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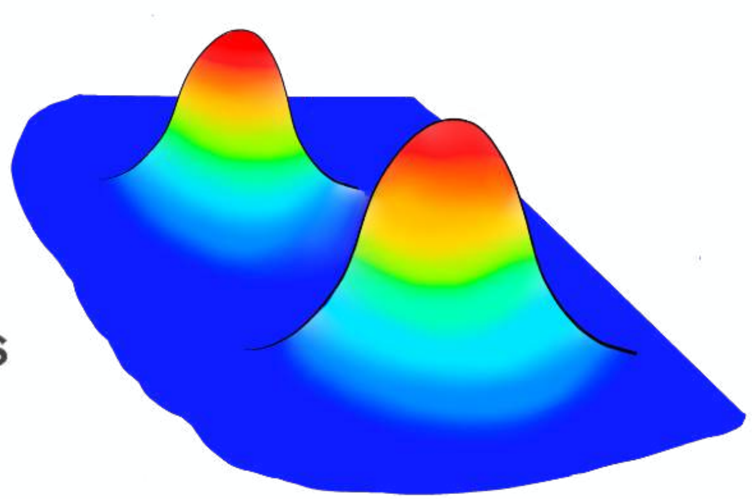
UAB Universitat Autònoma de Barcelona
IFAE Institut de Física d'Altes Energies
CERN

Quantum technologies for future particle physics experiments

Clara Murgui

CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL



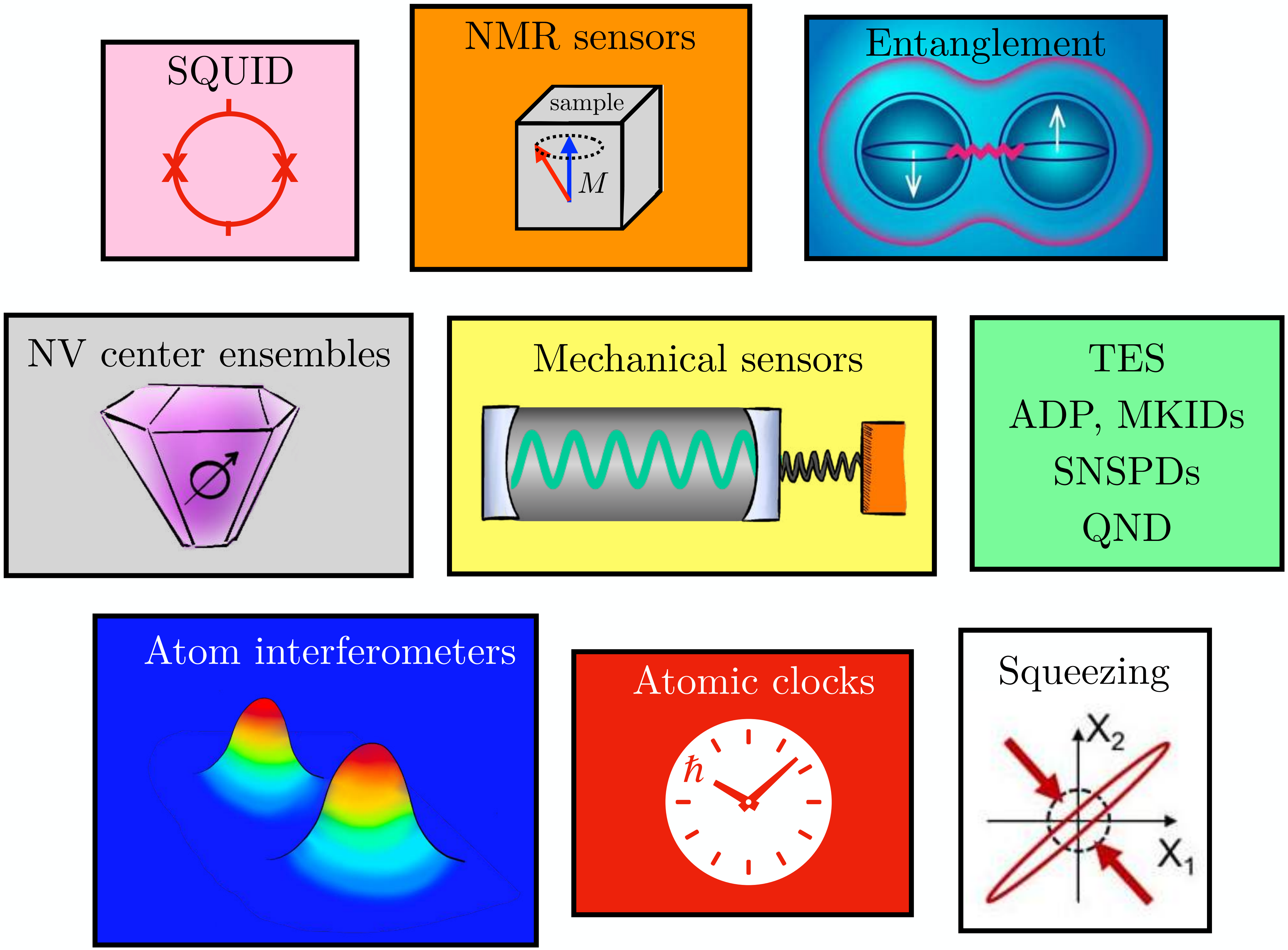
International Meeting on Fundamental Physics 2024, Sep 11

Quantum Sensing

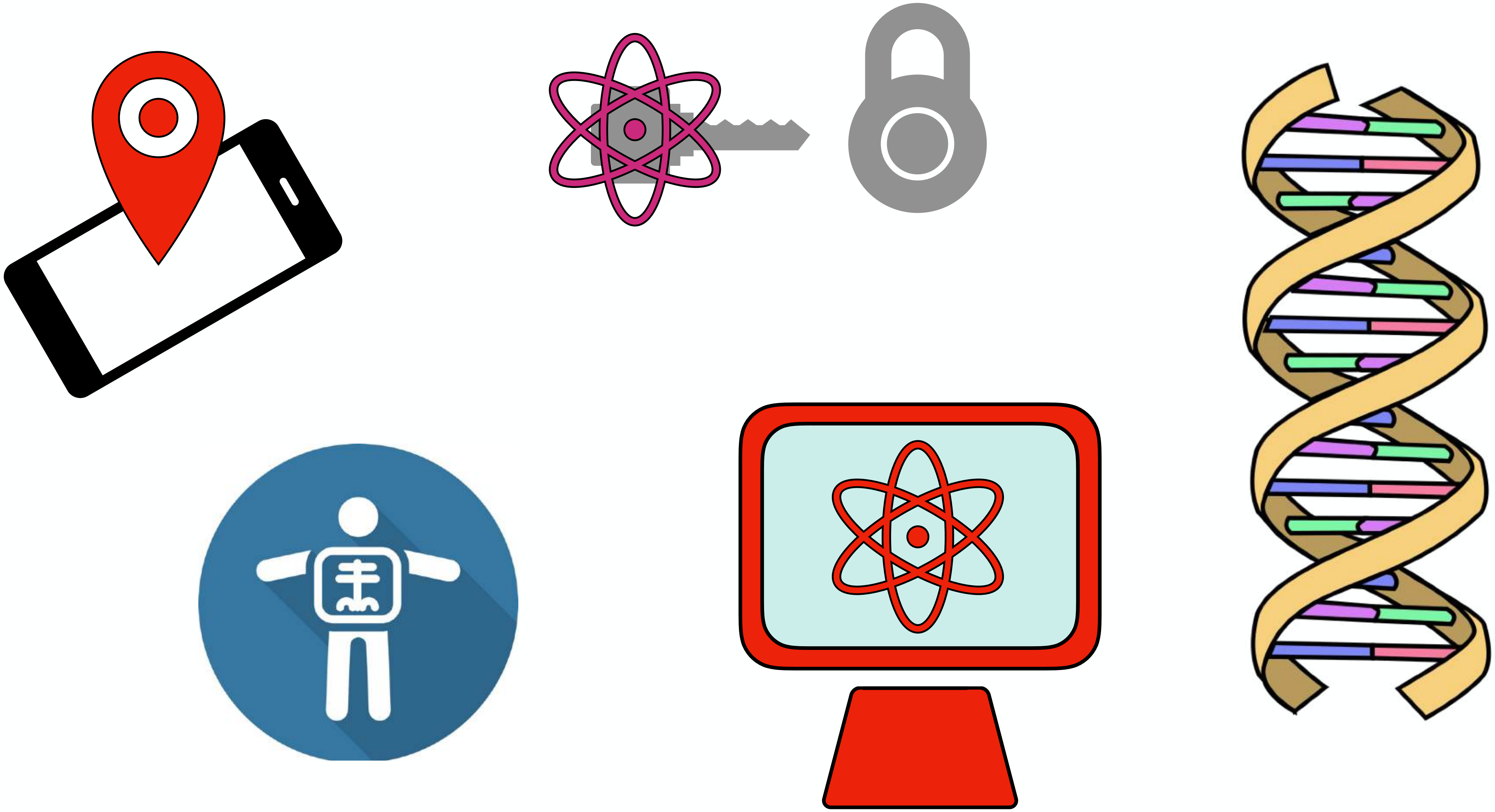
"Use of a quantum system, quantum properties o quantum phenomena to perform a measurement of a physical quantity"

[Degen, Reinhard, Cappellaro, 2017]

Quantum Sensors: examples

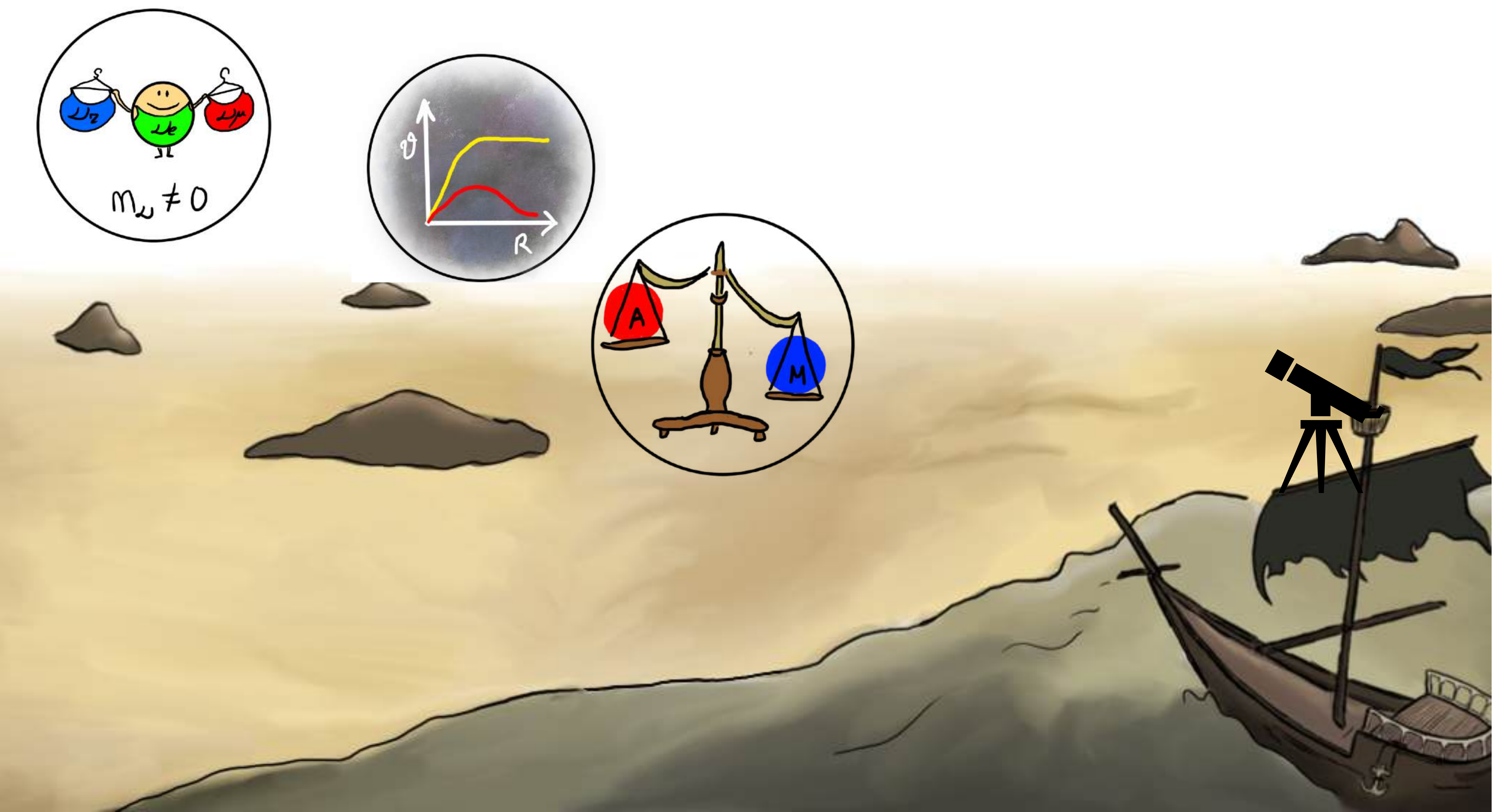


Quantum Sensing: applications

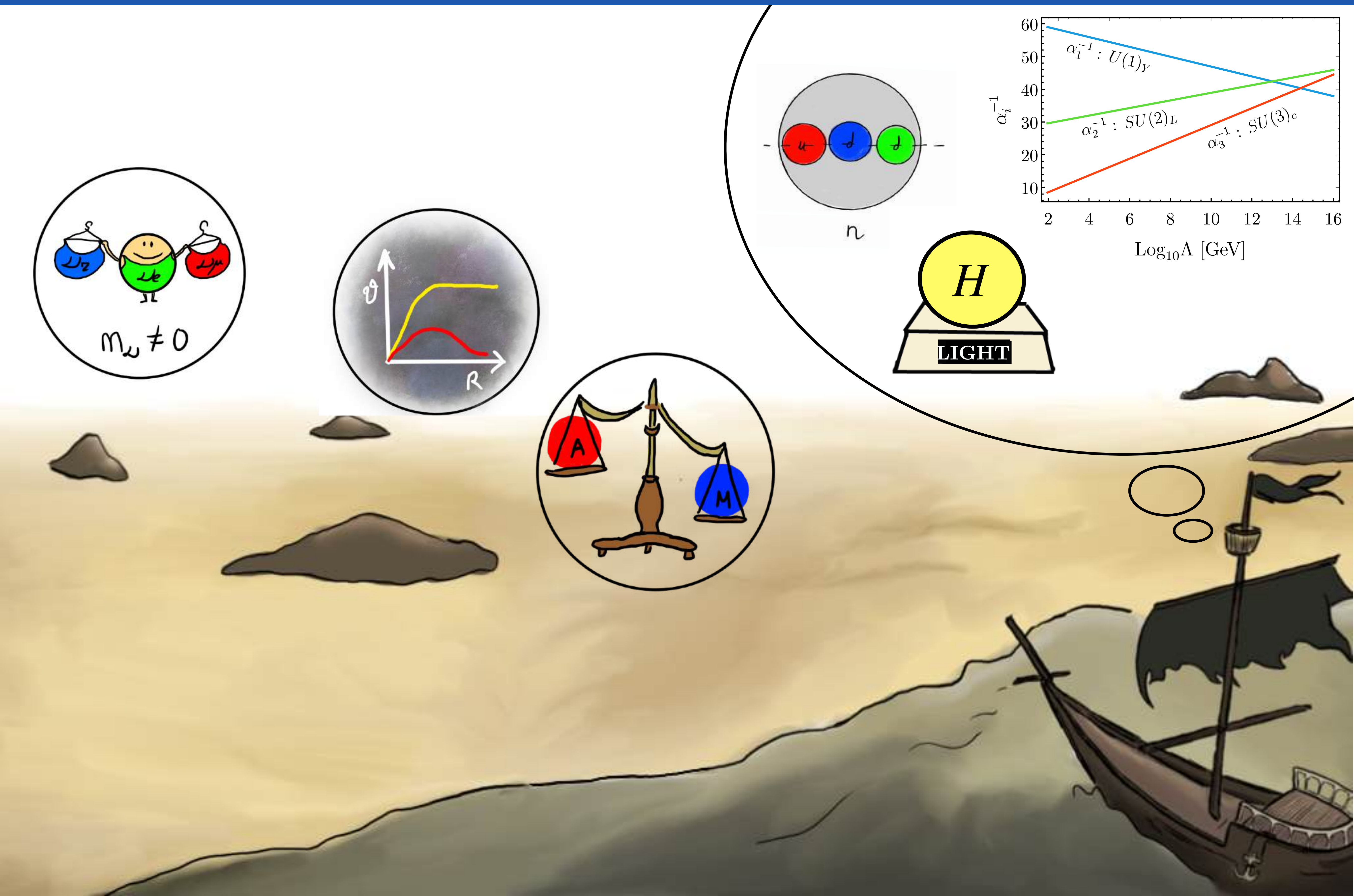


"Why a phenomenologist is given me this talk?"

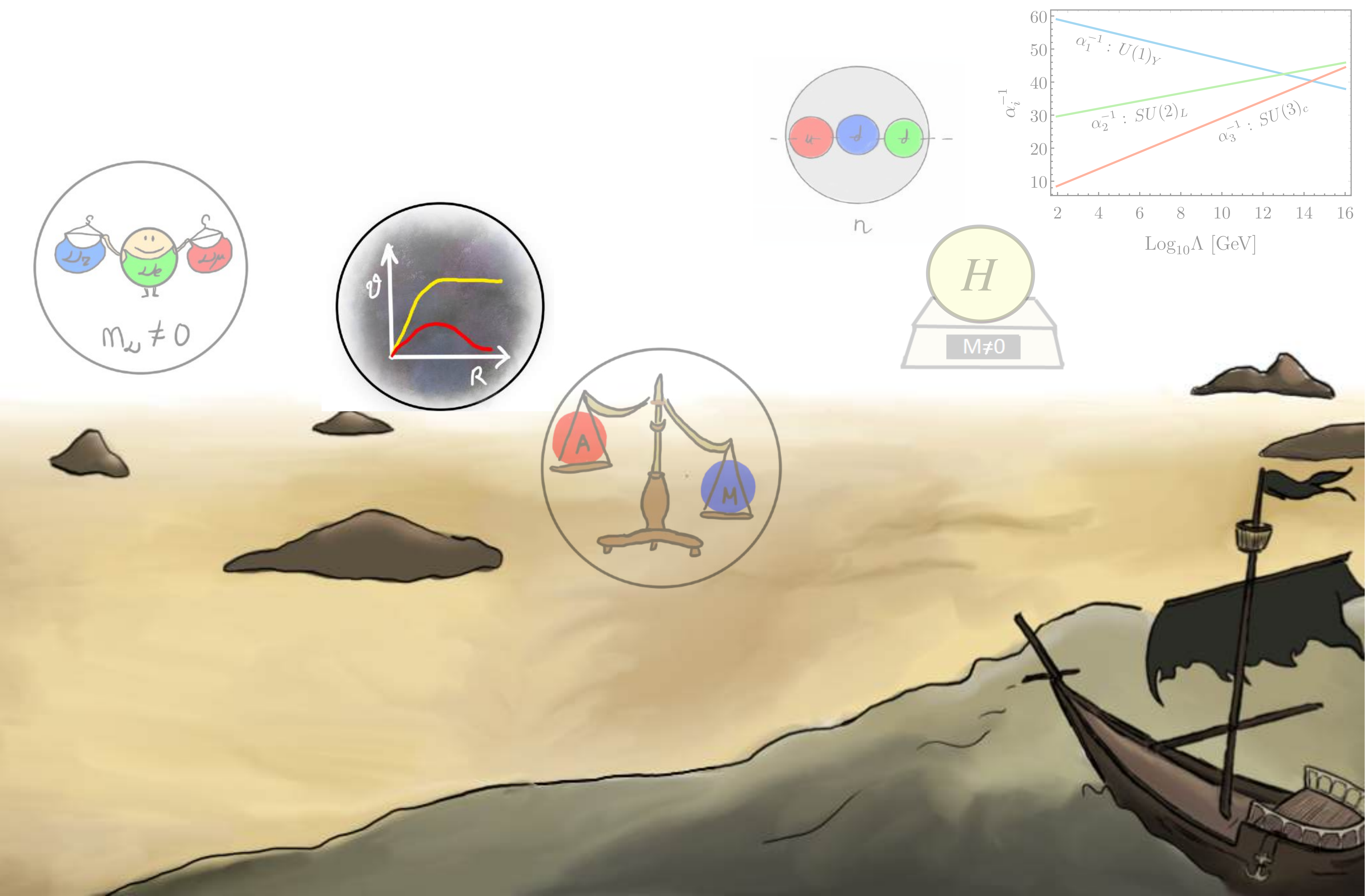
The Need for New Physics



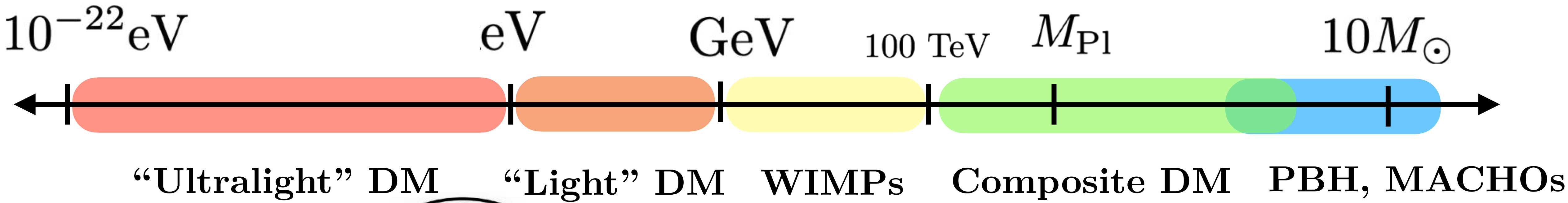
The Need for New Physics

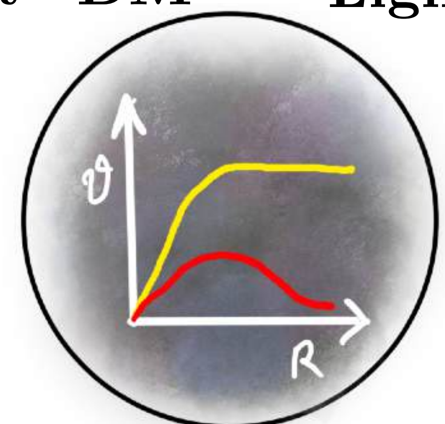


The Need for New Physics



Beyond the SM: where to look?





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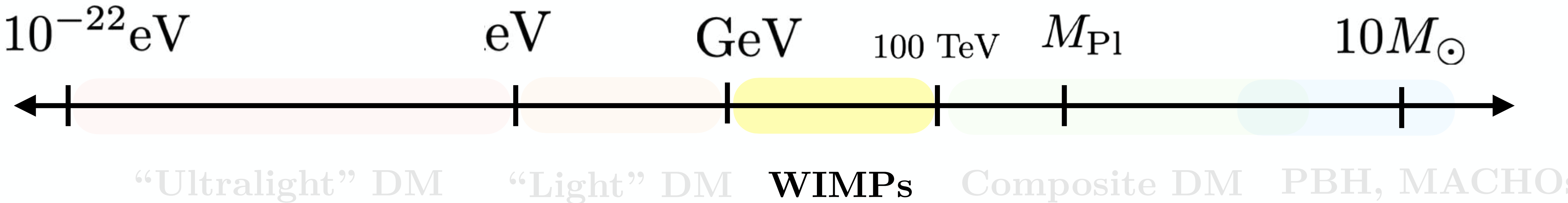
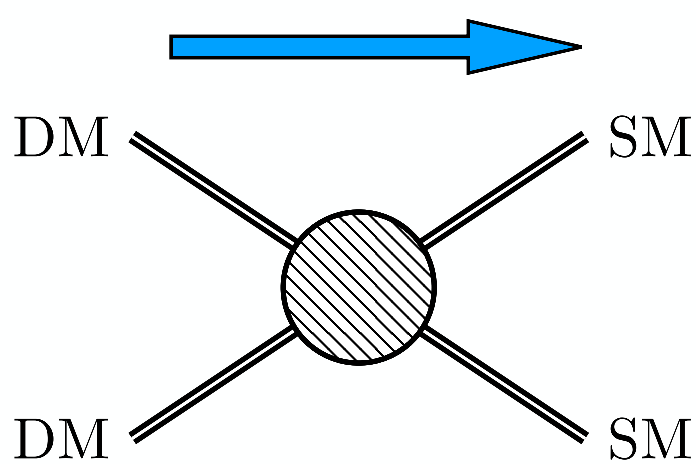


The WIMP miracle



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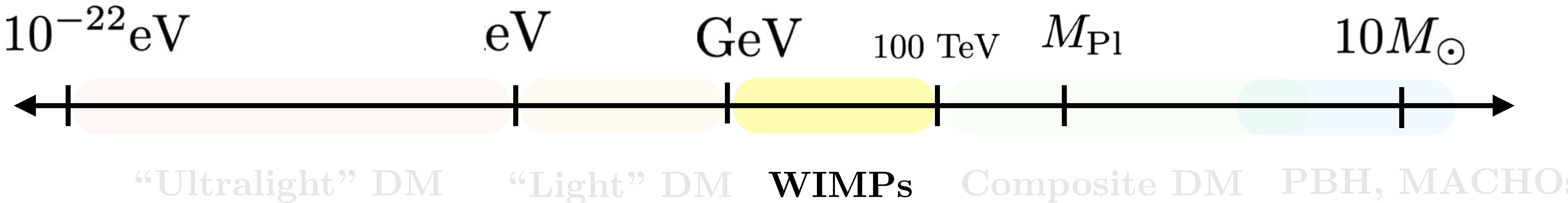

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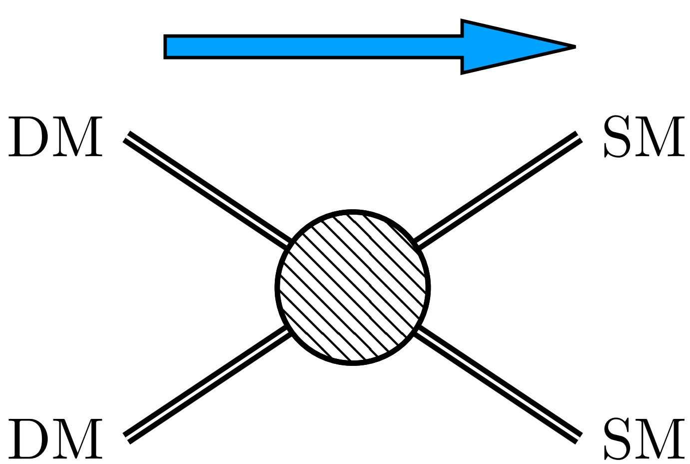
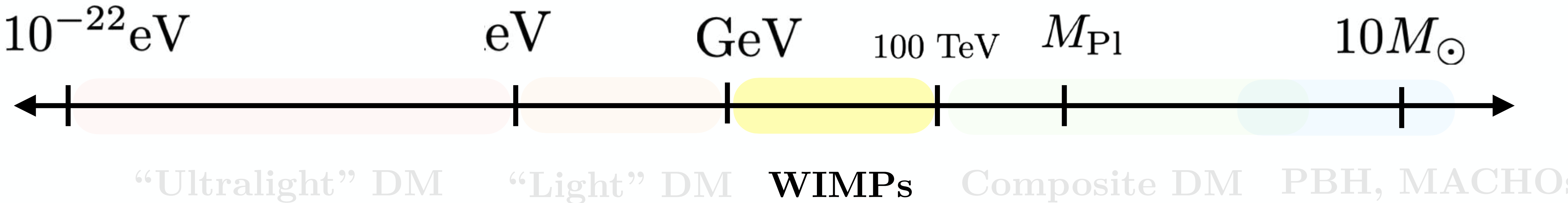


weak coupling

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

Beyond the SM: where to look?



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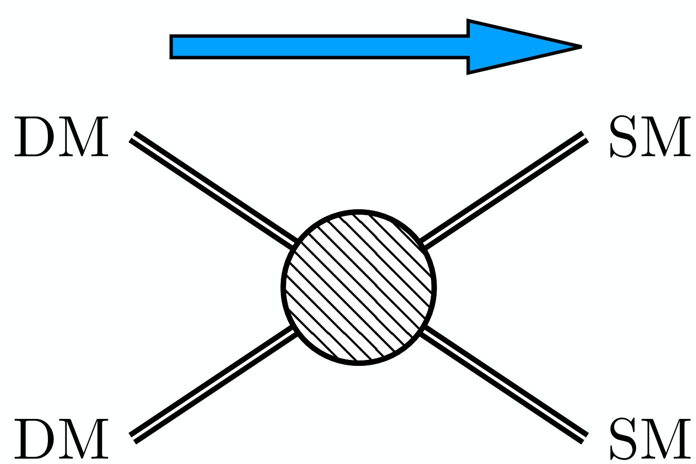

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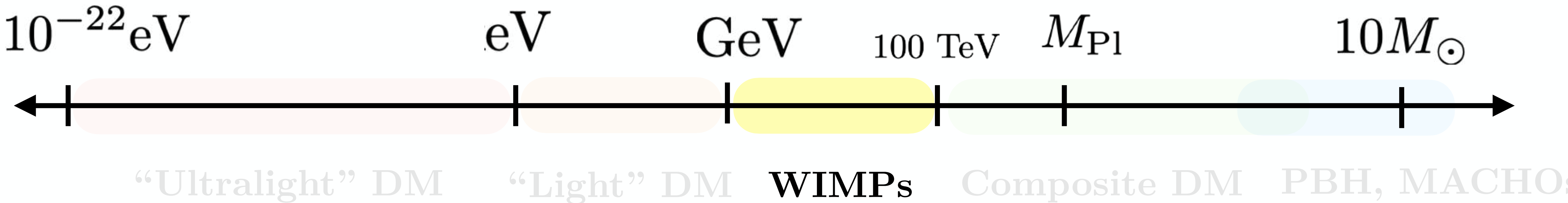
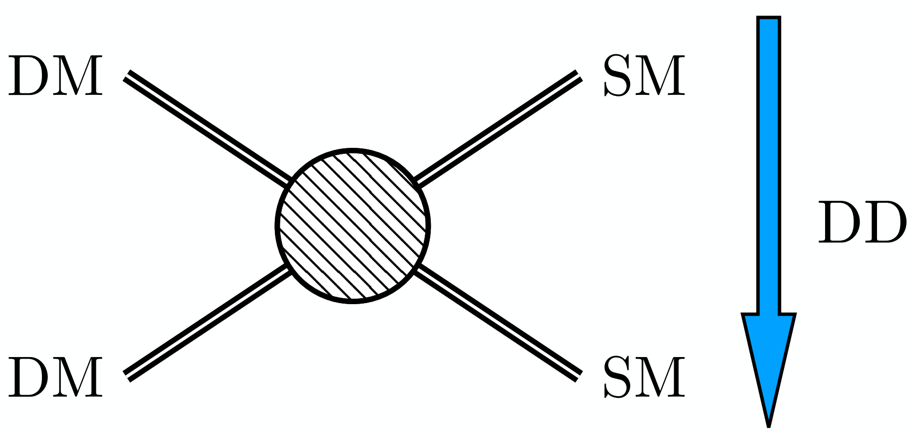
$$\Omega_{\rm DM} \sim 0.1 \times \left(\frac{3\times 10^{-26}\ \mathrm{cm^3/s}}{\langle\sigma v\rangle}\right)$$

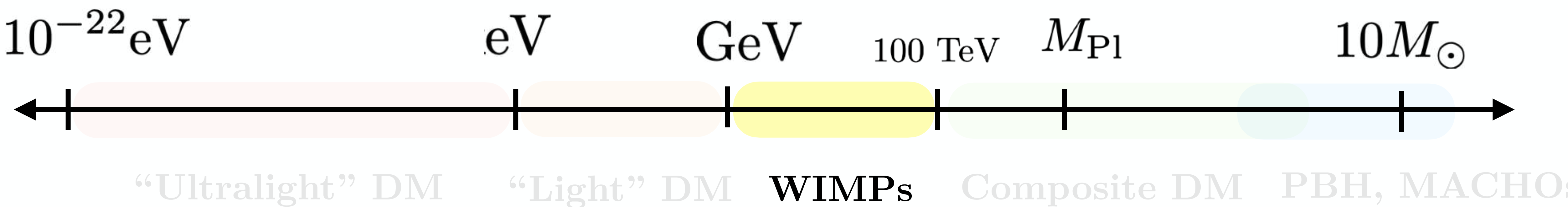
Beyond the SM: where to look?

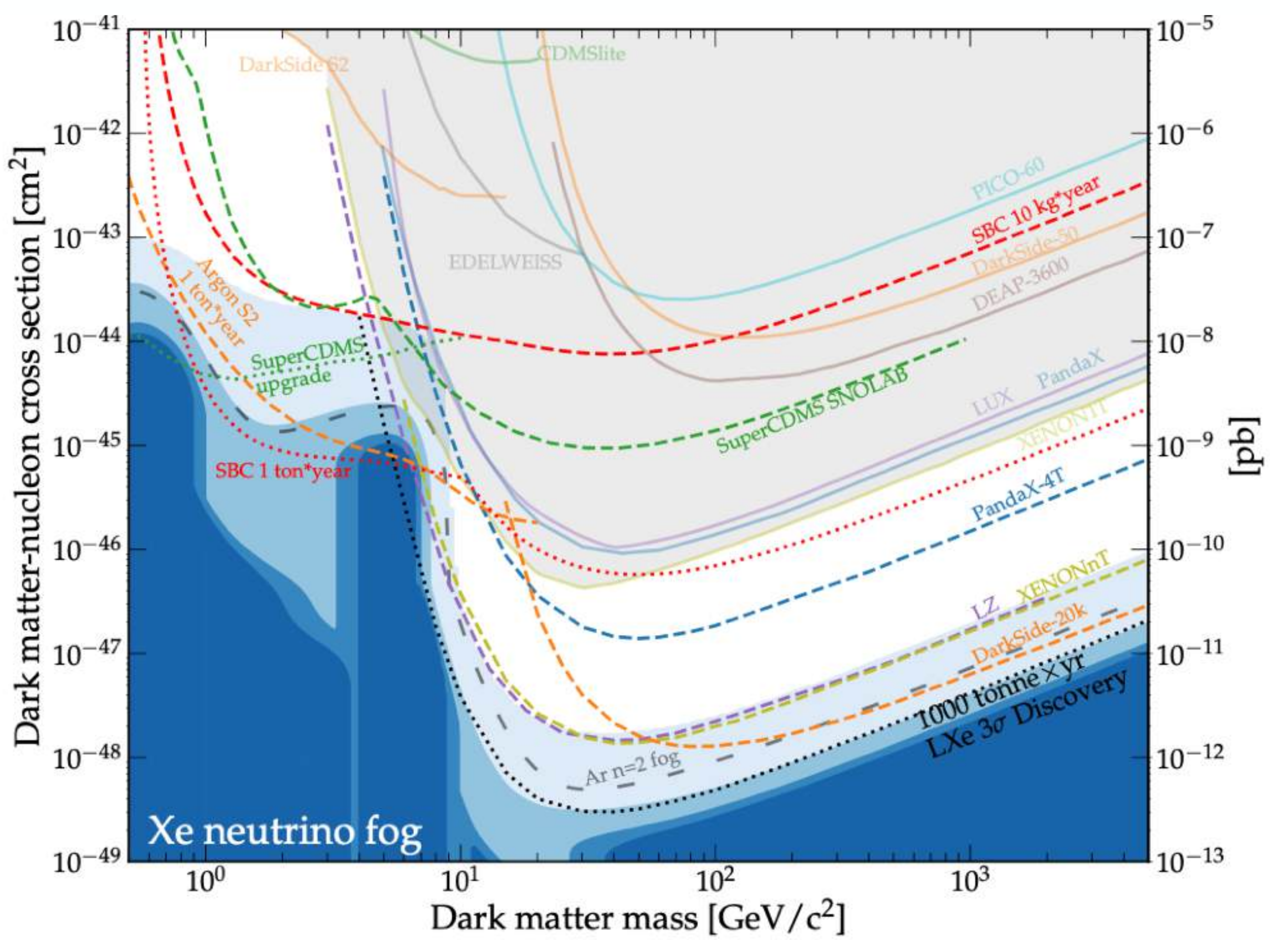




$$\sigma \sim 10^{-34}\mathrm{cm}^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

Beyond the SM: where to look?





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

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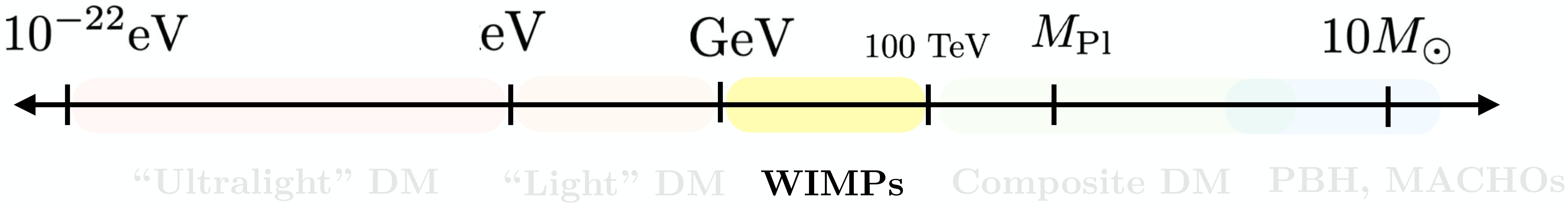
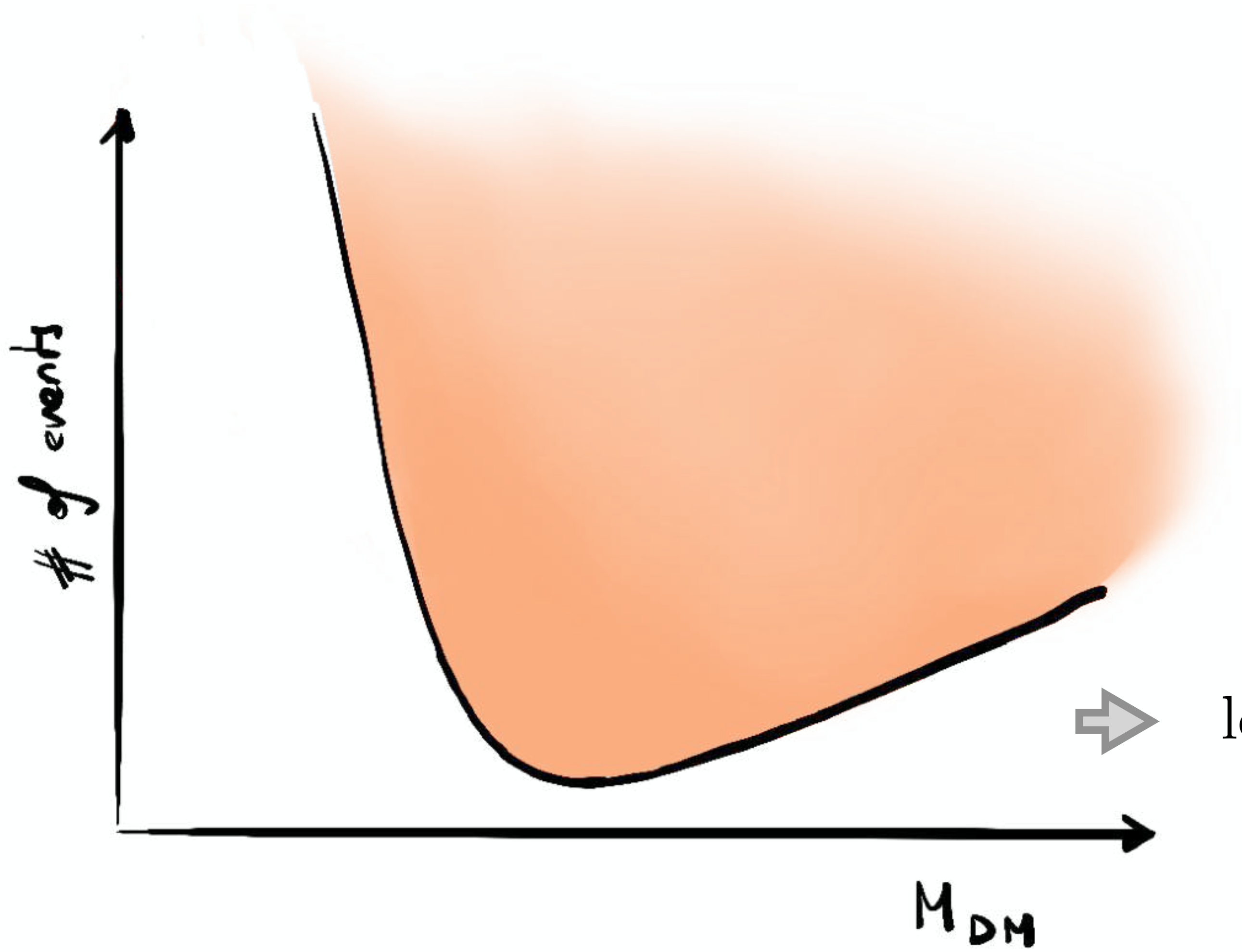
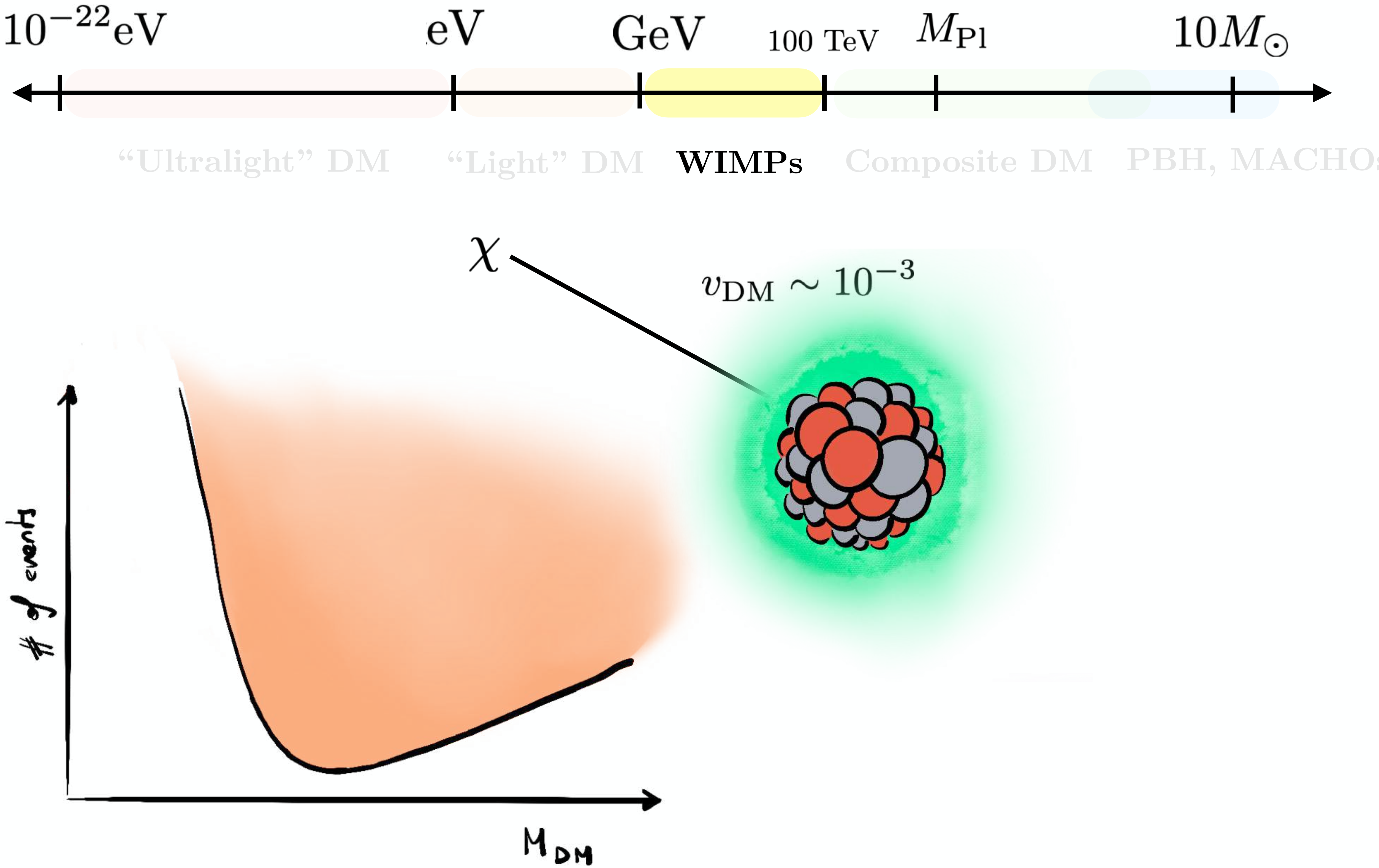




loss of "flux" $n_\chi = \frac{\rho_\chi}{m_\chi}$

Beyond the SM: where to look?



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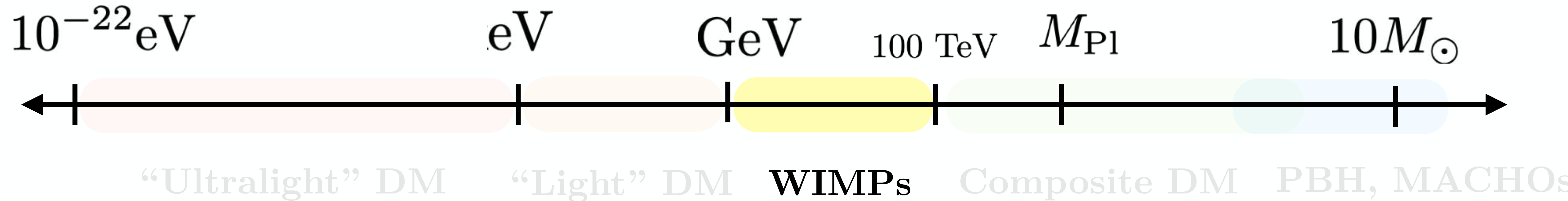
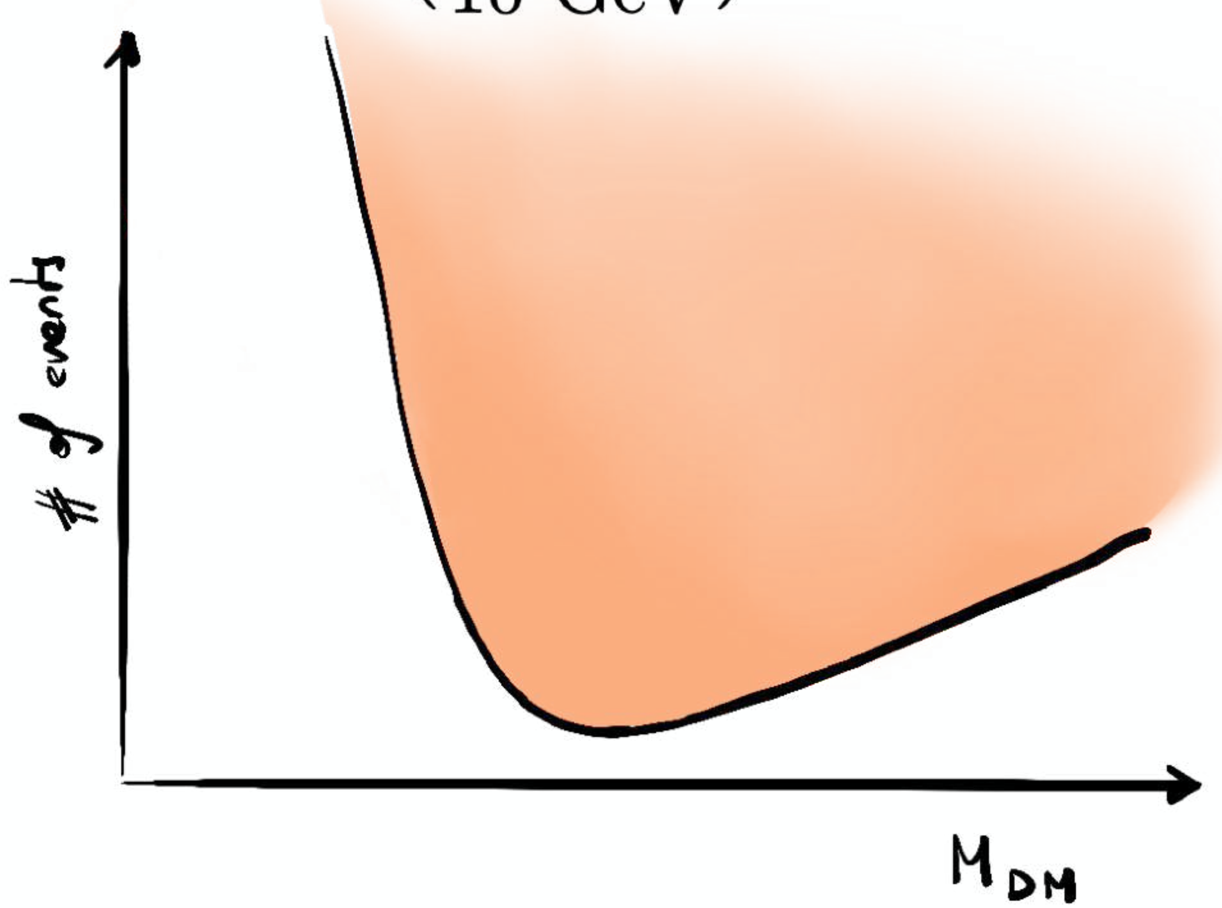
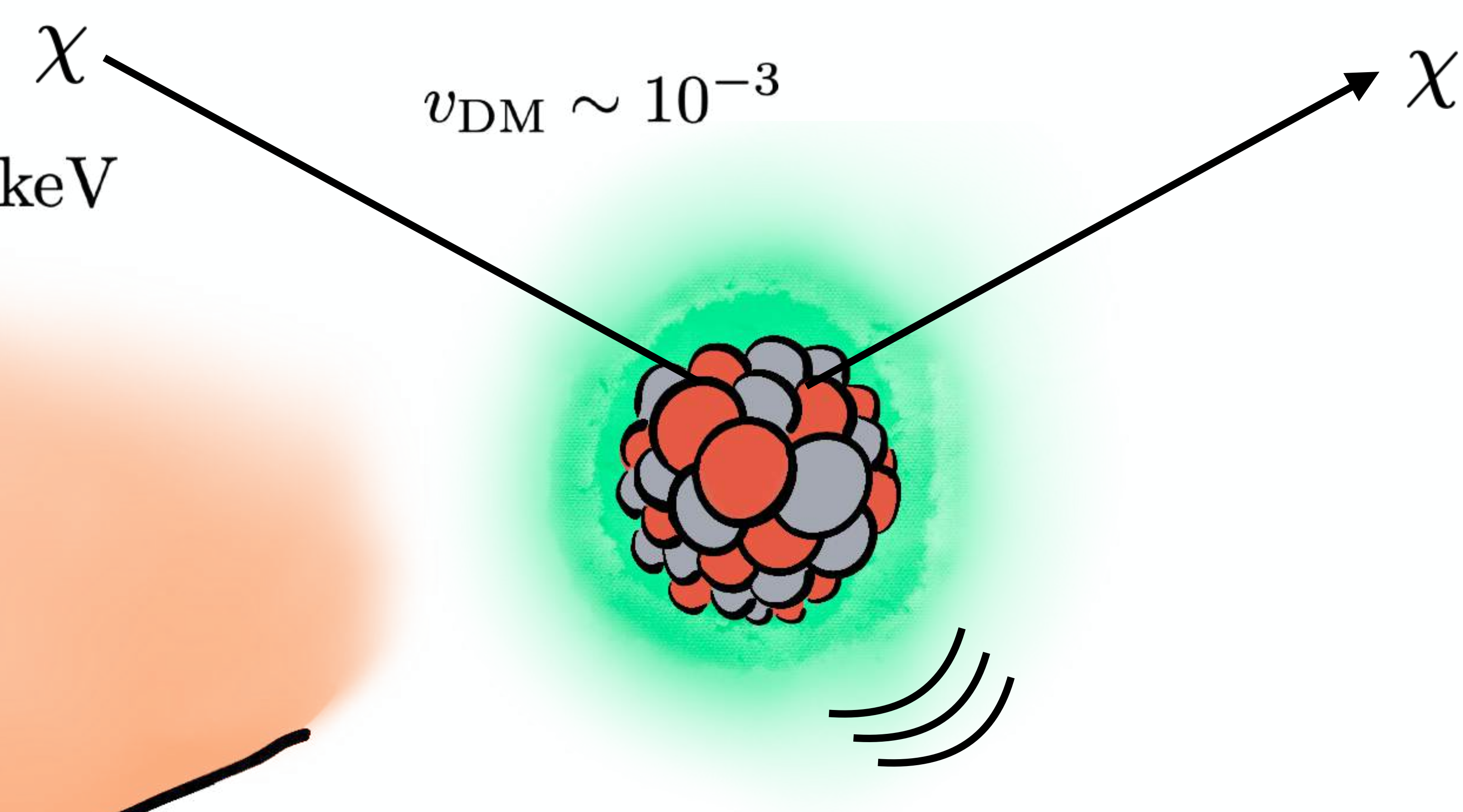
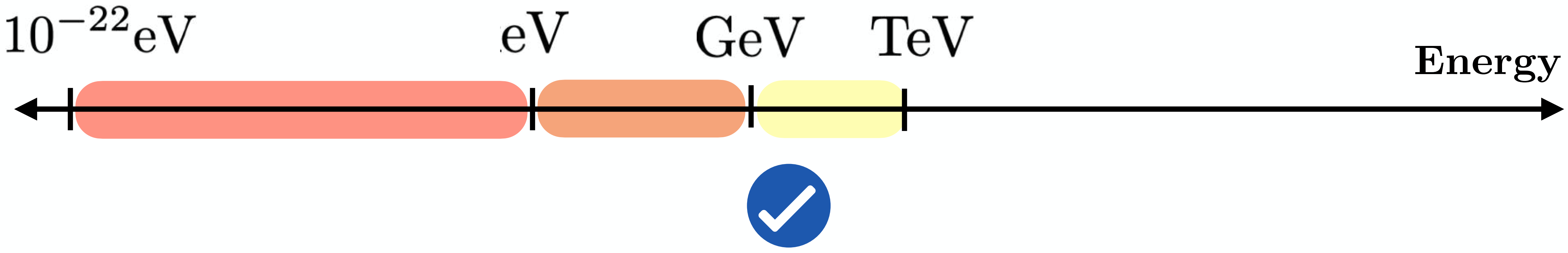


$$E_{\rm recoil}^{\rm max} \sim \left(\frac{m_\chi}{10\ \text{GeV}}\right)^2 \text{keV}$$



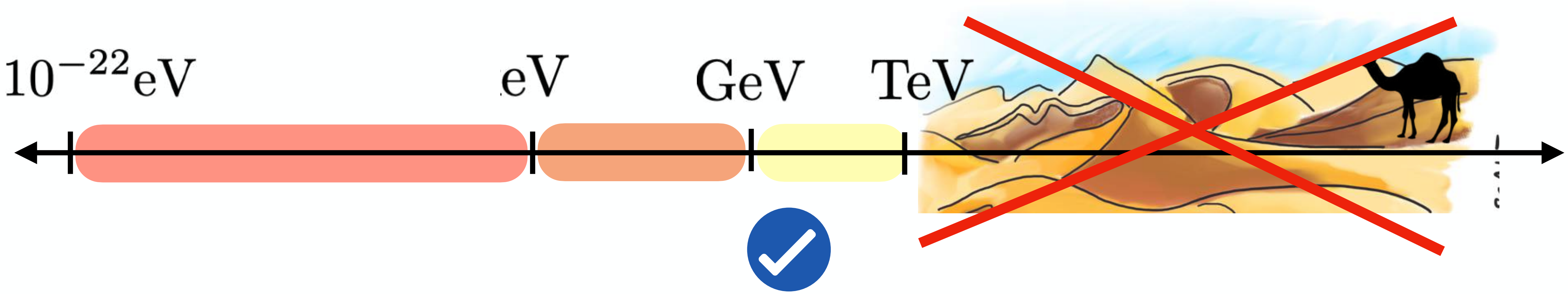


Beyond the SM: "how" to look?



