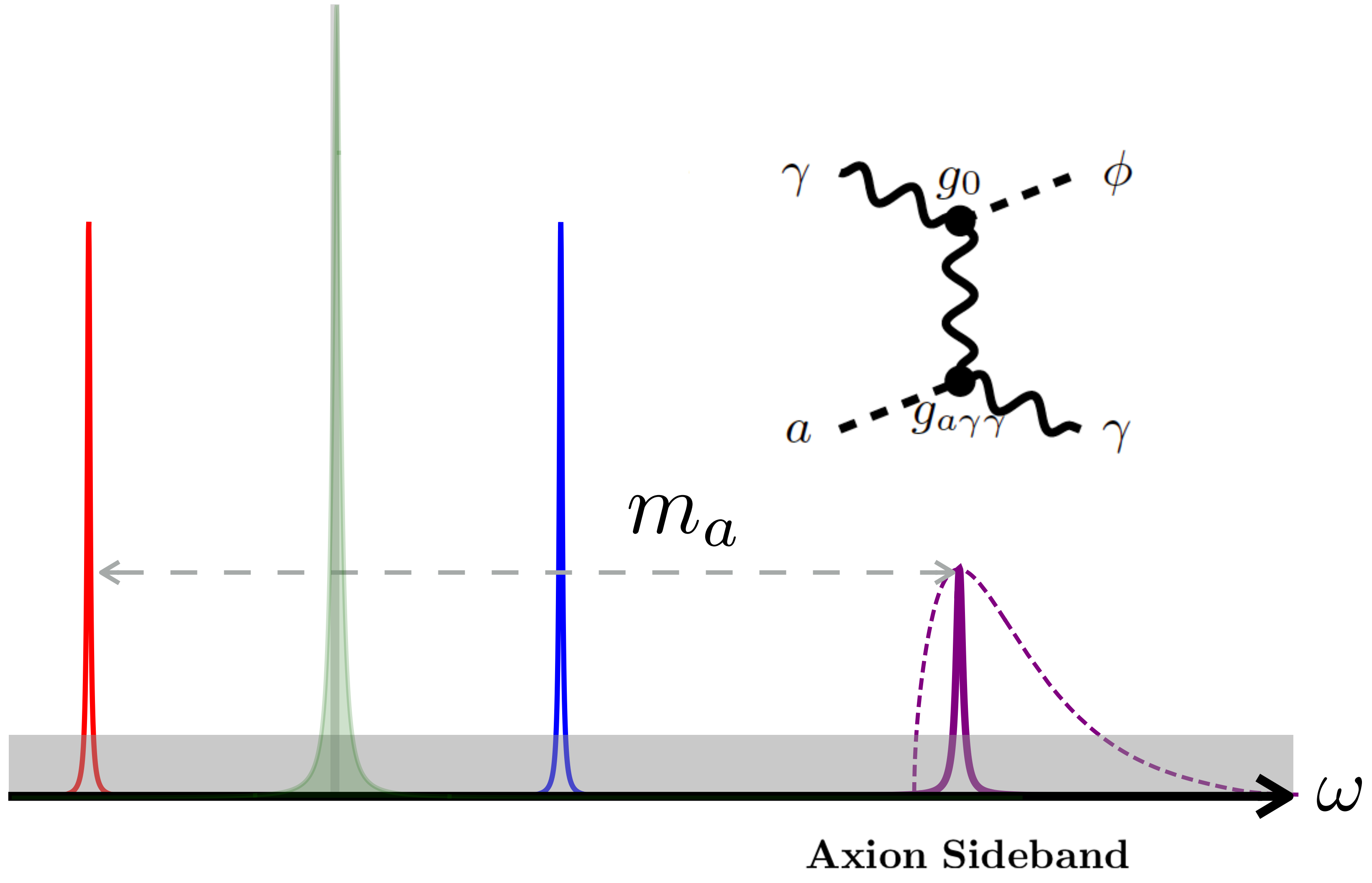


Axion Detection with Optomechanical Cavities

Yikun Wang

yikunw@caltech.edu

PASCOS 2023

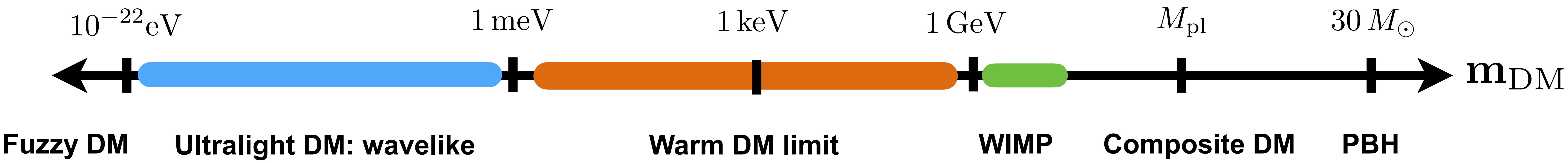
June 26, 2023, Irvine

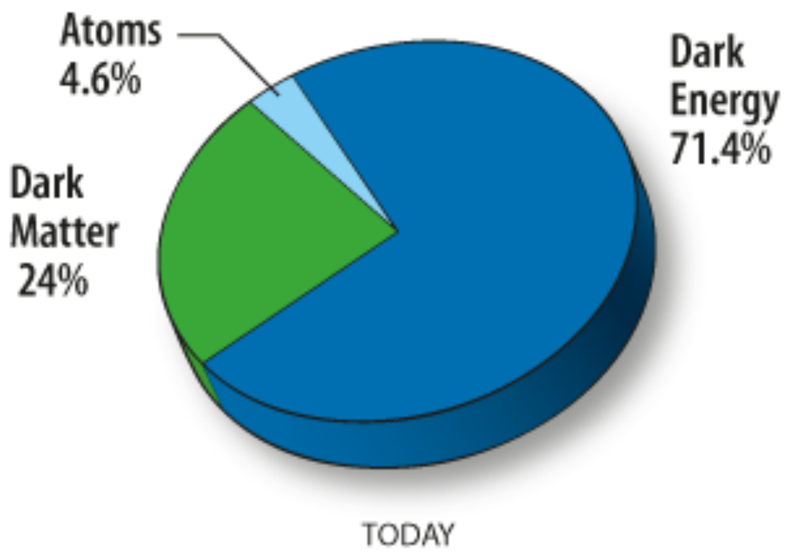
arXiv: 2211.08432

In Collaboration with: Clara Murgui, Kathryn Zurek

Upcoming: Experimental proposal with Rana Adhikari, Jack Harris, Yuta Michimura and Yogesh Patil

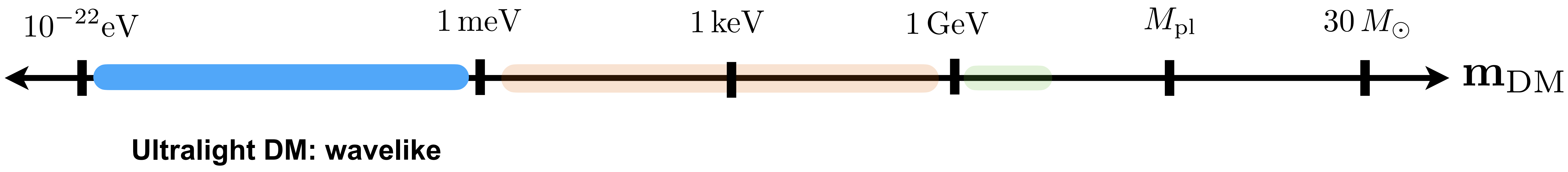
Dark Matter Direct Detection





$v_{\rm DM} \sim 200\,{\rm km/s}$ $\rho_{\rm DM} \sim 0.3\,{\rm GeV/cm^3}$

Axion Dark Matter



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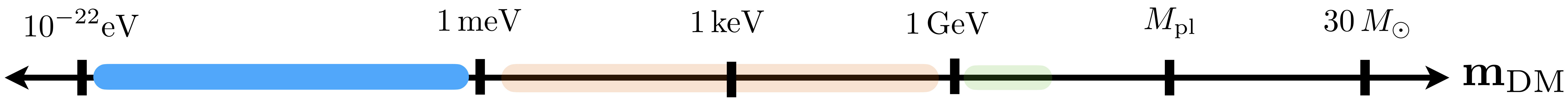


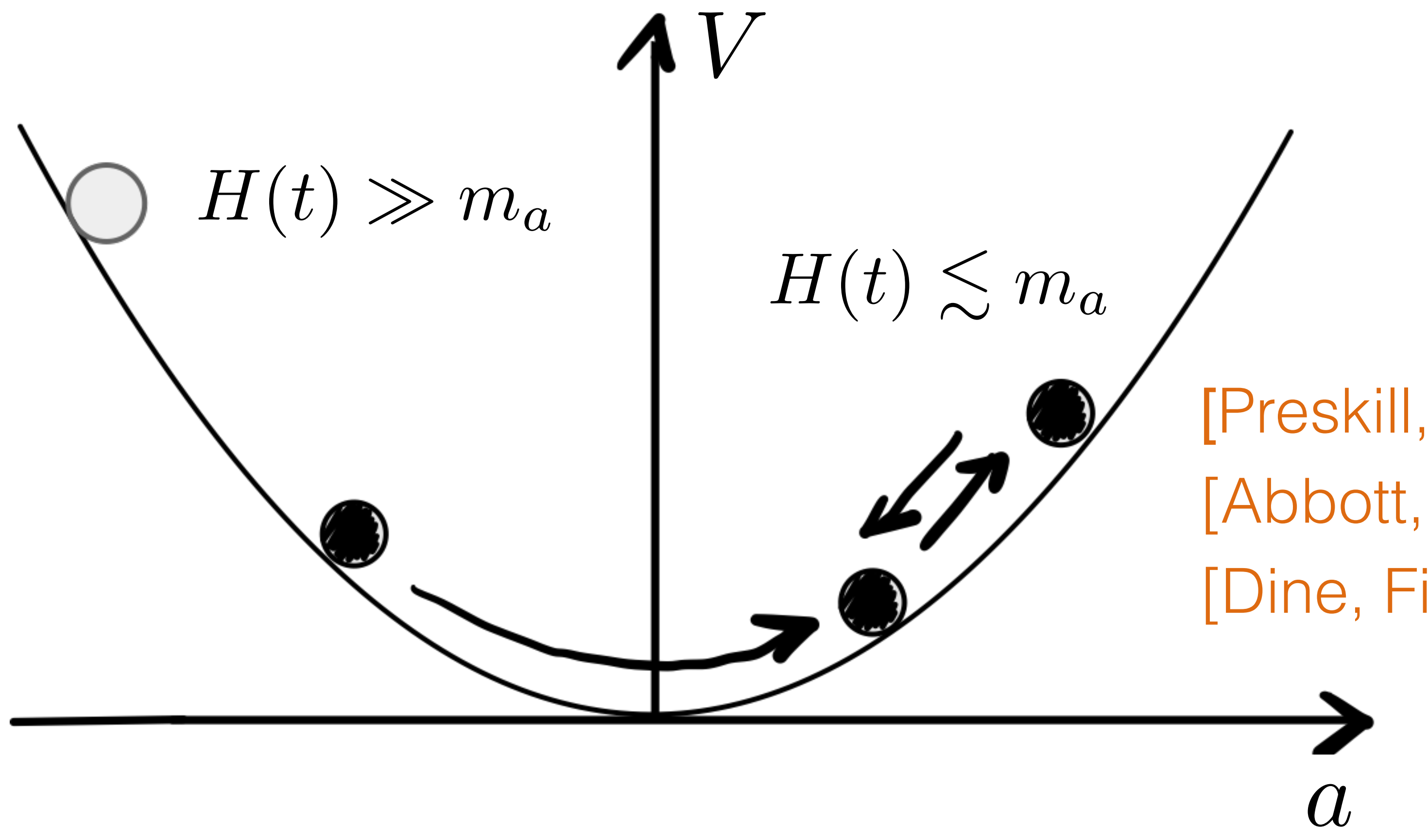
Ultralight DM: wavelike

Ultralight oscillating bosonic field

Production:

- Misalignment and variations
- Topological defects in early universe

…

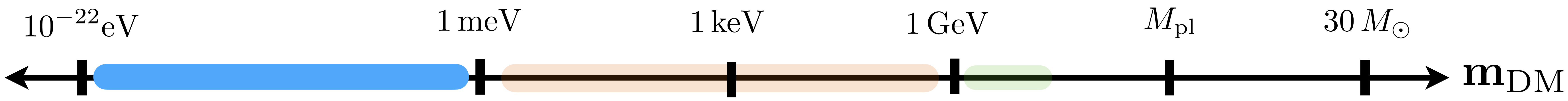


Misalignment

[Preskill, Wise, Wilczek 1977]
[Abbott, Sikivie, 1983]
[Dine, Fischler, 1983]

DM abundance $\Omega_a h^2 \sim 0.1 \left(\frac{10\mu\mathrm{eV}}{m_a}\right)^{7/6} \langle\theta_i^2\rangle$

Axion Dark Matter



Ultralight DM: wavelike

Ultralight oscillating bosonic field , that weakly couples to the SM

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

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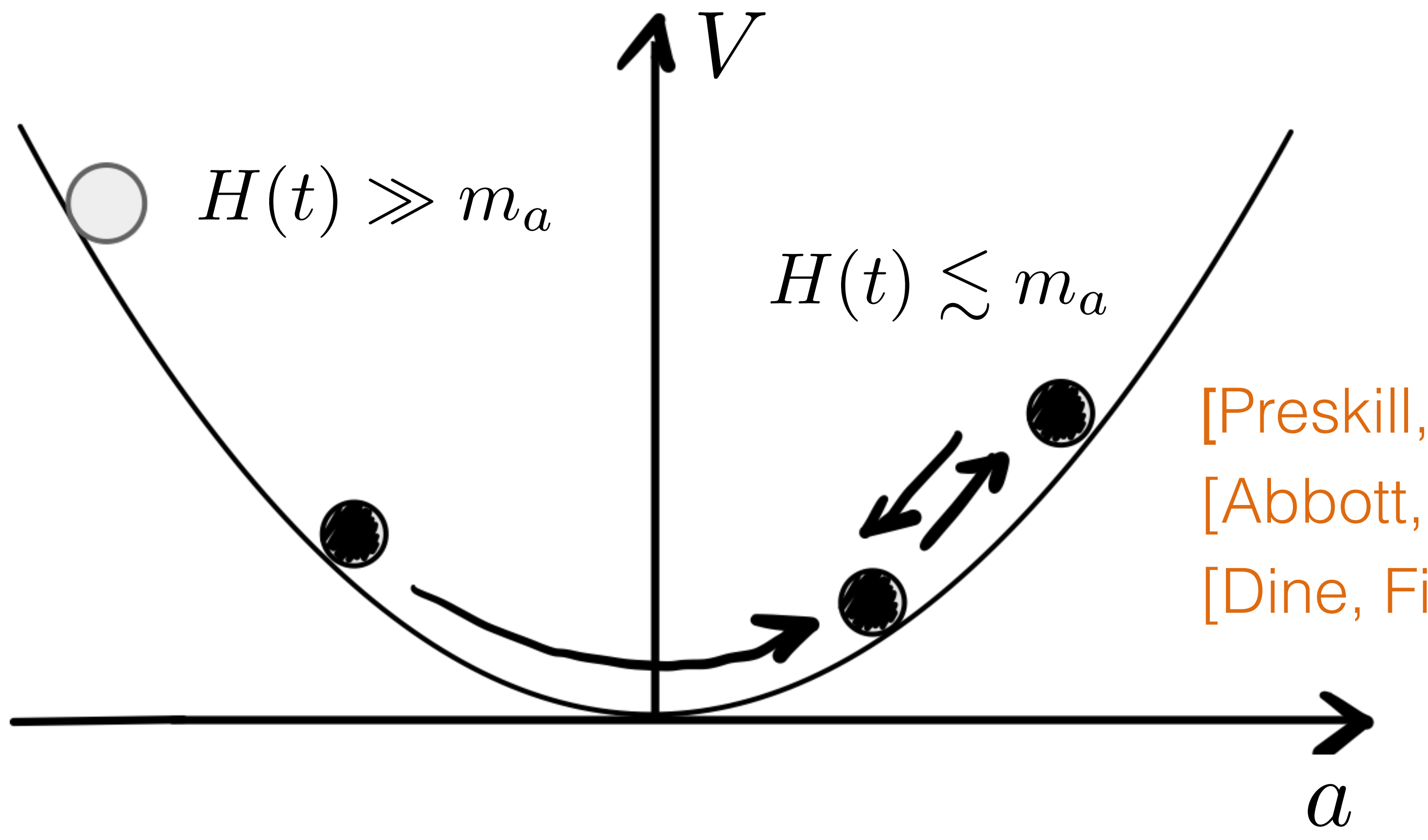

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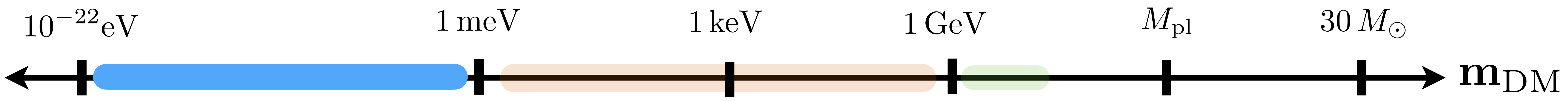

