Caltech

BURKE INSTITUTE

Hunting for Light DM with Atom Interferometers

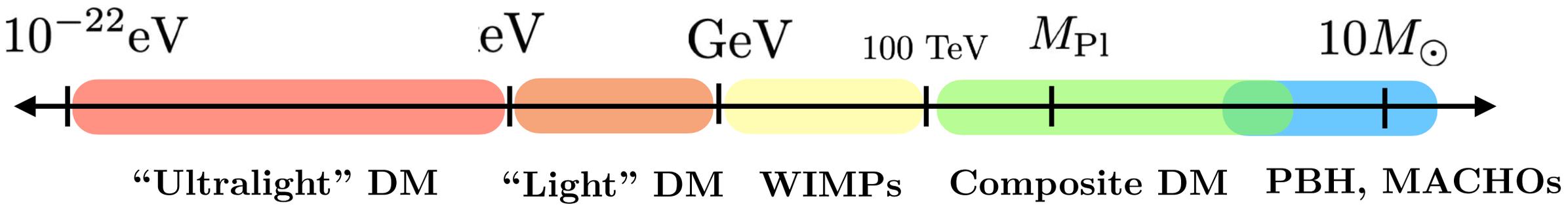
Clara Murgui

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

HiDDeN ITN network

25 October 2022

Dark Matter: where to look?



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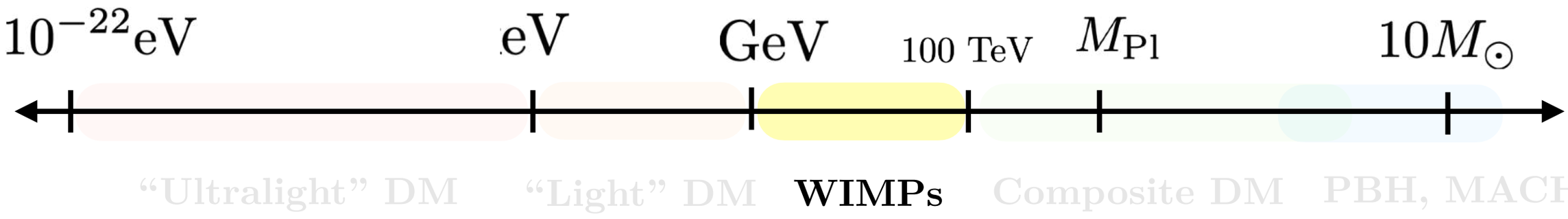
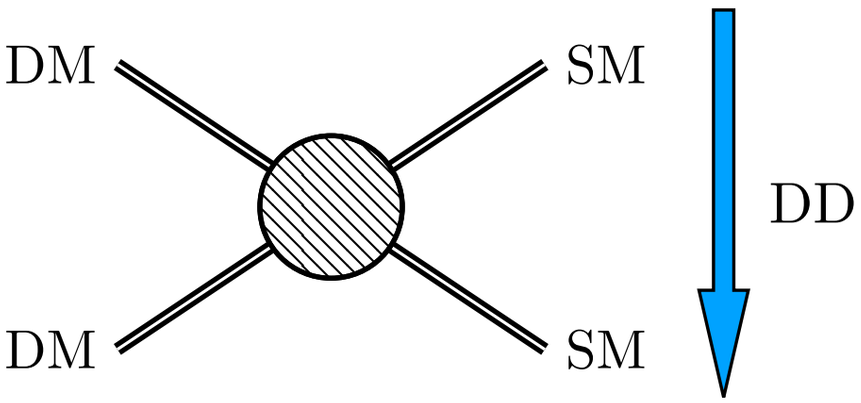
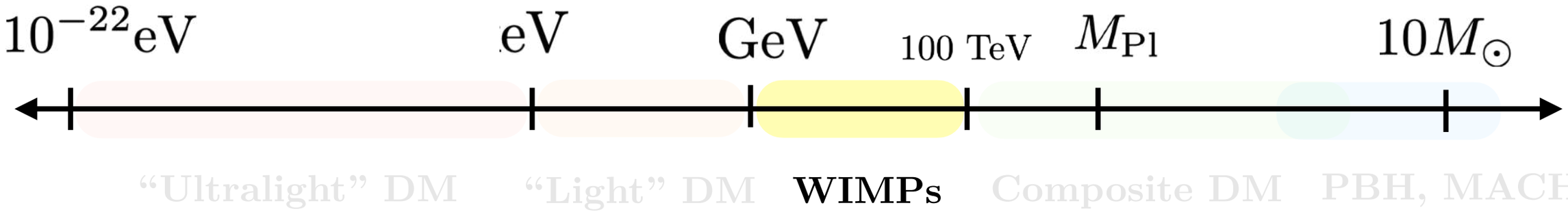
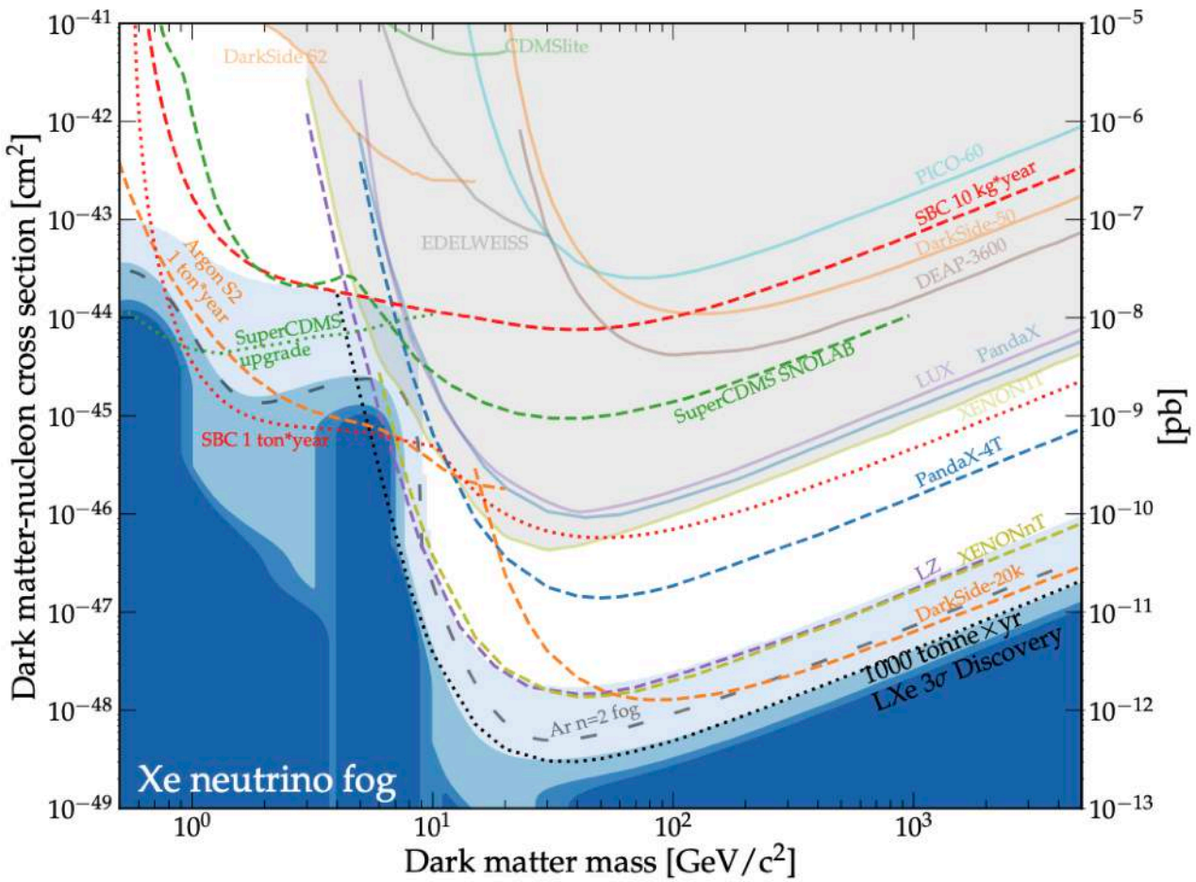




$$\sigma \sim 10^{-34}\text{cm}^2 \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2$$

Dark Matter: where to look?





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

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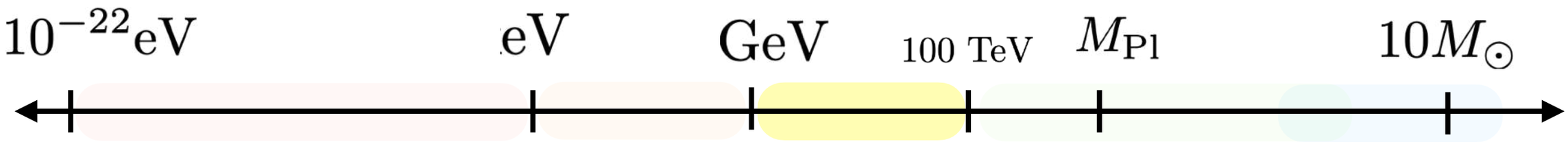
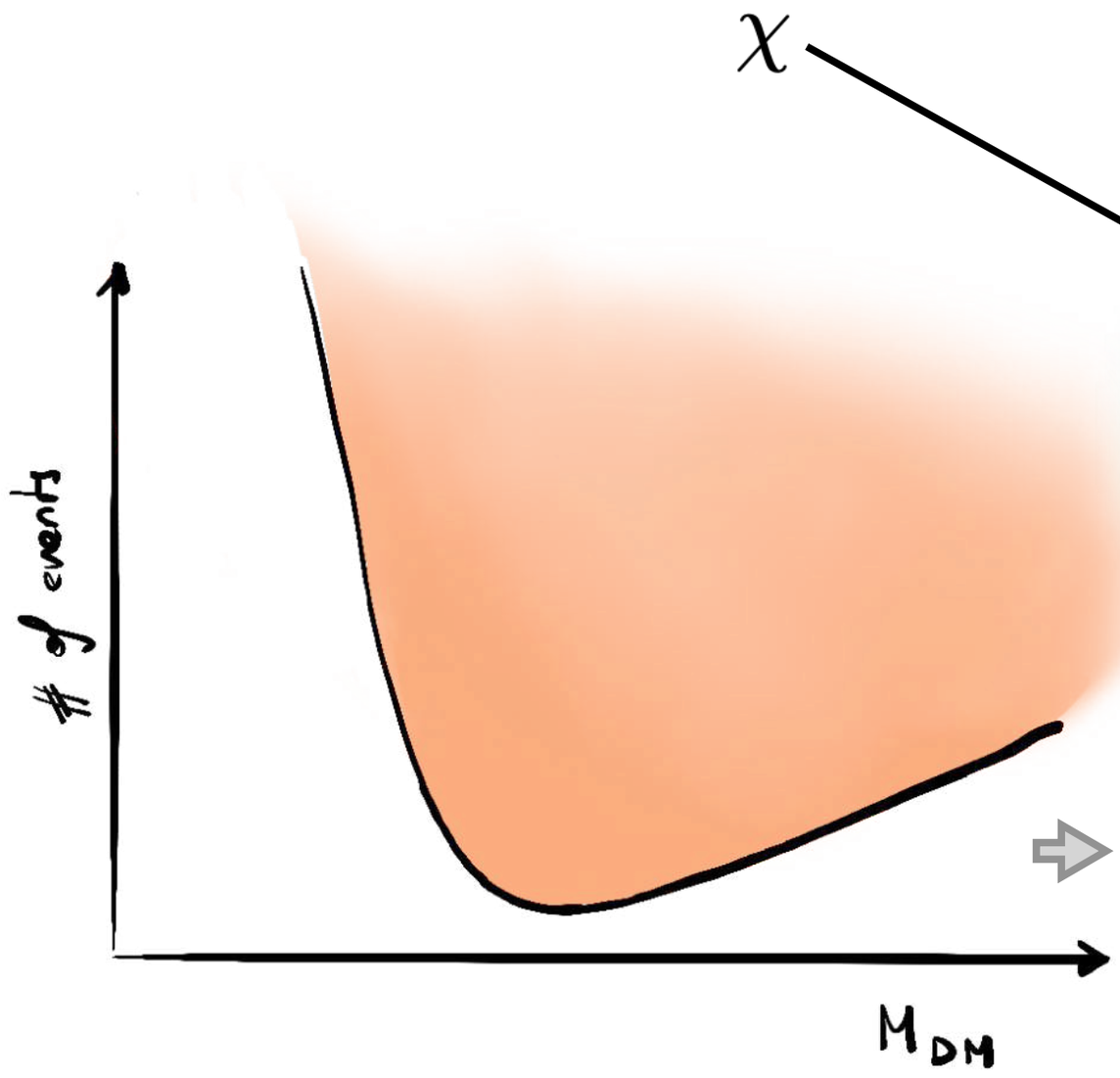
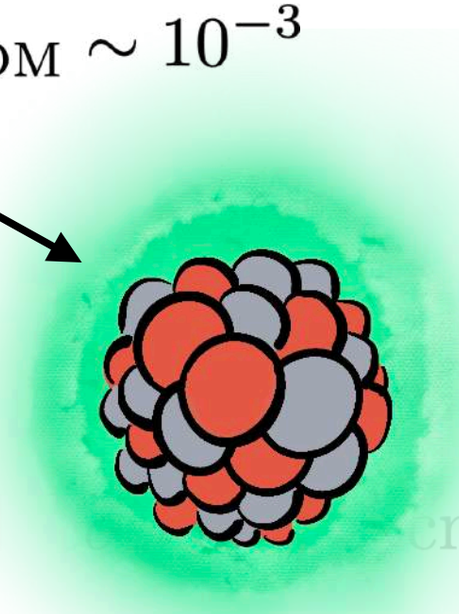




χ

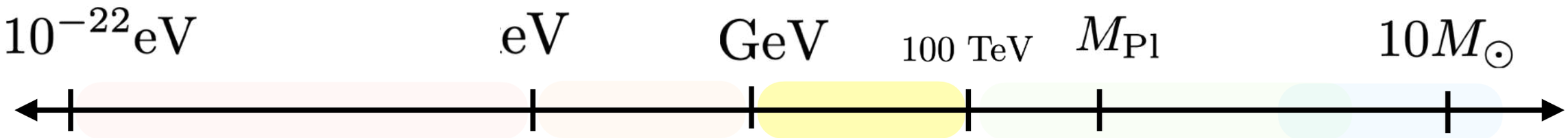
$v_{\rm DM} \sim 10^{-3}$



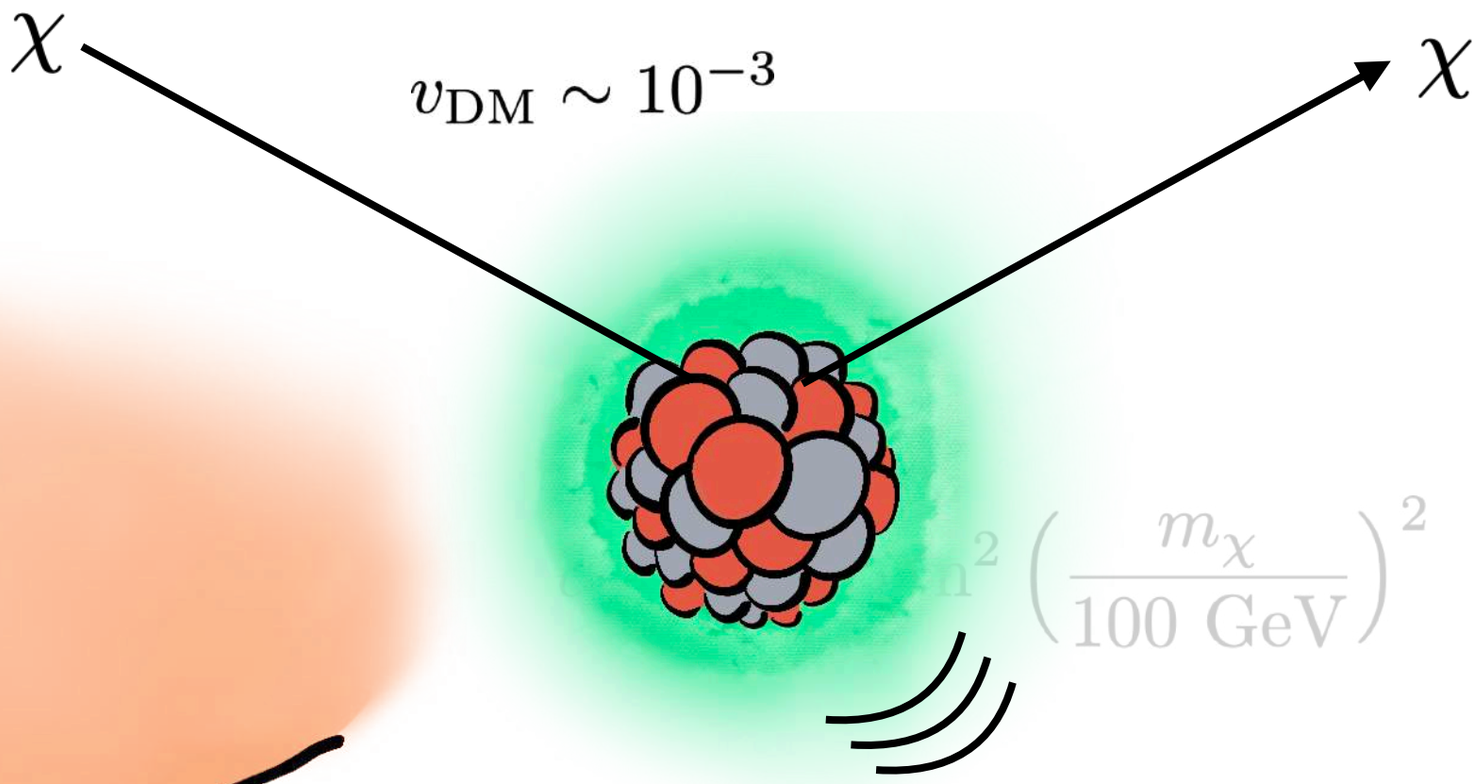
$\sigma \sim 10^{-45}\,\mathrm{cm}^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$

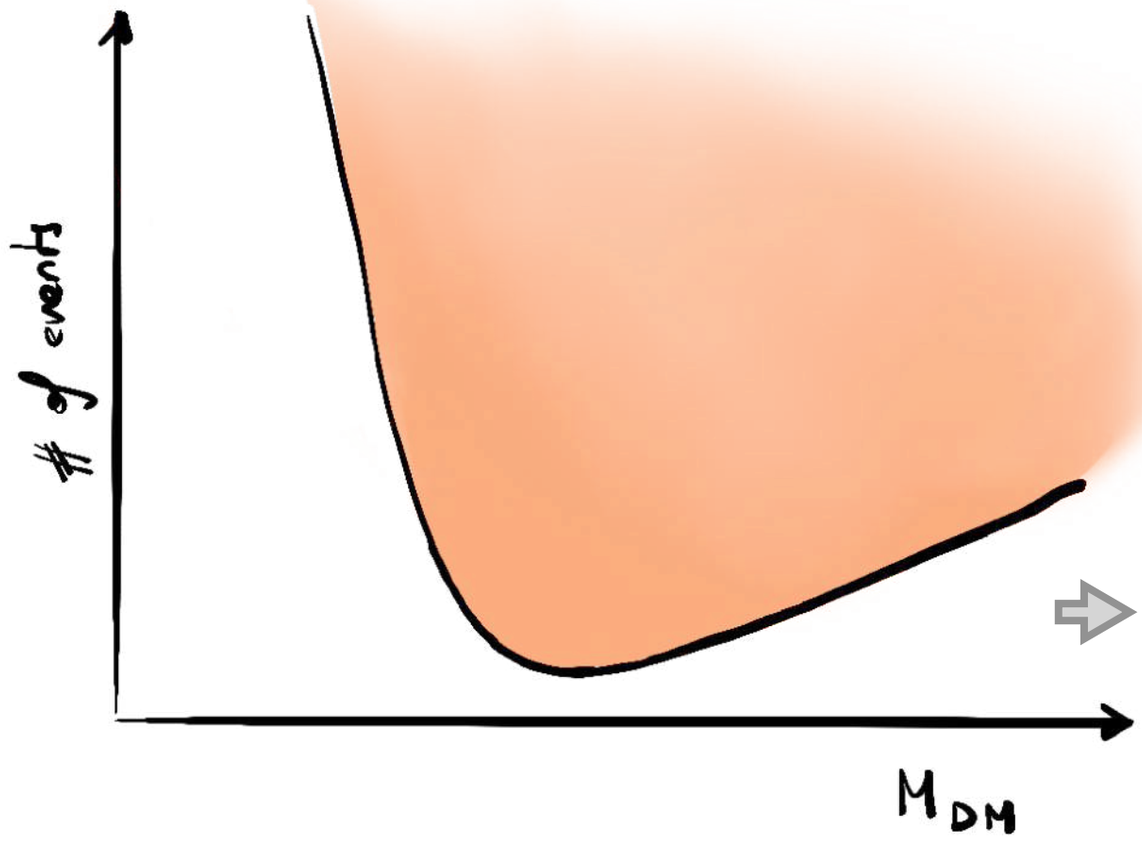
loss of "flux" $n_\chi = \frac{\rho_\chi}{m_\chi}$

Dark Matter: where to look?



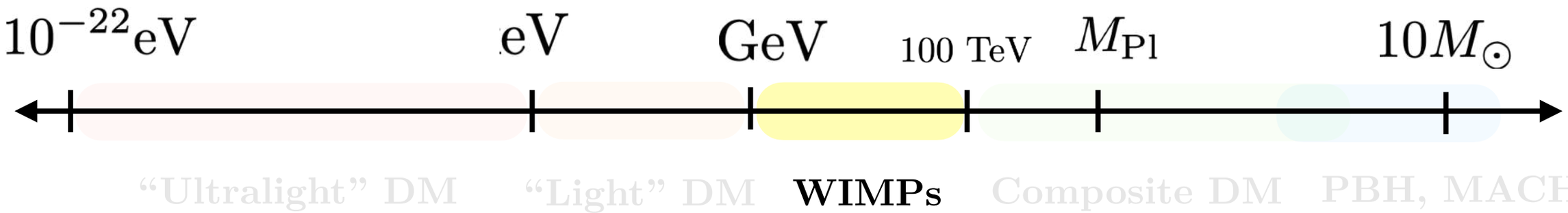
$$E_{\rm recoil} = \frac{q^2}{2m_T}$$



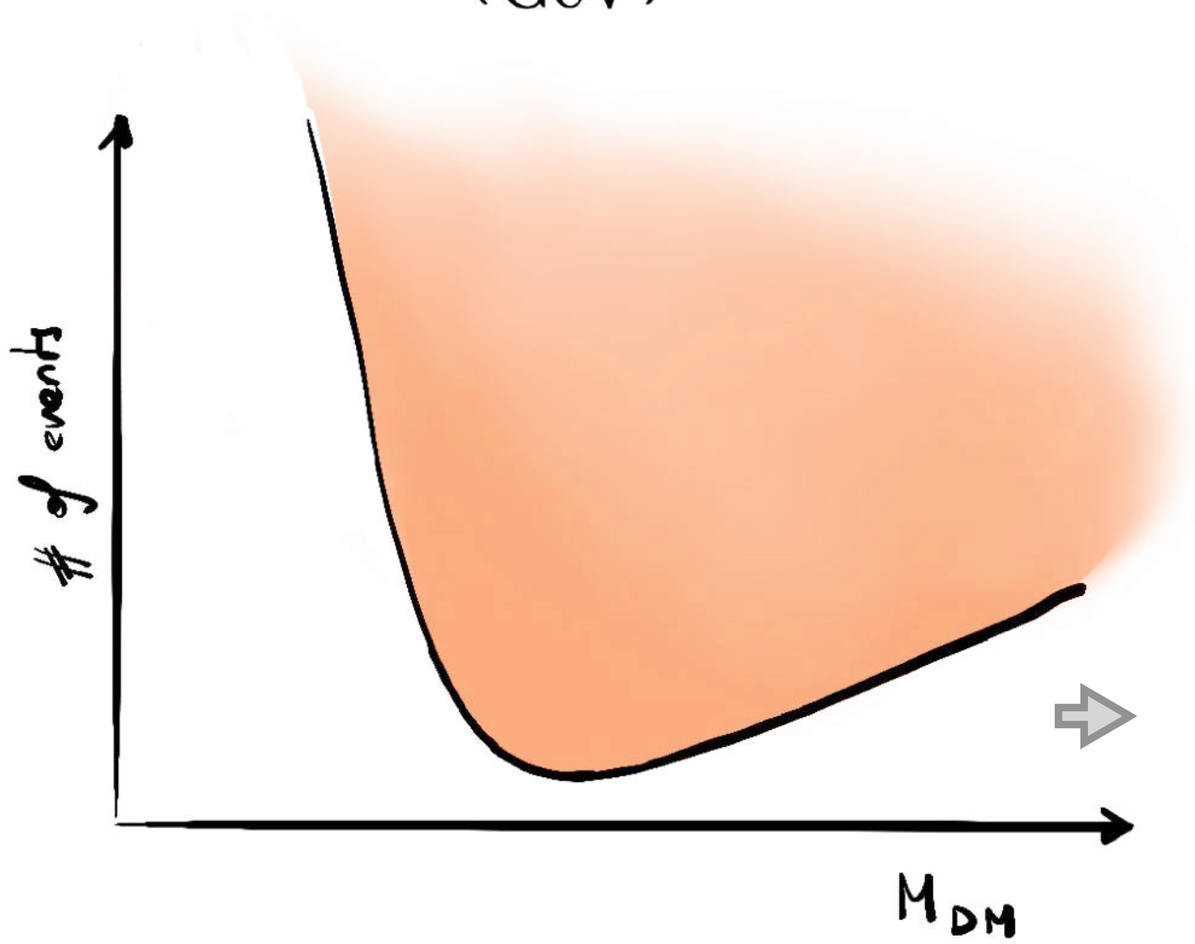


⇨ loss of "flux" $n_\chi = \frac{\rho_\chi}{m_\chi}$

Dark Matter: where to look?



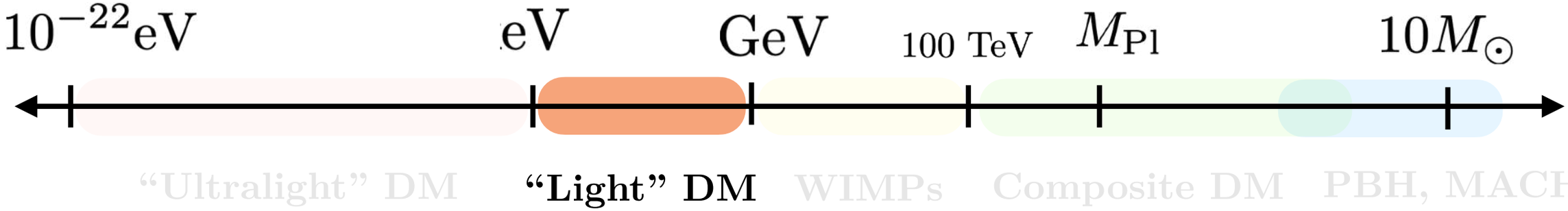
$$\Leftarrow \quad E_{\rm recoil}^{\rm max} \sim \left(\frac{m_\chi}{\rm GeV}\right) {\rm keV}$$

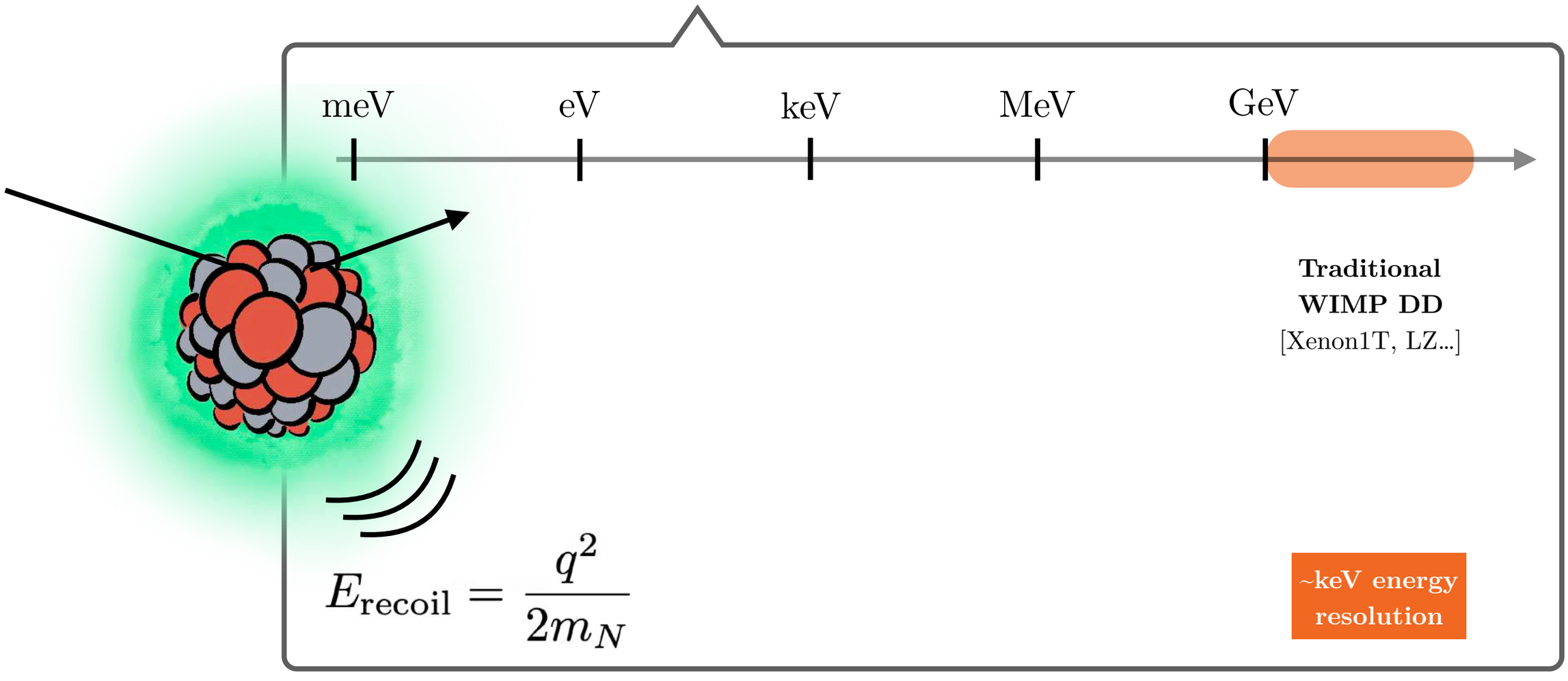


$$\sigma \sim 10^{-34}{\rm cm}^2 \left(\frac{m_\chi}{100\ {\rm GeV}}\right)^2$$

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

Dark Matter: where to look?





[adapted from K. Zurek's talks]

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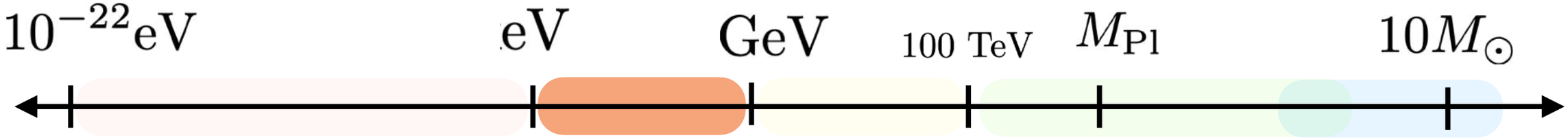

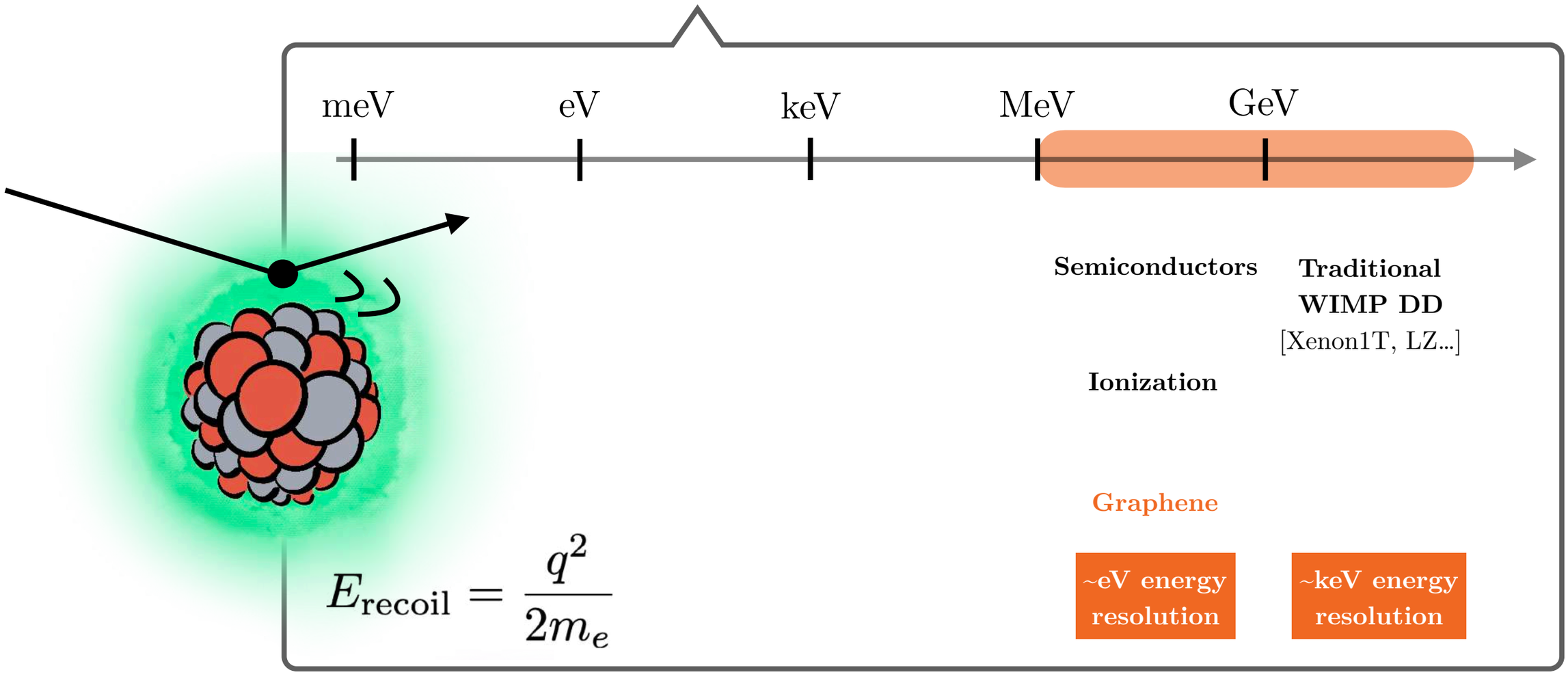

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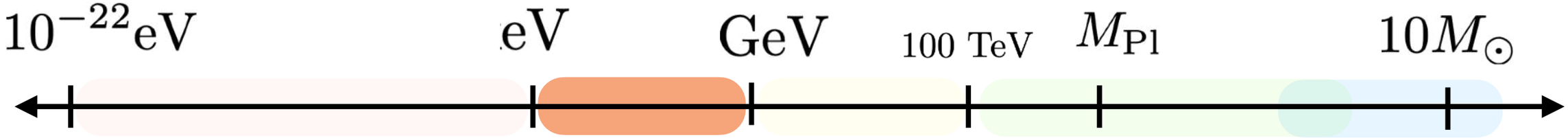
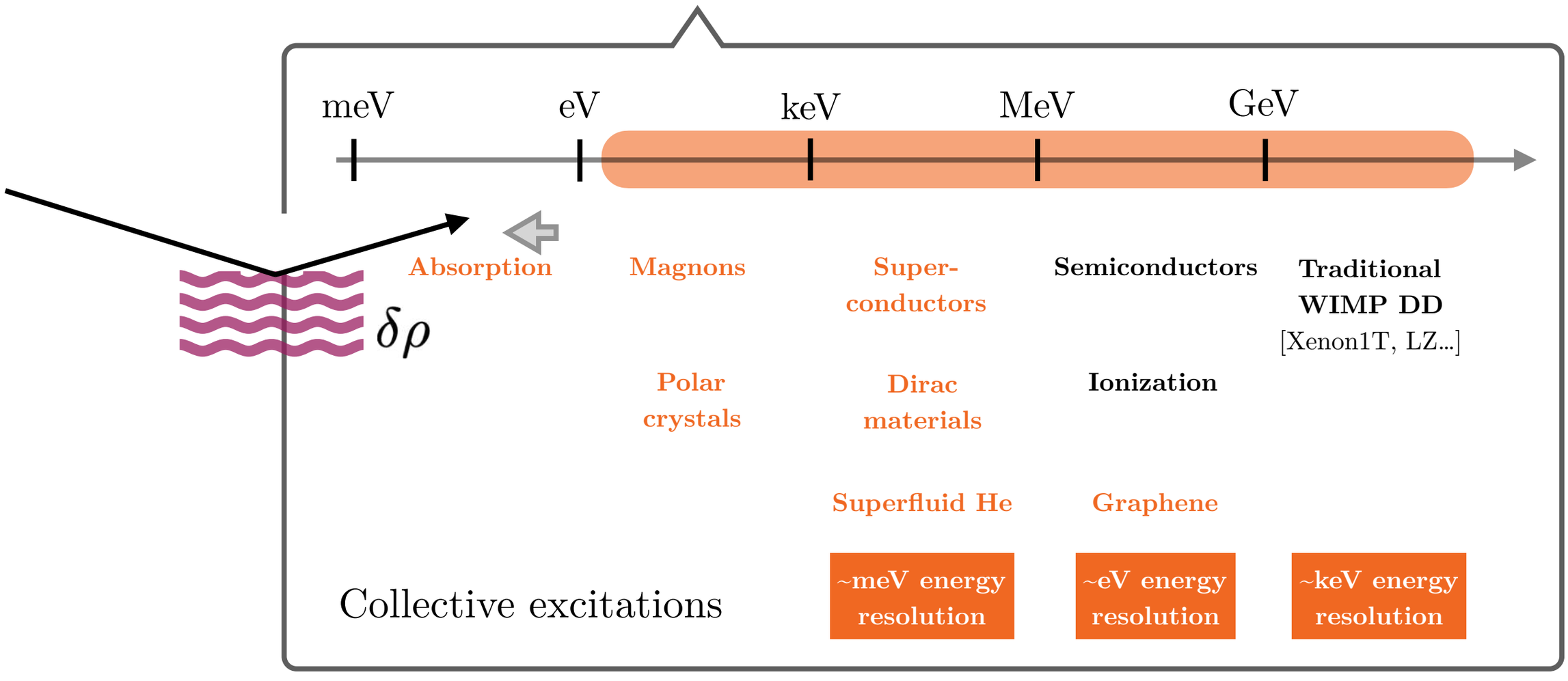


"Ultralight" DM **"Light" DM** WIMPs Composite DM PBH, MACHOs

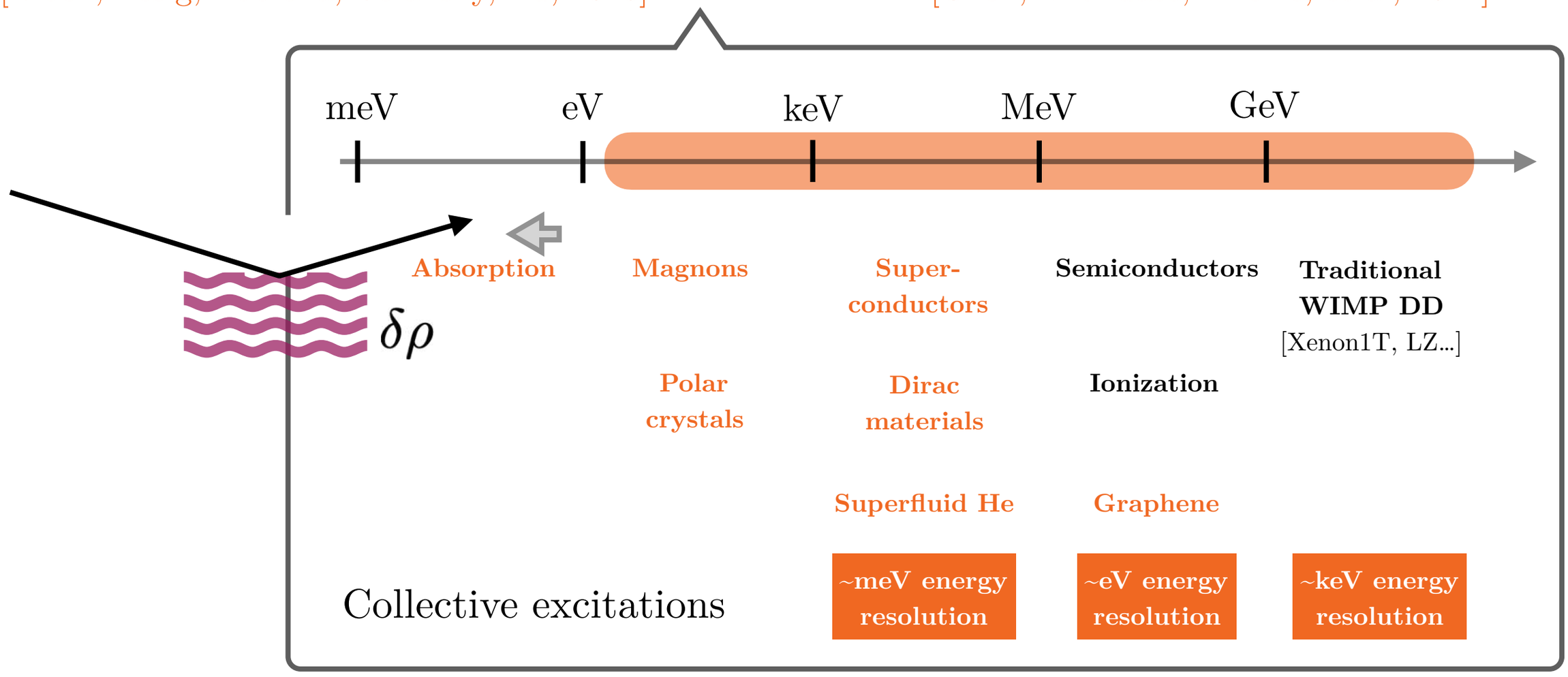


[adapted from K. Zurek's talks]

Dark Matter: where to look?