Nuclear recoil exp.
Colliders
...

Beyond the SM: "how" to look?



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Colliders

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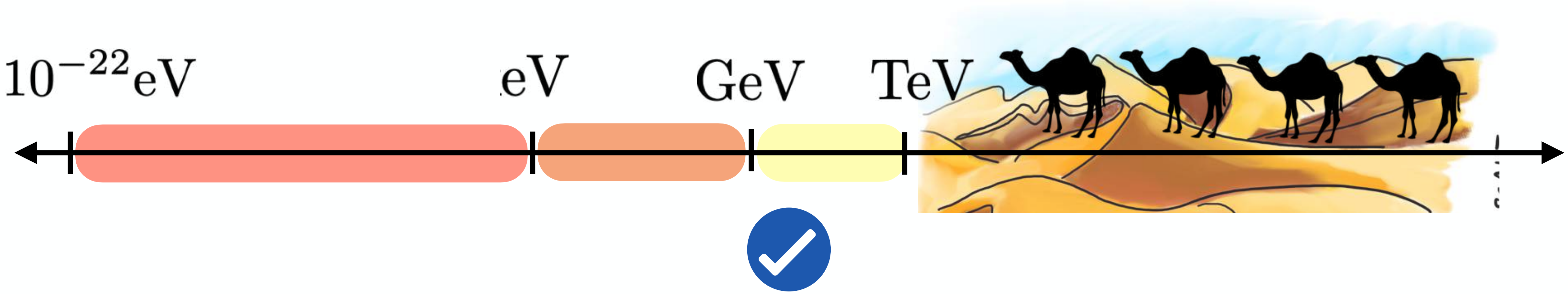

Nuclear recoil exp.

Colliders

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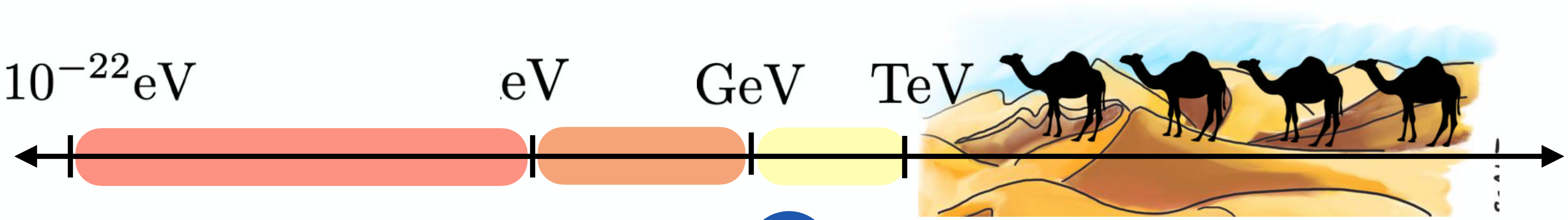
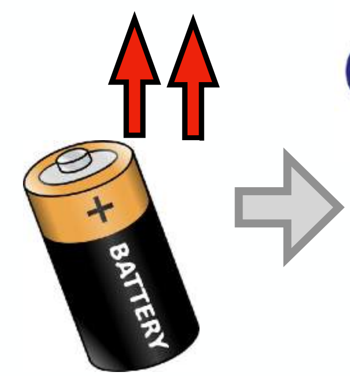


Nuclear recoil exp.

Colliders

...



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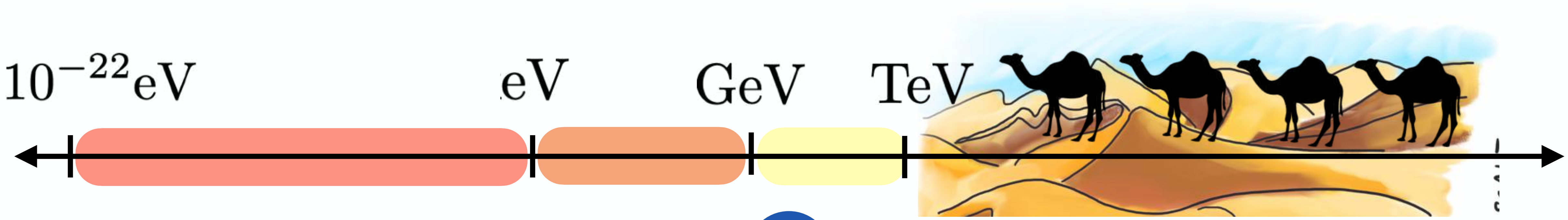

Nuclear recoil exp.

Colliders

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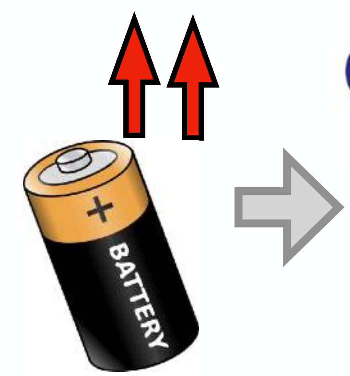

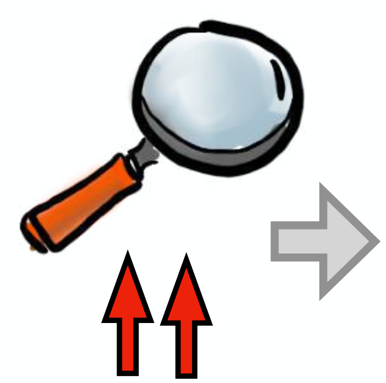

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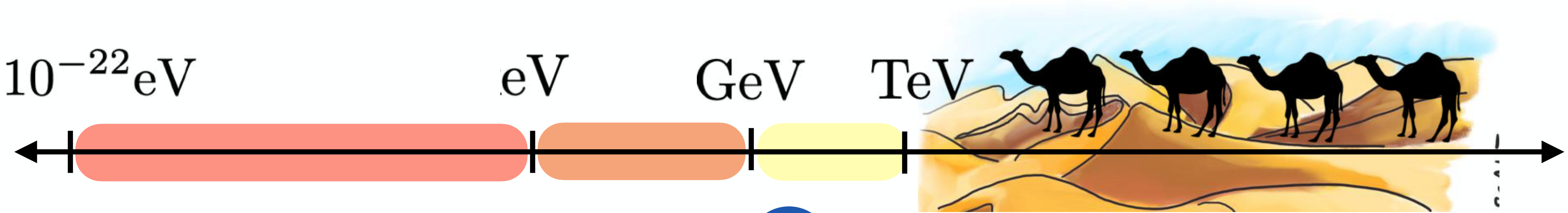
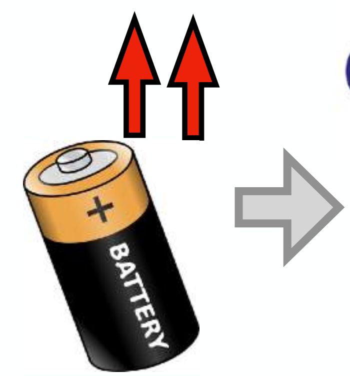


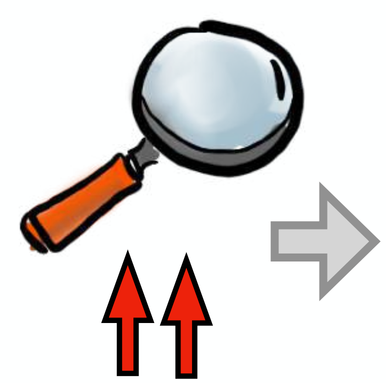
Nuclear recoil exp.

Colliders

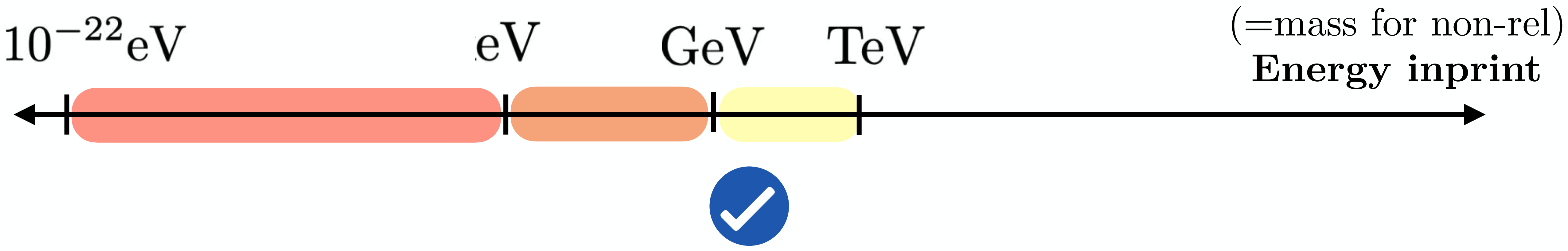
...

MOTIVATION FOR PRECISION IN HIGH ENERGY PHYSICS





Beyond the SM: "how" to look?



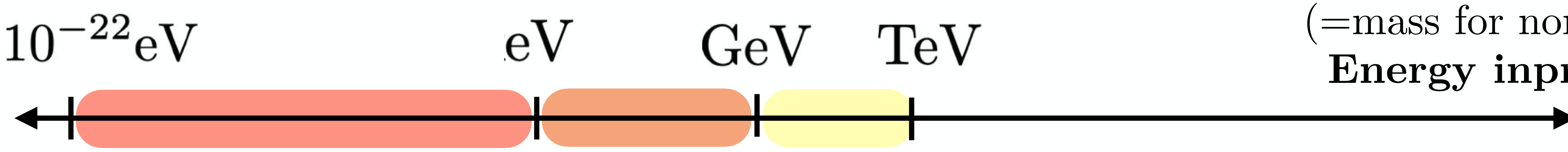
Nuclear recoil exp.

Colliders

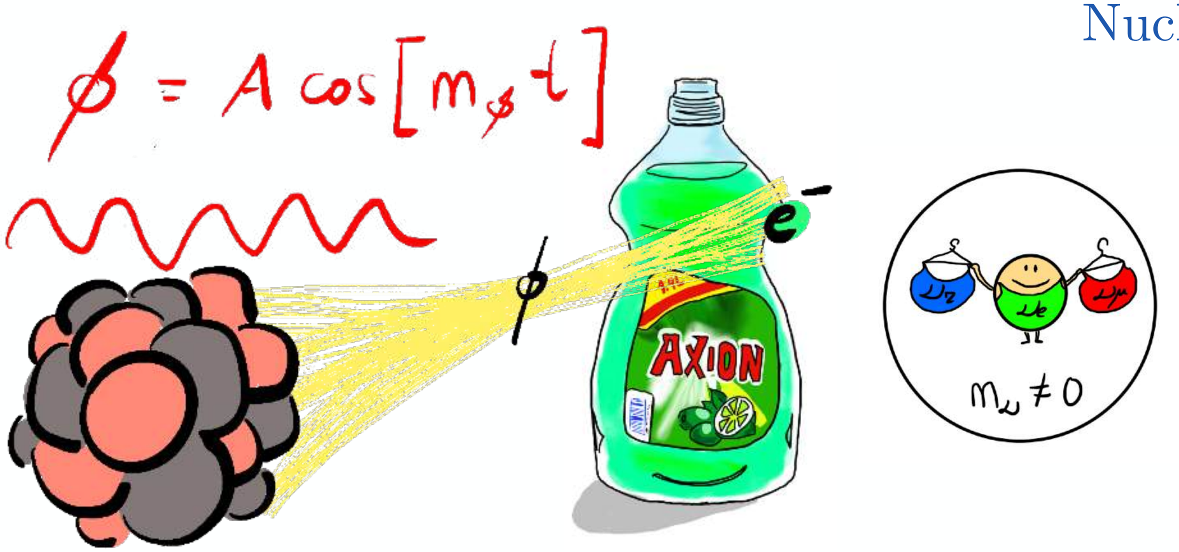
...

Beyond the SM: "how" to look?

(=mass for non-rel)
Energy inprint



Nuclear recoil exp.
Colliders
...



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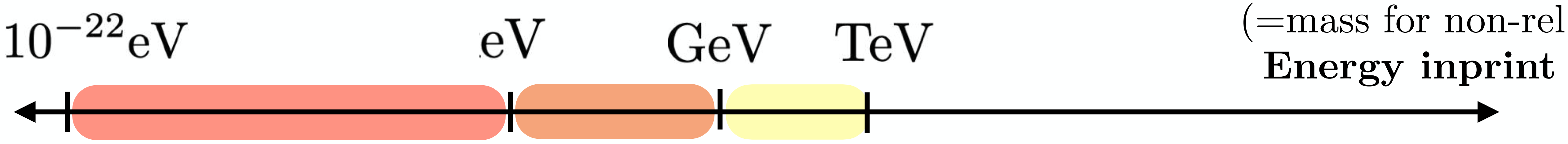
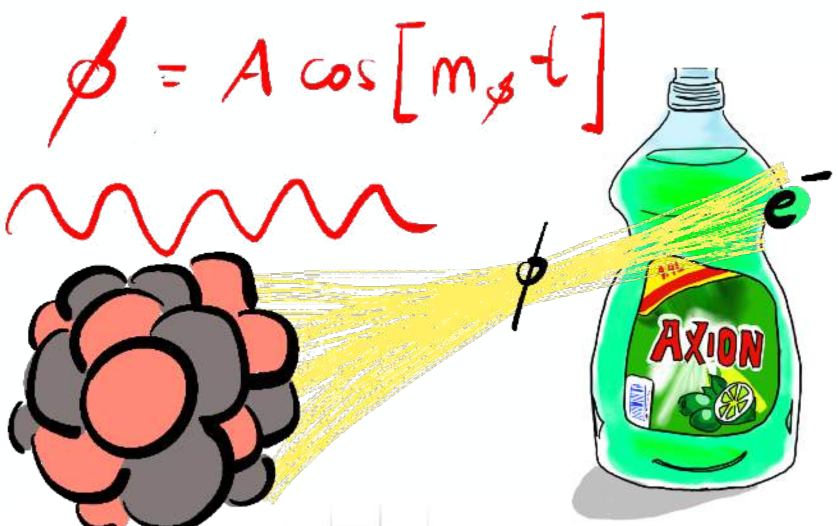
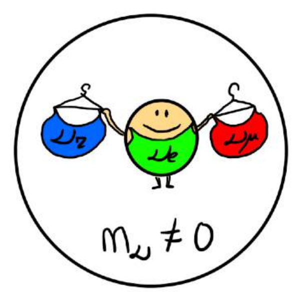


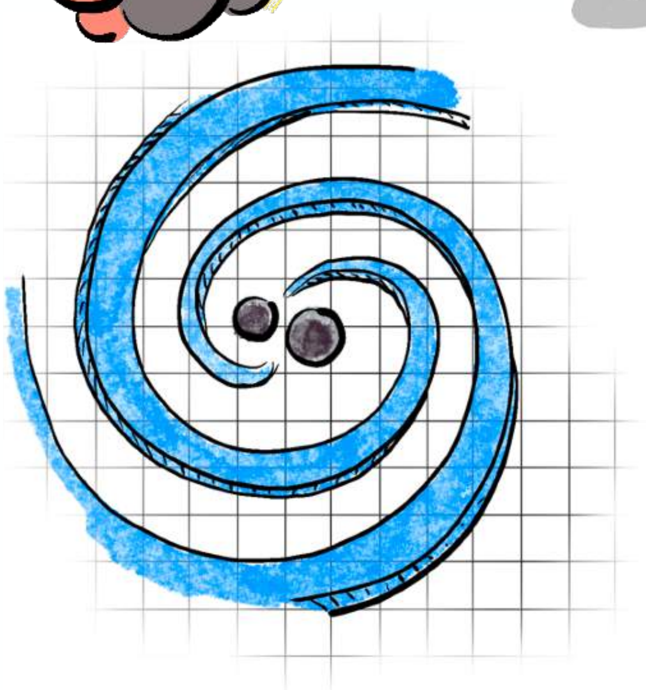
Nuclear recoil exp.

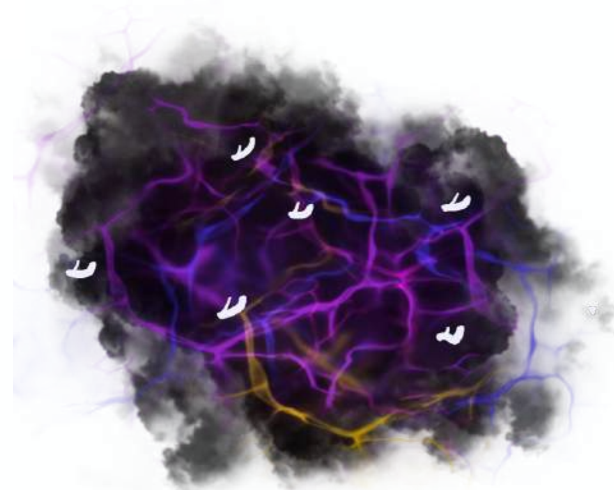
Colliders

...









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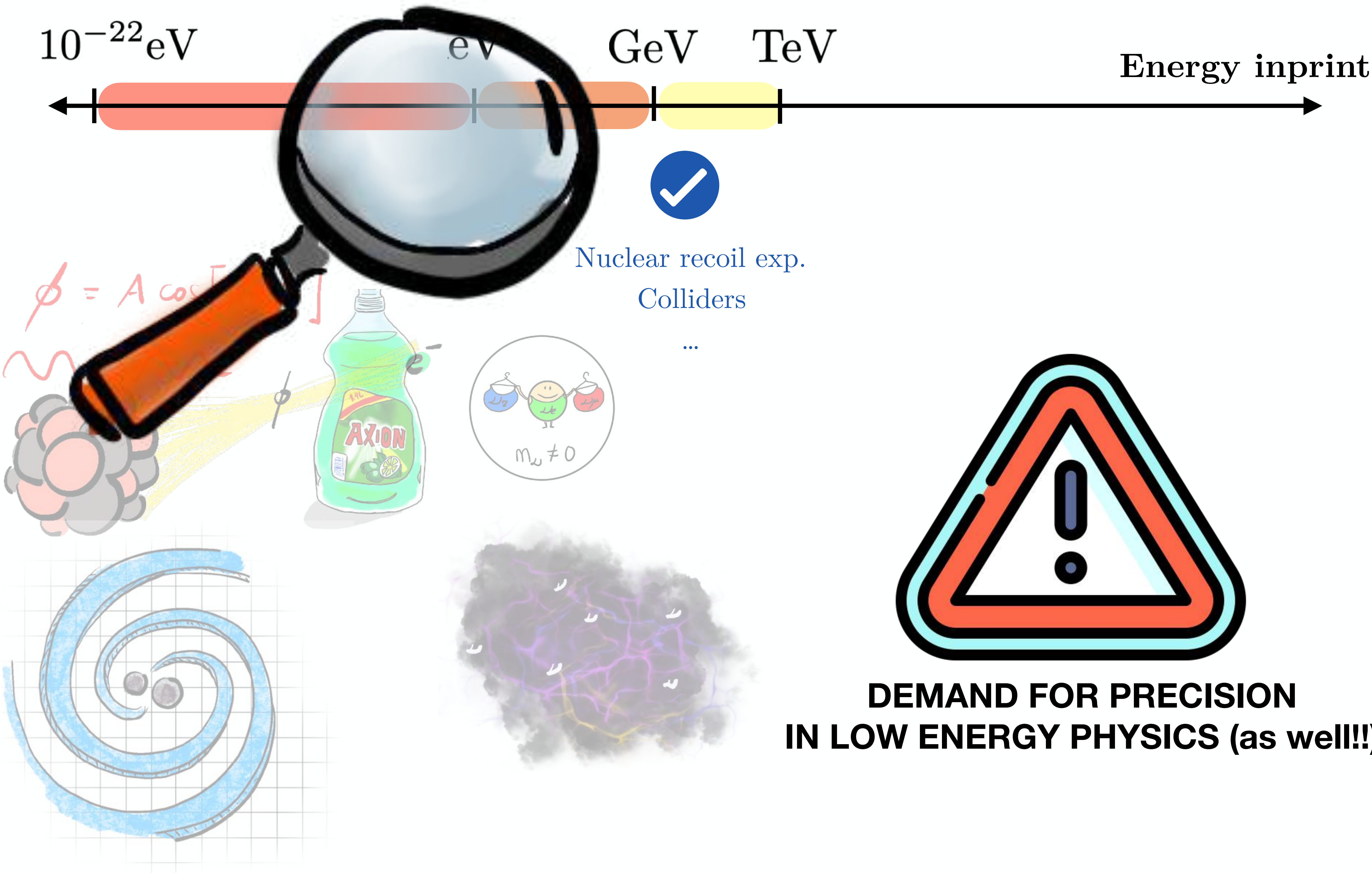
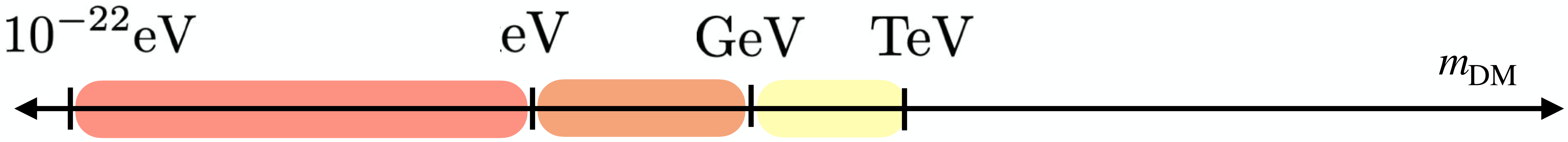
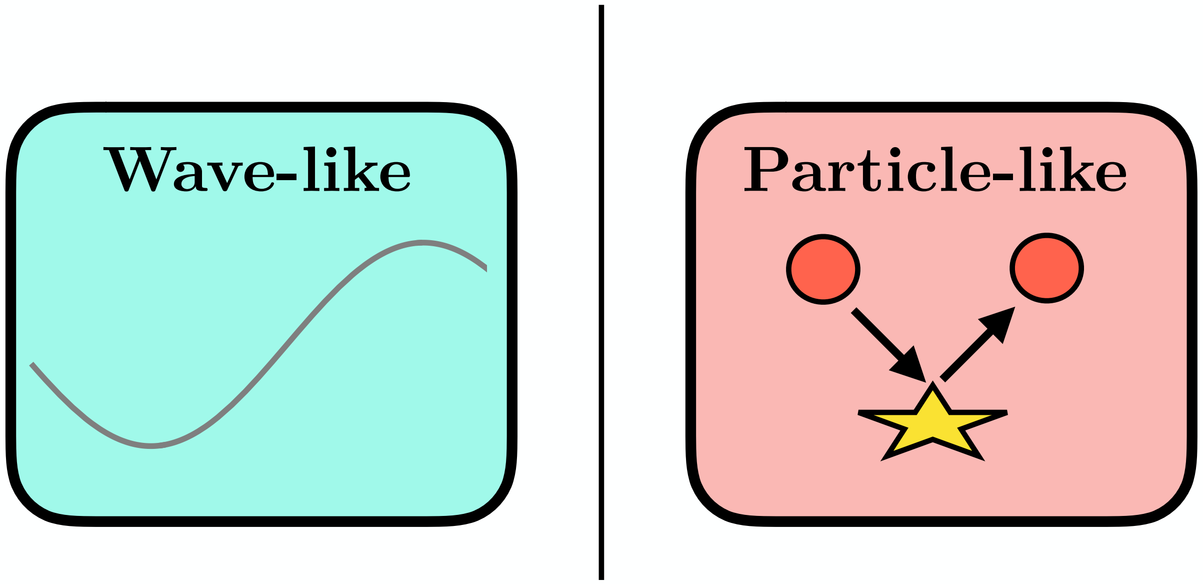


DEMAND FOR PRECISION
IN LOW ENERGY PHYSICS (as well!!)

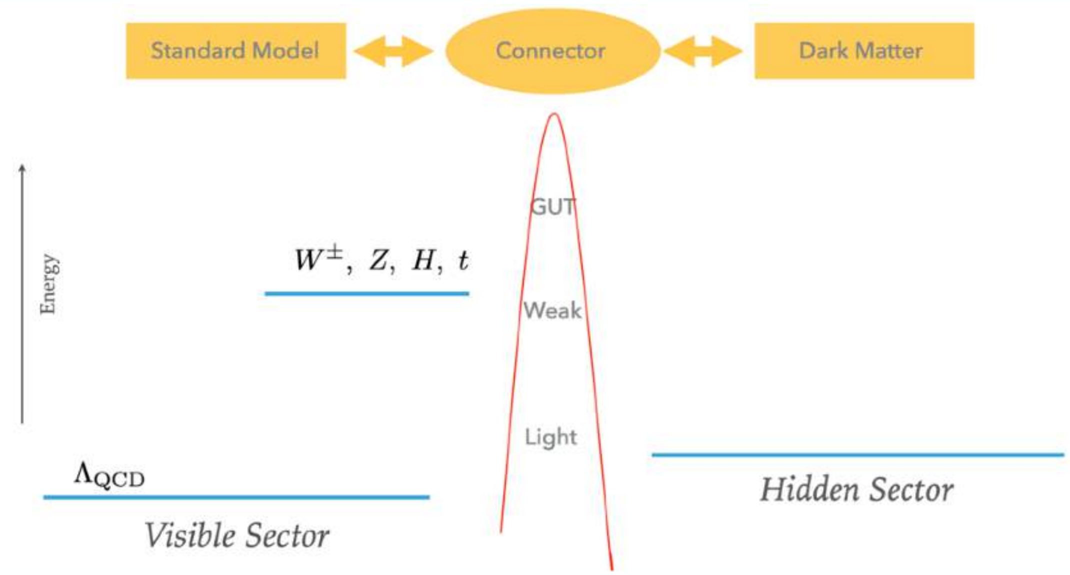
Low Energy Precision: **Nature**

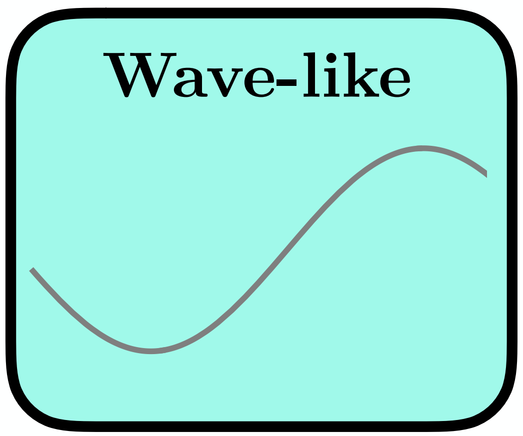


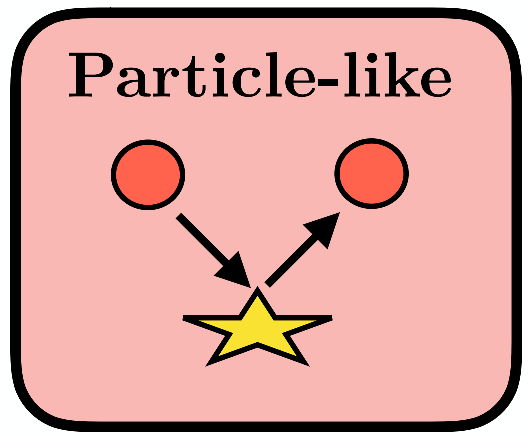


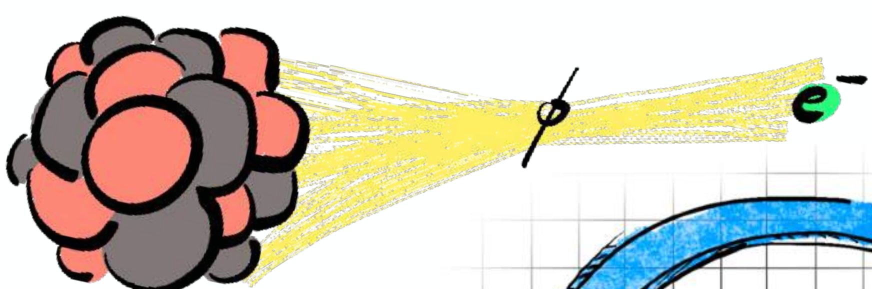
$$\left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\right)^{-1/3} < \lambda_{dB} = \frac{1}{m_{\mathrm{DM}} v_{\mathrm{DM}}}$$

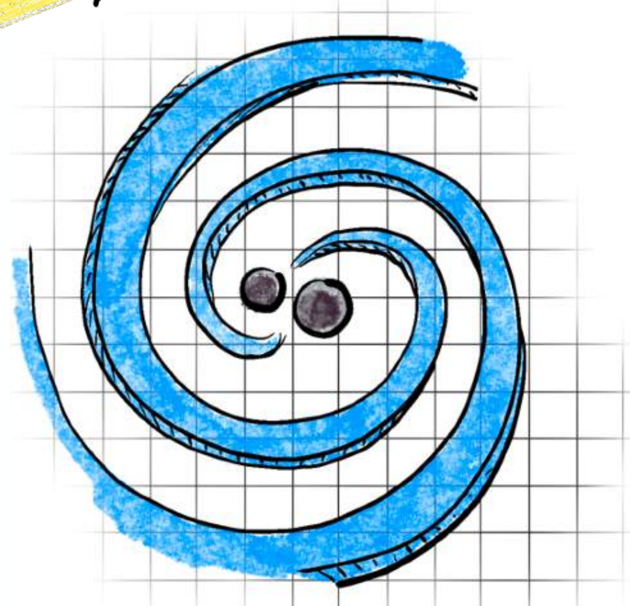
Low Energy Precision: **Nature**

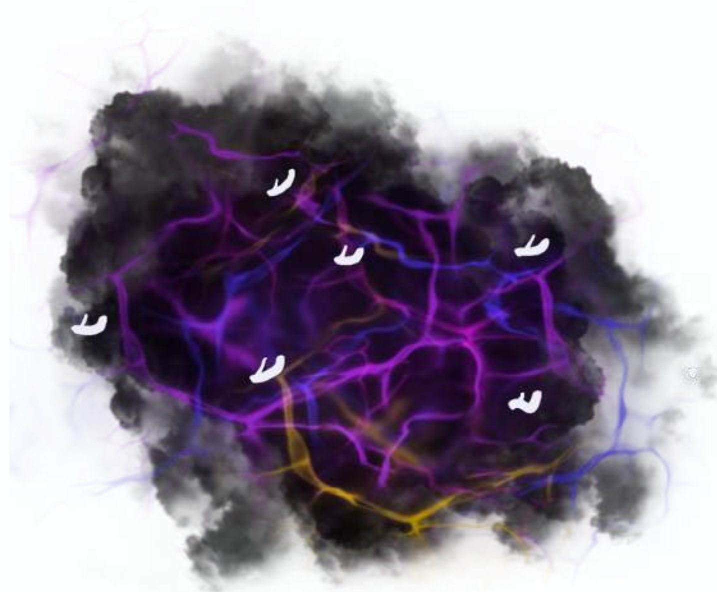


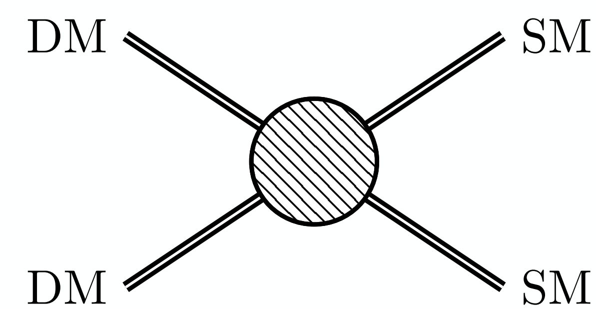












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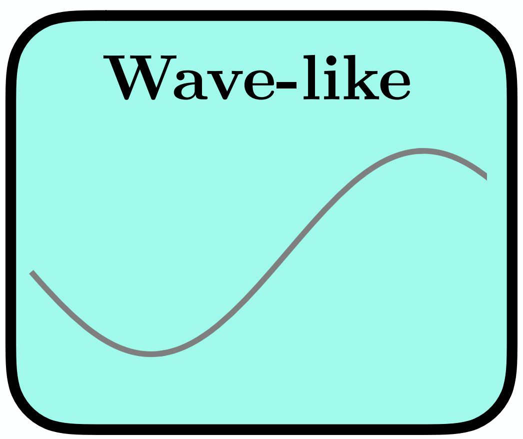
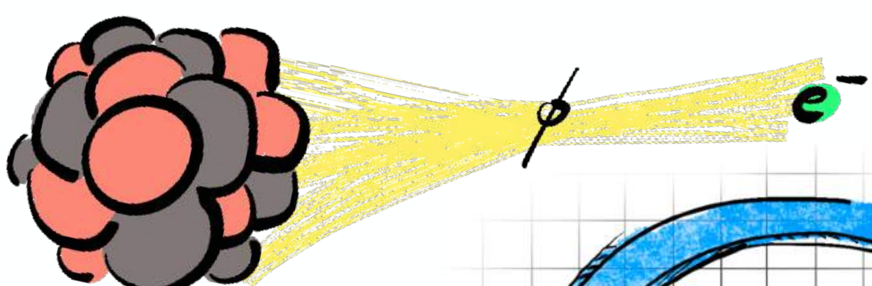
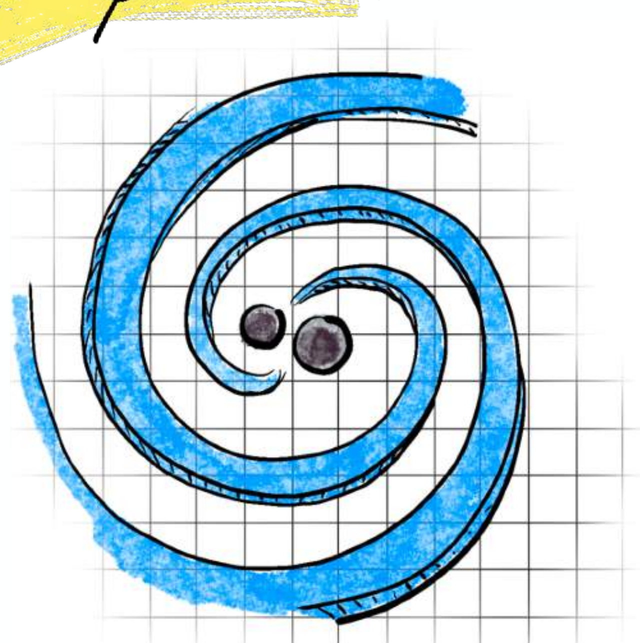


$$\frac{\delta X}{X} \propto \cos(\omega_{\rm UL} t + \varphi_{\rm UL})$$





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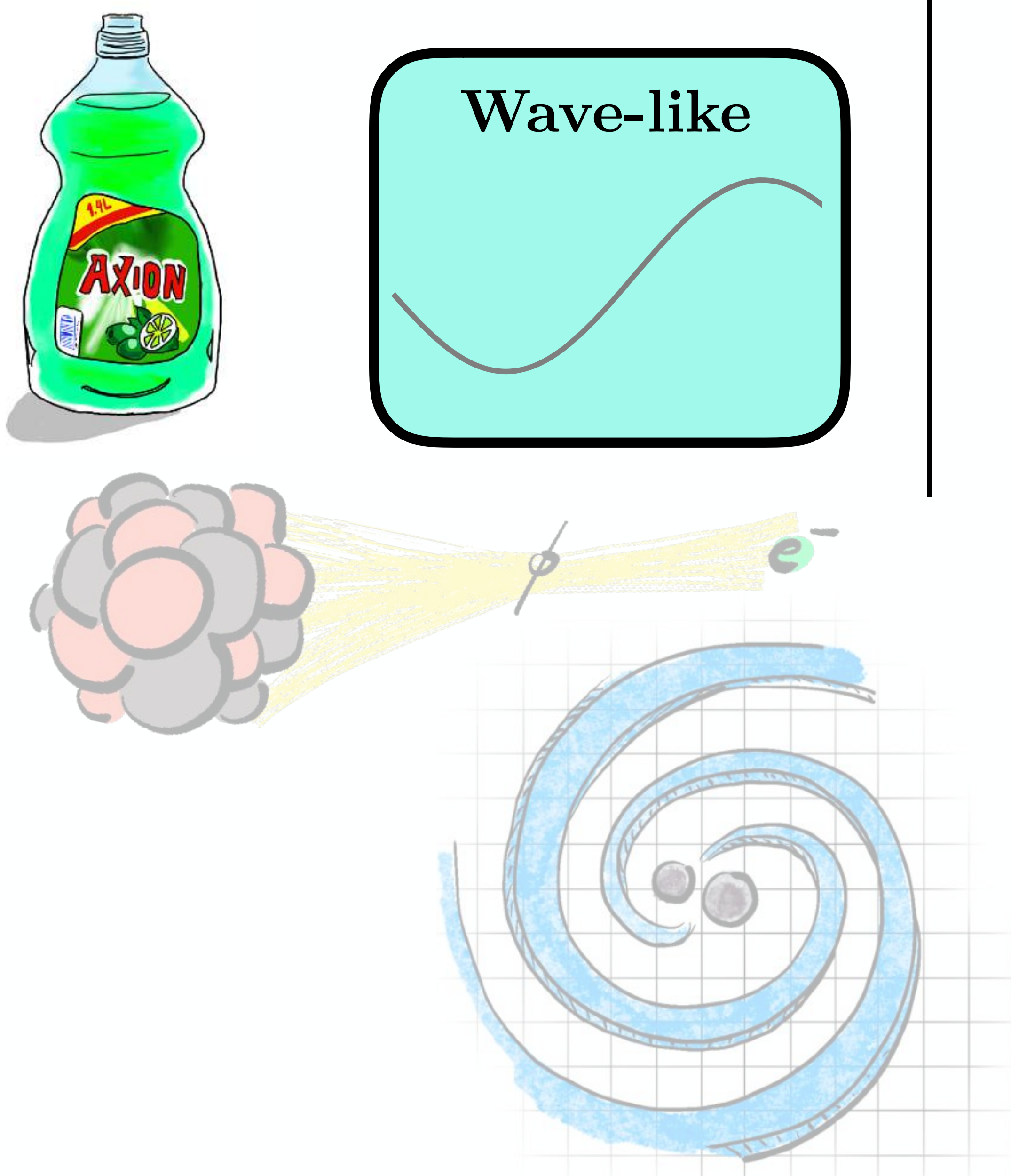

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$$\mathcal{L}_a \supset \frac{a}{f_a}\frac{g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{1}{4} a\, g_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\partial_\mu a}{2 f_a}(c_q \bar{q}\gamma^\mu\gamma_5 q)$$

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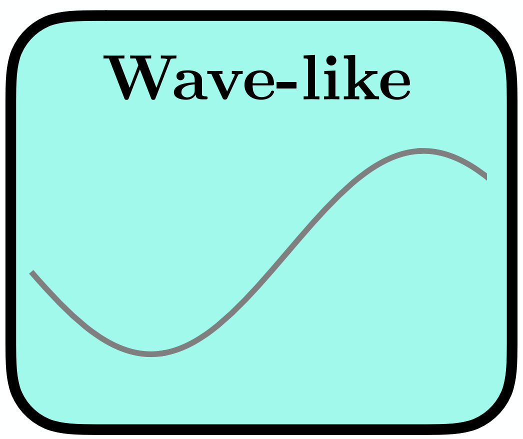

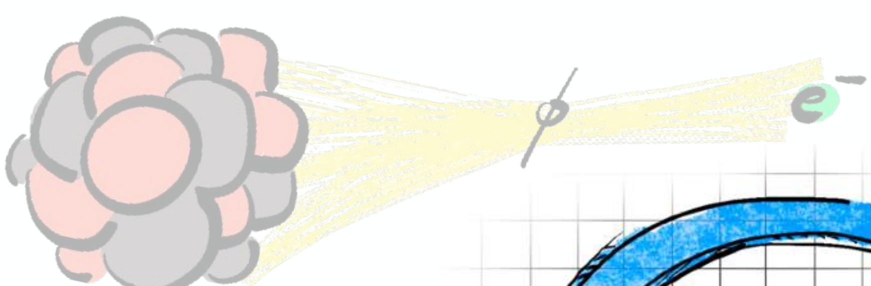

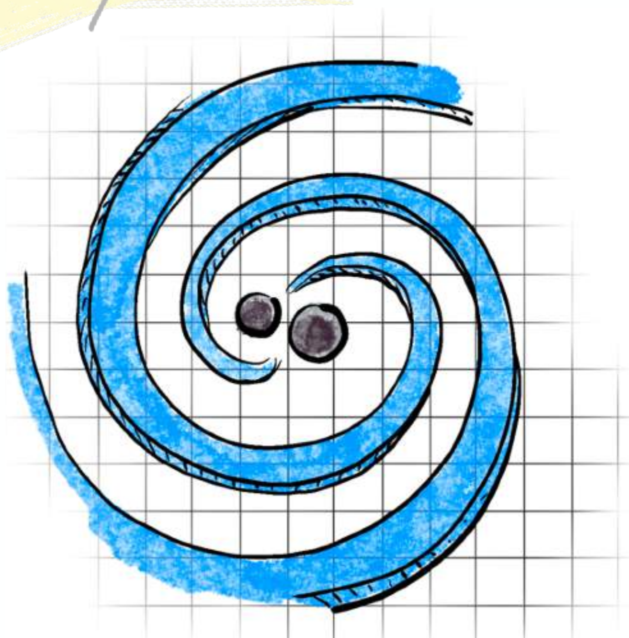

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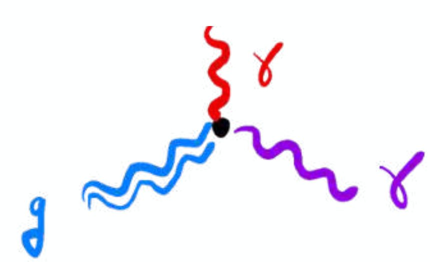
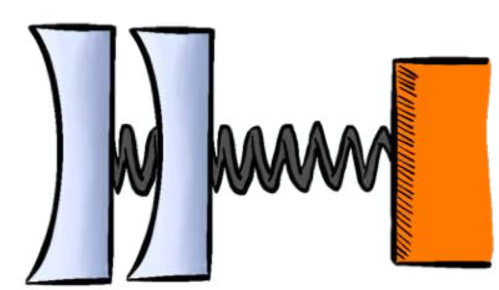
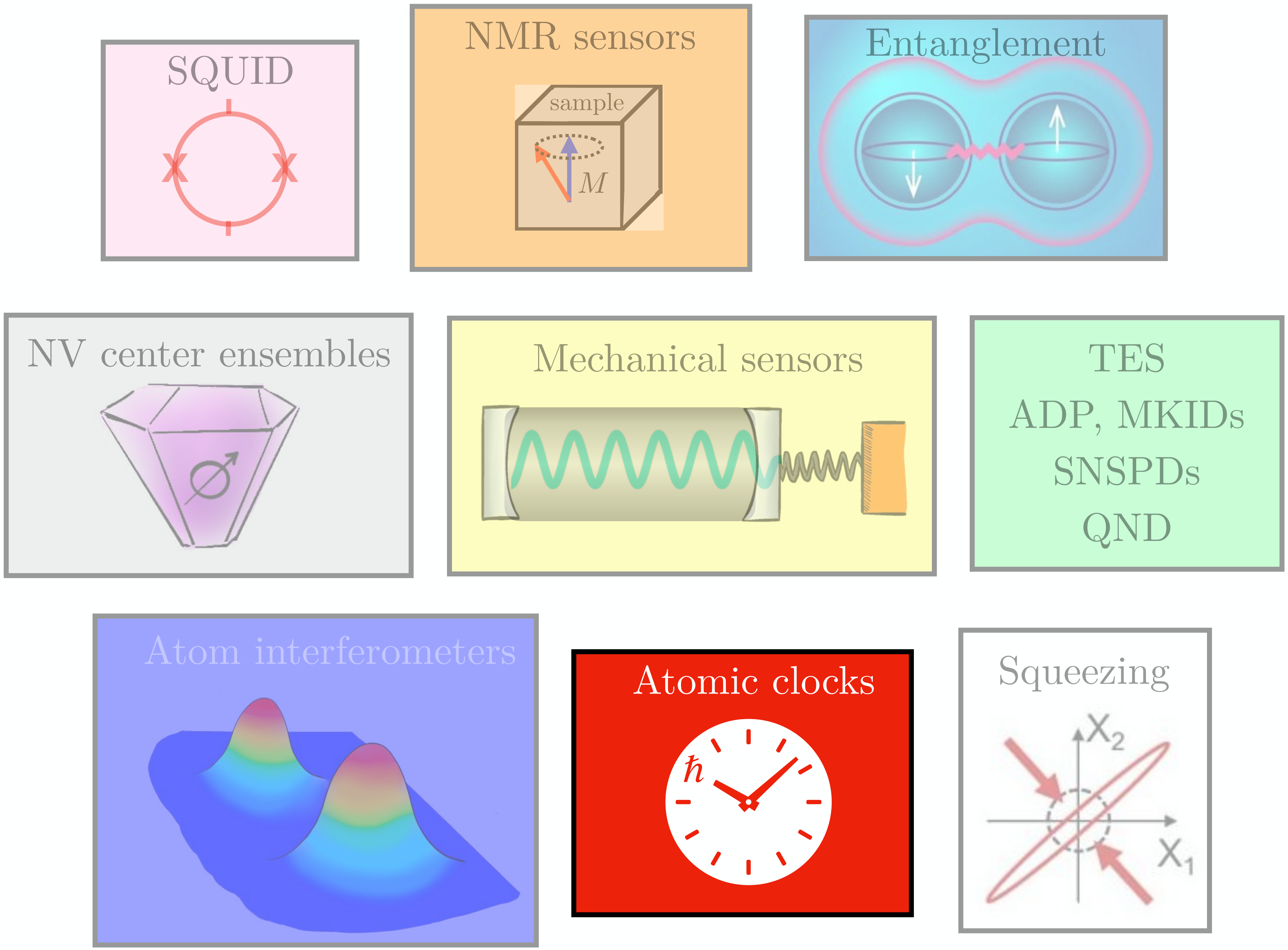
Gertsenshtein effect



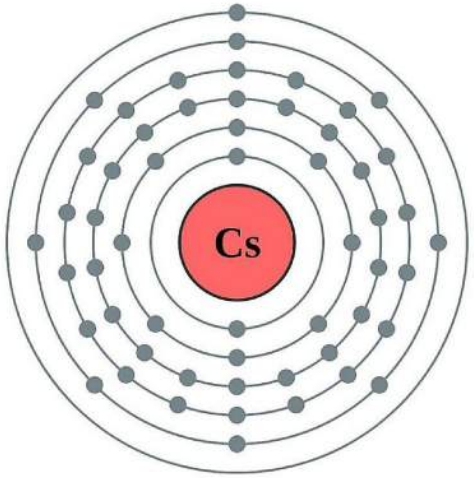
$$\delta L = hL$$

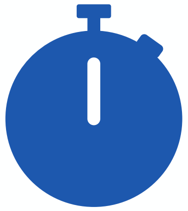


Quantum Sensors: examples



Atomic Clocks

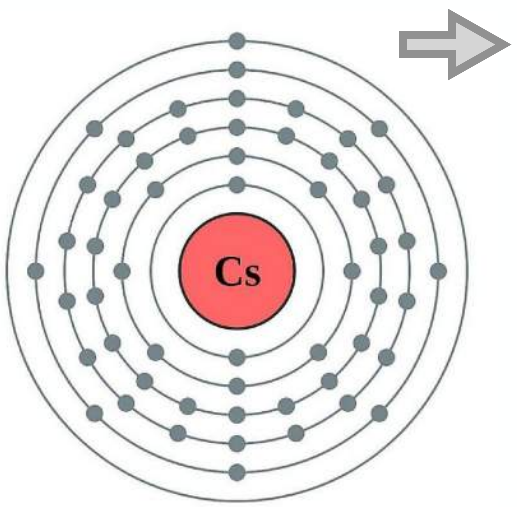


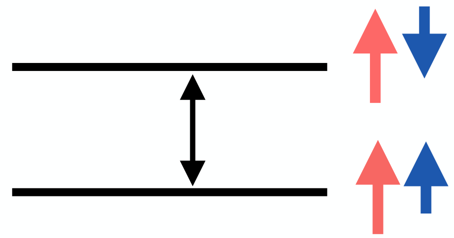


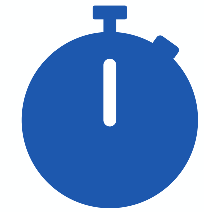
1 sec

Atomic Clocks

ground state





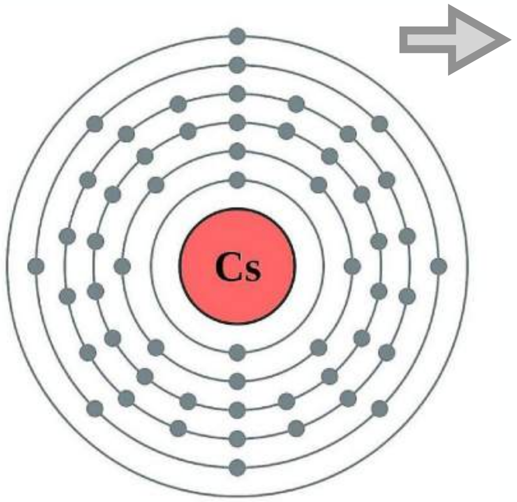


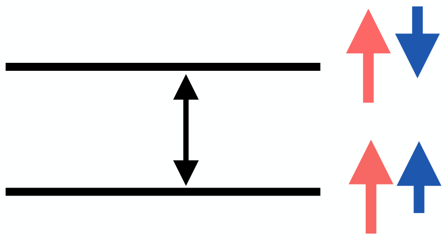
1 sec

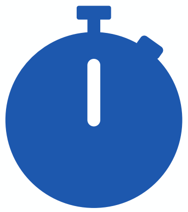
$$\Delta\nu_{\mathrm{Cs}} = 9192631770 \text{ Hz} = \mathcal{O}(10^{10}) \text{ Hz}$$

Atomic Clocks

ground state







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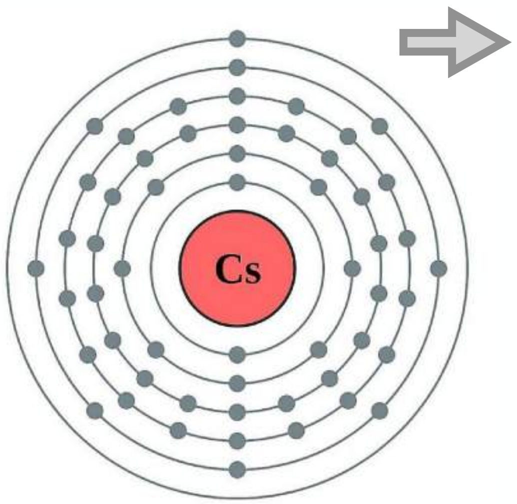
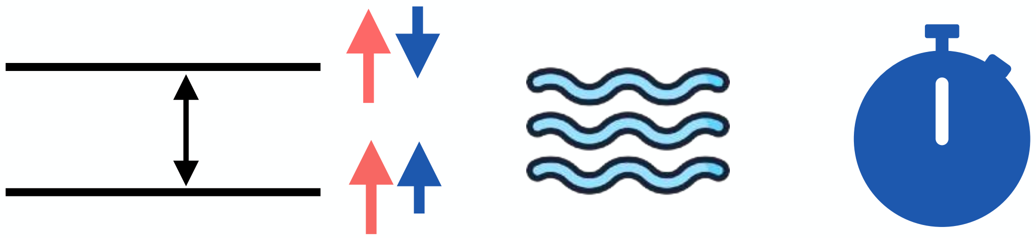
μwave clocks

Atomic Clocks

ground state





1 sec

$$\Delta\nu_{\mathrm{Cs}} = 9192631770\ \mathrm{Hz} = \mathcal{O}(10^{10})\ \mathrm{Hz}$$

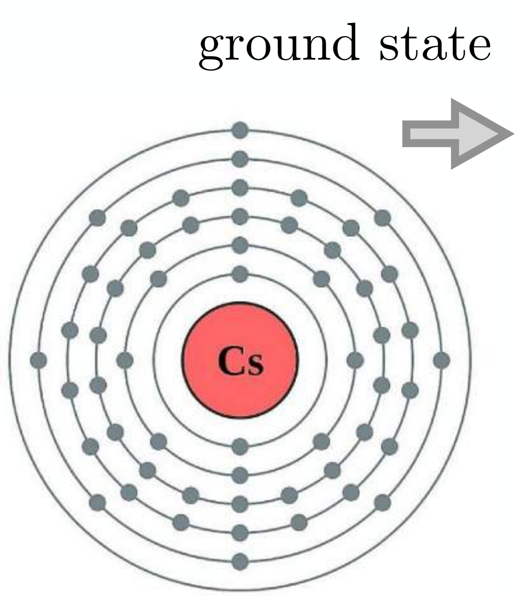
μwave clocks

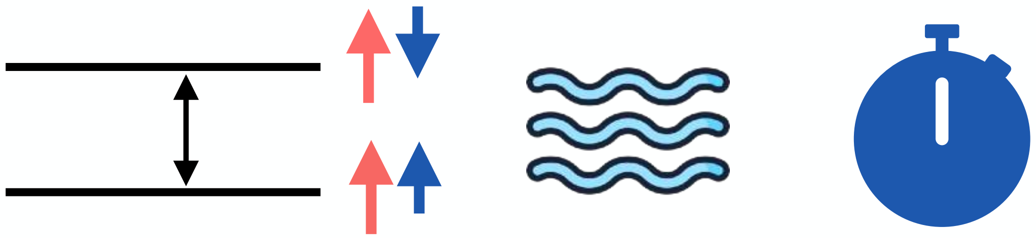
$\Delta\nu \sim$ 

Optical clocks

[Arvanitaki, Huang, Van Tilburg, 14]
[Derevianko, Pospelov, 14][Loeb, Maoz, 15]
[Derevianko, 16] [Stadnik, Flambaum, 15]
[Weislo, 18][Alonso, Blas, Wolf, 19]
[Kennedy, et al., 20] [Brzeminski, Chacko, 22]
[Safronova et al.]

Atomic Clocks

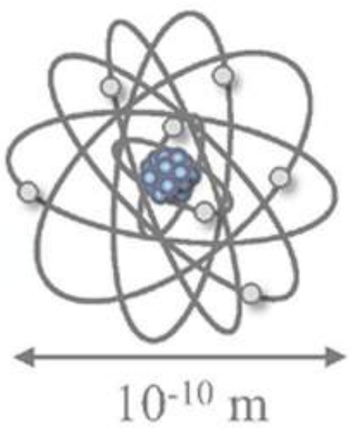




$$\Delta\nu_{\rm Cs} = 9192631770 \text{ Hz} = \mathcal{O}(10^{10}) \text{ Hz}$$

μwave clocks

Transitions in ATOMS



$\Delta\nu \sim$ 

Optical clocks

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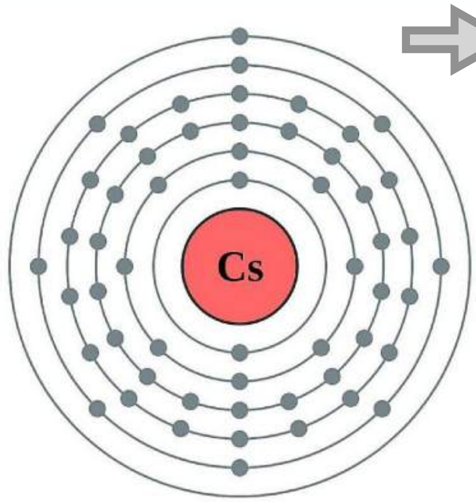
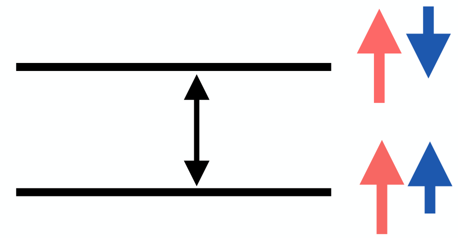
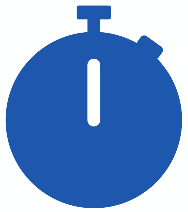
Atomic Clocks

ground state







1 sec

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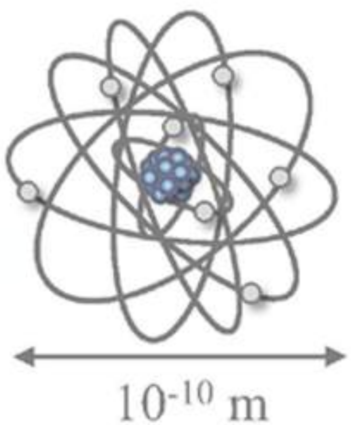
μwave clocks

Transitions in ~~ATOMS~~ NUCLEI!