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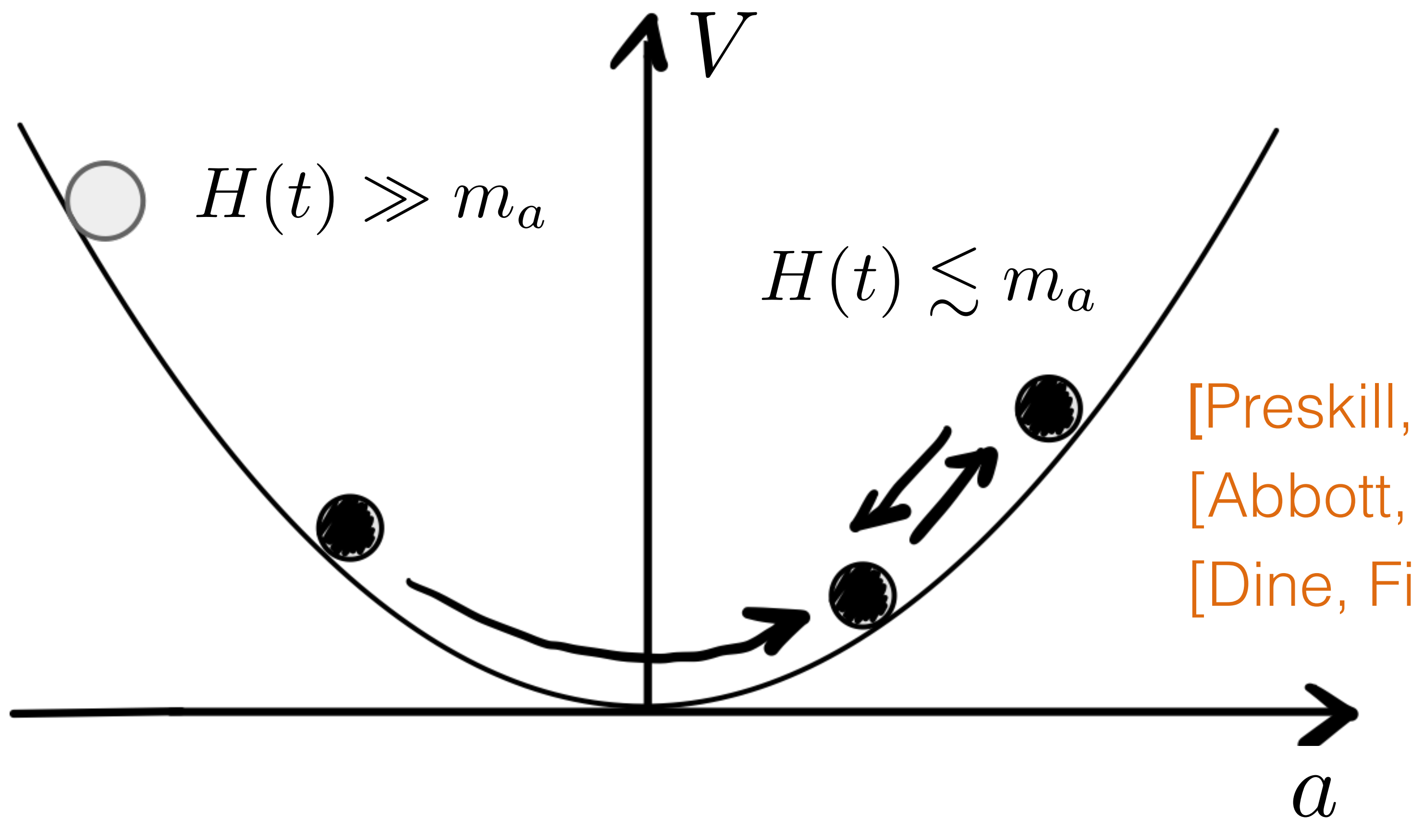

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QCD axion and axion like particles

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

QCD axion:
a solution to the strong CP problem

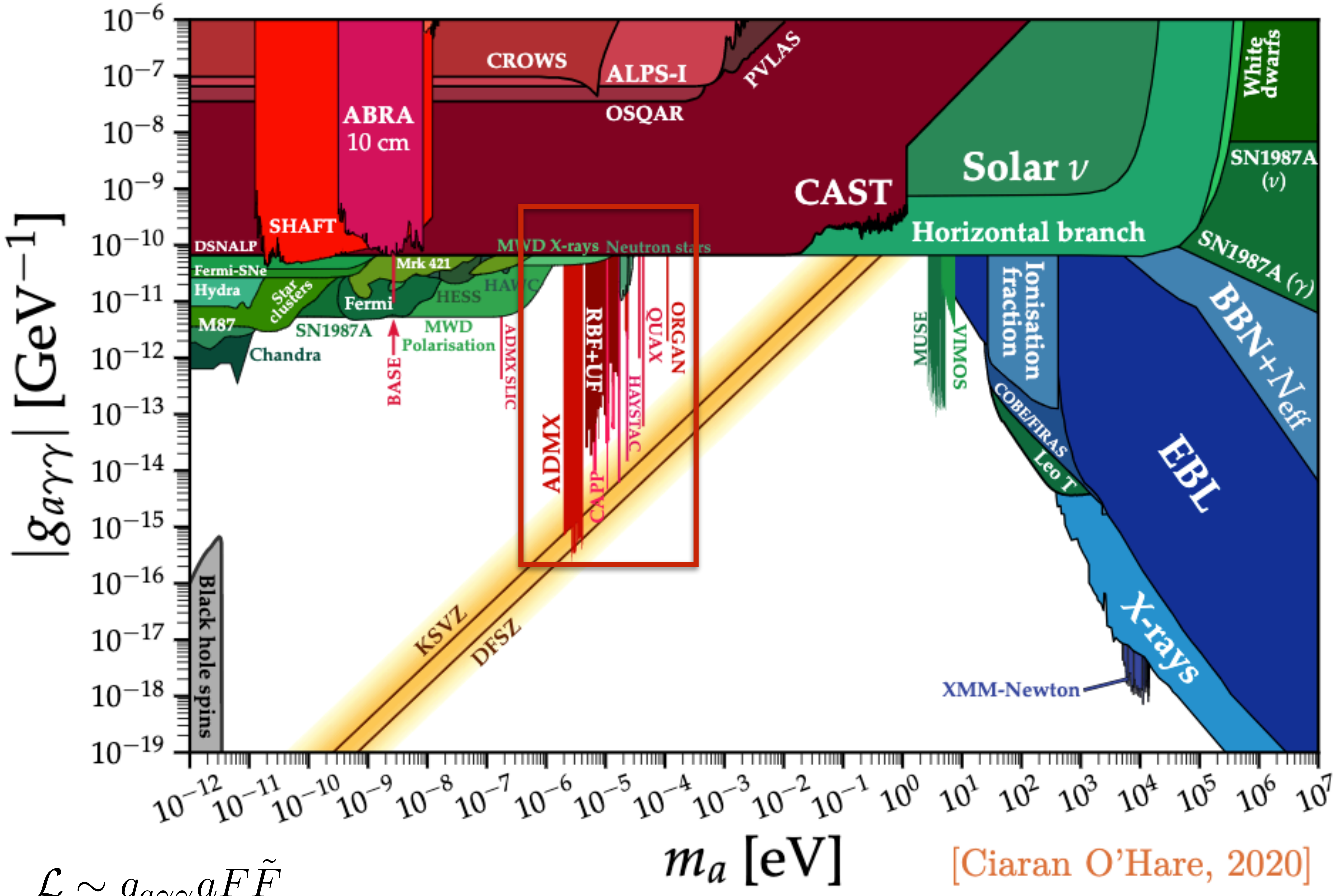
$$m_a \sim \frac{\Lambda^2_{\rm QCD}}{f_a}$$

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

Axion like particles

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

Axion Searches

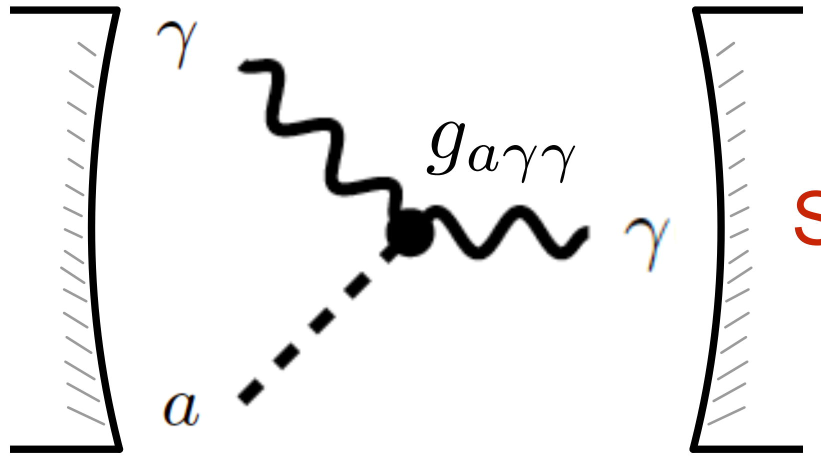


[Ciaran O'Hare, 2020]

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

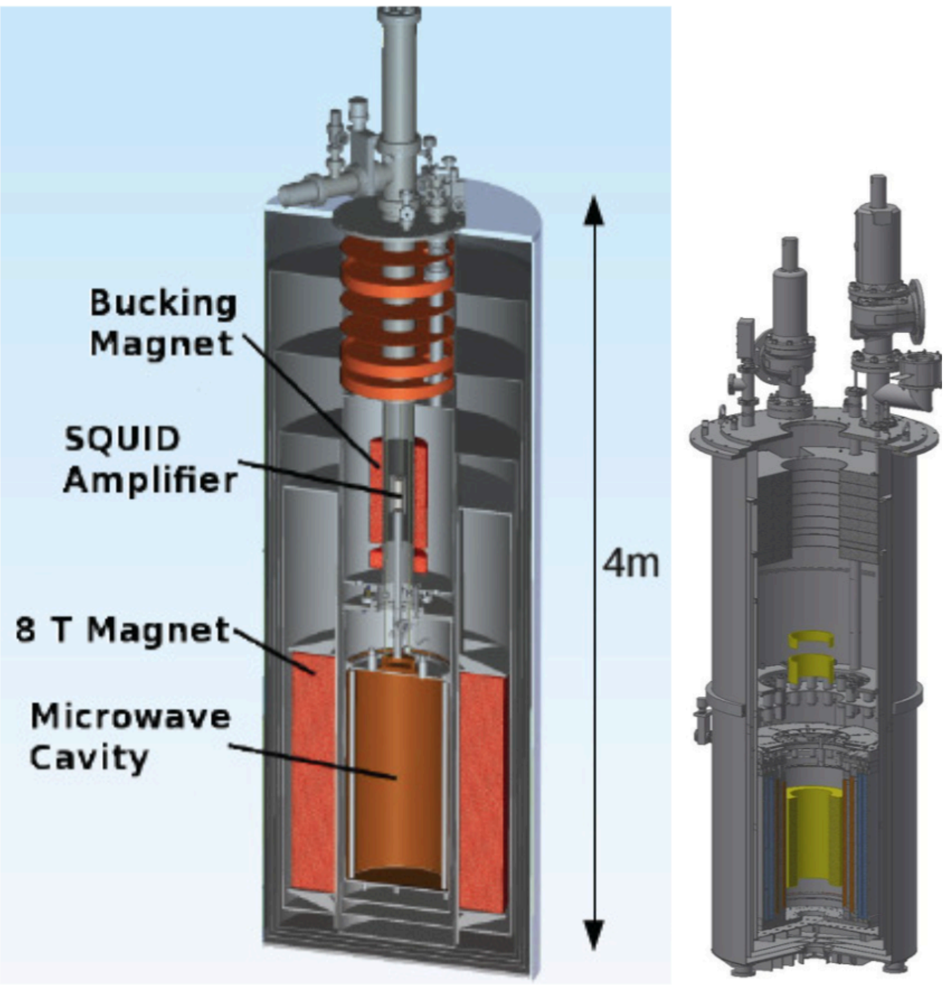
- Solar Axions (CAST etc)
- Astrophysical bounds
- Cosmological bounds
- Other laboratory experiments: LSW, fifth force, meson decay etc
- Axion as dark matter
  - Non-EM couplings
  - Axion electromagnetism (**Axion Haloscopes**, etc)

Static field/ initial photon



Signal photon: resonance enhancement

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



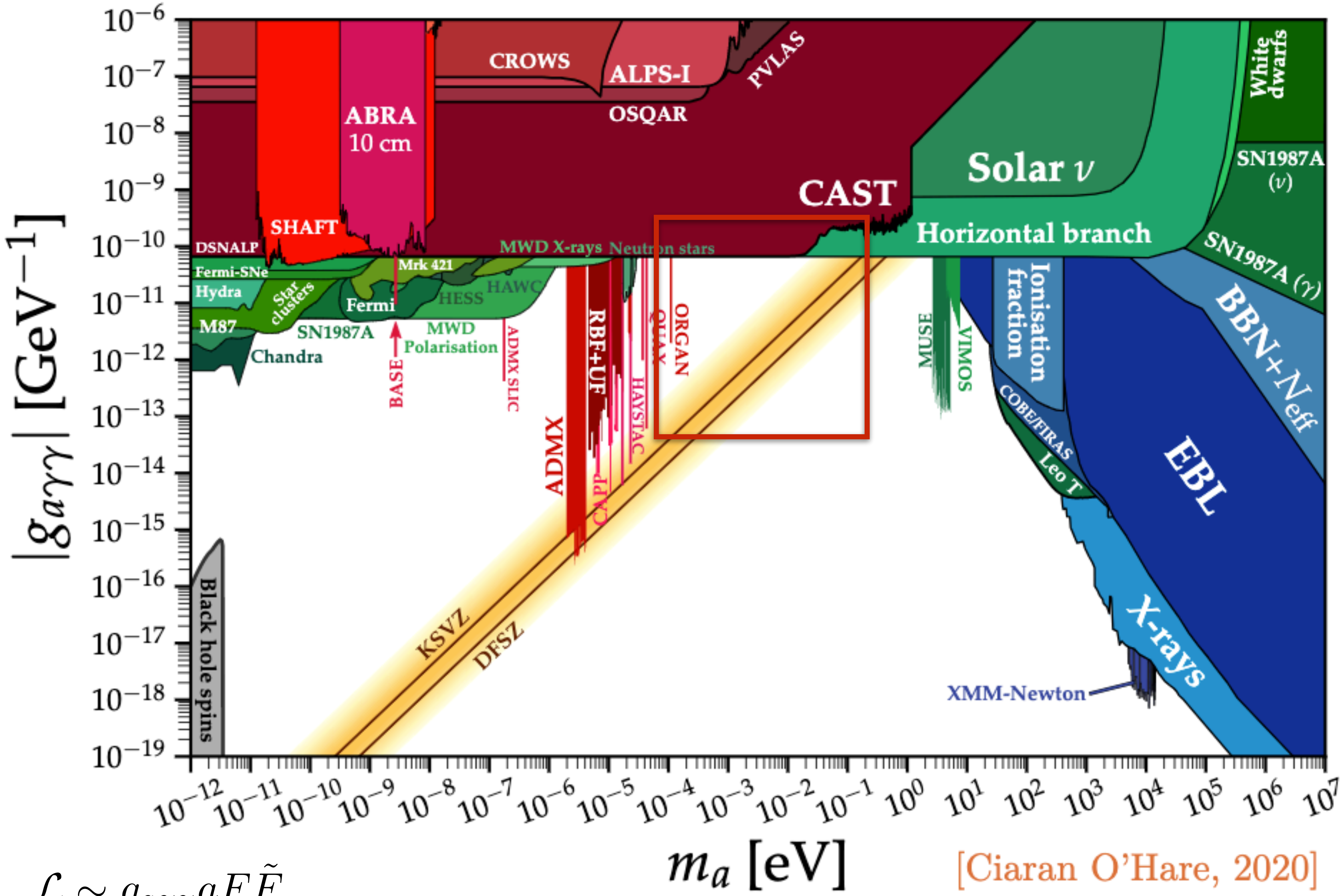
$$P_{\rm sig} \propto g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V Q$$

[Sikivie 1983]

ADMX experiment

RBF+UF, HAYSTAC, ORGAN, QUAX, CAPP, etc

Axion Searches



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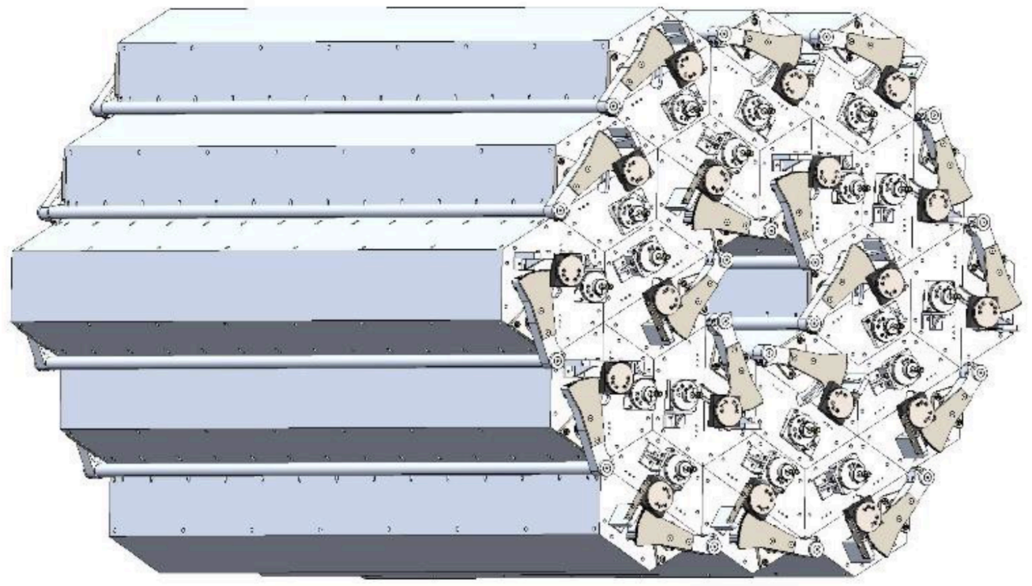
Super-μeV

