Title: Hunting for Light DM with Quantum Sensors

Speakers: Clara Murgui

Series: Particle Physics

Date: December 13, 2022 - 1:00 PM

URL: https://pirsa.org/22120019

Abstract: Direct detection experiments search for dark matter through its potential interactions with the SM particles. However, light dark matter models with particle masses below the GeV scale are still largely unconstrained. As we will see in this talk, sensitivity to such small momentum transfer can benefit from quantum sensors, which employ fundamental quantum mechanical phenomena to notice energy depositions otherwise unreachable. Quantum sensors can considerably extend the range in dark matter mass of traditional WIMP experiments and be complementary to other direct detection methods. In the first part of the talk, I will examine a proposal to use atom interferometers to detect a light dark matter subcomponent at sub-GeV masses. DM scattering off of one "arm" of the atom interferometer can cause trackable decoherence and phase shifts. Two key factors render atom interferometers highly competitive experiments for very low masses: they are sensitive to extremely low momentum deposition and their coherent atoms give them a boost in sensitivity. On the second part of the talk, I will present a new proposal to search for axions with optomechanical cavities.  As we will see, the Bose-enhancement of a final state coherent population of photons or phonons can help overcoming the strong suppression from the axion to photon coupling. A unique advantage of this novel search, axioptomechanics, is that the cavity size need no longer be matched to the axion mass, which allows to probe a wide window of axion masses.

Zoom Link:  https://pitp.zoom.us/j/92645586400?pwd=bm1VUEVqUzNOOXV2VnhEUkJtdWZrZz09

Caltech

BURKE INSTITUTE

# Hunting for Light DM with Quantum Sensors

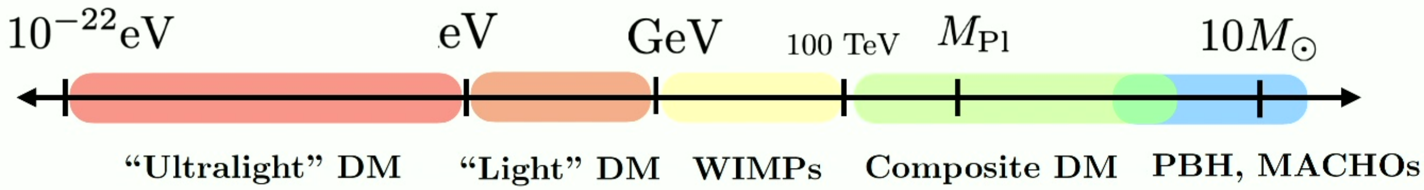
## Atom Interferometers & Optomechanical Cavities


Clara Murgui

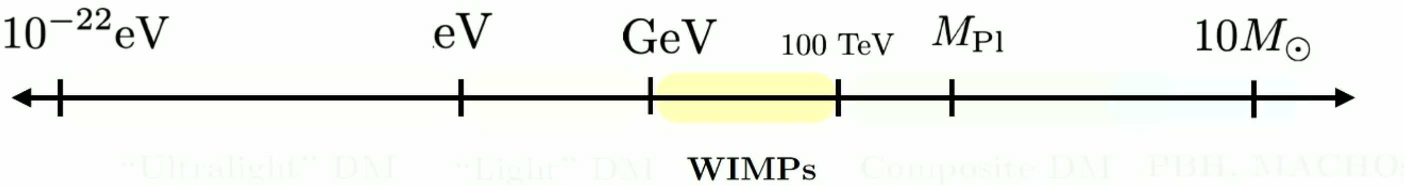
In collaboration with Yufeng Du, Kris Pardo, Yikun Wang, and Kathryn Zurek


Perimeter Institute
13 December 2022

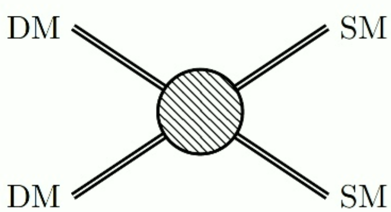
# Dark Matter: where to look?



# Dark Matter: where to look?



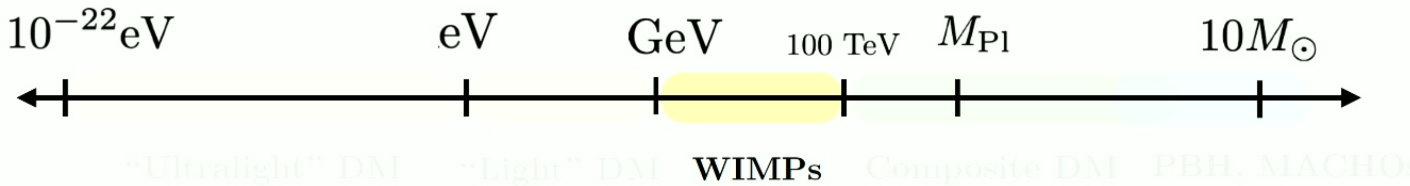

**The WIMP miracle**

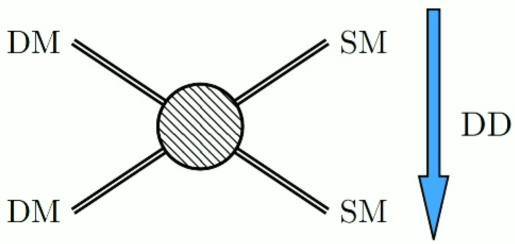



$$\langle \sigma v \rangle \sim \frac{G_F^2}{8\pi} m_\chi^2 \frac{c}{3} \sim 10^{-24} \mathrm{cm}^3/\mathrm{s} \left( \frac{m_\chi}{100 \ \mathrm{GeV}} \right)^2$$

$$\Omega_{\rm DM} \sim 0.1 \times \left( \frac{3 \times 10^{-26} \ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \right)$$

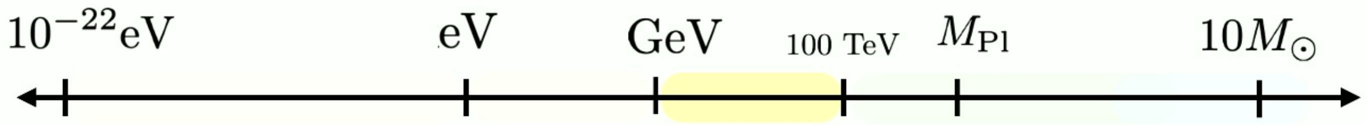
# Dark Matter: where to look?

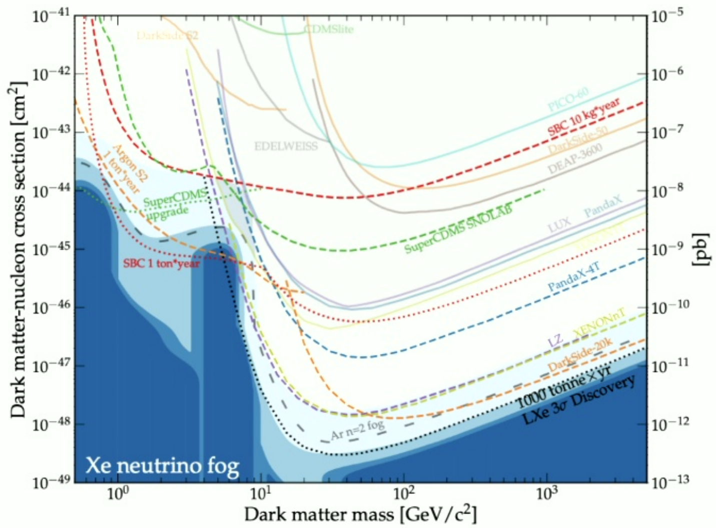



$$\sigma \sim 10^{-34}\text{cm}^2 \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2$$

# Dark Matter: where to look?

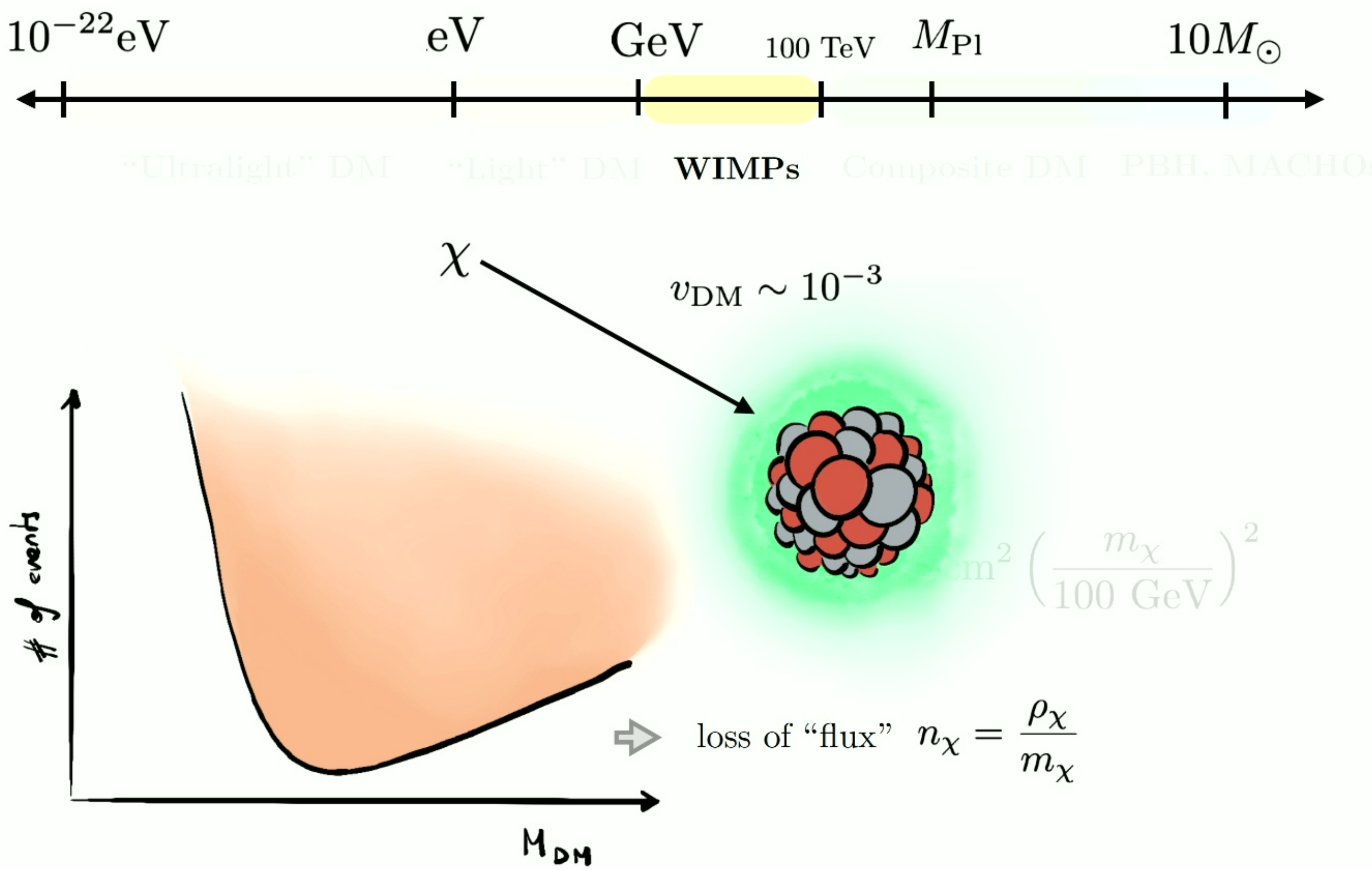


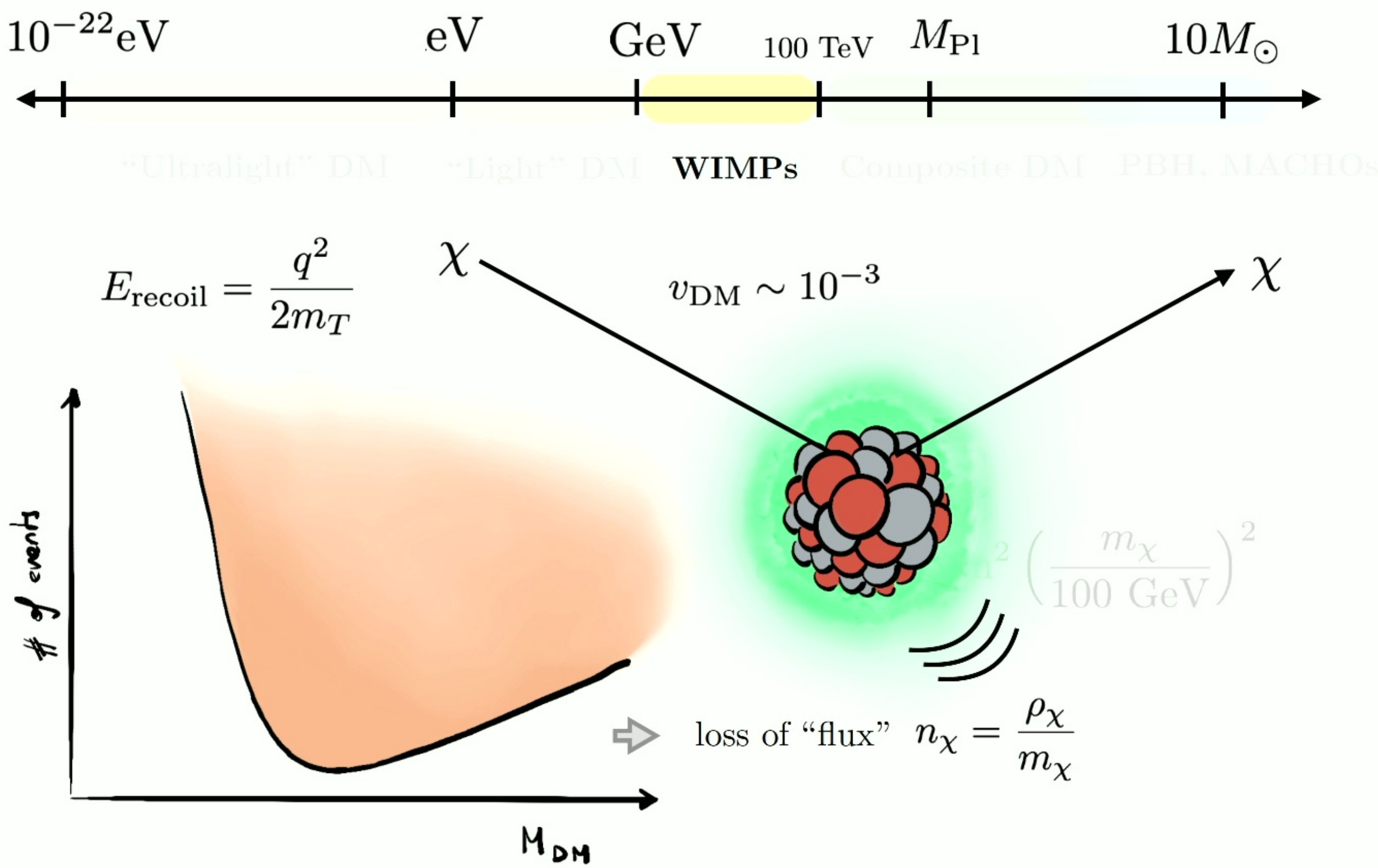

$$\sigma \sim 10^{-34}\text{cm}^2 \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2$$

[Akerib, D. S., et al., Snowmass2021, 2203.08084]

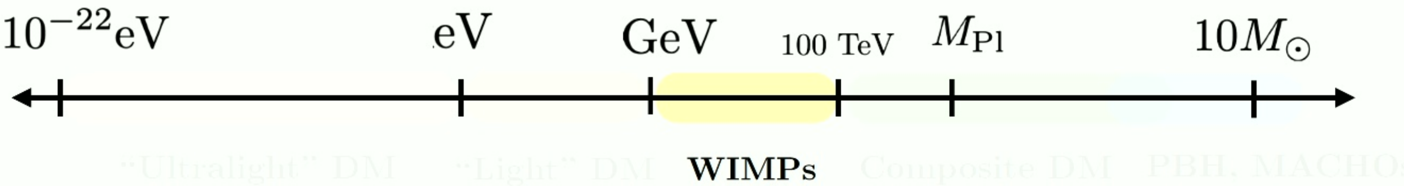
# Dark Matter: where to look?



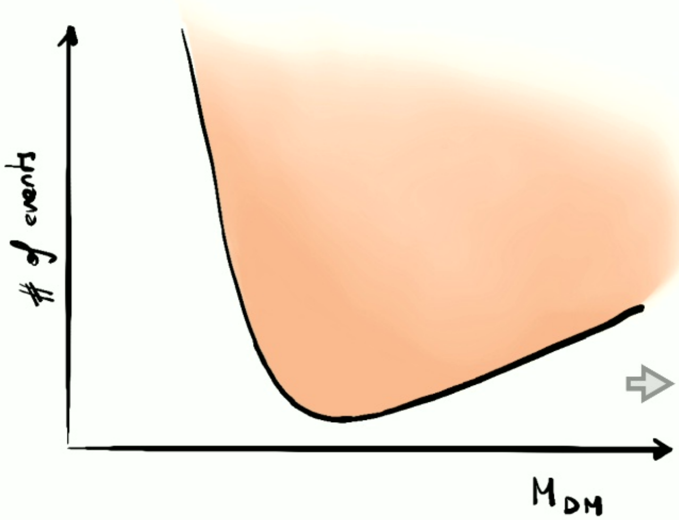
# Dark Matter: where to look?



# Dark Matter: where to look?



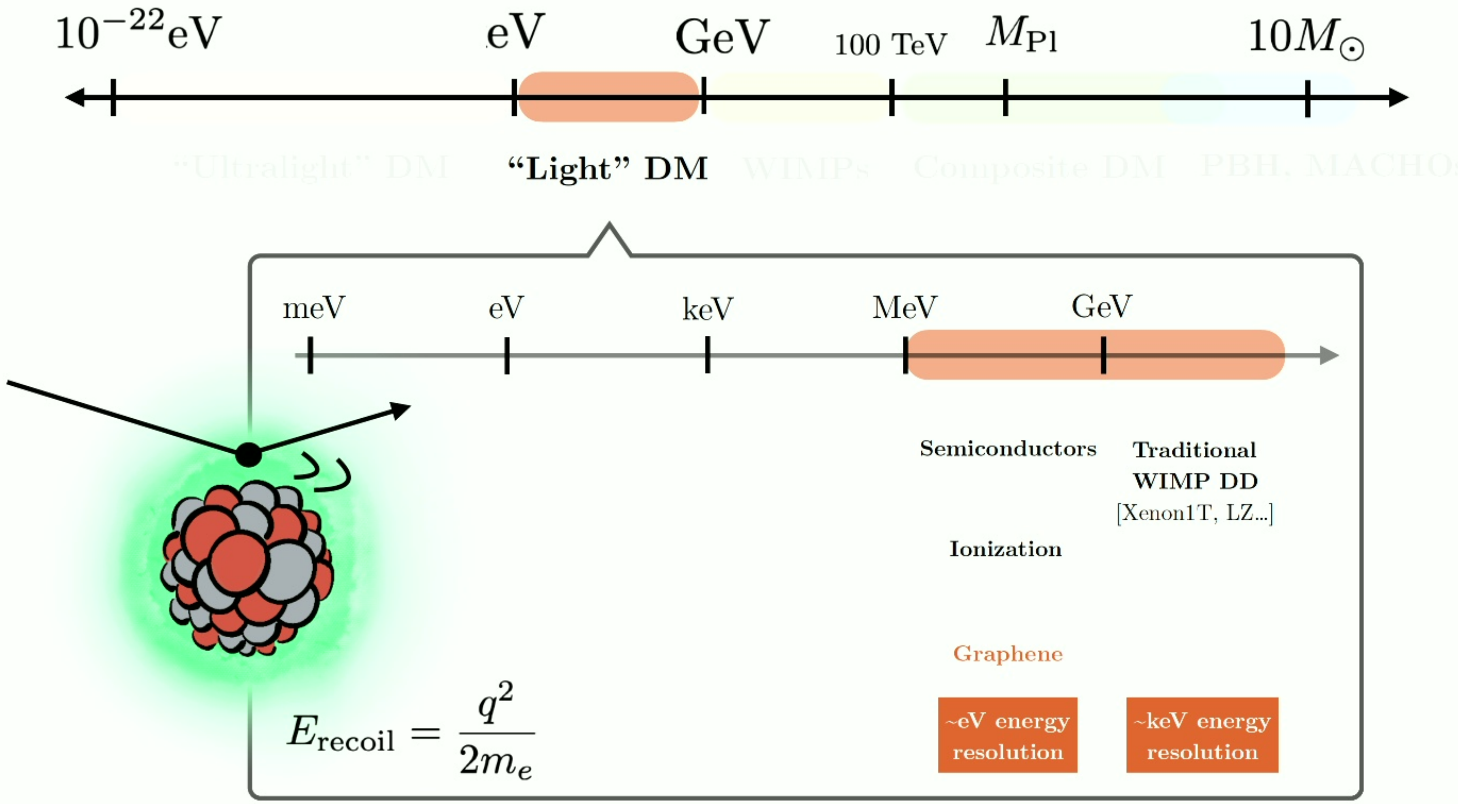

$E^{\rm max}_{\rm recoil} \sim \left(\frac{m_\chi}{\rm GeV}\right)$ keV




$\sigma \sim 10^{-34}{\rm cm}^2 \left(\frac{m_\chi}{100\ {\rm GeV}}\right)^2$

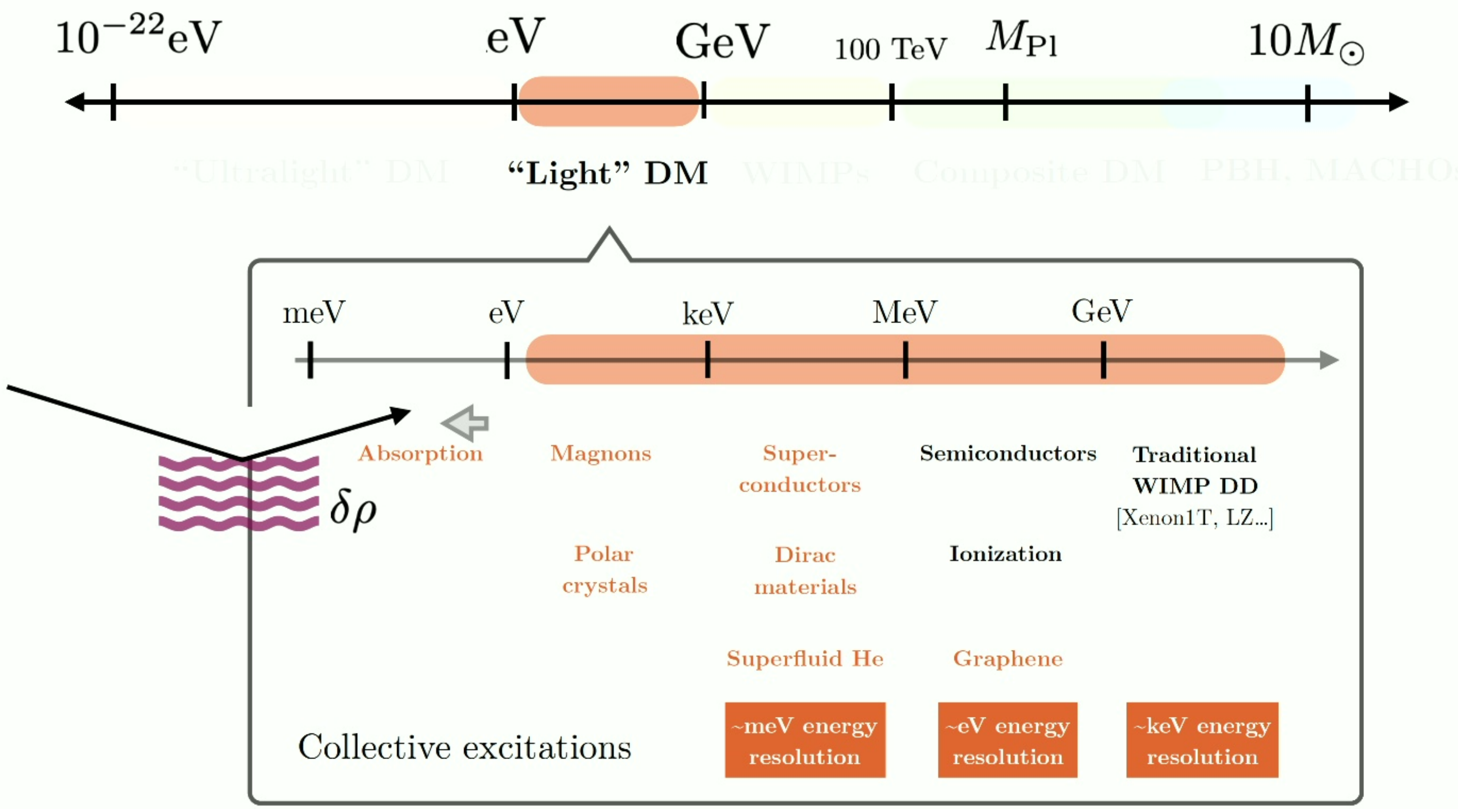
loss of "flux" $n_\chi = \frac{\rho_\chi}{m_\chi}$

# Dark Matter: where to look?



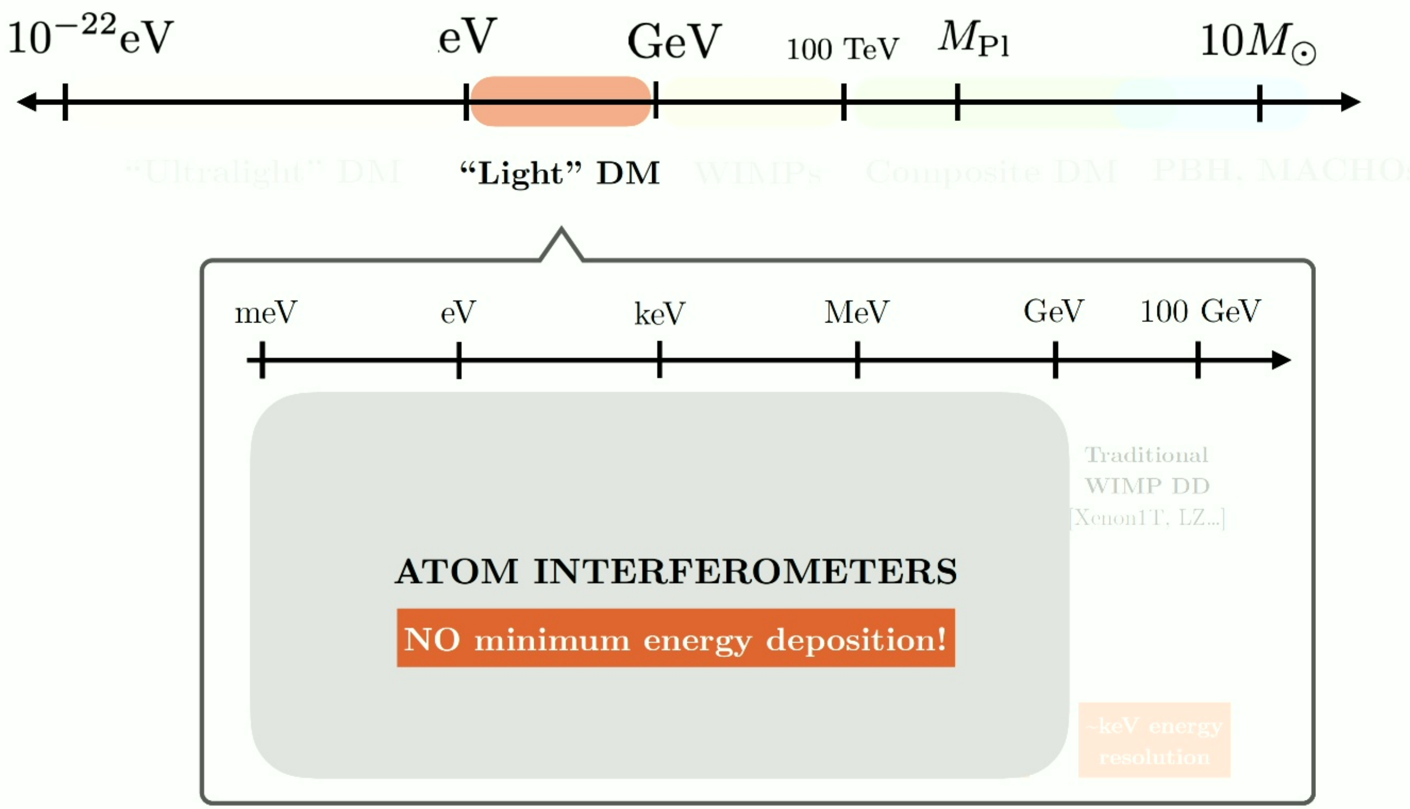

[adapted from K. Zurek's talks]