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

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



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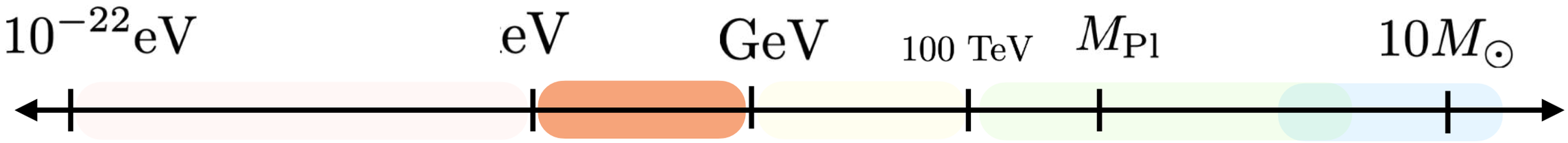
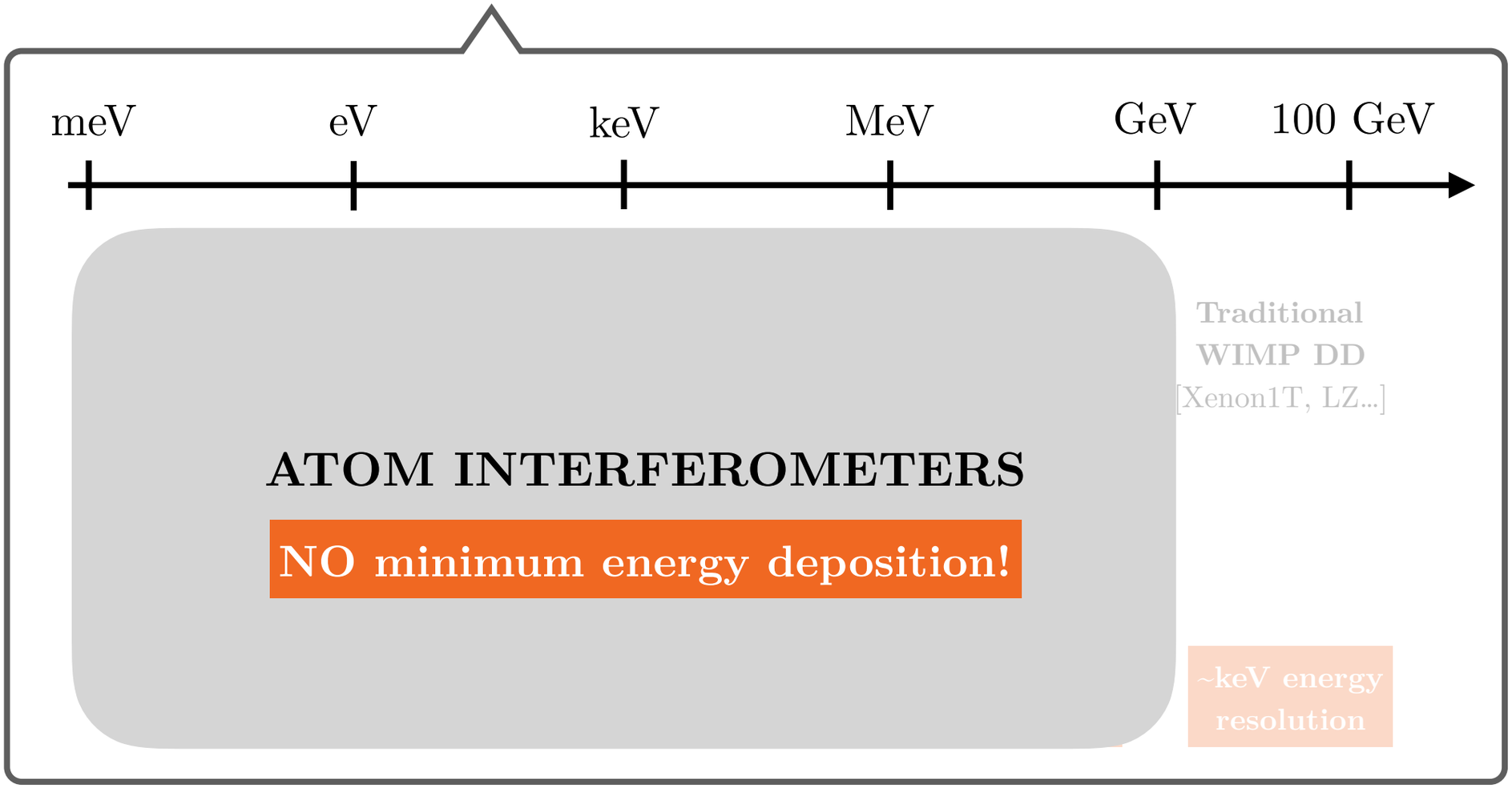




Atom Interferometer tests of **Dark Matter**

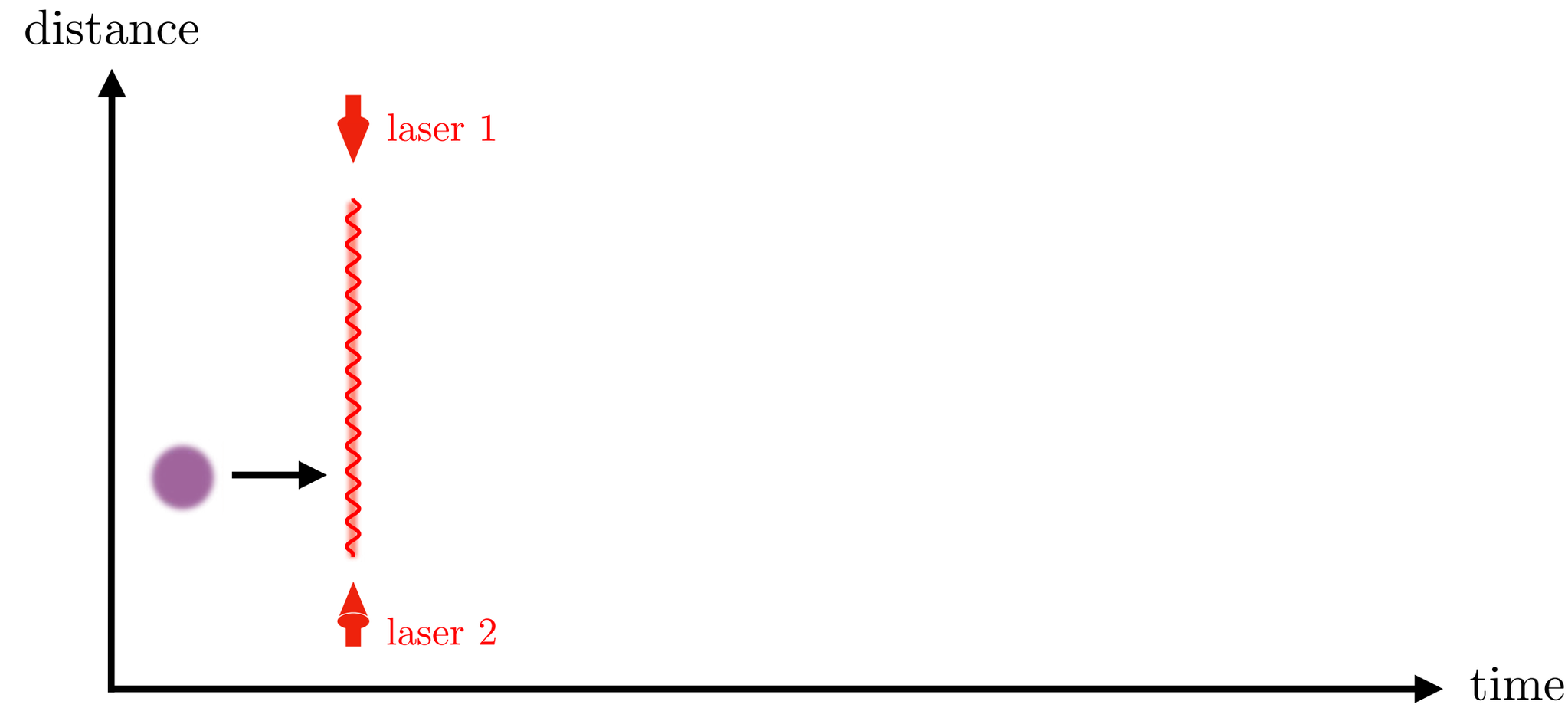
2205.13546

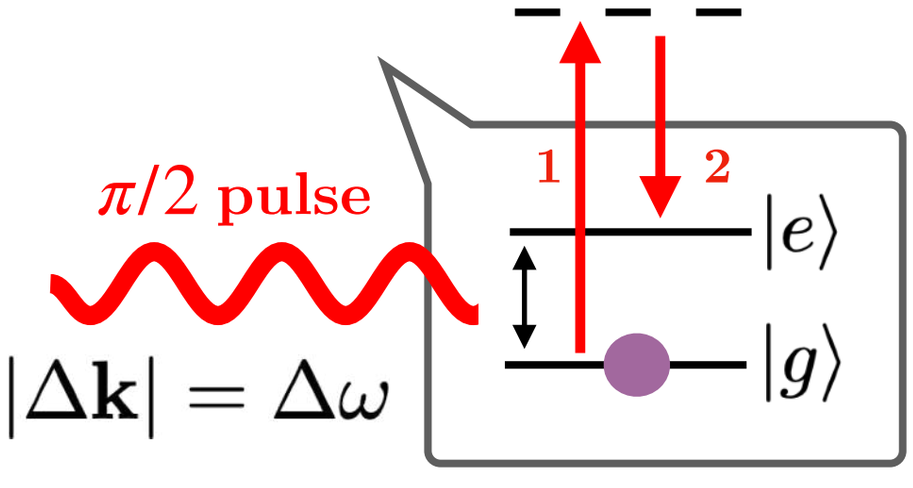
with Yufeng Du, Kris Pardo, Yikun Wang and Kathryn M. Zurek

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

AIs: the Principle

Review: arXiv:2003.12516



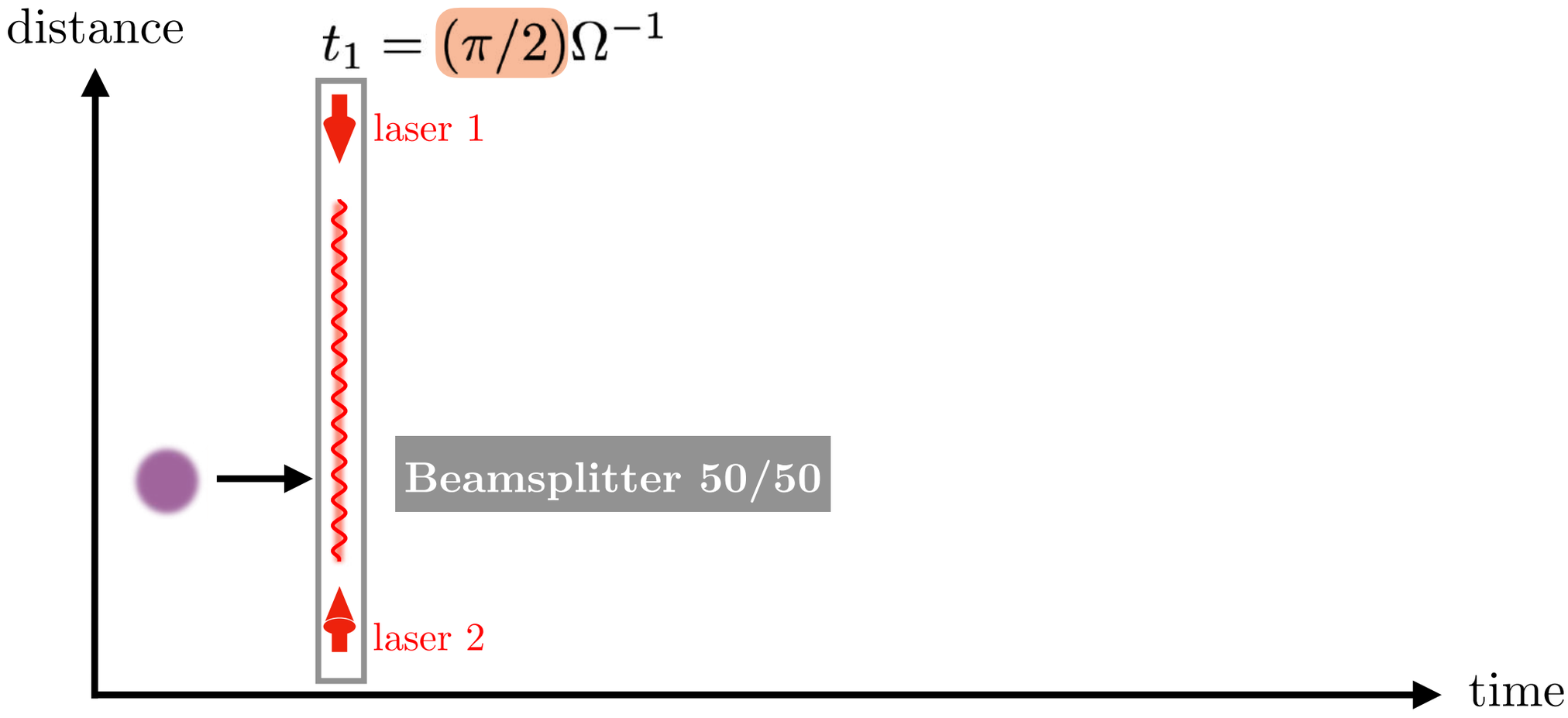


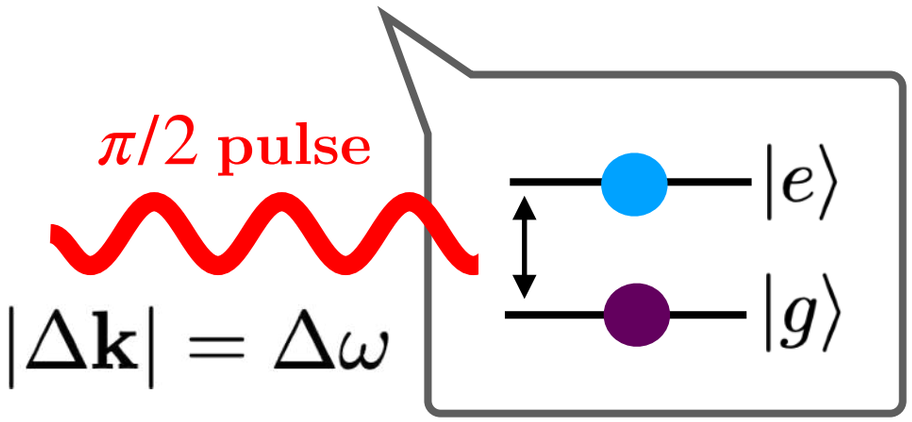
$$|\Psi\rangle_t = \cos(\Omega t/2)|g\rangle + i\sin(\Omega t/2)|e\rangle$$

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

AIs: the Principle

Review: arXiv:2003.12516





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

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

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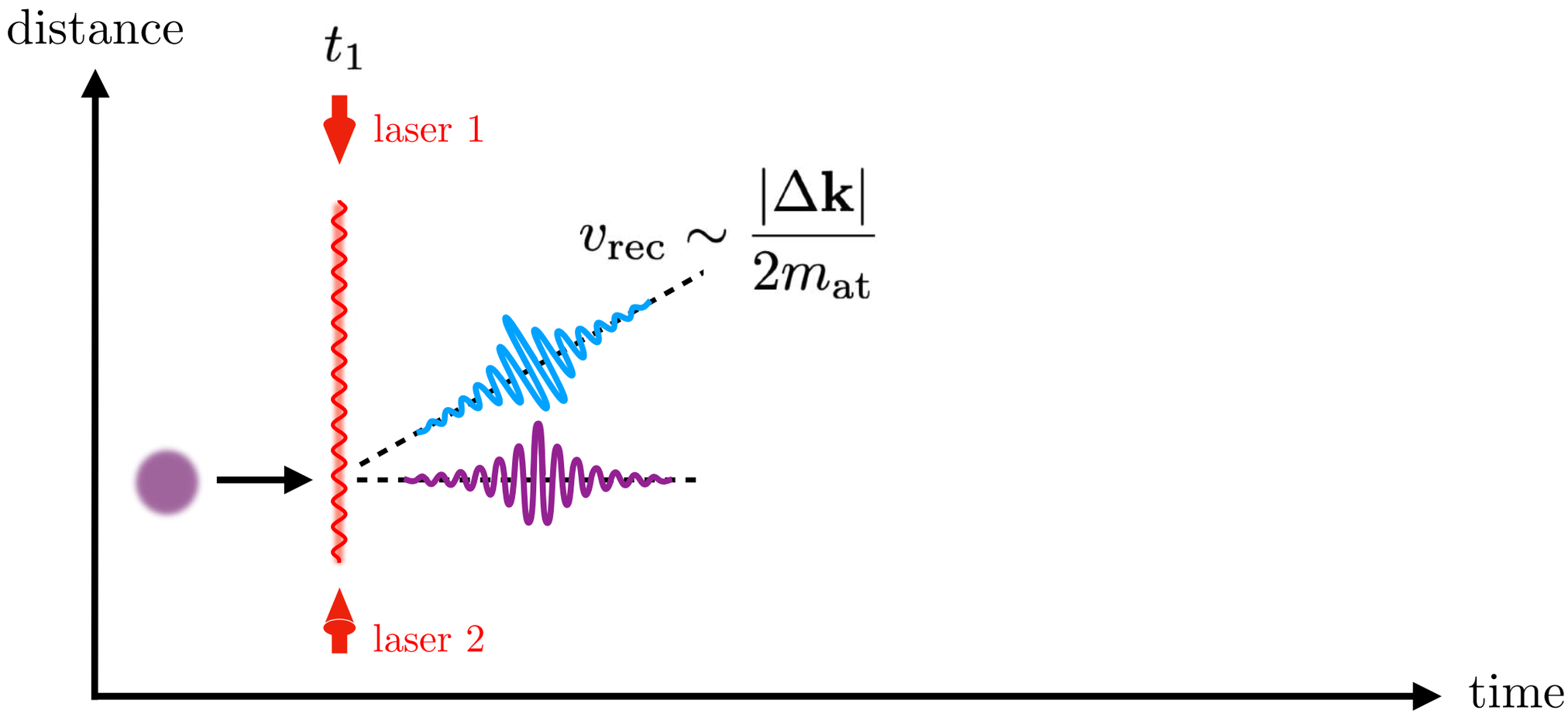

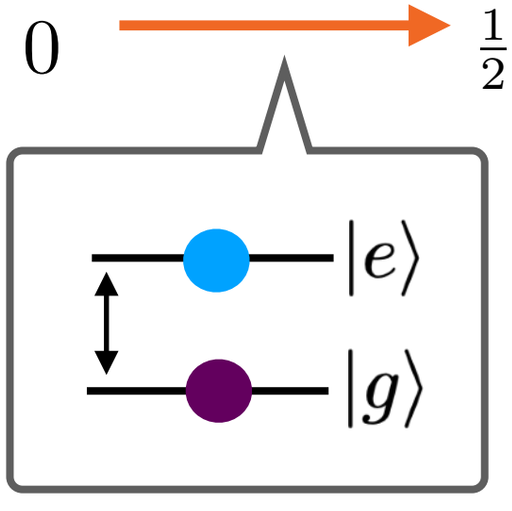

$$|\Delta\mathbf{k}| = \Delta\omega$$

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

AIs: the Principle

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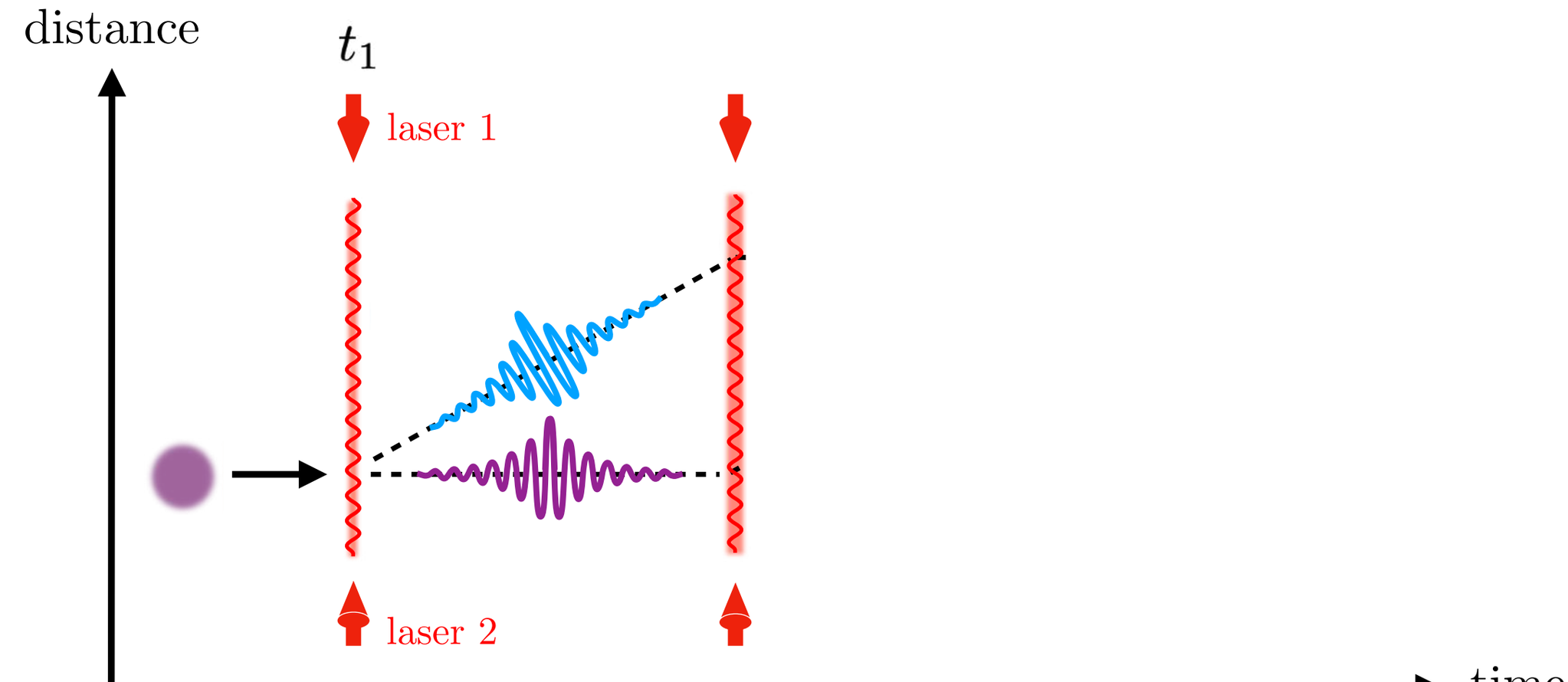

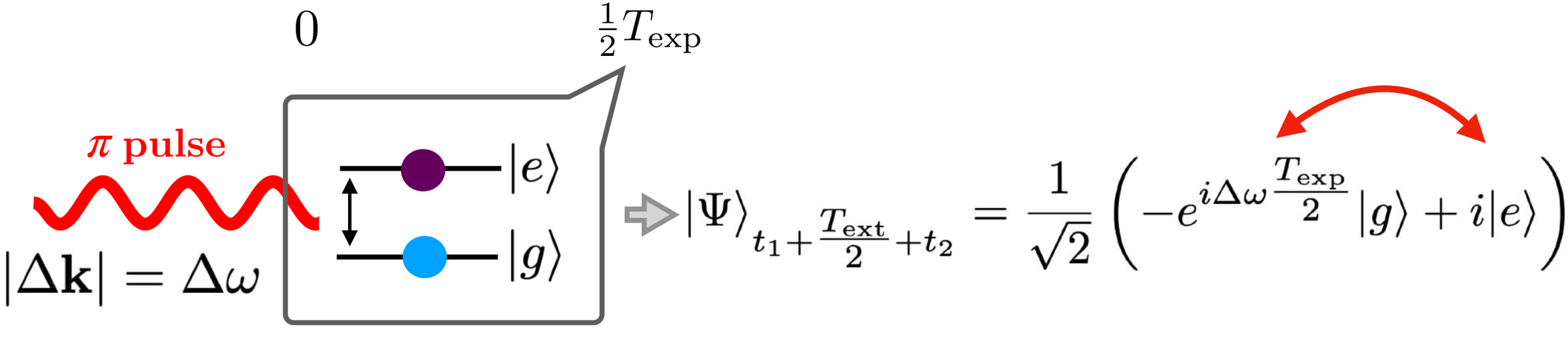

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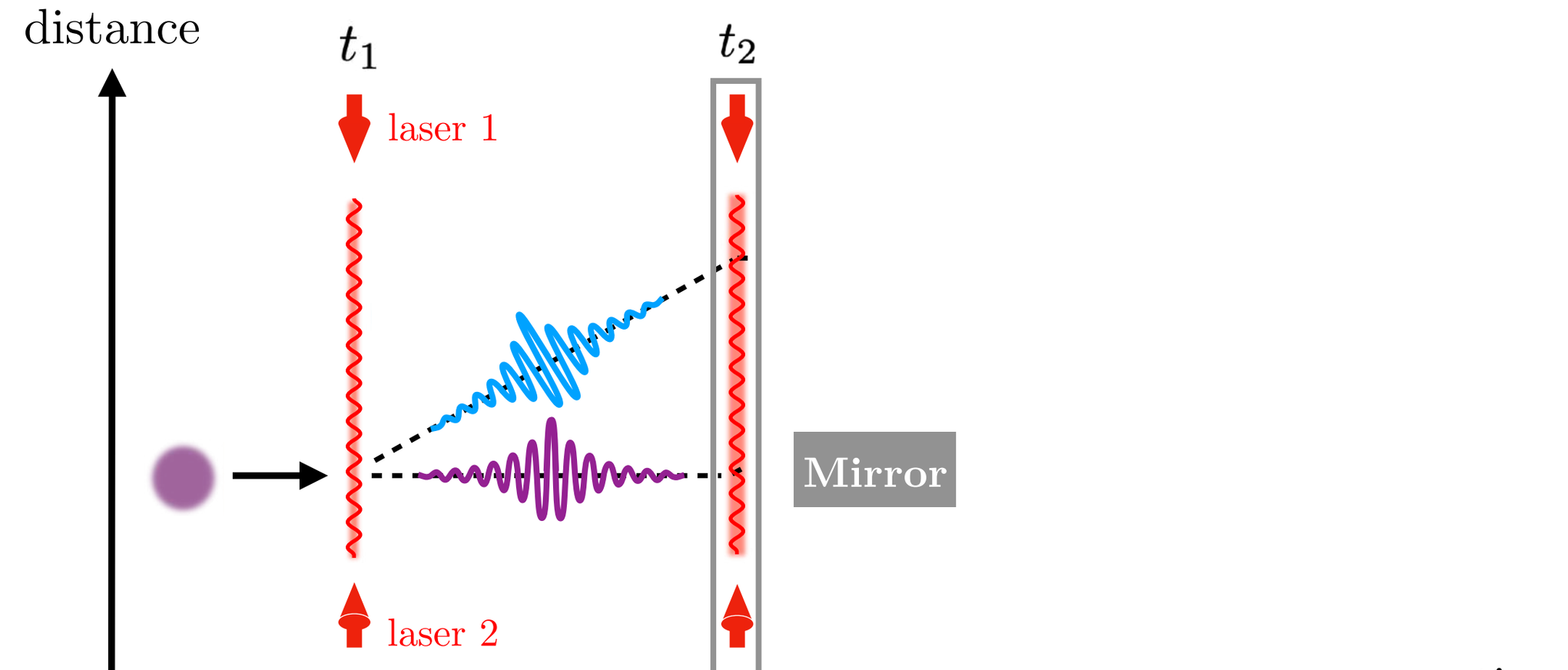

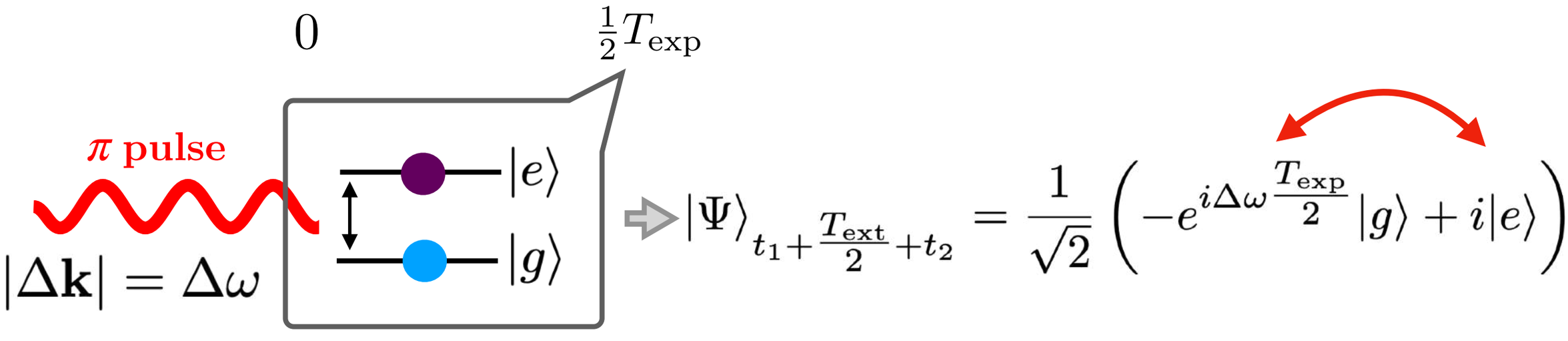

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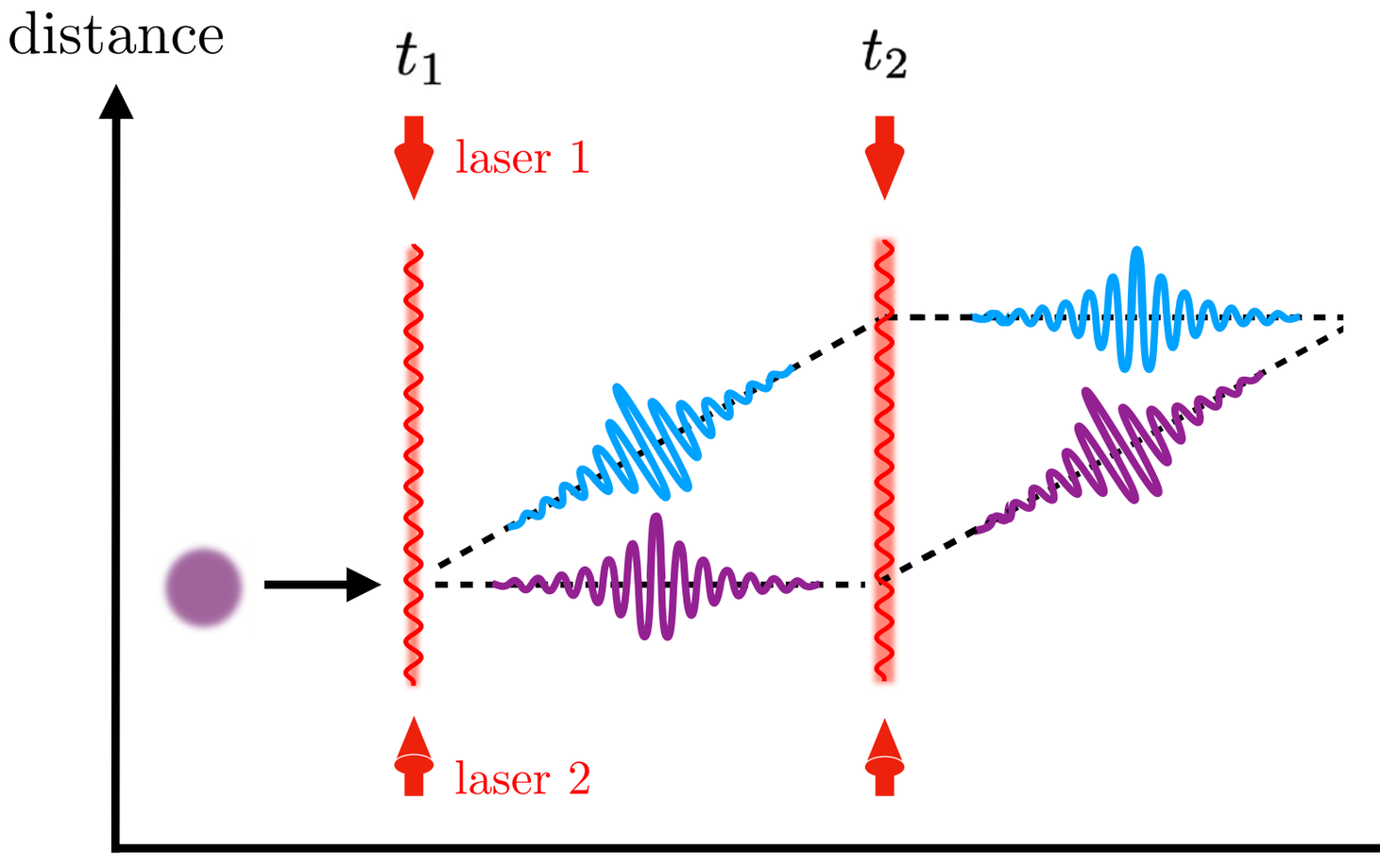

$|e\rangle$

$|g\rangle$

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

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

AIs: the Principle

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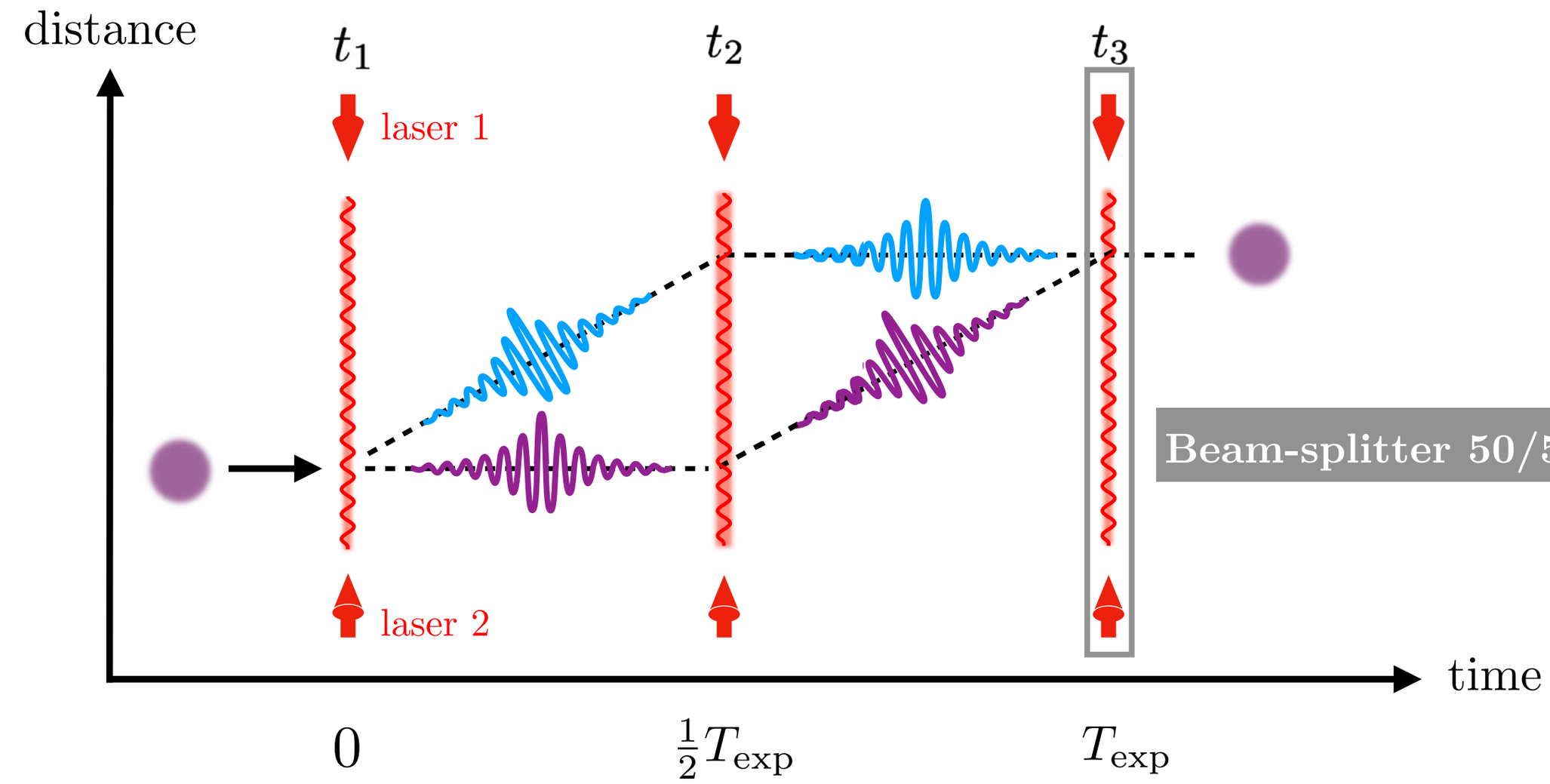

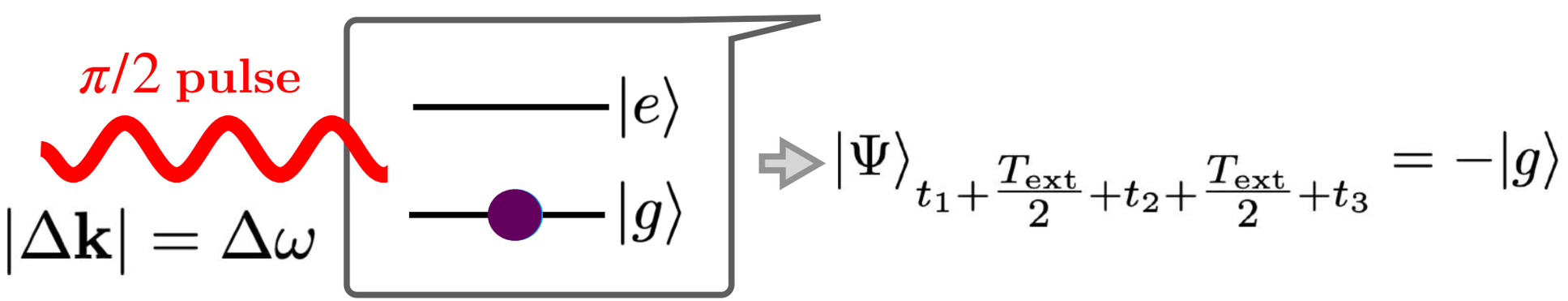

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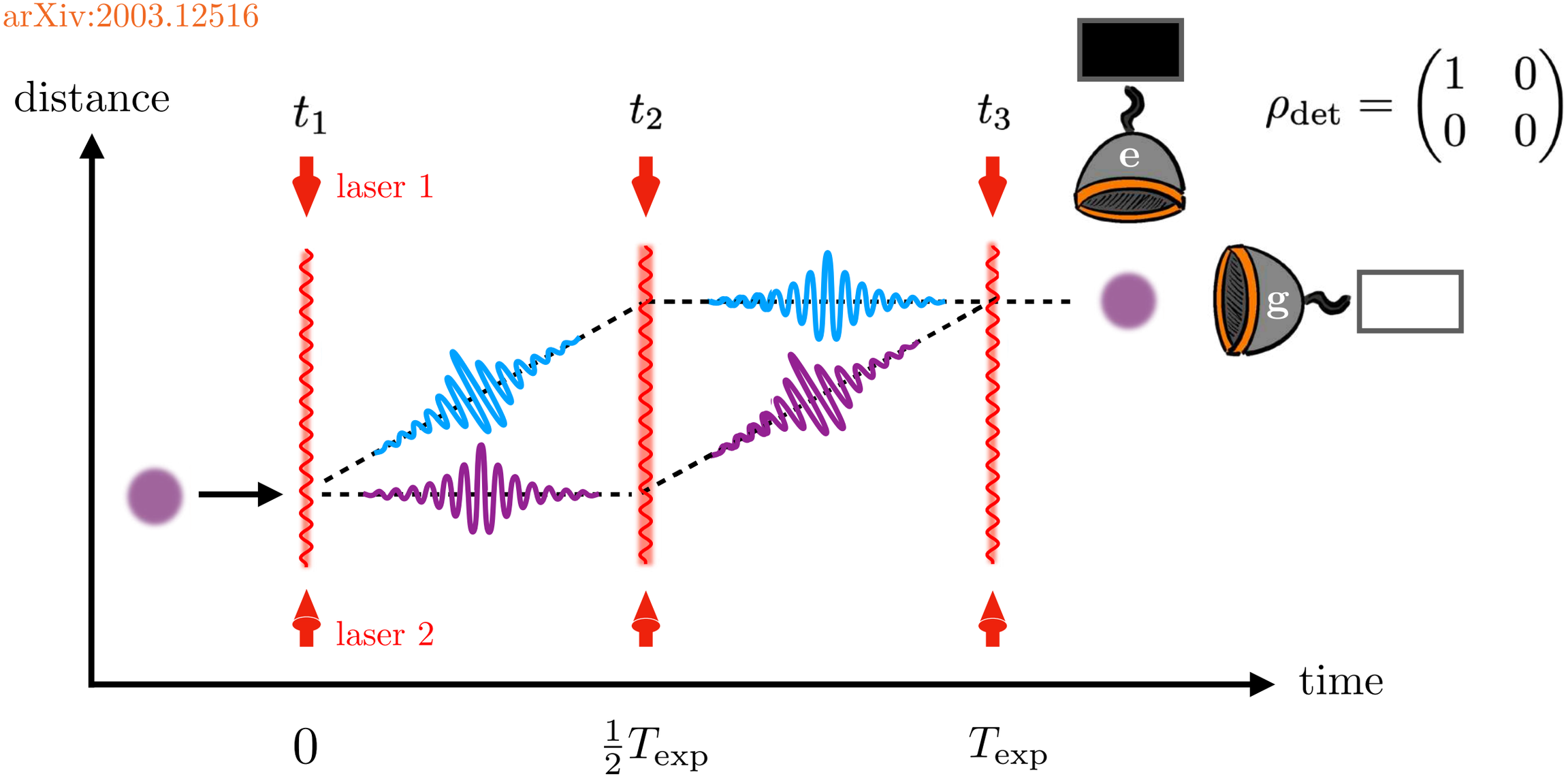

