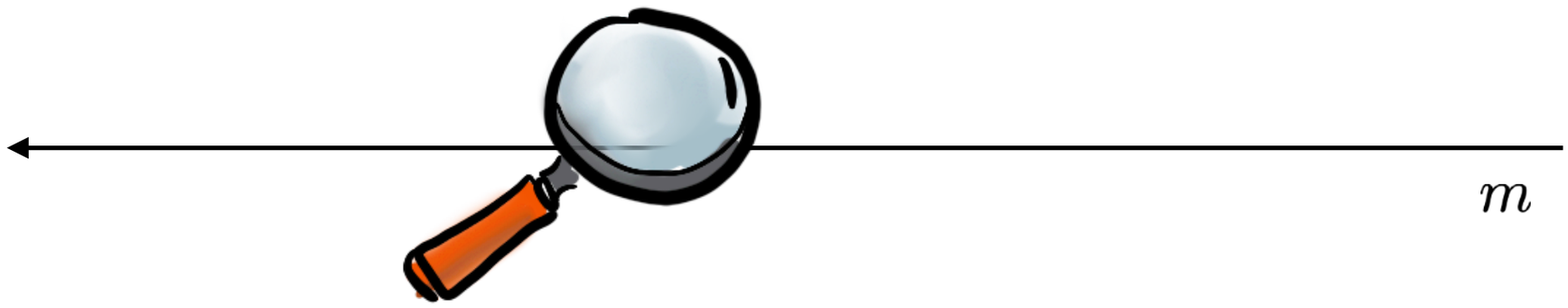
AYUDA BEATRIZ GALINDO JUNIOR BG23

Atomic sensors for BSM

Clara Murgui (UAB/CERN)



INVISIBLES 2024 Workshop (Bologna)

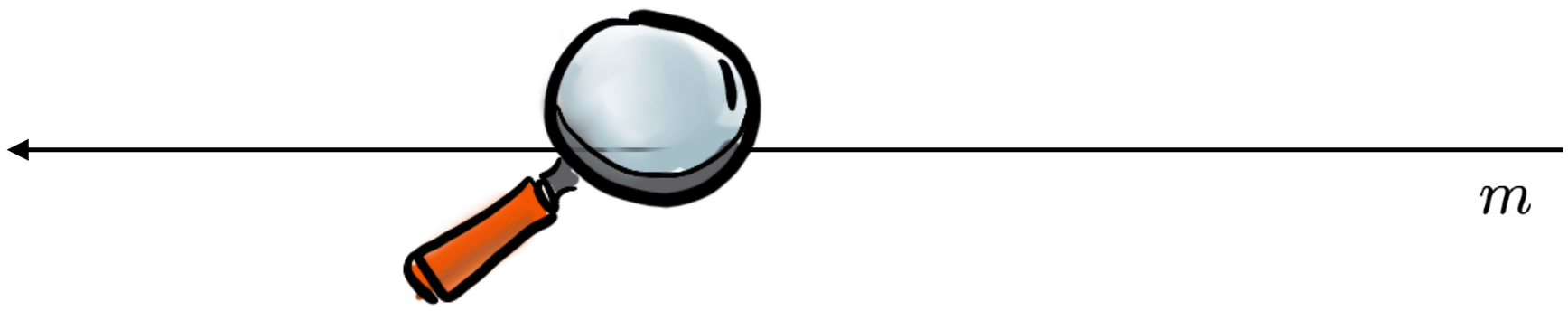
1st July 2024

AYUDA BEATRIZ GALINDO JUNIOR BG23

Atomic sensors for BSM

Clara Murgui (UAB/CERN)

L. Badurina, Y. Du, K. Pardo, R. Plestid, Y. Wang, and K. M. Zurek



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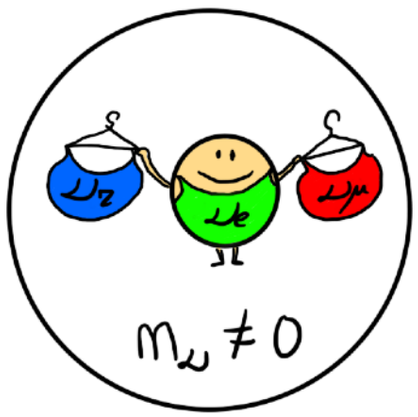
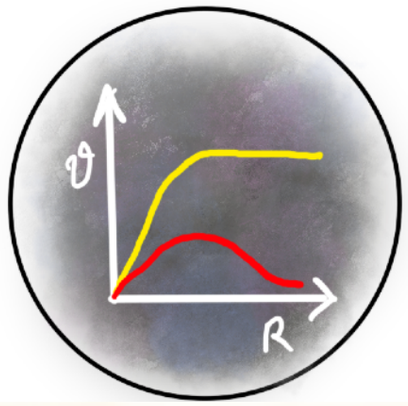
The Need for New Physics





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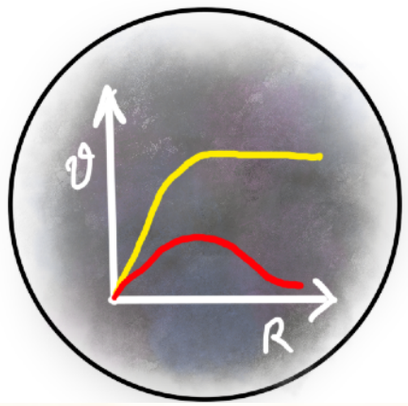
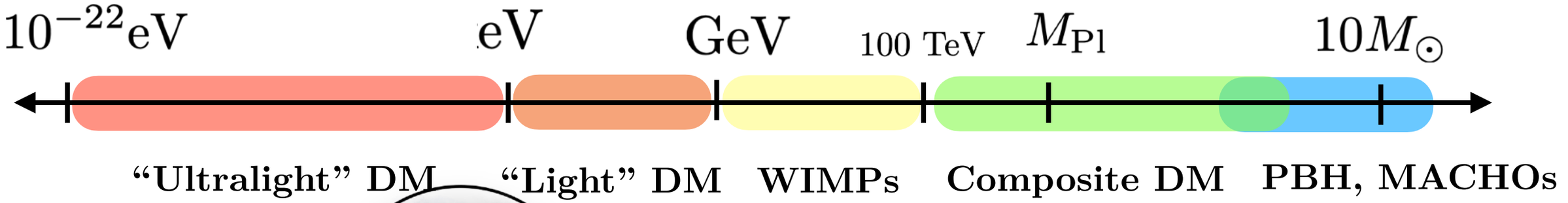
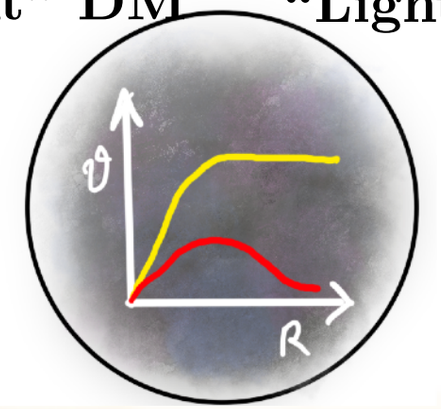
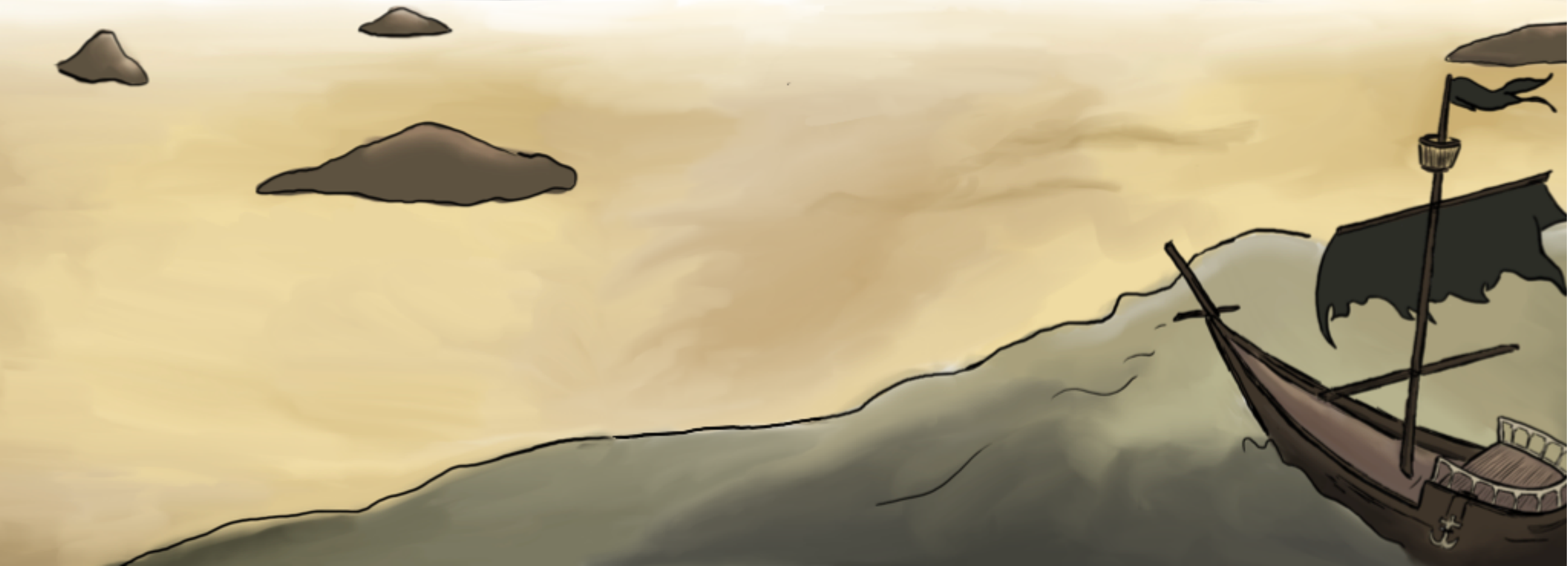


Beyond the SM: where to look?







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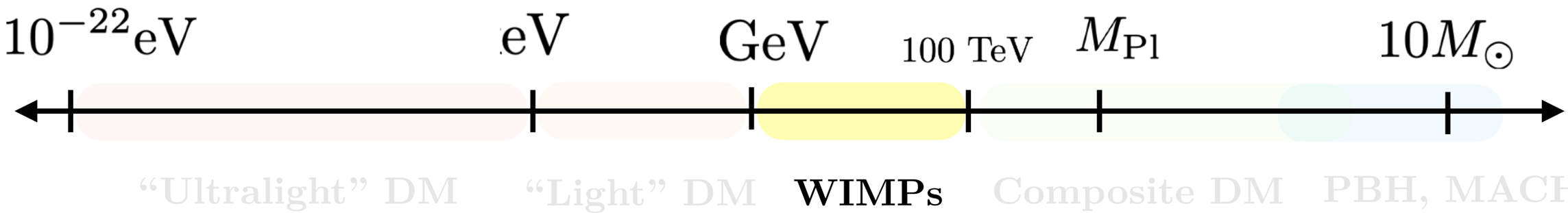
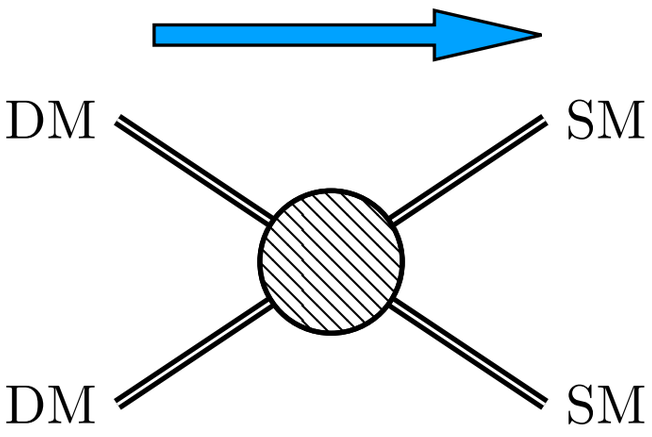


The WIMP miracle



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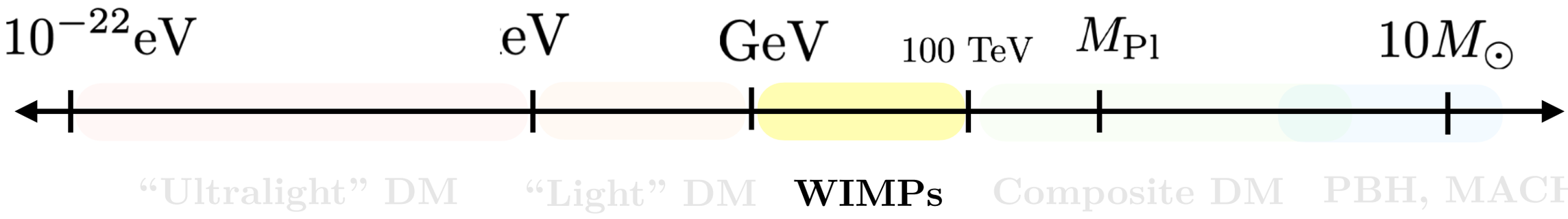

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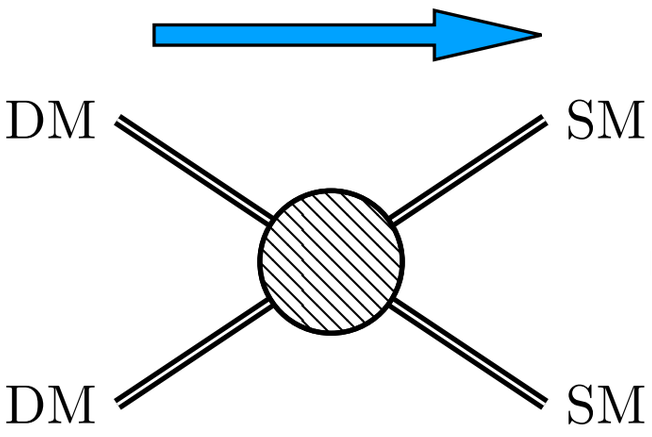
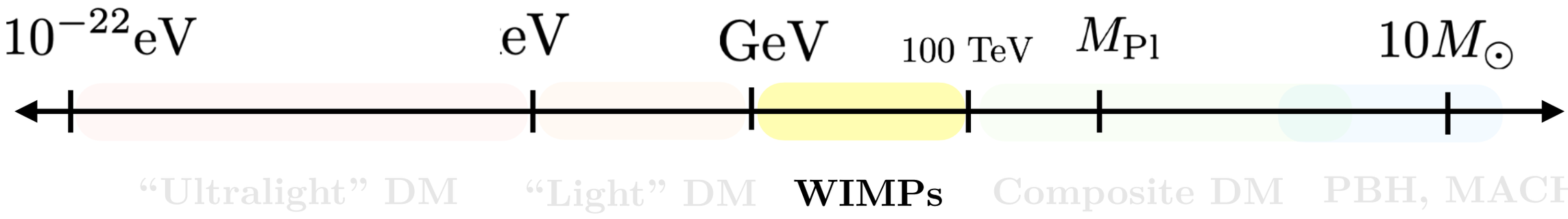


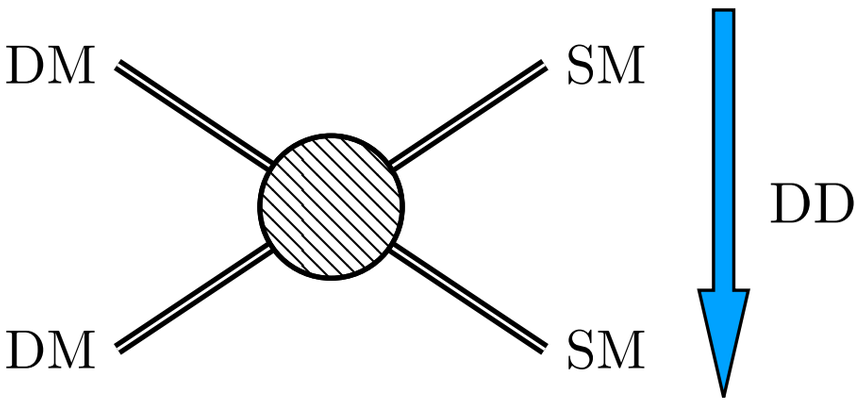
weak coupling

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

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

Beyond the SM: where to look?





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

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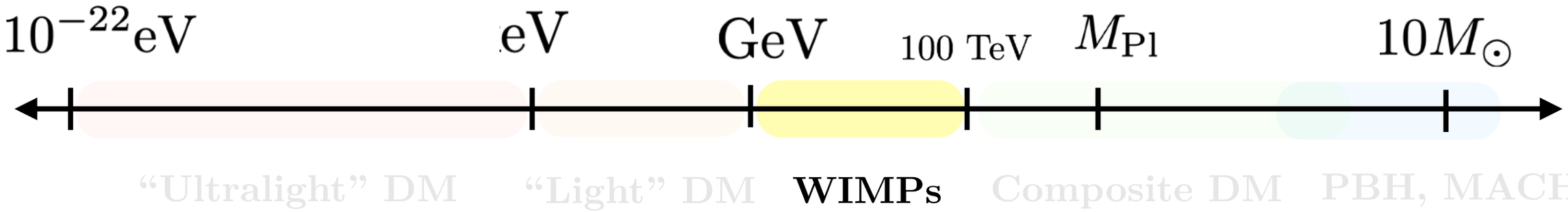

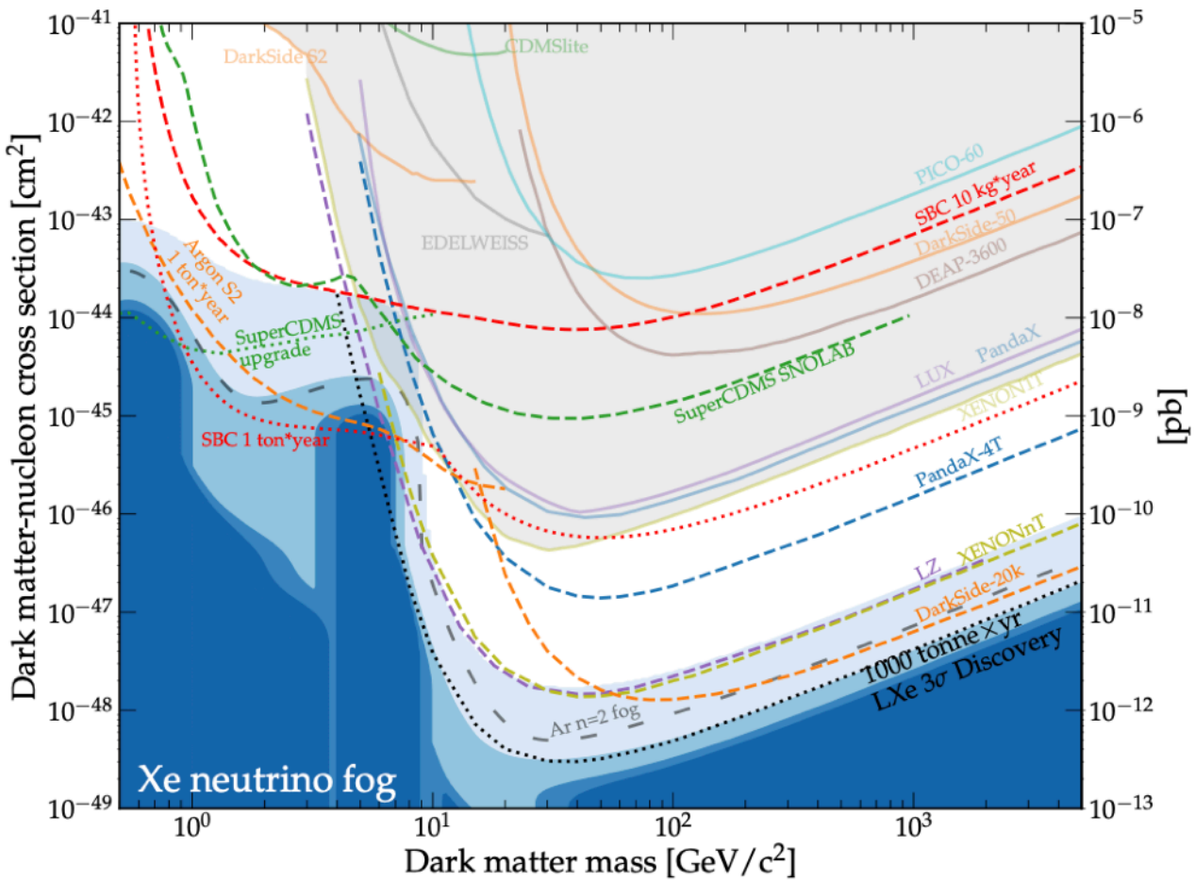

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[Akerib, D. S., et al., Snowmass2021, 2203.08084]

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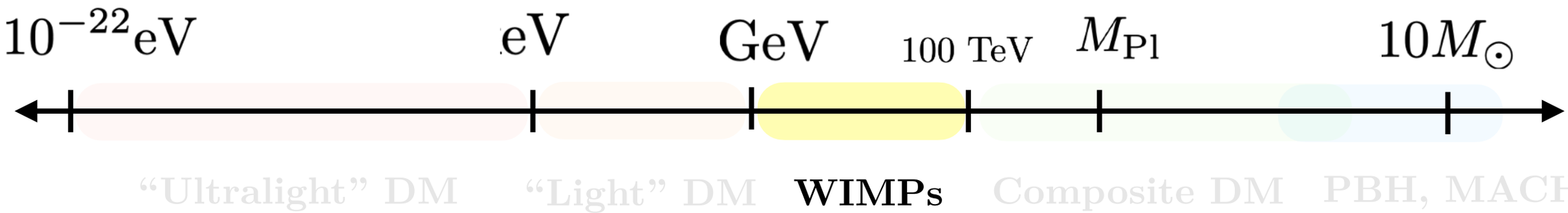

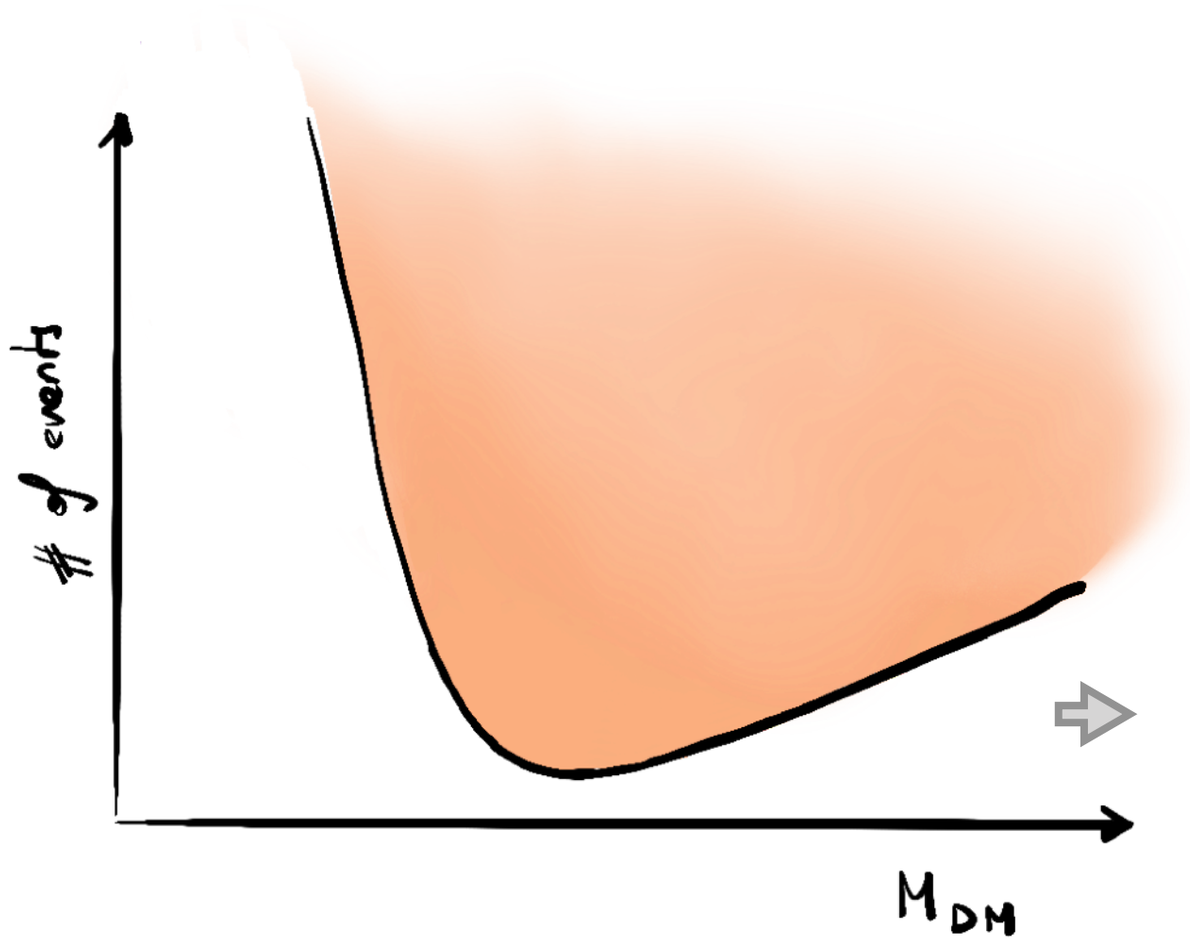

loss of "flux" $n_\chi = \dfrac{\rho_\chi}{m_\chi}$

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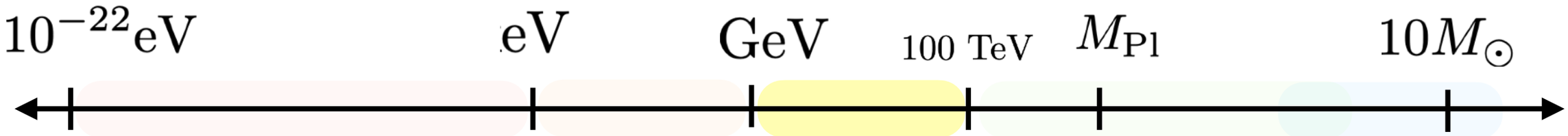

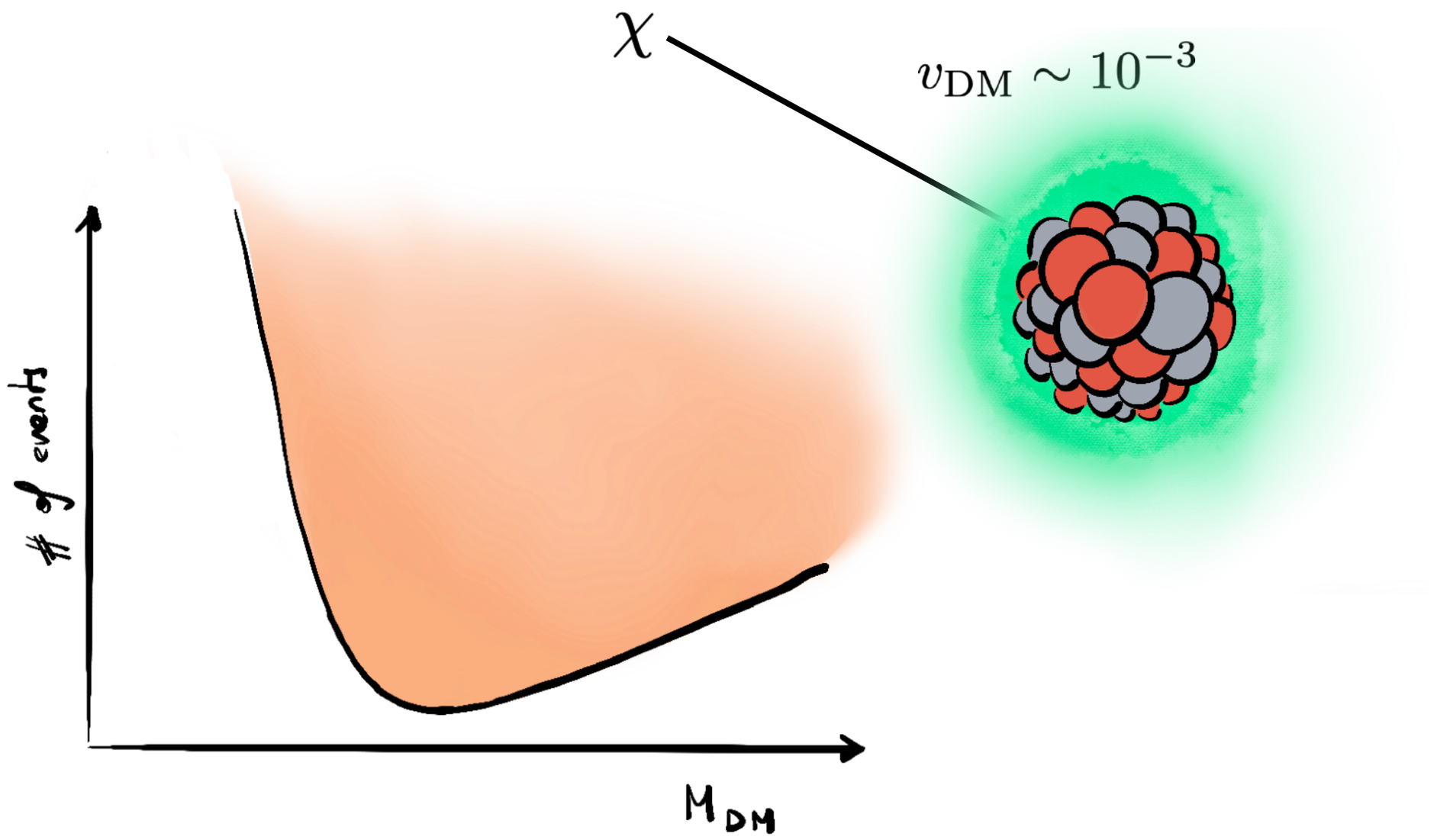

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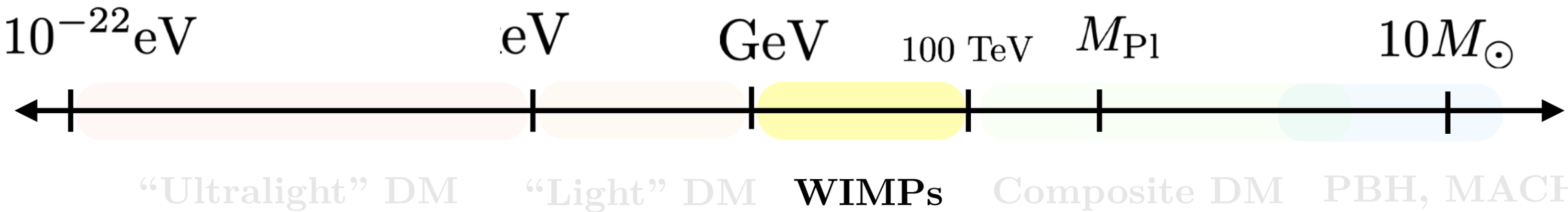
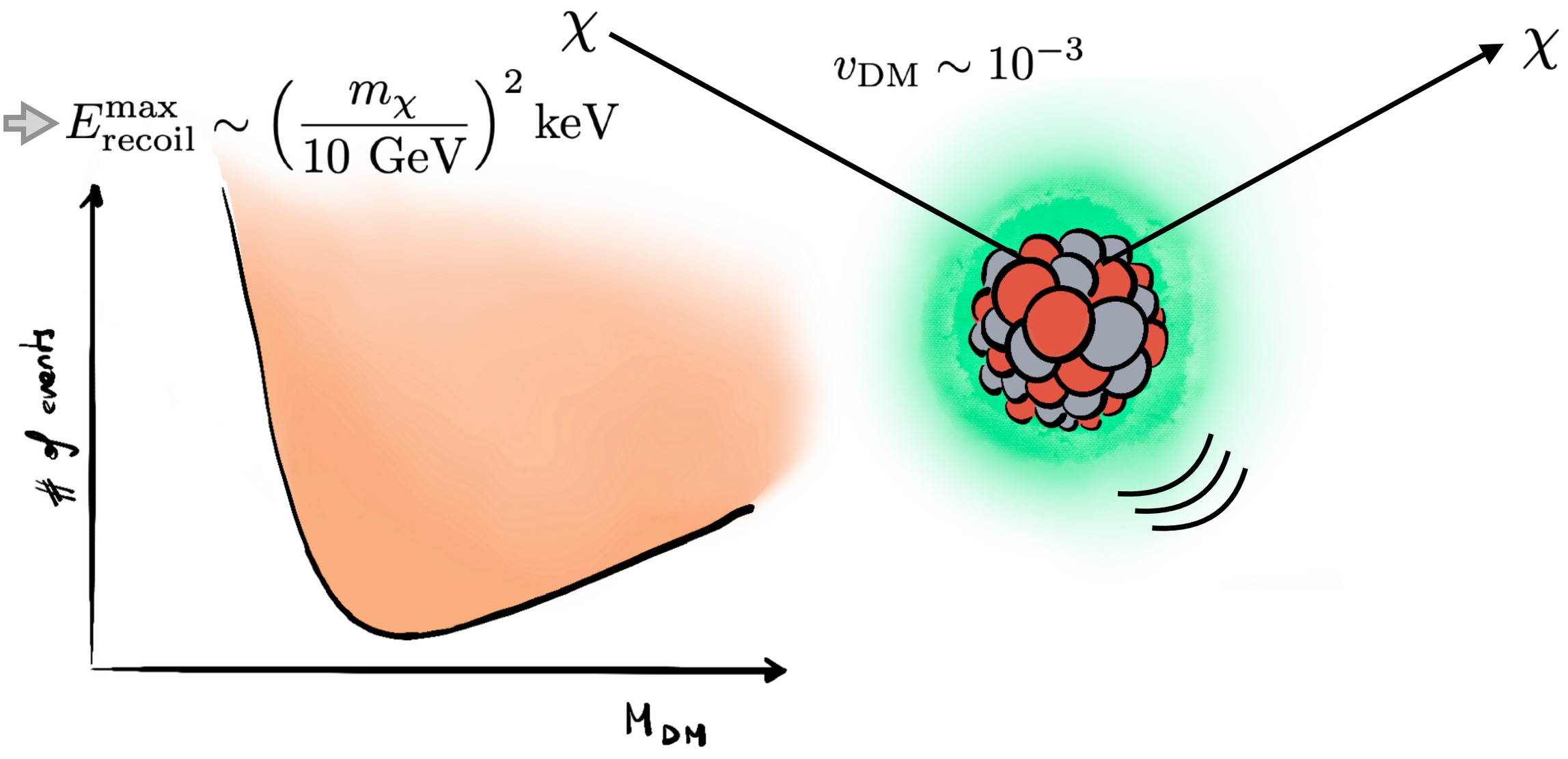


$$\Rightarrow E_{\rm recoil}^{\rm max} \sim \left(\frac{m_\chi}{10\ {\rm GeV}}\right)^2 {\rm keV}$$



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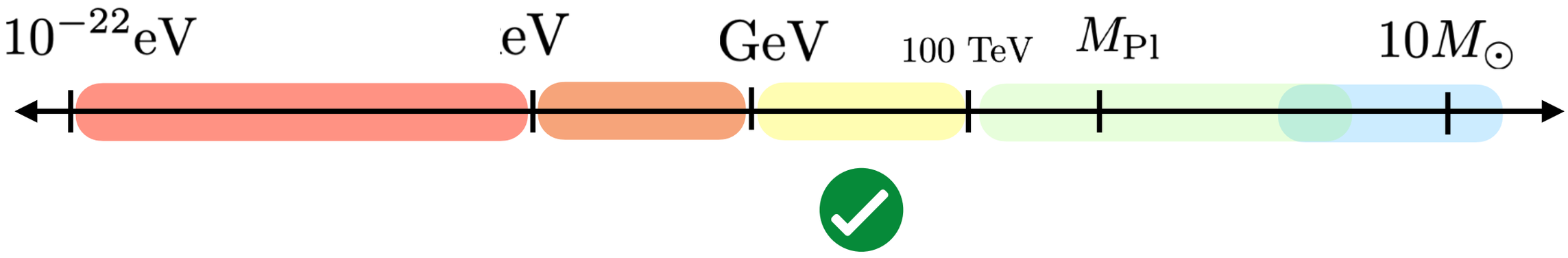

Nuclear recoil exp.