# Dark Matter: where to look?




[adapted from K. Zurek's talks]

# Dark Matter: where to look?



# **Atom Interferometer** tests of **Dark Matter**

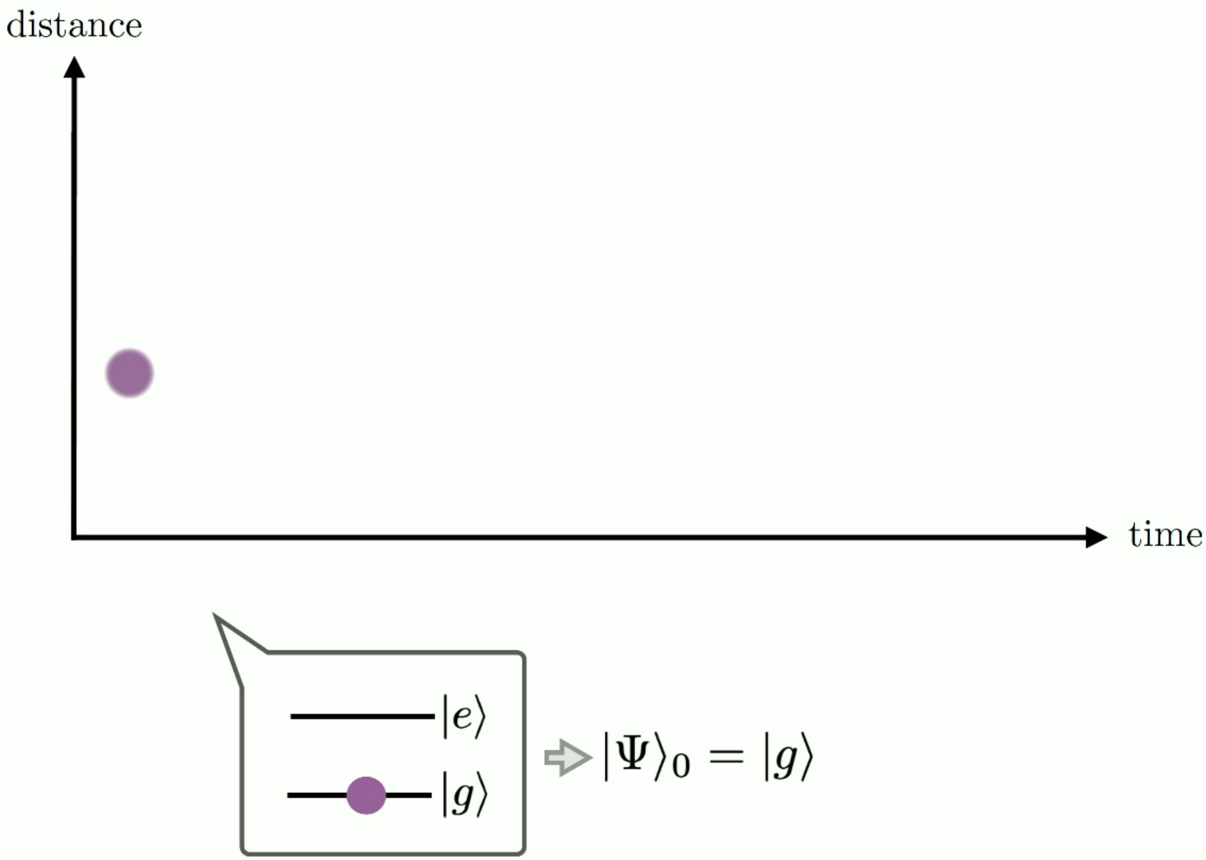
**2205.13546**

with Yufeng Du, Kris Pardo, Yikun Wang and Kathryn M. Zurek

[J. Riedel, 2013], [J. Riedel, I. Yavin, 2017]

# AIs: the Principle

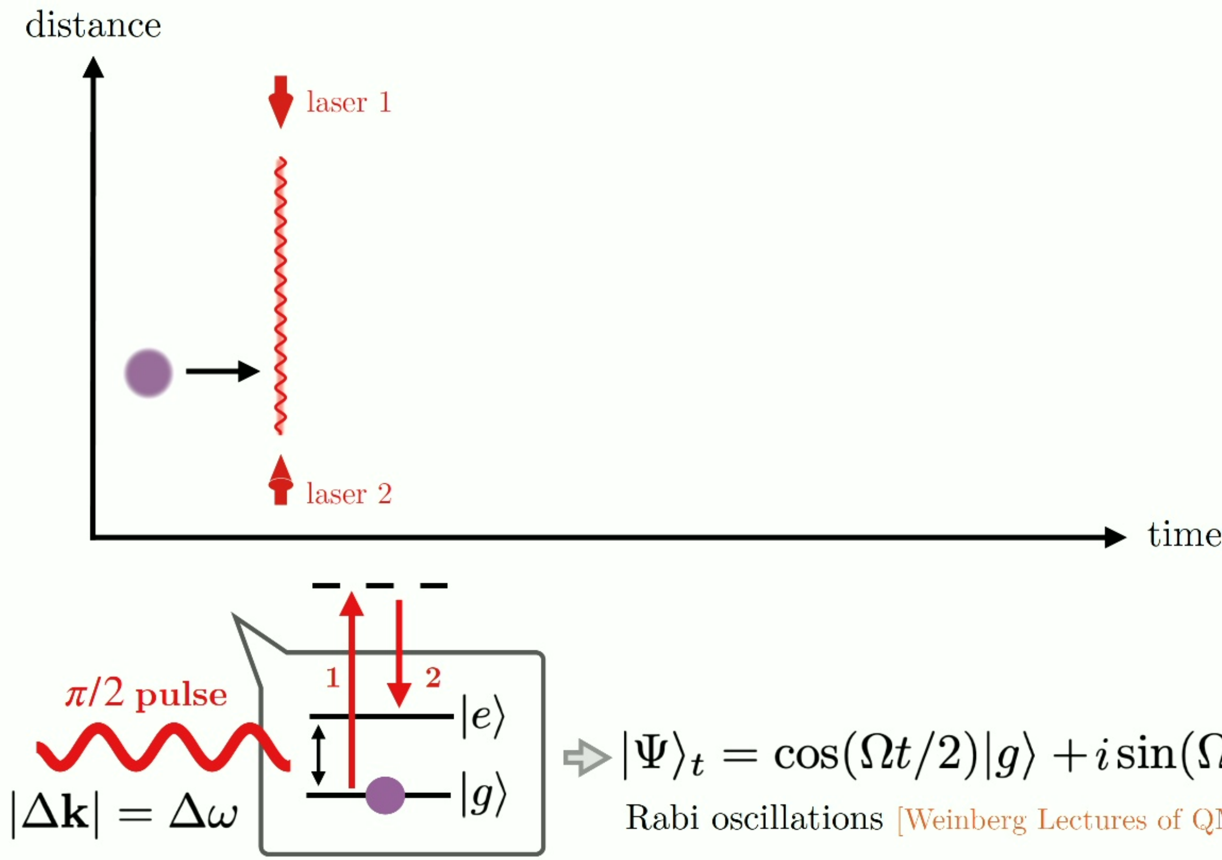
Review: arXiv:2003.12516




$$|\Psi\rangle_0 = |g\rangle$$

# AIs: the Principle

Review: arXiv:2003.12516

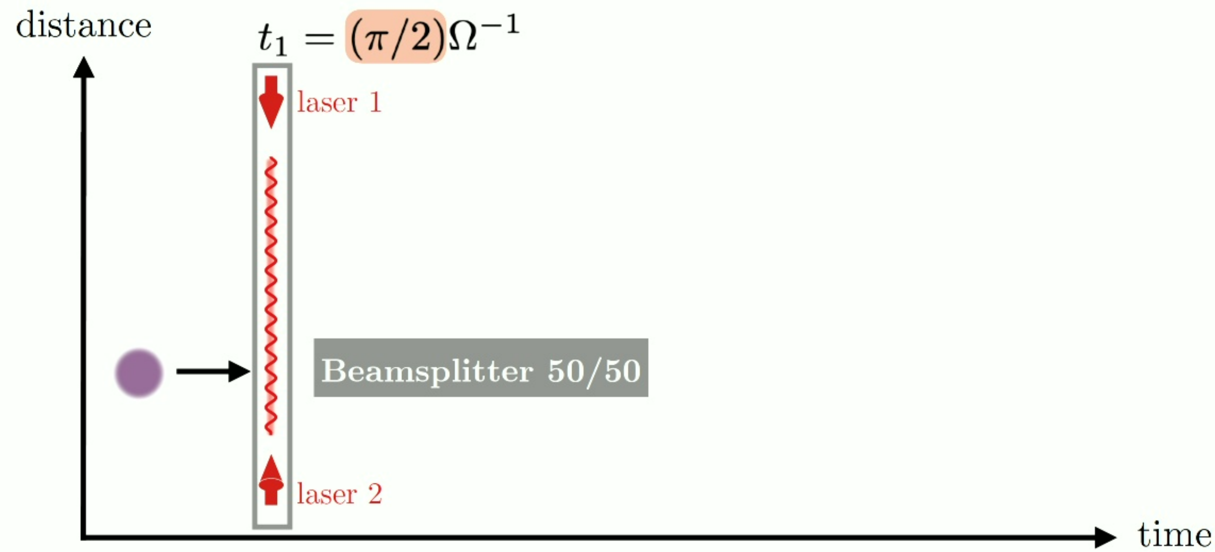


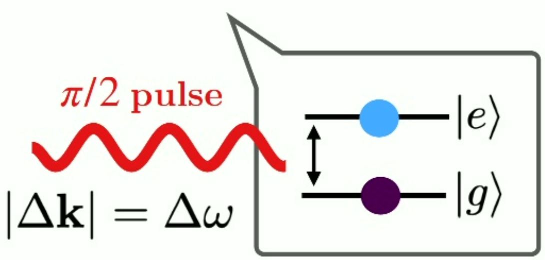

$$|\Psi\rangle_t = \cos(\Omega t/2)|g\rangle + i\sin(\Omega t/2)|e\rangle$$

Rabi oscillations [Weinberg Lectures of QM, Chap. 6]

# AIs: the Principle

Review: arXiv:2003.12516



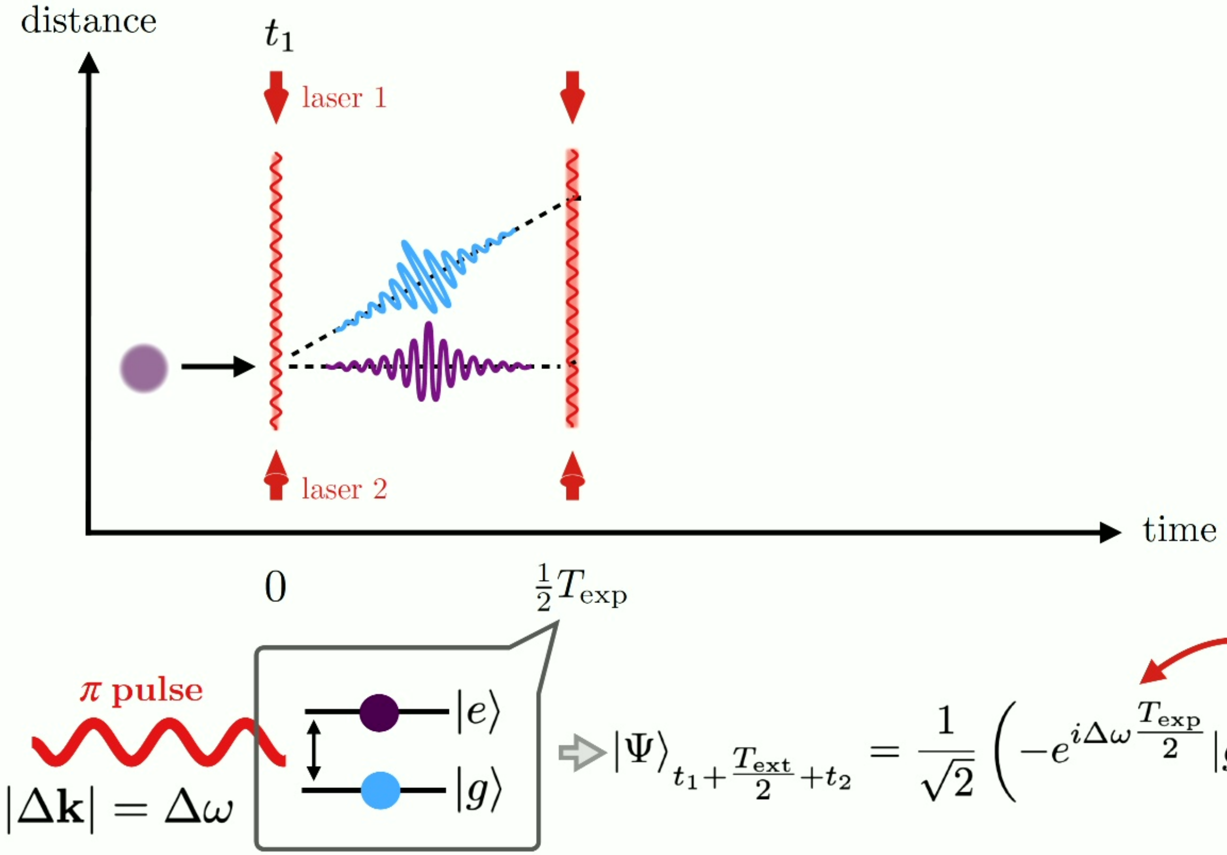




$$\Rightarrow |\Psi\rangle_{t_1} = \cos(\pi/4)|g\rangle + i\sin(\pi/4)|e\rangle$$

Rabi oscillations [Weinberg Lectures of QM, Chap. 6]

# AIs: the Principle

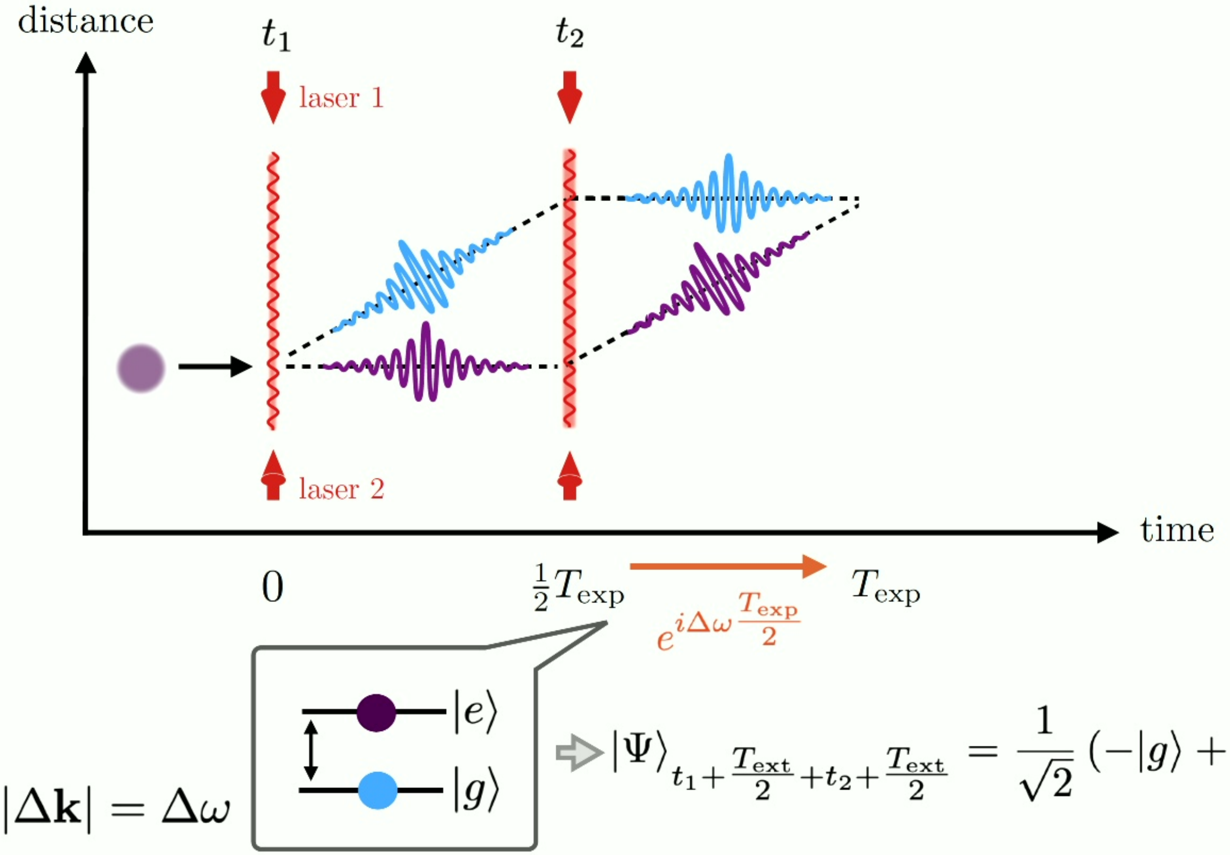
Review: arXiv:2003.12516




$$|\Psi\rangle_{t_1+\frac{T_{\rm ext}}{2}+t_2} = \frac{1}{\sqrt{2}}\left(-e^{i\Delta\omega\frac{T_{\rm exp}}{2}}|g\rangle + i|e\rangle\right)$$

# AIs: the Principle

Review: arXiv:2003.12516

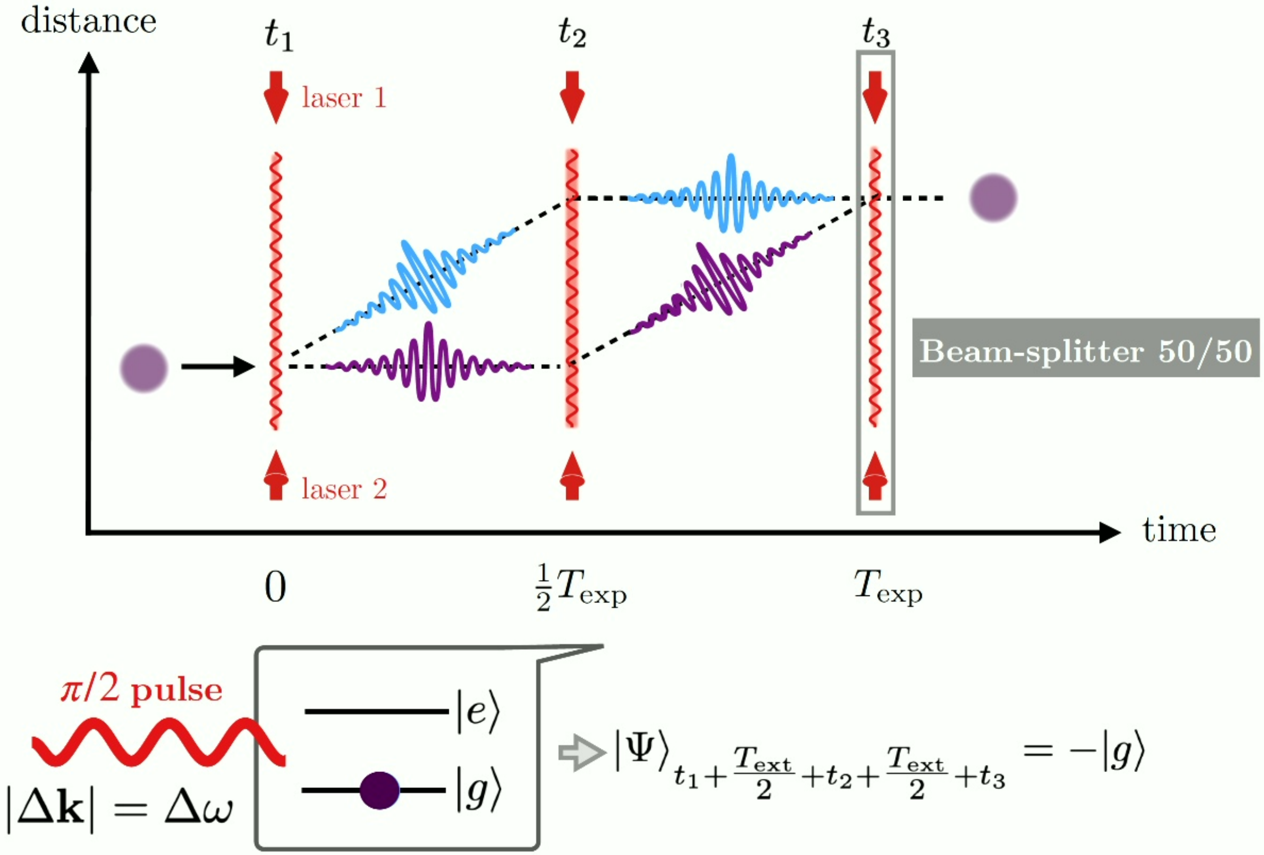



$$|\Delta\mathbf{k}| = \Delta\omega$$

$$|\Psi\rangle_{t_1+\frac{T_{\mathrm{ext}}}{2}+t_2+\frac{T_{\mathrm{ext}}}{2}} = \frac{1}{\sqrt{2}}\left(-|g\rangle + i|e\rangle\right)$$

# AIs: the Principle

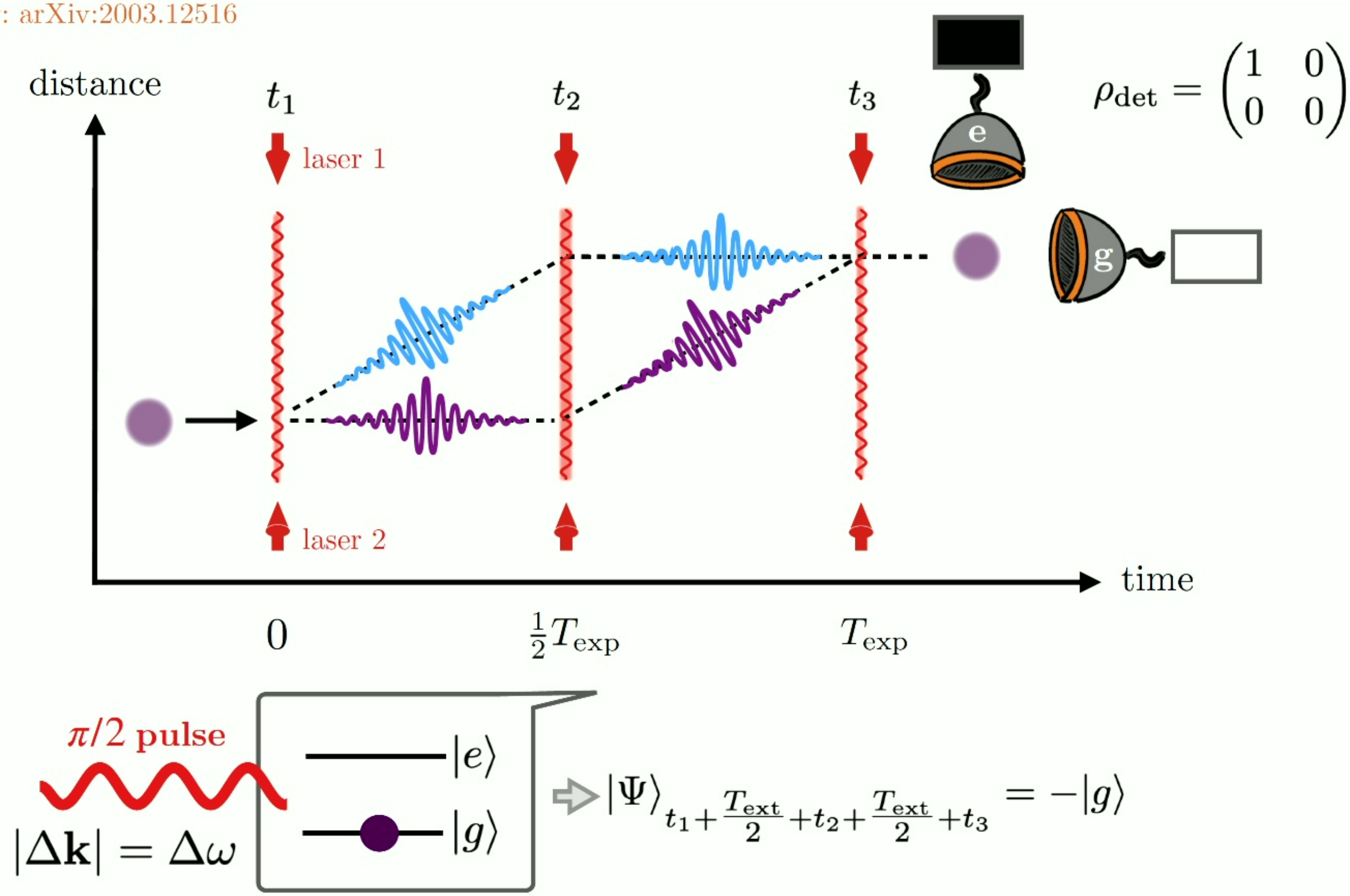
Review: arXiv:2003.12516




$$|\Psi\rangle_{t_1+\frac{T_{\text{ext}}}{2}+t_2+\frac{T_{\text{ext}}}{2}+t_3} = -|g\rangle$$

# AIs: the Principle

Review: arXiv:2003.12516




$$|\Psi\rangle_{t_1+\frac{T_{\rm ext}}{2}+t_2+\frac{T_{\rm ext}}{2}+t_3} = -|g\rangle$$