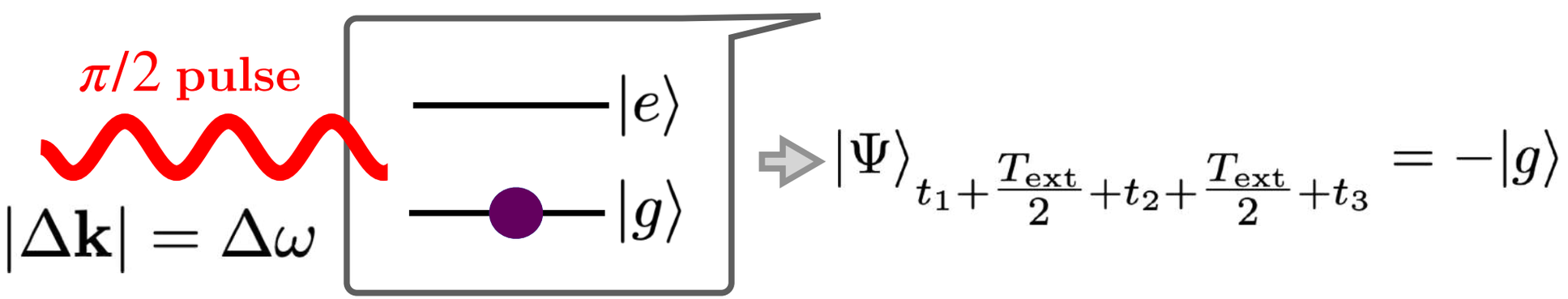

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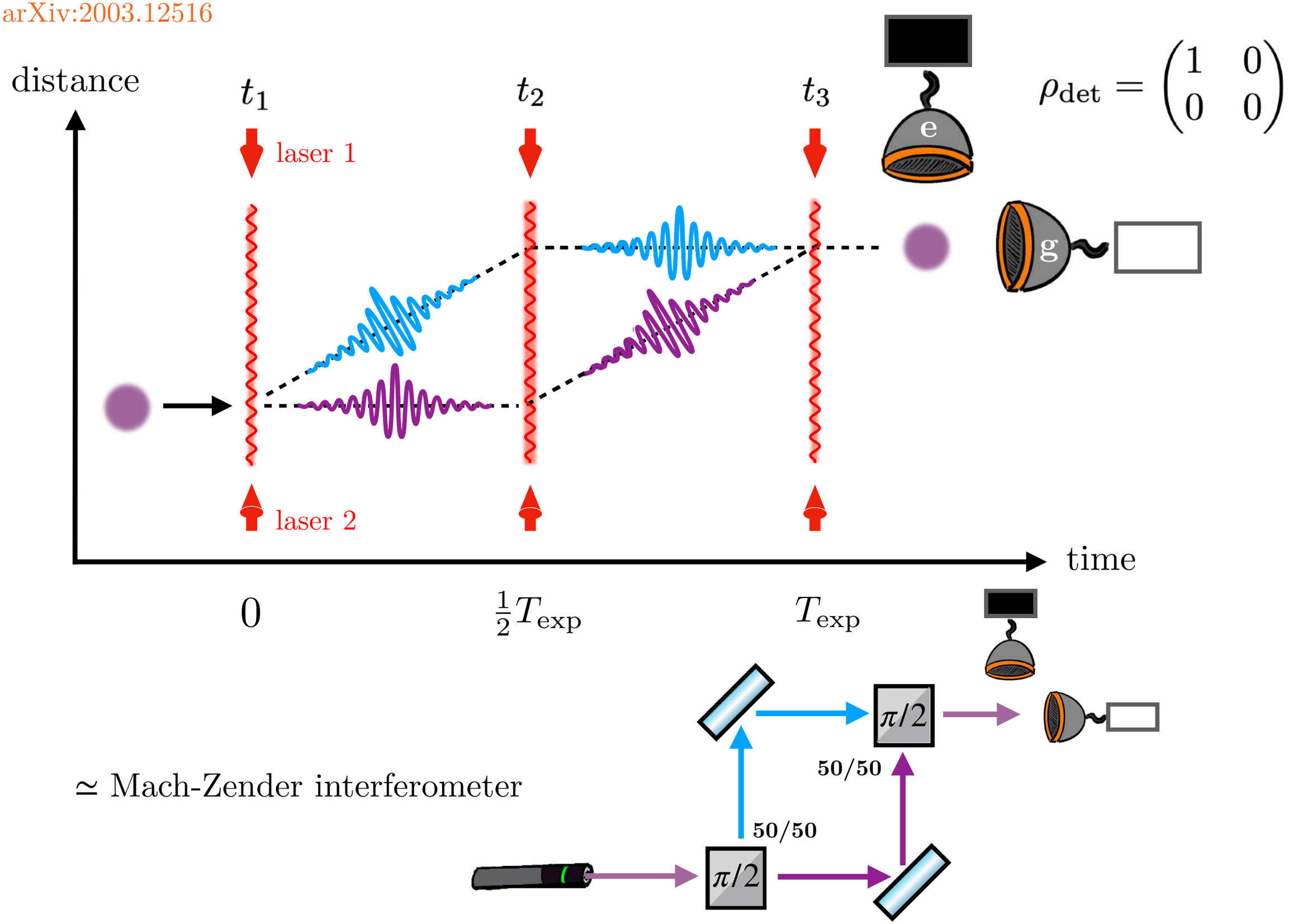
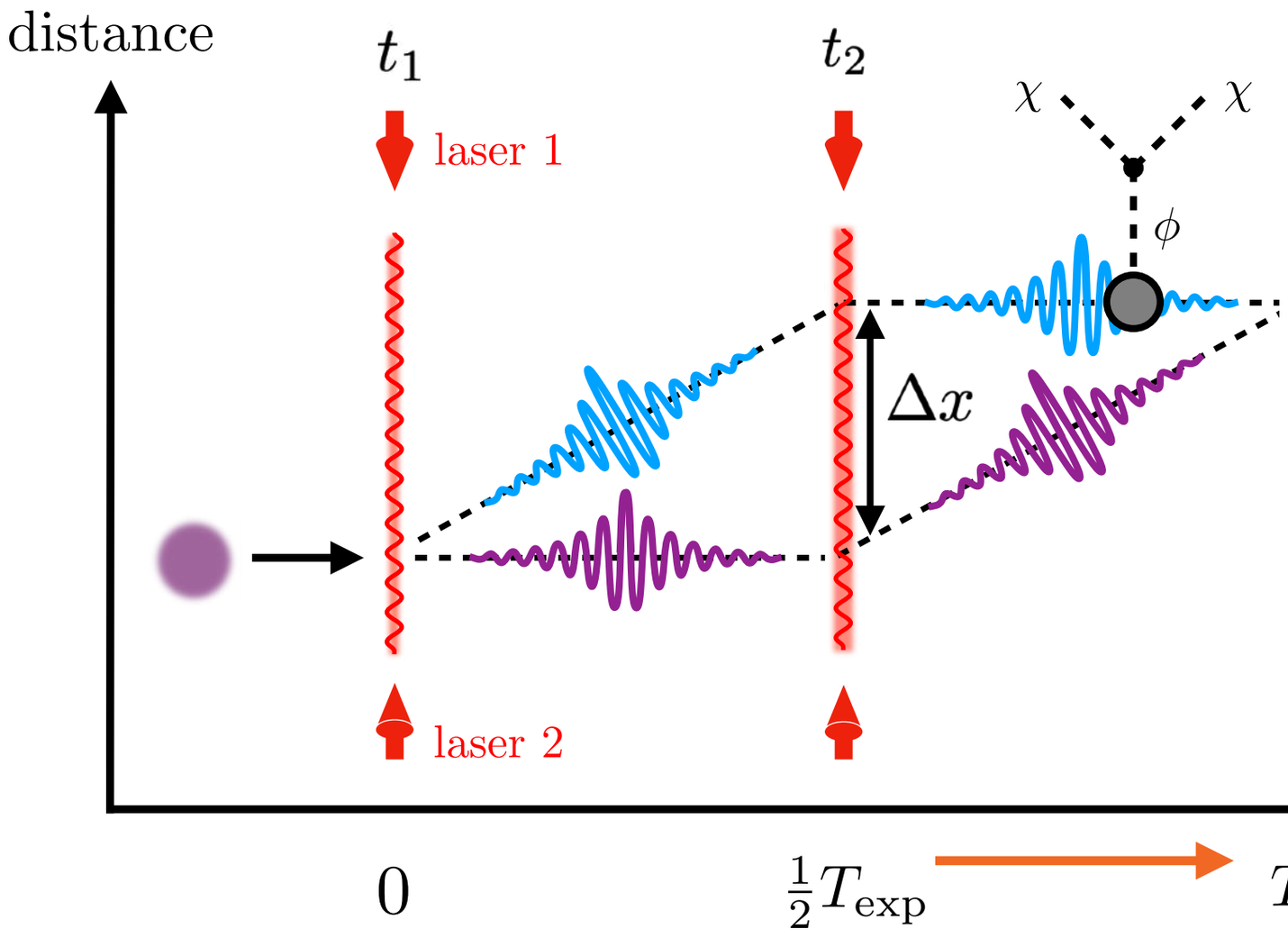


AIs: Decoherence

Review: arXiv:2003.12516



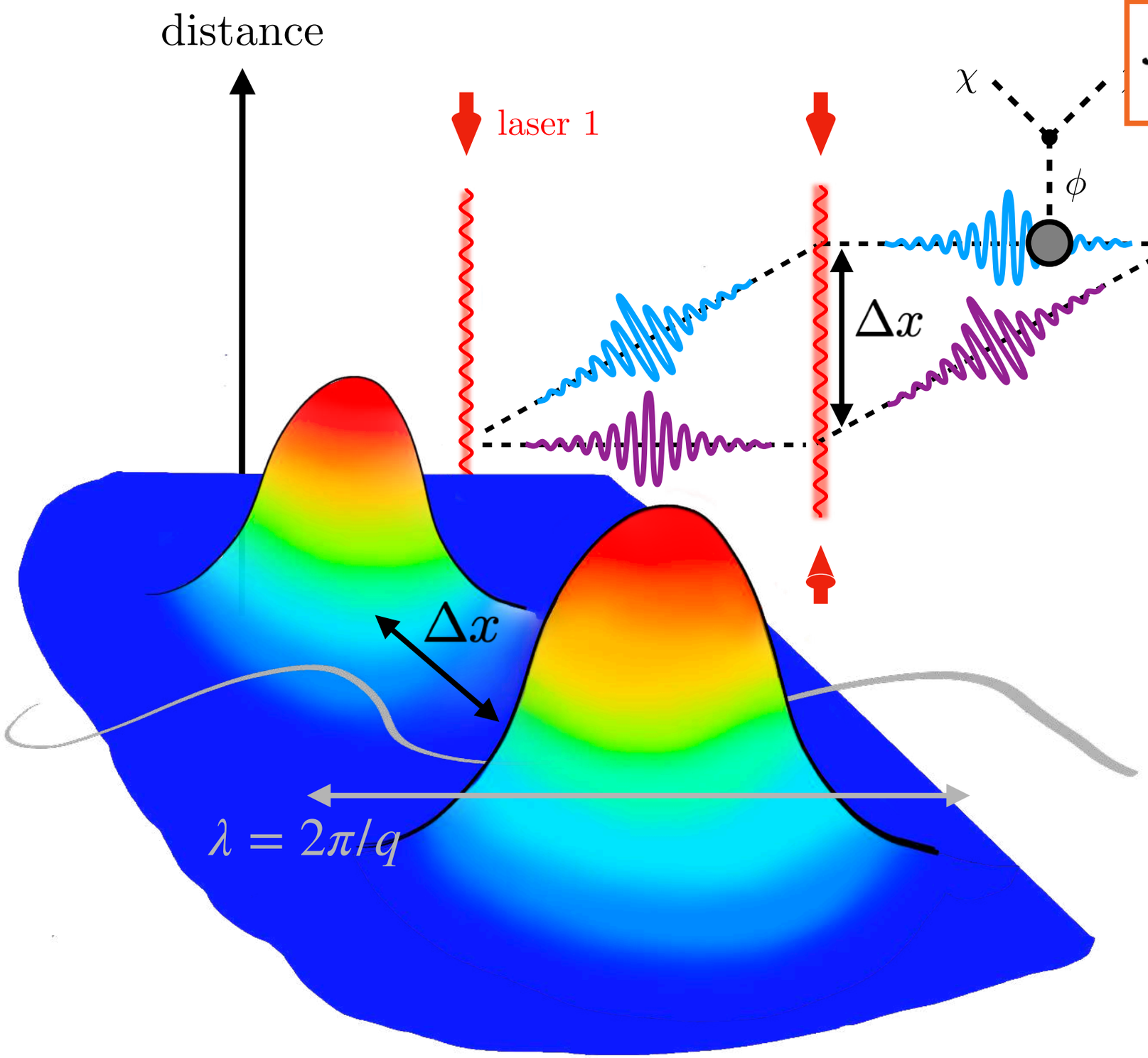
open system

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

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

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

AIs: Decoherence



Form Factor

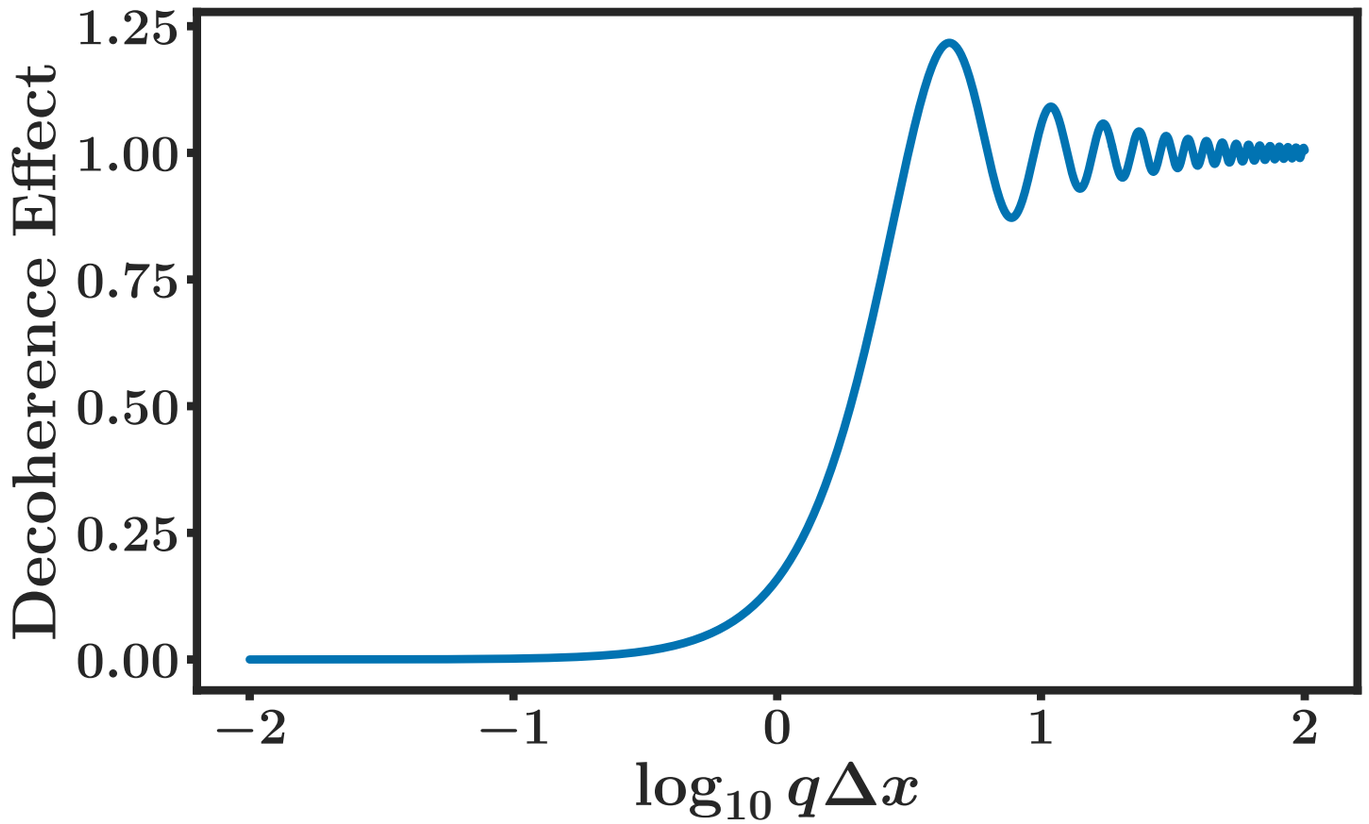
$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

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

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

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

AIs: Decoherence



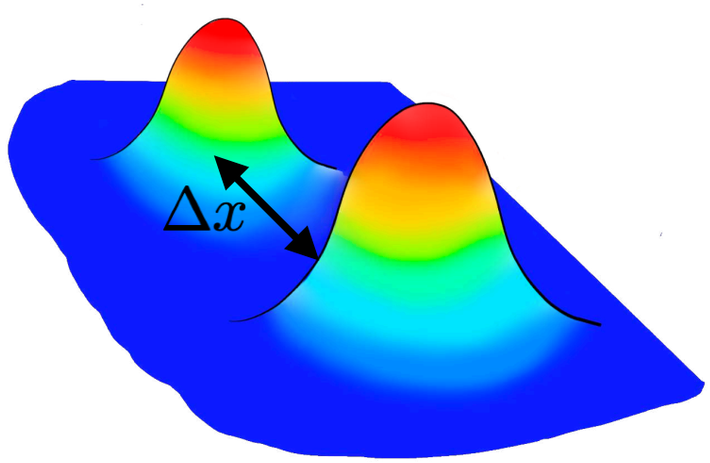
Form Factor

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

Visibility or Contrast ($\mathbf{V}$)

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

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

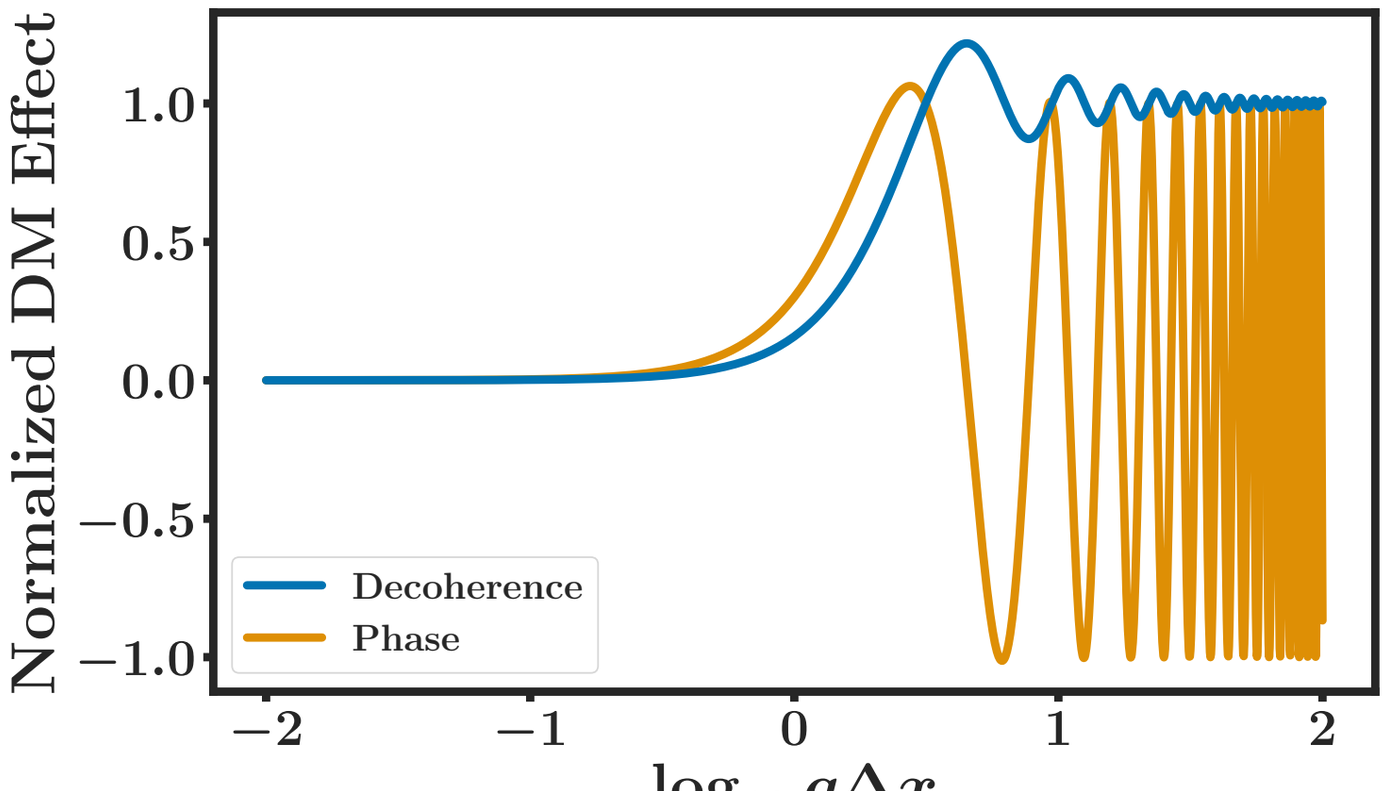


$$= e^{\left[-m_{\text{cloud}}\int_0^{t_{\text{exp}}} R\,dt\right]}$$

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

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

AIs: Decoherence



Form Factor

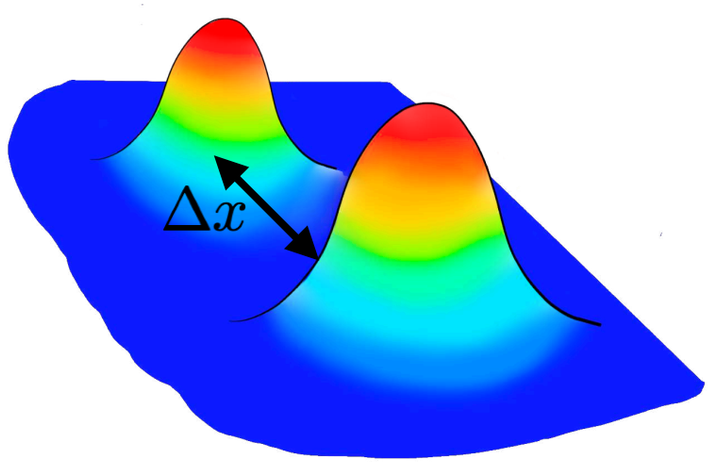
$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

Phase (ϕ)

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

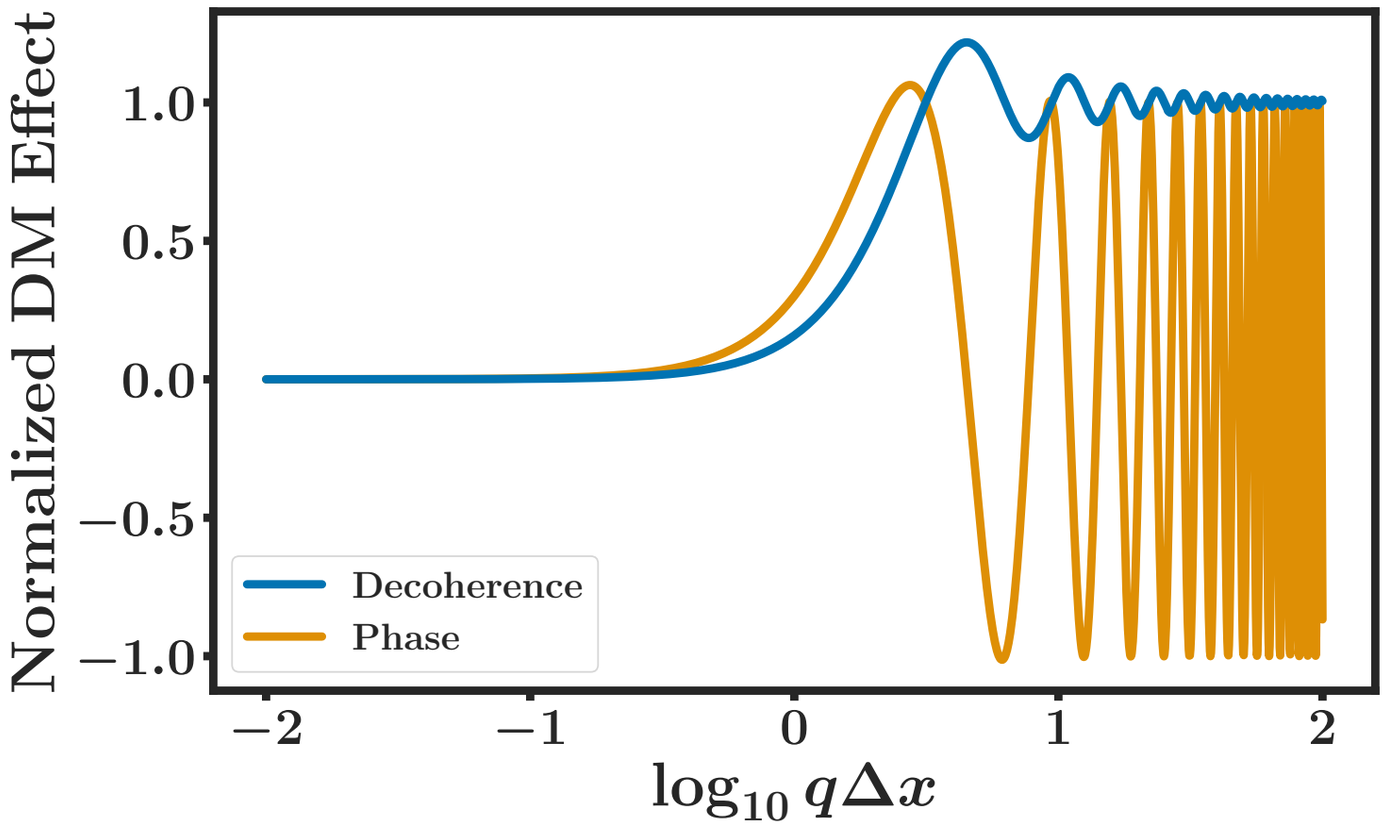
$$= 0$$

$$\log_{10} q\Delta x$$



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

AIs: Decoherence



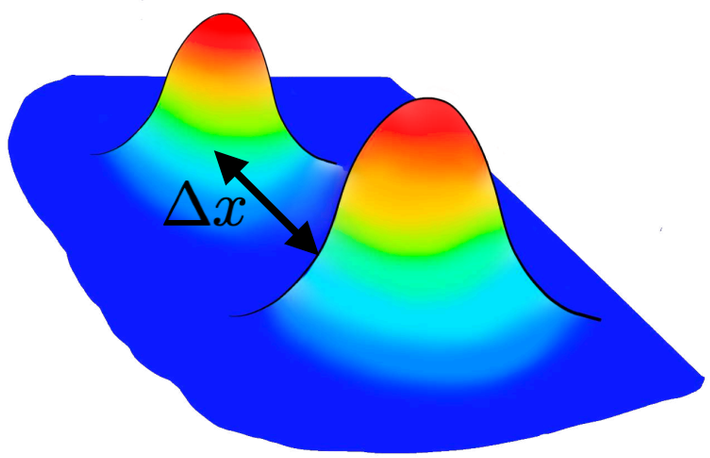
Form Factor

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

Phase (ϕ)

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

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

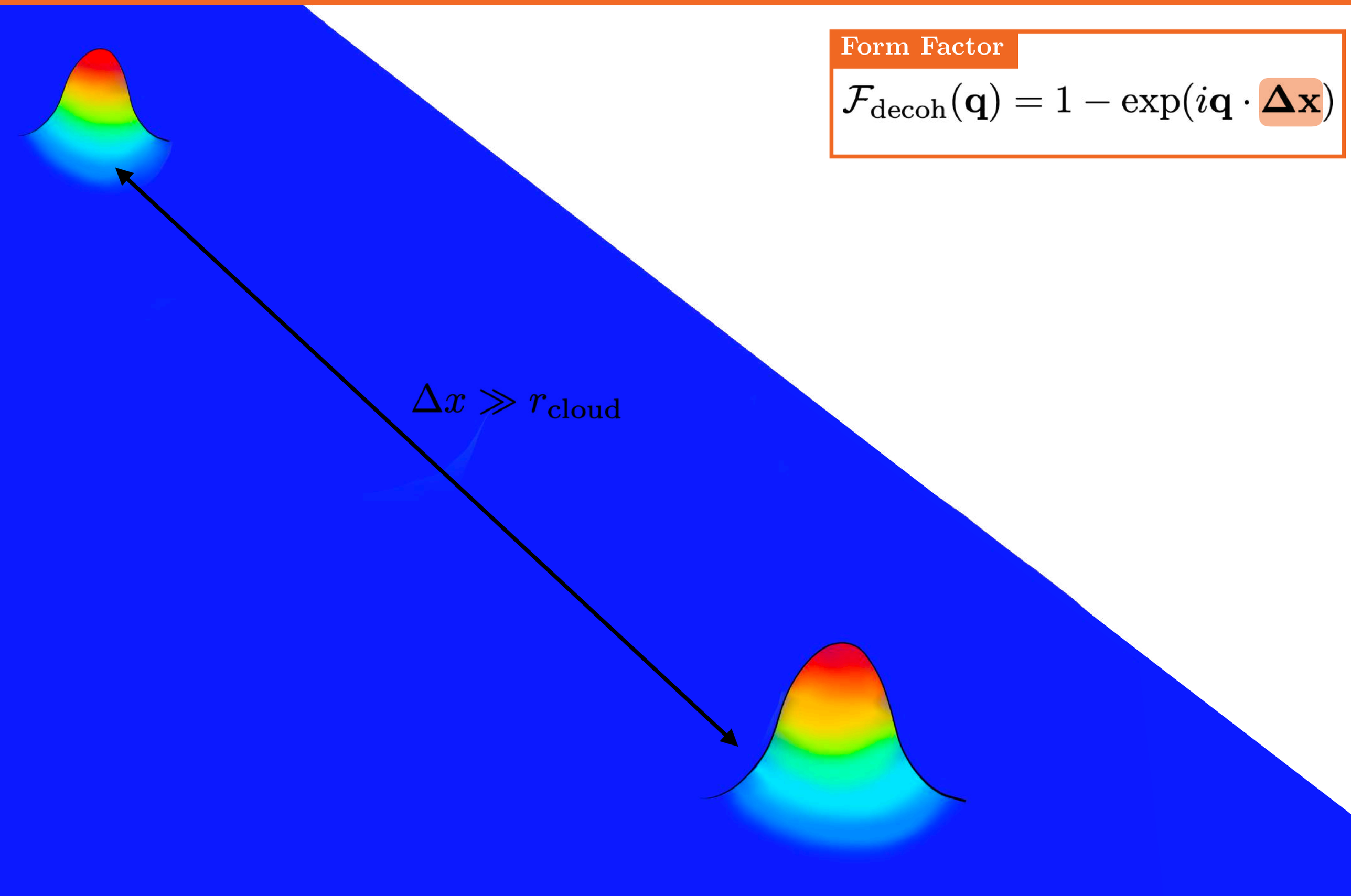


$$\gamma = e^{-s+i\phi} = \underbrace{e^{-s}}_{V} e^{i\phi}$$

AIs: Decoherence

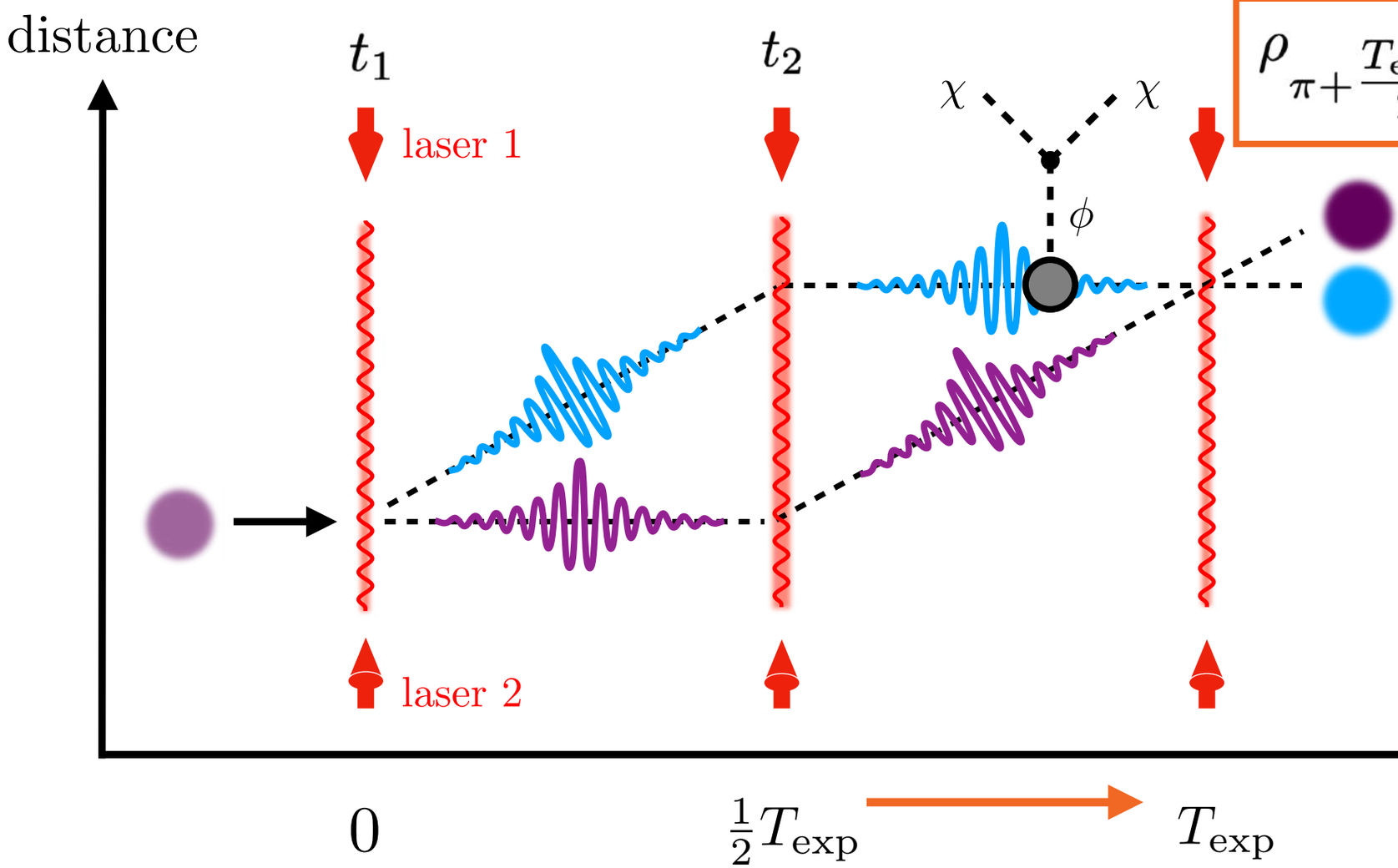
Form Factor

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



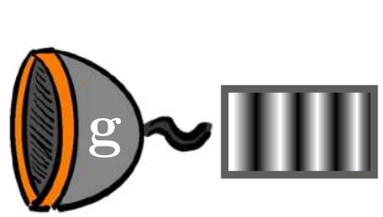
AIs: Measurement

Review: arXiv:2003.12516



open system

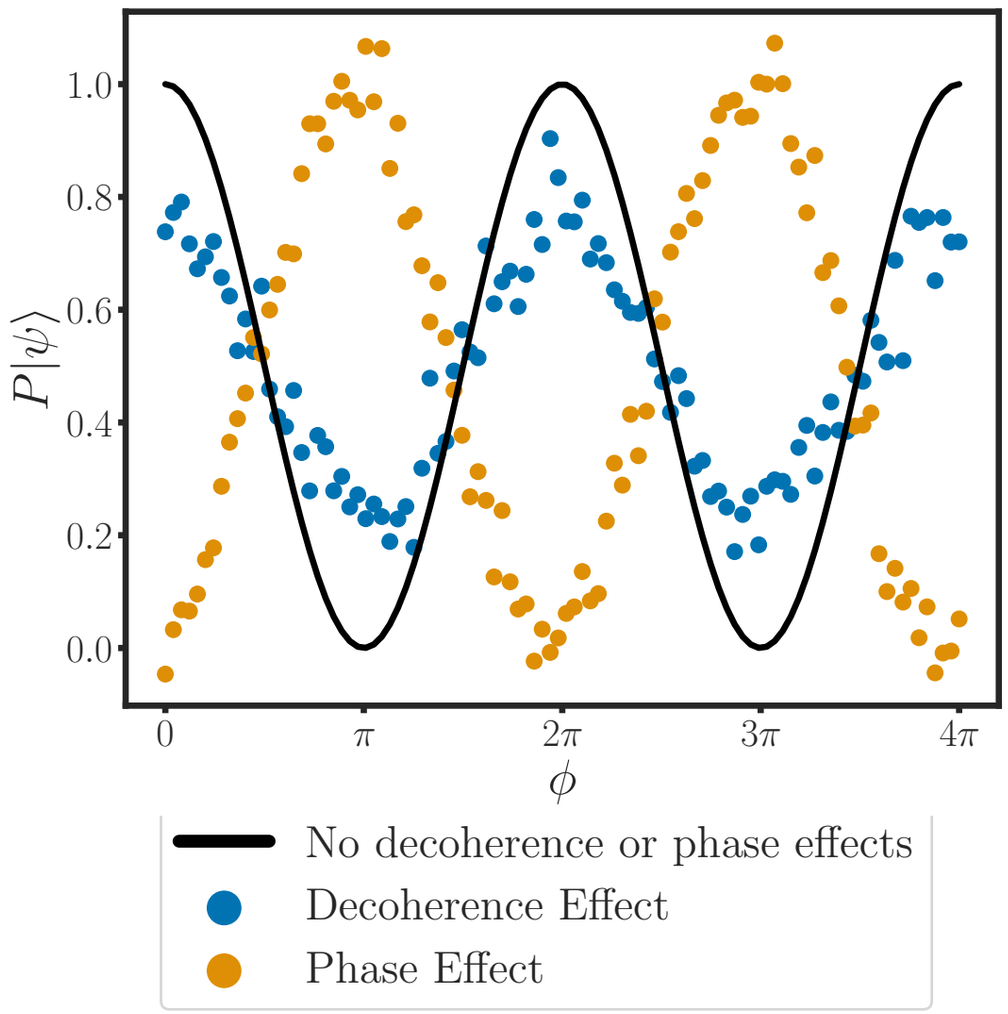
$$\rho_{\pi+\frac{T_{\rm exp}}{2}} = \frac{1}{2}\begin{pmatrix} 1 & i\gamma \\ -i\gamma & 1 \end{pmatrix}$$



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

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

AIs: Measurement



open system

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

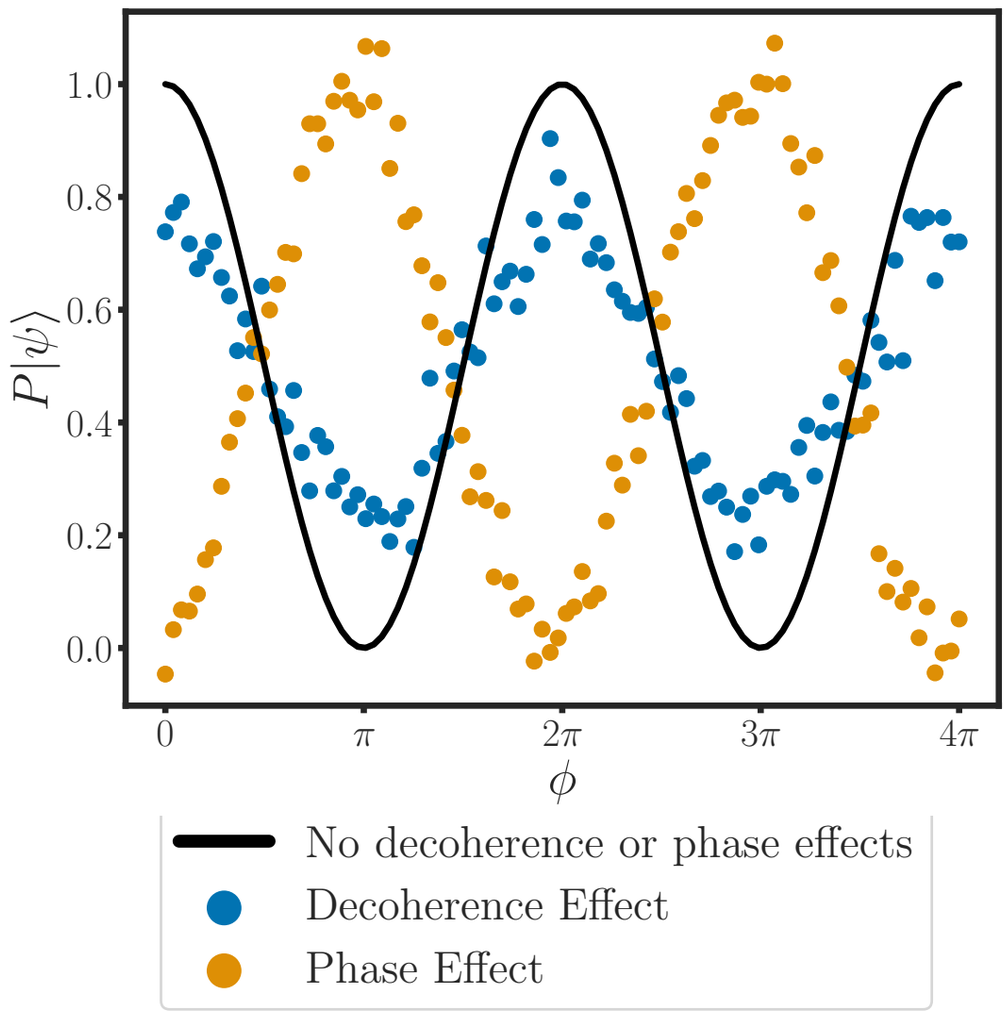
$$\mathcal{P}(|\Psi\rangle)_g = \text{Tr}\{\rho|g\rangle\langle g|\}$$
$$= \tfrac{1}{2}\left(1 + \text{Re}\{\gamma\}\right)$$
$$= \tfrac{1}{2}(1 + e^{-s}\cos\phi)$$

Accumulated decoherence: **Rate**

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

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

AIs: Statistics



Visibility

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

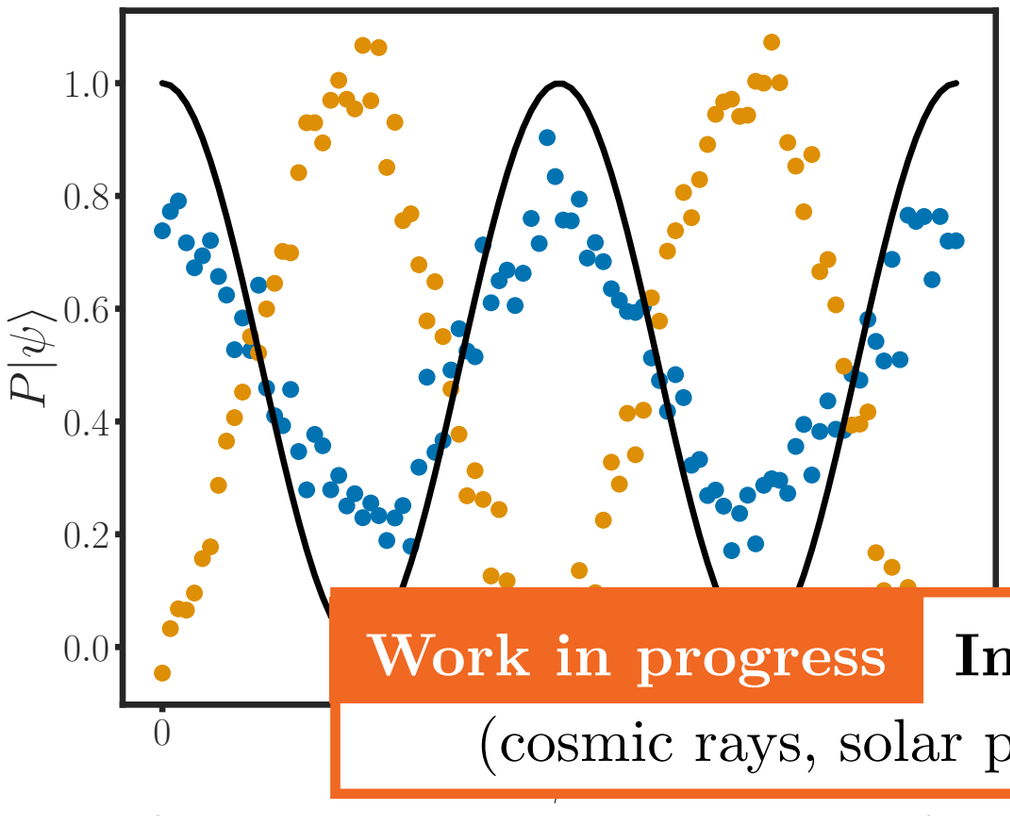
Accumulated decoherence: **Rate**

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

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

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

AIs: Statistics



Work in progress **Impact of potential backgrounds**

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

Visibility

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

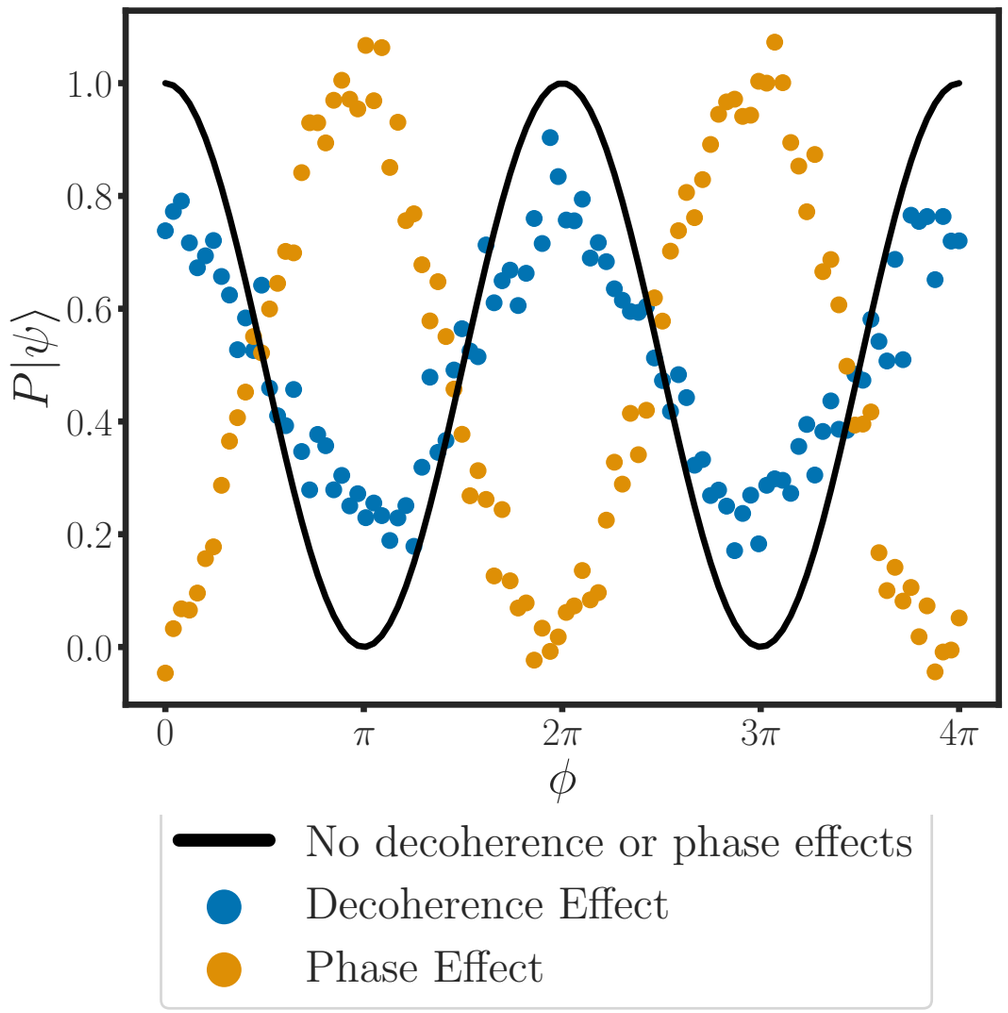
Accumulated decoherence: **Rate**

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

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

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

AIs: Statistics



Phase

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

Visibility

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

Accumulated decoherence: **Rate**

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

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

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

AIs: the Rate

Number of events / (target mass · time)

