Caltech

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# Hunting for Light DM with Quantum Sensors

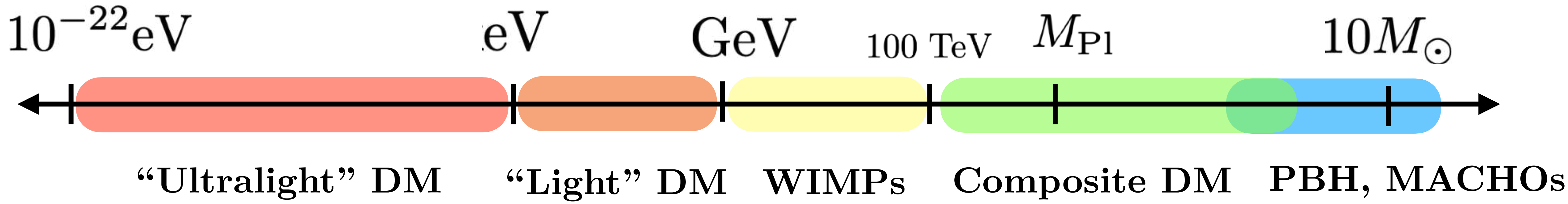
## Atom Interferometers & Optomechanical Cavities

Clara Murgui

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

DESY. 17th October 2022

# Dark Matter: where to look?



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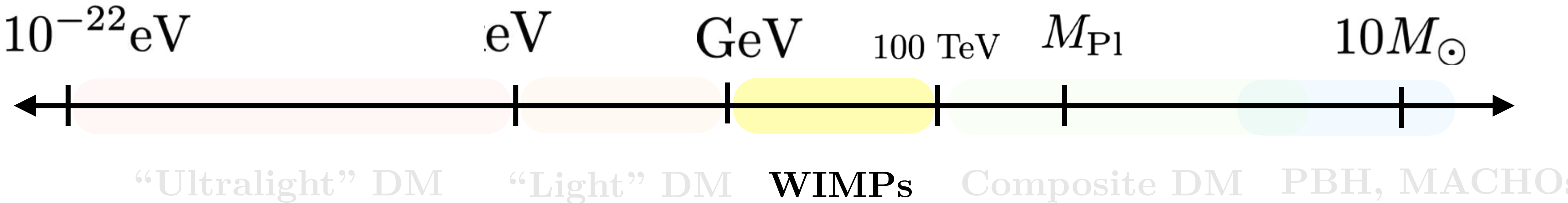
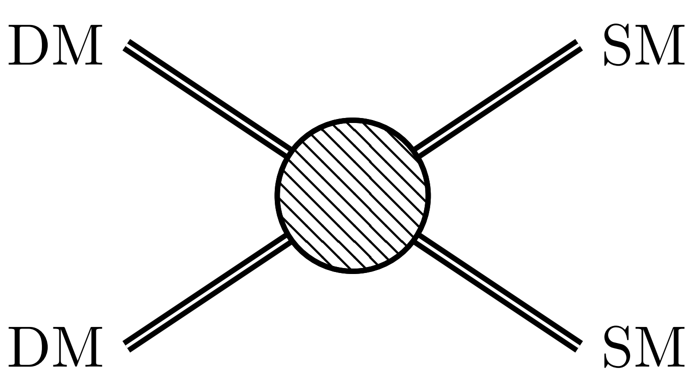


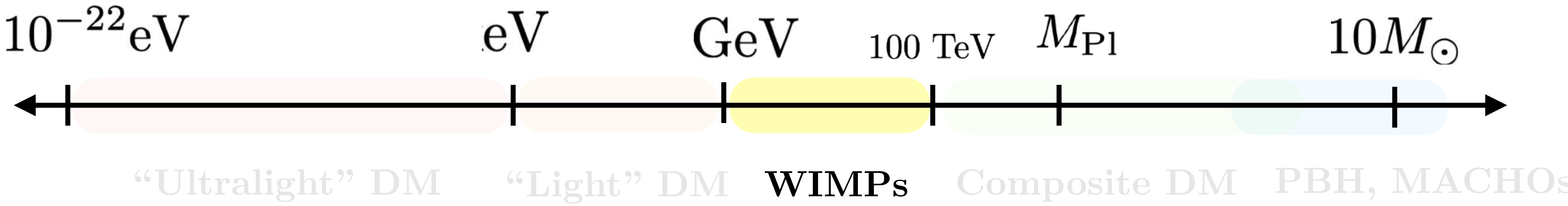

**The WIMP miracle**

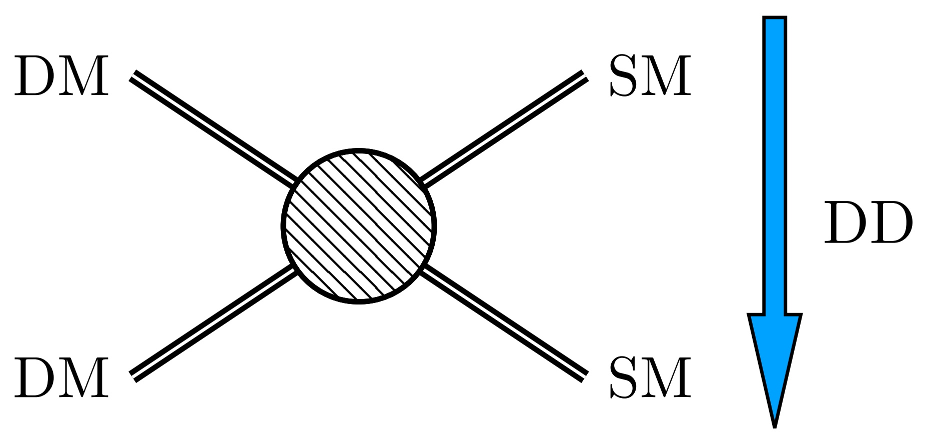



$$\langle \sigma v \rangle \sim \frac{G_F^2}{8\pi} m_\chi^2 \frac{c}{3} \sim 10^{-24} \text{cm}^3/\text{s} \left( \frac{m_\chi}{100 \text{ GeV}} \right)^2$$

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

# Dark Matter: where to look?




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

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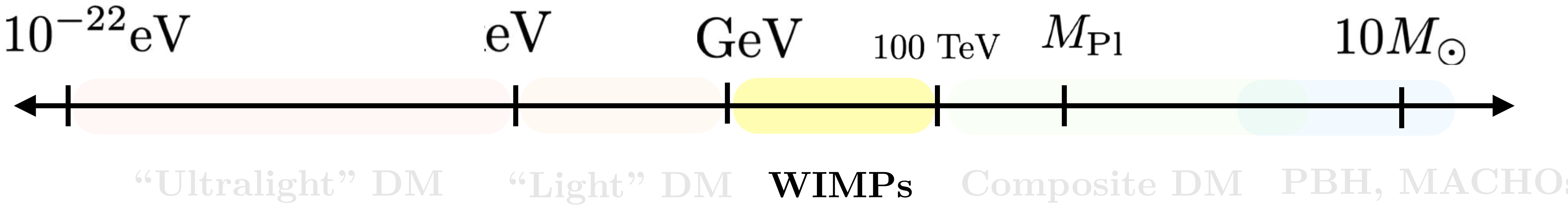


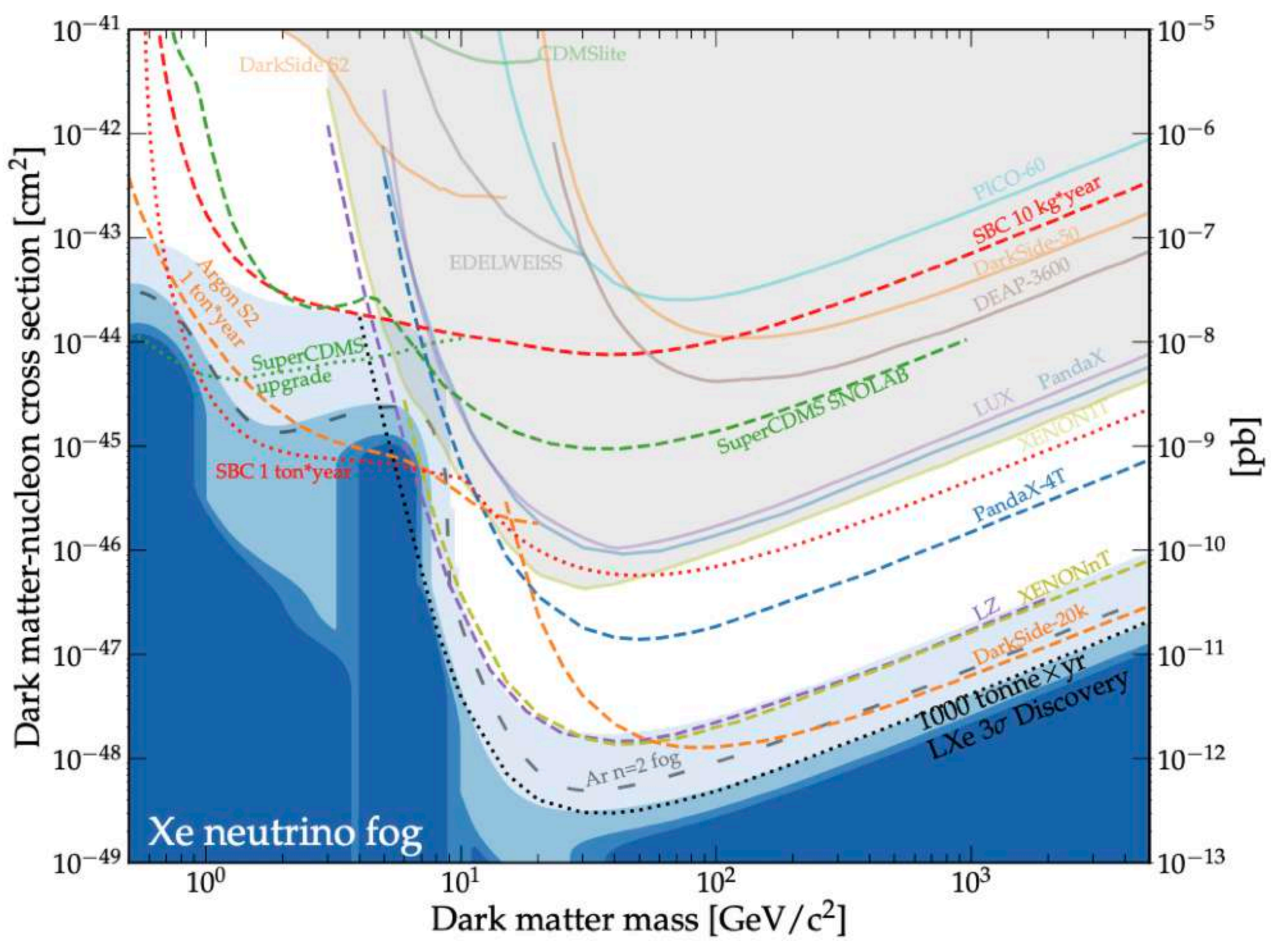


[Akerib, D. S., et al., Snowmass2021, 2203.08084]

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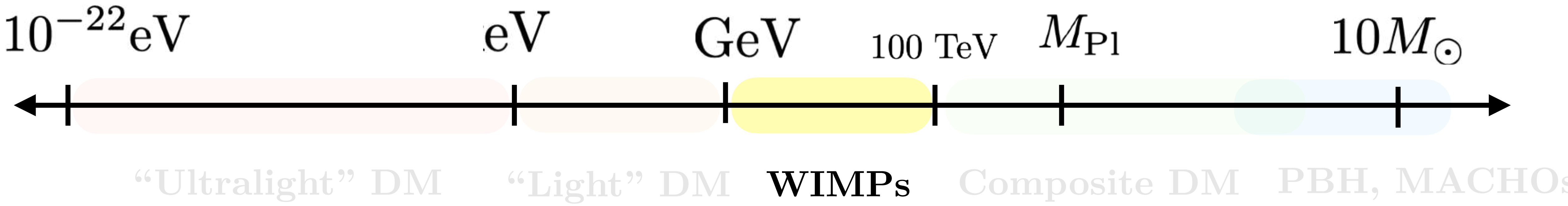


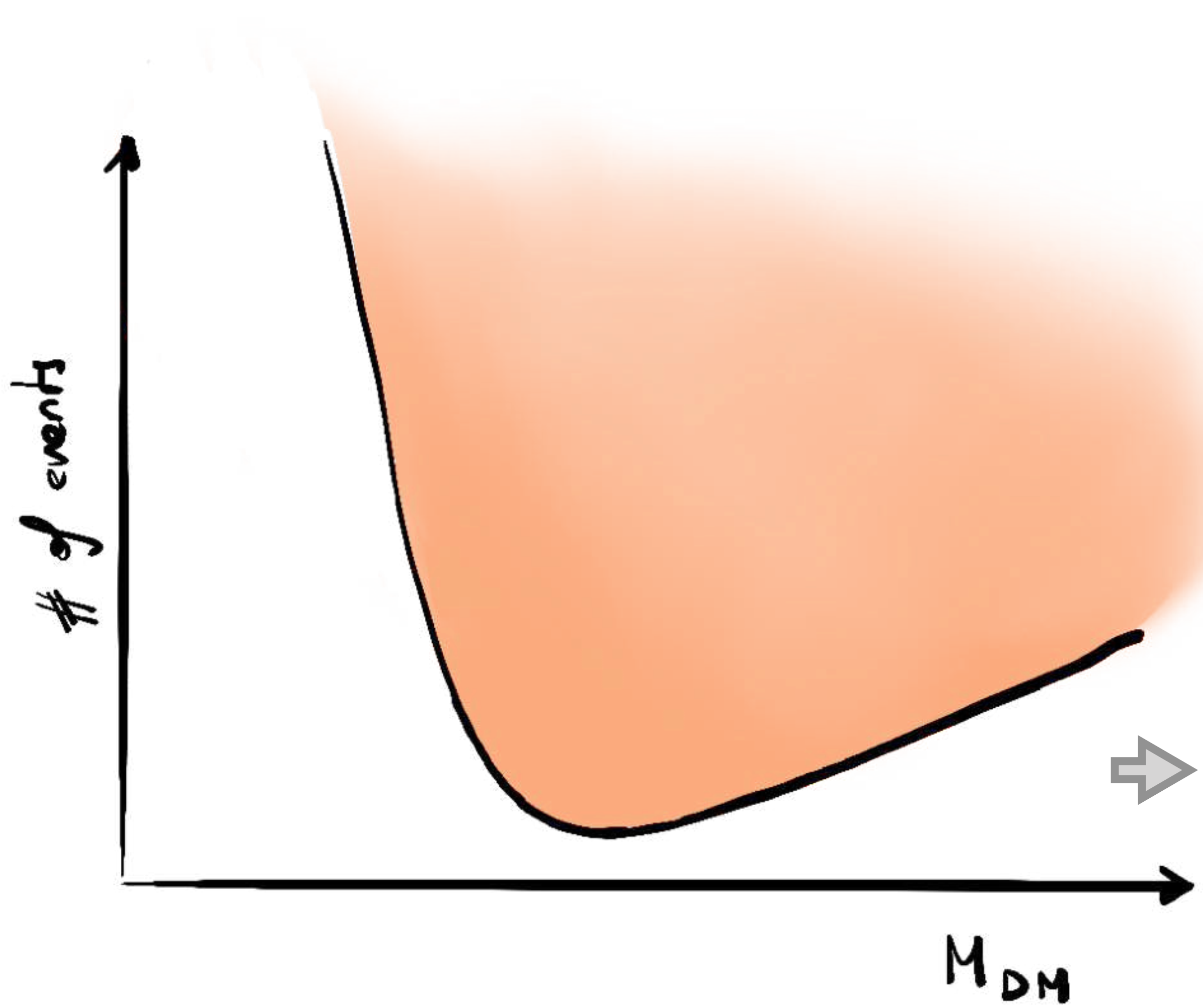


$$\sigma \sim 10^{-34}\text{cm}^2 \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2$$

loss of “flux” $n_\chi = \dfrac{\rho_\chi}{m_\chi}$

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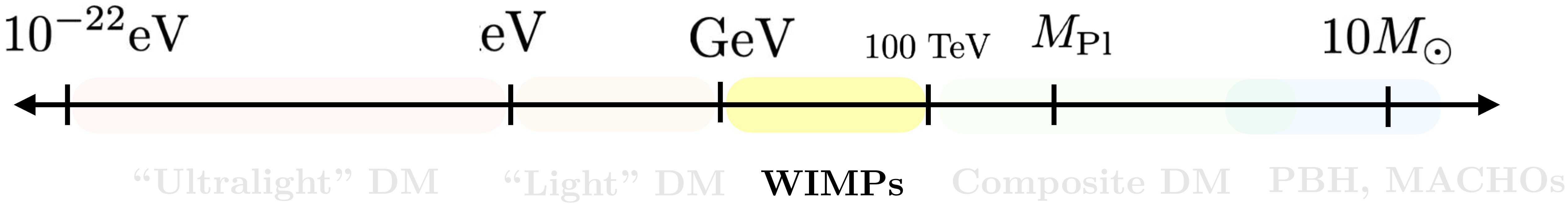


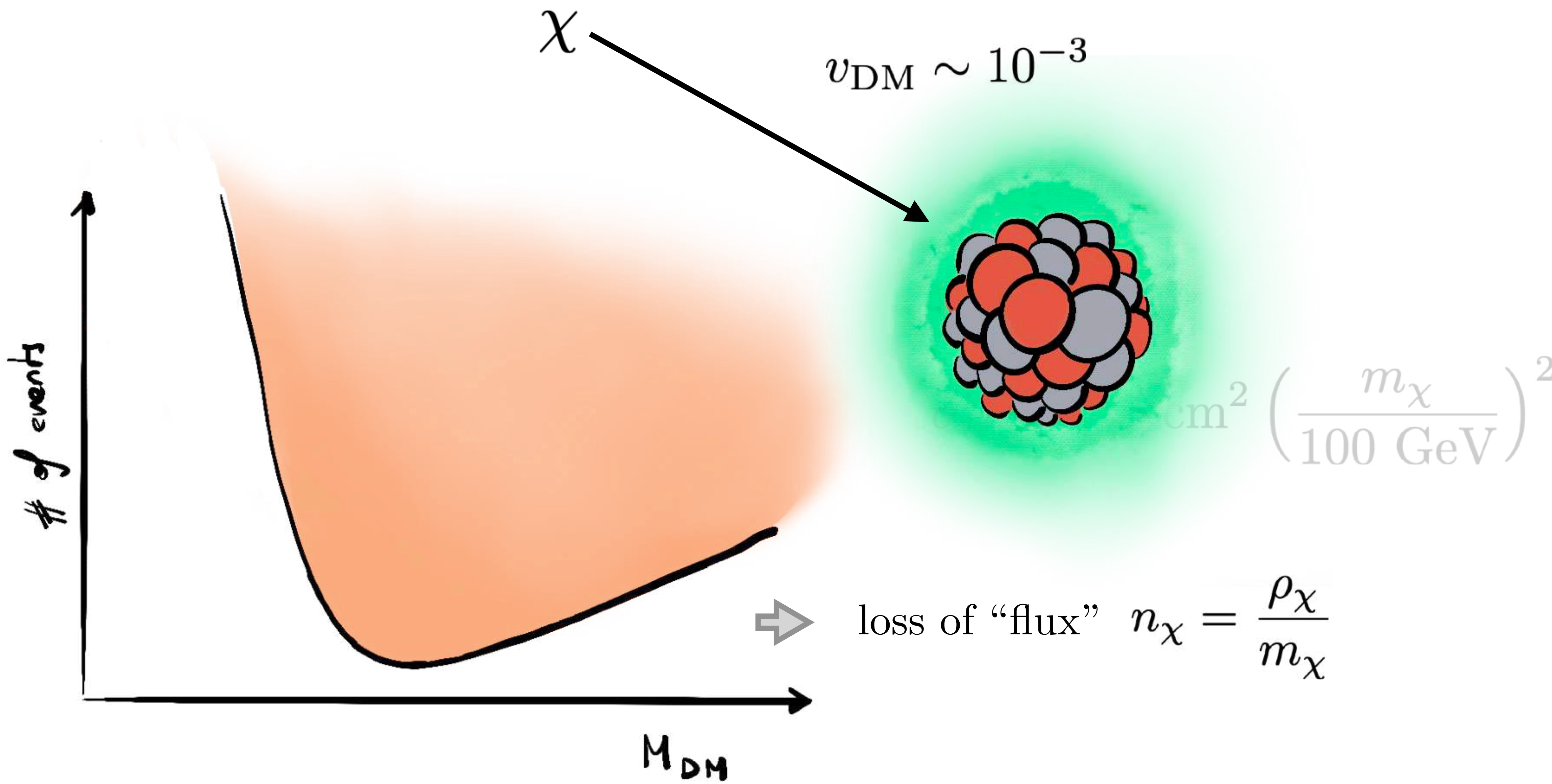

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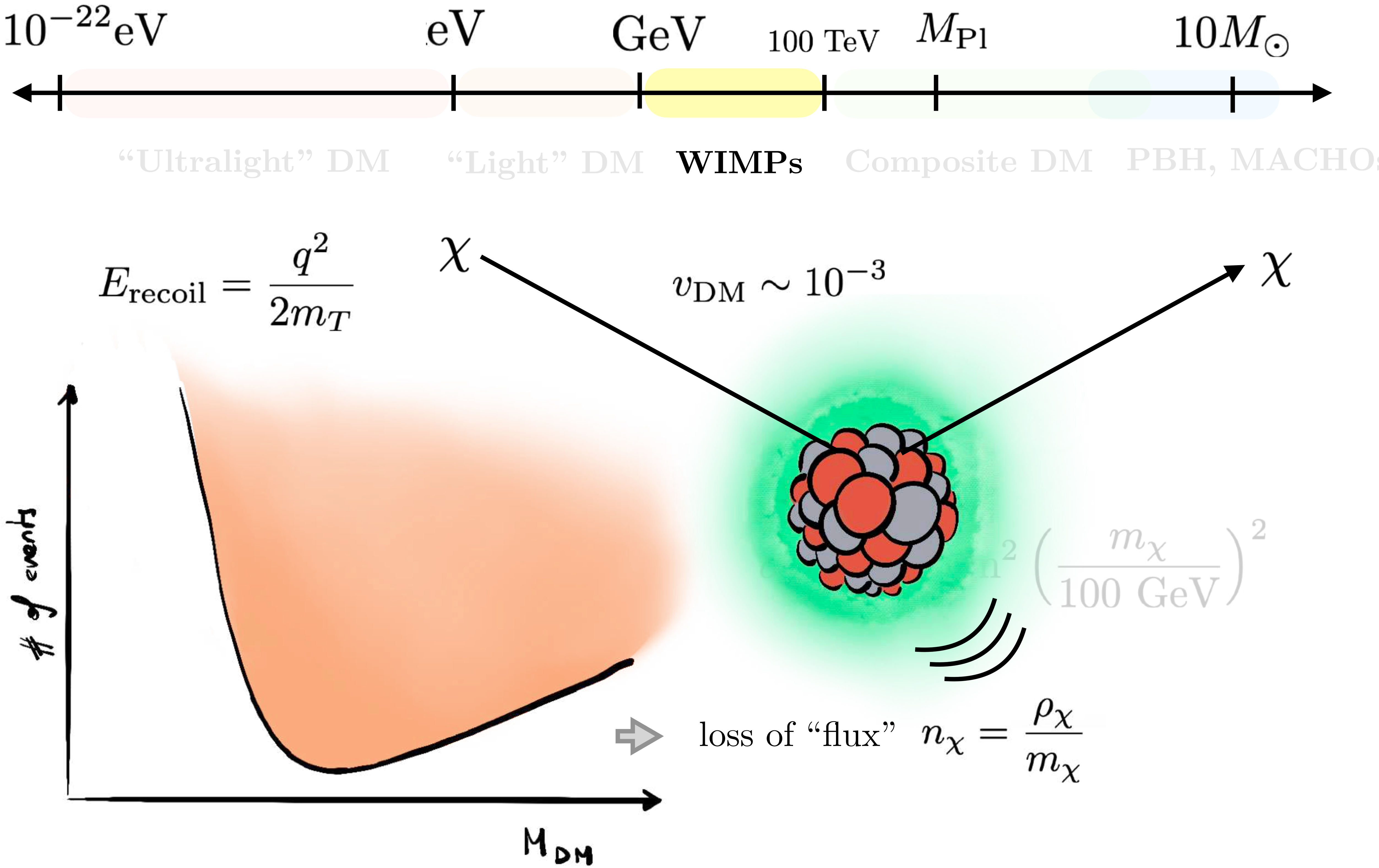

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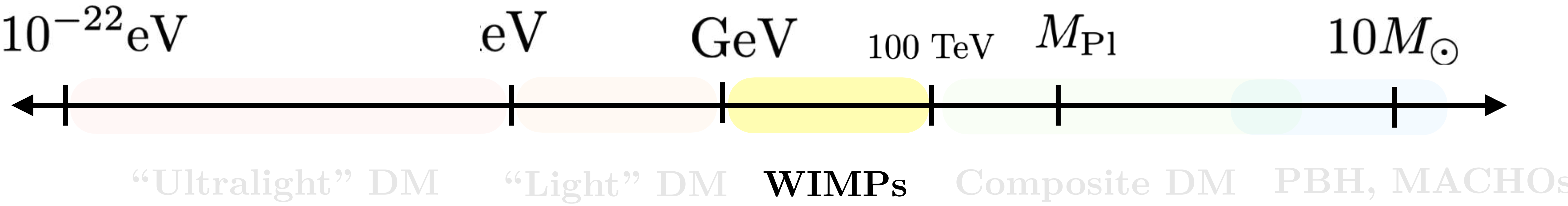
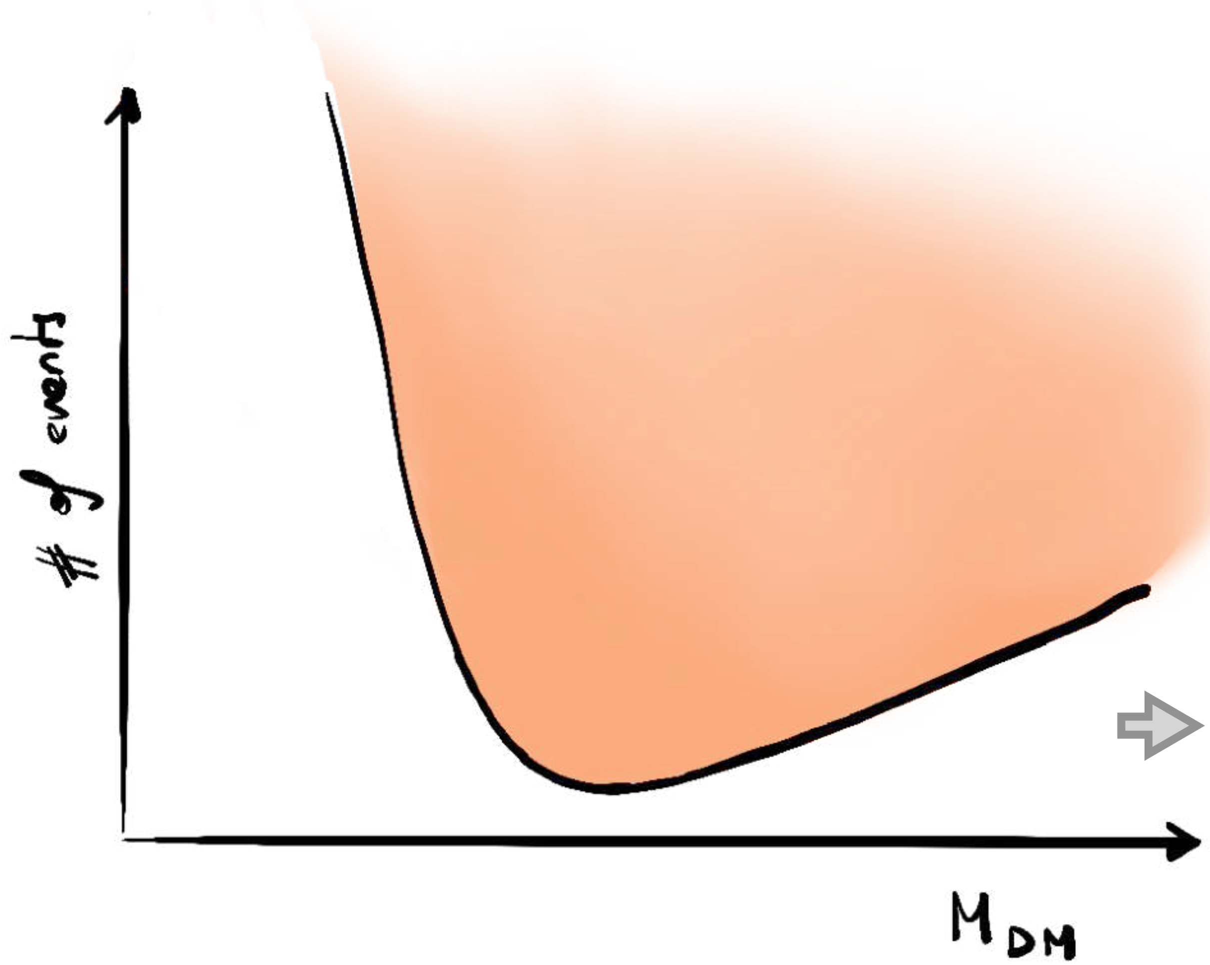



$$E_{\rm recoil}^{\rm max} \sim \left(\frac{m_\chi}{\rm GeV}\right) {\rm keV}$$

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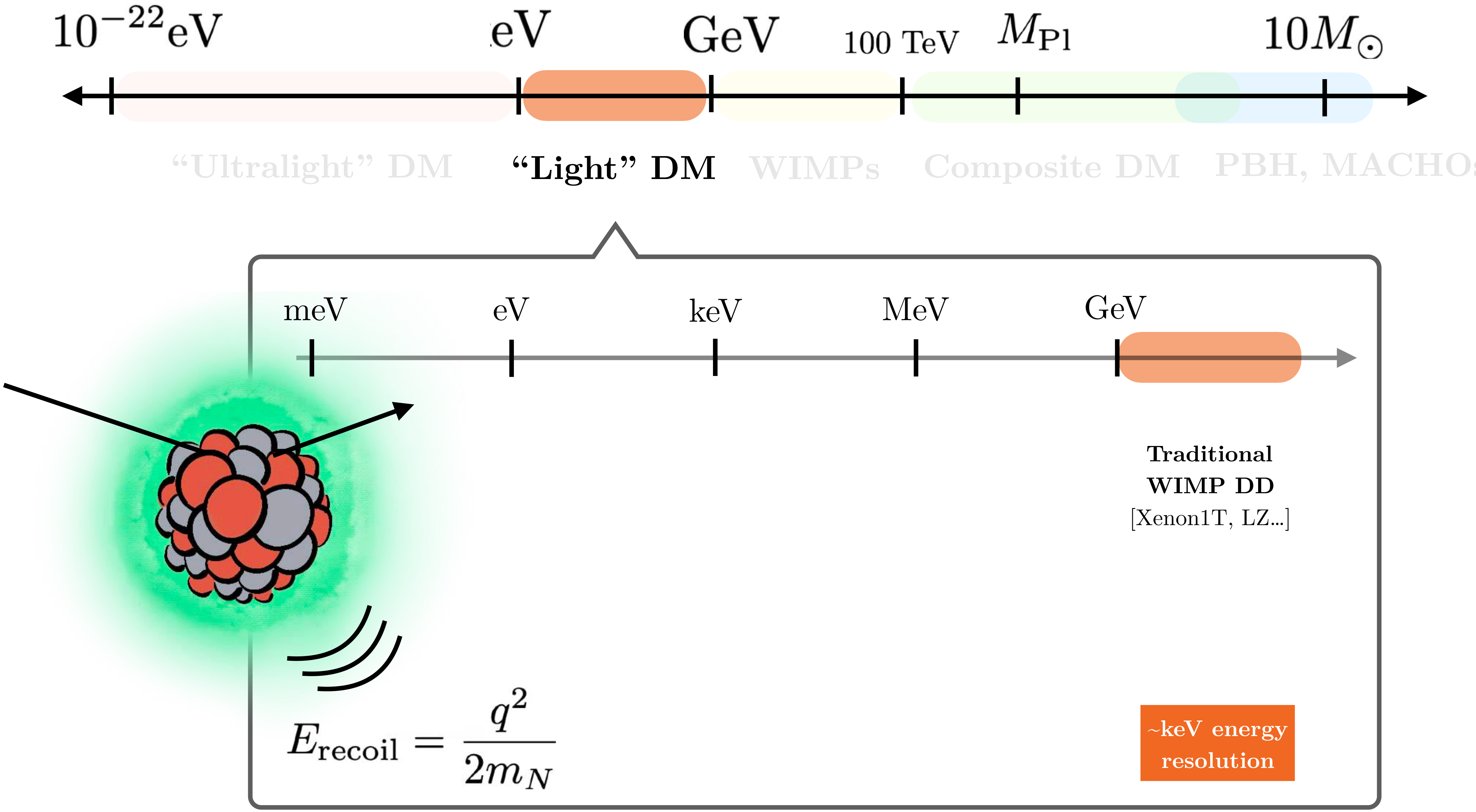


[adapted from K. Zurek’s talks]

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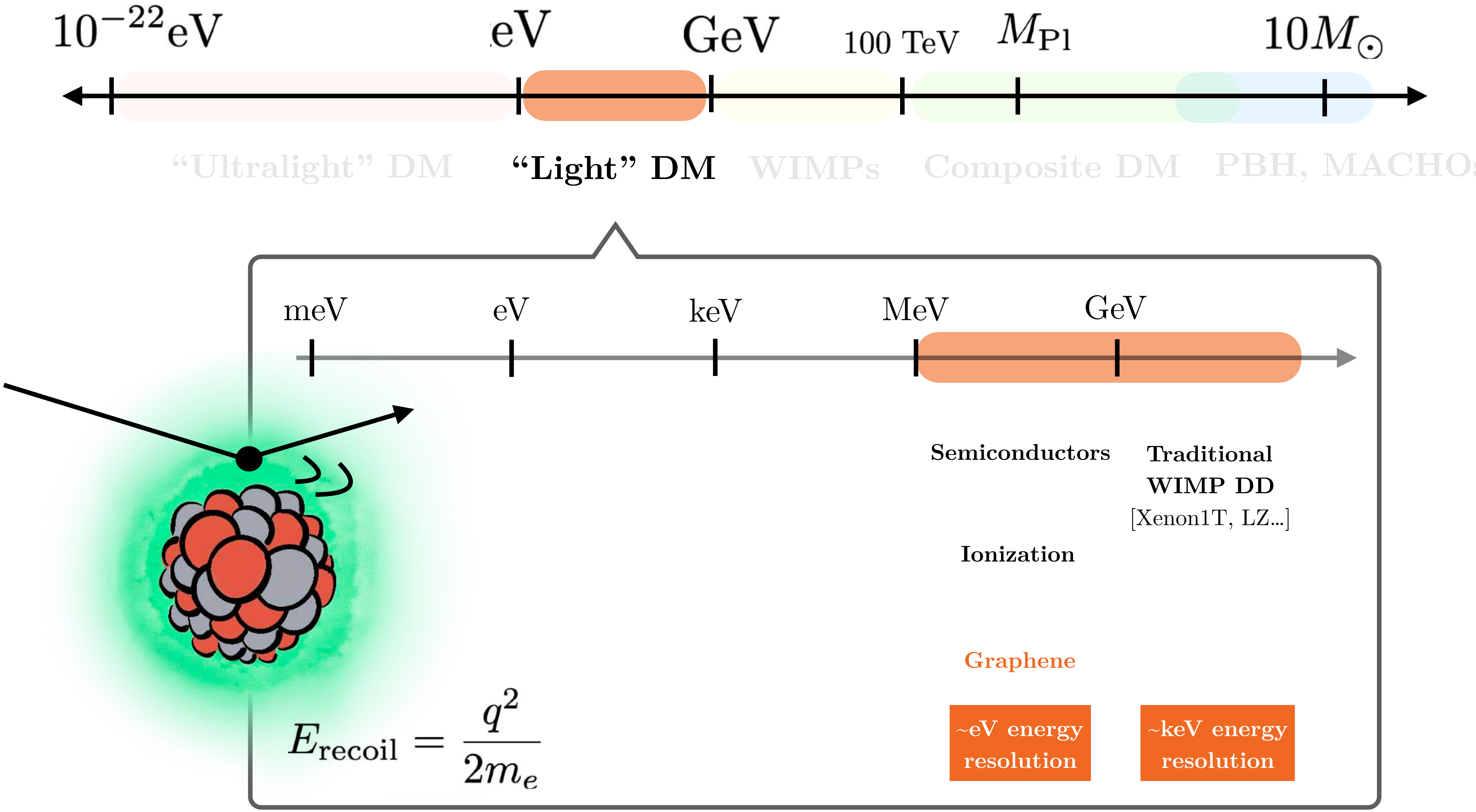


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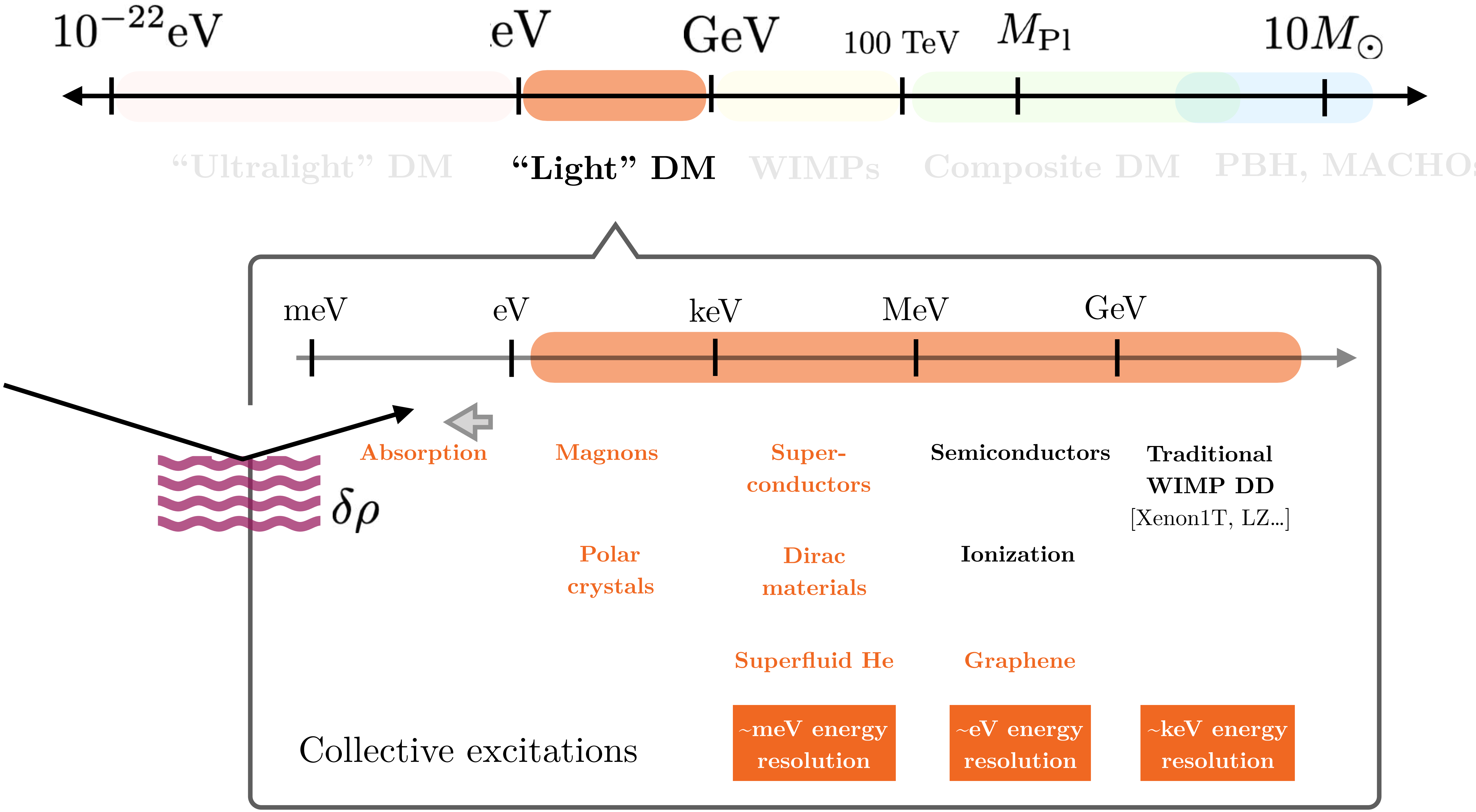
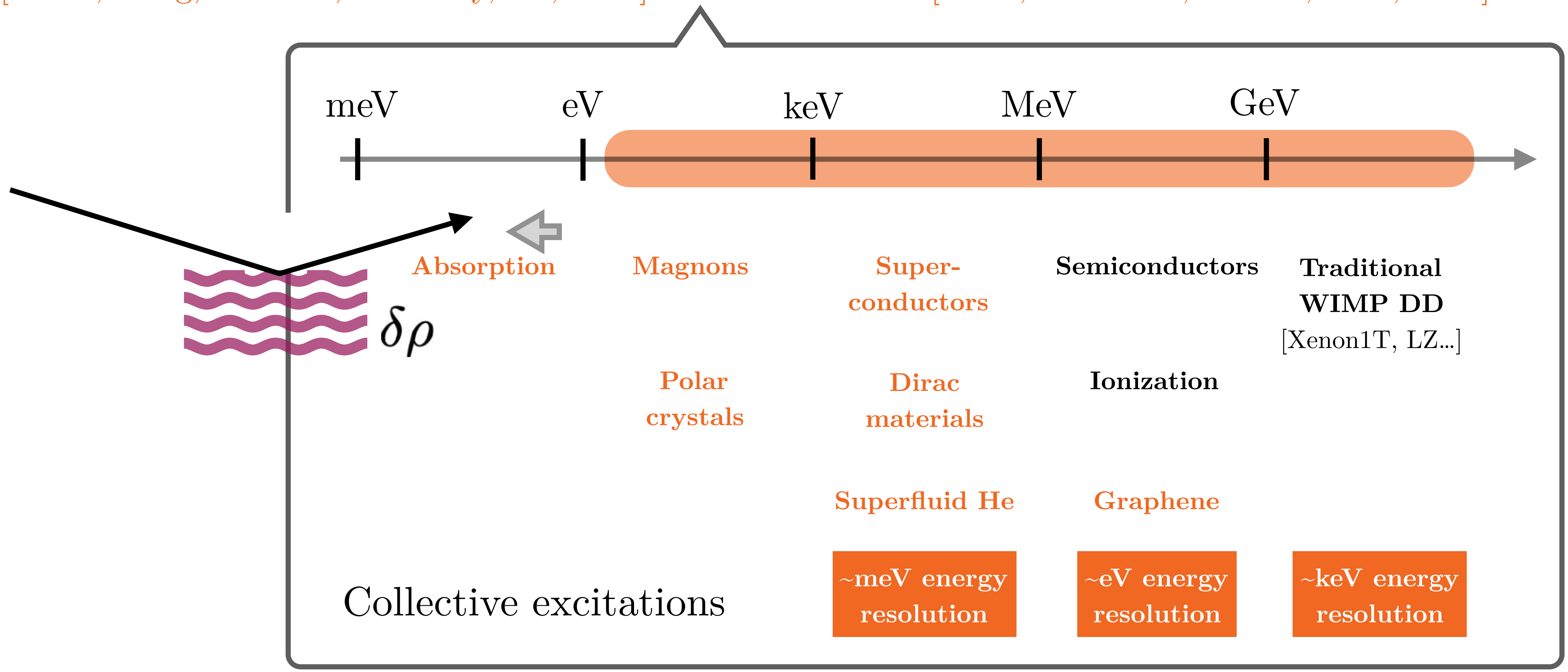



[adapted from K. Zurek's talks]

# Dark Matter: where to look?

[Essig, Mardon, Volansky, 2011]
[Graham, Kaplan, Rajendran, Walters, 2012]
[Lee, Lisanti, Mishra-Sharma, Safdi, 2015]
[Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu, 2015]
[Derenzo, Essig, Massari, Soto, Yu, 2016]
[Hochberg, Lin, Zurek, 2016]
[Bloch, Essig, Tobioka, Volansky, Yu, 2016]
[Essig, Volansky, Yu, 2017]
[Kurinsky, Yu, Hochberg, Cabrera, 2019]
[Emken, Essig, Kouvaris, Sholapurka, 2019]
[Griffin, Inzani, Trickle, Zhang, Zurek, 2019]
[Coskuner, Mitridate, Olivares, Zurek, 2020]
[Mitridate, Trickle, Zhang, Zurek, 2021]
[Chen, Mitridate, Trickle, et al, 2022]

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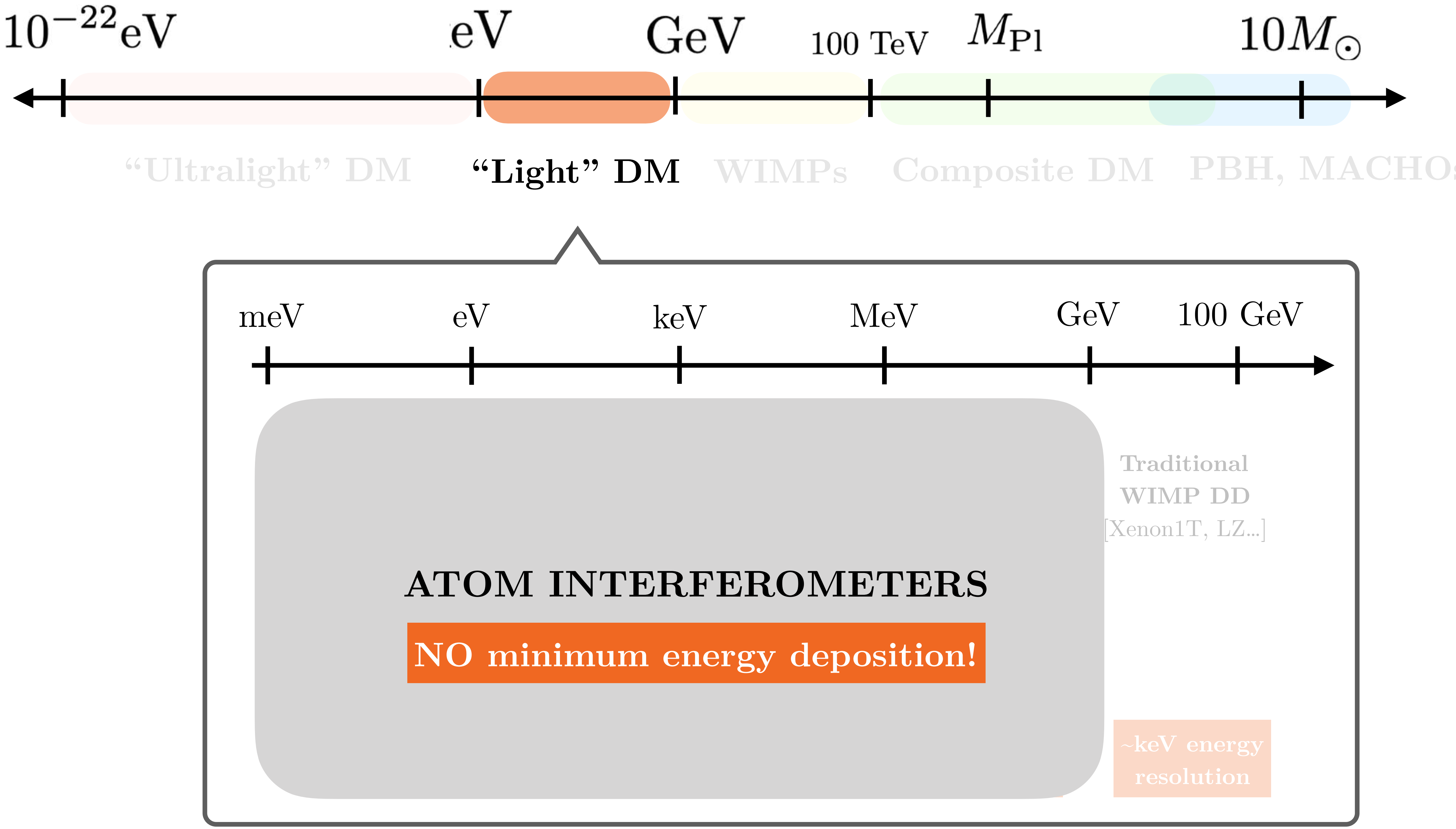