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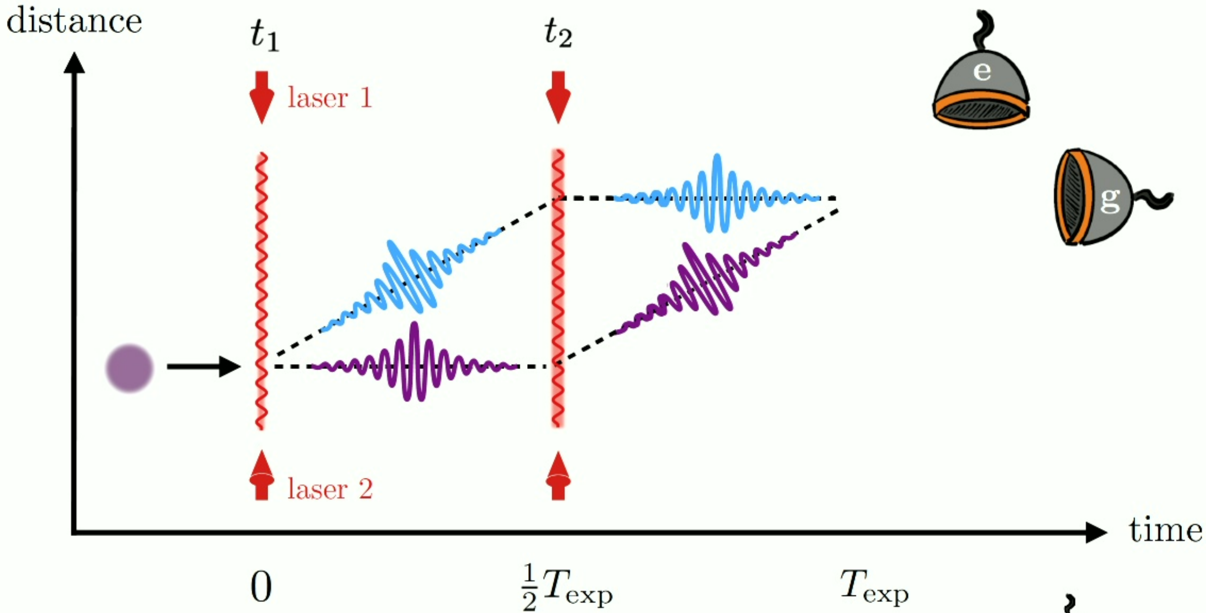
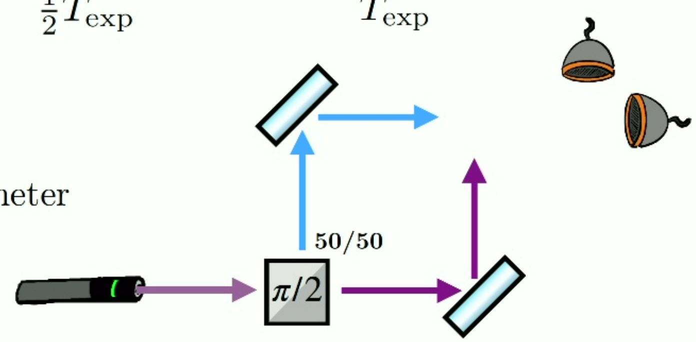
Review: arXiv:2003.12516



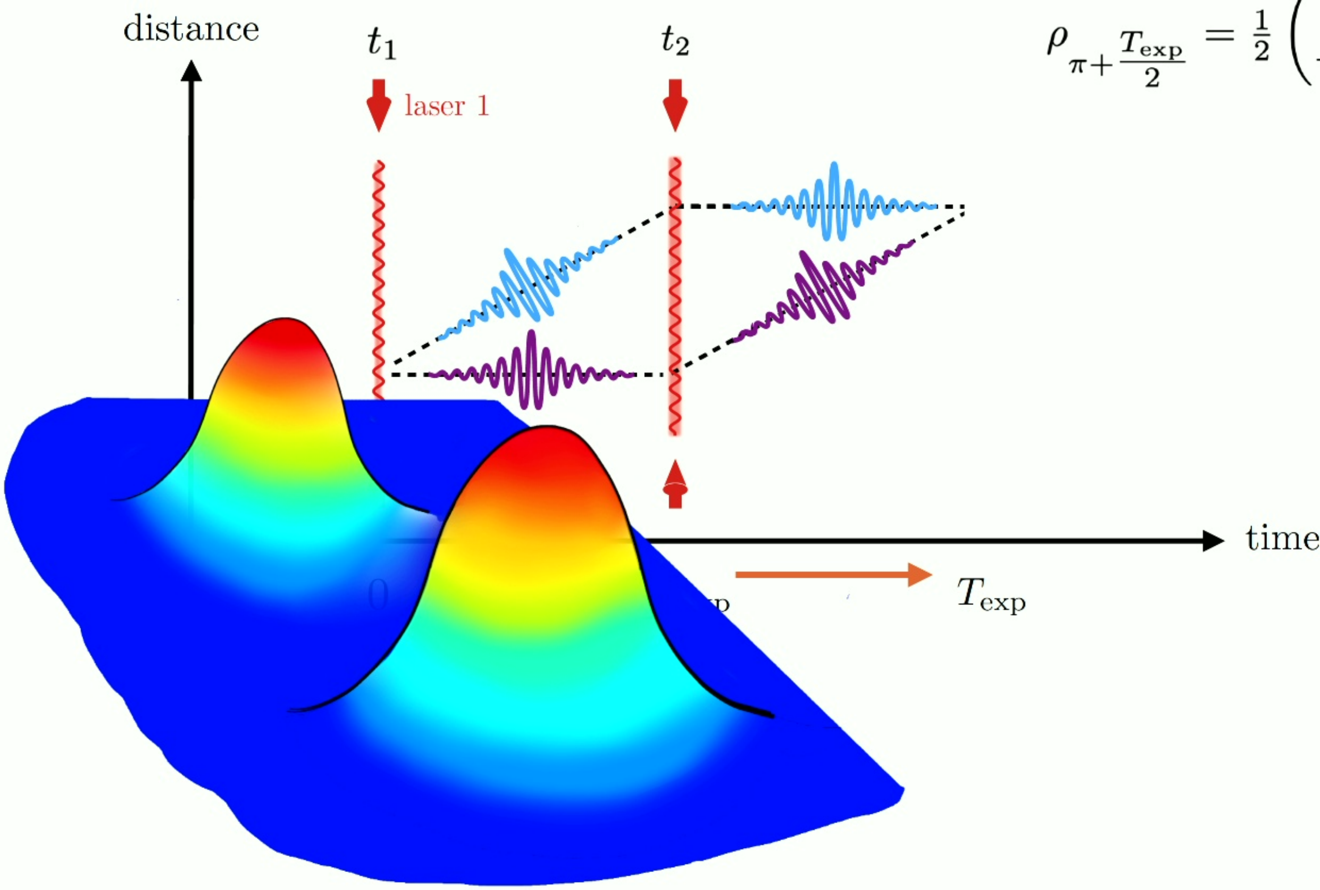

$\simeq$ Mach-Zender interferometer



# AIs: Decoherence

Review: arXiv:2003.12516

$$\rho_{\pi+\frac{T_{\mathrm{exp}}}{2}} = \frac{1}{2}\begin{pmatrix} 1 & i \\ -i & 1 \end{pmatrix}$$

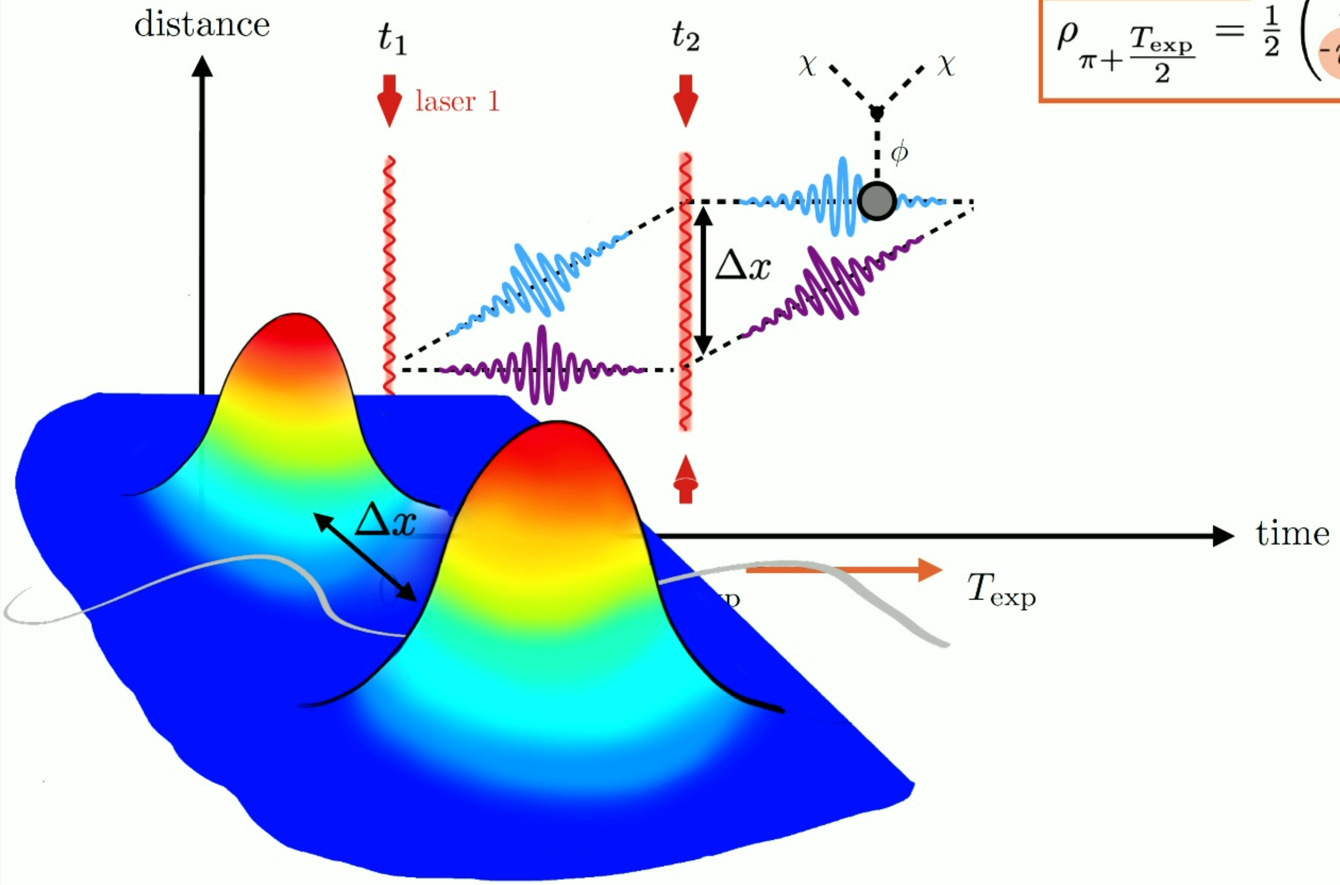


# AIs: Decoherence

Review: arXiv:2003.12516

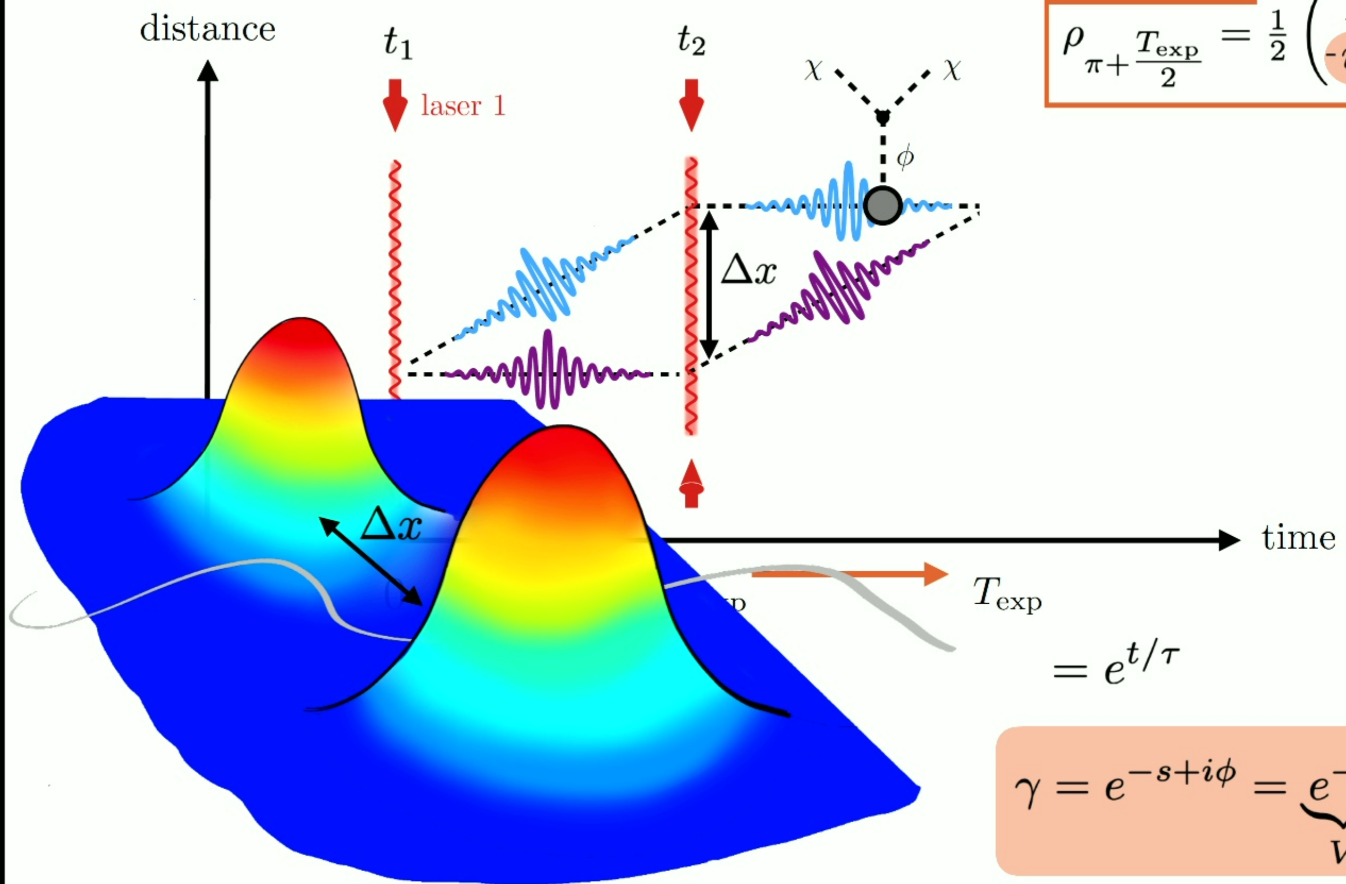
**open system**

$$\rho_{\pi+\frac{T_{\mathrm{exp}}}{2}} = \frac{1}{2}\begin{pmatrix} 1 & i\gamma \\ -i\gamma & 1 \end{pmatrix}$$



# AIs: Decoherence

Review: arXiv:2003.12516



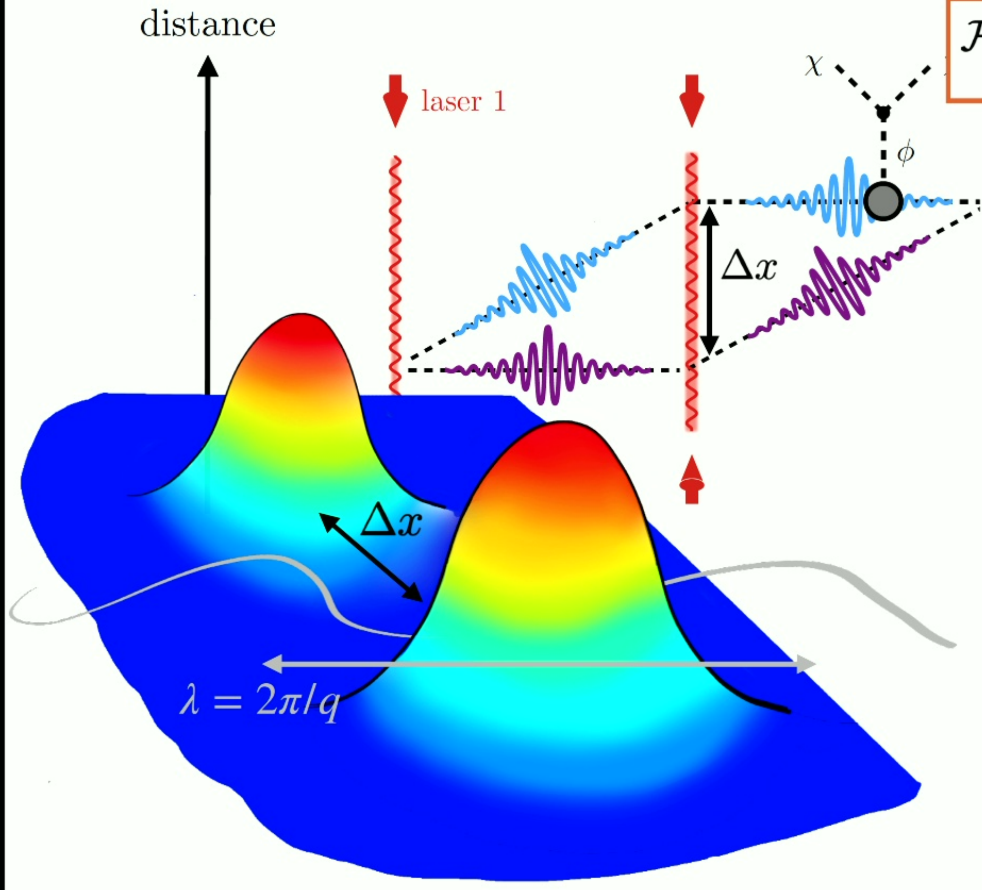

**open system**

$$\rho_{\pi+\frac{T_{\rm exp}}{2}} = \frac{1}{2}\begin{pmatrix} 1 & i\gamma \\ -i\gamma & 1 \end{pmatrix}$$

$= e^{t/\tau}$

$$\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}$$

# AIs: Decoherence




**Form Factor**

$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

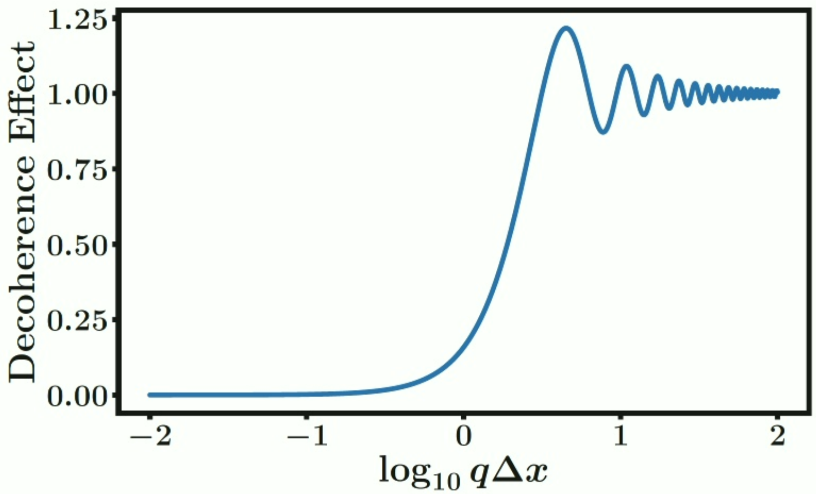
[Joss, Zeh, 1985]
[Hornberger, Sipe, 2003]

$$= e^{\left[-m_{\text{cloud}} \int_0^{t_{\text{exp}}} R\, dt\right]}$$

$$= e^{t/\tau}$$

$$\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}$$

# AIs: Decoherence



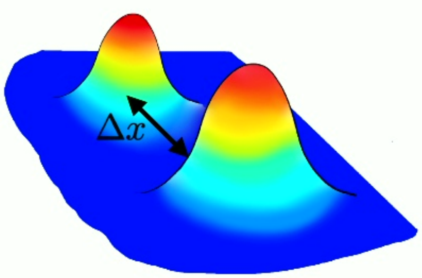

**Form Factor**

$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

Visibility or Contrast (**V**)

$$\frac{1}{2}\int_{-1}^{1} \text{Re}\{\mathcal{F}_{\text{decoh}}(\mathbf{q})\}\, d\cos\theta_{\mathbf{q\Delta x}}$$

$$= 1 - \frac{\sin(q\Delta x)}{q\Delta x}$$

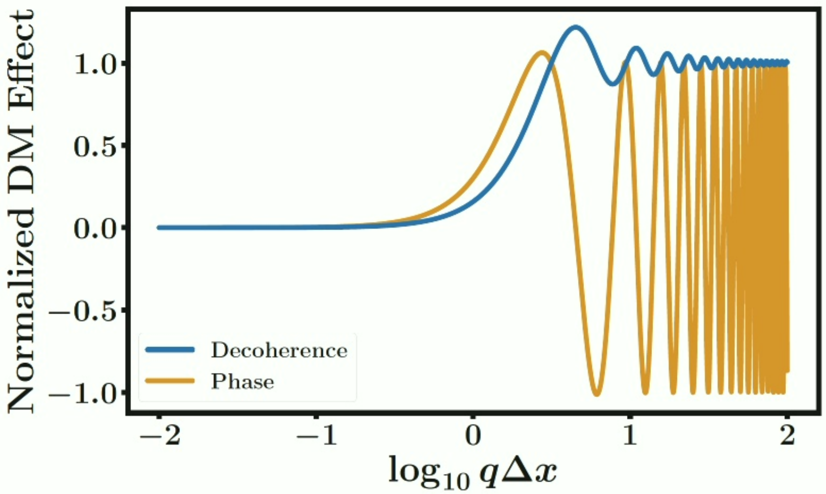



$$= e^{\left[-m_{\text{cloud}} \int_0^{t_{\text{exp}}} R\, dt\right]}$$

$$= e^{t/\tau}$$

$$\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}$$

# AIs: Decoherence



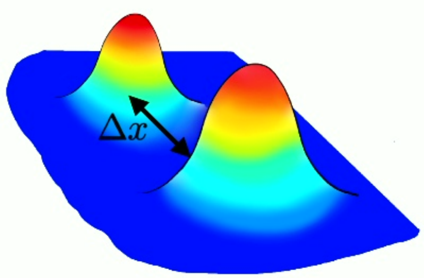

**Form Factor**

$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

Phase ($\phi$)

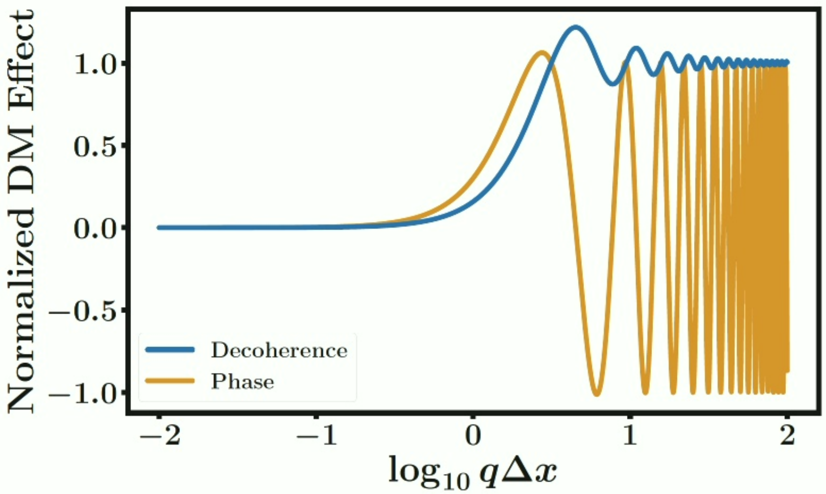
$$\frac{1}{2}\int_{-1}^{1} \mathrm{Im}\{\mathcal{F}_{\rm decoh}(\mathbf{q})\}\, d\cos\theta_{\mathbf{q\Delta x}}$$

$$= 0$$




$$\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}$$

# AIs: Decoherence




**Form Factor**

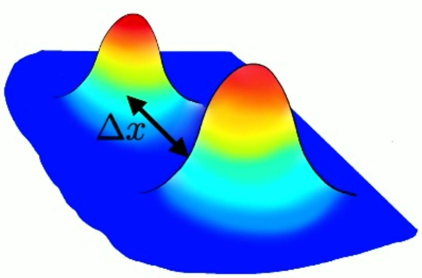
$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

Phase ($\phi$)

$$\frac{1}{2}\int_{-1}^{1} \mathrm{Im}\{\mathcal{F}_{\rm decoh}(\mathbf{q})\}\, d\cos\theta_{\mathbf{q}\mathbf{\Delta x}}$$

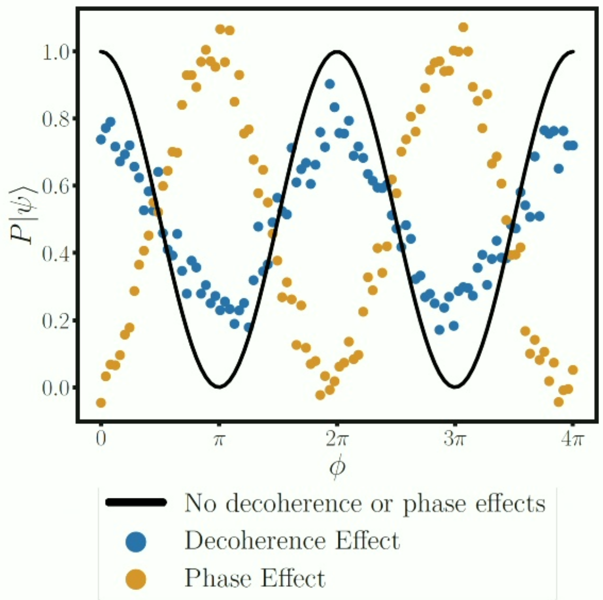
$$\lim_{q\ll\Delta x} \rightarrow \frac{q^2\Delta x\, v_e}{v_0^2 m_\chi}$$

**Crucial!**




$$\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}$$

# AIs: Measurement




**open system**

$$\rho_{\pi+\frac{T_{\exp}}{2}} = \frac{1}{2}\begin{pmatrix} 1 & i\gamma \\ -i\gamma^* & 1 \end{pmatrix}$$


Accumulated decoherence: **Rate**

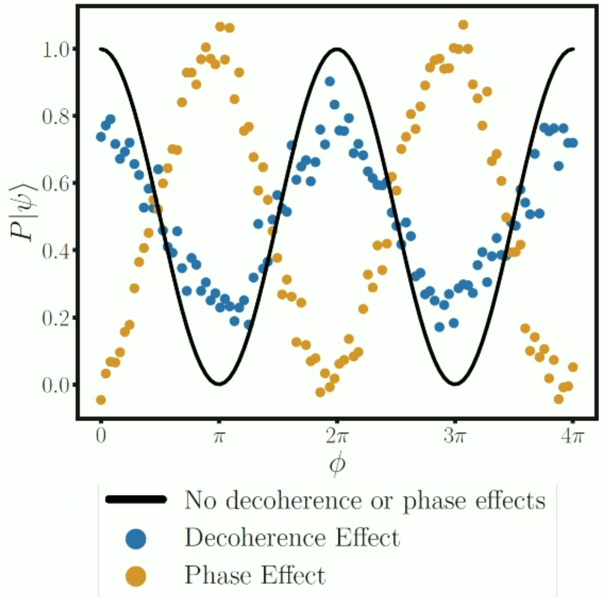
$$= e^{\left[-m_{\text{cloud}} \int_0^{t_{\exp}} R\, dt\right]}$$

$$= e^{t/\tau}$$

$$\mathcal{P}(|\Psi\rangle)_g = \frac{1}{2}(1 + \mathrm{Re}\{\gamma\})$$
$$= \frac{1}{2}(1 + e^{-s}\cos\phi)$$

$$\boxed{\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}}$$

# AIs: Statistics




**Visibility**

$$\mathrm{SNR} = \left| \frac{V - V_{\mathrm{bkg}}}{\sigma_V / \sqrt{N_{\mathrm{meas}}}} \right| > 1$$