Colliders

...

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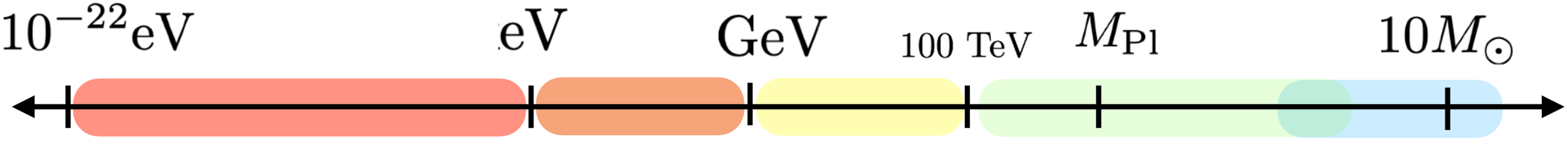

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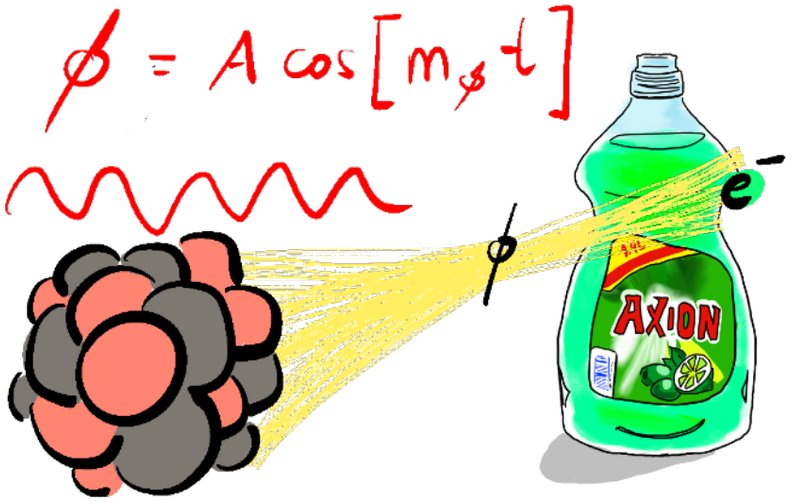

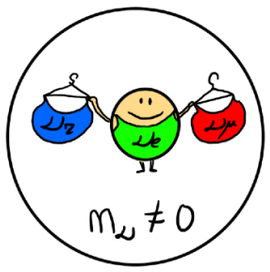

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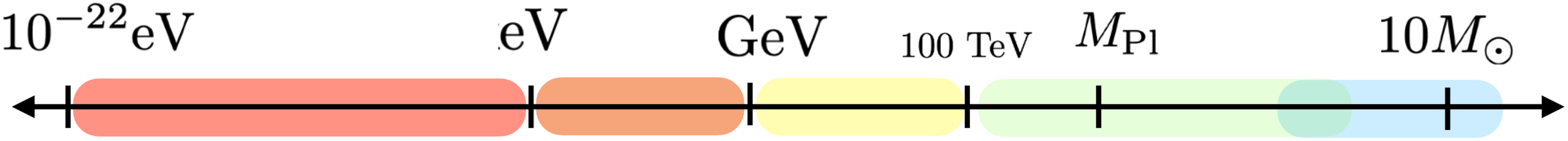

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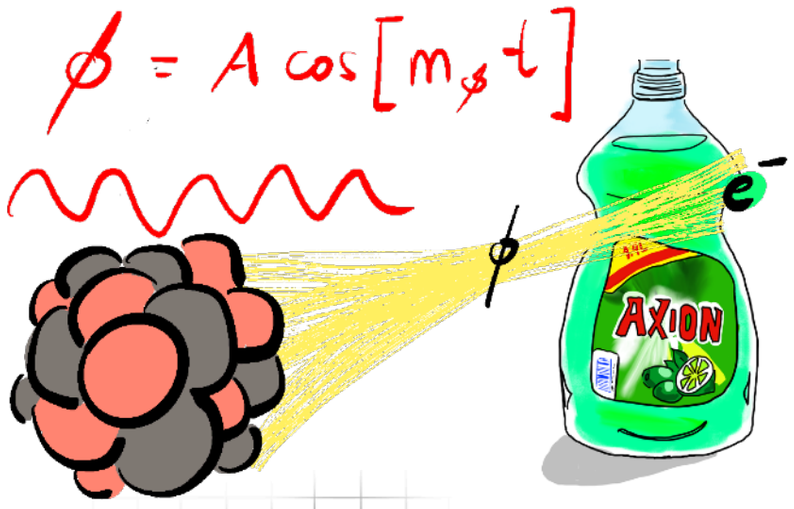

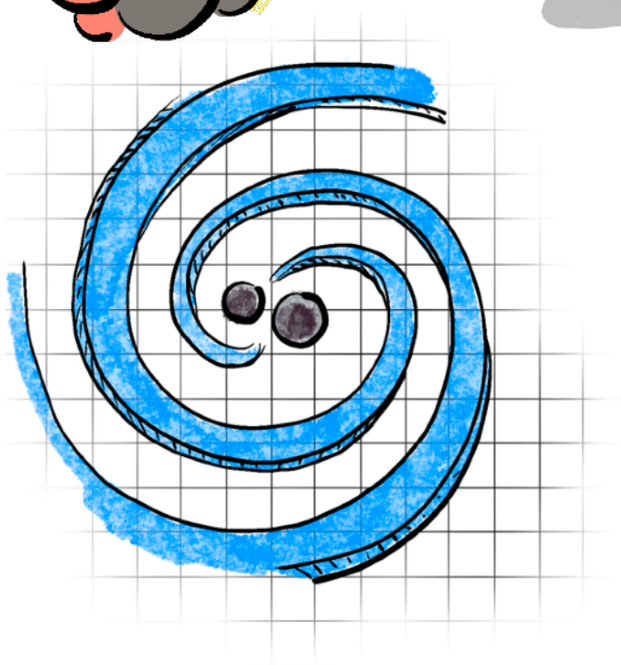

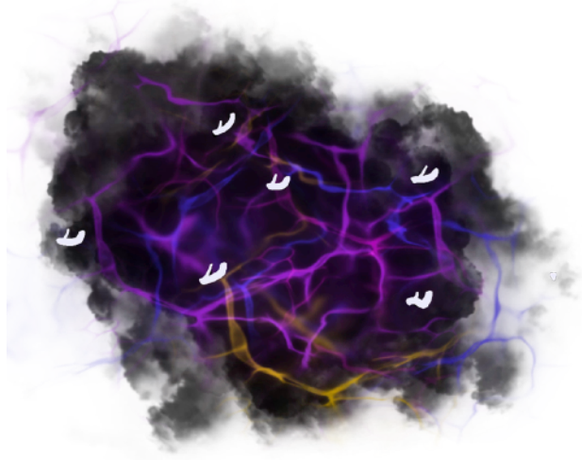

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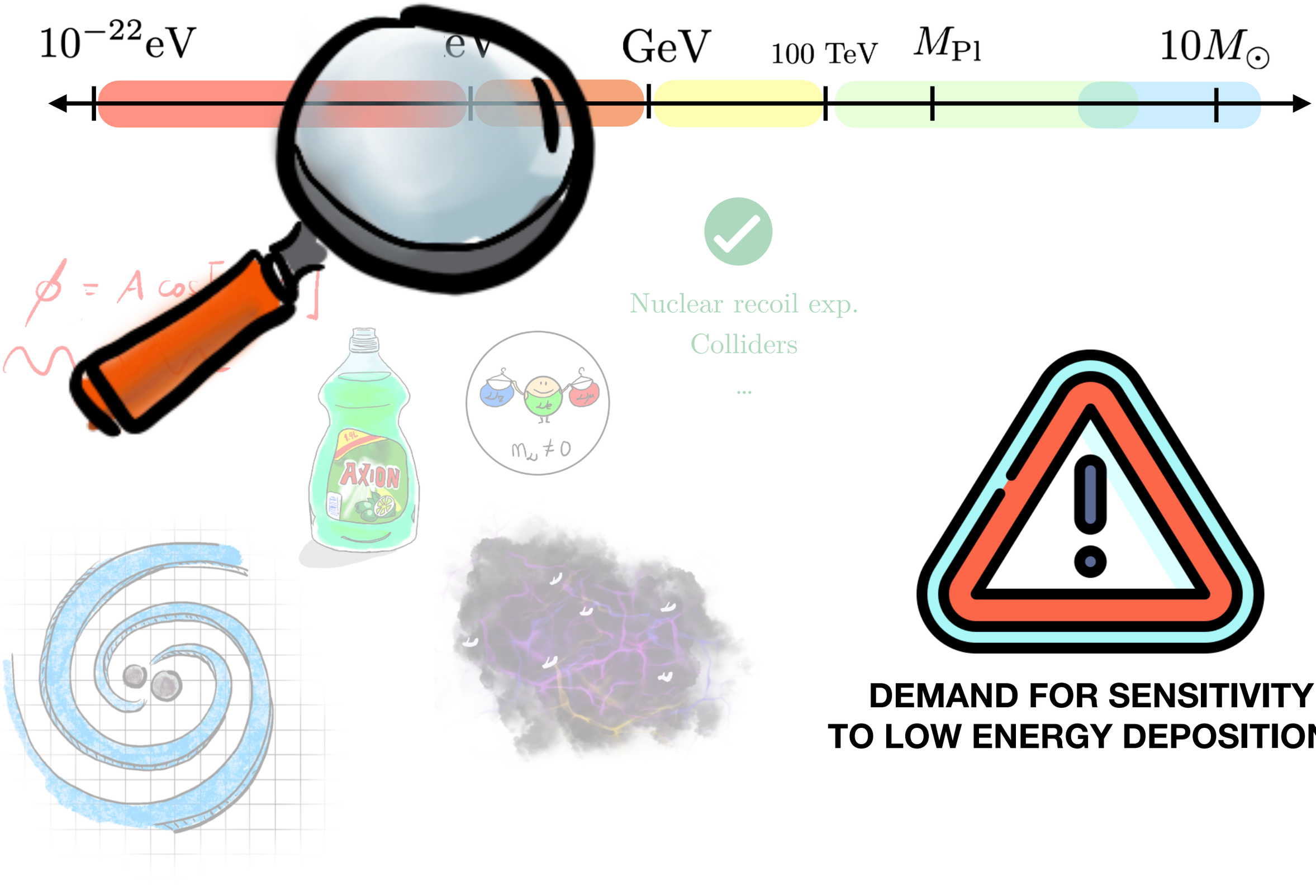


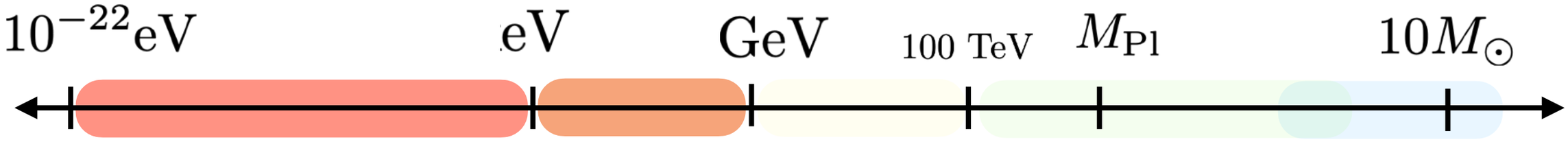
Nuclear recoil exp.

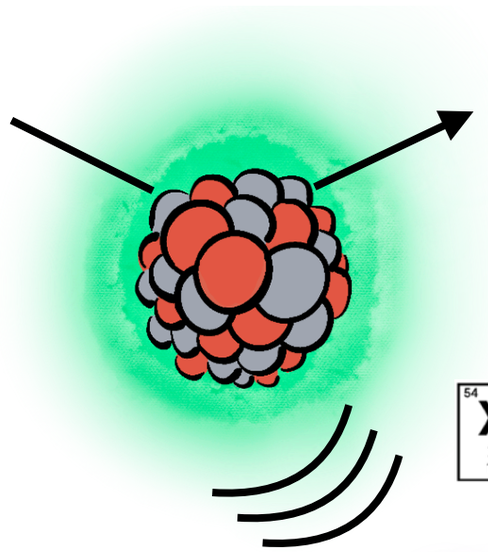
Colliders

...

DEMAND FOR SENSITIVITY TO LOW ENERGY DEPOSITIONS

(Beyond) the SM: "how" to look?





Traditional WIMP DD
(nuclear recoil)

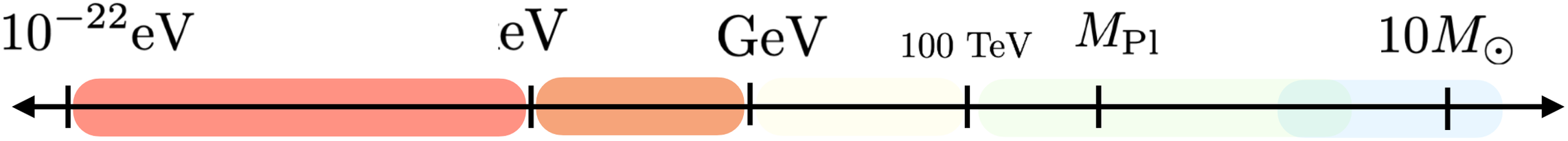
54 Xe Xenon 131.29 — 18 Ar Argon 39.9 — 32 Ge Germanium 72.630

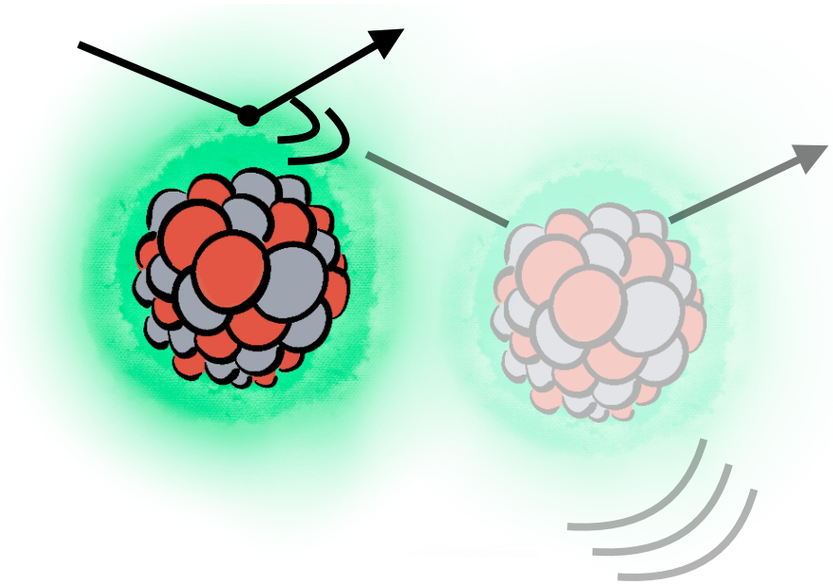
...

~keV energy resolution

LUX, PandaX, XENON1T, XENONnT, DarkSide-20k, SuperCDMS...

(Beyond) the SM: "how" to look?





Semiconductors

Migdal Effects

Fluoresence

Ionization

Graphene

~eV energy resolution

[Essig, Mardon, Volansky, 2011]
[Graham, Kaplan, Rajendran, Walters, 2012]
[Lee, Lisanti, Mishra-Sharma, Safdi, 2015]
[Essig, Volansky, Yu, 2017]
[Emken, Essig, Kouvaris, Sholapurka, 2019]
[Blanco, Collar, Kahn, Lillard, 2019]
[Blanco, Kahn, Lillard, McDermott, 2021]
[Blanco, Essig, Fernandez-Serra, Ramani, Slone, 2022]

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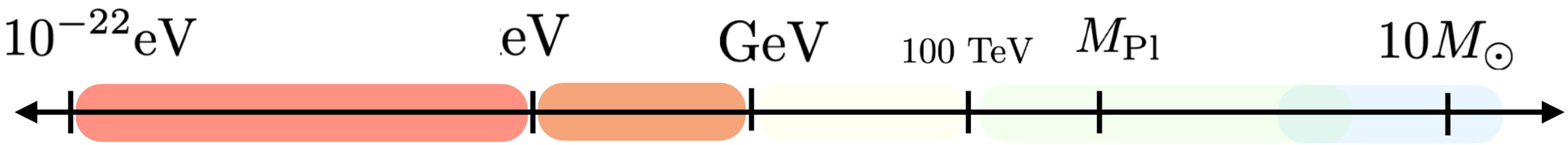

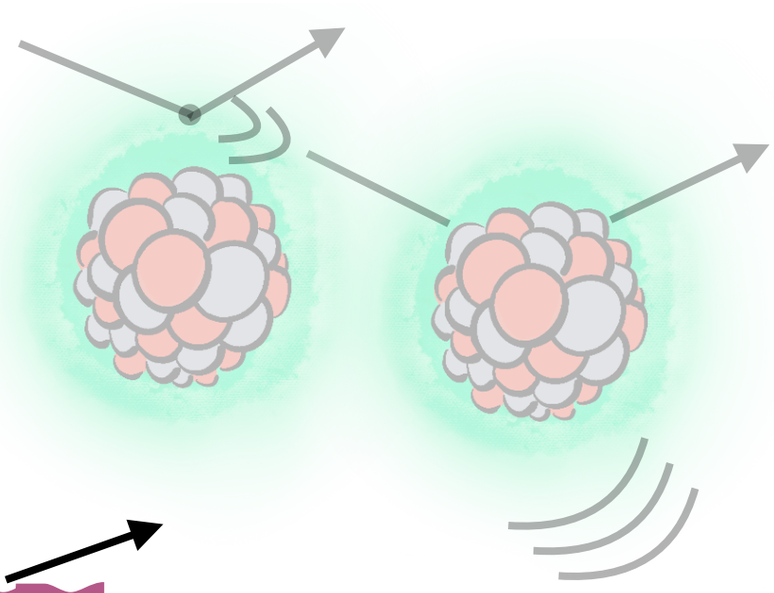

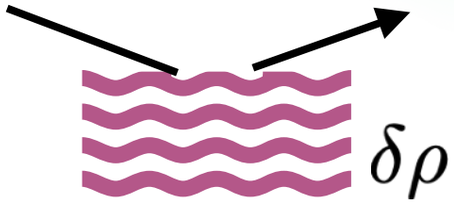

Collective excitations
(phonons, magnons, polaritons….)

~meV energy resolution

[Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu, 2015]
[Derenzo, Essig, Massari, Soto, Yu, 2016]
[Hochberg, Lin, Zurek, 2016]
[Bloch, Essig, Tobioka, Volansky, Yu, 2016]
[Kurinsky, Yu, Hochberg, Cabrera, 2019]
[Griffin, Inzani, Trickle, Zhang, Zurek, 2019]
[Coskuner, Mitridate, Olivares, Zurek, 2020]
[Mitridate, Trickle, Zhang, Zurek, 2021]
[Chen, Mitridate, Trickle, et al, 2022]
[Das, Kurinsky, Leane, 2024]

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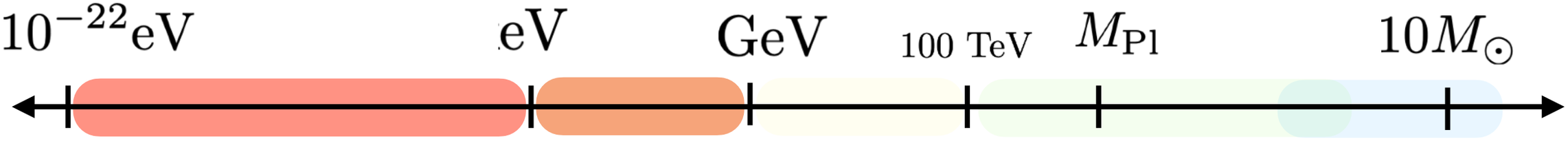
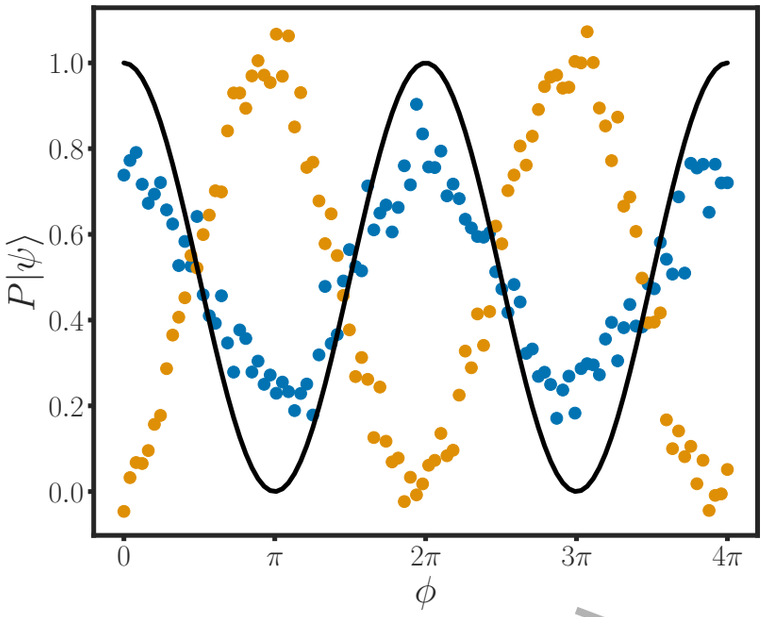
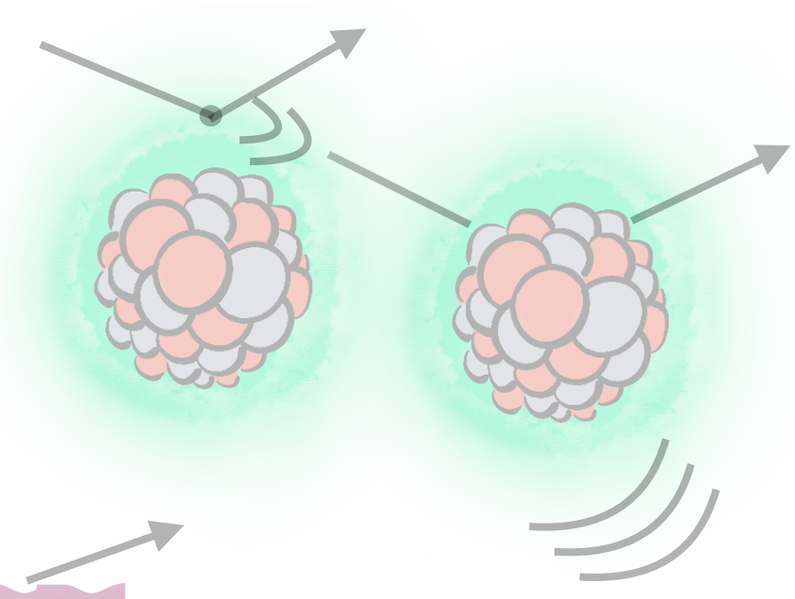
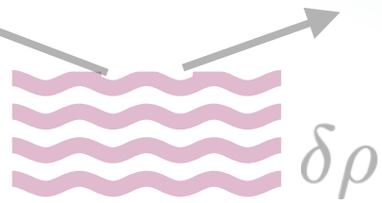






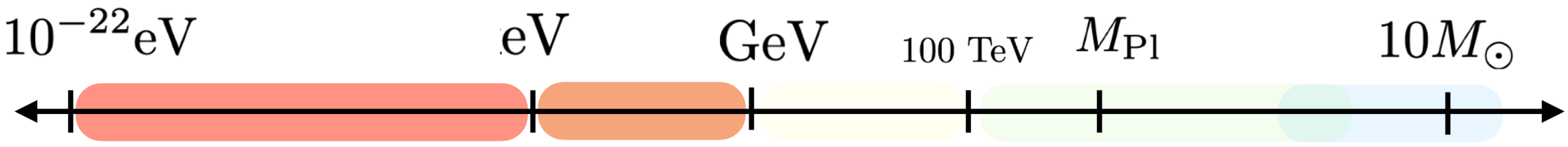


[Riedel, Yavin, 2016]

ATOM INTERFEROMETERS

NO minimum energy deposition!

AIs: low momentum transfers



COHERENT EFFECTS

[Riedel, Yavin, 2016]

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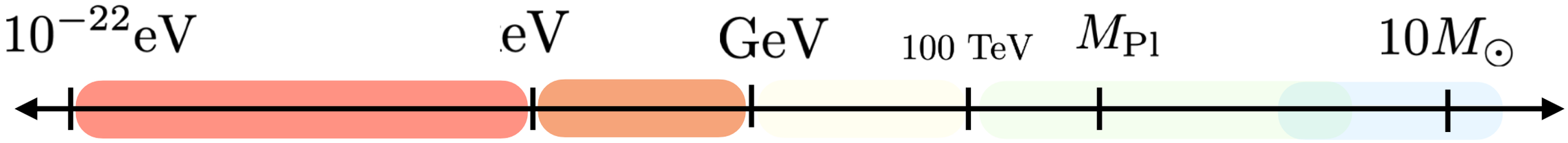

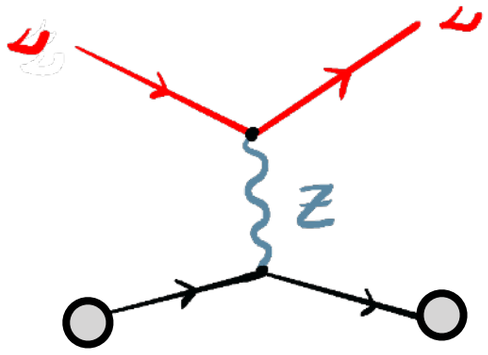

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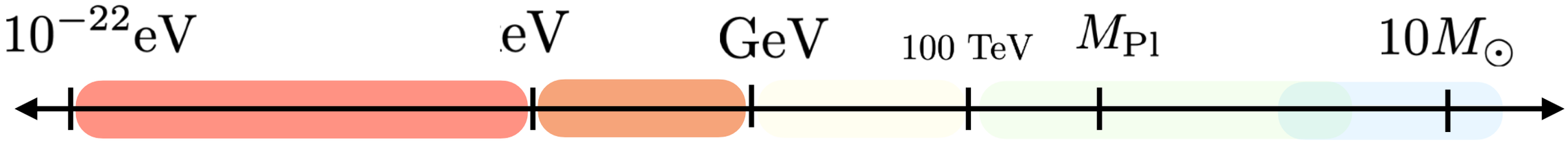

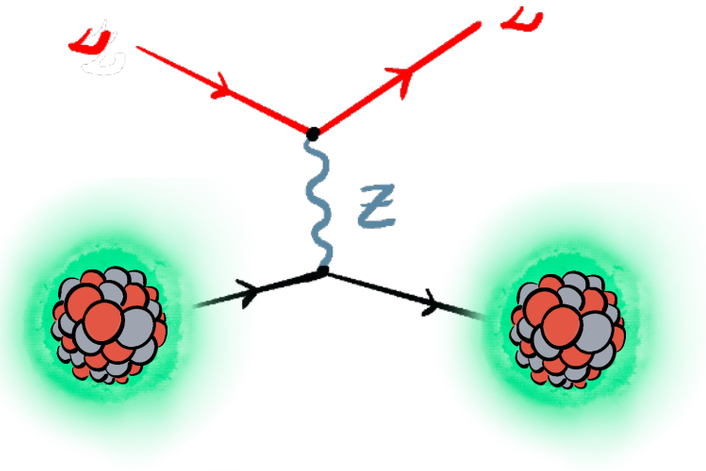

e.g. coherent neutrino scattering

[Freedman, 1973]

$$\sigma^{\rm coh}_{NA} \propto (A-Z)^2 |F_N(qr_N)|^2$$

COHERENT EFFECTS

ATOM INTERFEROMETERS

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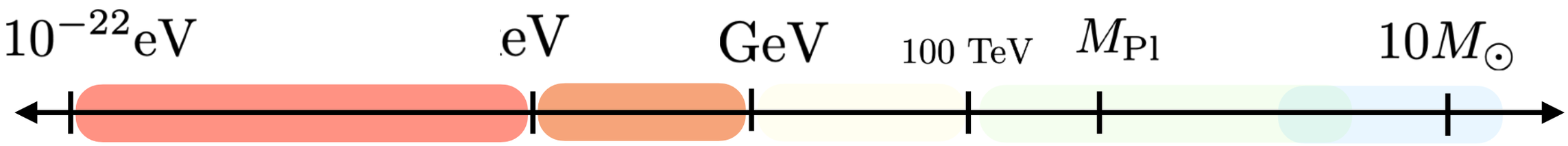

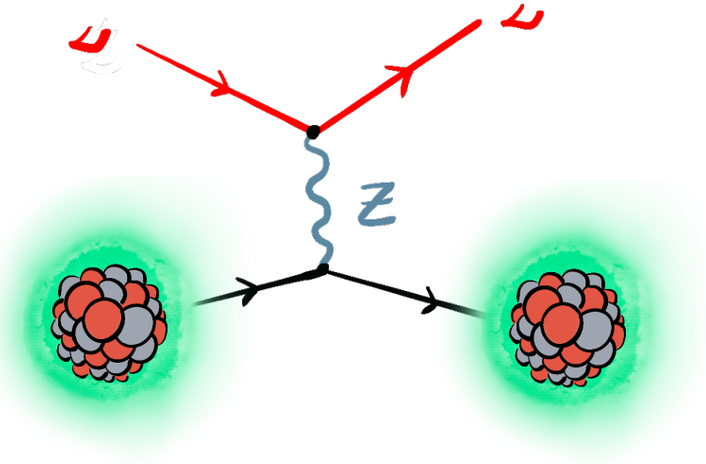

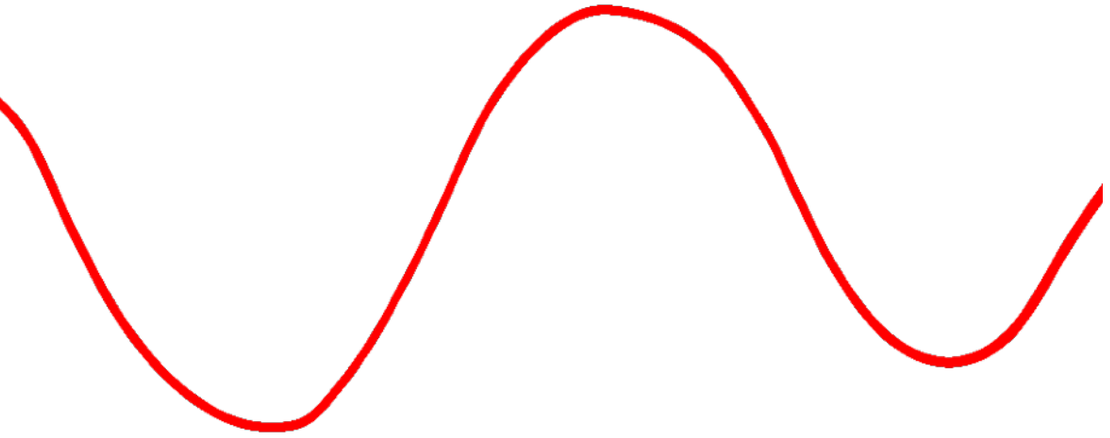

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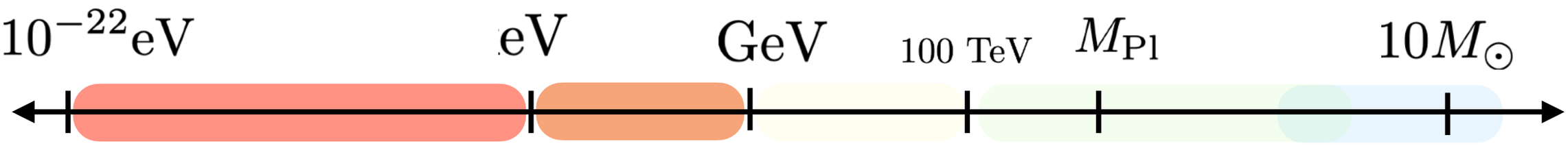
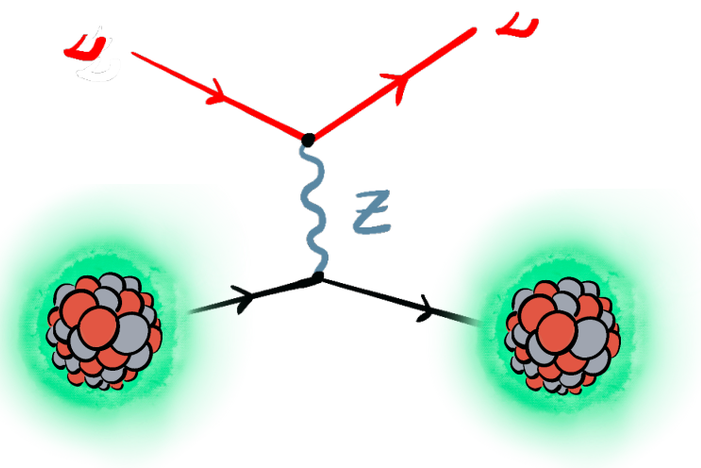
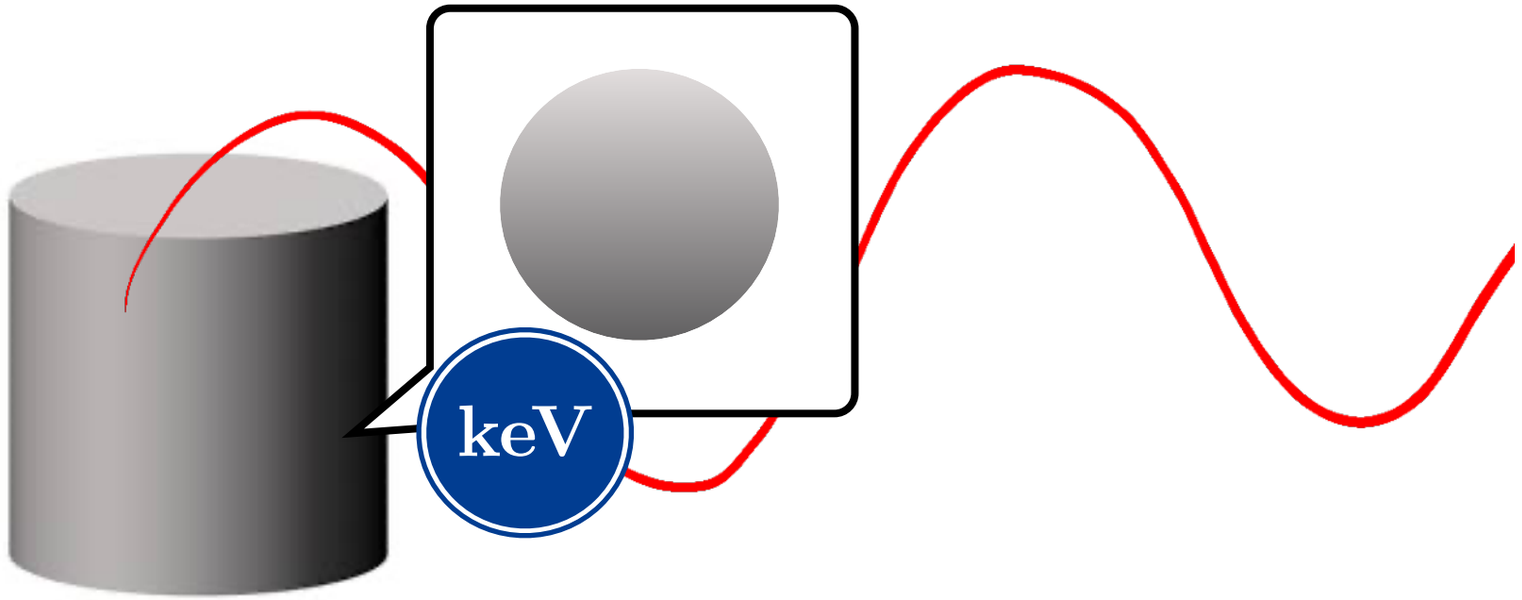
AIs: low momentum transfers





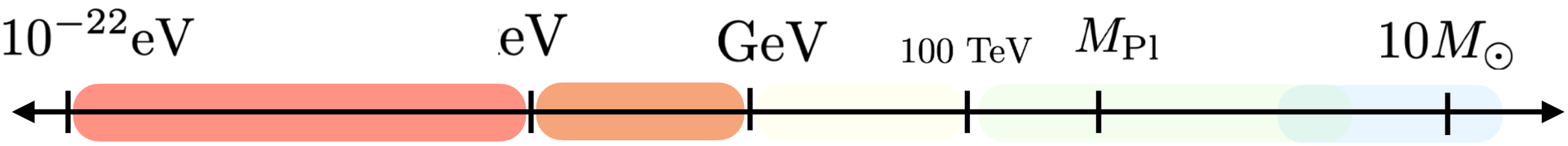


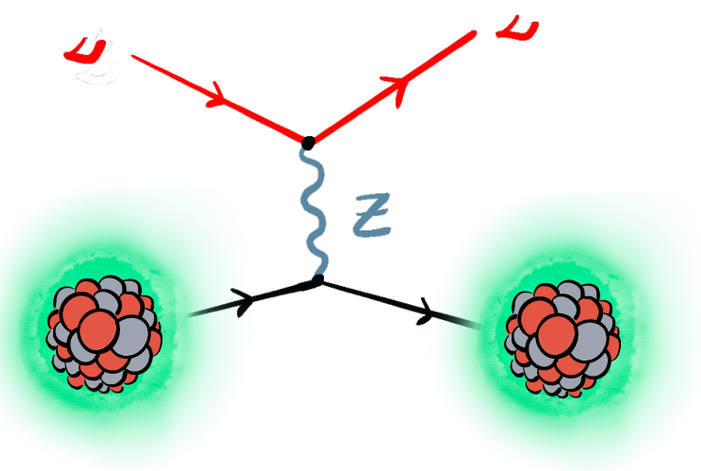
$$\Gamma \propto \int_{\rm keV}^{q_{\rm max}} dq\,(\cdots)$$

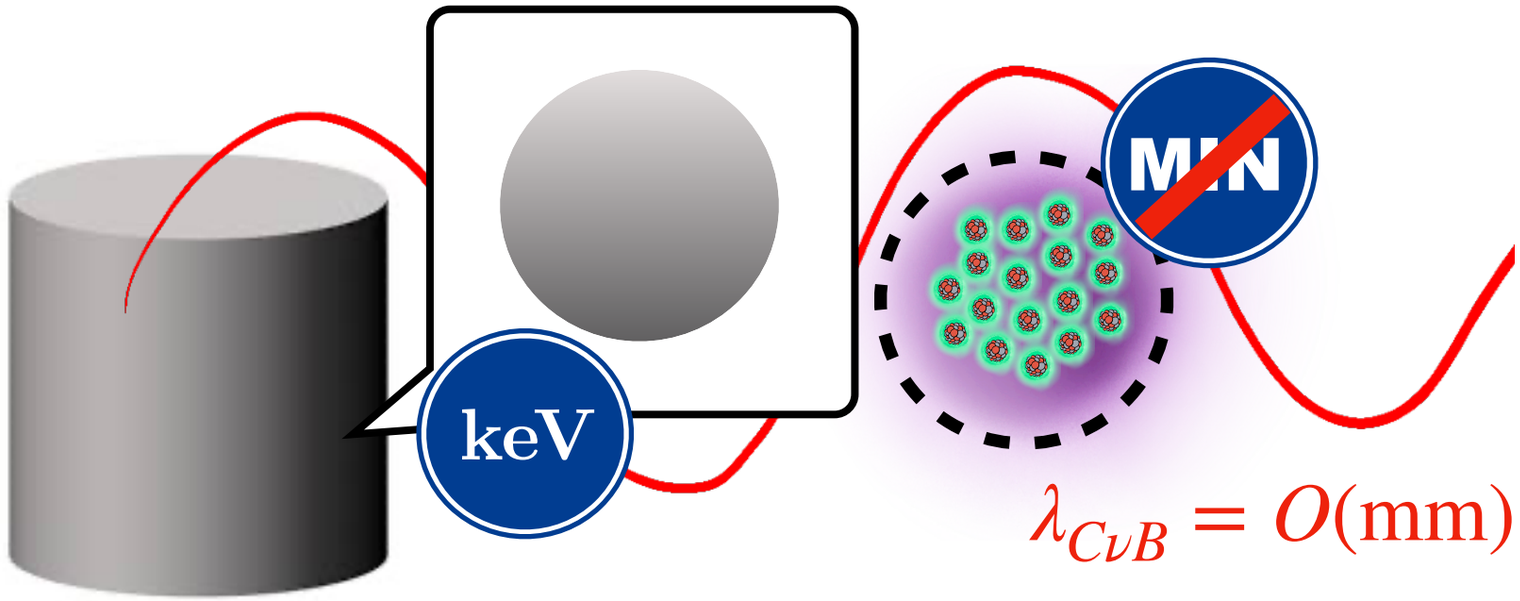
ATOM INTERFEROMETERS

NO minimum energy deposition!

