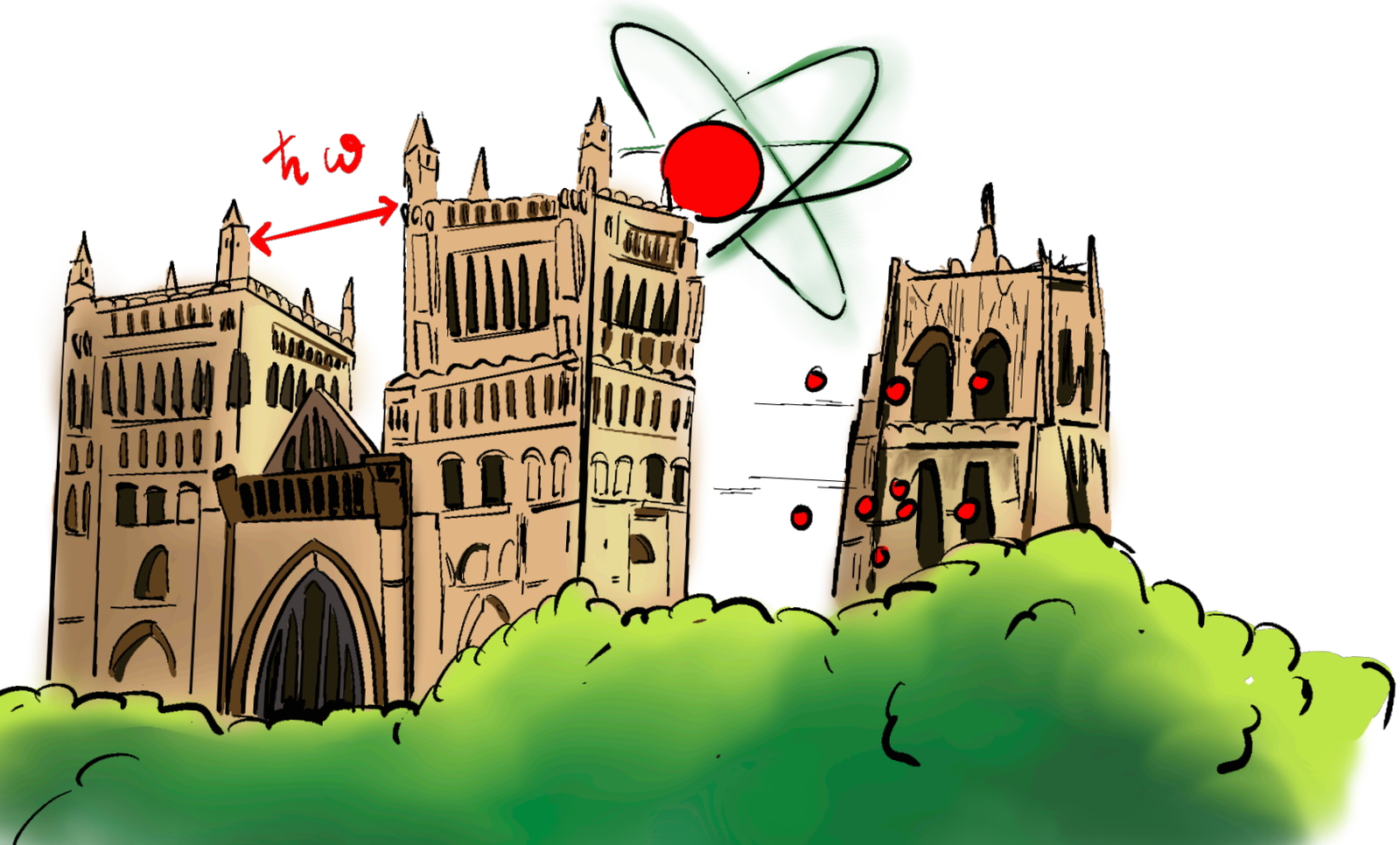
12th Desember 2023

Annual Theory Meeting

Durham

Quantum Sensing

Clara Murgui (UAB/IFAE)



AYUDA BEATRIZ GALINDO JUNIOR BG23

GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA E INNOVACIÓN

UAB Universitat Autònoma de Barcelona

IFAE Institut de Física d'Altes Energies

Quantum Sensing

"Use of a quantum system, quantum properties o quantum phenomena to perform a measurement of a physical quantity"

[Degen, Reinhard, Cappellaro, 2017]

Quantum Sensing: classification

"Use of a quantum system, quantum properties o quantum phenomena to perform a measurement of a physical quantity"

[Degen, Reinhard, Cappellaro, 2017]

1 Quantum object **2 Quantum coherence** **3 Quantum entanglement**

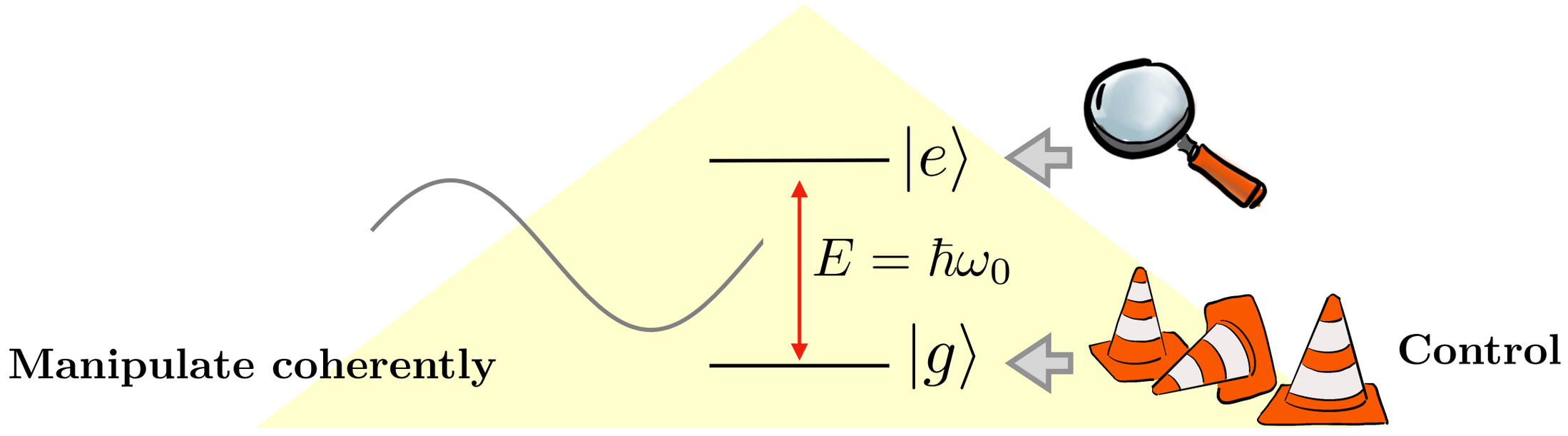
Quantum Sensing: requirements

"Use of a quantum system, quantum properties o quantum phenomena to perform a measurement of a physical quantity"

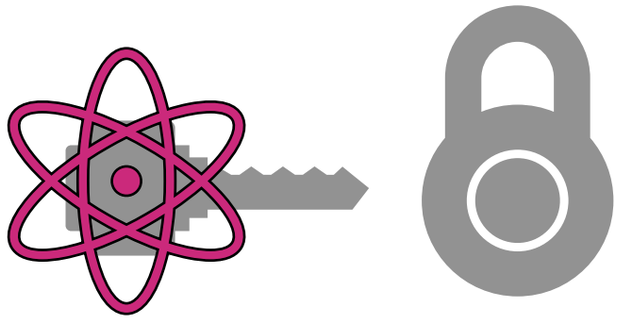
[Degen, Reinhard, Cappellaro, 2017]

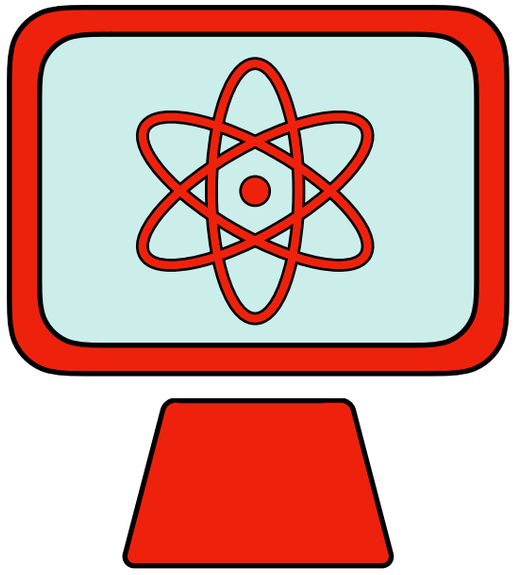
1 Quantum object **2 Quantum coherence** **3 Quantum entanglement**

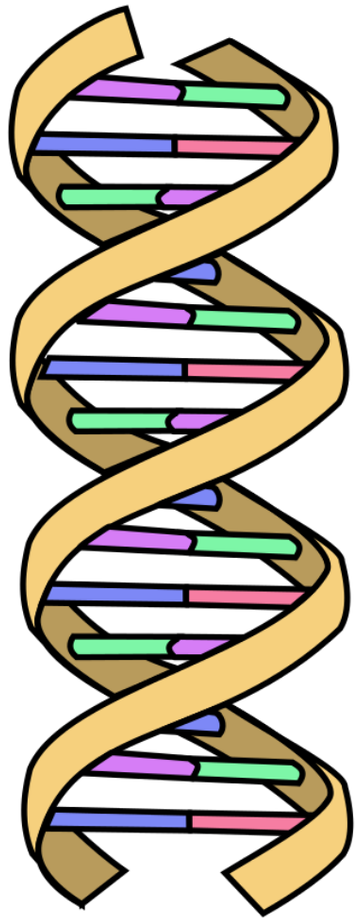
"Qubit"



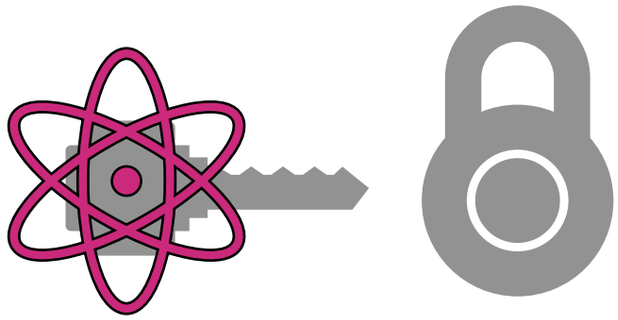
Quantum Sensing: applications

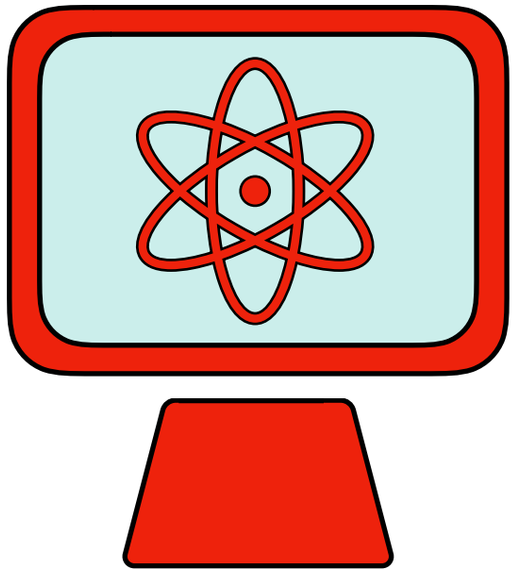


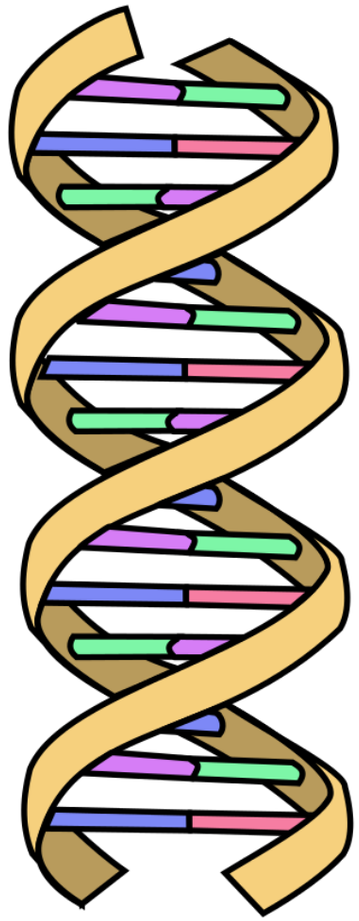




Quantum Sensing: applications

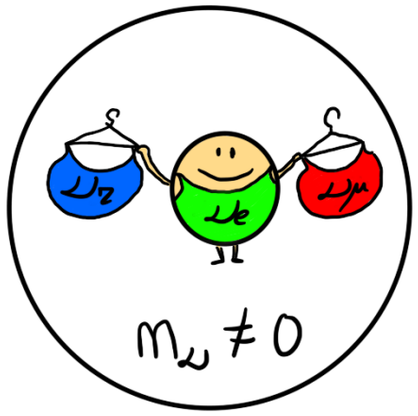


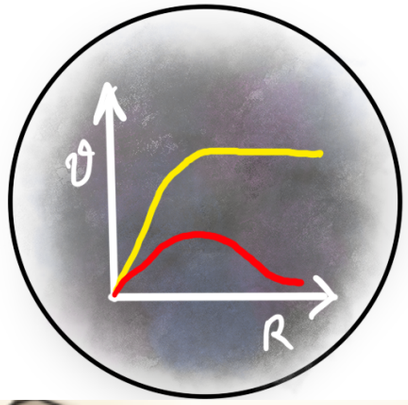




“Why a phenomenologist is given me this talk?”

The Need for New Physics





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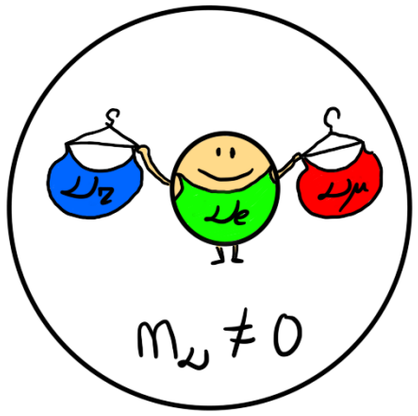

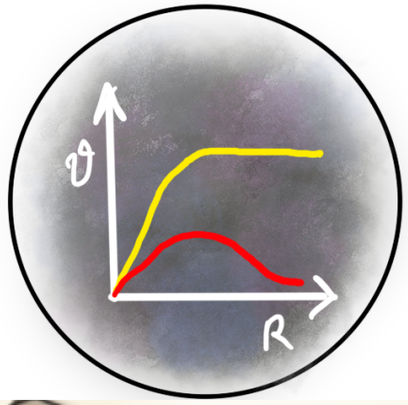

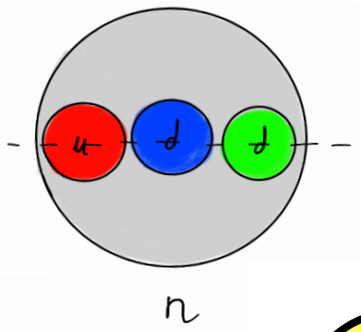

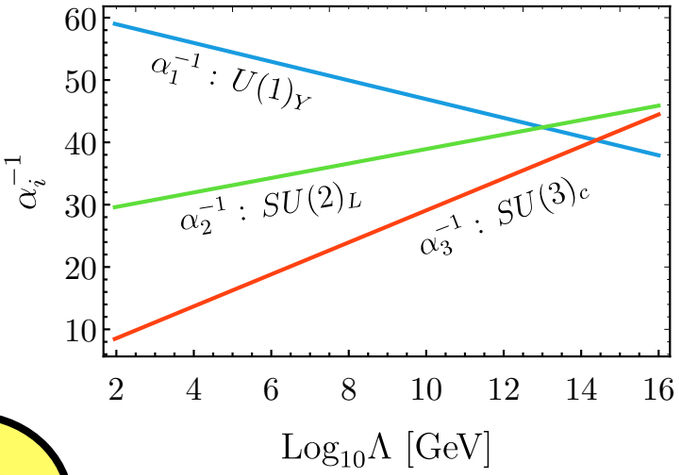

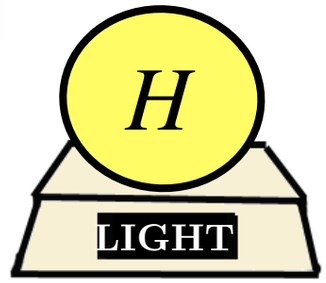

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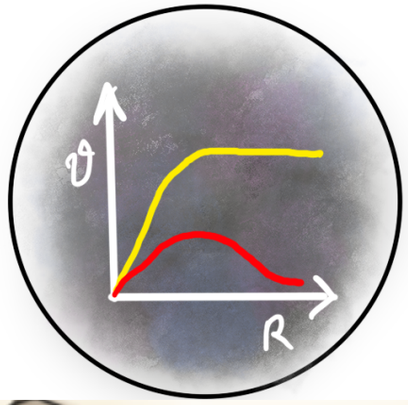
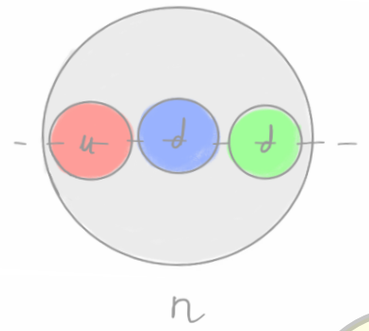
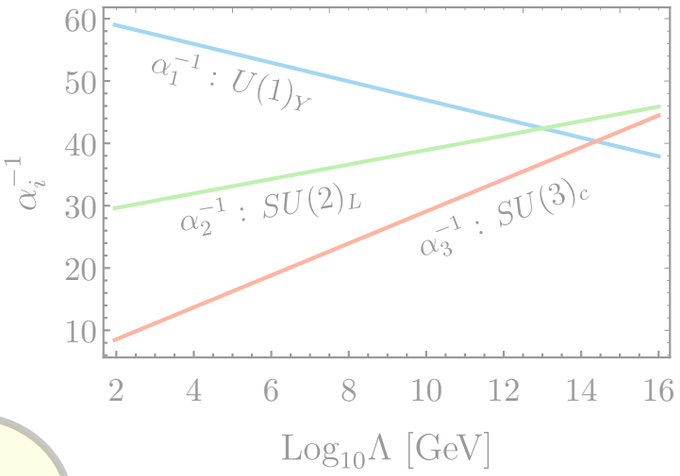
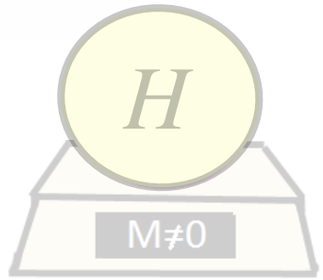
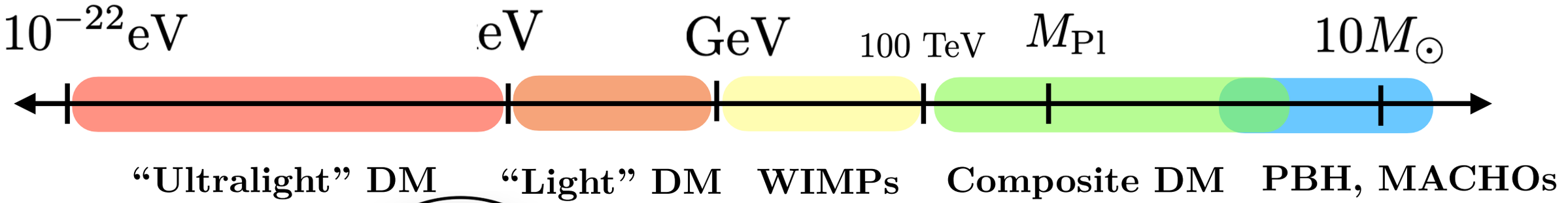


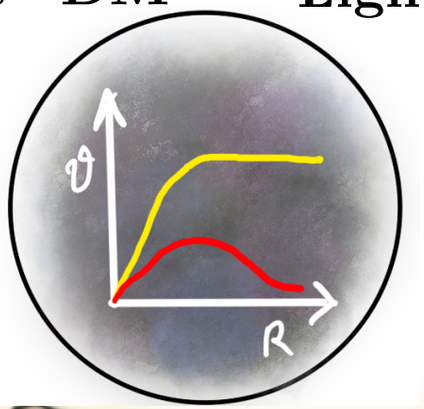


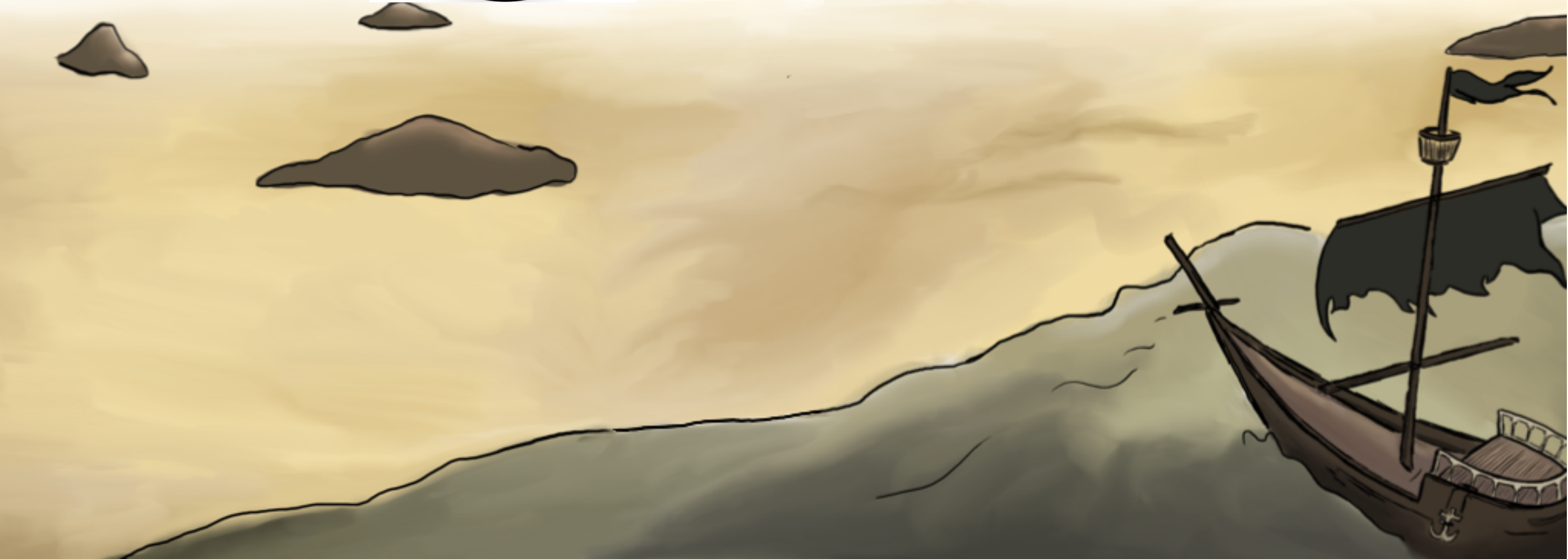




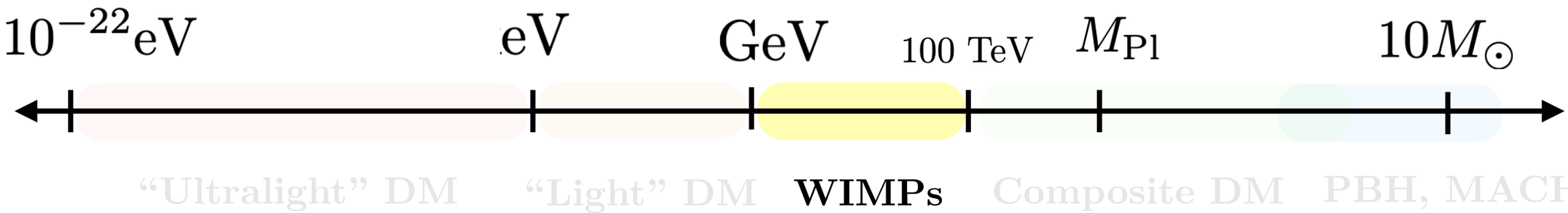
Beyond the SM: where to look?



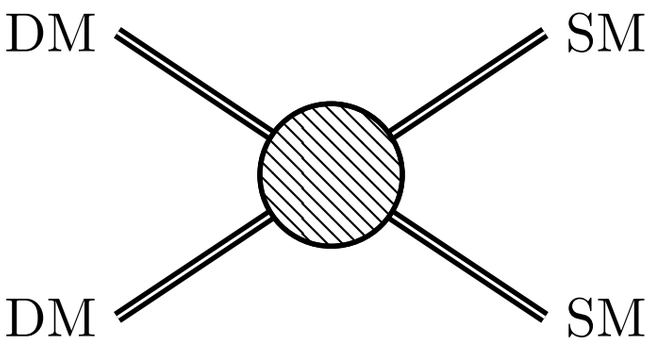




Dark Matter: where to look?



The WIMP miracle

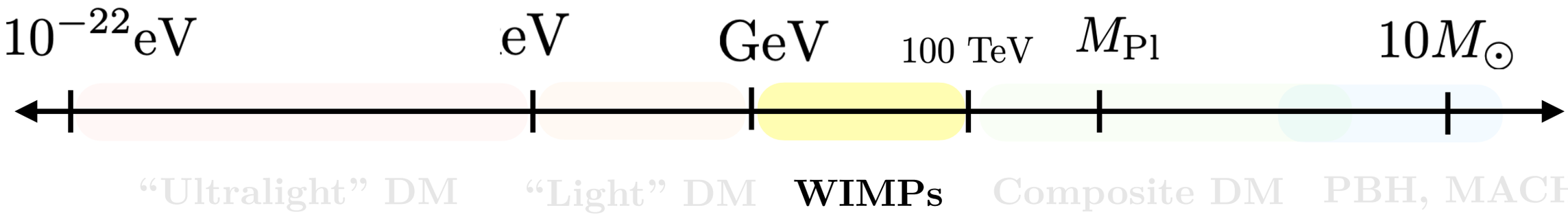


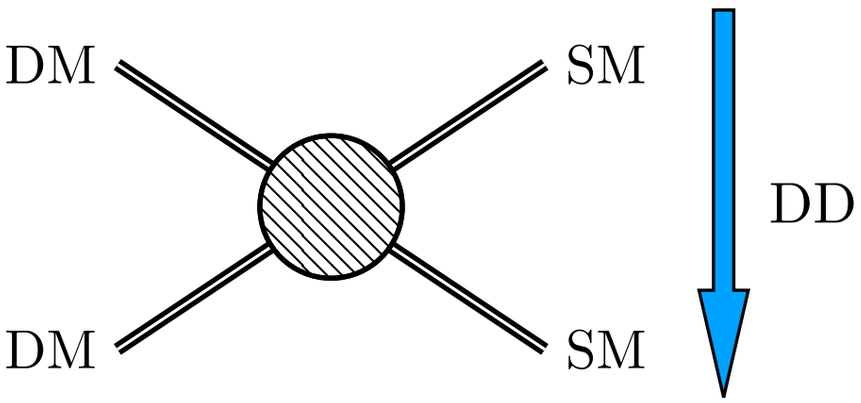
weak coupling

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

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

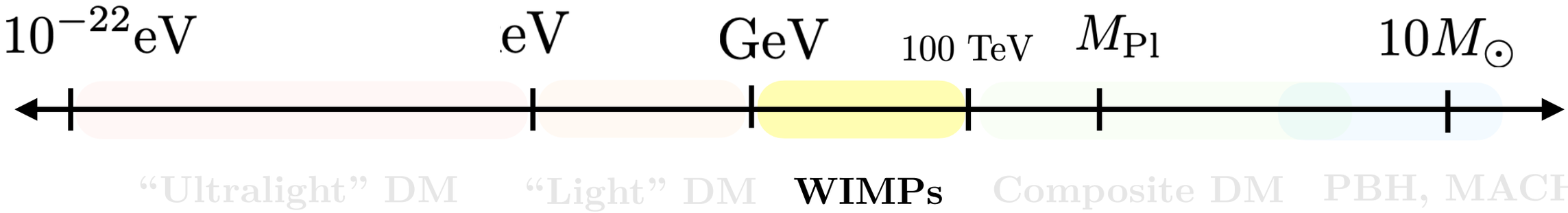
Dark Matter: where to look?

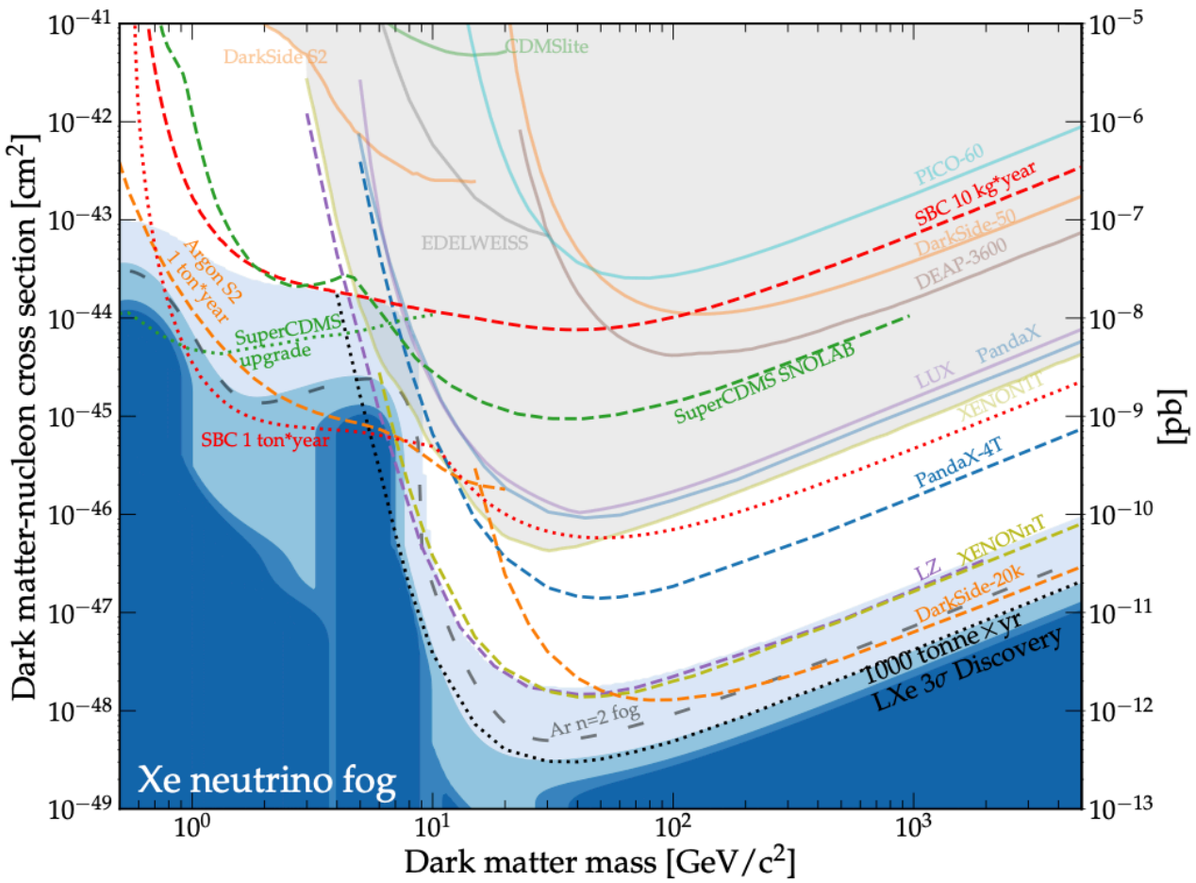




$$\sigma \sim 10^{-34}\text{cm}^2 \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2$$

Dark Matter: where to look?

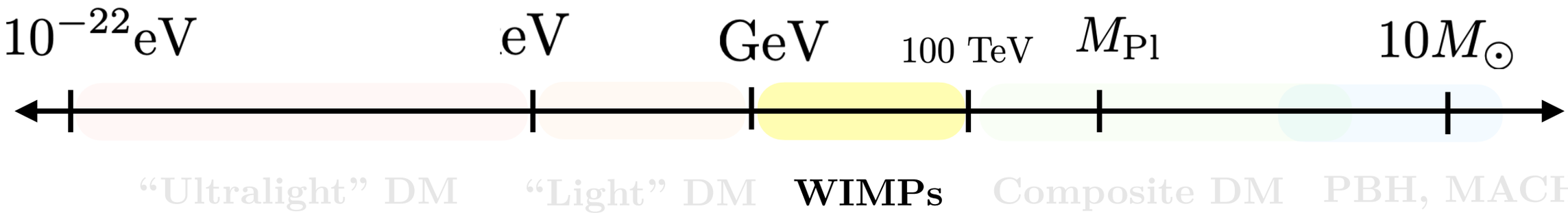




[Akerib, D. S., et al., Snowmass2021, 2203.08084]

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

Dark Matter: where to look?



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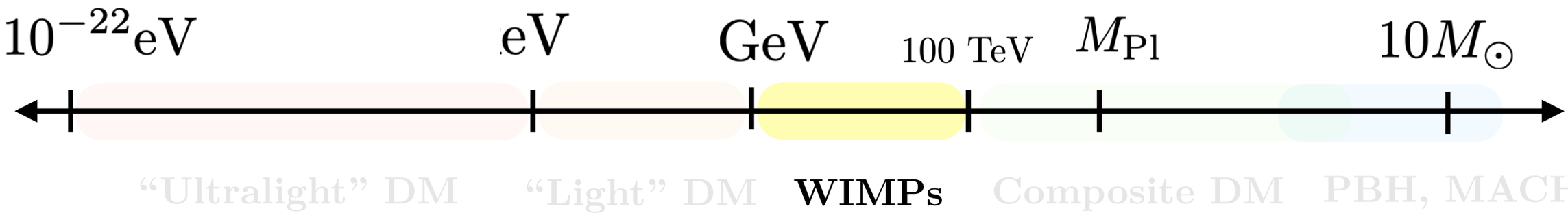
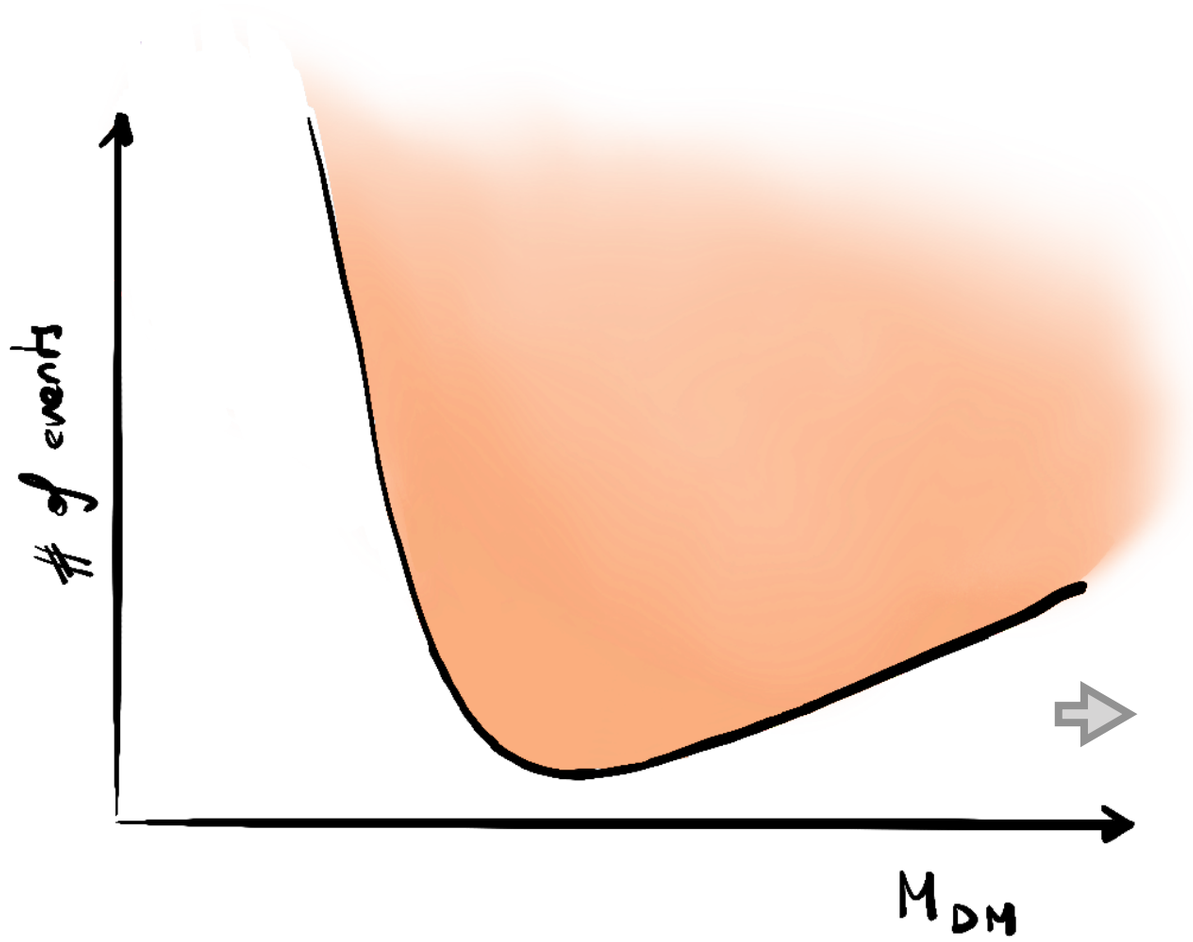
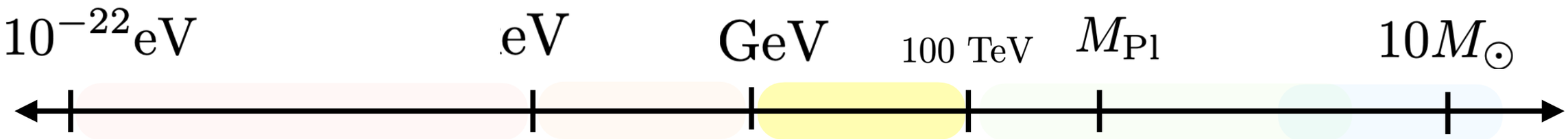


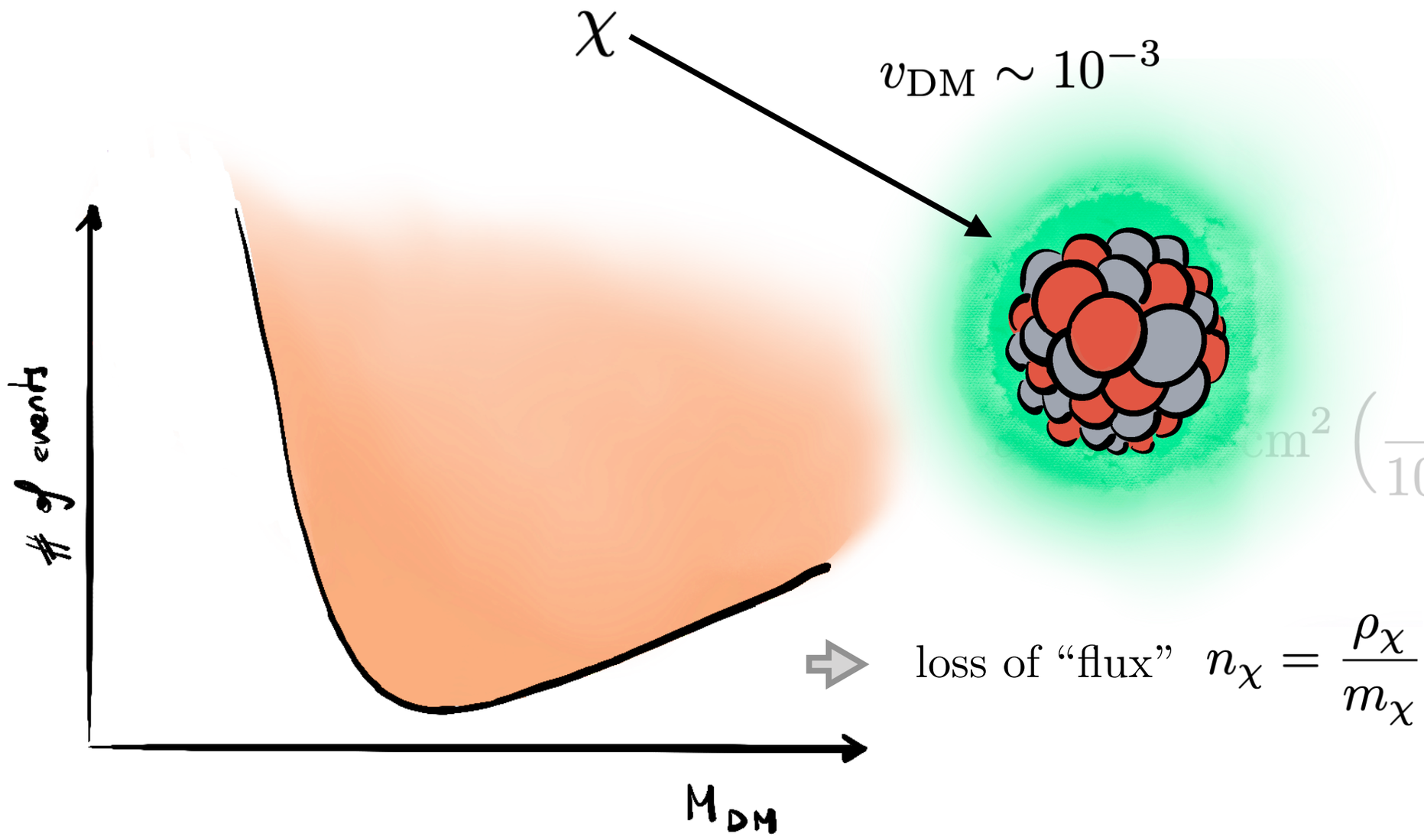


$$\sigma \sim 10^{-34}\text{cm}^2 \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2$$

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

Dark Matter: where to look?

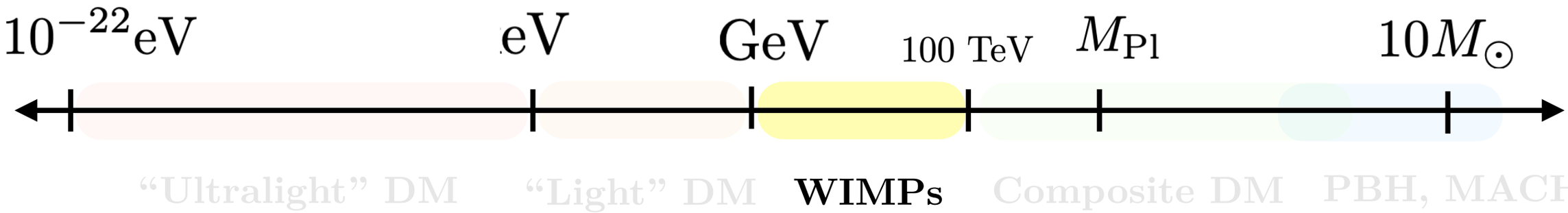




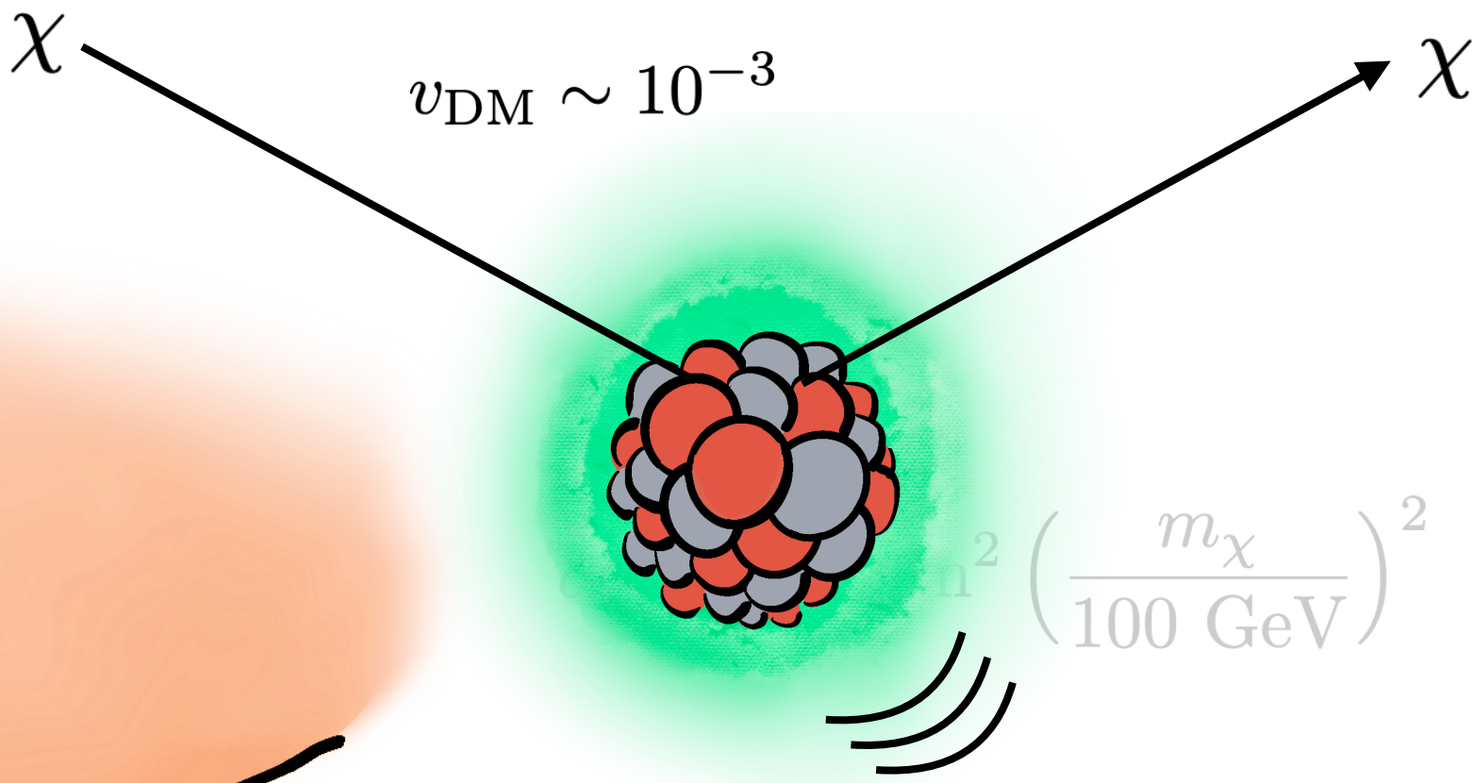
$$\sigma \sim 10^{-45}\,\text{cm}^2 \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2$$

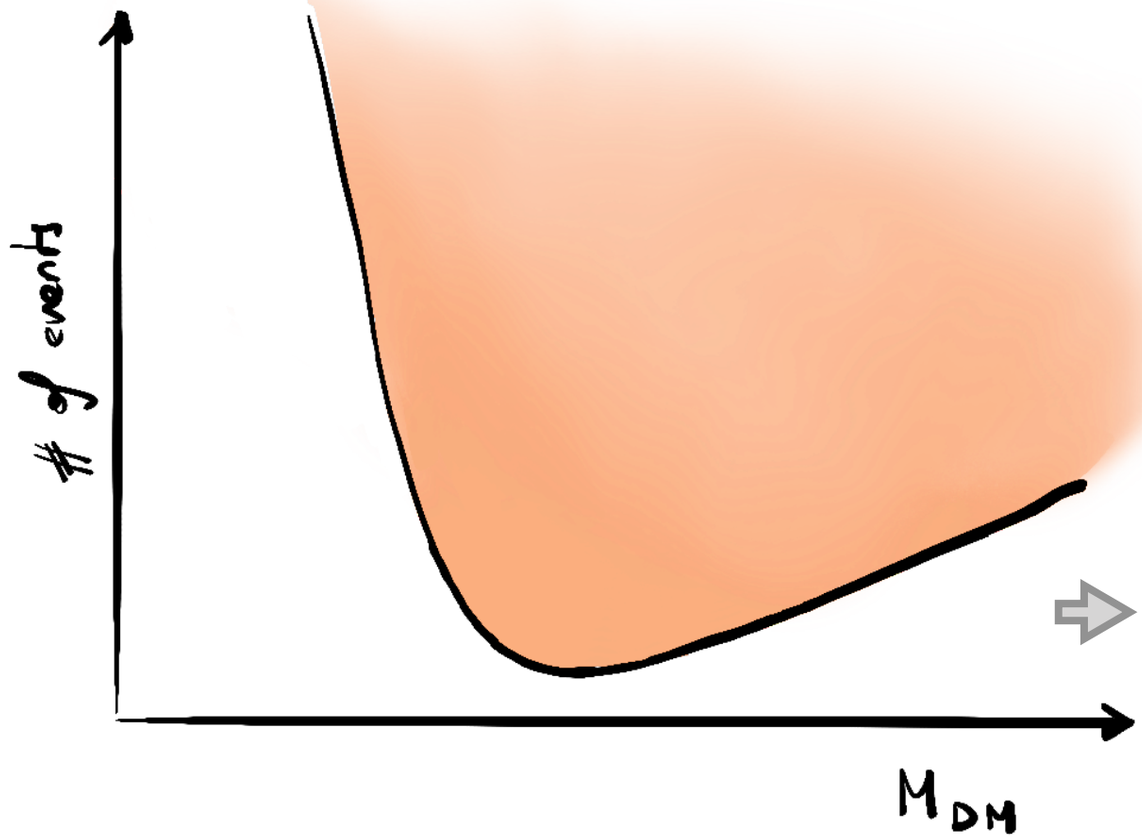
loss of "flux" $n_\chi = \dfrac{\rho_\chi}{m_\chi}$

Dark Matter: where to look?



$$E_{\rm recoil} = \frac{q^2}{2m_T}$$





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

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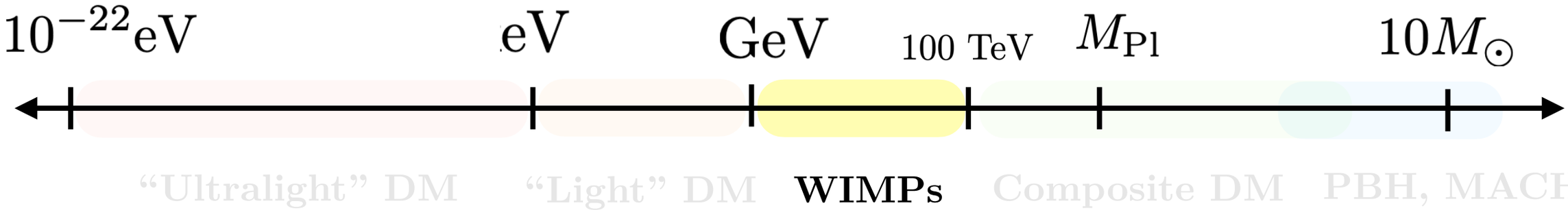
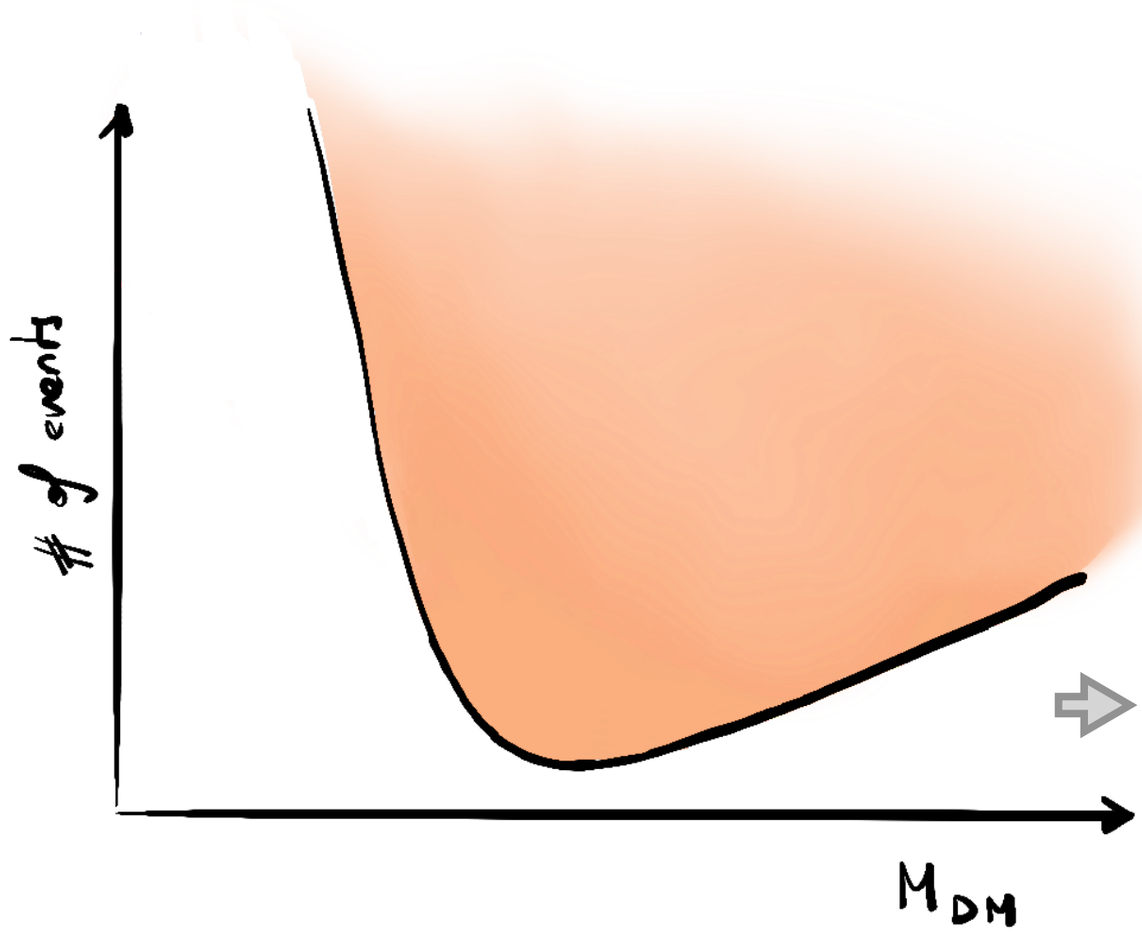


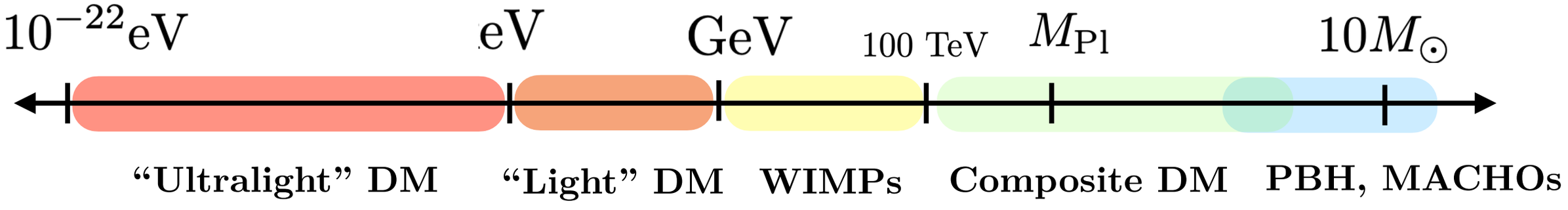
$$\Leftarrow \quad E^{\rm max}_{\rm recoil} \sim \left(\frac{m_\chi}{\rm GeV}\right) {\rm keV}$$

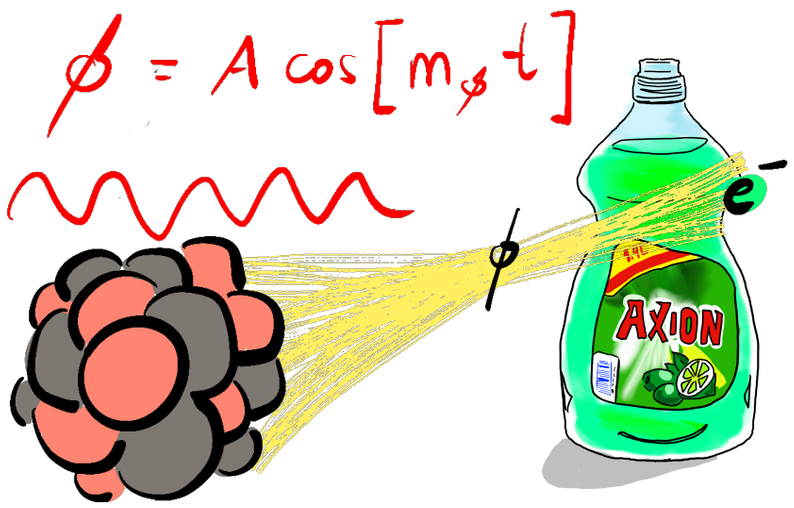


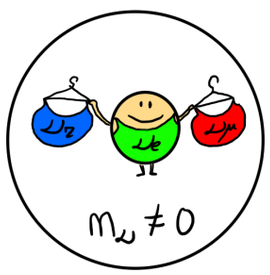
$$\sigma \sim 10^{-34}{\rm cm}^2 \left(\frac{m_\chi}{100\ {\rm GeV}}\right)^2$$

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

Beyond the SM: "how" to look?







Nuclear recoil exp.

Colliders

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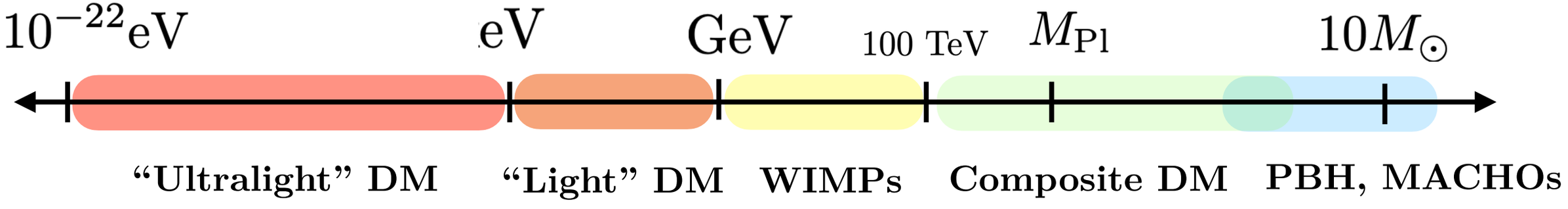

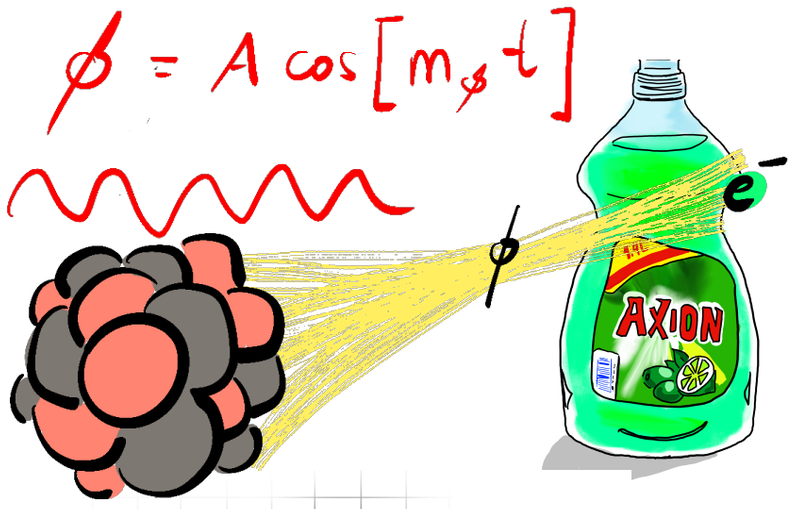

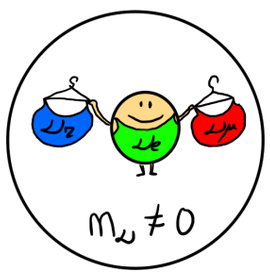

Nuclear recoil exp.

Colliders

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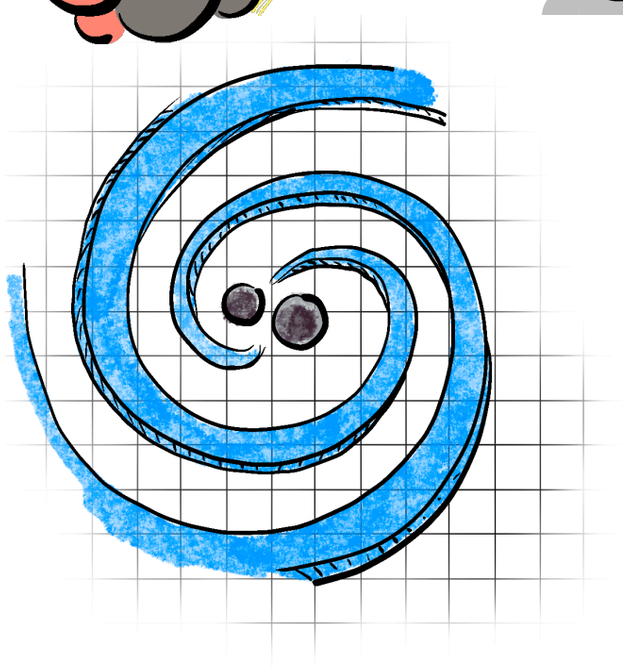

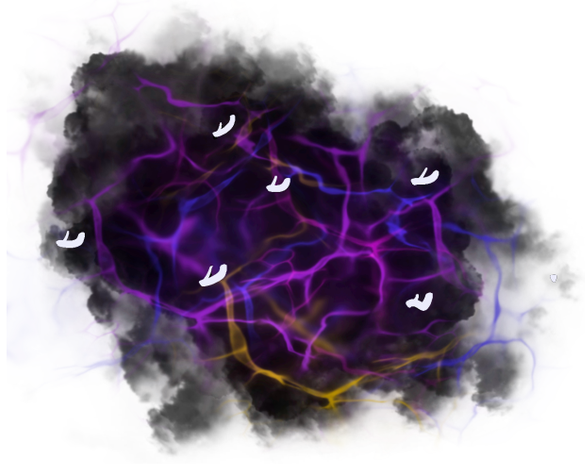

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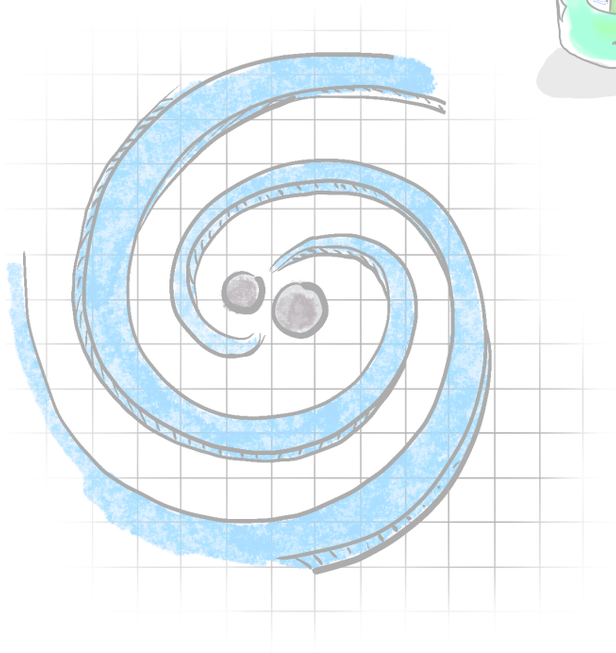

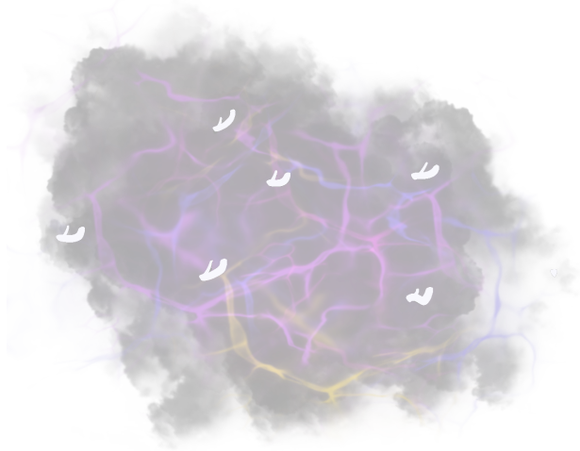

Nuclear recoil exp.