# **Atom Interferometer** tests of **Dark Matter**

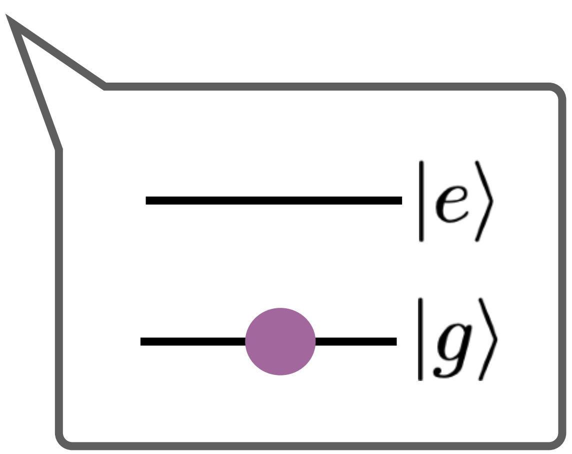
**2205.13546**

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

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

# AIs: the Principle

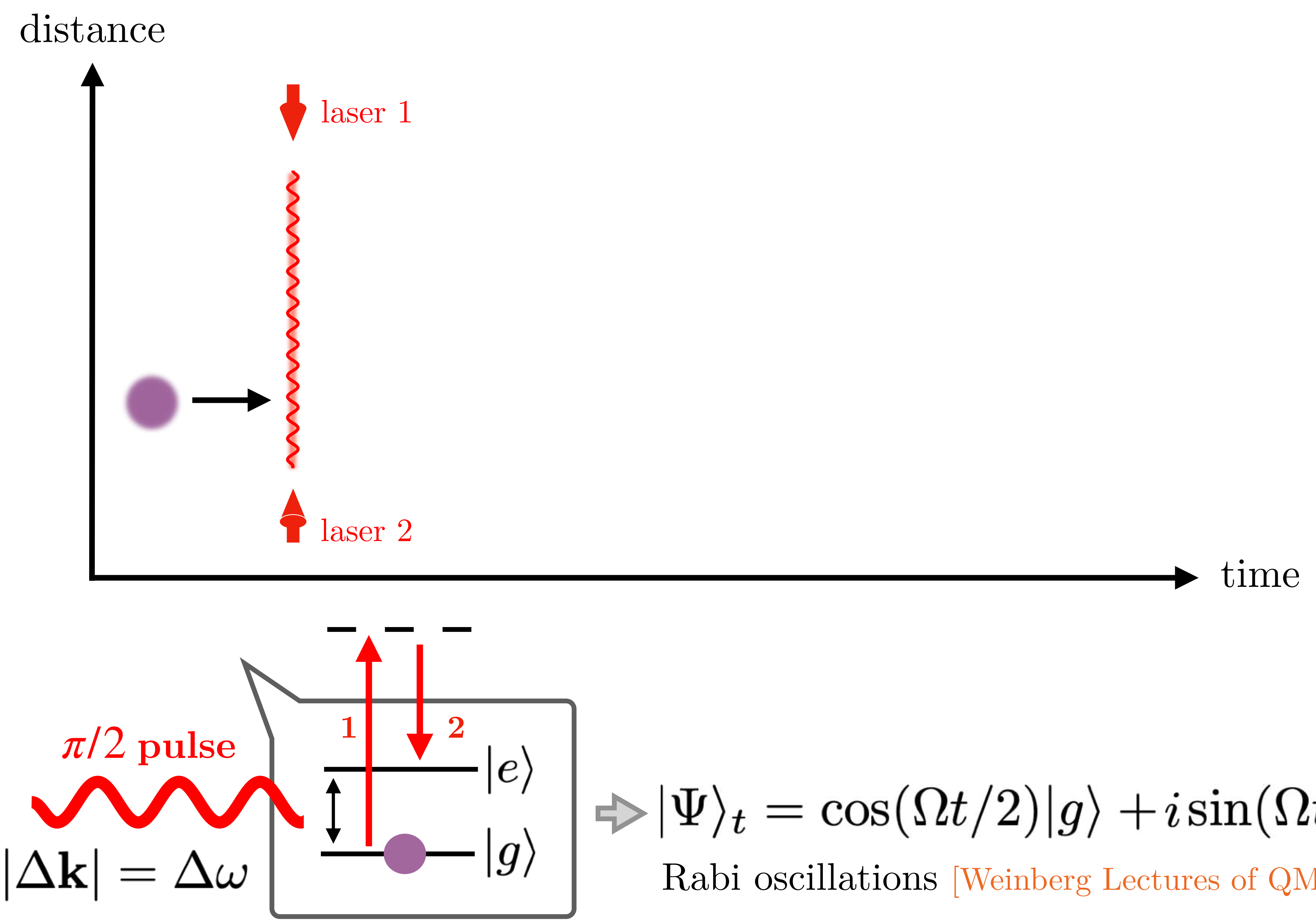
Review: arXiv:2003.12516


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

# AIs: the Principle

Review: arXiv:2003.12516

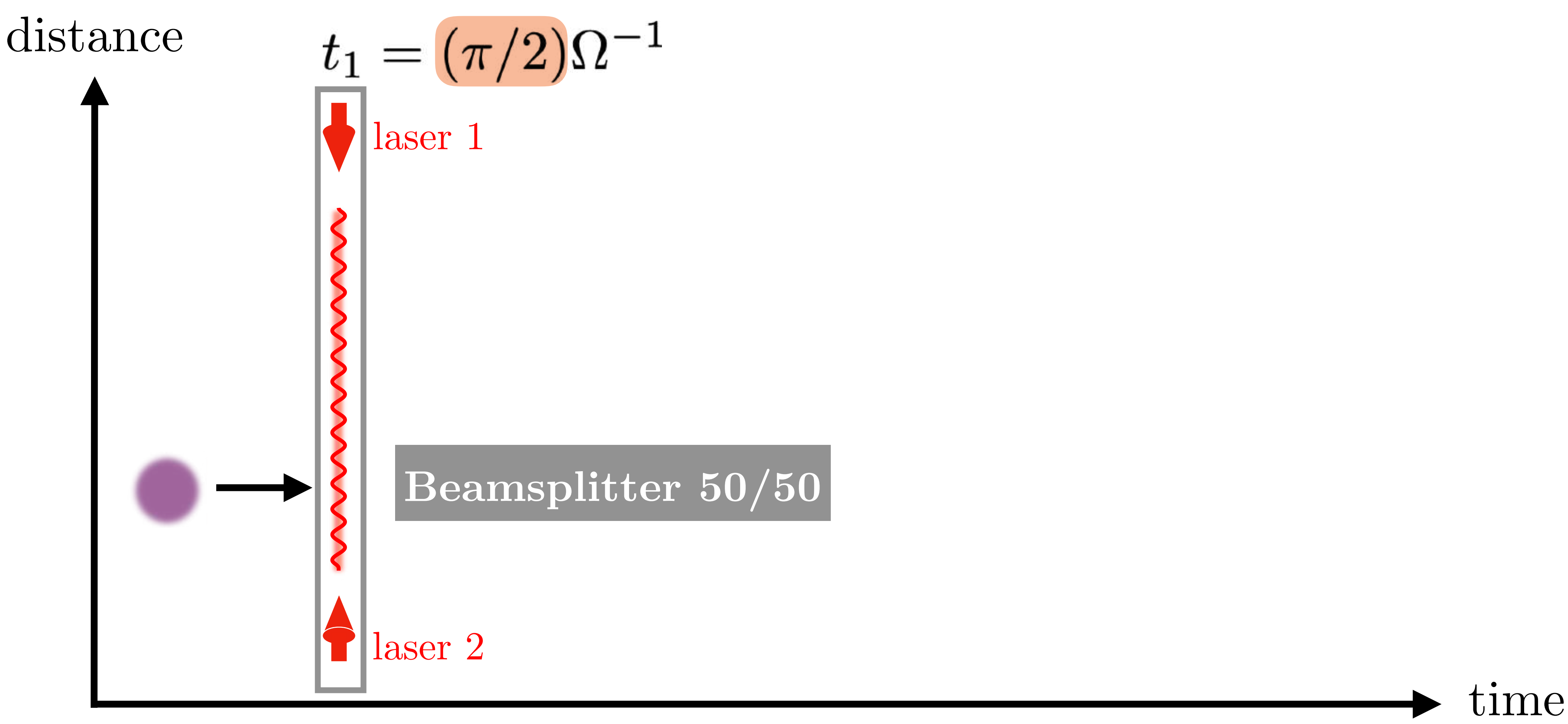


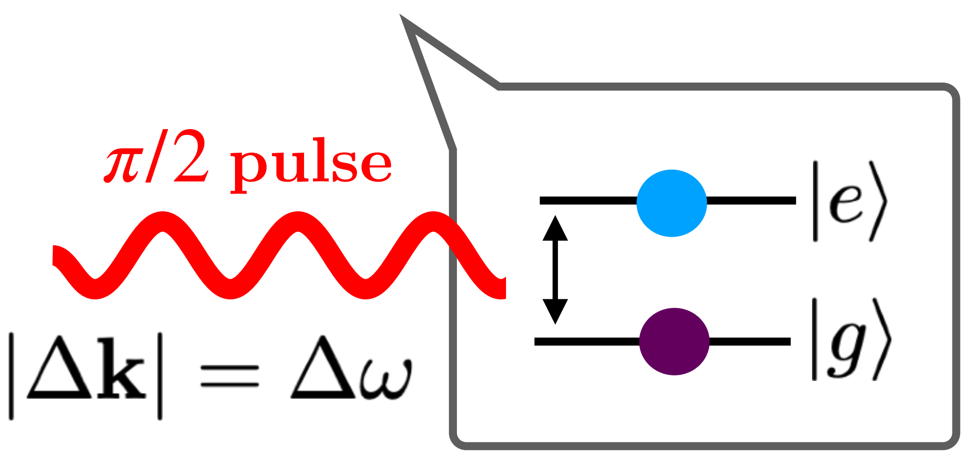

$$|\Psi\rangle_t = \cos(\Omega t/2)|g\rangle + i\sin(\Omega t/2)|e\rangle$$

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

# AIs: the Principle

Review: arXiv:2003.12516



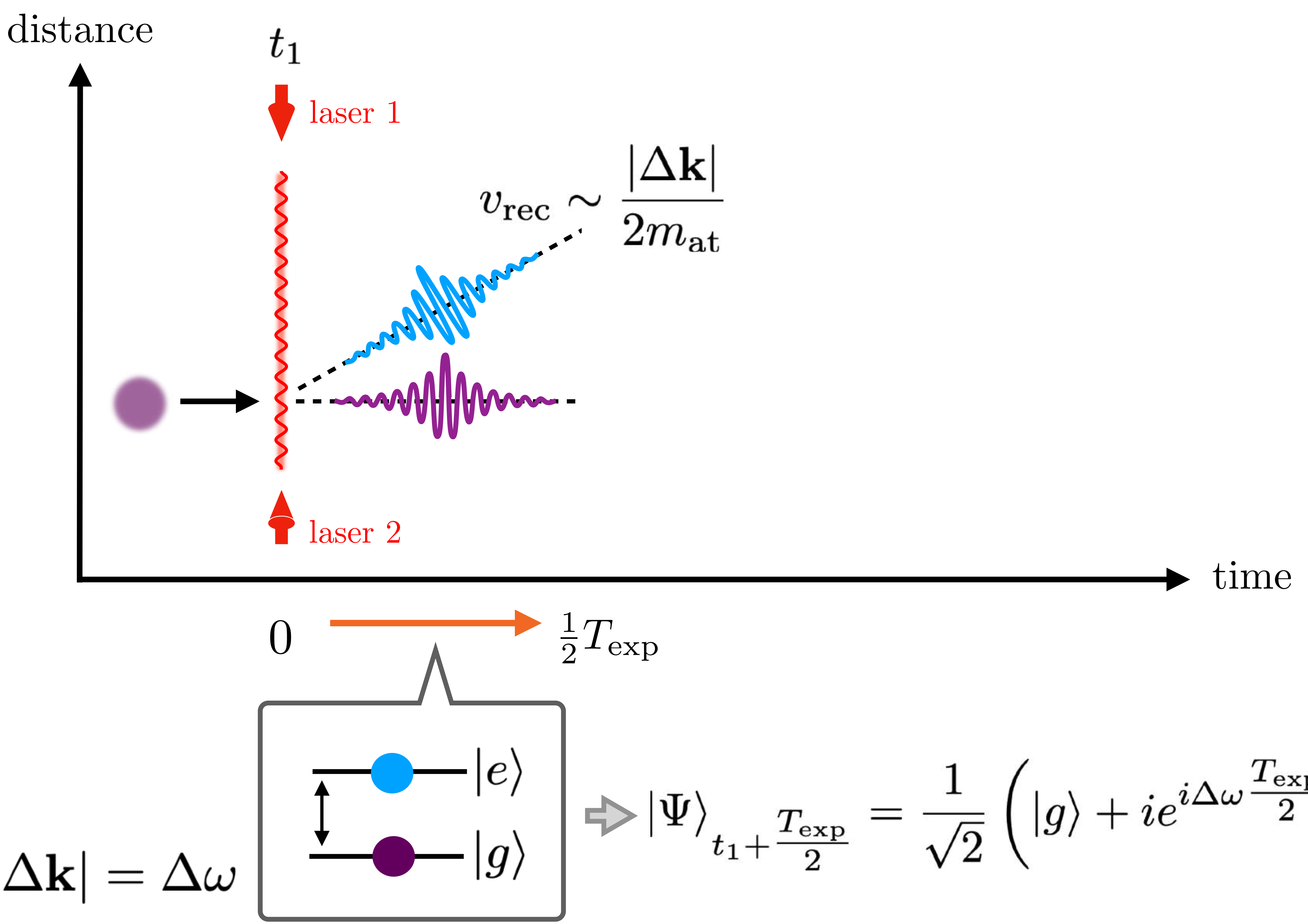




$$|\Psi\rangle_{t_1} = \cos(\pi/4)|g\rangle + i\sin(\pi/4)|e\rangle$$

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

# AIs: the Principle

Review: arXiv:2003.12516




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

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

# AIs: the Principle

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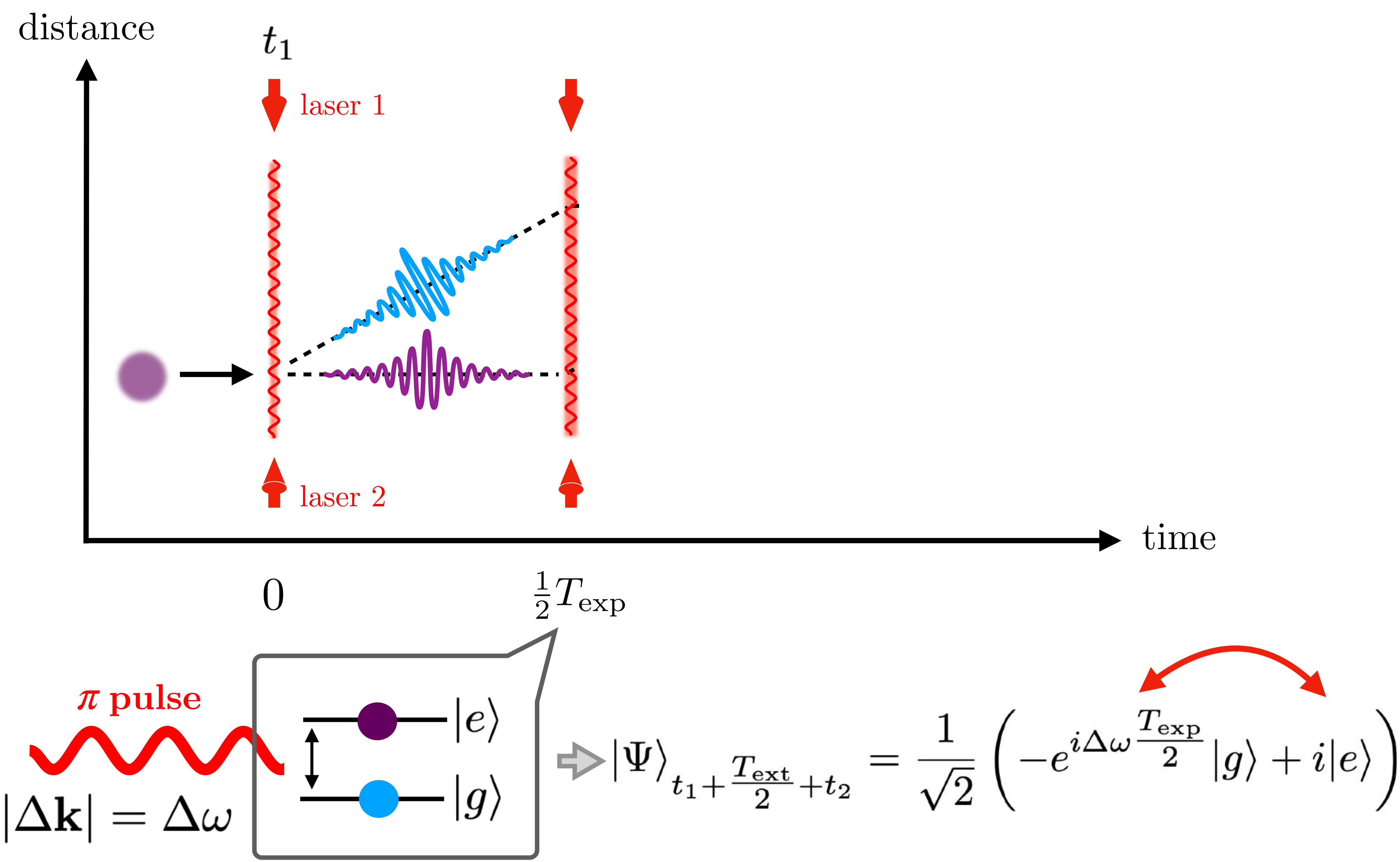
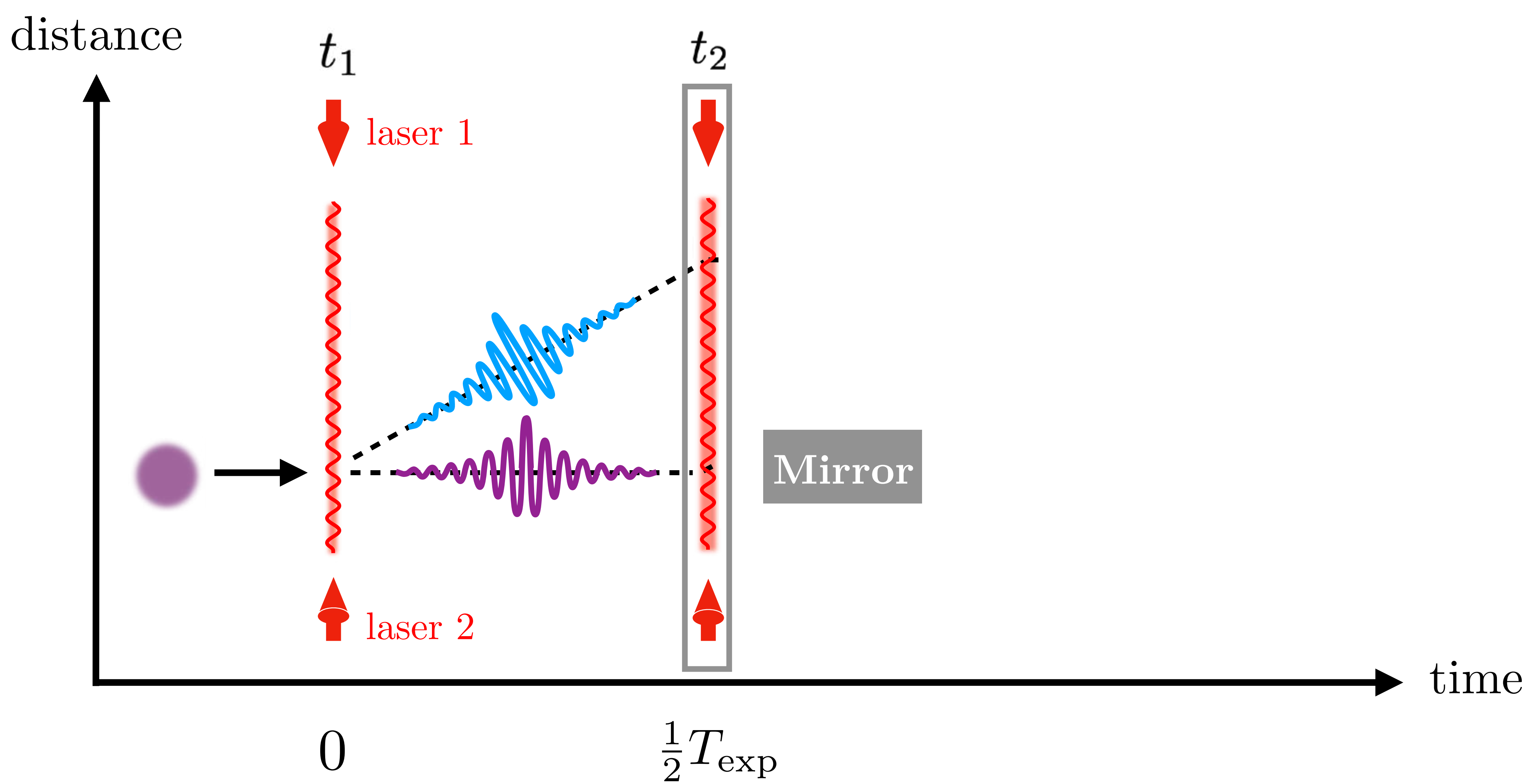
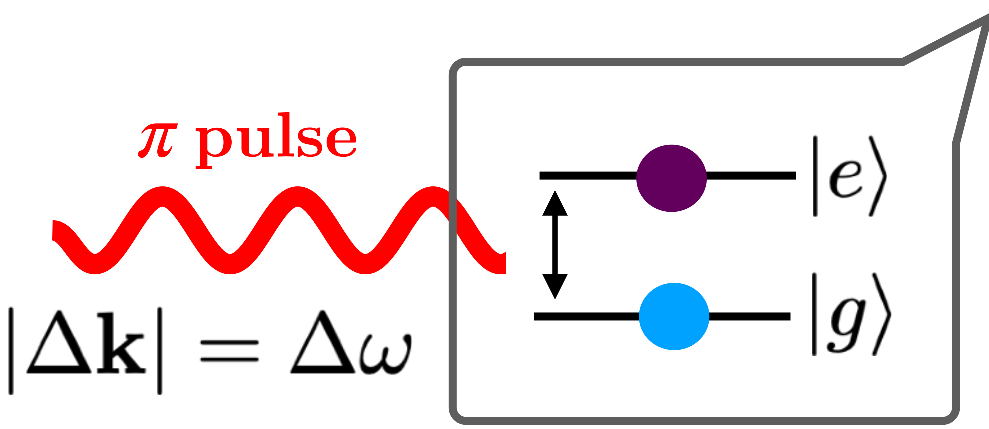



$$|\Psi\rangle_{t_1+\frac{T_{\rm ext}}{2}+t_2} = \frac{1}{\sqrt{2}}\left(-e^{i\Delta\omega\frac{T_{\rm exp}}{2}}|g\rangle + i|e\rangle\right)$$

# AIs: the Principle

Review: arXiv:2003.12516




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

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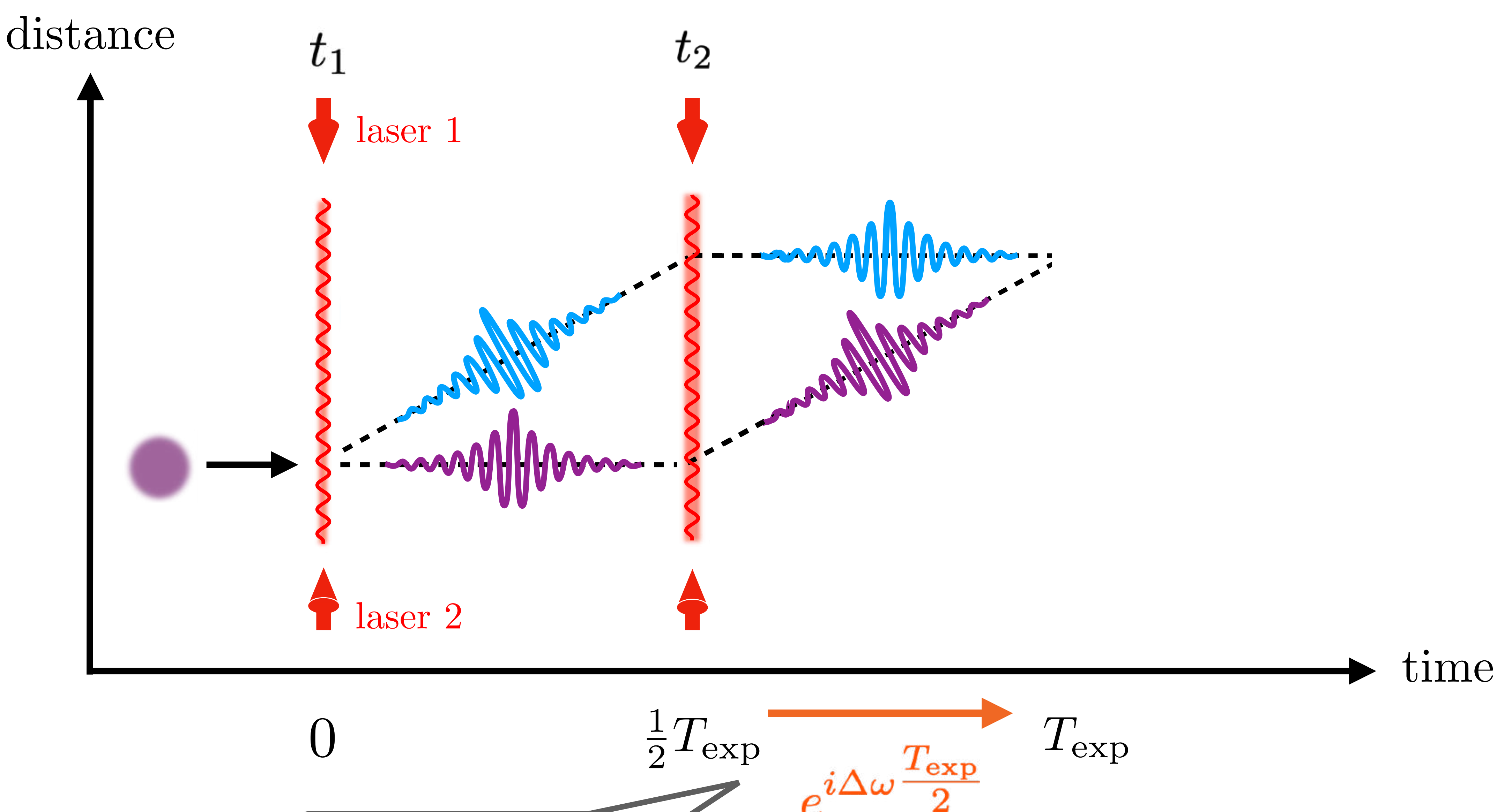
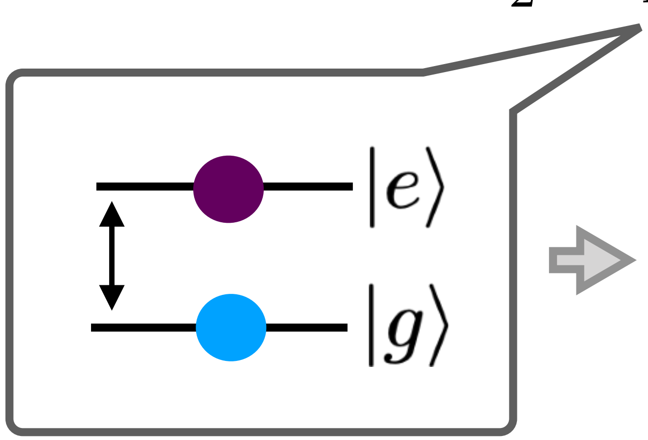


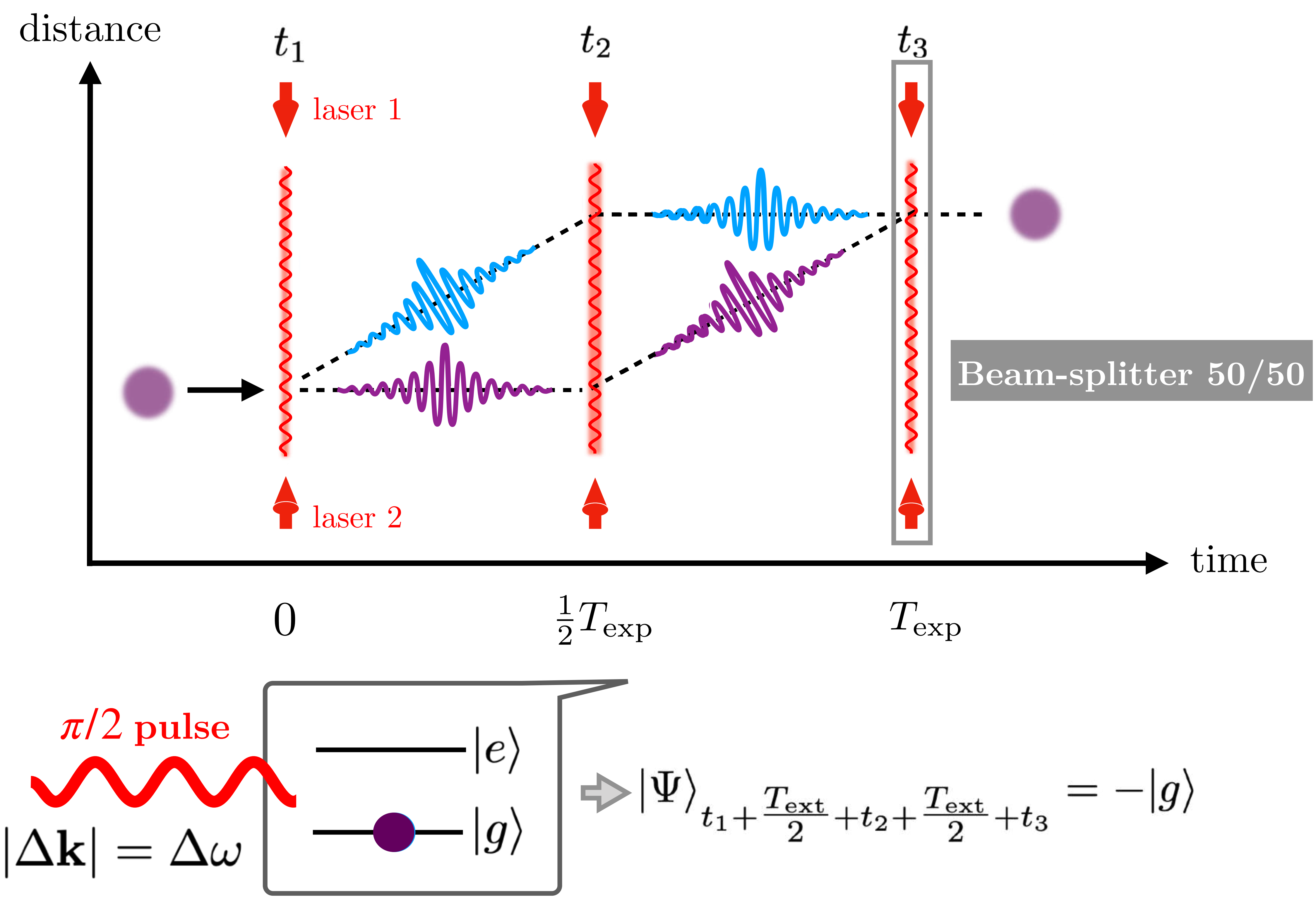




$$|\mathbf{\Delta k}| = \Delta\omega$$

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

# AIs: the Principle

Review: arXiv:2003.12516



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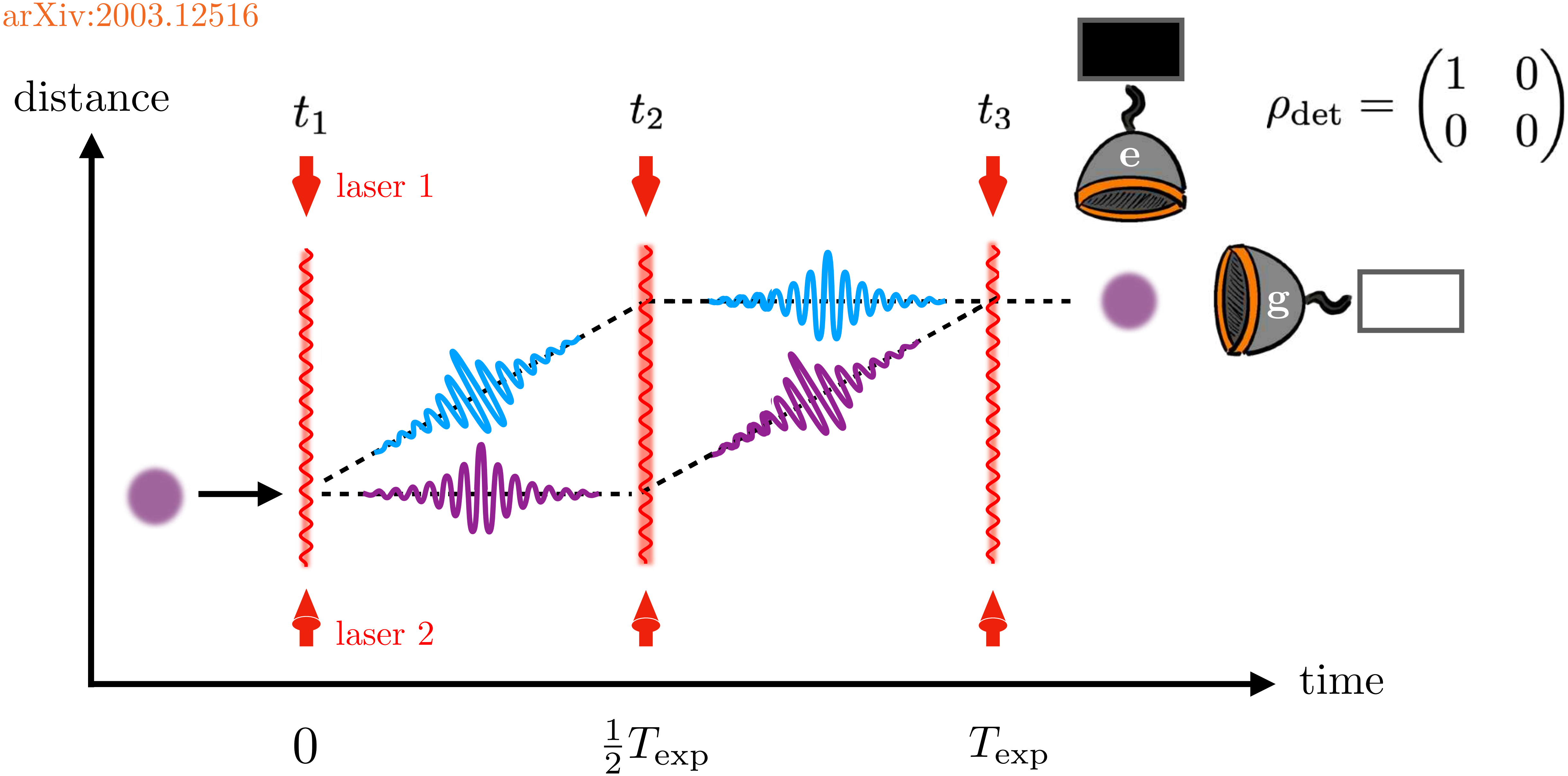


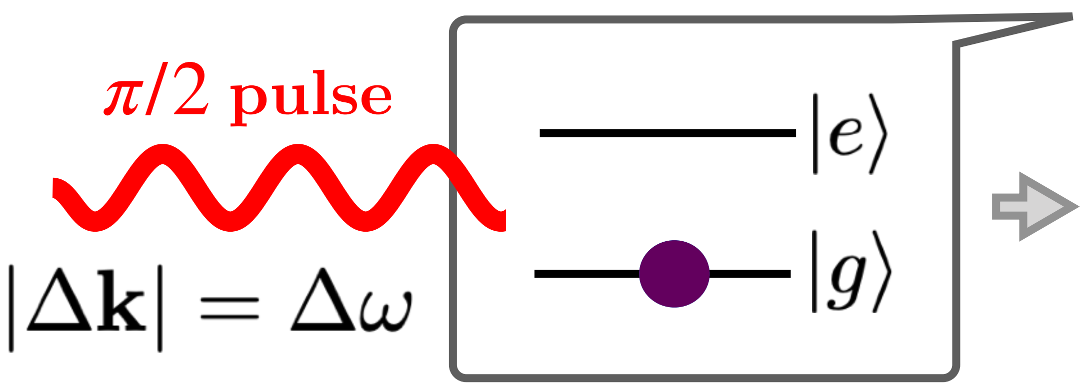


$$|\Psi\rangle_{t_1+\frac{T_{\rm ext}}{2}+t_2+\frac{T_{\rm ext}}{2}+t_3} = -|g\rangle$$

# AIs: the Principle

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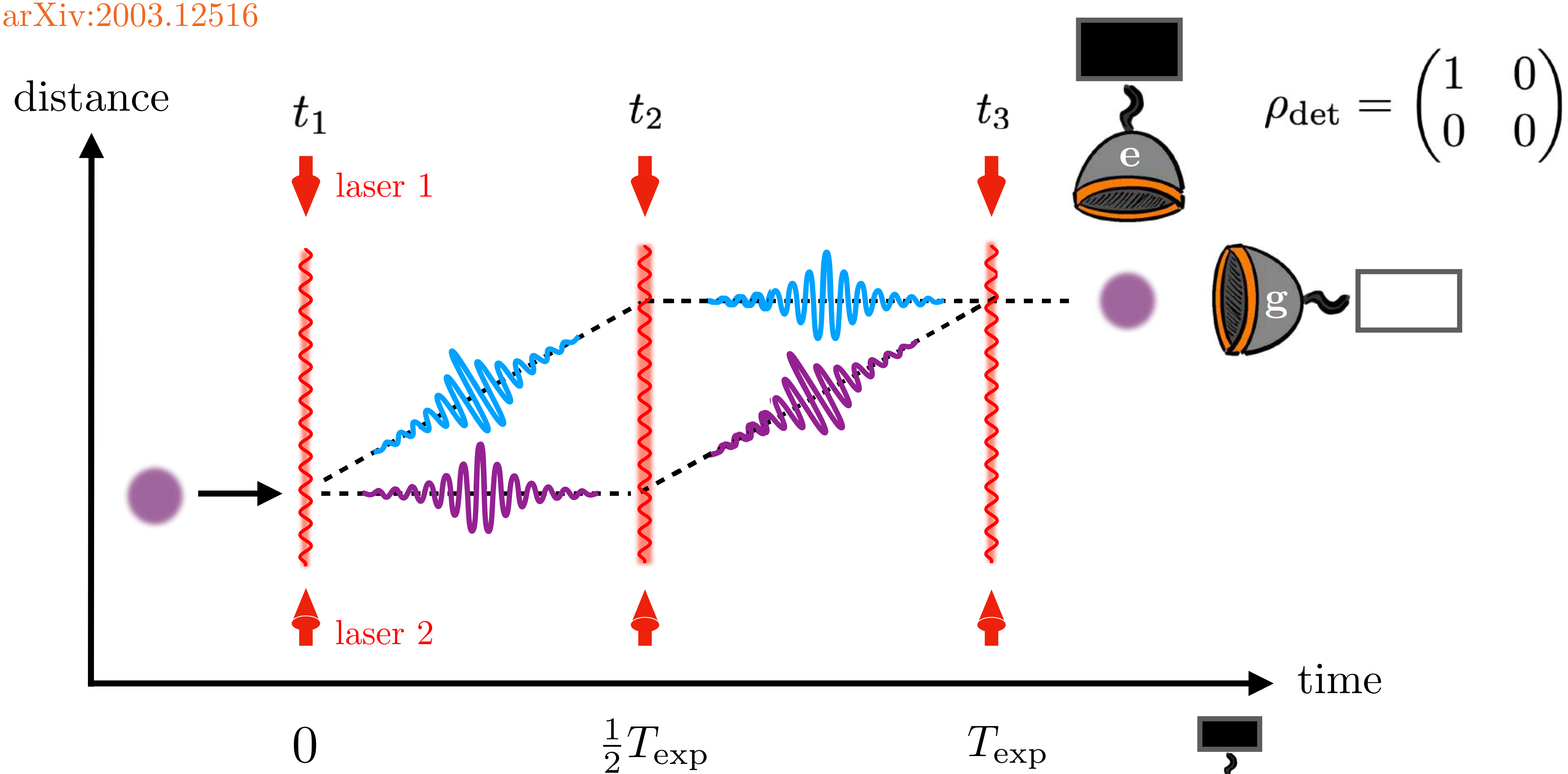
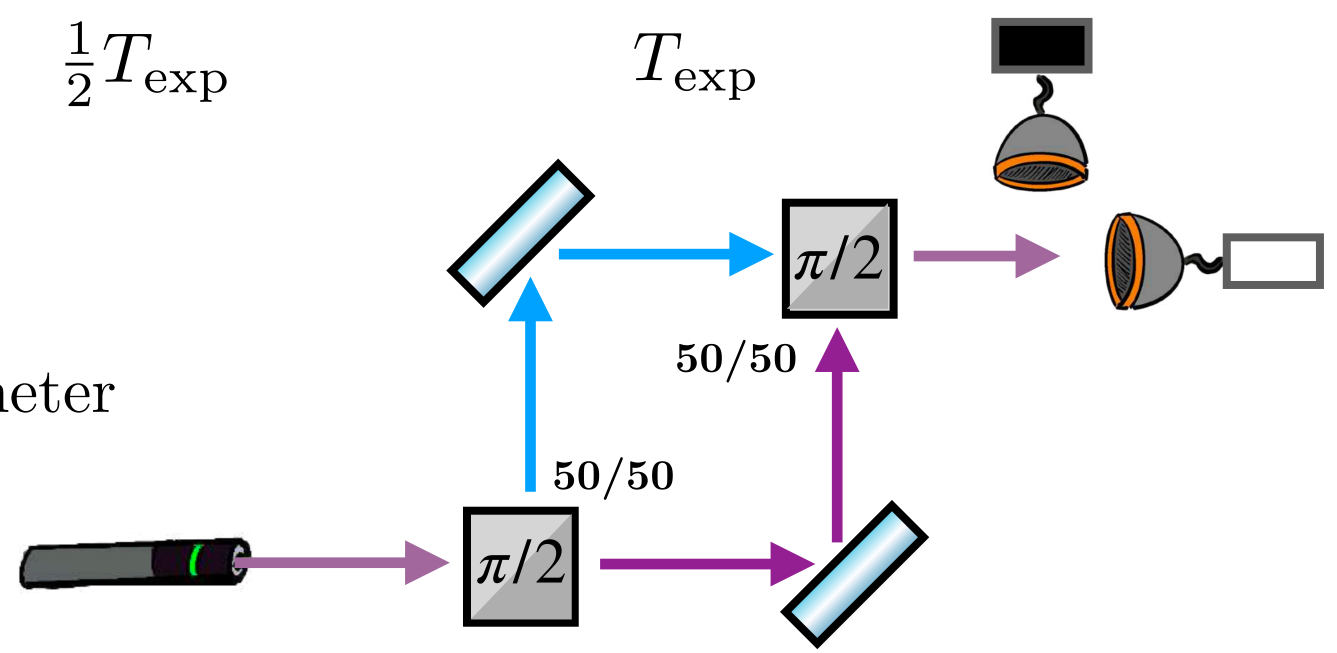



$\simeq$ Mach-Zender interferometer

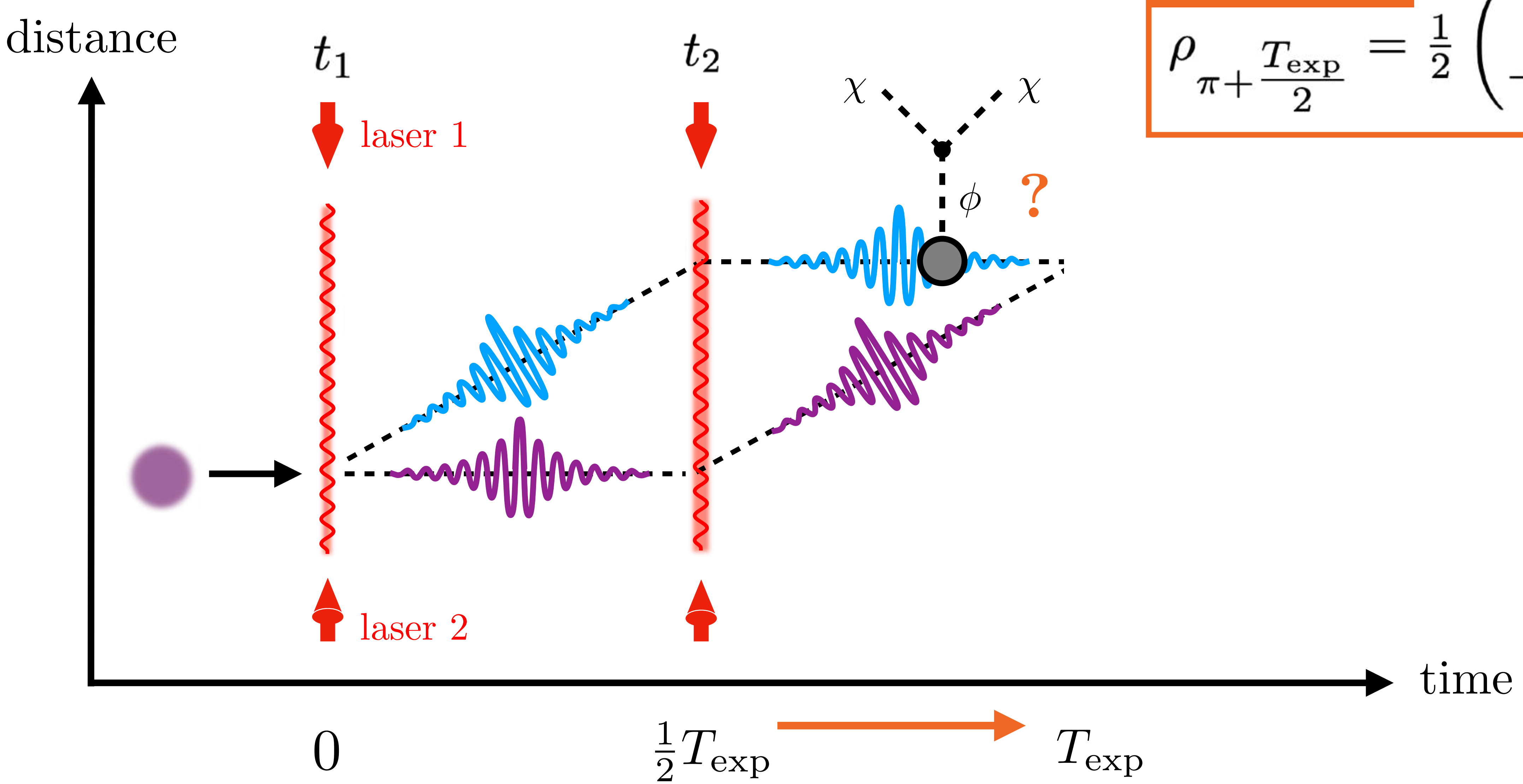


# AIs: Decoherence

Review: arXiv:2003.12516

**open system**

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



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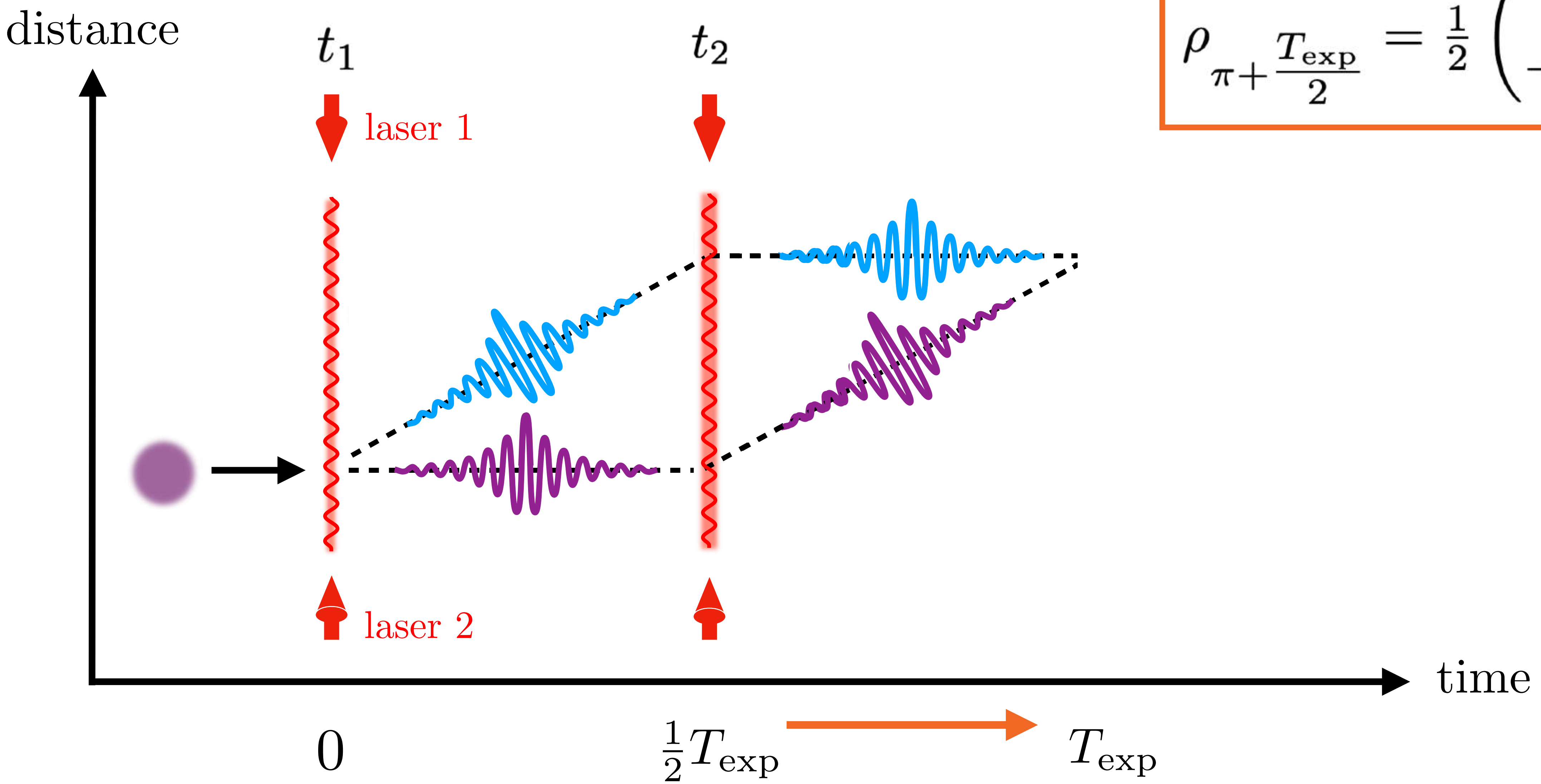
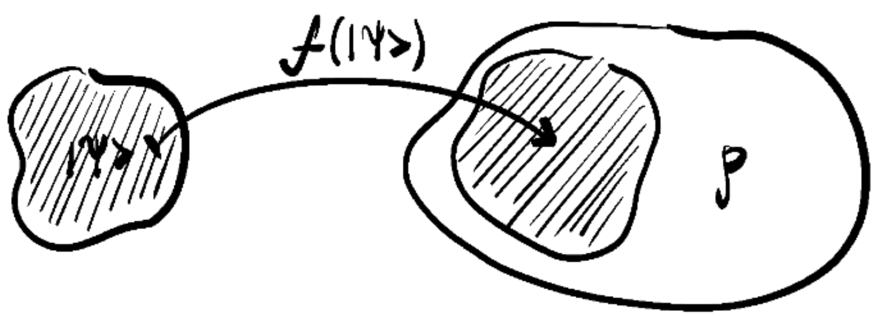



$$f : |\Psi\rangle \longmapsto \rho = |\Psi\rangle\langle\Psi|$$



Density matrix

- $\rho = \rho^\dagger$
- $\rho > 0$
- $\mathrm{Tr}\{\rho\} = 1$

# AIs: Decoherence

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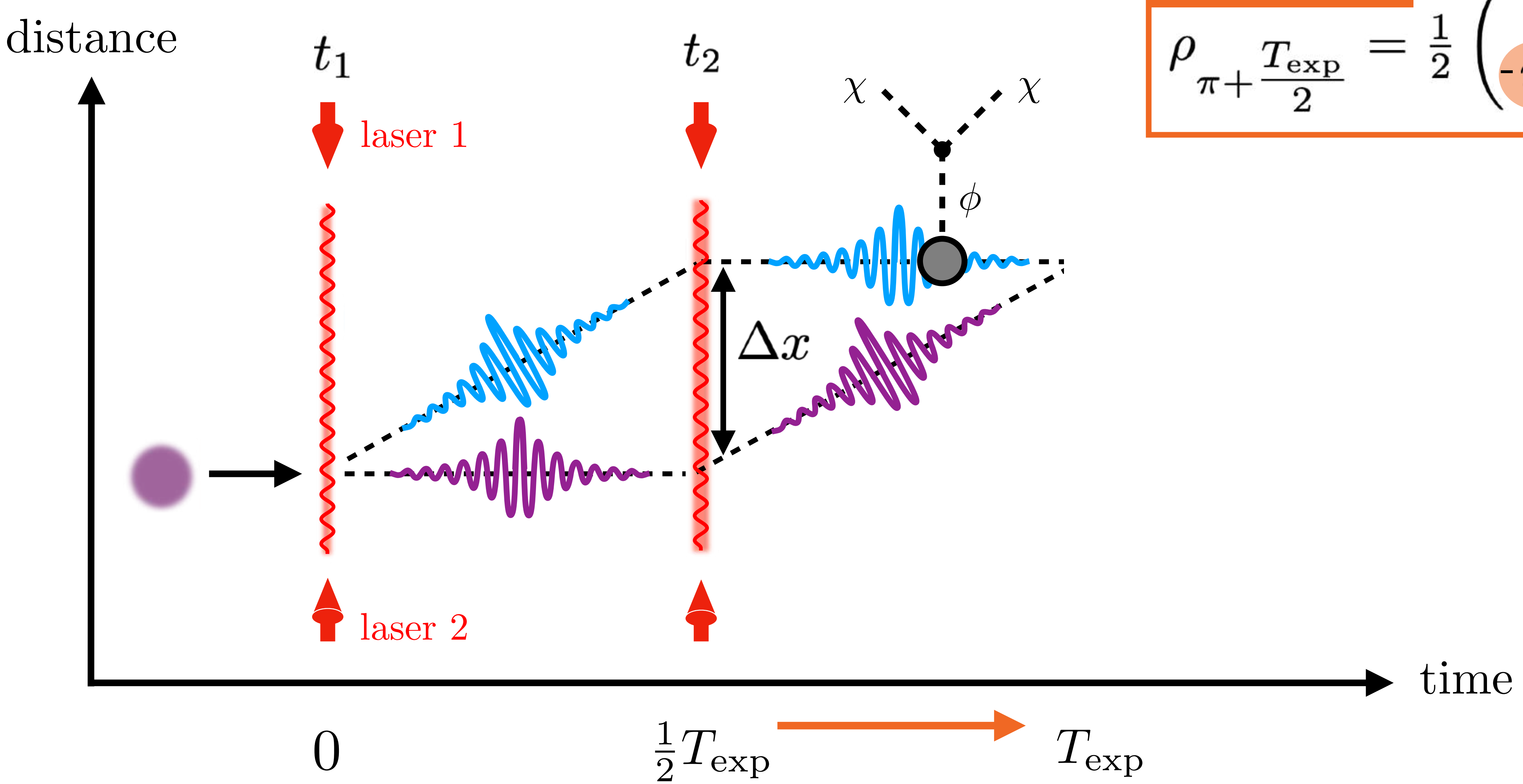


