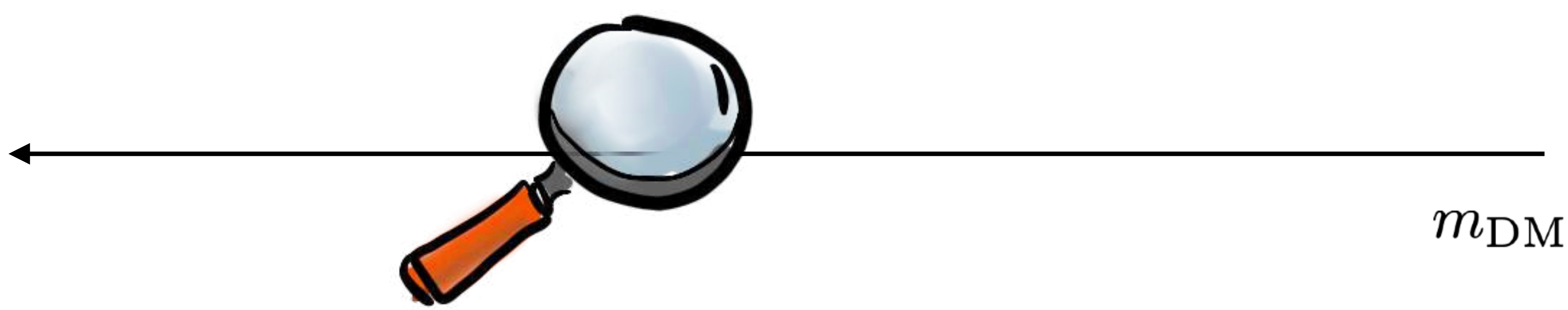
AYUDA BEATRIZ GALINDO JUNIOR BG23
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

Targeting soft imprints of dark matter

Clara Murgui (UAB/IFAE/CERN)

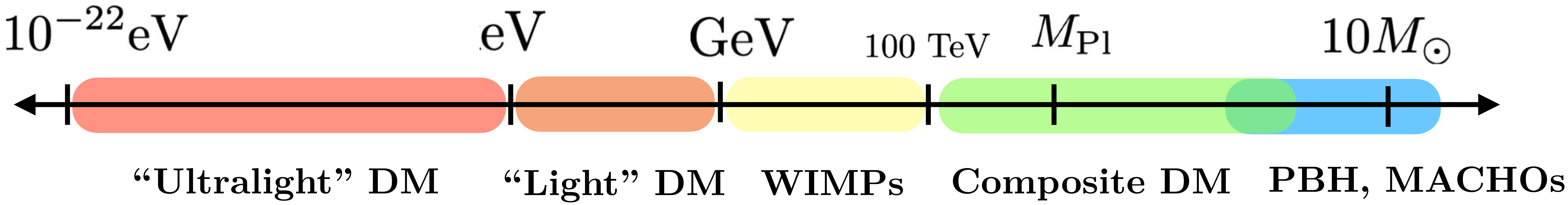
L. Badurina, Y. Du, K. Pardo, R. Plestid, Y. Wang, and K. M. Zurek [all @ Caltech]

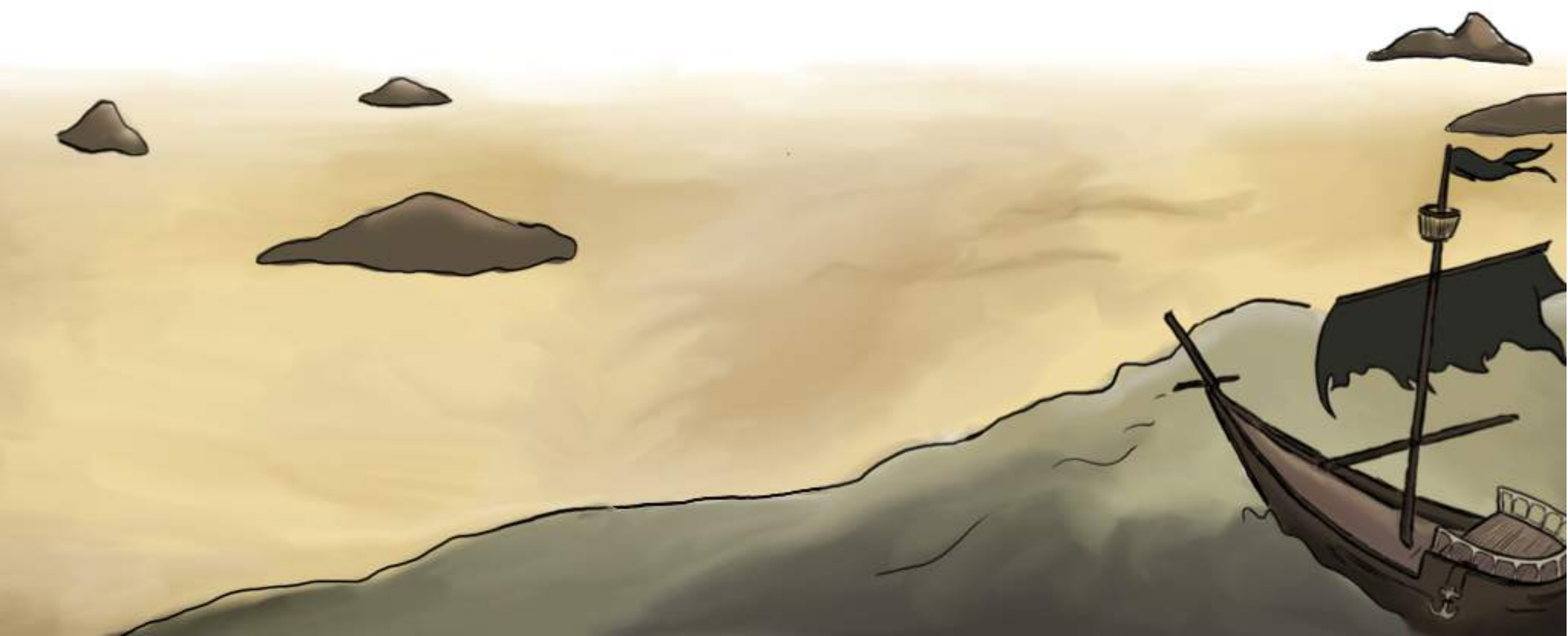


R. Adhikari [Caltech], S. Chiow [JPL], L. P. McCuller [Caltech], Y. Michimura [Caltech], K. Schwab [Caltech], Y. Patil [Yale U.], J. Harris [Yale U.]

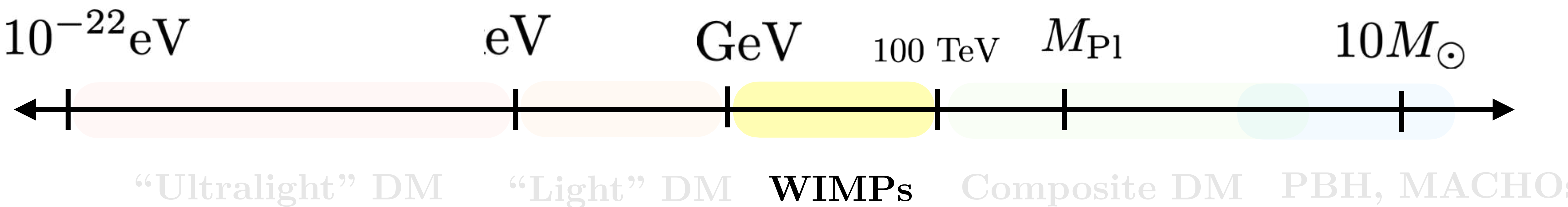
Dark Matter Beyond the Weak Scale II
26th March 2024

Dark Matter: where to look?

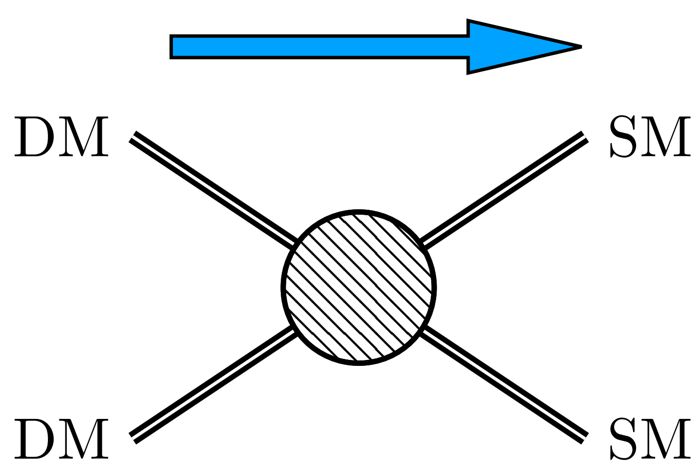




Dark Matter: where to look?



The WIMP miracle

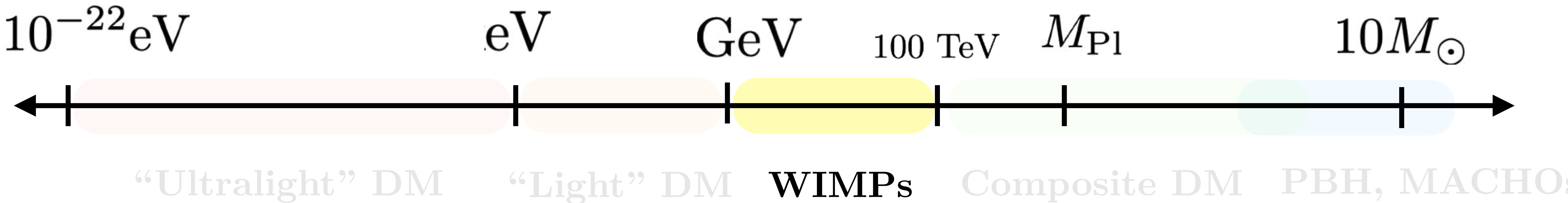


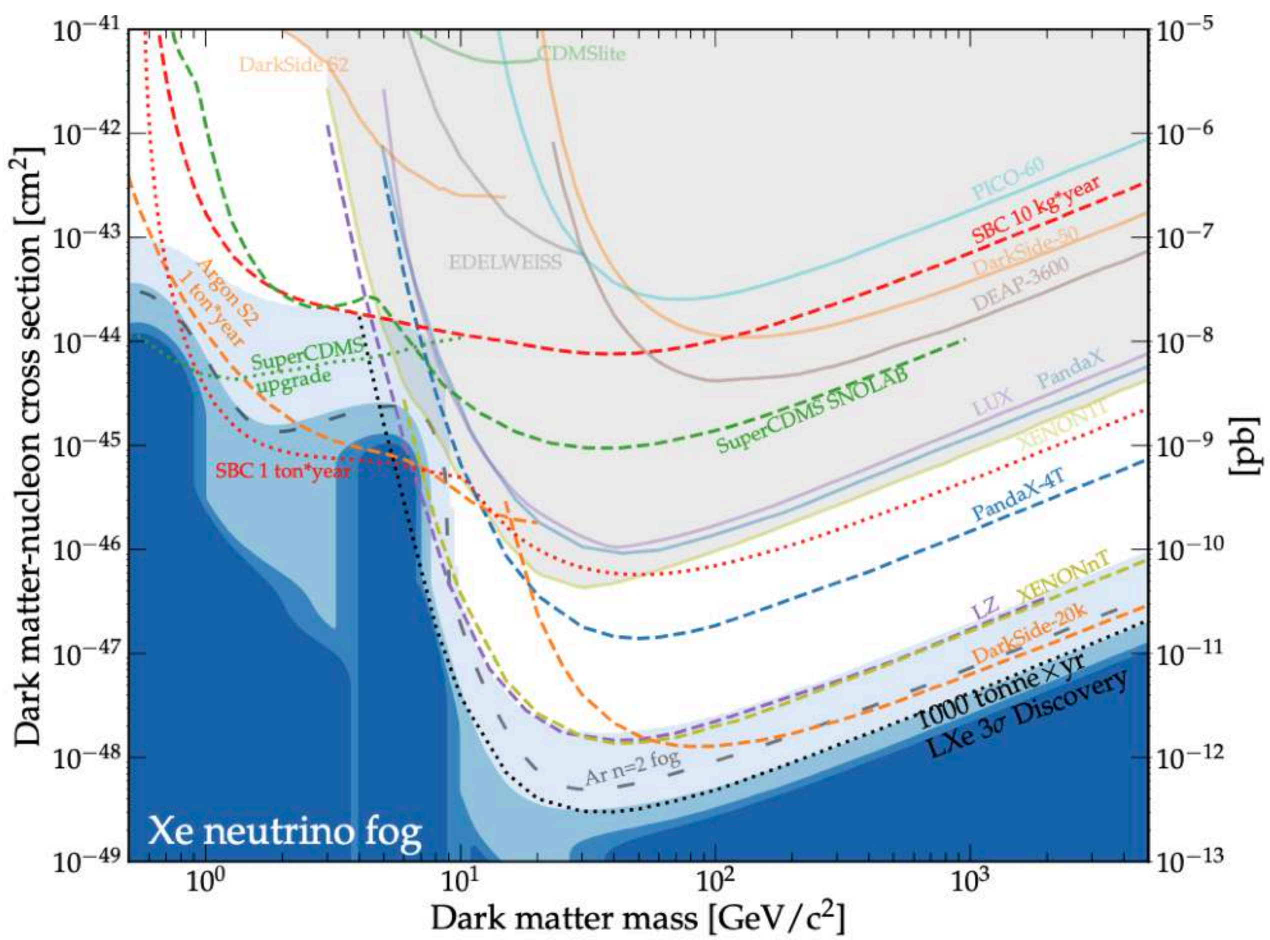
weak coupling

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

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

Dark Matter: where to look?

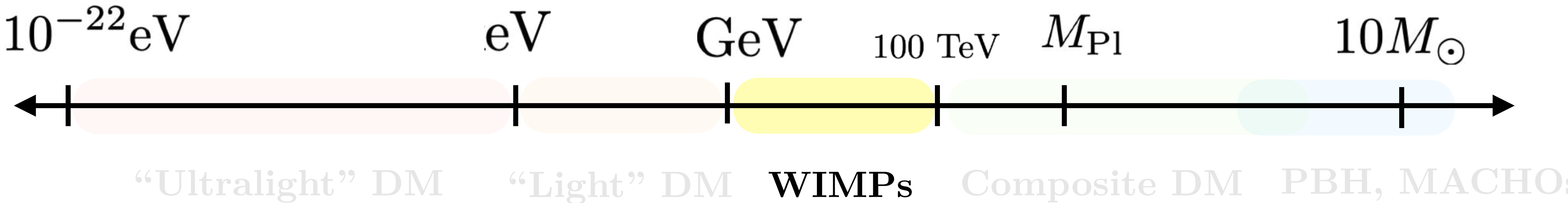


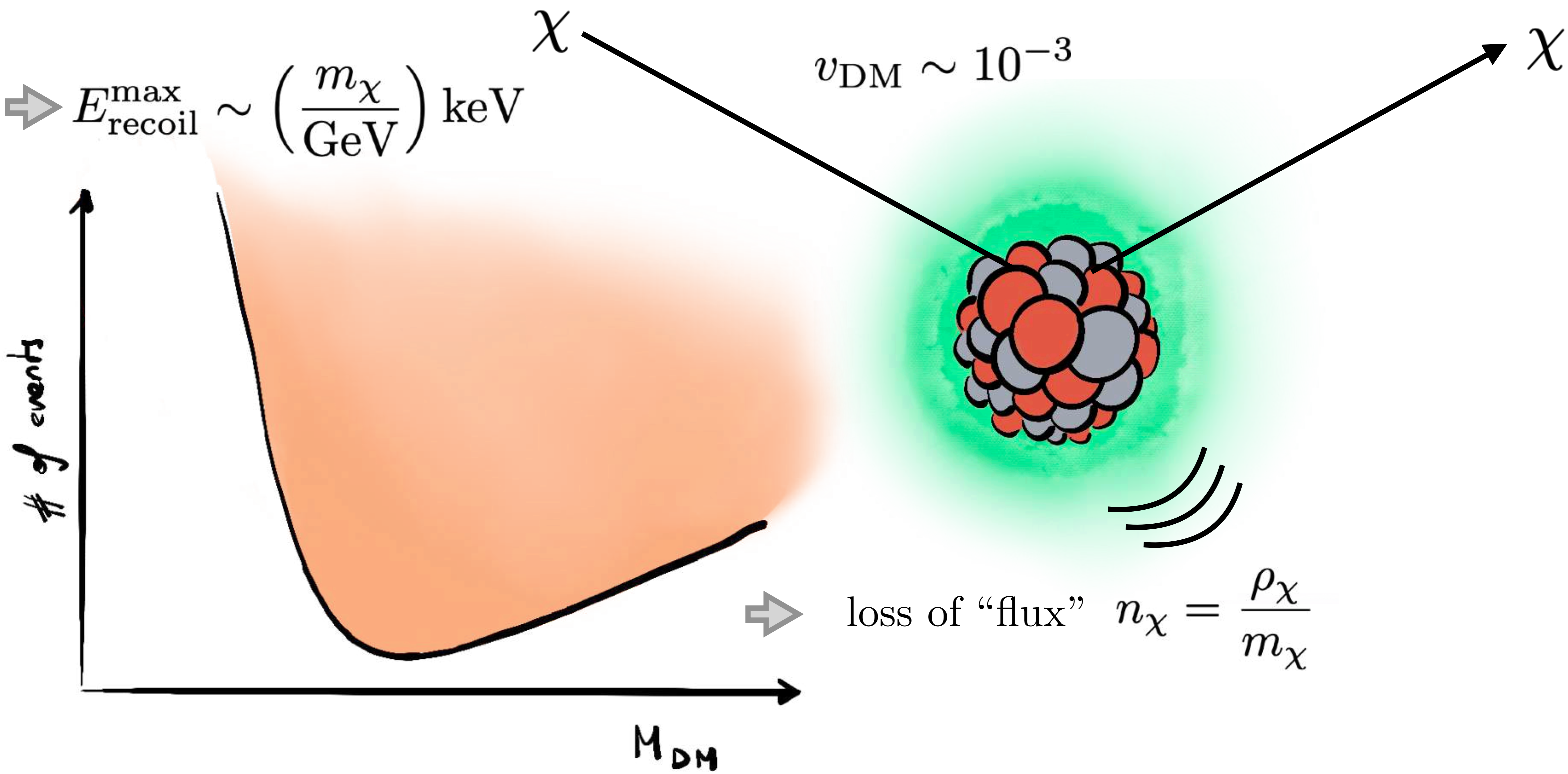


$$\sigma \sim 10^{-34}\text{cm}^2 \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2$$

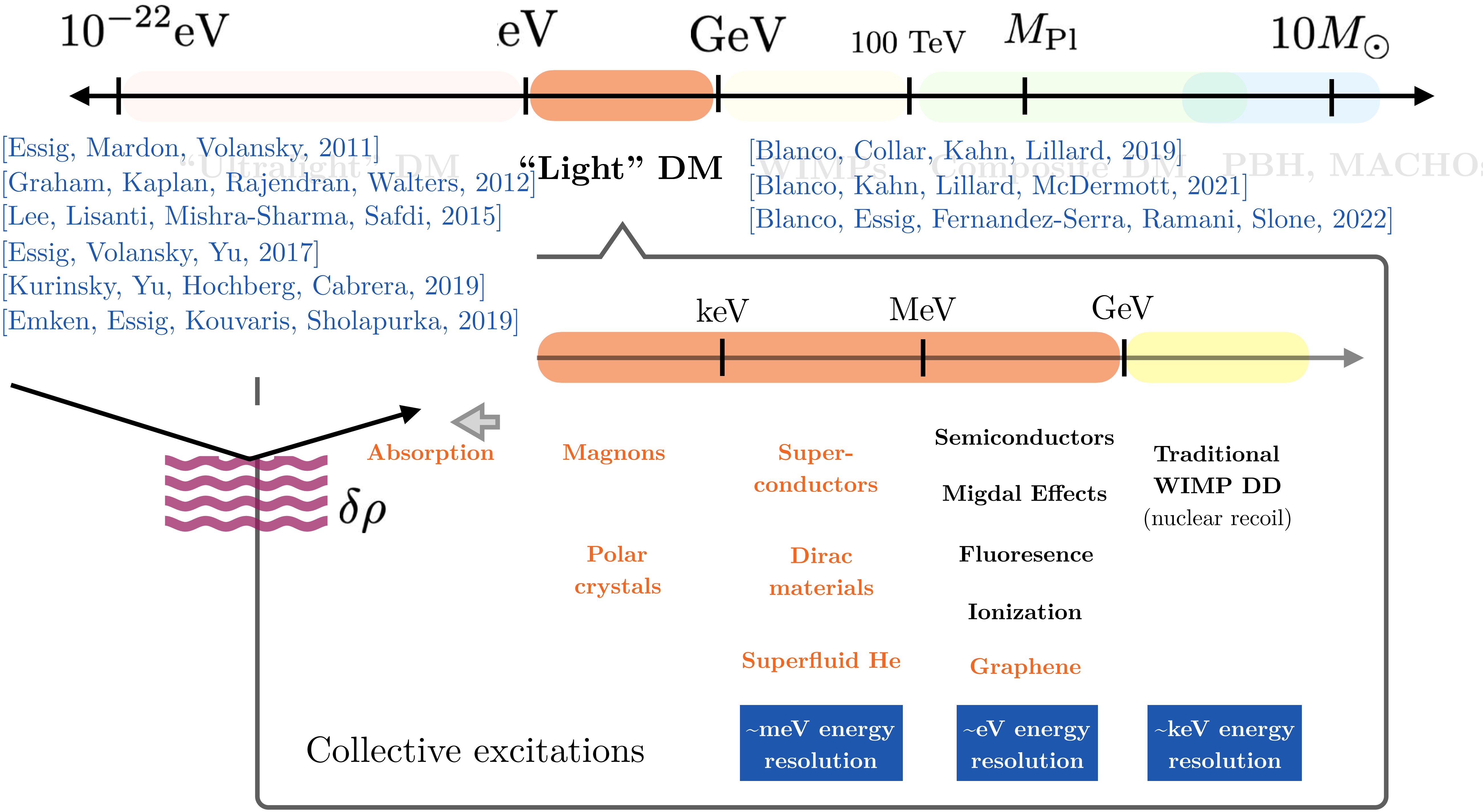
[Akerib, D. S., et al., Snowmass2021, 2203.08084]

Dark Matter: where to look?





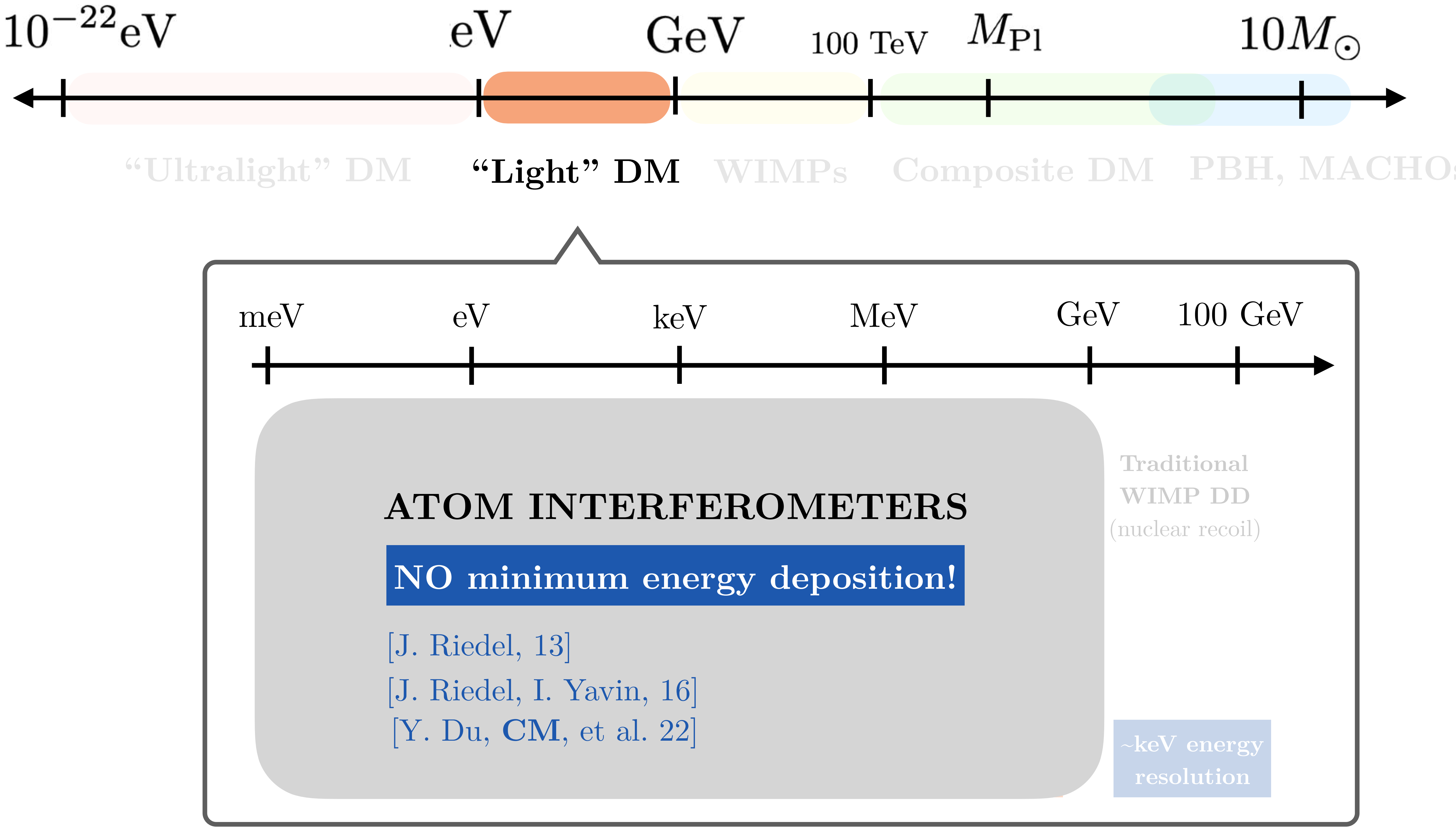
Dark Matter: where to look?



[Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu, 2015]
[Derenzo, Essig, Massari, Soto, Yu, 2016]
[Hochberg, Lin, Zurek, 2016]
[Bloch, Essig, Tobioka, Volansky, Yu, 2016]

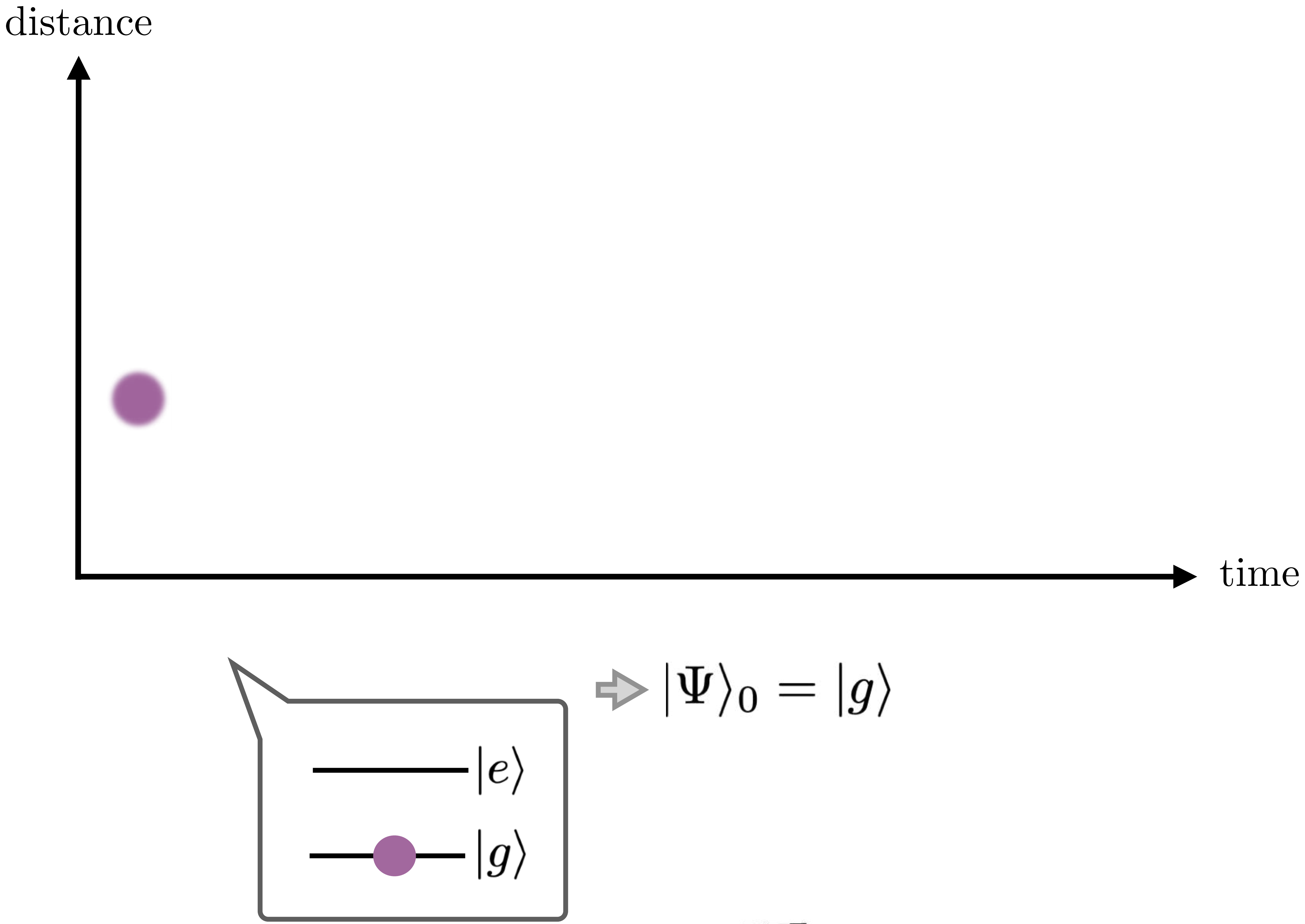
[Griffin, Inzani, Trickle, Zhang, Zurek, 2019]
[Coskuner, Mitridate, Olivares, Zurek, 2020]
[Mitridate, Trickle, Zhang, Zurek, 2021]
[Chen, Mitridate, Trickle, et al, 2022]

Dark Matter: where to look?



AIs: the Principle

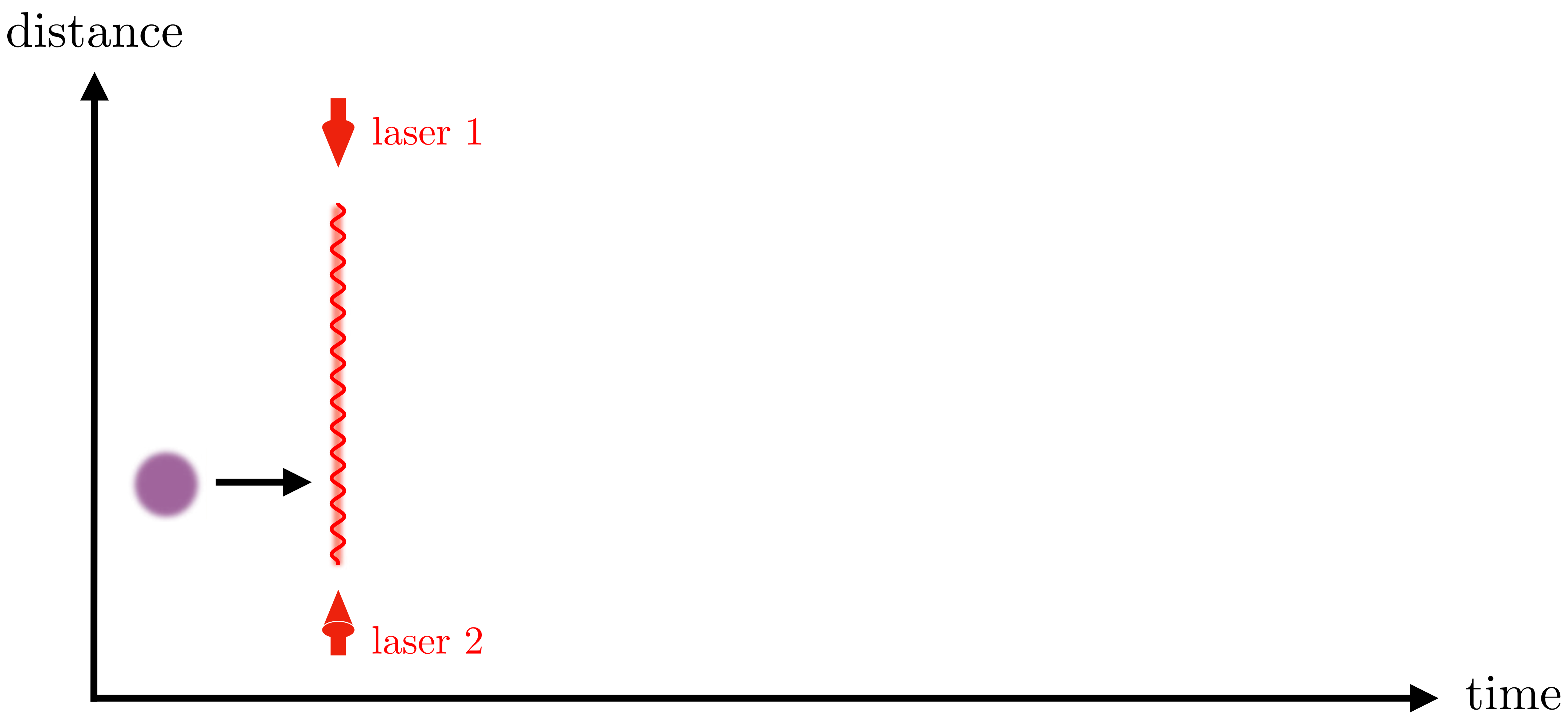
Review: arXiv:2003.12516

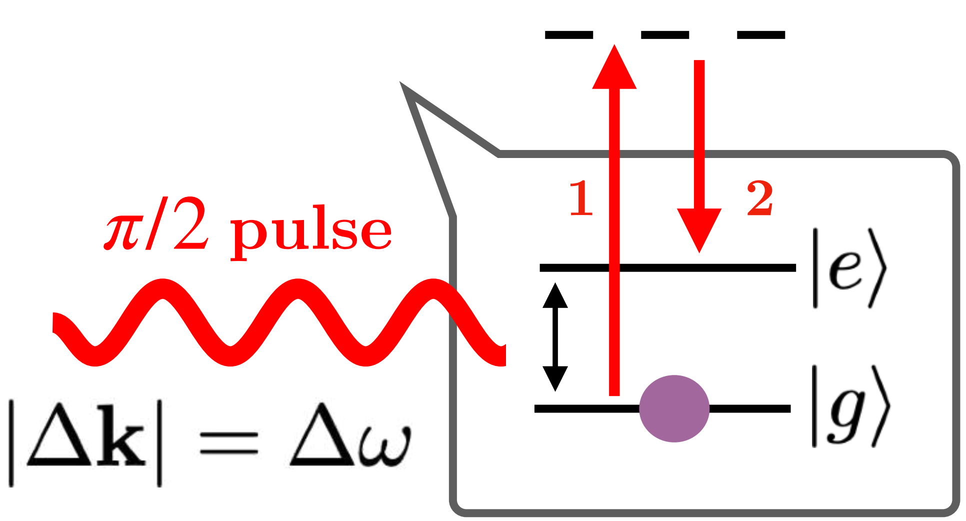


$$\Rightarrow |\Psi\rangle_0 = |g\rangle$$

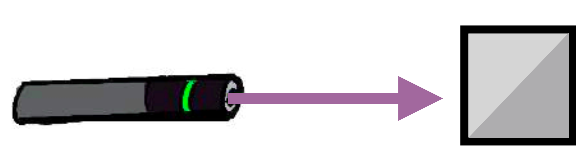
AIs: the Principle

Review: arXiv:2003.12516



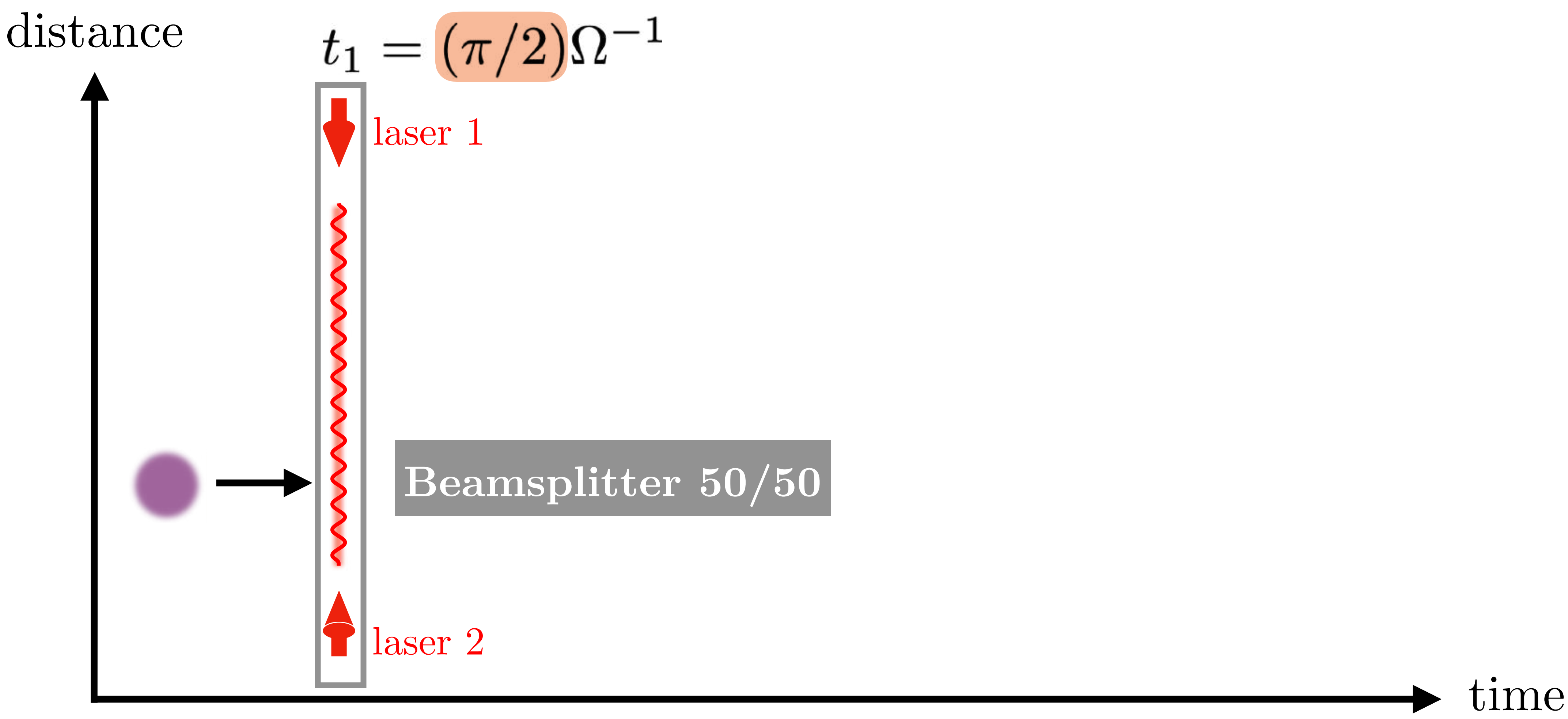


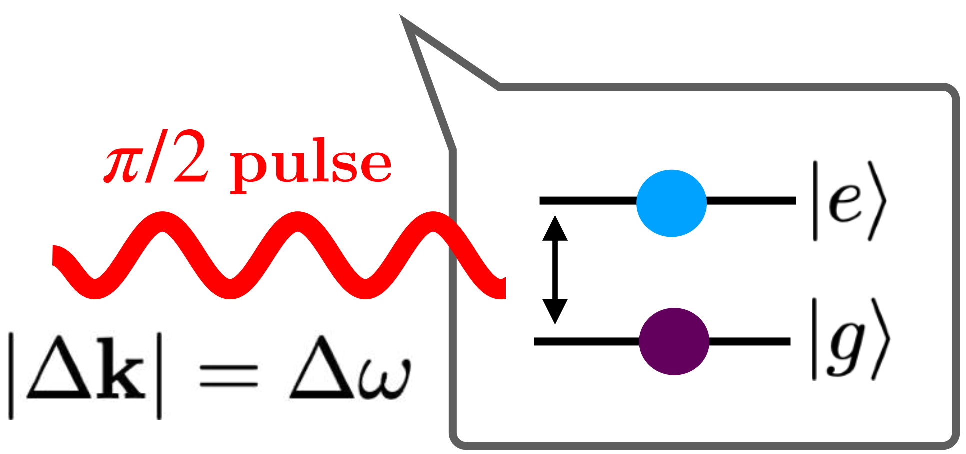
$$\Rightarrow |\Psi\rangle_t = \cos(\Omega t/2)|g\rangle + i\sin(\Omega t/2)|e\rangle$$



