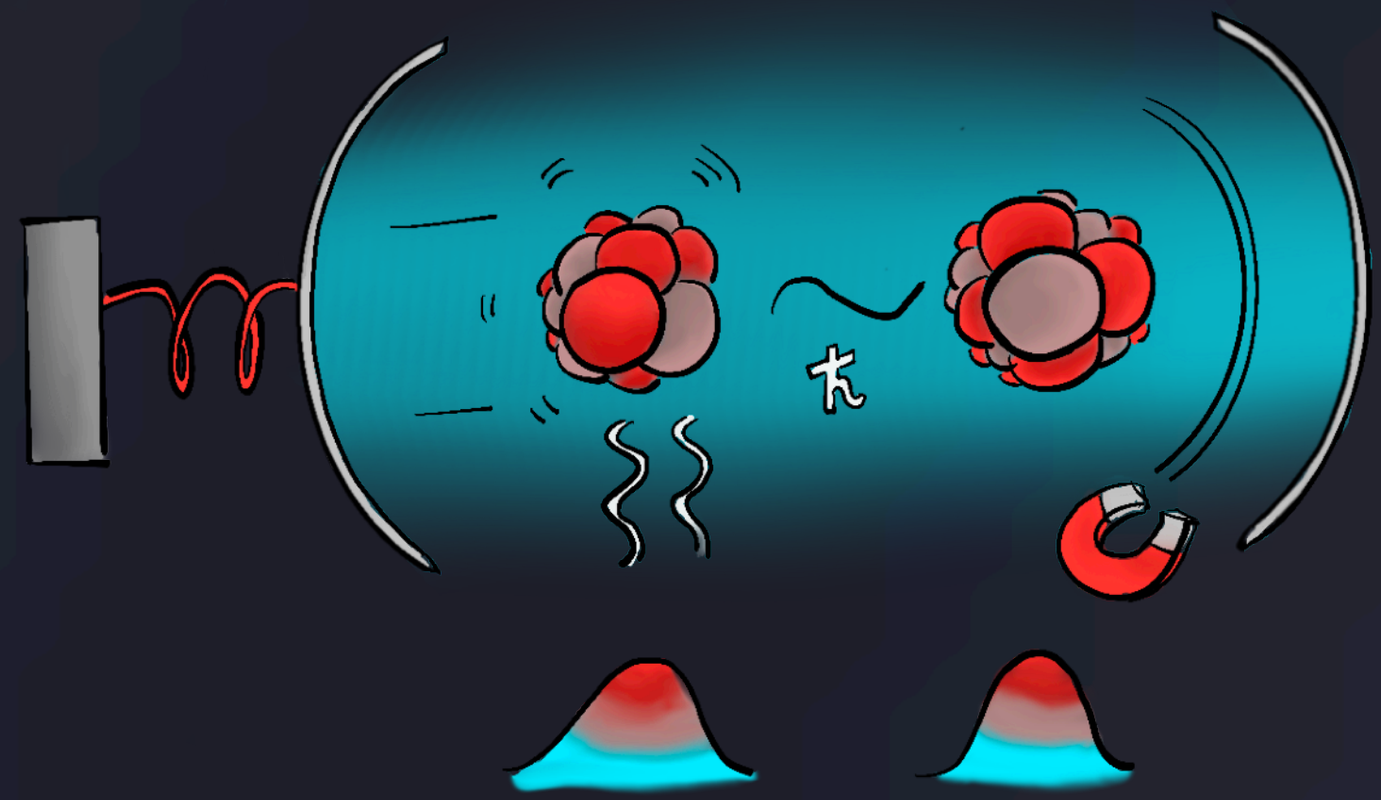
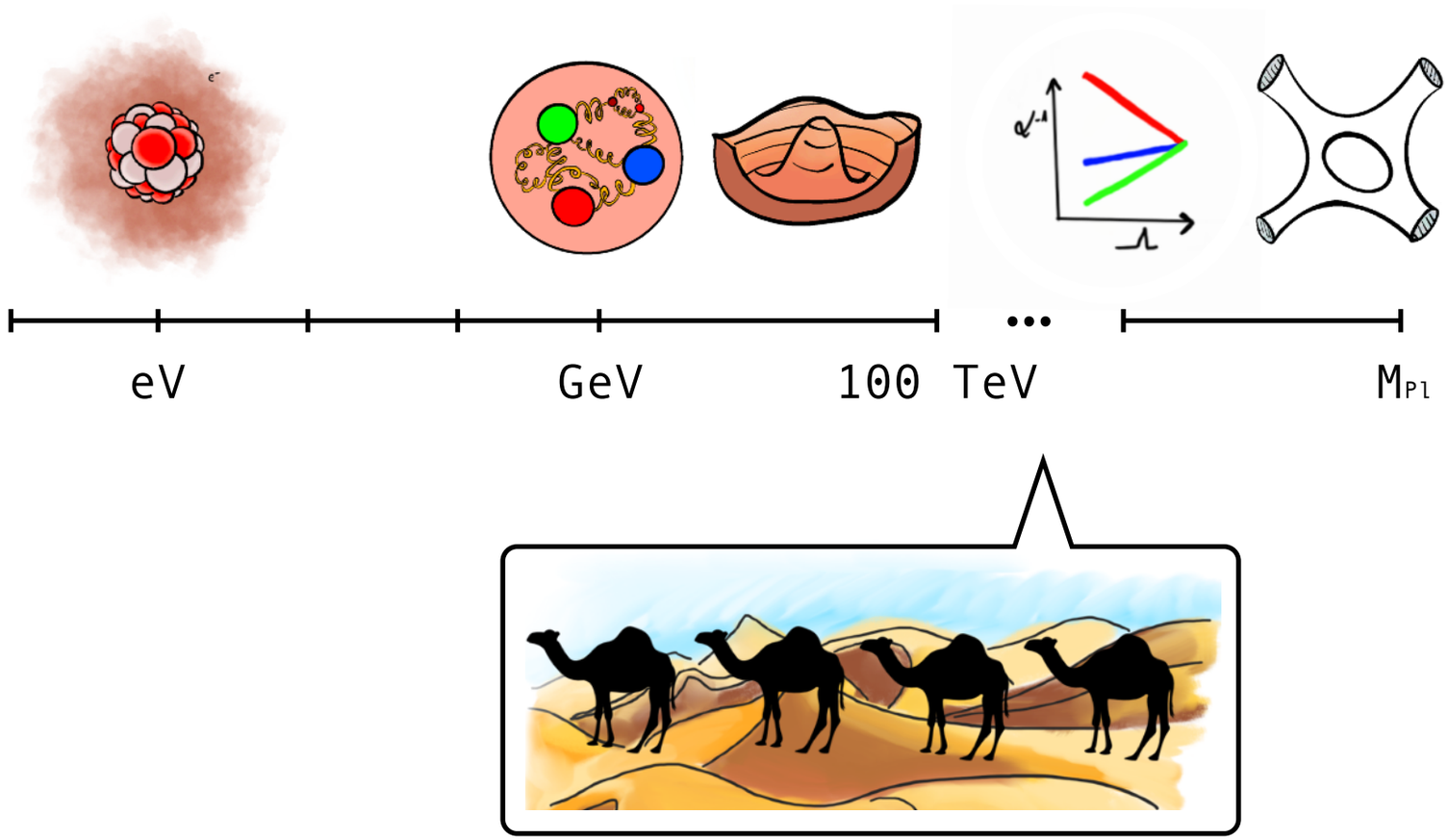
Coherently enhanced decoherence

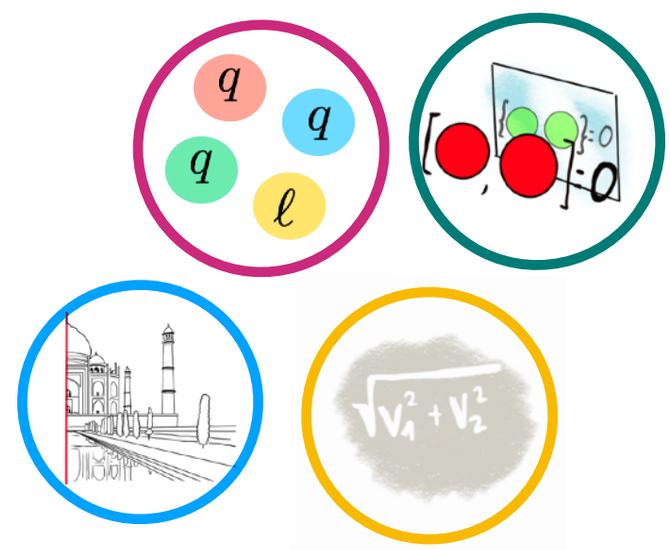
Clara Murgui (CERN)

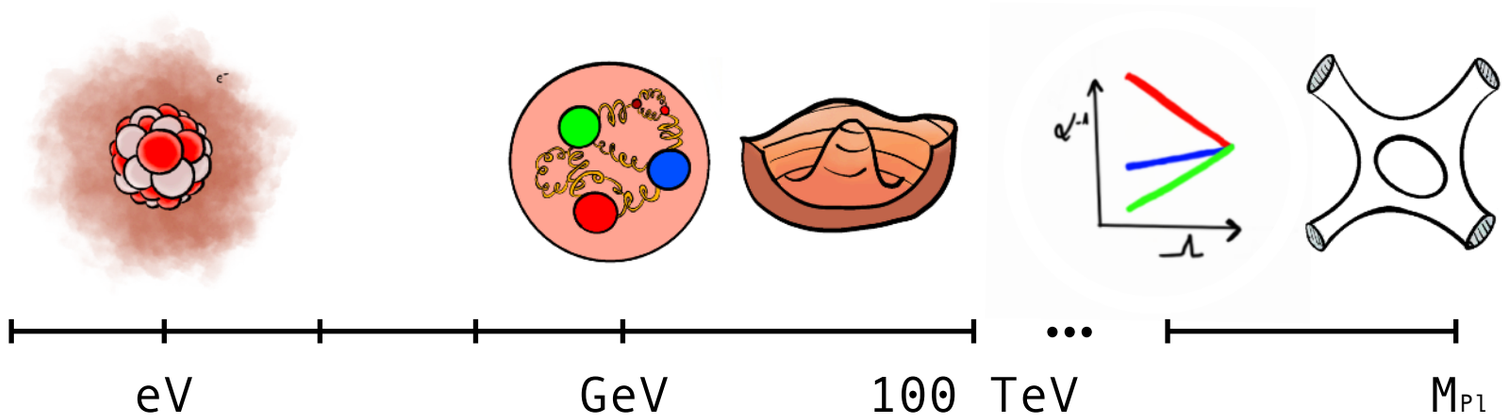
IJCLab – November 20th 2025 – Orsay

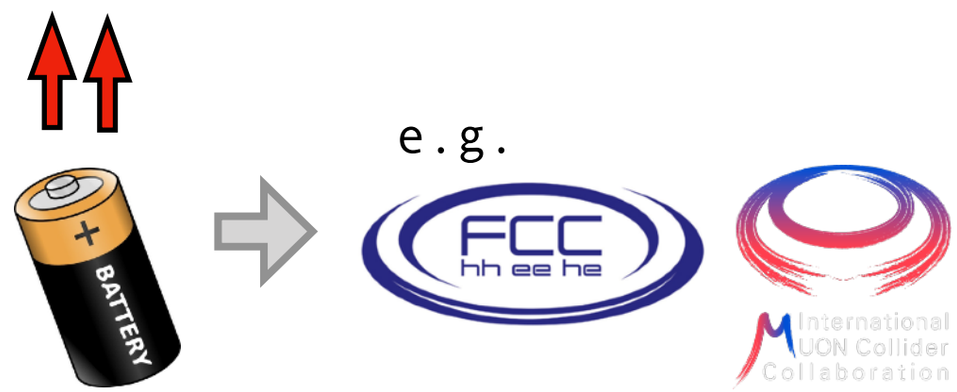
Why quantum sensors?