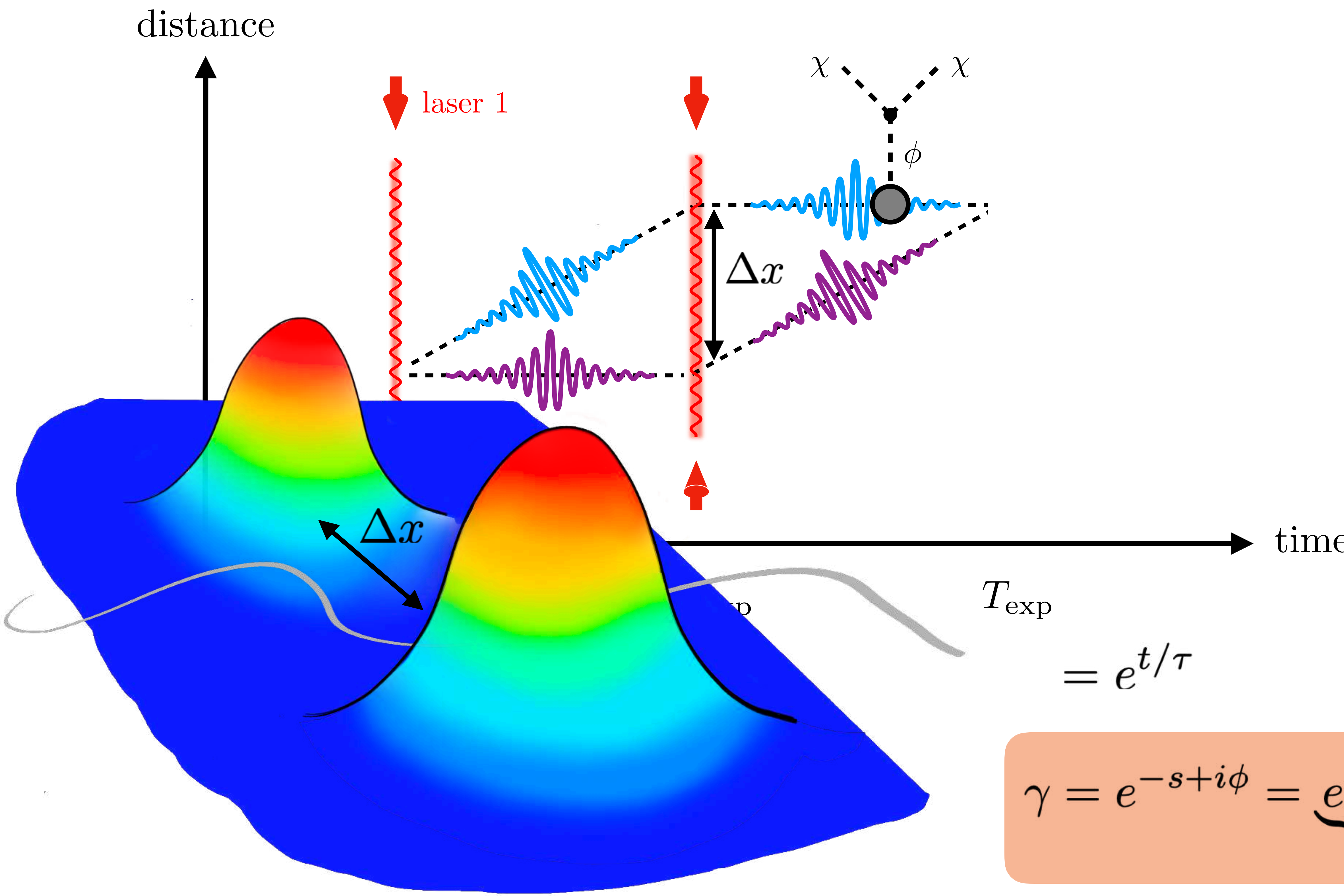

**open system**

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

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

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

# AIs: Decoherence

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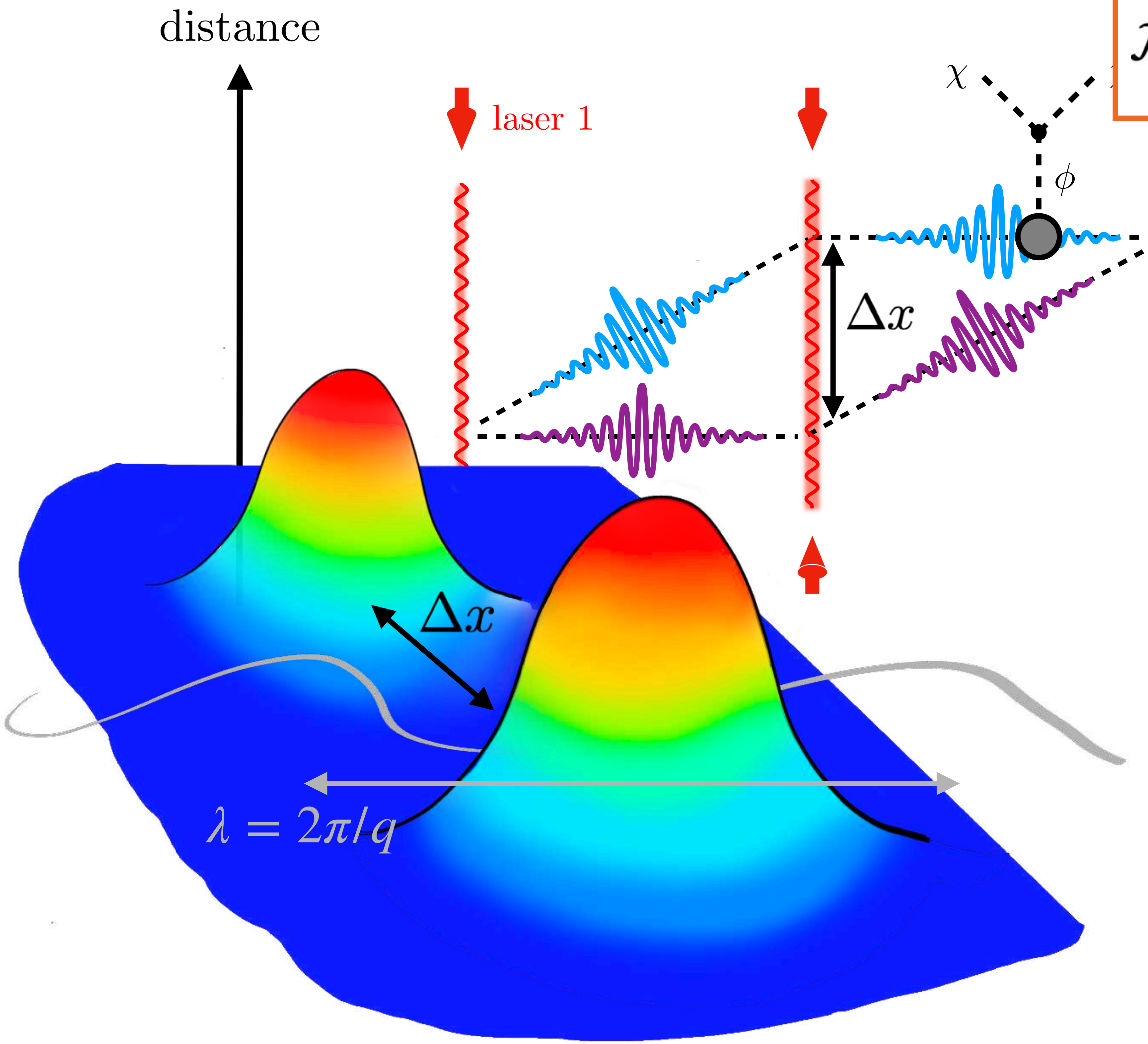



**Form Factor**

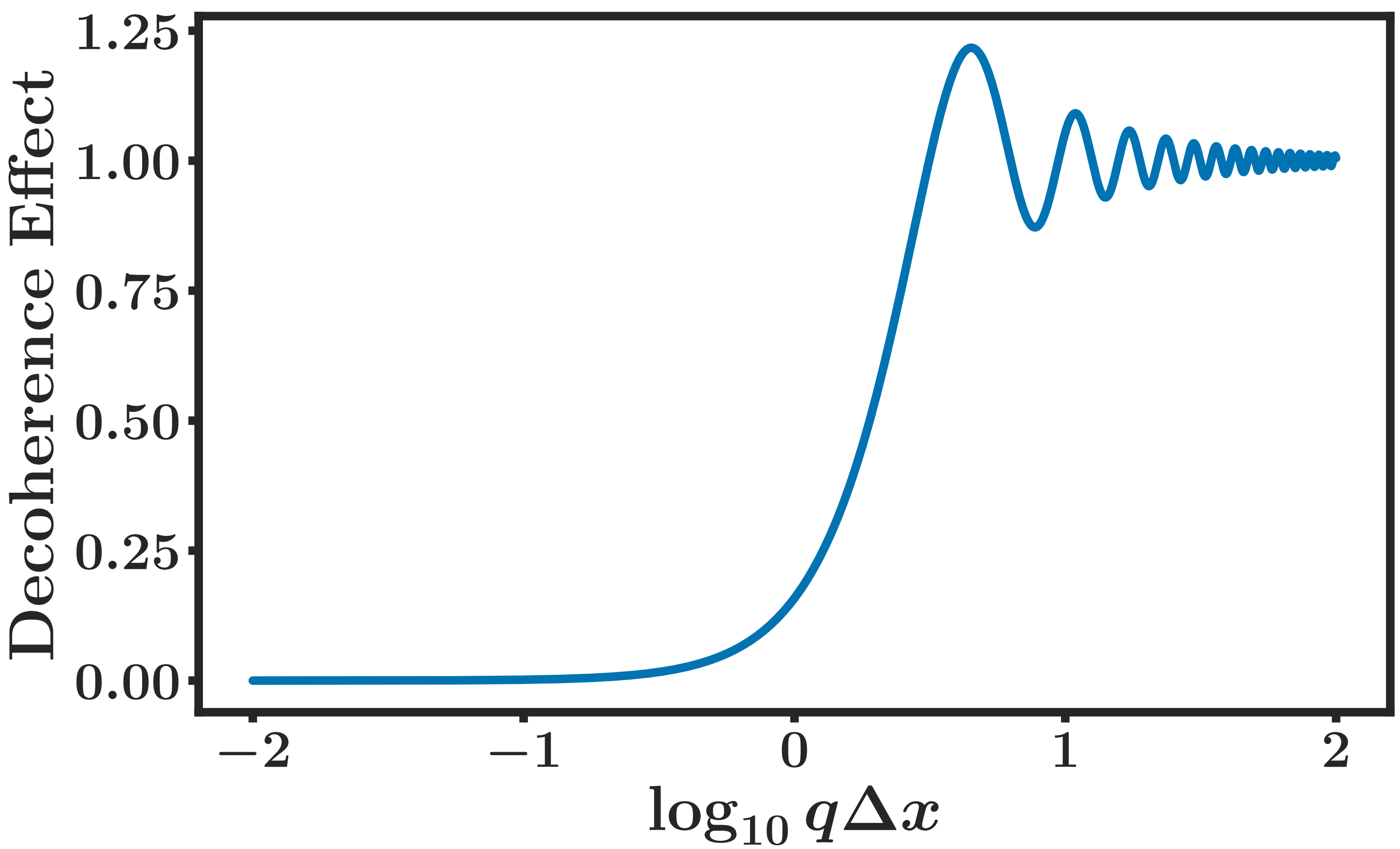
$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

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

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

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

# AIs: Decoherence



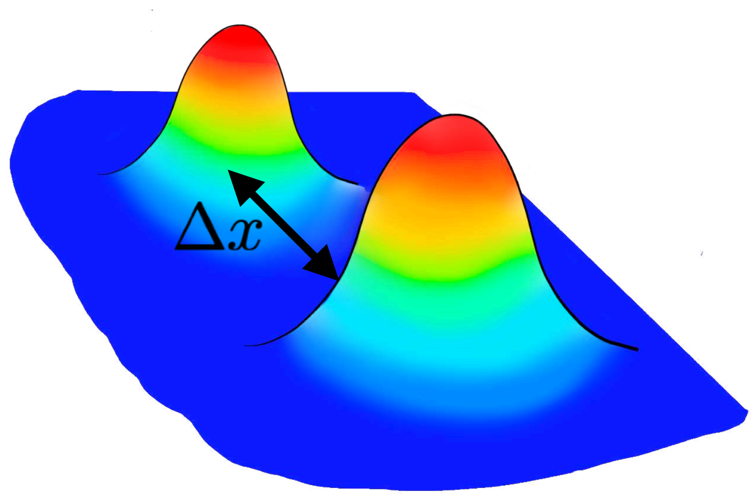

**Form Factor**

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

Visibility or Contrast (**V**)

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

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




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

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

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

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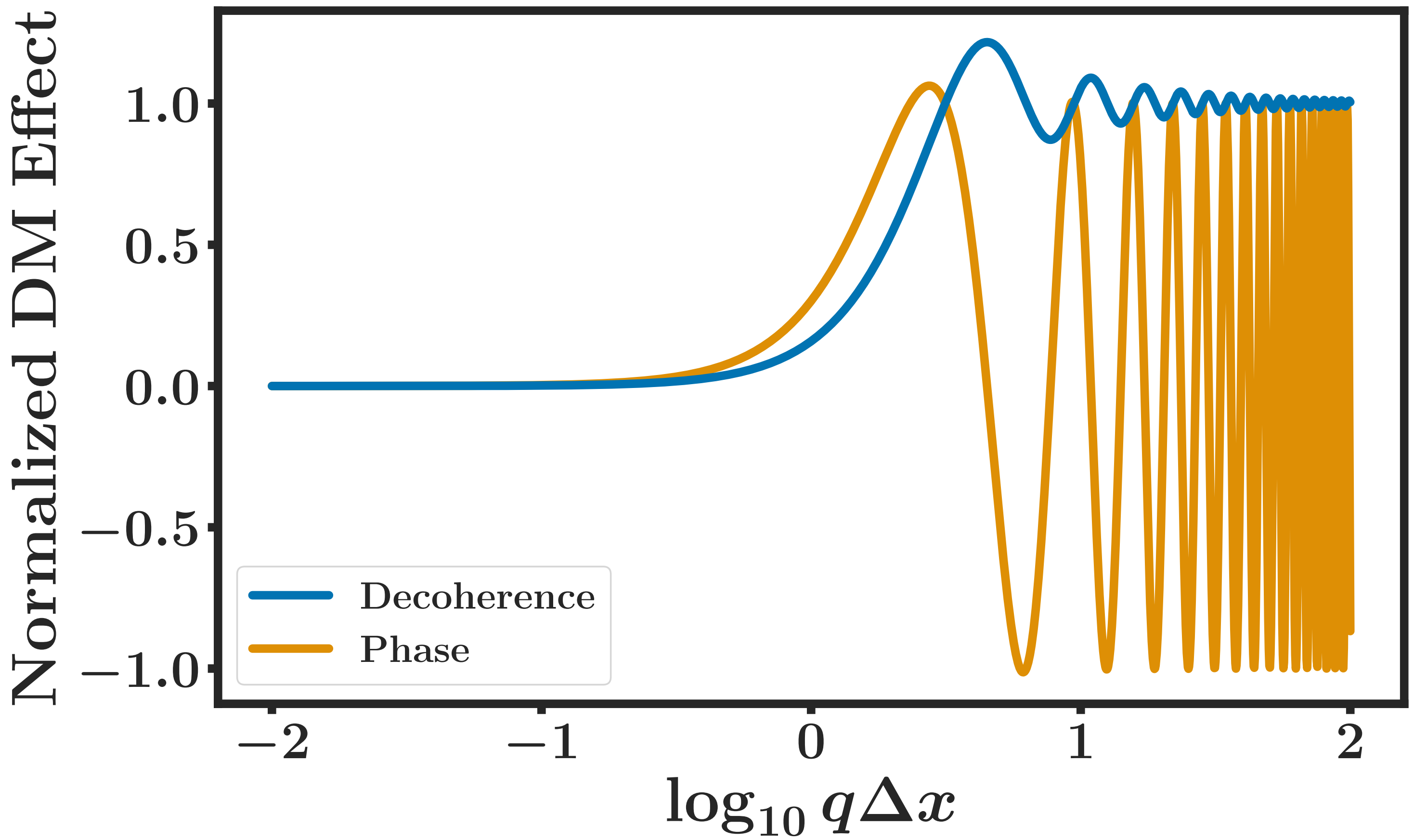


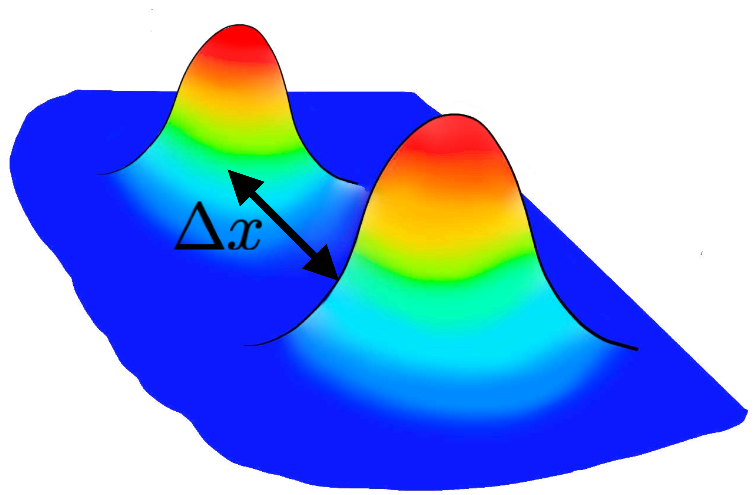

**Form Factor**

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

<u>Phase ($\phi$)</u>

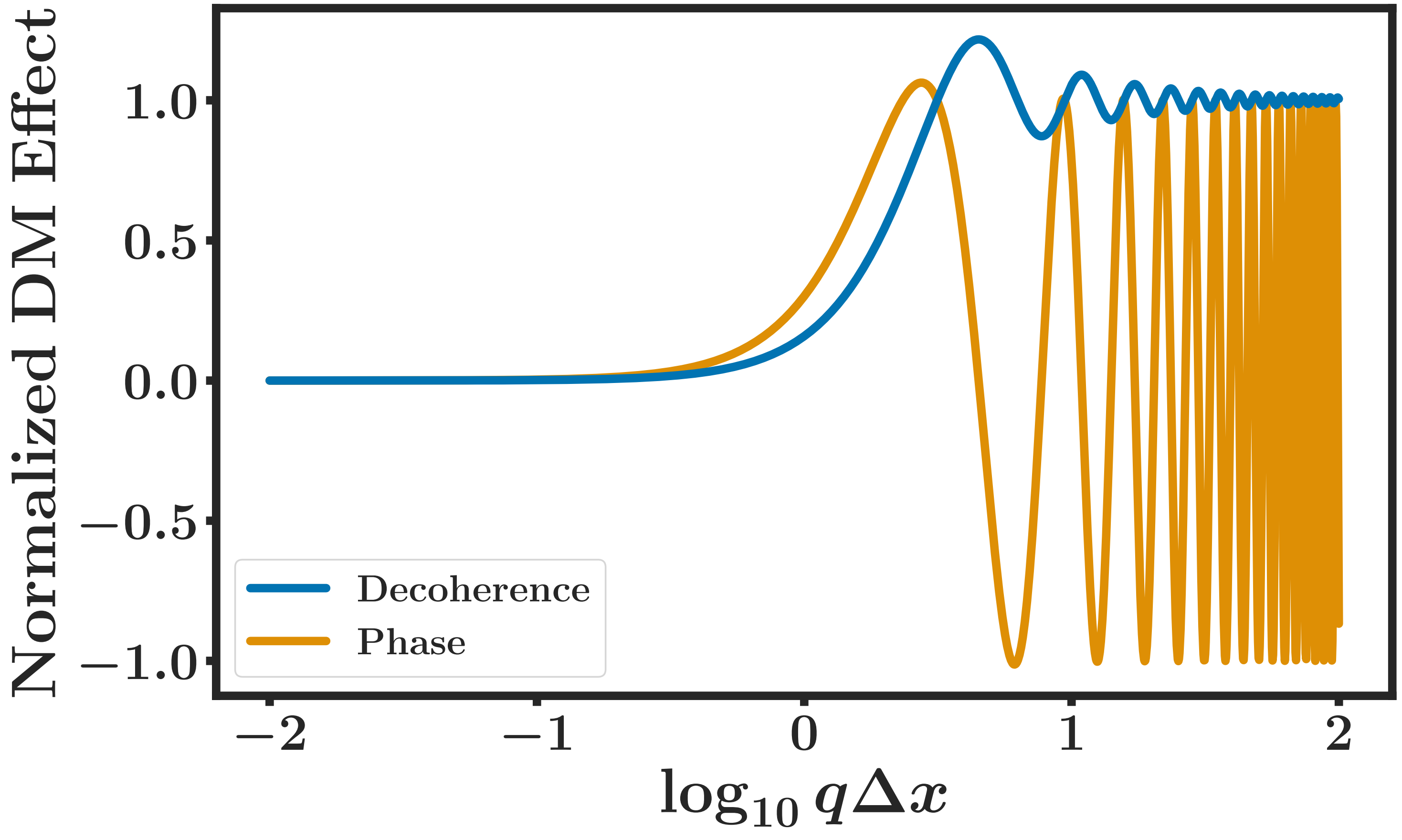
$$\frac{1}{2}\int_{-1}^{1} \mathrm{Im}\{\mathcal{F}_{\text{decoh}}(\mathbf{q})\}\, d\cos\theta_{\mathbf{q}\mathbf{\Delta x}}$$

$$= 0$$




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

# AIs: Decoherence



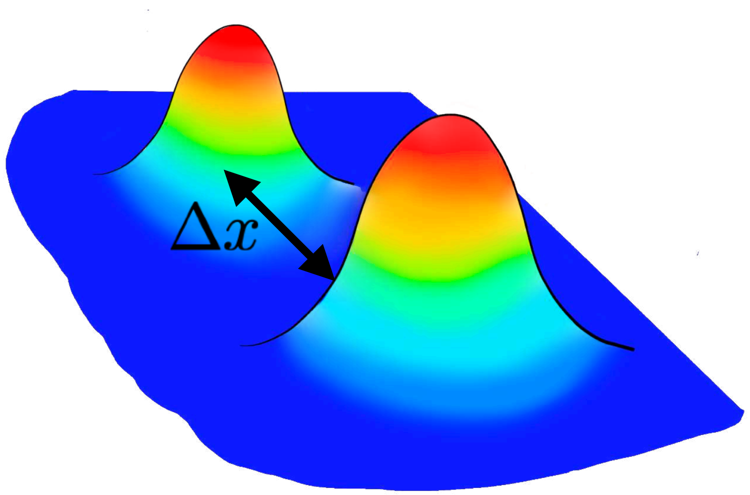

**Form Factor**

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

Phase ($\phi$)

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

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




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

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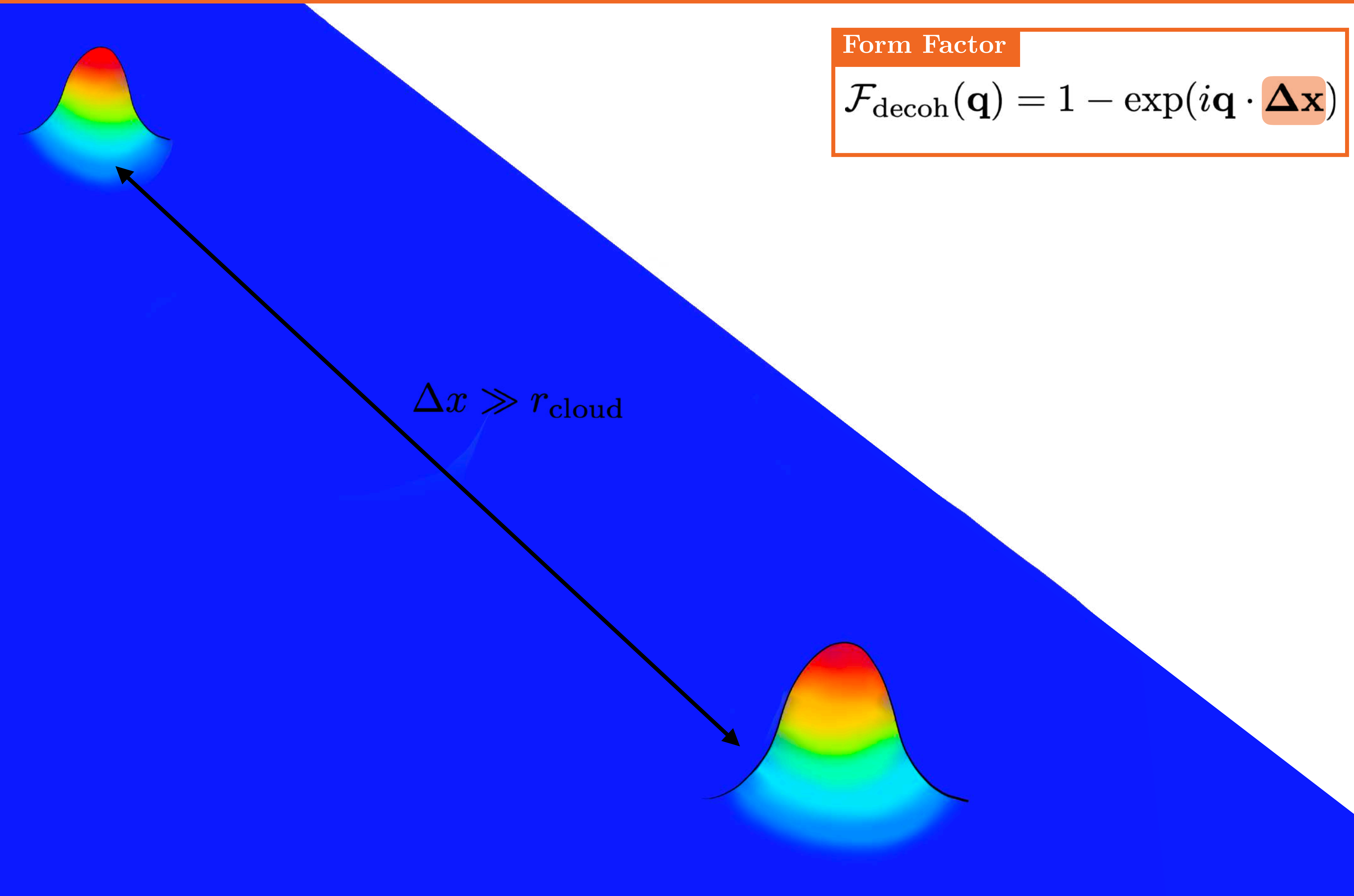



**Form Factor**

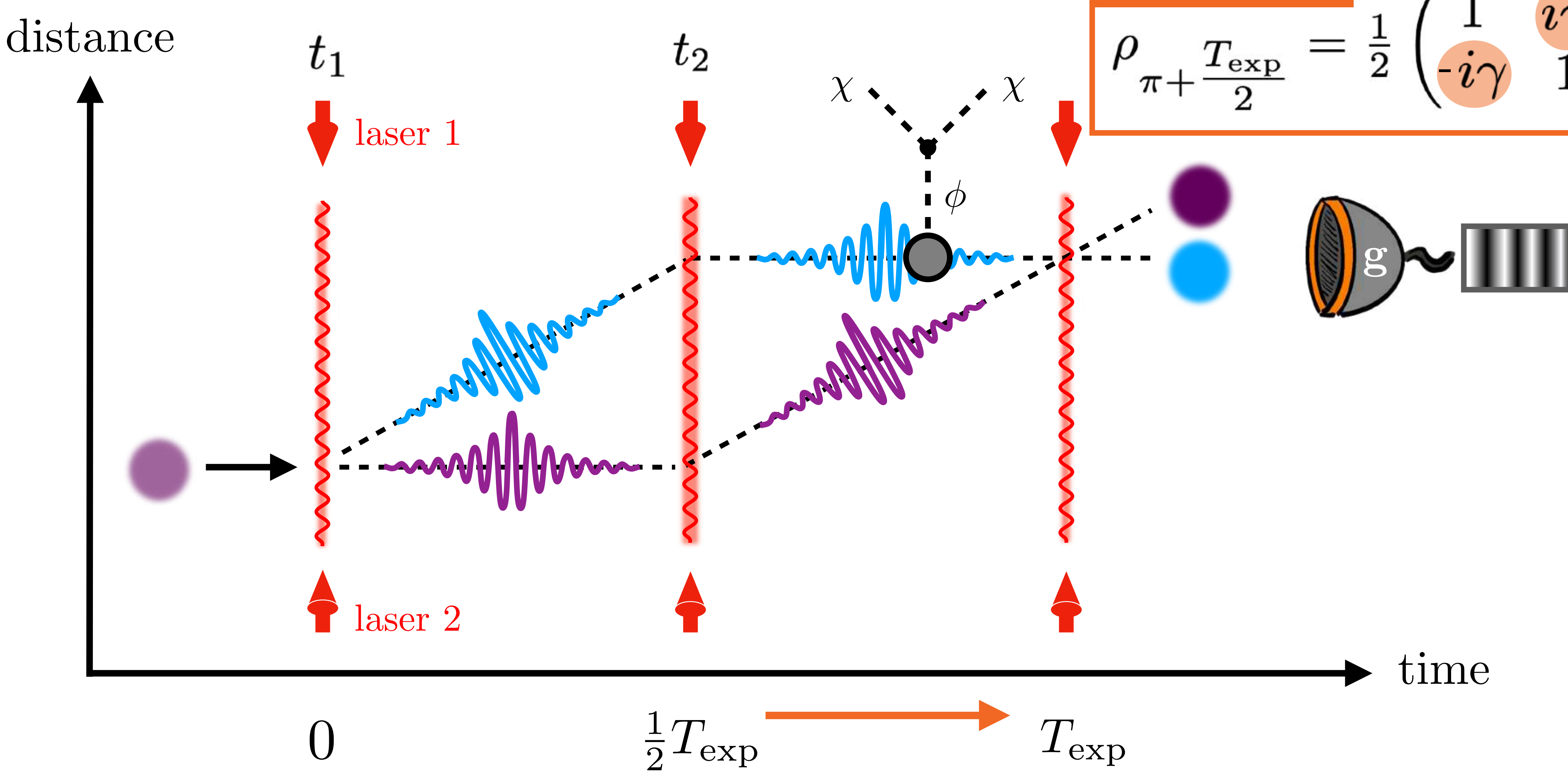
$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = 1 - \exp(i\mathbf{q} \cdot \mathbf{\Delta x})$$

# AIs: Measurement

Review: arXiv:2003.12516

**open system**

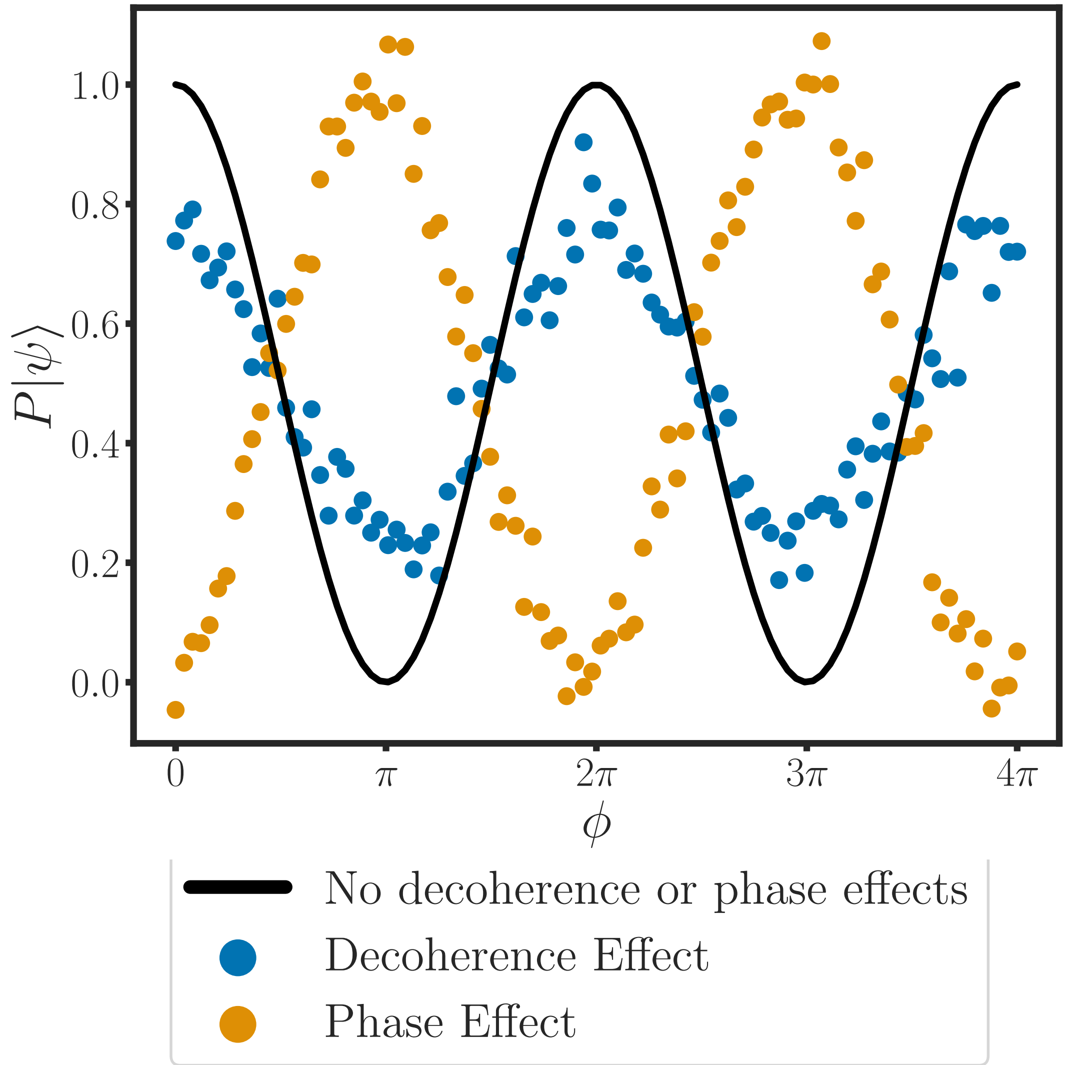
$$\rho_{\pi+\frac{T_{\rm exp}}{2}} = \frac{1}{2}\begin{pmatrix} 1 & i\gamma \\ -i\gamma & 1 \end{pmatrix}$$




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

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

# AIs: Measurement




**open system**

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


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

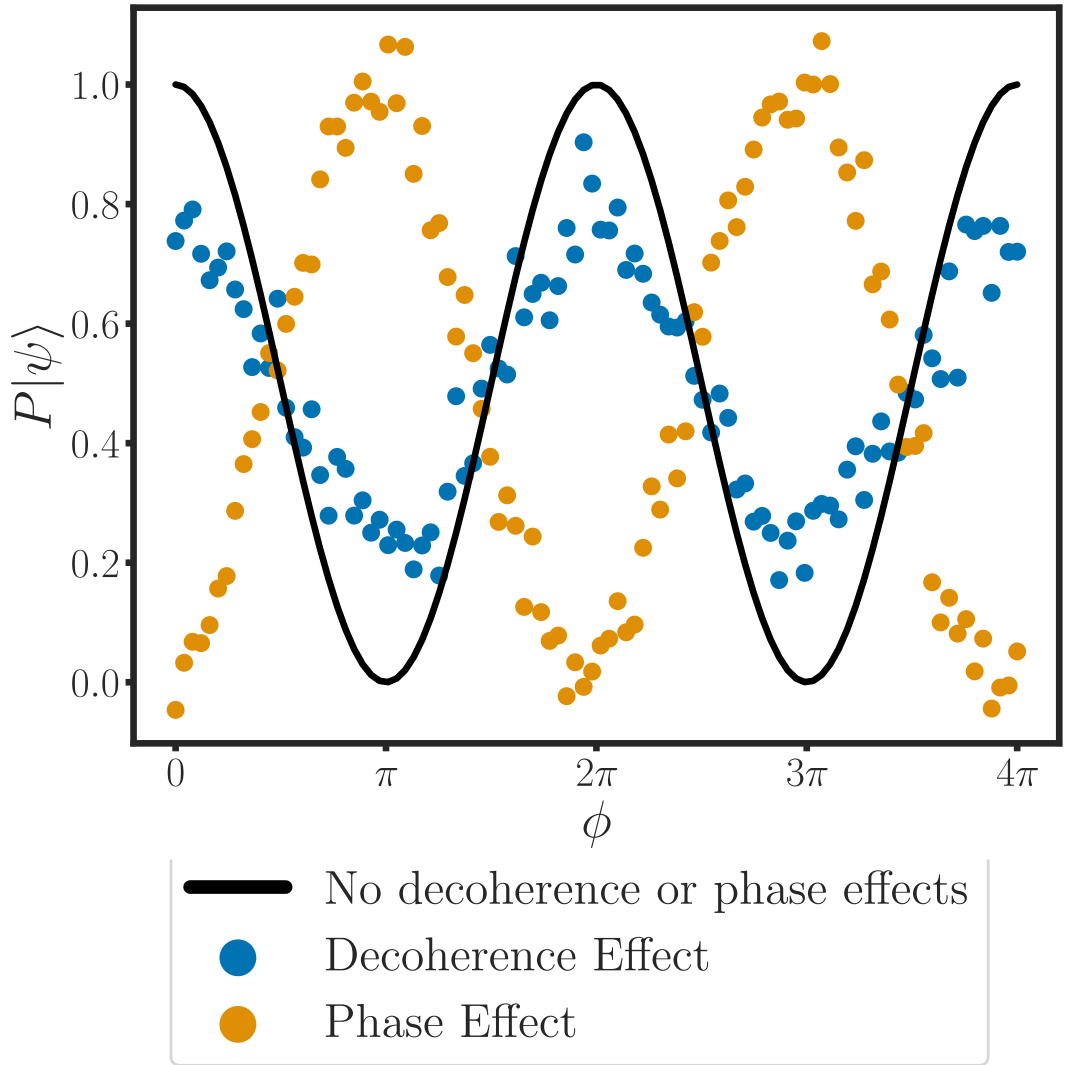
Accumulated decoherence: **Rate**

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

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

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

# AIs: Statistics




**Visibility**

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

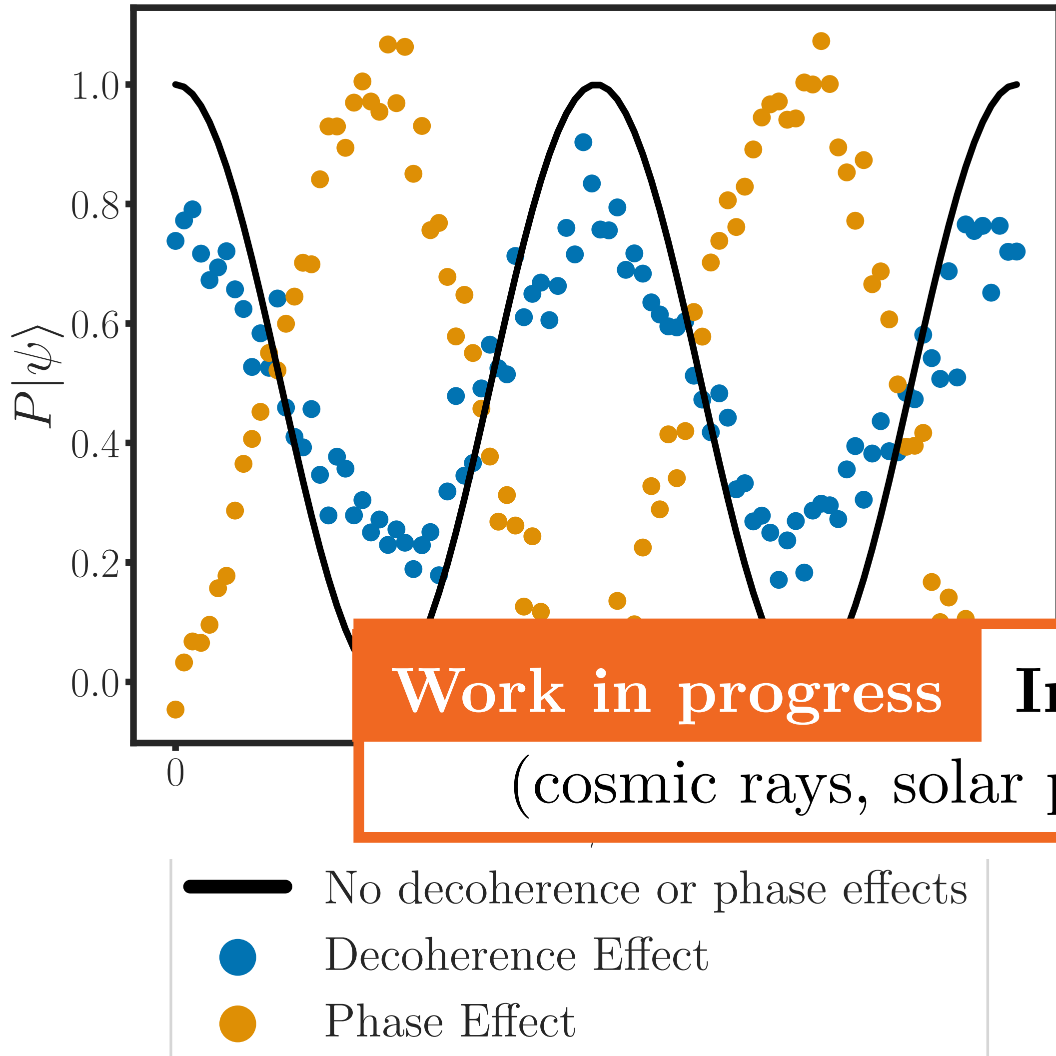
<u>Accumulated decoherence: **Rate**</u>

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

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

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

# AIs: Statistics




**Work in progress** **Impact of potential backgrounds**

(cosmic rays, solar photons, solar neutrinos, dust...)