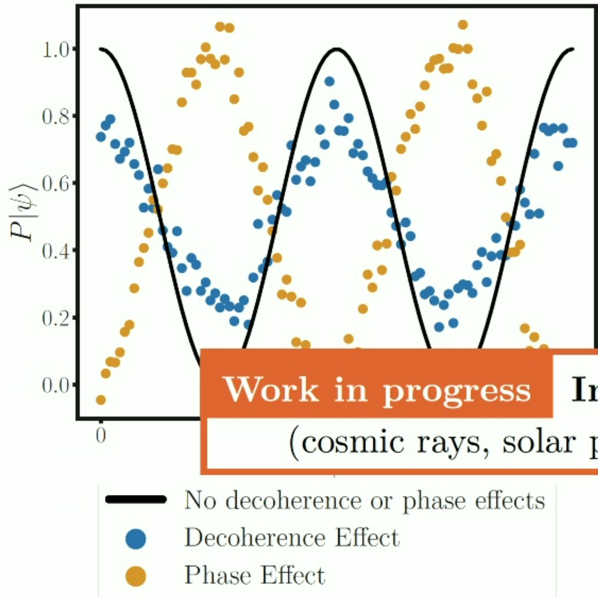
Accumulated decoherence: **Rate**

$$= e^{\left[-m_{\mathrm{cloud}} \int_0^{t_{\mathrm{exp}}} R\, dt\right]}$$

$$= e^{t/\tau}$$

$$\boxed{\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}}$$

# AIs: Statistics




[Kunjummen et al., 2022]

**Work in progress** **Impact of potential backgrounds**
(cosmic rays, solar photons, solar neutrinos, dust...)

**Visibility**

$$s_{\mathrm{DM}} > \frac{\sigma_V}{V_{\mathrm{bkg}}\sqrt{N_{\mathrm{meas}}}}$$

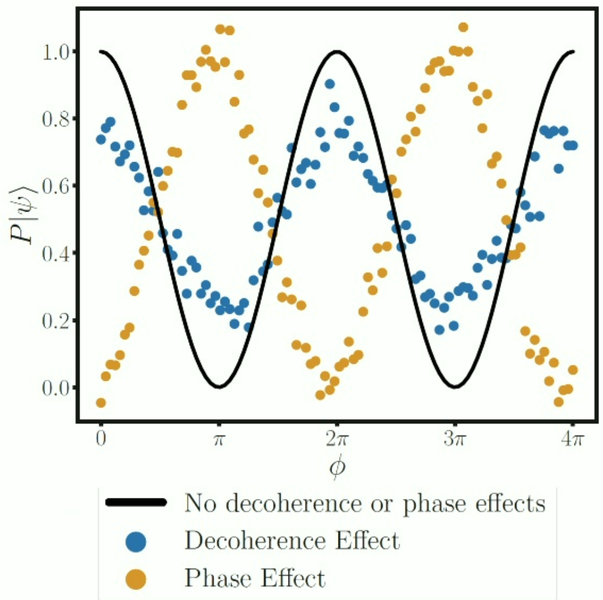
Accumulated decoherence: **Rate**

$$= e^{\left[-m_{\mathrm{cloud}} \int_0^{t_{\exp}} R\, dt\right]}$$

$$= e^{t/\tau}$$

$$\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}$$

# AIs: Statistics




**Phase**

$$\phi_{\min} = kx_{\min}$$
$$= \left(\frac{\Delta x}{t_{\exp}} m_A\right)\left(\tfrac{1}{2} a_{\min} t_{\exp}^2\right)$$

**Visibility**

$$s_{\mathrm{DM}} > \frac{\sigma_V}{V_{\mathrm{bkg}}\sqrt{N_{\mathrm{meas}}}}$$

Accumulated decoherence: **Rate**

$$= e^{\left[-m_{\mathrm{cloud}} \int_0^{t_{\exp}} R\, dt\right]}$$
$$= e^{t/\tau}$$

$$\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}$$

# AIs: the Rate

Number of events / (target mass · time)

$$R = \frac{n_\chi}{m_T} \int d^3\mathbf{v}\, f(\mathbf{v})\ \Gamma(\mathbf{v})\ \mathcal{F}_{\rm decoh}(\mathbf{q})$$

<u>Accumulated decoherence: **Rate**</u>

$$= e^{\left[-m_{\rm cloud} \int_0^{t_{\rm exp}} R\, dt\right]}$$

$$= e^{t/\tau}$$

$$\boxed{\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}}$$

# AIs: the Rate

$$f(\mathbf{v}) = \frac{1}{N_0} \exp\left(-\frac{(\mathbf{v}+\mathbf{v_e})^2}{v_0^2}\right) \Theta(v_{\rm esc} - ||\mathbf{v}+\mathbf{v_e}||)$$

$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

$$R = \boxed{\frac{n_\chi}{m_T}} \boxed{\int d^3\mathbf{v} f(\mathbf{v})} \boxed{\Gamma(\mathbf{v})} \boxed{\mathcal{F}_{\rm decoh}(\mathbf{q})}$$

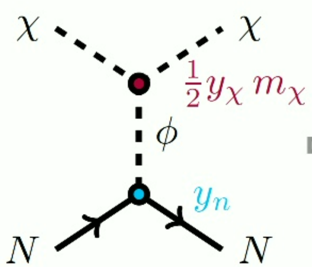
$$\frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}$$

$$\Gamma(\mathbf{v}) = V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \sum_f |\langle f|H_{\rm int}|i\rangle|^2 (2\pi)\delta(E_f - E_i - \omega_{\mathbf{q}})$$

# AIs: the Rate

$$\mathcal{F}_{\rm med}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{1}{V^2}\frac{\pi\bar{\sigma}}{\mu^2} \boxed{\mathcal{F}^2_{\rm med}(\mathbf{q})}\, \mathcal{F}^2_{\rm T}(\mathbf{q})\; g(\mathbf{q}, E_f - E_i)\mathcal{F}_{\rm decoh}(\mathbf{q})$$




$$\bar{\sigma} = \frac{y_\chi^2\, y_n^2}{4\pi}\frac{\mu^2}{(m_\chi^2 v_0^2 + m_\phi^2)^2}$$

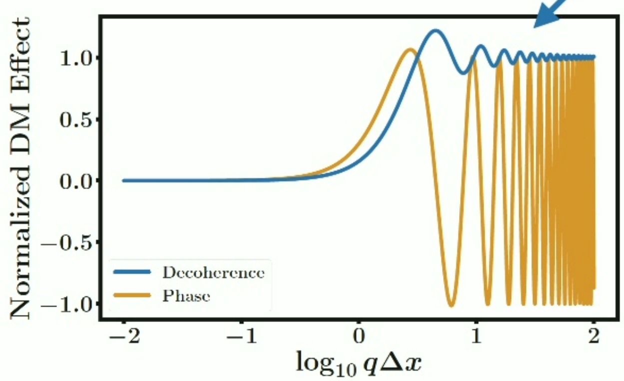
# AIs: the Rate

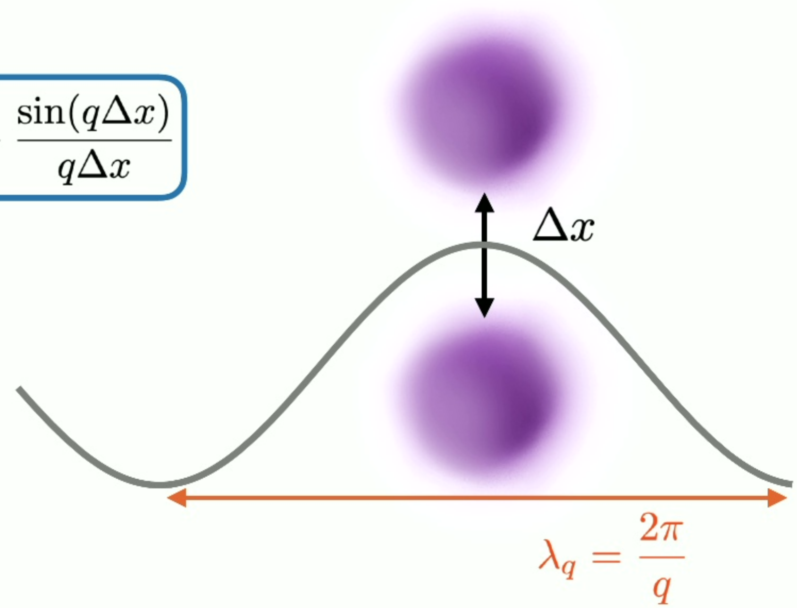
$$\mathcal{F}_{\mathrm{med}}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

$$\mathcal{F}_{\mathrm{decoh}}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{1}{V^2}\frac{\pi\bar{\sigma}}{\mu^2} \boxed{\mathcal{F}^2_{\mathrm{med}}(\mathbf{q})}\, \mathcal{F}^2_{\mathrm{T}}(\mathbf{q})\, g(\mathbf{q}, E_f - E_i) \boxed{\mathcal{F}_{\mathrm{decoh}}(\mathbf{q})}$$

$$\frac{1}{2}\int_{-1}^{1} \mathrm{Re}\{\mathcal{F}_{\mathrm{decoh}}(\mathbf{q})\}\, d\cos\theta_{\mathbf{q\Delta x}} = \boxed{1 - \frac{\sin(q\Delta x)}{q\Delta x}}$$



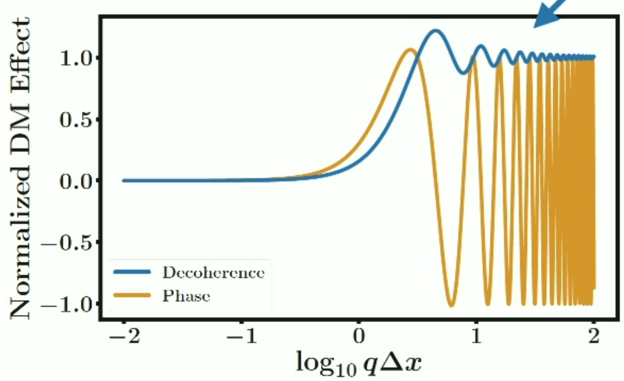
# AIs: the Rate

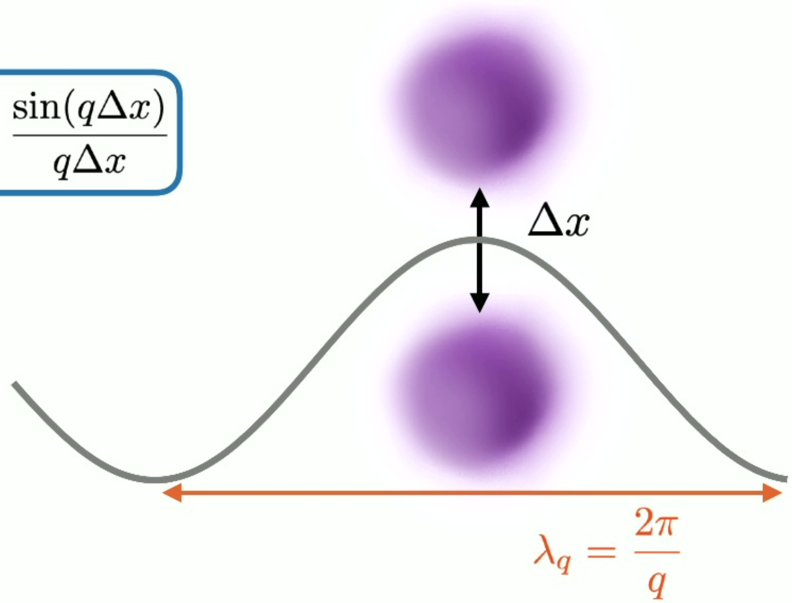
$$\mathcal{F}_{\rm med}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{1}{V^2}\frac{\pi\bar{\sigma}}{\mu^2} \boxed{\mathcal{F}^2_{\rm med}(\mathbf{q})}\, \mathcal{F}^2_{\rm T}(\mathbf{q})\, g(\mathbf{q}, E_f - E_i) \boxed{\mathcal{F}_{\rm decoh}(\mathbf{q})}$$

$$\frac{1}{2}\int_{-1}^{1} \mathrm{Re}\{\mathcal{F}_{\rm decoh}(\mathbf{q})\}\, d\cos\theta_{\mathbf{q\Delta x}} = \boxed{1 - \frac{\sin(q\Delta x)}{q\Delta x}}$$



# AIs: the Rate

$$\mathcal{F}_{\rm med}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

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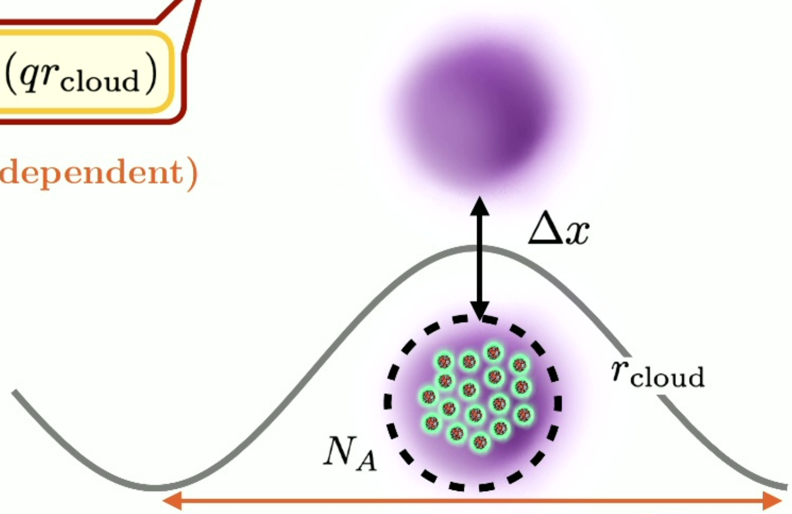
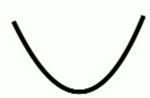
$$\mathcal{F}_T(\mathbf{q}) = N[1 + A(N_A - 1)\boxed{\mathcal{F}^2_{\rm cloud}(qr_{\rm cloud})}$$

Born (coherent) enhancement! **(spin-independent)**




[V. Bednyakov and D. V. Naumov, 2018]

$$\boxed{\mathcal{F}_{\rm cloud}(qr_{\rm cloud})} \begin{cases} \dfrac{3j_1(qr_{\rm cloud})}{qr_{\rm cloud}} \\[2ex] \exp\left(-\dfrac{(qr_{\rm BEC})^2}{2}\right) \end{cases}$$



$r_{\rm BEC} = 1/\sqrt{m_{\rm BEC}\,\omega_{\rm ho}}$

$\lambda_q = \dfrac{2\pi}{q}$

# AIs: the Rate

$$\mathcal{F}_{\rm med}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

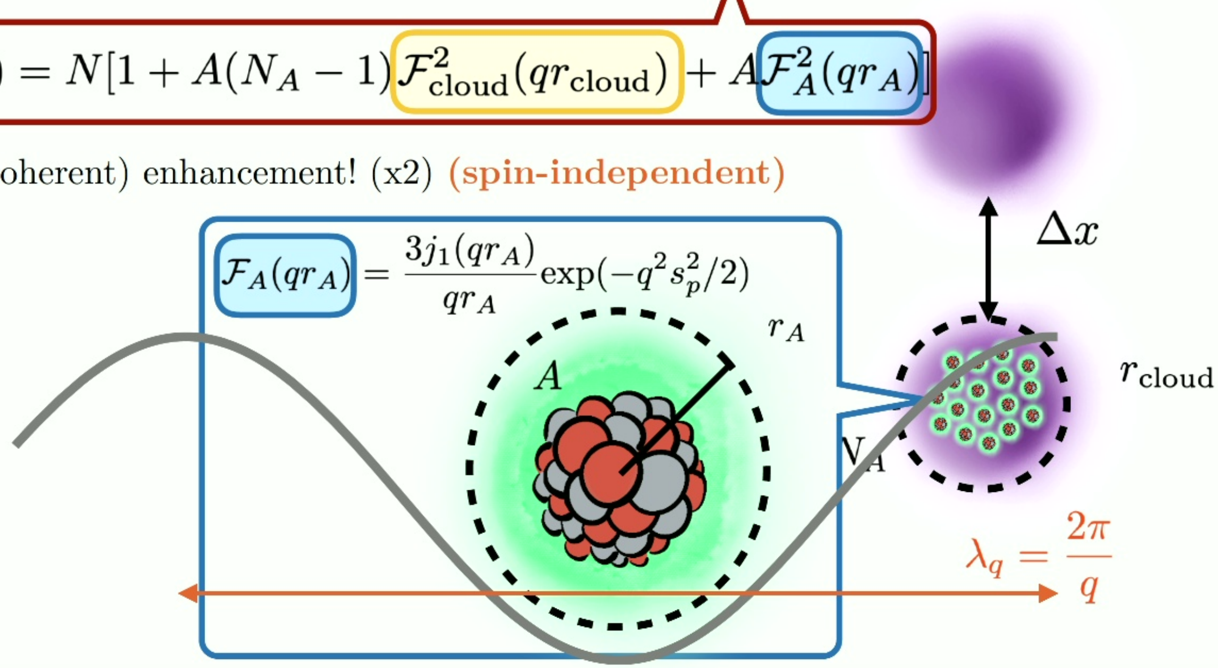
$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}V\int\frac{d^3\mathbf{q}}{(2\pi)^3}\frac{1}{V^2}\frac{\pi\bar{\sigma}}{\mu^2}\boxed{\mathcal{F}^2_{\rm med}(\mathbf{q})}\boxed{\mathcal{F}^2_{\rm T}(\mathbf{q})}\,g(\mathbf{q},E_f-E_i)\boxed{\mathcal{F}_{\rm decoh}(\mathbf{q})}$$

$$\mathcal{F}_T(\mathbf{q}) = N[1 + A(N_A-1)\boxed{\mathcal{F}^2_{\rm cloud}(qr_{\rm cloud})} + A\boxed{\mathcal{F}^2_A(qr_A)}]$$

Born (coherent) enhancement! (x2) **(spin-independent)**

$$\boxed{\mathcal{F}_A(qr_A)} = \frac{3j_1(qr_A)}{qr_A}\exp(-q^2s_p^2/2)$$



# AIs: the Rate

$$\mathcal{F}_{\text{med}}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

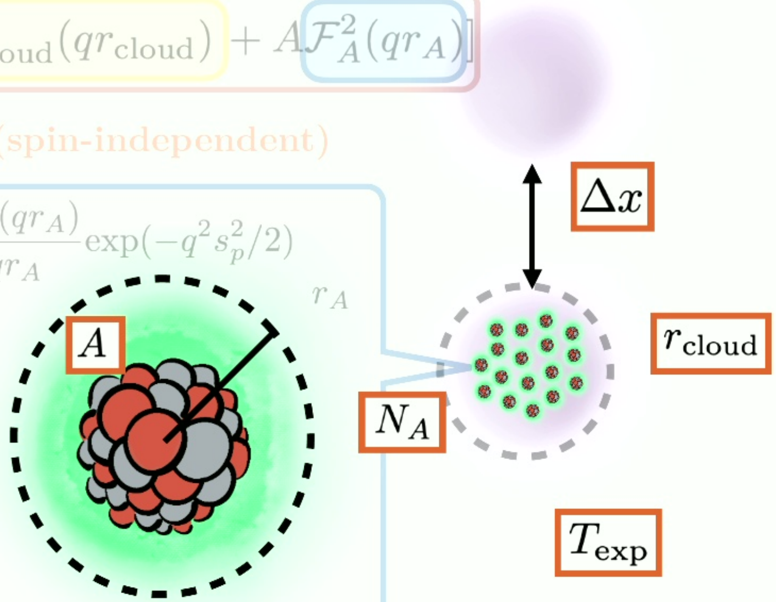
$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = 1 - \exp(i\mathbf{q} \cdot \mathbf{\Delta x})$$

$$R = \frac{1}{\rho_T} \frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{1}{V^2} \frac{\pi \bar{\sigma}}{\mu^2} \mathcal{F}^2_{\text{med}}(\mathbf{q}) \mathcal{F}^2_{\text{T}}(\mathbf{q})\, g(\mathbf{q}, E_f - E_i) \mathcal{F}_{\text{decoh}}(\mathbf{q})$$

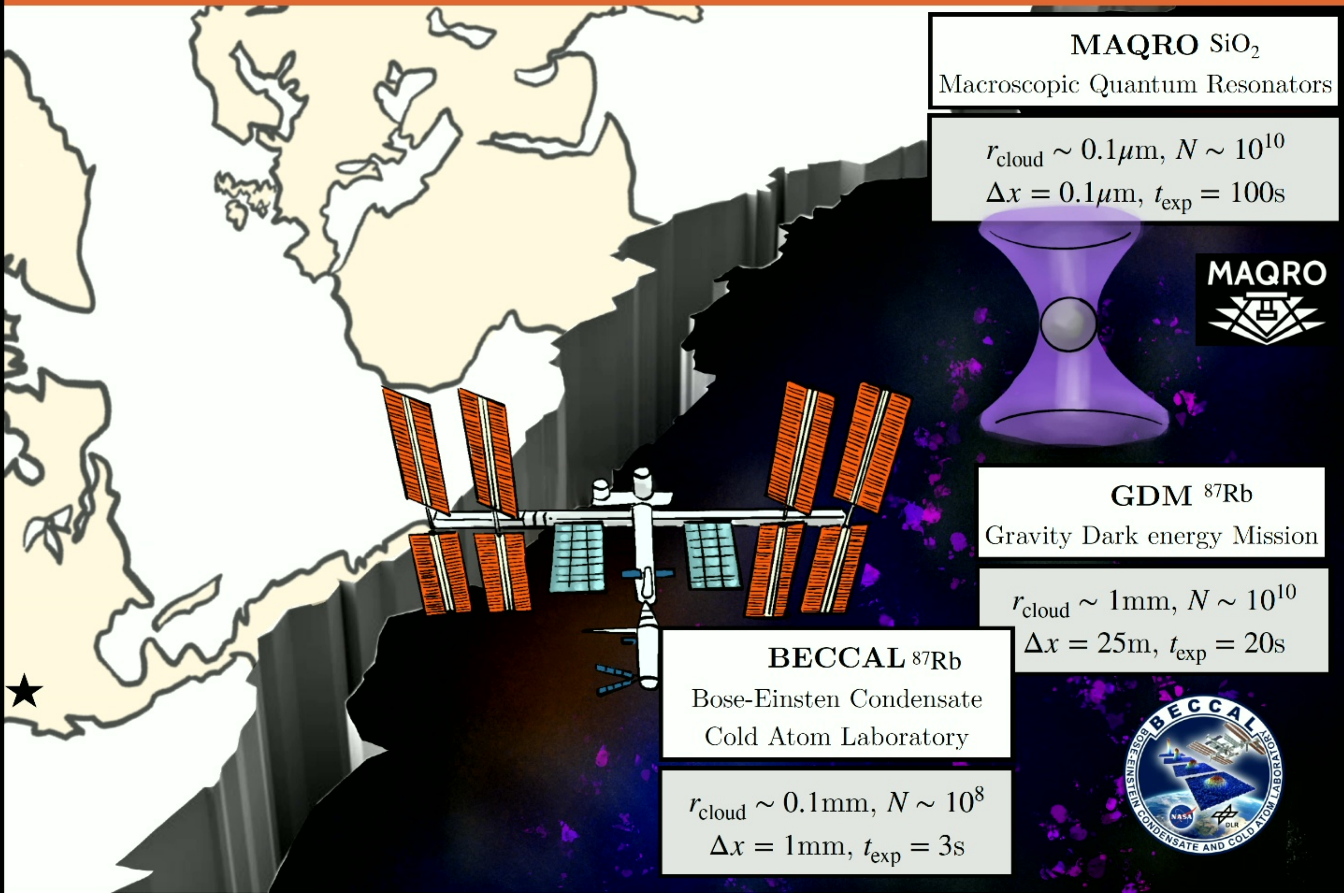
$$\mathcal{F}_T(\mathbf{q}) = N[1 + A(N_A - 1)\mathcal{F}^2_{\text{cloud}}(q r_{\text{cloud}}) + A \mathcal{F}^2_A(q r_A)]$$

Born (coherent) enhancement! (x2) (spin-independent)

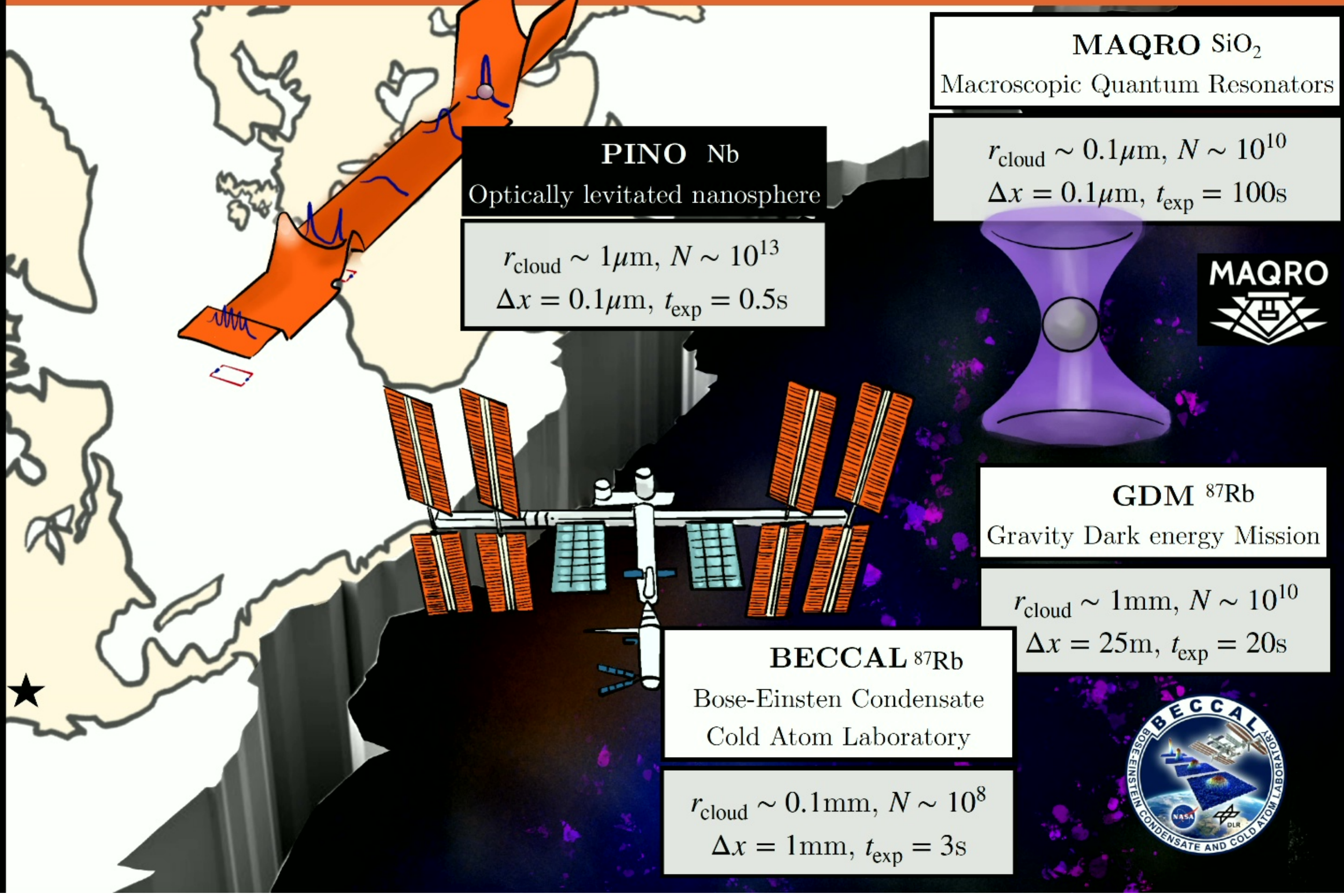
$$\mathcal{F}_A(q r_A) = \frac{3 j_1(q r_A)}{q r_A} \exp(-q^2 s_p^2/2)$$