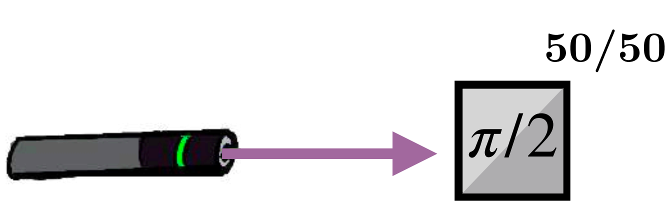
AIs: the Principle

Review: arXiv:2003.12516



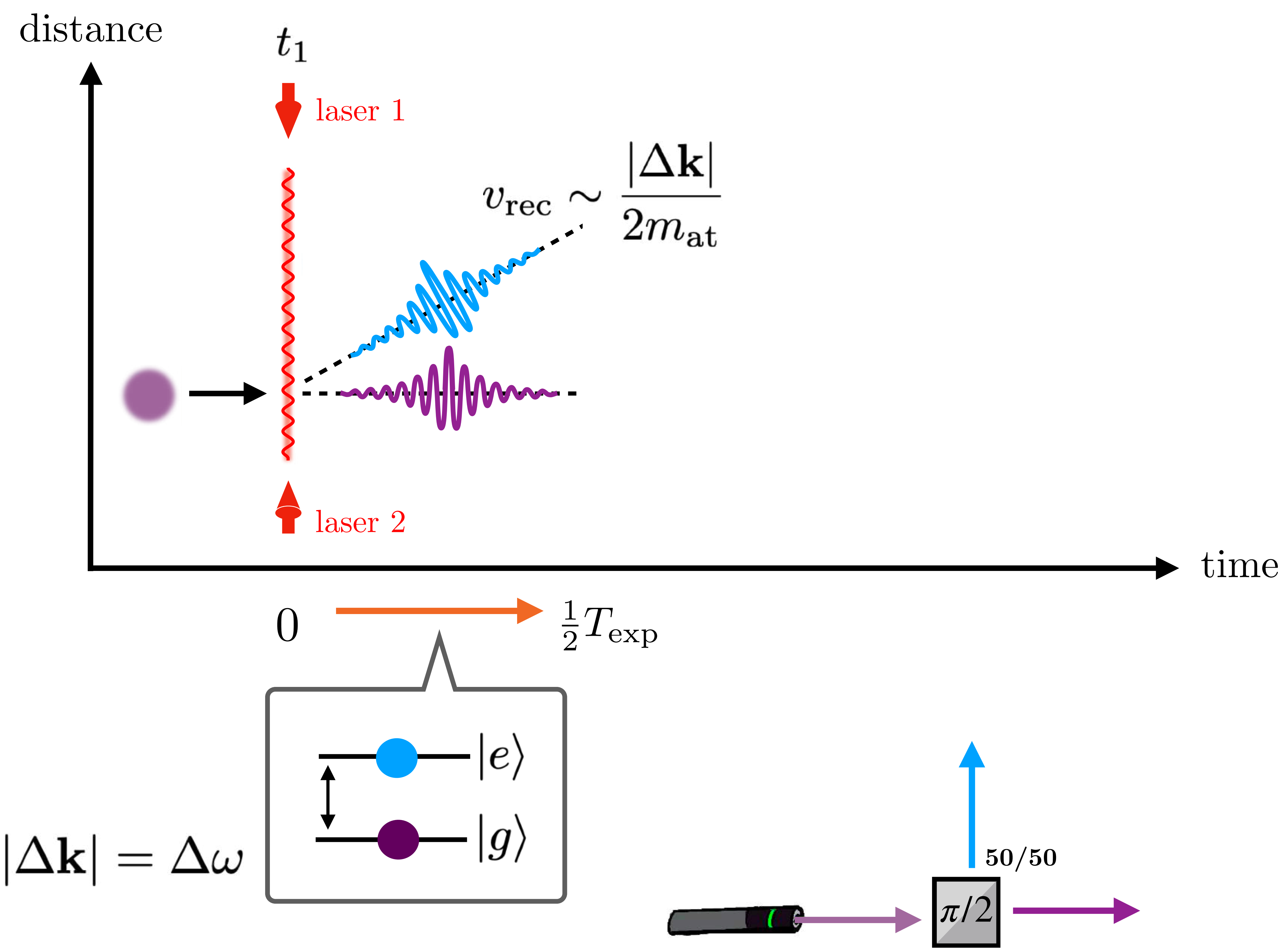


$$\Rightarrow |\Psi\rangle_t = \cos(\pi/4)|g\rangle + i\sin(\pi/4)|e\rangle$$



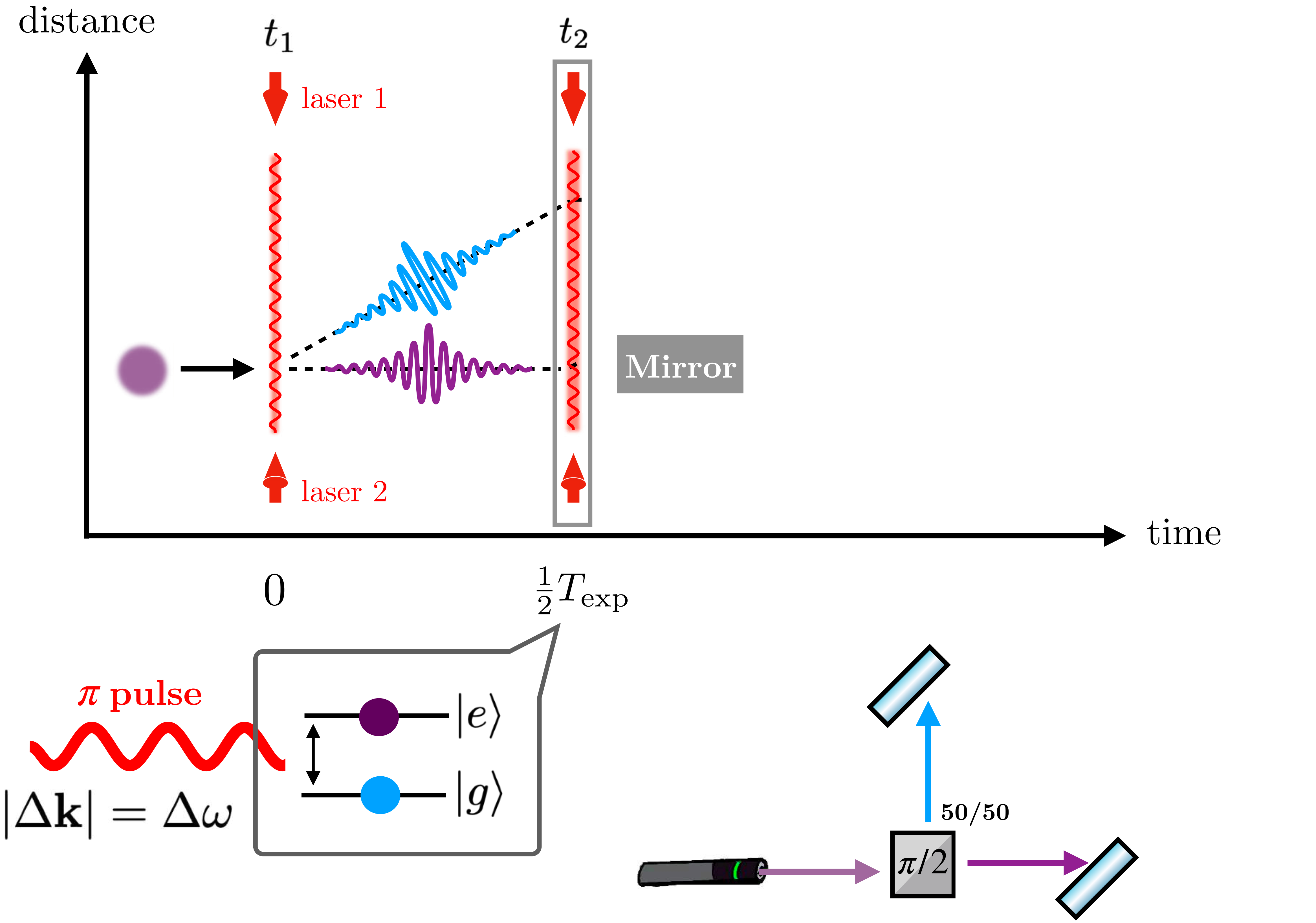
AIs: the Principle

Review: arXiv:2003.12516



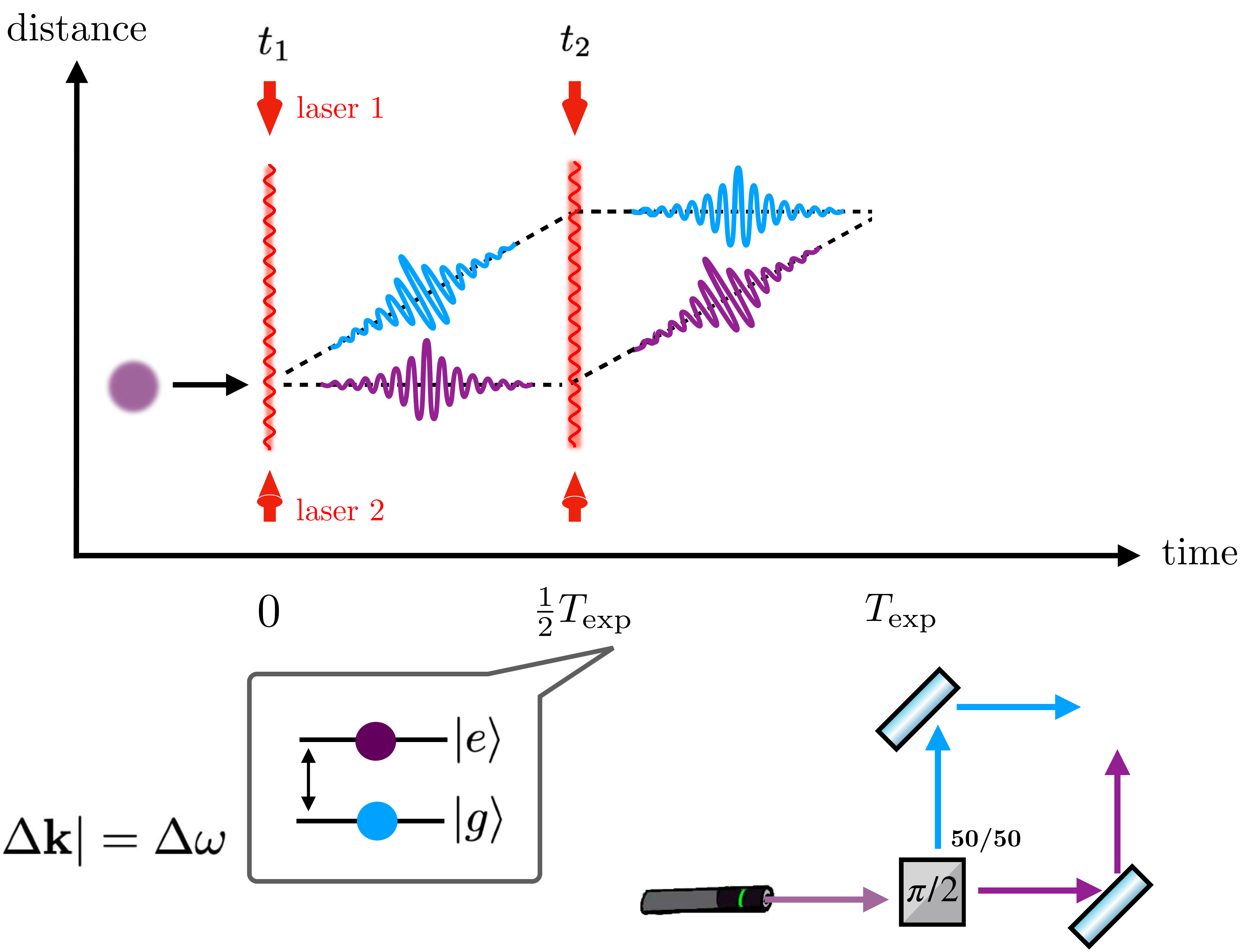
AIs: the Principle

Review: arXiv:2003.12516



AIs: the Principle

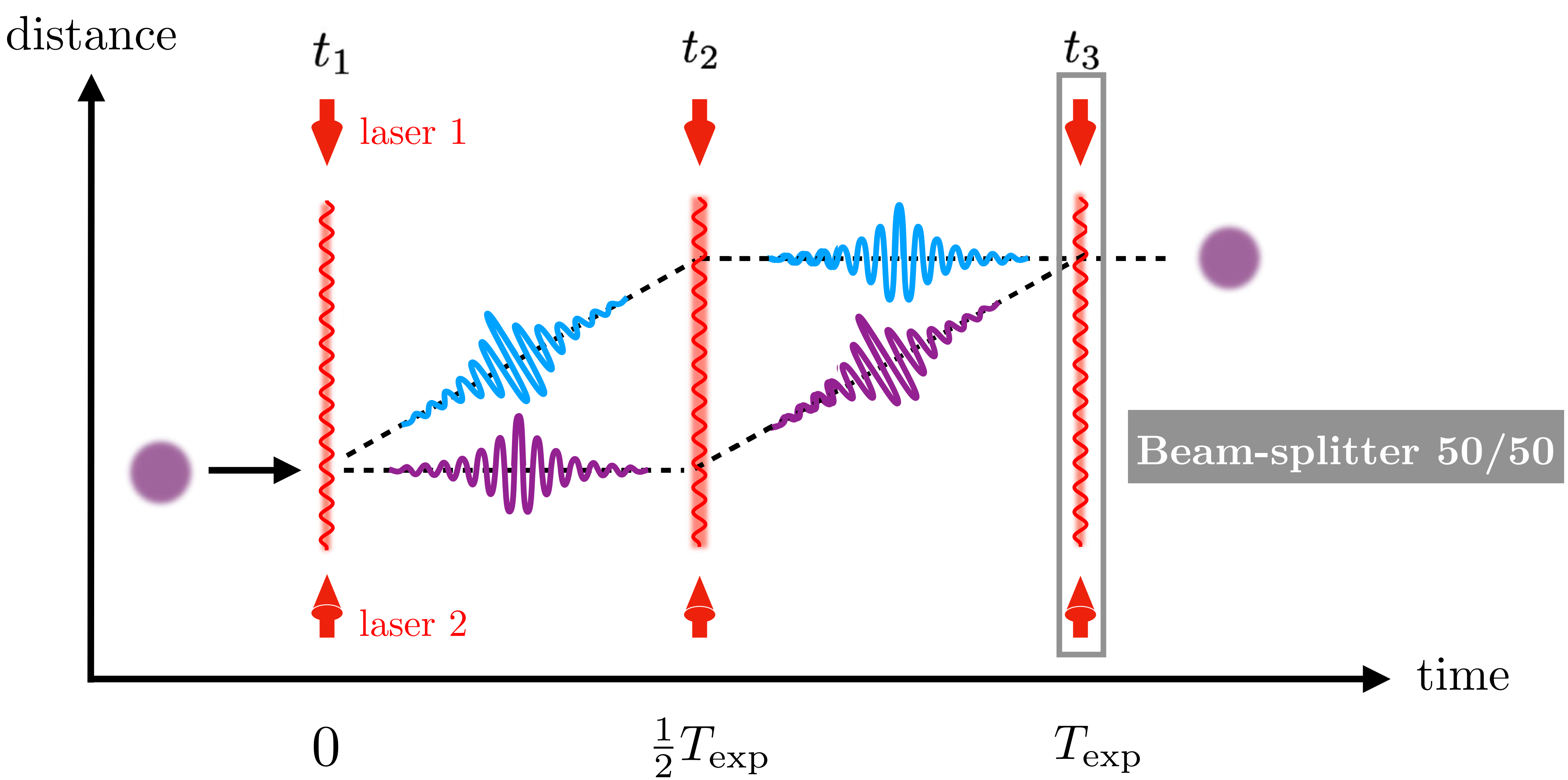
Review: arXiv:2003.12516

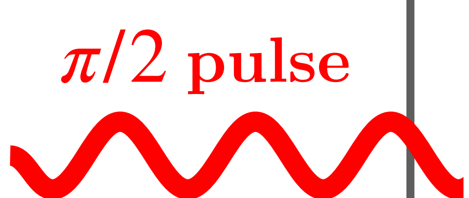


$$|\Delta \mathbf{k}| = \Delta\omega$$

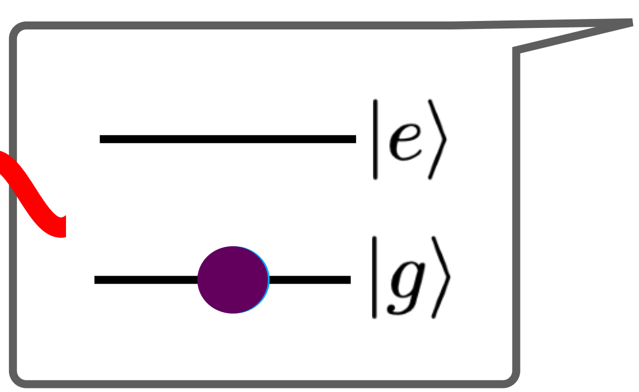
AIs: the Principle

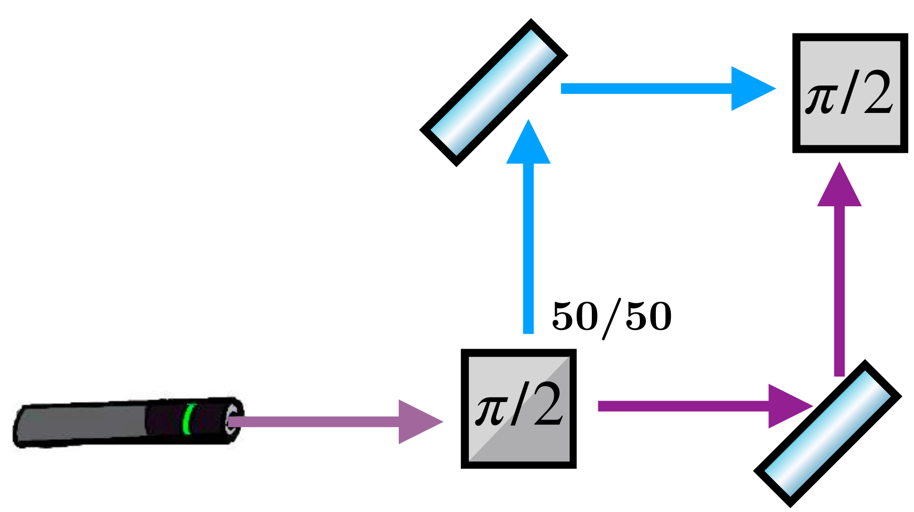
Review: arXiv:2003.12516





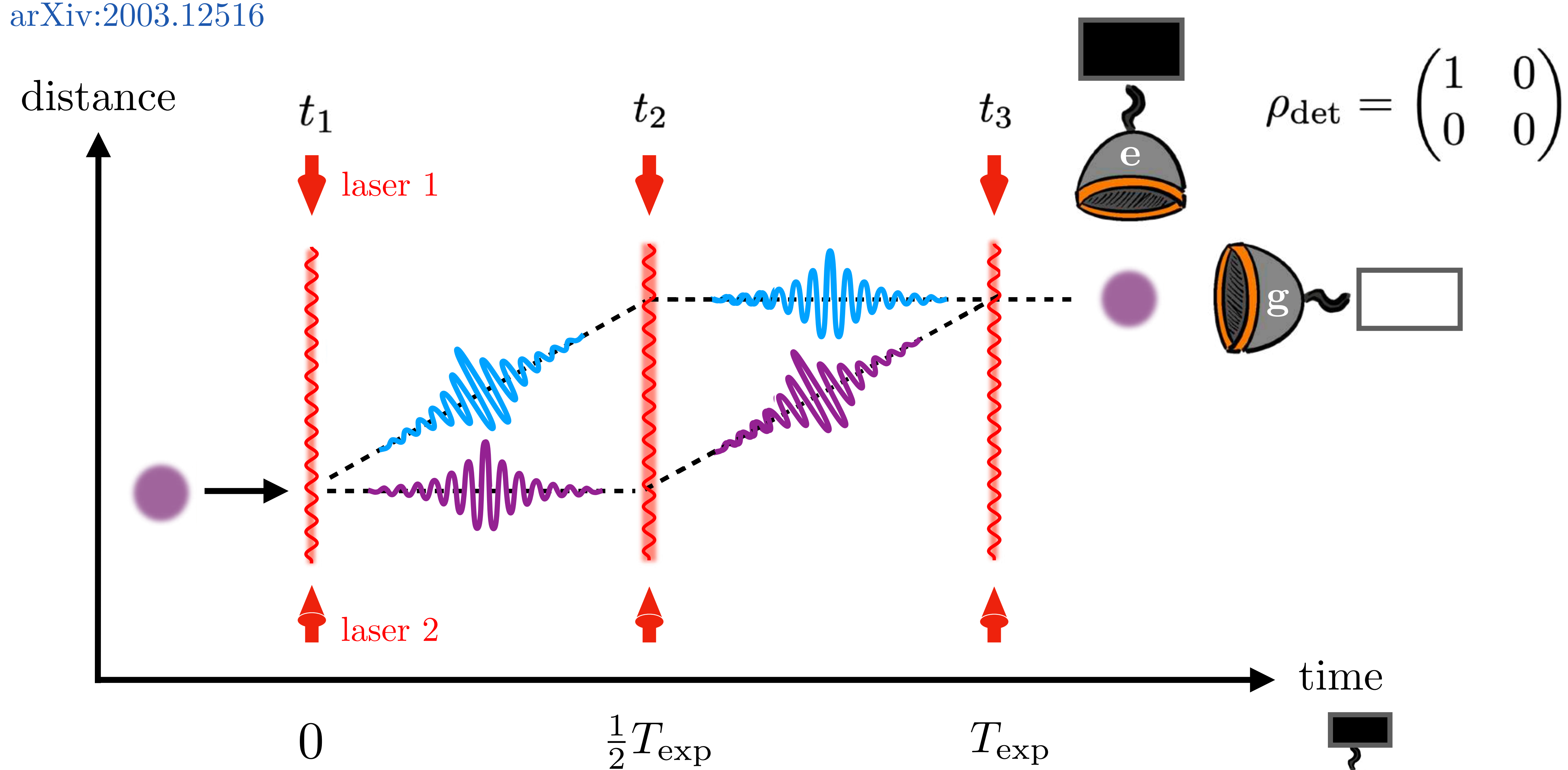
$$|\Delta \mathbf{k}| = \Delta\omega$$

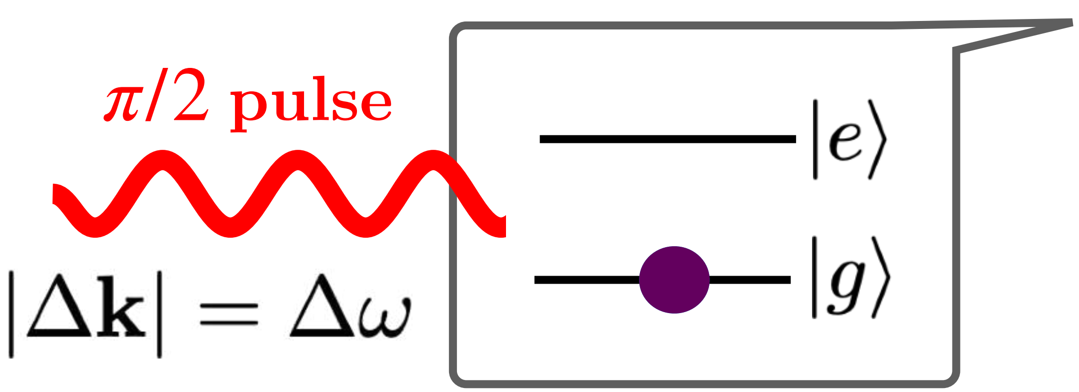


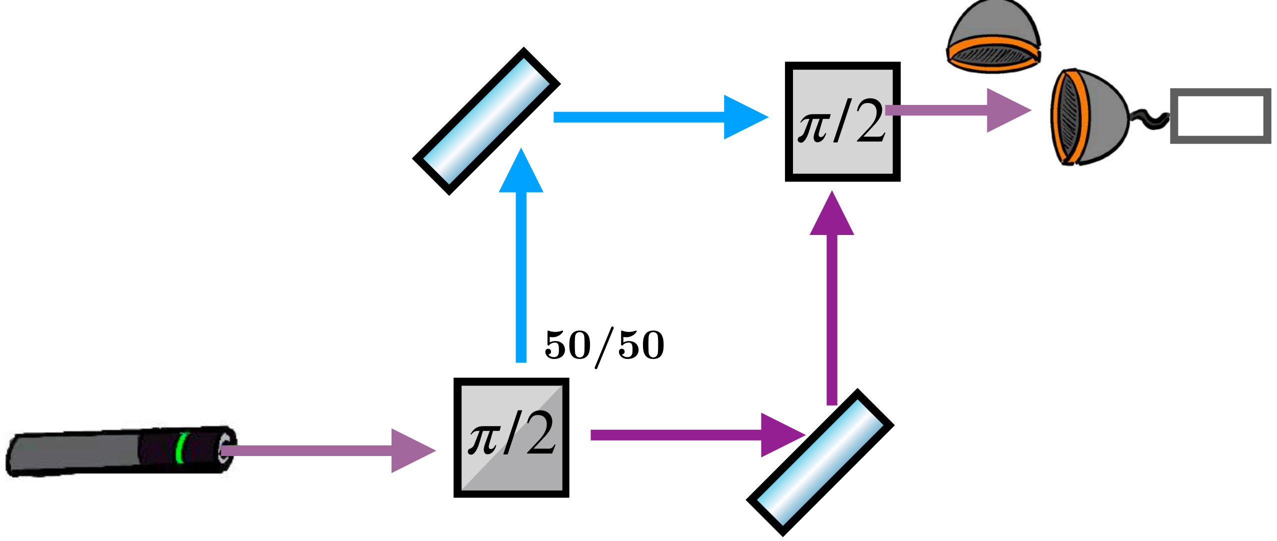


AIs: the Principle

Review: arXiv:2003.12516







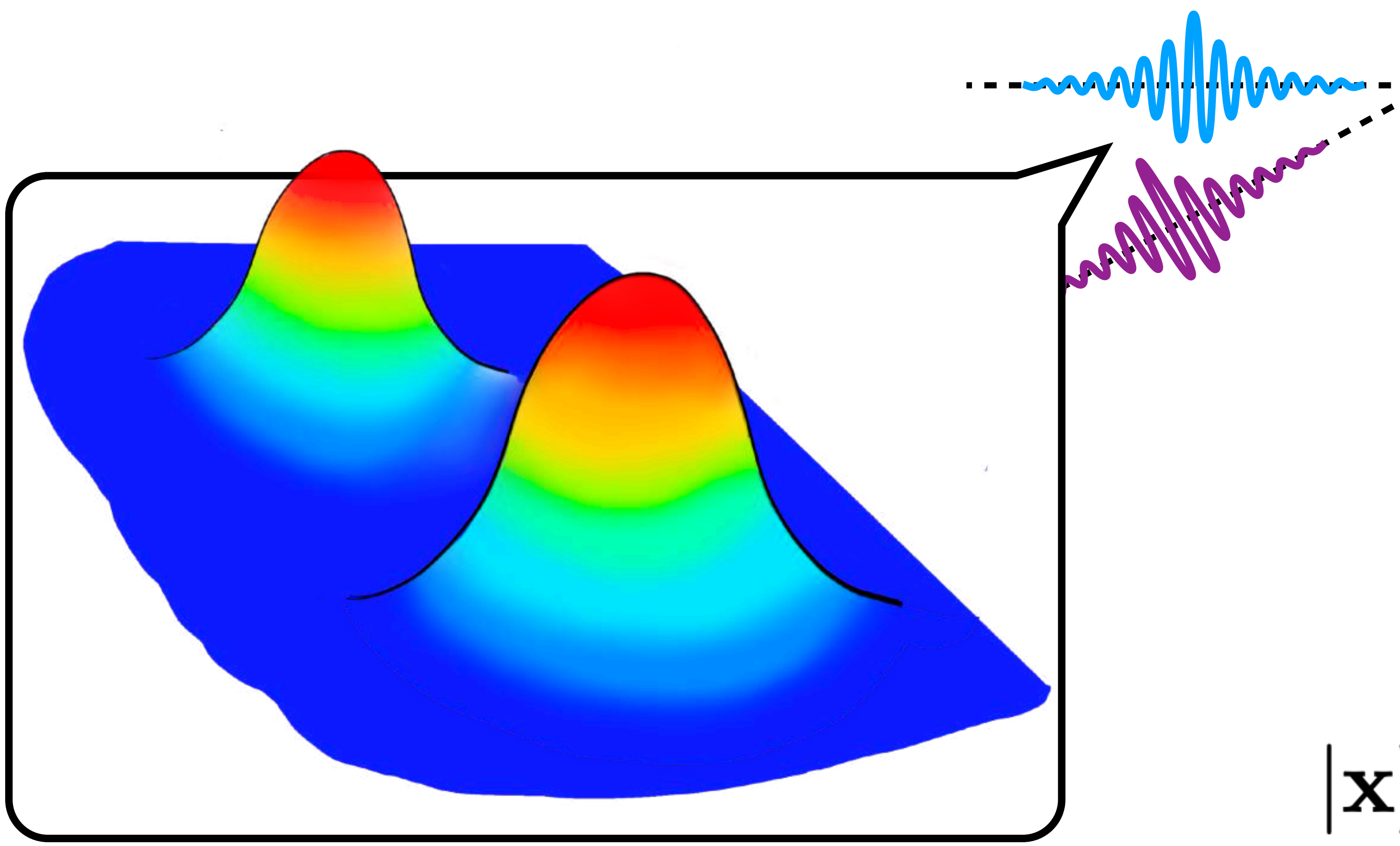
AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]

$$\rho = \frac{1}{2}\begin{pmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{pmatrix}$$



$|\mathbf{x}\rangle$

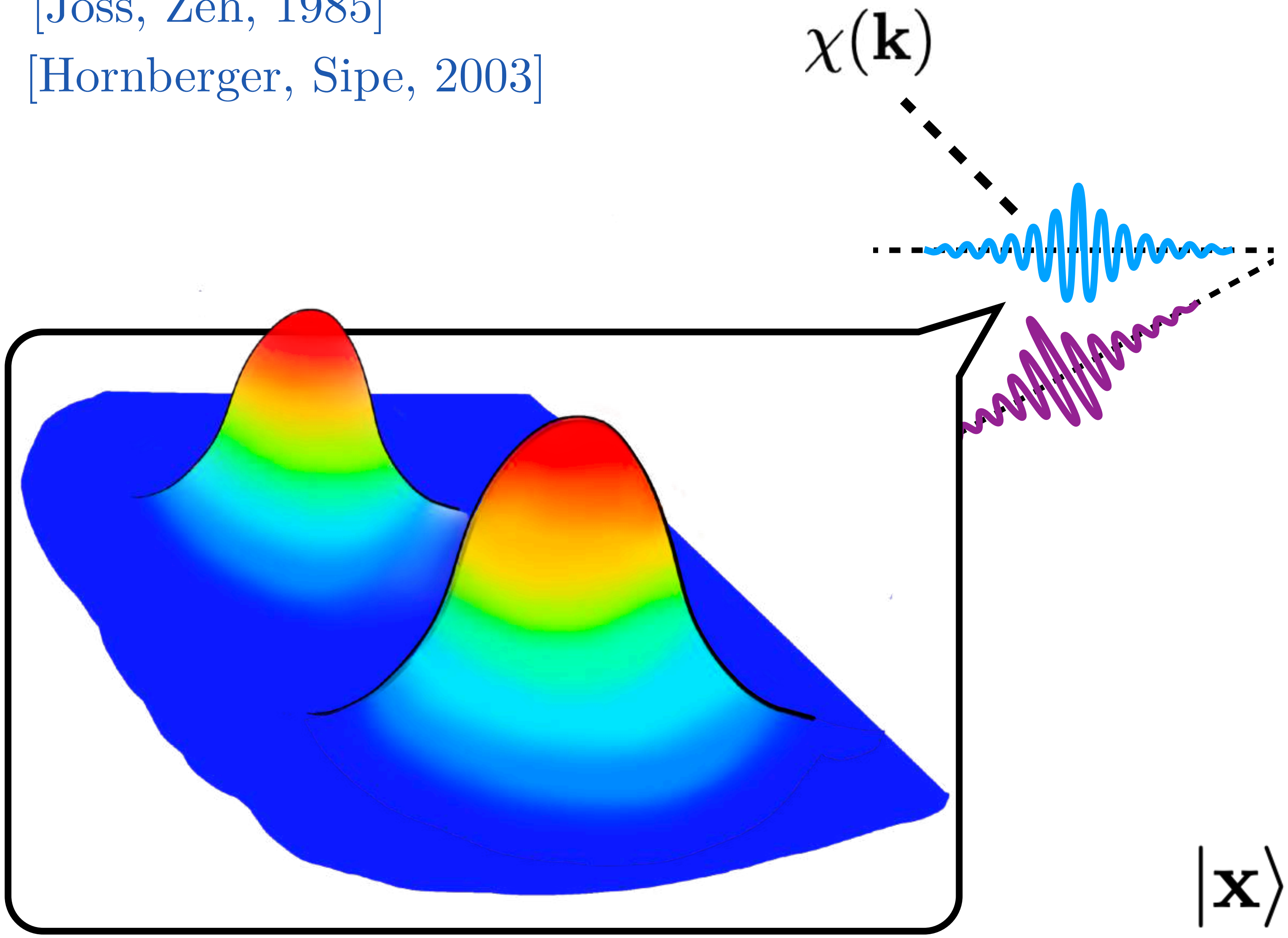
AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]

$$\rho = \frac{1}{2}\begin{pmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{pmatrix}$$



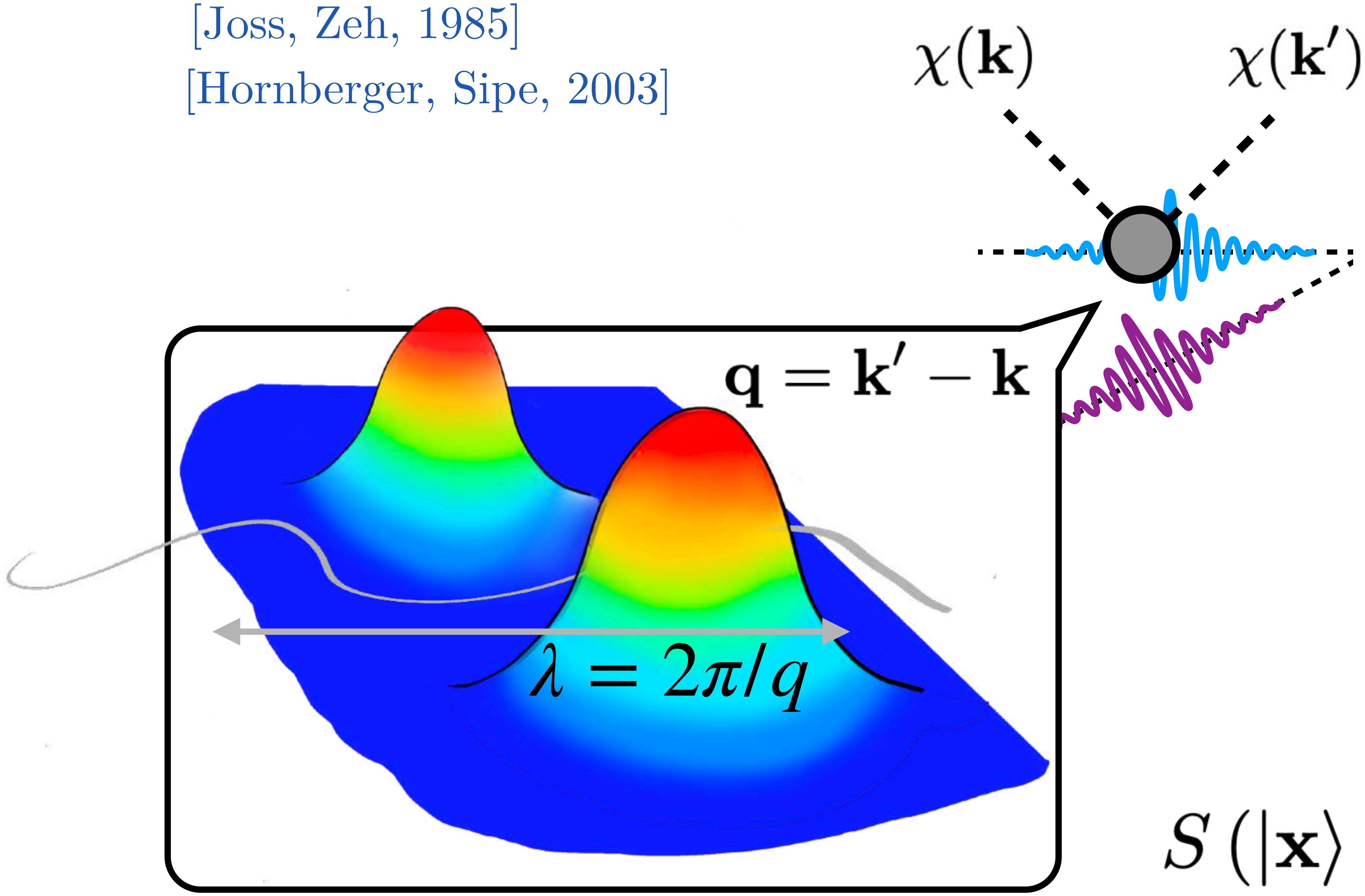
$$|\mathbf{x}\rangle \otimes |\mathbf{k}\rangle$$

AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]



$$\rho = \frac{1}{2}\begin{pmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{pmatrix}$$

$$S\left(|\mathbf{x}\rangle \otimes |\mathbf{k}\rangle\right) = |\mathbf{x}\rangle \otimes S_{\{\mathbf{x}\}}|\mathbf{k}\rangle$$

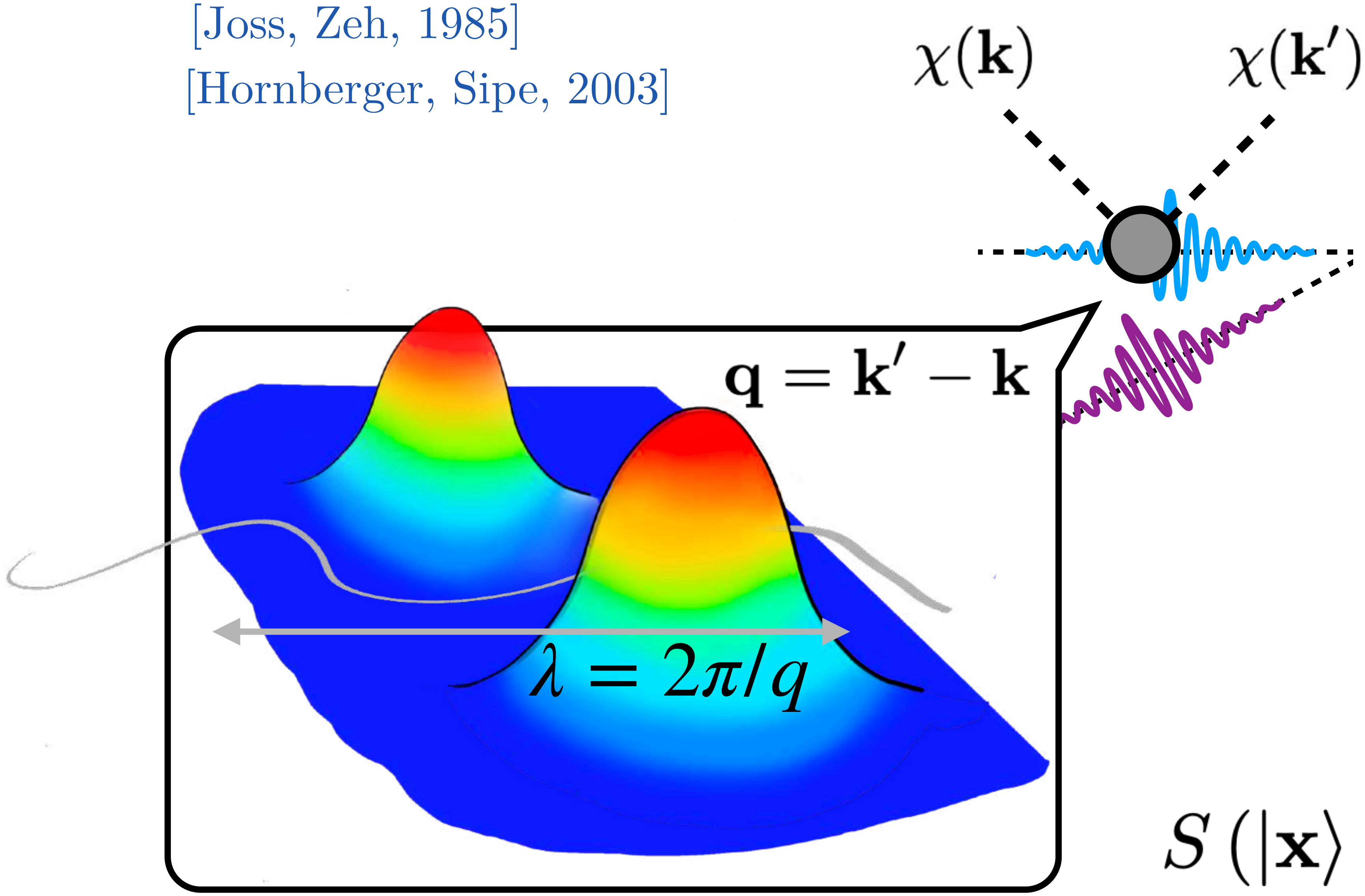
AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]

$$\rho = \frac{1}{2}\begin{pmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{pmatrix}$$



$$S\left(|\mathbf{x}\rangle \otimes |\mathbf{k}\rangle\right) = |\mathbf{x}\rangle \otimes S_{\{\mathbf{x}\}}|\mathbf{k}\rangle$$