## Visibility

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

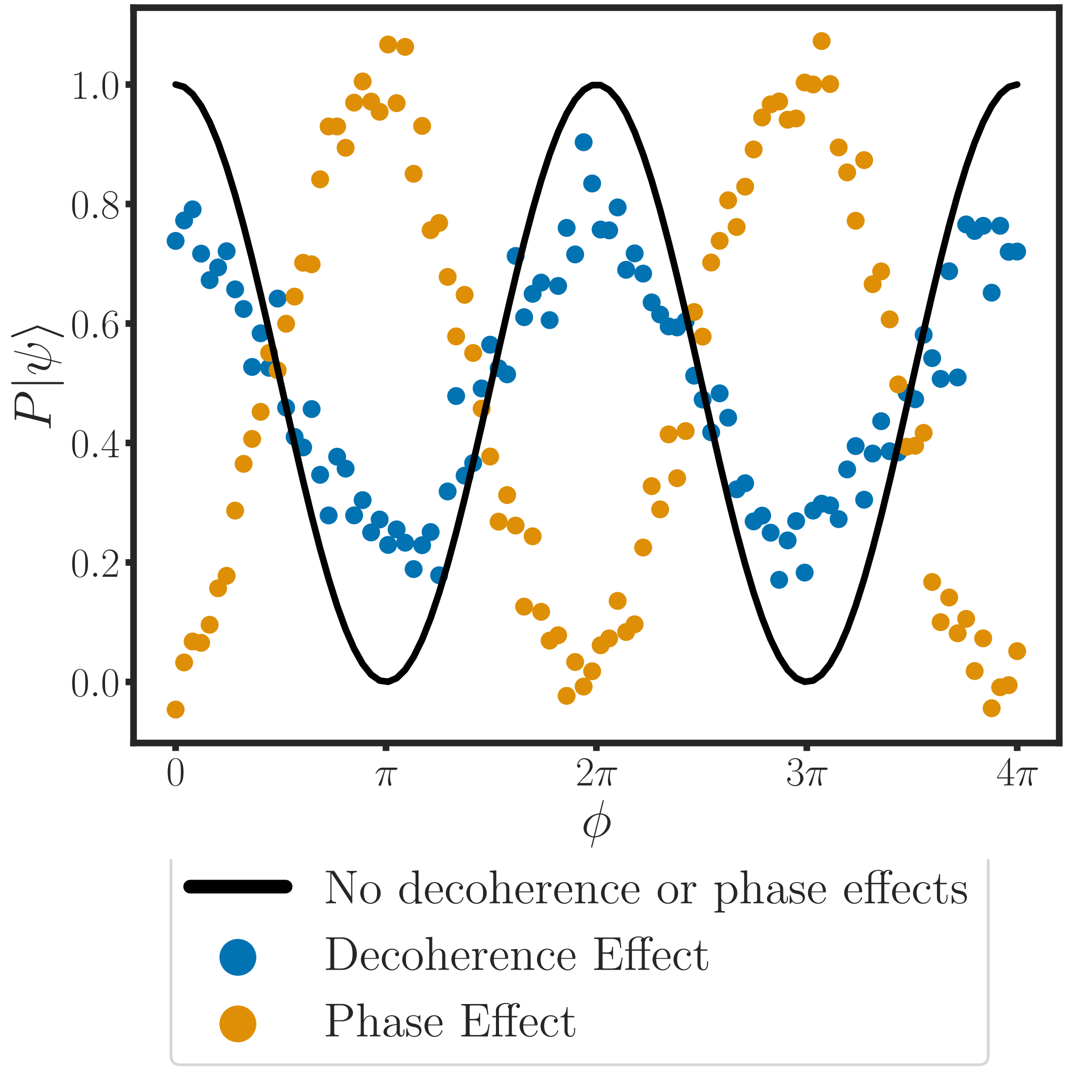
Accumulated decoherence: **Rate**

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

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

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

# AIs: Statistics




**Phase**

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

**Visibility**

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

Accumulated decoherence: **Rate**

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

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

# AIs: the Rate

Number of events / (target mass · time)

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

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

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

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

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

# AIs: the Rate

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

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

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

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

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

# AIs: the Rate

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

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

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

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

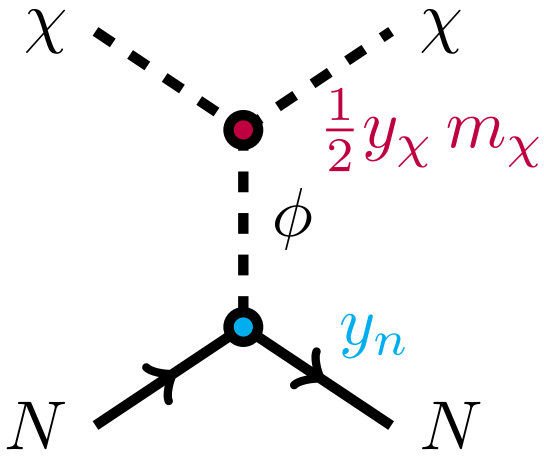
$$\Gamma(\mathbf{v}) = V\int \frac{d^3\mathbf{q}}{(2\pi)^3} \sum_f |\langle f|H_{\rm int}|i\rangle|^2 (2\pi)\delta(E_f - E_i - \omega_{\mathbf{q}})$$

# AIs: the Rate

$$R = \frac{1}{\rho_T} \frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \sum_f |\langle f | H_{\text{int}} | i \rangle|^2 g(\mathbf{q}, E_f - E_i) \mathcal{F}_{\text{decoh}}(\mathbf{q})$$

# AIs: the Rate

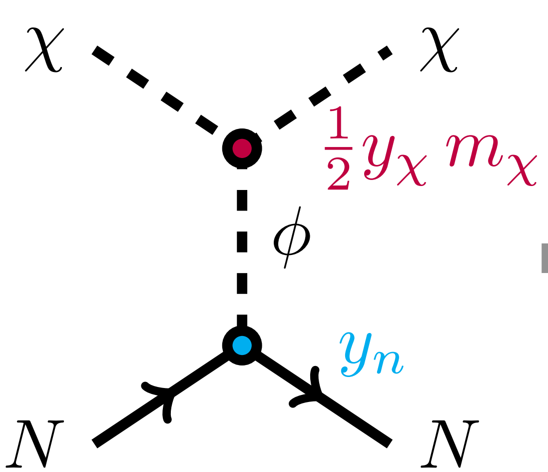
$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \sum_f |\langle f|H_{\mathrm{int}}|i\rangle|^2 g(\mathbf{q}, E_f - E_i)\mathcal{F}_{\mathrm{decoh}}(\mathbf{q})$$



# AIs: the Rate

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

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




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

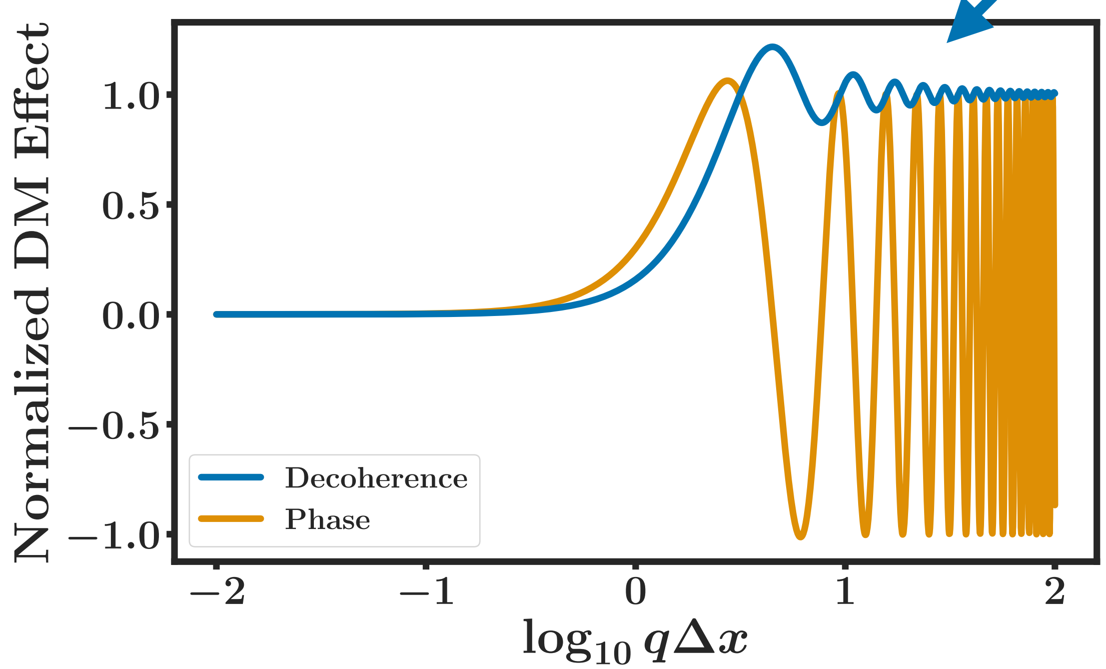
# AIs: the Rate

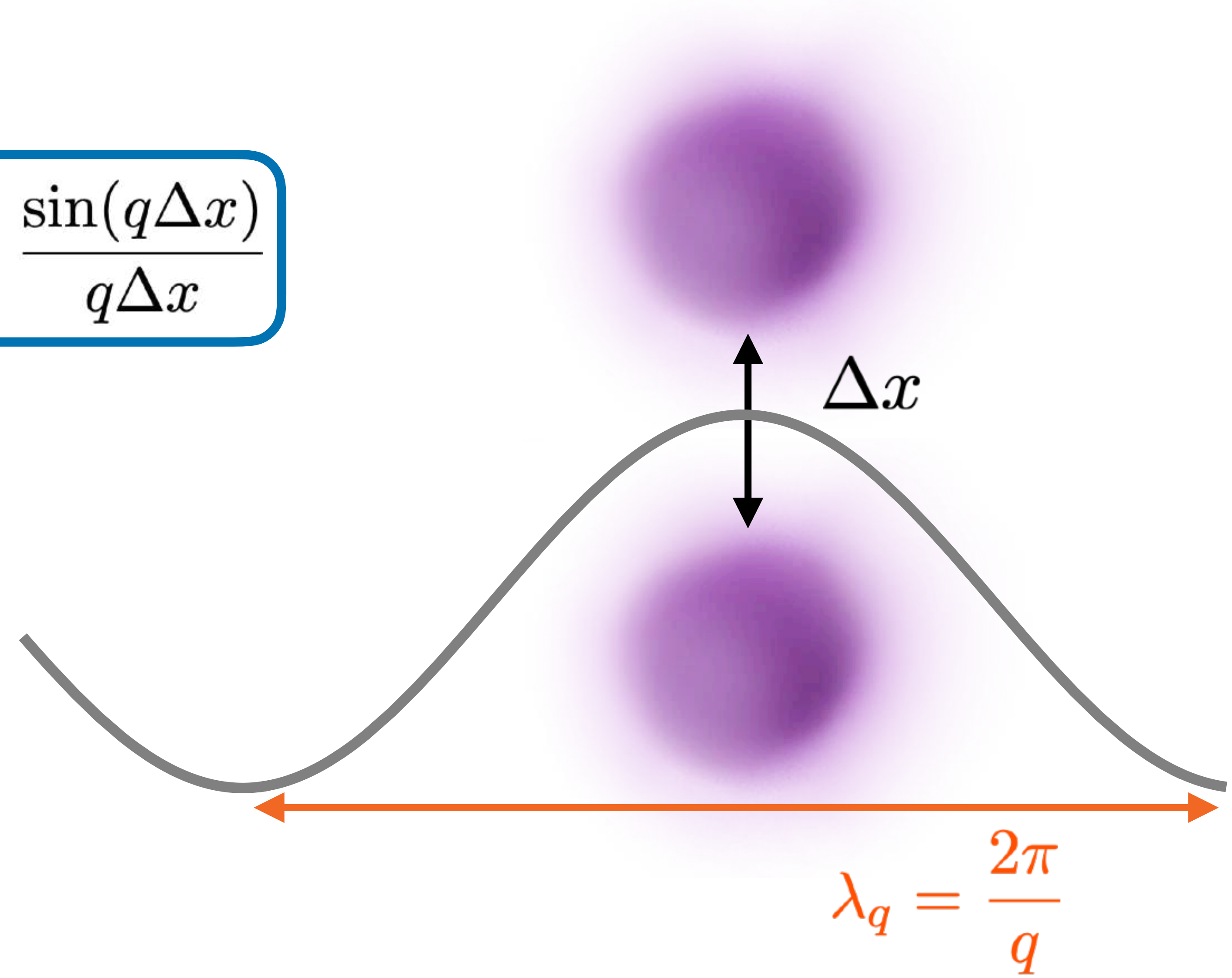
$$\mathcal{F}_{\rm med}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

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

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

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



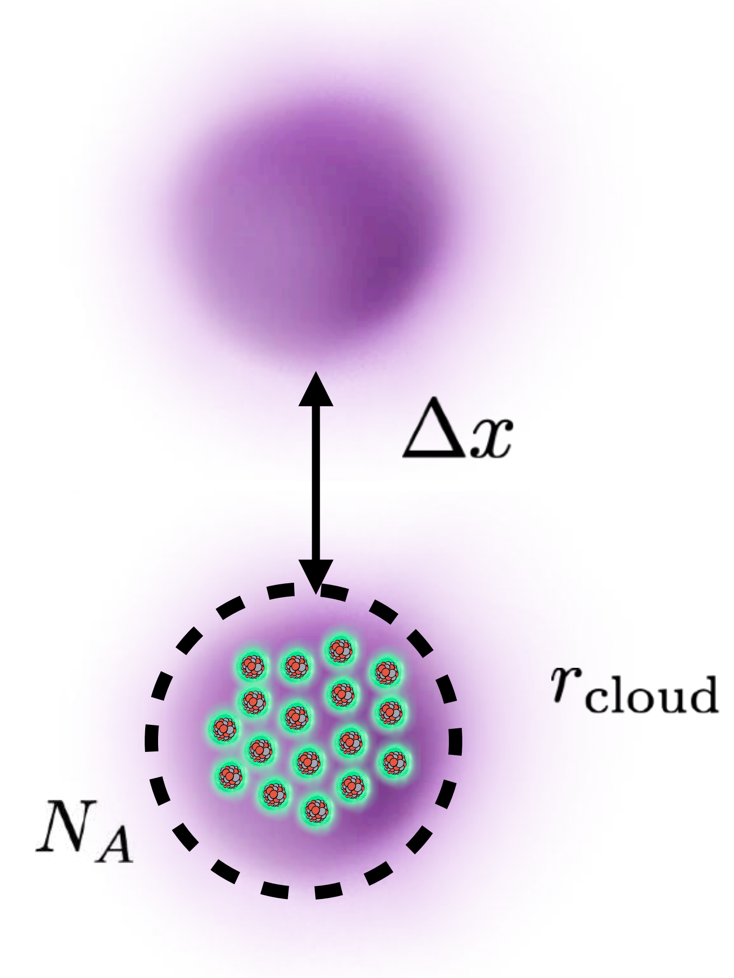



# AIs: the Rate

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

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

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



# AIs: the Rate

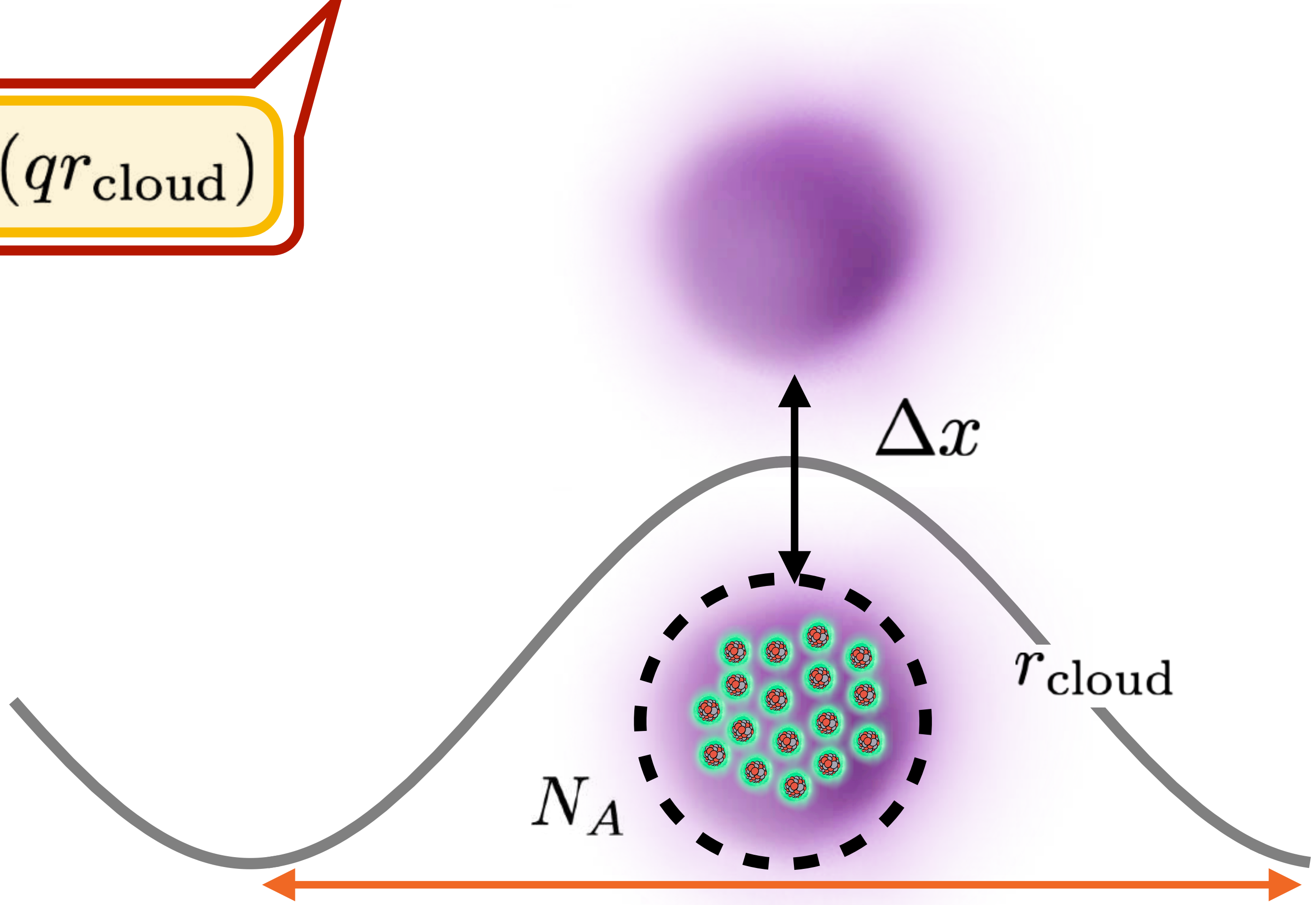
$$\mathcal{F}_{\text{med}}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

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

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

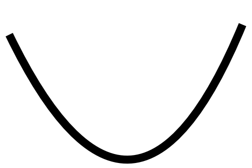
$$\mathcal{F}_T(\mathbf{q}) = N[1 + A(N_A - 1)\mathcal{F}^2_{\text{cloud}}(q r_{\text{cloud}})$$

Born (coherent) enhancement!




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

$$\mathcal{F}_{\text{cloud}}(q r_{\text{cloud}}) \begin{cases} \dfrac{3 j_1(q r_{\text{cloud}})}{q r_{\text{cloud}}} \\ \exp\left(-\dfrac{q^2}{(2 r_{\text{BEC}})^2}\right) \end{cases}$$



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

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

# AIs: the Rate

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

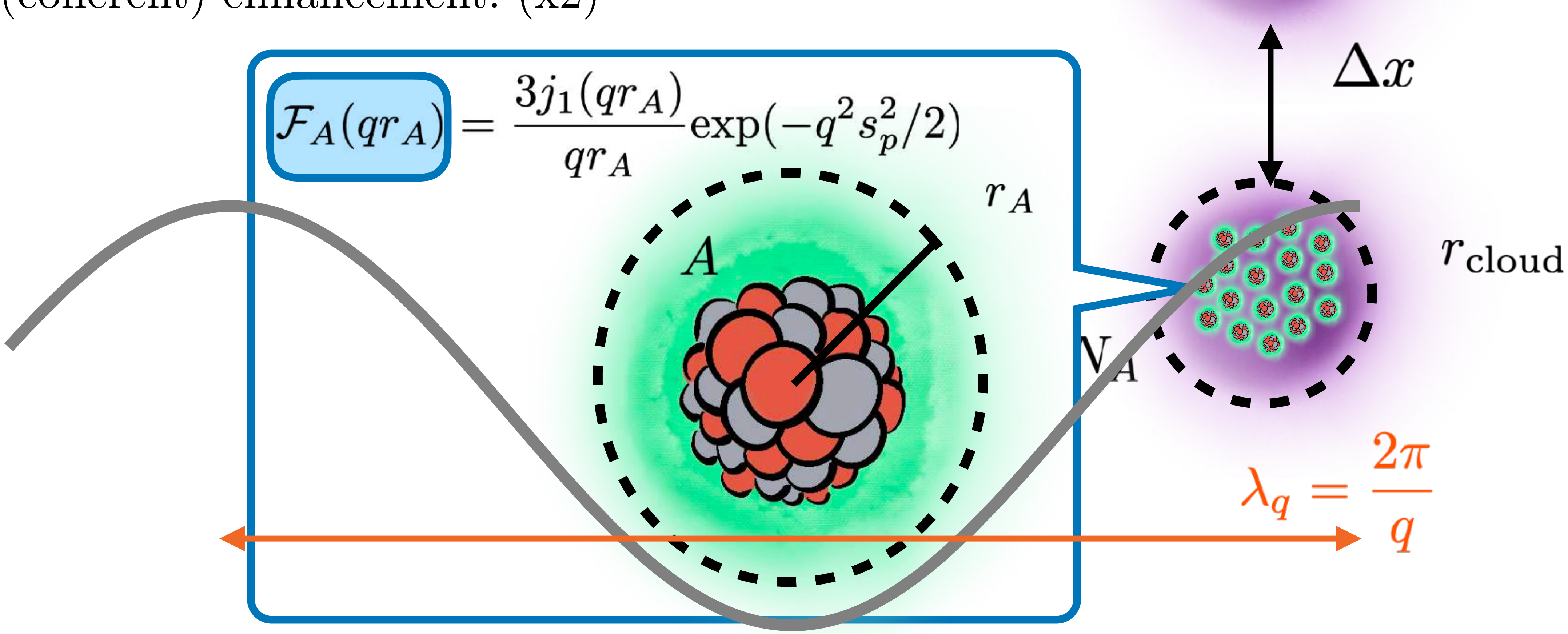
$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

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

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

Born (coherent) enhancement! (x2)

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



# AIs: the Rate

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

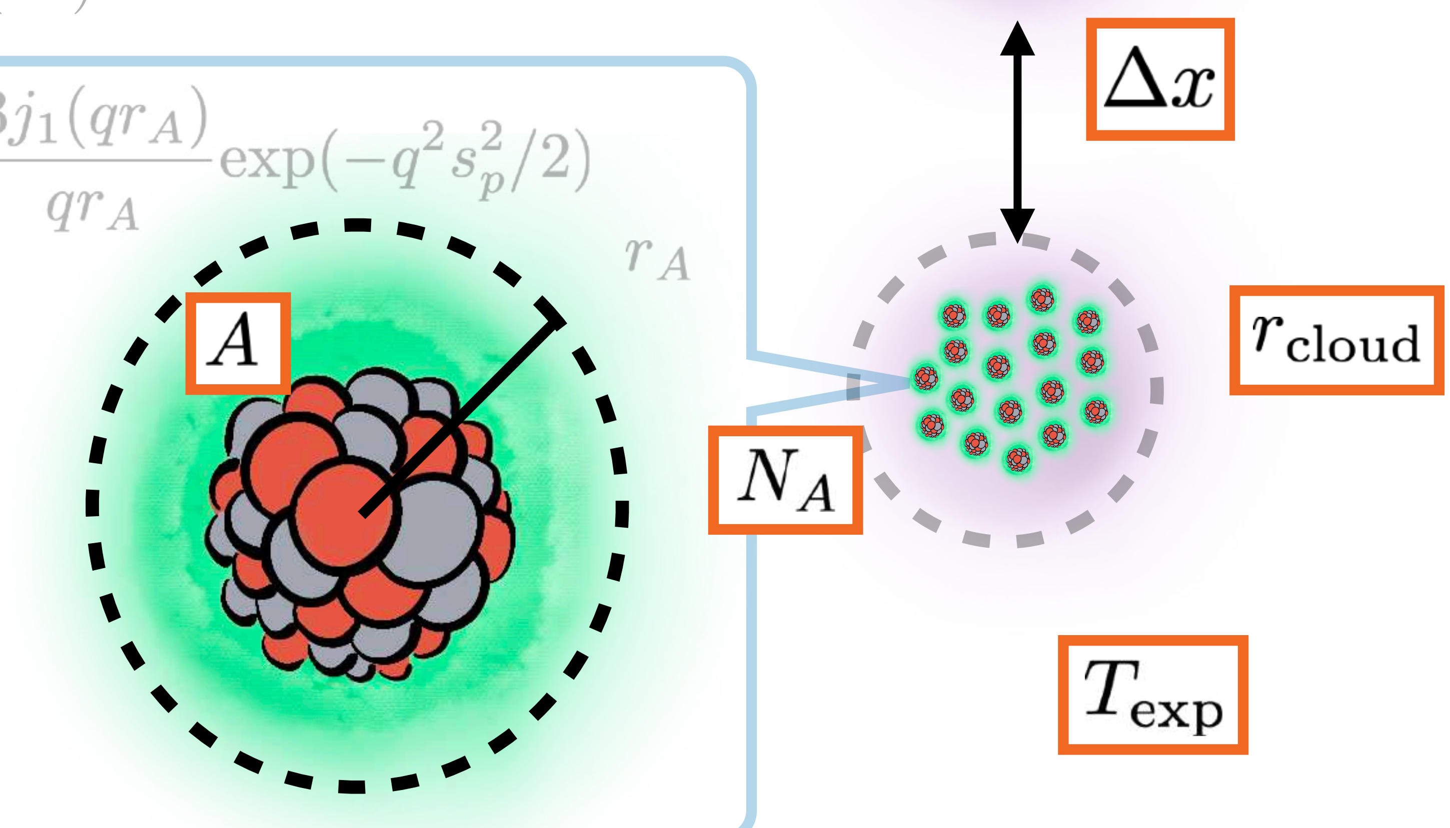
$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

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

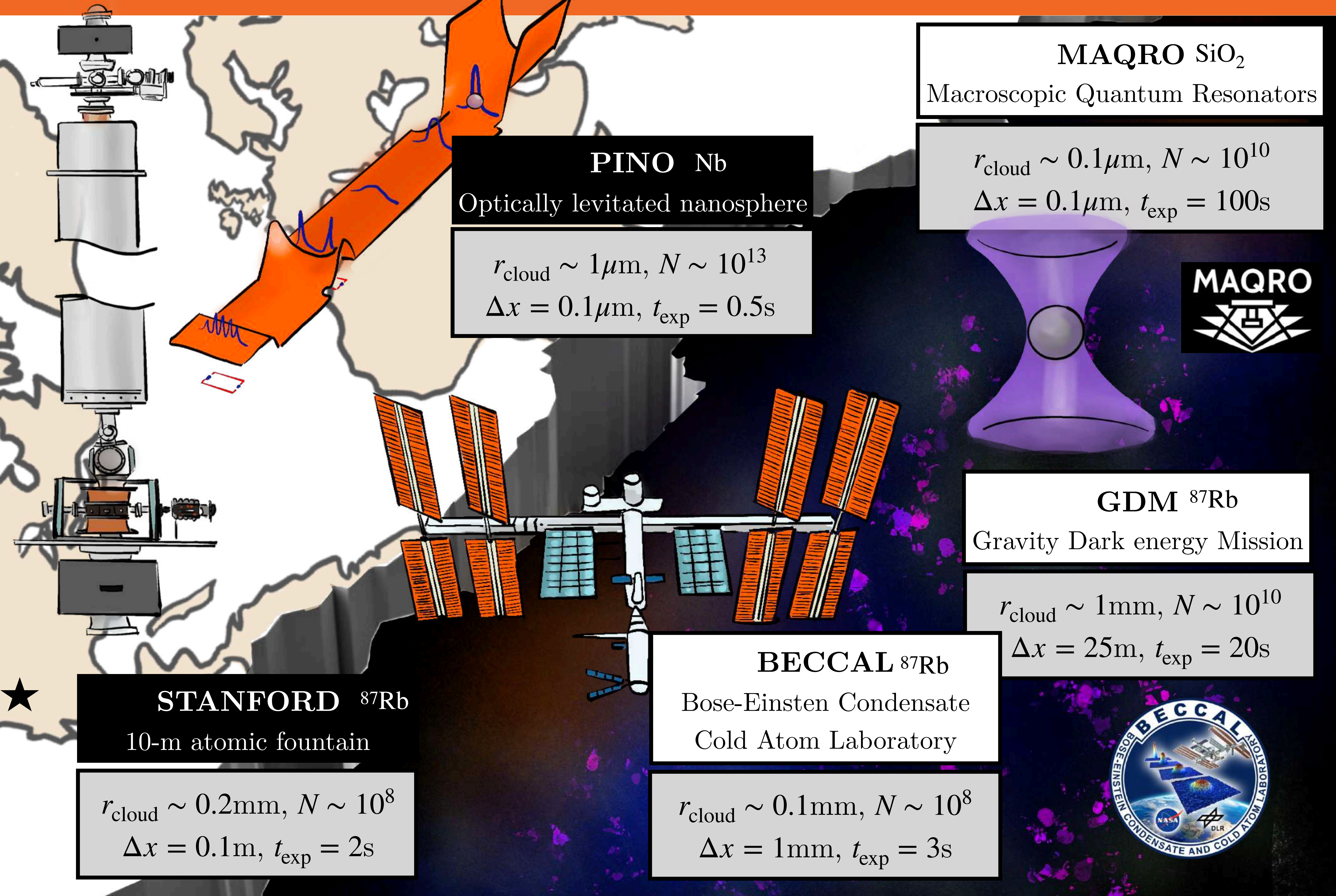
$$\mathcal{F}_T(\mathbf{q}) = N[1 + A(N_A - 1)\mathcal{F}^2_{\rm cloud}(q r_{\rm cloud}) + A\mathcal{F}^2_A(q r_A)]$$

Born (coherent) enhancement! (x2)

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



# AIs: Examples




**MAQRO** $SiO_2$
Macroscopic Quantum Resonators

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

**PINO** Nb
Optically levitated nanosphere

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

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

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

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

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

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

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

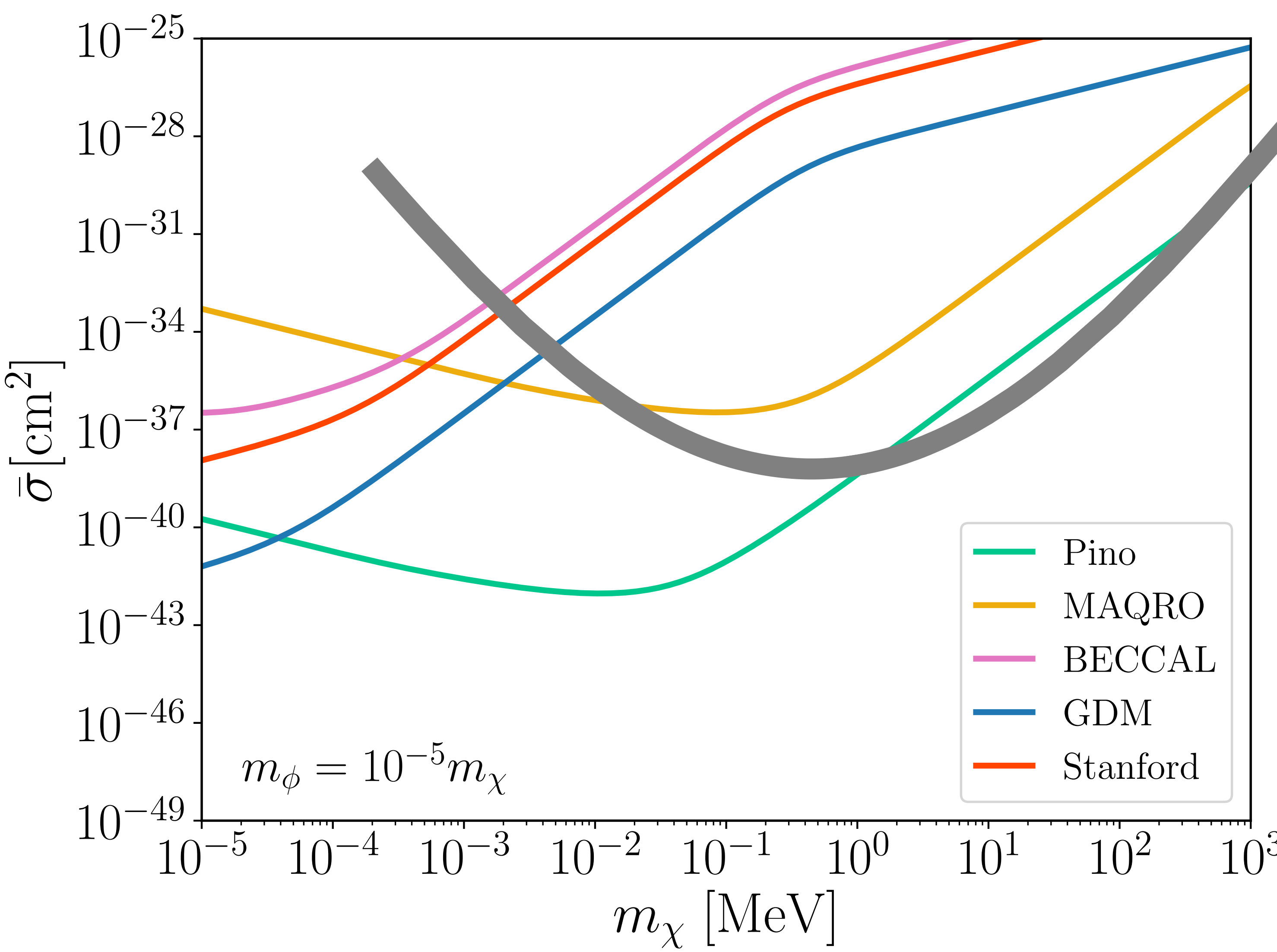
# AIs: Results

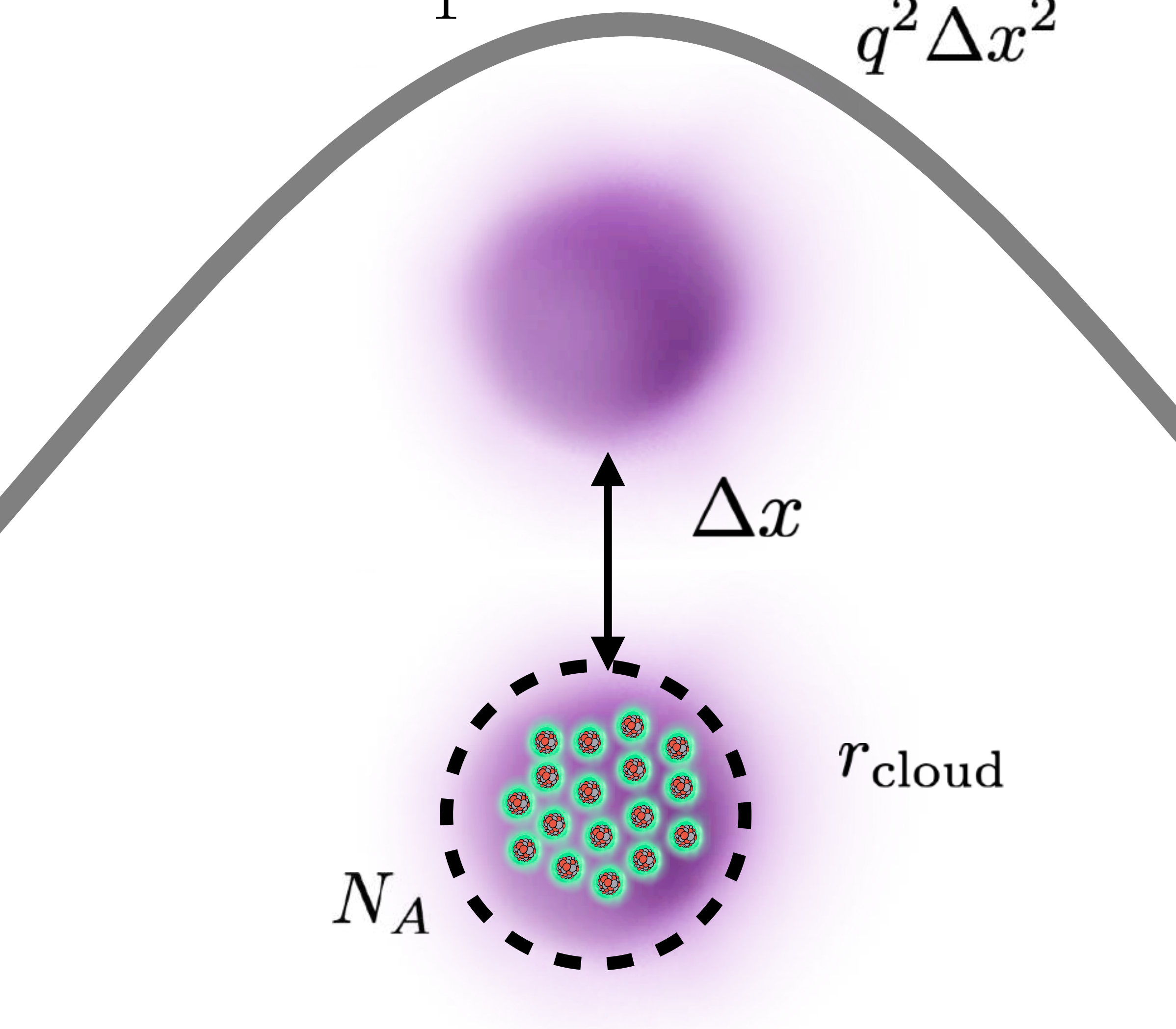
$$s \propto \frac{\bar{\sigma}\left((m_\chi v_0)^2 + m_\phi^2\right)^2}{m_\chi^3} \int dq \, \frac{q}{(q^2 + m_\phi^2)^2} N\left(1 + N F^2(q r_{\text{cloud}})\right)\left(1 - \frac{\sin(q\Delta x)}{q\Delta x}\right)$$

$1$

$q^2 \Delta x^2$

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



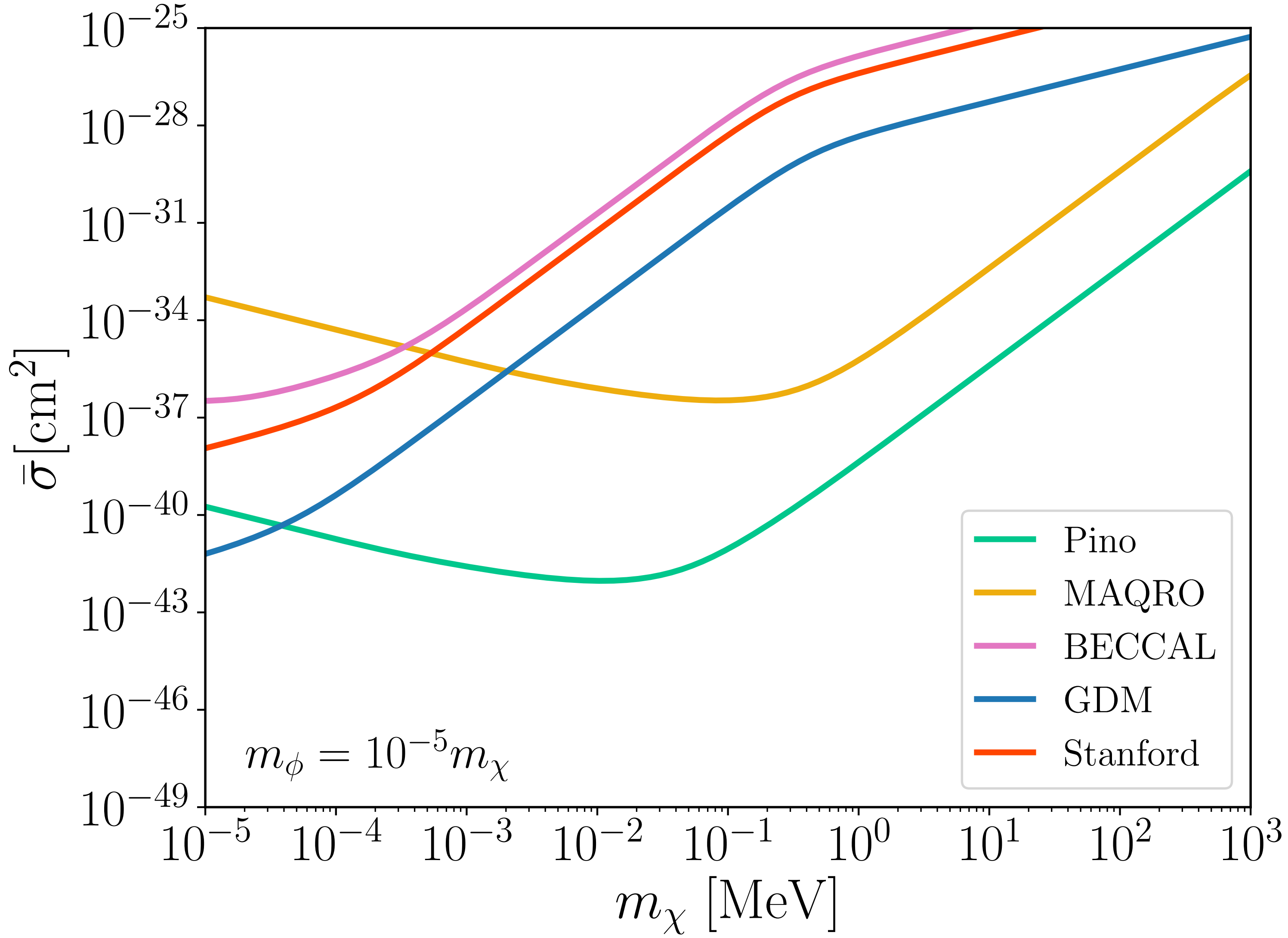




**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

$$s \propto \frac{\bar{\sigma}}{m_\chi^3} N^2 \int dq\, q^3 \Delta x^2$$

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

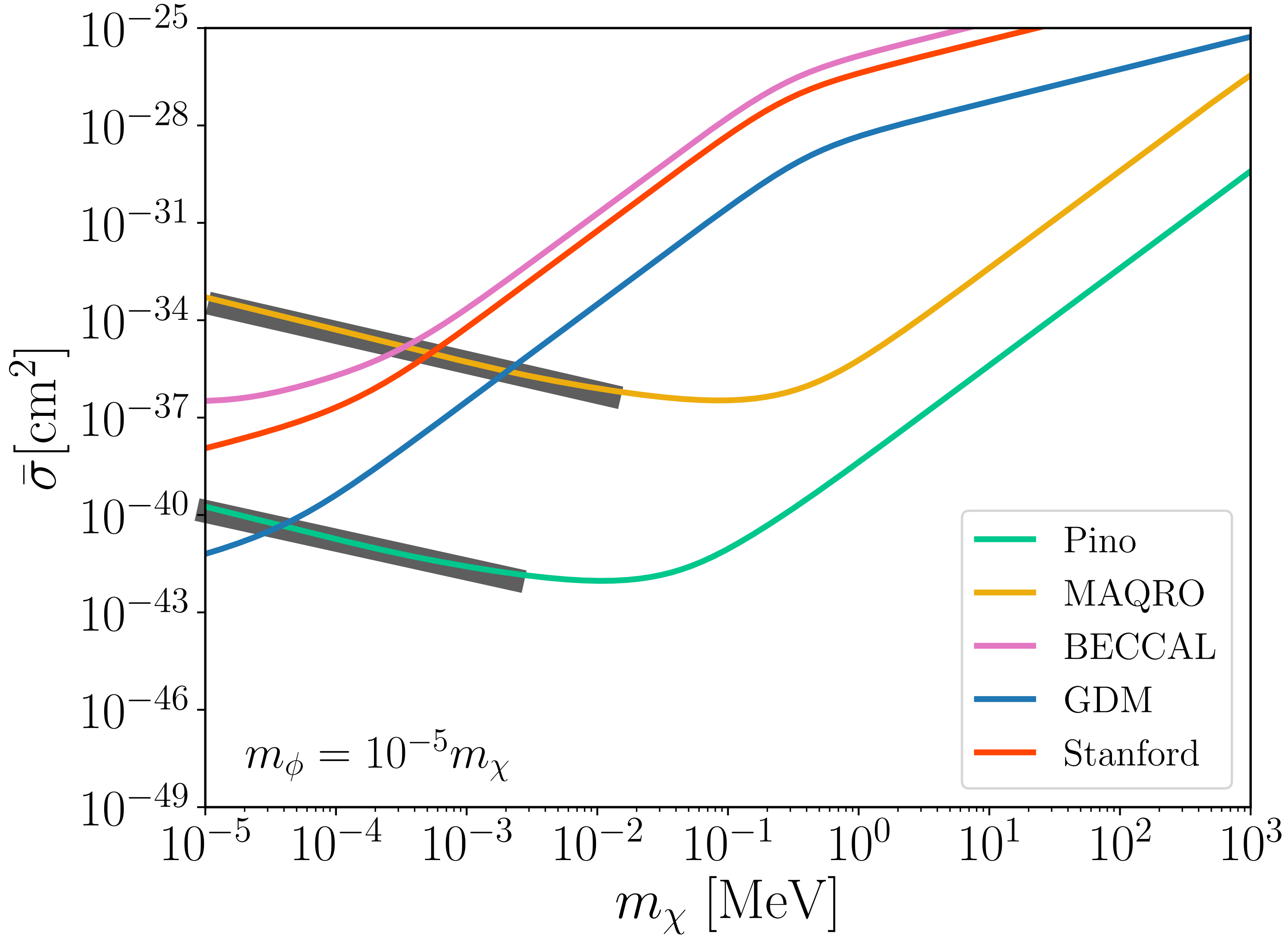



**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

$$s \propto \bar{\sigma} N^2 m_\chi v_0^4 \Delta x^2$$

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



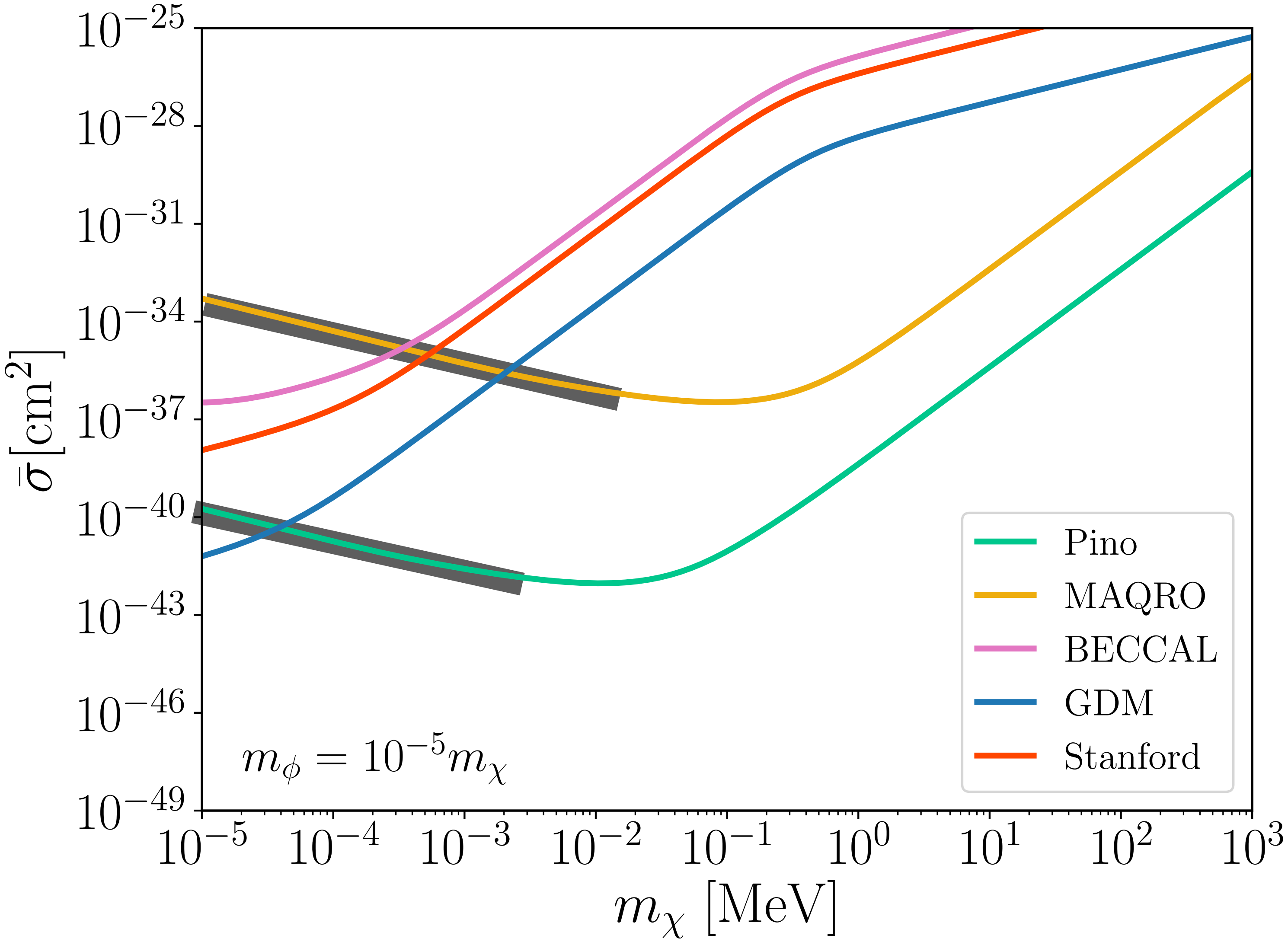

**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

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

**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** $m_\chi \to \infty$




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

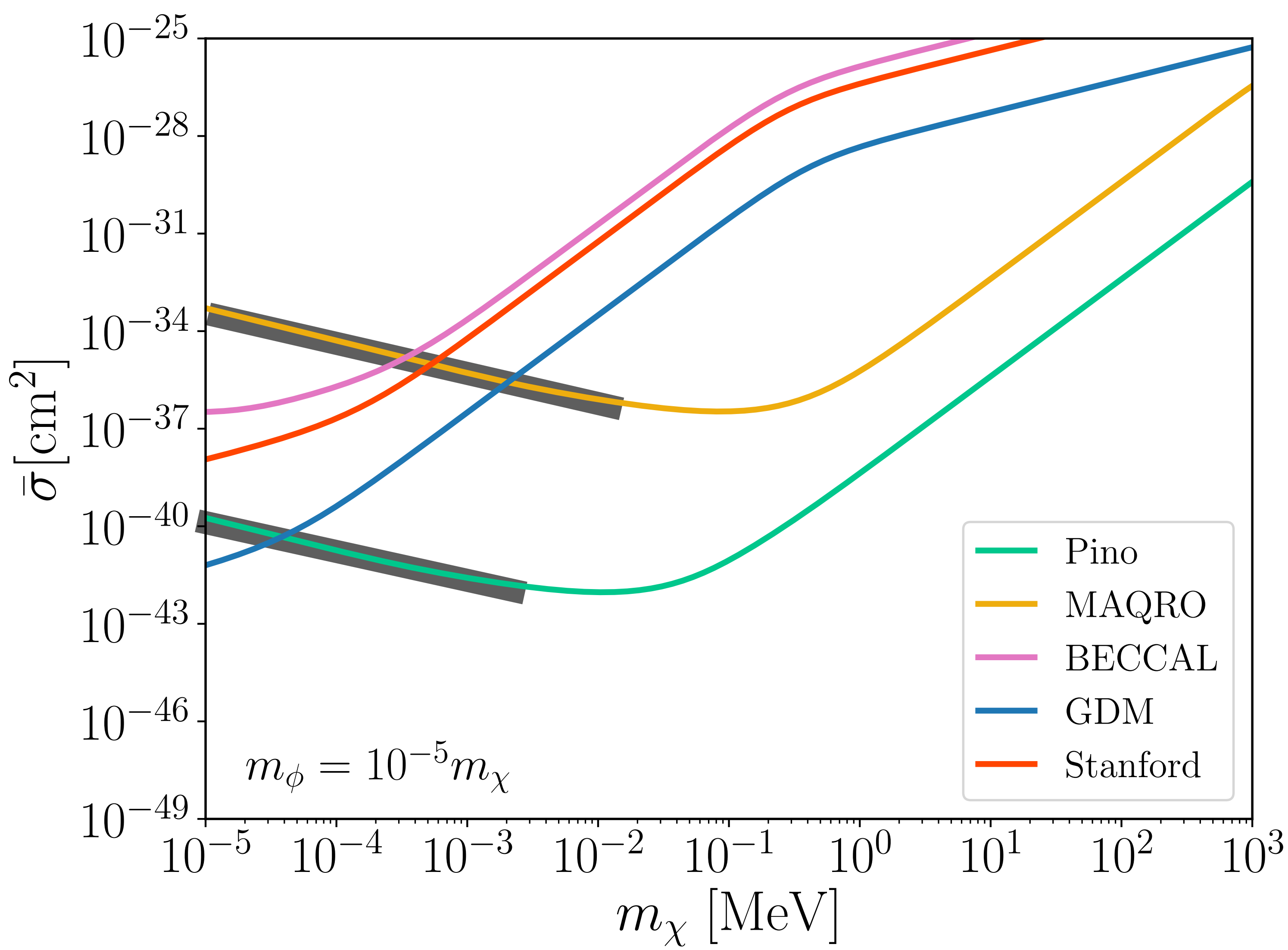
# AIs: Results

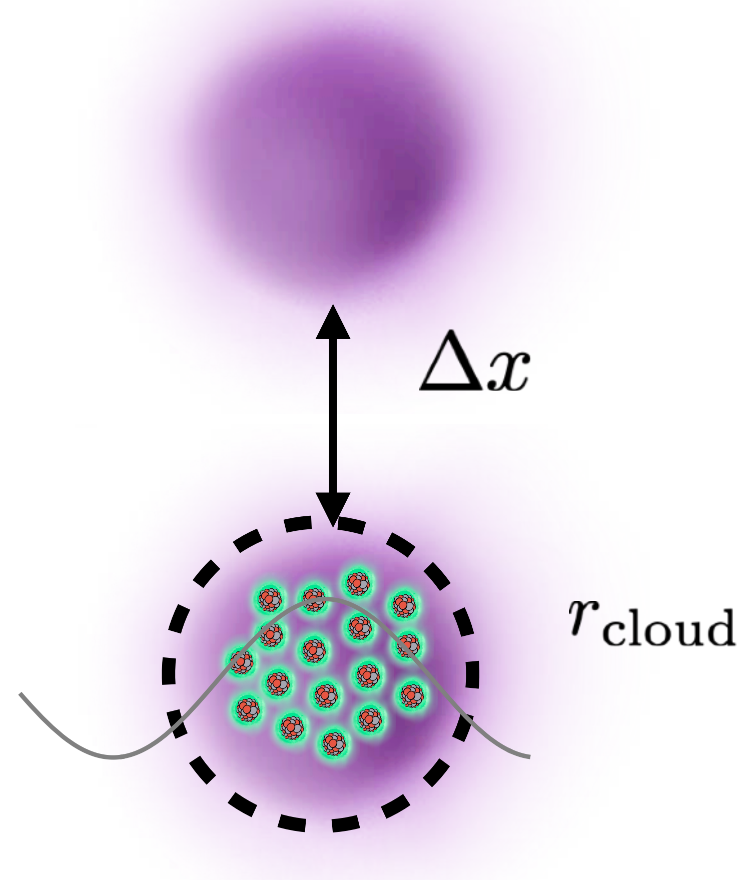
$$s \propto \frac{\bar{\sigma}((m_\chi v_0)^2 + m_\phi^2)^2}{m_\chi^3} \int dq \, \frac{q}{(q^2 + m_\phi^2)^2} N(1 + N F^2(q r_{\rm cloud}))\left(1 - \frac{\sin(q\Delta x)}{q \Delta x}\right)$$