AIs: low momentum transfers







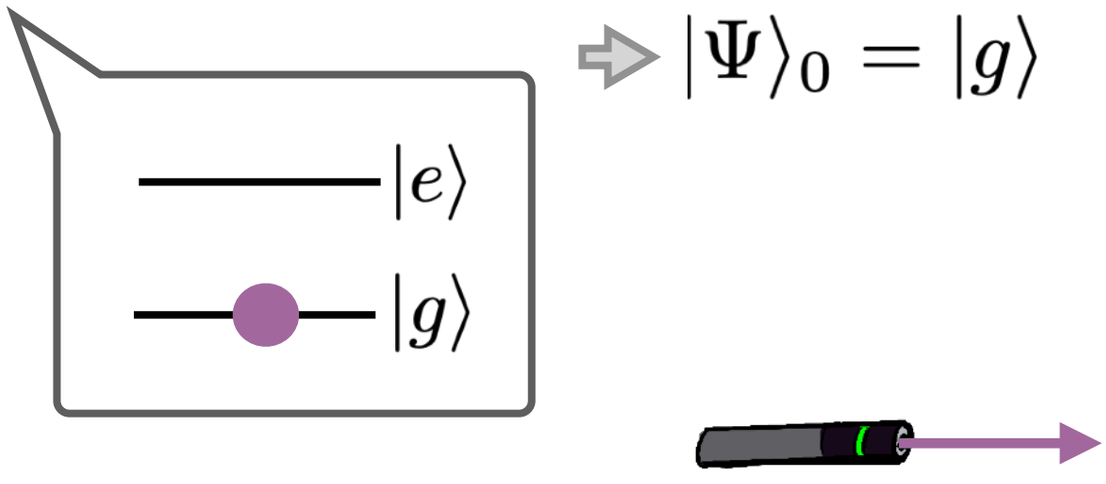
$$\Gamma \propto \int_0^{q_{\rm max}} dq\,(\cdots)$$

ATOM INTERFEROMETERS

NO minimum energy deposition!

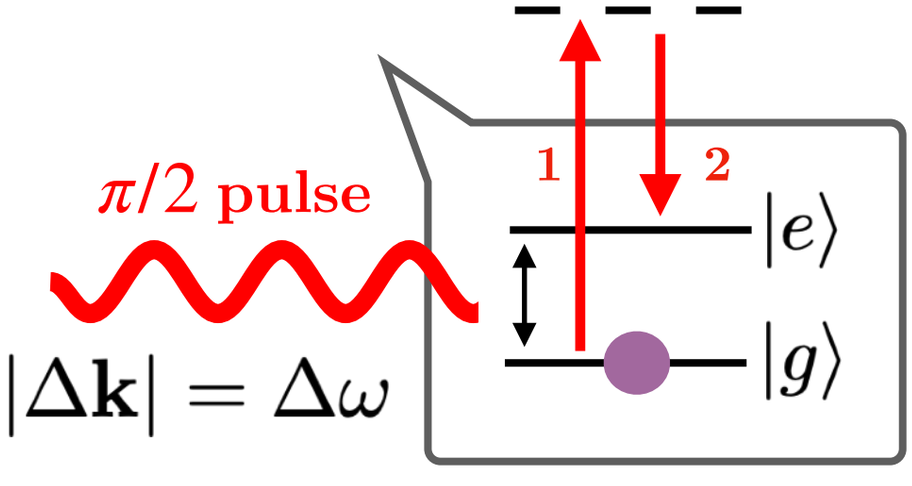
AIs: the Principle

Review: arXiv:2003.12516



AIs: the Principle

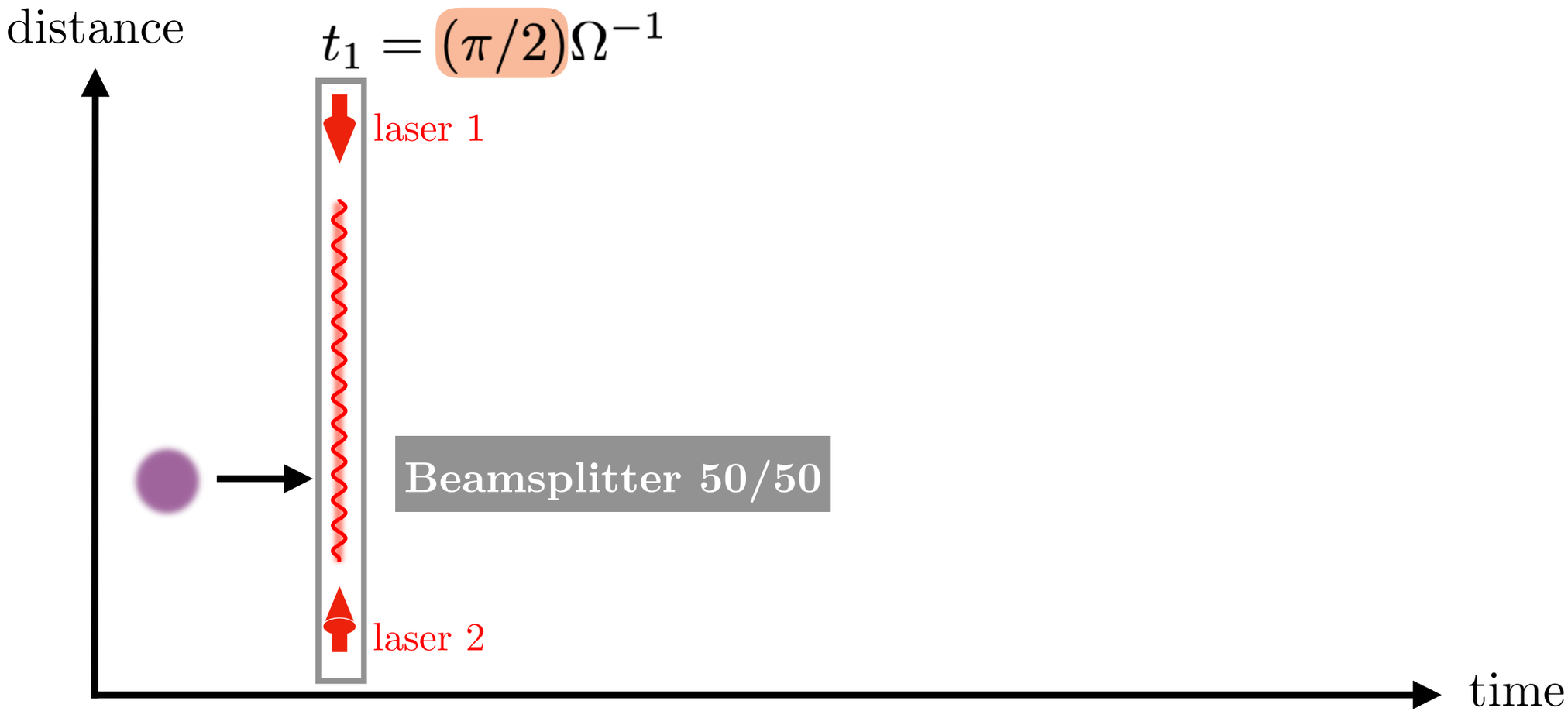
Review: arXiv:2003.12516

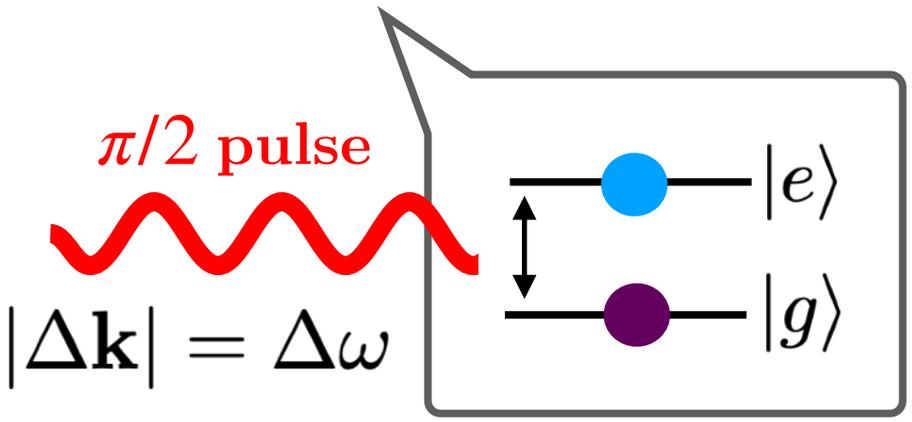


$$\Rightarrow |\Psi\rangle_t = \cos(\Omega t/2)|g\rangle + i\sin(\Omega t/2)|e\rangle$$

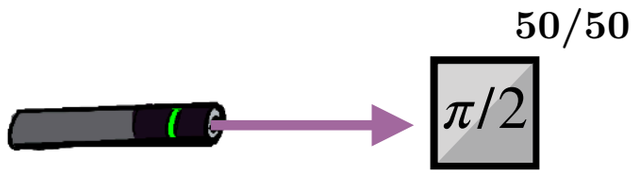
AIs: the Principle

Review: arXiv:2003.12516



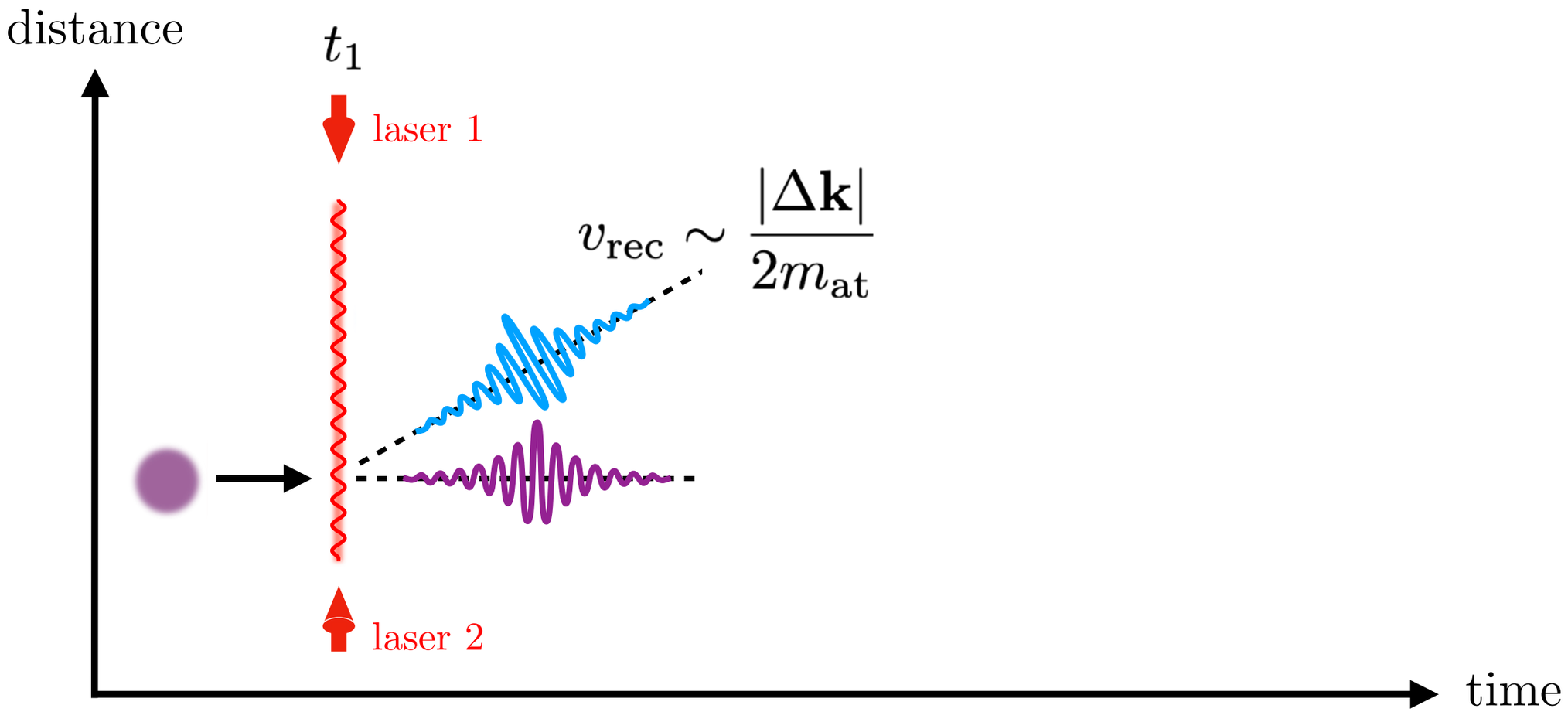


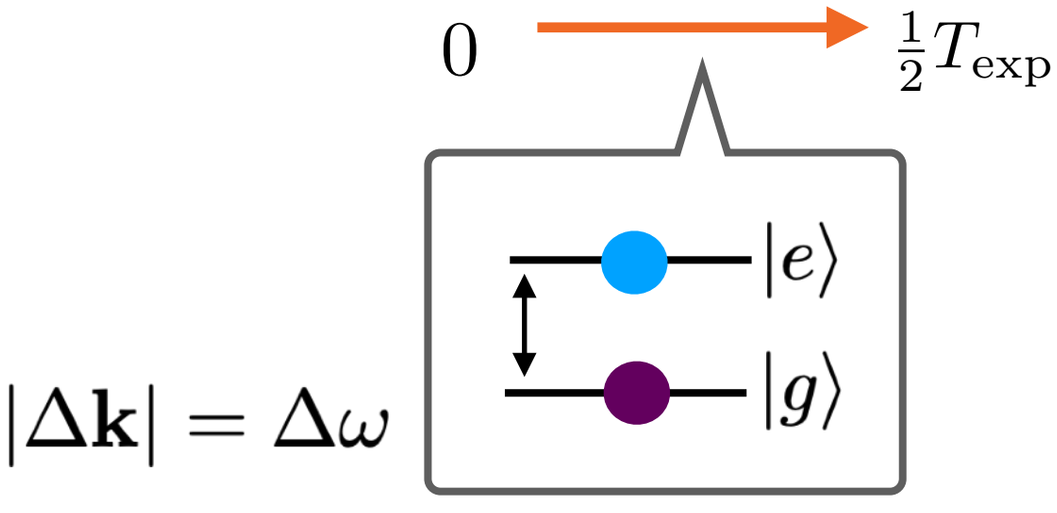
$$\Rightarrow |\Psi\rangle_t = \cos(\,\pi/4\,)|g\rangle + i\sin(\,\pi/4\,)|e\rangle$$