$\Delta\nu \sim$ 

Optical clocks

[Arvanitaki, Huang, Van Tilburg, 14]
[Derevianko, Pospelov, 14] [Loeb, Maoz, 15]
[Derevianko, 16] [Stadnik, Flambaum, 15]
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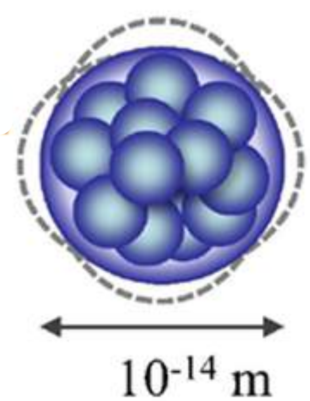
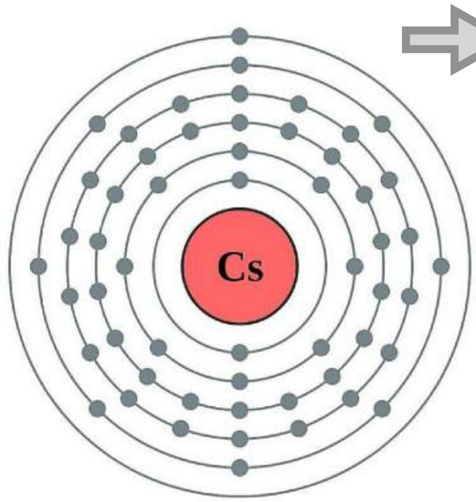
[Safronova et al.]

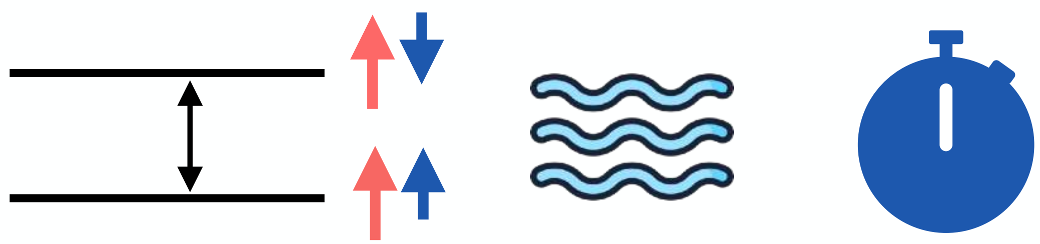


Nuclear clocks

Atomic Clocks

ground state





1 sec

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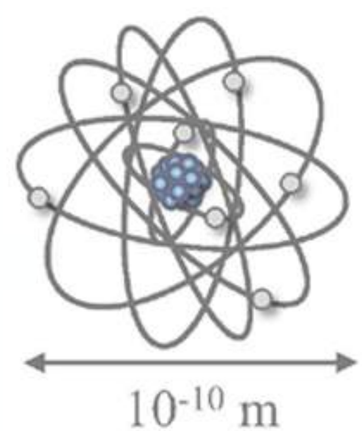
μwave clocks



$\Delta\nu \sim$ 

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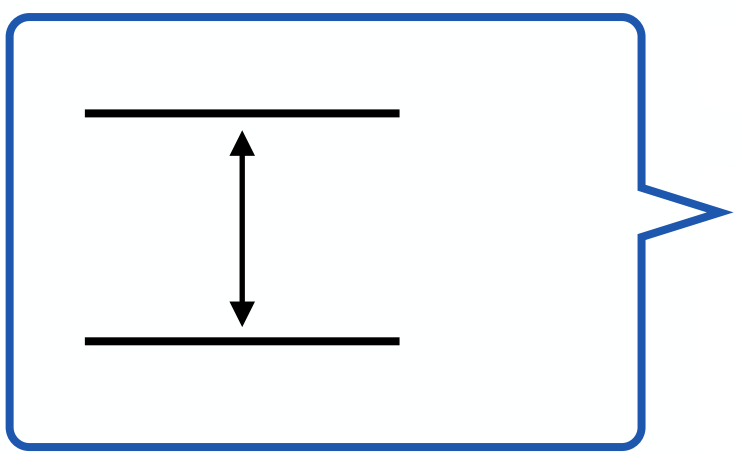
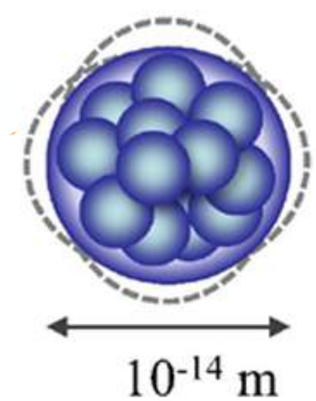
Transitions in ~~ATOMS~~ NUCLEI!





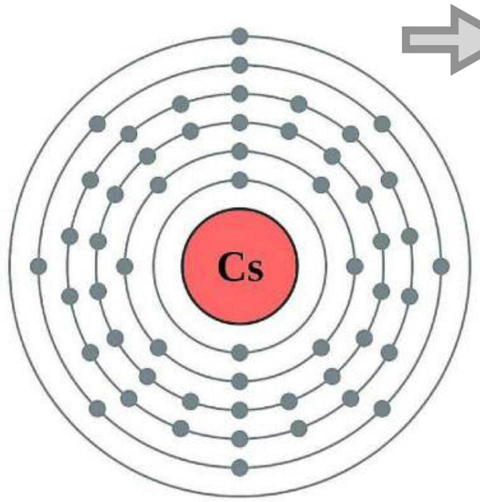
Nuclear clocks

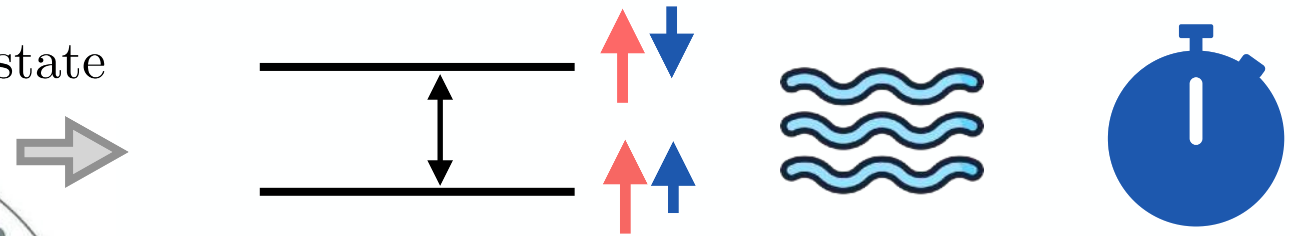
$$\Delta E = \Delta E_{\mathrm{em}} + \Delta E_{\mathrm{nuc}}$$

$$|\Delta E_{\mathrm{em}}| \sim |\Delta E_{\mathrm{nuc}}| = \mathcal{O}(\mathrm{MeV})$$

Atomic Clocks

ground state

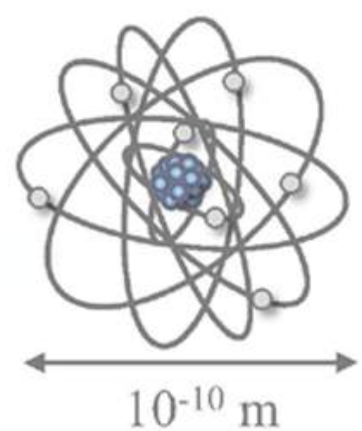




1 sec

$$\Delta\nu_{\mathrm{Cs}} = 9192631770 \text{ Hz} = \mathcal{O}(10^{10}) \text{ Hz}$$

μwave clocks



$\Delta\nu \sim$ 

Optical clocks

[Arvanitaki, Huang, Van Tilburg, 14]
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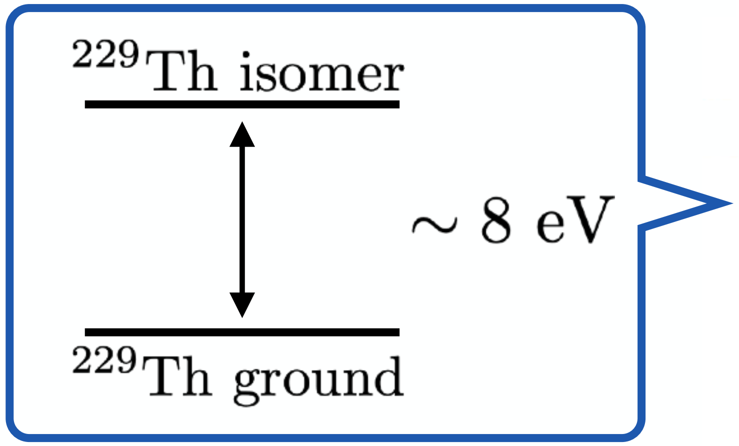
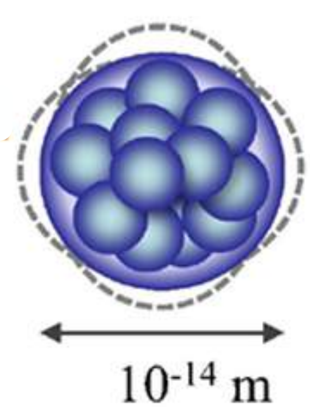
Transitions in ~~ATOMS~~ NUCLEI!





[Peik et al., 20]
[Caputo et al., 24]
[Fuchs et al., 24]

Nuclear clocks

Fine tuning!

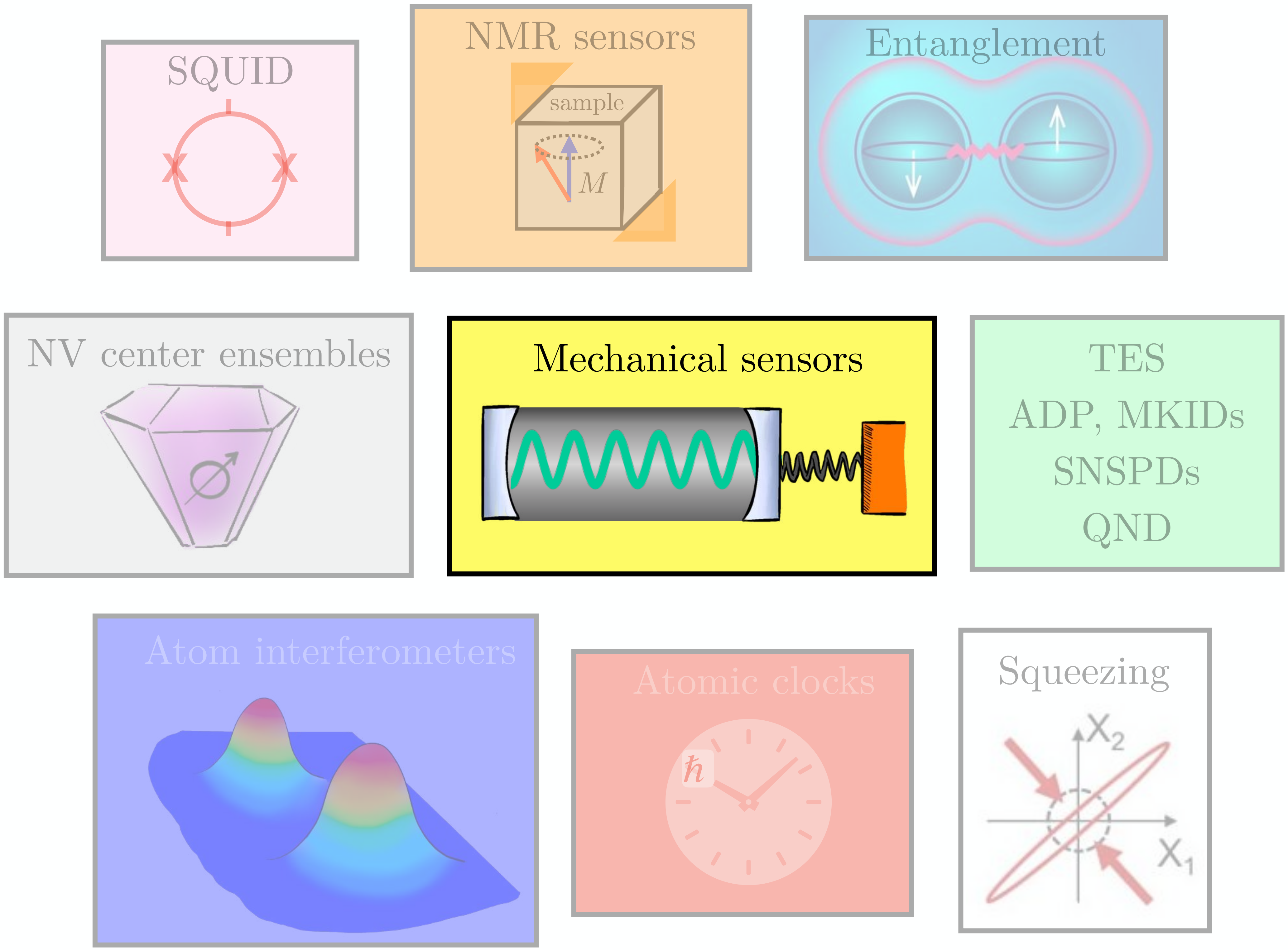
$$\Delta E = \Delta E_{\mathrm{em}} + \Delta E_{\mathrm{nuc}}$$

[Laser excitation April 24]

$$|\Delta E_{\mathrm{em}}| \sim |\Delta E_{\mathrm{nuc}}| = \mathcal{O}(\mathrm{MeV}) \gg \Delta E \sim 8 \text{ eV}$$

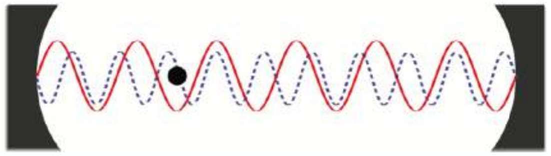
Unique Low energy isomeric state

Quantum Sensors: examples



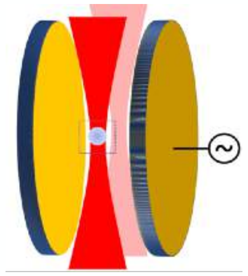
Mechanical sensors

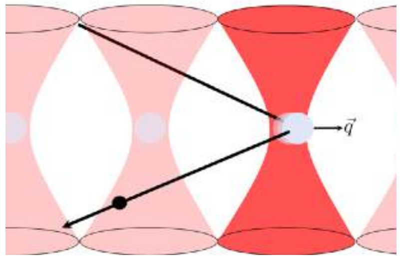
High-frequency gravitational waves with optically levitated sensors
[Arvanitaki, Geraci, 2013]



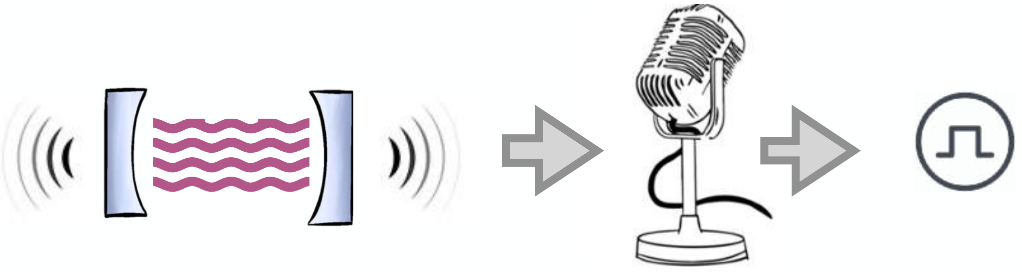
Dark Matter searches with optically levitated sensors

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



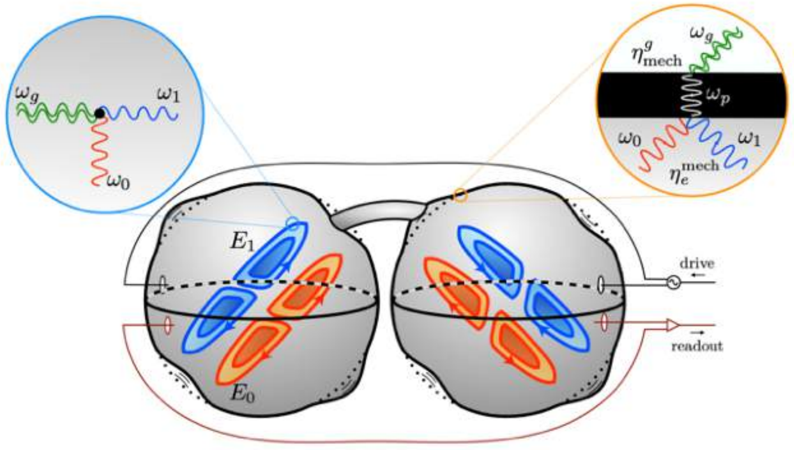


Axion searches via the *piezoaxionic* effect
[Arvanitaki, Madden, et al., 2023]



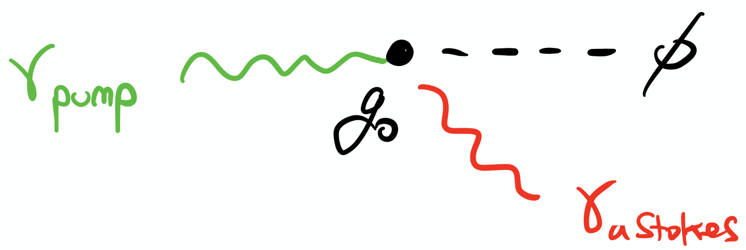
Electromagnetic cavities as mechanical bars for gravitational waves
[Berlin, Blas, et al., 2023]

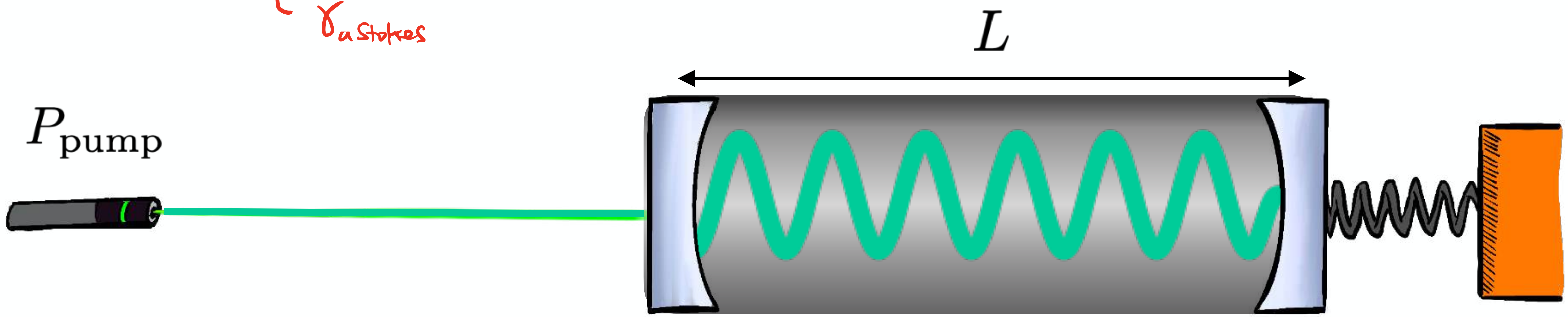
Magnets as weber bar gravitational wave detectors
[Domcke, Ellis, Rodd, 2024]
[Carney, Higgins, et al., 2024]

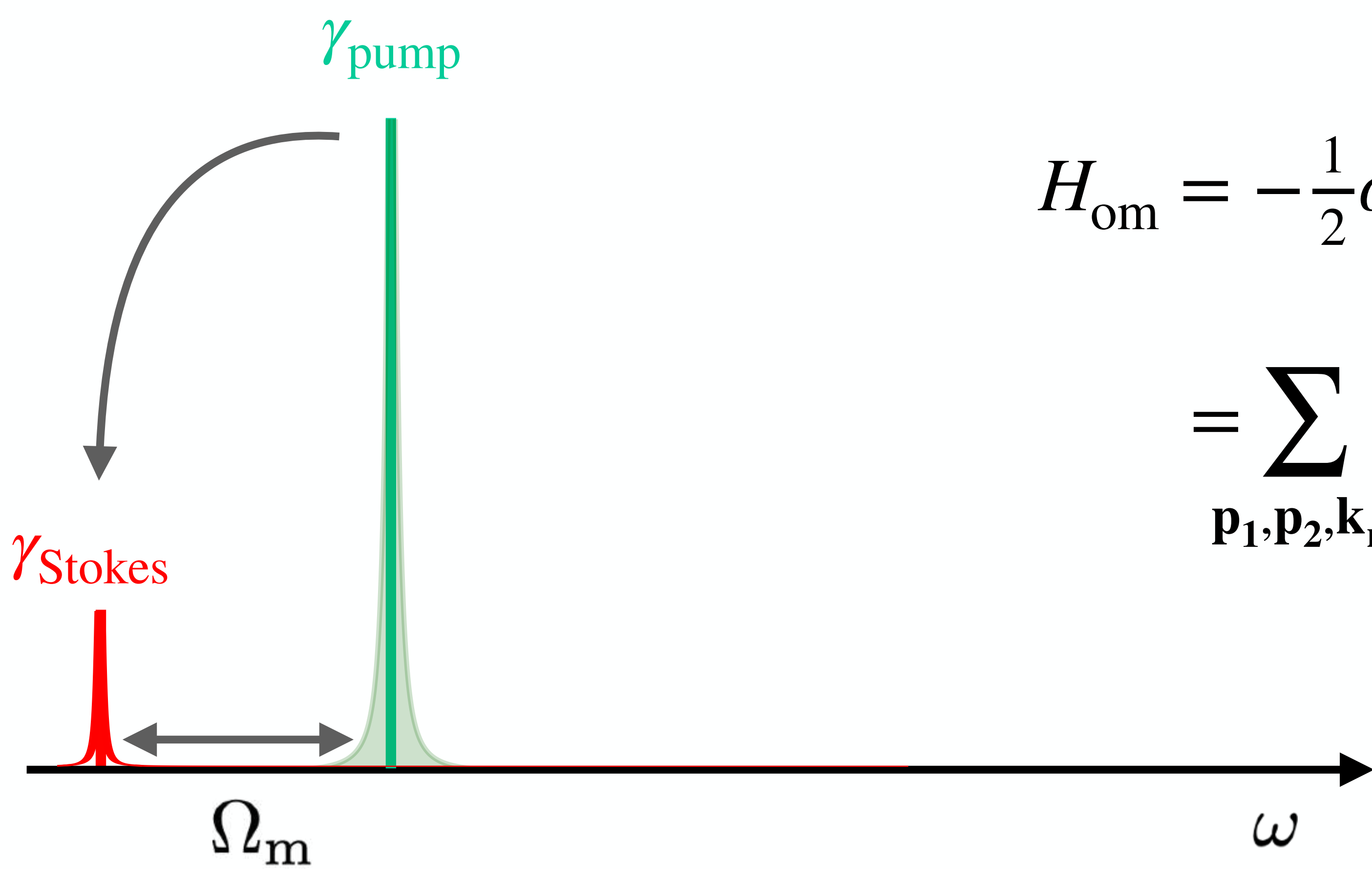


Mechanical sensors: **Optomechanics**

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





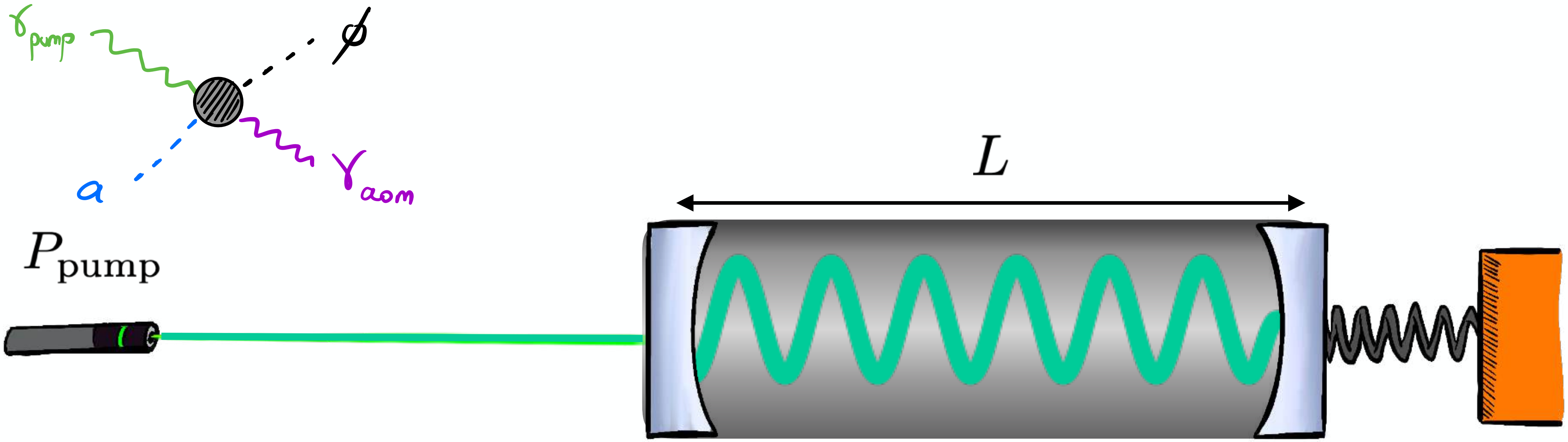


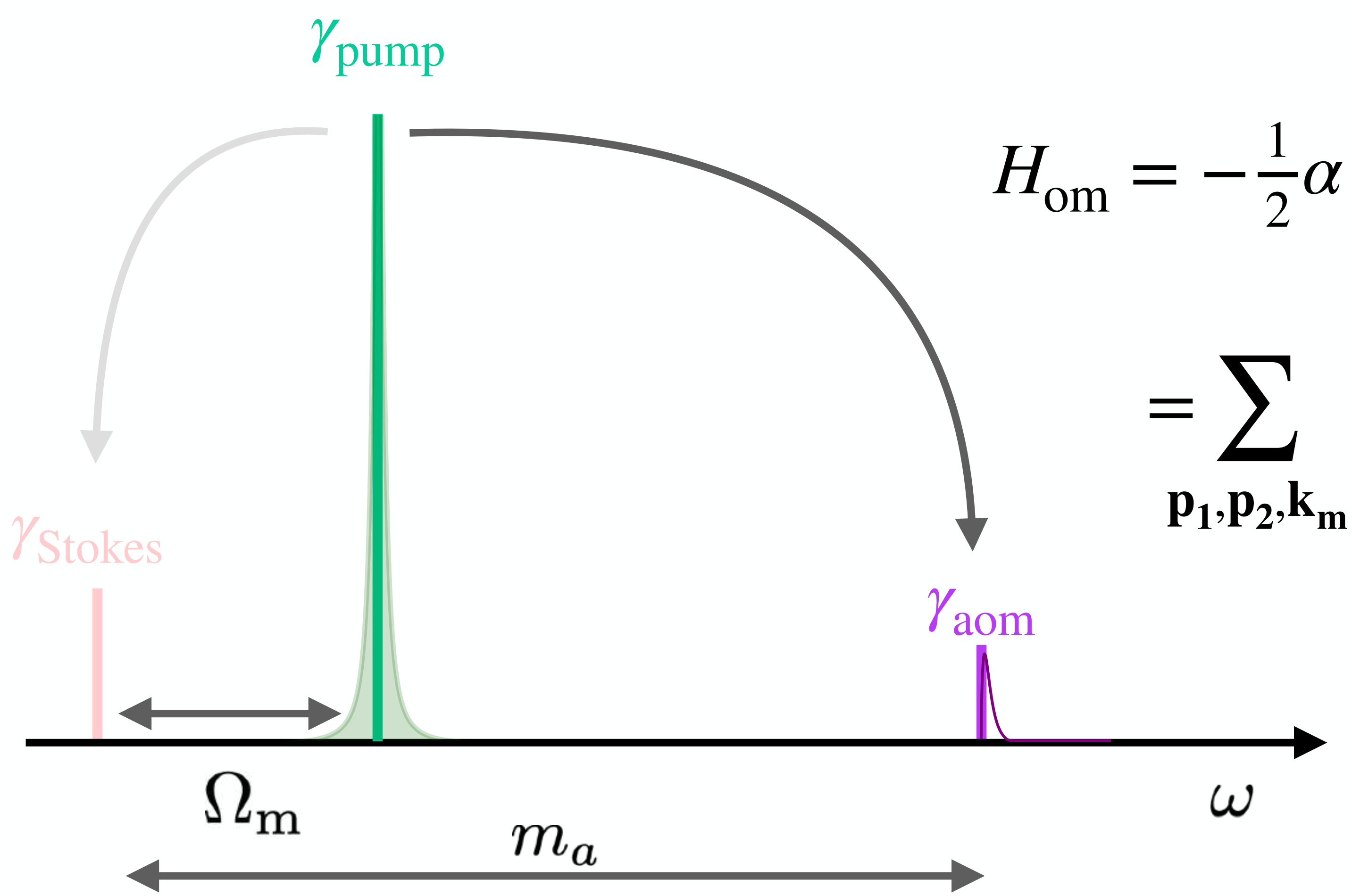
$$H_{\text{om}} = -\frac{1}{2}\alpha \int d^3\mathbf{r}\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{E}(\mathbf{r})$$

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

Mechanical sensors: **AxiOptomechanics**

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





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

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

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

Mechanical sensors: **AxiOptomechanics**

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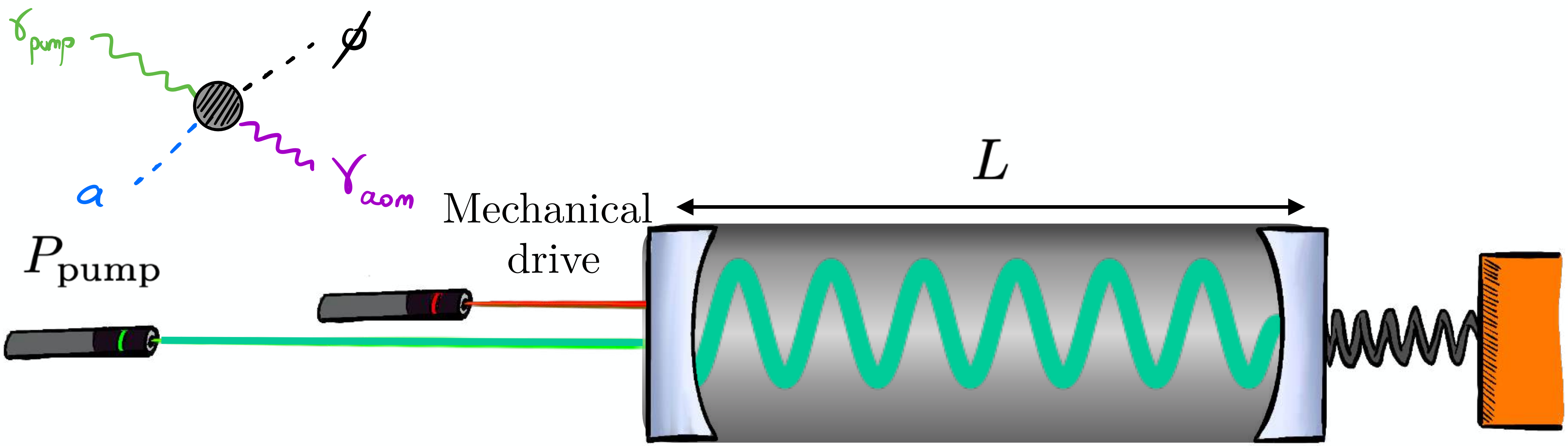

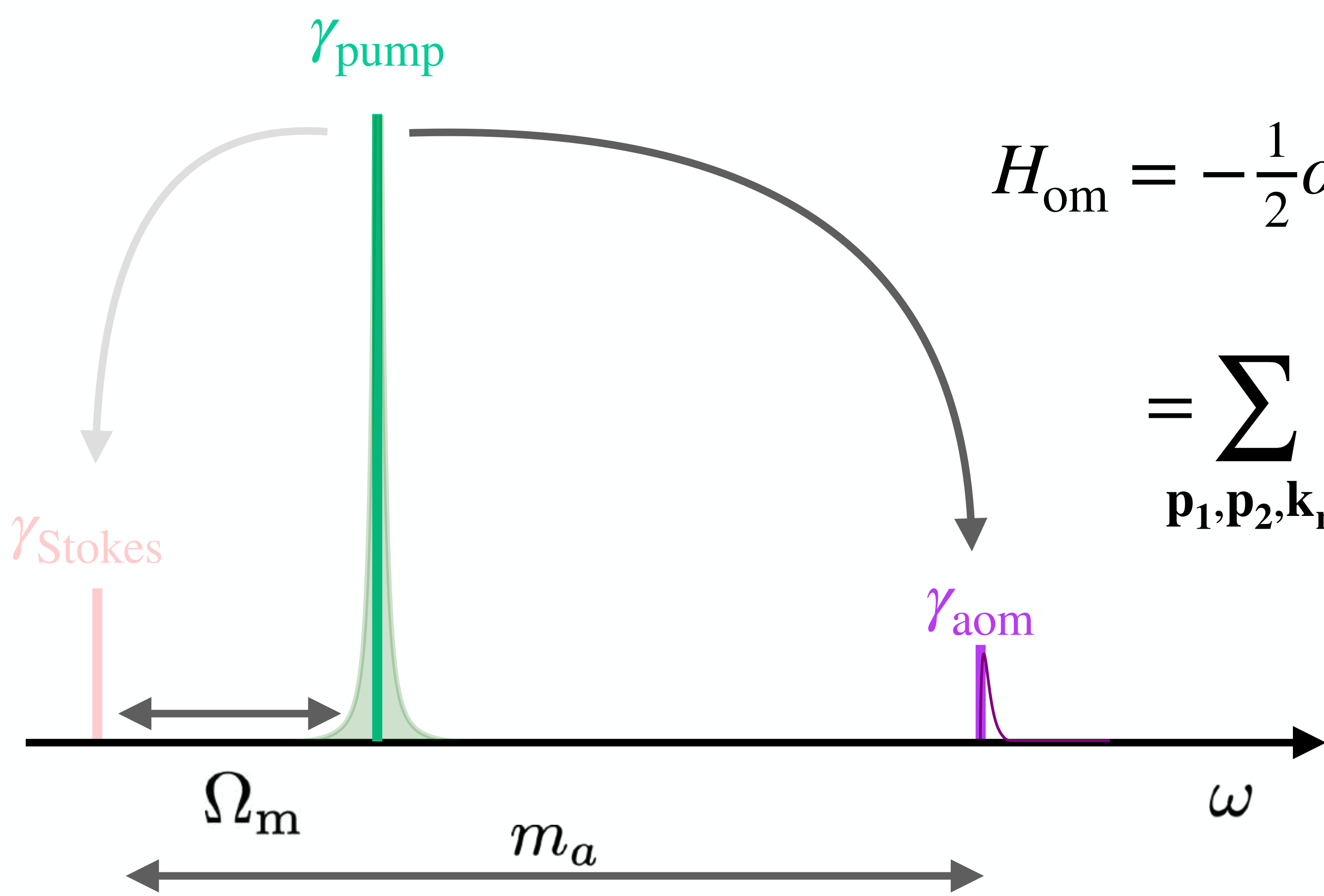

$$H_{\rm om} = -\frac{1}{2}\alpha\, g_{a\gamma\gamma}\int d^3\mathbf{r}\, a(\mathbf{r})\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r})\cdot\mathbf{B}(\mathbf{r})$$

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

Mechanical sensors: **AxiOptomechanics**

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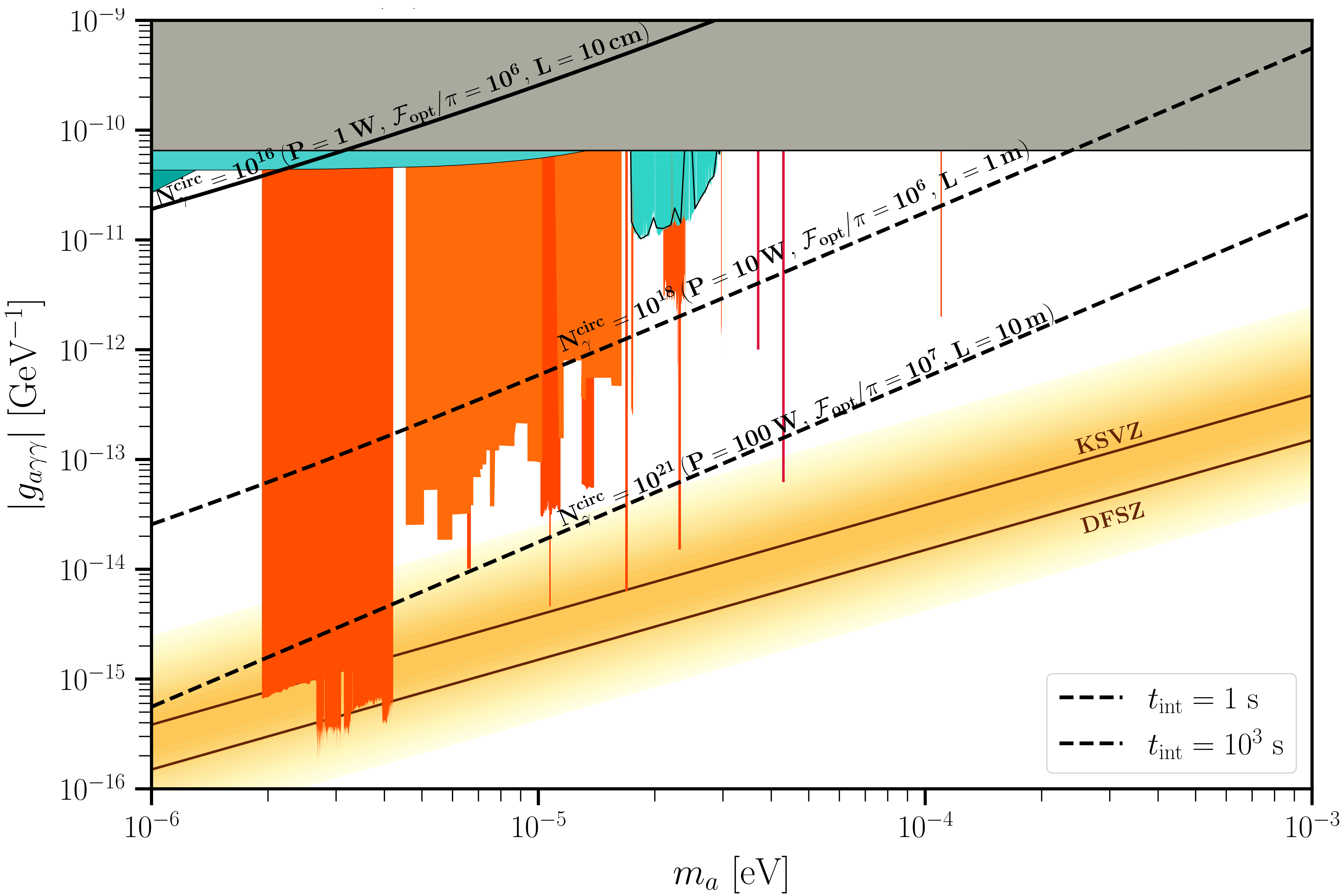
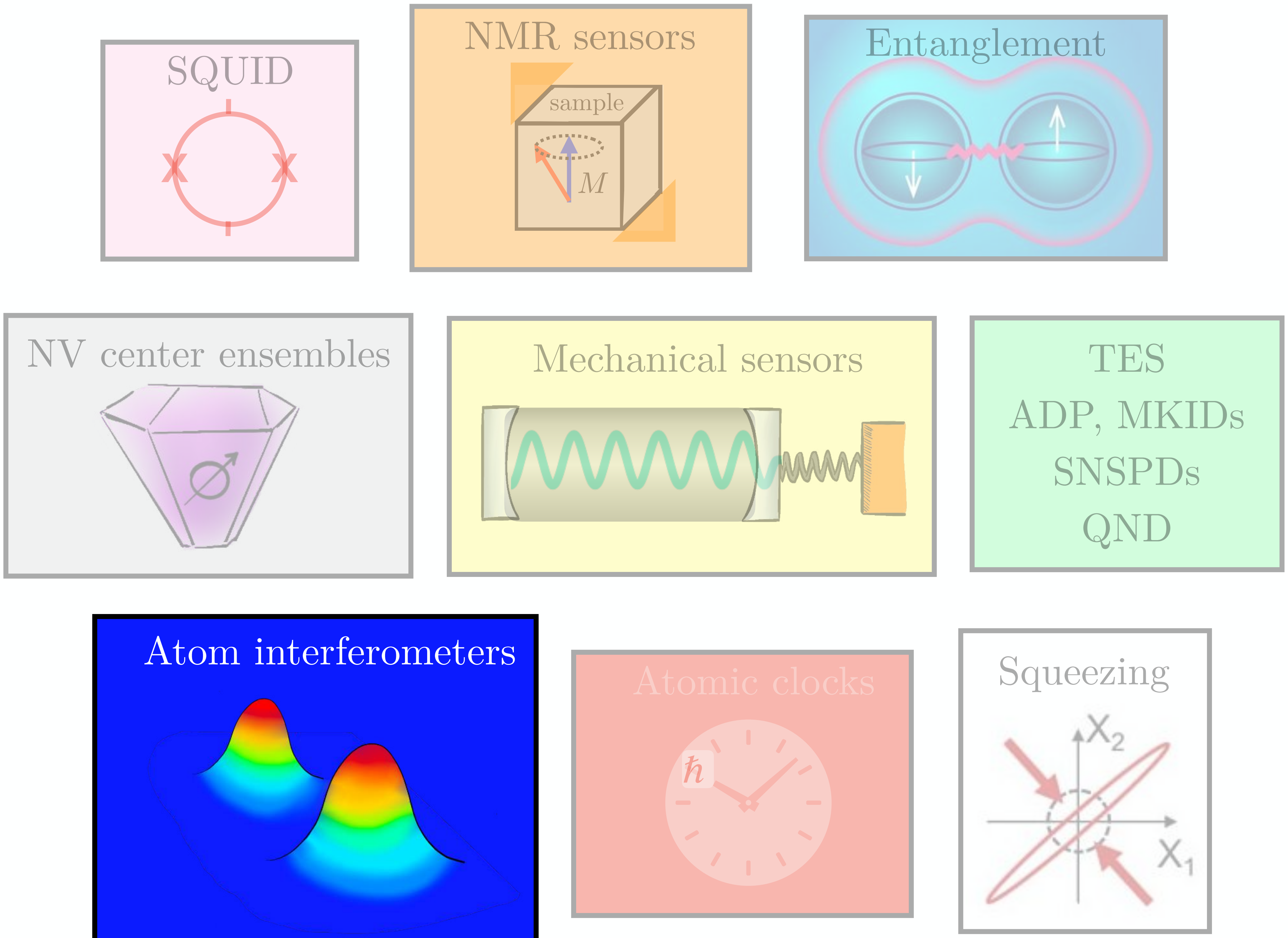


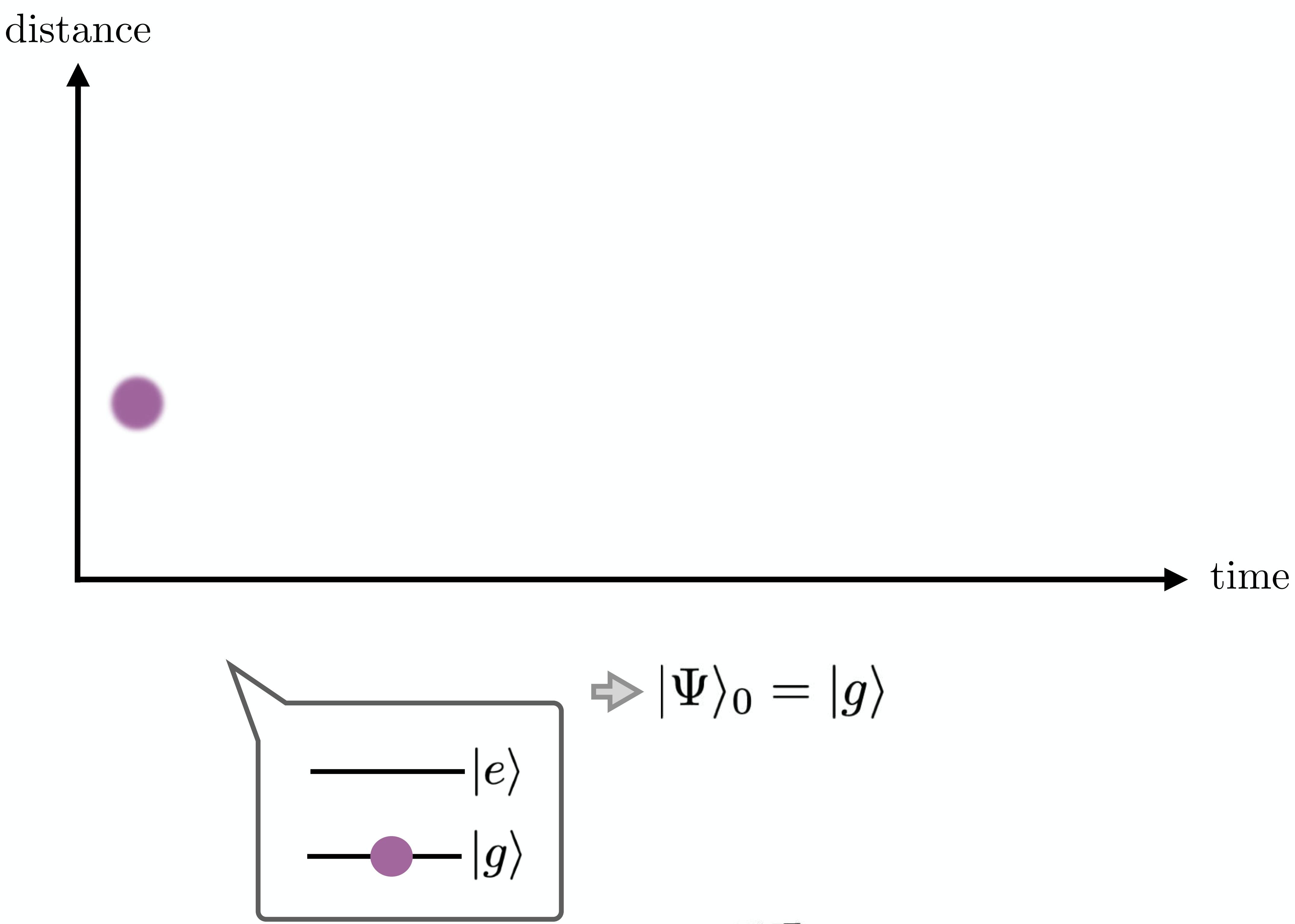
$$g_{a\gamma\gamma}^{\phi-\rm pop} \propto \frac{\epsilon_r + 2}{\epsilon_r - 1}\epsilon_r^{1/2}\frac{1}{\mathcal{F}_{\rm opt}^{1/2}}\frac{1}{L^{1/2}}\frac{1}{\omega_{\rm opt}^{1/2}}\frac{1}{P_{\rm pump}^{1/2}}\frac{m_a^{3/2}}{\rho_a^{1/2}}\Gamma_{\rm DCR}^{1/2}$$

