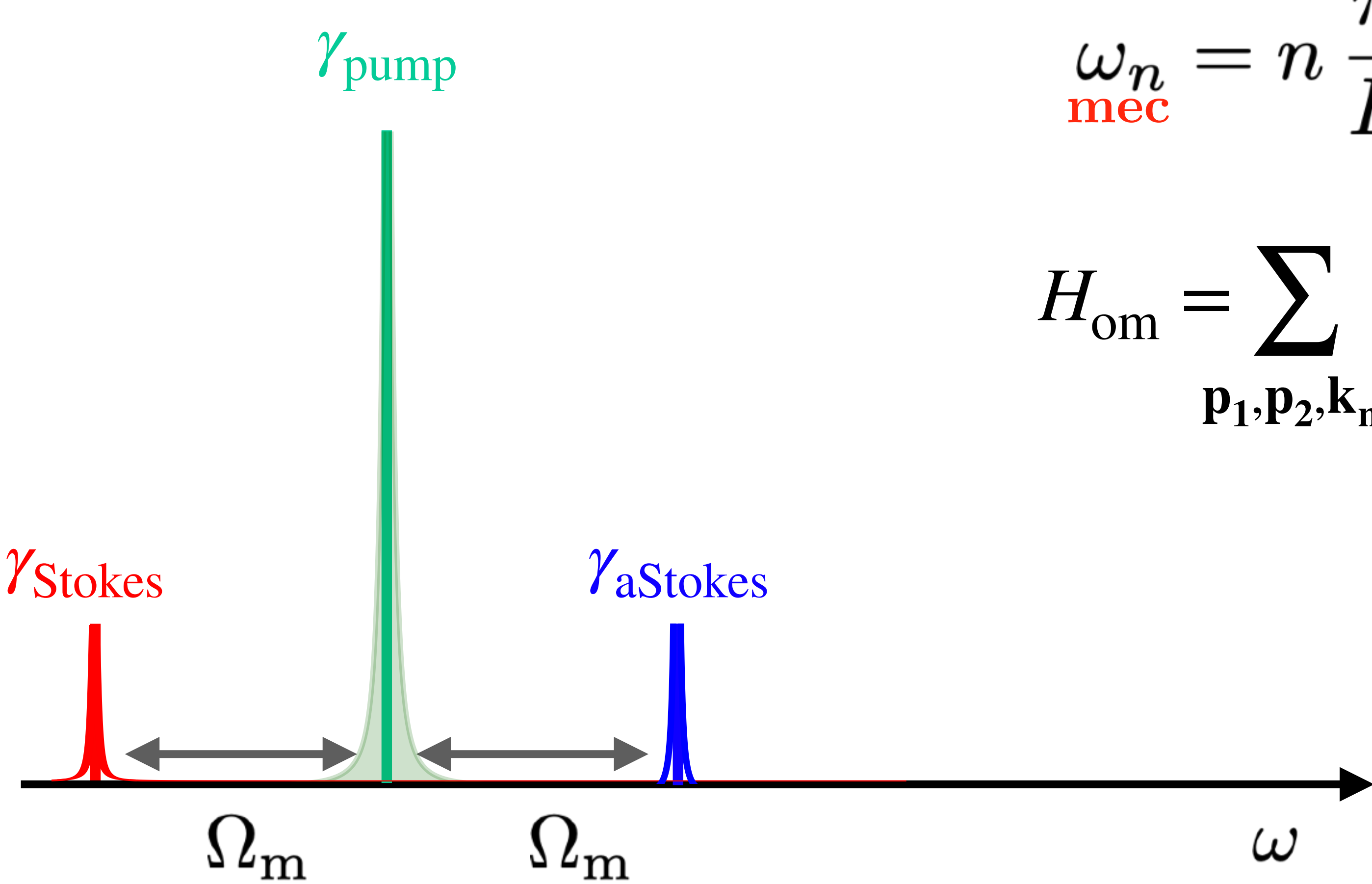
$$H_{om} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0\left(a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b^\dagger_{\mathbf{k_m}} + a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b_{\mathbf{k_m}}\right)$$



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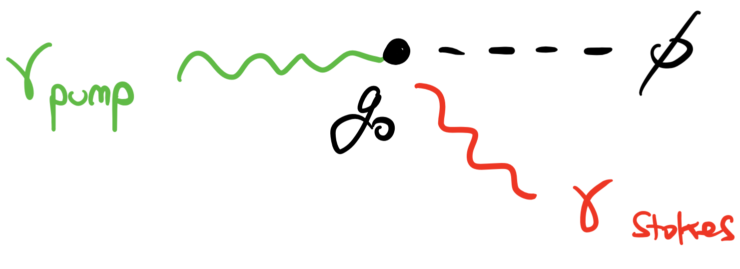

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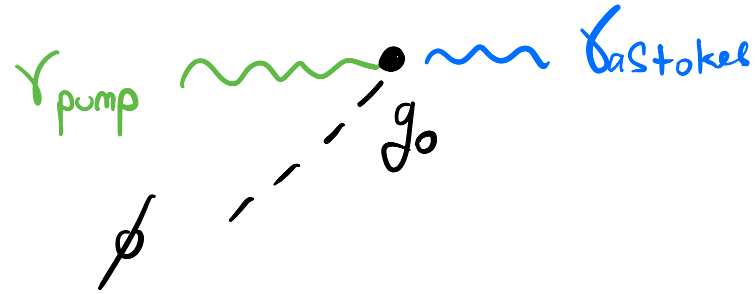

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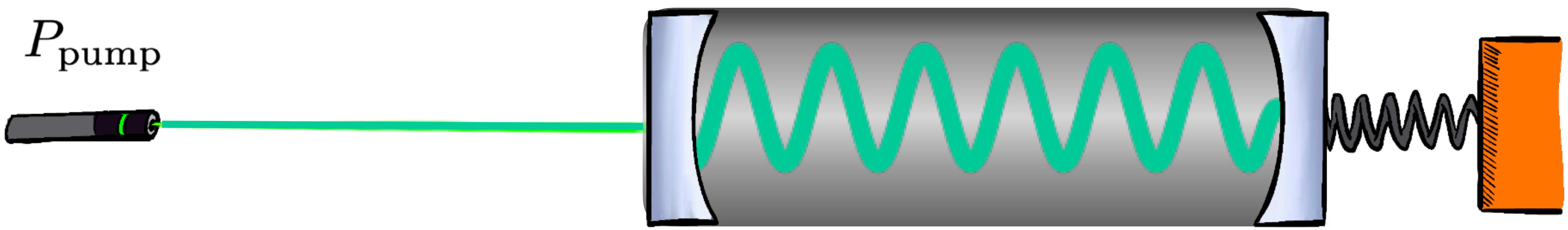
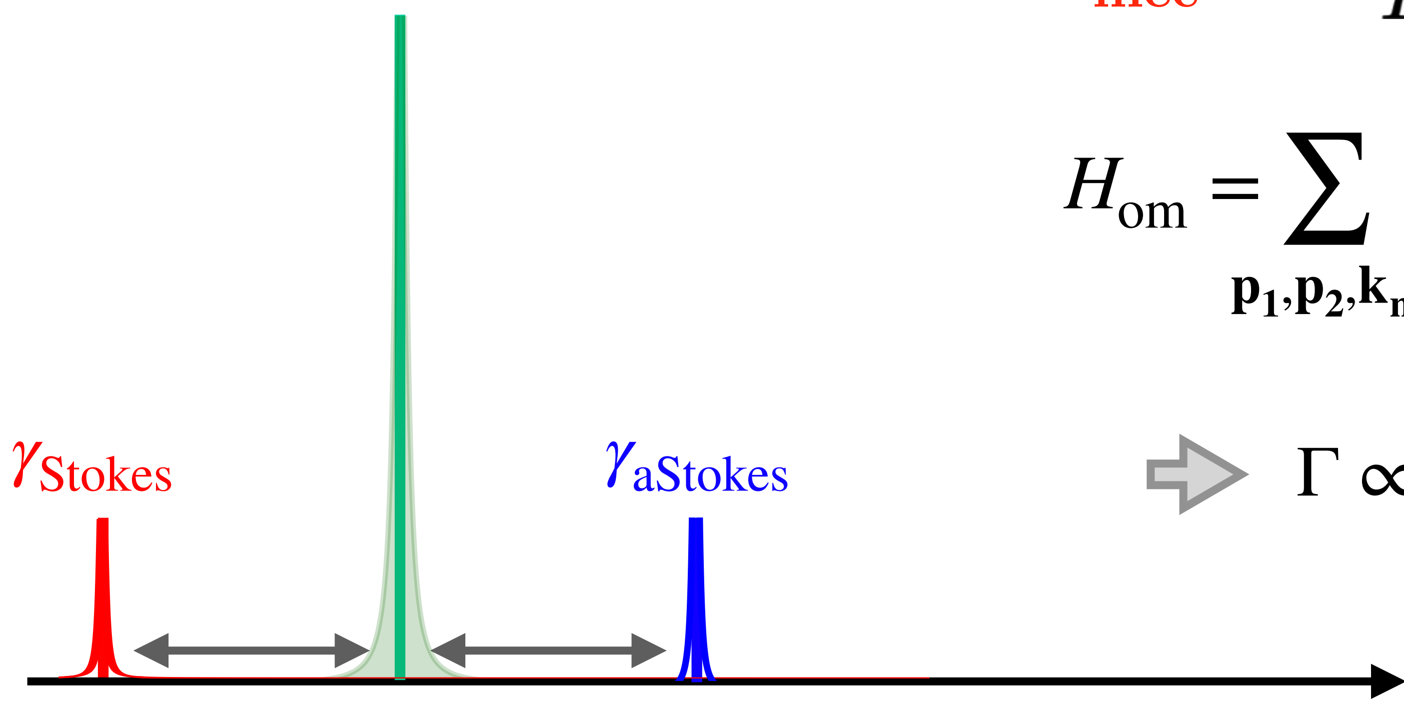
P_pump



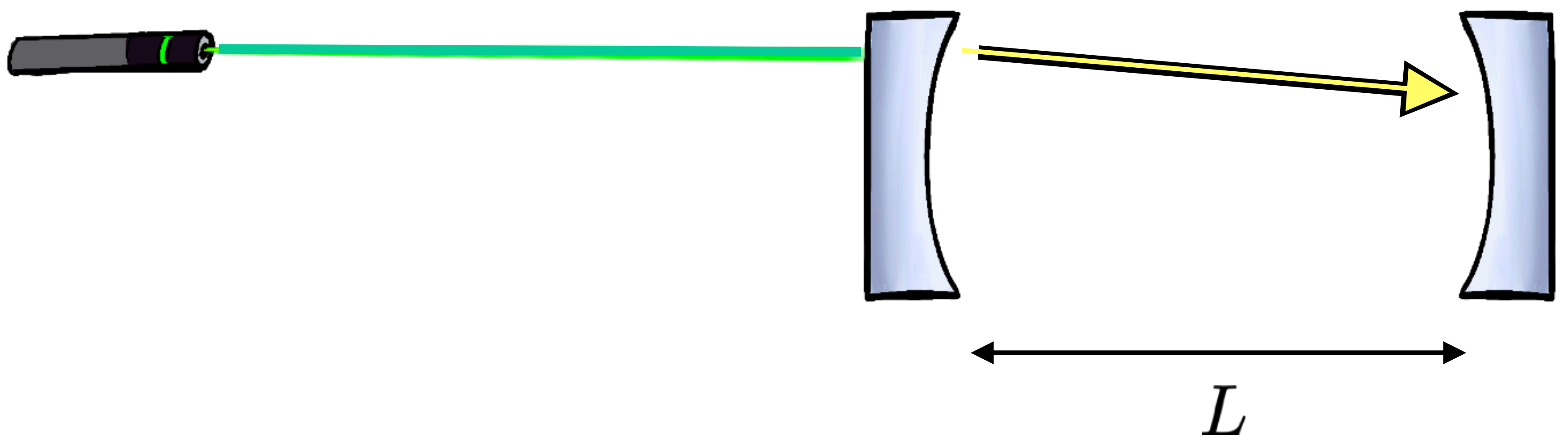
$$\omega_{n_\mathbf{mec}} = n\frac{\pi}{L}c_s, \quad n \subset \mathbb{Z}$$



$$H_\mathrm{om} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0\left(a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b^\dagger_{\mathbf{k_m}} + a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b_{\mathbf{k_m}}\right)$$

$$\Rightarrow \quad \Gamma \propto |g_0|^2\, N^\mathrm{circ}_{\gamma,\mathrm{pump}}[\Delta_\mathrm{pump}]$$

Standard Optomechanics



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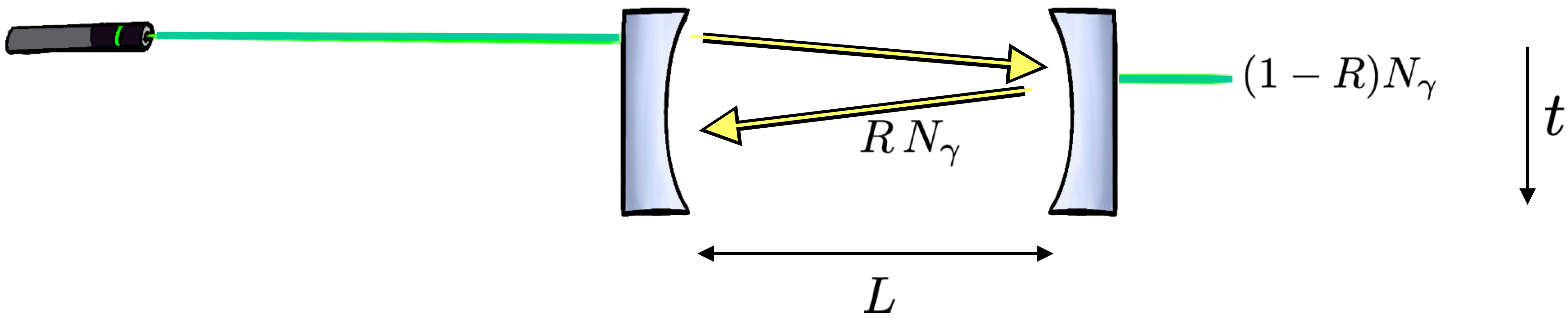

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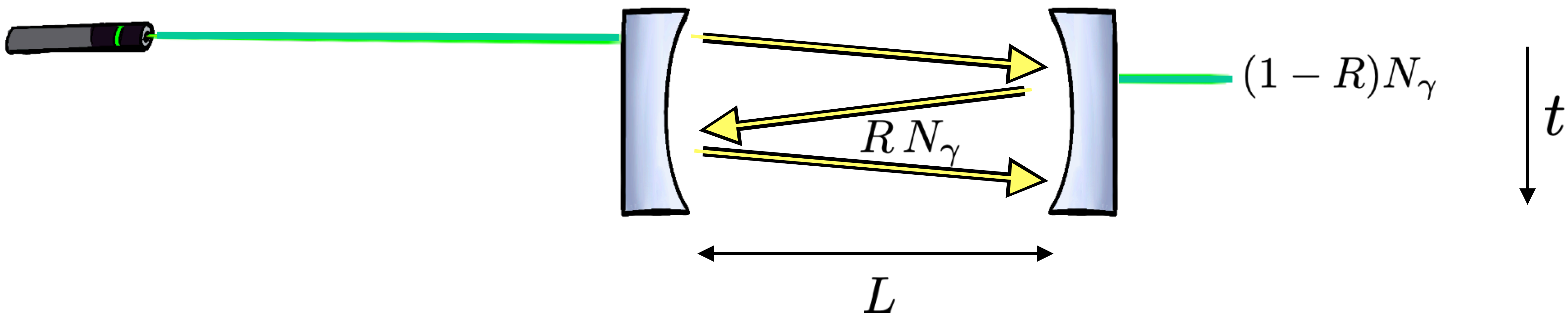
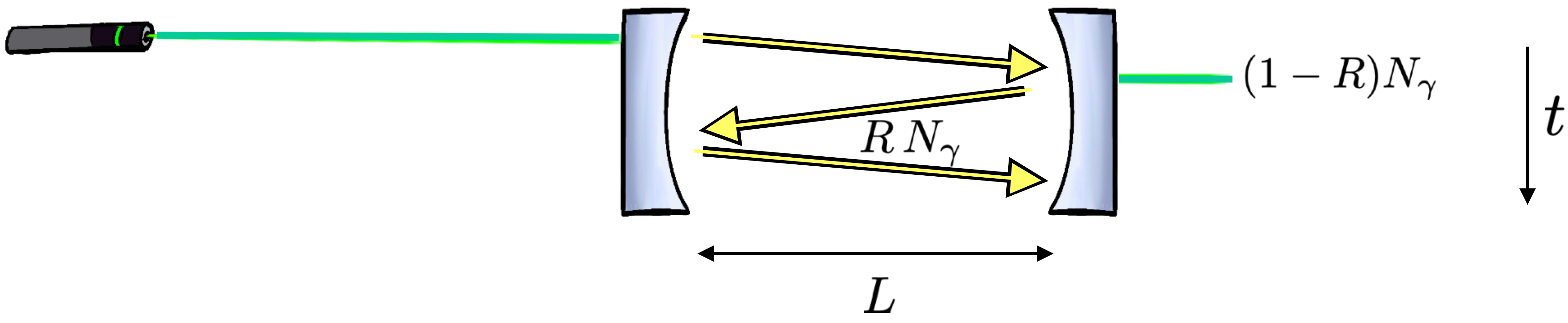


$$\frac{dN_\gamma}{dt} \simeq \frac{\Delta N_\gamma}{L/c} = \frac{c(1-R)}{L}N_\gamma \quad \Rightarrow \quad \tau_\gamma^{-1} \equiv \kappa \simeq \frac{c}{(1-R)^{-1}L}$$

