Caltech

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Hunting for Light DM with Quantum Sensors

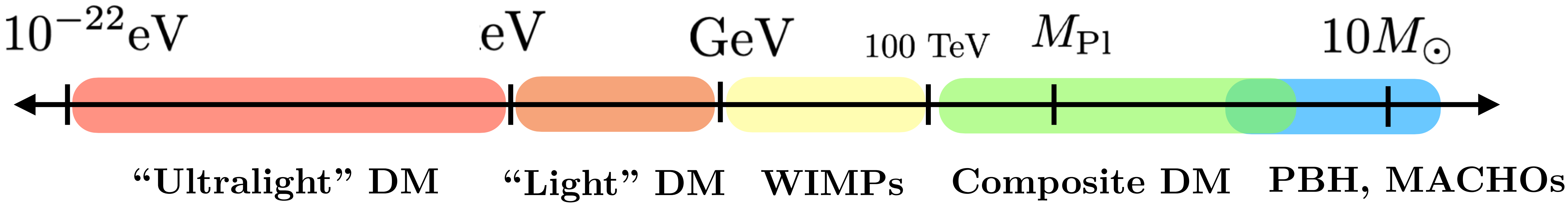
Atom Interferometers & Optomechanical Cavities

Clara Murgui

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

PPC workshop. IFT (Madrid). 14 October 2022

Dark Matter: where to look?



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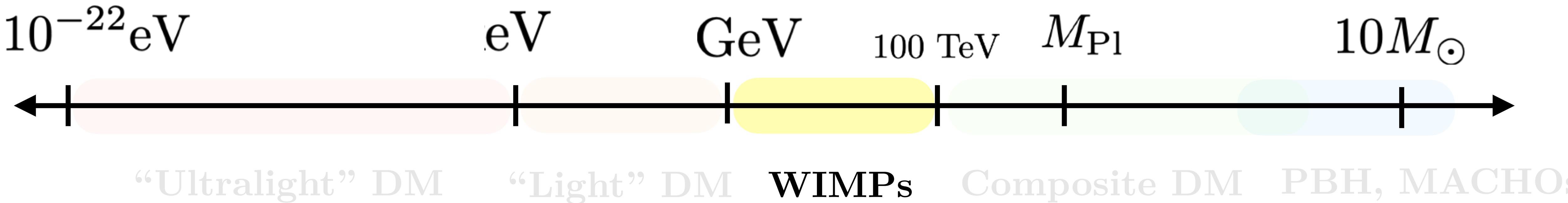
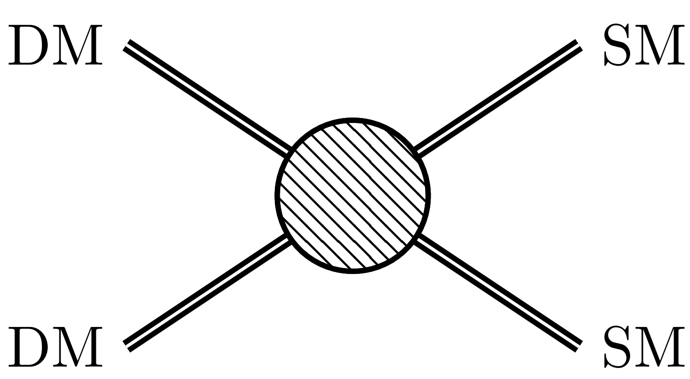
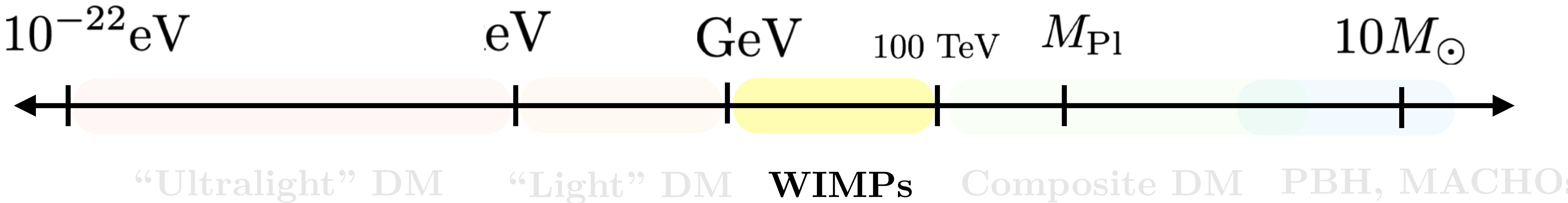


The WIMP miracle



$$\Omega_{\rm DM} = \frac{\rho_{\rm DM}}{\rho_c}$$

Dark Matter: where to look?



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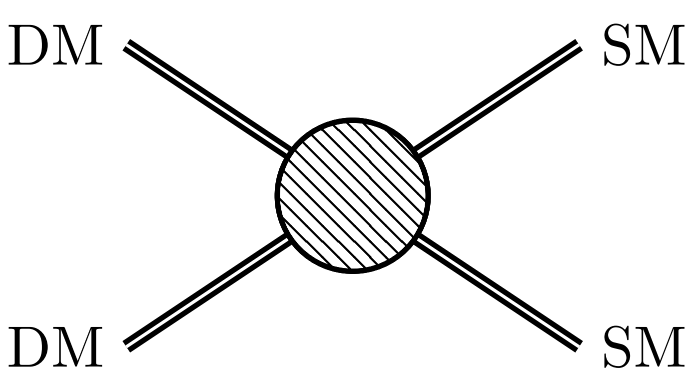
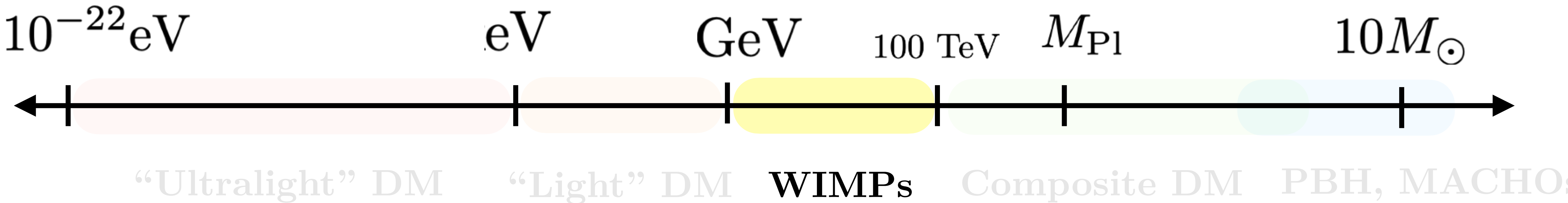


$$\Omega_{\rm DM} = \frac{m_\chi (n_\chi)_0}{\rho_c}$$

Dark Matter: where to look?



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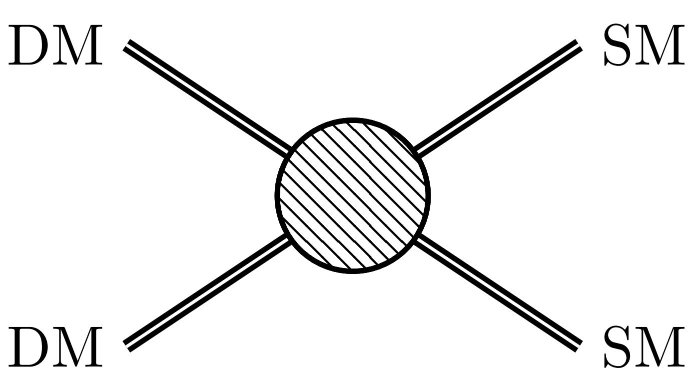

$$\Omega_{\rm DM} \sim \frac{m_\chi n_\chi T_0^3}{\rho_c T^3}$$

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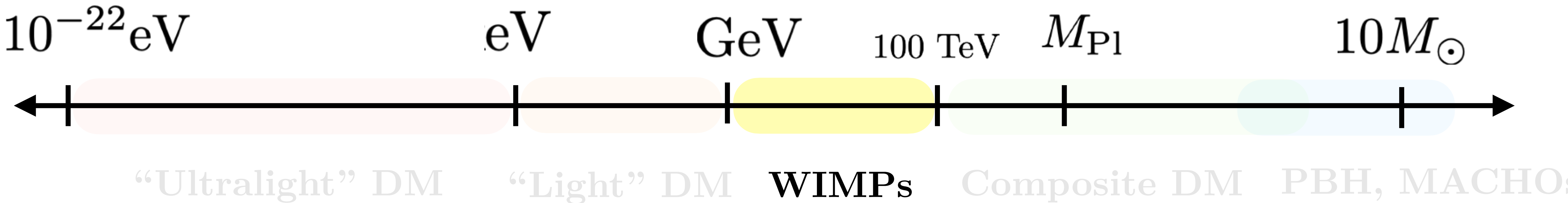

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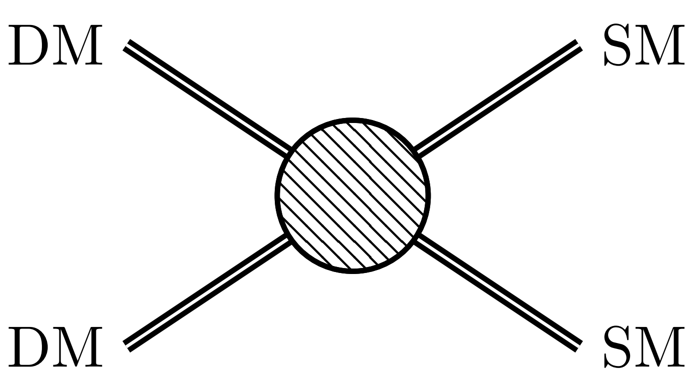
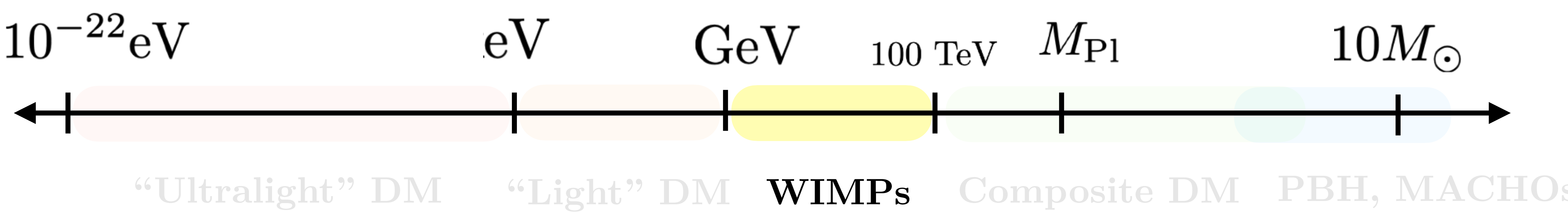


$$\Omega_{\rm DM} \sim \frac{m_\chi (1.66\sqrt{g_*}T^2/M_{\rm Pl})T_0^3}{\rho_c T^3 \langle \sigma v \rangle}$$

Dark Matter: where to look?



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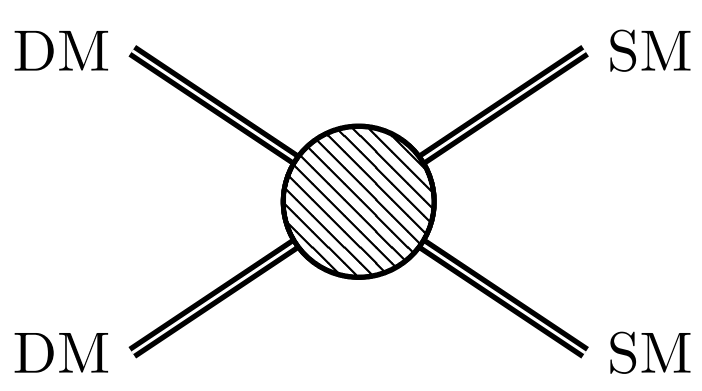
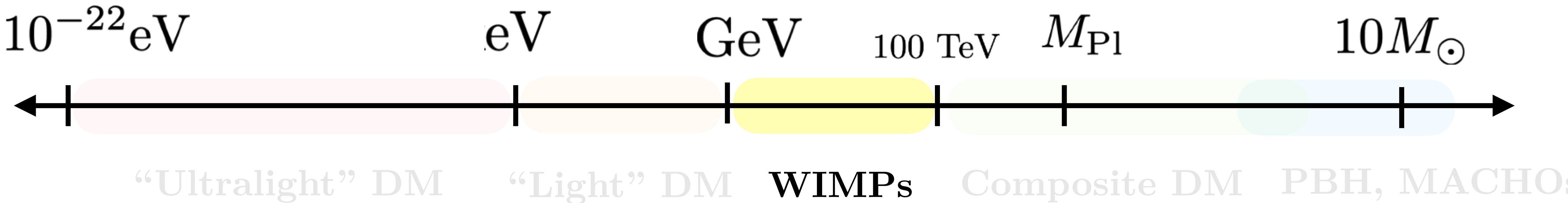


$$\Omega_{\rm DM} \sim 0.1 \times \left(\frac{3 \times 10^{-26}\ {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle} \right)$$

Dark Matter: where to look?



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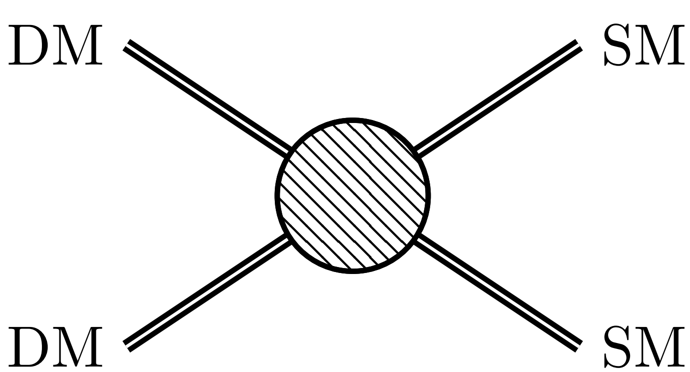

$$\sigma \sim \frac{G_F^2}{8\pi} m_\chi^2$$

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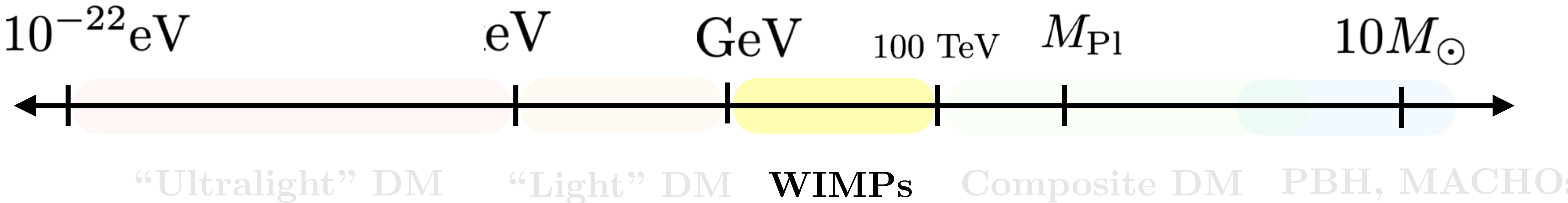

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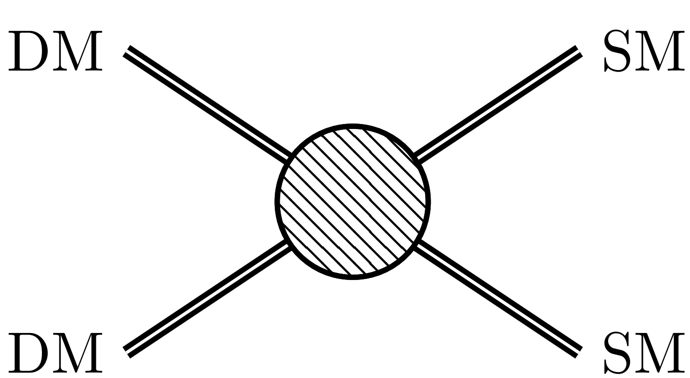

$$\langle \sigma v \rangle \sim \frac{G_F^2}{8\pi} m_\chi^2 \frac{c}{3} \sim 10^{-24} \mathrm{cm}^3/\mathrm{s} \left(\frac{m_\chi}{100\ \mathrm{GeV}} \right)^2$$

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

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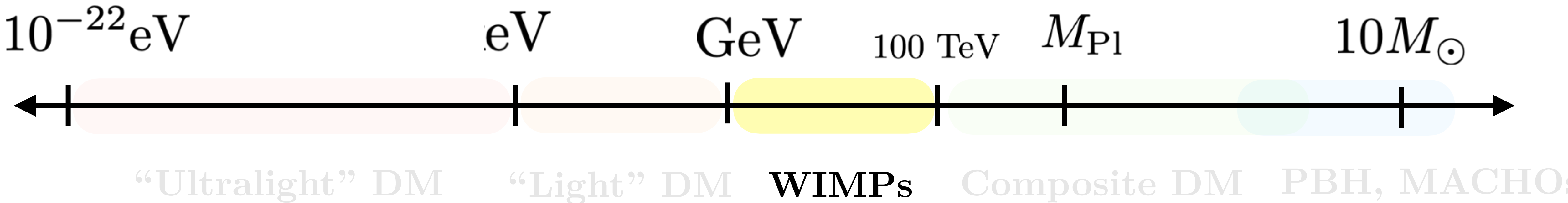

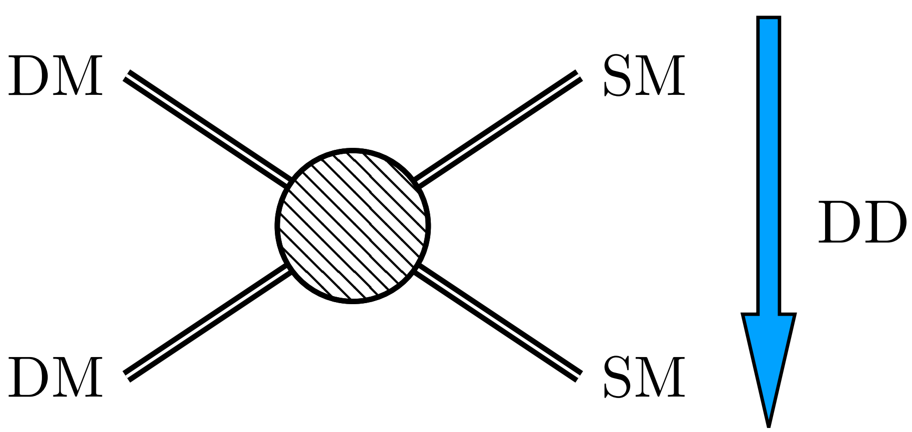

$$\sigma \sim 10^{-34}\mathrm{cm}^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

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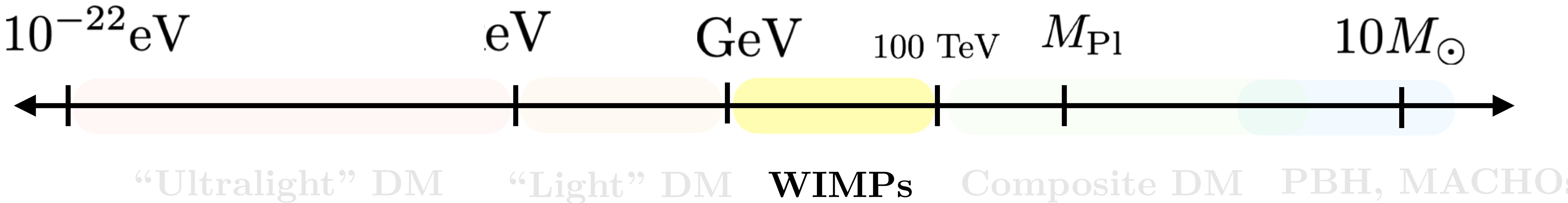

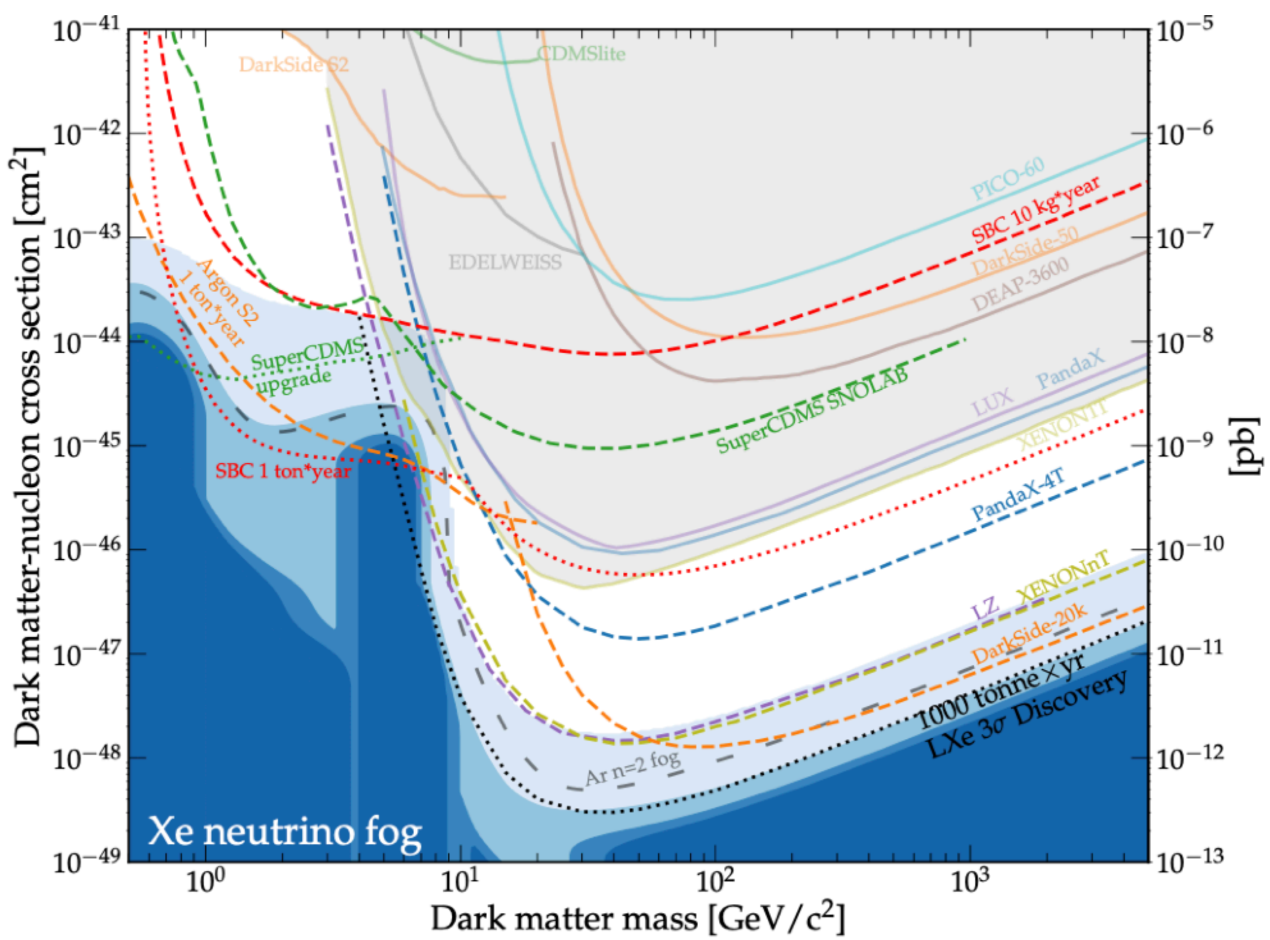

[Akerib, D. S., et al., Snowmass2021, 2203.08084]

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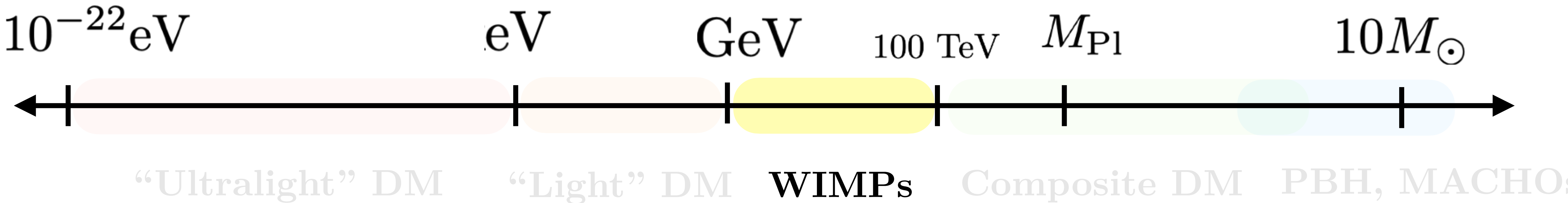

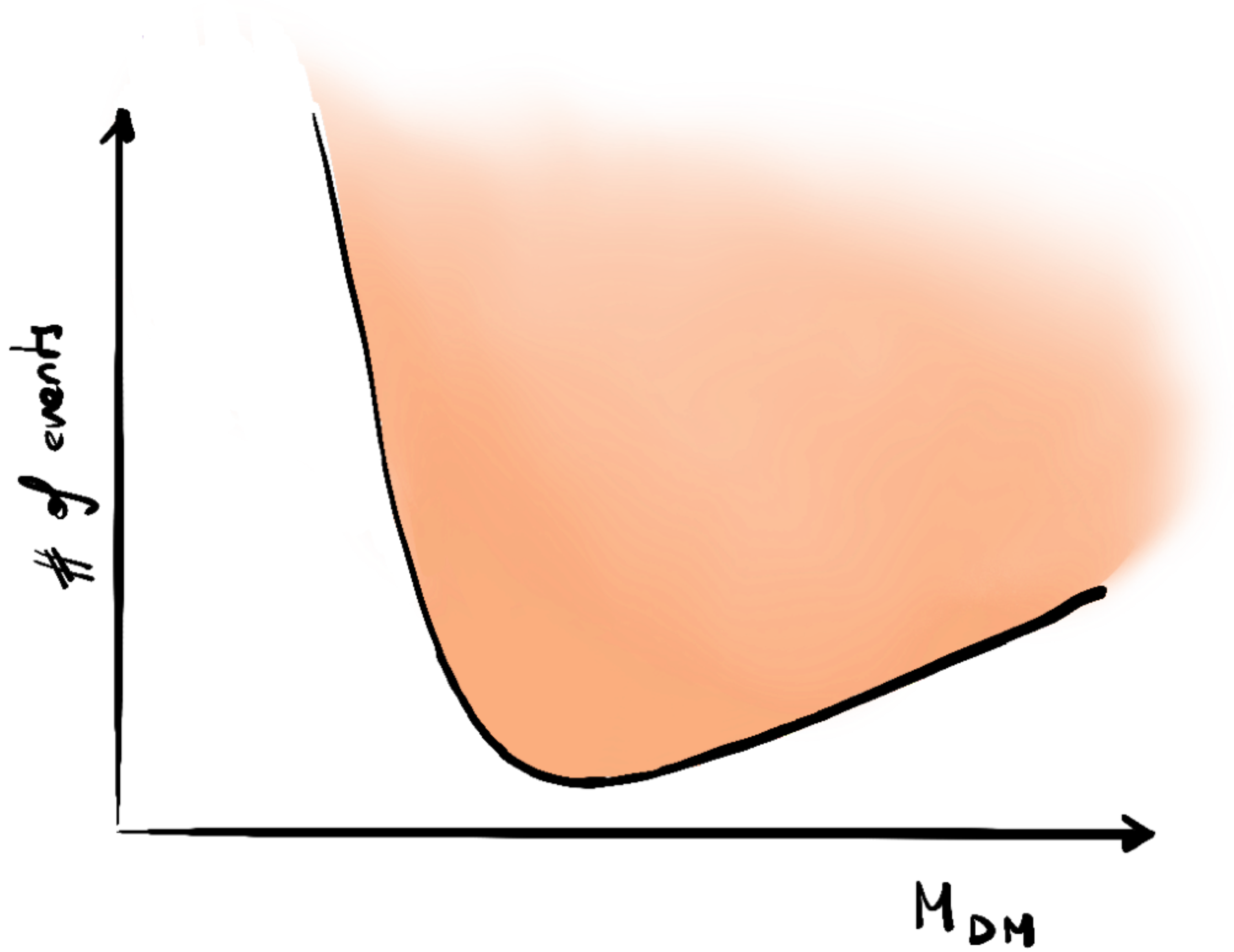

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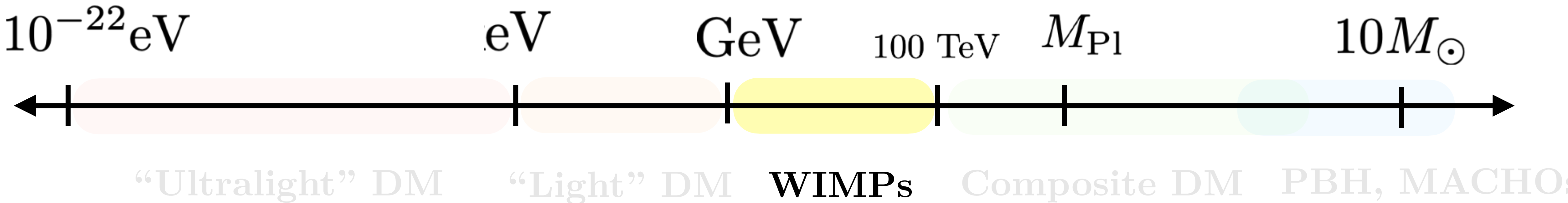

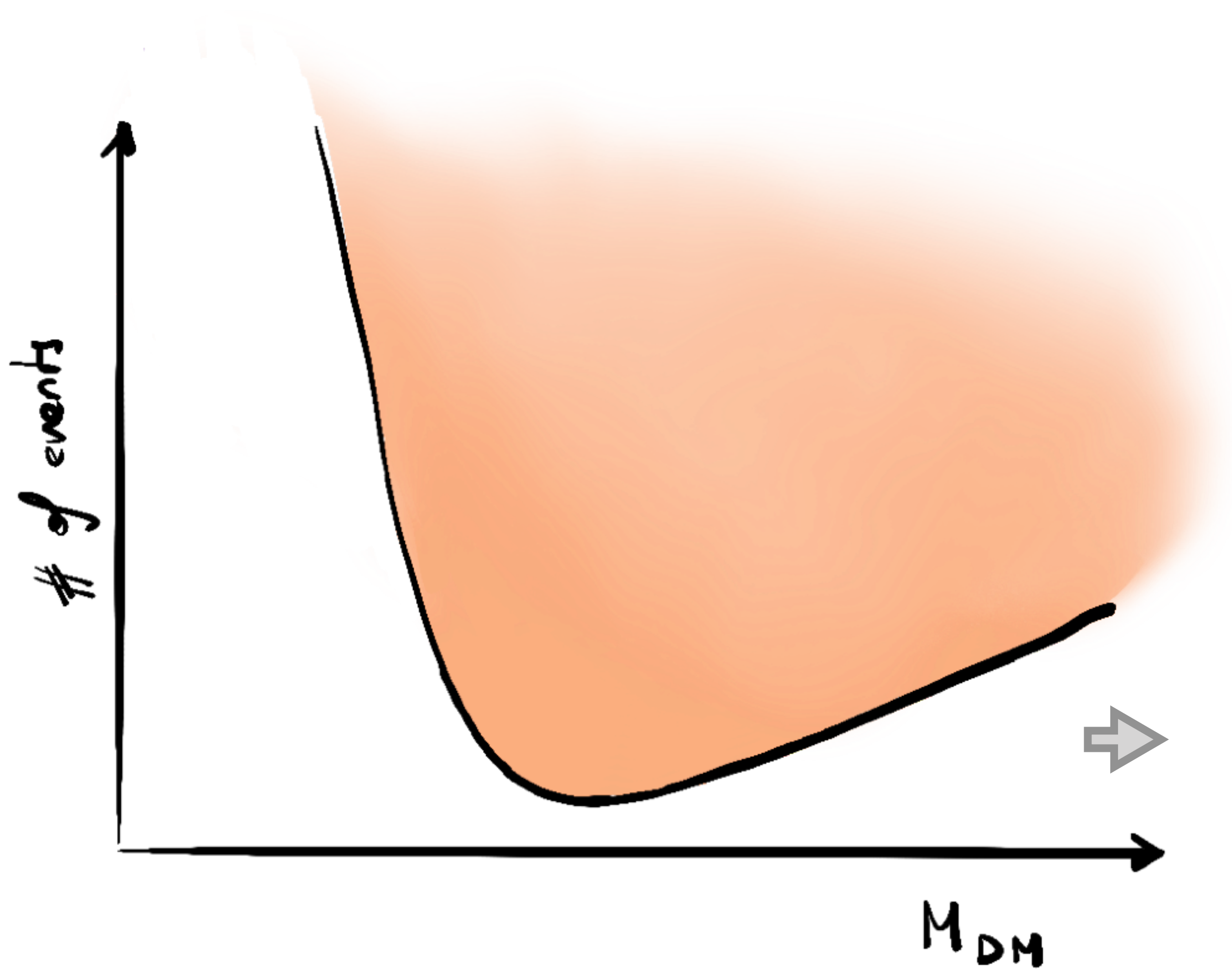

$$\sigma \sim 10^{-34}\mathrm{cm}^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

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

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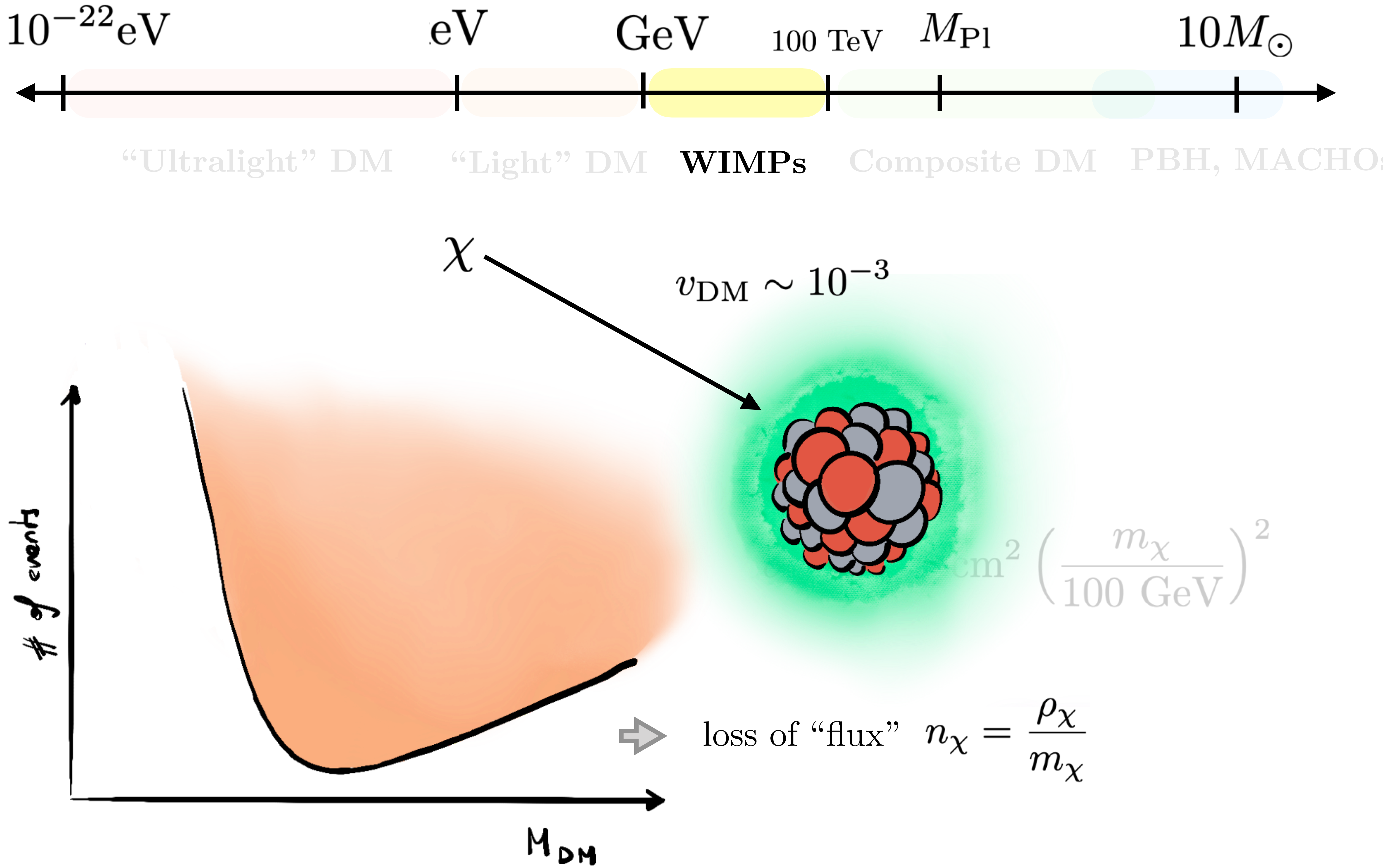

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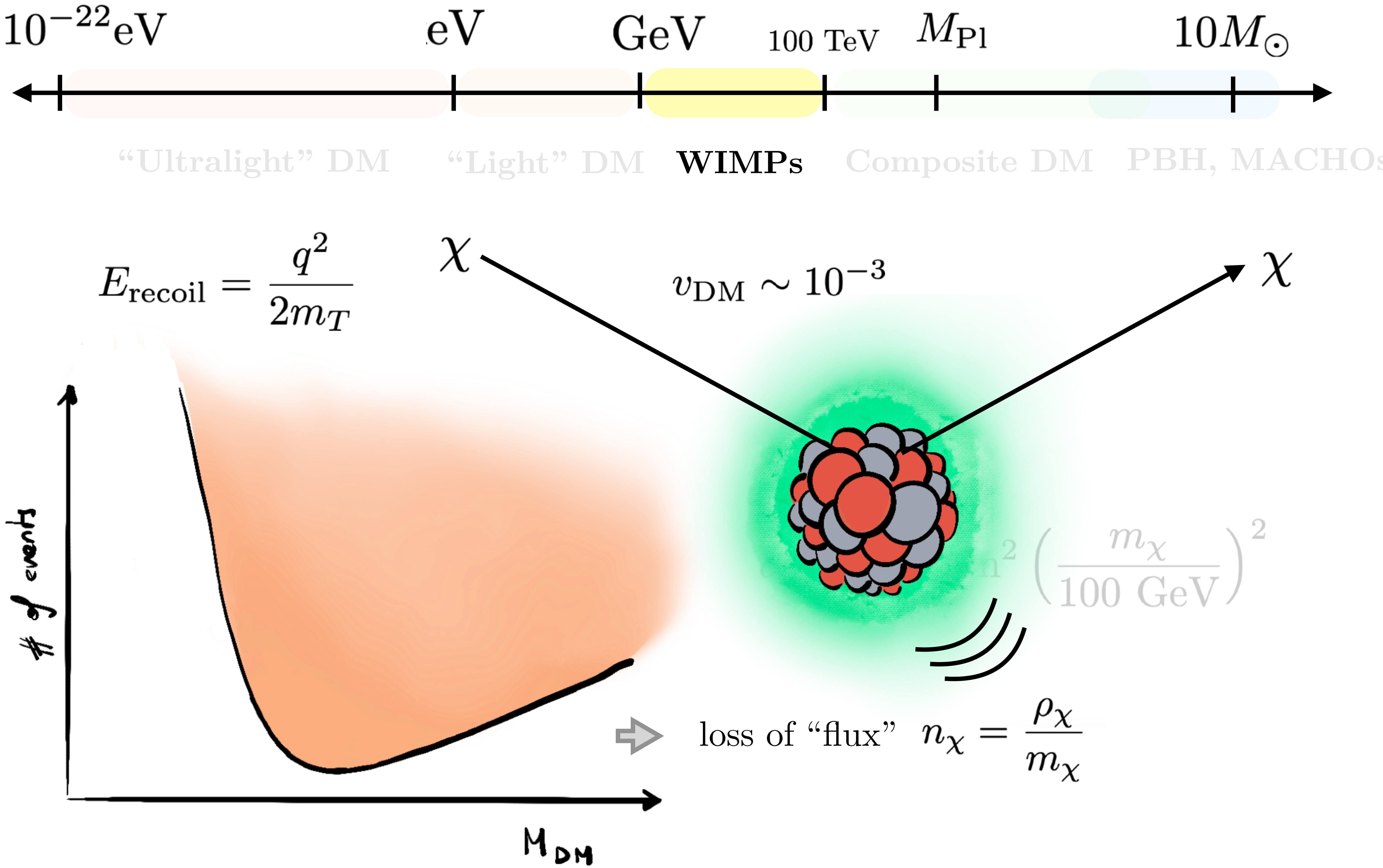

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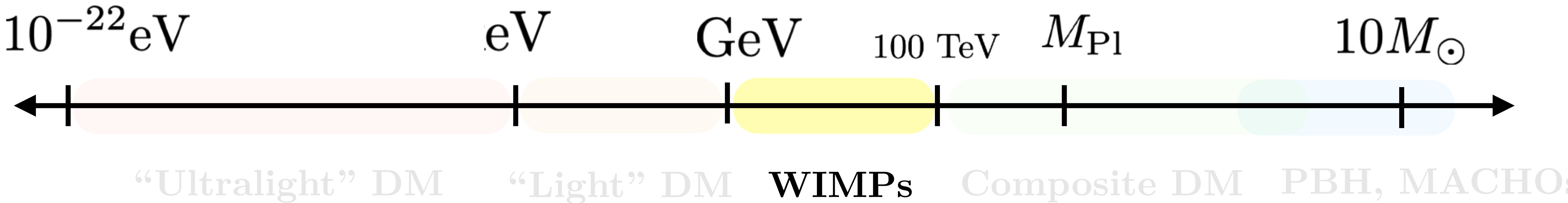
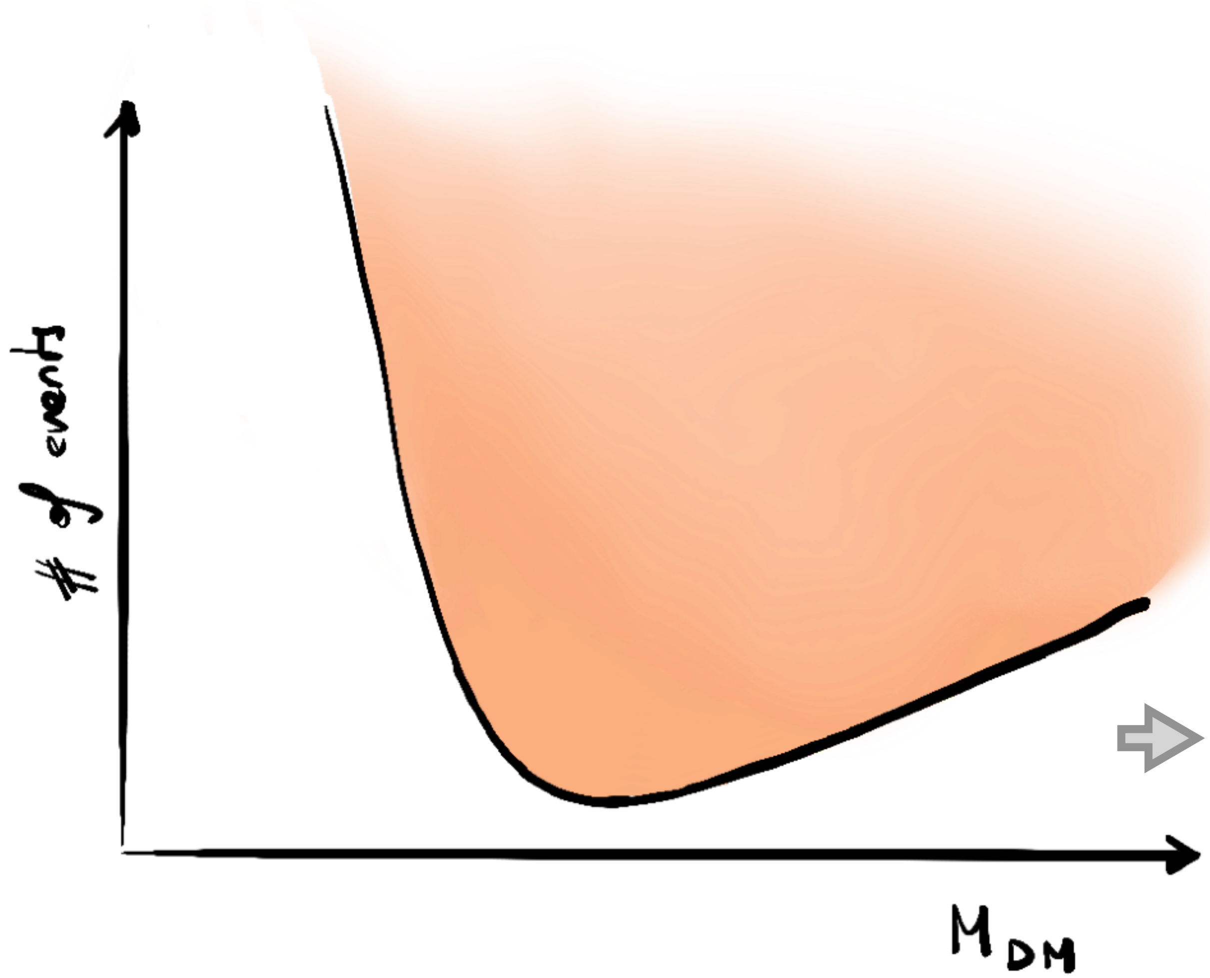


$$E_{\rm recoil}^{\rm max} \sim \left(\frac{m_\chi}{\rm GeV}\right) \rm keV$$



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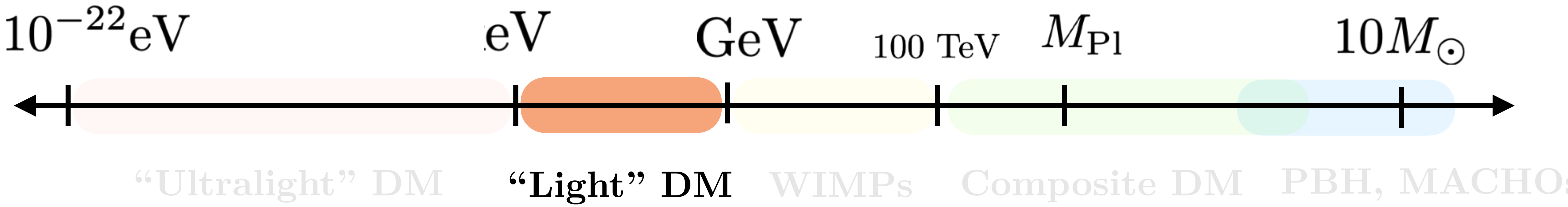
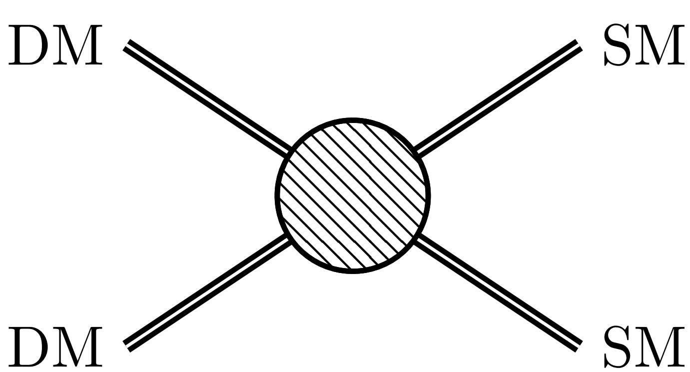
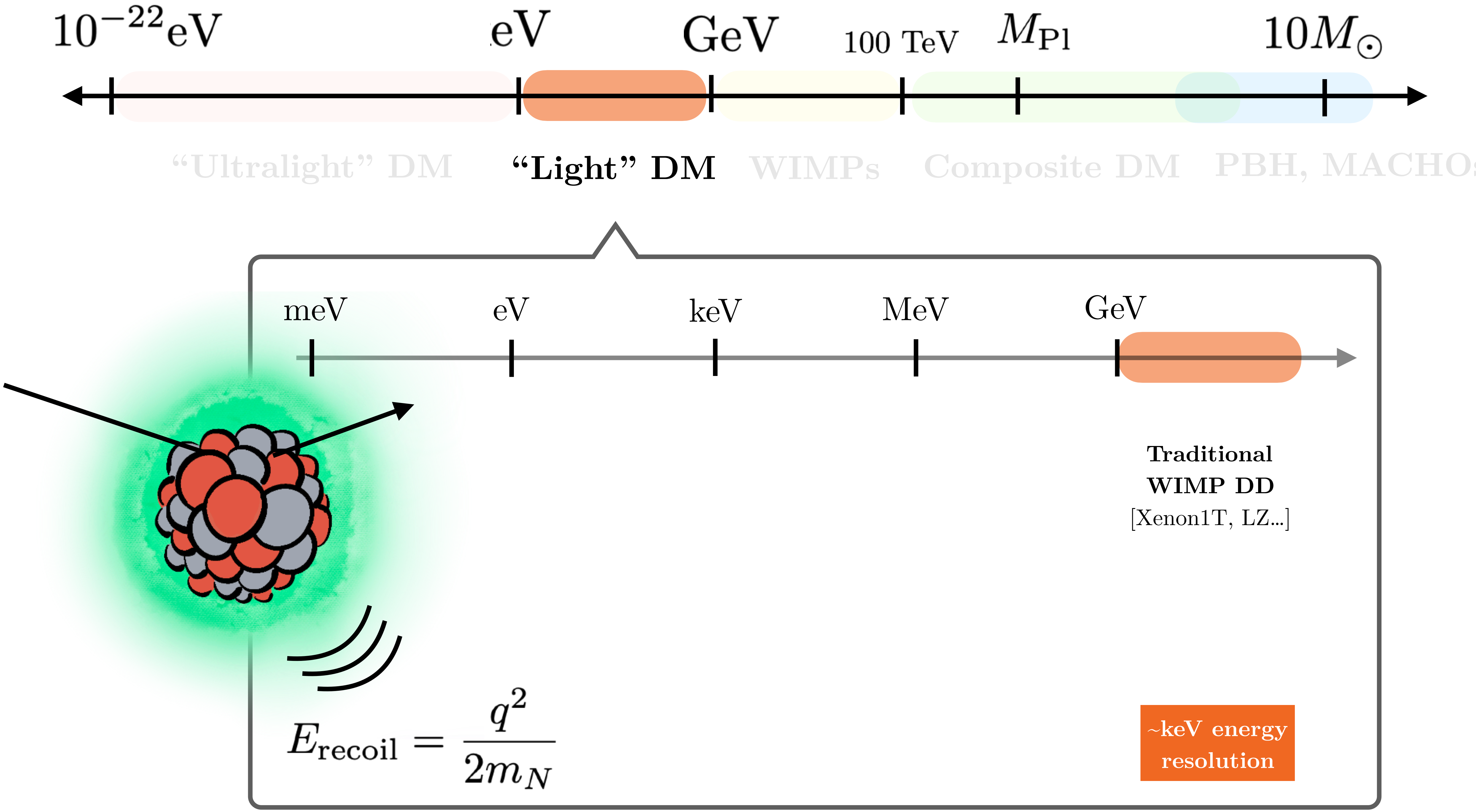




$$\langle \sigma v \rangle \sim \frac{g^2}{8\pi m_\chi^2} \sim 10^{-25}\mathrm{cm}^3/\mathrm{s}\left(\frac{g}{10^{-6}}\right)^2\left(\frac{\mathrm{MeV}}{m_\chi}\right)^2$$

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

Dark Matter: where to look?



[adapted from K. Zurek's talks]

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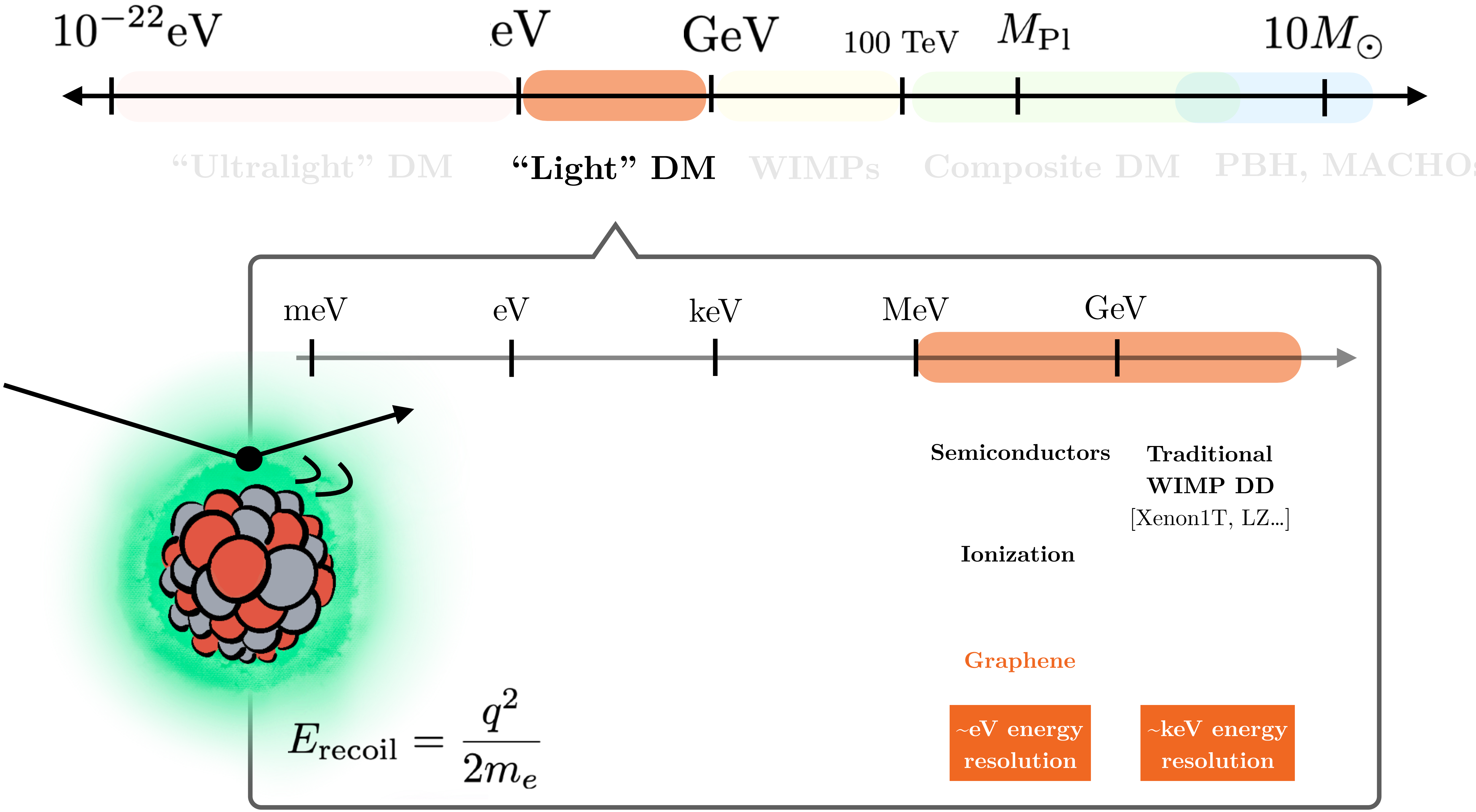

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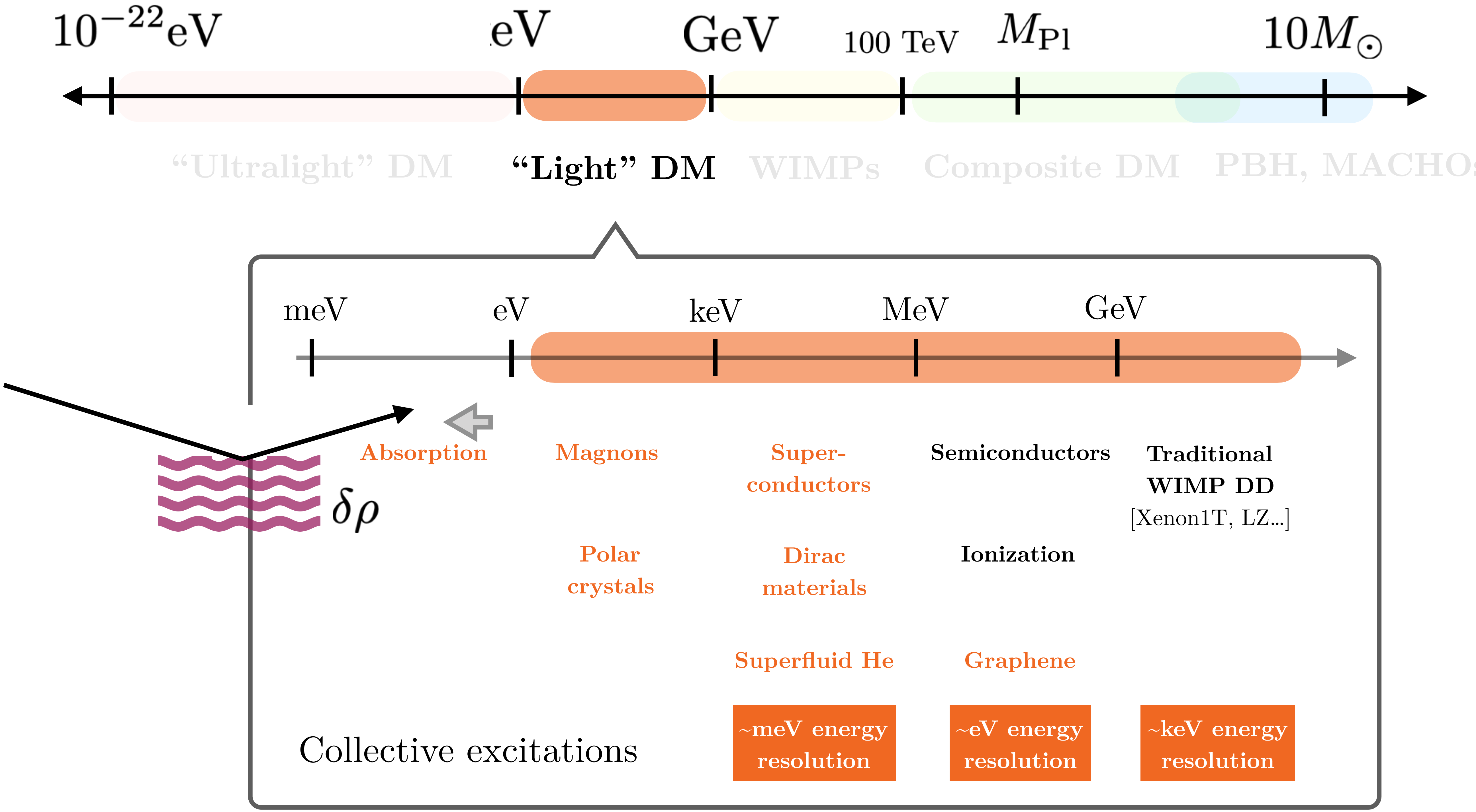

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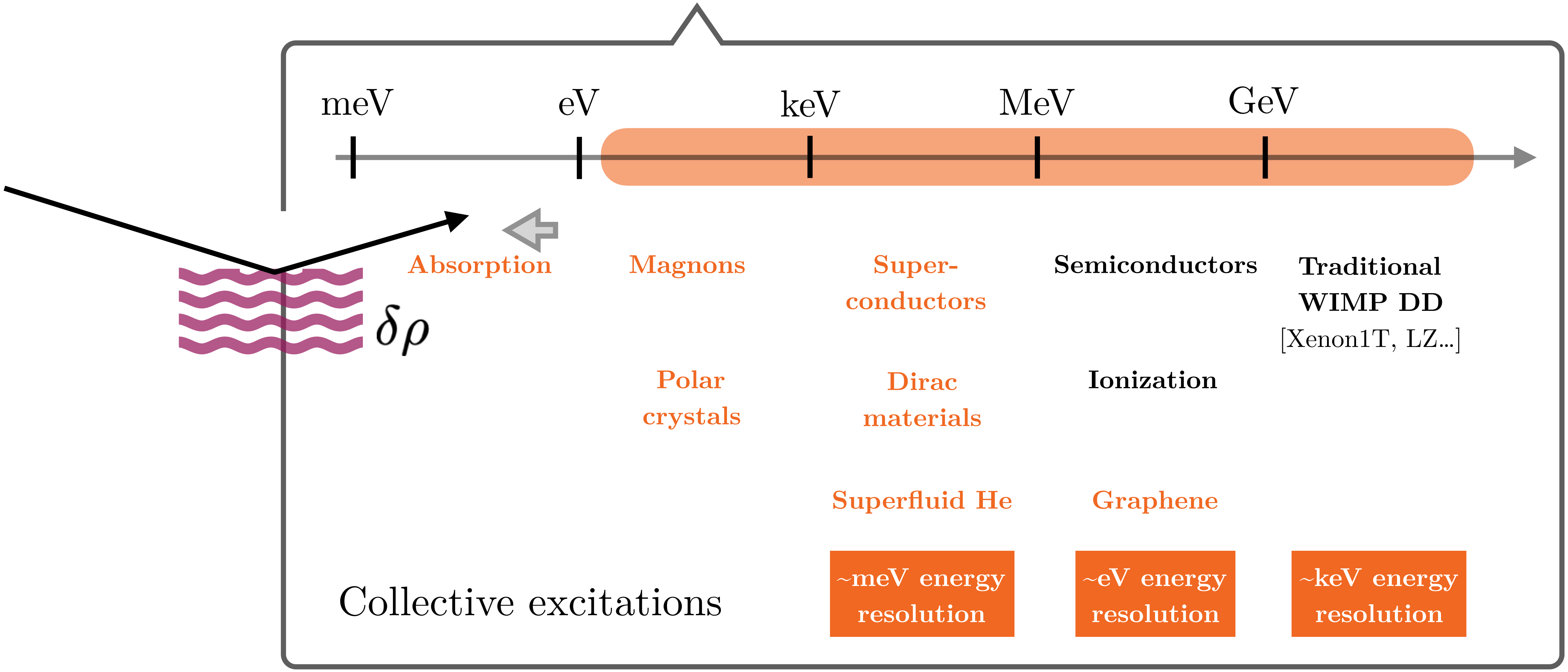
Dark Matter: where to look?

[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]



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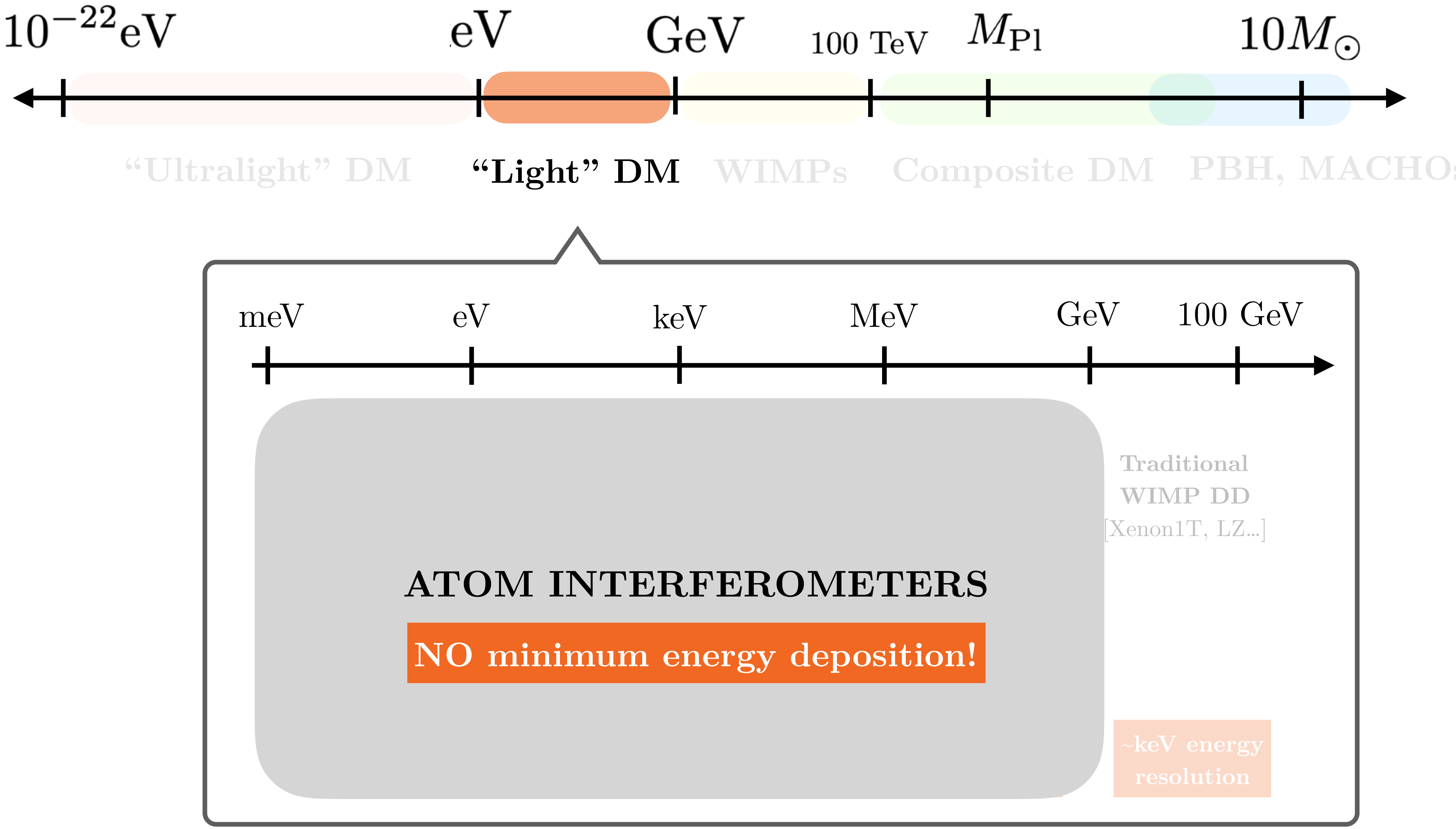


Atom Interferometer tests of **Dark Matter**

2205.13546

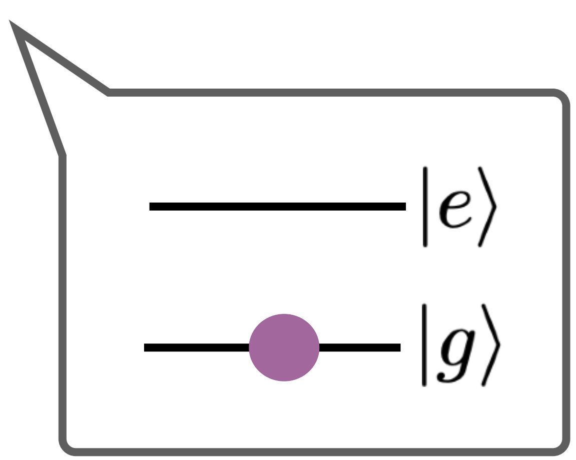
with Yufeng Du, Kris Pardo, Yikun Wang and Kathryn M. Zurek

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

AIs: the Principle

Review: arXiv:2003.12516

$$\rho_0 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$



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

AIs: the Principle

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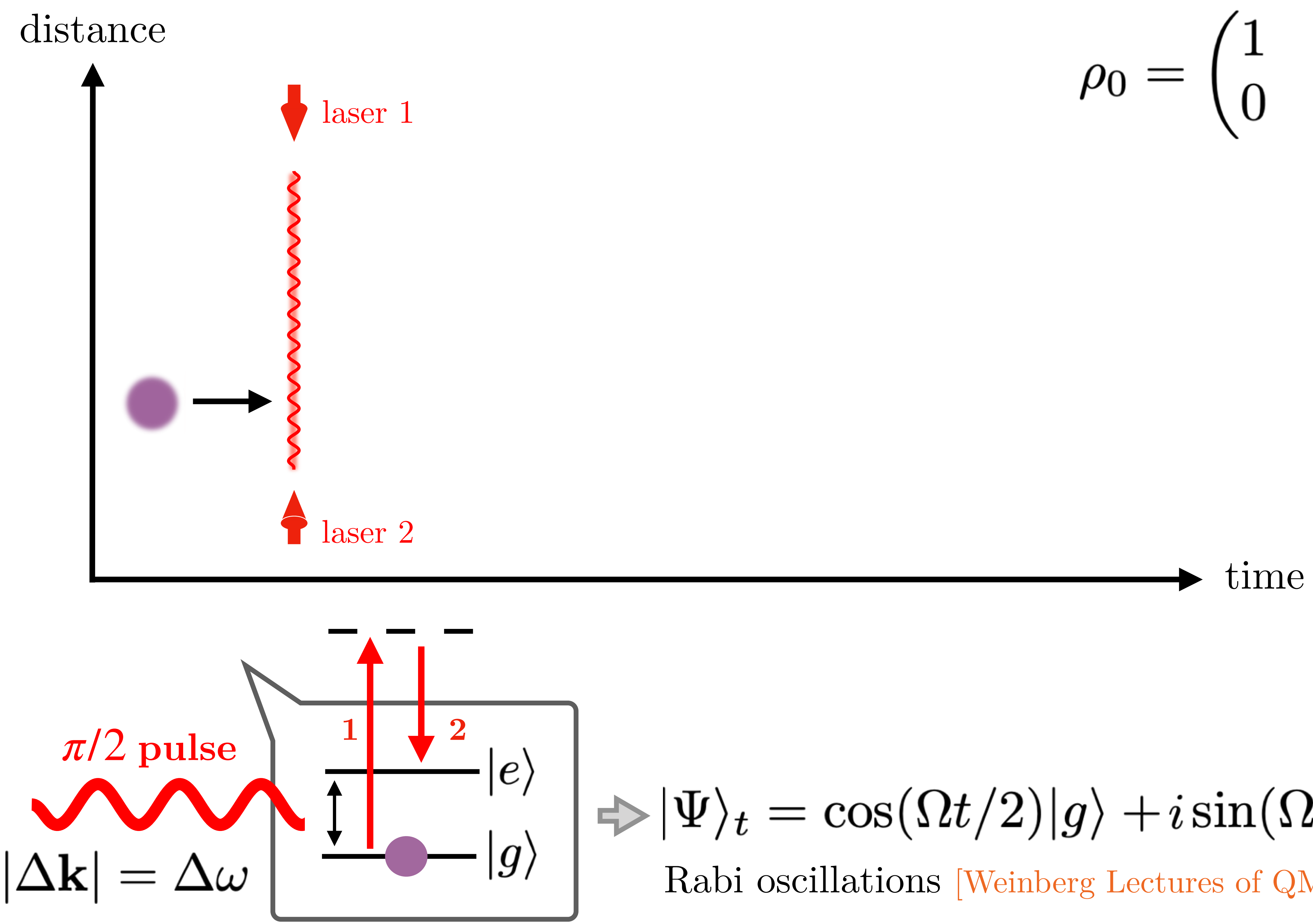
$$\rho_0 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

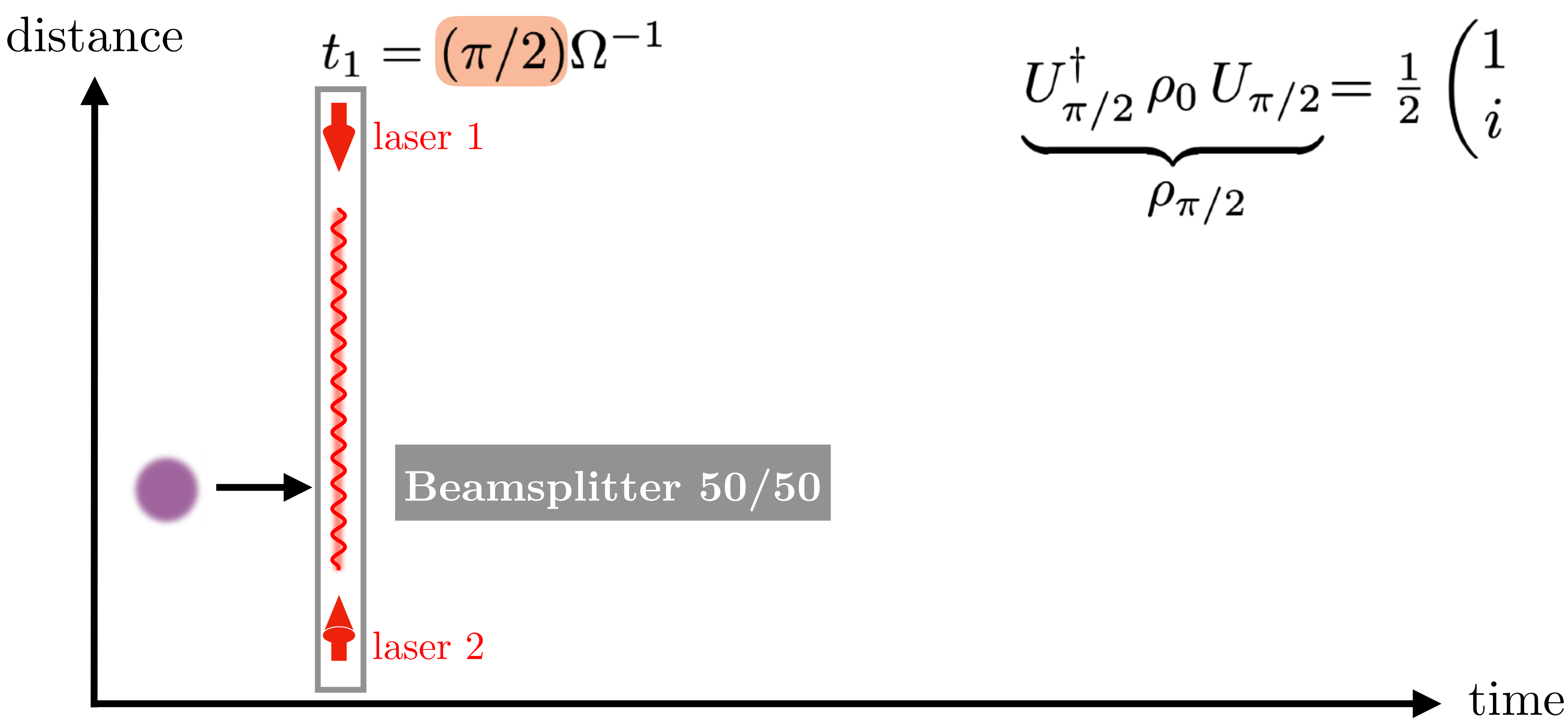


$$|\Psi\rangle_t = \cos(\Omega t/2)|g\rangle + i\sin(\Omega t/2)|e\rangle$$

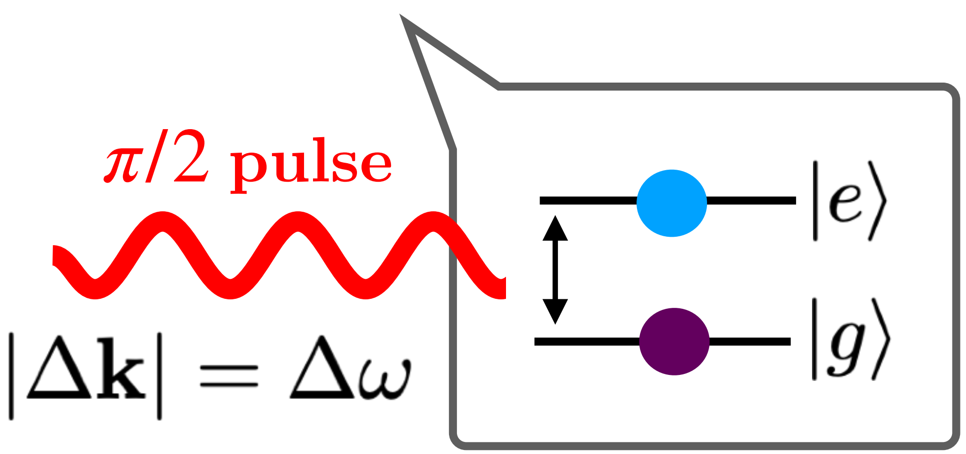
Rabi oscillations [Weinberg Lectures of QM, Chap. 6]