$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

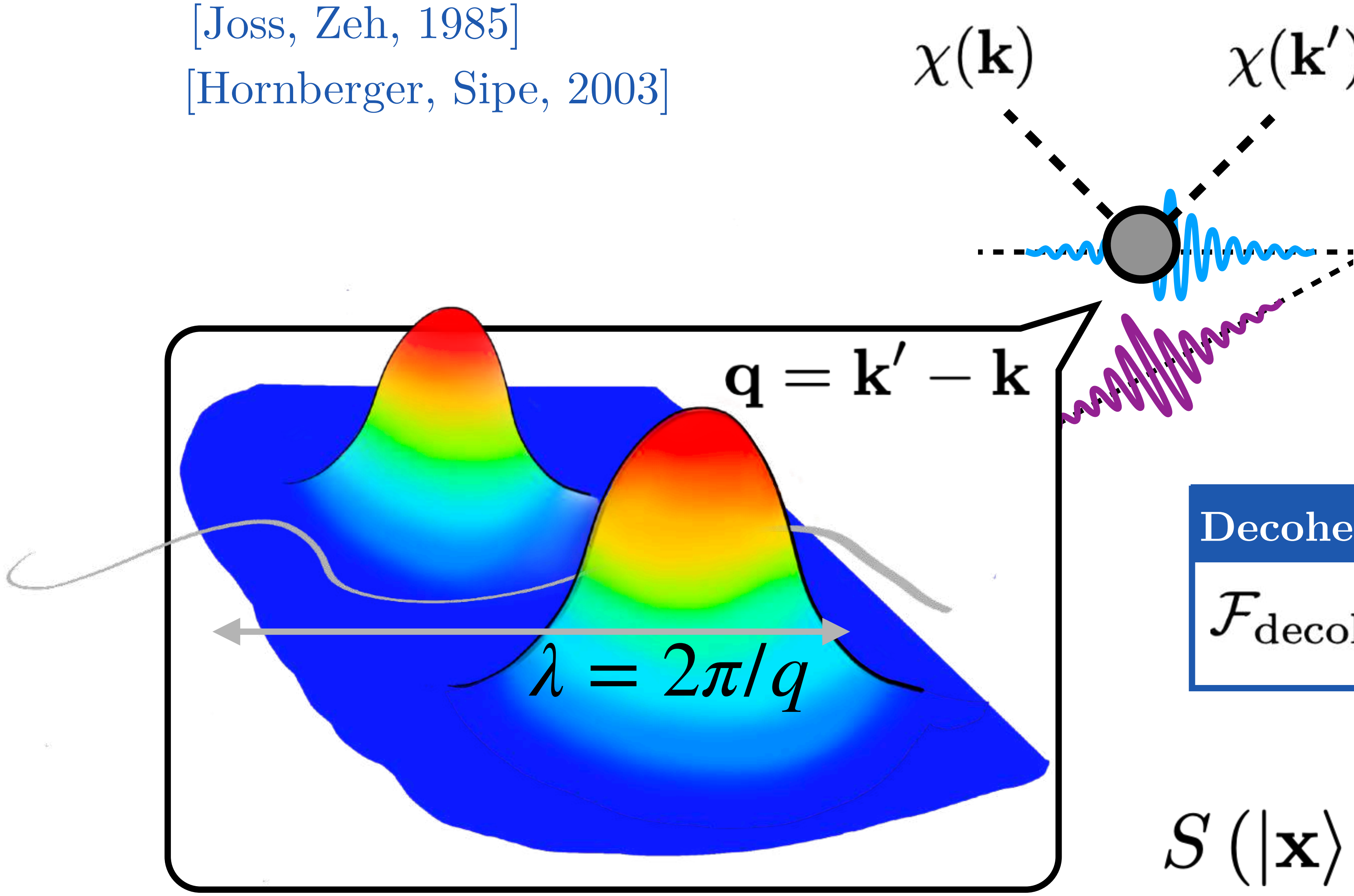
$$\Rightarrow \Delta\rho = \frac{i}{2}[T + T^\dagger, \rho] - \frac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]



$$\rho = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

$$\ln \gamma = -\int_{q,t} R(\mathbf{q}) \mathcal{F}_{\text{decoh}}(\mathbf{q})$$

Decoherence Kernel

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

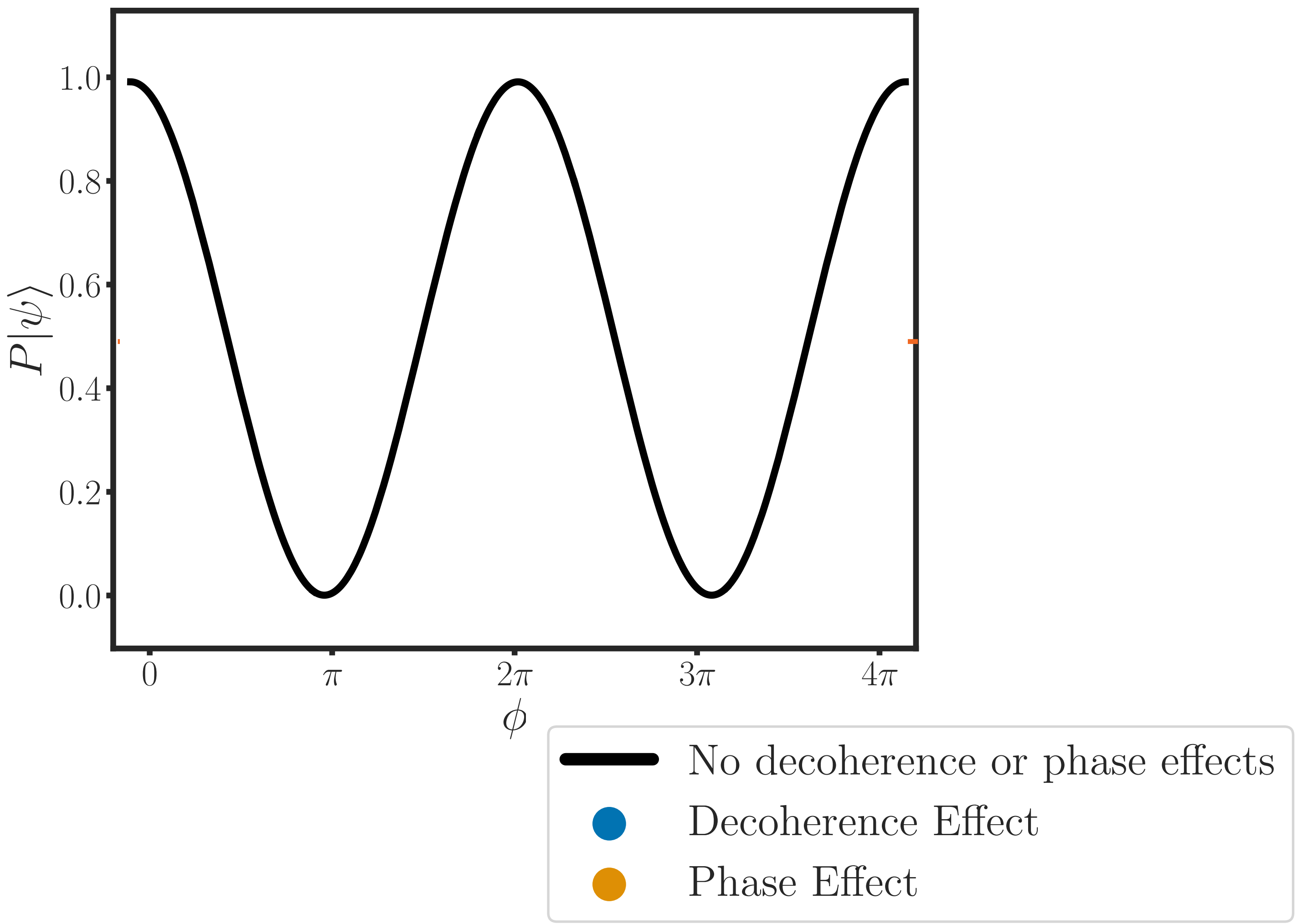
$$S\left(|\mathbf{x}\rangle \otimes |\mathbf{k}\rangle\right) = |\mathbf{x}\rangle \otimes S_{\{\mathbf{x}\}}|\mathbf{k}\rangle$$

$$\rho'_A = \mathrm{Tr}_{\mathbf{k}} \rho'$$

$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

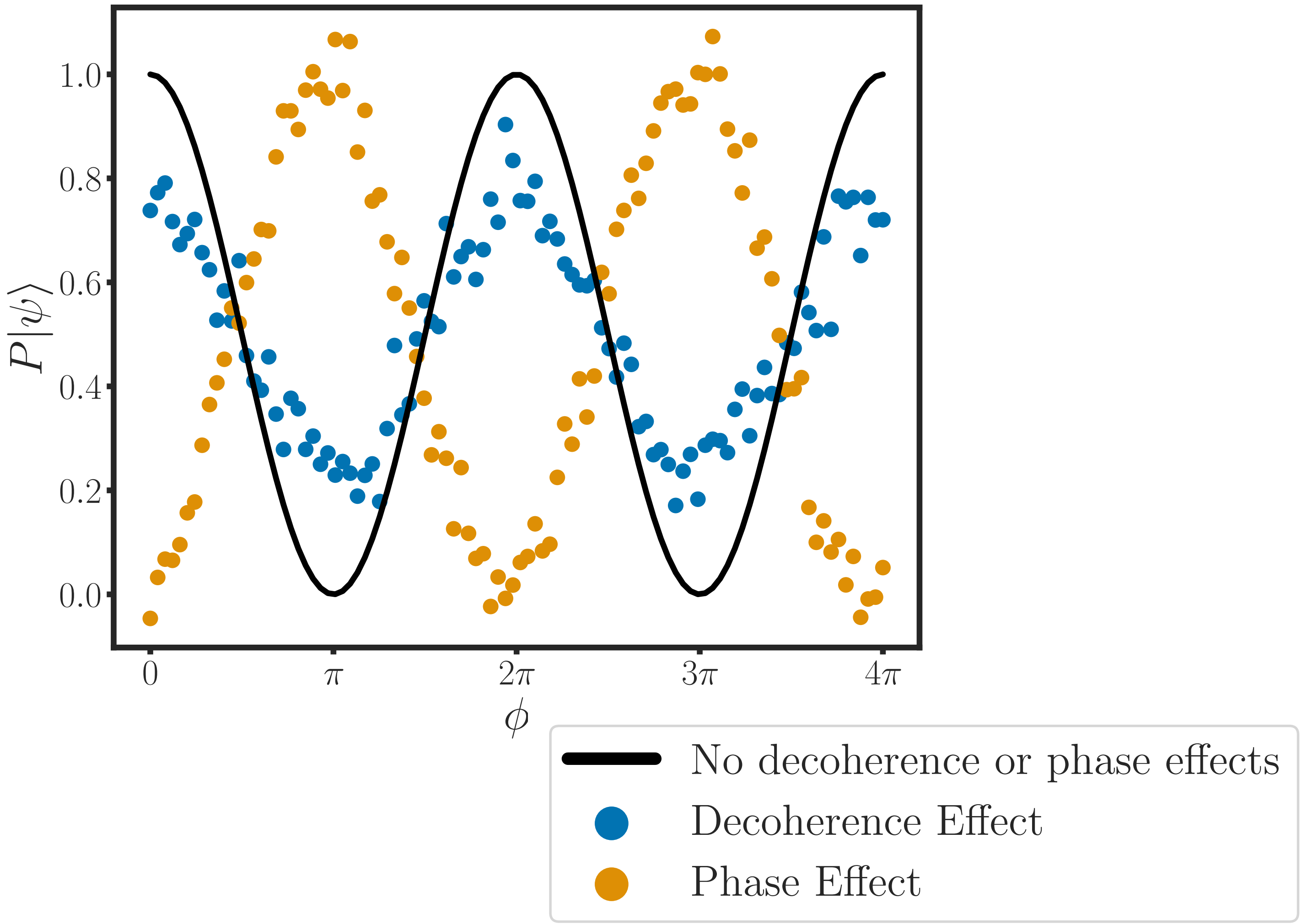
$$\Rightarrow \Delta\rho = \frac{i}{2}[T + T^\dagger, \rho] - \frac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

AIs: Collisional Decoherence



$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\mathrm{exp}} = \frac{1}{2}\left(1 + V \cos\left(\phi + \Delta\phi\right)\right)$$

AIs: Collisional Decoherence



$$\rho = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

$$\ln \gamma = -\int_{q,t} R(\mathbf{q}) \mathcal{F}_{\text{decoh}}(\mathbf{q})$$

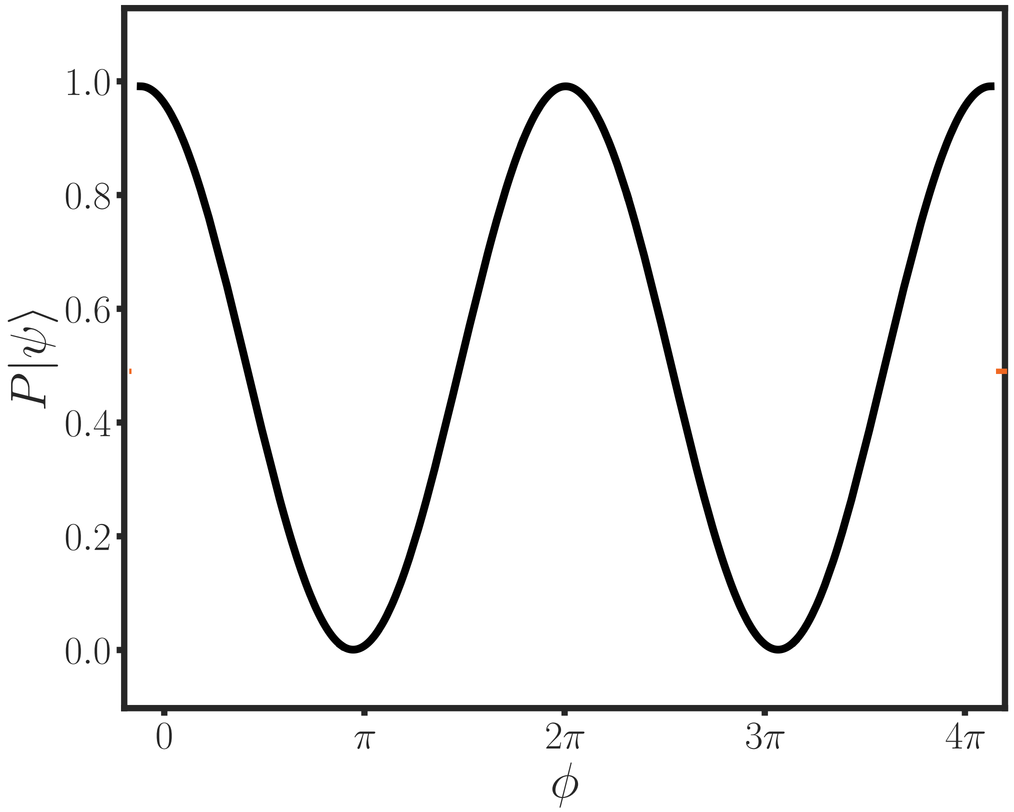
Decoherence Kernel

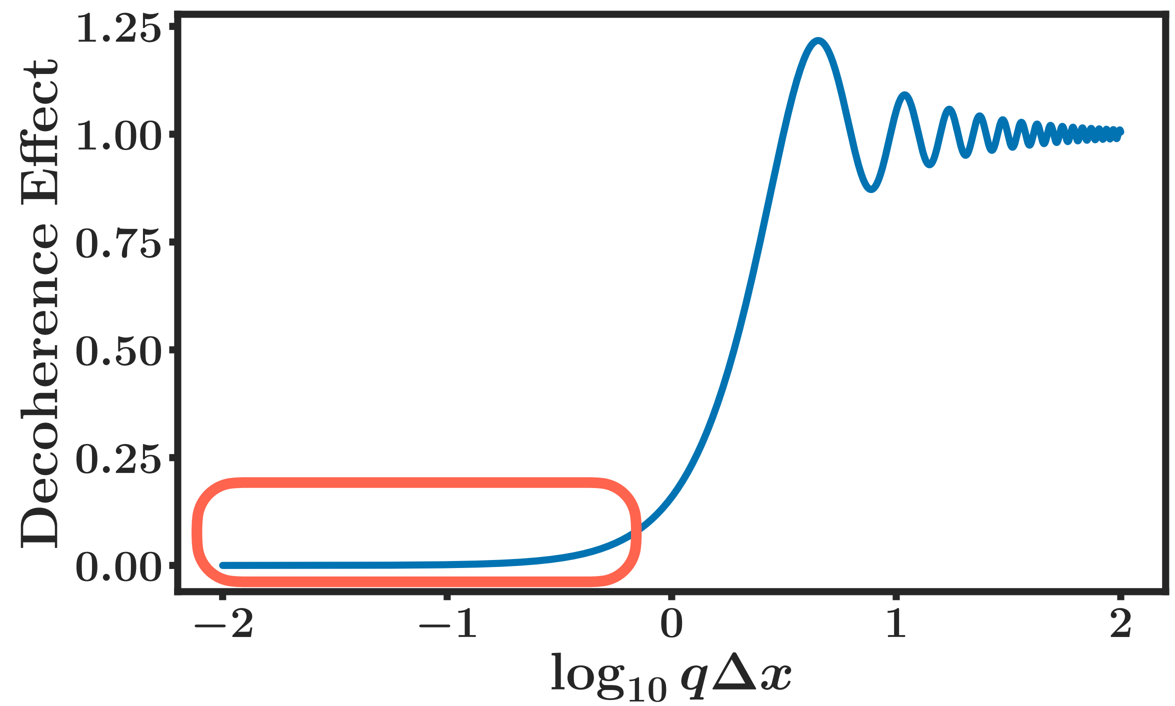
$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = 1 - \exp(i\mathbf{q} \cdot \mathbf{\Delta x})$$

$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\text{exp}} = \frac{1}{2}\left(1 + V \cos\left(\phi + \Delta\phi\right)\right)$$

$$\text{Tr}\{\rho\, \mathcal{O}_1\} = \frac{1}{2}\left[1 + e^{-\int_{\mathbf{q},t} R(\mathbf{q})(1-\cos(\mathbf{q}\cdot\mathbf{\Delta x}))} \cos\left(\phi + \int_{\mathbf{q},t} R(\mathbf{q}) \sin(\mathbf{q} \cdot \mathbf{\Delta x})\right)\right]$$

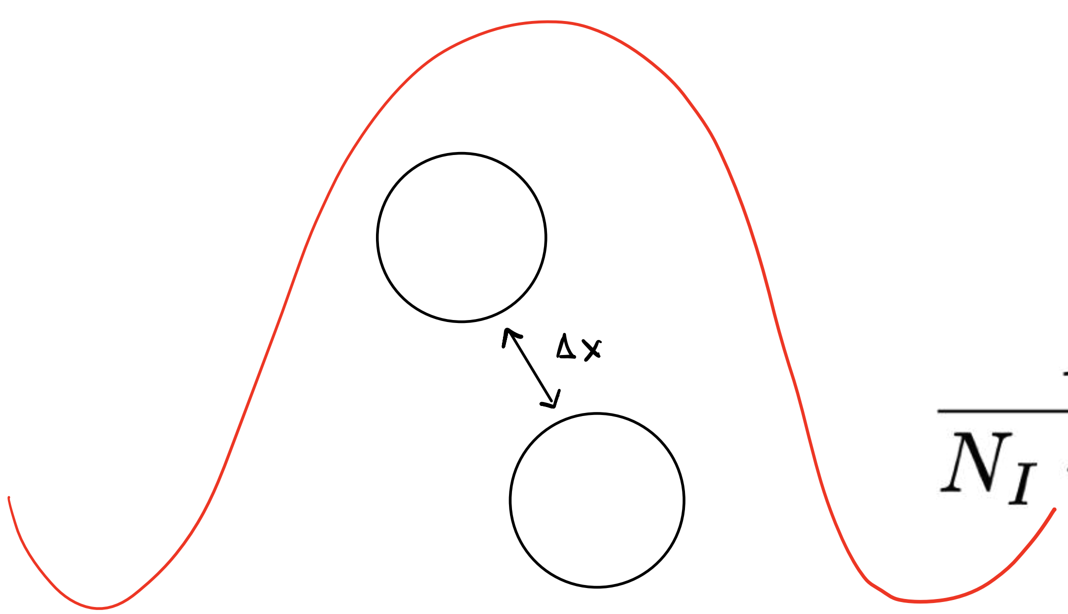
AIs: Collisional Decoherence





Decoherence Kernel

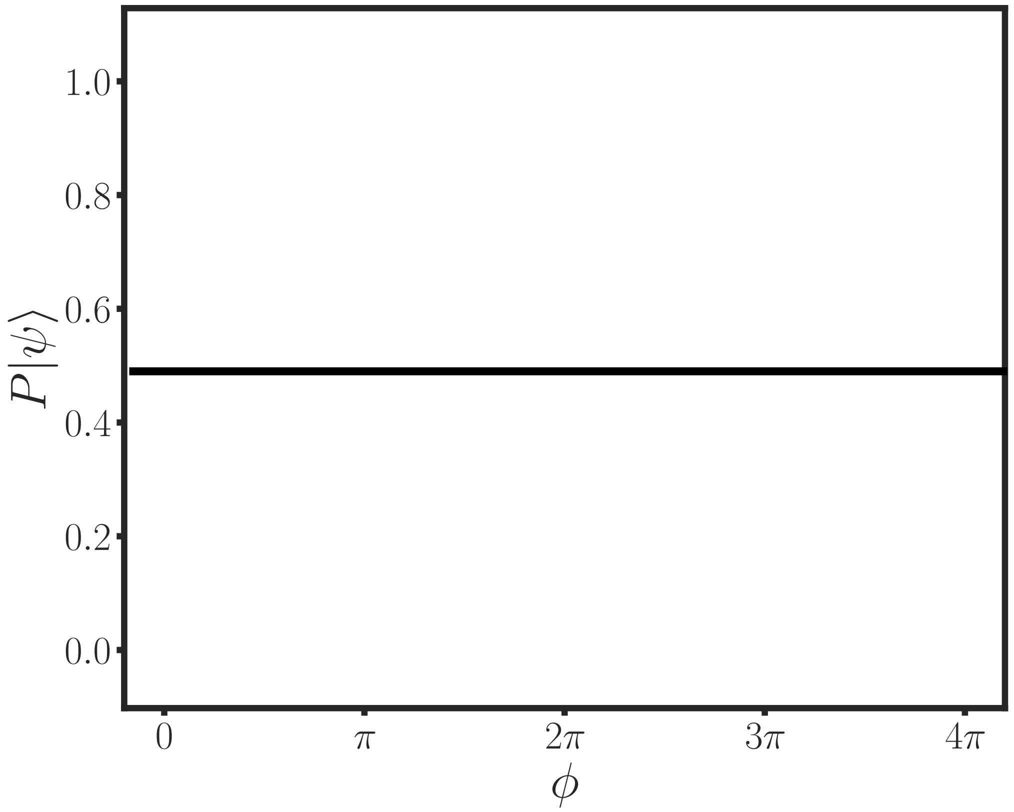
$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

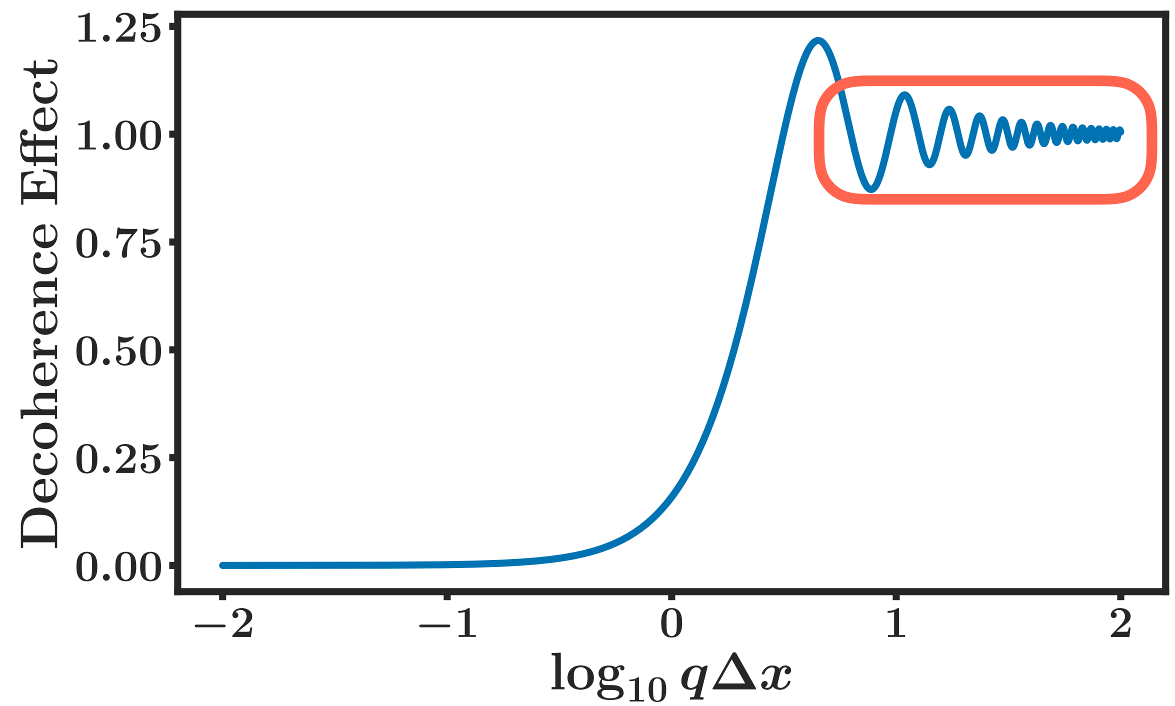


$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\text{exp}} = \frac{1}{2}\left(1 + V\cos\left(\phi + \Delta\phi\right)\right)$$

$$\text{Tr}\{\rho\,\mathcal{O}_1\} = \frac{1}{2}\left[1 + e^{-\int_{\mathbf{q},t} R(\mathbf{q})(1-\cos(\mathbf{q}\cdot\mathbf{\Delta x}))}\cos\left(\phi + \int_{\mathbf{q},t} R(\mathbf{q})\sin(\mathbf{q}\cdot\mathbf{\Delta x})\right)\right]$$

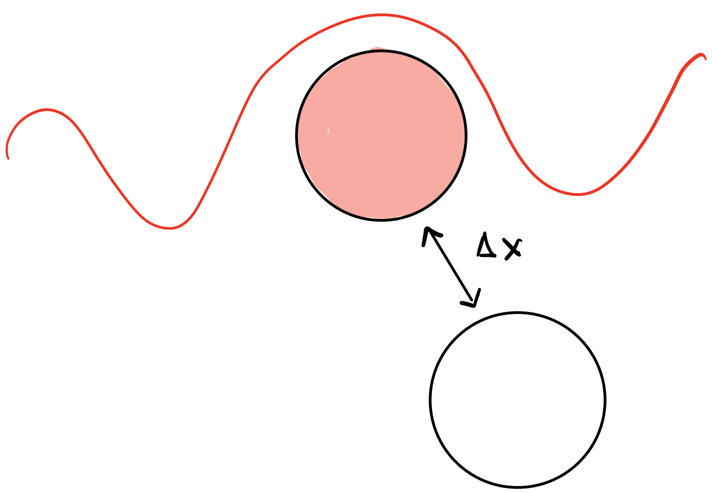
AIs: Collisional Decoherence





Decoherence Kernel

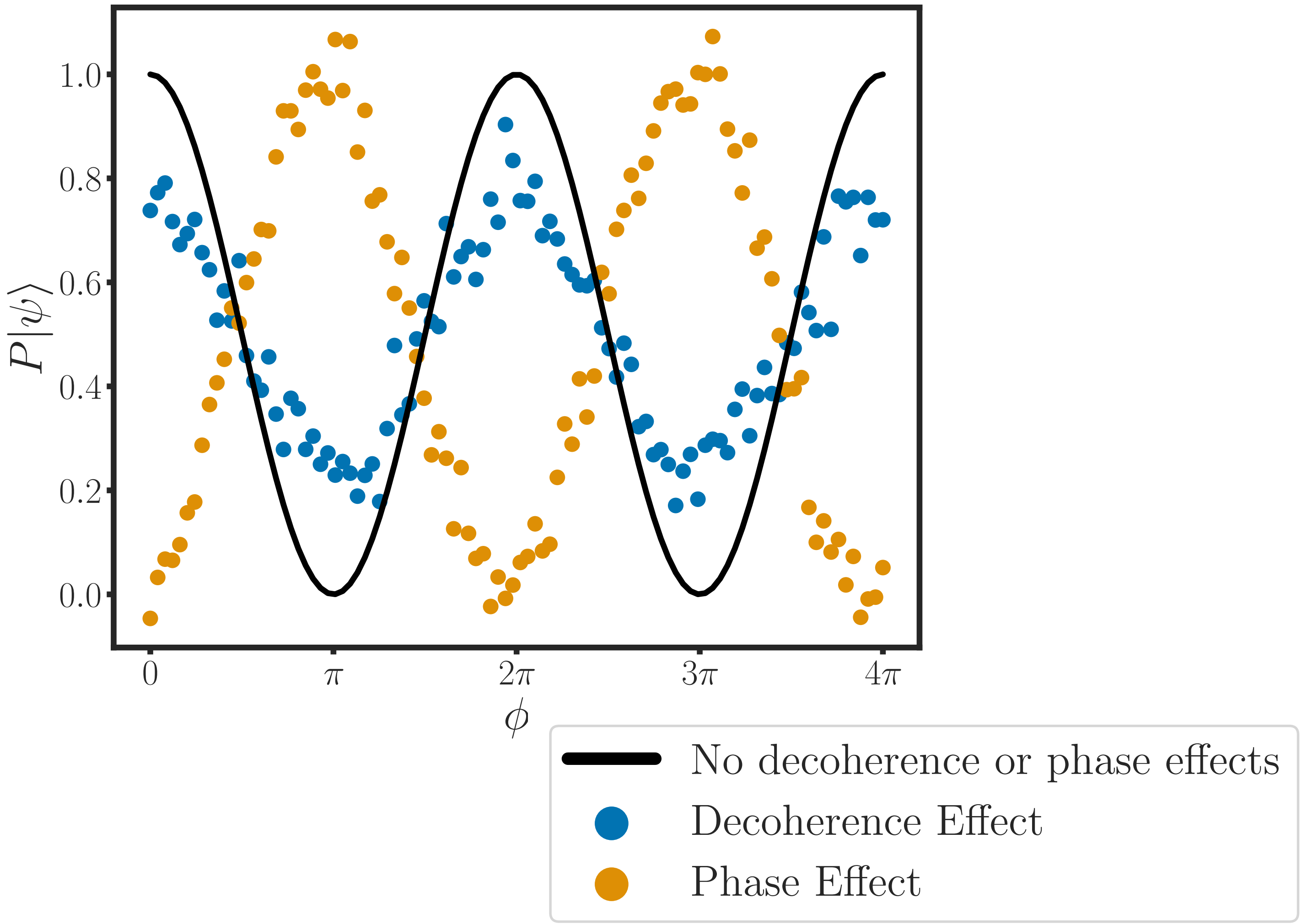
$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\boldsymbol{\Delta}\mathbf{x})$$



$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\text{exp}} = \frac{1}{2}\left(1 + V\cos\left(\phi + \Delta\phi\right)\right)$$

$$\text{Tr}\{\rho\,\mathcal{O}_1\} = \frac{1}{2}\left[1 + e^{-\int_{\mathbf{q},t} R(\mathbf{q})(1-\cos(\mathbf{q}\cdot\boldsymbol{\Delta}\mathbf{x}))}\cos\left(\phi + \int_{\mathbf{q},t} R(\mathbf{q})\sin(\mathbf{q}\cdot\boldsymbol{\Delta}\mathbf{x})\right)\right]$$

AIs: Collisional Decoherence



$$\rho = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

$$\ln \gamma = -\int_{q,t} R(\mathbf{q})\mathcal{F}_{\text{decoh}}(\mathbf{q})$$

Decoherence Kernel

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

$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\text{exp}} = \frac{1}{2}\left(1 + V\cos\left(\phi + \Delta\phi\right)\right)$$

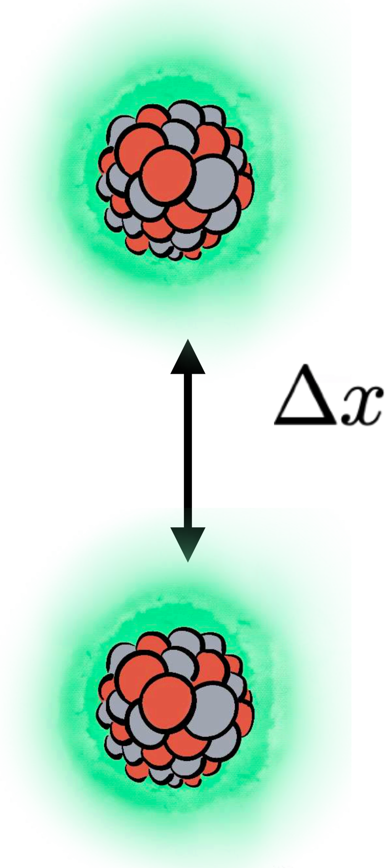
$$\text{Tr}\{\rho\,\mathcal{O}_1\} = \frac{1}{2}\left[1 + e^{-\int_{\mathbf{q},t} R(\mathbf{q})(1-\cos(\mathbf{q}\cdot\mathbf{\Delta x}))}\cos\left(\phi + \int_{\mathbf{q},t} R(\mathbf{q})\sin(\mathbf{q}\cdot\mathbf{\Delta x})\right)\right]$$

AIs: Collisional Decoherence

Single-atom system

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]



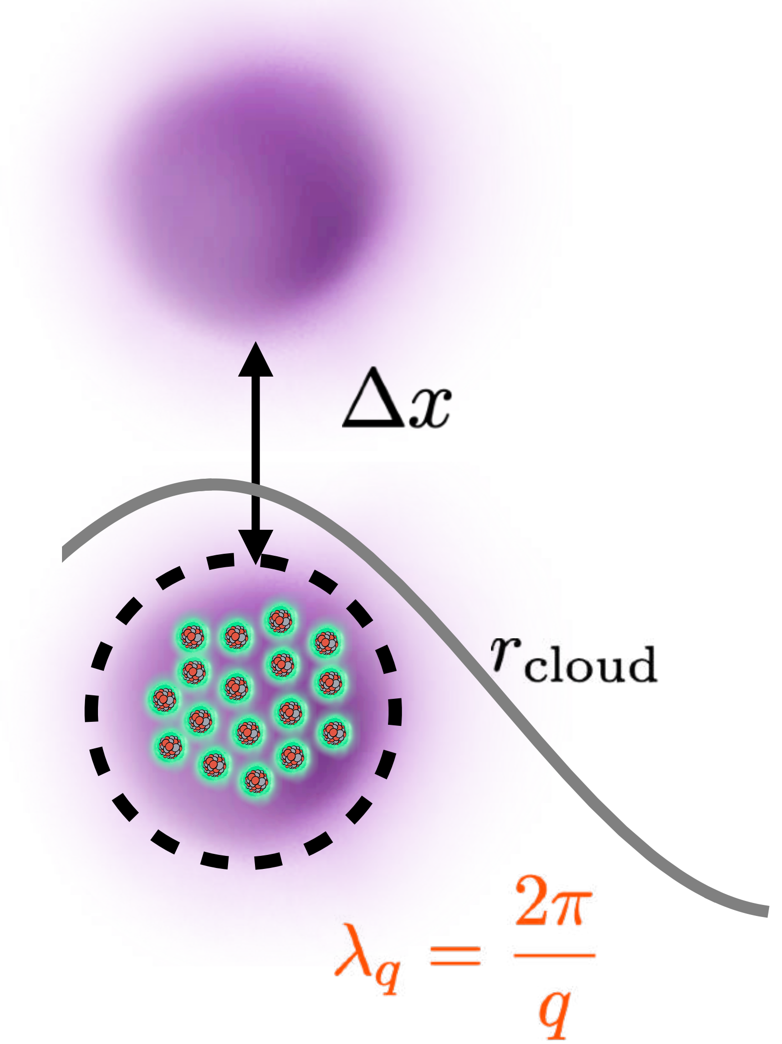
$$\lambda_q = \frac{2\pi}{q}$$

$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

$$\Rightarrow \Delta\rho = \frac{i}{2}[T + T^\dagger, \rho] - \frac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

AIs: Collisional Decoherence

Multi-atom system (distinguishable)
[Badurina, **CM**, Plestid, 2024]



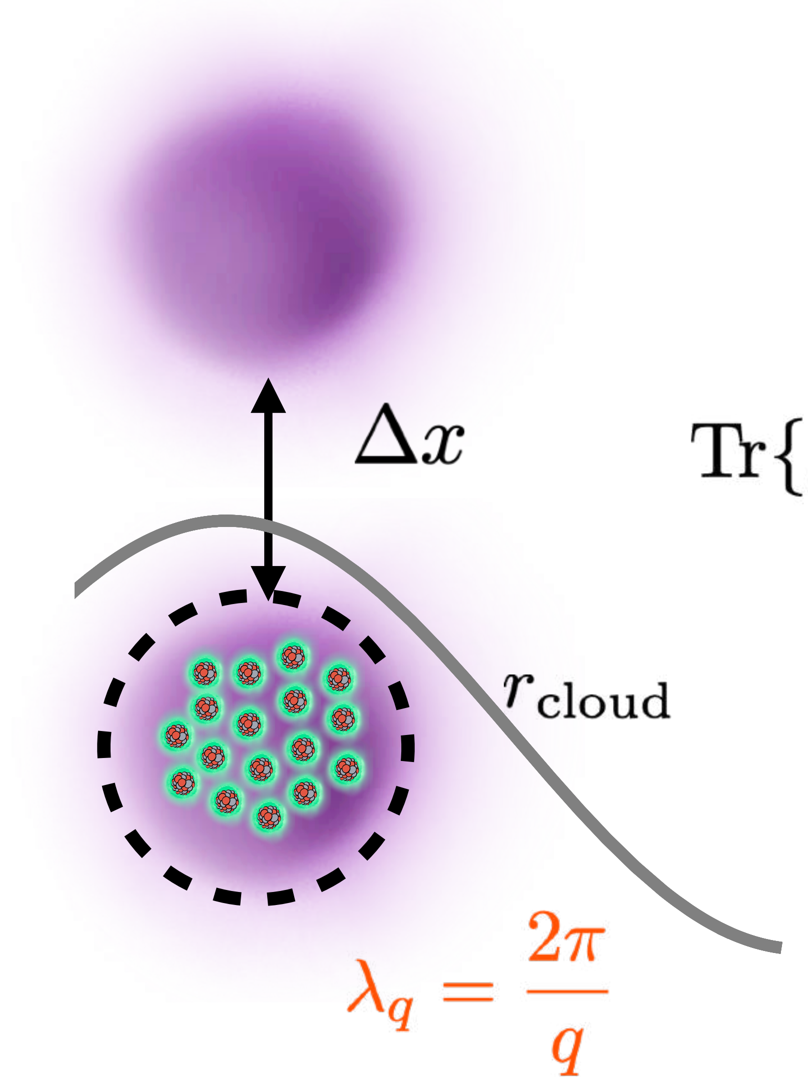
$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

$$\Rightarrow \Delta\rho = \frac{i}{2}[T + T^\dagger, \rho] - \frac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

AIs: Collisional Decoherence

Multi-atom system (distinguishable)

[Badurina, **CM**, Plestid, 2024]



$$\rho_{(N=2)} = \begin{pmatrix} \circ & \blacksquare & \blacksquare & \star \\ \blacksquare & \circ & \circ & \blacksquare \\ \blacksquare & \circ & \circ & \blacksquare \\ \star & \blacksquare & \blacksquare & \circ \end{pmatrix}$$

$$\mathrm{Tr}\{\rho_N \sum_i^N \mathcal{O}_i\} \stackrel{!}{=} N\,\tfrac{1}{2}\left(1 + V\cos\left(\phi + \Delta\phi\right)\right)$$

$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

$$\Rightarrow \Delta\rho = \tfrac{i}{2}[T + T^\dagger, \rho] - \tfrac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

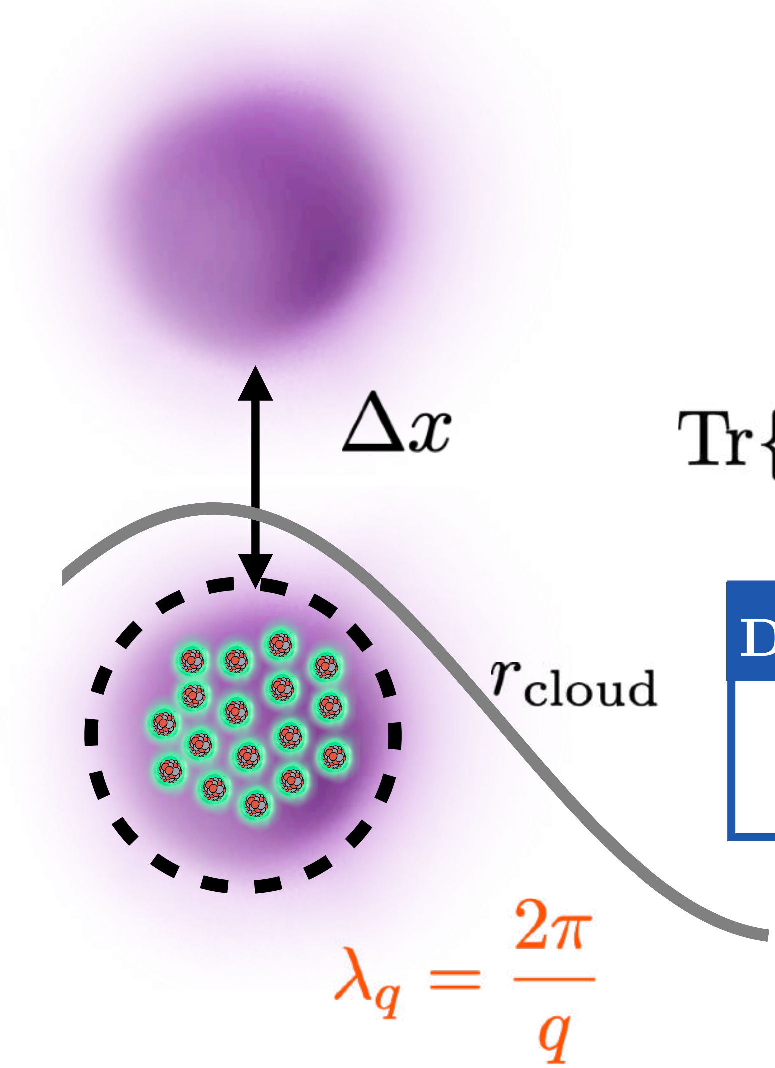
AIs: Collisional Decoherence

Multi-atom system (distinguishable)

[Badurina, **CM**, Plestid, 2024]

$$\rho_1 = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

$$\ln \gamma = -\int_{q,t} R(\mathbf{q}) \mathcal{F}_{\text{decoh}}(\mathbf{q})$$



$$\text{Tr}\{\rho_N \sum_i^N \mathcal{O}_i\} = N\,\text{Tr}\{\rho_1 \mathcal{O}_i\} \stackrel{!}{=} N\,\tfrac{1}{2}(1 + V\cos(\phi + \Delta\phi))$$

Decoherence Kernel 1-body measurement

$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = \left(1 - \cos(\mathbf{q}\cdot\mathbf{\Delta x})\right) - iN \sin(\mathbf{q}\cdot\mathbf{\Delta x})$$