Quantum Sensors: examples



AIs: the Principle

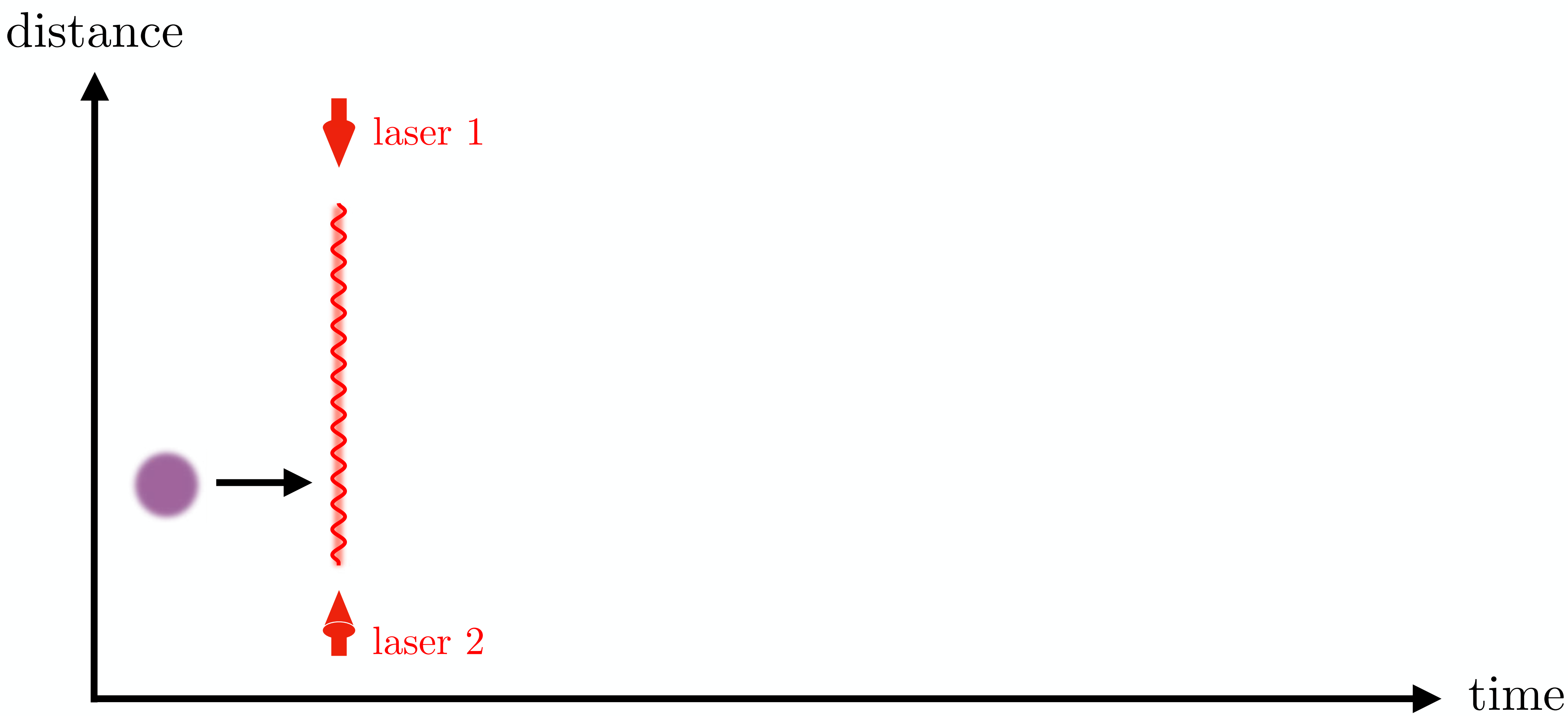
Review: arXiv:2003.12516

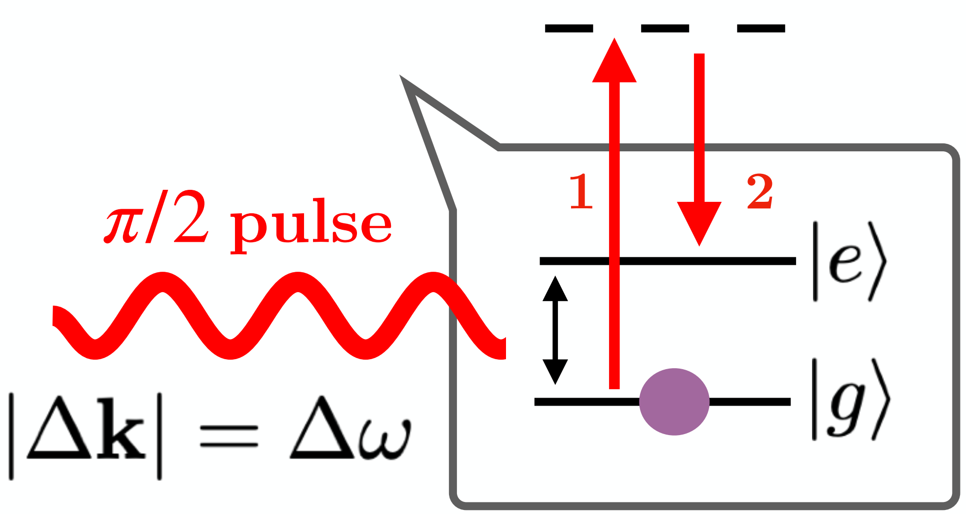


$\Rightarrow |\Psi\rangle_0 = |g\rangle$

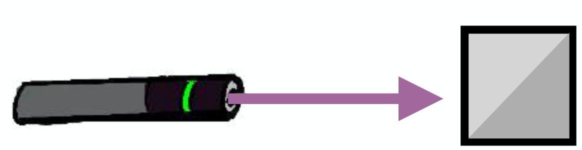
AIs: the Principle

Review: arXiv:2003.12516





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



AIs: the Principle

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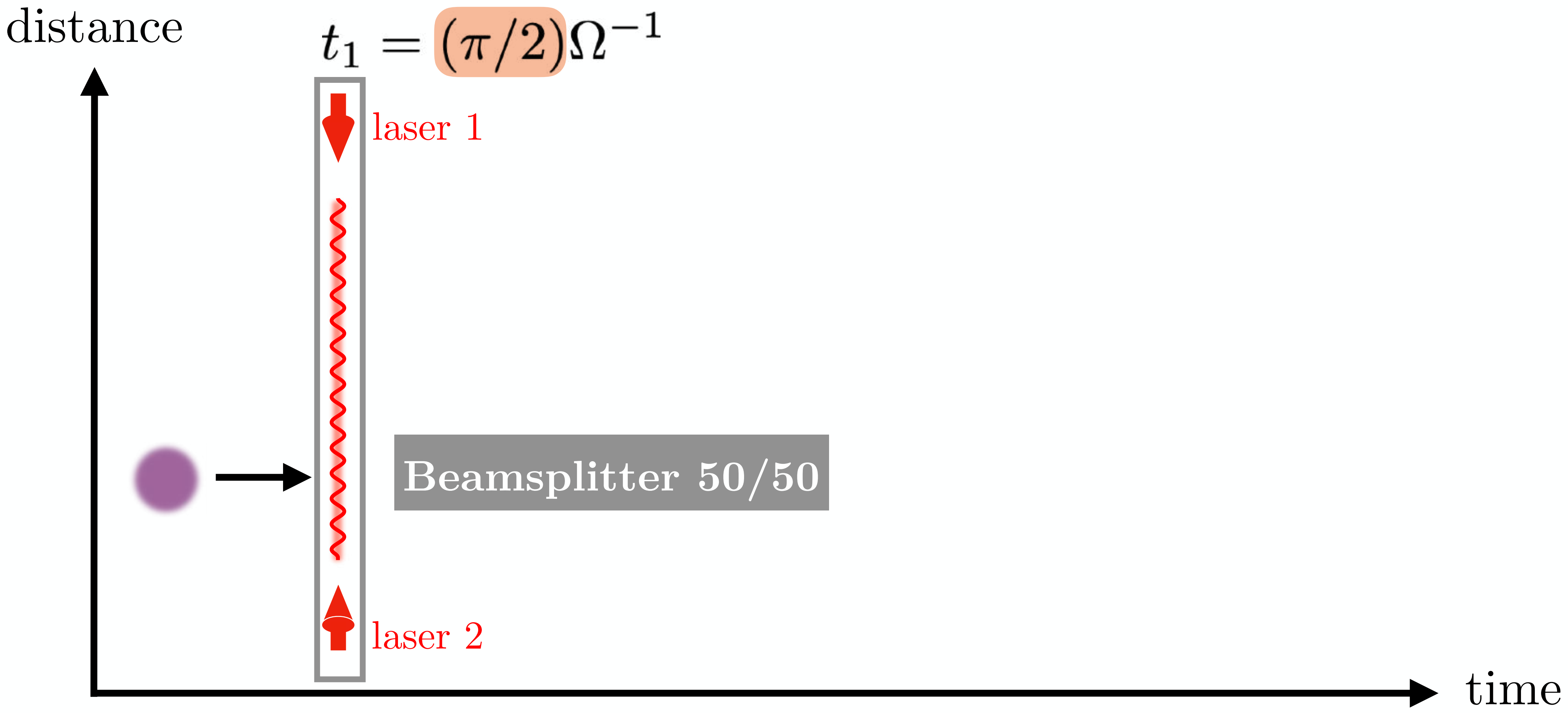
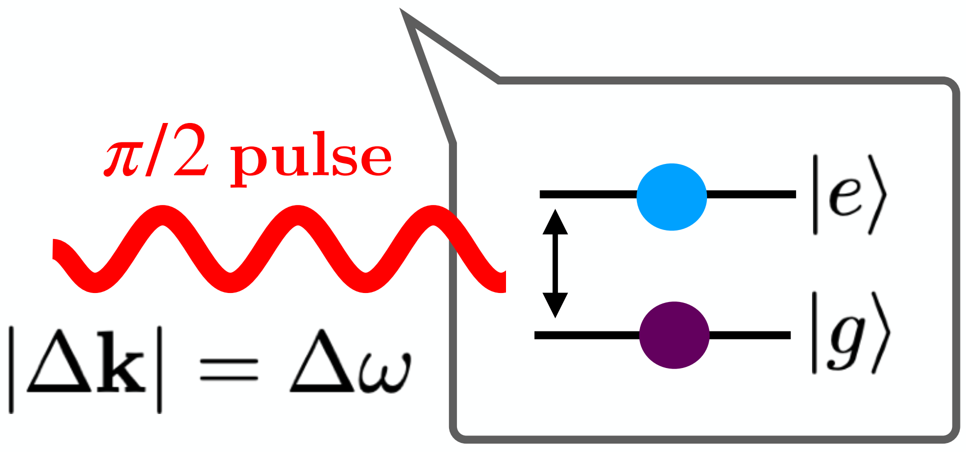
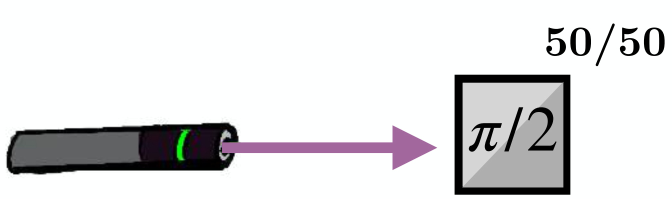




$$\Rightarrow |\Psi\rangle_t = \cos(\pi/4)|g\rangle + i\sin(\pi/4)|e\rangle$$



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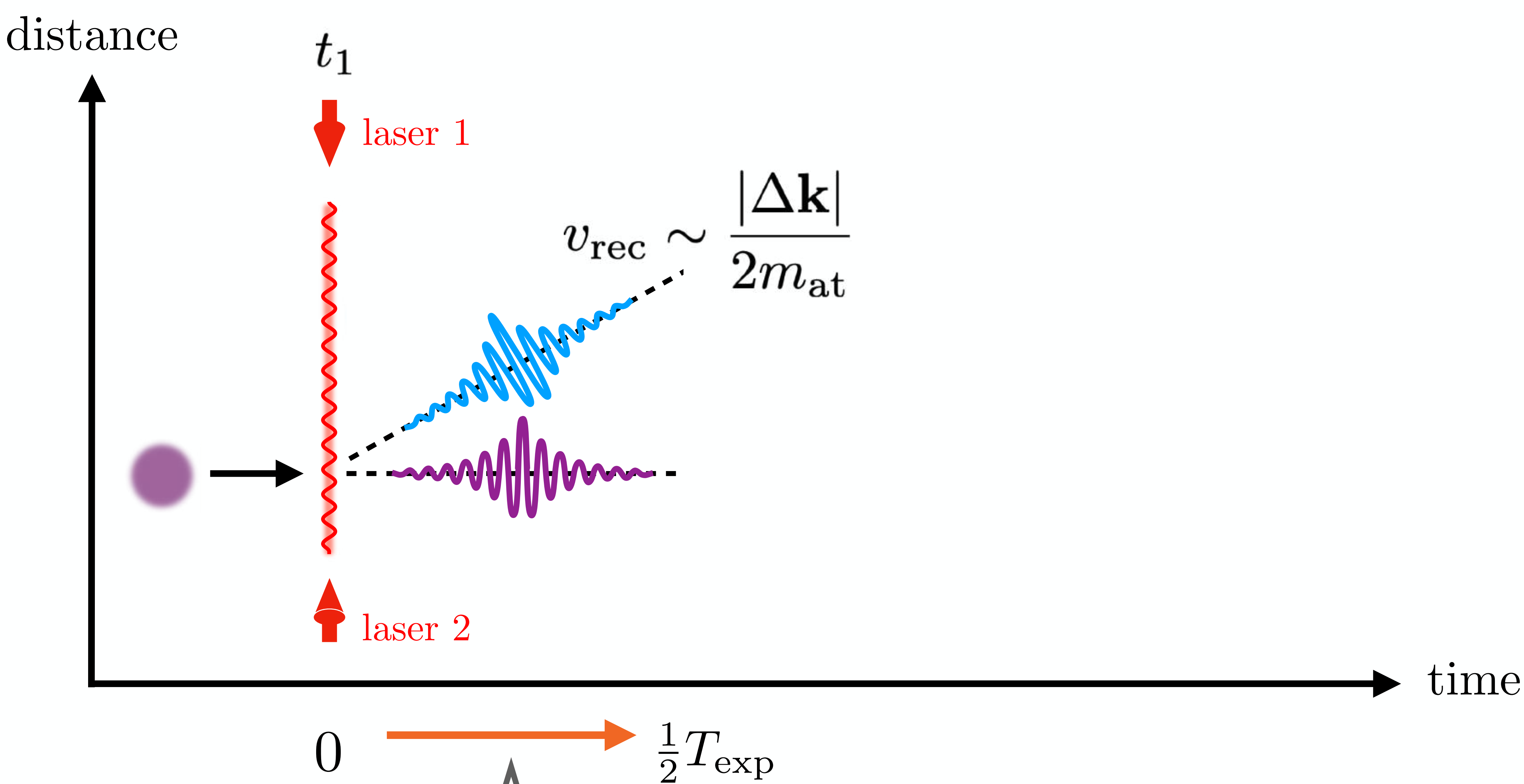
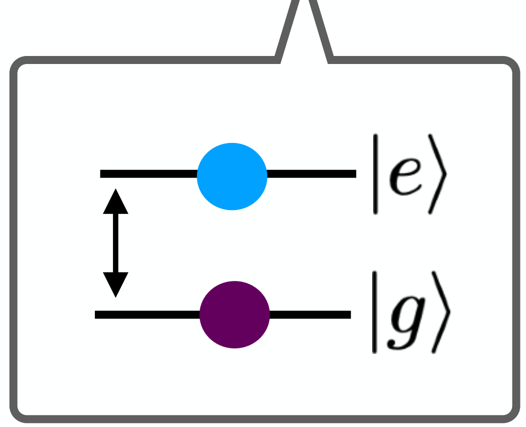
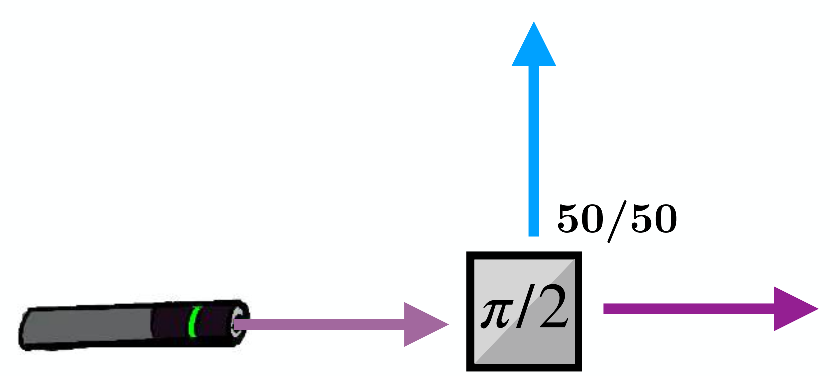




$$|\Delta \mathbf{k}| = \Delta\omega$$



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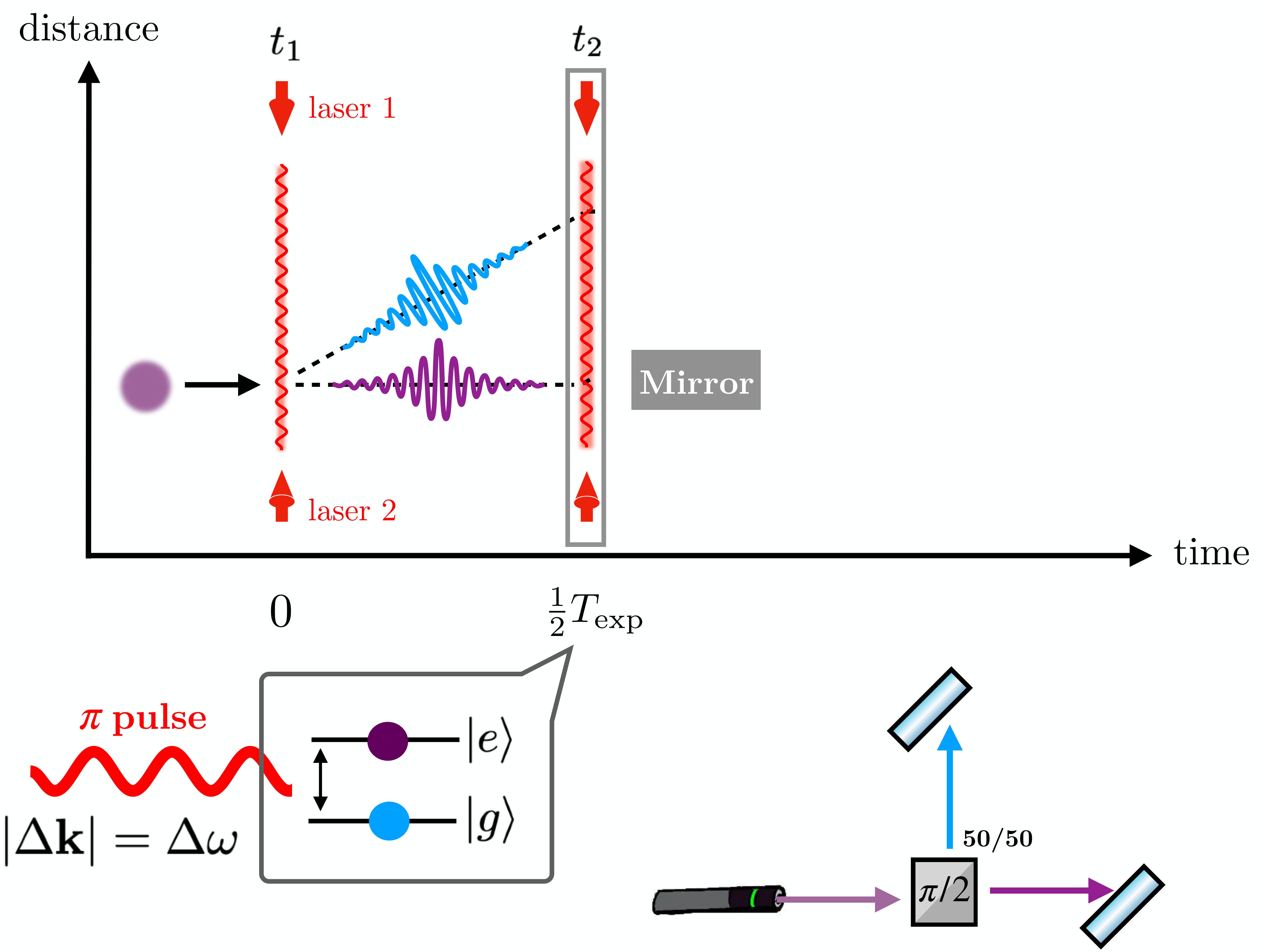

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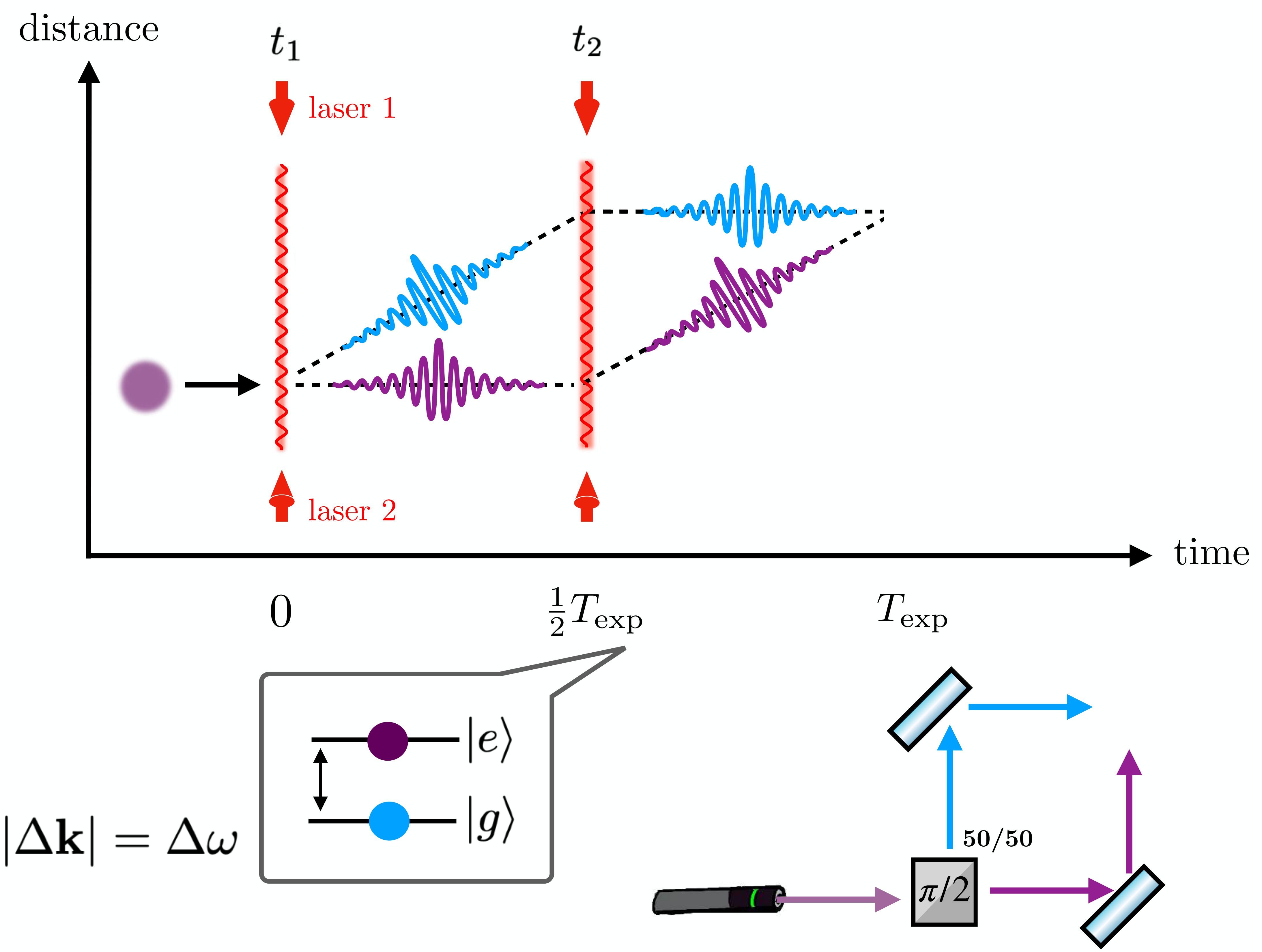

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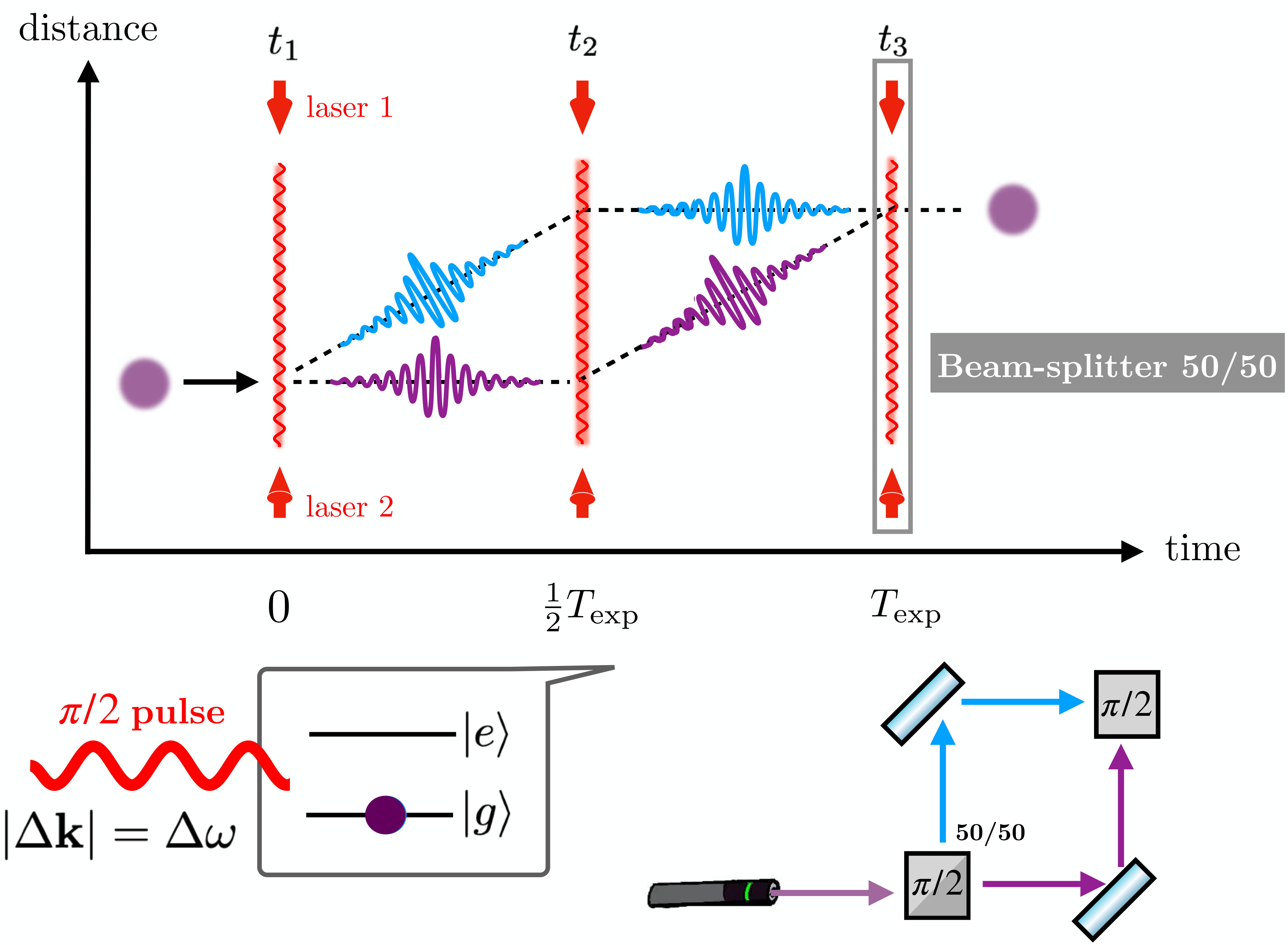

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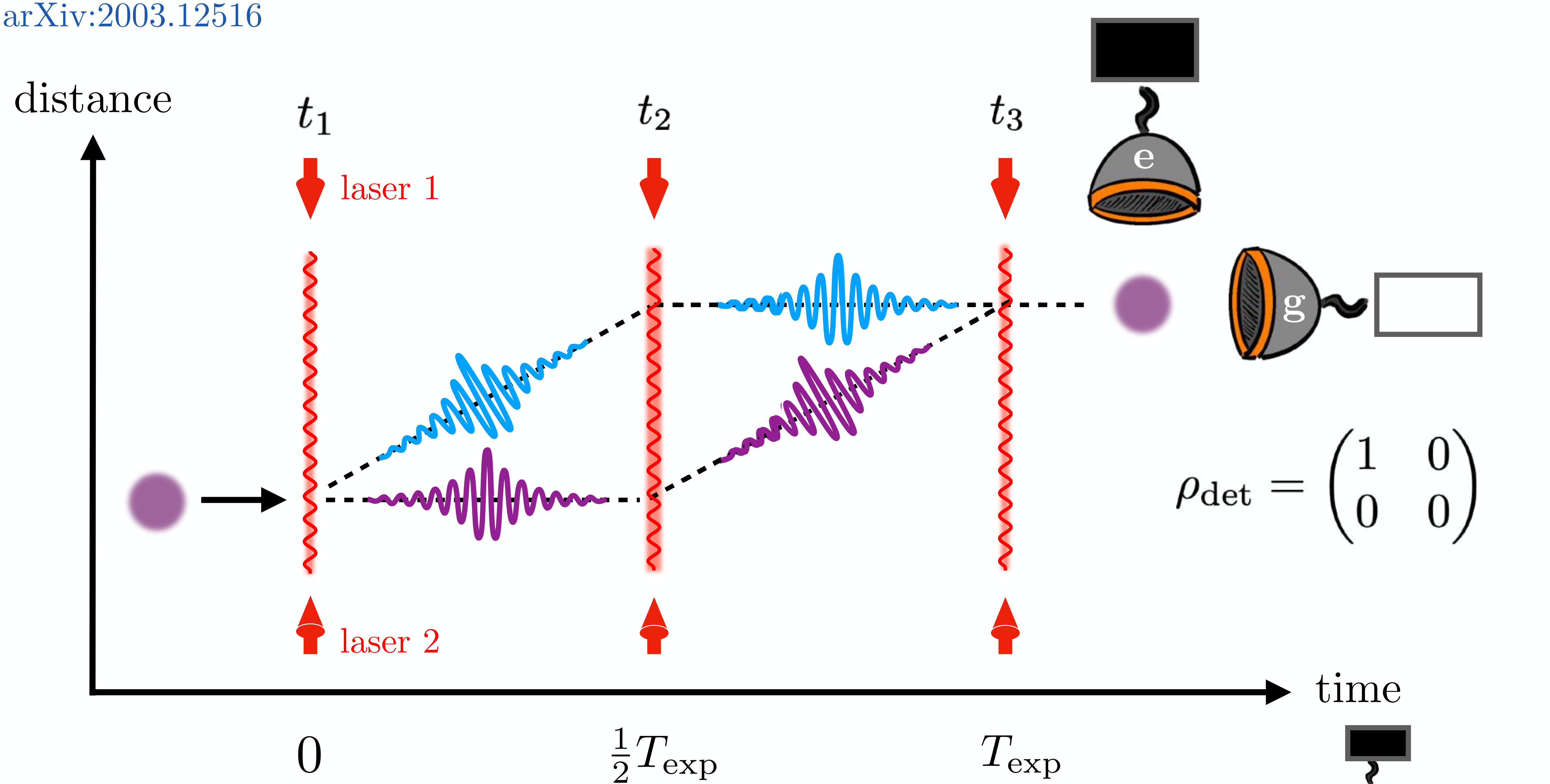
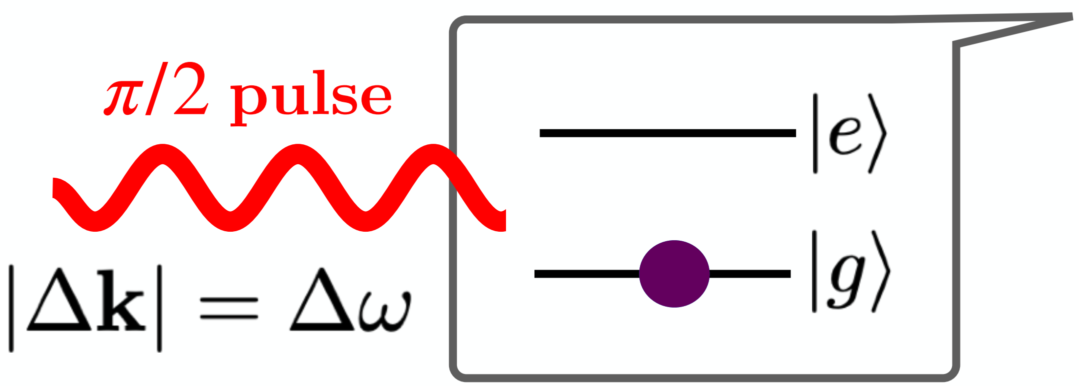
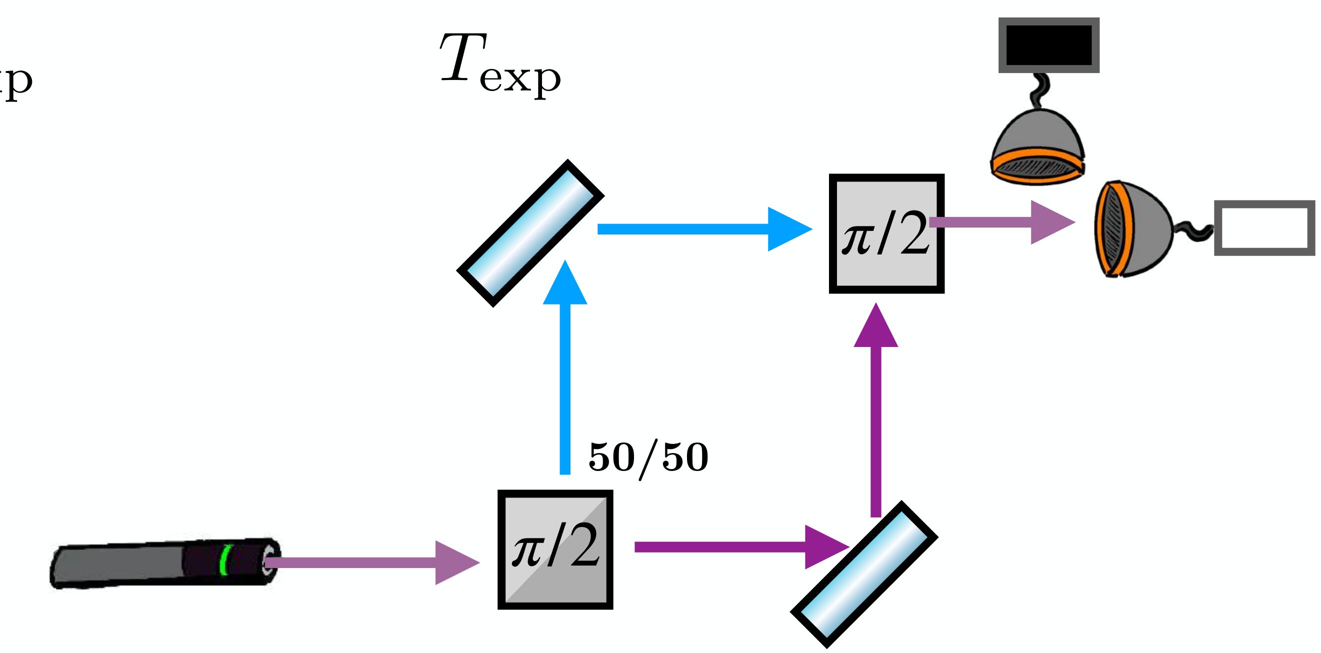
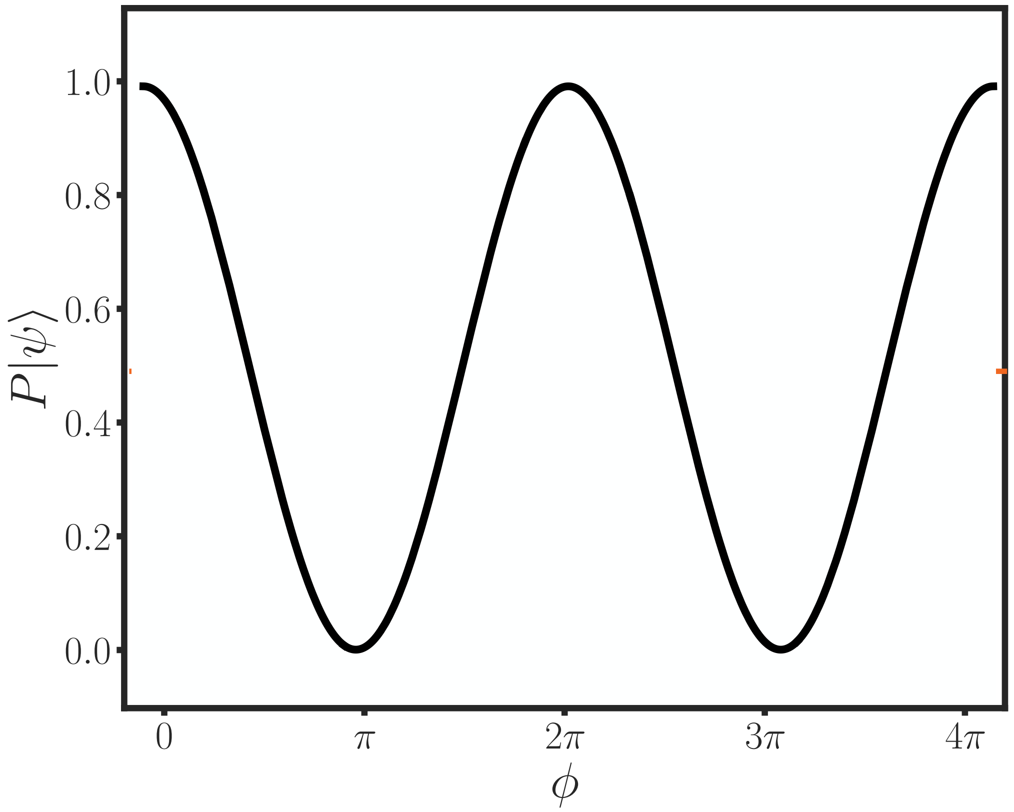
Review: arXiv:2003.12516

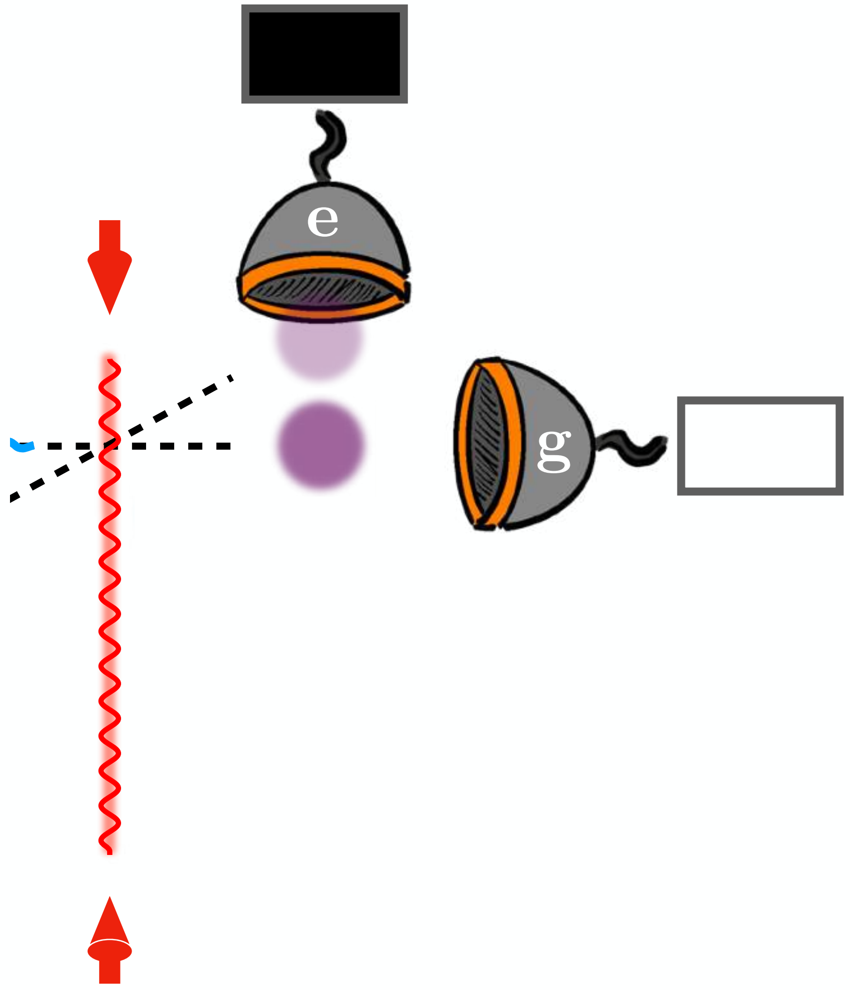






AIs: Measurement

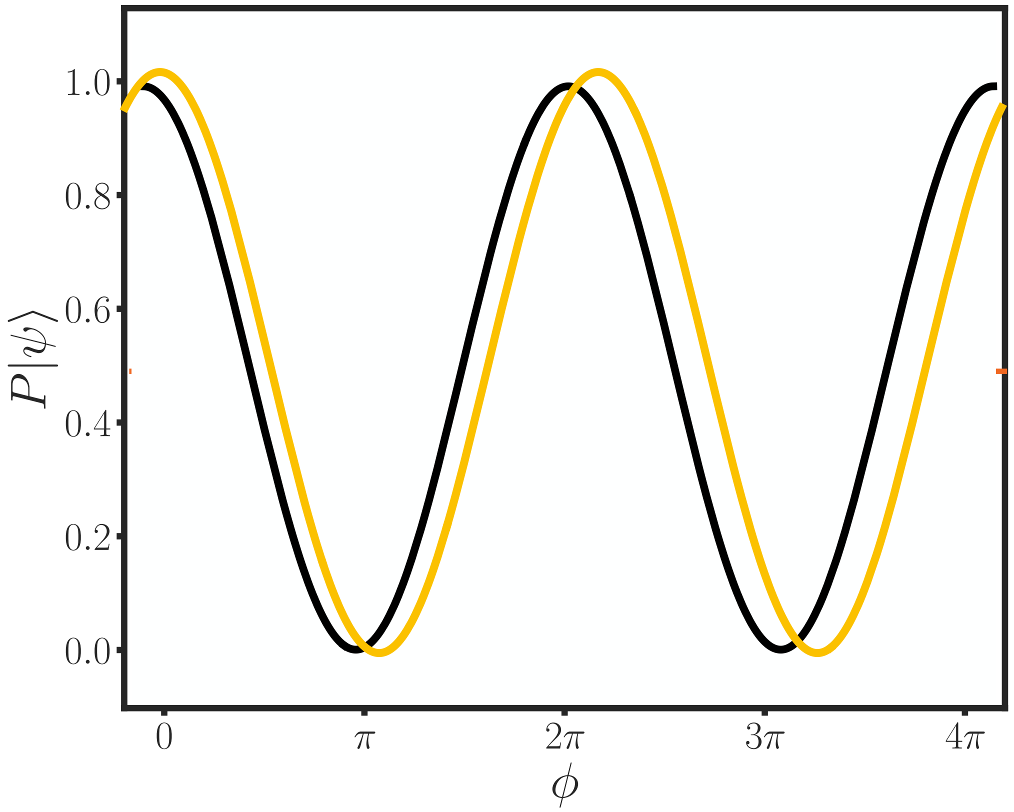


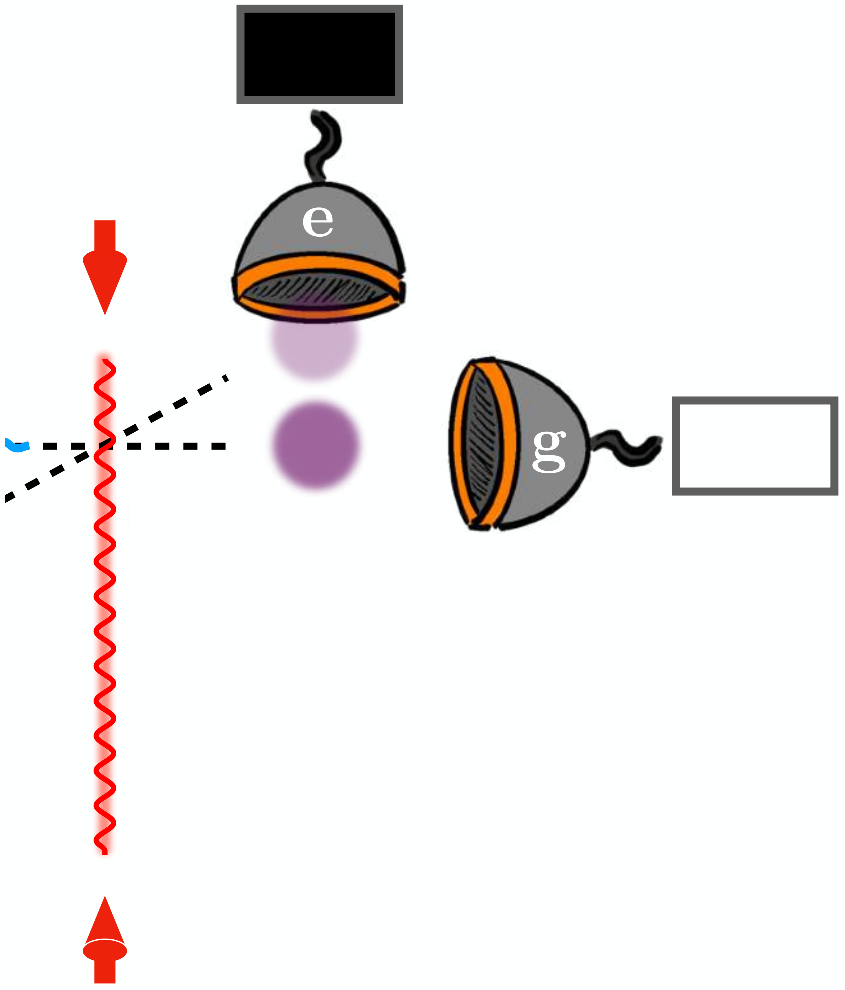


$$\rho = \frac{1}{2}\begin{pmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{pmatrix}$$

$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\text{exp}} = \frac{1}{2}\left(1 + \overset{=1}{V} \cos\left(\phi + \overset{\to 0}{\Delta\phi}\right)\right)$$

AIs: Measurement - Phase-shift

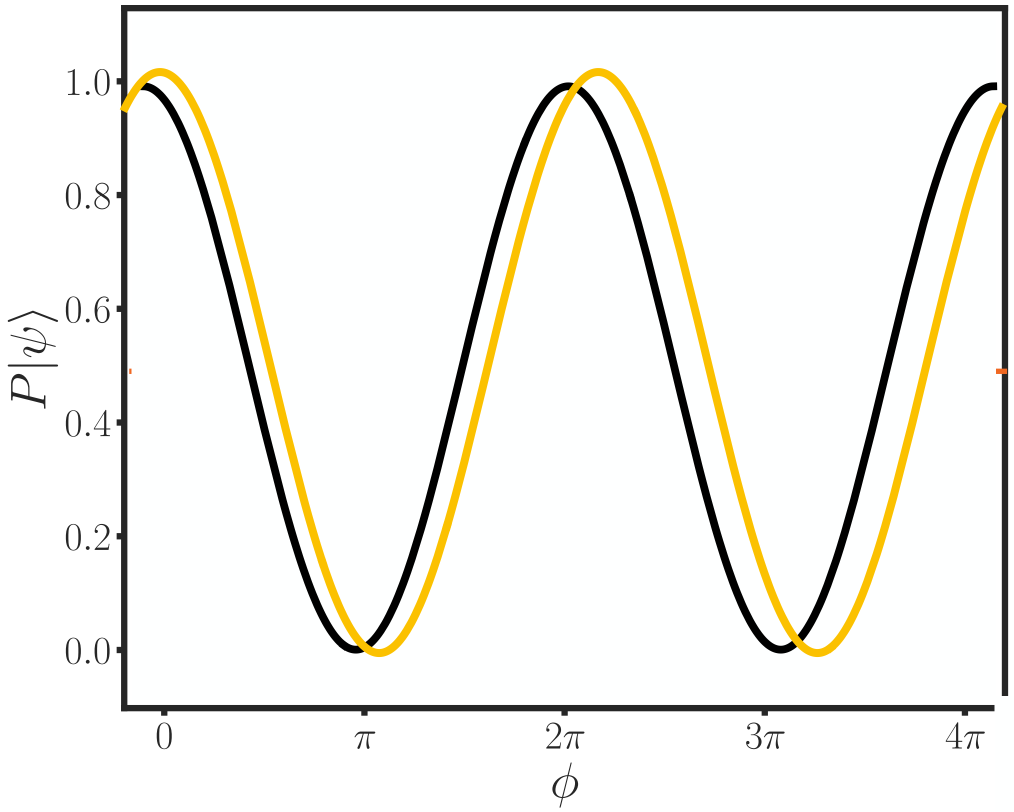




$$\rho = \frac{1}{2}\begin{pmatrix} 1 & e^{i(\phi+\Delta\phi)} \\ e^{-i(\phi+\Delta\phi)} & 1 \end{pmatrix}$$

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

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

[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

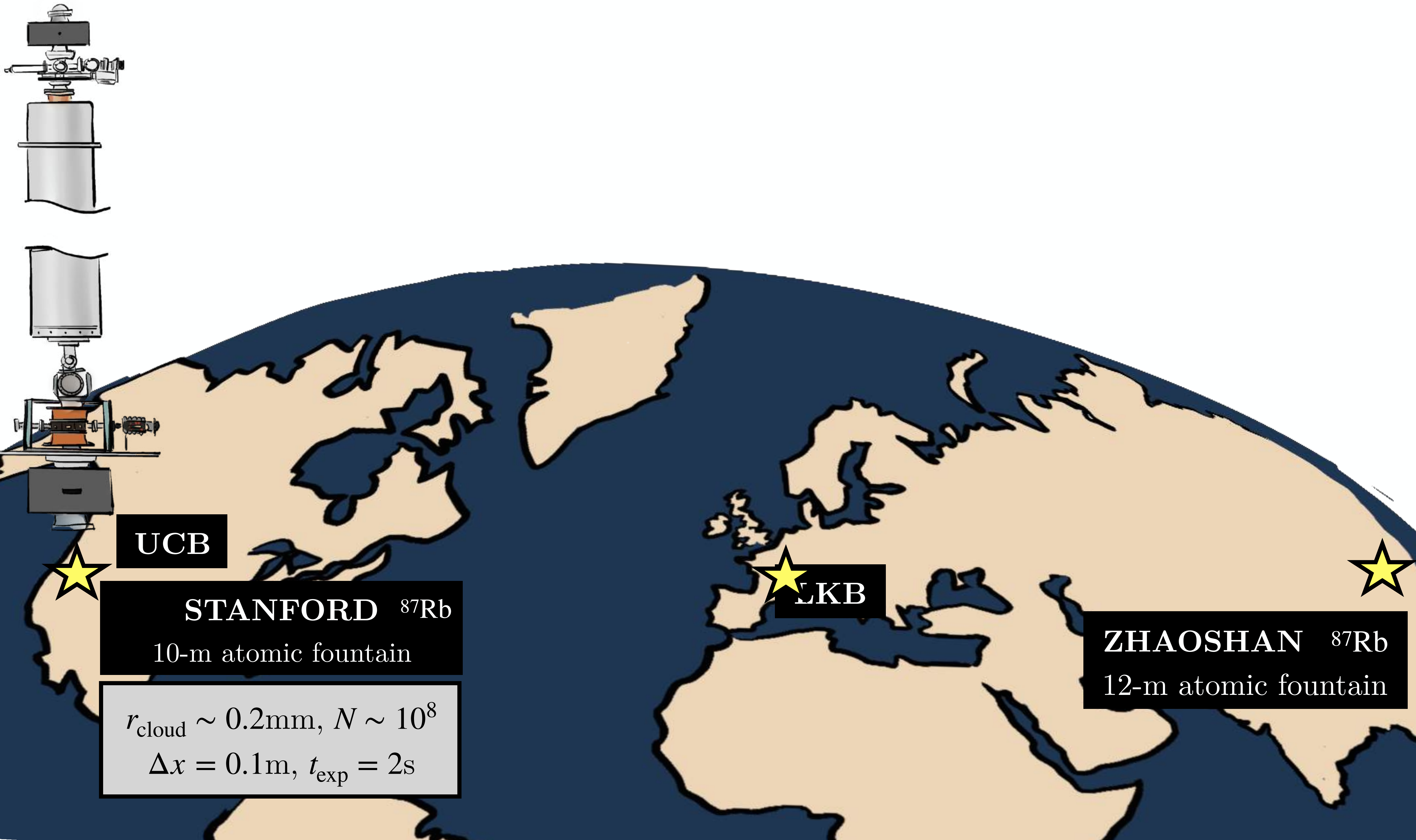
[Wacker, 2010], [Rosi, Sorrentino, et al. 2014] [Biedermann, Wu, et al. 2015] [Rosi, D'Amico, et al. 2017] [Fray, Diez, et al. 2004] [Schlippert, Hartwig, et al. 2014] [Zhou, Long, et al. 2015] [Barrett, Antoni-Micollier, et al. 2016] [Kuhn, McDonald, et al. 2014] [Barrett, Antoni-Micollier, et al. 2015] [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] ....