Colliders

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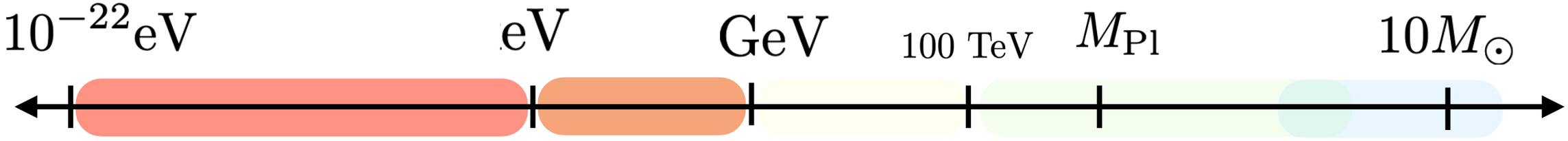
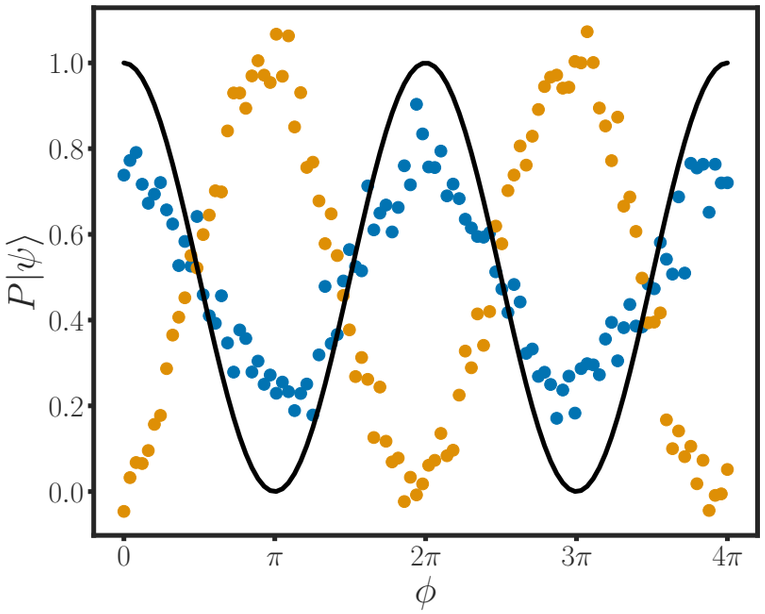
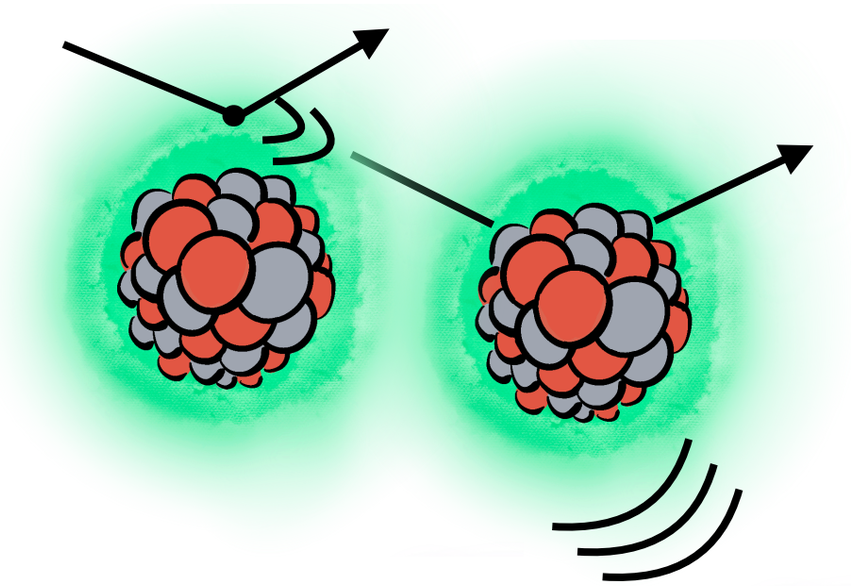
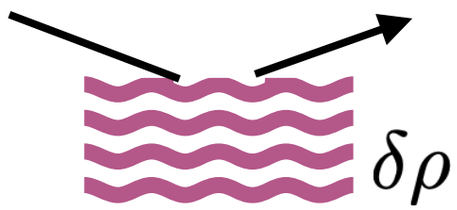
DEMAND FOR SENSITIVITY TO LOW ENERGY DEPOSITIONS

~~Beyond the~~ SM: "how" to look?









$$\mathrm{SNR} \propto \frac{\sigma}{\Delta\sigma}$$

1 Quantum object

2 Quantum coherence

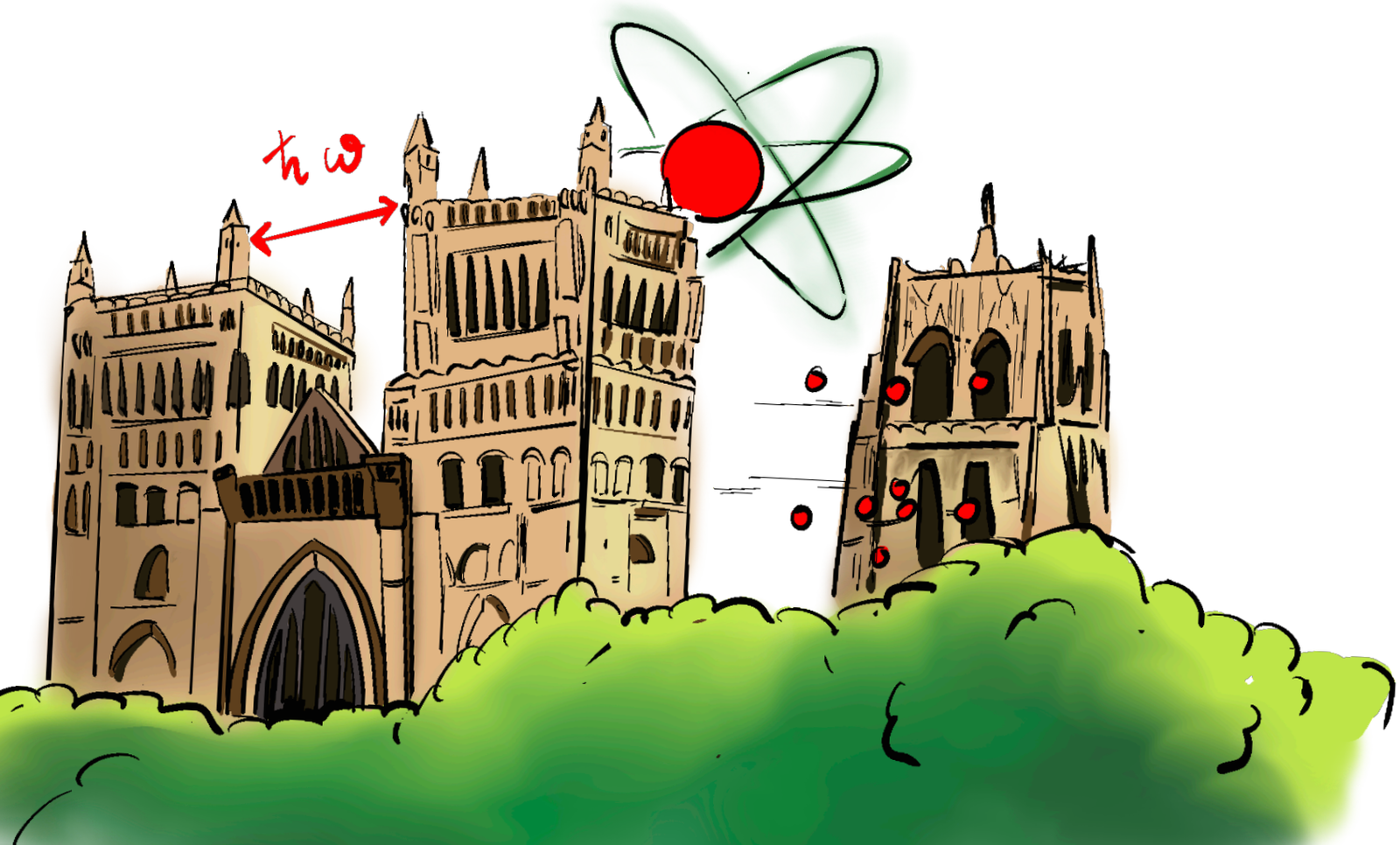
3 Quantum entanglement

12th Desember 2023

Annual Theory Meeting

Durham

Quantum Sensors as Particle(-wave) detectors



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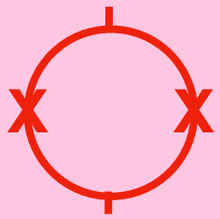
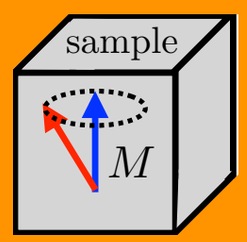
Quantum Sensing: examples

[van Bibber et al., 1803.11306] [Chou et al., 2311.01930] [Blas, 2311.10187]

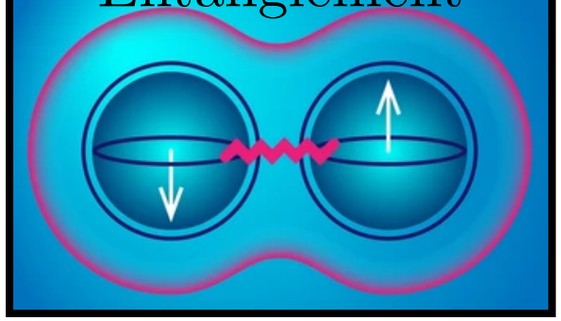
SQUID



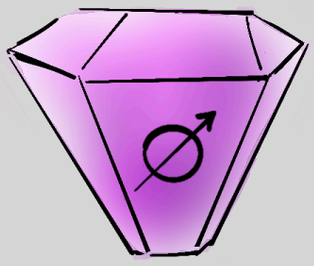
NMR sensors



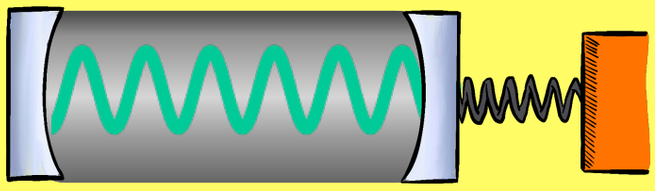
Entanglement



NV center ensembles

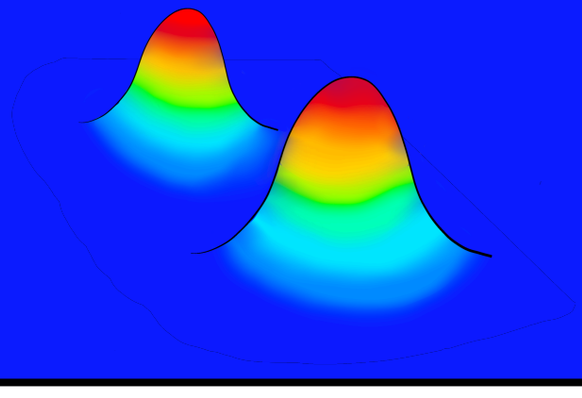


Optomechanics



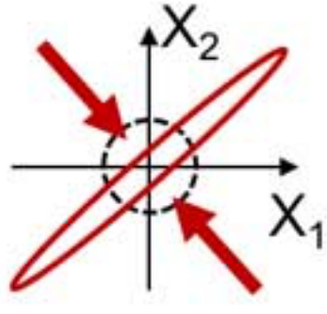
TES
ADP, MKIDs
SNSPDs
QND

Atom interferometers



Atom clocks

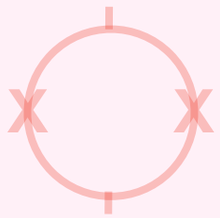
Squeezing



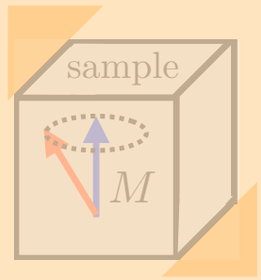
[Buchmuller et al., 2203.07250] [Golwala and Figeroa-Feliciano, 2203.07250]

Quantum Sensing: examples

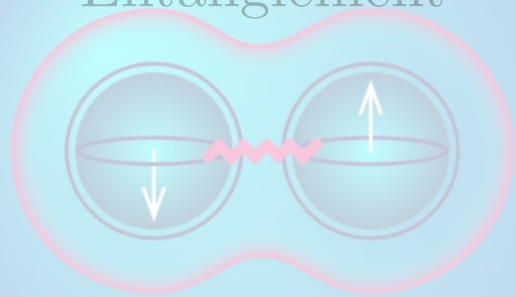
SQUID



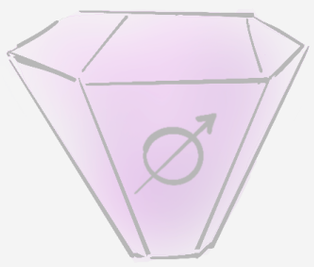
NMR sensors



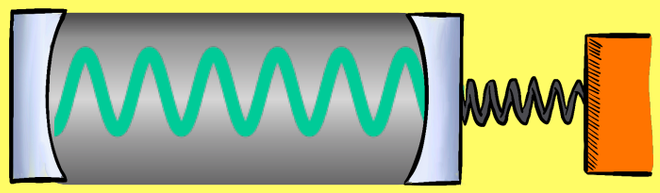
Entanglement



NV center ensembles



Optomechanics



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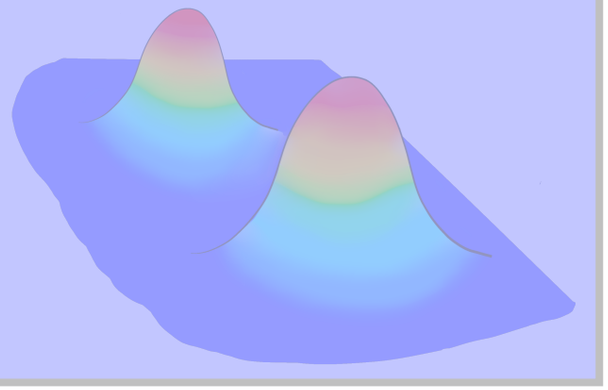
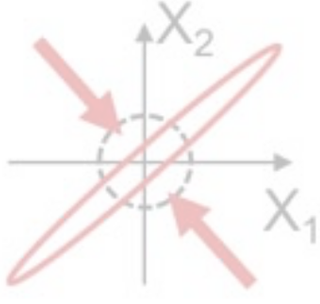


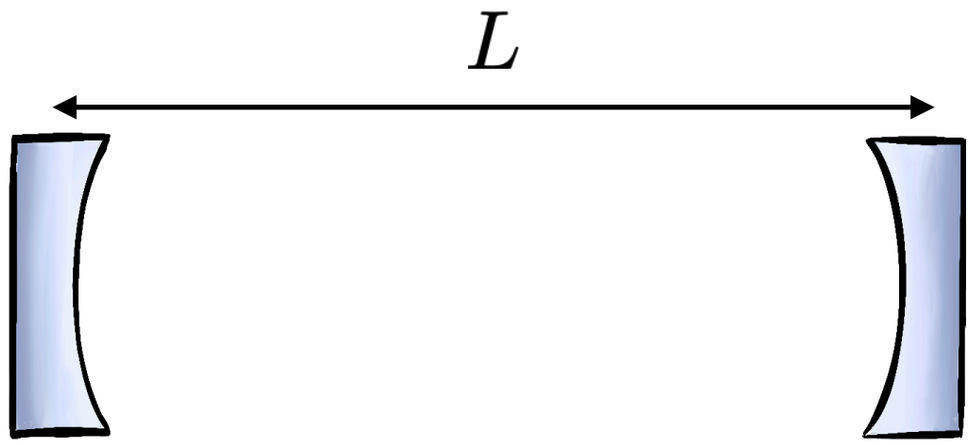
Atom clocks

Squeezing



Standard **Optomechanics**

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



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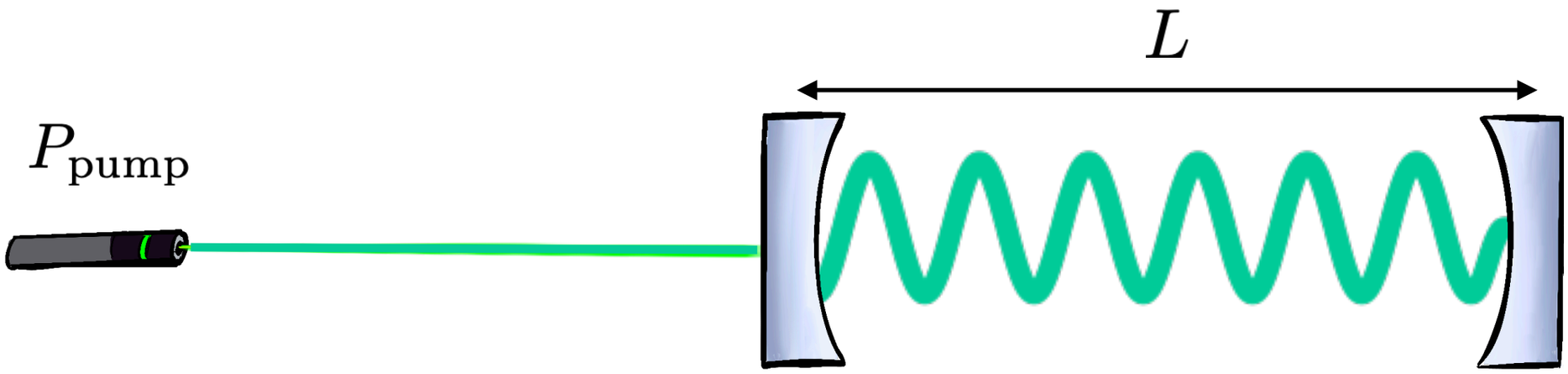
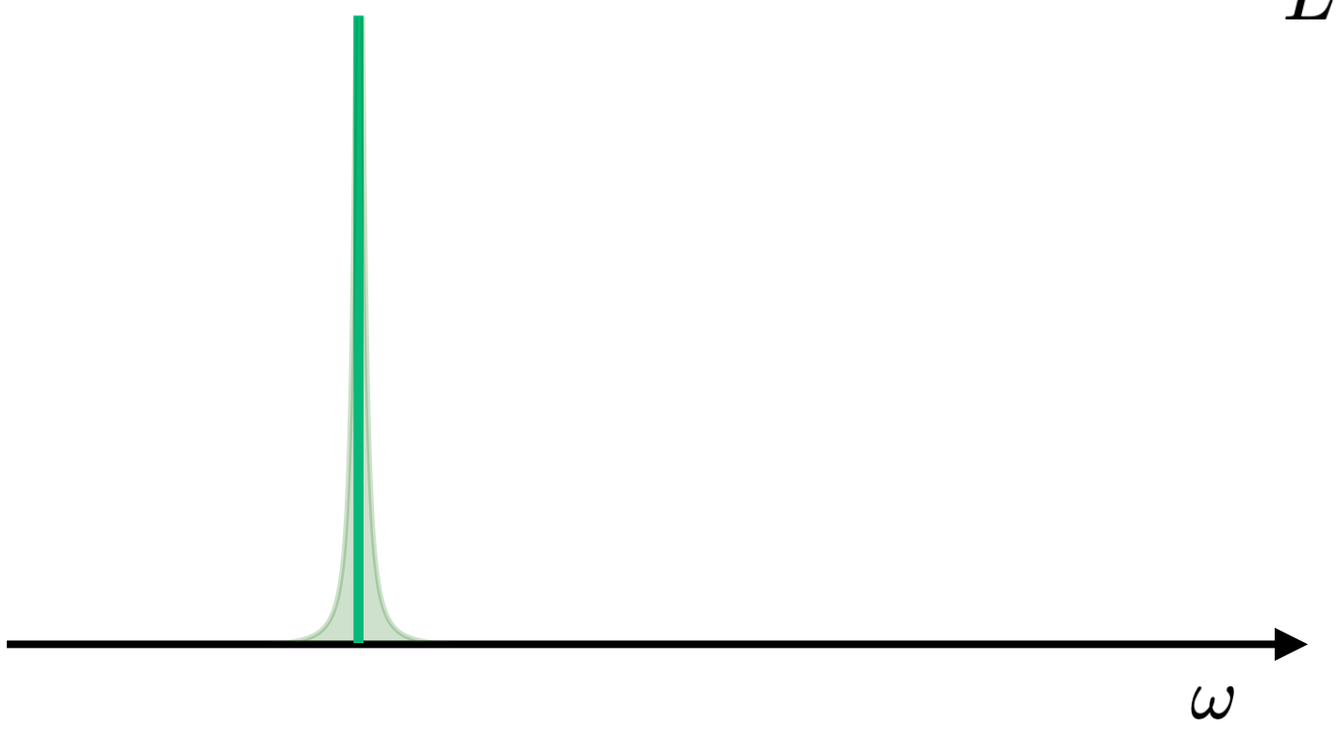


$$\omega_n = n\,\frac{\pi}{L}, \qquad n \subset \mathbb{Z}$$



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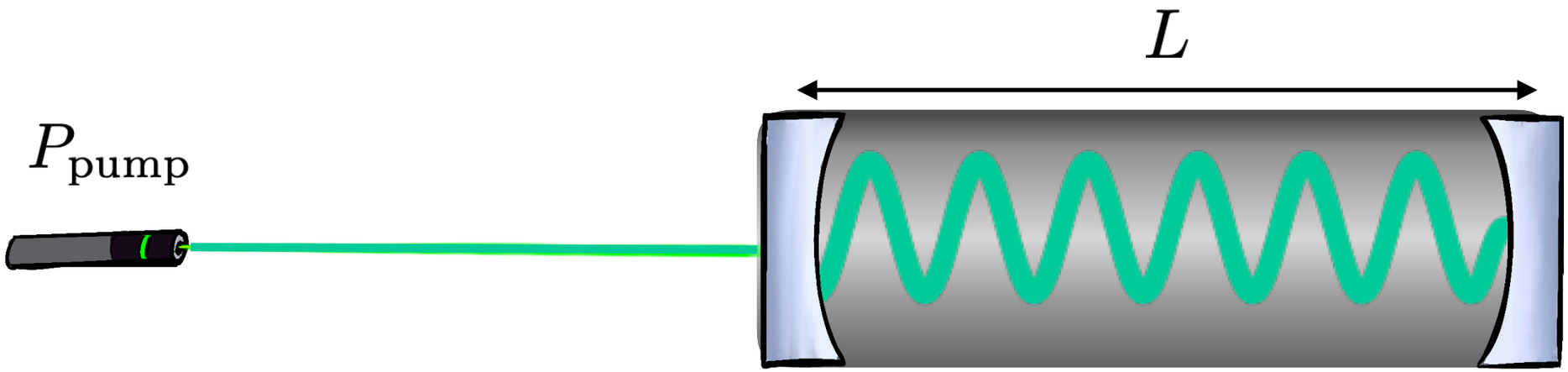
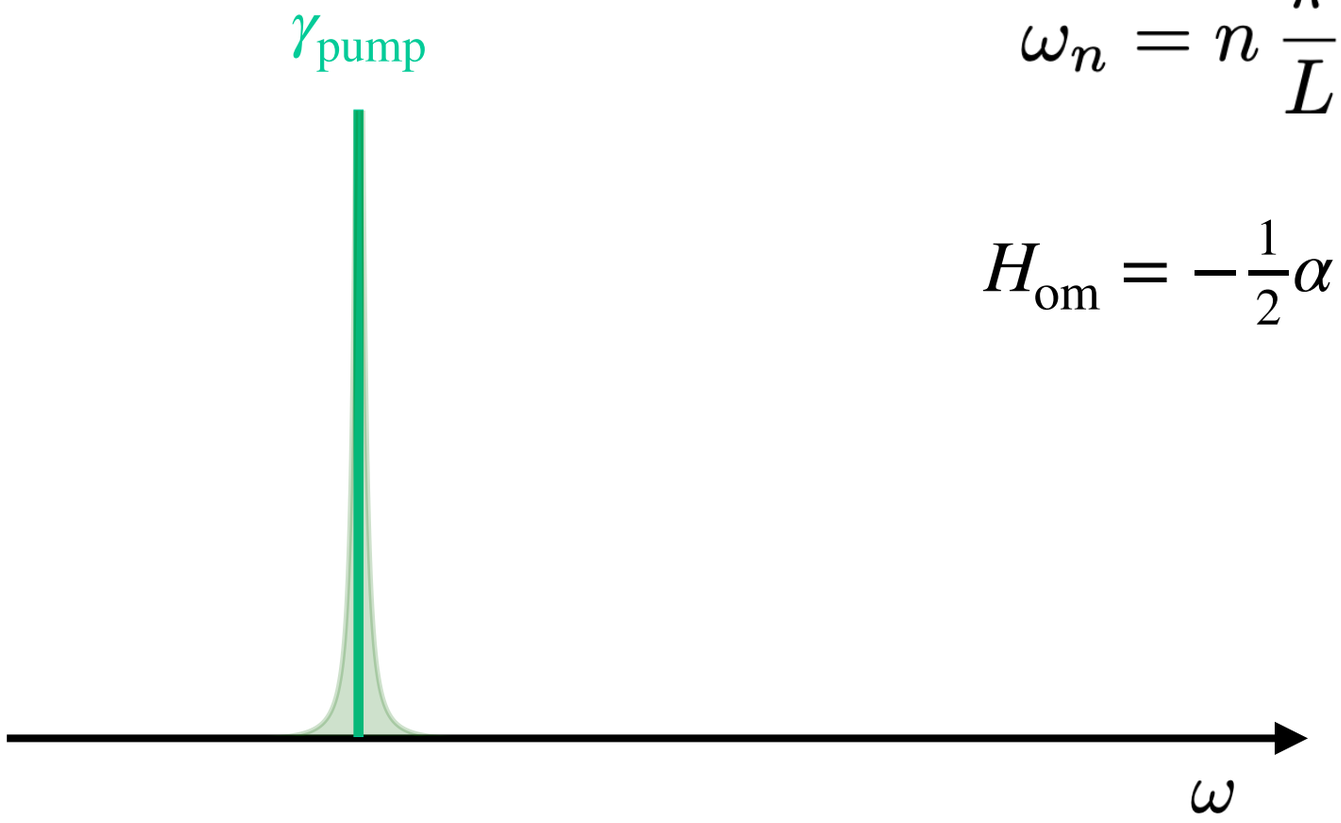


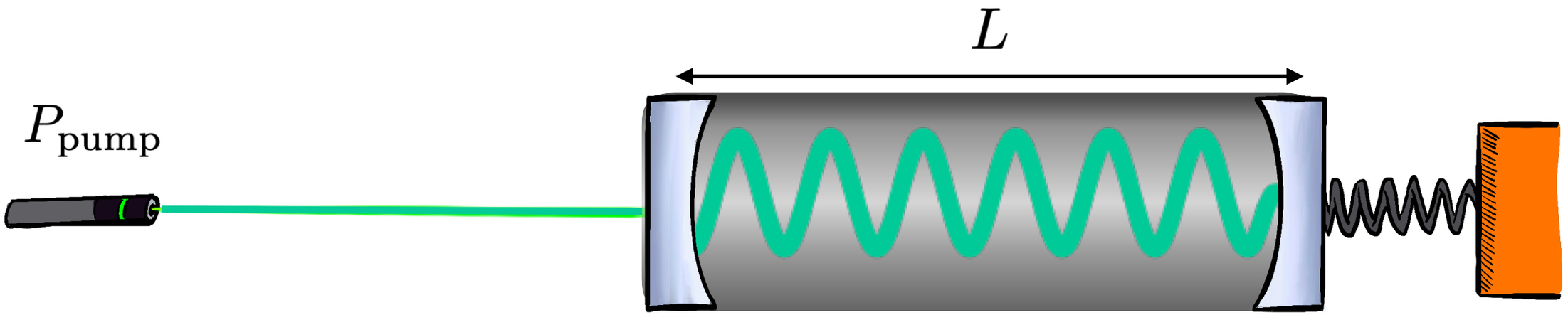


$$\omega_n = n\,\frac{\pi}{L}, \qquad n \subset \mathbb{Z}$$

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

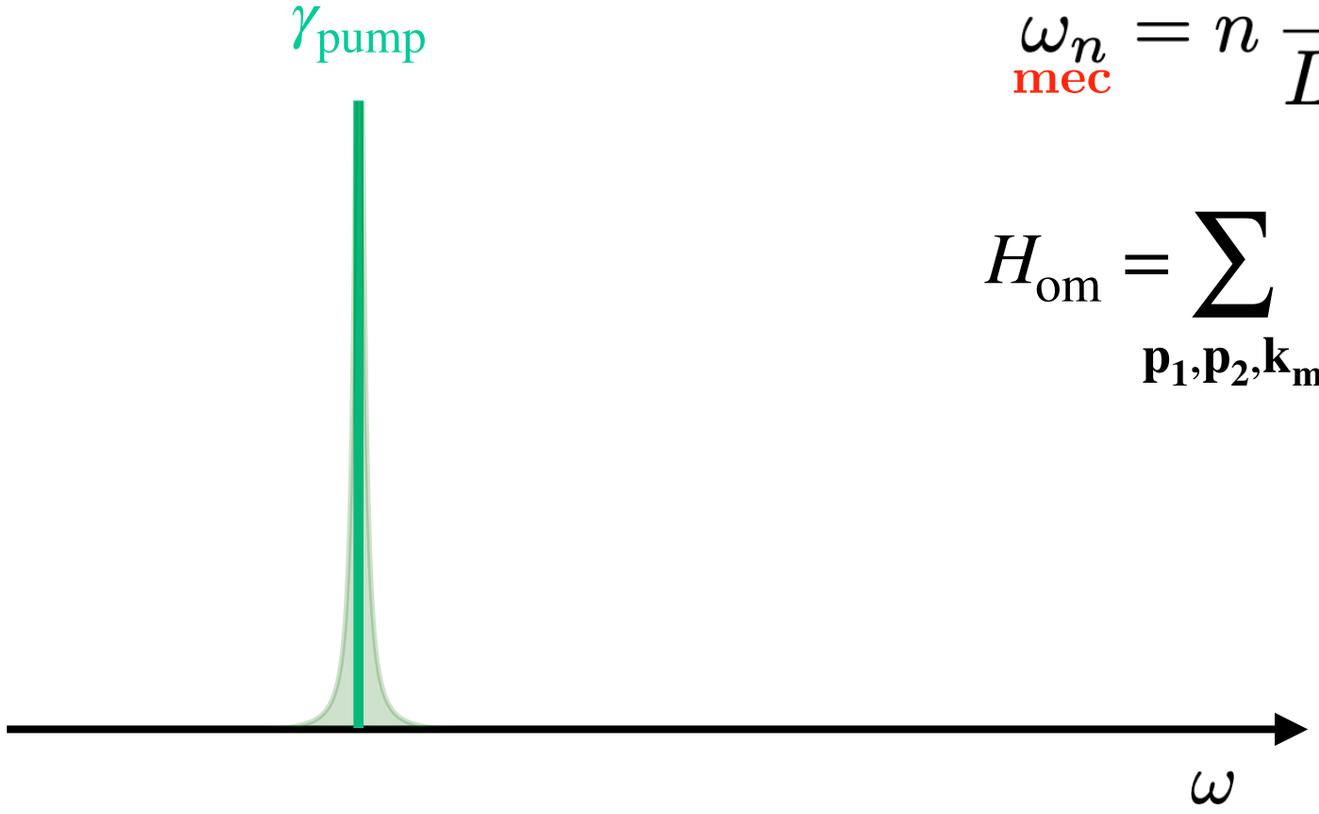
Standard **Optomechanics**

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

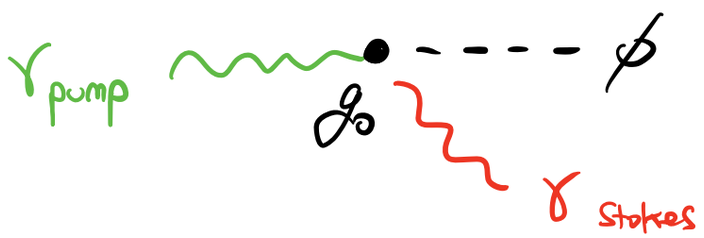


$$\omega_{\substack{n \\ \text{mec}}} = n \frac{\pi}{L} c_s, \quad n \subset \mathbb{Z}$$

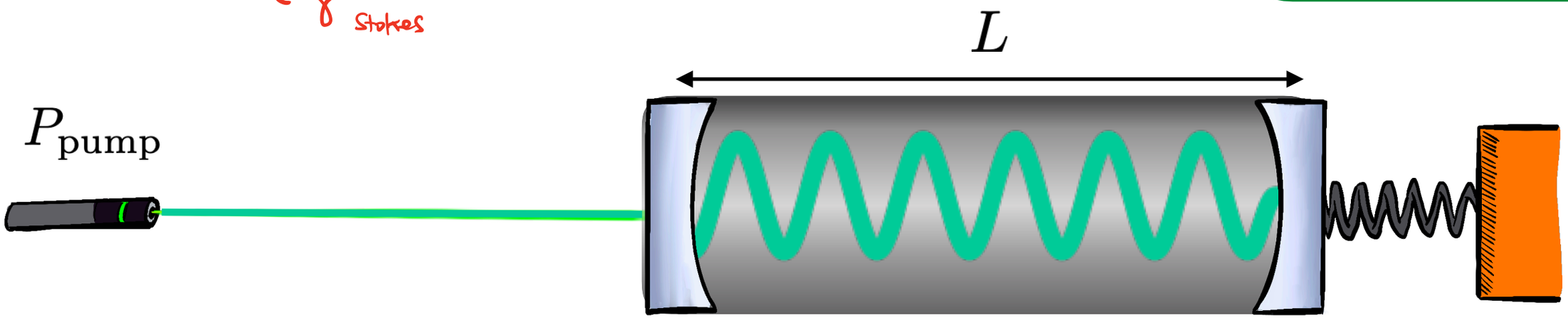
$$H_{\text{om}} = \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0 \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} + \cdots \right.$$

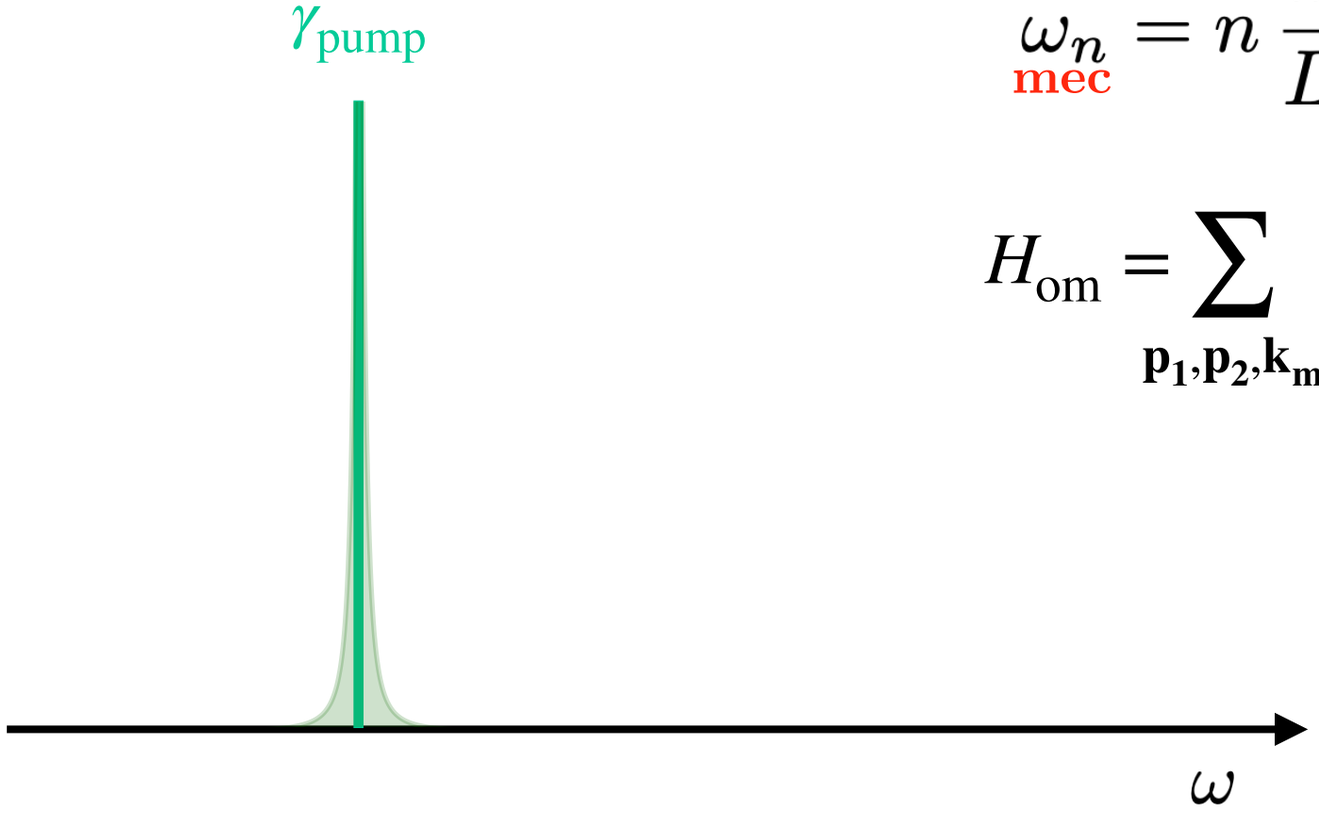


Standard **Optomechanics**



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

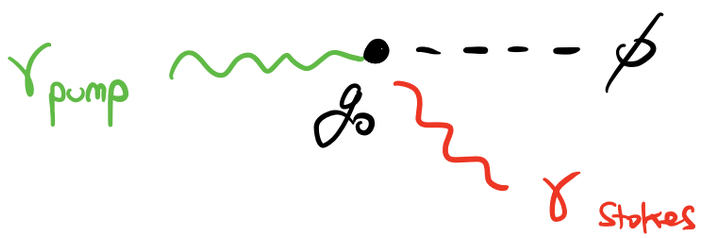




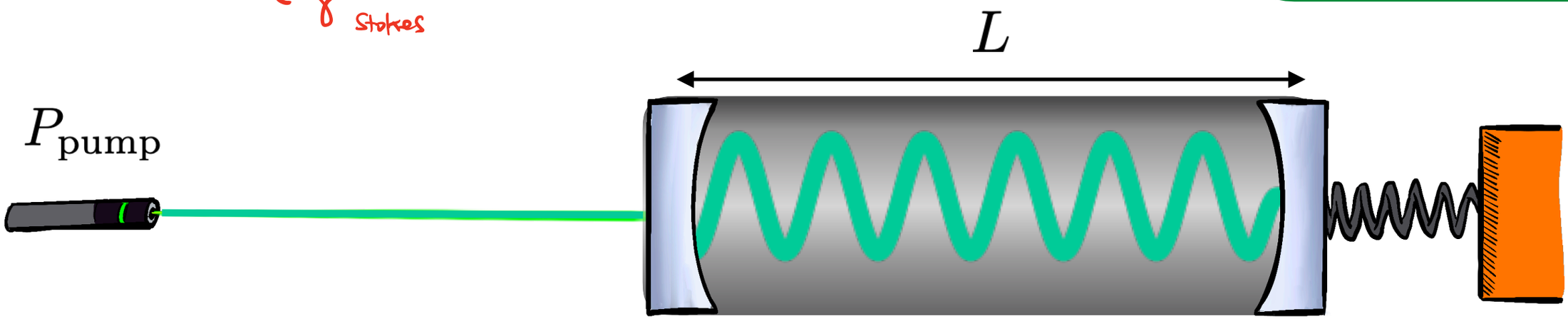
$$\underset{\mathbf{mec}}{\omega_n} = n\,\frac{\pi}{L}\,c_s, \qquad n \subset \mathbb{Z}$$

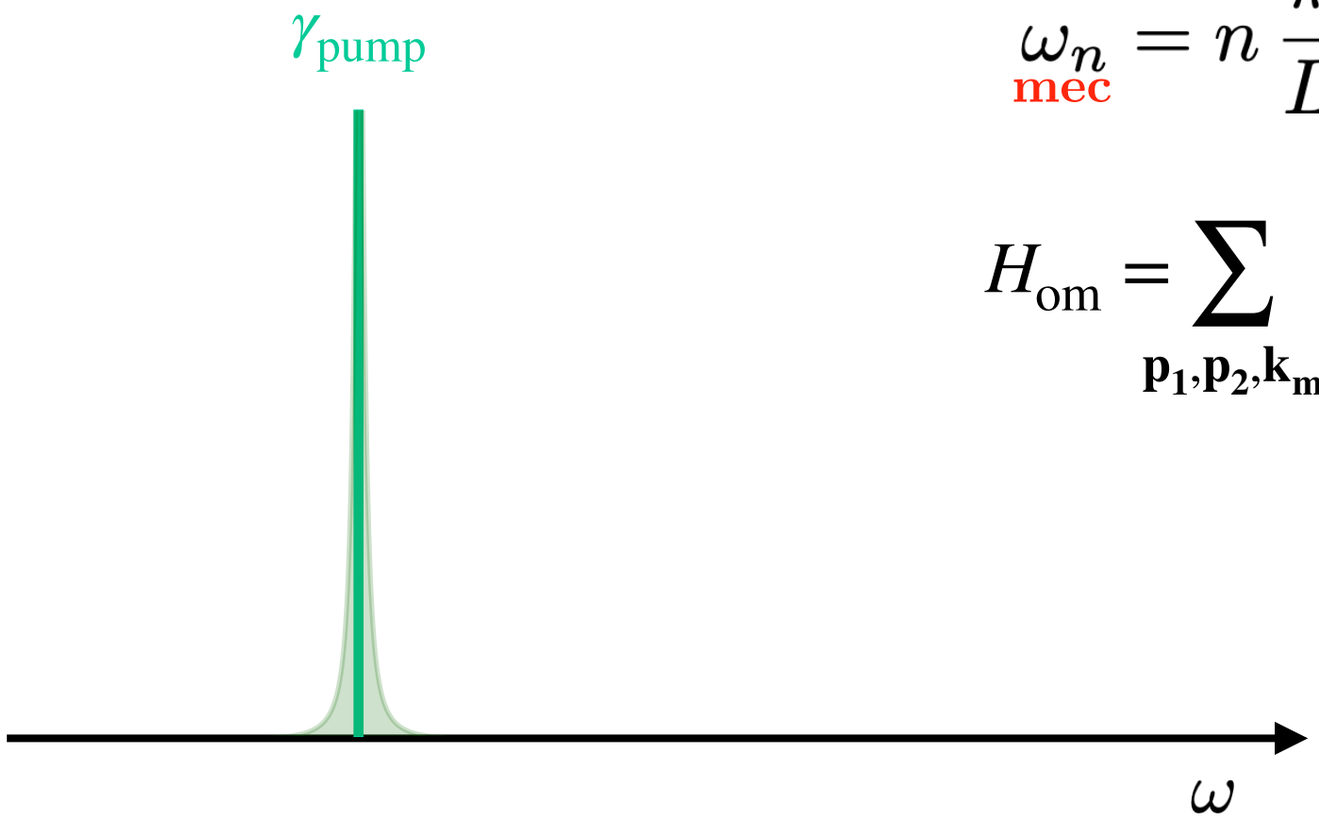
$$H_{\mathrm{om}} = \sum_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{k}_m} g_0 \left(a_{\mathbf{p}_1} a^{\dagger}_{\mathbf{p}_2} b^{\dagger}_{\mathbf{k}_m} + \cdots \right.$$

Standard **Optomechanics**



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





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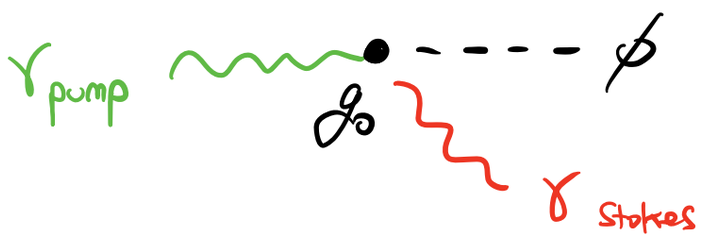
Standard **Optomechanics**



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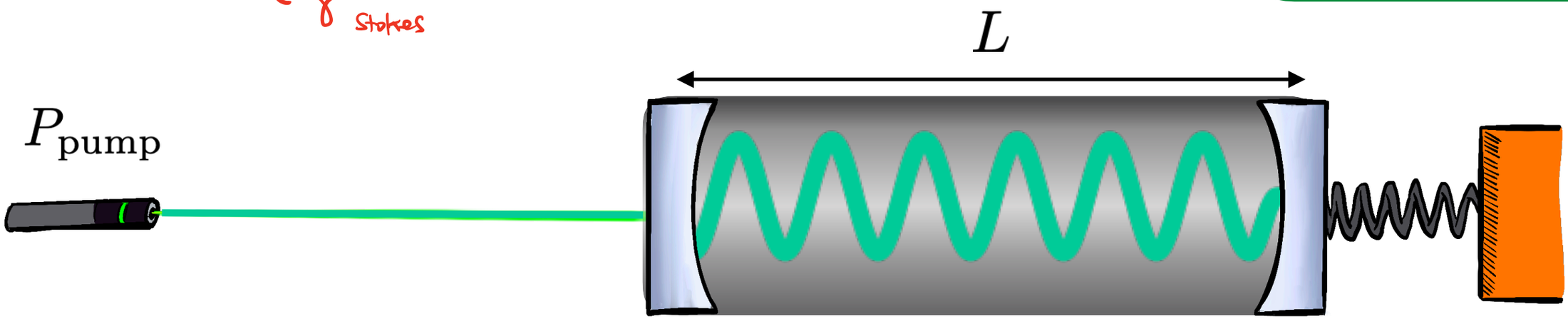

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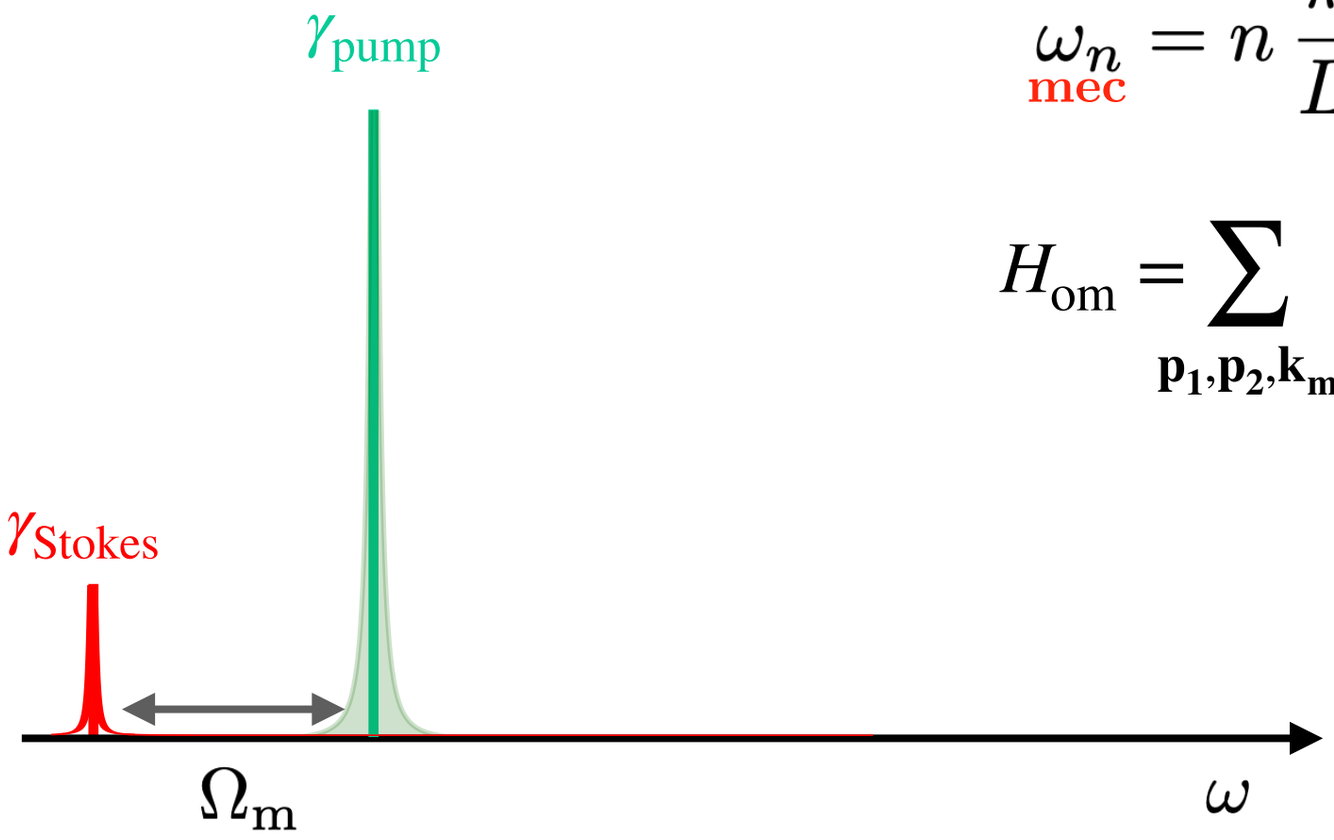
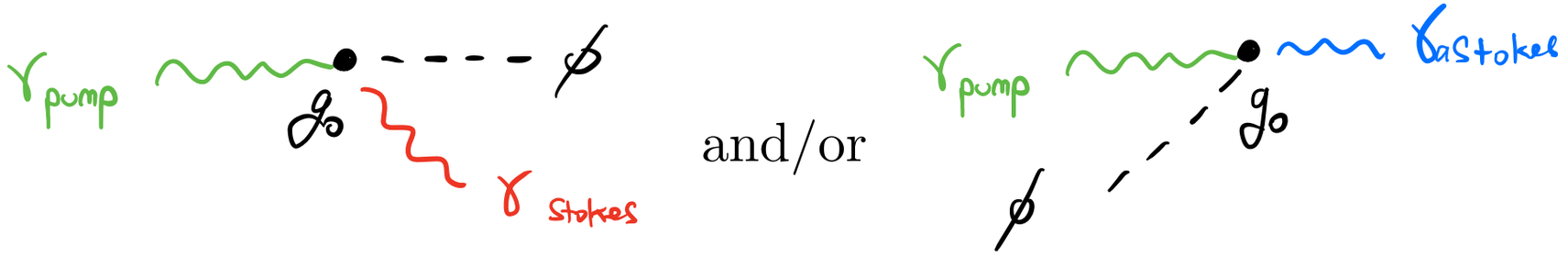


Standard **Optomechanics**



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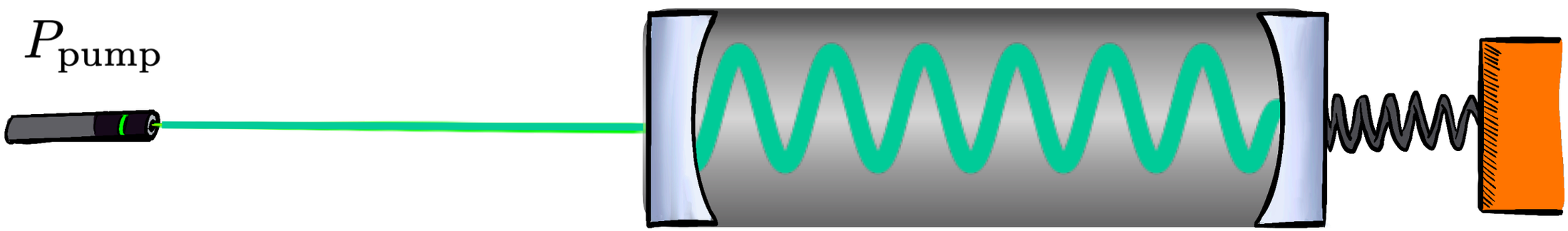

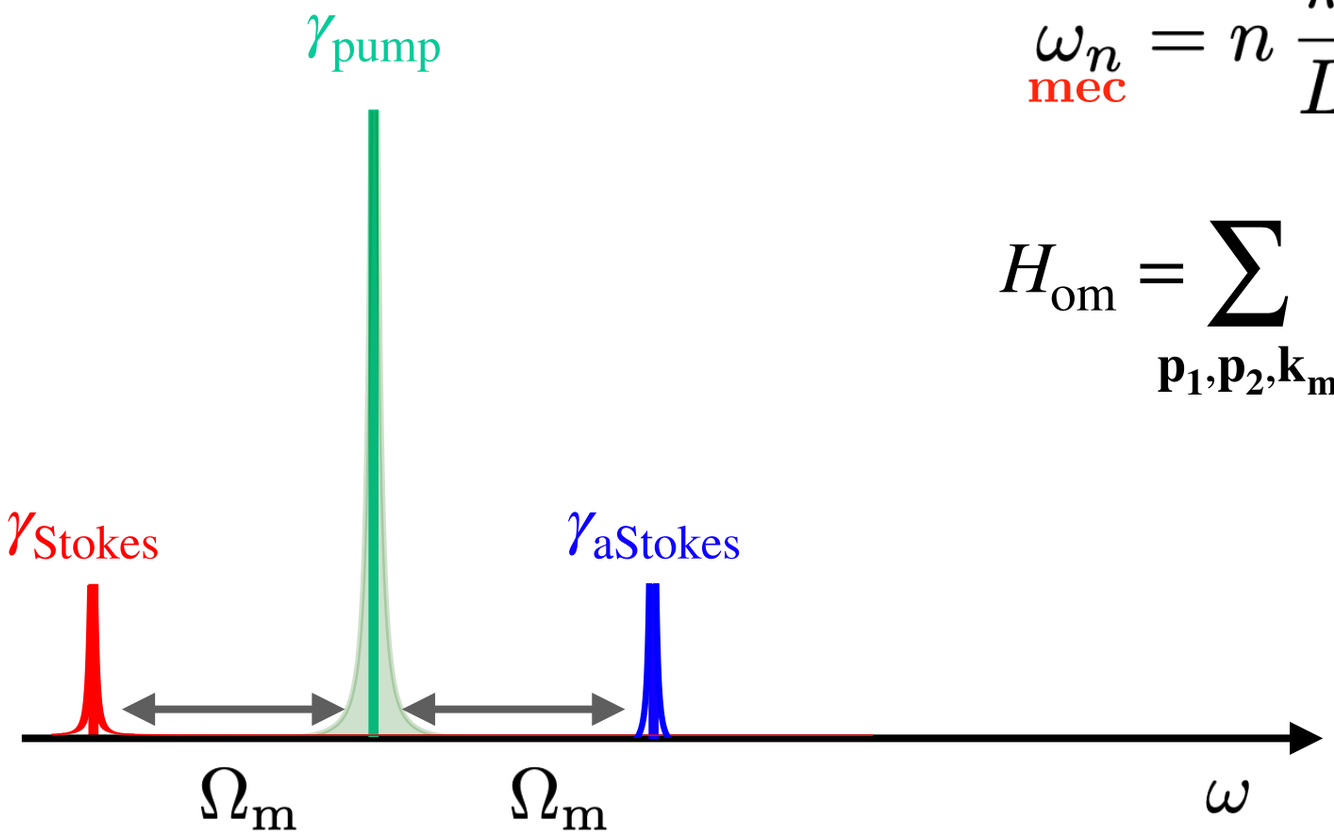

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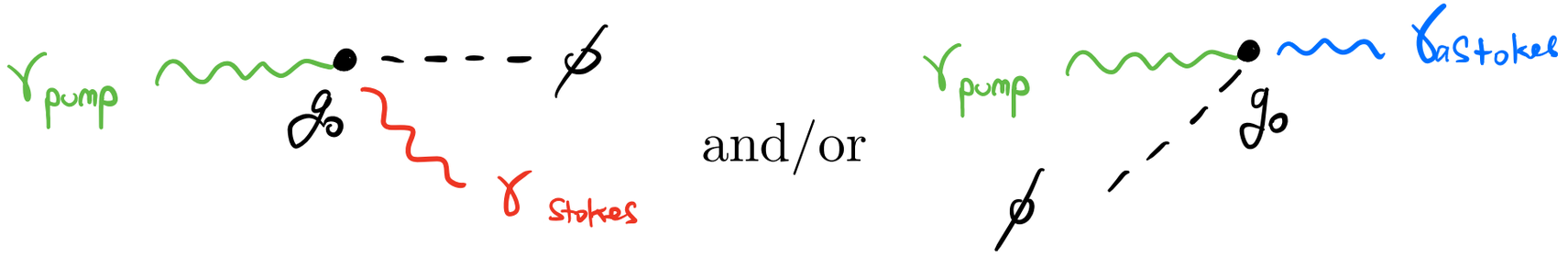
$$H_\mathrm{om} = \sum_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{k}_\mathrm{m}} g_0 \left(a_{\mathbf{p}_1} a^\dagger_{\mathbf{p}_2} b^\dagger_{\mathbf{k}_\mathrm{m}} + a_{\mathbf{p}_1} a^\dagger_{\mathbf{p}_2} b_{\mathbf{k}_\mathrm{m}} \right)$$

Standard **Optomechanics**



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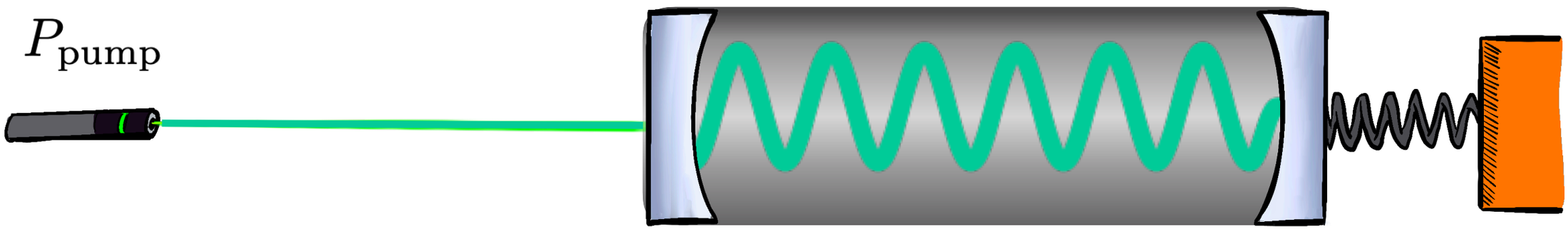

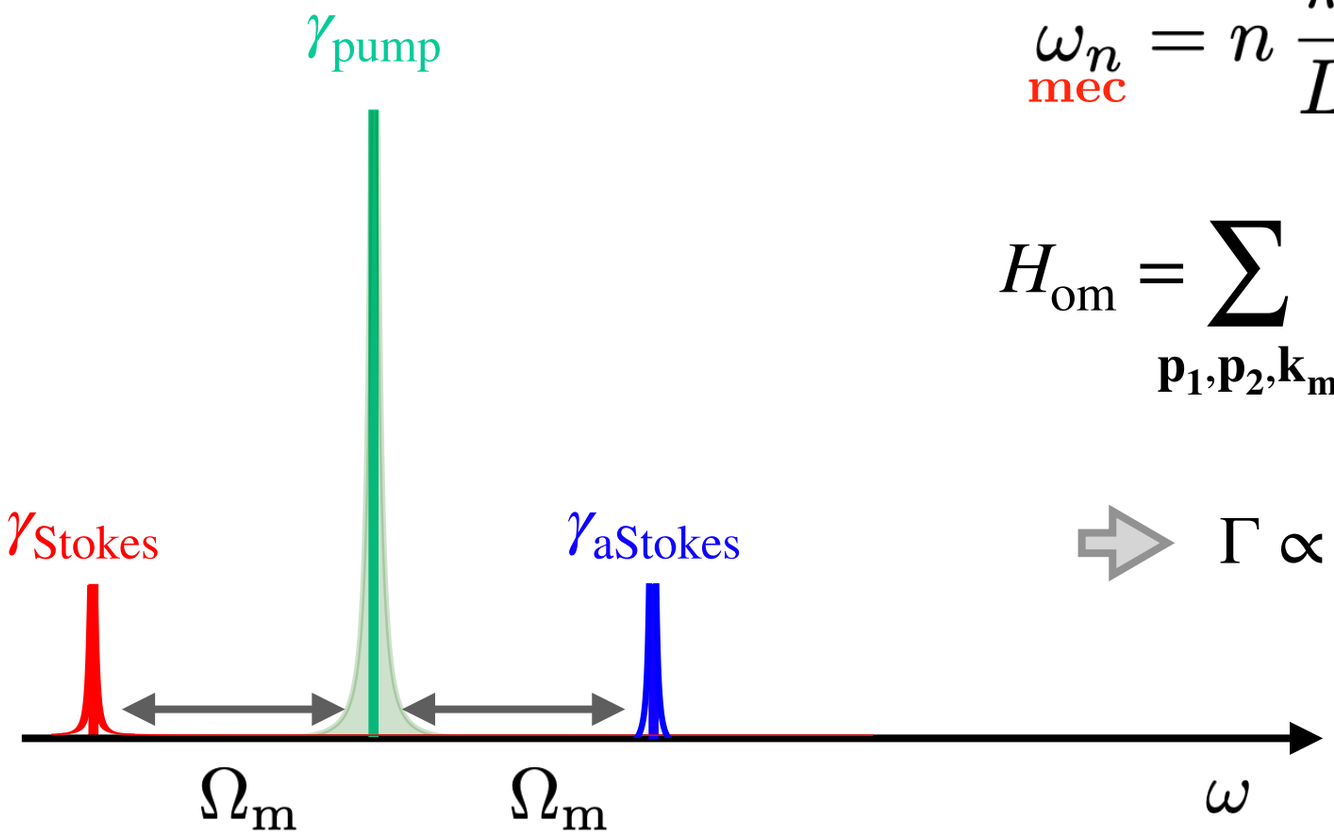

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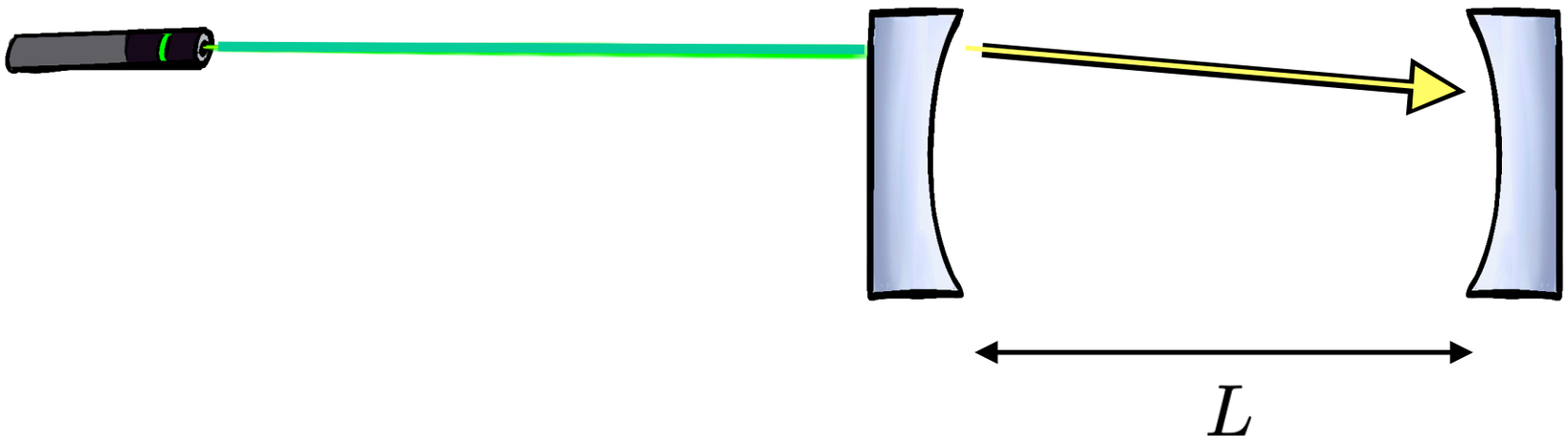
$$\Rightarrow \quad \Gamma \propto |g_0|^2 \, N^{\mathrm{circ}}_{\gamma,\mathrm{pump}}\,[\Delta_\mathrm{pump}]$$

Standard **Optomechanics**



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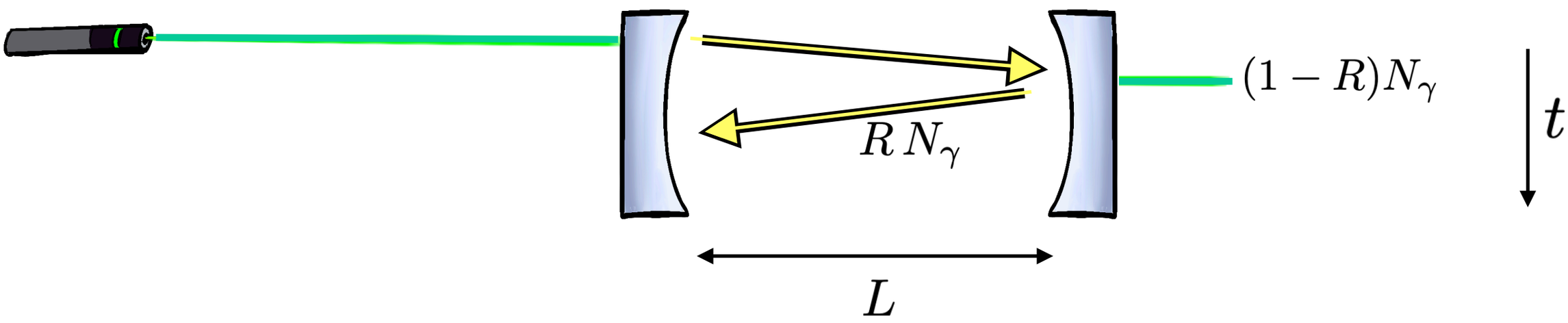