$\mathscr{F}_{\text{opt}}$

Standard Optomechanics



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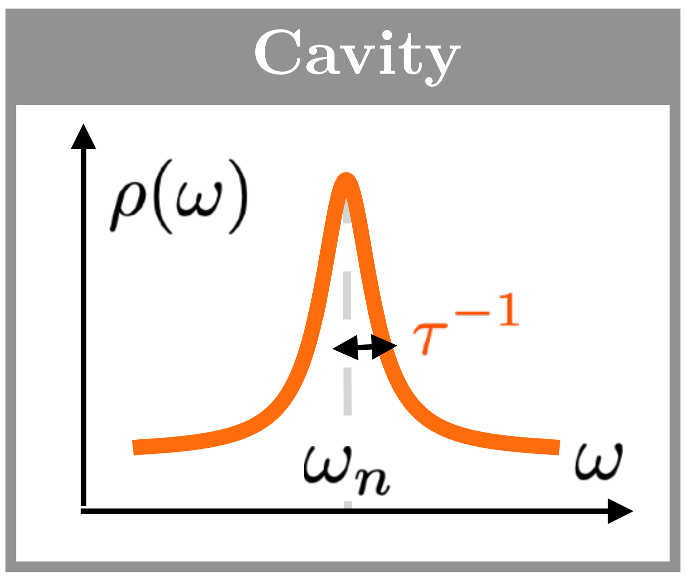
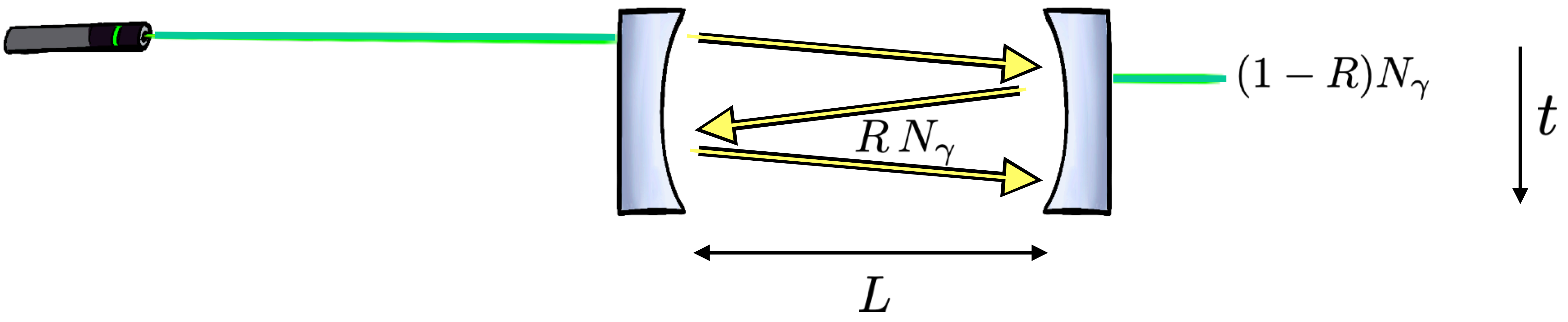


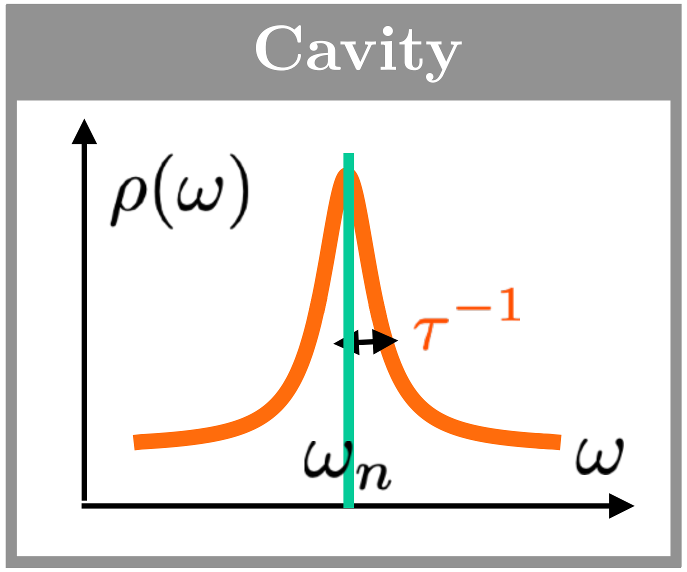
$$\rho(\omega) = \sum_i \delta(\omega - \omega_i) = \sum_n \frac{1}{2\pi} \int dt\, e^{i(\omega-\omega_n)t} e^{-t/(2\tau)} = \sum_n \frac{\tau^{-1}/2}{(\omega-\omega_n)^2 + (\tau^{-1}/2)^2}$$

Standard Optomechanics



$$\frac{dN_\gamma}{dt} \simeq \frac{\Delta N_\gamma}{L/c} = \frac{c(1-R)}{L} N_\gamma \quad \Rightarrow \quad \tau_\gamma^{-1} \equiv \kappa \simeq \frac{c}{(1-R)^{-1}L}$$

$$N_{\gamma,L}^{\text{circ}} \sim \frac{4P_L\tau}{\omega_L}$$



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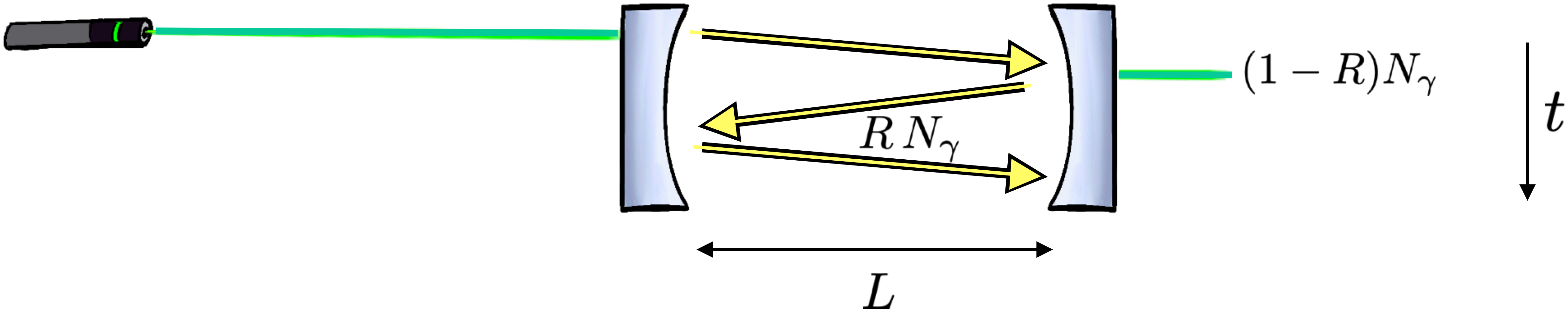
Standard Optomechanics



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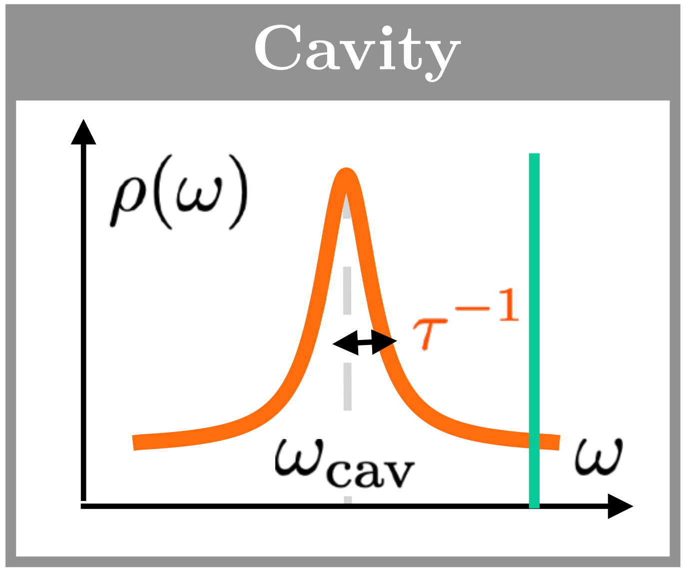

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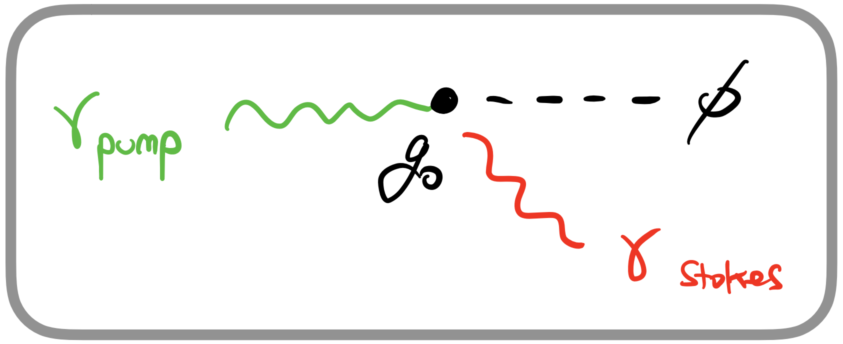
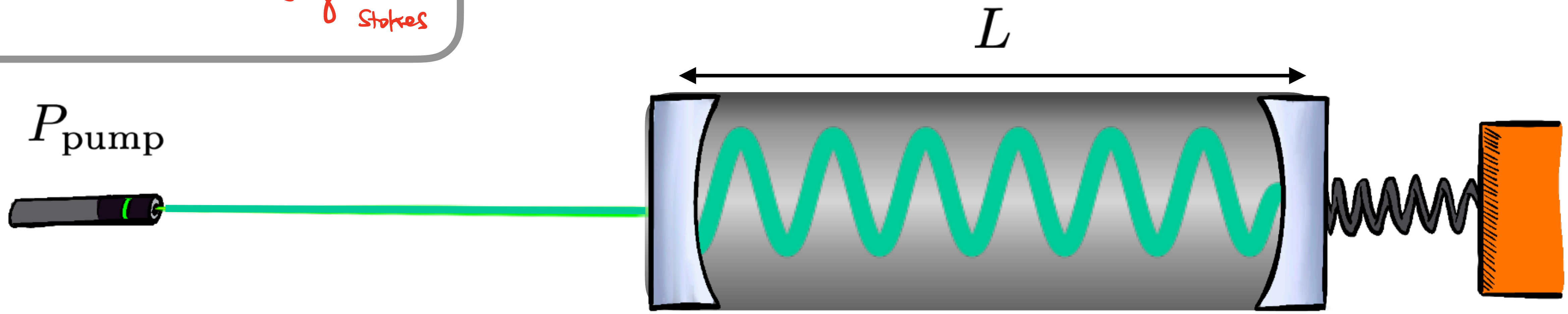
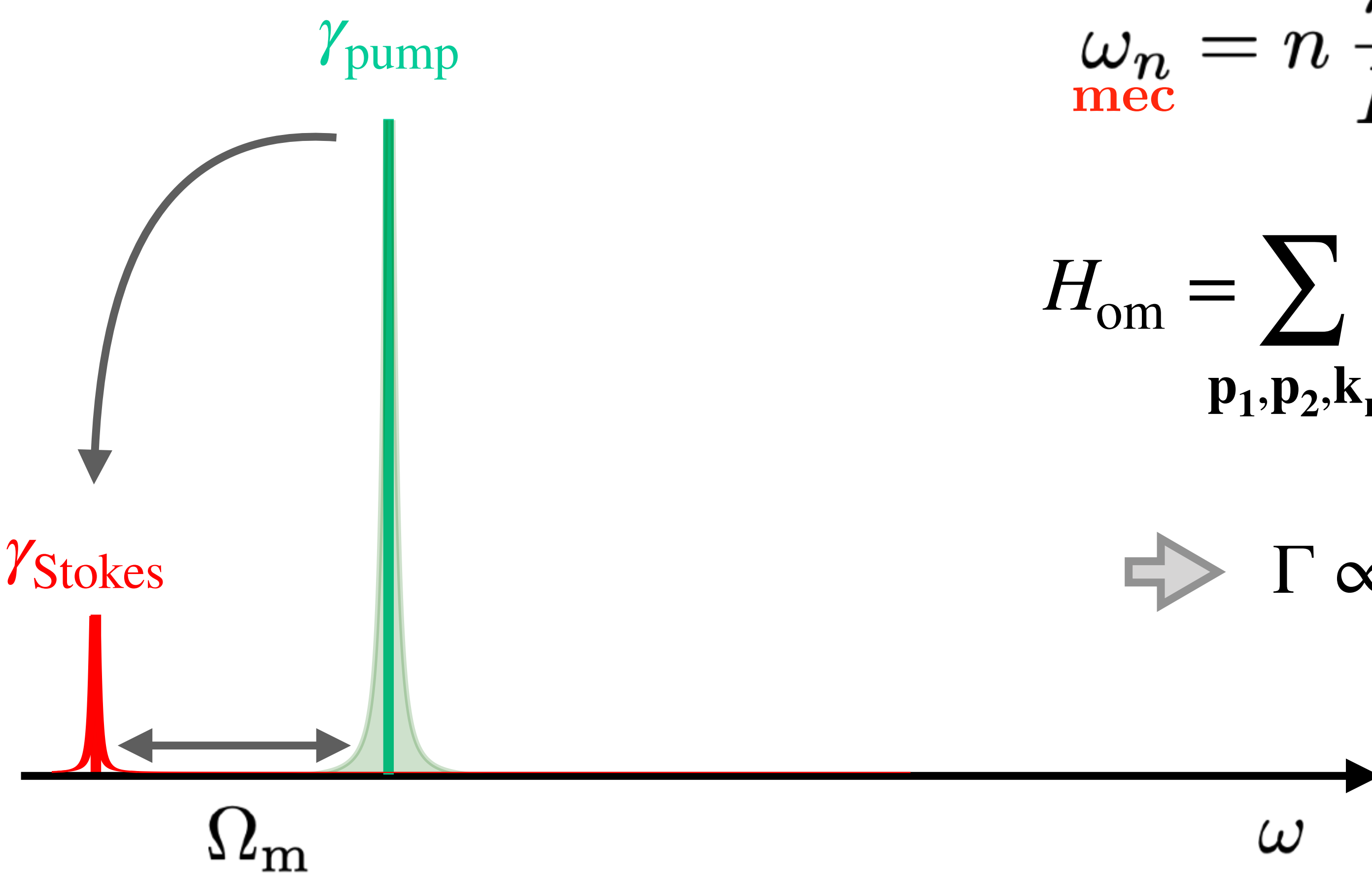
Standard Optomechanics