0 1

**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** $m_\chi \to \infty$



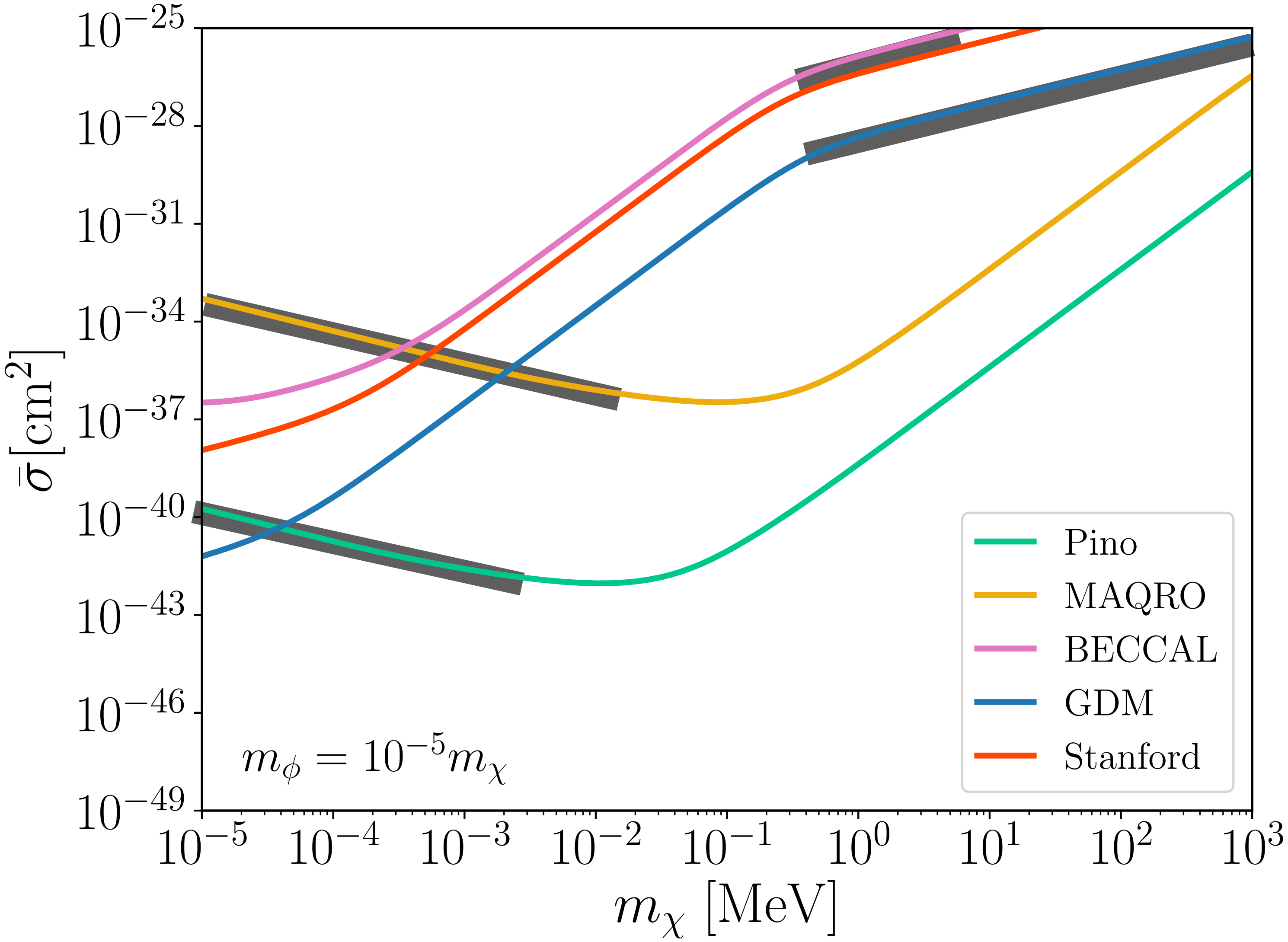

**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

$$s \propto \bar{\sigma}\frac{N}{m_\chi}$$

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



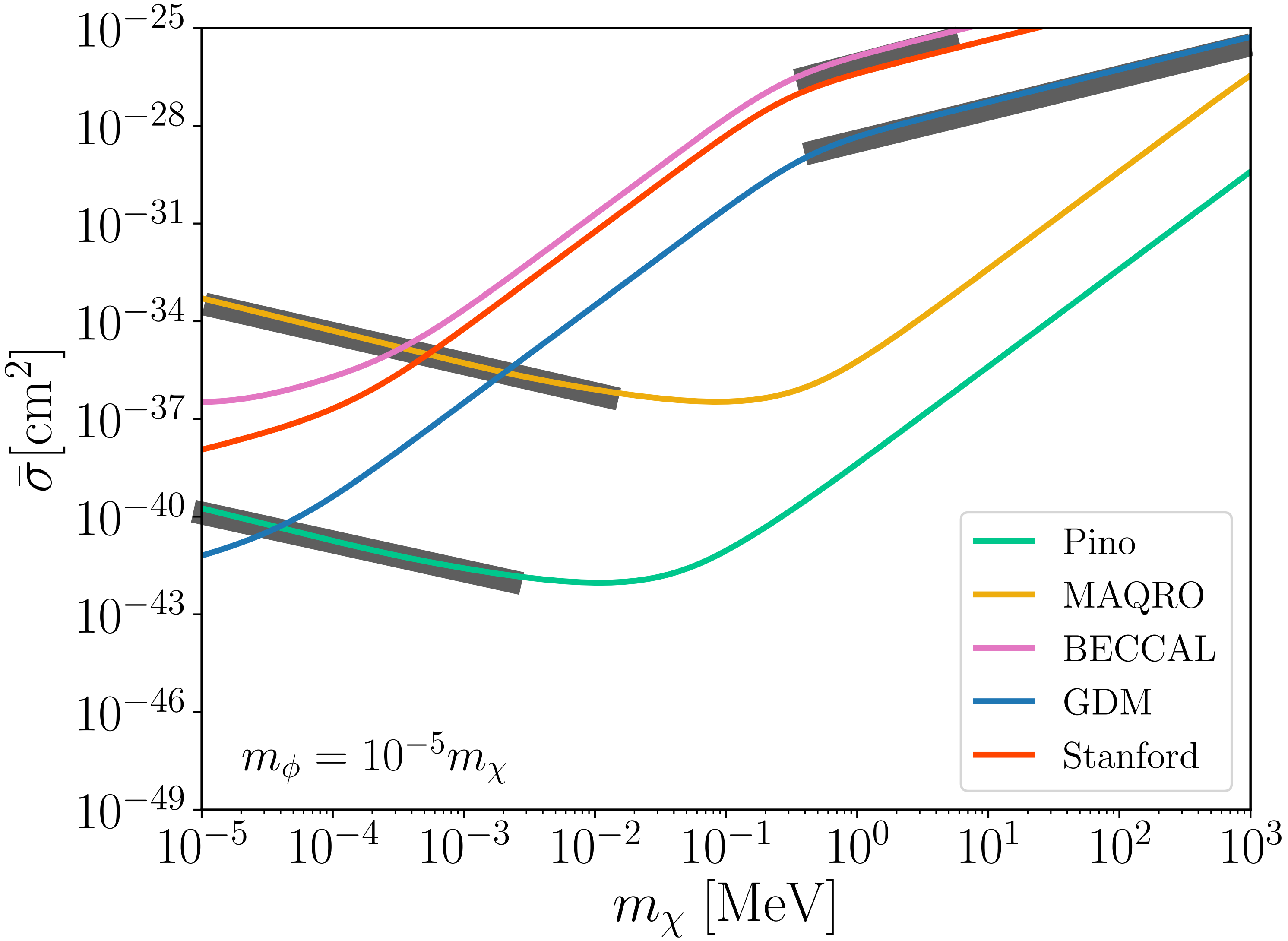

**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

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

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

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




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

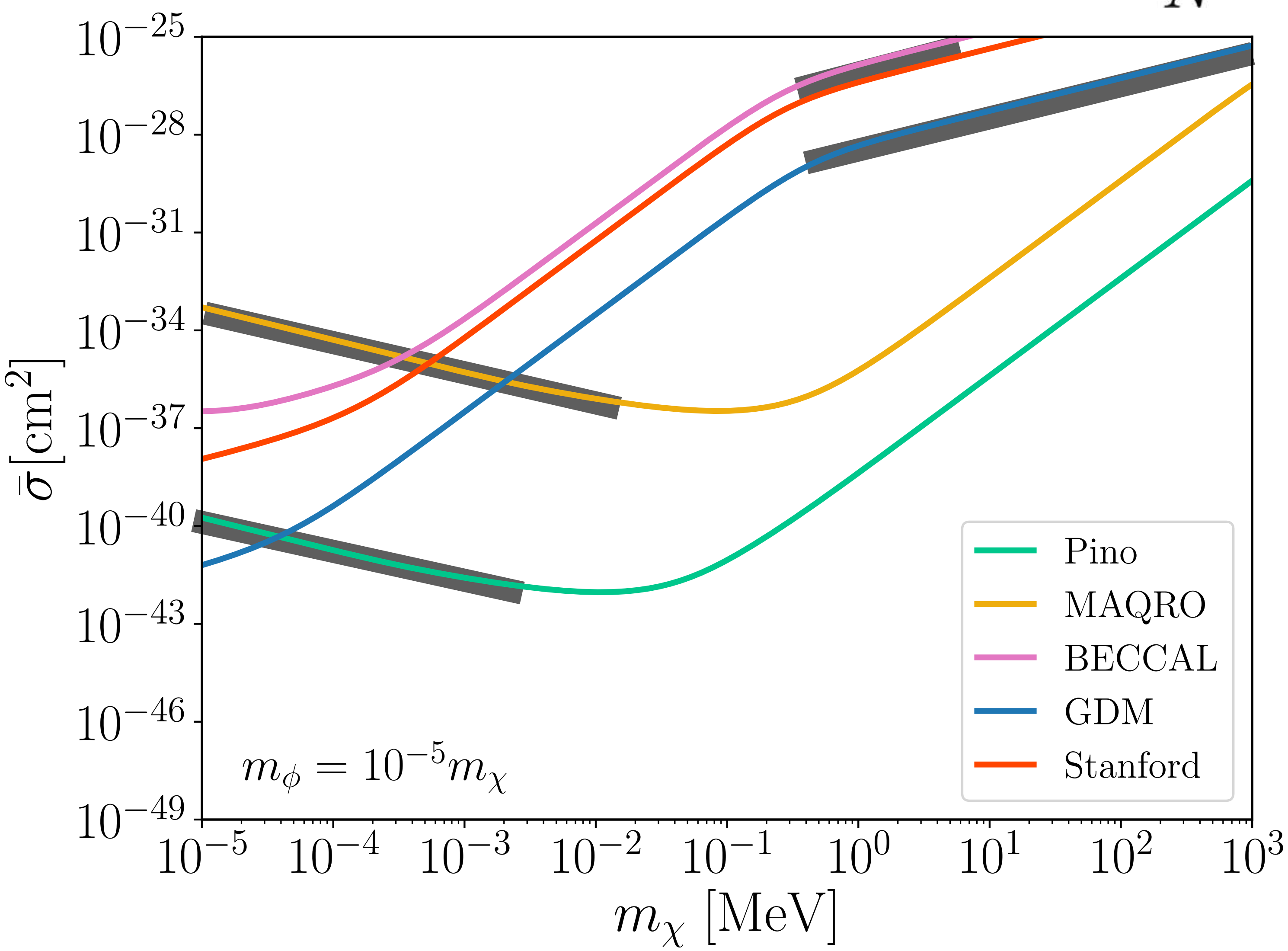
**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

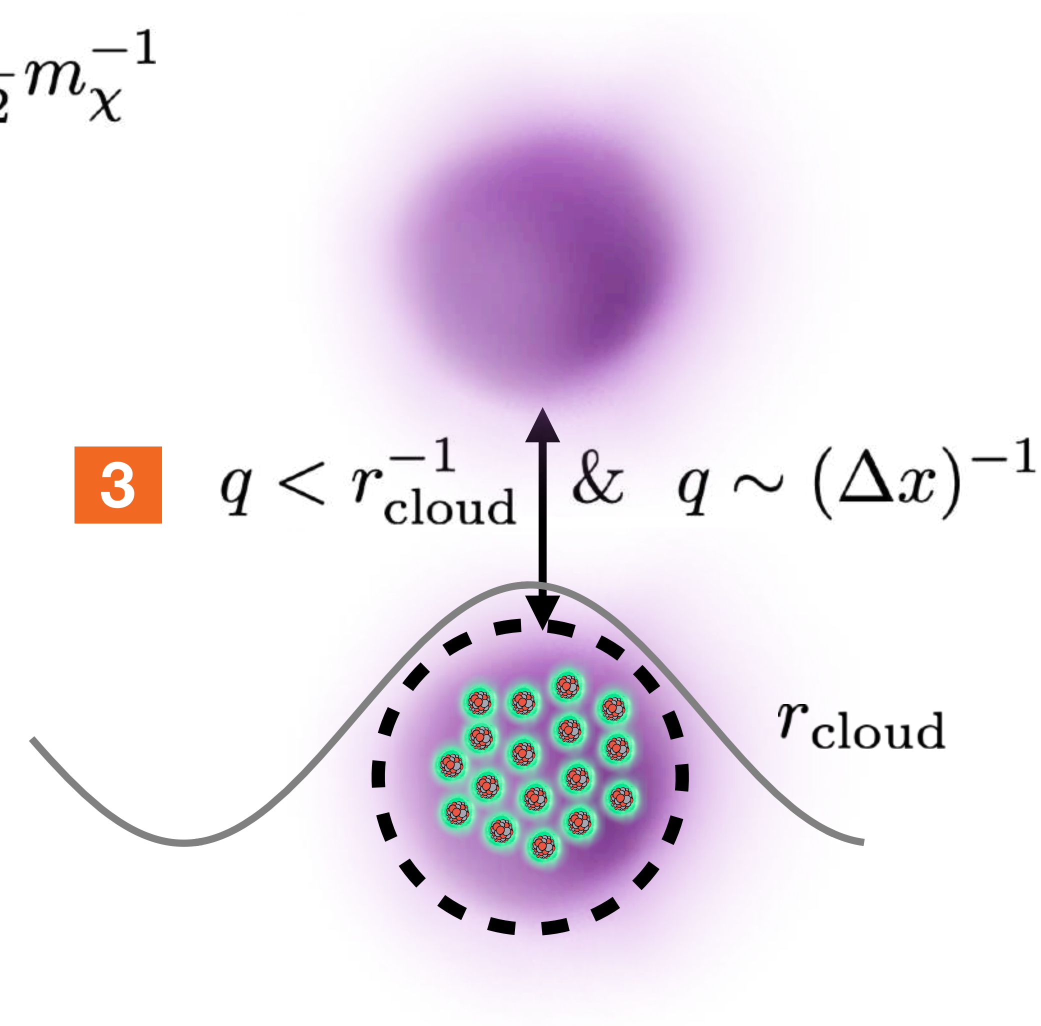
$$s \propto \frac{\bar{\sigma}((m_\chi v_0)^2 + m_\phi^2)^2}{m_\chi^3} \int dq \, \frac{q}{(q^2 + m_\phi^2)^2} N(1+N \cancelto{1}{F^2(q r_{\rm cloud})}) \Big(1 - \cancelto{1}{\frac{\sin(q\Delta x)}{q\Delta x}}\Big)$$

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



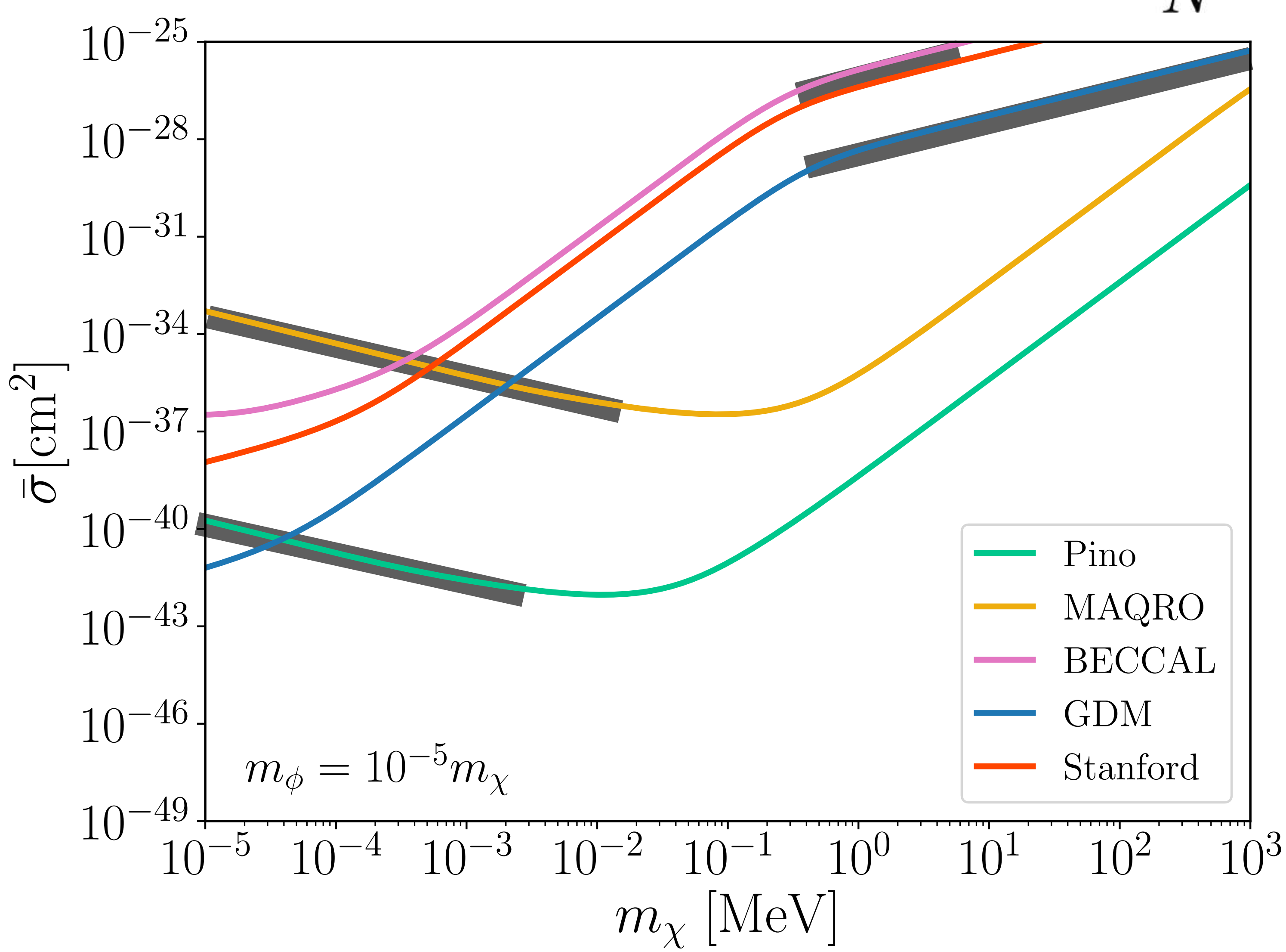

**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

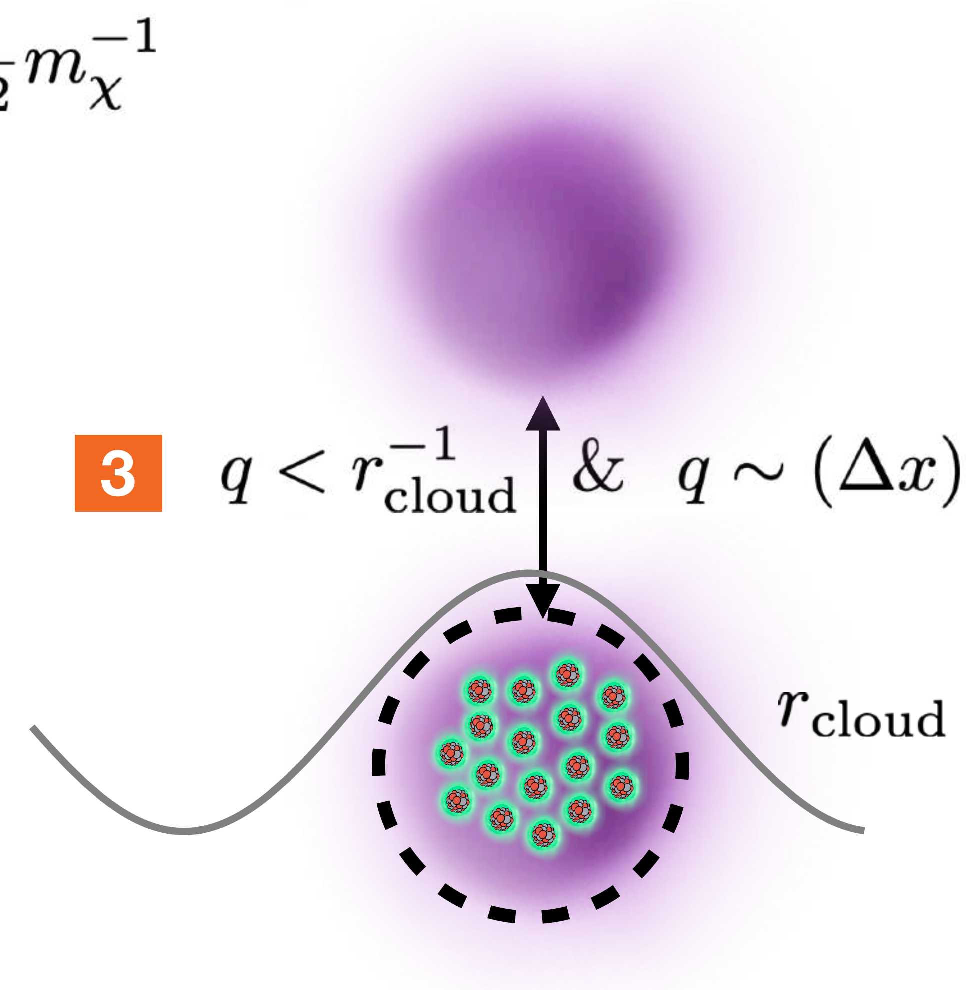
$$s \propto \frac{\bar{\sigma}((m_\chi v_0)^2 + \cancel{m_\phi^2})^2}{m_\chi^3} \int dq \, \frac{q}{(\cancel{q^2} + m_\phi^2)^2} N(1+N \underbrace{F^2(q r_{\text{cloud}})}_{\to 1}) \Big(1 - \underbrace{\frac{\sin(q\Delta x)}{q\Delta x}}_{\to 1}\Big)$$

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



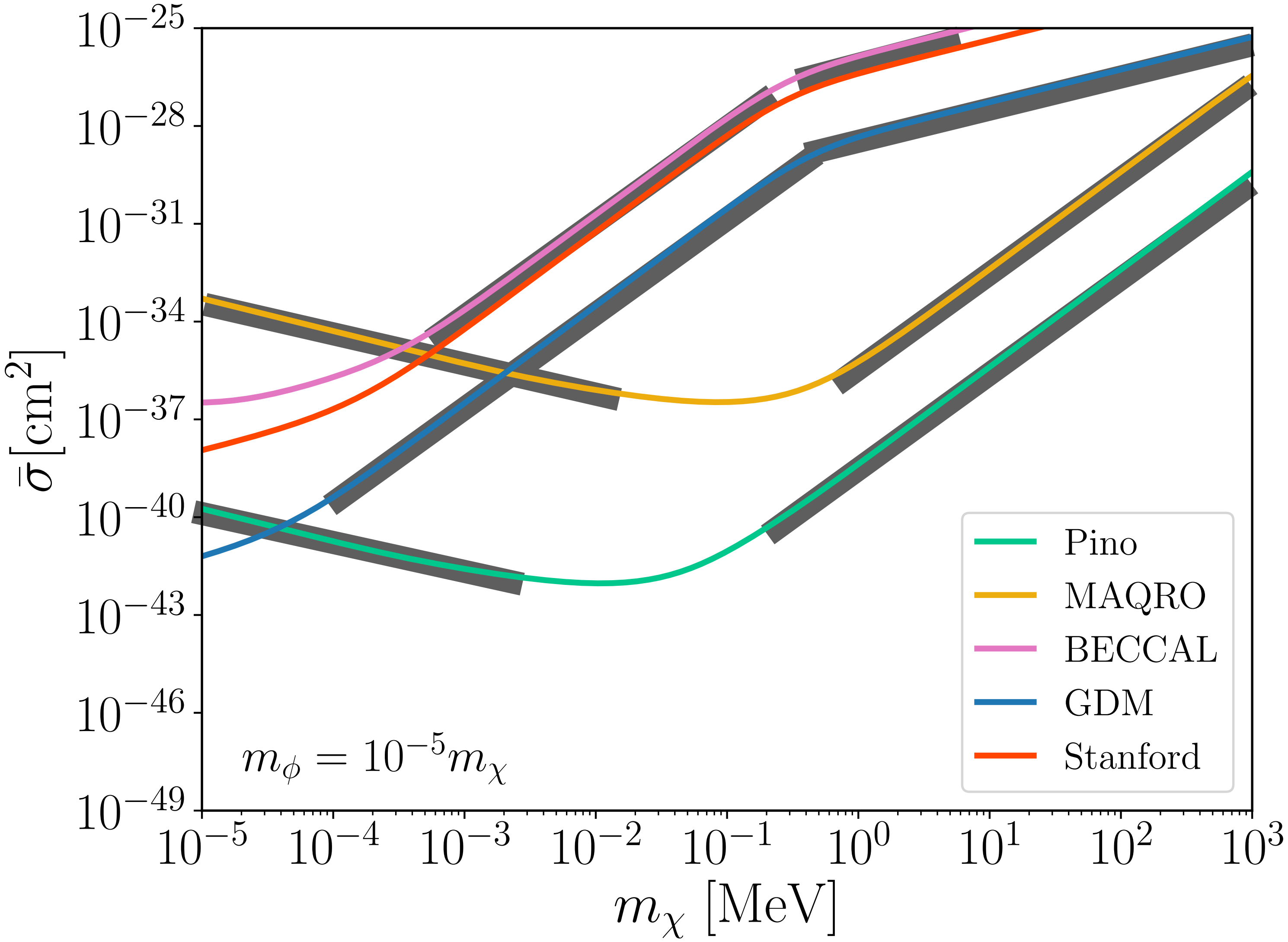

**Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$**

# AIs: Results

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

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

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

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

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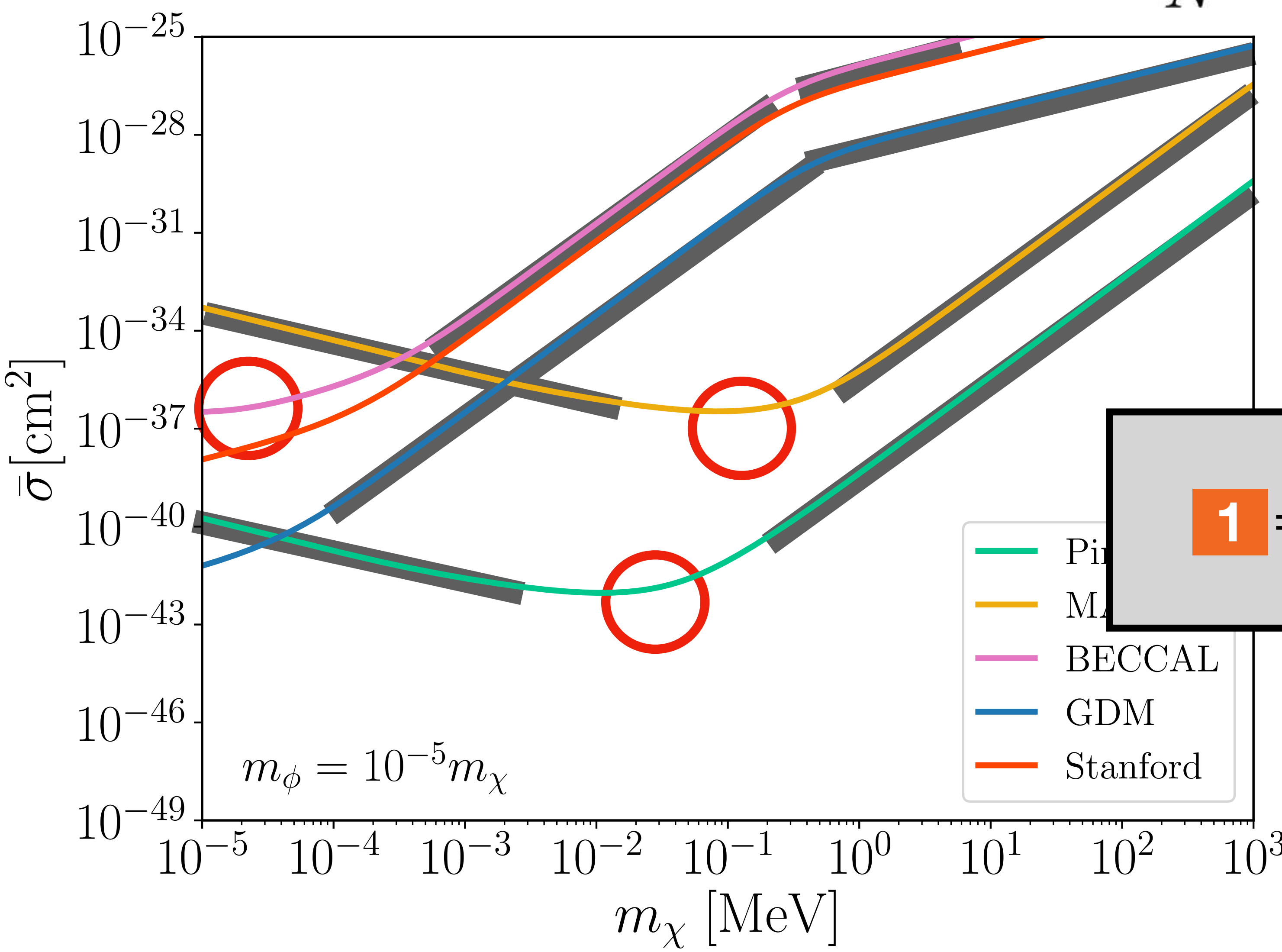
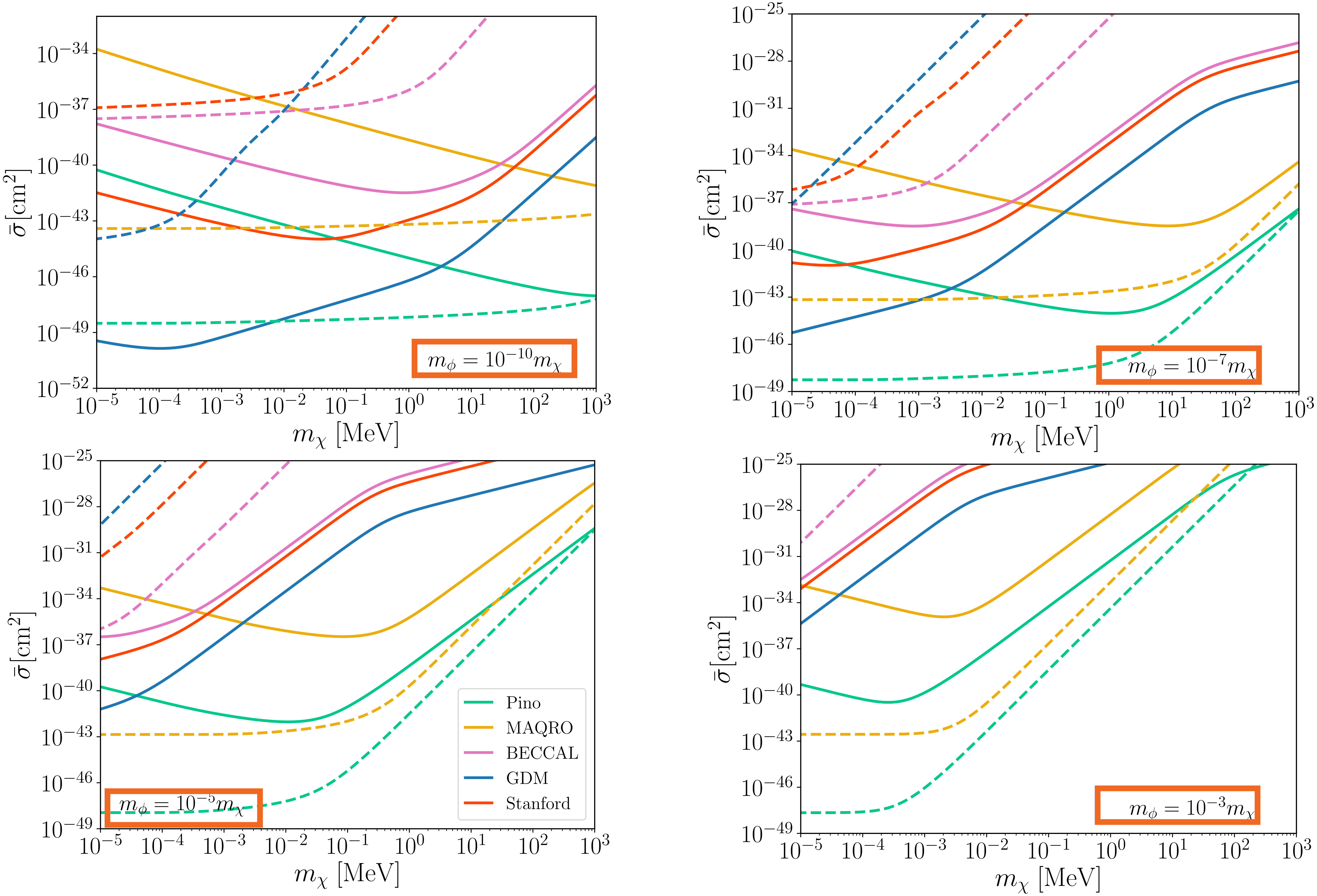



**1** = **3** ⇨ $m_\chi^{\text{knee}} \sim \frac{1}{\sqrt{r_{\text{cloud}} \Delta x R_{\phi\chi}}}$

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

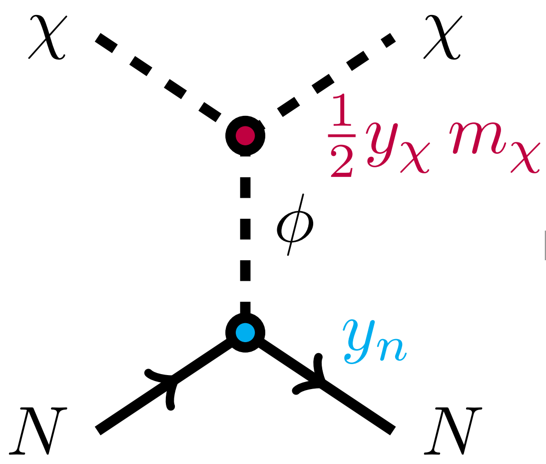
# AIs: Results



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

# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

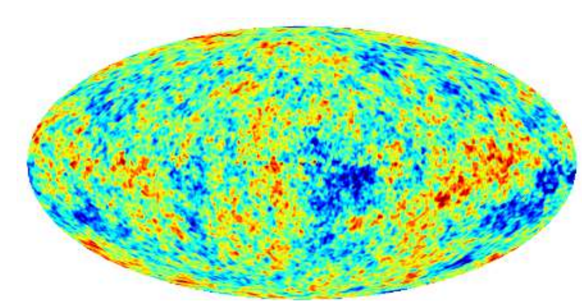



$$\bar{\sigma} = \frac{y_\chi^2\, y_n^2}{4\pi} \frac{\mu^2}{(m_\chi^2 v_0^2 + m_\phi^2)^2}$$

**Terrestial**

**Astrophysical**

**Cosmological**

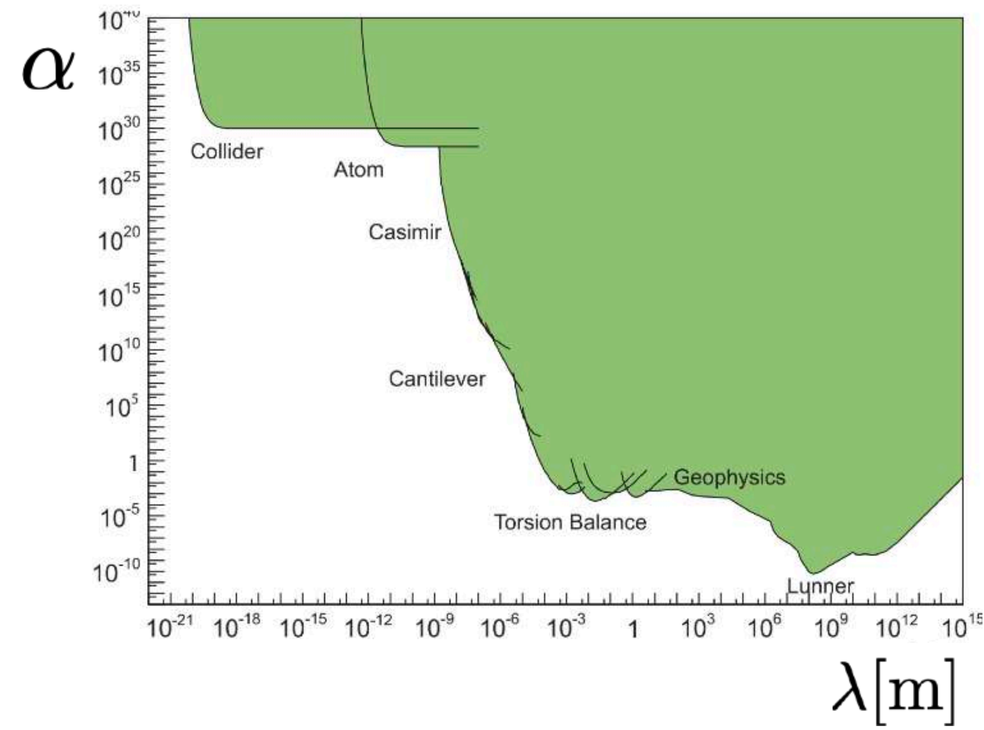


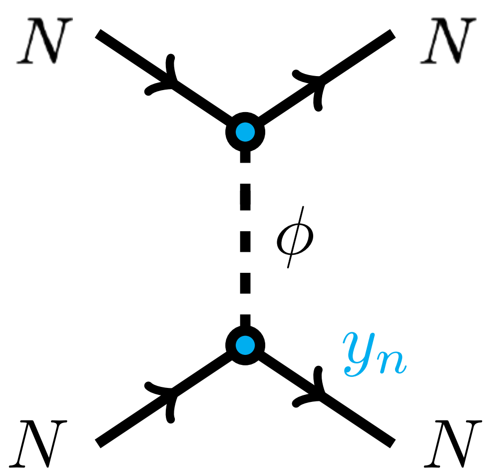
# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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

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




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

[Murata, Tanaka, 2014]

**Terrestial**

Collider

5th force

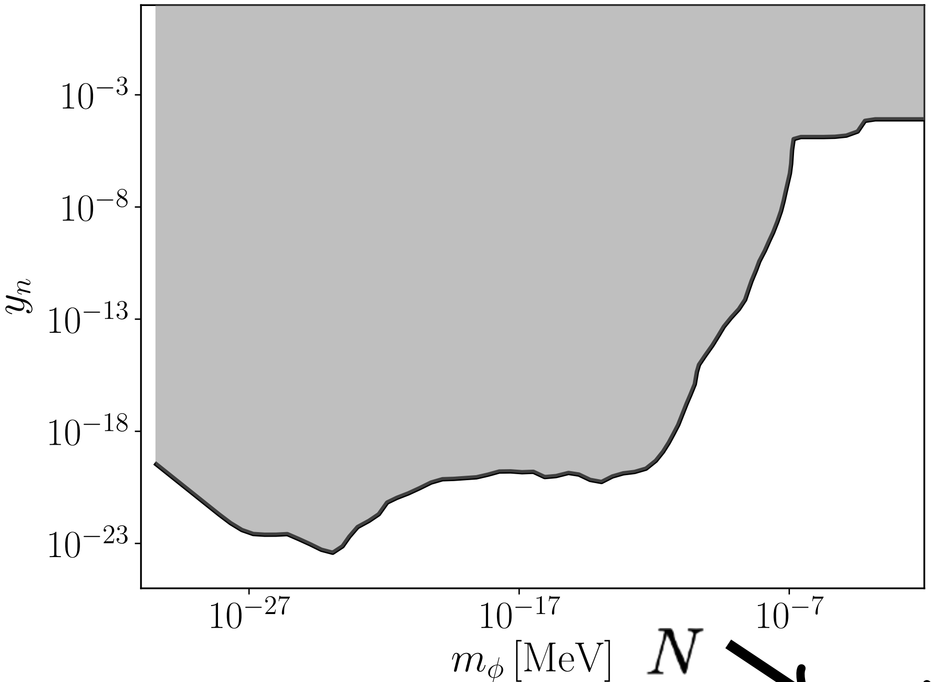
**Astrophysical**

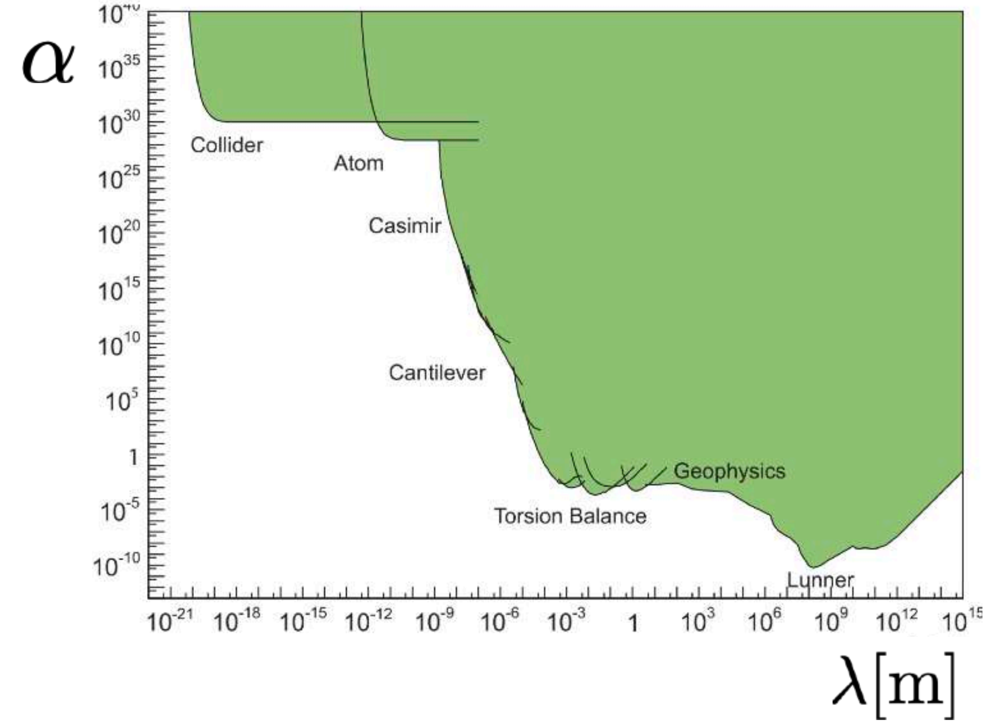


**Cosmological**

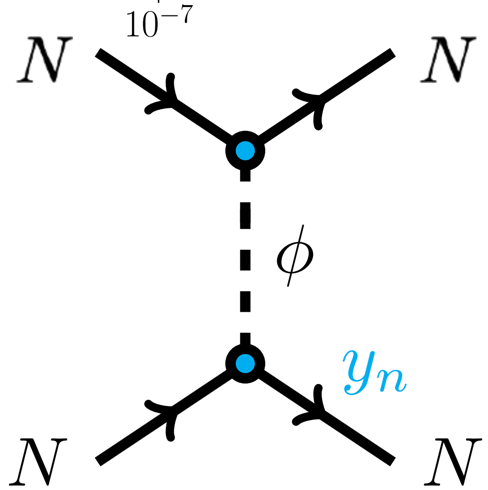
# AIs: Constraints

[Knapen, Lin, Zurek, 2017]




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

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[Murata, Tanaka, 2014]

## Terrestial

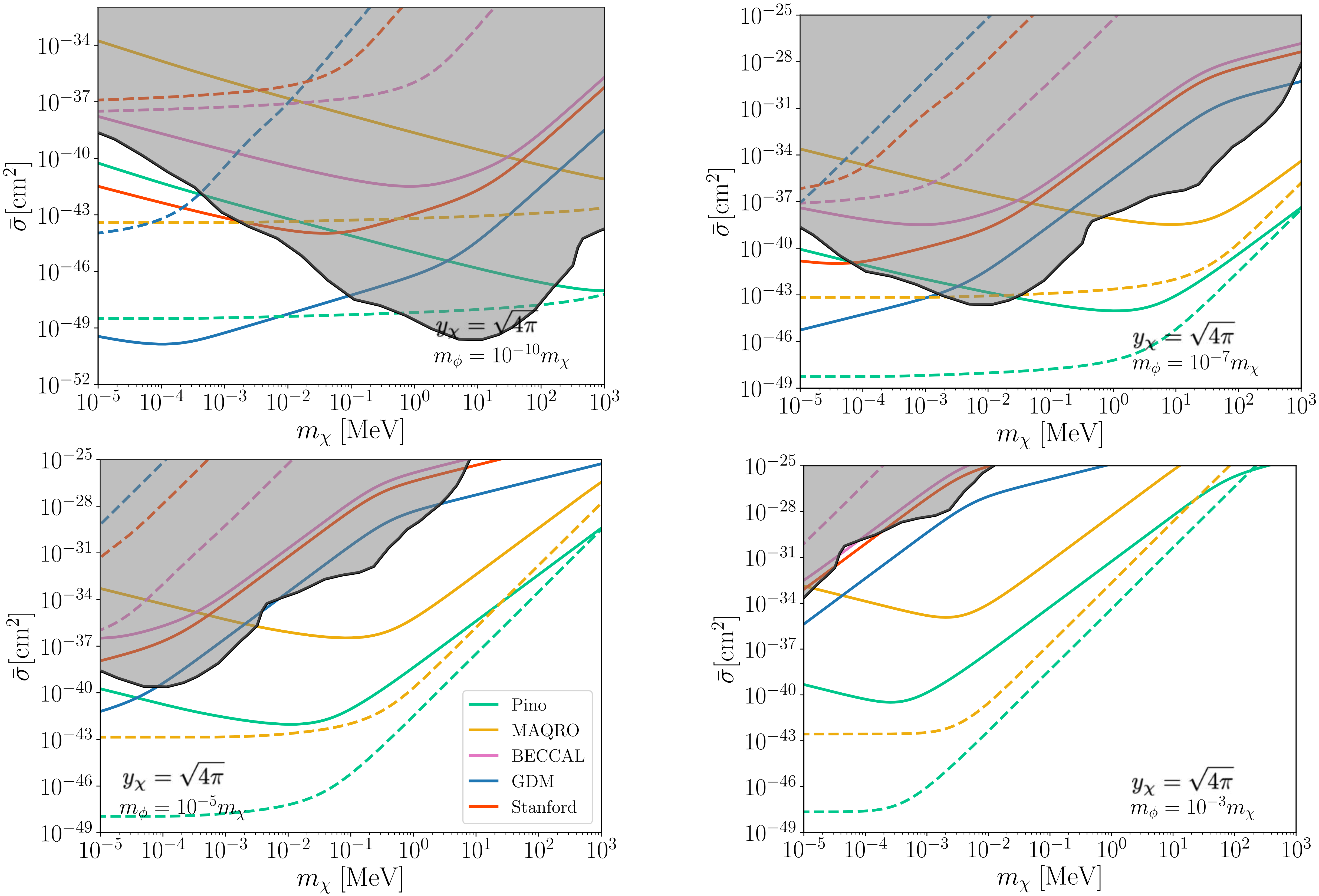
- Collider
- 5th force

## Astrophysical



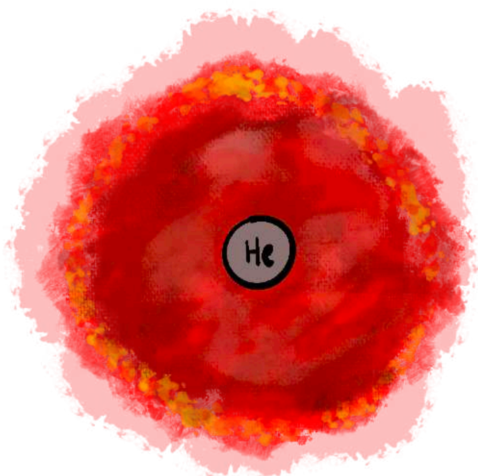
## Cosmological

# AIs: Constraints



# AIs: Constraints

[Knapen, Lin, Zurek, 2017]