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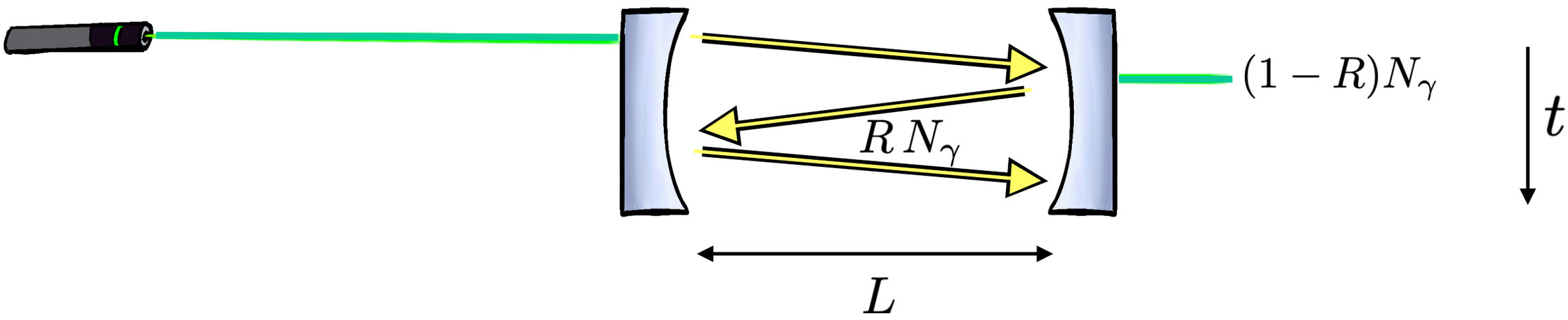
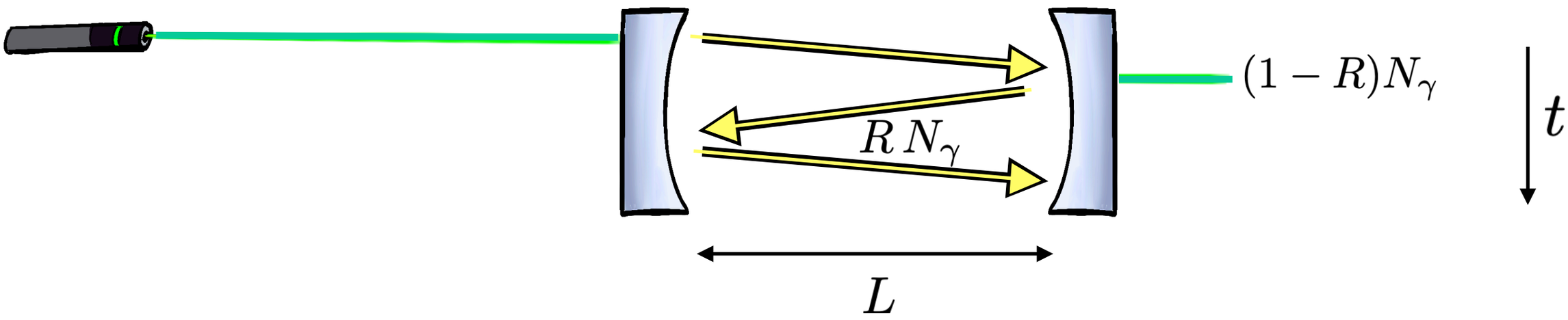


$$\frac{dN_\gamma}{dt} \simeq \frac{\Delta N_\gamma}{L/c} = \frac{c(1-R)}{L} N_\gamma \quad \Rightarrow \quad \tau_\gamma^{-1} \equiv \kappa \simeq \frac{c}{(1-R)^{-1} L}$$

$$\mathcal{F}_{\rm opt}$$

Standard **Optomechanics**



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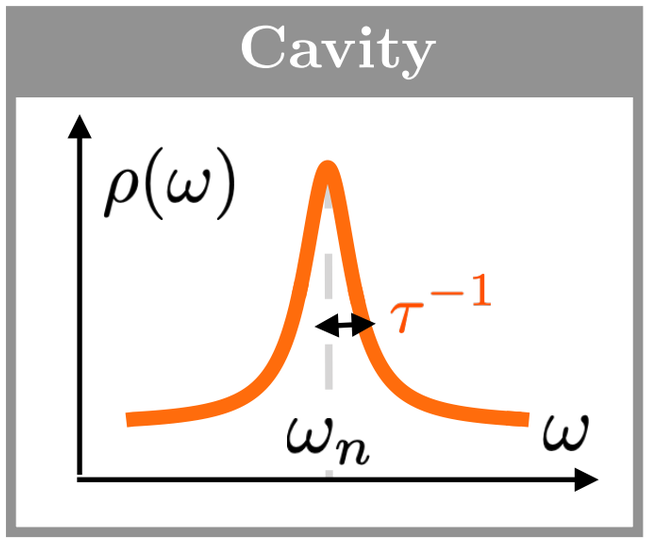
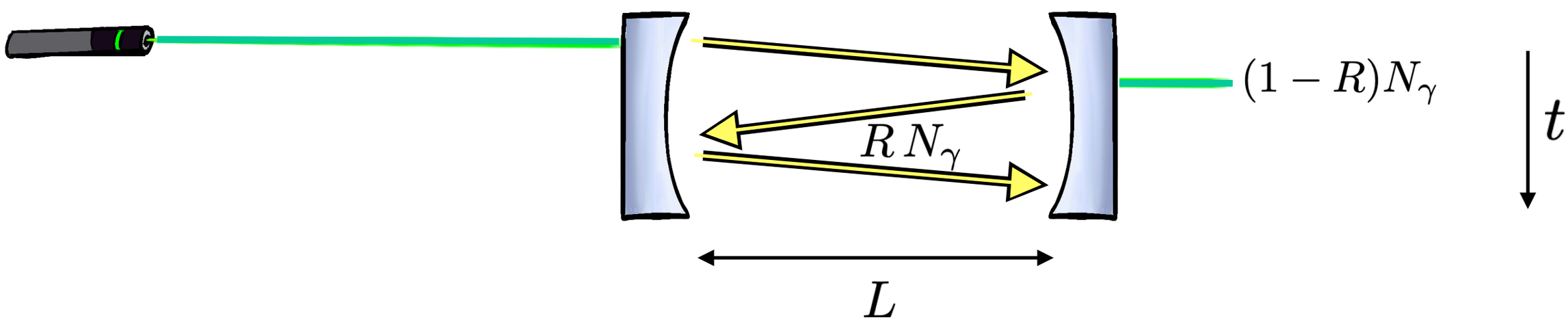
$\mathscr{F}_{\text{opt}}$



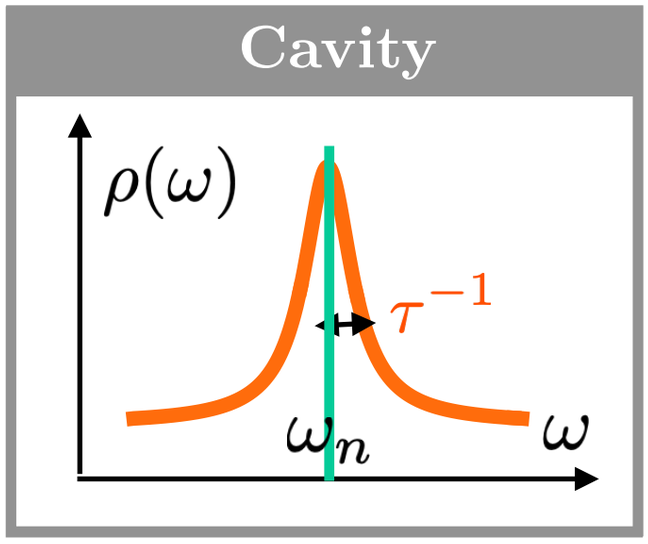
$$\rho(\omega) = \sum_i \delta(\omega - \omega_i) = \sum_n \frac{1}{2\pi} \int dt\, e^{i(\omega-\omega_n)t} e^{-t/(2\tau)} = \sum_n \frac{\tau^{-1}/2}{(\omega-\omega_n)^2 + (\tau^{-1}/2)^2}$$

Standard **Optomechanics**



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

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



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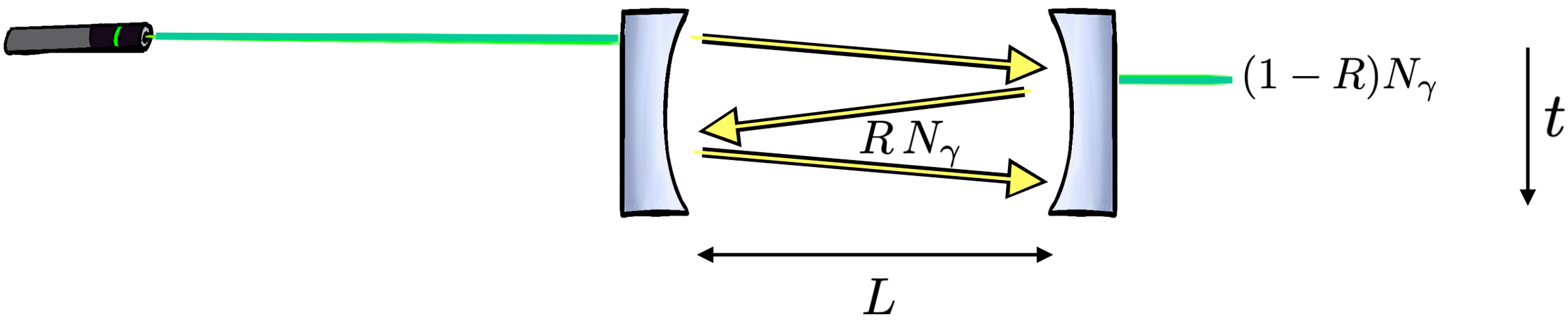
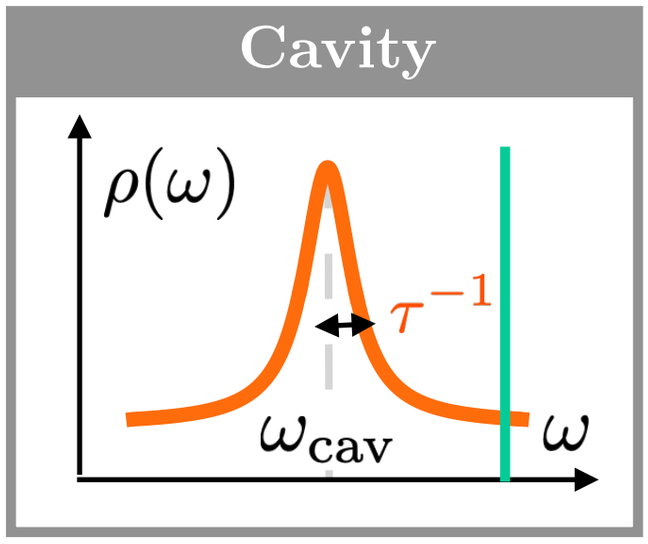
Standard **Optomechanics**



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

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



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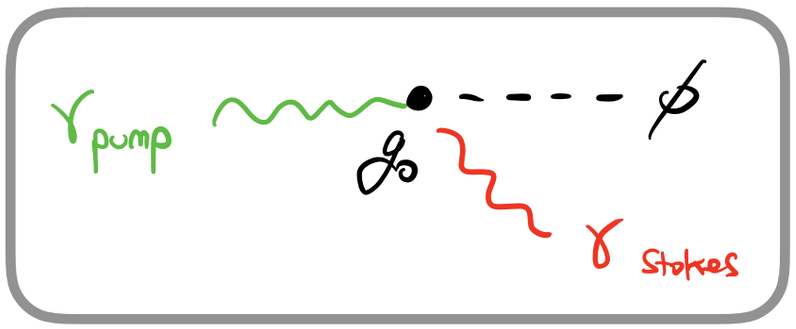
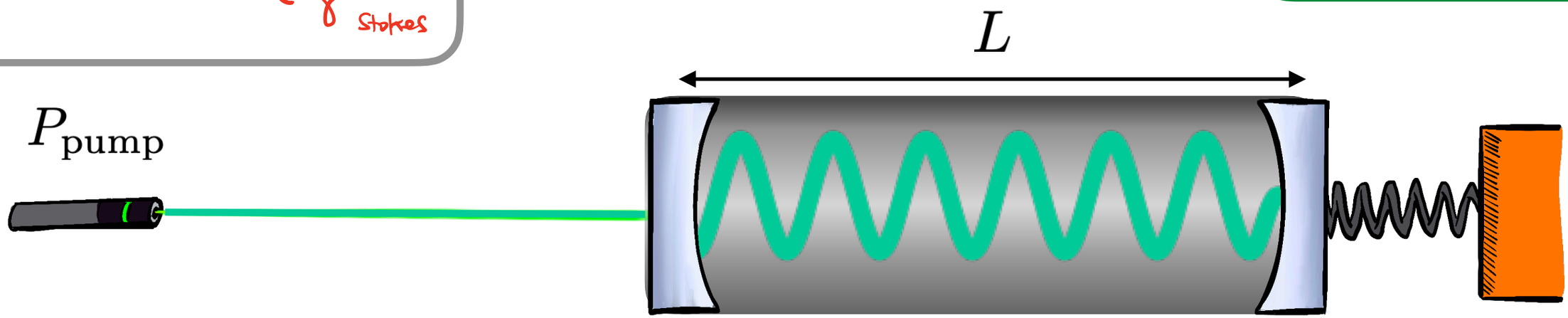
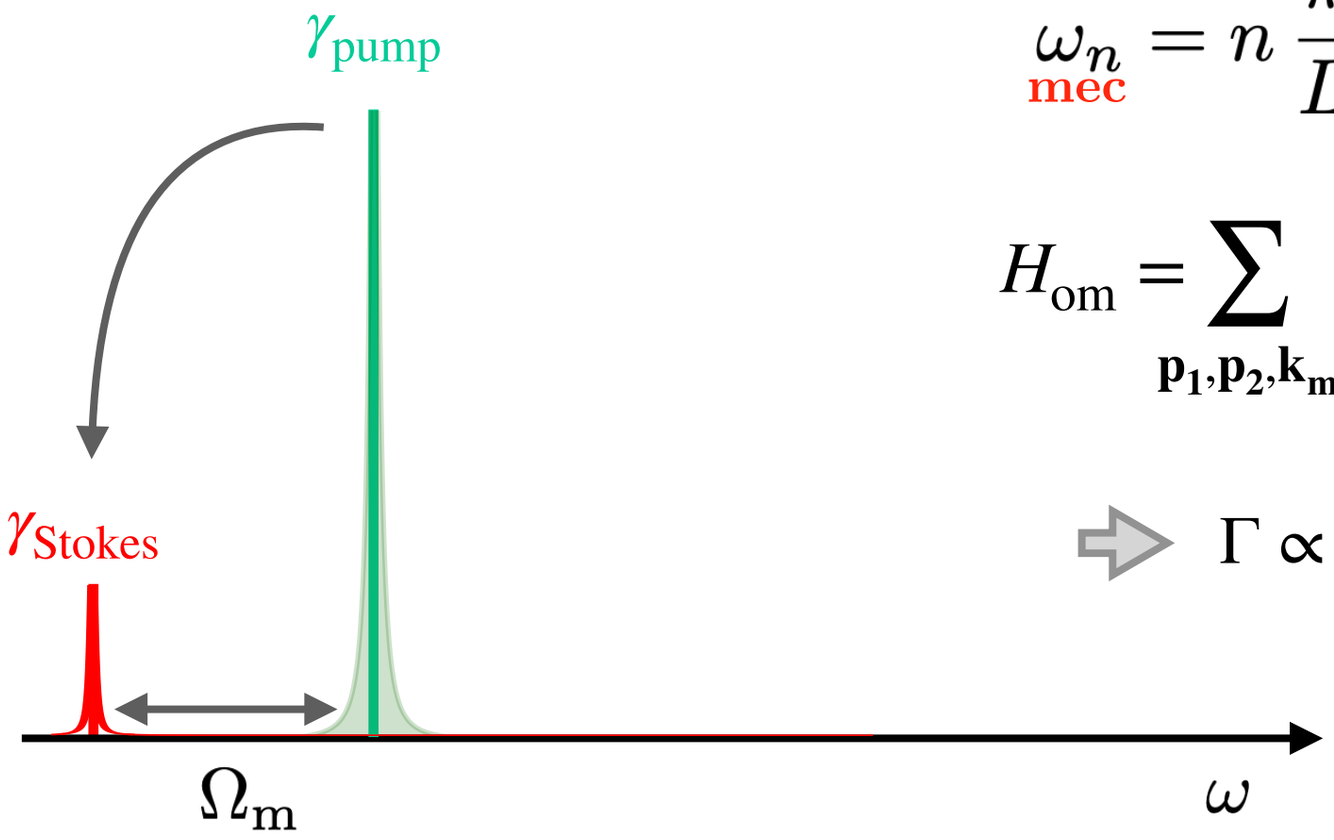
Standard **Optomechanics**



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





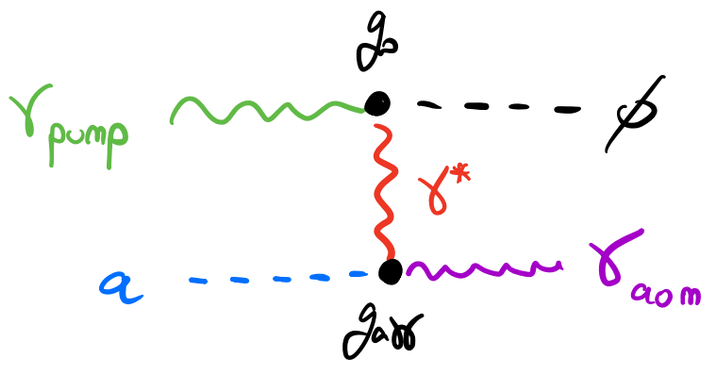
$$\omega_{\underset{\mathbf{mec}}{n}} = n\,\frac{\pi}{L}\,c_s, \qquad n \subset \mathbb{Z}$$

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

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

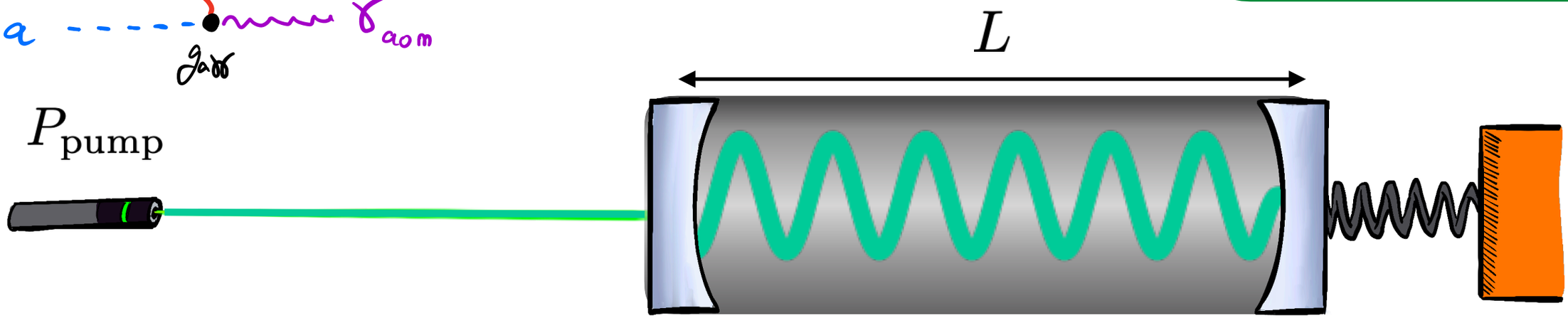
[Kashkanova et al., 2017]
[Reningner et al., 2017]

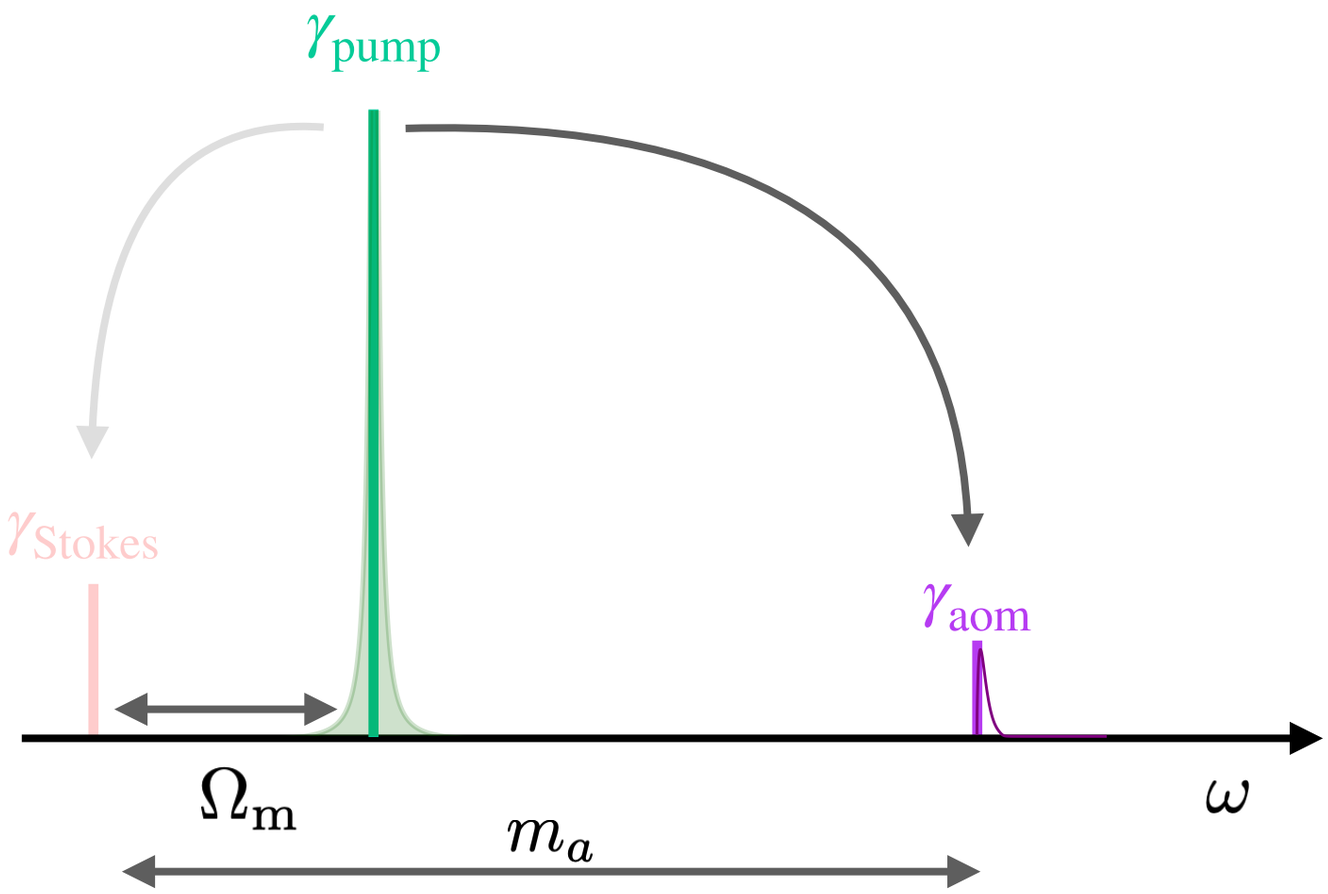
~~Standard~~ Axioptomechanics



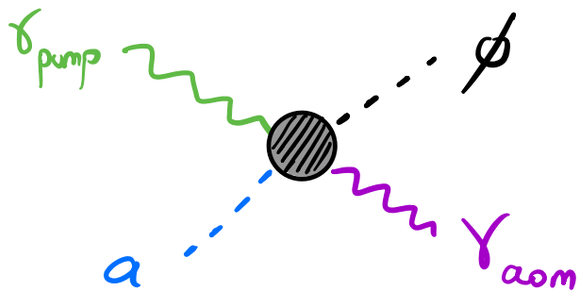
[CM, Y. Wang, K. M. Zurek. 2022]

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





~~Standard~~ Axioptomechanics



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

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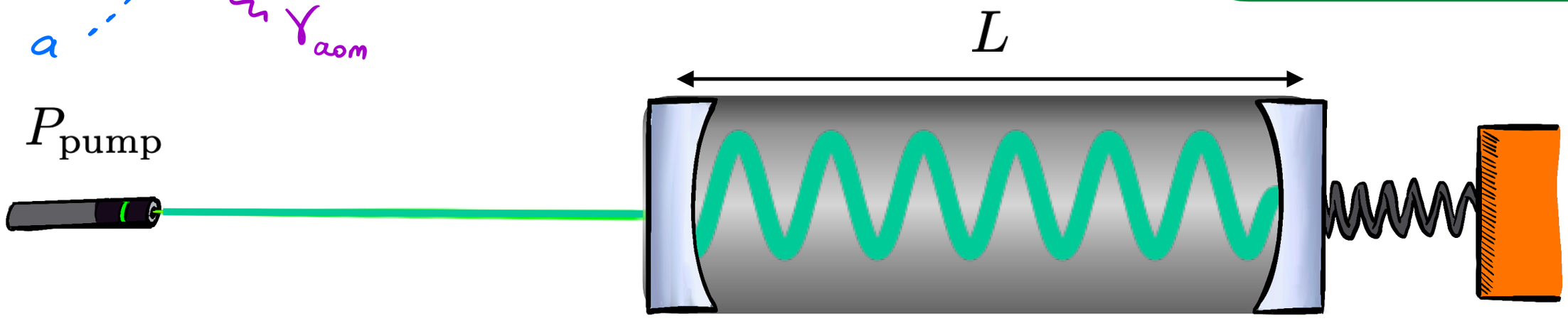

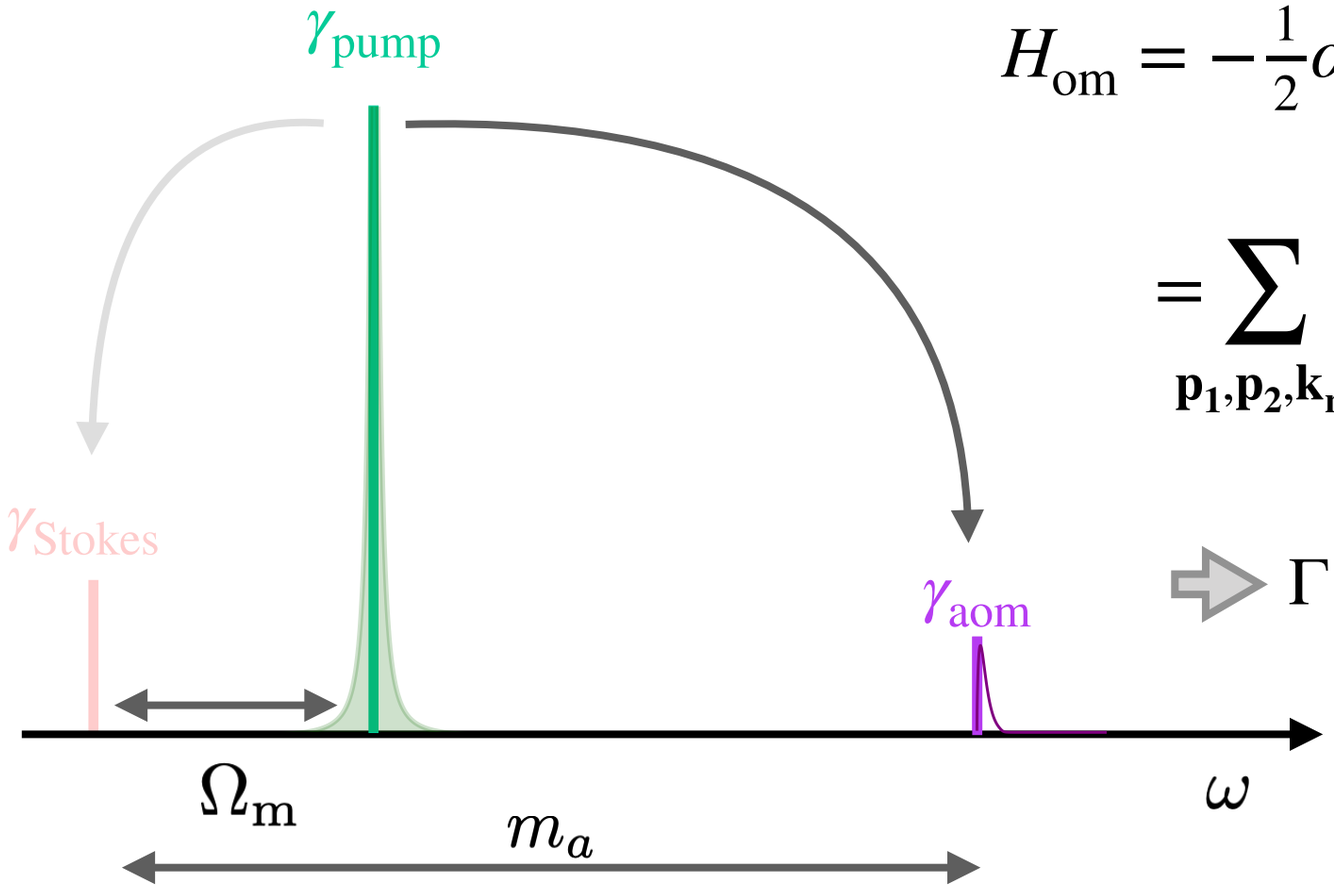

$$H_{\rm om} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma} \int d^3\mathbf{r}\, a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$$

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

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

~~Standard~~ Axioptomechanics

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

$$p_\phi \simeq 2p_\gamma$$
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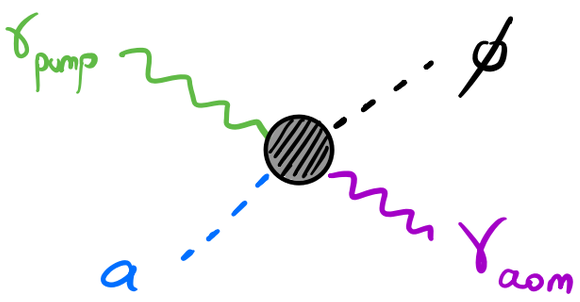
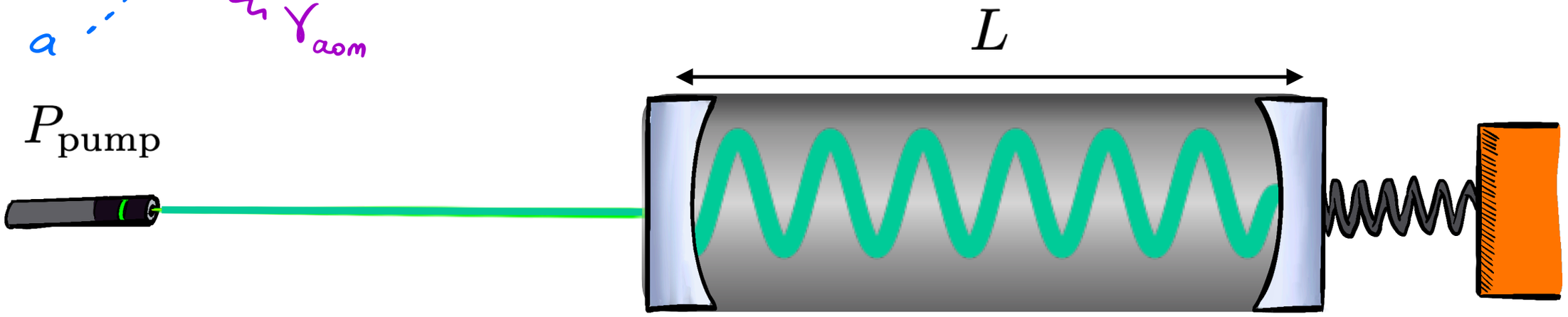
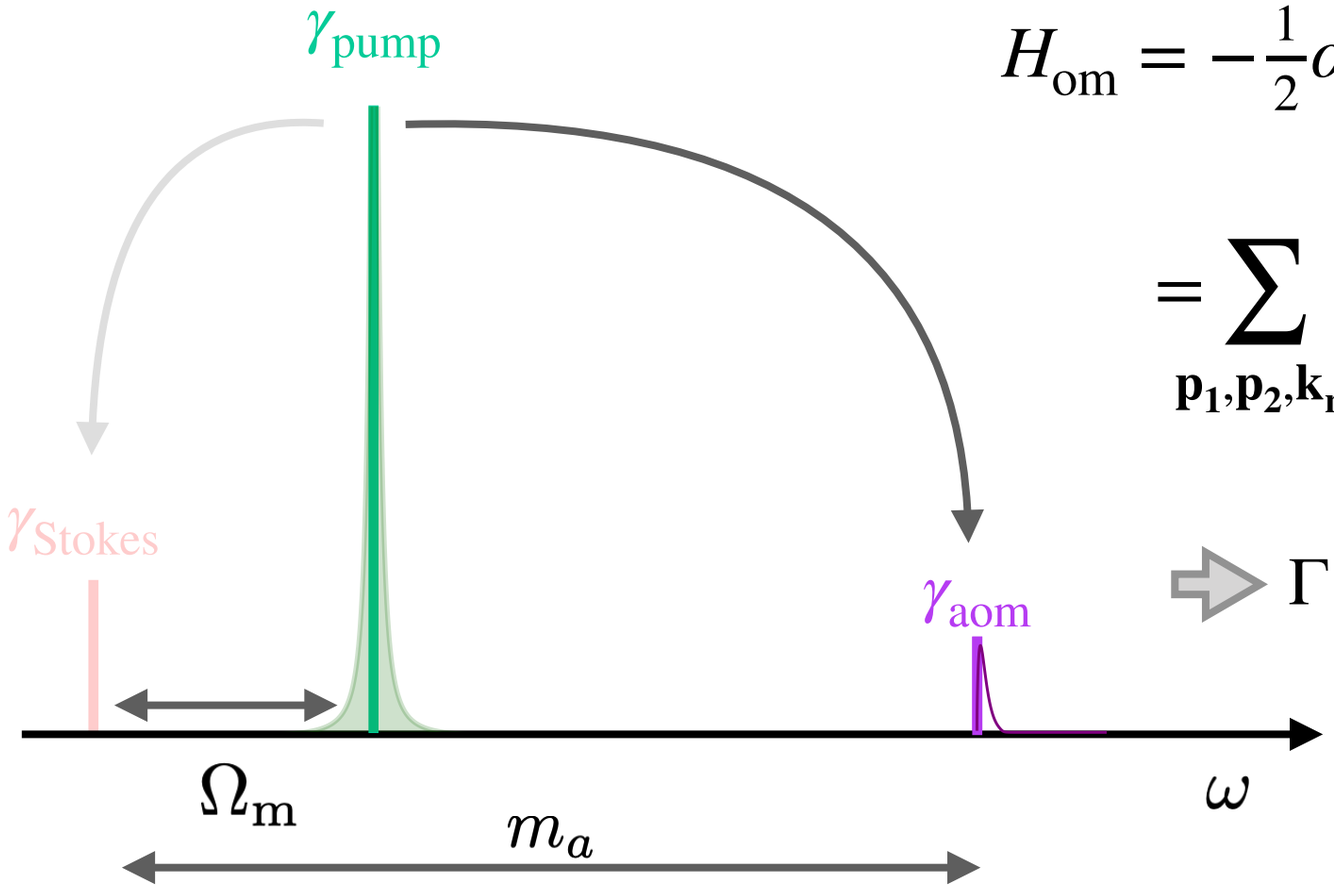






$$H_{\rm om} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma} \int d^3\mathbf{r}\, a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$$

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

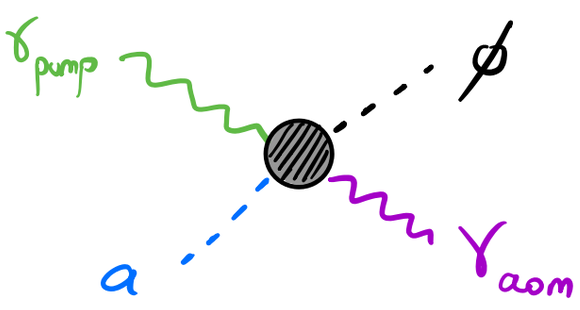
$$\Rightarrow \Gamma \propto |g_0^{(a)}|^2 \left(g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \right) \times N_{\gamma,\rm pump}$$

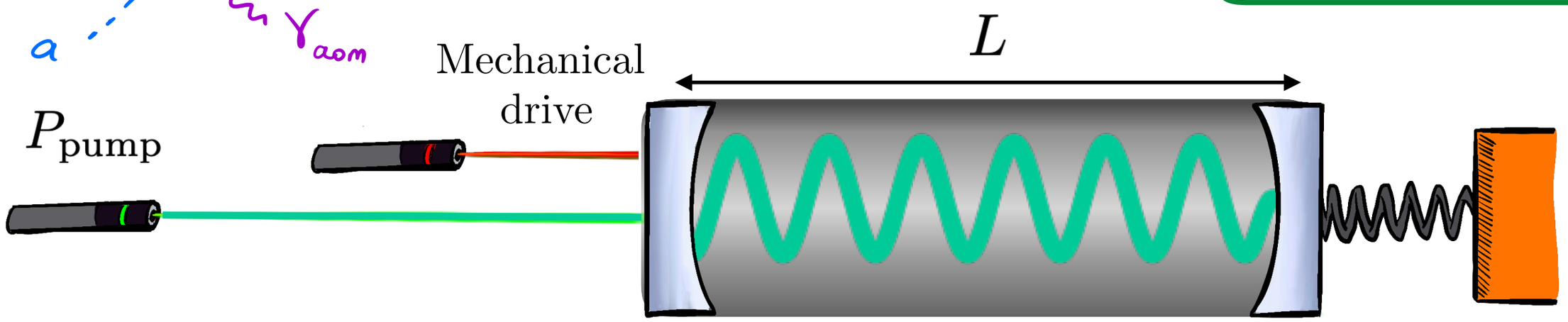
$\sim 10^{-22}$ for QCD axion

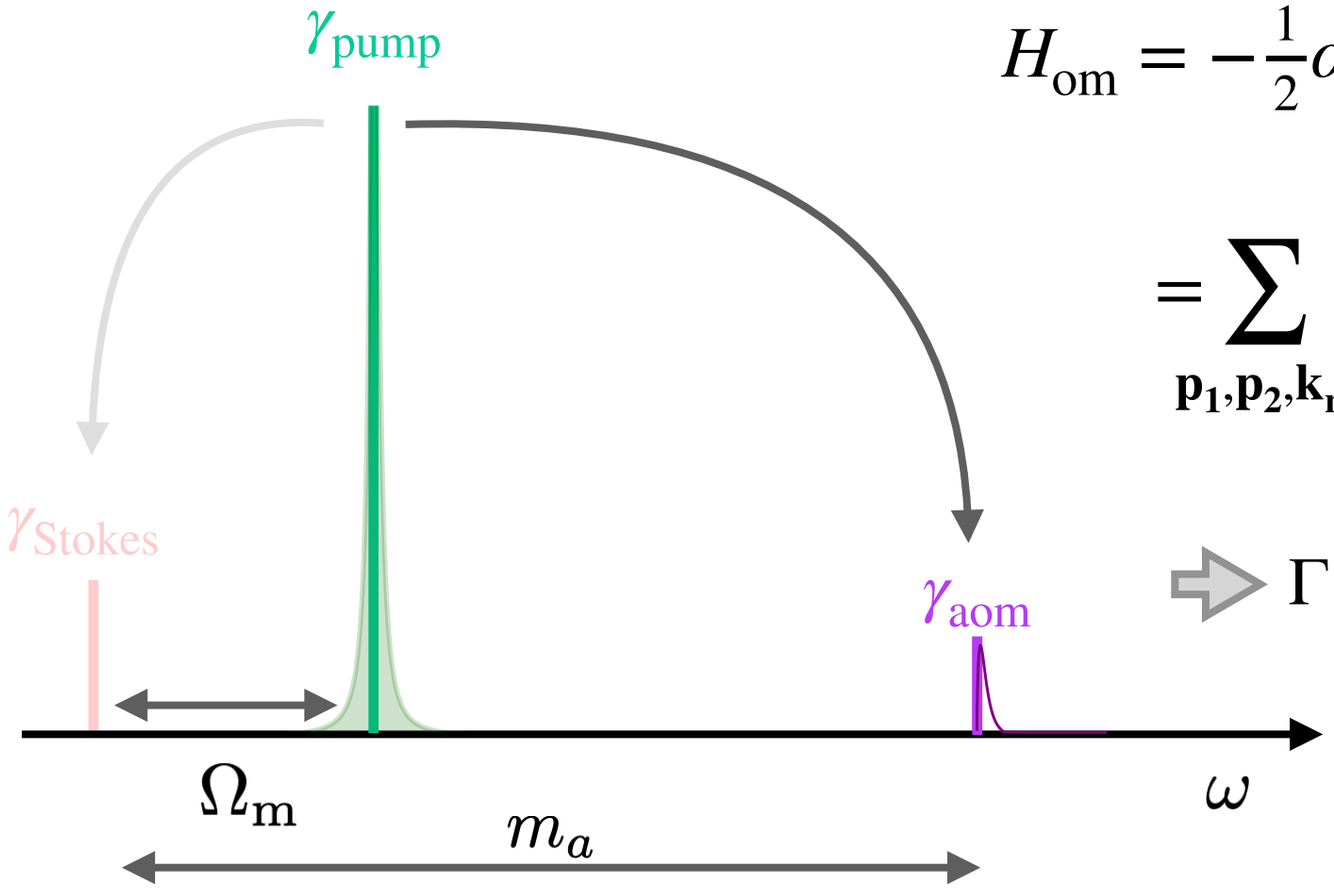
Coherent enhancement: **Phonons**

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

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







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

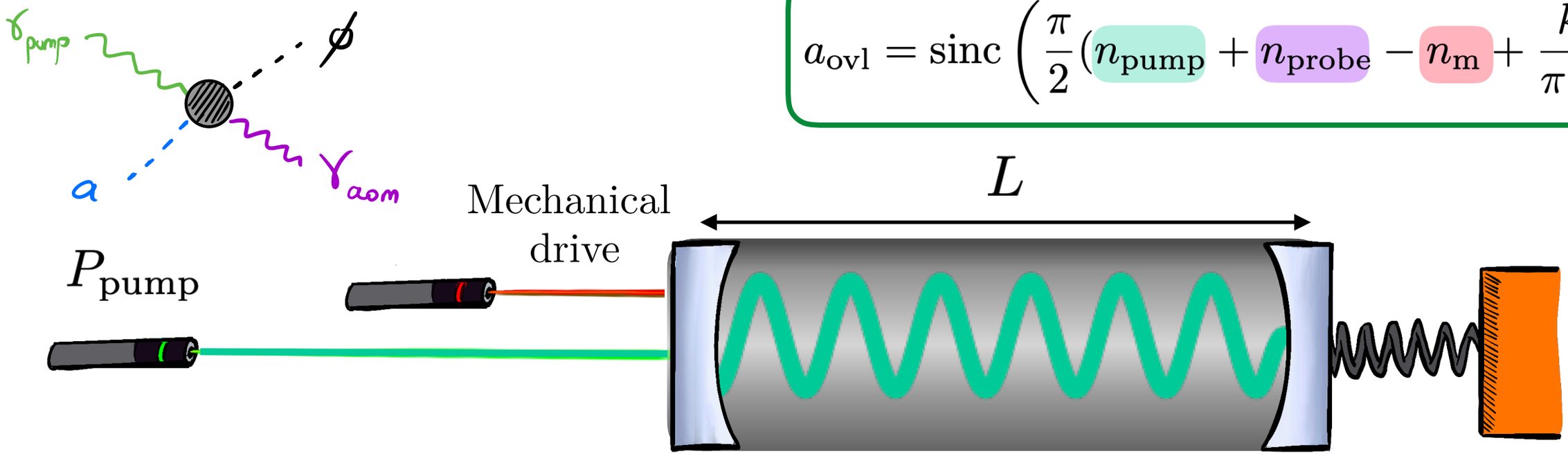
$$= \sum_{\mathbf{p_1},\mathbf{p_2},\mathbf{k_m}} g_0^{(a)} \left(g_{a\gamma\gamma} \frac{\sqrt{2\rho_a}}{m_a} \right) \left(a_{\mathbf{p_1}} a^\dagger_{\mathbf{p_2}} b^\dagger_{\mathbf{k_m}} \right)$$

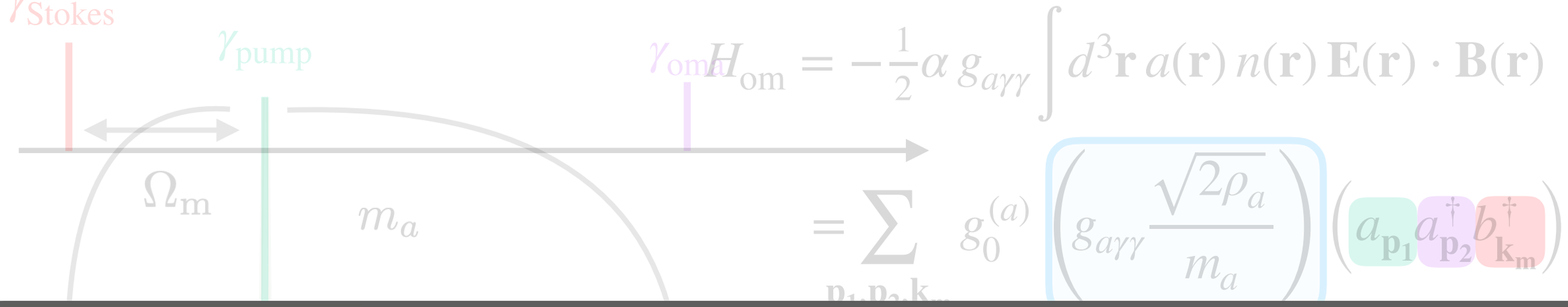
$$\Rightarrow \Gamma \propto |g_0^{(a)}|^2 \left(g^2_{a\gamma\gamma} \frac{\rho_a}{m_a^2} \right) \times N_{\gamma,\rm pump}\; N_\phi^{\rm circ}\,[\Delta_{\rm m}]$$

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

Axioptomechanics: **Rates**

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





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

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

Phonon populated

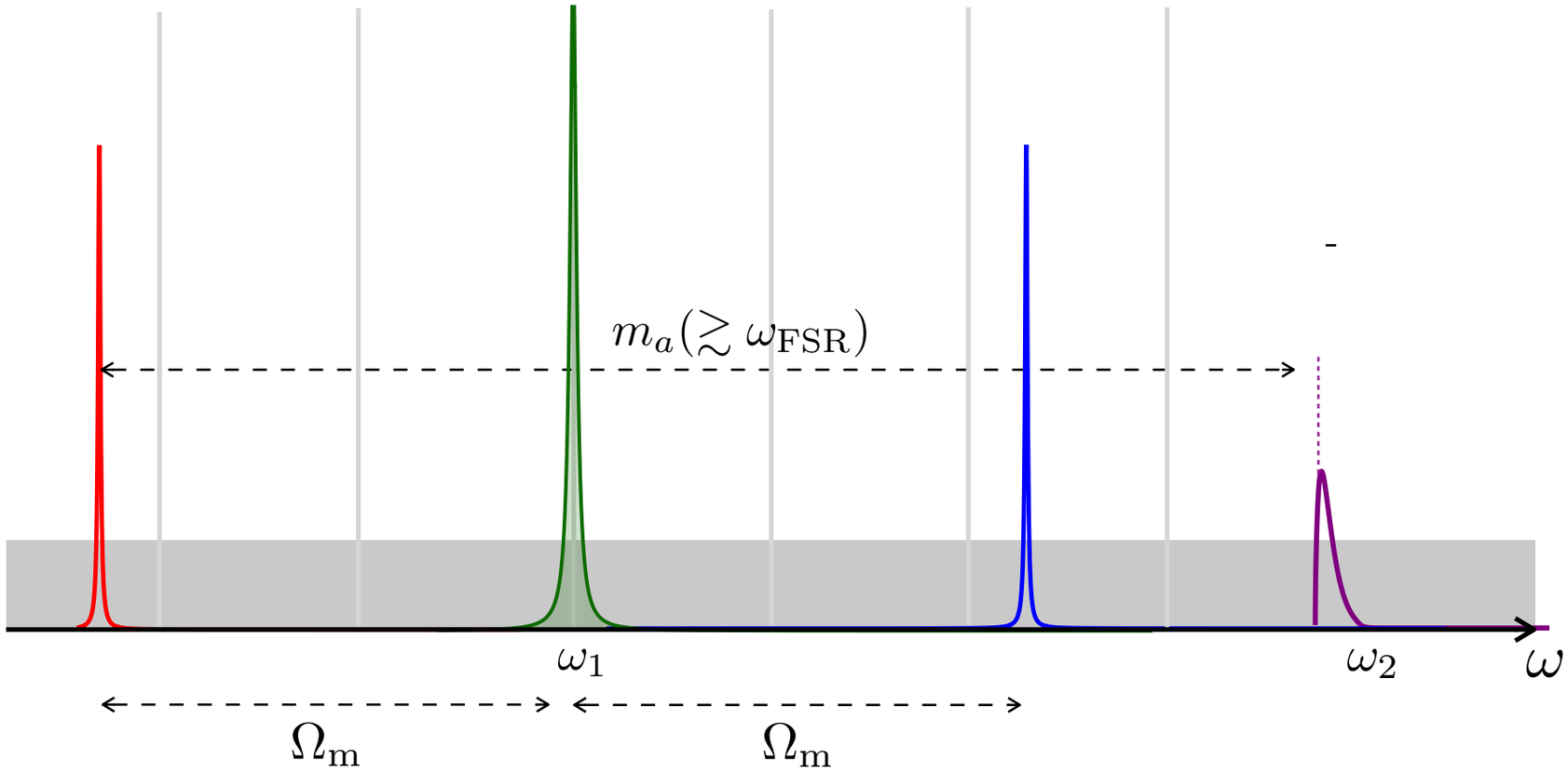
$$\Rightarrow \Gamma = (2\pi)\,|\,g_0^{(a)}\,|^2\left(g_{a\gamma\gamma}^2\frac{\rho_a}{m_a^2}\right)\int d\omega_{\gamma_{\text{aom}}} B_{m_a}(\omega_{\gamma_{\text{aom}}} + \Omega_{\text{m}} - \omega_{\text{pump}}) L(\omega_{\gamma_{\text{aom}}} - \omega_{\text{res}}, \kappa)$$

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

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

Axioptomechanics: **Sensitivity**

$$\mathrm{SNR} = \frac{\Gamma_{\mathrm{sig}}\,(t_{\mathrm{int}}/\tau_a)}{\Gamma_{\mathrm{back}}} > 3$$



Phonon populated

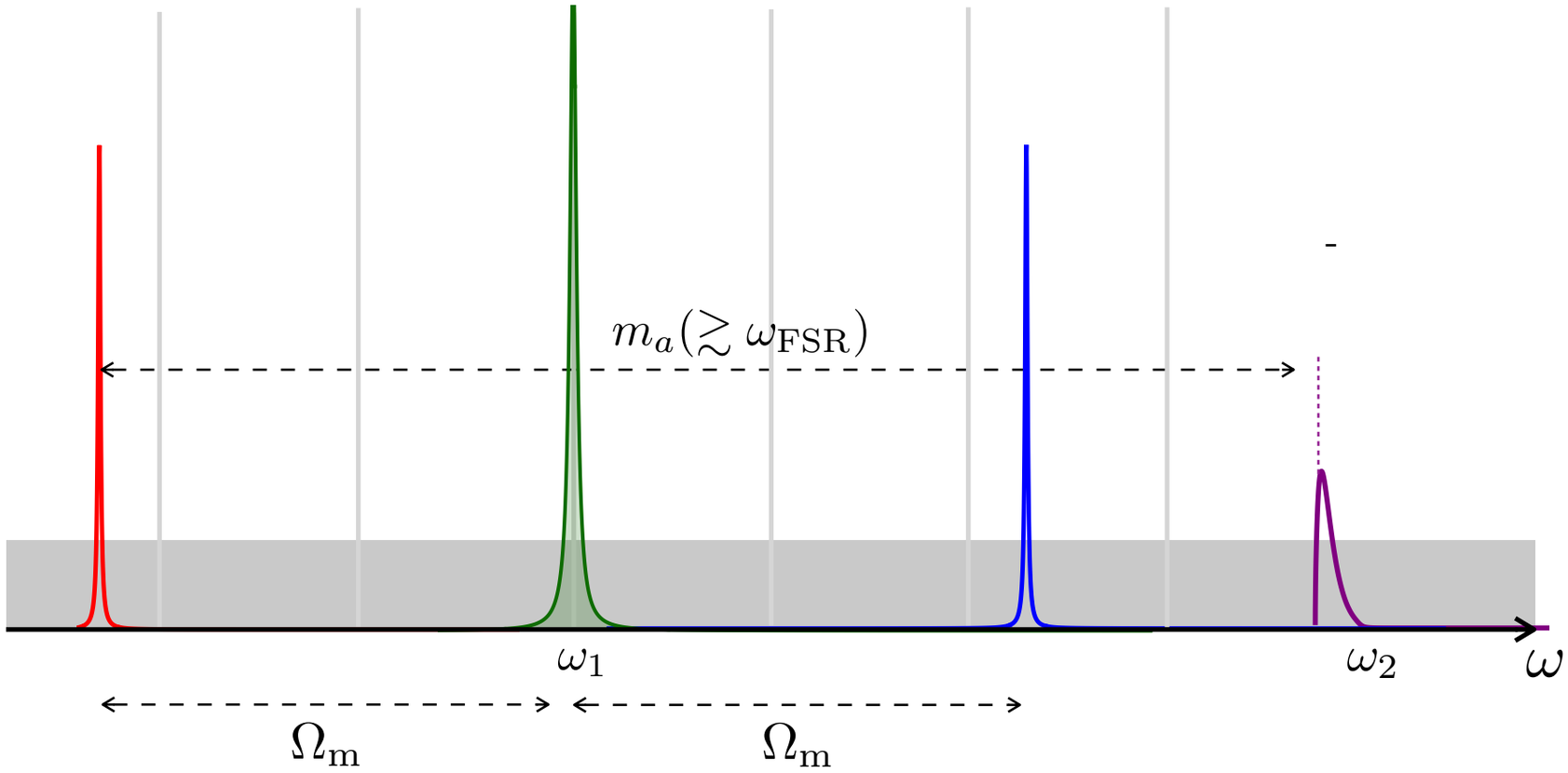
$$\Rightarrow \Gamma = (2\pi)\,|\,g_0^{(a)}\,|^2 \left(g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \right) \int d\omega_{\gamma_{\mathrm{aom}}} B_{m_a}(\omega_{\gamma_{\mathrm{aom}}} + \Omega_{\mathrm{m}} - \omega_{\mathrm{pump}}) L(\omega_{\gamma_{\mathrm{aom}}} - \omega_{\mathrm{res}}, \kappa)$$

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

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

Axioptomechanics: **Sensitivity**

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



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: Numbers

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

He For usual experiments in their lab:

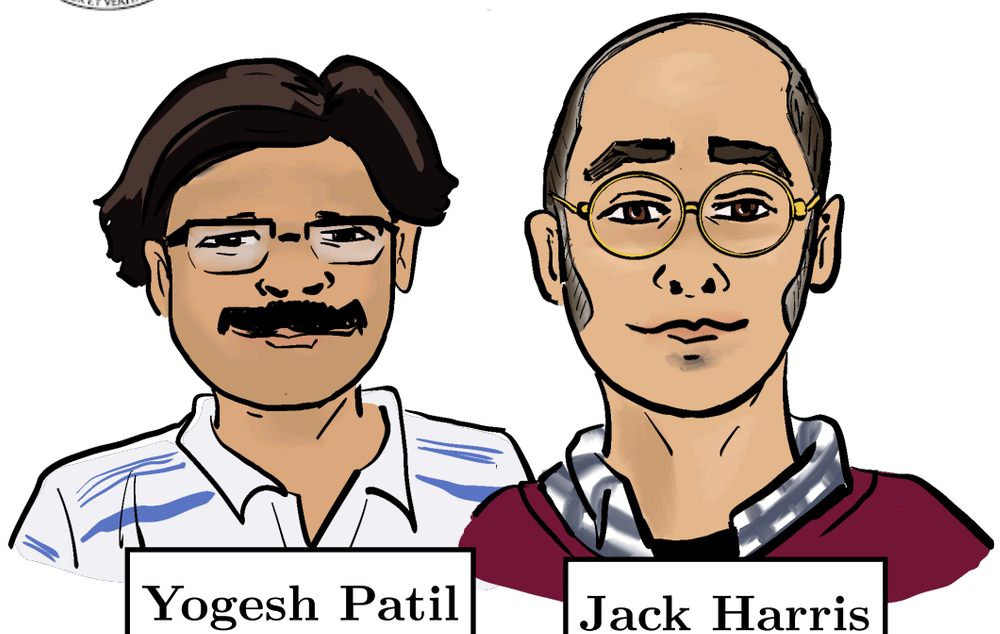
- $N_{\rm pump} \simeq 10^6$
- $N_\phi \simeq 10^5$

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

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

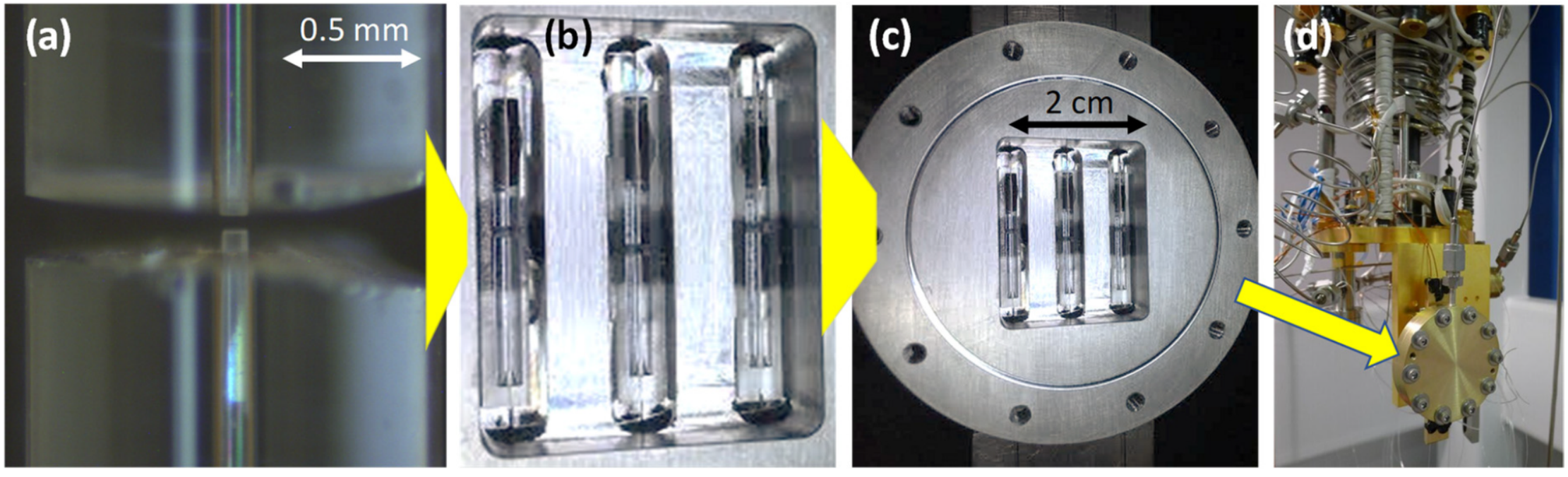
$\mathcal{F}_{\rm opt}/\pi \sim 10^5$

Yale University Jack Harris Lab



Yogesh Patil
Yale University

Jack Harris
Yale University



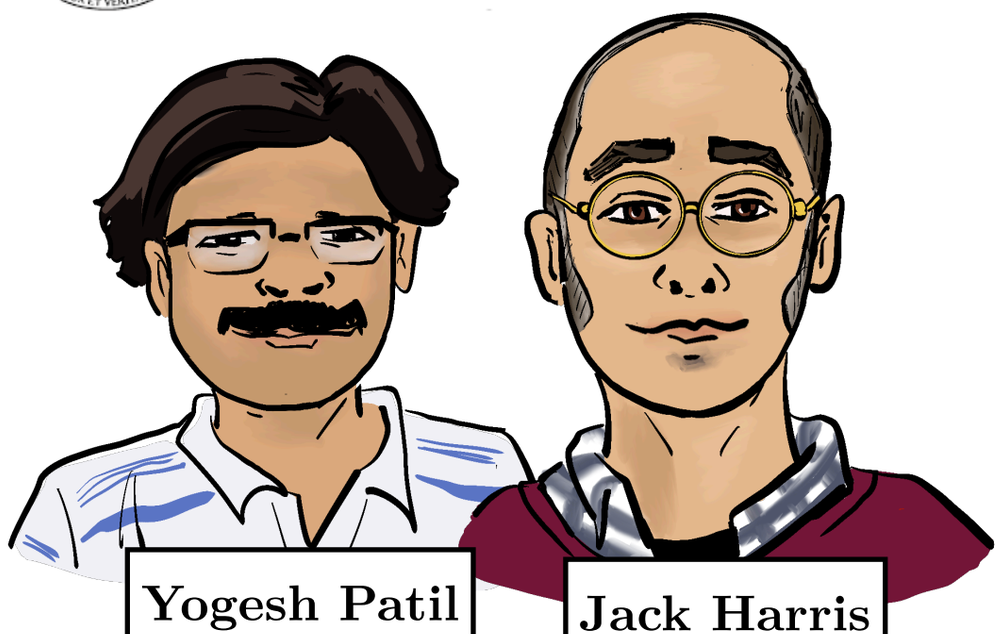
Axioptomechanics: Numbers

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

He What could be feasible to achieve:

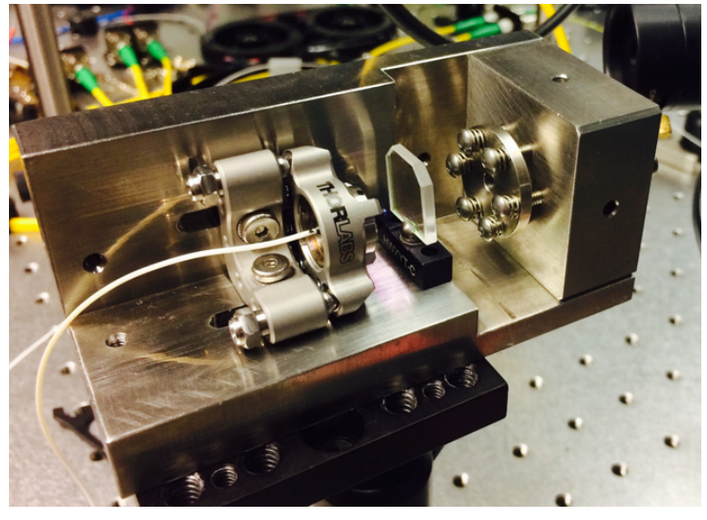
- $N_{\rm pump} \simeq 10^{17}$ $\quad P_{\rm pump} \sim 1$ W
- $N_\phi \simeq 10^{14}$ $\quad L \sim 1$ m
- $\mathcal{F}_{\rm opt}/\pi \sim 10^6$

Yale University Jack Harris Lab



Yogesh Patil
Yale University

Jack Harris
Yale University



RadioOptomechanics: Numbers

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

He What could be feasible to achieve:

- $N_{\text{pump}} \simeq 10^{17}$ $\quad P_{\text{pump}} \sim 1\ \text{W}$
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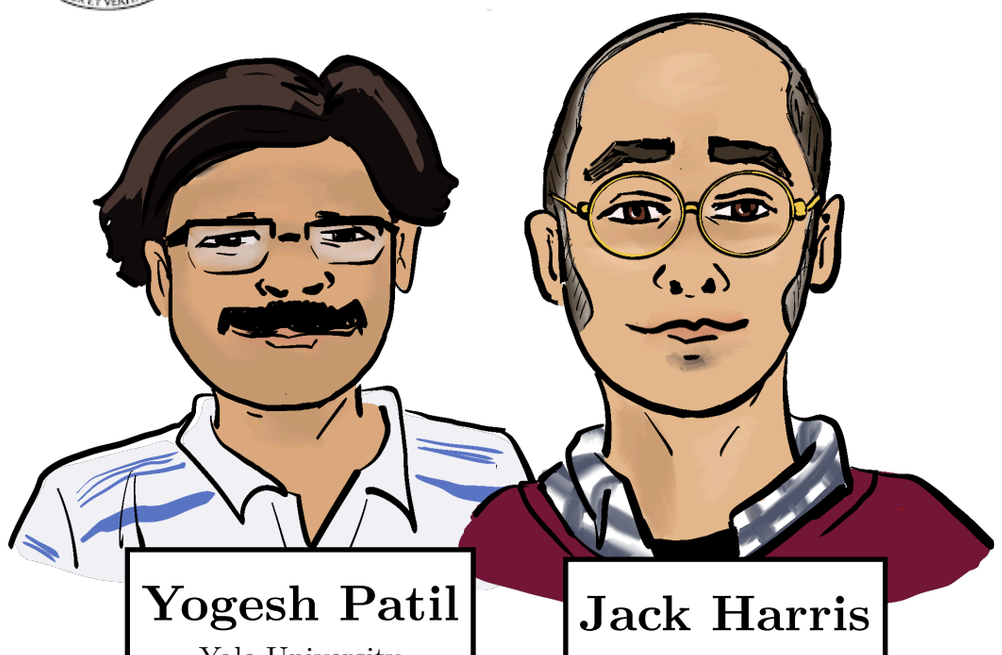
- $\mathcal{F}_{\text{opt}}/\pi \sim 10^6$