AIs: the Principle

Review: arXiv:2003.12516



$$\underbrace{U^{\dagger}_{\pi/2}\,\rho_0\,U_{\pi/2}}_{\rho_{\pi/2}} = \frac{1}{2}\begin{pmatrix} 1 & -i \\ i & 1 \end{pmatrix}$$



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

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

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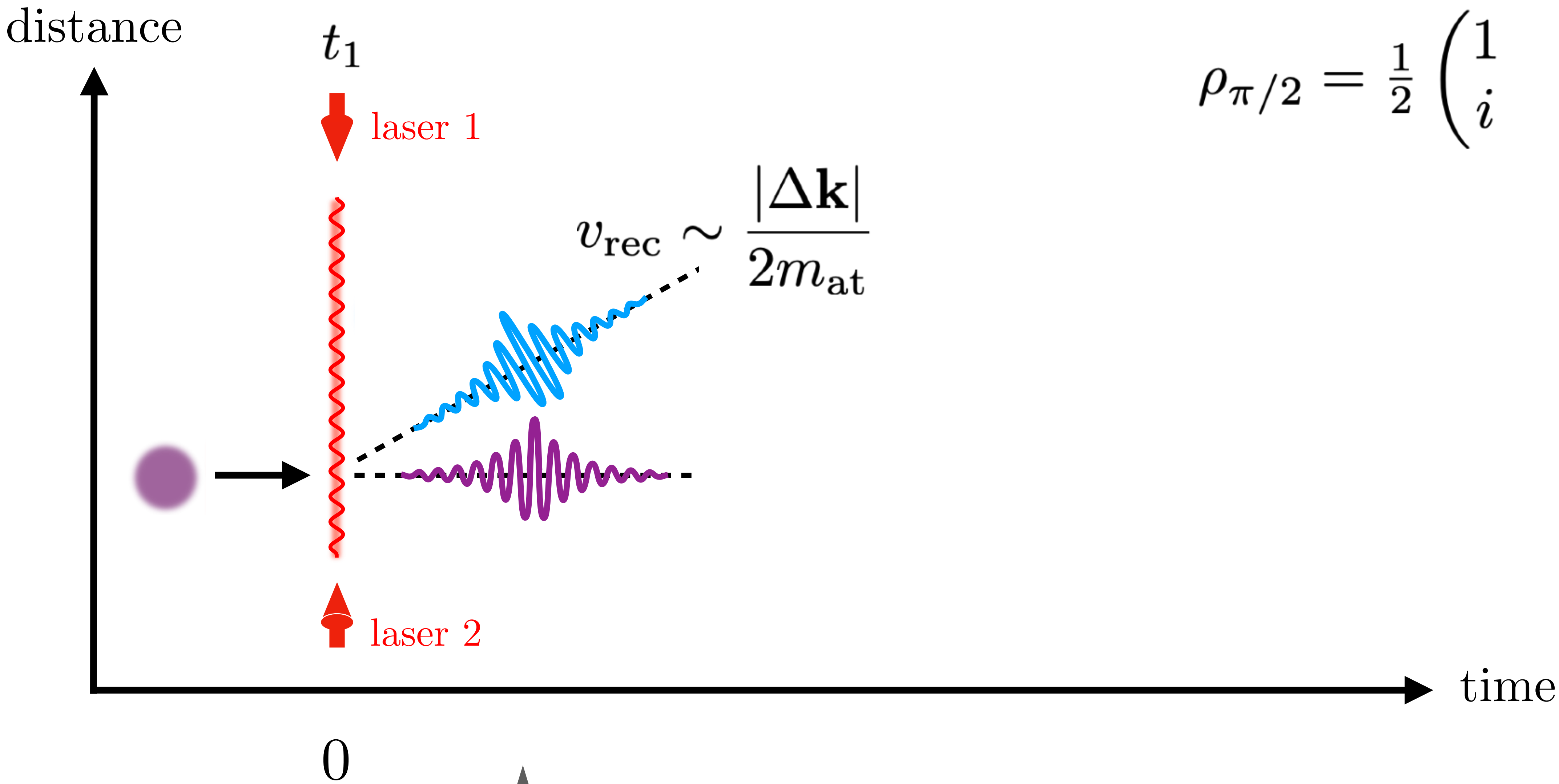
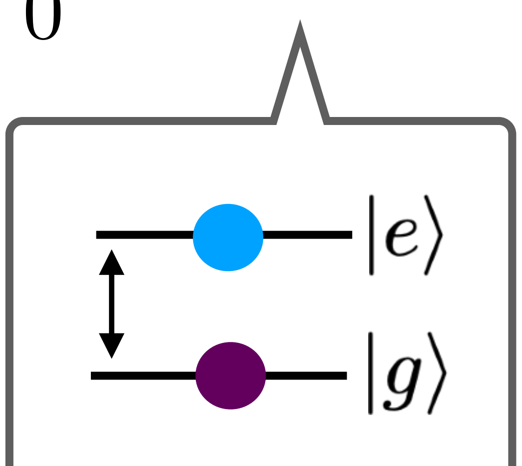
$$\rho_{\pi/2} = \frac{1}{2}\begin{pmatrix} 1 & -i \\ i & 1 \end{pmatrix}$$



$$v_{\mathrm{rec}} \sim \frac{|\Delta \mathbf{k}|}{2m_{\mathrm{at}}}$$

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

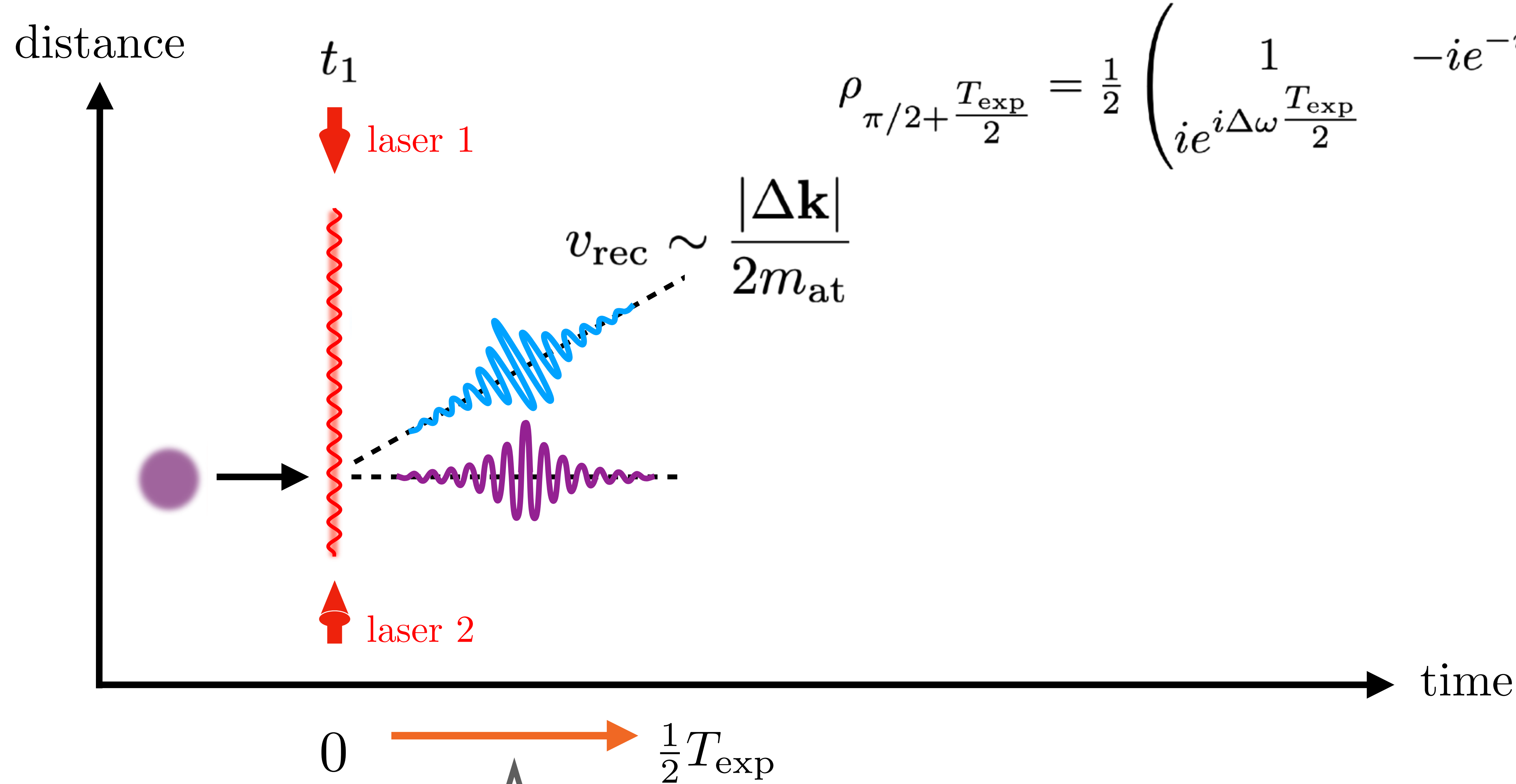


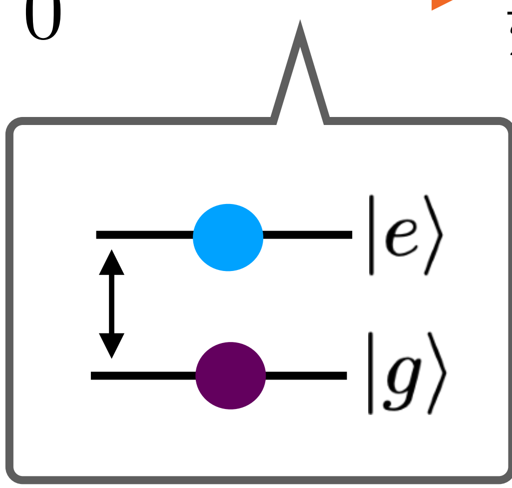
$$\Rightarrow |\Psi\rangle_{t_1} = \frac{1}{\sqrt{2}}\left(|g\rangle + i|e\rangle\right)$$

AIs: the Principle

Review: arXiv:2003.12516

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





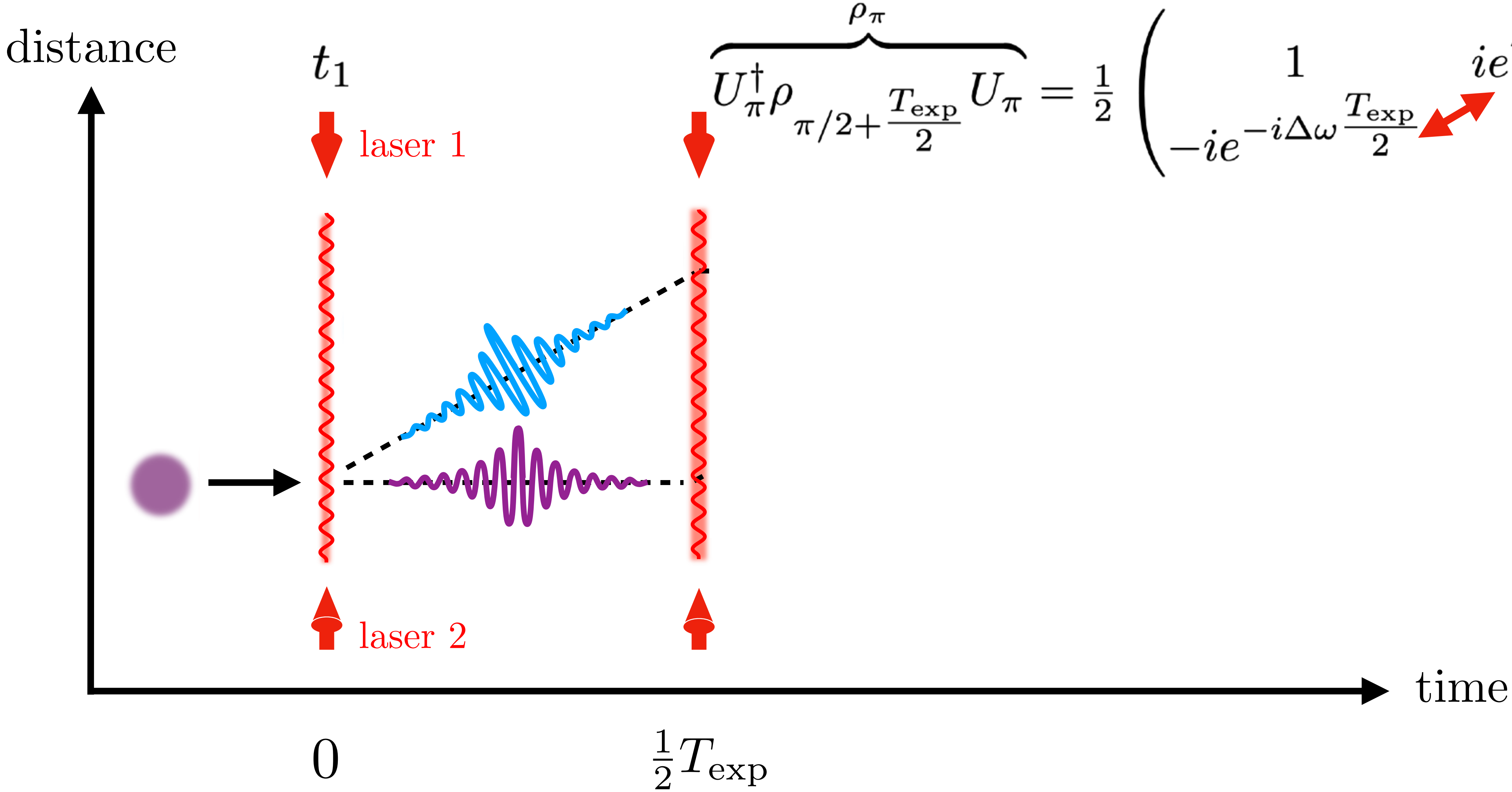
$$|\mathbf{\Delta k}| = \Delta\omega$$

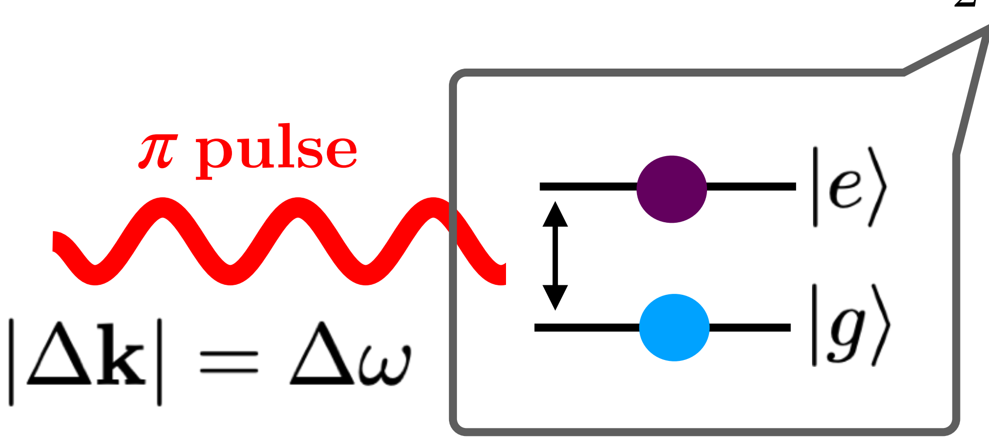
$$|\Psi\rangle_{t_1+\frac{T_{\rm exp}}{2}} = \frac{1}{\sqrt{2}}\left(|g\rangle + ie^{i\Delta\omega\frac{T_{\rm exp}}{2}}|e\rangle\right)$$

AIs: the Principle

Review: arXiv:2003.12516

$$\overbrace{U_\pi^\dagger \rho_{\pi/2+\frac{T_{\mathrm{exp}}}{2}} U_\pi}^{\rho_\pi} = \frac{1}{2}\begin{pmatrix} 1 & ie^{i\Delta\omega\frac{T_{\mathrm{exp}}}{2}} \\ -ie^{-i\Delta\omega\frac{T_{\mathrm{exp}}}{2}} & 1 \end{pmatrix}$$





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

AIs: the Principle

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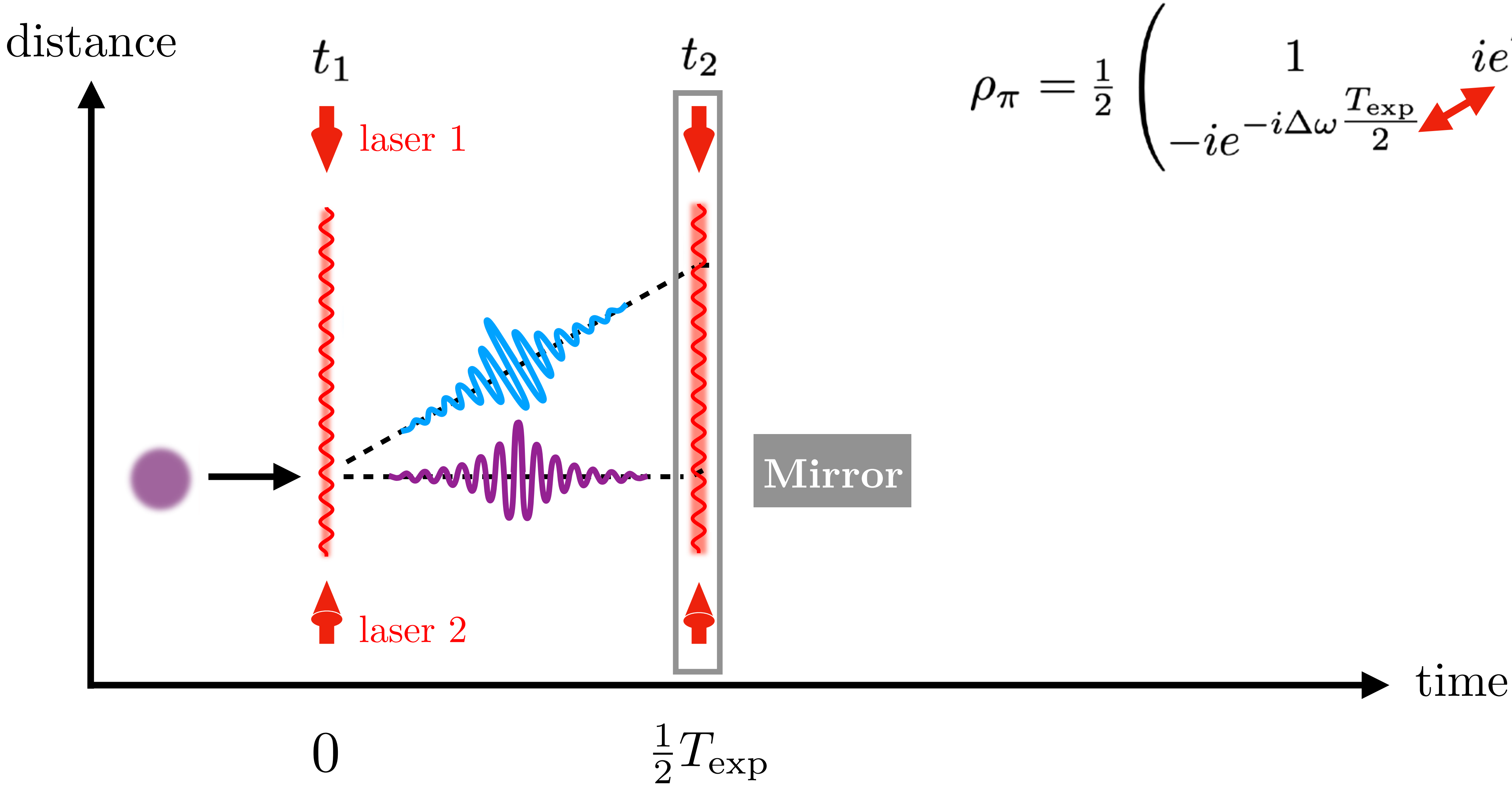
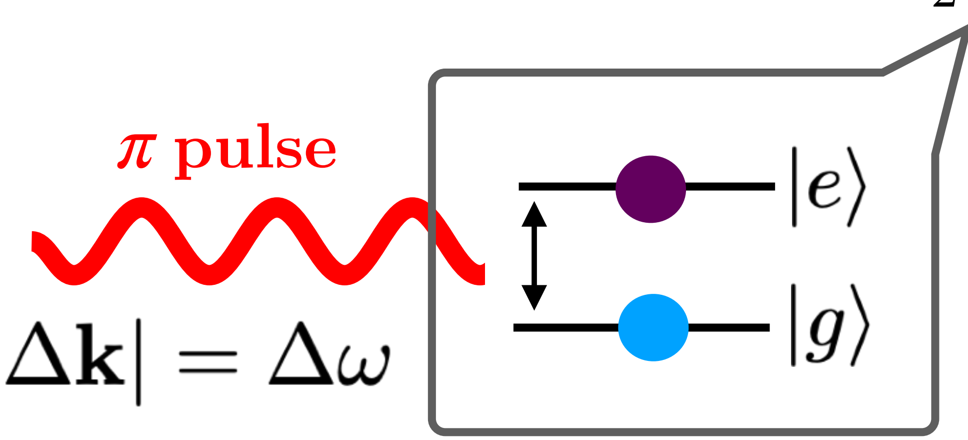


$$\rho_\pi = \frac{1}{2}\begin{pmatrix} 1 & ie^{i\Delta\omega\frac{T_{\rm exp}}{2}} \\ -ie^{-i\Delta\omega\frac{T_{\rm exp}}{2}} & 1 \end{pmatrix}$$



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

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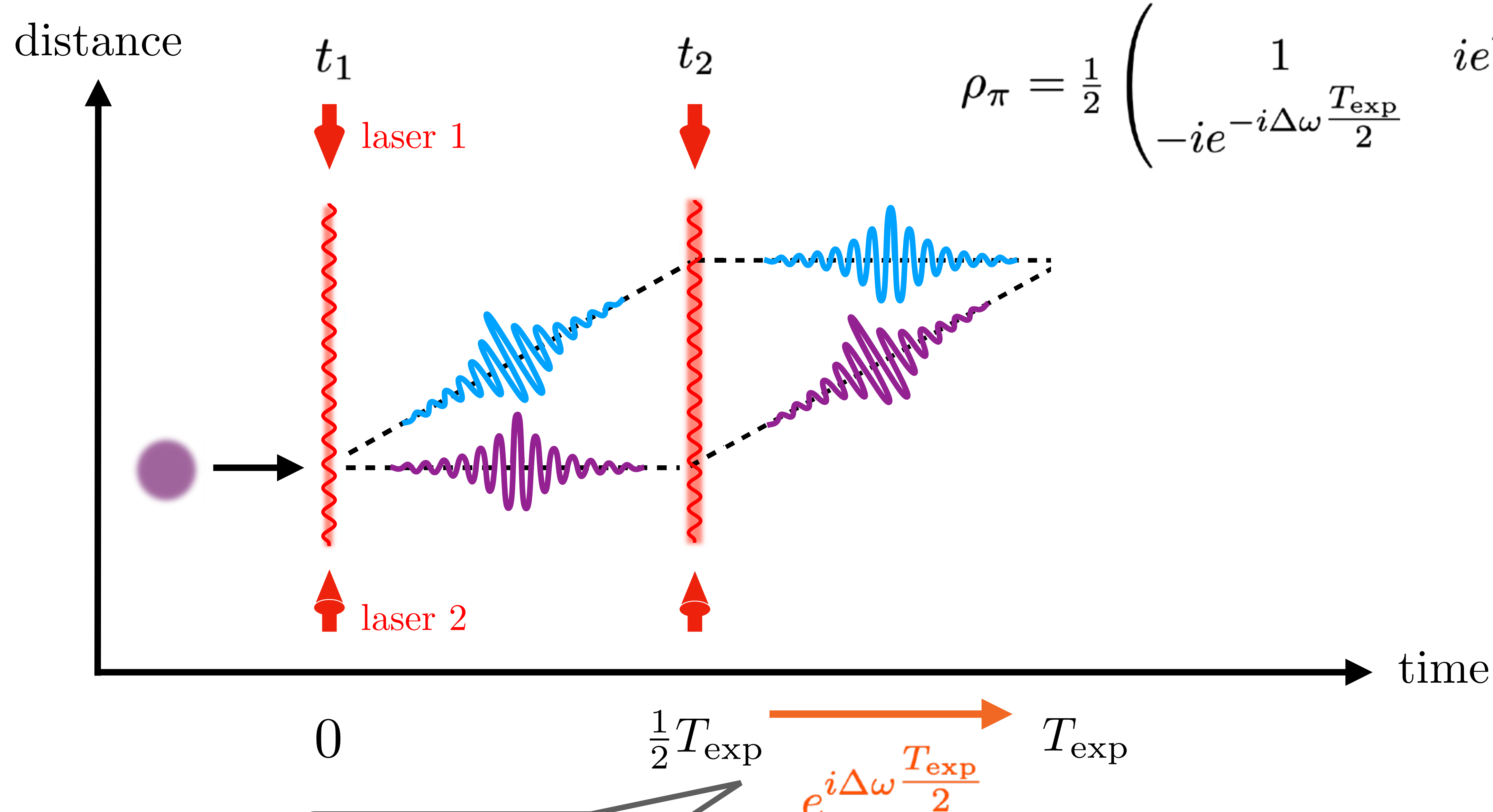

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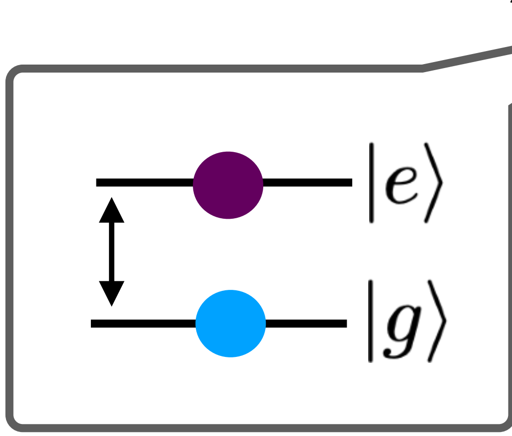
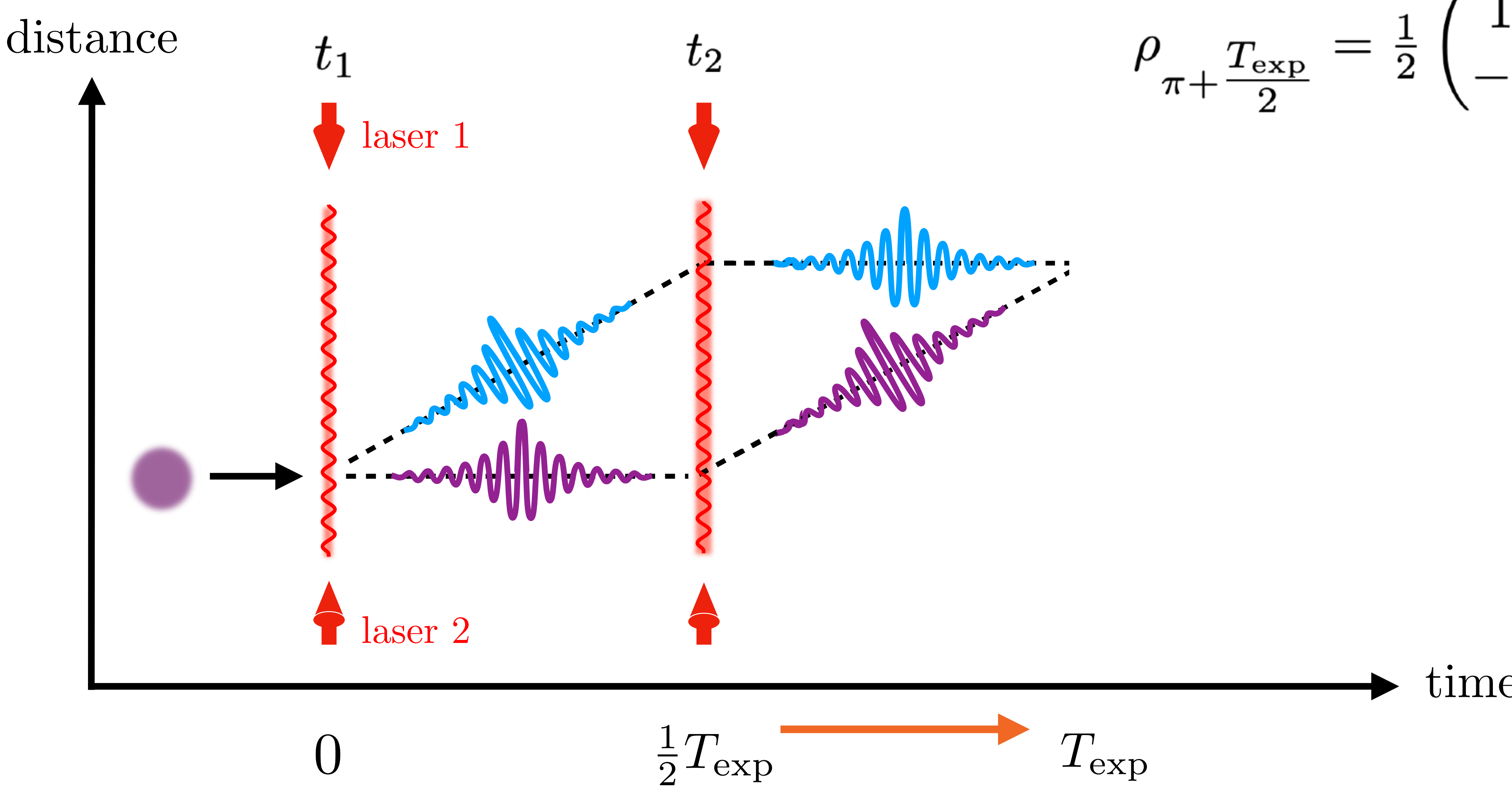


$$|\Psi\rangle_{t_1+\frac{T_{\mathrm{ext}}}{2}+t_2} = \frac{1}{\sqrt{2}}\left(-e^{i\Delta\omega\frac{T_{\mathrm{exp}}}{2}}|g\rangle + i\boxed{|e\rangle}\right)$$

AIs: the Principle

Review: arXiv:2003.12516

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



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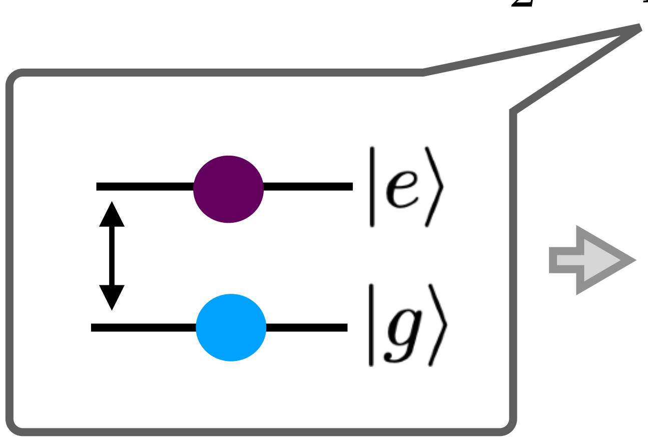
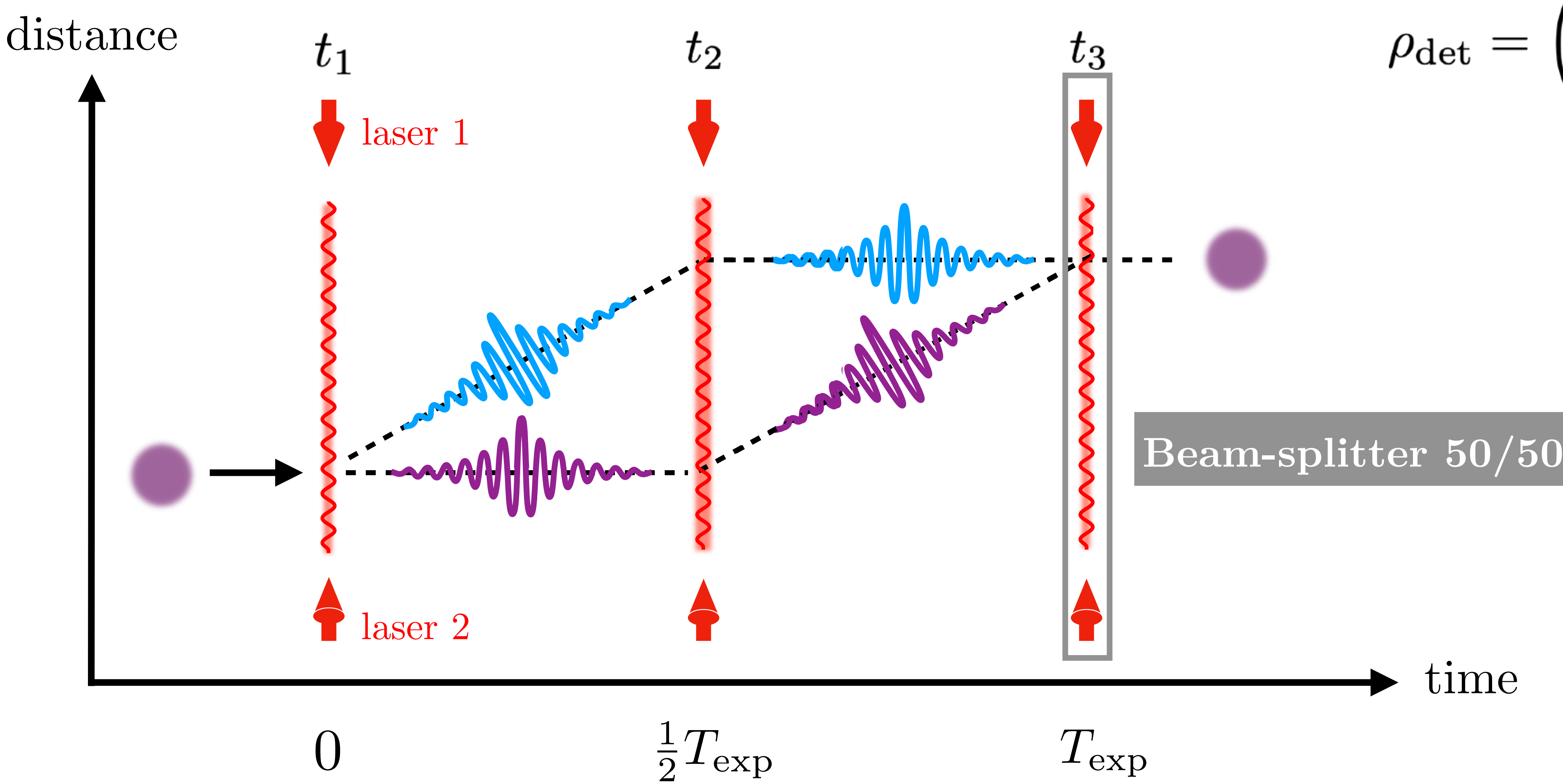


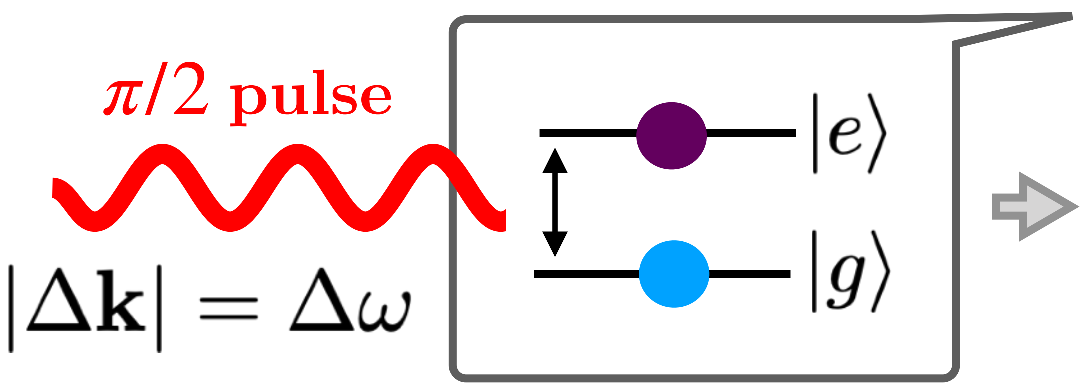
$$|\Psi\rangle_{t_1+\frac{T_{\rm ext}}{2}+t_2+\frac{T_{\rm ext}}{2}} = \frac{1}{\sqrt{2}}\left(-|g\rangle + i|e\rangle\right)$$

AIs: the Principle

Review: arXiv:2003.12516

$$\rho_{\text{det}} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

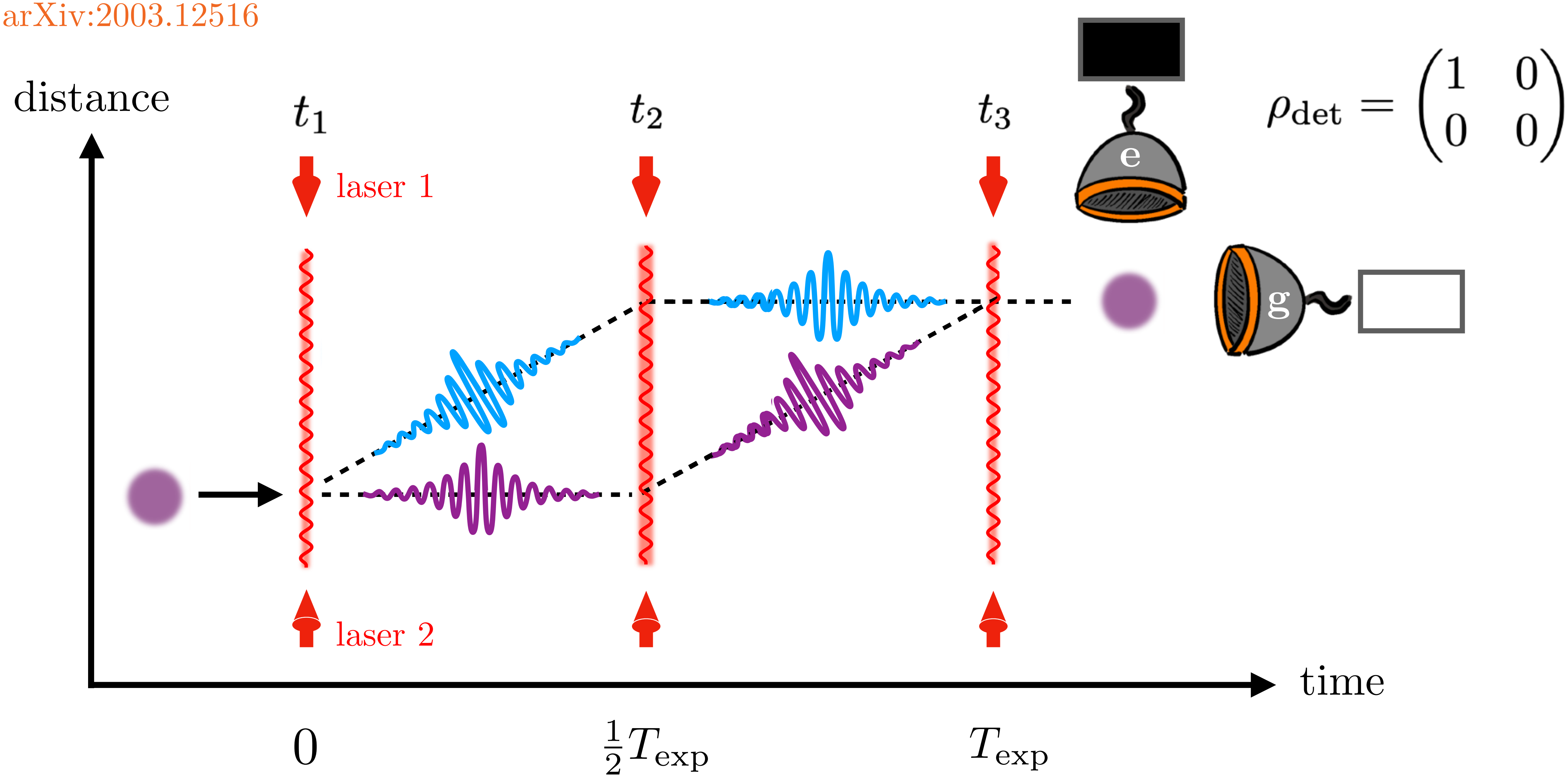


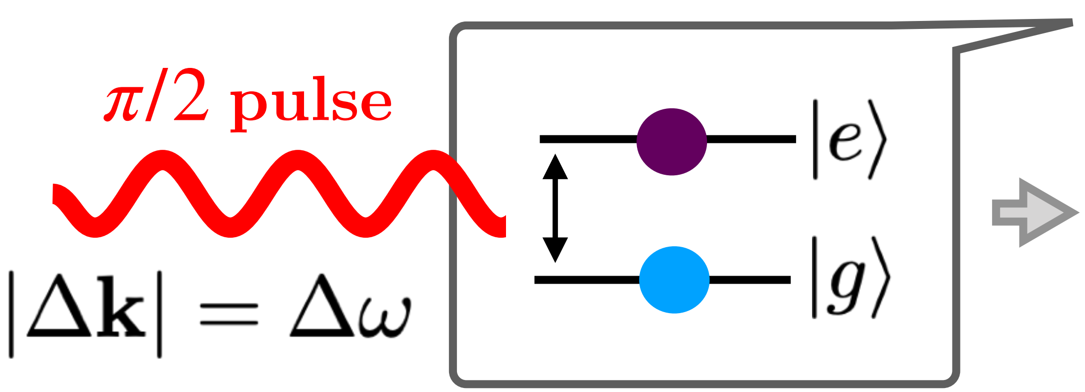


$$|\Psi\rangle_{t_1+\frac{T_{\text{ext}}}{2}+t_2+\frac{T_{\text{ext}}}{2}+t_3} = -|g\rangle$$

AIs: the Principle

Review: arXiv:2003.12516

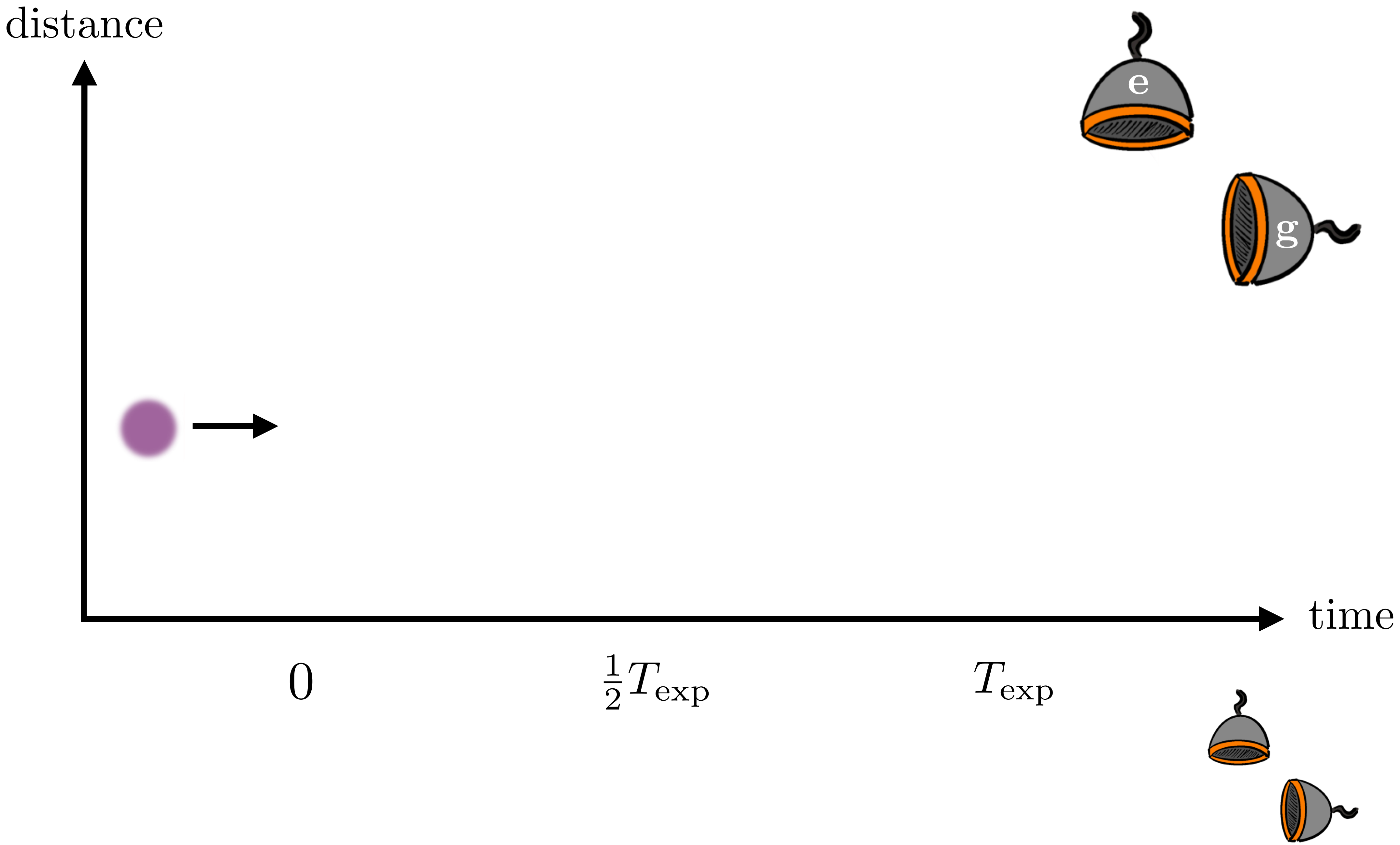




$$|\Psi\rangle_{t_1+\frac{T_{\text{ext}}}{2}+t_2+\frac{T_{\text{ext}}}{2}+t_3} = -|g\rangle$$

AIs: the Principle

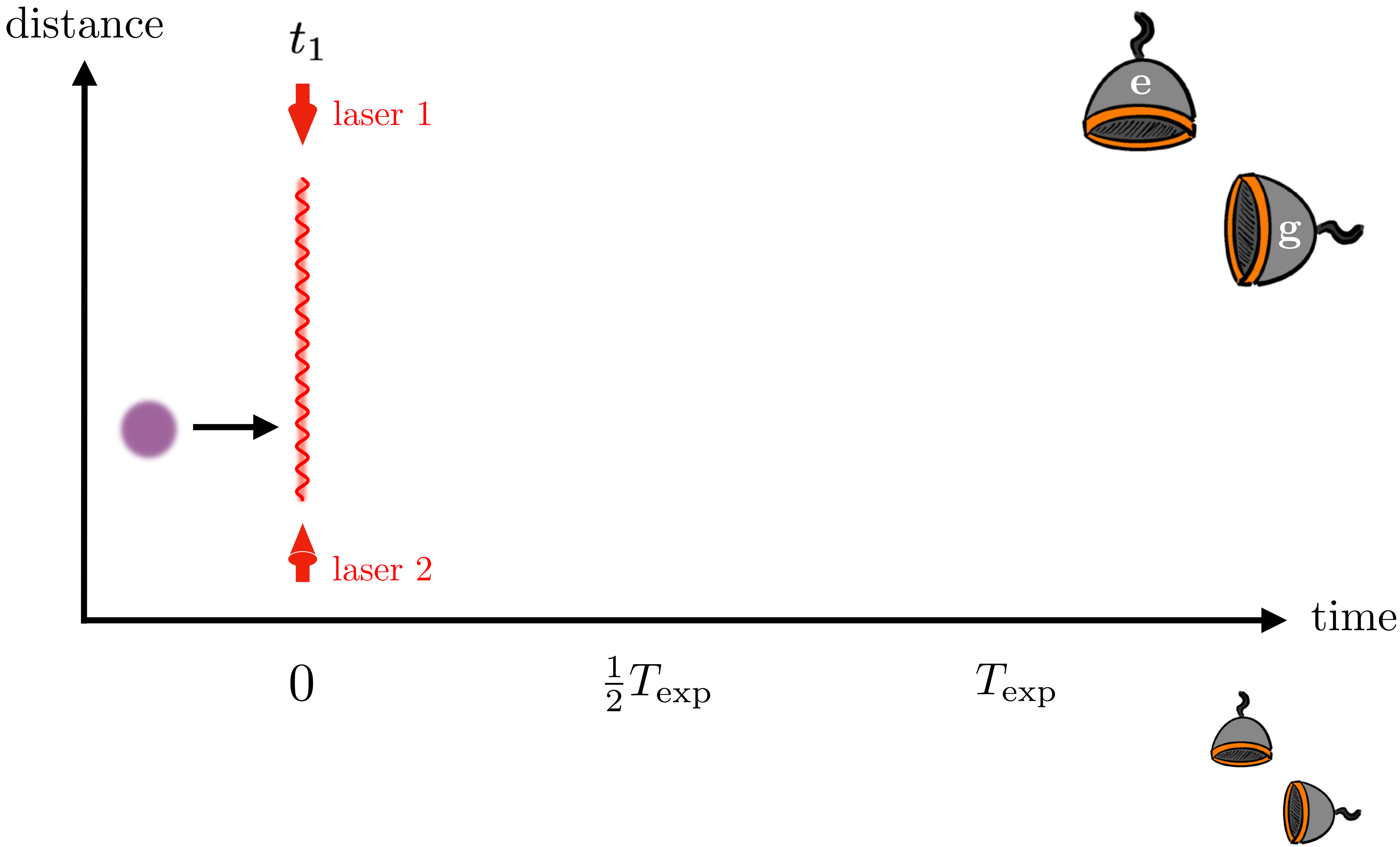
Review: arXiv:2003.12516



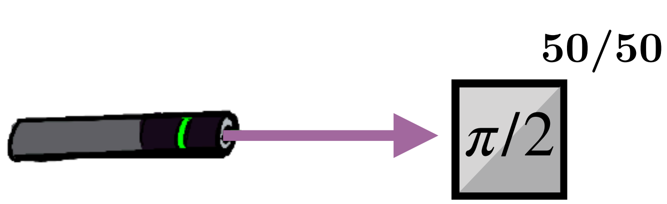
$\simeq$ Mach-Zender interferometer

AIs: the Principle

Review: arXiv:2003.12516

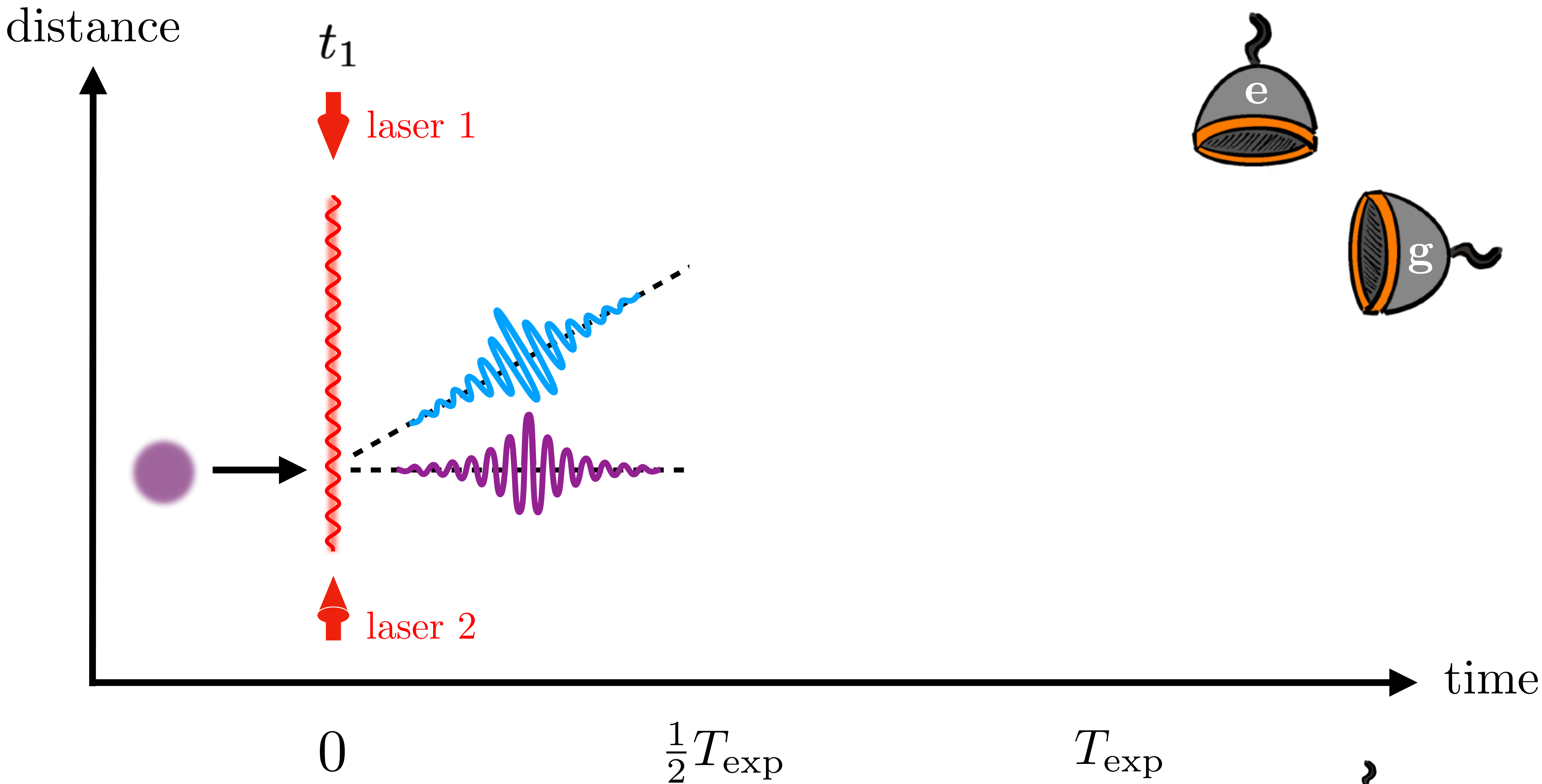


$\simeq$ Mach-Zender interferometer

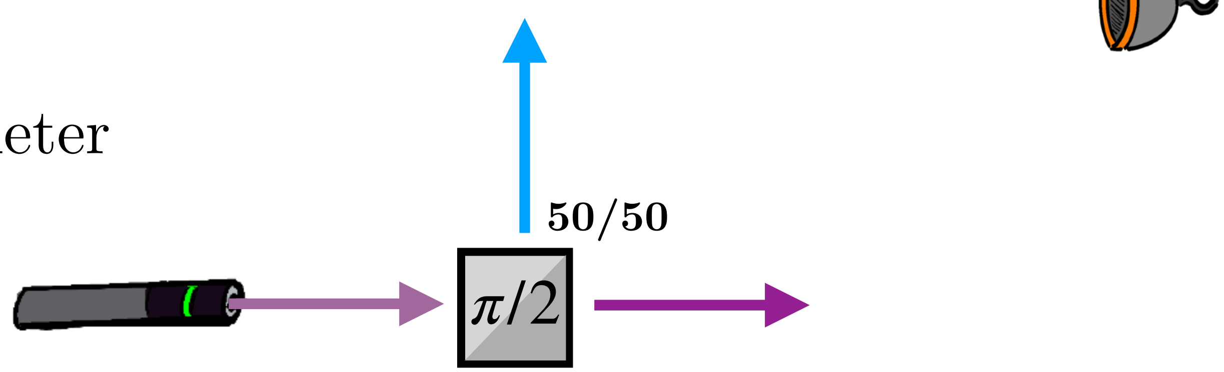


AIs: the Principle

Review: arXiv:2003.12516



$\simeq$ Mach-Zender interferometer



AIs: the Principle

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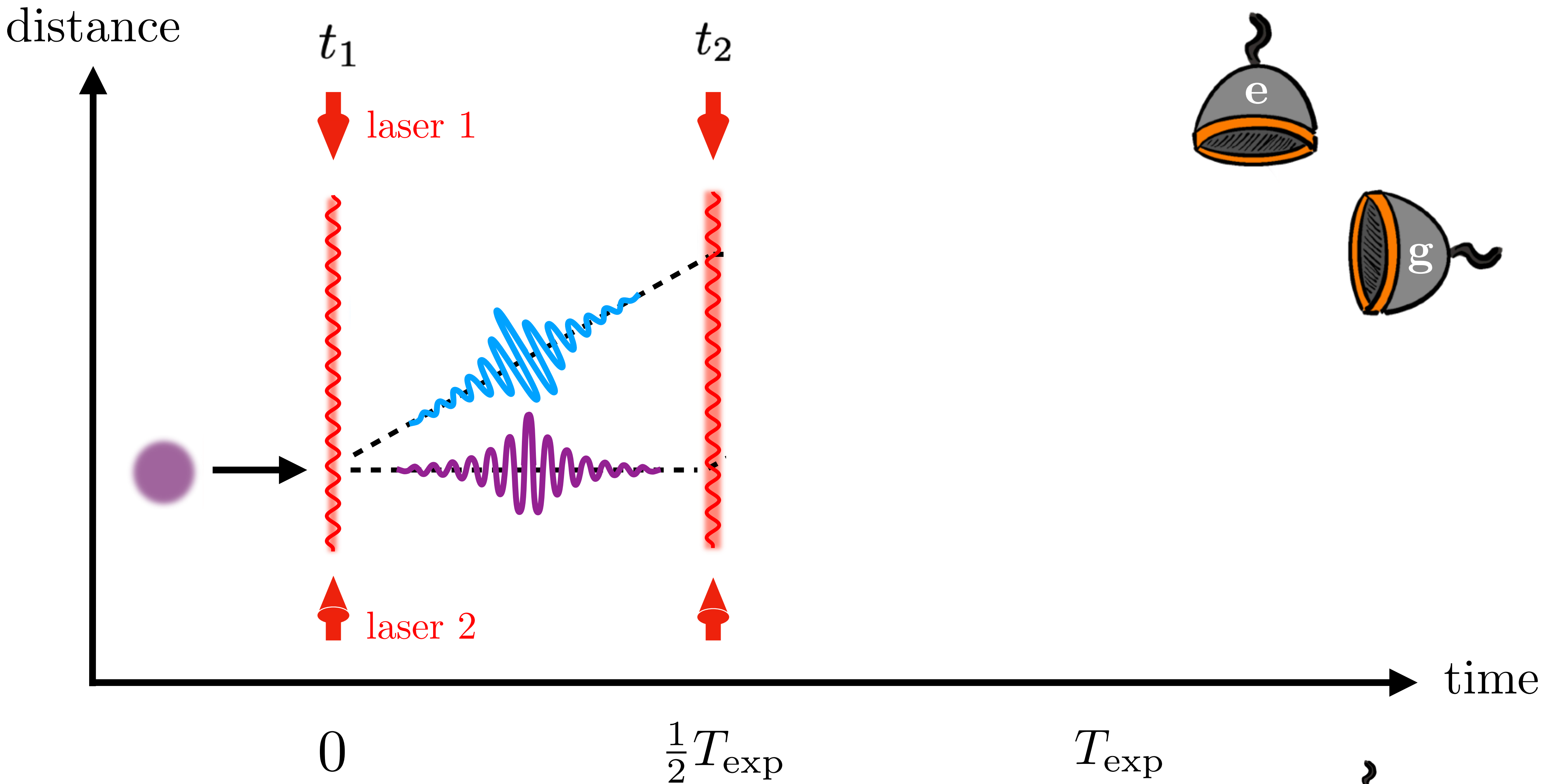

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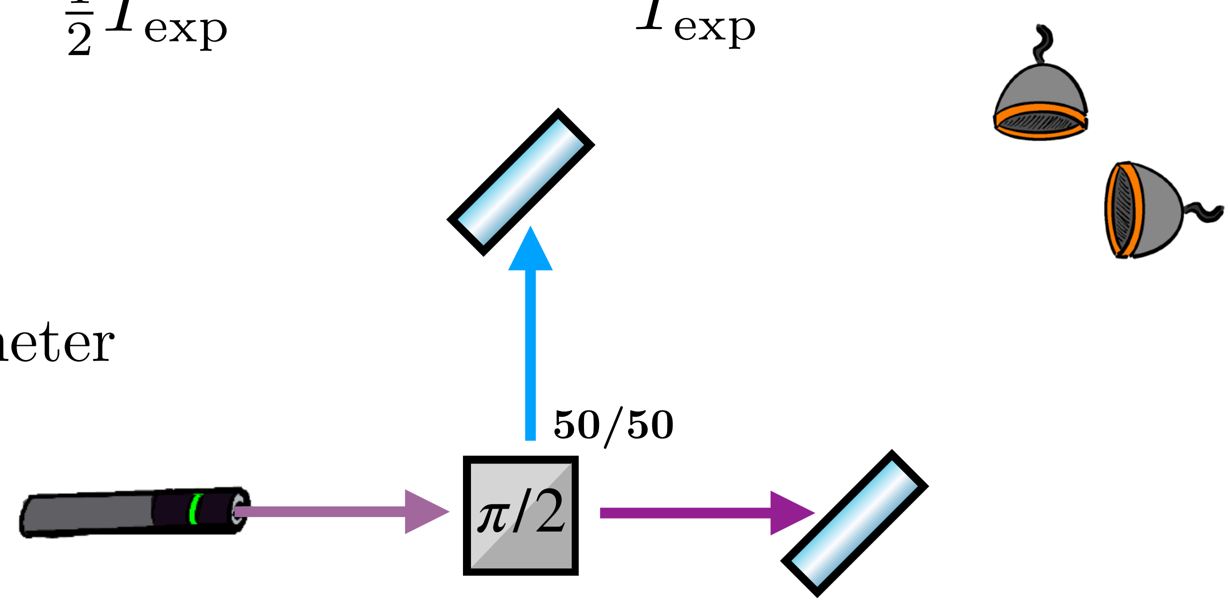
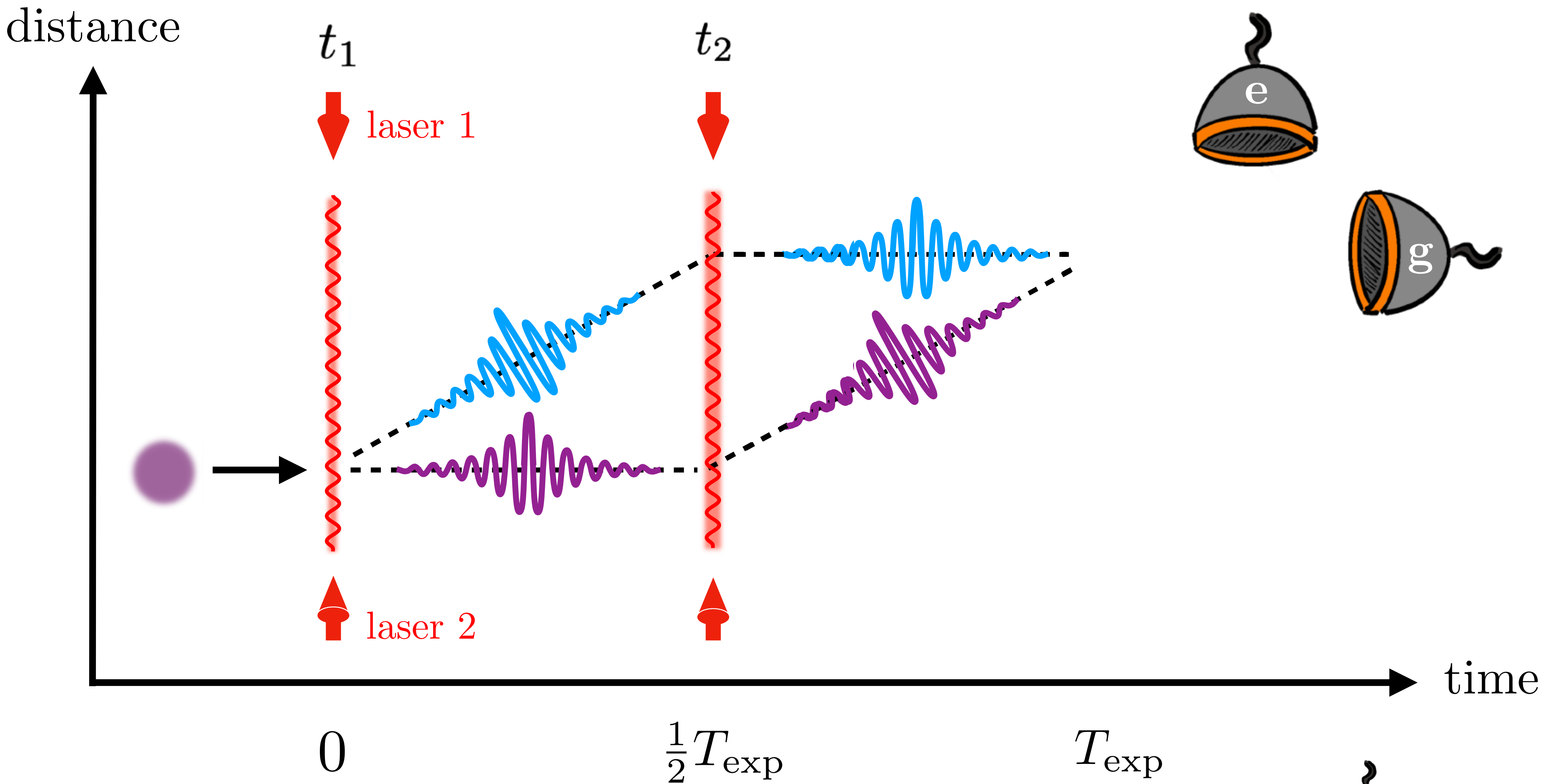
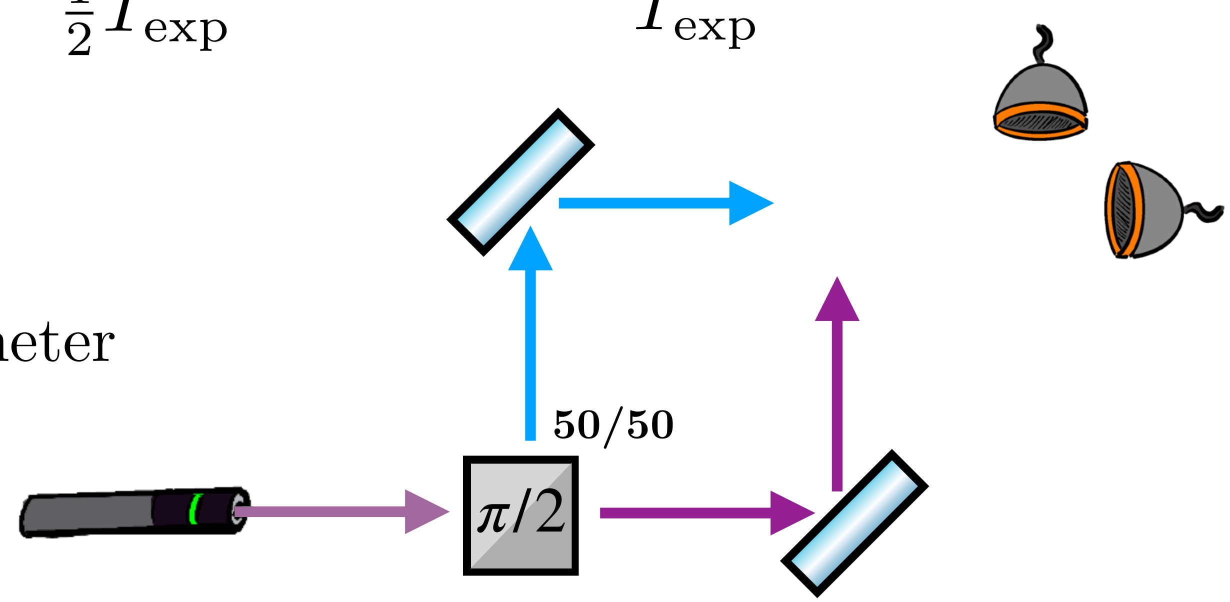