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

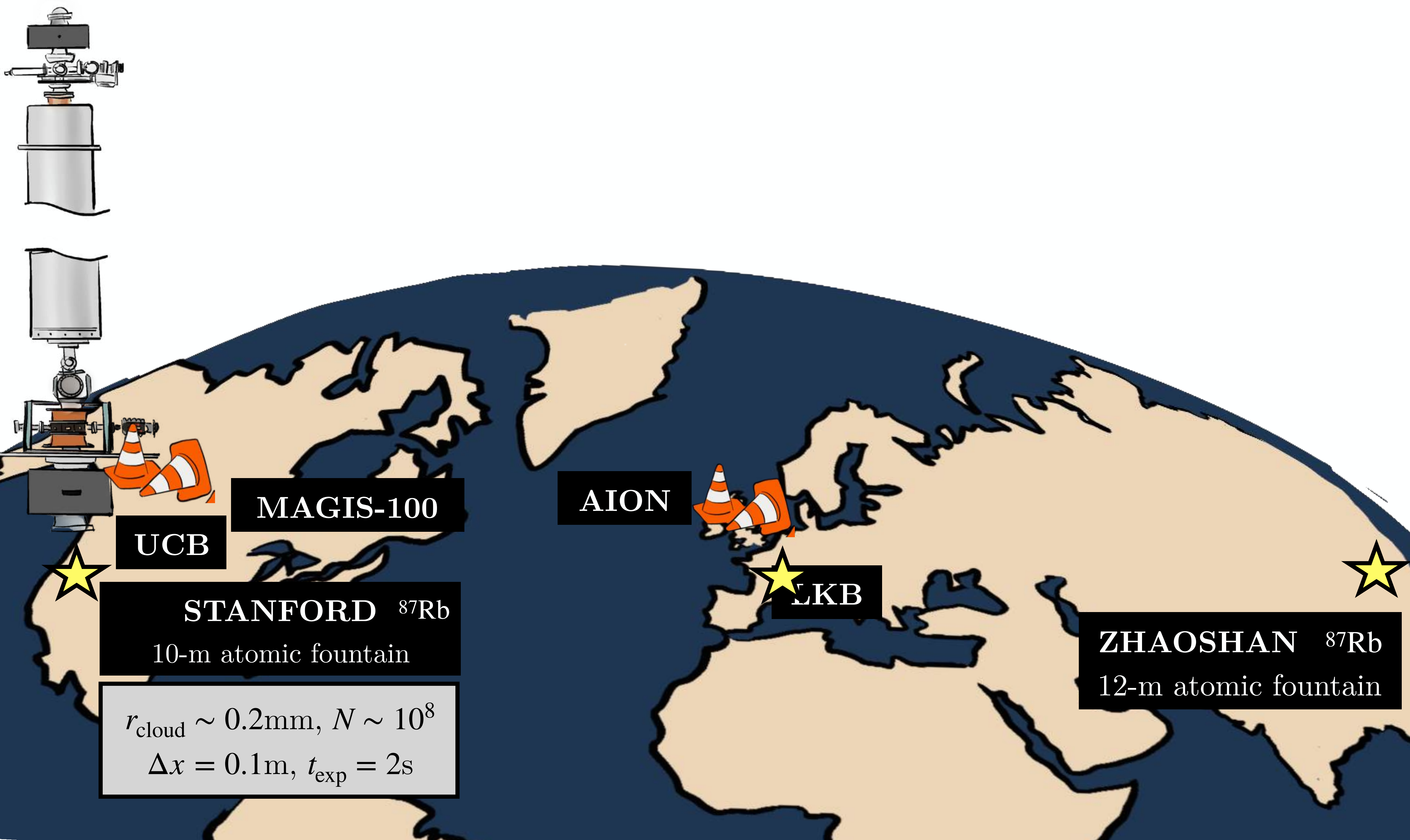
EDMs

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

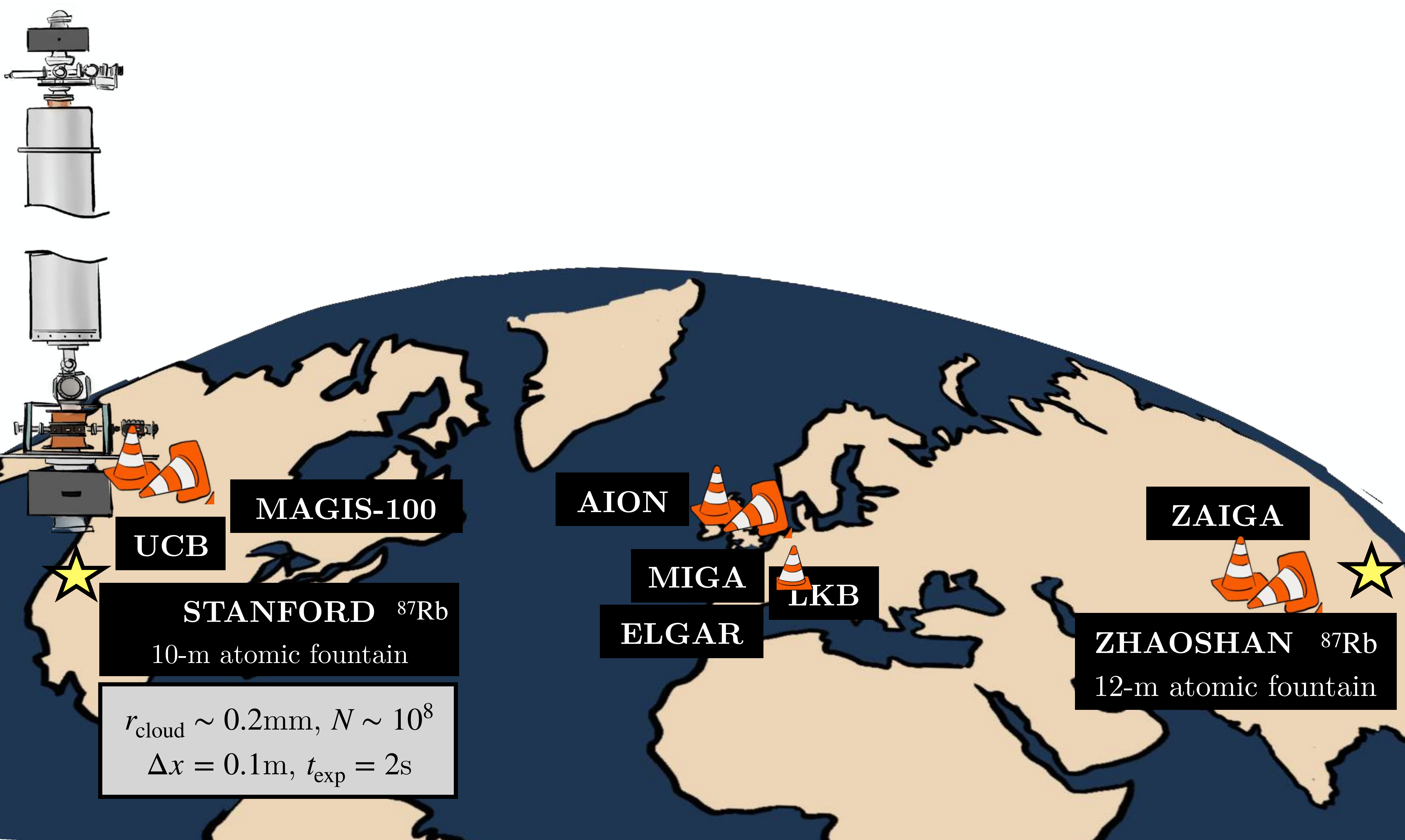
AIs: Examples



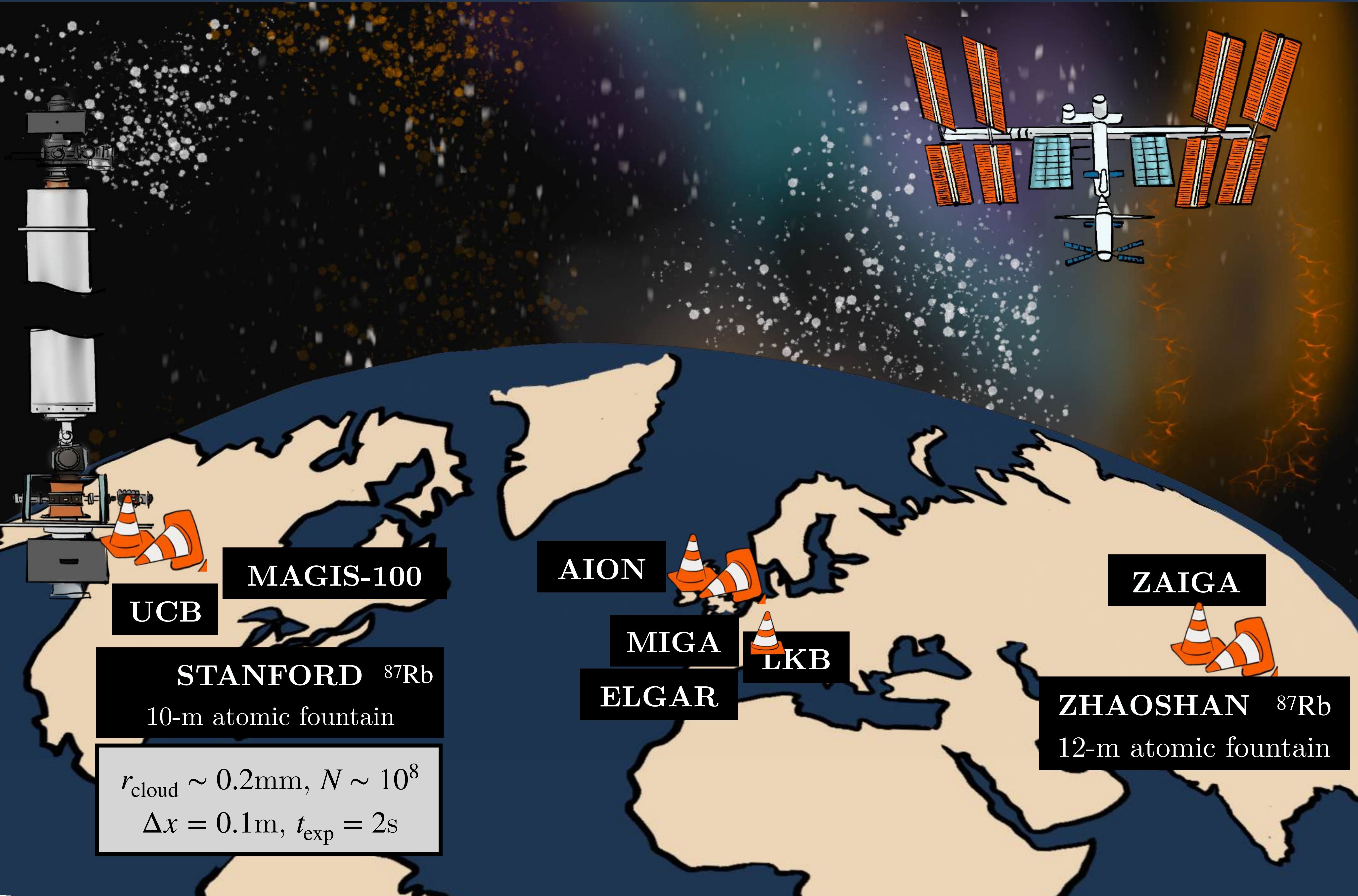
AIs: Examples



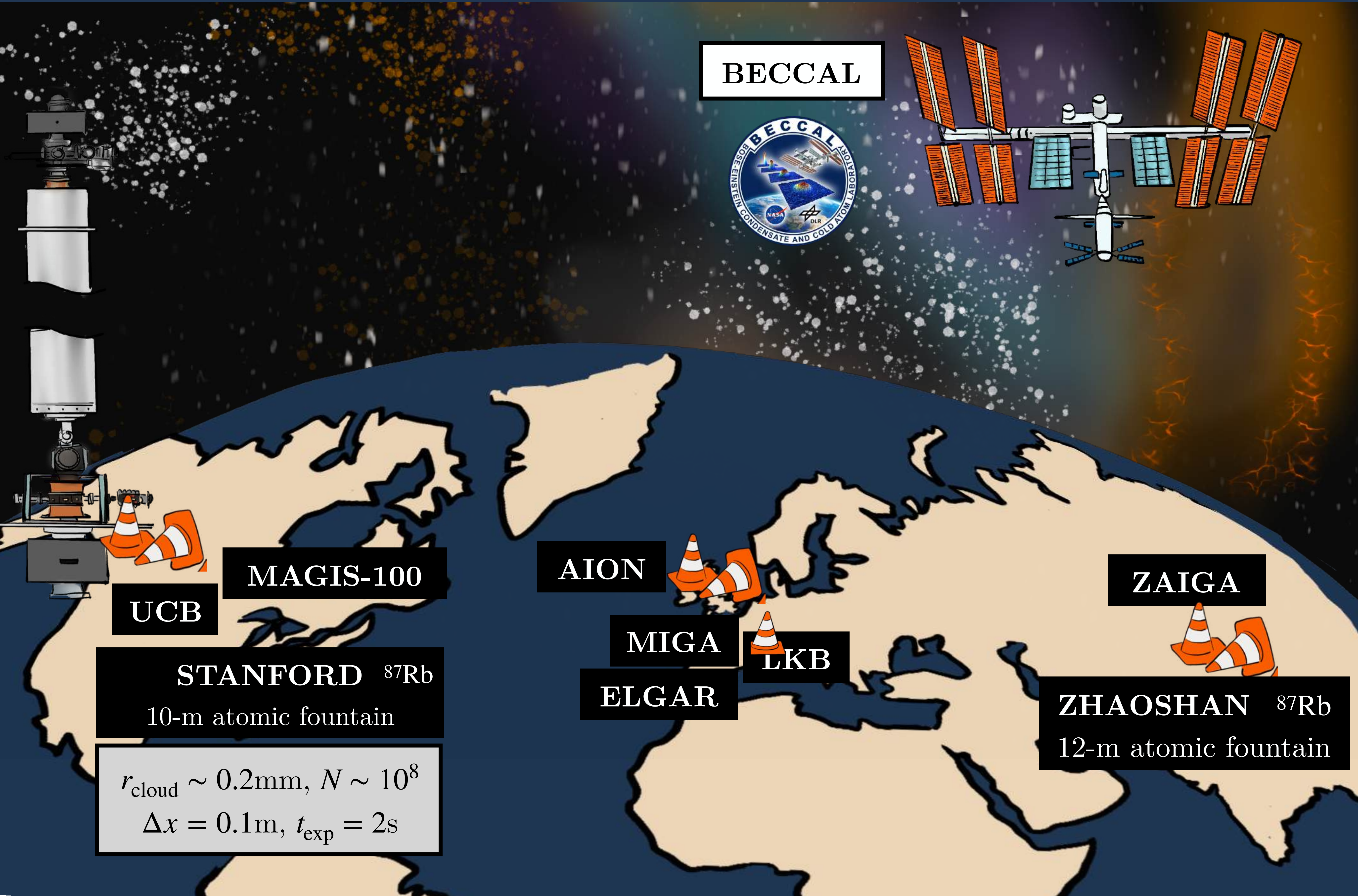
AIs: Examples



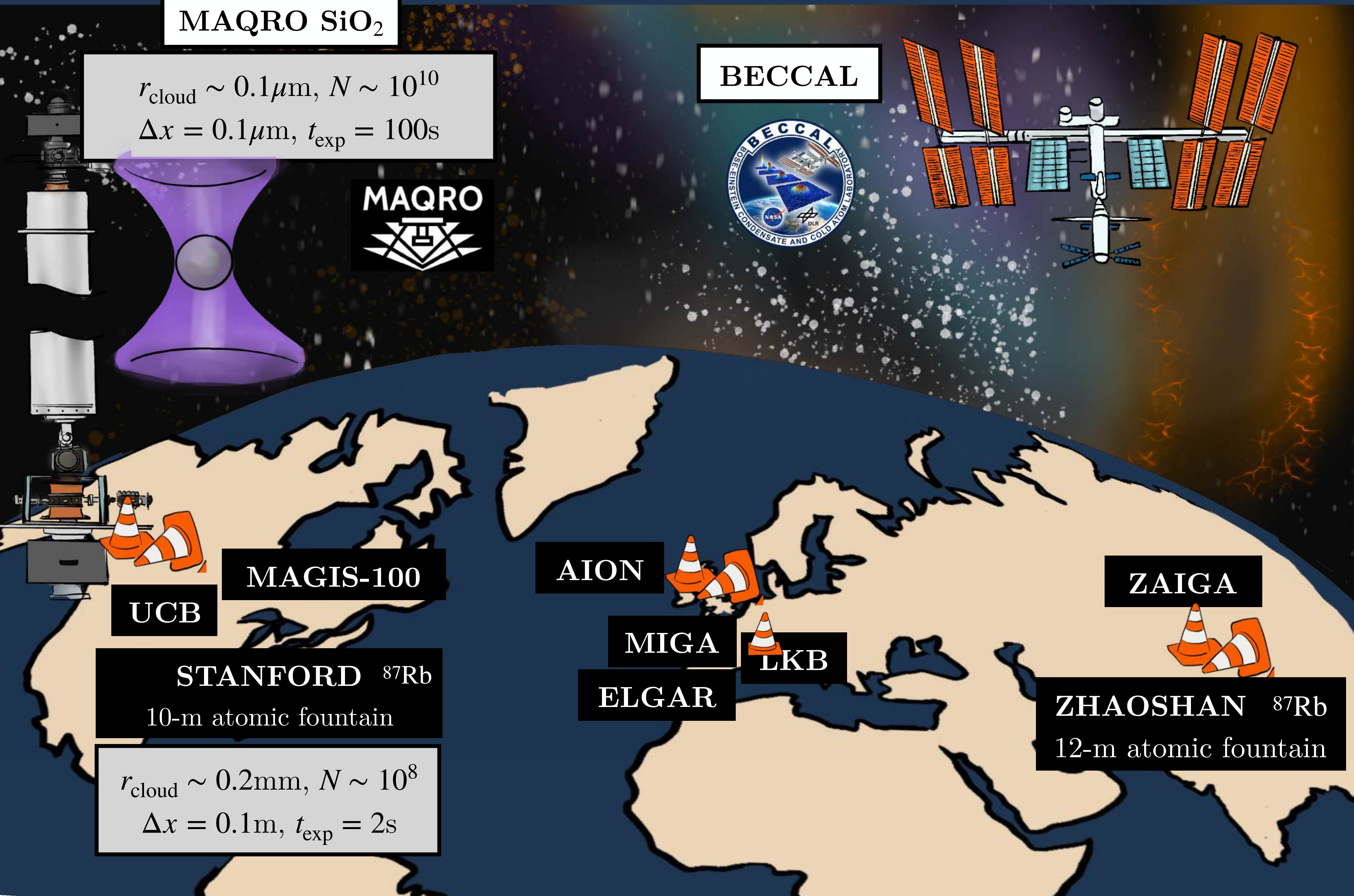
AIs: Examples



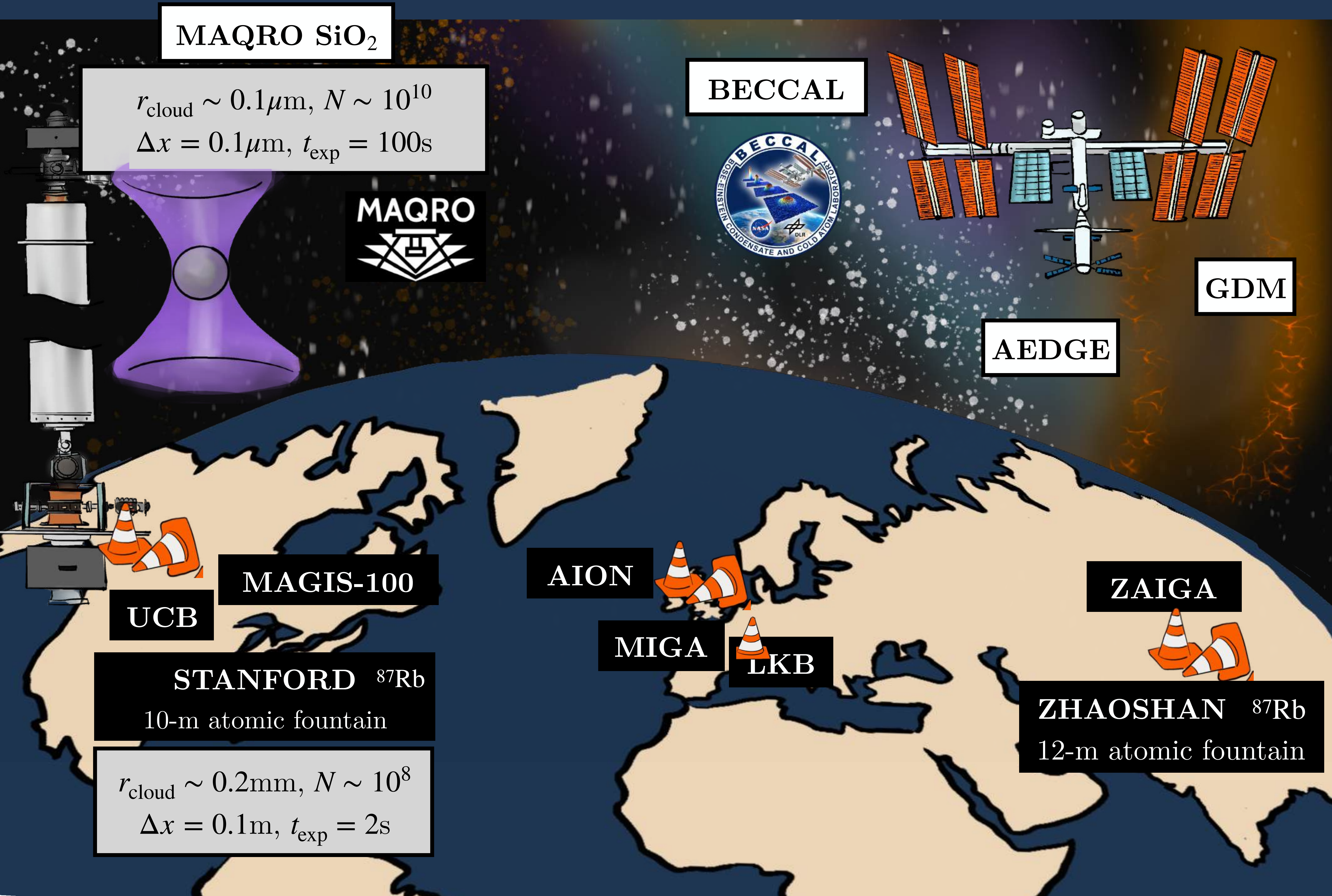
AIs: Examples



AIs: Examples



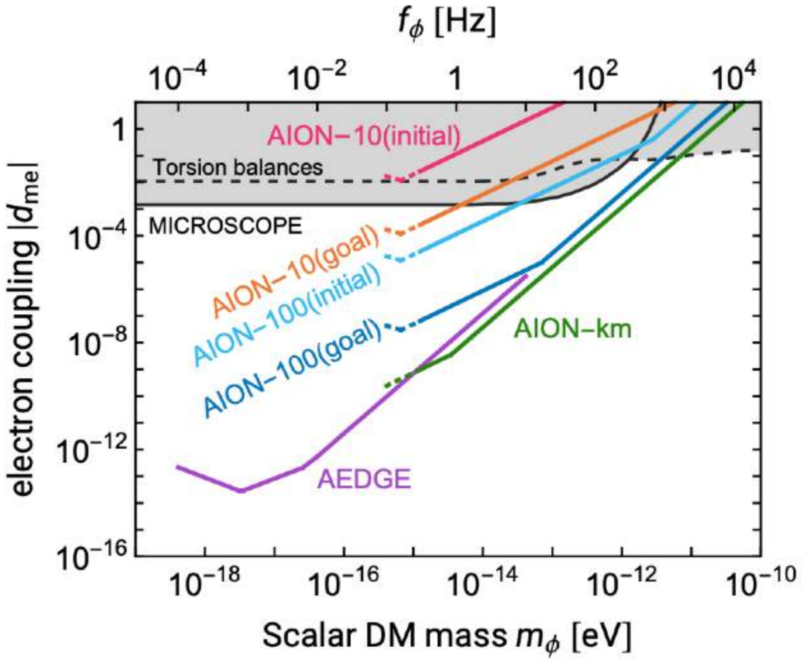
AIs: Examples

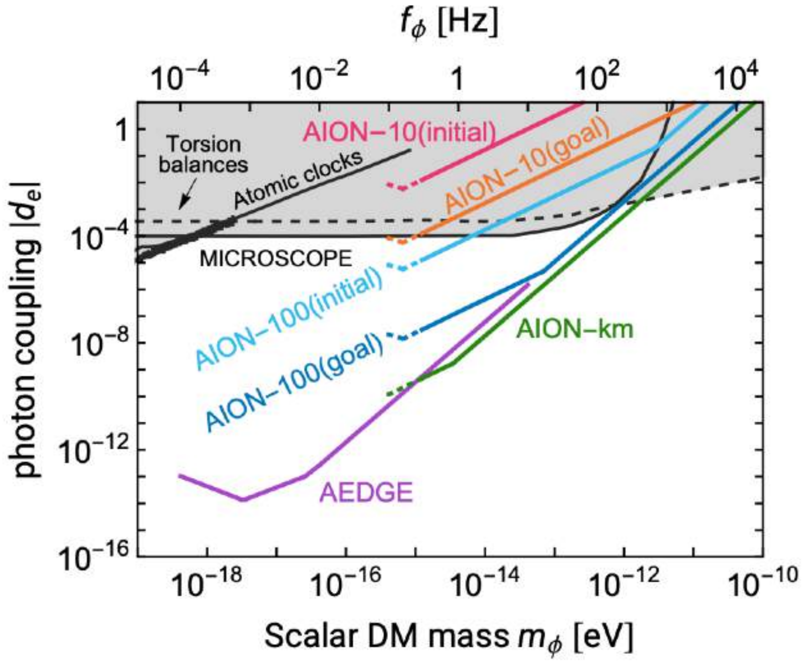


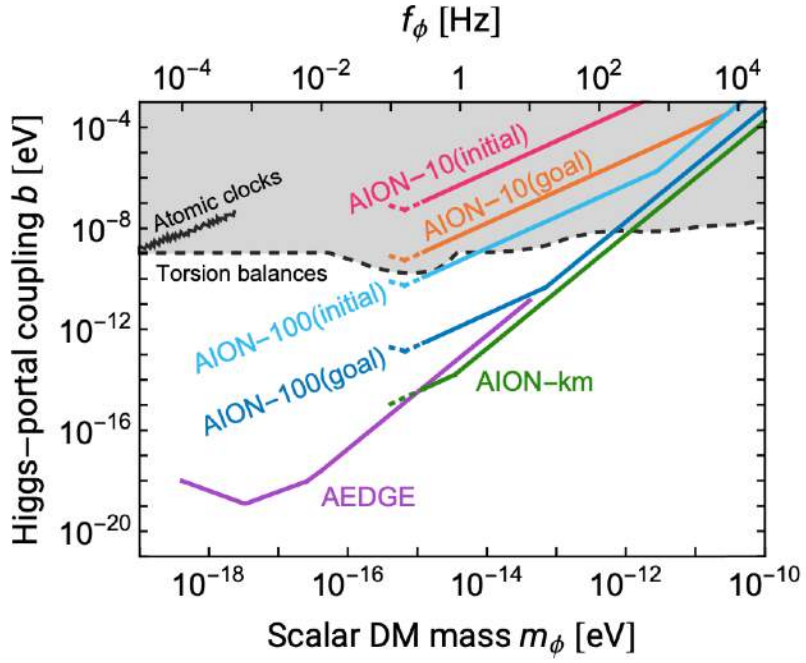
AIs: e.g. AION

https://arxiv.org/pdf/1911.11755

ULDM

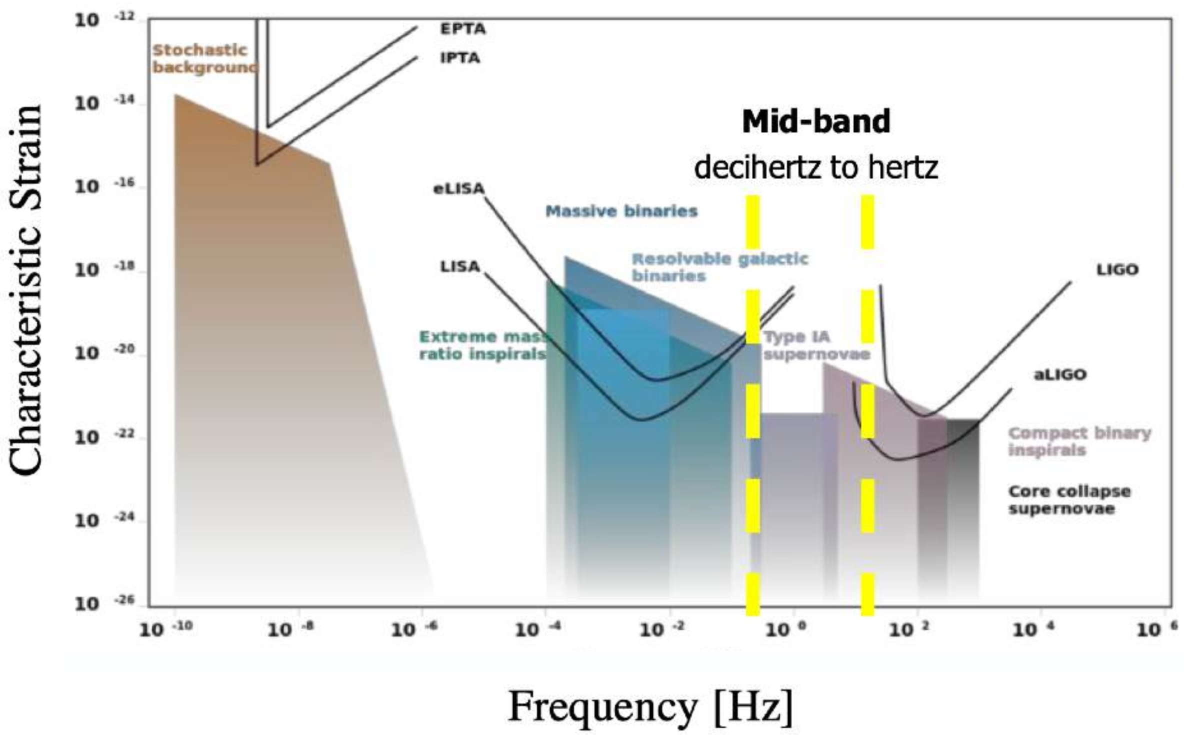


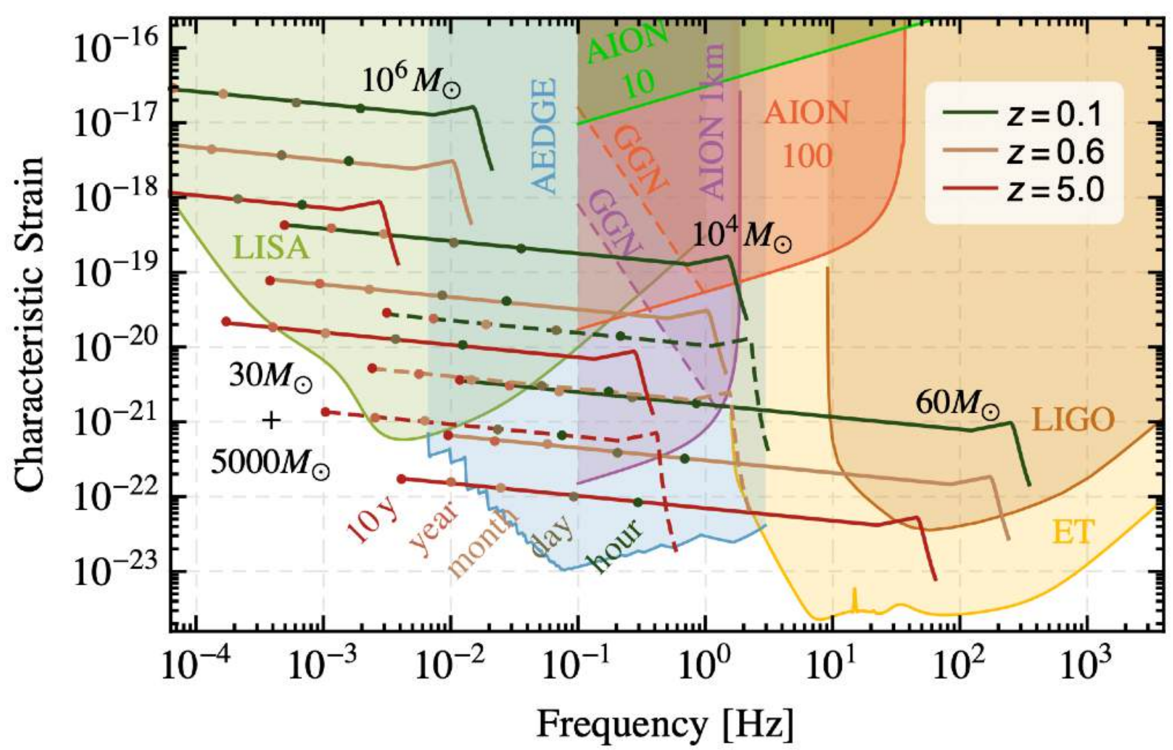




GWs

[from O. Buchmuller's slides]



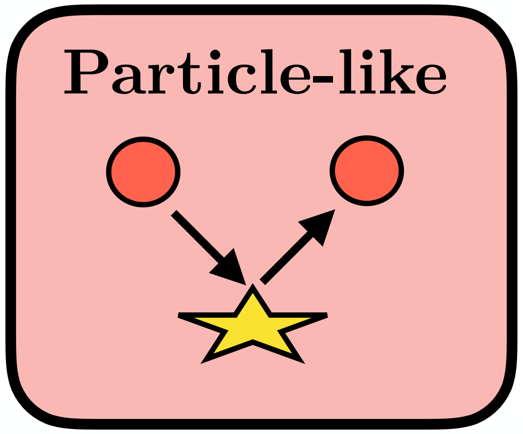


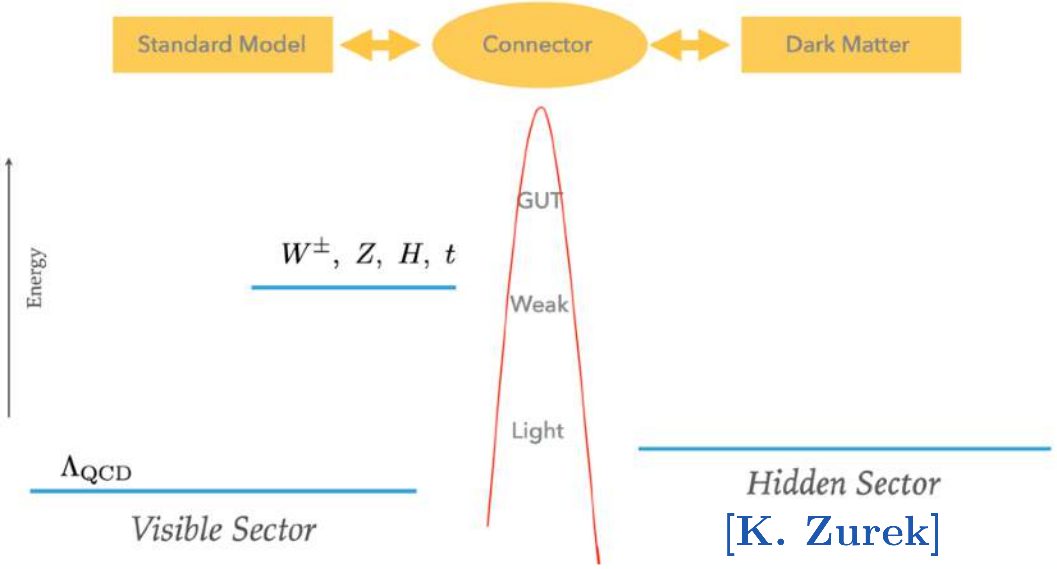
Low Energy Precision: **Nature**

Quantum Sensors as **Particle Detectors**

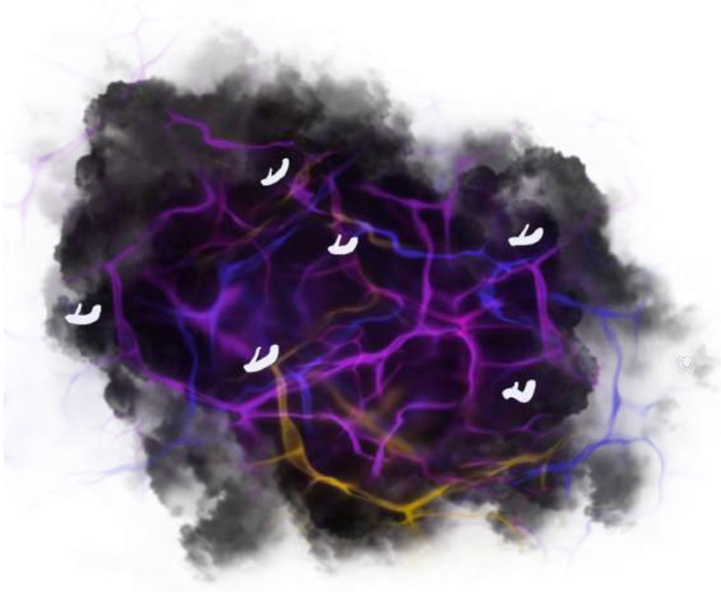
$$S = \mathbb{I} + iT$$

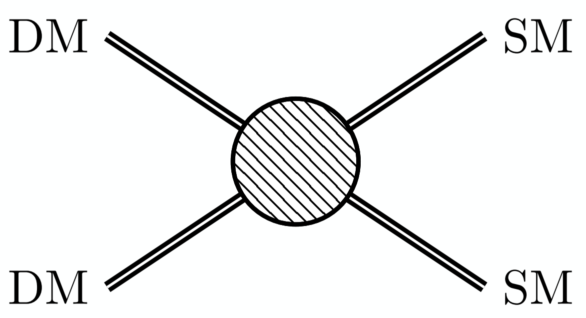
$$\Gamma_{i\to f} = \frac{2\pi}{\hbar}|\langle f|H|i\rangle|^2\rho(E_f)$$





[K. Zurek]





Quantum Sensors as **Particle Detectors**

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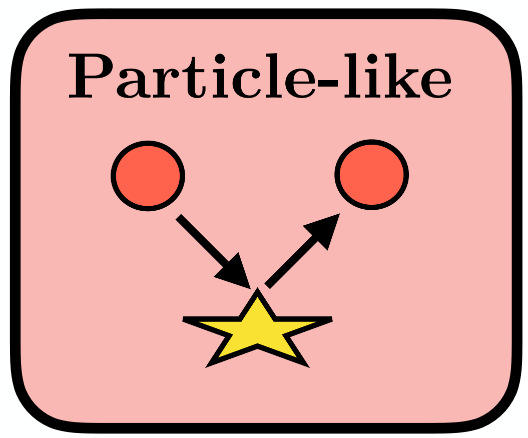
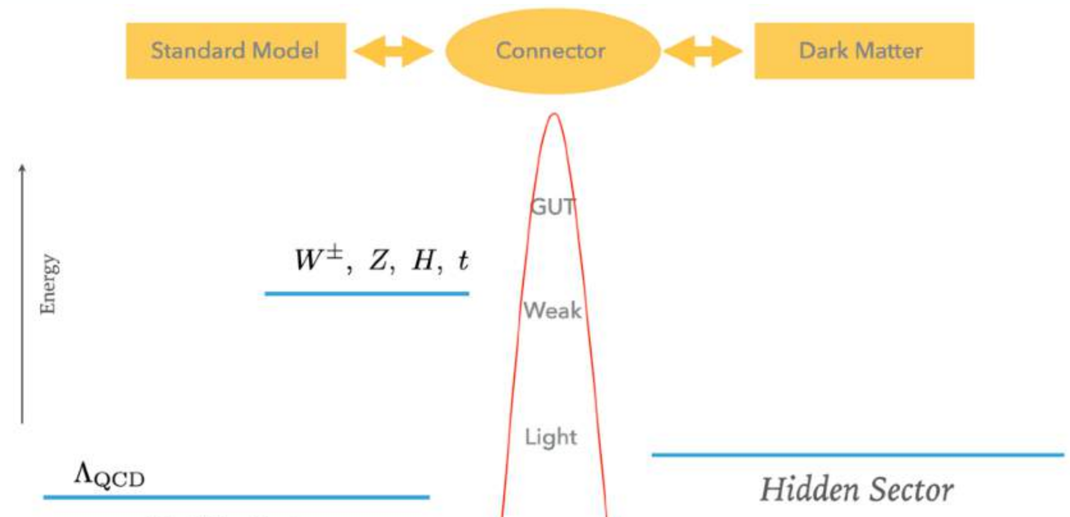
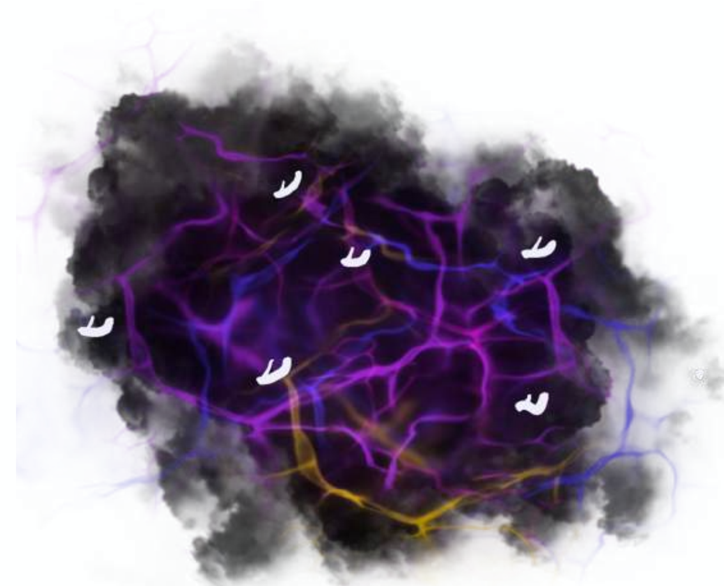
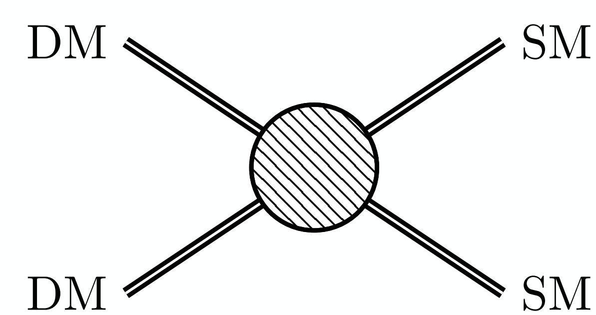


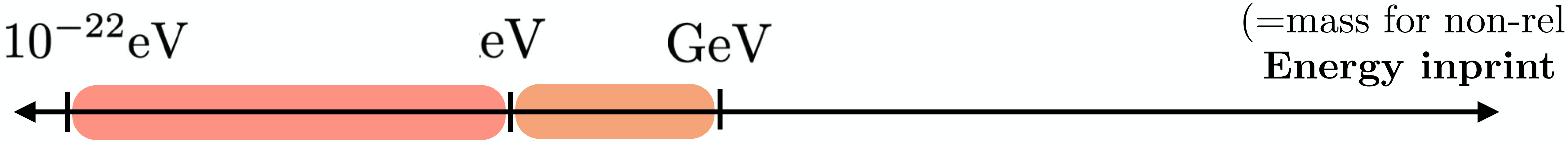


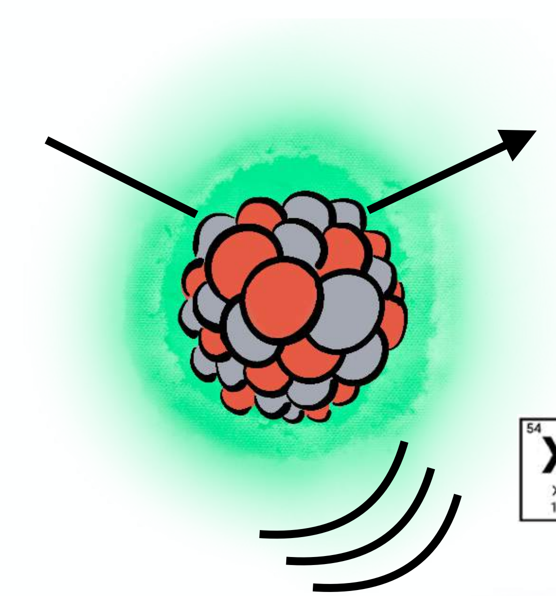
[K. Zurek]



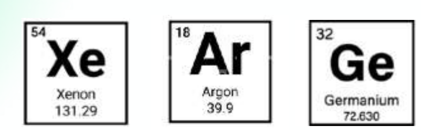


Low Energy Precision: **experiments**





Traditional WIMP DD
(nuclear recoil)

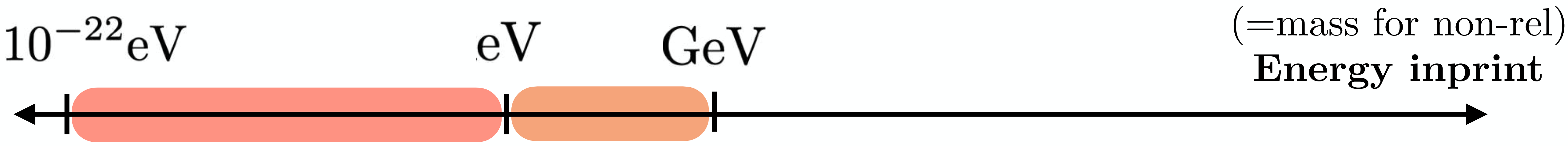


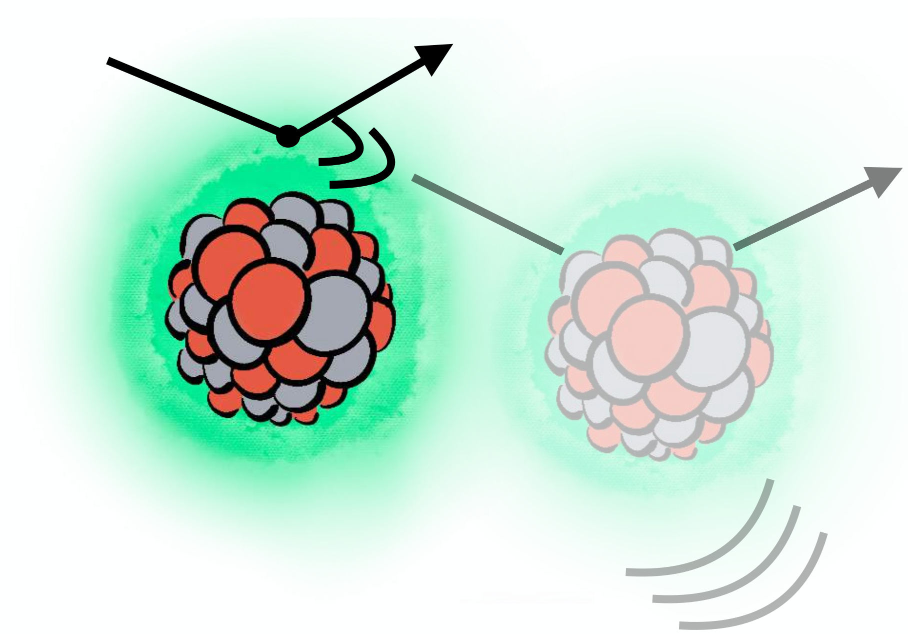
...

~keV energy resolution

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

Low Energy Precision: **experiments**





~eV energy resolution

Semiconductors

Migdal Effects

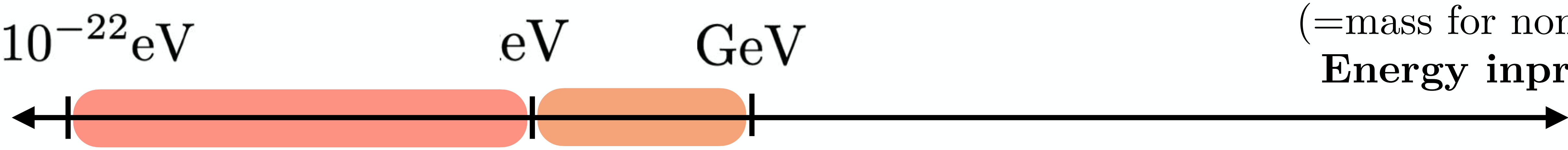
Fluoresence

Ionization

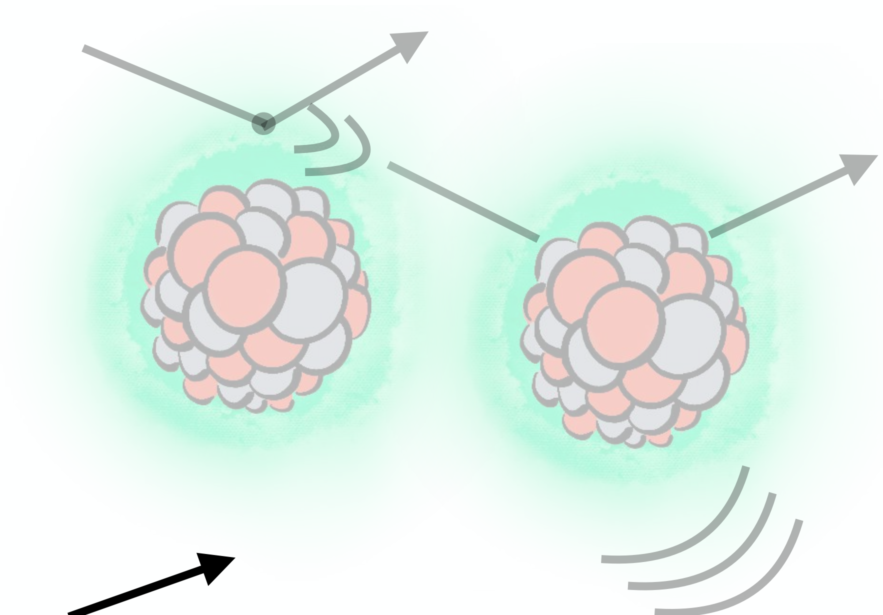
Graphene

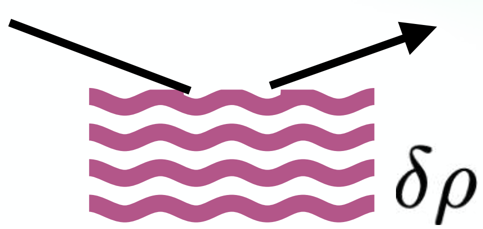
[Essig, Mardon, Volansky, 2011]
[Graham, Kaplan, Rajendran, Walters, 2012]
[Lee, Lisanti, Mishra-Sharma, Safdi, 2015]
[Essig, Volansky, Yu, 2017]
[Emken, Essig, Kouvaris, Sholapurka, 2019]
[Blanco, Collar, Kahn, Lillard, 2019]
[Blanco, Kahn, Lillard, McDermott, 2021]
[Blanco, Essig, Fernandez-Serra,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

Low Energy Precision: experiments



(=mass for non-rel)
Energy inprint



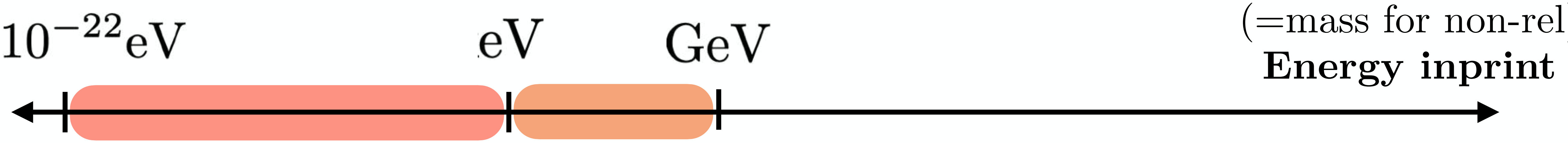


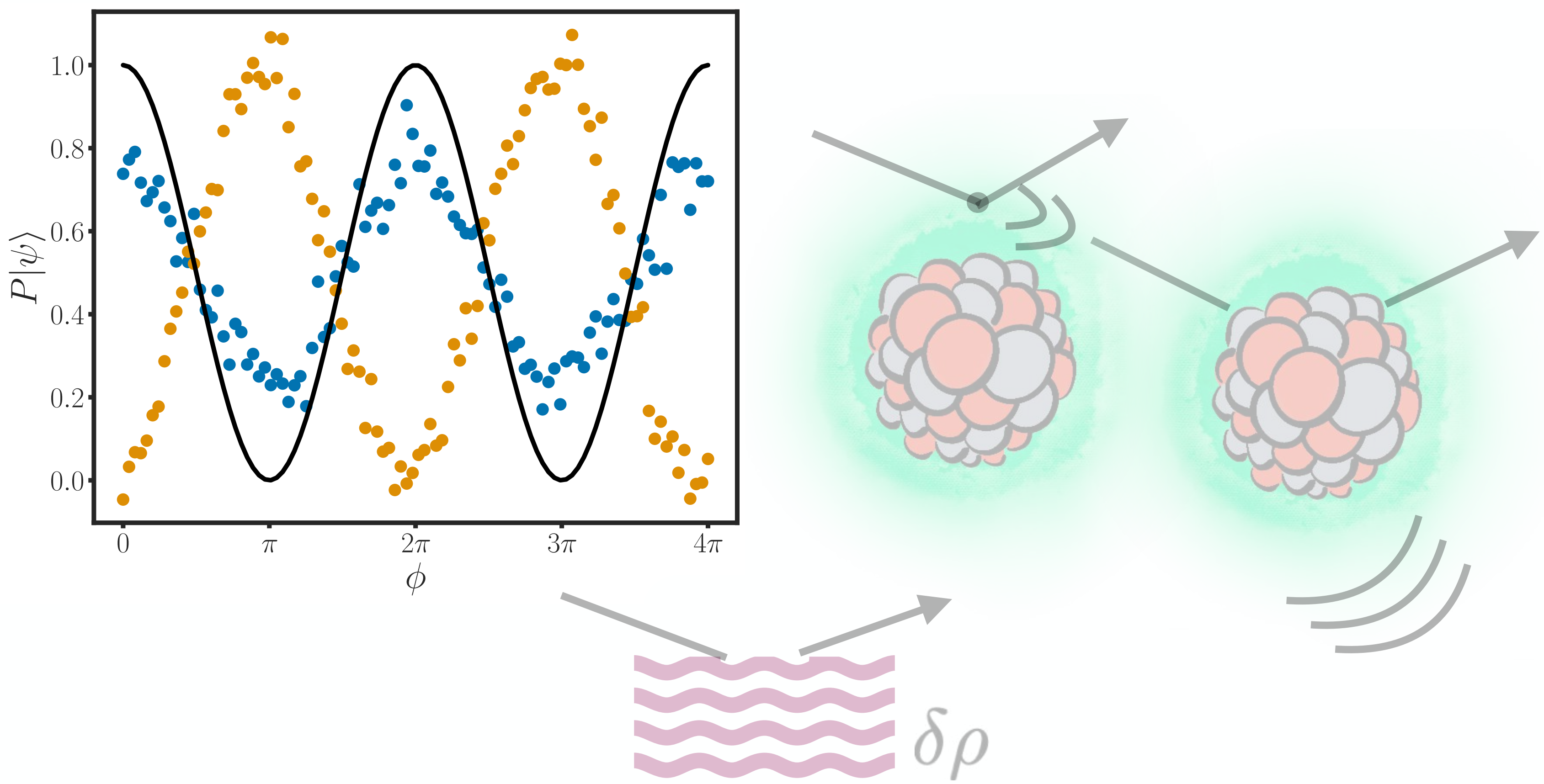
Collective excitations
(phonons, magnons, polaritons....)

~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]

Low Energy Precision: **experiments**



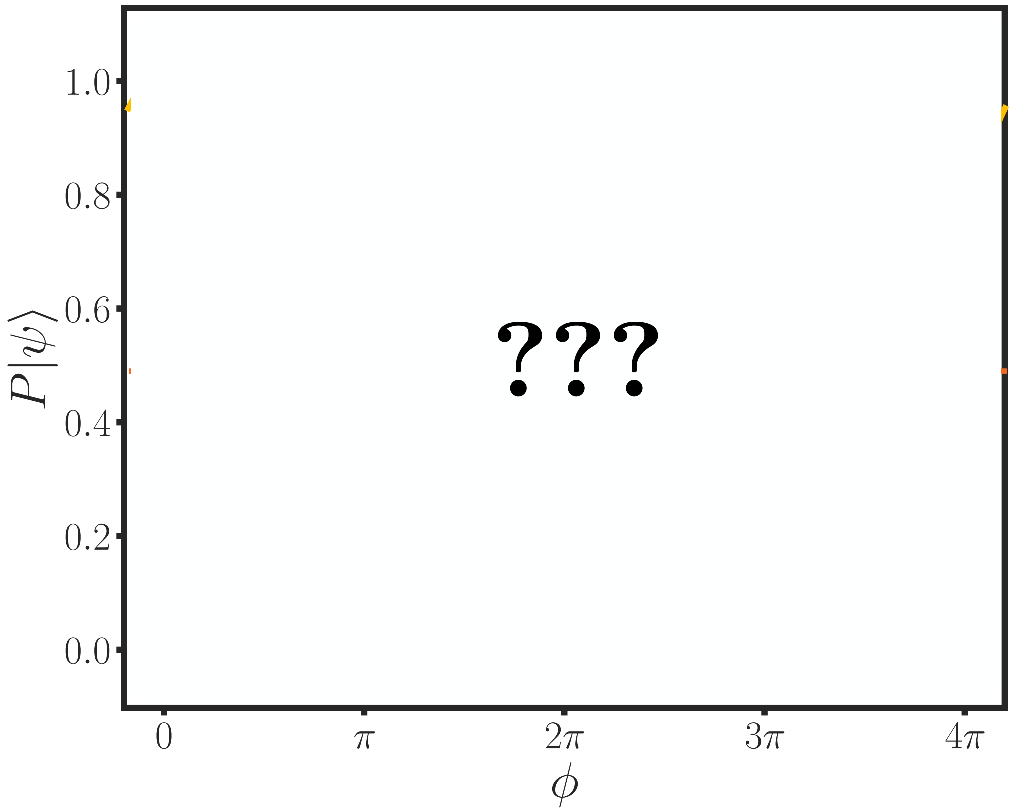


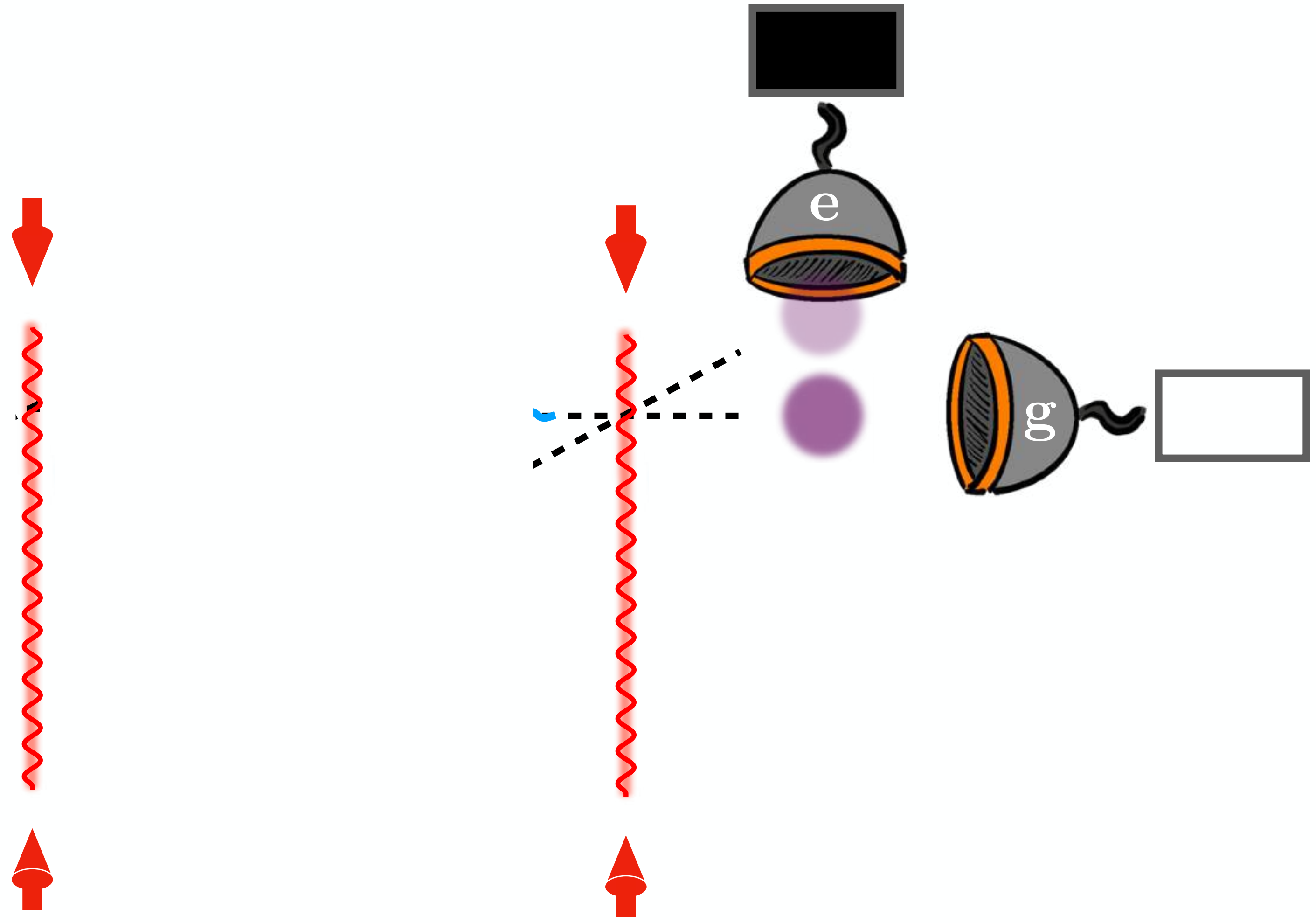
[Riedel, Yavin, 2016]

ATOM INTEROMETERS

Threshold-less detectors!!

AIs: Measurement - Particle scattering?