ADMX-G2(EFR), ALPHA, LAMPOST, MADMAX, …

E.g. ADMX-G2(EFR)

- Cavity arrays
- Better magnetic field and cavity quality factor
- Squeezed light



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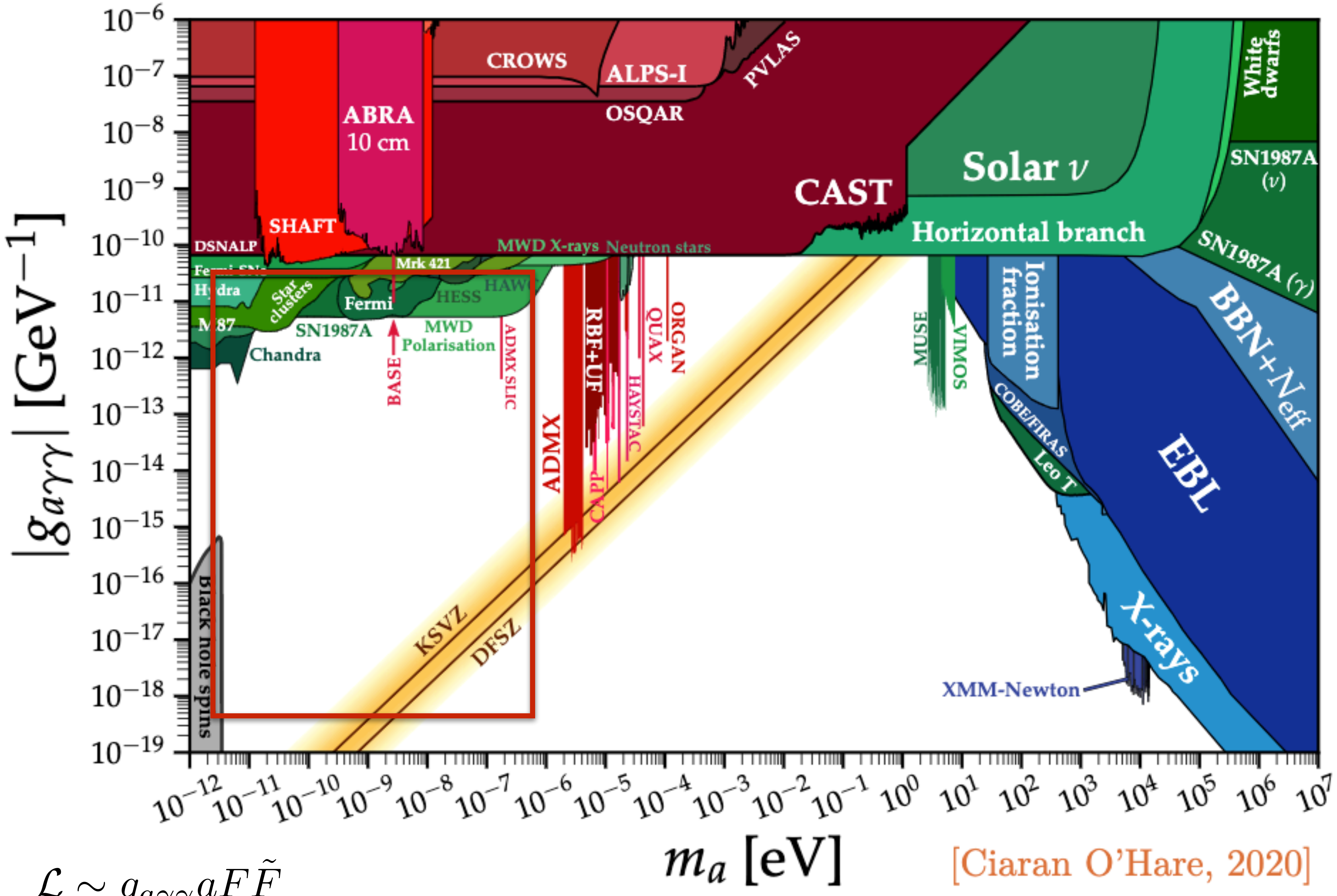

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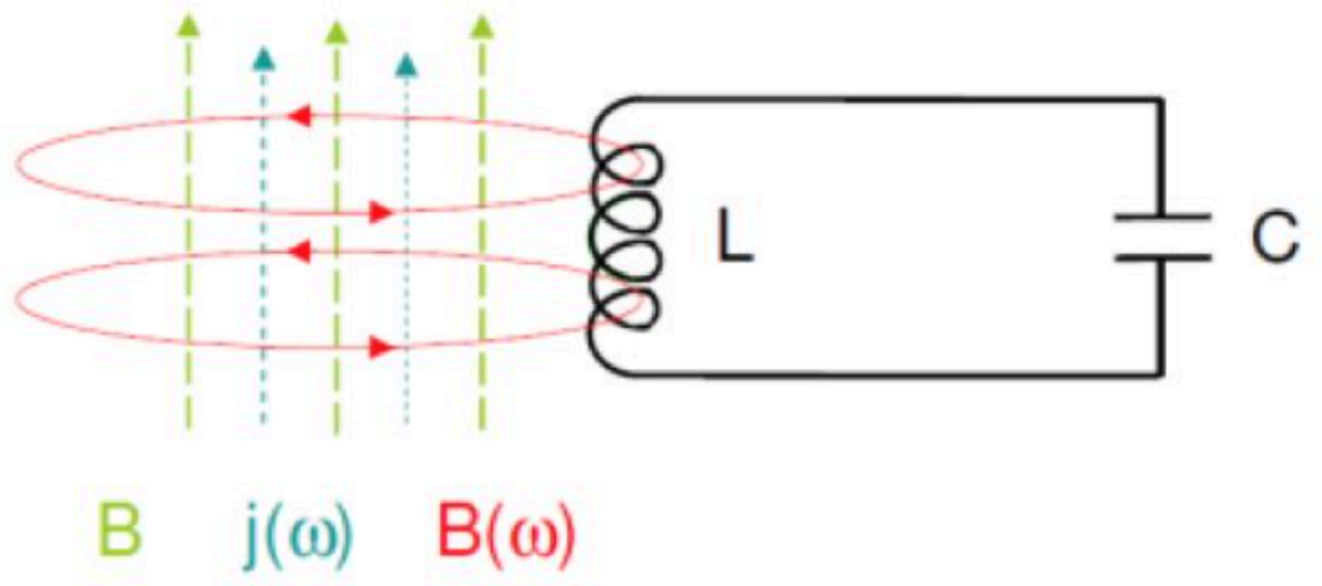
Sub-μeV

DM-Radio, SRF cavity, WISPLC, DANCE, CASPEr …

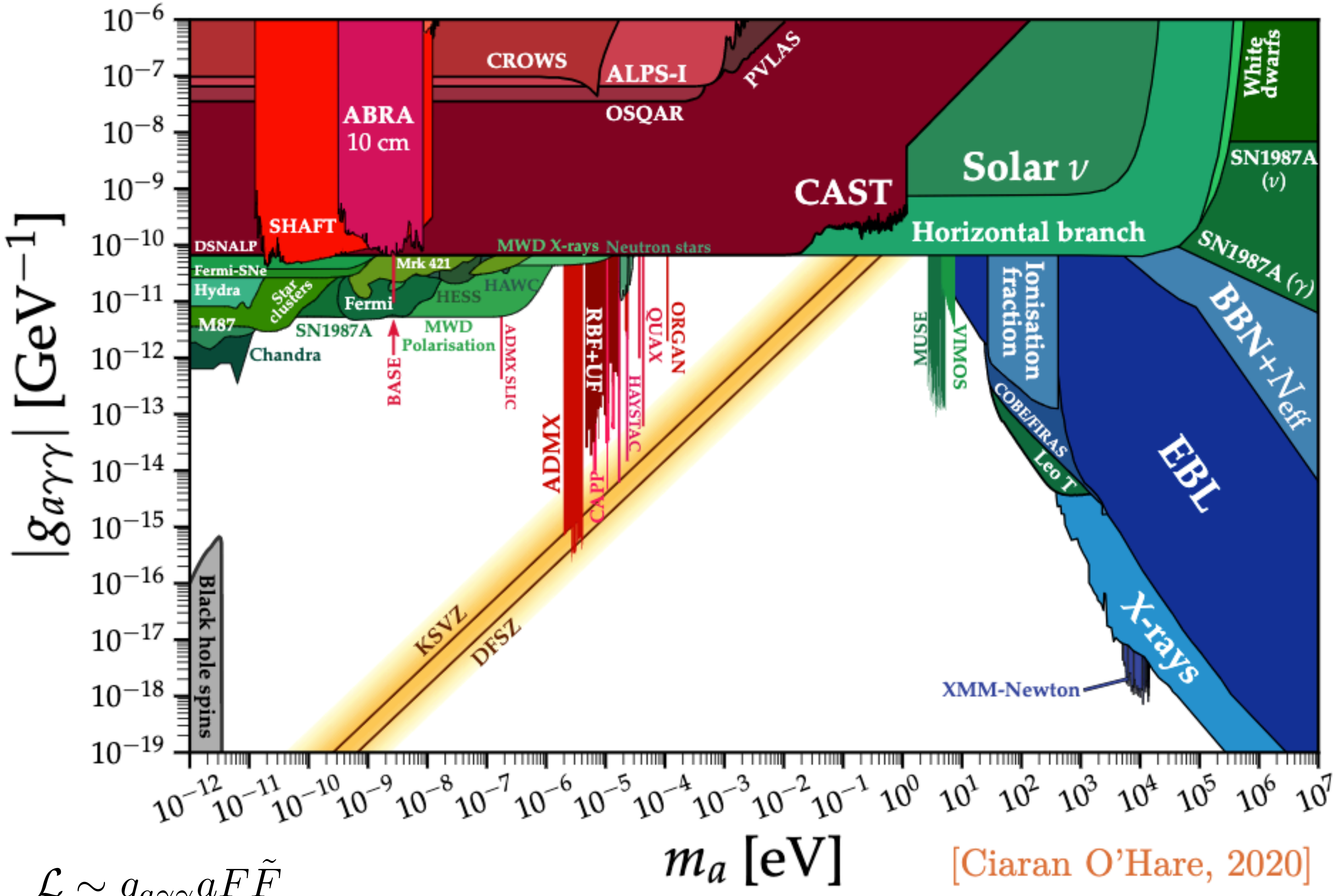
E.g. Lumped element



(From Maria Simanovskaia's slides)

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

Axion Searches



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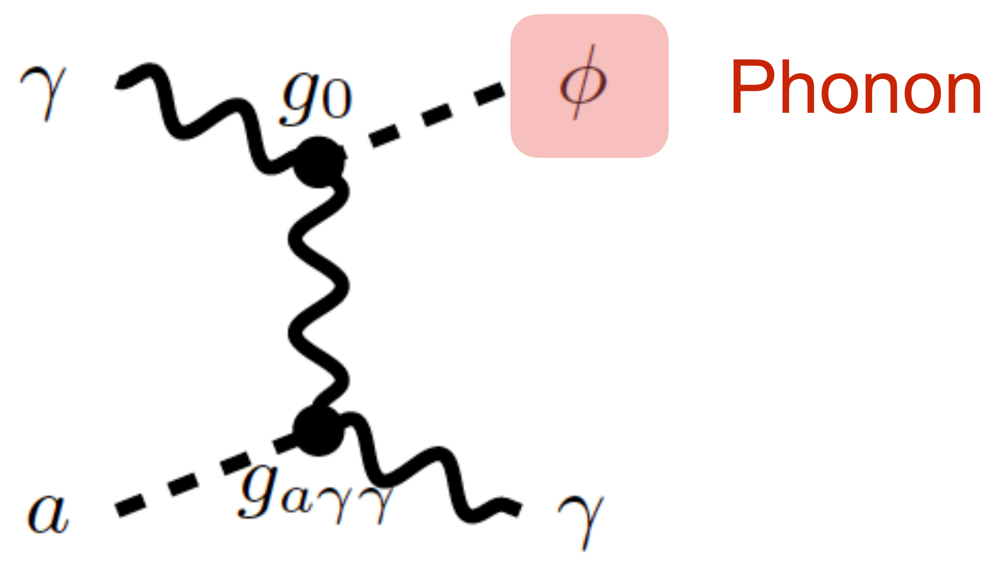
Axion direct detection with optomechanical cavities



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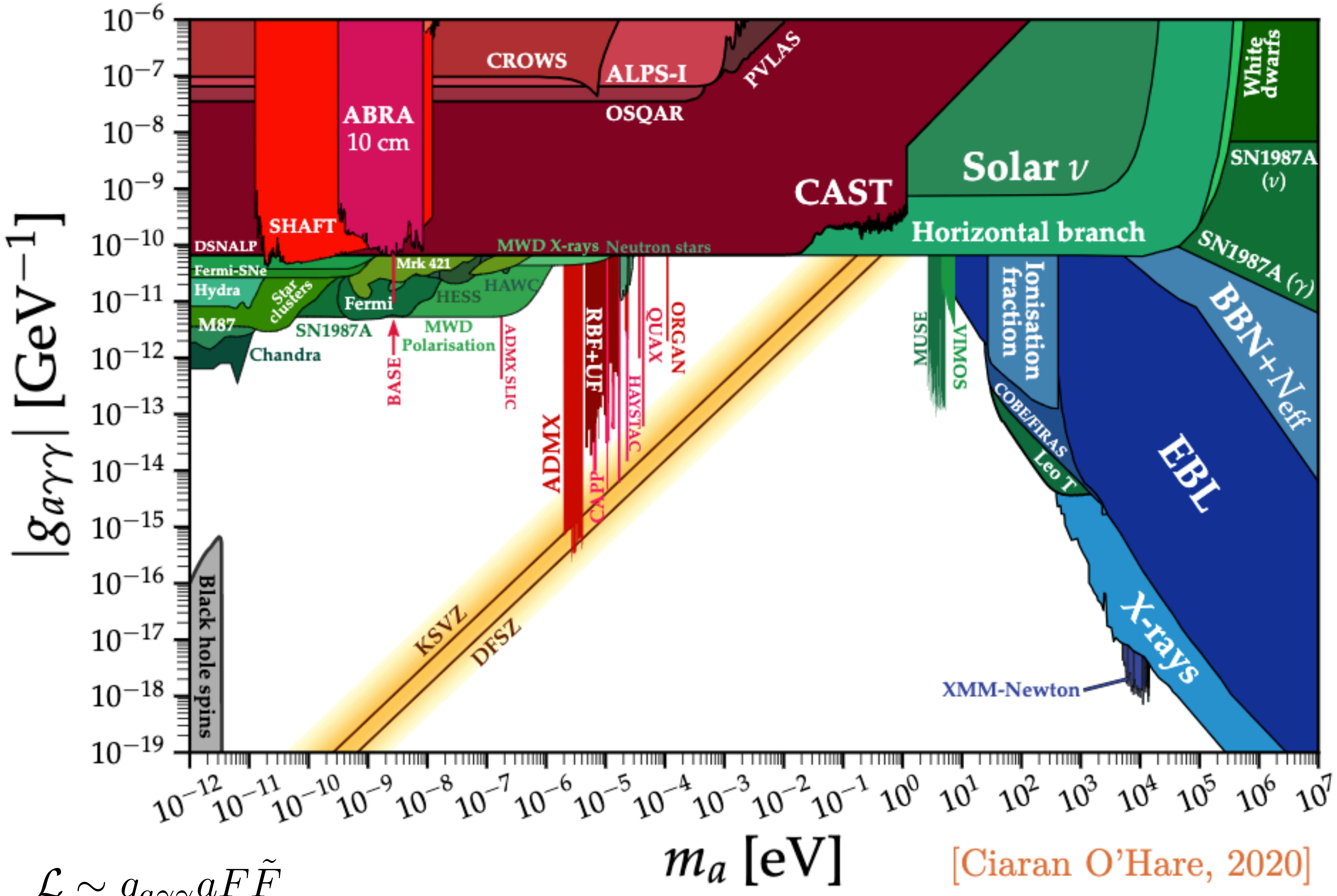

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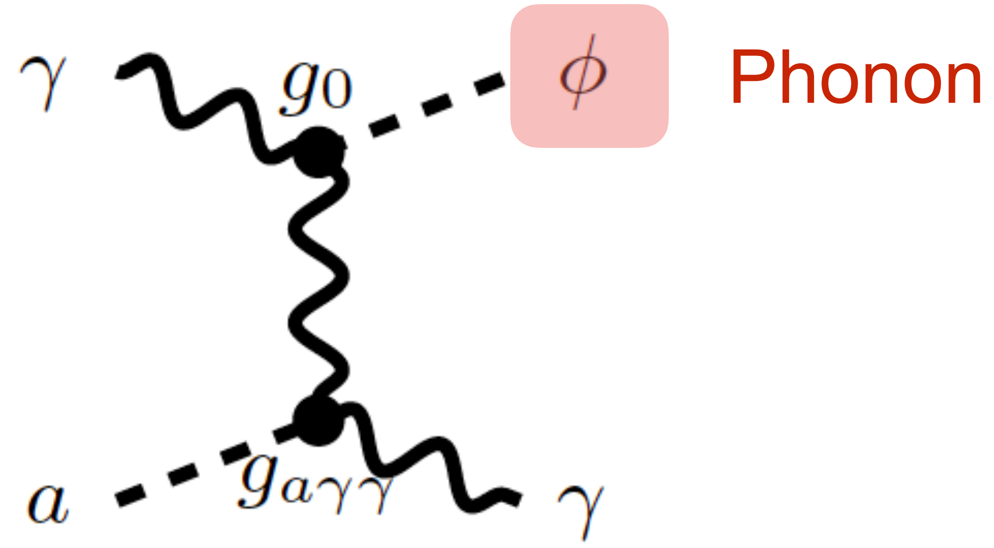