AIs: the Principle

Review: arXiv:2003.12516

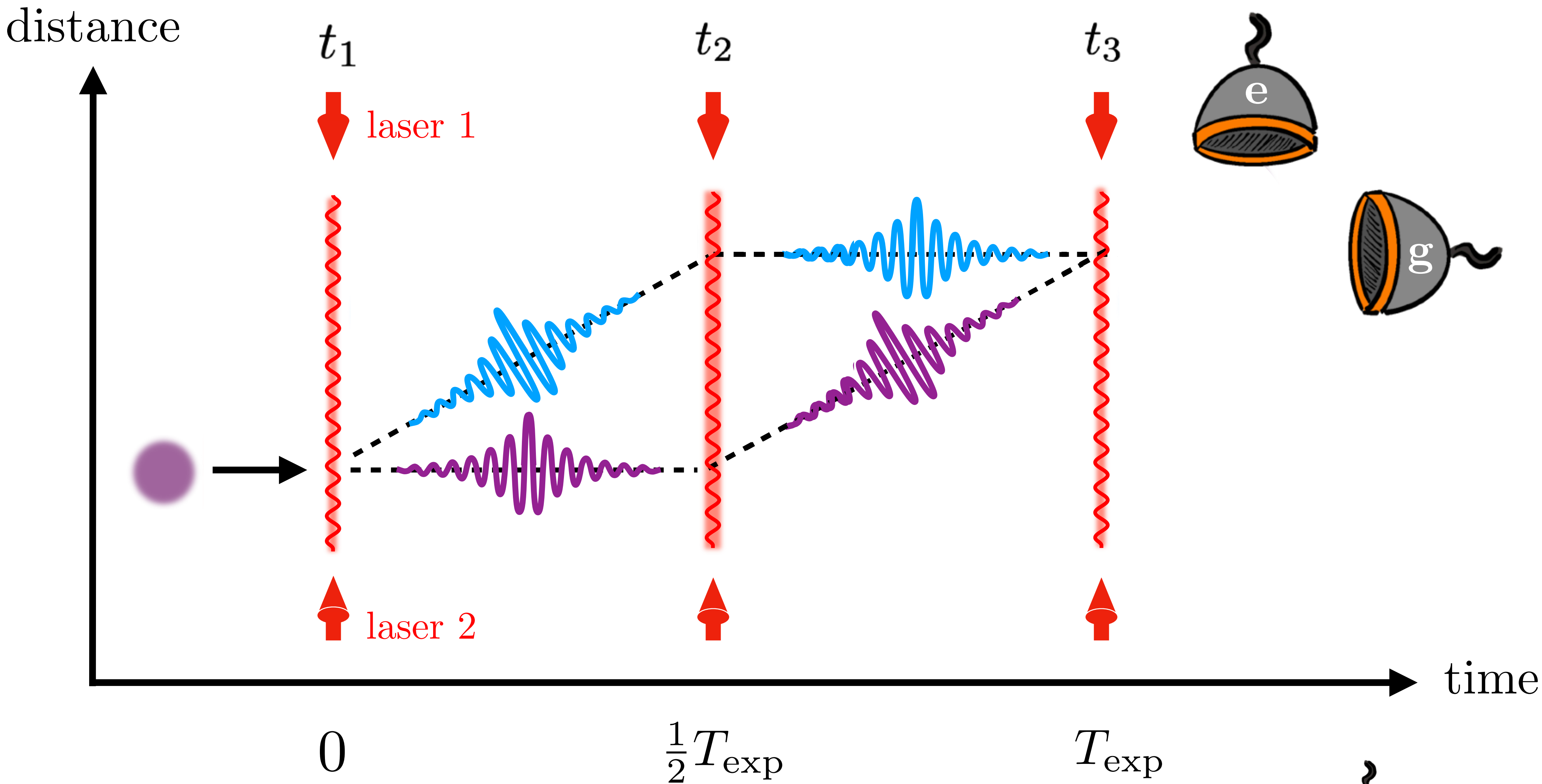


$\simeq$ Mach-Zender interferometer

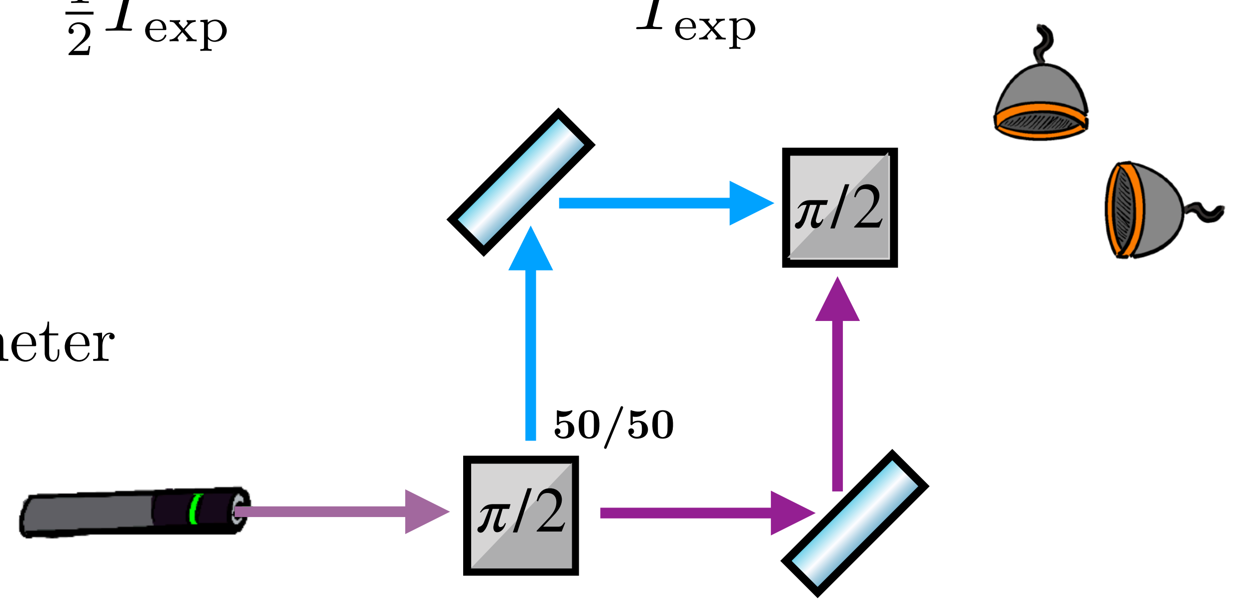


AIs: the Principle

Review: arXiv:2003.12516

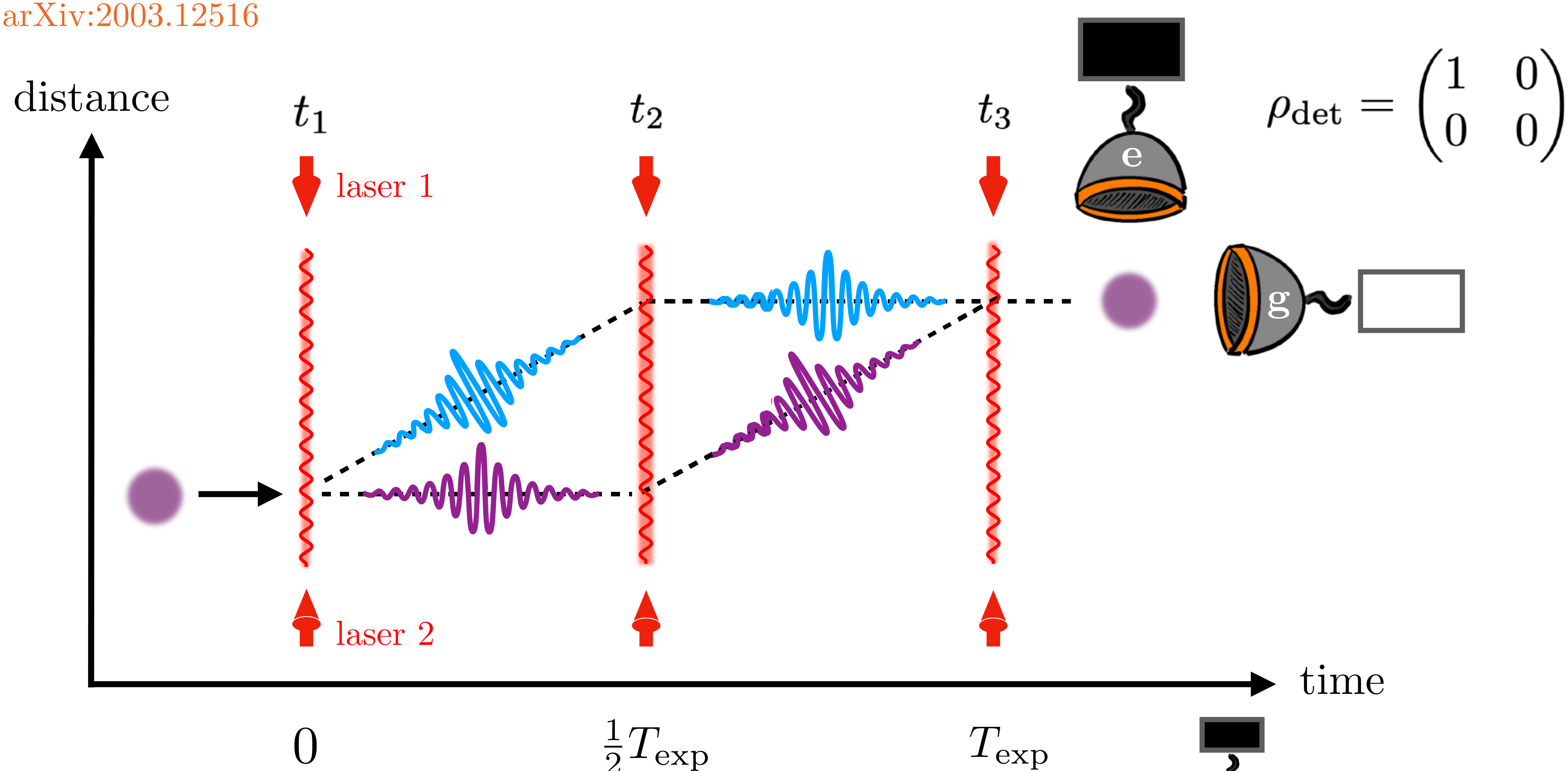


$\simeq$ Mach-Zender interferometer

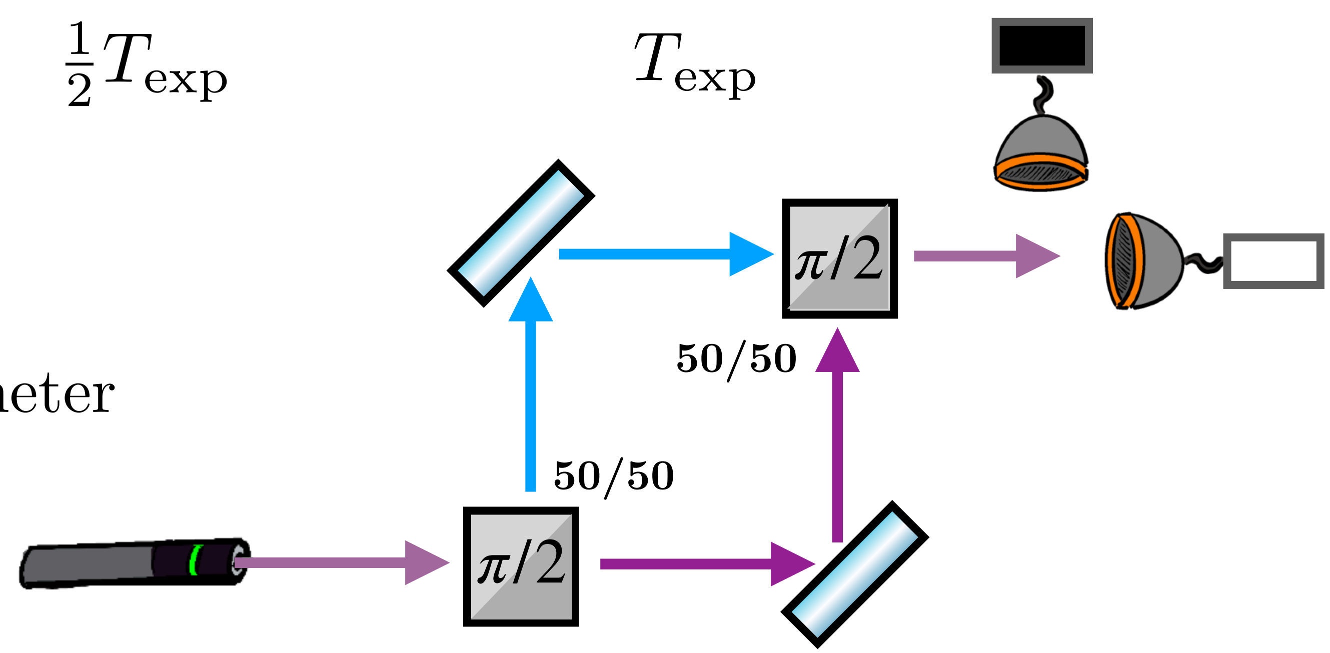


AIs: the Principle

Review: arXiv:2003.12516



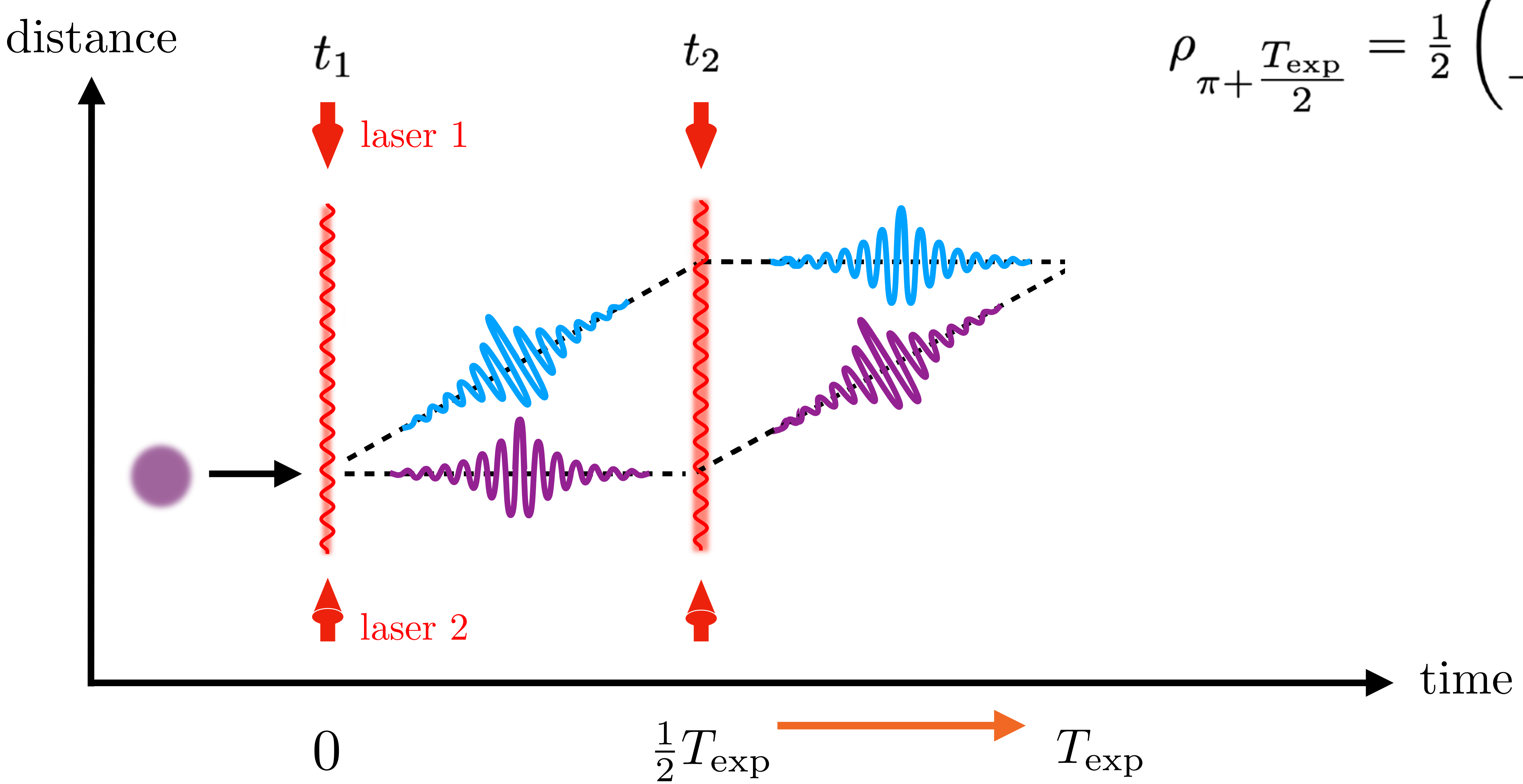
$\simeq$ Mach-Zender interferometer



AIs: Decoherence

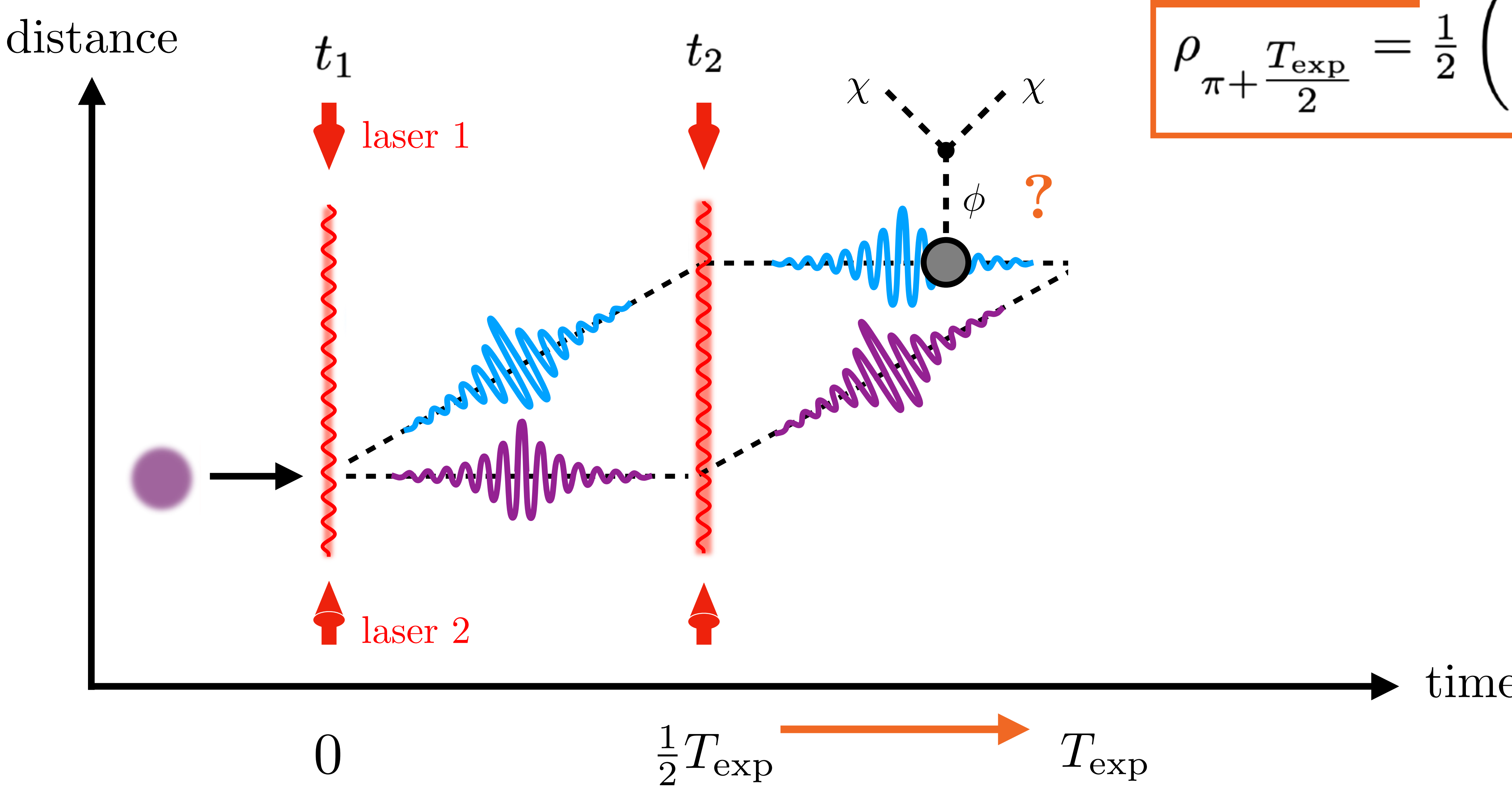
Review: arXiv:2003.12516

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



AIs: Decoherence

Review: arXiv:2003.12516



open system

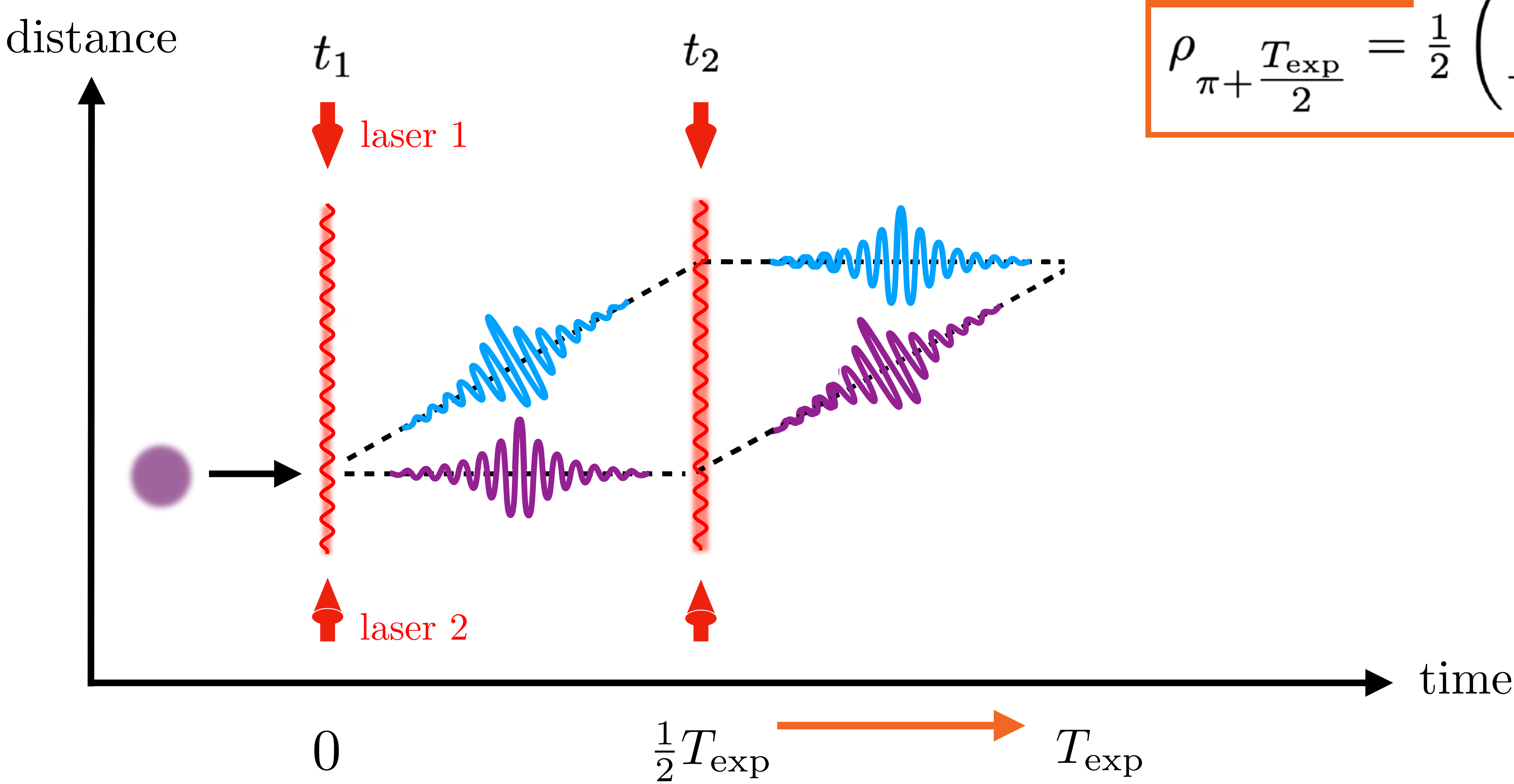
$$\rho_{\pi + \frac{T_{\text{exp}}}{2}} = \frac{1}{2}\begin{pmatrix} 1 & i \\ -i & 1 \end{pmatrix}$$

AIs: Decoherence

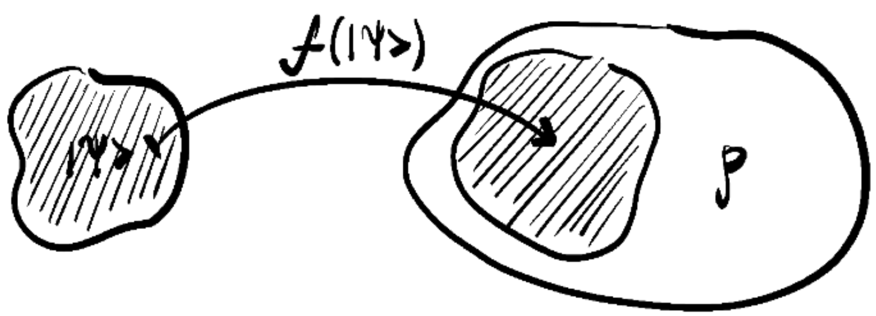
Review: arXiv:2003.12516

open system

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



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

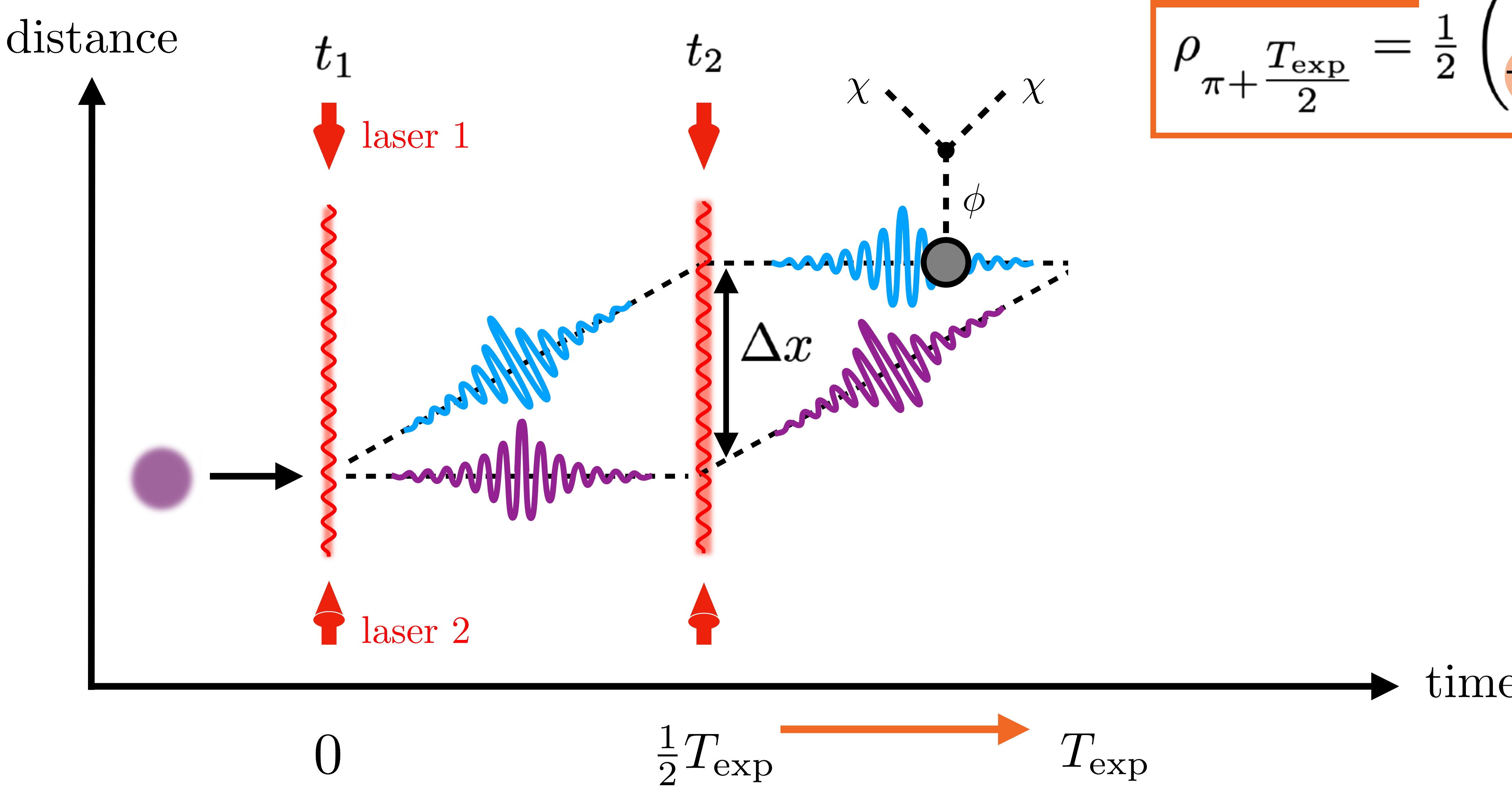


Density matrix

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

AIs: Decoherence

Review: arXiv:2003.12516



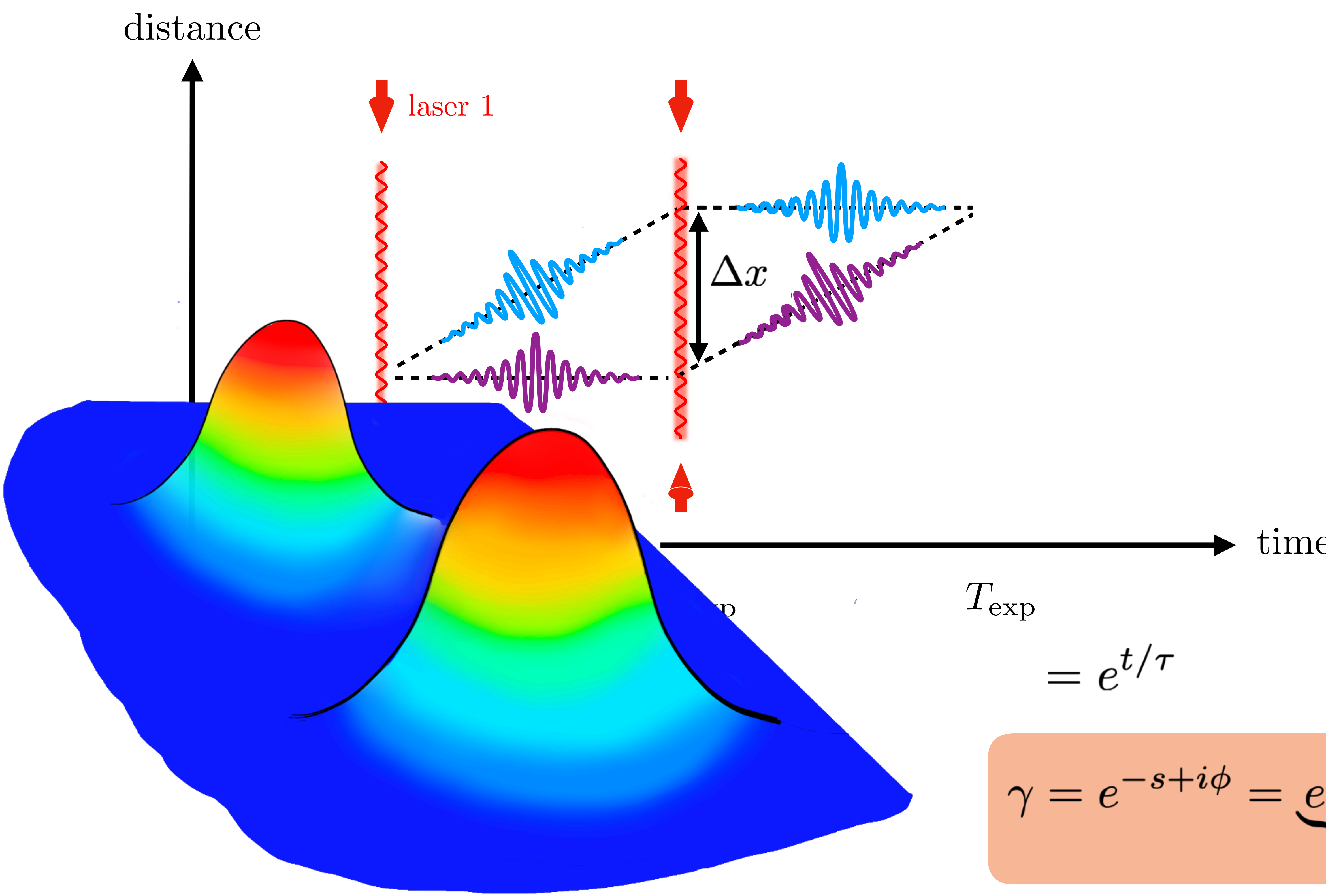
open system

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

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

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

AIs: Decoherence



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

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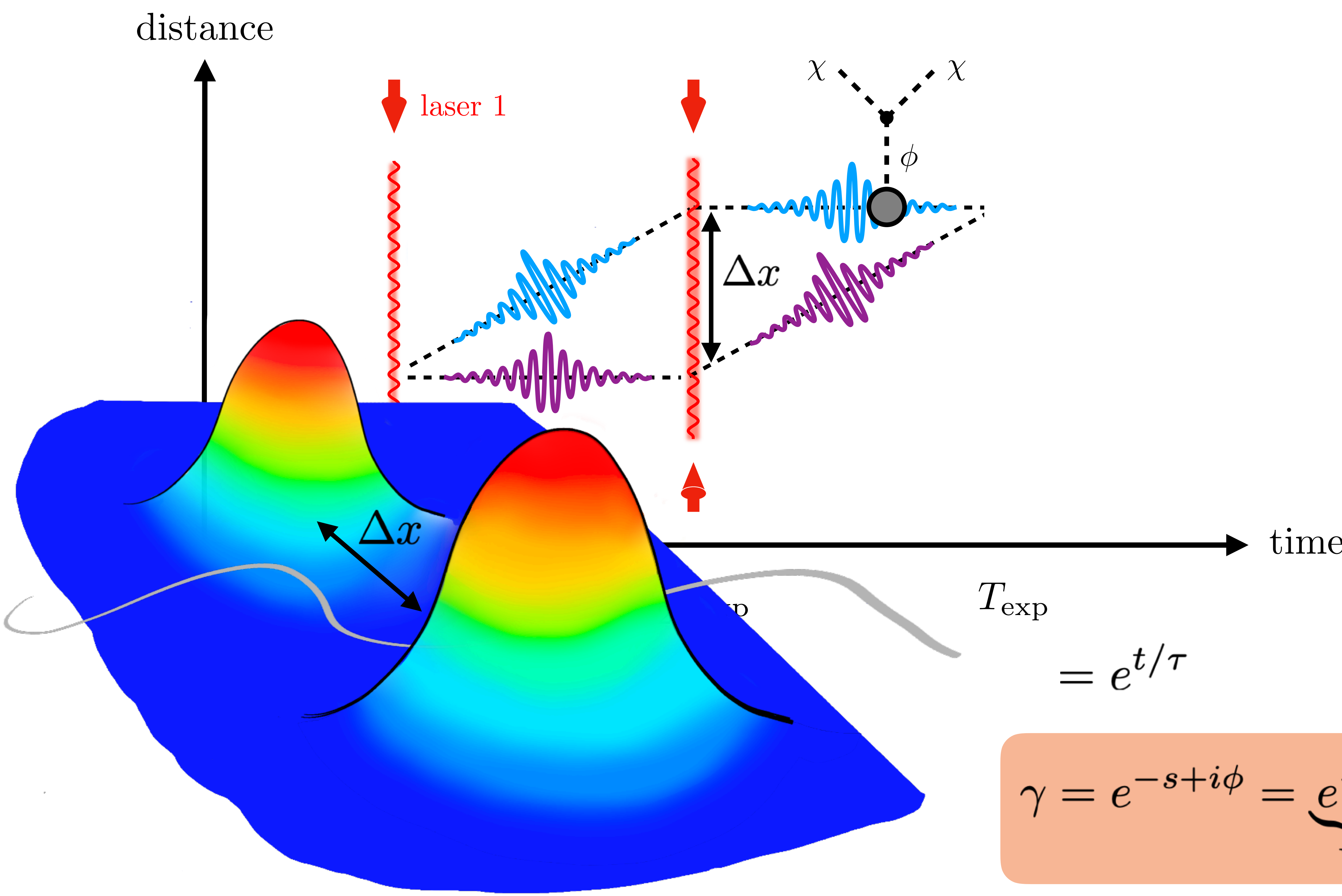
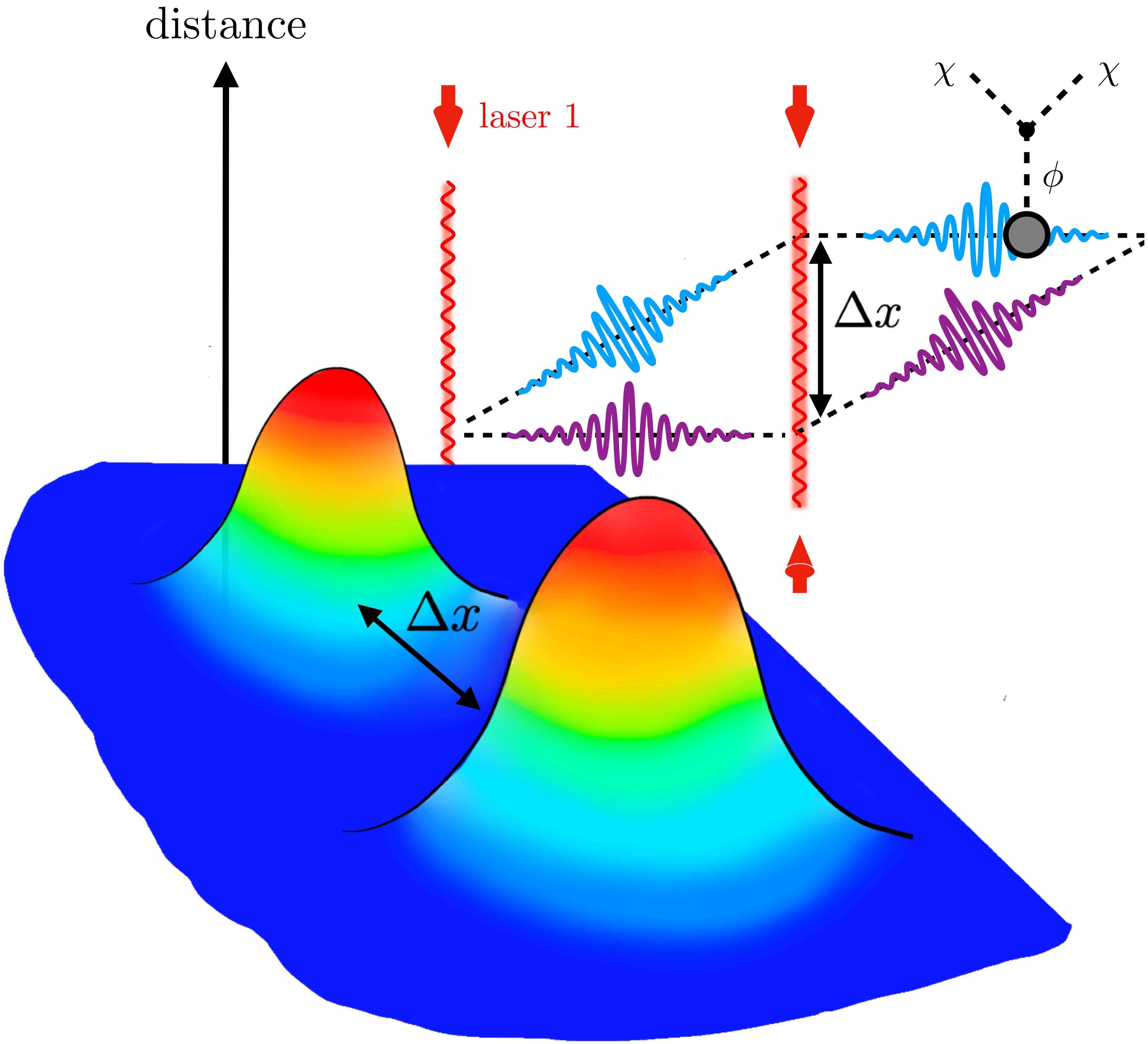
AIs: Decoherence



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

AIs: Decoherence

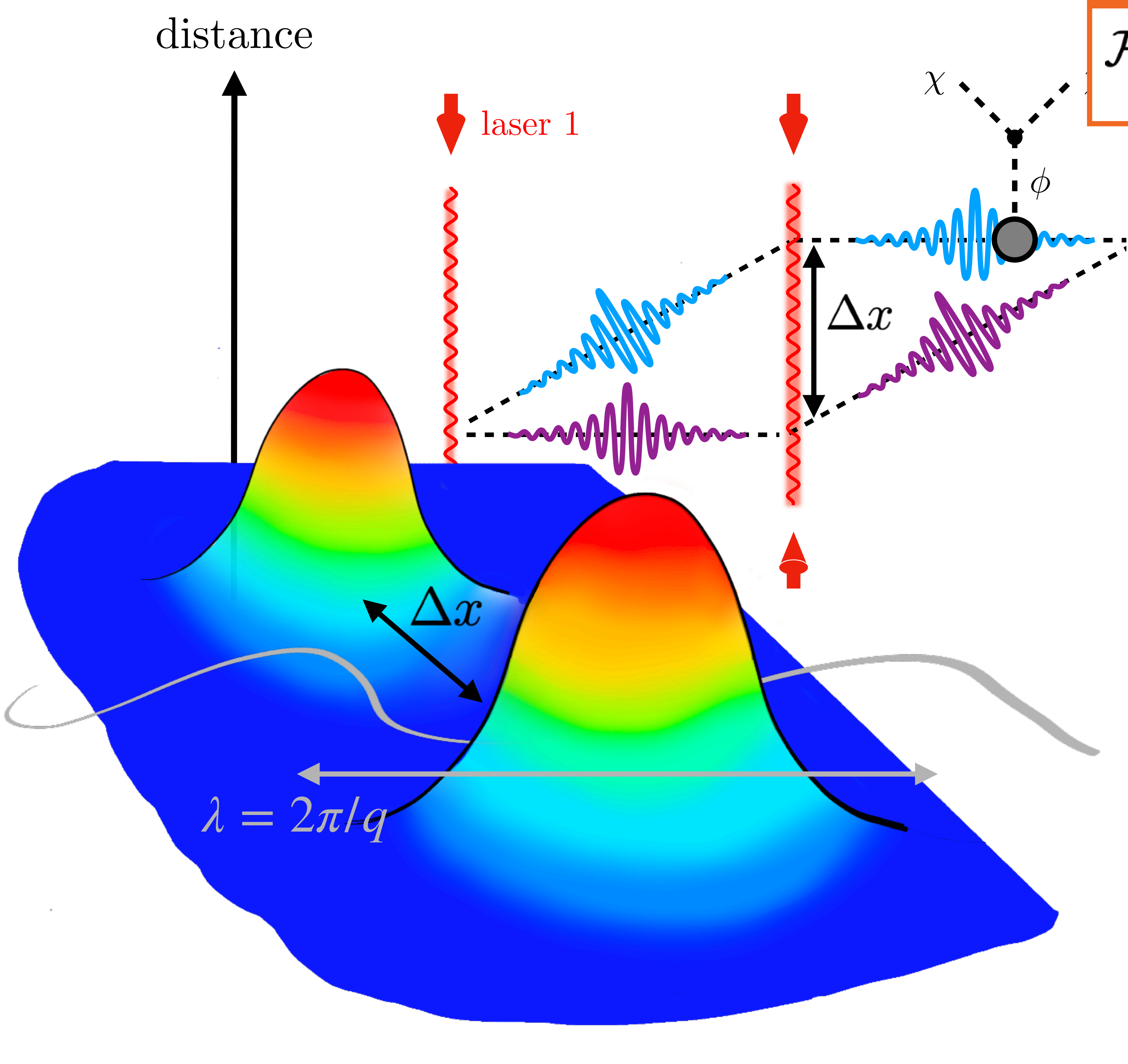


$$= e^{\left[-m_{\text{cloud}} \int_0^{t_{\text{exp}}} R\, dt\right]}$$

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

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

AIs: Decoherence



Form Factor

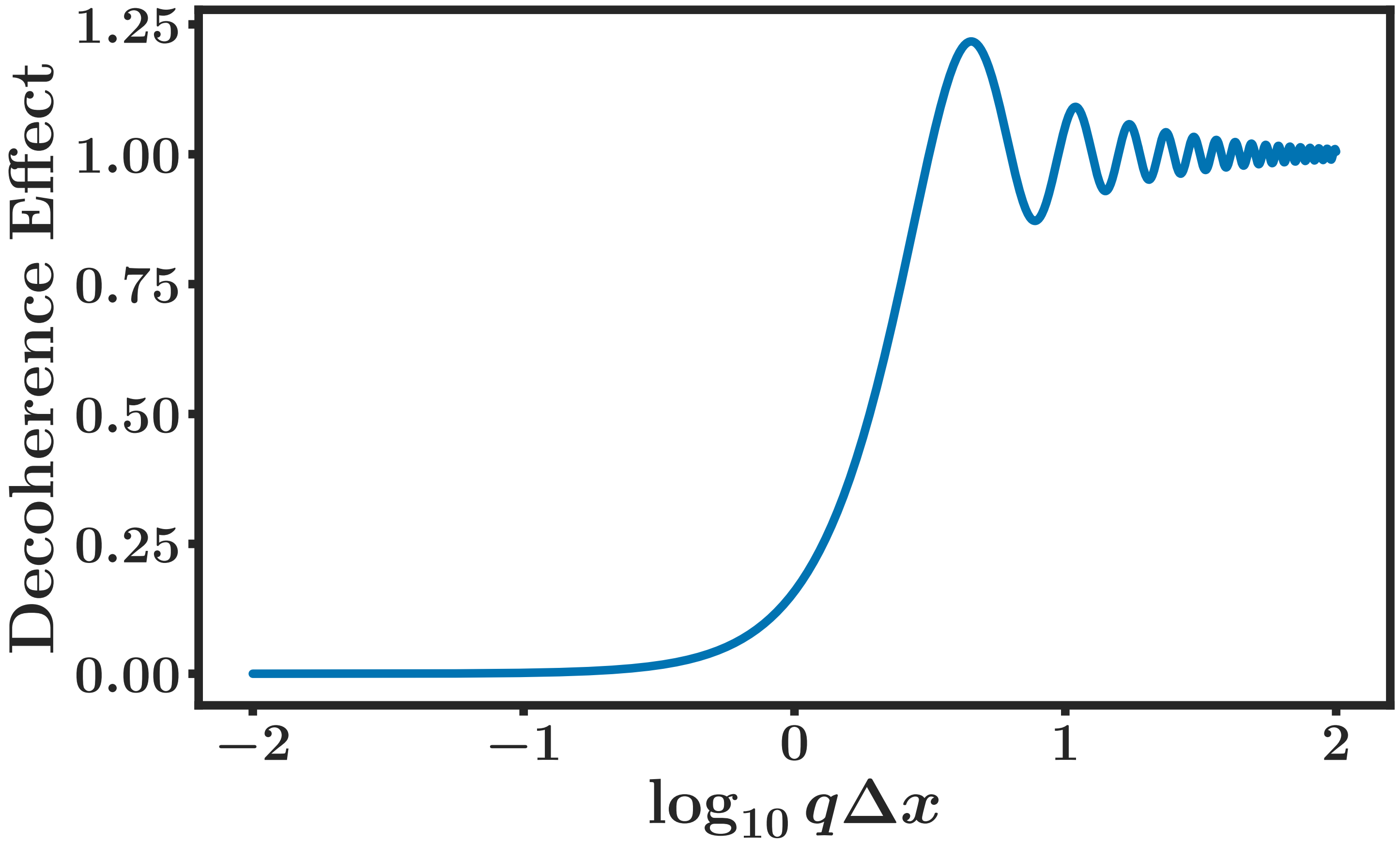
$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

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

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

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

AIs: Decoherence



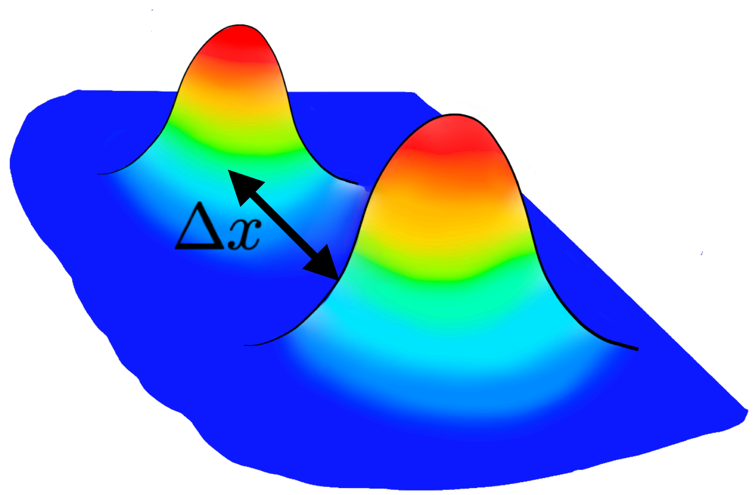
Form Factor

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

<u>Visibility or Contrast (**V**)</u>

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

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

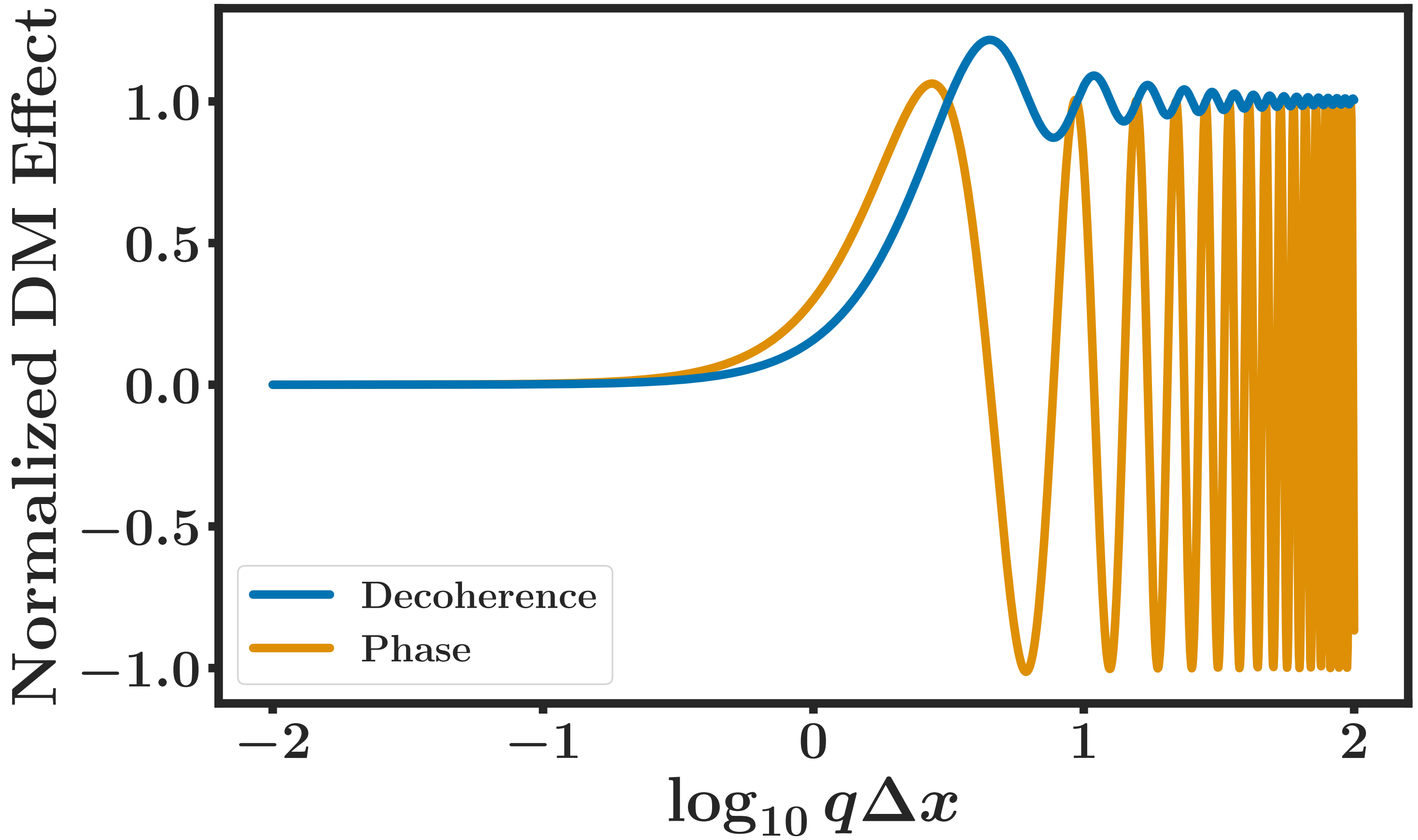


$$= e^{\left[-m_{\text{cloud}}\int_0^{t_{\text{exp}}} R\,dt\right]}$$

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

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

AIs: Decoherence



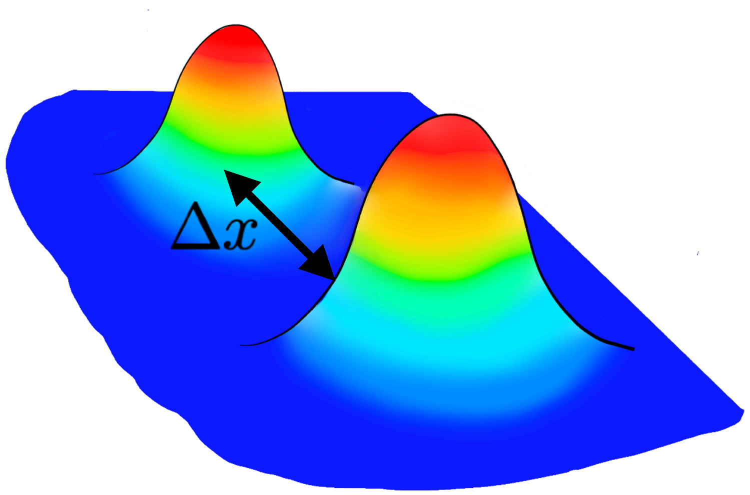
Form Factor

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

Phase (ϕ)

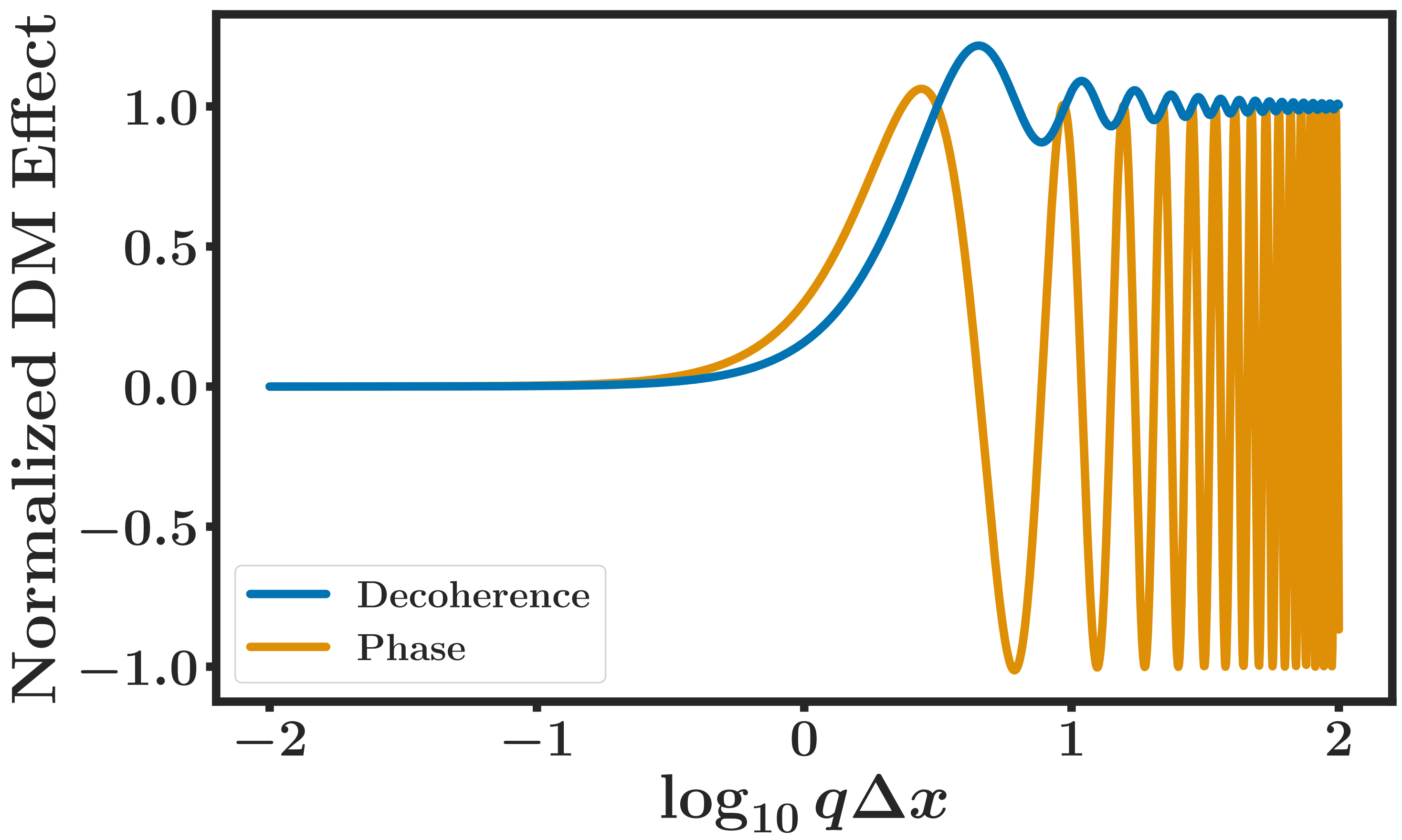
$$\frac{1}{2}\int_{-1}^{1} \mathrm{Im}\{\mathcal{F}_{\text{decoh}}(\mathbf{q})\}\, d\cos\theta_{\mathbf{q}\mathbf{\Delta x}}$$

$$= 0$$



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

AIs: Decoherence



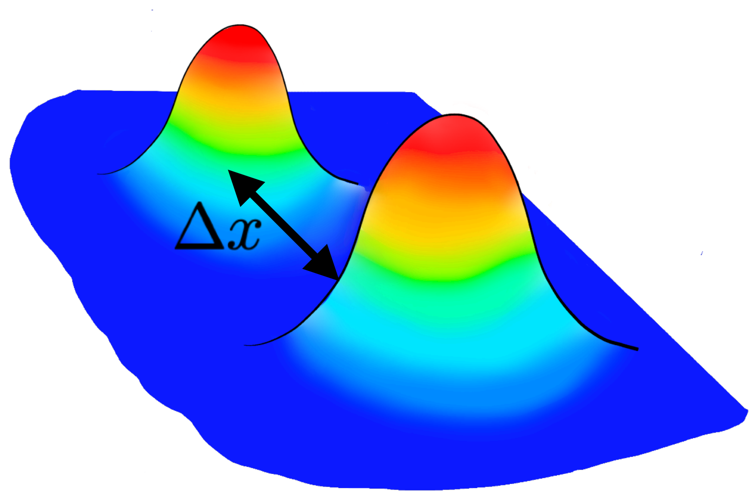
Form Factor

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

<u>Phase (ϕ)</u>

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

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

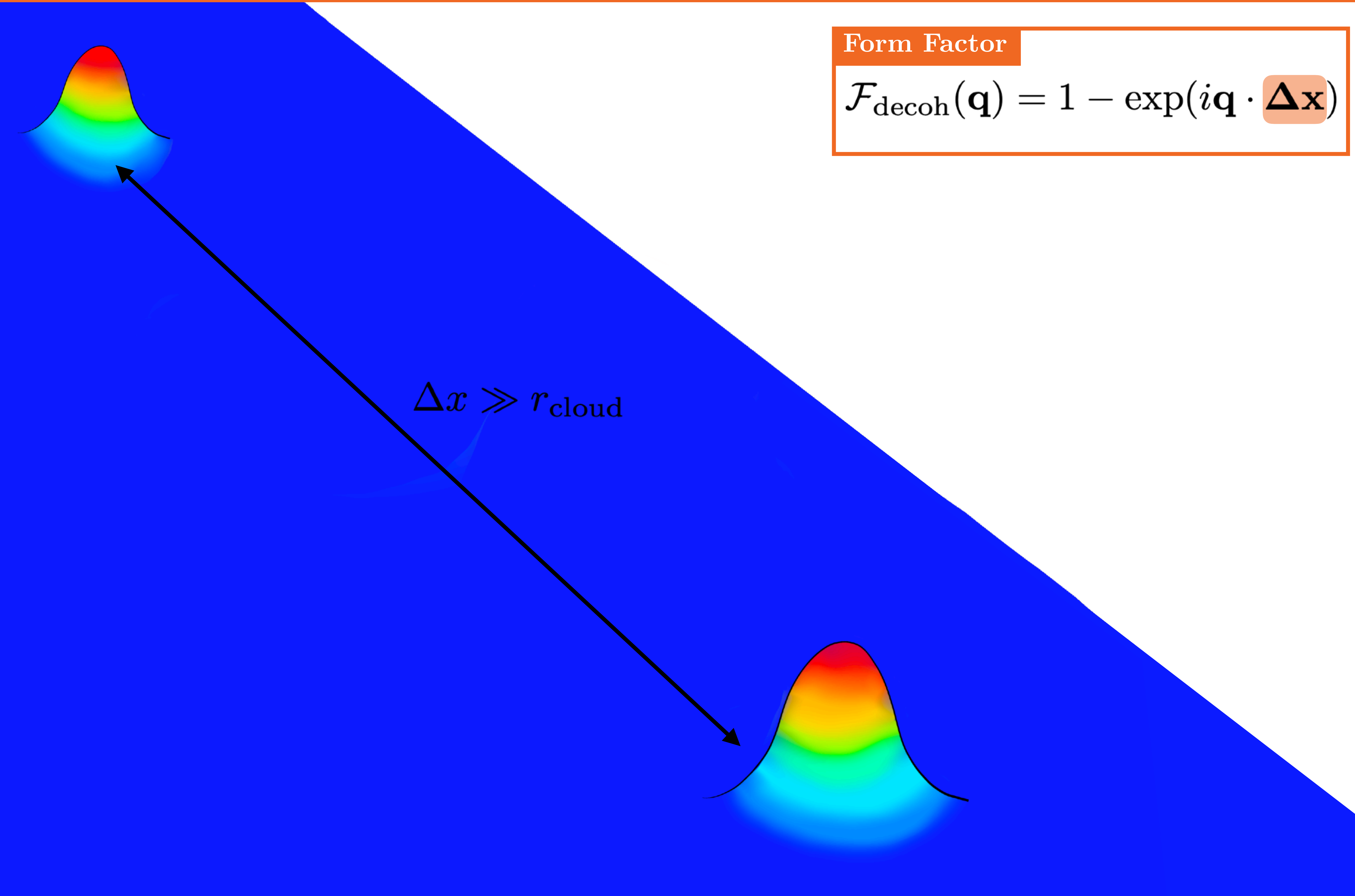


$$\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}$$

AIs: Decoherence

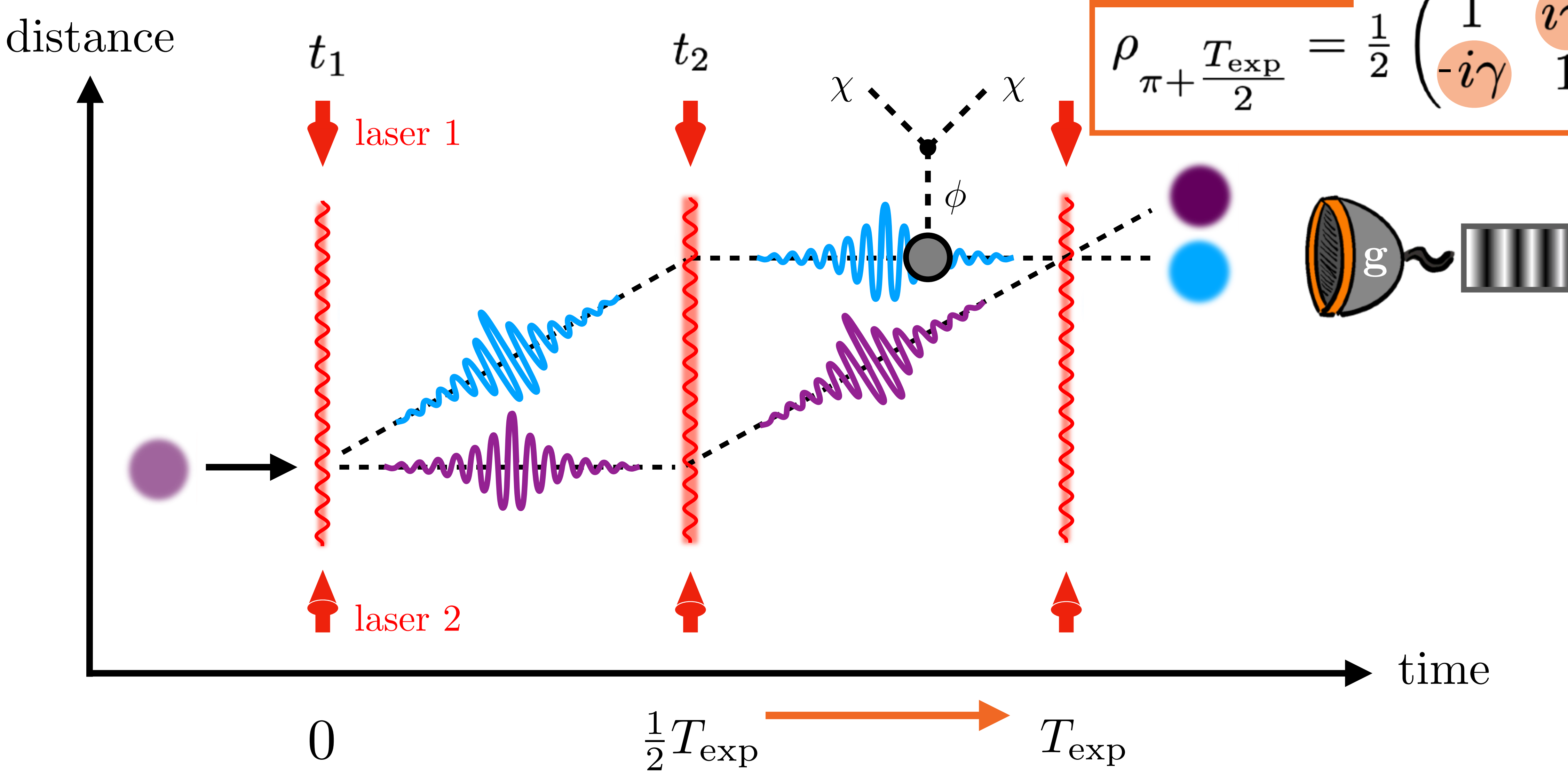
Form Factor

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



AIs: Measurement

Review: arXiv:2003.12516



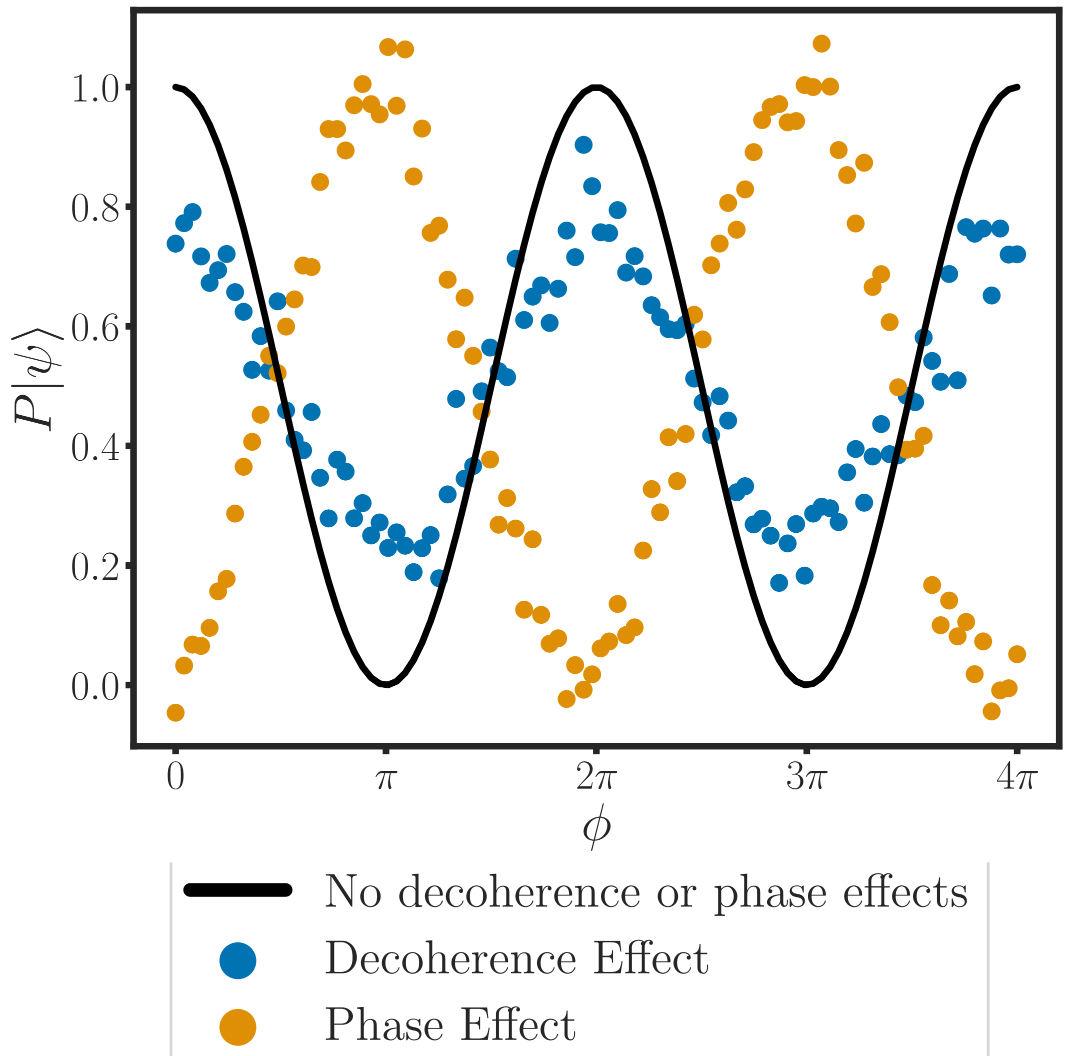
open system

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

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

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

AIs: Measurement



open system

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

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

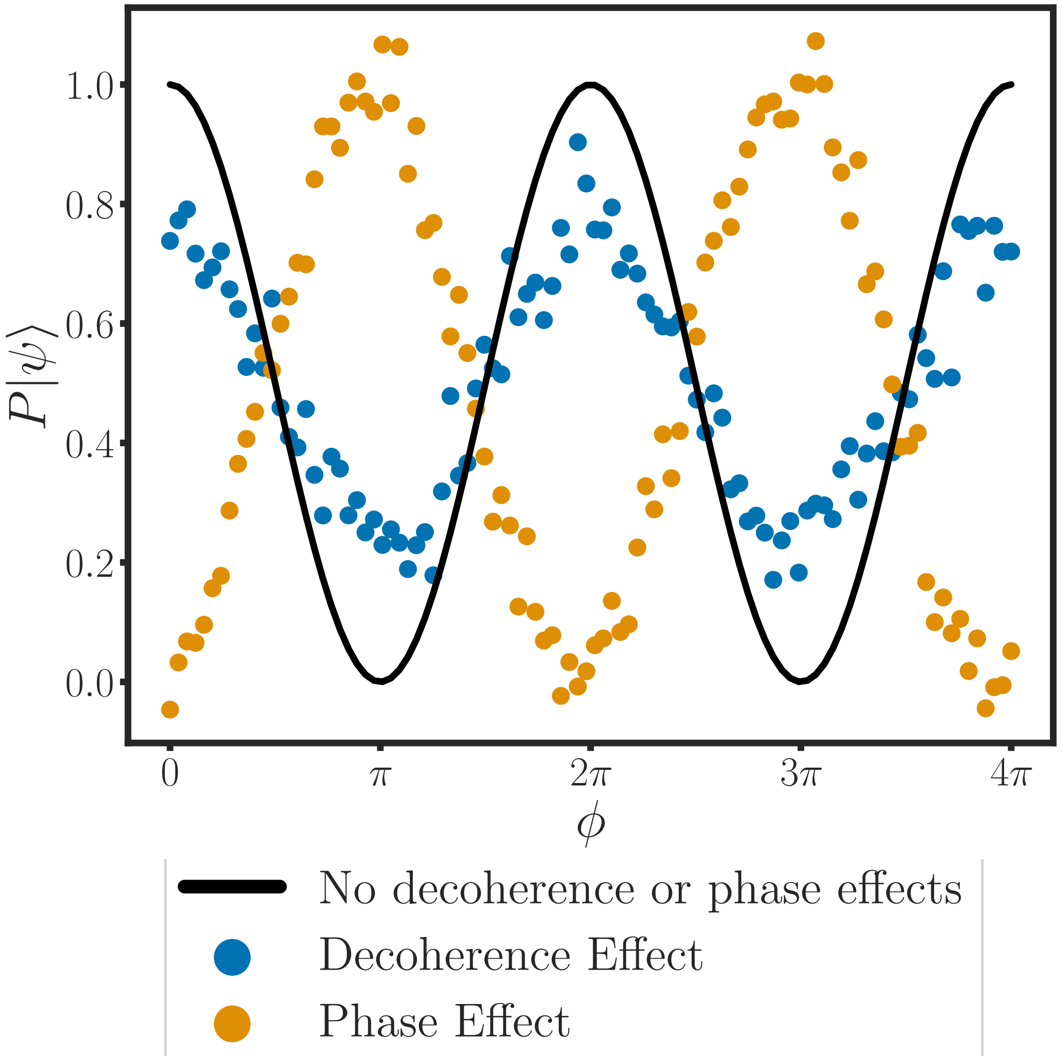
$$= e^{\left[-m_{\text{cloud}}\int_0^{t_{\text{exp}}} R\,dt\right]}$$

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

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

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

AIs: Statistics



Visibility

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

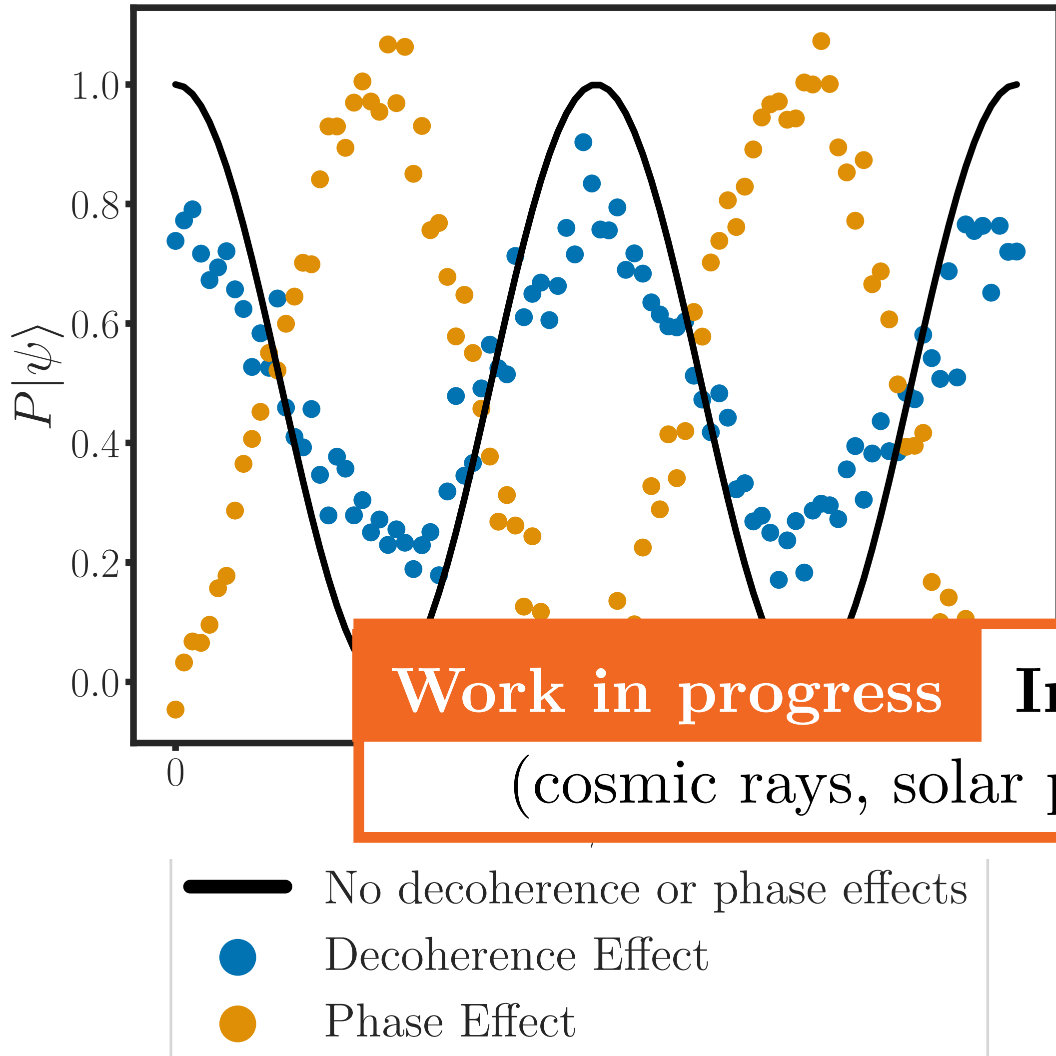
<u>Accumulated decoherence: **Rate**</u>