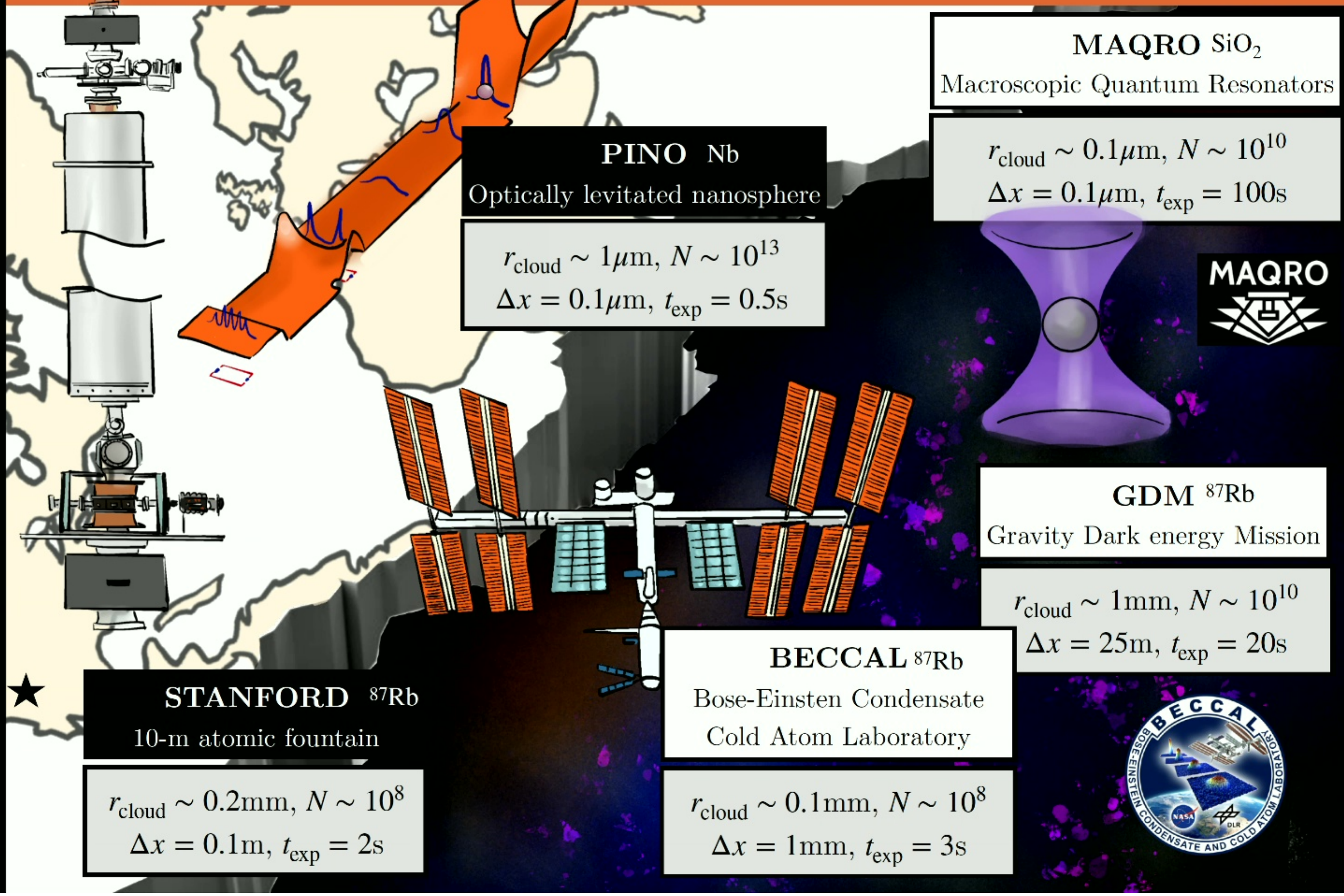
# AIs: Examples



# AIs: Examples



# AIs: Examples




**MAQRO** $SiO_2$
Macroscopic Quantum Resonators

$r_{\rm cloud} \sim 0.1\mu{\rm m}$, $N \sim 10^{10}$
$\Delta x = 0.1\mu{\rm m}$, $t_{\rm exp} = 100{\rm s}$

**PINO** Nb
Optically levitated nanosphere

$r_{\rm cloud} \sim 1\mu{\rm m}$, $N \sim 10^{13}$
$\Delta x = 0.1\mu{\rm m}$, $t_{\rm exp} = 0.5{\rm s}$

**GDM** $^{87}$Rb
Gravity Dark energy Mission

$r_{\rm cloud} \sim 1{\rm mm}$, $N \sim 10^{10}$
$\Delta x = 25{\rm m}$, $t_{\rm exp} = 20{\rm s}$

★ **STANFORD** $^{87}$Rb
10-m atomic fountain

$r_{\rm cloud} \sim 0.2{\rm mm}$, $N \sim 10^{8}$
$\Delta x = 0.1{\rm m}$, $t_{\rm exp} = 2{\rm s}$

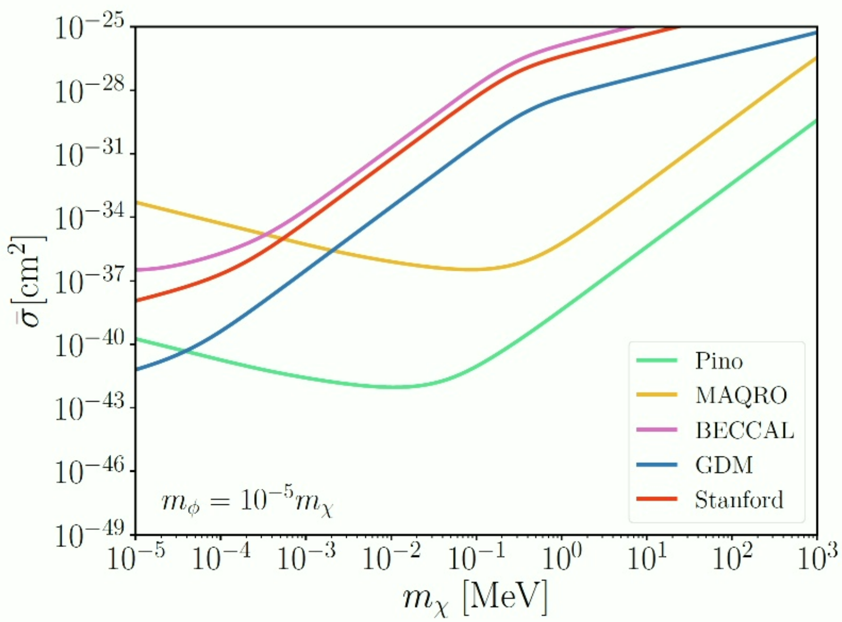
**BECCAL** $^{87}$Rb
Bose-Einsten Condensate
Cold Atom Laboratory

$r_{\rm cloud} \sim 0.1{\rm mm}$, $N \sim 10^{8}$
$\Delta x = 1{\rm mm}$, $t_{\rm exp} = 3{\rm s}$

# AIs: Results

$$s \propto \frac{\bar{\sigma}((m_\chi v_0)^2 + m_\phi^2)^2}{m_\chi^3} \int dq \, \frac{q}{(q^2+m_\phi^2)^2} N(1+NF^2(qr_{\text{cloud}}))\left(1 - \frac{\sin(q\Delta x)}{q\Delta x}\right)$$

**1** $m_\chi \to 0 \quad \Rightarrow \quad q \to 0$

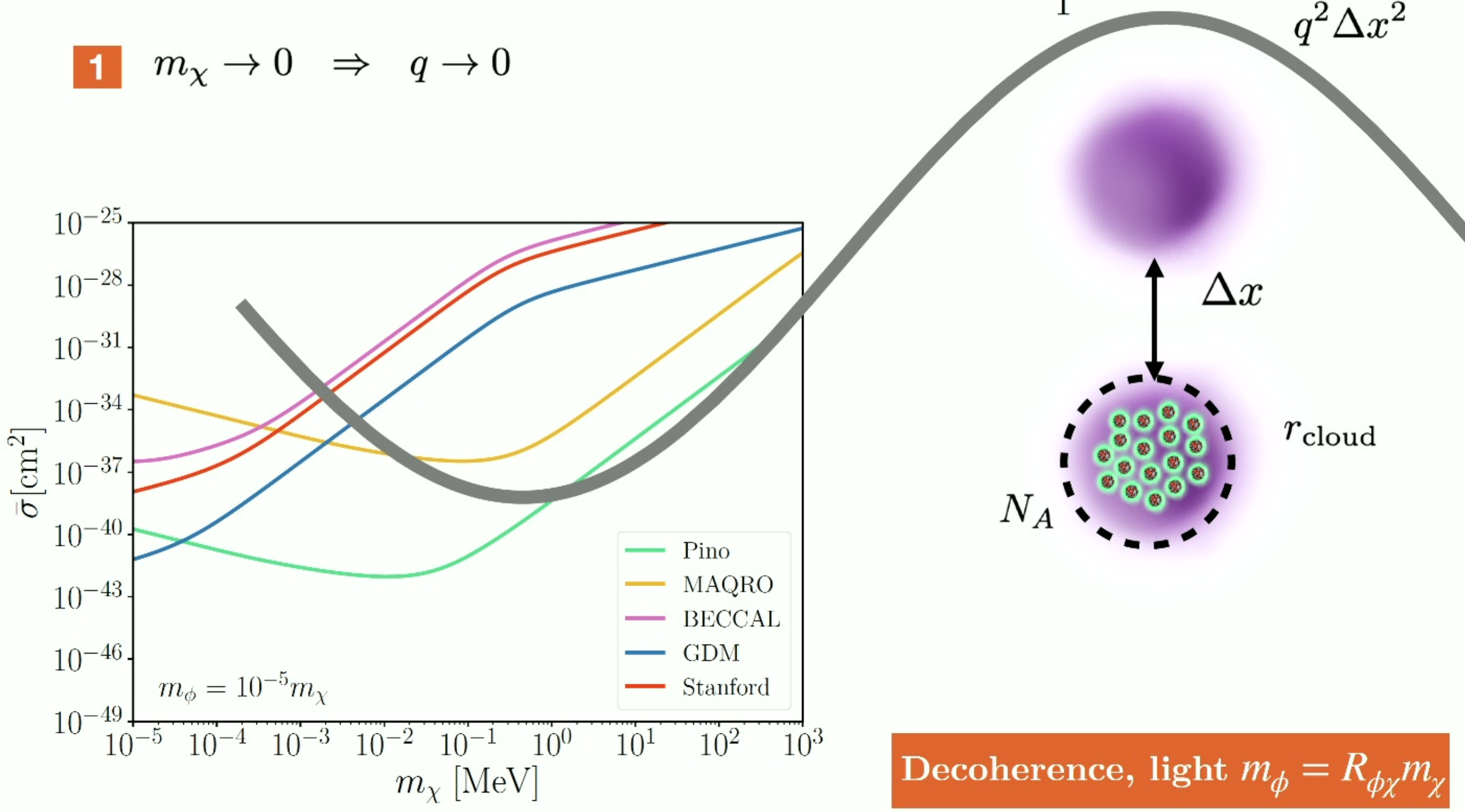



**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

$$s \propto \frac{\bar{\sigma}((m_\chi v_0)^2 + \cancel{m_\phi^2})^2}{m_\chi^3} \int dq \, \frac{q}{(q^2 + \cancel{m_\phi^2})^2} N(1 + N \underbrace{F^2(q r_{\rm cloud})}_{1}) \Big( \underbrace{1 - \frac{\sin(q\Delta x)}{q\Delta x}}_{q^2\Delta x^2} \Big)$$

$\boxed{1}$ $m_\chi \to 0 \;\; \Rightarrow \;\; q \to 0$



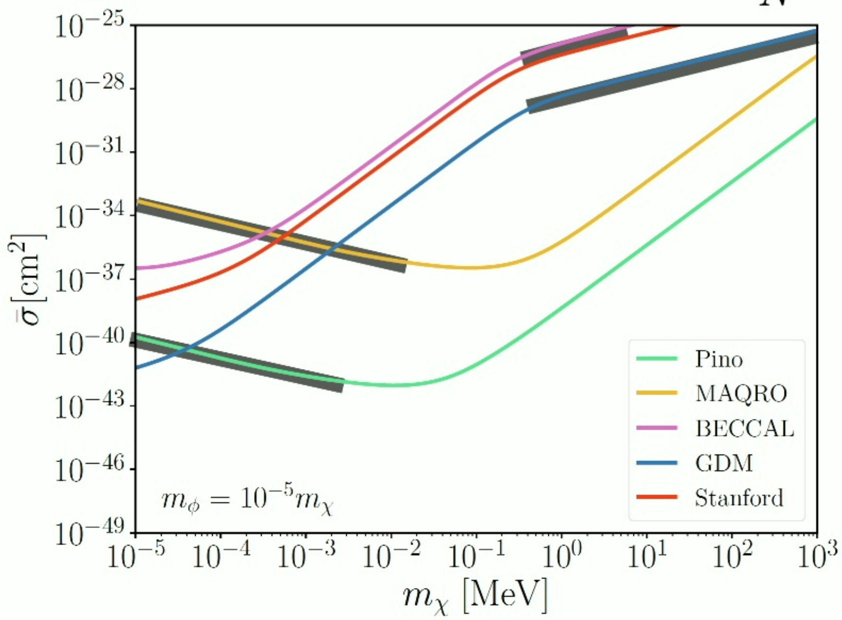

**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

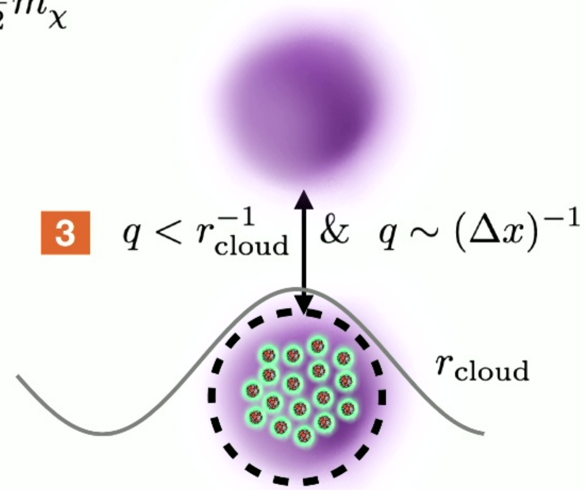
$$s \propto \frac{\bar{\sigma}((m_\chi v_0)^2 + m_\phi^2)^2}{m_\chi^3} \int dq \, \frac{q}{(q^2+m_\phi^2)^2} N(1+N\underbrace{\cancel{F^2(qr_{\text{cloud}})}}_{1})\Big(1-\underbrace{\cancel{\frac{\sin(q\Delta x)}{q\Delta x}}}_{1}\Big)$$

**1** $m_\chi \to 0 \quad \Rightarrow \quad q \to 0 \qquad \Rightarrow \bar{\sigma} \propto \frac{1}{N^2 \Delta x^2} m_\chi^{-1}$

**2** $m_\chi \to \infty \qquad \Rightarrow \bar{\sigma} \propto \frac{1}{N} m_\chi$




**3** $q < r_{\text{cloud}}^{-1}$ & $q \sim (\Delta x)^{-1}$



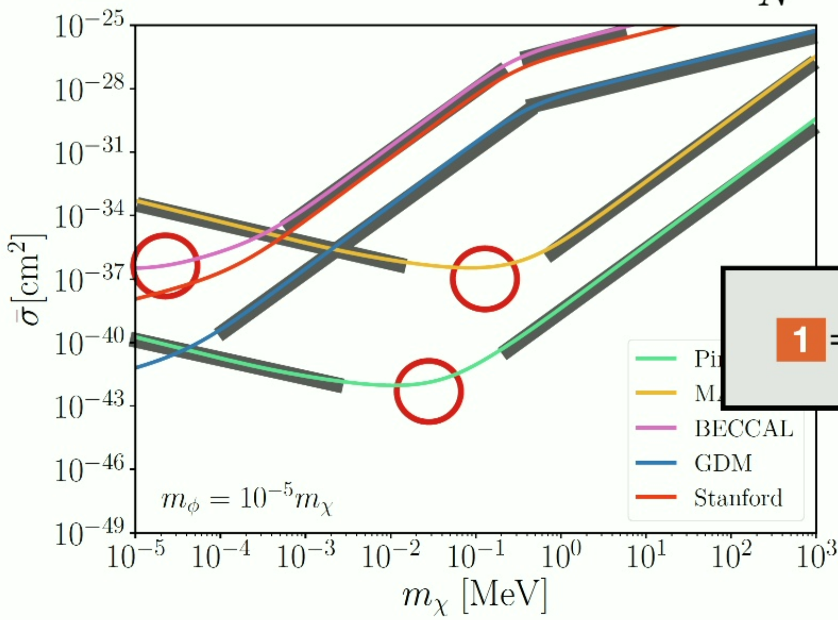

**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

$$s \propto N^2 \frac{\bar{\sigma} v_0^4 \cancel{m_\chi^4}}{m_\chi^3} \frac{r_{\text{cloud}}^{-2}}{\cancel{m_\chi^4} R_{\phi\chi}^4}$$

**1** $m_\chi \to 0 \quad \Rightarrow \quad q \to 0 \qquad \Rightarrow \bar{\sigma} \propto \frac{1}{N^2 \Delta x^2} m_\chi^{-1}$

**2** $m_\chi \to \infty \qquad \Rightarrow \bar{\sigma} \propto \frac{1}{N} m_\chi$



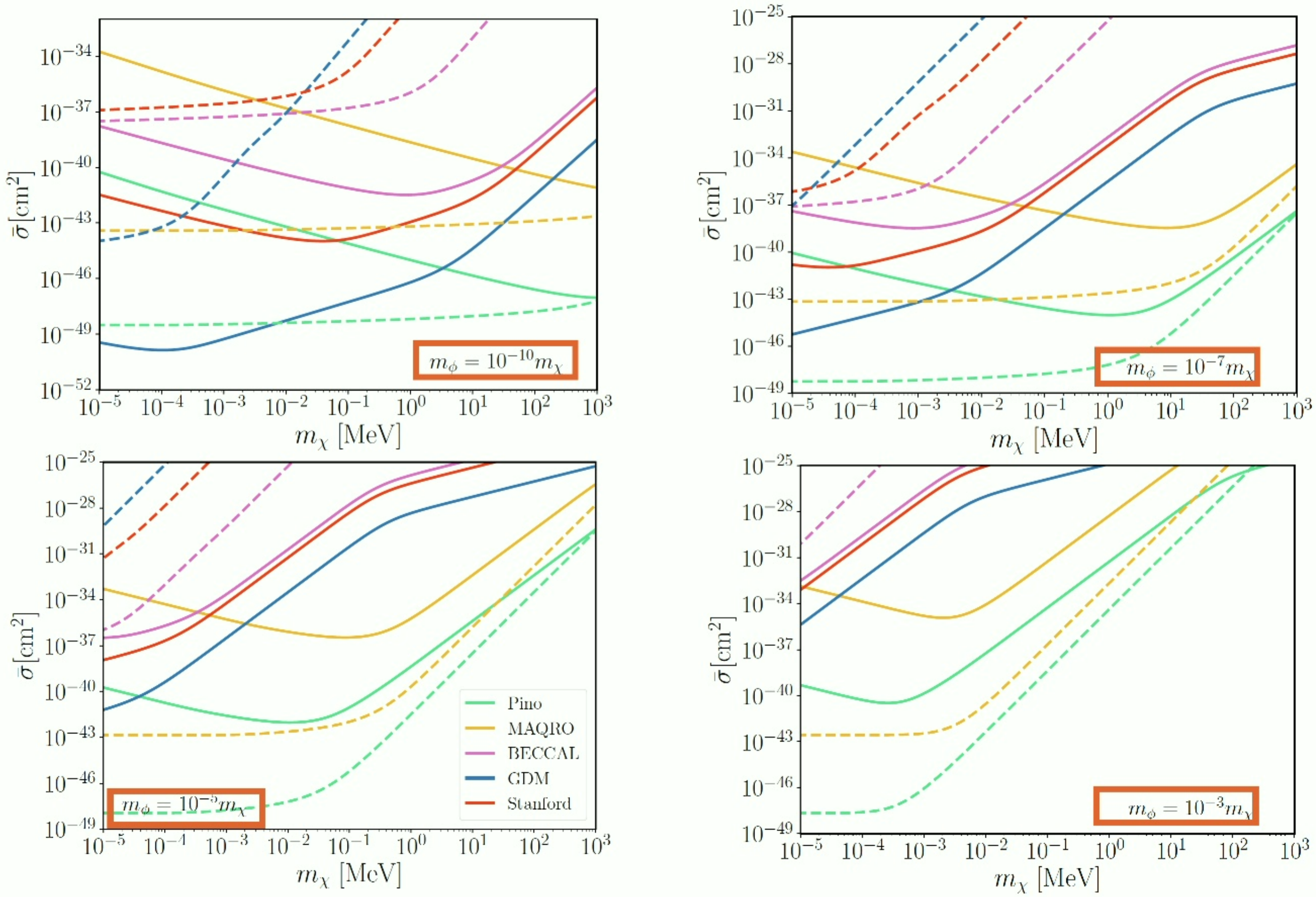

**3** $q < r_{\text{cloud}}^{-1}$ & $q \sim (\Delta x)^{-1}$

$$\Rightarrow \bar{\sigma} \propto \frac{r_{\text{cloud}}^2 R_{\phi\chi}^4}{N^2} m_\chi^3$$

**1** = **3** ⇨ $m_\chi^{\text{knee}} \sim \frac{1}{\sqrt{r_{\text{cloud}} \Delta x R_{\phi\chi}}}$

**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

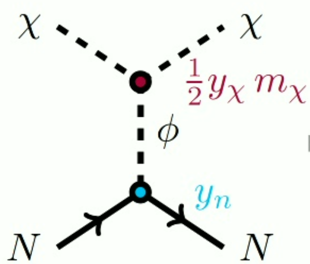
# AIs: Results



$m_\phi = 10^{-10} m_\chi$
$m_\phi = 10^{-7} m_\chi$
$m_\phi = 10^{-5} m_\chi$
$m_\phi = 10^{-3} m_\chi$
$\bar{\sigma}[\mathrm{cm}^2]$
$m_\chi$ [MeV]
Pino
MAQRO
BECCAL
GDM
Stanford

# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

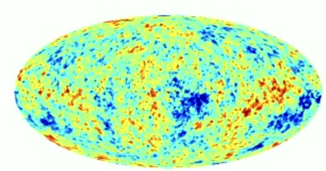



$$\bar{\sigma} = \frac{y_\chi^2\, y_n^2}{4\pi} \frac{\mu^2}{(m_\chi^2 v_0^2 + m_\phi^2)^2}$$

**Terrestial**

**Astrophysical**

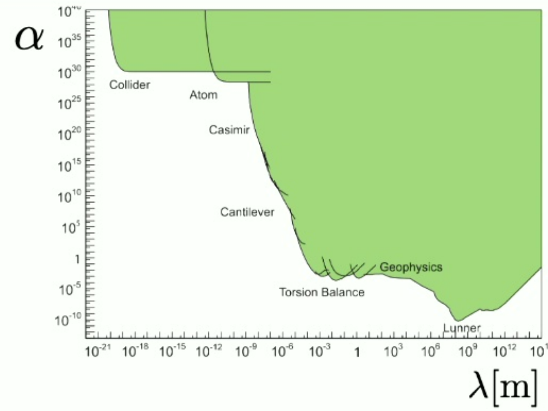
**Cosmological**

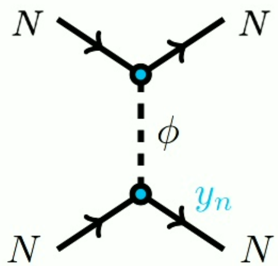


# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

$$V(r) = -G_N \frac{m_N^2}{r}\left(1 + \alpha e^{-m_\phi r}\right)$$




$$V(r) = -\frac{y_n^2}{4\pi}\frac{1}{r}e^{-m_\phi r}$$

[Murata, Tanaka, 2014]

**Terrestial**

- Collider
- 5th force

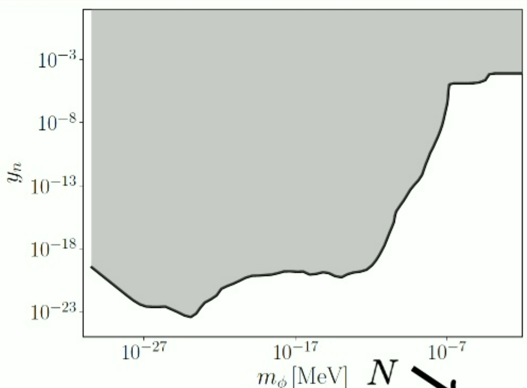
**Astrophysical**



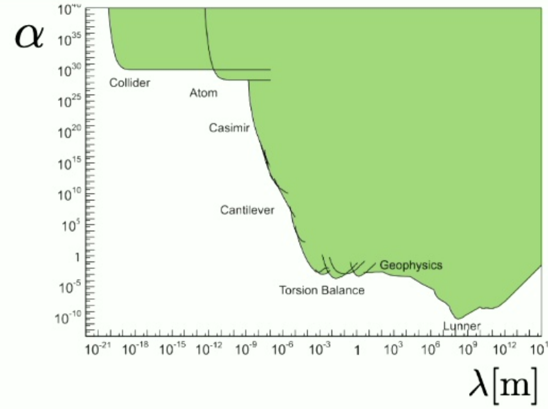
**Cosmological**

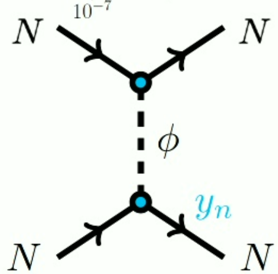
# AIs: Constraints

[Knapen, Lin, Zurek, 2017]




$$\alpha = \frac{y_n^2}{4\pi}\frac{M_{\rm Pl}^2}{m_N^2}$$




$$V(r) = -\frac{y_n^2}{4\pi}\frac{1}{r}e^{-m_\phi r}$$

[Murata, Tanaka, 2014]