Phonons provide the **kinematic matching**: break the scaling between m_a and the cavity size;

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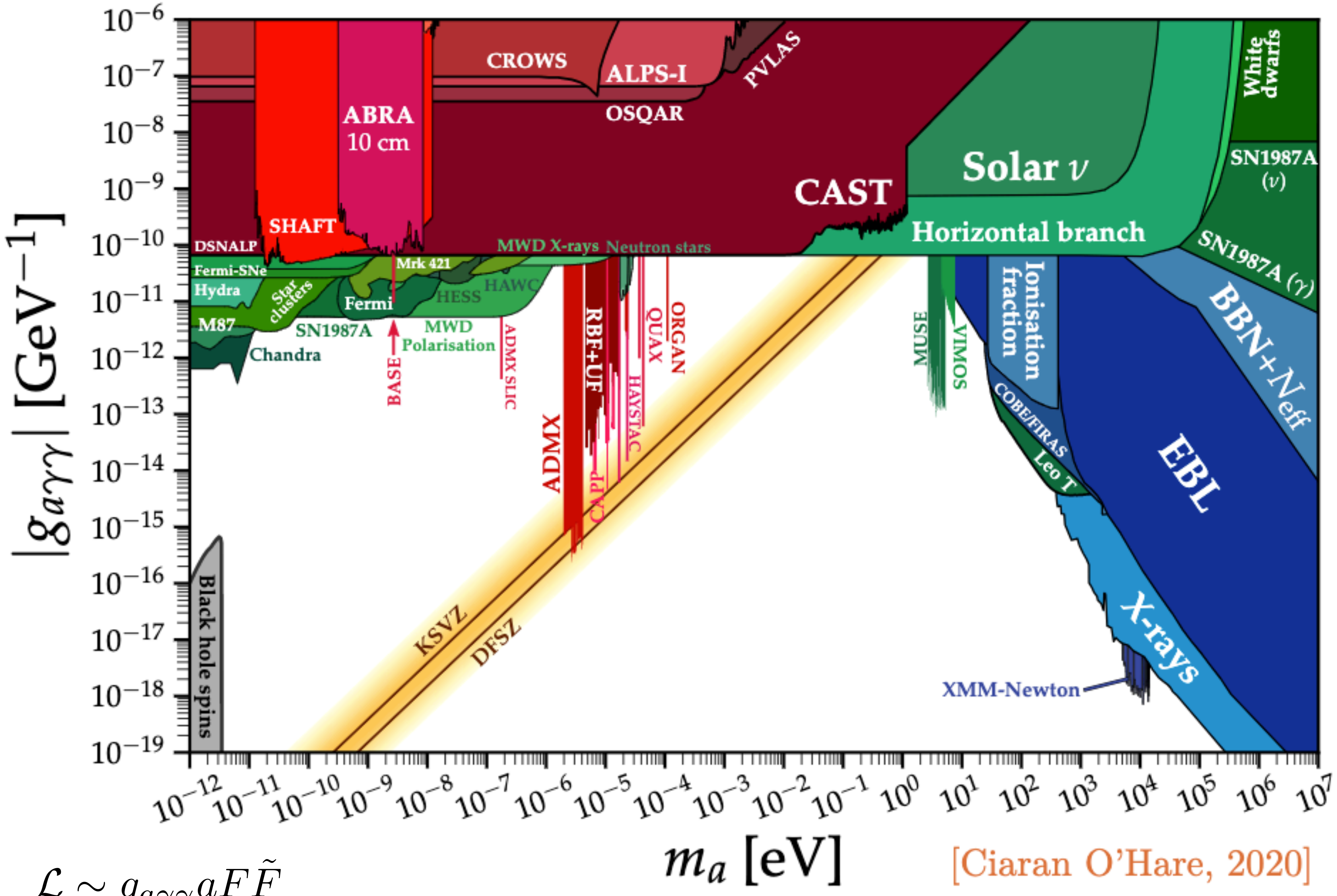

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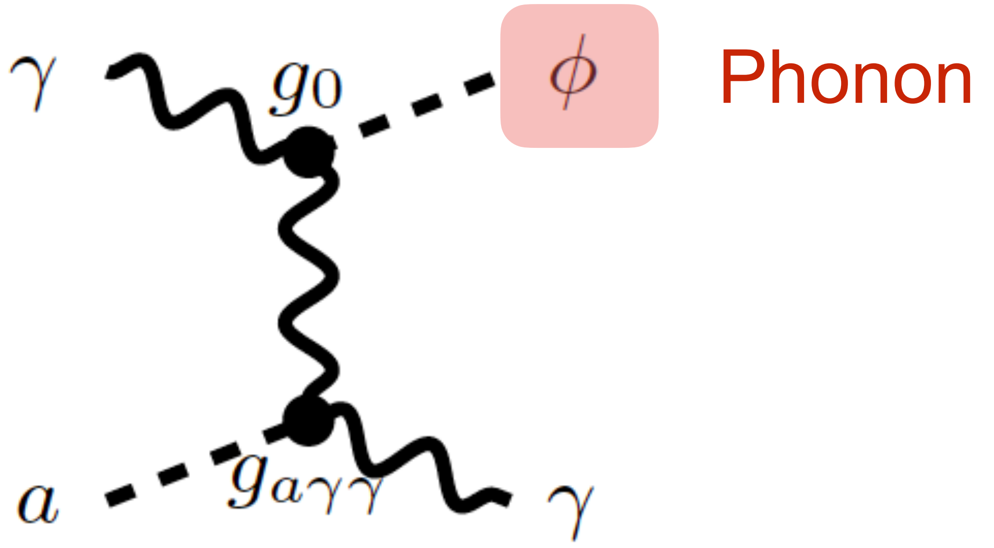
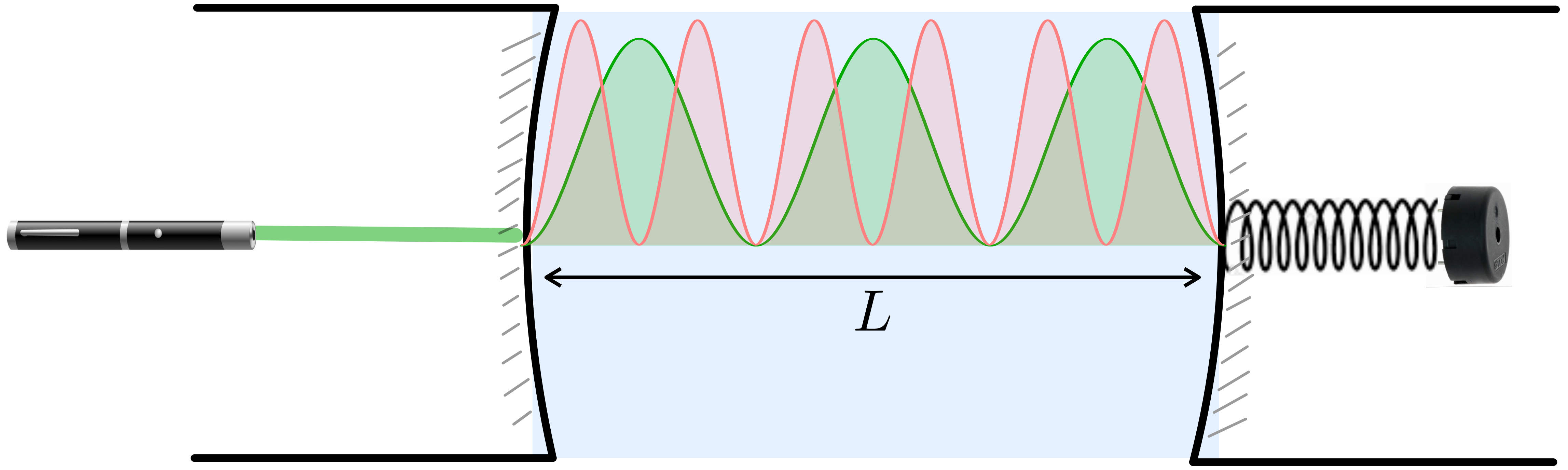


Phonons provide the **kinematic matching**: break the scaling between m_a and the cavity size;

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

Cavity Optomechanics

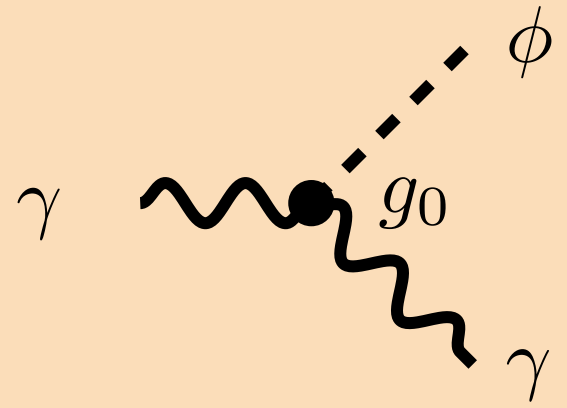


Mirrors confine light & sound

Optomecanical interaction

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

'mech' 'opts' photons phonon



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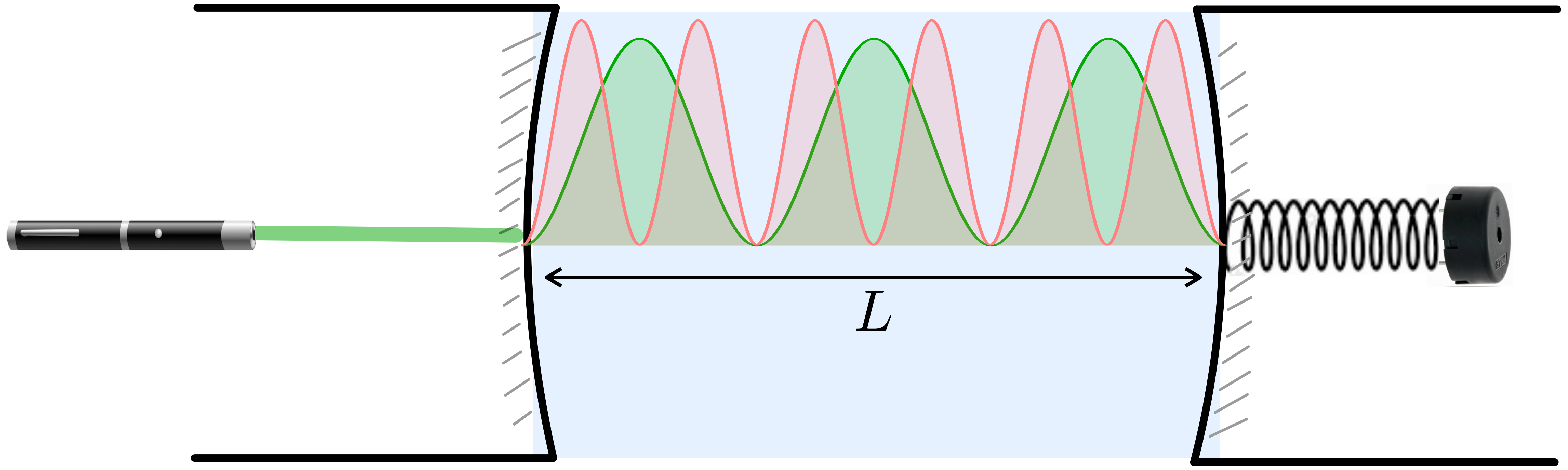

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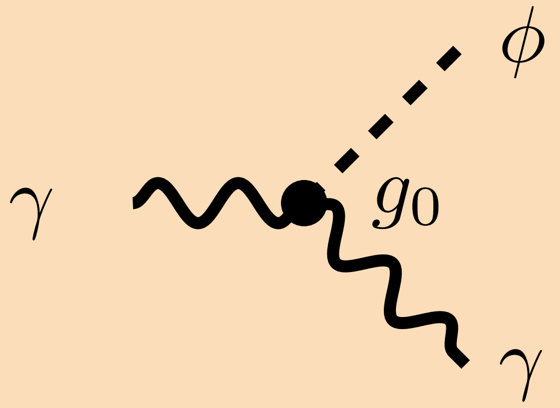


Optical resonance: $\omega_{\mathrm{opt}} = n\frac{\pi}{L}$ Optical width: $\kappa = \tau_{\mathrm{opt}}^{-1} = \frac{\pi}{L\mathcal{F}_{\mathrm{opt}}}$

Quantization of light Photon population: $N_\gamma^{\mathrm{circ}} = \frac{4P_{\mathrm{laseer}}}{\omega_{\mathrm{opt}}\kappa}$

Integer mechanical mode number

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

speed of sound

Acoustic finesse

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

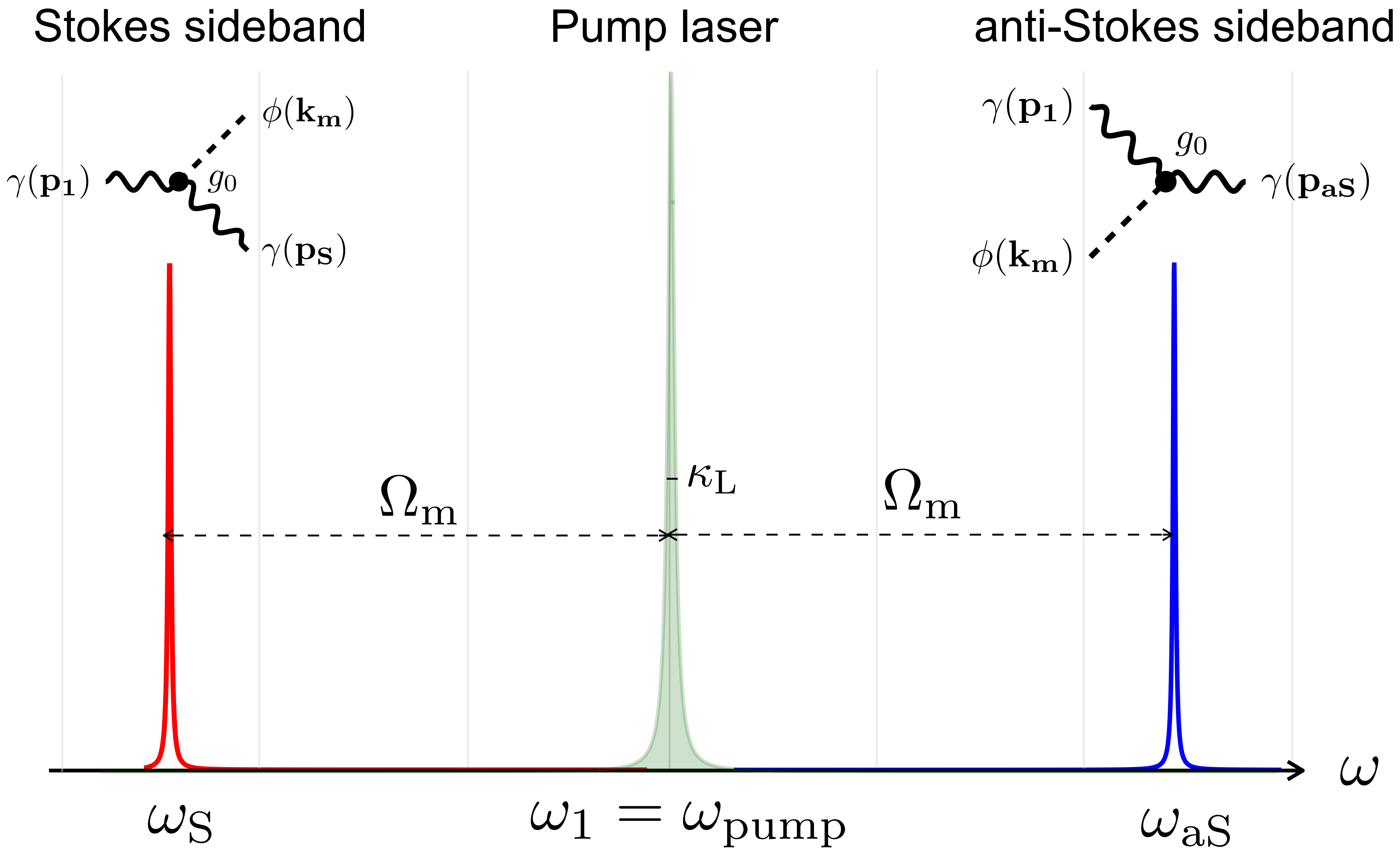
Quantization of sound Phonon population: $N_\phi^{\mathrm{circ}} = N_{\mathrm{phi}} \frac{(\Gamma_{\mathrm{m}}/2)^2}{(\Omega_{\mathrm{m}} - \Omega_{\mathrm{m.d.}})^2 + (\Gamma_{\mathrm{m}}/2)^2}$