Keith Schwab
Caltech

Yale University Jack Harris Lab



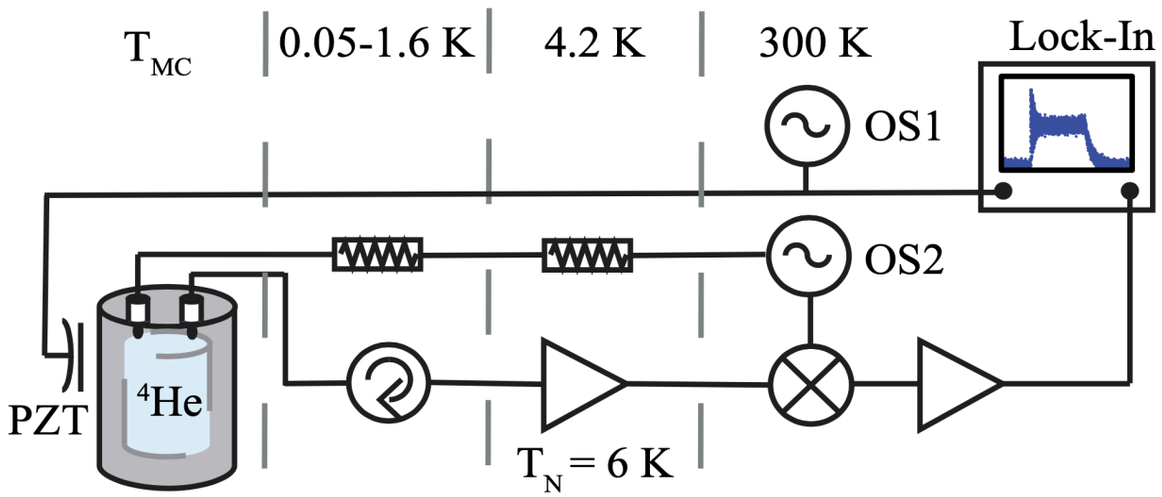
Yogesh Patil
Yale University

Jack Harris
Yale University

[A. L. De Lorenzo, K. C. Schwab, 2017]

He

- $N_{\text{pump}} \simeq 10^{12}$ $\quad P_{\text{pump}} \sim 1\,\mu\text{W}$
- $N_\phi \simeq 10^{15}$ $\quad L \sim 4\,\text{cm}$
- $\mathcal{F}_{\text{opt}}/\pi \sim 10^8$



Axioptomechanics: Numbers

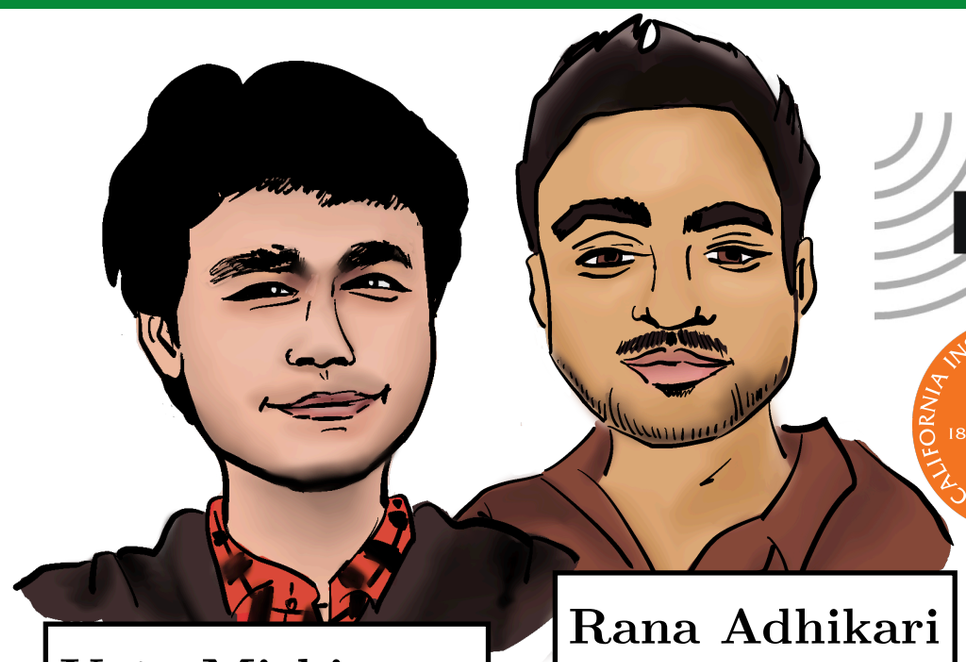
Si What could be feasible to achieve:

- $N_{\rm pump} \simeq 10^{16}$
- $N_\phi \simeq 10^{19}$

$P_{\rm pump} \sim 1\,{\rm W}$

$L \sim 10\,{\rm cm}$

$\mathcal{F}_{\rm opt}/\pi \sim 10^6$



Yuta Michimura
Caltech, U. Tokyo

Rana Adhikari
Caltech

LIGO

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Axioptomechanics: Numbers

Si What could be feasible to achieve:

- $N_{\rm pump} \simeq 10^{16}$ $\quad P_{\rm pump} \sim 1\ {\rm W}$
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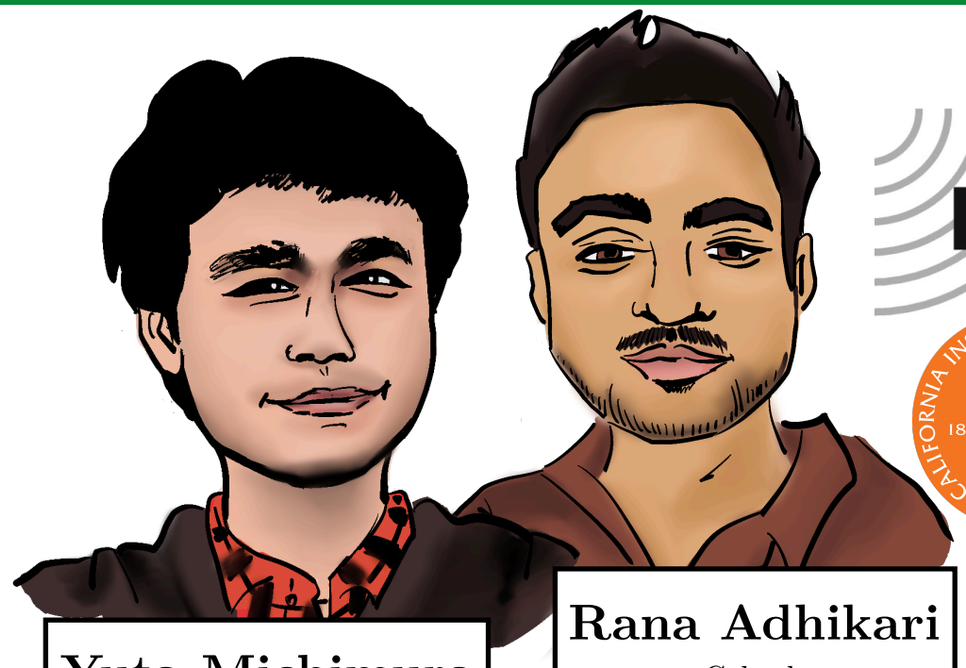
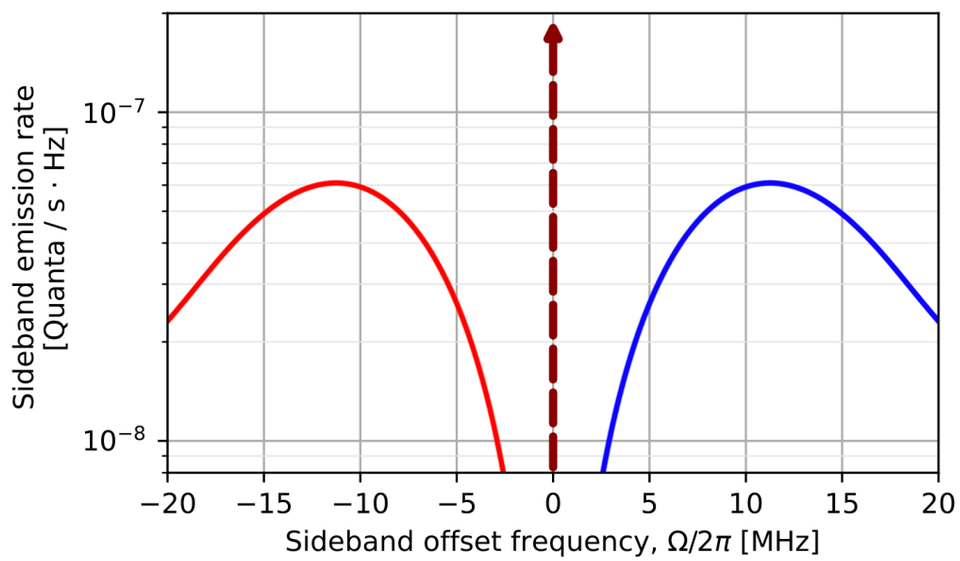


Yuta Michimura
Caltech, U. Tokyo

Rana Adhikari
Caltech

Lee McCuller
Caltech,

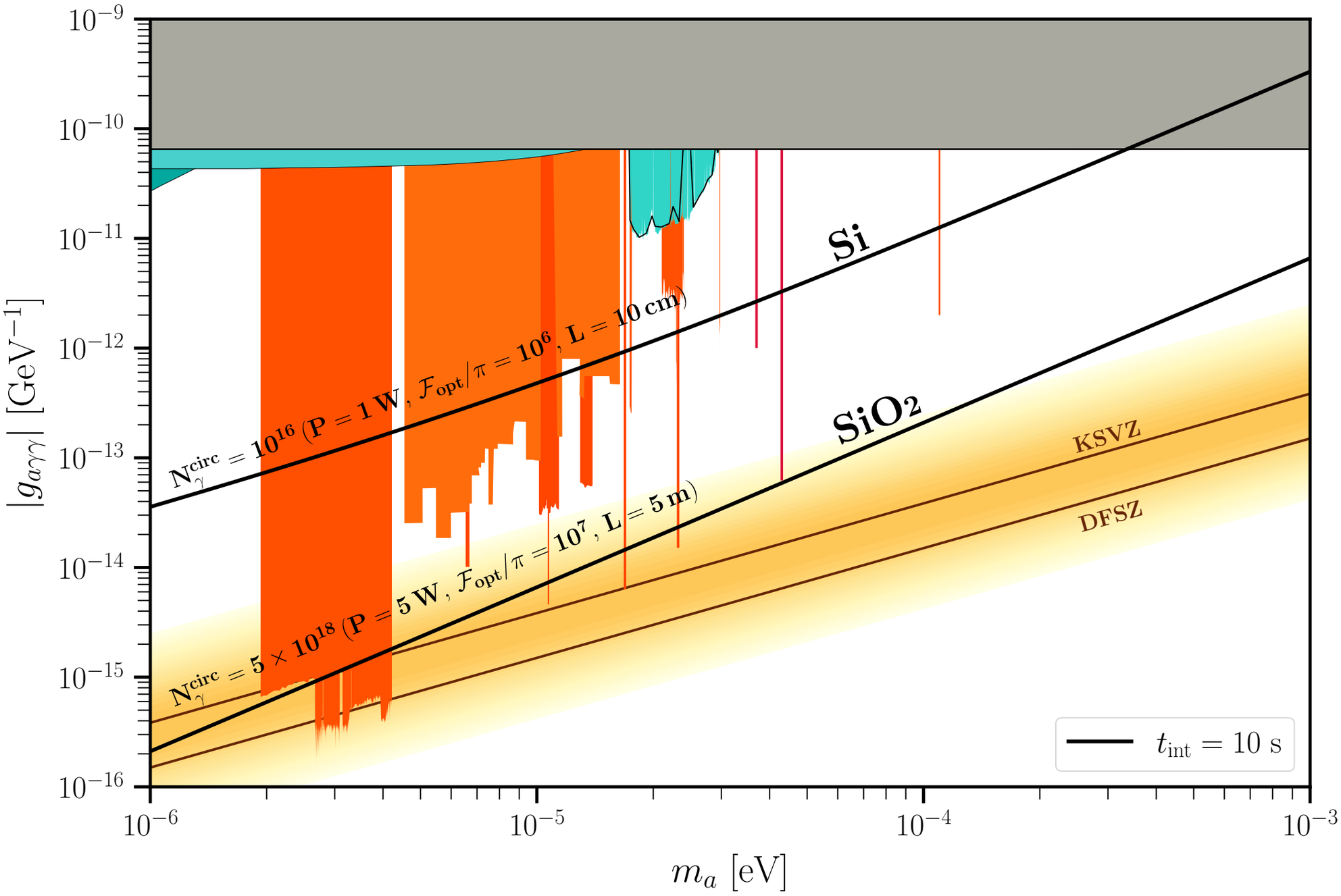
[L. McCuller, 2022]



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

Sensitivity: heavy axion regime

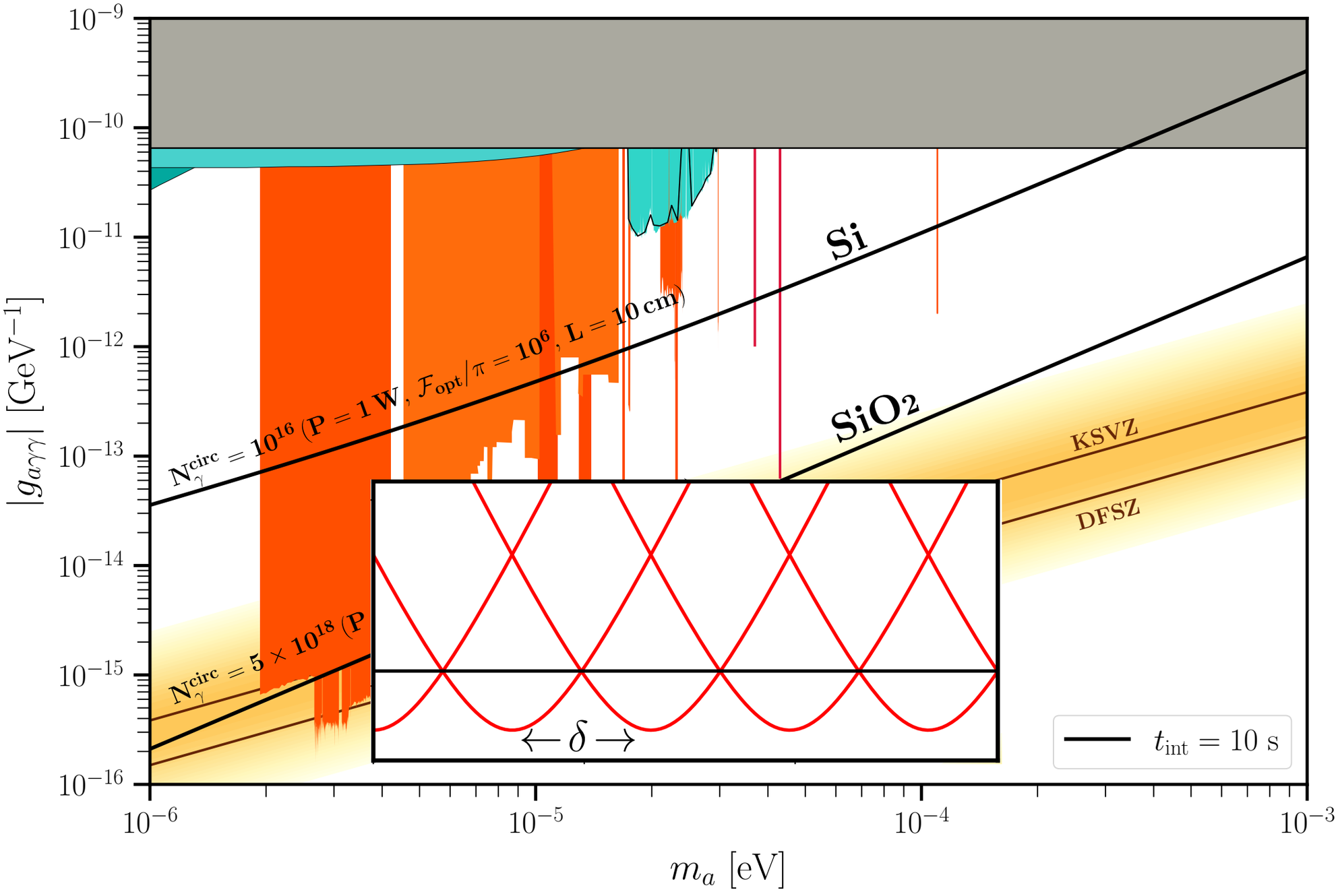
[**CM**, Y. Wang, K. M. Zurek. 2022]



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

Sensitivity: heavy axion regime

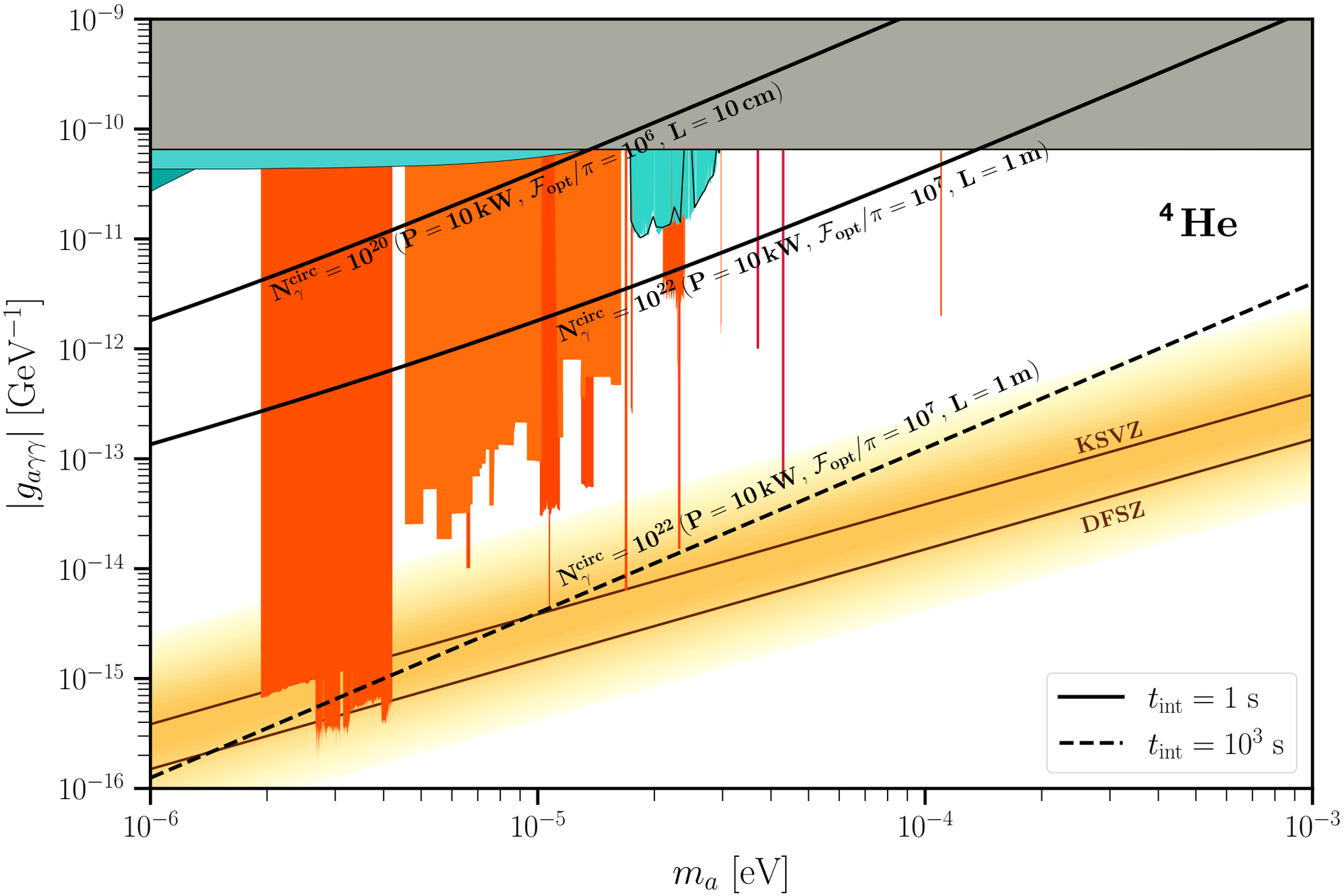
[**CM**, Y. Wang, K. M. Zurek. 2022]



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

Sensitivity: heavy axion regime

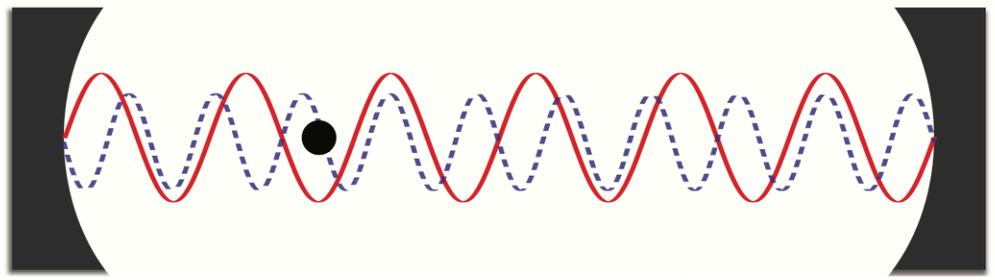
[**CM**, Y. Wang, K. M. Zurek. 2022]



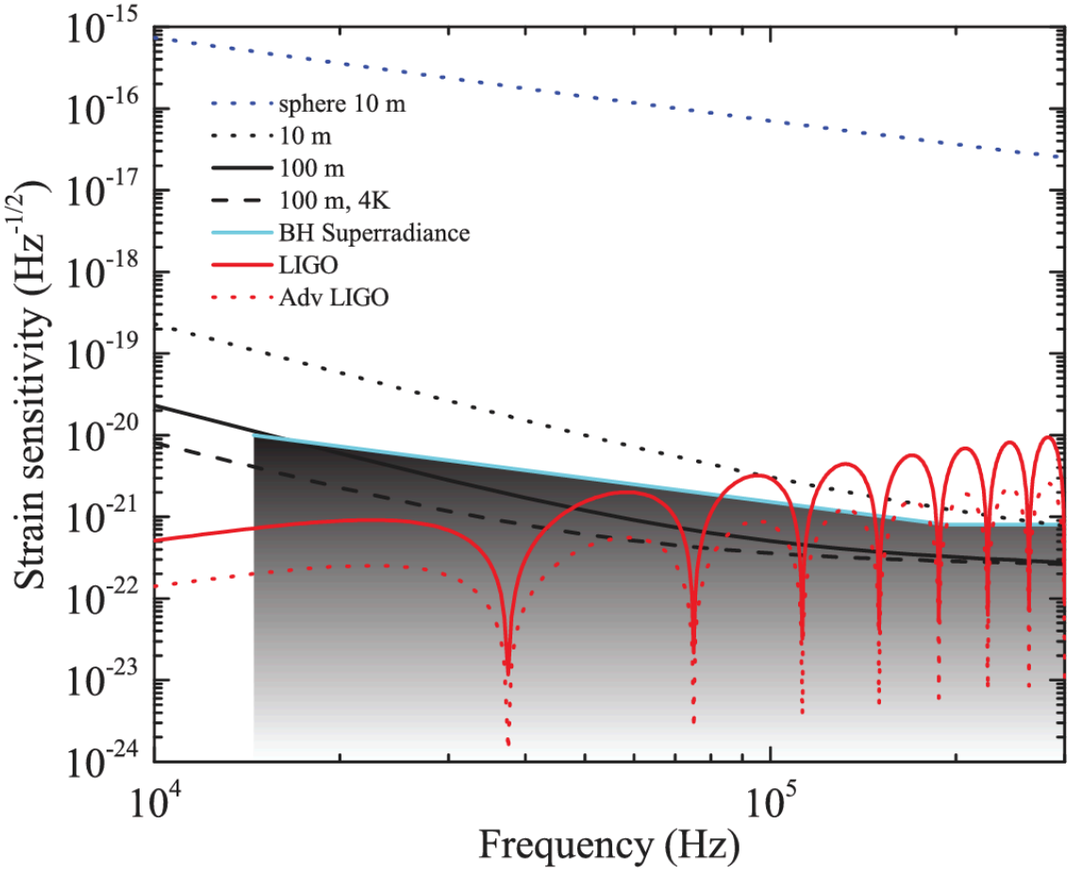
$$g_{a\gamma\gamma}^{\phi-\rm pop} \propto \frac{\epsilon_r + 2}{\epsilon_r - 1}\epsilon_r^{1/2}\frac{1}{\mathcal{F}_{\rm opt}^{1/2}}\frac{1}{L^{1/2}}\frac{1}{\omega_{\rm opt}^{1/2}}\frac{1}{P_{\rm pump}^{1/2}}\frac{m_a^{3/2}}{\rho_a^{1/2}}\Gamma_{\rm DCR}^{1/2}$$

Optomechanics

High-Frequency Gravitational Waves with Optically Levitated Sensors
[Arvanitaki, Geraci, 2013]



$$F_{gw} = -\frac{m\omega_{gw}^2}{2}(x_s - \ell_m)h_o \cos(\omega_{gw}t + \Delta\phi)$$



Optomechanics

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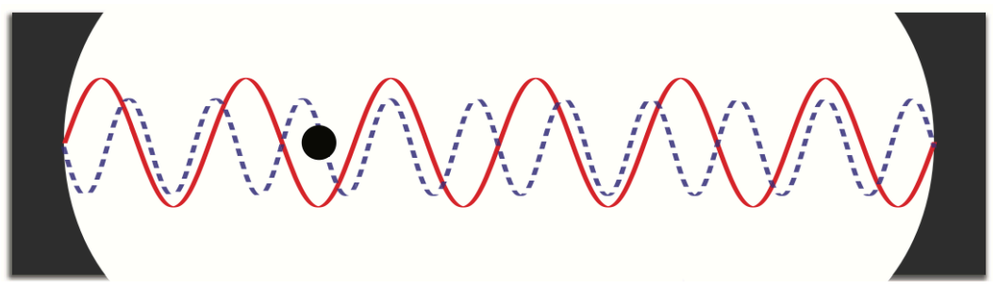
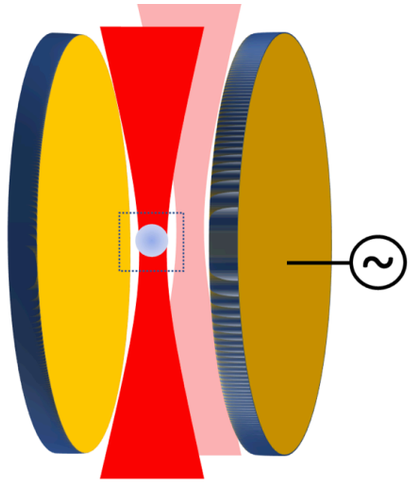
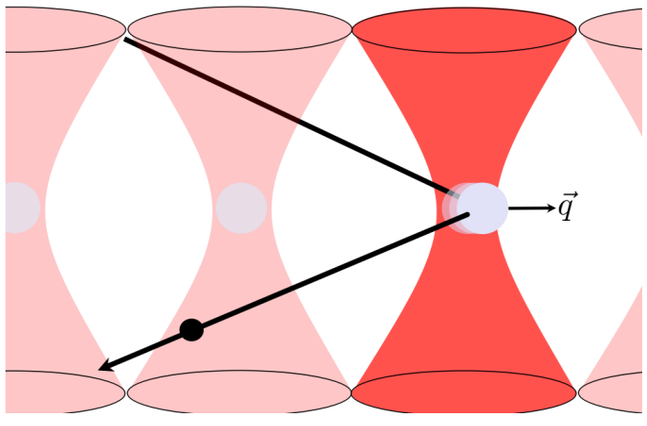


Dark Matter searches with optically levitated sensors

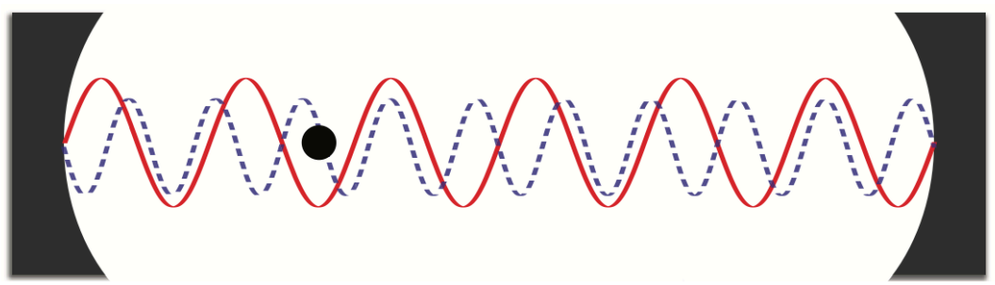
[Monteiro et al., 2020]
[Afek, et. al., 2021]
[Carney, et al., 2021]
[Afek, Carney, Moore, 2022]





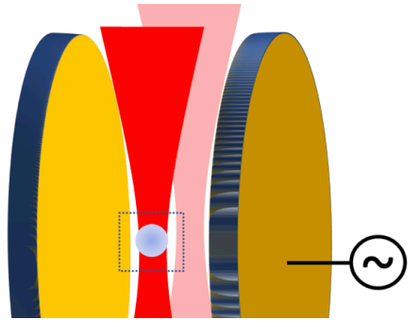
Optomechanics

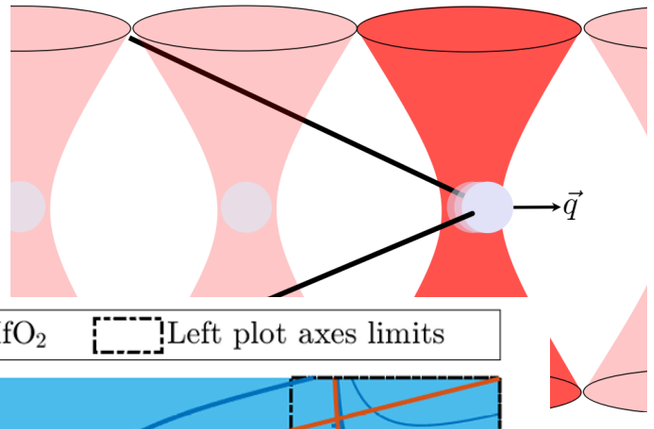
High-Frequency Gravitational Waves with Optically Levitated Sensors
[Arvanitaki, Geraci, 2013]

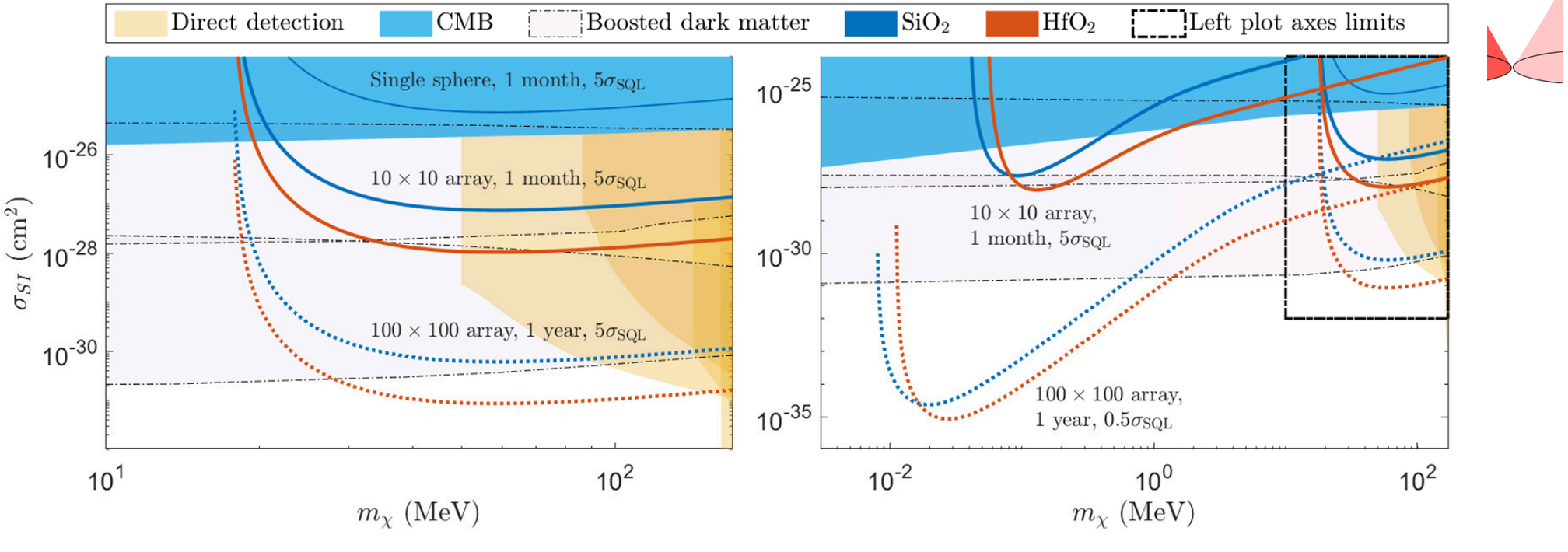


Dark Matter searches with optically levitated sensors

[Monteiro et al., 2020]
[Afek, et. al., 2021]
[Carney, et al., 2021]
[Afek, Carney, Moore, 2022]

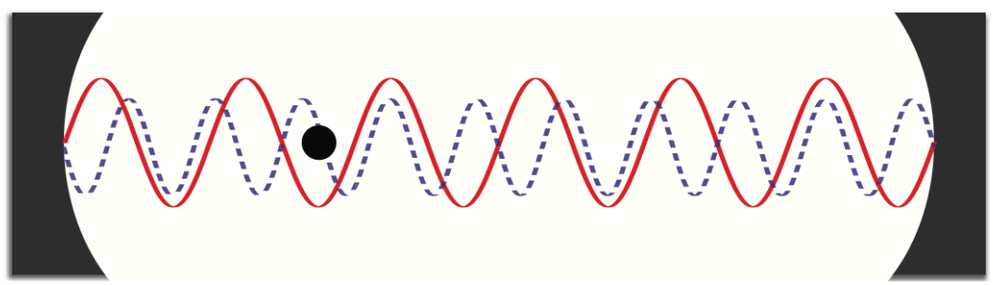






Optomechanics

High-Frequency Gravitational Waves with Optically Levitated Sensors
[Arvanitaki, Geraci, 2013]



Dark Matter searches with optically levitated sensors
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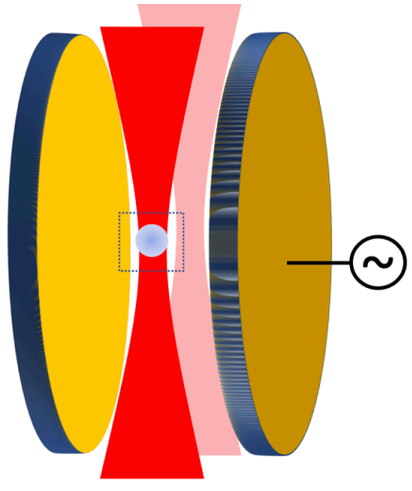
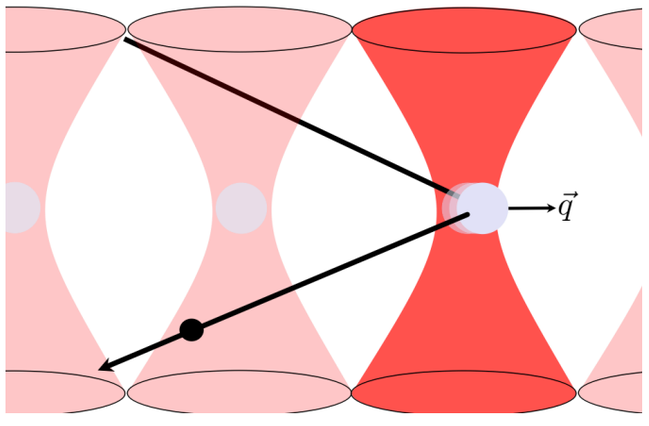
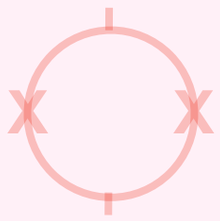




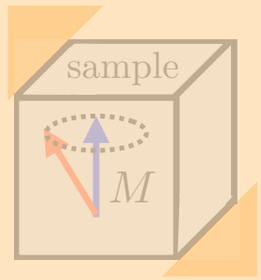
Axion searches via the *piezoaxionic* effect
[Arvanitaki, Madden, et al., 2023]

Quantum Sensing: examples

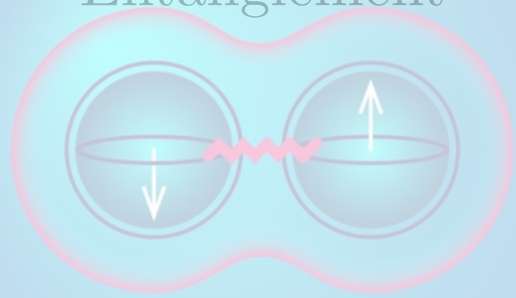
SQUID



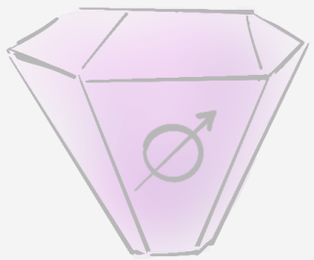
NMR sensors



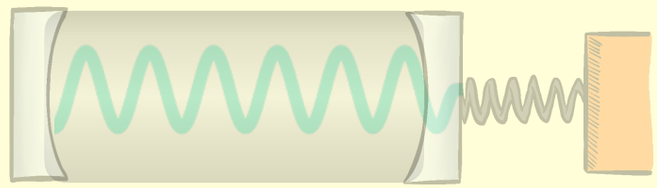
Entanglement



NV center ensembles

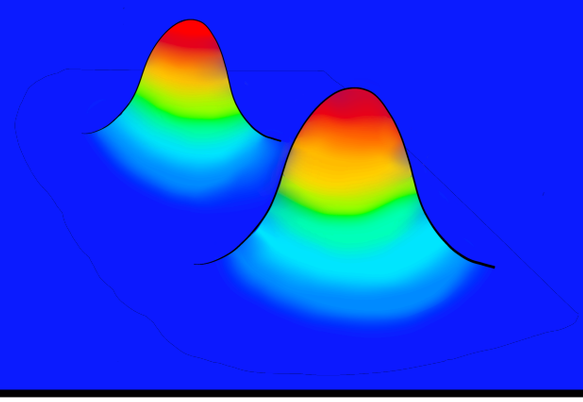


Optomechanics



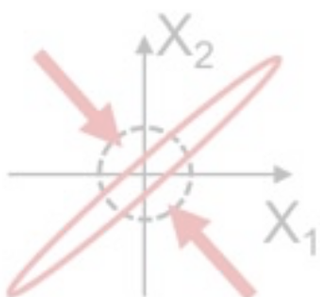
TES
ADP, MKIDs
SNSPDs
QND

Atom interferometers



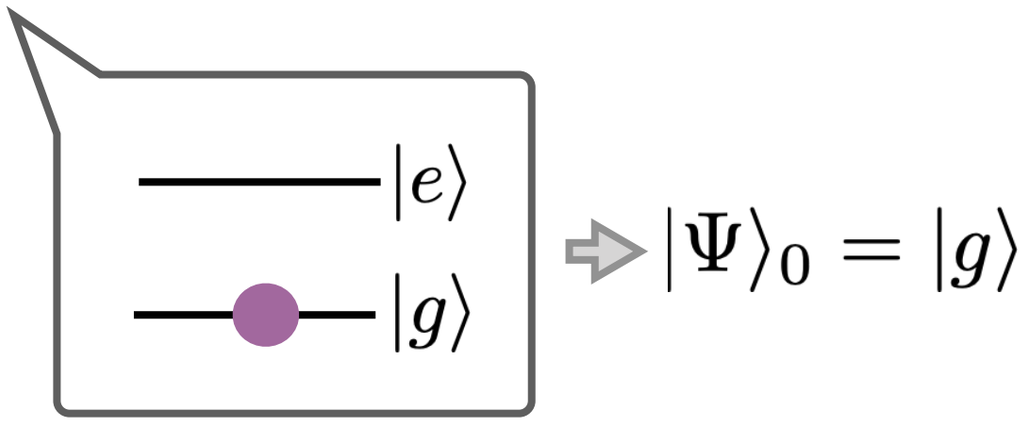
Atom clocks

Squeezing



AIs: the Principle

Review: arXiv:2003.12516



AIs: the Principle

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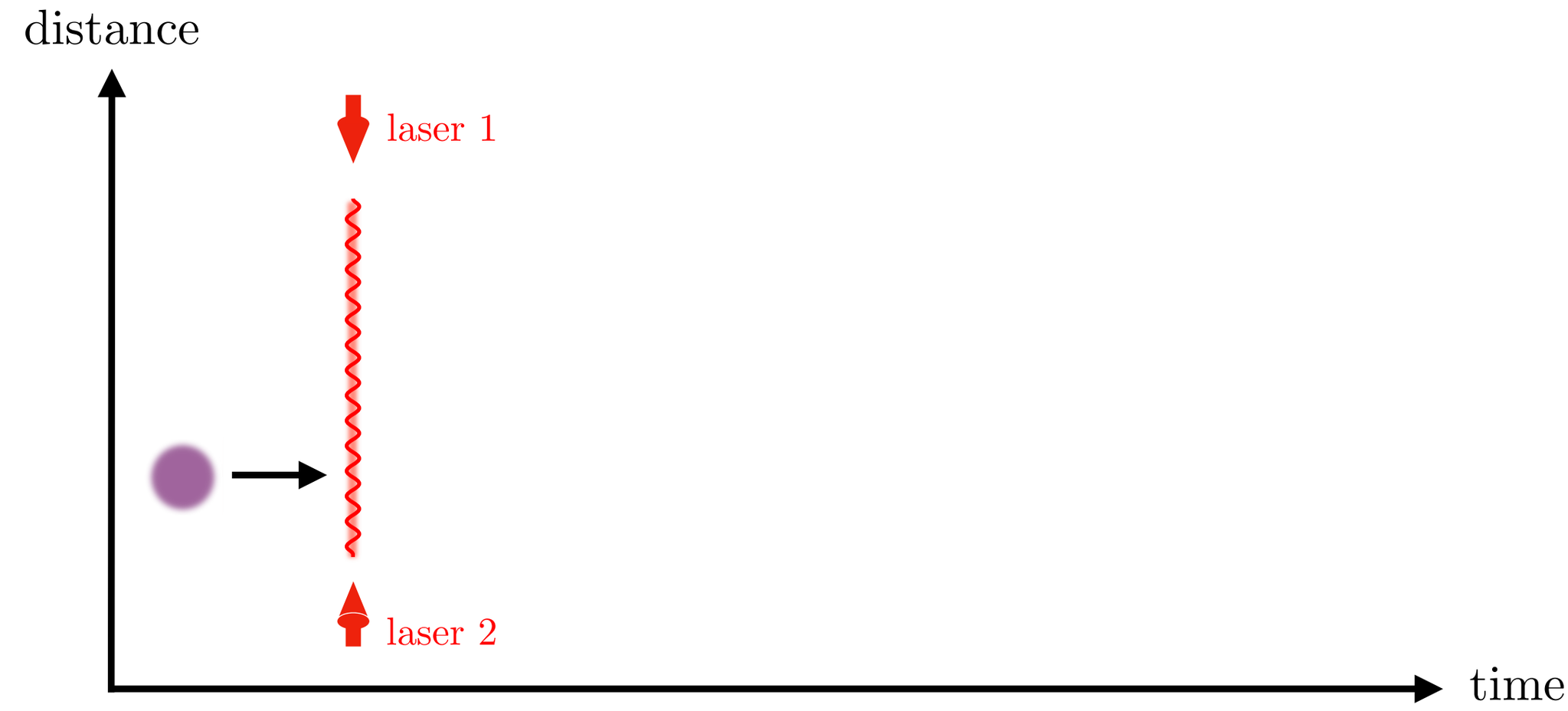
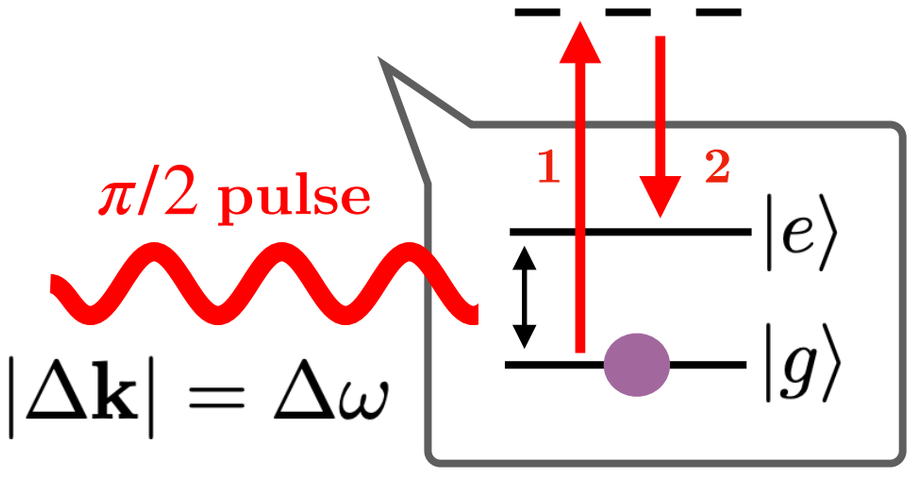
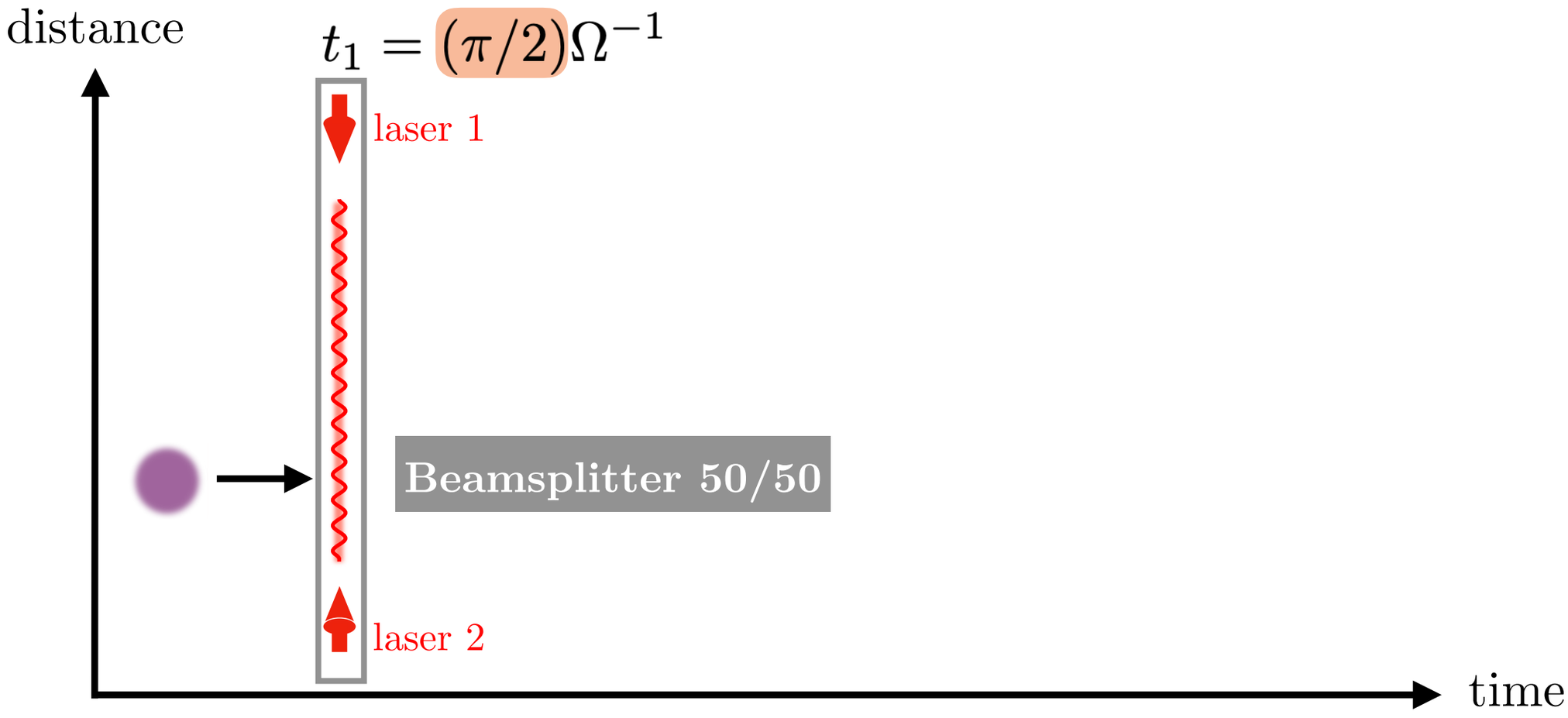


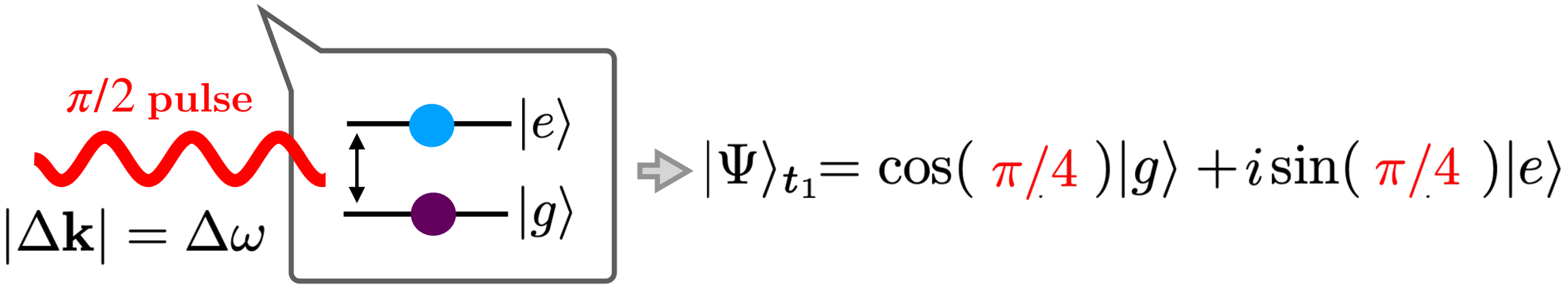


$$|\Psi\rangle_t = \cos(\Omega t/2)|g\rangle + i\sin(\Omega t/2)|e\rangle$$

AIs: the Principle

Review: arXiv:2003.12516





AIs: the Principle

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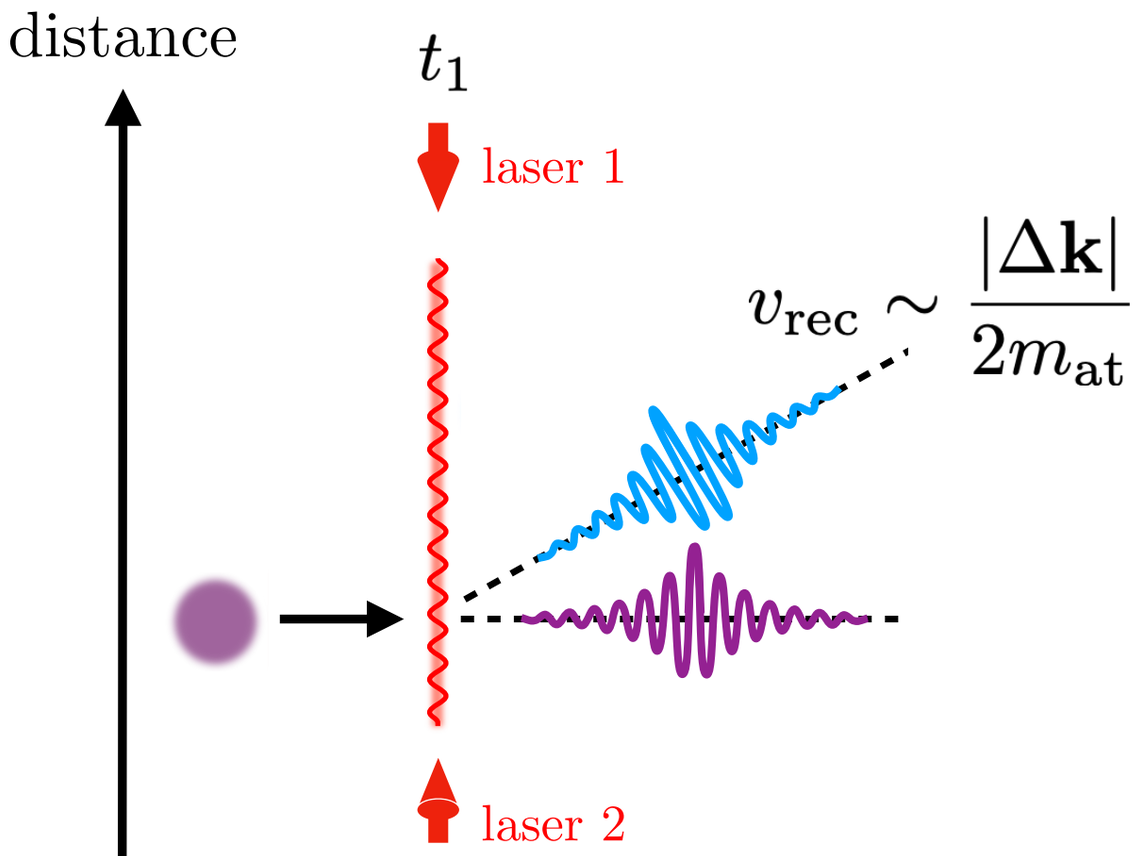
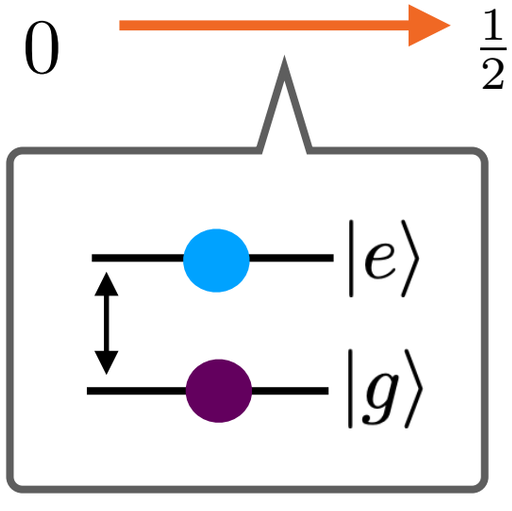


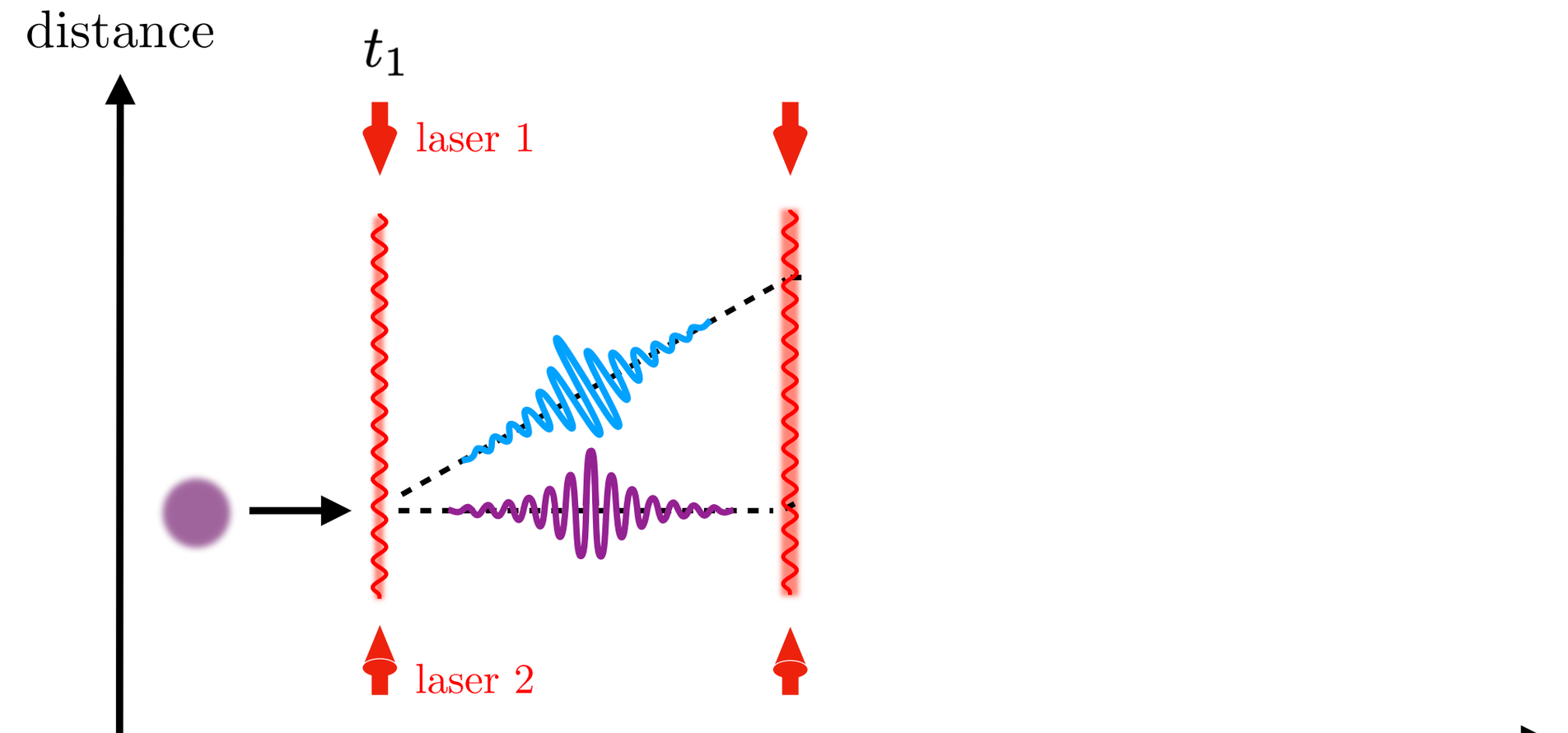


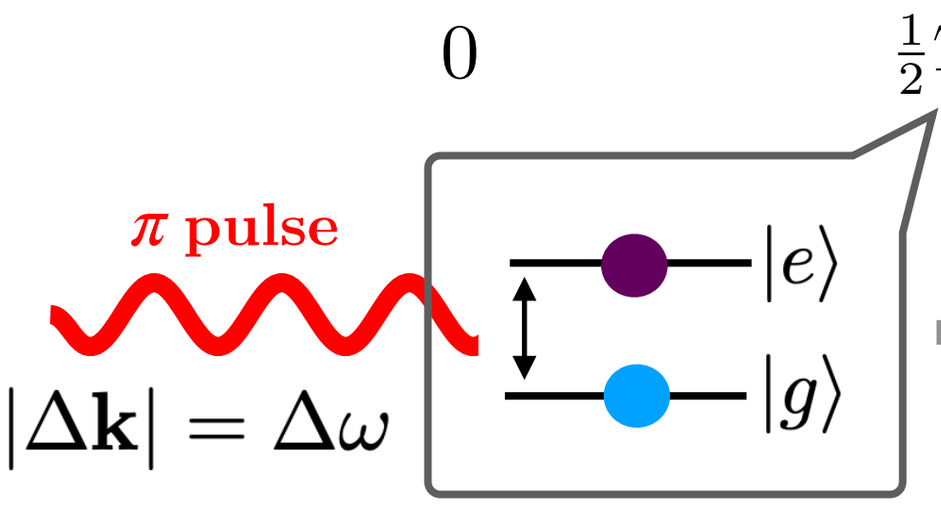
$$|\Delta\mathbf{k}| = \Delta\omega$$

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

AIs: the Principle

Review: arXiv:2003.12516

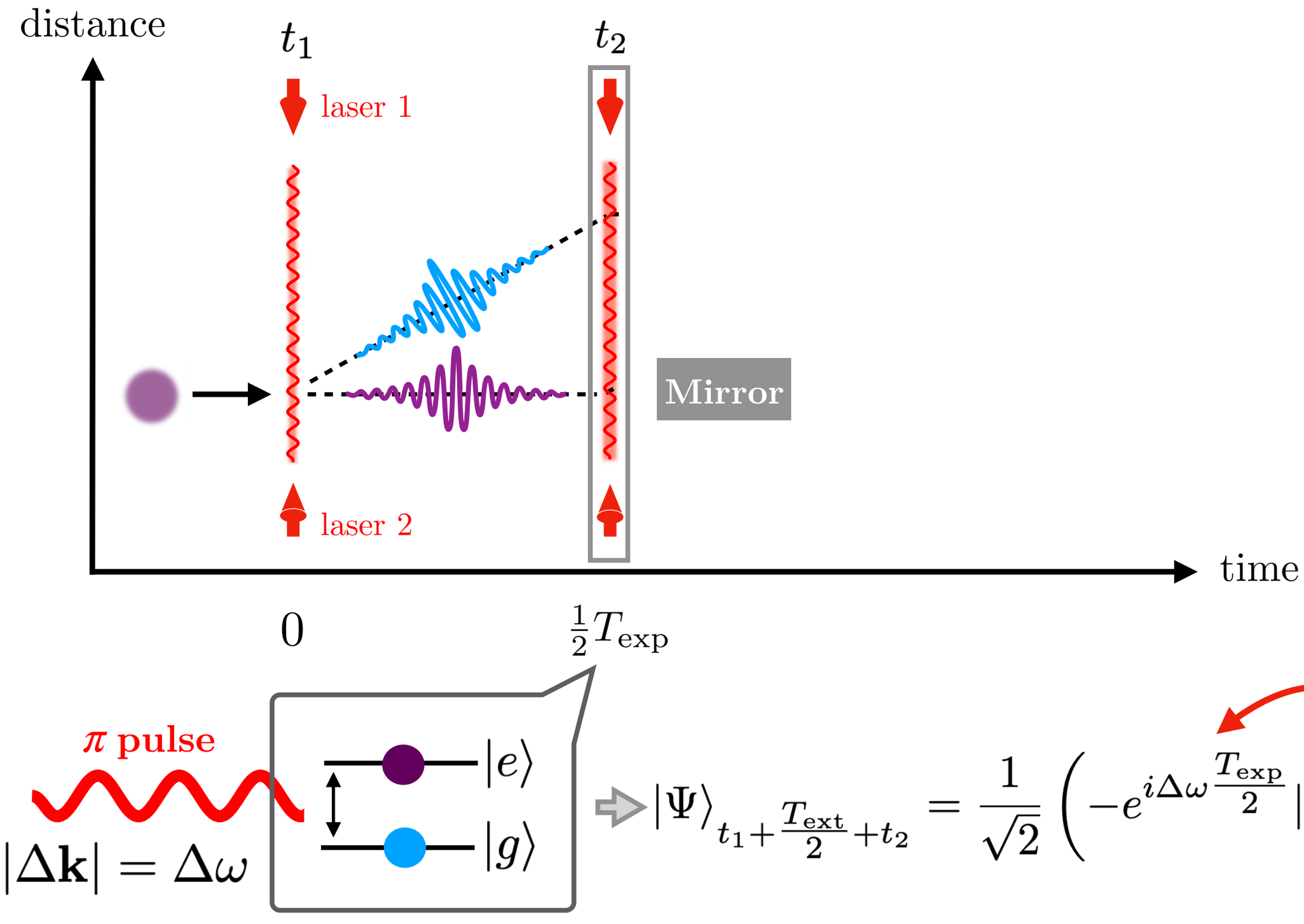




$$|\Psi\rangle_{t_1+\frac{T_{\rm ext}}{2}+t_2} = \frac{1}{\sqrt{2}}\left(-e^{i\Delta\omega\frac{T_{\rm exp}}{2}}|g\rangle + i|e\rangle\right)$$

AIs: the Principle

Review: arXiv:2003.12516



AIs: the Principle

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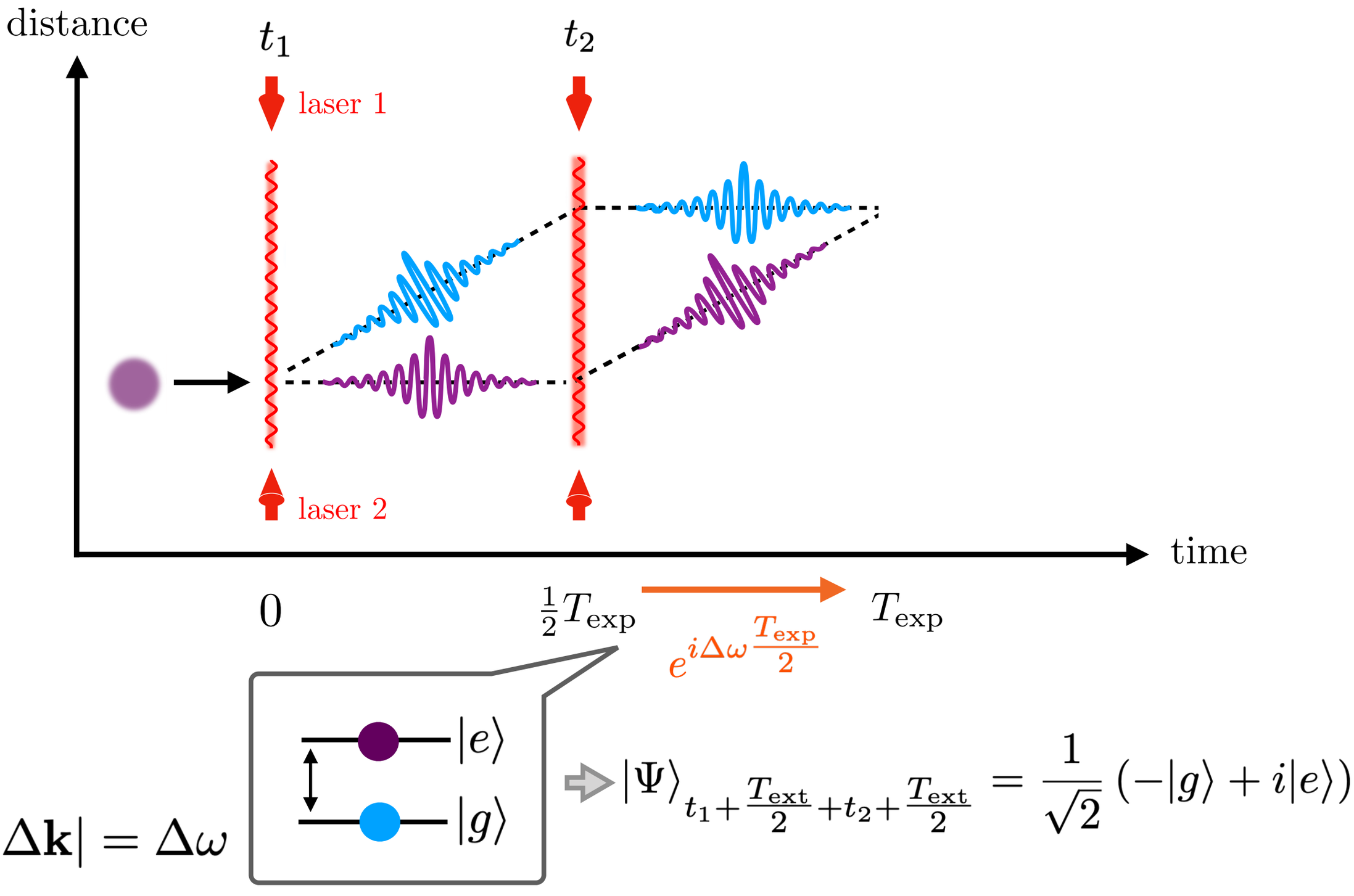