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

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

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

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

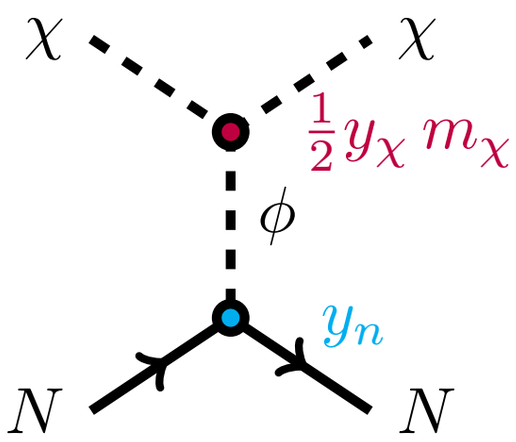
$$R = \frac{n_\chi}{m_T}\int d^3\mathbf{v}\, f(\mathbf{v})\,\Gamma(\mathbf{v})\,\mathcal{F}_{\rm decoh}(\mathbf{q})$$

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

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

AIs: the Rate

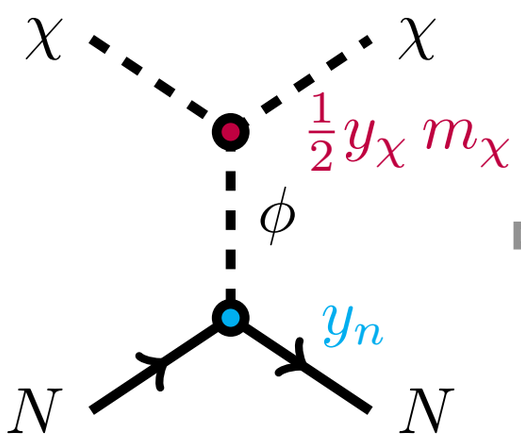
$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \sum_f |\langle f|H_{\rm int}|i\rangle|^2 g(\mathbf{q}, E_f - E_i)\mathcal{F}_{\rm decoh}(\mathbf{q})$$



AIs: the Rate

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

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



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

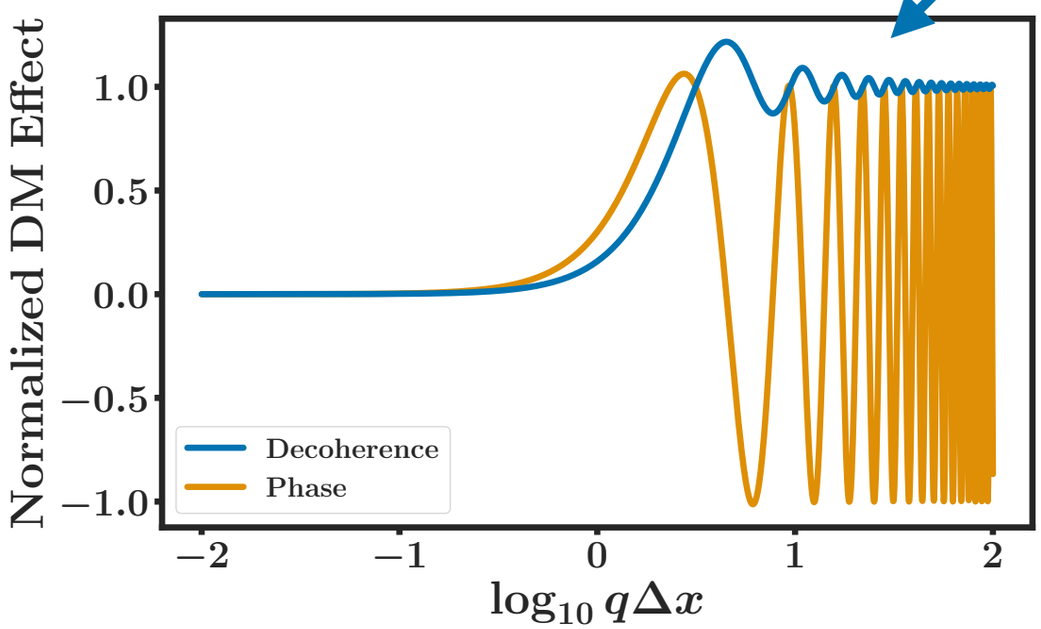
AIs: the Rate

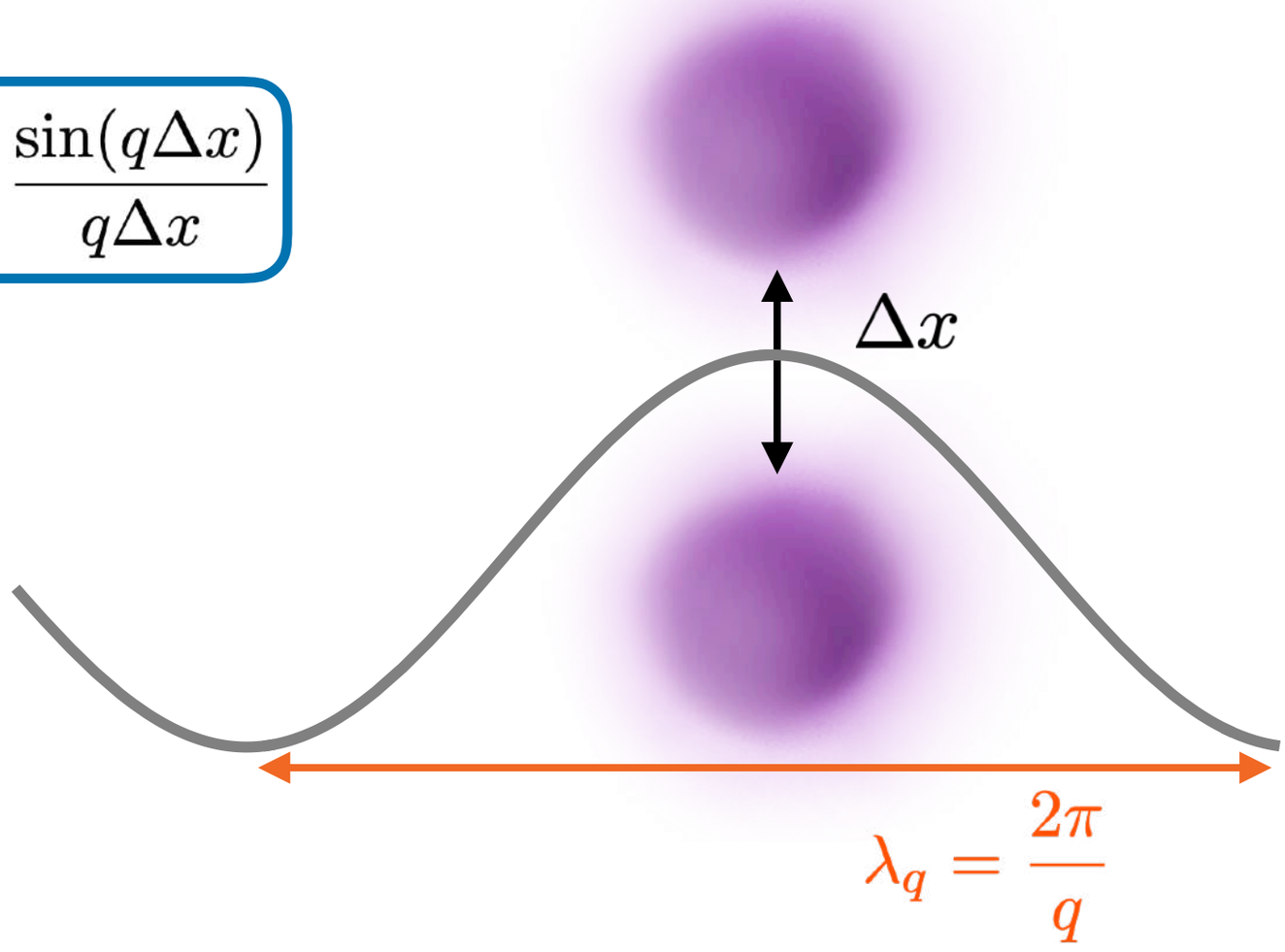
$$\mathcal{F}_{\rm med}(\mathbf{q}) = \begin{cases} 1 & \text{heavy mediator} \\ (m_\chi v_0/q)^2 & \text{light mediator} \end{cases}$$

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

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

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





AIs: the Rate

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

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

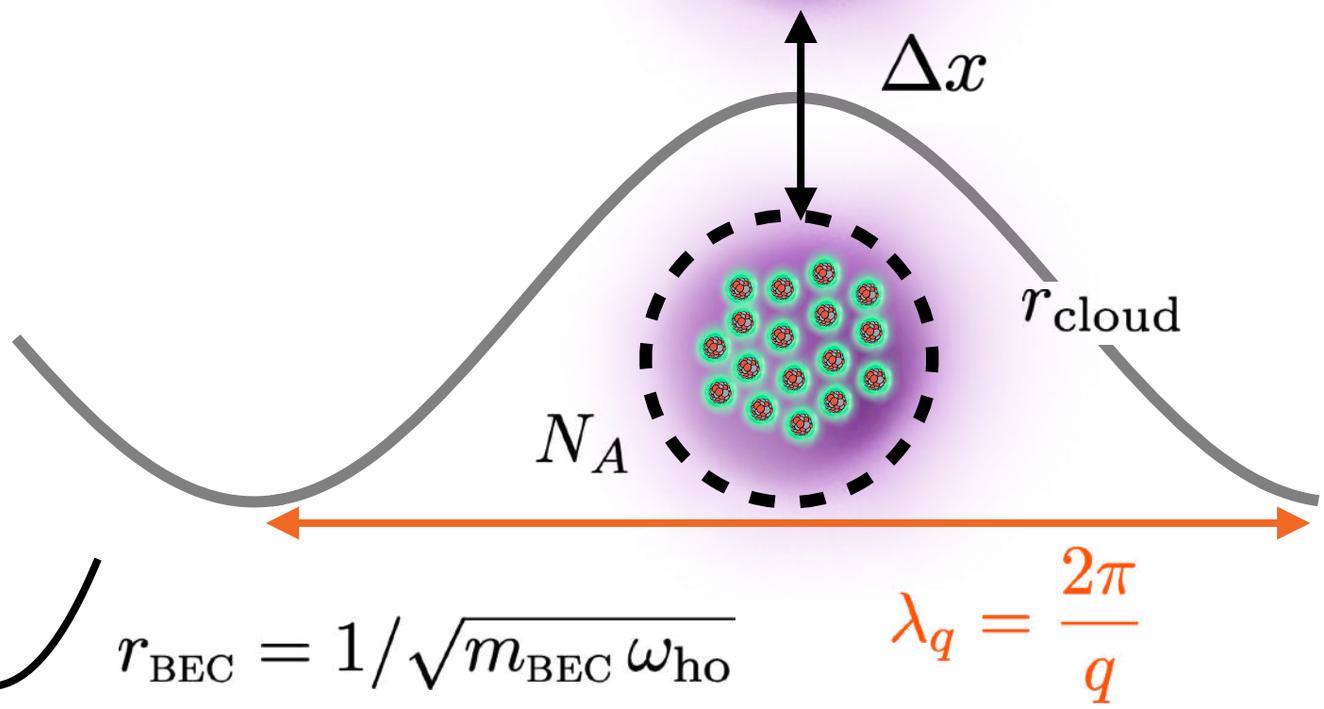
$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi} V \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{1}{V^2}\frac{\pi\bar{\sigma}}{\mu^2} \mathcal{F}^2_{\rm med}(\mathbf{q})\, \mathcal{F}^2_{\rm T}(\mathbf{q})\, g(\mathbf{q}, E_f - E_i)\, \mathcal{F}_{\rm decoh}(\mathbf{q})$$

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

Born (coherent) enhancement!

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

$$\mathcal{F}_{\rm cloud}(qr_{\rm cloud}) \begin{cases} \dfrac{3j_1(qr_{\rm cloud})}{qr_{\rm cloud}} \\ \exp\left(-\dfrac{q^2}{(2r_{\rm BEC})^2}\right) \end{cases} \qquad r_{\rm BEC} = 1/\sqrt{m_{\rm BEC}\,\omega_{\rm ho}}$$



AIs: the Rate

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

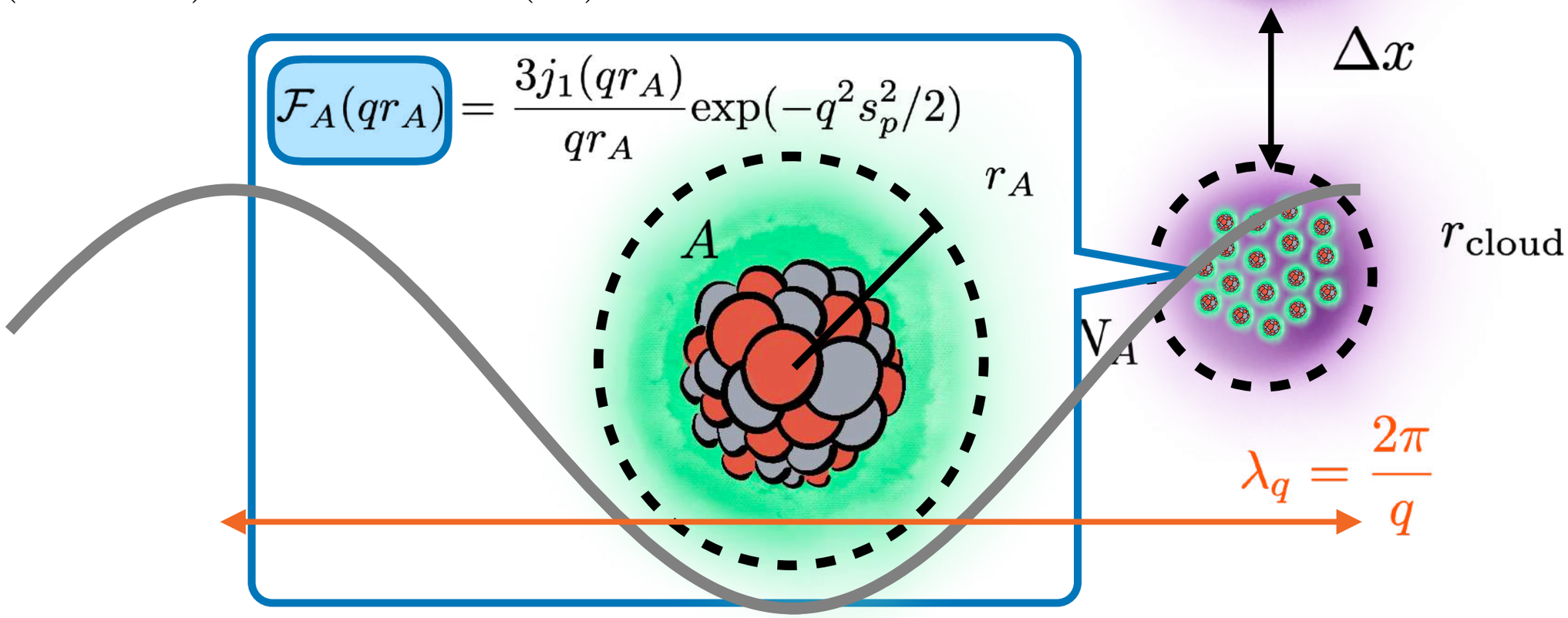
$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\mathbf{\Delta x})$$

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

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

Born (coherent) enhancement! (x2)

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



AIs: the Rate

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

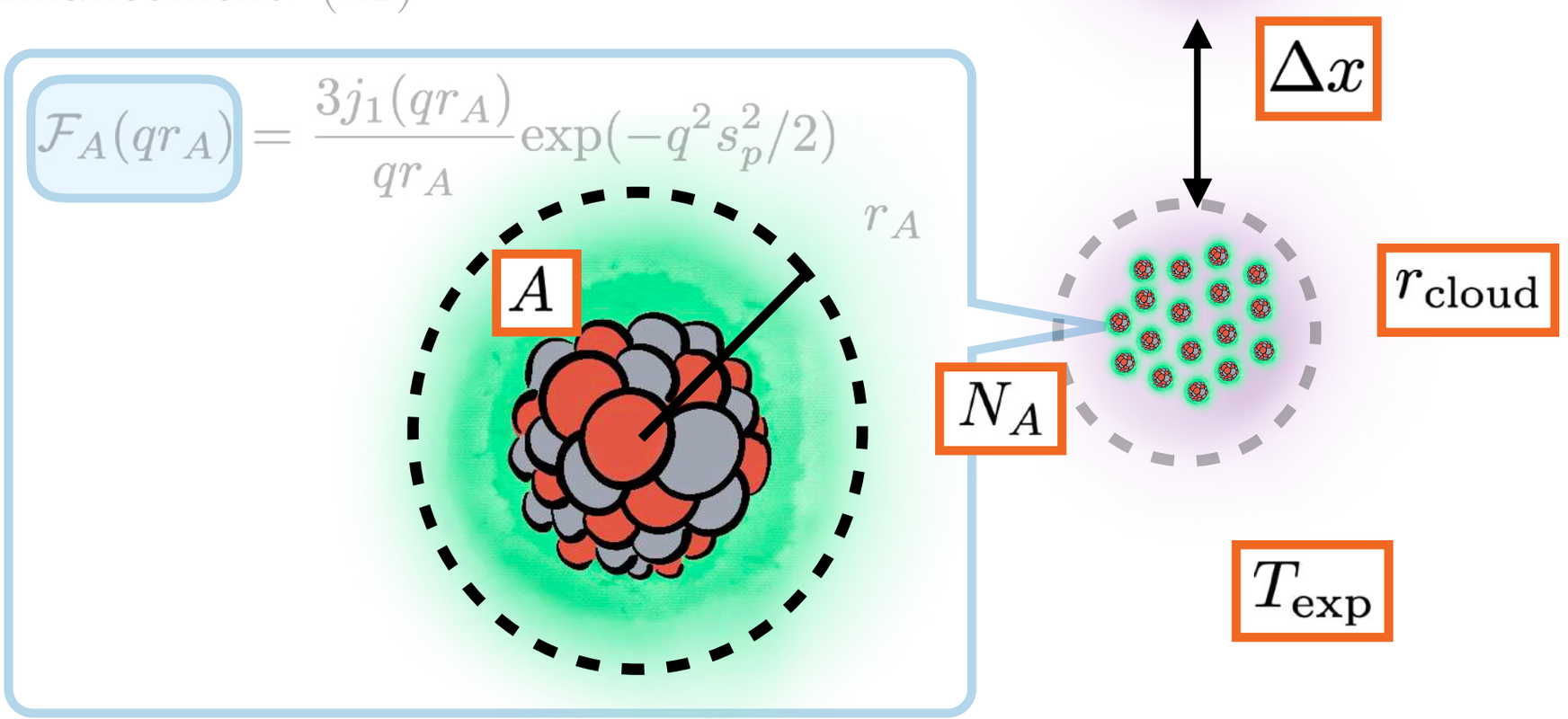
$$\mathcal{F}_{\rm decoh}(\mathbf{q}) = 1 - \exp(i\mathbf{q}\cdot\boldsymbol{\Delta x})$$

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

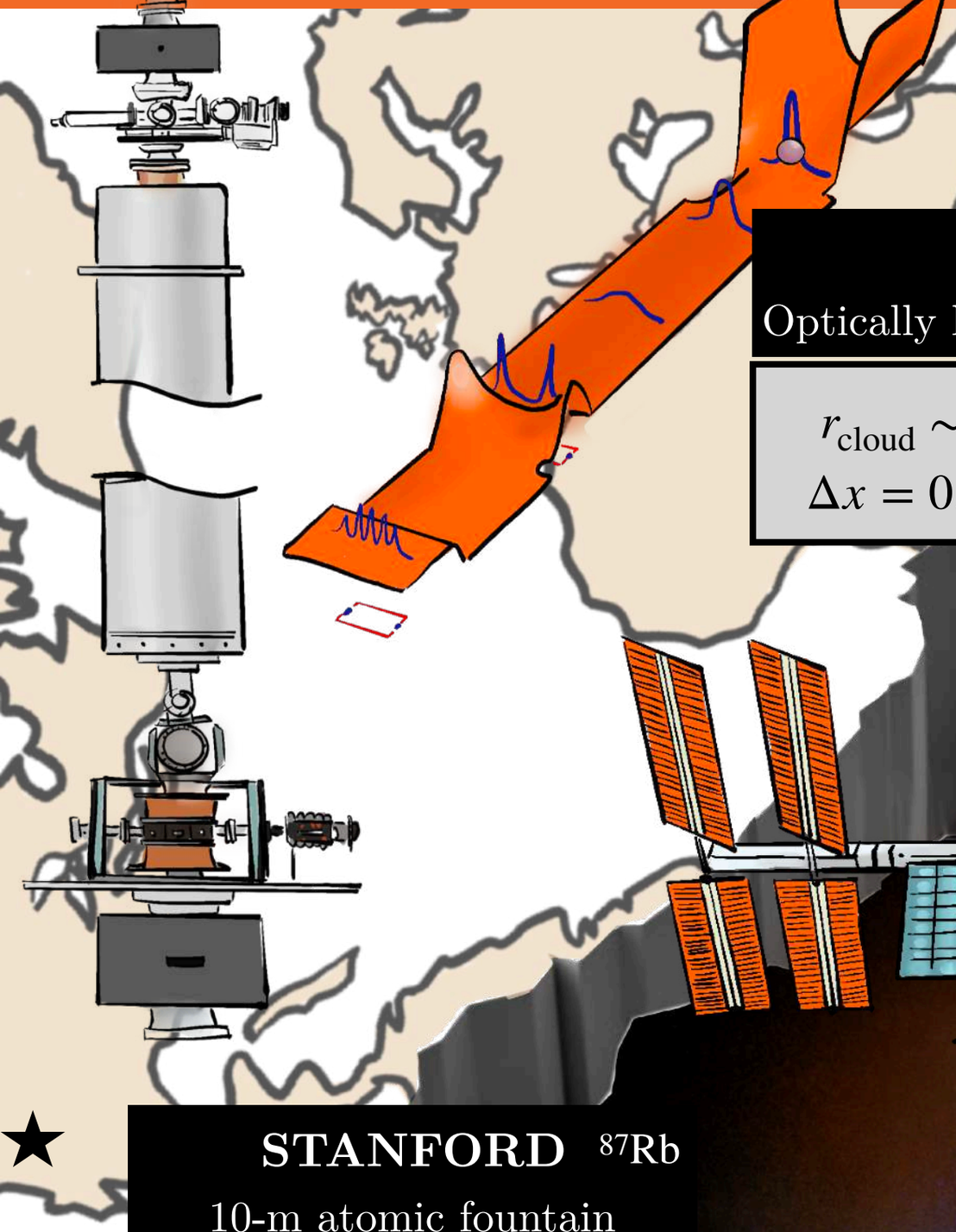
$$\mathcal{F}_T(\mathbf{q}) = N[1 + A(N_A - 1)\mathcal{F}^2_{\rm cloud}(qr_{\rm cloud}) + A\mathcal{F}^2_A(qr_A)]$$

Born (coherent) enhancement! (x2)

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



AIs: Examples



PINO Nb

Optically levitated nanosphere

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

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

MAQRO SiO_2

Macroscopic Quantum Resonators

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

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

GDM ^{87}Rb

Gravity Dark energy Mission

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

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

BECCAL ^{87}Rb

Bose-Einsten Condensate

Cold Atom Laboratory

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

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

★

STANFORD ^{87}Rb

10-m atomic fountain

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

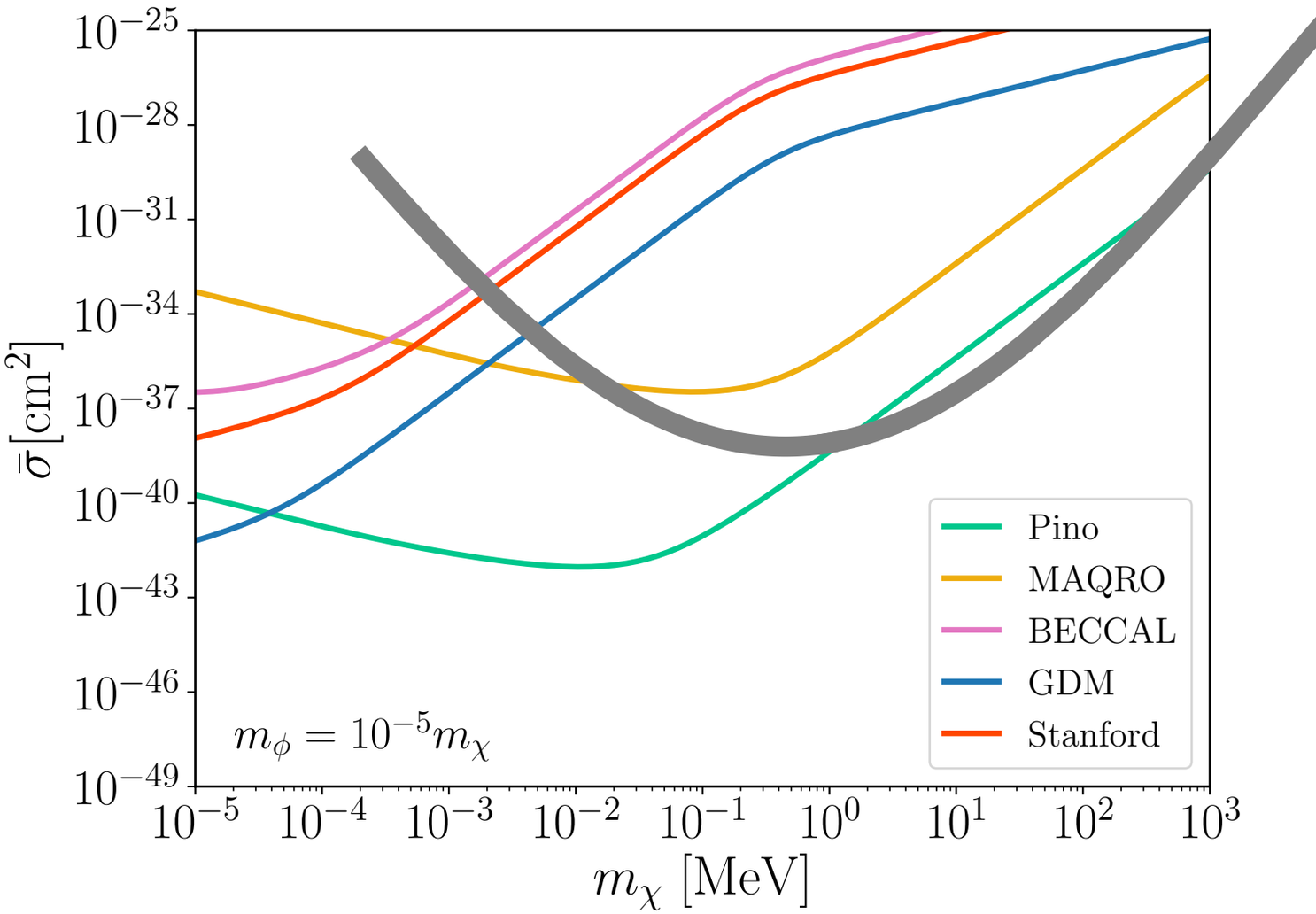
$\Delta x = 0.1\text{m}$, $t_{\text{exp}} = 2\text{s}$

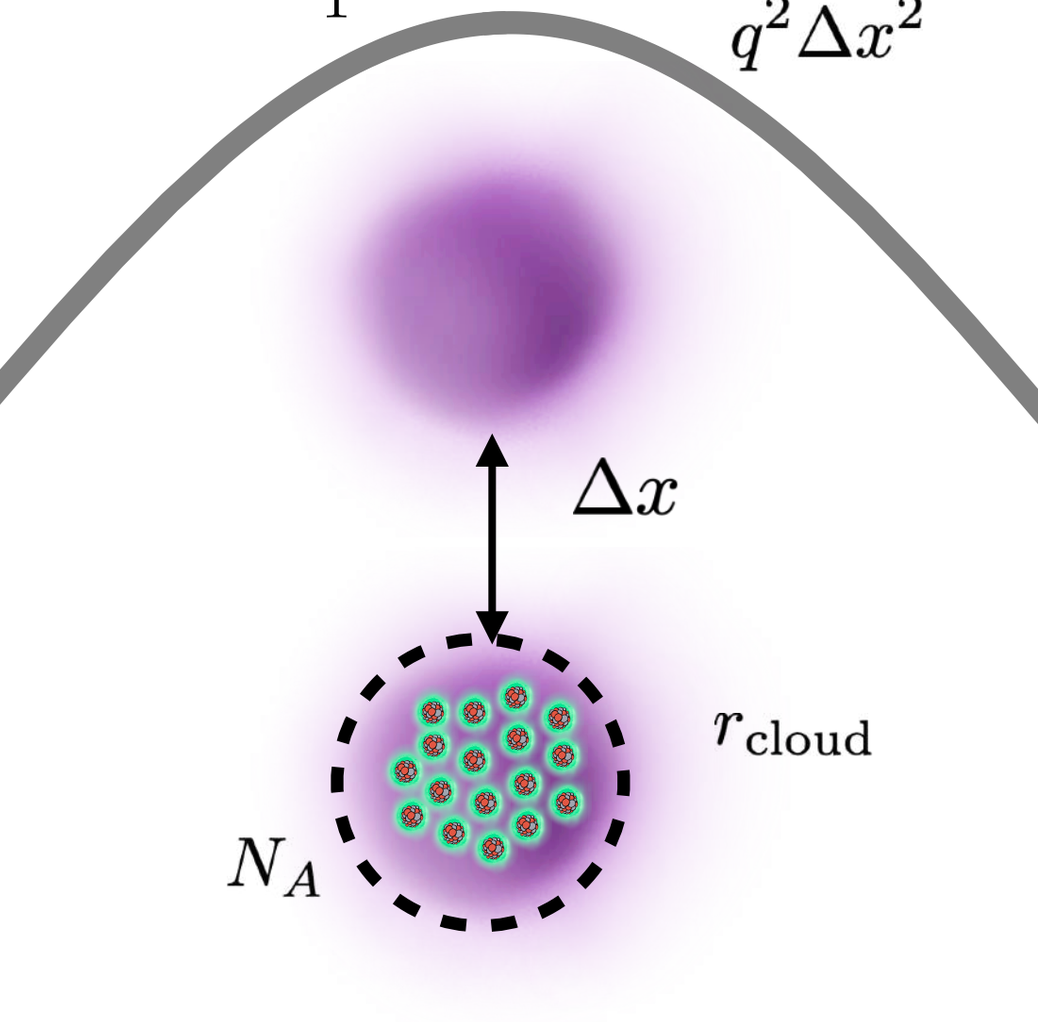
AIs: Results

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

$F \to 1$; $\left(1 - \frac{\sin(q\Delta x)}{q\Delta x}\right) \to q^2\Delta x^2$

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



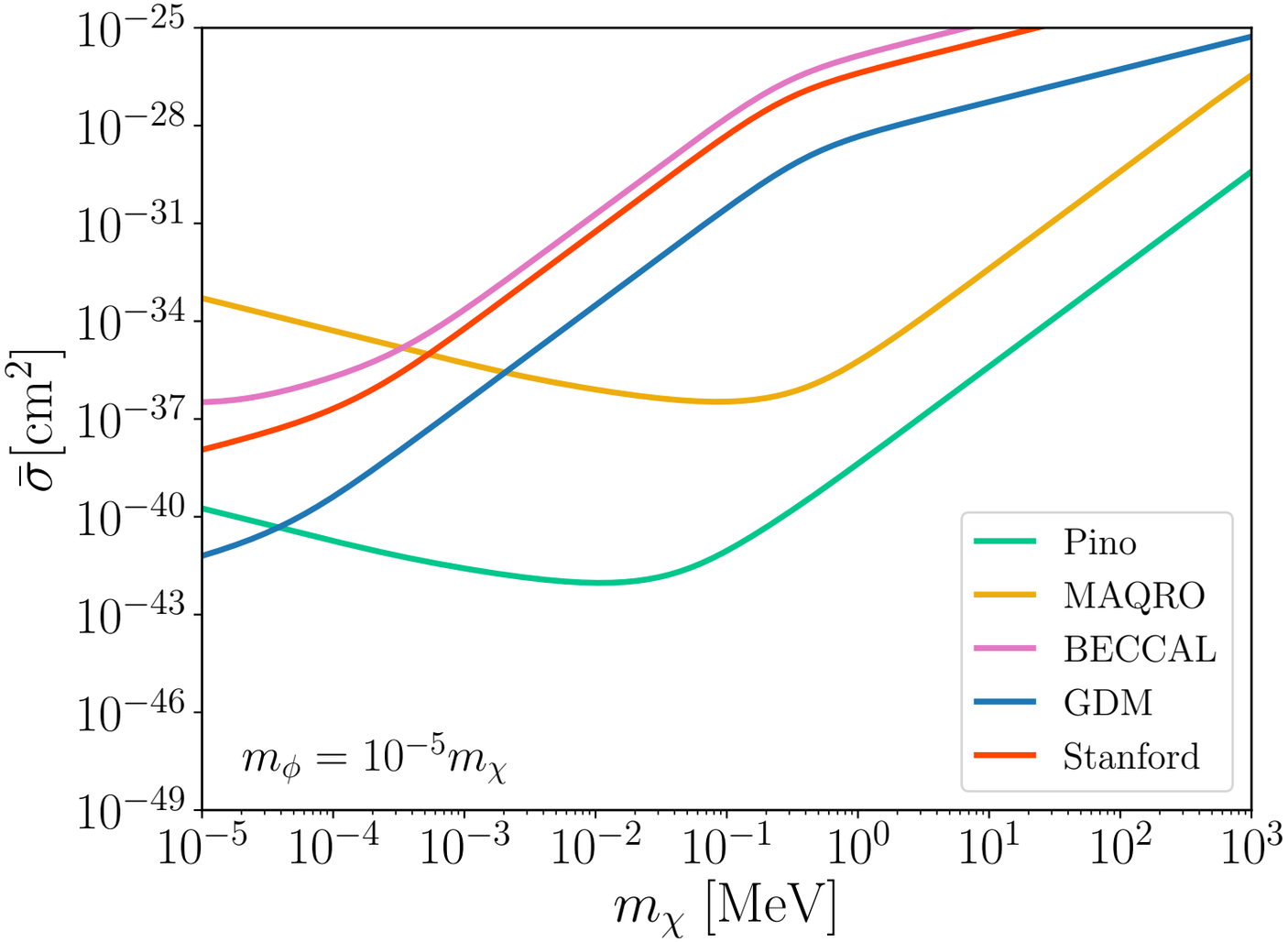


Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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

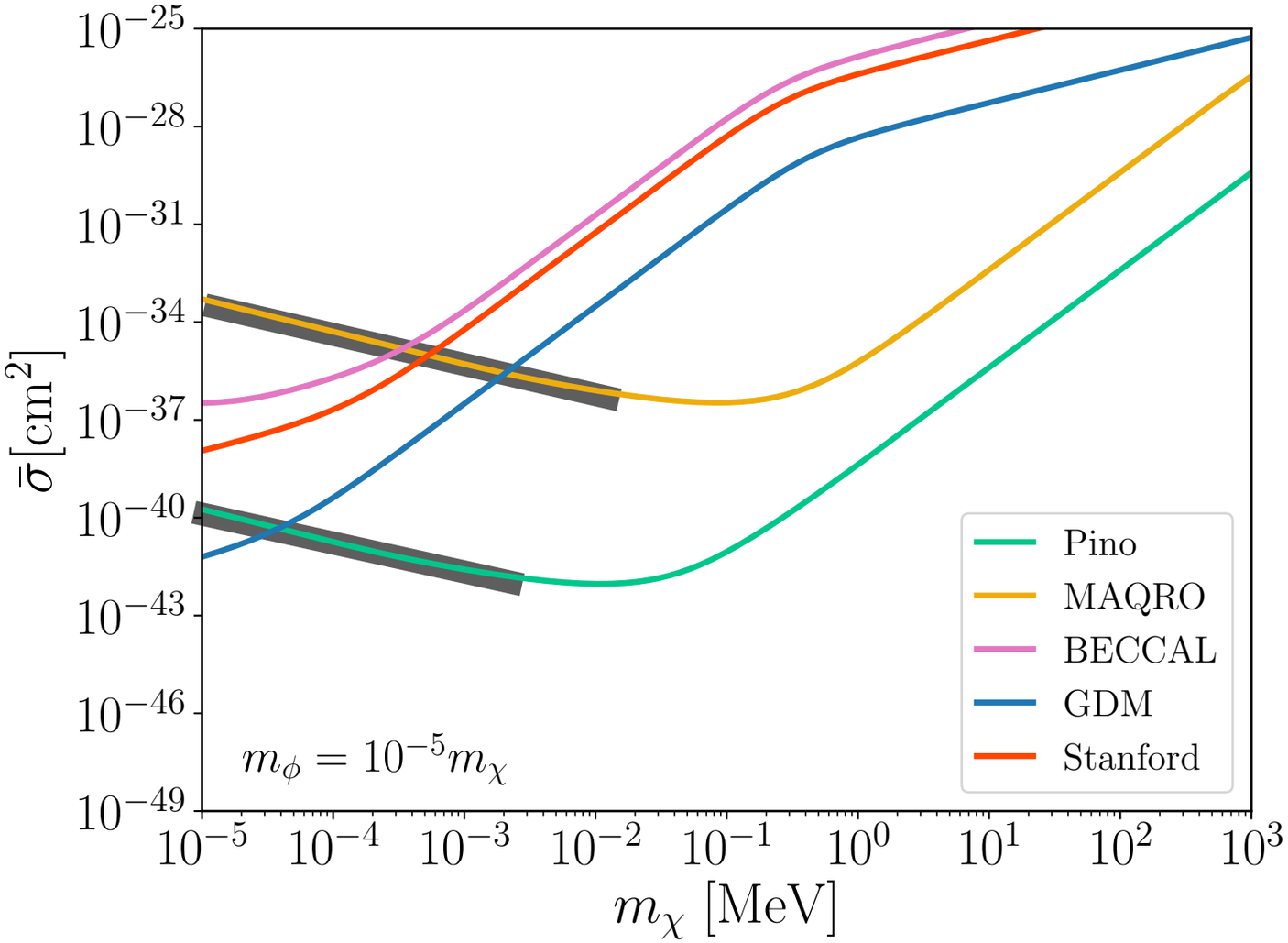


Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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



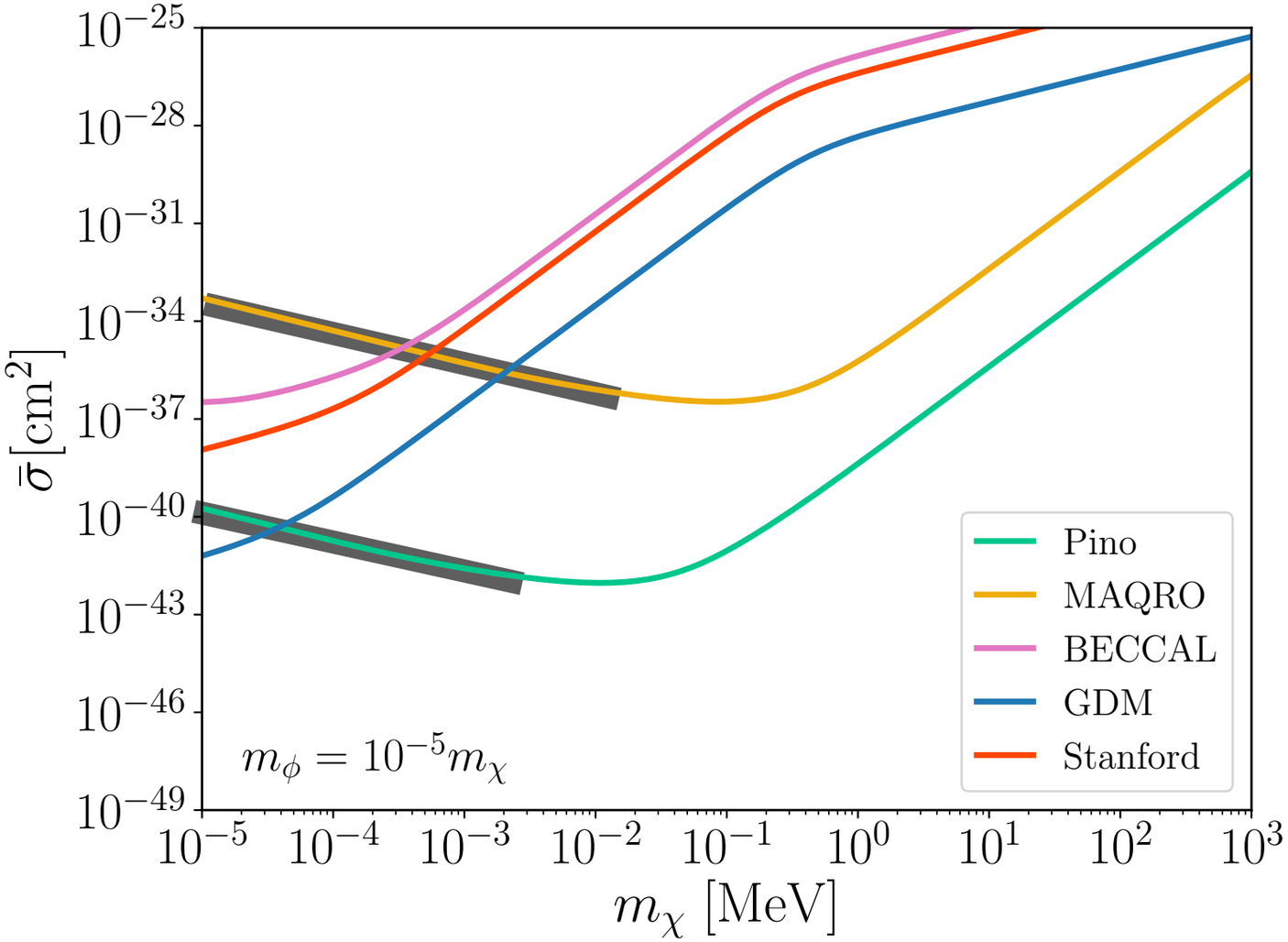
Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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