Cavity Optomechanics

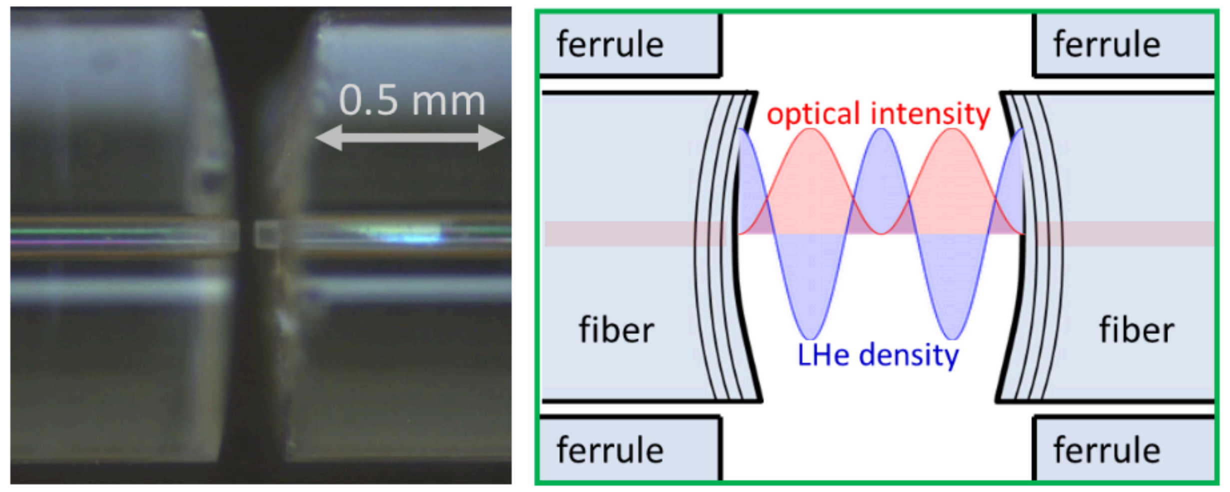
[Aspelmeyer et al., 2013]
[Kashkanova et al., 2017]
[Reningner et al., 2017]

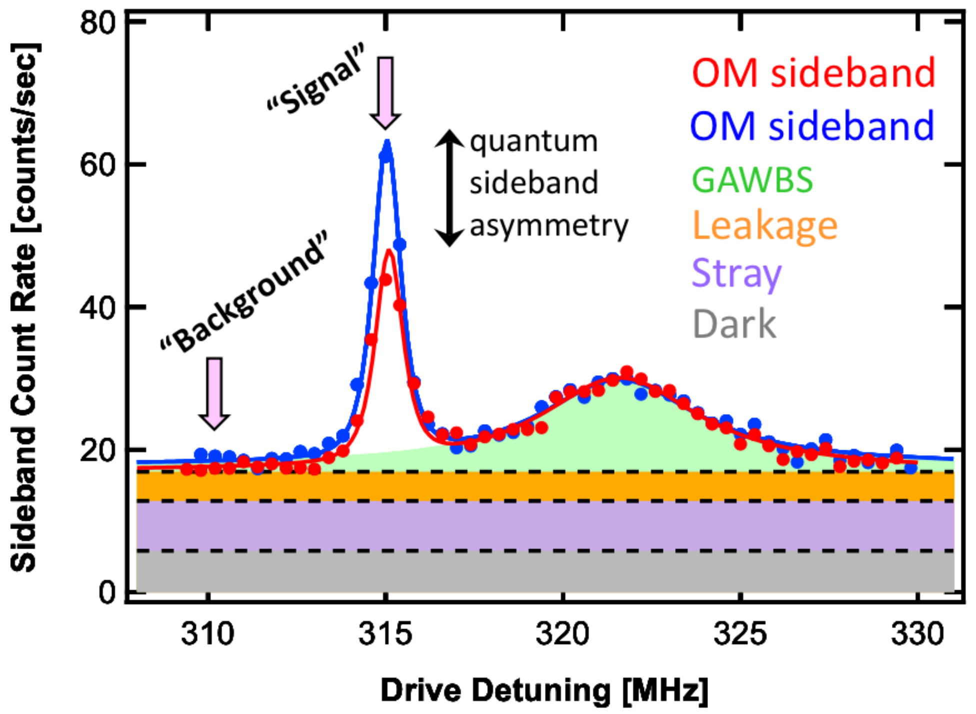
$$H_{\mathrm{OM}} \ni g_0\, a_{n_1}\, a^\dagger_{n_2}\ \left(b_{n_\mathrm{m}} + b^\dagger_{n_\mathrm{m}}\right)$$

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



[Shkarin A, et al., 2019]



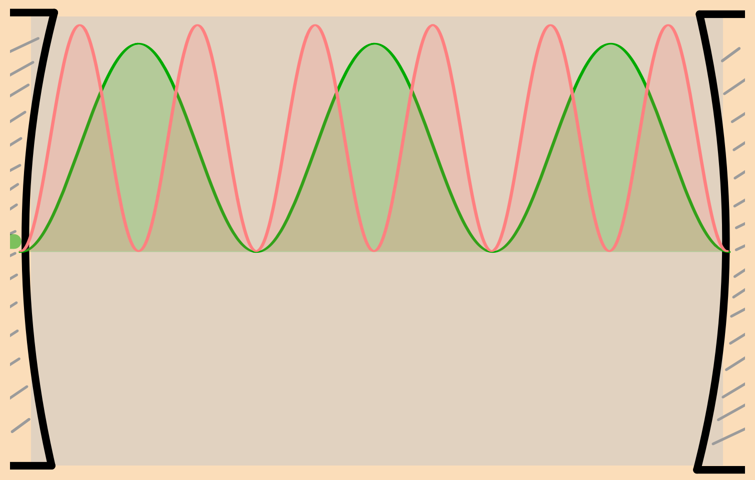


(From Jack Harris's slides)

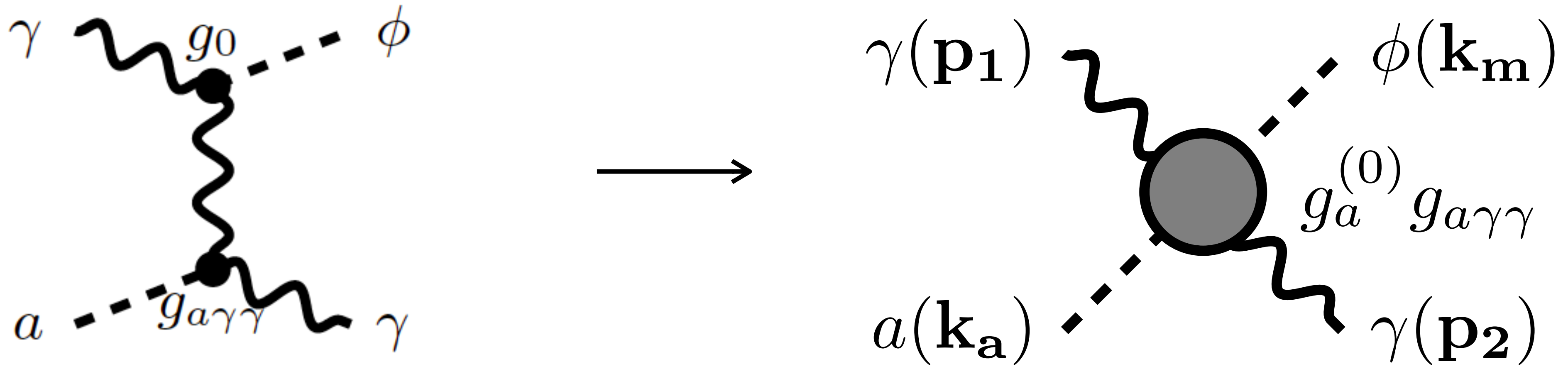
Cavity optomecanical kinematics

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

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



Axioptomechanics - kinematics



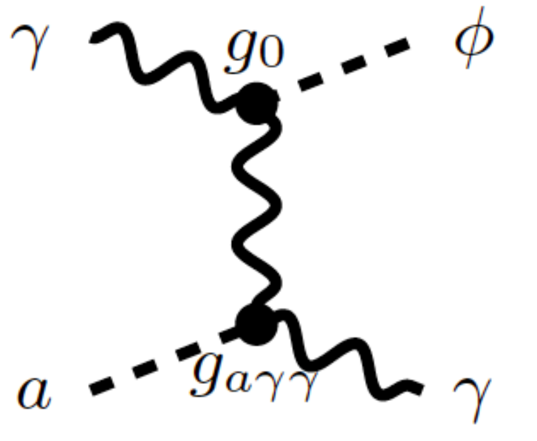
$$g_a^{(0)} \propto a_{\rm ovl} = \mathrm{sinc}\left(\frac{\pi}{2}(n_1 + n_2 - n_{\rm m} + \frac{k_a}{\pi/L})\right)$$

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

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

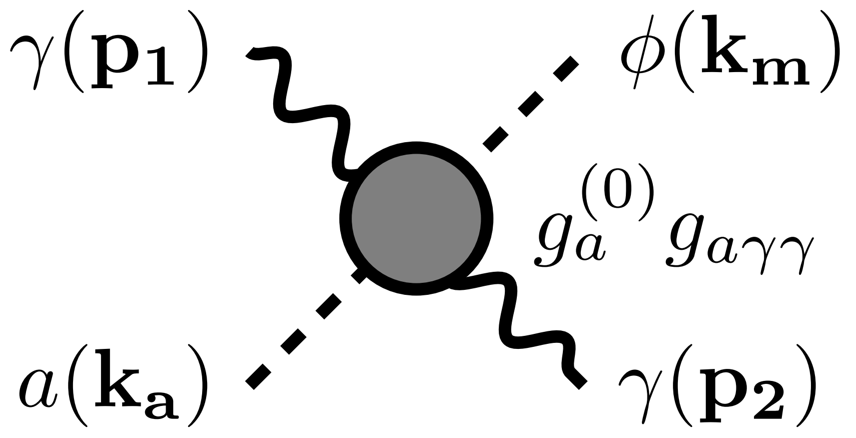
$$H_{\rm eff} \ni g_{a\gamma\gamma}\, g_a^{(0)}\, a(t)\, a_{n_1}\, a^\dagger_{n_2}\, b^\dagger_{n_{\rm m}}$$

Axioptomechanics - kinematics



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

$\longrightarrow$



$g_a^{(0)} g_{a\gamma\gamma}$

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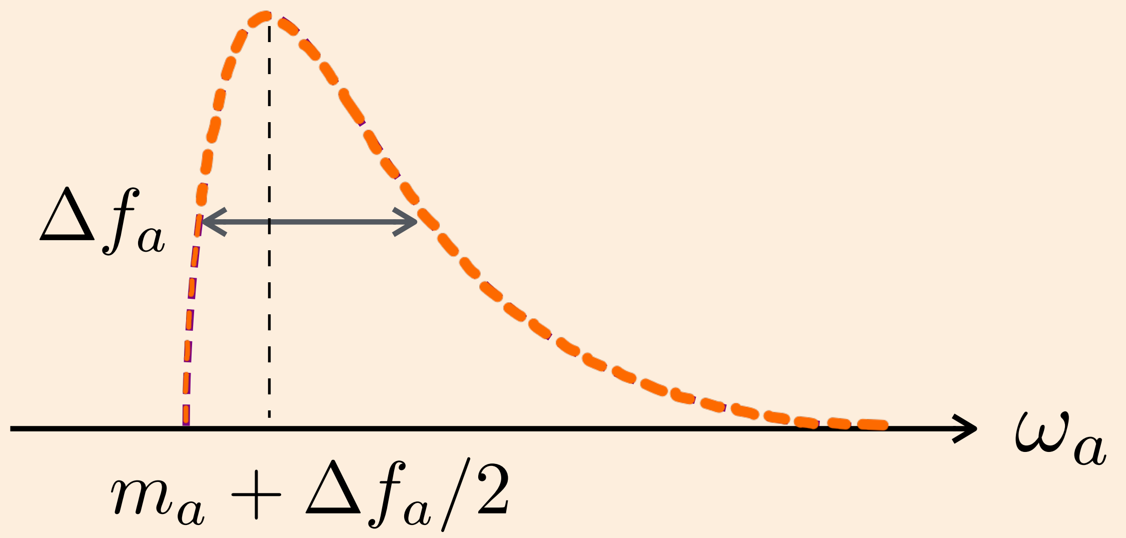
Axion dark matter $|a(\omega_a)|^2 = \frac{2\rho_a}{m_a^2} B(\omega_a)$

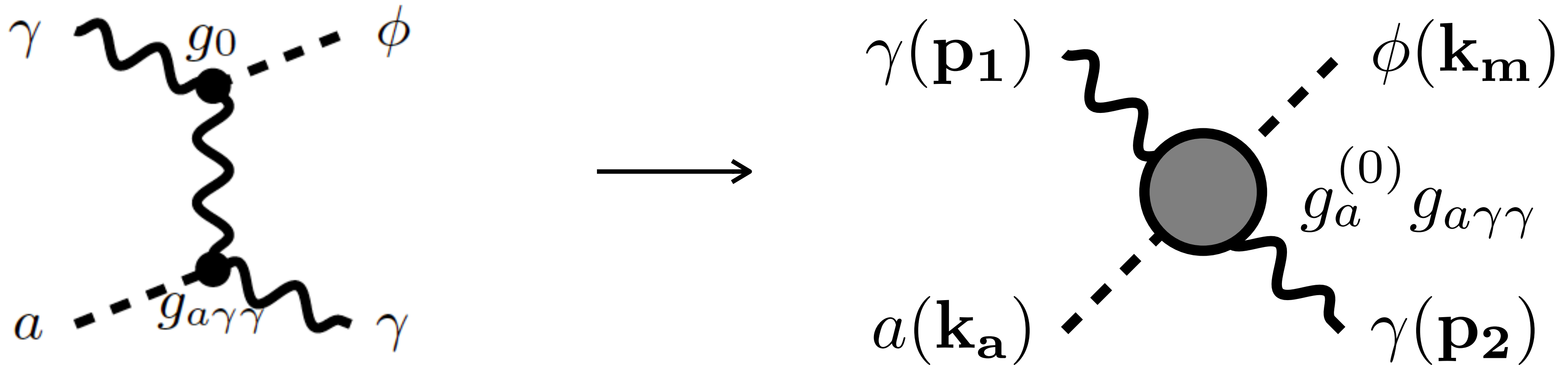
$$k_a \sim v_a m_a \sim v_a \omega_a$$

(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



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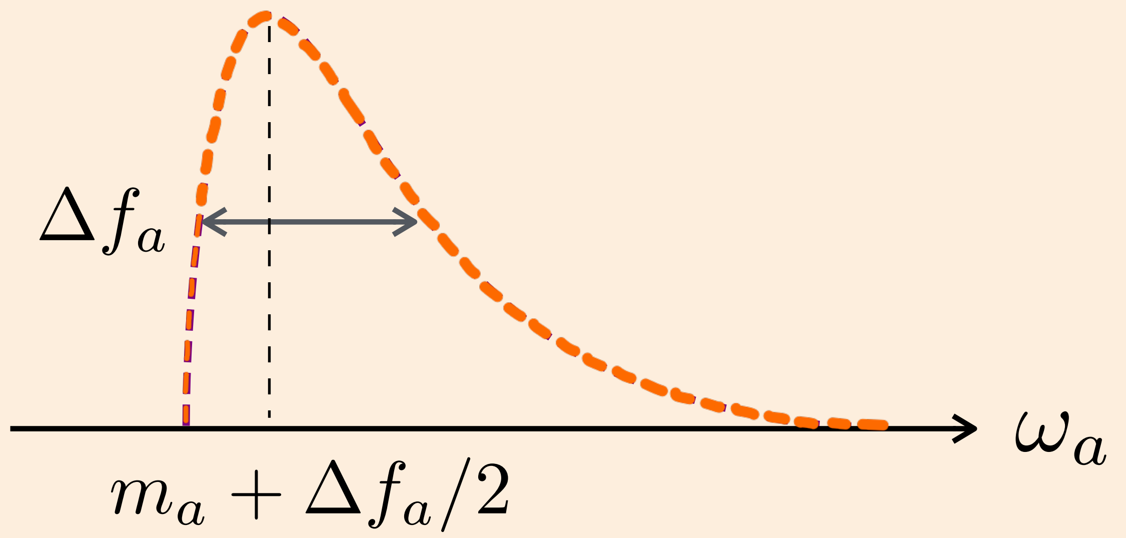

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Energy conservation: $\omega_1 + m_a \simeq \omega_2 + \Omega_{\rm m}$

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

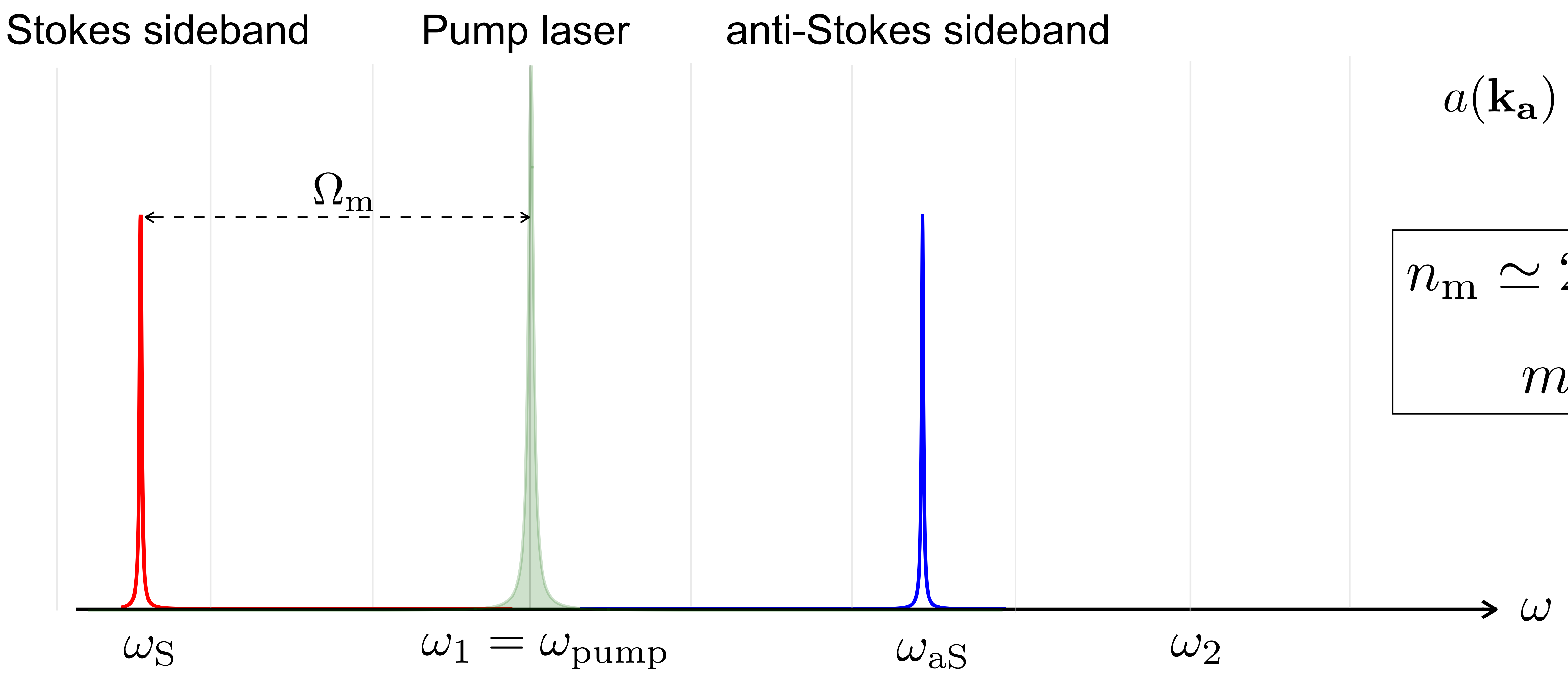
Axioptomechanics kinematics:

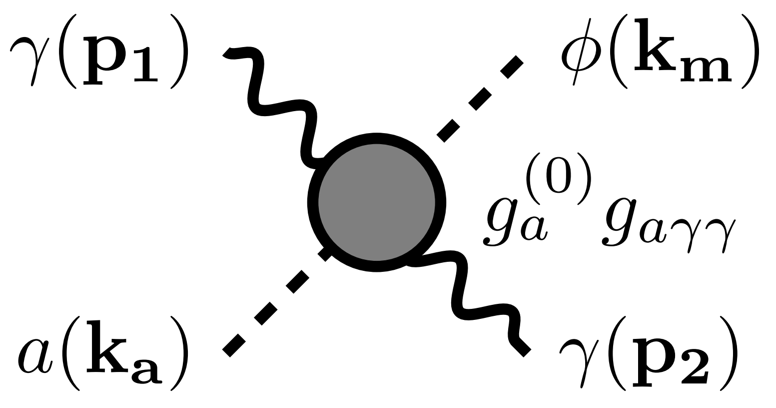
$$n_{\rm m} \simeq 2\, n_1 + [m_a/\omega_{\rm FSR}]$$
$$m_a \simeq \Delta + \Omega_{\rm m}$$

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

Axioptomechanics - the signal and the rate

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



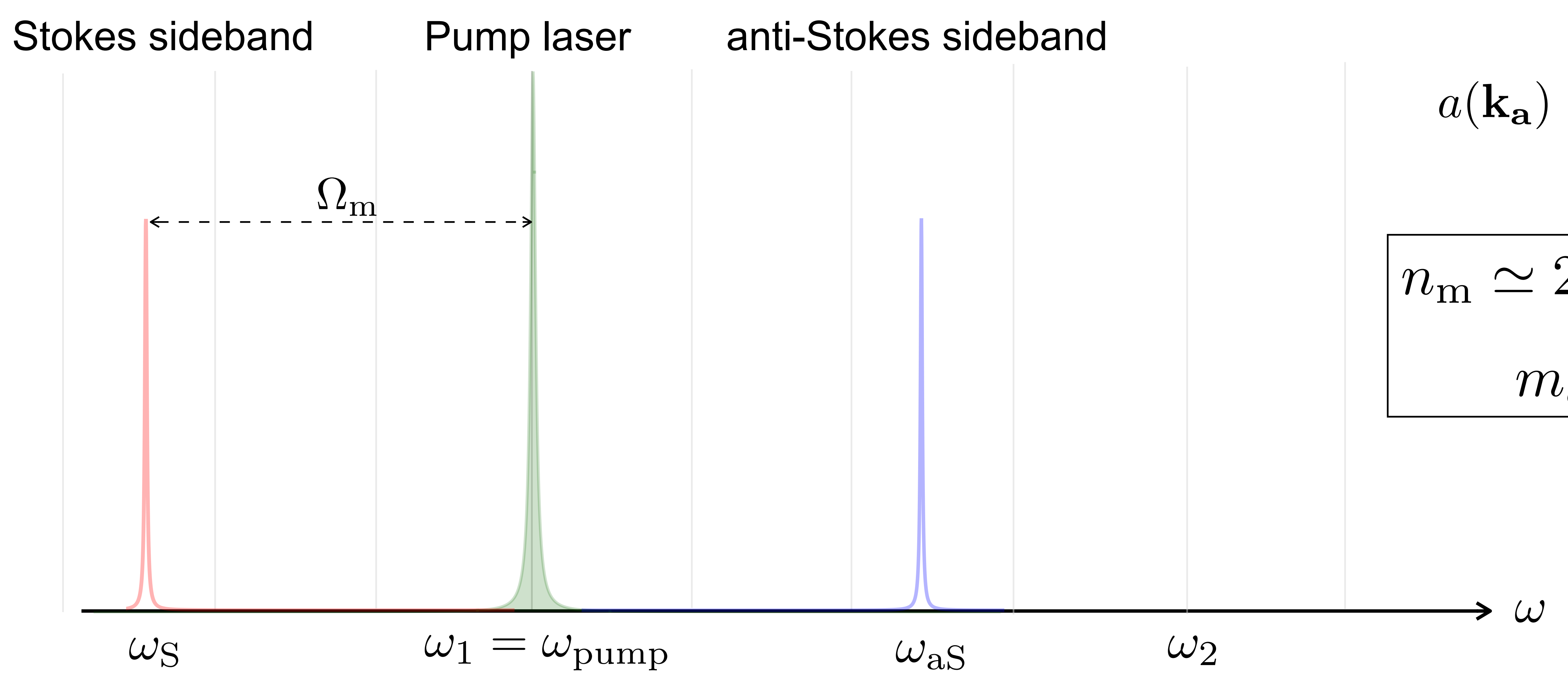


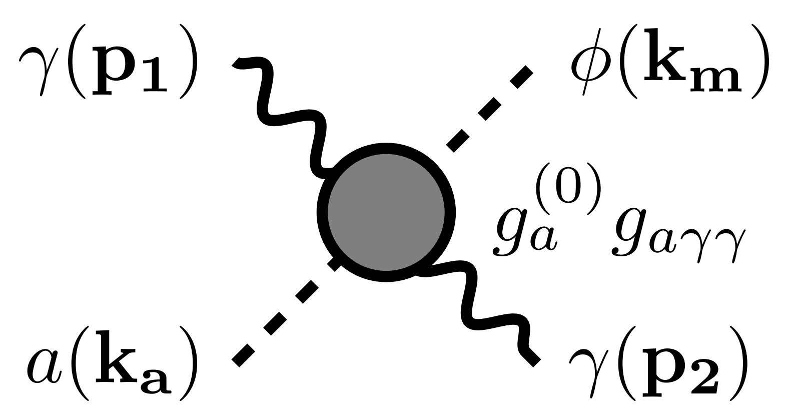
$$n_{\rm m} \simeq 2\, n_1 + [m_a/\omega_{\rm FSR}]$$

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

Axioptomechanics - the signal and the rate

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



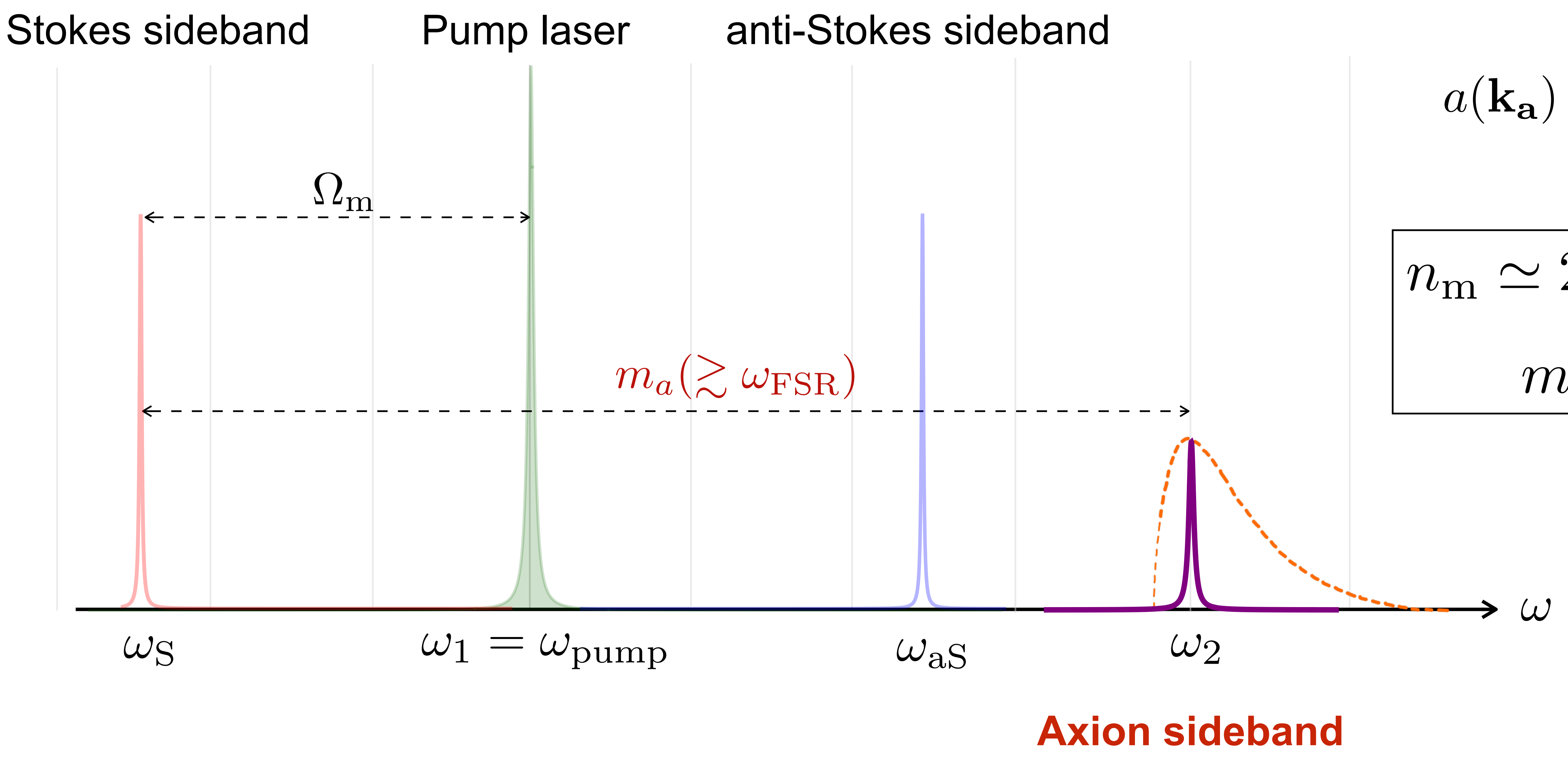


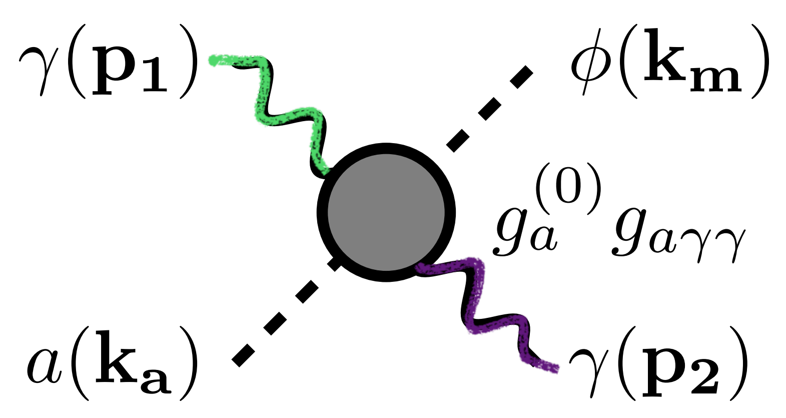
$$n_\text{m} \simeq 2\, n_1 + [m_a/\omega_\text{FSR}]$$

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

Axioptomechanics - the signal and the rate

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





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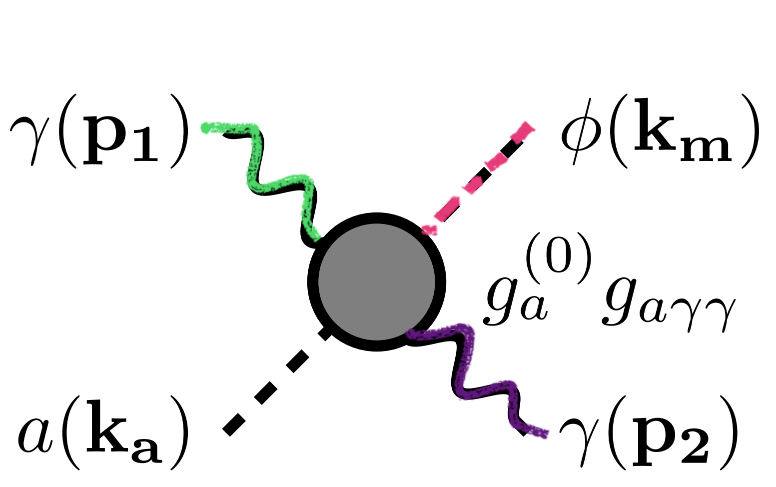
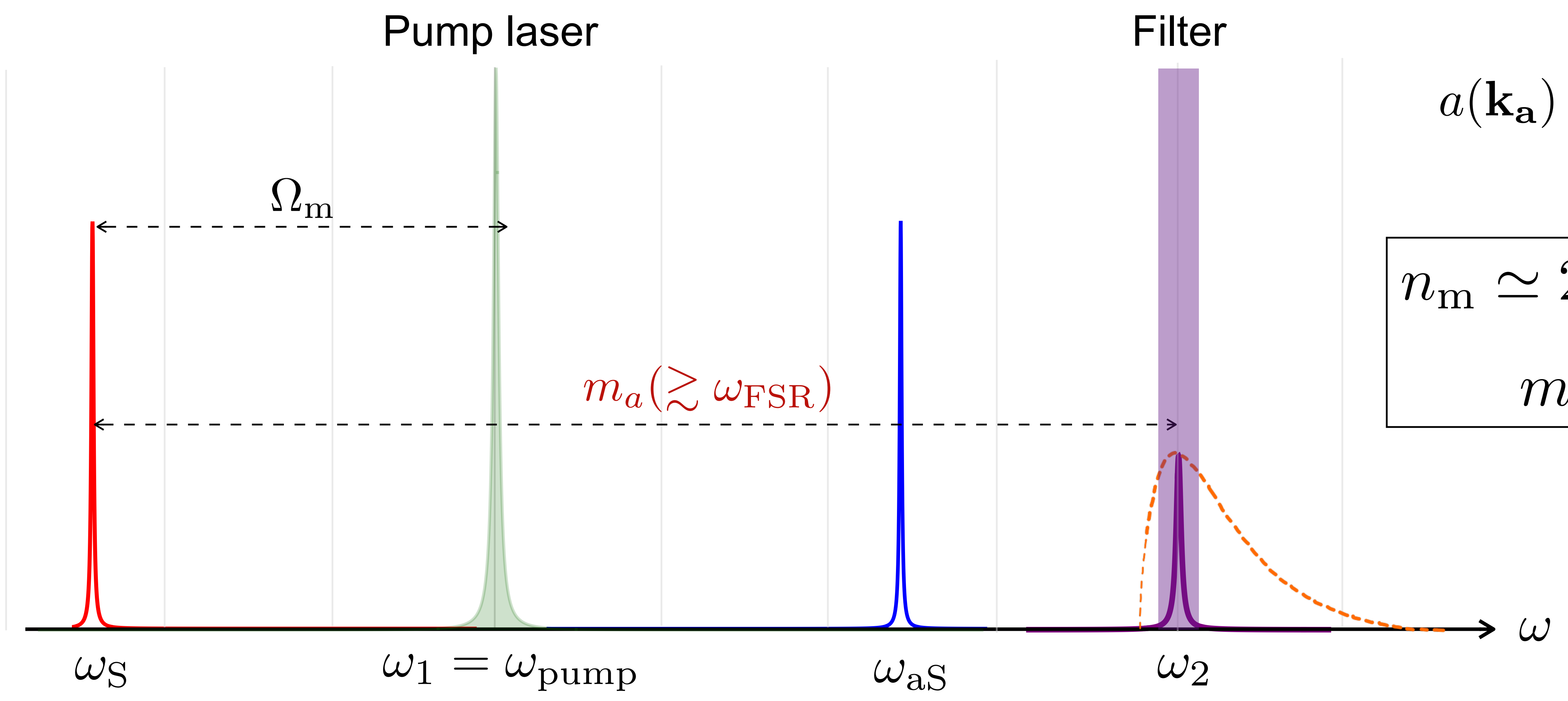




$$n_\text{m} \simeq 2\,n_1 + [m_a/\omega_\text{FSR}]$$
$$m_a \simeq \Delta + \Omega_\text{m}$$