eV
GeV
100 TeV
...
M_{Pl}

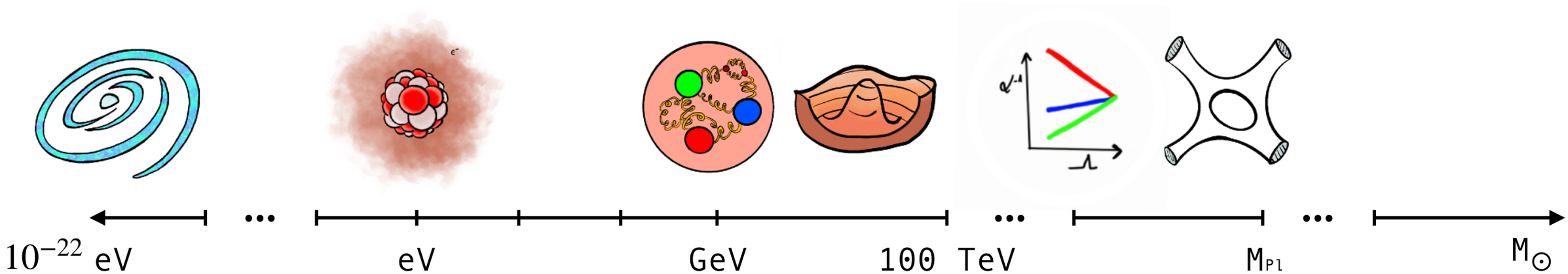

q
q
q
ℓ

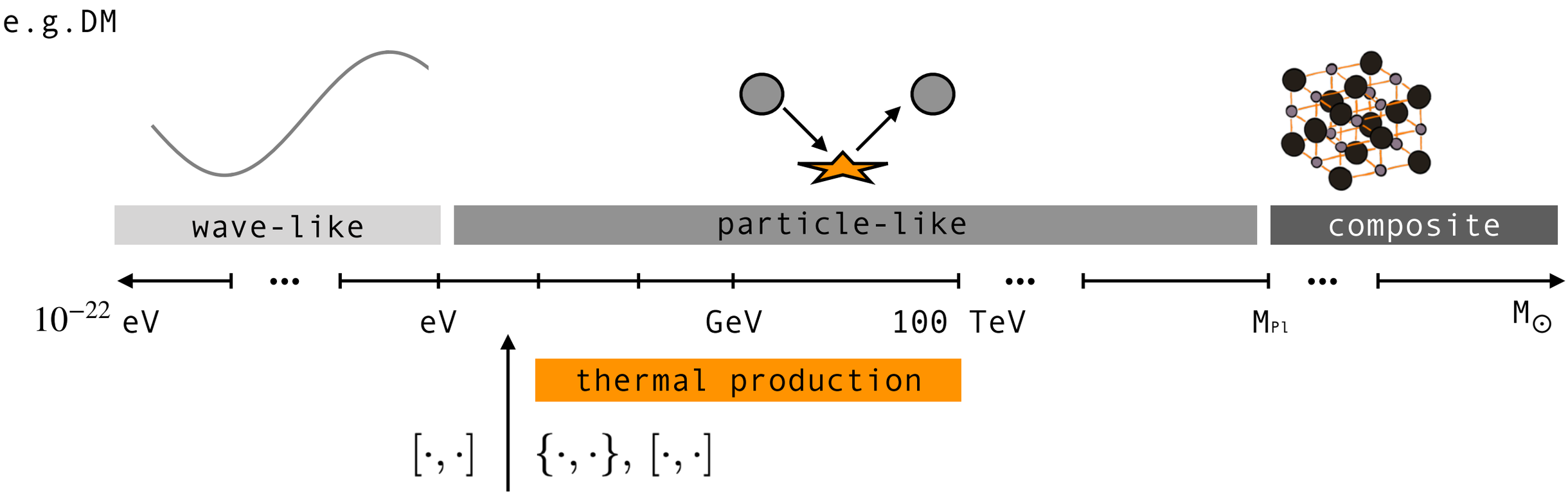




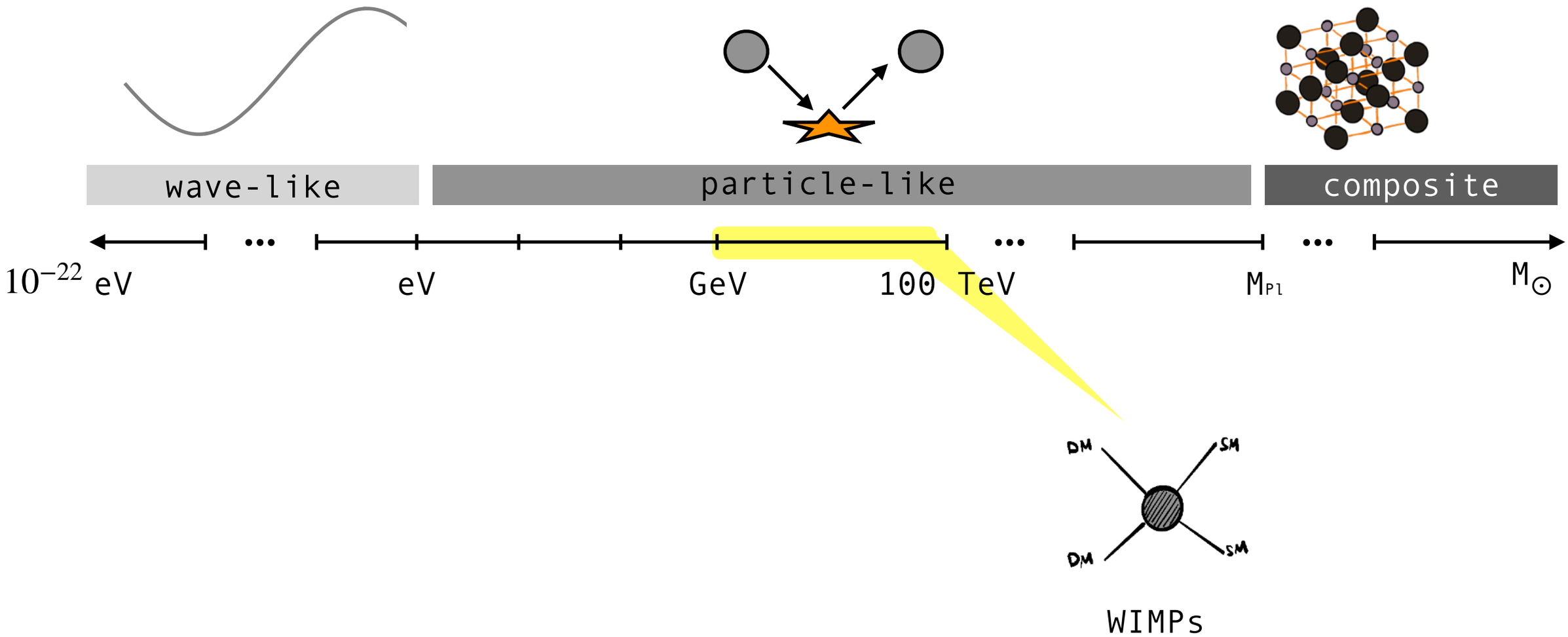
$$\mathcal{L} = \mathcal{L}^{\mathrm{d}\leq 4} + \sum_{d=5}^{\infty} \frac{\mathcal{O}_d}{\Lambda_{\mathrm{NP}}^{d-4}}$$

e.g. DM



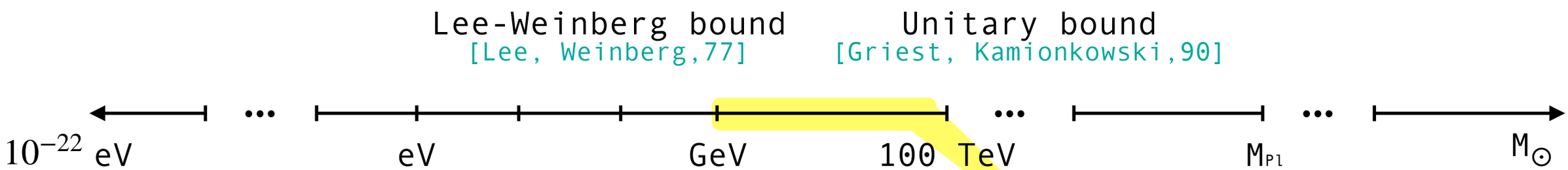

e.g.DM
wave-like
particle-like
composite
10^{-22} eV
eV
GeV
100 TeV
M_{Pl}
$M_\odot$
thermal production
$[\cdot,\cdot]$
$\{\cdot,\cdot\}$, $[\cdot,\cdot]$

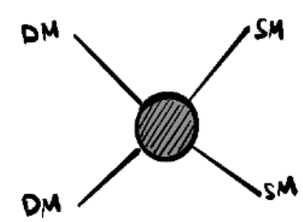
e.g. DM


wave-like
particle-like
composite
10^{-22} eV
eV
GeV
100 TeV
M_{Pl}
$M_\odot$
DM
SM
DM
SM
WIMPs