$$p_\phi = 2p_\gamma$$
$$\Omega_m = 2c_s\omega_{opt}$$



$$\omega_{n}^{\text{mec}} = n\,\frac{\pi}{L}\,c_s, \quad n \subset \mathbb{Z}$$



$$H_{om} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} \right)$$

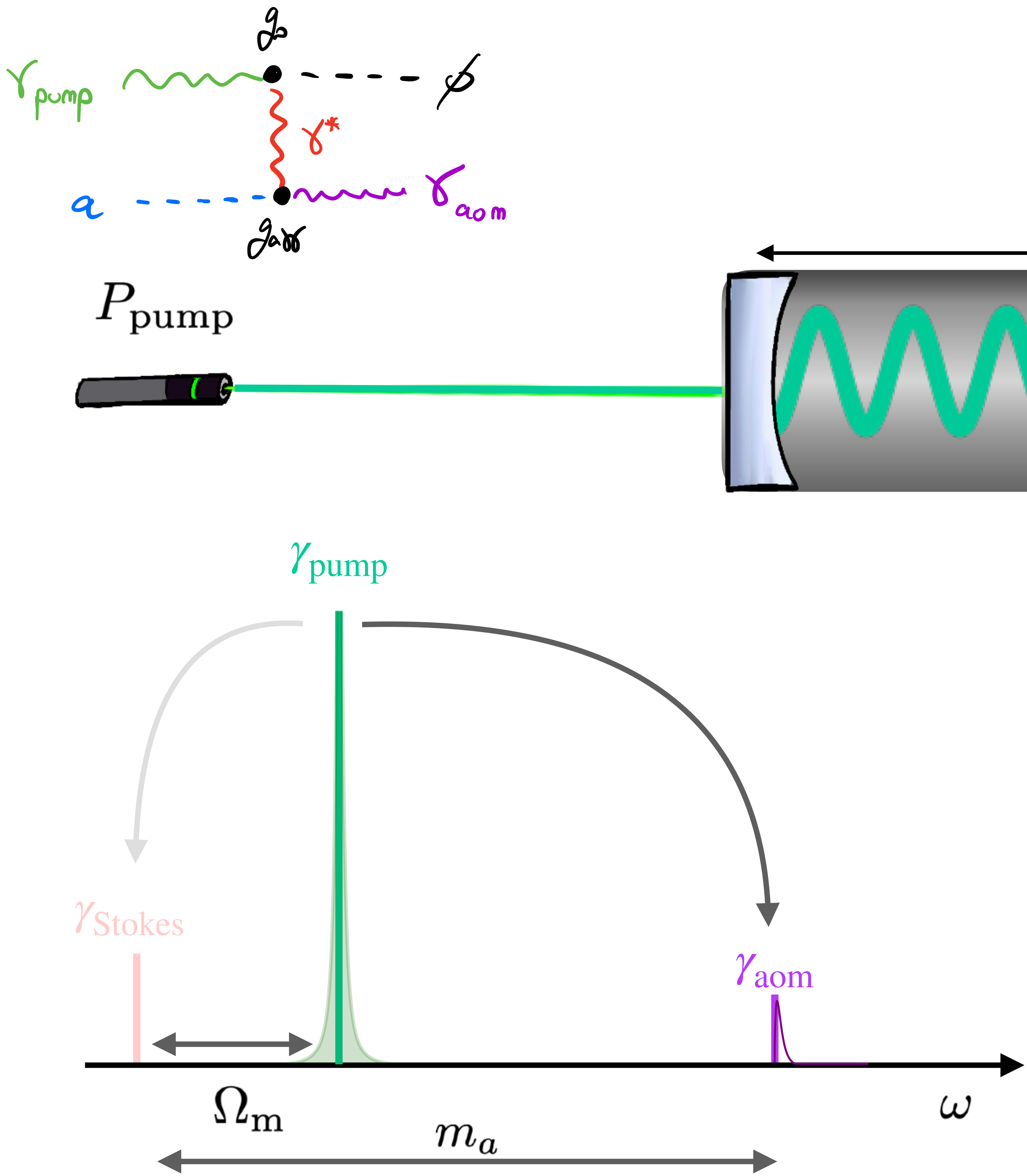
$$\Rightarrow \Gamma \propto |g_0|^2 N_{\gamma,\text{pump}}$$

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

~~Standard~~ Axioptomechanics

$$p_\phi \simeq 2p_\gamma$$

$$\omega_{\gamma 1} + \omega_a = \omega_{\gamma 2} + \omega_\phi$$



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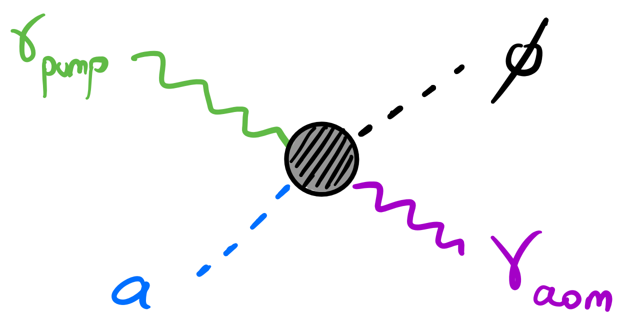

$$p_\phi \simeq 2p_\gamma$$
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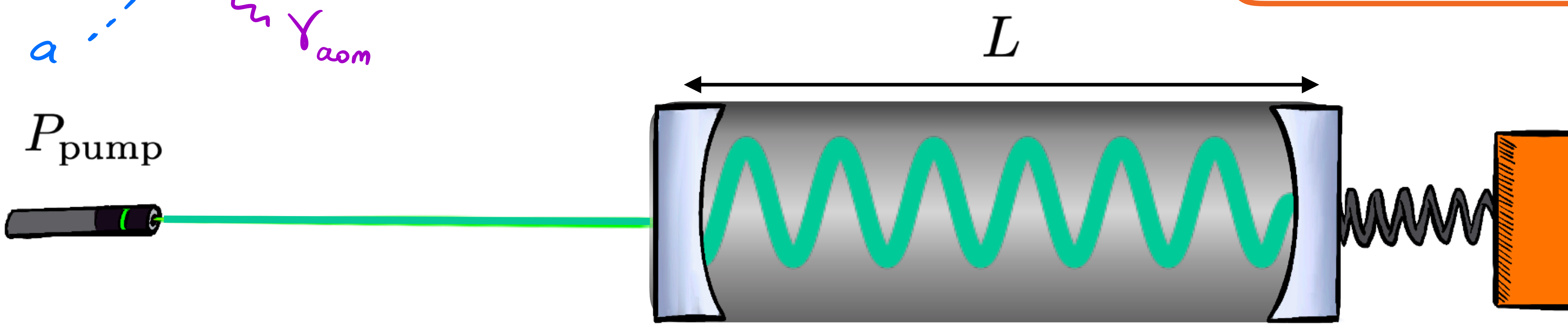
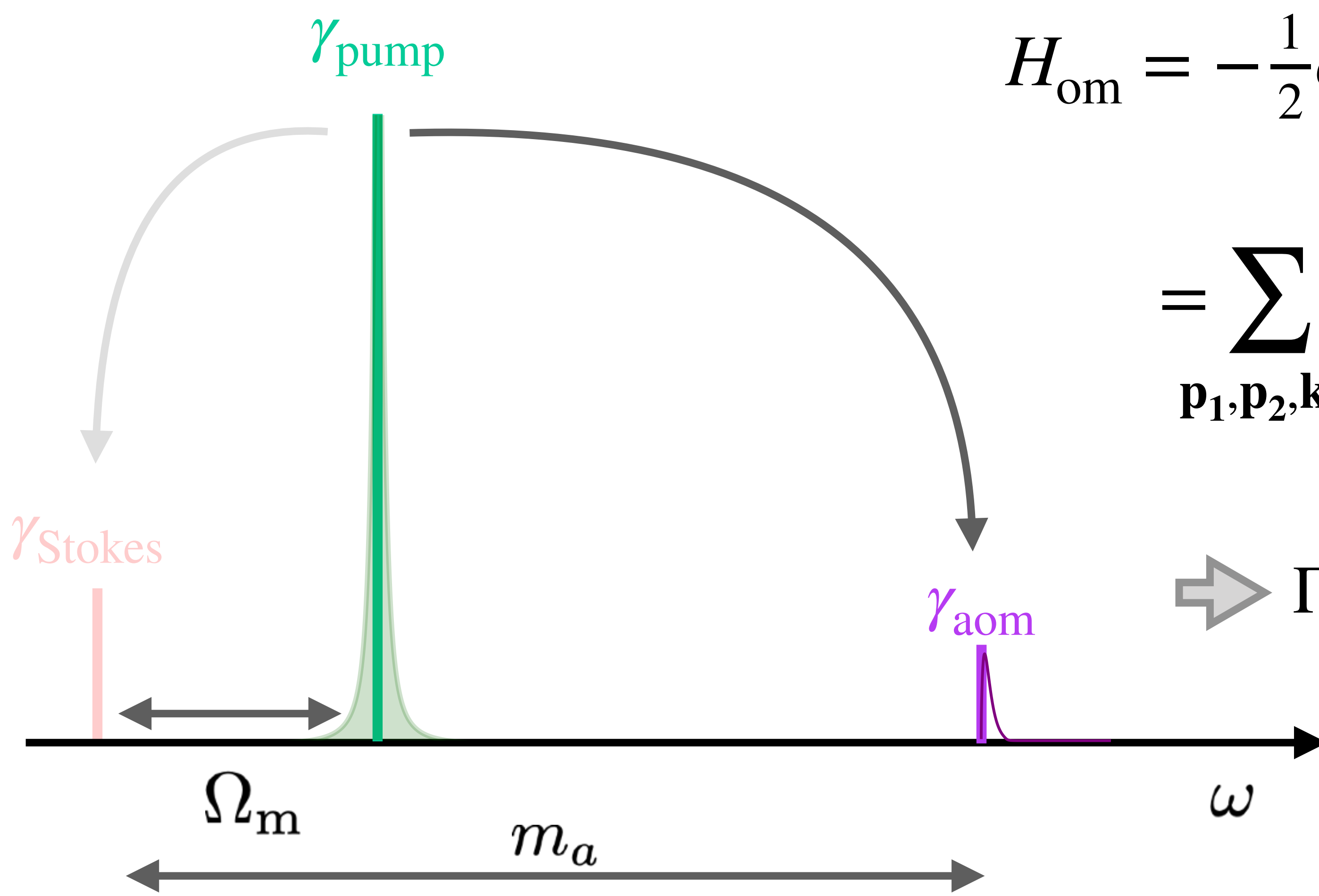


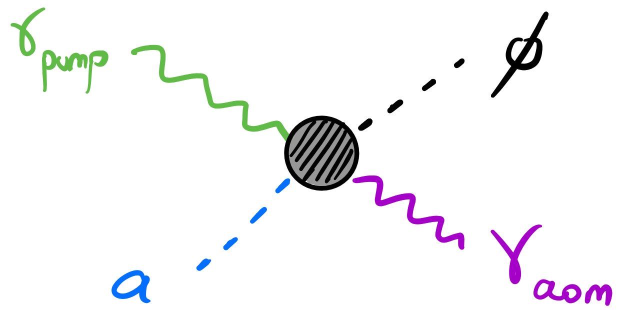


$$H_{\rm om} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma} \int d^3\mathbf{r}\, a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$$

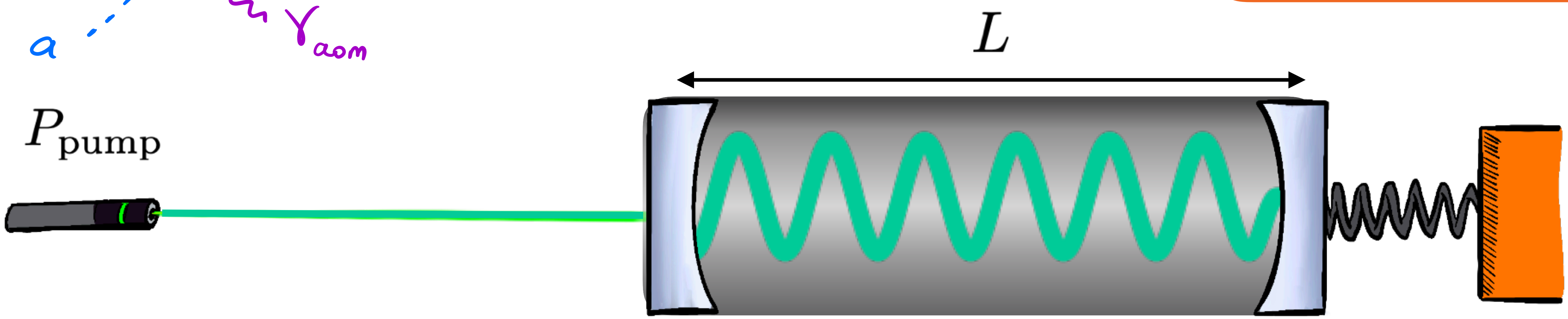
$$= \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0^{(a)} \left(g_{a\gamma\gamma} \frac{\sqrt{2\rho_a}}{m_a} \right) \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} \right)$$

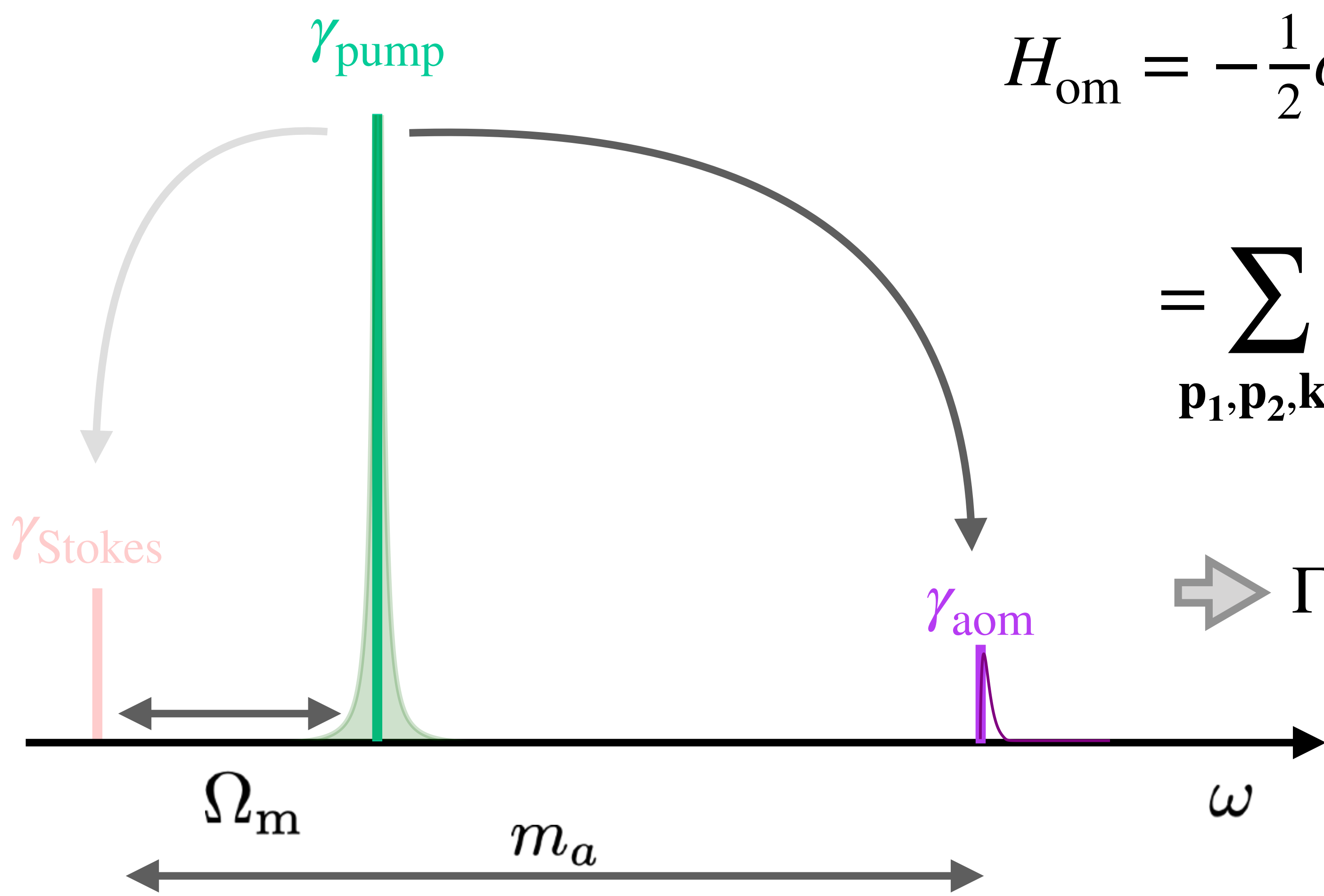
$$\Rightarrow \Gamma \propto |g_0^{(a)}|^2 \left(g^2_{a\gamma\gamma} \frac{\rho_a}{m_a^2} \right) \times N_{\gamma,\rm pump}$$

~~Standard~~ Axioptomechanics



$$p_\phi \simeq 2p_\gamma$$
$$\omega_{\gamma 1} + \omega_a = \omega_{\gamma 2} + \omega_\phi$$





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

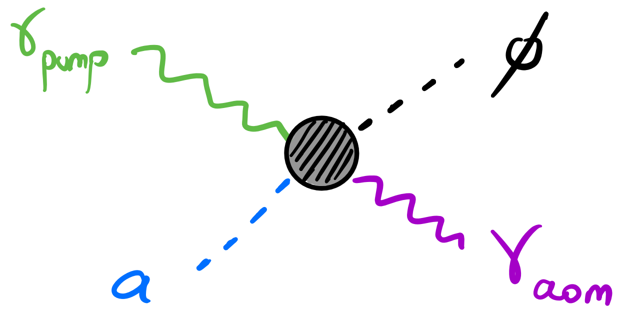
$$= \sum_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{k}_{\text{m}}} g_0^{(a)} \left(g_{a\gamma\gamma} \frac{\sqrt{2\rho_a}}{m_a} \right) \left(a_{\mathbf{p}_1} a^\dagger_{\mathbf{p}_2} b^\dagger_{\mathbf{k}_{\text{m}}} \right)$$