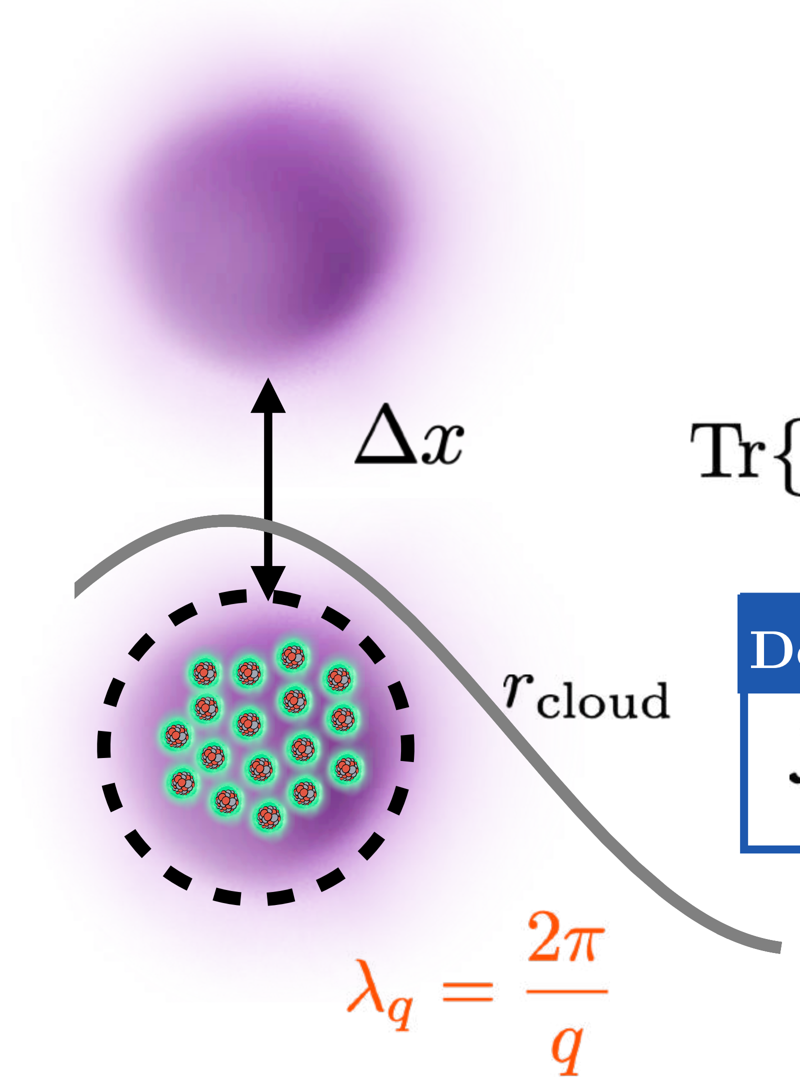
$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

$$\Rightarrow \Delta\rho = \tfrac{i}{2}[T + T^\dagger, \rho] - \tfrac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

AIs: Collisional Decoherence

Multi-atom system (distinguishable)

[Badurina, **CM**, Plestid, 2024]



$$\rho_{(N=2)} = \begin{pmatrix} \circ & \blacksquare & \blacksquare & \bigstar \\ \blacksquare & \circ & \circ & \blacksquare \\ \blacksquare & \circ & \circ & \blacksquare \\ \bigstar & \blacksquare & \blacksquare & \circ \end{pmatrix}$$

$$\mathrm{Tr}\{\rho_N \sum_i^N \mathcal{O}_i\} = N\,\mathrm{Tr}\{\rho_1 \mathcal{O}_i\} \stackrel{!}{=} N\,\tfrac{1}{2}(1 + V\cos(\phi + \Delta\phi))$$

Decoherence Kernel n-body measurement

$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = n^2(1 - \cos(\mathbf{q}\cdot\mathbf{\Delta x})) - iNn\sin(\mathbf{q}\cdot\mathbf{\Delta x})$$

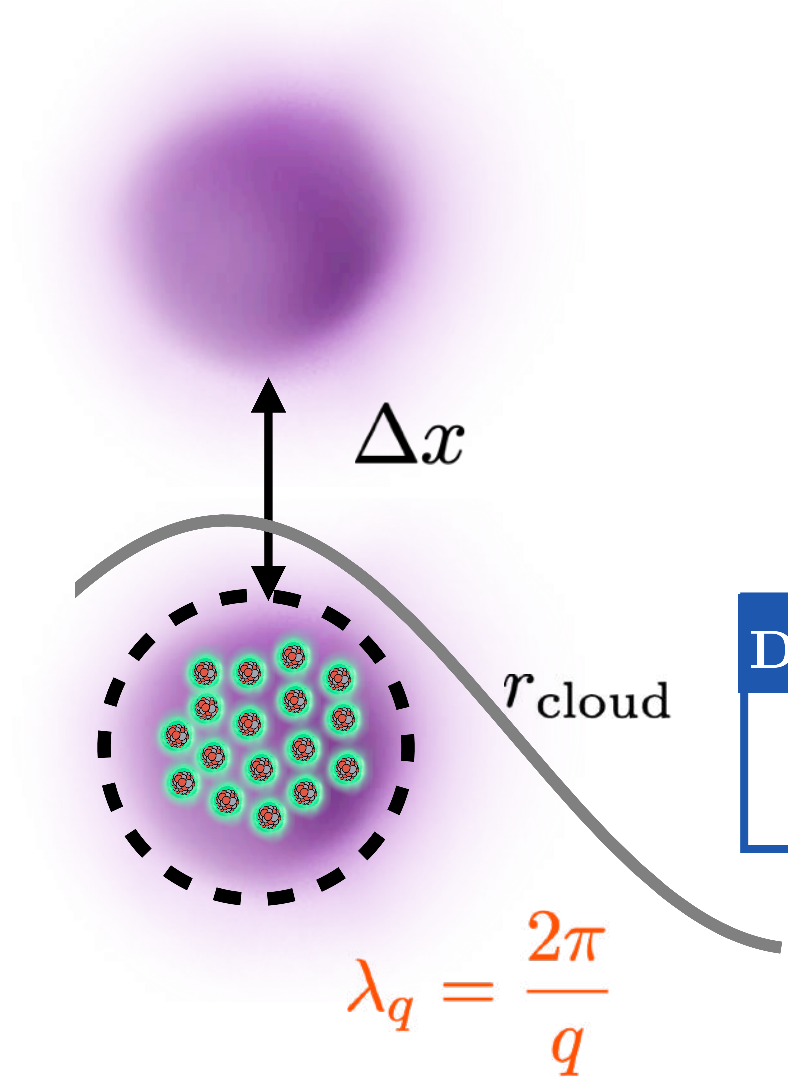
$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

$$\Rightarrow \Delta\rho = \tfrac{i}{2}[T + T^\dagger, \rho] - \tfrac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

AIs: Collisional Decoherence

Multi-atom system (distinguishable)

[Badurina, **CM**, Plestid, 2024]



$$\rho_{(N=2)} = \begin{pmatrix} \circ & \blacksquare & \blacksquare & \bigstar \\ \blacksquare & \circ & \circ & \blacksquare \\ \blacksquare & \circ & \circ & \blacksquare \\ \bigstar & \blacksquare & \blacksquare & \circ \end{pmatrix}$$

$$\mathrm{Tr}\{\rho_N \mathcal{O}_\star\} \stackrel{!}{=} \tfrac{1}{2}\left(1 + V\cos\left(\phi + \Delta\phi\right)\right)$$

Decoherence Kernel n-body measurement

$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = N^2\left(1 - \cos(\mathbf{q}\cdot\mathbf{\Delta x})\right) - i\, N^2 \sin(\mathbf{q}\cdot\mathbf{\Delta x})$$

$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

$$\Rightarrow \Delta\rho = \tfrac{i}{2}[T + T^\dagger, \rho] - \tfrac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

AIs: Collisional Decoherence

Particle scattering

[Riedel, 2013]
[Riedel, Yavin, 2017]
[Du, **CM**, Pardo, Wang, Zurek, 2022]
[Du, **CM**, Pardo, Wang, Zurek, 2023]

$$\rho_1 = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

$$\ln \gamma = -\int_{q,t} R(\mathbf{q}) \mathcal{F}_{\text{decoh}}(\mathbf{q})$$

$$R(\mathbf{q}) = n_\chi \int d^3\mathbf{v} f(\mathbf{v}) \Gamma(\mathbf{v}, \mathbf{q})$$

AIs: Collisional Decoherence

Particle scattering

[Riedel, 2013]
[Riedel, Yavin, 2017]
[Du, **CM**, Pardo, Wang, Zurek, 2022]
[Du, **CM**, Pardo, Wang, Zurek, 2023]

$$\rho_1 = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

$$\ln \gamma = -\int_{q,t} R(\mathbf{q})\mathcal{F}_{\text{decoh}}(\mathbf{q})$$

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

$$R(\mathbf{q}) = n_\chi \int d^3\mathbf{v} f(\mathbf{v}) \Gamma(\mathbf{v},\mathbf{q})$$

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

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

AIs: Collisional Decoherence

Particle scattering

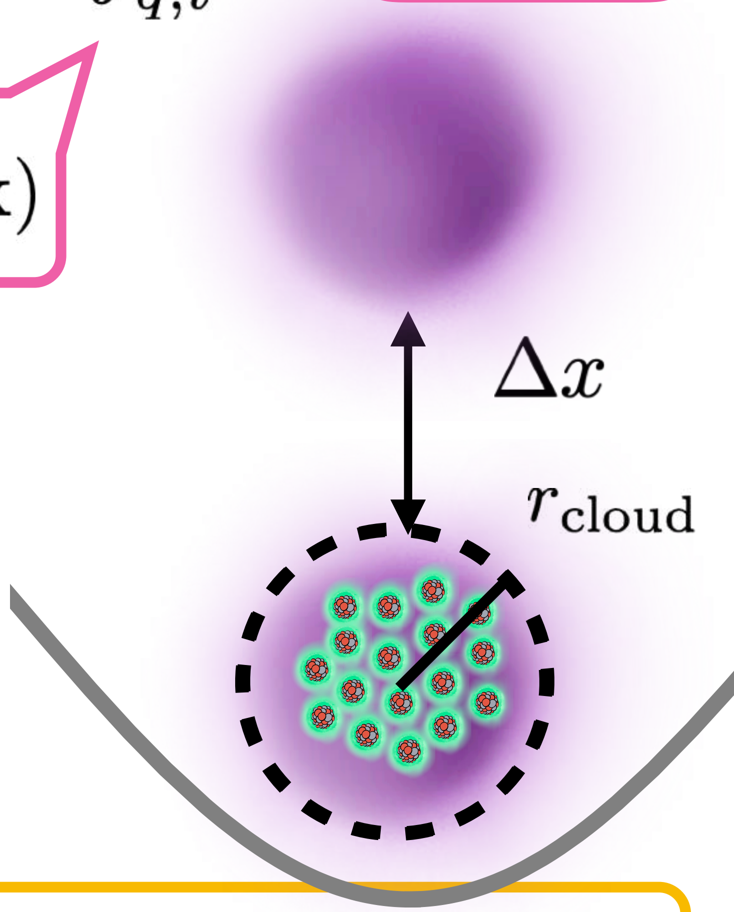
[Riedel, 2013]
[Riedel, Yavin, 2017]
[Du, **CM**, Pardo, Wang, Zurek, 2022]
[Du, **CM**, Pardo, Wang, Zurek, 2023]
[Badurina, **CM**, Plestid, 2024]

$$\rho_1 = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

$$\ln \gamma = -\int_{q,t} R(\mathbf{q}) \mathcal{F}_{\rm decoh}(\mathbf{q})$$

$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = n^2(1-\cos(\mathbf{q}\cdot\mathbf{\Delta x})) - iNn\sin(\mathbf{q}\cdot\mathbf{\Delta x})$$

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



$$R(\mathbf{q}) = n_\chi \int d^3\mathbf{v}\, f(\mathbf{v}) \Gamma(\mathbf{v},\mathbf{q})$$

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

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

AIs: Collisional Decoherence

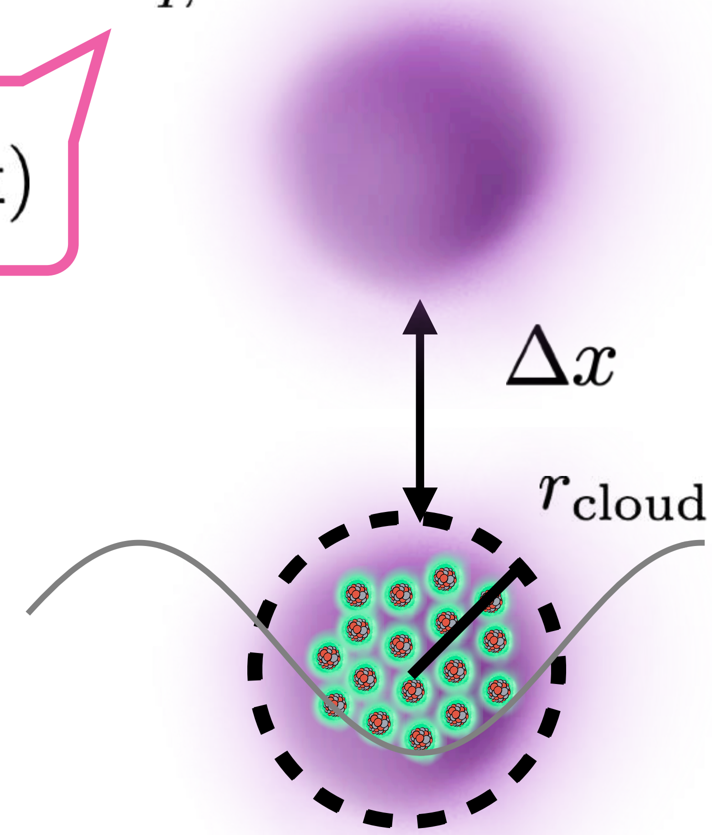
Particle scattering

[Riedel, 2013]
[Riedel, Yavin, 2017]
[Du, **CM**, Pardo, Wang, Zurek, 2022]
[Du, **CM**, Pardo, Wang, Zurek, 2023]
[Joss, Zeh, 1985]
[Hornberger, Sipe, 2003]

$$\rho_1 = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

$$\ln \gamma = -\int_{q,t} R(\mathbf{q}) \mathcal{F}_{\text{decoh}}(\mathbf{q})$$

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



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

$$R(\mathbf{q}) = n_\chi \int d^3\mathbf{v} f(\mathbf{v}) \Gamma(\mathbf{v},\mathbf{q})$$

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

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

AIs: Collisional Decoherence

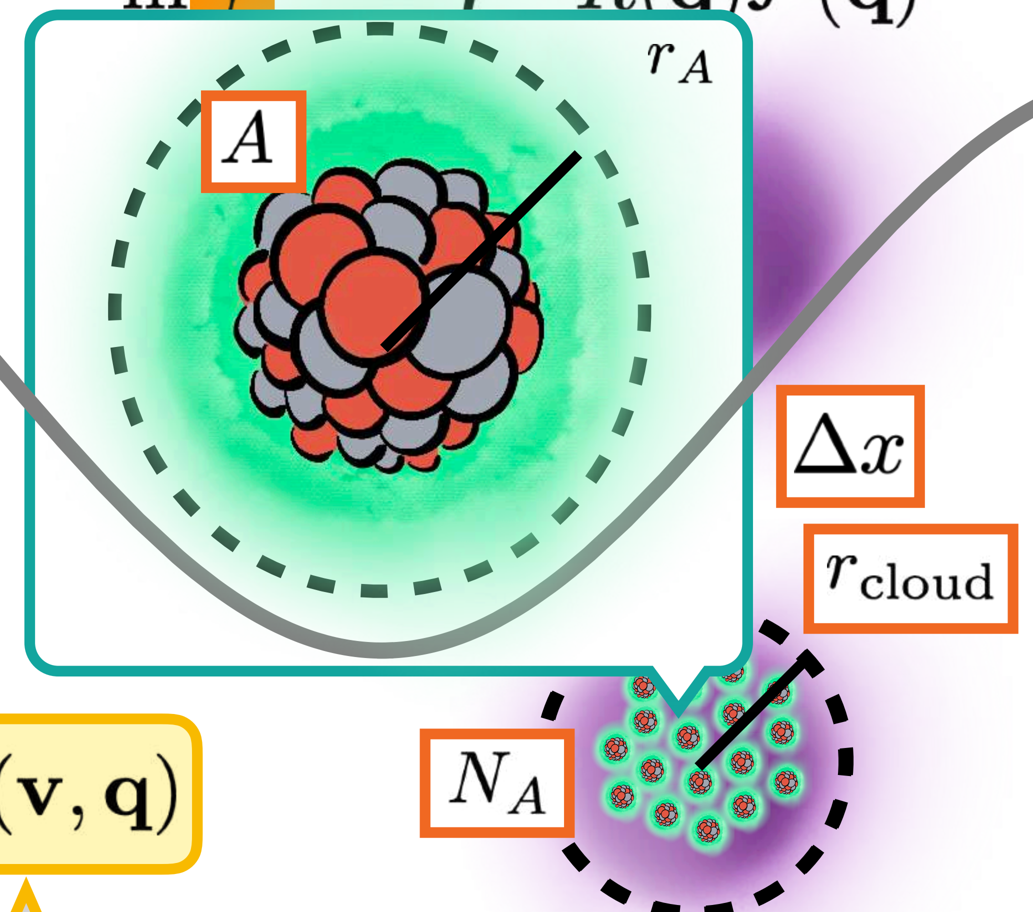
Particle scattering

[Riedel, 2013]
[Riedel, Yavin, 2017]
[Du, **CM**, Pardo, Wang, Zurek, 2022]
[Du, **CM**, Pardo, Wang, Zurek, 2023]

$$\rho_1 = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

$T_{\rm exp}$

$$\ln \gamma = -\int R(\mathbf{q})\mathcal{F}(\mathbf{q})$$



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

$$R(\mathbf{q}) = n_\chi \int d^3\mathbf{v} f(\mathbf{v})\Gamma(\mathbf{v},\mathbf{q})$$

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

$$\frac{1}{V^2}\frac{\pi\bar{\sigma}}{\mu^2}\mathcal{F}^2_{\rm med}(\mathbf{q})\,\mathcal{F}^2_{\rm T}(\mathbf{q})$$

$$\mathcal{F}_T(\mathbf{q}) = A\mathcal{F}^2_A(qr_A)]$$

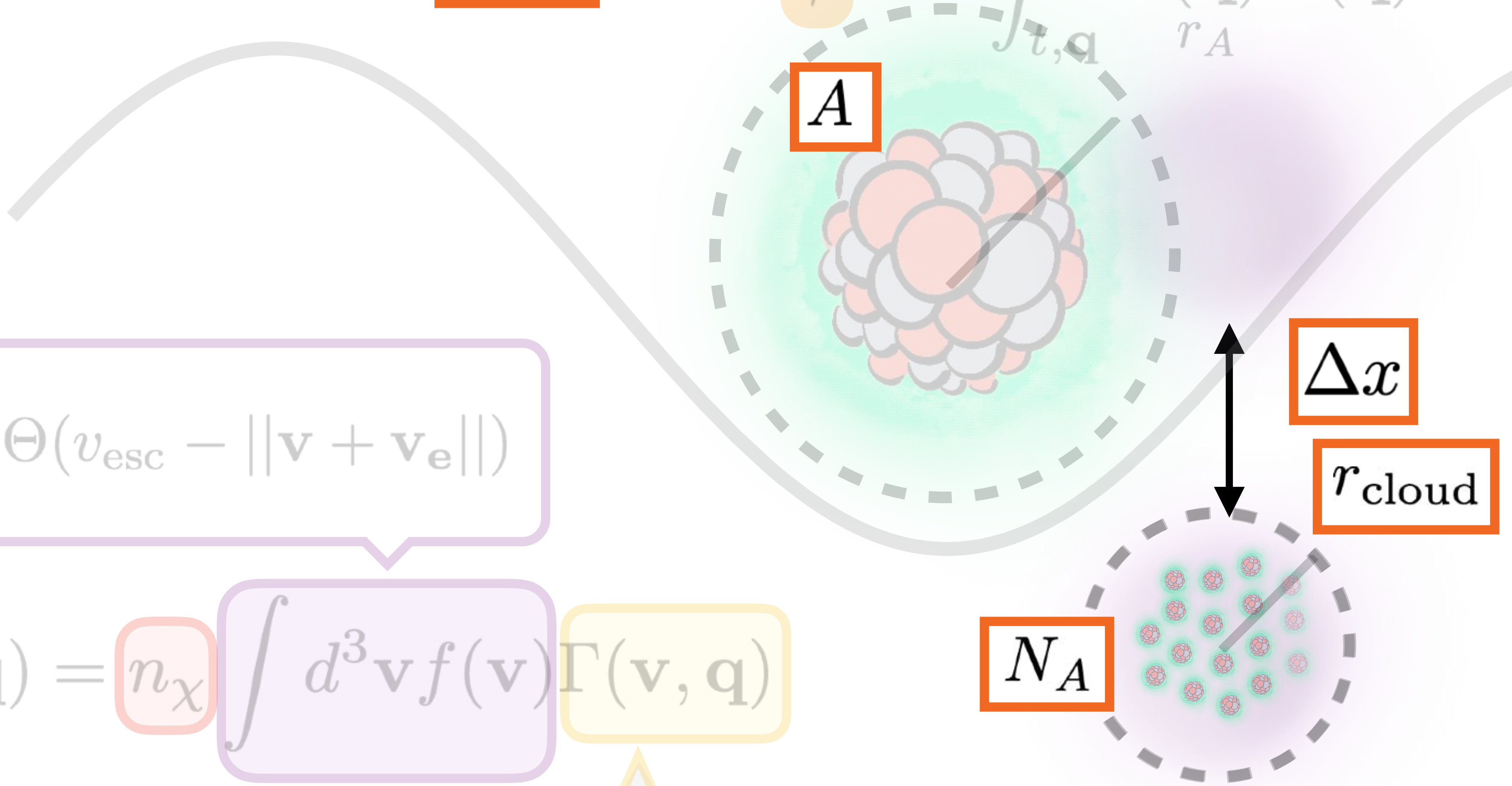
AIs: Collisional Decoherence

Particle scattering

[Riedel, 2013]
[Riedel, Yavin, 2017]
[Du, **CM**, Pardo, Wang, Zurek, 2022]
[Du, **CM**, Pardo, Wang, Zurek, 2023]

$$\rho_1 = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

$$\ln \gamma = -\int_{t,\mathbf{q}} R(\mathbf{q})\mathcal{F}(\mathbf{q})$$



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

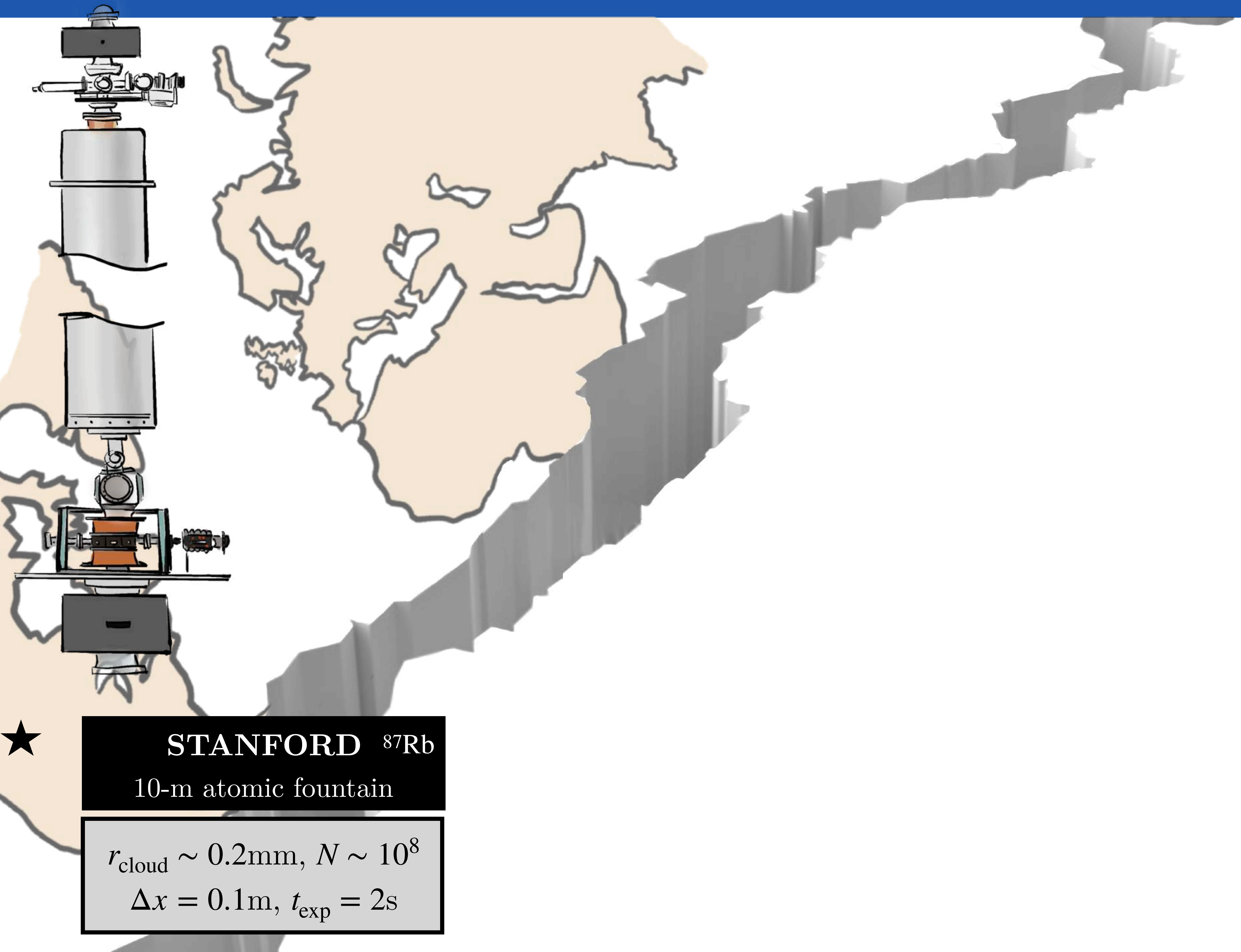
$$R(\mathbf{q}) = n_\chi \int d^3\mathbf{v} f(\mathbf{v}) \Gamma(\mathbf{v},\mathbf{q})$$

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

$$\frac{1}{V^2}\frac{\pi\bar{\sigma}}{\mu^2}\mathcal{F}^2_{\rm med}(\mathbf{q})\,\mathcal{F}^2_{\rm T}(\mathbf{q})$$

$$\mathcal{F}_T(\mathbf{q}) = A\mathcal{F}^2_A(qr_A)]$$

AIs: Examples

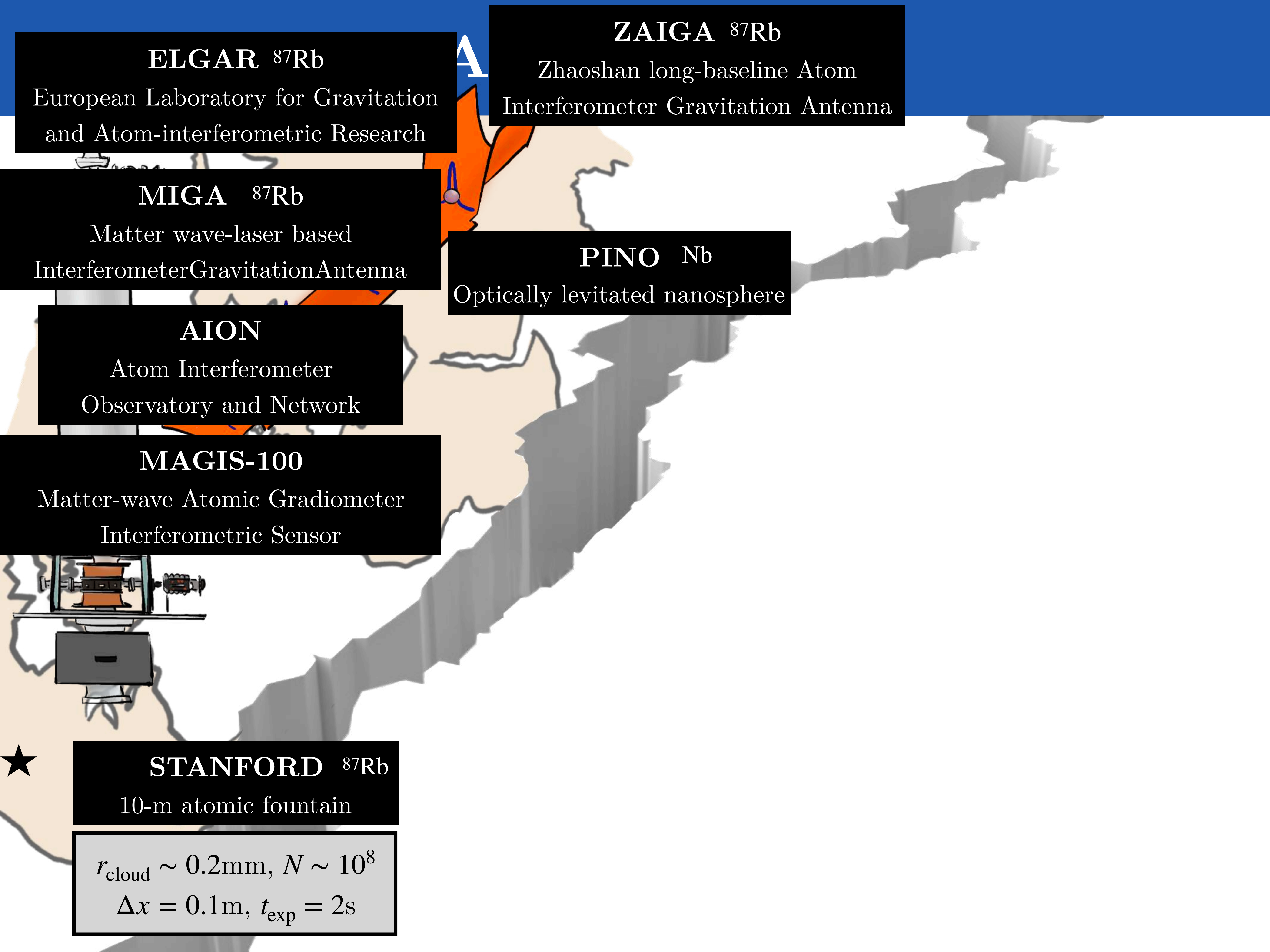


★ **STANFORD** ^{87}Rb

10-m atomic fountain

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

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



ELGAR ^{87}Rb
European Laboratory for Gravitation and Atom-interferometric Research

ZAIGA ^{87}Rb
Zhaoshan long-baseline Atom Interferometer Gravitation Antenna

MIGA ^{87}Rb
Matter wave-laser based InterferometerGravitationAntenna

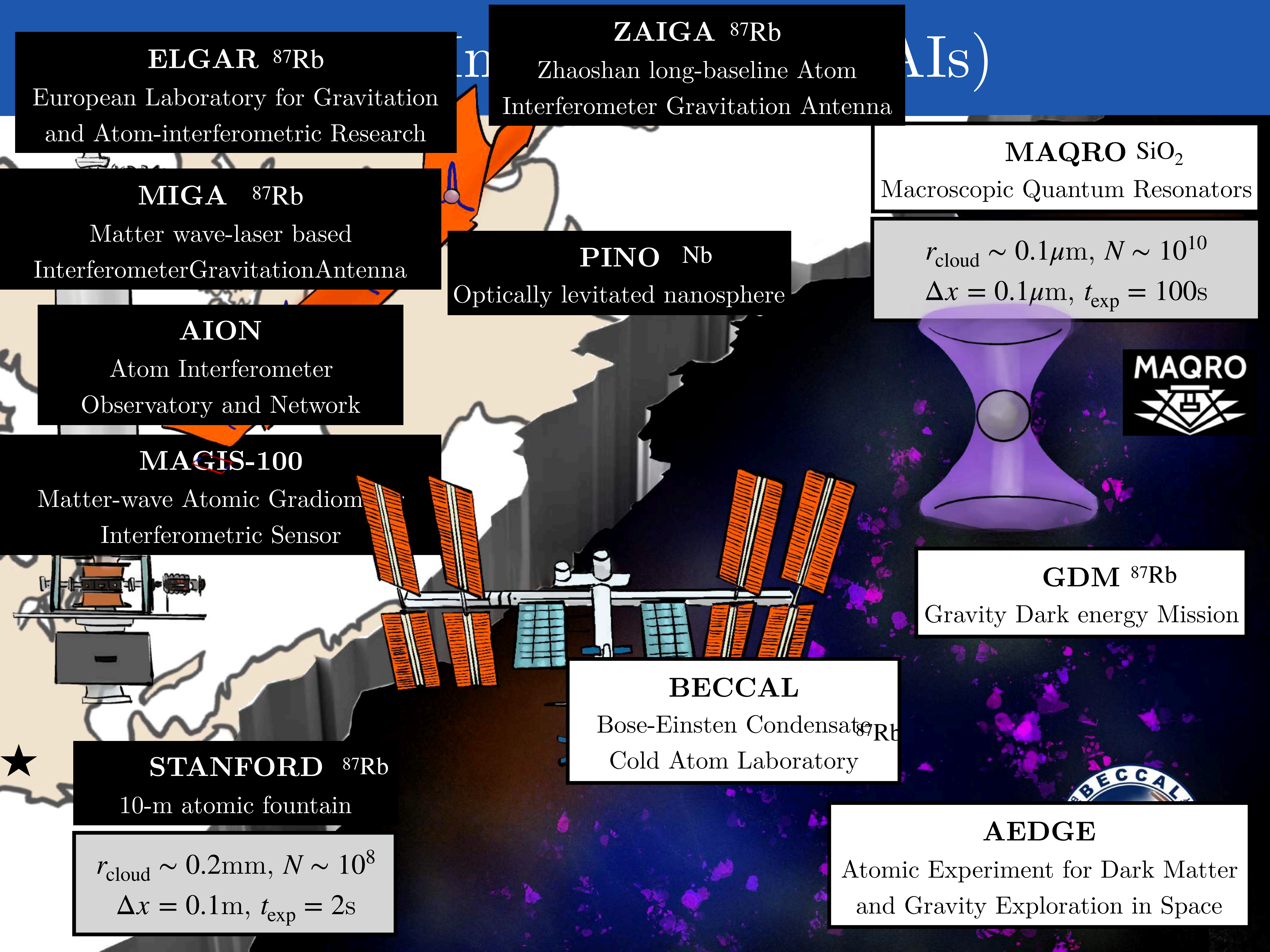
PINO Nb
Optically levitated nanosphere

AION
Atom Interferometer Observatory and Network

MAGIS-100
Matter-wave Atomic Gradiometer Interferometric Sensor

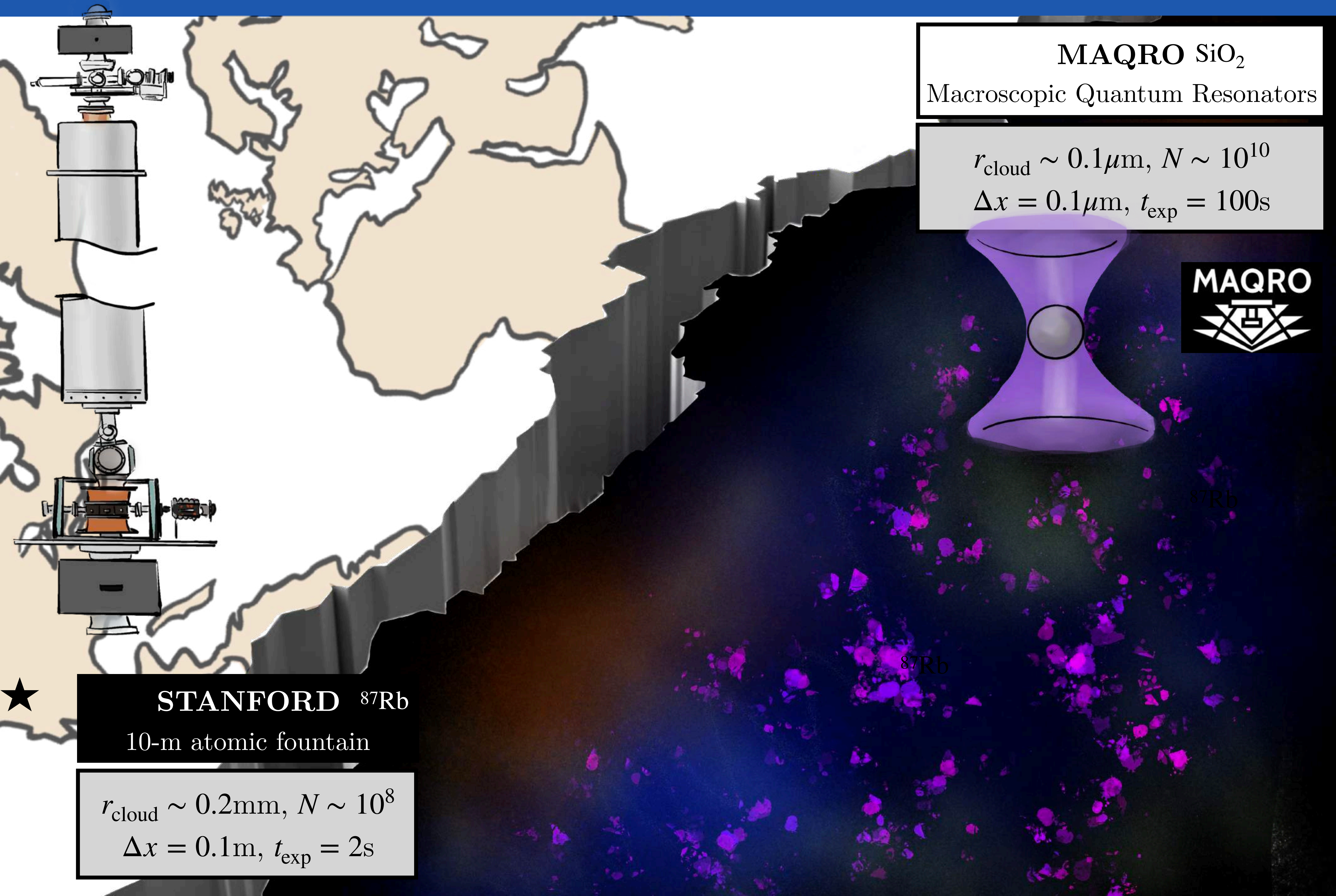
★ **STANFORD** ^{87}Rb
10-m atomic fountain

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



ELGAR ^{87}Rb
European Laboratory for Gravitation and Atom-interferometric Research
ZAIGA ^{87}Rb
Zhaoshan long-baseline Atom Interferometer Gravitation Antenna
MAQRO SiO_2
Macroscopic Quantum Resonators
$r_{\text{cloud}} \sim 0.1\mu\text{m}$, $N \sim 10^{10}$
$\Delta x = 0.1\mu\text{m}$, $t_{\text{exp}} = 100\text{s}$
MIGA ^{87}Rb
Matter wave-laser based InterferometerGravitationAntenna
PINO Nb
Optically levitated nanosphere
AION
Atom Interferometer Observatory and Network
MAQRO
MAGIS-100
Matter-wave Atomic Gradiom... Interferometric Sensor
GDM ^{87}Rb
Gravity Dark energy Mission
BECCAL ^{87}Rb
Bose-Einsten Condensate Cold Atom Laboratory
STANFORD ^{87}Rb
10-m atomic fountain
$r_{\text{cloud}} \sim 0.2\text{mm}$, $N \sim 10^{8}$
$\Delta x = 0.1\text{m}$, $t_{\text{exp}} = 2\text{s}$
AEDGE
Atomic Experiment for Dark Matter and Gravity Exploration in Space

AIs: Examples



MAQRO SiO_2

Macroscopic Quantum Resonators

$r_{\text{cloud}} \sim 0.1\mu\text{m},\ N \sim 10^{10}$

$\Delta x = 0.1\mu\text{m},\ t_{\text{exp}} = 100\text{s}$

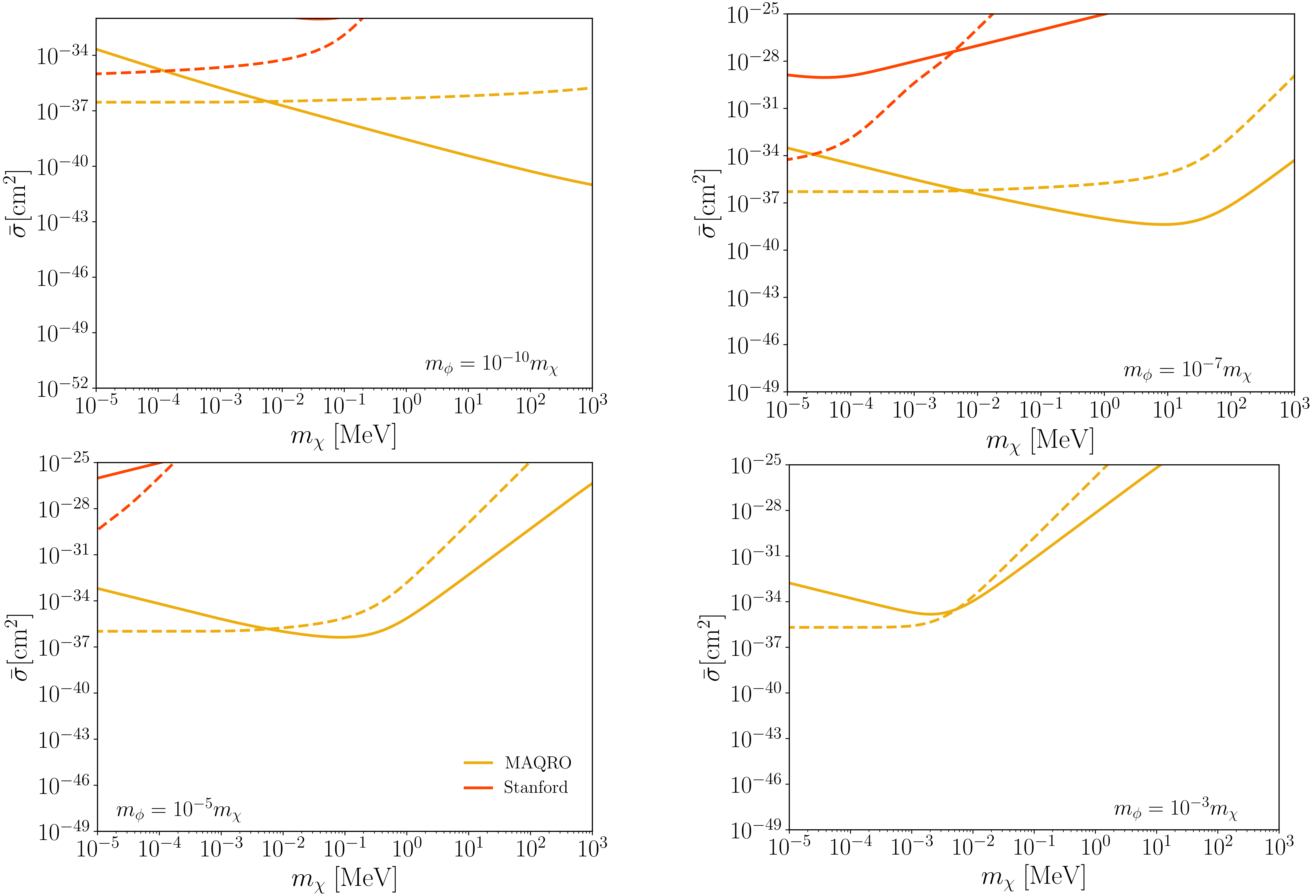
★ **STANFORD** ^{87}Rb

10-m atomic fountain

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

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

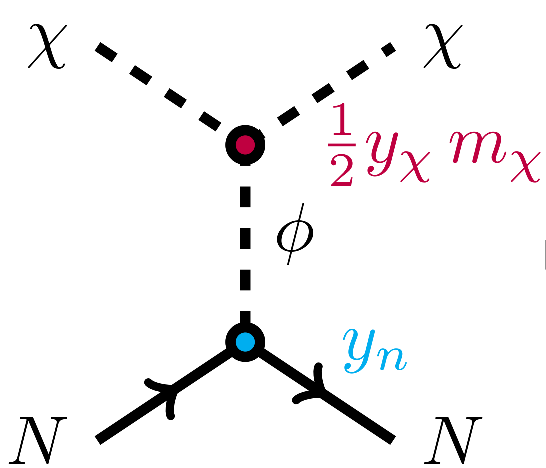
AIs: Limits


$m_\phi = 10^{-10} m_\chi$
$m_\phi = 10^{-7} m_\chi$
$m_\phi = 10^{-5} m_\chi$
$m_\phi = 10^{-3} m_\chi$
$\bar{\sigma} [\mathrm{cm}^2]$
m_χ [MeV]
10^{-52} 10^{-49} 10^{-46} 10^{-43} 10^{-40} 10^{-37} 10^{-34} 10^{-31} 10^{-28} 10^{-25}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
MAQRO
Stanford

AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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

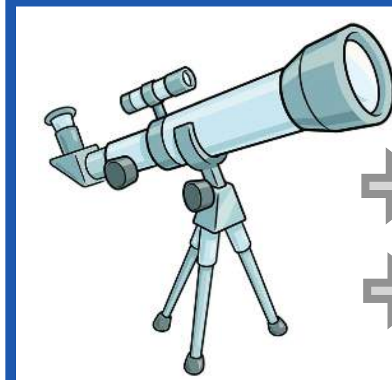


$$\bar{\sigma} = \frac{y_\chi^2\, y_n^2}{4\pi} \frac{\mu^2}{(m_\chi^2 v_0^2 + m_\phi^2)^2}$$

Terrestial

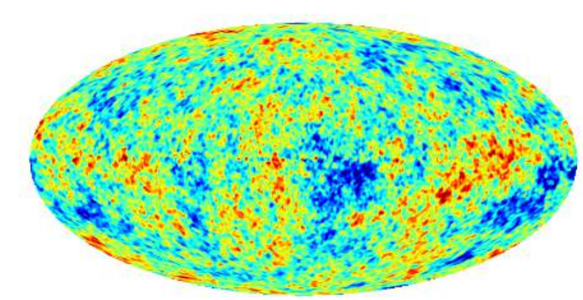
- Collider
- 5th force

Astrophysical

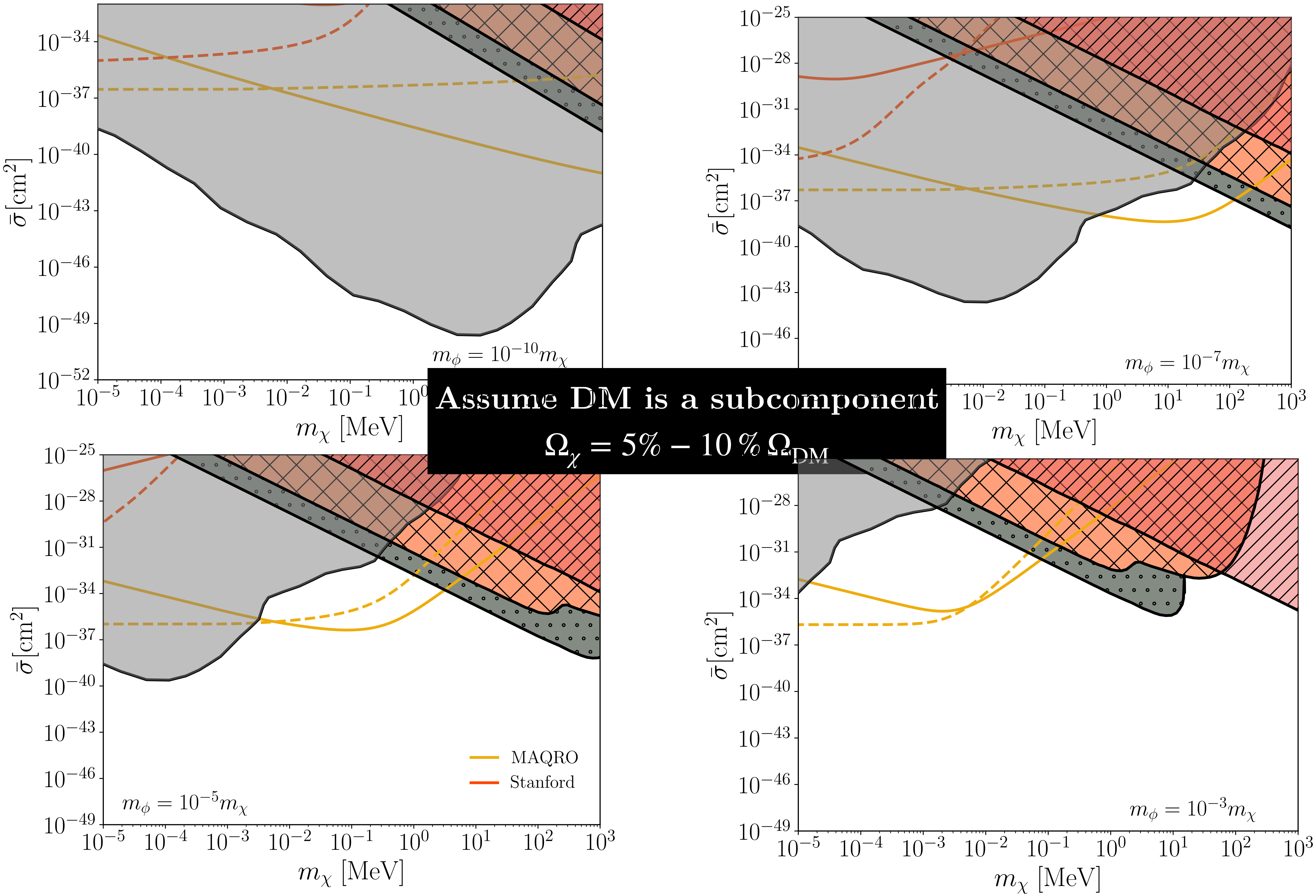


- Stellar emission
- DMSI

Cosmological



AIs: Constraints



Assume DM is a subcomponent

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

AIs: Applications

GWs

[Dimopoulos, Graham, et al. 2008] [Hogan, Johnson, et al . 2011], [Yu, Tinto, 2011] [Graham, Hogan, 2013], [Canuel, Bertoldi, et al. 2018] [Canuel, Abend, et al. 2020] [Kolkowitz, Pikovski, et al., 2016] [Zhan, Wang, et al. 2020] [El-Neaj, Alpigiani, et al. 2020] [Badurina, Bentine, et. Al. 2020], [Graham, Hogan, et al. 2016] [Graham, Hogan, et al. 2017], [Ballmer, Adhikari, et al. 2022]

EDMs

[Wicht et al, 2002] [Bennet et al. 2006] [Cadoret et al. 2008] [Terranova, Tino, 2014]...

$$N_I \stackrel{!}{=} \frac{1}{2}\left(1 + V\cos\left(\phi + \Delta\phi\right)\right)$$

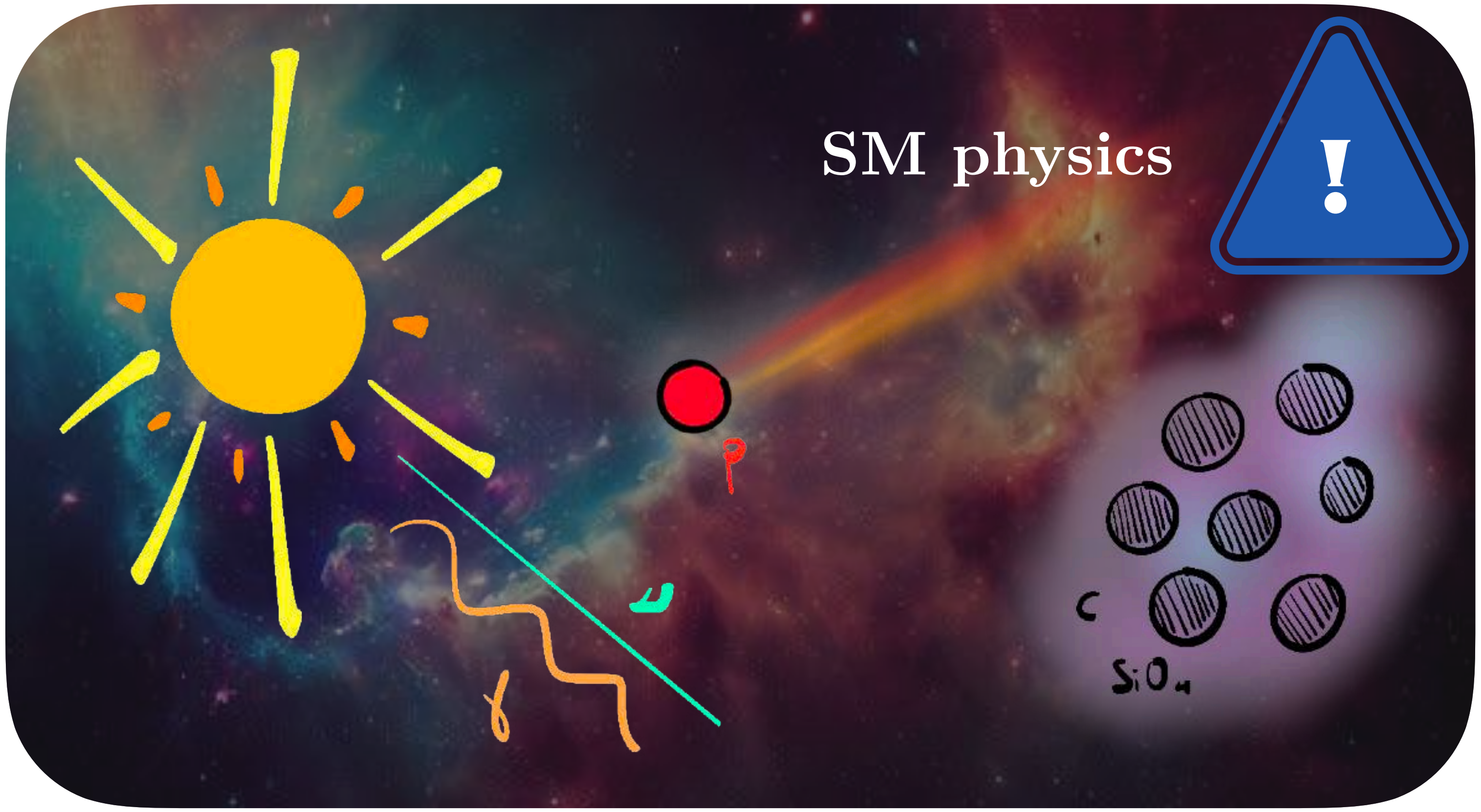
5th forces

[Wacker, 2010], [Rosi, Sorrentino, et al. 2014] [Biedermann, Wu, et al. 2015] [Rosi, D'Amico, et al. 2017] [Fray, Diez, et al. 2004] [Schlippert, Hartwig, et al. 2014] [Zhou, Long, et al. 2015] [Barrett, Antoni-Micollier, et al. 2016] [Kuhn, McDonald, et al. 2014] [Barrett, Antoni-Micollier, et al. 2015] [[illegible]llo, Mazzoni, et al 2014] [Bonnin, Zahzam et al. 2013] [Har[illegible], Abend, et al. 2015] [Asenbaum, Overstreet, et al 2020] [Williams, Chiow, et al. 2016] [Battelier, Berge, et al., 2019] ....

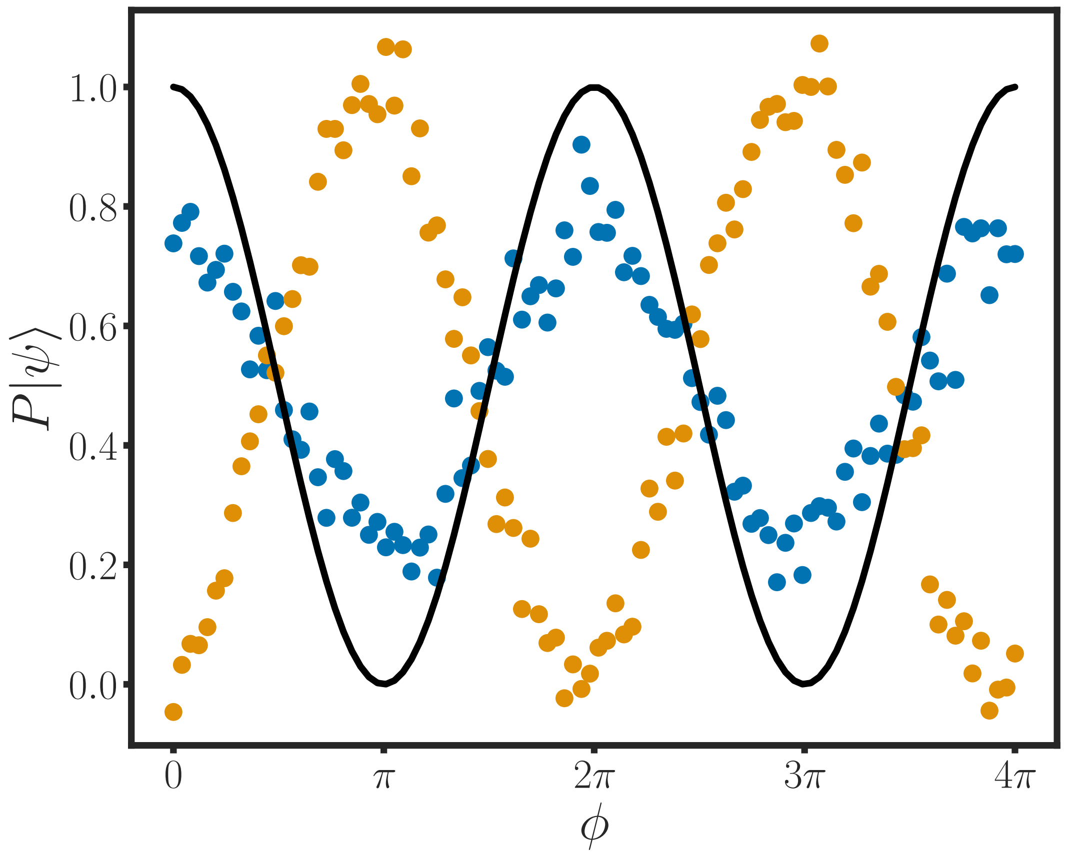
ULDM

[Graham, Kaplan, et al. 2016]
[Arvanitaki, Graham, et al. 2018]
[Kolb, Weers, et al. 2018]
[Badurina, Blas, McCabe, 2021]
[Antypas, Banerjee, 2022]
[Badurnina, Gipson, et al. 2022]
[Badurnina, Beniwal, et al. 2023]

AIs: Measurement



$$\frac{1}{2}\left(1 + V \cos\left(\phi + \Delta\phi\right)\right)$$



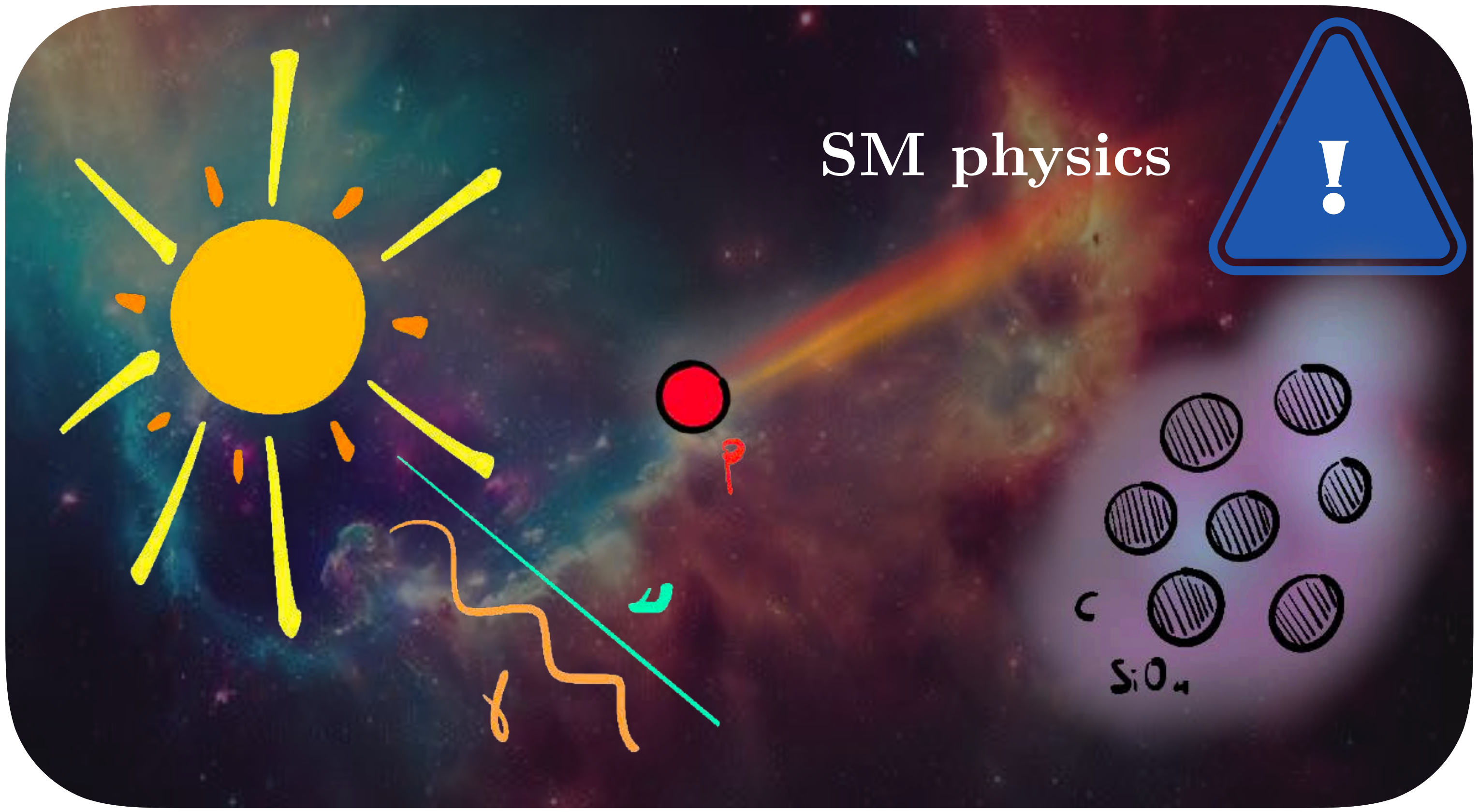
Visibility

$$\mathrm{SNR}|_{\mathrm{shot}} \equiv \frac{|\Delta V|}{\sigma_V}$$

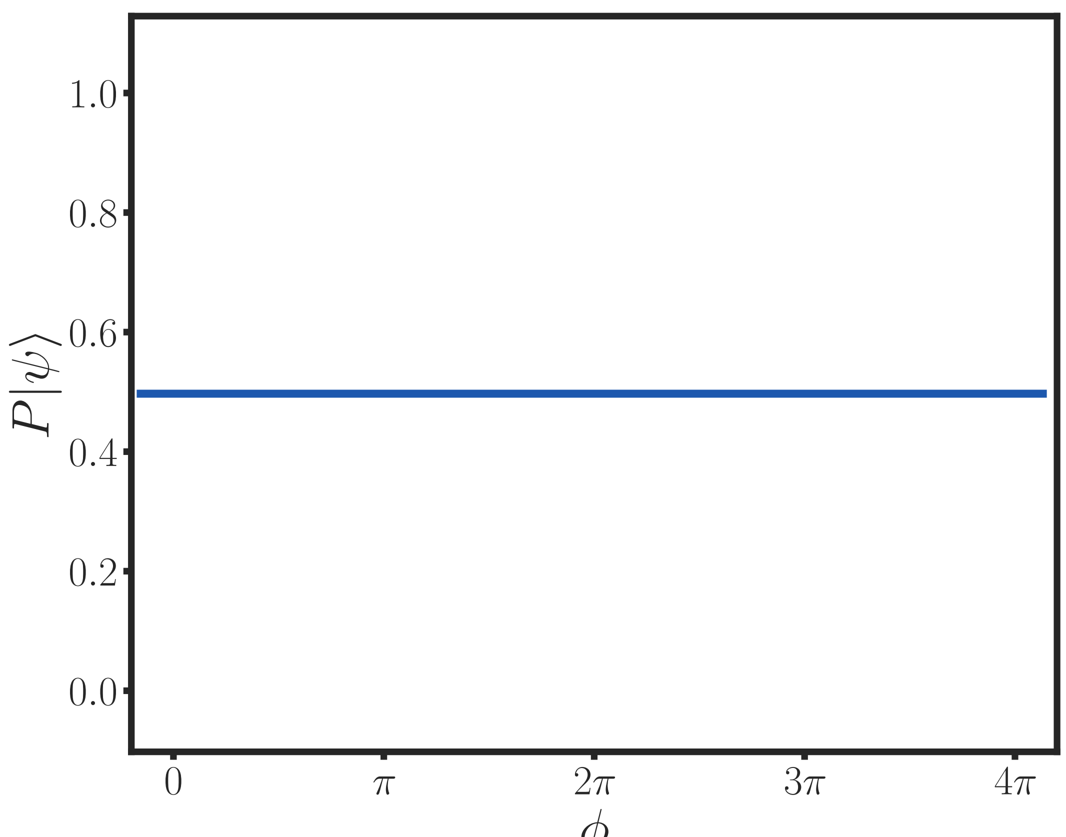
- No decoherence or phase effects
- Decoherence Effect
- Phase Effect

[Du, **CM**, Pardo, Wang, Zurek, 2023]

AIs: Measurement



$$\frac{1}{2}\left(1 + V \cos\left(\phi + \Delta\phi\right)\right)$$



Visibility

$$\mathrm{SNR}|_{\mathrm{shot}} \equiv \frac{|\Delta V|}{\sigma_V}$$

- No decoherence or phase effects
- Decoherence Effect
- Phase Effect

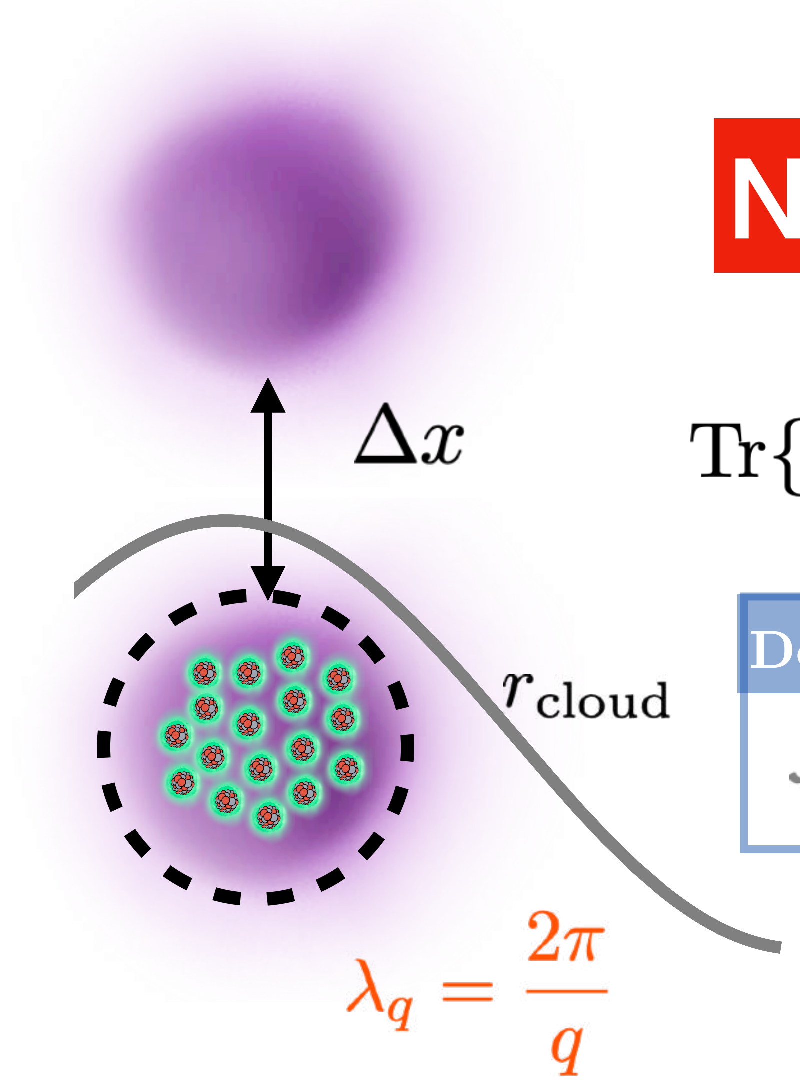
[Du, **CM**, Pardo, Wang, Zurek, 2023]

AIs: Destructive Decoherence

Multi-atom system (distinguishable)
[Badurina, **CM**, Plestid, 2024]

NEW!

$$\rho_{(N=2)} = \begin{pmatrix} \circ & \blacksquare & \blacksquare & \bigstar \\ \blacksquare & \circ & \circ & \blacksquare \\ \blacksquare & \circ & \circ & \blacksquare \\ \bigstar & \blacksquare & \blacksquare & \circ \end{pmatrix}$$



$$\mathrm{Tr}\{\rho_N \sum_i^N \mathcal{O}_i\} = N\,\mathrm{Tr}\{\rho_1 \mathcal{O}_i\} \stackrel{!}{=} N\,\tfrac{1}{2}(1 + V\cos(\phi + \Delta\phi))$$

Decoherence Kernel n-body measurement

$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = n^2\left(1 - \cos(\mathbf{q}\cdot\mathbf{\Delta x})\right) - iNn\sin(\mathbf{q}\cdot\mathbf{\Delta x})$$

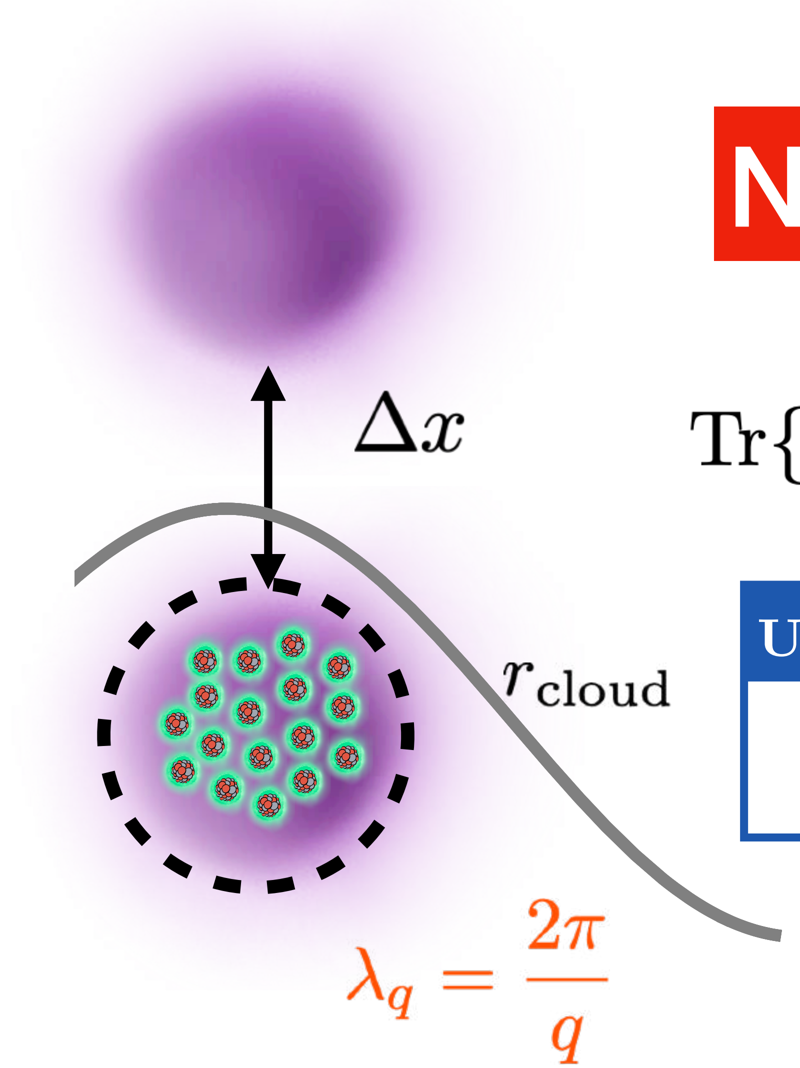
$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

$$\Rightarrow \Delta\rho = \tfrac{i}{2}[T + T^\dagger, \rho] - \tfrac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

AIs: Destructive Decoherence

Multi-atom system (distinguishable)

[Badurina, **CM**, Plestid, 2024]



NEW!

$$\rho_{(N=2)} = \begin{pmatrix} \circ & \blacksquare & \blacksquare & \bigstar \\ \blacksquare & \circ & \circ & \blacksquare \\ \blacksquare & \circ & \circ & \blacksquare \\ \bigstar & \blacksquare & \blacksquare & \circ \end{pmatrix}$$

$$\mathrm{Tr}\{\rho_N \sum_i^N \mathcal{O}_i\} = N\,\mathrm{Tr}\{\rho_1 \mathcal{O}_i\} \overset{!}{=} N\,\tfrac{1}{2}(1 + V\cos(\phi + \Delta\phi))$$

Unitary Kernel n-body measurement

$$\mathcal{F}_{\text{unitary}}(\mathbf{q}') = in(n + N - 2N_g)[1 - \cos(\mathbf{q}' \cdot \mathbf{\Delta x})]$$

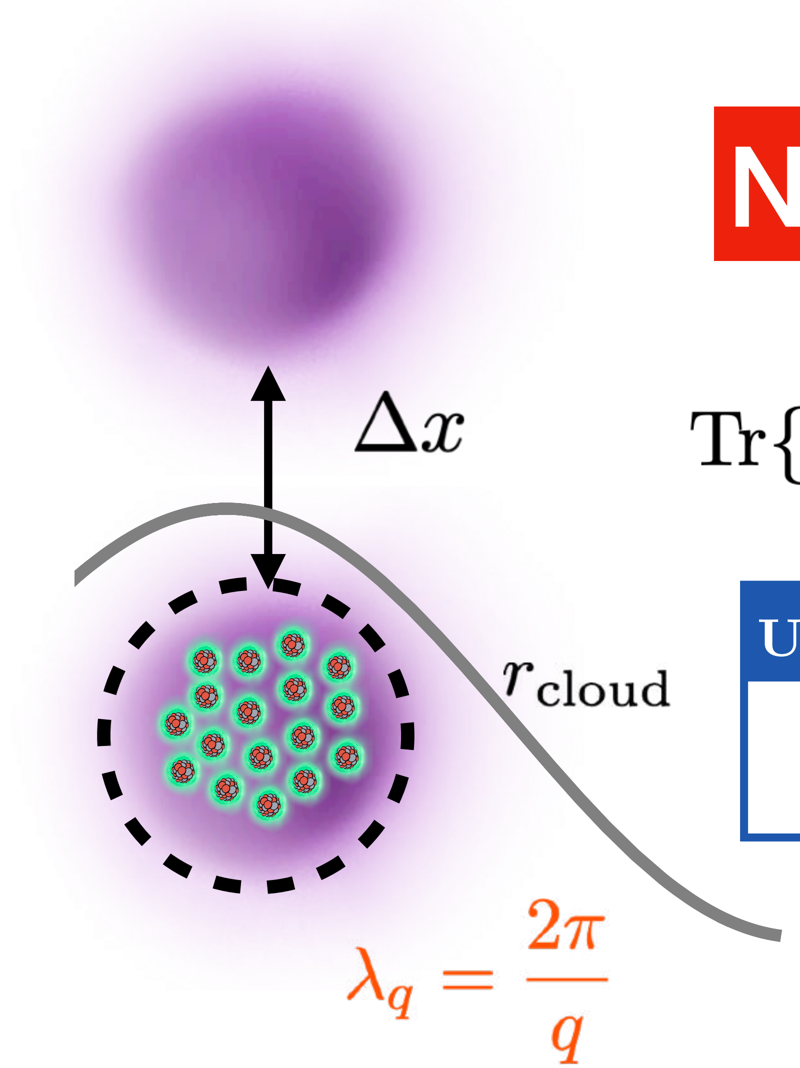
$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

$$\Rightarrow \Delta\rho = \tfrac{i}{2}[T + T^\dagger, \rho] - \tfrac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

AIs: Destructive Decoherence

Multi-atom system (distinguishable)

[Badurina, **CM**, Plestid, 2024]



NEW!

$$\rho_{(N=2)} = \begin{pmatrix} \circ & \blacksquare & \blacksquare & \bigstar \\ \blacksquare & \circ & \circ & \blacksquare \\ \blacksquare & \circ & \circ & \blacksquare \\ \bigstar & \blacksquare & \blacksquare & \circ \end{pmatrix}$$

$$\mathrm{Tr}\{\rho_N \sum_i^N \mathcal{O}_i\} = N\,\mathrm{Tr}\{\rho_1 \mathcal{O}_i\} \stackrel{!}{=} N\,\tfrac{1}{2}(1 + V\cos(\phi + \Delta\phi))$$

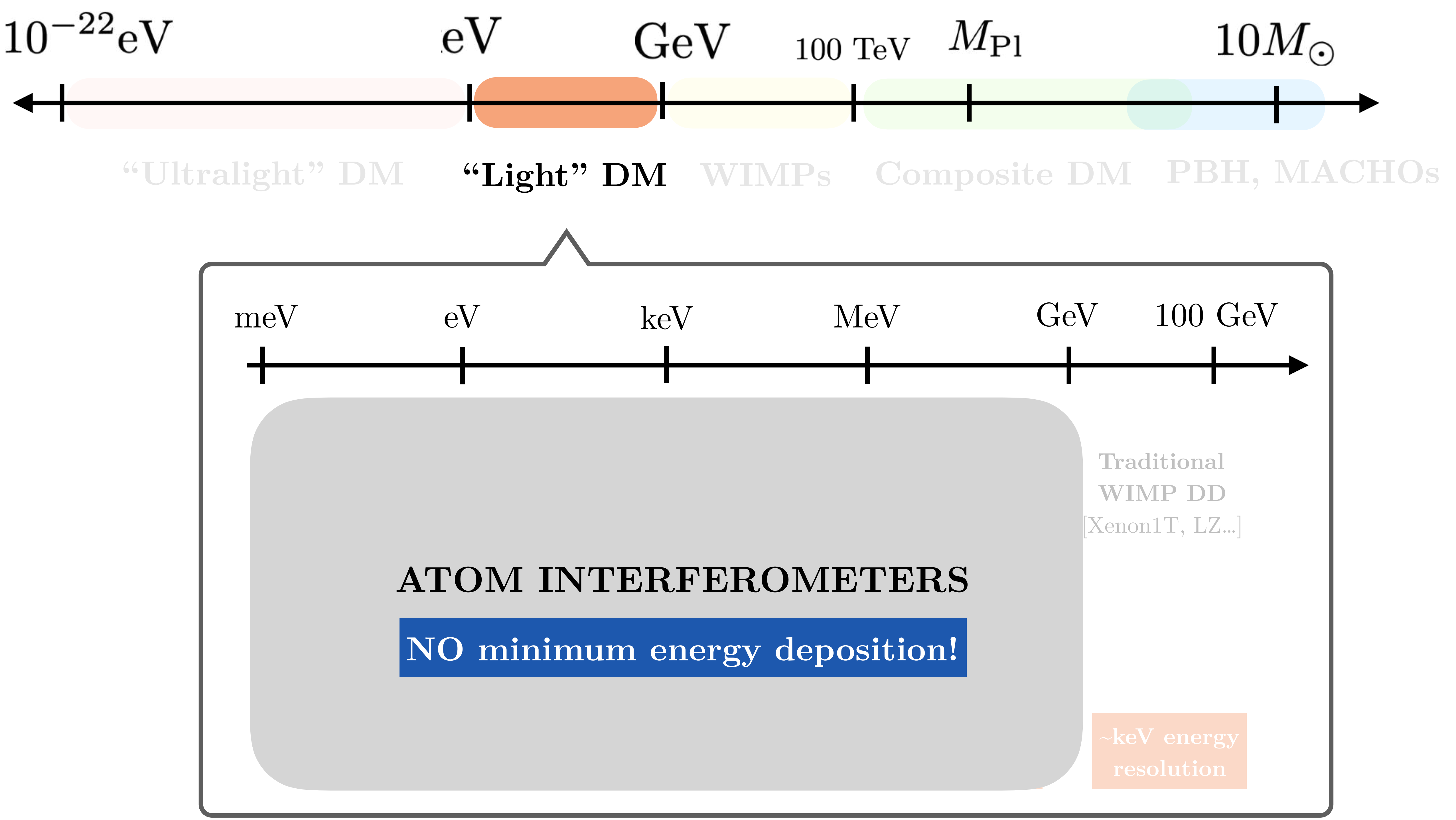
Unitary Kernel n-body measurement

$$\mathcal{F}_{\text{unitary}}(\mathbf{q}') = in(n + N - 2N_g)[1 - \cos(\mathbf{q}' \cdot \mathbf{\Delta x})]$$

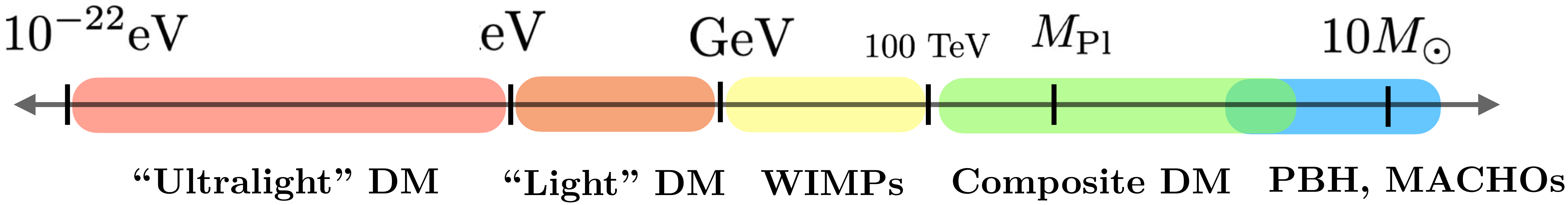
$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\text{exp}} = \tfrac{1}{2}(1 + V\cos(\phi + \Delta\phi))$$

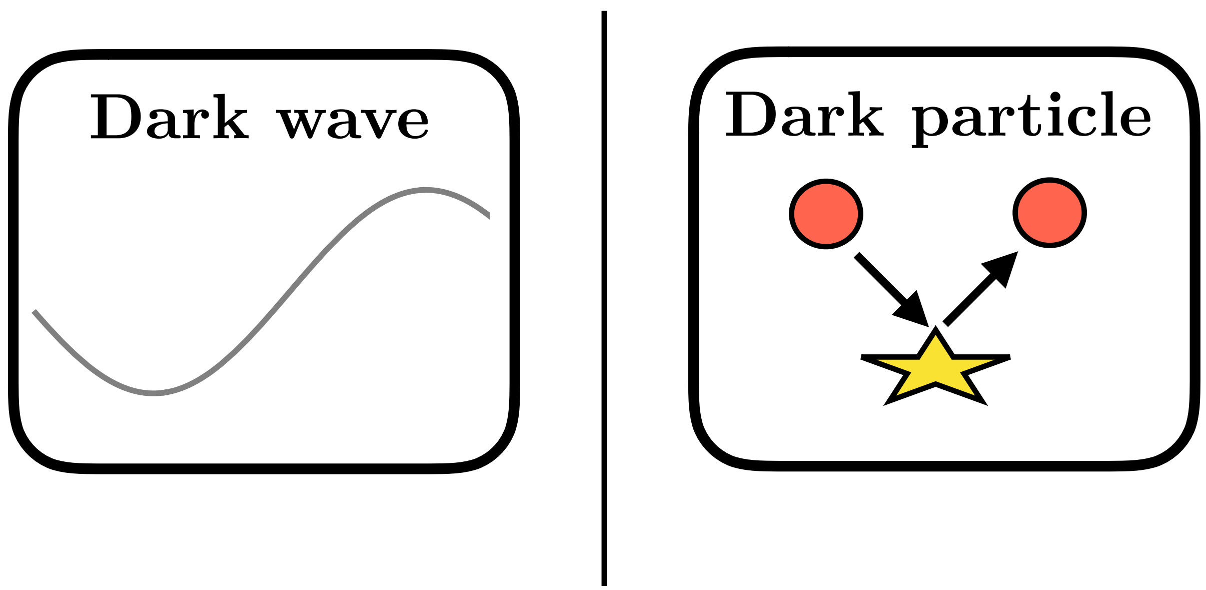
$$\mathrm{Tr}\{\rho\,\mathcal{O}_1\} = \tfrac{1}{2}\Big[1 + e^{-\int_{\mathbf{q},t} R(\mathbf{q})(1-\cos(\mathbf{q}\cdot\mathbf{\Delta x}))} \cos^{N-1}\Big(\int_{\mathbf{q}',t} \omega(\mathbf{q}')(1 - \cos(\mathbf{q}' \cdot \mathbf{\Delta x}))\Big)$$
$$\times \cos\Big(\phi + \int_{\mathbf{q},t} R(\mathbf{q}) \sin(\mathbf{q} \cdot \mathbf{\Delta x})\Big)\Big]$$

Dark Matter: where to look?