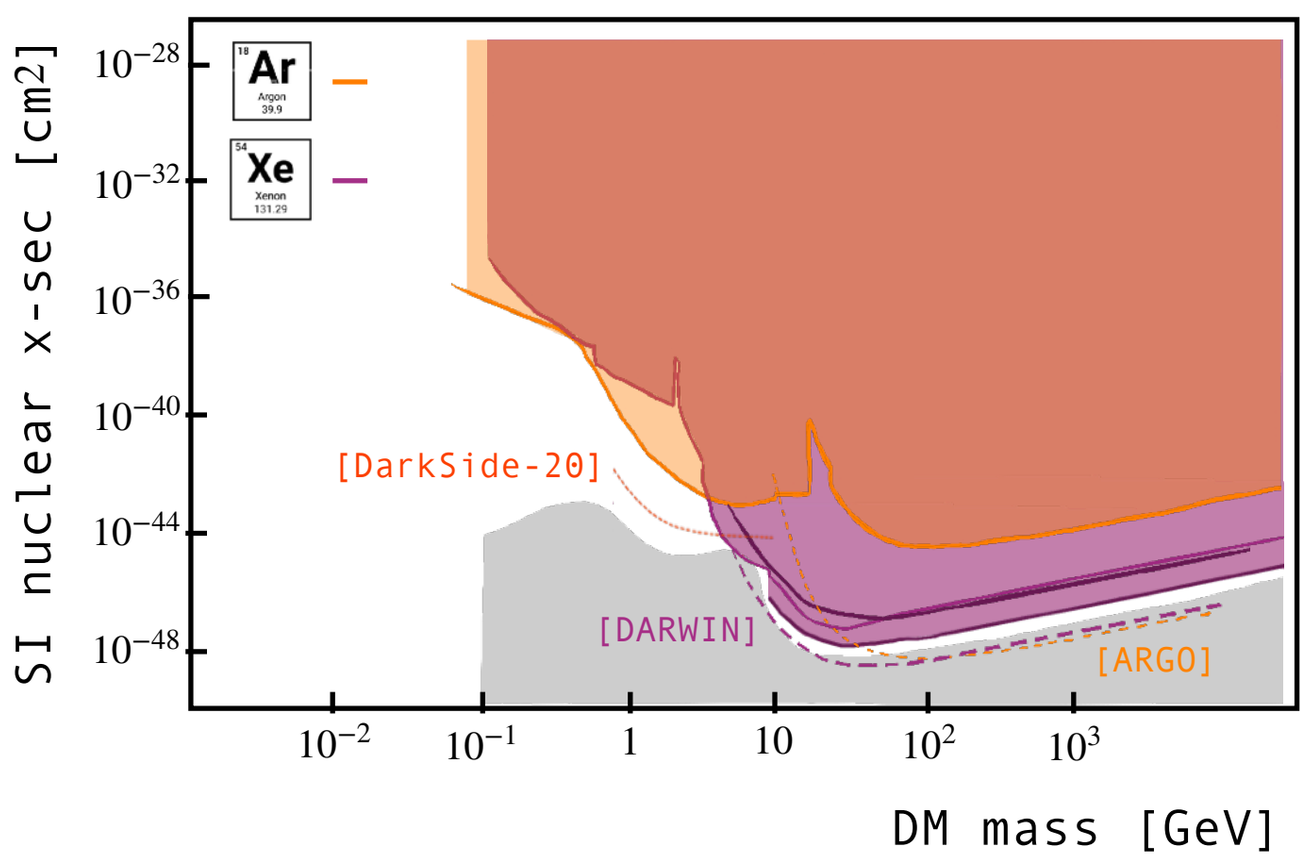
“Traditional” direct detection

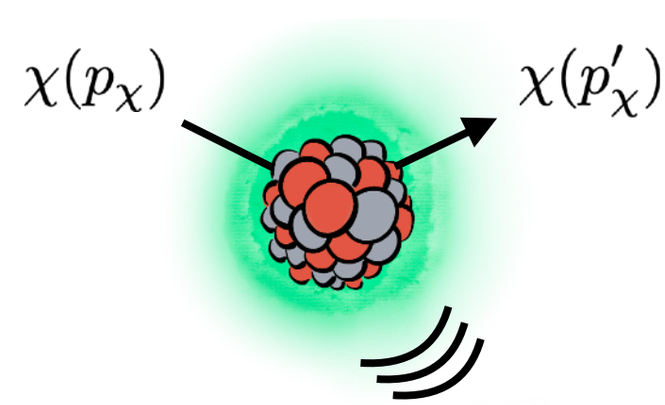
Nuclear recoils





WIMPs [2 x miracle]