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

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

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

AIs: Statistics



Work in progress **Impact of potential backgrounds**

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

Visibility

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

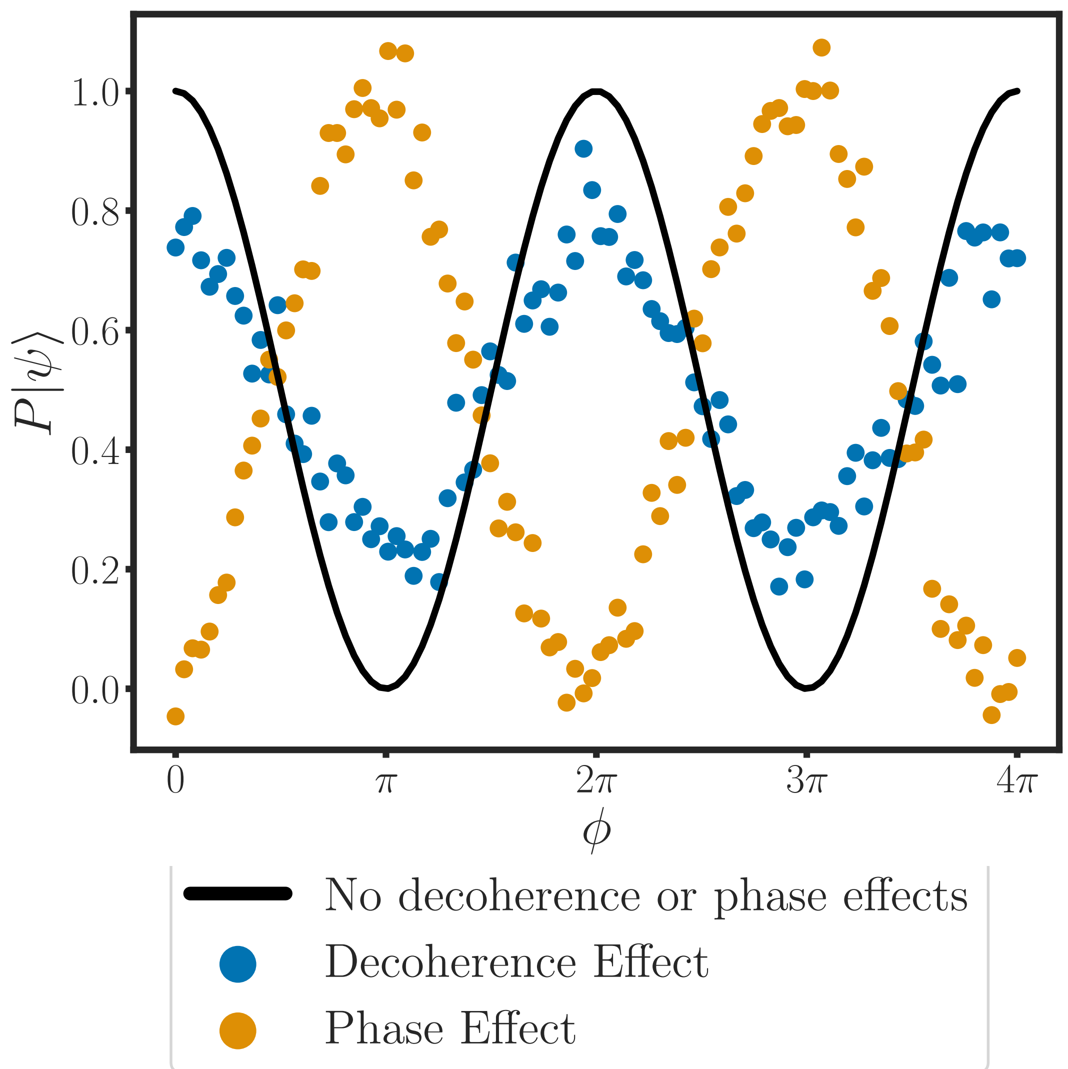
Accumulated decoherence: **Rate**

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

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

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

AIs: Statistics



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

Number of events / (target mass · time)

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

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

AIs: the Rate

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

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

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

AIs: the Rate

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

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

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

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

AIs: the Rate

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

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

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

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

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

AIs: the Rate

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

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

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

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

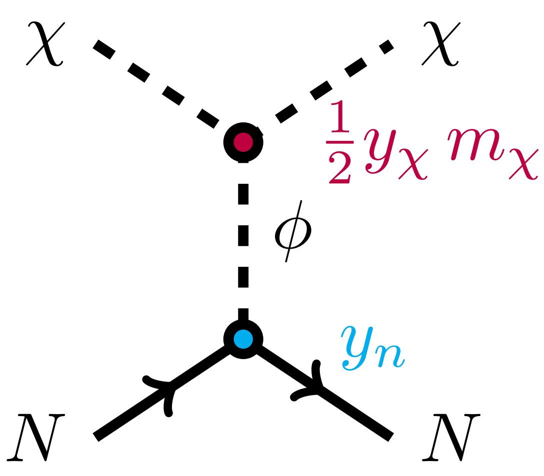
$$\Gamma(\mathbf{v}) = V\int\frac{d^3\mathbf{q}}{(2\pi)^3}\sum_f |\langle f|H_{\mathrm{int}}|i\rangle|^2 (2\pi)\delta(E_f - E_i - \omega_{\mathbf{q}})$$

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

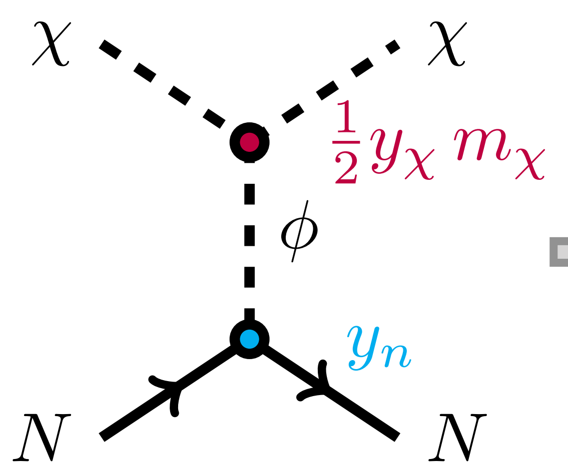
$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \sum_f |\langle f | H_{\text{int}} | i \rangle|^2 g(\mathbf{q}, E_f - E_i) \mathcal{F}_{\text{decoh}}(\mathbf{q})$$



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

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

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

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

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

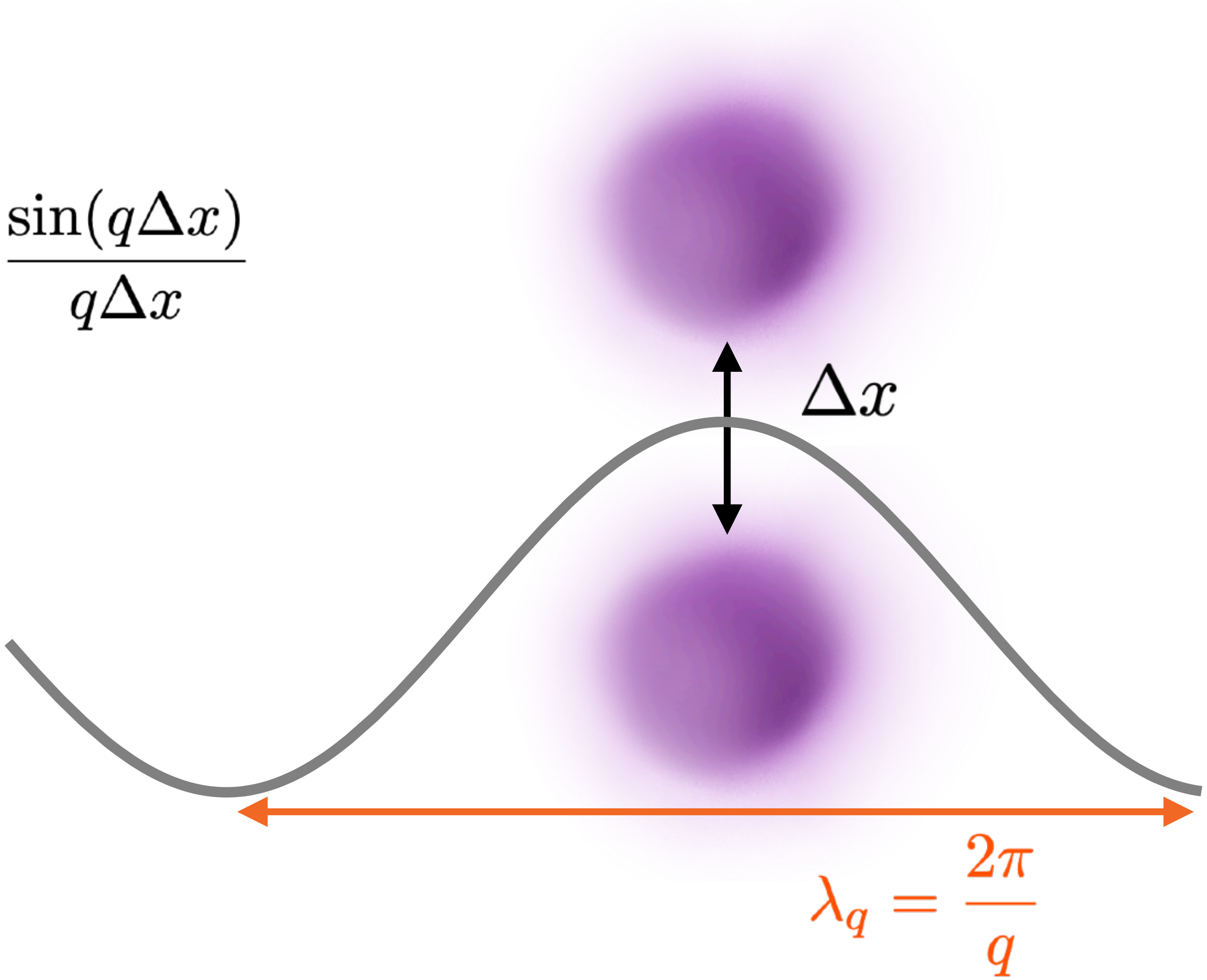
AIs: the Rate

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

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

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

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



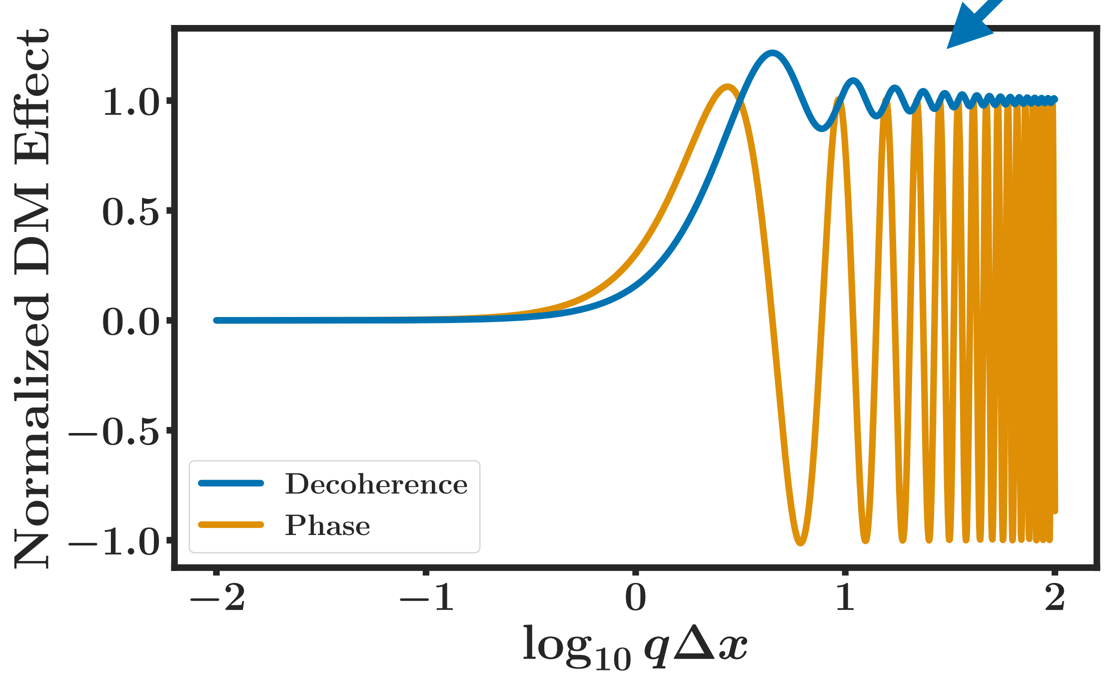
AIs: the Rate

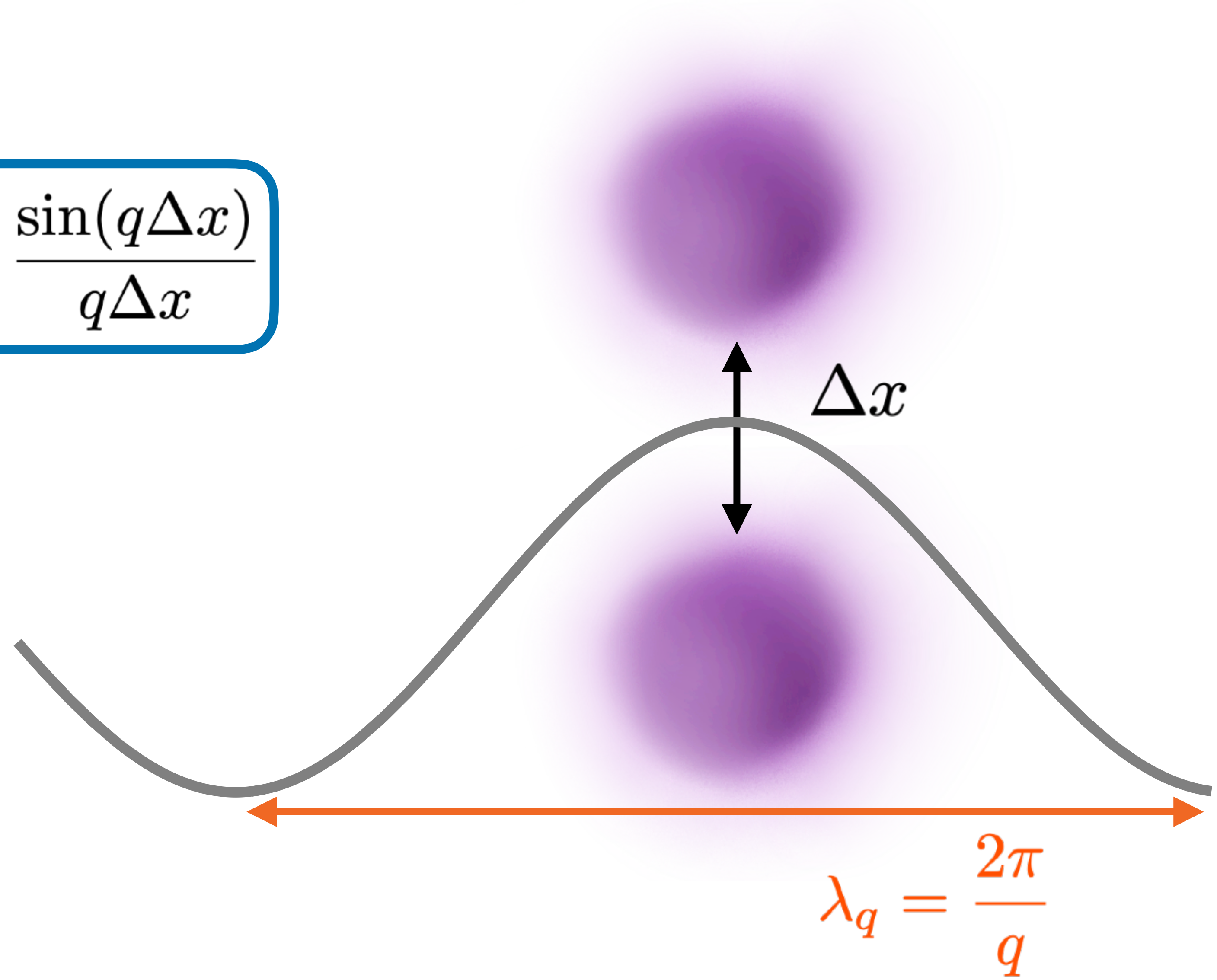
$$\mathcal{F}_{\mathrm{med}}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

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

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

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





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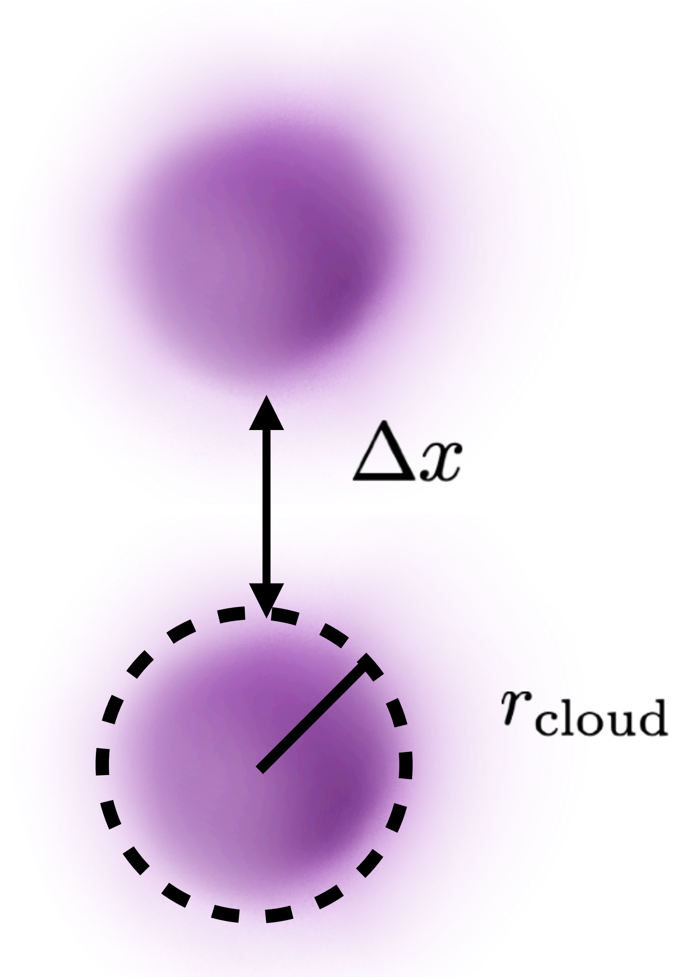
$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{1}{V^2}\frac{\pi\bar{\sigma}}{\mu^2} \boxed{\mathcal{F}^2_{\rm med}(\mathbf{q})}\,\boxed{\mathcal{F}^2_{\rm T}(\mathbf{q})}\, g(\mathbf{q}, E_f - E_i)\boxed{\mathcal{F}_{\rm decoh}(\mathbf{q})}$$



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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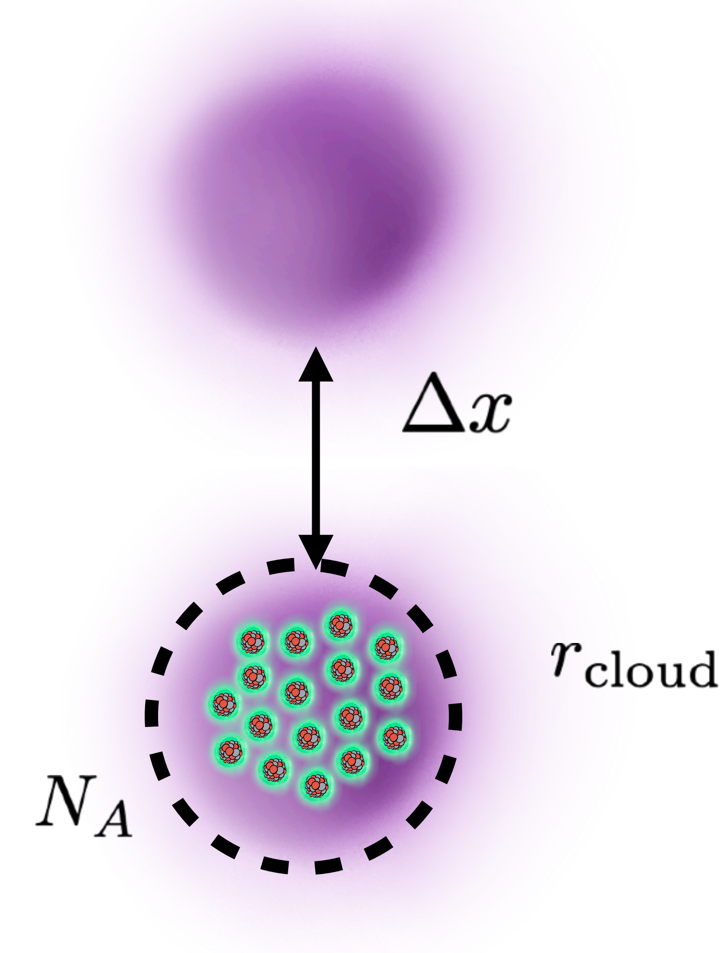

AIs: the Rate

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

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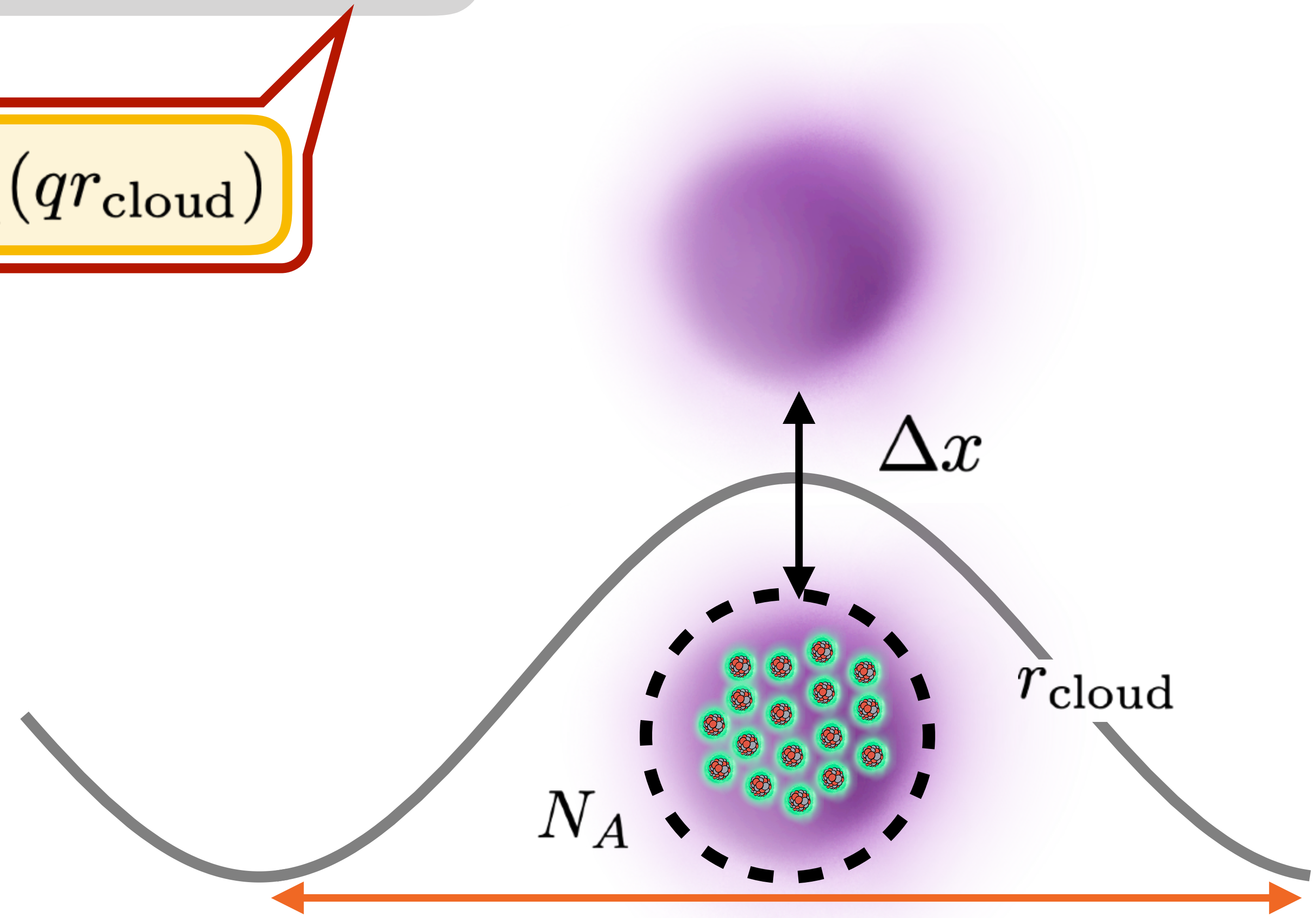
$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \boxed{\frac{1}{V^2}\frac{\pi\bar{\sigma}}{\mu^2} \boxed{\mathcal{F}^2_{\rm med}(\mathbf{q})} \boxed{\mathcal{F}^2_{\rm T}(\mathbf{q})}} g(\mathbf{q}, E_f - E_i) \boxed{\mathcal{F}_{\rm decoh}(\mathbf{q})}$$

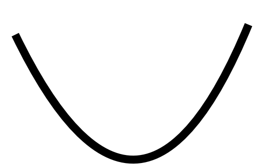
$$\mathcal{F}_T(\mathbf{q}) = N[1 + A(N_A - 1)\boxed{\mathcal{F}^2_{\rm cloud}(q r_{\rm cloud})}$$

Born (coherent) enhancement!



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

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



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

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

AIs: the Rate

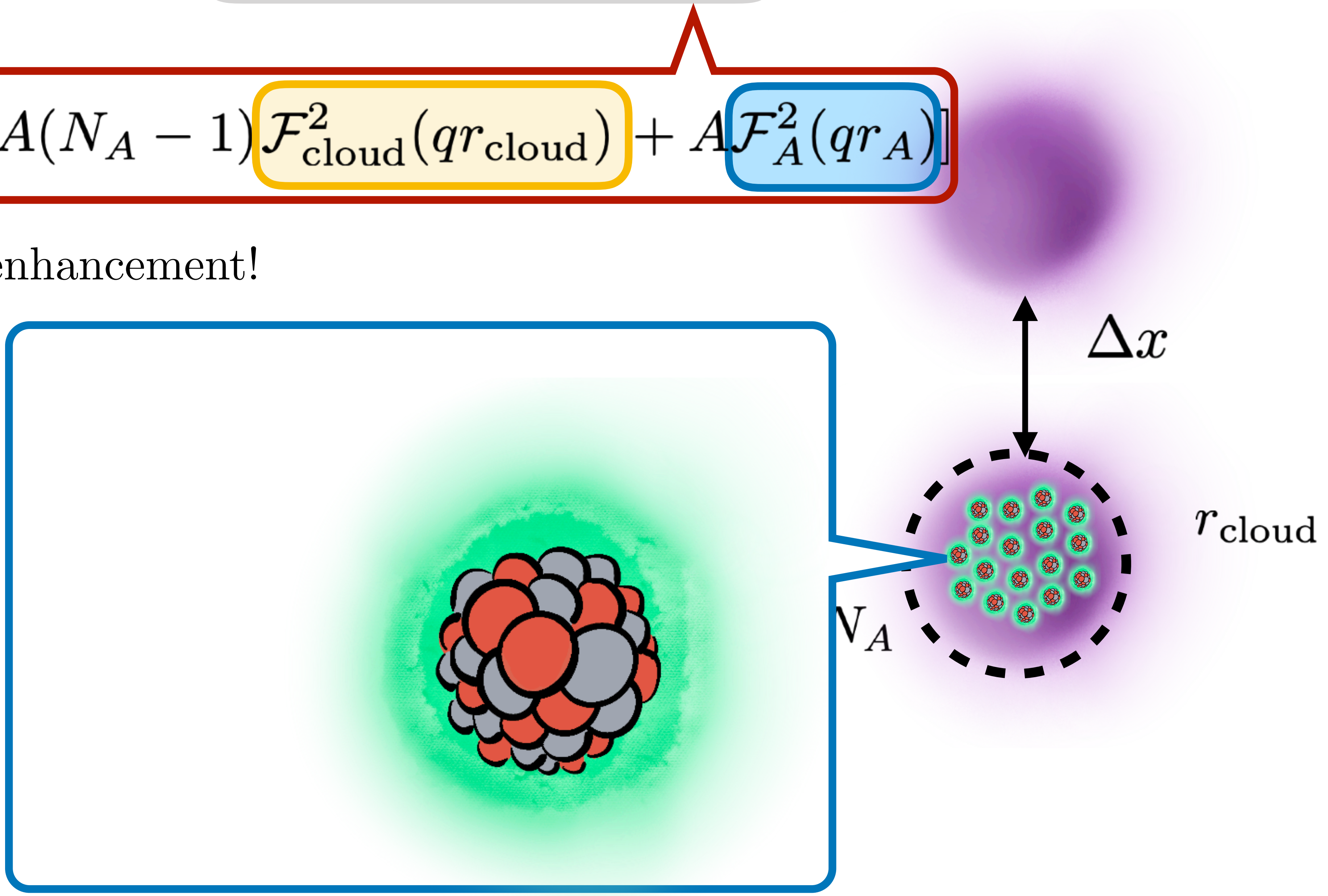
$$\mathcal{F}_{\text{med}}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

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

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

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

Born (coherent) enhancement!



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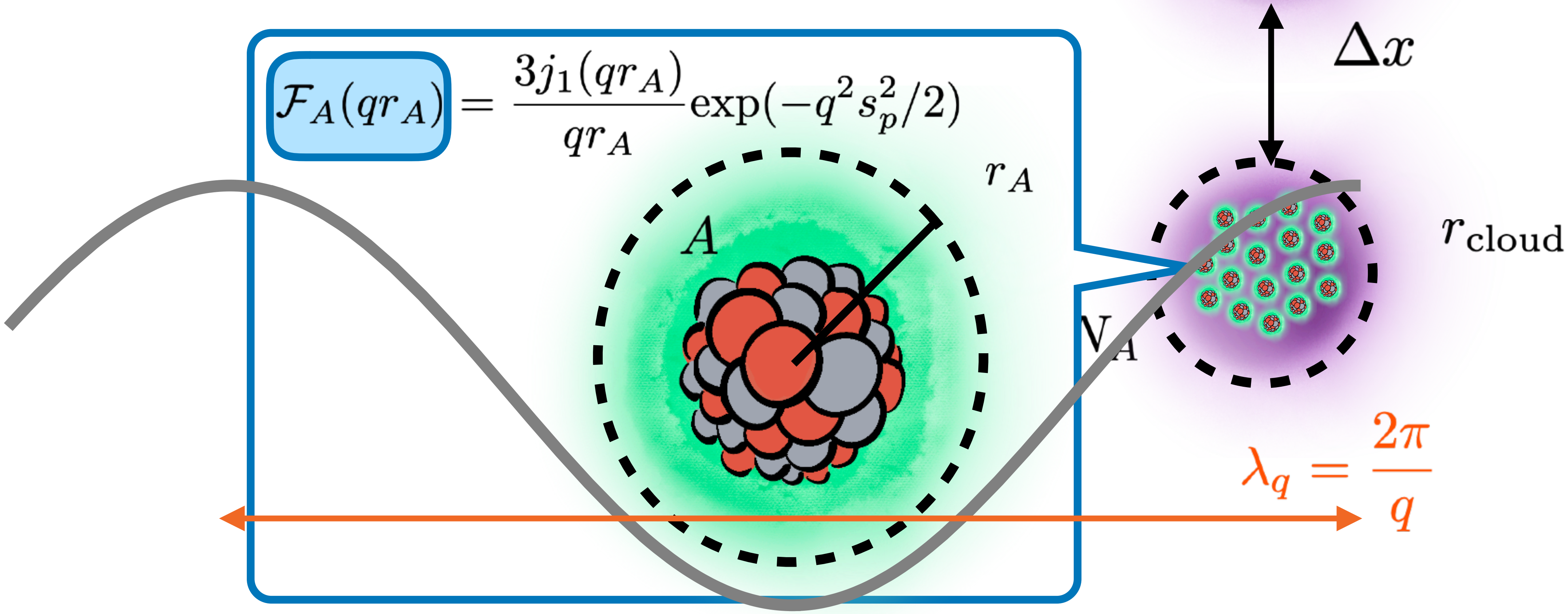
$$\mathcal{F}_T(\mathbf{q}) = N[1 + A(N_A - 1)\mathcal{F}^2_{\rm cloud}(qr_{\rm cloud}) + A\mathcal{F}^2_A(qr_A)]$$

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

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

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

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

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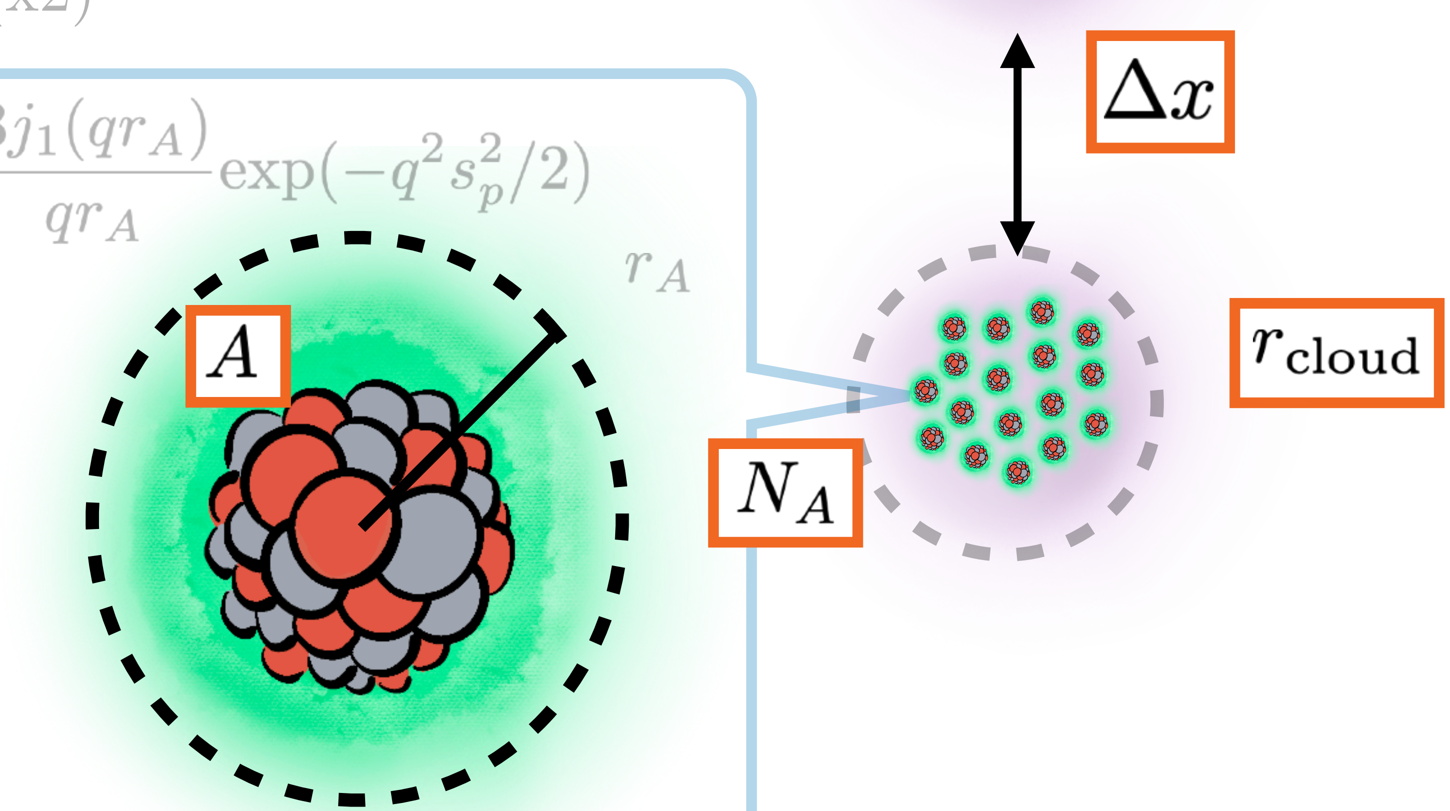

AIs: the Rate

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

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

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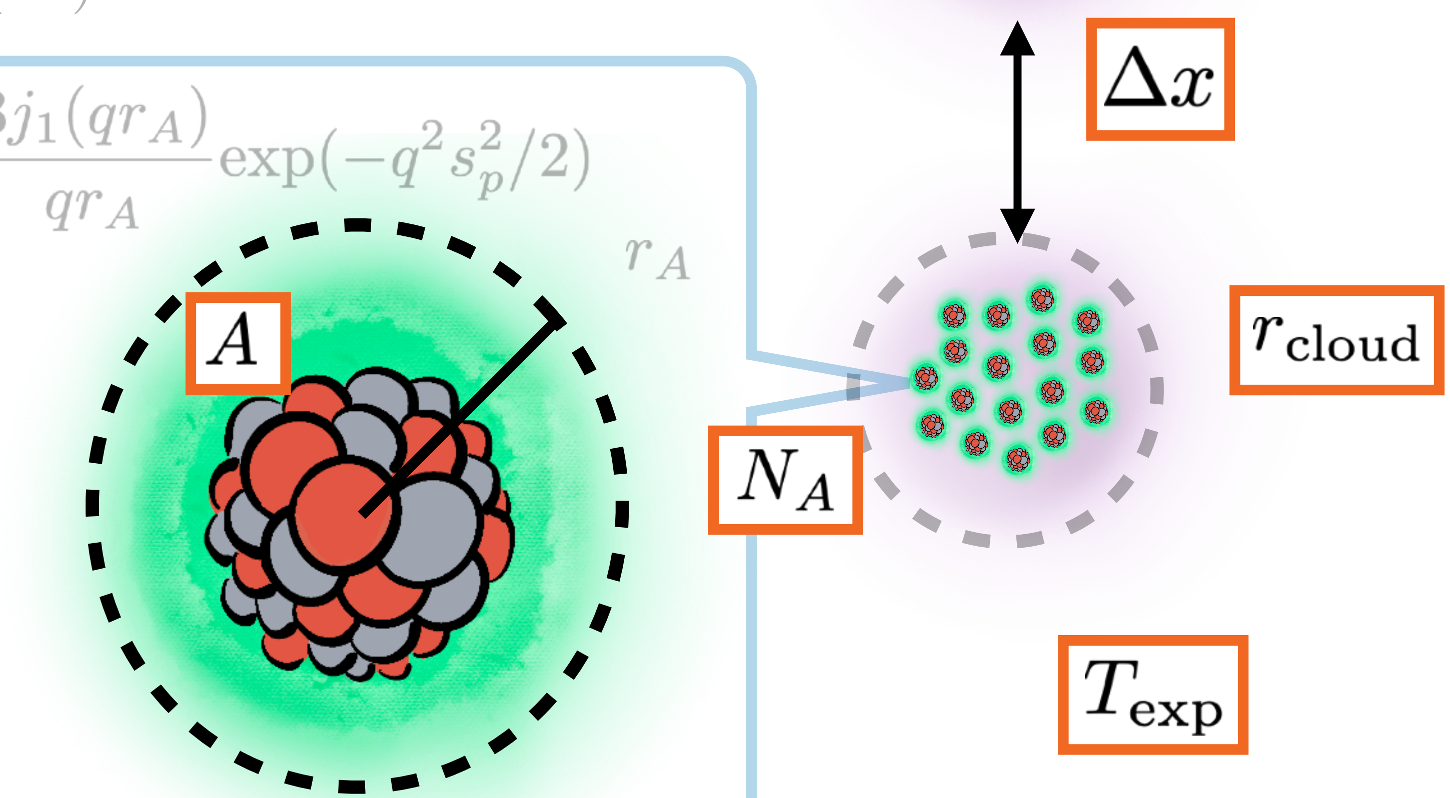
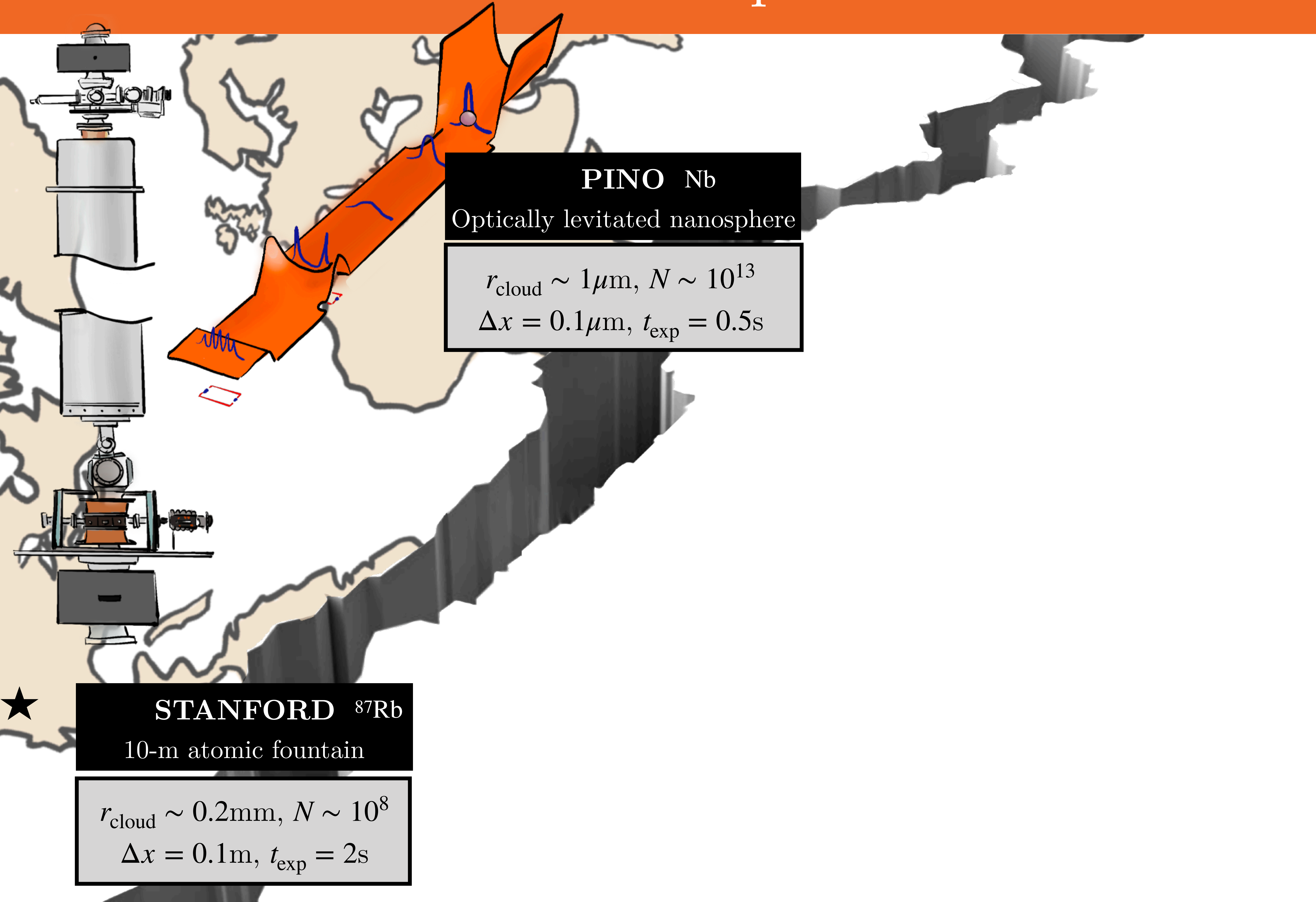


AIs: Examples



PINO Nb

Optically levitated nanosphere

$r_{\text{cloud}} \sim 1\mu\text{m},\ N \sim 10^{13}$

$\Delta x = 0.1\mu\text{m},\ t_{\text{exp}} = 0.5\text{s}$

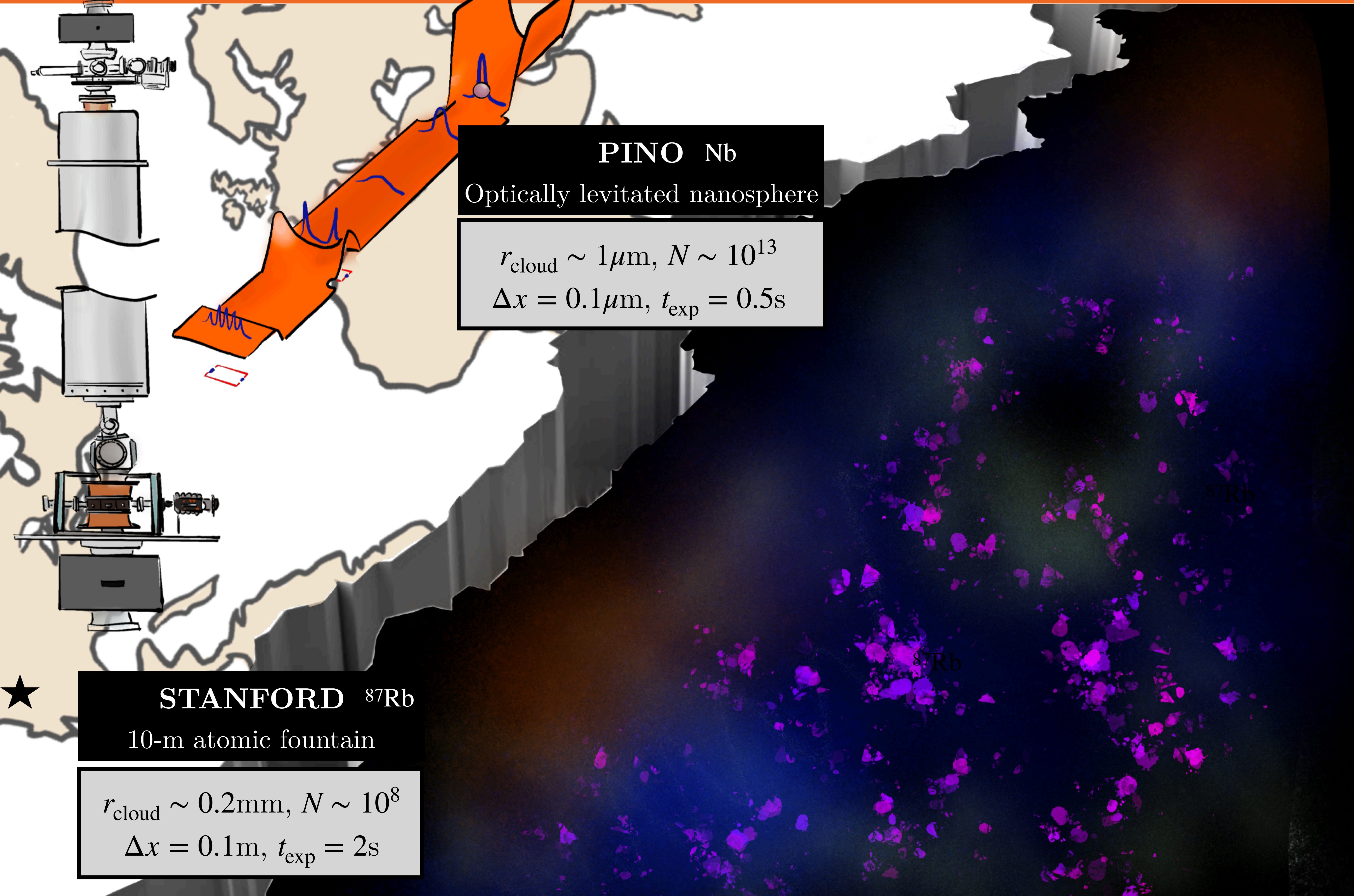
★ **STANFORD** ^{87}Rb

10-m atomic fountain

$r_{\text{cloud}} \sim 0.2\text{mm},\ N \sim 10^{8}$

$\Delta x = 0.1\text{m},\ t_{\text{exp}} = 2\text{s}$

AIs: Examples



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Optically levitated nanosphere

$r_{\text{cloud}} \sim 1\mu\text{m}$, $N \sim 10^{13}$

$\Delta x = 0.1\mu\text{m}$, $t_{\text{exp}} = 0.5\text{s}$

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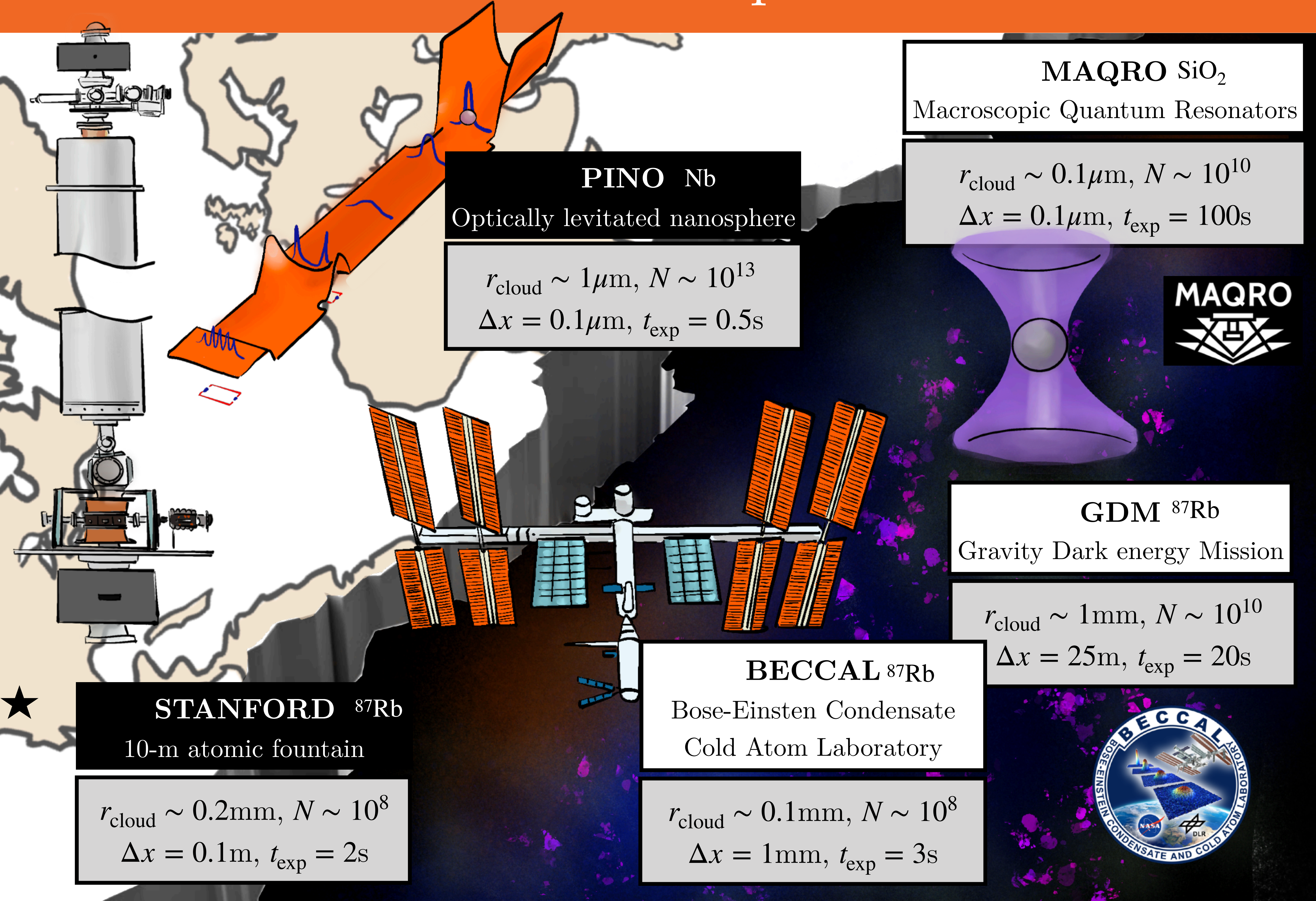
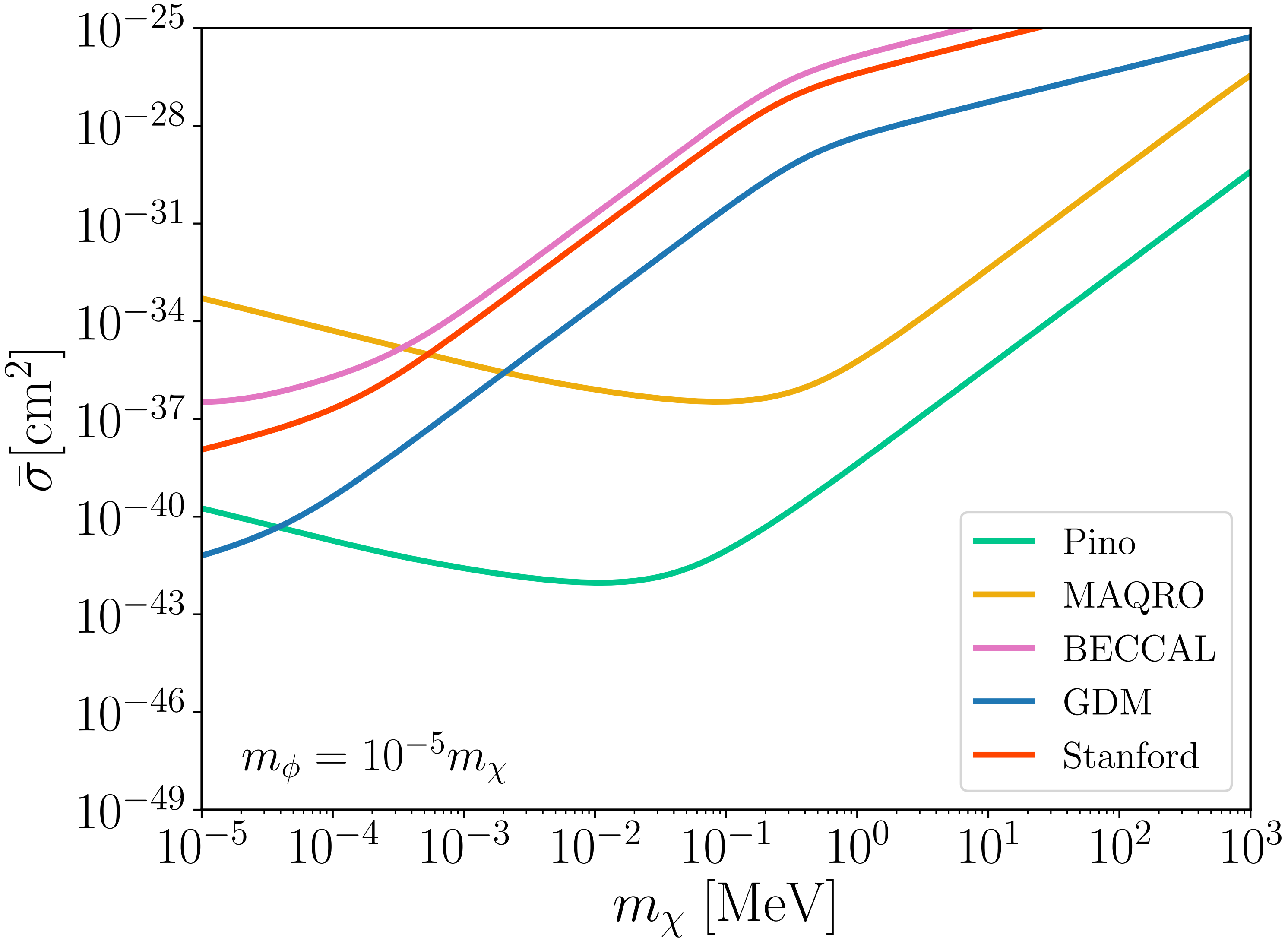
AIs: Examples



AIs: Results

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

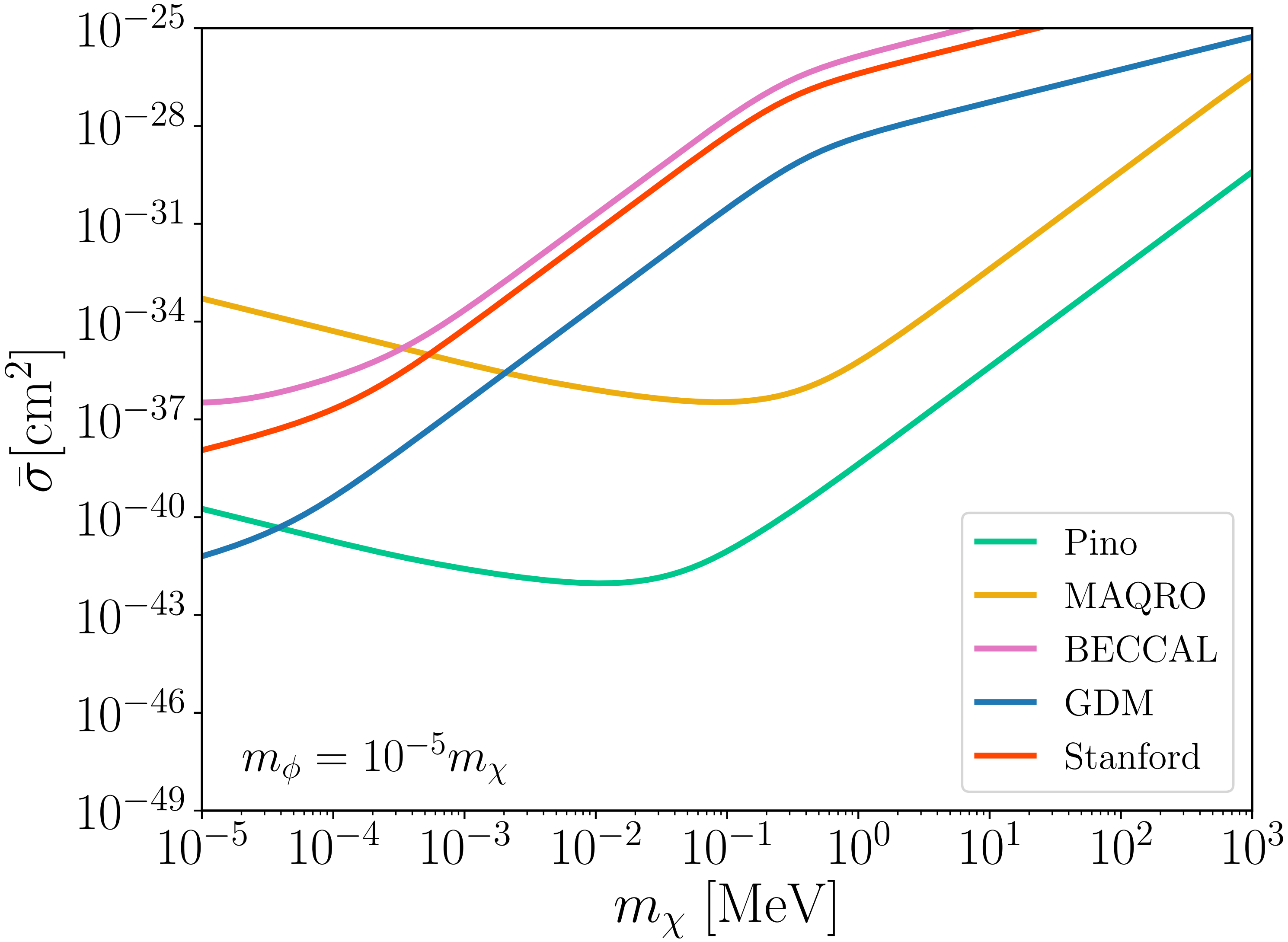


Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

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

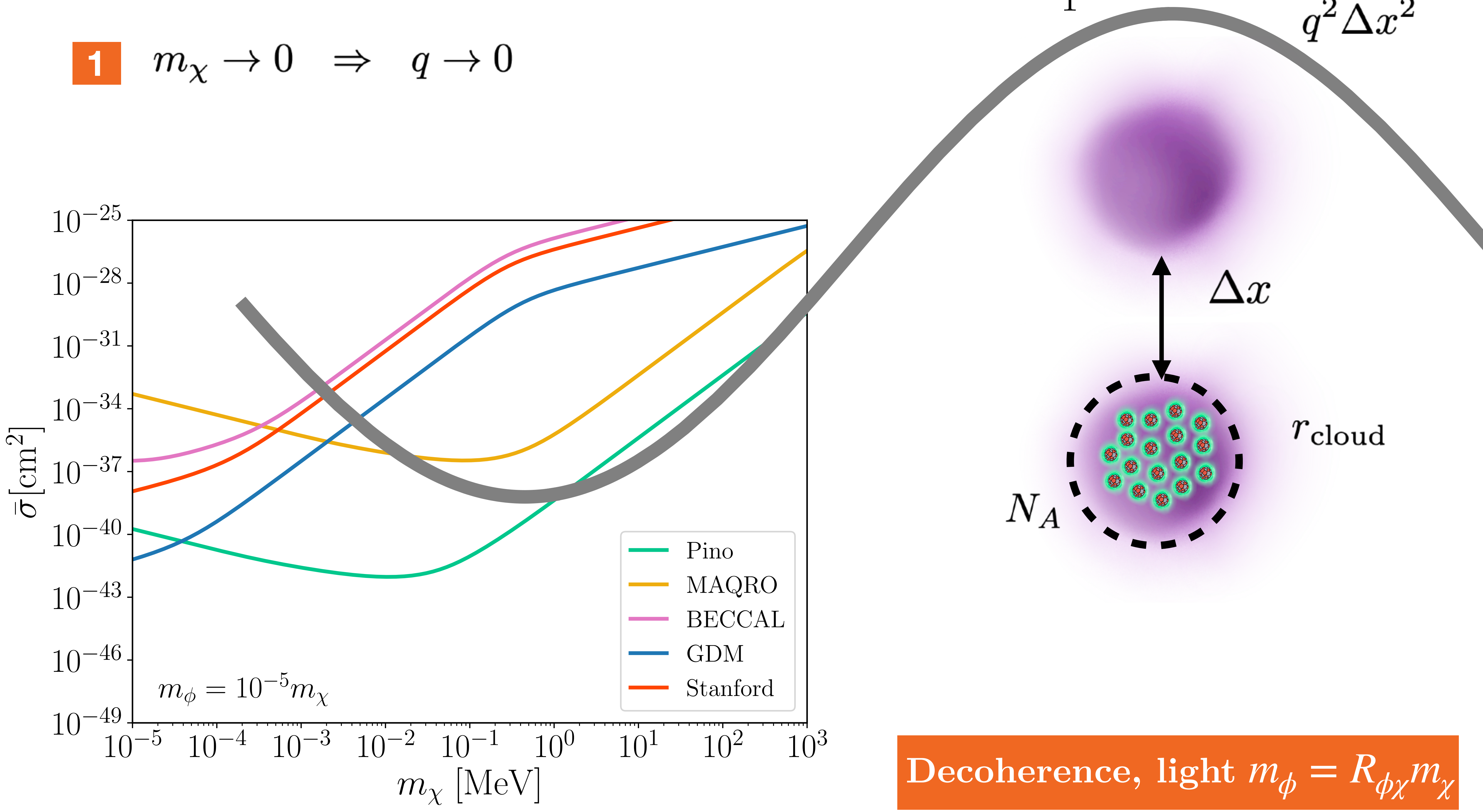


Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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

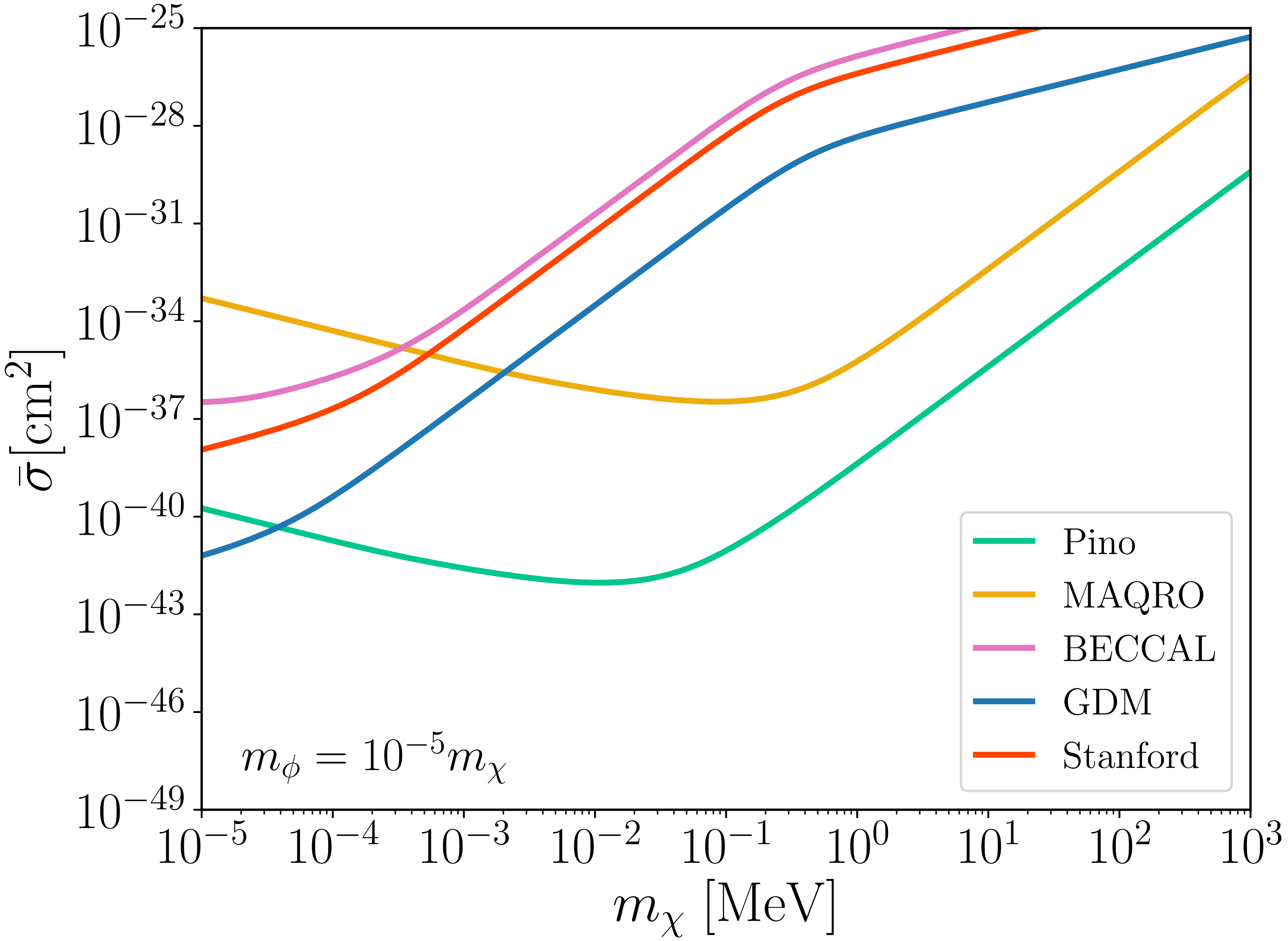


Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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

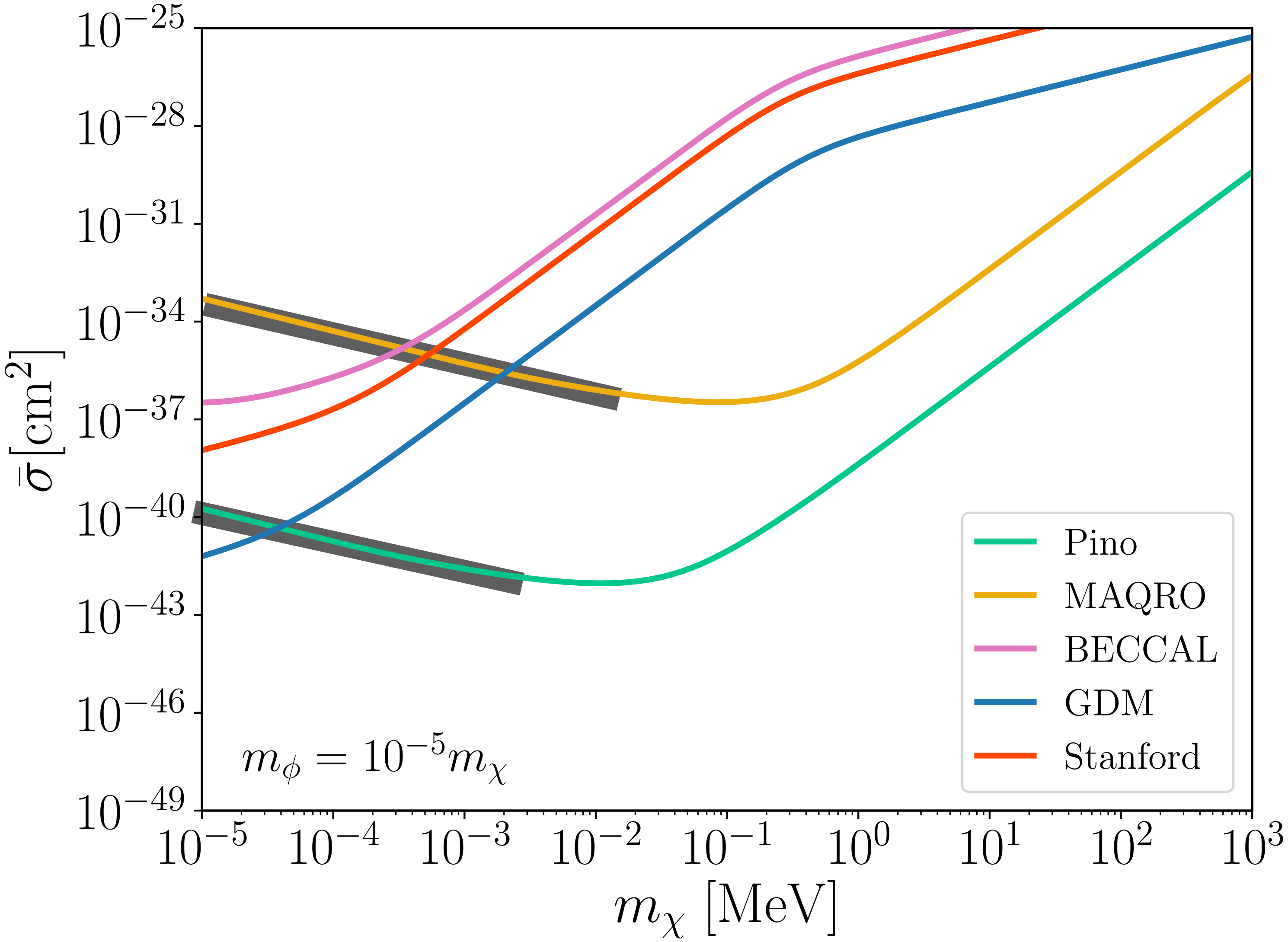


Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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



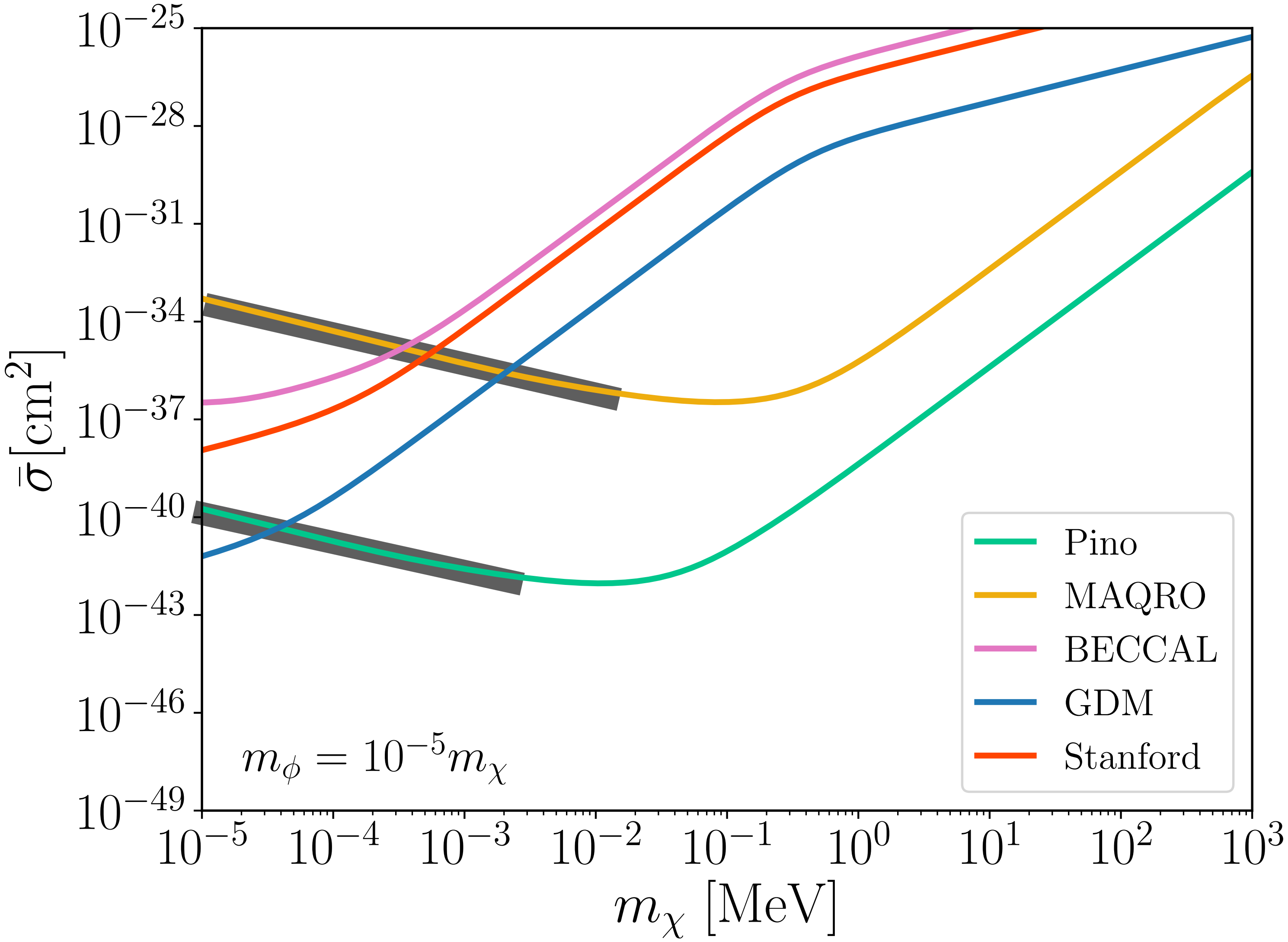
Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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 $m_\chi \to \infty$