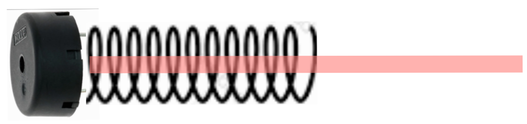
Heavy Axion Regime

$m_a \gtrsim \omega_\text{FSR}$

Background free

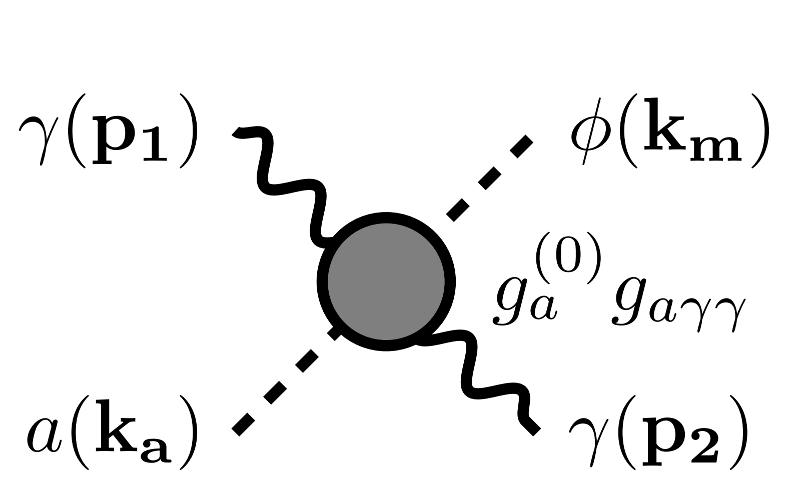
Single photon

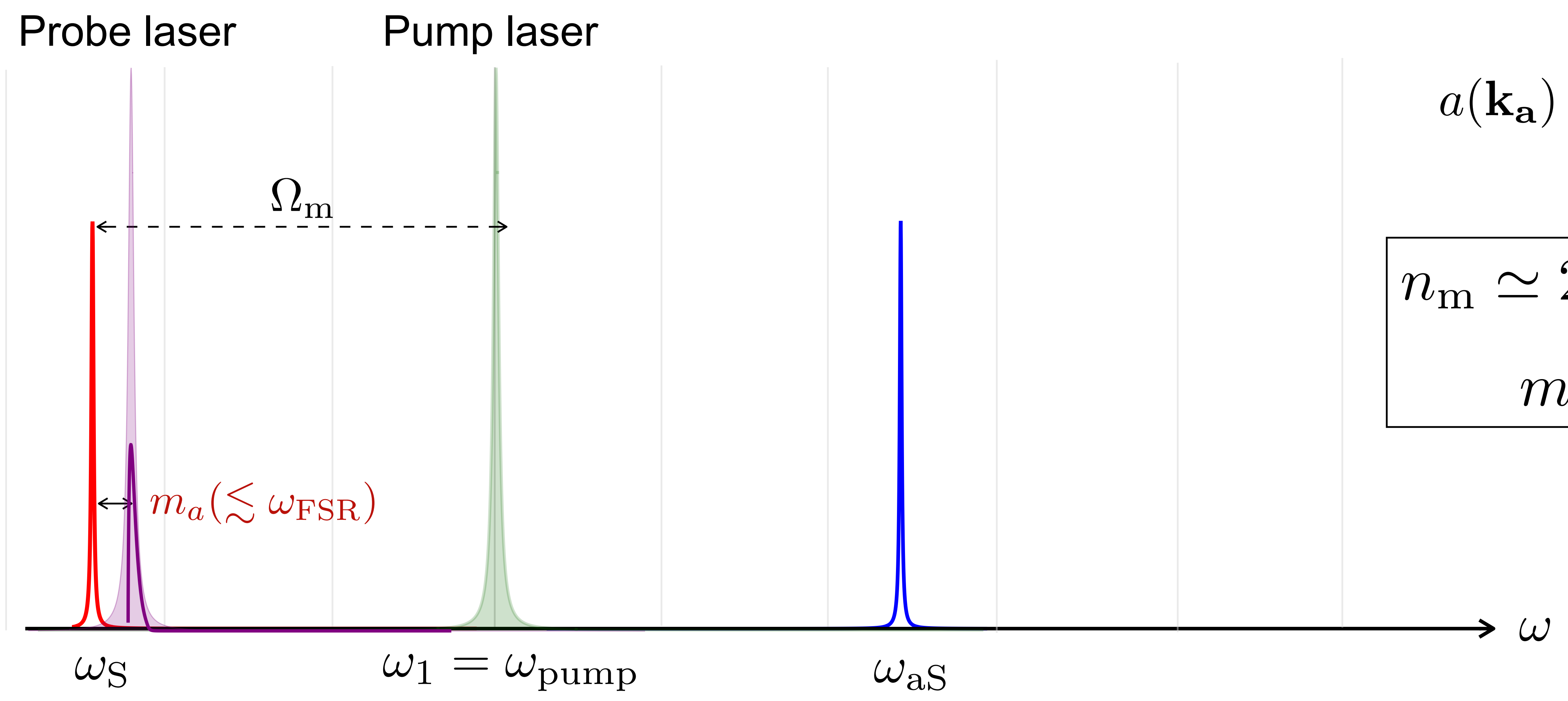
$$\Gamma \sim (2\pi)|g_a^{(0)}|^2 \left(\frac{2\rho_a}{m_a^2}\, g_{a\gamma\gamma}^2\right) N^{\text{circ}}_{\gamma,\text{pump}}\, N^{\text{circ}}_{\phi}(\Delta_\text{m}) \int d\omega_2\, B_{m_a}(\omega_2 + \Omega_\text{m} - \omega_\text{pump}) L(\omega_2 - \omega_{n_2}, \kappa)$$

Axioptomechanics - the signal and the rate

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





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

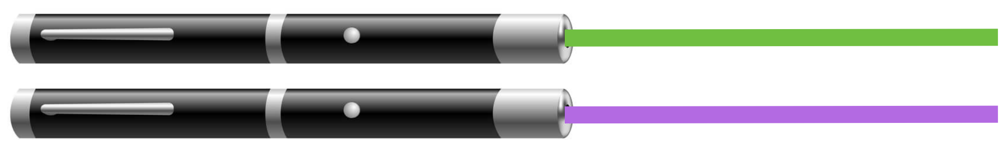
Light Axion Regime

$m_a \lesssim \omega_{\rm FSR}$

Large background

Power readout

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



Axioptomechanics - the signal and the rate

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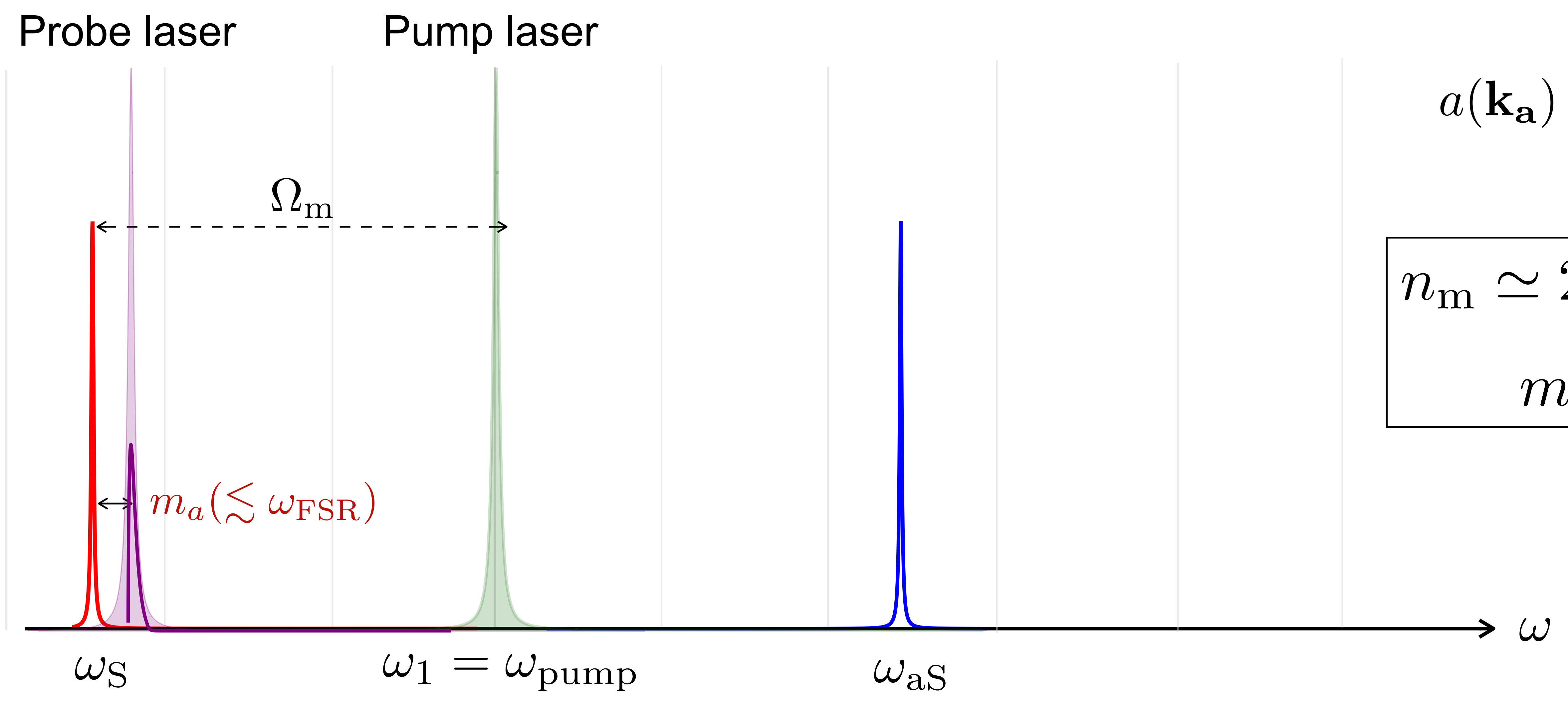
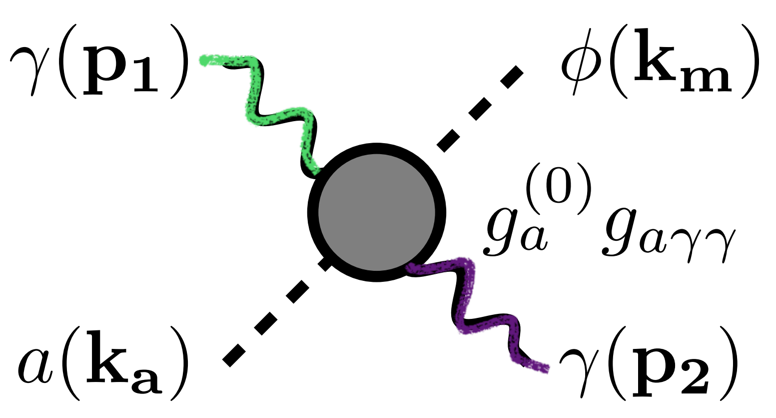




$$n_{\mathrm{m}} \simeq 2\, n_1 + [m_a/\omega_{\mathrm{FSR}}]$$

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

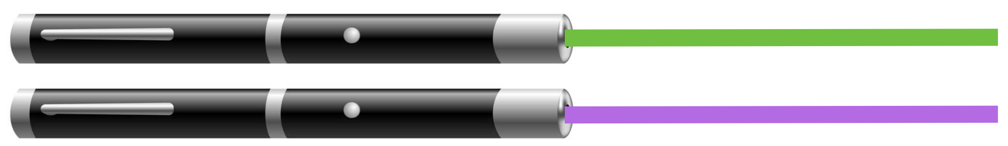
Light Axion Regime

$m_a \lesssim \omega_{\mathrm{FSR}}$

Large background

Power readout

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



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:

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

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

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

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

Single photon $\Gamma_{\mathrm{back}} = \Gamma_{\mathrm{DCR}}$ ⇒ $\mathrm{SNR} \propto N_\gamma N_\phi$

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

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

Scales with a one meter cavity

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

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

1 For usual experiments in their lab:

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

2 What could be feasible to achieve:

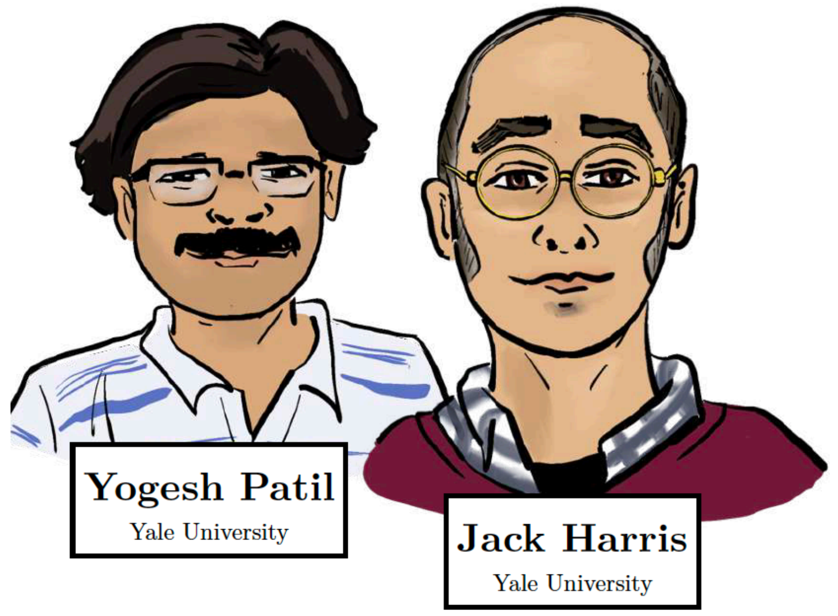
- $N_{\text{pump}} \simeq 10^{17}$ — $P_{\text{pump}} \sim 1$ W
- $N_{\text{probe}} \simeq 10^{17}$ — $P_{\text{probe}} \sim 1$ W
- $N_\phi \simeq 10^{14}$ — $L \sim 1$ m, $\mathcal{F}_{\text{opt}}/\pi \sim 10^6$

3 What other experiments are aiming for:

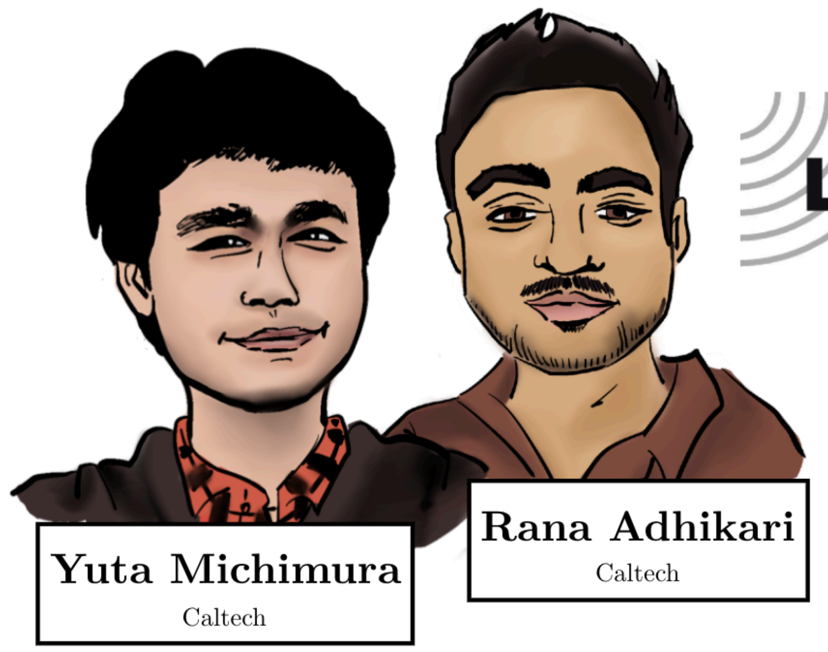
- $N_{\text{pump}} \simeq 10^{22}$ — $P_{\text{pump}} \sim 10$ kW, $L \sim 5$ m, $\mathcal{F}_{\text{opt}}/\pi \sim 10^6$

GQuEST

Yale University
Jack Harris Lab

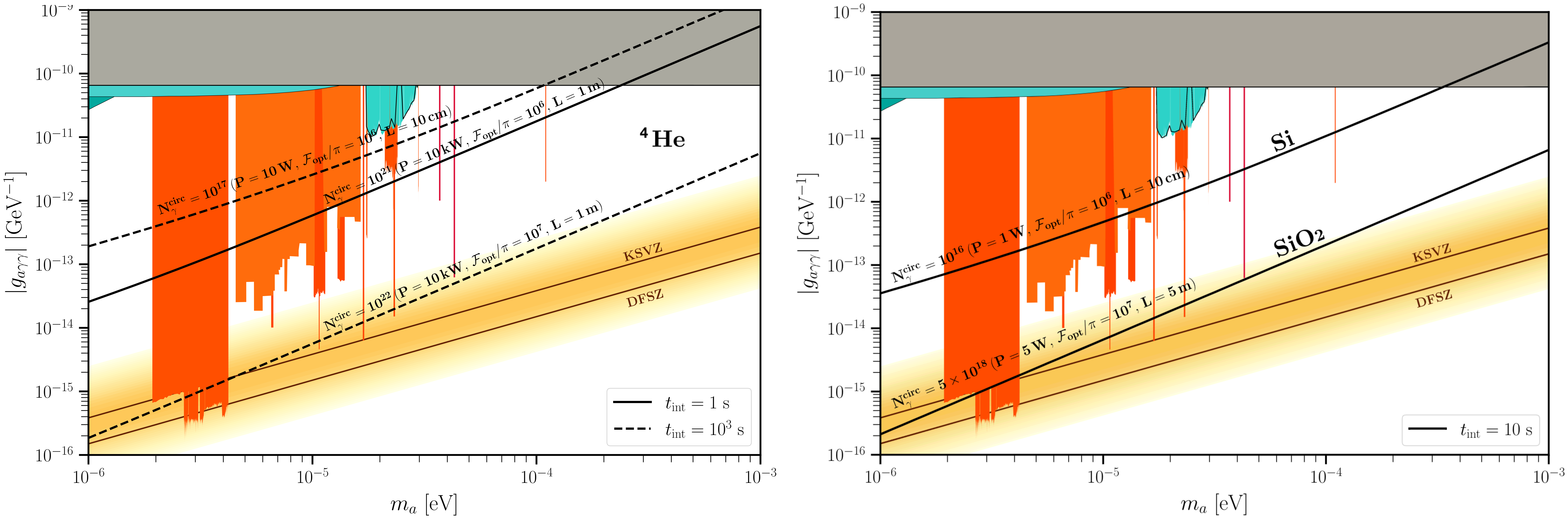


(by Clara Murgui)