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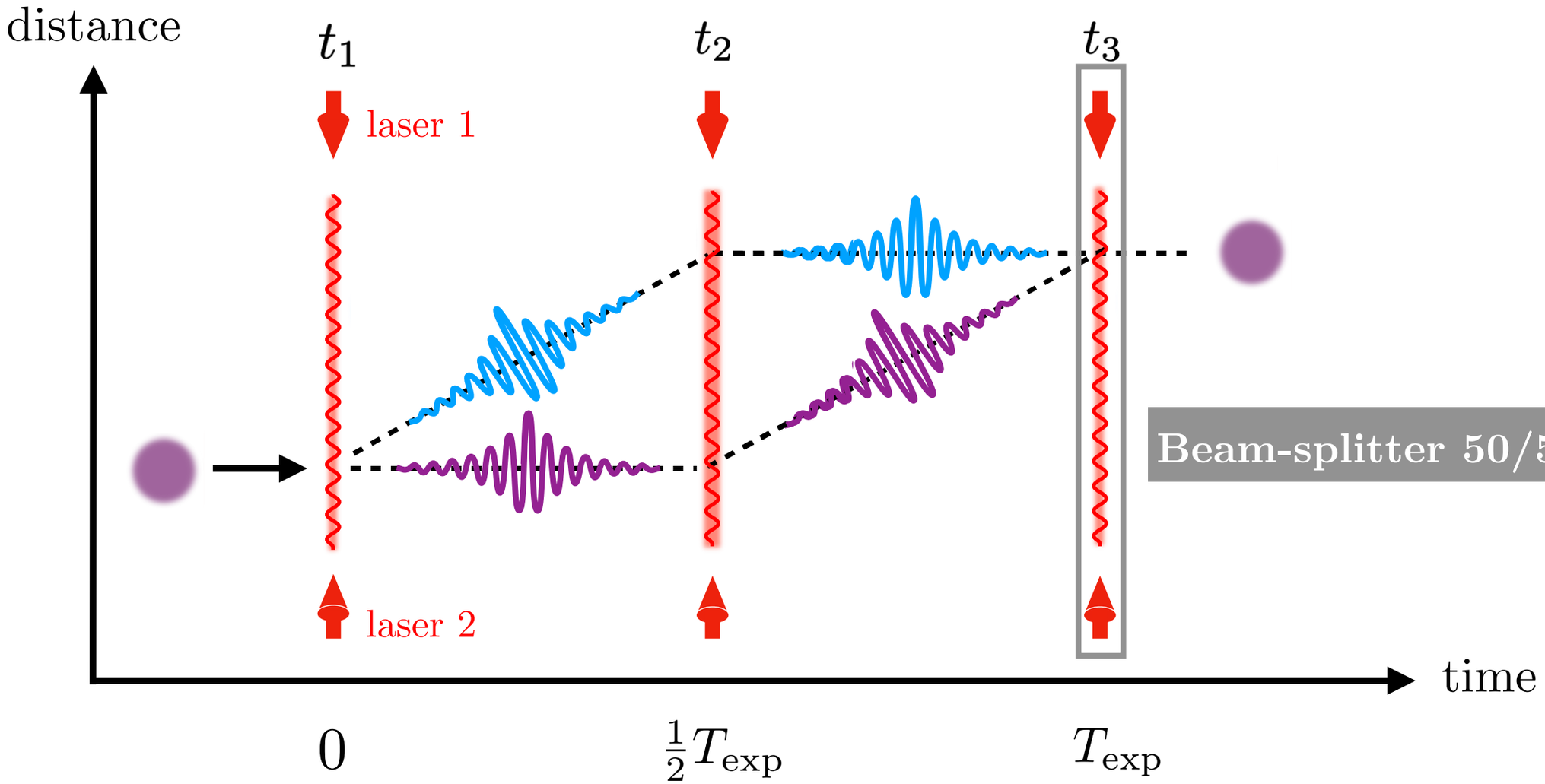

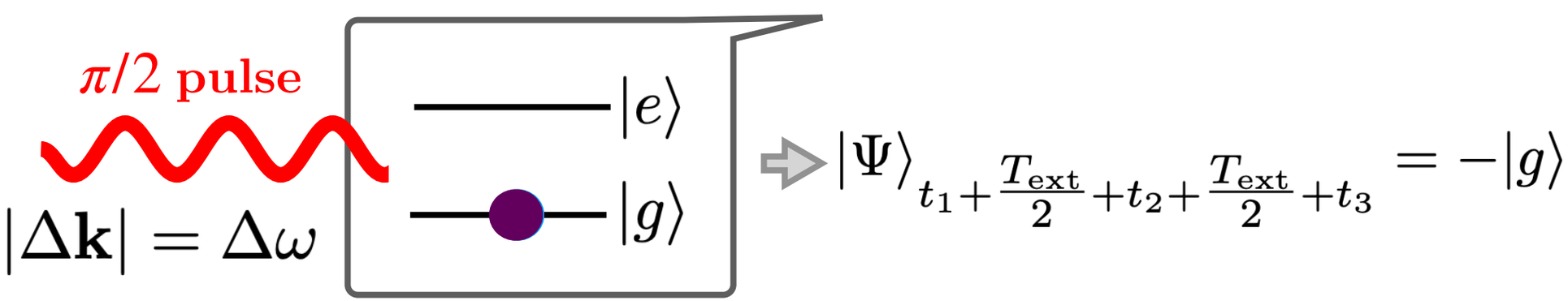

AIs: the Principle

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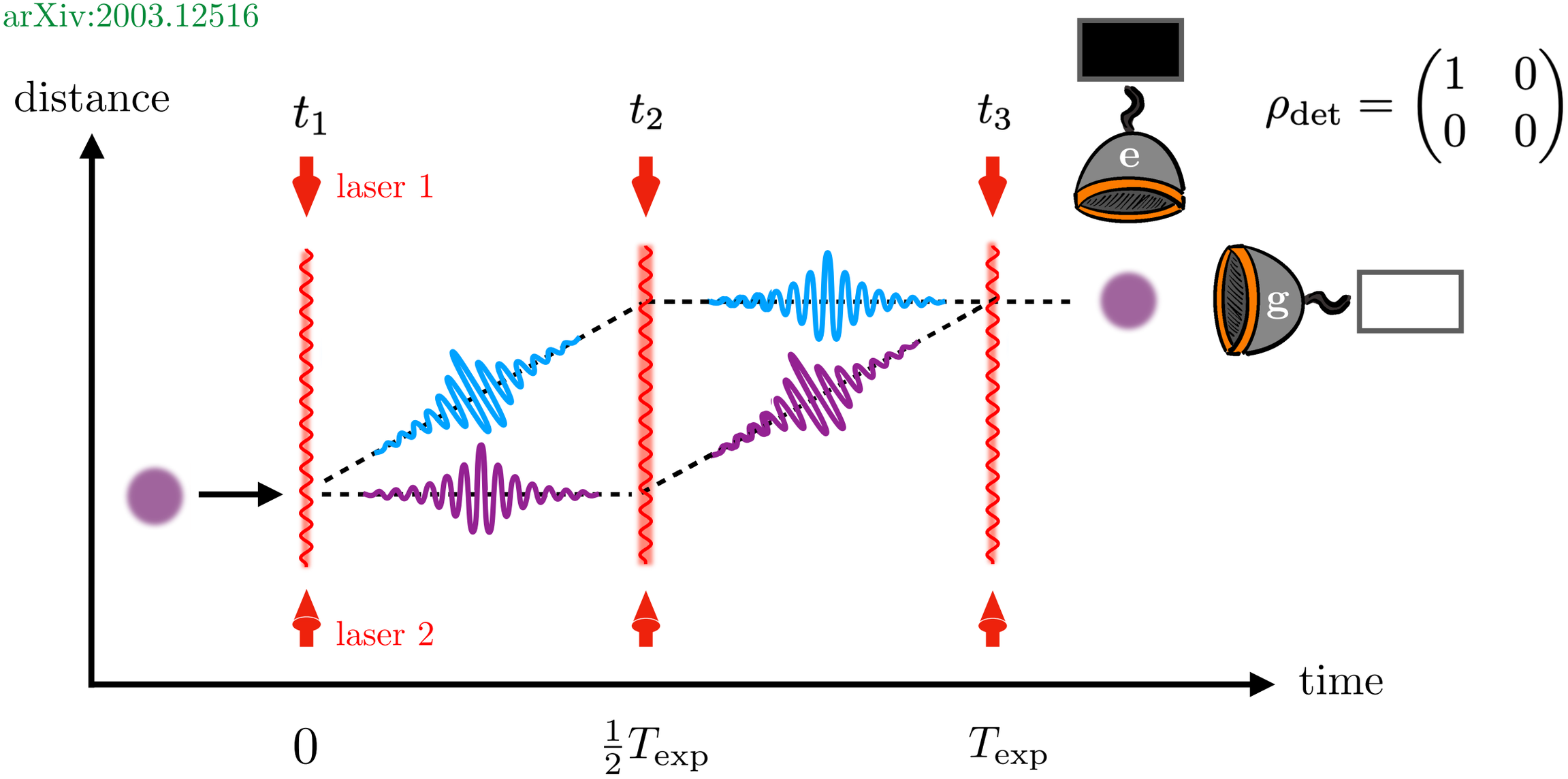
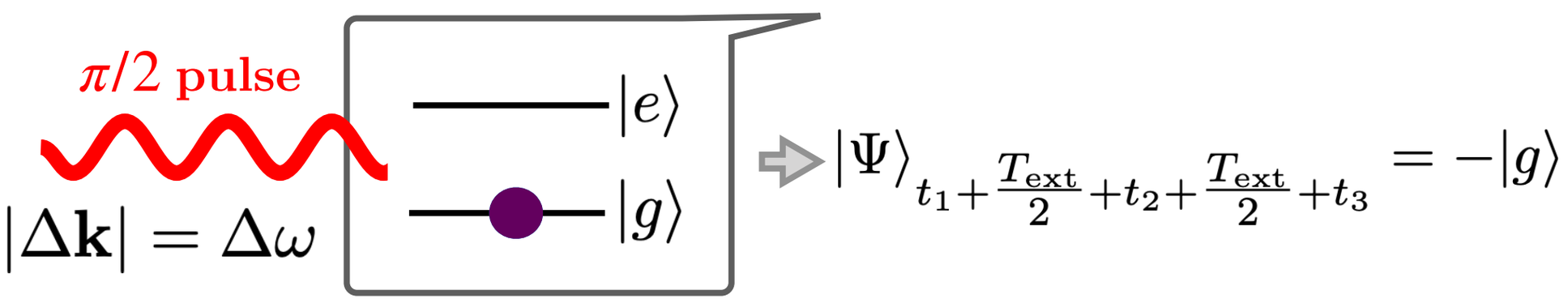
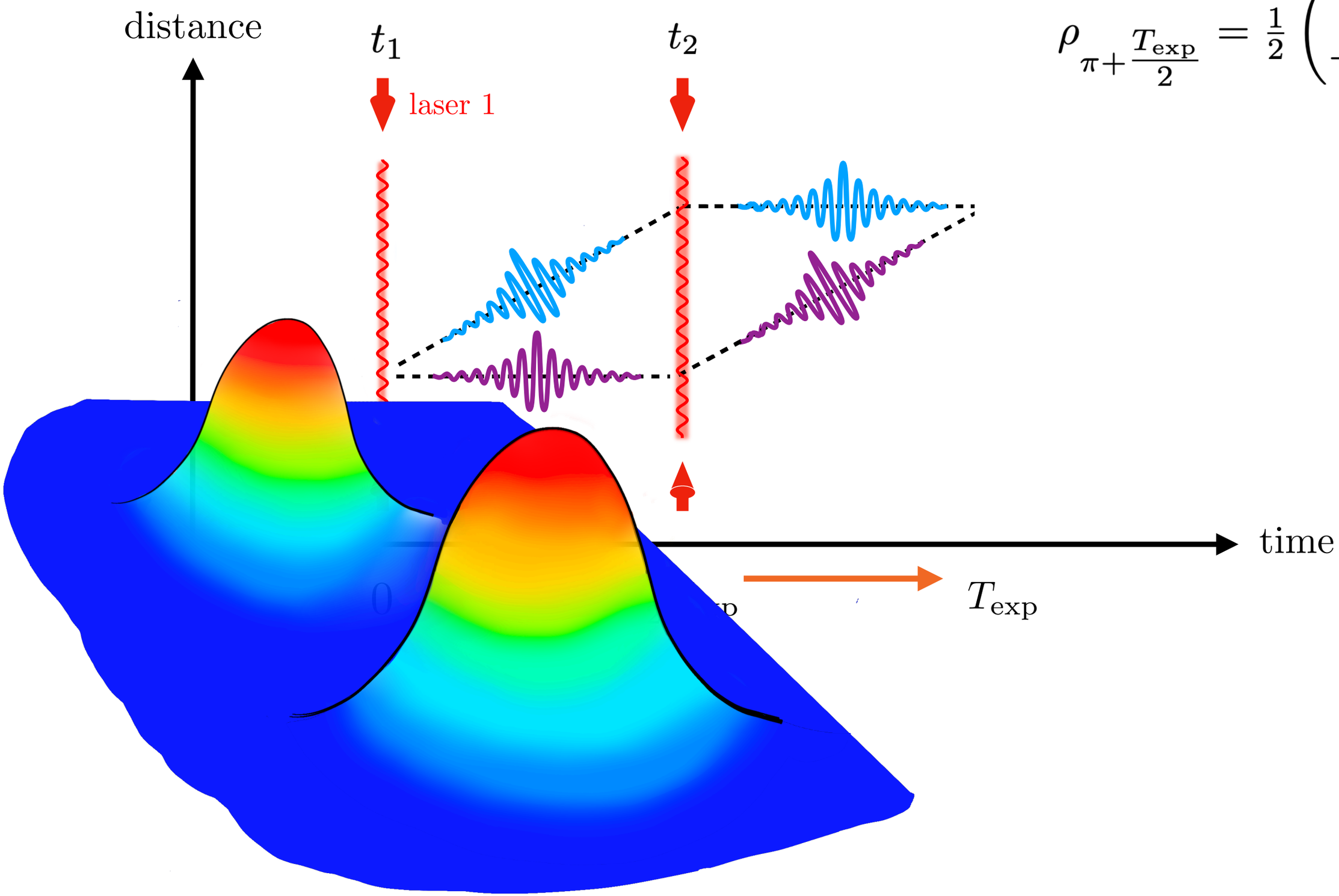


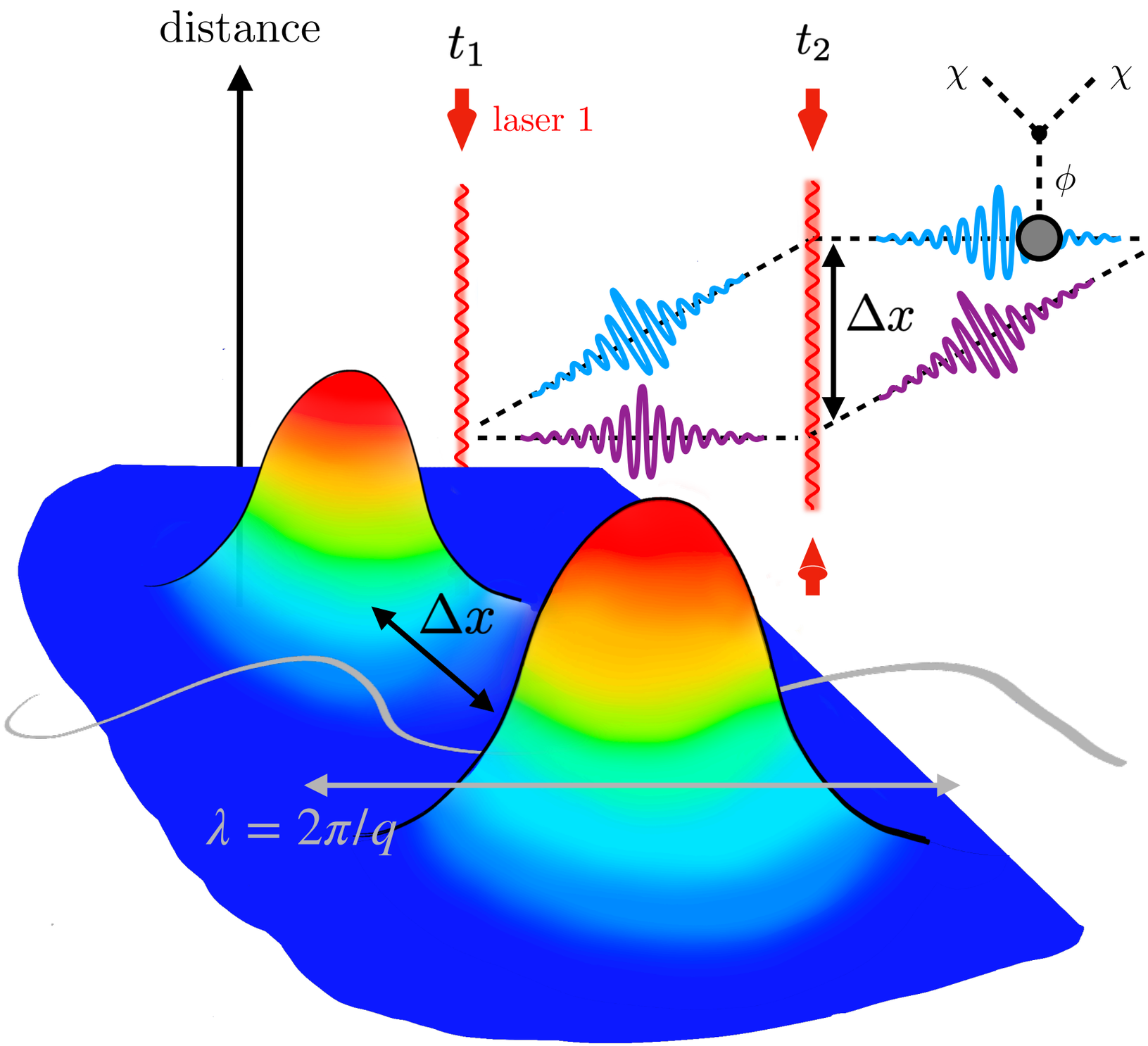


AIs: Decoherence



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

AIs: Decoherence



open system

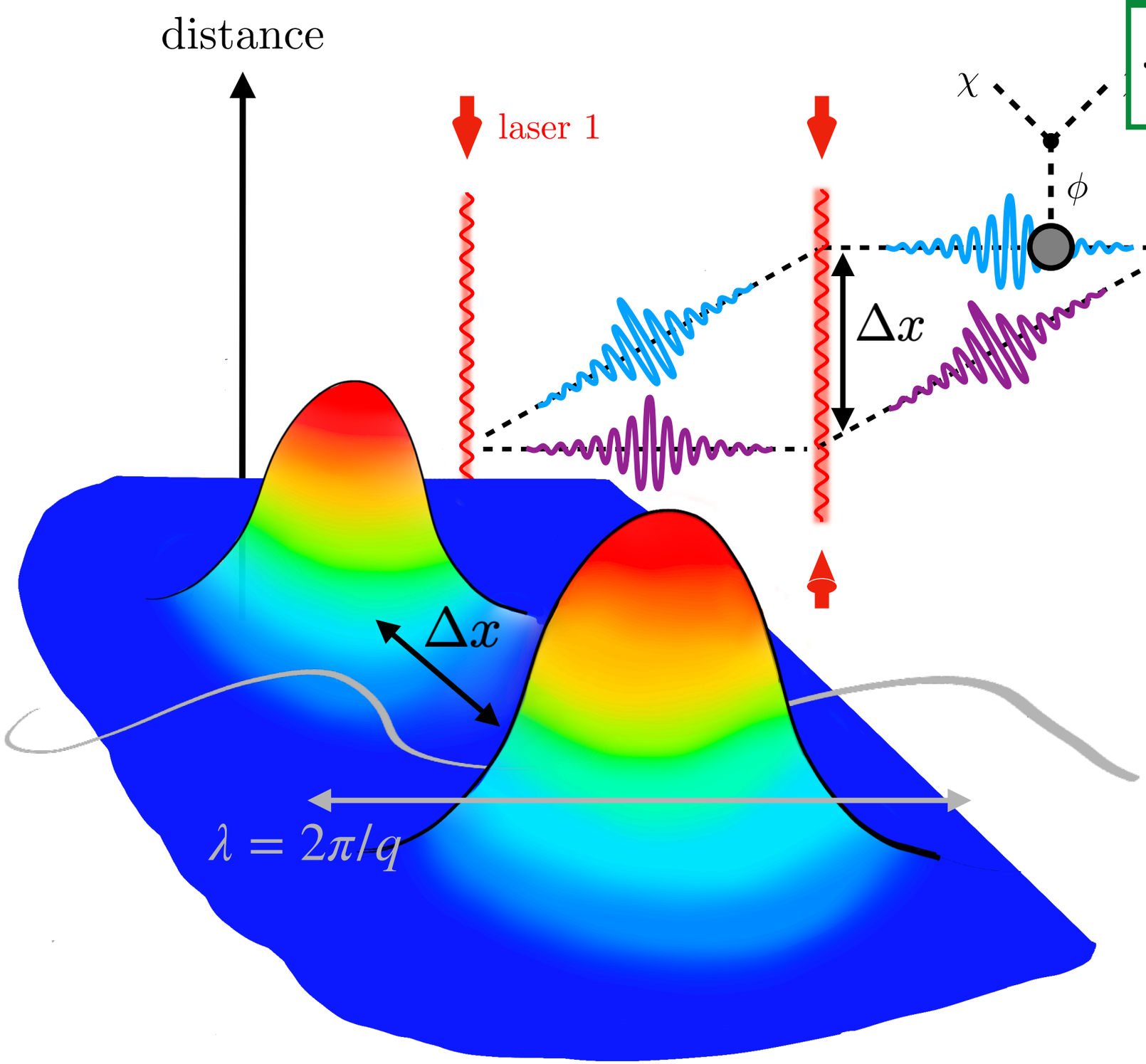
$$\rho_{\pi+\frac{T_{\rm exp}}{2}} = \frac{1}{2}\begin{pmatrix} 1 & i\gamma \\ -i\gamma & 1 \end{pmatrix}$$

$$= e^{-t_{\rm exp}\,\Gamma_{\rm cloud}\,\mathcal{F}_{\rm dec}/N_{\rm ind}}$$

$$= e^{-t_{\rm exp}/\tau_{\rm dec}}$$

$$\gamma = e^{-s+i\phi} = e^{-s}\,e^{i\phi}$$

AIs: Decoherence



Form Factor

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

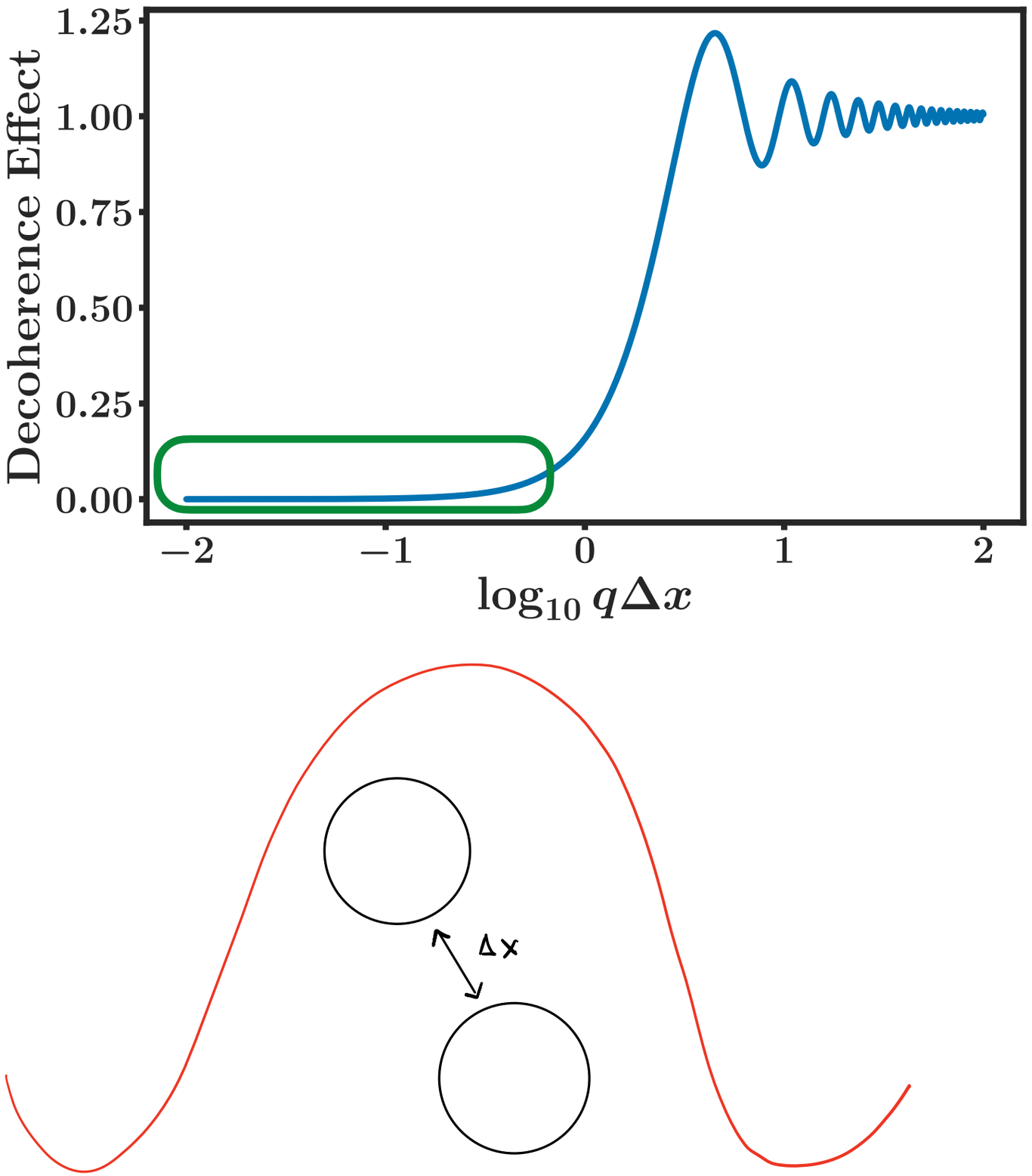
[Joss, Zeh, 1985]
[Gallis, Fleming, 1990]
[Hornberger, Sipe, 2003]

$$= e^{-t_{\text{exp}}\,\Gamma_{\text{cloud}}\,\mathcal{F}_{\text{dec}}/N_{\text{ind}}}$$

$$= e^{-t_{\text{exp}}/\tau_{\text{dec}}}$$

$$\gamma = e^{-s+i\phi} = e^{-s}\,e^{i\phi}$$

AIs: Decoherence



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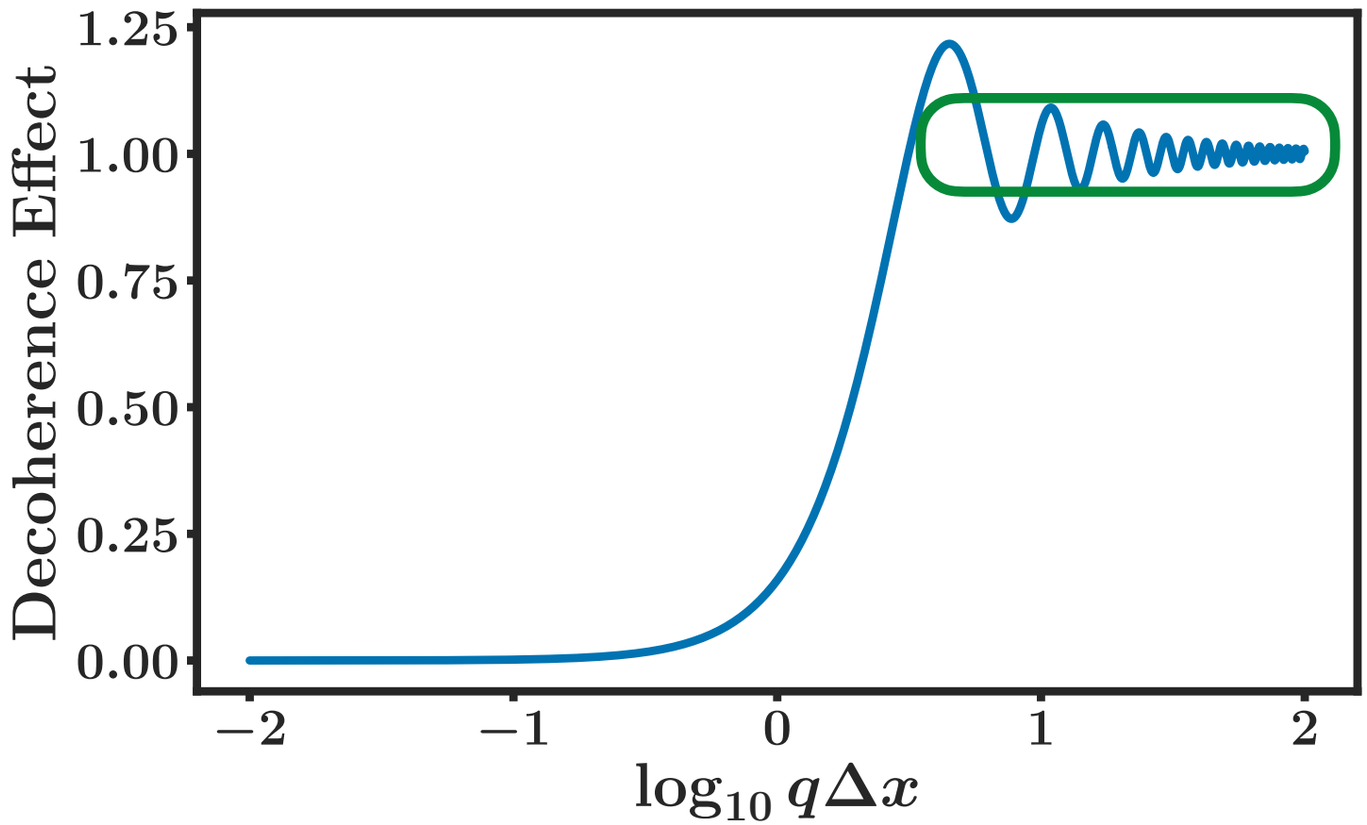
AIs: Decoherence



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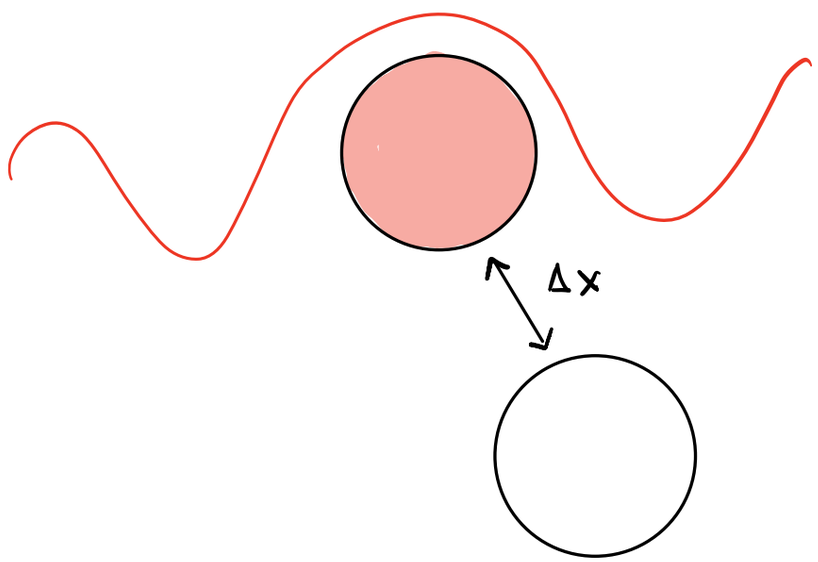
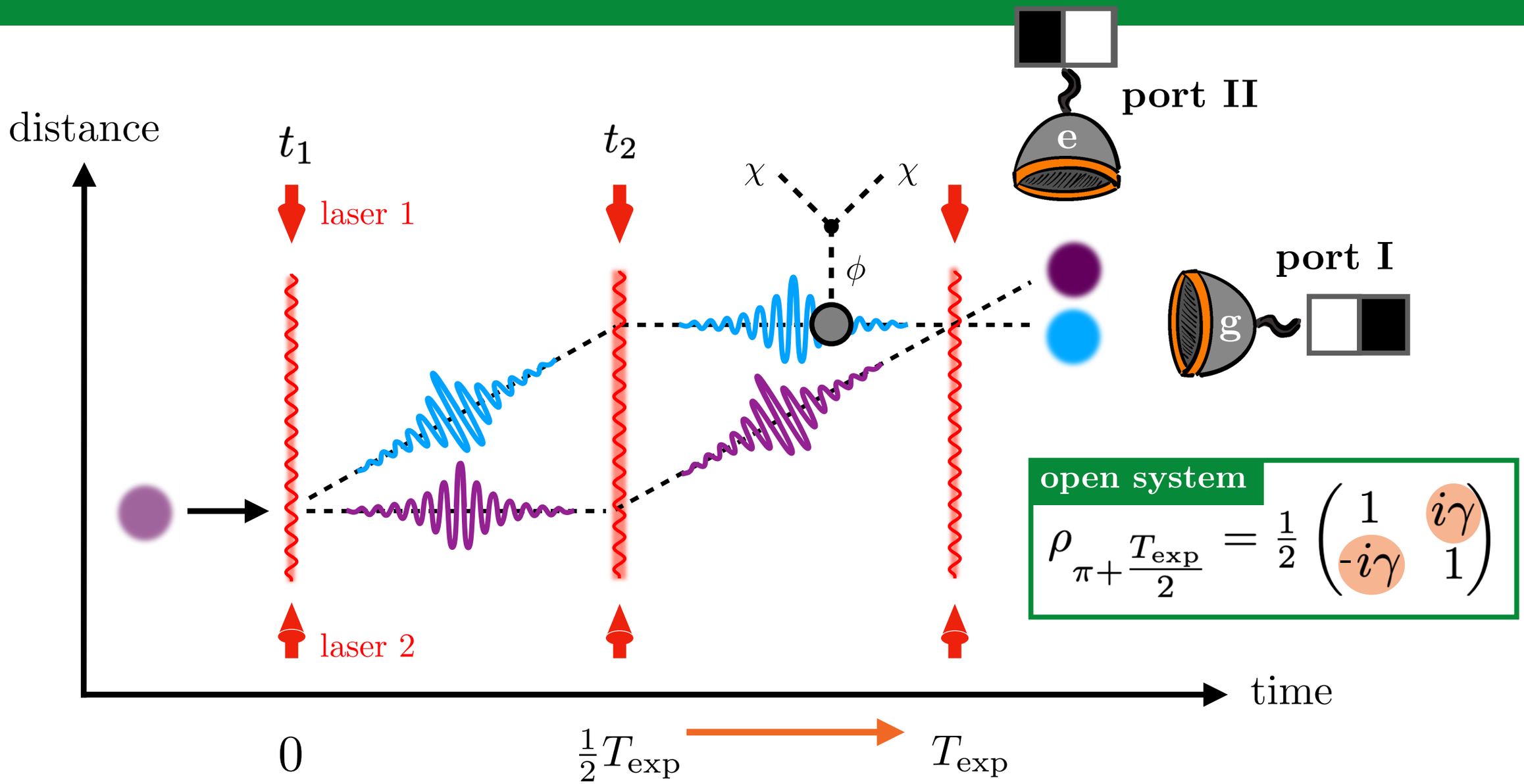


$$= e^{-t_{\text{exp}}\,\Gamma_{\text{cloud}}\,\mathcal{F}_{\text{dec}}/N_{\text{ind}}}$$

$$= e^{-t_{\text{exp}}/\tau_{\text{dec}}}$$

$$\gamma = e^{-s+i\phi} = e^{-s}\,e^{i\phi}$$

AIs: **single** measurement



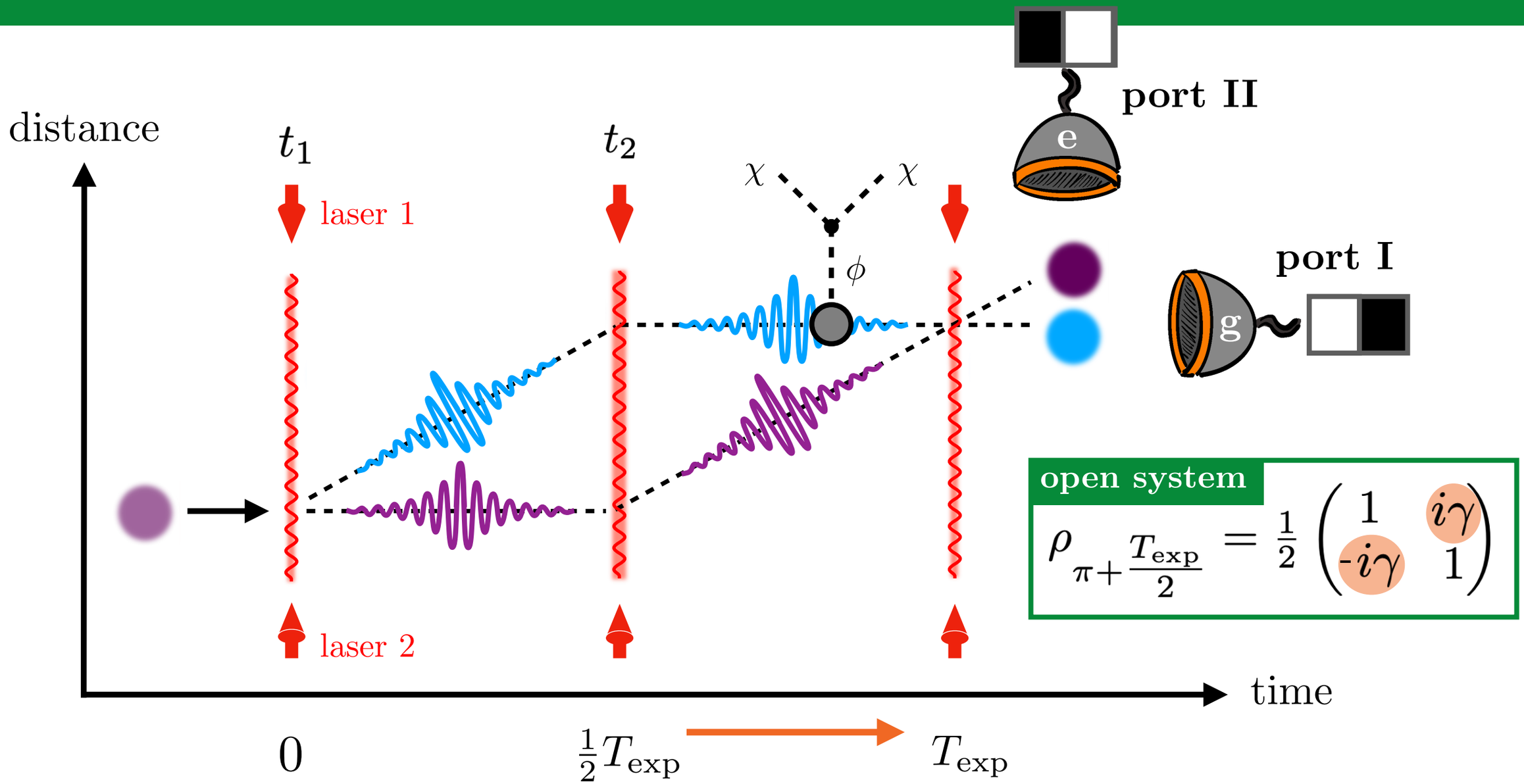
open system

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

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

$$\gamma = e^{-s+i\phi} = e^{-s}\,e^{i\phi}$$

AIs: **single** measurement



open system

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(assume fully decohered)

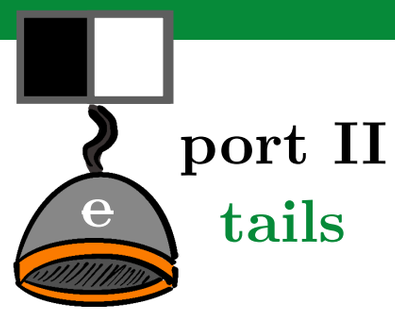
$$\gamma = e^{-s+i\phi} = e^{-s}\,e^{i\phi}$$

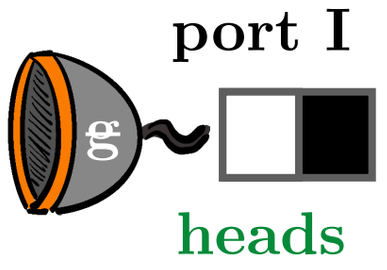
AIs: **single** measurement

$|g\rangle$

$\equiv$

$|e\rangle$





$p_I = \frac{1}{2}$

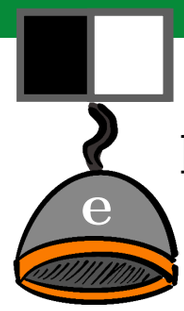
(assume fully decohered)

AIs: **single** measurement

$|g\rangle$

$\equiv$

$|e\rangle$

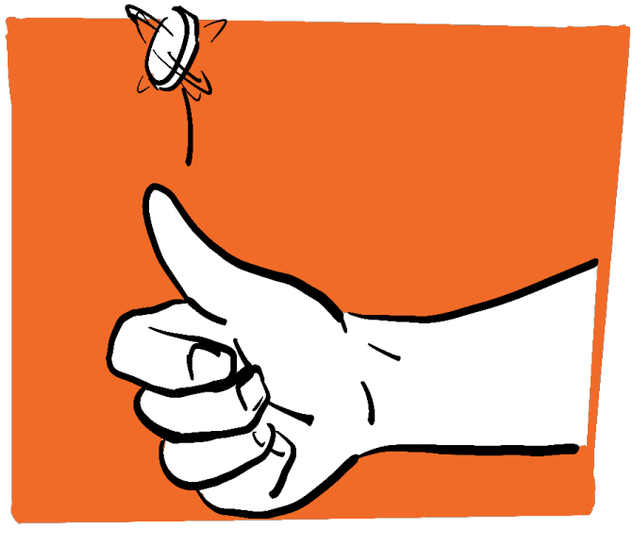


port II

tails

port I

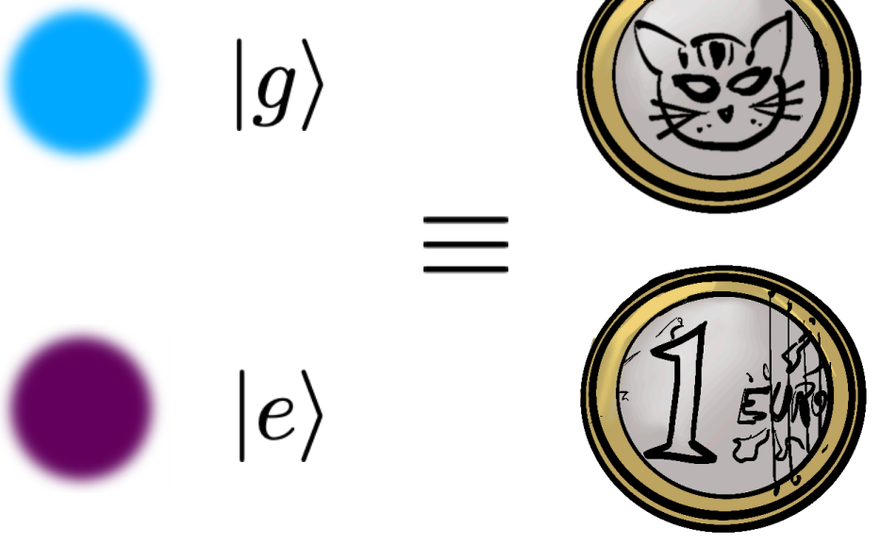
heads



$p_I = \frac{1}{2}$

(assume fully decohered)

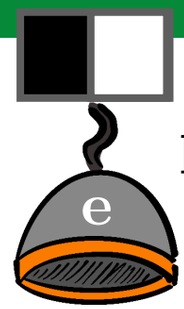
AIs: $\mathbf{N_{ind}}$ measurements



$|g\rangle$

$\equiv$

$|e\rangle$



port II

tails

port I

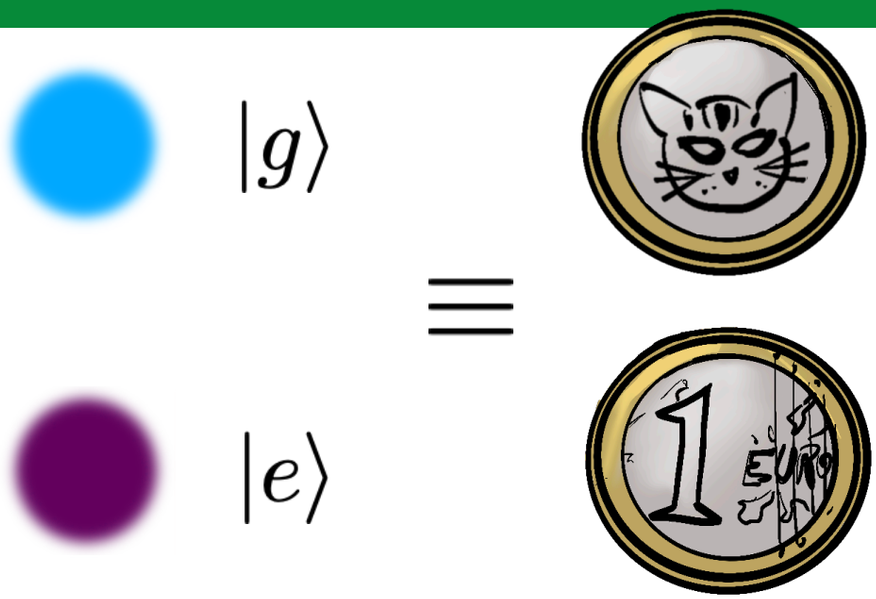
heads

$N_{\text{ind}} =$

$p_I = \frac{1}{2}$

(assume fully decohered)

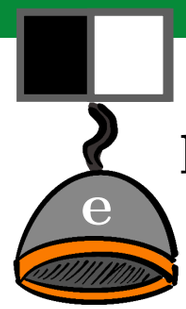
AIs: $\mathbf{N_{ind}}$ measurements



$|g\rangle$

$\equiv$

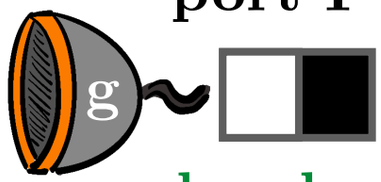
$|e\rangle$



port II

tails

port I



heads

$N_{\text{ind}} =$

$$P_I = \binom{N_{\text{ind}}}{N_I} p_I^{N_I} (1 - p_I)^{N_{II}}$$

$p_I = \frac{1}{2}$

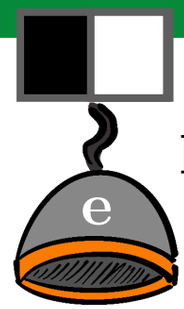
(assume fully decohered)

AIs: $\mathbf{N_{ind}}$ measurements

$|g\rangle$

$|e\rangle$

$\equiv$



port II

tails

port I

heads

$N_{\text{ind}} =$

$$P_I = \binom{N_{\text{ind}}}{N_I} p_I^{N_I} (1-p_I)^{N_{II}}$$

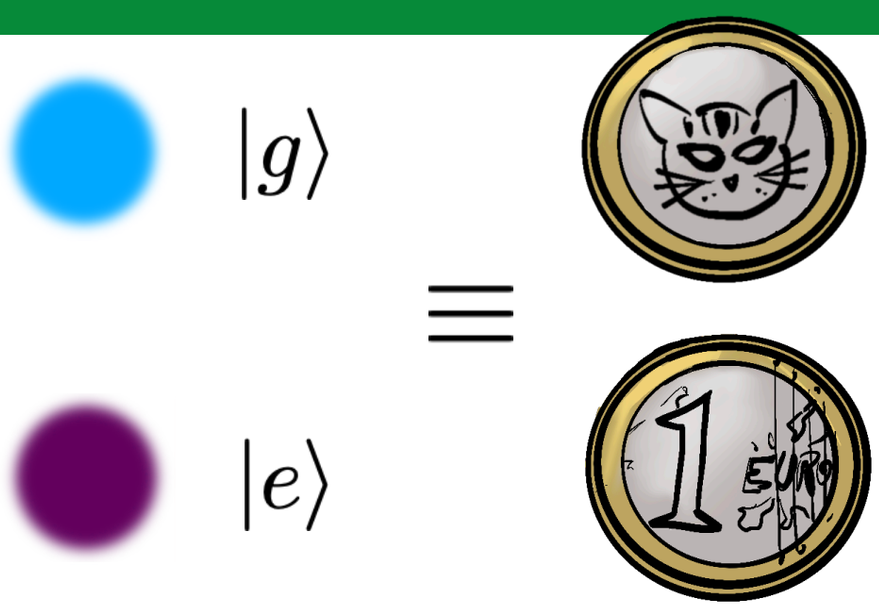
$p_I = \frac{1}{2}$

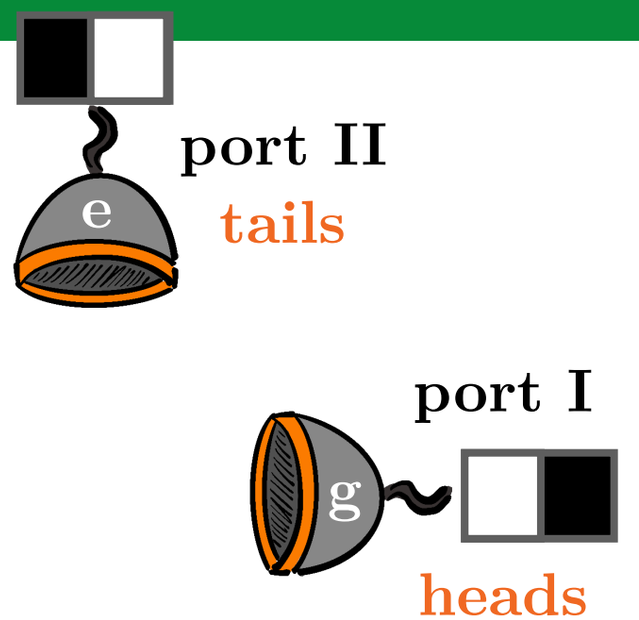
(assume fully decohered)

$$\Rightarrow \langle P_I \rangle = (N_I + N_{II}) p_I = N_{\text{ind}}\, p_I$$

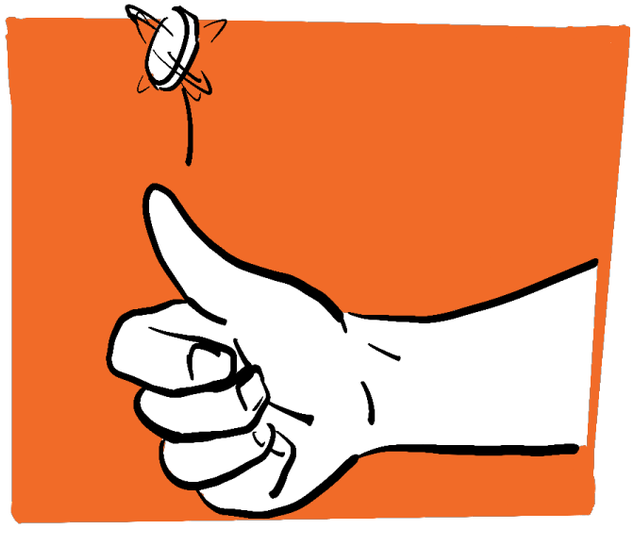
$$\Rightarrow \sigma^2 = N_{\text{ind}}\, p_I (1-p_I)$$

AIs: N_{ind} measurements





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



$$P_I = \binom{N_{\text{ind}}}{N_I} p_I^{N_I} (1 - p_I)^{N_{II}}$$

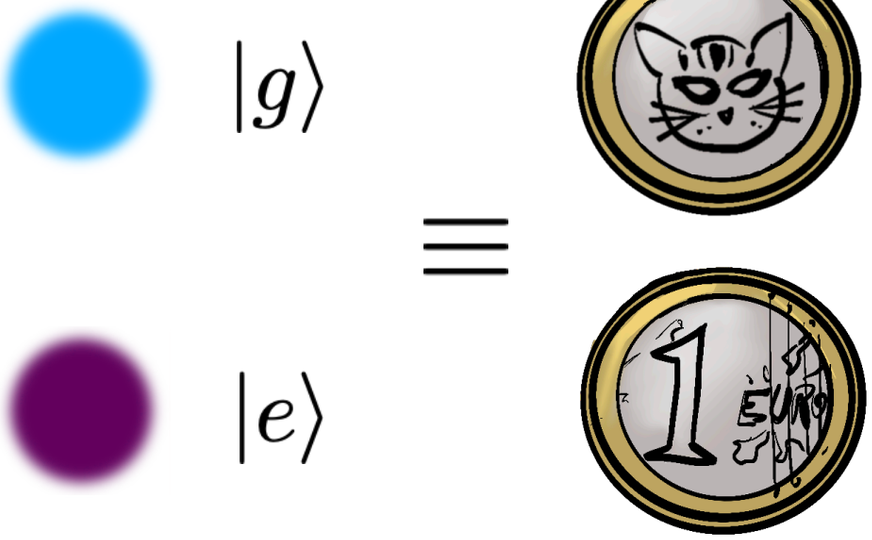
$p_I = \frac{1}{2}$

(assume fully decohered)

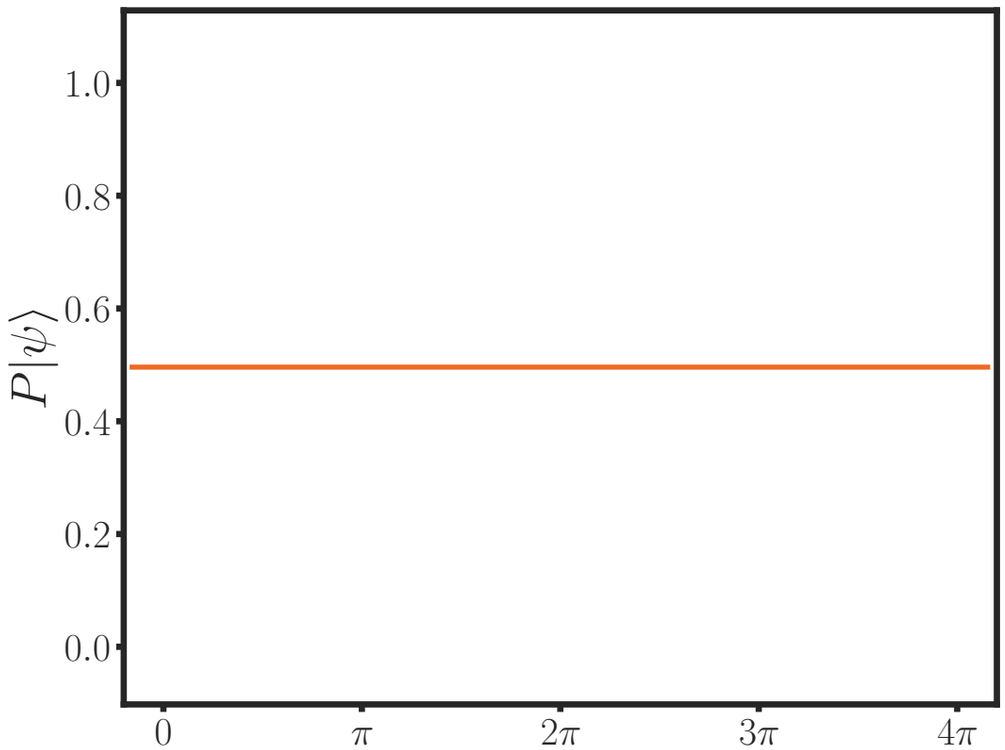
$$\Rightarrow \langle P_I \rangle = (N_I + N_{II}) p_I = N_{\text{ind}}\, p_I$$

$$\Rightarrow \sigma^2 = N_{\text{ind}}\, p_I (1 - p_I)$$

AIs: $\mathbf{N_{ind}}$ measurements



$$\equiv$$



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

$$V = 0$$

$$P_I = \binom{N_{\text{ind}}}{N_I} p_I^{N_I} (1 - p_I)^{N_{II}}$$

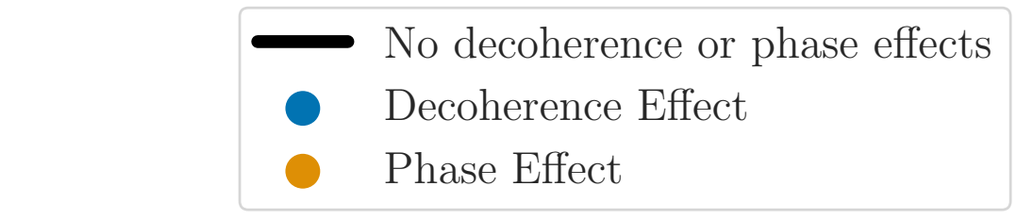
$$p_I = \tfrac{1}{2}$$

(assume fully decohered)

$$\Rightarrow \langle P_I \rangle = (N_I + N_{II}) p_I = N_{\text{ind}}\, p_I$$

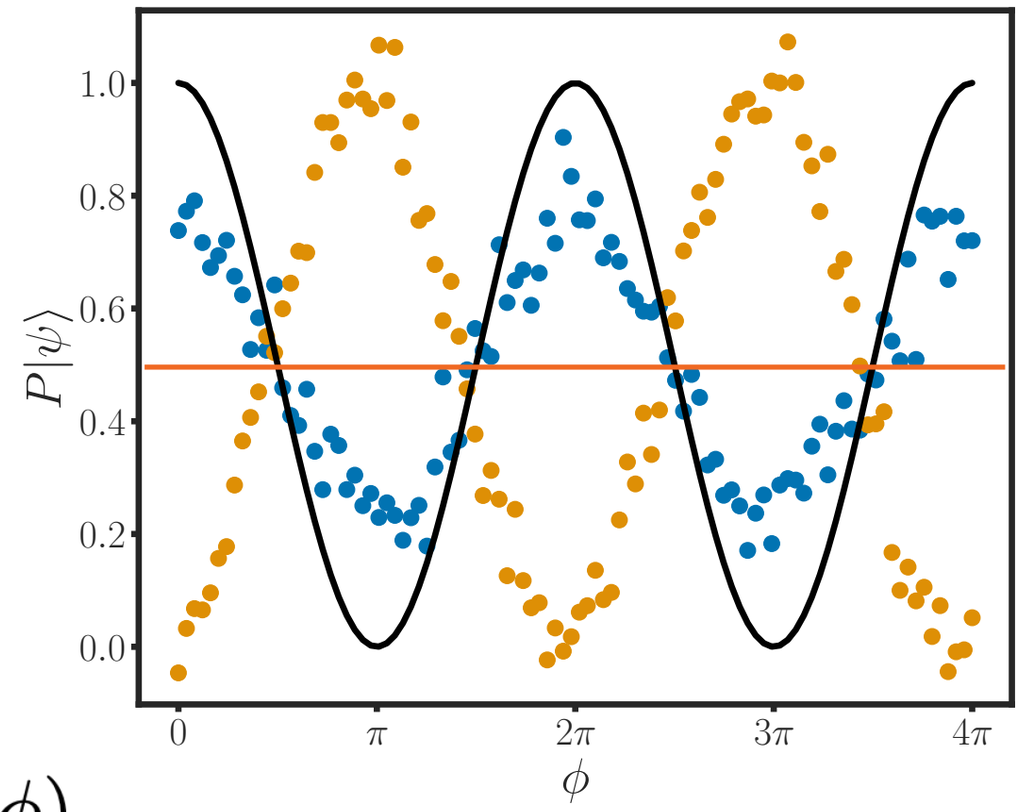
$$\Rightarrow \sigma^2 = N_{\text{ind}}\, p_I (1 - p_I)$$

AIs: N_{ind} measurements



Visibility

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



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

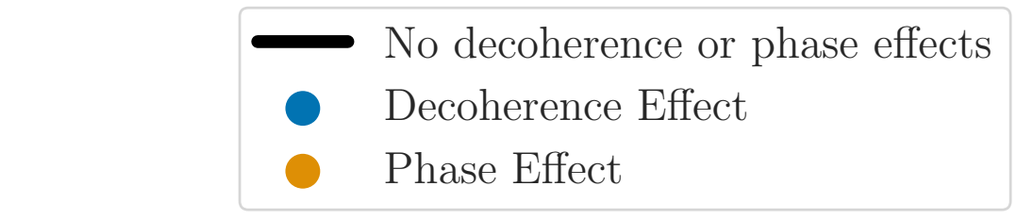
$$V = e^{-s}$$

$$\sigma^{\mathrm{QNL}} = \frac{\sqrt{N_{\mathrm{ind}}}}{2}$$

$$\langle P_I \rangle = (N_I + N_{II})p_I = N_{\mathrm{ind}}\,p_I$$

$$\sigma^2 = N_{\mathrm{ind}}\,p_I(1 - p_I)$$

AIs: N_{ind} measurements



Visibility

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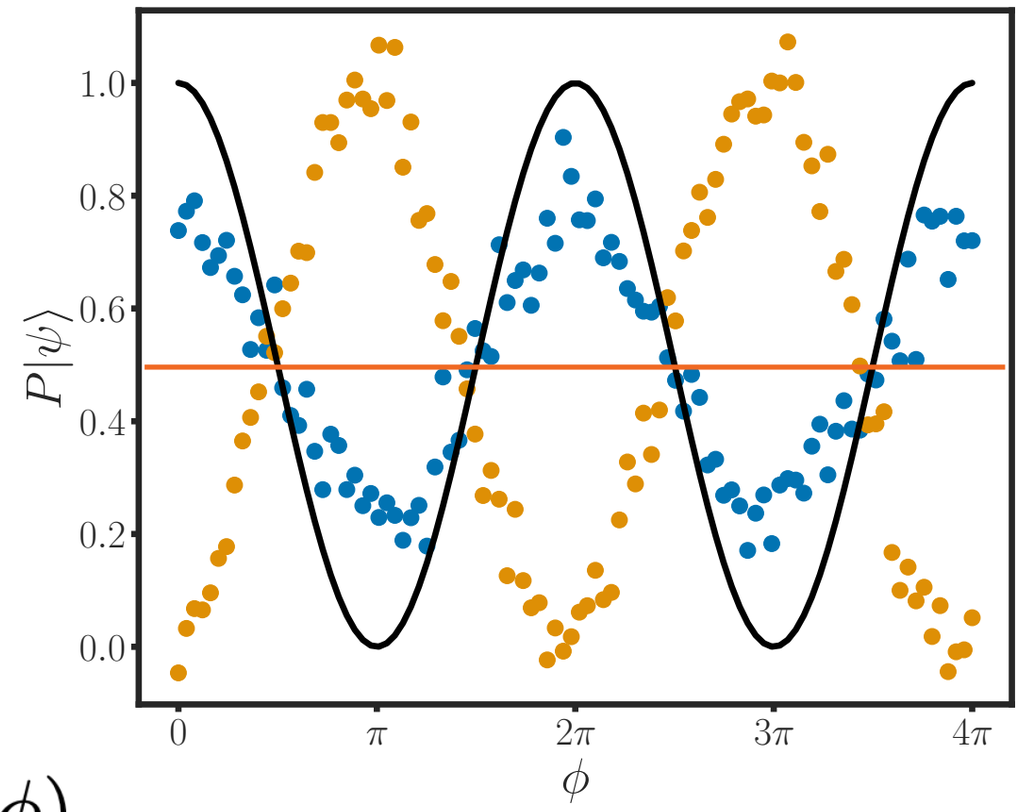