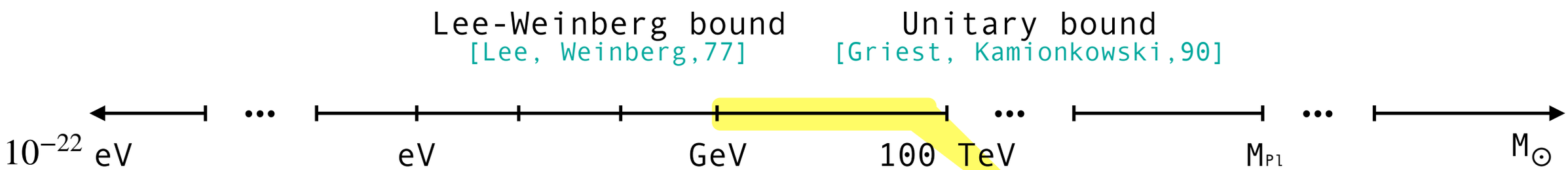


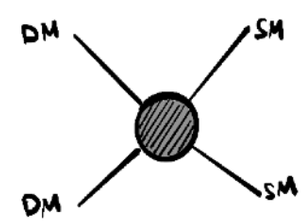


$$E_{\rm rec}^{\rm max} = \frac{q_{\rm max}^2}{2(A\ {\rm GeV})} > {\rm keV}$$

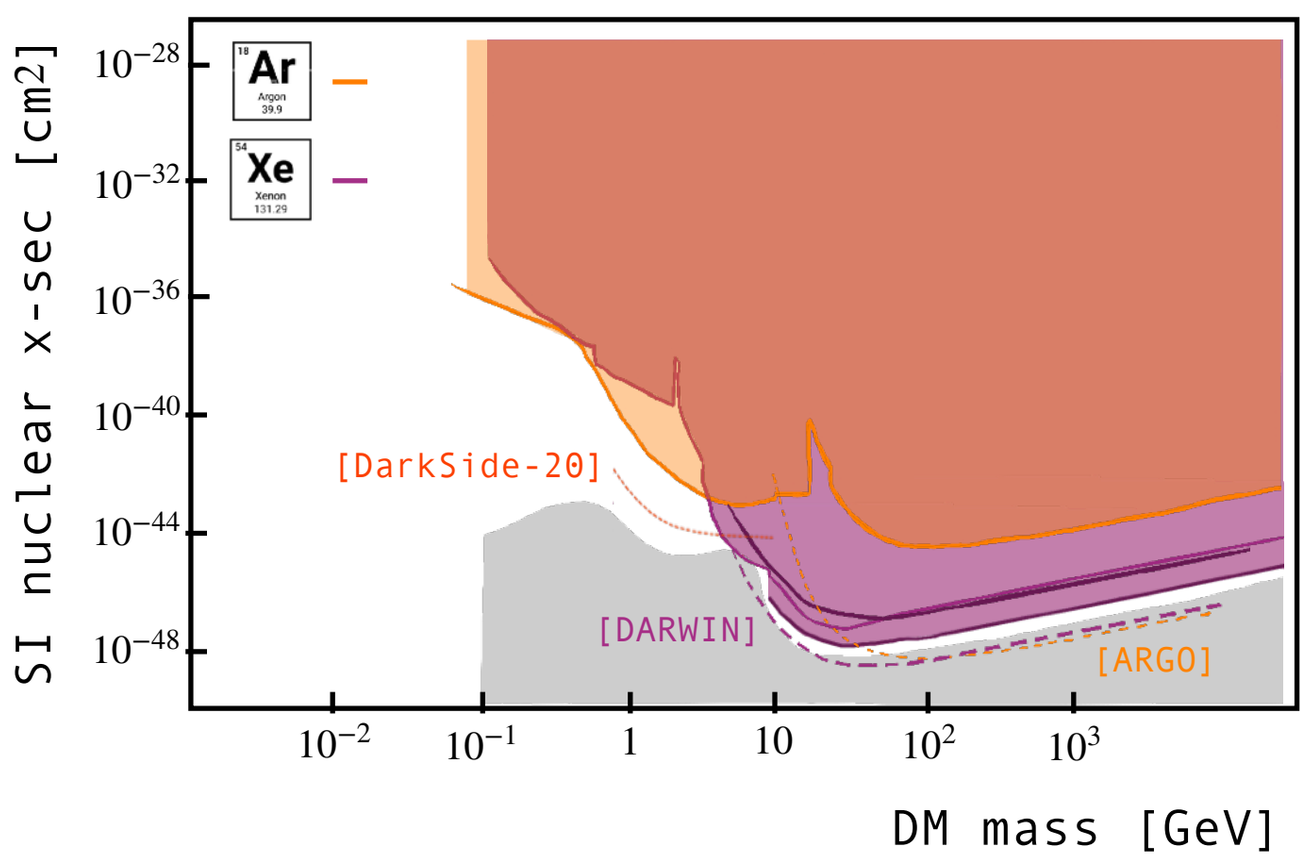
“Traditional” direct detection

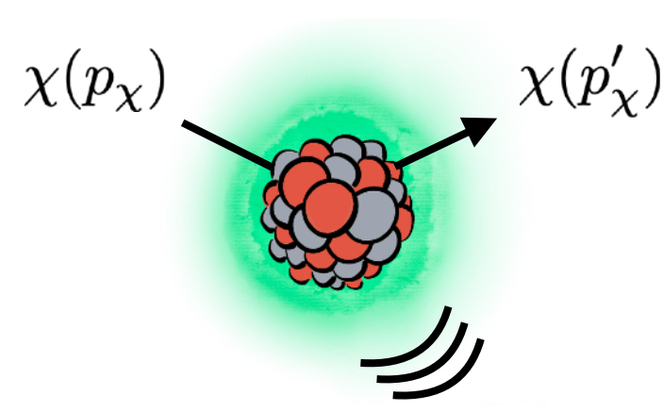
Nuclear recoils



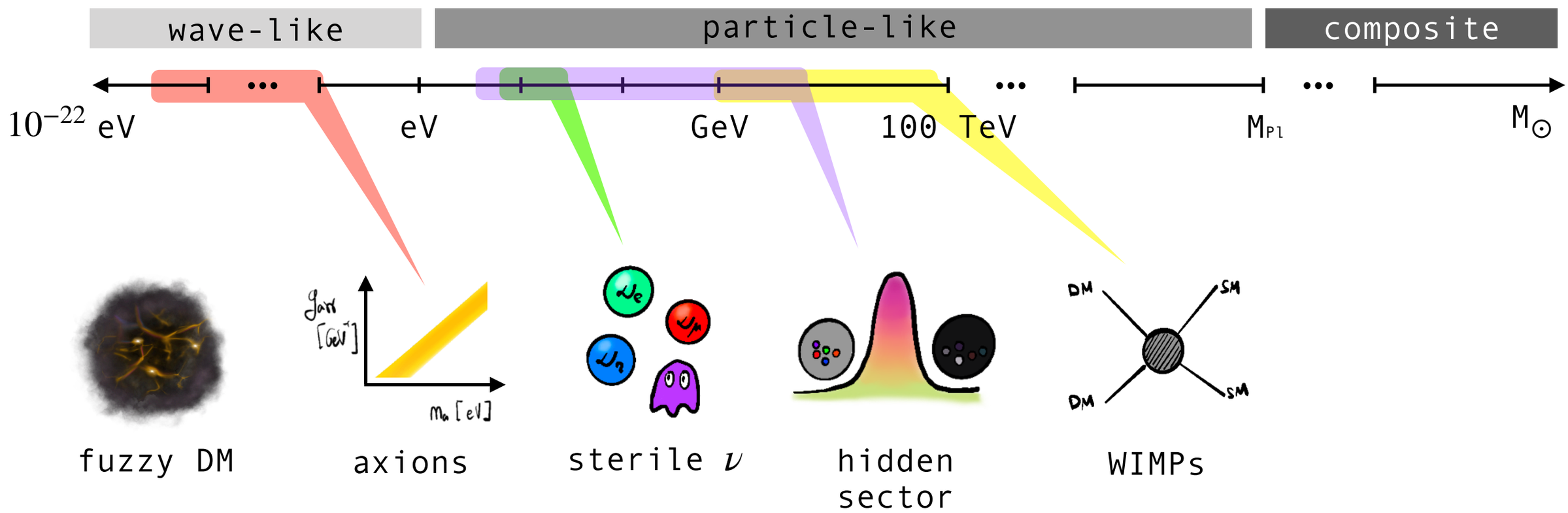


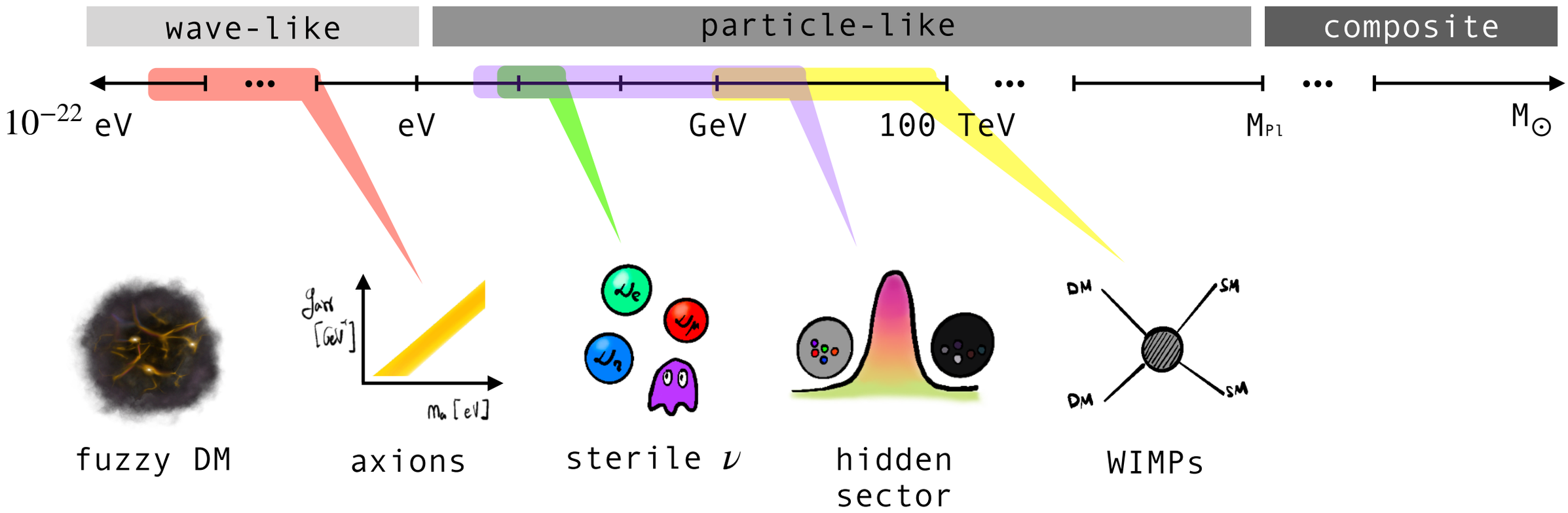
WIMPs [2 x miracle]

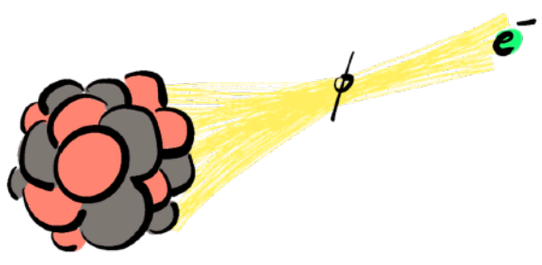


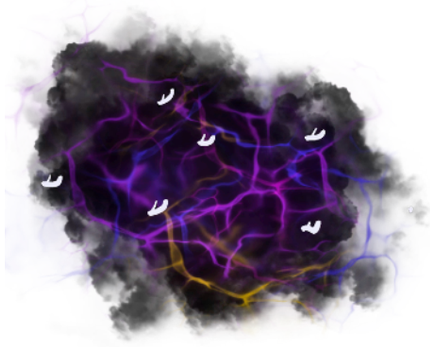


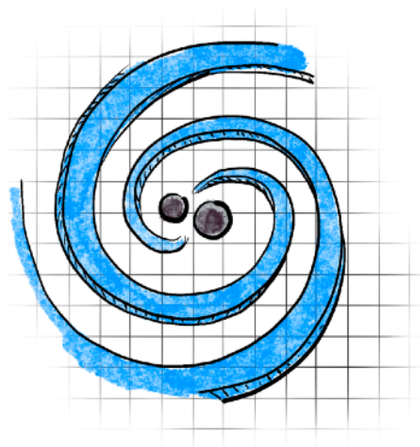
$$E_{\rm rec}^{\rm max} = \frac{4m_\chi^2 v_\chi^2}{2(A\ {\rm GeV})} > {\rm keV}$$


wave-like
particle-like
composite
10^{-22} eV
eV
GeV
100 TeV
M_{Pl}
$M_\odot$
$g_{a\gamma\gamma}$ [GeV^{-1}]
m_a [eV]
ν_e
ν_μ
ν_τ
DM
SM
DM
SM
fuzzy DM
axions
sterile ν
hidden sector
WIMPs







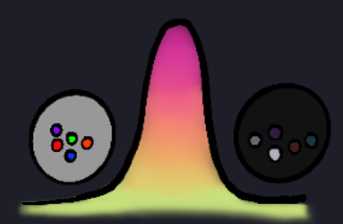


Also SM!

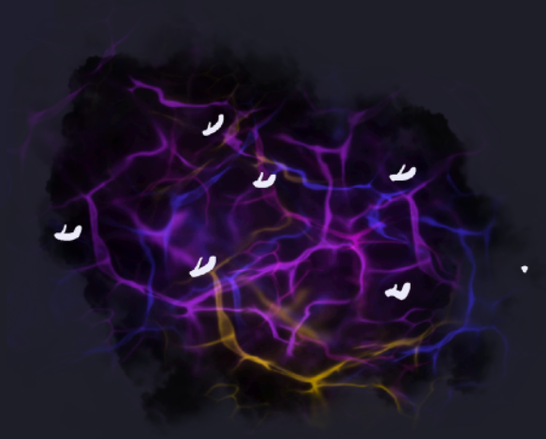
DEMAND FOR PRECISION IN LOW ENERGY PHYSICS (as well!!)

Lowering the threshold

There is plenty of room at the bottom!



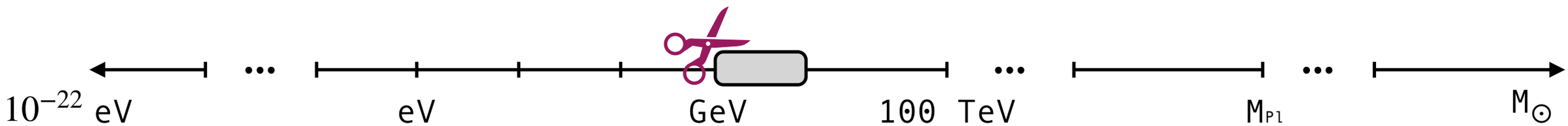
WIMPs



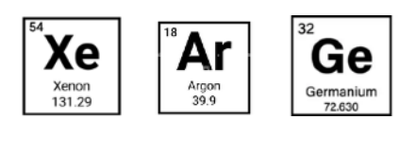
How do we “direct-detect” elusive particles?

Lowering the threshold

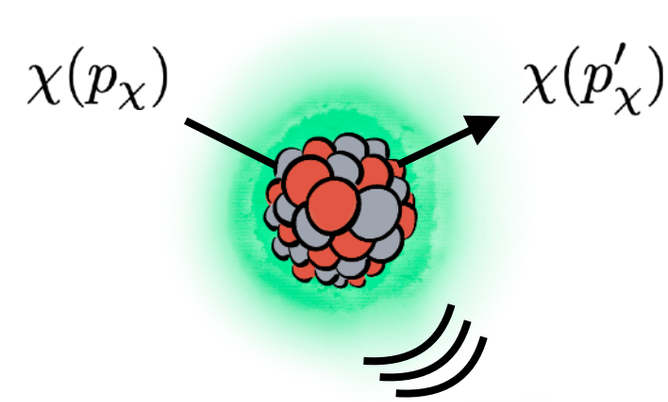
Direct detection



Nuclear recoil
PTM exp.



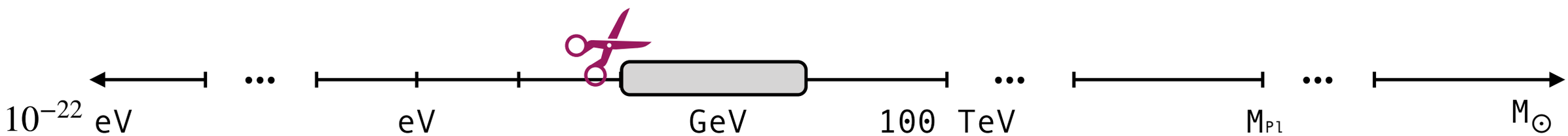
~keV energy resolution



LZ, PandaX, XENON, DarkSide, DEAP…

Lowering the threshold

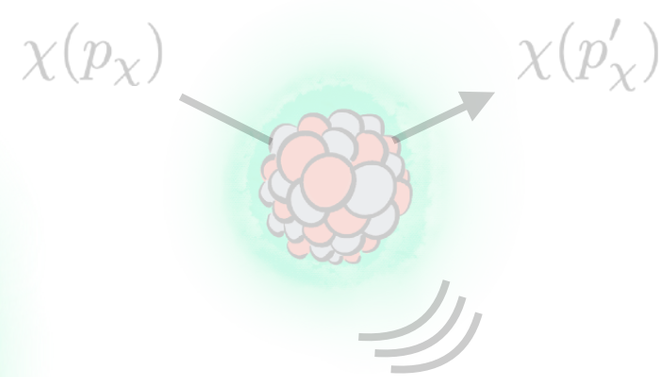
Direct detection



Nuclear recoil
PTM exp.

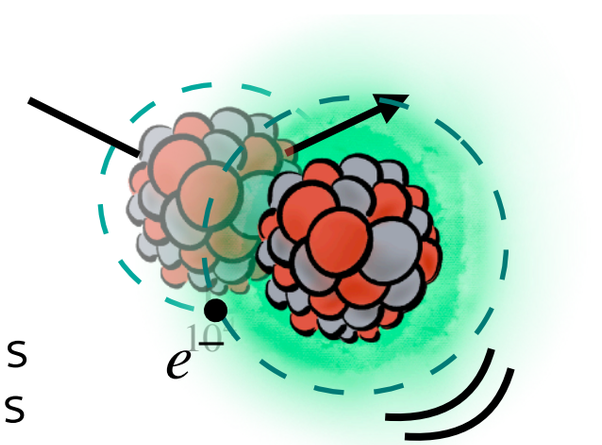
...

~keV energy resolution



~eV energy resolution

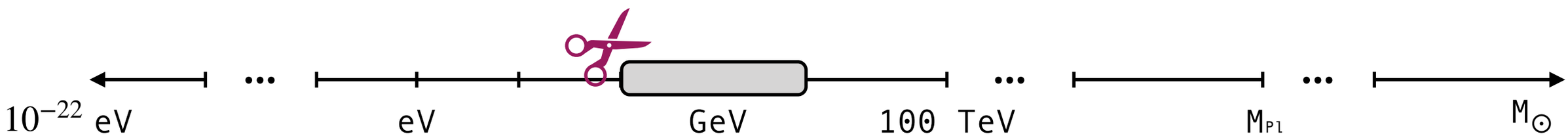
Migdal Effects
Semiconductors



LZ, PandaX, XENON, DarkSide, DEAP…

Lowering the threshold

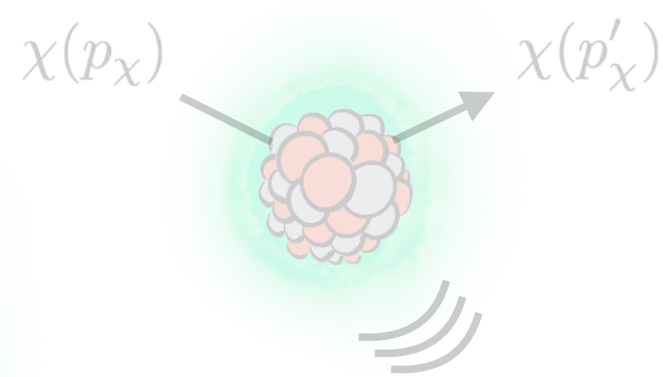
Direct detection

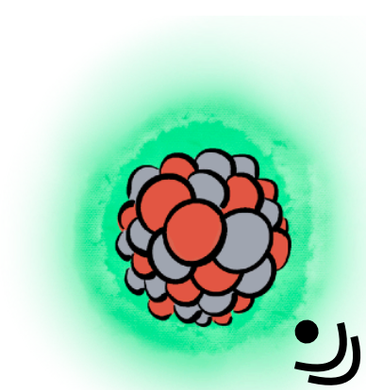


Nuclear recoil
PTM exp.