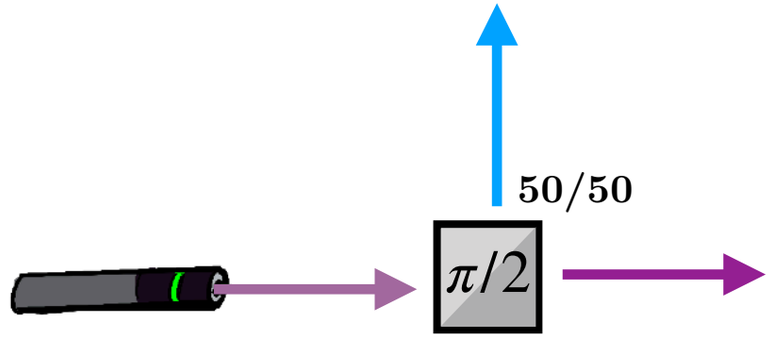


AIs: the Principle

Review: arXiv:2003.12516

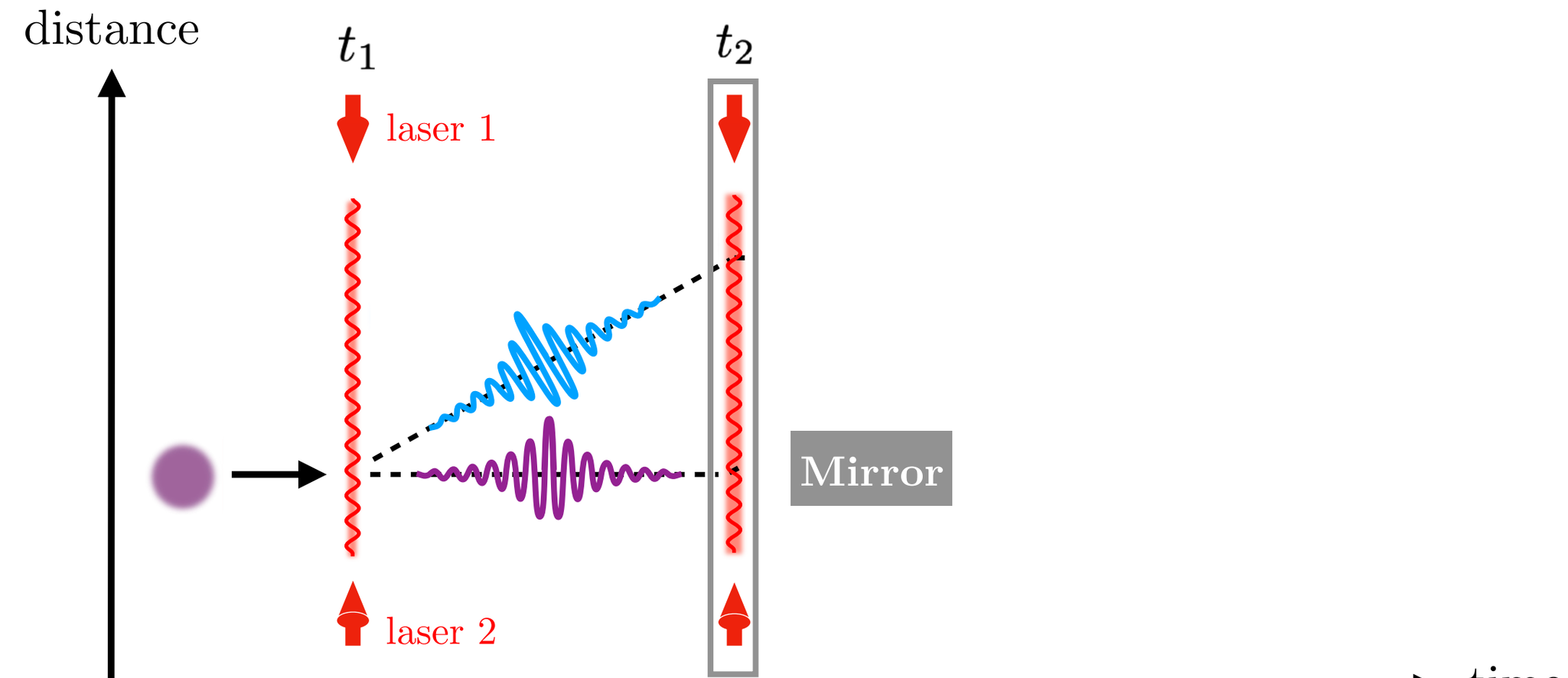


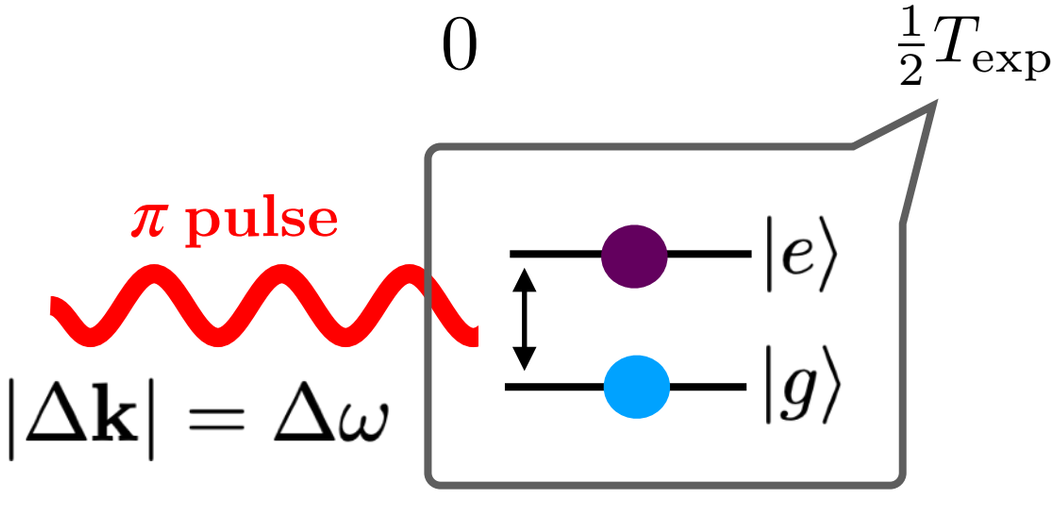


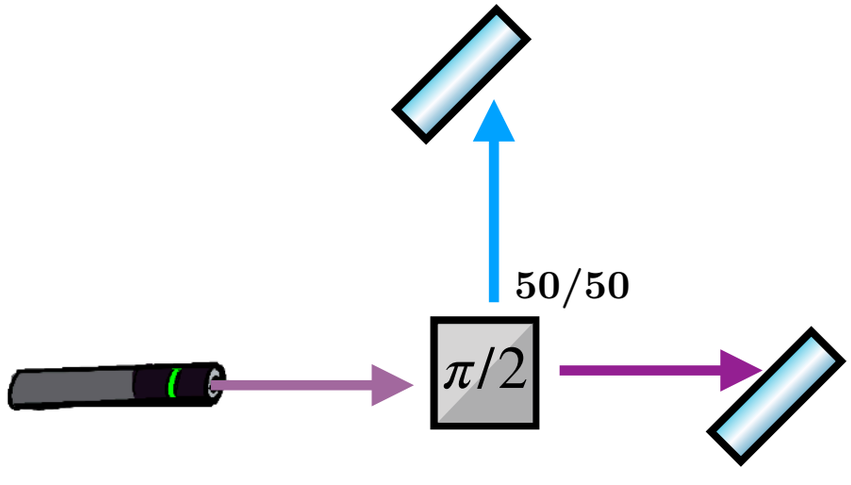


AIs: the Principle

Review: arXiv:2003.12516

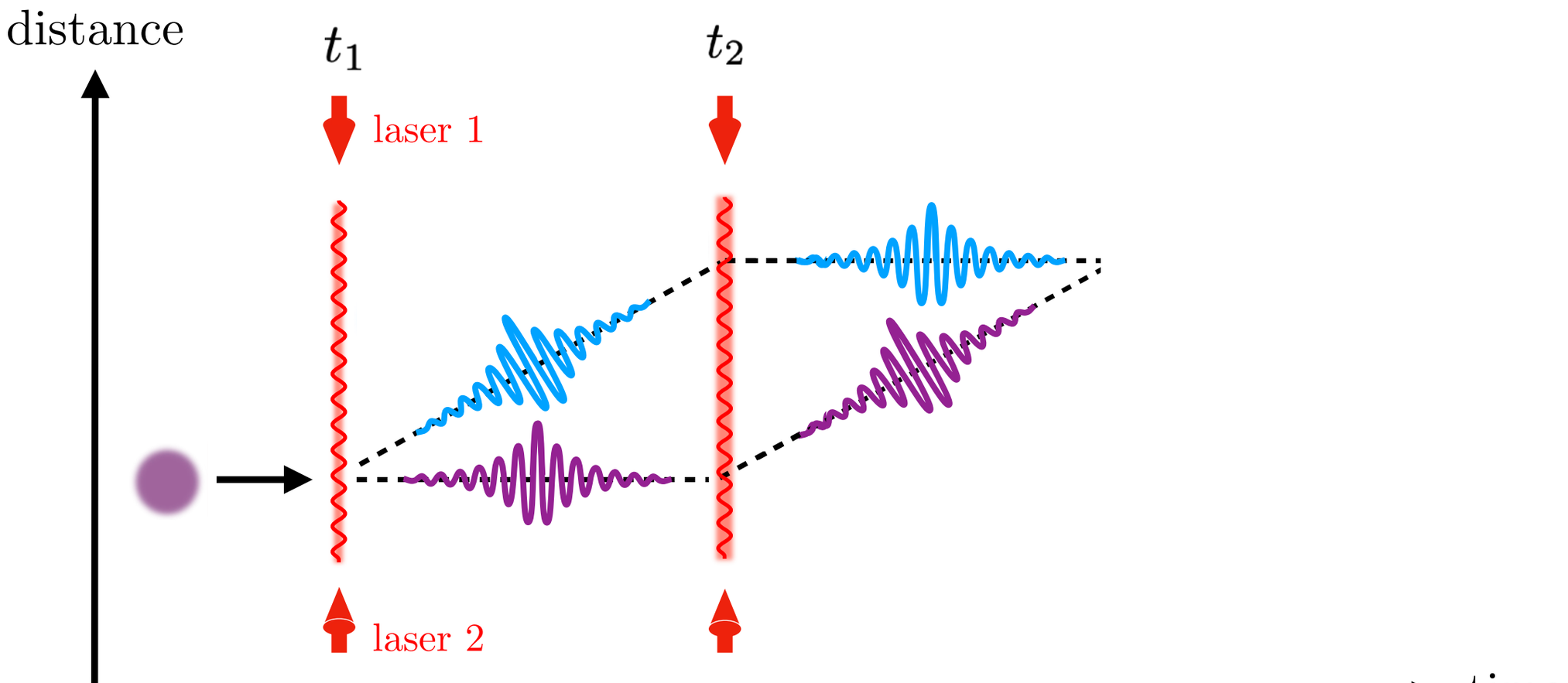


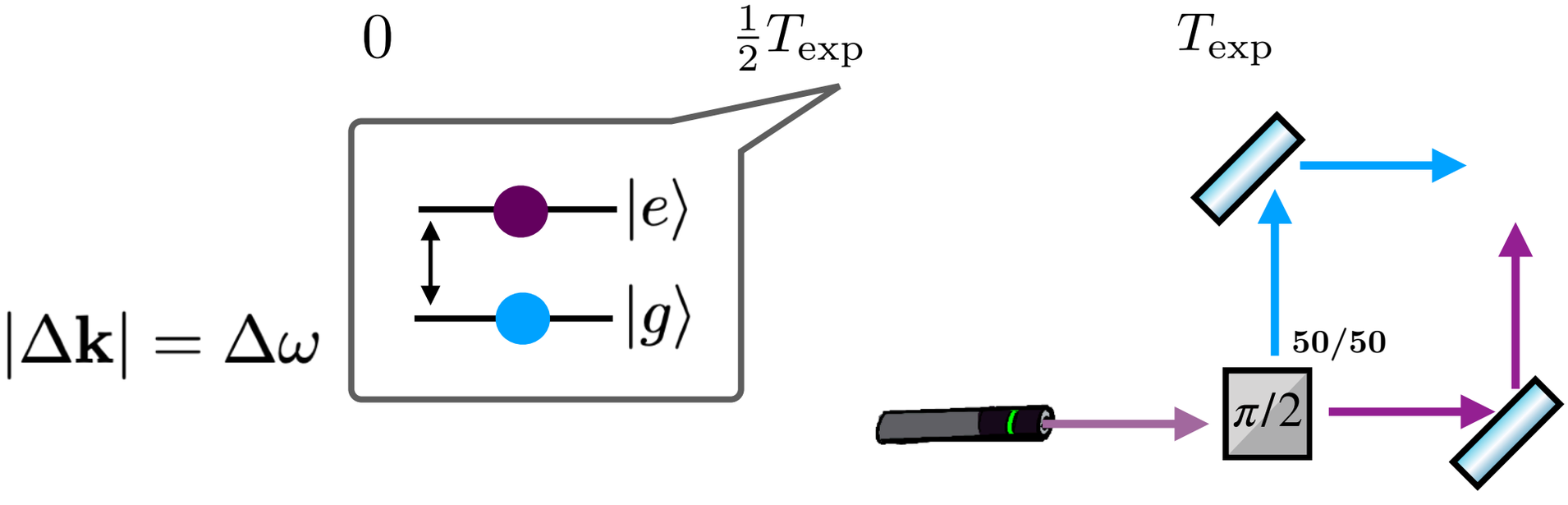




AIs: the Principle

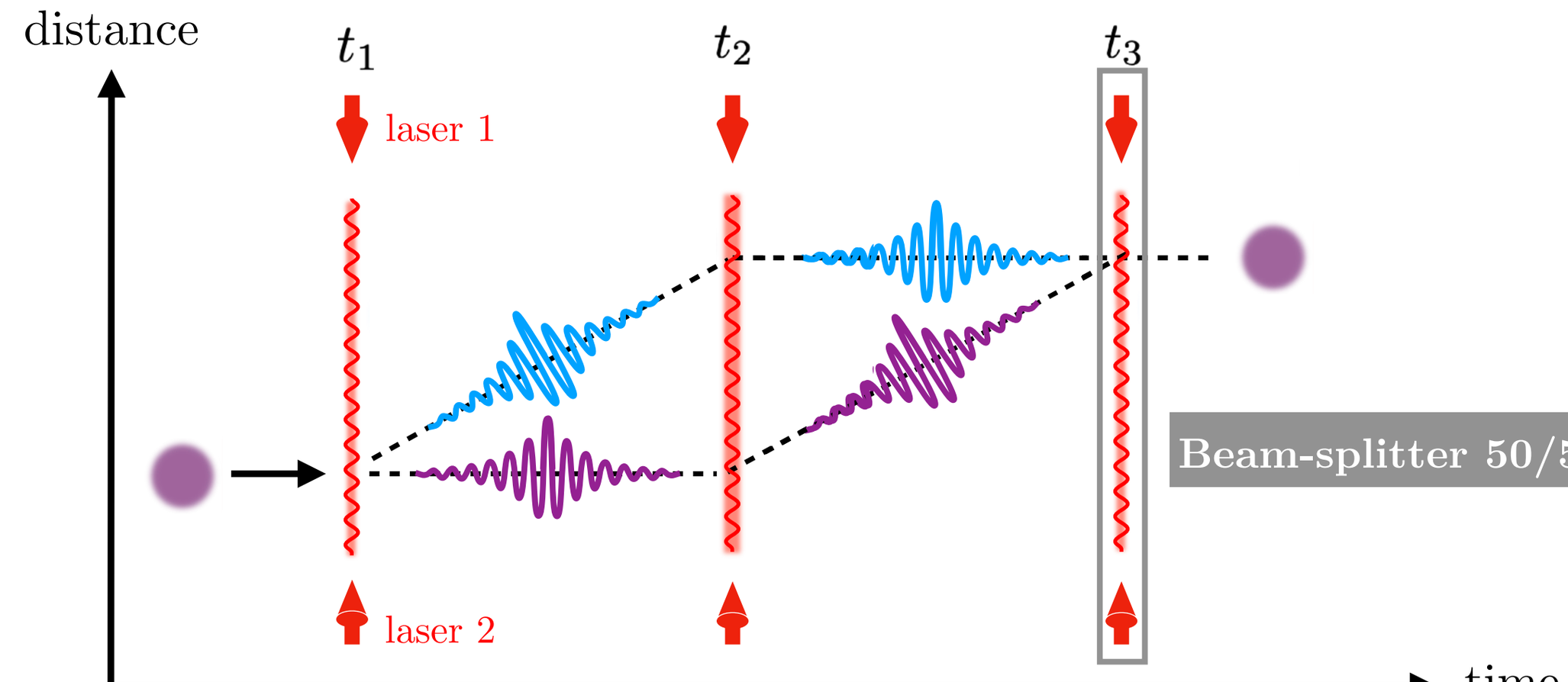
Review: arXiv:2003.12516

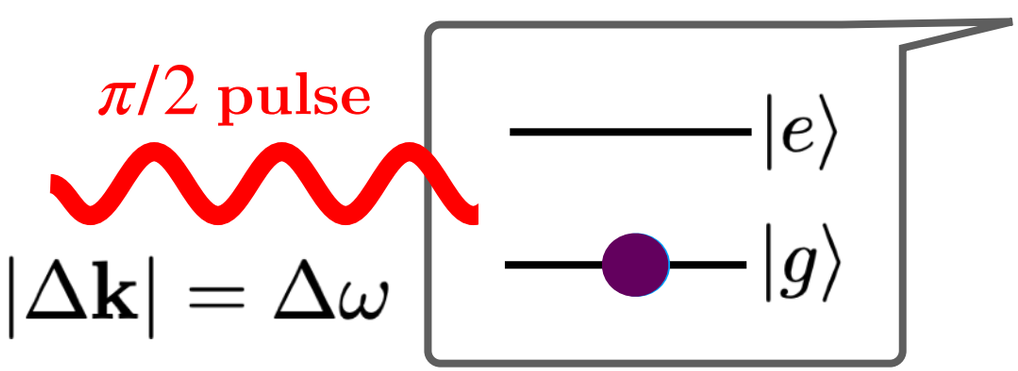


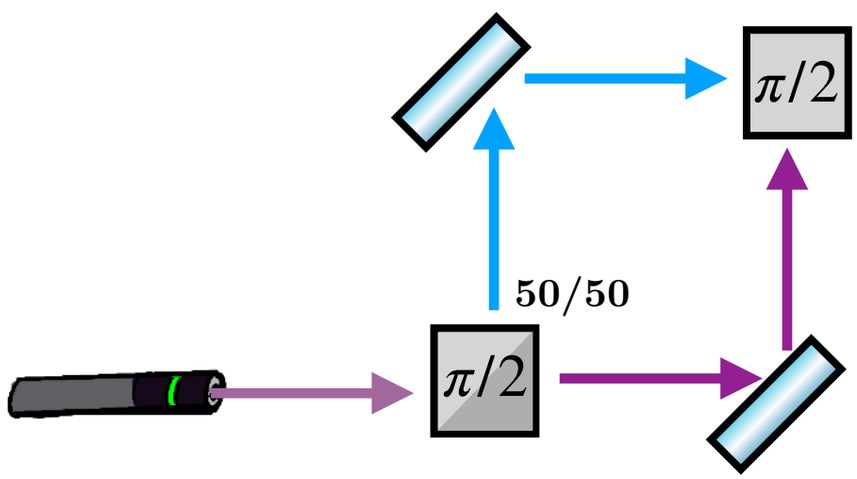


AIs: the Principle

Review: arXiv:2003.12516

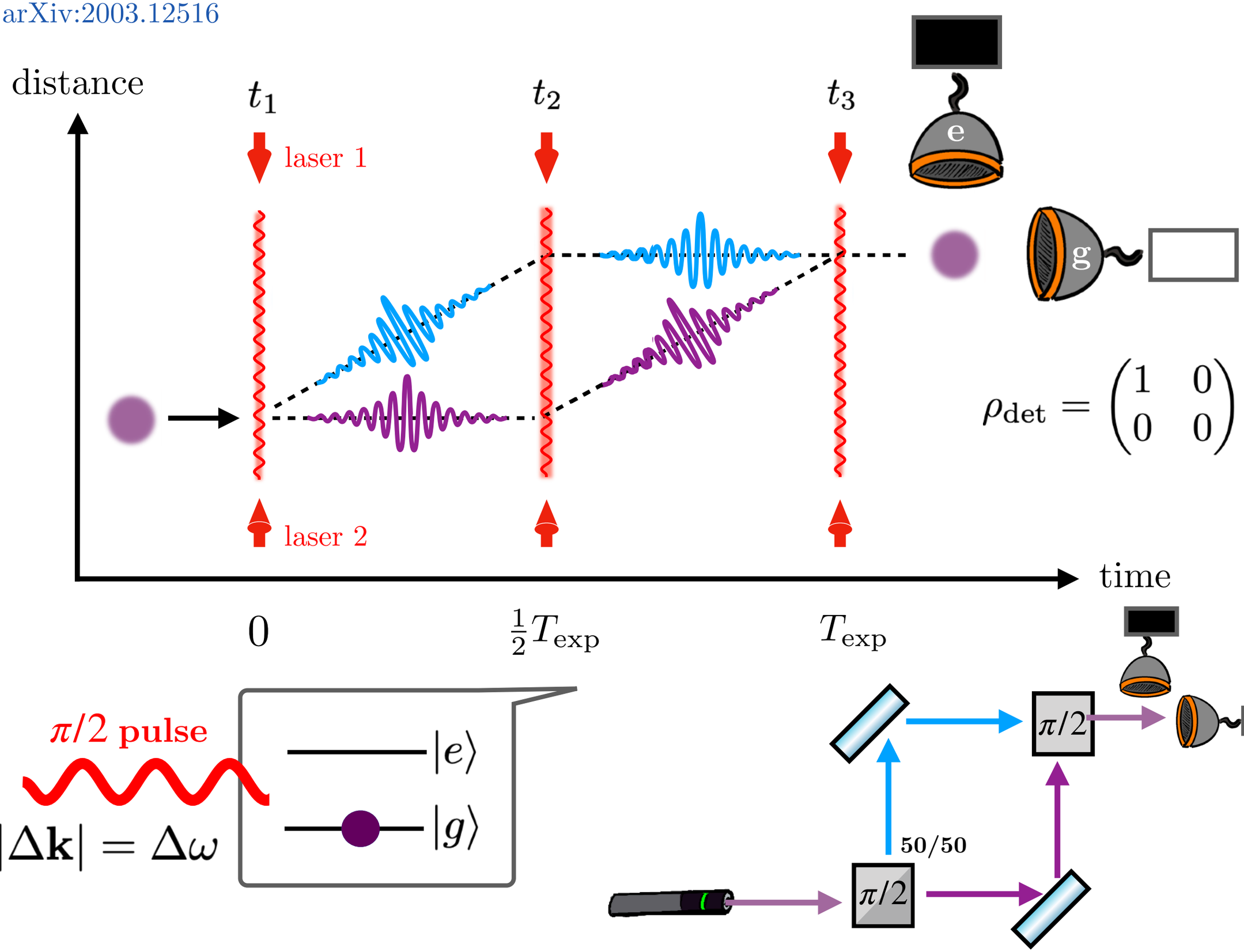




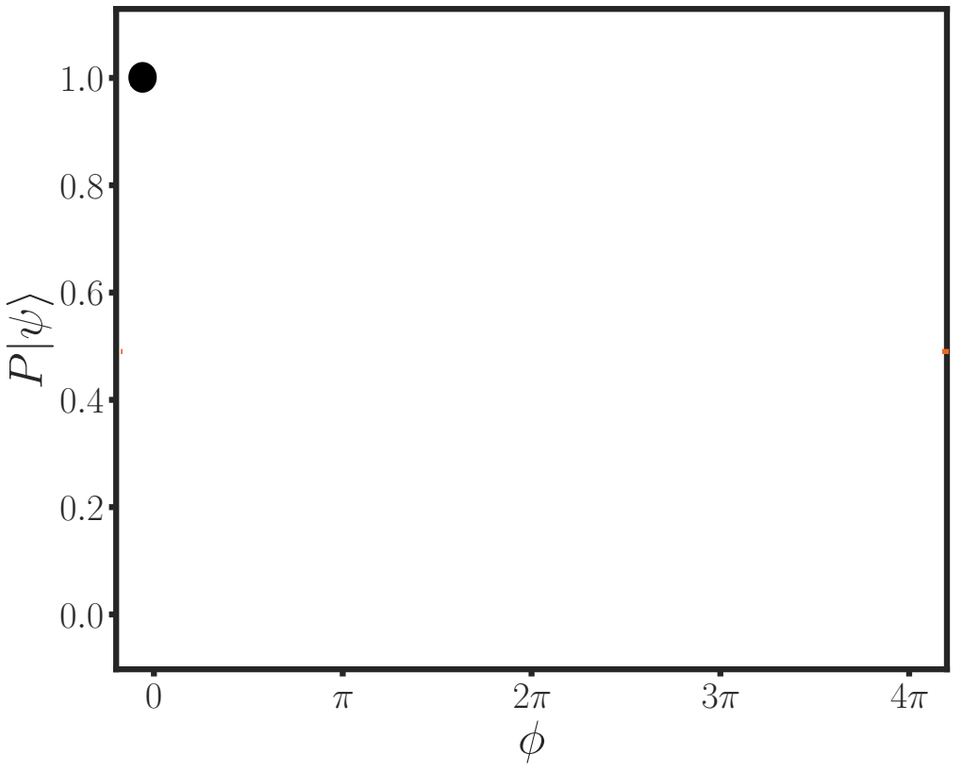


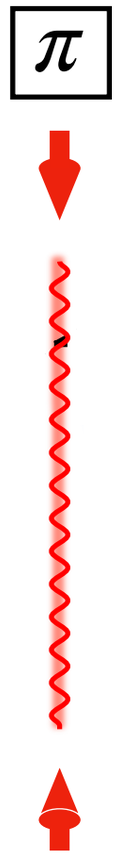
AIs: the Principle

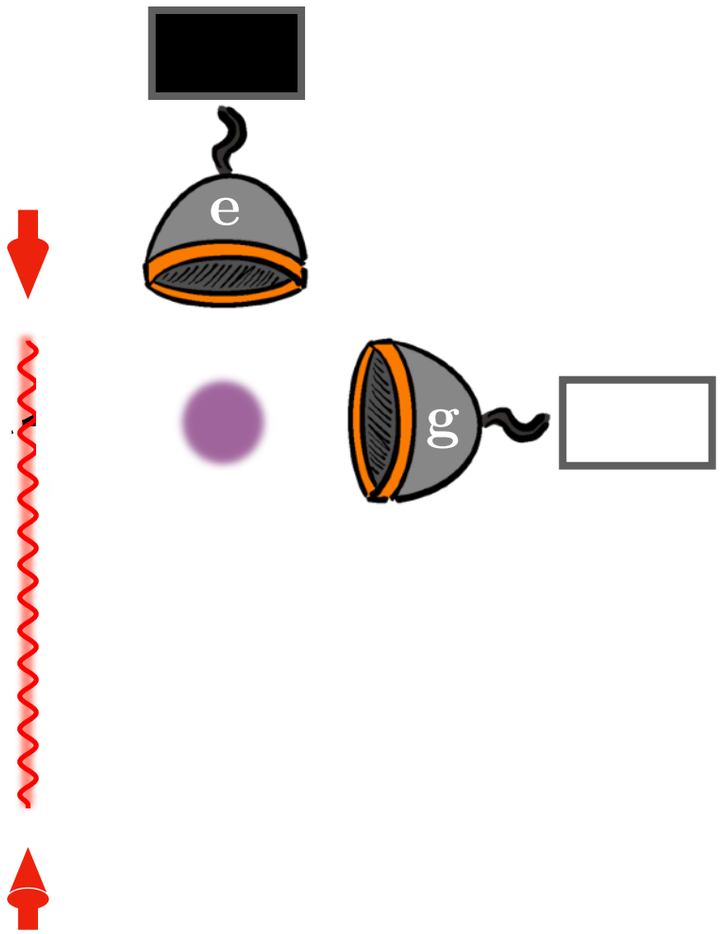
Review: arXiv:2003.12516



AIs: Measurement

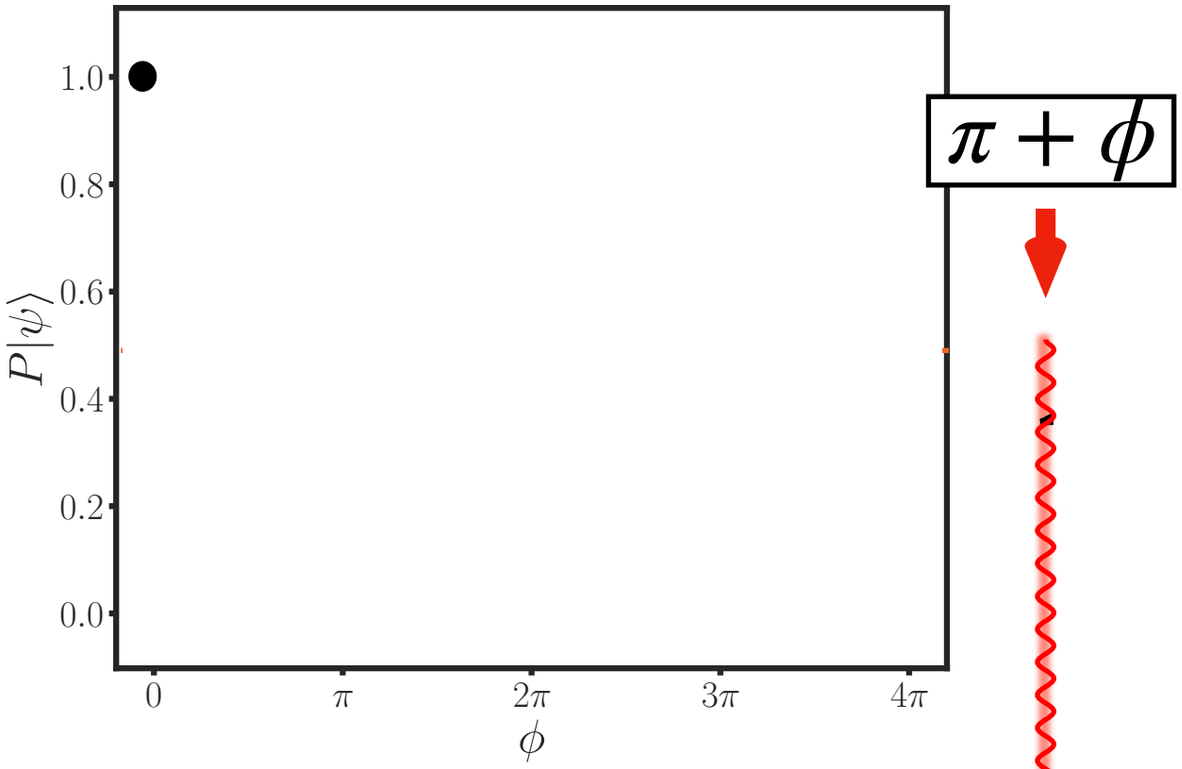


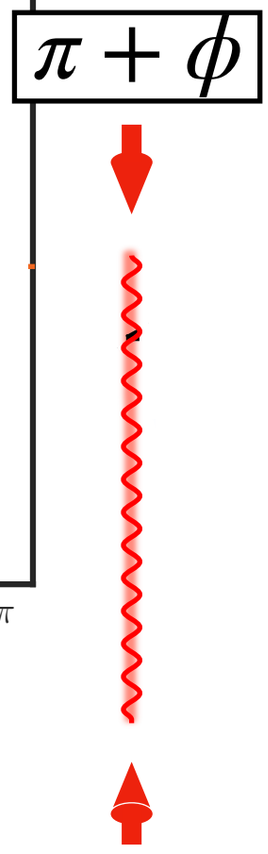


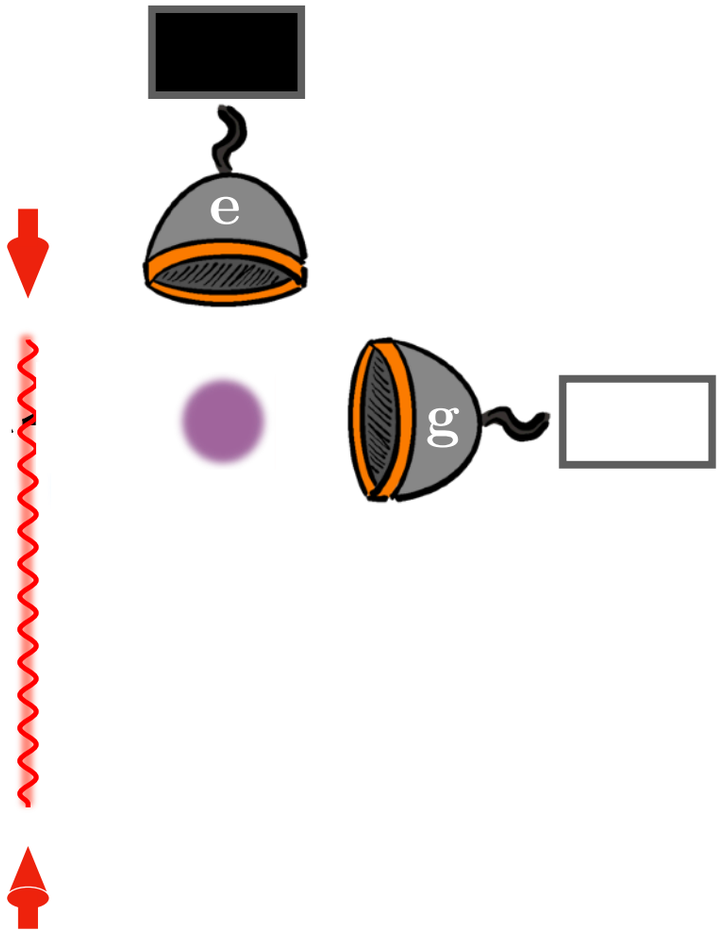


$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\text{exp}}$$

AIs: Measurement



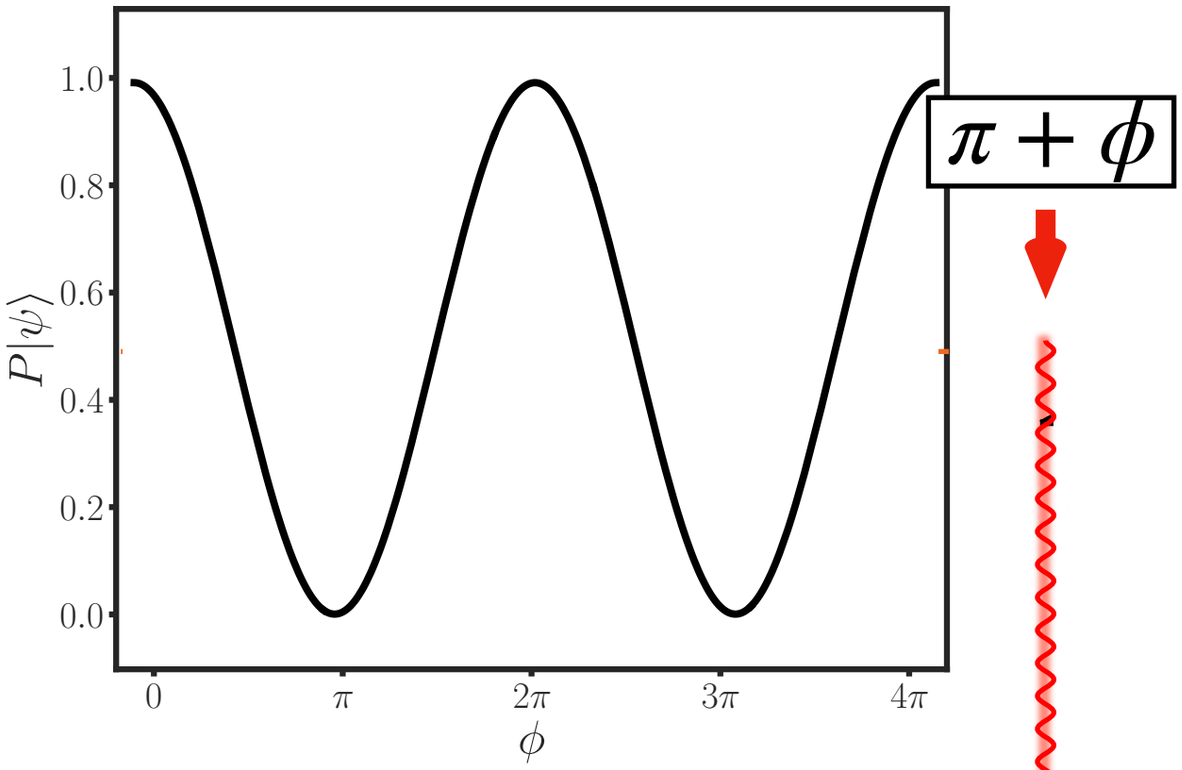


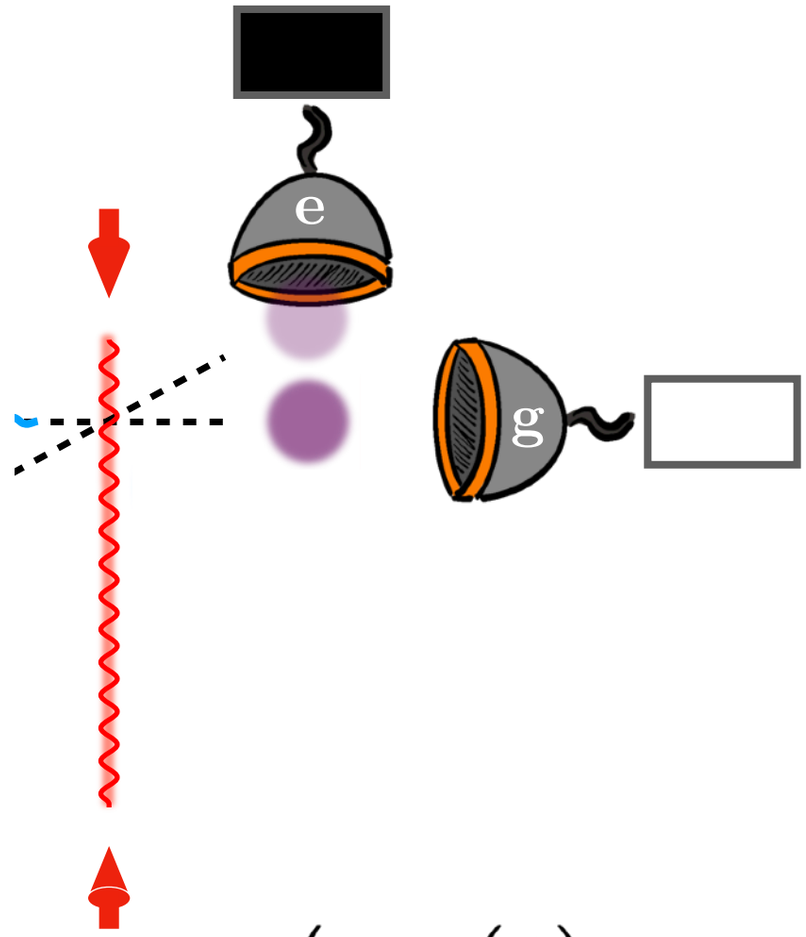


$$\rho = \frac{1}{2}\begin{pmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{pmatrix}$$

$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\text{exp}}$$

AIs: Measurement

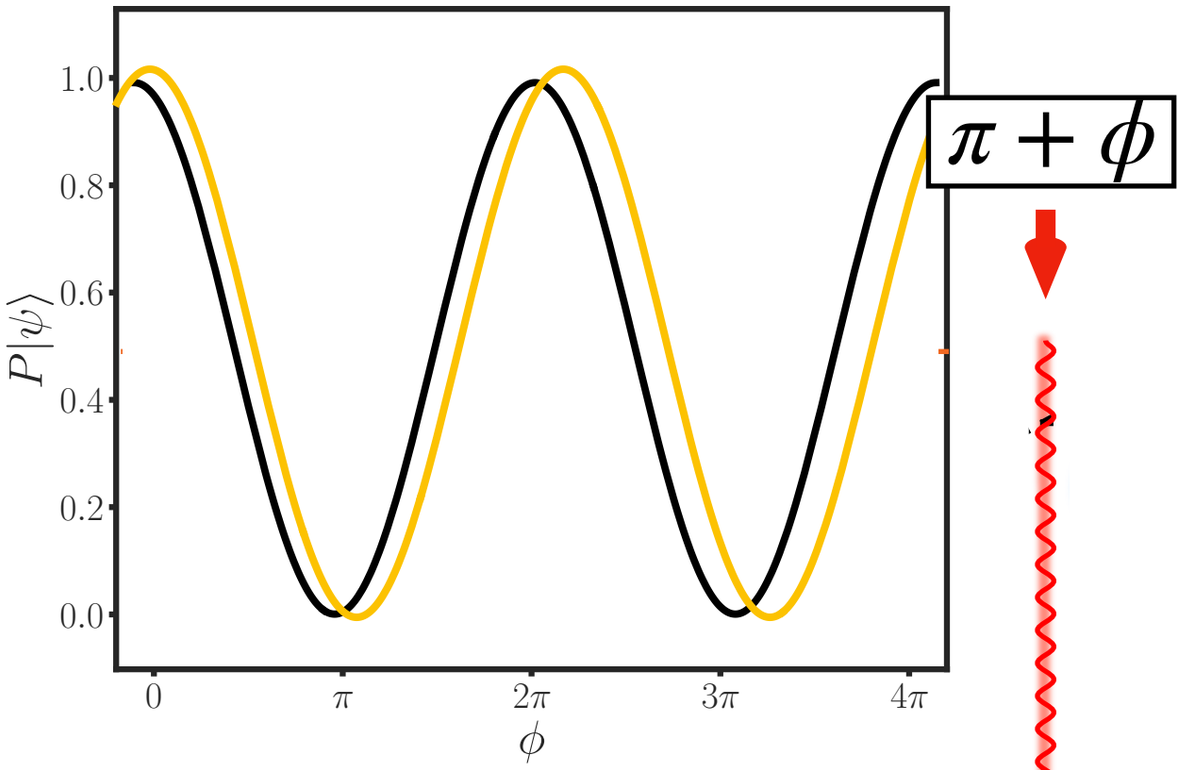


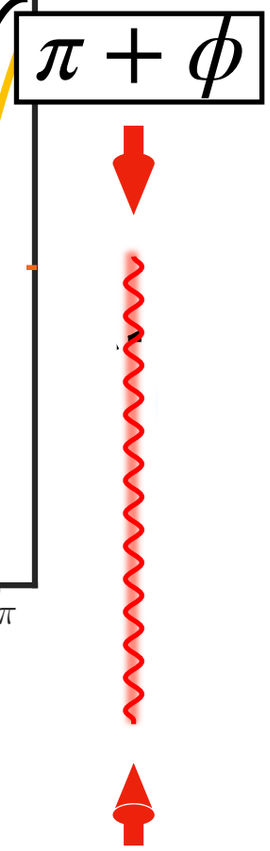


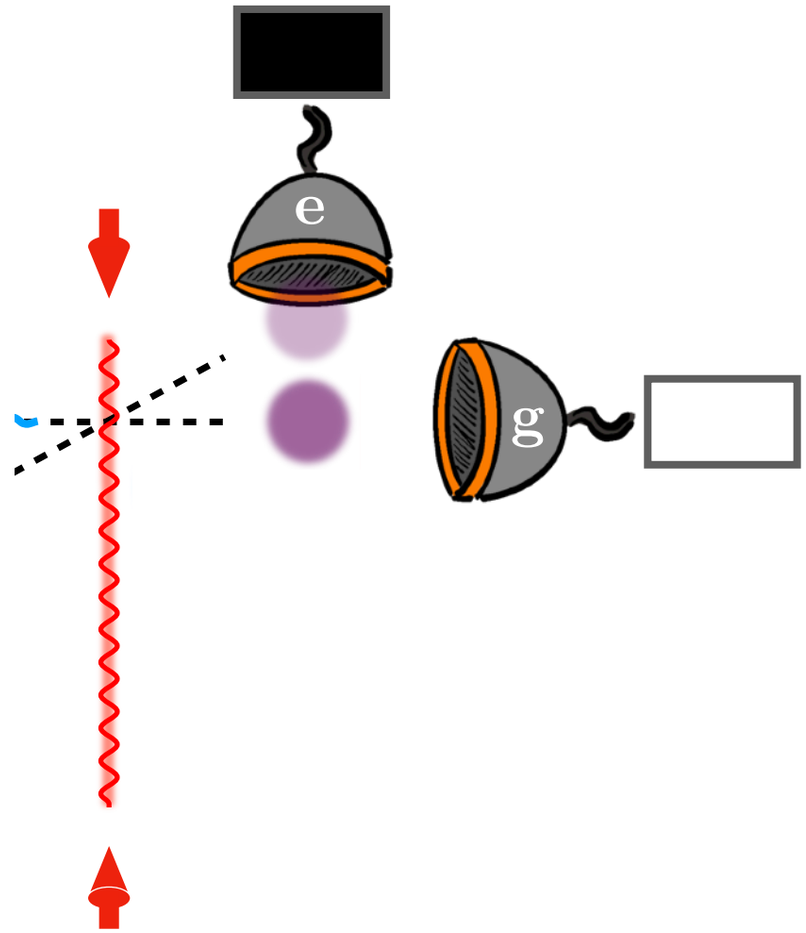
$$\rho = \frac{1}{2}\begin{pmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{pmatrix} \Rightarrow \rho = \begin{pmatrix} \cos^2\left(\frac{\phi}{2}\right) & -\frac{1}{2}i\sin\phi \\ \frac{1}{2}i\sin\phi & \sin^2\left(\frac{\phi}{2}\right) \end{pmatrix}$$

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

AIs: Measurement - Phase-shift



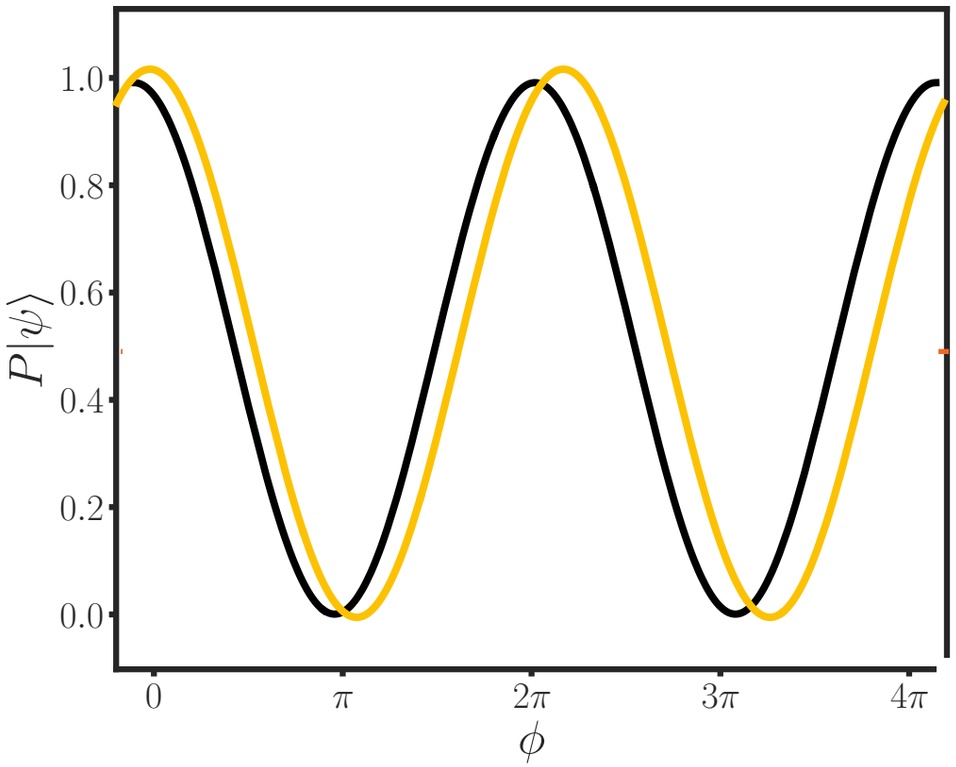




$$\rho = \frac{1}{2}\begin{pmatrix} 1 & e^{i(\phi+\Delta\phi)} \\ e^{-i(\phi+\Delta\phi)} & 1 \end{pmatrix}$$

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

AIs: Measurement - Phase-shift



[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]
...

ULDM

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

EDMs

[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]

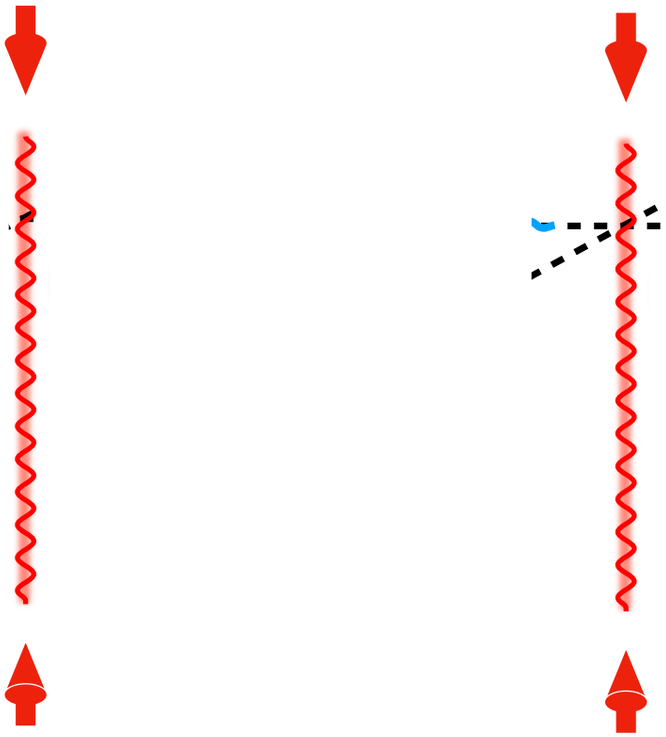
GWs

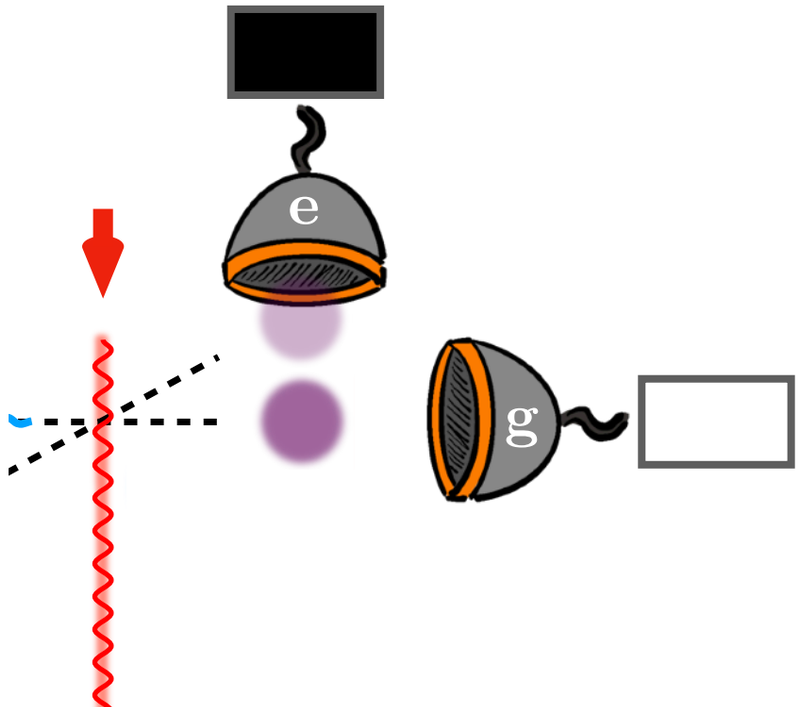
5th forces

[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] ....

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

AIs: Measurement - Particle scattering?