$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\mathrm{exp}} = \frac{1}{2}(1 + V\,\cos\Delta\phi)$$

$$V = e^{-s}$$

$$\sigma^{\mathrm{QNL}} = \frac{\sqrt{N_{\mathrm{ind}}}}{2}$$

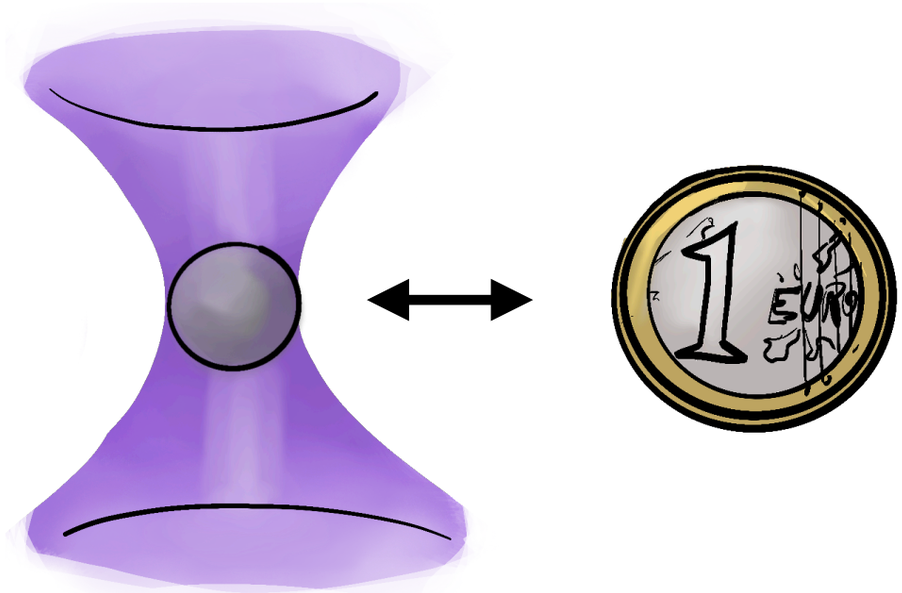
$$\langle P_I \rangle = (N_I + N_{II})p_I = N_{\mathrm{ind}}\,p_I$$

$$\sigma^2 = N_{\mathrm{ind}}\,p_I(1 - p_I)$$

Beating the classical sensitivity

Visibility

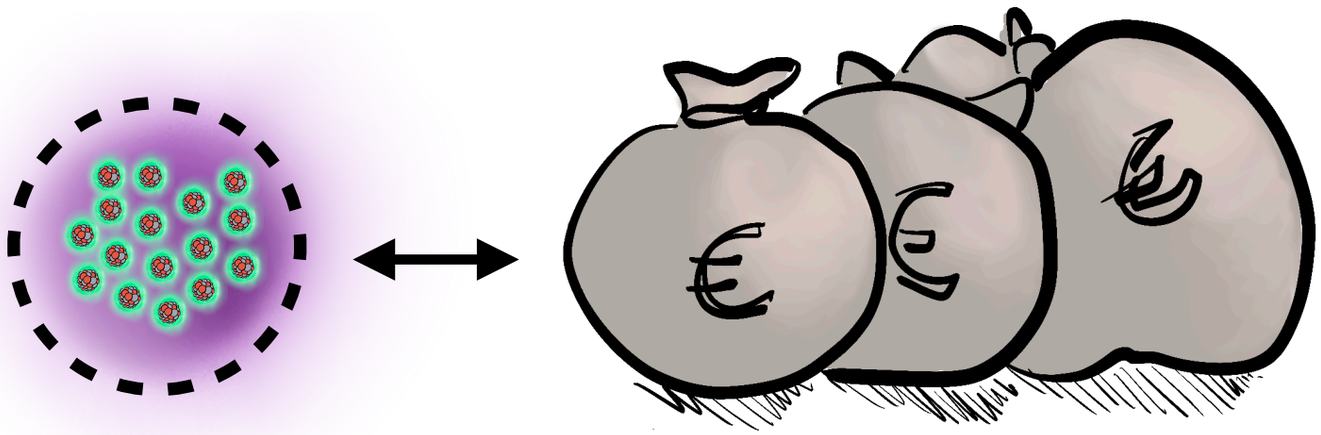
$$\mathrm{SNR}|_{\mathrm{shot}} \equiv \frac{|\Delta V|}{\sigma_V}$$



Matter Interferometers

VS

Atom Interferometers



$$\sigma^{\mathrm{QNL}} = \frac{\sqrt{N_{\mathrm{ind}}}}{2}$$

$$\Rightarrow \langle P_I \rangle = (N_I + N_{II}) p_I = N_{\mathrm{ind}}\, p_I$$

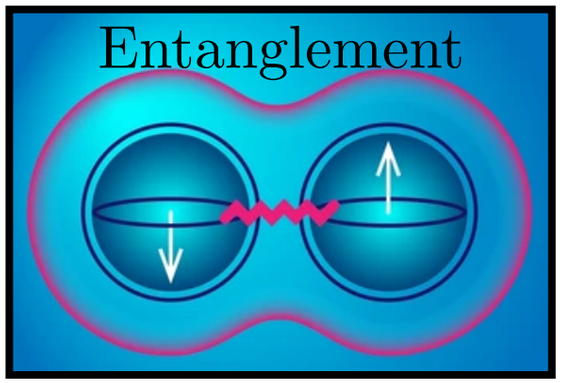
$$\Rightarrow \sigma^2 = N_{\mathrm{ind}}\, p_I (1 - p_I)$$

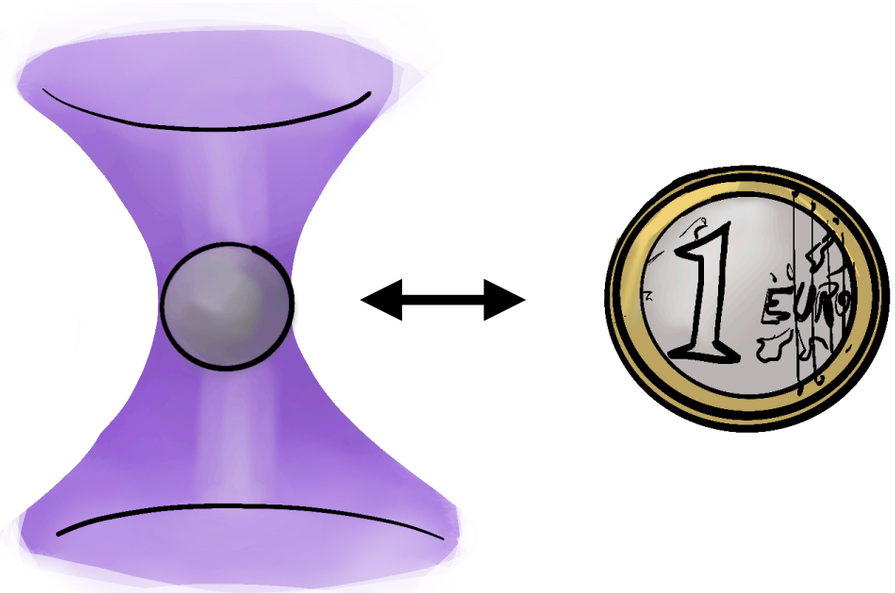
Beating the classical sensitivity

$$|\mathrm{GHZ}\rangle = \frac{|000\rangle + |111\rangle}{\sqrt{2}}$$

N00N states

Cat states

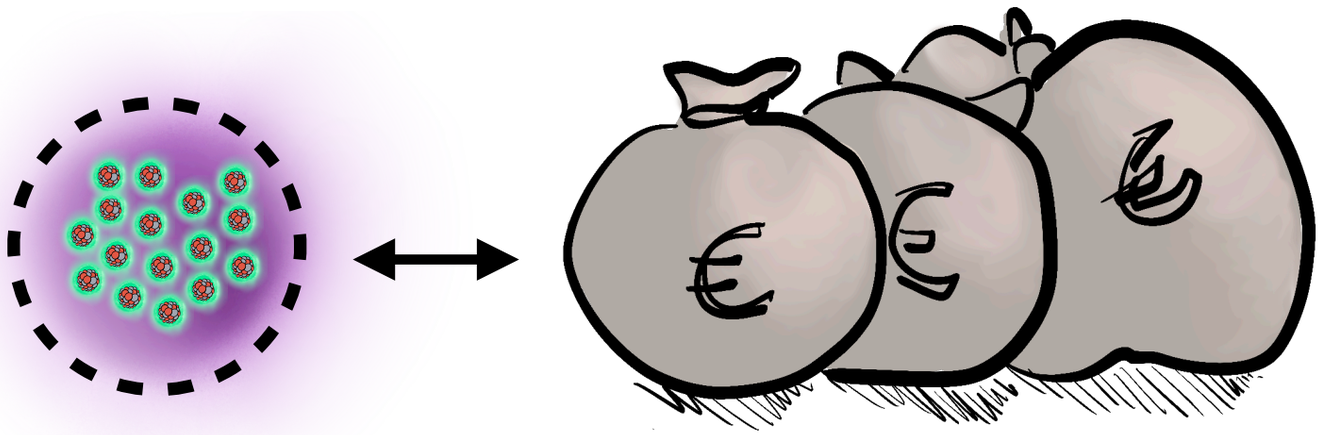




Matter Interferometers

VS

Atom Interferometers

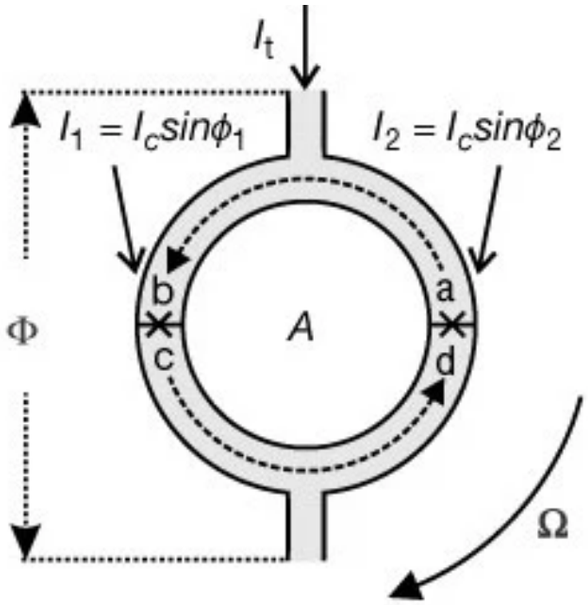


$$\sigma^{\mathrm{QNL}} = \frac{\sqrt{N_{\mathrm{ind}}}}{2}$$

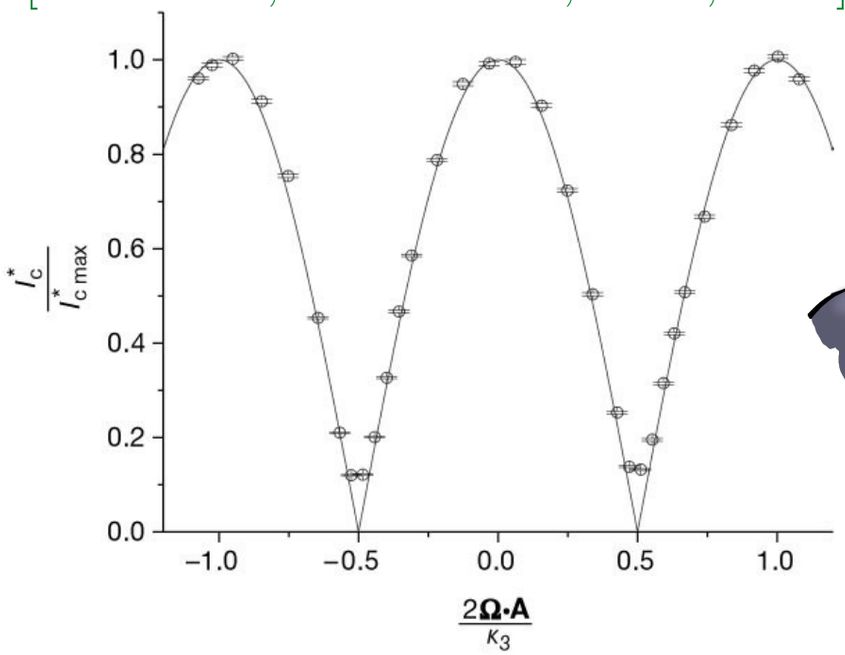
$$\Rightarrow \langle P_I \rangle = (N_I + N_{II}) p_I = N_{\mathrm{ind}}\, p_I$$

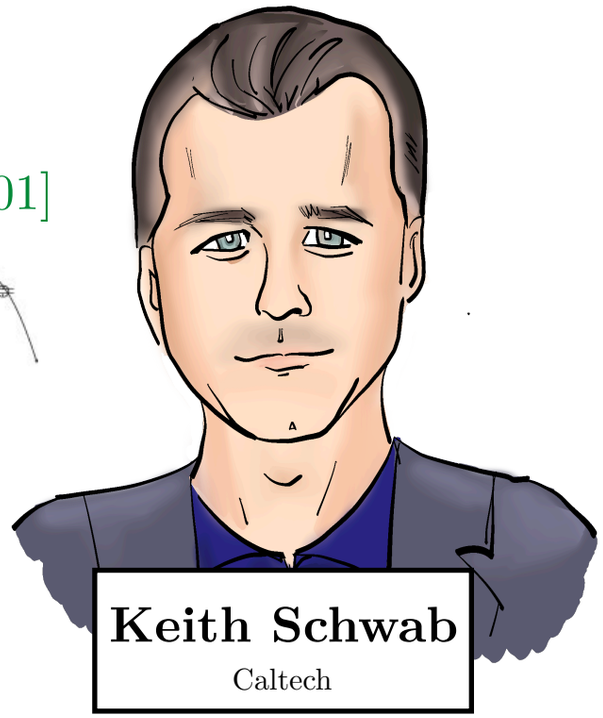
$$\Rightarrow \sigma^2 = N_{\mathrm{ind}}\, p_I (1 - p_I)$$

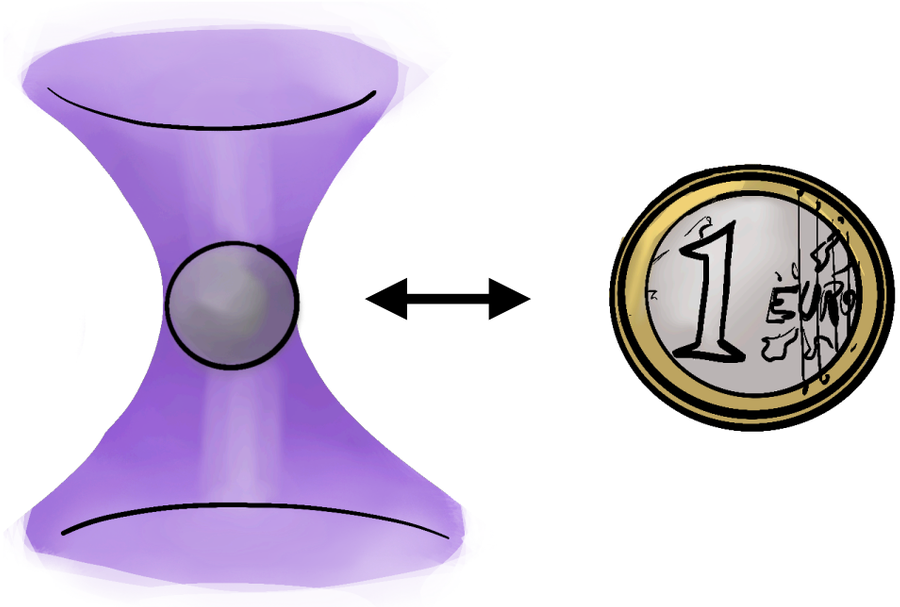
Beating the classical sensitivity



[Simmonds, Marchenkov, et al., 2001]







Matter Interferometers

VS

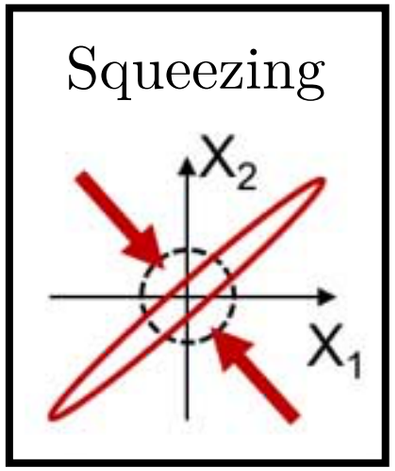
Atom Interferometers

$$\sigma^{\mathrm{QNL}} = \frac{\sqrt{N_{\mathrm{ind}}}}{2}$$

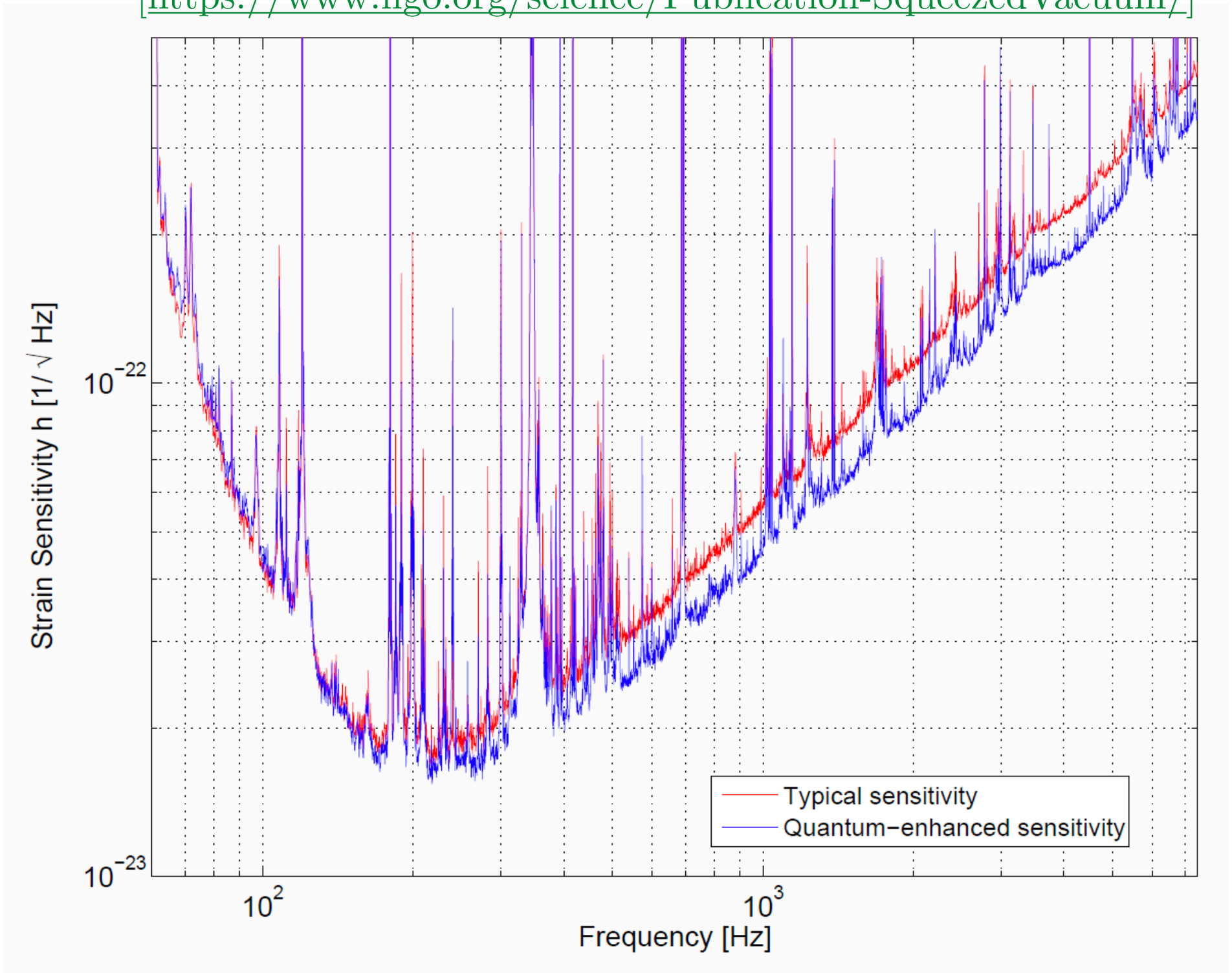
$$\Rightarrow \langle P_I \rangle = (N_I + N_{II}) p_I = N_{\mathrm{ind}}\, p_I$$

$$\Rightarrow \sigma^2 = N_{\mathrm{ind}}\, p_I (1 - p_I)$$

Beating the classical sensitivity



[https://www.ligo.org/science/Publication-SqueezedVacuum/]

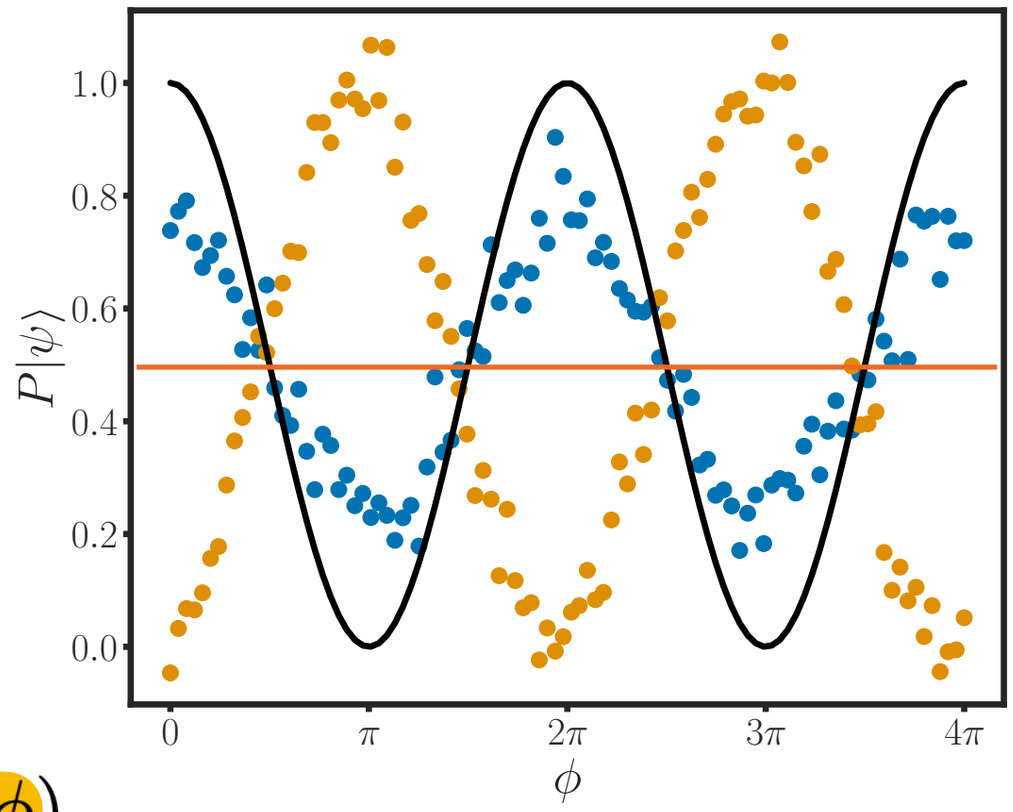


AIs: N_{ind} measurements

No decoherence or phase effects
Decoherence Effect
Phase Effect

Visibility

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



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

$$V = e^{-s}$$

$$\sigma_V^{\mathrm{QNL}} = \frac{2}{\sqrt{N_{\mathrm{ind}}}}$$

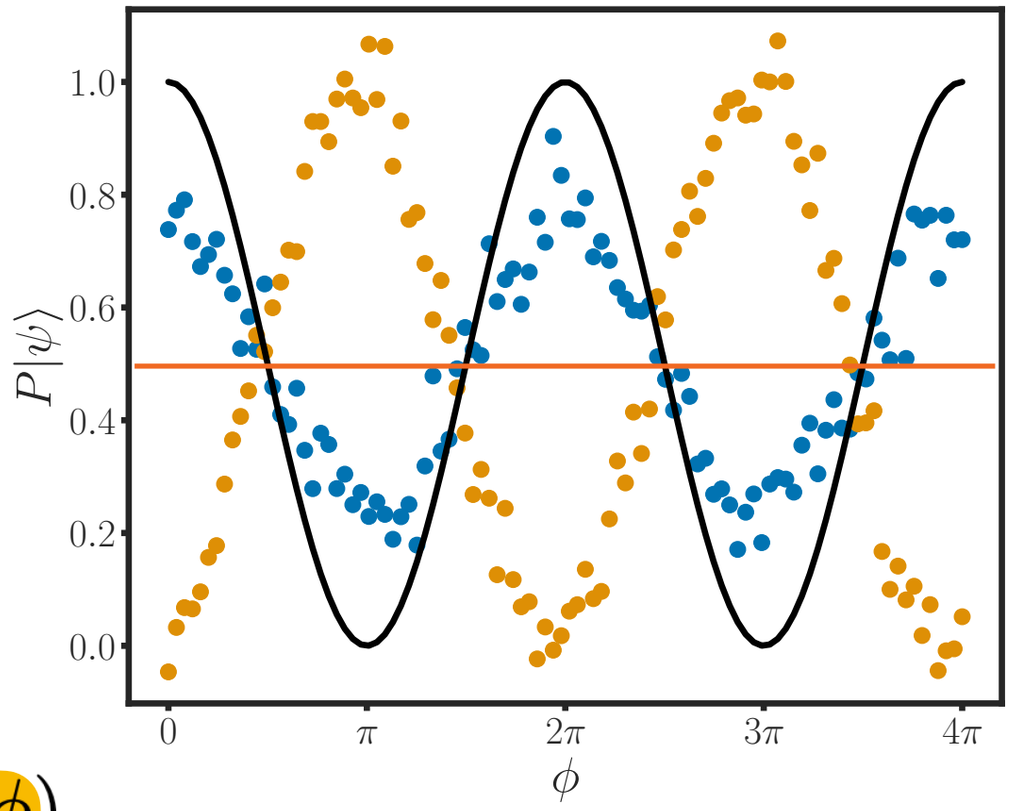
$$\langle P_I \rangle = (N_I + N_{II})p_I = N_{\mathrm{ind}}\, p_I$$

$$\sigma^2 = N_{\mathrm{ind}}\, p_I(1 - p_I)$$

Phase Shifts in Atom Interferometers

[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]

GWs



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

EDMs

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

ULDM

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

5th forces

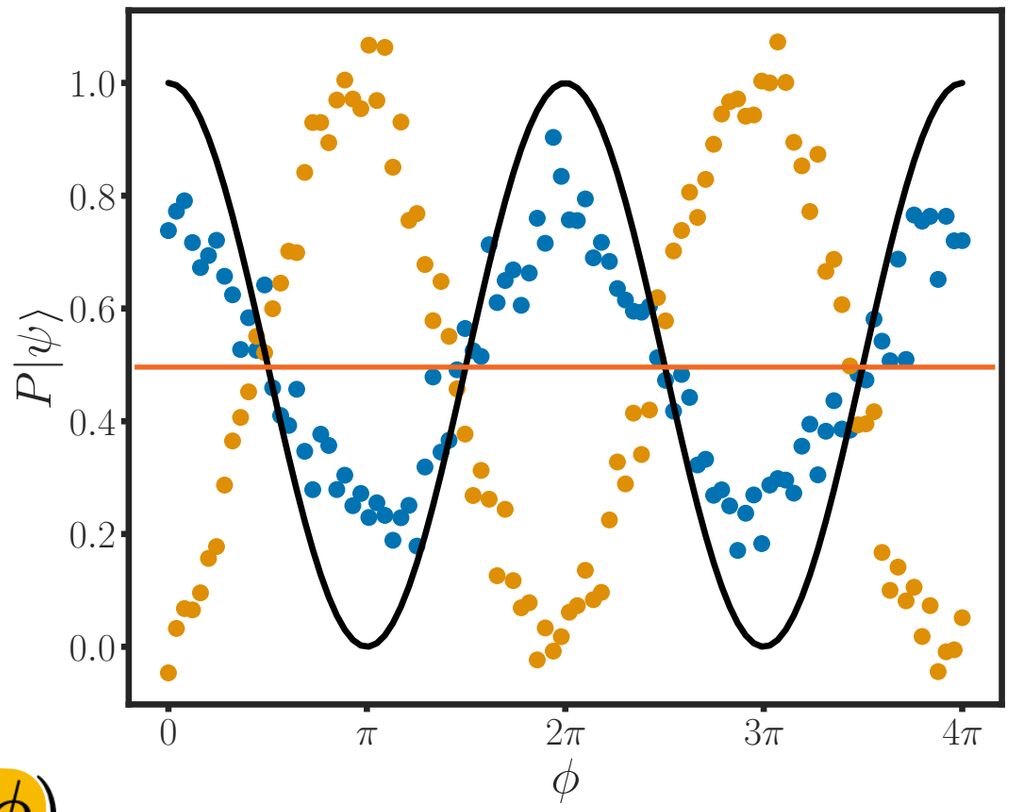
[Wacker, 2010], [Rosi, Sorrentino, et al. 2014] [Biedermann, Wu, et al. 2015] [Rosi, D'Amico, et al. 2017] [Fray, Diez, et al. 2004] [Schlippert, Hartwig, et al. 2014] [Zhou, Long, et al. 2015] [Barrett, Antoni-Micollier, et al. 2016] [Kuhn, McDonald, et al. 2014] [Barrett, Antoni-Micollier, et al. 2015]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

Decoherence in Atom Interferometers

No decoherence or phase effects
Decoherence Effect
Phase Effect

Visibility

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



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

$$V = e^{-s}$$

Particle scattering

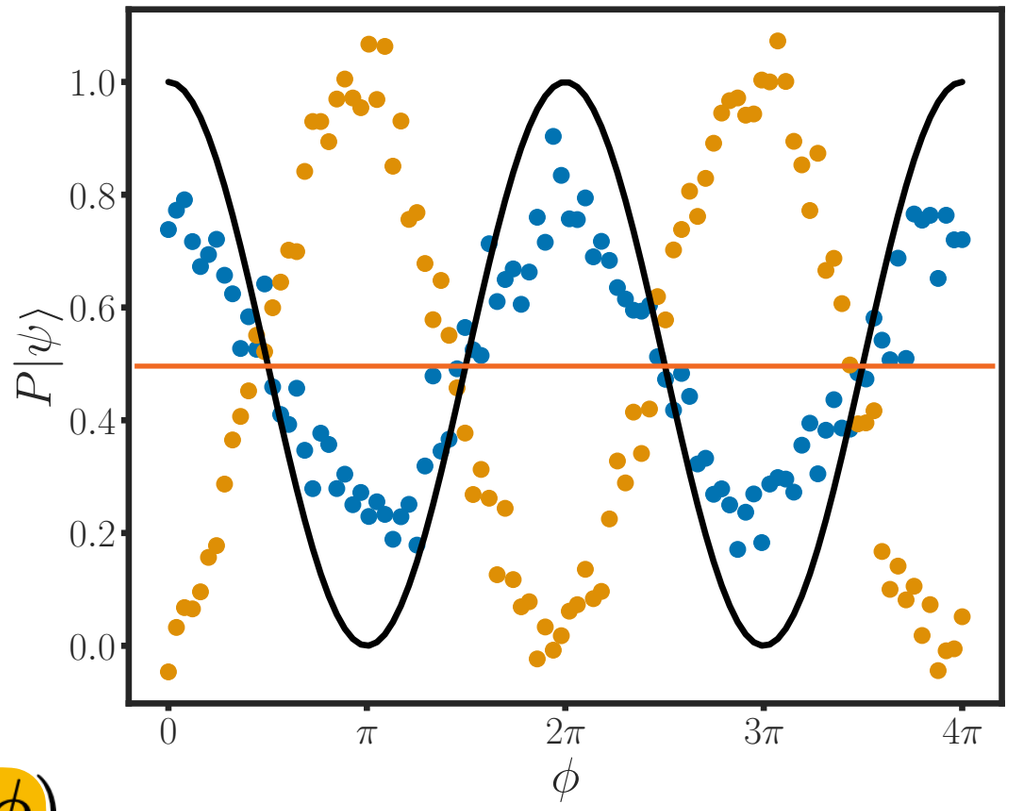
[Riedel, 2013]
[Riedel, Yavin, 2017]
[Du, **CM**, Pardo, Wang, Zurek, 2022]
[Du, **CM**, Pardo, Wang, Zurek, 2023]

Decoherence in Atom Interferometers

No decoherence or phase effects
Decoherence Effect
Phase Effect

Visibility

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



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

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

Particle scattering

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

AIs: the Rate

[Y. Du, **CM**, et al. 2022]

Number of events / (target mass · time)

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

Accumulated decoherence: **Rate**

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

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

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

AIs: the Rate

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

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

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

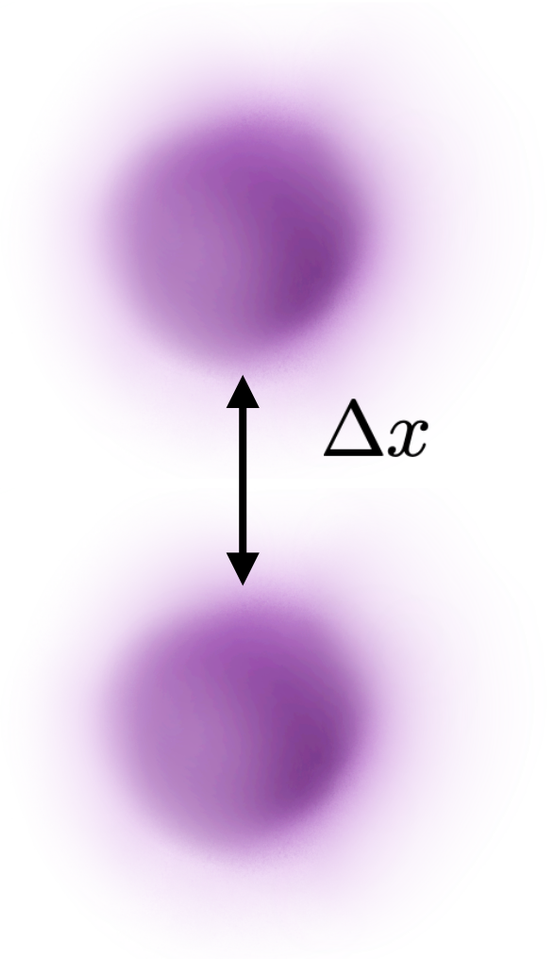
$$\frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}$$

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

AIs: the Rate

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

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

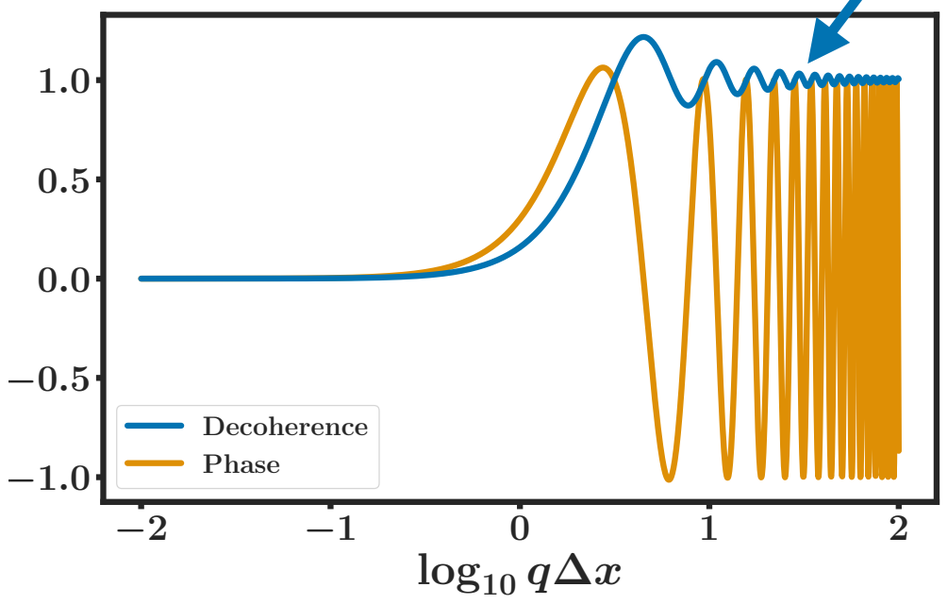


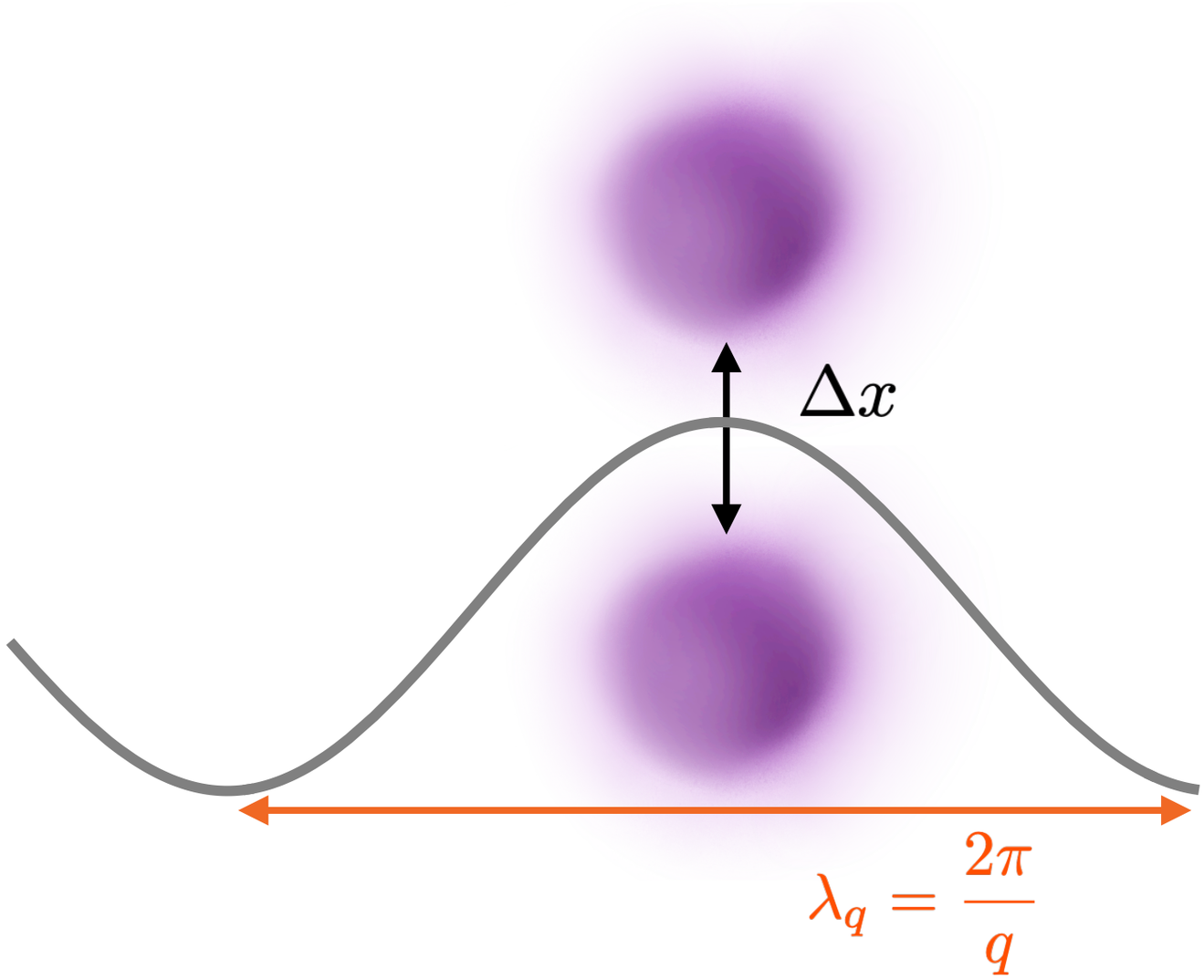
AIs: the Rate

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

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

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

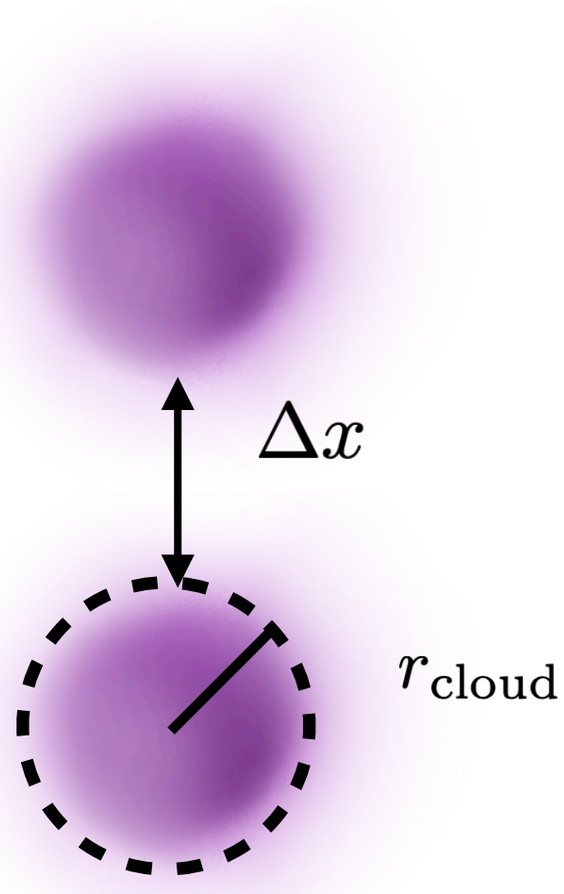




AIs: the Rate

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

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



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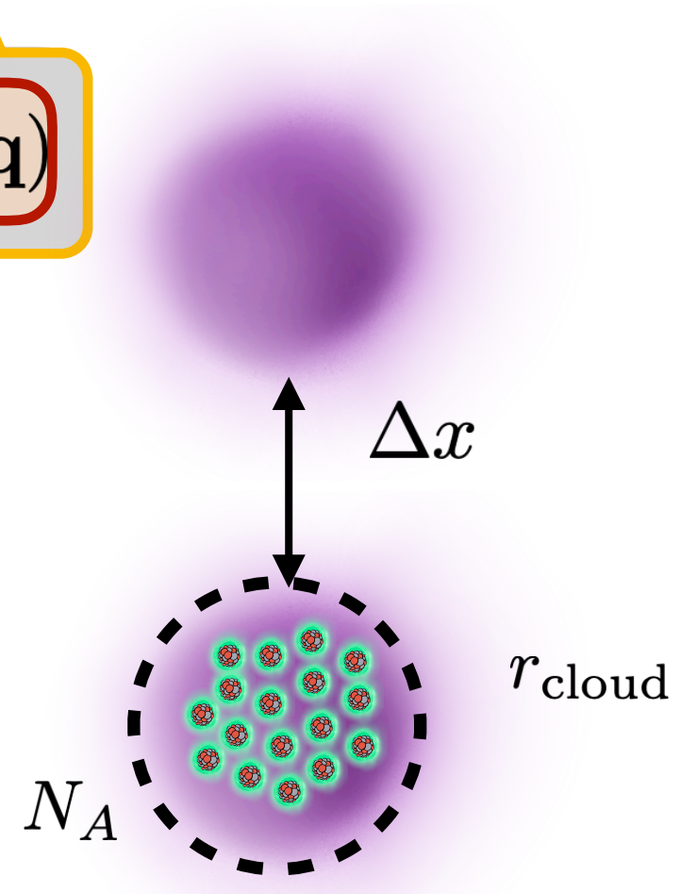


AIs: the Rate

[Y. Du, **CM**, et al. 2022]

Number of events / (target mass · time)

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

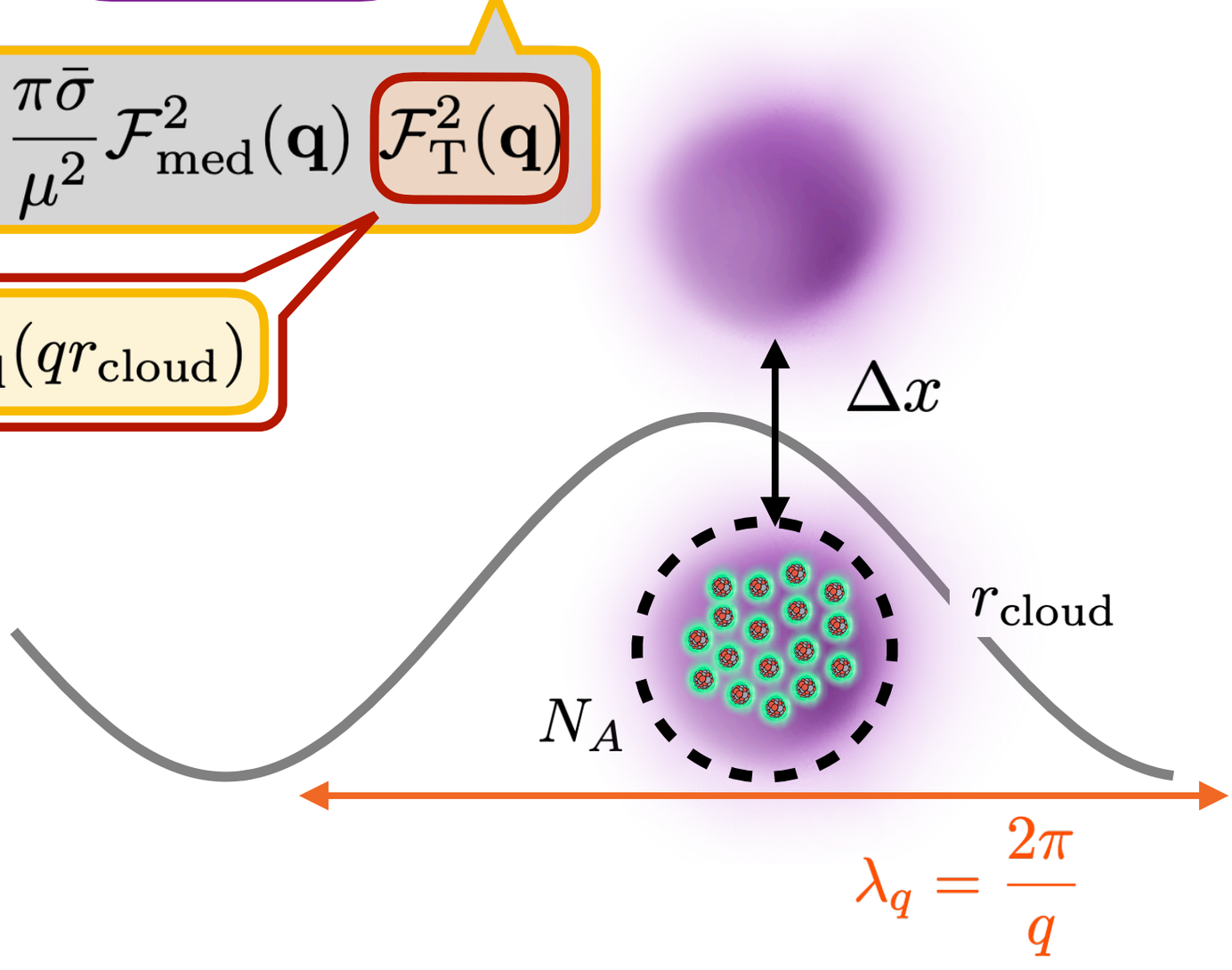
Born (coherent) **enhancement**!

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

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

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

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



AIs: the Rate

[Y. Du, **CM**, et al. 2022]

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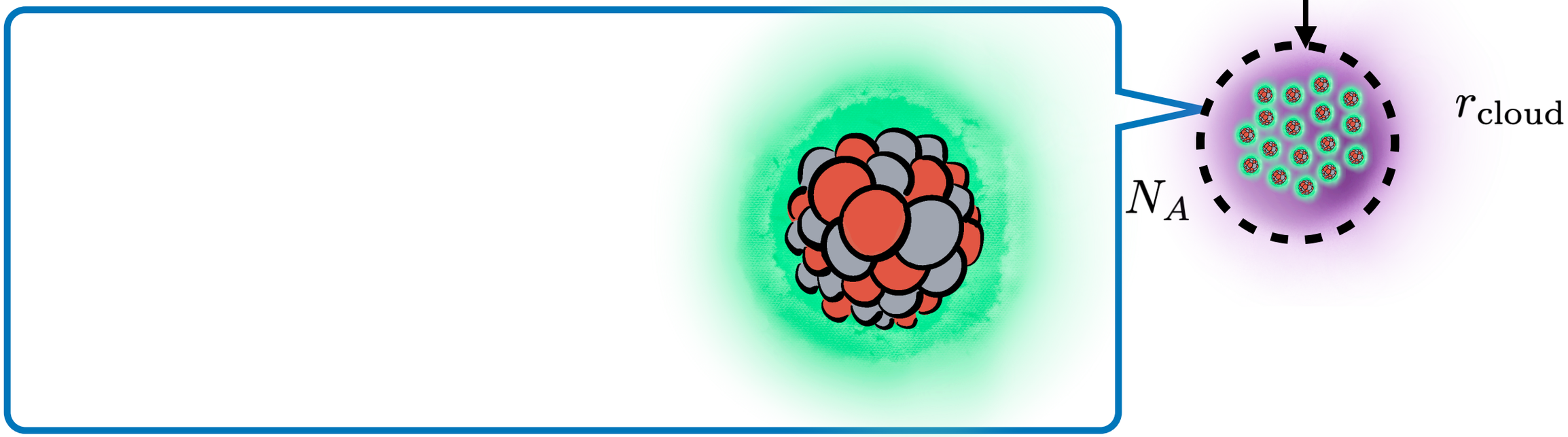


AIs: the Rate

[Y. Du, **CM**, et al. 2022]

Number of events / (target mass · time)

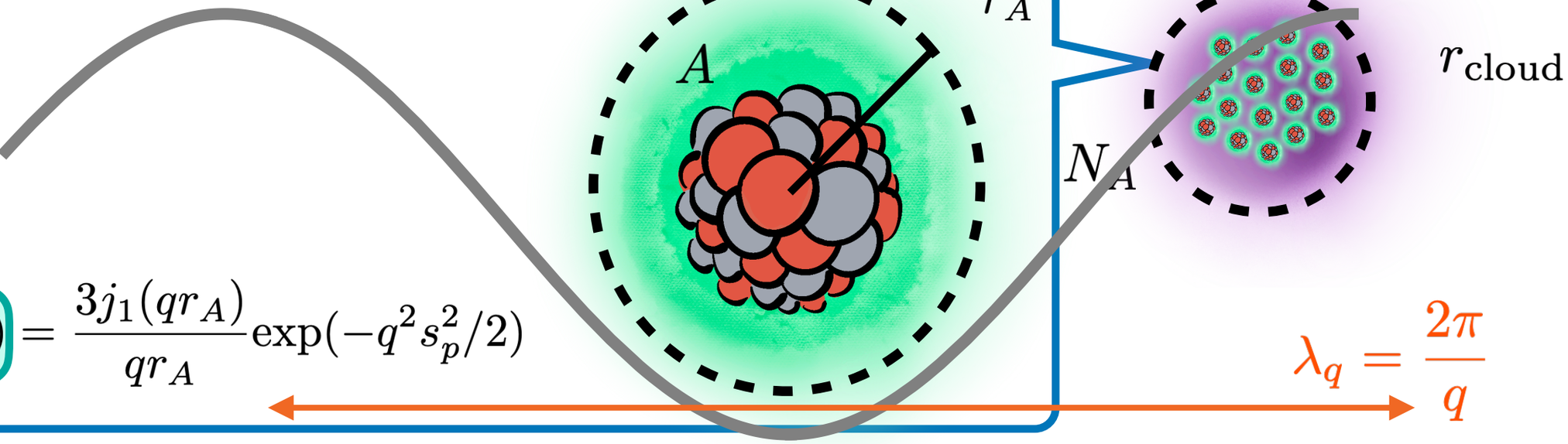
$$R = \frac{n_\chi}{m_T} \int d^3\mathbf{v}\, f(\mathbf{v})\, \Gamma(\mathbf{v})\, \mathcal{F}_{\rm decoh}(\mathbf{q})$$

Born (coherent) **enhancement**! (x2)

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

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

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



AIs: the Rate

[Y. Du, **CM**, et al. 2022]

Number of events / (target mass · time)

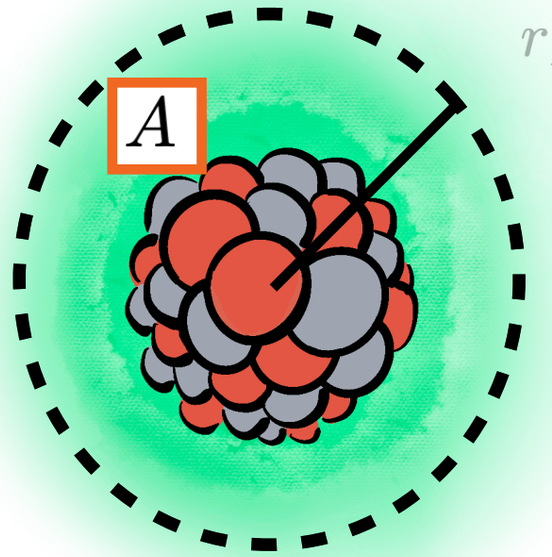
$$R = \frac{n_\chi}{m_T} \int d^3\mathbf{v}\, f(\mathbf{v})\, \Gamma(\mathbf{v})\, \mathcal{F}_{\rm decoh}(\mathbf{q})$$

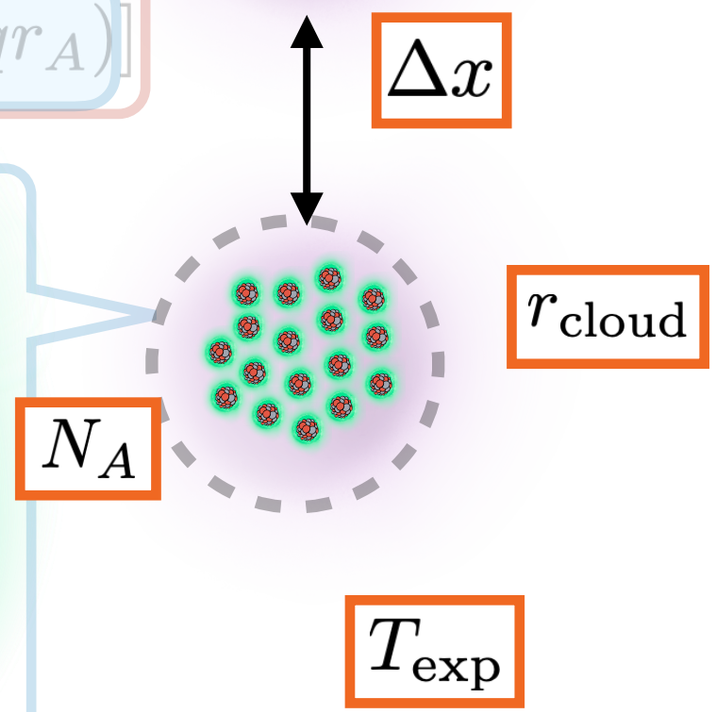
Born (coherent) **enhancement**! (x2)

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

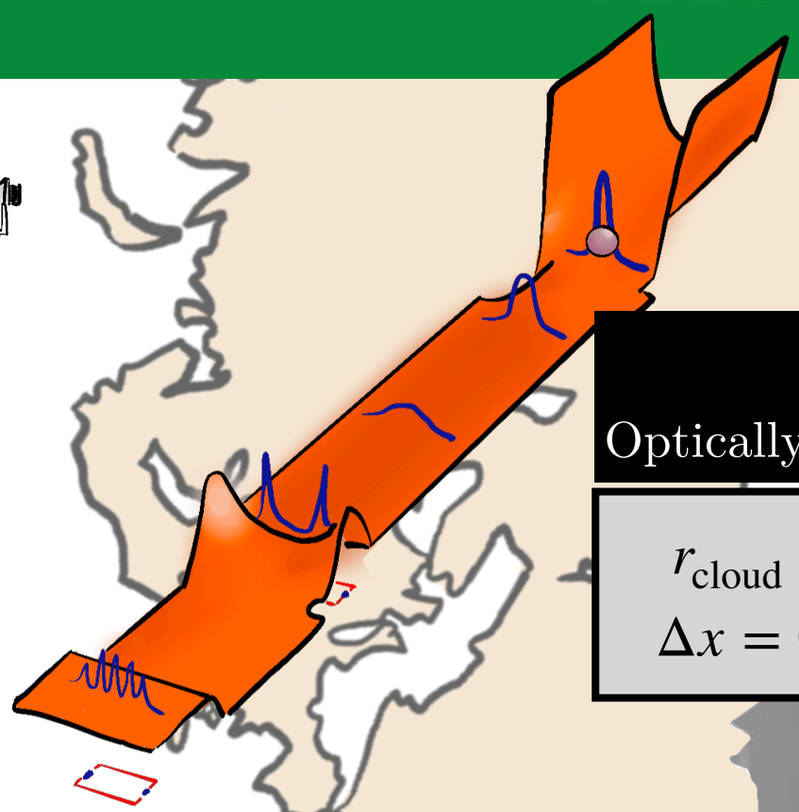
$$\mathcal{F}_T(\mathbf{q}) = N[1 + A(N_A - 1)\mathcal{F}^2_{\rm cloud}(qr_{\rm cloud}) + A\mathcal{F}^2_A(qr_A)]$$

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





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

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

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

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

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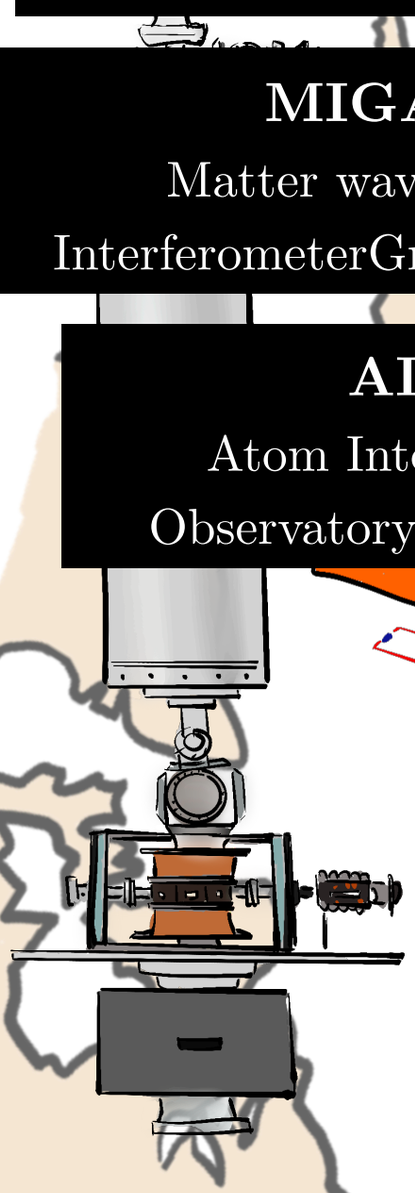
$\Delta x = 0.1\mu\text{m}$, $t_{\text{exp}} = 0.5\text{s}$

AION

Atom Interferometer Observatory and Network



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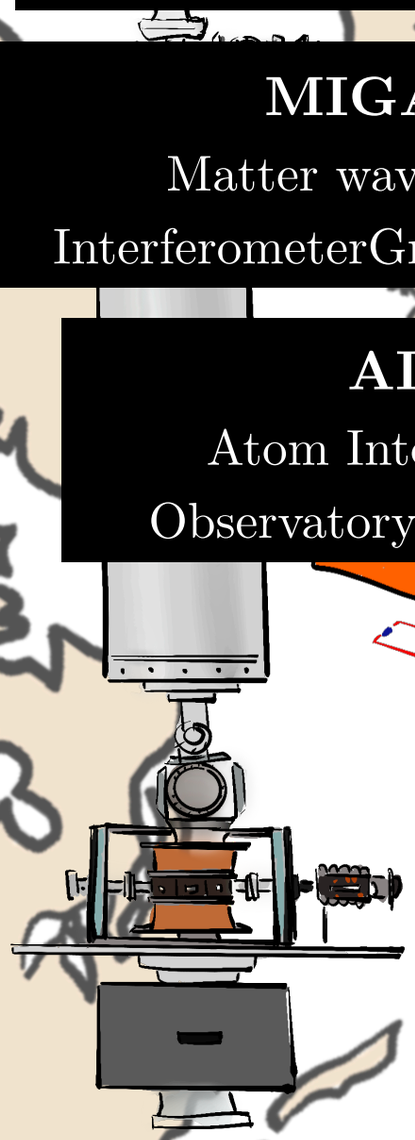

★

STANFORD

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

^{87}Rb

^{87}Rb

ELGAR ^{87}Rb

European Laboratory for Gravitation and Atom-interferometric Research

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AION

Atom Interferometer Observatory and Network

PINO Nb

Optically levitated nanosphere

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

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

MAQRO SiO_2

Macroscopic Quantum Resonators

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

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

MAQRO

GDM ^{87}Rb

Gravity Dark energy Mission

$r_{\text{cloud}} \sim 1\text{mm}$, $N \sim 10^{10}$

$\Delta x = 25\text{m}$, $t_{\text{exp}} = 20\text{s}$

STANFORD ^{87}Rb

10-m atomic fountain

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

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

BECCAL ^{87}Rb

Bose-Einsten Condensate Cold Atom Laboratory

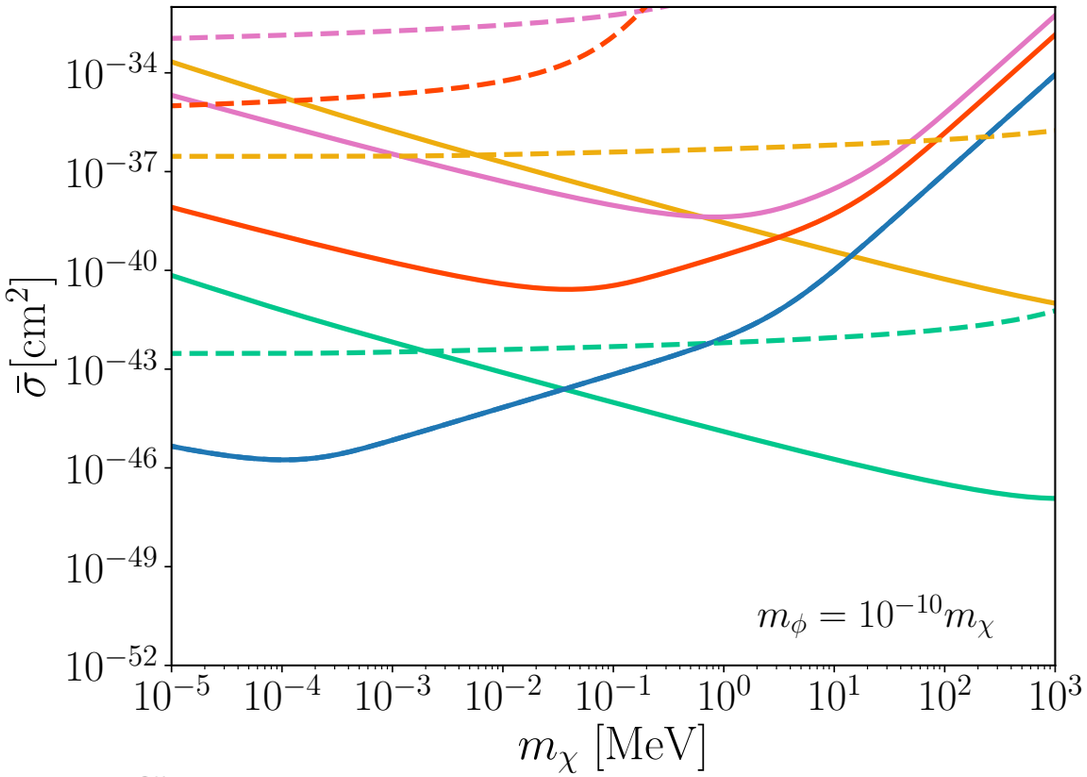
$r_{\text{cloud}} \sim 0.1\text{mm}$, $N \sim 10^{8}$

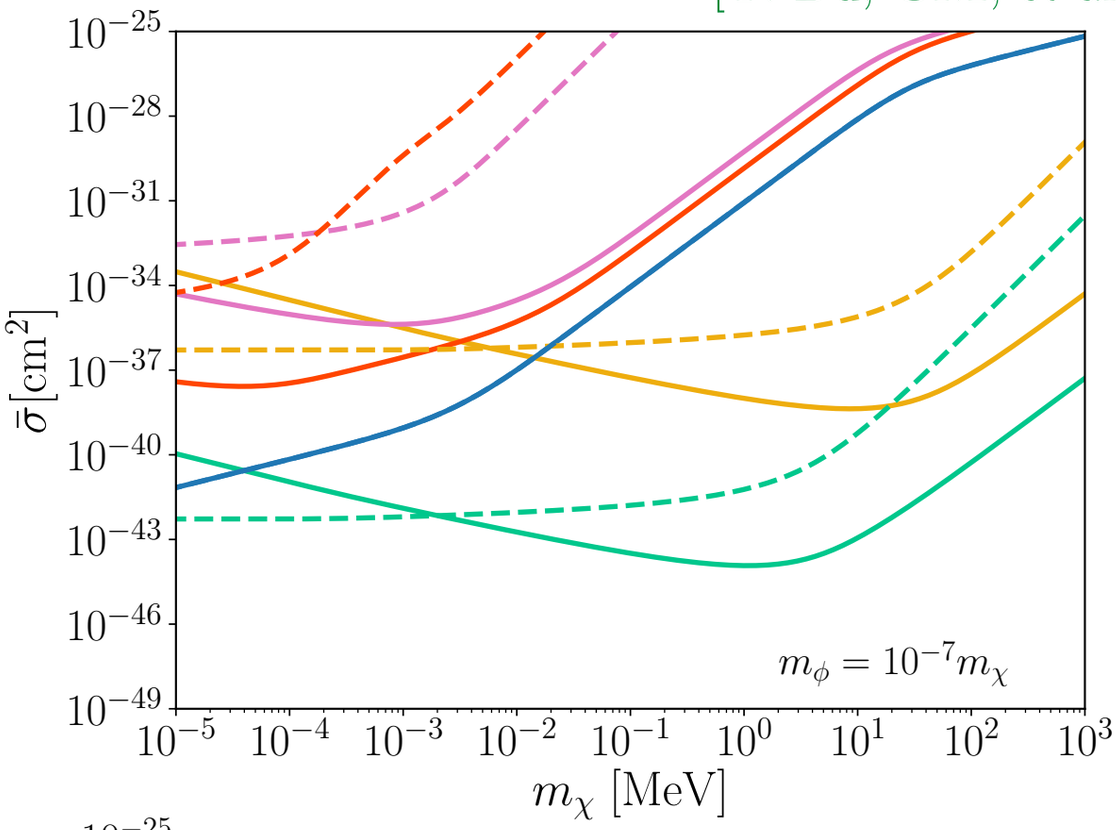
$\Delta x = 1\text{mm}$, $t_{\text{exp}} = 3\text{s}$