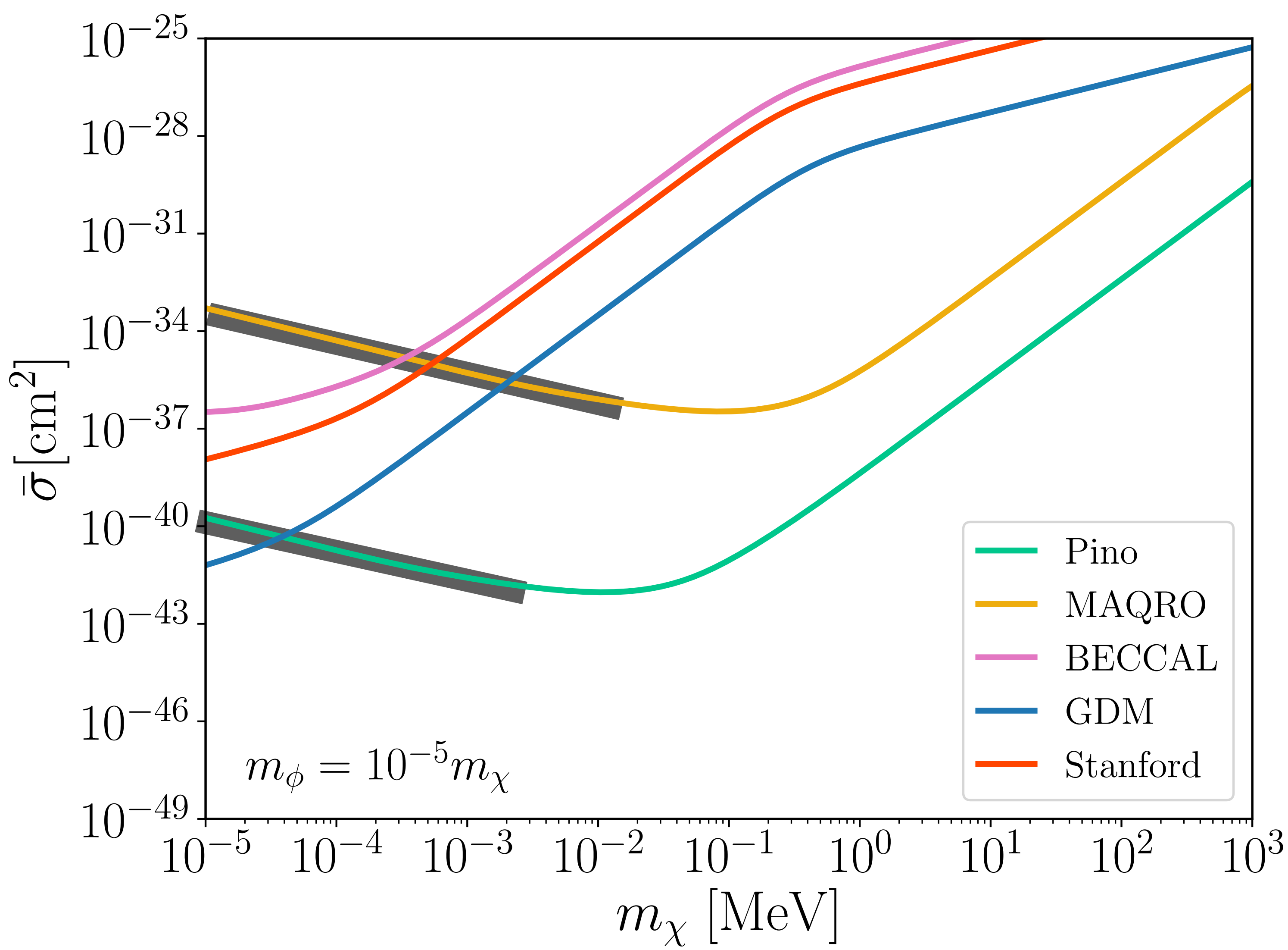
Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

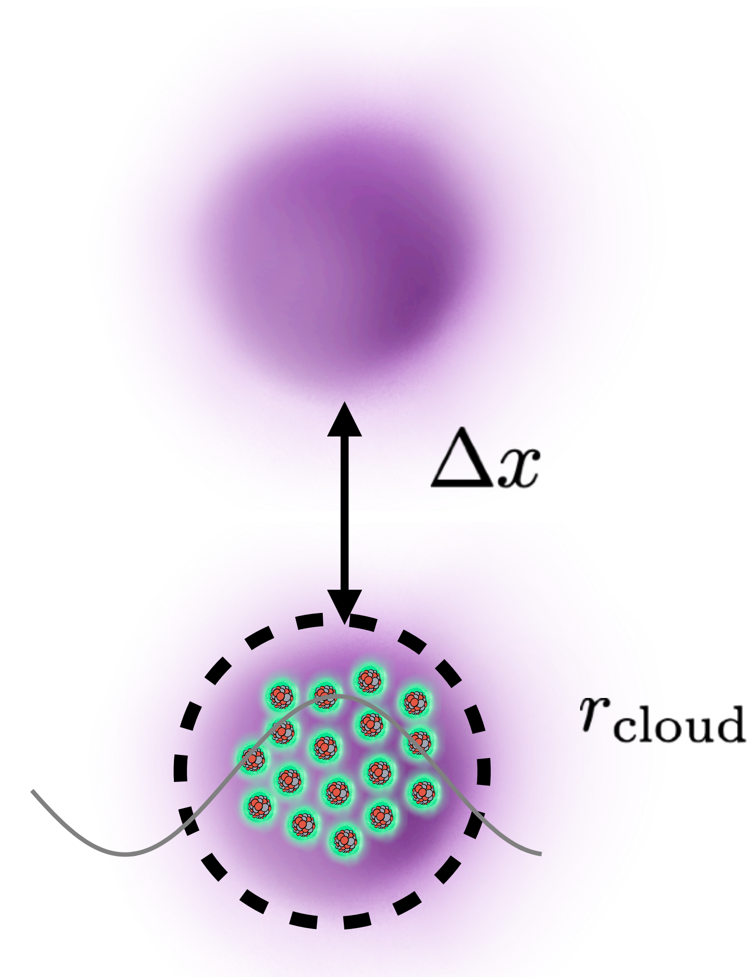
AIs: Results

$$s \propto \frac{\bar{\sigma}(\cancel{(m_\chi v_0)^2 + m_\phi^2})^2}{m_\chi^3} \int dq \, \frac{q}{(\cancel{q^2 + m_\phi^2})^2} N(1 + N \underbrace{F^2(q r_{\text{cloud}})}_{0}) \underbrace{\left(1 - \frac{\sin(q\Delta x)}{q\Delta x}\right)}_{1}$$

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 $m_\chi \to \infty$





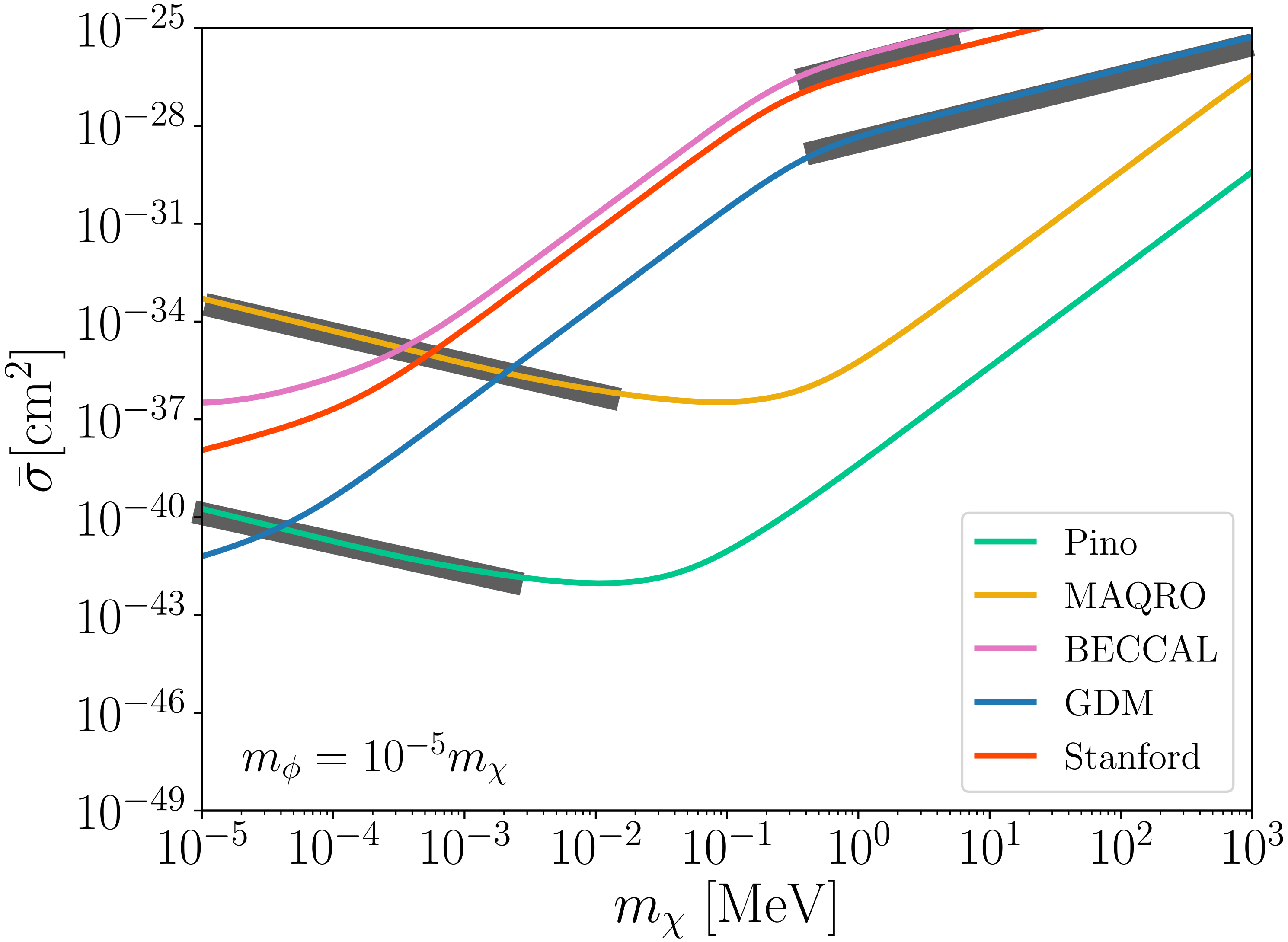
Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

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

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

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

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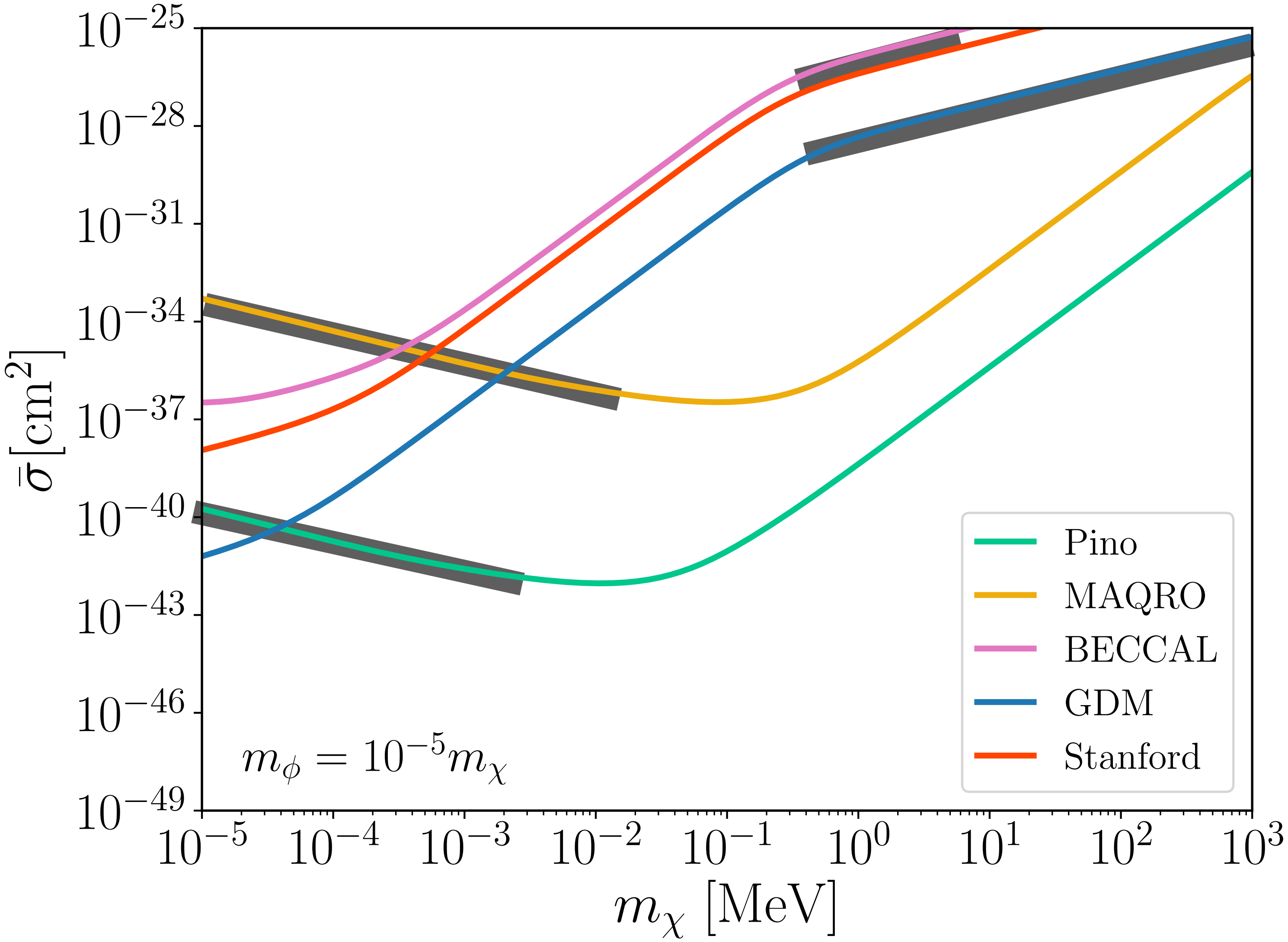

3 $q < r_{\mathrm{cloud}}^{-1} \quad \& \quad q \sim (\Delta x)^{-1}$

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

AIs: Results

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

1 1

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

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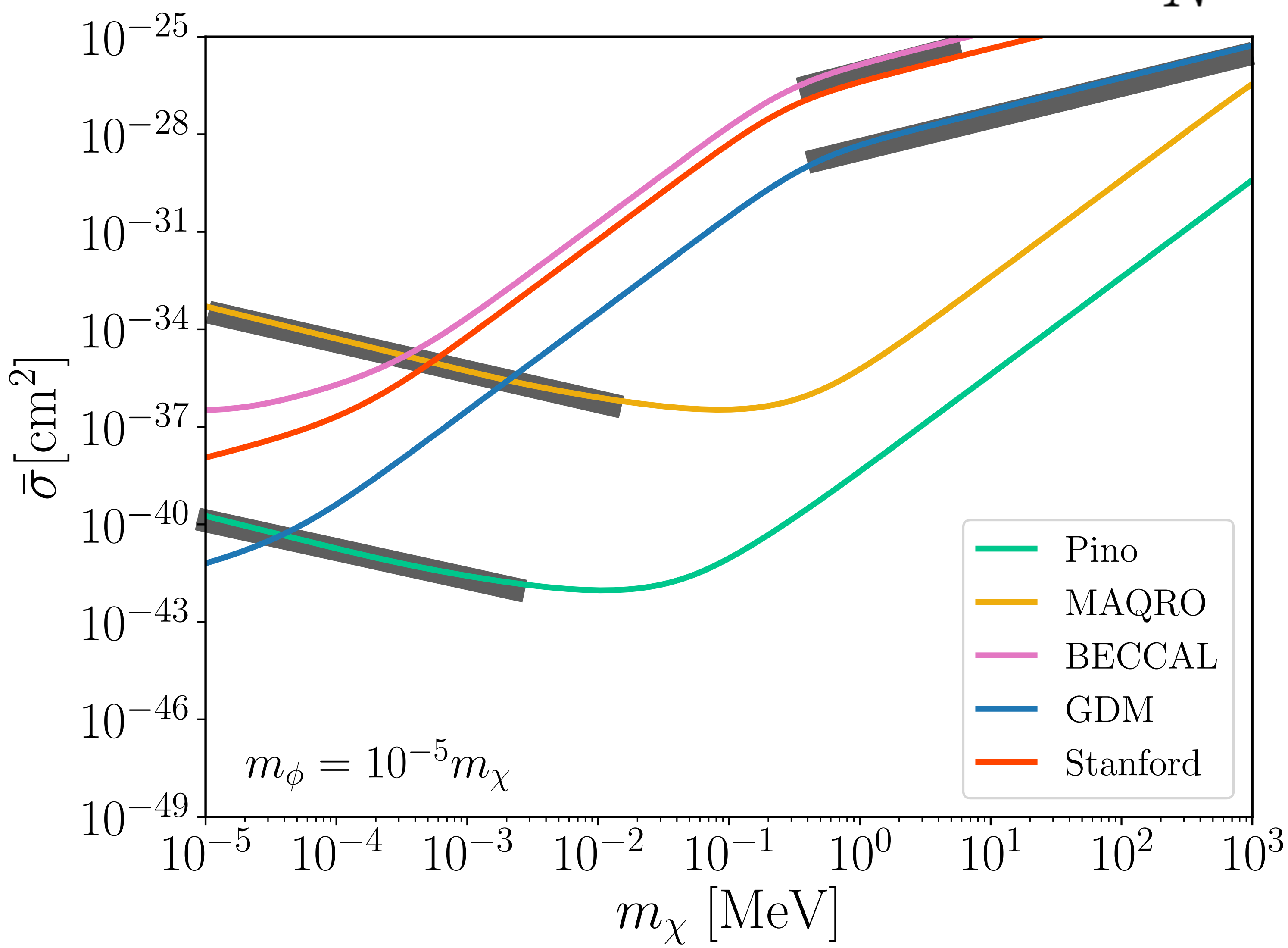
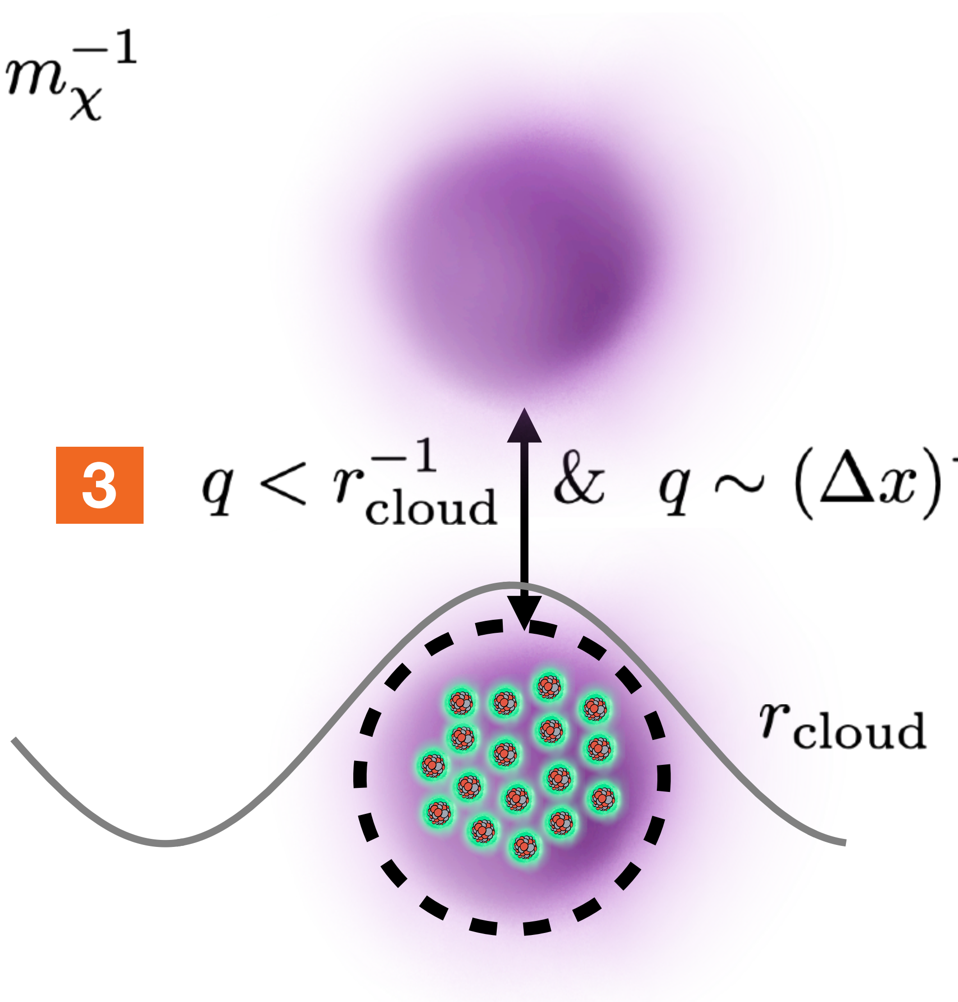


3 $q < r_{\text{cloud}}^{-1}$ & $q \sim (\Delta x)^{-1}$



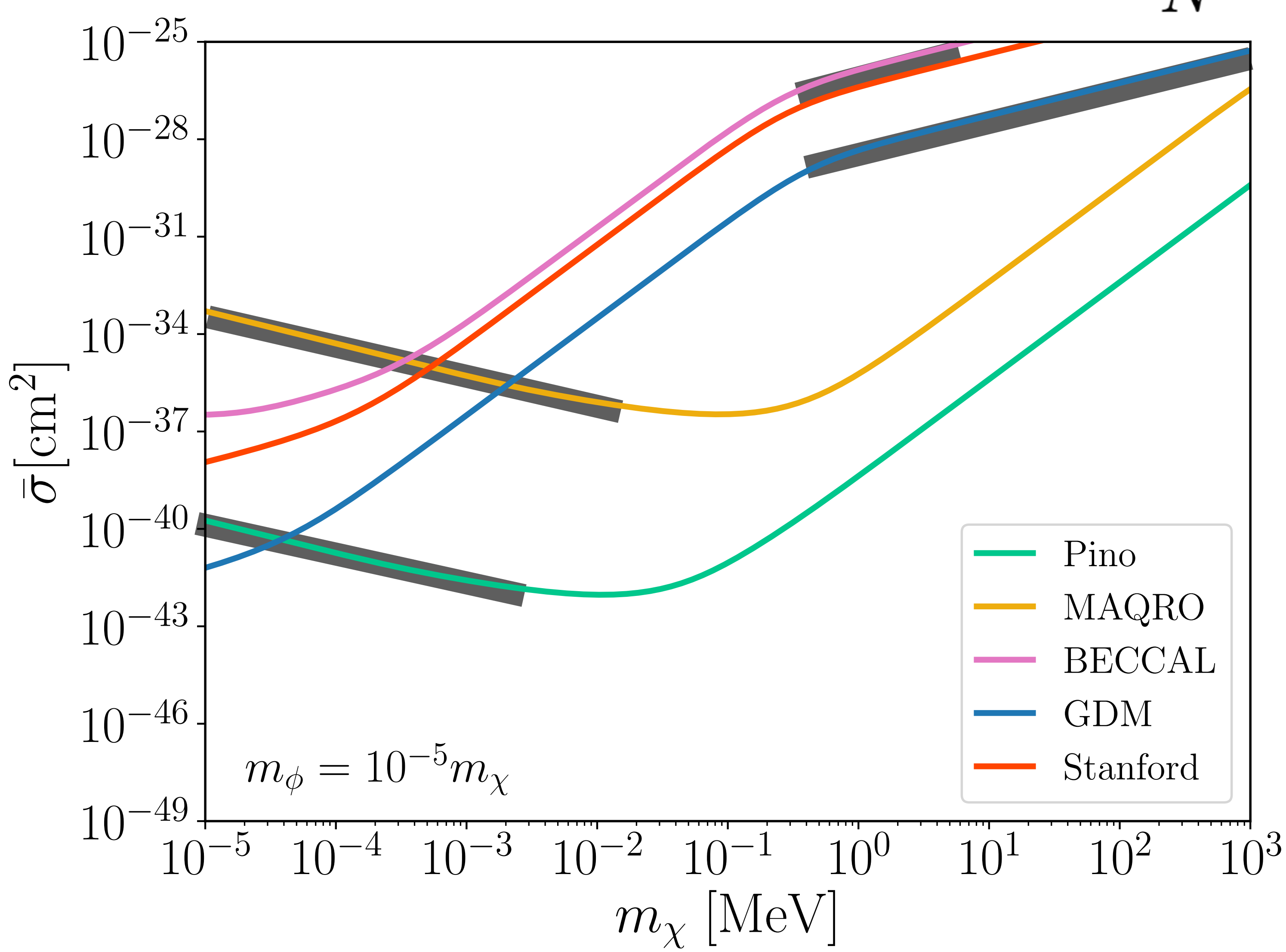
Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

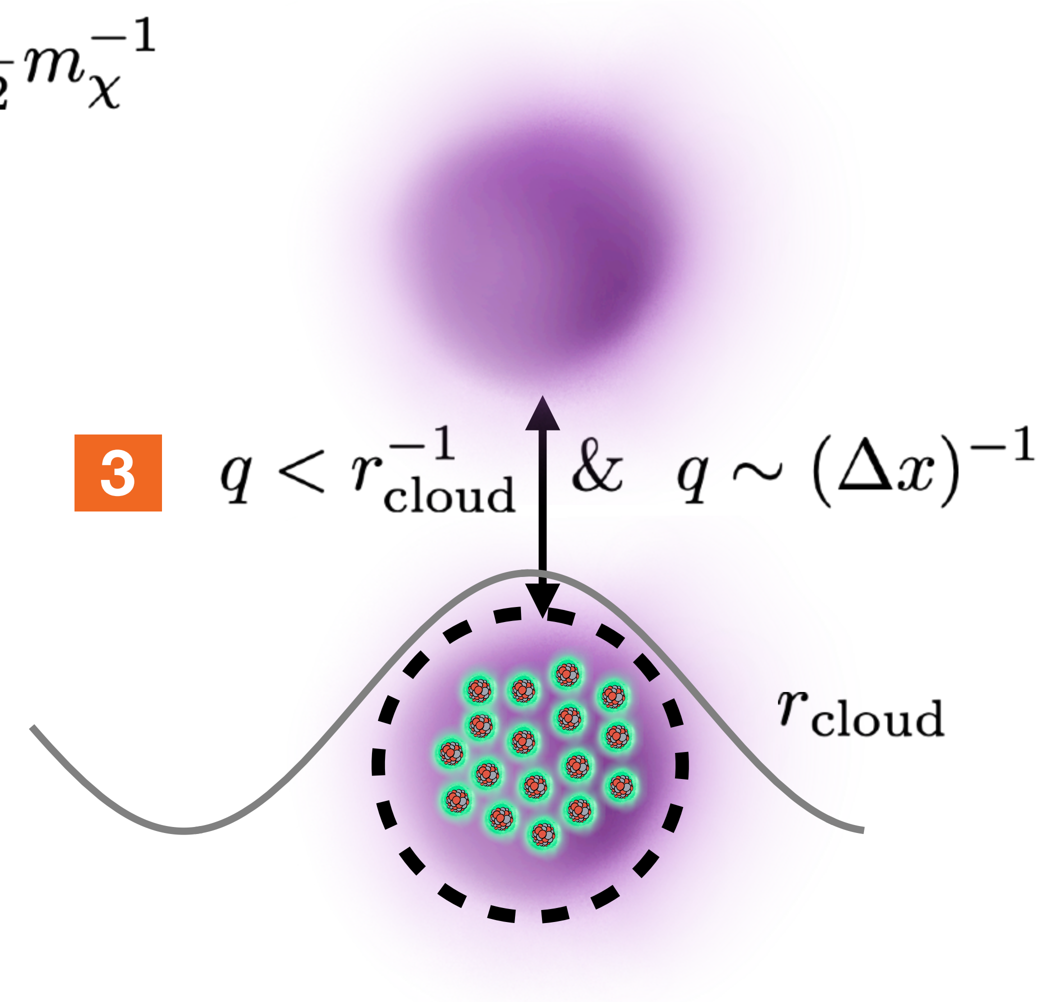
$$s \propto \frac{\bar{\sigma}((m_\chi v_0)^2 + \cancel{m_\phi^2})^2}{m_\chi^3} \int dq \, \frac{q}{(\cancel{q^2} + m_\phi^2)^2} N(1+N\underbrace{F^2(qr_{\text{cloud}})}_{\to 1})\Big(1 - \underbrace{\frac{\sin(q\Delta x)}{q\Delta x}}_{\to 1}\Big)$$

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



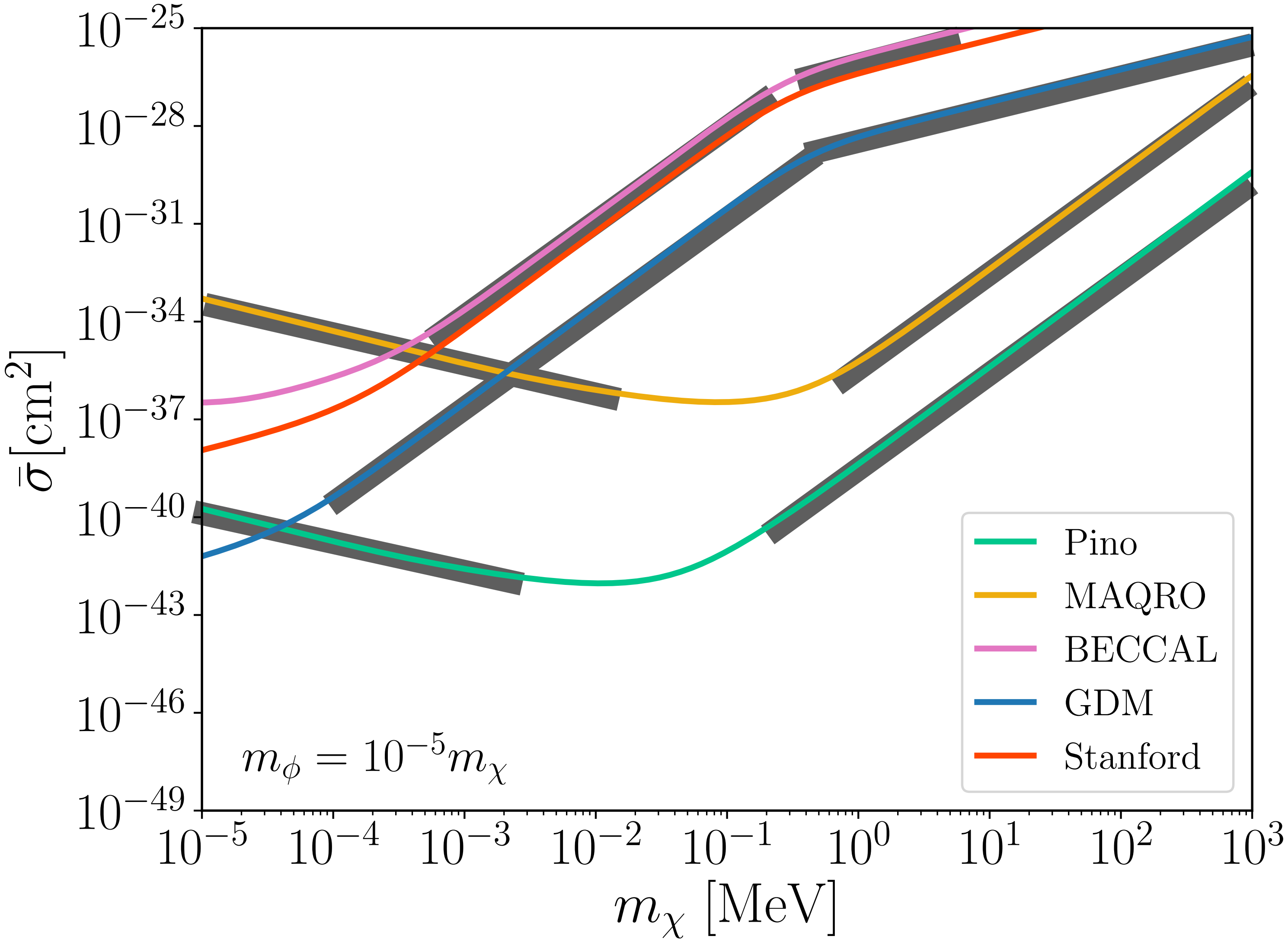
Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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

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

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

AIs: Results

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

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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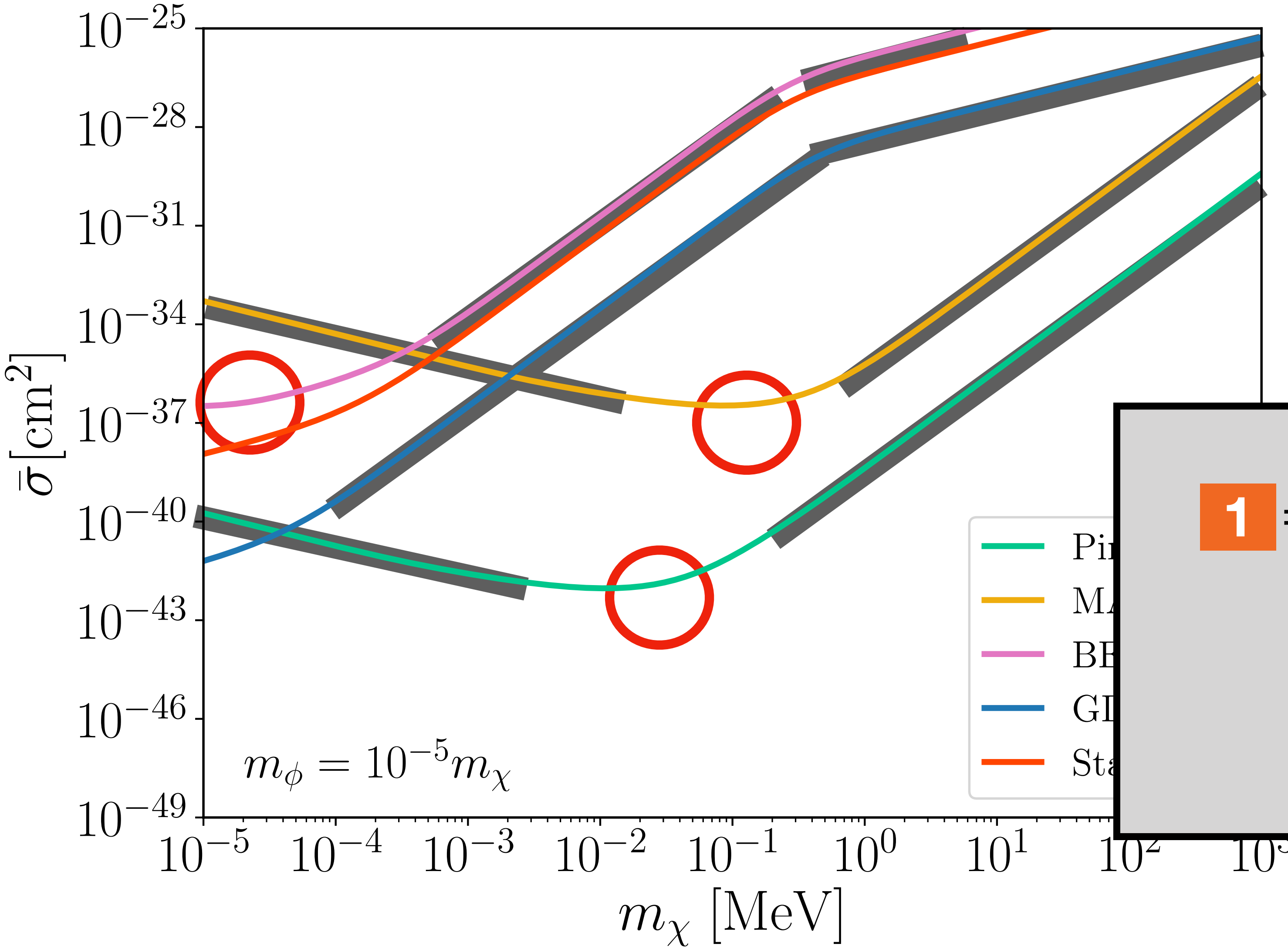

3 $q < r_{\rm cloud}^{-1} \quad \& \quad q \sim (\Delta x)^{-1}$

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

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

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

AIs: Results

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

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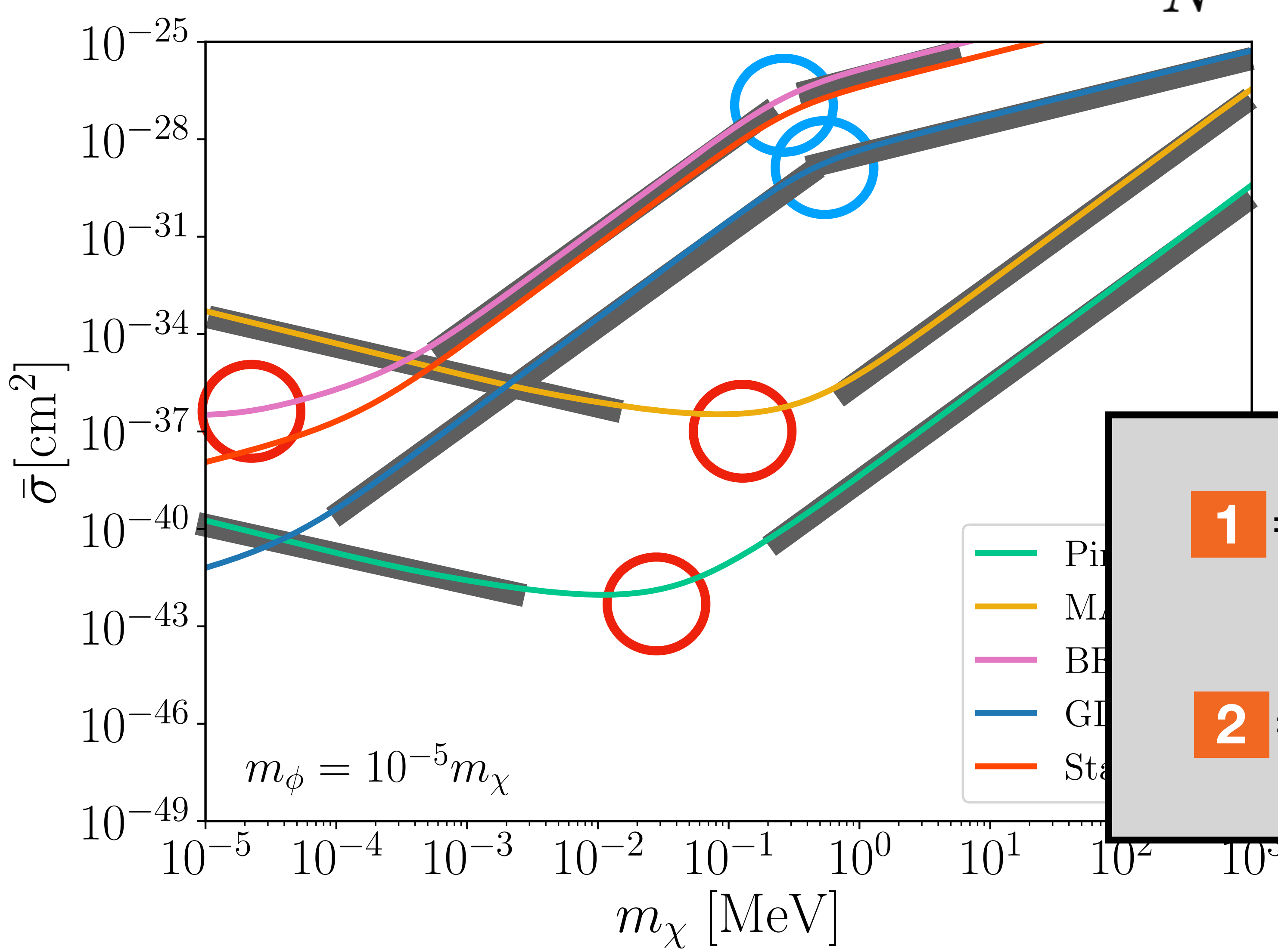
2 $m_\chi \to \infty \qquad \Rightarrow \bar{\sigma} \propto \frac{1}{N} m_\chi$



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

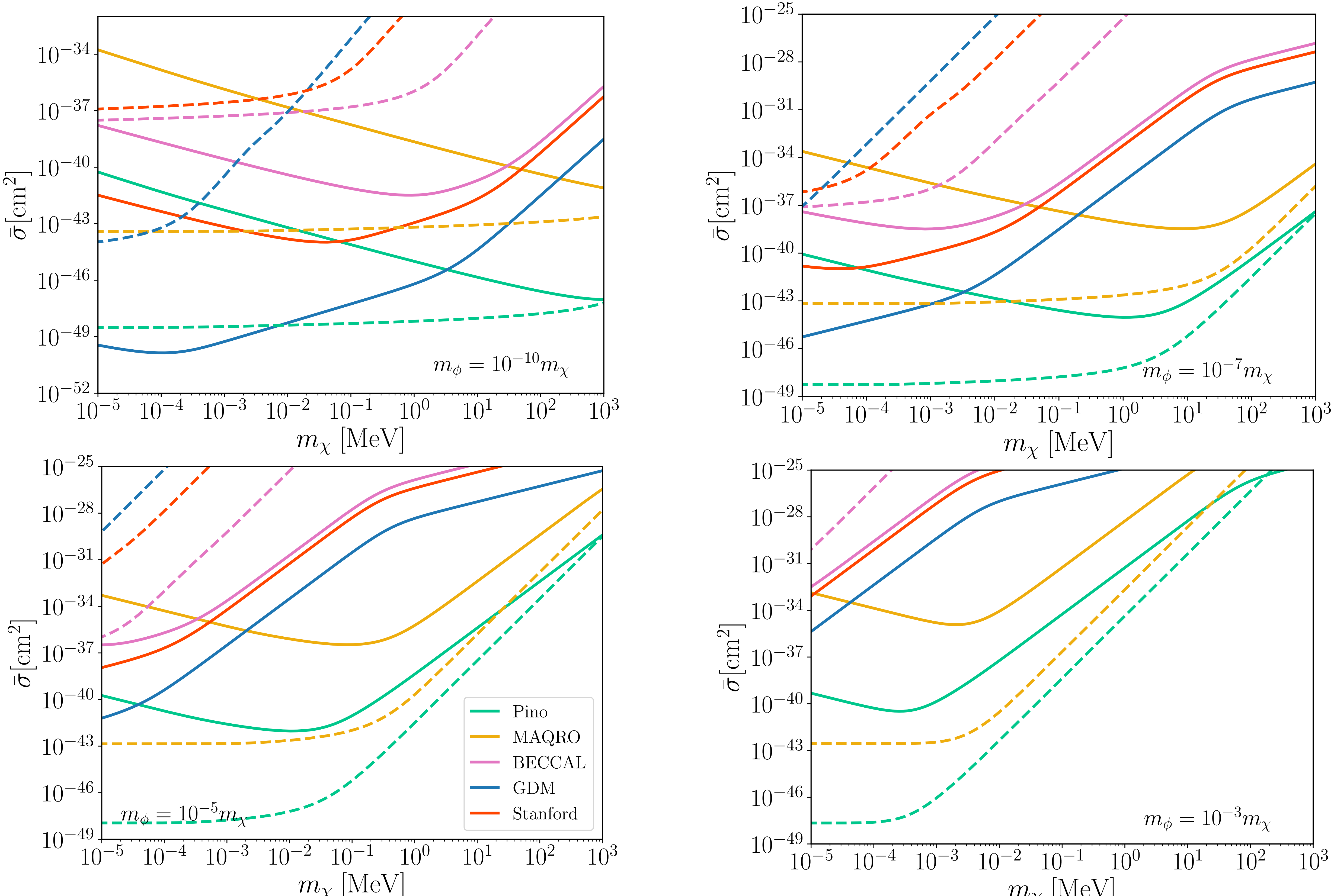
$$\Rightarrow \bar{\sigma} \propto \frac{r_{\rm cloud}^2 R_{\phi\chi}^4}{N^2} m_\chi^3$$

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

2 = **3** $\Rightarrow$ $m_\chi^{\rm knee} \sim \frac{\sqrt{N}}{r_{\rm cloud} R_{\phi\chi}^2}$

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

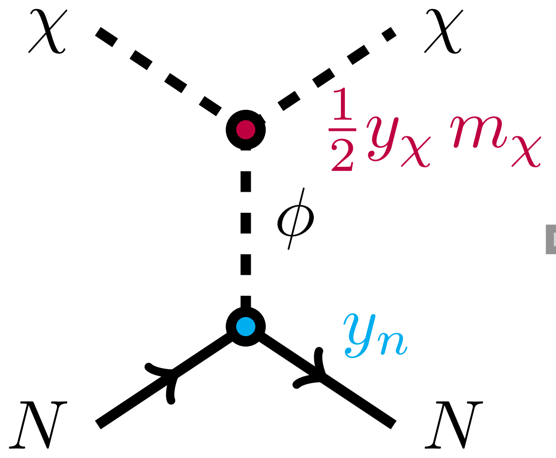
AIs: Results



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

AIs: Constraints

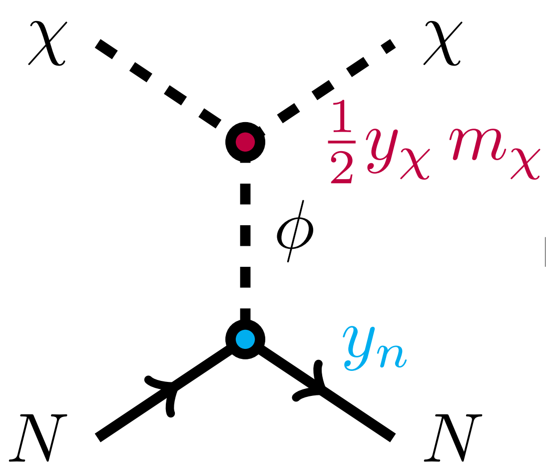
[Knapen, Lin, Zurek, 2017]



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

AIs: Constraints

[Knapen, Lin, Zurek, 2017]

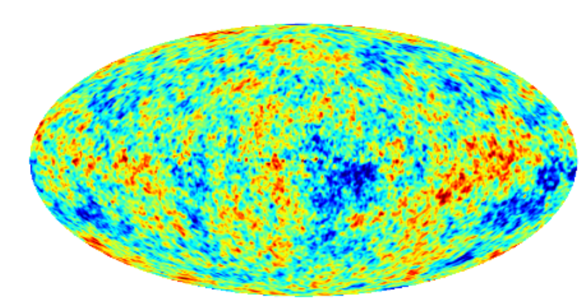


$$\bar{\sigma} = \frac{y_\chi^2 \, y_n^2}{4\pi} \frac{\mu^2}{(m_\chi^2 v_0^2 + m_\phi^2)^2}$$

Terrestial

Astrophysical

Cosmological

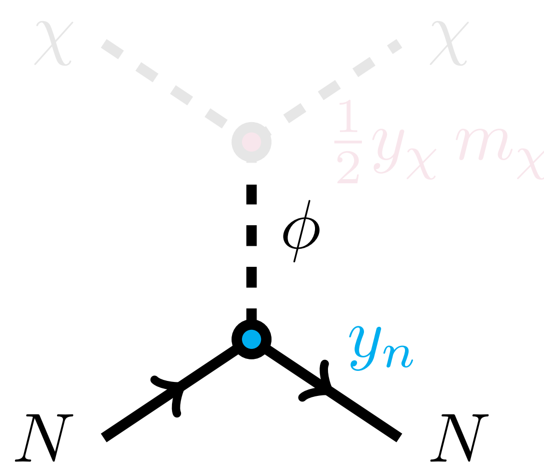


AIs: Constraints

[Knapen, Lin, Zurek, 2017]

@ low E

$$\mathcal{L} \supset \frac{\epsilon}{\sqrt{2}} \frac{m_f}{v} \phi \bar{f} f \quad \Rightarrow \quad \epsilon \frac{\alpha_s}{12\pi v} \phi G^a_{\mu\nu} G^{a\mu\nu} \quad \Rightarrow \quad y_n \phi \bar{N} N$$



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

Terrestial

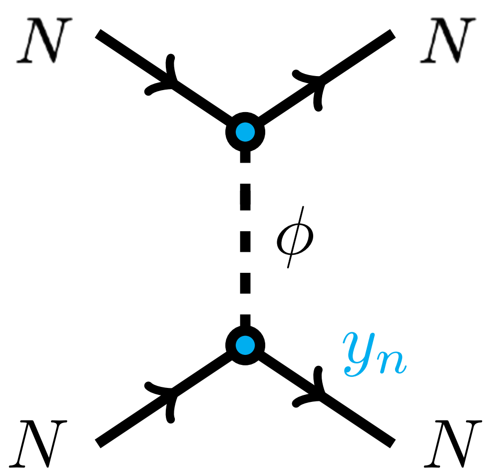
$\Rightarrow$ Collider

Astrophysical

Cosmological

AIs: Constraints

[Knapen, Lin, Zurek, 2017]



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

Terrestial

Collider

5th force

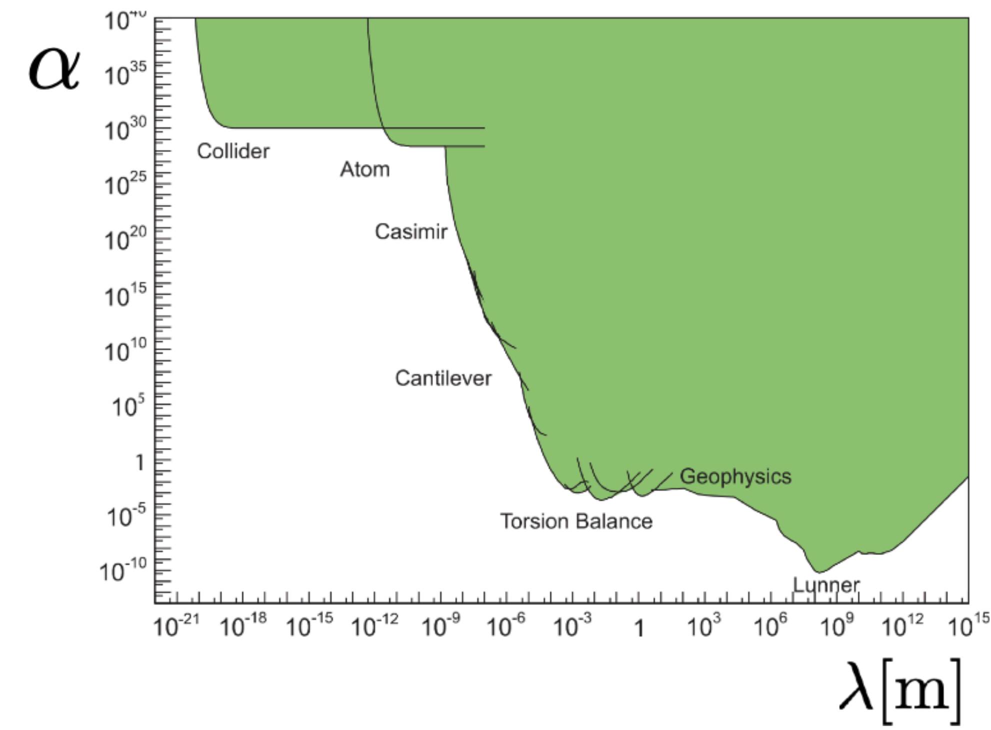
Astrophysical

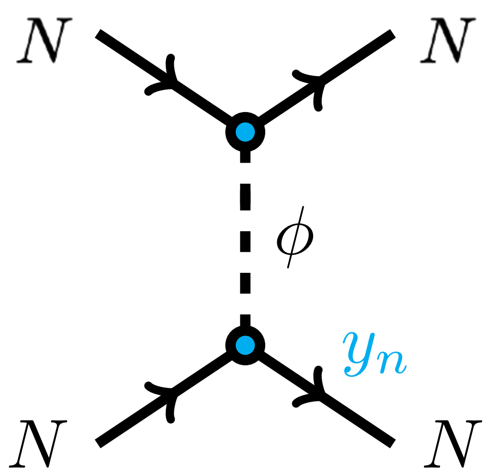
Cosmological

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

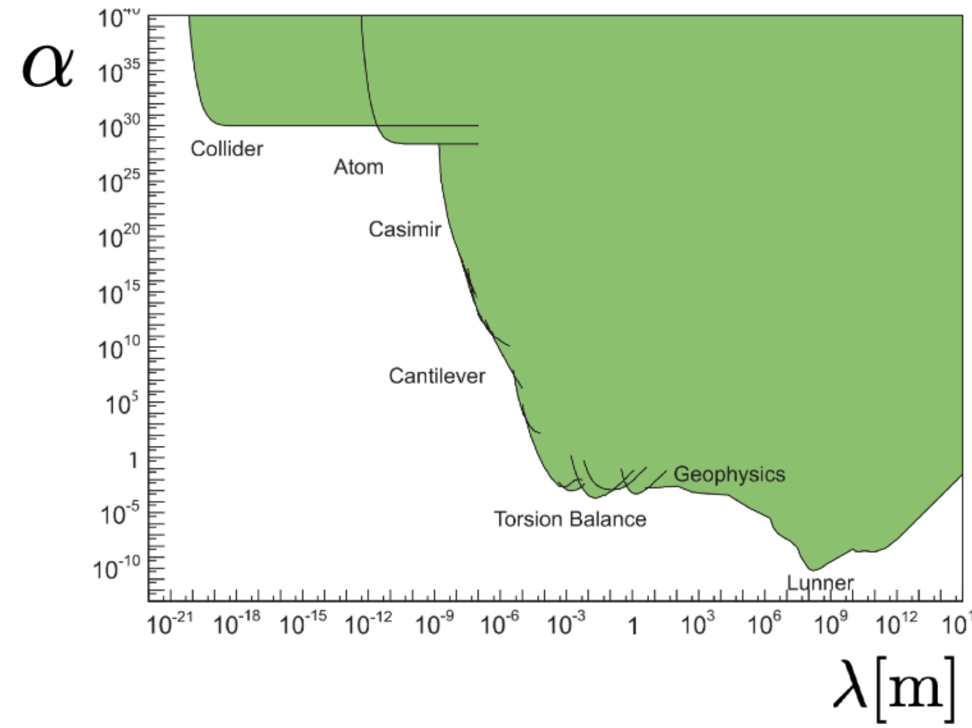
Cosmological

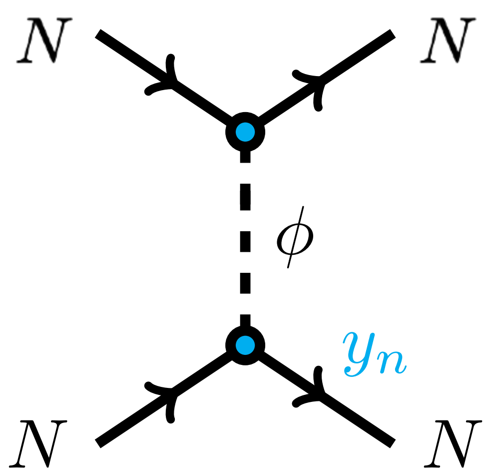
AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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

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





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

[Murata, Tanaka, 2014]

Terrestial

Collider

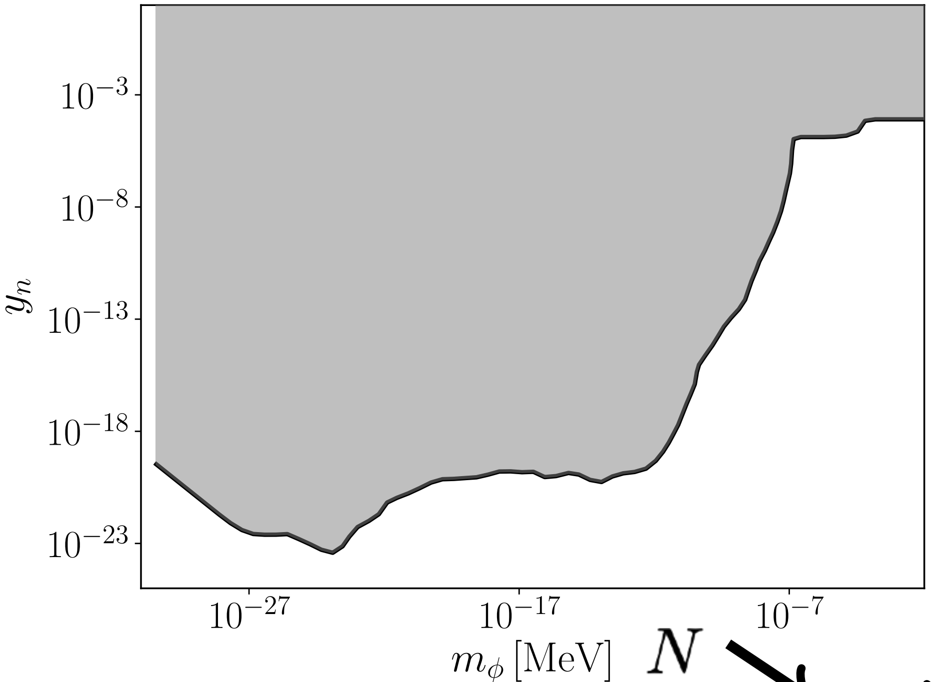
5th force

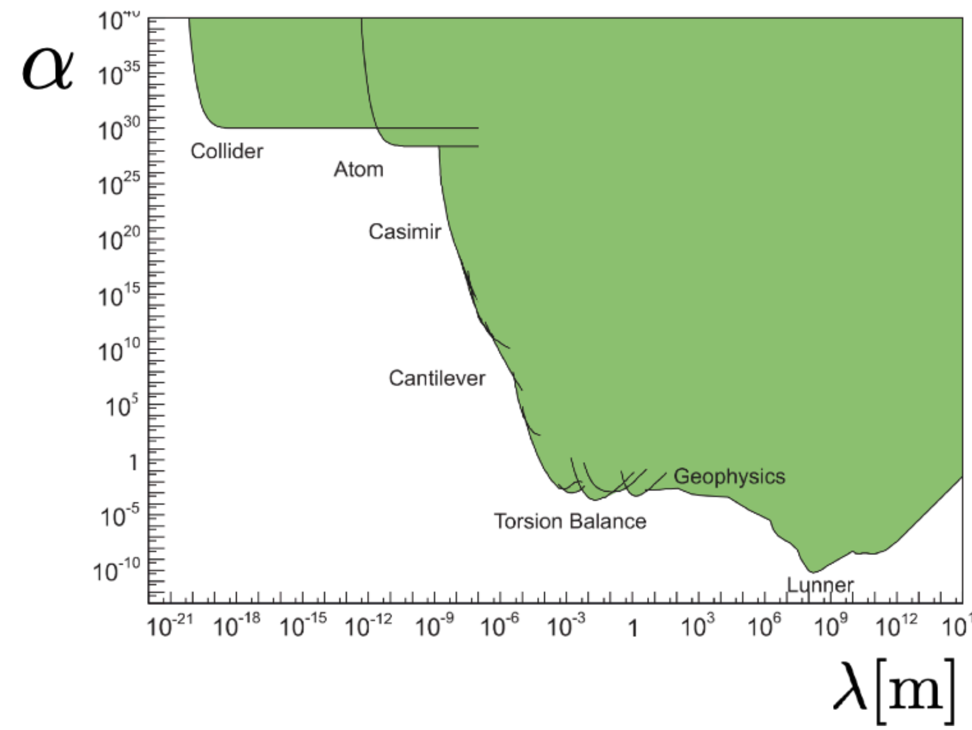
Astrophysical

Cosmological

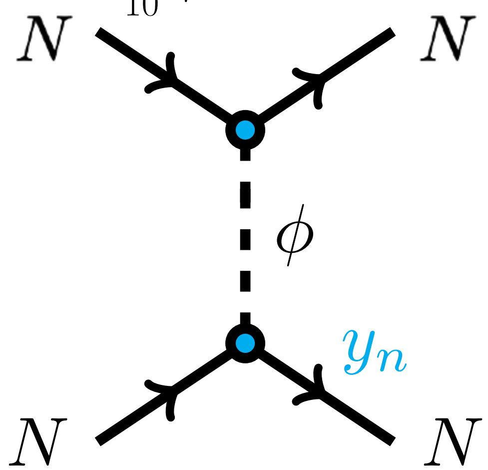
AIs: Constraints

[Knapen, Lin, Zurek, 2017]





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



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

[Murata, Tanaka, 2014]

Terrestial

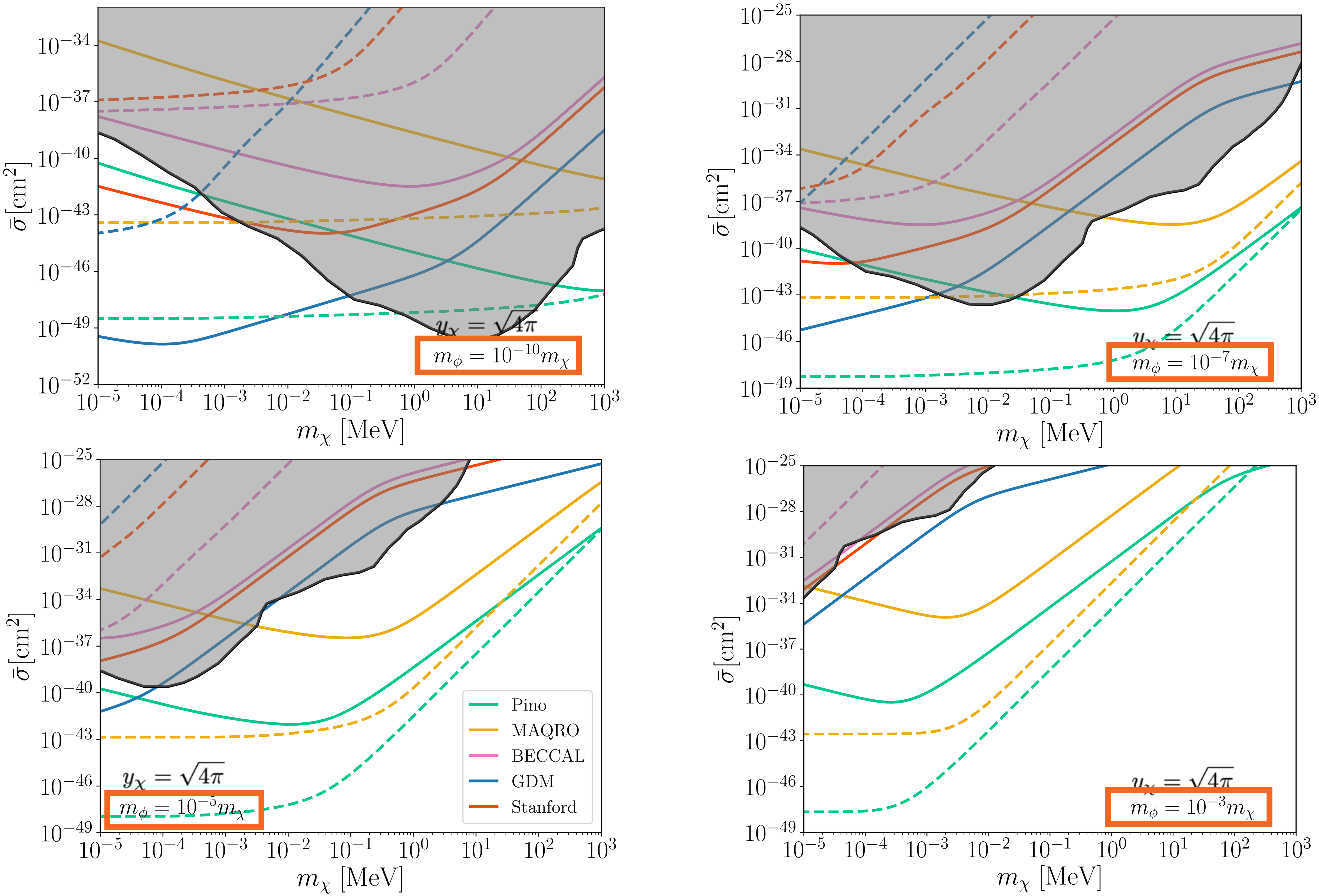
Collider

5th force

Astrophysical

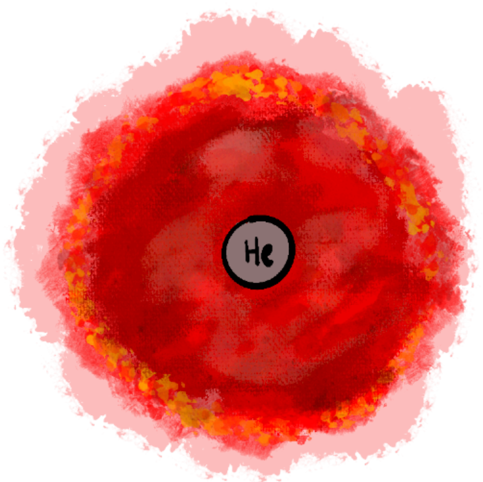
Cosmological

AIs: Constraints



AIs: Constraints

[Knapen, Lin, Zurek, 2017]



RG and HB stars

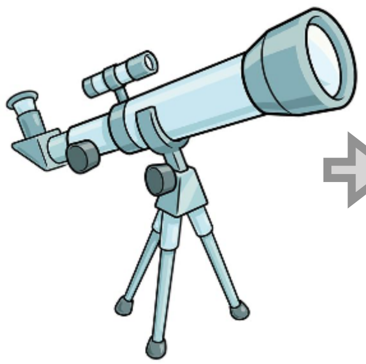
$m_\phi < T \sim 10$ keV (He )

Terrestial

Collider

5th force

Astrophysical

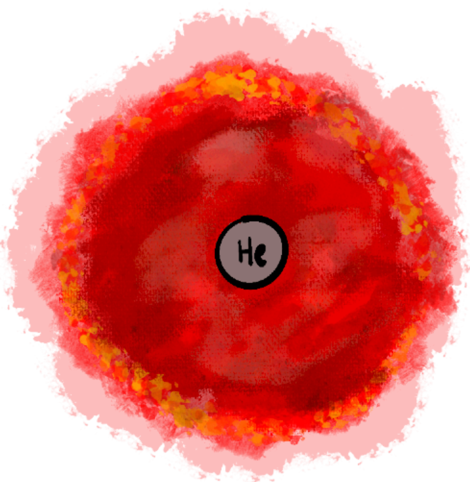


Stellar emission

Cosmological

AIs: Constraints

[Knapen, Lin, Zurek, 2017]



RG and HB stars

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

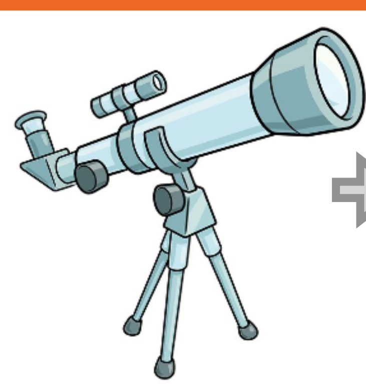
$\epsilon \lesssim 10$ erg/g/s $\Rightarrow$ $y_n \lesssim 4 \times 10^{-11}$

Terrestial

Collider

5th force

Astrophysical

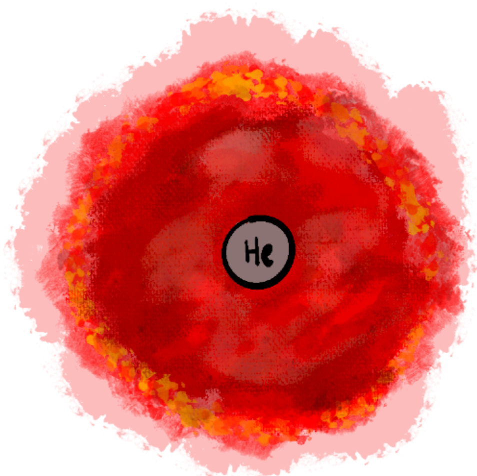


Stellar emission

Cosmological

AIs: Constraints

[Knapen, Lin, Zurek, 2017]



RG and HB stars

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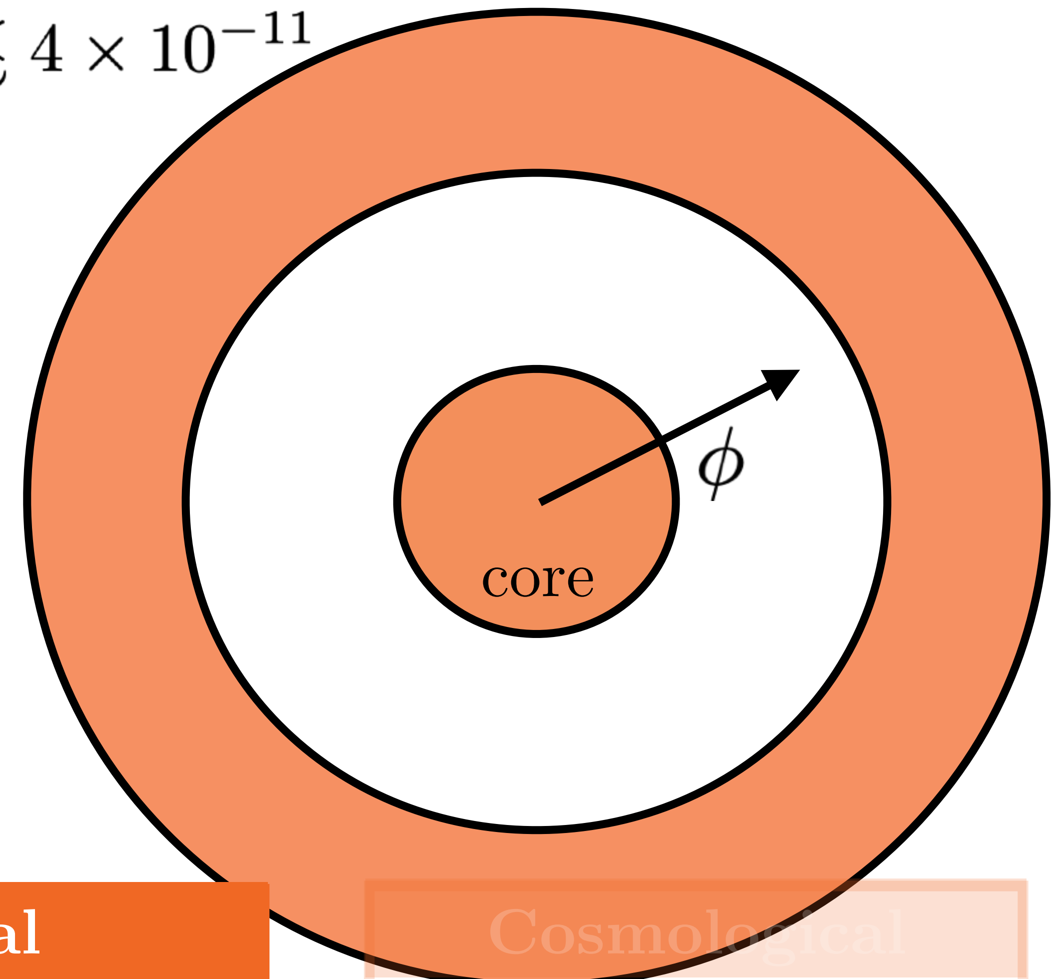


SN1987A

$T = 30$ MeV

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

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

Terrestrial

Collider

5th force

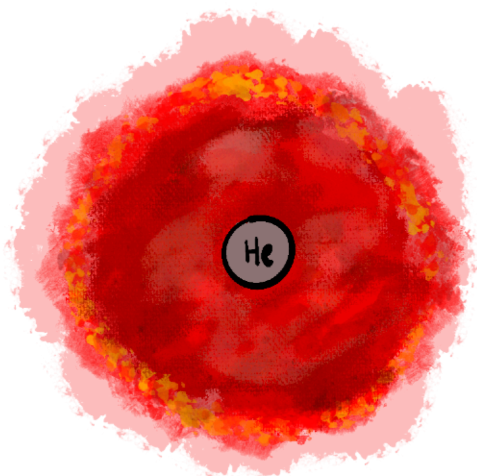
Astrophysical

Stellar emission

Cosmological

AIs: Constraints

[Knapen, Lin, Zurek, 2017]



RG and HB stars

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

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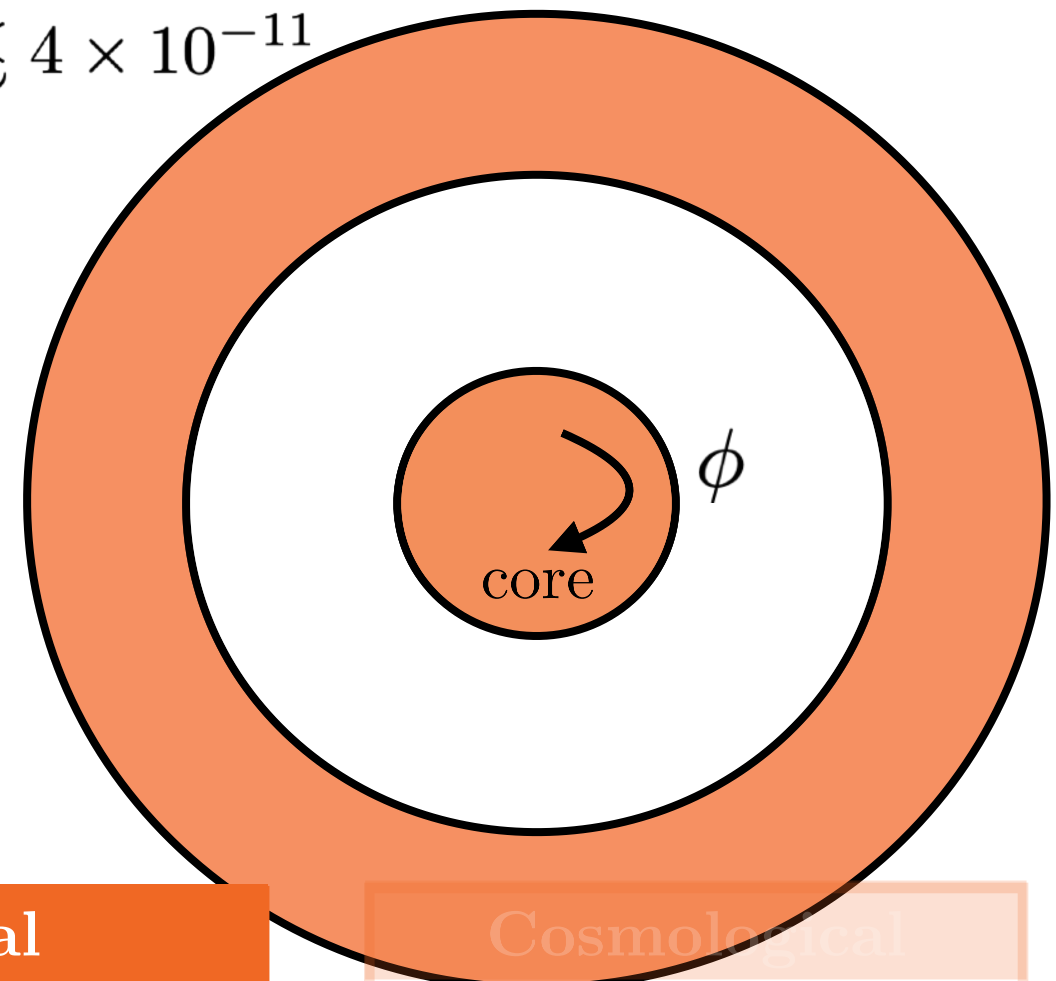
SN1987A