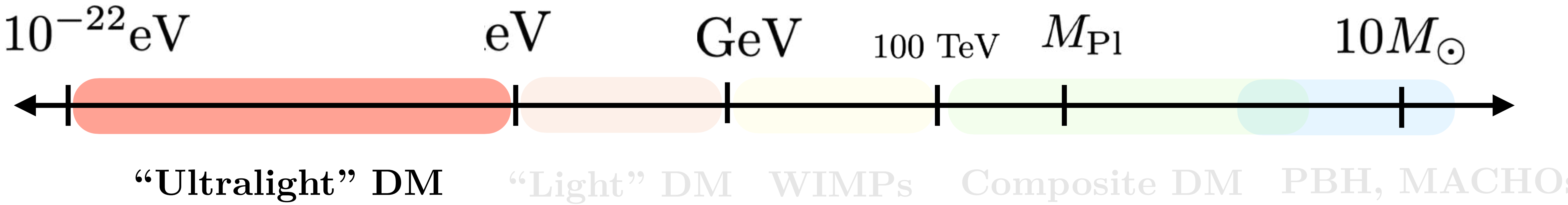
Dark Matter: where to look?

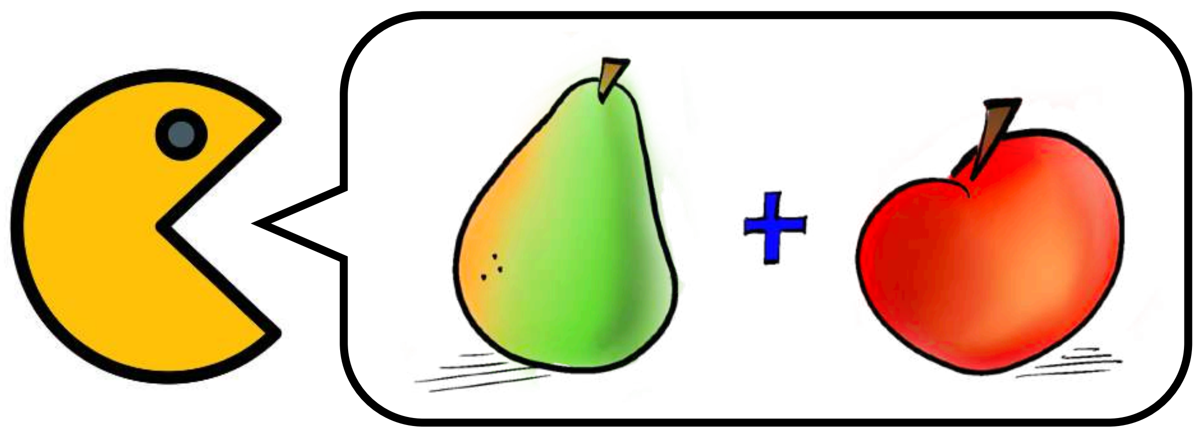




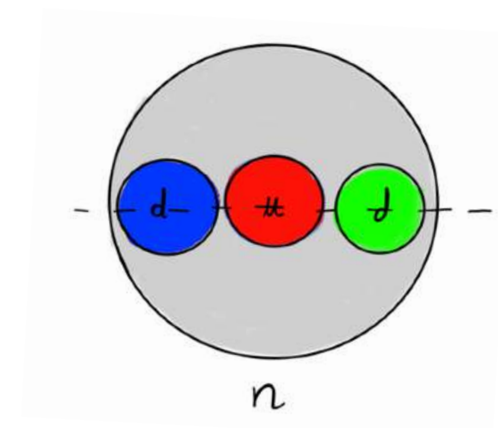
$$\left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^{-1/3} < \lambda_{dB} = \frac{1}{m_{\mathrm{DM}} v_{\mathrm{DM}}}$$

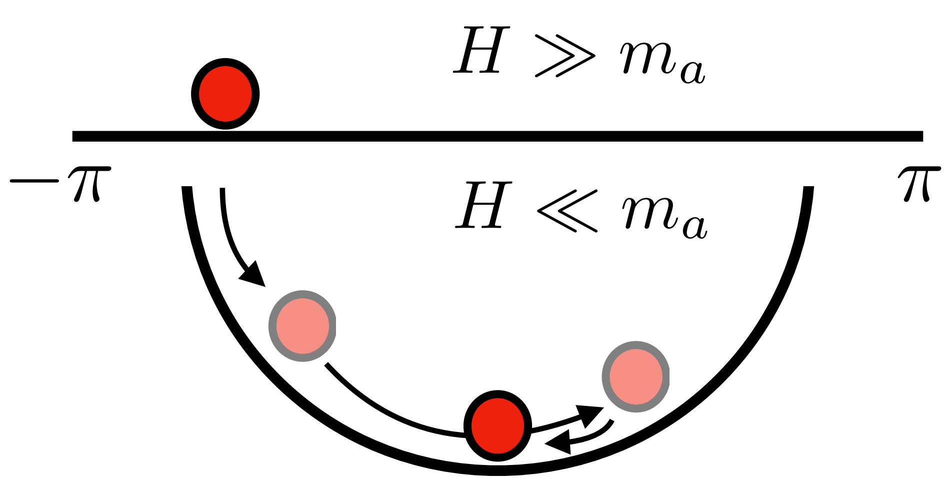
Axion Dark Matter





$< 10^{-10}$

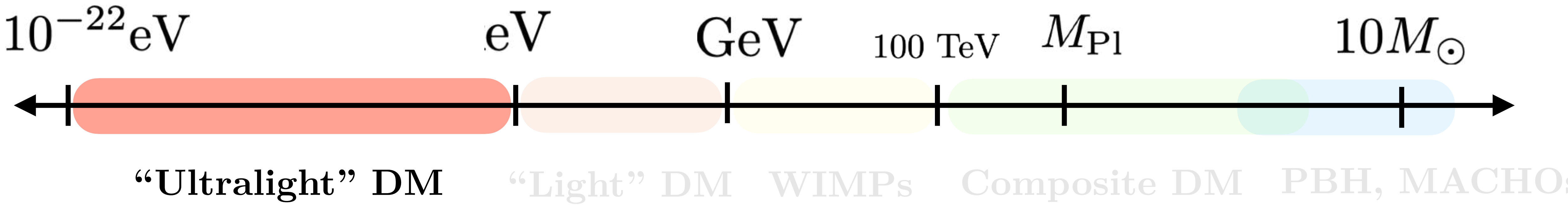


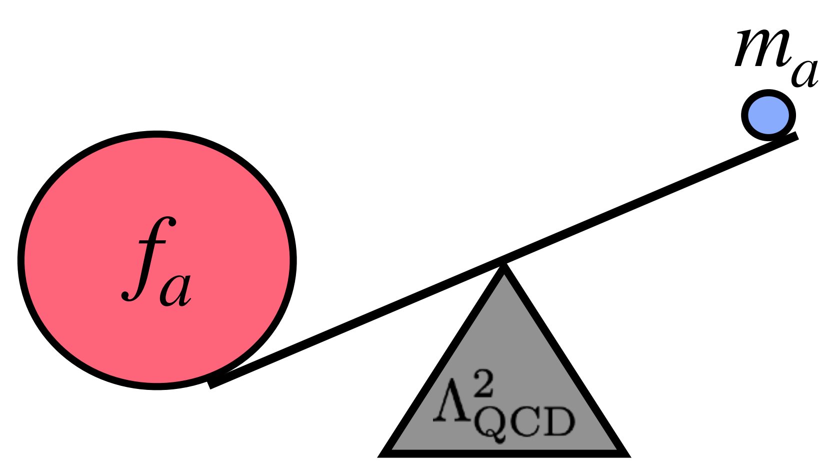


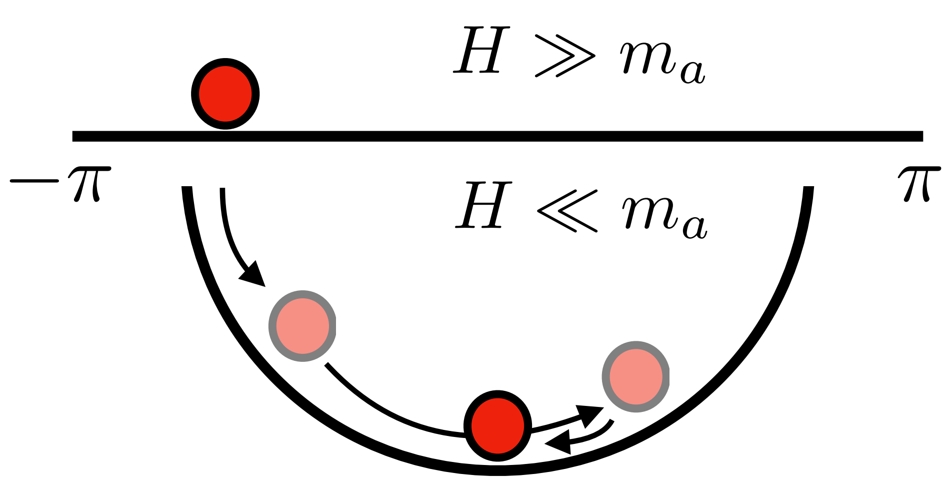
[Preskill, Wise, Wilczek, 1983]
[Abbott, Sikivie, 1983]
[Dine, Fischler, 1983]

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

Axion Dark Matter





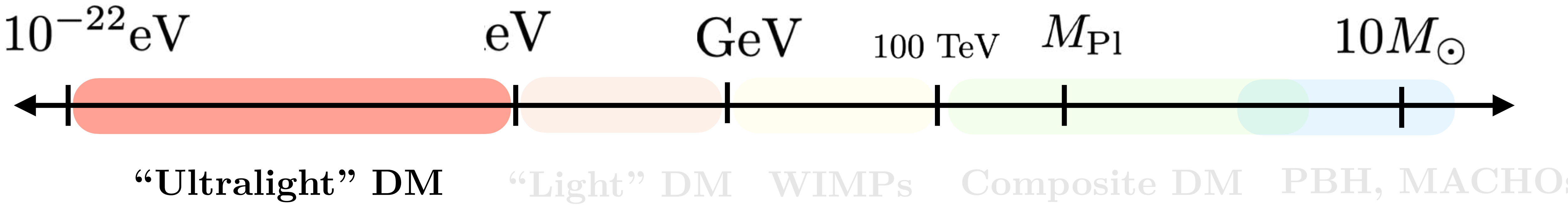


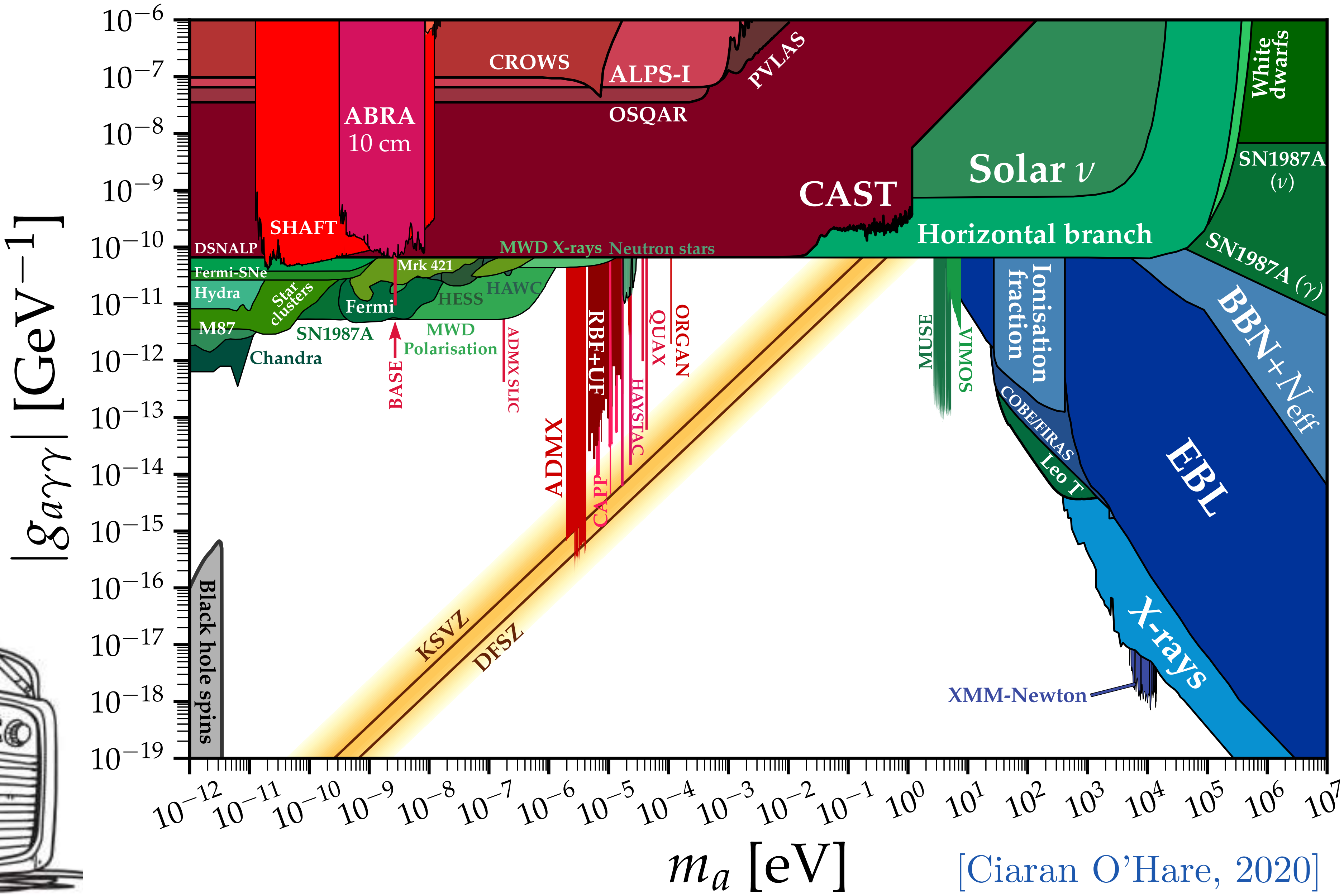
$$m_a \sim \frac{\Lambda^2_{\rm QCD}}{f_a}$$

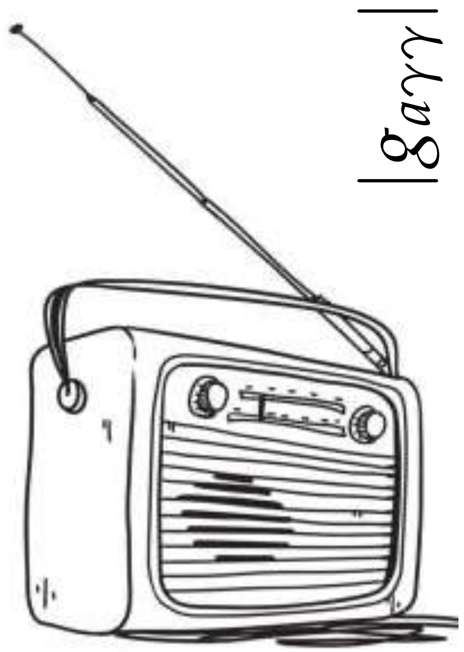
[Preskill, Wise, Wilczek, 1983]
[Abbott, Sikivie, 1983]
[Dine, Fischler, 1983]

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

Axion Dark Matter

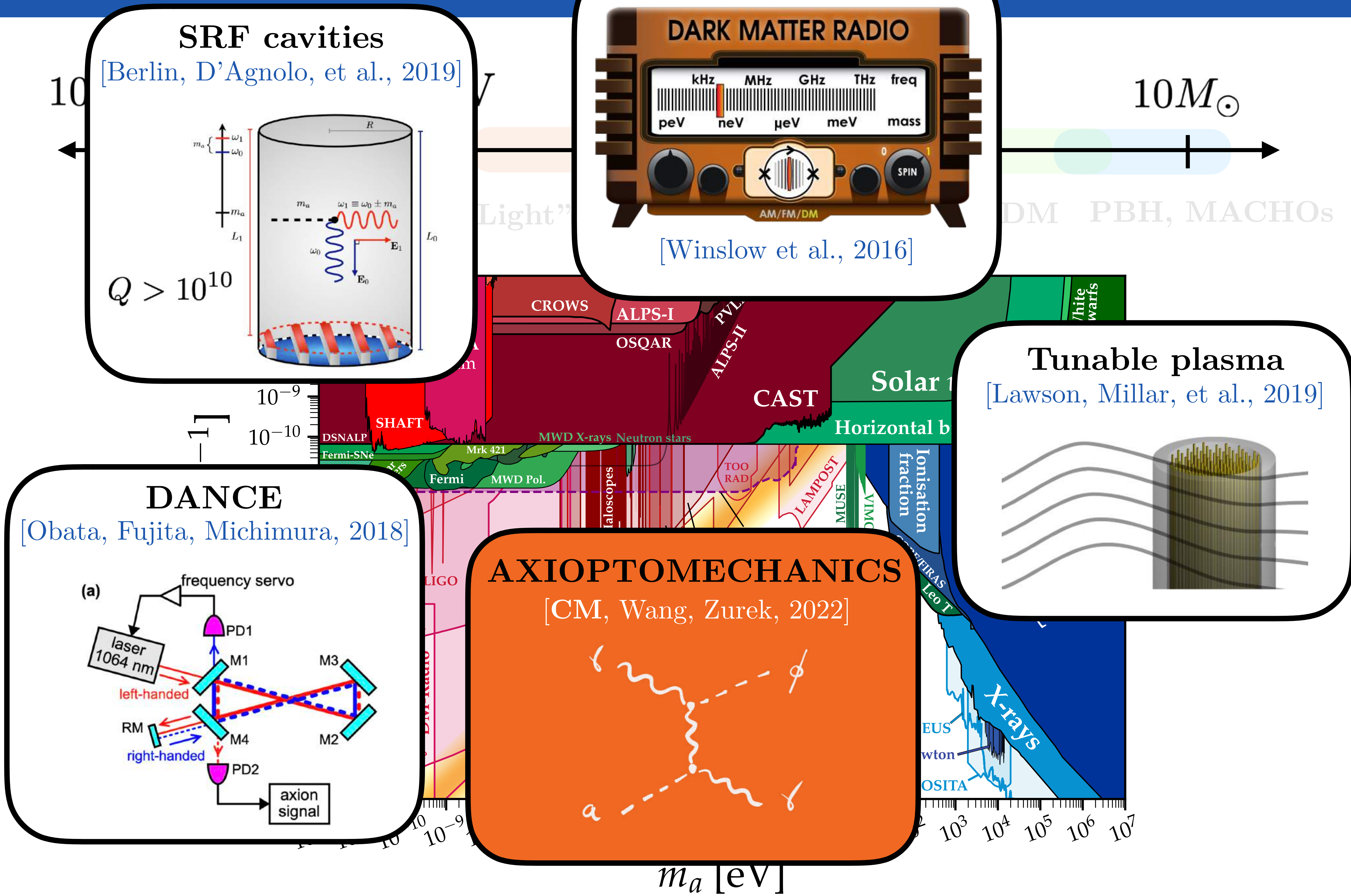






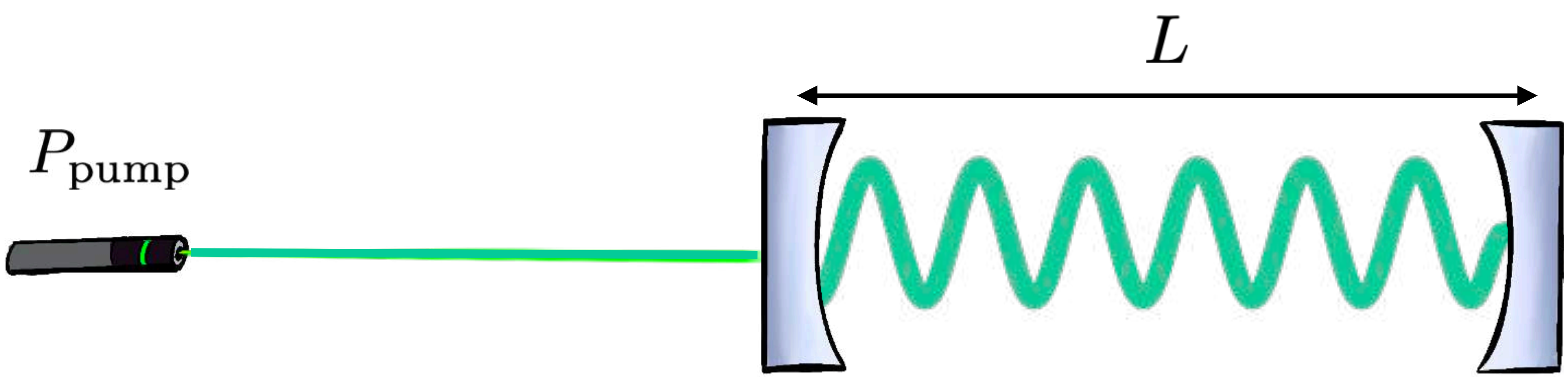
[Ciaran O'Hare, 2020]

Axion Dark Matter

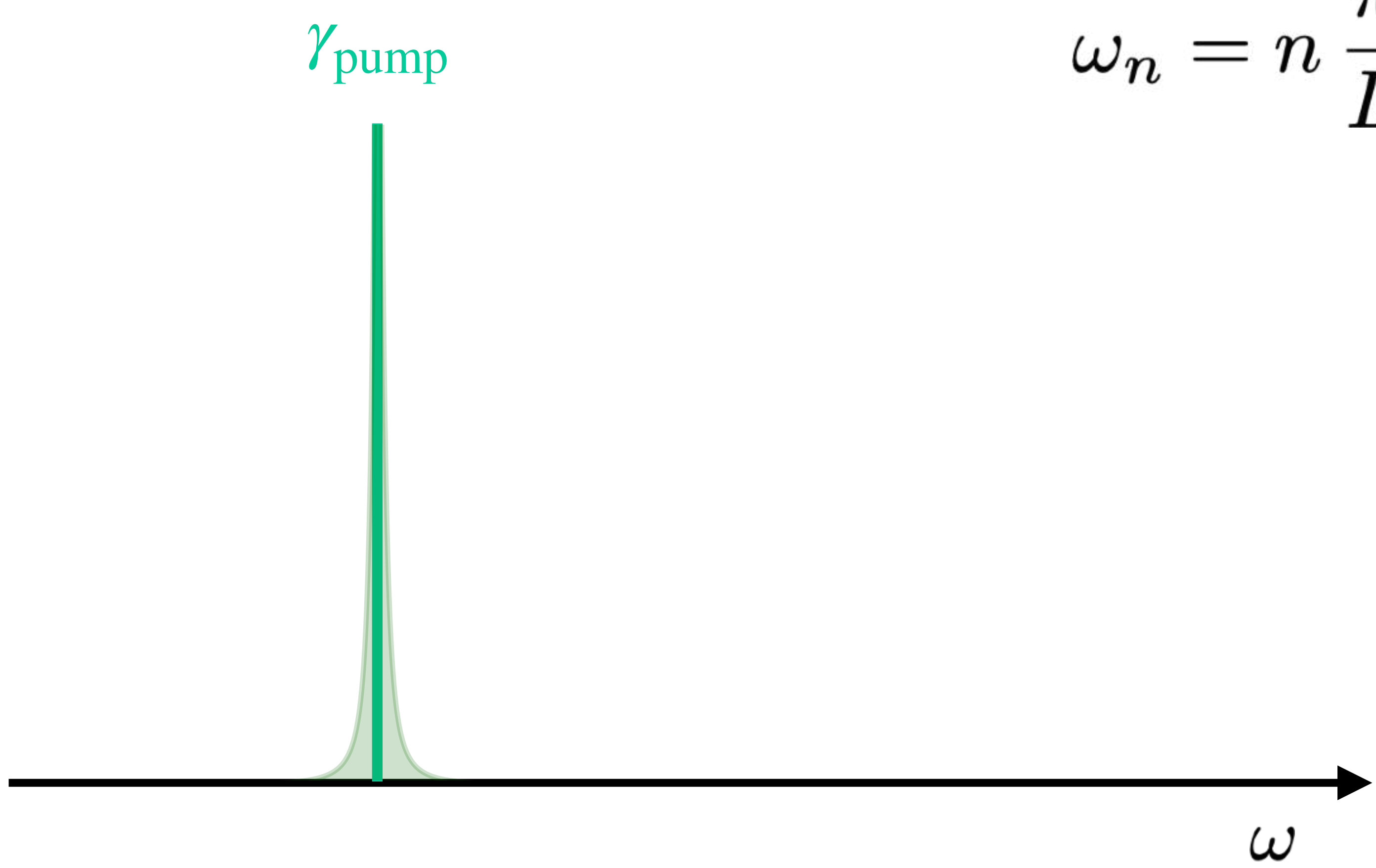


Standard **Optomechanics**

[Review: M. Aspelmeyer, T. J. Kippenberg, F. Marquardt, 2013. Thesis at J. Harris lab.]

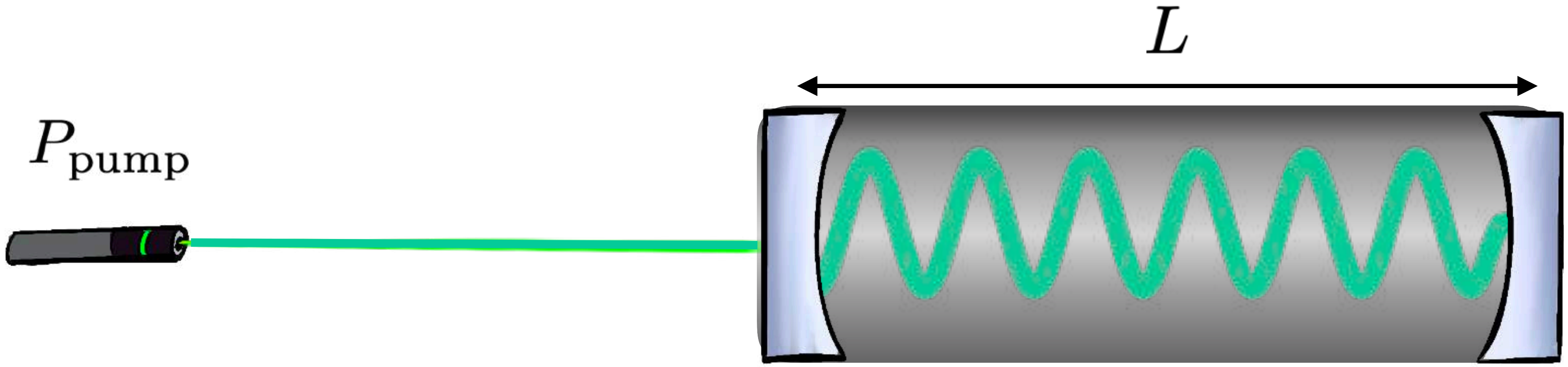


$$\omega_n = n\,\frac{\pi}{L}, \qquad n \subset \mathbb{Z}$$



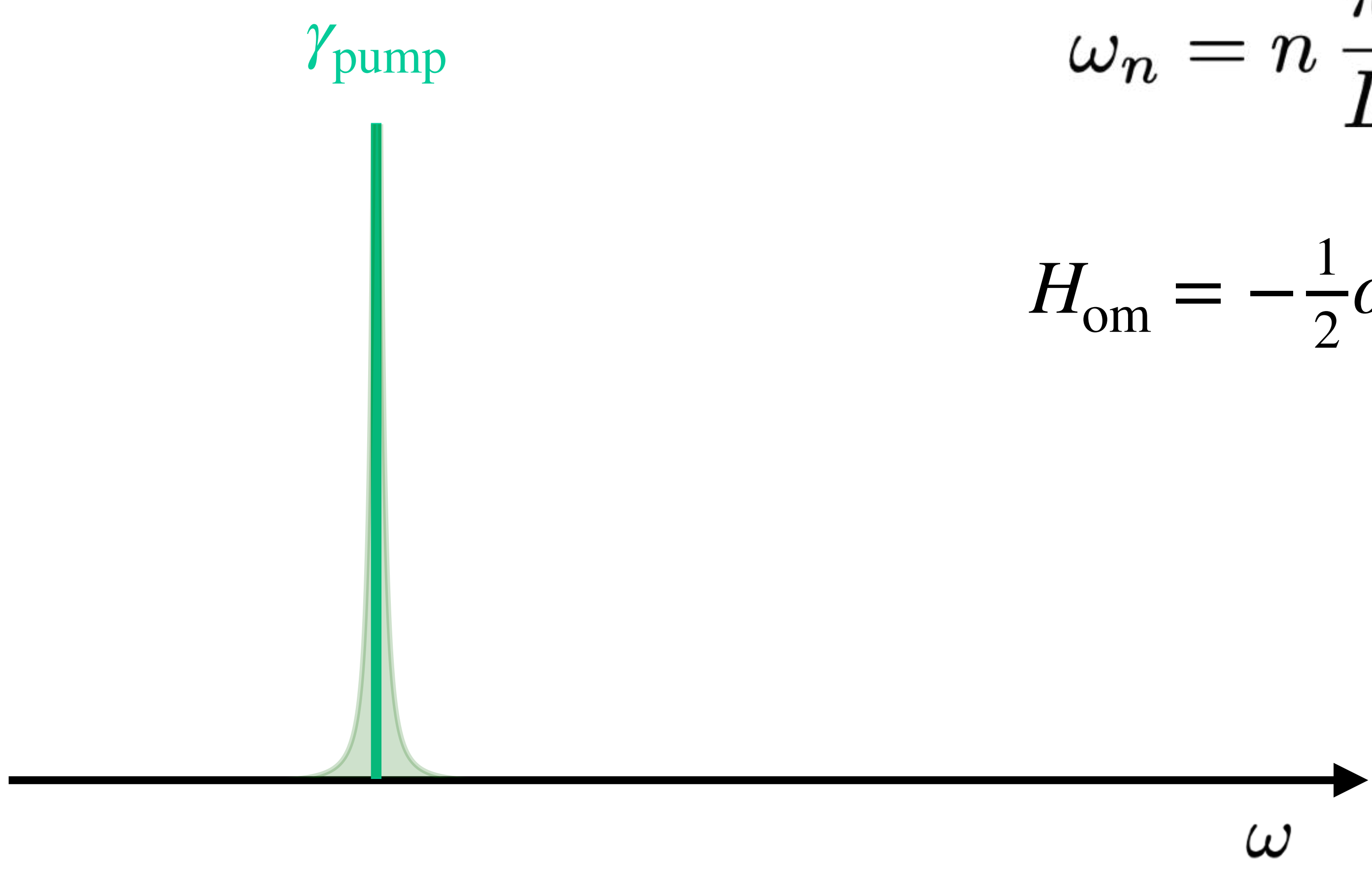
Standard **Optomechanics**

[Review: M. Aspelmeyer, T. J. Kippenberg, F. Marquardt, 2013. Thesis at J. Harris lab.]



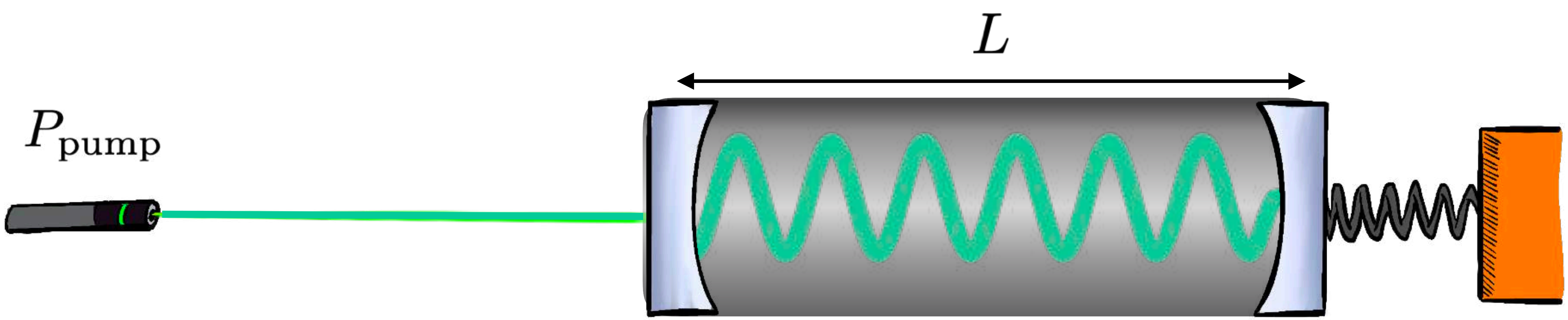
$$\omega_n = n\,\frac{\pi}{L}, \qquad n \subset \mathbb{Z}$$

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

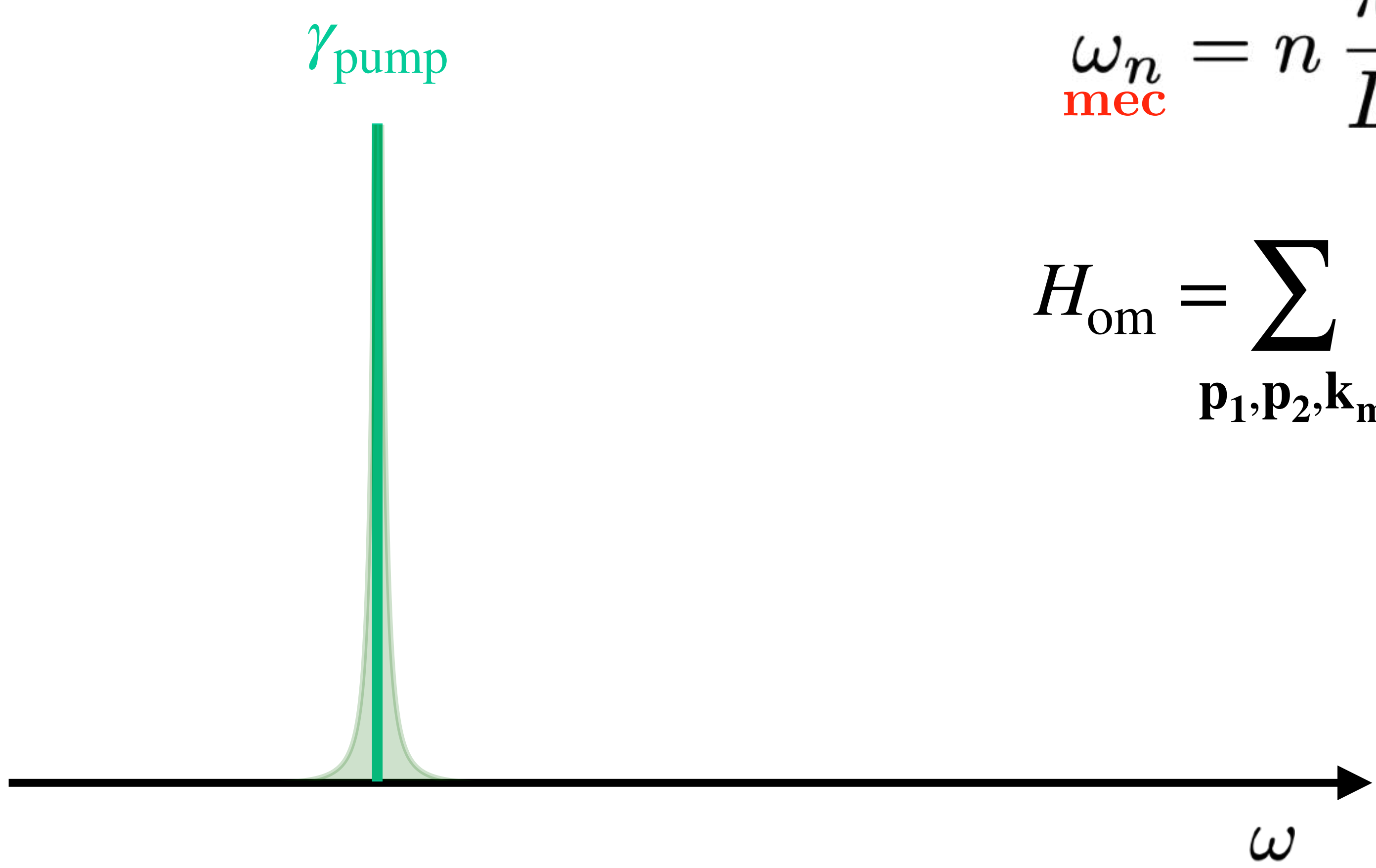


Standard **Optomechanics**

[Review: M. Aspelmeyer, T. J. Kippenberg, F. Marquardt, 2013. Thesis at J. Harris lab.]

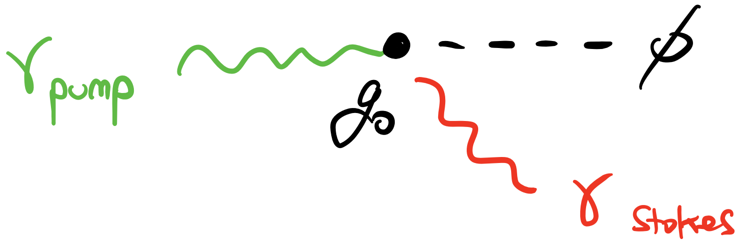


$$\underset{\text{mec}}{\omega_n} = n\,\frac{\pi}{L}\,c_s, \quad n \subset \mathbb{Z}$$

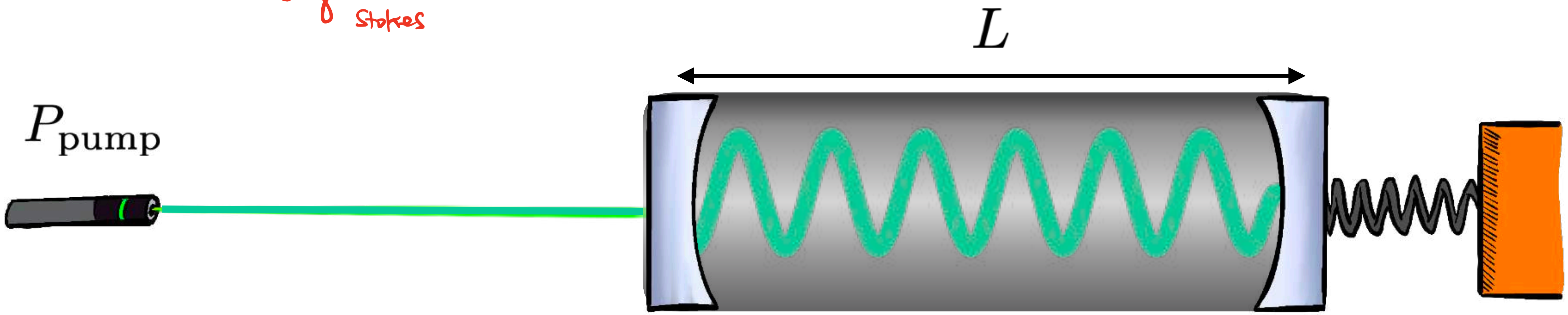


$$H_{\text{om}} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} + \cdots \right.$$

Standard **Optomechanics**

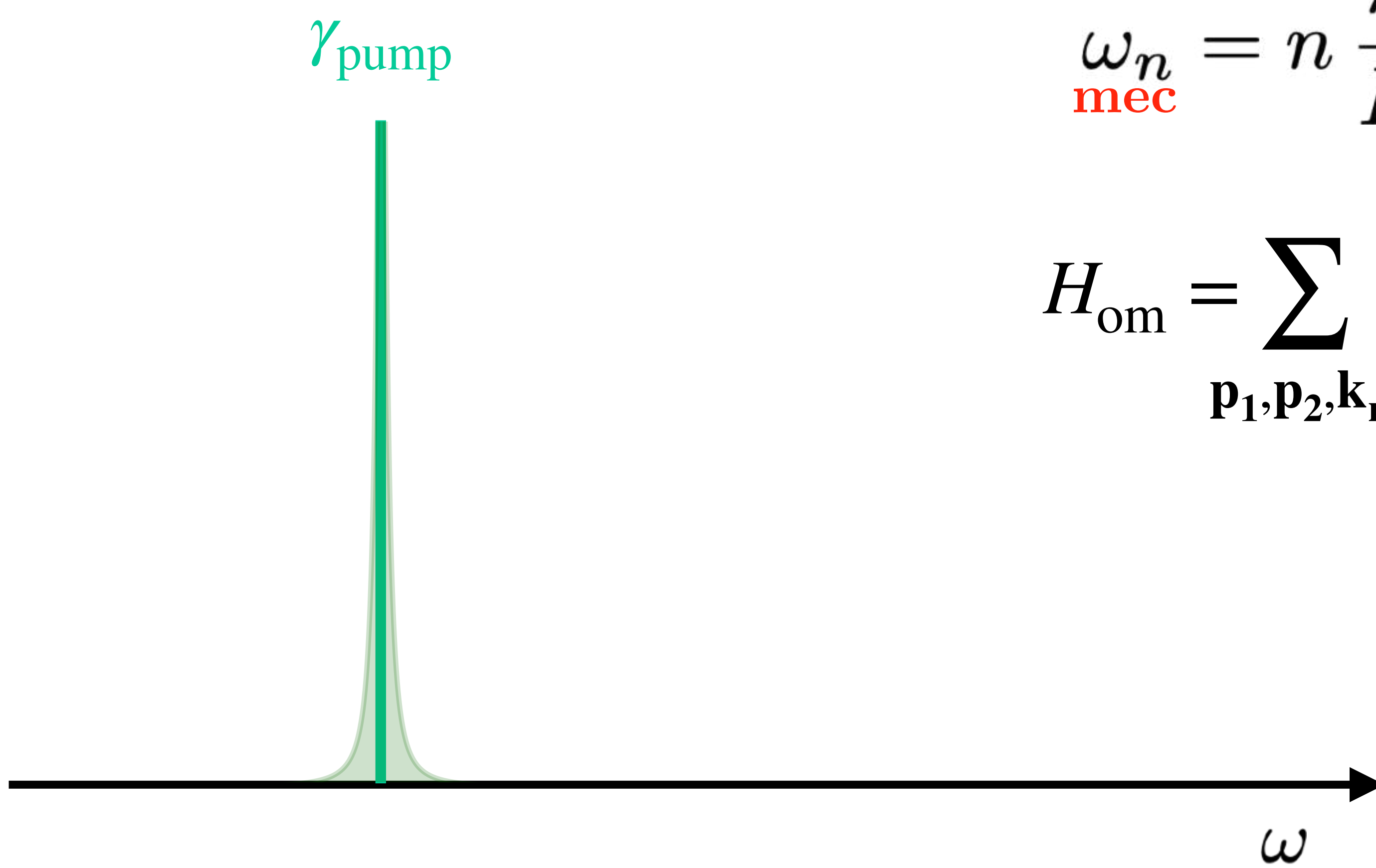


$$\vec{p}_{\gamma 1} = \vec{p}_{\phi} + \vec{p}_{\gamma 2}$$
$$\omega_{\gamma 1} = \omega_{\mathrm{m}} + \omega_{\gamma 2}$$