2 $m_\chi \to \infty$



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

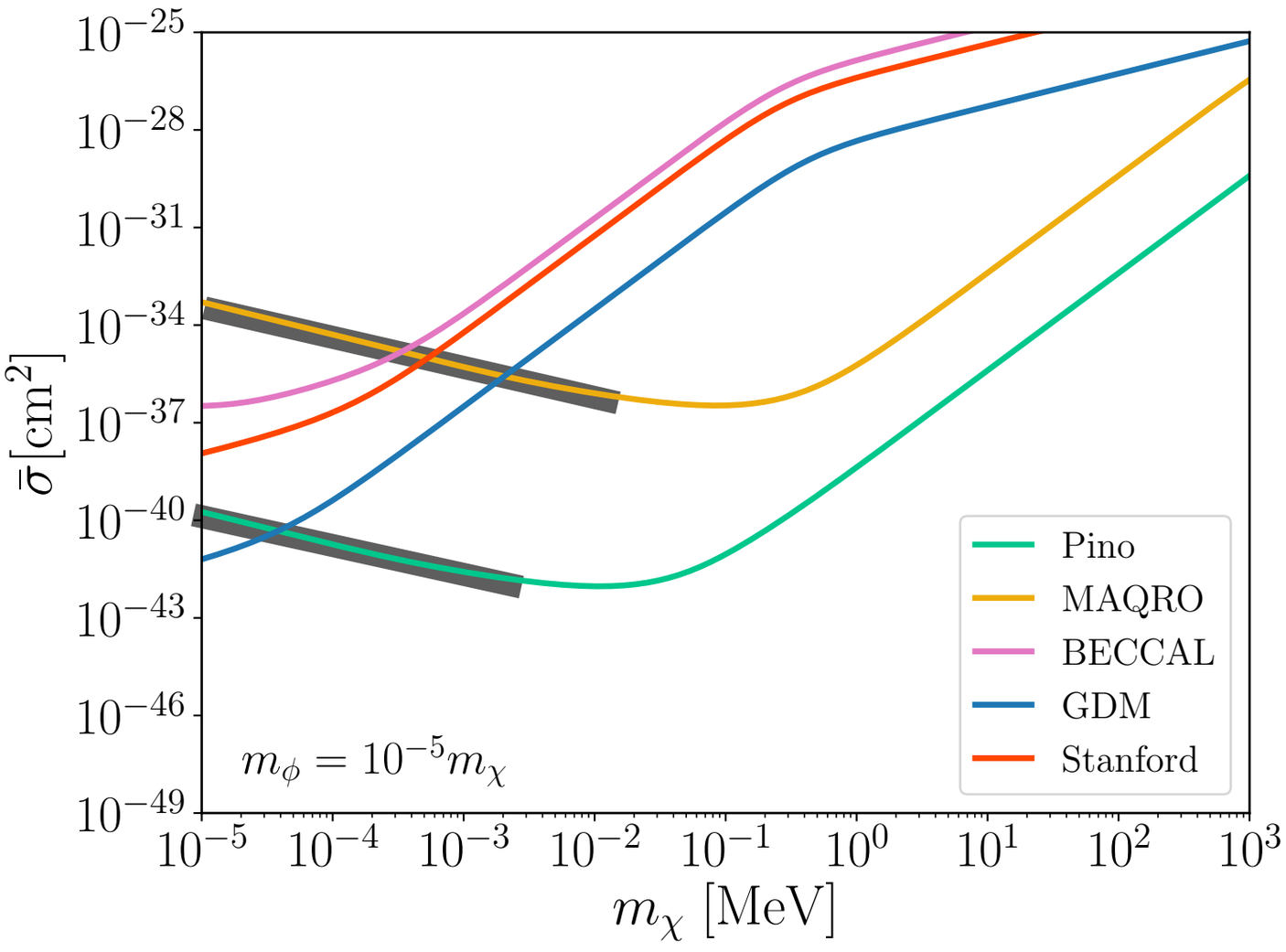
AIs: Results

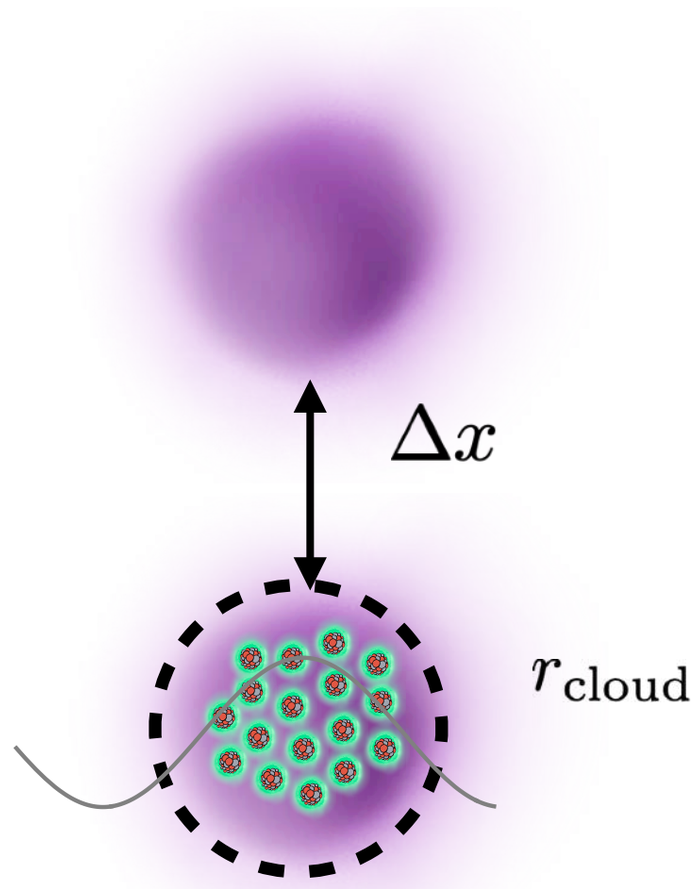
$$s \propto \frac{\bar{\sigma}((m_\chi v_0)^2 + m_\phi^2)^2}{m_\chi^3} \int dq \, \frac{q}{(q^2 + m_\phi^2)^2} N(1 + N F^2(q r_{\rm cloud}))\left(1 - \frac{\sin(q\Delta x)}{q\Delta x}\right)$$

$F^2(q r_{\rm cloud}) \to 0$, $\left(1 - \frac{\sin(q\Delta x)}{q\Delta x}\right) \to 1$

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

2 $m_\chi \to \infty$





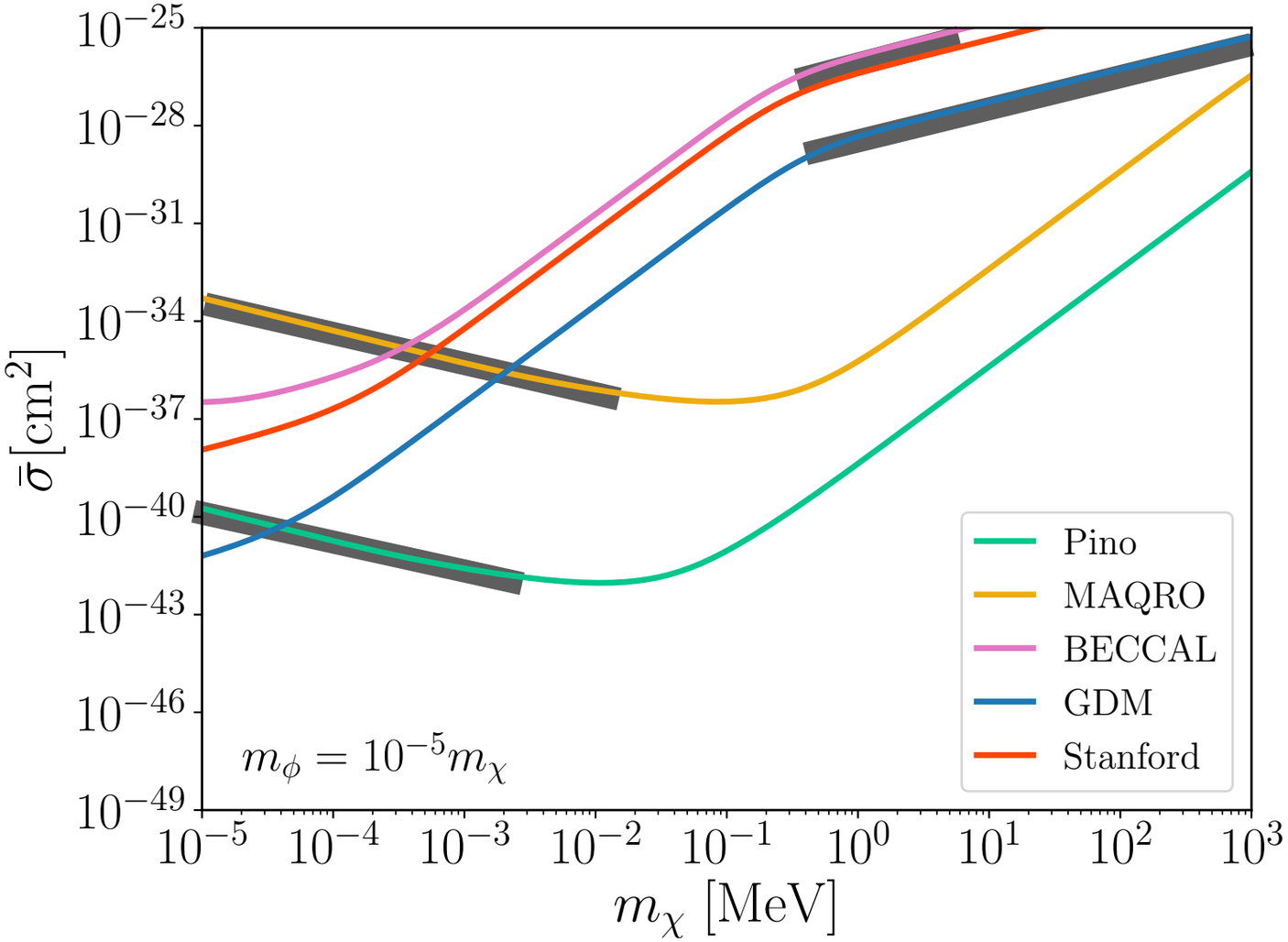
Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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

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



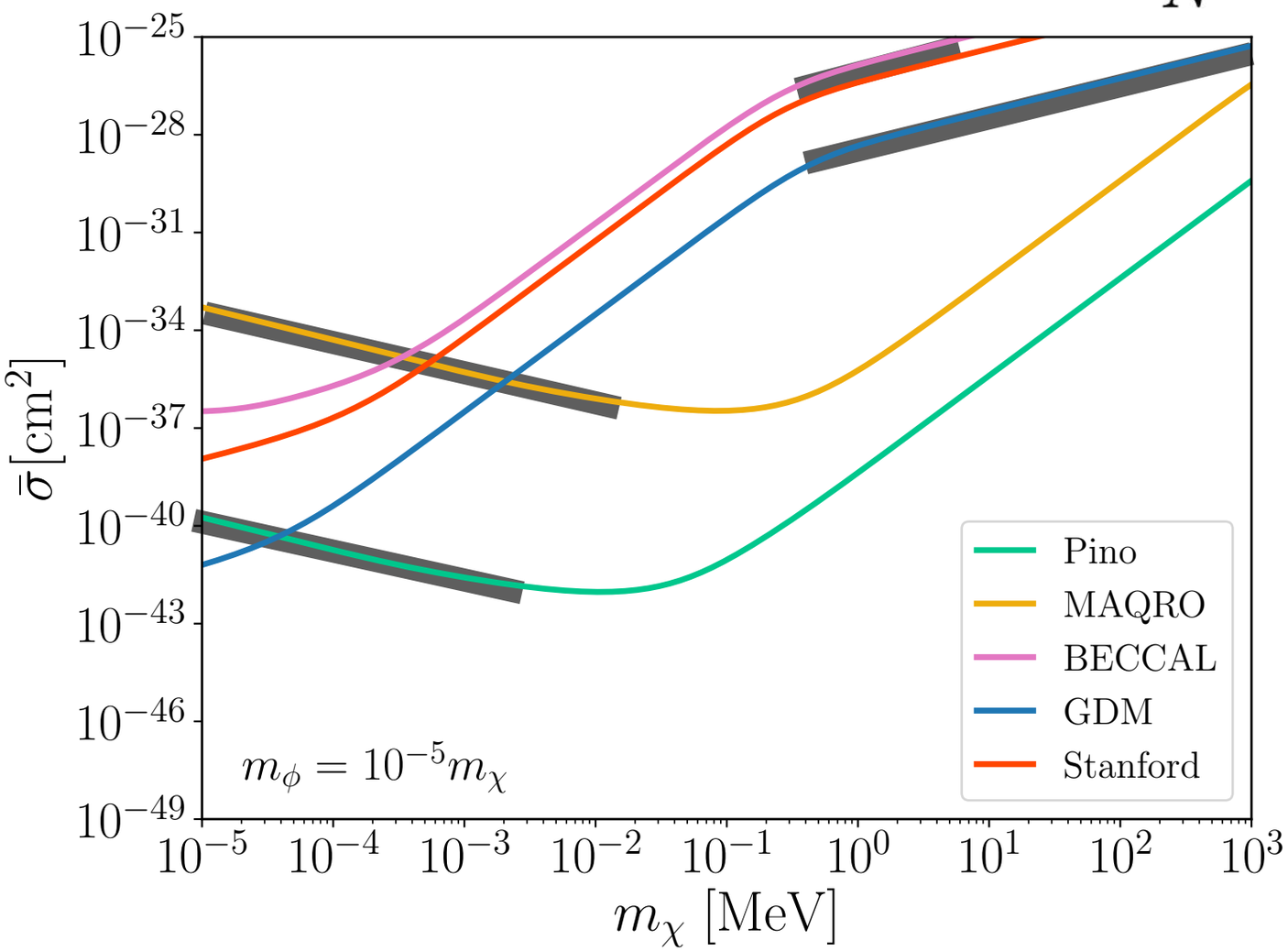
Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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

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



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

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

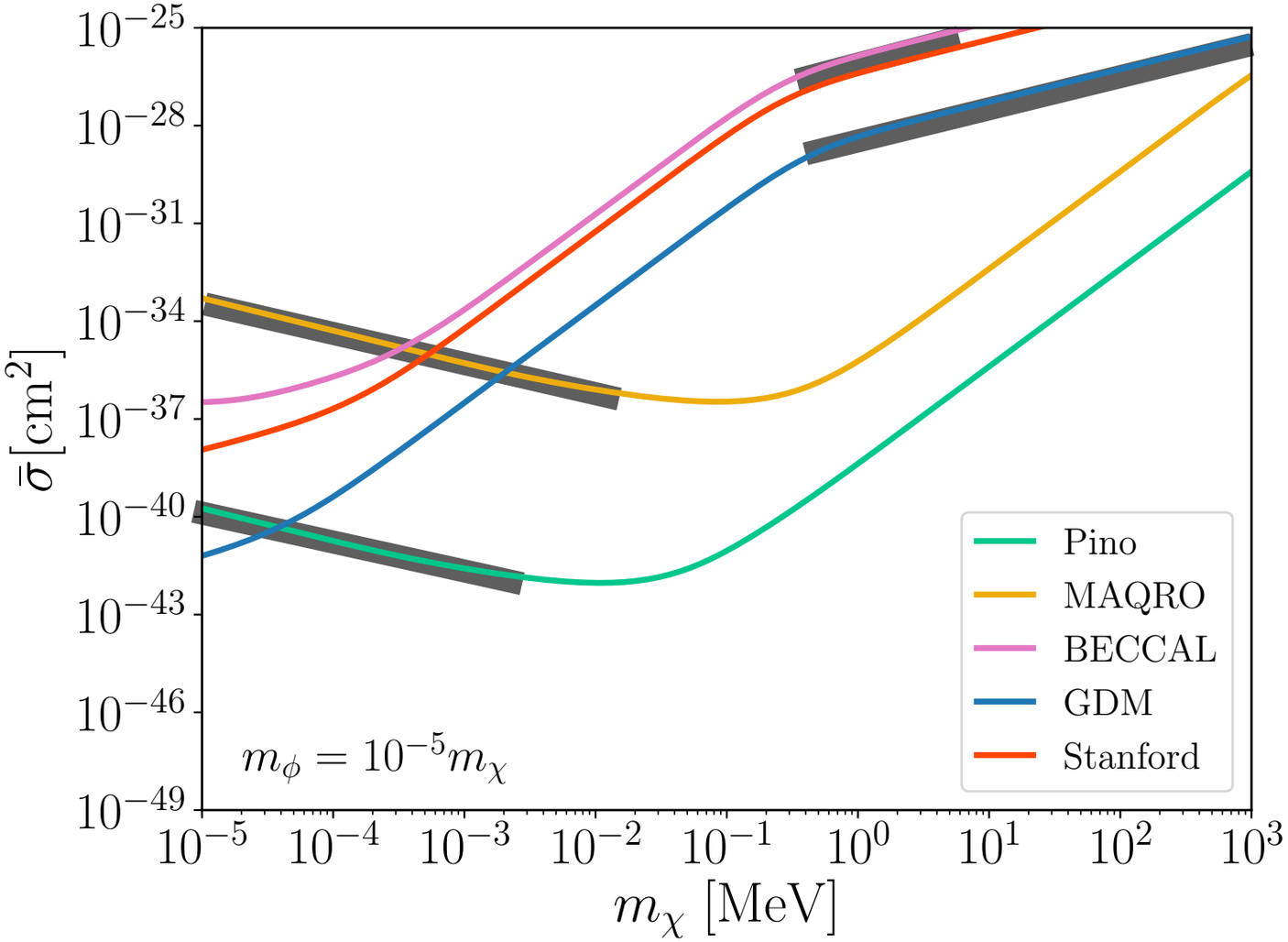
AIs: Results

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

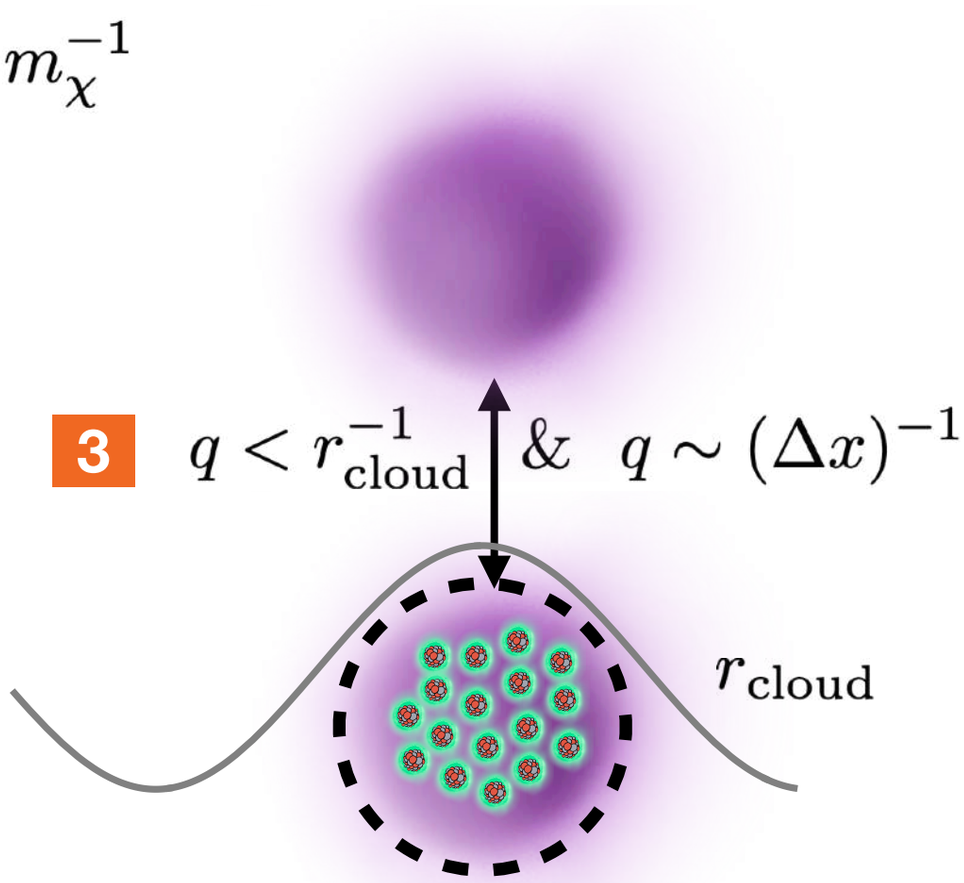
$\cancel{q^2}$ → 1 ; $\cancel{q} r_{\rm cloud}$ → 1

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

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



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



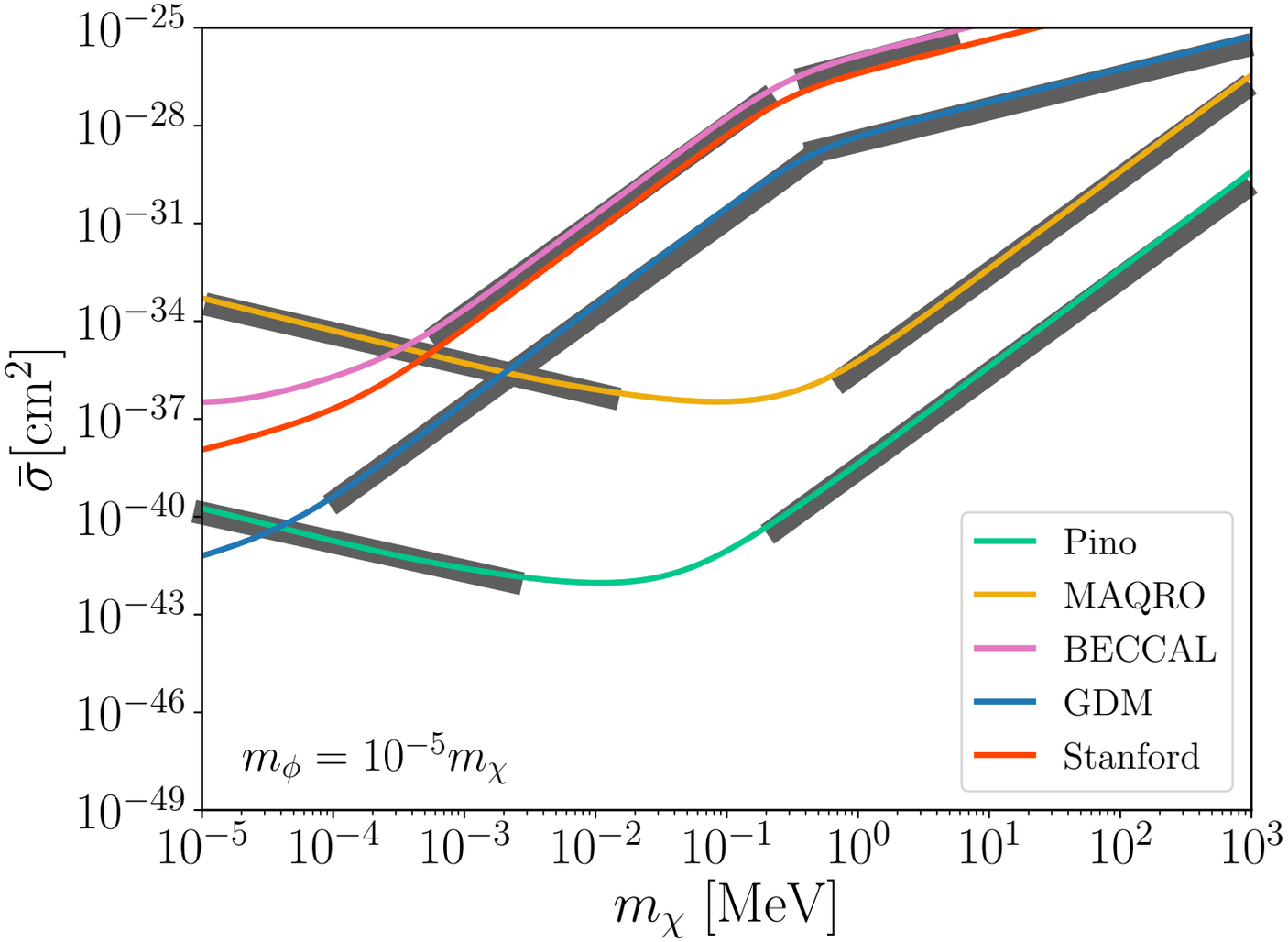
Decoherence, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

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

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



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

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

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

AIs: Results

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

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

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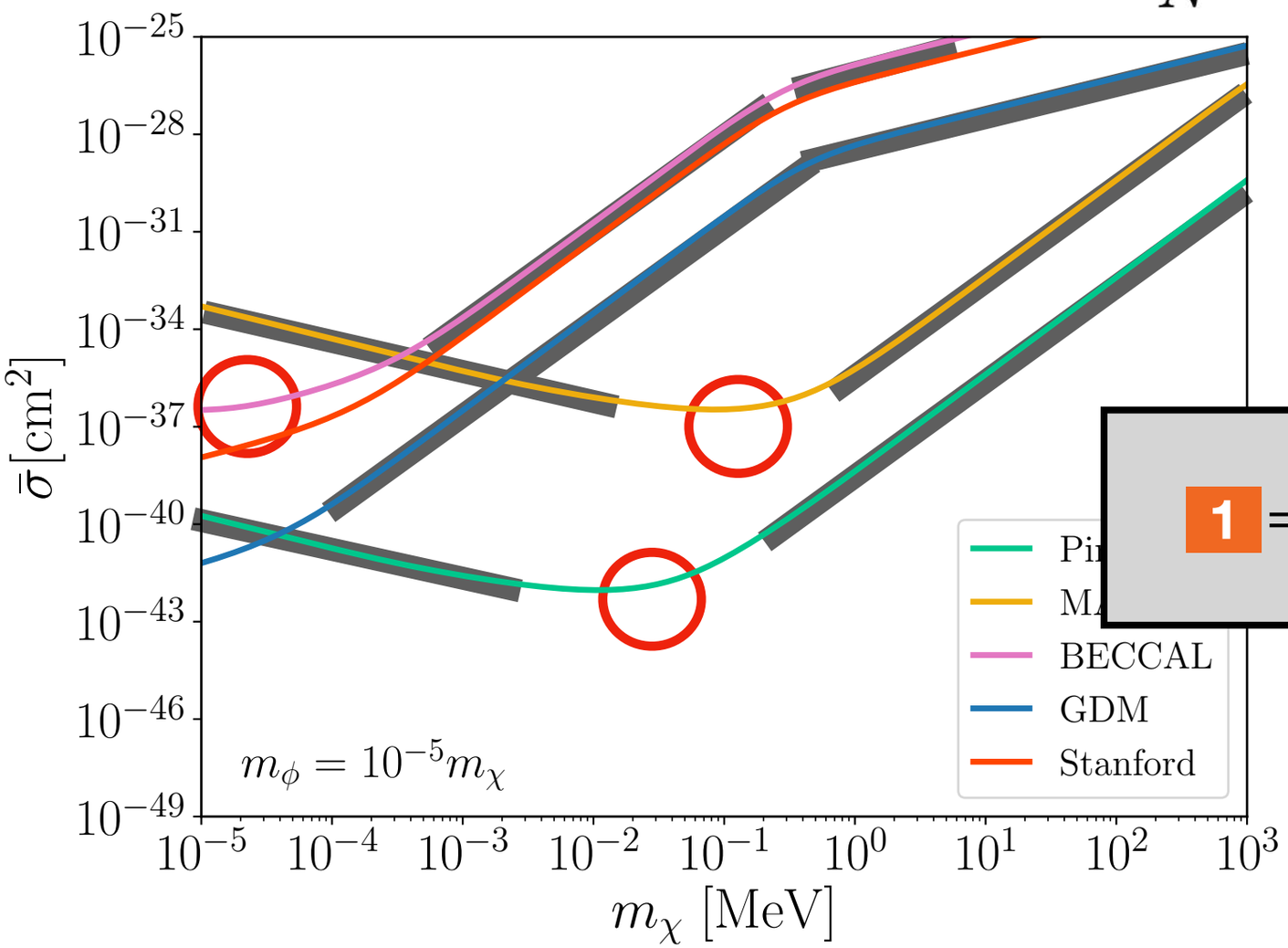


3 $q < r_{\rm cloud}^{-1} \quad \& \quad q \sim (\Delta x)^{-1}$

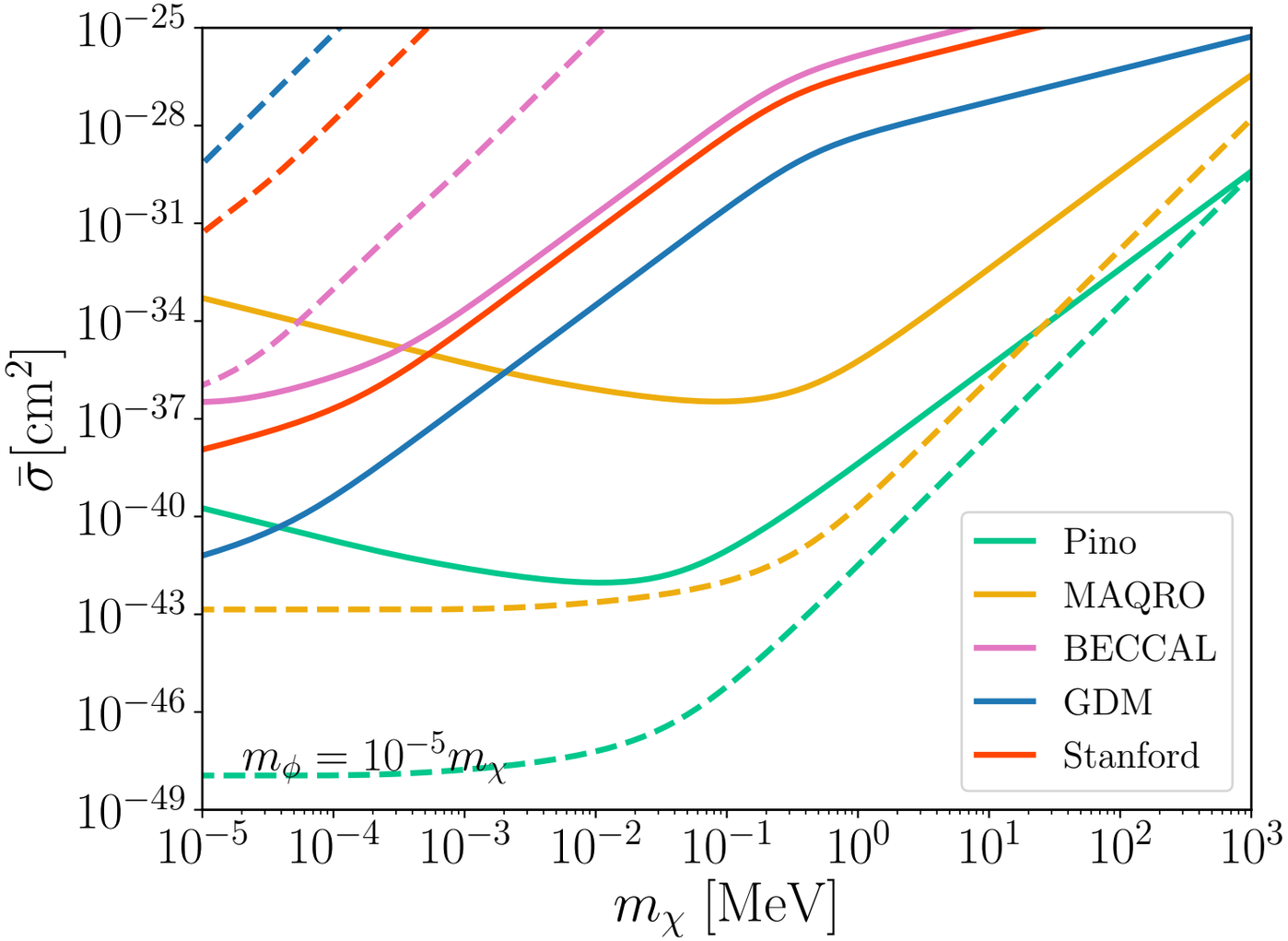
$$\Rightarrow \bar{\sigma} \propto \frac{r_{\rm cloud}^2 R_{\phi\chi}^4}{N^2} m_\chi^3$$

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

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

AIs: Results

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



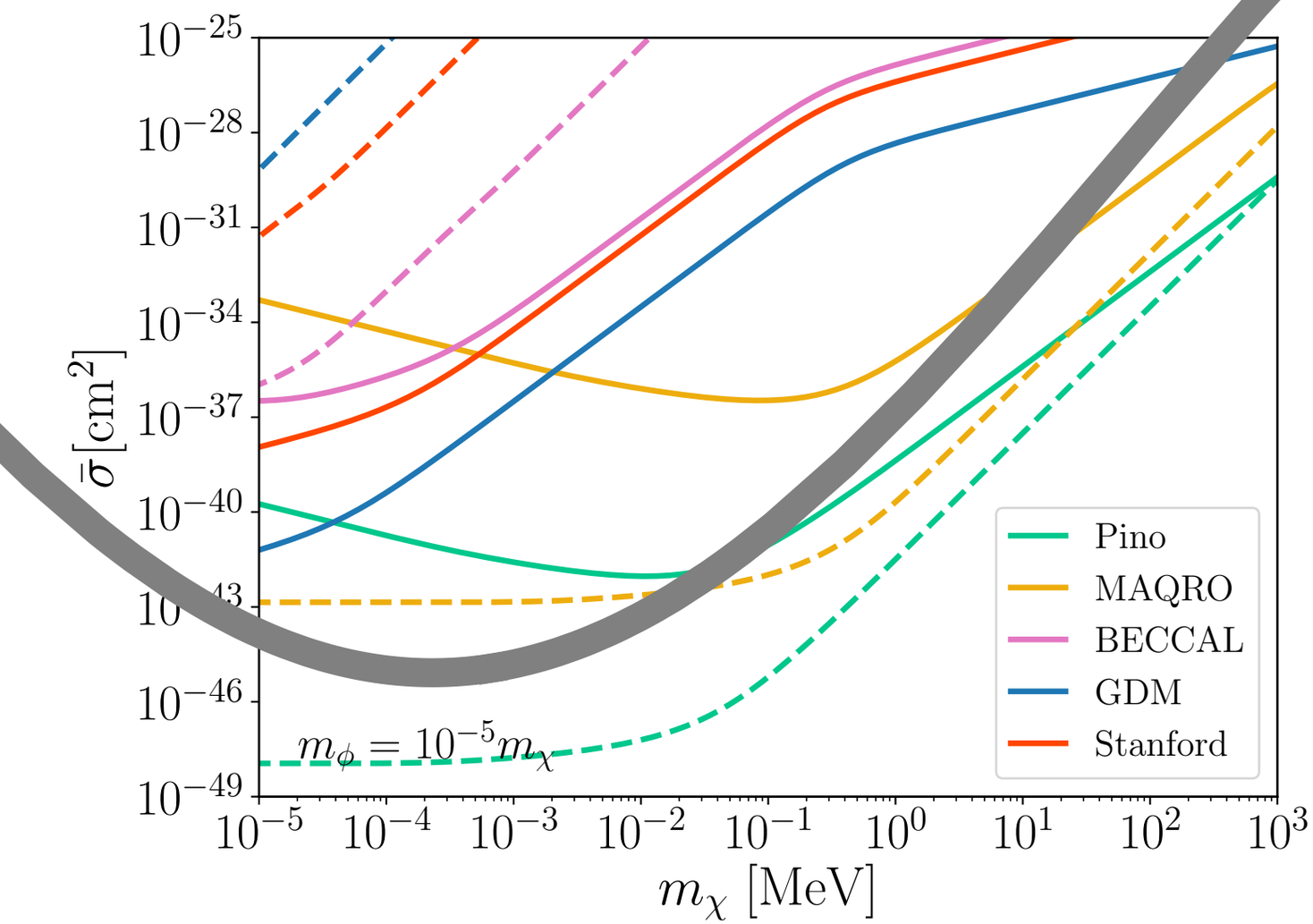
Phase, light $m_\phi = R_{\phi\chi} m_\chi$

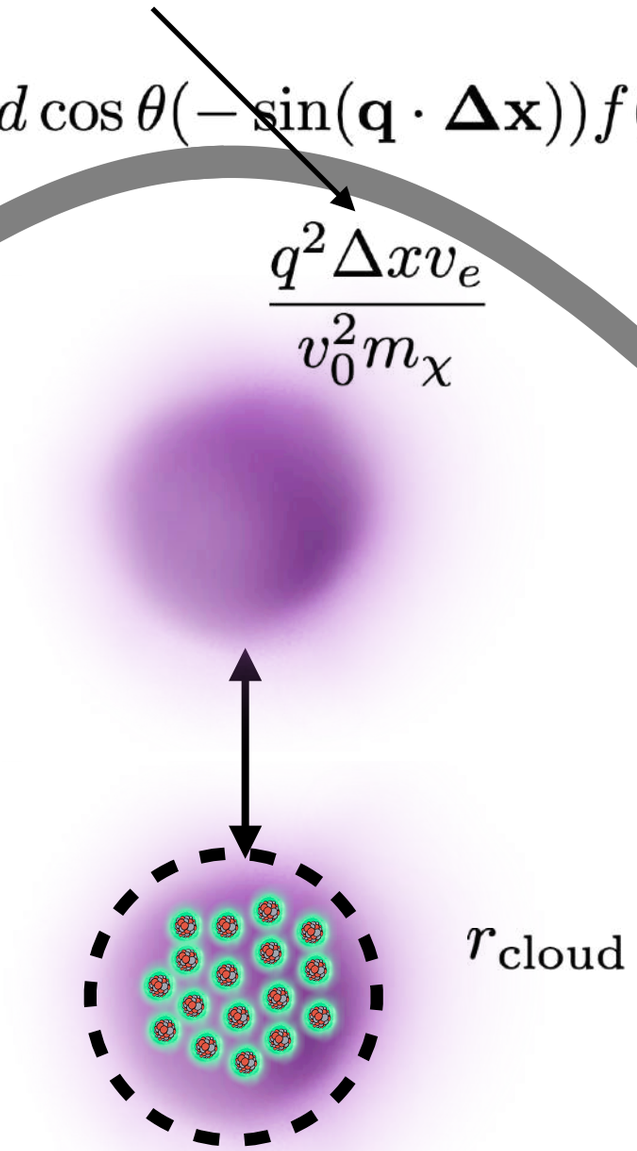
AIs: Results

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

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

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



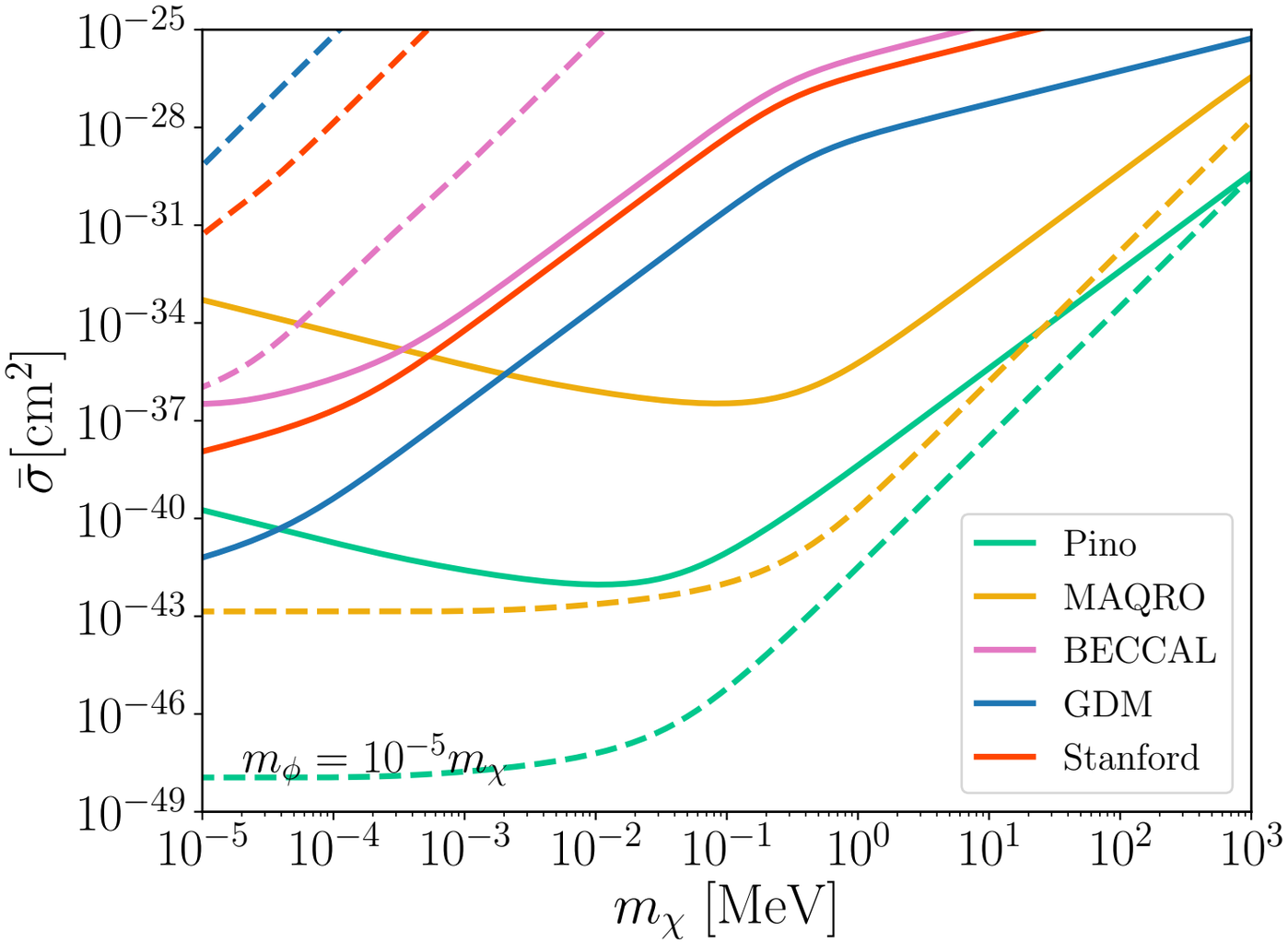


Phase, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

$$s \propto \frac{\bar{\sigma}}{m_\chi^3} \int dq\, q^3 N^2 \frac{\Delta x\, v_e}{v_0^2 m_\chi}$$