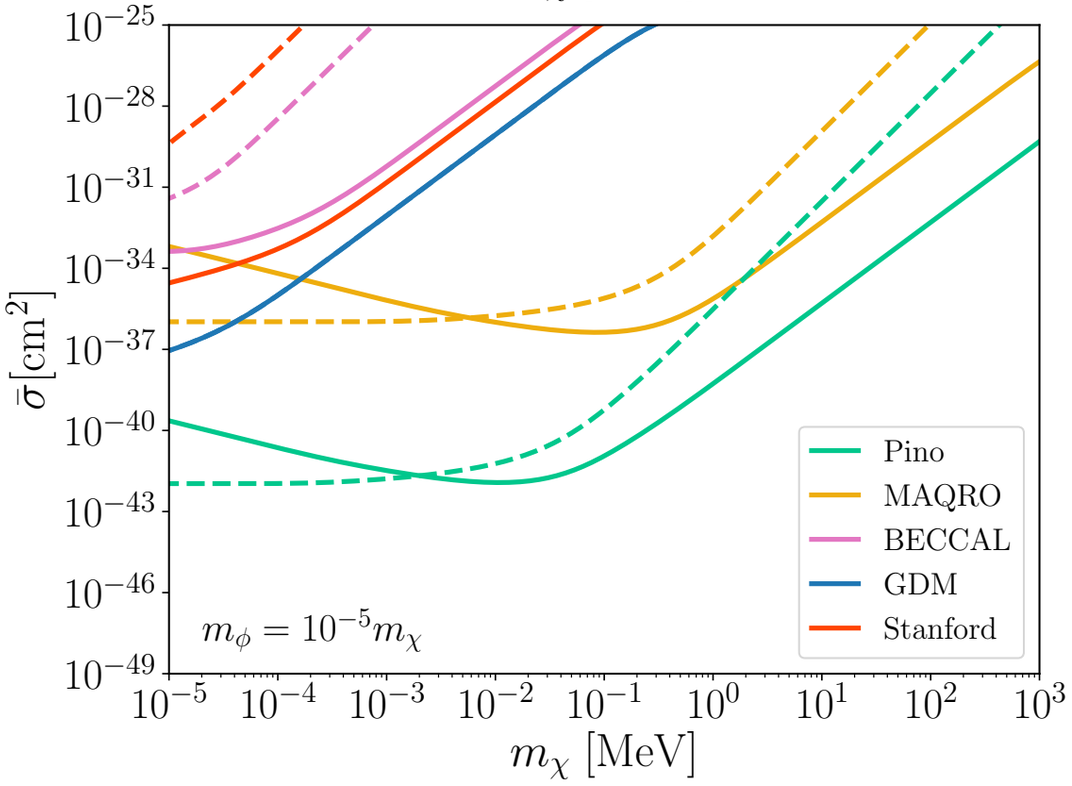
BECCAL BOSE-EINSTEIN CONDENSATE AND COLD ATOM LABORATORY NASA DLR

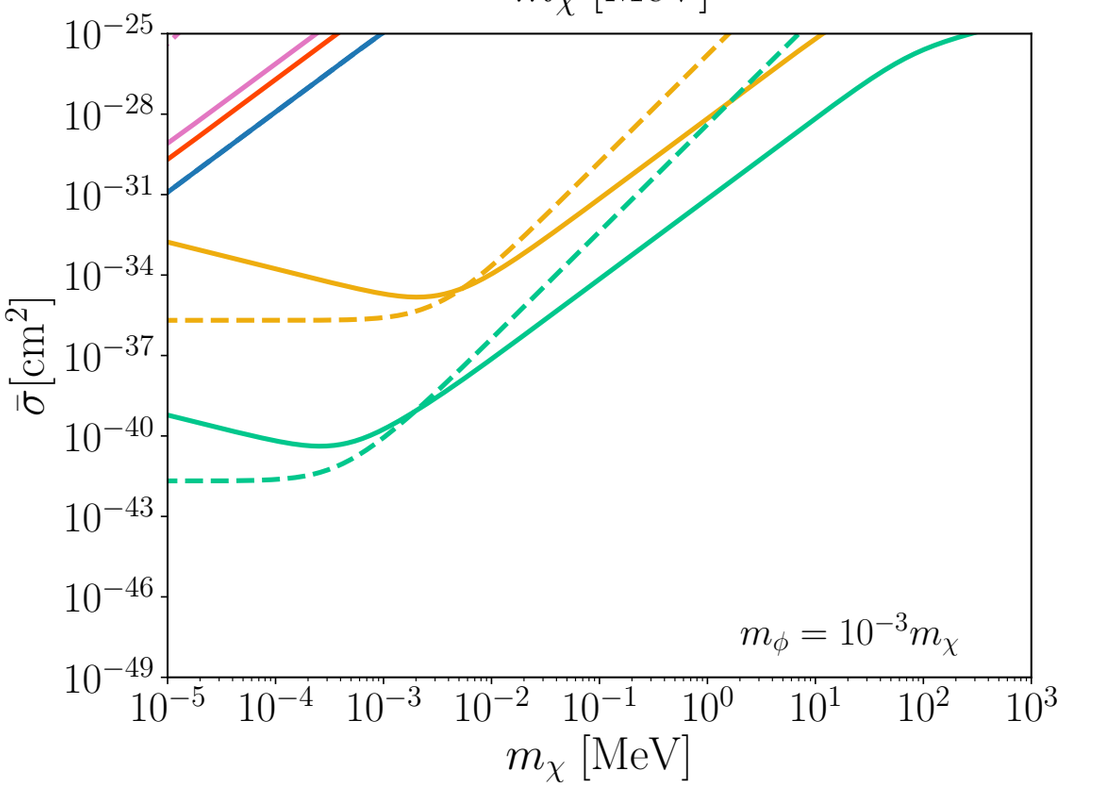
AIs: Results

[Y. Du, **CM**, et al. 2022]





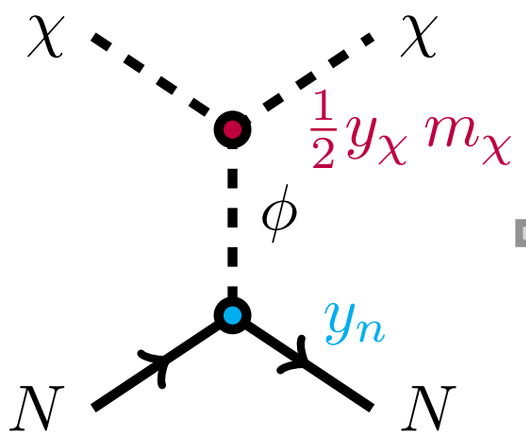




AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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



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

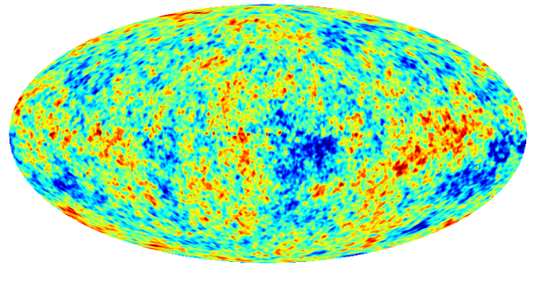
Terrestial

- Collider
- 5th force

Astrophysical

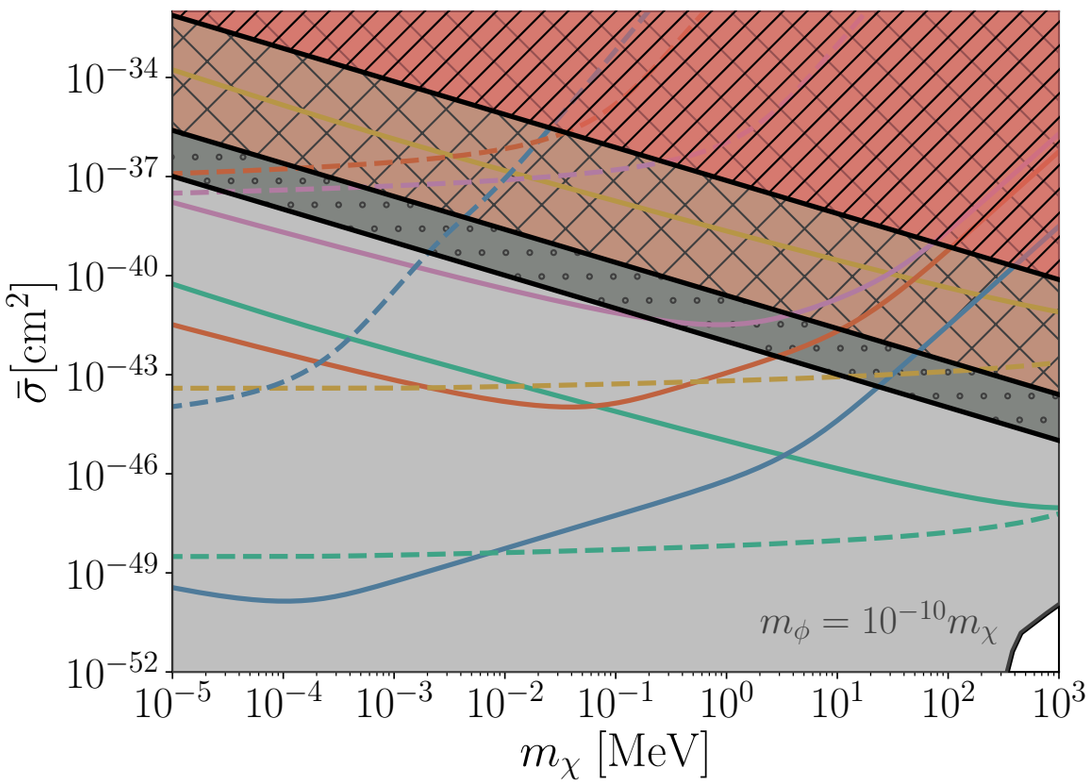
- Stellar emission
- DMSI

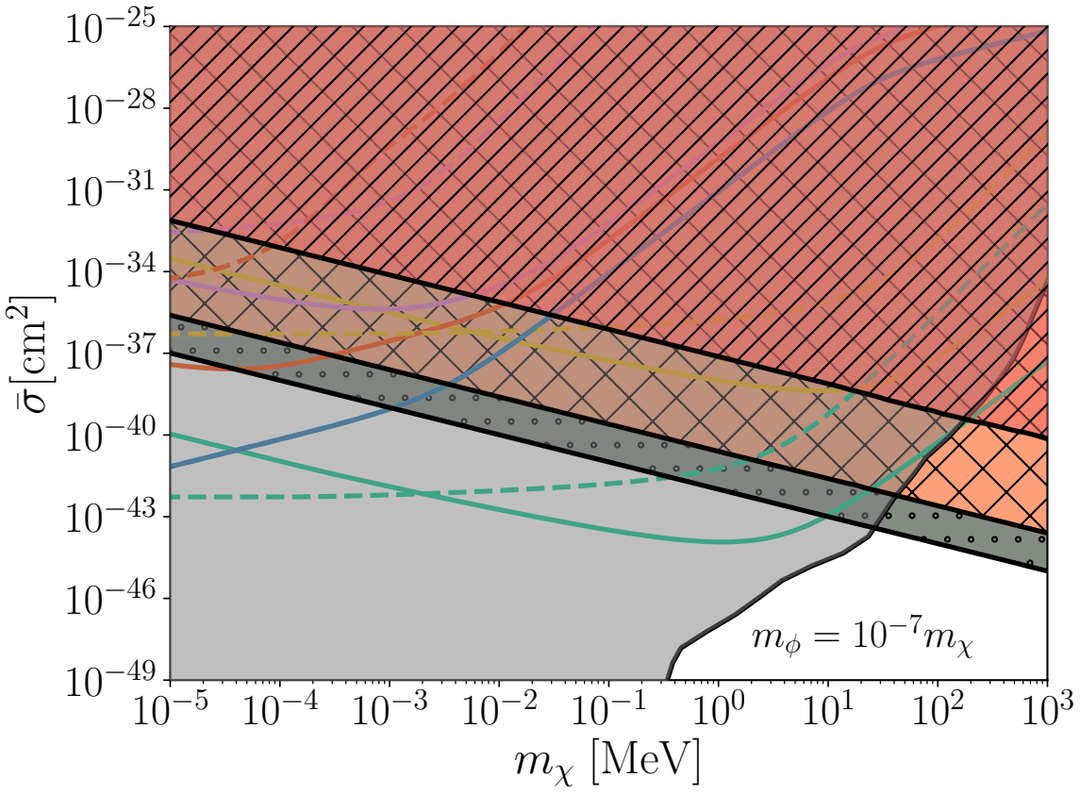
Cosmological

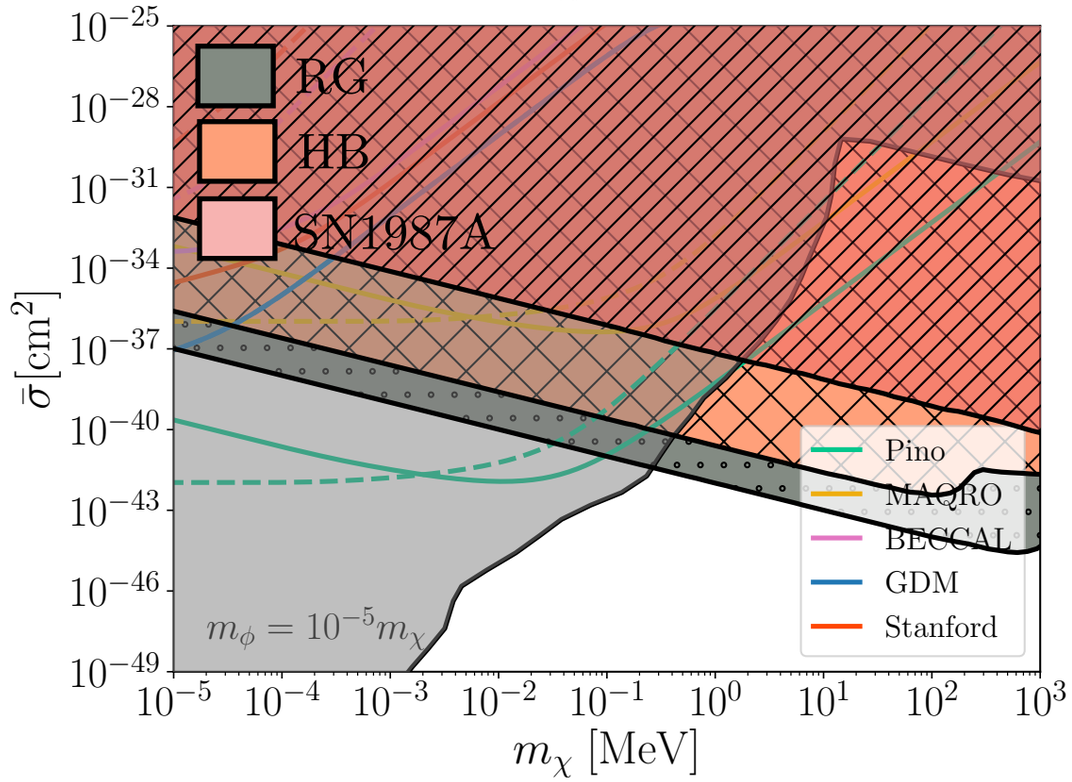


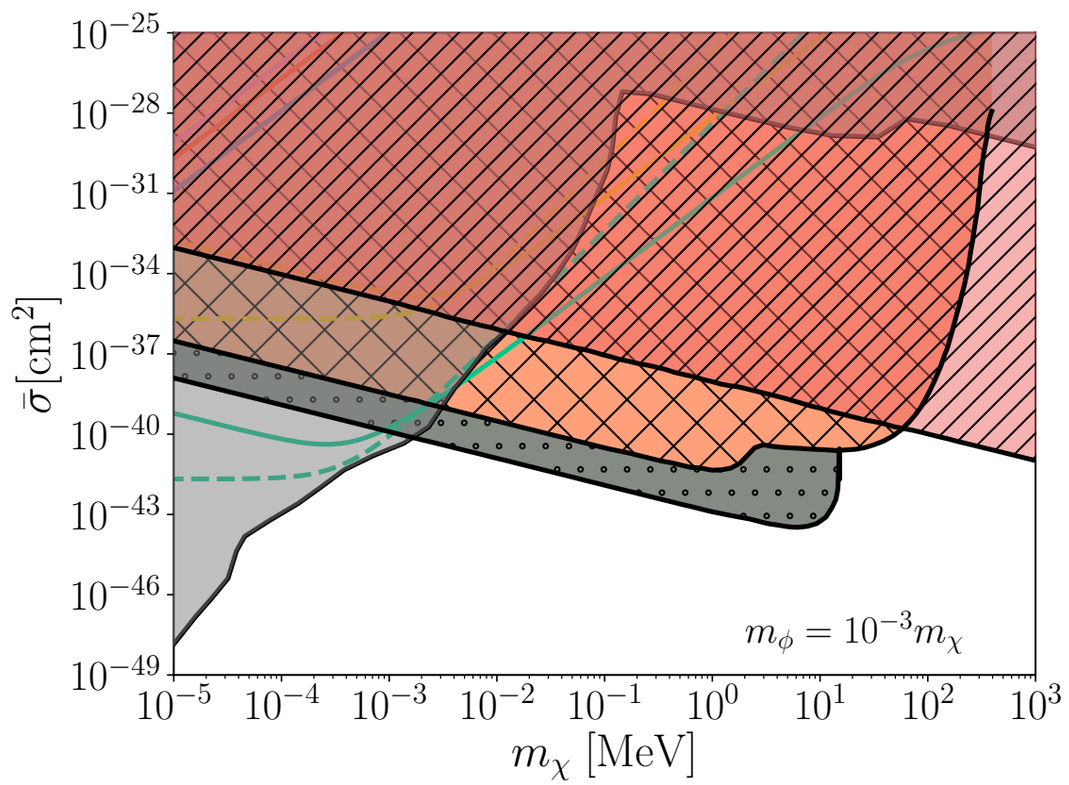
AIs: Constraints

[Y. Du, **CM**, et al. 2022]



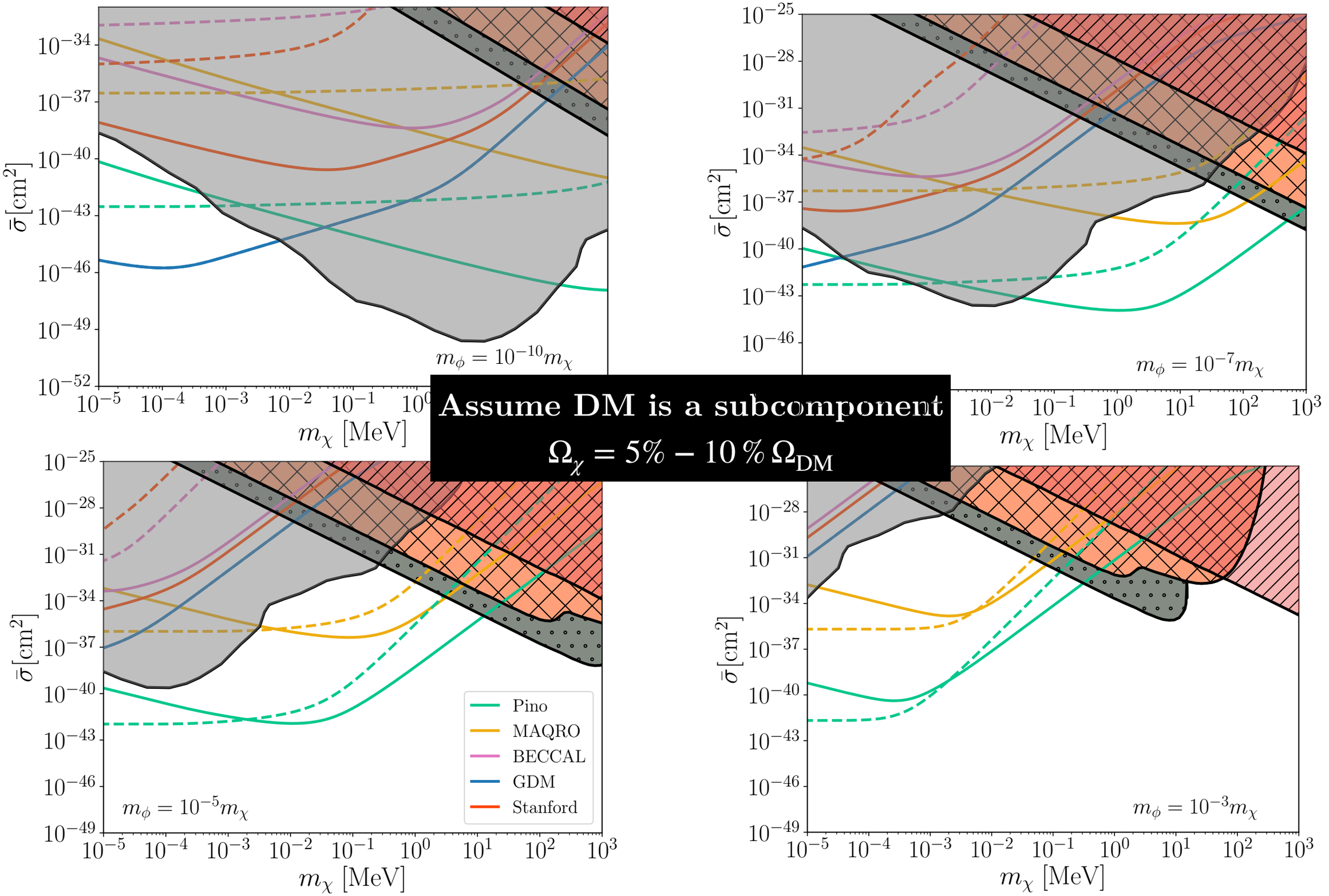






AIs: Constraints

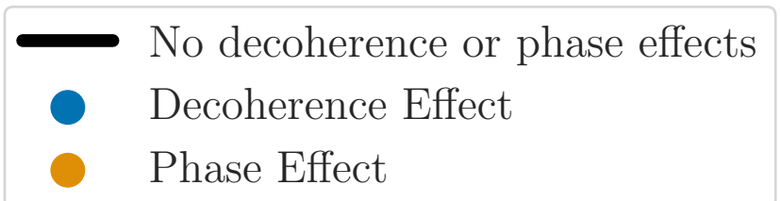
[Y. Du, **CM**, et al. 2022]



Assume DM is a subcomponent

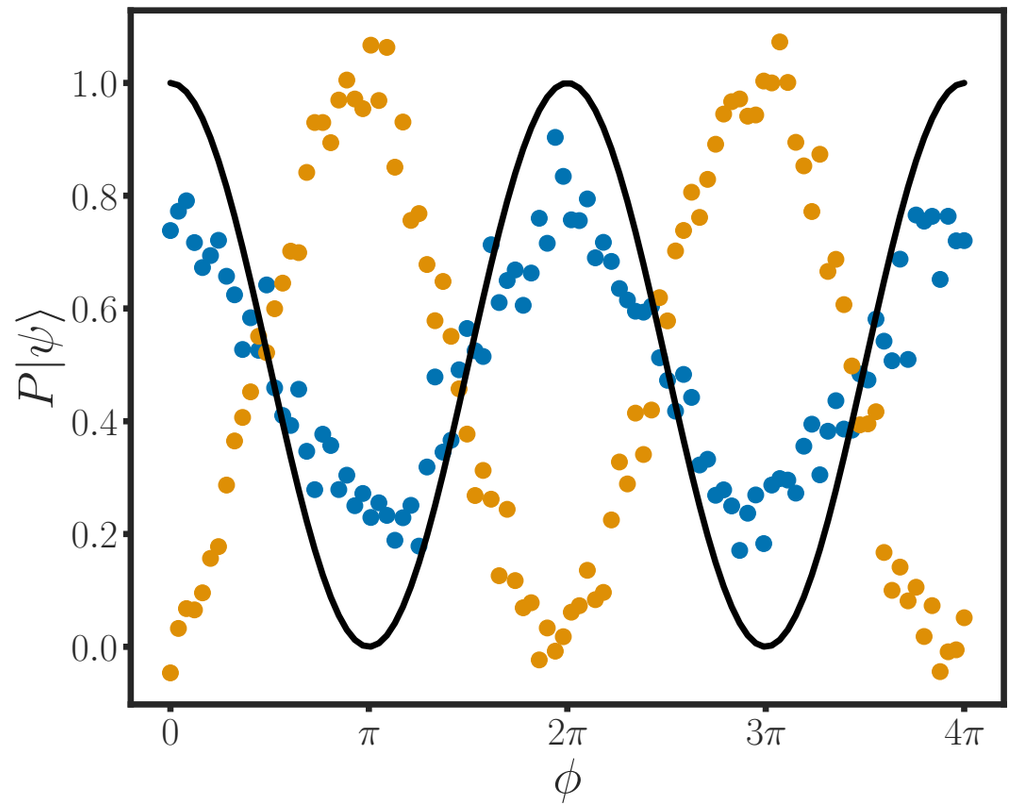
$\Omega_\chi = 5\% - 10\,\% \,\Omega_{\mathrm{DM}}$

AIs: Measurement

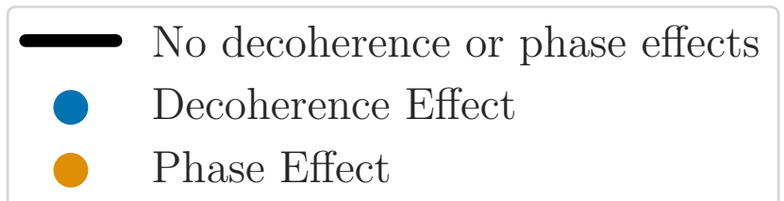


Visibility

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

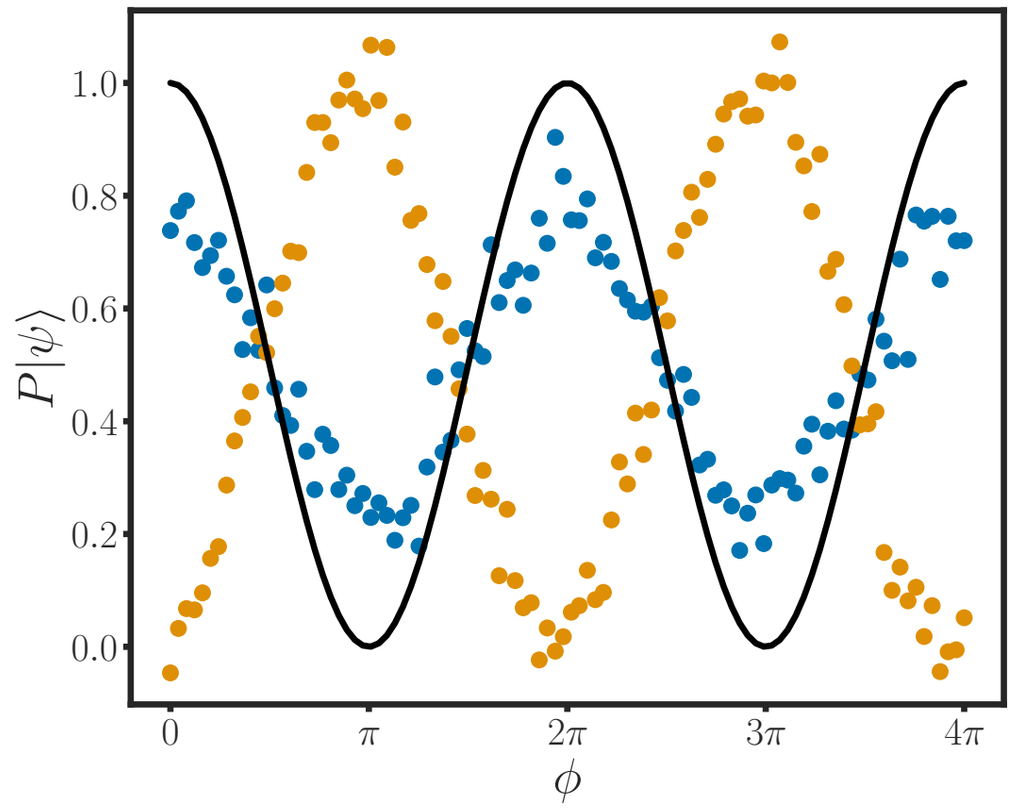


AIs: Measurement

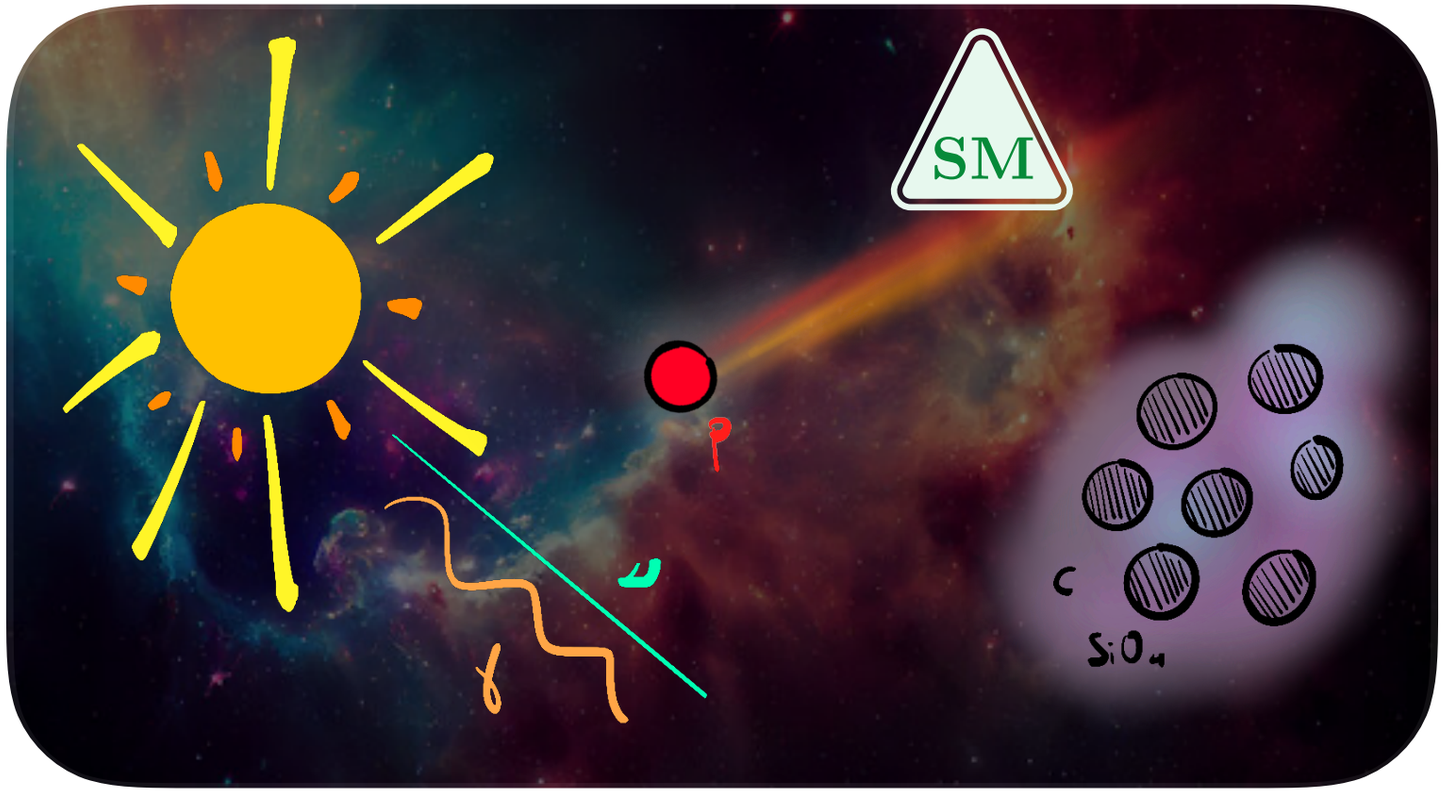


Visibility

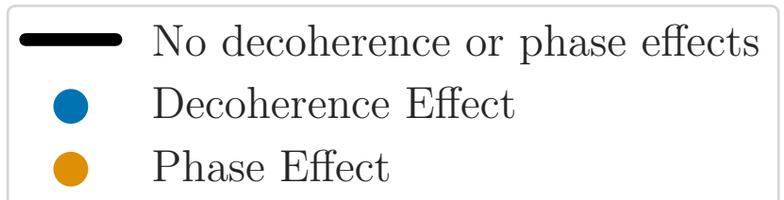
$$\mathrm{SNR}|_{\mathrm{shot}} \equiv \frac{|\Delta V|}{\sigma_V}$$



[Y. Du, **CM**, et al. 2022]

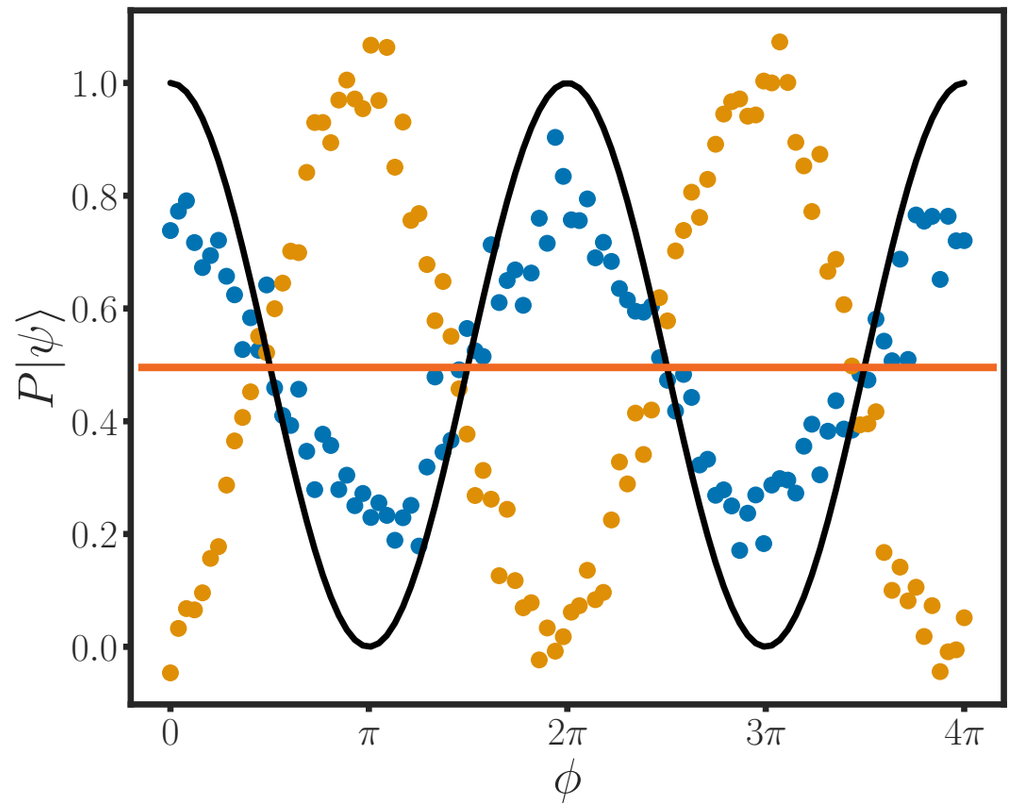


AIs: Measurement

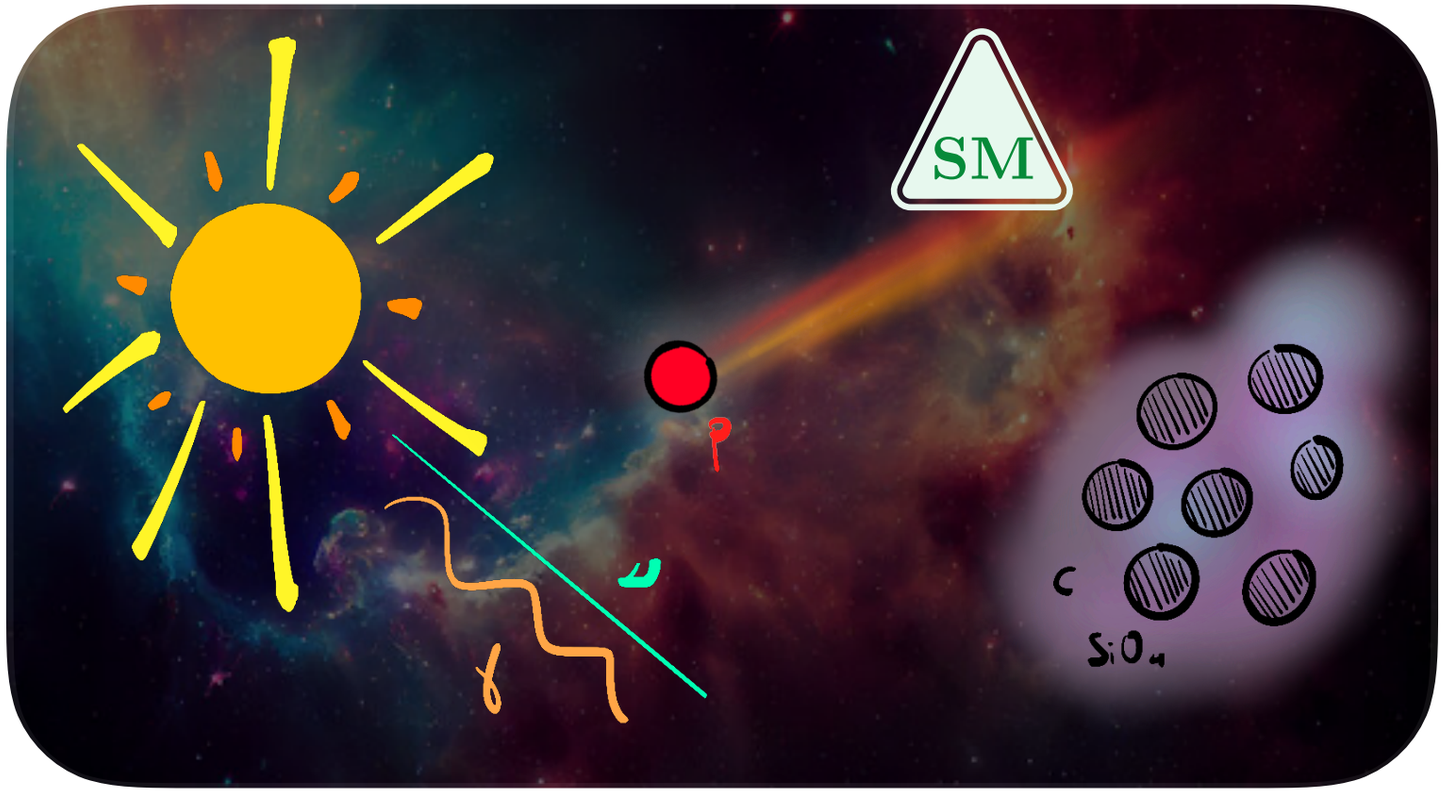


Visibility

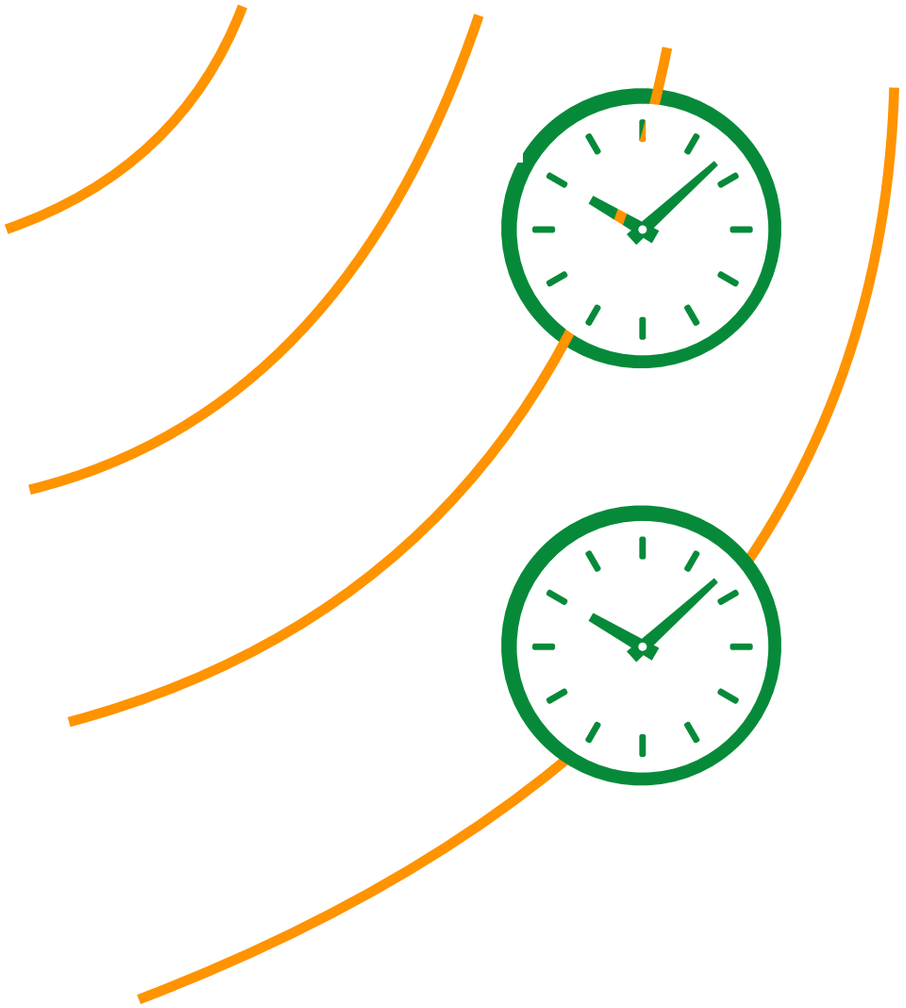
$$\mathrm{SNR}|_{\mathrm{shot}} \equiv \frac{|\Delta V|}{\sigma_V}$$



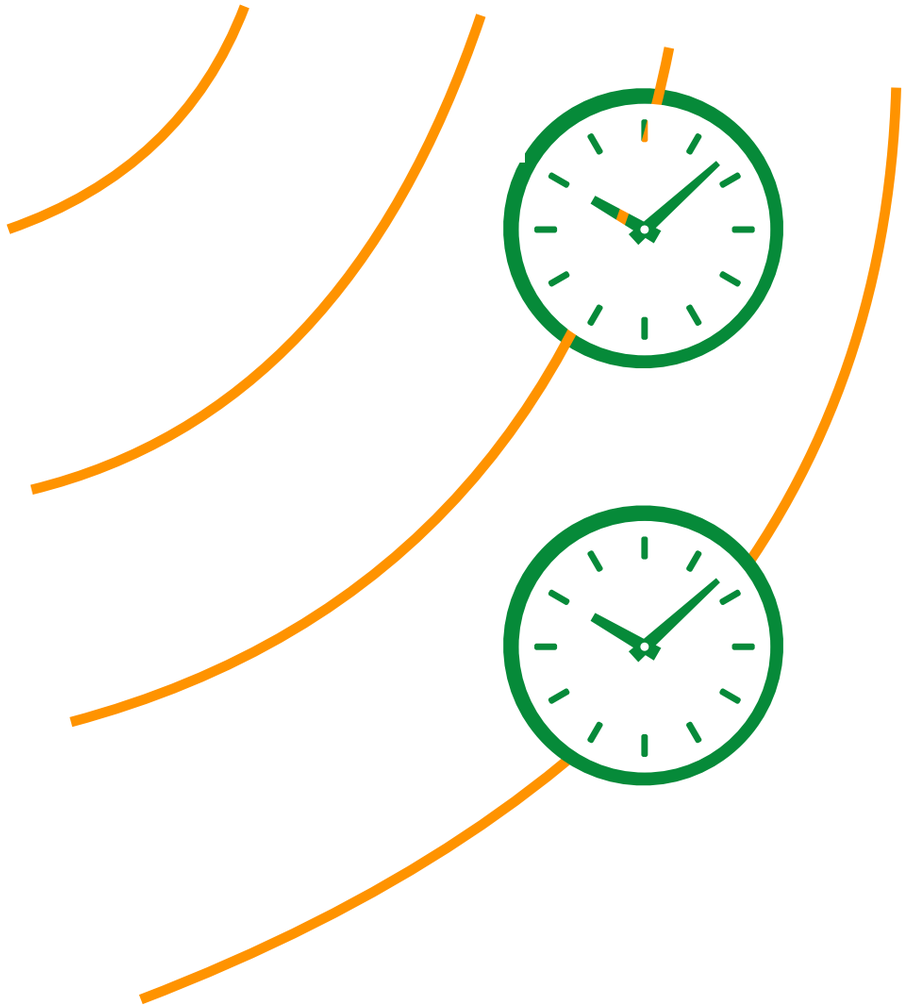
[Y. Du, **CM**, et al. 2022]

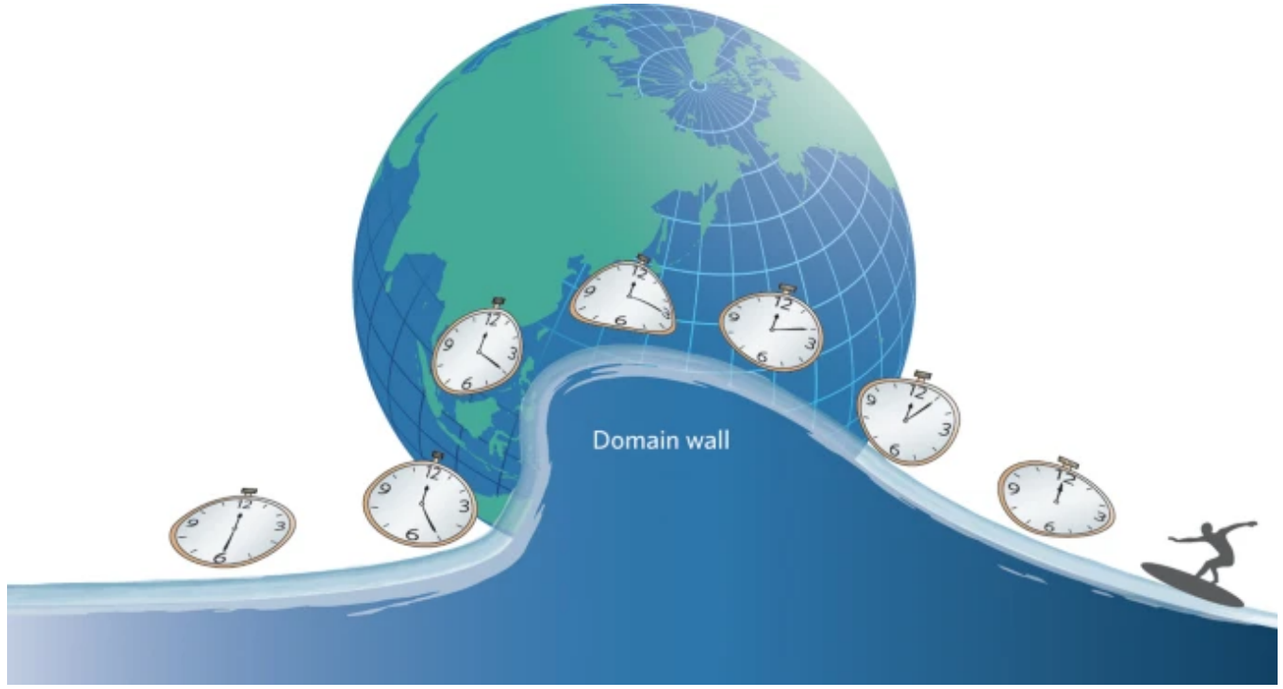


Atomic Clocks



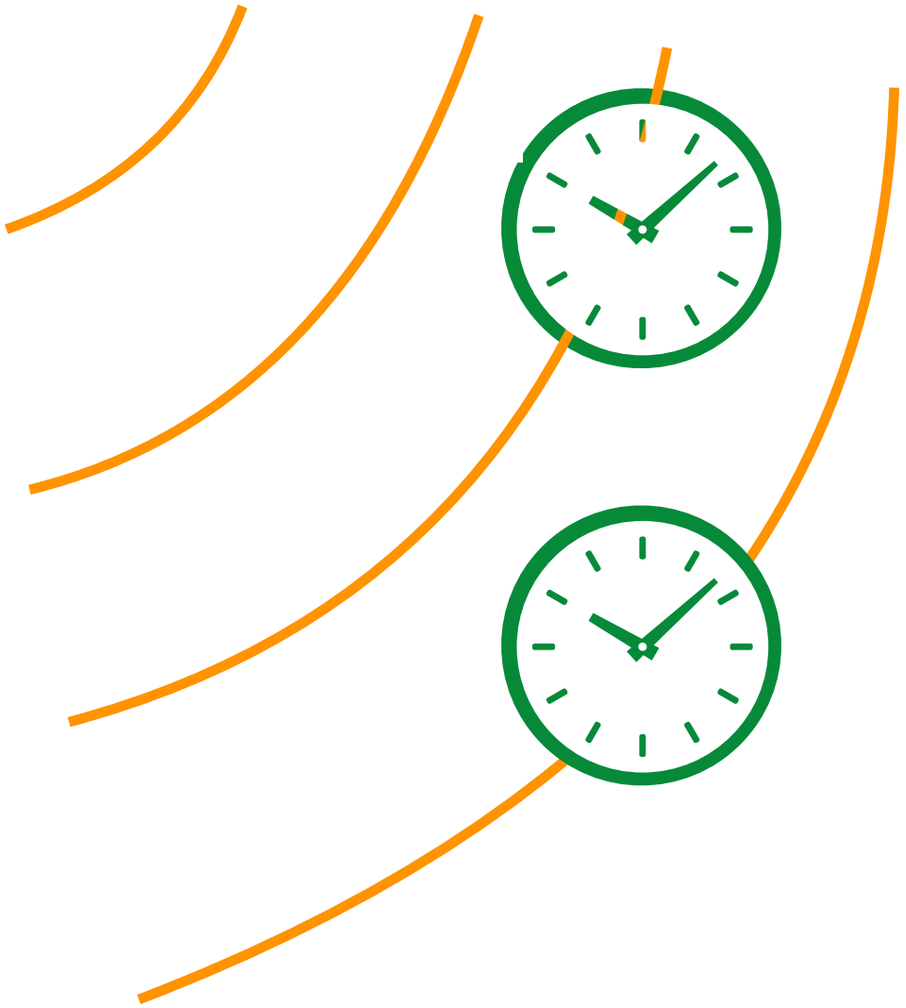
Atomic Clocks

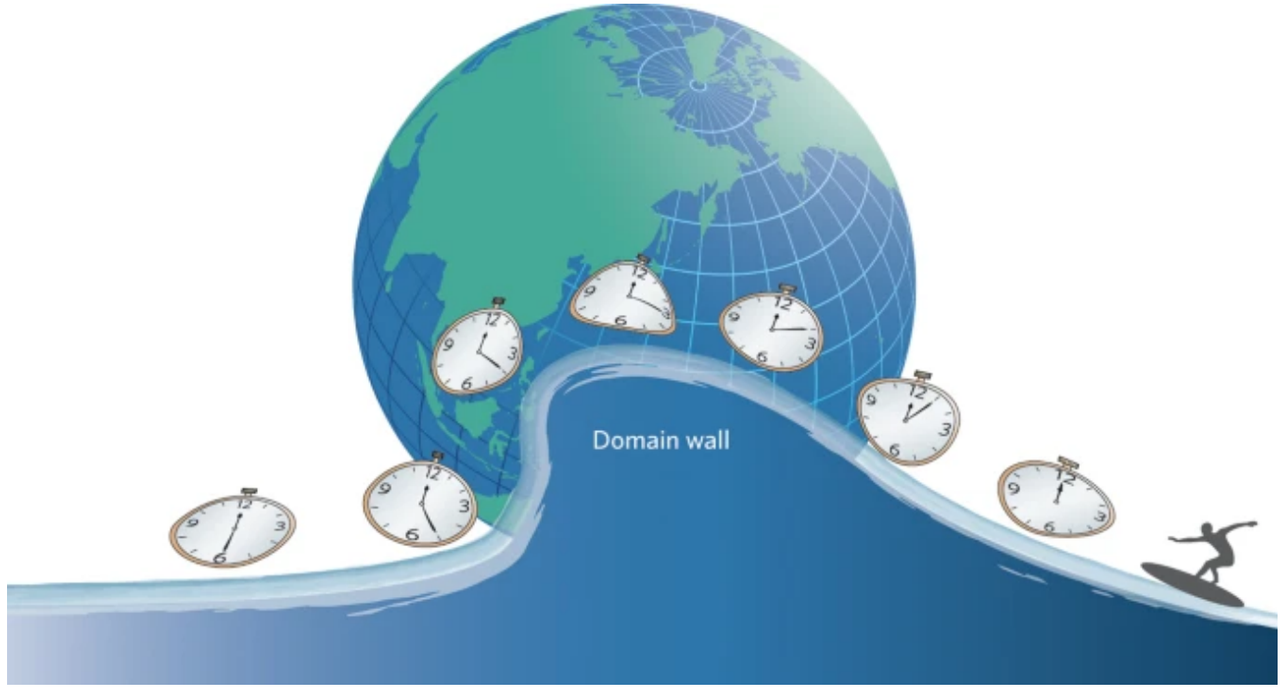




[Adhikari, Hamilton, et. al, 2014]

Atomic Clocks



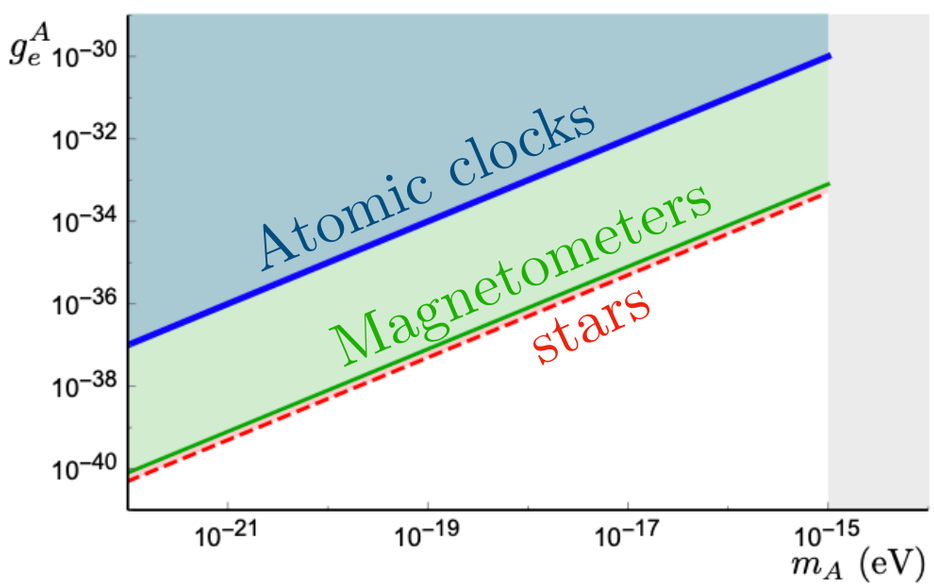


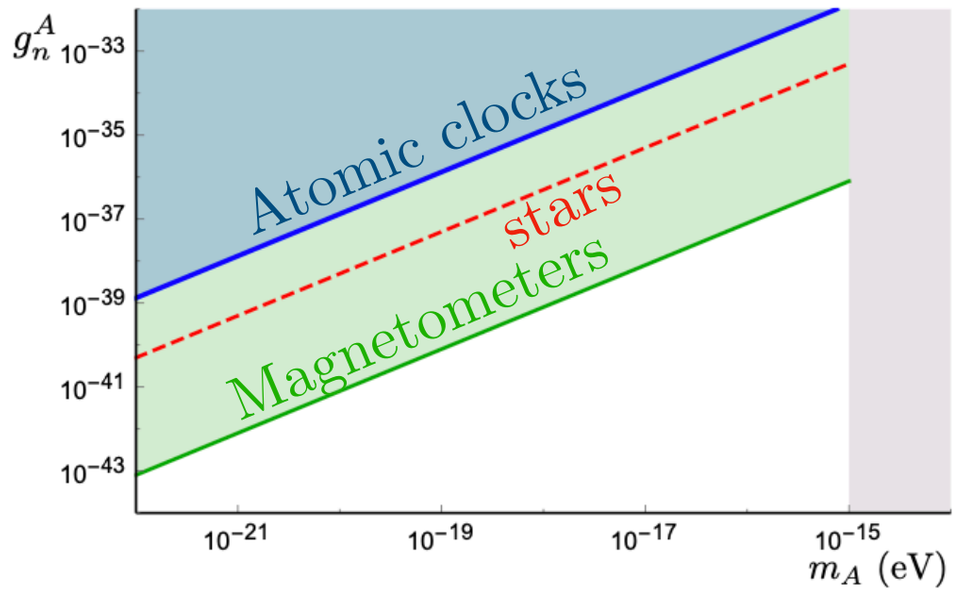
[Adhikari, Hamilton, et. al, 2014]

Topological DM	[Derevianko, Pospelov, 2014],[Derevianko, 2016 [Wcislo et al. 2018]
Wave DM	[Arvanitaki et al. 2015]
5th forces	[Brzeminski, Chacko, et al. 2022]
GWs	[Loeb, Maoz, 2015]
Particle DM	[Alonso, Blas, Wolf, 2018]

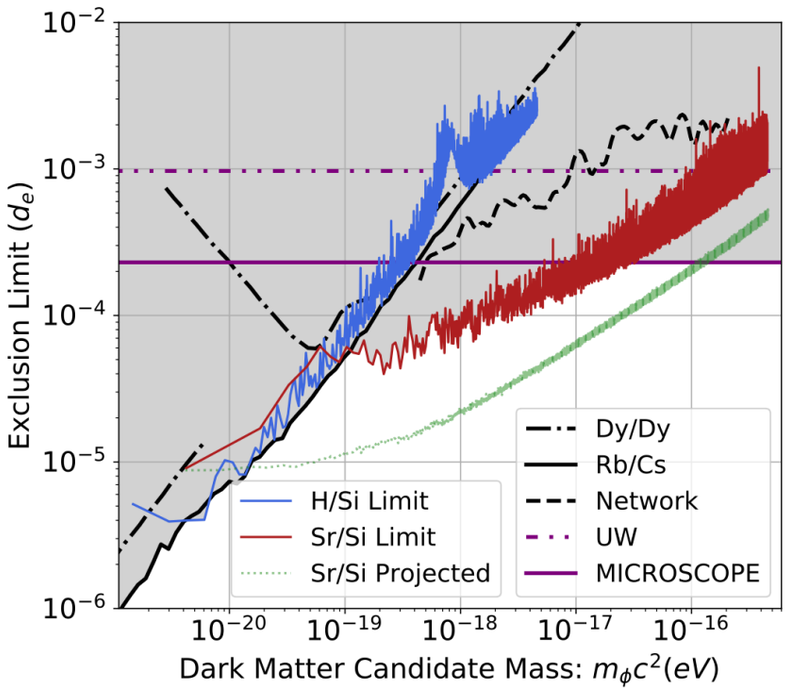
Atomic Clocks

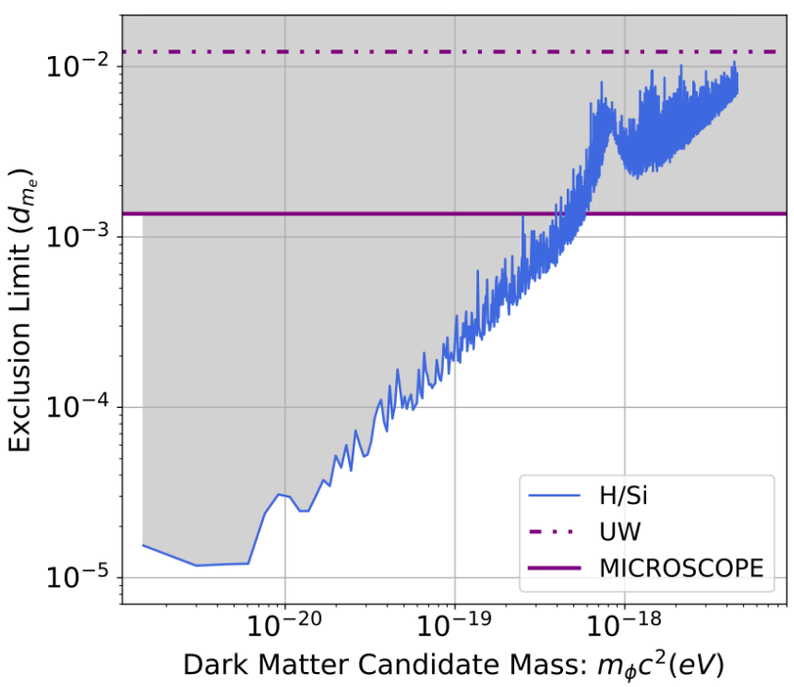
[Alonso, Blas, Wolf, 2019]



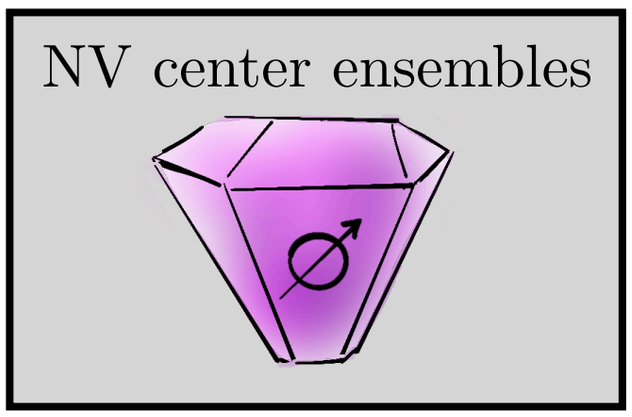


$$\mathcal{L}_\phi = \sqrt{4\pi G_N}\phi\left(\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu} - d_{m_e}m_e\bar{\Psi}_e\Psi_e\right)$$ [Kennedy, Oelker, et al. 2020]

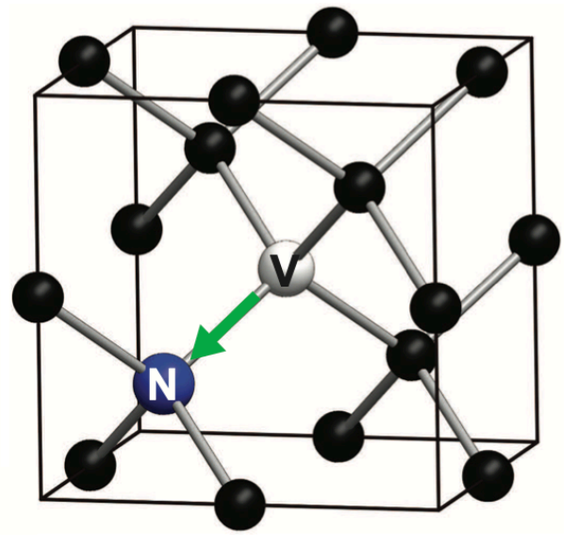




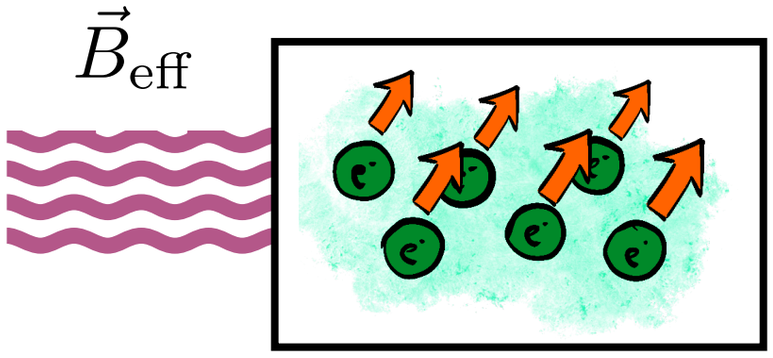
NV center ensembles



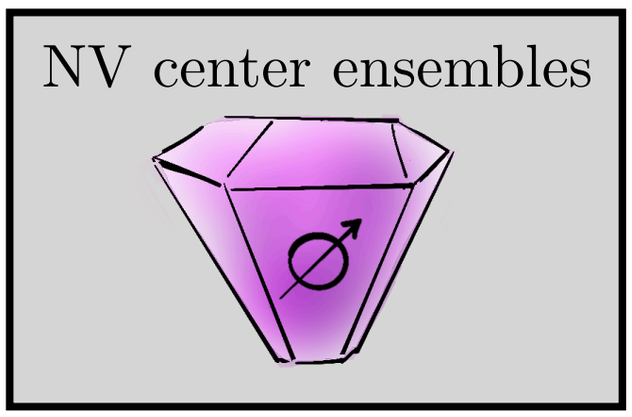
[Pham, 2013]
[Degen, Reinhard, et al, 2017]
[Schloss, et al, 2018]
[Barry, Schloss, et al, 2019]
[Chigusa, Hazumi, et al, 2023