...

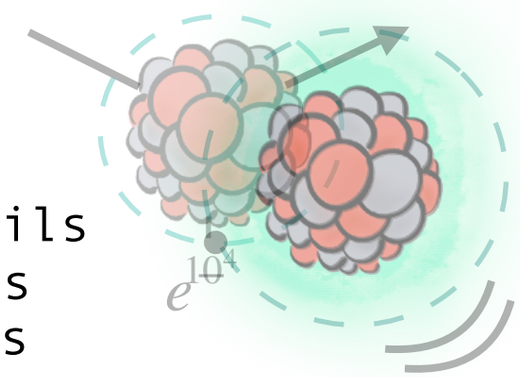
~keV energy resolution





~eV energy resolution

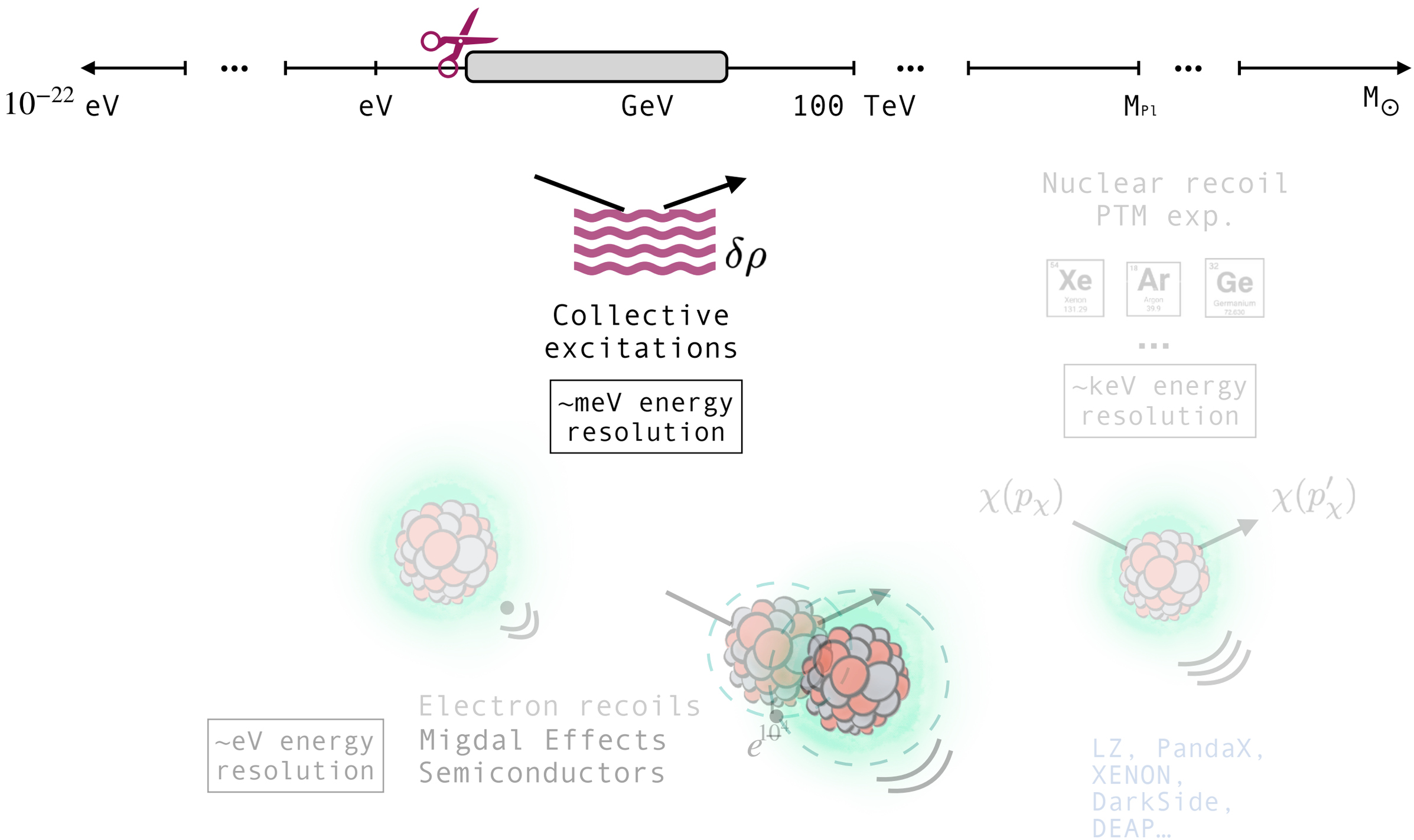
Electron recoils
Migdal Effects
Semiconductors



LZ, PandaX, XENON, DarkSide, DEAP…

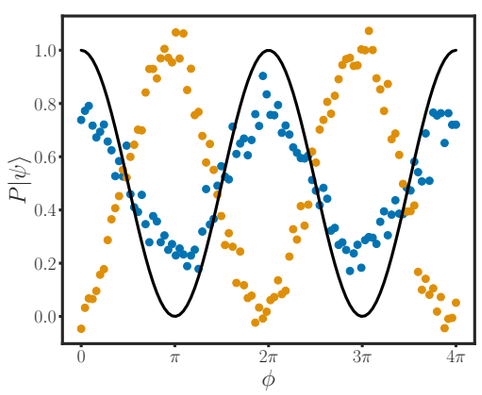
Lowering the threshold

Direct detection



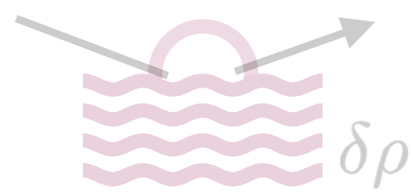
Lowering the threshold

Direct detection



Atom interferometers

nearly thresholdless



Collective excitations

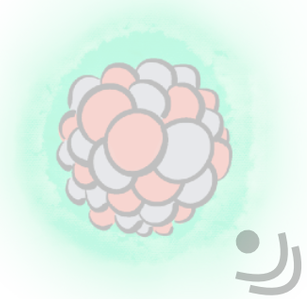
~meV energy resolution

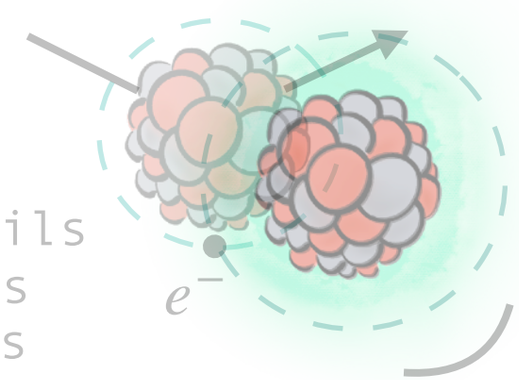
Nuclear recoil PTM exp.

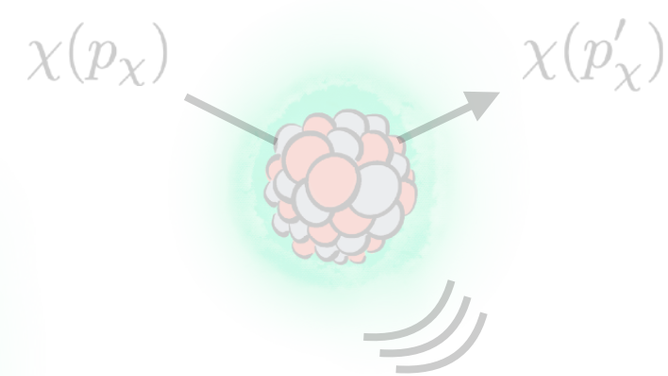
Xe Ar Ge

...