The reach

Populated final state of phonons



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

Summary and outlook

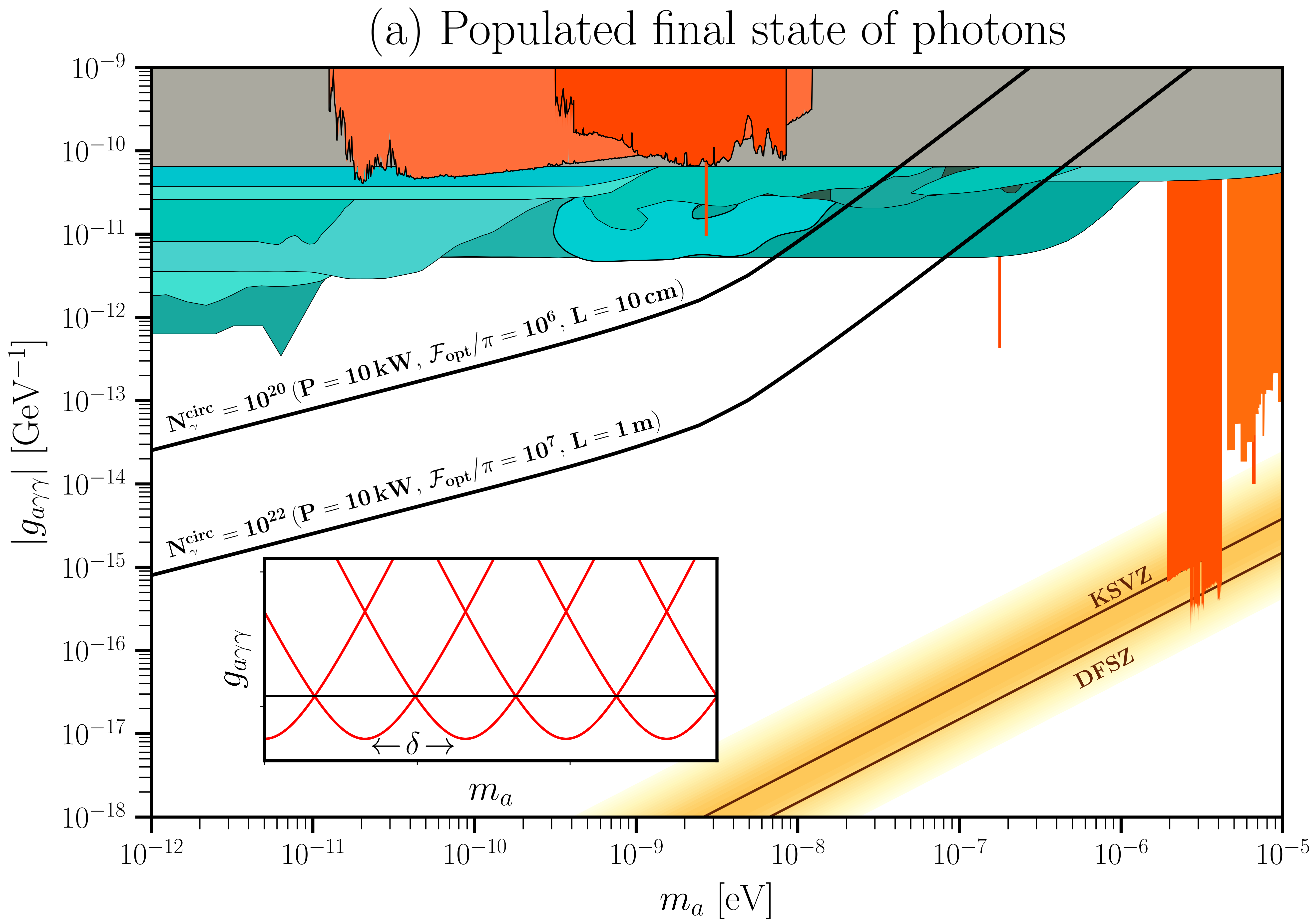
- **Axioptomechical coupling** allows the decoupling of the axion mass from the resonance frequency of the system, thus the system size, for resonance searches of the axion dark matter;
- **Highly coherent acoustic modes** that can be hosted in well developed optomechanical systems can coherently enhance 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**.

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!

The reach



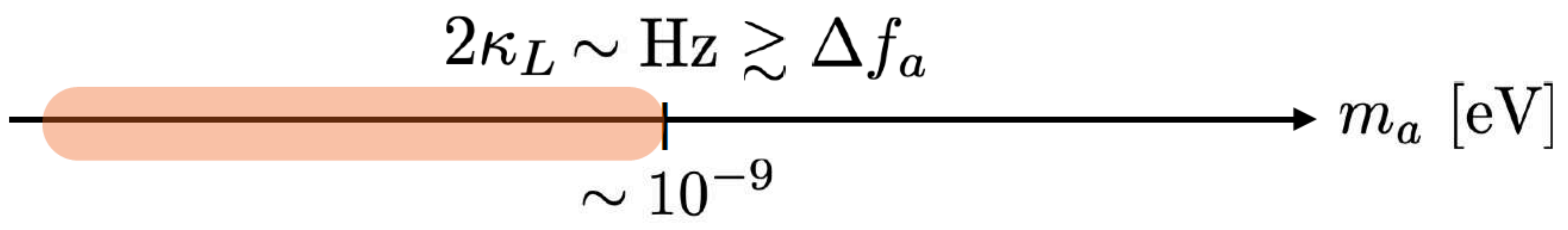
$$g_{a\gamma\gamma}^{\gamma-\rm pop} \propto \left(\rho^{1/2} c_s^{1/2} \frac{\epsilon_r + 2}{\epsilon_r - 1} \epsilon_r^{3/4}\right)\left(\frac{1}{\mathcal{F}_{\rm opt}^{5/4}} \frac{1}{L^{1/4}}\right)\left(\frac{1}{\omega_{\rm opt}^{5/4}} \frac{1}{P_{\rm pump}^{1/2}} \frac{1}{P_{\rm probe}^{1/4}}\right)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

Sensitivity and scanning

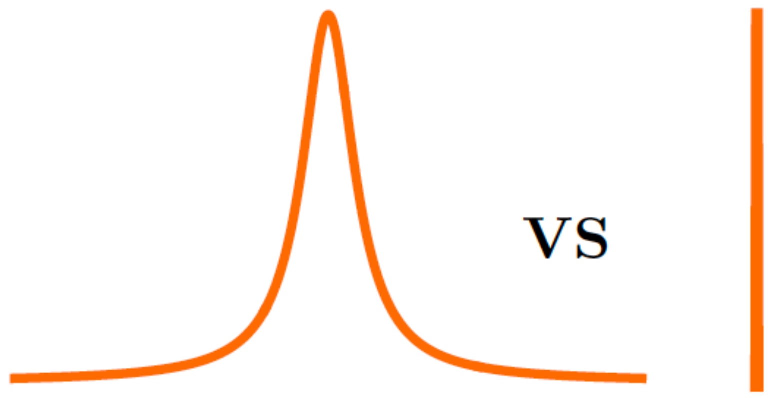
$$\text{SNR} \geq 3 \quad \rightarrow \quad g_{a\gamma\gamma} > f(m_a, \text{cavity}, \text{lasers}, \text{material})$$

Scanning: covering an extended mass range

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



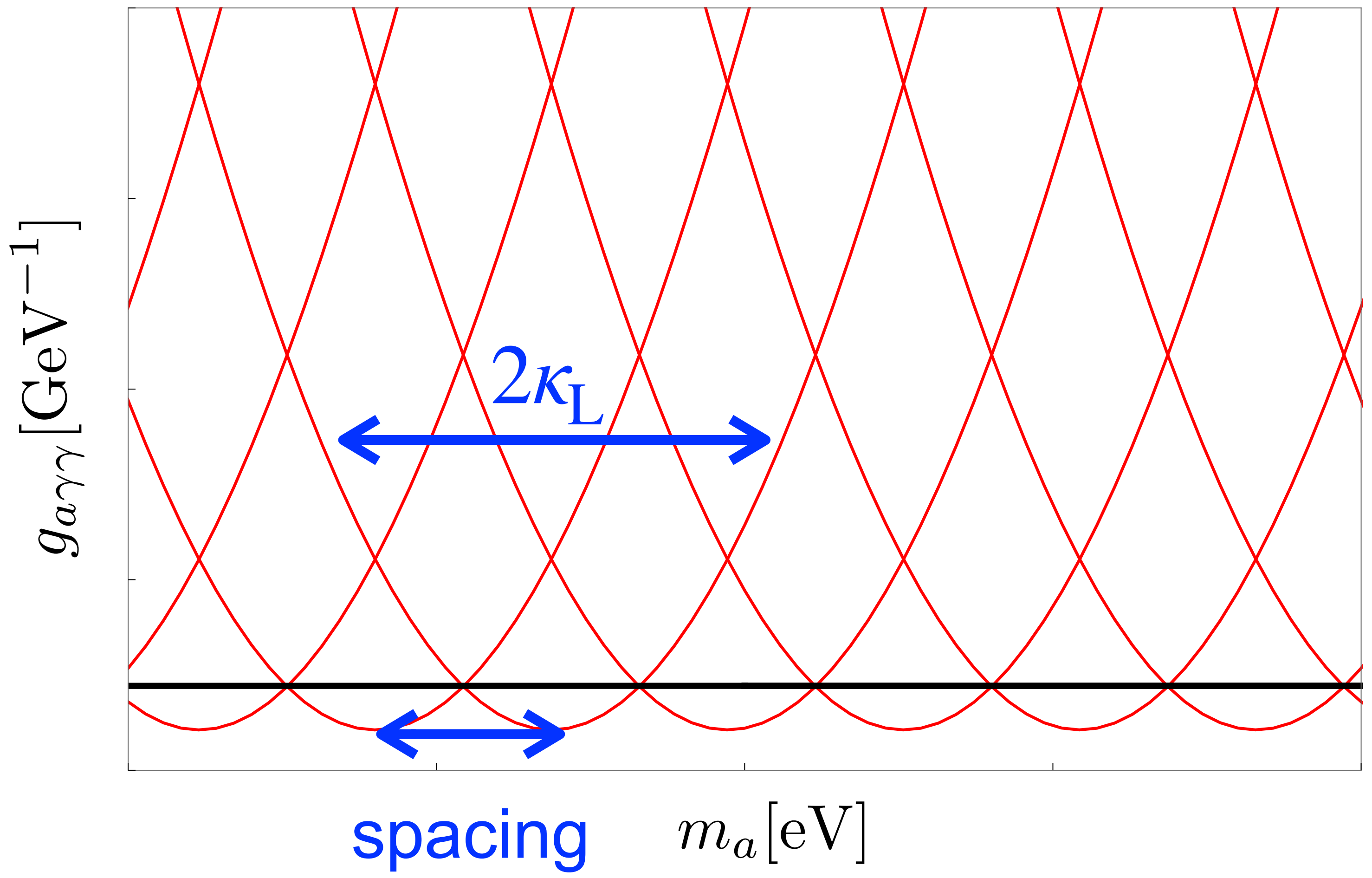
Lorenzian regime



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

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

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



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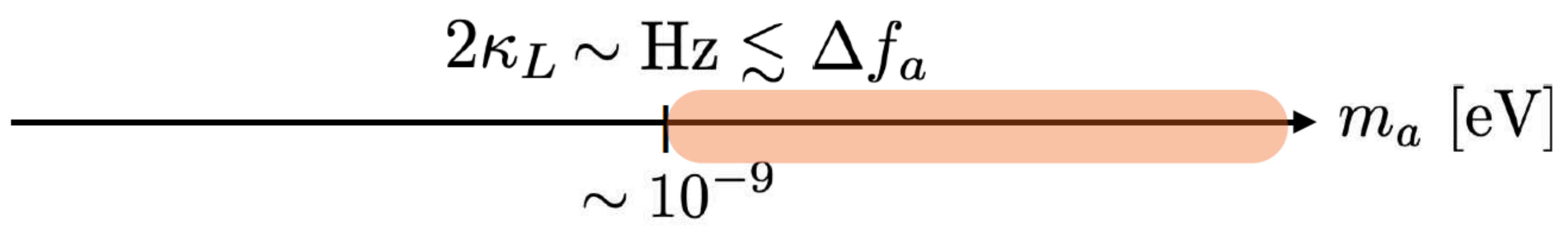
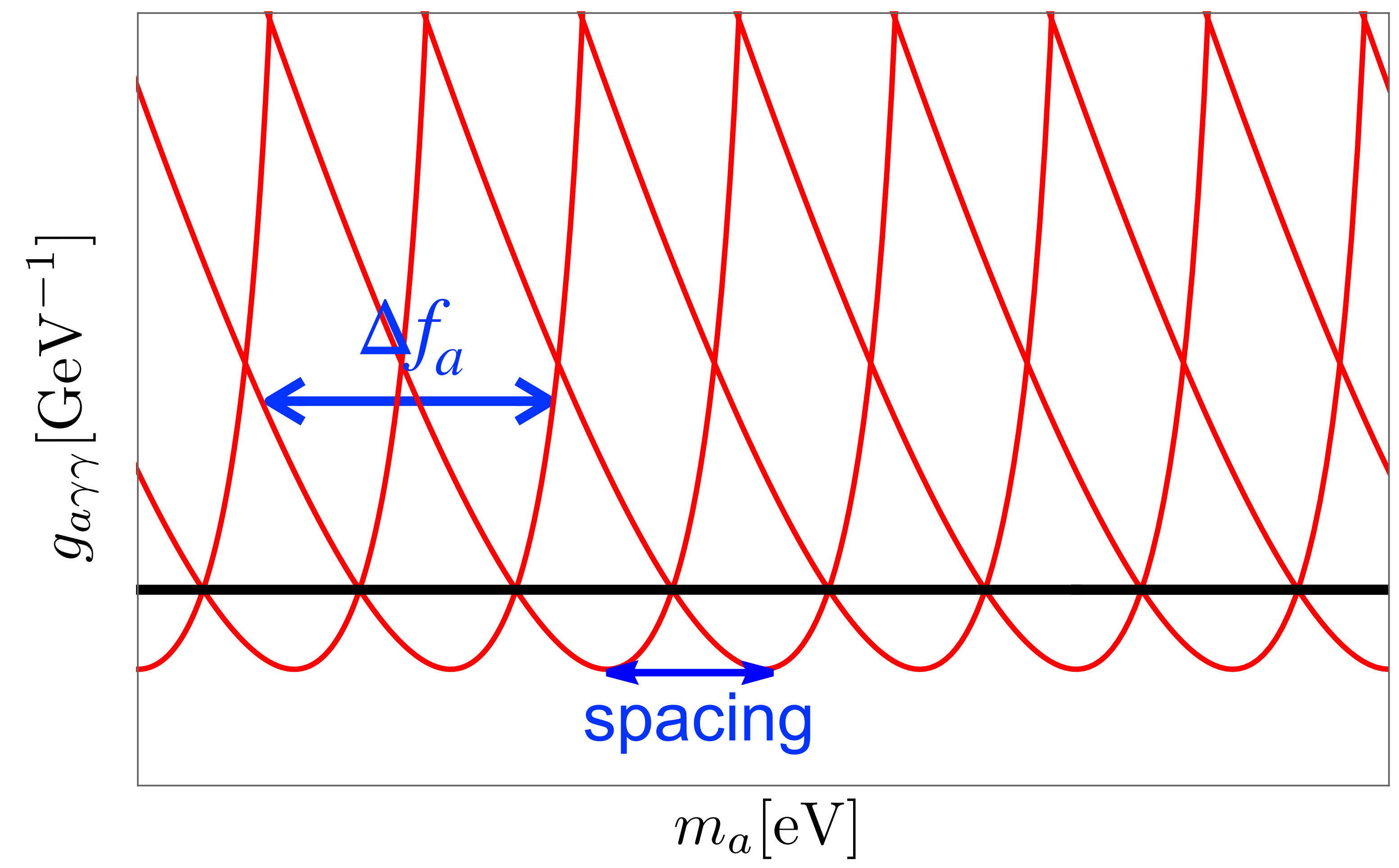
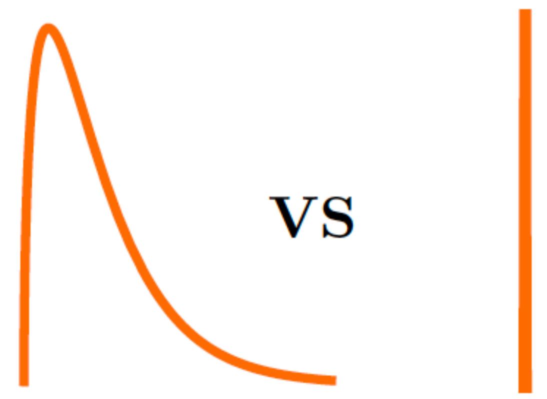
E.g. $\Gamma_{\mathrm{sig}} \propto \int d\omega_2 \, B_{m_a}(\omega_2 + \Omega_{n_{\mathrm{m}}} - \omega_{\mathrm{pump}}) L(\omega_2 - \omega_{\mathrm{probe}}, 2\kappa_{\mathrm{L}})$





Boltzmann regime



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

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

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