**RG and HB stars**

$m_\phi < T \sim 10$ keV ( He )

$\epsilon \lesssim 10$ erg/g/s ⇨ $y_n \lesssim 4 \times 10^{-11}$

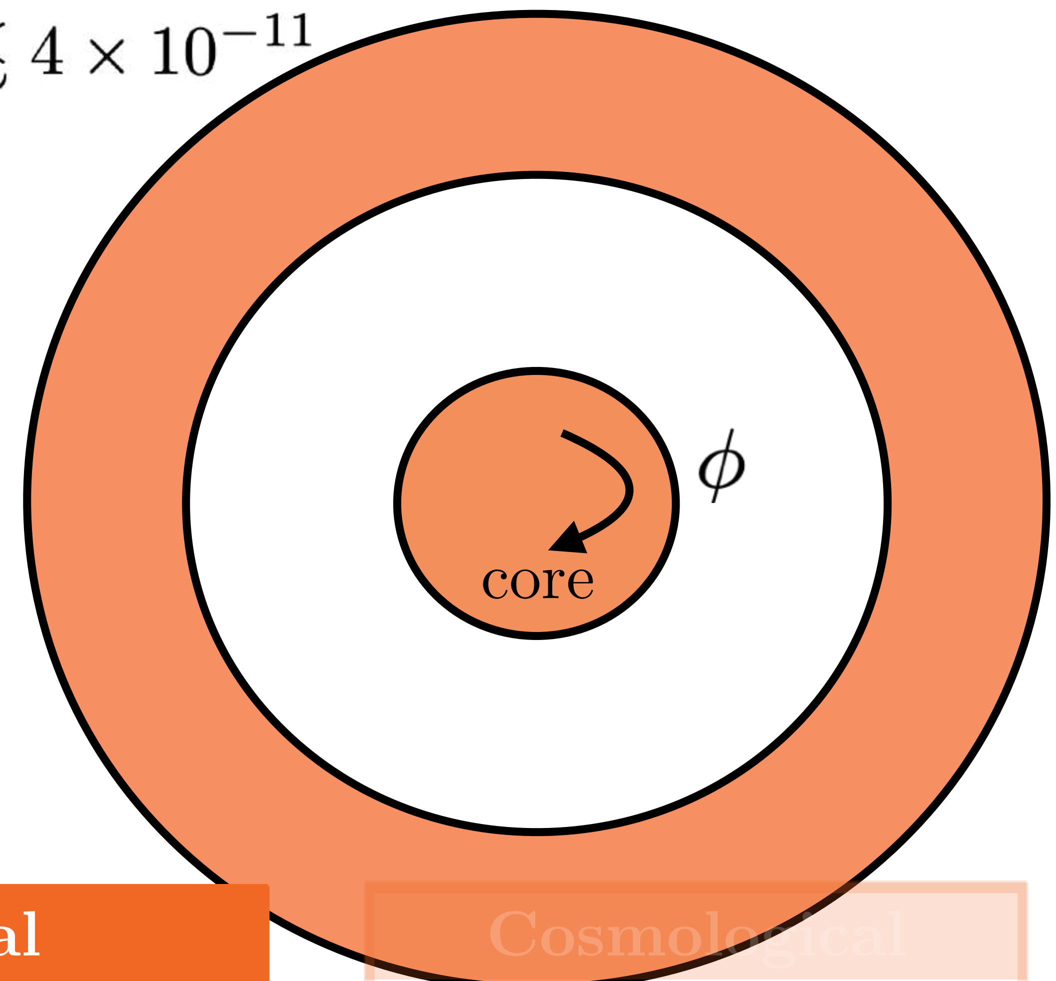
**SN1987A**

$T = 30$ MeV

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

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

$$\ell_{\rm abs} \sim \frac{T^4}{\epsilon \rho}$$




**Terrestrial**



⇨ Collider

⇨ 5th force

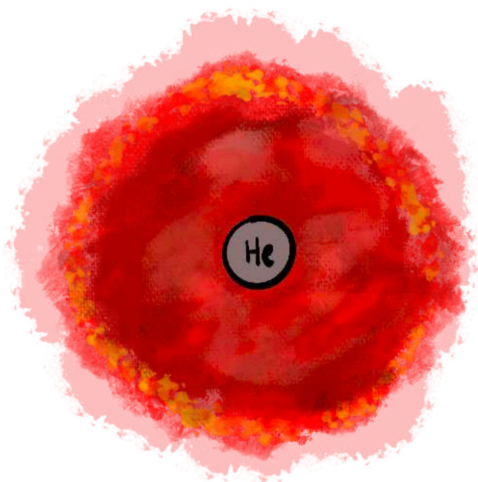
**Astrophysical**

⇨ Stellar emission

**Cosmological**

# AIs: Constraints

[Knapen, Lin, Zurek, 2017]



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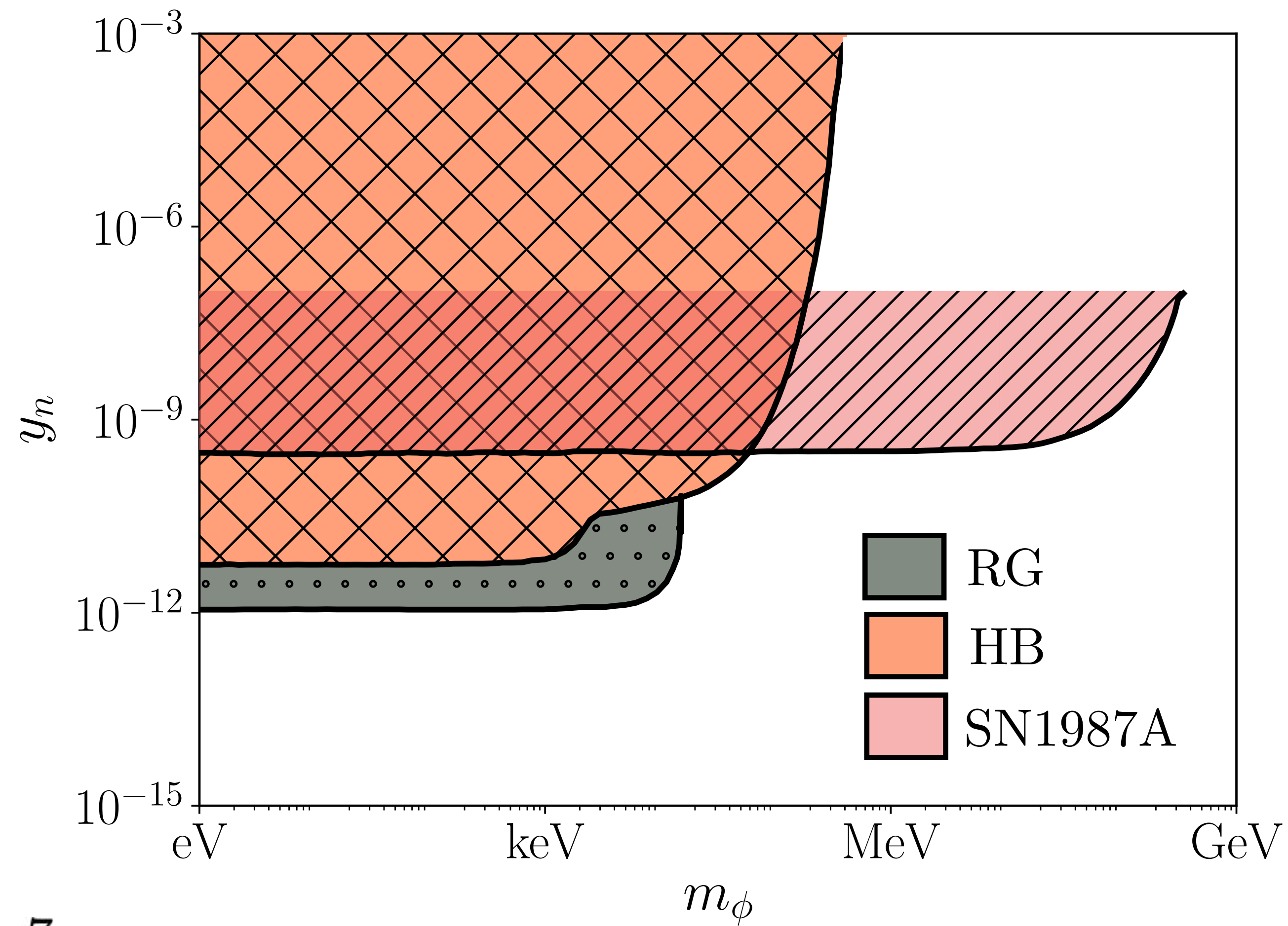


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Terrestrial



⇨ Collider

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**Astrophysical**

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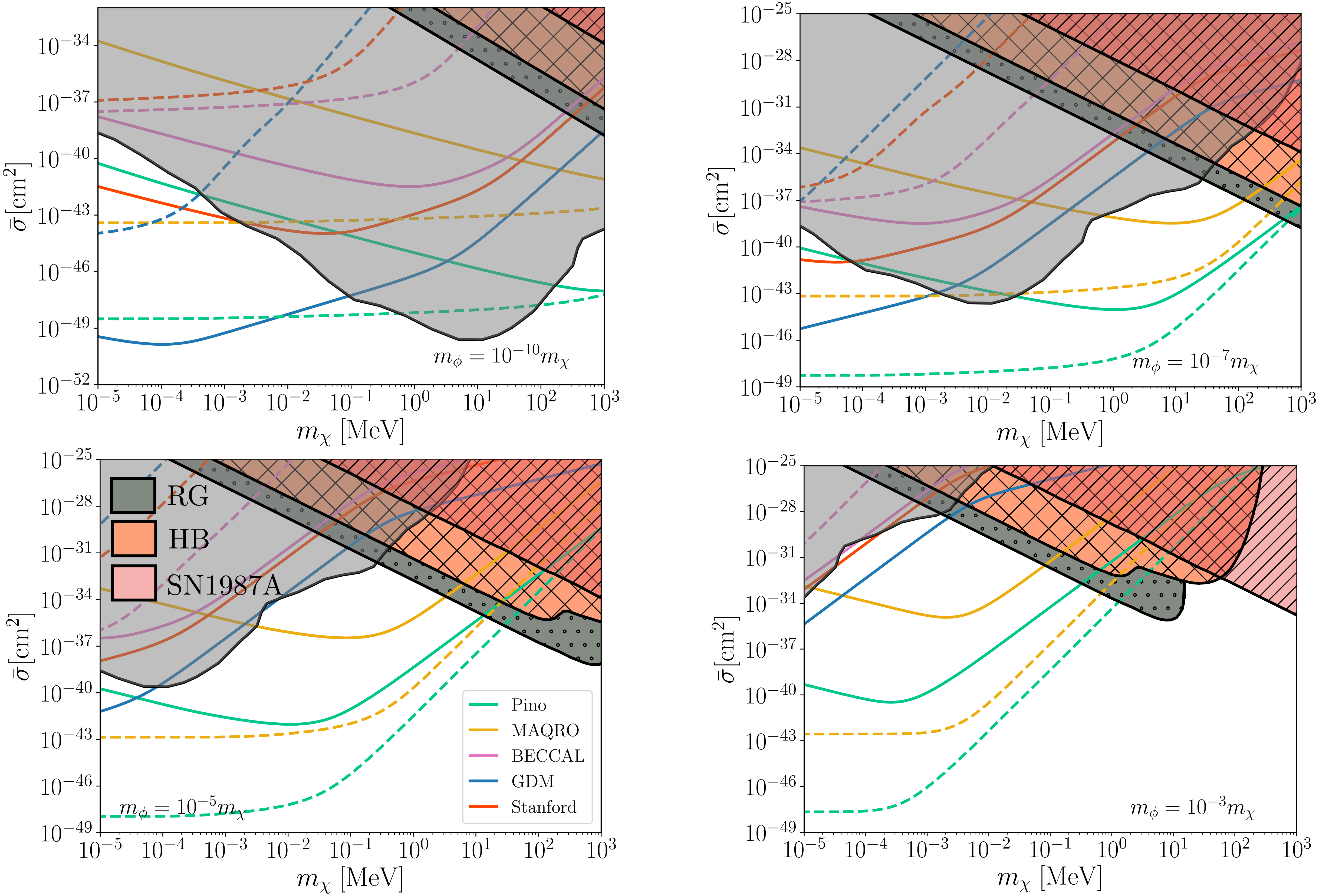
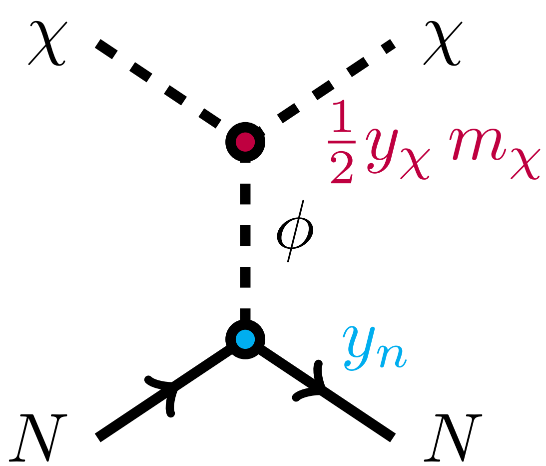
Cosmological

# AIs: Constraints



# AIs: Constraints

[Knapen, Lin, Zurek, 2017]



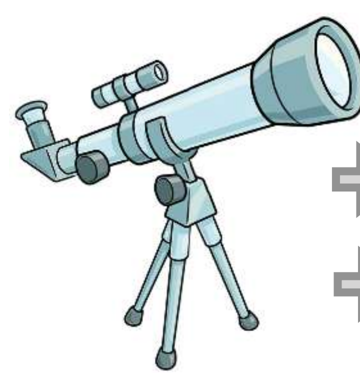

**Terrestrial**



Collider

5th force

**Astrophysical**



Stellar emission

DMSI

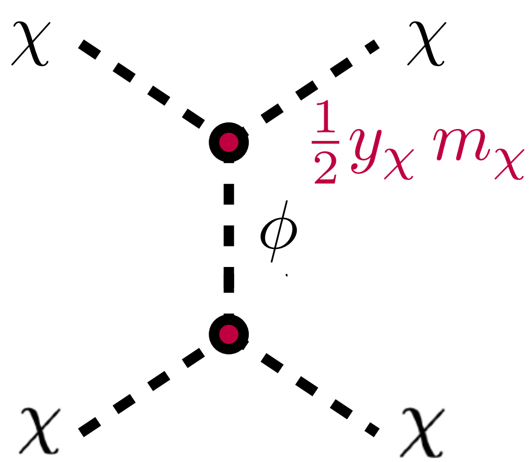
**Cosmological**

# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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

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

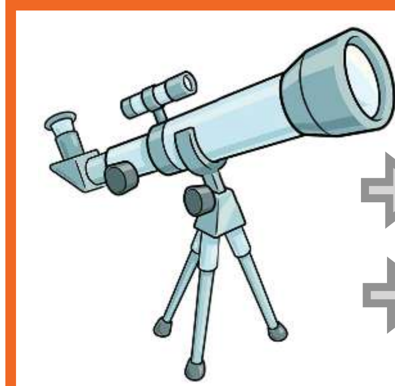



## Terrestrial



- Collider
- 5th force

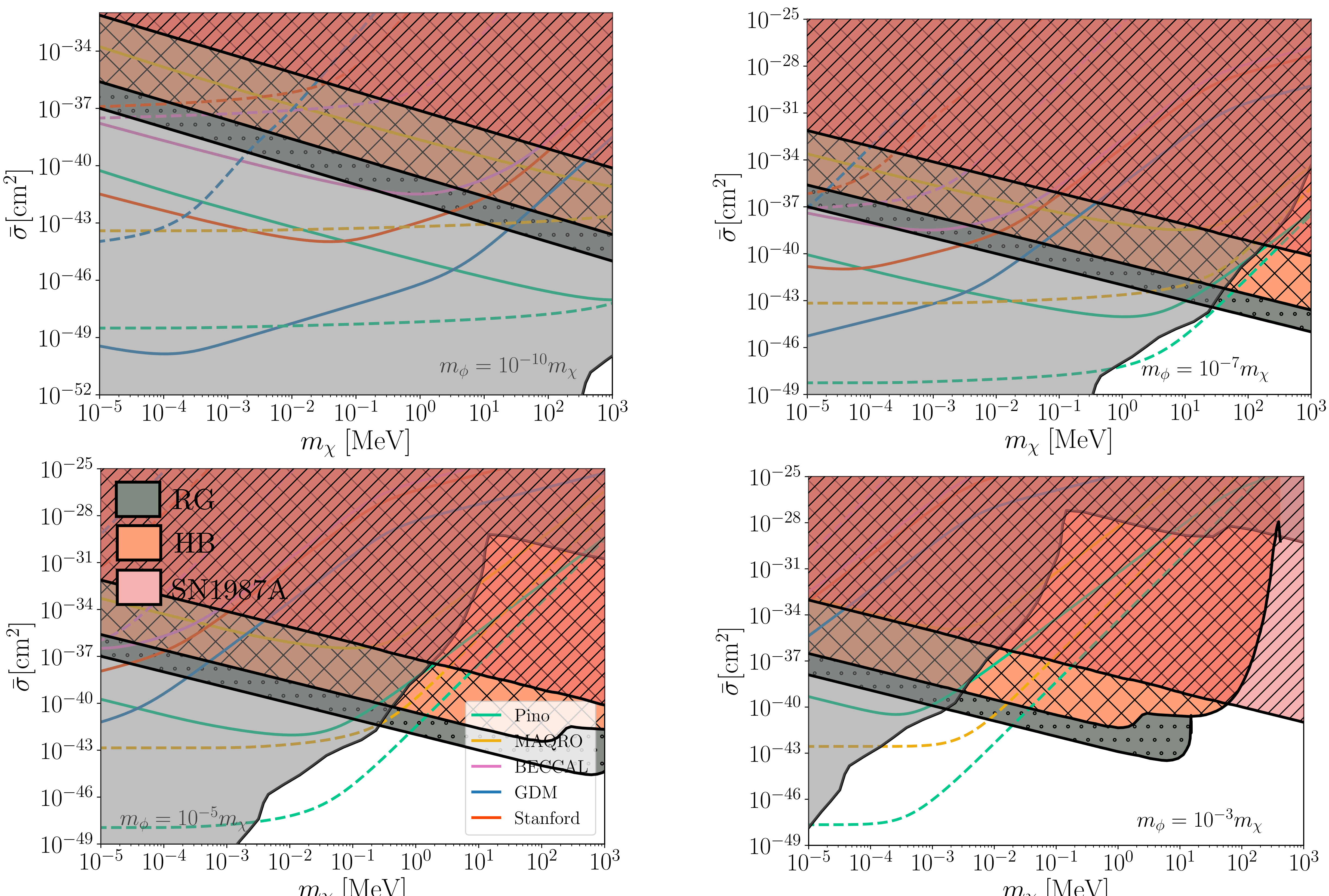
## Astrophysical



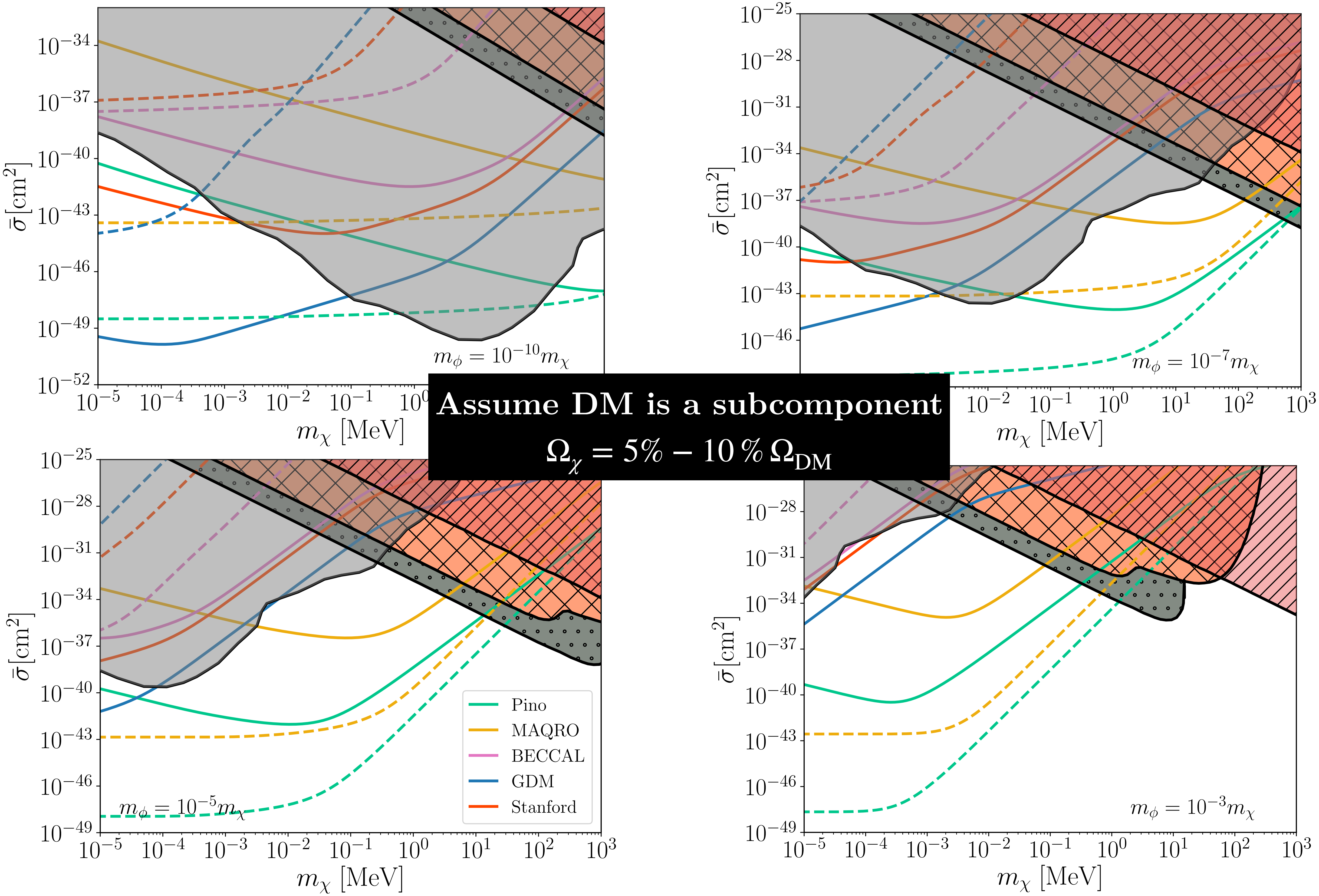
- Stellar emission
- DMSI

## Cosmological

# AIs: Constraints



# AIs: Constraints



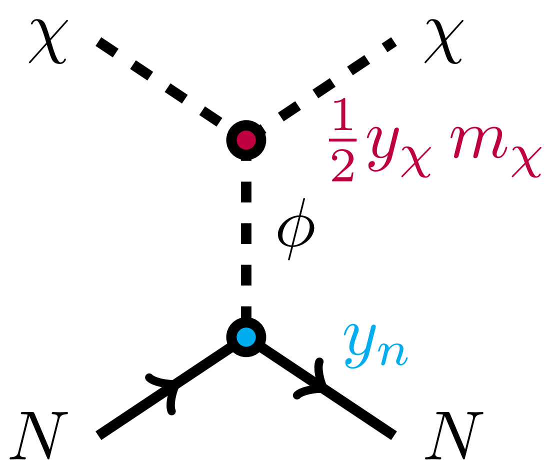

**Assume DM is a subcomponent**

$\Omega_\chi = 5\% - 10\,\%\,\Omega_{DM}$

# 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

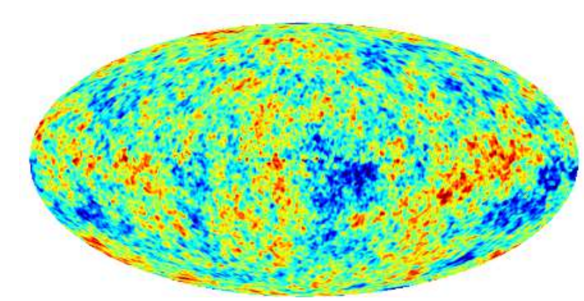
**Astrophysical**



Stellar emission

DMSI

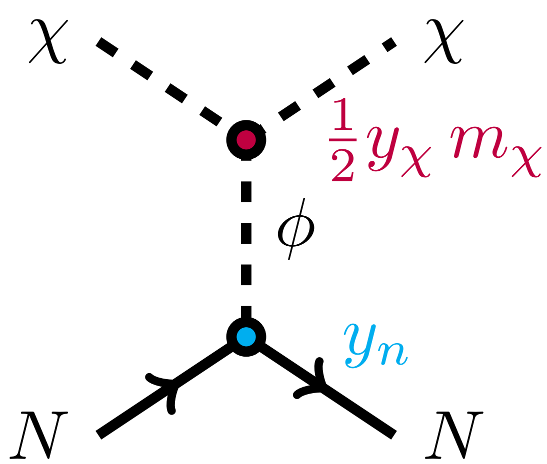
**Cosmological**

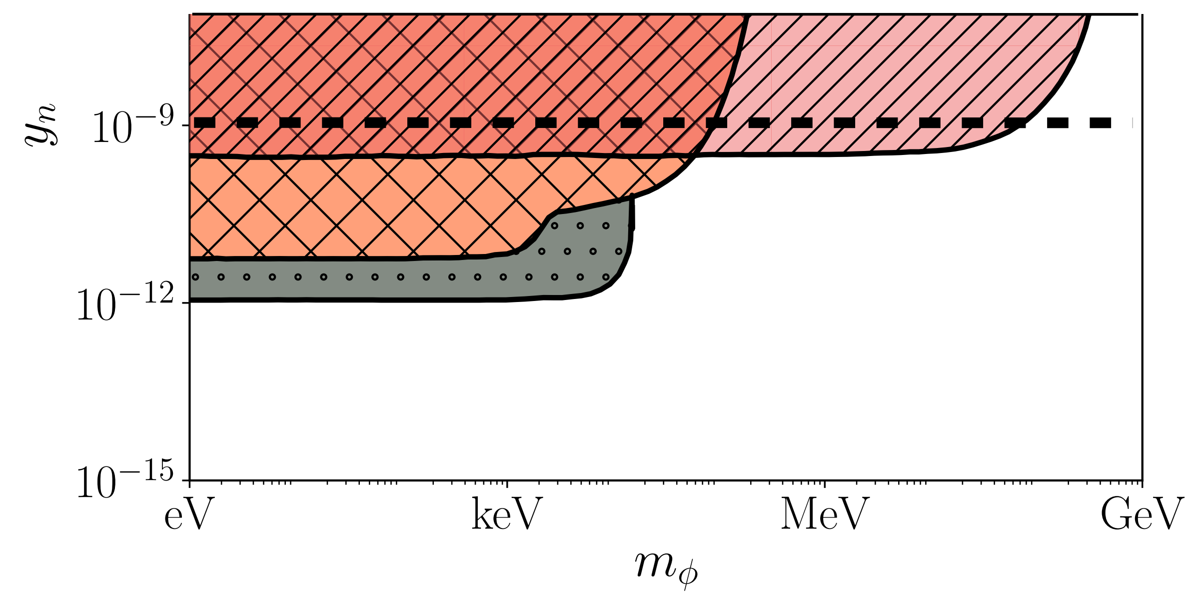


# AIs: Constraints

[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

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Stellar emission

DMSI

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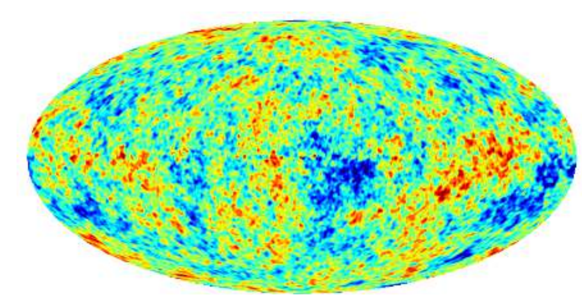
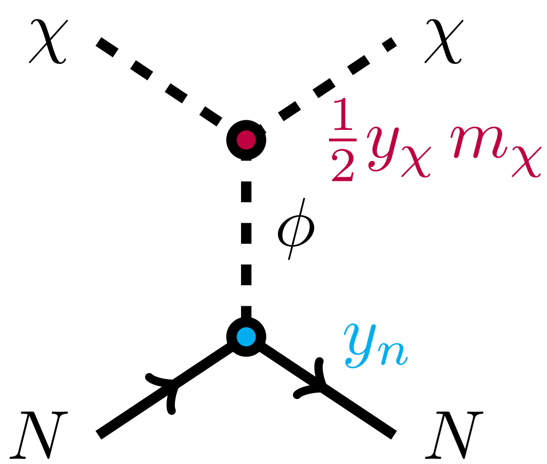
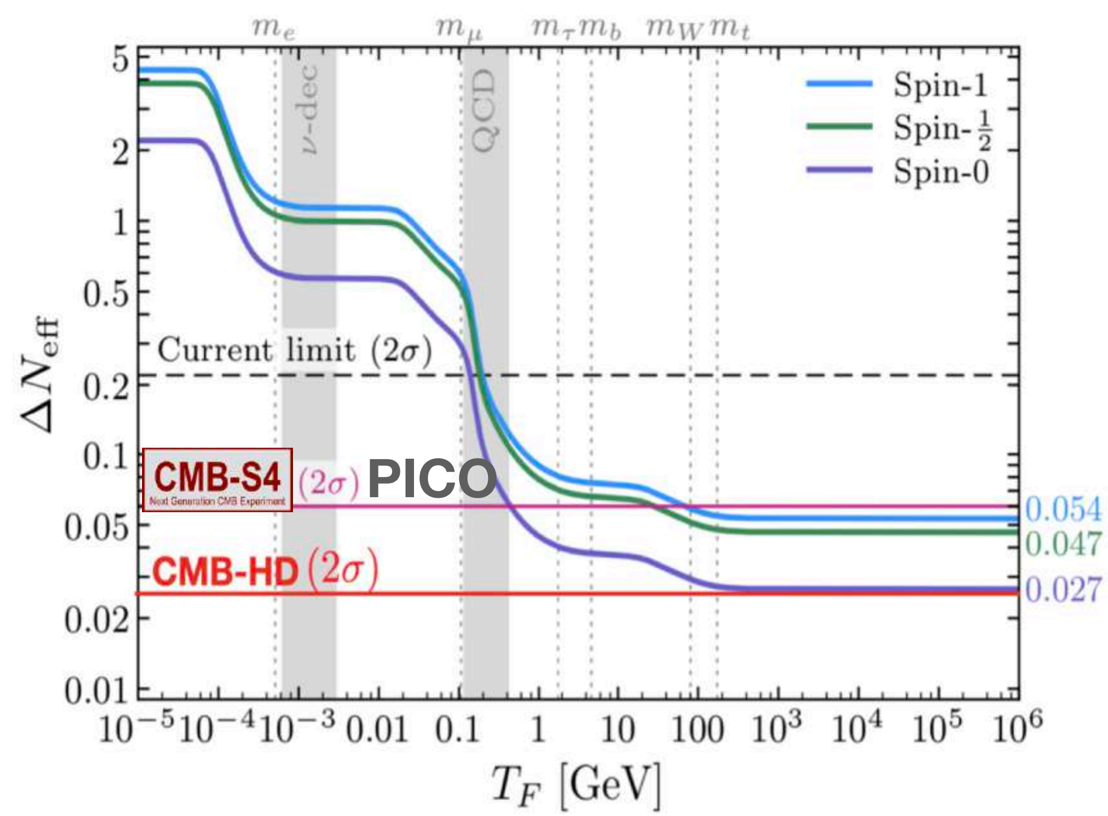


# AIs: Constraints

[Knapen, Lin, Zurek, 2017]

$$\Delta N_{\text{eff}} \sim 0.06 \sum_i g_i$$




Terrestrial



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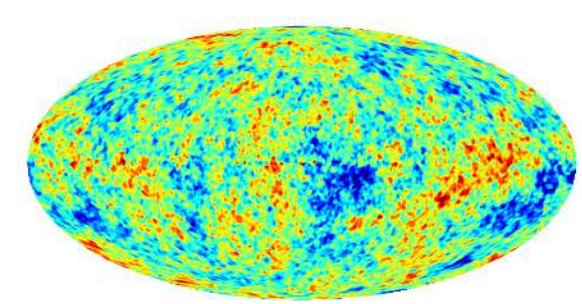
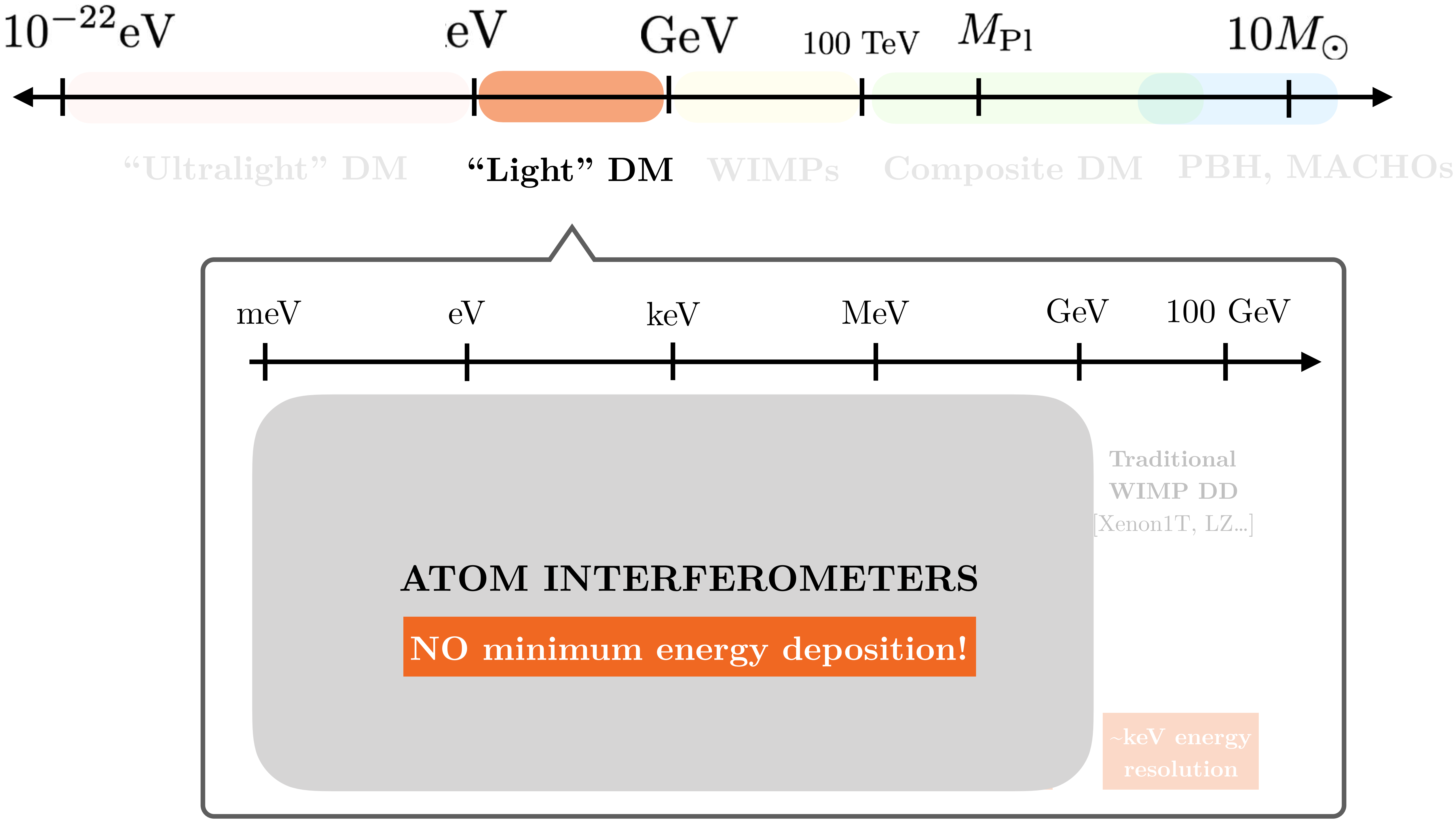
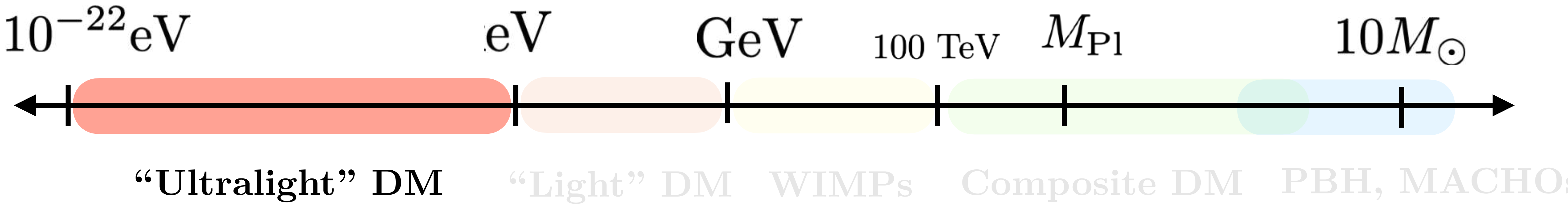
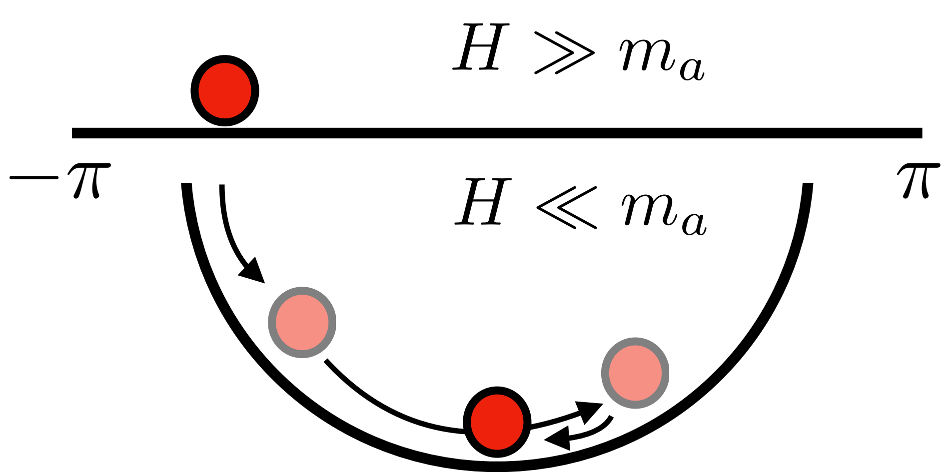


# Dark Matter: where to look?



# Dark Matter: where to look?





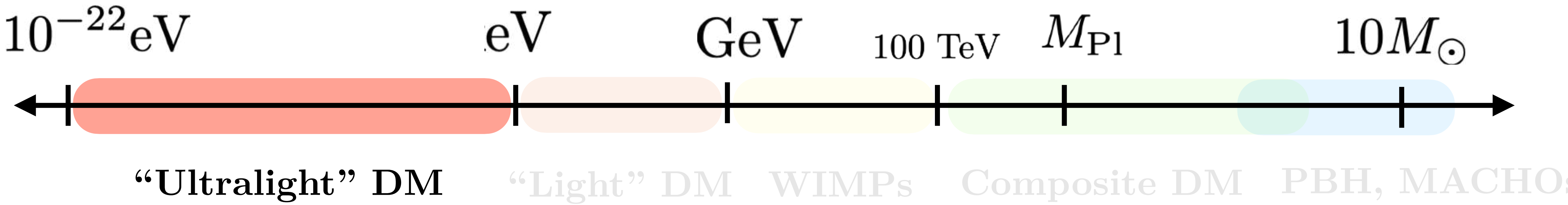
[Preskill, Wise, Wilczek, 1983]

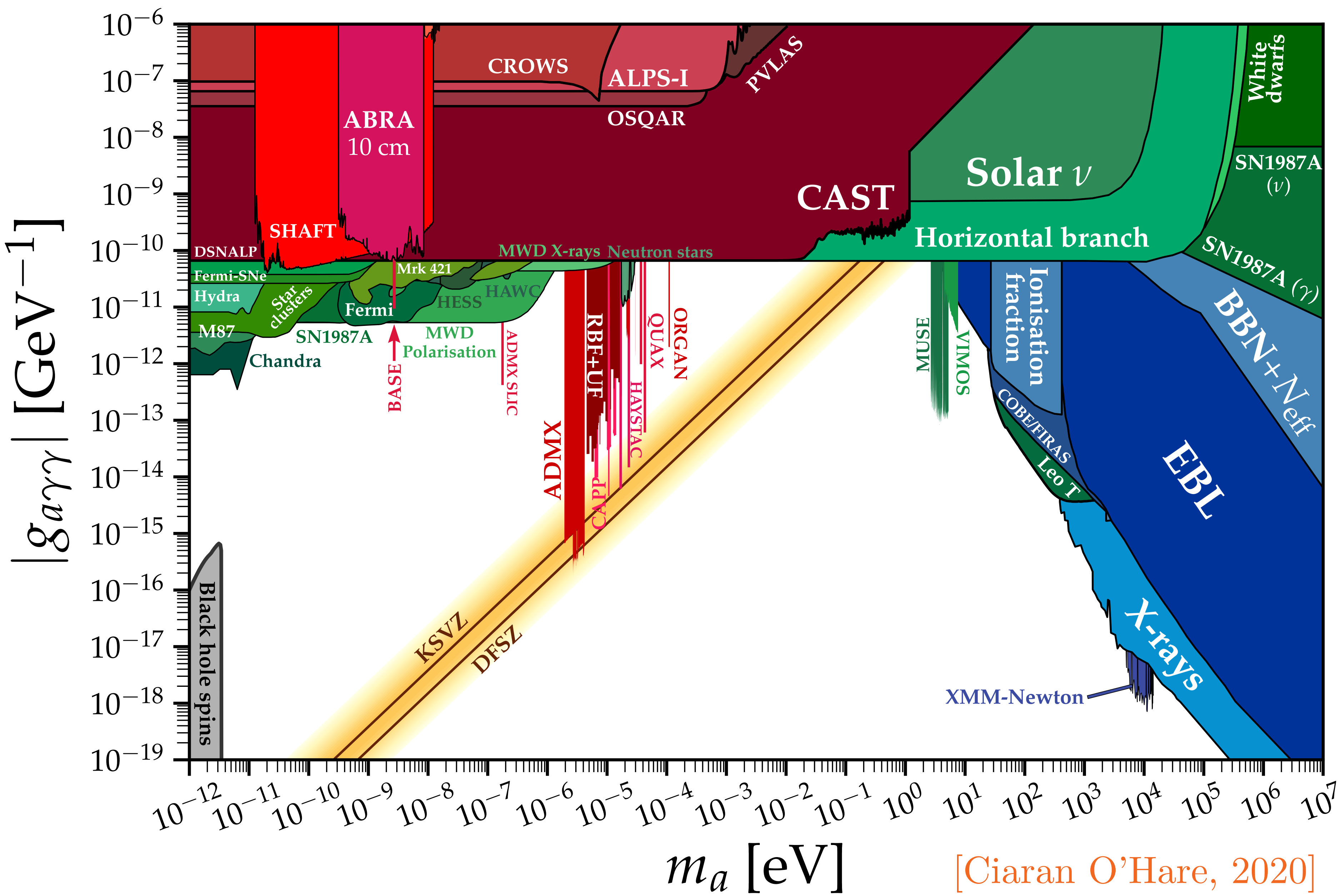
[Peccei, Quinn, 1977] [Wilzeck]

[Dine, Fischler, Srednicki, 1981] [Zhitnitsky, 1980]

[Kim, 1979] [Shifman, Vainshtein, Zakharov, 1980]

# Dark Matter: where to look?




[Ciaran O'Hare, 2020]

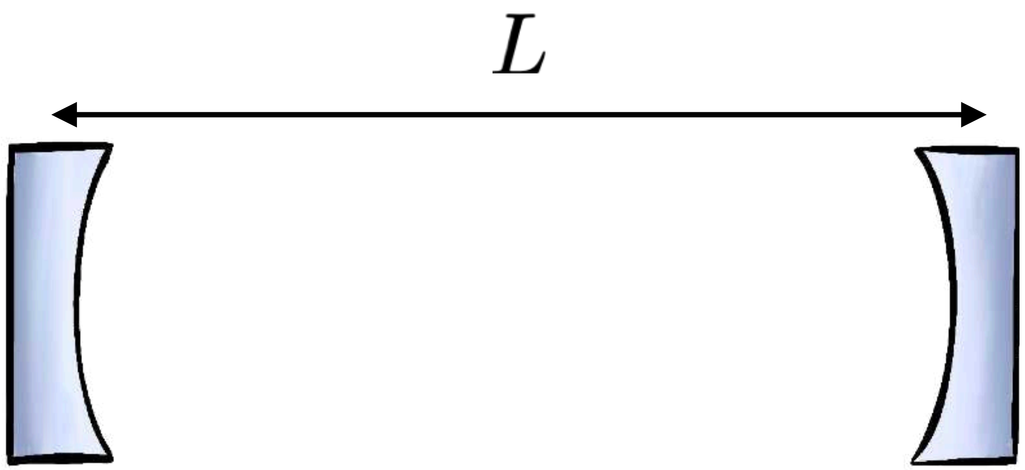
Optomechanical Cavities

# Axioptomechanics

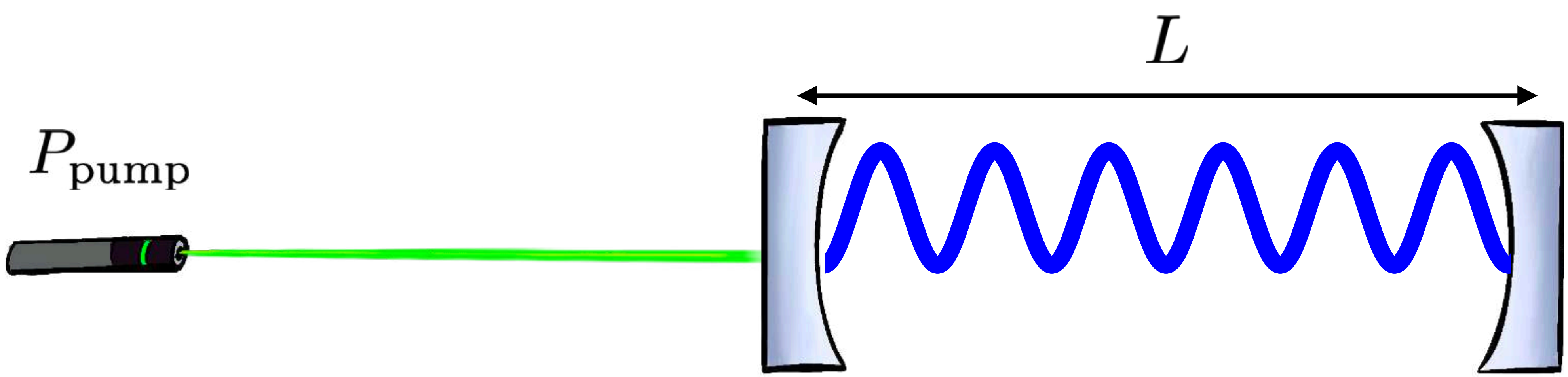
[work in progress]

with Yikun Wang and Kathryn M. Zurek

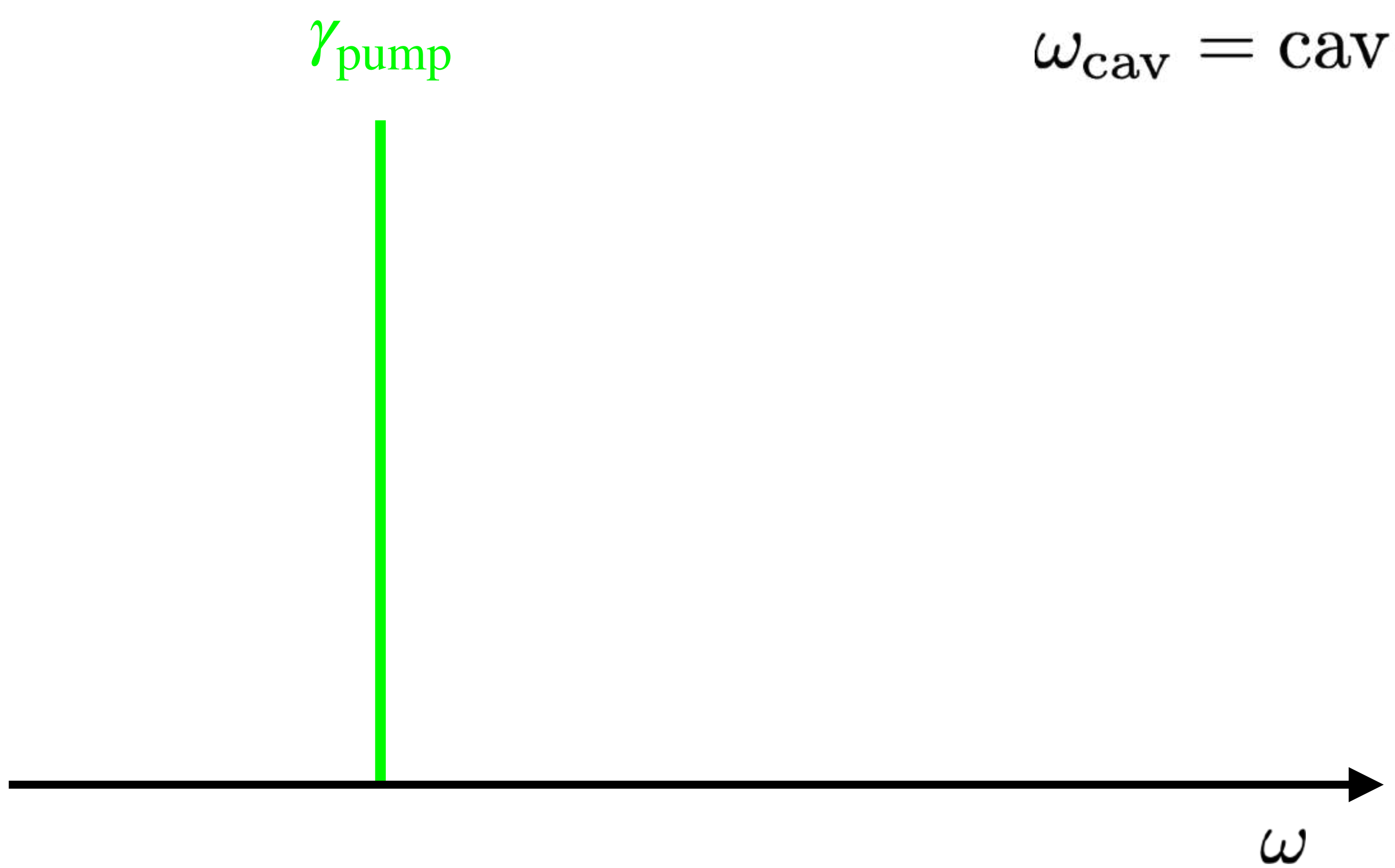
# Standard Optomechanics



# Standard Optomechanics




$$\omega_{\text{cav}} = \text{cav}\frac{\pi}{L}, \quad \text{cav} \subset \mathbb{Z}$$