~keV energy resolution







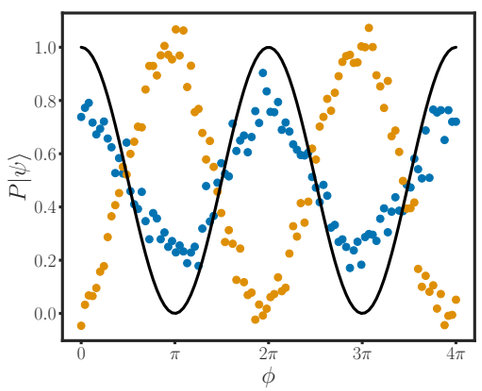
~eV energy resolution

Electron recoils
Migdal Effects
Semiconductors

LZ, PandaX, XENON, DarkSide, DEAP…

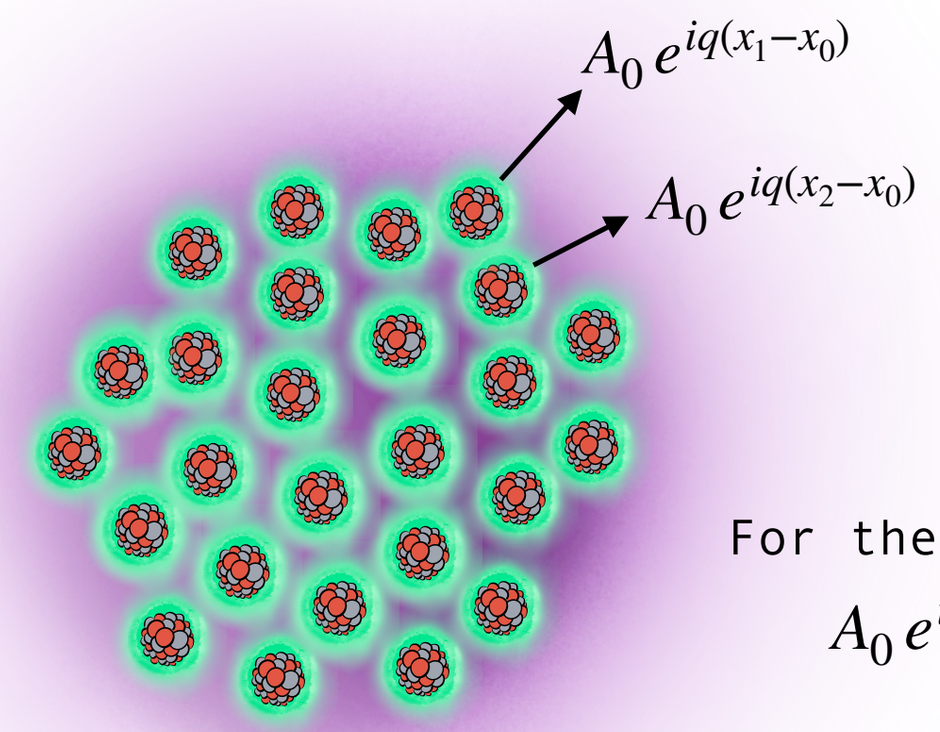
Advantages of low threshold detectors

1 coherent enhancements



Atom interferometers

nearly thresholdless



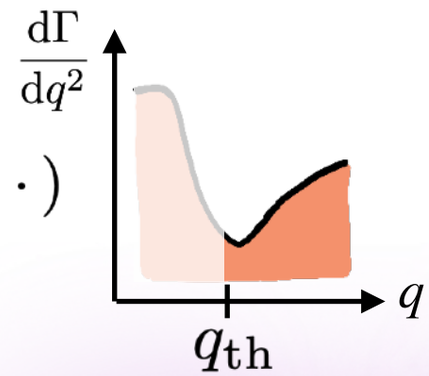
For the ith atom,

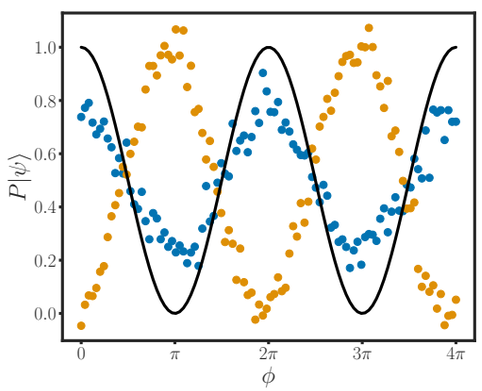
$$A_0\, e^{iq(x_i-x_0)}$$

Advantages of low threshold detectors

1 coherent enhancements

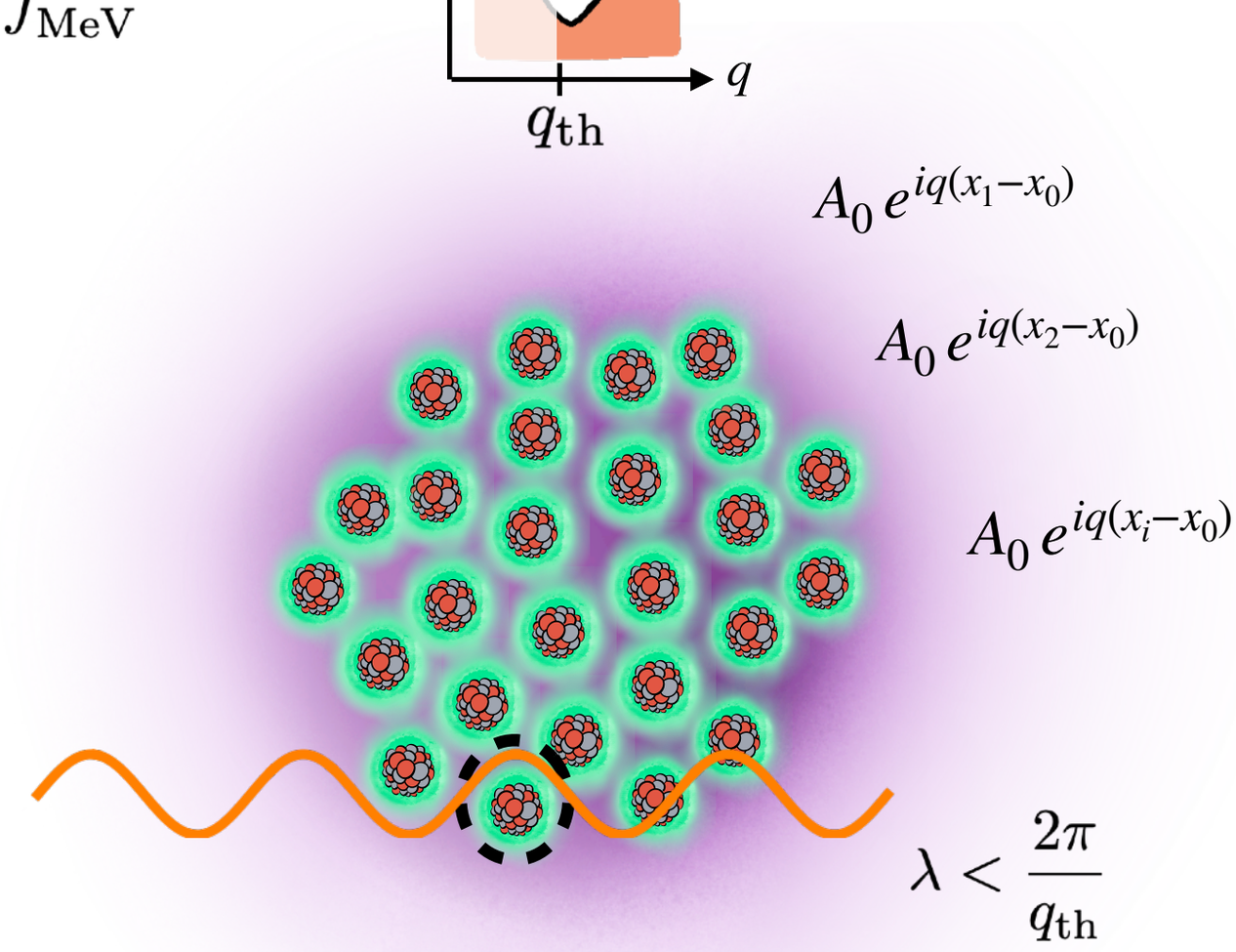
$$\Gamma \propto \int_{\mathrm{MeV}}^{q_{\max}} \mathrm{d}q^2\,(\cdots)$$





Atom interferometers

nearly thresholdless

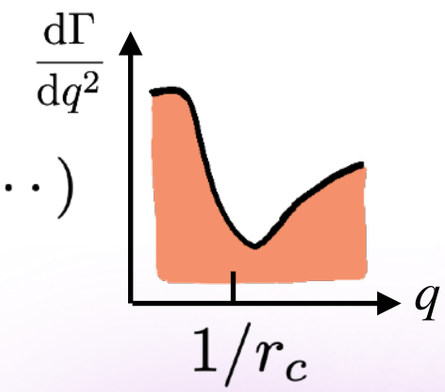


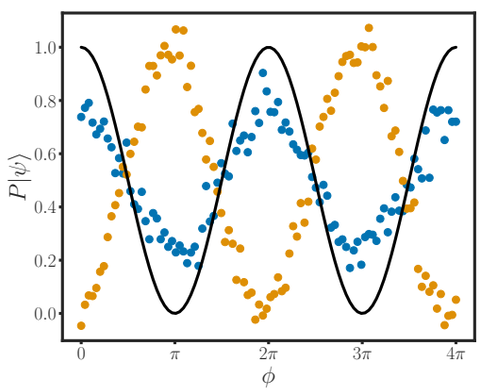
$$\Gamma = |\sum_{i=1}^{N} A_i|^2 \simeq N|A_0|^2$$

Advantages of low threshold detectors

1 coherent enhancements

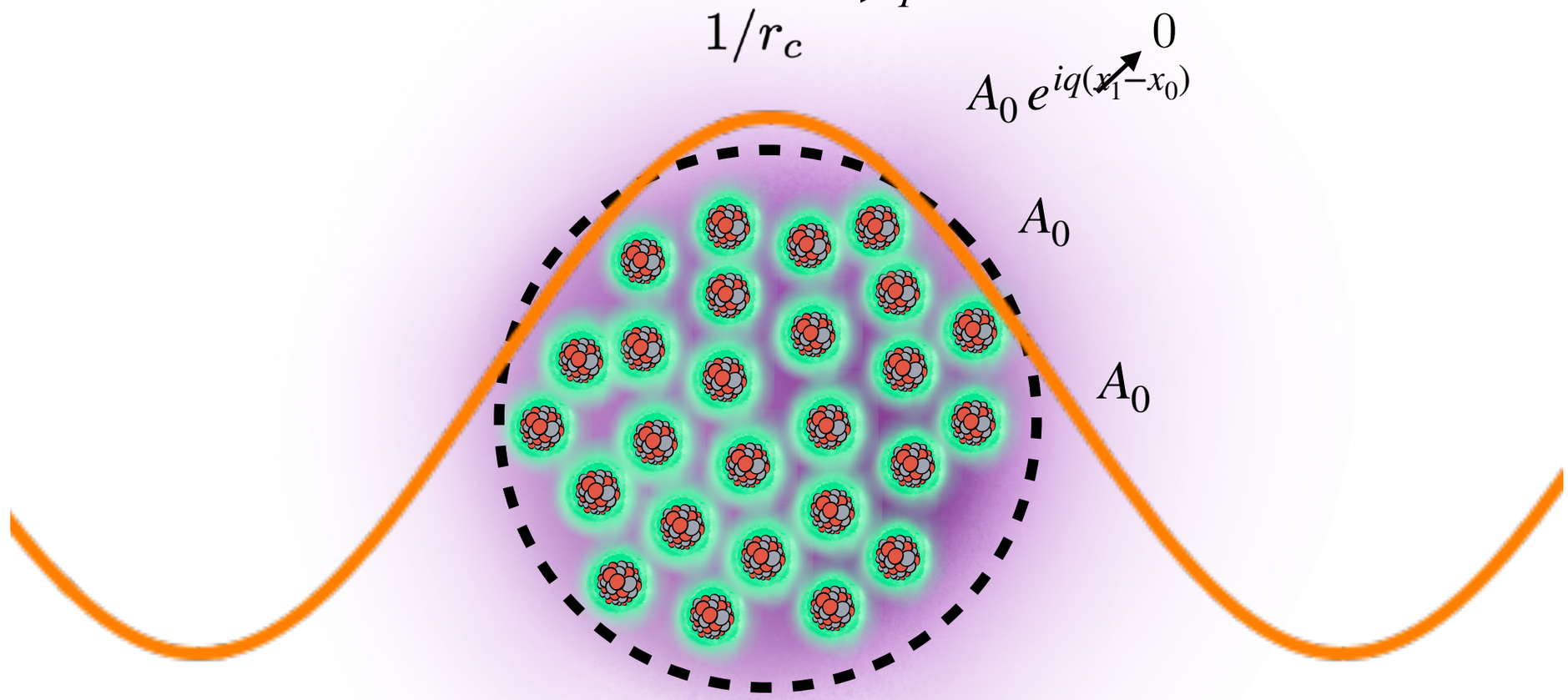
$$\Gamma \propto \int_0^{q_{\max}} \mathrm{d}q^2\,(\cdots)$$





Atom interferometers

nearly thresholdless

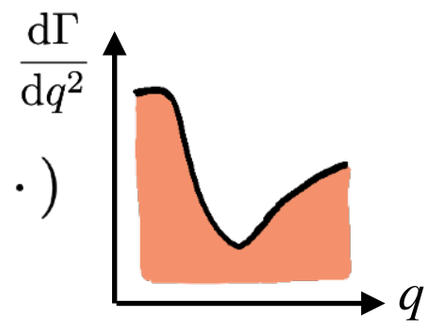


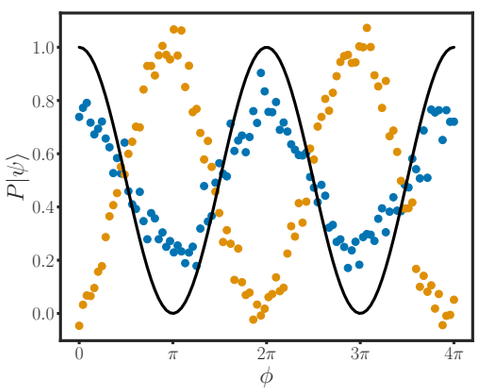
$$\Gamma = |\sum_{i=1}^{N} A_i|^2 = N^2 |A_0|^2$$