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

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

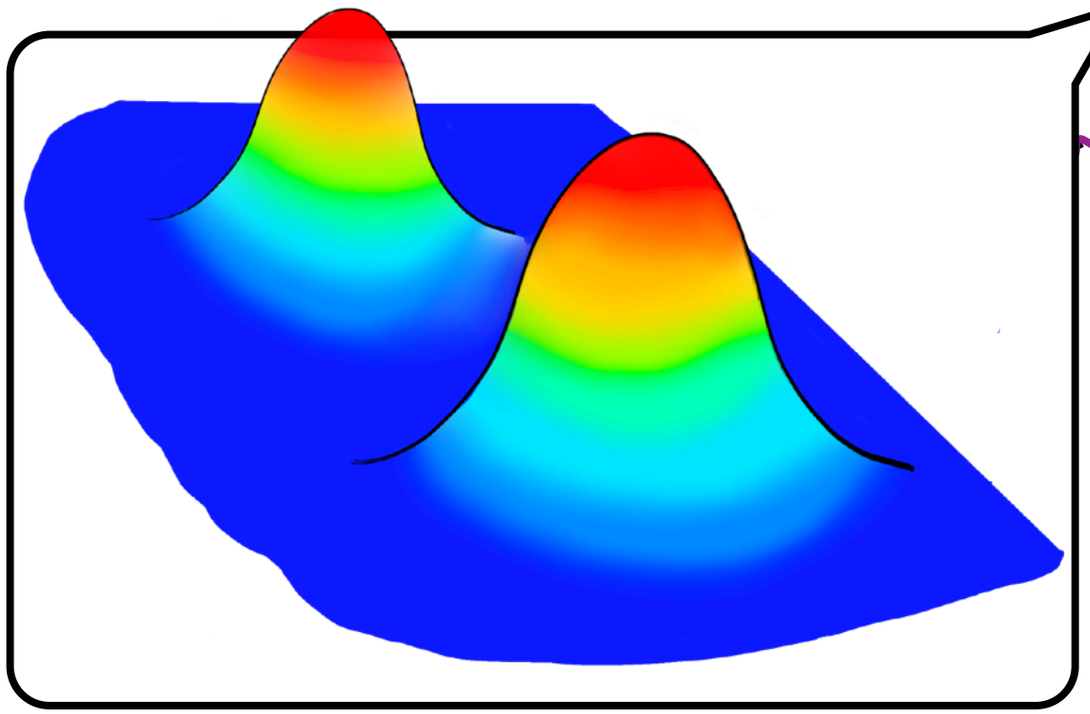
AIs: Collisional Decoherence

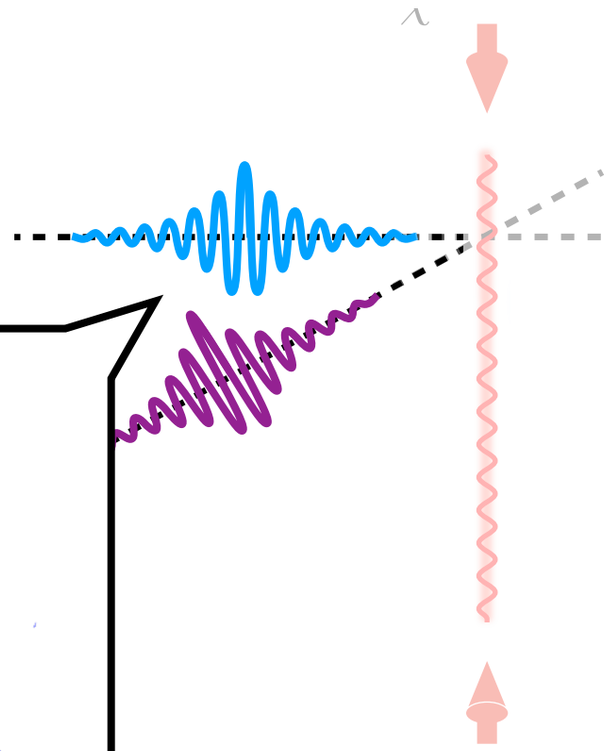
A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]

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





$|\mathbf{x}\rangle$

AI

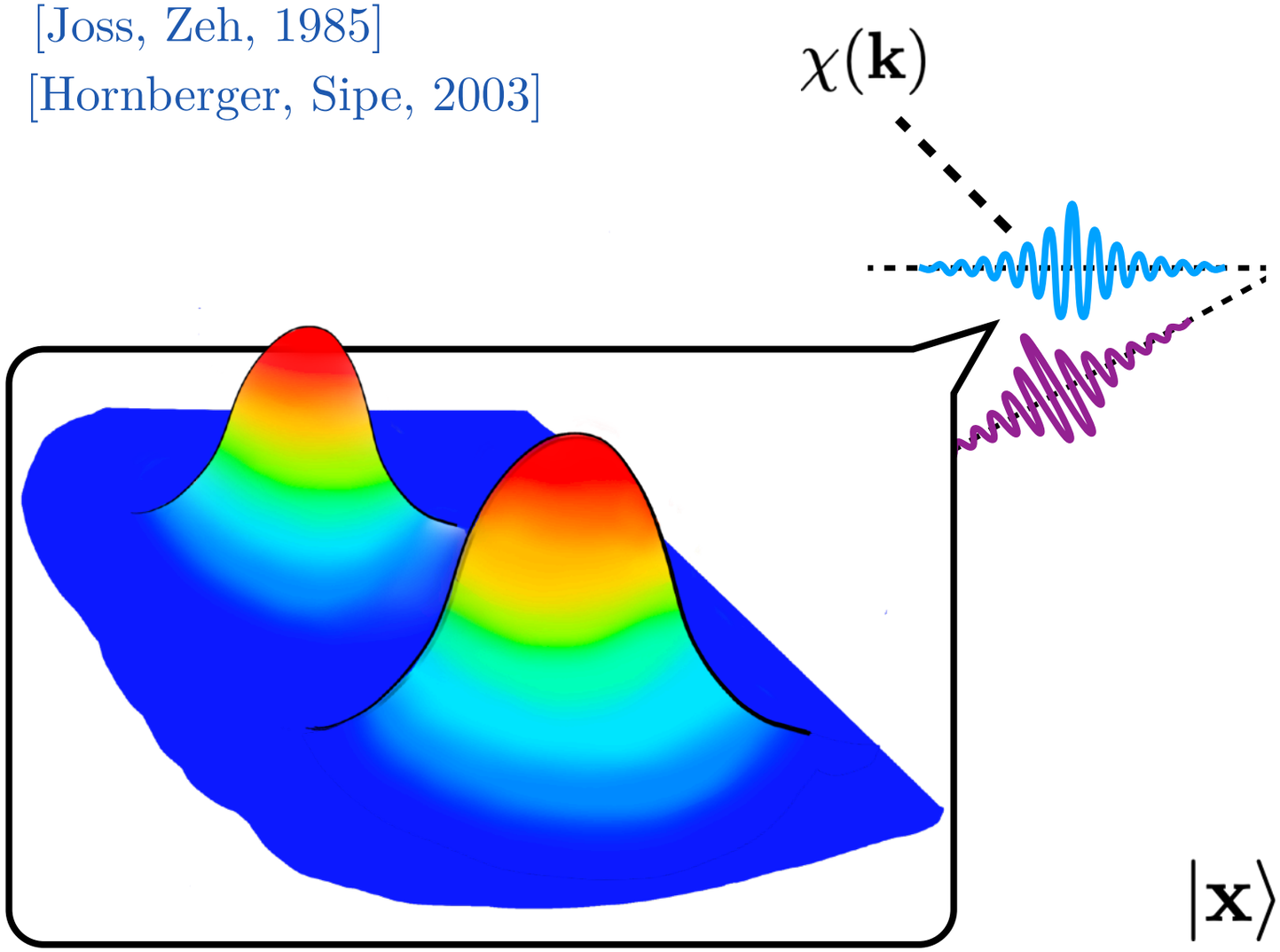
AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]

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



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

AI

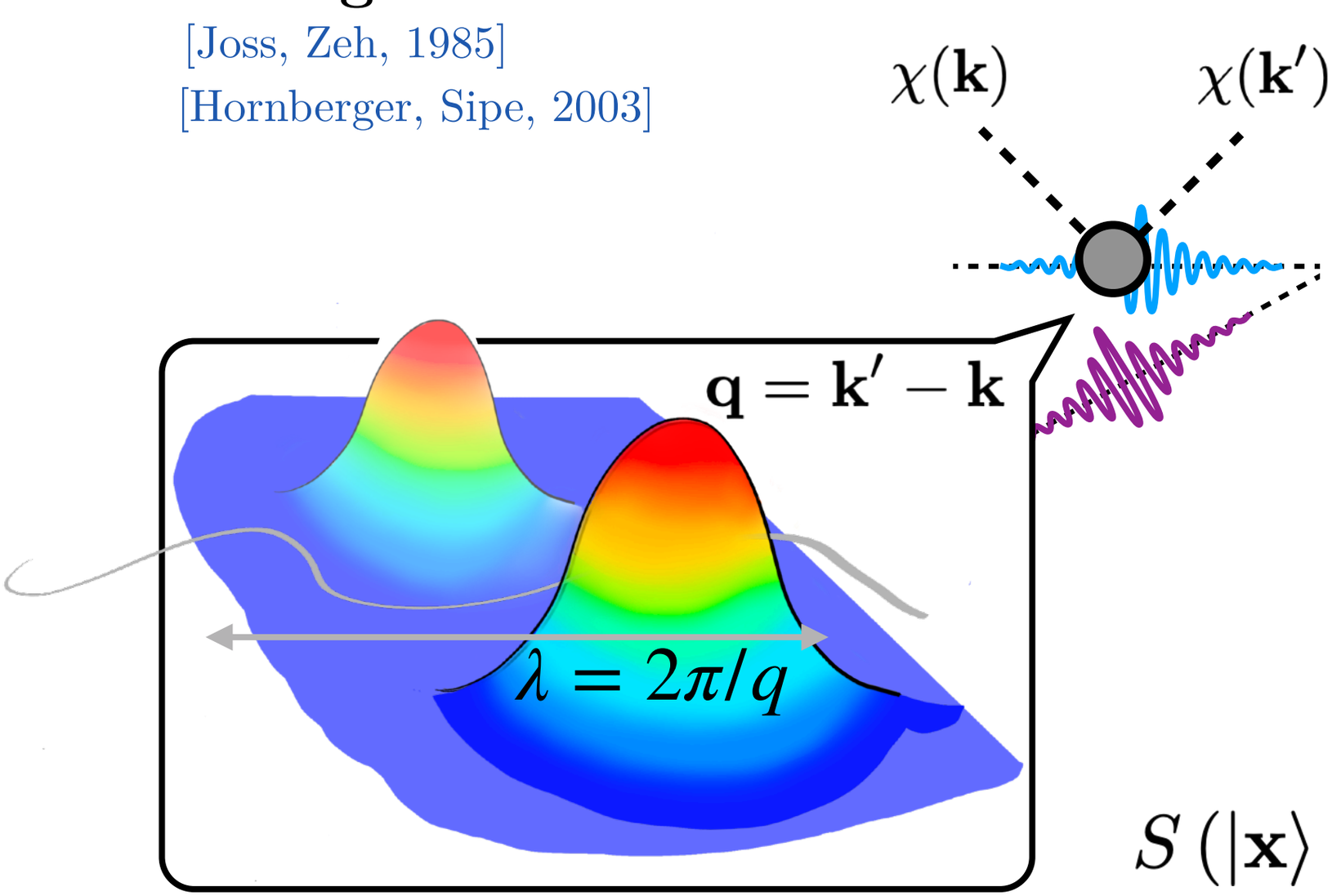
env

AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]



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

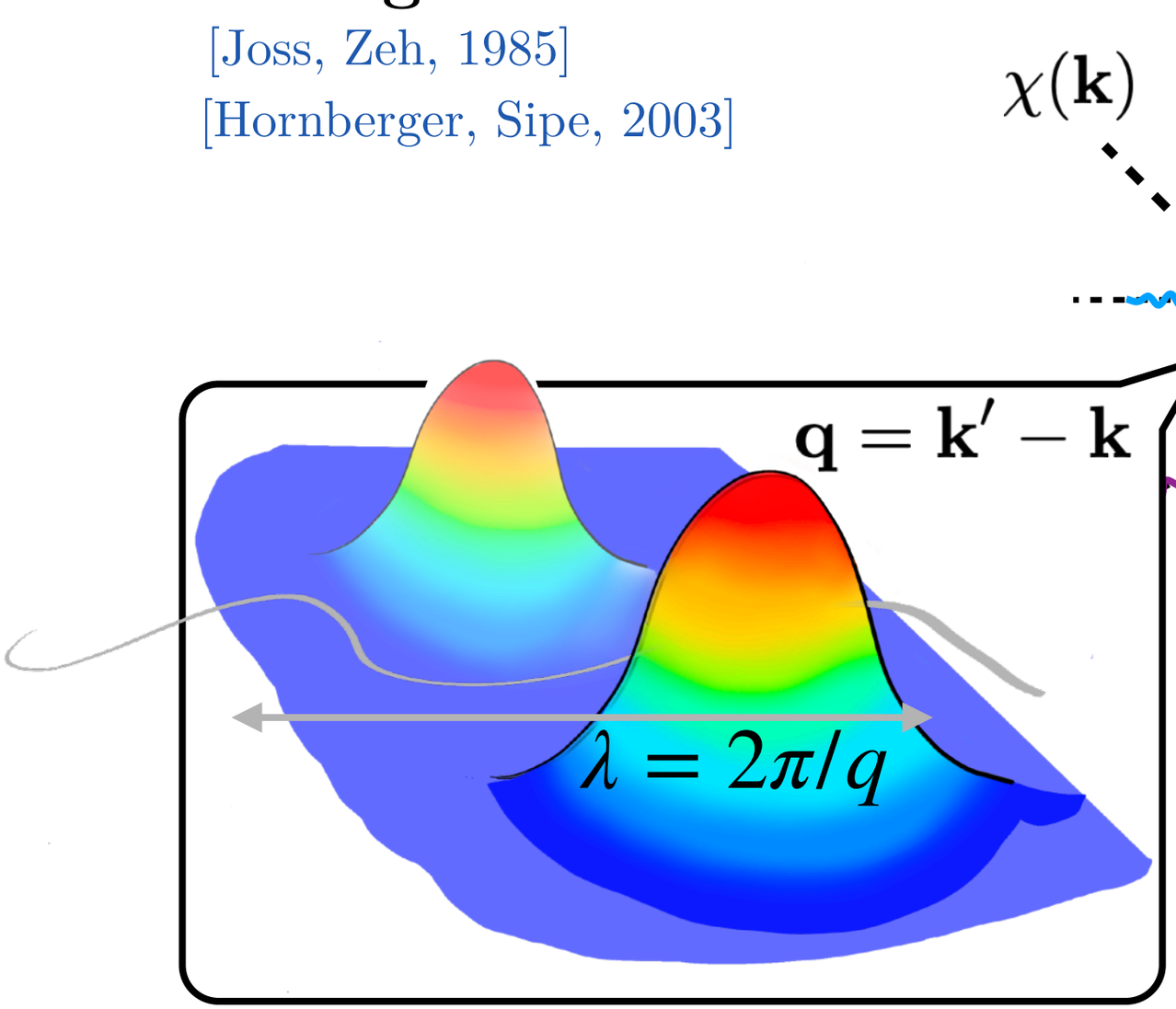
$$S\left(|\mathbf{x}\rangle \otimes |\mathbf{k}\rangle\right)$$

AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]



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

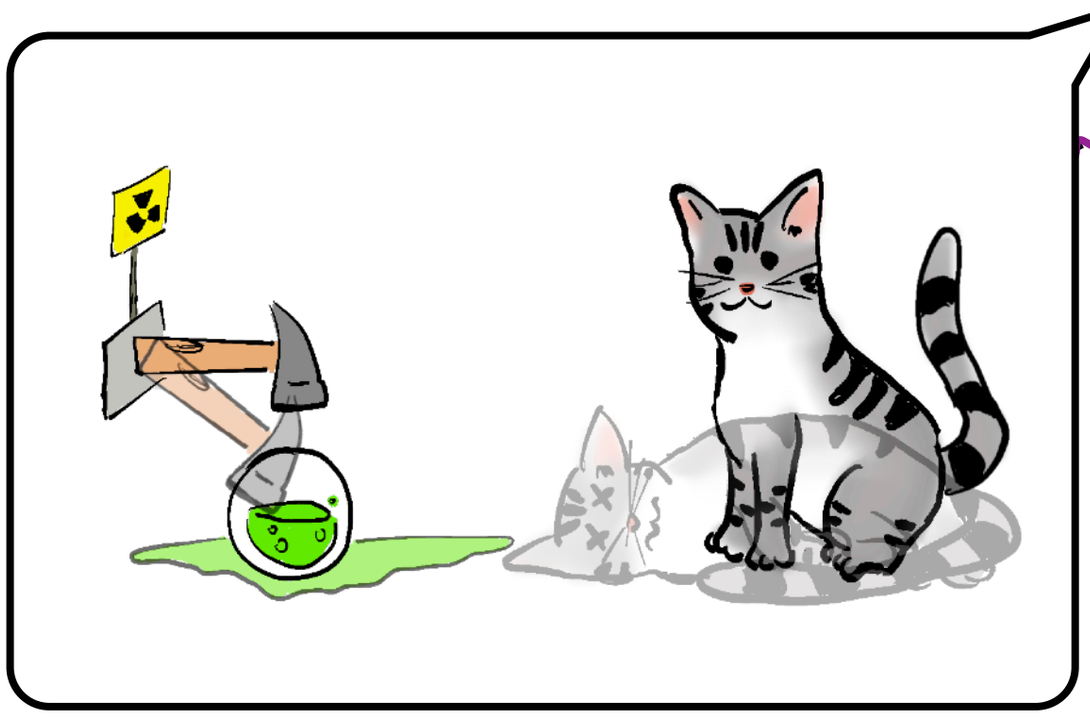
$$S\left(|\mathbf{x}\rangle \otimes |\mathbf{k}\rangle\right) = |\mathbf{x}\rangle \otimes S_{\{\mathbf{x}\}}|\mathbf{k}\rangle$$

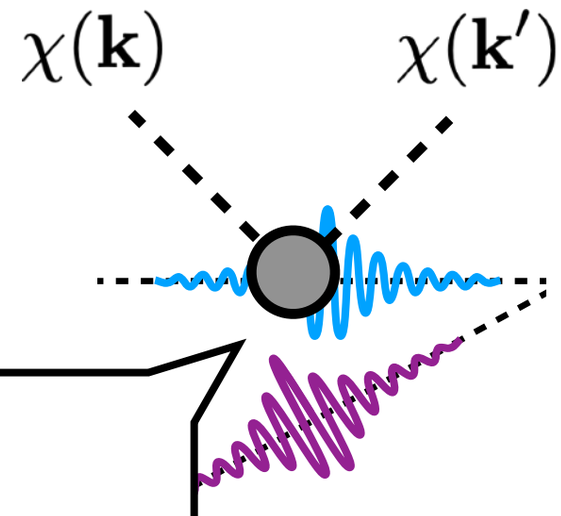
AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]





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

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

AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

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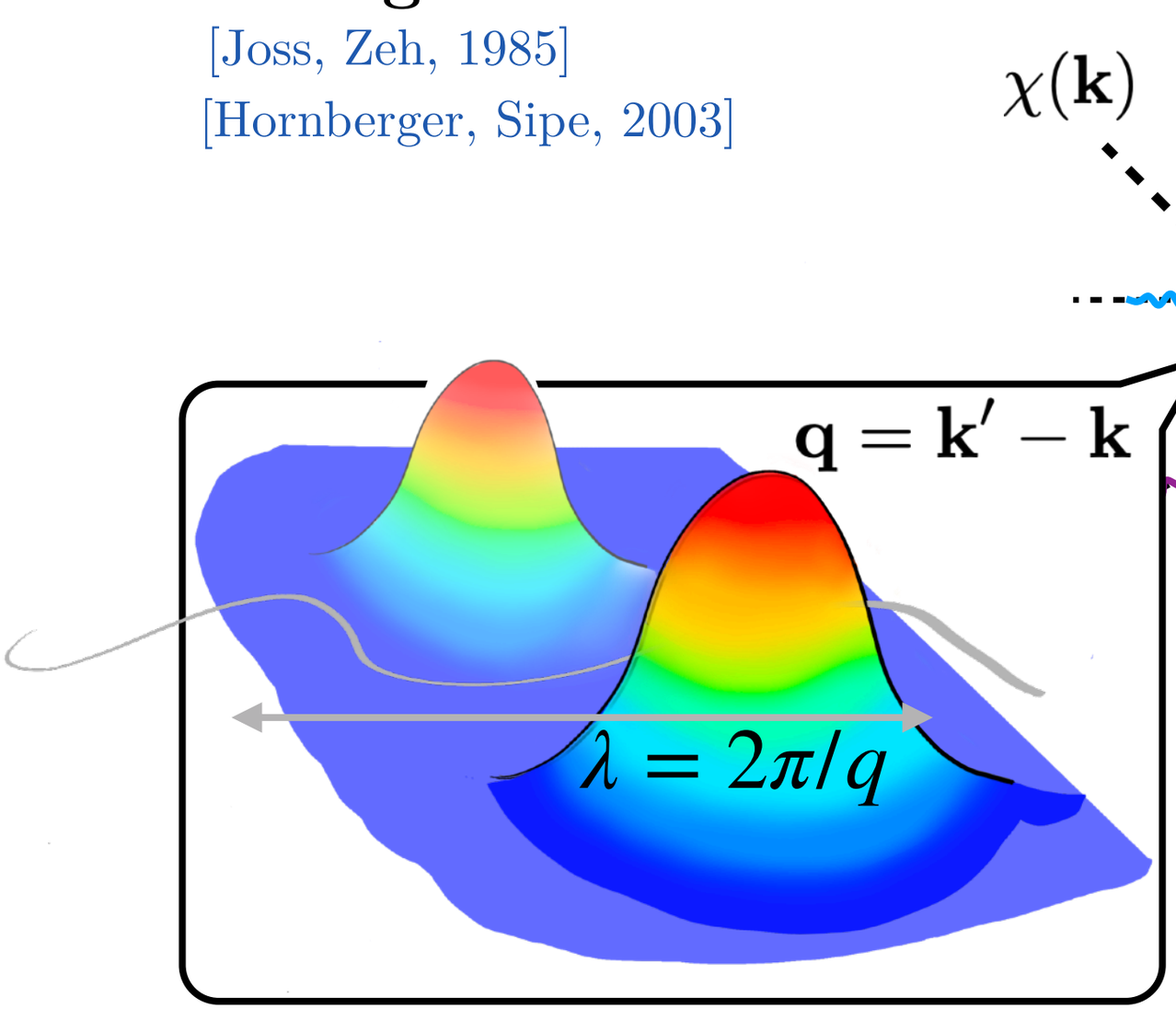


$$\rho = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

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

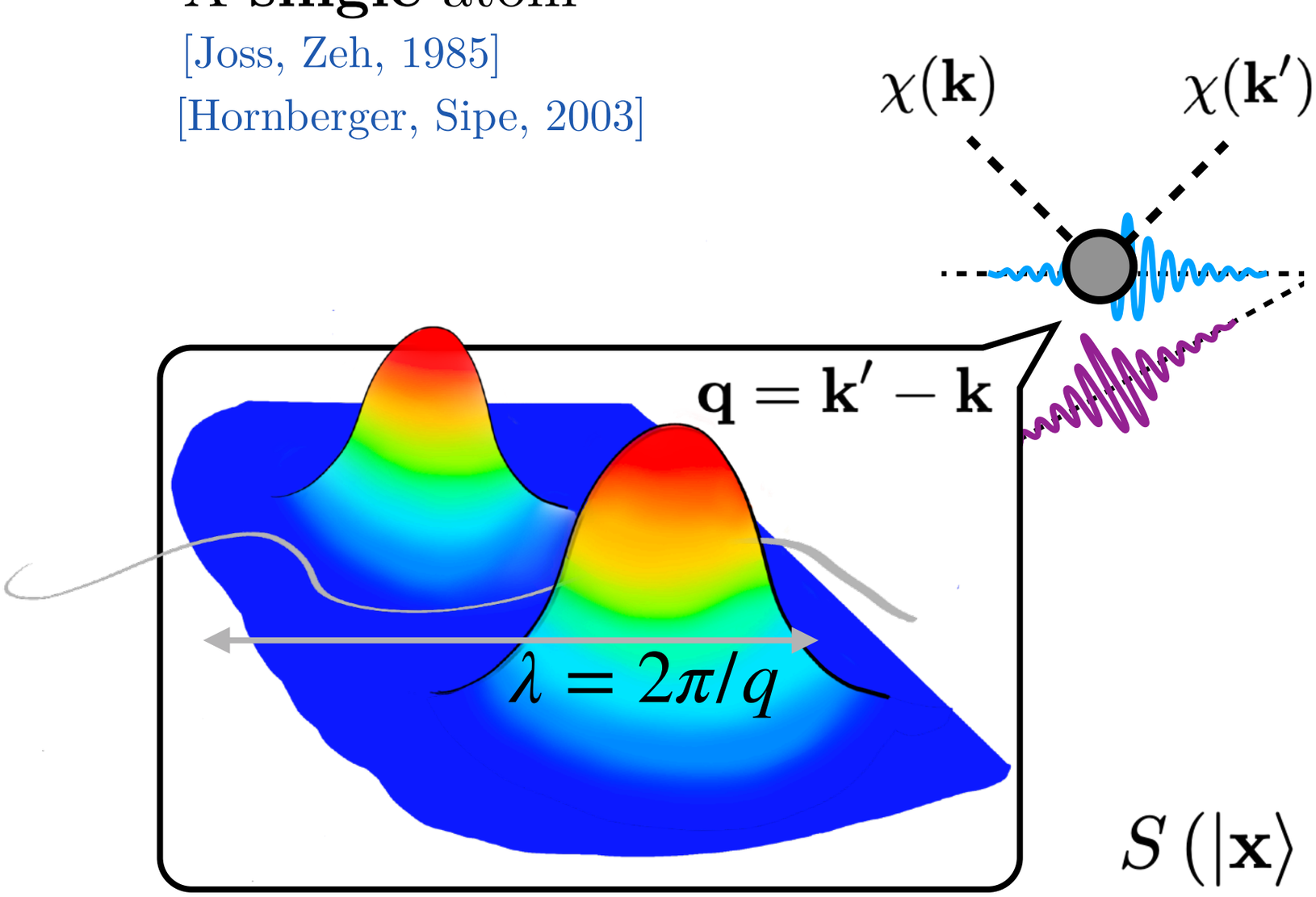
$$\rho'_A = \mathrm{Tr}_{\mathbf{k}}\rho'$$

AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]



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

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

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

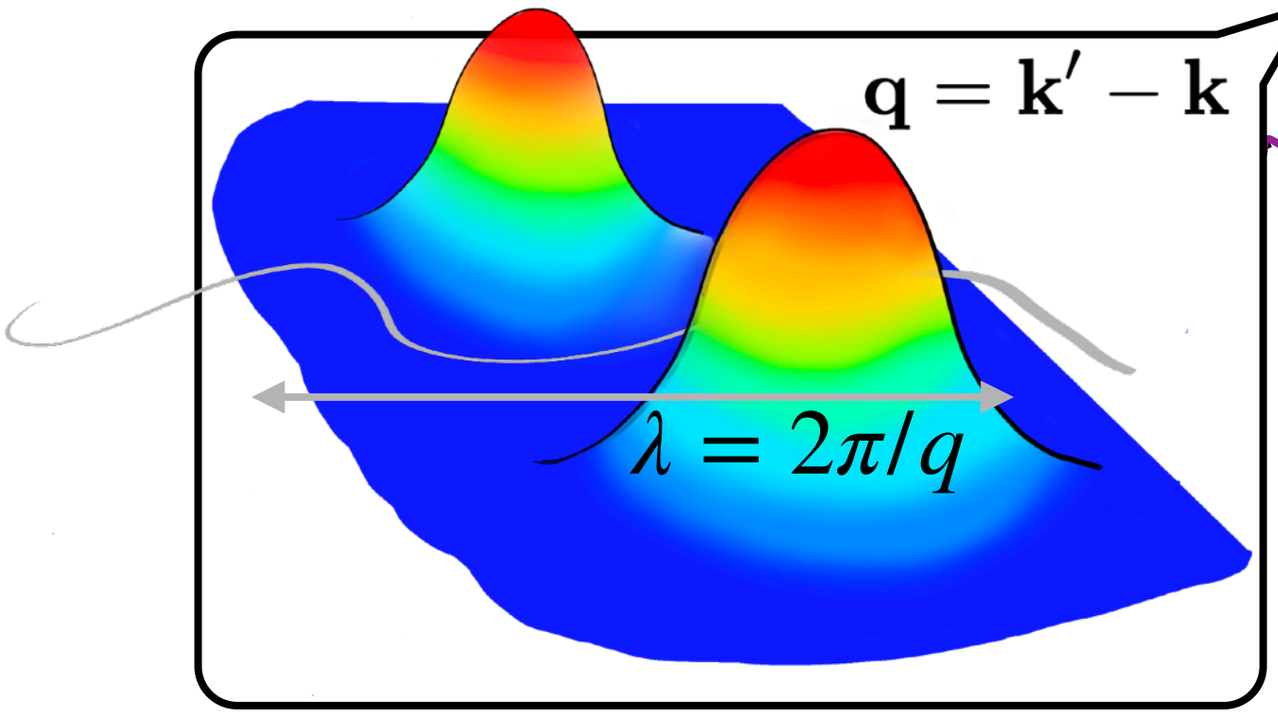
$$\rho'_A = \mathrm{Tr}_{\mathbf{k}}\rho'$$

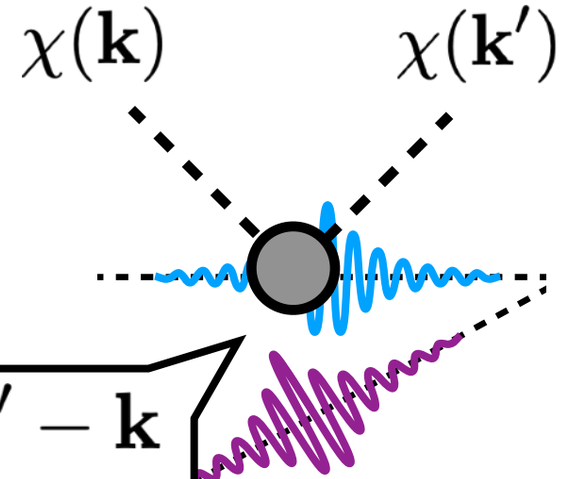
AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]





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AIs: Collisional Decoherence

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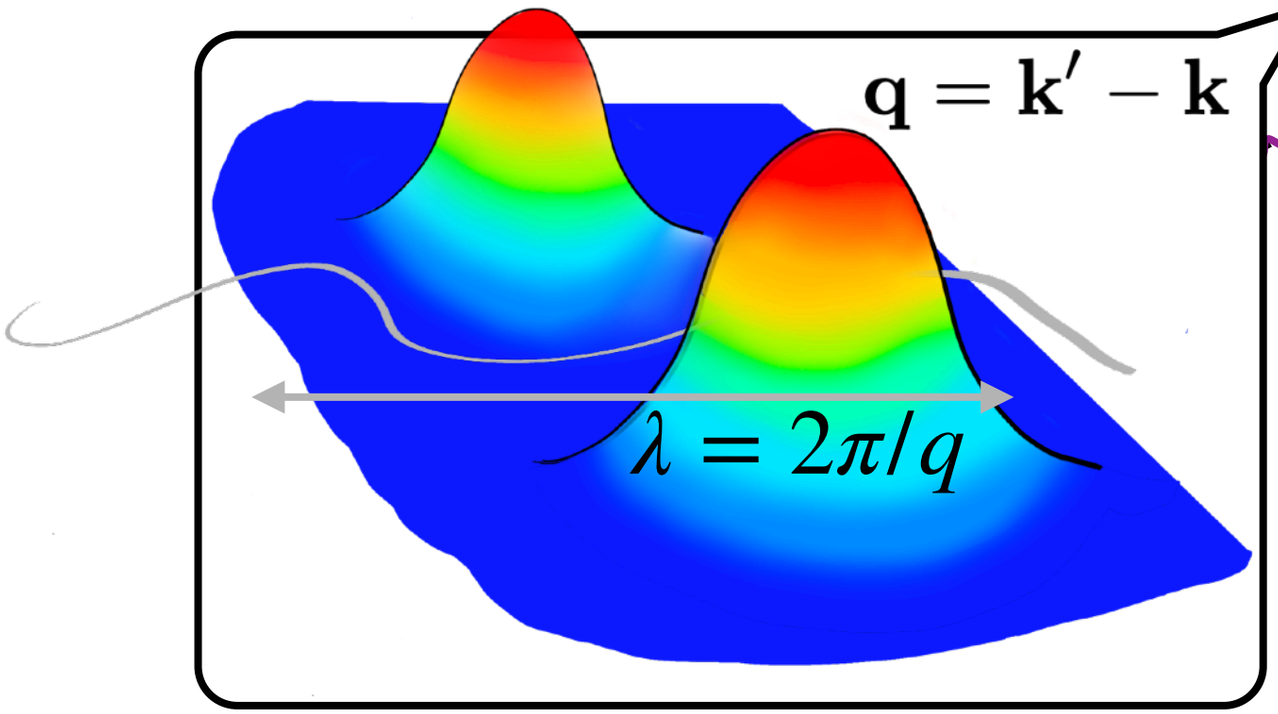

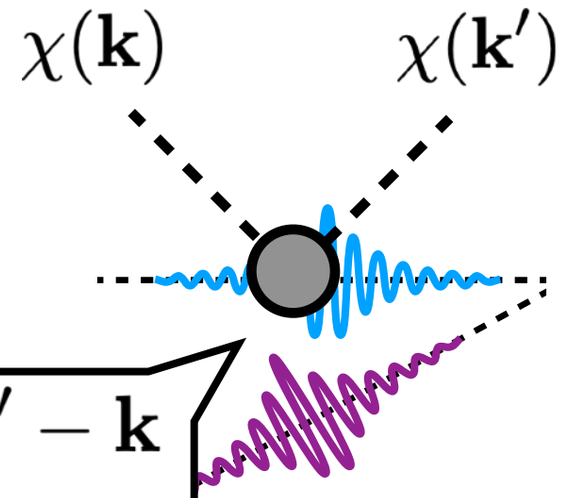

$$\rho = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

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

Decoherence Kernel

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

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

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AIs: Collisional Decoherence

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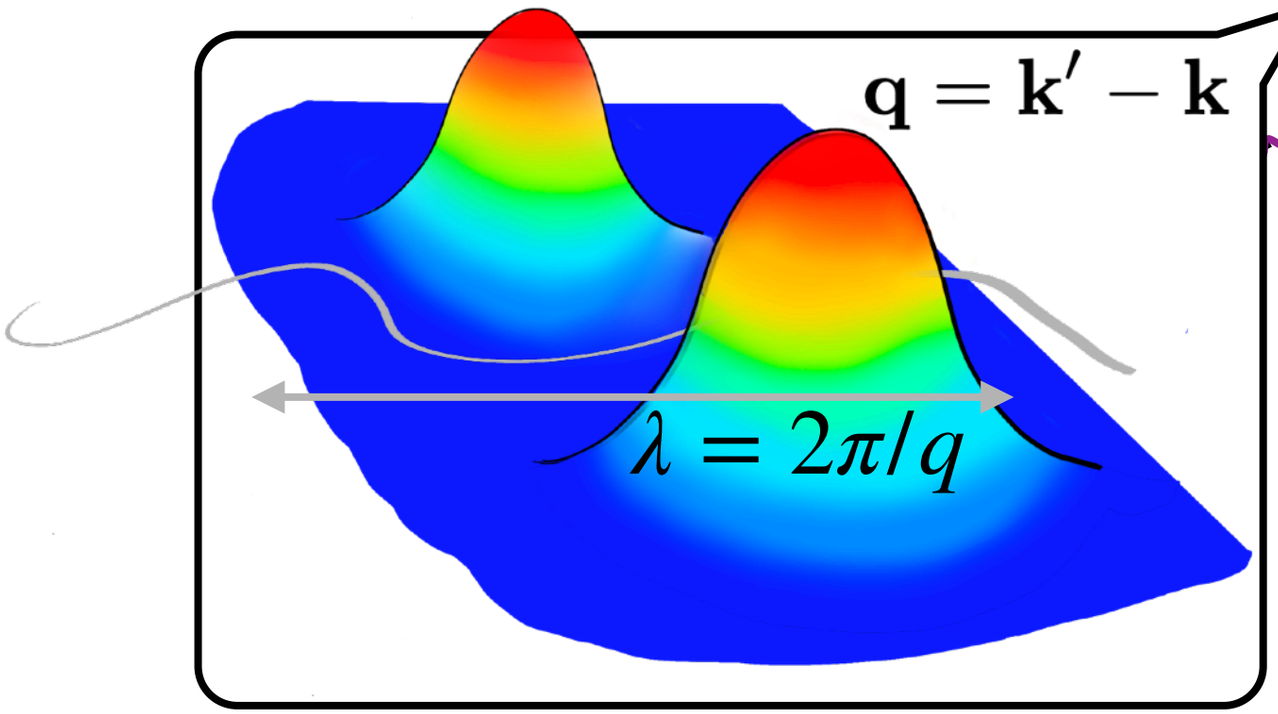