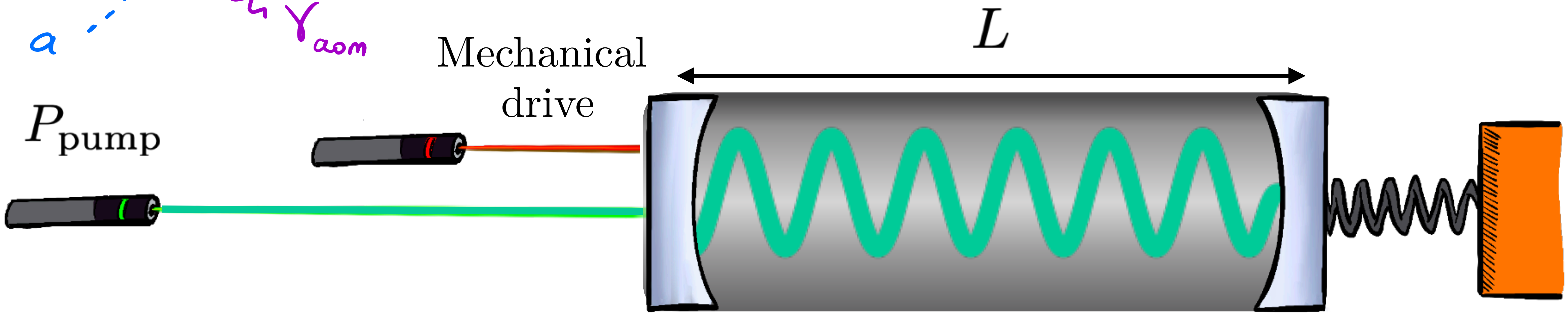
$\sim 10^{-22}$ for QCD axion

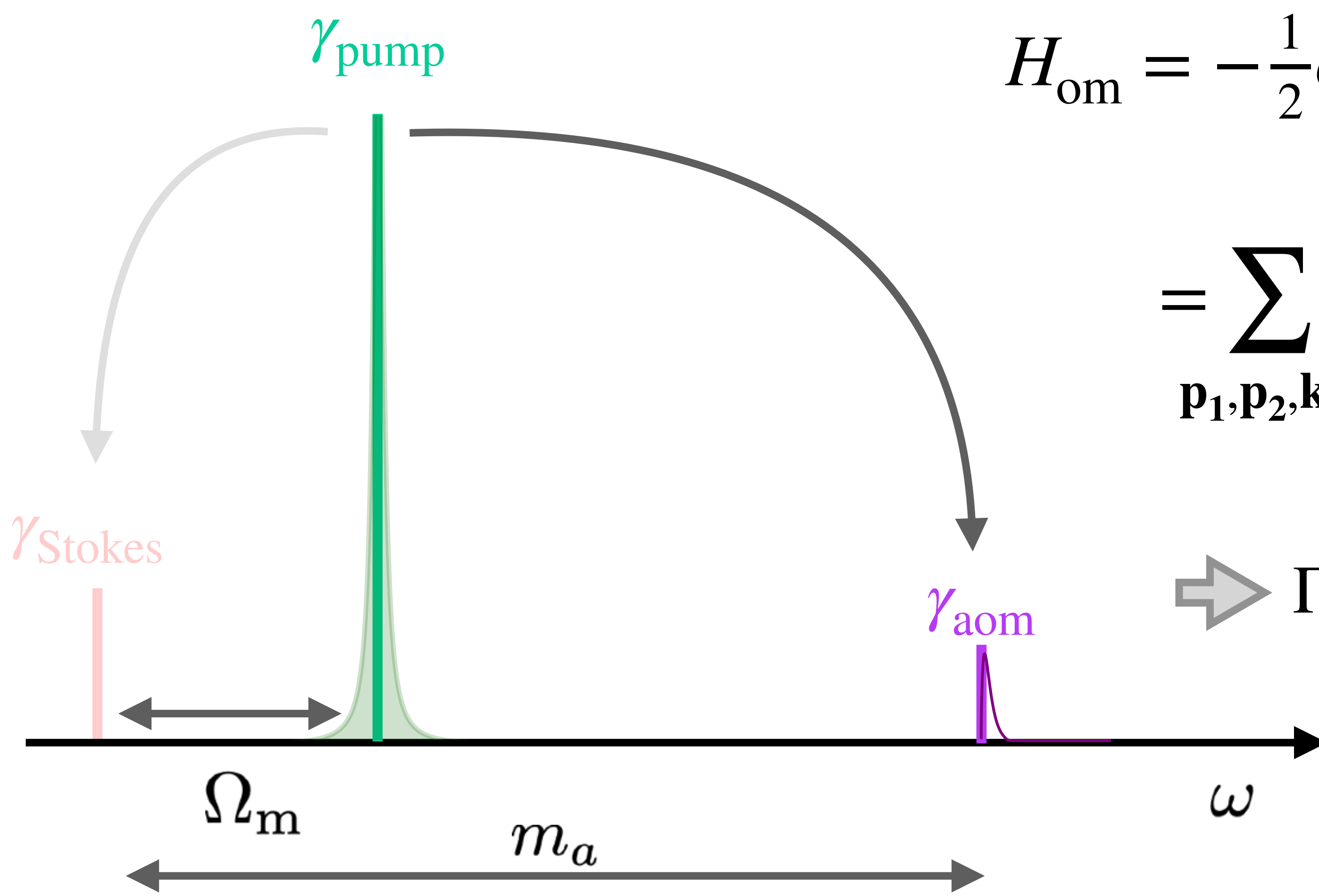
$$\Rightarrow \Gamma \propto |g_0^{(a)}|^2 \left(g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \right) \times N_{\gamma,\text{pump}}$$

Coherent enhancement: Phonons

$$p_\phi \simeq 2p_\gamma$$
$$\omega_{\gamma 1} + \omega_a = \omega_{\gamma 2} + \omega_\phi$$







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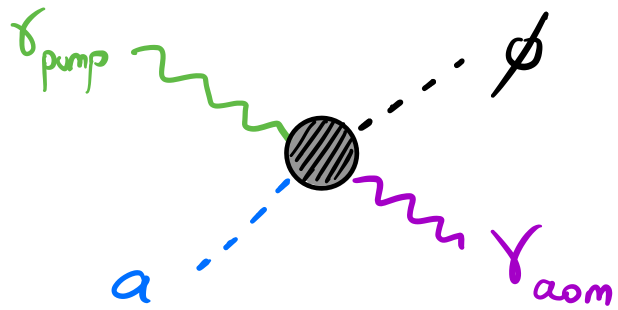
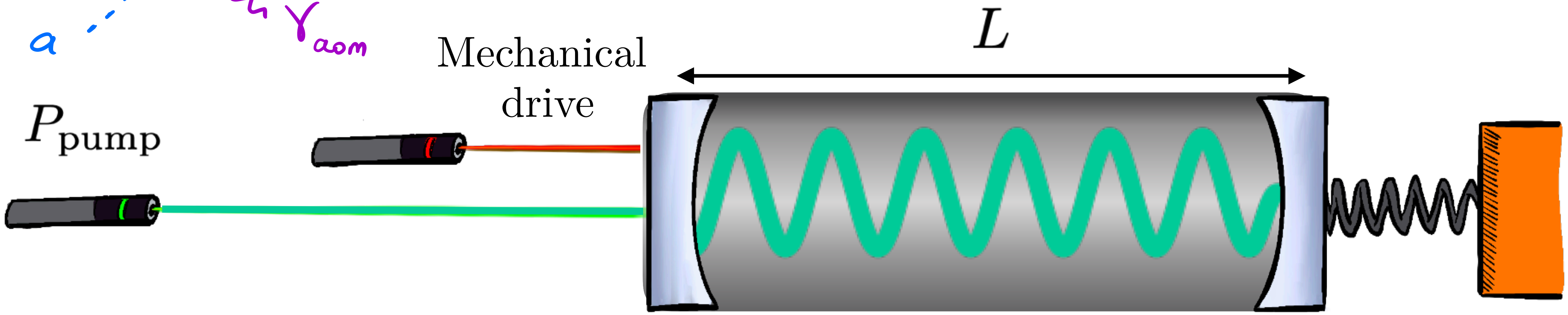
$\sim 10^{-22}$ for QCD axion

$$\Rightarrow \Gamma \propto |g_0^{(a)}|^2 \left(g^2_{a\gamma\gamma} \frac{\rho_a}{m_a^2} \right) \times N_{\gamma,\rm pump}\; N_\phi^{\rm circ}[\Delta_{\rm m}]$$

Axioptomechanics: Rates



$$a_{\rm ovl} = {\rm sinc}\left(\frac{\pi}{2}\left(n_{\rm pump} + n_{\rm probe} - n_{\rm m} + \frac{k_a}{\pi/L}\right)\right)$$



Phonon populated

$$\Rightarrow \Gamma = (2\pi)\,|\,g_0^{(a)}\,|^2\left(g_{a\gamma\gamma}^2\frac{\rho_a}{m_a^2}\right)\int d\omega_{\gamma_{\rm aom}} B_{m_a}(\omega_{\gamma_{\rm aom}} + \Omega_{\rm m} - \omega_{\rm pump}) L(\omega_{\gamma_{\rm aom}} - \omega_{\rm res}, \kappa)$$

$$\times\; N_{\gamma,{\rm pump}}\; N_\phi^{\rm circ}\,[\Delta_{\rm m}]$$

Sensitivity & Scanning Strategy

$$\mathrm{SNR} = \frac{\Gamma_{\mathrm{sig}}}{\Gamma_{\mathrm{back}}} > 3$$

Phonon populated

$$\Gamma = (2\pi)\,|\,g_0^{(a)}\,|^2 \left(g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \right) \int d\omega_{\gamma_{\mathrm{aom}}} B_{m_a}(\omega_{\gamma_{\mathrm{aom}}} + \Omega_{\mathrm{m}} - \omega_{\mathrm{pump}}) L(\omega_{\gamma_{\mathrm{aom}}} - \omega_{\mathrm{res}}, \kappa) \times N_{\gamma,\mathrm{pump}}\; N_{\phi}^{\mathrm{circ}}\,[\Delta_{\mathrm{m}}]$$

Sensitivity & Scanning Strategy

$$\mathrm{SNR} = \frac{\Gamma_{\mathrm{sig}}}{\Gamma_{\mathrm{back}}} > 3 \quad \Rightarrow \quad g_{a\gamma\gamma} > f(m_a, \mathrm{cavity}, \mathrm{lasers}, \mathrm{material})$$

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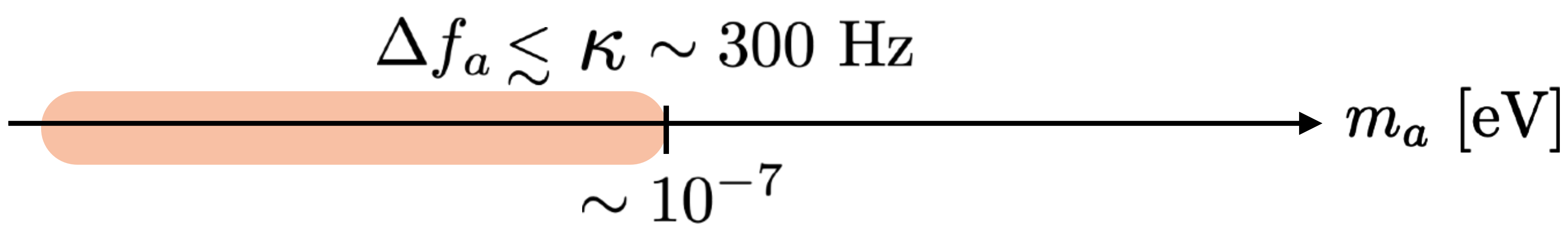
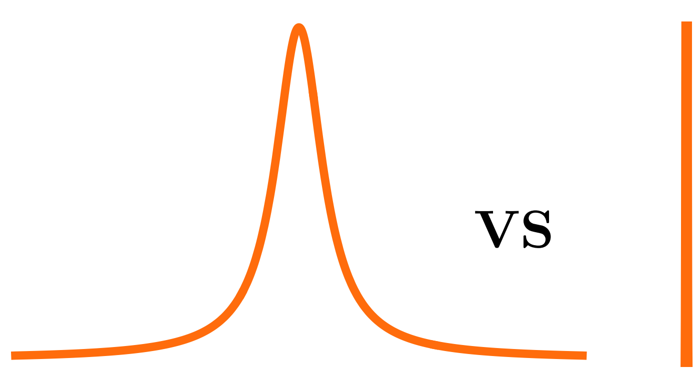


Lorenzian regime



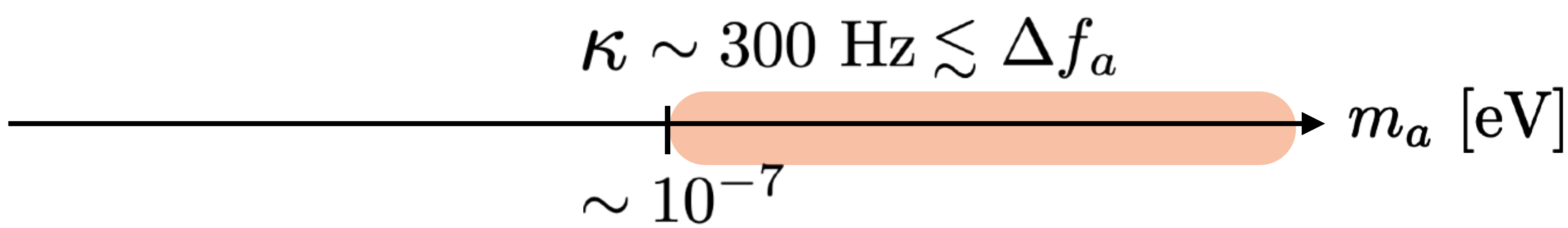
$$\Gamma \propto \frac{\kappa}{\kappa^2 + (\Delta + \Omega_{\mathrm{m}} - m_a)^2}$$

$$\mathrm{spacing} = \epsilon\, \kappa$$

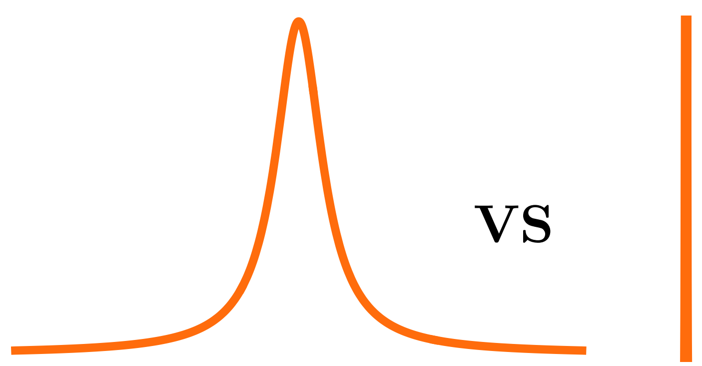
$$t_{\mathrm{int}} = 1\,\mathrm{s} \Rightarrow \sim 6\ \mu\mathrm{eV/year}$$

Sensitivity & **Scanning Strategy**

$$\mathrm{SNR} = \frac{\Gamma_{\mathrm{sig}}}{\Gamma_{\mathrm{back}}} > 3 \quad \Rightarrow \quad g_{a\gamma\gamma} > f(m_a, \mathrm{cavity}, \mathrm{lasers}, \mathrm{material})$$



Lorenzian regime



vs

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

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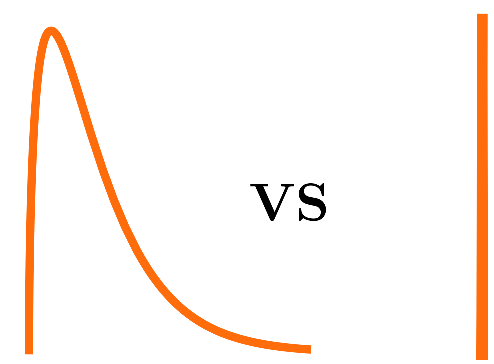
$$t_{\mathrm{int}} = 1\,\mathrm{s} \Rightarrow \sim 6\ \mu\mathrm{eV/year}$$

Boltzmann regime



vs

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

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

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

Axioptomechanics: Numbers

[A.D. Kashkanova, A.B. Shkarin, C.D. Brown, et al. , 2017]

Yale University Jack Harris Lab

He For usual experiments in their lab:

- $N_{\text{pump}} \simeq 10^6$
- $N_\phi = 1$

$P_{\text{pump}} \sim 1\,\mu\text{W}$

$L \sim 100\,\mu\text{m}$

$\mathcal{F}_{\text{opt}}/\pi \sim 10^5$

Axioptomechanics: **Numbers**

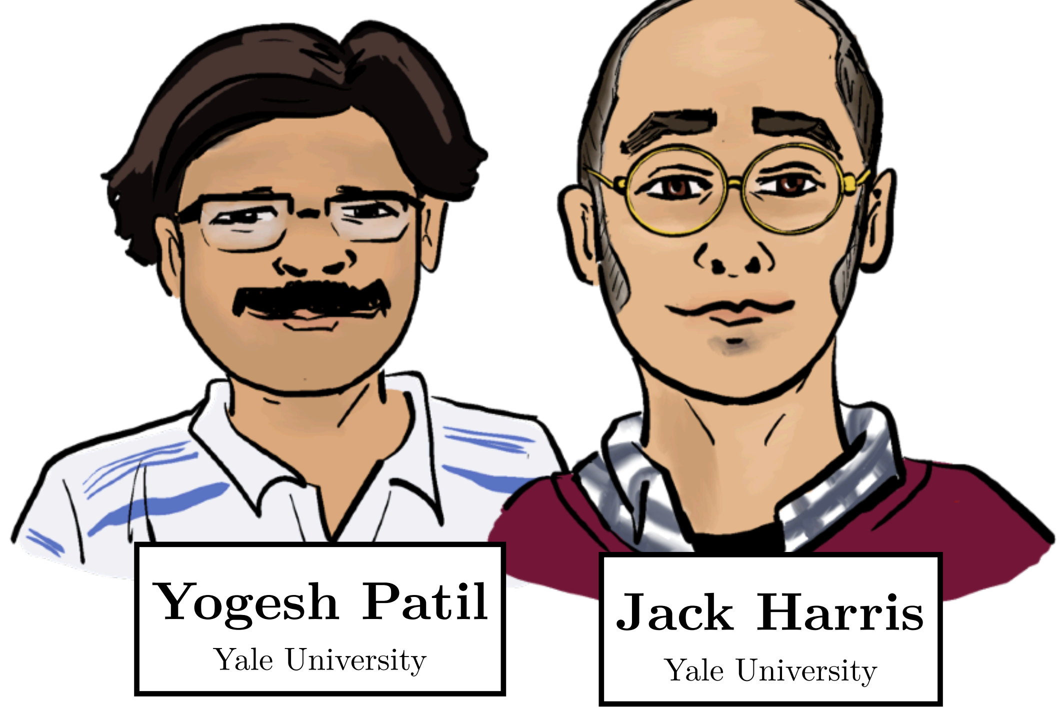
[A.D. Kashkanova, A.B. Shkarin, C.D. Brown, et al. , 2017]

Yale University Jack Harris Lab

He What could be feasible to achieve:

- $N_{\text{pump}} \simeq 10^{17}$ $\quad$ $P_{\text{pump}} \sim 1$ W
- $N_{\phi} \simeq 10^{14}$ $\quad$ $L \sim 1$ m

$\mathcal{F}_{\text{opt}}/\pi \sim 10^{6}$



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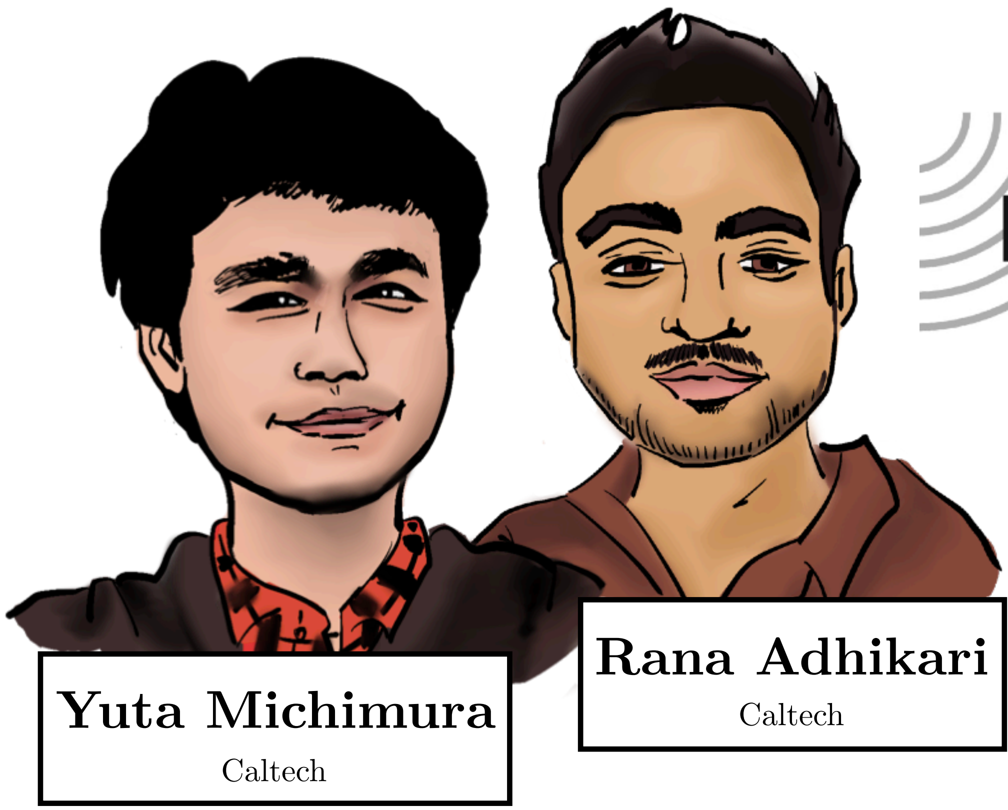

Si

- $N_{\rm pump} \simeq 10^{16}$ $\quad P_{\rm pump} \sim 1$ W
- $N_\phi \simeq 10^{19}$ $\quad L \sim 10$ cm

$\mathcal{F}_{\rm opt}/\pi \sim 10^6$

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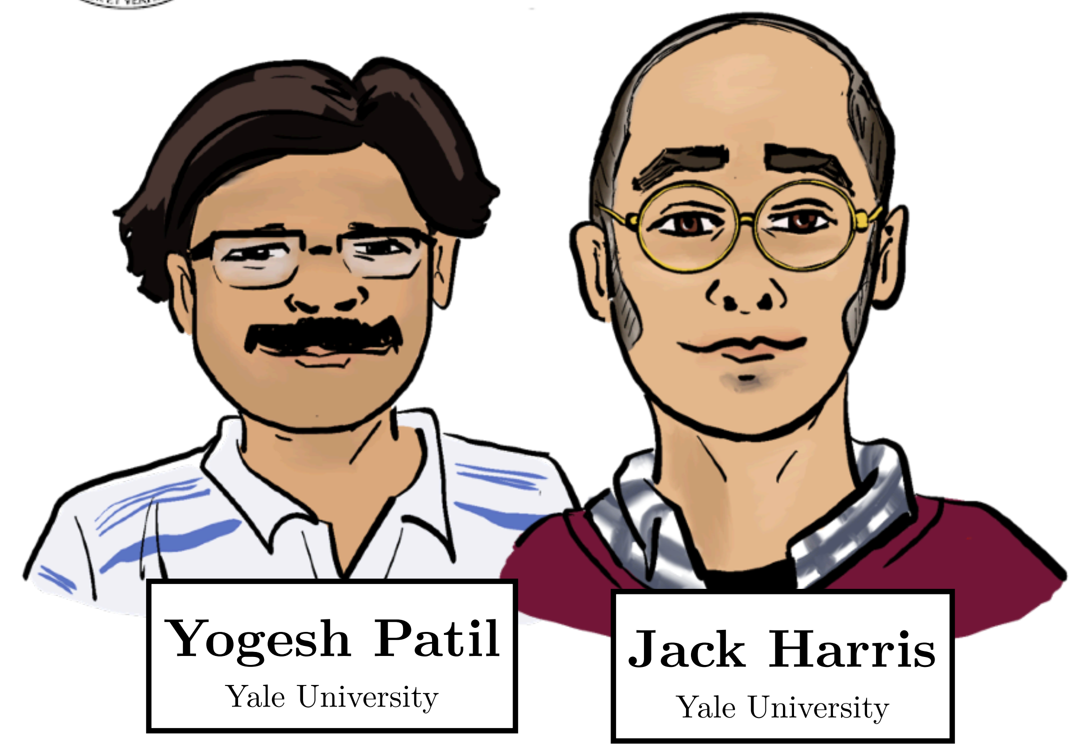
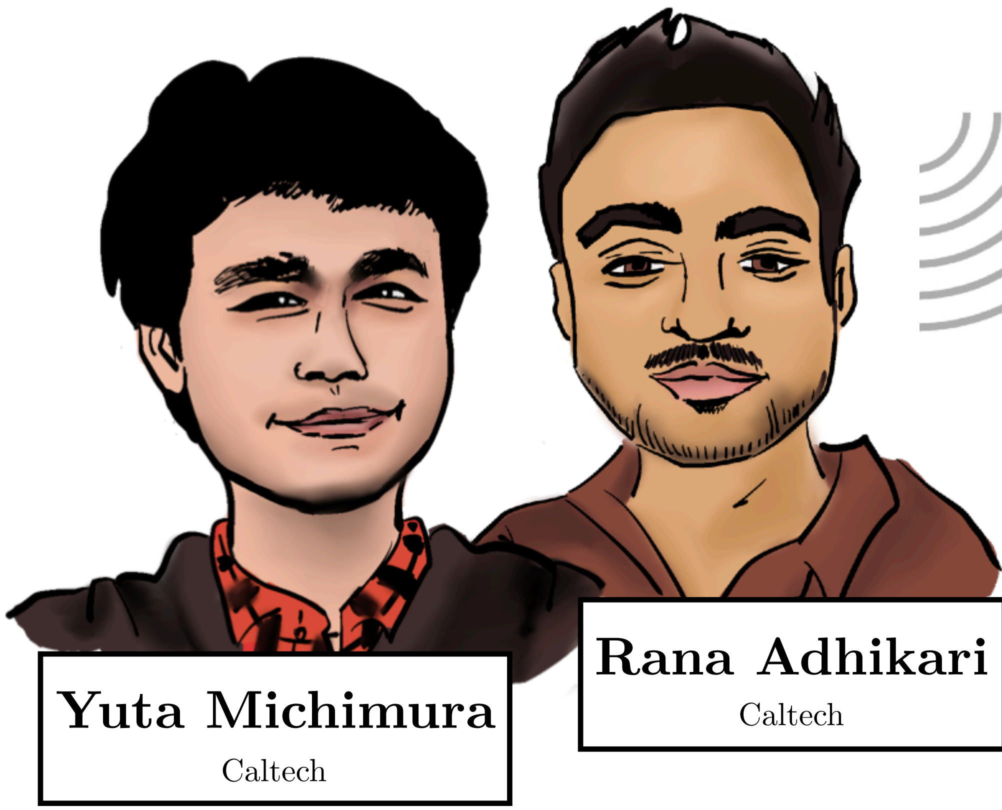
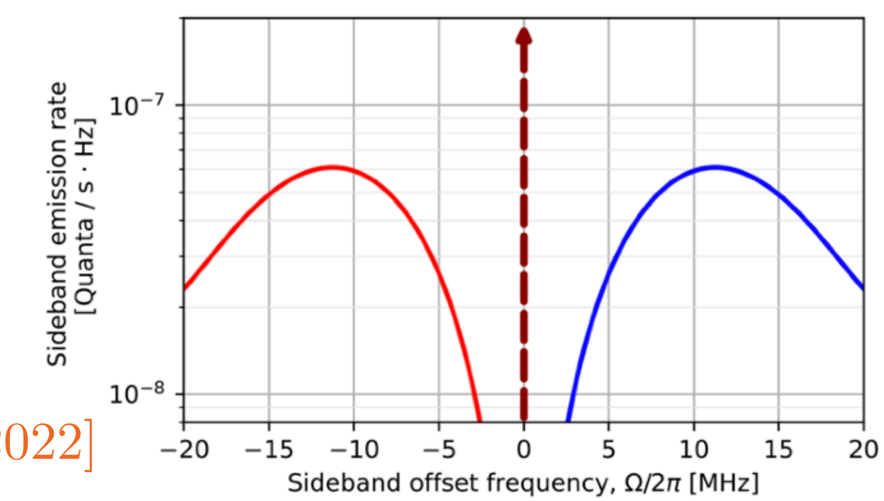
Yale University Jack Harris Lab





LIGO



[L. McCuller, 2022]

Si

- $N_{\text{pump}} \simeq 10^{16}$
- $N_{\phi} \simeq 10^{19}$

$P_{\text{pump}} \sim 1$ W
$L \sim 10$ cm
$\mathcal{F}_{\text{opt}}/\pi \sim 10^6$

GQuEST

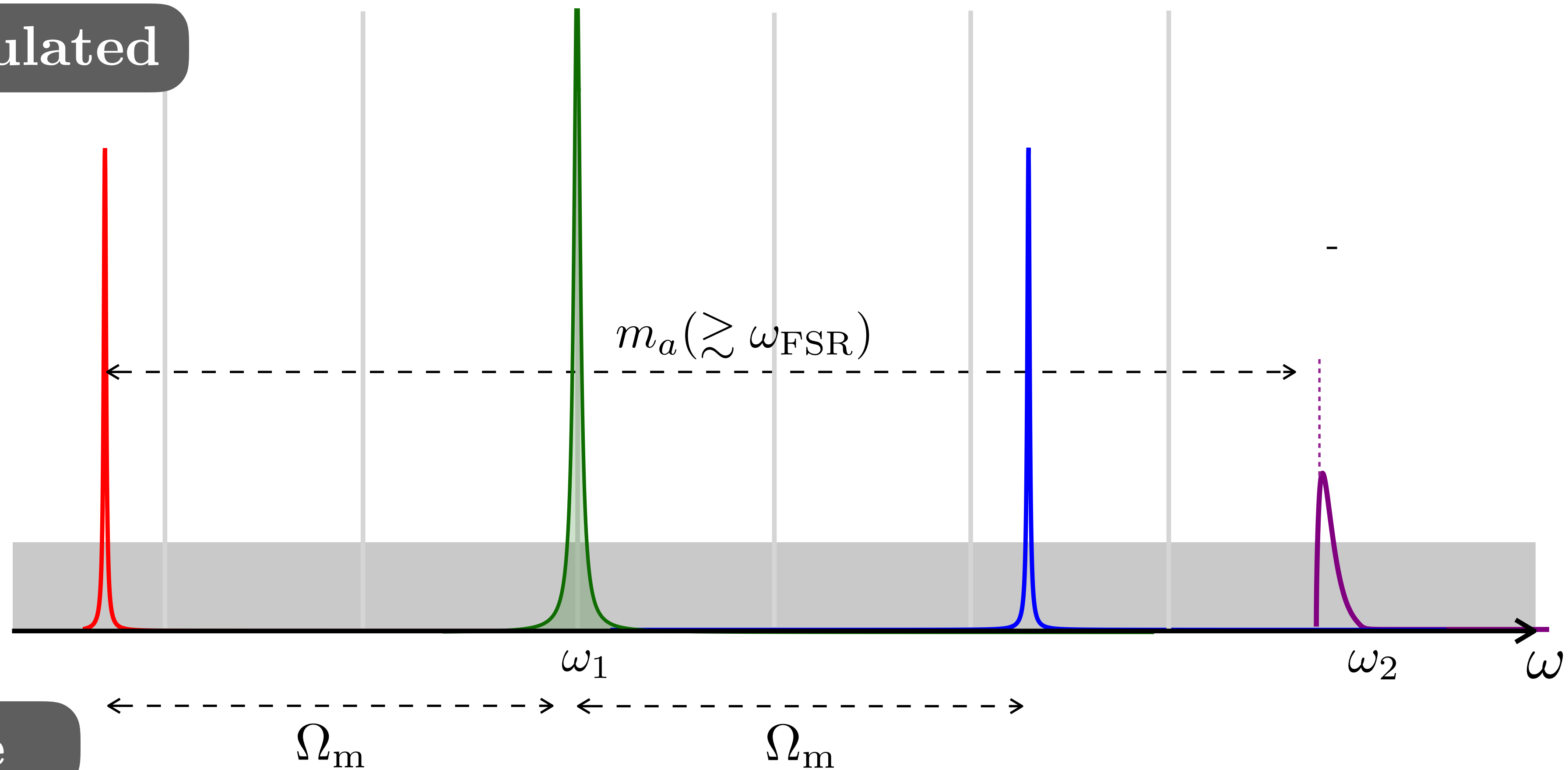
- $N_{\text{pump}} \simeq 10^{22}$

$P_{\text{pump}} \sim 10$ kW
$L \sim 5$ m
$\mathcal{F}_{\text{opt}}/\pi \sim 10^6$