Advantages of low threshold detectors

1 coherent enhancements

$$\Gamma \propto \int_0^{q_{\max}} \mathrm{d}q^2 \, (\cdots)$$





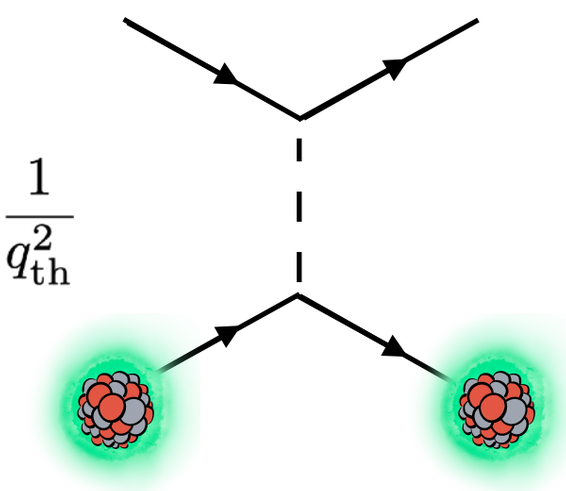
Atom interferometers

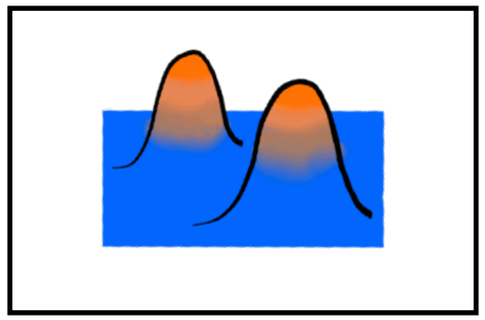
nearly thresholdless

$$\Gamma = |\sum_{i=1}^{N} A_i|^2 = N^2 |A_0|^2$$

2 boosted rates

$$\Gamma \propto \int_{q_{\mathrm{th}}}^{q_{\max}} \mathrm{d}q^2 \, \frac{1}{(q^2 + m_{\mathrm{med}}^2)^2} \sim \frac{1}{q_{\mathrm{th}}^2}$$

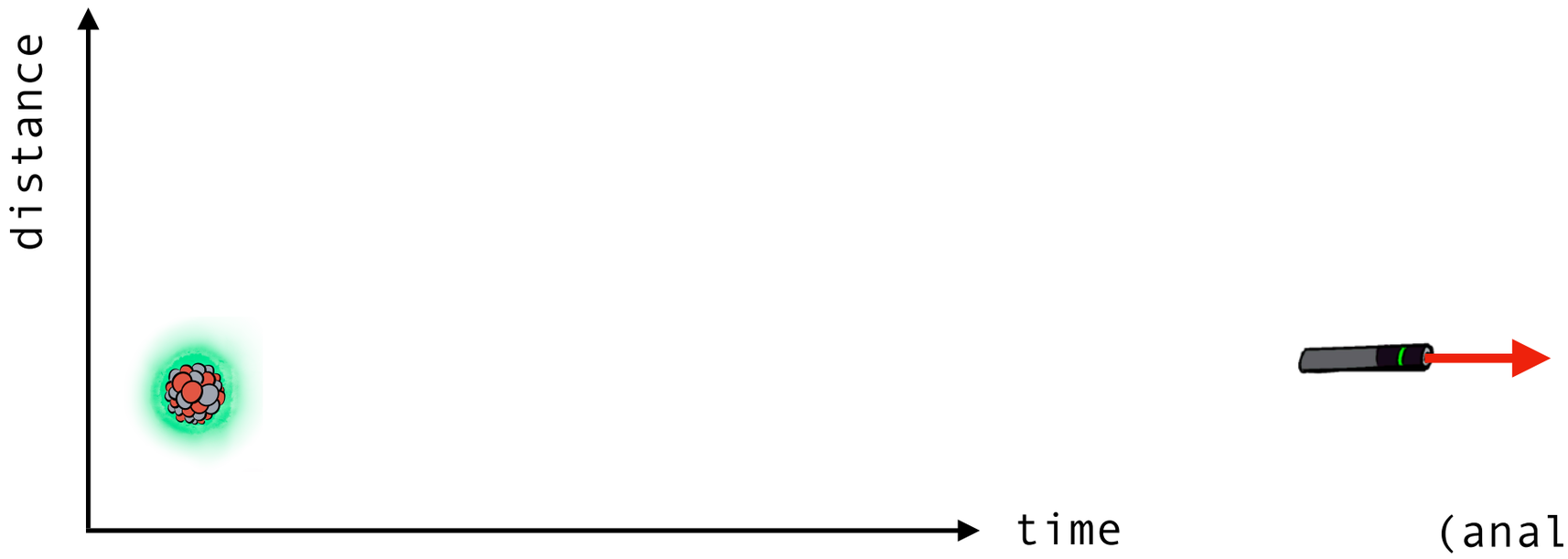




How do atom interferometers access Γ?

Atom interferometry

1 atom

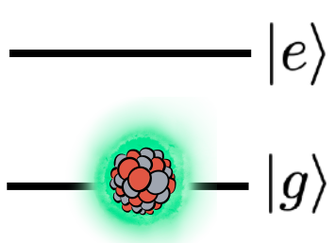


(analogy with light)

state preparation

evolution

measurement



Atom interferometry

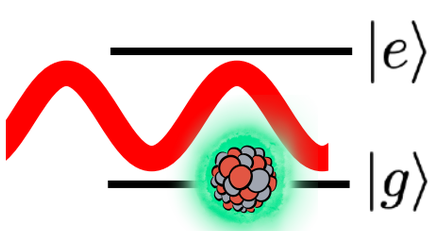
1 atom

(analogy with light)

state preparation

evolution

measurement



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

$$|\Psi(t_p)\rangle = c_g(t_p)|g\rangle \otimes |0\rangle + c_e(t_p)|e\rangle \otimes |k_\gamma\rangle$$

Atom interferometry

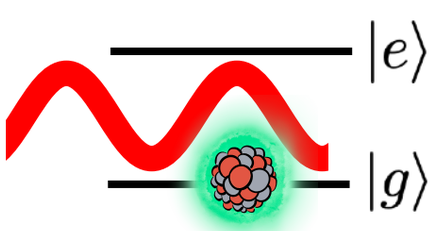
1 atom

(analogy with light)

state preparation

evolution

measurement

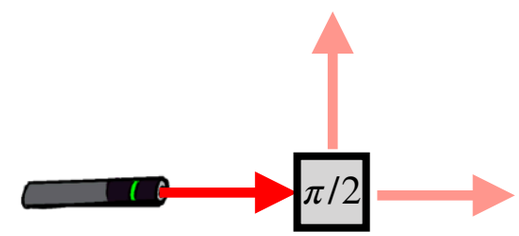


$|\Delta \mathbf{k}| = \Delta\omega$

$$\Rightarrow |\Psi(t_p)\rangle = \cos\left(\frac{\Omega\, t_p}{2}\right)|g\rangle \otimes |0\rangle + \sin\left(\frac{\Omega\, t_p}{2}\right) \mathrm{e}^{\mathrm{i}\phi}|e\rangle \otimes |k_\gamma\rangle$$

Atom interferometry

1 atom

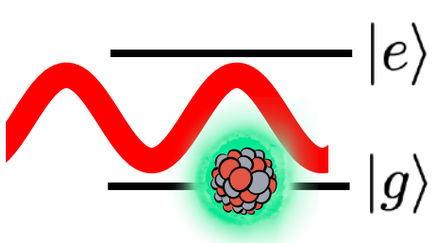


(analogy with light)

state preparation

evolution

measurement

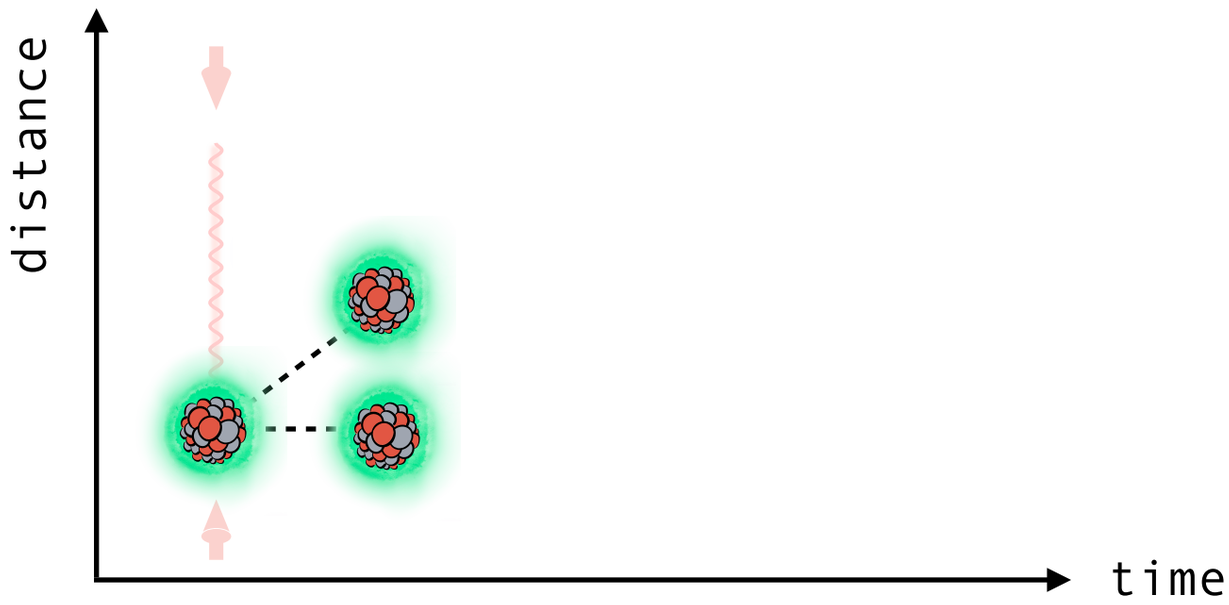


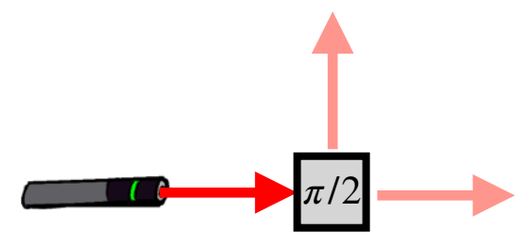
$$|\Delta \mathbf{k}| = \Delta\omega$$

$$\Rightarrow |\Psi(t_{\pi/2})\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle \otimes |0\rangle + \mathrm{e}^{\mathrm{i}\phi}|e\rangle \otimes |k_\gamma\rangle\right)$$