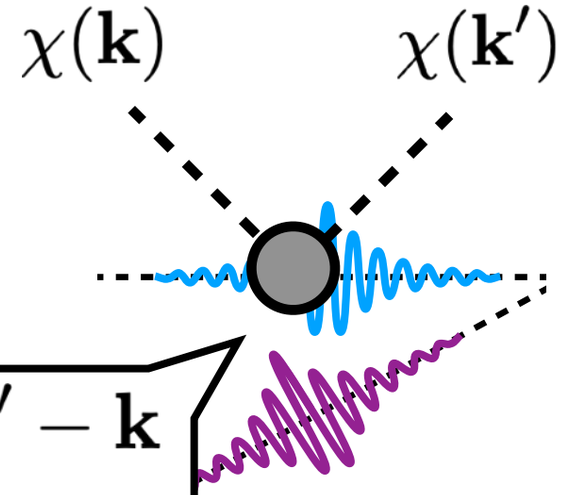

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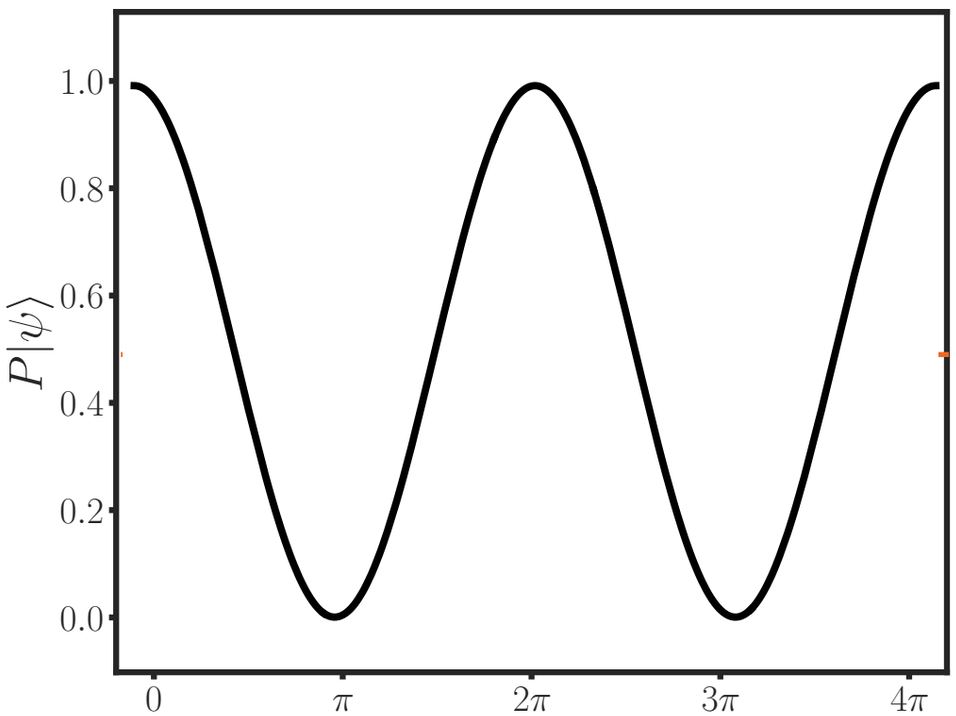
DECOHERENCE

$$\lambda = 1/q \gtrsim \Delta x$$

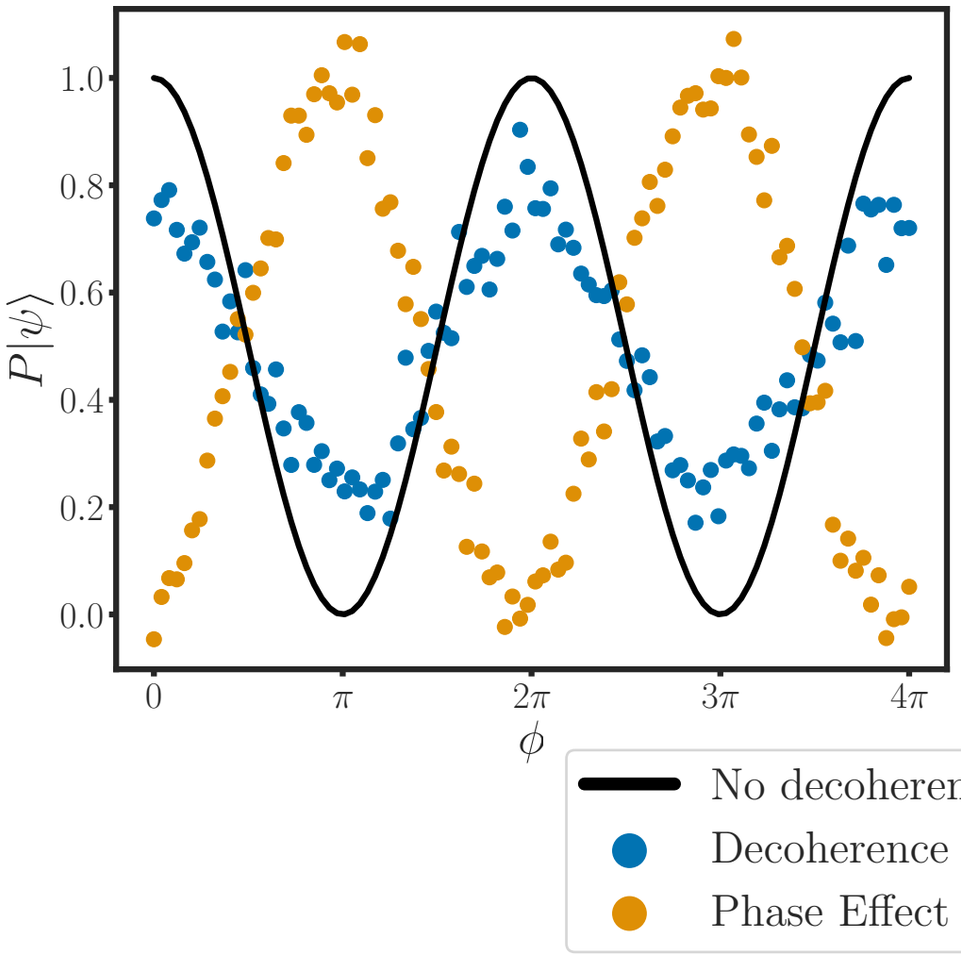
AIs: Collisional Decoherence



No decoherence or phase effects

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

AIs: Collisional Decoherence



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Decoherence Kernel

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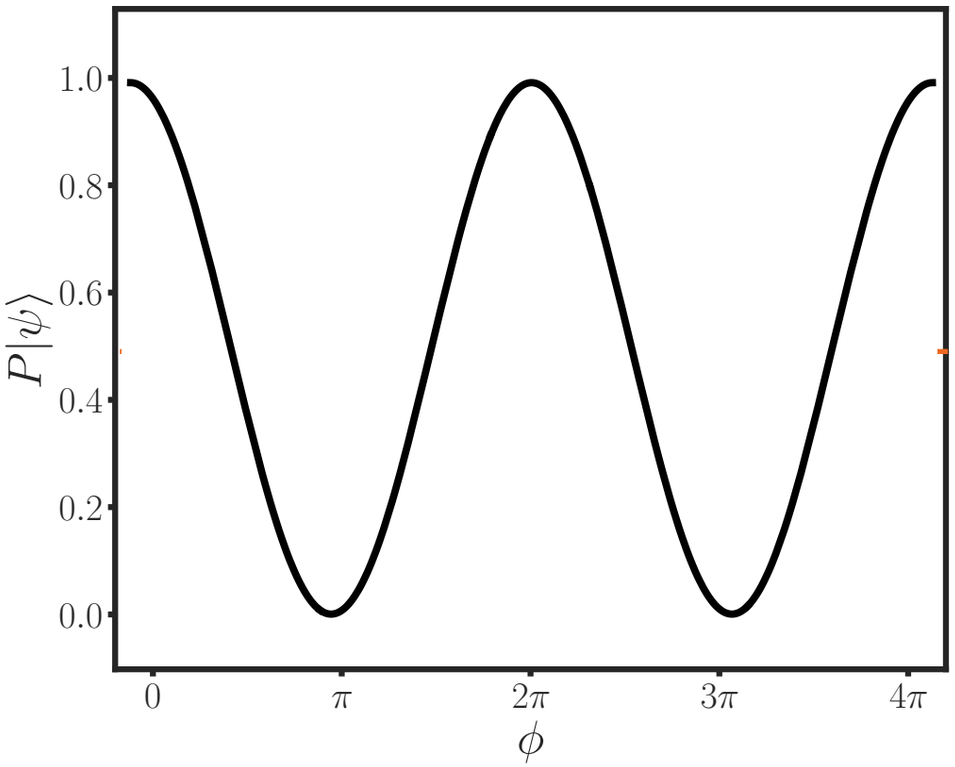
$$\frac{N_I}{N_I + N_{II}}\bigg|_{\text{exp}} = \frac{1}{2}(1 + V\cos(\phi + \Delta\phi))$$

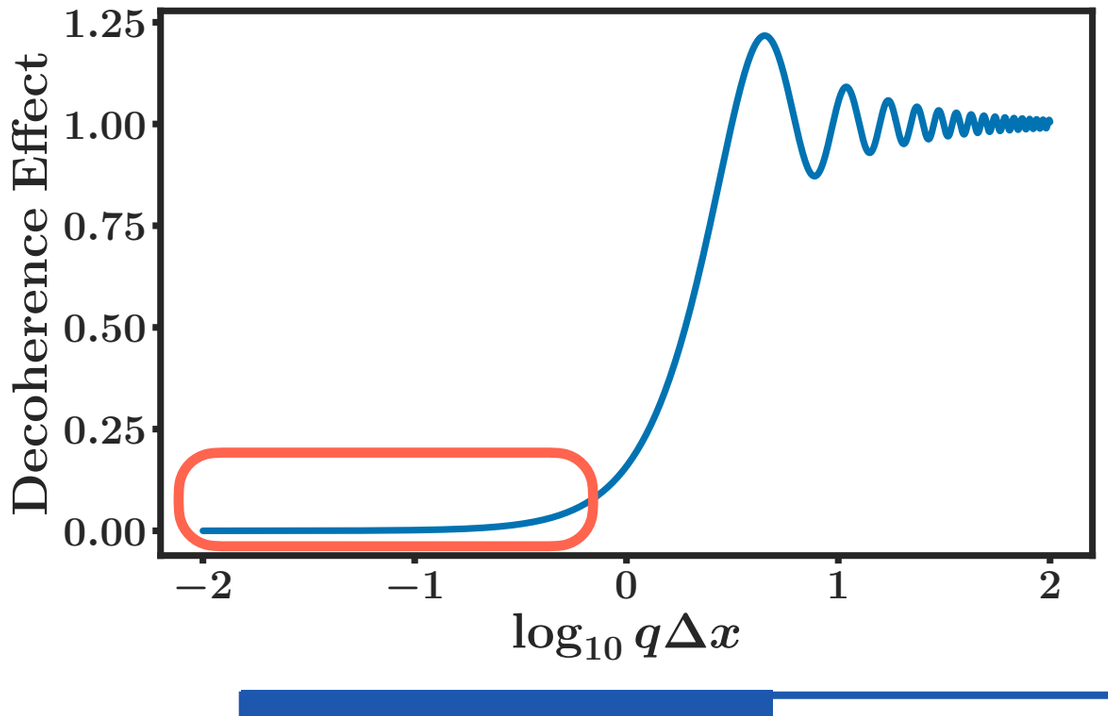
$^*|+\rangle\langle+|$

$|g\rangle\langle g|$

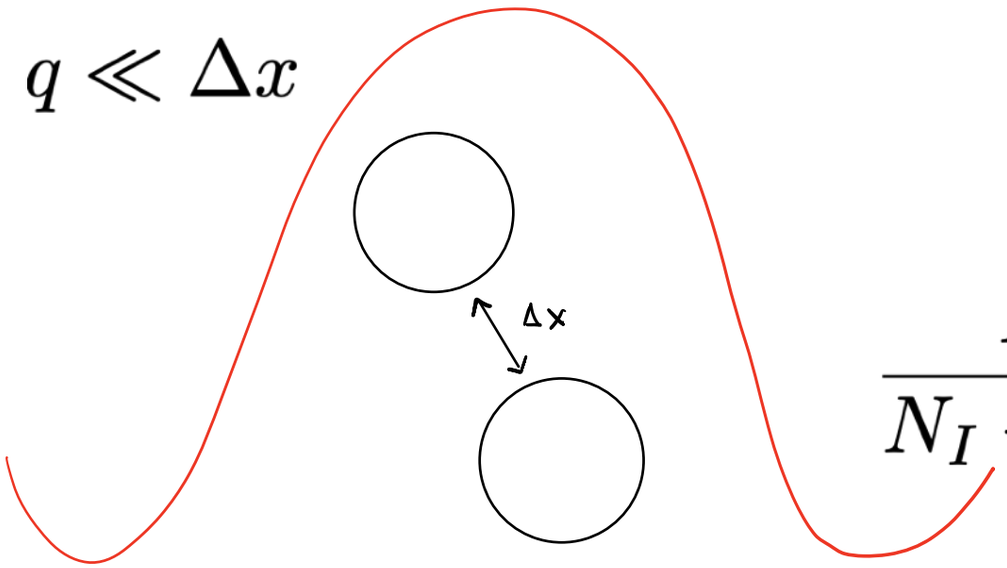
$$\text{Tr}\{\rho\,\mathcal{O}_1\} = \frac{1}{2}\left[1 + e^{-\int_{\mathbf{q},t} R(\mathbf{q})(1-\cos(\mathbf{q}\cdot\boldsymbol{\Delta x}))}\cos\left(\phi + \int_{\mathbf{q},t} R(\mathbf{q})\sin(\mathbf{q}\cdot\boldsymbol{\Delta x})\right)\right]$$

AIs: Collisional Decoherence





$q \ll \Delta x$



Decoherence Kernel

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

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

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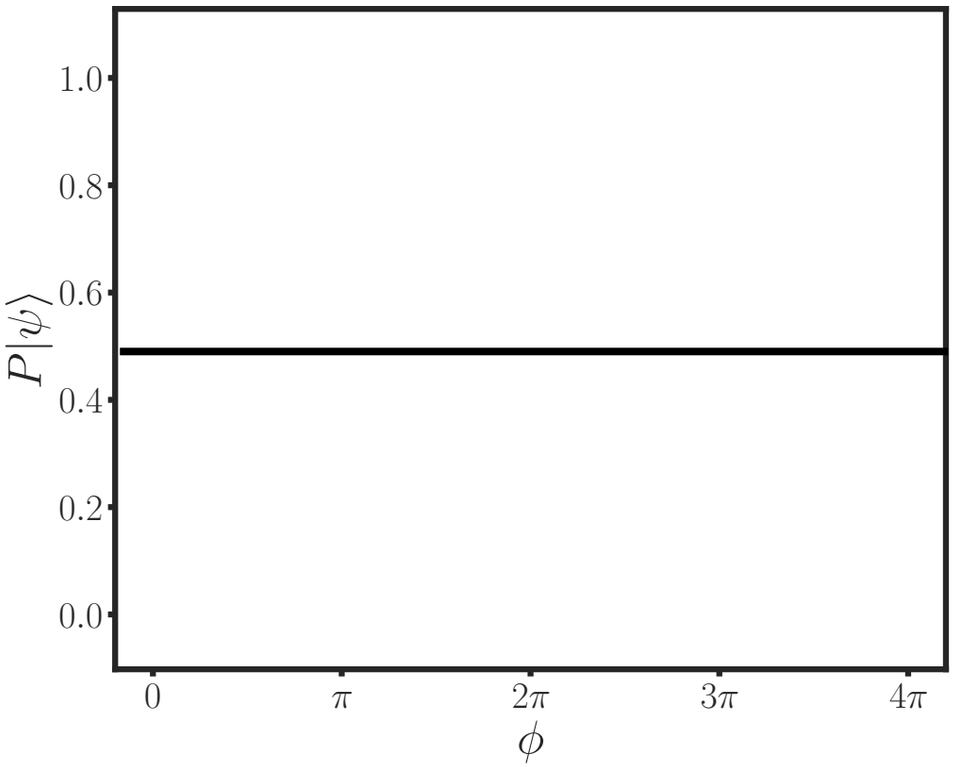
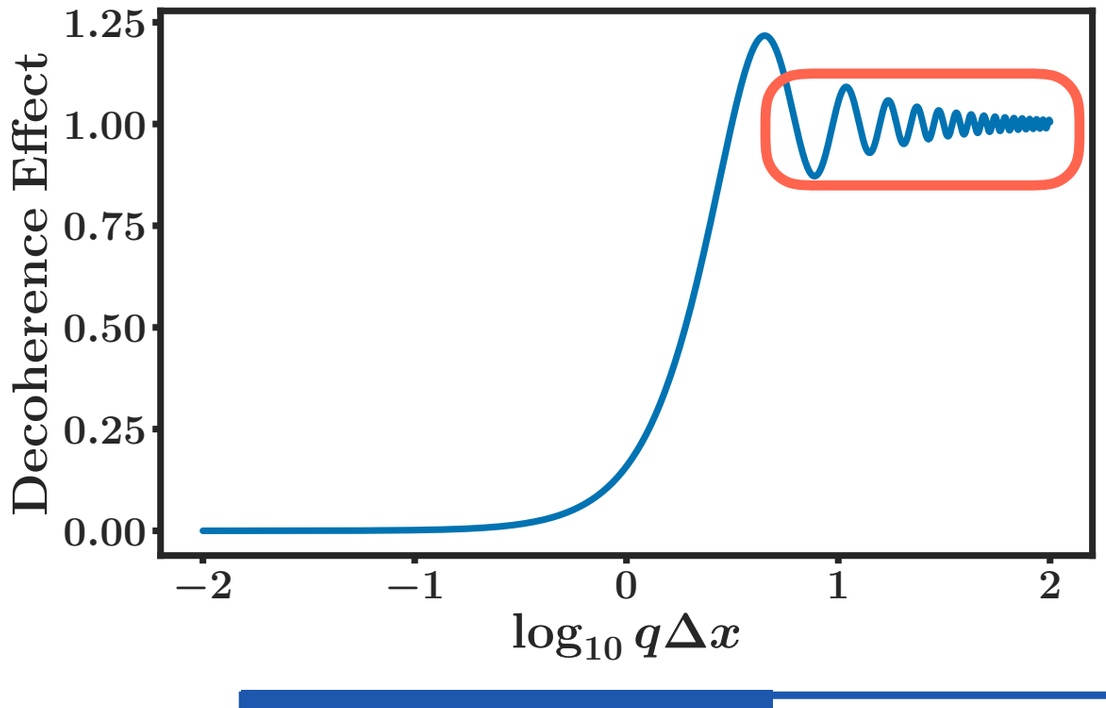
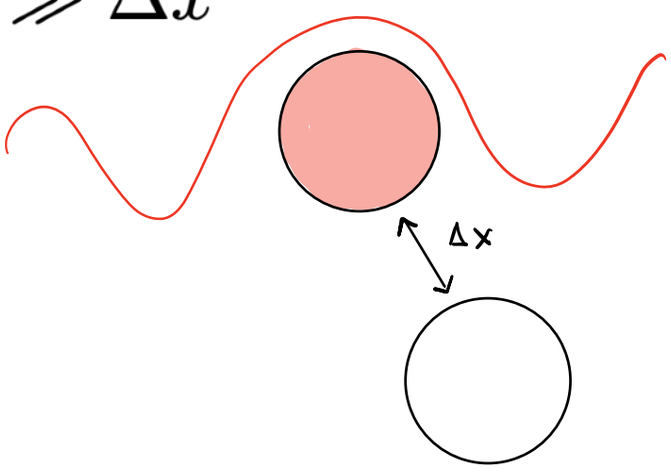
AIs: Collisional Decoherence





$q \gg \Delta x$



Decoherence Kernel

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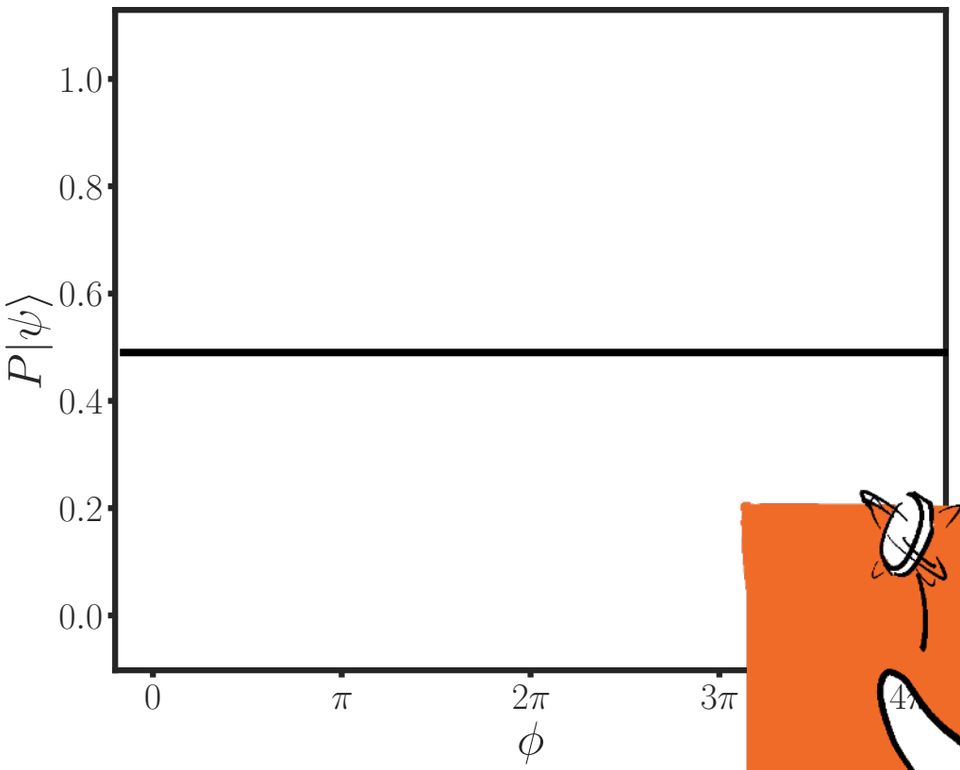
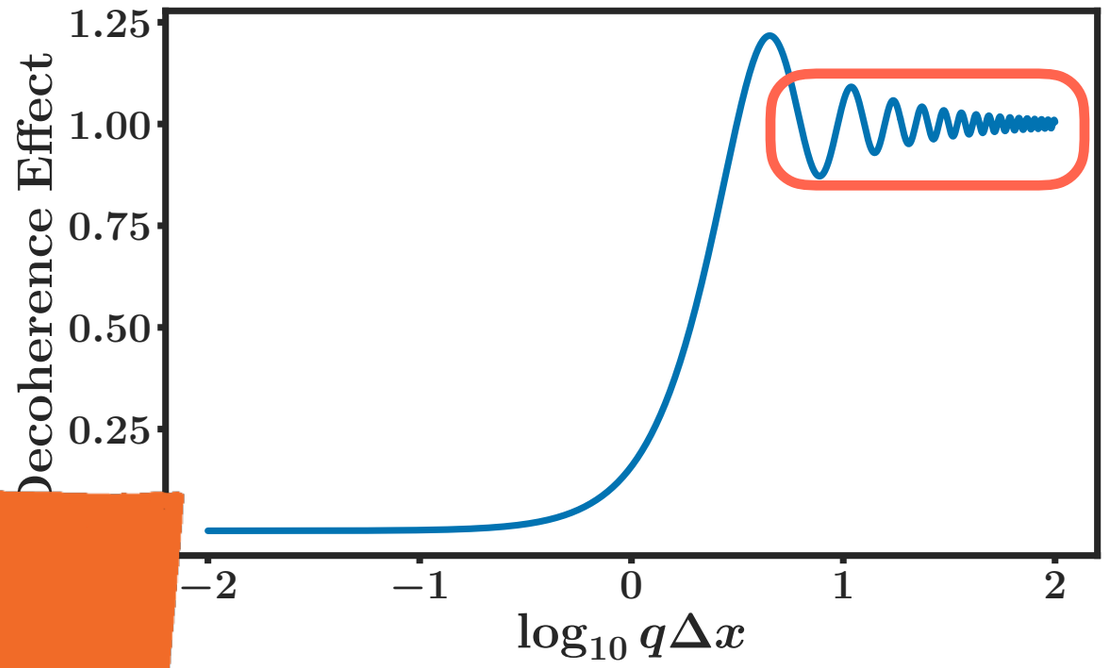
AIs: Collisional Decoherence





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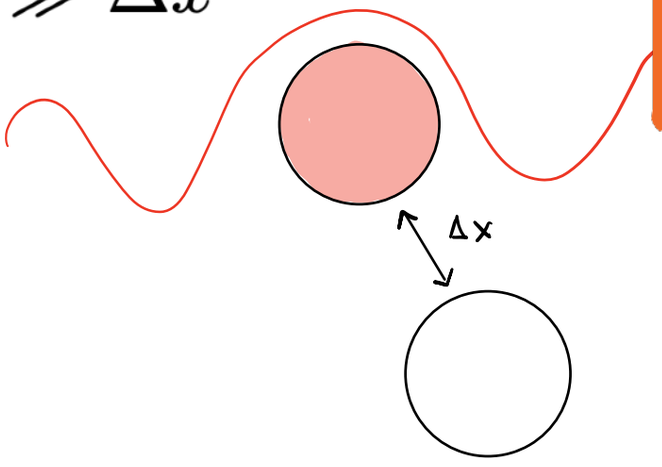

Decoherence Kernel

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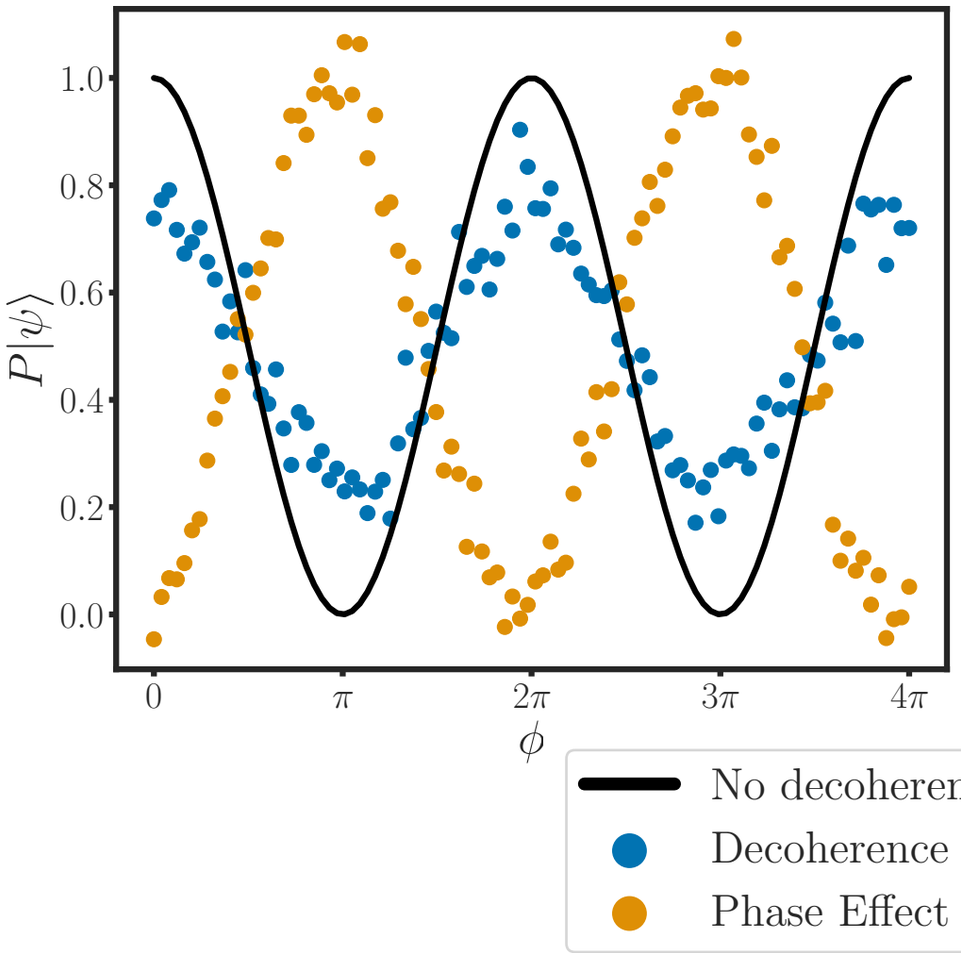
AIs: Collisional Decoherence



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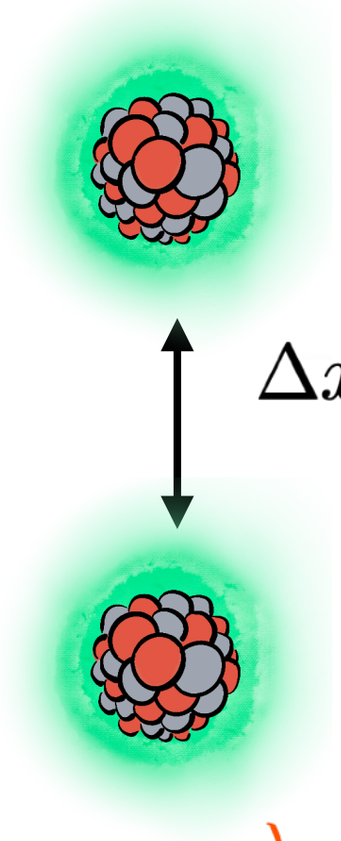
AIs: Collisional Decoherence

Single-atom system

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]



Decoherence Kernel

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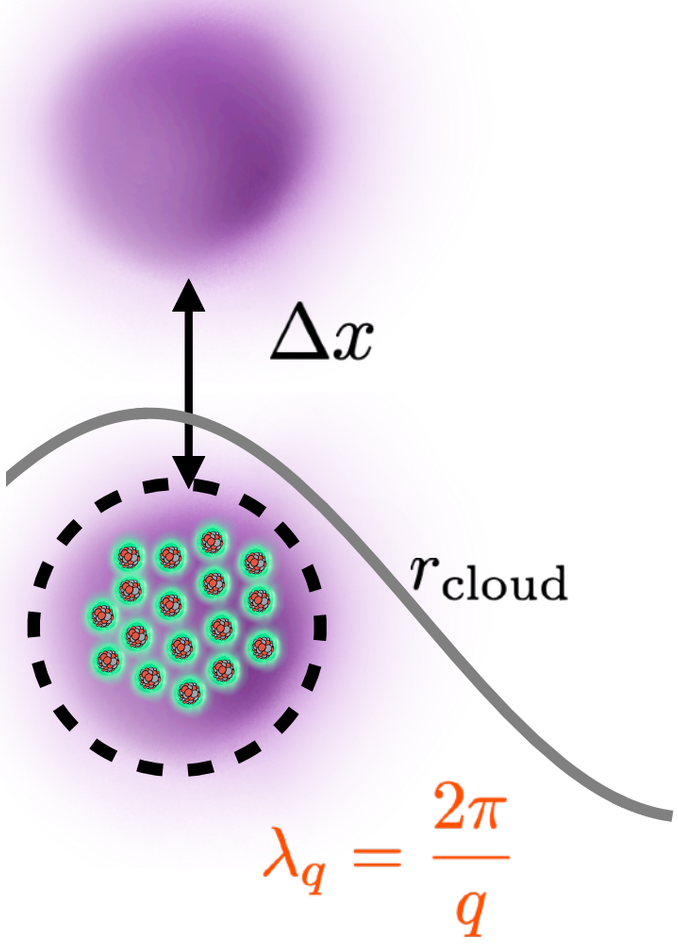
$$\rho' = S\rho S^\dagger = (\mathbb{I} + T)\rho(\mathbb{I} + T)^\dagger$$

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

AIs: Collisional Decoherence

Multi-atom system (distinguishable)

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



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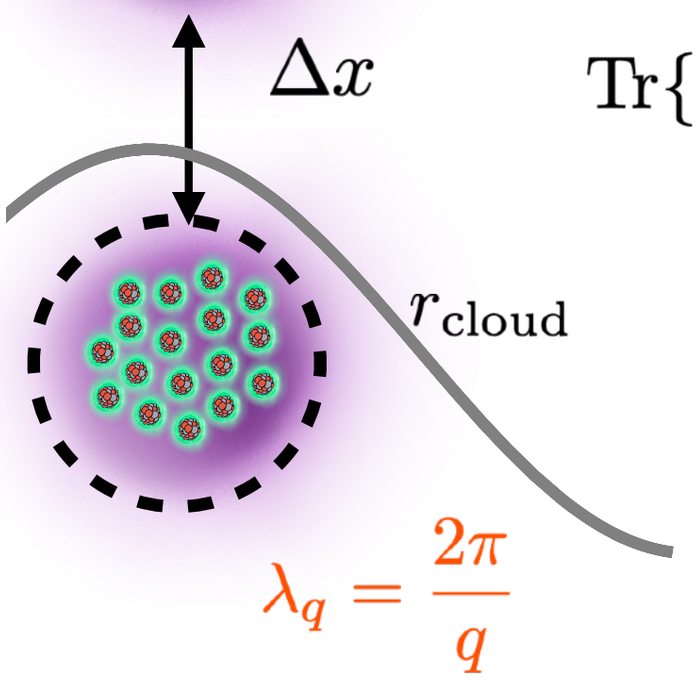
AIs: Collisional Decoherence

Multi-atom system (distinguishable)

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

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



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

$$\mathcal{O}_i = \mathbb{I} \otimes \cdots \otimes |g_i\rangle\langle g_i| \otimes \cdots \otimes \mathbb{I}$$

$$* \, |+_i\rangle\langle +_i|$$

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

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

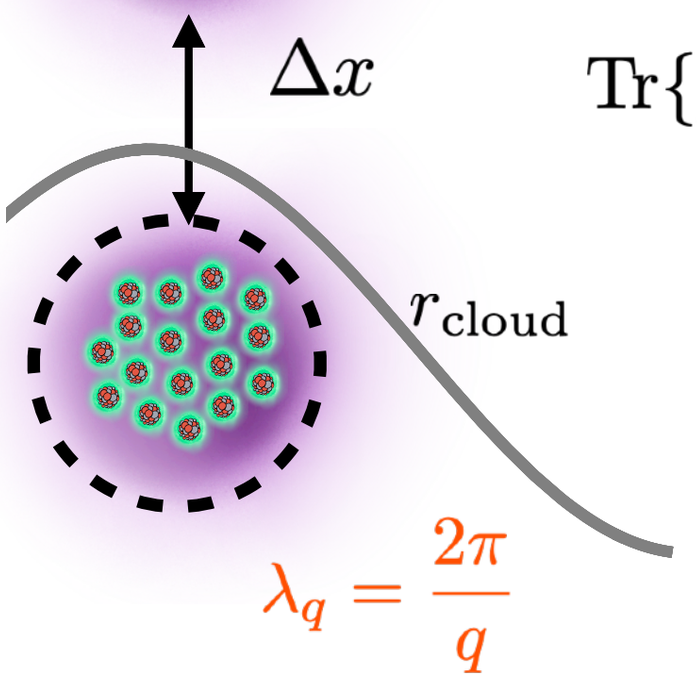
AIs: Collisional Decoherence

Multi-atom system (distinguishable)

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

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

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



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

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AIs: Collisional Decoherence

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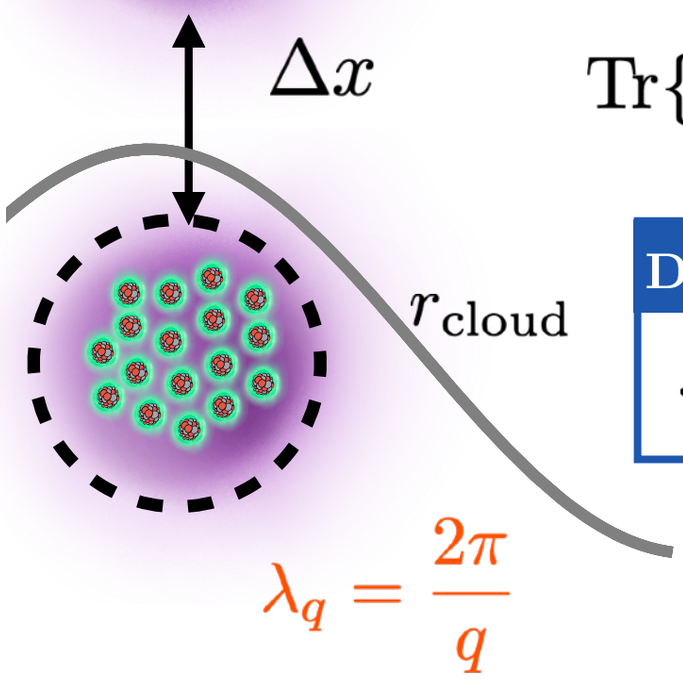

$$\mathrm{Tr}\{\rho_N \sum_i^N \mathcal{O}_i\} = N\,\mathrm{Tr}\{\rho_1 \mathcal{O}_i\} \stackrel{!}{=} N\,\tfrac{1}{2}(1 + V\cos(\phi + \Delta\phi))$$

Decoherence Kernel 1-body measurement

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

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

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

AIs: Collisional Decoherence

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

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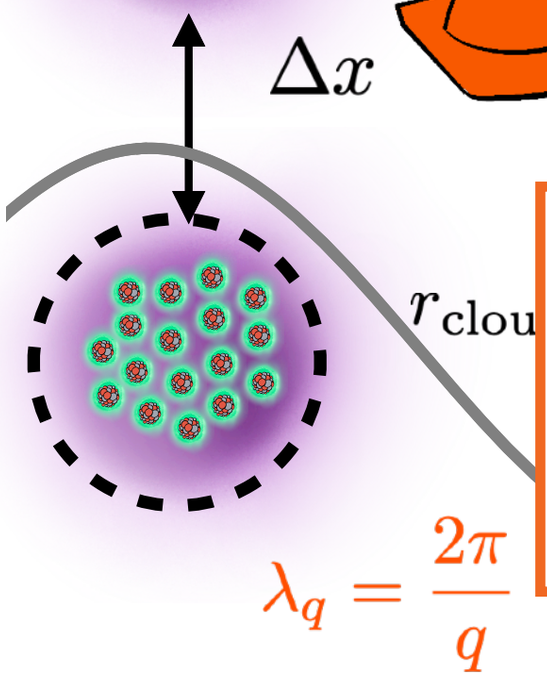

$$\mathrm{Tr}\{\rho_N \sum_i^N \mathcal{O}_i\} \stackrel{!}{=} \tfrac{1}{2}(1 + V\cos(\phi + \Delta\phi))$$

Extended formalism

w/ L. Badurina, R. Plestid, Y. Wang

(including shape of the cloud, undistinguishable atoms, thermal effects...)