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

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

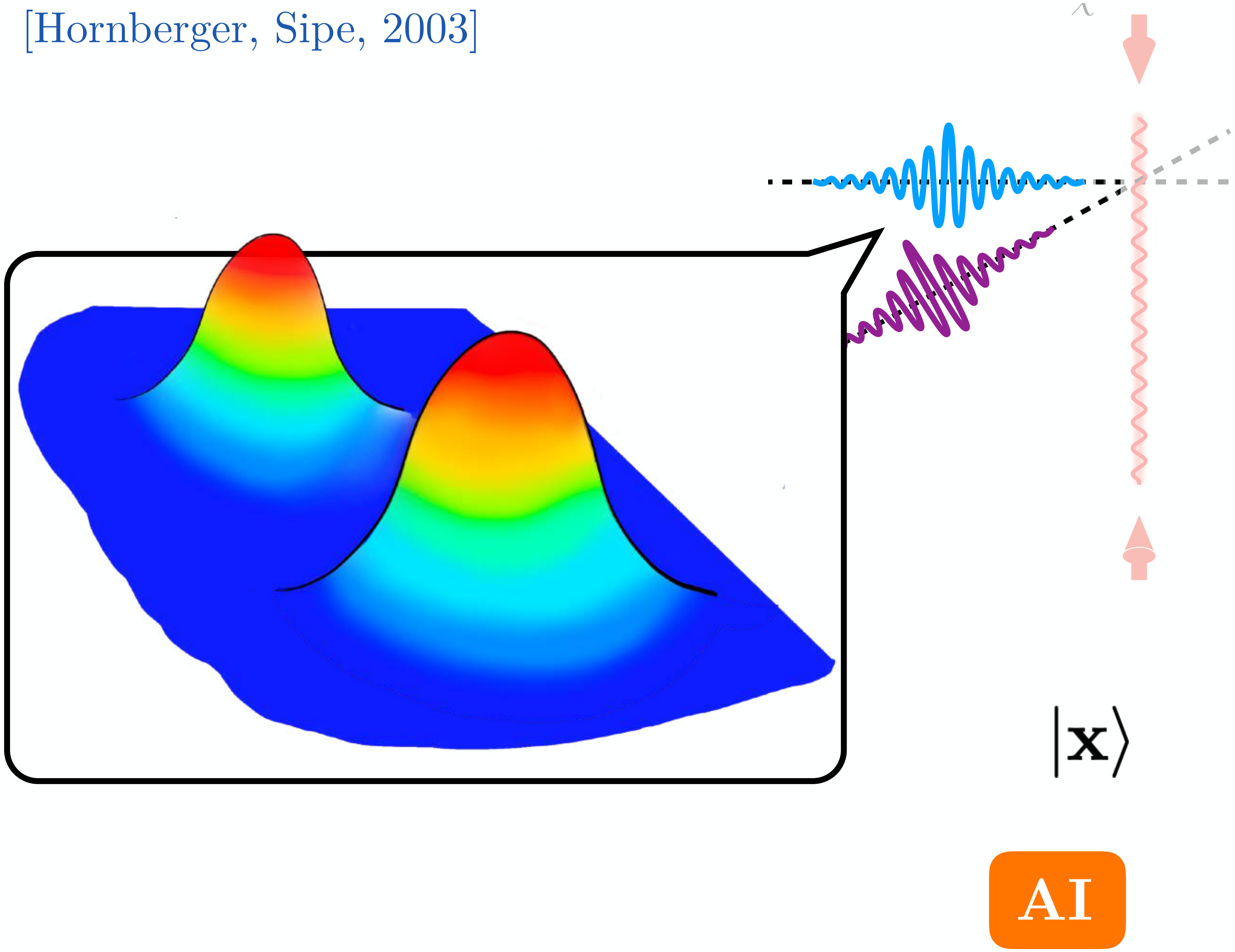
AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]

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



AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

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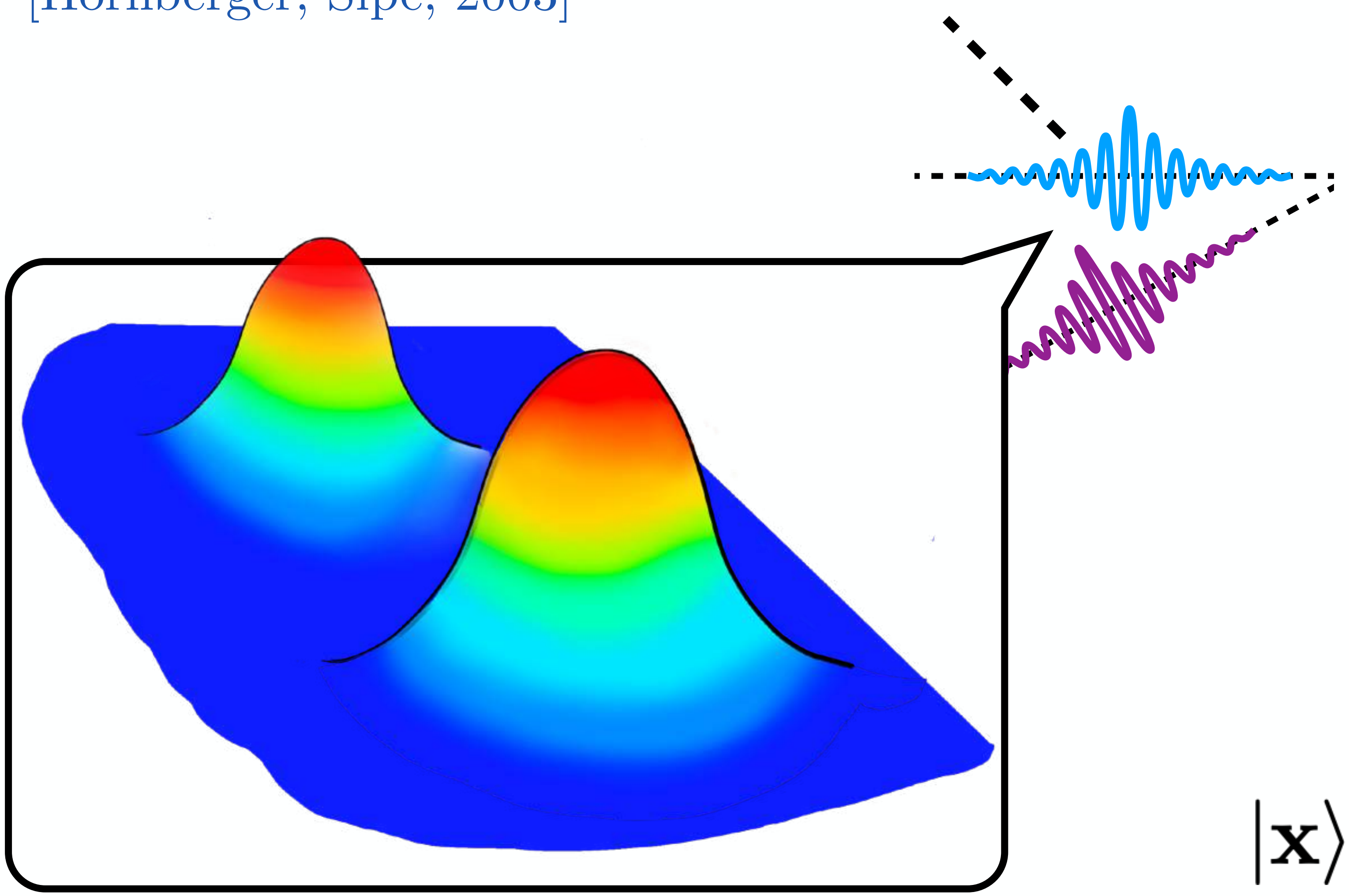
$\chi(\mathbf{k})$

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



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

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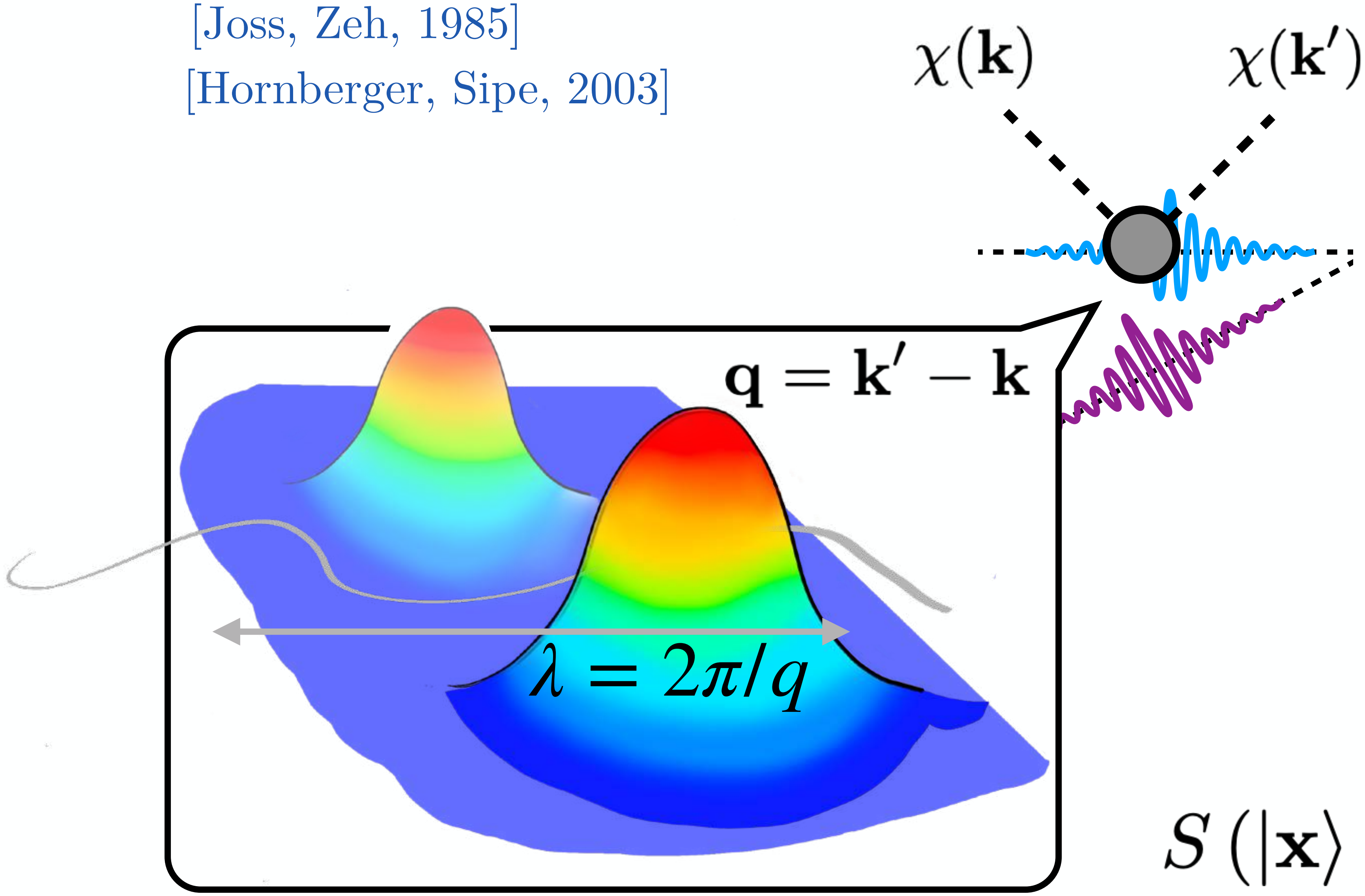

$$S\left(|\mathbf{x}\rangle \otimes |\mathbf{k}\rangle\right)$$

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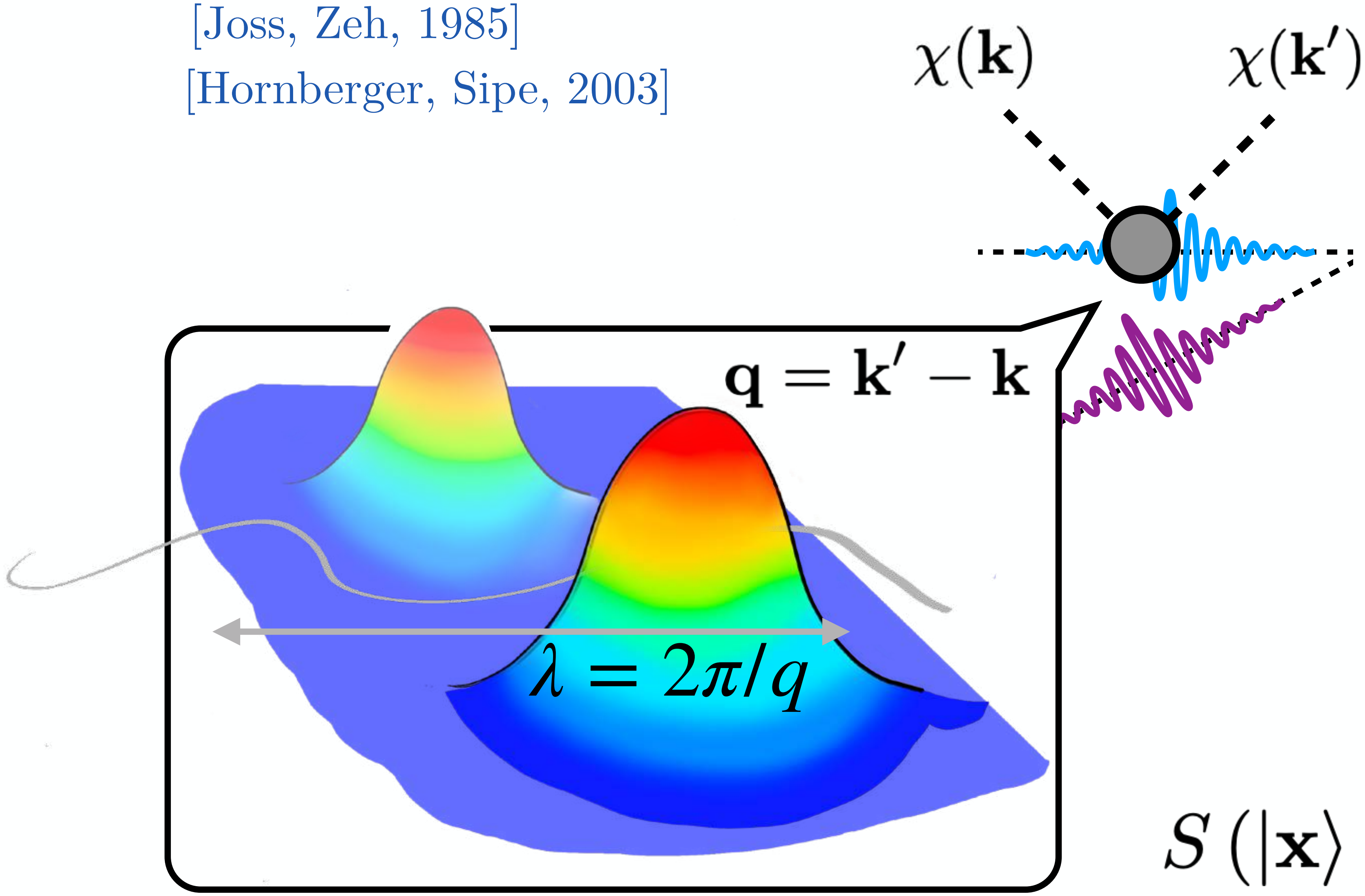

$$S\left(|\mathbf{x}\rangle \otimes |\mathbf{k}\rangle\right) = |\mathbf{x}\rangle \otimes S_{\{\mathbf{x}\}}|\mathbf{k}\rangle$$

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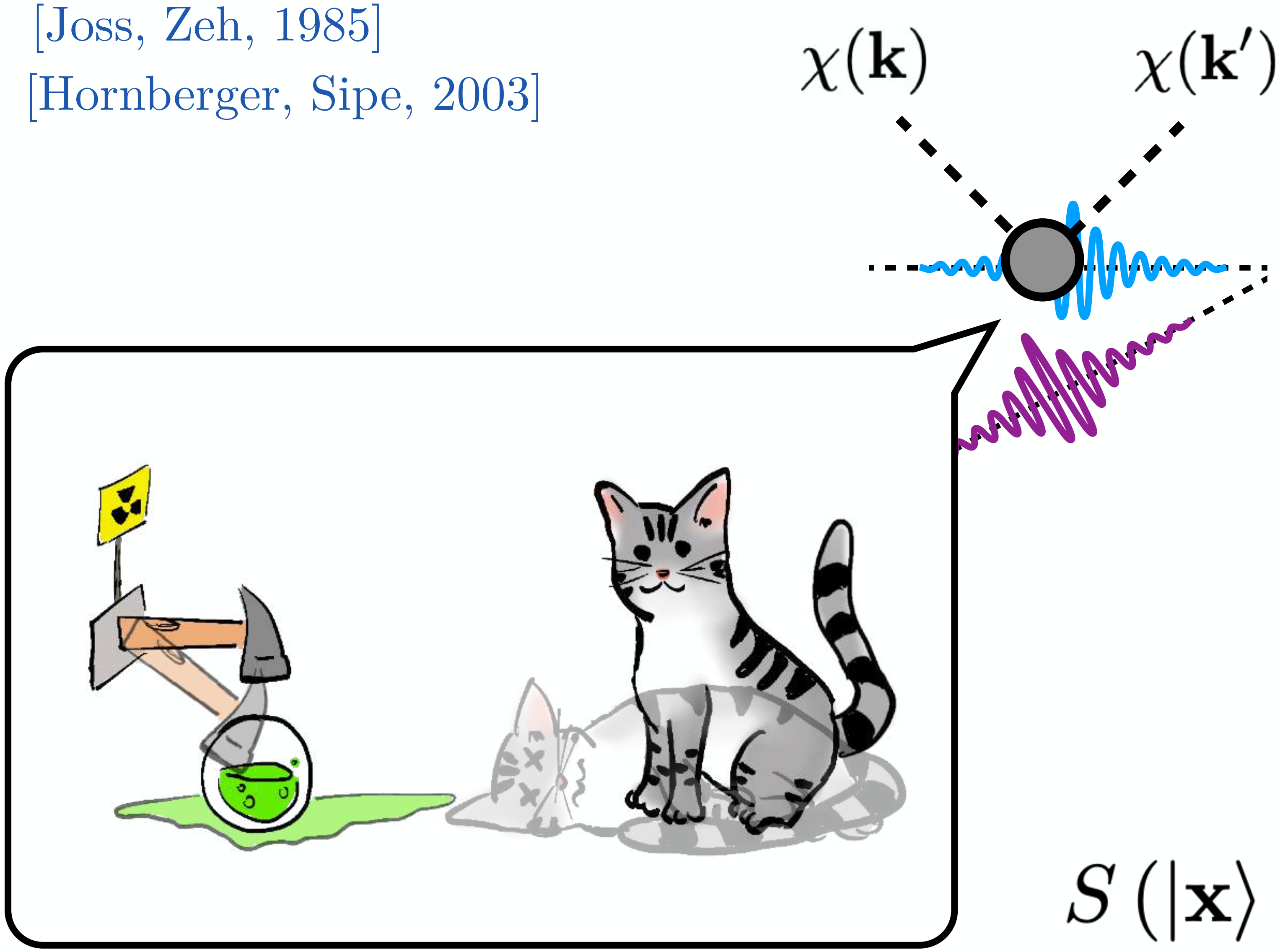

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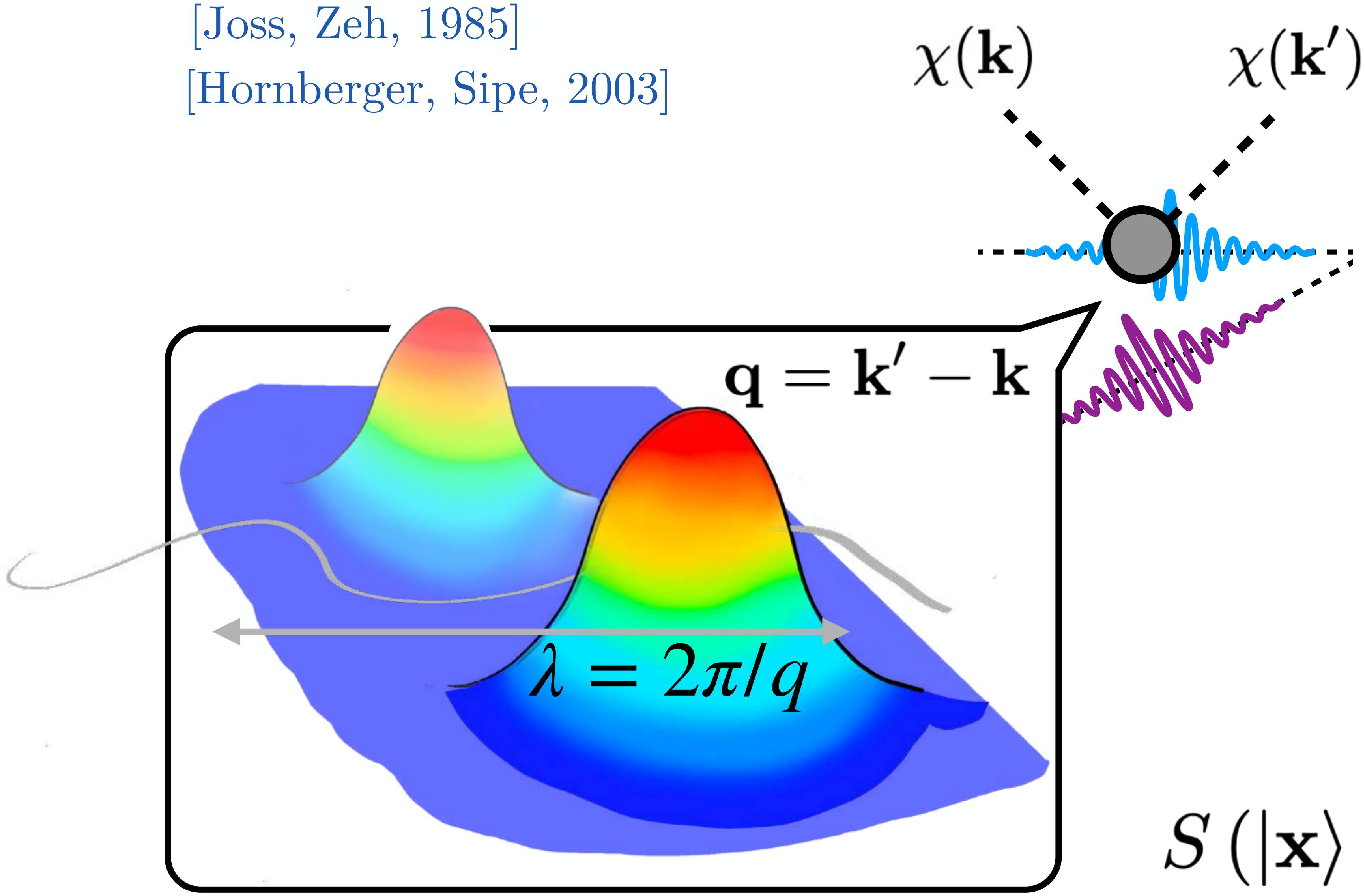

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$$\rho'_A = \mathrm{Tr}_{\mathbf{k}}\rho'$$

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A **single** atom

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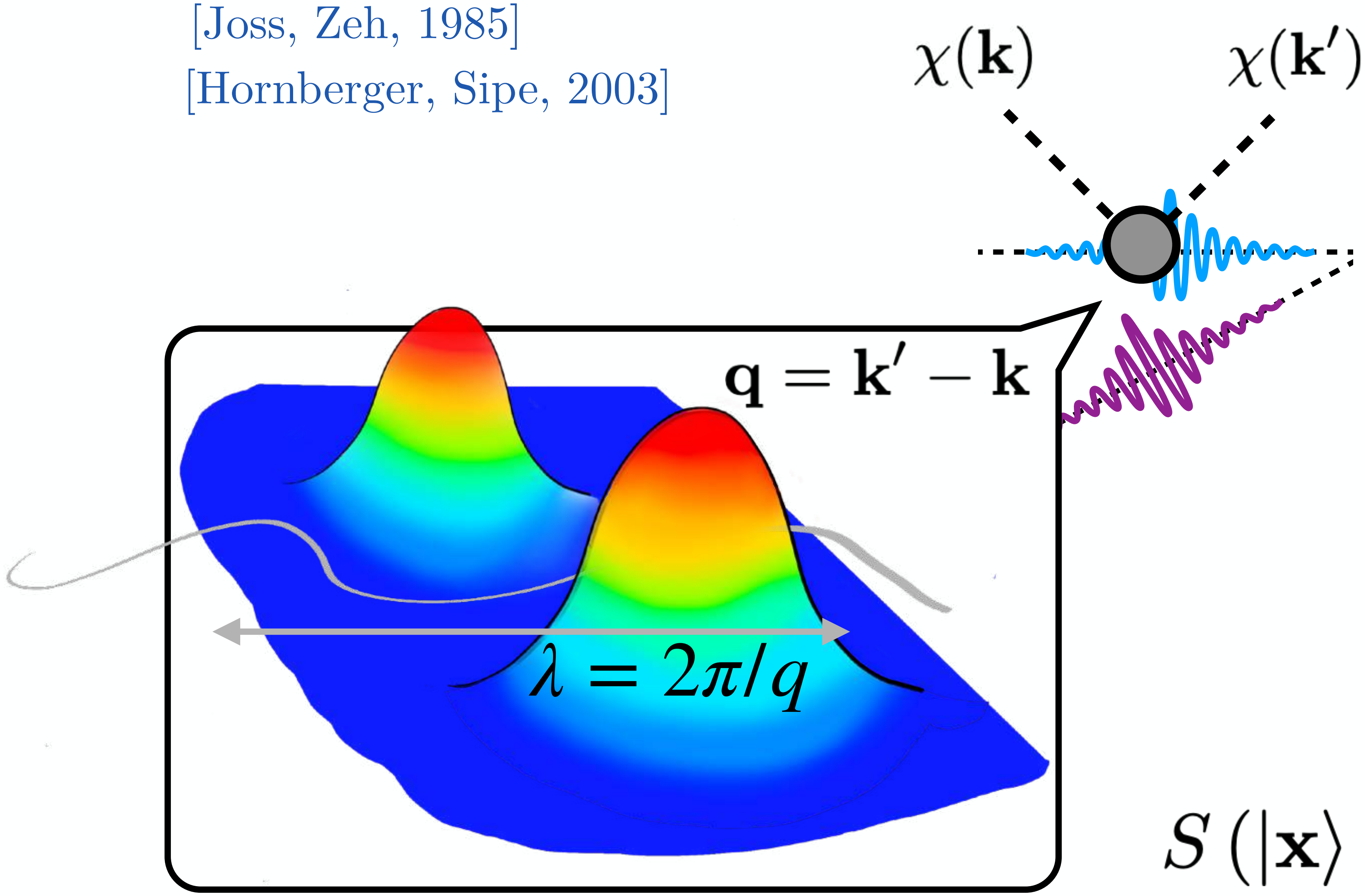

$$S\left(|\mathbf{x}\rangle \otimes |\mathbf{k}\rangle\right) = |\mathbf{x}\rangle \otimes S_{\{\mathbf{x}\}}|\mathbf{k}\rangle$$

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

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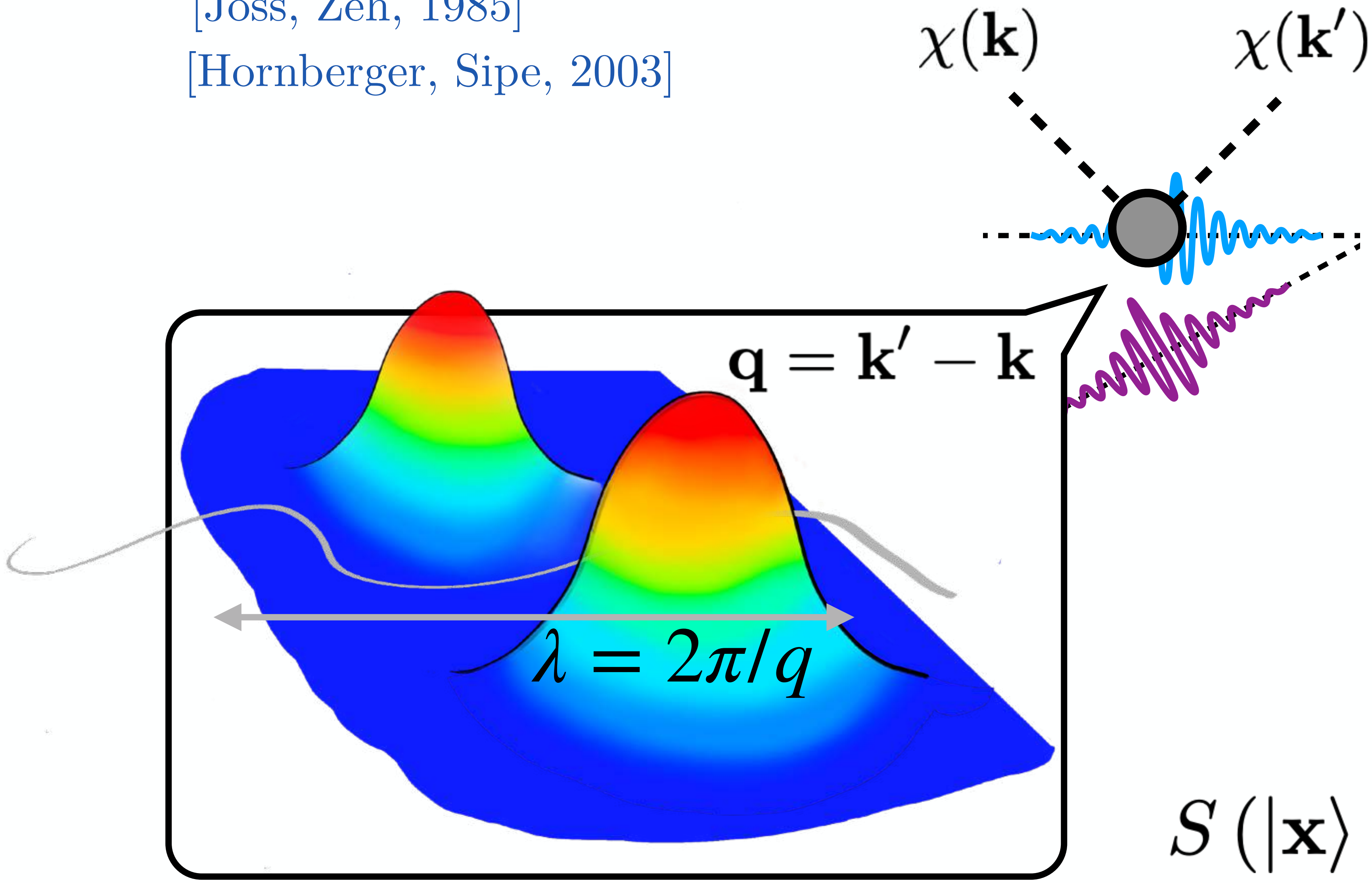

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$$\Rightarrow \Delta\rho = \frac{i}{2}[T + T^\dagger, \rho] - \frac{1}{2}\{T^\dagger T, \rho\} + T\rho T^\dagger$$

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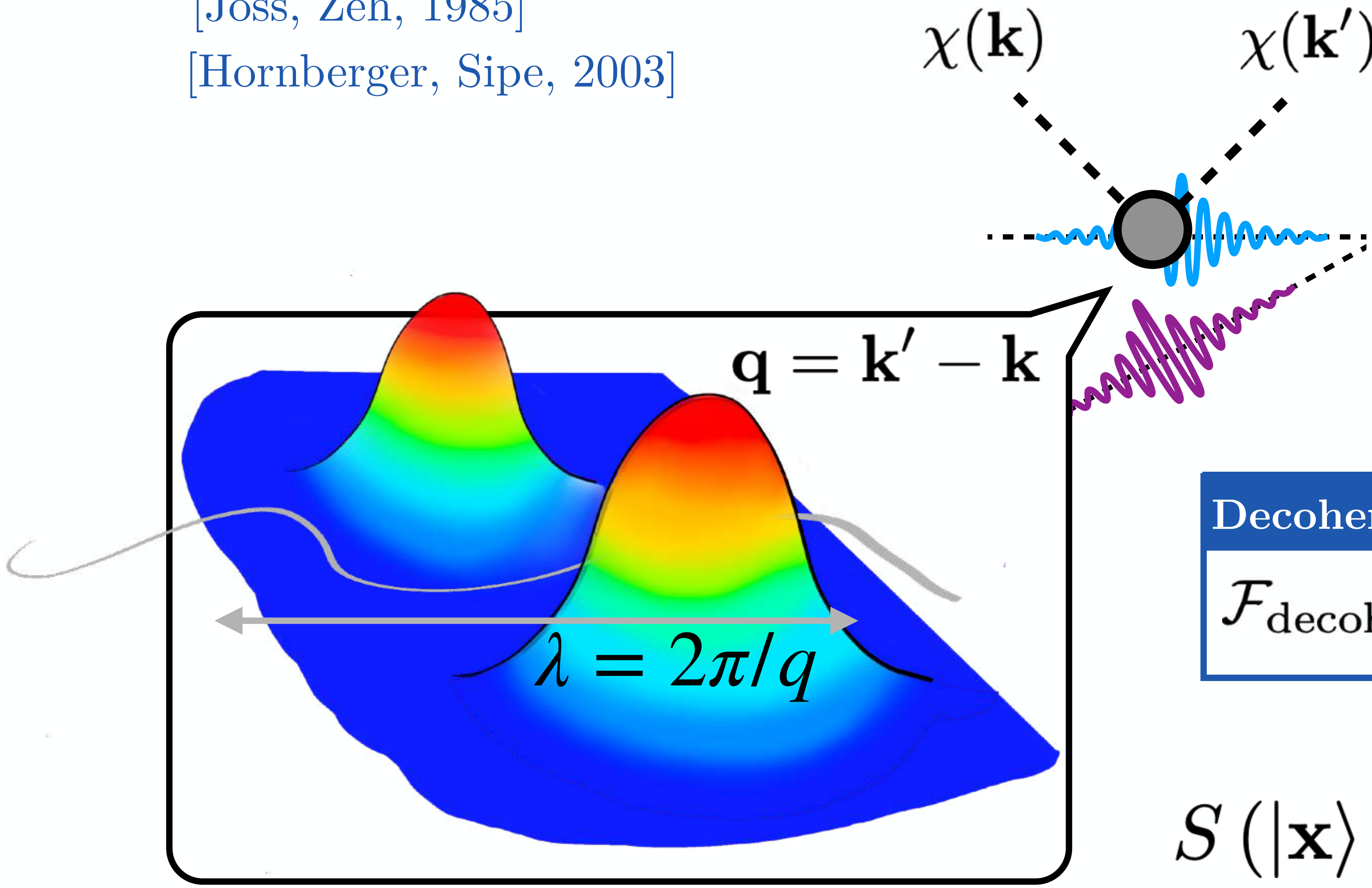

$$\rho = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

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

Decoherence Kernel

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

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

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

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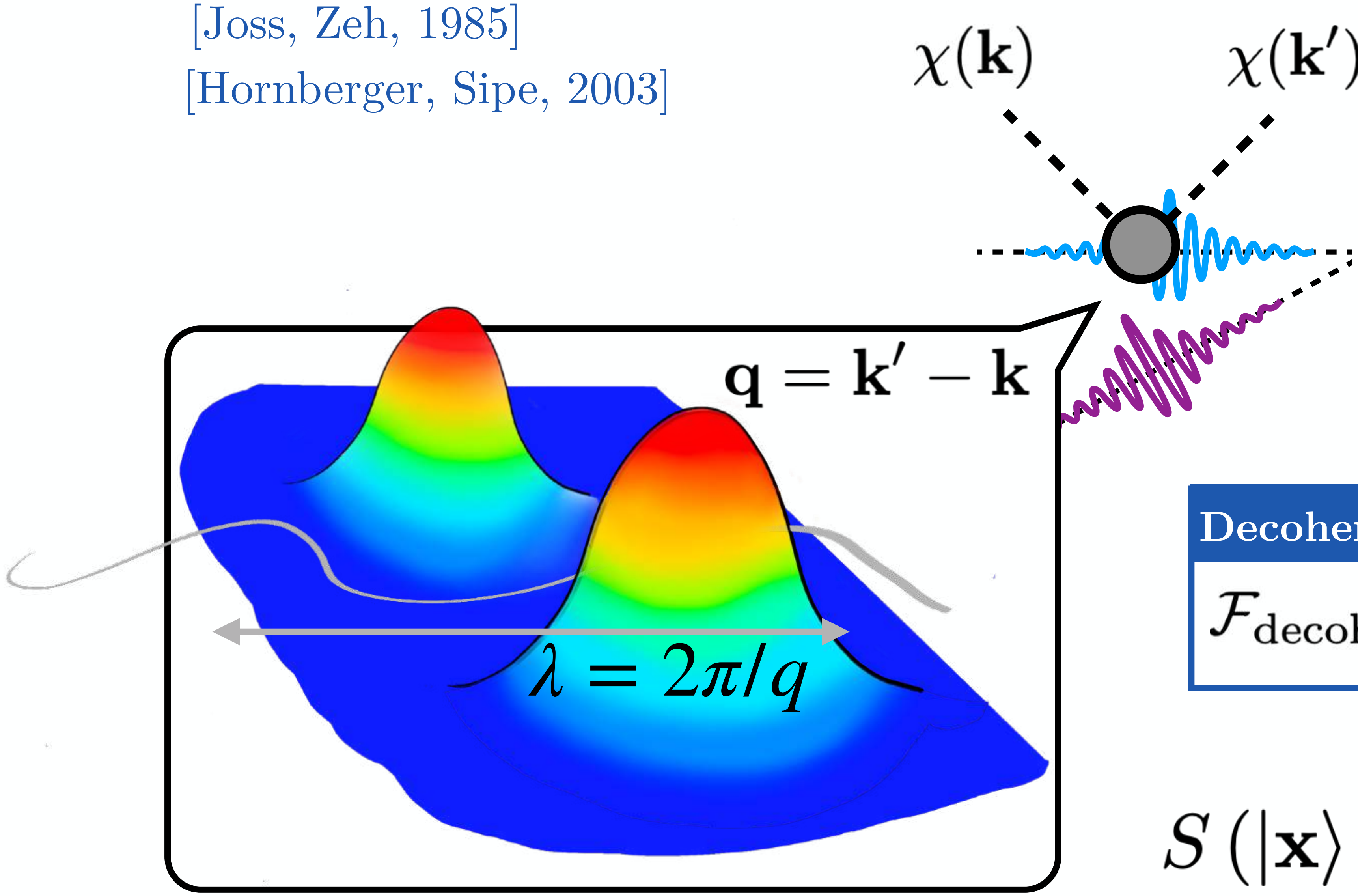
AIs: Collisional Decoherence

A **single** atom

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]



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

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

Decoherence Kernel

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

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

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

DECOHERENCE

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

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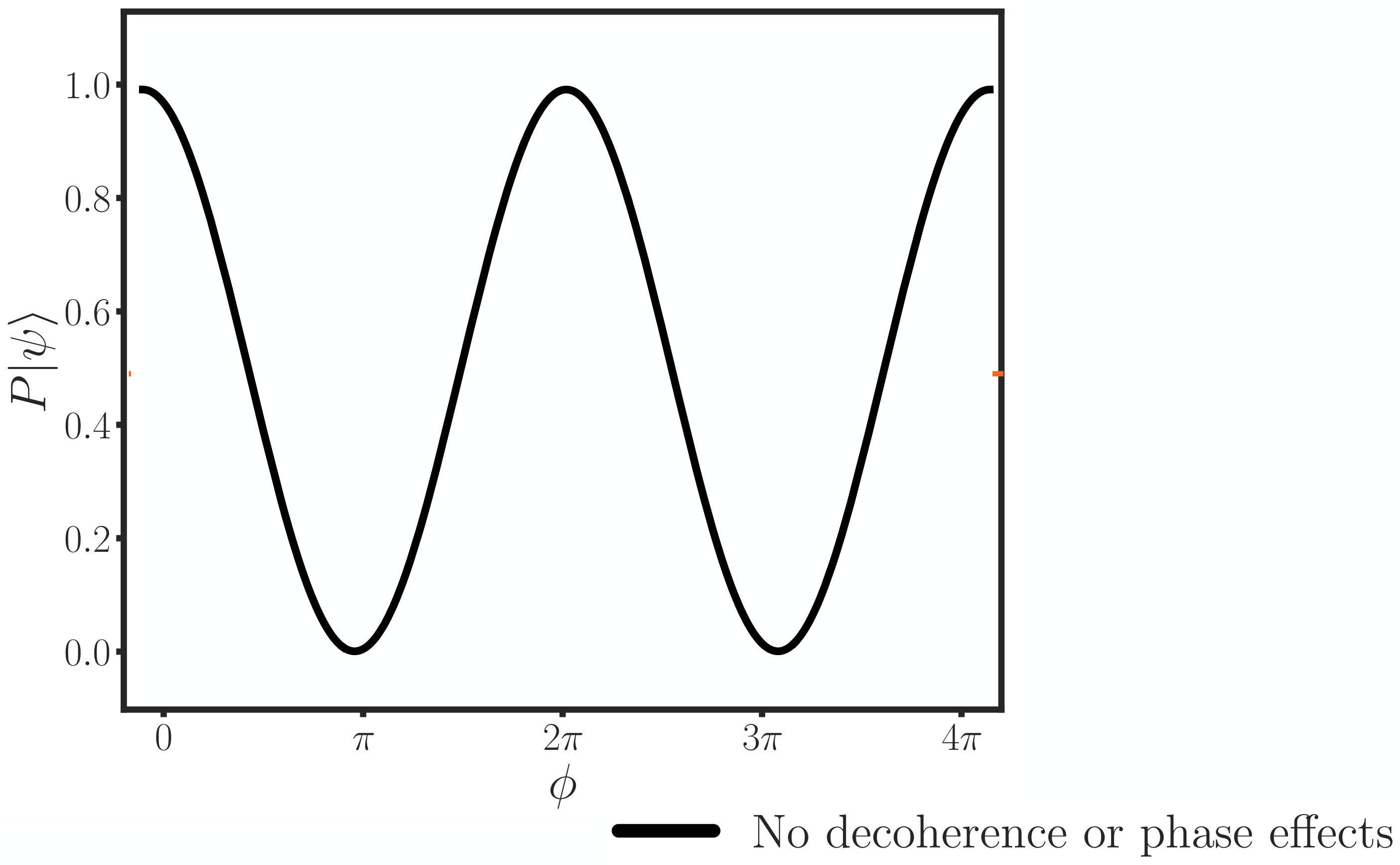

$$\left.\frac{N_I}{N_I + N_{II}}\right|_{\mathrm{exp}} = \frac{1}{2}\left(1 + V \cos\left(\phi + \Delta\phi\right)\right)$$

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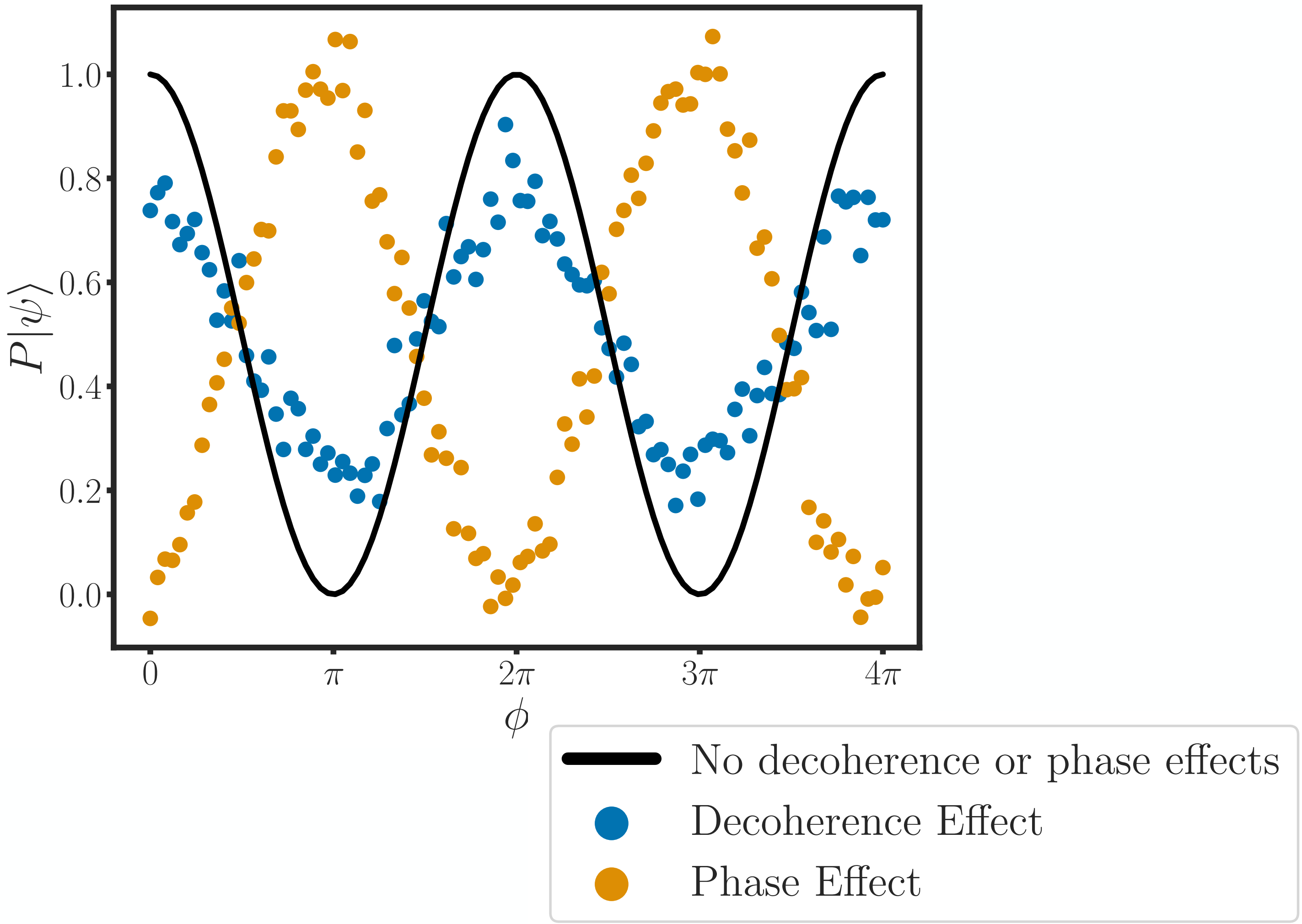

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$^*|+\rangle\langle+|$

$|g\rangle\langle g|$

$\parallel$

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

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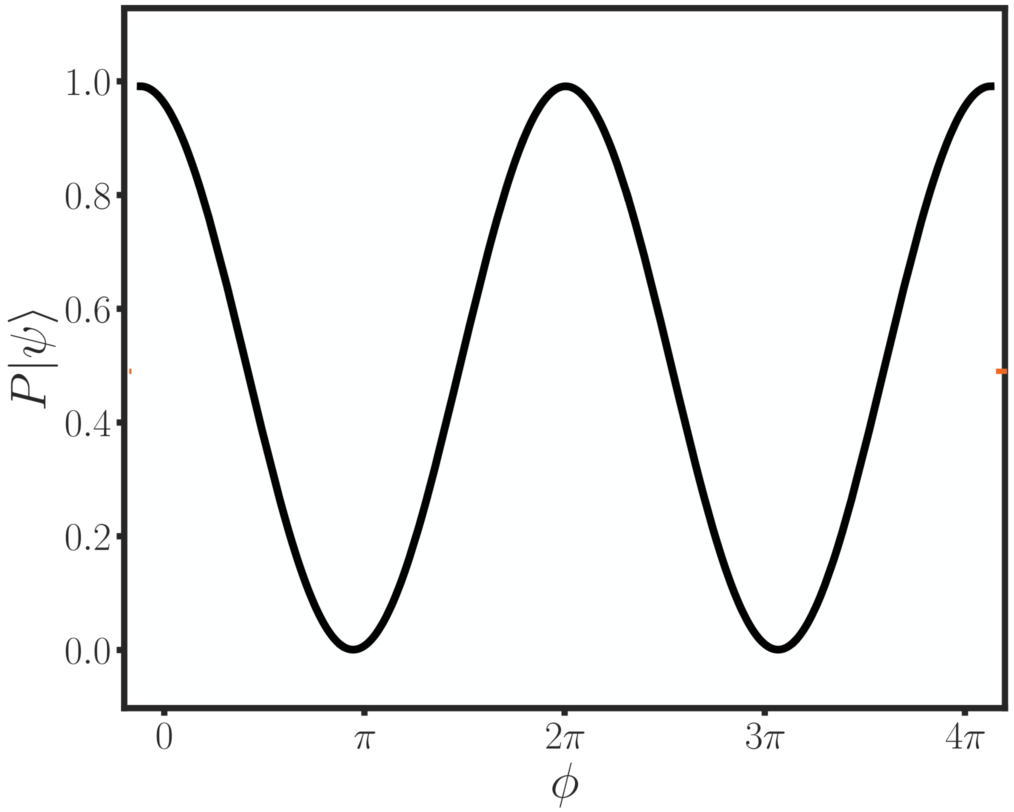
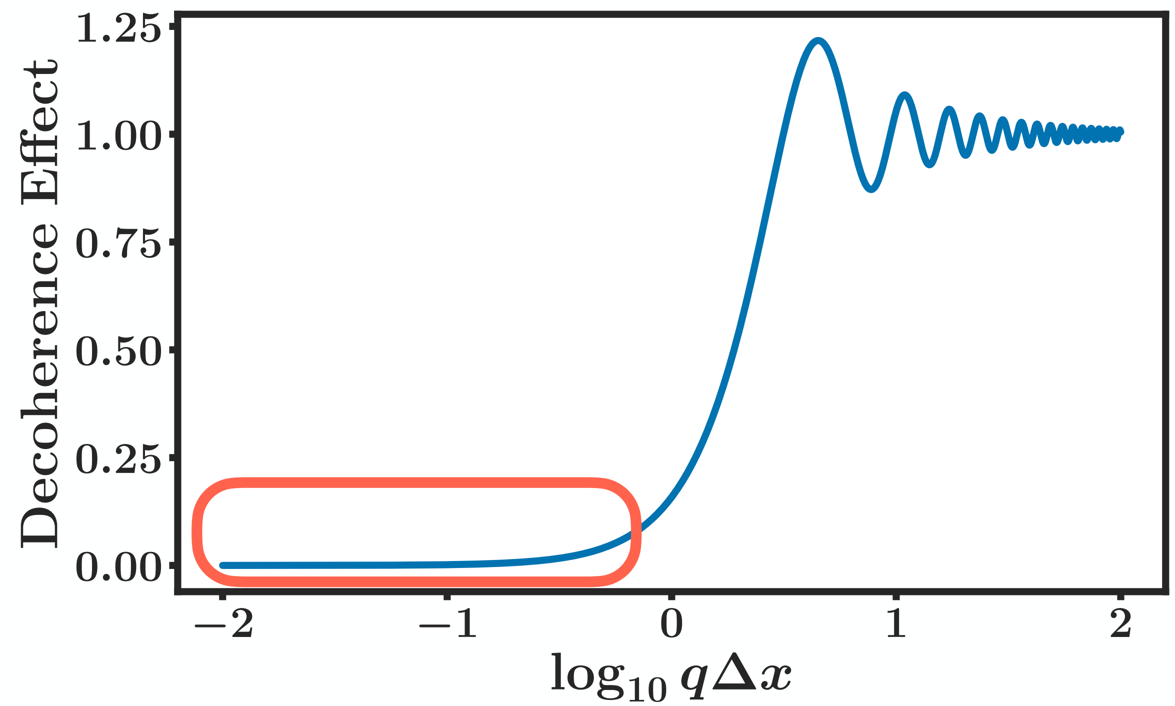
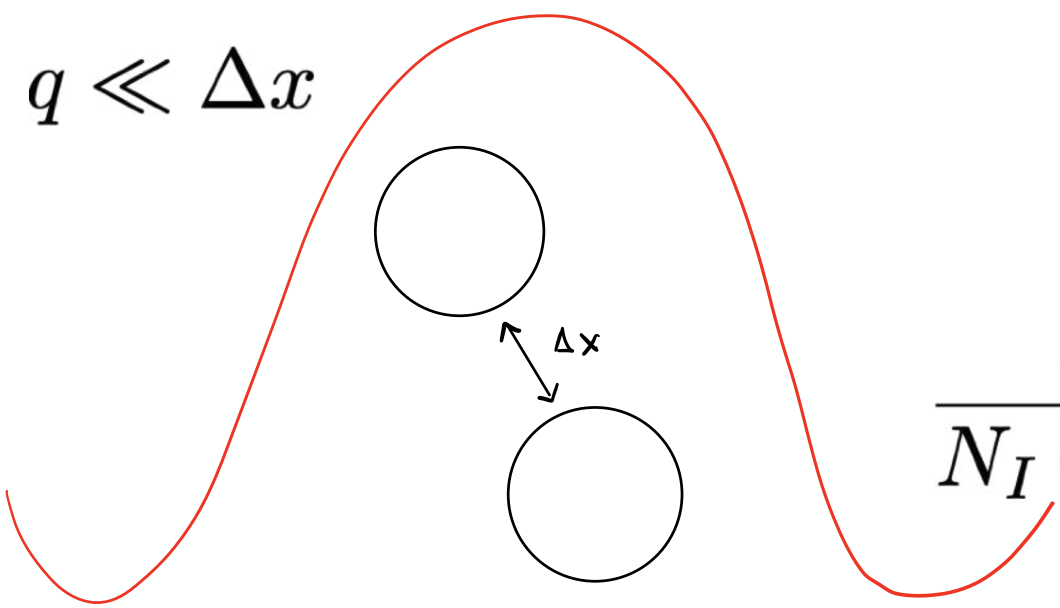




Decoherence Kernel

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

$q \ll \Delta x$



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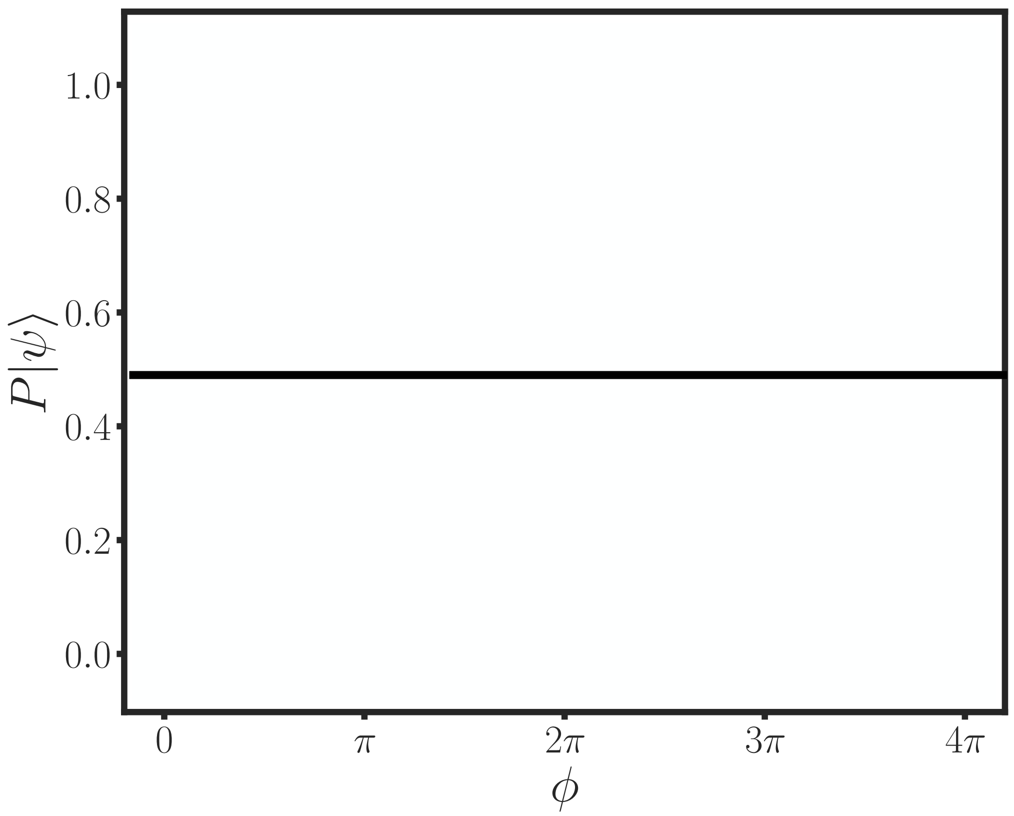
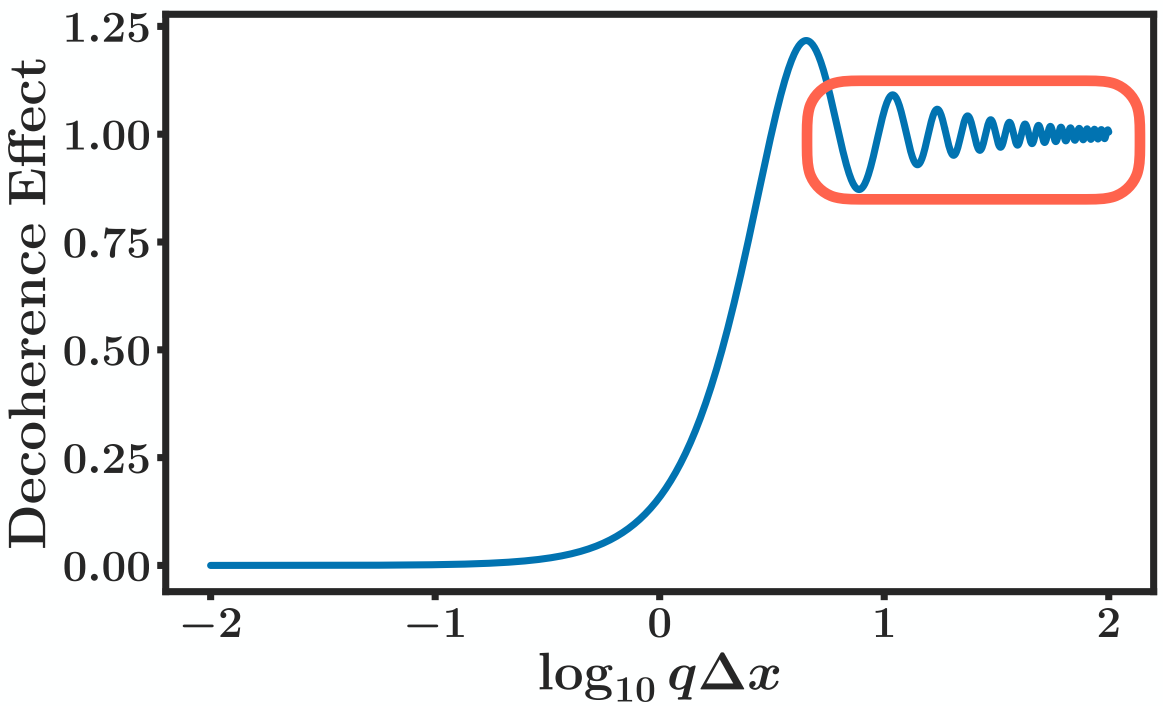
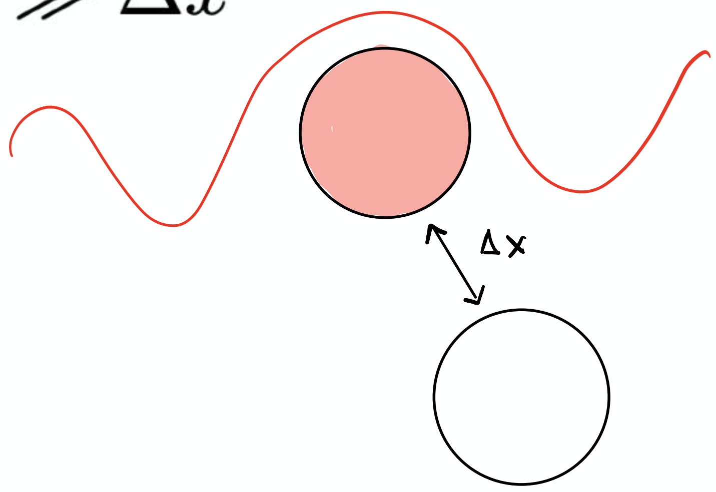