**Terrestial**

Collider

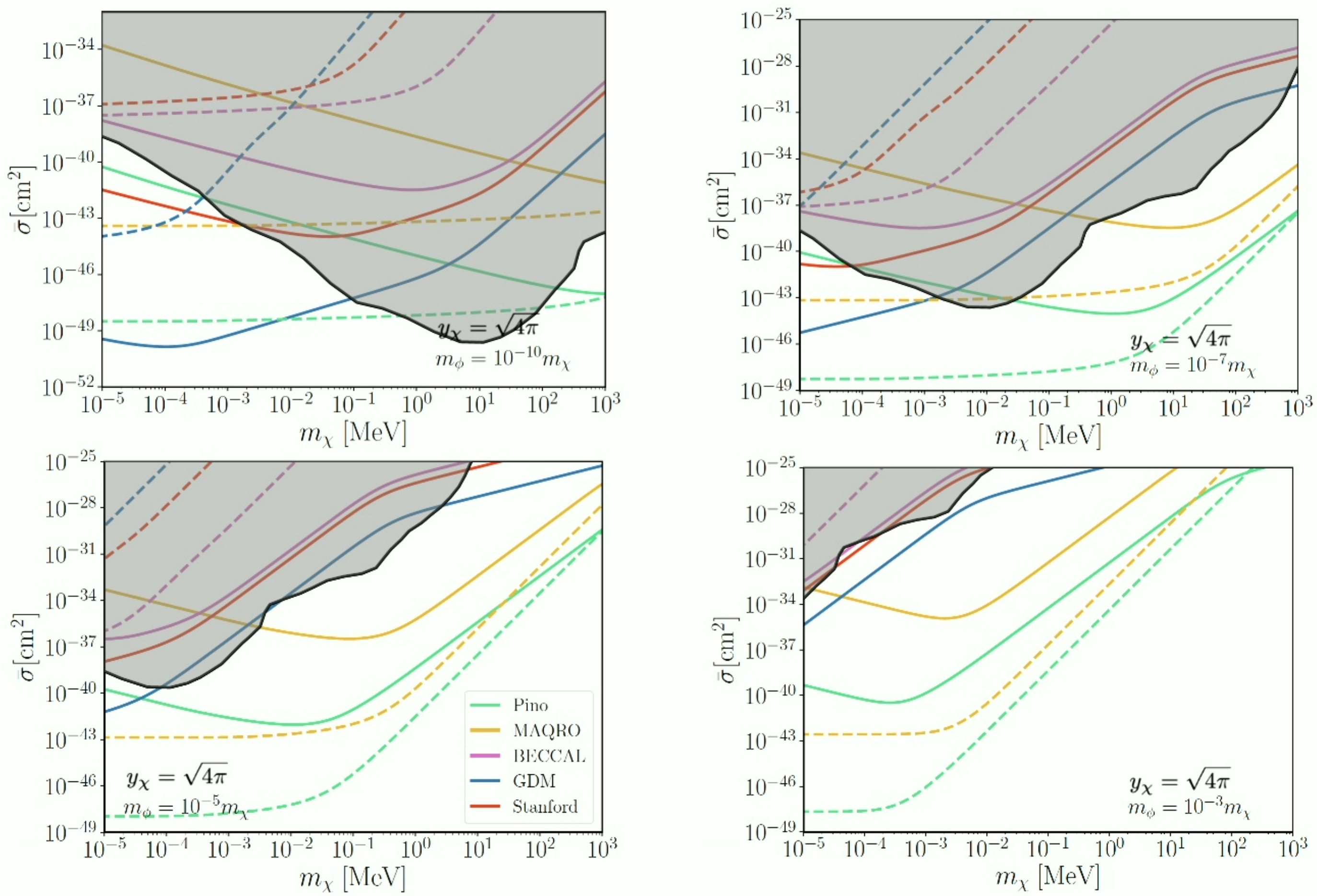
5th force

**Astrophysical**



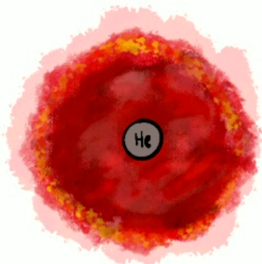
**Cosmological**

# AIs: Constraints



# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

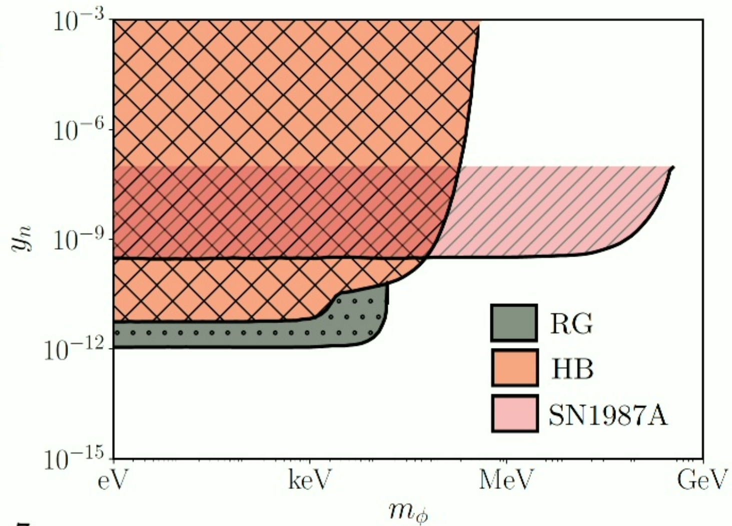


**RG and HB stars**

$m_\phi < T \sim 10$ keV

$\epsilon \lesssim 10$ erg/g/s

$y_n \lesssim 4 \times 10^{-11}$




**SN1987A**

$T = 30$ MeV

$\rho = 3 \times 10^{14}$ g/cm$^3$

$\epsilon < 10^{19}$ erg/g/s ⇨ $10^{-10} < y_n < 10^{-7}$

Terrestrial



⇨ Collider

⇨ 5th force

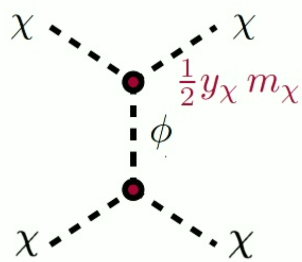
**Astrophysical**

⇨ Stellar emission

Cosmological

# AIs: Constraints

[Knapen, Lin, Zurek, 2017]




**Terrestrial**



- Collider
- 5th force

**Astrophysical**

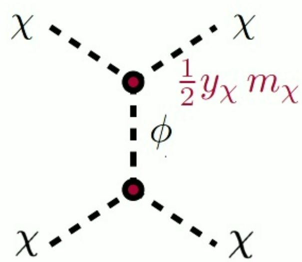
- Stellar emission
- DMSI

**Cosmological**

# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

$$\frac{\sigma}{m_\chi} \lesssim 1\text{–}10\ \mathrm{cm}^2/\mathrm{g}$$




$$\frac{y_\chi^2}{4\pi} < 6 \times 10^{-10} \left(\frac{m_\chi}{1\ \mathrm{MeV}}\right)^{3/2}$$

**Terrestrial**



Collider

5th force

**Astrophysical**

Stellar emission

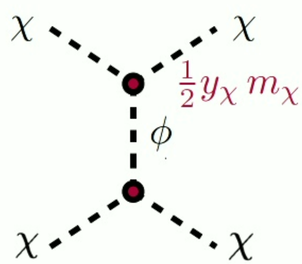
DMSI

**Cosmological**

# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

$$\frac{\sigma}{m_\chi} \lesssim 1\text{–}10\ \mathrm{cm}^2/\mathrm{g}$$




$$\frac{y_\chi^2}{4\pi} < 6 \times 10^{-10} \left(\frac{m_\chi}{1\ \mathrm{MeV}}\right)^{3/2}$$

**Terrestrial**



Collider

5th force

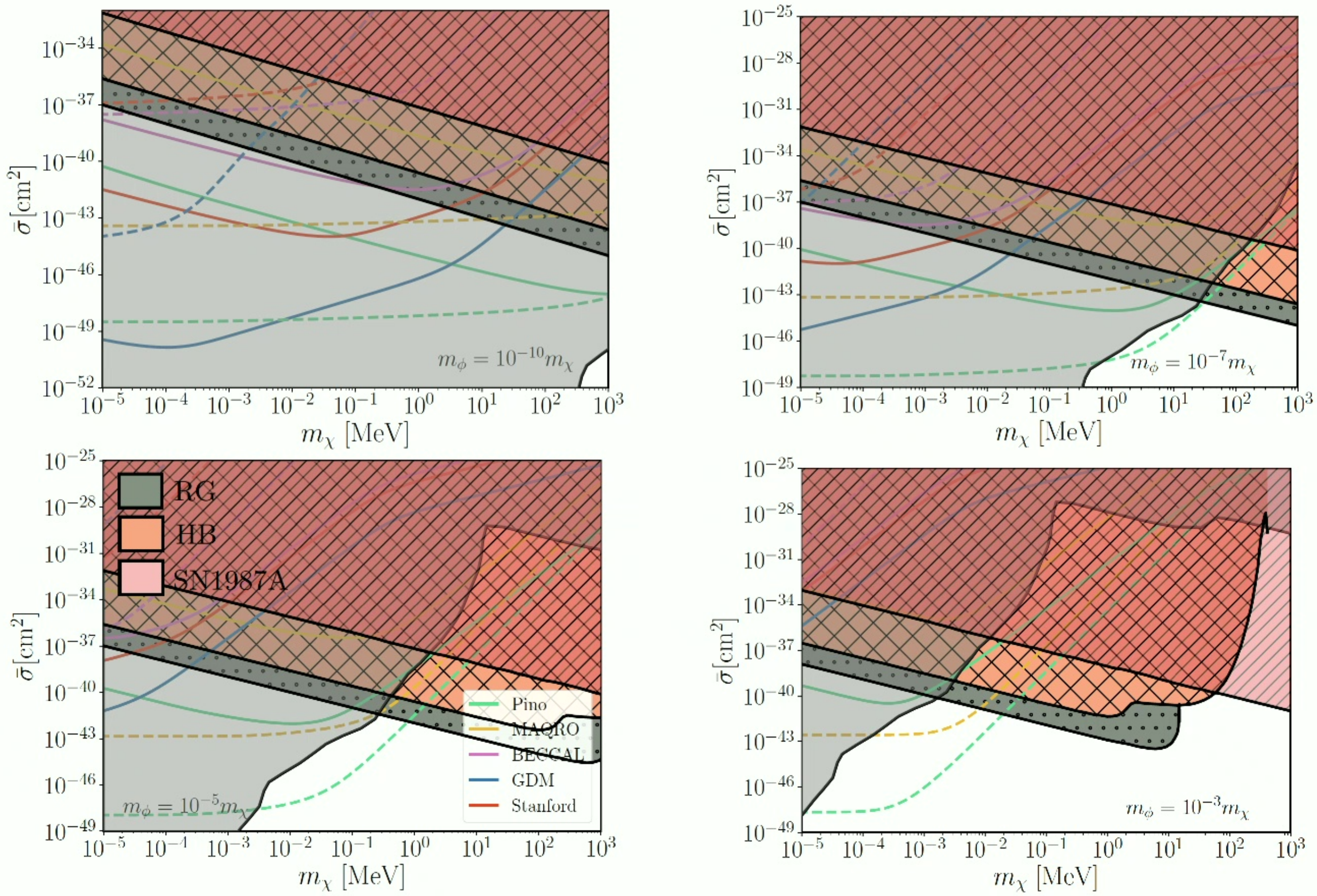
**Astrophysical**

Stellar emission

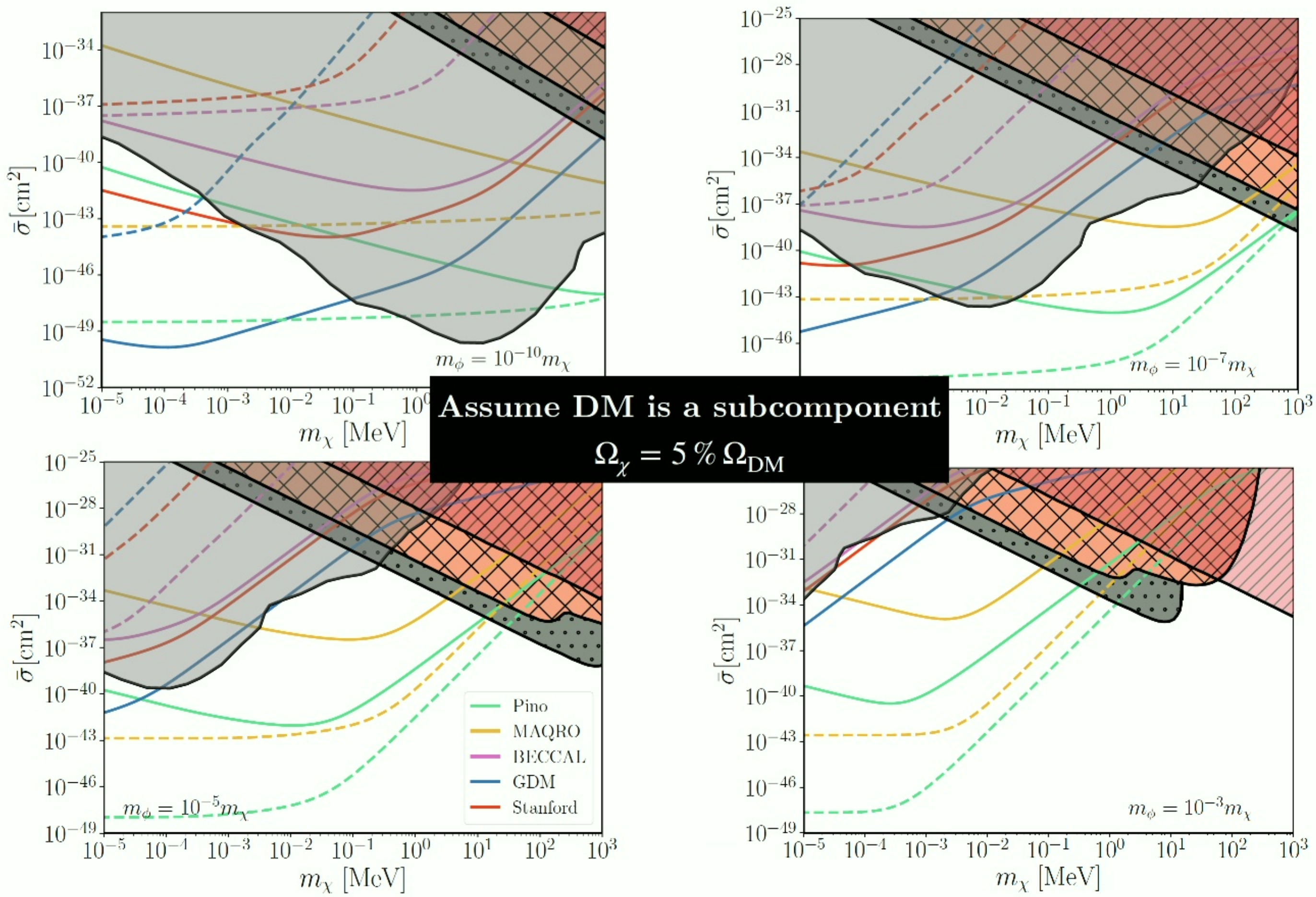
DMSI

**Cosmological**

# AIs: Constraints



# AIs: Constraints



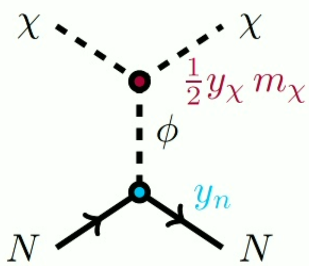

**Assume DM is a subcomponent**

$\Omega_\chi = 5\,\%\,\Omega_{\mathrm{DM}}$

# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

$$\Delta N_{\rm eff} = \frac{4}{7}\sum_i g_i \left(\frac{T_i}{T_\nu}\right)^4$$




**Terrestrial**



Collider

5th force

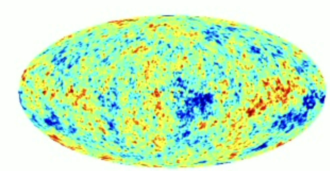
**Astrophysical**



Stellar emission

DMSI

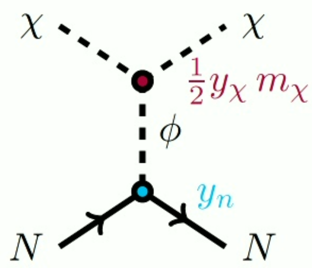
**Cosmological**

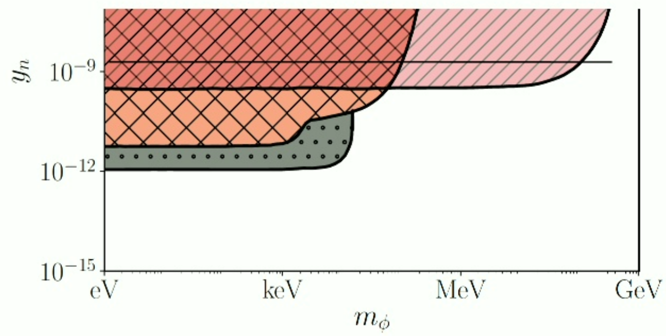


# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

$$\Delta N_{\text{eff}} = \frac{4}{7}\left(\frac{g(T_\nu^{\text{dec}})}{g(T_{\text{QCD}})}\right)^{\frac{4}{3}} \sum_{\text{i}} g_i$$




**Terrestrial**



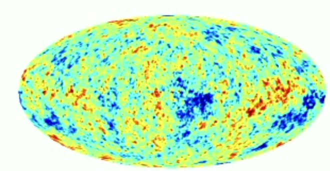
- Collider
- 5th force

**Astrophysical**

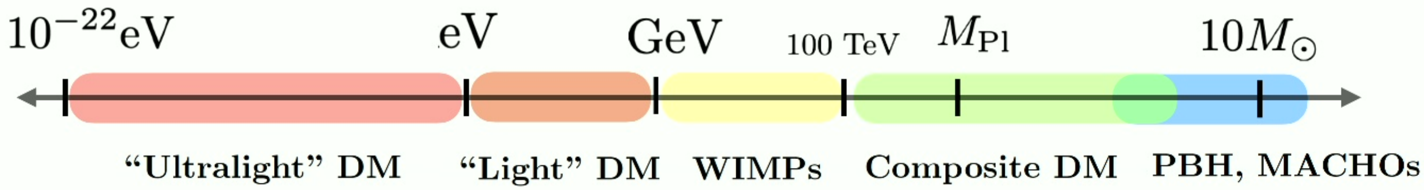


- Stellar emission
- DMSI

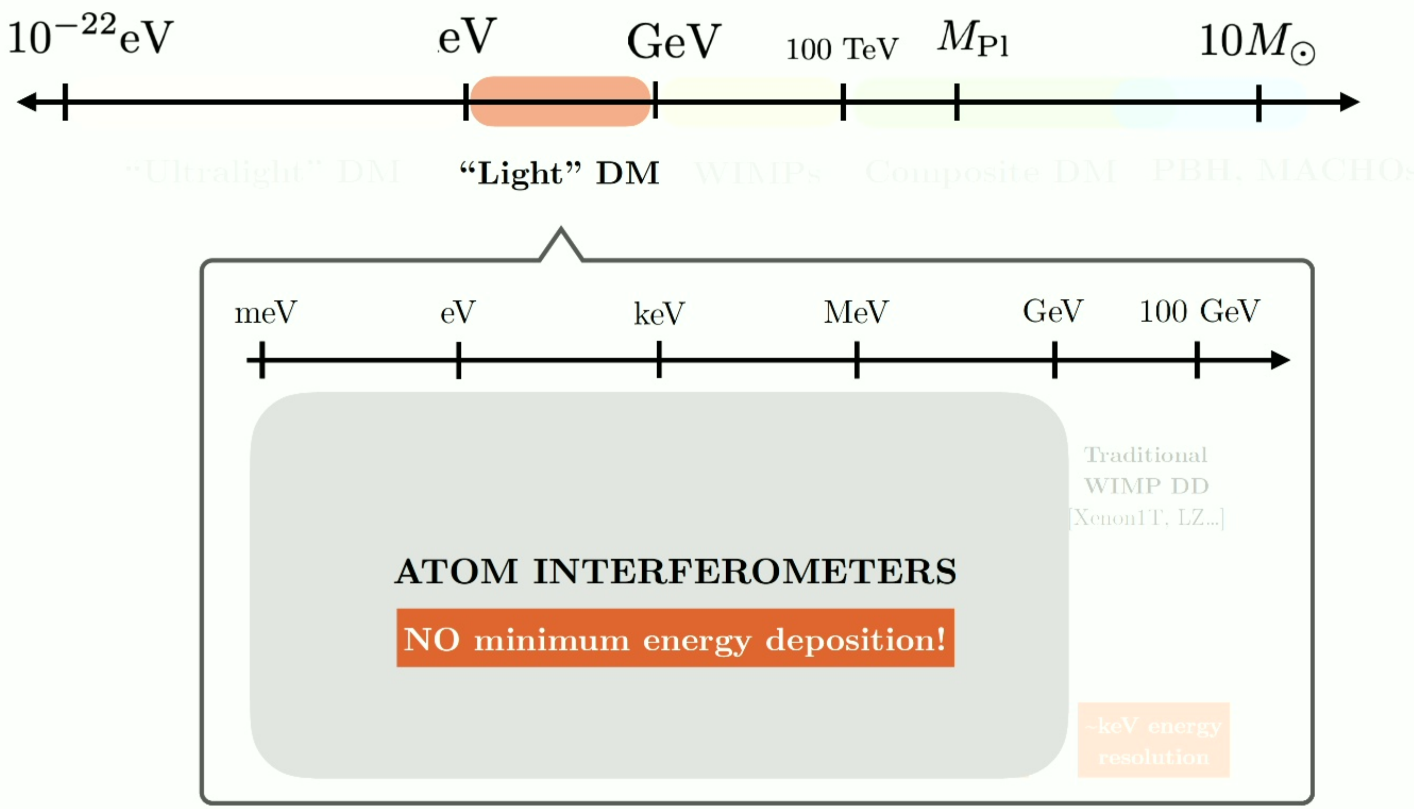
**Cosmological**



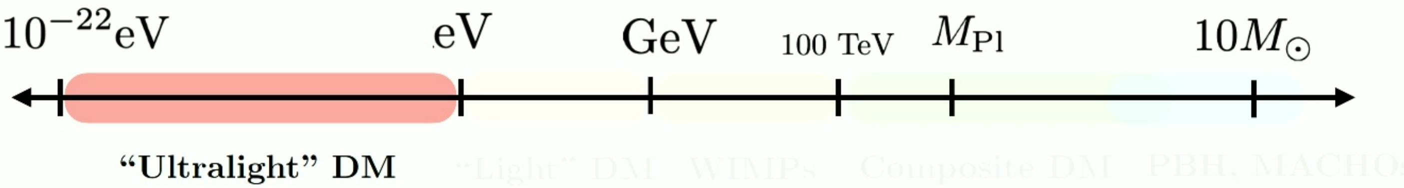
# Dark Matter: where to look?



# Dark Matter: where to look?



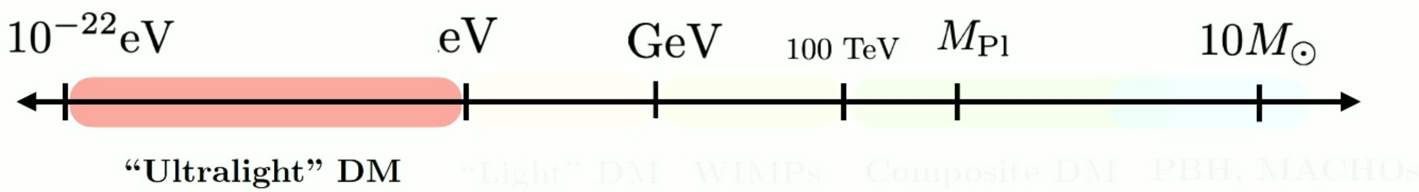
# Axion Dark Matter

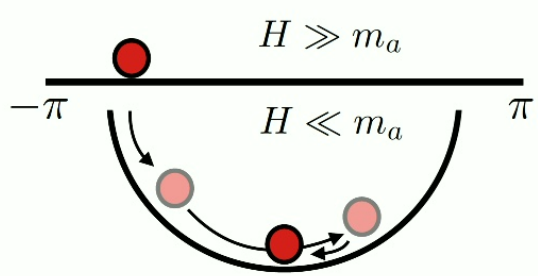




[Peccei, Quinn, 1977] [Wilczek, 1978] [Weinberg, 1978]
[Dine, Fischler, Srednicki, 1981] [Zhitnitsky, 1980]
[Kim, 1979] [Shifman, Vainshtein, Zakharov, 1980]

# Axion Dark Matter



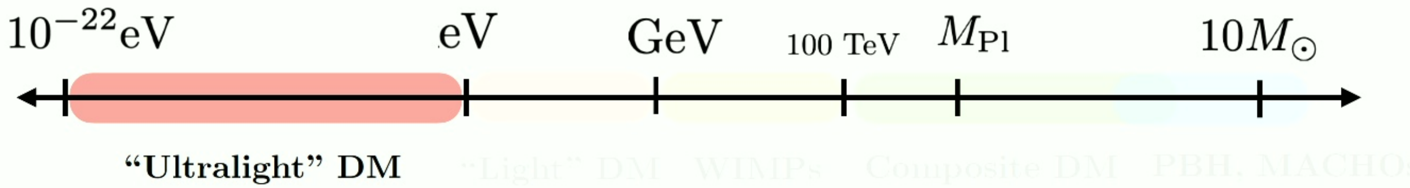



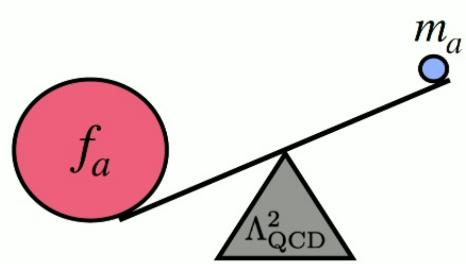


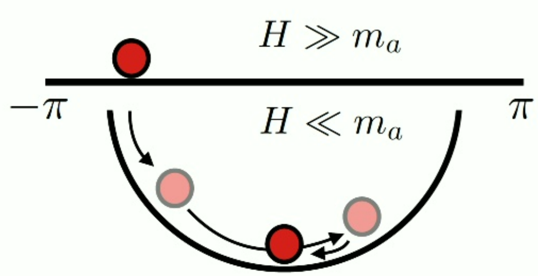
[Preskill, Wise, Wilczek, 1983]
[Abbott, Sikivie, 1983]
[Dine, Fischler, 1983]

[Peccei, Quinn, 1977] [Wilczek, 1978] [Weinberg, 1978]
[Dine, Fischler, Srednicki, 1981] [Zhitnitsky, 1980]
[Kim, 1979] [Shifman, Vainshtein, Zakharov, 1980]

# Axion Dark Matter



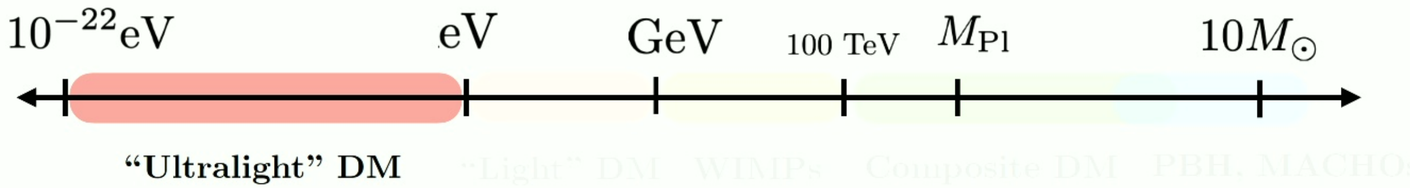



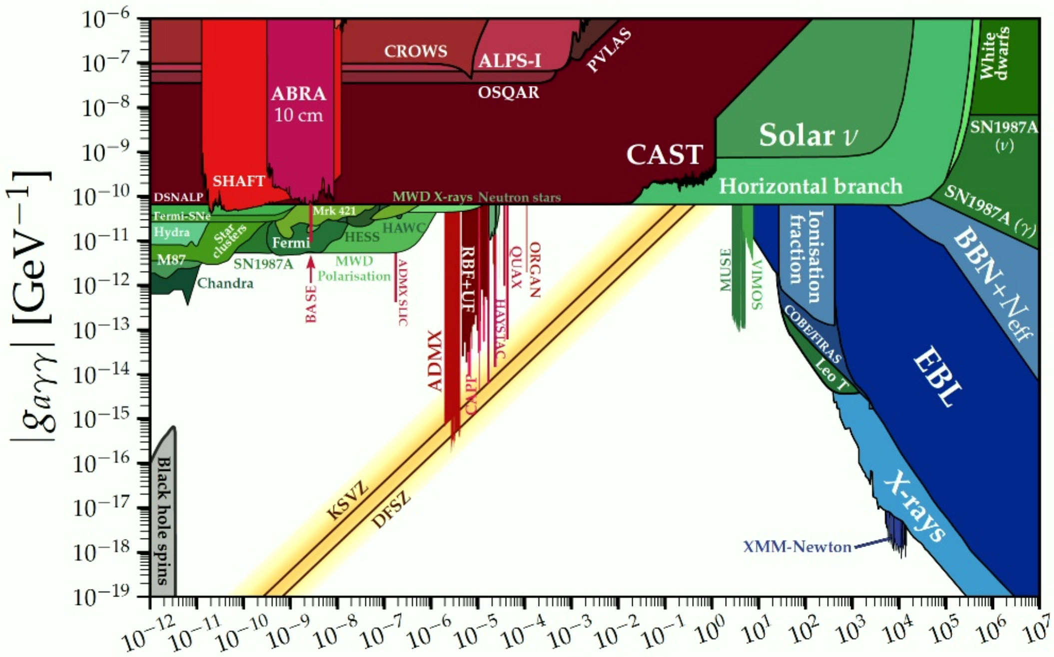

$$m_a \sim \frac{\Lambda^2_{\rm QCD}}{f_a}$$


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

[Peccei, Quinn, 1977] [Wilczek, 1978] [Weinberg, 1978]
[Dine, Fischler, Srednicki, 1981] [Zhitnitsky, 1980]
[Kim, 1979] [Shifman, Vainshtein, Zakharov, 1980]