Sensitivity & Scanning Strategy

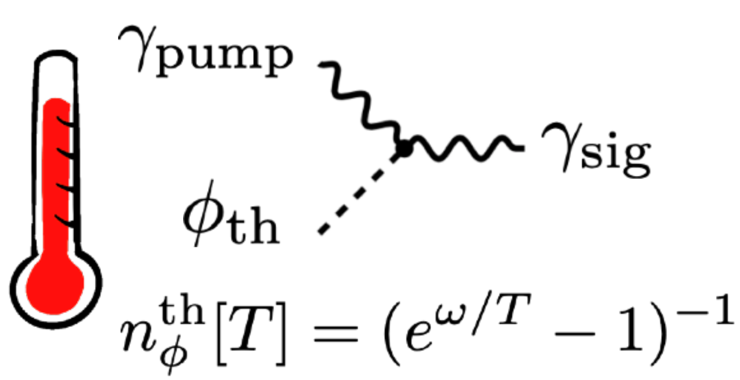
$$\mathrm{SNR} = \frac{\Gamma_{\mathrm{sig}}\,(t_{\mathrm{int}}/\tau_a)}{\Gamma_{\mathrm{back}}} > 3 \;\Rightarrow\; g_{a\gamma\gamma} > f(m_a, \mathrm{cavity}, \mathrm{lasers}, \mathrm{material})$$

Phonon populated



Sources of noise

Thermal phonons



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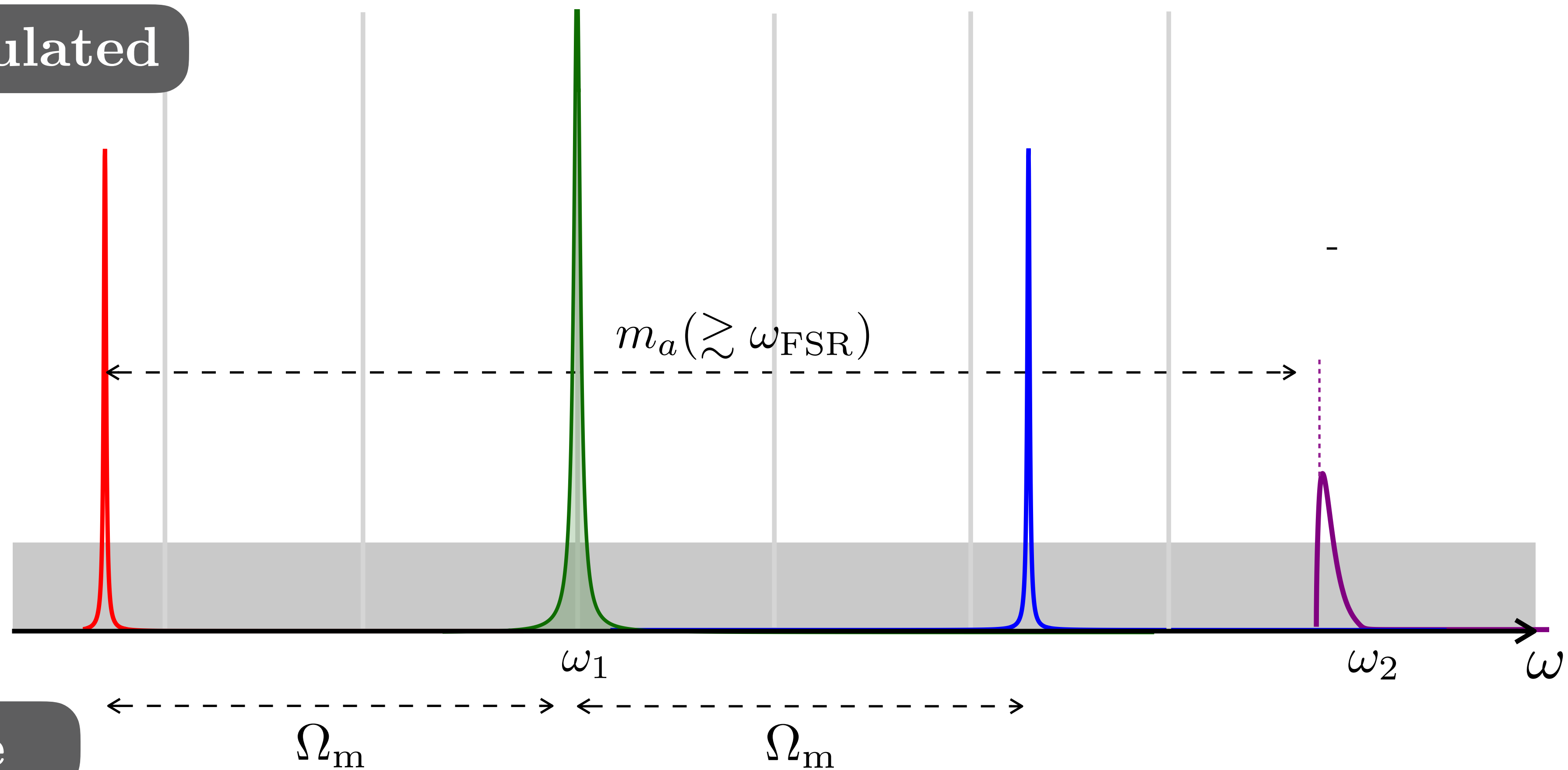
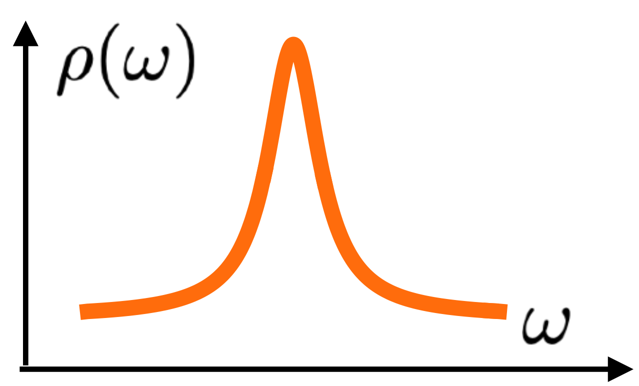
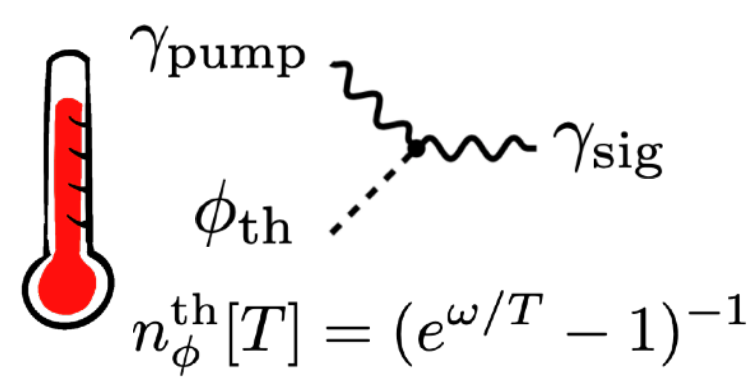


Sources of noise

Laser frequency noise



Thermal phonons



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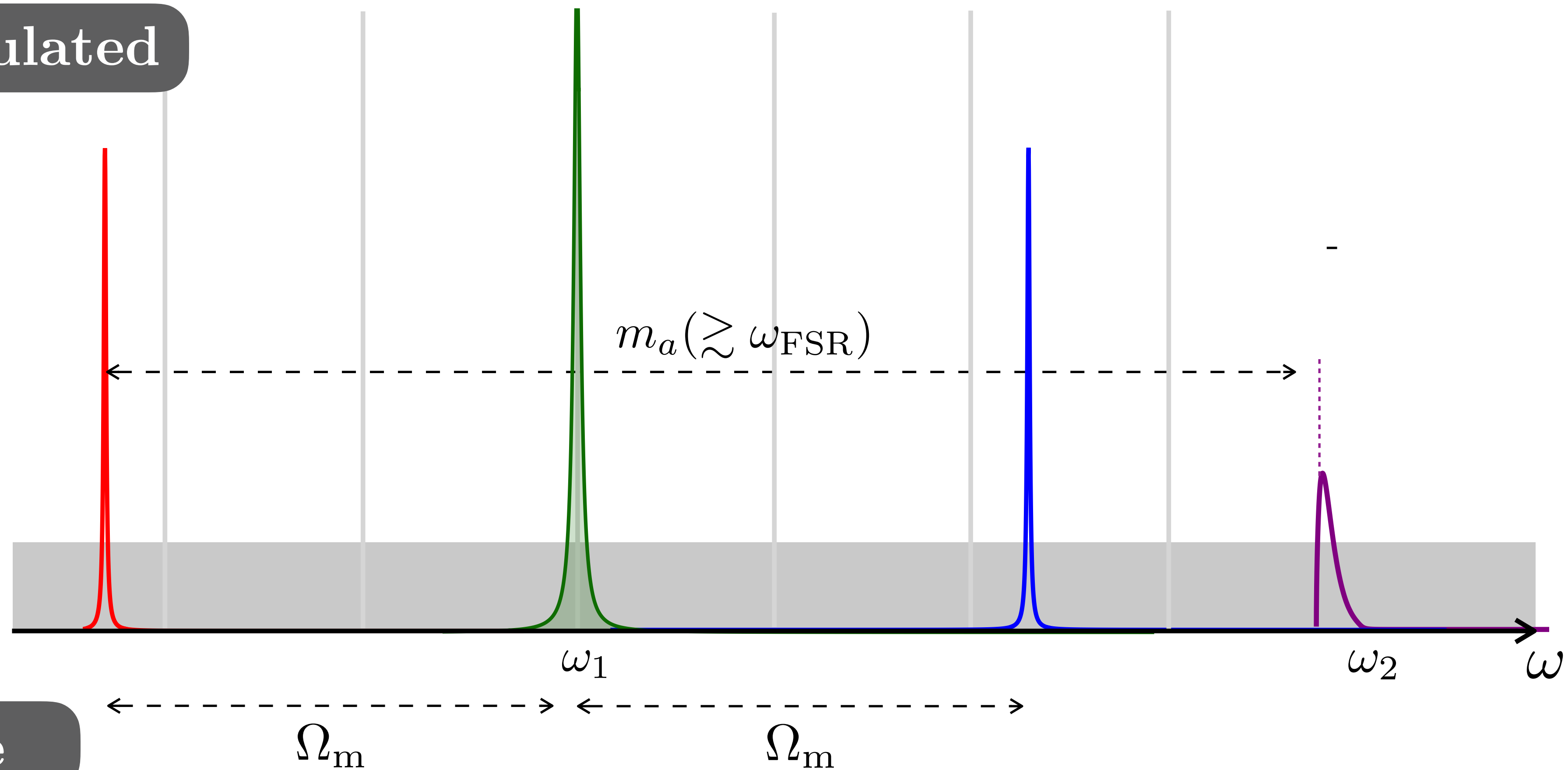


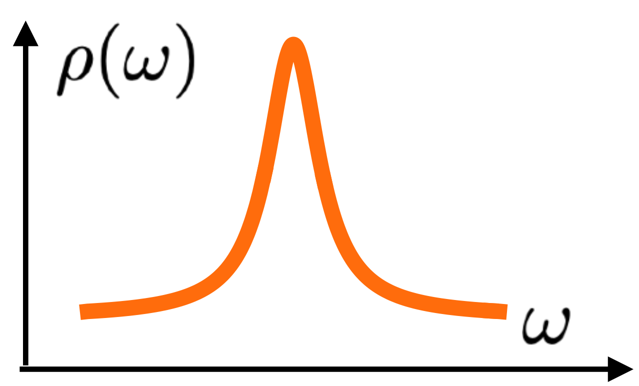
Sources of noise

Dark Count Rate

[irreducible noise]

$$\mathrm{SNR} = \frac{\Gamma_{\mathrm{sig}}}{\Gamma_{\mathrm{DCR}}} > 3$$

Laser frequency noise



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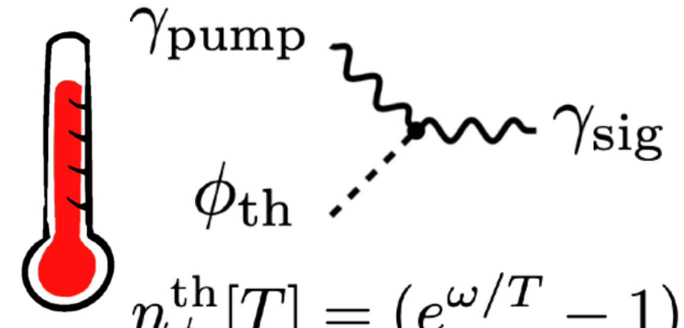
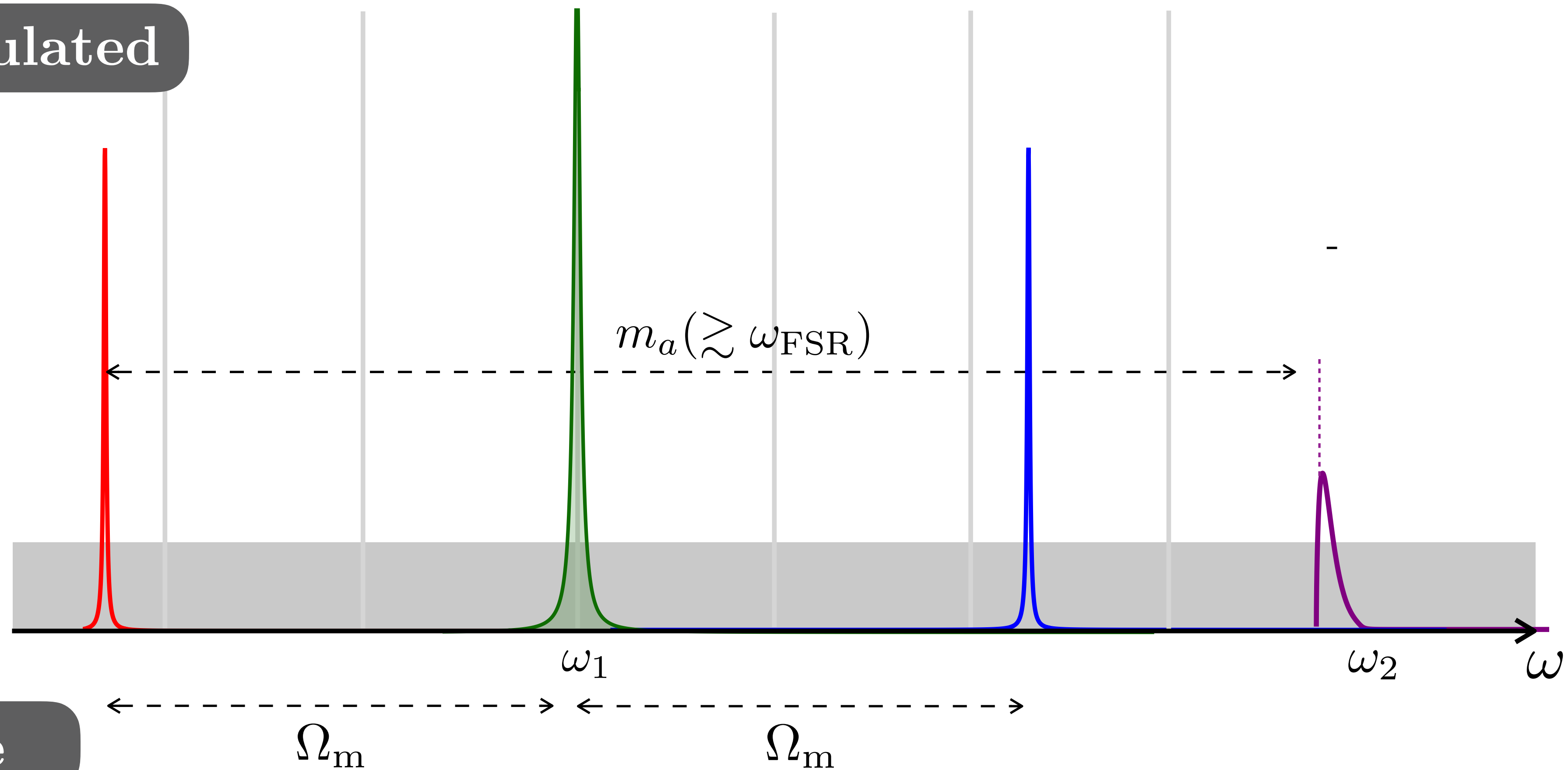


$$n_\phi^{\mathrm{th}}[T] = (e^{\omega/T} - 1)^{-1}$$

Sensitivity & Scanning Strategy

$$\mathrm{SNR} = \frac{\Gamma_{\mathrm{sig}}\,(t_{\mathrm{int}}/\tau_a)}{\Gamma_{\mathrm{back}}} > 3 \;\Rightarrow\; g_{a\gamma\gamma} > f(m_a, \text{cavity}, \text{lasers}, \text{material})$$