COHERENCE

$$\lambda = 1/q \gtrsim r_c$$

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

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

AIs: Collisional Decoherence

Particle scattering

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

e.g. Dark Matter

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

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

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

AIs: Collisional Decoherence

Particle scattering

[Riedel, 2013]
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$$\ln\gamma = -\int_{q,t} R(\mathbf{q})\mathcal{F}_{\rm decoh}(\mathbf{q})$$

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

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

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

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

AIs: Collisional Decoherence

Particle scattering

[Riedel, 2013]
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[Du, **CM**, Pardo, Wang, Zurek, 2022]
[Du, **CM**, Pardo, Wang, Zurek, 2023]
[Joss, Zeh, 1985]
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[Badurina, **CM**, Plestid, 2024]

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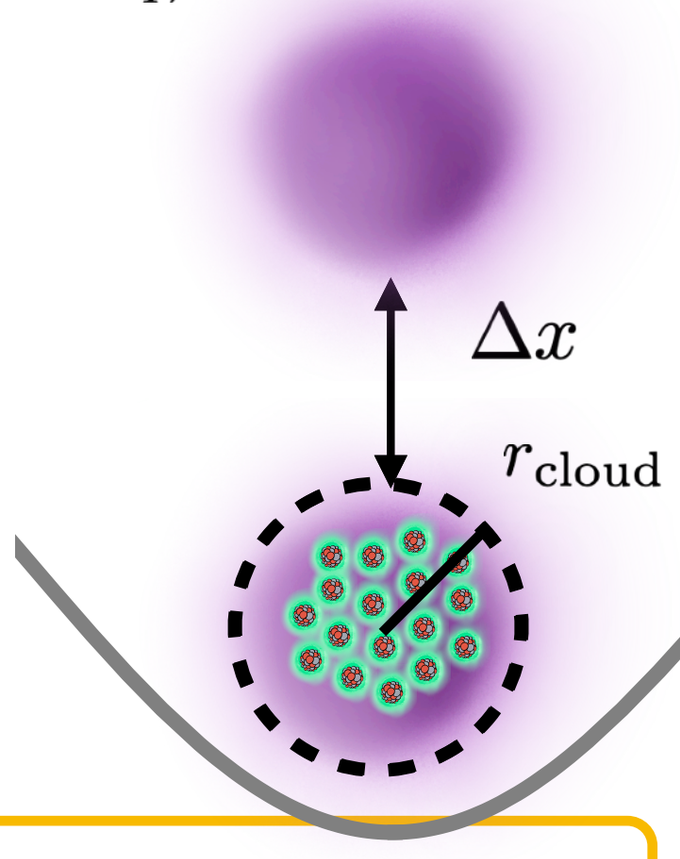

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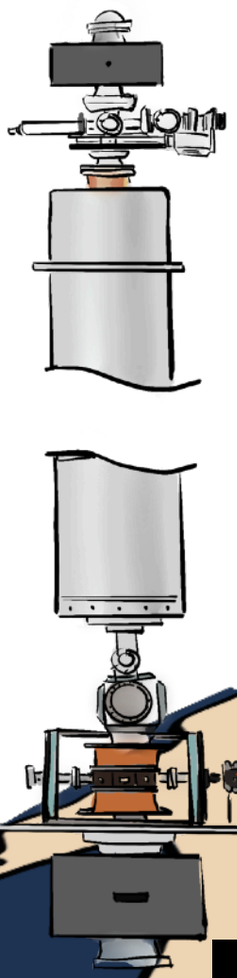
$$R(\mathbf{q}) = n_\chi \int d^3\mathbf{v} f(\mathbf{v}) \Gamma(\mathbf{v},\mathbf{q})$$

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

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

AIs: Examples



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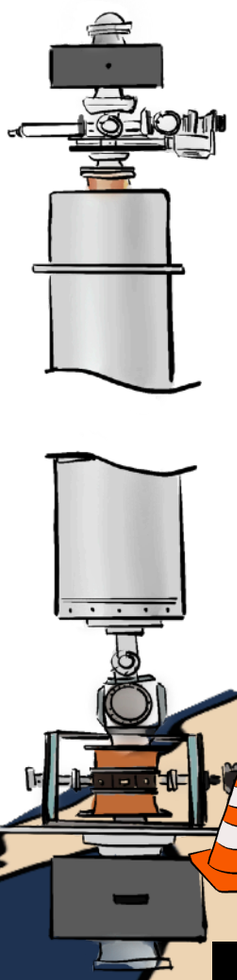

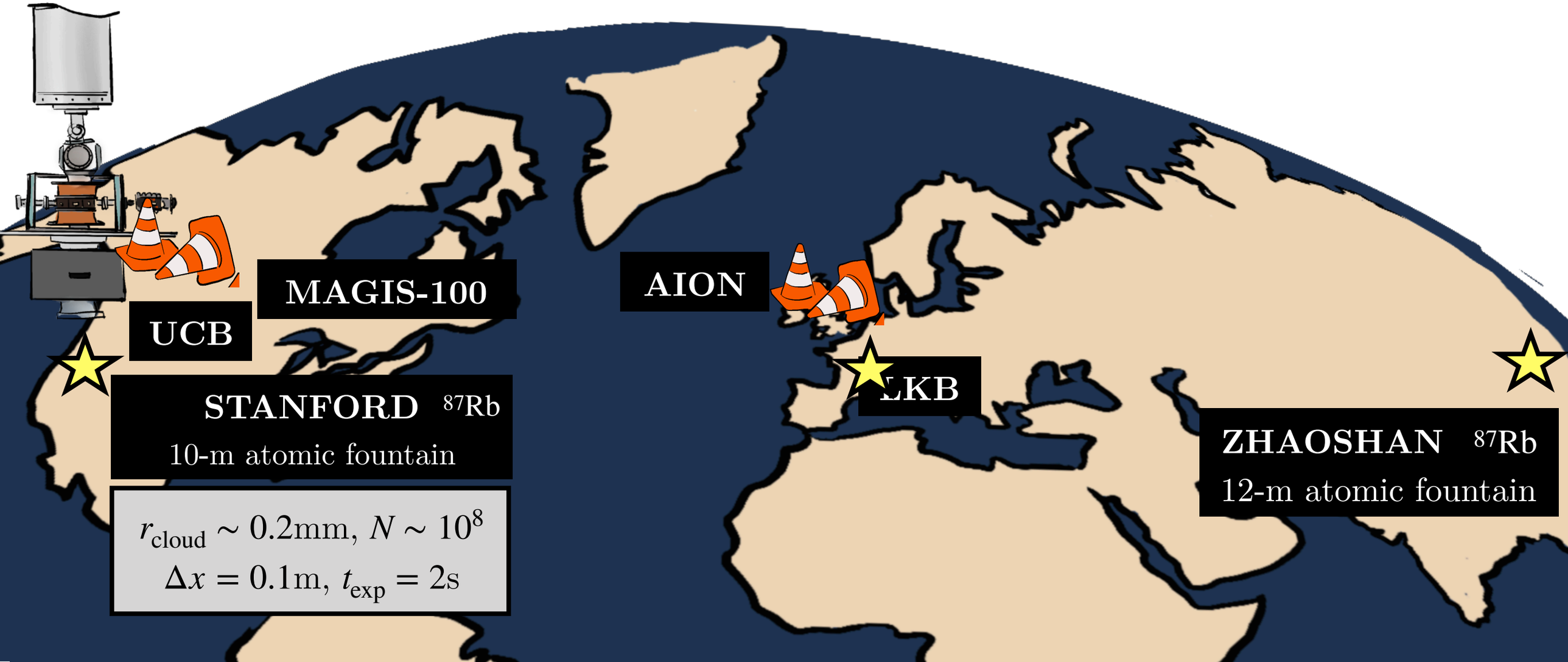

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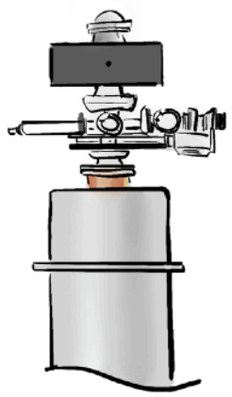

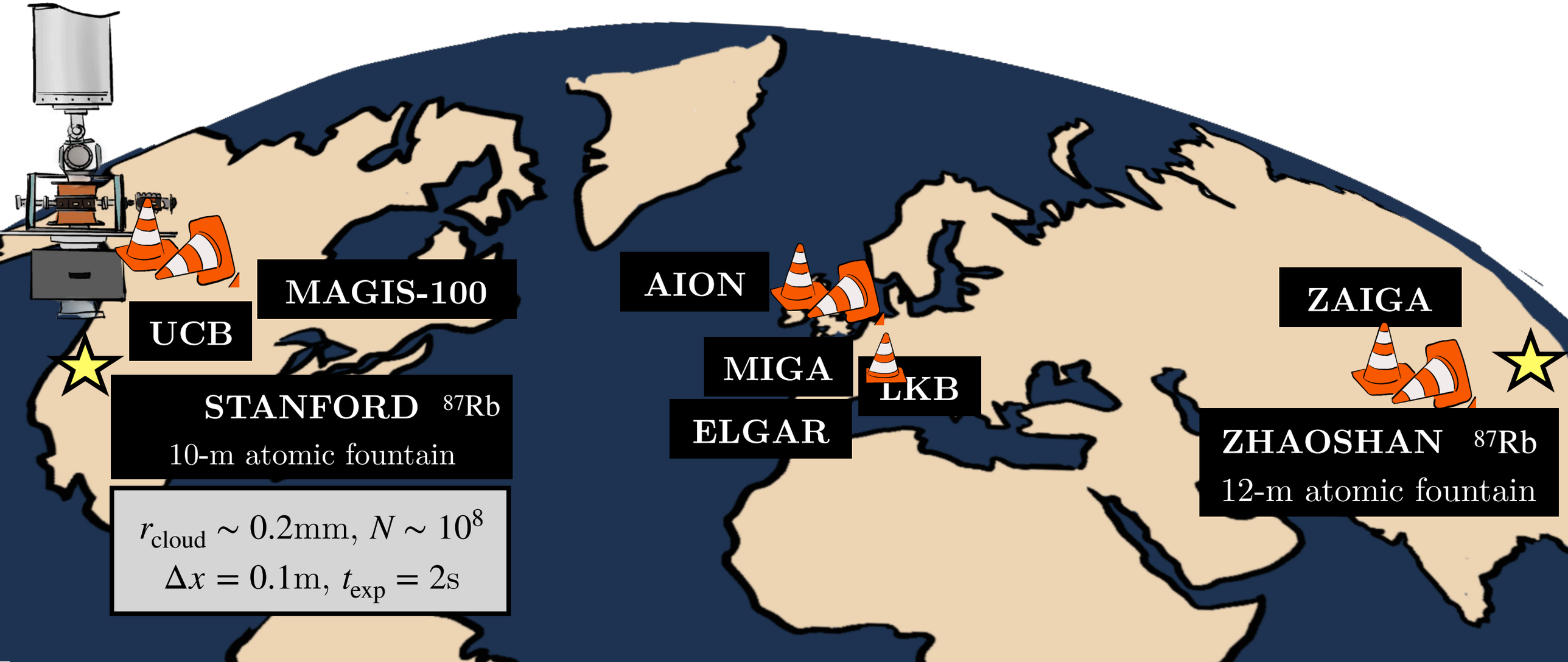

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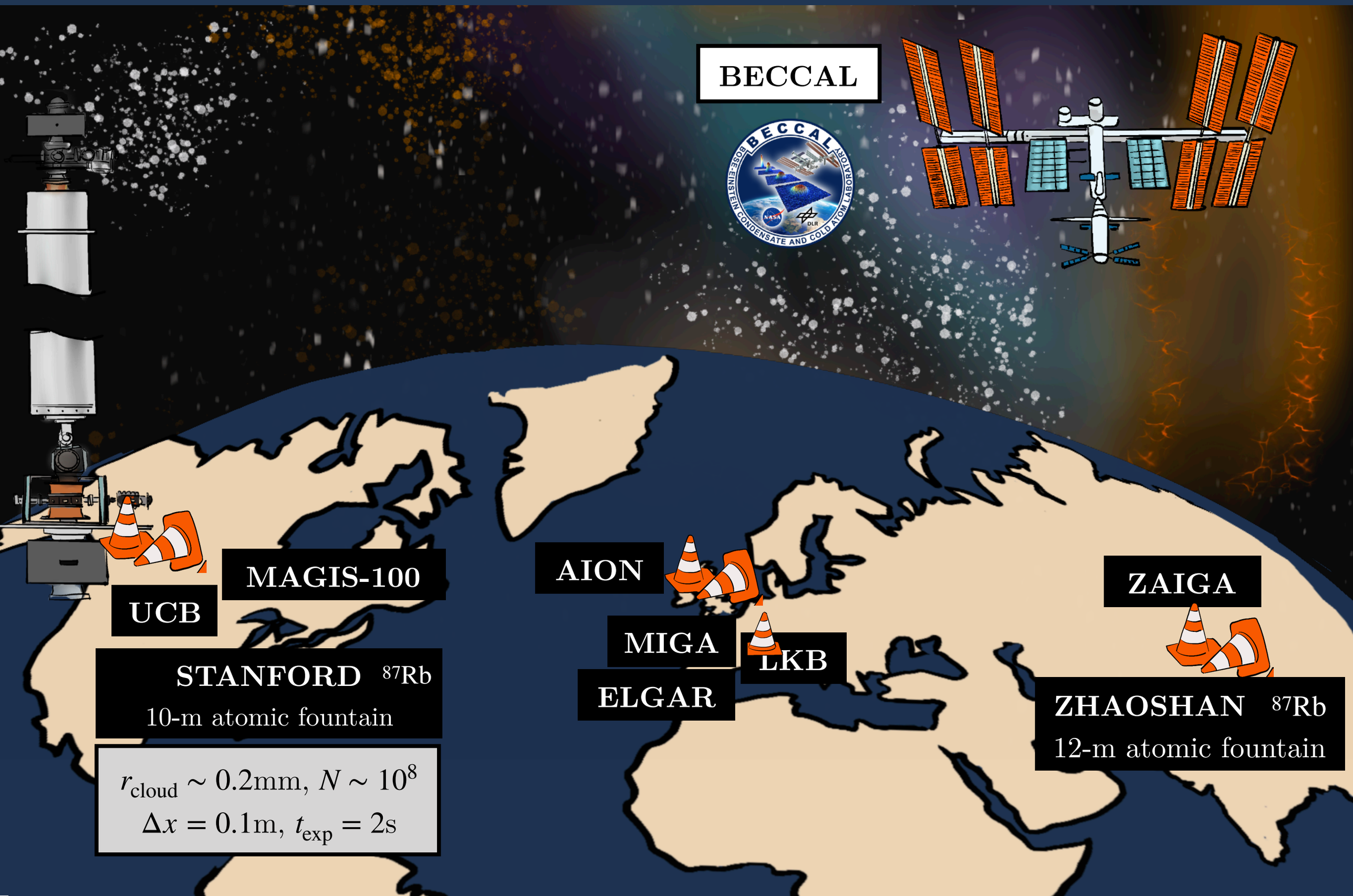

AIs: Examples

MAQRO SiO_2

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

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

MAQRO

BECCAL

BECCAL — BOSE-EINSTEIN CONDENSATE AND COLD ATOM LABORATORY

UCB

MAGIS-100

STANFORD ^{87}Rb

10-m atomic fountain

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

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

AION

MIGA

ELGAR

LKB

ZAIGA

ZHAOSHAN ^{87}Rb

12-m atomic fountain

AIs: Examples

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MAQRO

BECCAL

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GDM

AEDGE

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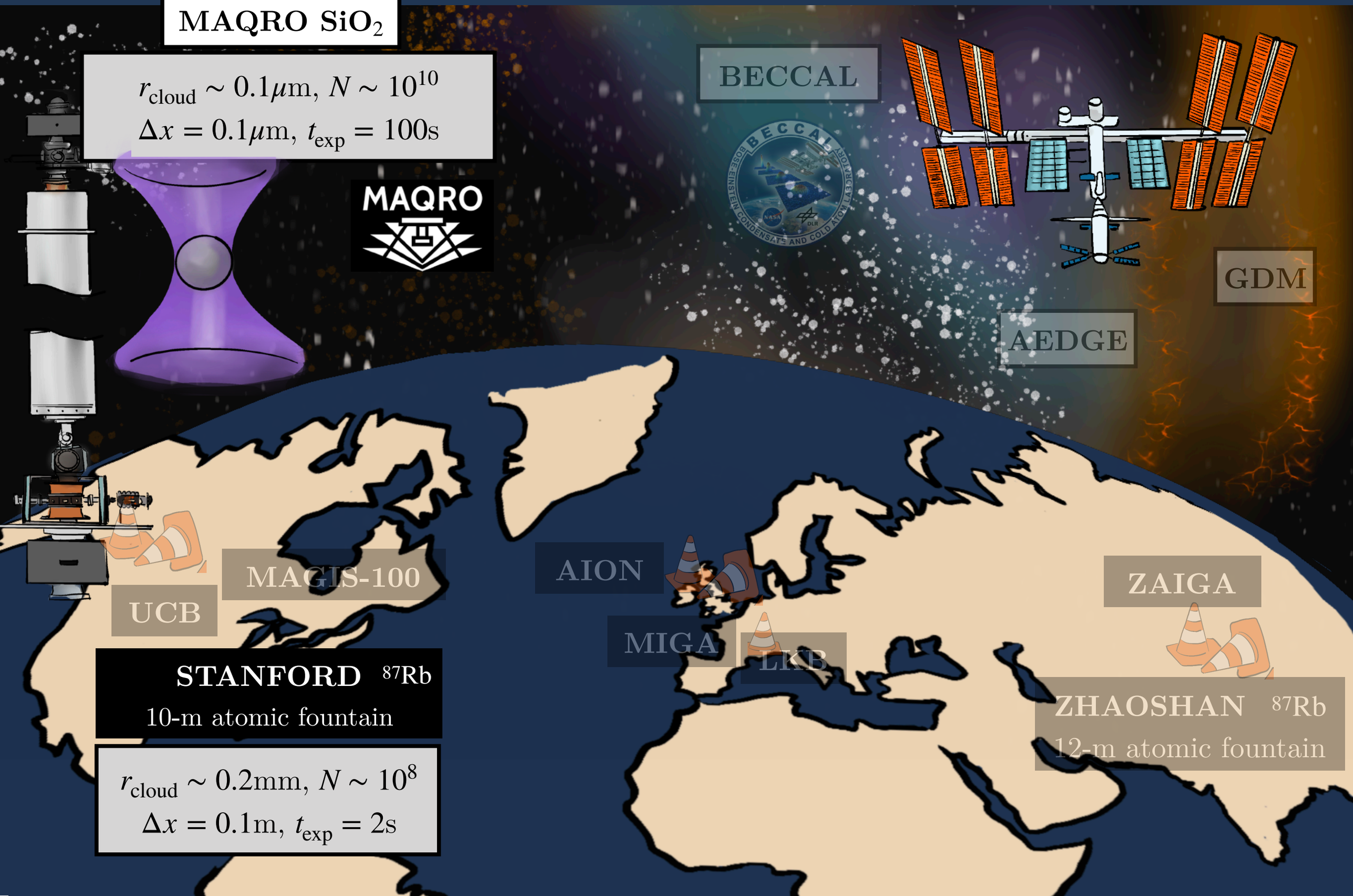
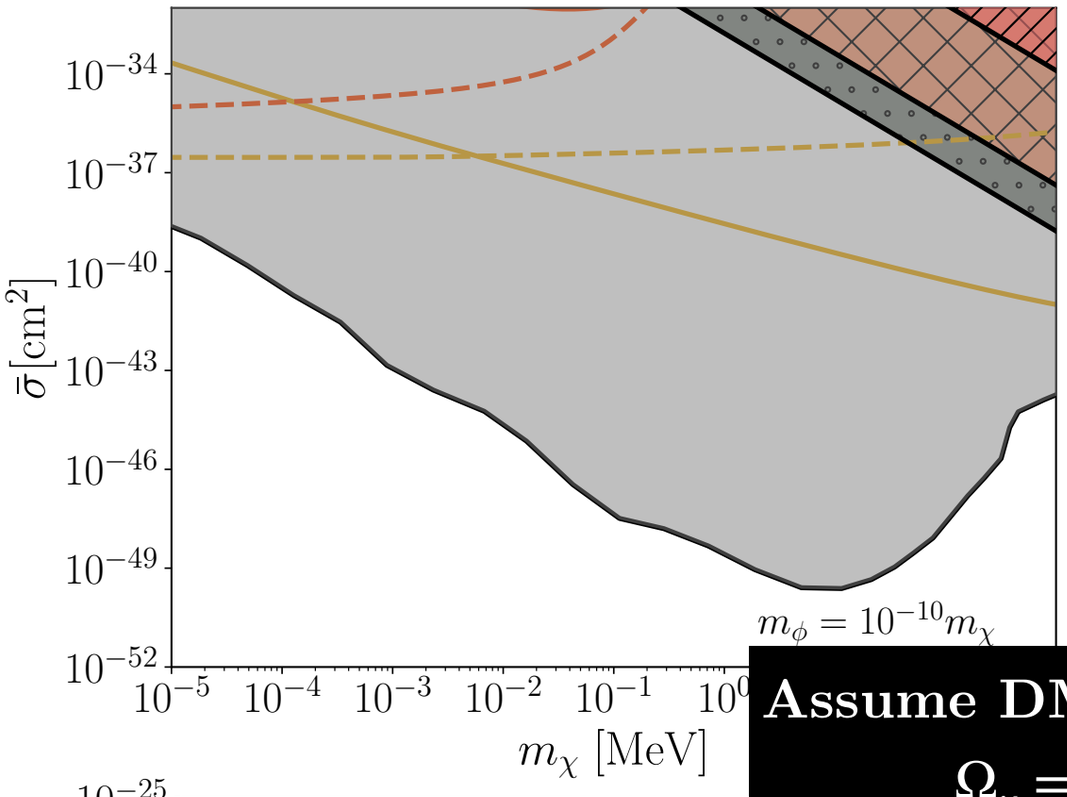
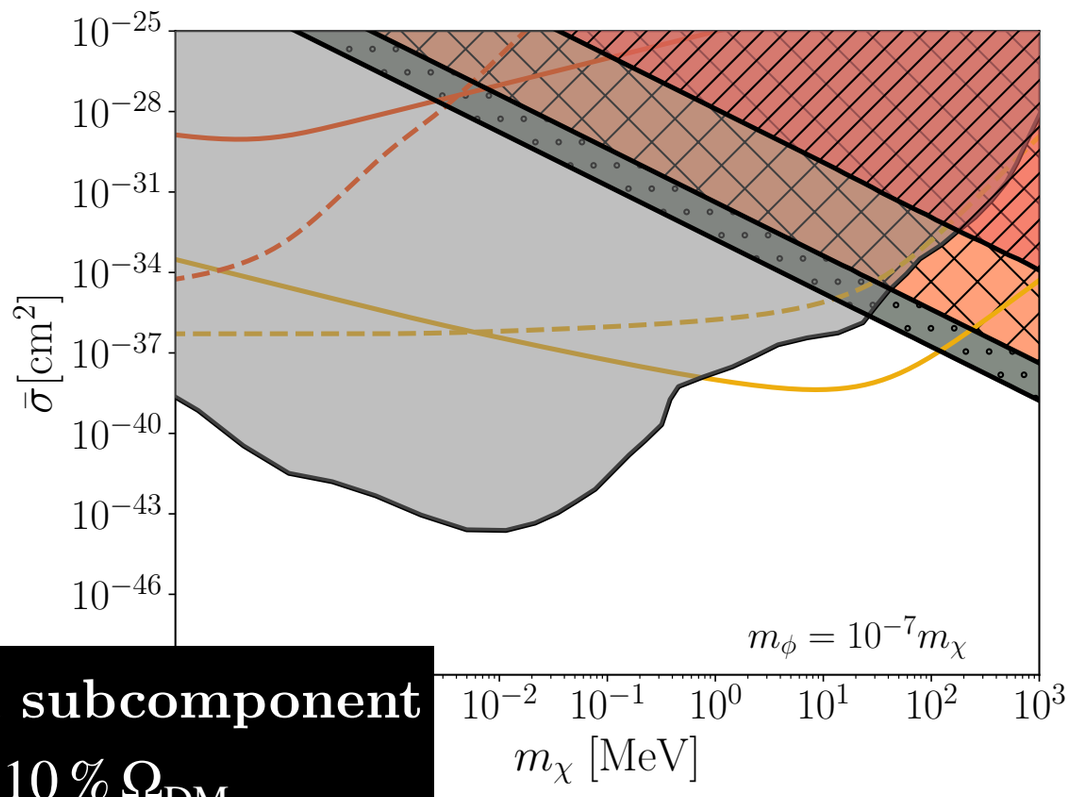


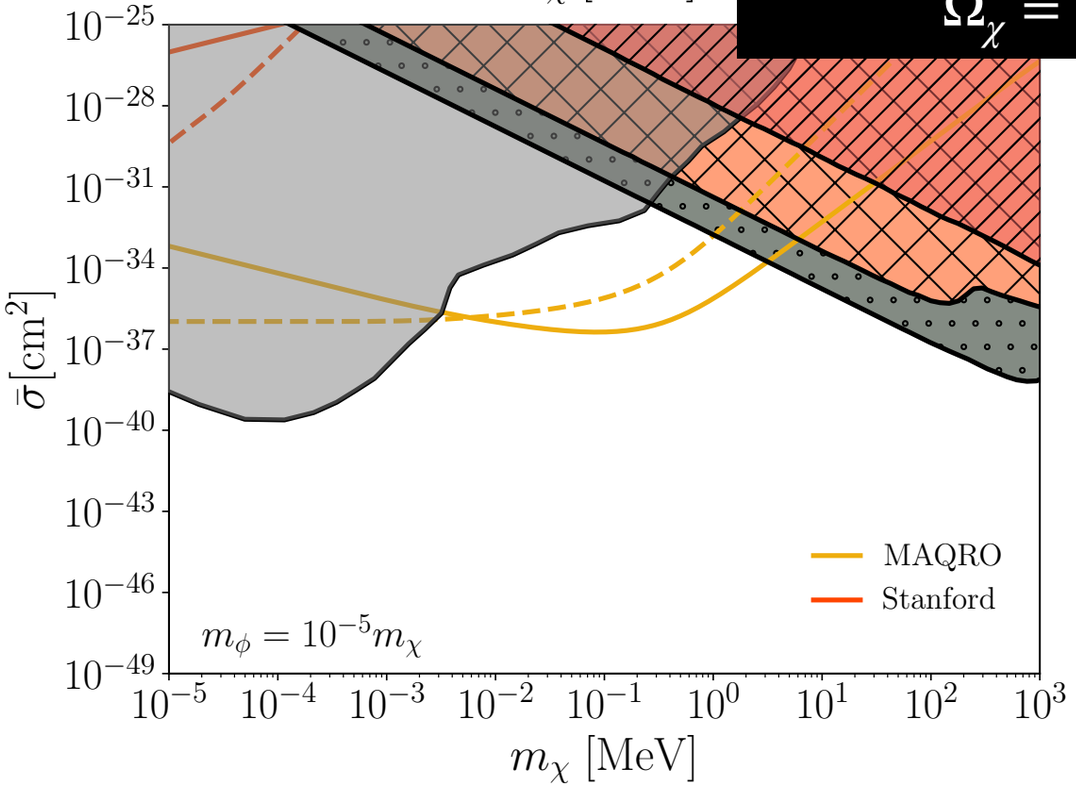
AIs: Some constraints on DM

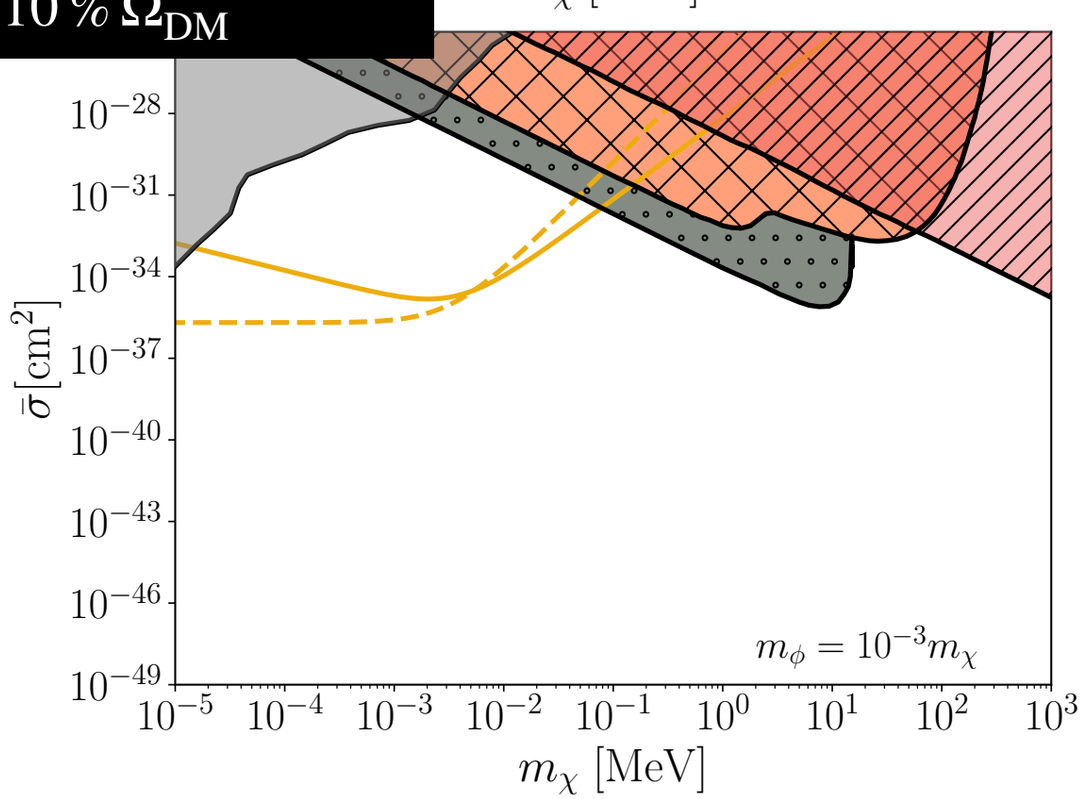




Assume DM is a subcomponent

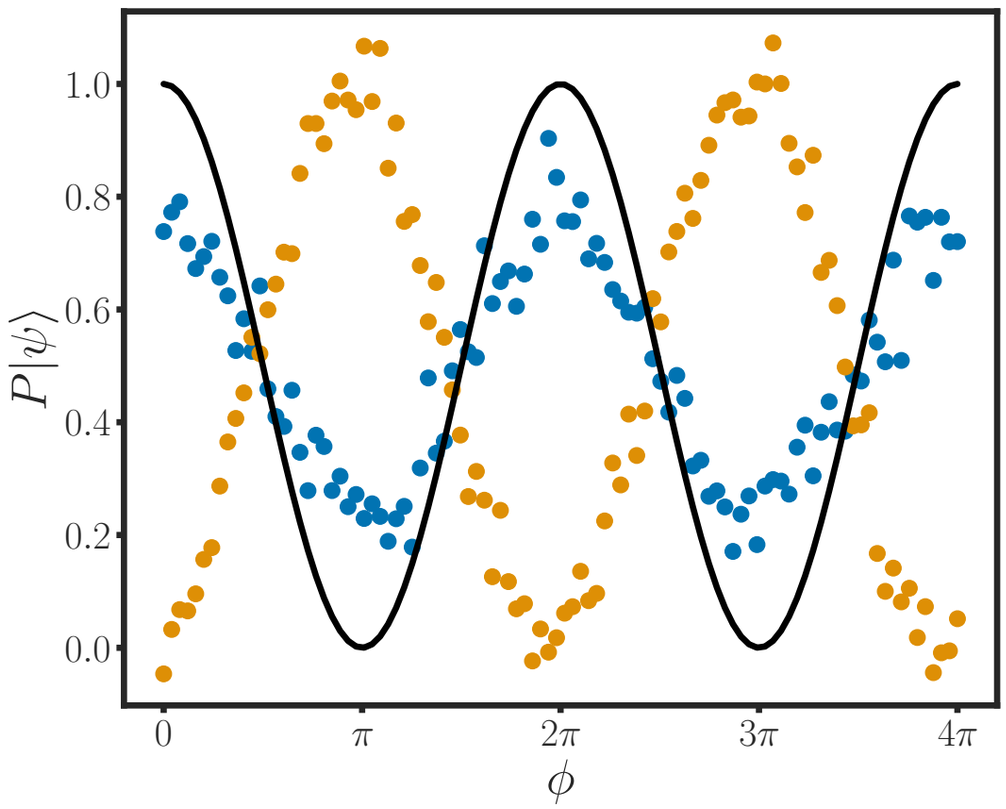
$\Omega_\chi = 5\% - 10\,\% \,\Omega_{\mathrm{DM}}$