NV center ensembles



$$\mathcal{H} \supset -\vec{\mu} \cdot \vec{B}$$



[Pham, 2013]
[Degen, Reinhard, et al, 2017]
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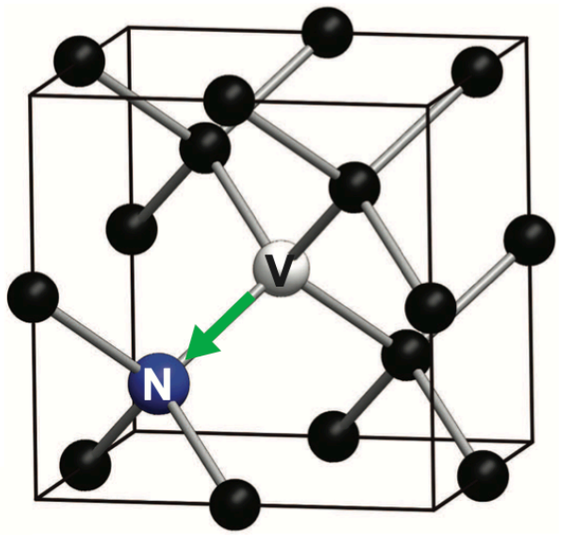
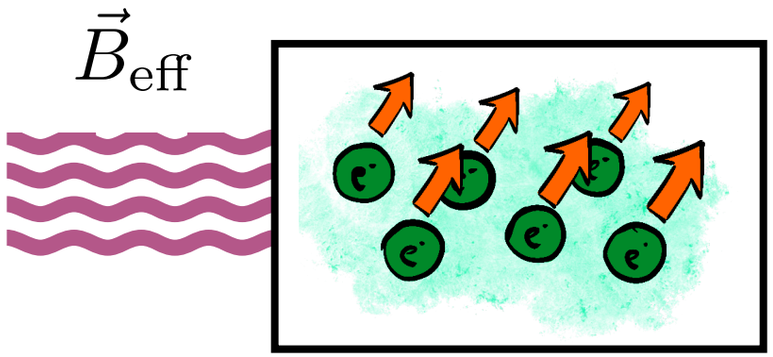
[Barry, Schloss, et al, 2019]
[Chigusa, Hazumi, et al, 2023



NV center ensembles

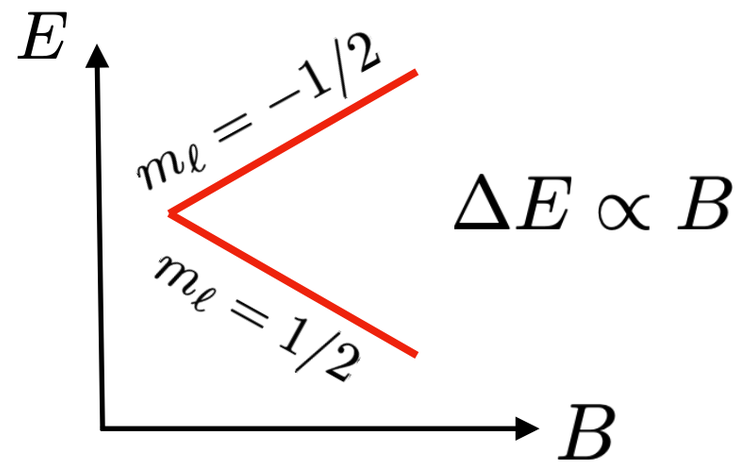


$$\mathcal{H} \supset -\vec{\mu} \cdot \vec{B}$$

$$g_{aee}\frac{\partial_\mu a}{2m_e}\bar{\Psi}_e\gamma_\mu\gamma_5\Psi_e \Rightarrow \frac{g_{aee}}{m_e}\nabla a \cdot \vec{S}_e$$

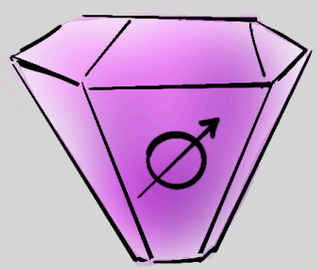
e.g.

$$\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} \Rightarrow \frac{\epsilon e}{m_e}(\nabla \times \vec{A}) \cdot \vec{S}_e$$

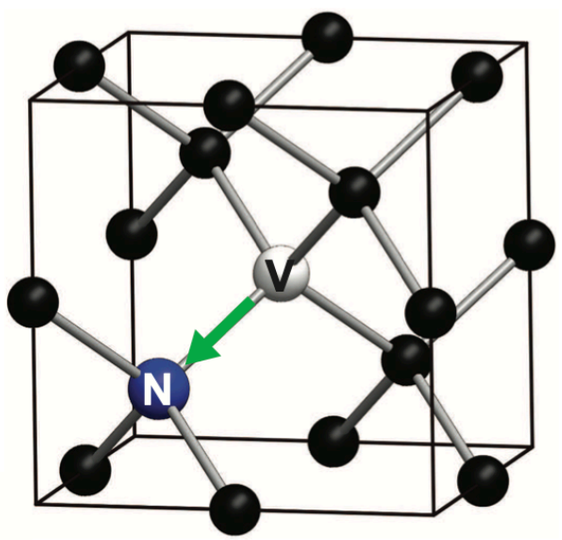


$$\Delta E \propto B$$

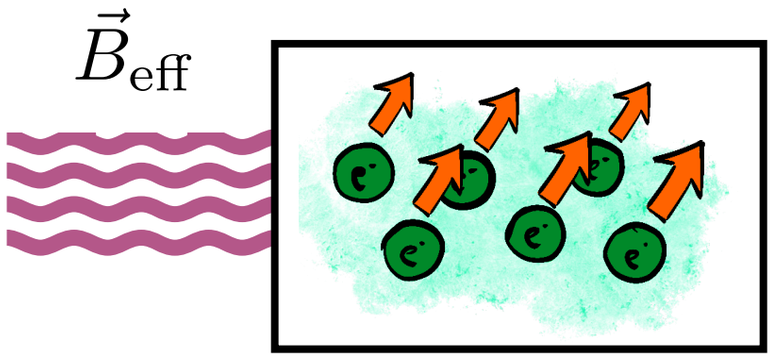
NV center ensembles



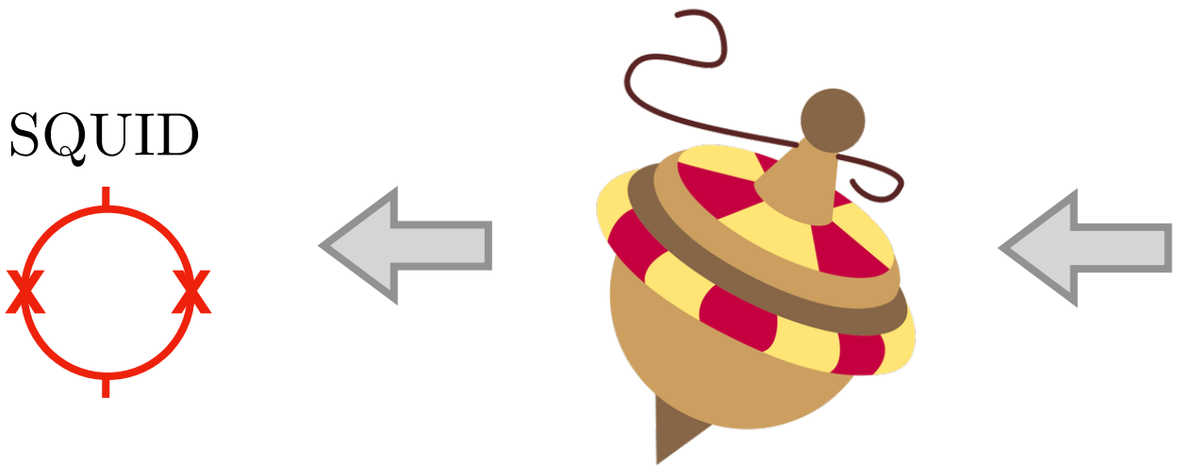
[Pham, 2013]
[Degen, Reinhard, et al, 2017]
[Schloss, et al, 2018]
[Barry, Schloss, et al, 2019]
[Chigusa, Hazumi, et al, 2023

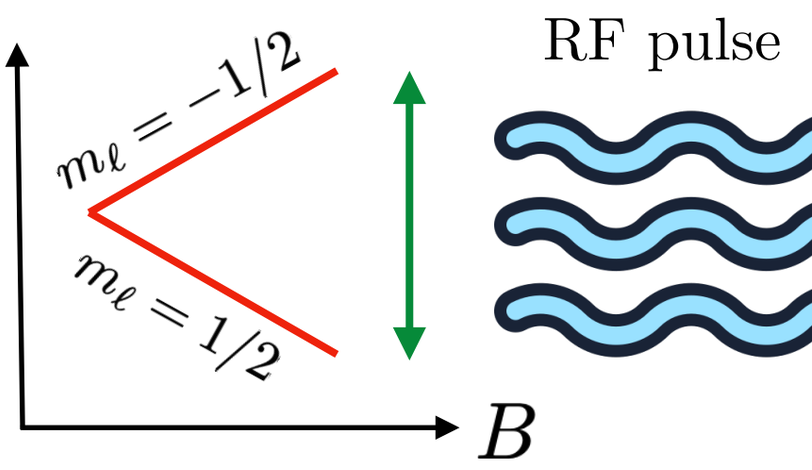


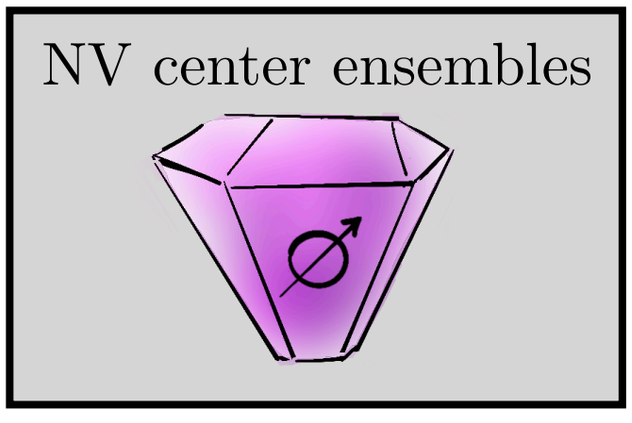
NV center ensembles



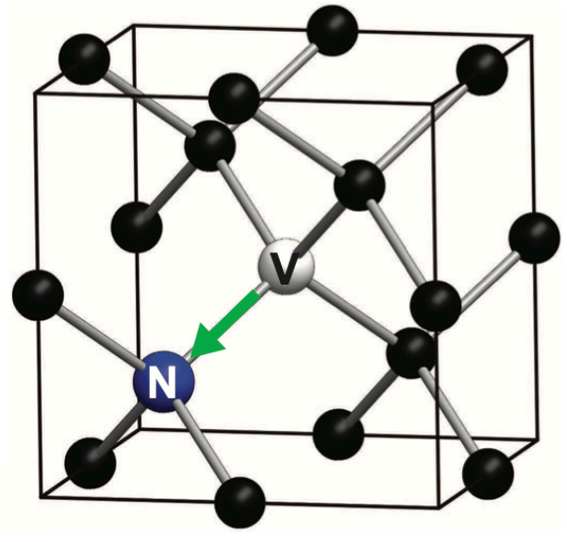
$$\mathcal{H} \supset -\vec{\mu} \cdot \vec{B}$$





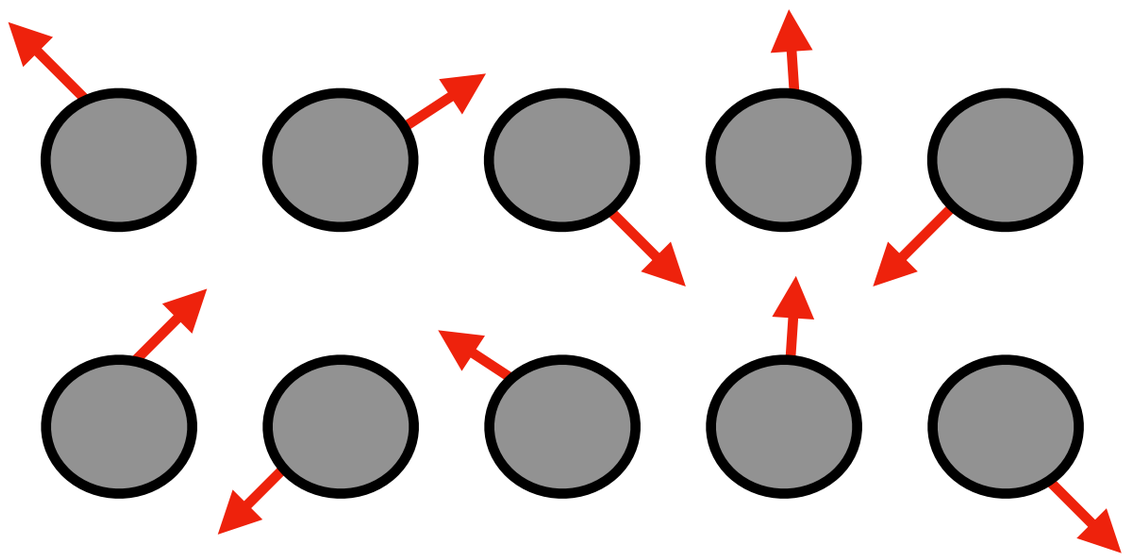


[Pham, 2013]
[Degen, Reinhard, et al, 2017]
[Schloss, et al, 2018]
[Barry, Schloss, et al, 2019]
[Chigusa, Hazumi, et al, 2023



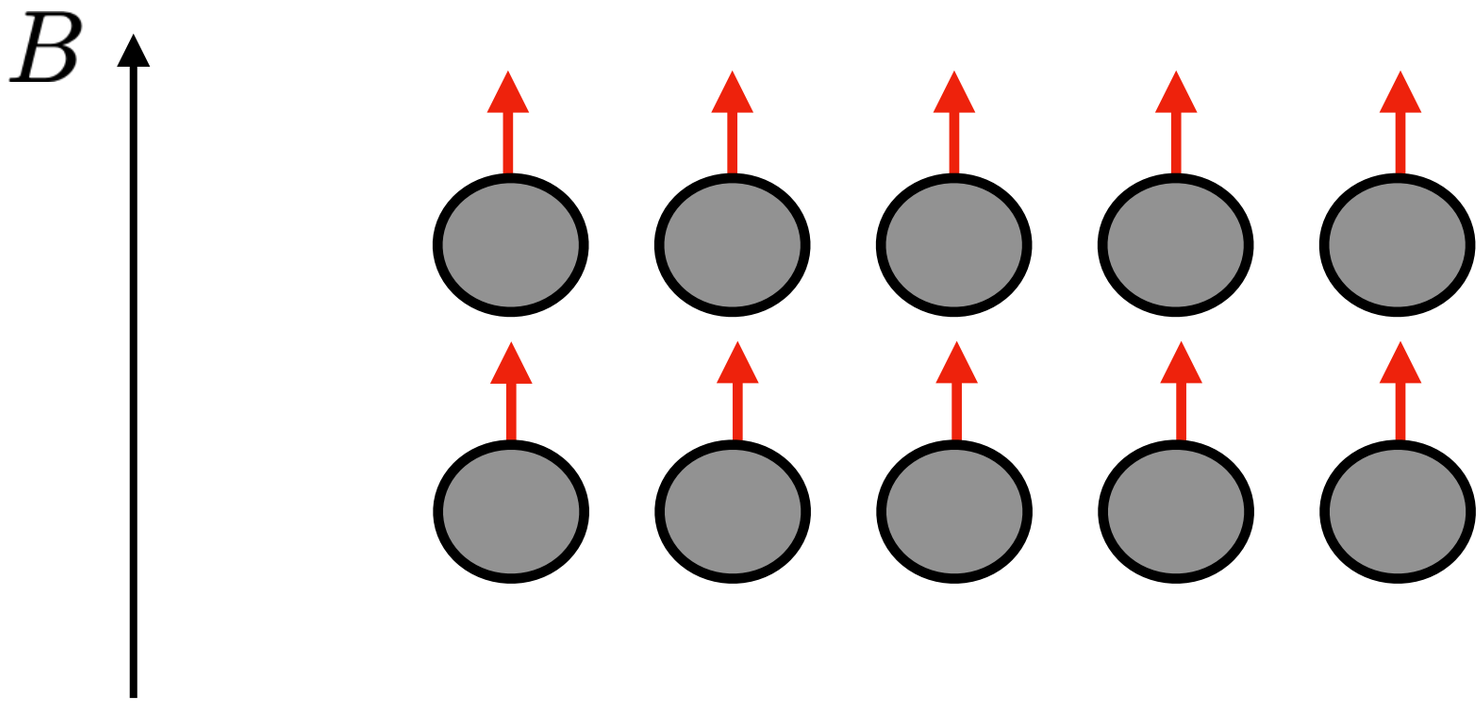
CASPER

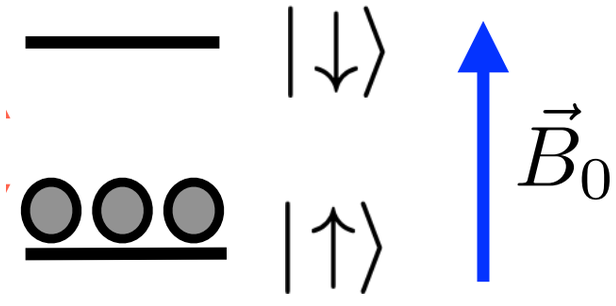
[Budker, Graham, et al. 2014]
[Garcon, Blanchard, et al. 2019]



CASPER

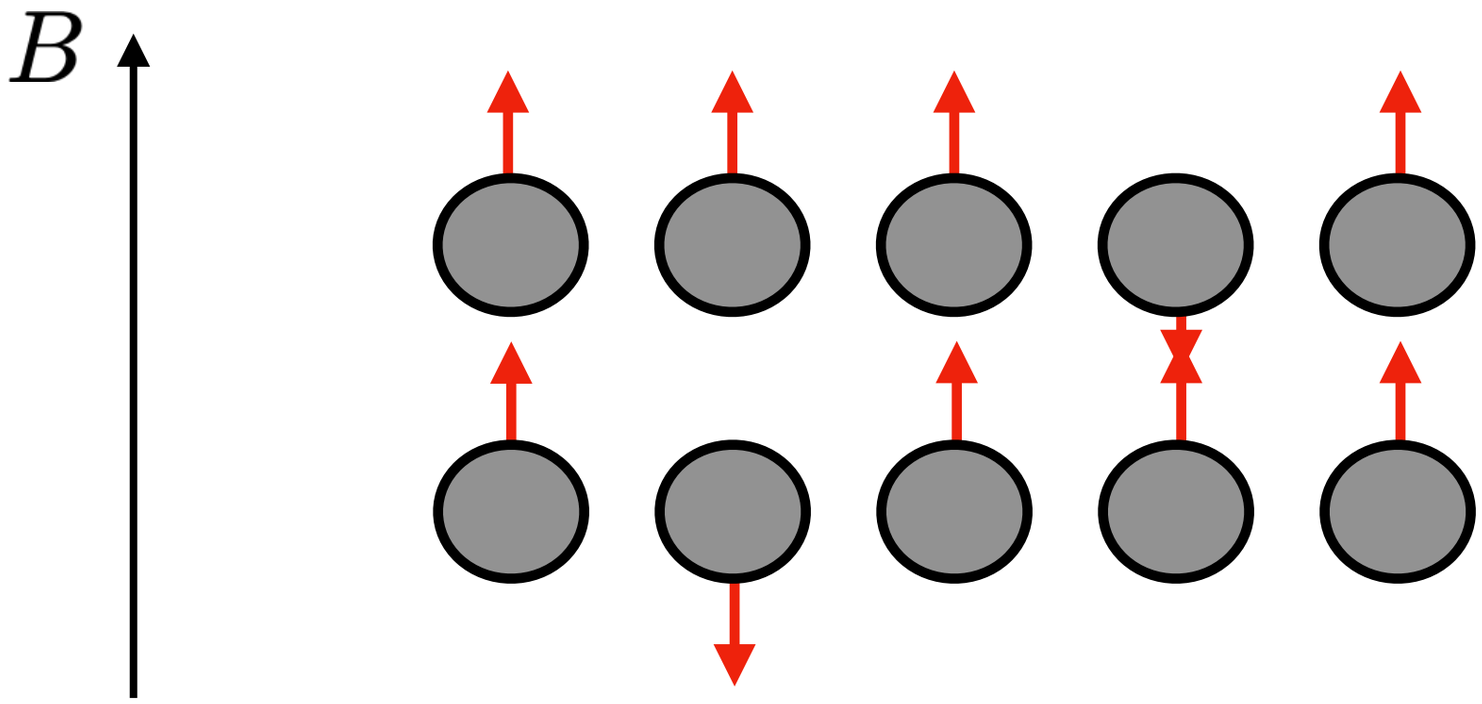
[Budker, Graham, et al. 2014]
[Garcon, Blanchard, et al. 2019]

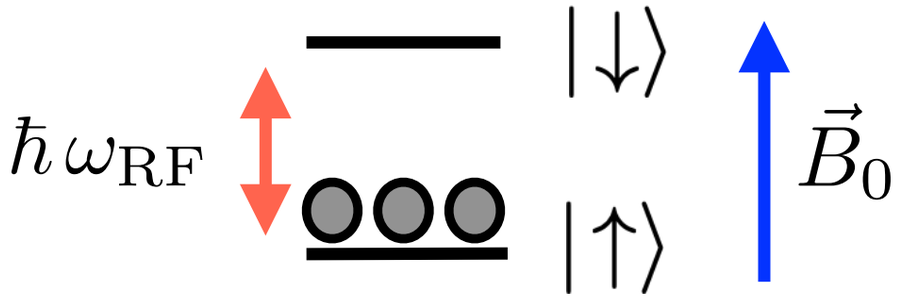


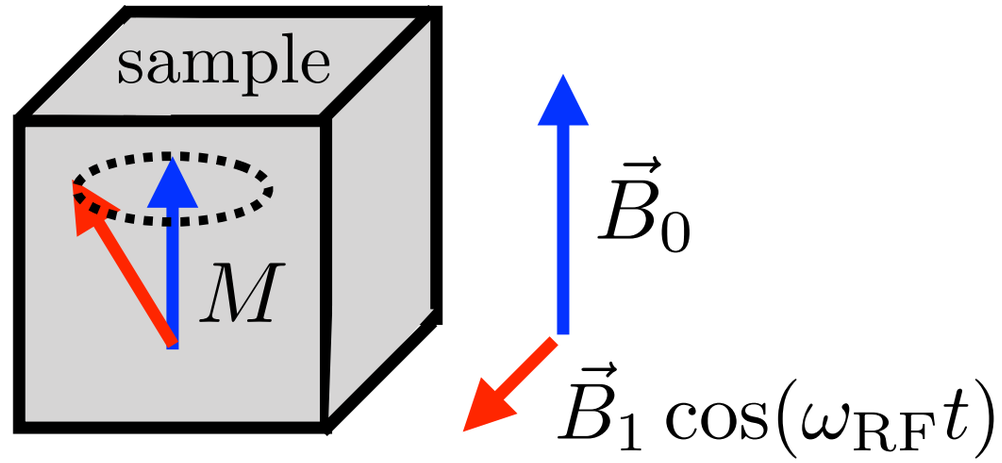


CASPER

[Budker, Graham, et al. 2014]
[Garcon, Blanchard, et al. 2019]

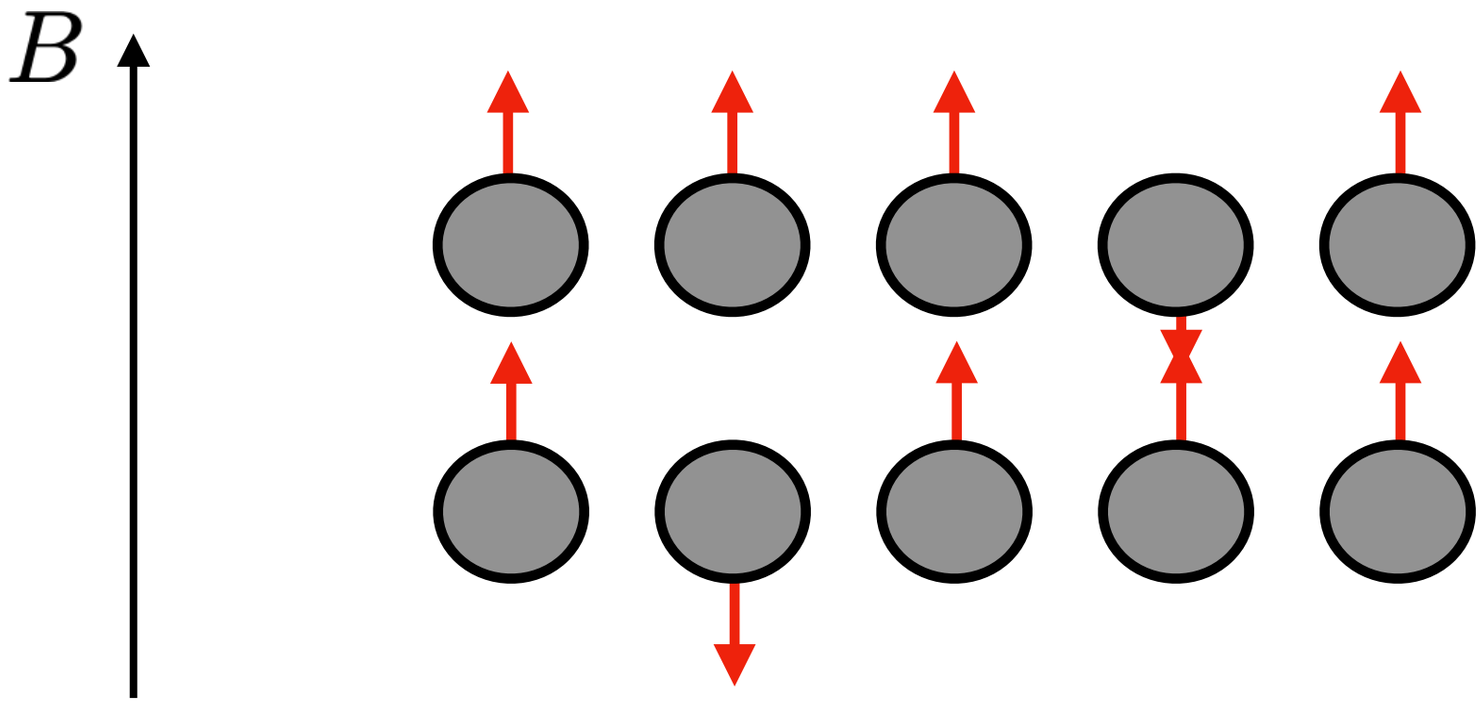


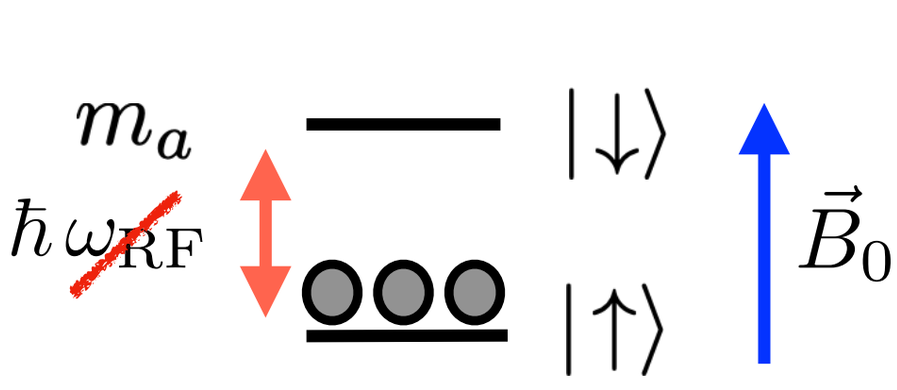


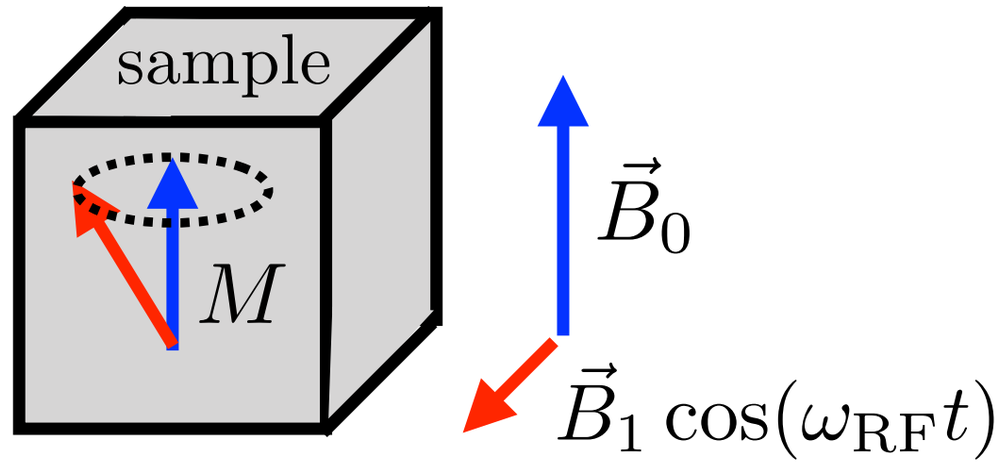


CASPER

[Budker, Graham, et al. 2014]
[Garcon, Blanchard, et al. 2019]







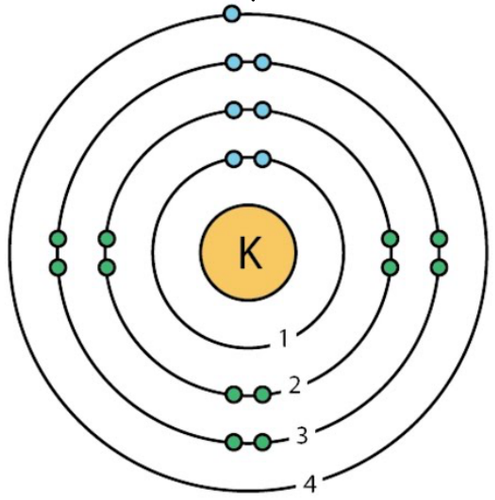
Co-Magnetometers

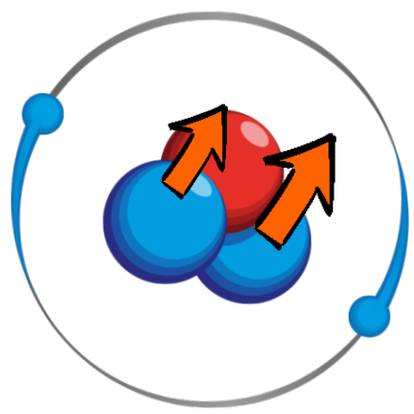
sensitive to the difference between the magnetic fields measured by two strongly interacting magnetometers

$$\mathcal{H}_{\text{spin}} = \mathcal{H}_{\text{mag}} + \mathcal{H}_{\text{anomalous}}$$

Noble-alkali comagnetometers

[Kornack, Romalis, 2002] e.g. K – ^{3}He

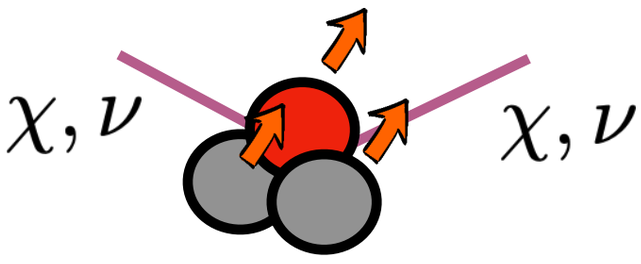


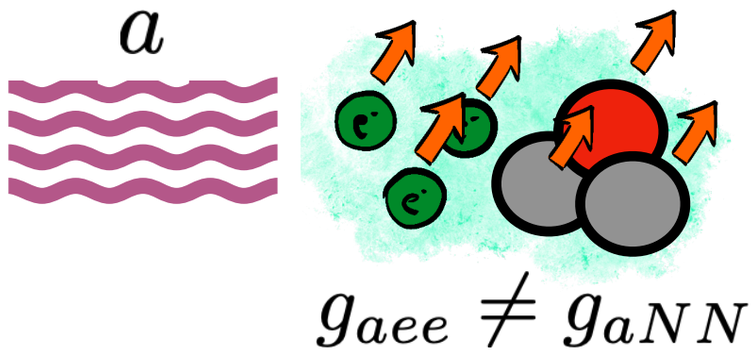


[Graham, Kaplan, et al. 2018]

[Bloch, Hochberg et al 2020]
[Agrawal, Hutzler et al 2023]

[Alonso, Blas, Wolf, 2019]
[Terrano, Romalis, 2021]





Co-Magnetometers

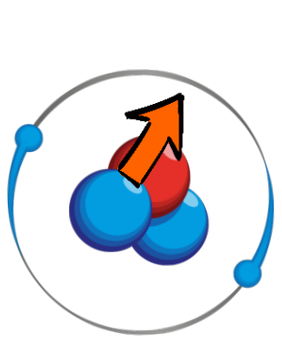
sensitive to the difference between the magnetic fields measured by two strongly interacting magnetometers

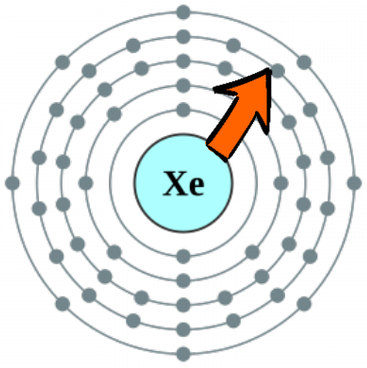
$$\mathcal{H}_{\text{spin}} = \mathcal{H}_{\text{mag}} + \mathcal{H}_{\text{anomalous}}$$

Noble-Noble comagnetometers

e.g. $^3\text{He} - ^{129}\text{Xe}$

[Allmendiger, Heil, et al. 2013]



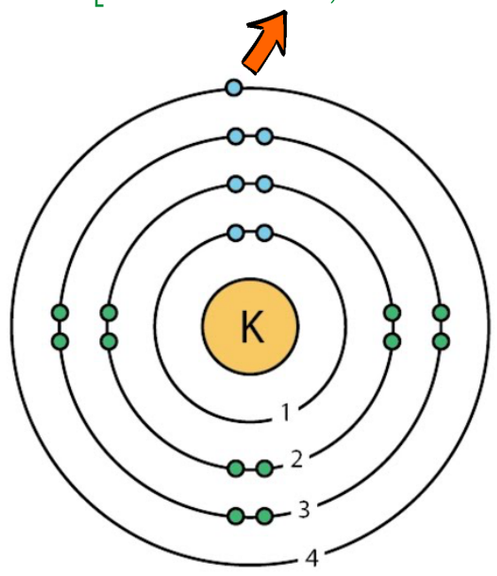


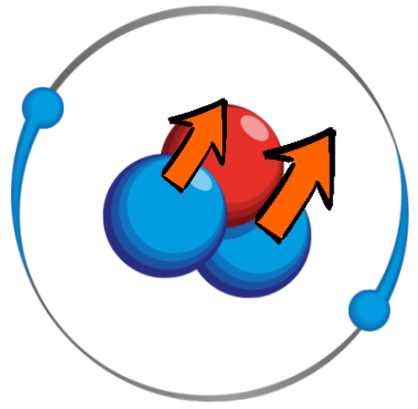
$$\Delta\omega = \omega_{\text{He}} - \frac{\gamma_{\text{He}}}{\gamma_{\text{Xe}}}\omega_{\text{Xe}}$$

[Alonso, Blas, Wolf, 2019]
[Terrano, Romalis, 2021]

Noble-alkali comagnetometers

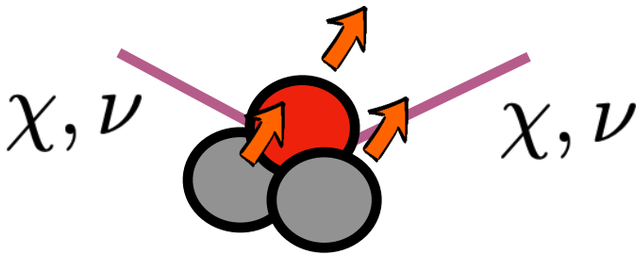
[Kornack, Romalis, 2002] e.g. $\text{K} - ^3\text{He}$

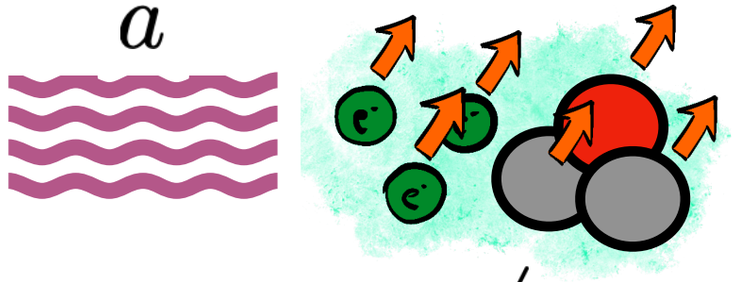




[Bloch, Hochberg et al 2020]
[Agrawal, Hutzler et al 2023]

[Graham, Kaplan, et al. 2018]





$g_{aee} \neq g_{aNN}$

Collective excitations

[Essig, Mardon, Volansky, 2011]
[Graham, Kaplan, Rajendran, Walters, 2012]
[Lee, Lisanti, Mishra-Sharma, Safdi, 2015]
[Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu, 2015]
[Derenzo, Essig, Massari, Soto, Yu, 2016]
[Hochberg, Lin, Zurek, 2016]
[Bloch, Essig, Tobioka, Volansky, Yu, 2016]

[Essig, Volansky, Yu, 2017]
[Kurinsky, Yu, Hochberg, Cabrera, 2019]
[Emken, Essig, Kouvaris, Sholapurka, 2019]
[Griffin, Inzani, Trickle, Zhang, Zurek, 2019]
[Coskuner, Mitridate, Olivares, Zurek, 2020]
[Mitridate, Trickle, Zhang, Zurek, 2021]
[Chen, Mitridate, Trickle, et al, 2022]

Absorption

Magnons

Super-conductors

Semiconductors

Traditional WIMP DD (nuclear recoil)

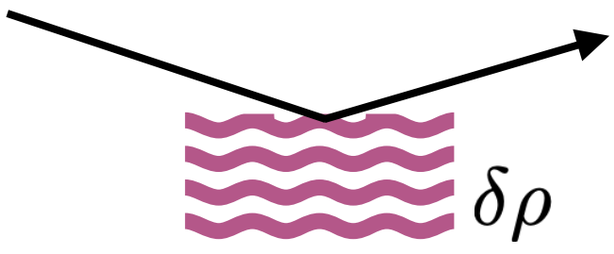
Polar crystals

Dirac materials

Ionization

Superfluid He

Graphene



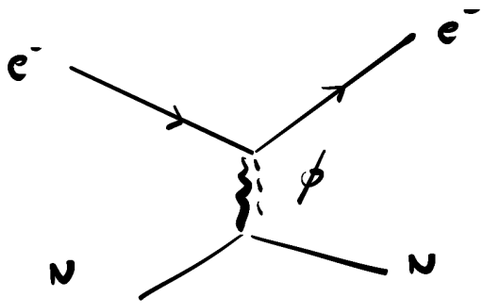
~meV energy resolution

~eV energy resolution

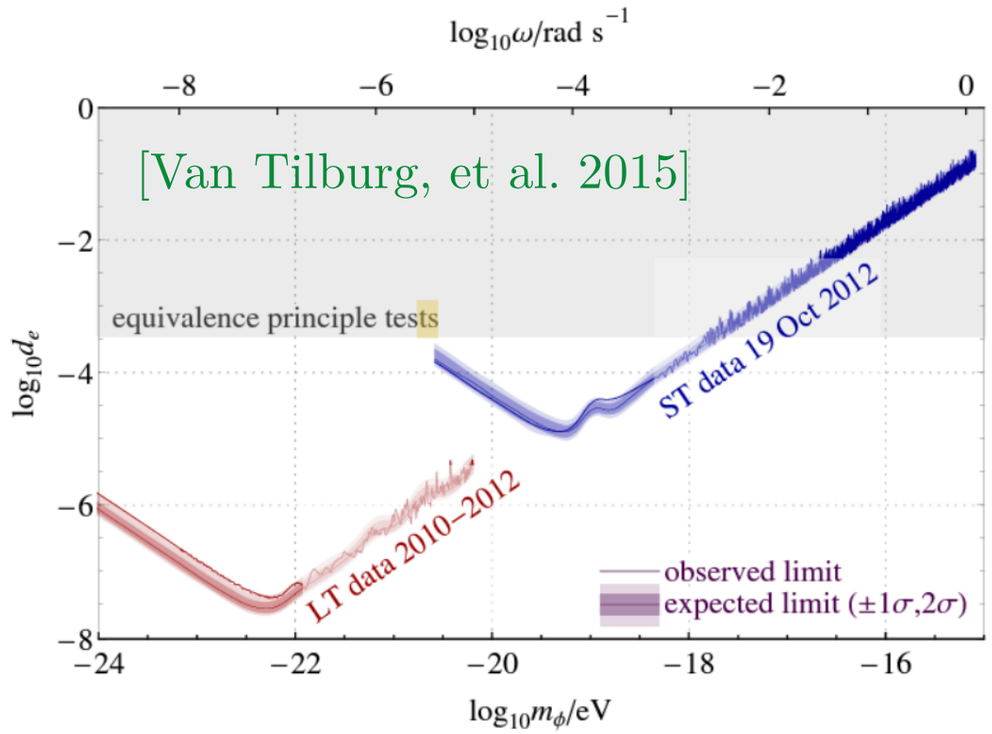
~keV energy resolution

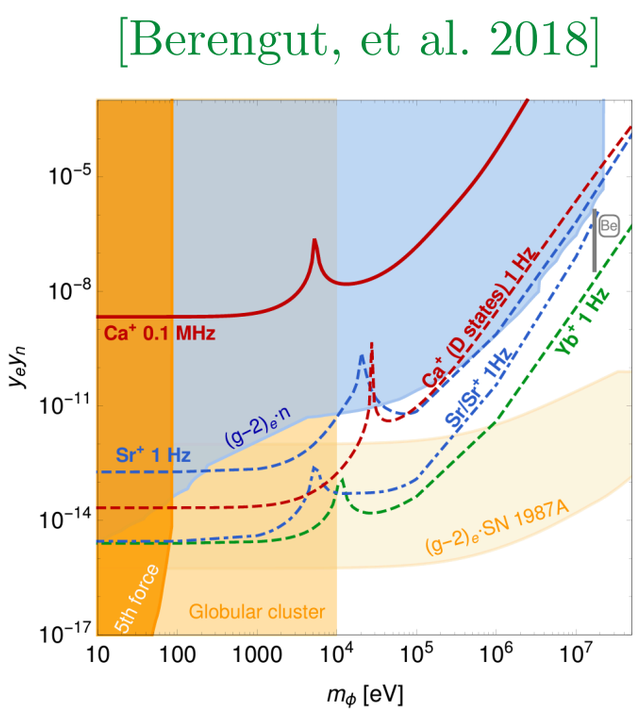
Etc etc etc

⇨ Atom spectroscopy

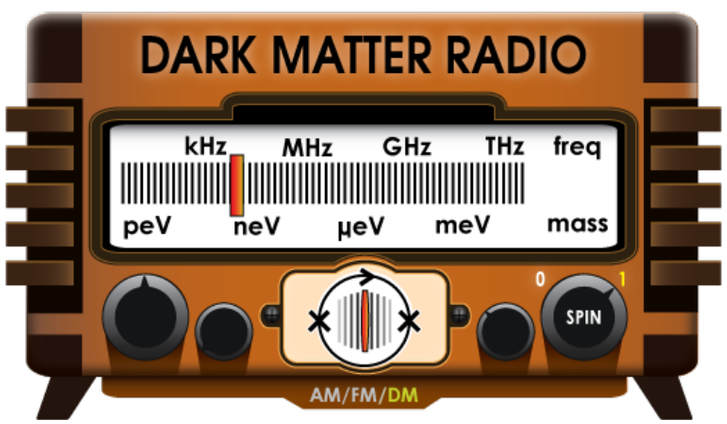


$$\mathcal{L} \supset \frac{-1 + d_e \kappa \phi}{4e^2} F_{\mu\nu} F^{\mu\nu}$$





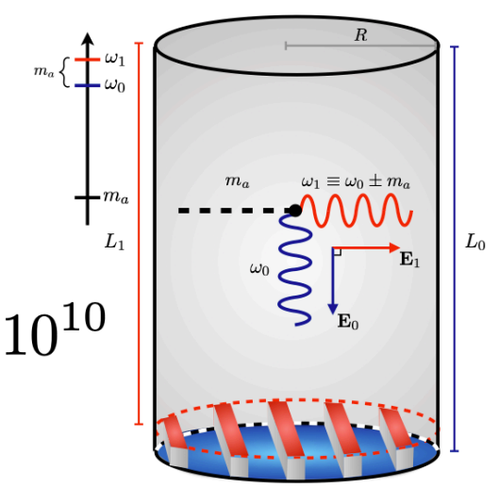
⇨ Microwave / radiowave cavities



[Winslow et al., 2016]

SRF cavities

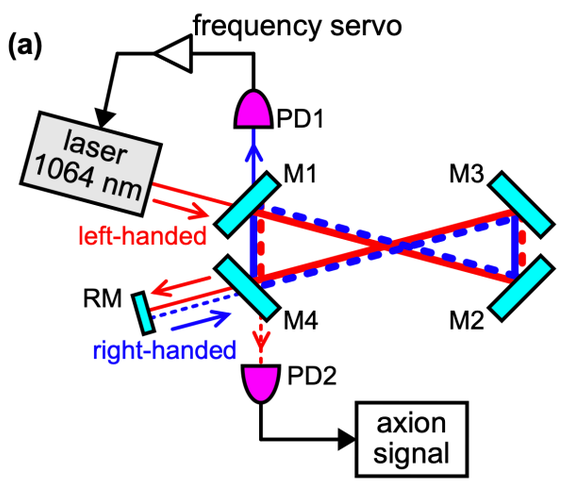
[Berlin, D'Agnolo, et al., 2019]



$Q > 10^{10}$

DANCE

[Obata, Fujita, Michimura, 2018]

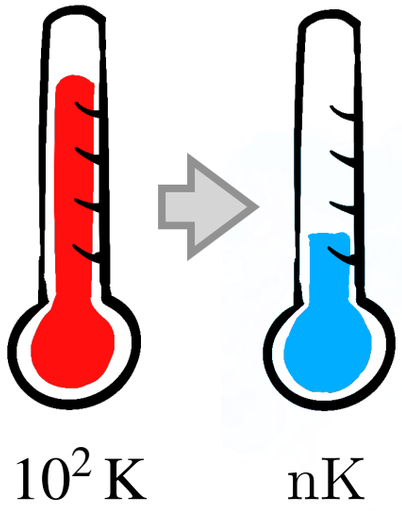


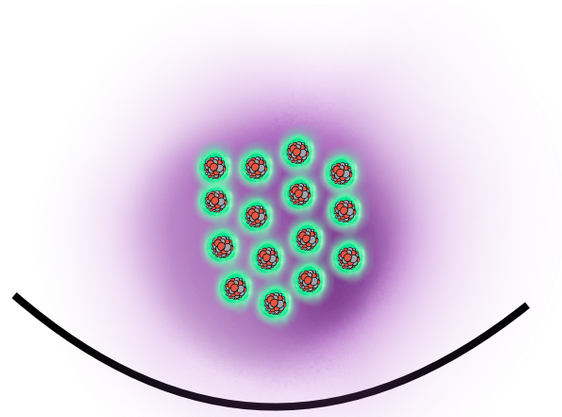
Quantum Sensing: impact

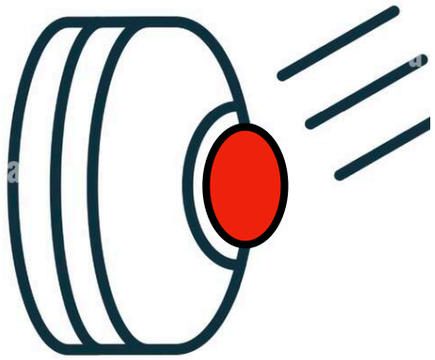
Emmergent field

DYNAMICAL

Unkown boundaries

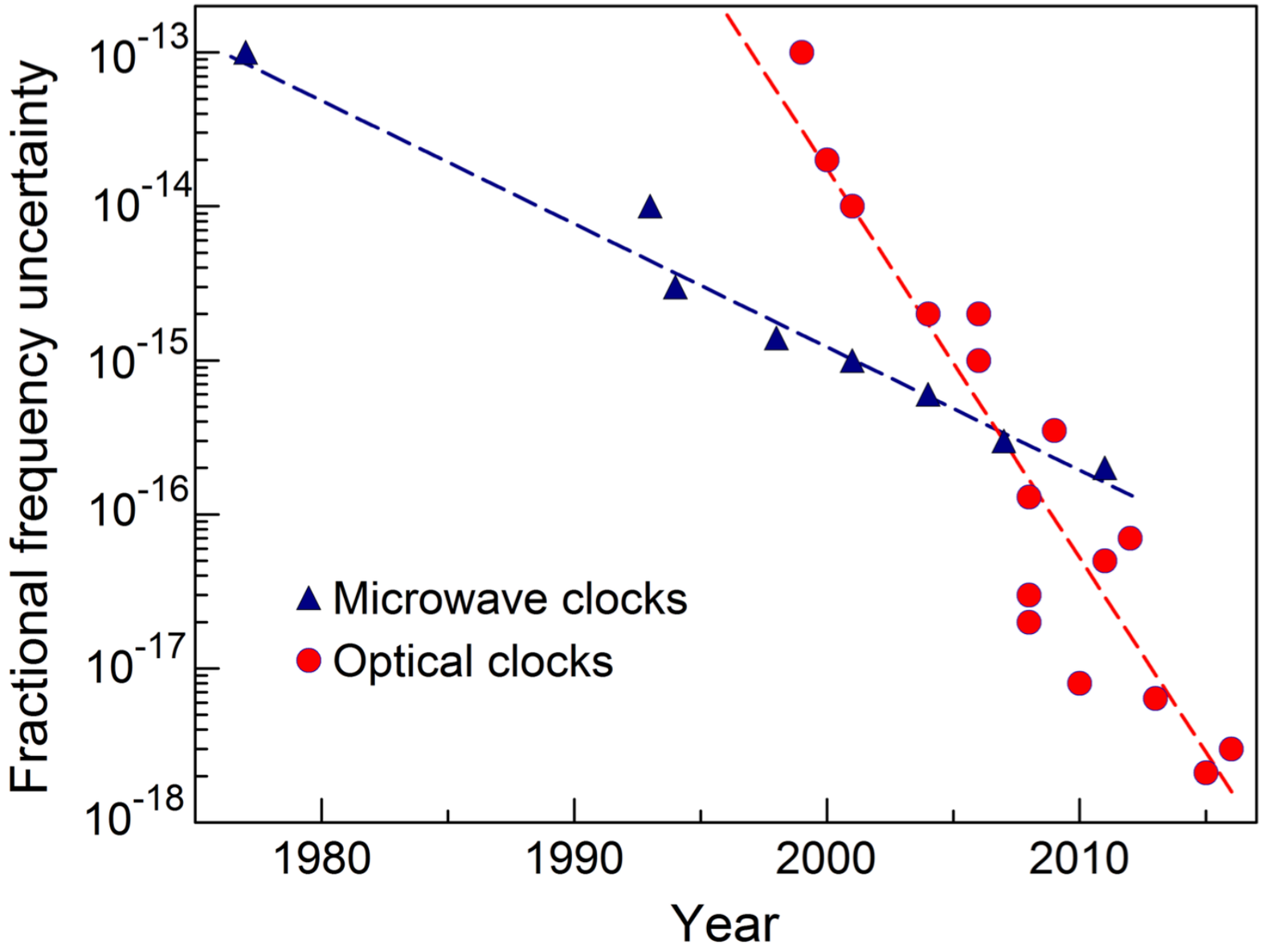




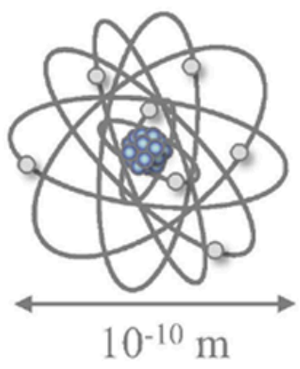


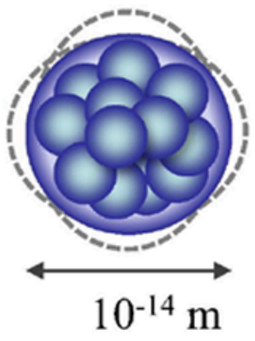
Quantum Sensing: impact

e.g. Atomic clocks



[Huntemann et al., 2016]
[Nicholson et al. 2015]
[Poli et al. 2013]
[Safranova et al. 2017]

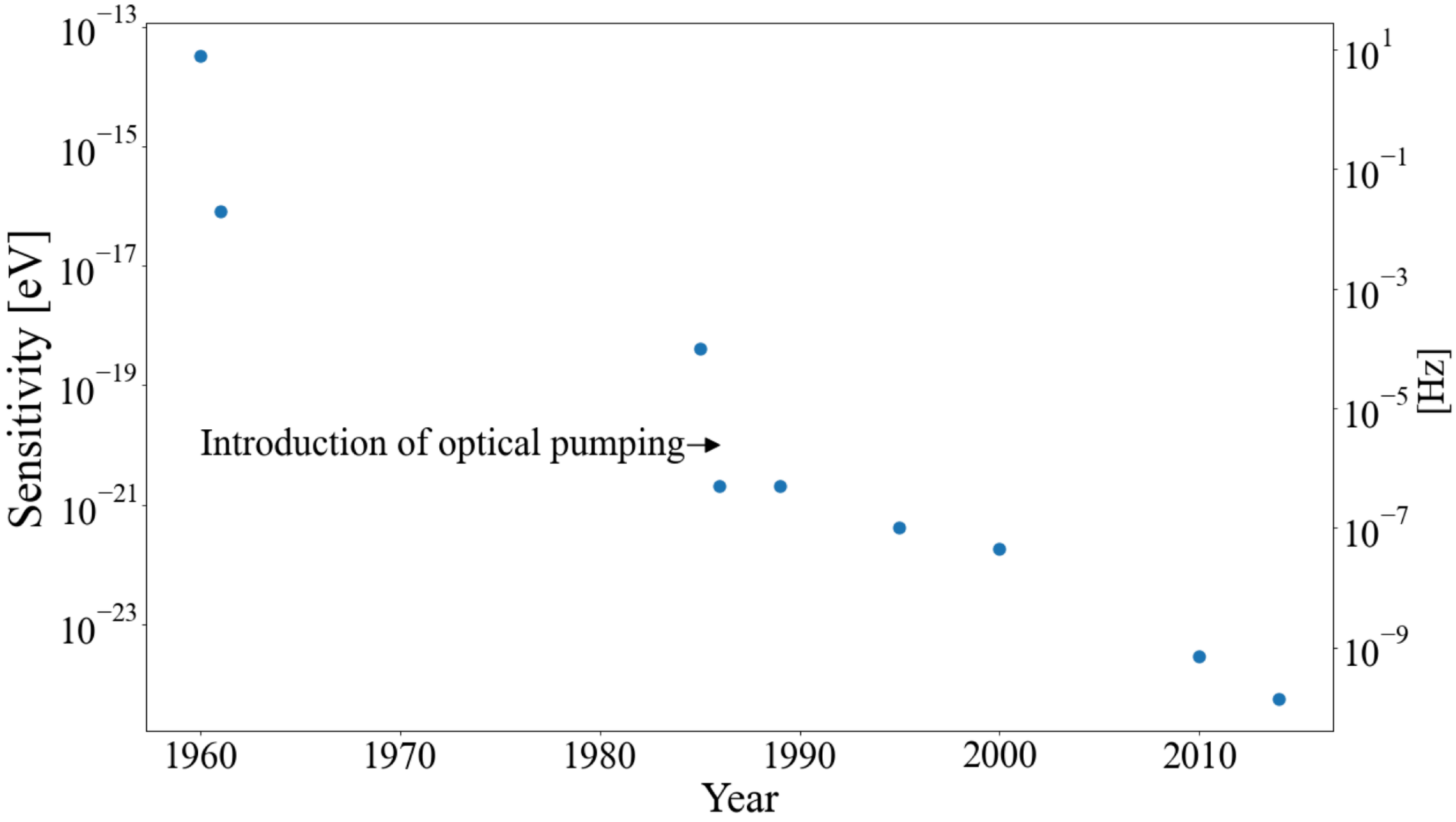




Nuclear clocks [Peik et al. 2021]

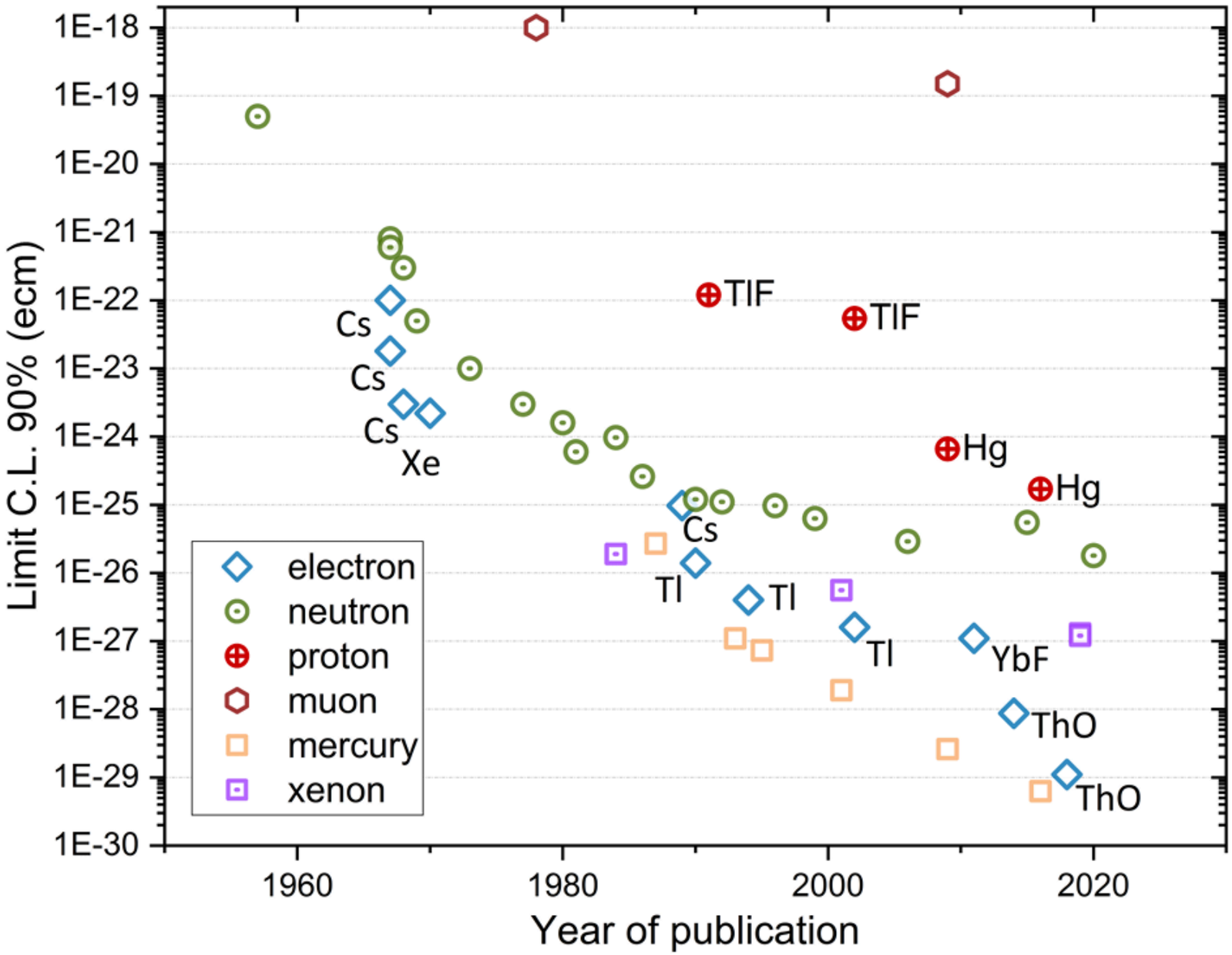
Quantum Sensing: impact

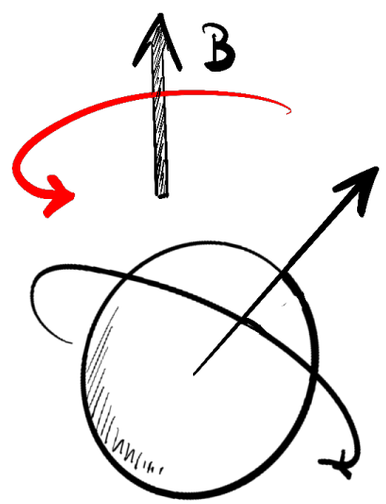
e.g. Magnetometers [Terrano and M. V. Romalis, 2021]



Quantum Sensing: impact

e.g. eEDM [Adelman et al, 2021]





Conclusions

- WE NEED quantum sensors to detect elusive phenomena / particles
  - Will allow us to access unexplored parameter space

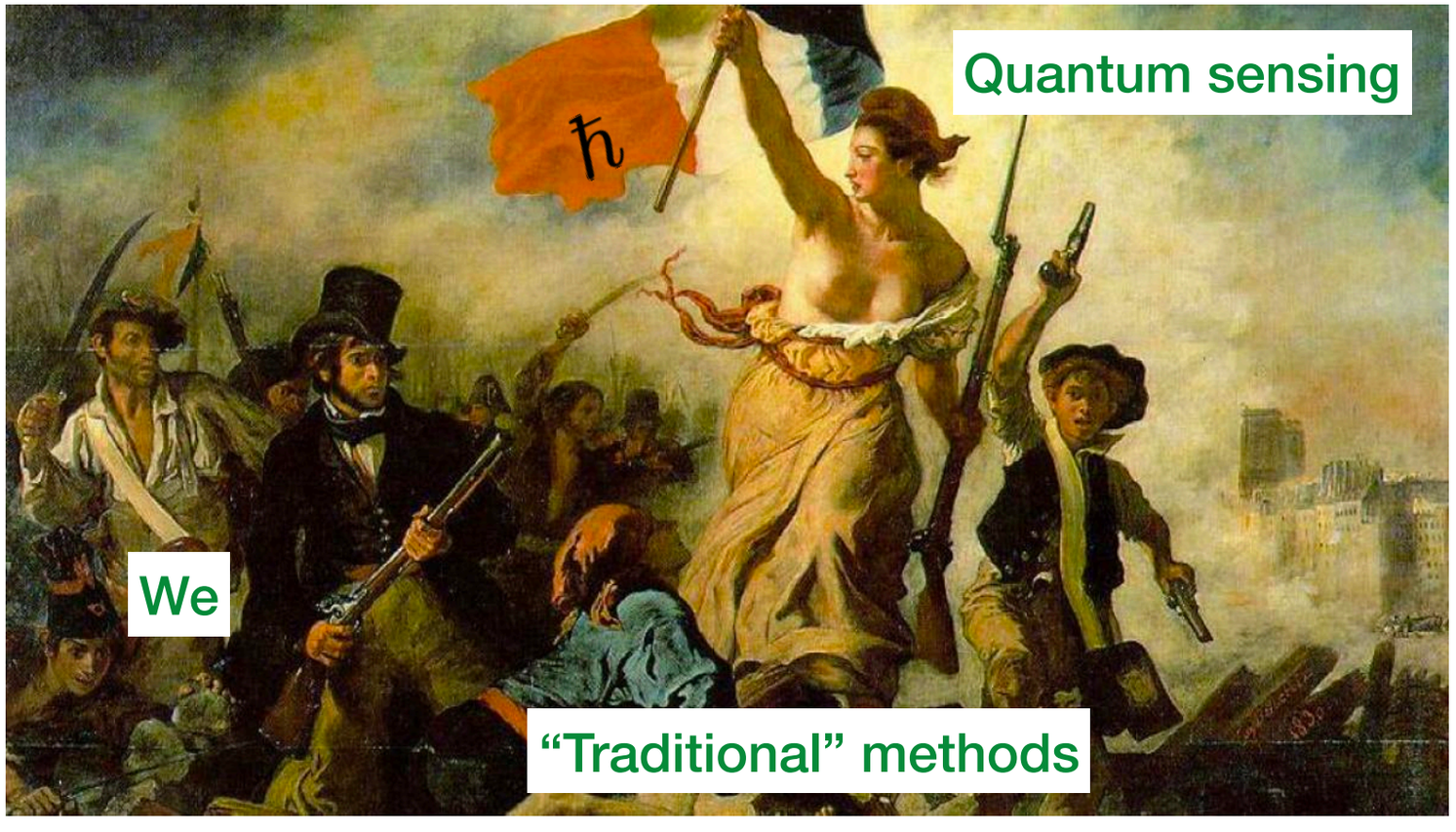
Conclusions

⇨ WE NEED quantum sensors to detect elusive phenomena / particles

👁 Will allow us to access unexplored parameter space

⇨ WE SHOULD BE EXCITED!

Quantum sensing is an emmergent field: lots of improvement expected



[*La Liberté guidant le peuple*. Delacroix, 1839]

Thank you!