Phonon populated



Sources of noise

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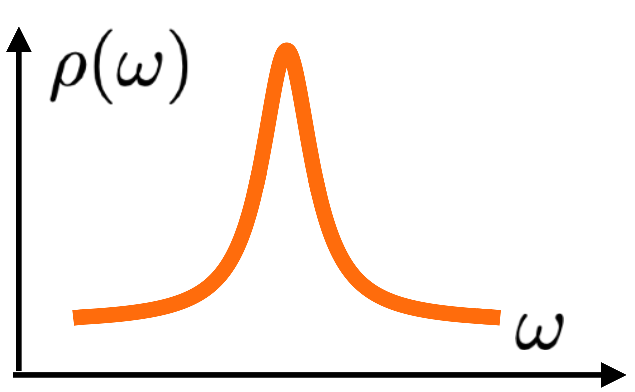
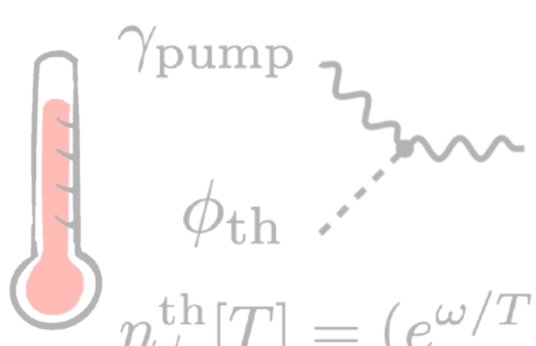
Laser frequency noise



Thermal phonons



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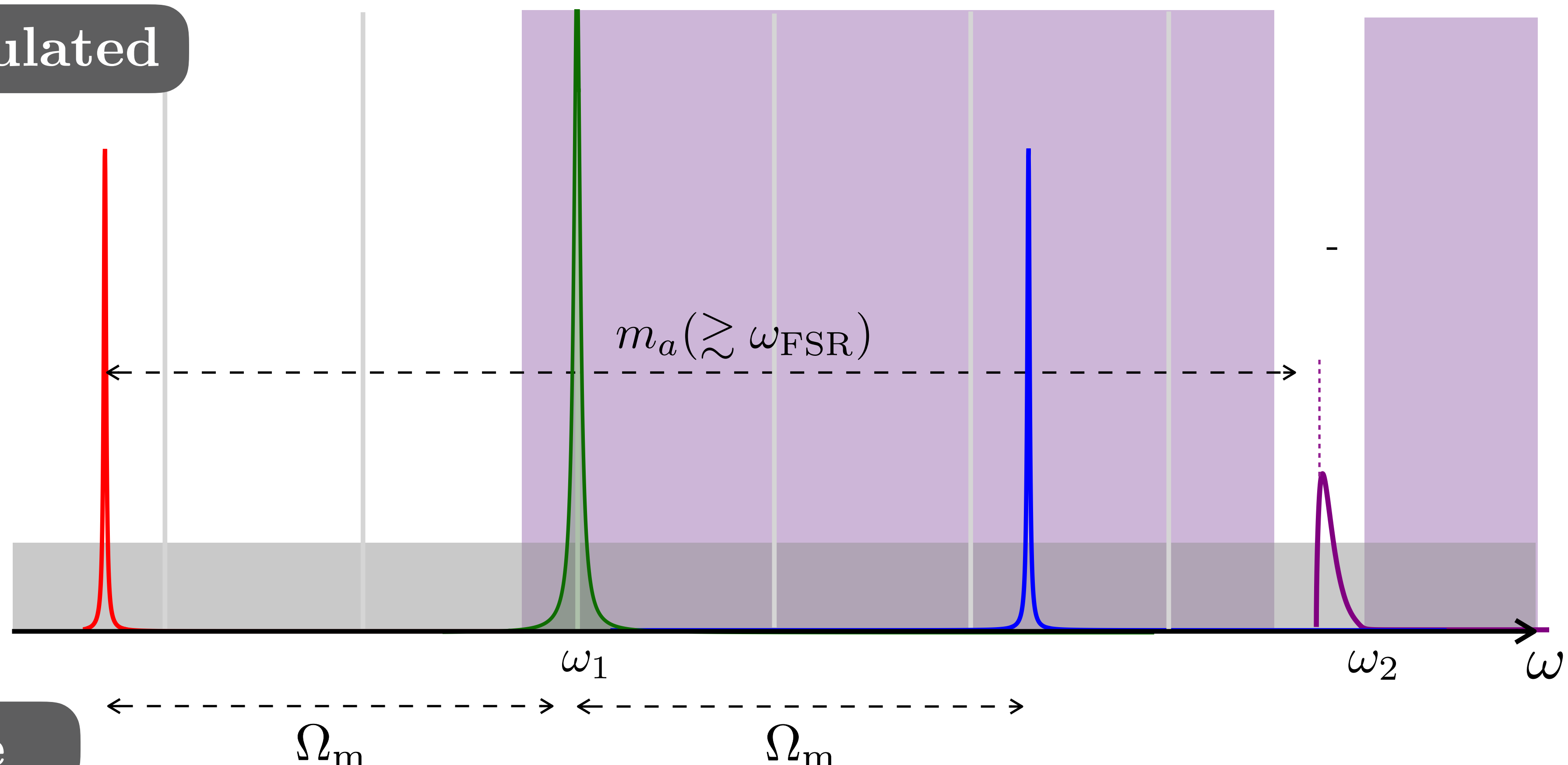

Sources of noise

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[irreducible noise]

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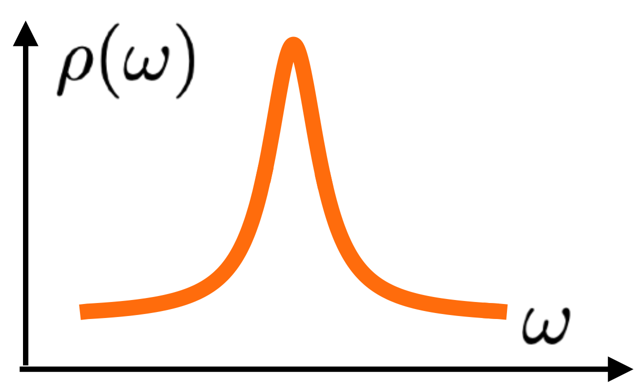
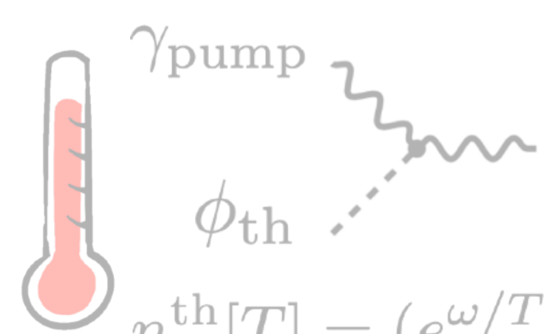
Laser frequency noise



Thermal phonons



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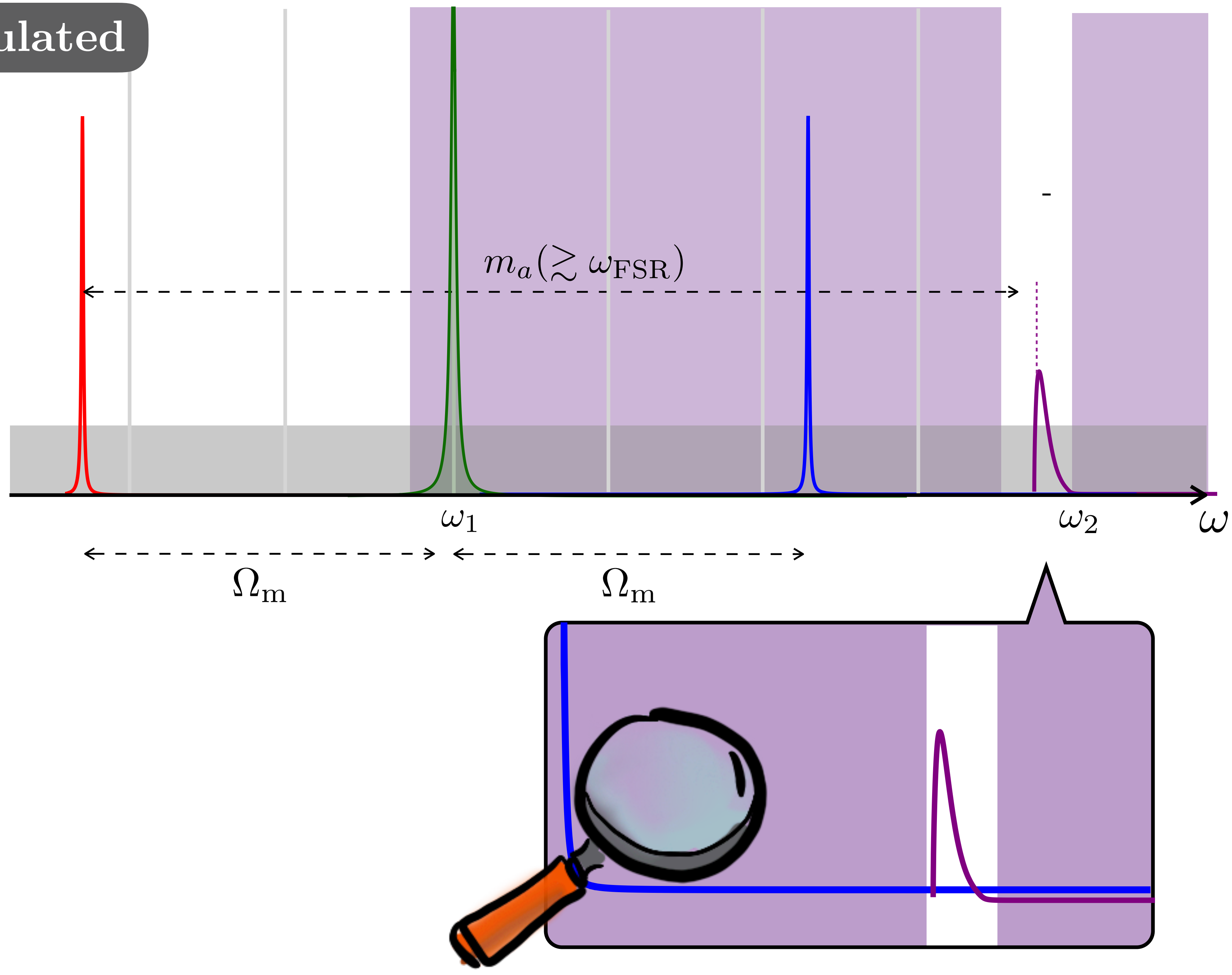

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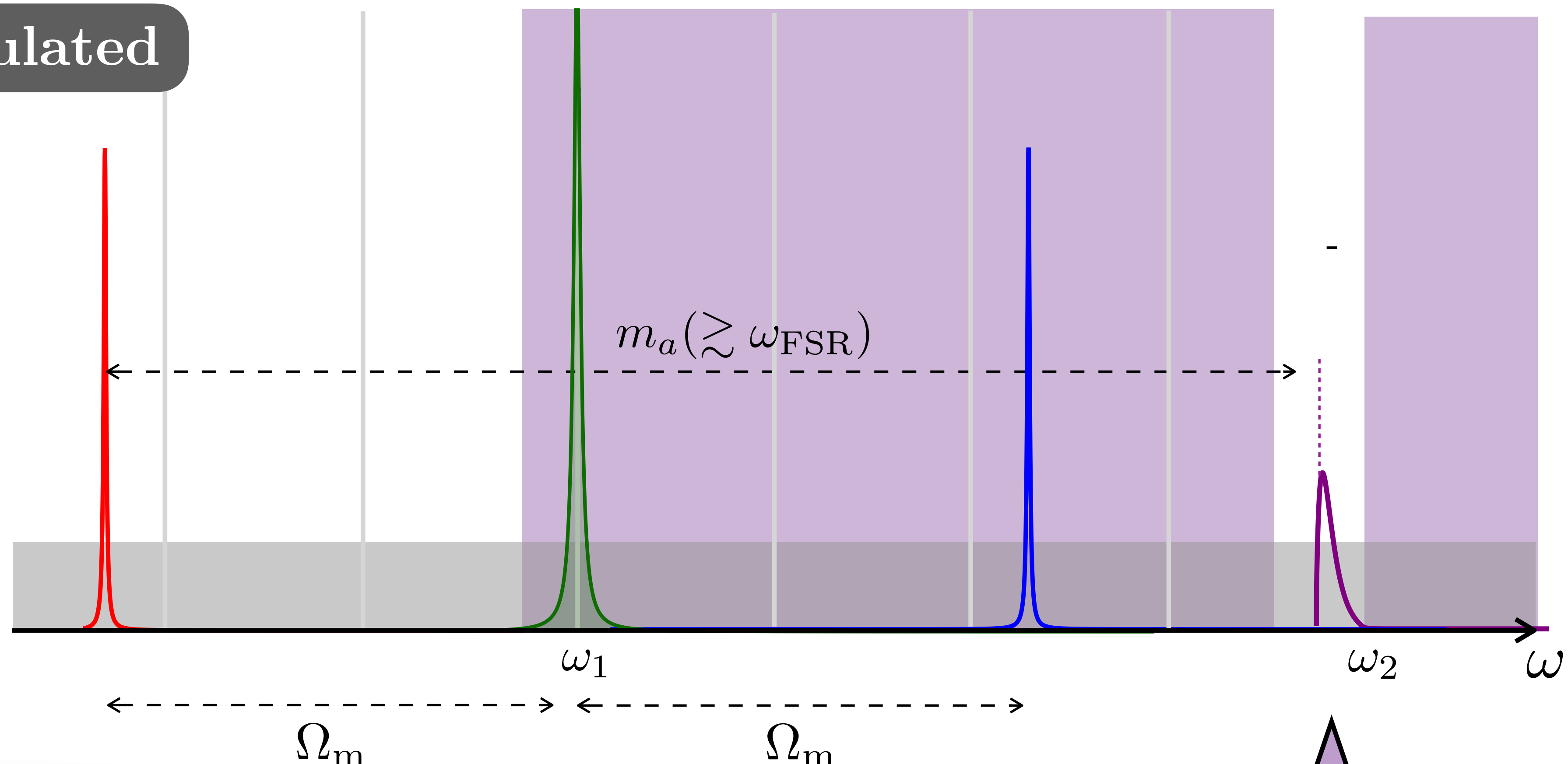
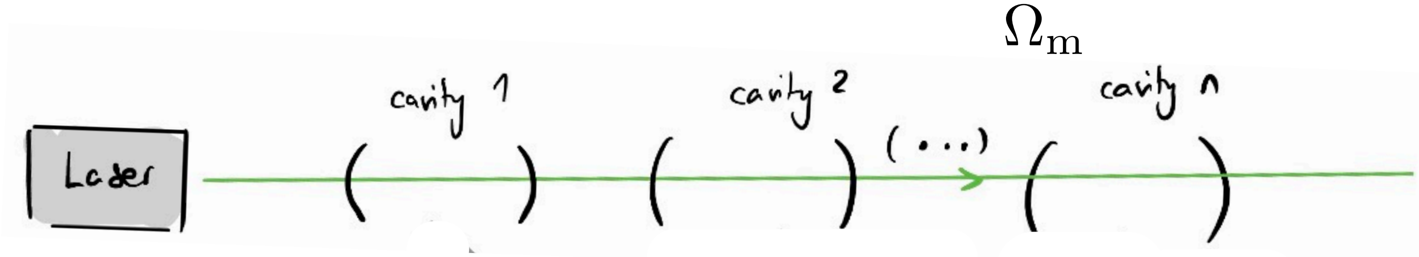
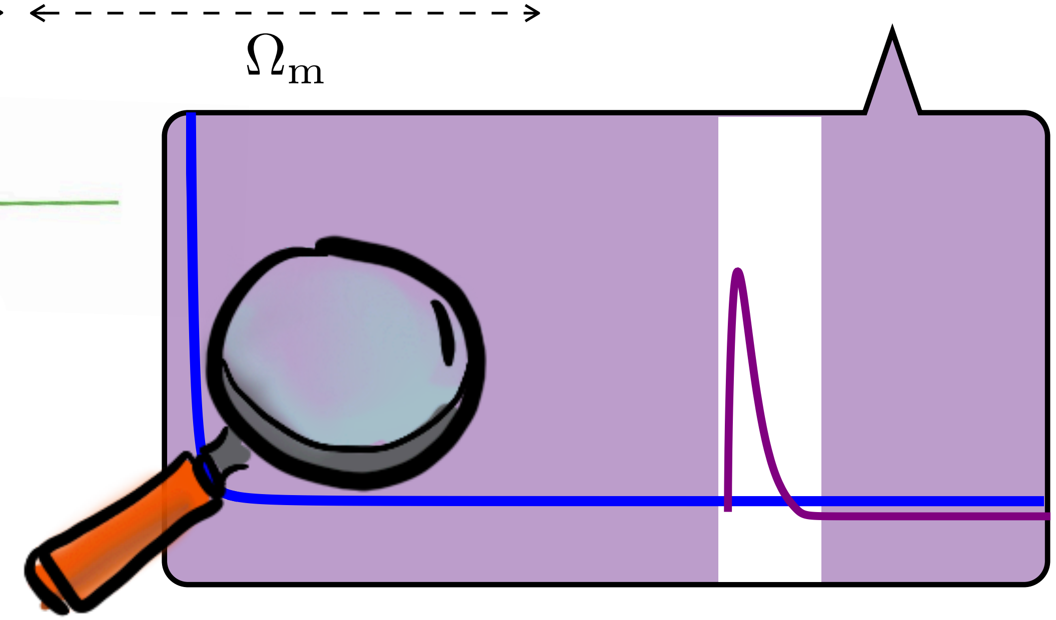
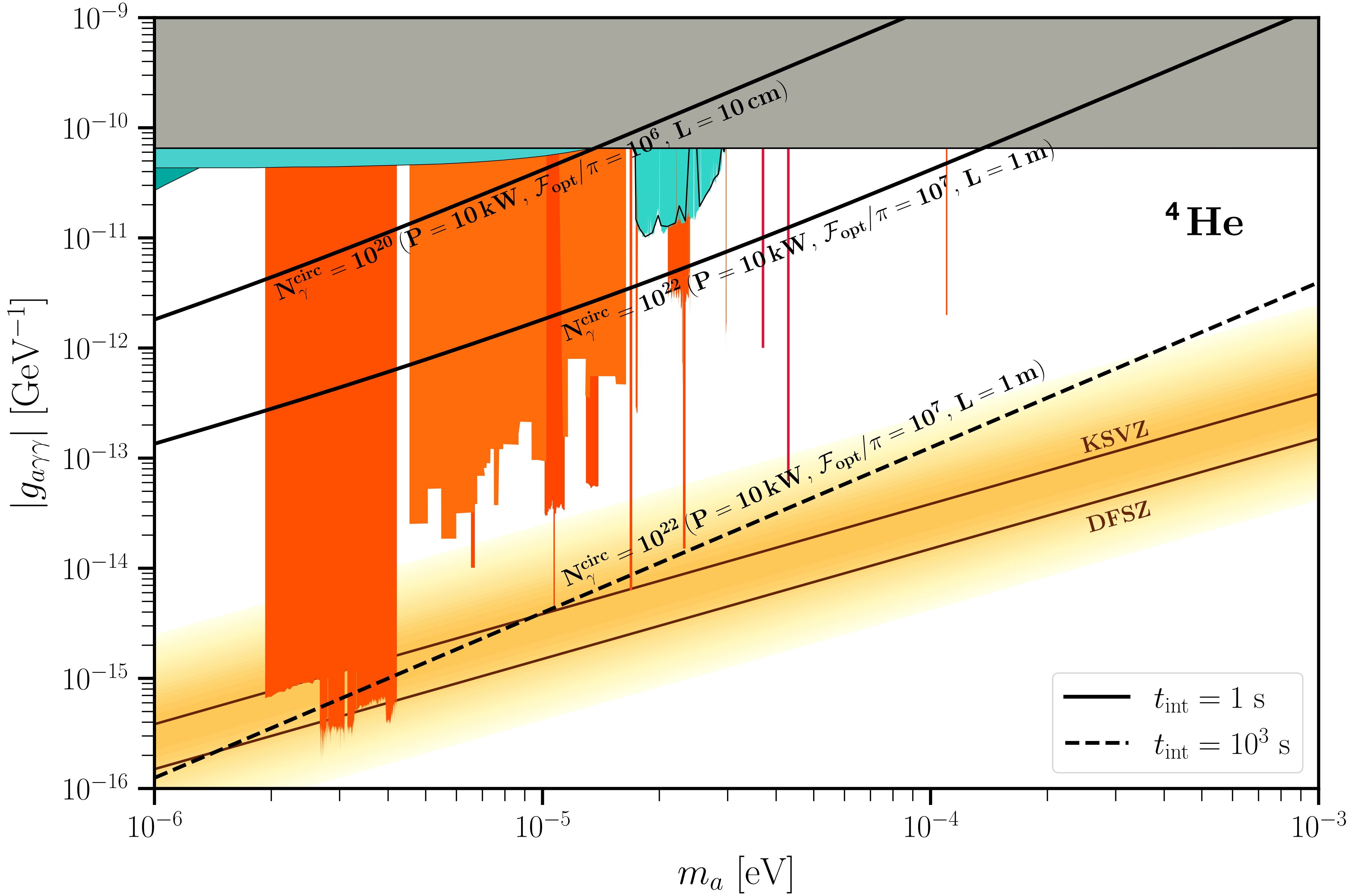