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



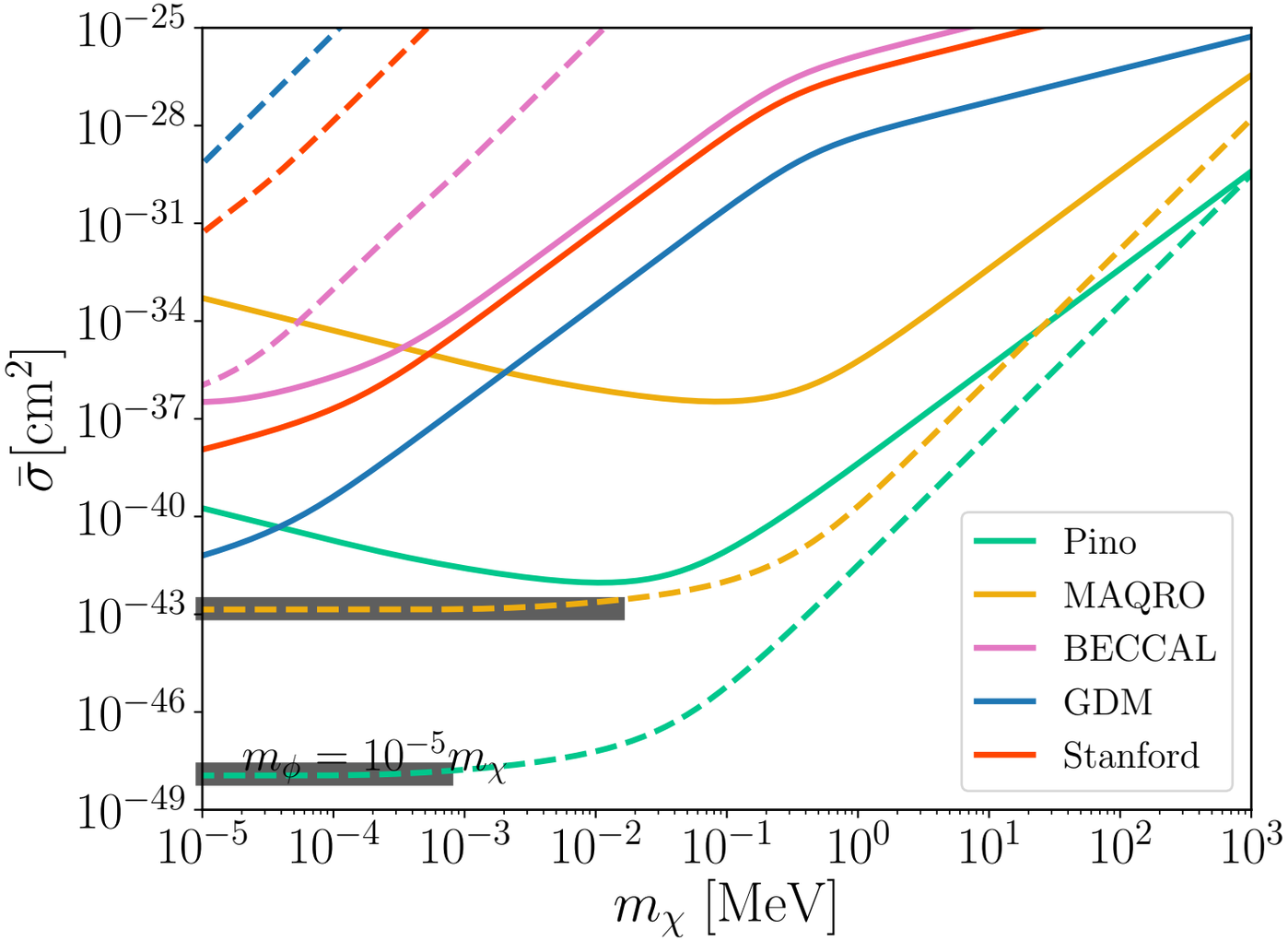
Phase, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

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

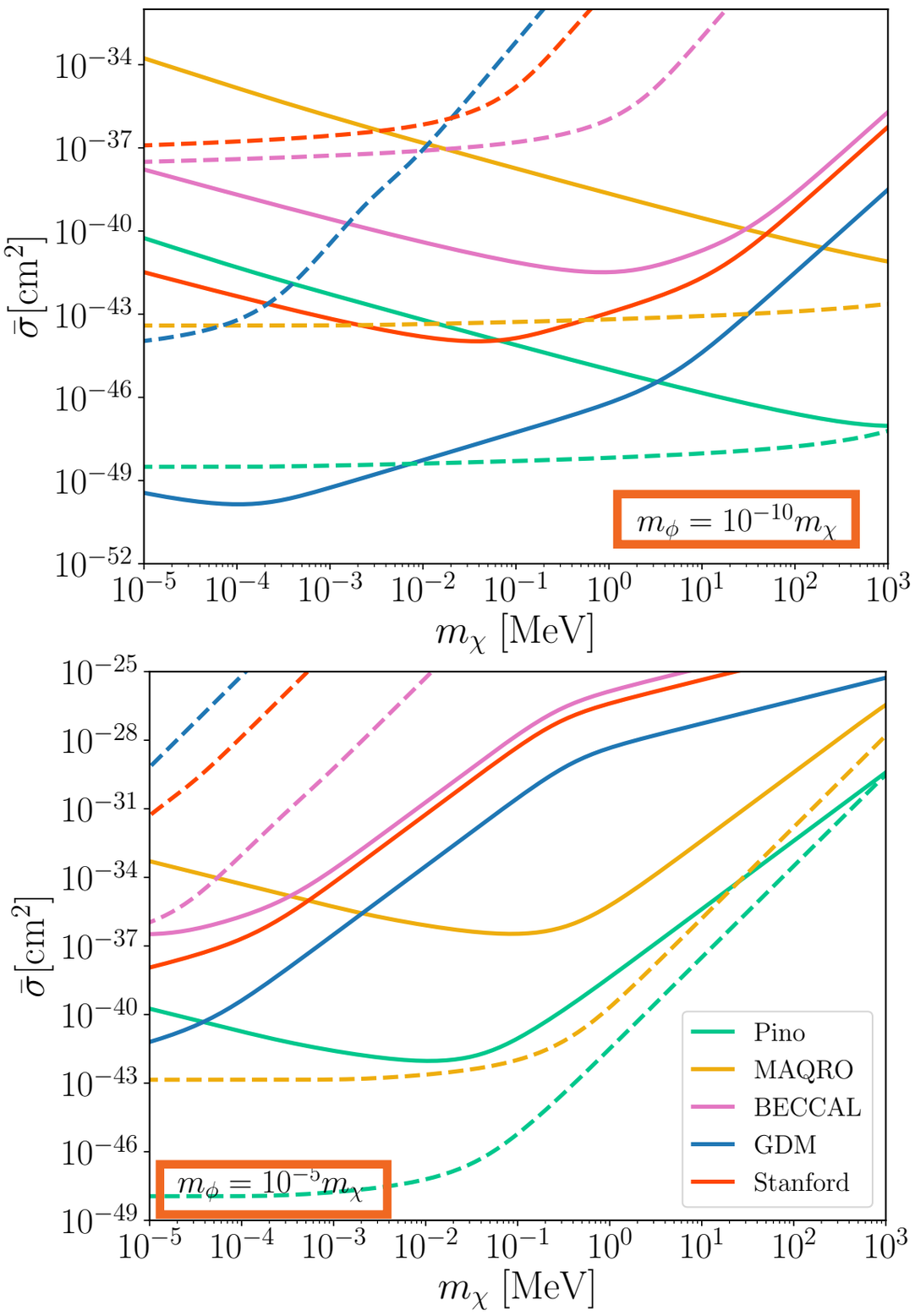
1 $m_\chi \to 0 \quad \Rightarrow \quad q \to 0$

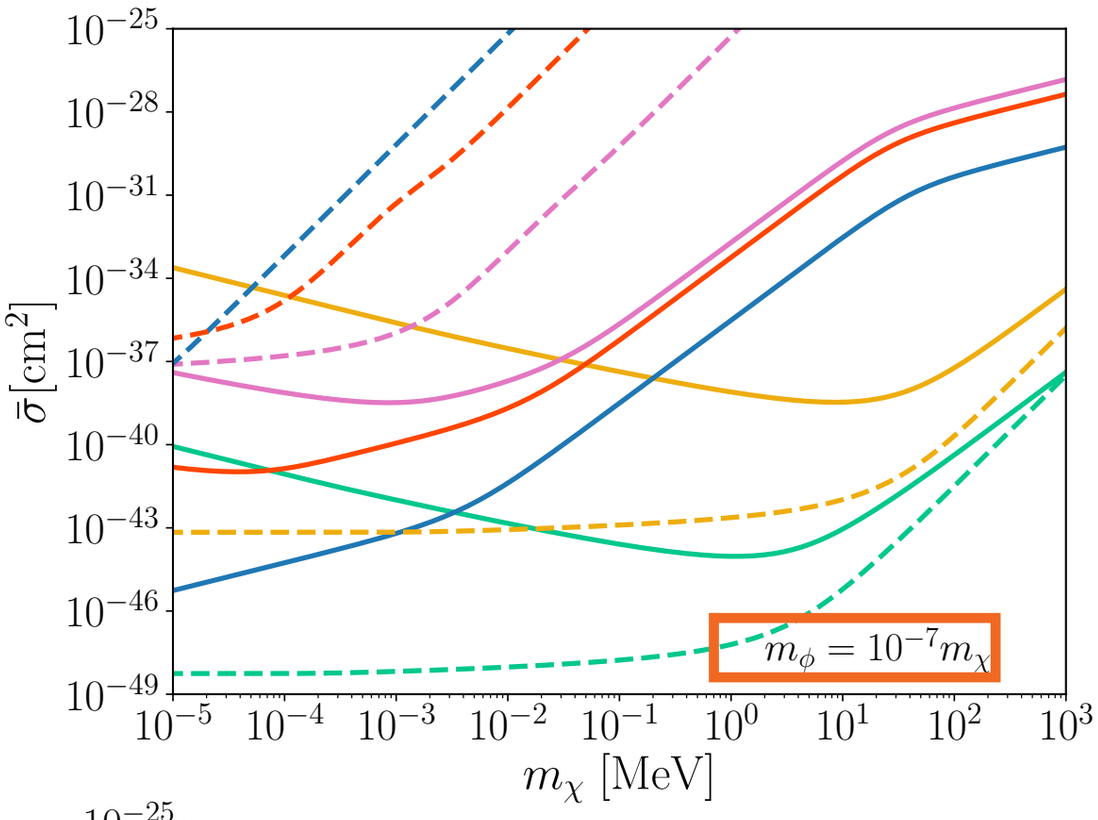
$$\Rightarrow \quad \bar{\sigma} \propto \frac{1}{\Delta x \, N^2}$$

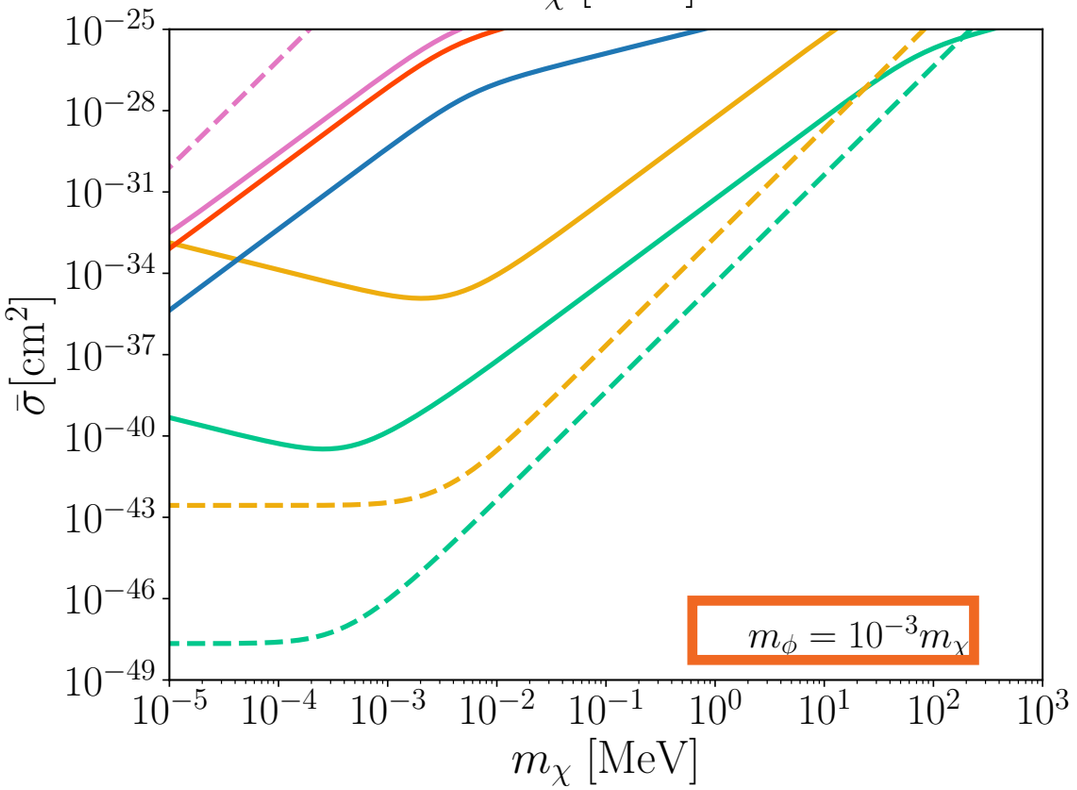


Phase, light $m_\phi = R_{\phi\chi} m_\chi$

AIs: Results

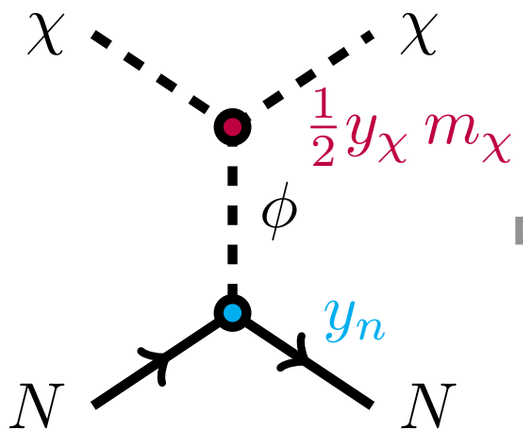

$\bar{\sigma}[\mathrm{cm}^2]$
m_χ [MeV]
$m_\phi = 10^{-10} m_\chi$
$m_\phi = 10^{-5} m_\chi$
Pino
MAQRO
BECCAL
GDM
Stanford


$\bar{\sigma}[\mathrm{cm}^2]$
m_χ [MeV]
$m_\phi = 10^{-7} m_\chi$


$\bar{\sigma}[\mathrm{cm}^2]$
m_χ [MeV]
$m_\phi = 10^{-3} m_\chi$

AIs: Constraints

[Knapen, Lin, Zurek, 2017]

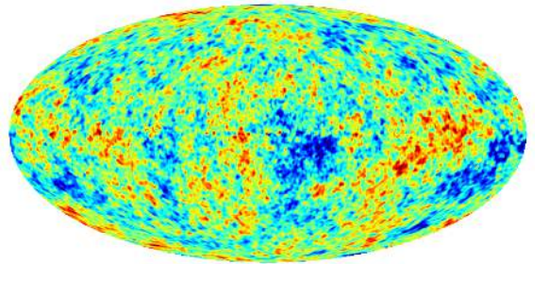


$$\bar{\sigma} = \frac{y_\chi^2 \, y_n^2}{4\pi} \frac{\mu^2}{(m_\chi^2 v_0^2 + m_\phi^2)^2}$$

Terrestial

Astrophysical

Cosmological

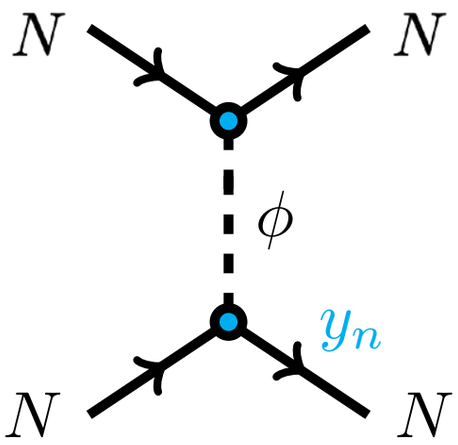


AIs: Constraints

[Knapen, Lin, Zurek, 2017]

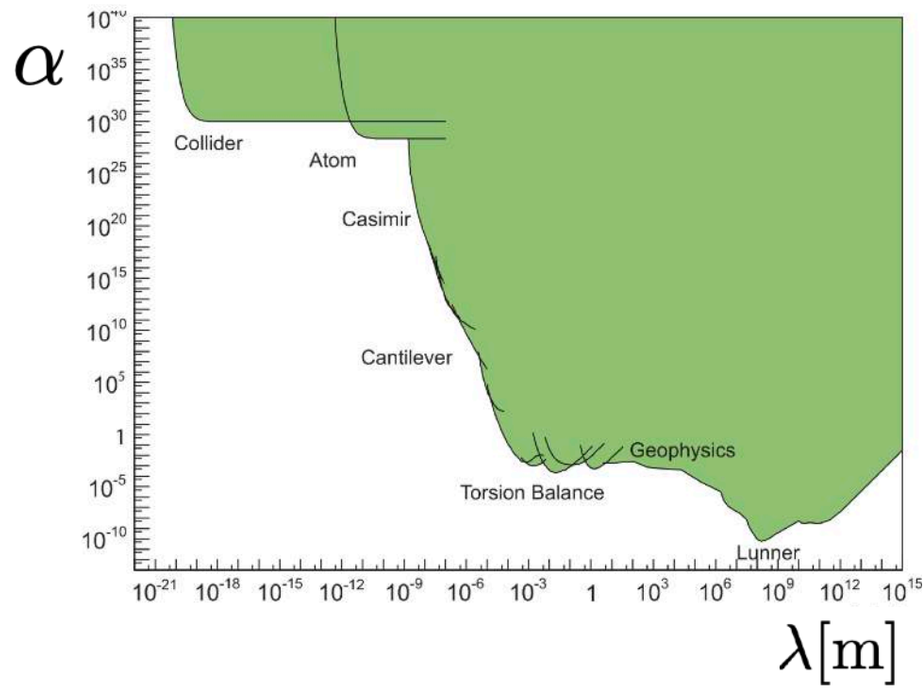
$$V(r) = -G_N \frac{m_N^2}{r}(1 + \alpha e^{-m_\phi r})$$

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



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

[Murata, Tanaka, 2014]



Terrestial

Collider

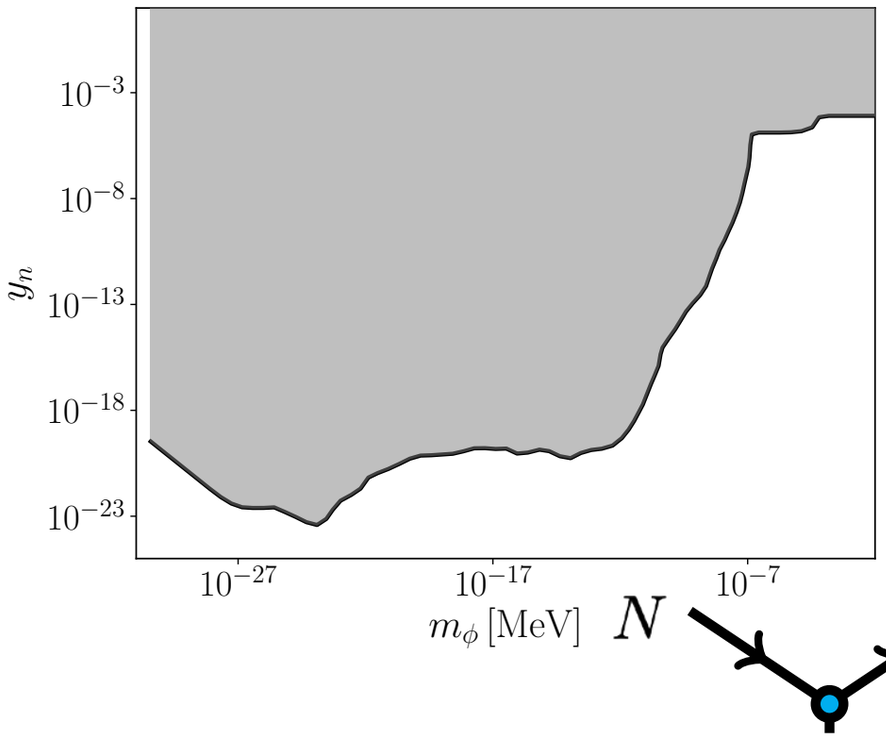
5th force

Astrophysical

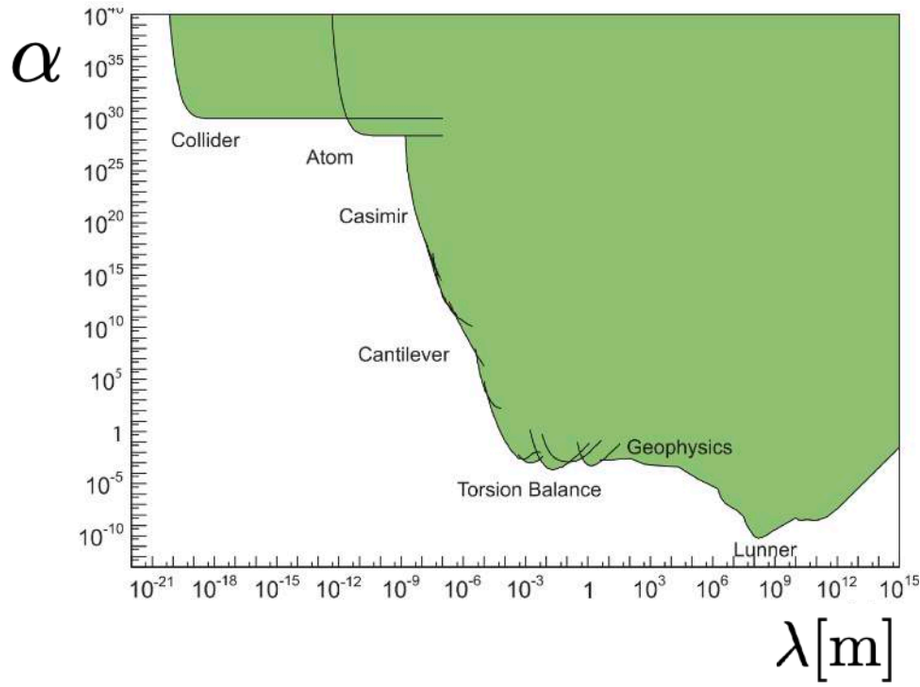
Cosmological

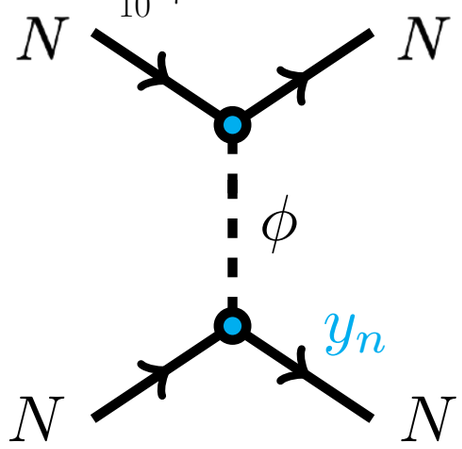
AIs: Constraints

[Knapen, Lin, Zurek, 2017]



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





$$V(r) = -\frac{y_n^2}{4\pi}\frac{1}{r}e^{-m_\phi r}$$ [Murata, Tanaka, 2014]

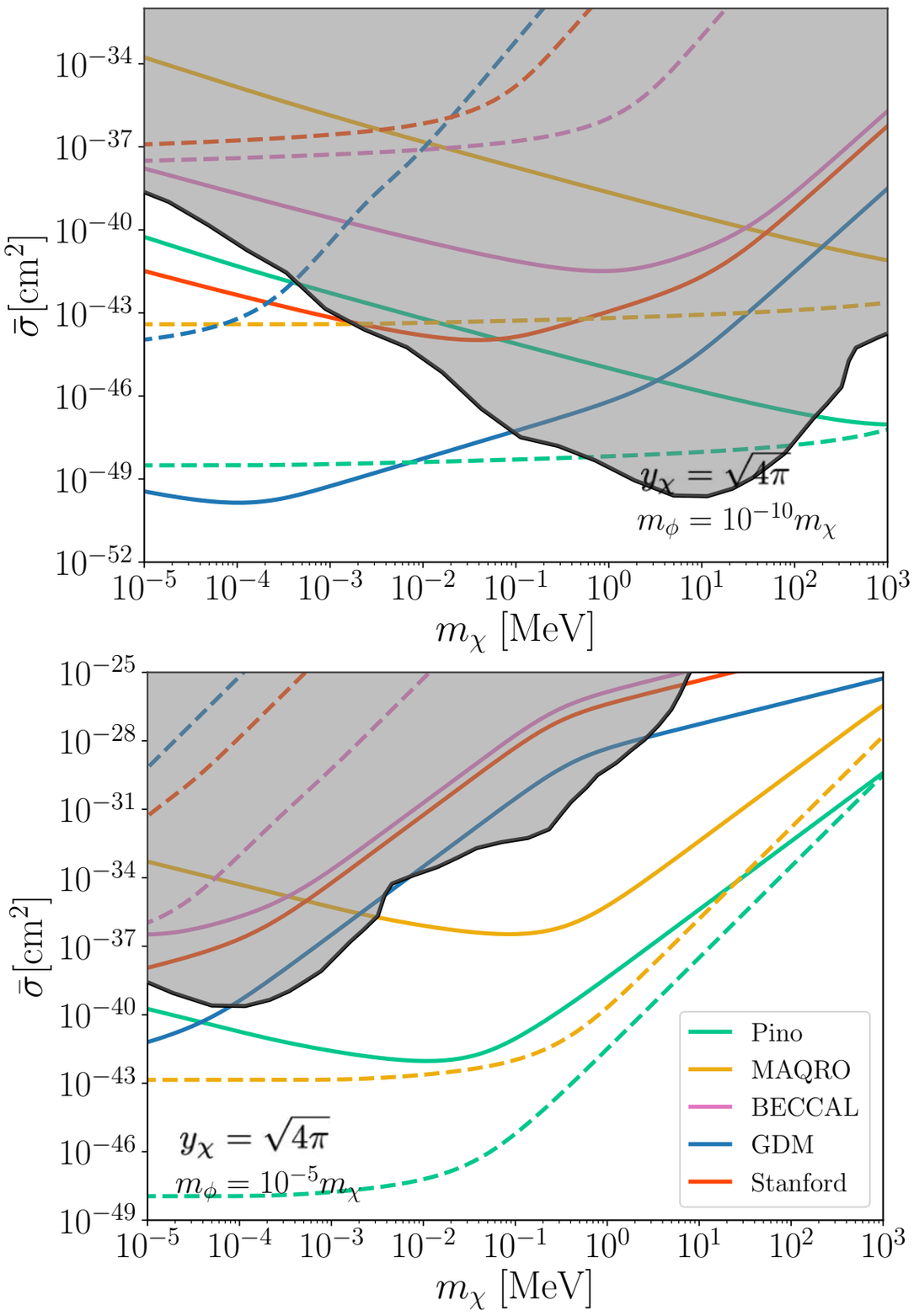
Terrestial

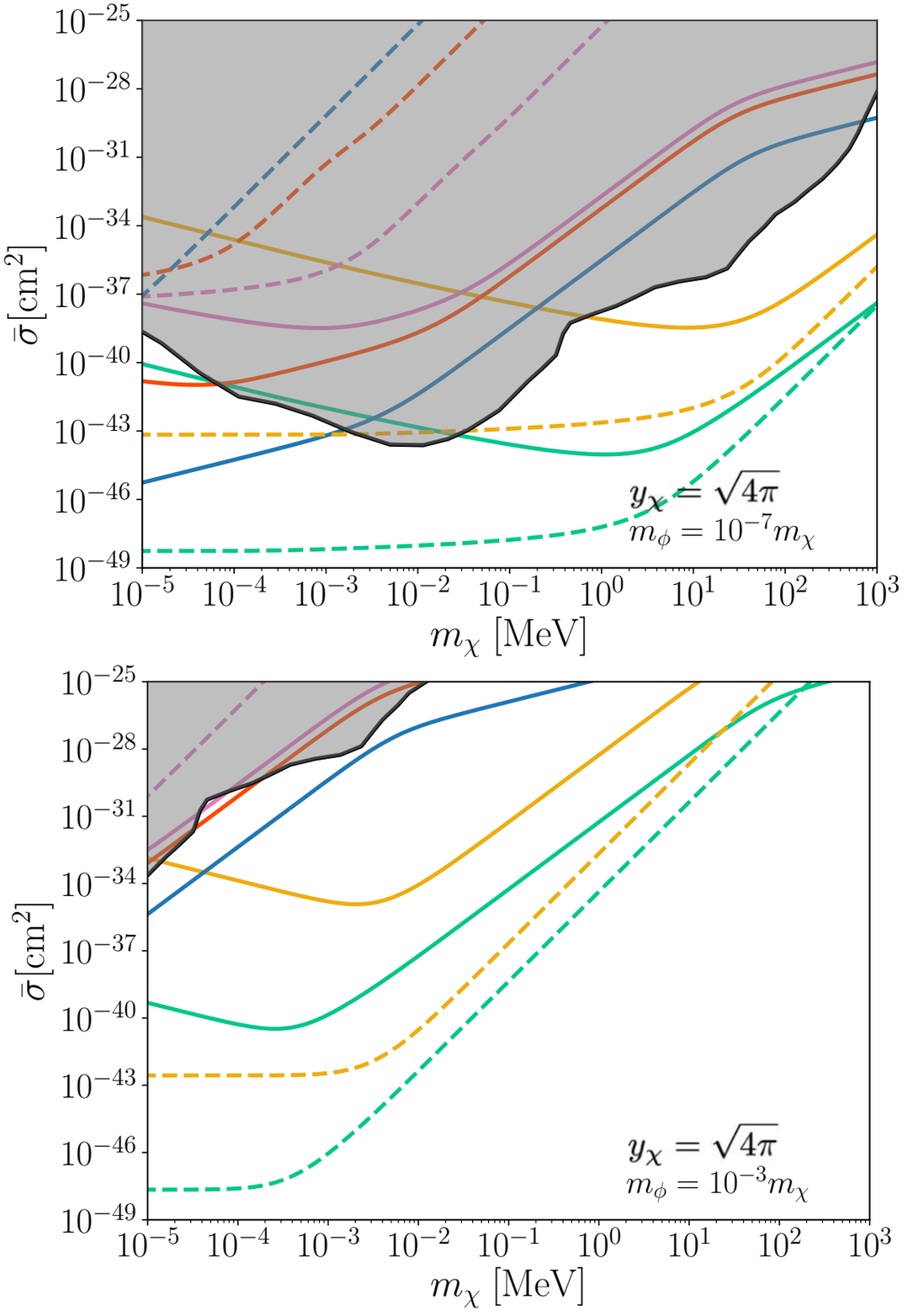
- Collider
- 5th force

Astrophysical

Cosmological

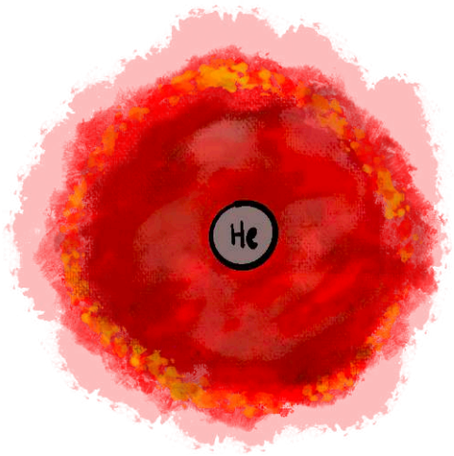
AIs: Constraints





AIs: Constraints

[Knapen, Lin, Zurek, 2017]



RG and HB stars

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

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

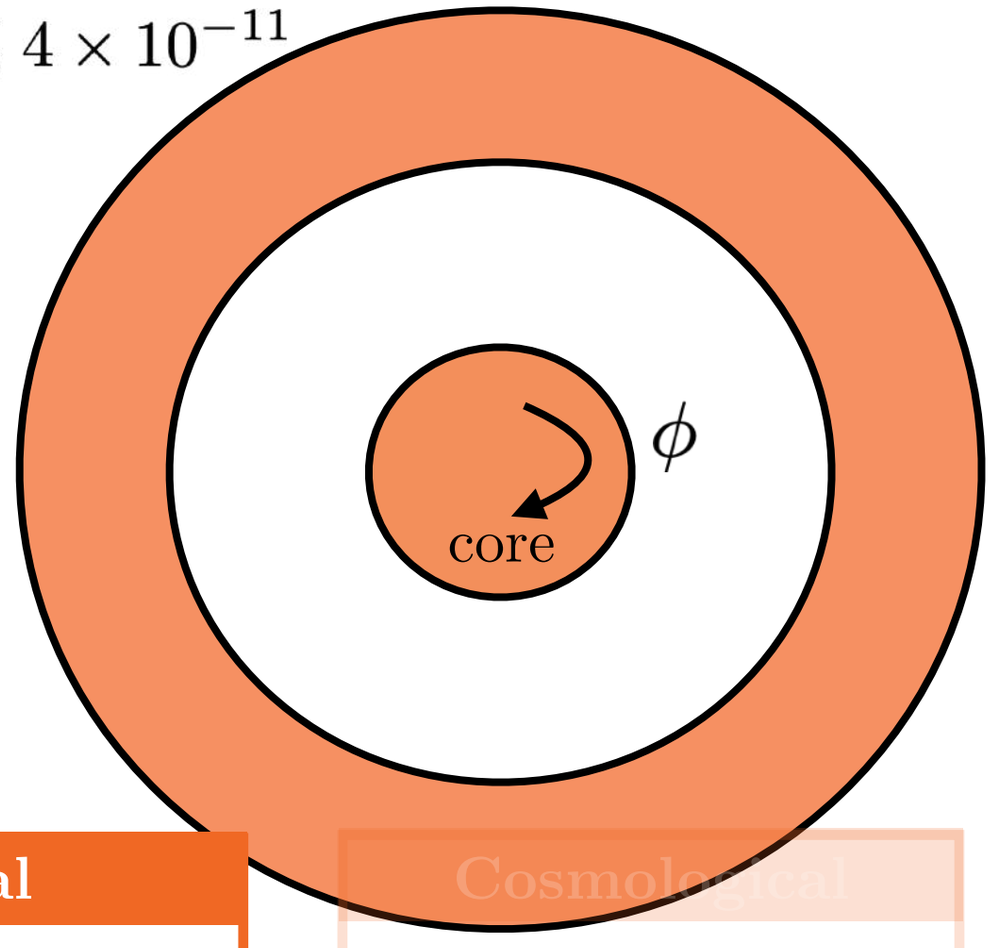
SN1987A

$T = 30$ MeV

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

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

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

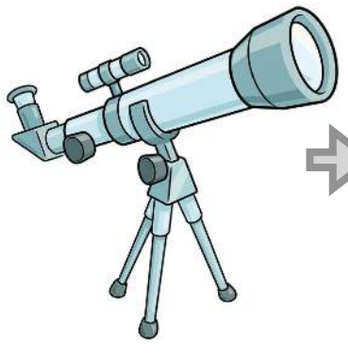


Terrestial

⇨ Collider

⇨ 5th force

Astrophysical

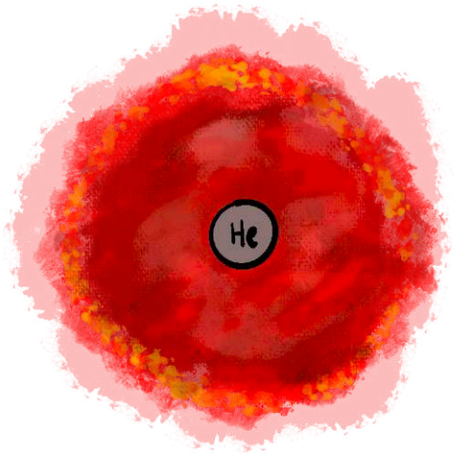


⇨ Stellar emission

Cosmological

AIs: Constraints

[Knapen, Lin, Zurek, 2017]

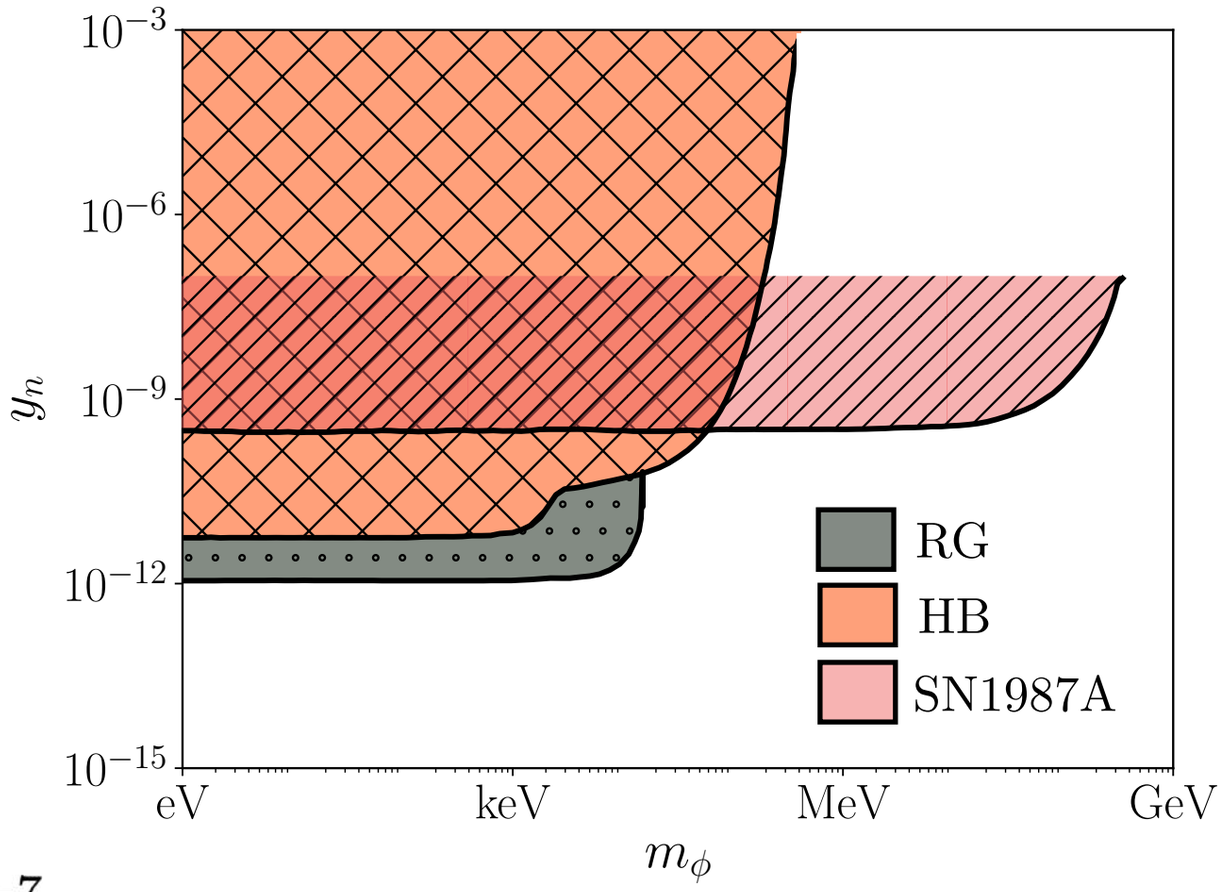


RG and HB stars

$$m_\phi < T \sim 10 \text{ keV}$$

$$\epsilon \lesssim 10 \text{ erg/g/s}$$

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



SN1987A

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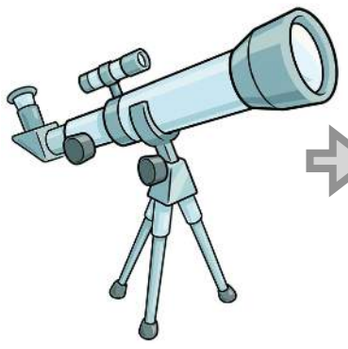
Terrestial