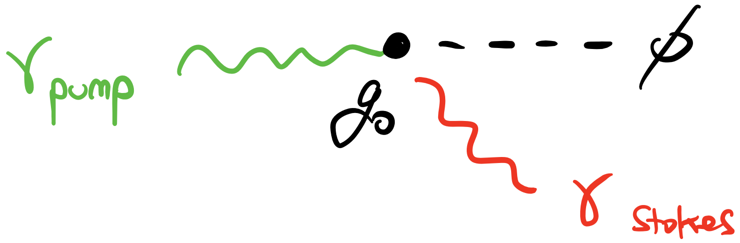
$$\underset{\mathbf{mec}}{\omega_n} = n\,\frac{\pi}{L}\,c_s, \qquad n \subset \mathbb{Z}$$

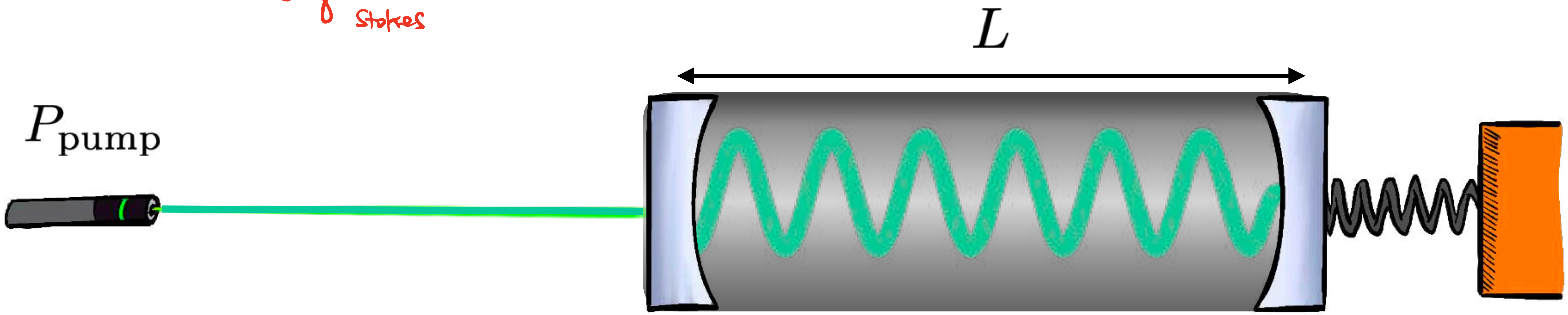
$$H_{\mathrm{om}} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left(a_{\mathbf{p_1}} a^{\dagger}_{\mathbf{p_2}} b^{\dagger}_{\mathbf{k_m}} + \cdots \right.$$



Standard **Optomechanics**

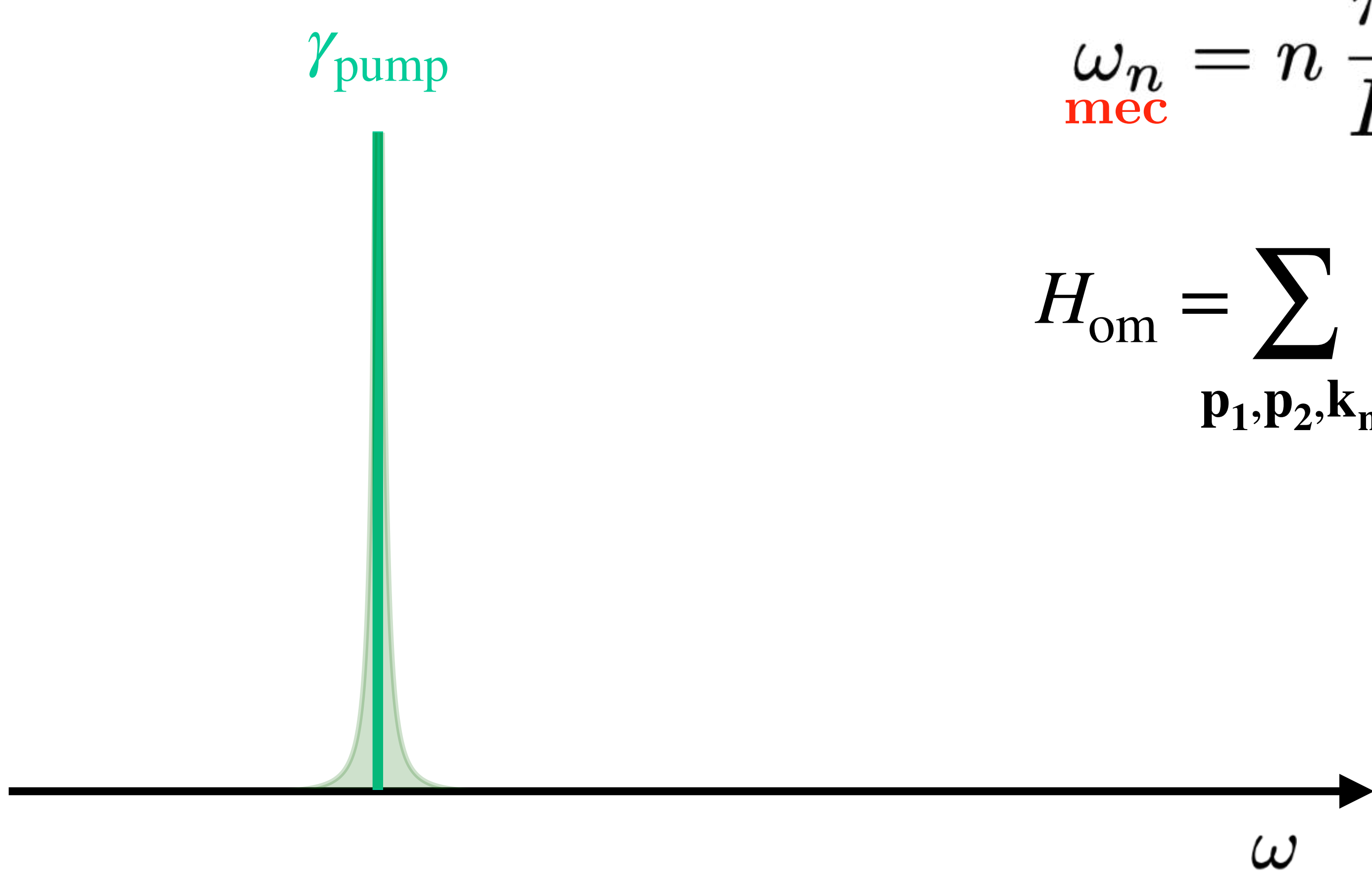
$$p_\phi = 2p_\gamma$$
$$\Omega_{\mathrm{m}} = 2c_s\omega_{\mathrm{opt}}$$





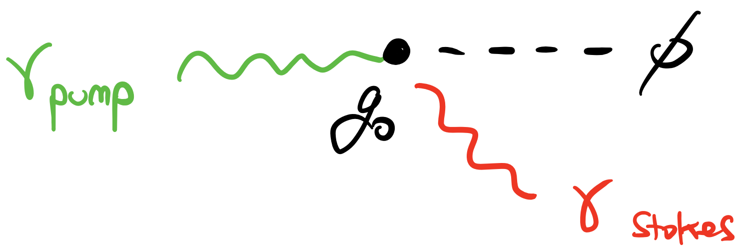
$$\underset{\mathbf{mec}}{\omega_n} = n\,\frac{\pi}{L}\,c_s, \quad n \subset \mathbb{Z}$$

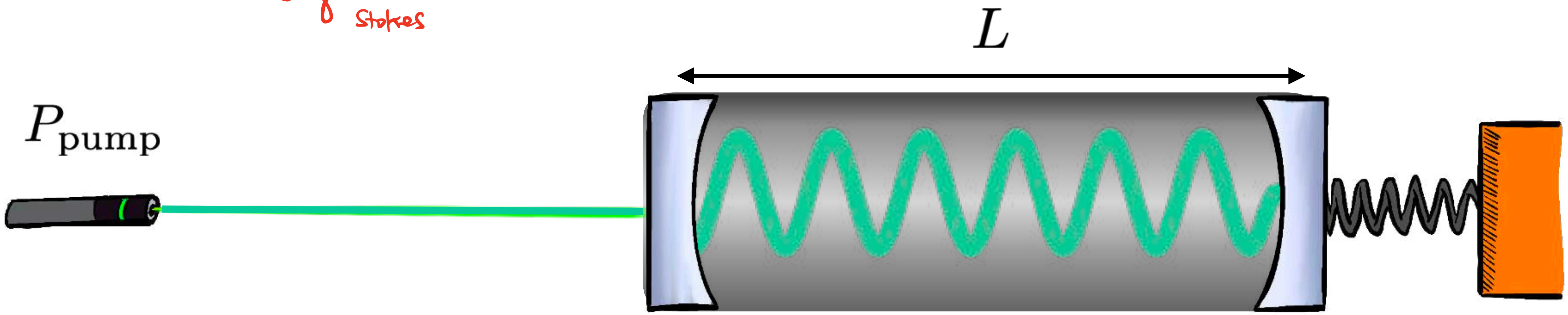
$$H_{\mathrm{om}} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} + \cdots \right.$$



Standard **Optomechanics**

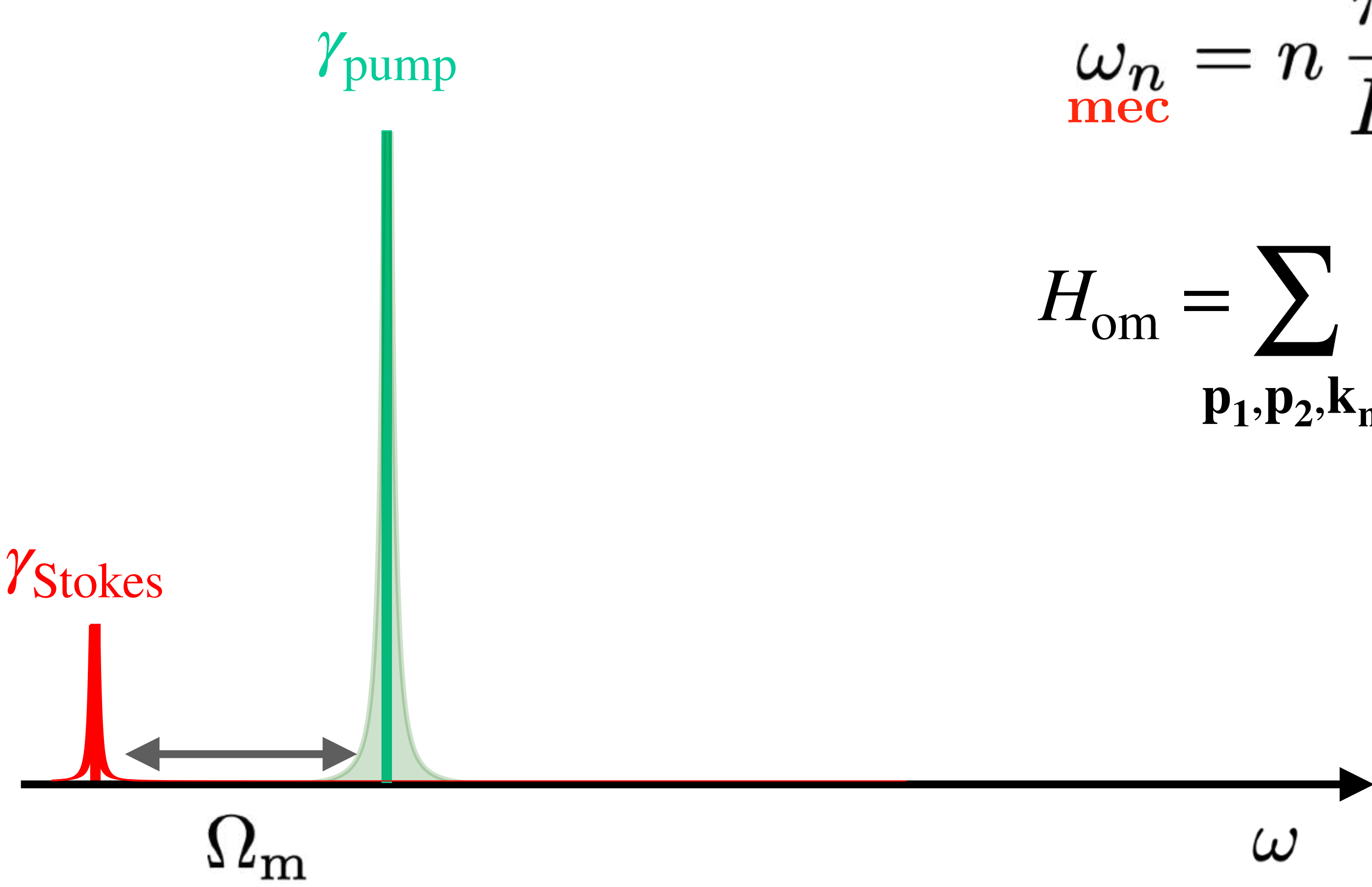
$$p_\phi = 2p_\gamma$$
$$\Omega_{\rm m} = 2c_s\omega_{\rm opt}$$



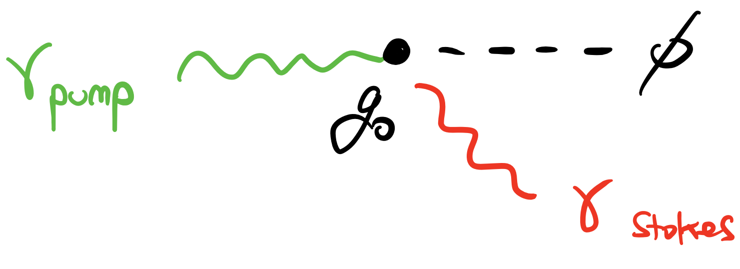


$$\omega_{n}^{\rm mec} = n\frac{\pi}{L}c_s, \quad n \subset \mathbb{Z}$$

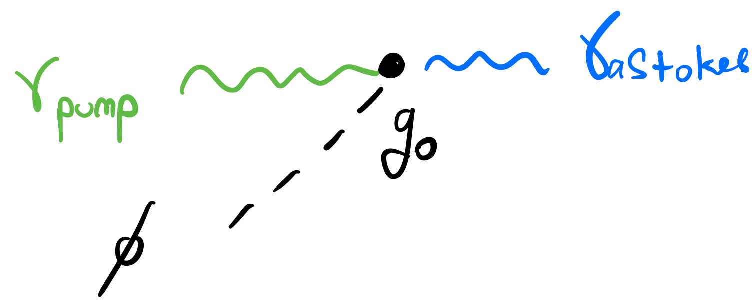
$$H_{\rm om} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0\left(a_{\mathbf{p_1}}a^\dagger_{\mathbf{p_2}}b^\dagger_{\mathbf{k_m}} + \cdots\right.$$



Standard **Optomechanics**

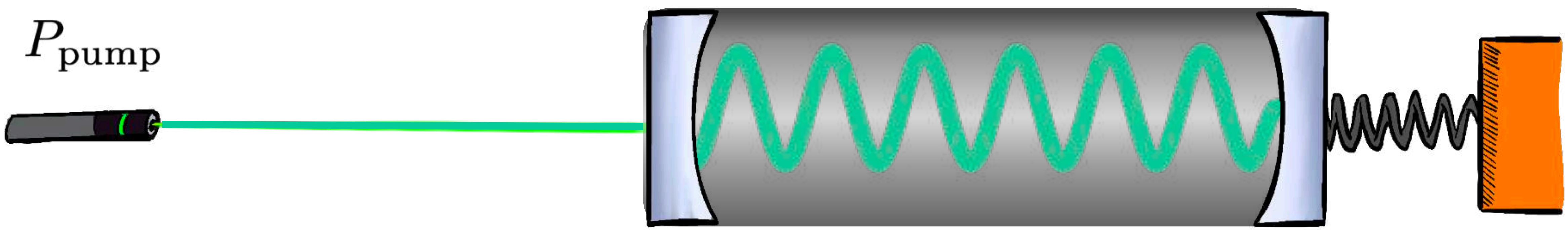


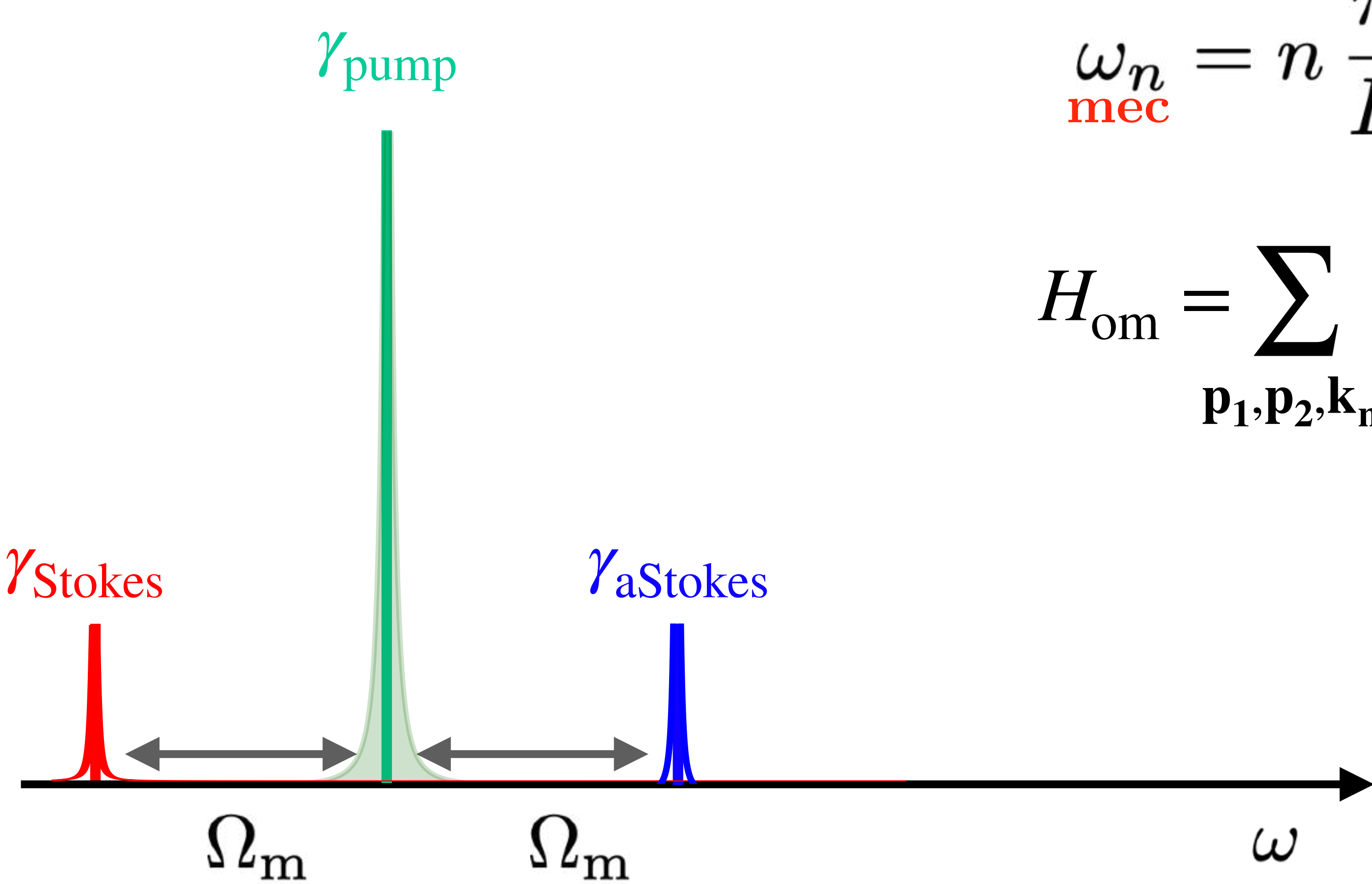
and/or



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

P_pump

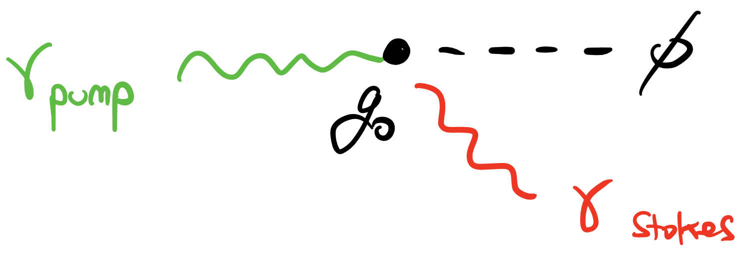




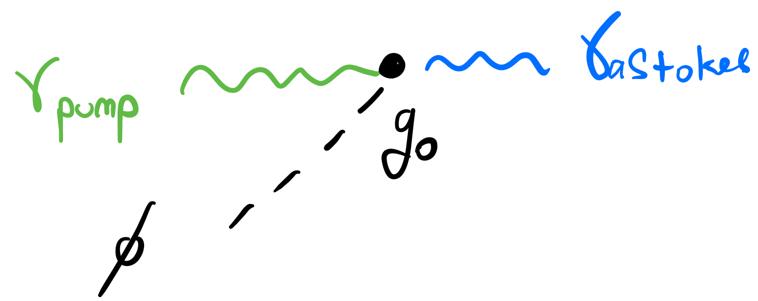
$$\underset{\mathbf{mec}}{\omega_n} = n\frac{\pi}{L}c_s, \quad n \subset \mathbb{Z}$$

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

Standard **Optomechanics**

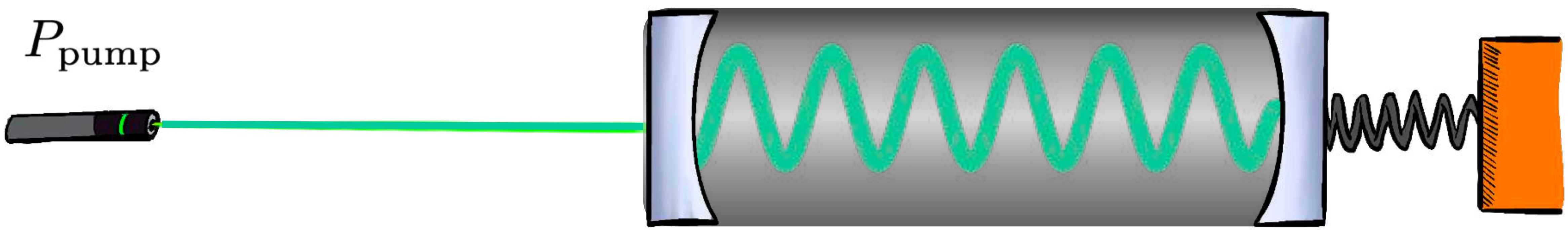


and/or



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

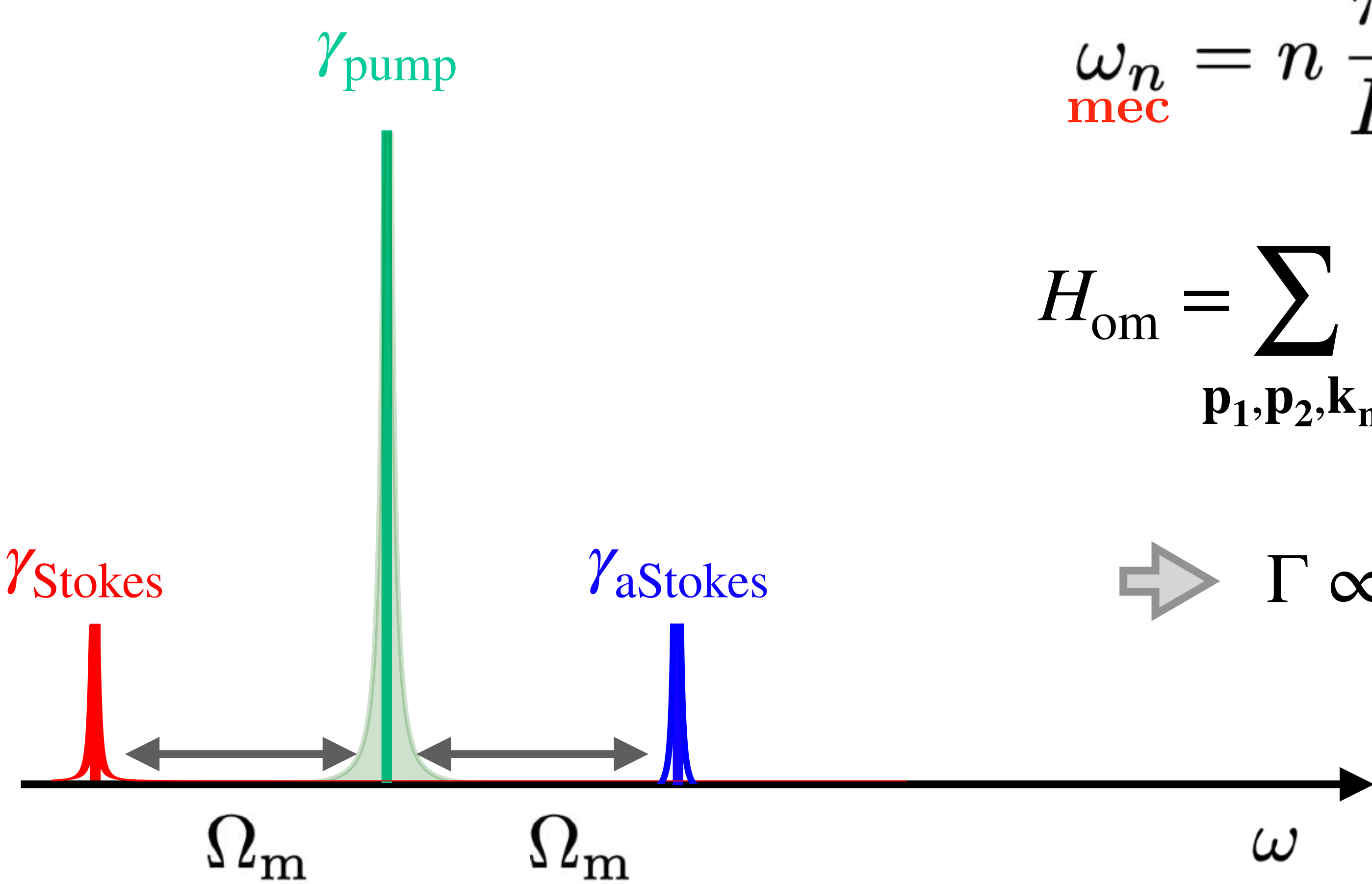
P_{pump}



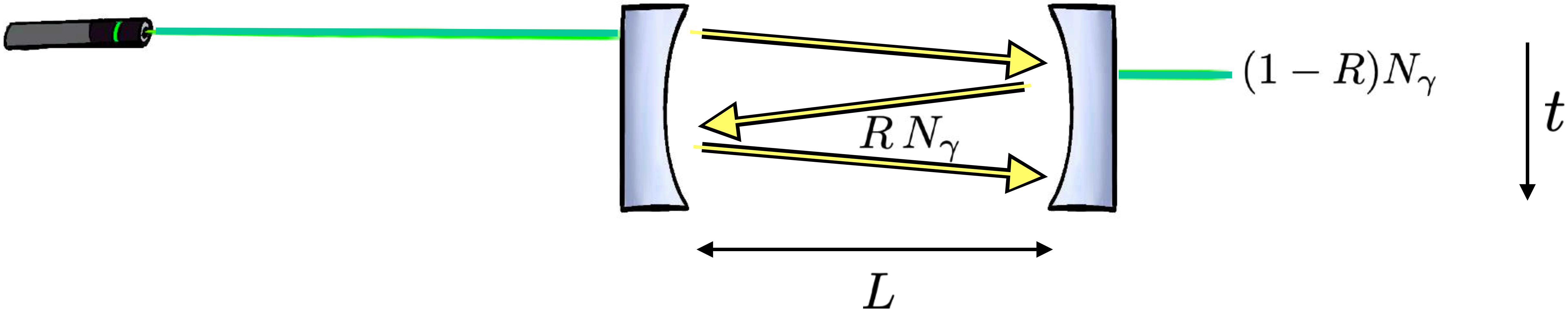
$$\omega_{n,\,\mathbf{mec}} = n\frac{\pi}{L}c_s, \quad n \subset \mathbb{Z}$$

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

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

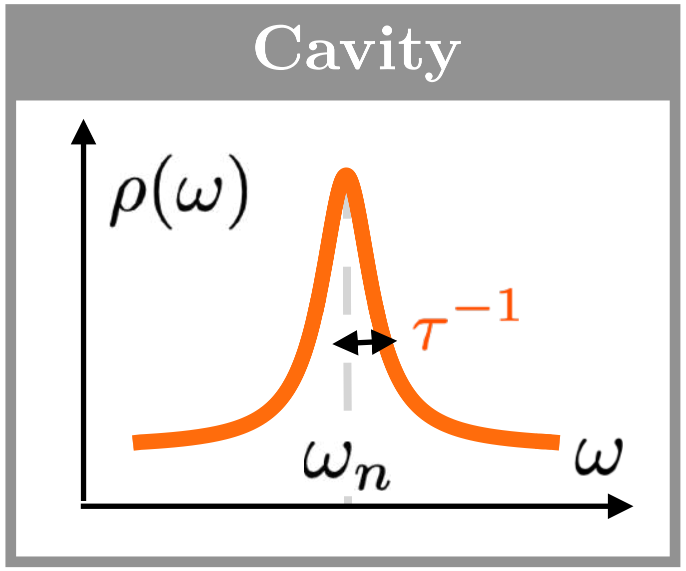


Standard **Optomechanics**



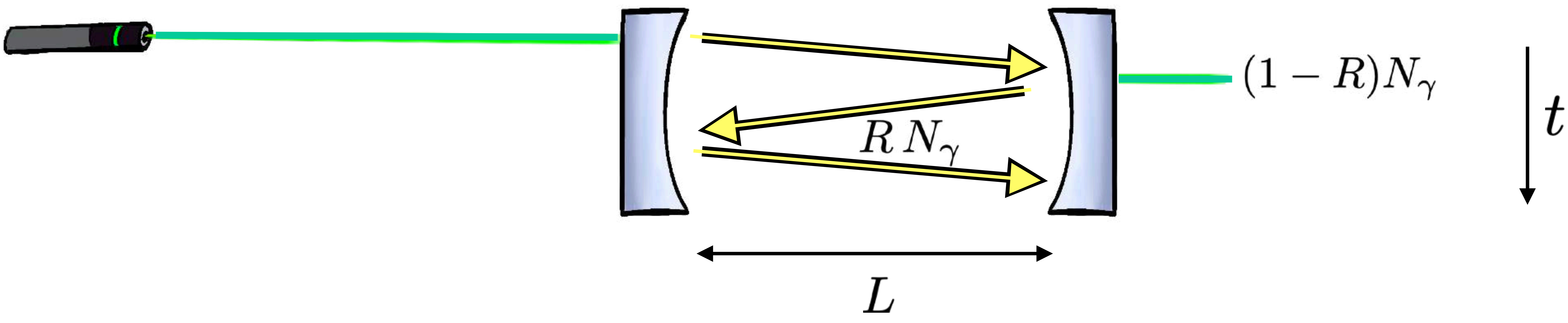
$$\frac{dN_\gamma}{dt} \simeq \frac{\Delta N_\gamma}{L/c} = \frac{c(1-R)}{L} N_\gamma \quad \Rightarrow \quad \tau_\gamma^{-1} \equiv \kappa \simeq \frac{c}{(1-R)^{-1}L}$$

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



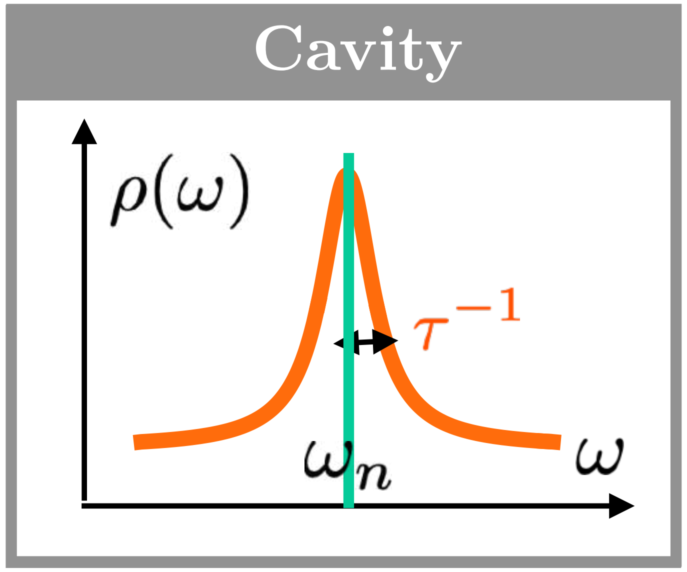
$$\rho(\omega) = \sum_i \delta(\omega - \omega_i) = \sum_n \frac{1}{2\pi} \int dt\, e^{i(\omega-\omega_n)t} e^{-t/(2\tau)} = \sum_n \frac{\tau^{-1}/2}{(\omega-\omega_n)^2 + (\tau^{-1}/2)^2}$$

Standard **Optomechanics**



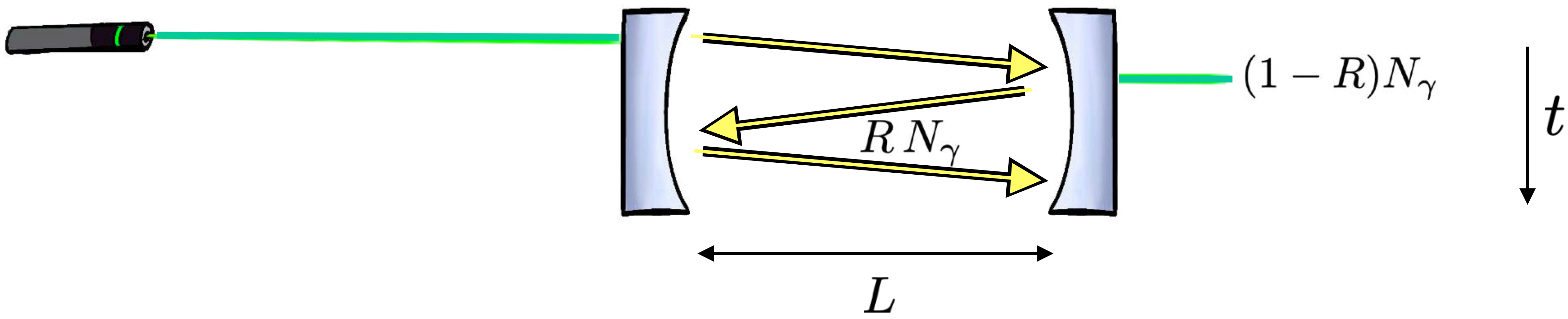
$$\frac{dN_\gamma}{dt} \simeq \frac{\Delta N_\gamma}{L/c} = \frac{c(1-R)}{L} N_\gamma \quad \Rightarrow \quad \tau_\gamma^{-1} \equiv \kappa \simeq \frac{c}{(1-R)^{-1}L}$$

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



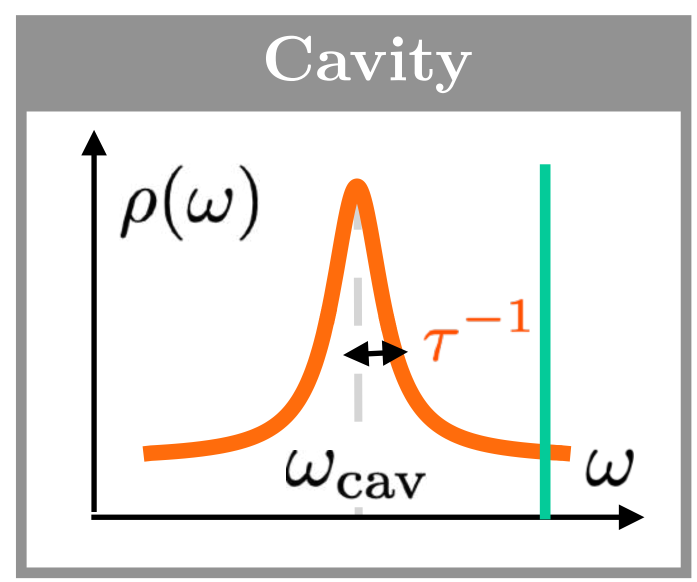
$$\rho(\omega) = \sum_i \delta(\omega-\omega_i) = \sum_n \frac{1}{2\pi}\int dt\, e^{i(\omega-\omega_n)t} e^{-t/(2\tau)} = \sum_n \frac{\tau^{-1}/2}{(\omega-\omega_n)^2 + (\tau^{-1}/2)^2}$$

Standard **Optomechanics**



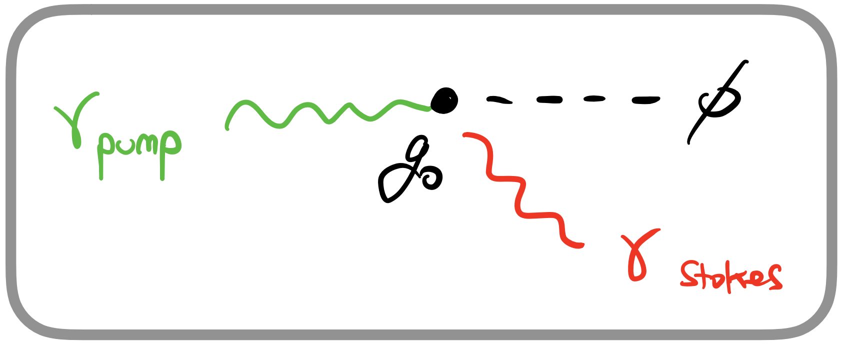
$$\frac{dN_\gamma}{dt} \simeq \frac{\Delta N_\gamma}{L/c} = \frac{c(1-R)}{L} N_\gamma \quad \Rightarrow \quad \tau_\gamma^{-1} \equiv \kappa \simeq \frac{c}{(1-R)^{-1}L}$$

$$N_{\gamma,L}^{\text{circ}} \sim \frac{4P_L\tau}{\omega_L}\frac{(\tau^{-1}/2)^2}{\Delta_L^2 + (\tau^{-1}/2)^2}$$

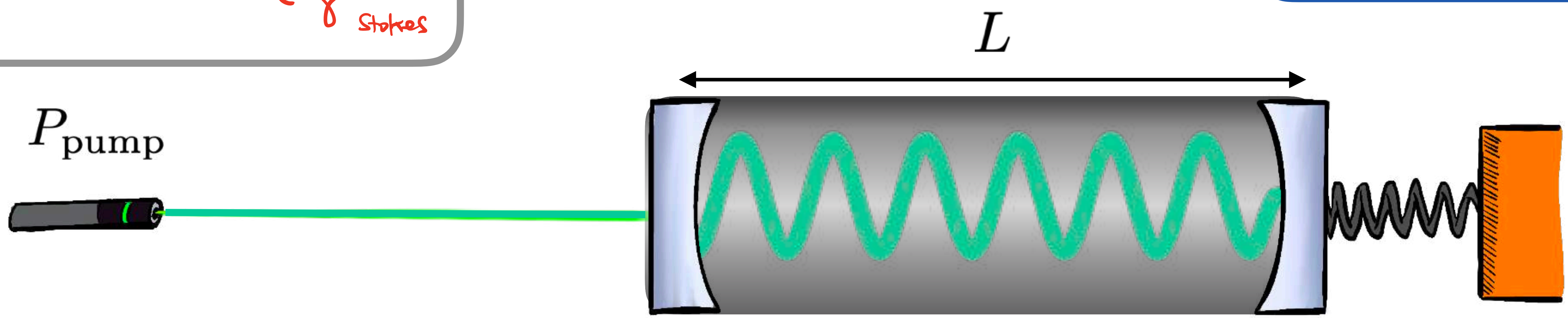


$$\rho(\omega) = \sum_i \delta(\omega - \omega_i) = \sum_n \frac{1}{2\pi}\int dt\, e^{i(\omega-\omega_n)t} e^{-t/(2\tau)} = \sum_n \frac{\tau^{-1}/2}{(\omega-\omega_n)^2 + (\tau^{-1}/2)^2}$$

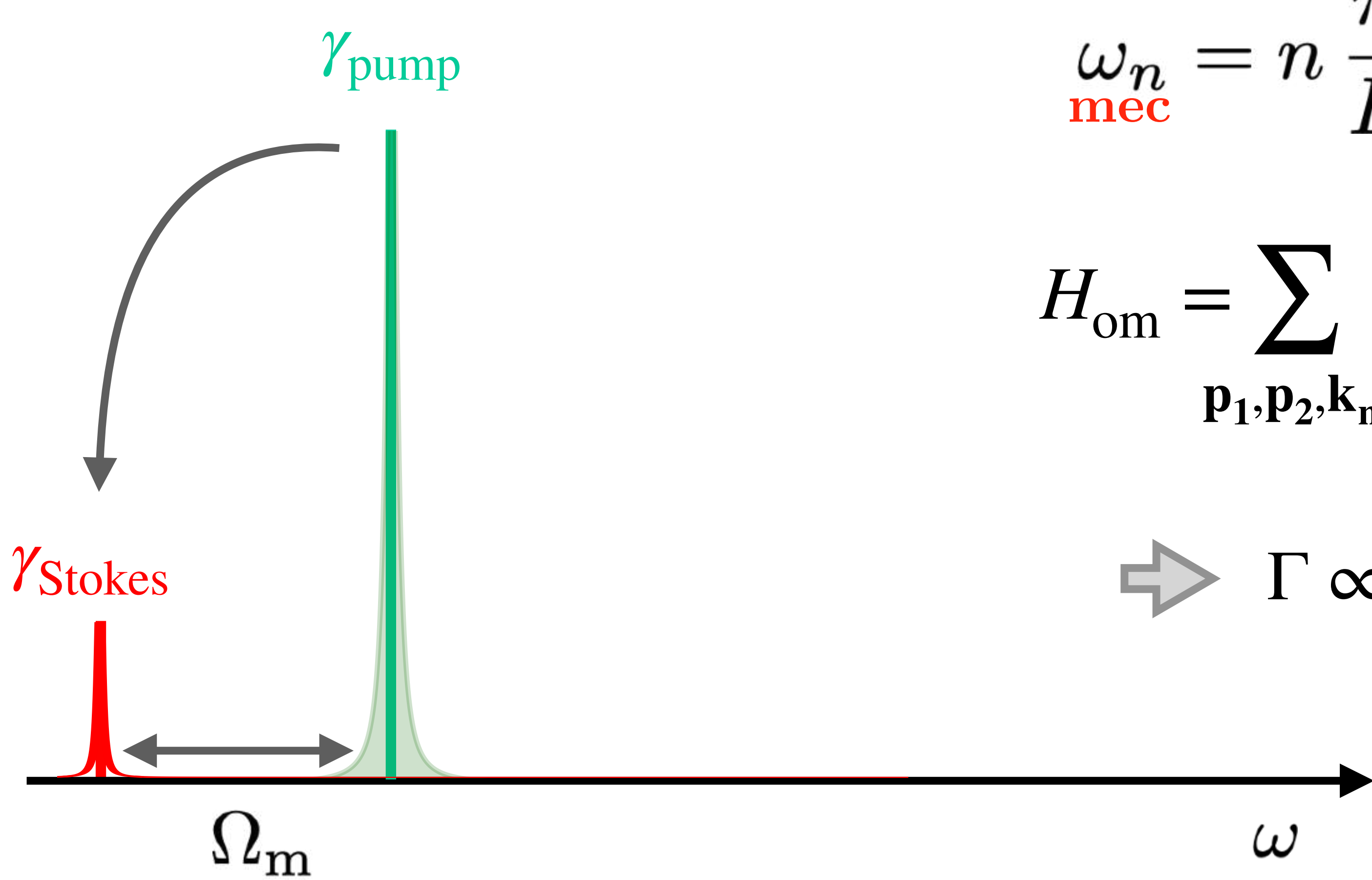
Standard **Optomechanics**



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



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



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

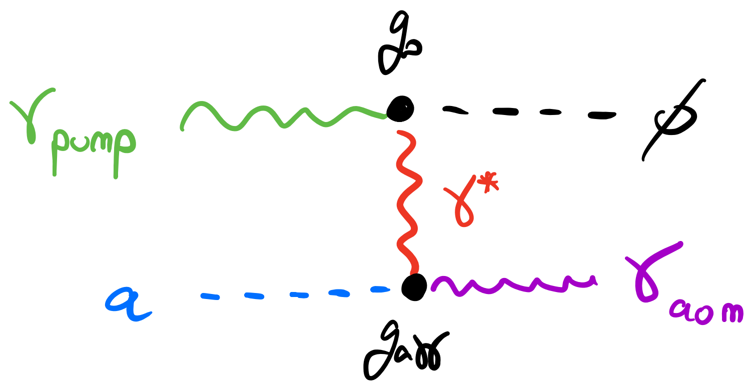
$$\Rightarrow \Gamma \propto |g_0|^2 N_{\gamma,\rm pump}$$