$T = 30$ MeV

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

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

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



Terrestrial

⇨ Collider

⇨ 5th force

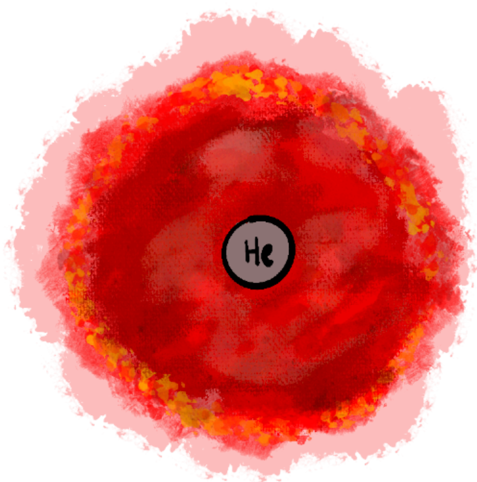
Astrophysical

⇨ Stellar emission

Cosmological

AIs: Constraints

[Knapen, Lin, Zurek, 2017]



RG and HB stars

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

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

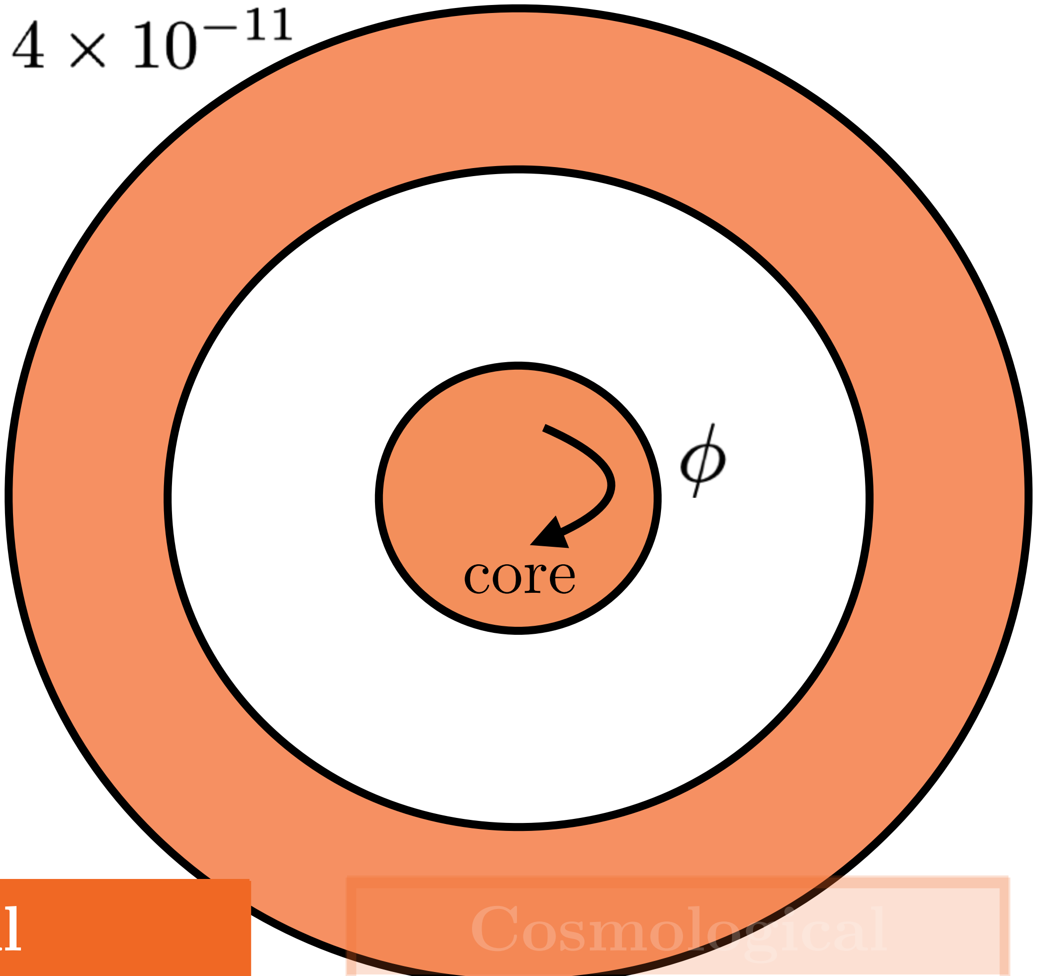
SN1987A

$T = 30$ MeV

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

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

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

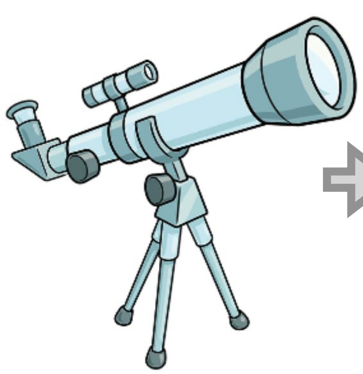


Terrestial

⇨ Collider

⇨ 5th force

Astrophysical

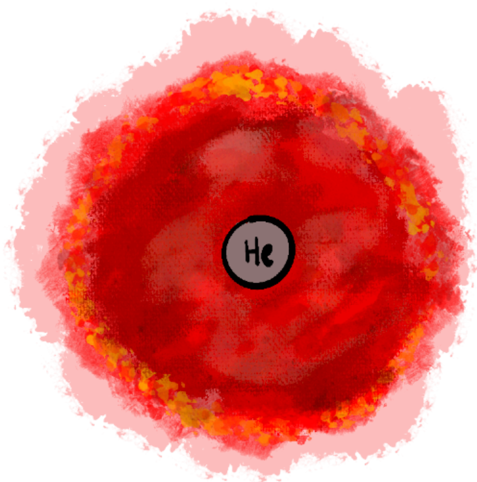


⇨ Stellar emission

Cosmological

AIs: Constraints

[Knapen, Lin, Zurek, 2017]



RG and HB stars

$m_\phi < T \sim 10$ keV

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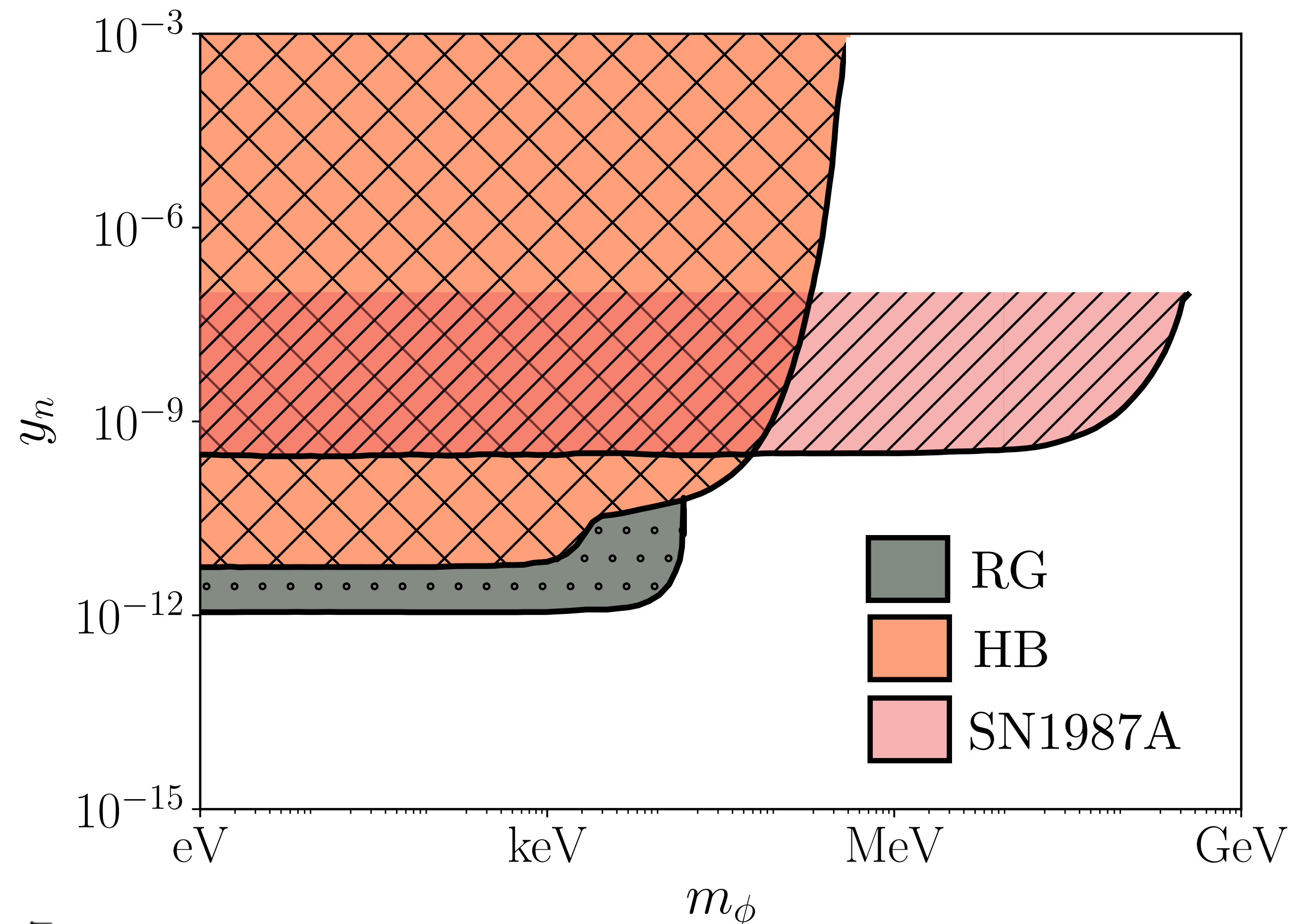

SN1987A

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Terrestrial

Collider

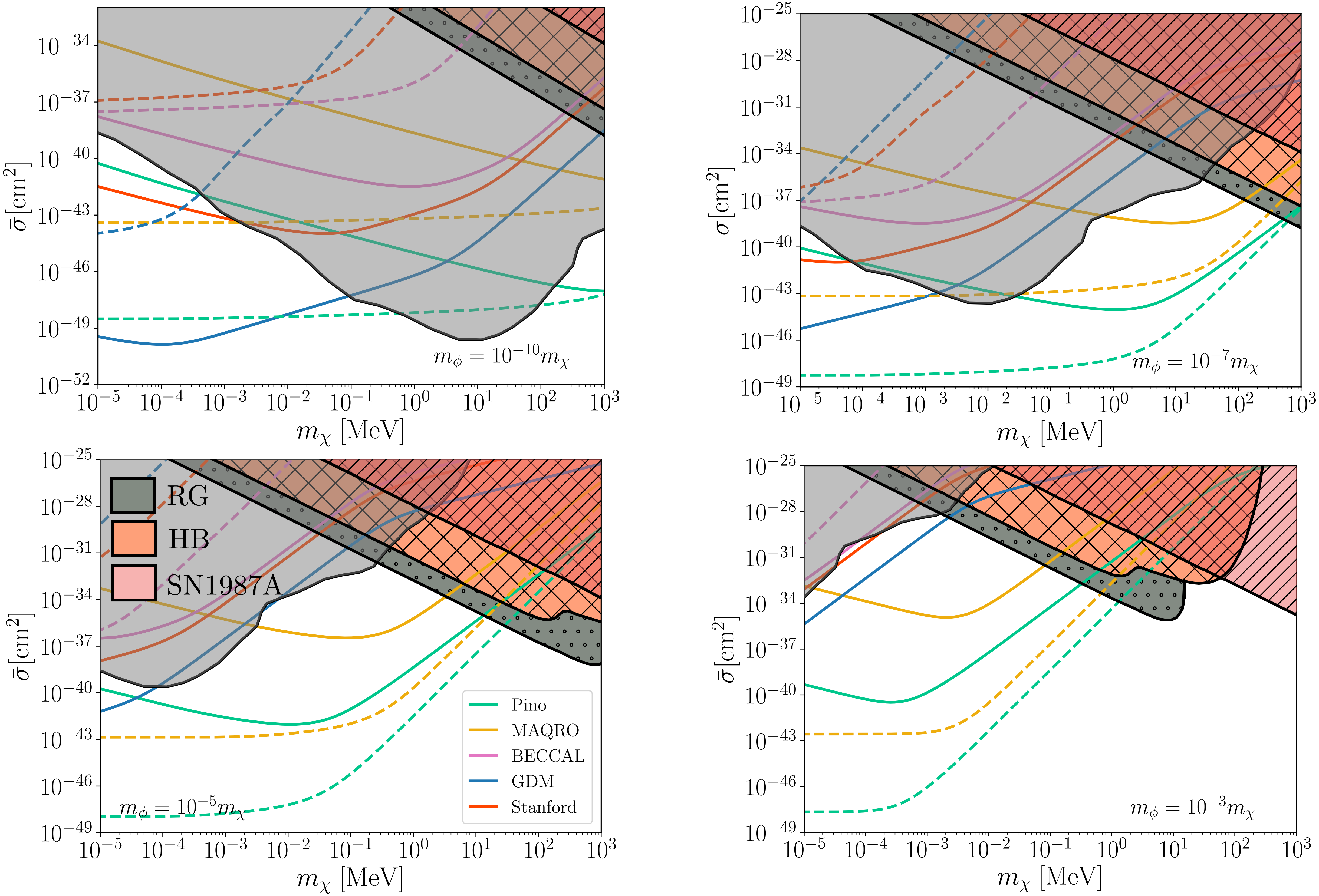
5th force

Astrophysical

Stellar emission

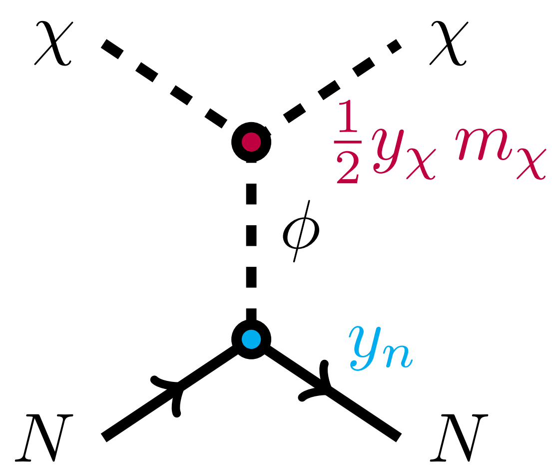
Cosmological

AIs: Constraints



AIs: Constraints

[Knapen, Lin, Zurek, 2017]

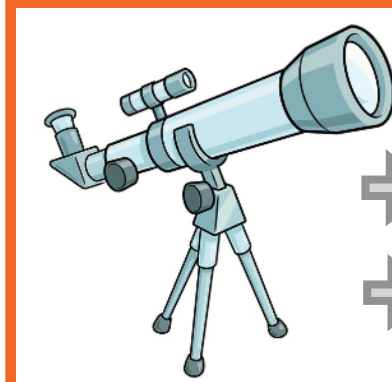


Terrestrial

Collider

5th force

Astrophysical



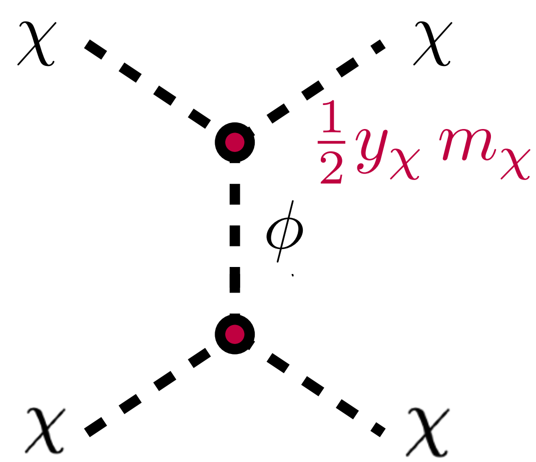
Stellar emission

DMSI

Cosmological

AIs: Constraints

[Knapen, Lin, Zurek, 2017]



Terrestrial

Collider

5th force

Astrophysical

Stellar emission

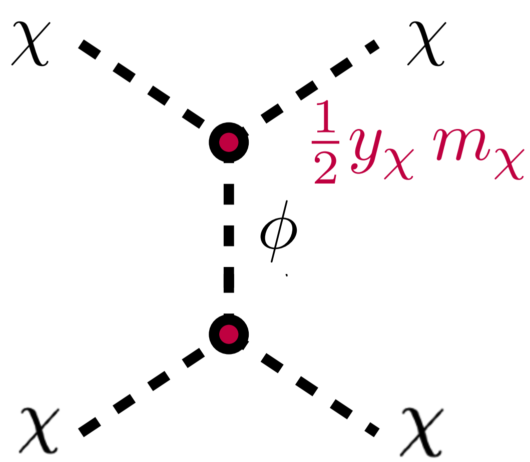
DMSI

Cosmological

AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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



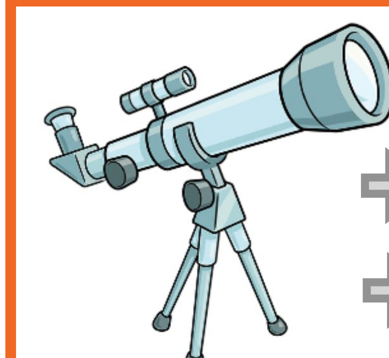
$$\frac{y_\chi^2}{4\pi} < 6 \times 10^{-10} \left(\frac{m_\chi}{1\ \mathrm{MeV}}\right)^{3/2}$$

Terrestrial

Collider

5th force

Astrophysical

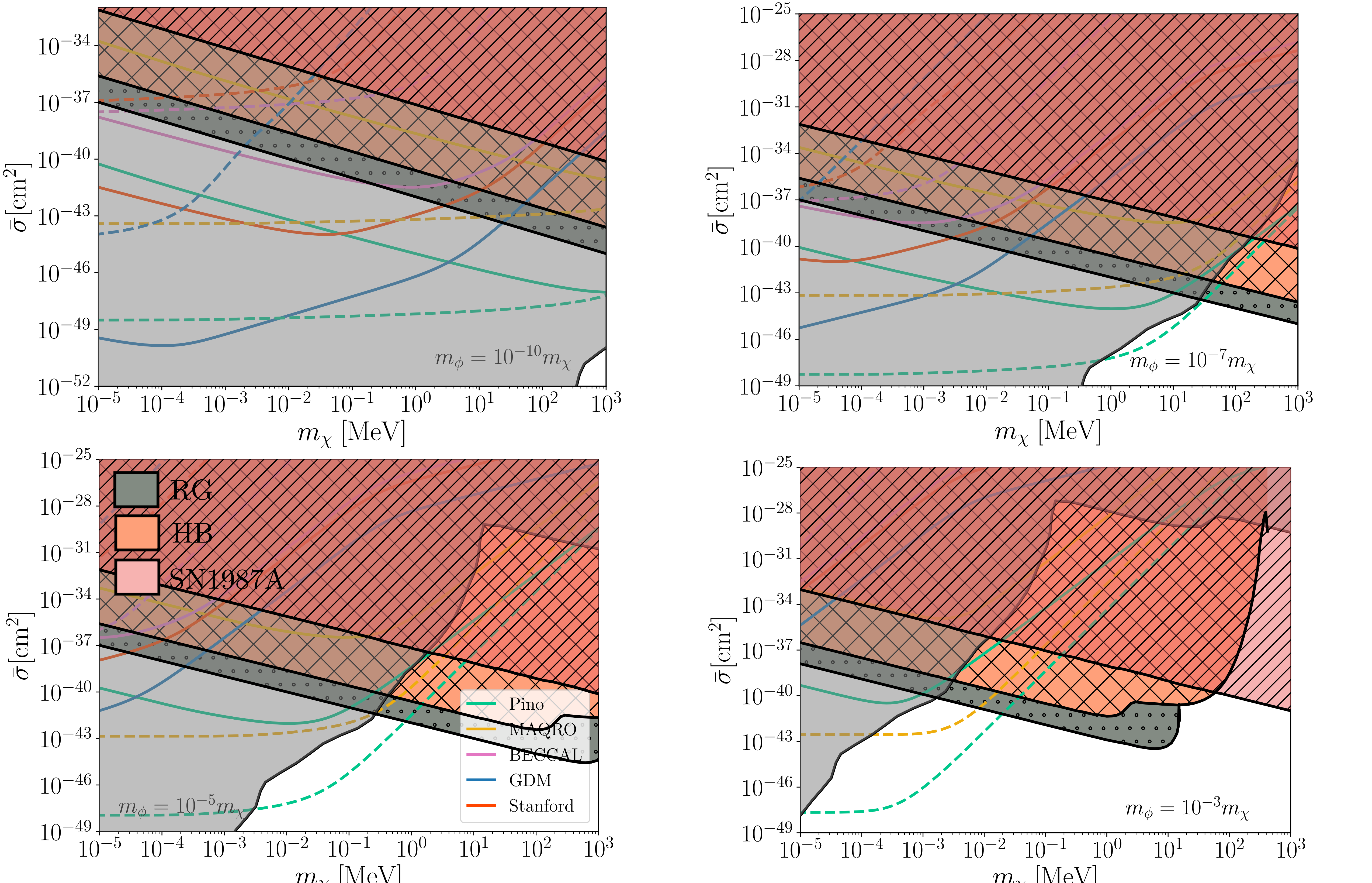


Stellar emission

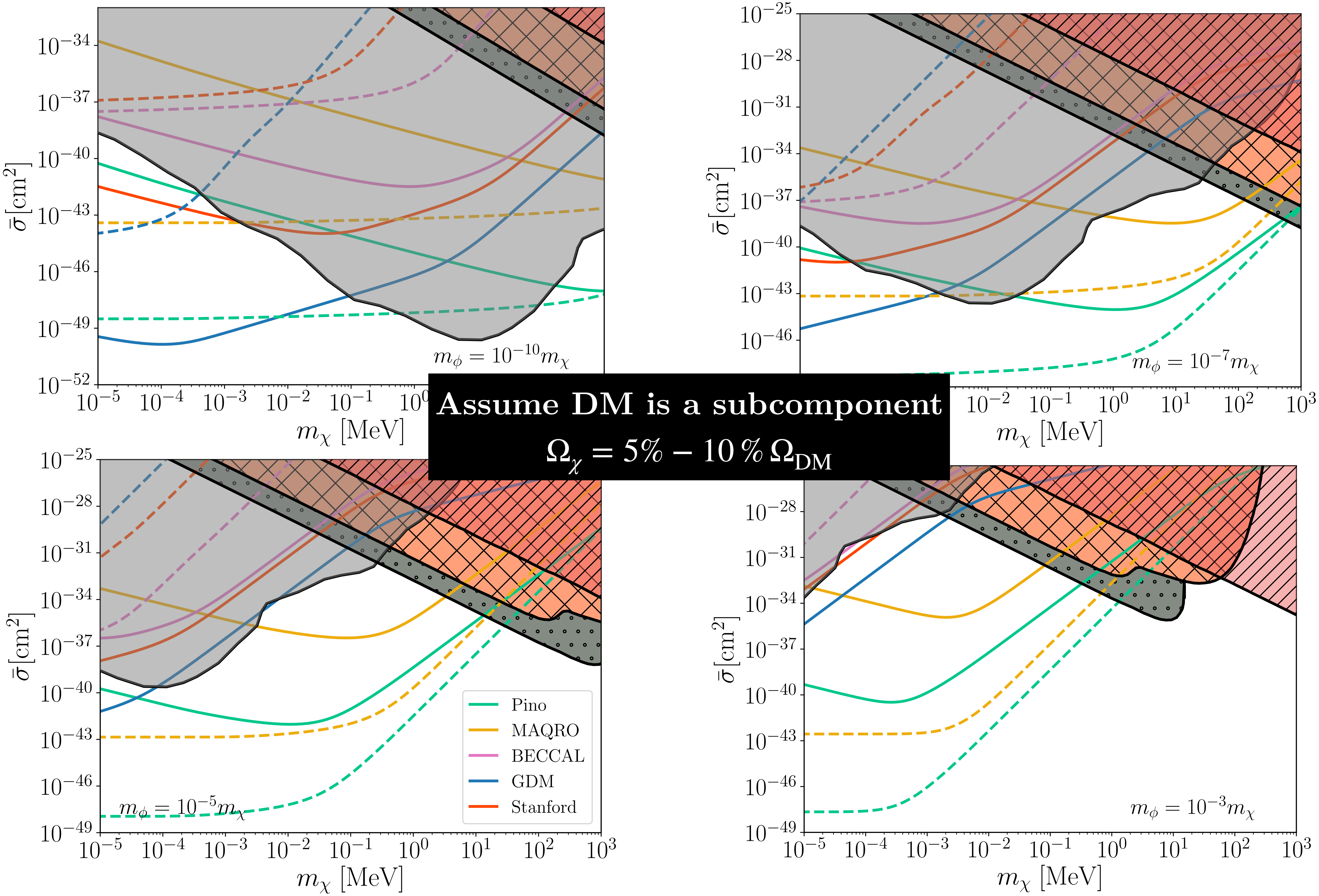
DMSI

Cosmological

AIs: Constraints



AIs: Constraints



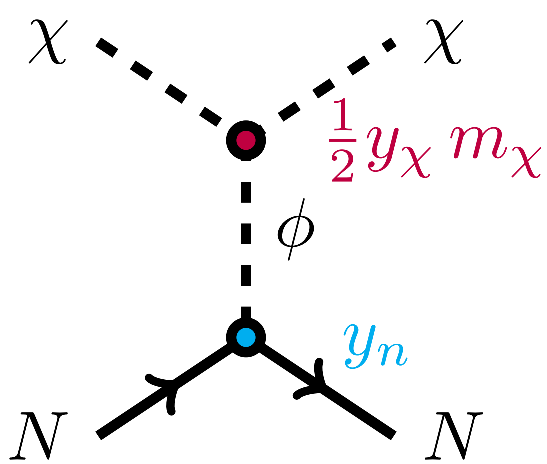
Assume DM is a subcomponent

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

AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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



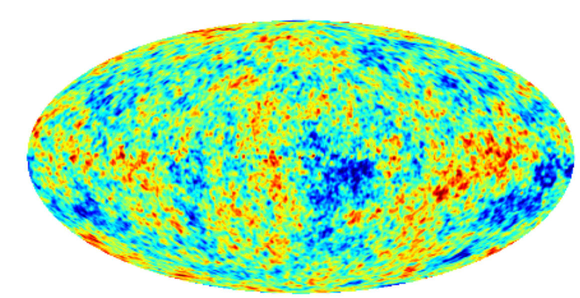
Terrestrial

- Collider
- 5th force

Astrophysical

- Stellar emission
- DMSI

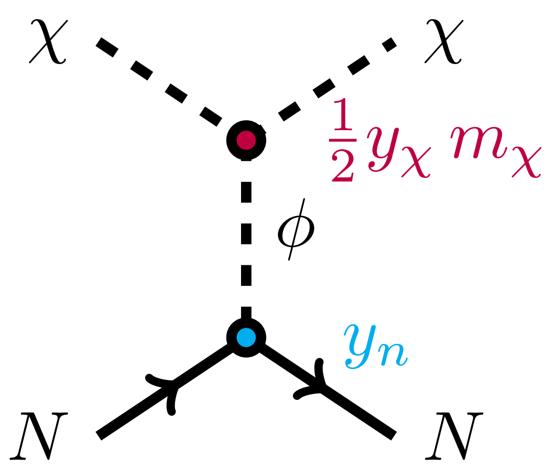
Cosmological

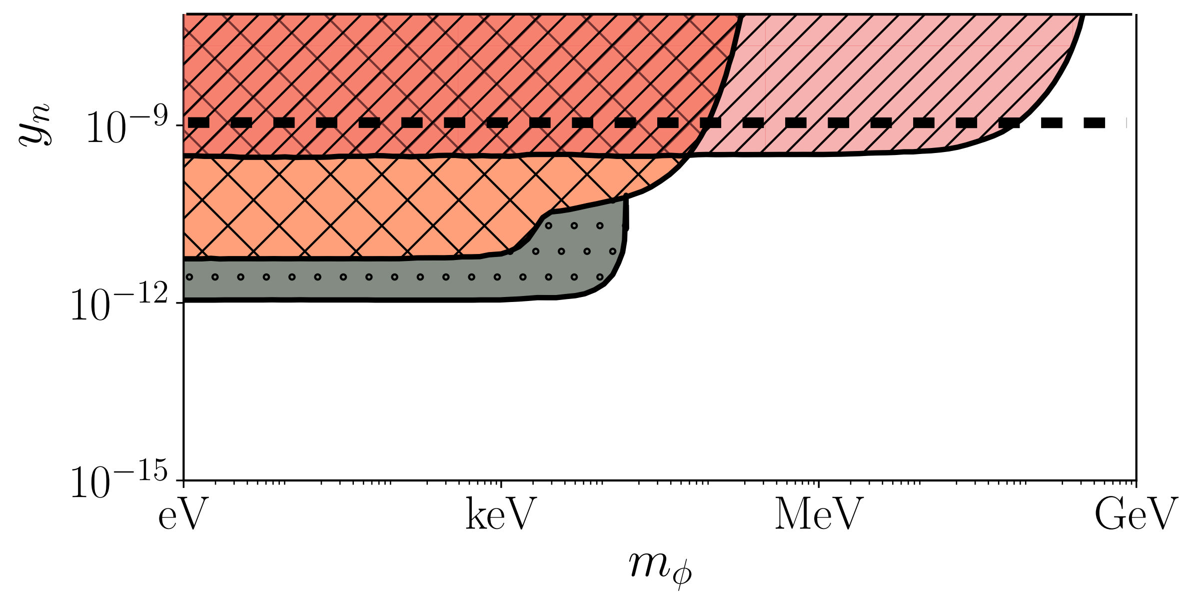


AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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





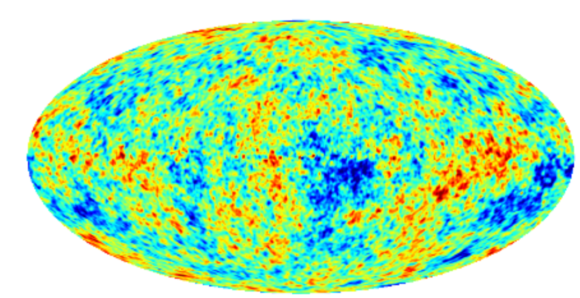
Terrestrial

- Collider
- 5th force

Astrophysical

- Stellar emission
- DMSI

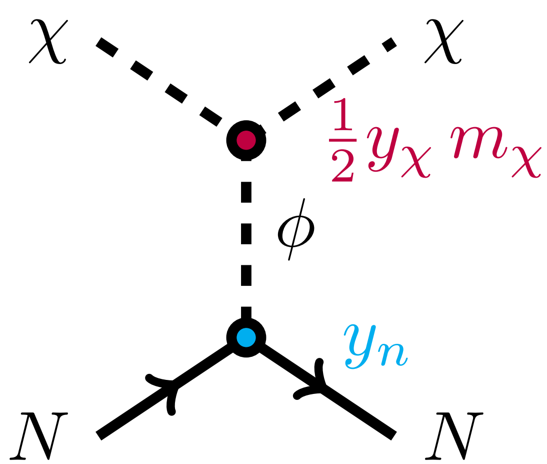
Cosmological

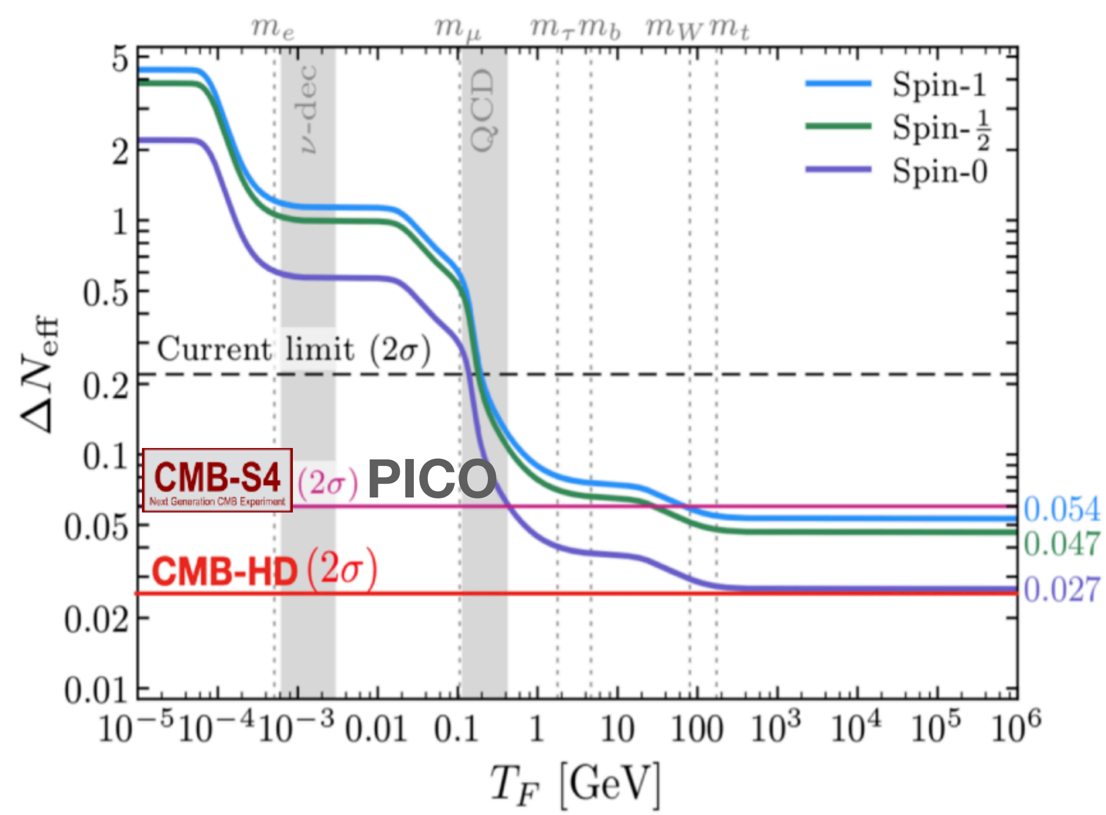


AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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





Terrestial

Collider

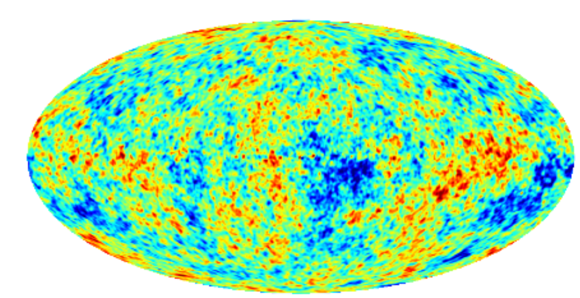
5th force

Astrophysical

Stellar emission

DMSI

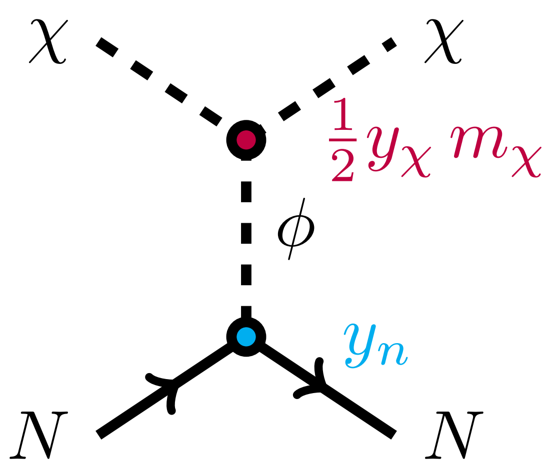
Cosmological



AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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



$$\left.\begin{aligned} v_\chi^{\text{esc}} &\sim \sqrt{\frac{T_\chi}{m_\chi^{\text{min}}}} \\ T_\chi &\sim \left(\frac{g(\text{today})}{g(T_\chi^{\text{dec}})}\right)^{\frac{1}{3}} T_\gamma \end{aligned}\right\} \quad m_\chi \gtrsim 10\ \text{eV}$$

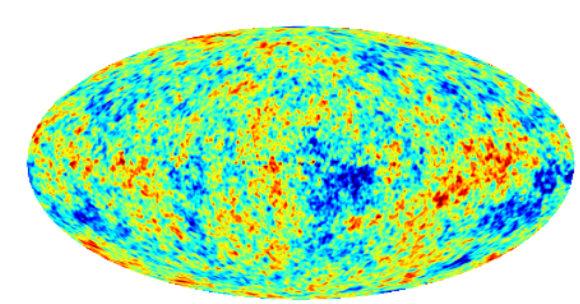
Terrestrial

- Collider
- 5th force

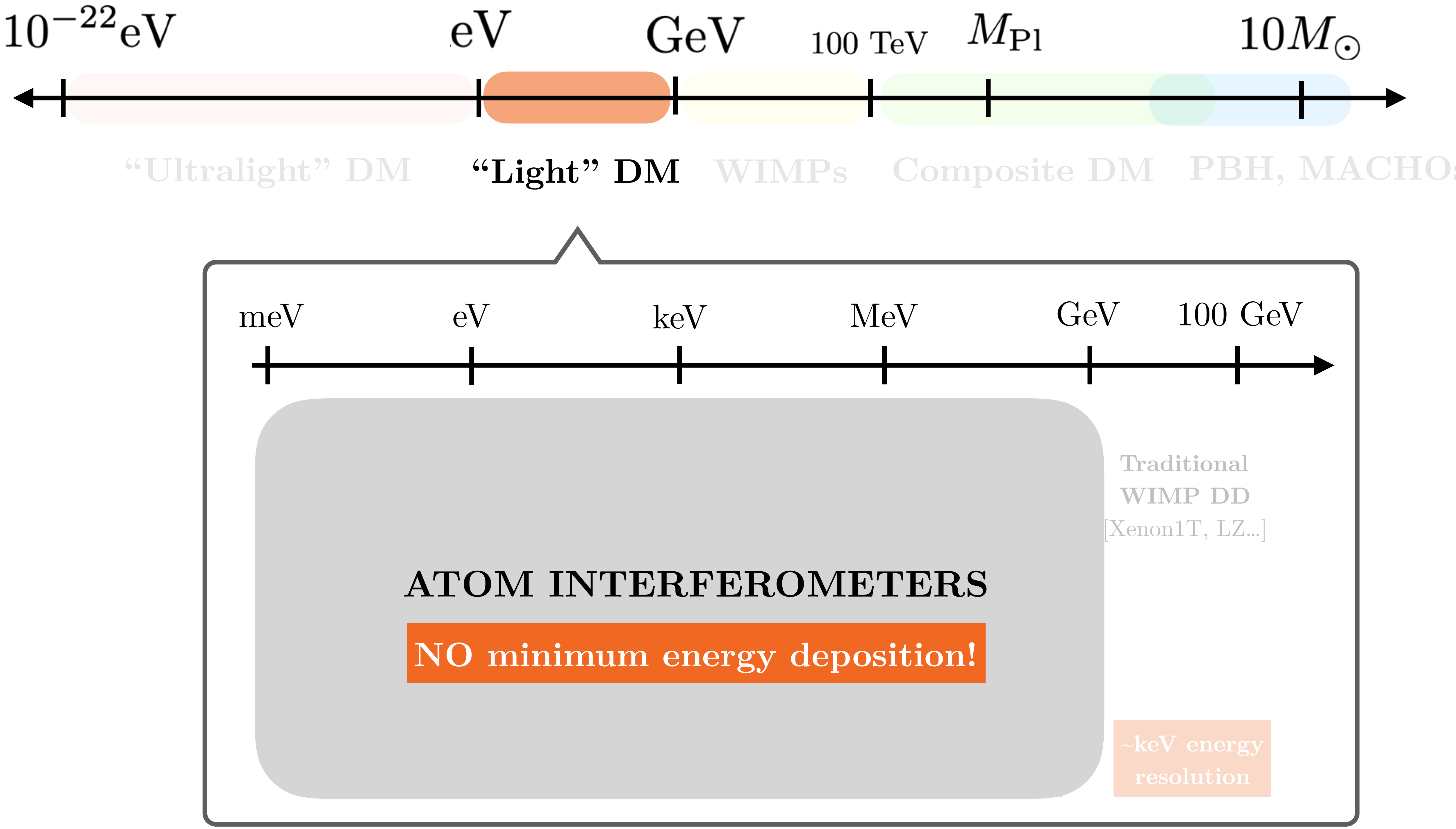
Astrophysical

- Stellar emission
- DMSI

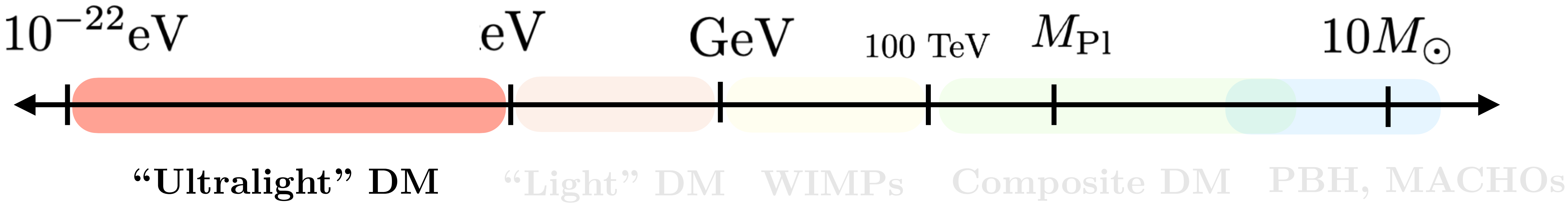
Cosmological



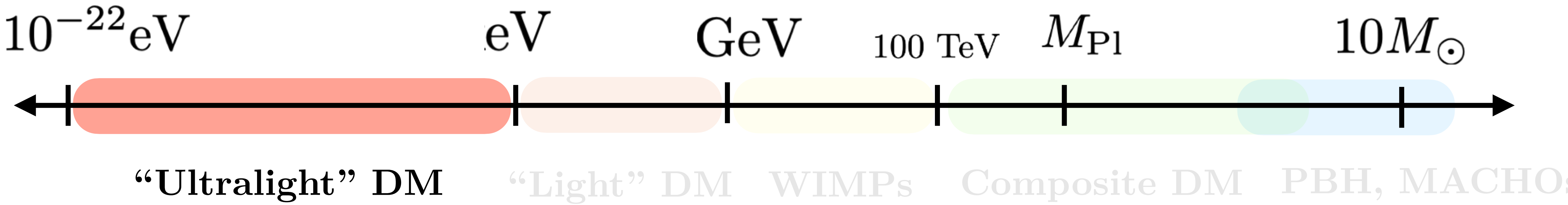
Dark Matter: where to look?

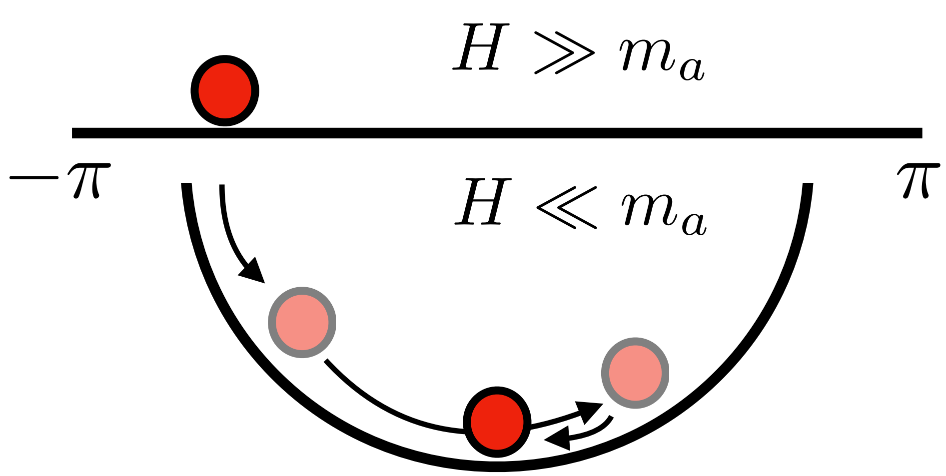


Dark Matter: where to look?



Dark Matter: where to look?





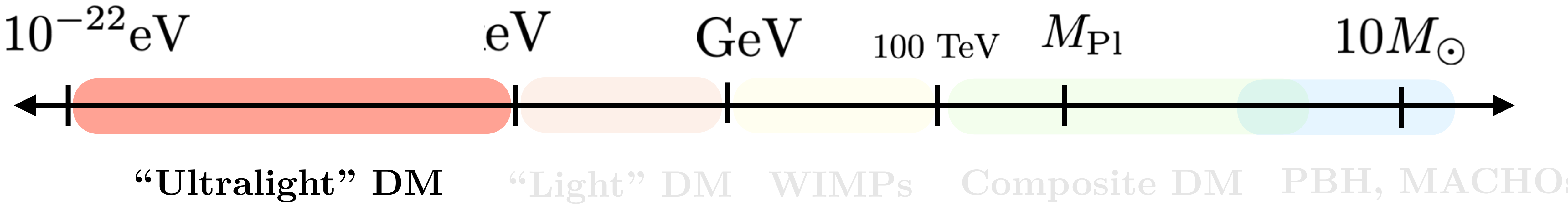
[Preskill, Wise, Wilczek, 1983]

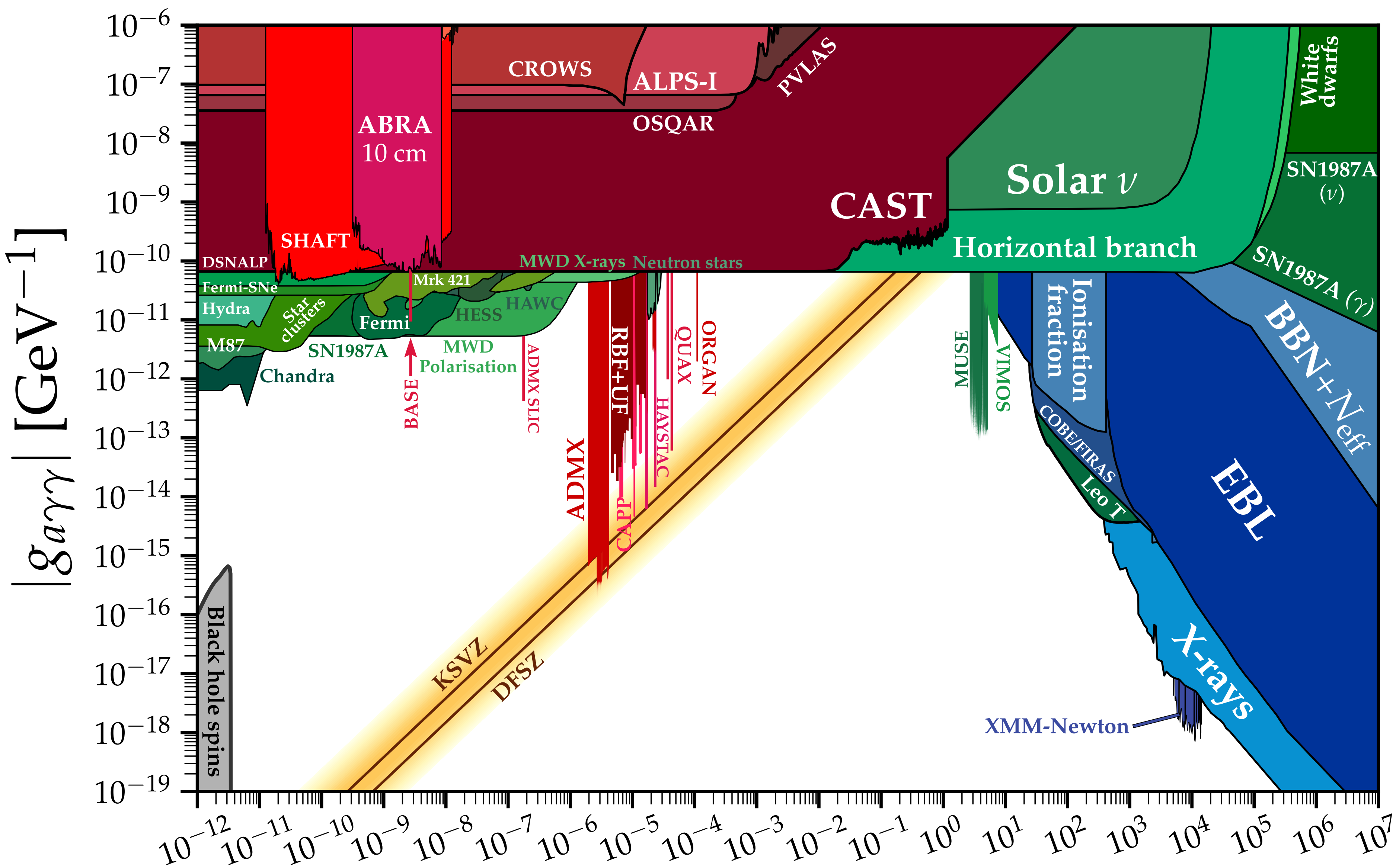
[Peccei, Quinn, 1977] [Wilzeck]

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

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

Dark Matter: where to look?





[Ciaran O'Hare, 2020]

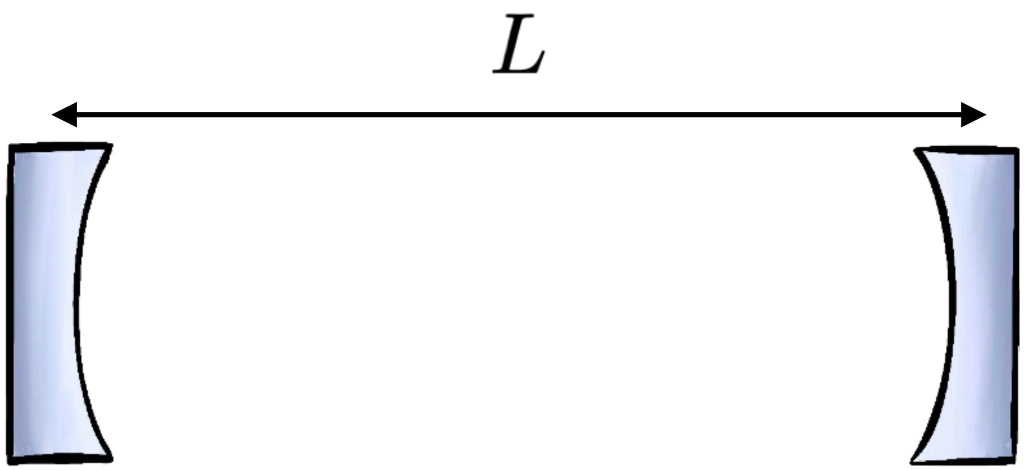
Optomechanical Cavities

Axioptomechanics

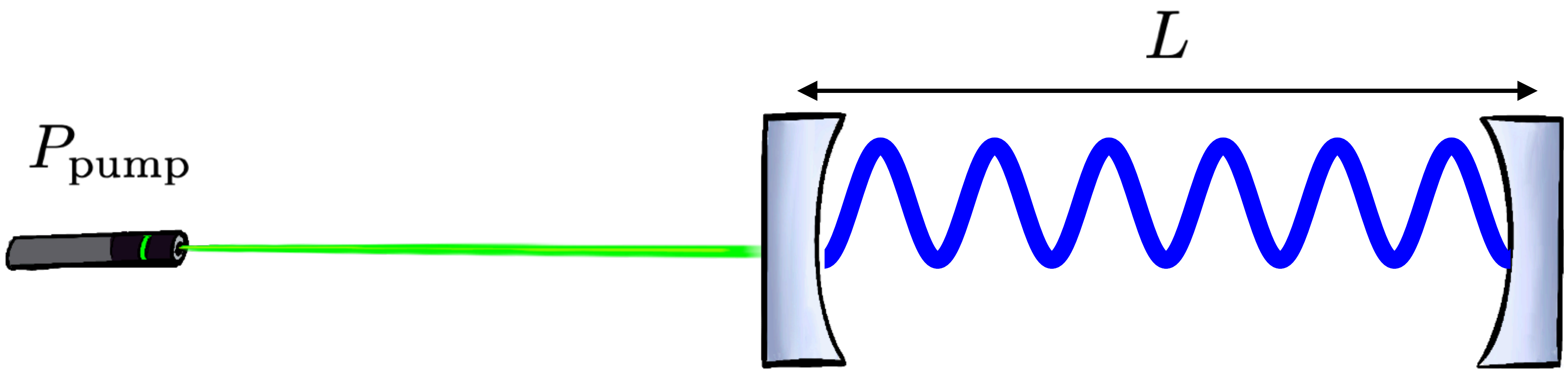
[work in progress]

with Yikun Wang and Kathryn M. Zurek

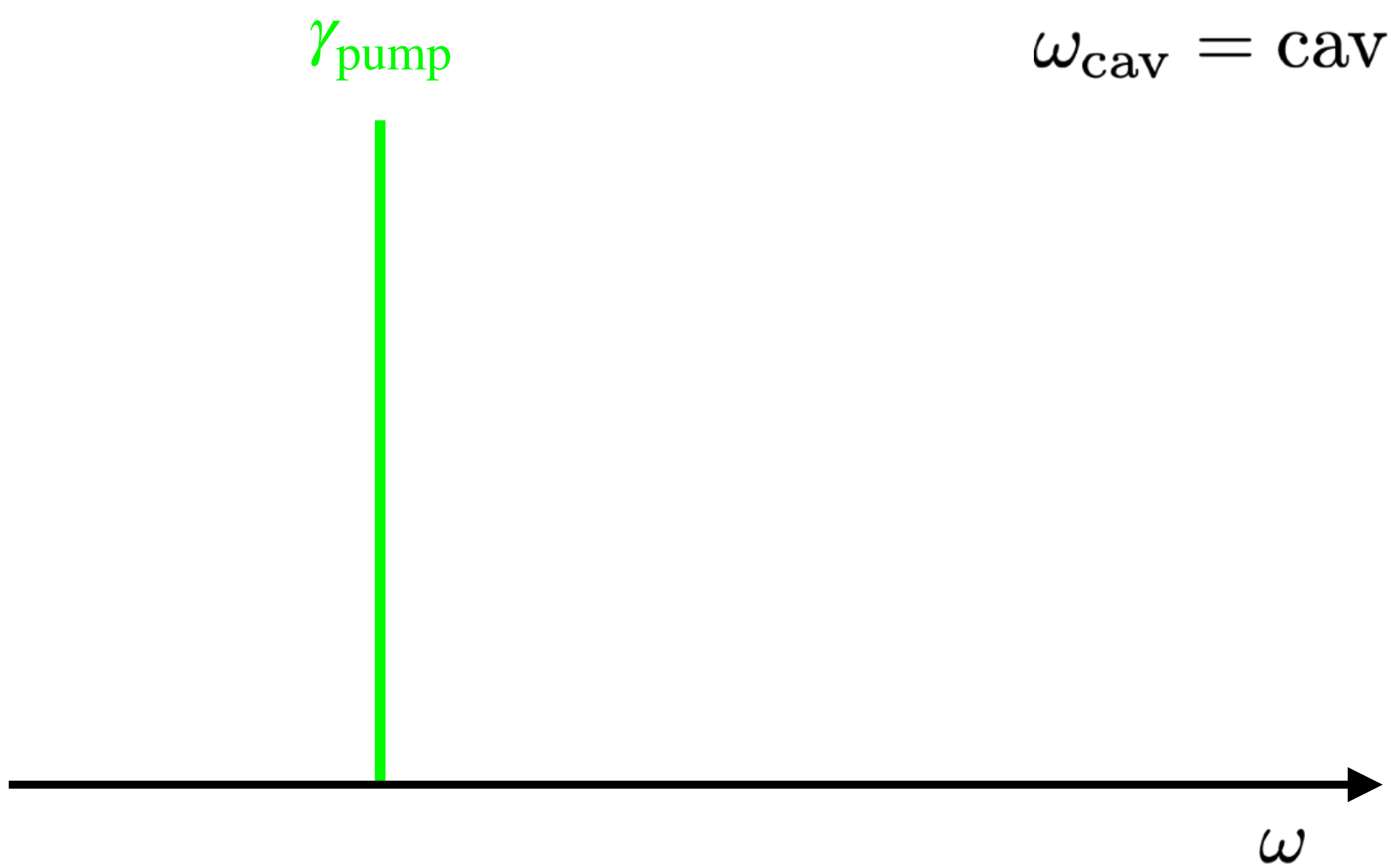
Standard Optomechanics



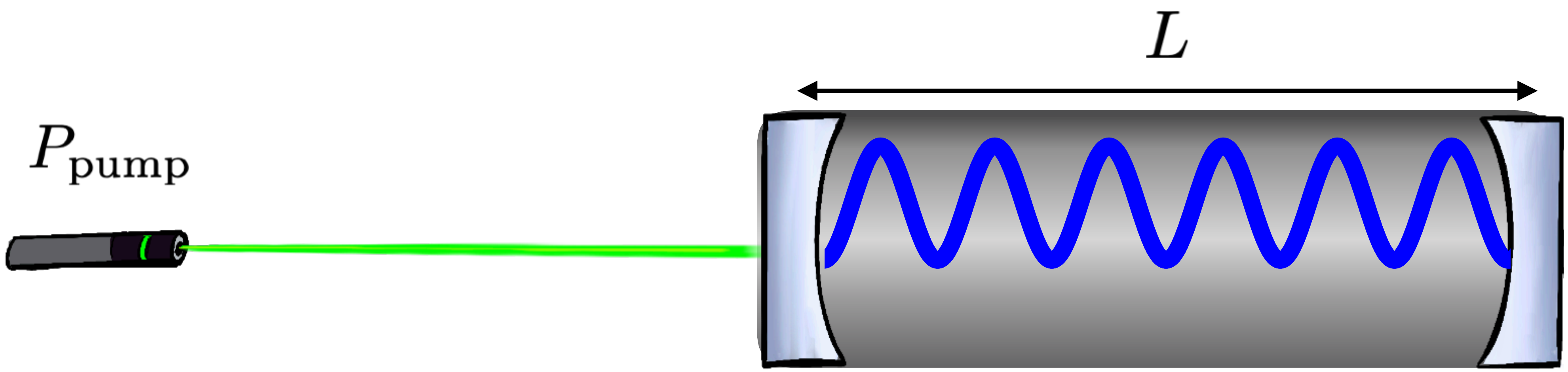
Standard Optomechanics



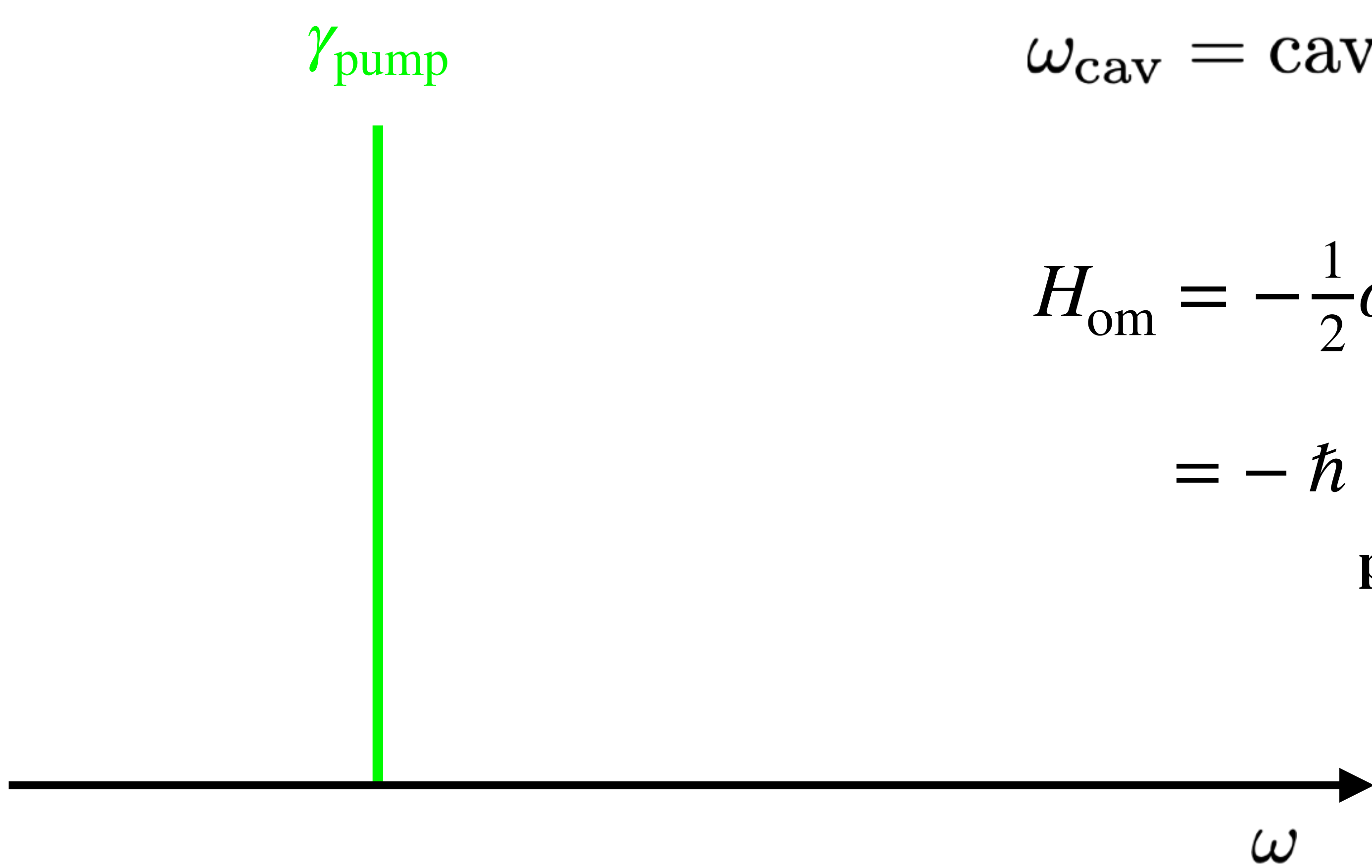
$$\omega_{\mathbf{cav}} = \mathbf{cav}\frac{\pi}{L}, \quad \mathbf{cav} \subset \mathbb{Z}$$



Standard Optomechanics



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

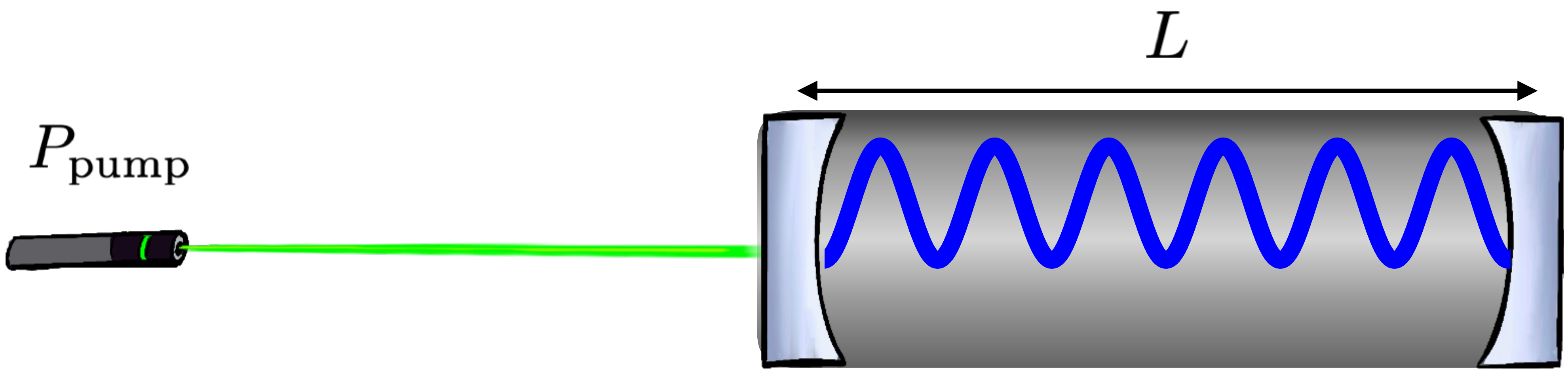


$$\begin{aligned} H_{\text{om}} &= -\frac{1}{2}\alpha \int d^3\mathbf{r}\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{E}(\mathbf{r}) \\ &= -\hbar \sum_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{k}_\mathrm{m}} g_0 \left(a_{\mathbf{p}_1} a^\dagger_{\mathbf{p}_2} b_{\mathbf{k}_\mathrm{m}} + a_{\mathbf{p}_1} a^\dagger_{\mathbf{p}_2} b^\dagger_{\mathbf{k}_\mathrm{m}} \right) \end{aligned}$$

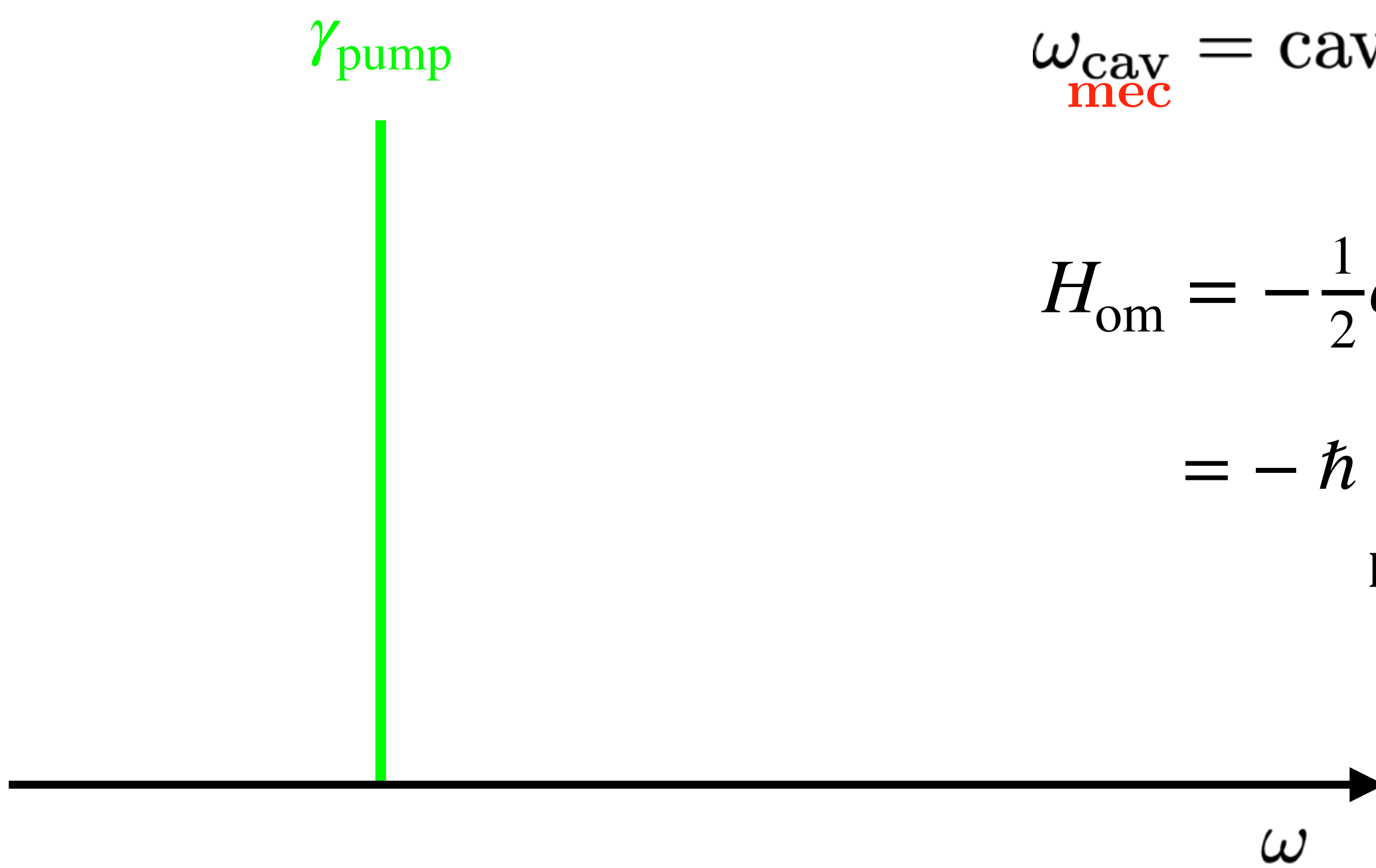
Standard Optomechanics

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

$$\omega_{\gamma 1} = \omega_{\mathrm{m}} + \omega_{\gamma 2}$$



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

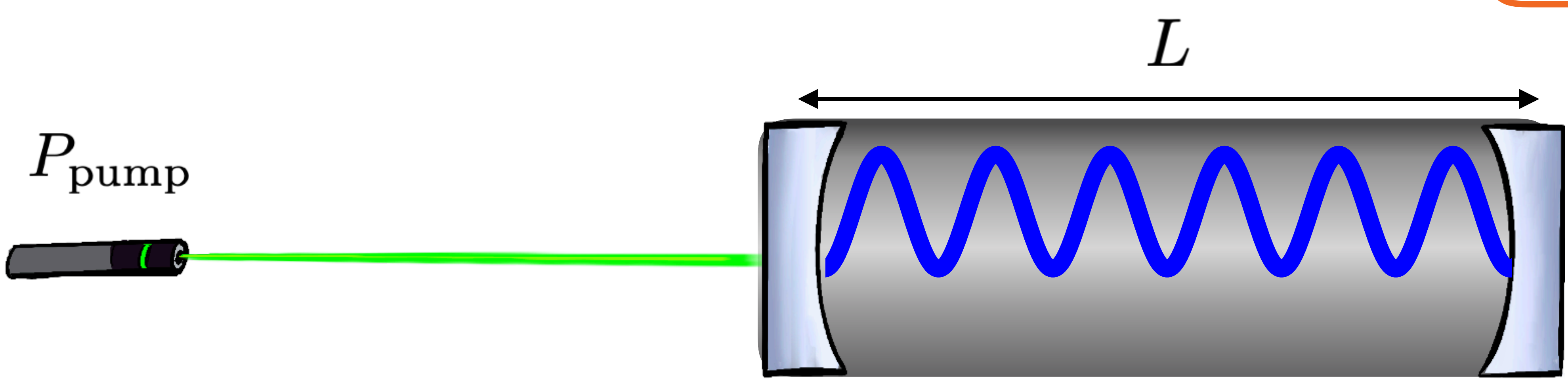


$$H_{\text{om}} = -\frac{1}{2}\alpha \int d^3\mathbf{r}\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{E}(\mathbf{r})$$

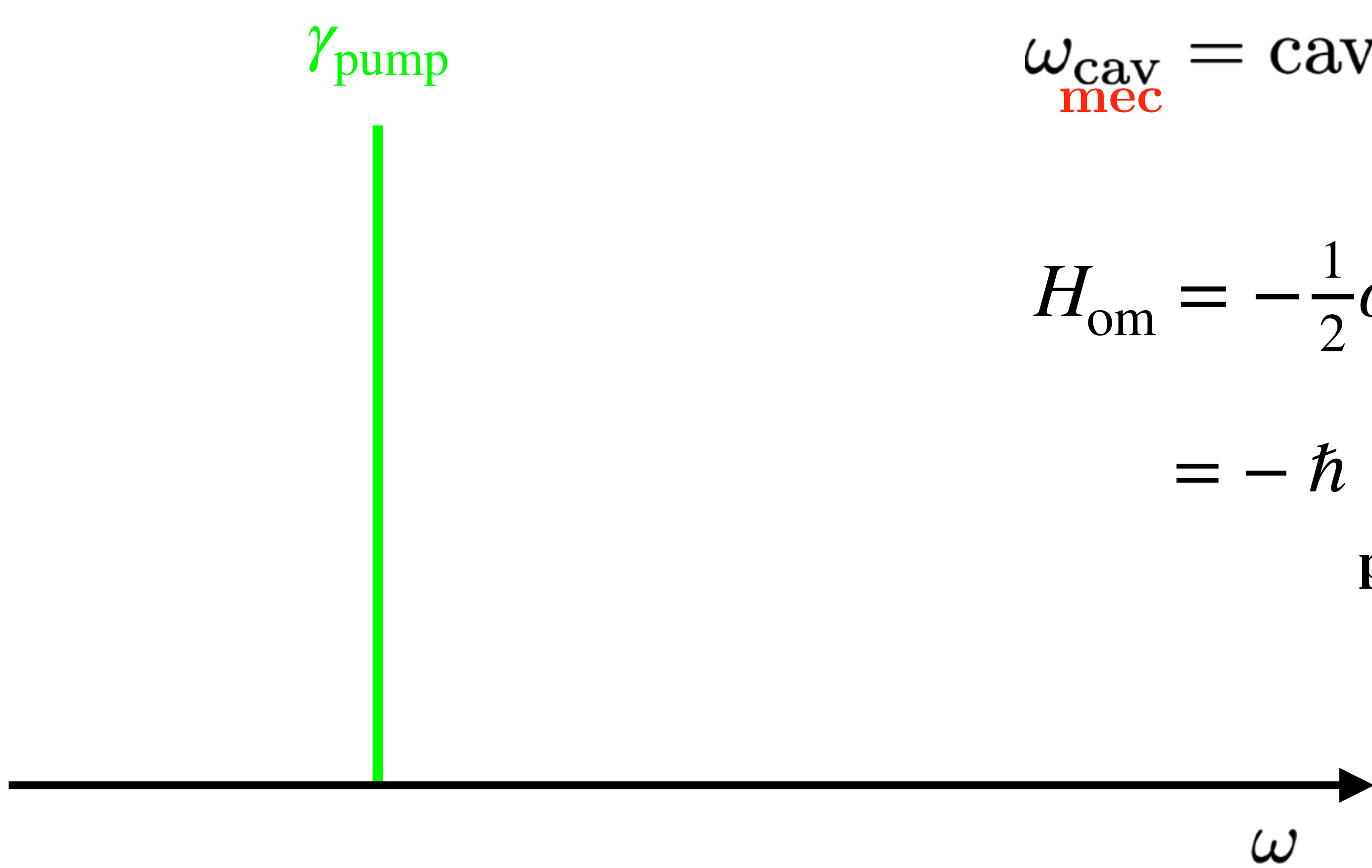
$$= -\hbar \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left(a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b_{\mathbf{k_m}} + a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b^{\dagger}_{\mathbf{k_m}} \right)$$