⇨ Collider

⇨ 5th force

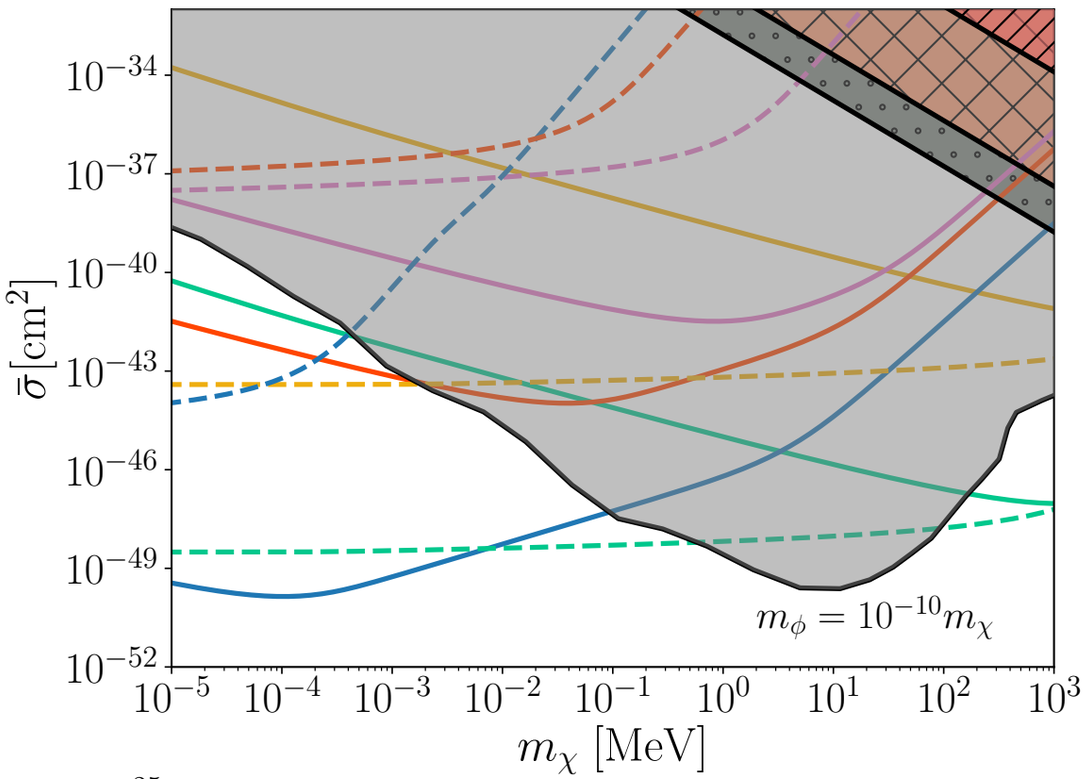
Astrophysical

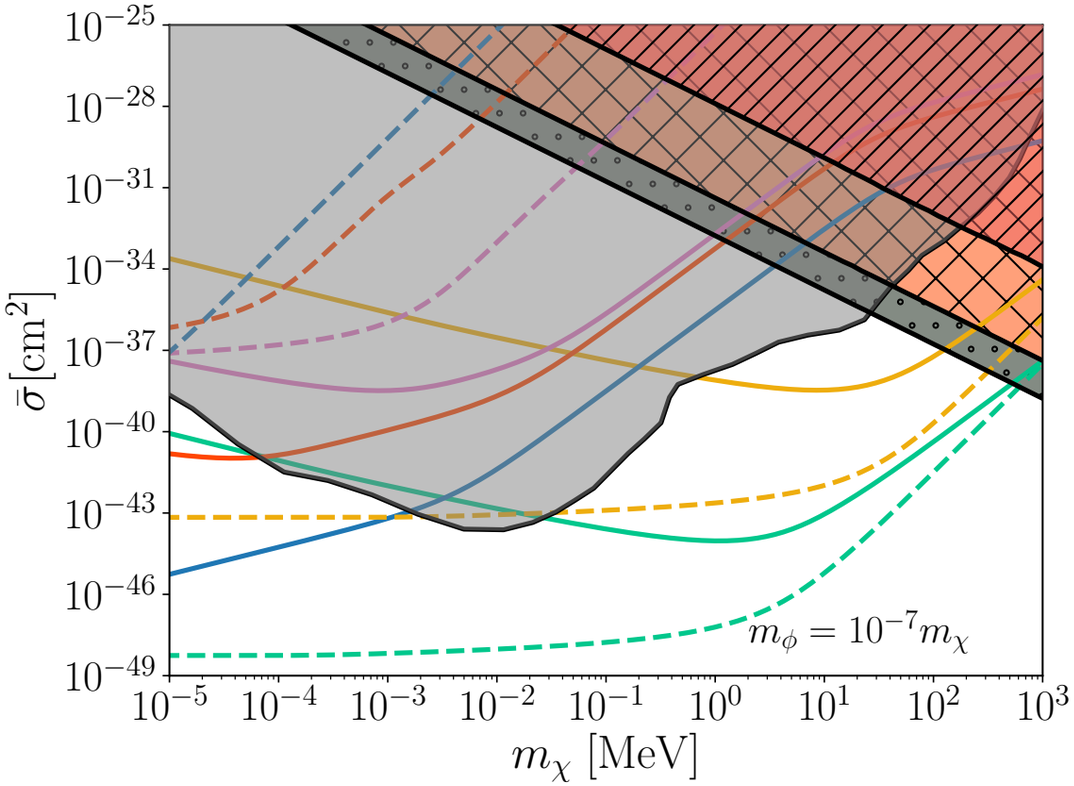


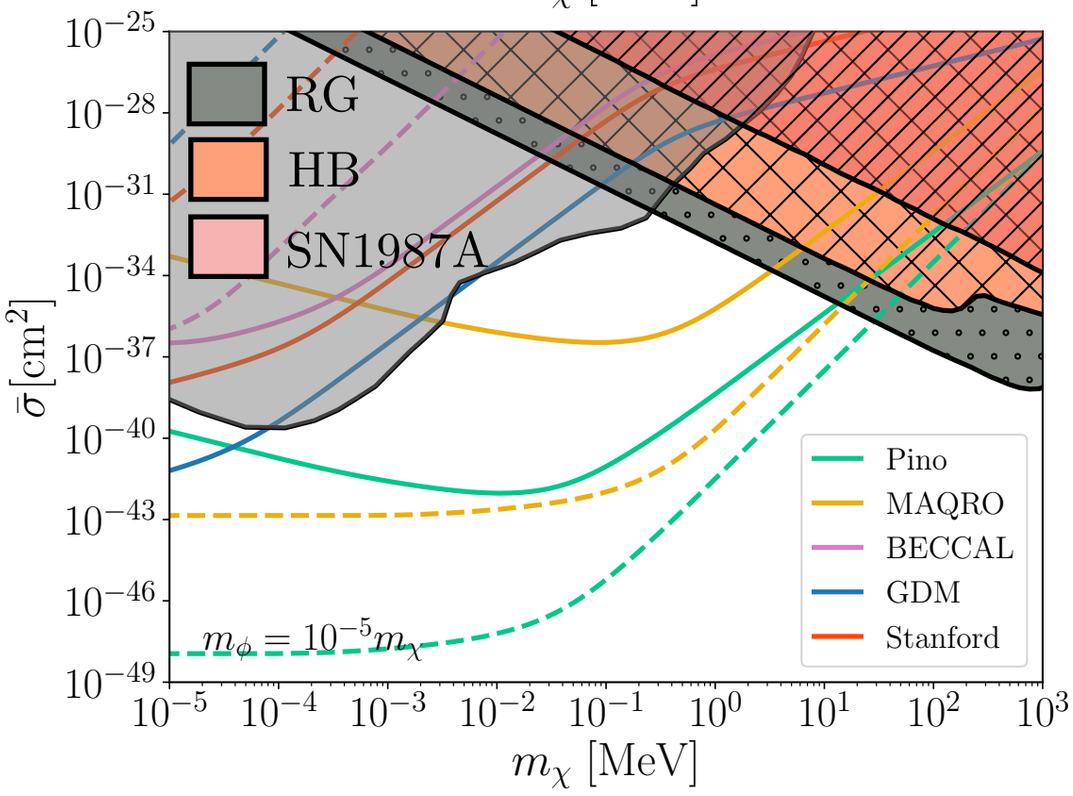
⇨ Stellar emission

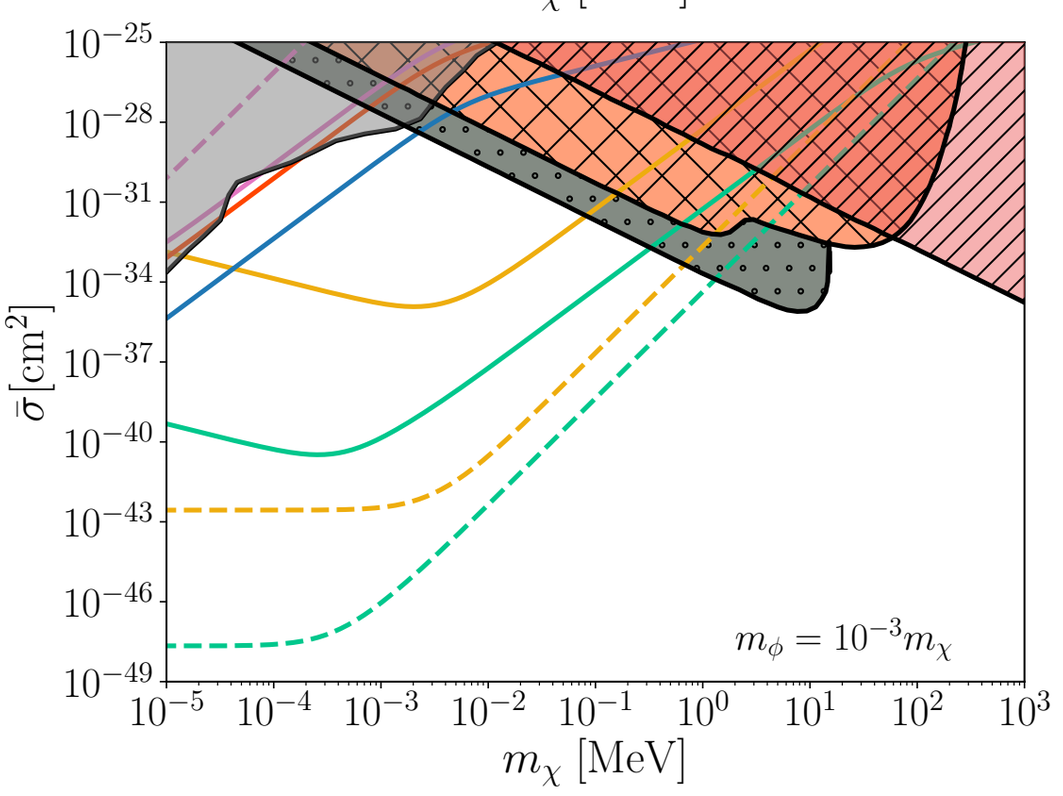
Cosmological

AIs: Constraints



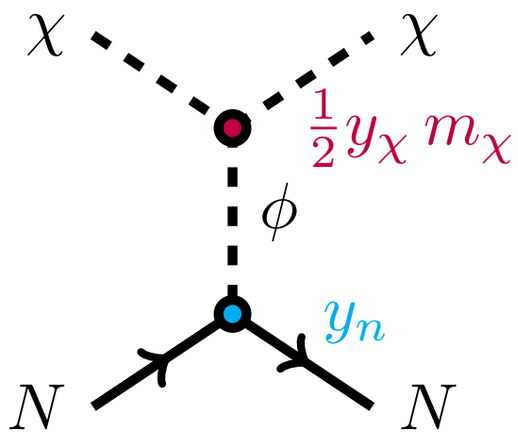






AIs: Constraints

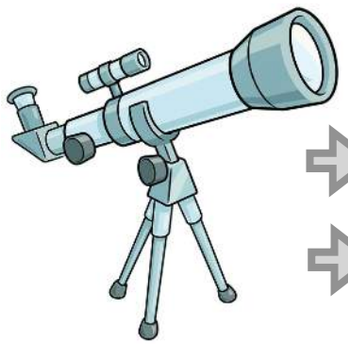
[Knapen, Lin, Zurek, 2017]



Terrestial

- Collider
- 5th force

Astrophysical

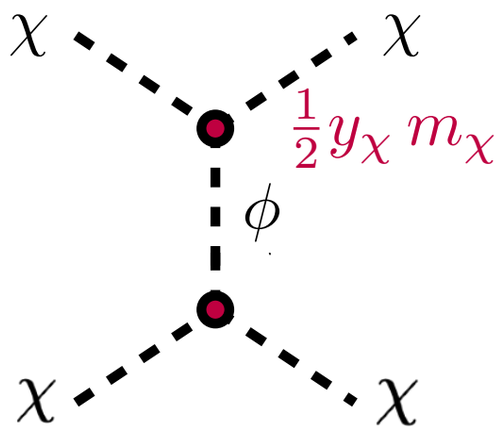


- Stellar emission
- DMSI

Cosmological

AIs: Constraints

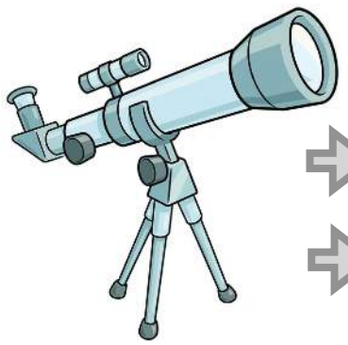
[Knapen, Lin, Zurek, 2017]



Terrestial

- Collider
- 5th force

Astrophysical



- Stellar emission
- DMSI

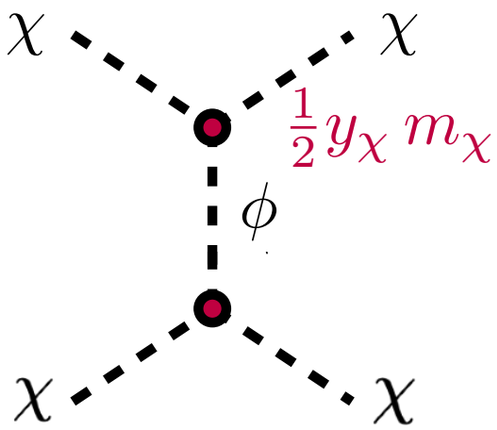
Cosmological

AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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

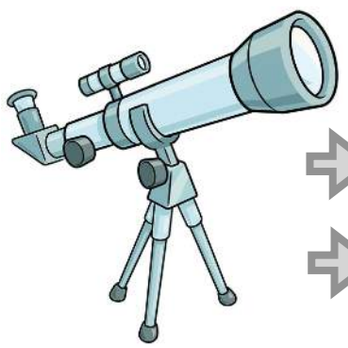
$$\frac{y_\chi^2}{4\pi} < 6 \times 10^{-10} \left(\frac{m_\chi}{1\ \mathrm{MeV}}\right)^{3/2}$$



Terrestial

- Collider
- 5th force

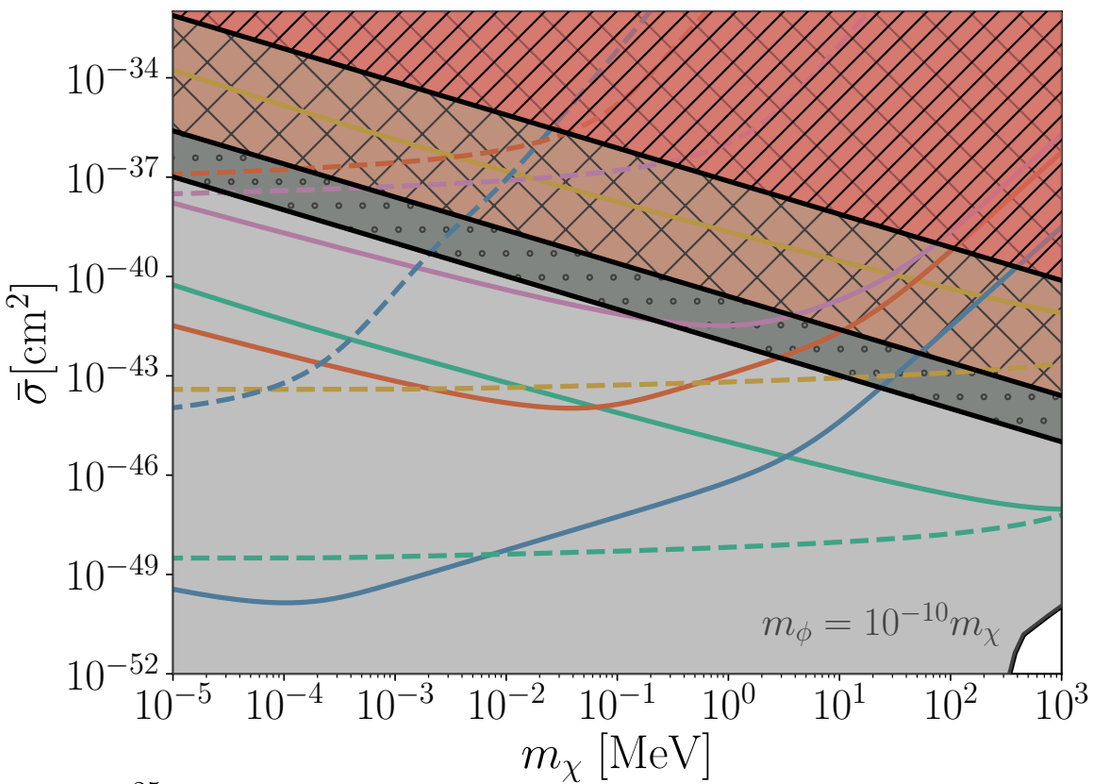
Astrophysical

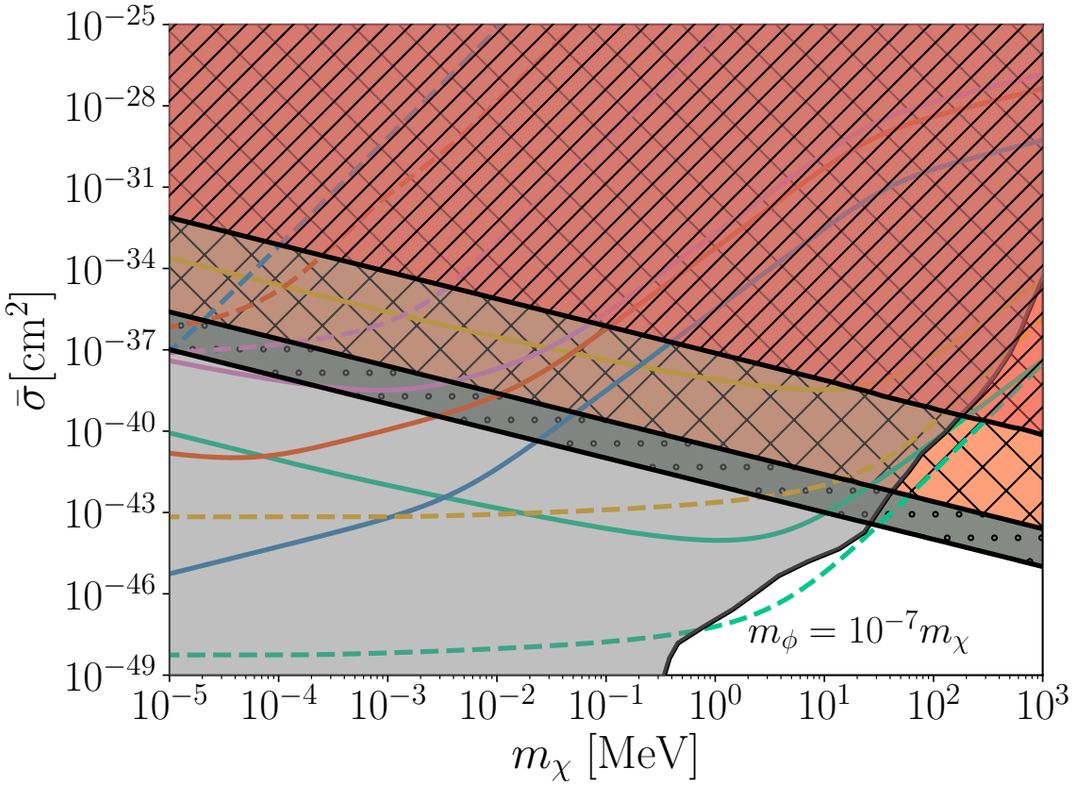


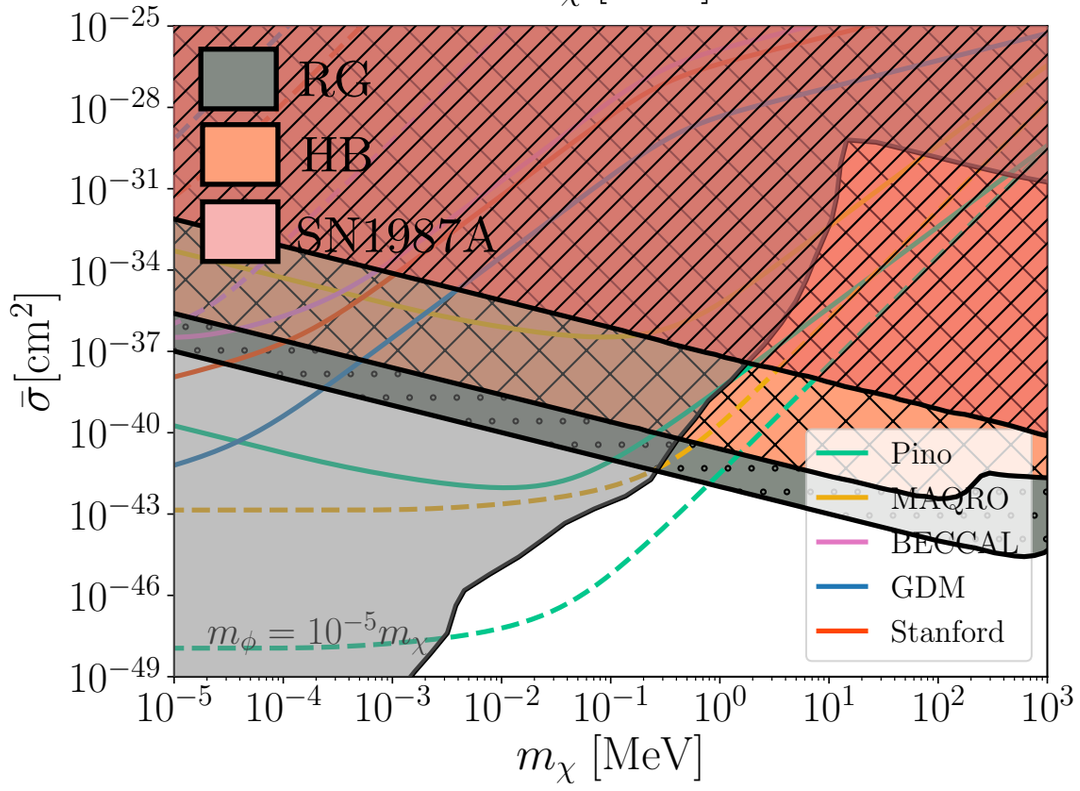
- Stellar emission
- DMSI

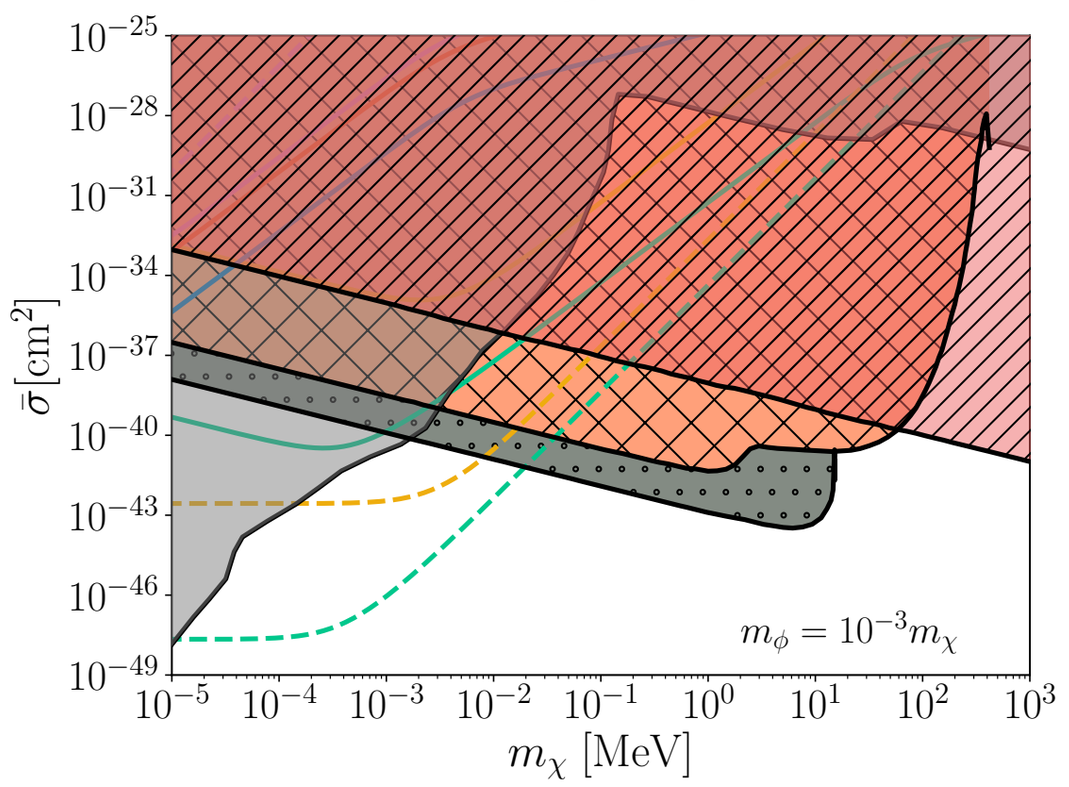
Cosmological

AIs: Constraints

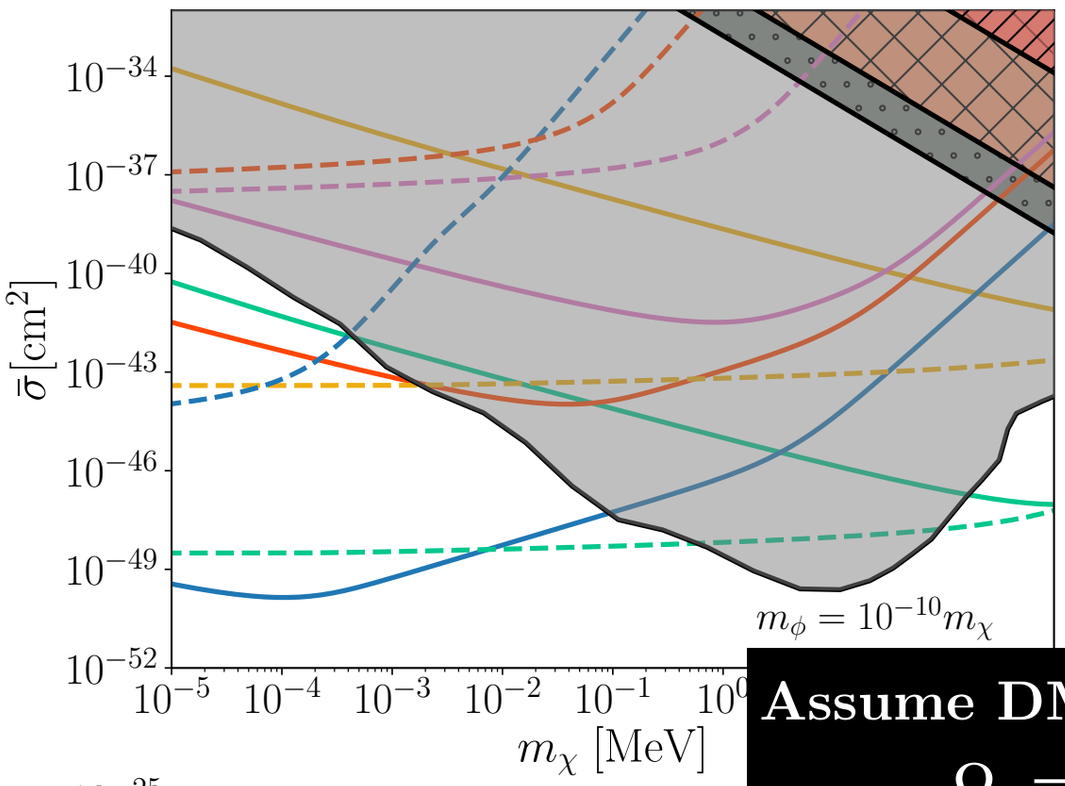


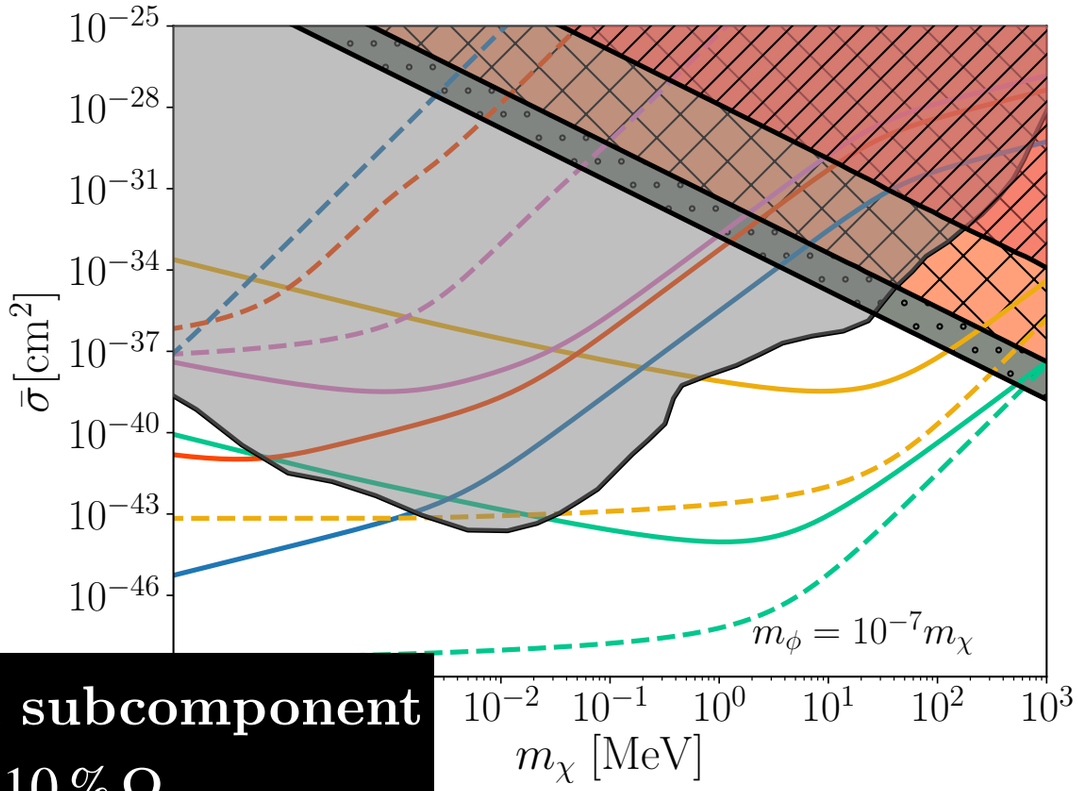






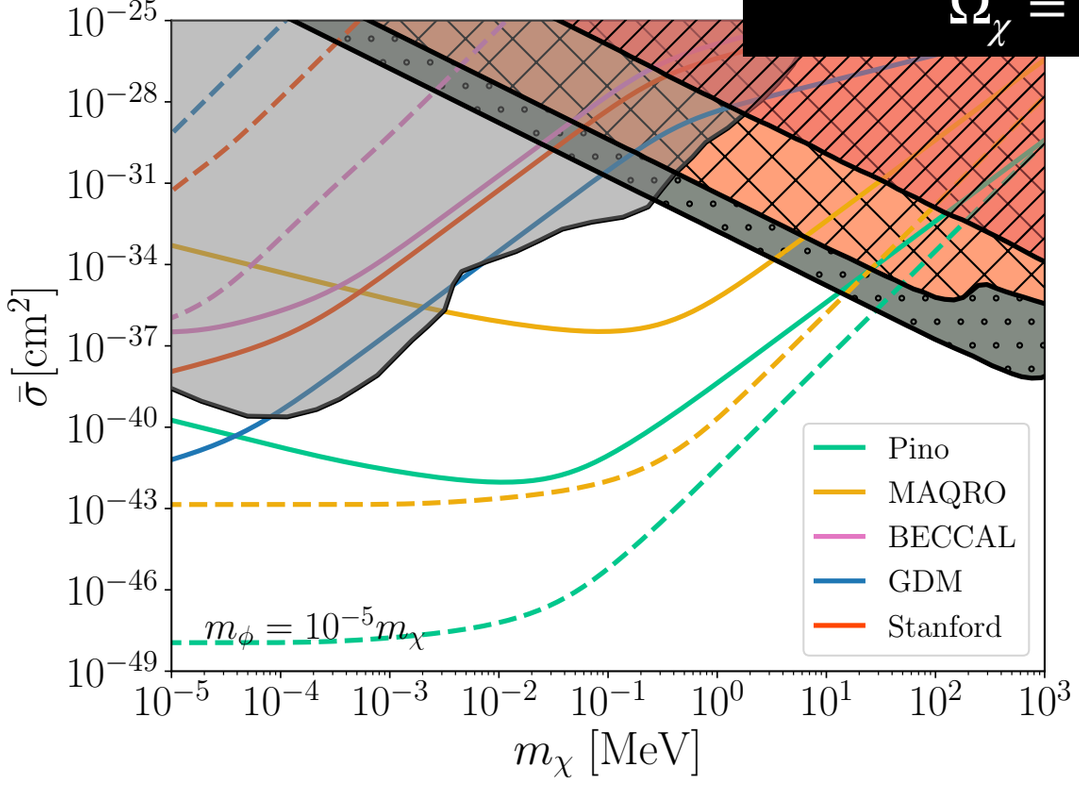
AIs: Constraints

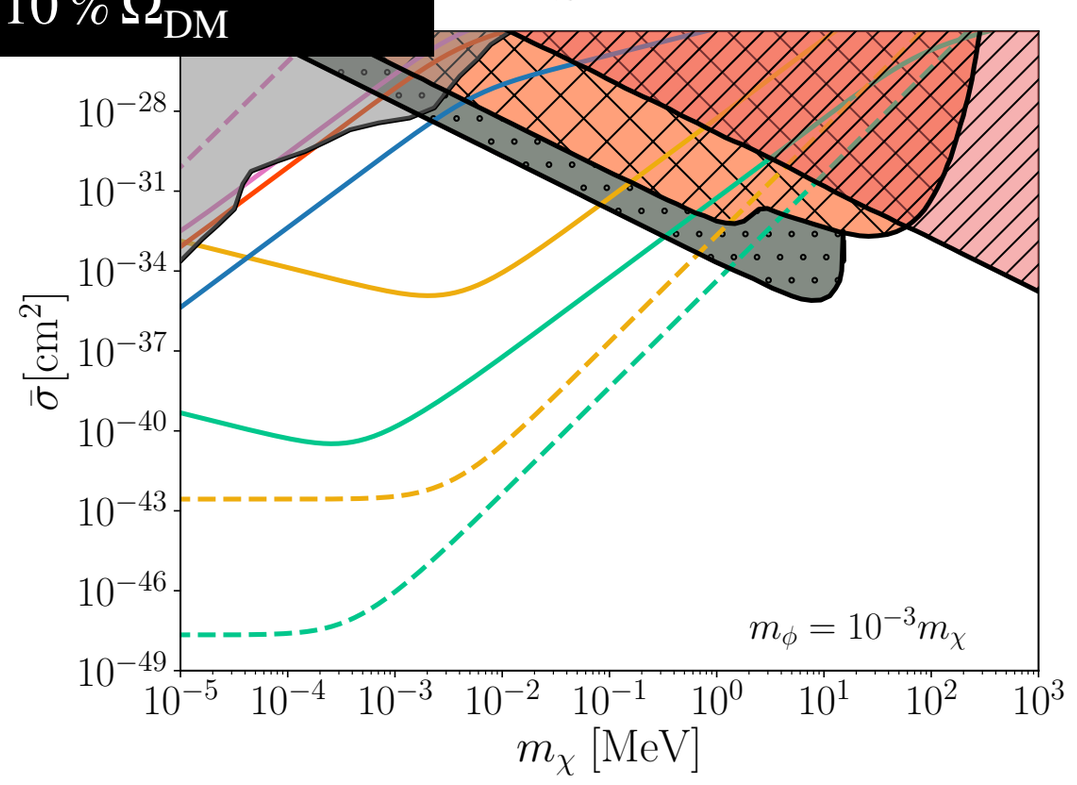




Assume DM is a subcomponent

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

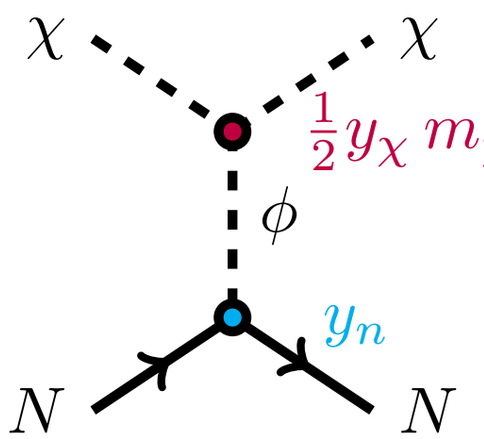




AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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



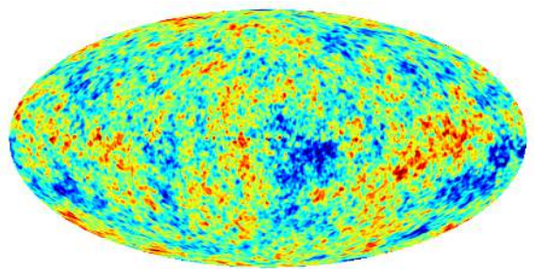
Terrestial

- Collider
- 5th force

Astrophysical

- Stellar emission
- DMSI

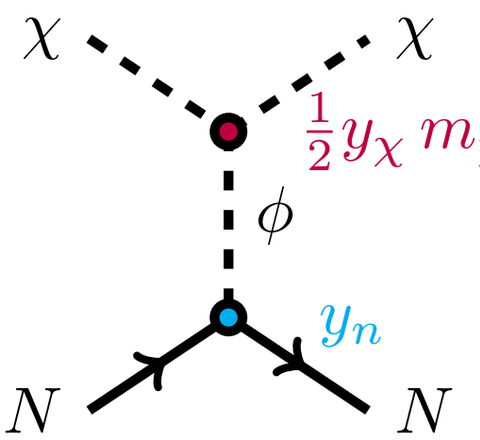
Cosmological

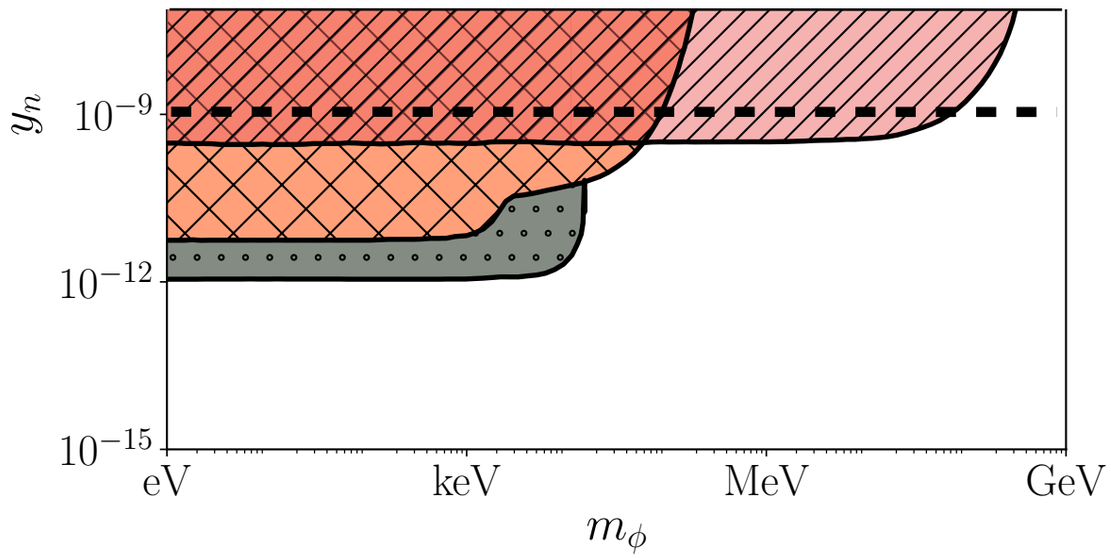


AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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





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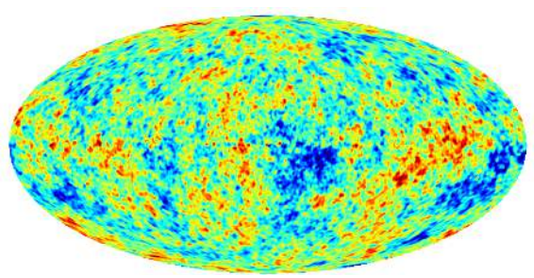
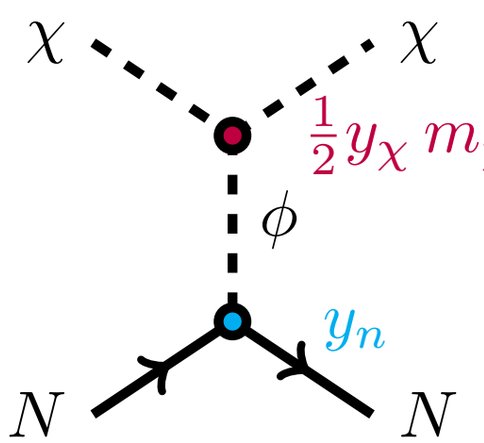
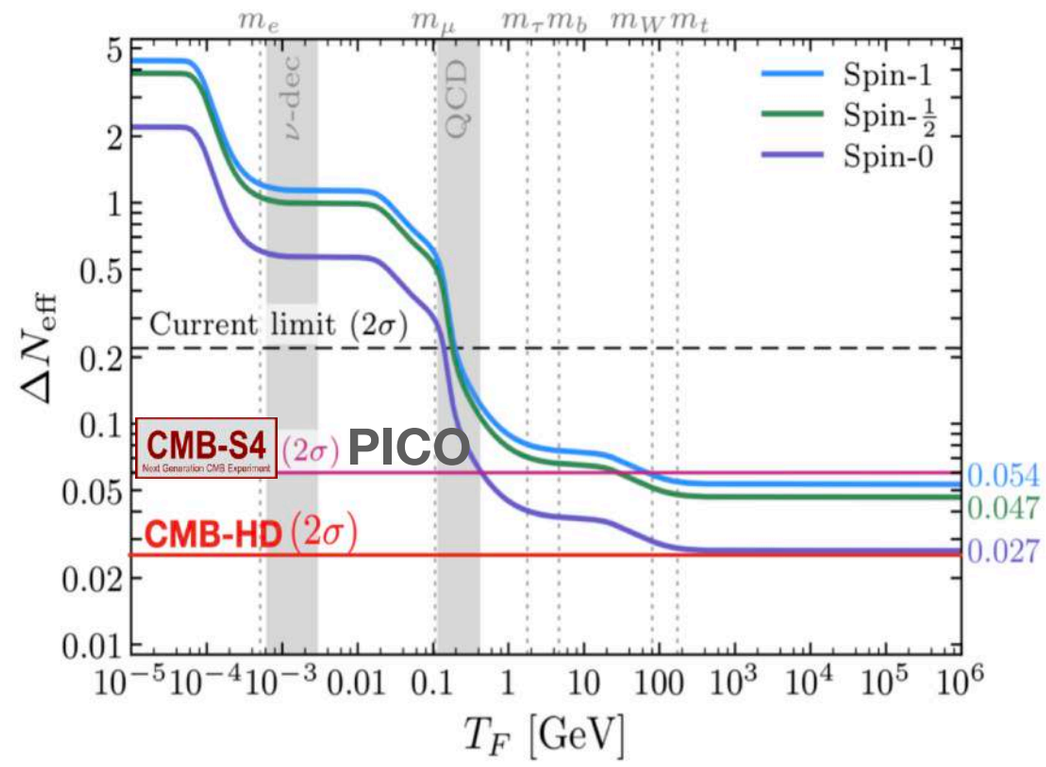


AIs: Constraints

[Knapen, Lin, Zurek, 2017]

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





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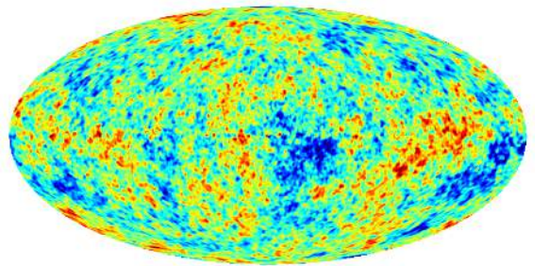