Decoherence Kernel

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

$q \gg \Delta x$



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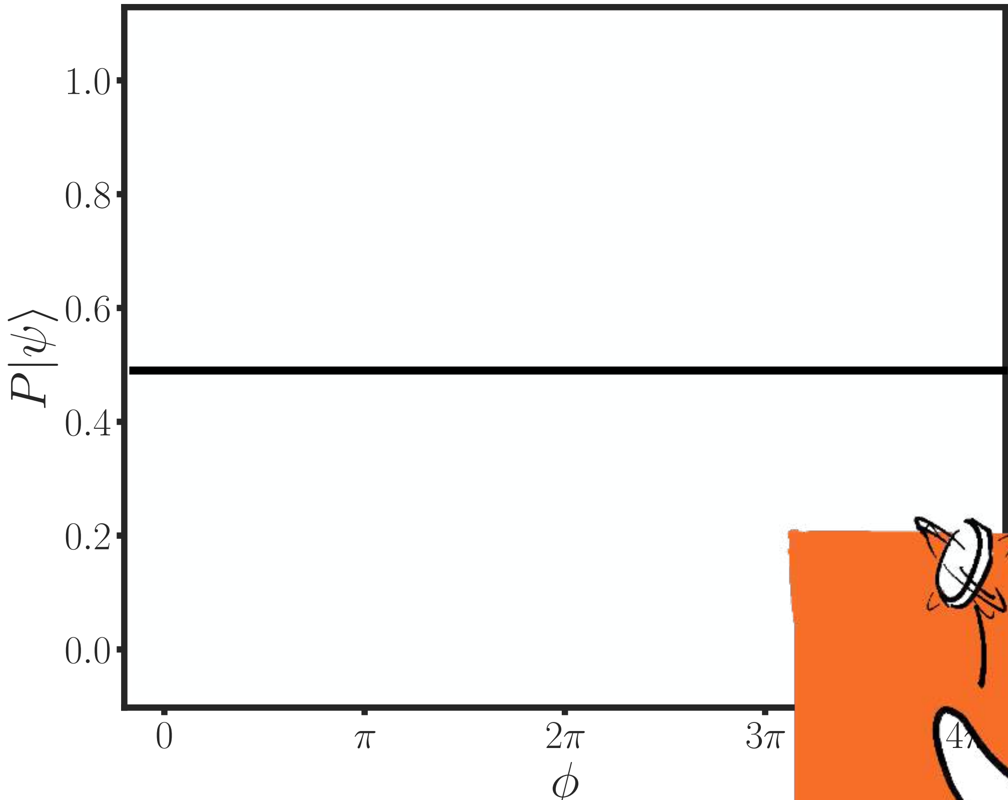

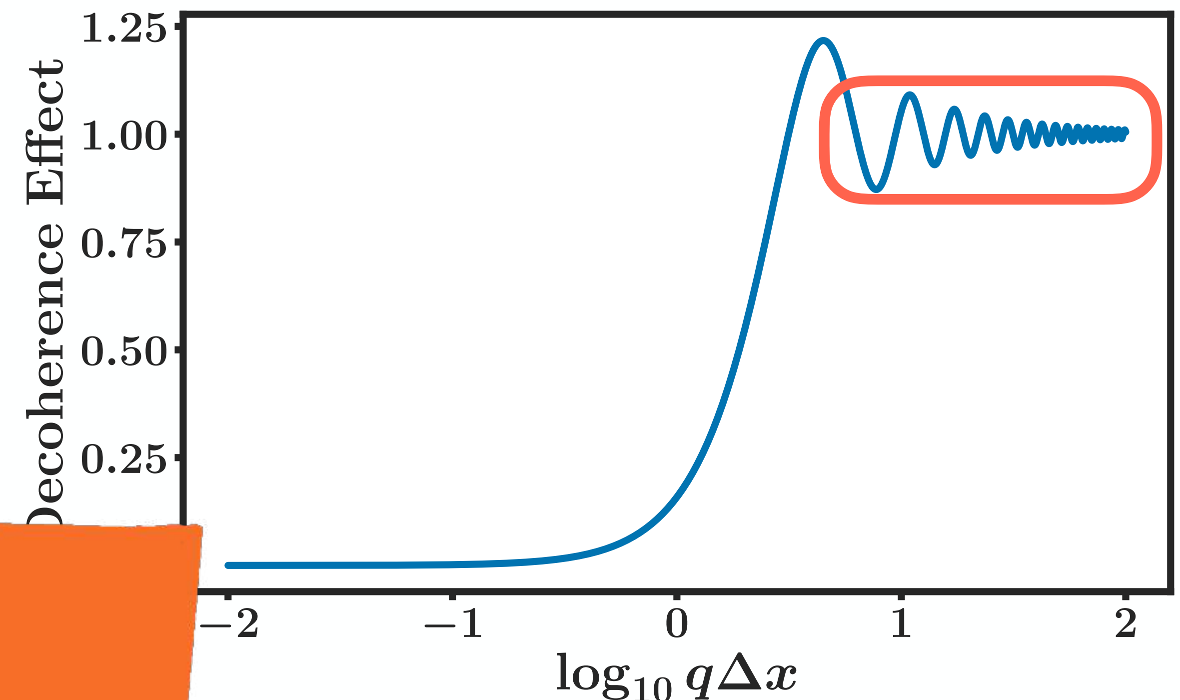

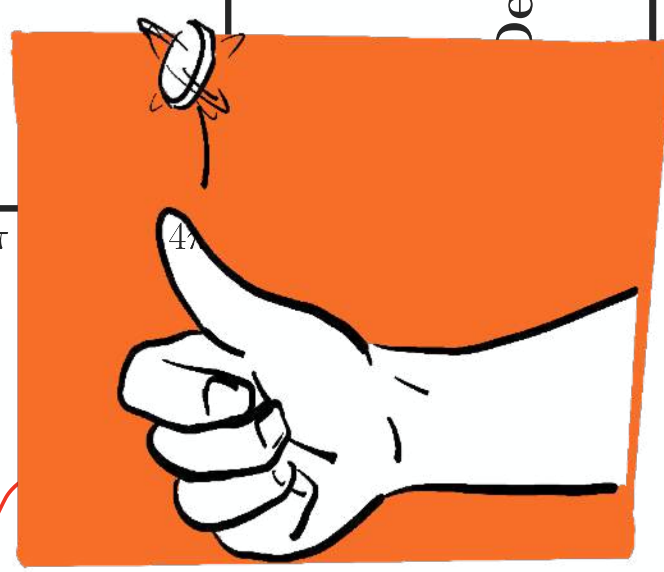

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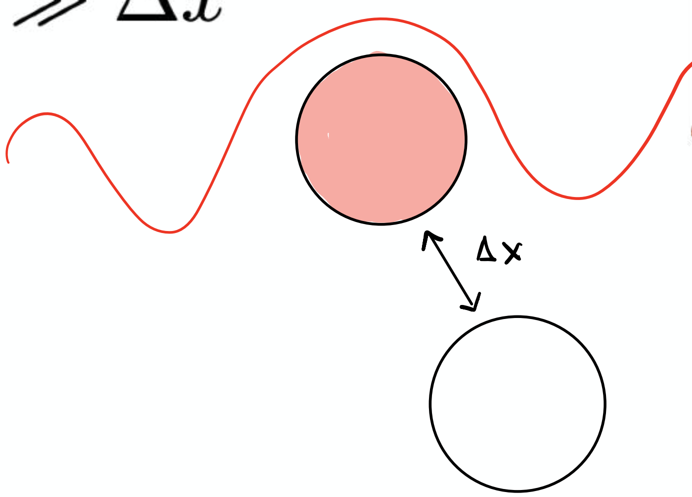

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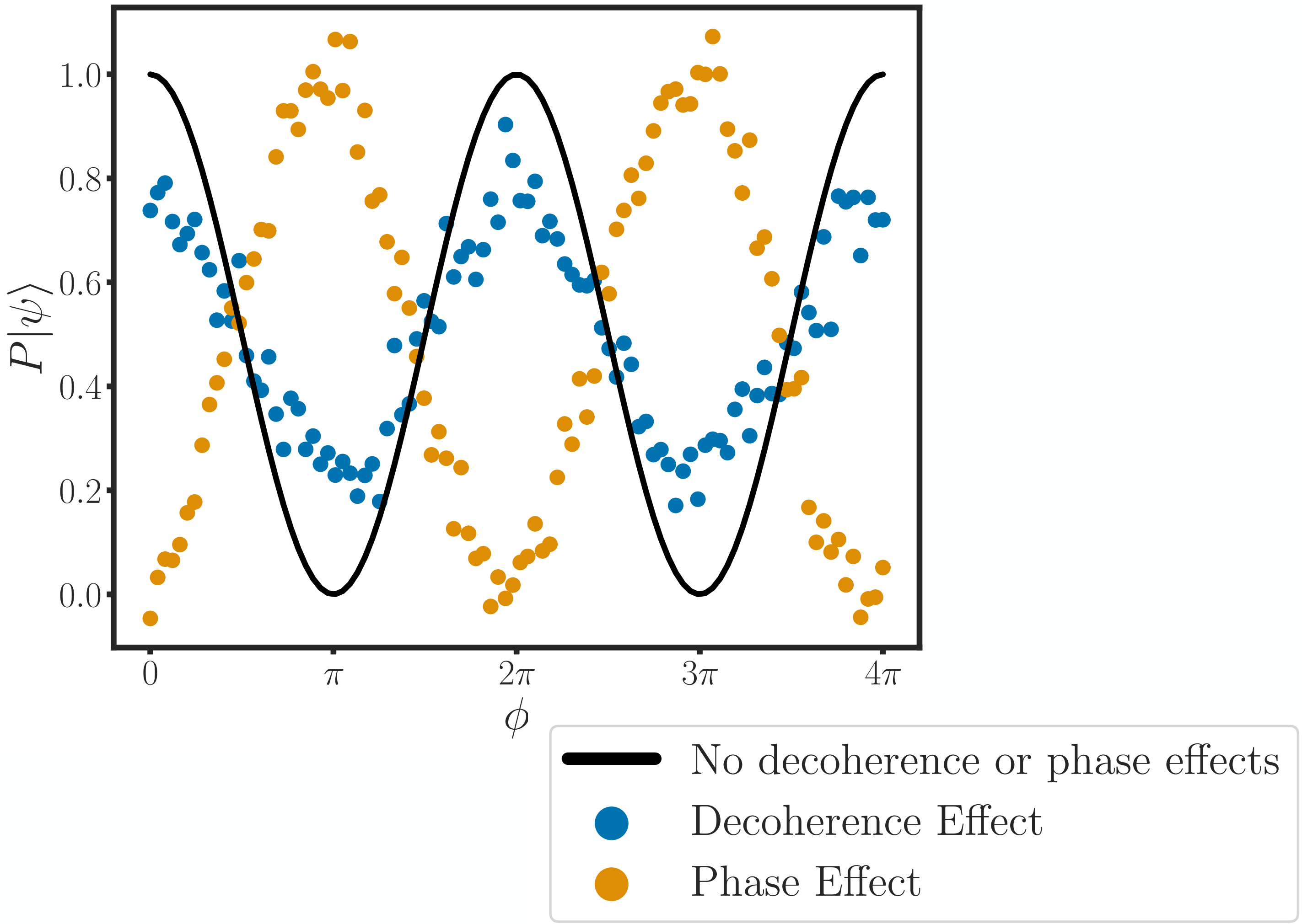

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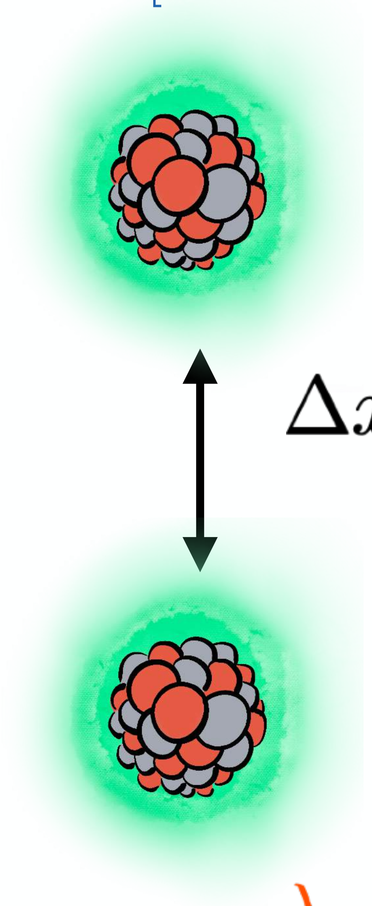
AIs: Collisional Decoherence

Single-atom system

[Joss, Zeh, 1985]

[Hornberger, Sipe, 2003]



Δx

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

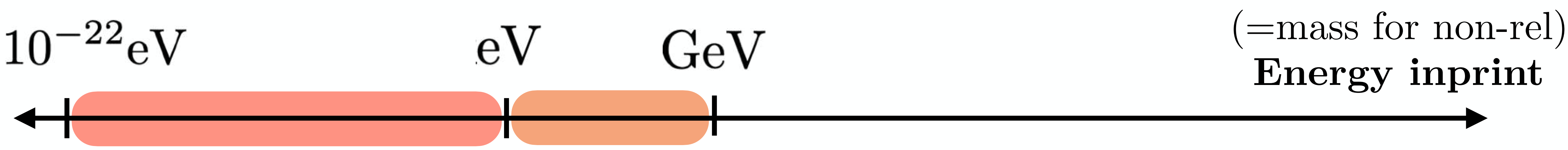
Decoherence Kernel

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

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

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

Low Energy Precision: N^2

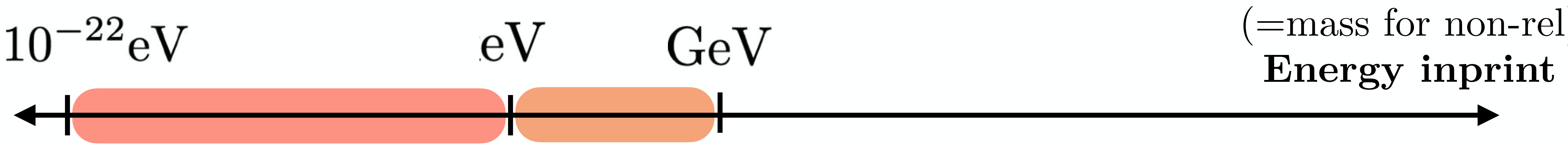


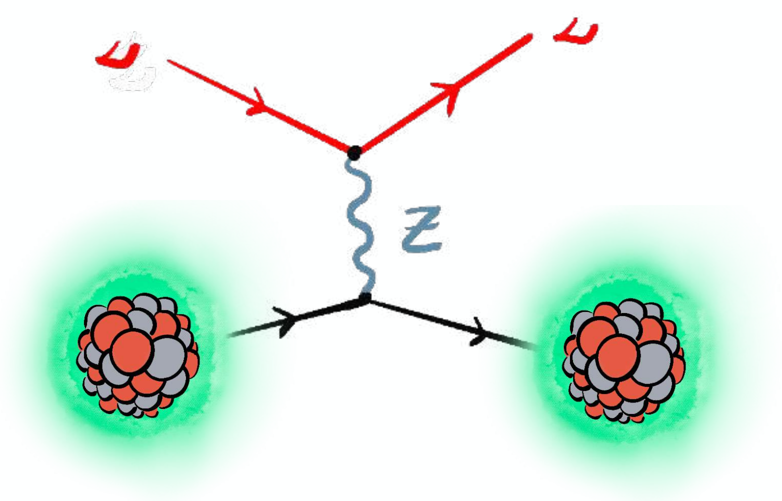
COHERENT EFFECTS

ATOM INTEROMETERS

Threshold-less detectors!!

Low Energy Precision: N^2





e.g. coherent neutrino scattering

[Freedman, 1973]

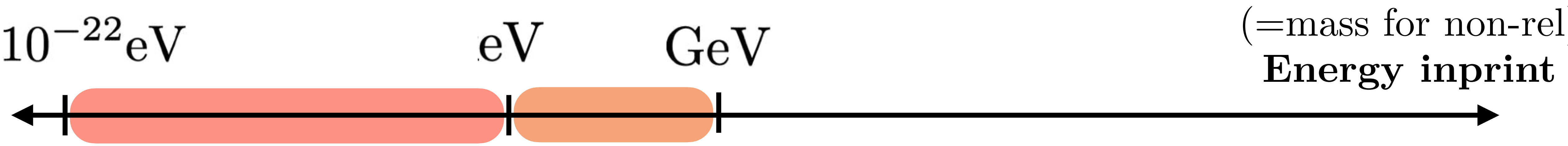
$$\sigma_{NA}^{\text{coh}} \propto (A-Z)^2 |F_N(q r_N)|^2$$

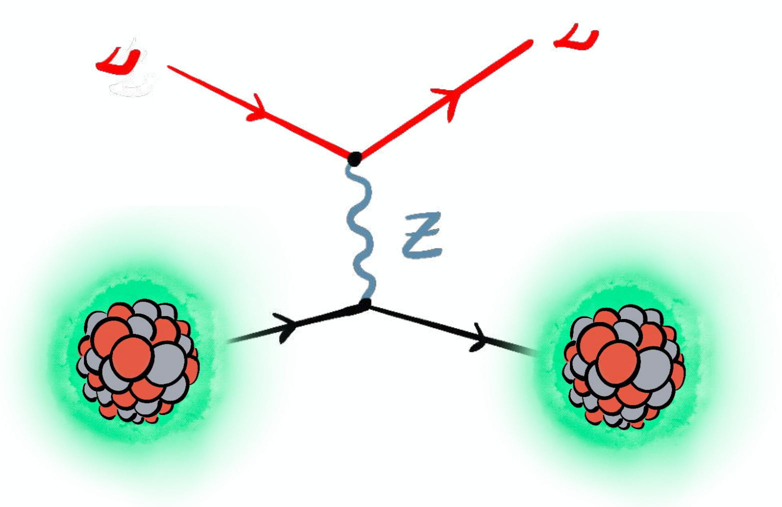
COHERENT EFFECTS

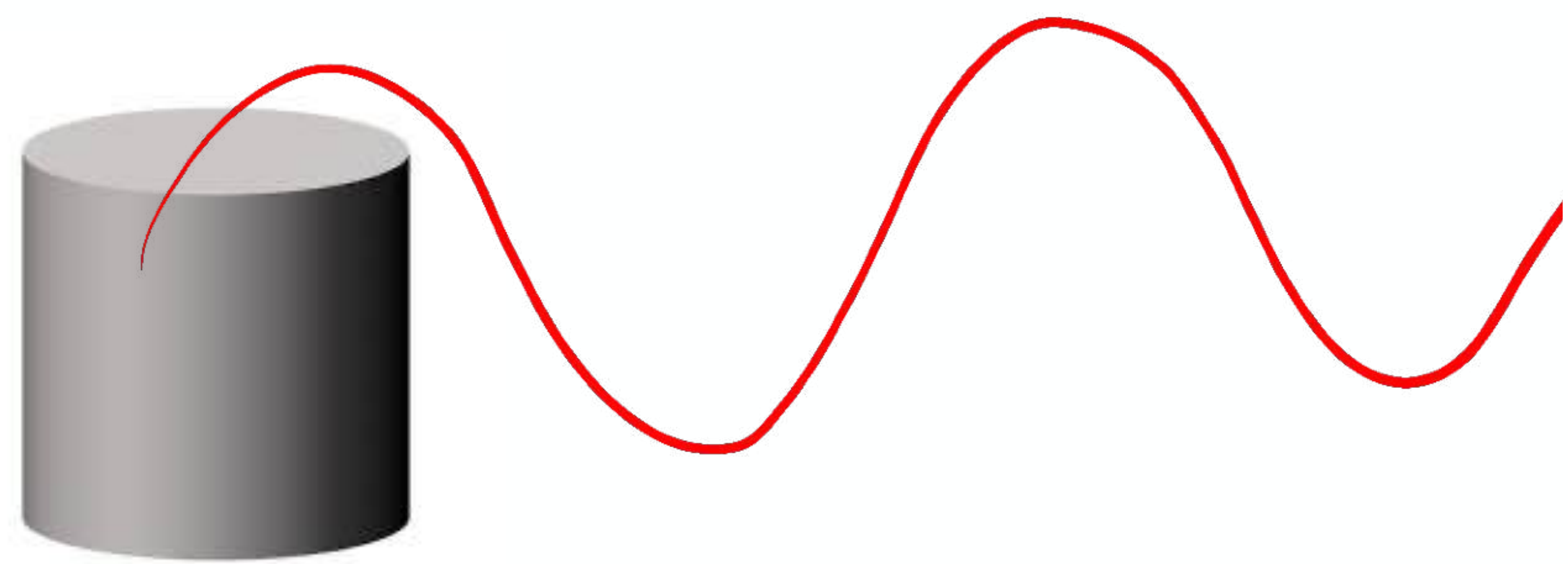
ATOM INTEROMETERS

Threshold-less detectors!!

Low Energy Precision: $\mathbf{N^2}$







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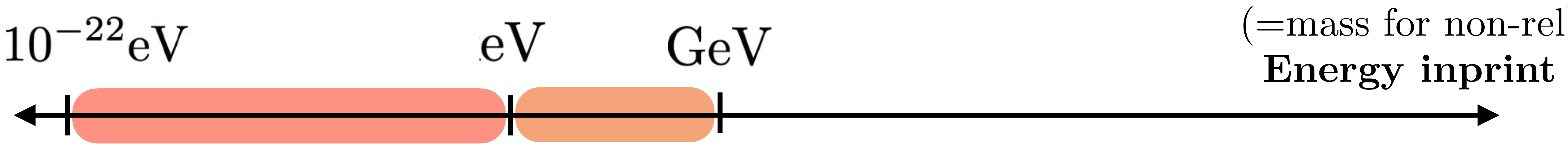

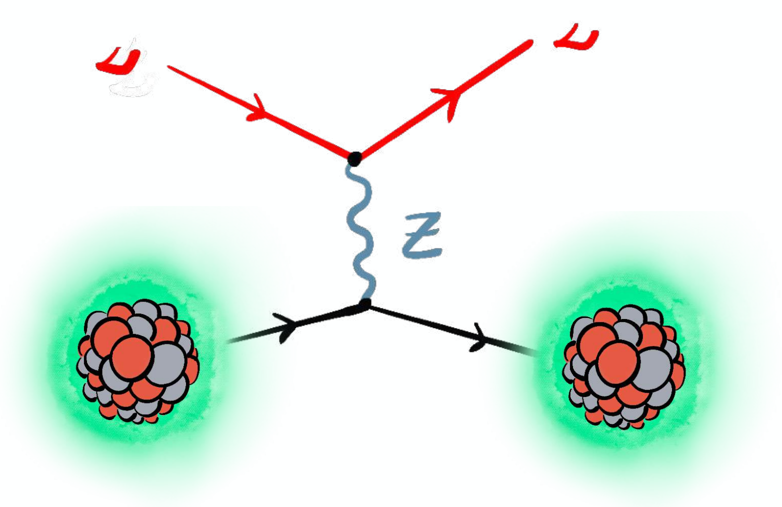

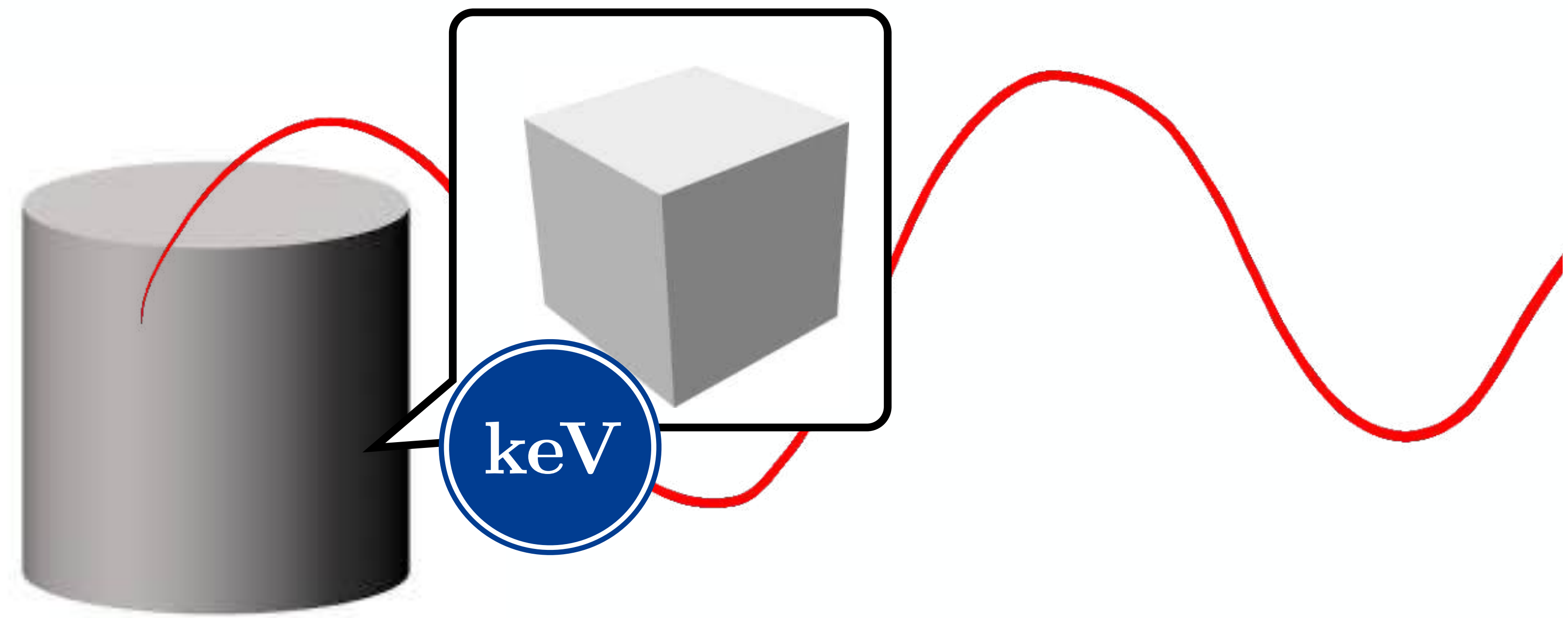

$$\Gamma \propto \int_{\mathrm{keV}}^{q_{\mathrm{max}}} dq\,(\cdots)$$

ATOM INTEROMETERS

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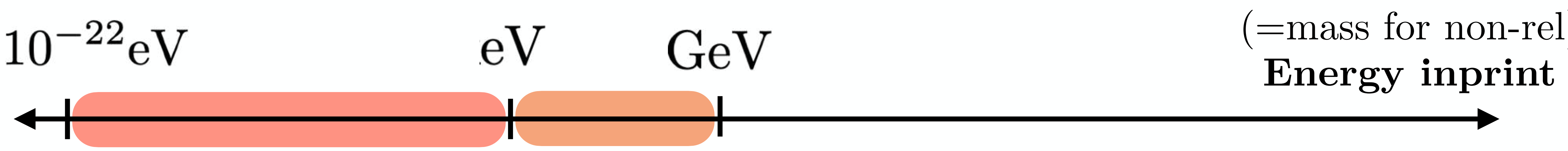
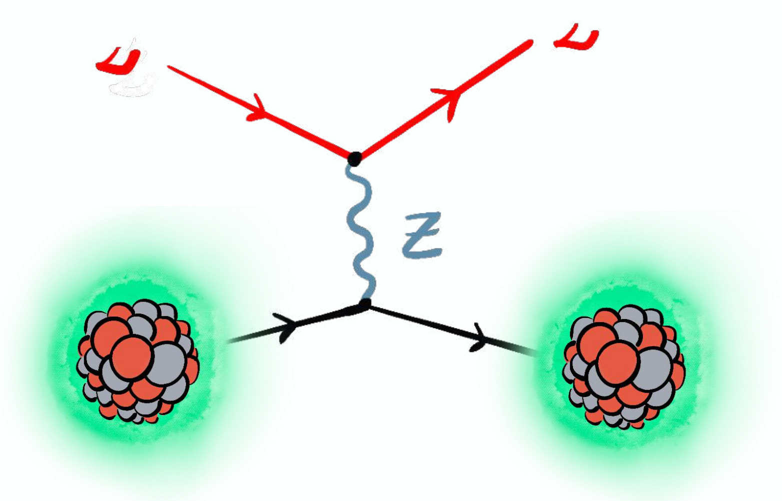
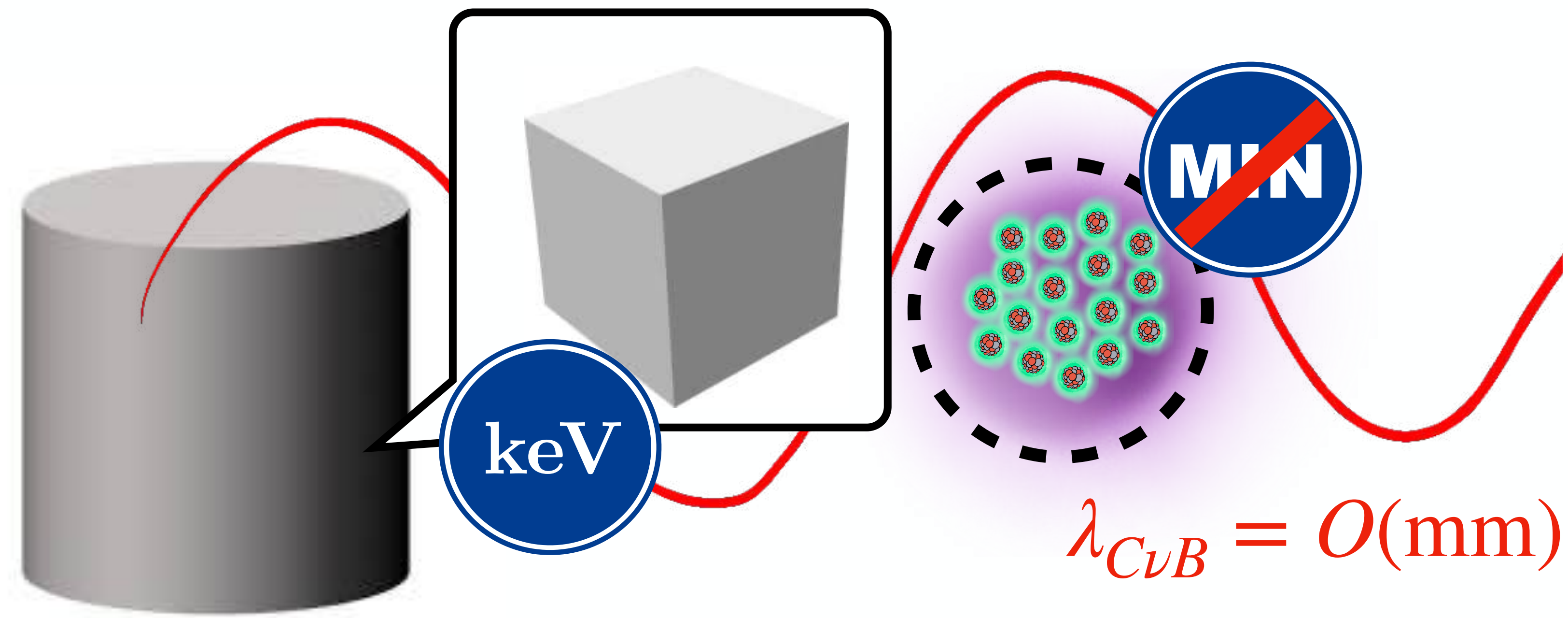






$$\Gamma \propto \int_0^{q_{\max}} dq\,(\cdots)$$

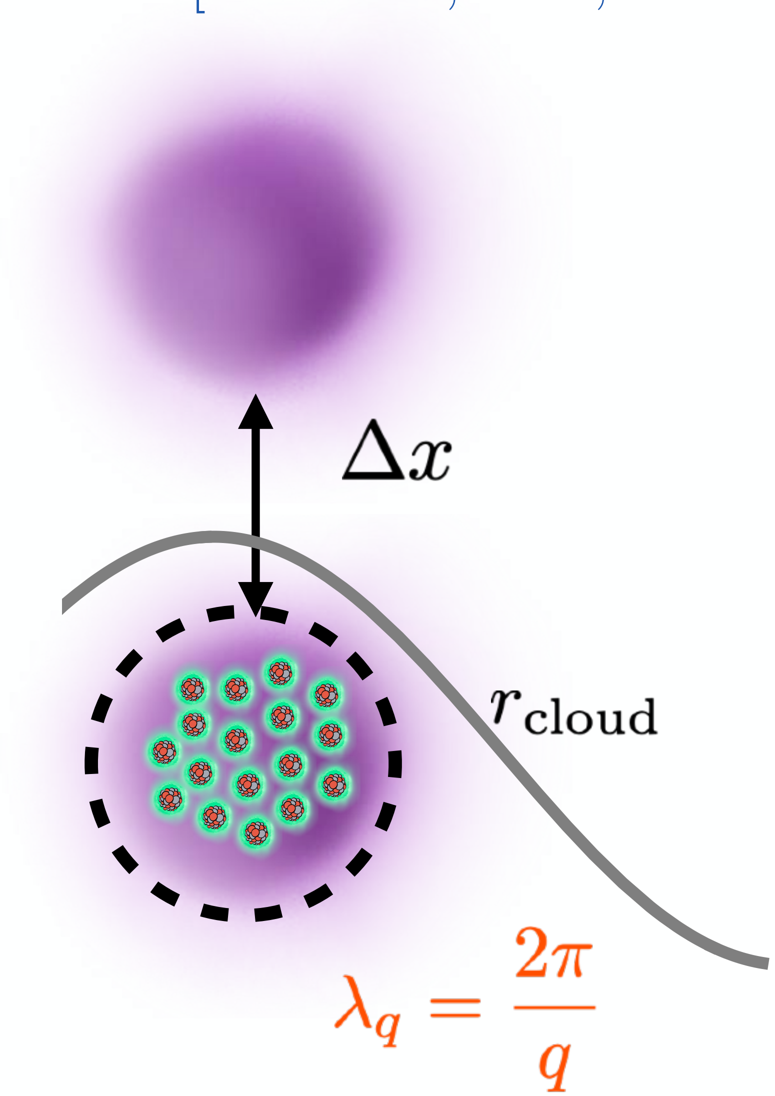
ATOM INTEROMETERS

Threshold-less detectors!!

AIs: Collisional Decoherence

Multi-atom system (distinguishable)

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



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

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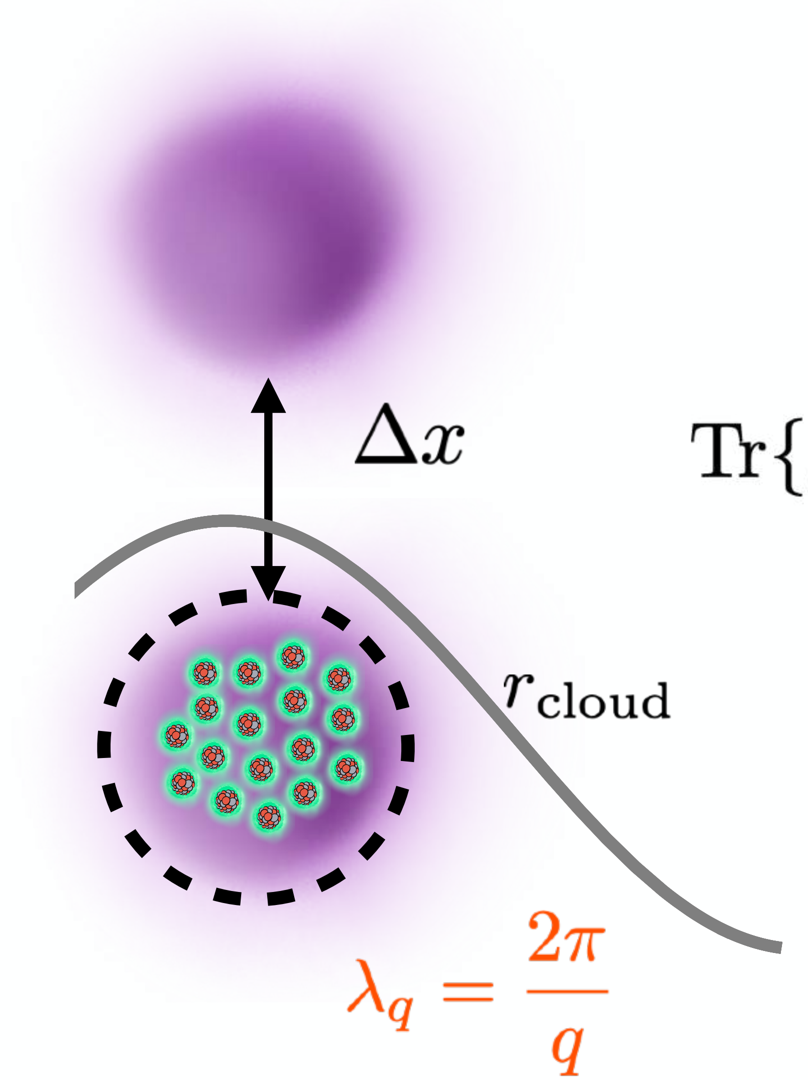

$$\rho_{(N=2)} = \begin{pmatrix} \circ & \blacksquare & \blacksquare & \bigstar \\ \blacksquare & \circ & \circ & \blacksquare \\ \blacksquare & \circ & \circ & \blacksquare \\ \bigstar & \blacksquare & \blacksquare & \circ \end{pmatrix}$$

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

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

$\star\ |+_i\rangle\langle +_i|$

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

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Multi-atom system (distinguishable)

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

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

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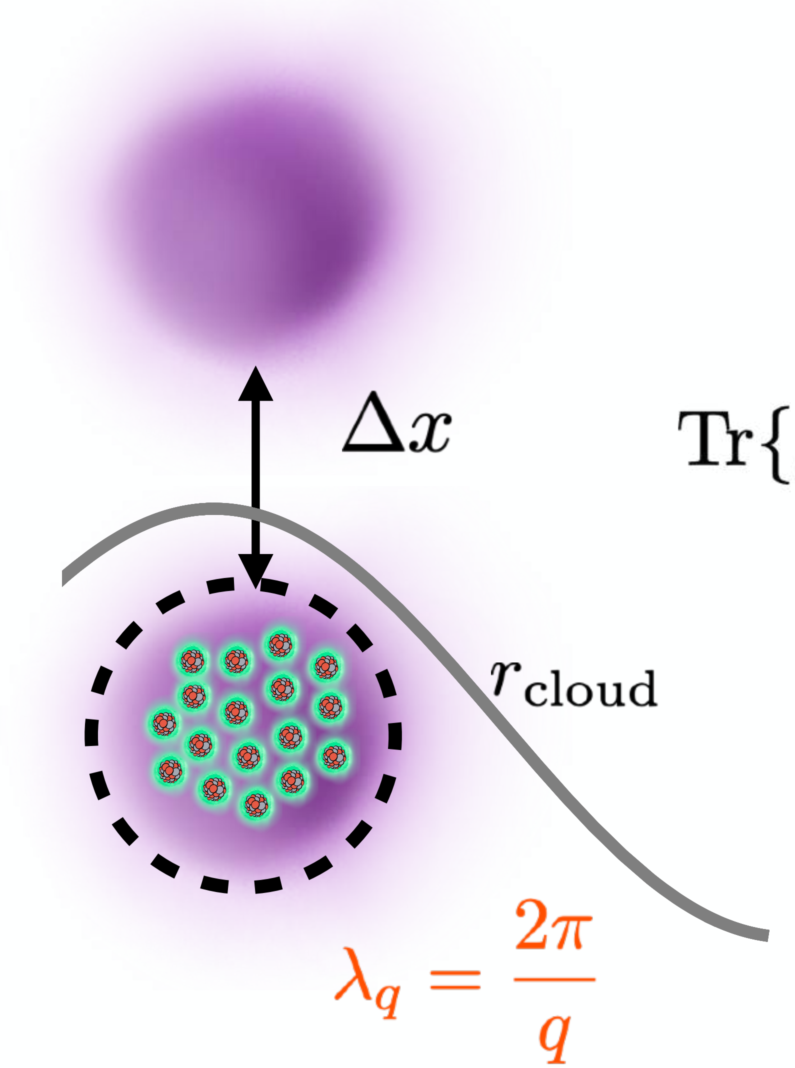

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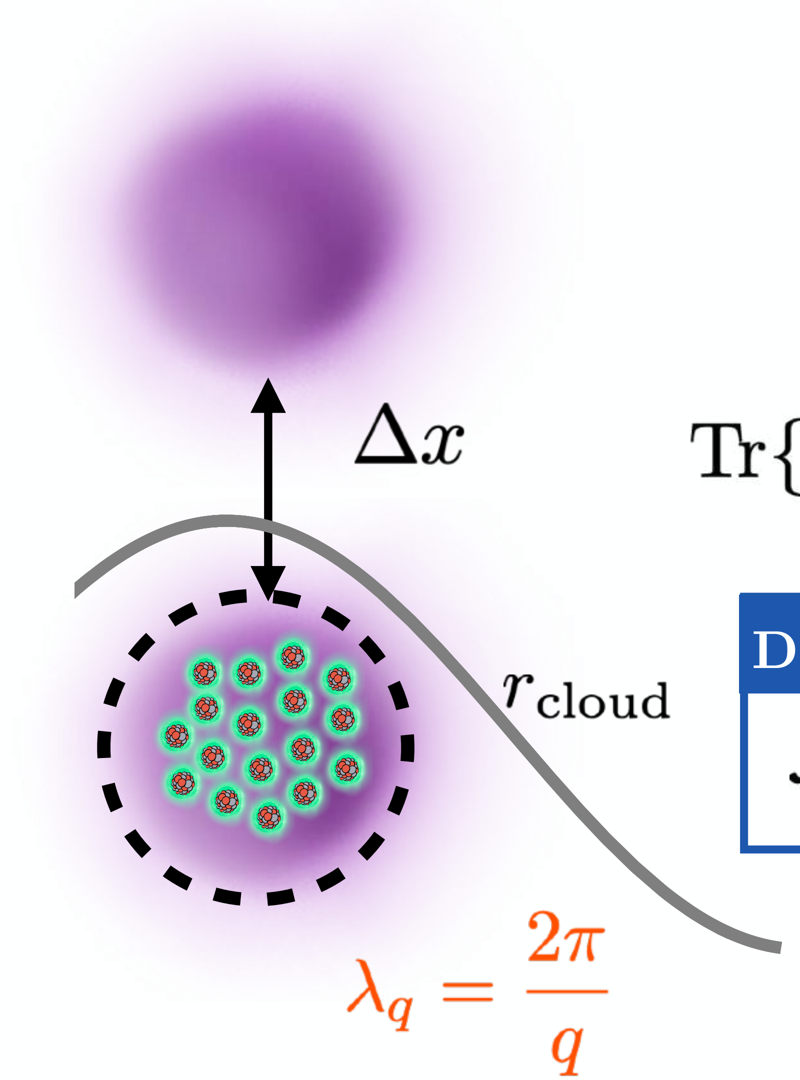

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Decoherence Kernel 1-body measurement

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

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

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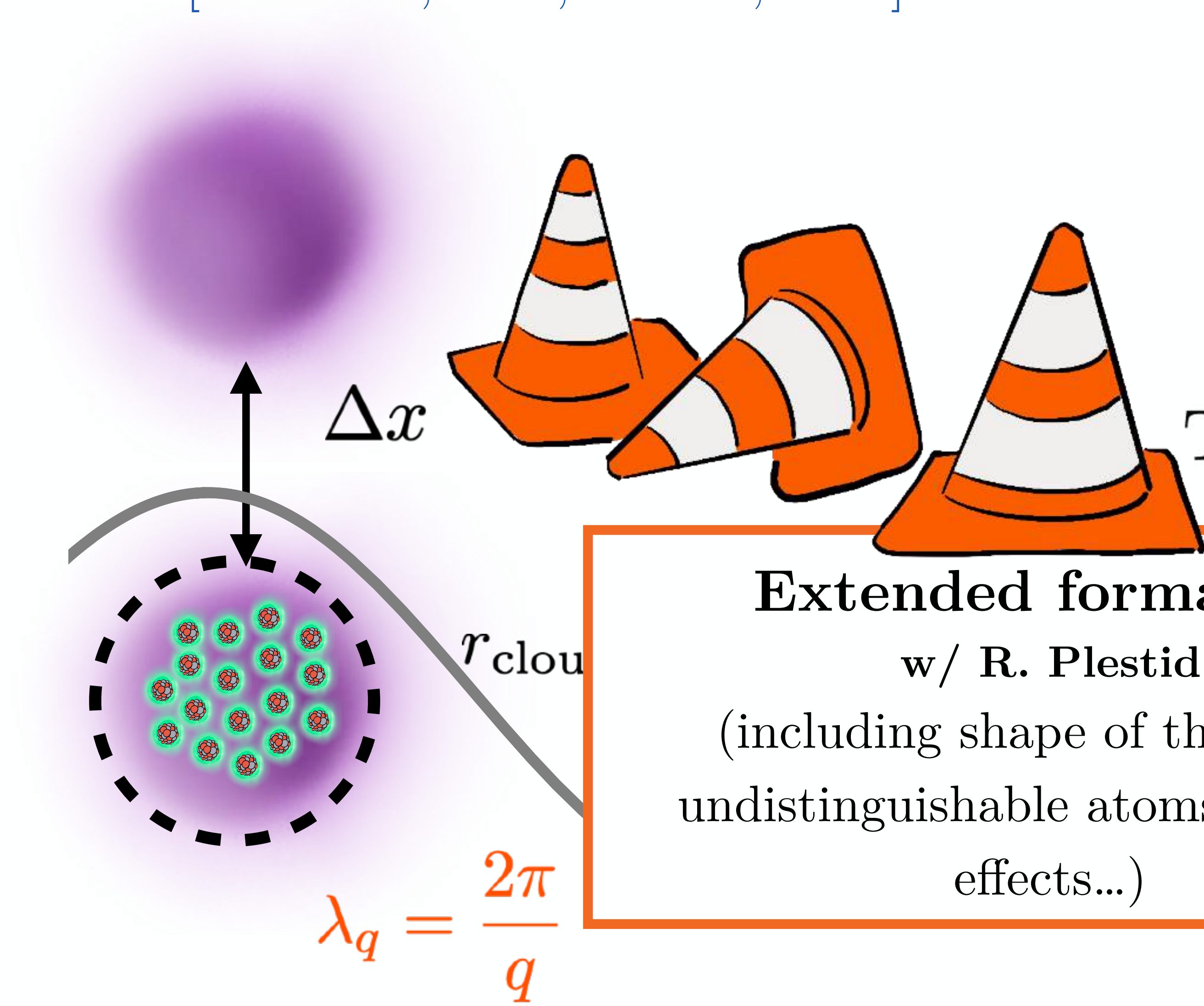

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Extended formalism
w/ R. Plestid
(including shape of the cloud, undistinguishable atoms, thermal effects...)

COHERENCE
$\lambda = 1/q \gtrsim r_{\mathrm{c}}$

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AIs: Collisional Decoherence

e.g. Dark Matter

Particle scattering

[Riedel, 2013]
[Riedel, Yavin, 2017]
[Du, **CM**, Pardo, Wang, Zurek, 2022]
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$$R(\mathbf{q}) = n_\chi \int d^3\mathbf{v} f(\mathbf{v}) \Gamma(\mathbf{v}, \mathbf{q})$$

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

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

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

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

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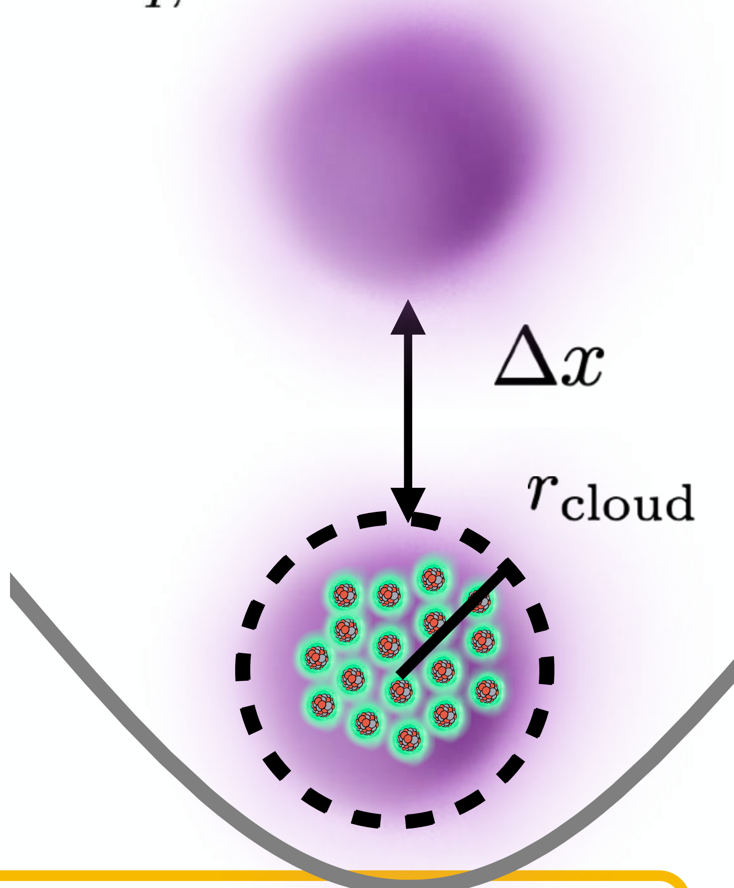

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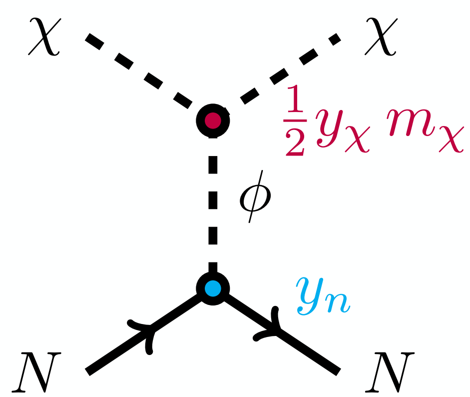
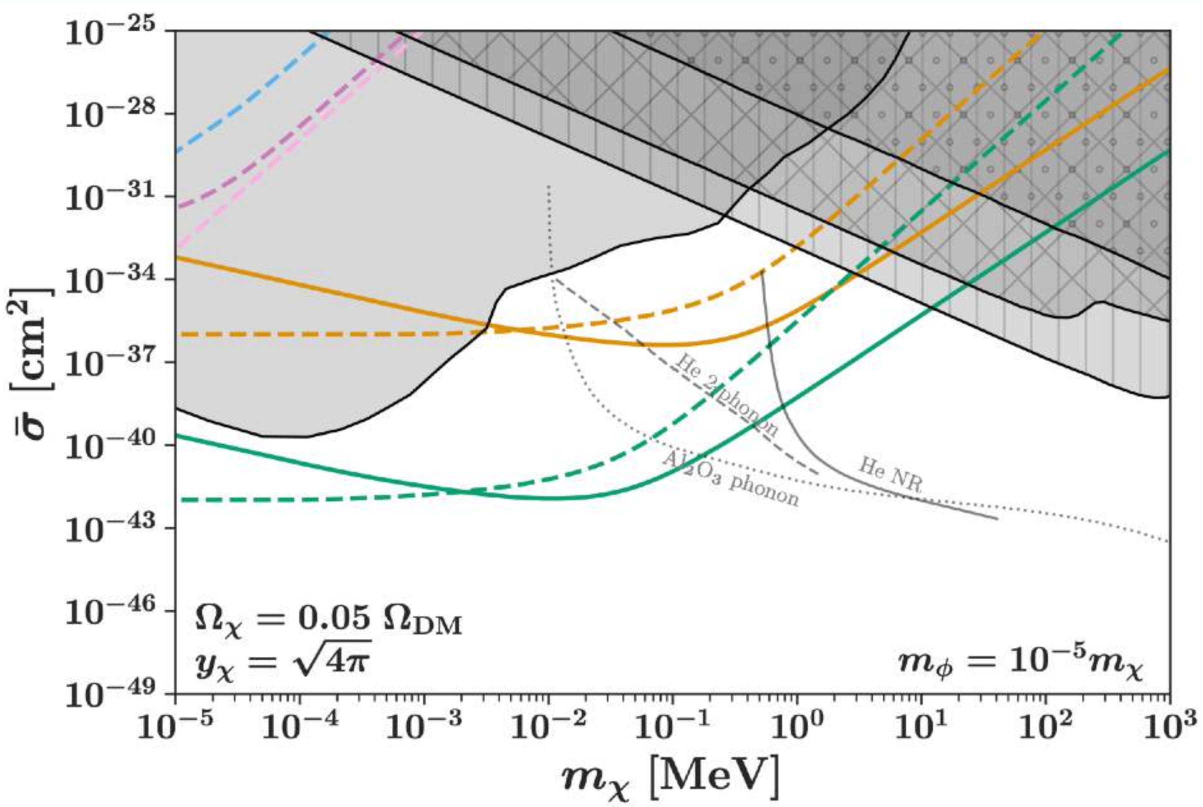
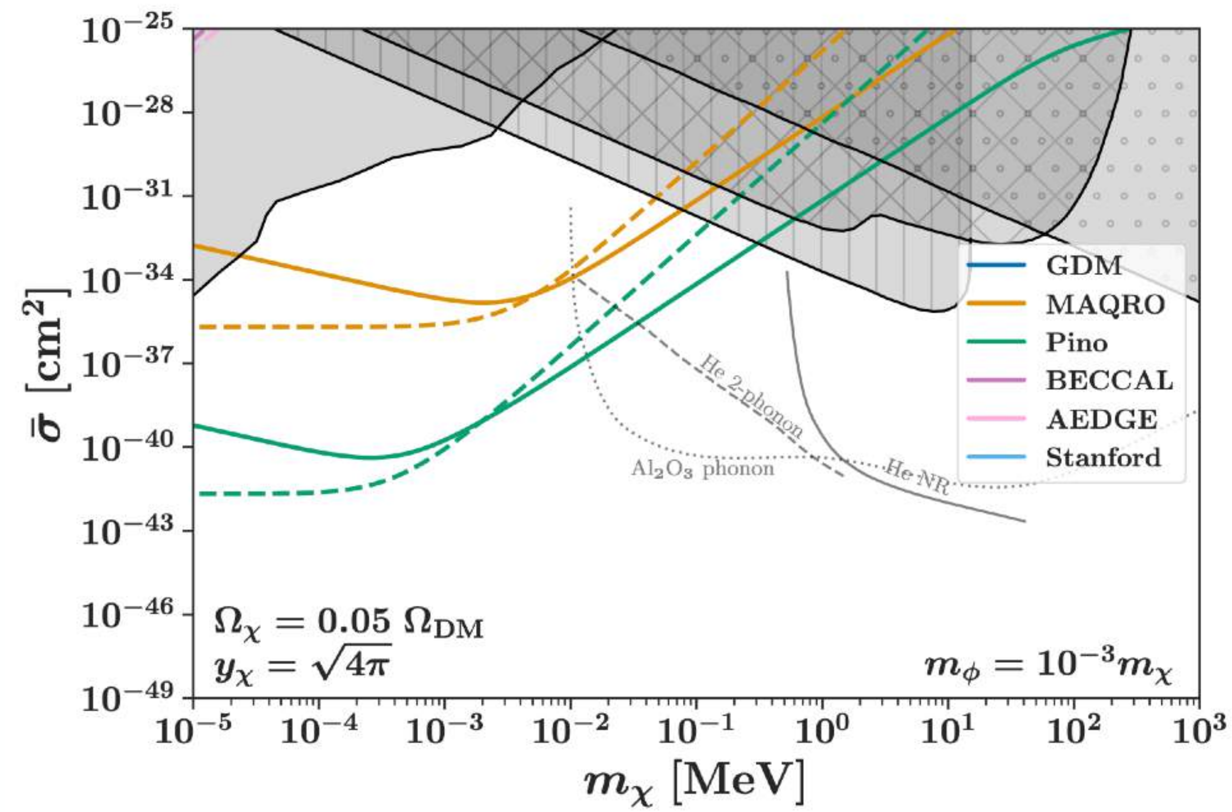
AIs: Some bounds (dark matter)