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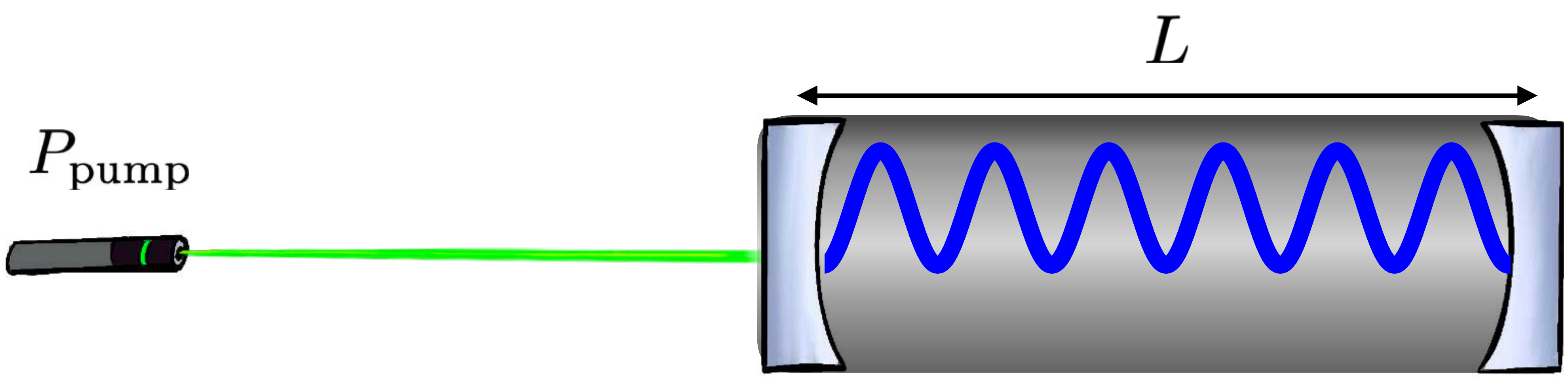


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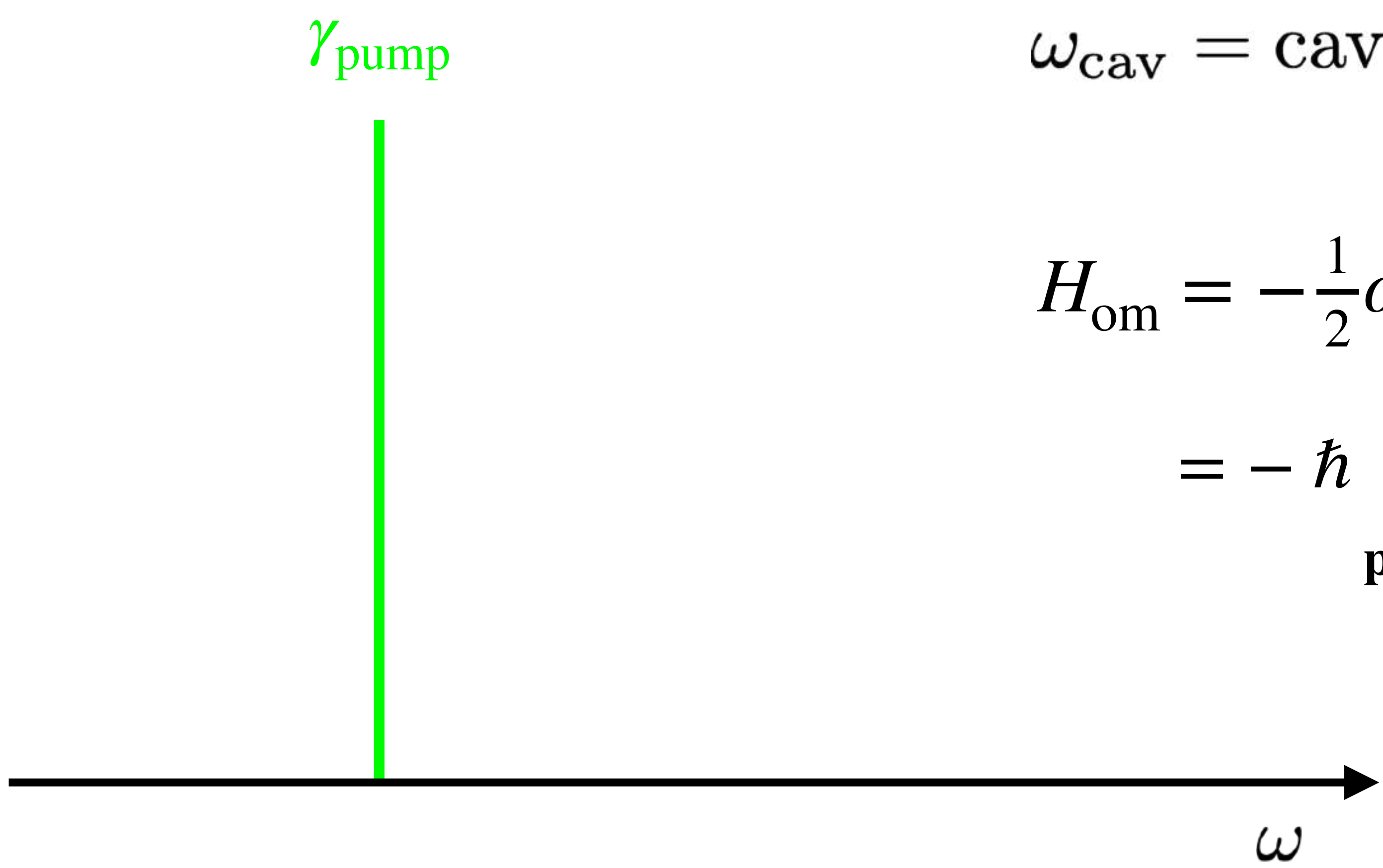
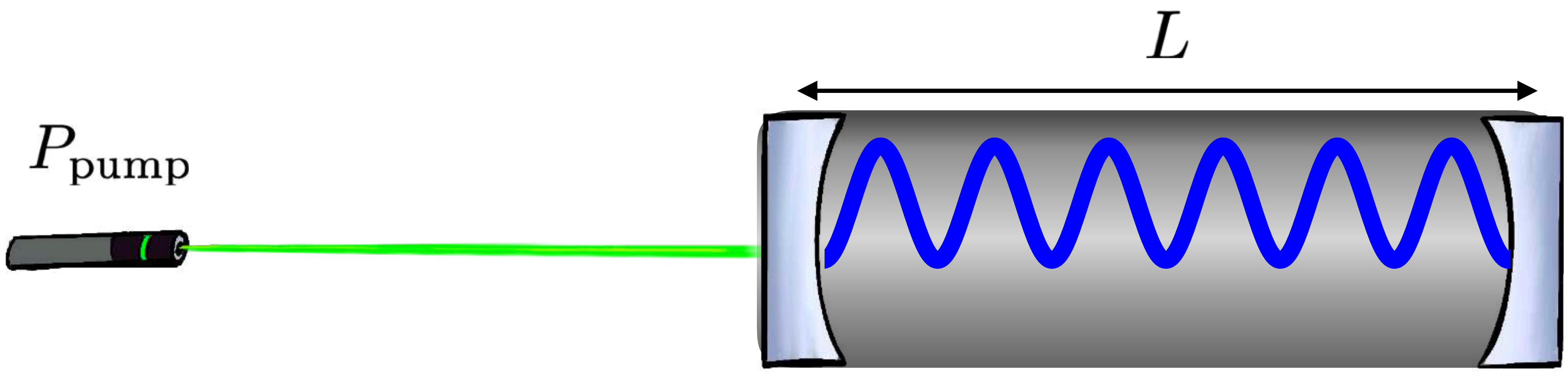



$$H_{\mathrm{om}} = -\frac{1}{2}\alpha \int d^3\mathbf{r}\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{E}(\mathbf{r})$$
$$= -\hbar \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left( a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b_{\mathbf{k_m}} + a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b^{\dagger}_{\mathbf{k_m}} \right)$$

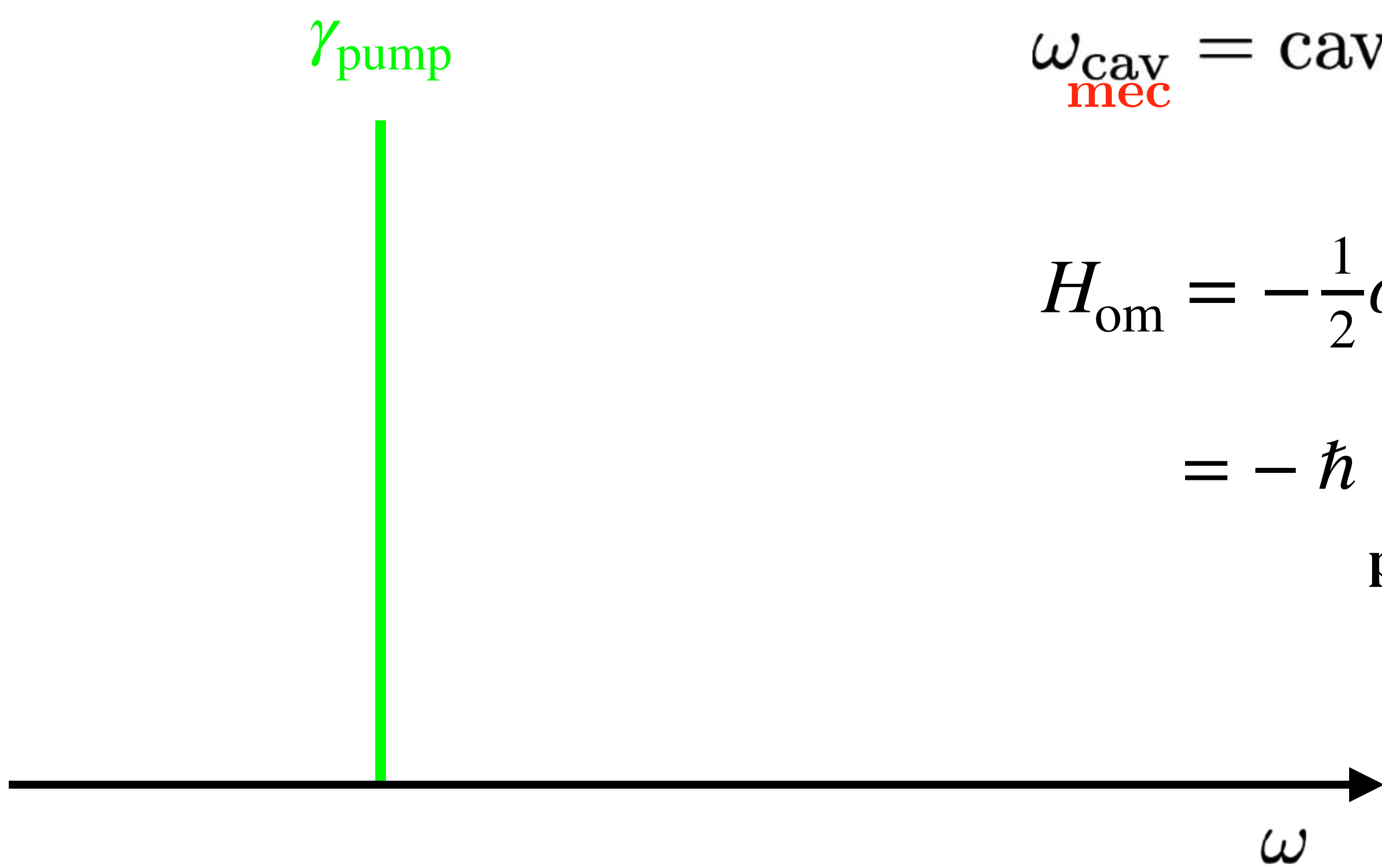
# Standard Optomechanics

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



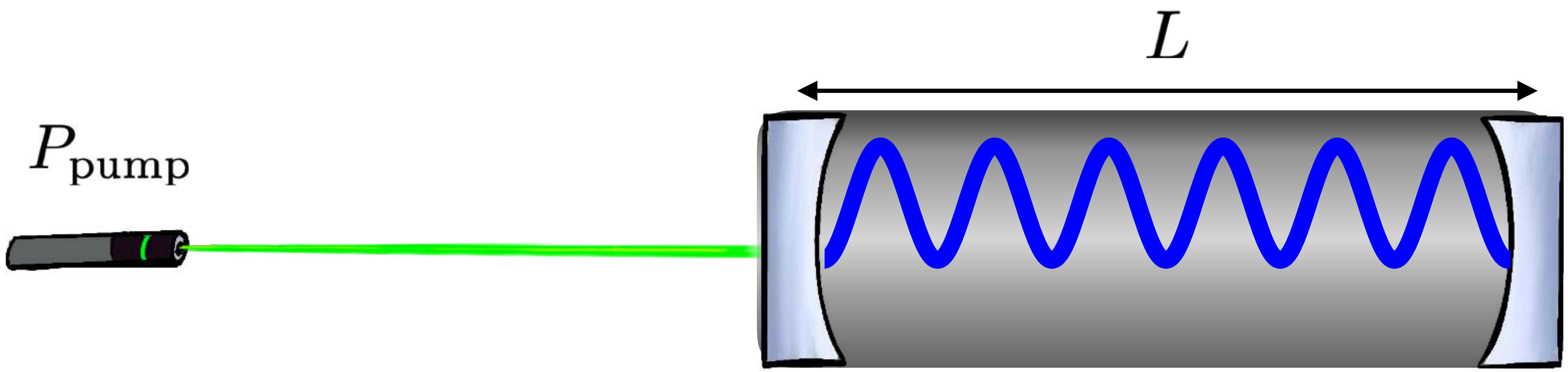

$$\omega_{\substack{\text{cav}\\ \text{mec}}} = \text{cav}\,\frac{\pi}{L} c_s, \quad \text{cav} \subset \mathbb{Z}$$

$$H_{\text{om}} = -\frac{1}{2}\alpha \int d^3\mathbf{r}\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{E}(\mathbf{r})$$
$$= -\hbar \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left( a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b_{\mathbf{k_m}} + a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b^{\dagger}_{\mathbf{k_m}} \right)$$



# Standard Optomechanics

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

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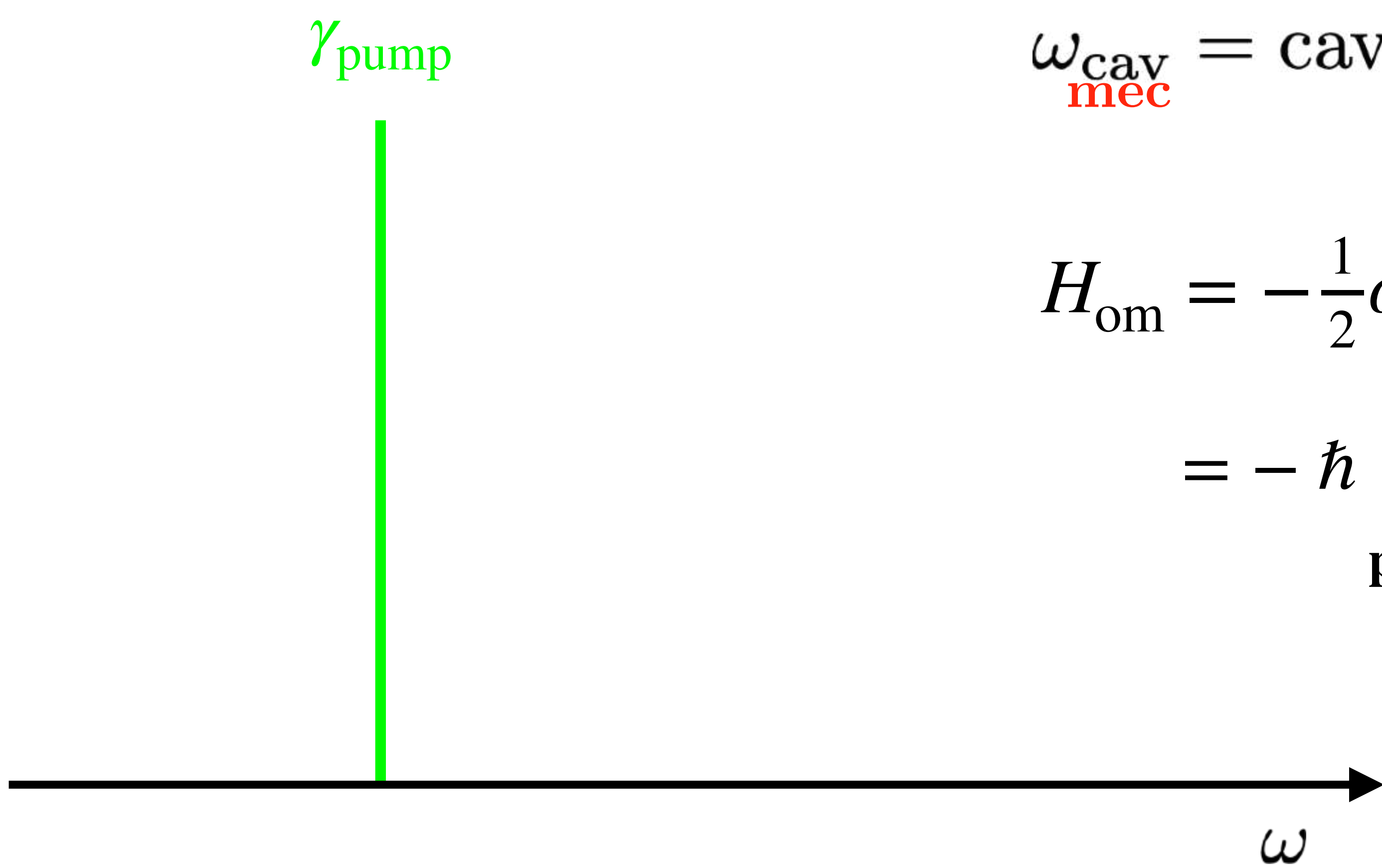


$$H_{\text{om}} = -\frac{1}{2}\alpha \int d^3\mathbf{r}\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{E}(\mathbf{r})$$
$$= -\hbar \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left( a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b_{\mathbf{k_m}} + a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} \right)$$

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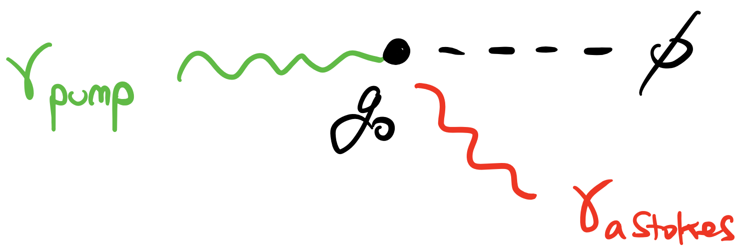
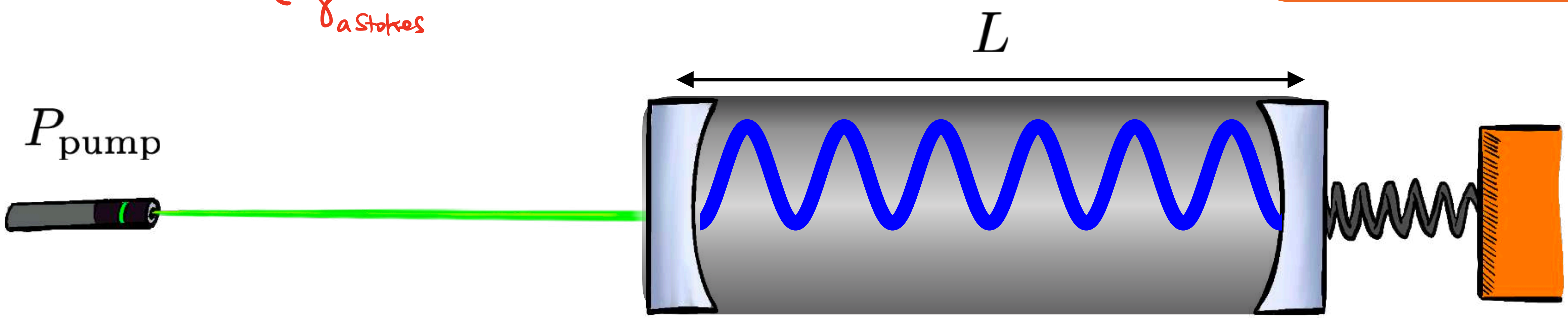
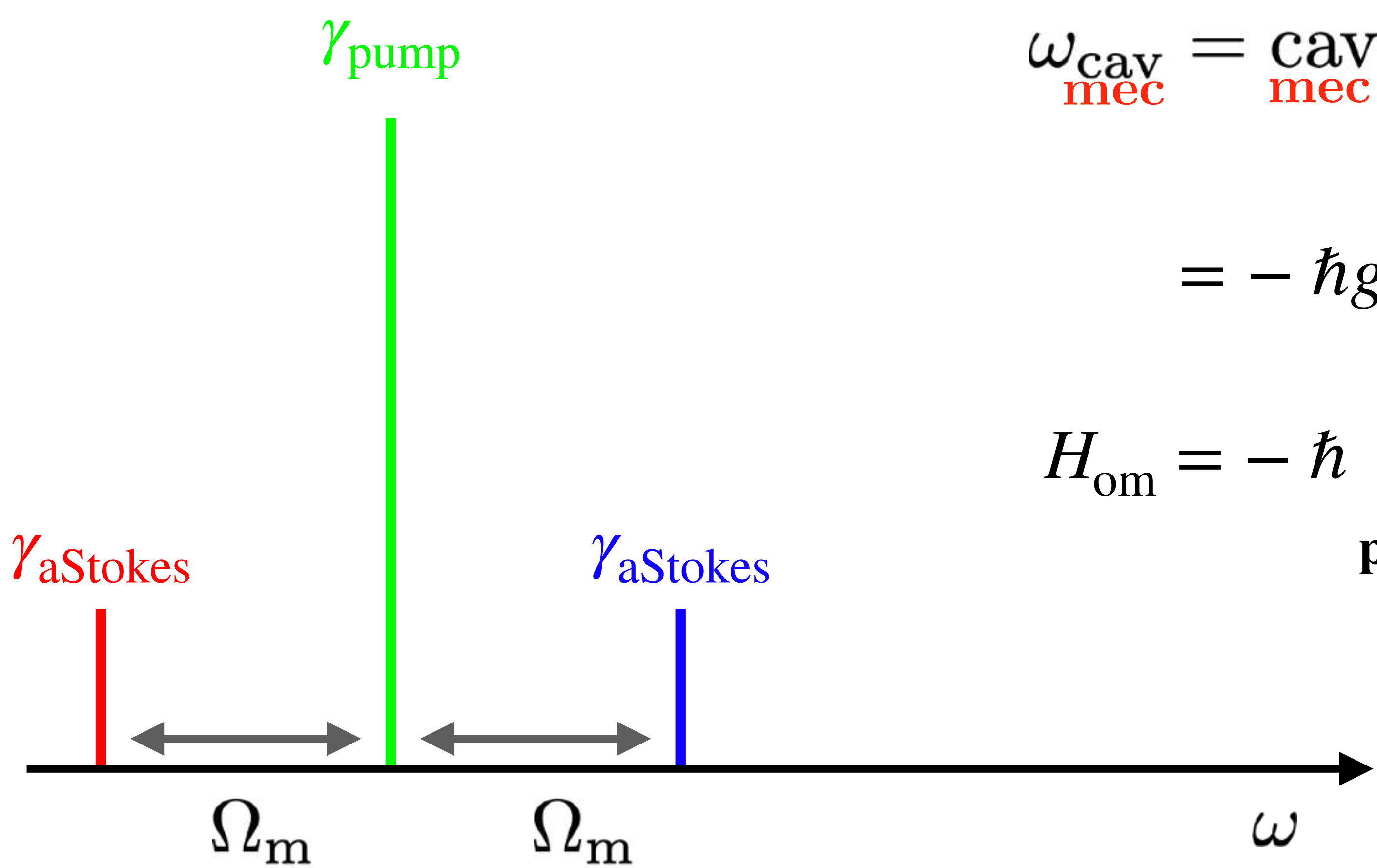


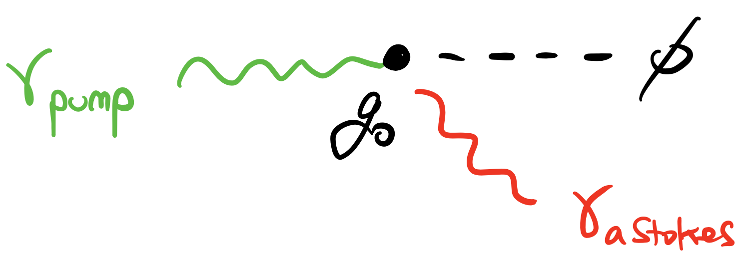

$$\omega_{\substack{\text{cav}\\ \text{mec}}} = \substack{\text{cav}\\ \text{mec}}\,\frac{\pi}{L}c_s, \quad \text{cav} \subset \mathbb{Z}$$

$$= -\hbar g_0 \sqrt{n_{\gamma_{\text{pump}}}}\left(\gamma_{\text{pump}}\gamma^\dagger\phi^\dagger\right)$$

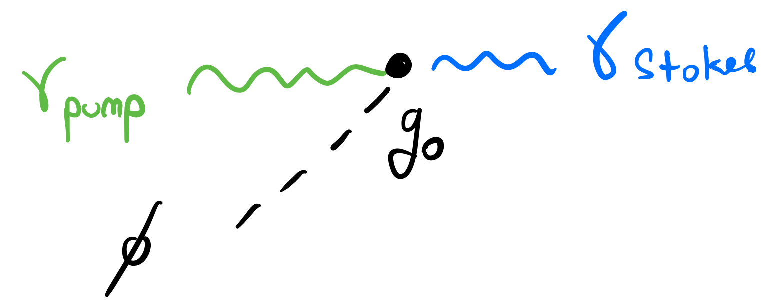
$$H_{\text{om}} = -\hbar \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0\left(a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b_{\mathbf{k_m}}\right)$$



# Standard Optomechanics




and/or

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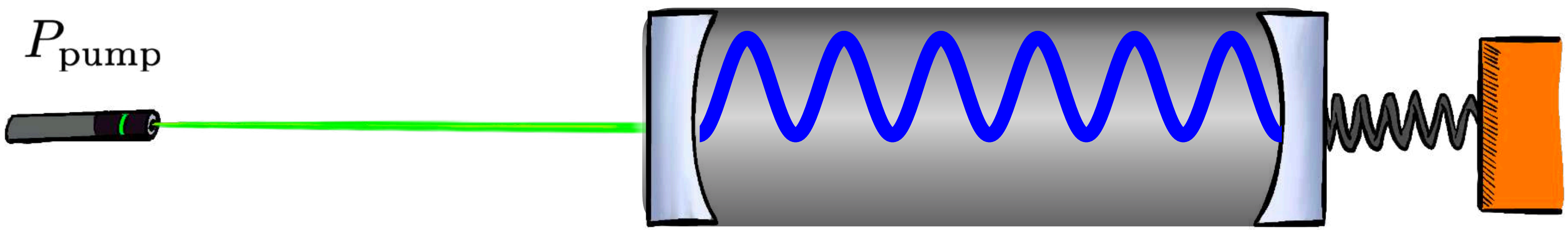
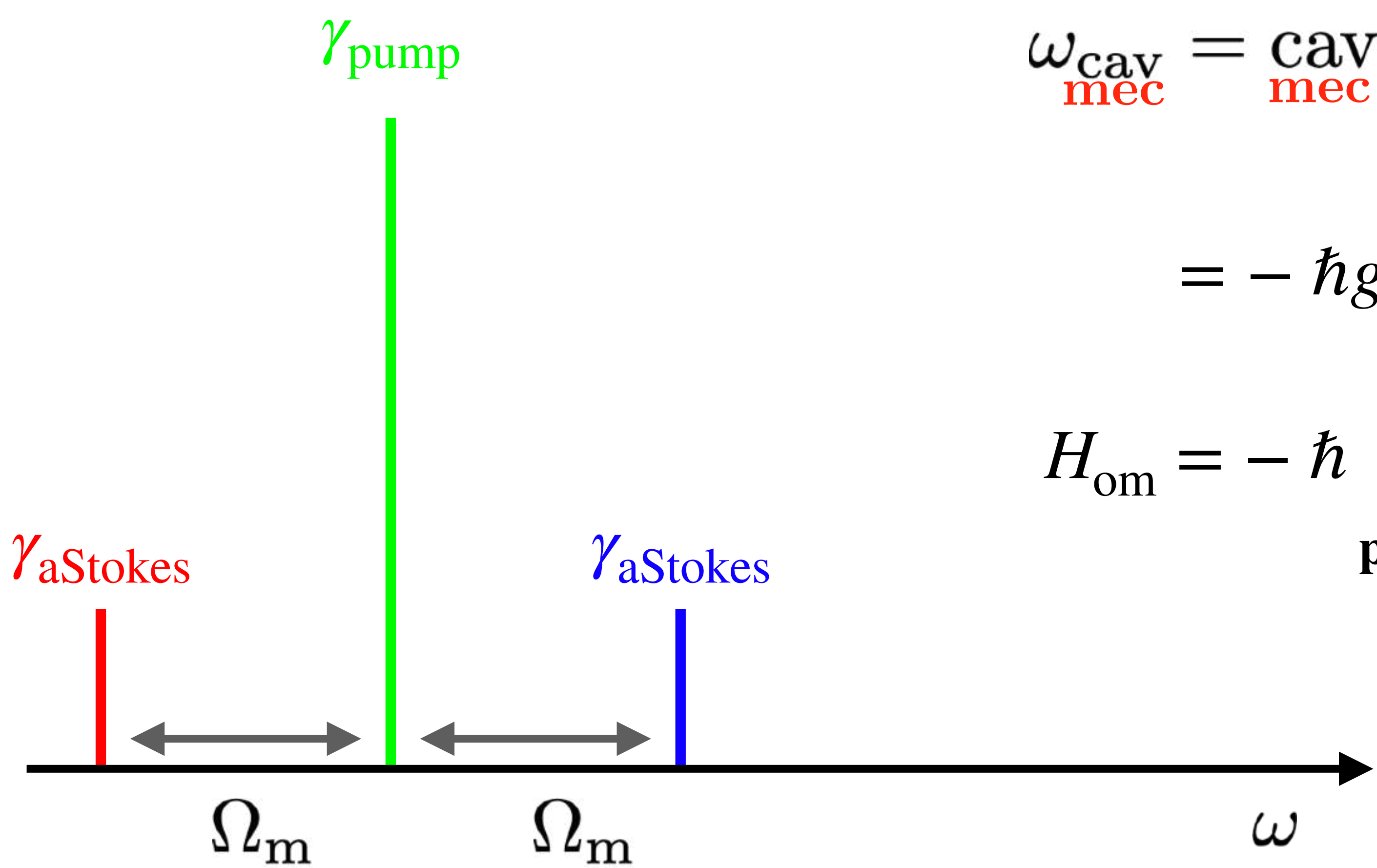


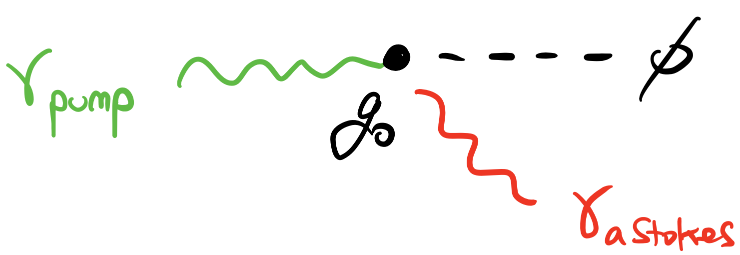

$$\omega_{\substack{\mathrm{cav}\\ \mathrm{mec}}} = \substack{\mathrm{cav}\\ \mathrm{mec}}\frac{\pi}{L}c_s,\quad \mathrm{cav} \subset \mathbb{Z}$$



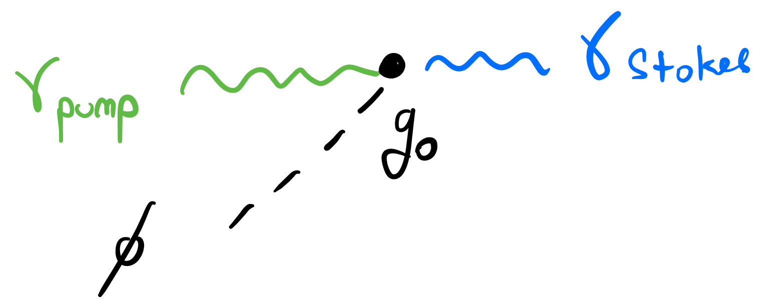

$$= -\hbar g_0\sqrt{n_{\gamma_{\mathrm{pump}}}}\left(\gamma_{\mathrm{pump}}\gamma^\dagger\phi^\dagger + \gamma_{\mathrm{pump}}\gamma^\dagger\phi\right)$$

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

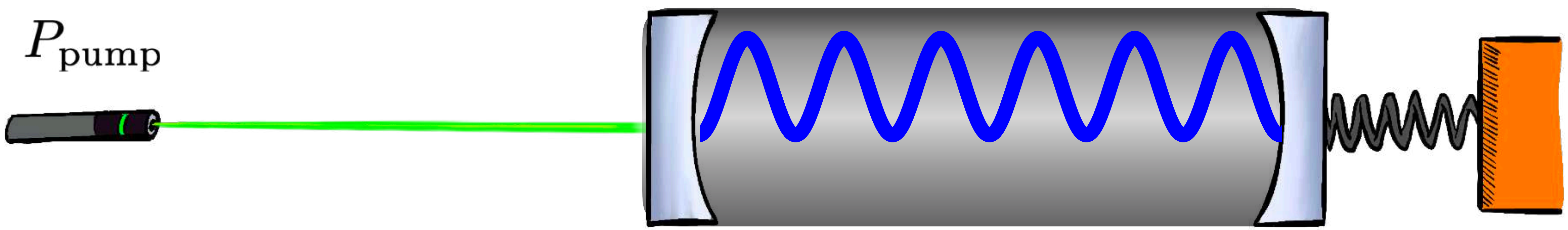
# Standard Optomechanics




and/or




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




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

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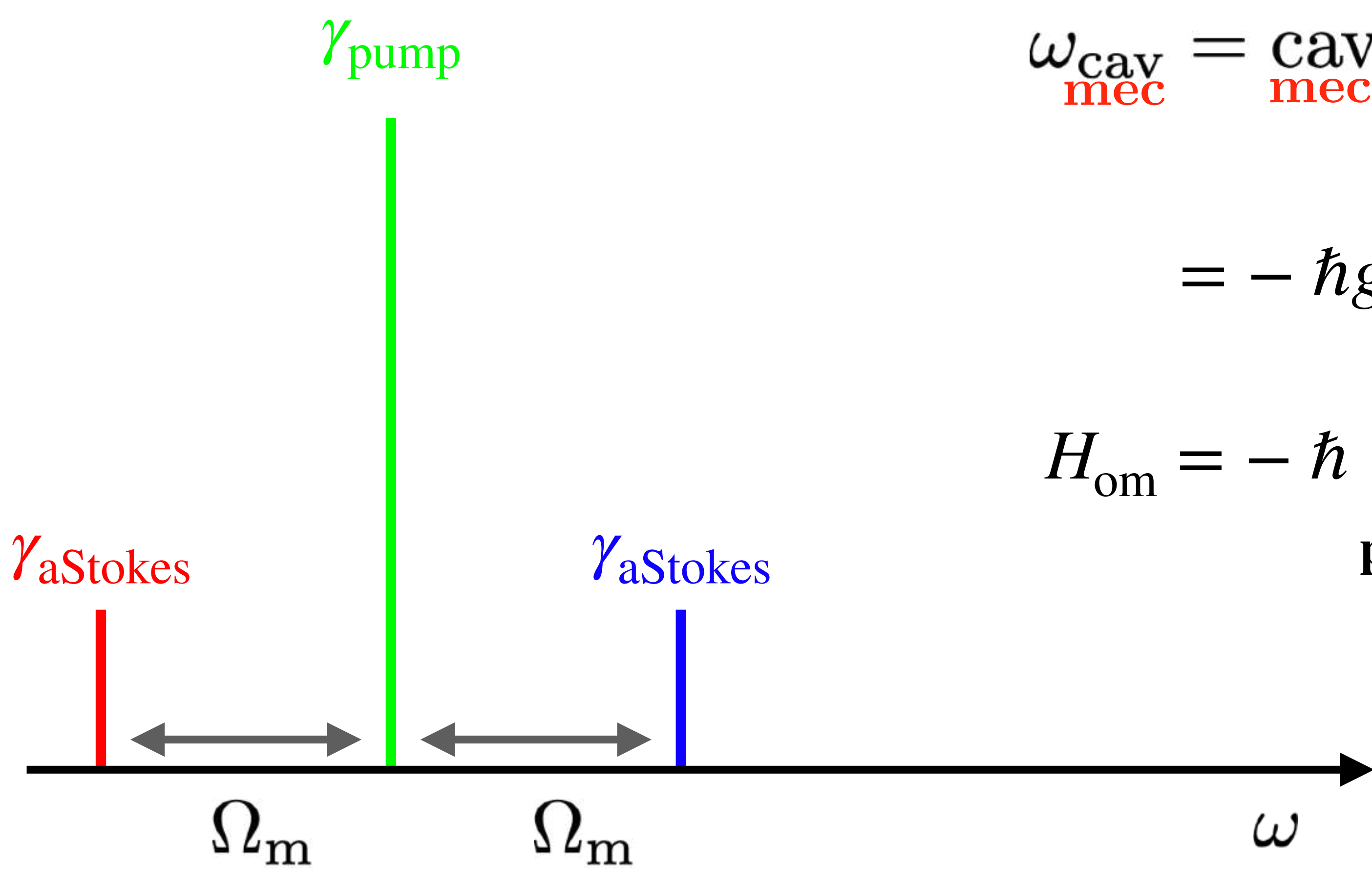

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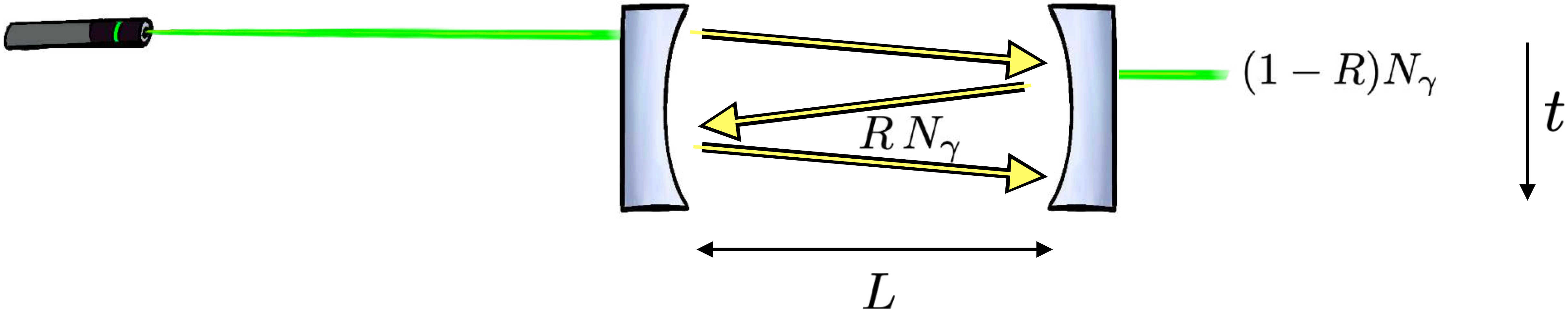
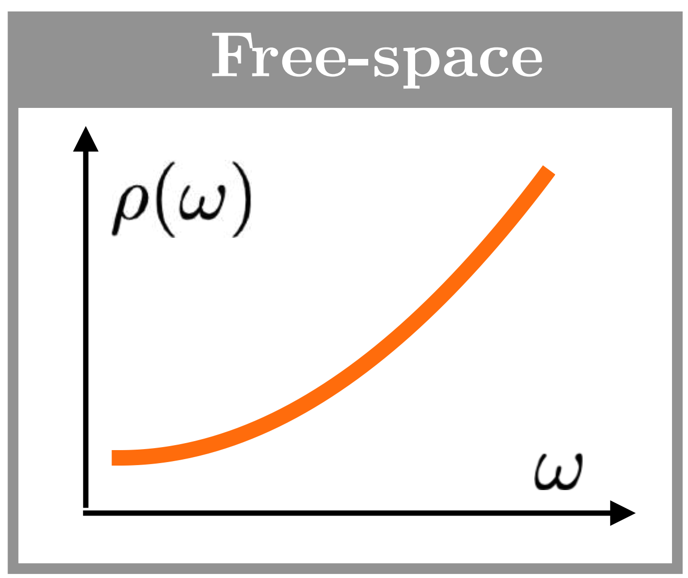
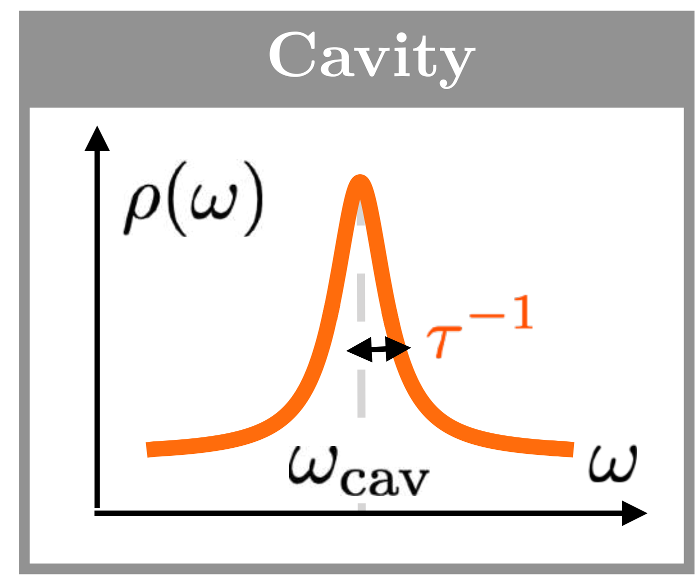



$$\frac{dN}{dt} \simeq \frac{\Delta N_\gamma}{L/c} = \frac{c(1-R)}{L} N_\gamma \quad \Rightarrow \quad \tau_\gamma^{-1} \equiv \kappa \simeq \frac{c}{(1-R)^{-1}L}$$

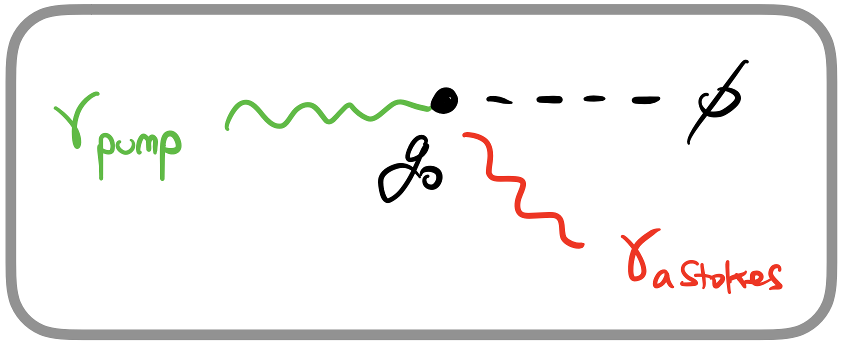
$$N_\gamma \sim \frac{4P\tau}{\omega}$$




$$\rho(\omega) = \sum_i \delta(\omega-\omega_i) = \sum_{\rm cav} \frac{1}{2\pi}\int dt e^{i(\omega-\omega_{\rm cav})t} e^{-t/(2\tau)} = \sum_{\rm cav} \frac{\tau^{-1}/2}{(\omega-\omega_{\rm cav})^2 + (\tau^{-1}/2)^2}$$

# Standard Optomechanics




$$p_\phi = 2p_\gamma$$
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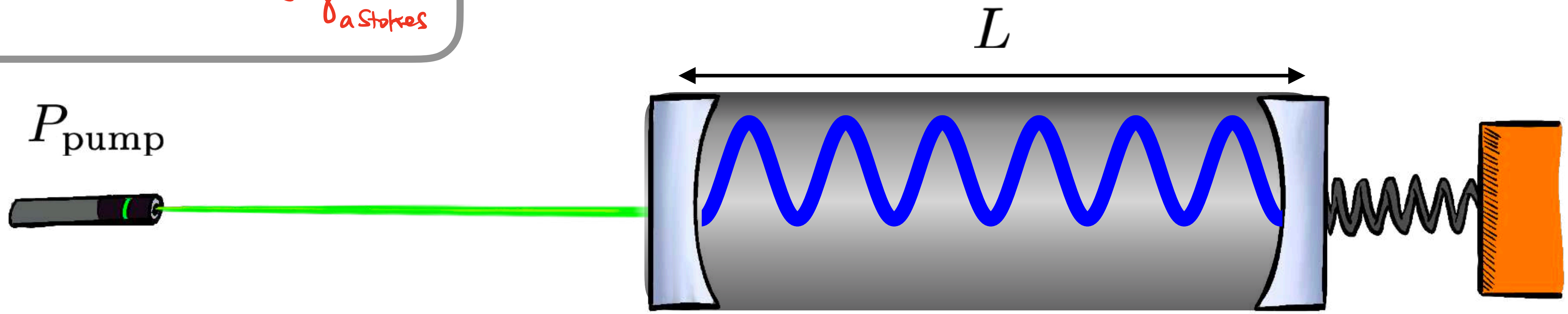


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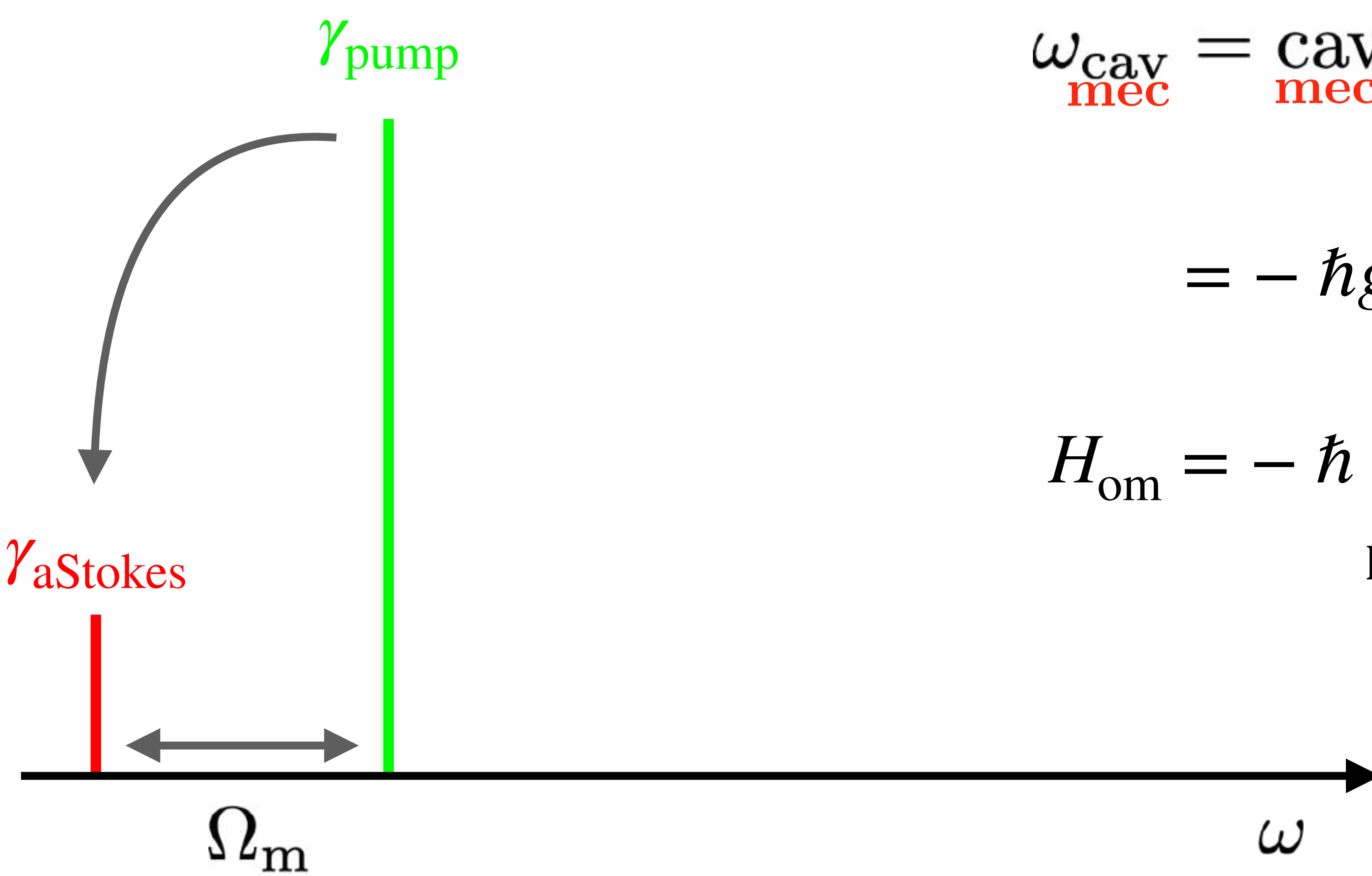


$$= -\hbar g_0 \sqrt{n_{\gamma_{\text{pump}}}}\,\gamma_{\text{pump}}\,\gamma^\dagger\phi^\dagger$$