Standard Optomechanics

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



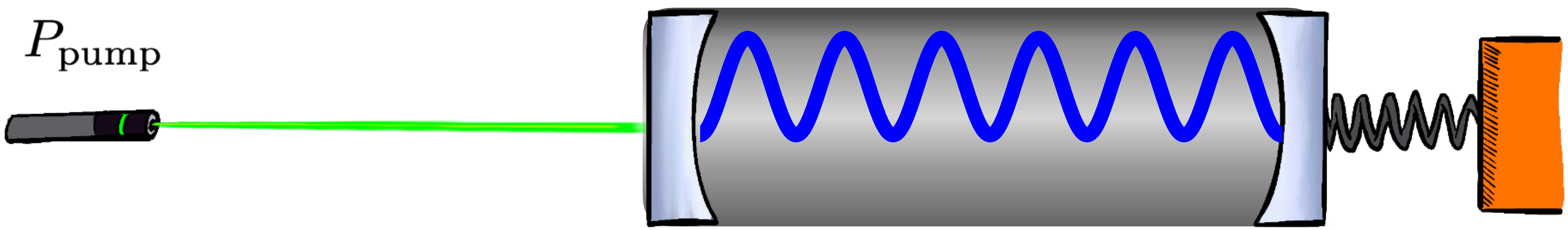
$$\omega_{\substack{\text{cav}\\ \text{mec}}} = \text{cav}\,\frac{\pi}{L}\,c_s\,,\quad \text{cav} \subset \mathbb{Z}$$



$$H_{\mathrm{om}} = -\frac{1}{2}\alpha\int d^3\mathbf{r}\, n(\mathbf{r})\,\mathbf{E}(\mathbf{r})\cdot\mathbf{E}(\mathbf{r})$$
$$= -\hbar\sum_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{k}_\mathrm{m}} g_0\left(a_{\mathbf{p}_1}a^\dagger_{\mathbf{p}_2}b_{\mathbf{k}_\mathrm{m}} + a_{\mathbf{p}_1}a^\dagger_{\mathbf{p}_2}b^\dagger_{\mathbf{k}_\mathrm{m}}\right)$$

Standard Optomechanics

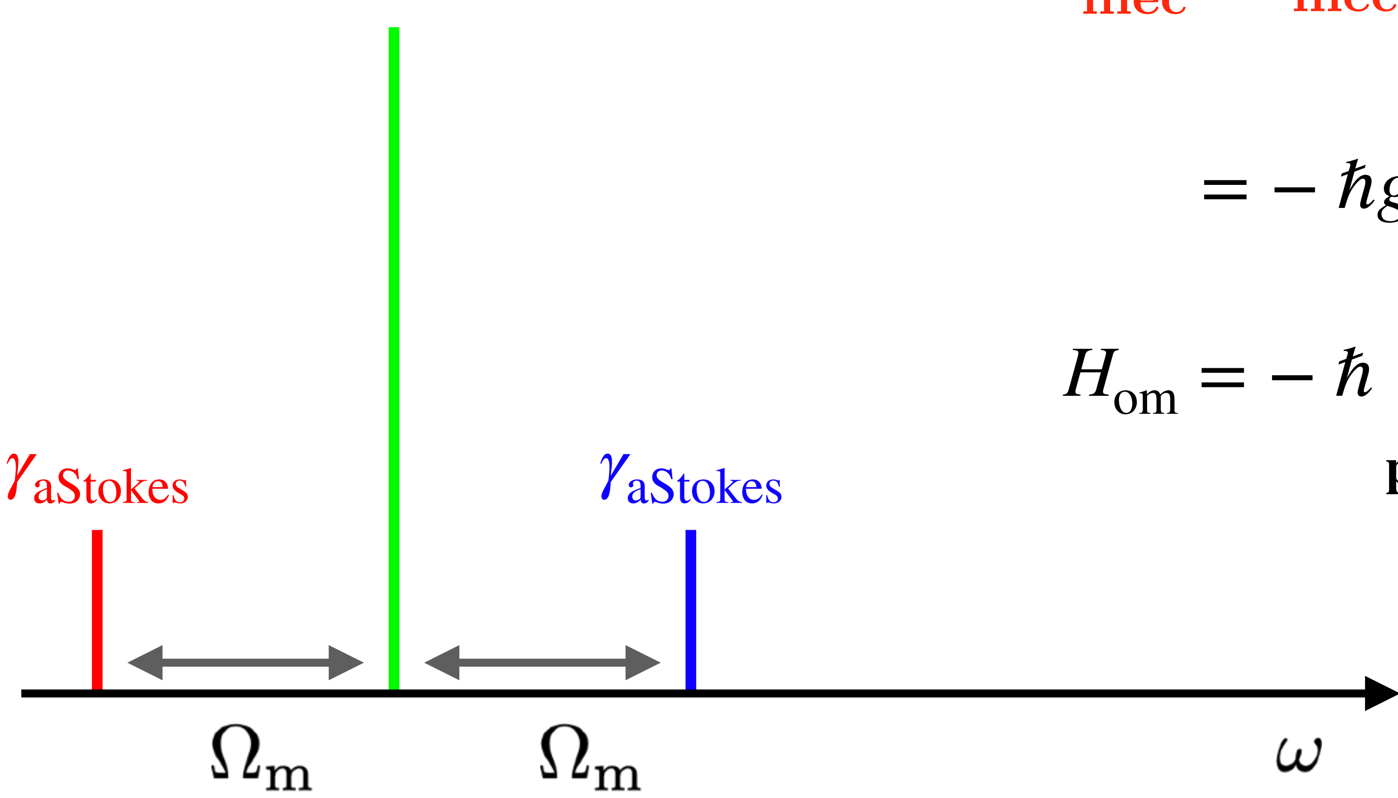
$$\Omega_{\mathrm{m}} = 2c_s\omega_{\mathrm{opt}}$$



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

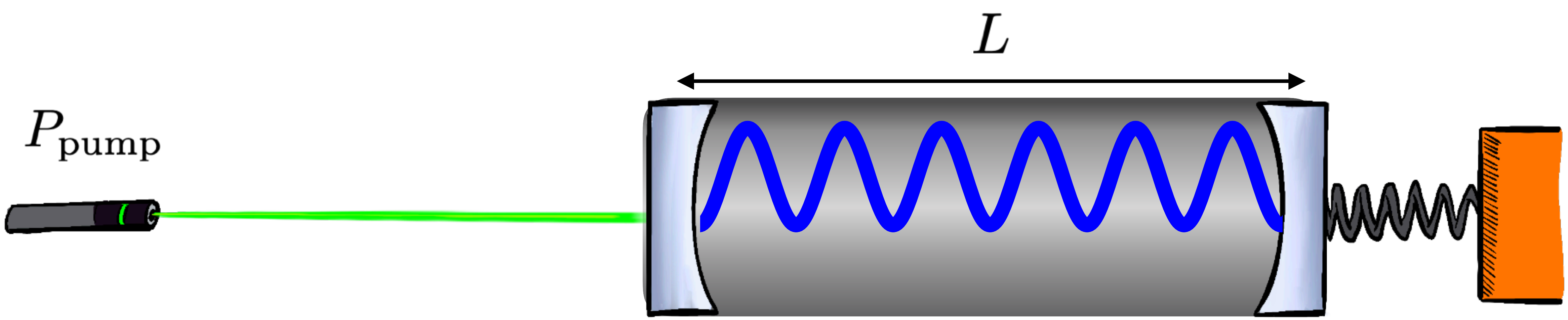
$$= -\hbar g_0\sqrt{n_{\gamma_{\mathrm{pump}}}}\left(\gamma_{\mathrm{pump}}\gamma^\dagger\phi^\dagger + \gamma_{\mathrm{pump}}\gamma^\dagger\phi\right)$$

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



Standard Optomechanics

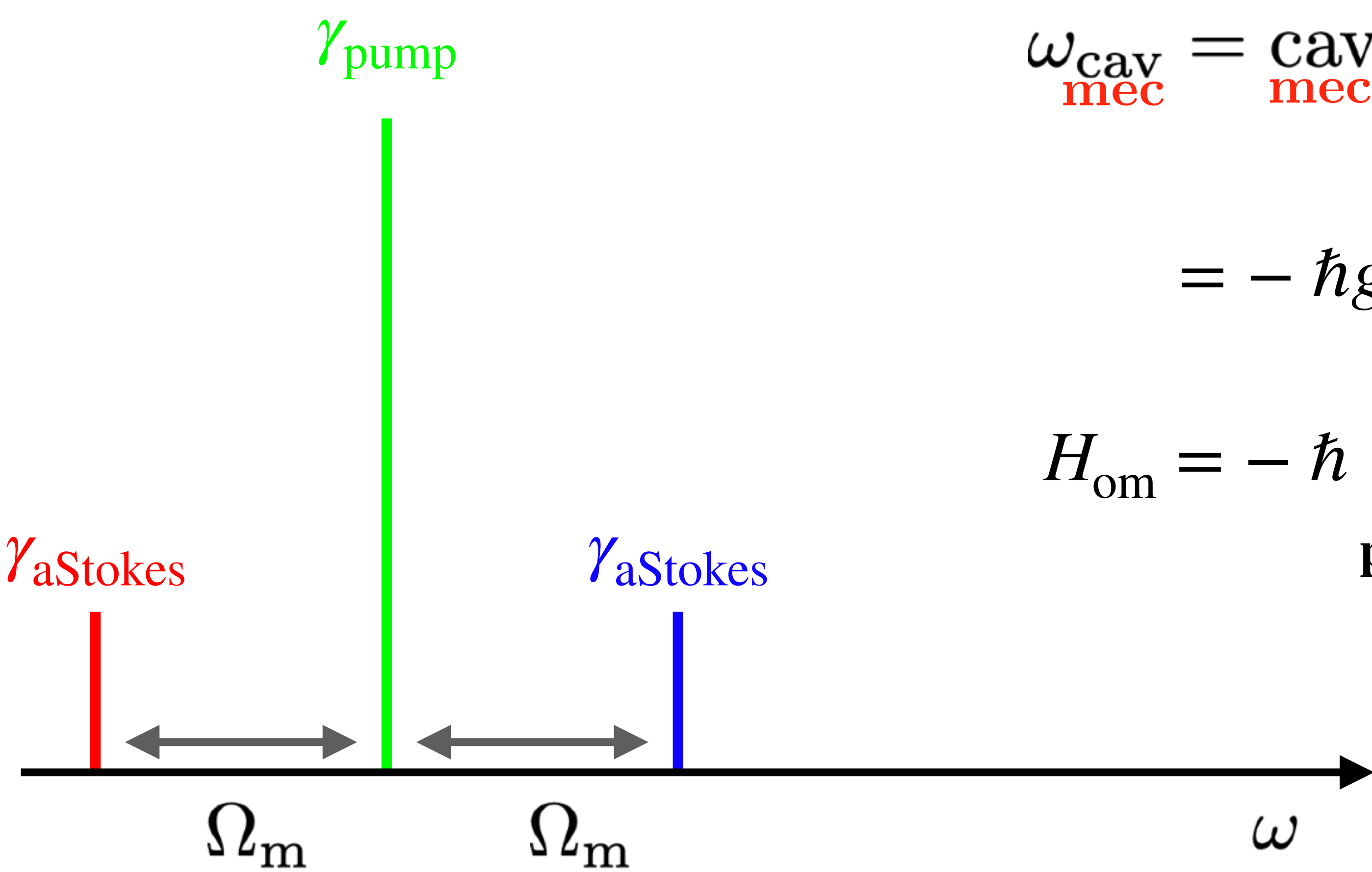
$$\Omega_{\mathrm{m}} = 2 c_s \omega_{\mathrm{opt}}$$



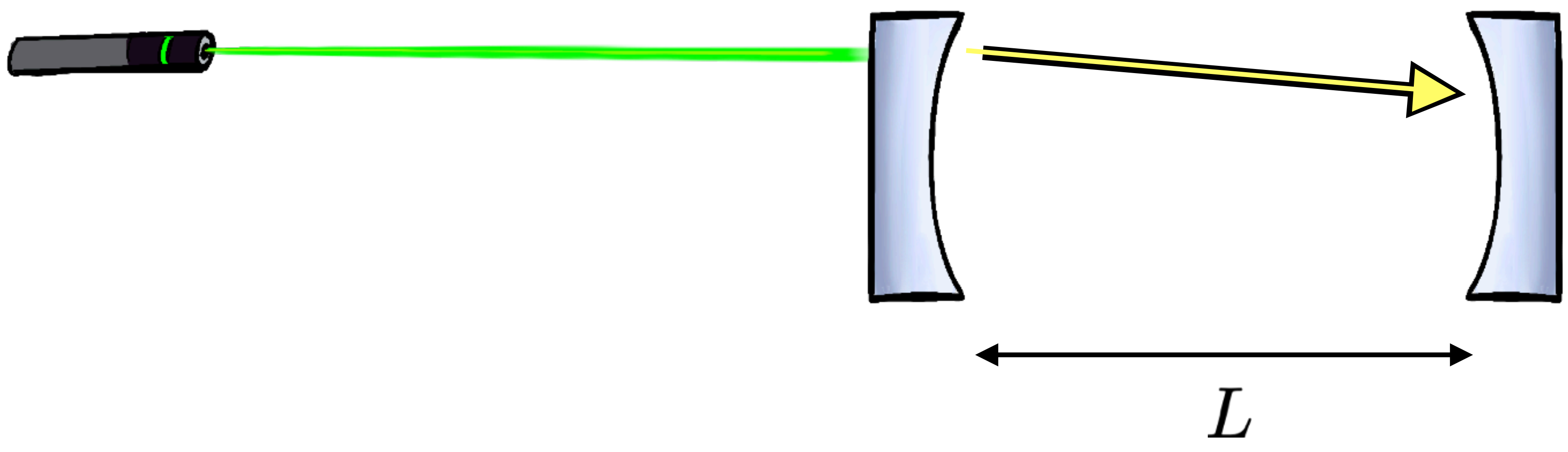
$$\omega_{\substack{\mathrm{cav}\\ \mathrm{mec}}} = \substack{\mathrm{cav}\\ \mathrm{mec}}\, \frac{\pi}{L} c_s, \quad \mathrm{cav} \subset \mathbb{Z}$$

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

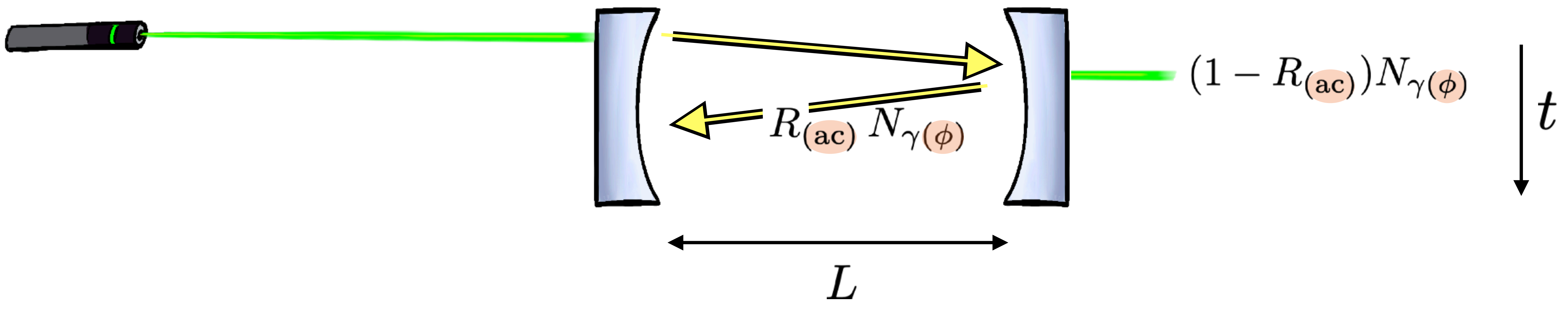
$$H_{\mathrm{om}} = -\hbar \sum_{\mathbf{p_1}, \mathbf{p_2}, \mathbf{k_m}} g_0 \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b_{\mathbf{k_m}} + a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} \right)$$



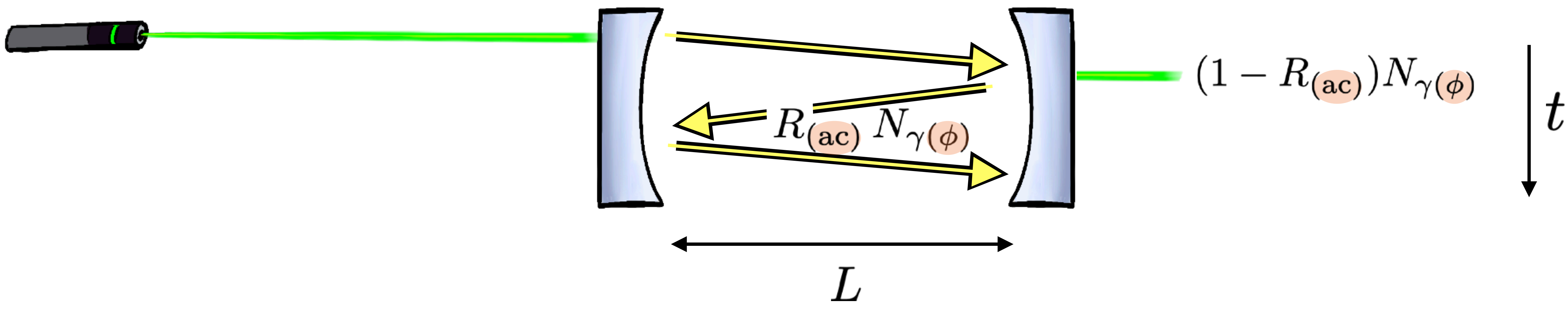
Standard Optomechanics



Standard Optomechanics

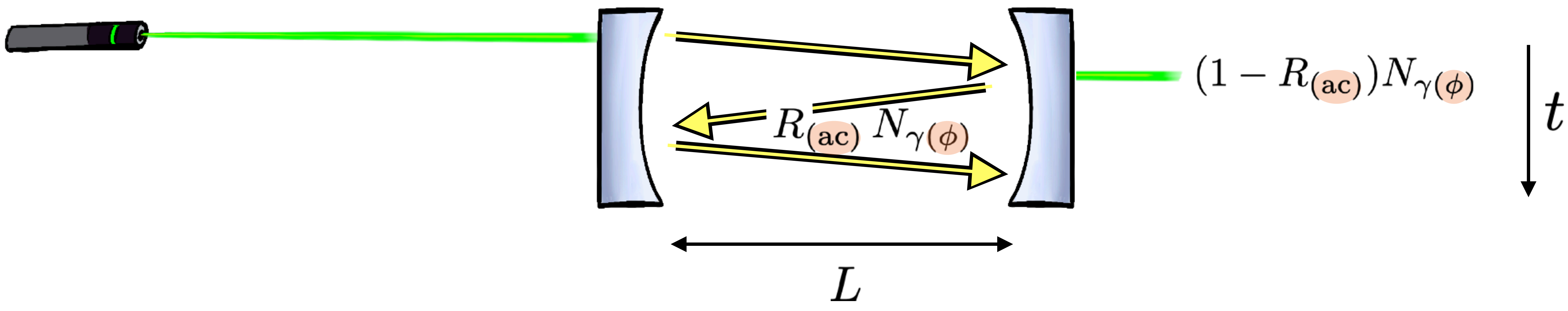


Standard Optomechanics



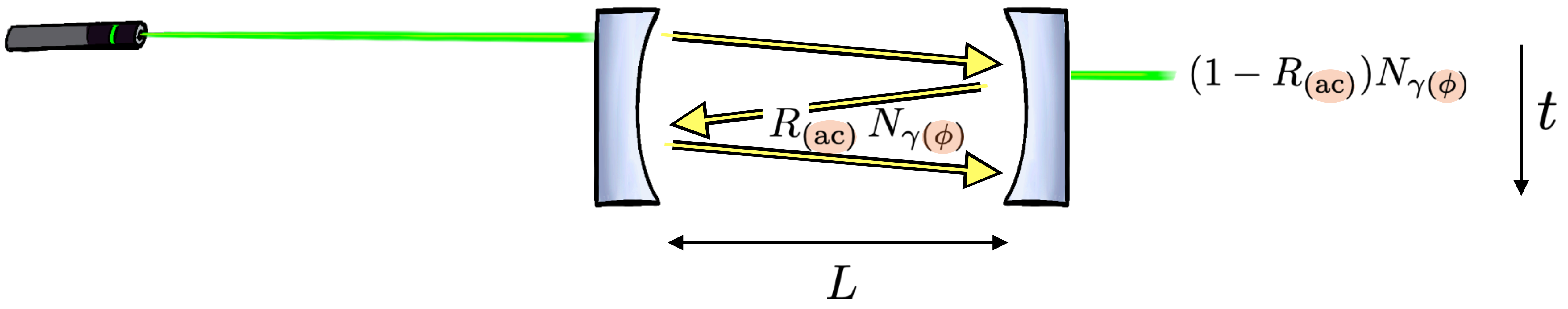
$$\frac{dN}{dt} \simeq \frac{\Delta N_{\gamma(\phi)}}{L/c_{(s)}}$$

Standard Optomechanics



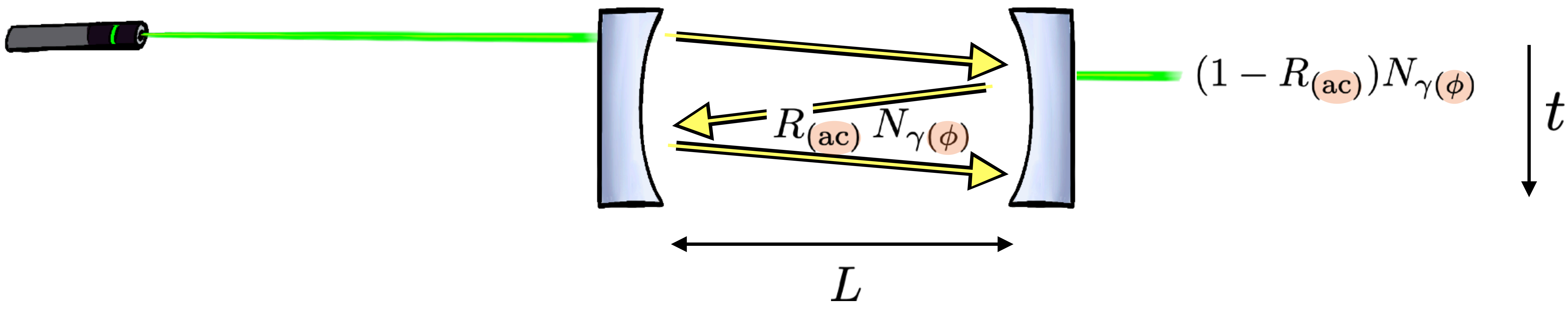
$$\frac{dN}{dt} \simeq \frac{\Delta N_{\gamma(\phi)}}{L/c_{(s)}} = \frac{c_{(s)}(1 - R_{(\mathrm{ac})})}{L} N_{\gamma(\phi)}$$

Standard Optomechanics

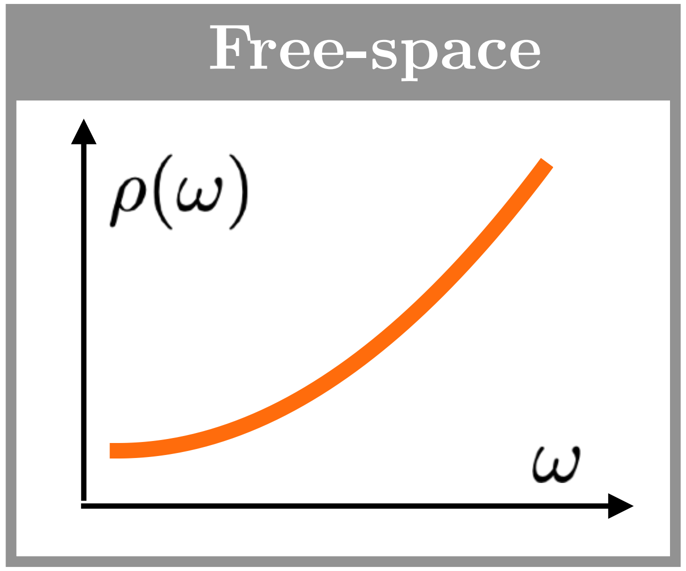


$$\frac{dN}{dt} \simeq \frac{\Delta N_{\gamma(\phi)}}{L/c_{(s)}} = \frac{c_{(s)}(1-R_{(ac)})}{L} N_{\gamma(\phi)} \quad \Rightarrow \quad \tau^{-1}_{\gamma(\phi)} \equiv \kappa(\Gamma_m) \simeq \frac{c_{(s)}}{(1-R_{(a)})^{-1}L}$$

Standard Optomechanics

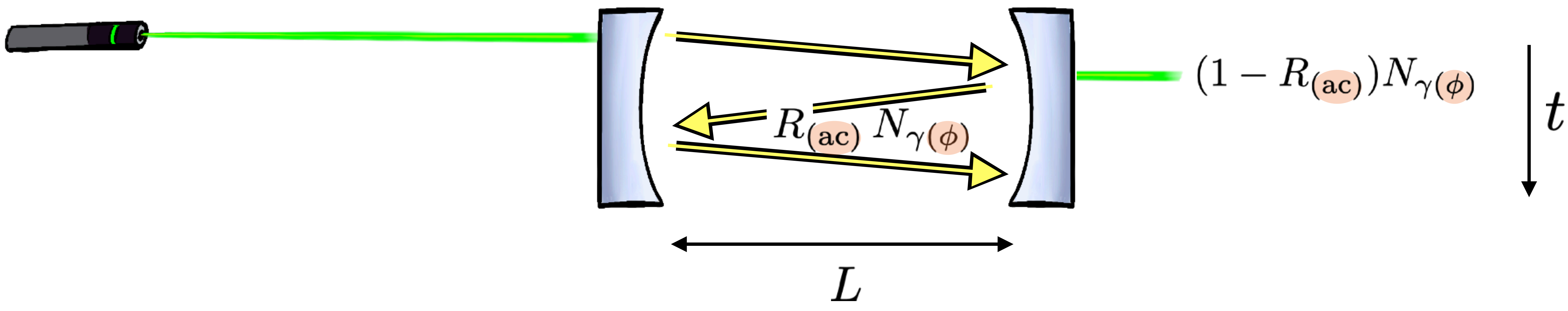


$$\frac{dN}{dt} \simeq \frac{\Delta N_{\gamma(\phi)}}{L/c_{(s)}} = \frac{c_{(s)}(1 - R_{(\mathrm{ac})})}{L} N_{\gamma(\phi)} \Rightarrow \tau^{-1}_{\gamma(\phi)} \equiv \kappa(\Gamma_m) \simeq \frac{c_{(s)}}{(1 - R_{(a)})^{-1} L}$$



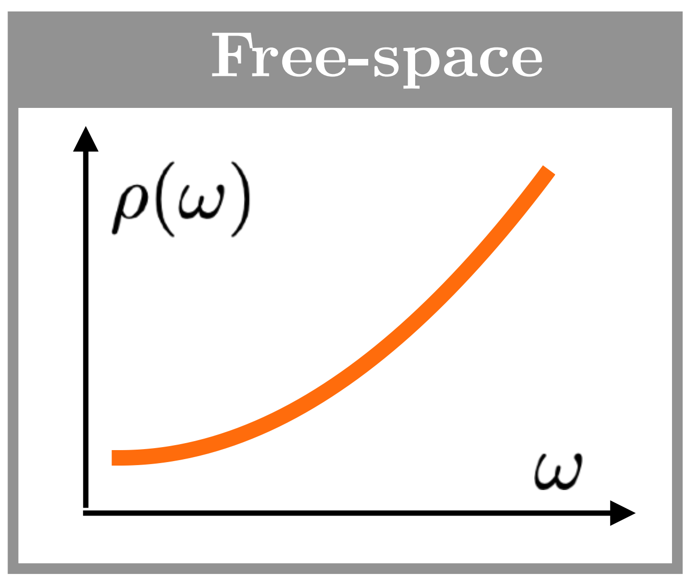
$$\rho(\omega) = \sum_i \delta(\omega - \omega_i) = \sum_{\mathrm{cav}} \frac{1}{2\pi} \int dt e^{i(\omega - \omega_{\mathrm{cav}})t}$$

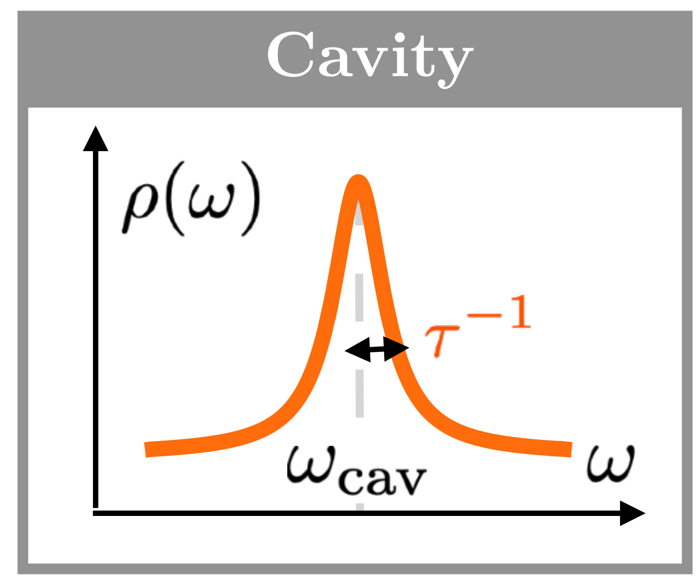
Standard Optomechanics



$$\frac{dN}{dt} \simeq \frac{\Delta N_{\gamma(\phi)}}{L/c_{(s)}} = \frac{c_{(s)}(1-R_{(ac)})}{L} N_{\gamma(\phi)}$$

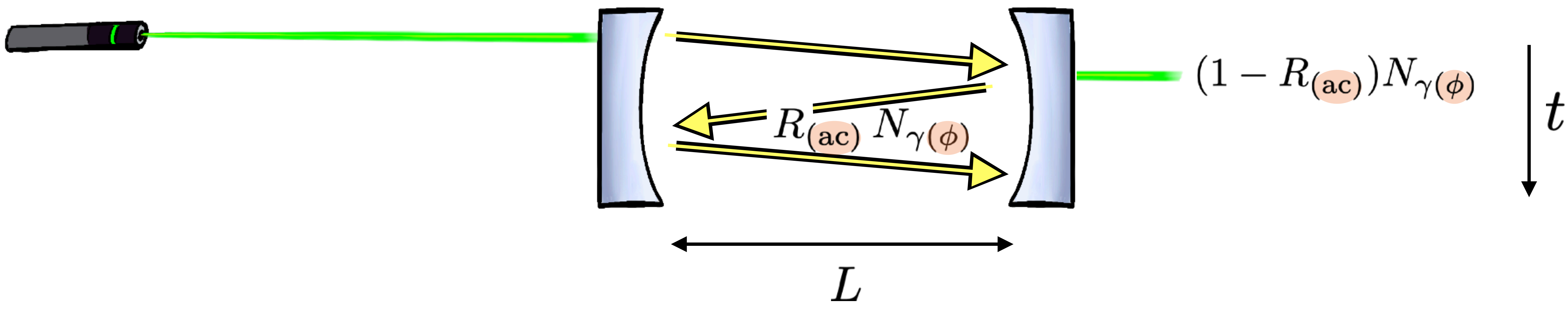
$$\tau_{\gamma(\phi)}^{-1} \equiv \kappa(\Gamma_m) \simeq \frac{c_{(s)}}{(1-R_{(a)})^{-1}L}$$





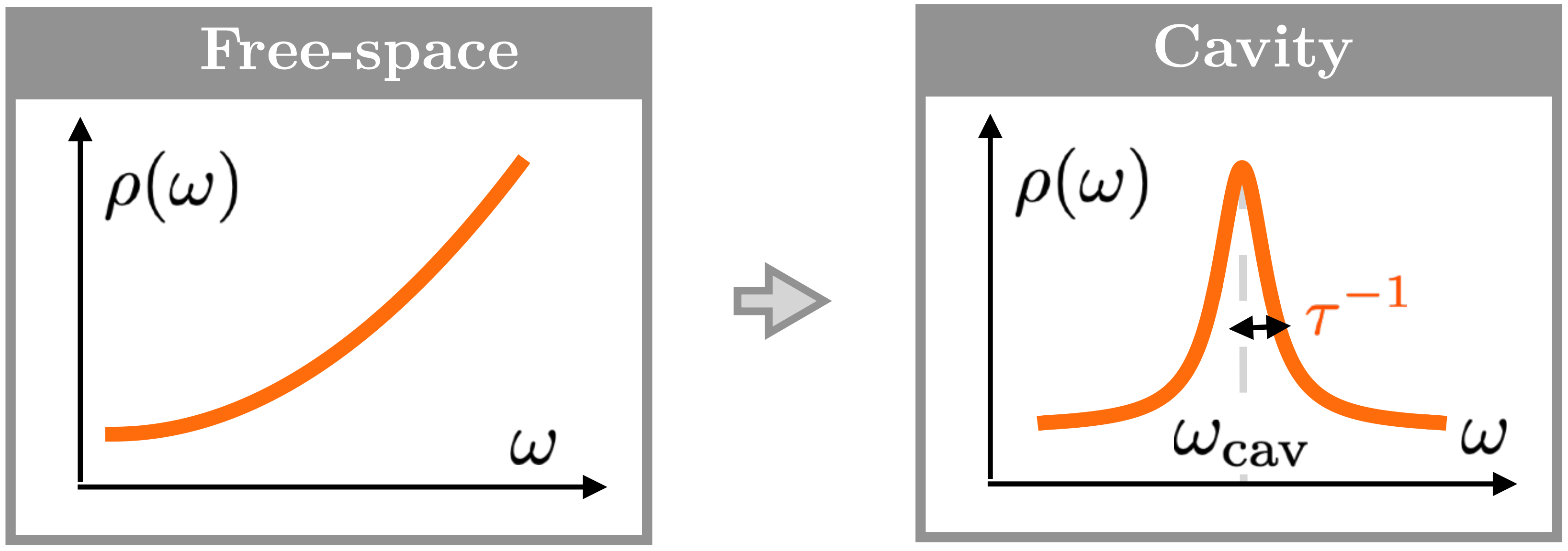
$$\rho(\omega) = \sum_i \delta(\omega-\omega_i) = \sum_{\text{cav}} \frac{1}{2\pi}\int dt e^{i(\omega-\omega_{\text{cav}})t} e^{-t/(2\tau)} = \sum_{\text{cav}} \frac{\tau^{-1}/2}{(\omega-\omega_{\text{cav}})^2+(\tau^{-1}/2)^2}$$

Standard Optomechanics



$$\frac{dN}{dt} \simeq \frac{\Delta N_{\gamma(\phi)}}{L/c_{(s)}} = \frac{c_{(s)}(1-R_{(ac)})}{L} N_{\gamma(\phi)} \Rightarrow \tau^{-1}_{\gamma(\phi)} \equiv \kappa(\Gamma_m) \simeq \frac{c_{(s)}}{(1-R_{(a)})^{-1}L}$$

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



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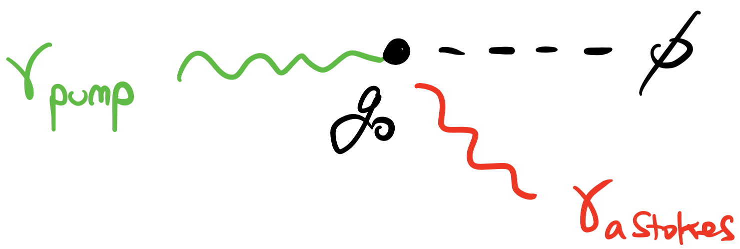
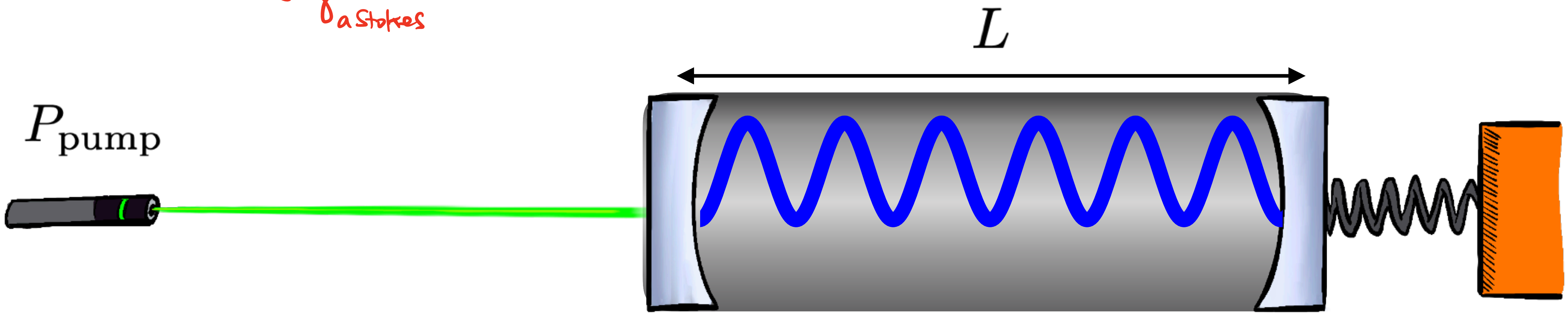
Standard Optomechanics

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

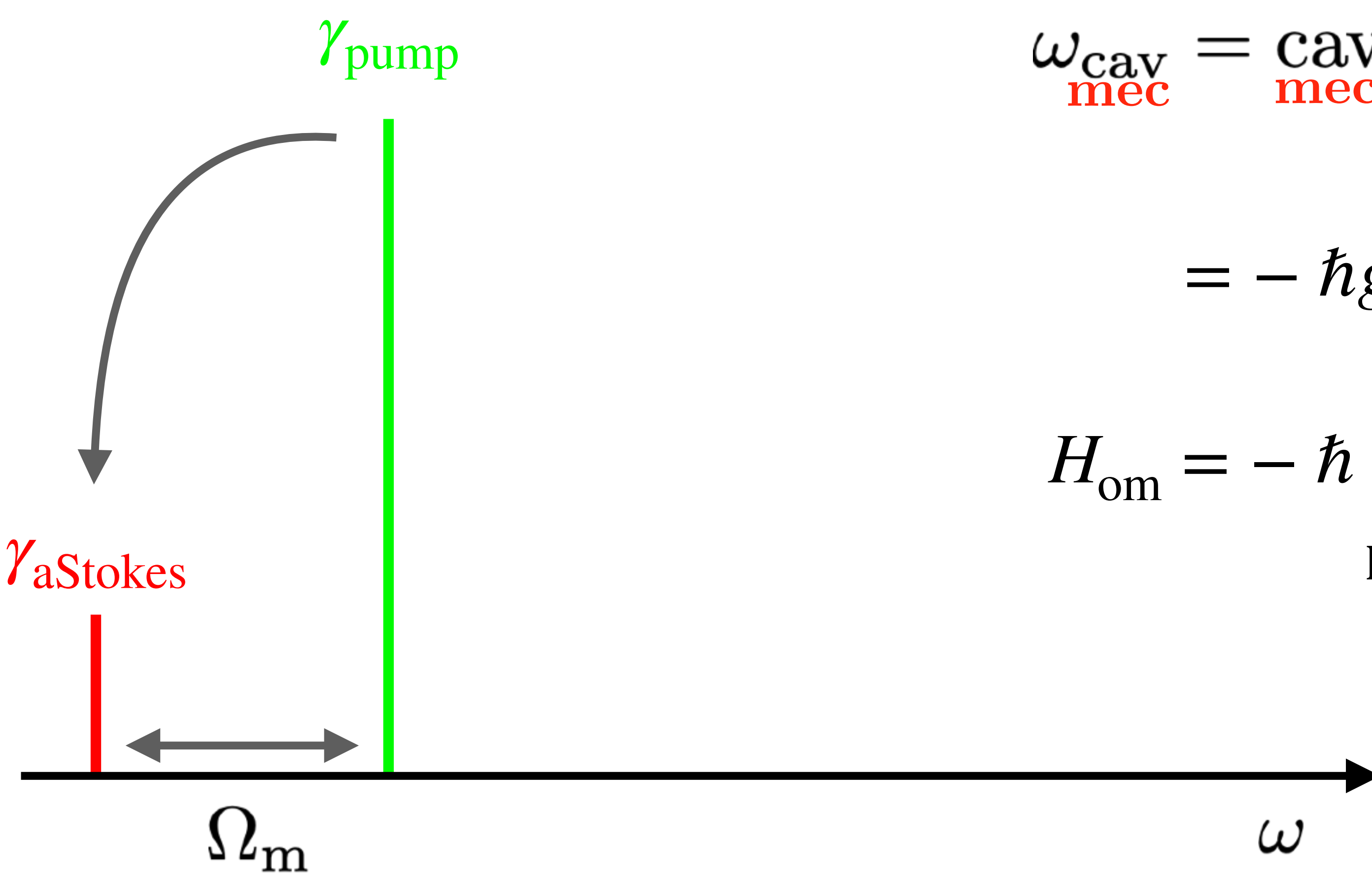




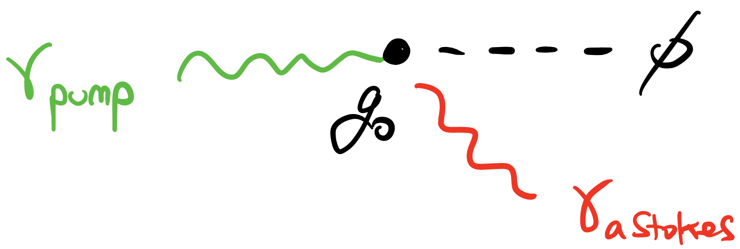
$$\omega_{\underset{\text{mec}}{\text{cav}}} = \underset{\text{mec}}{\text{cav}}\,\frac{\pi}{L}\,c_s, \quad \text{cav} \subset \mathbb{Z}$$

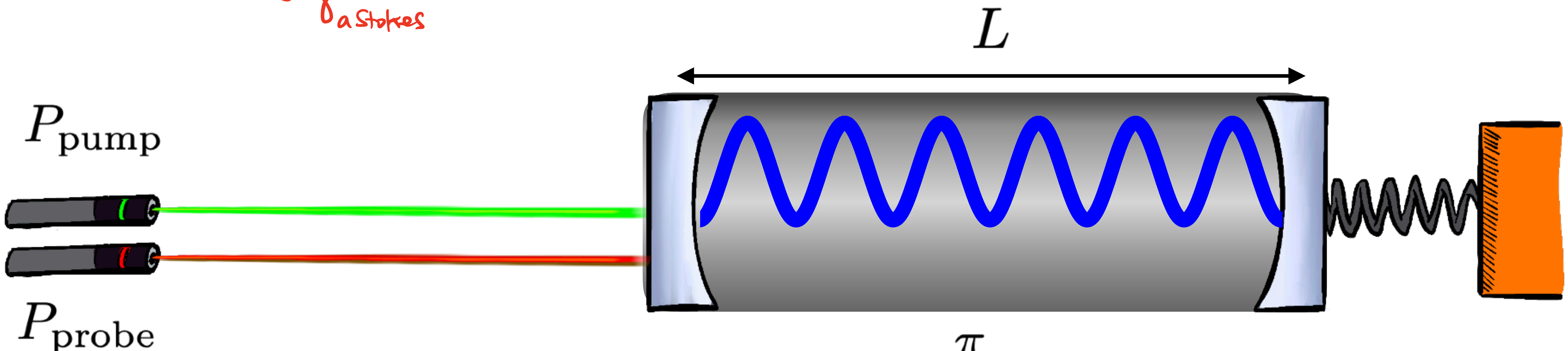
$$= -\hbar g_0 \sqrt{n_{\gamma_{\text{pump}}}}\,\gamma_{\text{pump}}\,\gamma^\dagger \phi^\dagger$$

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

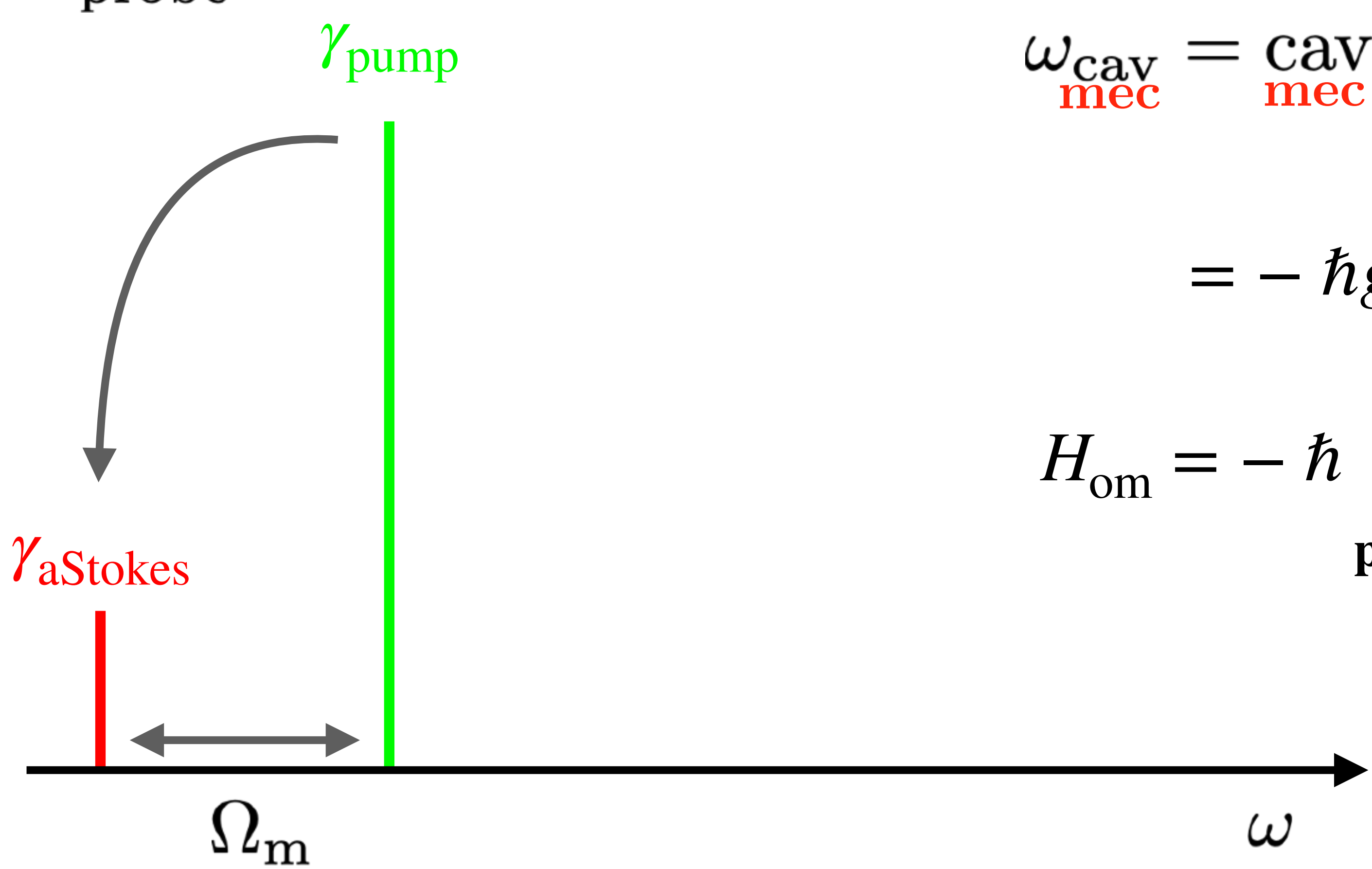


Standard Optomechanics





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



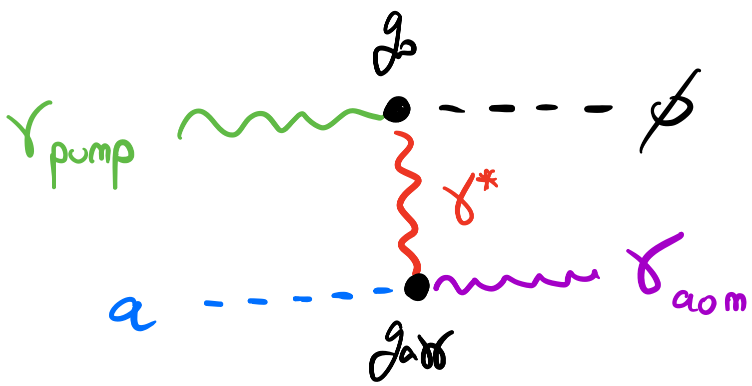
$$= -\hbar g_0 \boxed{\sqrt{n_{\gamma_{\text{pump}}}}}\,\boxed{\sqrt{n_{\gamma_{\text{probe}}}}}\,\gamma_{\text{pump}}\,\gamma^{\dagger}_{\text{probe}}\,\phi^{\dagger}$$

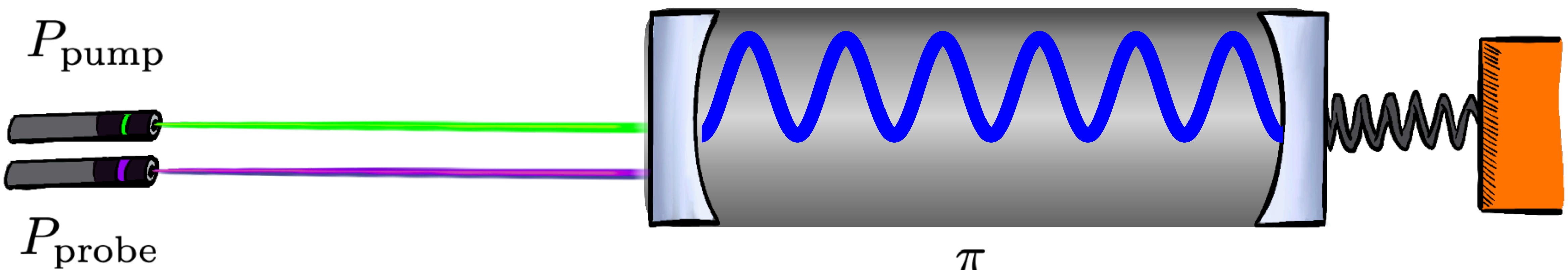
$$H_{\text{om}} = -\hbar \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left(a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b_{\mathbf{k_m}} + a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b^{\dagger}_{\mathbf{k_m}} \right)$$

~~Standard~~ Axioptomechanics

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

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

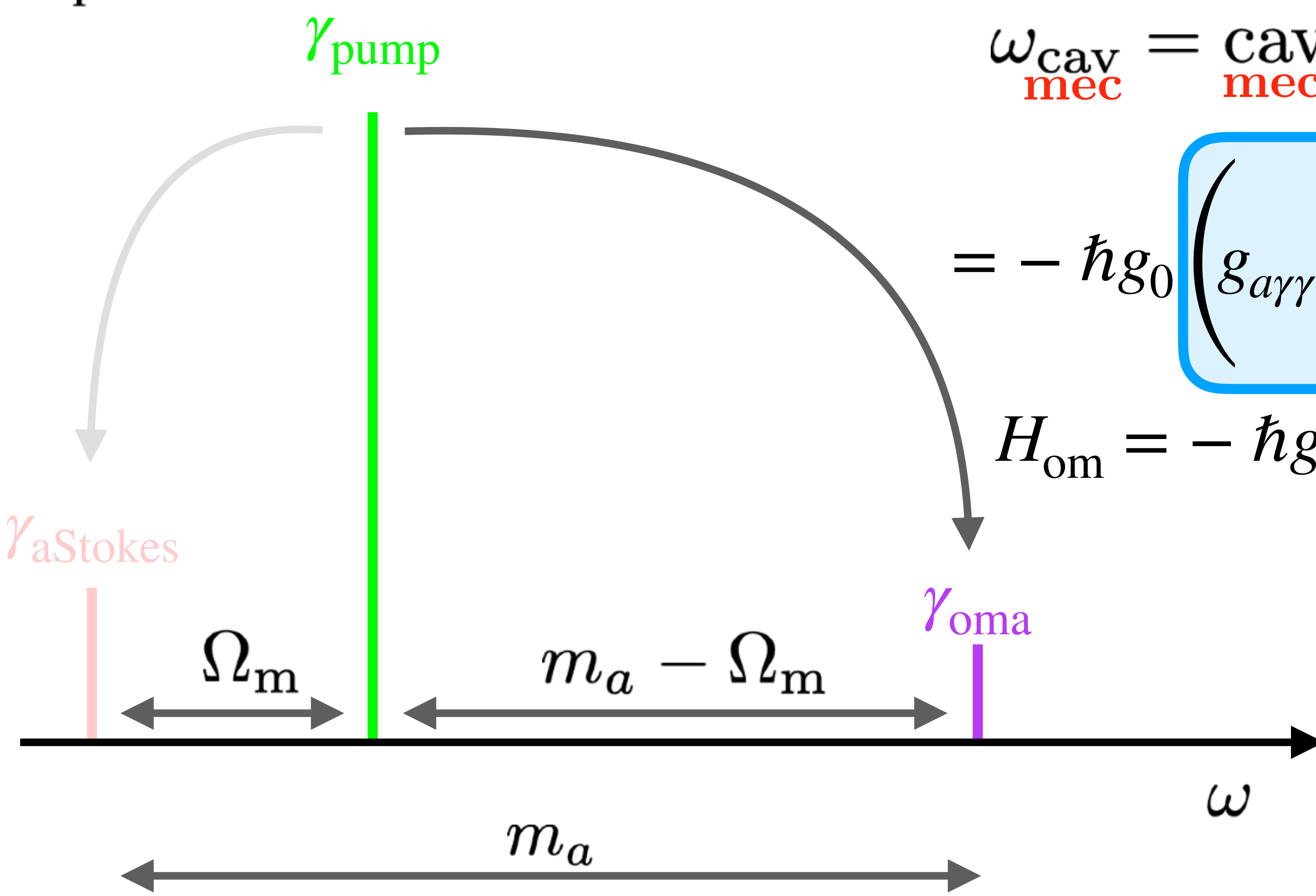




$$\omega_{\substack{\text{cav}\\ \text{mec}}} = \substack{\text{cav}\\ \text{mec}}\,\frac{\pi}{L} c_s, \quad \text{cav} \subset \mathbb{Z}$$

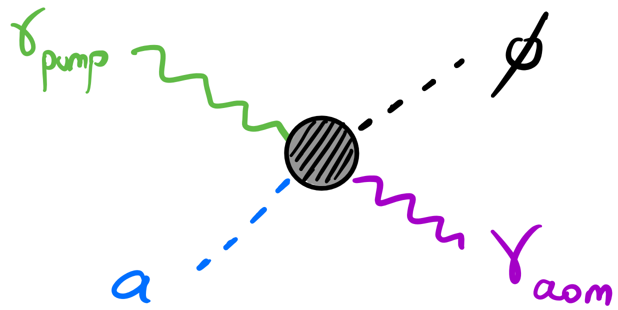
$$= -\hbar g_0 \boxed{\left(g_{a\gamma\gamma}\frac{\sqrt{2\rho_a}}{m_a}\right)} \boxed{\sqrt{n_{\gamma_{\text{pump}}}}} \boxed{\sqrt{n_{\gamma_{\text{probe}}}}}\, \gamma_{\text{pump}} \gamma^\dagger_{\text{probe}} \phi^\dagger$$

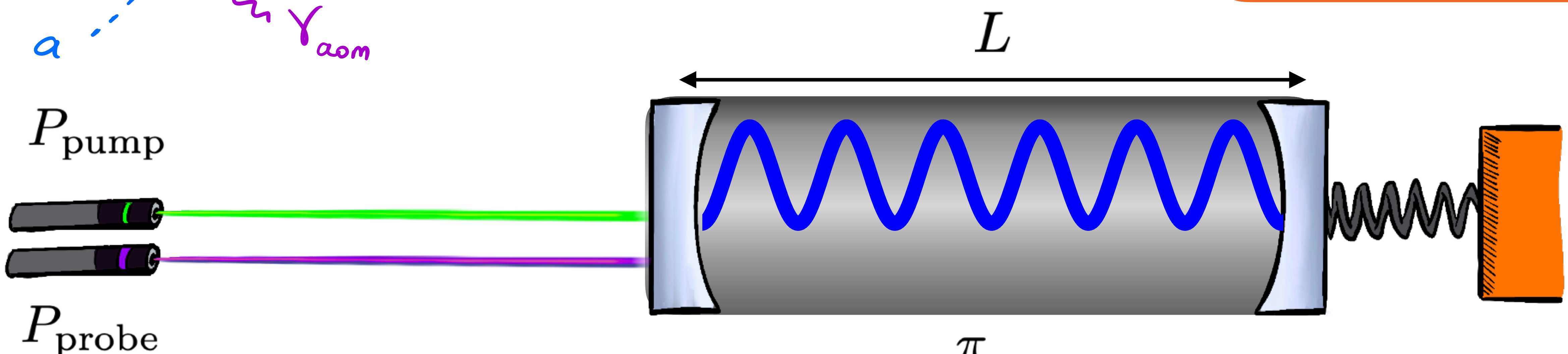
$$H_{\text{om}} = -\hbar g_{a\gamma\gamma} \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0\, a_0 \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b_{\mathbf{k_m}} + a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}}\right)$$



~~Standard~~ Axioptomechanics

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





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

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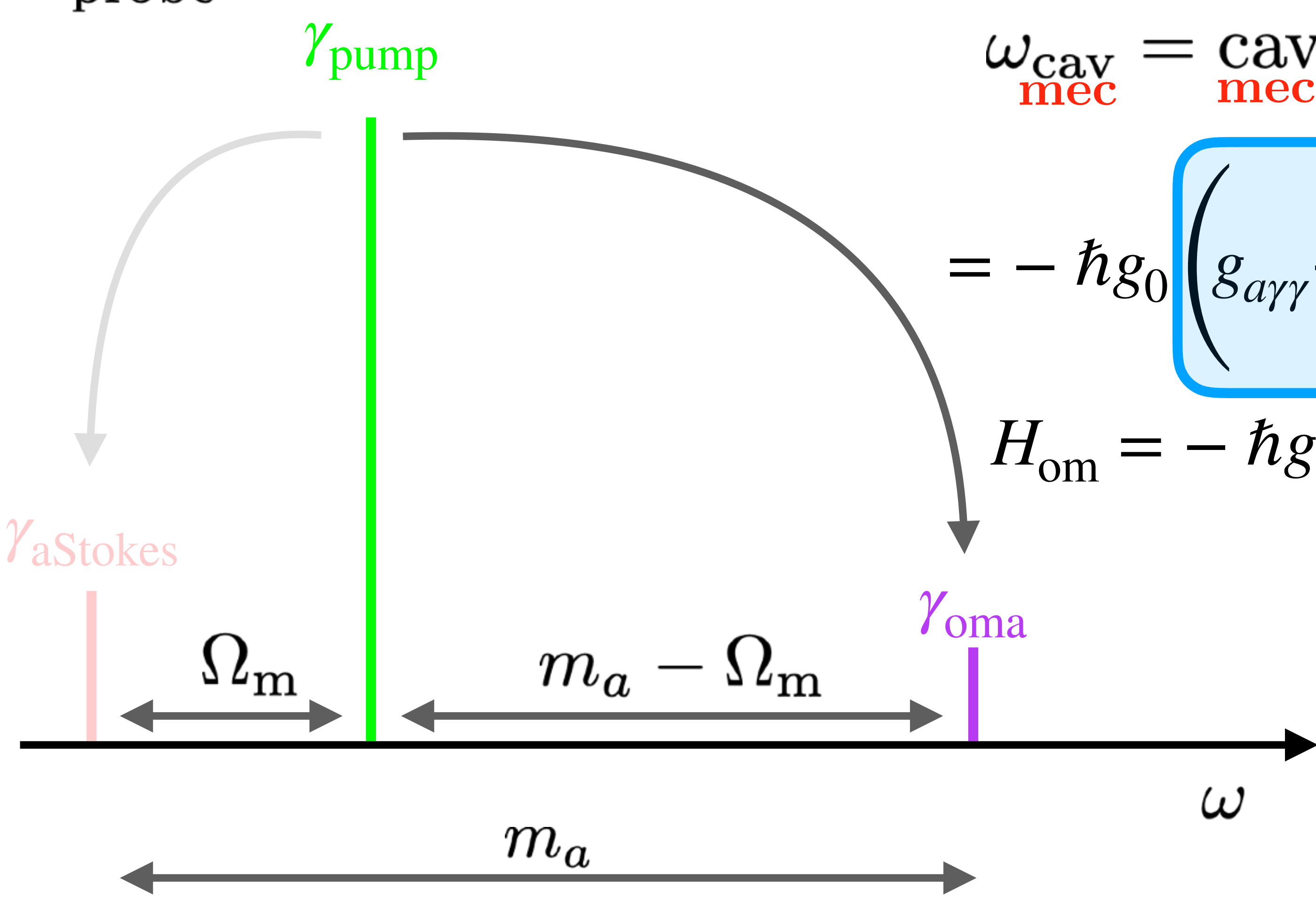
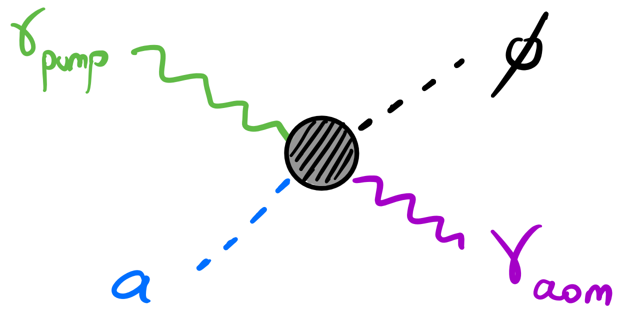
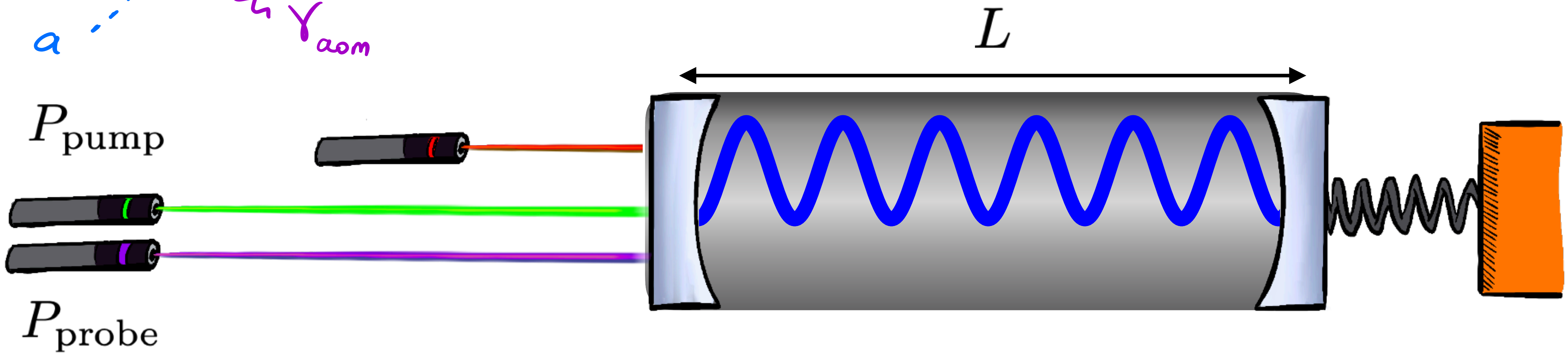
$$H_{\text{om}} = -\hbar g_{a\gamma\gamma}\sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0\, a_0 \left(a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b_{\mathbf{k_m}} + a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b^\dagger_{\mathbf{k_m}}\right)$$

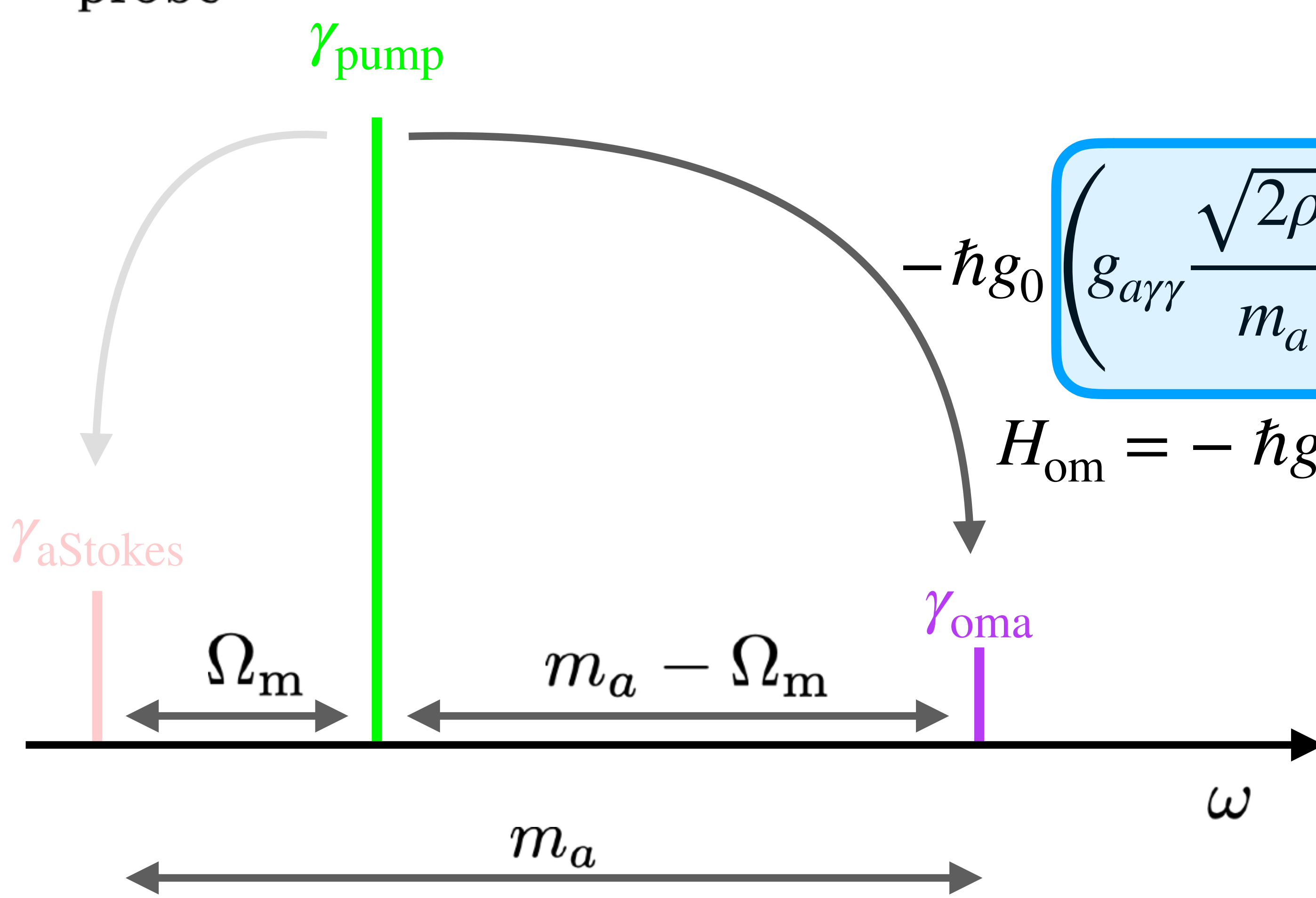


~~Standard~~ Axioptomechanics

$$\boxed{\begin{aligned} p_\phi &= 2p_\gamma \\ \omega_{\gamma 1} + \omega_a &= \omega_{\gamma 2} + \omega_\phi \end{aligned}}$$







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

$$H_{\rm om} = -\hbar g_{a\gamma\gamma} \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0\, a_0 \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b_{\mathbf{k_m}} + a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}}\right)$$

Let's give some numbers!