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





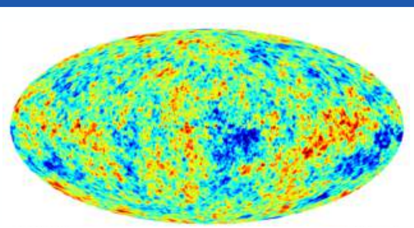
Terrestial

- Collider
- 5th force

Astrophysical

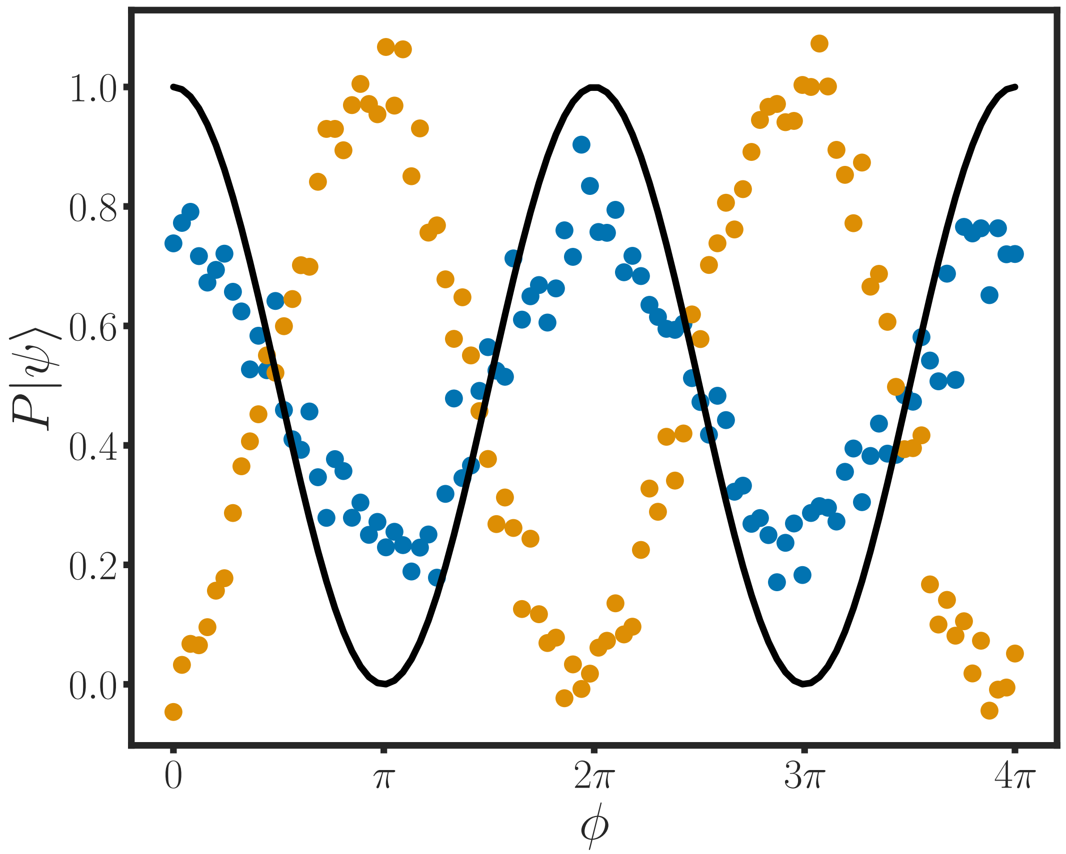
- Stellar emission
- DMSI

Cosmological



AIs: Backgrounds

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

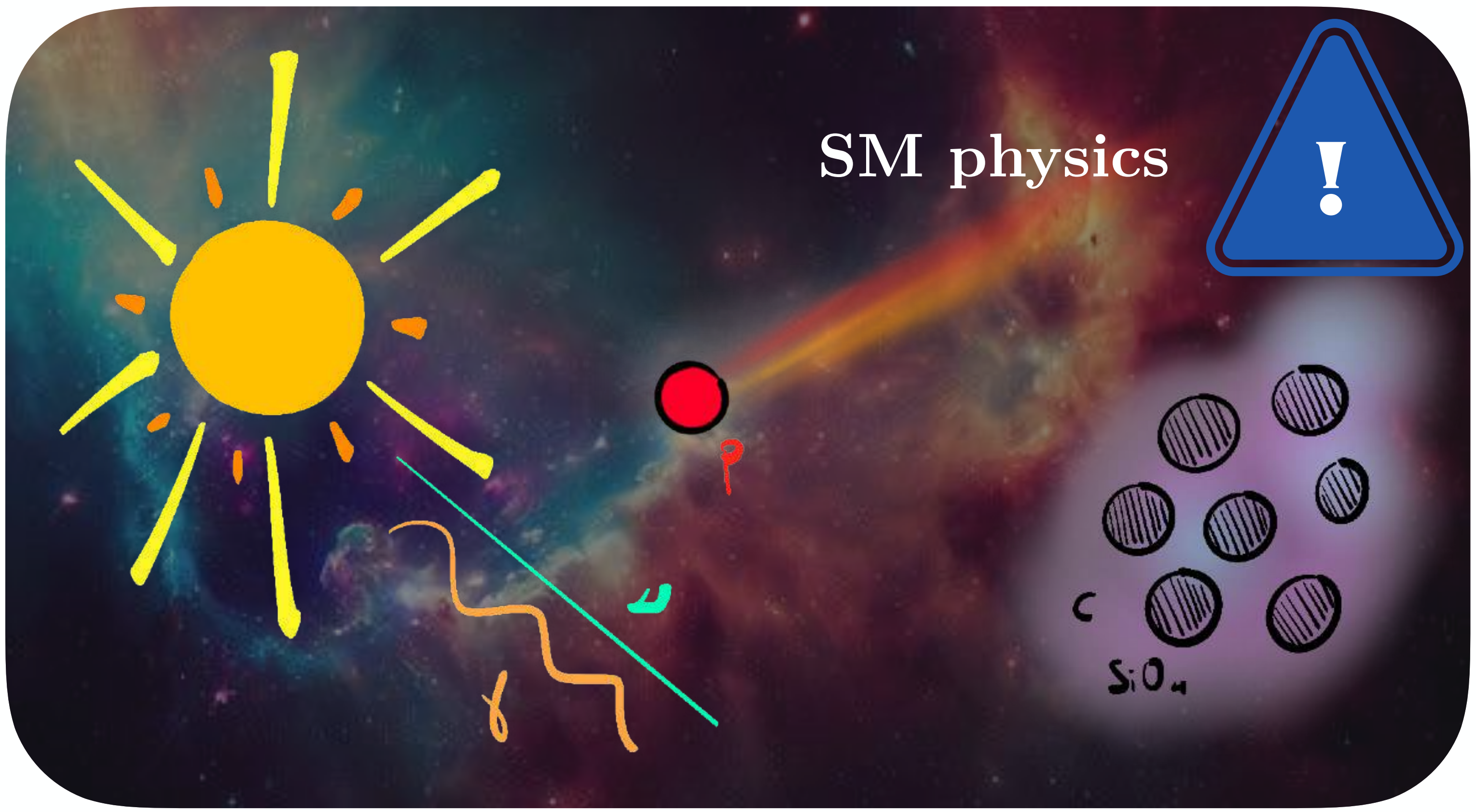


Visibility

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

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

AIs: Backgrounds



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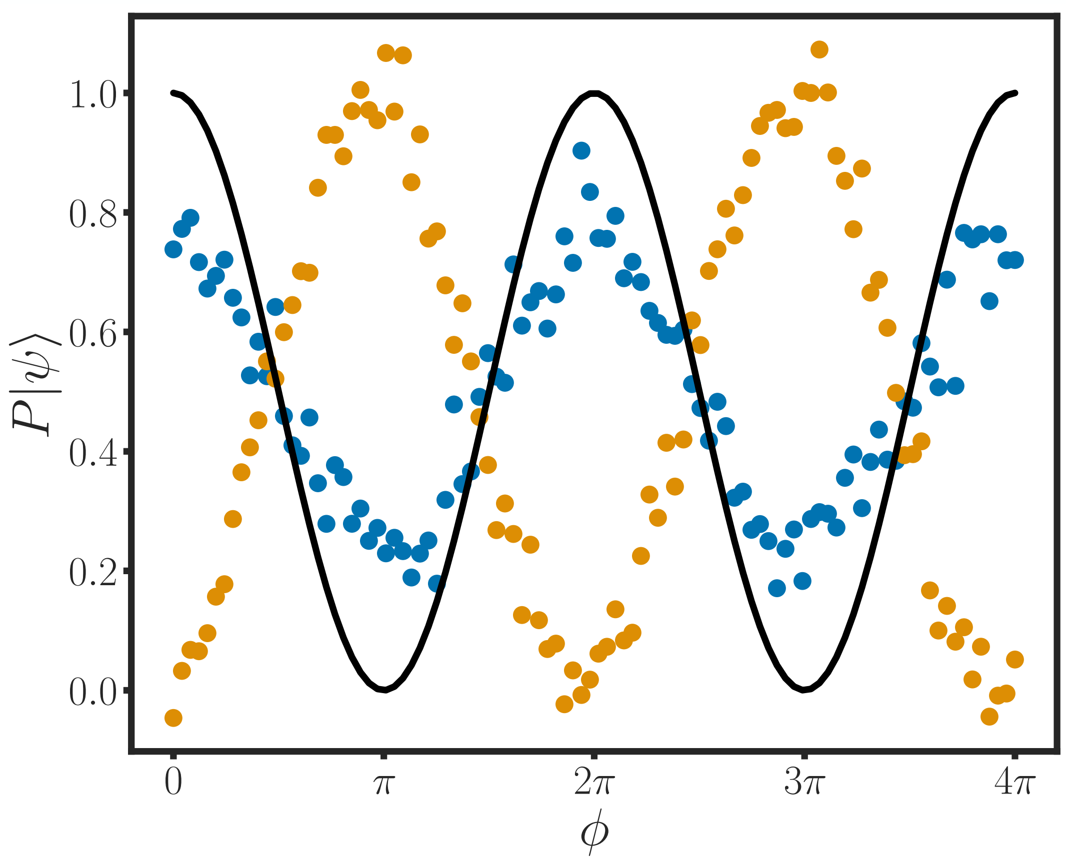

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[Du, **CM**, Pardo, Wang, Zurek, 2023]

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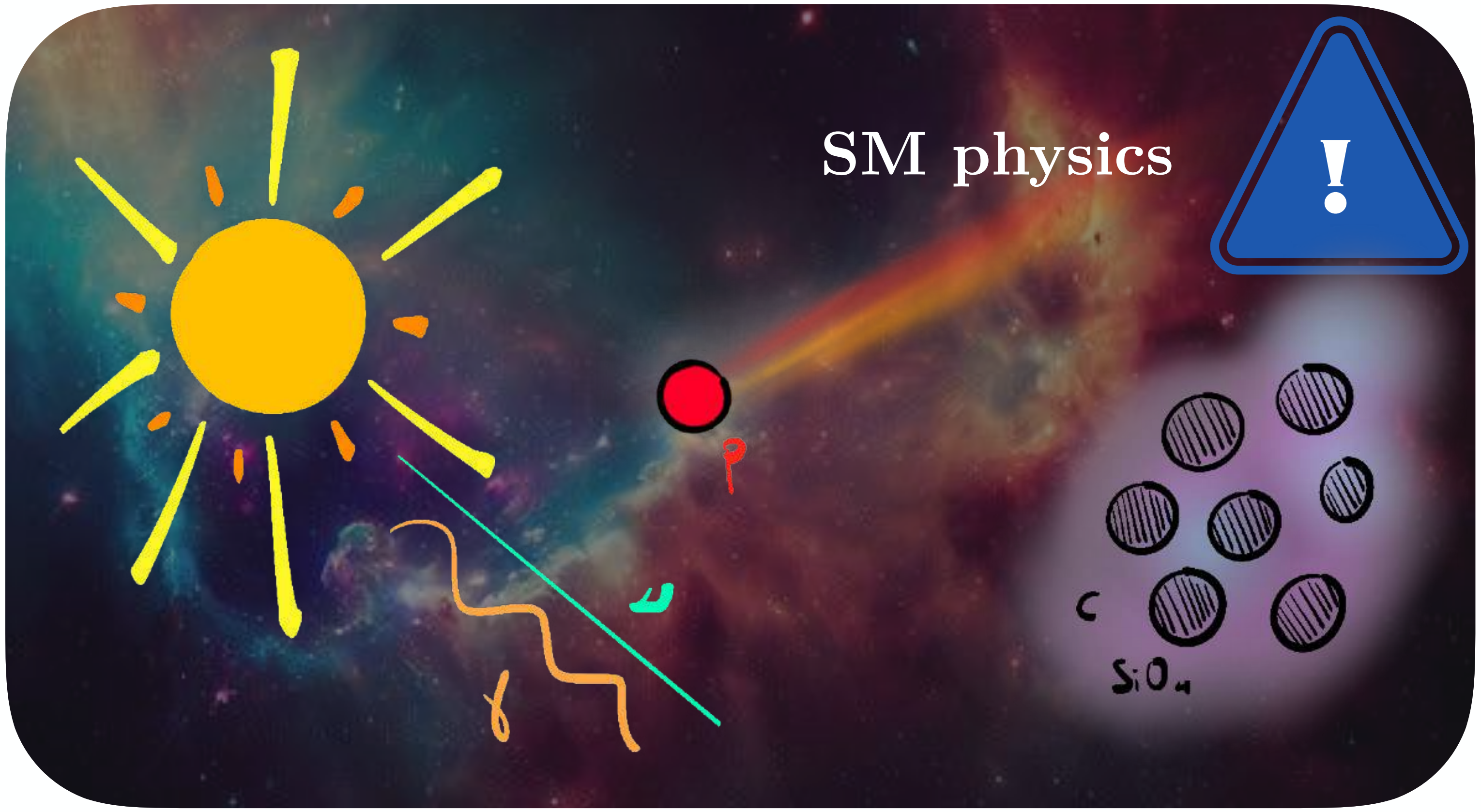

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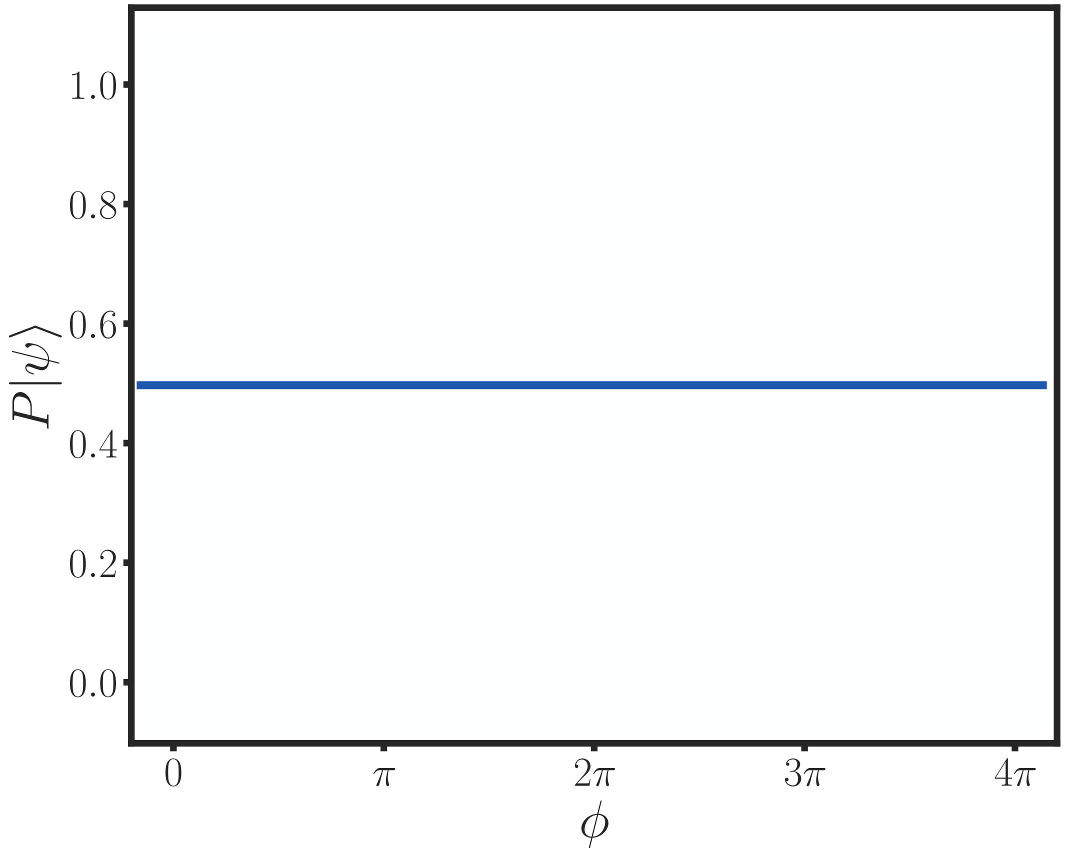

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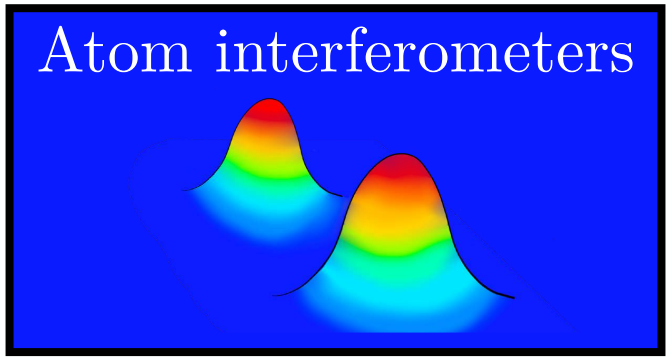
[Du, **CM**, Pardo, Wang, Zurek, 2023]

“Take home” message

Table-top experiments already ∃ !

e.g.



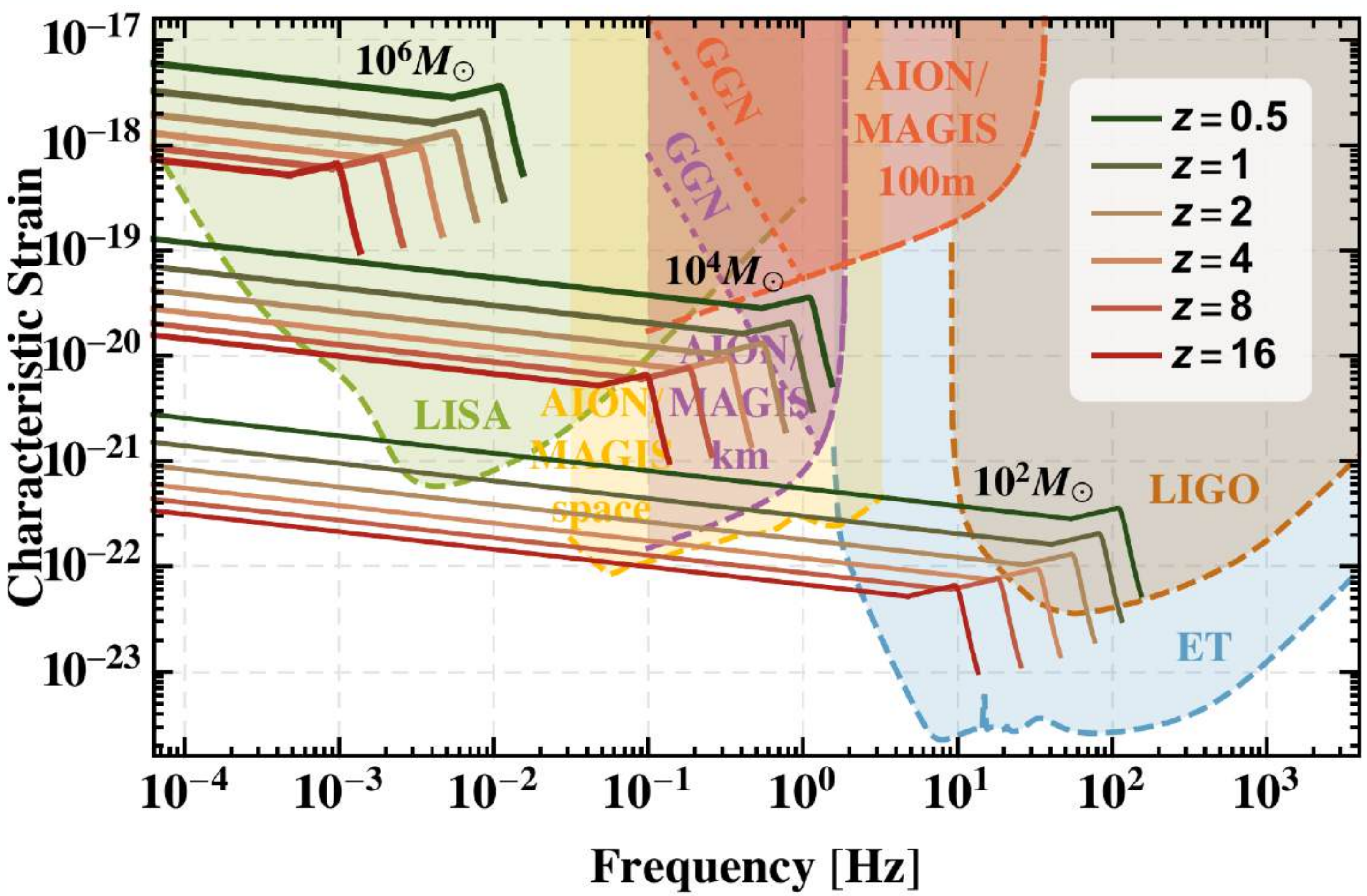
L. Kastler Brossel

BERKELEY

$(\cdots)$

ZHAOSHAN
12-m atomic fountain

STANFORD
10-m atomic fountain



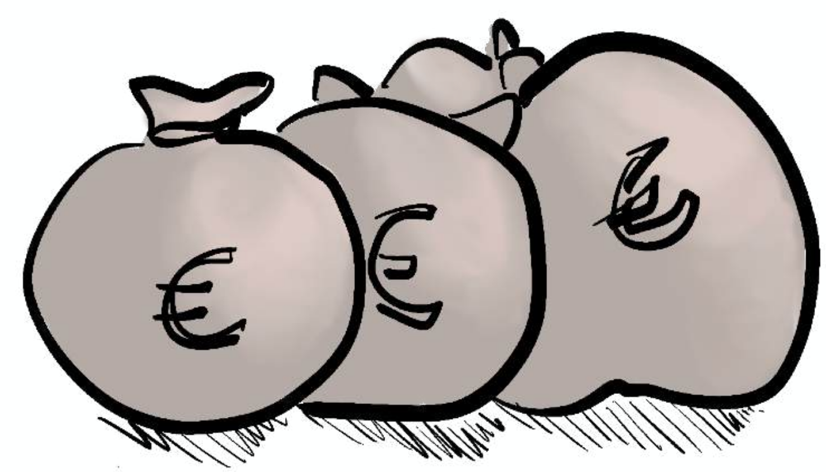
Or under construction:

AION

MAGIS-100

MIGA

$(\cdots)$



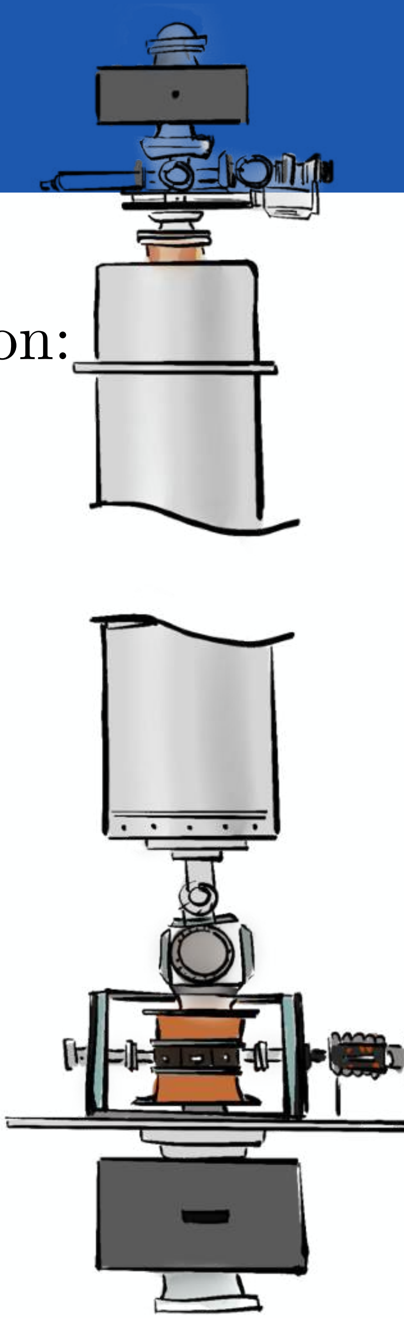


Table-top experiments already ∃ !

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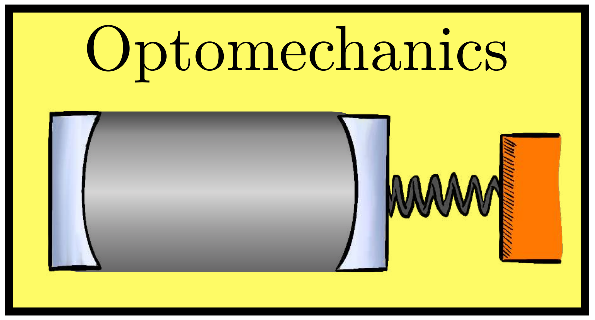
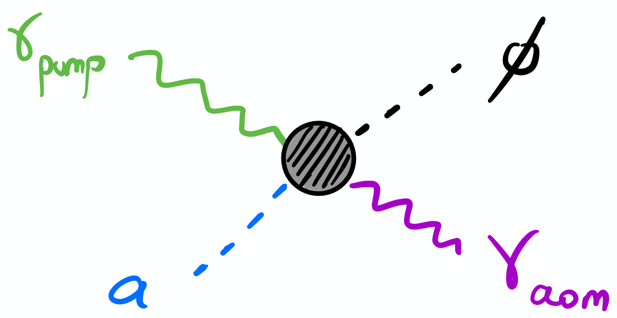
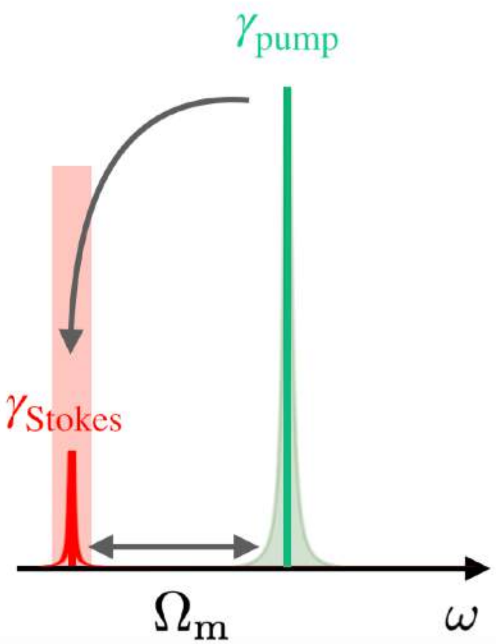




[**CM**, Y. Wang, K. M. Zurek. 2022]



He

$\Rightarrow N_{\rm pump} \simeq 10^6$

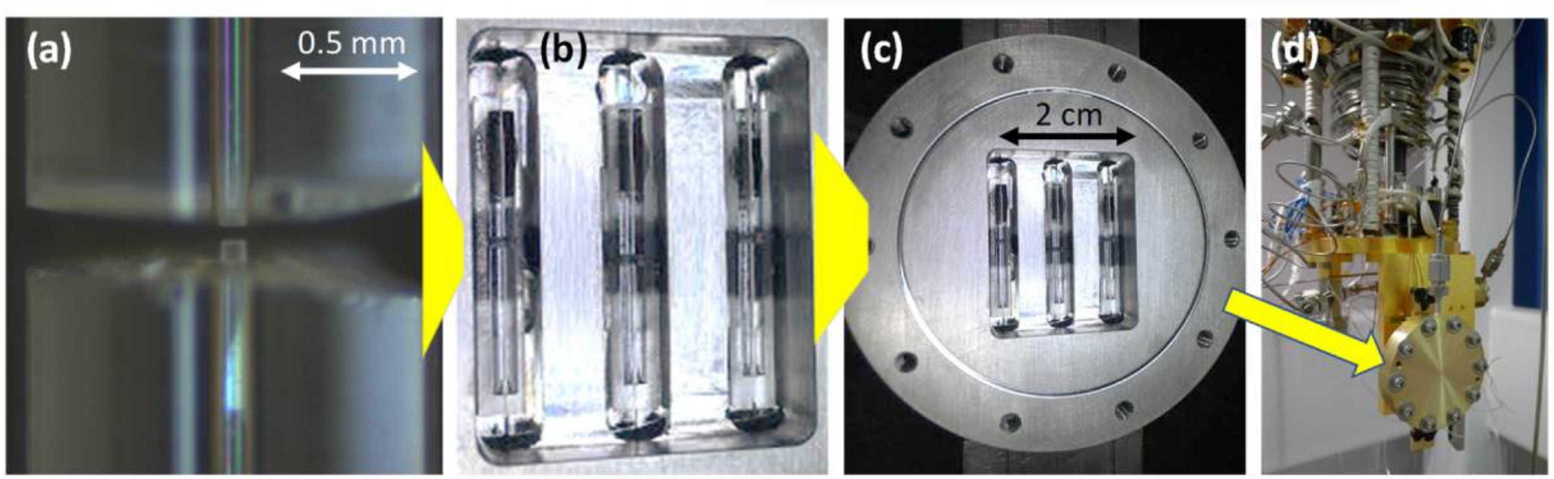
$\Rightarrow N_\phi \simeq 10^5$

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

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

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

Yale University



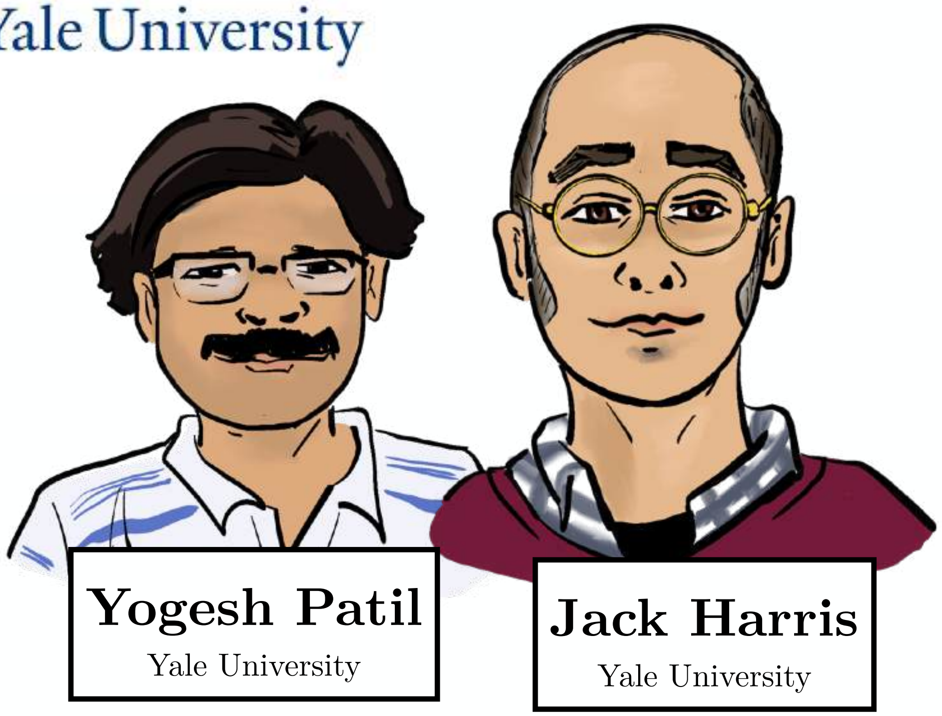
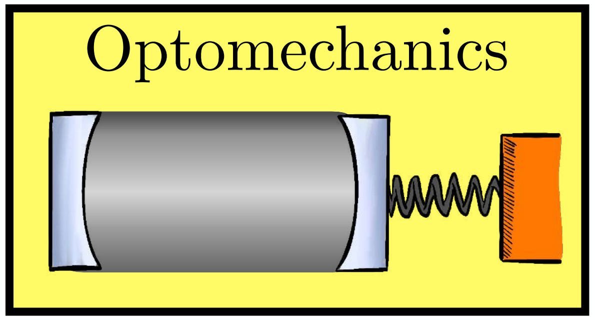
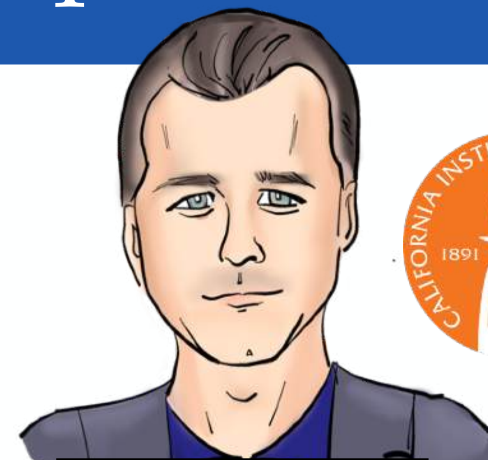


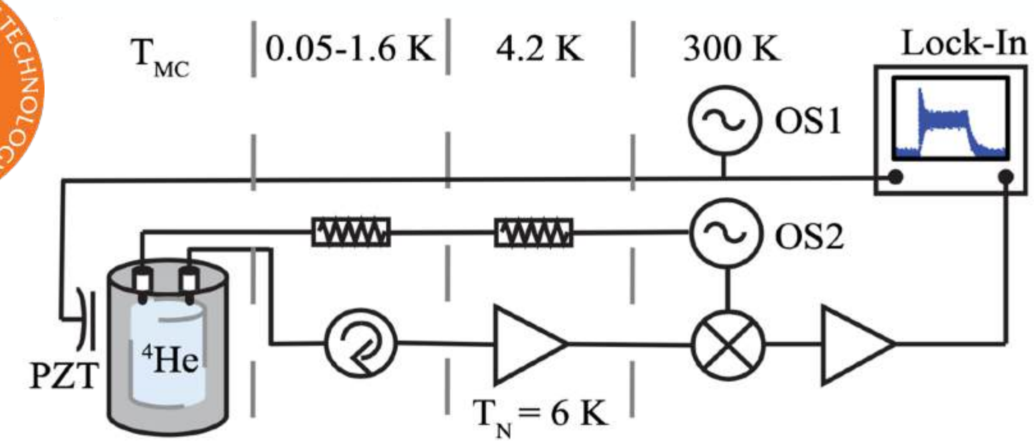
Table-top experiments already ∃ !

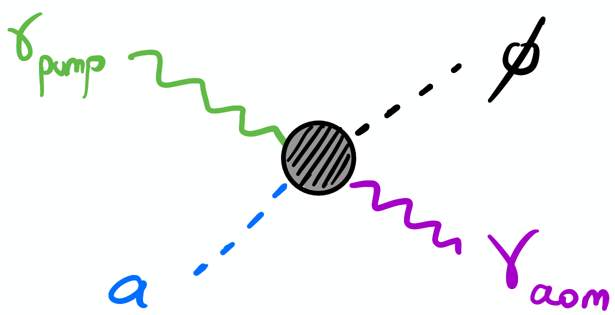
e.g.



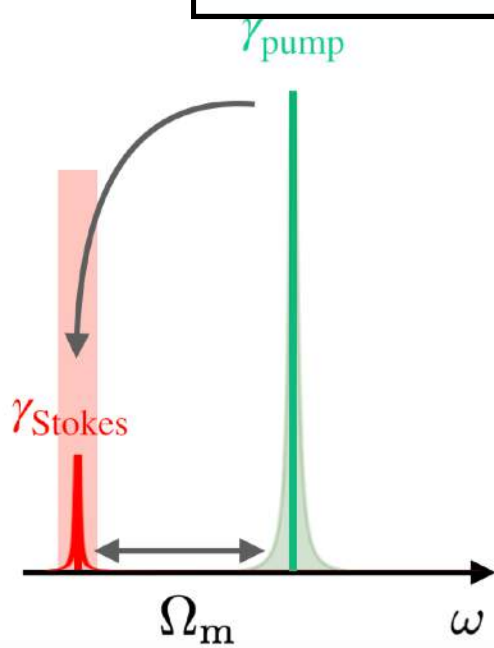


Keith Schwab
Caltech





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

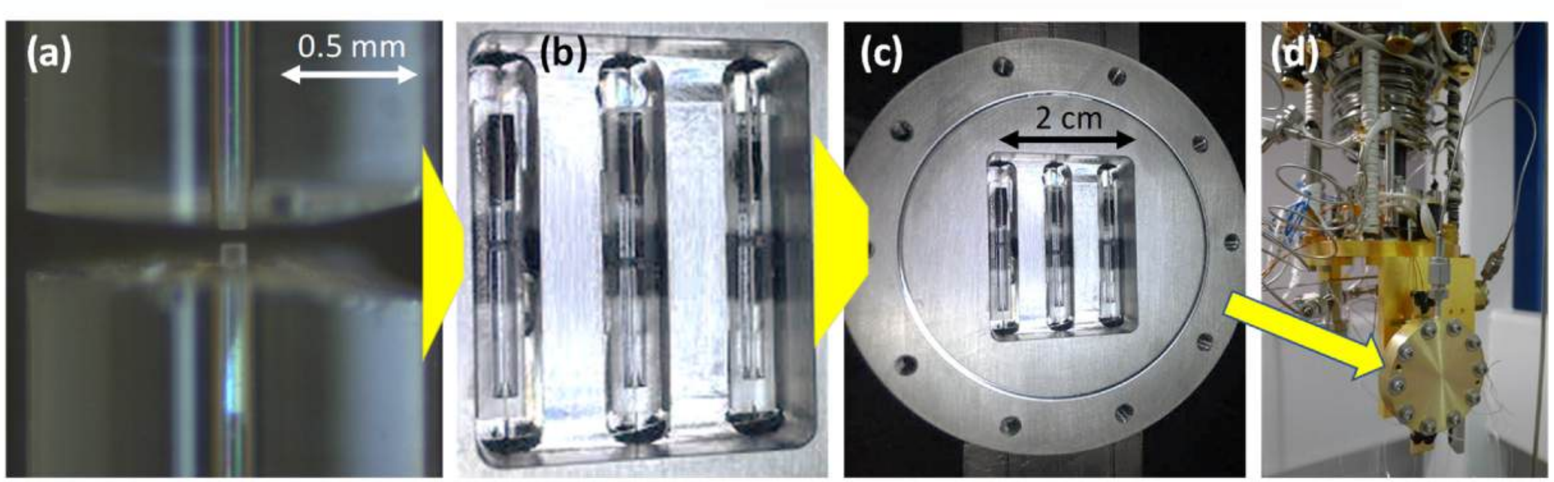


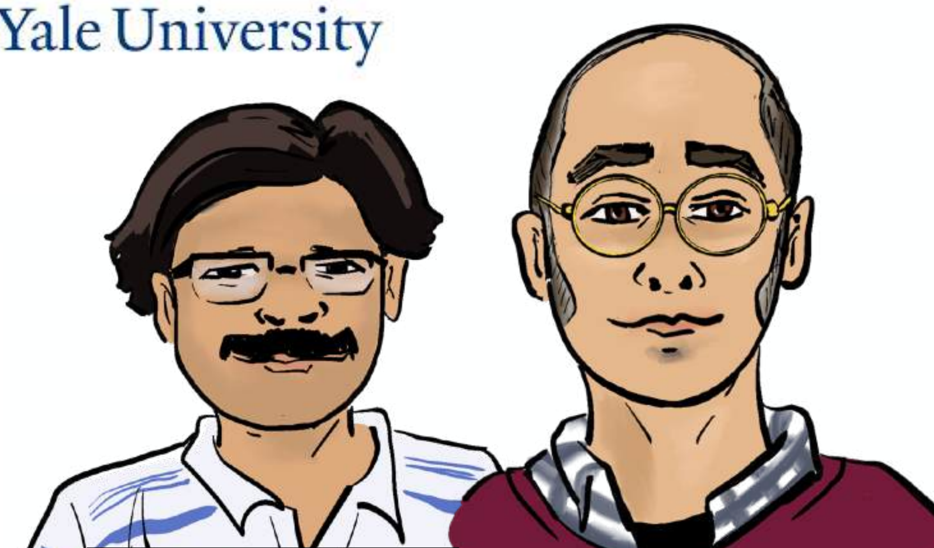
He

➡ $N_{\rm pump} \simeq 10^{12}$
➡ $N_\phi \simeq 10^{15}$

$P_{\rm pump} \sim 1\,\mu{\rm W}$
$L \sim 4\,{\rm cm}$
$\mathcal{F}_{\rm opt}/\pi \sim 10^8$

Yale University



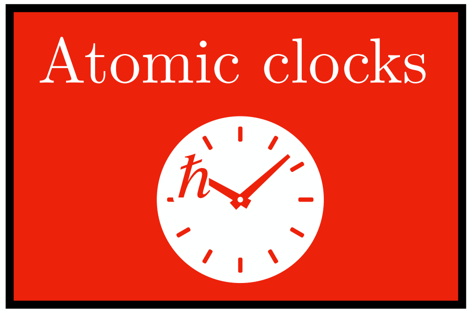


Yogesh Patil
Yale University

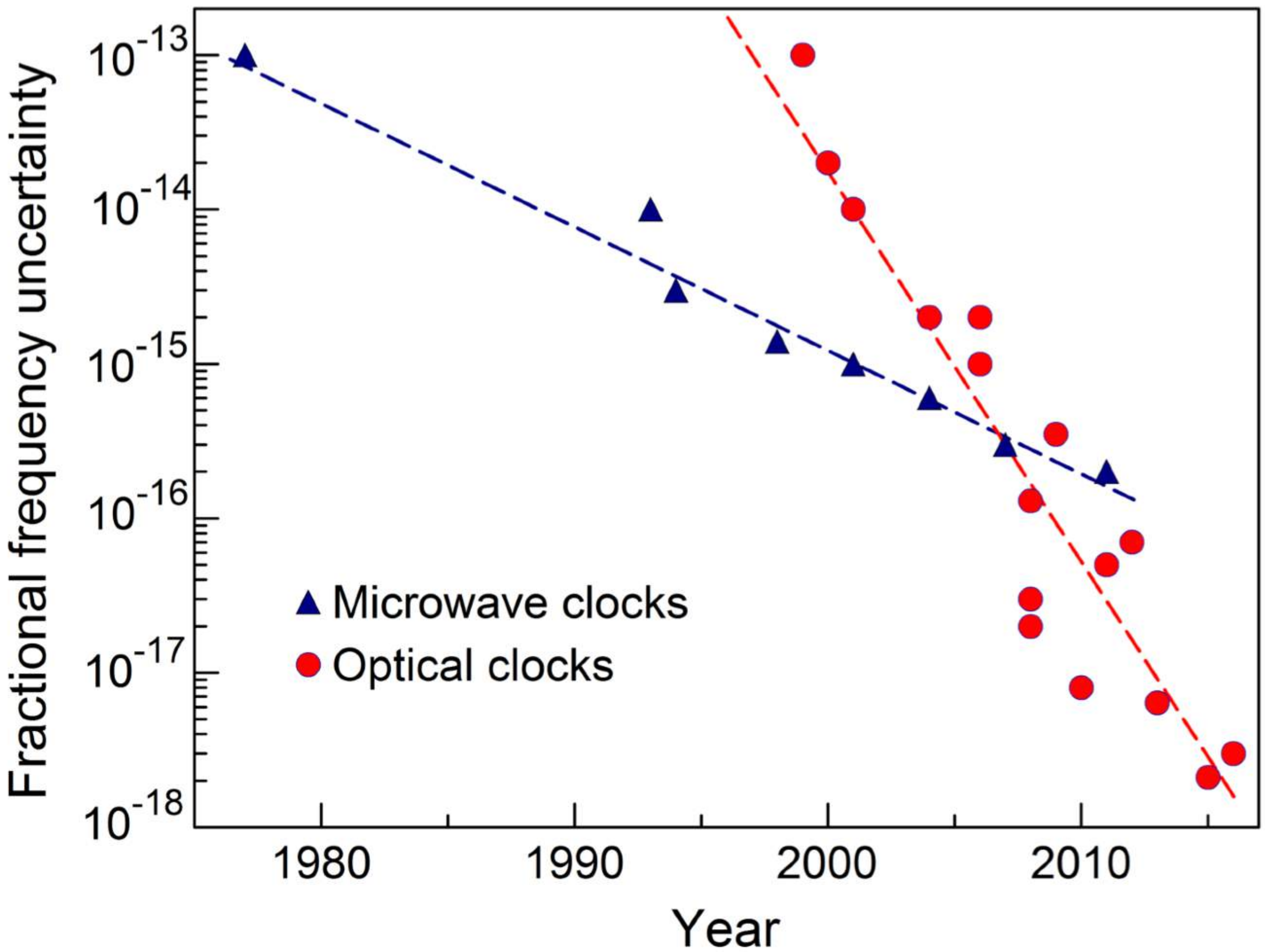
Jack Harris
Yale University

Boundaries unreached !!

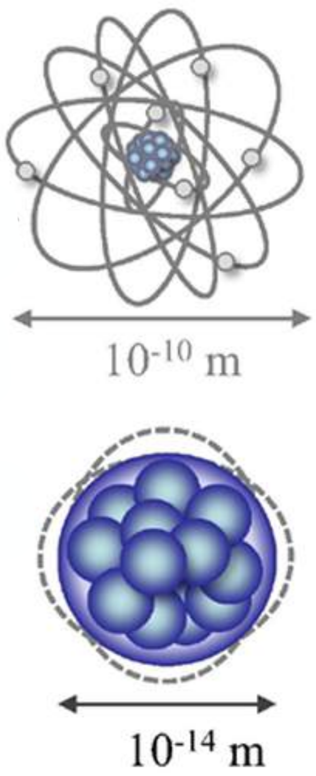
e.g.



Nuclear clocks [Peik et al. 2021]

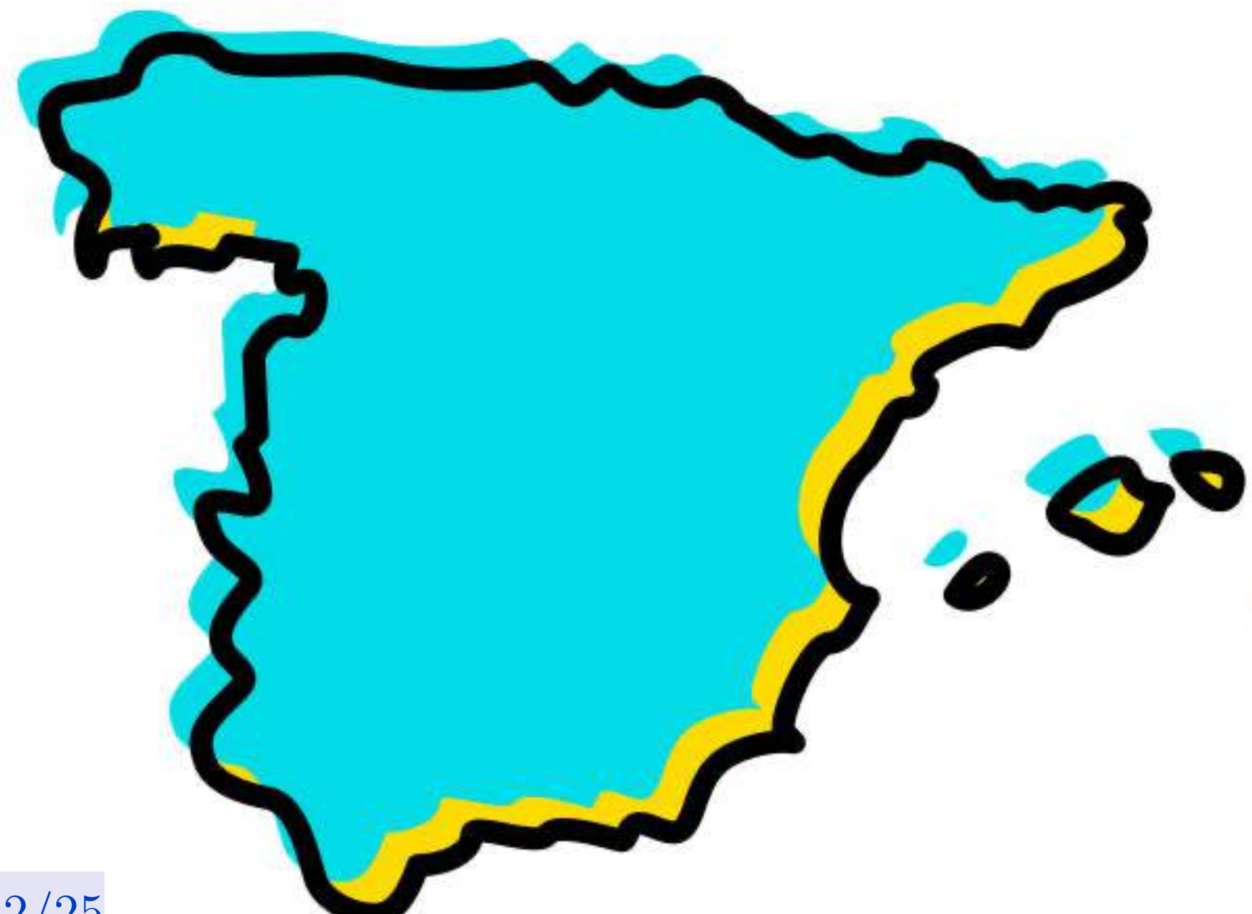


[Huntemann et al., 2016]
[Nicholson et al. 2015]
[Poli et al. 2013]
[Safranova et al. 2017]



Spain is going quantum!

QTEP - CSIC



BUDGET
EUR 22 Million
EXECUTION
01/01/22 – 31/12/25

Quantum SPAIN

Spain is going quantum!

ICFO

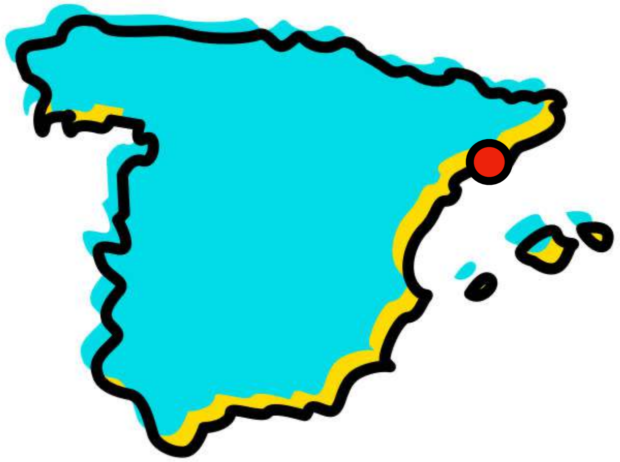
(a biased example)

Quantum sensing using ultra-cold atoms

M. Mitchell
ICFO

R. Sewell
ICFO

O. Romero-Isart
ICFO



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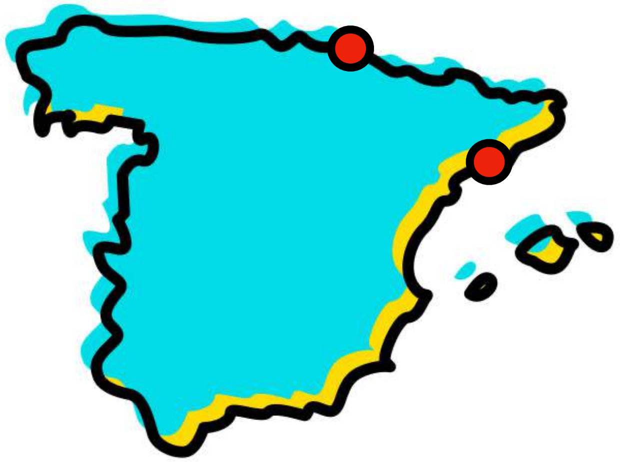


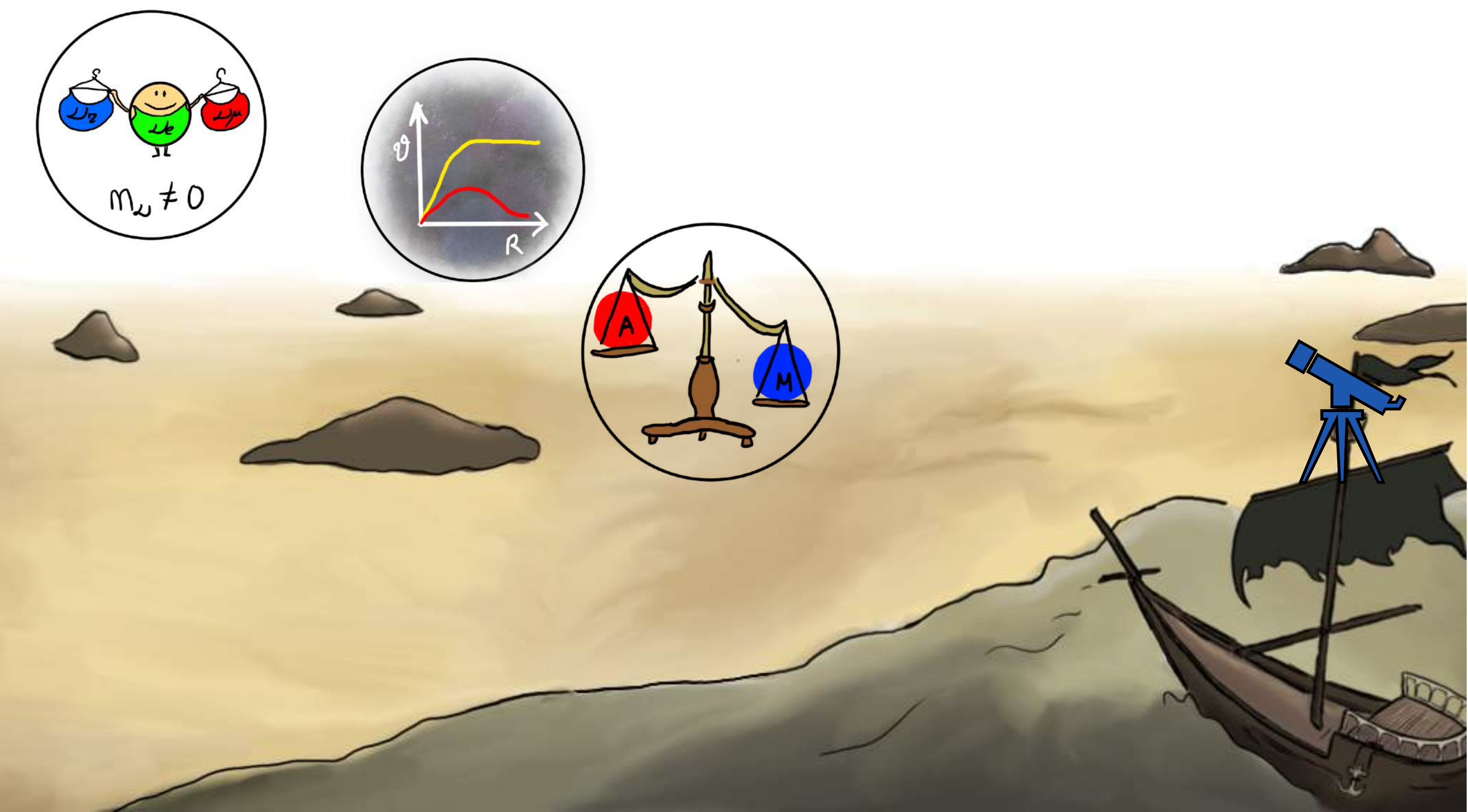
IQ QUANTUM TECHNOLOGY INITIATIVE

CERN

(another biased example)

Enrique Rico Ortega
UPV/EHU/CERN

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



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