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

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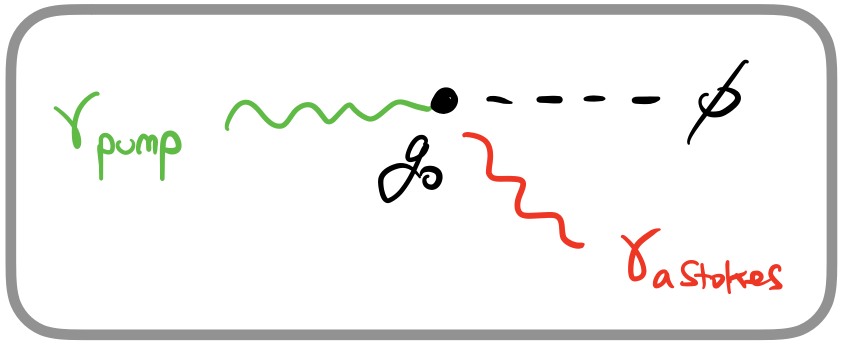


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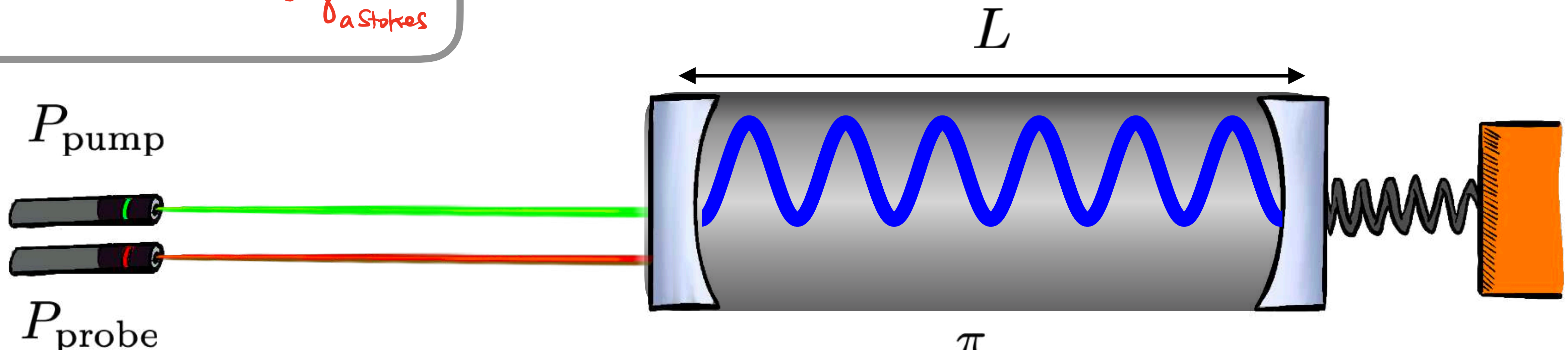
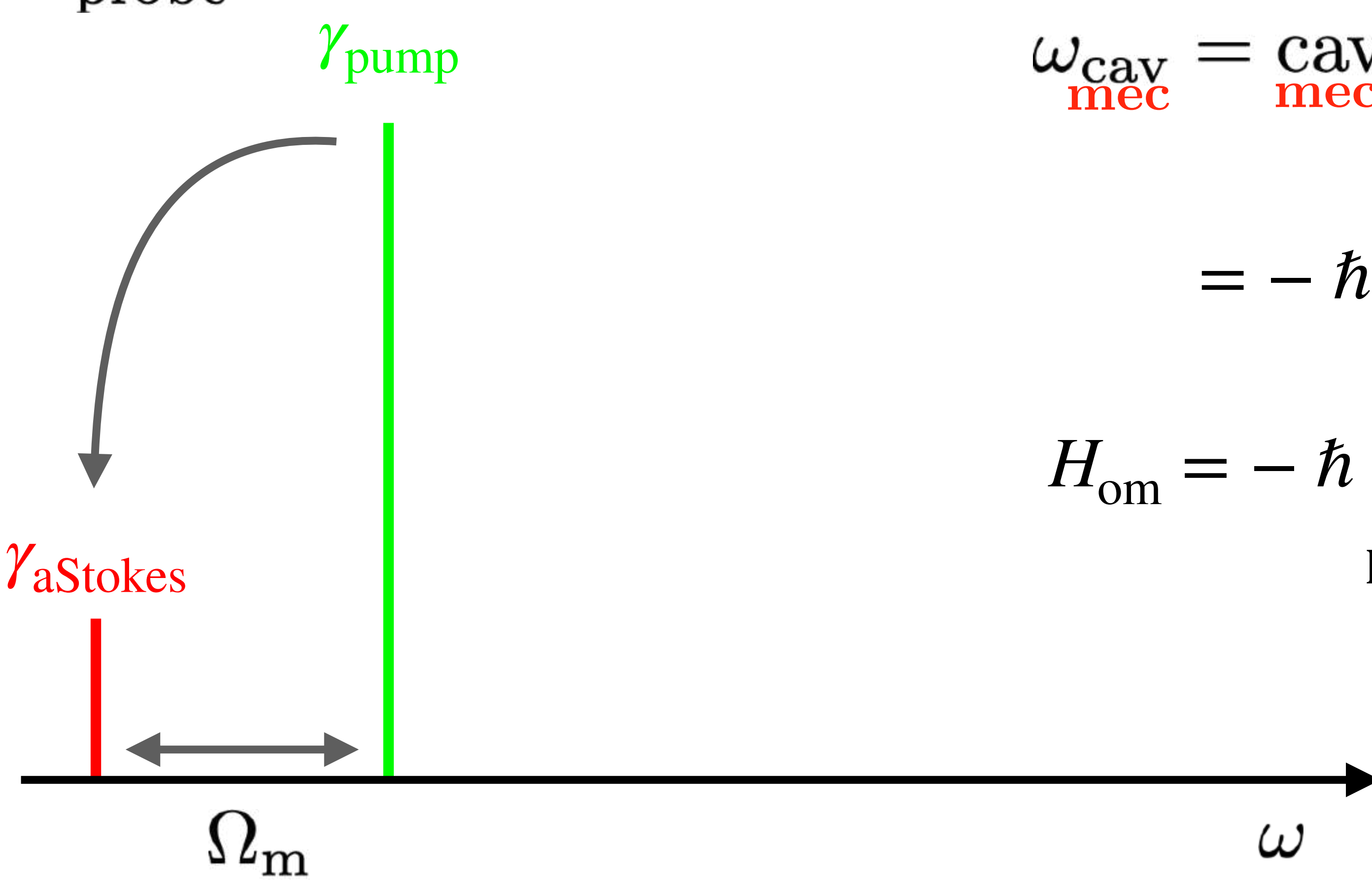


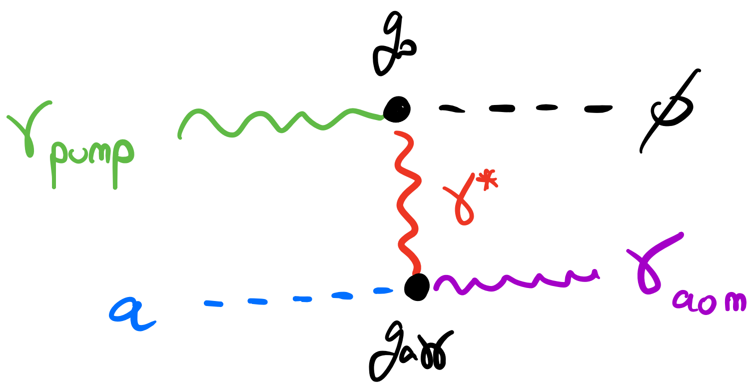

$$\omega_{\underset{\text{mec}}{\text{cav}}} = \underset{\text{mec}}{\text{cav}}\frac{\pi}{L}c_s,\quad \text{cav} \subset \mathbb{Z}$$




$$= -\hbar g_0 \sqrt{n_{\gamma_{\text{pump}}}}\sqrt{n_{\gamma_{\text{probe}}}}\,\gamma_{\text{pump}}\gamma^\dagger_{\text{probe}}\phi^\dagger$$

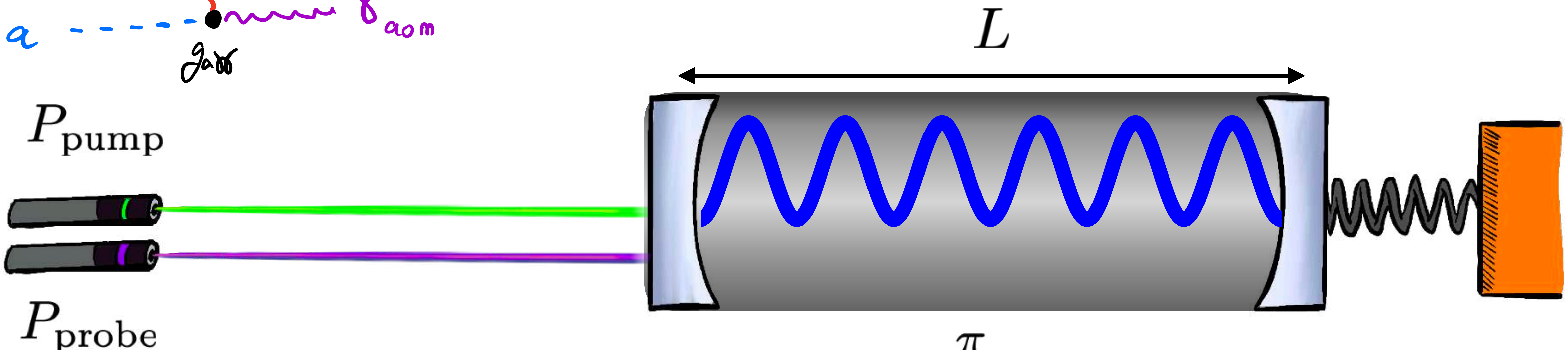
$$H_{\text{om}} = -\hbar \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0\left(a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b_{\mathbf{k_m}} + a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b^\dagger_{\mathbf{k_m}}\right)$$

# ~~Standard~~ Axioptomechanics




$$\vec{p}_{\gamma 1} + \vec{p}_a = \vec{p}_\phi + \vec{p}_{\gamma 2}$$

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




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

$$= -\hbar g_0 \left( g_{a\gamma\gamma}\frac{\sqrt{2\rho_a}}{m_a} \right) \sqrt{n_{\gamma_{\rm pump}}}\sqrt{n_{\gamma_{\rm probe}}}\,\gamma_{\rm pump}\,\gamma^\dagger_{\rm probe}\,\phi^\dagger$$

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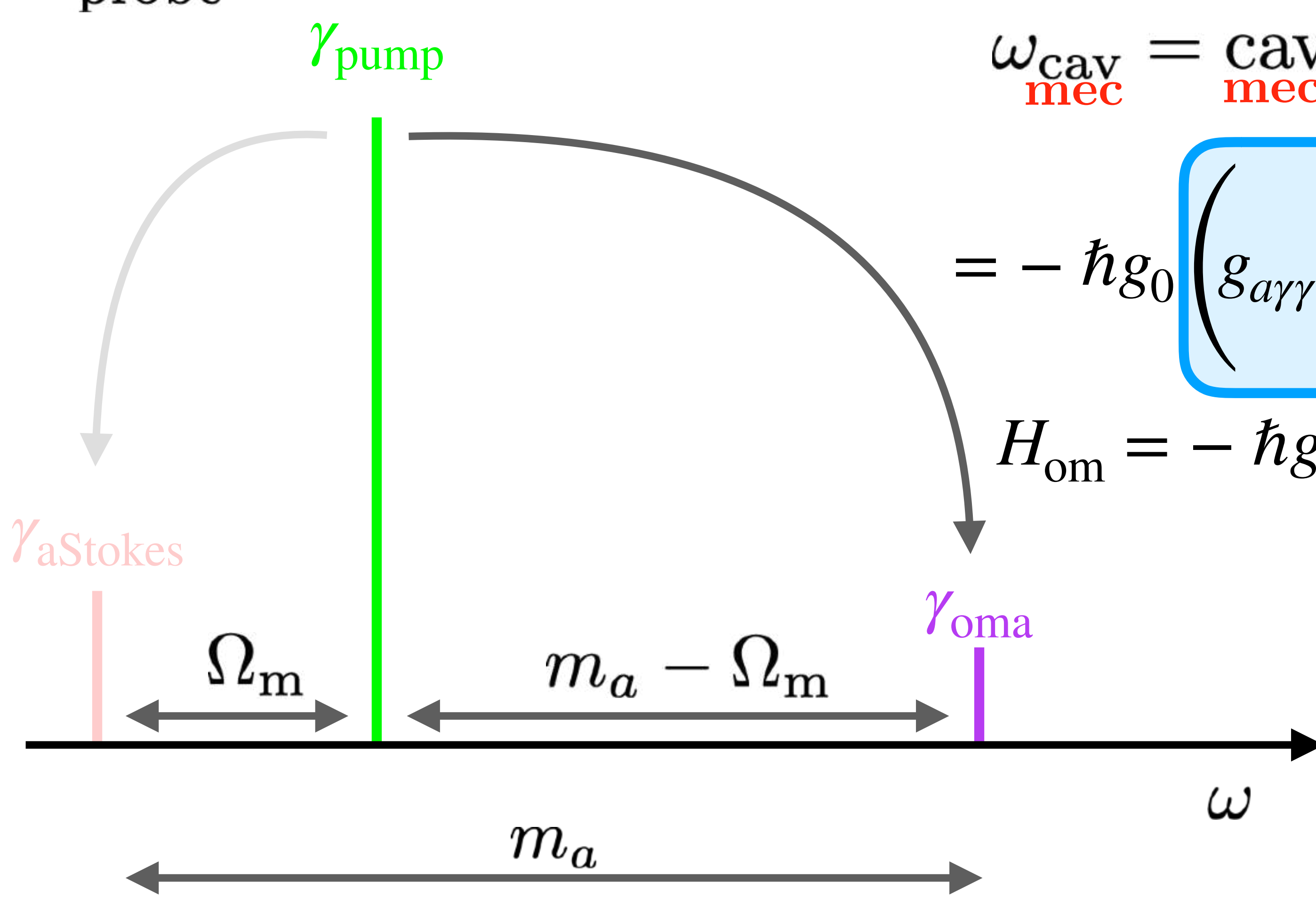

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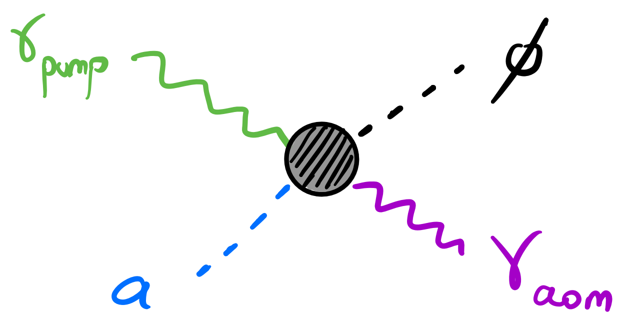


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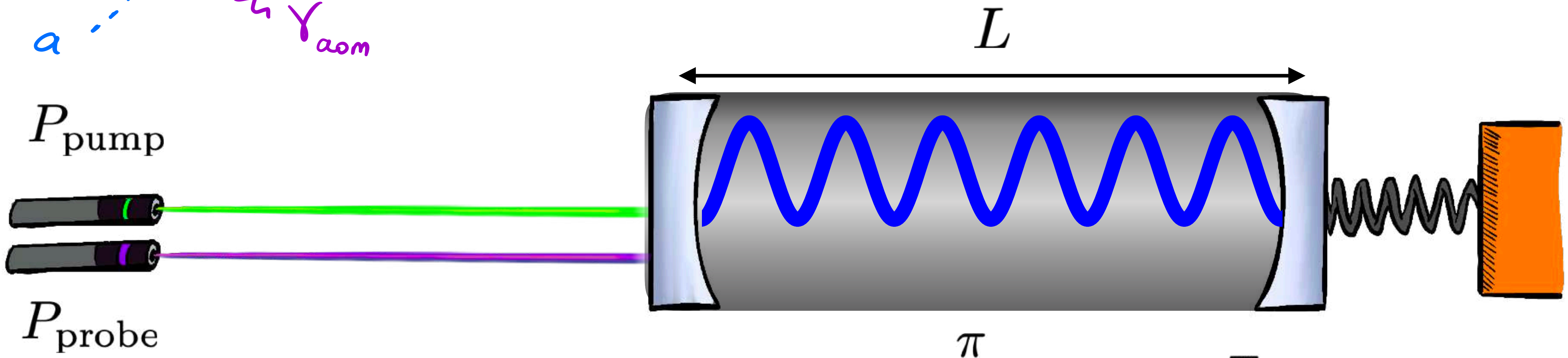


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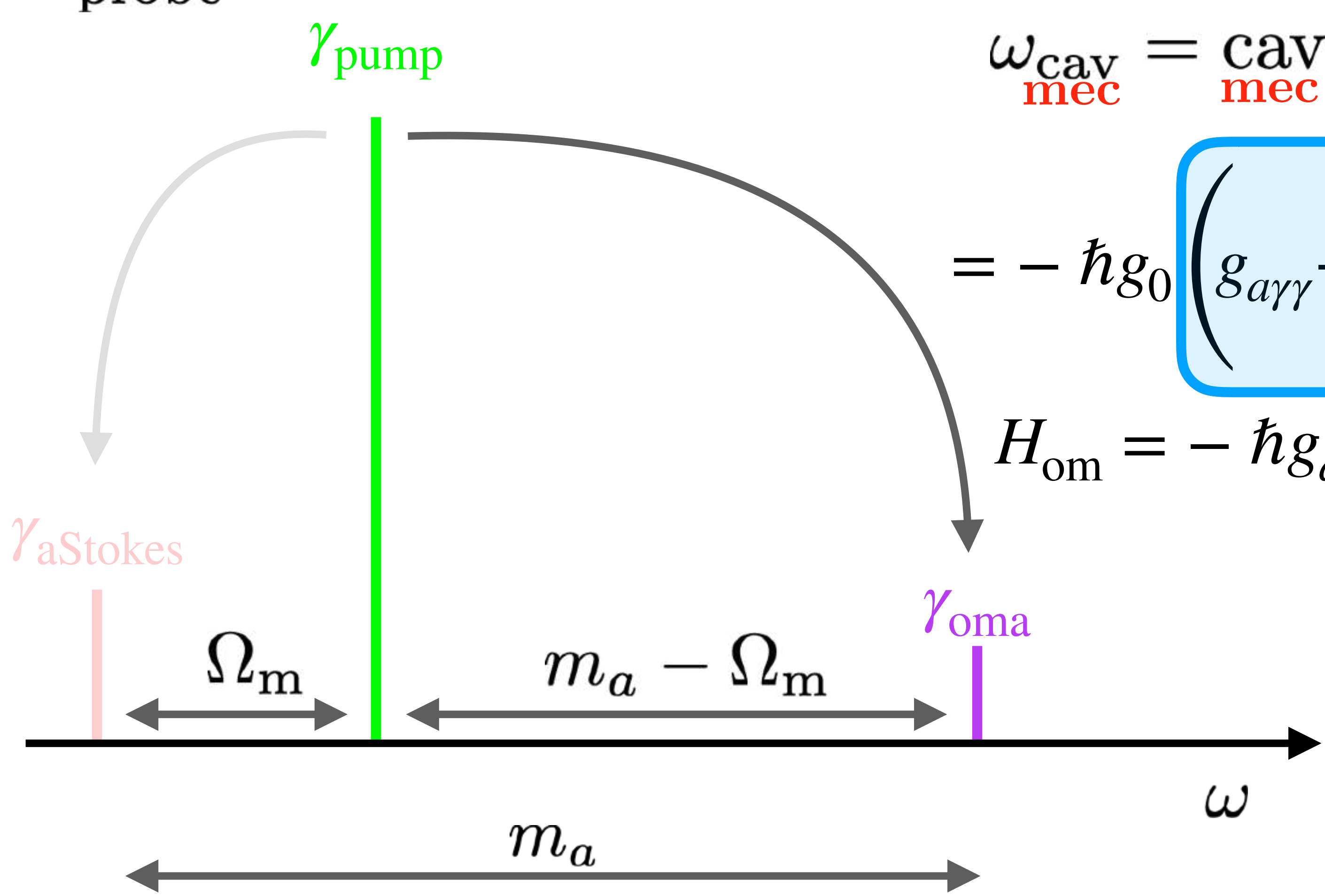

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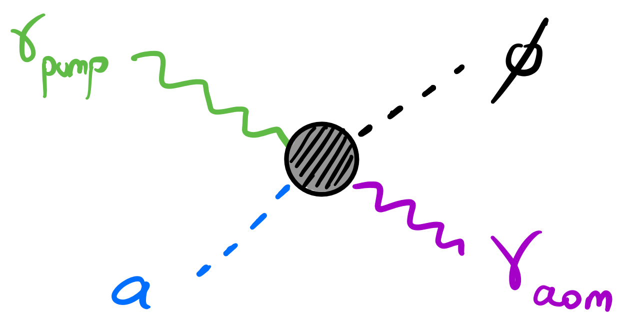


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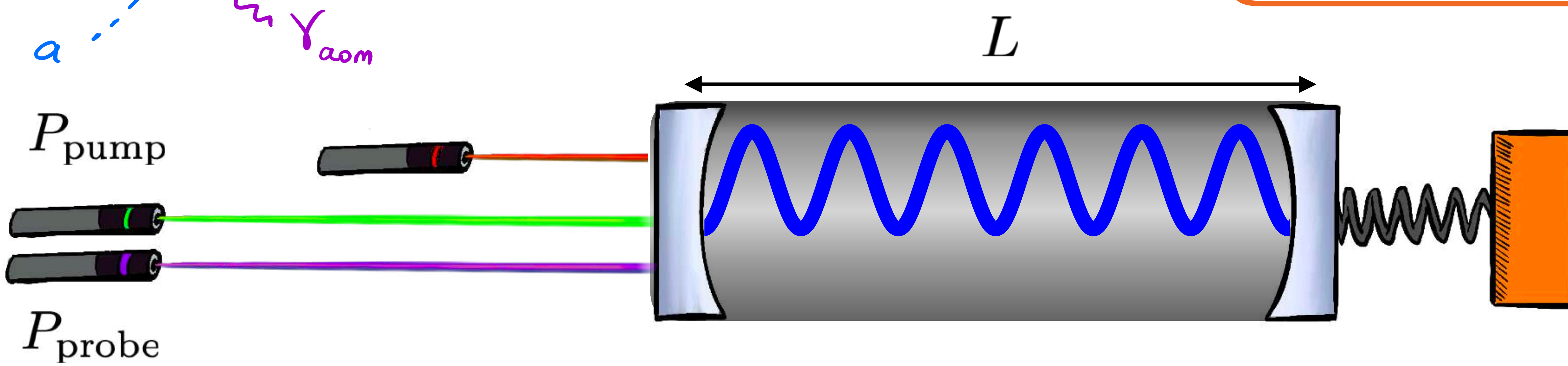


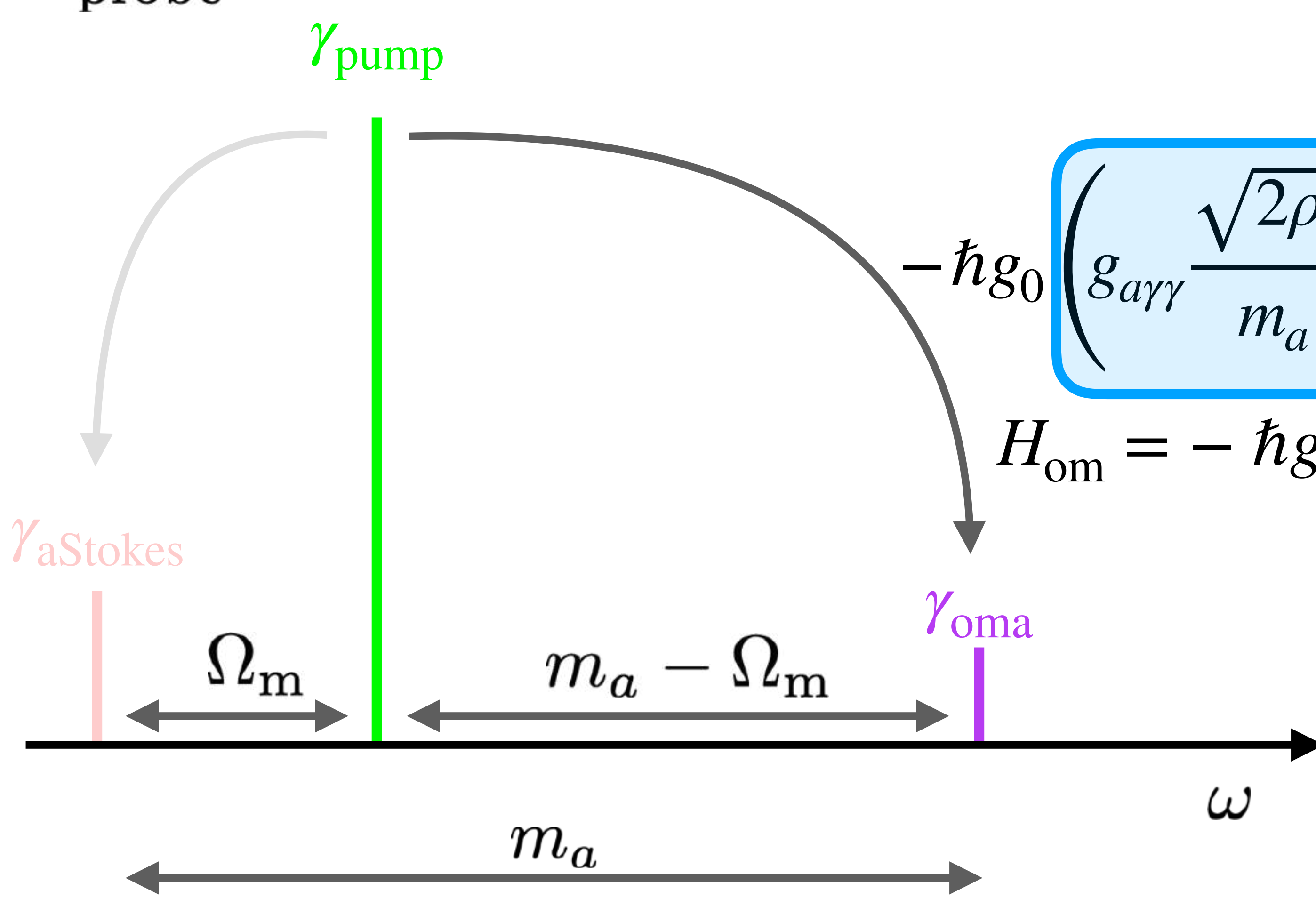


$$-\hbar g_0 \left( g_{a\gamma\gamma} \frac{\sqrt{2\rho_a}}{m_a} \right) \sqrt{n_{\gamma_{\rm pump}}} \sqrt{n_{\gamma_{\rm probe}}} \sqrt{n_\phi}\, \gamma_{\rm pump}\, \gamma^\dagger_{\rm probe}\, \phi^\dagger_{\rm cav}$$

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# Let's give some numbers!

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

Yale University
Jack Harris Lab

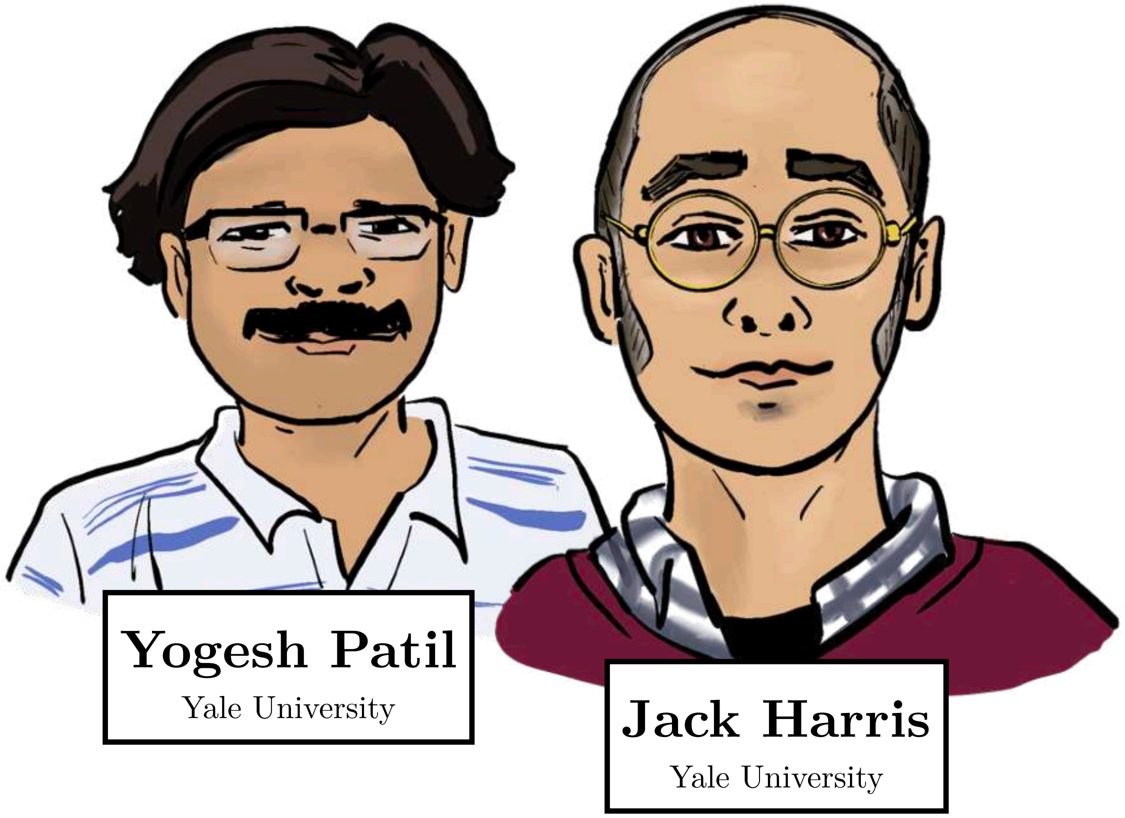
**1** For usual experiments in their lab:

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

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

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

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



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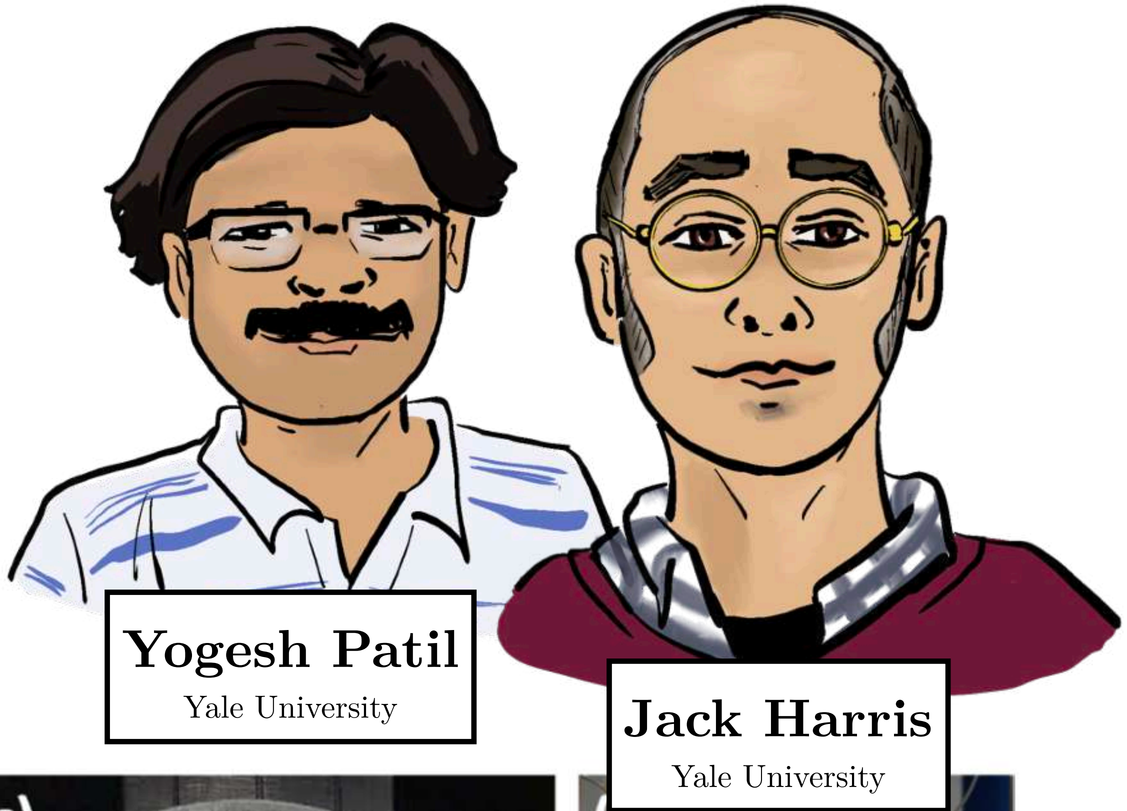


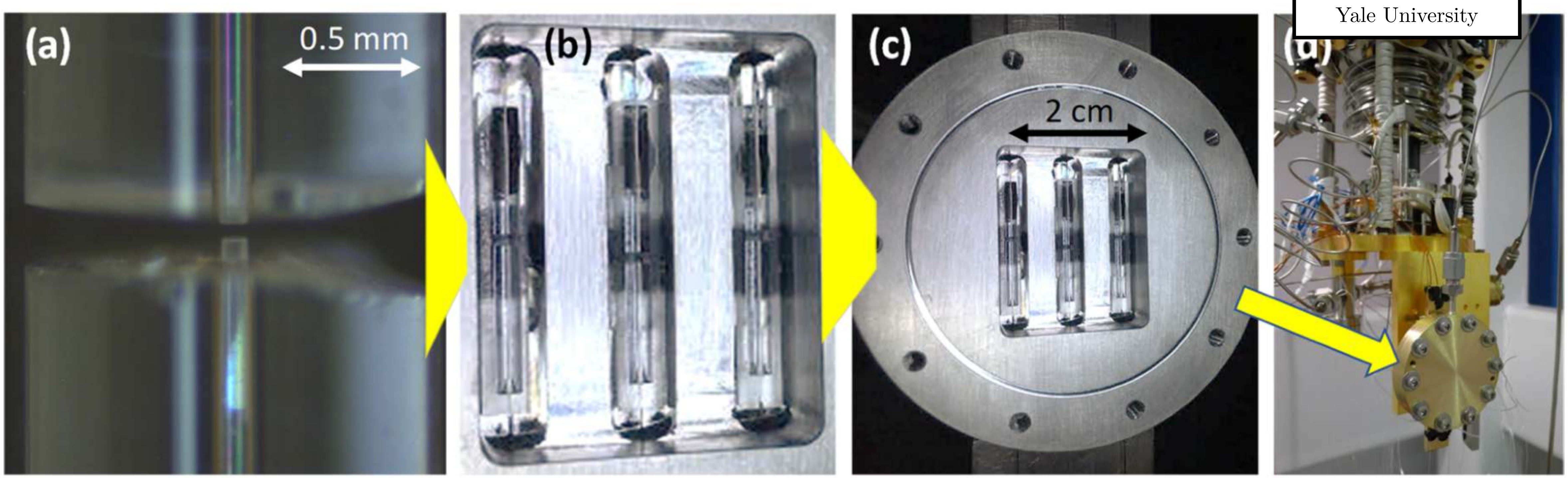

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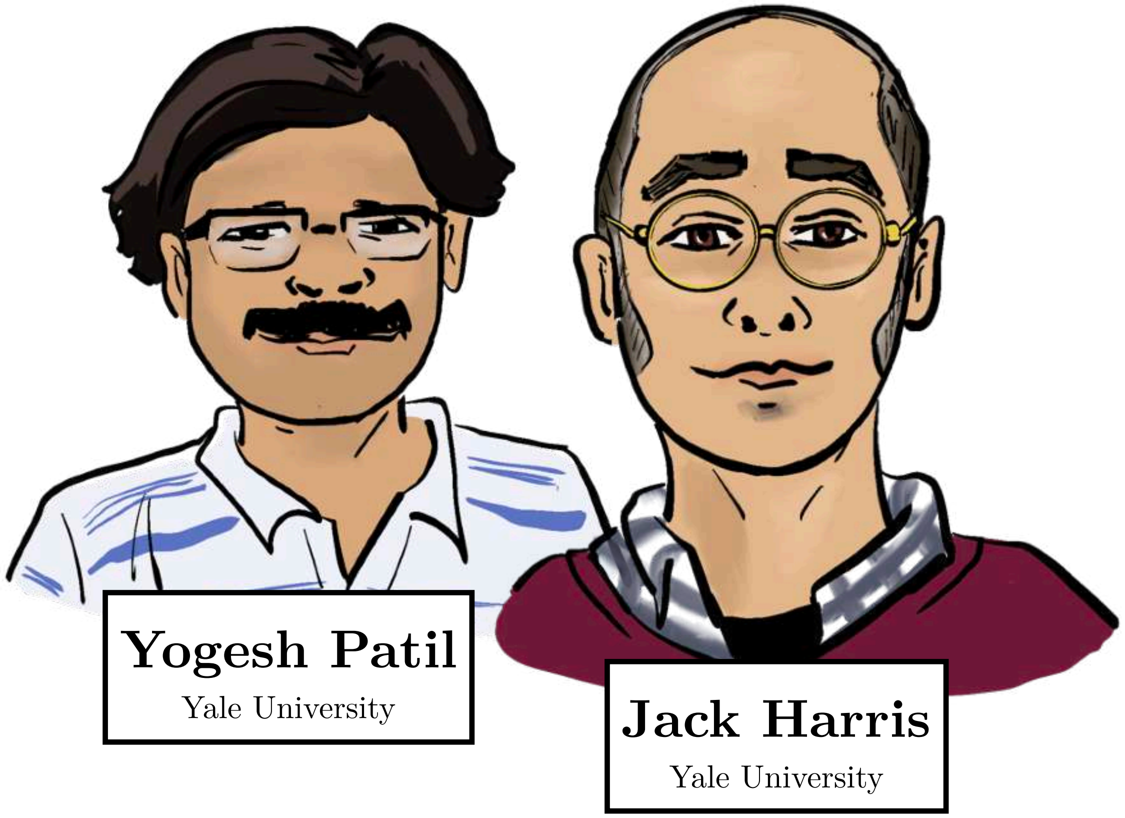



**2** What they can "easily" do, **even now**:

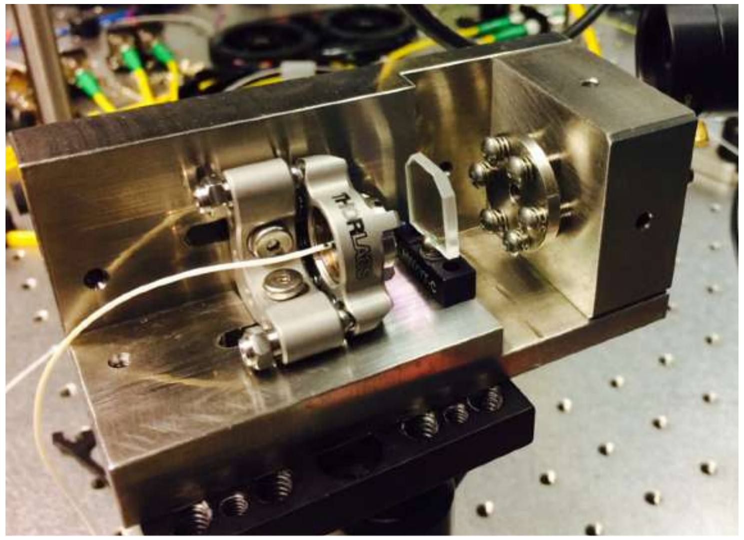
- $N_{\text{pump}} \simeq 10^{11}$
- $N_{\text{probe}} \simeq 10^{11}$
- $N_{\phi} \simeq 10^{14}$

$P_{\text{pump}} \sim 1\text{ mW}$

$P_{\text{probe}} \sim 1\text{ mW}$

$L \sim 1\text{ cm}$

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



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Yale University
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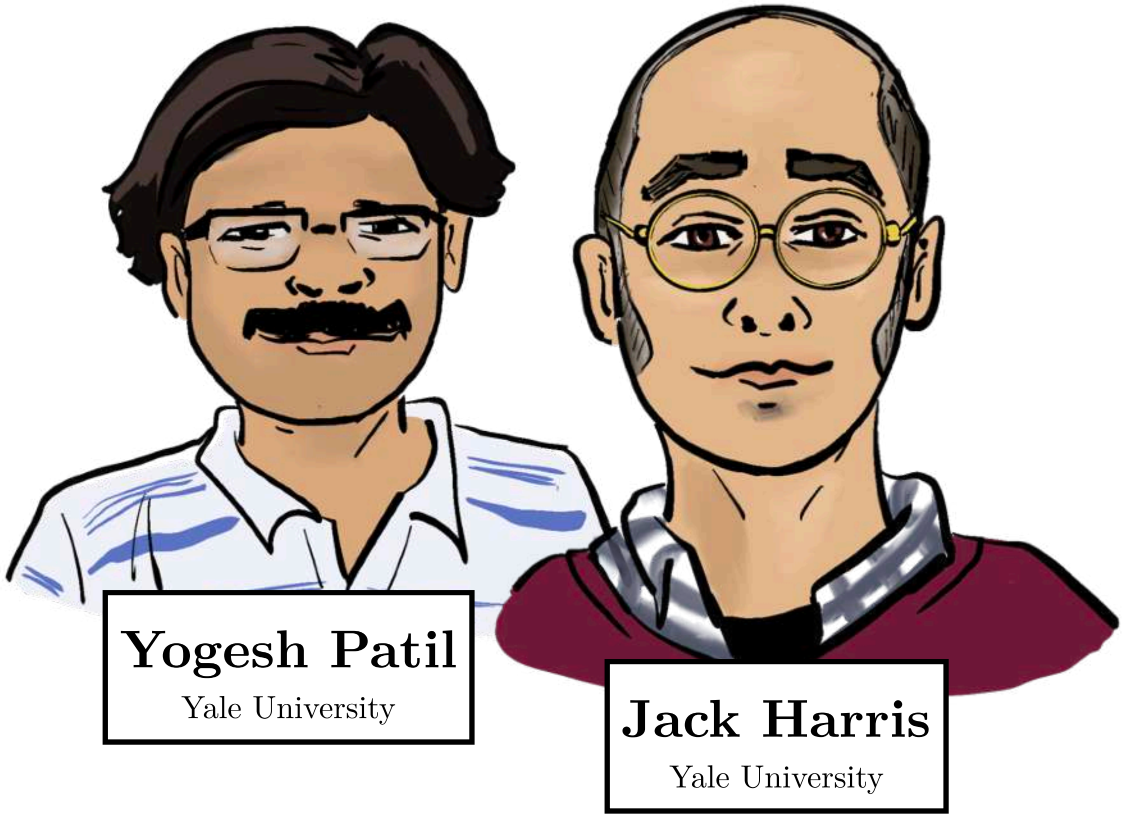



**1** For usual experiments in their lab:

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

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

- $N_{\text{pump}} \simeq 10^{11}$ — $P_{\text{pump}} \sim 1$ mW
- $N_{\text{probe}} \simeq 10^{11}$ — $P_{\text{probe}} \sim 1$ mW
- $N_\phi \simeq 10^{14}$ — $L \sim 1$ cm

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

**3** What we need to do for the QCD axion search:

- $N_{\text{pump}} \simeq 10^{17}$ — $P_{\text{pump}} \sim 1$ W
- $N_{\text{probe}} \simeq 10^{17}$ — $P_{\text{probe}} \sim 1$ W
- $N_\phi \simeq 10^{19}$ — $L \sim 1$ m

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

**"apparently FEASIBLE!!"**

# Sensitivity and scanning strategy

$$\mathrm{SNR} = \frac{N_{\mathrm{sig}}}{\sqrt{N_{\mathrm{shot}}}}$$

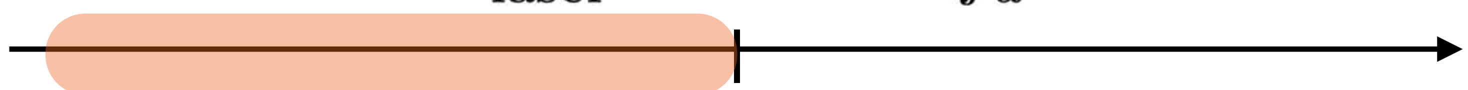
# Sensitivity and scanning strategy

$$\mathrm{SNR} = \frac{P_{\mathrm{sig}}}{\sqrt{P_{\mathrm{probe}}\,\omega_{\mathrm{opt}}\,\kappa}}\frac{1}{N_{\mathrm{meas}}^{1/4}} > 1 \quad \Rightarrow \quad g_{a\gamma\gamma} > f(m_a, \mathrm{cavity}, \mathrm{lasers}, \mathrm{material})$$

# Sensitivity and scanning strategy

$$\mathrm{SNR} = \frac{P_{\mathrm{sig}}}{\sqrt{P_{\mathrm{probe}}\,\omega_{\mathrm{opt}}\,\kappa}}\frac{1}{N_{\mathrm{meas}}^{1/4}} > 1 \;\Rightarrow\; g_{a\gamma\gamma} > f(m_a, \mathrm{cavity}, \mathrm{lasers}, \mathrm{material})$$

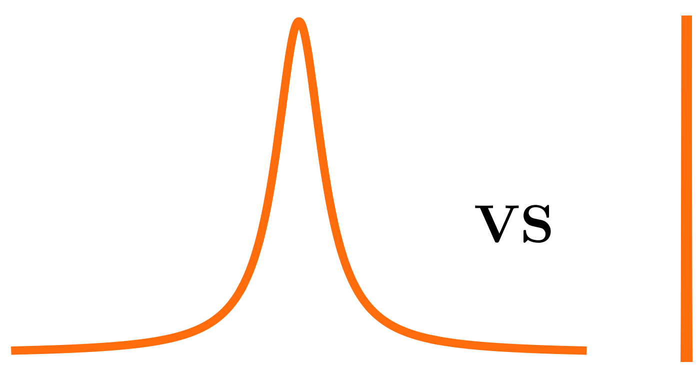
$\kappa_{\mathrm{laser}} \sim \mathrm{Hz} < \Delta f_a$



$m_a$ [eV]

$\sim 10^{-9}$

## Lorenzian regime



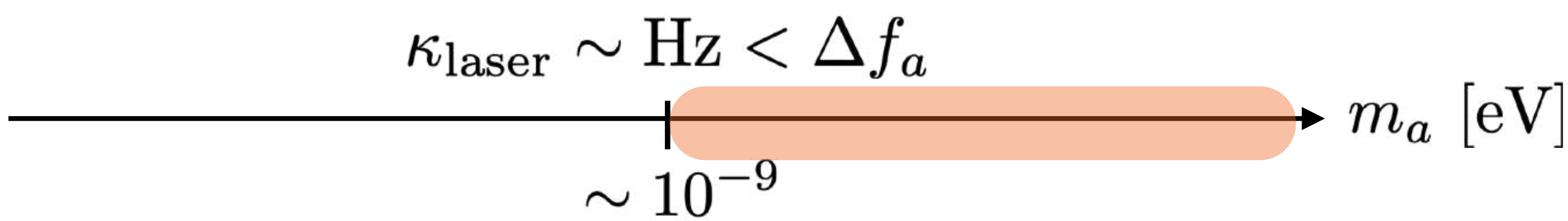

$$\Gamma \propto \frac{(\kappa_{\mathrm{laser}}/2)}{(\kappa_{\mathrm{laser}}/2)^2 + (\Delta + \Omega_m - m_a)^2}$$

$$\mathrm{spacing} = \epsilon\left(\frac{\kappa_{\mathrm{laser}}}{2}\right)$$

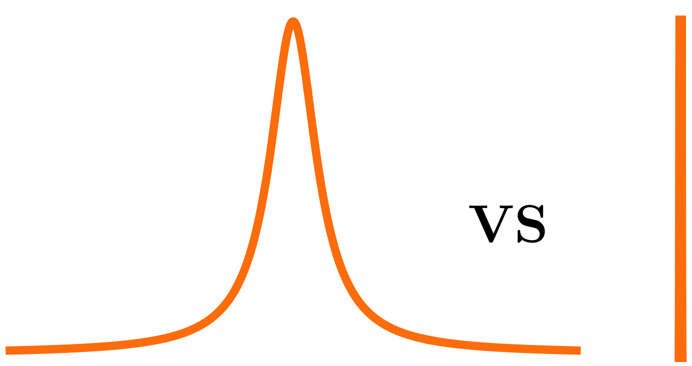
~10 neV/year

# Sensitivity and scanning strategy

$$\mathrm{SNR} = \frac{P_{\mathrm{sig}}}{\sqrt{P_{\mathrm{probe}}\,\omega_{\mathrm{opt}}\,\kappa}}\frac{1}{N_{\mathrm{meas}}^{1/4}} > 1 \;\Rightarrow\; g_{a\gamma\gamma} > f(m_a, \mathrm{cavity}, \mathrm{lasers}, \mathrm{material})$$




## Lorenzian regime

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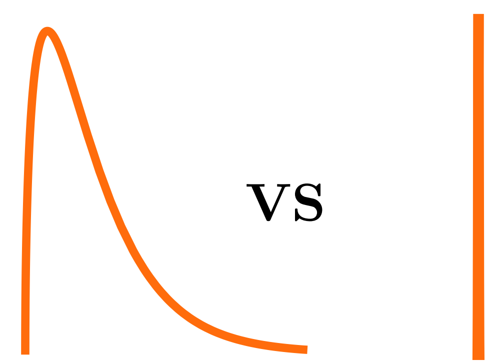
~10 neV/year

## Boltzmann regime




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

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

~1 oom/year

# Conclusions

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

- Atom interferometers at low transferred momentum:
  - Decoherence has no lower bound on energy deposition
  - Coherent enhancement
  - Boost in the rate
- Axioptopmechanics:
  - Coherent enhancement
  - Decoupling of the cavity geometry with the axion mass
  - Axions do not spoil the matching conditions

# Future directions

**Work in progress**

- Atom interferometers (AIs):
  - Understand the possible backgrounds.
  - Study the implications of enjoying a AIs network.
  - Study decoherence in other quantum sensors: atomic clocks?

- Axioptopmechanics:
  - Experimental proposal with J. Harris lab at Yale University.
  - Study the effect of using other materials ($SiO_2$, $Ta_2O_5$...)

Thank you!