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

1 For usual experiments in their lab:

- $N_{\rm pump} \simeq 10^6$ — $P_{\rm pump} \sim 1\,\mu$W
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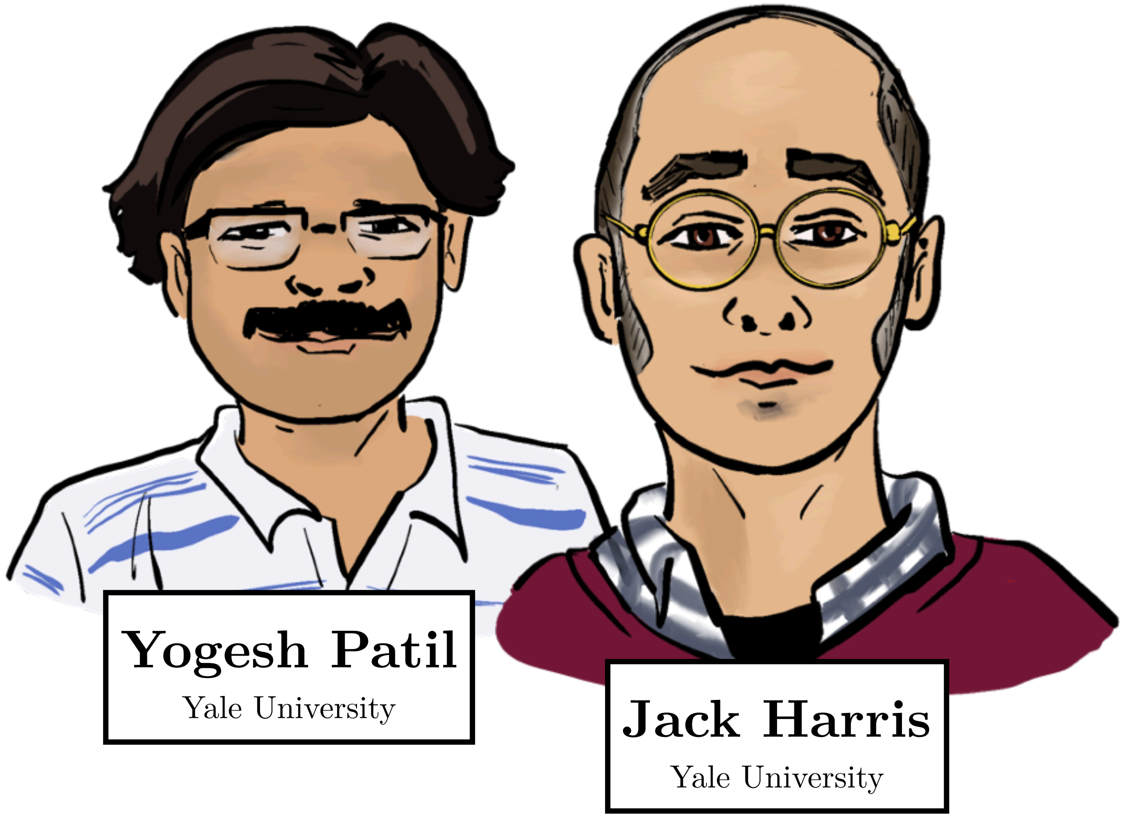
Jack Harris Lab (Yale)



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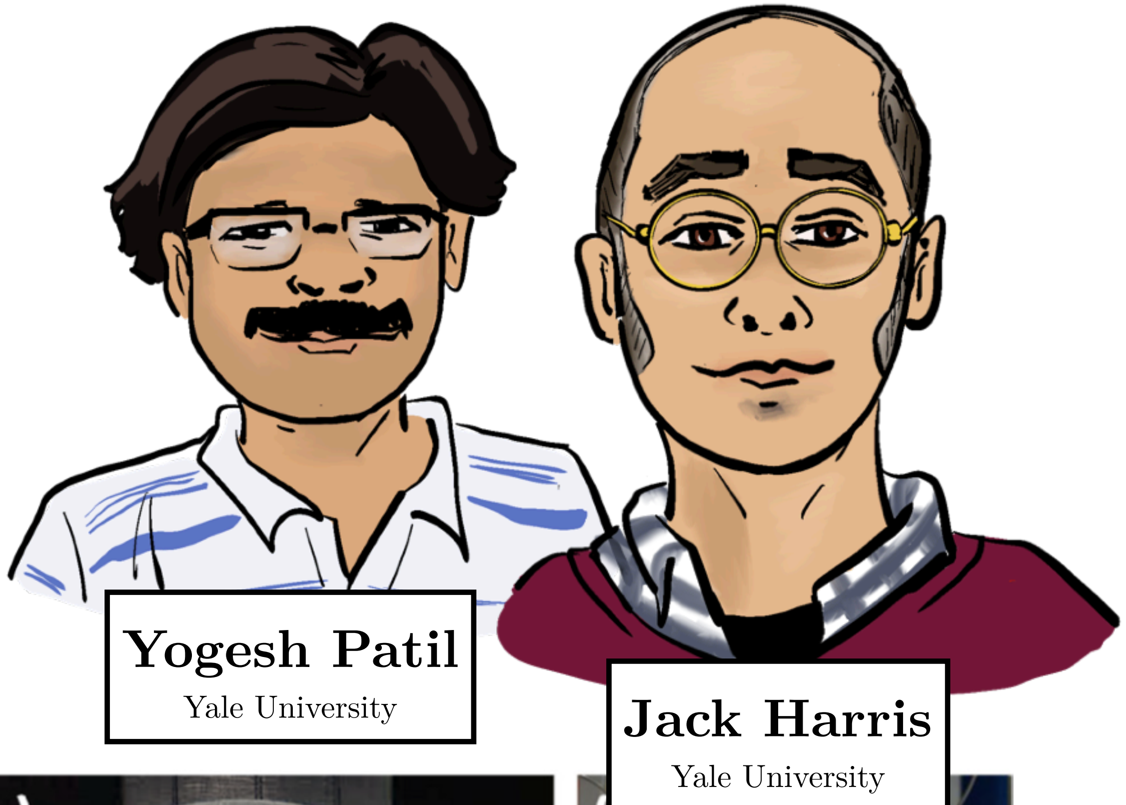

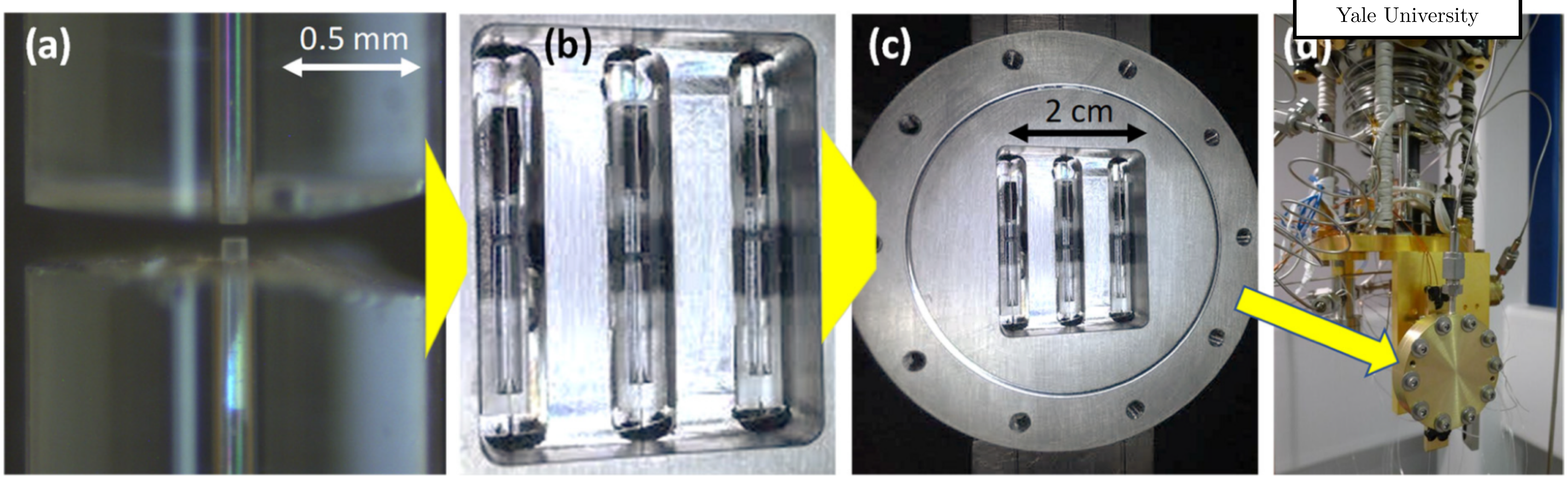

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- $N_{\text{pump}} \simeq 10^{11}$
- $N_{\text{probe}} \simeq 10^{11}$
- $N_\phi \simeq 10^{14}$

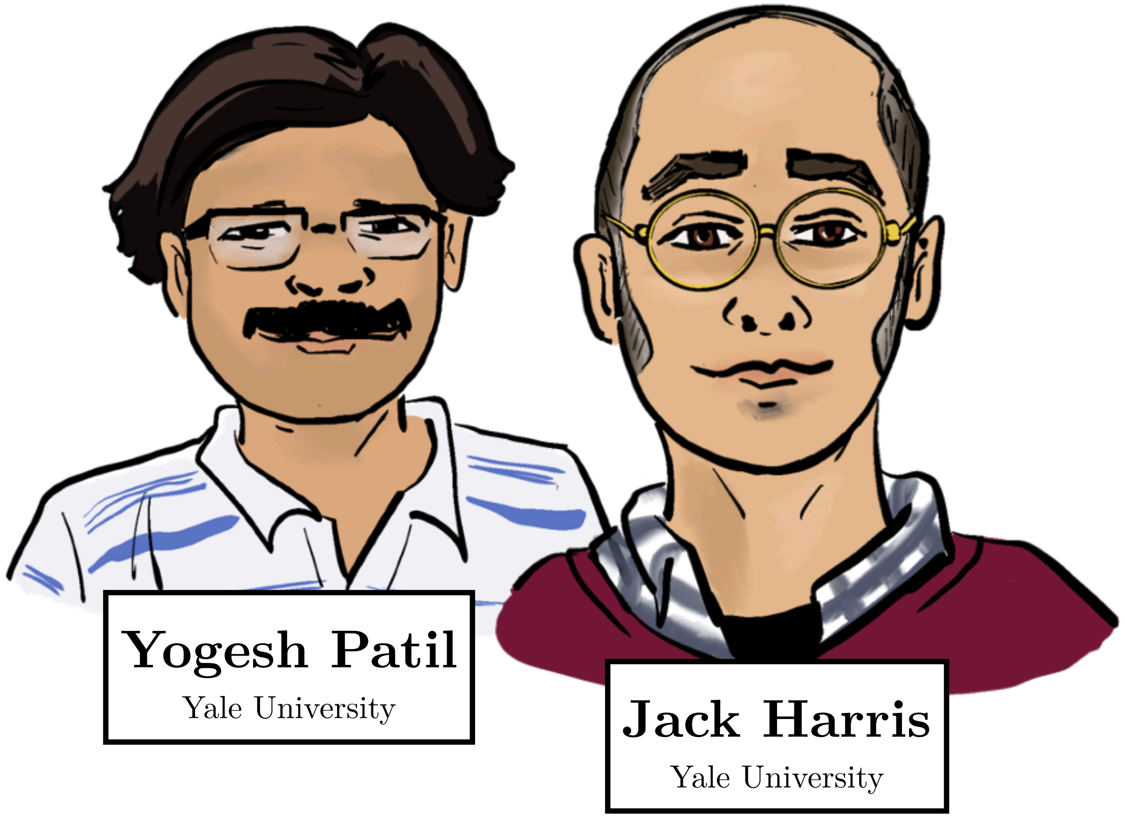
$P_{\text{pump}} \sim 1$ mW

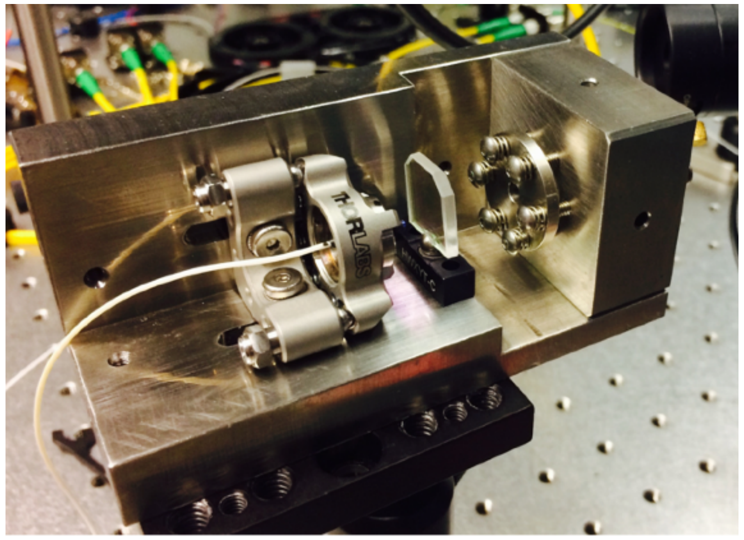
$P_{\text{probe}} \sim 1$ mW

$L \sim 1$ cm

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

Jack Harris Lab (Yale)





Sensitivity and scanning strategy

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

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

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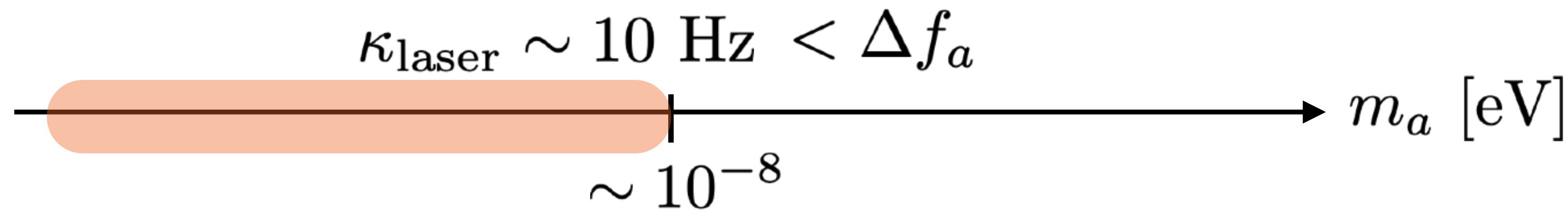
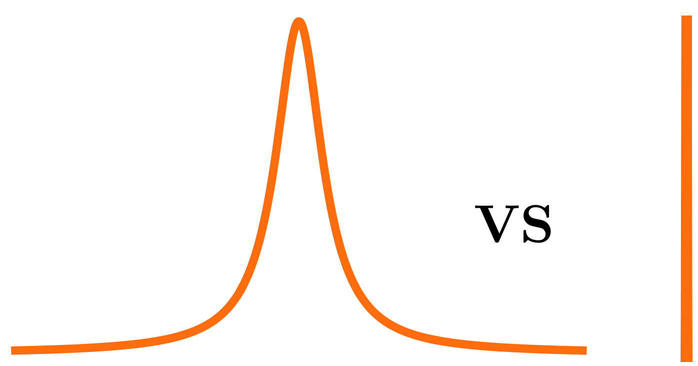


Lorenzian regime



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

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

~0.1 μeV/year

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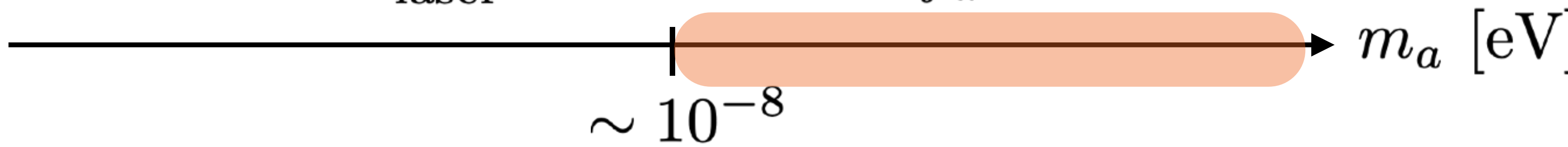
$\kappa_{\mathrm{laser}} \sim 10$ Hz $< \Delta f_a$



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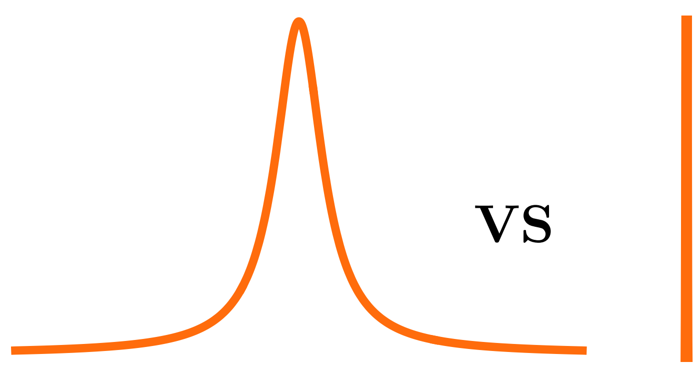

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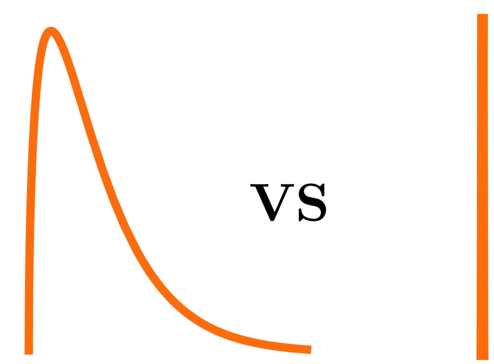
Boltzmann regime

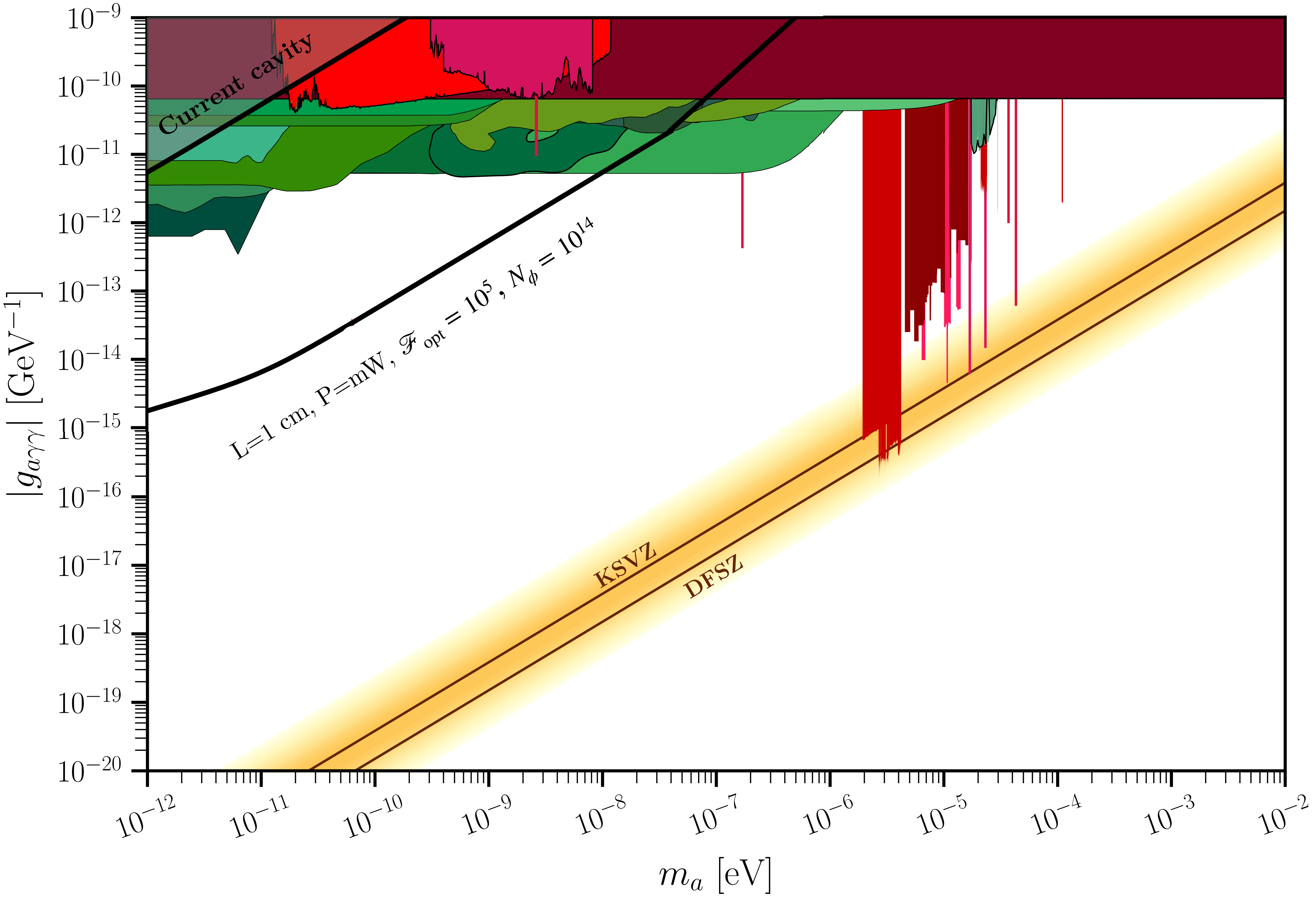


$$\Gamma \propto B_{m_a}(\Delta + \Omega_{\mathrm{m}})$$

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

~1 oom/year

Results


Current cavity
L=1 cm, P=mW, $\mathscr{F}_{\rm opt} = 10^5$, $N_\phi = 10^{14}$
KSVZ
DFSZ
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
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10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}

Let's give some numbers!

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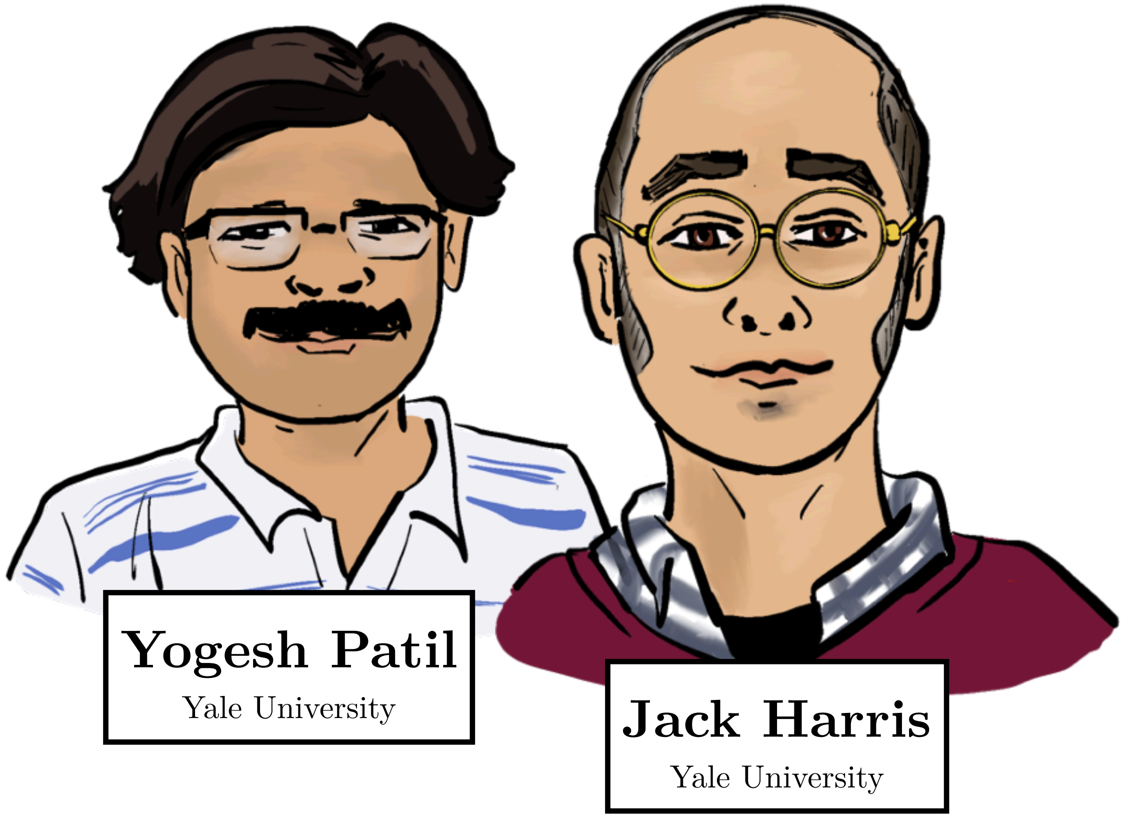
- $\mathcal{F}_{\text{opt}} \sim 10^5$

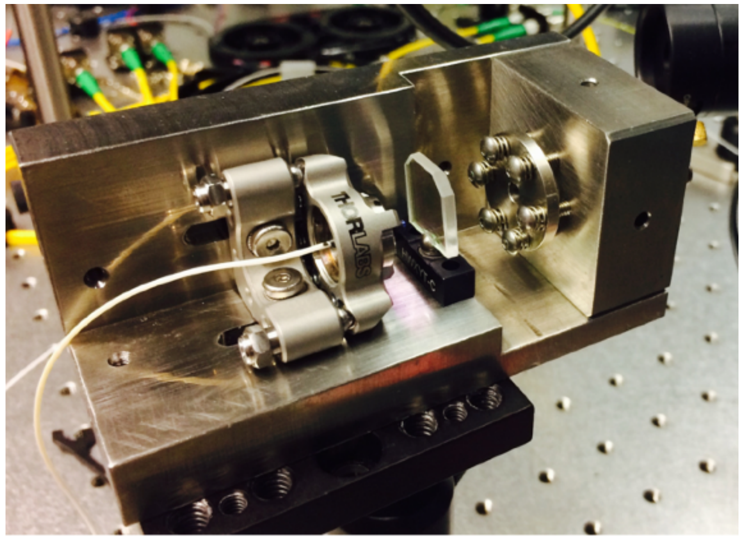
3 What we need to do for the QCD axion search:

- $N_{\text{pump}} \simeq 10^{15}$ — $P_{\text{pump}} \sim 10$ mW
- $N_{\text{probe}} \simeq 10^{15}$ — $P_{\text{probe}} \sim 10$ mW
- $N_\phi \simeq 10^{23}$ — $L \sim 1$ m
- $\mathcal{F}_{\text{opt}} \sim 10^6$

"FEASIBLE!!"

Jack Harris Lab (Yale)





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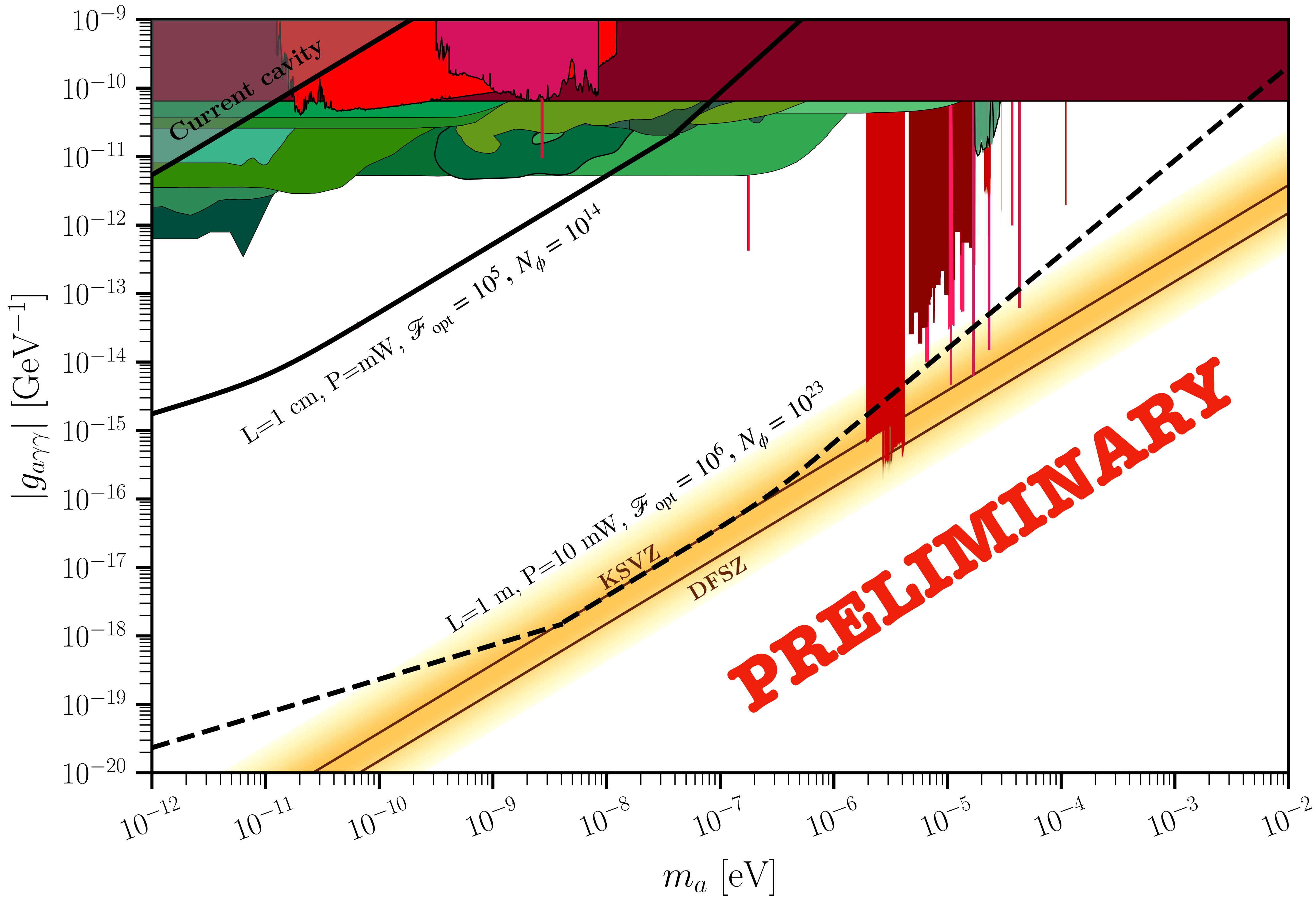

Current cavity
L=1 cm, P=mW, $\mathscr{F}_{\rm opt} = 10^5$, $N_\phi = 10^{14}$
L=1 m, P=10 mW, $\mathscr{F}_{\rm opt} = 10^6$, $N_\phi = 10^{23}$
KSVZ
DFSZ
PRELIMINARY
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
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Conclusions

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

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- Atom interferometers at low transferred momentum:
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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 q
    - 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?

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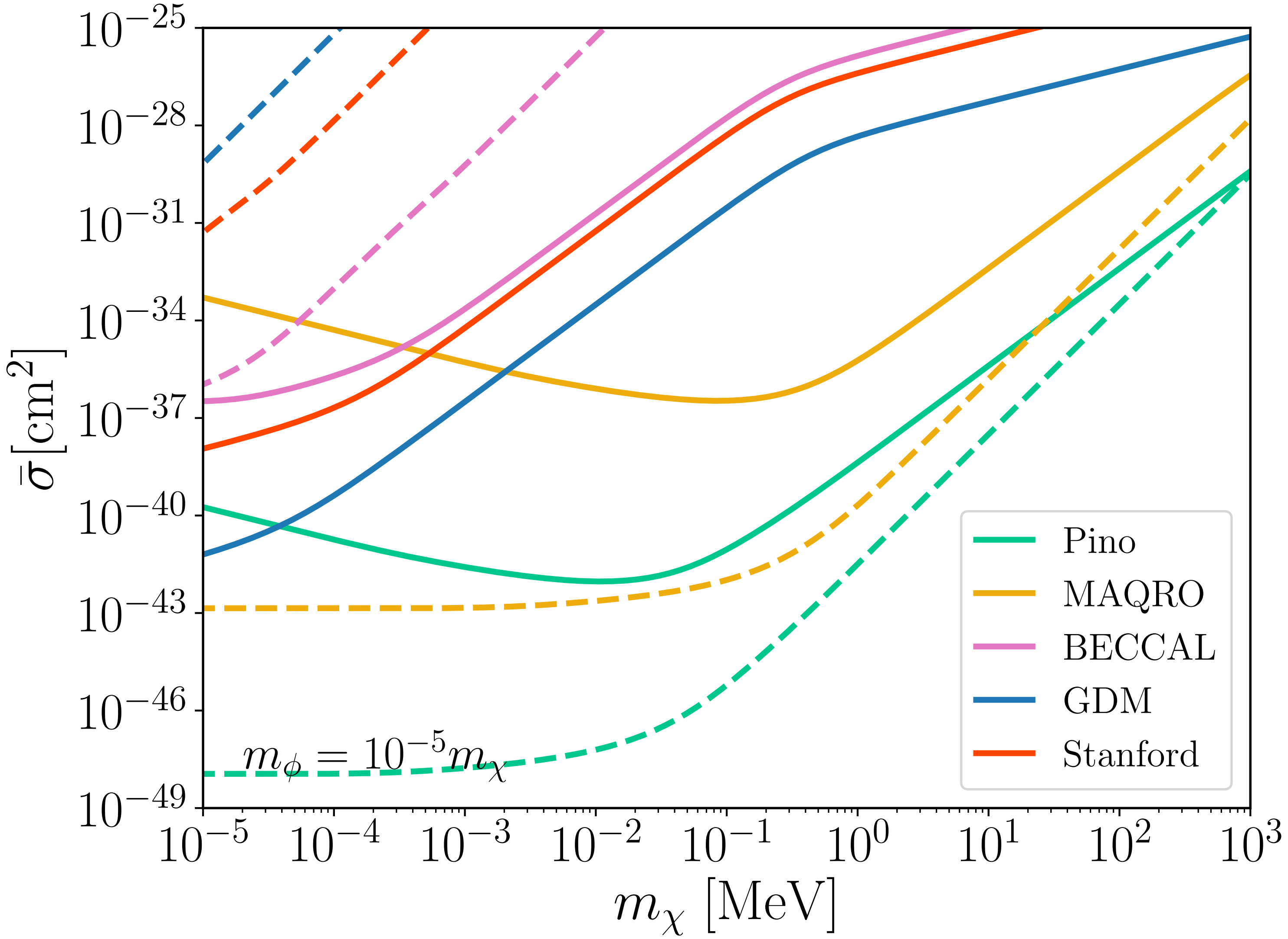
- Axioptopmechanics:
  - Experimental proposal with J. Harris lab at Yale University.
  - Study the effect of using other materials (SiO_2, Ta_2O_5...)

Thank you!

AIs: Results

$$s \propto \frac{\bar{\sigma}((m_\chi v_0)^2 + m_\phi^2)^2}{m_\chi^3} \int dq \, \frac{q}{(q^2 + m_\phi^2)^2} N(1 + N F^2(q r_{\mathrm{cloud}})) \int_{-1}^{1} d\cos\theta (-\sin(\mathbf{q} \cdot \mathbf{\Delta x})) f(v_e)$$



Phase, light $m_\phi = R_{\phi\chi} m_\chi$

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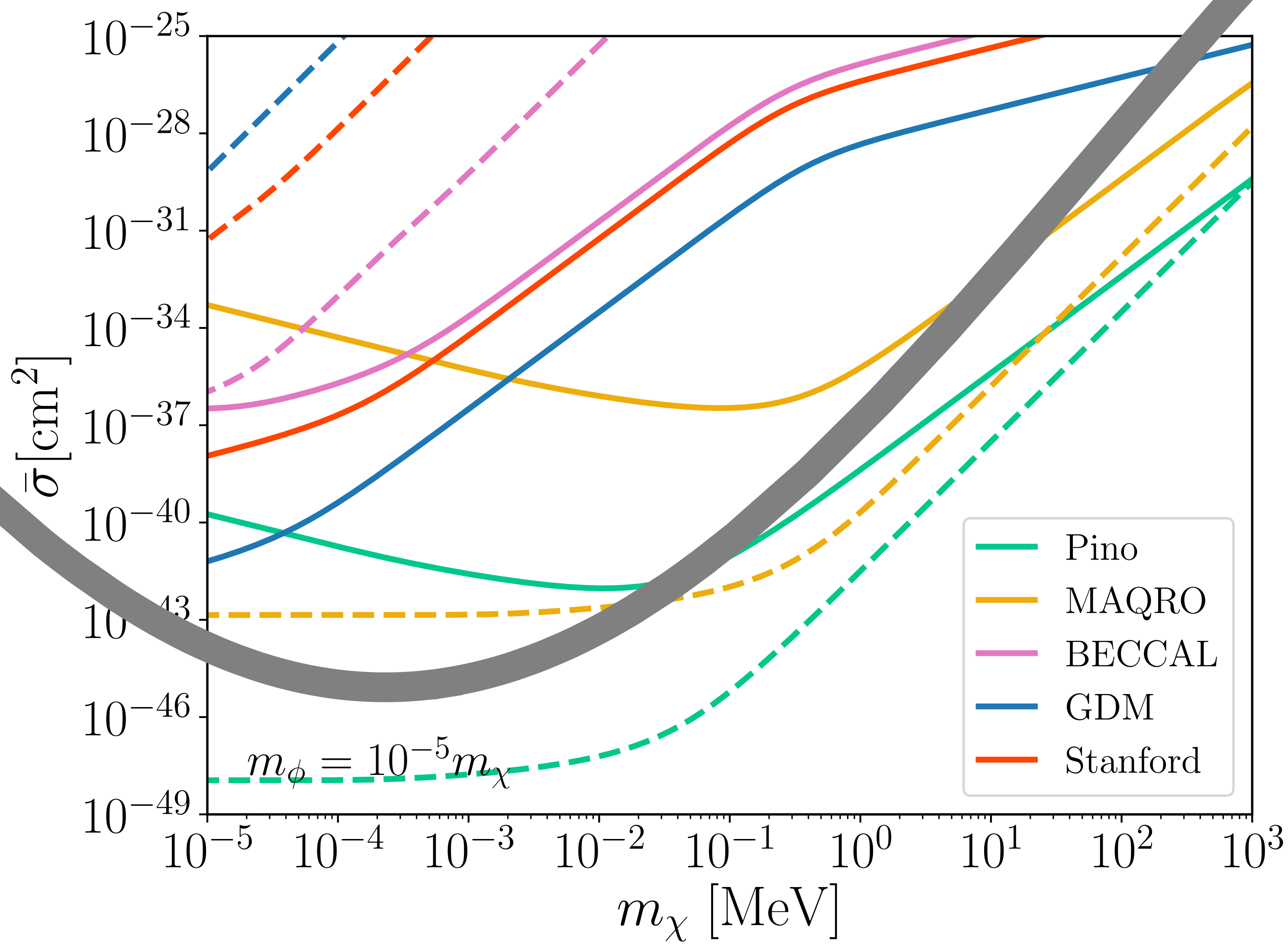
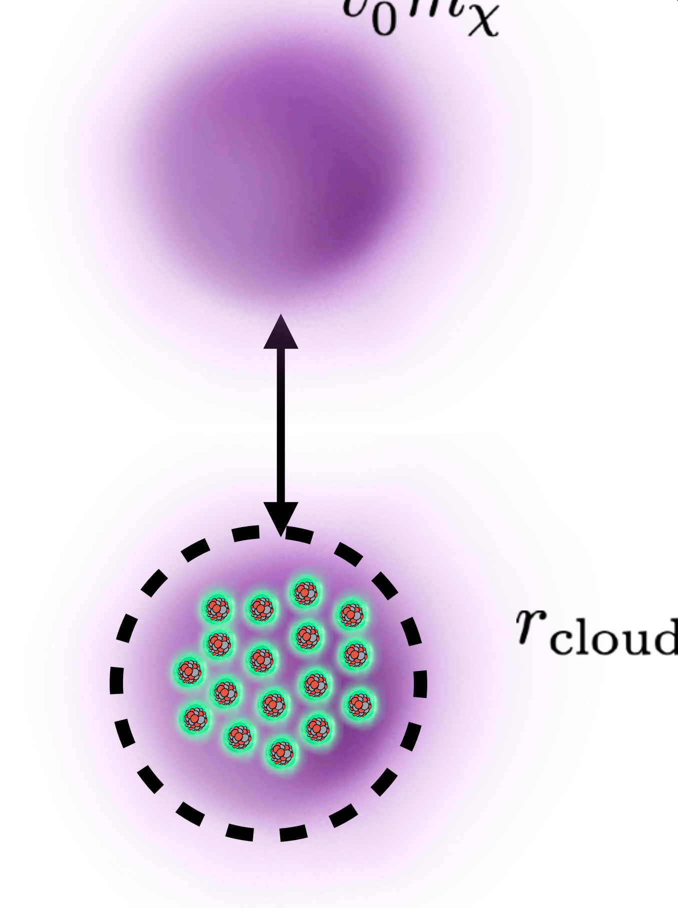
$$\xrightarrow{} 1 \qquad \xrightarrow{} \frac{q^2 \Delta x v_e}{v_0^2 m_\chi}$$

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





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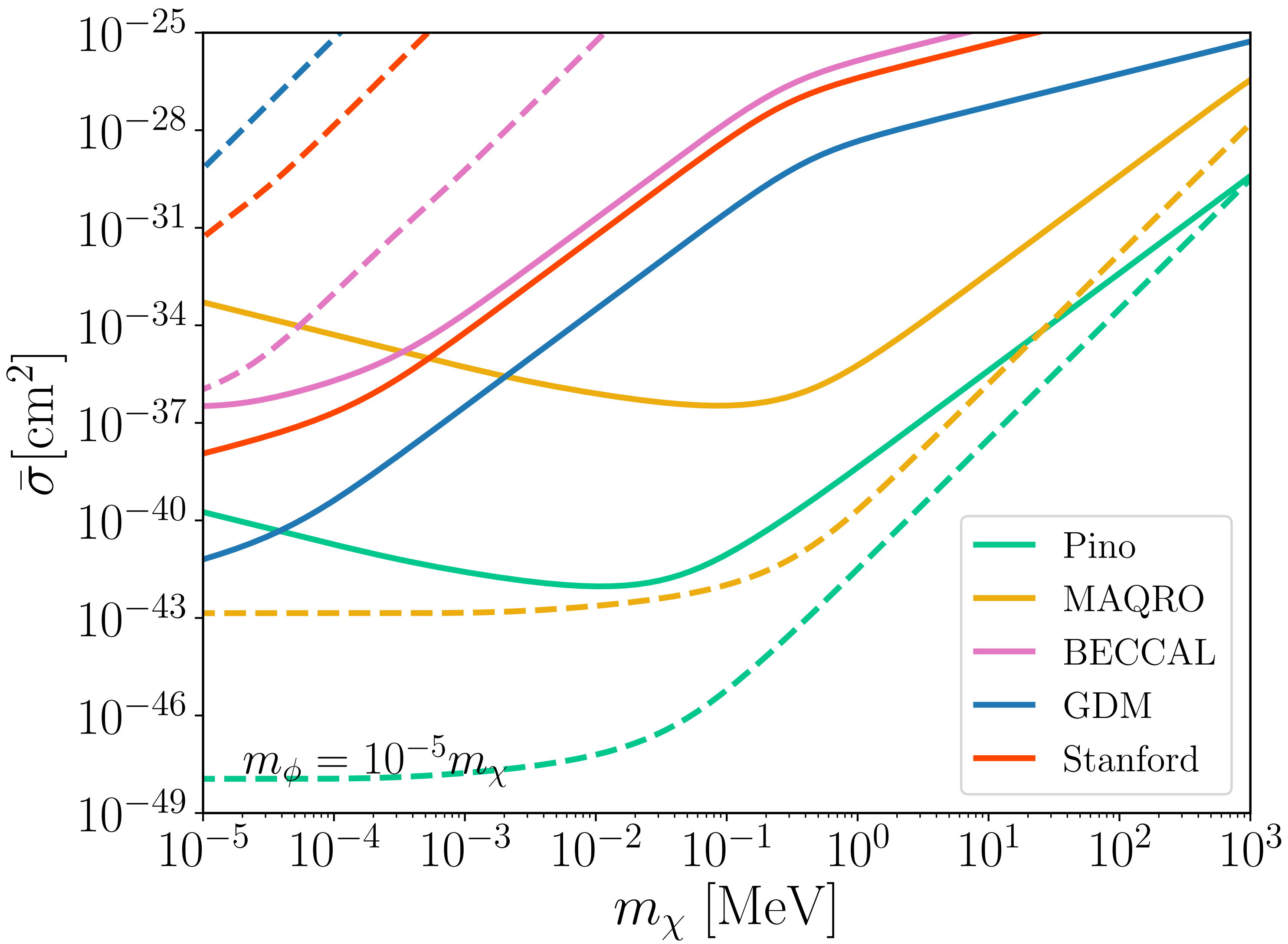

Phase, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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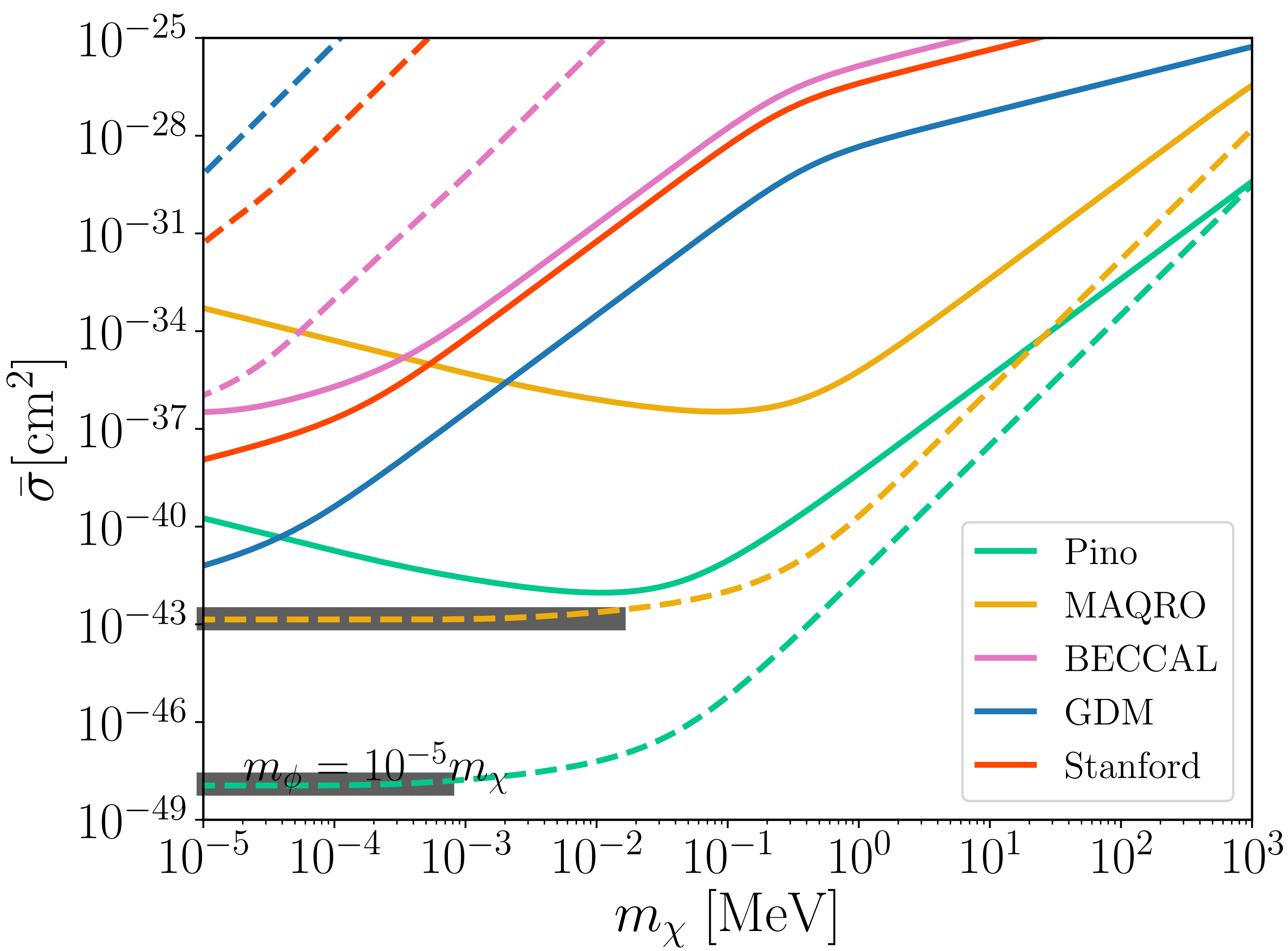
$$\Rightarrow \quad \bar{\sigma} \propto \frac{1}{\Delta x\, N^2}$$

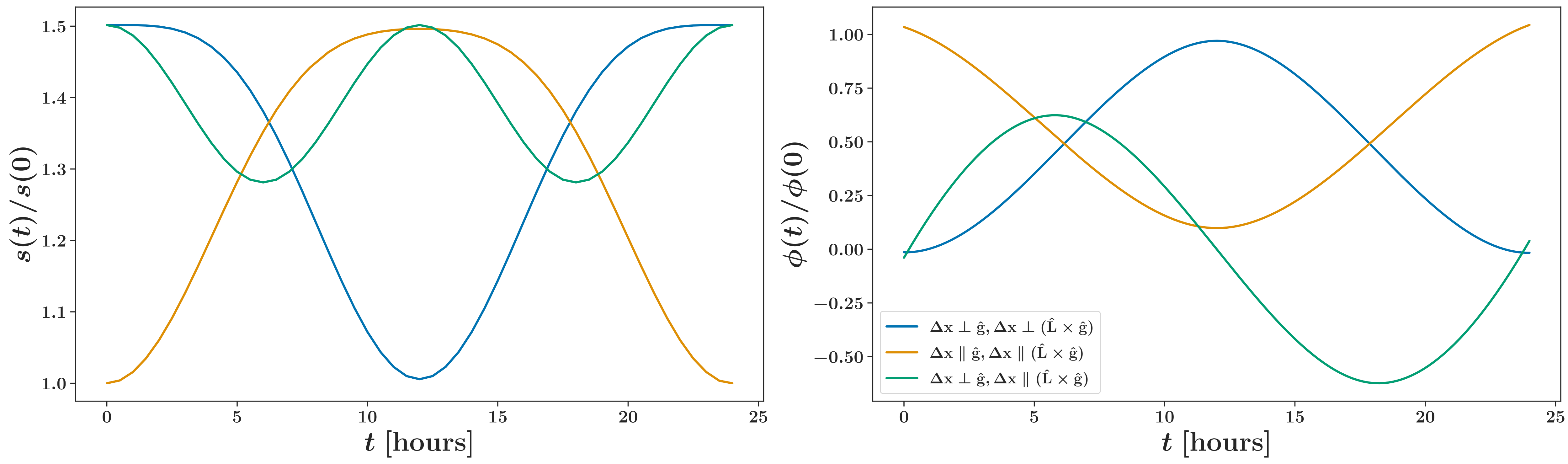


Phase, light $m_\phi = R_{\phi\chi} m_\chi$

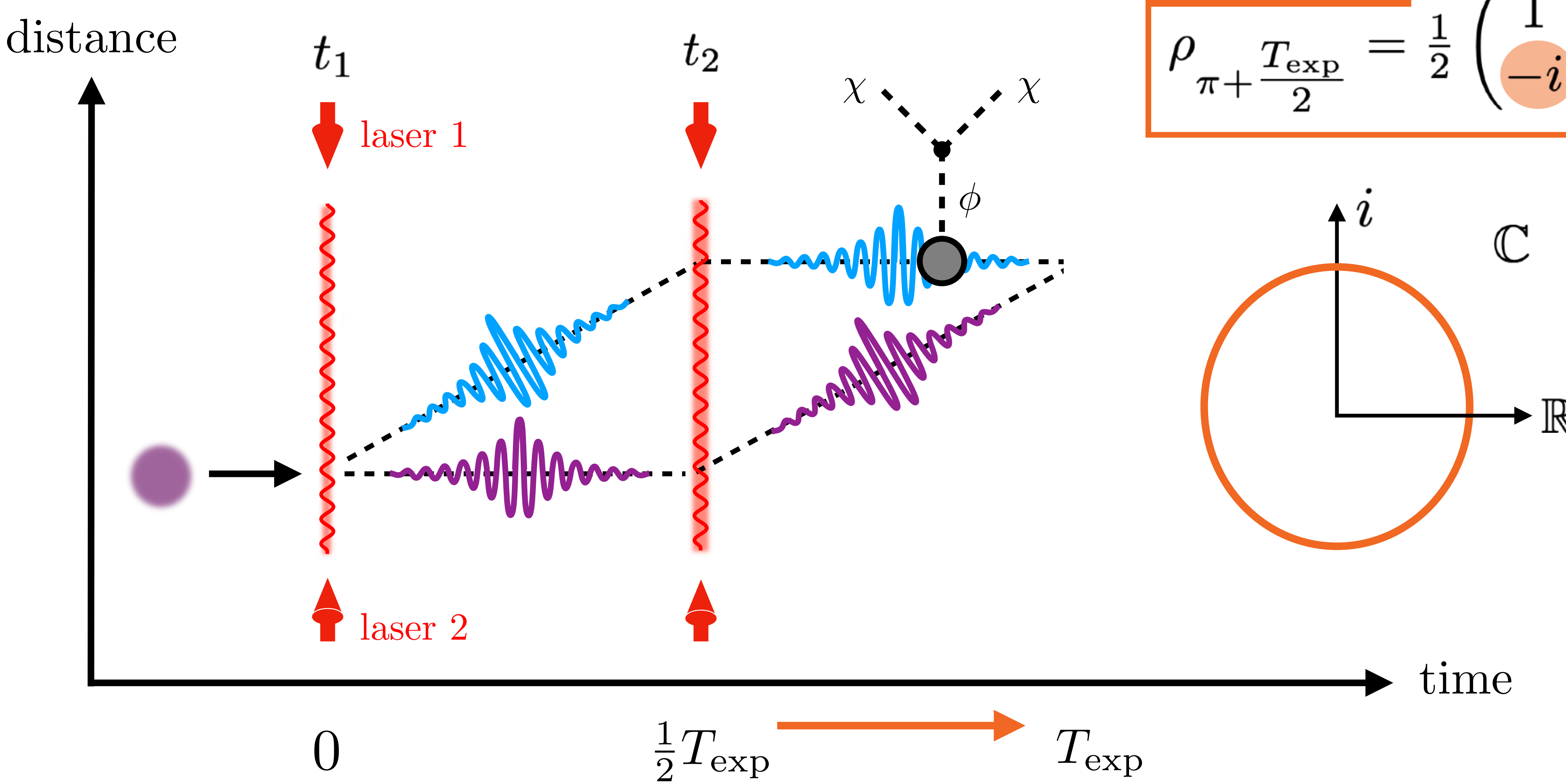
AIs: Daily modulation

$$\mathbf{v}_\mathrm{e}(t) = \|\mathbf{v}_e\| \begin{pmatrix} \mathrm{s}\theta_\mathrm{e}\,\mathrm{c}\theta_\mathrm{x}\,\mathrm{s}\phi(t) - \mathrm{s}\theta_\mathrm{x}\,\mathrm{s}\theta_\mathrm{e}\,\mathrm{c}\theta_\mathrm{l}\,\mathrm{c}\phi(t) + \mathrm{s}\theta_\mathrm{x}\,\mathrm{c}\theta_\mathrm{e}\,\mathrm{s}\theta_\mathrm{l} \\ \mathrm{c}\theta_\mathrm{e}\,\mathrm{s}\theta_\mathrm{g}\,\mathrm{s}\theta_\mathrm{l}\,\mathrm{c}\theta_\mathrm{x} - \mathrm{s}\theta_\mathrm{e}\,\mathrm{s}\theta_\mathrm{g}\,\mathrm{c}\theta_\mathrm{l}\,\mathrm{c}\theta_\mathrm{x}\,\mathrm{c}\phi(t) - \mathrm{s}\theta_\mathrm{e}\,\mathrm{c}\theta_\mathrm{g}\,\mathrm{s}\theta_\mathrm{l}\,\mathrm{c}\phi(t) - \mathrm{c}\theta_\mathrm{e}\,\mathrm{c}\theta_\mathrm{g}\,\mathrm{c}\theta_\mathrm{l} - \mathrm{s}\theta_\mathrm{e}\,\mathrm{s}\theta_\mathrm{g}\,\mathrm{s}\theta_\mathrm{x}\,\mathrm{s}\phi(t) \\ \mathrm{s}\theta_\mathrm{e}\,\mathrm{c}\theta_\mathrm{g}\,\mathrm{c}\theta_\mathrm{l}\,\mathrm{c}\theta_\mathrm{x}\,\mathrm{c}\phi(t) - \mathrm{c}\theta_\mathrm{e}\,\mathrm{c}\theta_\mathrm{g}\,\mathrm{s}\theta_\mathrm{l}\,\mathrm{c}\theta_\mathrm{x} - \mathrm{s}\theta_\mathrm{e}\,\mathrm{s}\theta_\mathrm{g}\,\mathrm{s}\theta_\mathrm{l}\,\mathrm{c}\phi(t) - \mathrm{c}\theta_\mathrm{e}\,\mathrm{s}\theta_\mathrm{g}\,\mathrm{c}\theta_\mathrm{l} + \mathrm{s}\theta_\mathrm{e}\,\mathrm{c}\theta_\mathrm{g}\,\mathrm{s}\theta_\mathrm{x}\,\mathrm{s}\phi(t) \end{pmatrix}$$

e.g. Pino



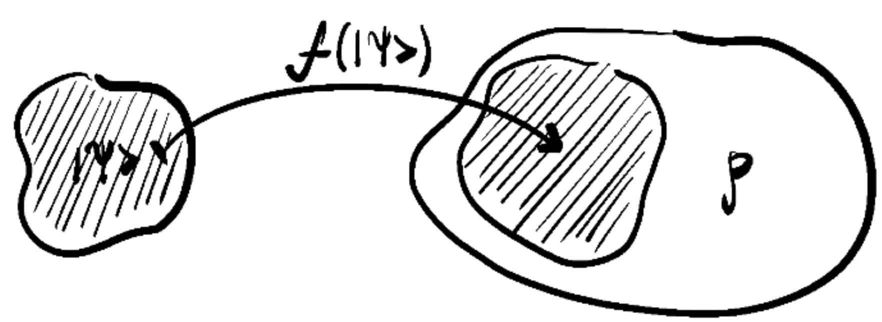
AIs: Decoherence



open system

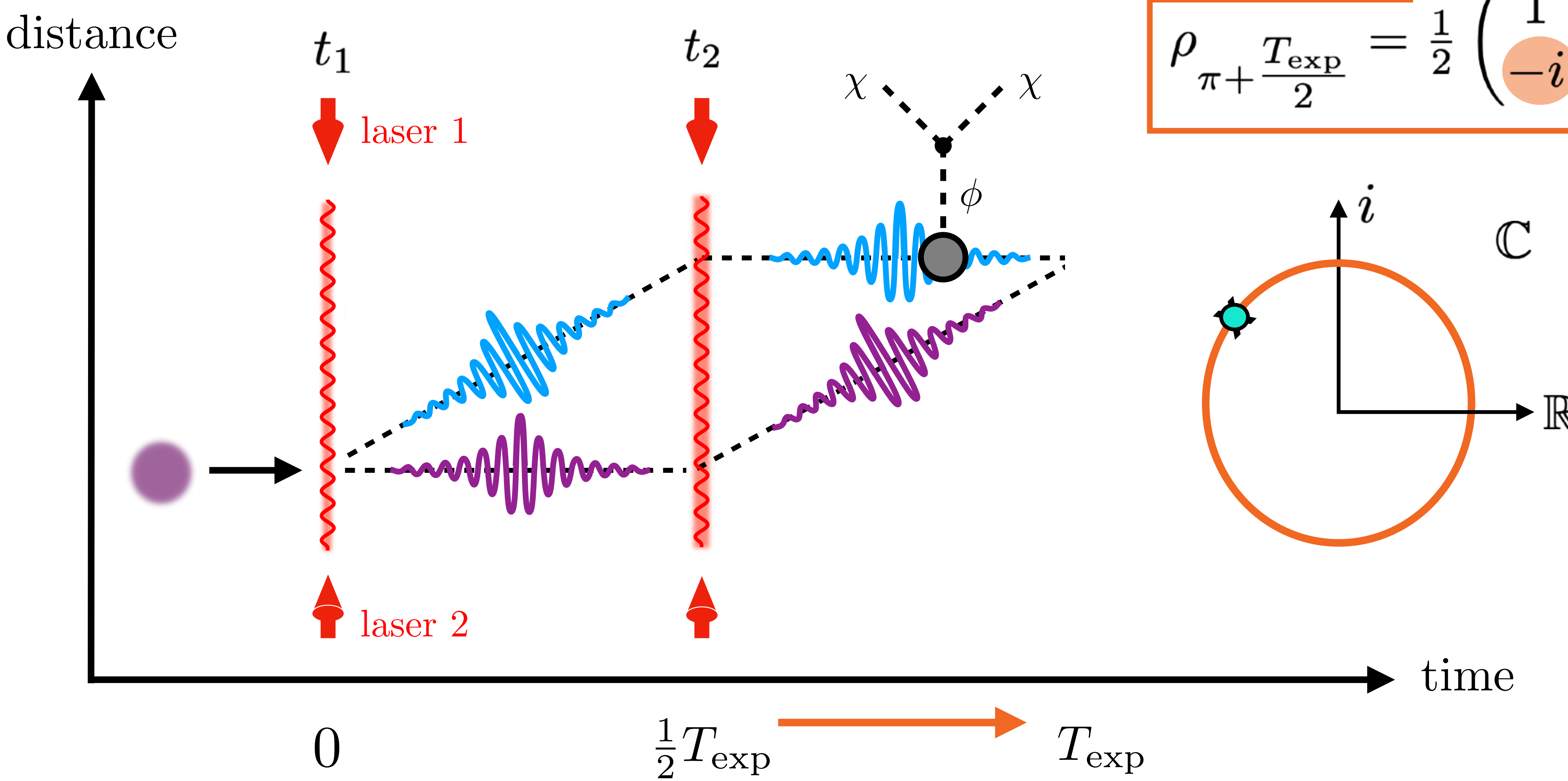
$$\rho_{\pi+\frac{T_{\text{exp}}}{2}} = \frac{1}{2}\begin{pmatrix} 1 & i \\ -i & 1 \end{pmatrix}$$

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



AIs: Decoherence

Long-wavelength decoherence



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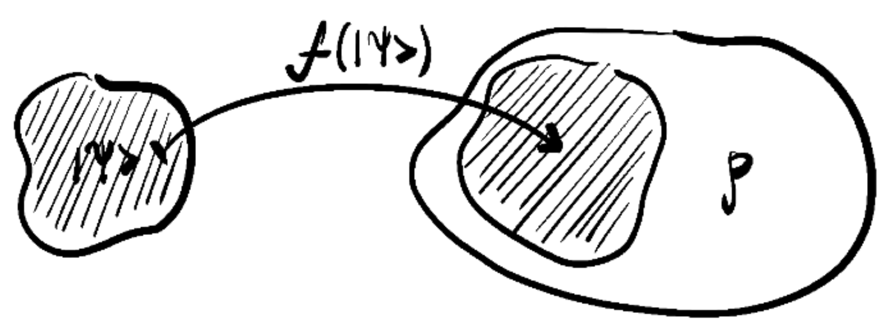

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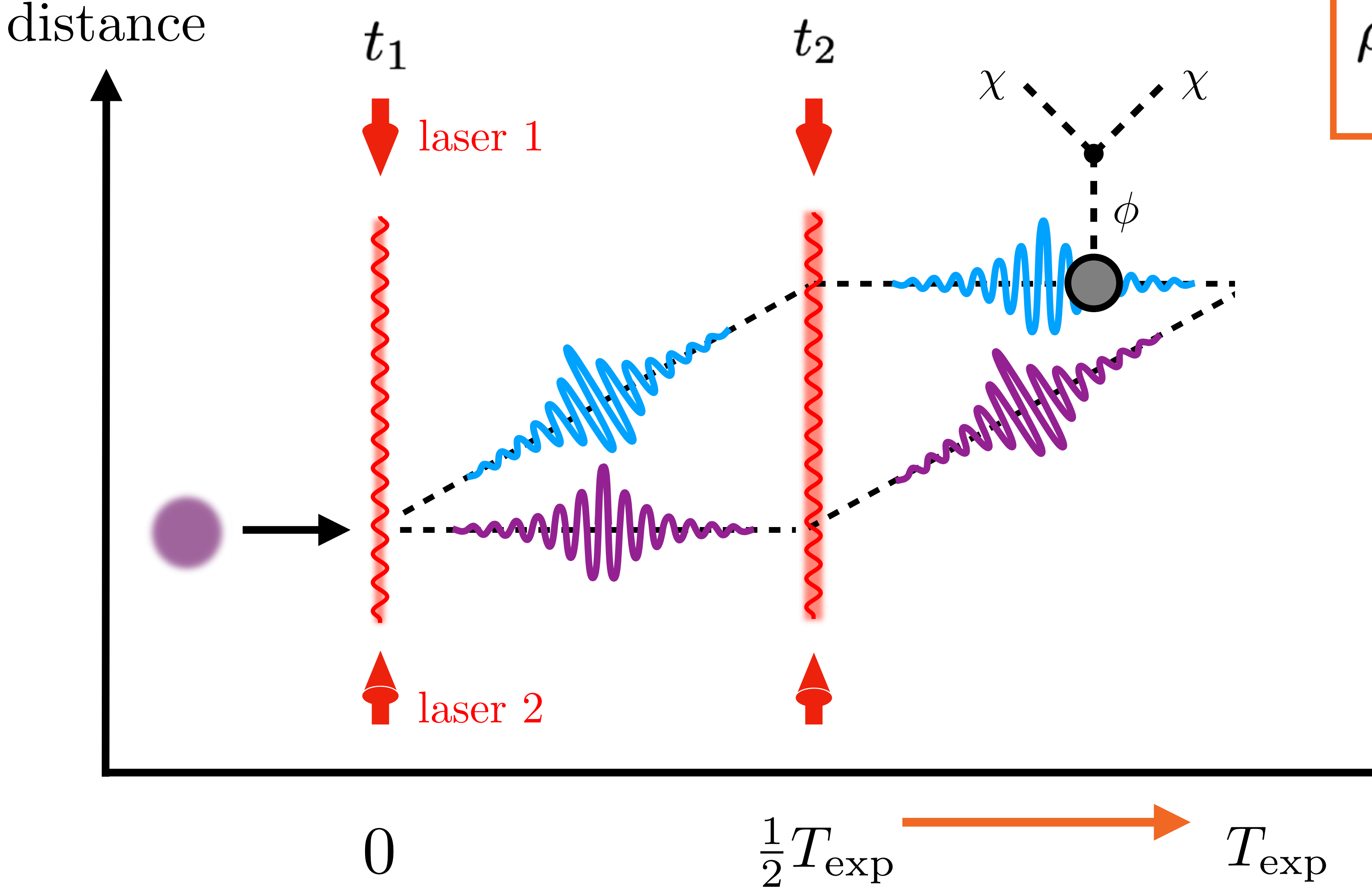
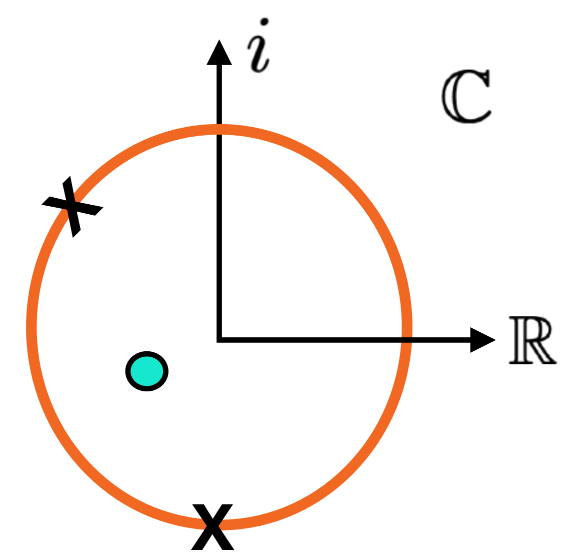


open system

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



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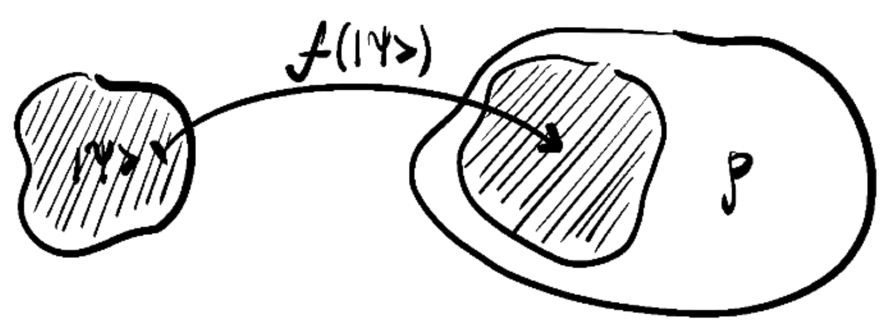

$$\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}$$

AIs: Decoherence

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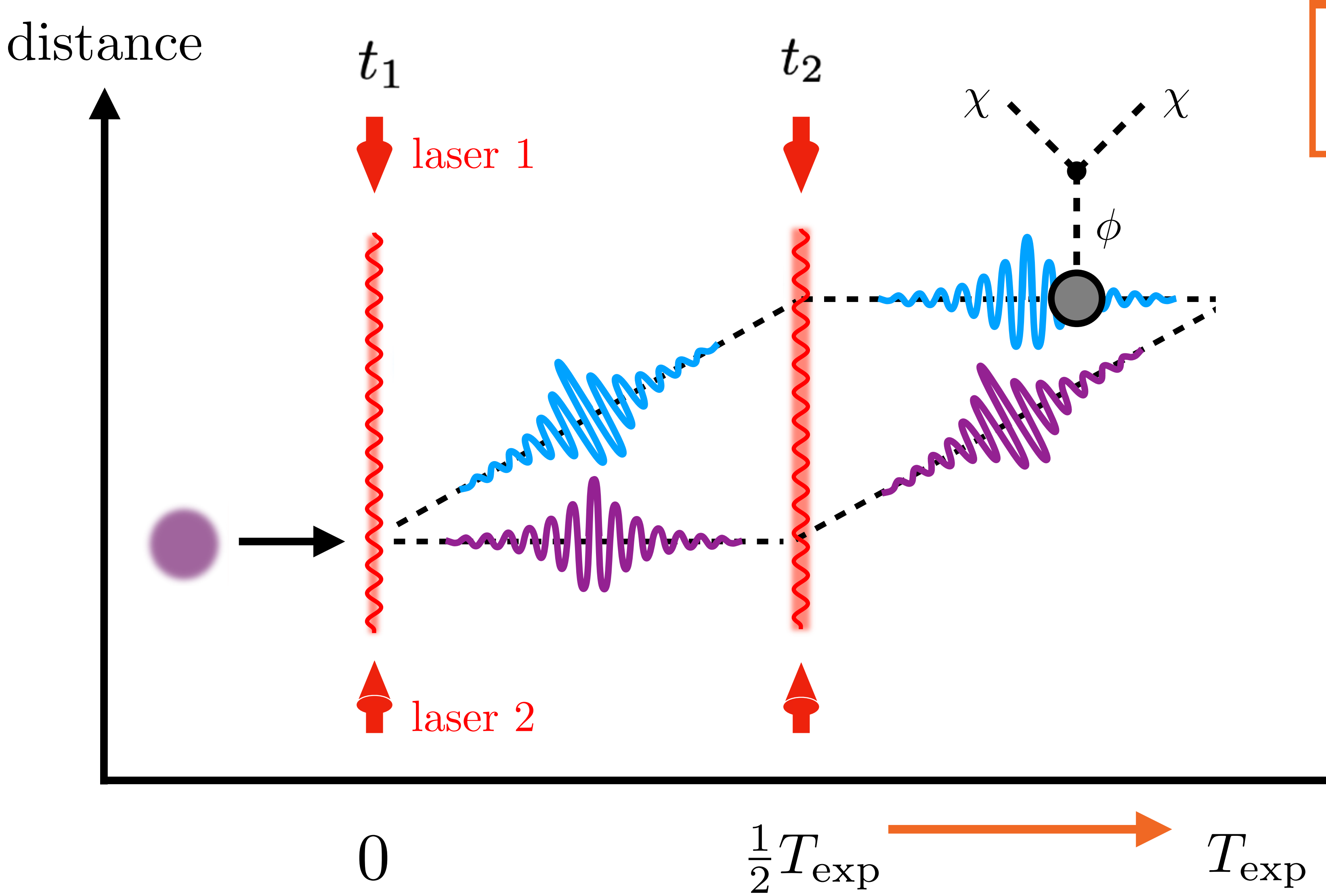

open system

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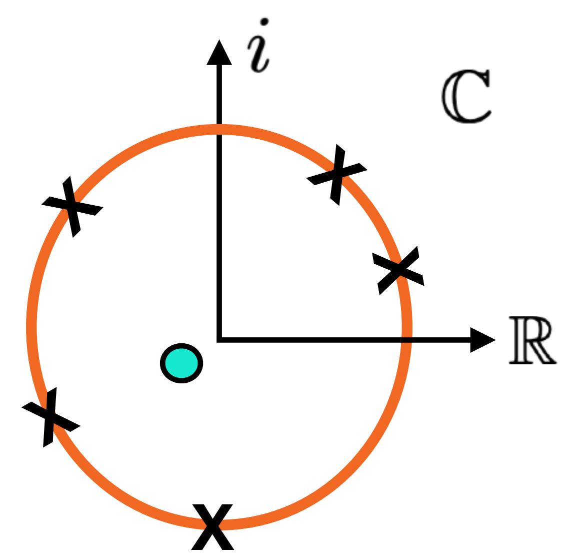

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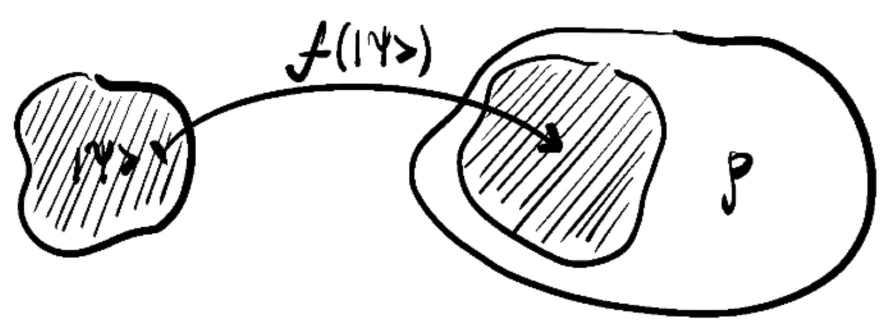

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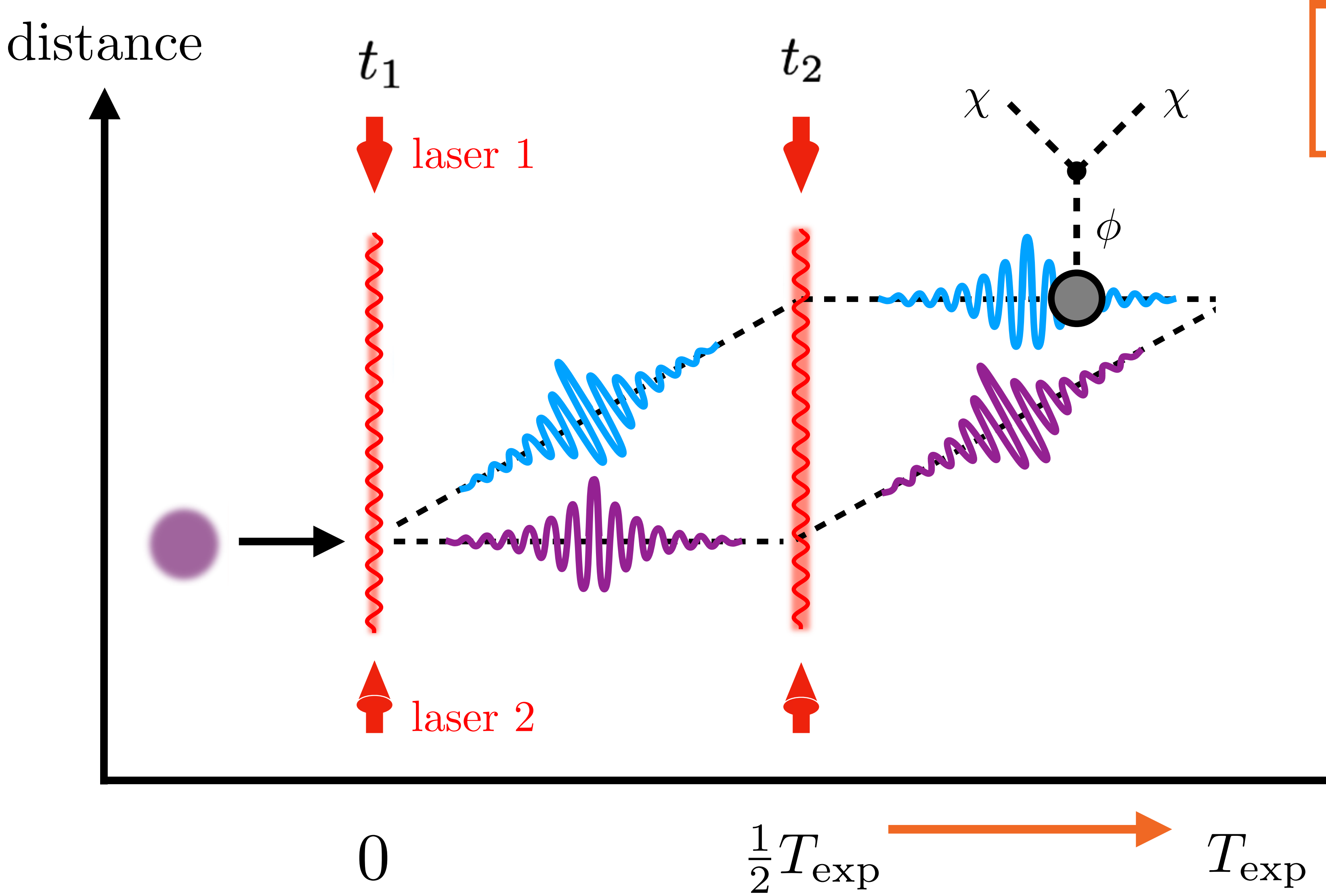

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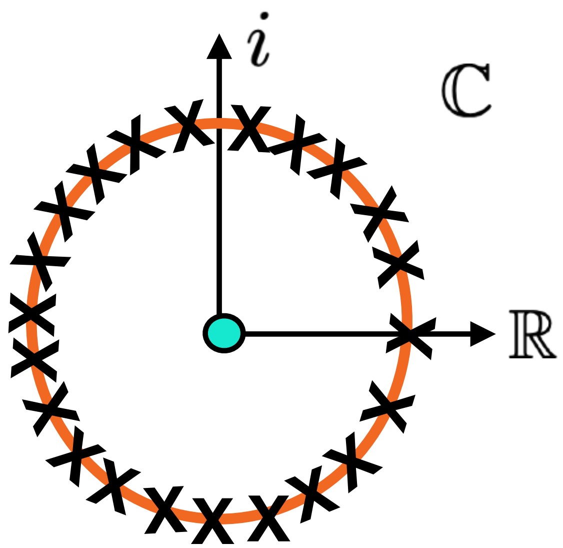

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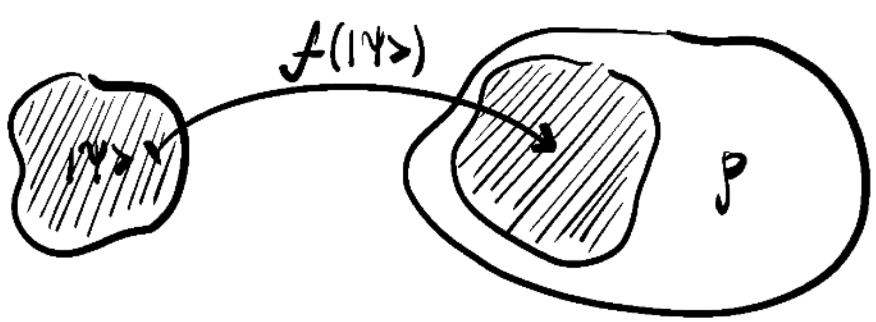

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Atom Interferometers (AIs)

Heavy mediator case: other applications

Dark Photon

Axion scattering