AIs: Backgrounds

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



Visibility

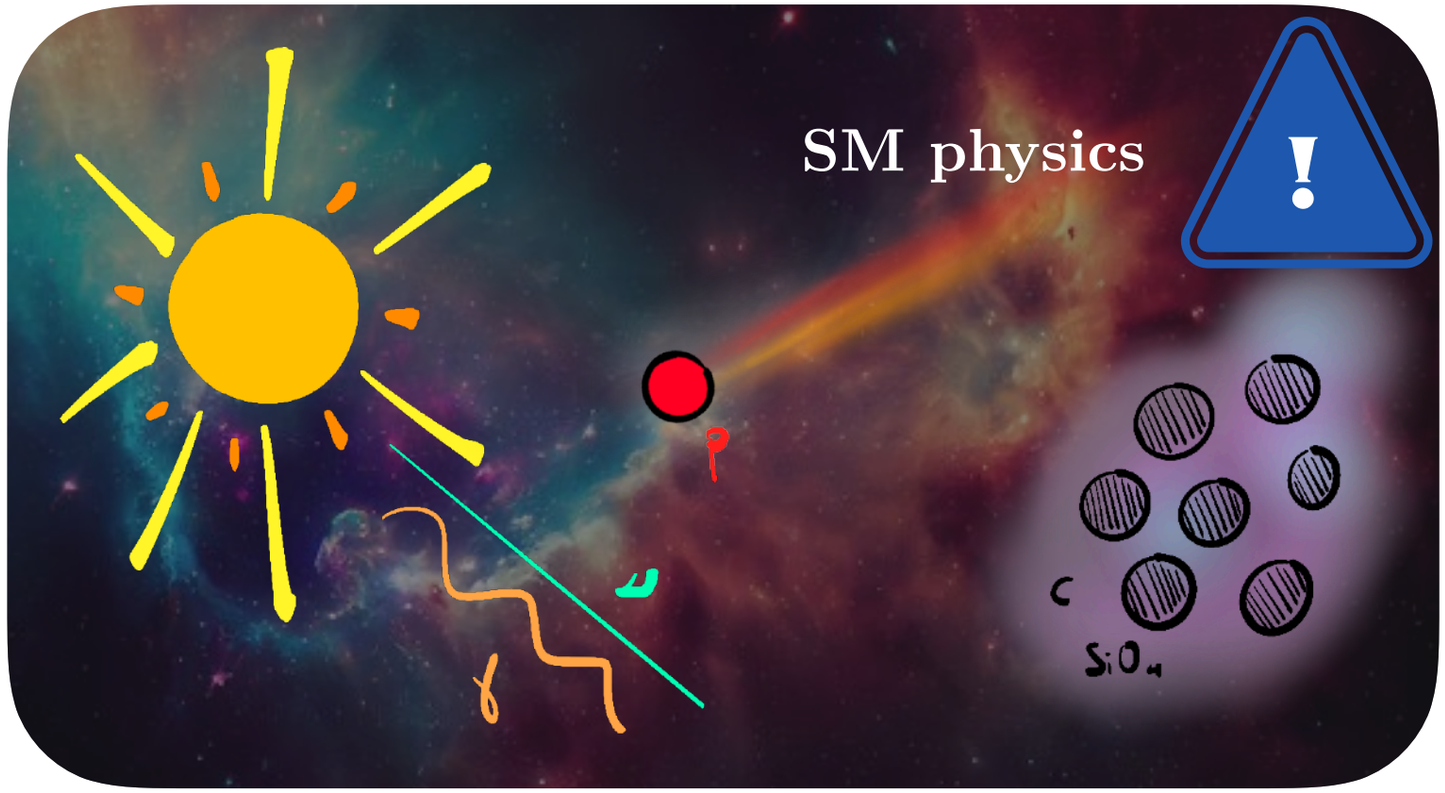
$$\text{SNR}|_{\text{shot}} \equiv \frac{|\Delta V|}{\sigma_V}$$

No decoherence or phase effects

Decoherence Effect

Phase Effect

AIs: Backgrounds



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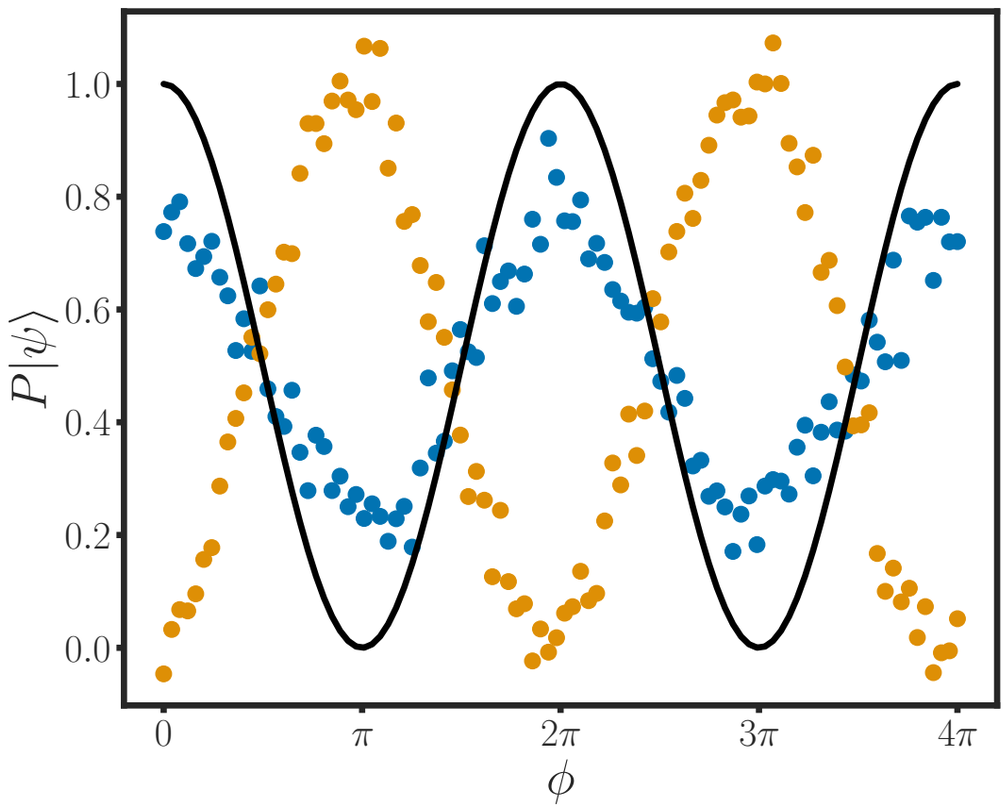

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[Du, **CM**, Pardo, Wang, Zurek, 2023]

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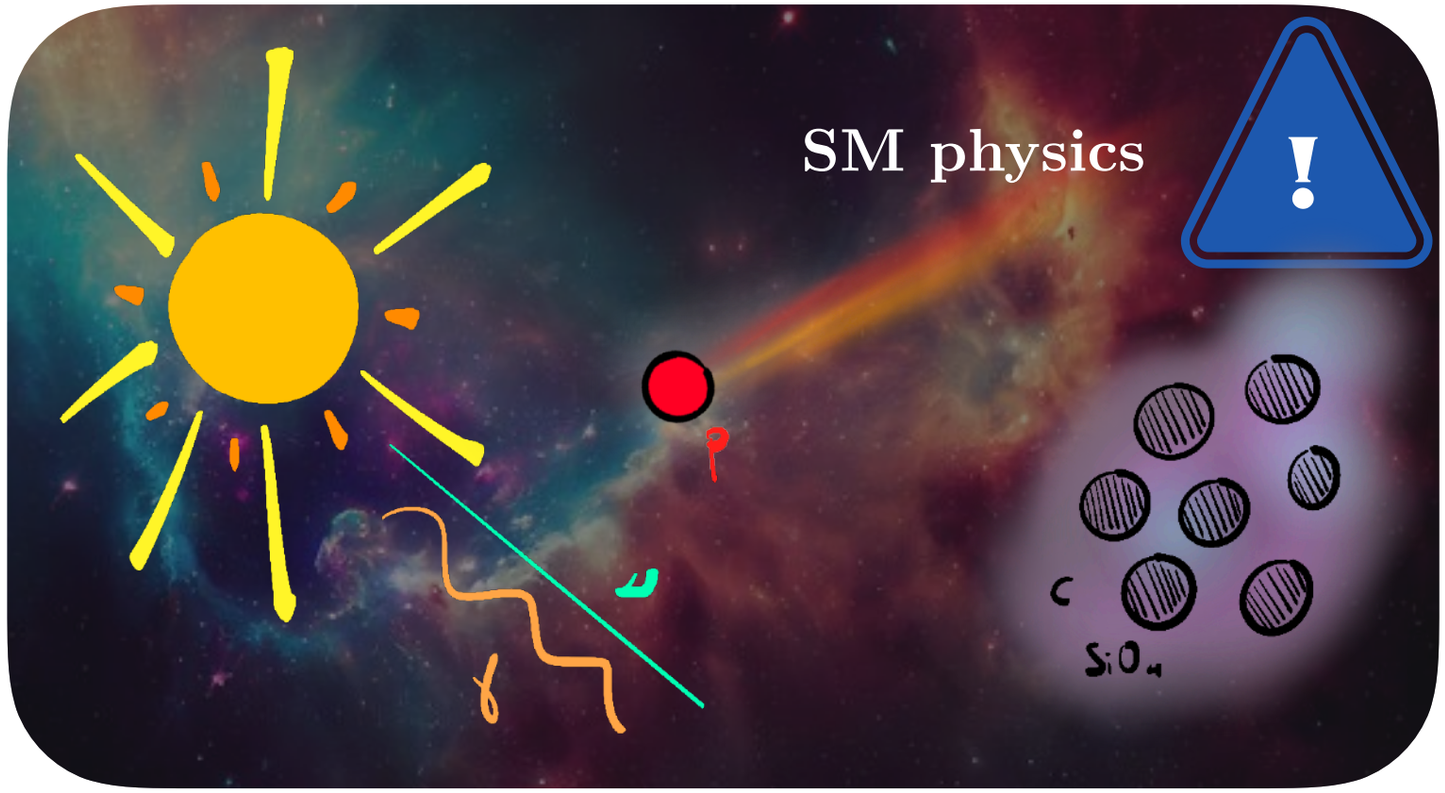

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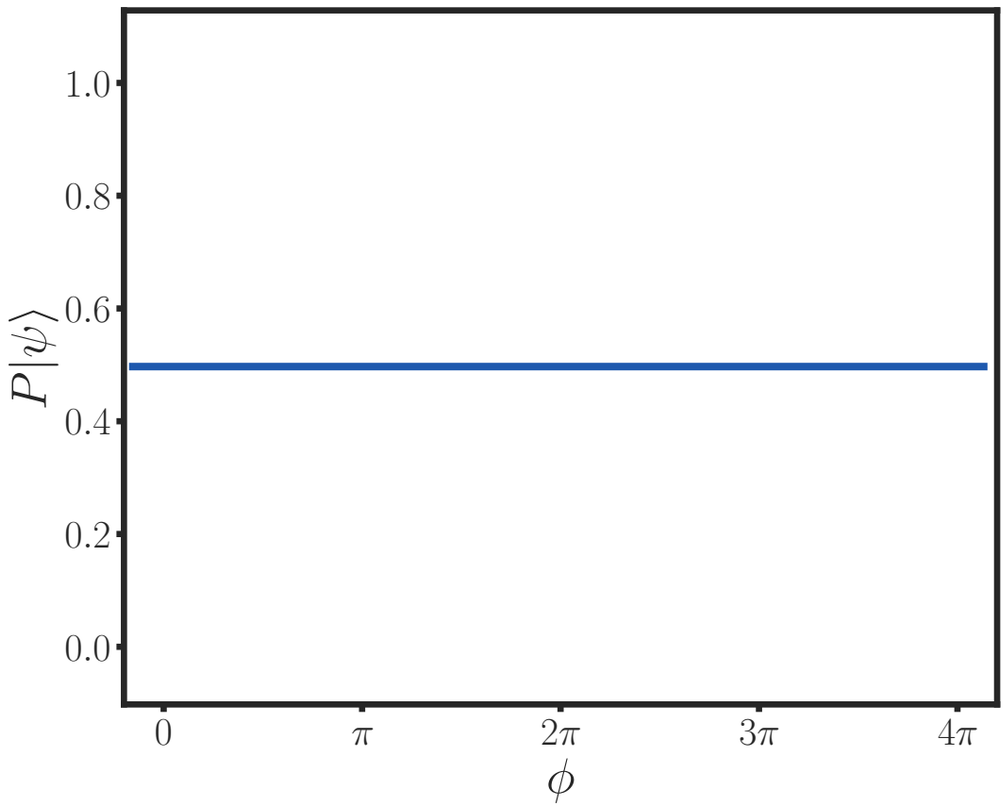

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AIs: Future directions

Extended formalism

Undistinguishable atoms, extended cloud, temperature effects

[with Leonardo Badurina, Ryan Plestid, Yikun Wang]

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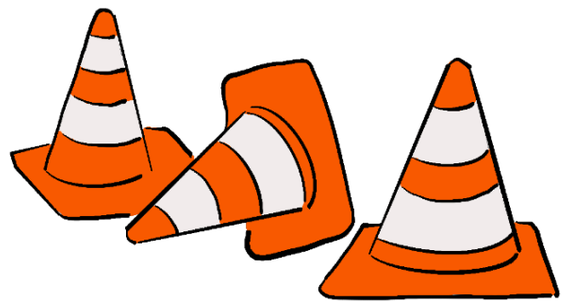
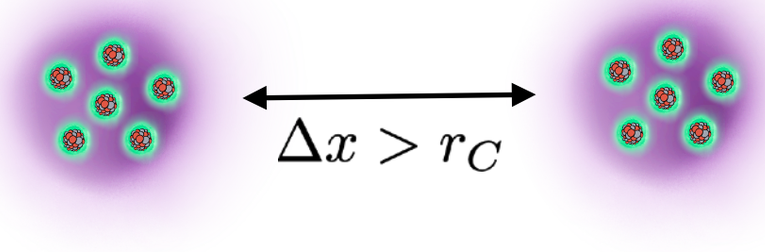


Testing scattering decoherence / coherence at the lab



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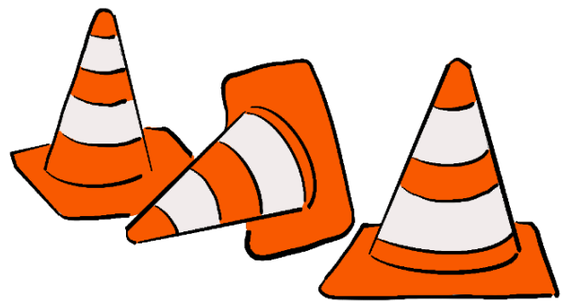

Extended formalism

Undistinguishable atoms, extended cloud, temperature effects

[with Leonardo Badurina, Ryan Plestid, Yikun Wang]

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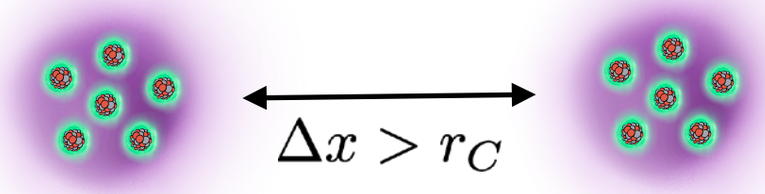
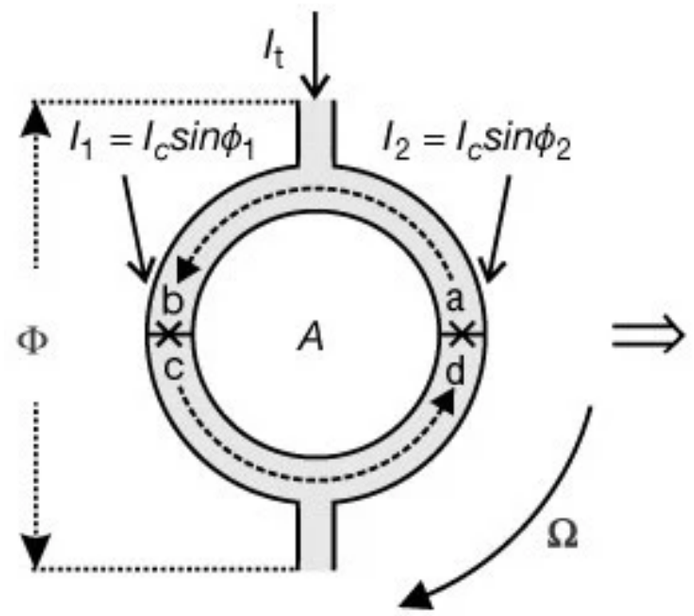
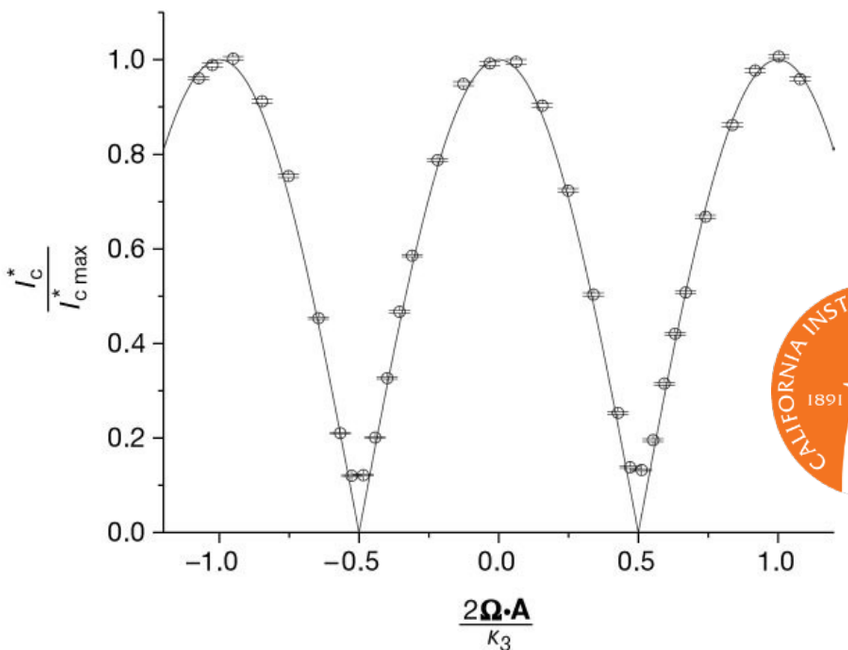


Liquids as AIs?

e.g. QUEST-DMC [conversations with Juri Smirnov]

[Simmonds, Marchenkov, et al., 2001]



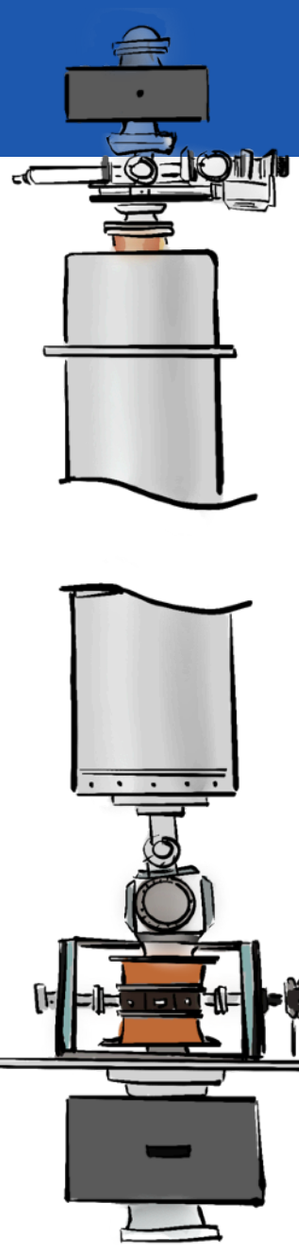


Keith Schwab

Caltech

Conclusions

Table-top experiments already ∃ !



L. Kastler Brossel

BERKELEY

$(\cdots)$

STANFORD
10-m atomic fountain

ZHAOSHAN
12-m atomic fountain

Or under construction:

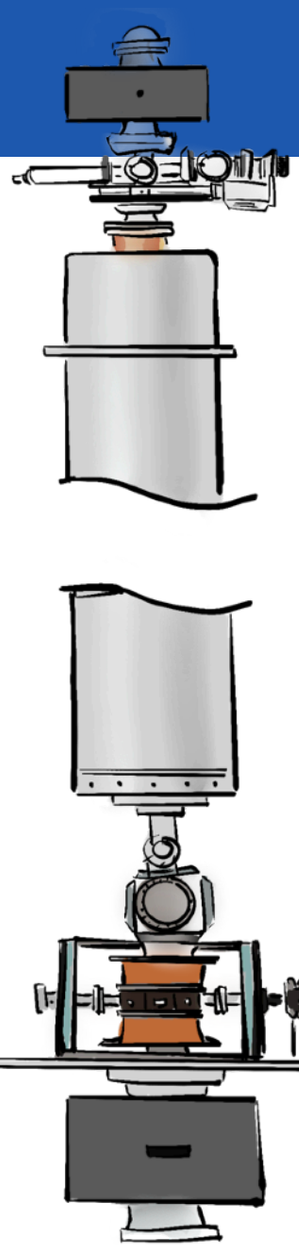
AION

MAGIS-100

MIGA

$(\cdots)$

Table-top experiments already ∃ !



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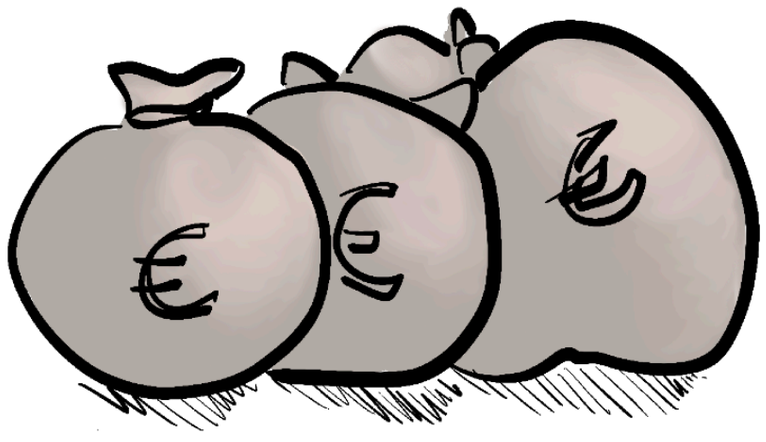

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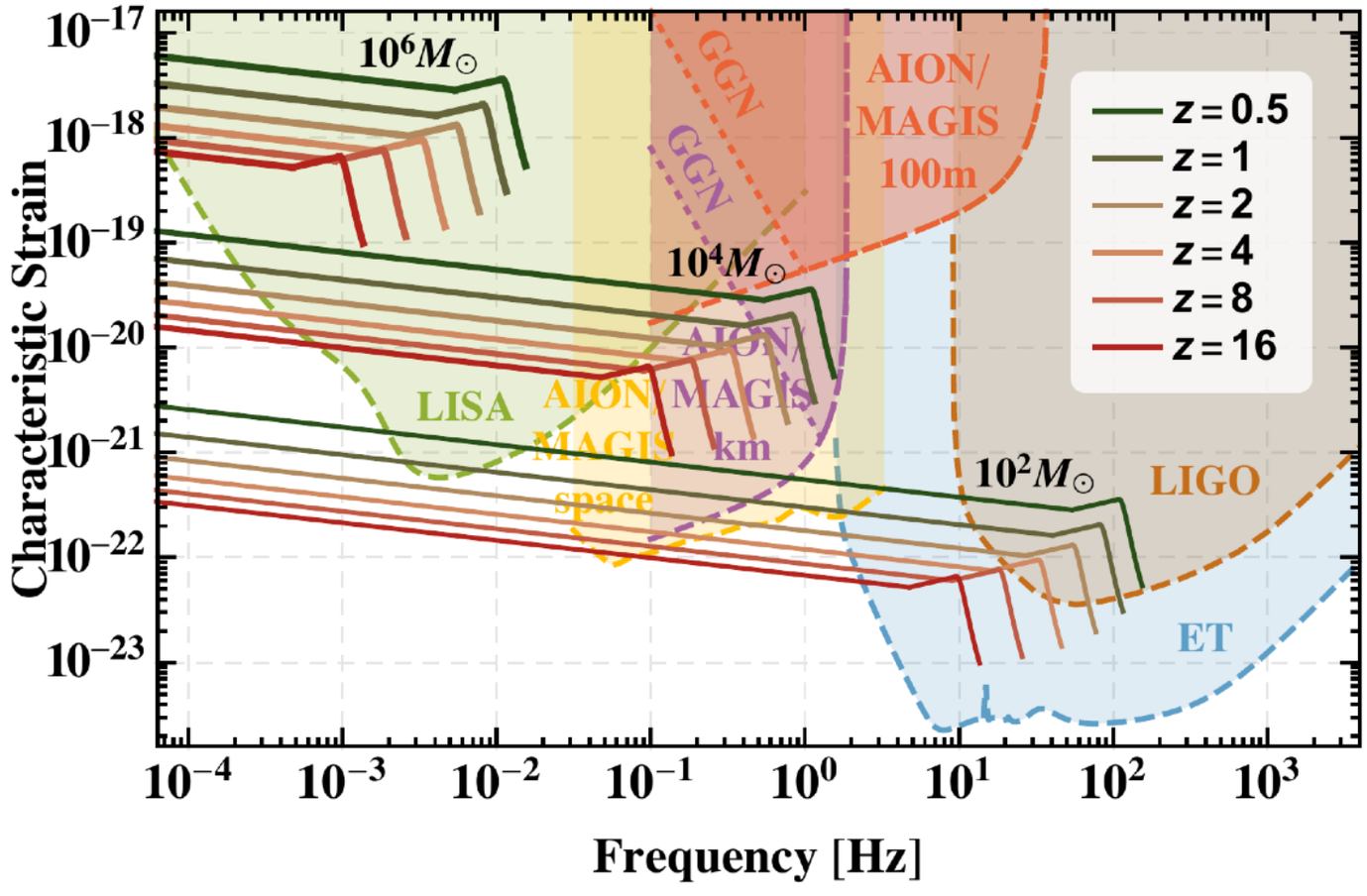
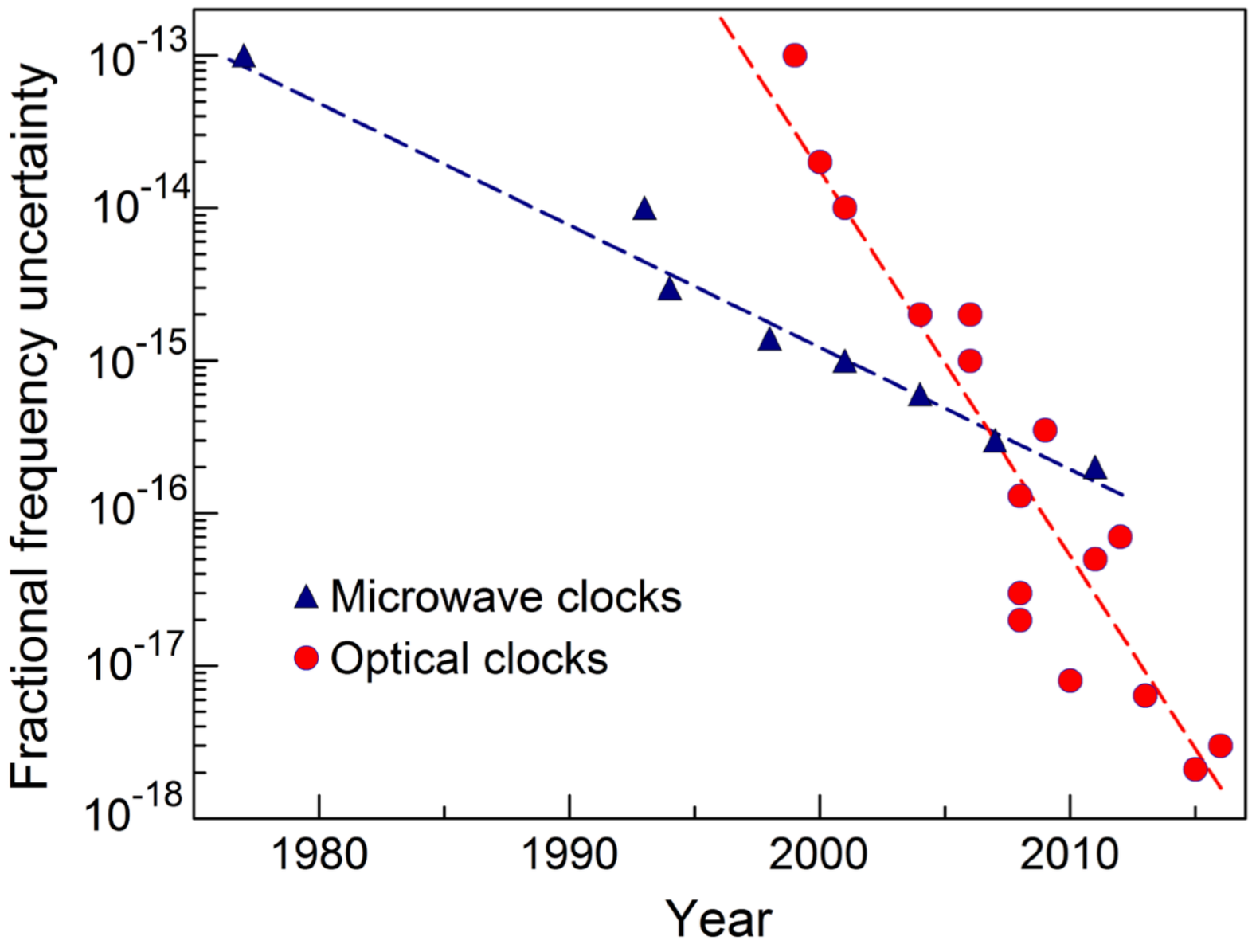
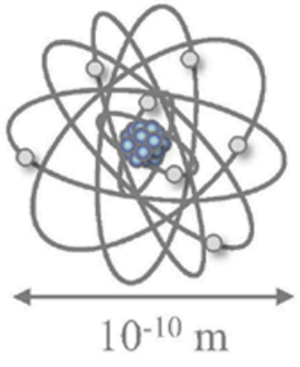


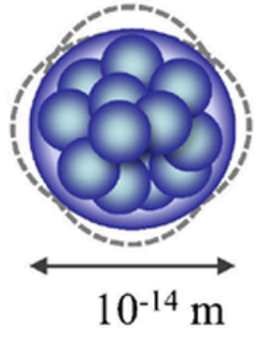
Boundaries unreached !!

e.g. Atomic clocks



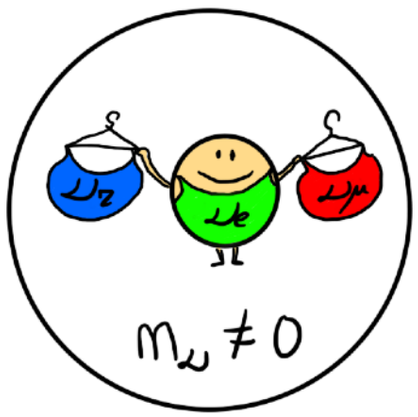
[Huntemann et al., 2016]
[Nicholson et al. 2015]
[Poli et al. 2013]
[Safranova et al. 2017]

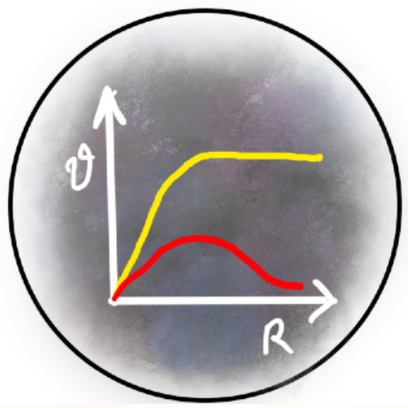




Nuclear clocks [Peik et al. 2021]

Unexplored parameter space !!!





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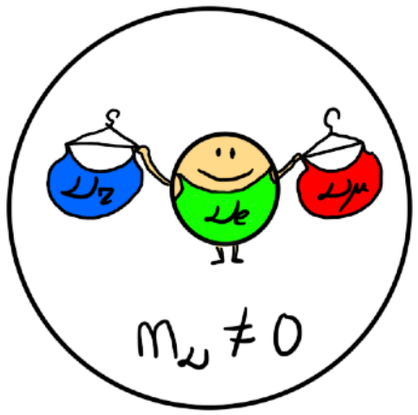


DECOHERENCE

$$\lambda = 1/q \gtrsim \Delta x$$

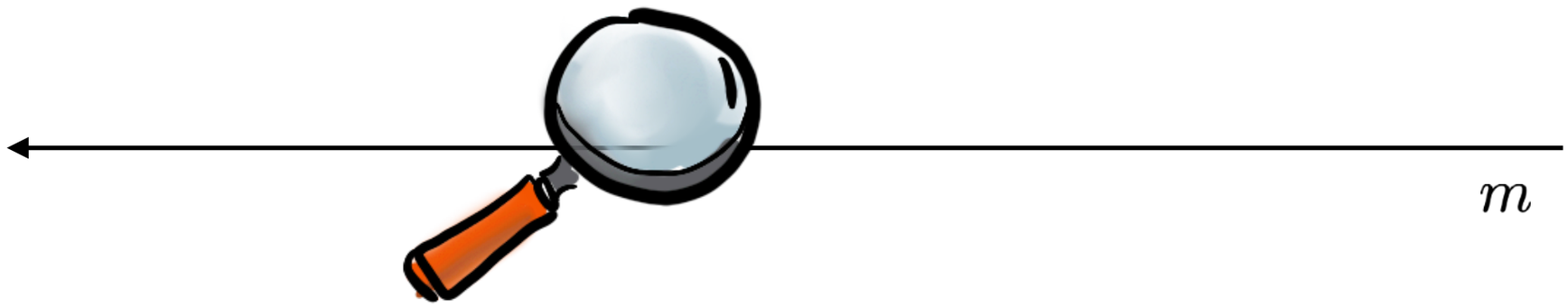
COHERENCE

$$\lambda = 1/q \gtrsim r_c$$

AYUDA BEATRIZ GALINDO JUNIOR BG23

~~Atomic sensors for BSM~~

Clara Murgui (UAB/CERN)



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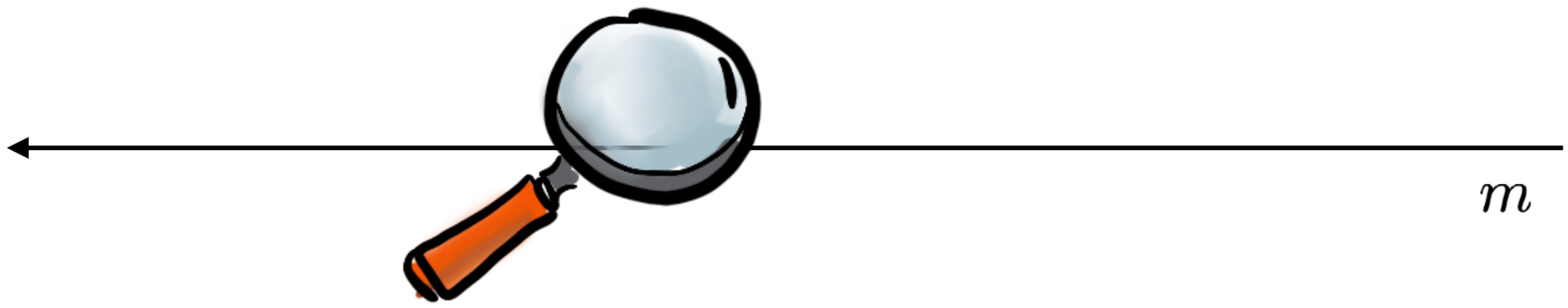
1st July 2024

AYUDA BEATRIZ GALINDO JUNIOR BG23

Atomic sensors as particle detectors

Clara Murgui (UAB/CERN)



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Thanks for your attention!