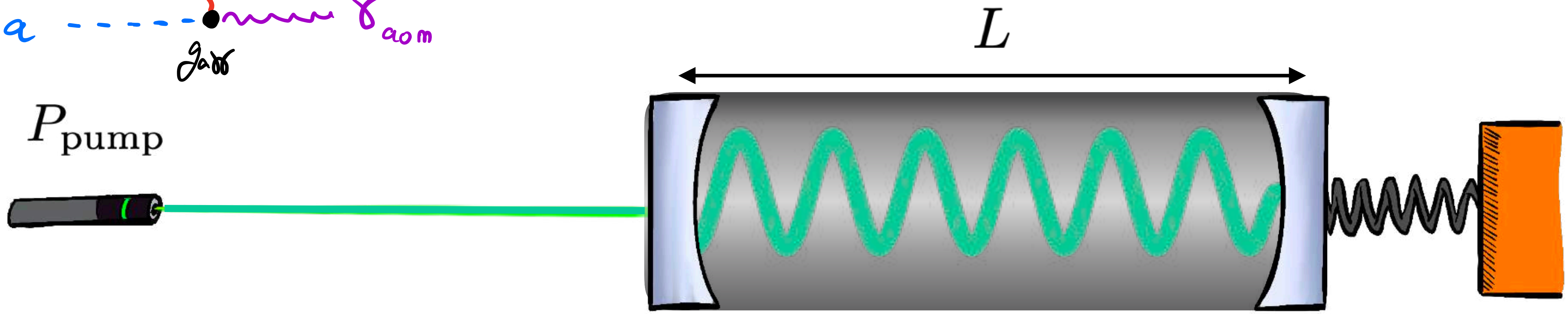
[Kashkanova et al., 2017]
[Reningner et al., 2017]

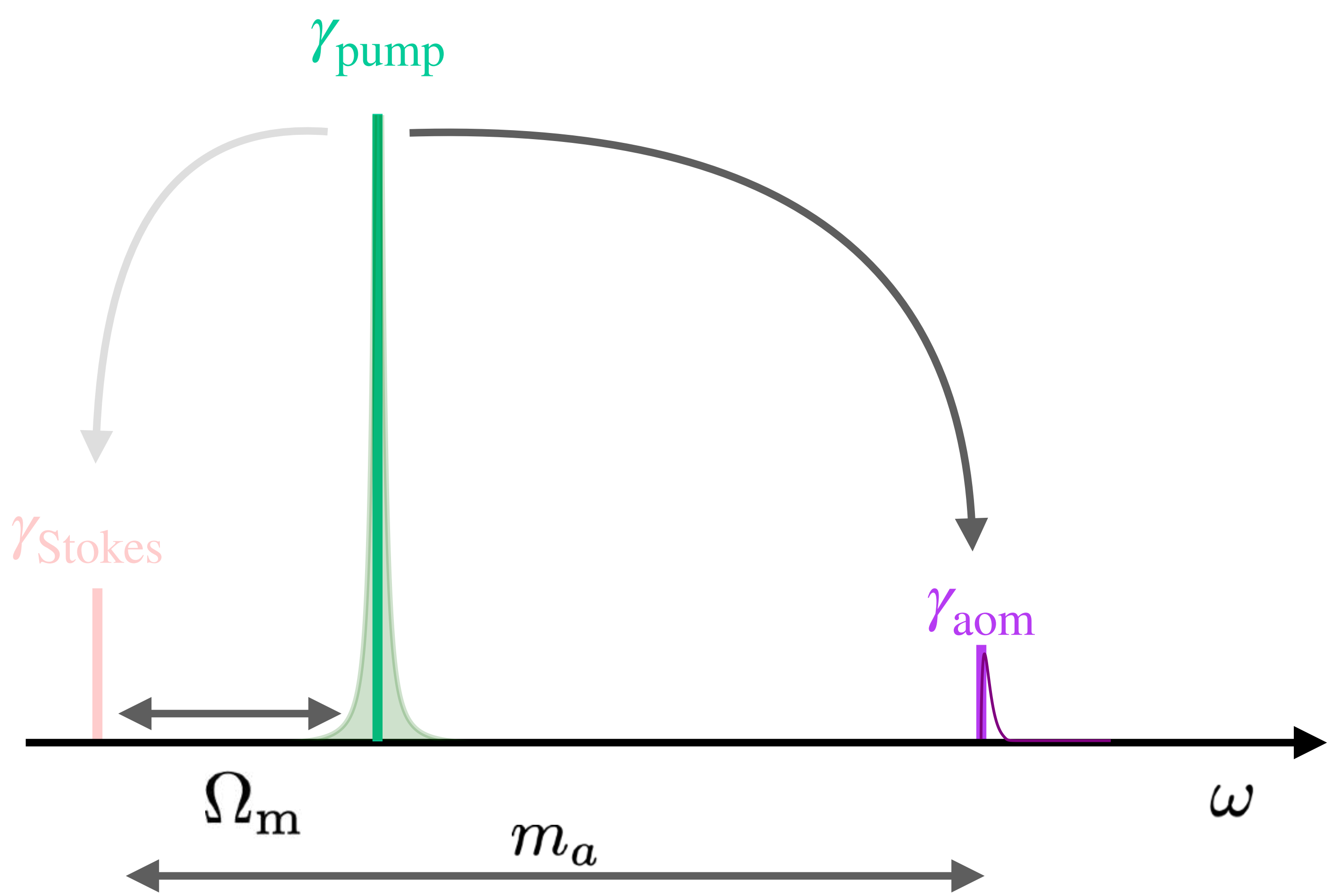
~~Standard~~ Axioptomechanics

[**CM**, Y. Wang, K. M. Zurek. 2022]

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



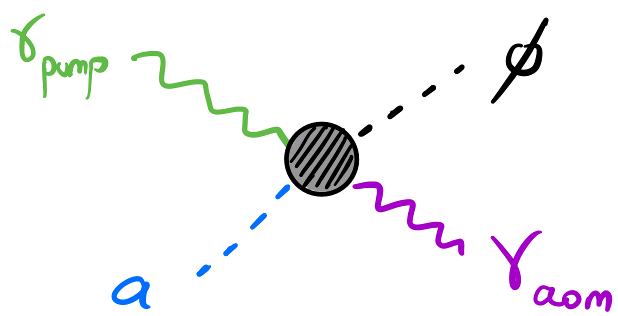


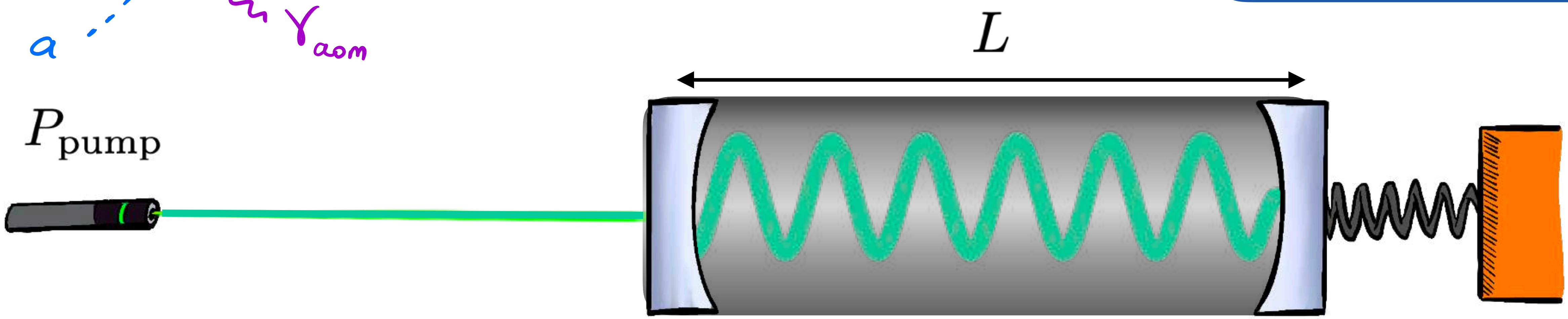


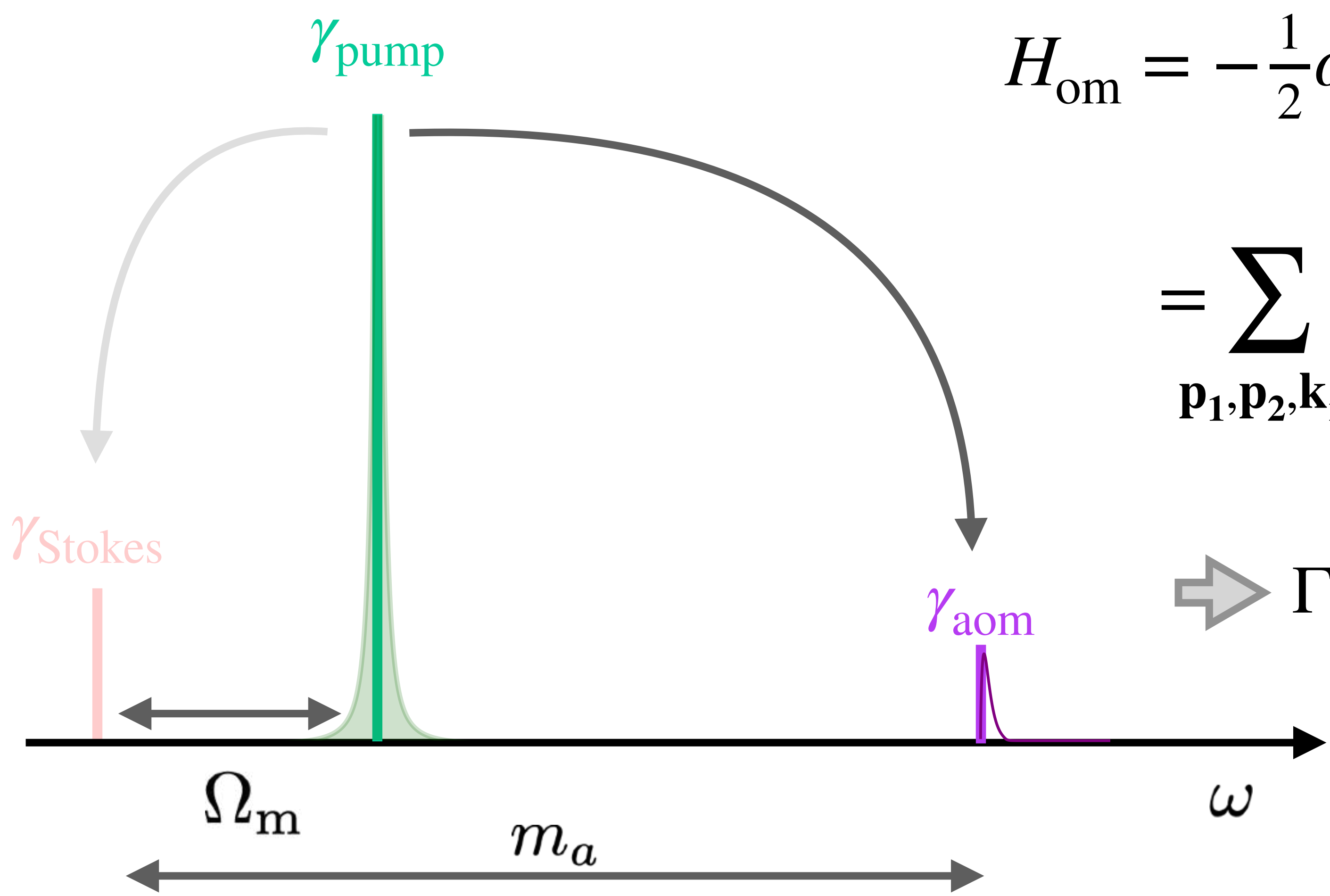
~~Standard~~ Axioptomechanics

[**CM**, Y. Wang, K. M. Zurek. 2022]

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







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

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

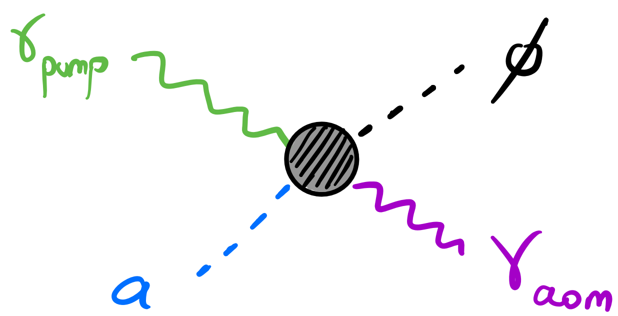
$\sim 10^{-22}$ for QCD axion

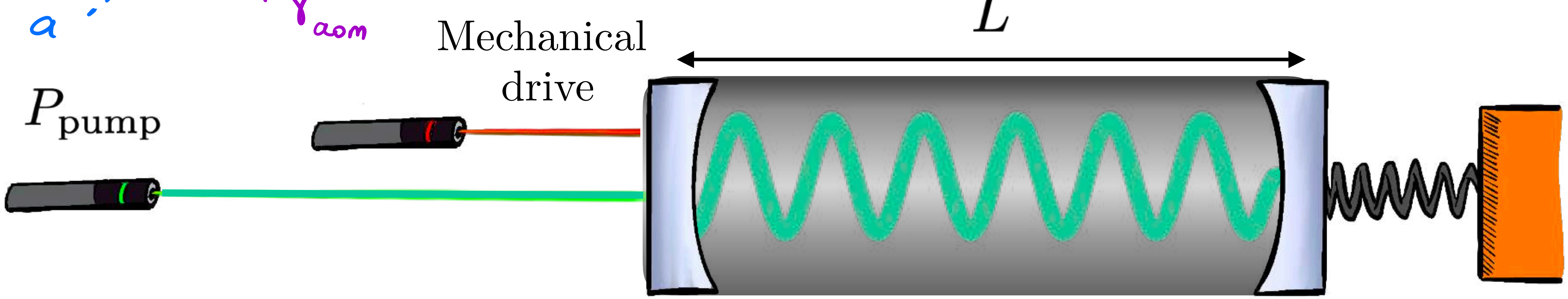
$$\Rightarrow \Gamma \propto |g_0^{(a)}|^2 \left(g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \right) \times N_{\gamma,\rm pump}$$

Coherent enhancement: Phonons

[**CM**, Y. Wang, K. M. Zurek. 2022]

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



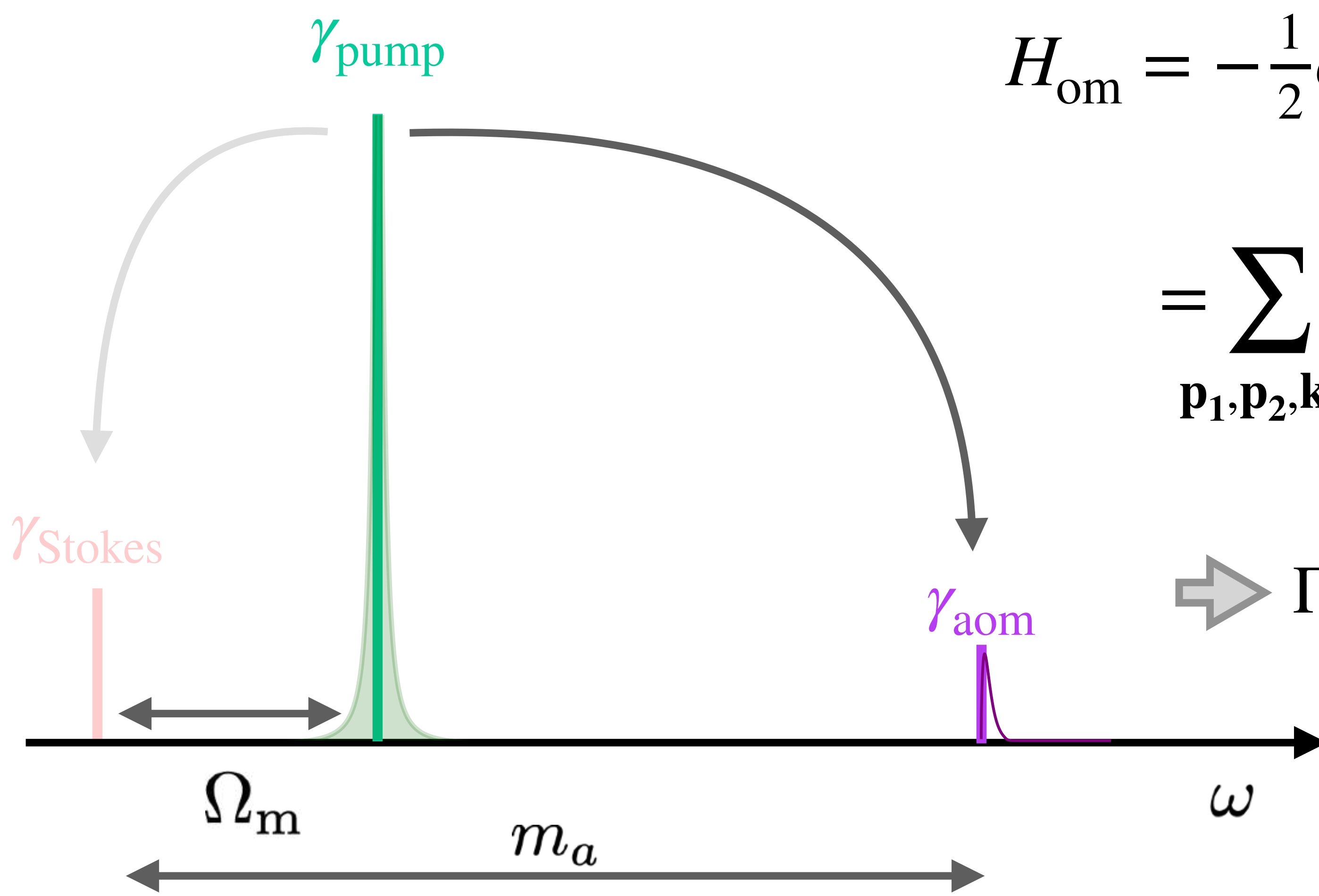


$$H_{\rm om} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma} \int d^3\mathbf{r}\, a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$$

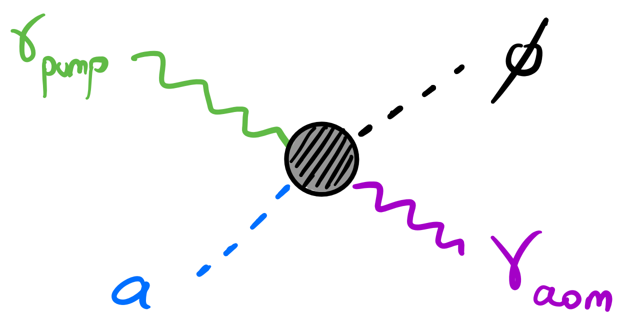
$$= \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0^{(a)} \left(g_{a\gamma\gamma} \frac{\sqrt{2\rho_a}}{m_a} \right) \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} \right)$$

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

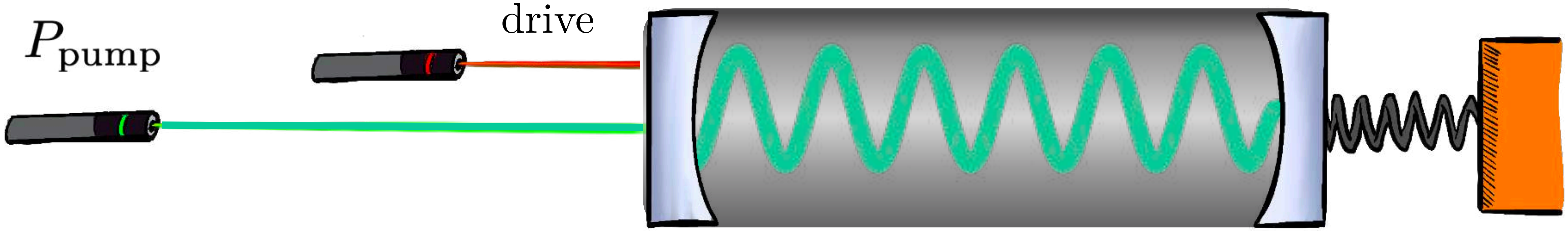
$$\Rightarrow \Gamma \propto |g_0^{(a)}|^2 \left(g^2_{a\gamma\gamma} \frac{\rho_a}{m_a^2} \right) \times N_{\gamma,\rm pump}\; N_\phi^{\rm circ}[\Delta_{\rm m}]$$



Axioptomechanics: Rates



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



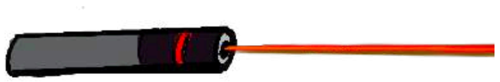
$$H_{\mathrm{om}} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma} \int d^3\mathbf{r}\, a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$$

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

Phonon populated

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

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



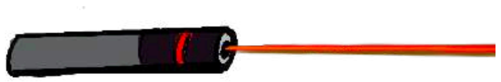
[**CM**, Y. Wang, K. M. Zurek. 2022]

Axioptomechanics: **Sensitivity**

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

Phonon populated

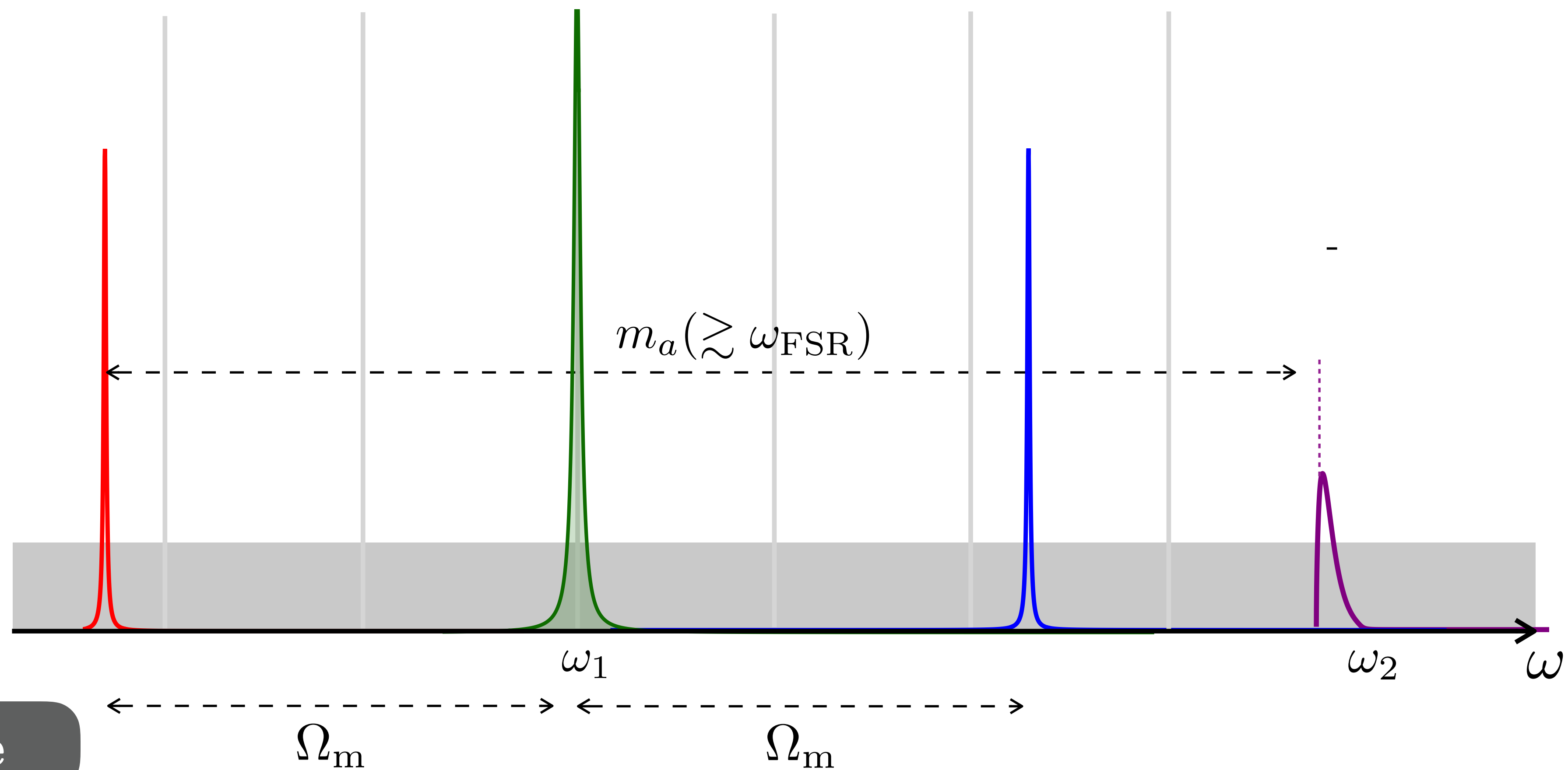
$$\Rightarrow \Gamma = (2\pi)\,|g_0^{(a)}|^2 \left(g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \right) \int d\omega_{\gamma_{\mathrm{aom}}} B_{m_a}(\omega_{\gamma_{\mathrm{aom}}} + \Omega_{\mathrm{m}} - \omega_{\mathrm{pump}}) L(\omega_{\gamma_{\mathrm{aom}}} - \omega_{\mathrm{res}}, \kappa)$$
$$\times\,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



[**CM**, Y. Wang, K. M. Zurek. 2022]

Axioptomechanics: **Sensitivity**

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



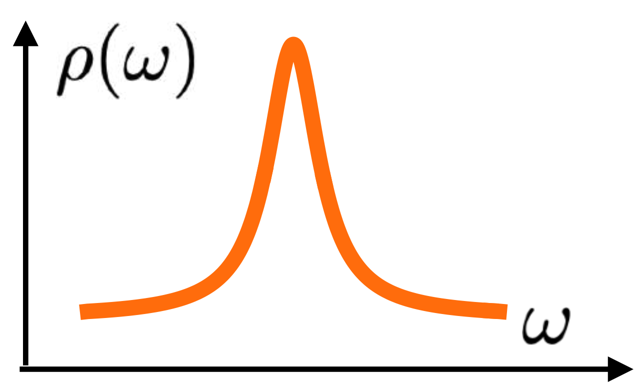
Sources of noise

Dark Count Rate

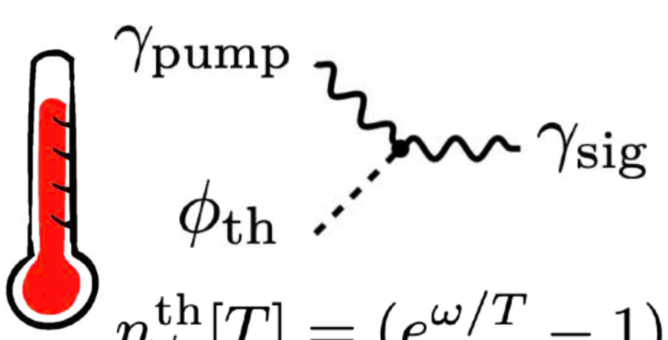
[irreducible noise]

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

Laser frequency noise



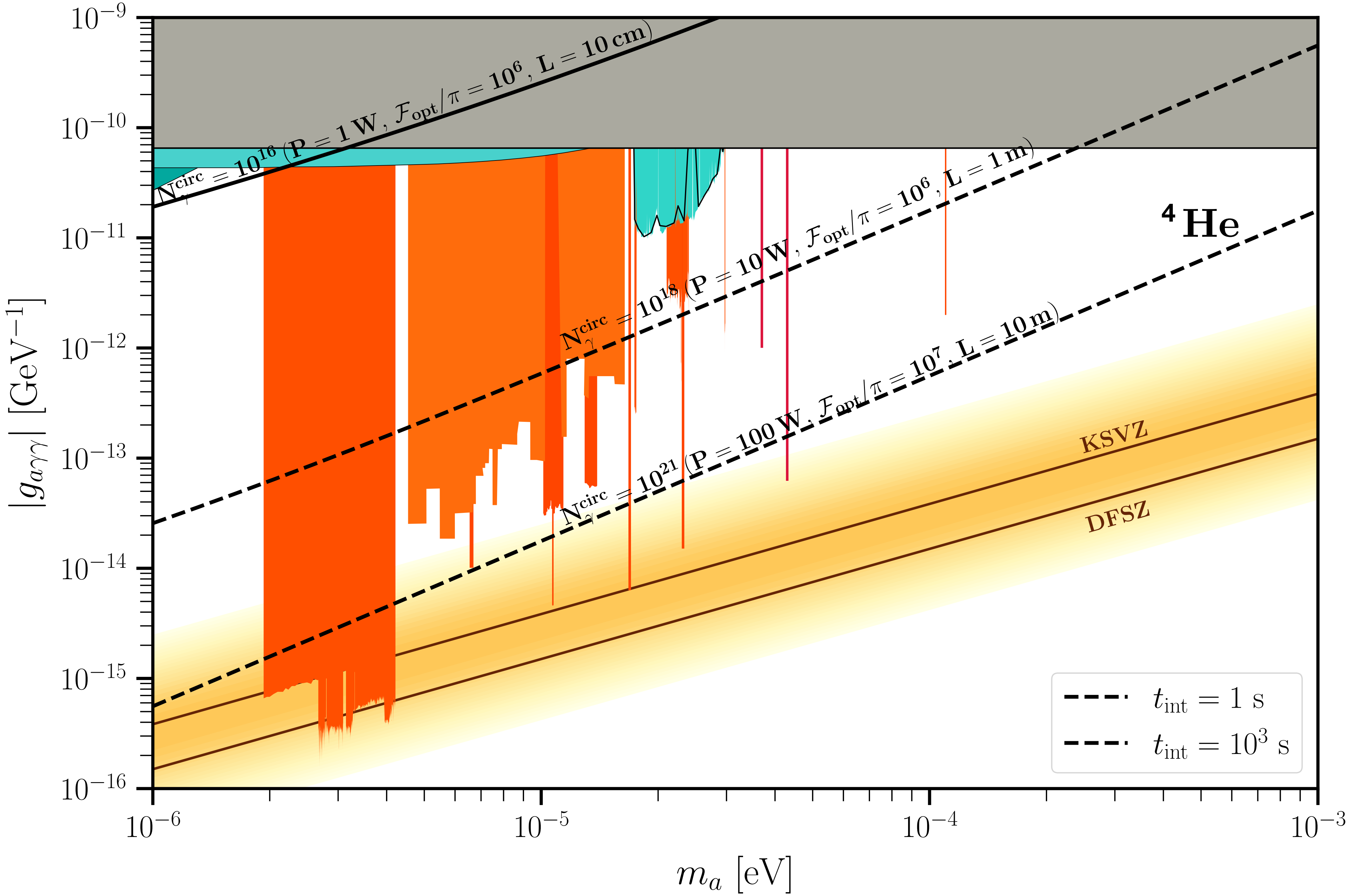
Thermal phonons



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

Curves: heavy axion regime

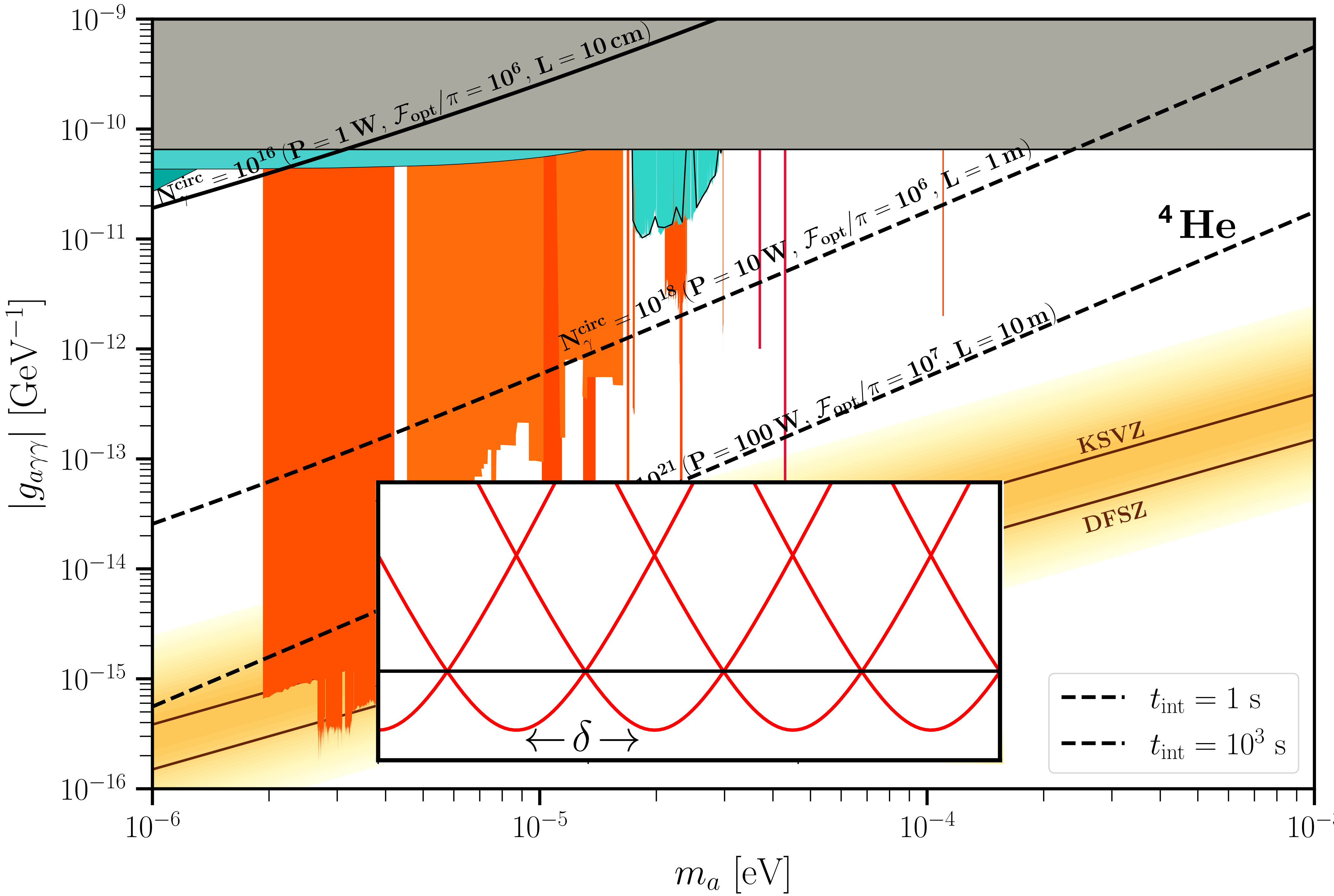
[**CM**, Y. Wang, K. M. Zurek. 2022]



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

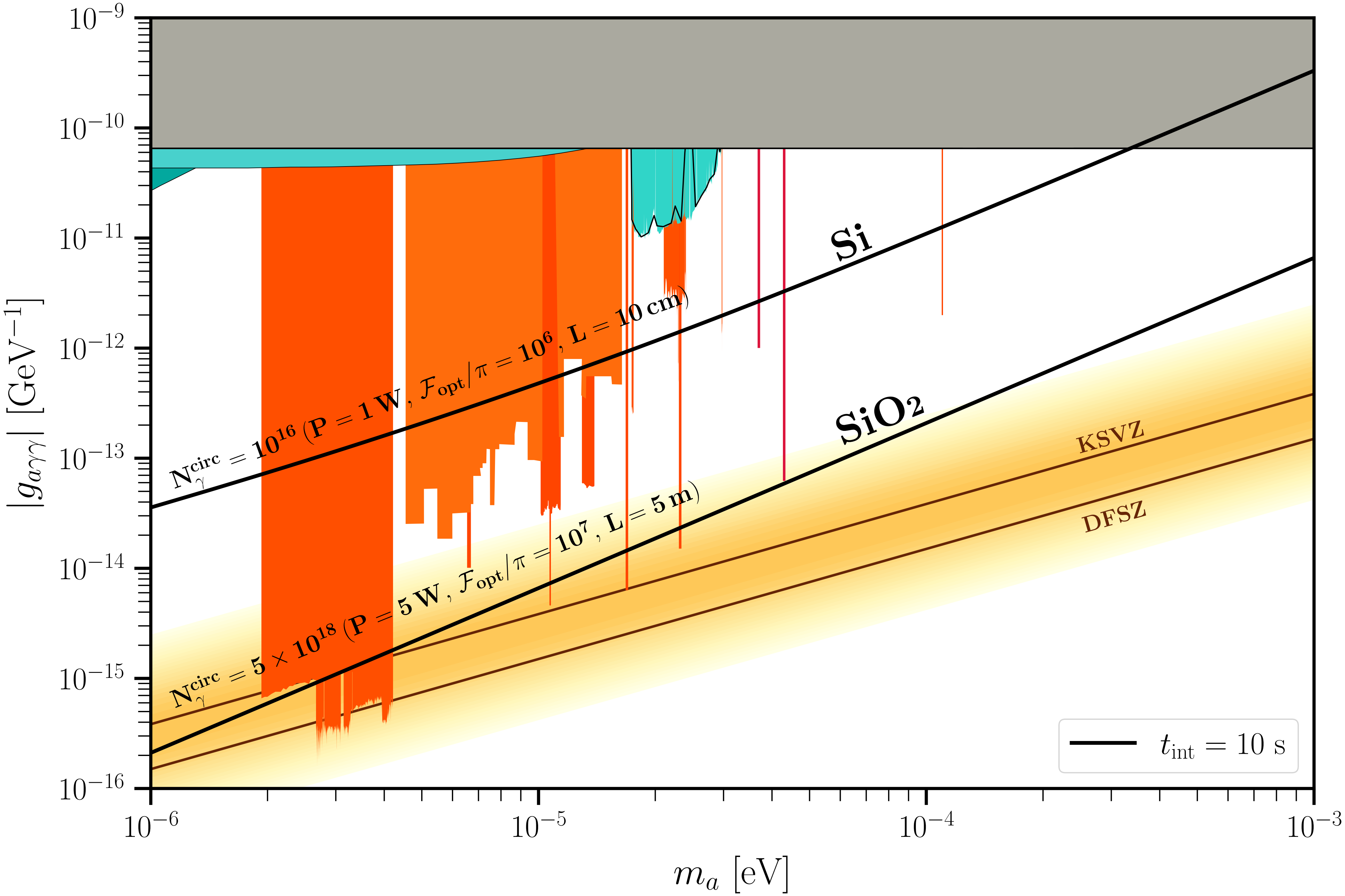
Curves: heavy axion regime

[**CM**, Y. Wang, K. M. Zurek. 2022]



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

Curves: heavy axion regime



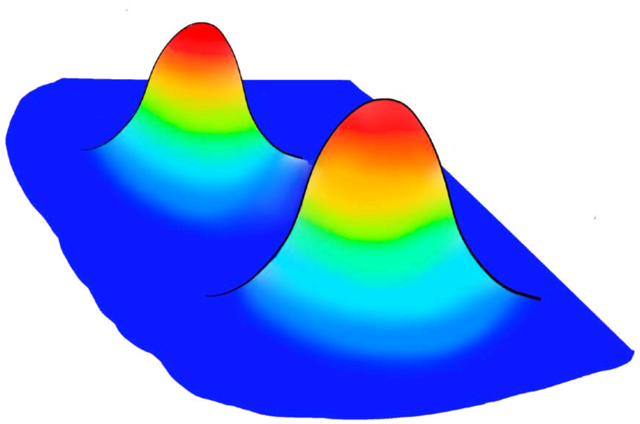
$$g_{a\gamma\gamma}^{\phi-\text{pop}} \propto \frac{\epsilon_r + 2}{\epsilon_r - 1}\epsilon_r^{1/2}\frac{1}{\mathcal{F}_{\text{opt}}^{1/2}}\frac{1}{L^{1/2}}\frac{1}{\omega_{\text{opt}}^{1/2}}\frac{1}{P_{\text{pump}}^{1/2}}\frac{m_a^{3/2}}{\rho_a^{1/2}}\Gamma_{\text{DCR}}^{1/2}$$

Conclusions

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

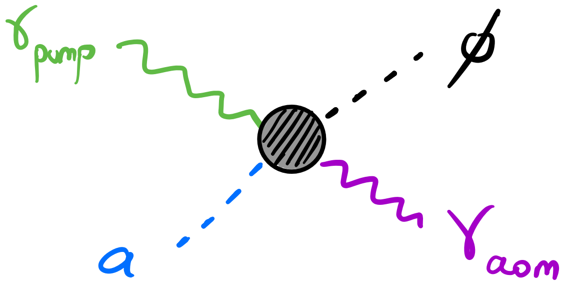
Atom Interferometers

- Already (or will) exist!
- No minimum energy deposition — decoherence
- Coherent enhancement



Axioptomechanics

- Decoupling length — axion mass: phonons!
- ~ background-free experiment
- Complementary to other axion searches



Thank you!