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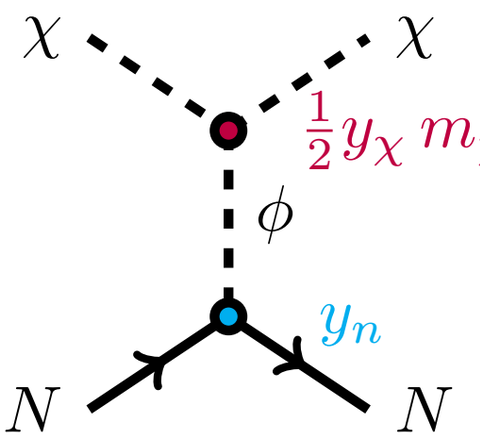

$$v_\chi^{\rm esc} \sim \sqrt{\frac{T_\chi}{m_\chi^{\rm min}}}$$

$$T_\chi \sim \left(\frac{g(\text{today})}{g(T_\chi^{\rm dec})}\right)^{\frac{1}{3}} T_\gamma$$

$$\Big\} \; m_\chi \gtrsim 10 \text{ eV}$$

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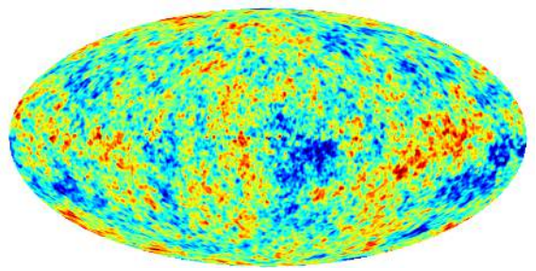

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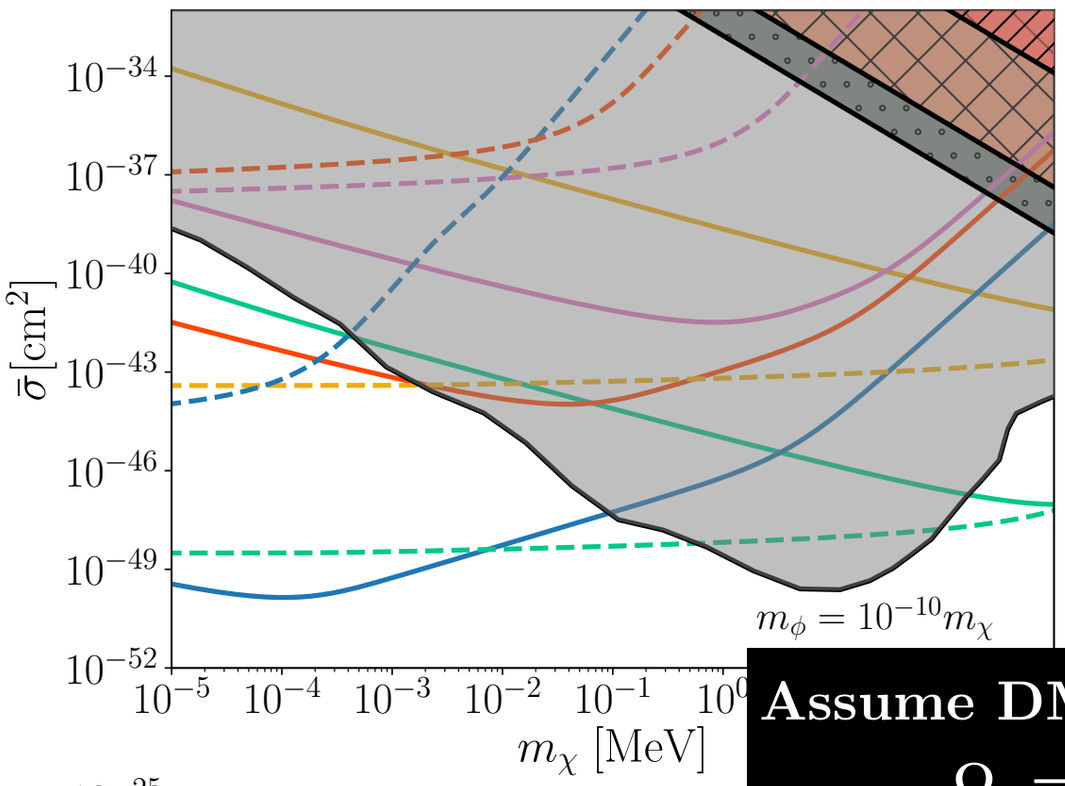
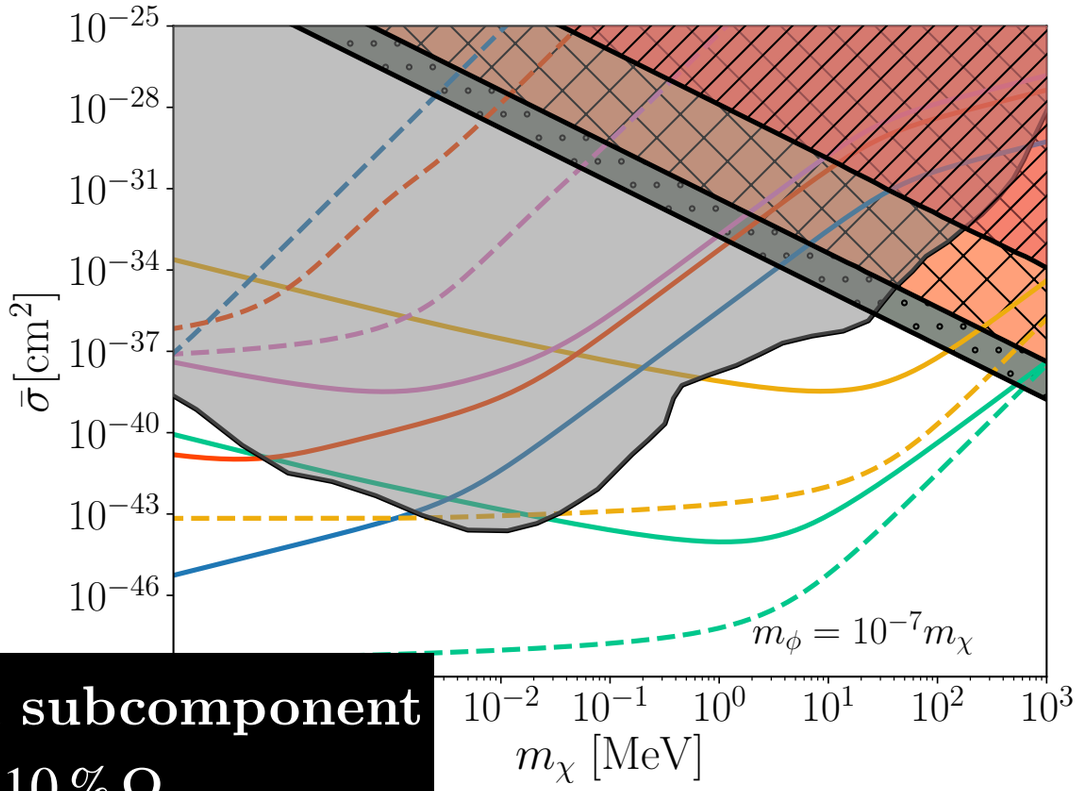
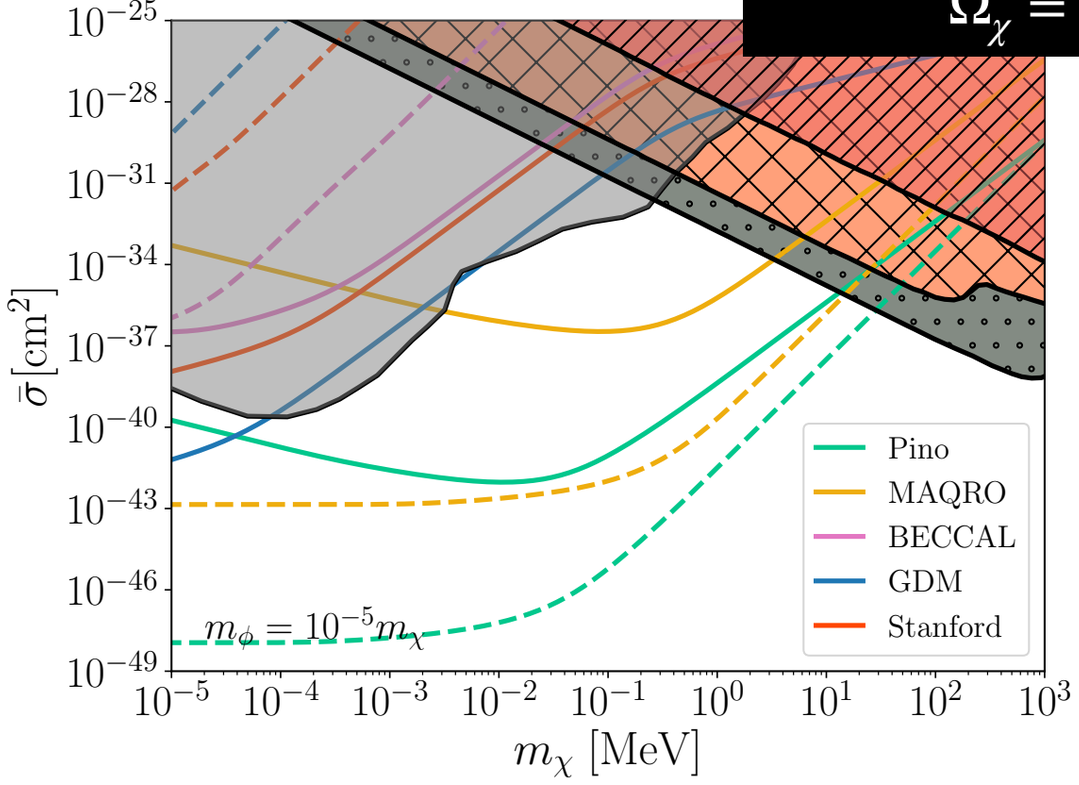
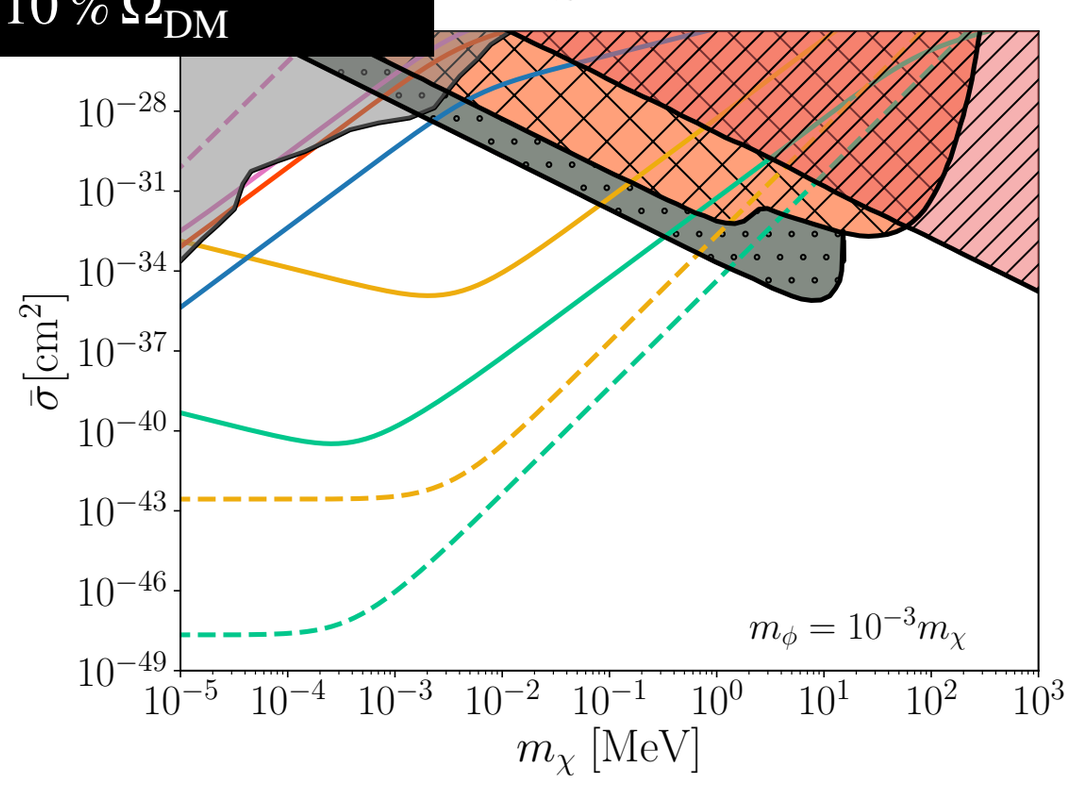




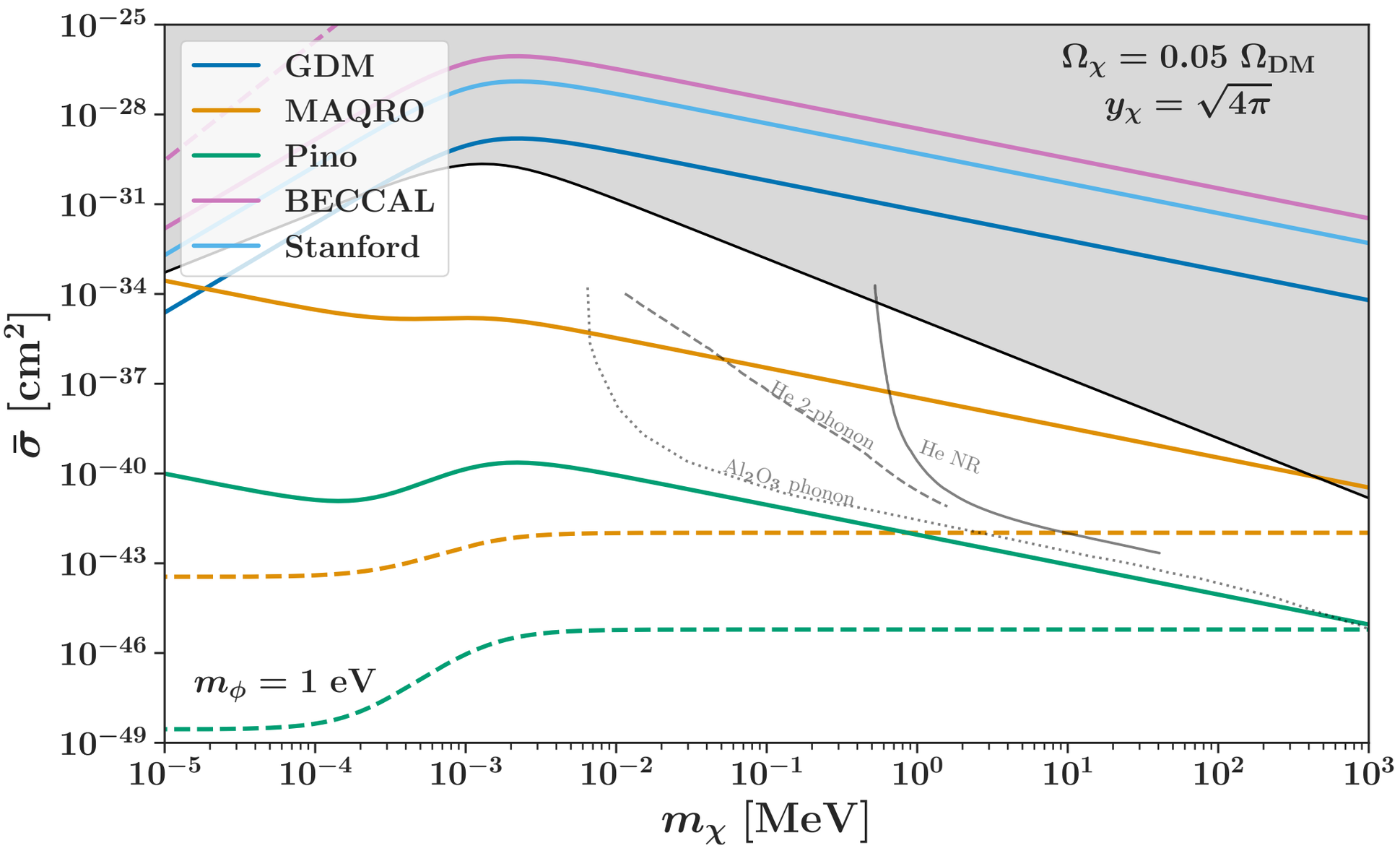
Assume DM is a subcomponent

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

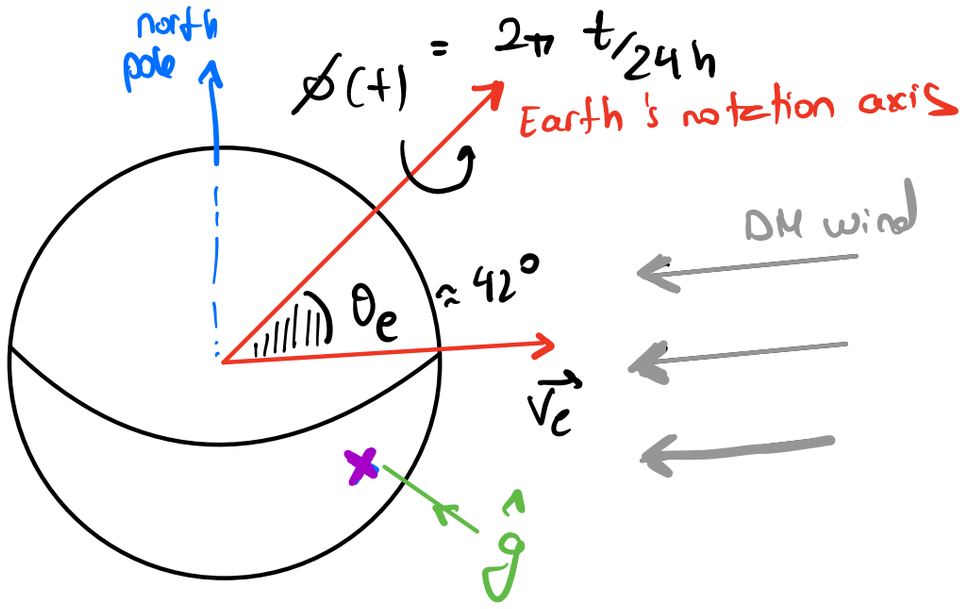




AIs: Fixed (light) mediator mass

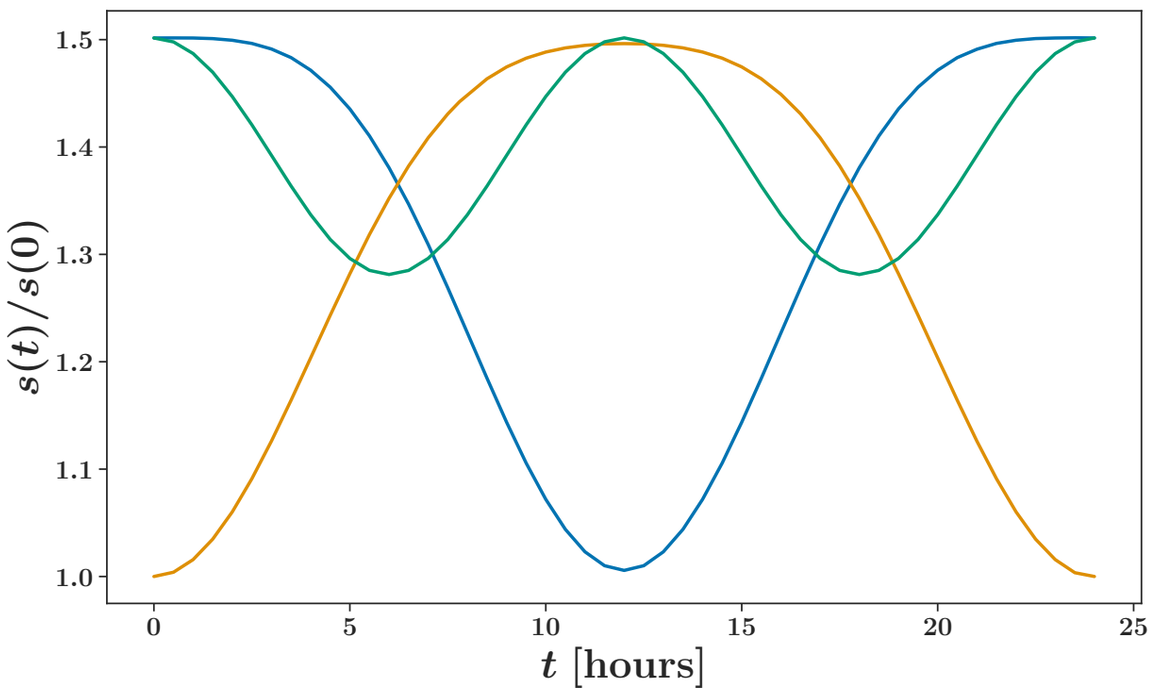


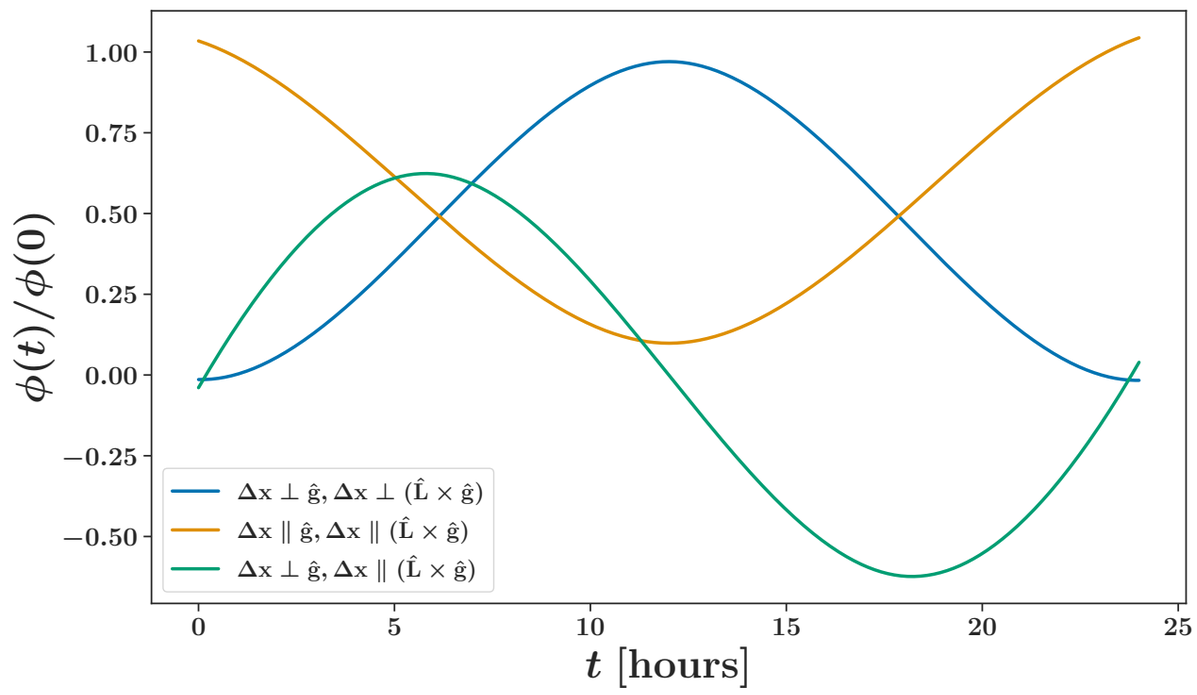
AIs: Daily modulation



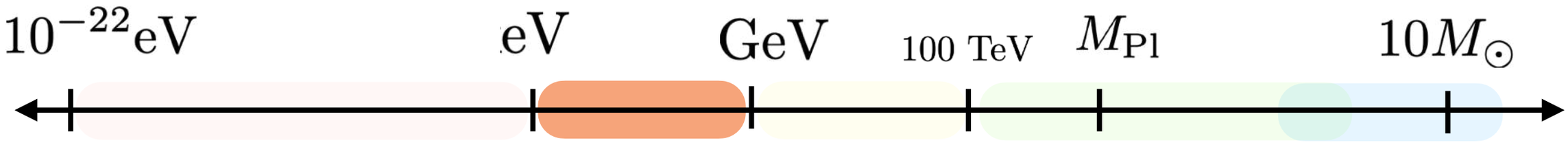
$$\mathbf{v}_e(t) = \|\mathbf{v}_e\| \begin{pmatrix} \mathrm{s}\theta_e\,\mathrm{c}\theta_x\,\mathrm{s}\phi(t) - \mathrm{s}\theta_x\,\mathrm{s}\theta_e\,\mathrm{c}\theta_l\,\mathrm{c}\phi(t) + \mathrm{s}\theta_x\,\mathrm{c}\theta_e\,\mathrm{s}\theta_l \\ \mathrm{c}\theta_e\,\mathrm{s}\theta_g\,\mathrm{s}\theta_l\,\mathrm{c}\theta_x - \mathrm{s}\theta_e\,\mathrm{s}\theta_g\,\mathrm{c}\theta_l\,\mathrm{c}\theta_x\,\mathrm{c}\phi(t) - \mathrm{s}\theta_e\,\mathrm{c}\theta_g\,\mathrm{s}\theta_l\,\mathrm{c}\phi(t) - \mathrm{c}\theta_e\,\mathrm{c}\theta_g\,\mathrm{c}\theta_l - \mathrm{s}\theta_e\,\mathrm{s}\theta_g\,\mathrm{s}\theta_x\,\mathrm{s}\phi(t) \\ \mathrm{s}\theta_e\,\mathrm{c}\theta_g\,\mathrm{c}\theta_l\,\mathrm{c}\theta_x\,\mathrm{c}\phi(t) - \mathrm{c}\theta_e\,\mathrm{c}\theta_g\,\mathrm{s}\theta_l\,\mathrm{c}\theta_x - \mathrm{s}\theta_e\,\mathrm{s}\theta_g\,\mathrm{s}\theta_l\,\mathrm{c}\phi(t) - \mathrm{c}\theta_e\,\mathrm{s}\theta_g\,\mathrm{c}\theta_l + \mathrm{s}\theta_e\,\mathrm{c}\theta_g\,\mathrm{s}\theta_x\,\mathrm{s}\phi(t) \end{pmatrix}$$

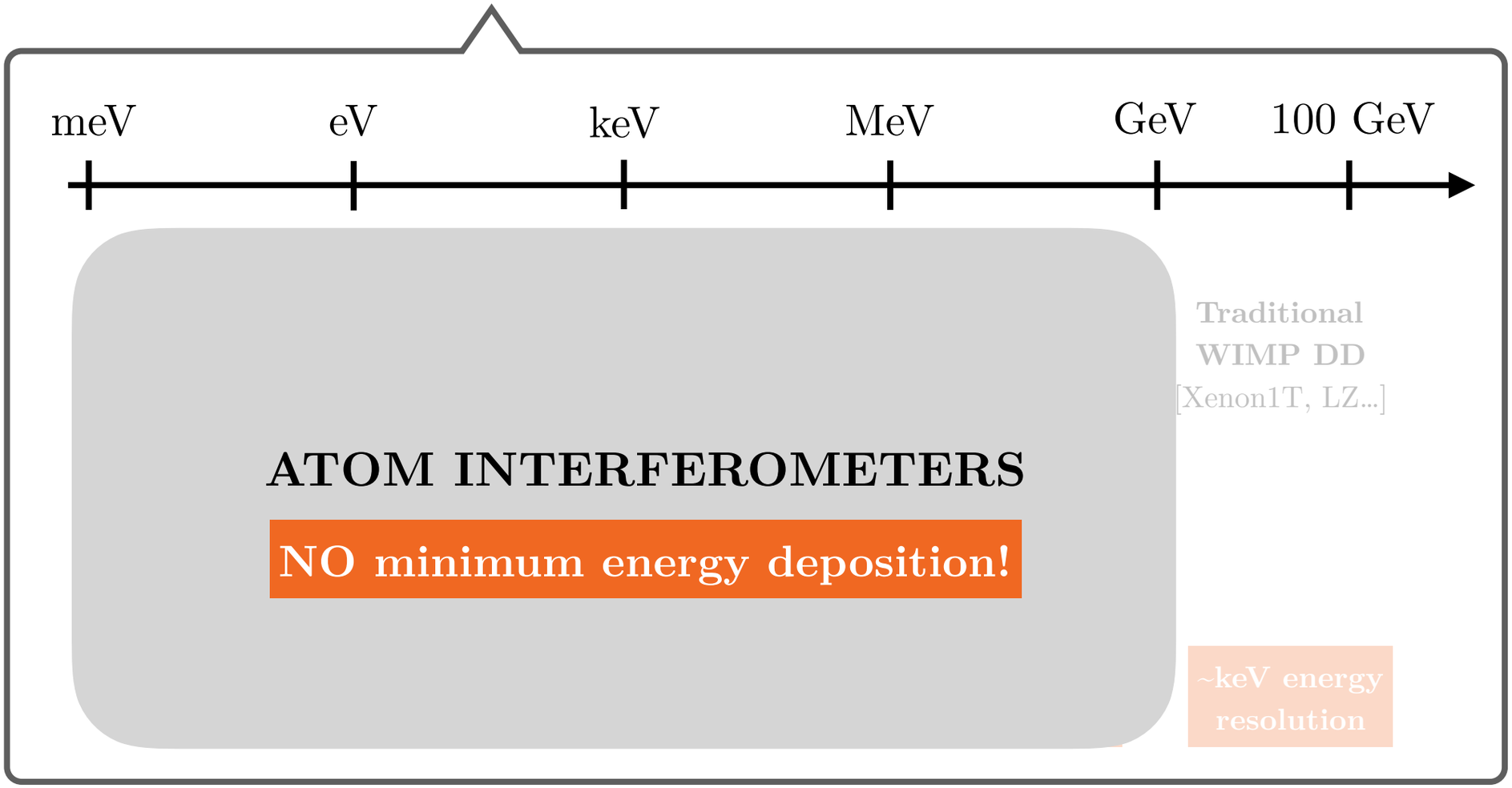
e.g. Pino





Dark Matter: where to look?





Conclusions

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

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Atom interferometers at low transferred momentum:

- ⇨ Decoherence has no lower bound on energy deposition
- ⇨ Coherent enhancement
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Conclusions

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

Atom interferometers at low transferred momentum:

- ⇨ Decoherence has no lower bound on energy deposition
- ⇨ Coherent enhancement
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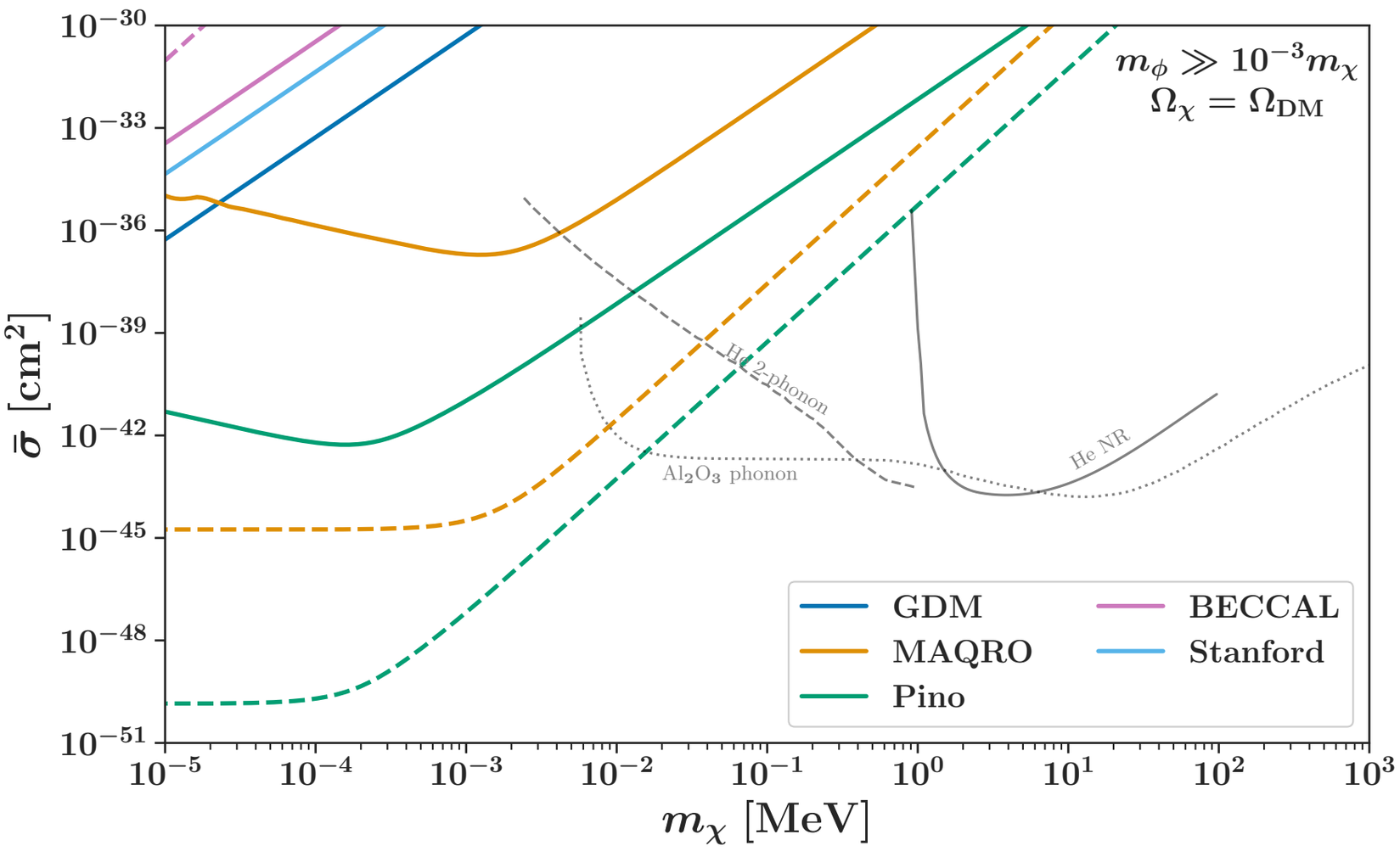
Future directions:

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

Thank you!

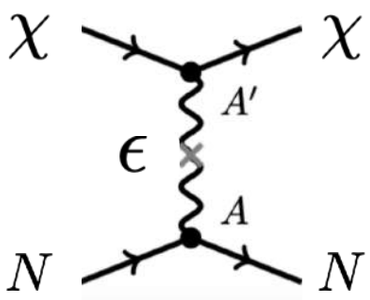
AIs: Heavy mediator

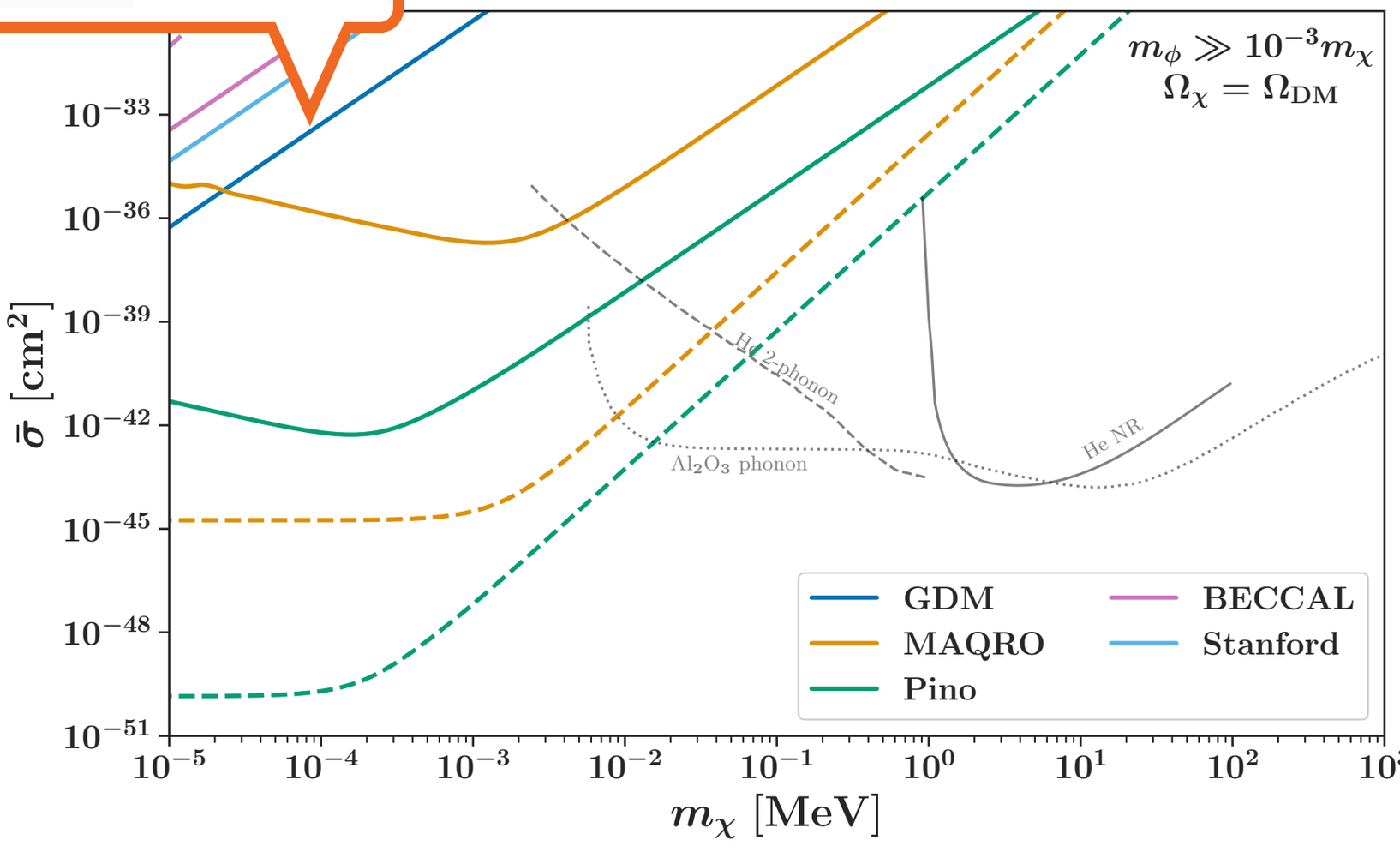


AIs: Heavy mediator

Hidden photon via epsilon

$$\mathcal{L} \supset \alpha\,\epsilon \int d^3\mathbf{r}\, n(\mathbf{r})\mathbf{E}(\mathbf{r}) \cdot \mathbf{E}'(\mathbf{r})$$





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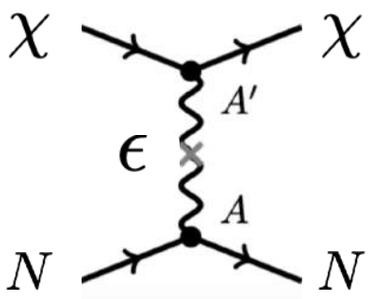
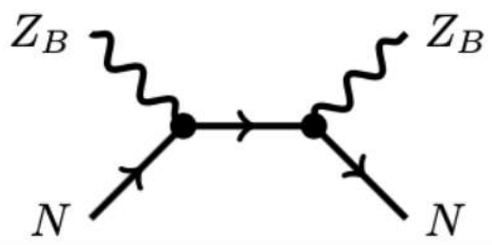
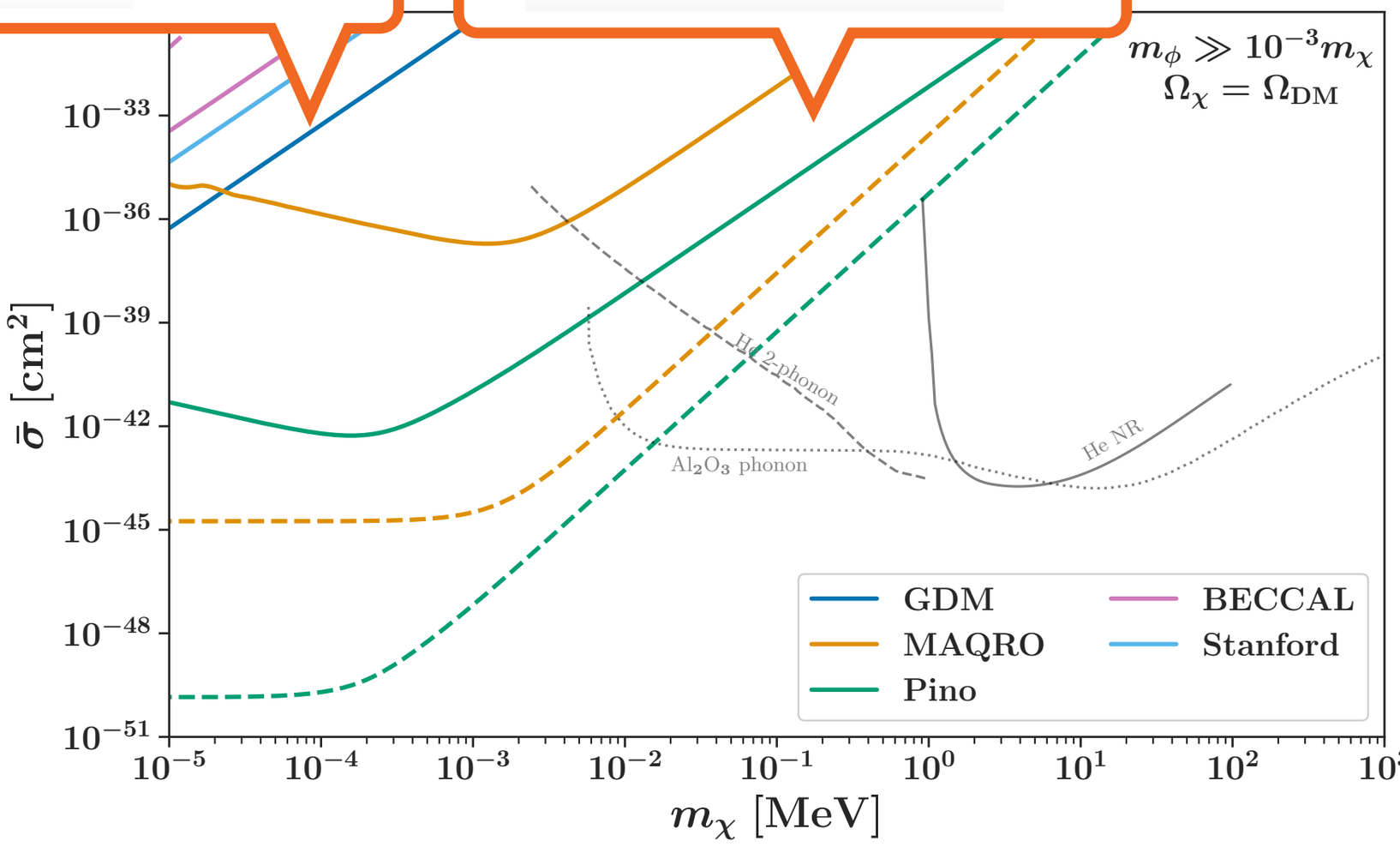


Hidden photon scat. via B

$$\mathcal{L} \supset \frac{g_B}{3}\bar{q}\gamma_\mu q Z_B^\mu$$





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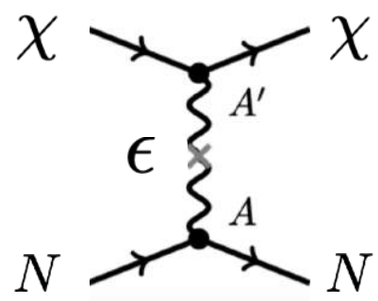

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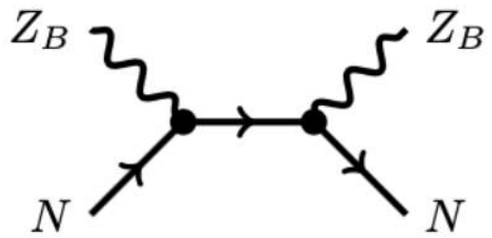

Coherent axion scattering

$$\mathcal{L} \supset \frac{a^2}{8f_a^2} \sum_{N=p,n} \delta m_N \bar{N} N$$

2112.13536