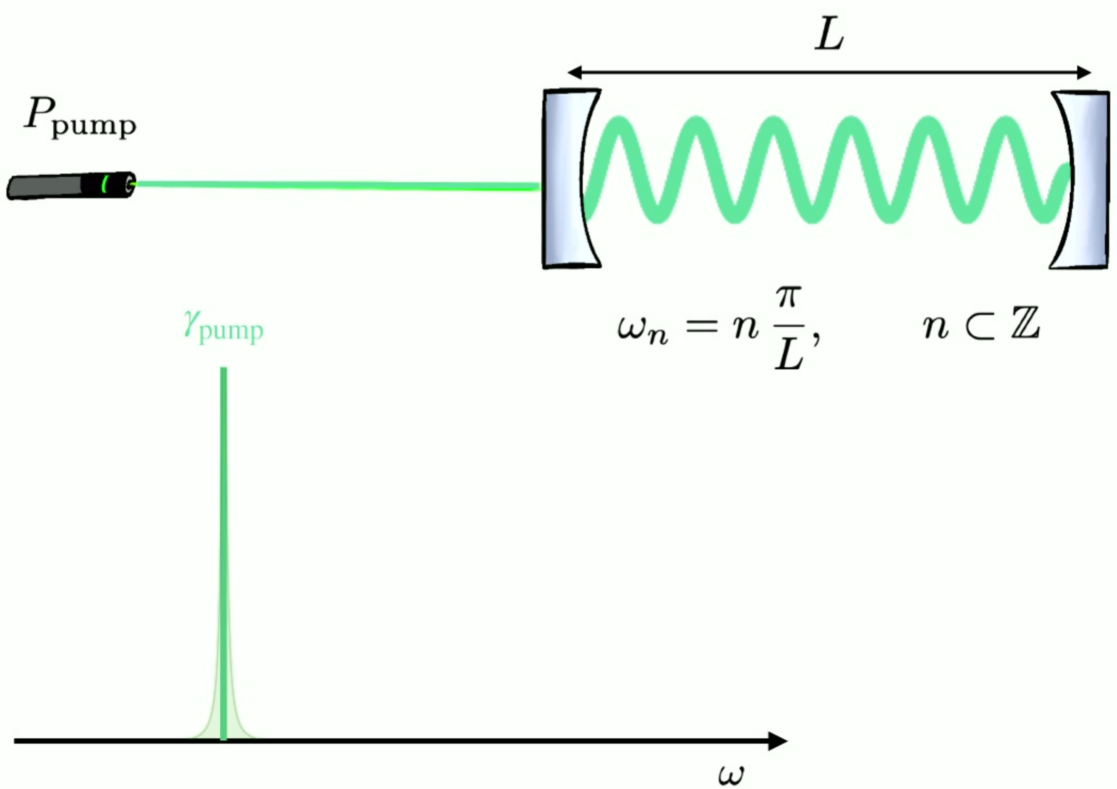
# Axion Dark Matter



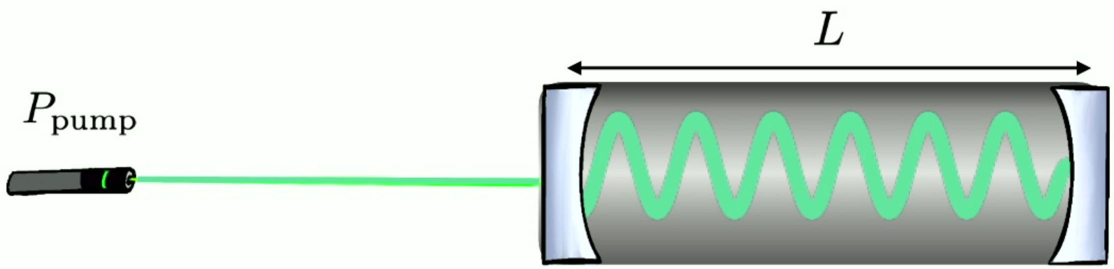

[Ciaran O'Hare, 2020]

# Standard Optomechanics



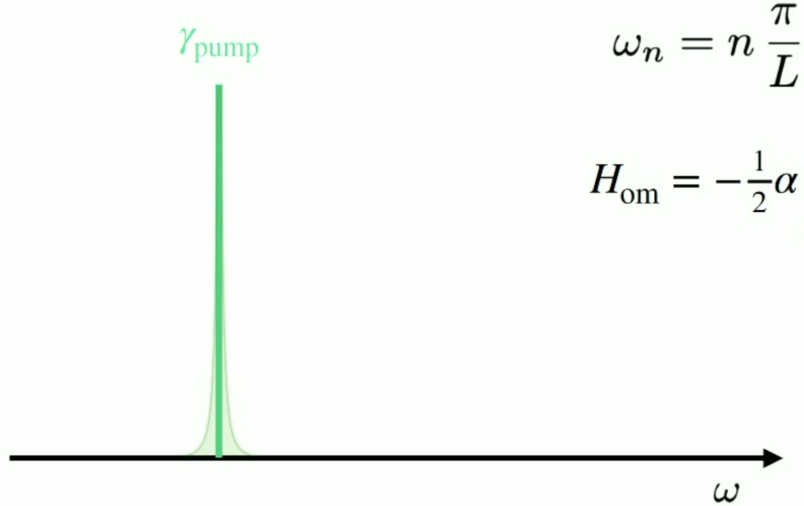

$$\omega_n = n\frac{\pi}{L}, \qquad n \subset \mathbb{Z}$$

# Standard Optomechanics

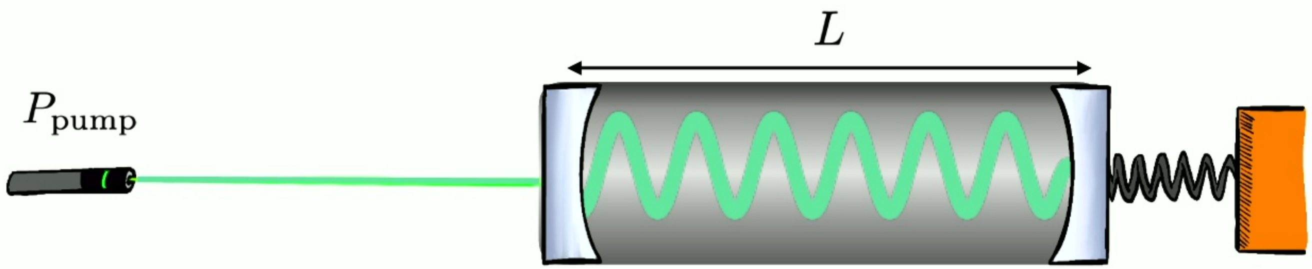



$$\omega_n = n\,\frac{\pi}{L}, \qquad n \subset \mathbb{Z}$$

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

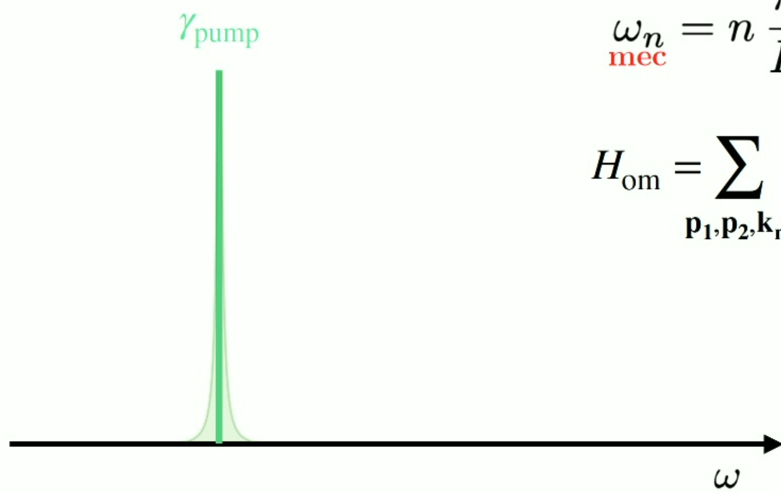


# Standard Optomechanics



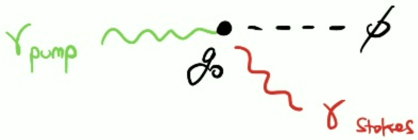

$$\underset{\color{red}{\text{mec}}}{\omega_n} = n\,\frac{\pi}{L}\,{\color{red}{c_s}}, \quad n \subset \mathbb{Z}$$

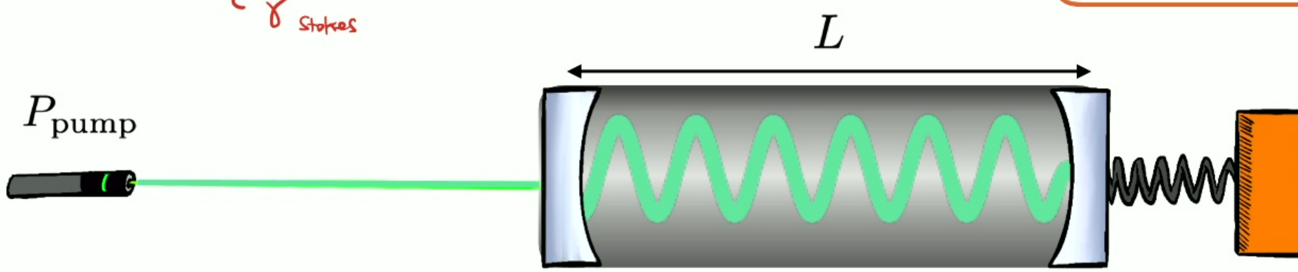
$$H_{\text{om}} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left( a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b^{\dagger}_{\mathbf{k_m}} + \cdots \right.$$



# Standard Optomechanics

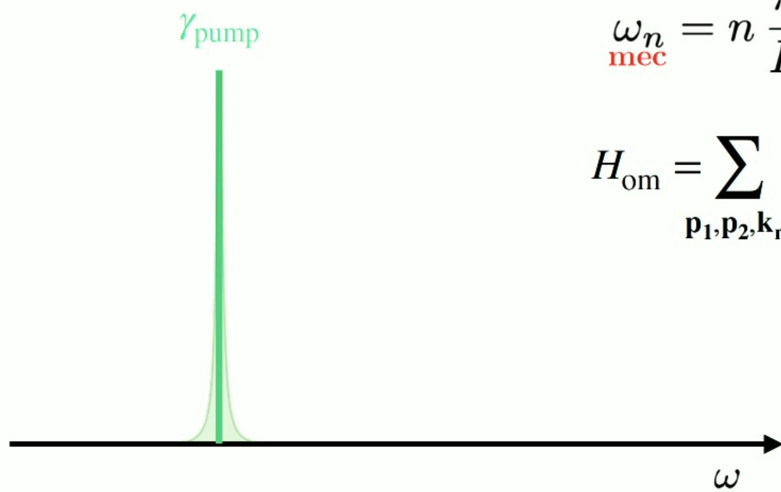
$$\vec{p}_{\gamma 1} = \vec{p}_\phi + \vec{p}_{\gamma 2}$$
$$\omega_{\gamma 1} = \omega_{\mathrm{m}} + \omega_{\gamma 2}$$



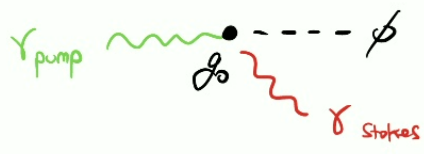




$$\underset{\mathbf{mec}}{\omega_n} = n\,\frac{\pi}{L}\,c_s, \quad n \subset \mathbb{Z}$$

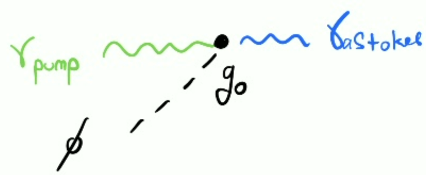
$$H_{\mathrm{om}} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left( a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} + \cdots \right.$$



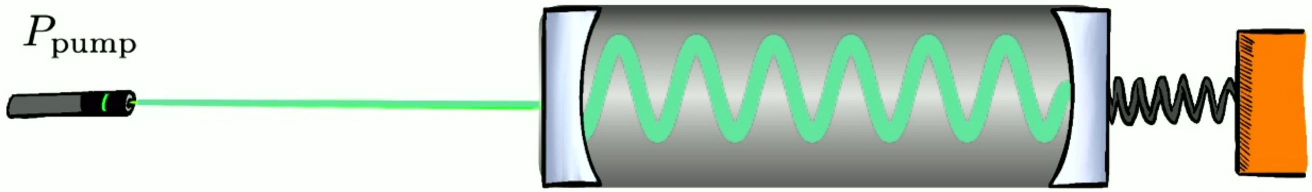
# Standard Optomechanics




and/or

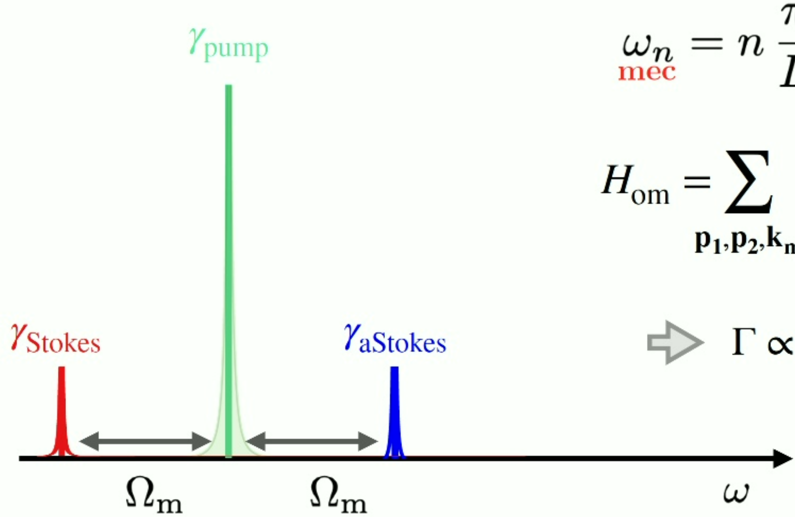



$$p_\phi = 2p_\gamma$$
$$\Omega_{\mathrm{m}} = 2c_s\omega_{\mathrm{opt}}$$



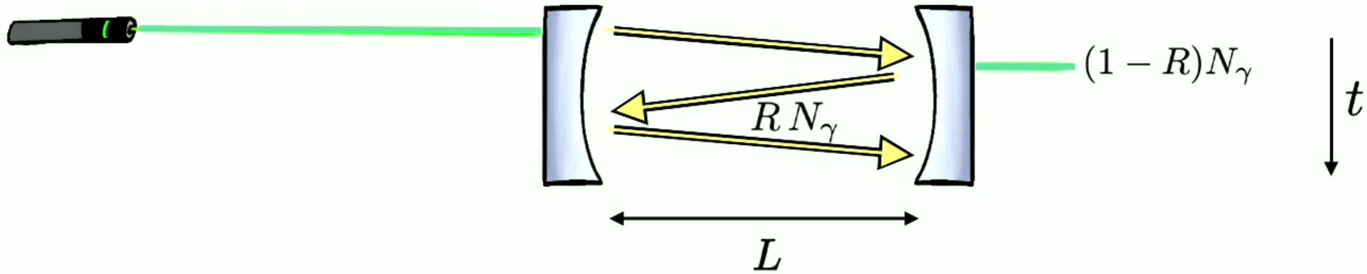

$$\underset{\mathrm{mec}}{\omega_n} = n\frac{\pi}{L}c_s, \quad n \subset \mathbb{Z}$$

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



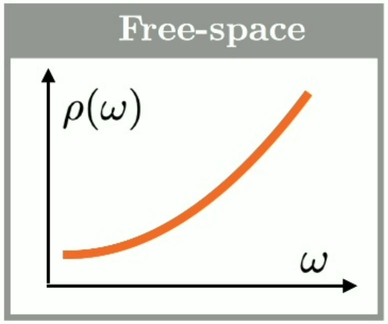

$$\Rightarrow \Gamma \propto |g_0|^2 N^{\mathrm{circ}}_{\gamma,\mathrm{pump}}[\Delta_{\mathrm{pump}}]$$

# Standard Optomechanics



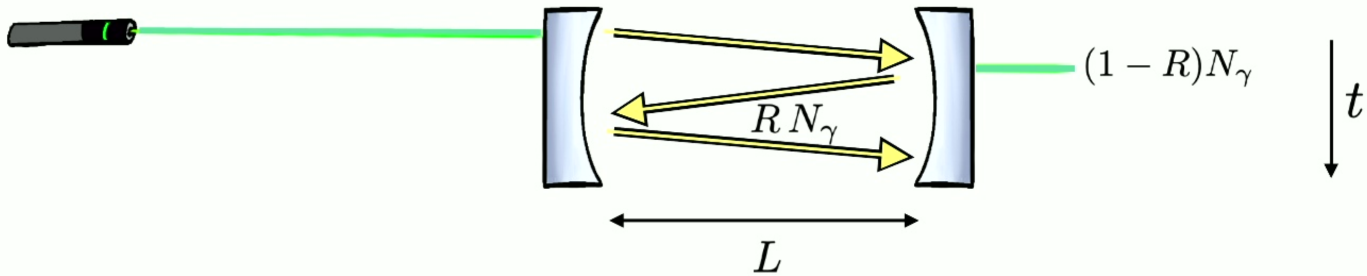

$$\frac{dN_\gamma}{dt} \simeq \frac{\Delta N_\gamma}{L/c} = \frac{c(1-R)}{L} N_\gamma \quad \Rightarrow \quad \tau_\gamma^{-1} \equiv \kappa \simeq \frac{c}{(1-R)^{-1} L}$$

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

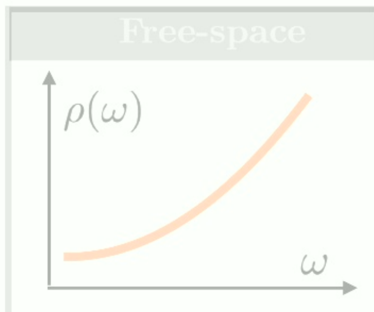


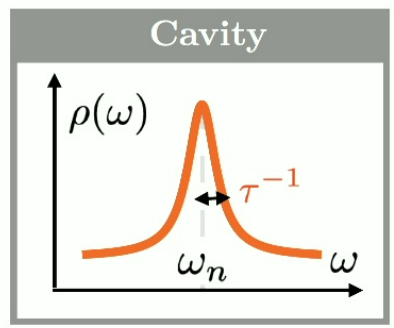

$$\rho(\omega) = \sum_i \delta(\omega - \omega_i) = \sum_n \frac{1}{2\pi} \int dt\, e^{i(\omega-\omega_n)t}$$

# Standard Optomechanics



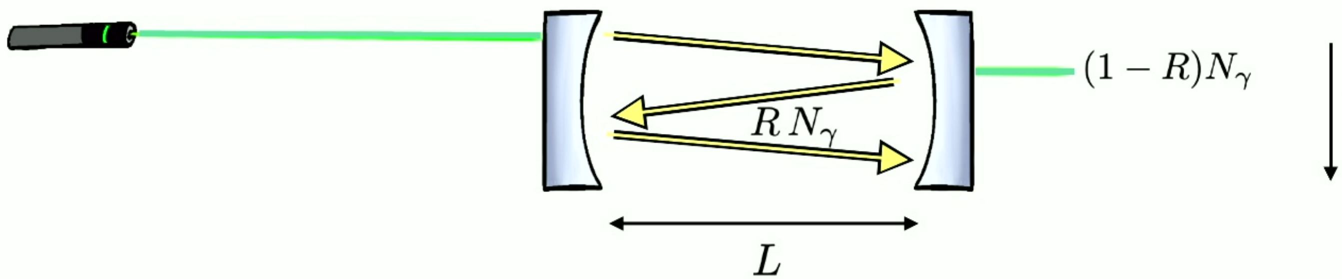

$$\frac{dN_\gamma}{dt} \simeq \frac{\Delta N_\gamma}{L/c} = \frac{c(1-R)}{L} N_\gamma \quad \Rightarrow \quad \tau_\gamma^{-1} \equiv \kappa \simeq \frac{c}{(1-R)^{-1}L}$$



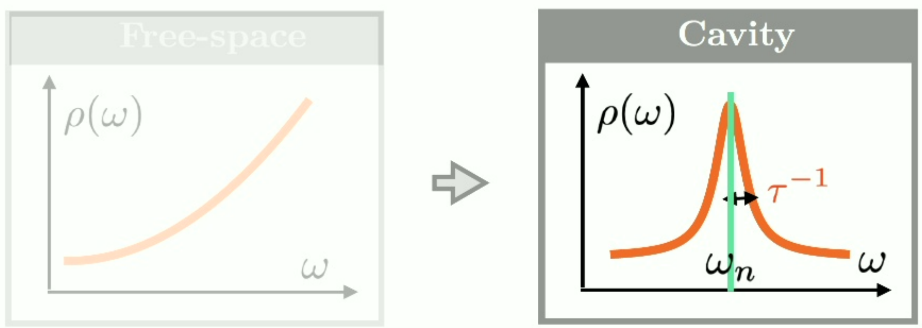

$$\rho(\omega) = \sum_i \delta(\omega - \omega_i) = \sum_n \frac{1}{2\pi} \int dt\, e^{i(\omega-\omega_n)t} e^{-t/(2\tau)} = \sum_n \frac{\tau^{-1}/2}{(\omega-\omega_n)^2 + (\tau^{-1}/2)^2}$$

# Standard Optomechanics



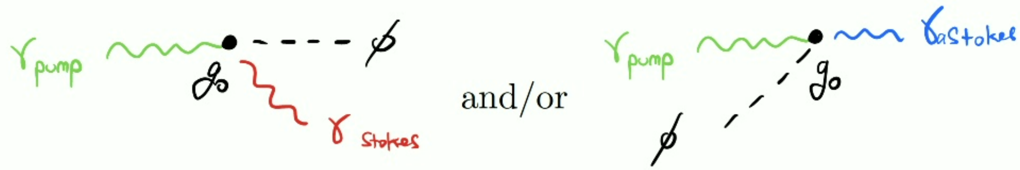

$$\frac{dN_\gamma}{dt} \simeq \frac{\Delta N_\gamma}{L/c} = \frac{c(1-R)}{L} N_\gamma \quad \Rightarrow \quad \tau_\gamma^{-1} \equiv \kappa \simeq \frac{c}{(1-R)^{-1}L}$$

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

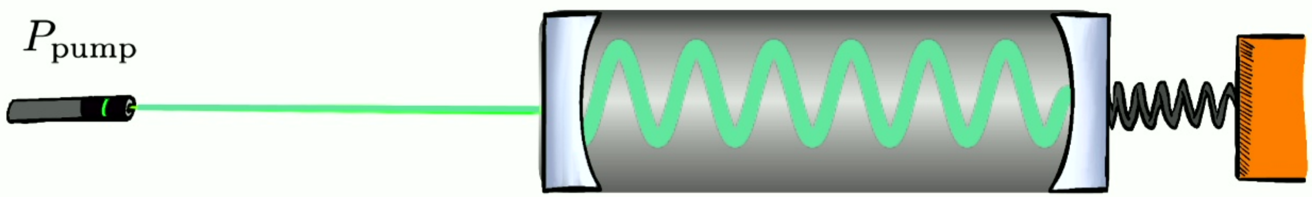



$$\rho(\omega) = \sum_i \delta(\omega - \omega_i) = \sum_n \frac{1}{2\pi} \int dt\, e^{i(\omega-\omega_n)t} e^{-t/(2\tau)} = \sum_n \frac{\tau^{-1}/2}{(\omega-\omega_n)^2 + (\tau^{-1}/2)^2}$$

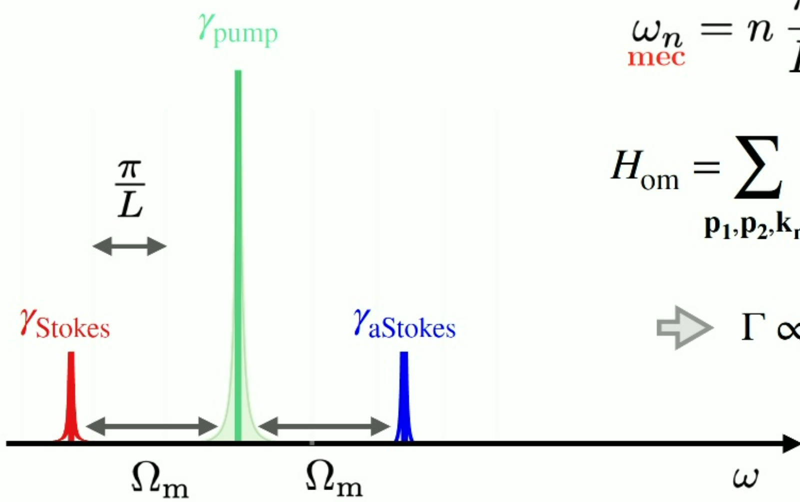
# Standard Optomechanics




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



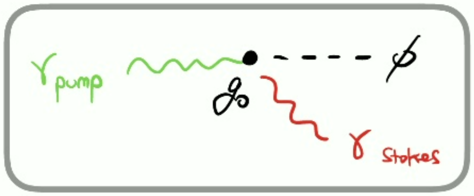

$$\omega_{n \atop \mathrm{mec}} = n\,\frac{\pi}{L}\,c_s, \quad n \subset \mathbb{Z}$$



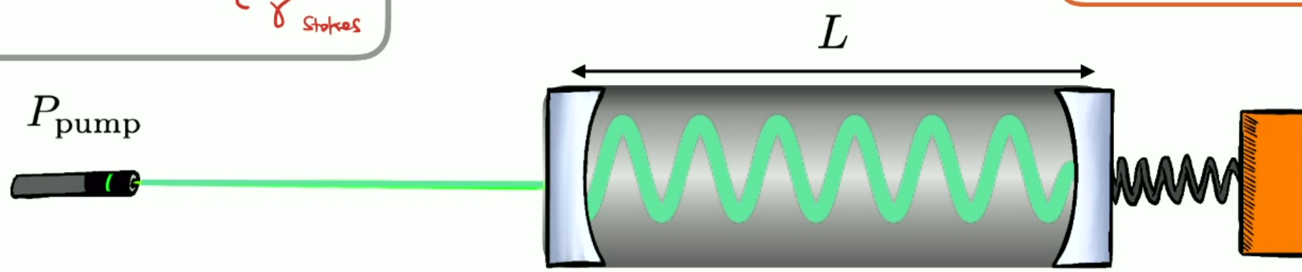

$$H_{\mathrm{om}} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left( a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} + a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b_{\mathbf{k_m}} \right)$$