$$\frac{\delta P_{\mathrm{filtered}}}{\delta P_{\mathrm{input}}} = \left(\frac{1}{1 + (\omega/\kappa)^2}\right)^n$$

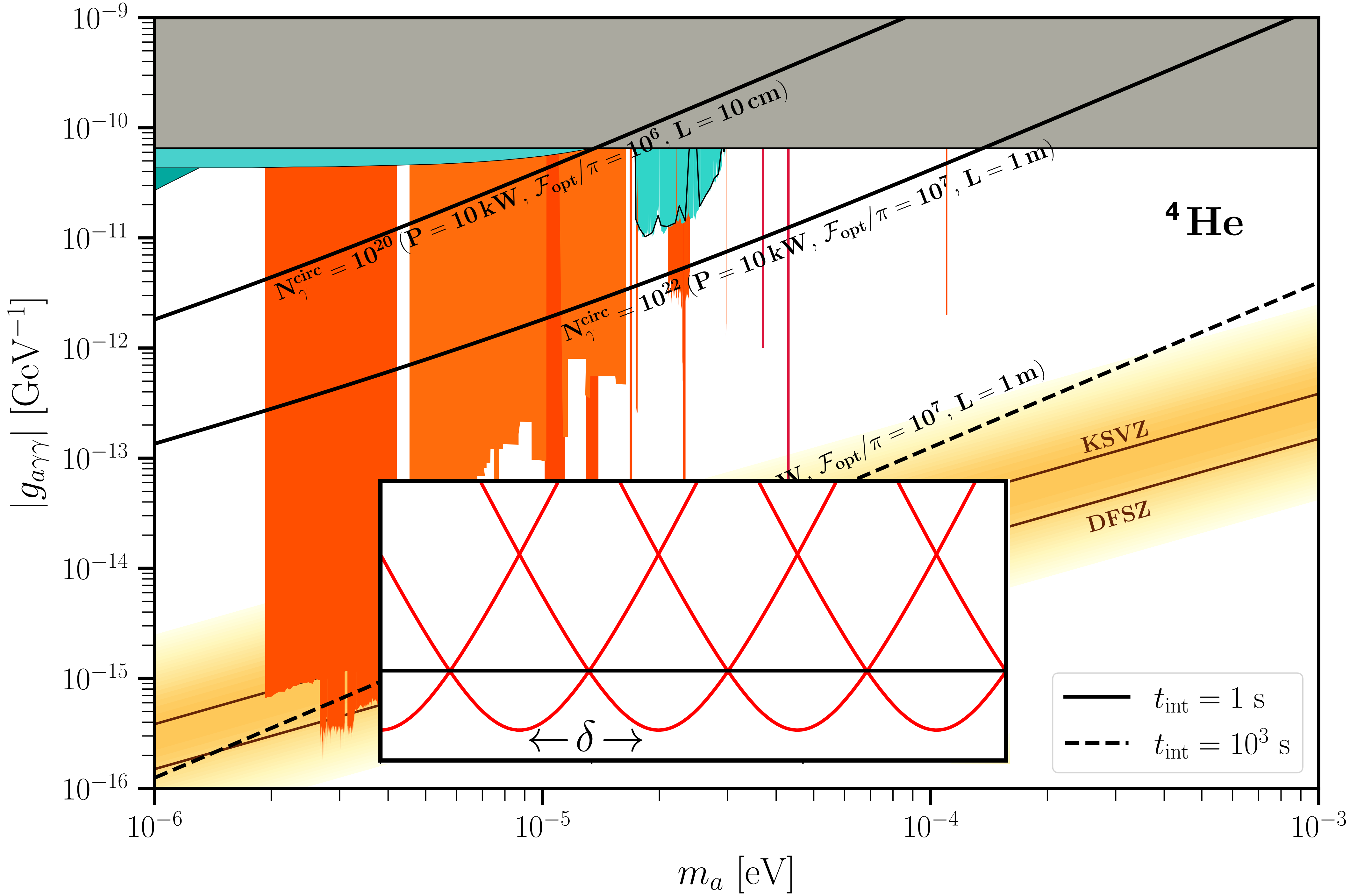


Curves: heavy axion regime



$$g_{a\gamma\gamma}^{\phi-\mathrm{pop}} \propto \frac{\epsilon_r+2}{\epsilon_r-1}\epsilon_r^{1/2}\frac{1}{\mathcal{F}_{\mathrm{opt}}^{1/2}}\frac{1}{L^{1/2}}\frac{1}{\omega_{\mathrm{opt}}^{1/2}}\frac{1}{P_{\mathrm{pump}}^{1/2}}\frac{m_a^{3/2}}{\rho_a^{1/2}}\Gamma_{\mathrm{DCR}}^{1/2}$$

Curves: heavy axion regime



$$g_{a\gamma\gamma}^{\phi-\text{pop}} \propto \frac{\epsilon_r + 2}{\epsilon_r - 1}\epsilon_r^{1/2}\frac{1}{\mathcal{F}_{\text{opt}}^{1/2}}\frac{1}{L^{1/2}}\frac{1}{\omega_{\text{opt}}^{1/2}}\frac{1}{P_{\text{pump}}^{1/2}}\frac{m_a^{3/2}}{\rho_a^{1/2}}\Gamma_{\text{DCR}}^{1/2}$$

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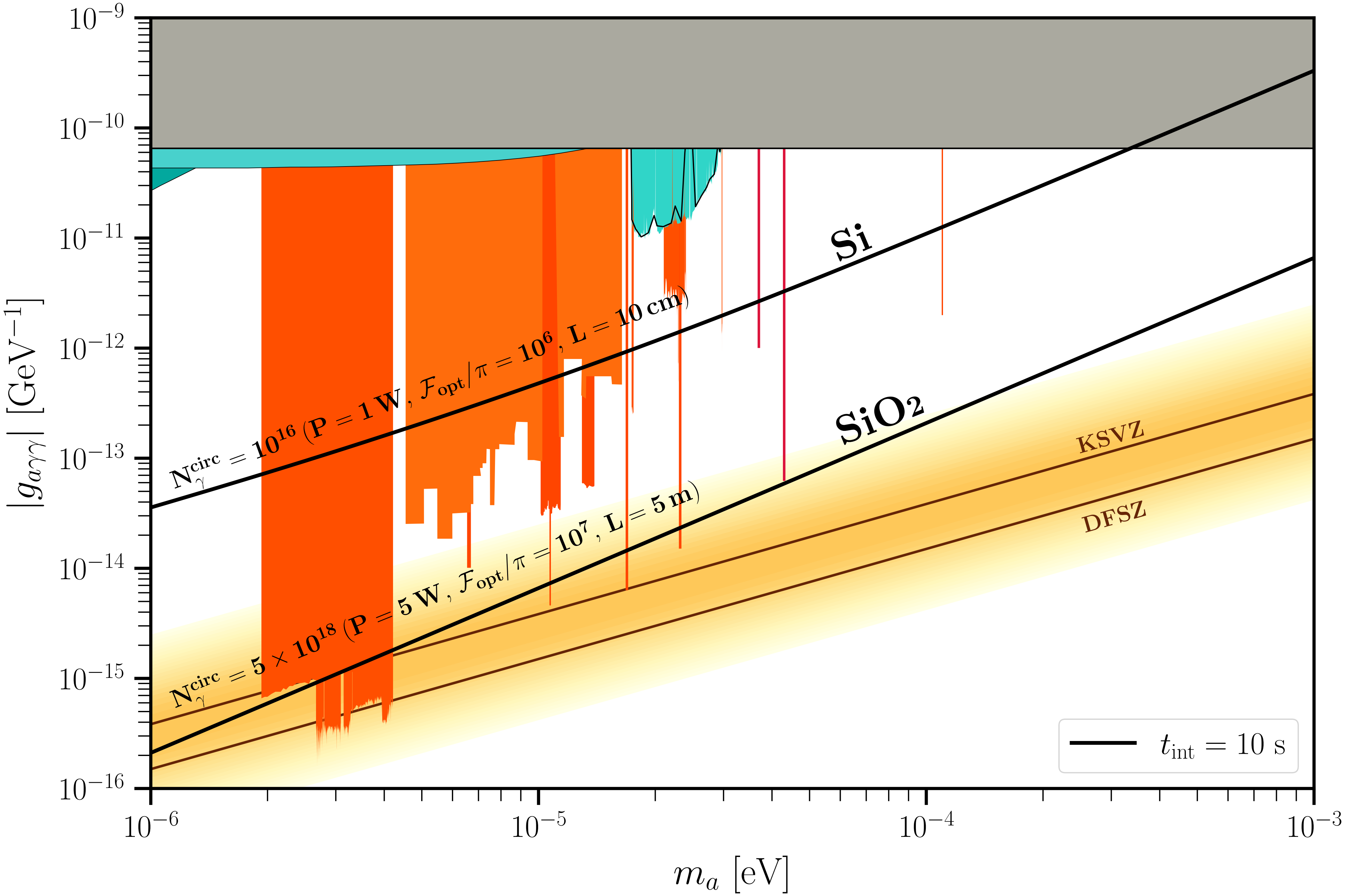

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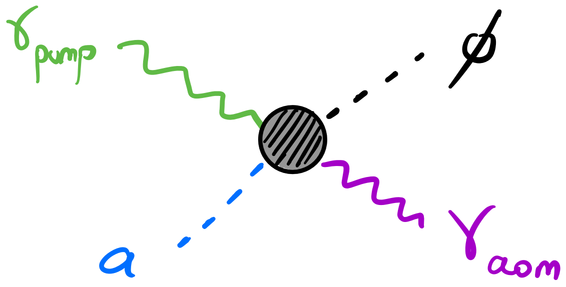
Conclusions

Importance of exploiting potential of existing /upcoming experiments to explore dark matter possibilities (the more motivated the better).

Axioptomechanics

Advantages

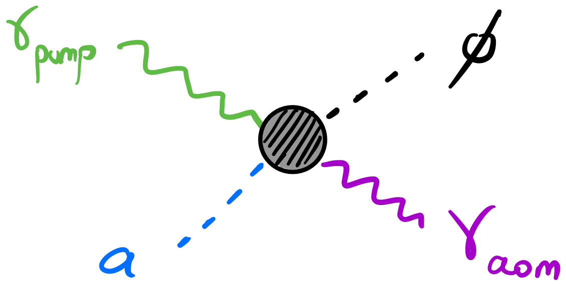
- Decoupling length — axion mass: phonons!
- ~ background-free experiment
- Very peculiar kinematics



Conclusions

Importance of exploiting potential of existing /upcoming experiments to explore dark matter possibilities (the more motivated the better).

Axioptomechanics



Advantages

- Decoupling length — axion mass: phonons!
- ∼ background-free experiment
- Very peculiar kinematics

Future Directions

- Two regimes — two techniques: light & heavy axions
- Explore other materials
- Overcome experimental challenges. Keep backgrounds low.
- Further applications: GW?

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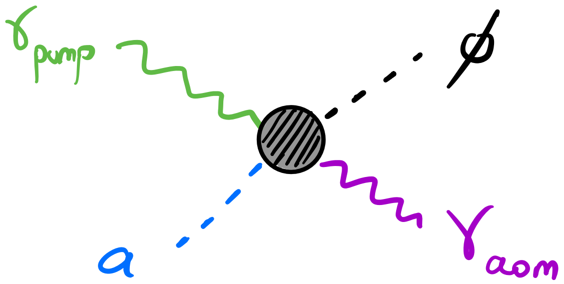

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[14] **Si** **Yuta Michimura** and **Rana Adhikari at Caltech**

O = Si = O [4] **He** **Jack Harris** and **Yogesh Patil at Yale U.**

[experimental proposal]

Thank you!