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

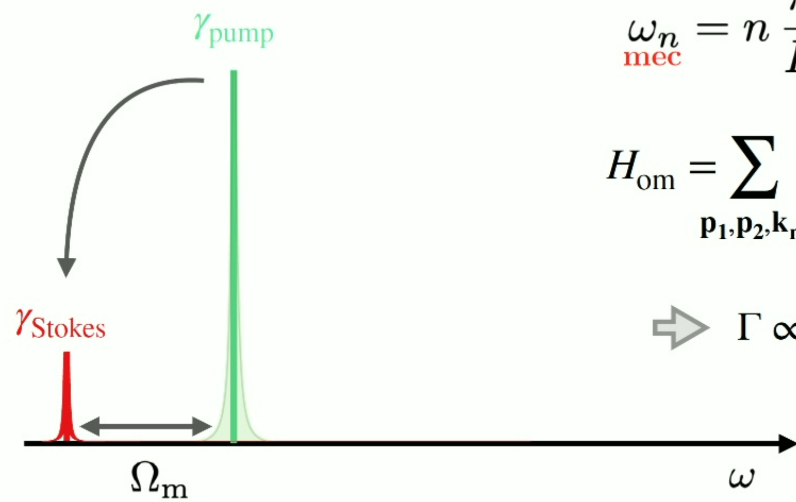
# Standard Optomechanics




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




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

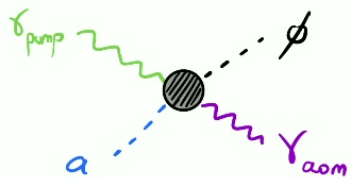



$$H_{om} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left( a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} \right)$$

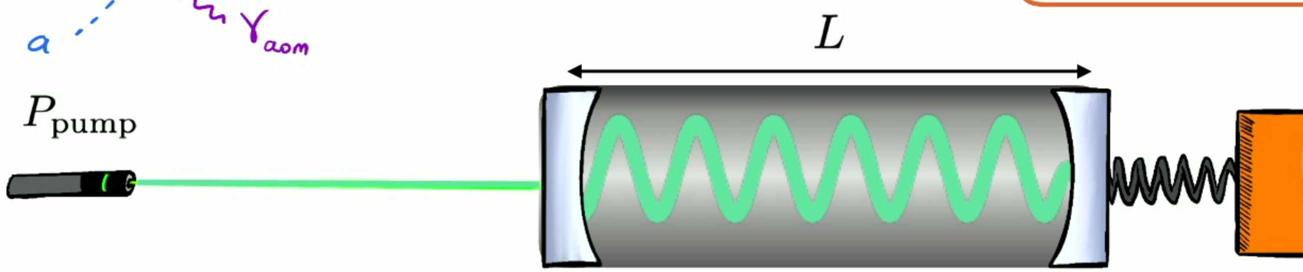
$$\Rightarrow \Gamma \propto |g_0|^2 N_{\gamma,\text{pump}}$$

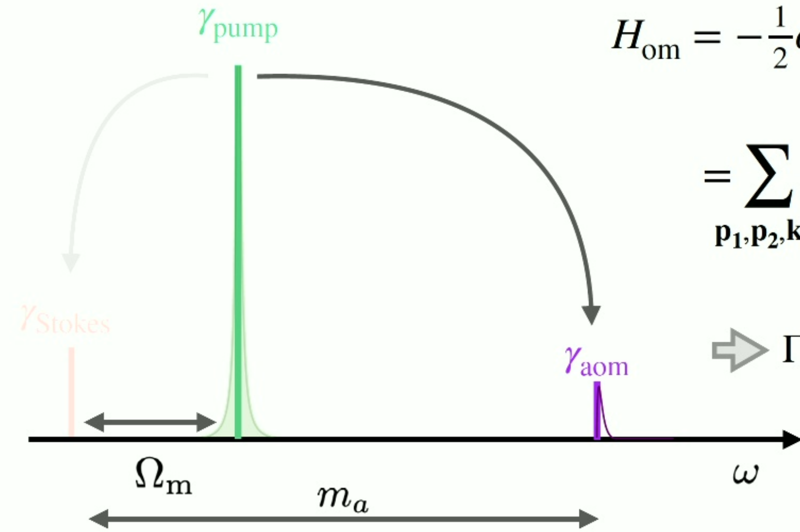

[Kashkanova et al., 2017]
[Reningner et al., 2017]

# ~~Standard~~ Axioptomechanics




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



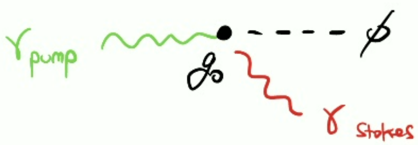

$$H_{\rm om} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma} \int d^3\mathbf{r}\, a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$$

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

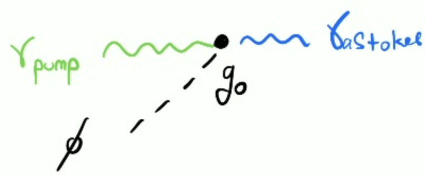
$\sim 10^{-22}$ for QCD axion

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

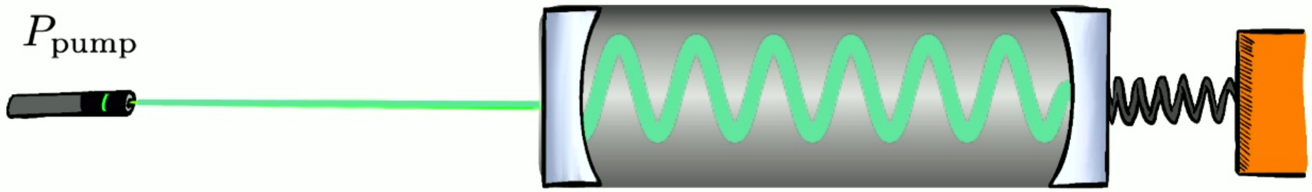
# Standard Optomechanics



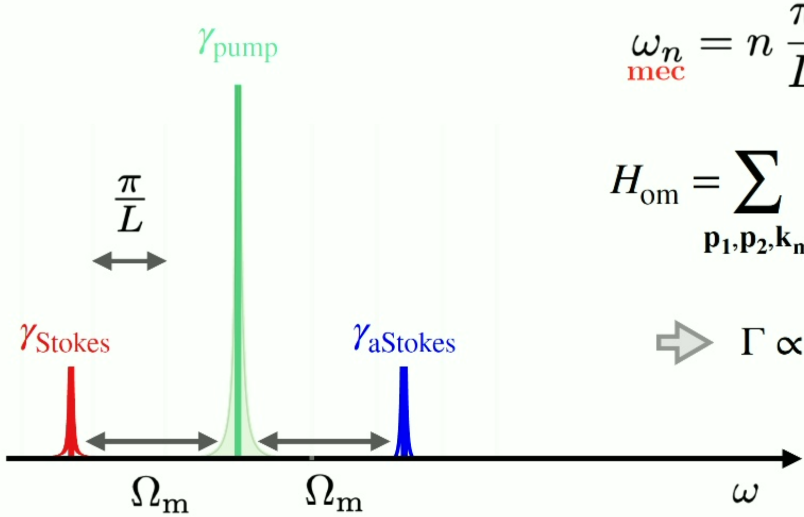

and/or




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




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



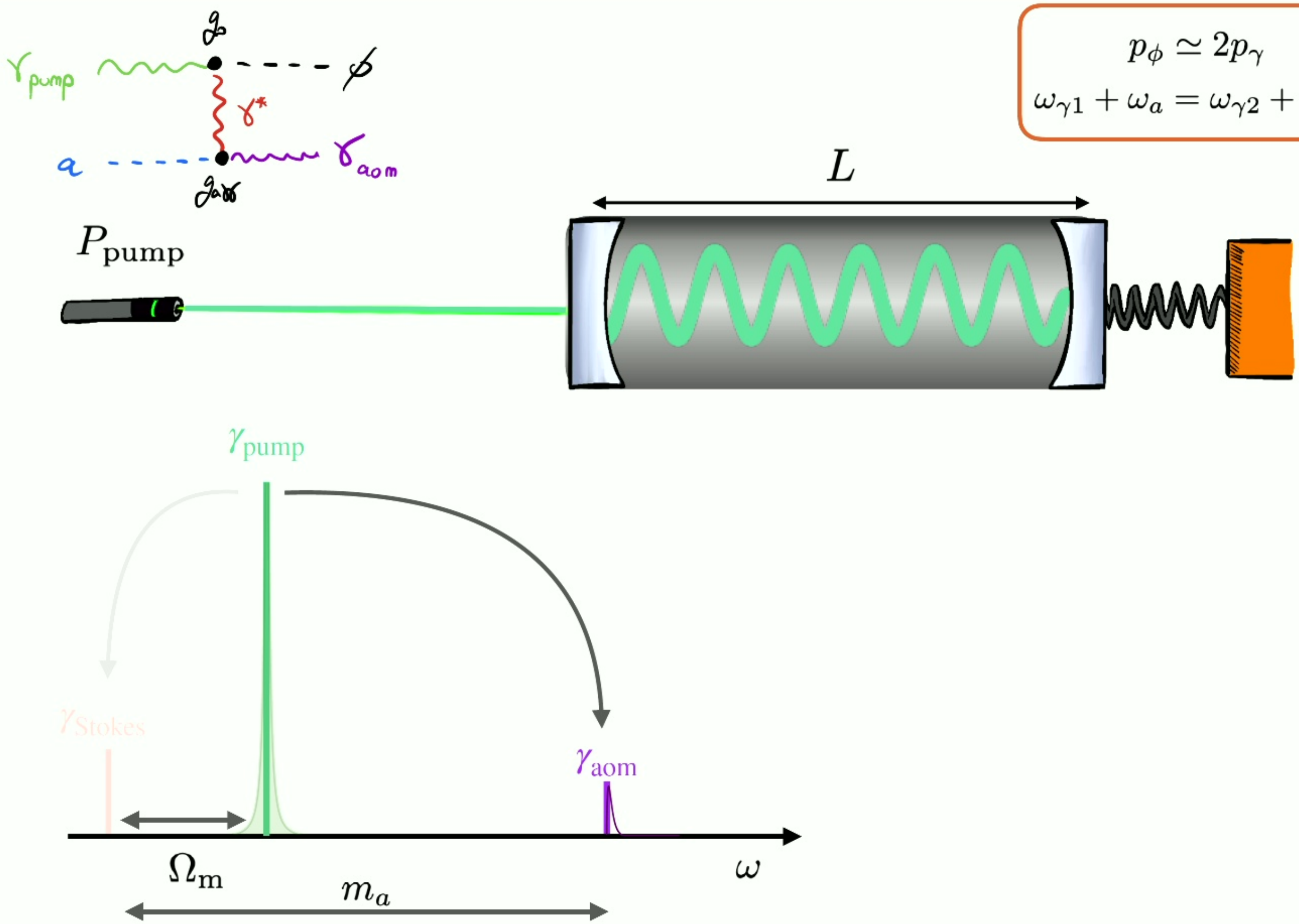

$$H_{\mathrm{om}} = \sum_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{k}_\mathrm{m}} g_0\left(a_{\mathbf{p}_1}a^\dagger_{\mathbf{p}_2}b^\dagger_{\mathbf{k}_\mathrm{m}} + a_{\mathbf{p}_1}a^\dagger_{\mathbf{p}_2}b_{\mathbf{k}_\mathrm{m}}\right)$$

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

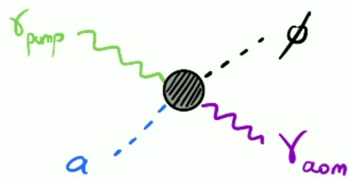
# ~~Standard~~ Axioptomechanics

$p_\phi \simeq 2p_\gamma$

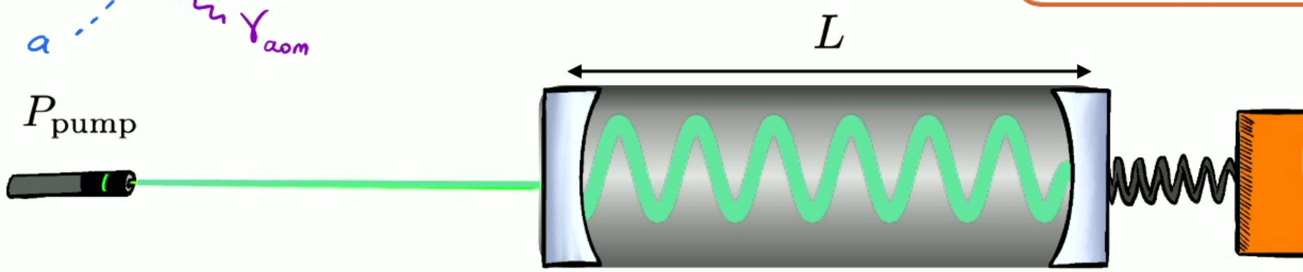
$\omega_{\gamma 1} + \omega_a = \omega_{\gamma 2} + \omega_\phi$

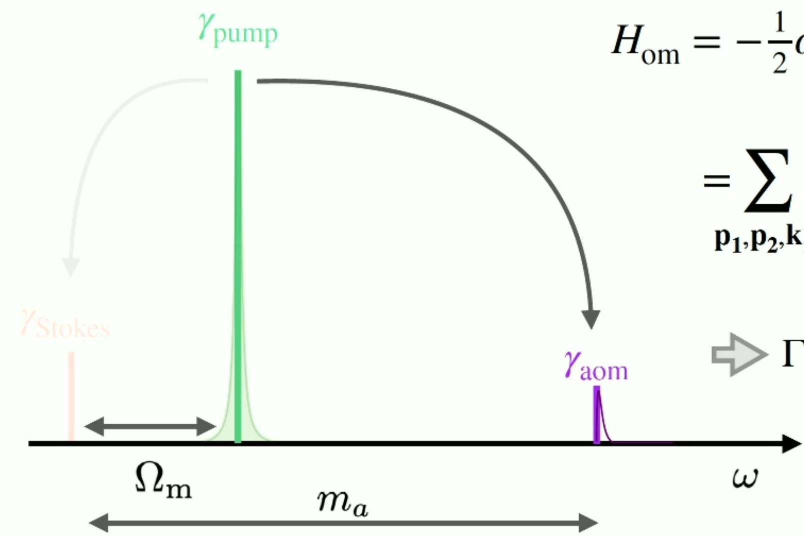


# ~~Standard~~ Axioptomechanics




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



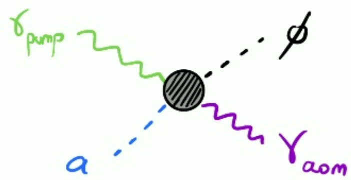

$$H_{\text{om}} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma} \int d^3\mathbf{r}\, a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$$

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

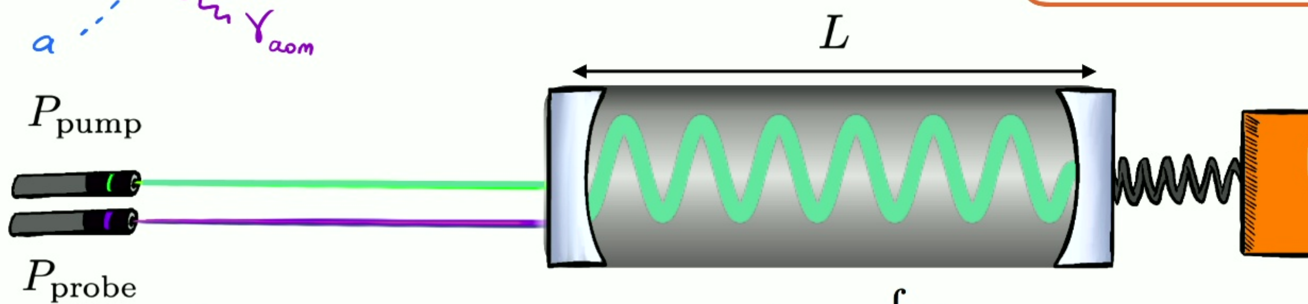
$$\Rightarrow \Gamma \propto |g_0^{(a)}|^2 \left( g^2_{a\gamma\gamma} \frac{\rho_a}{m_a^2} \right)$$

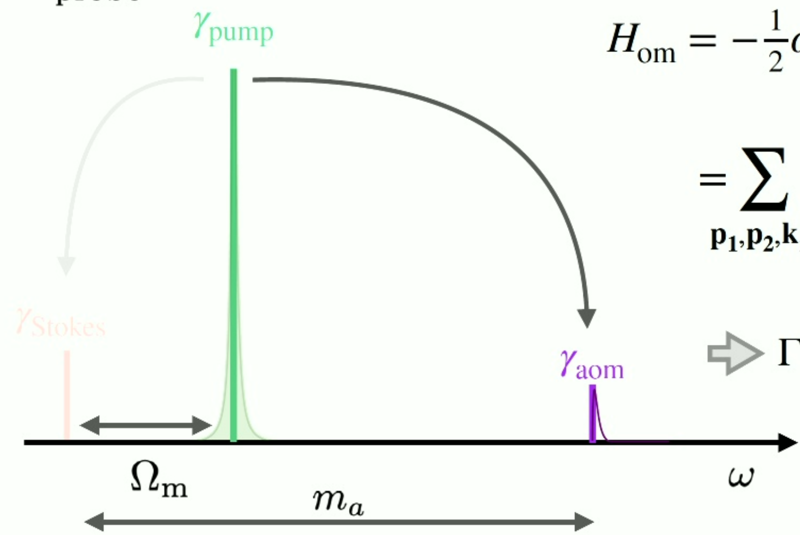
$$\times N_{\gamma,\text{pump}}$$

# Coherent enhancement: **Photons**




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



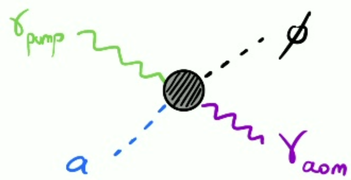

$$H_{\mathrm{om}} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma} \int d^3\mathbf{r}\, a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$$

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

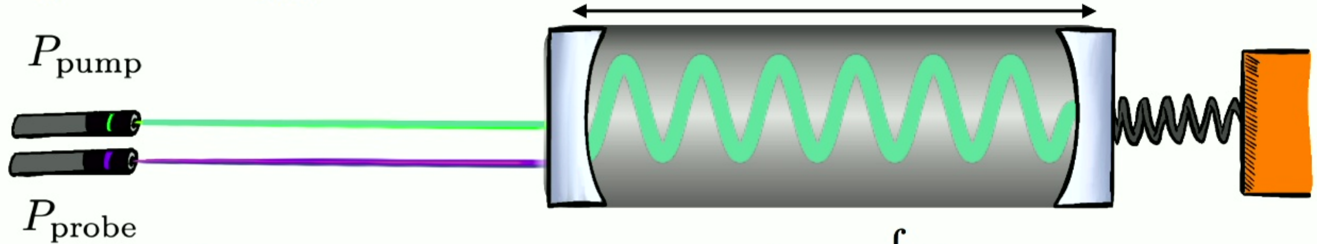
$\sim 10^{-22}$ for QCD axion

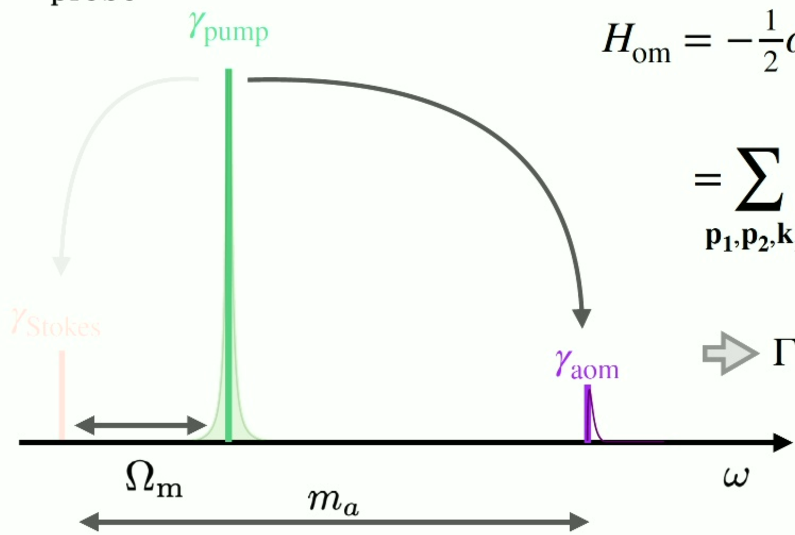
$$\Rightarrow \Gamma \propto |g_0^{(a)}|^2 \left( g^2_{a\gamma\gamma} \frac{\rho_a}{m_a^2} \right)$$
$$\times\, N_{\gamma,\mathrm{pump}}\; N^{\mathrm{circ}}_{\gamma,\mathrm{probe}}\, [\Delta_{\mathrm{probe}}]$$

# Coherent enhancement: **Photons**




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



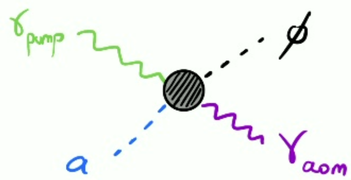

$$H_{\rm om} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma} \int d^3\mathbf{r}\; a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$$

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

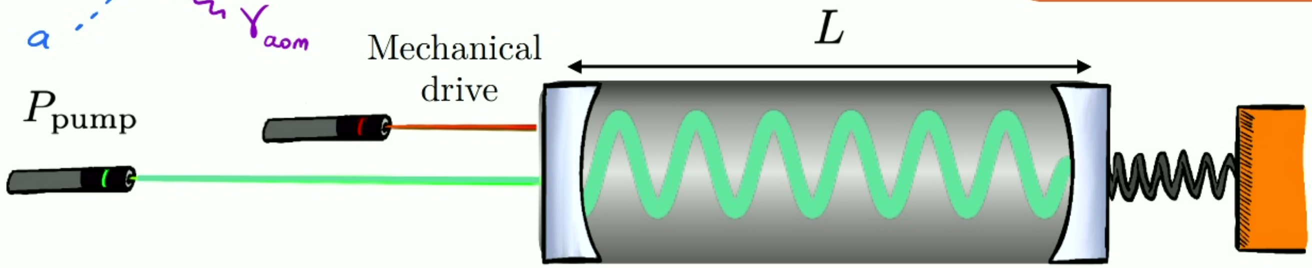
$\sim 10^{-22}$ for QCD axion

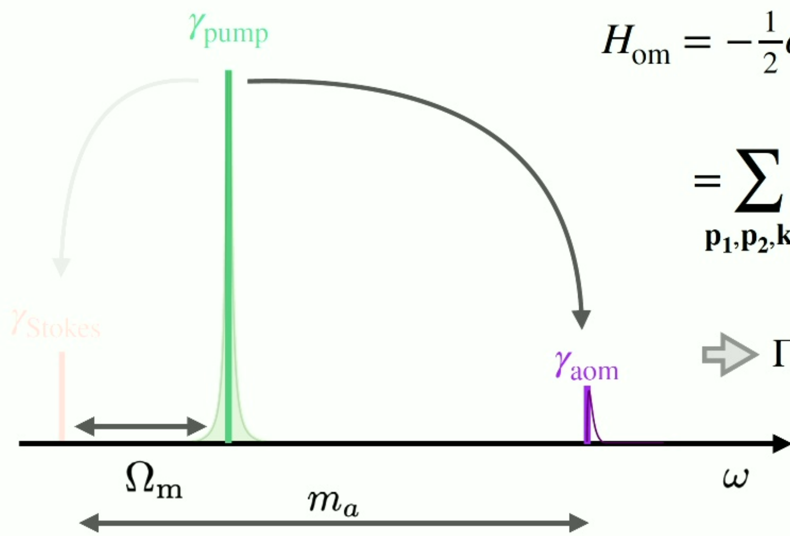
$$\Rightarrow \Gamma \propto |g_0^{(a)}|^2 \left( g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \right) \times N_{\gamma,\rm pump}\; N_{\gamma,\rm probe}^{\rm circ}\, [\Delta_{\rm probe}]$$

# Coherent enhancement: **Phonons**




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




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

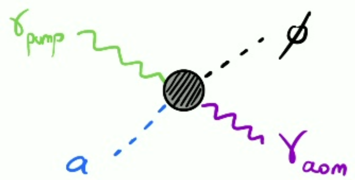
$$= \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0^{(a)} \boxed{\left( g_{a\gamma\gamma} \frac{\sqrt{2\rho_a}}{m_a} \right)} \left( a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} \right)$$

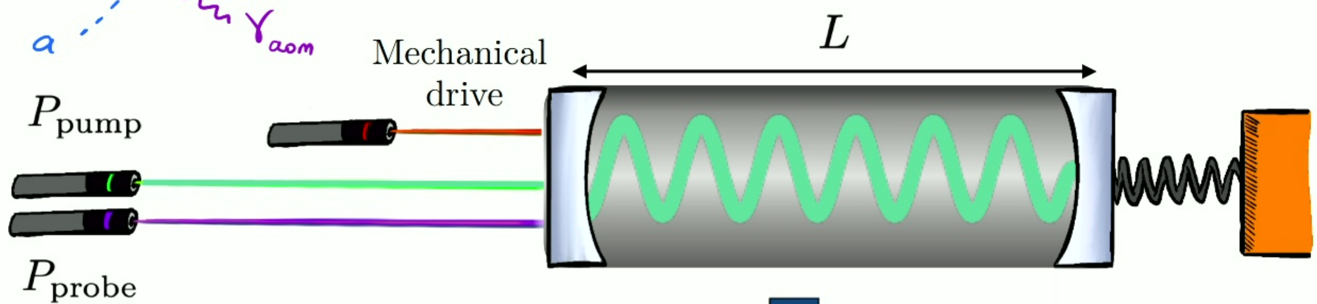
$\sim 10^{-22}$ for QCD axion

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

# Axioptomechanics

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




**1** For usual experiments in their lab:

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

**2** What they can "easily" do, **even now**:

- $N_{\text{pump}} \simeq 10^{14}$ $\quad P_{\text{pump}} \sim 10\,\text{mW}$
- $N_{\text{probe}} \simeq 10^{14}$ $\quad P_{\text{probe}} \sim 10\,\text{mW}$
- $N_\phi \simeq 10^{14}$ $\quad L \sim 1$ cm
- $\mathcal{F}_{\text{opt}}/\pi \sim 10^5$

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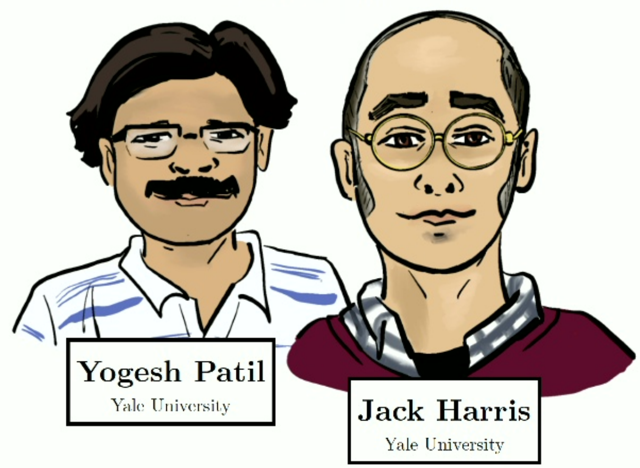
Jack Harris Lab



# Conclusions

Importance of exploiting potential of existing /upcoming experiments to explore dark matter possibilities.

**Atom Interferometers**

Advantages
- Decoherence has no lower bound on energy deposition
- Coherent enhancement
- Boost in the rate for light DM and mediator

Future Directions
- Understand the possible backgrounds.
- Study the implications of enjoying a network of AIs.
- Constrain other new physics: DM nuggets?
- Study decoherence in other quantum sensors: atomic clocks?

**Axioptomechanics**

Advantages
- Coherent enhancement/number state enhancement (?)
- Decoupling length from axion mass

Future Directions
- Study backgrounds in specific experiment [experimental proposal]
- Explore other materials

**J. Harris and J. Patil at Yale U.**

Thank you!