Atom interferometry

1 atom



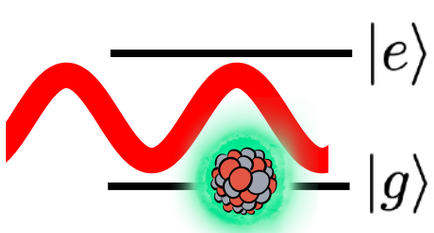


(analogy with light)

state preparation

evolution

measurement

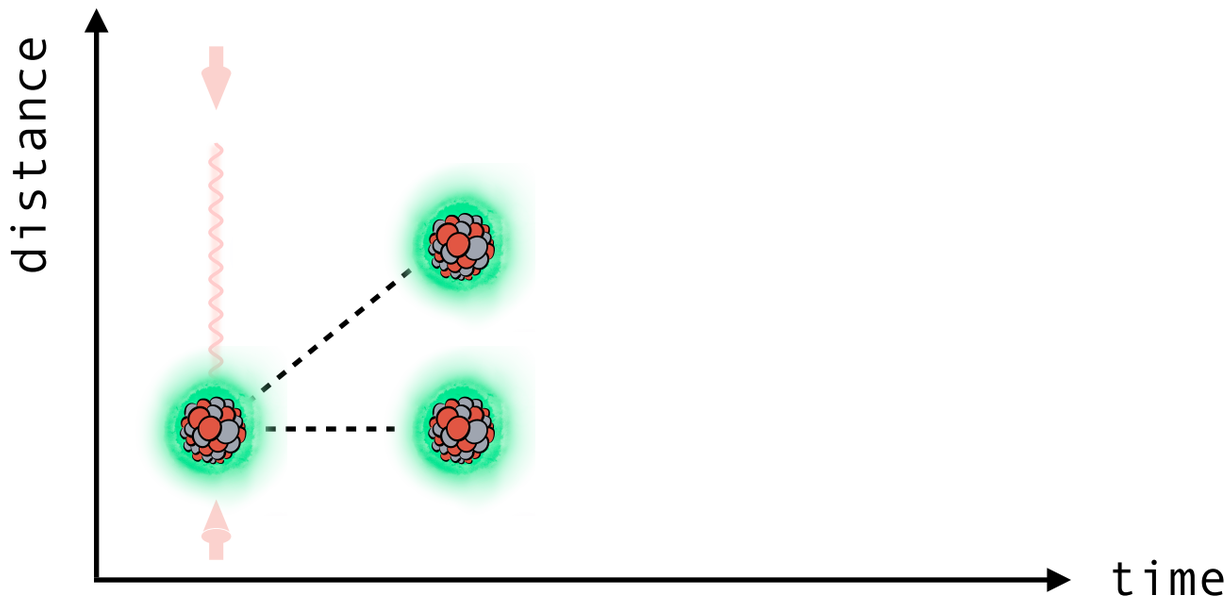


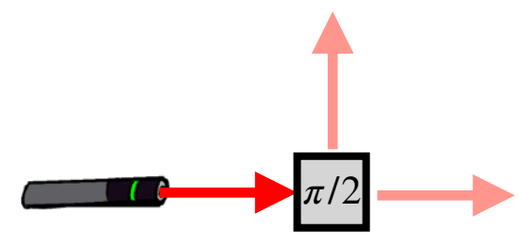
$|\Delta \mathbf{k}| = \Delta\omega$

$$|\Psi(t_{\pi/2})\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle \otimes |0\rangle + \mathrm{e}^{\mathrm{i}\phi}|e\rangle \otimes |k_\gamma\rangle\right)$$

Atom interferometry

1 atom



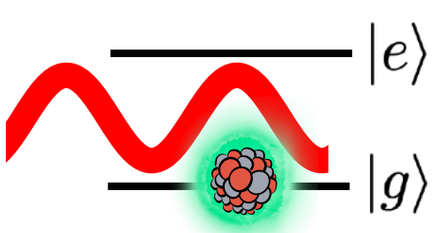


(analogy with light)

state preparation

evolution

measurement

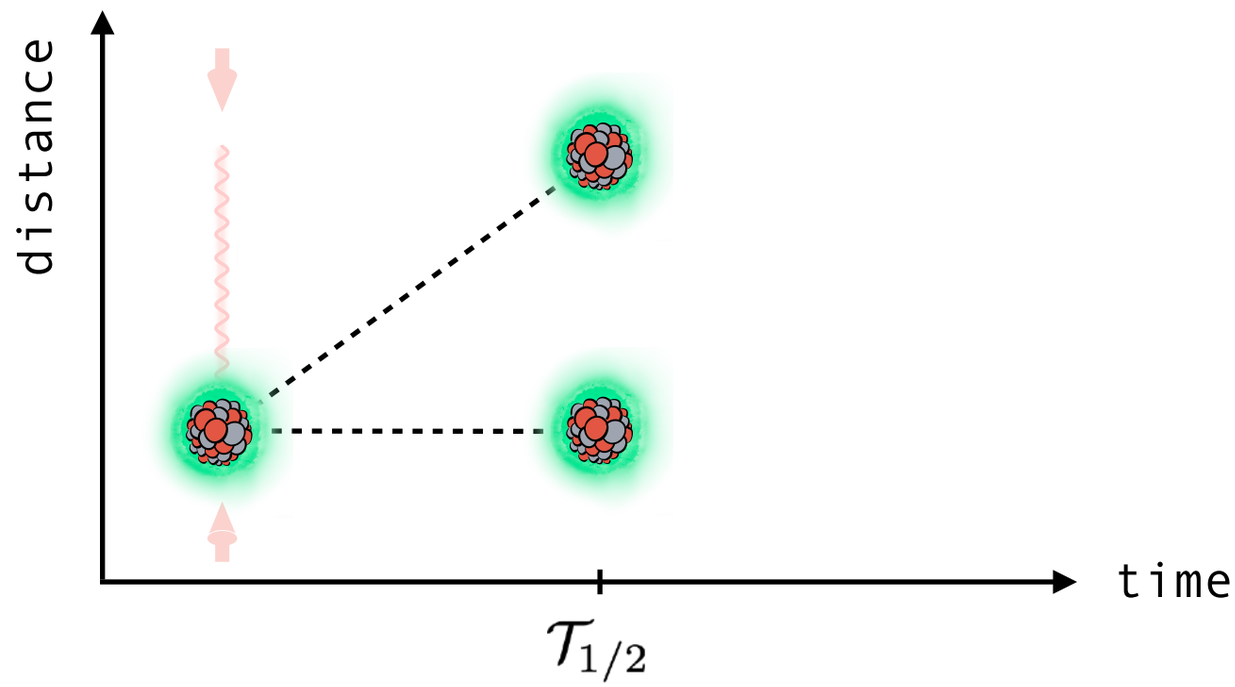


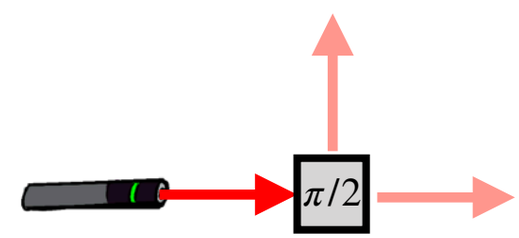
$|\Delta \mathbf{k}| = \Delta\omega$

$$|\Psi(t_{\pi/2})\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle \otimes |0\rangle + \mathrm{e}^{\mathrm{i}\phi}|e\rangle \otimes |k_\gamma\rangle\right)$$

Atom interferometry

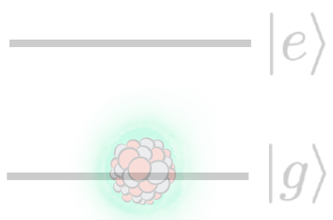
1 atom





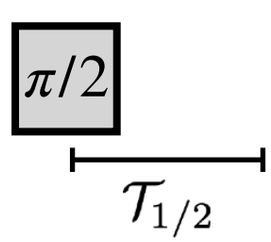
(analogy with light)

state preparation



evolution

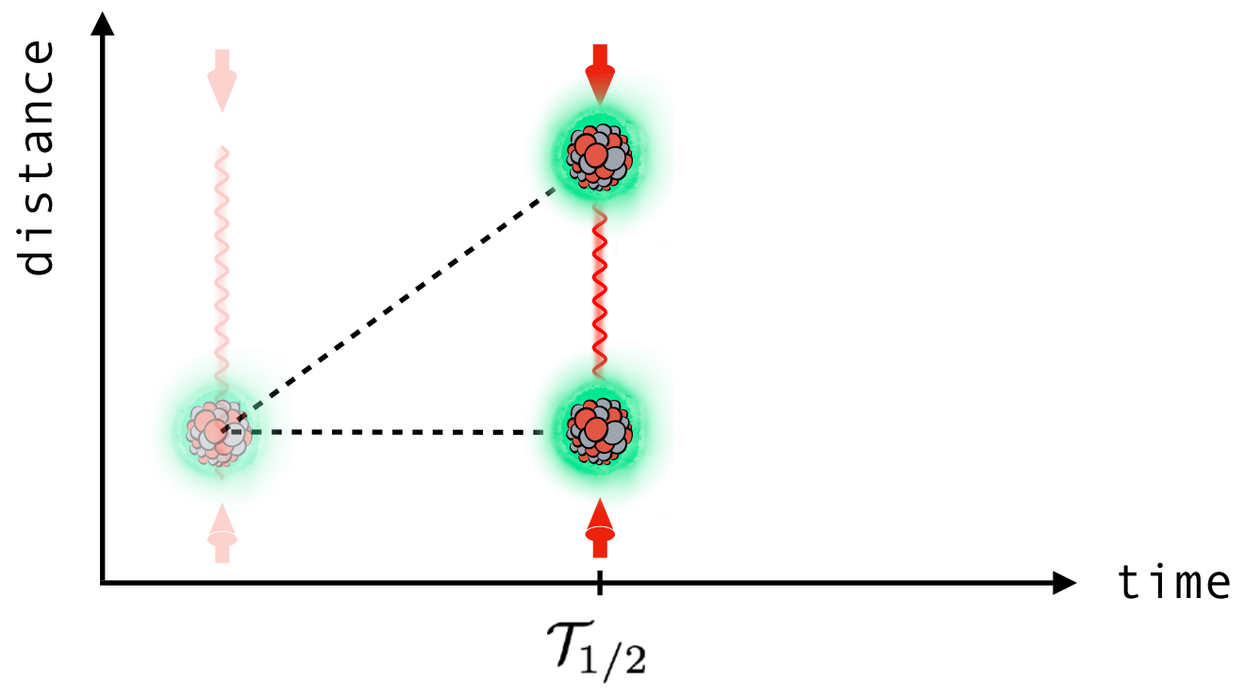
$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$$

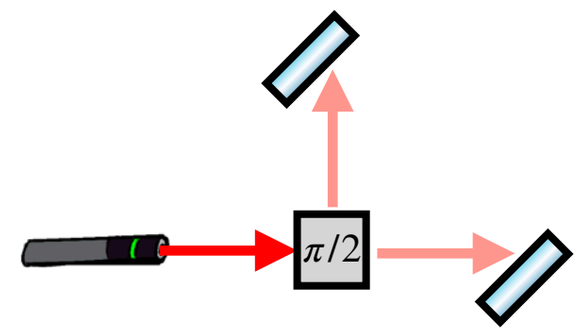


measurement

Atom interferometry

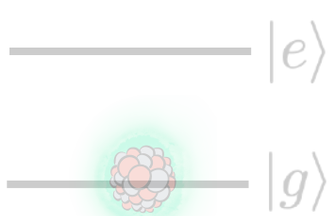
1 atom





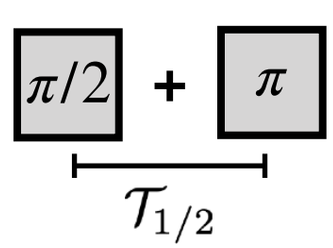
(analogy with light)

state preparation



evolution

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$$

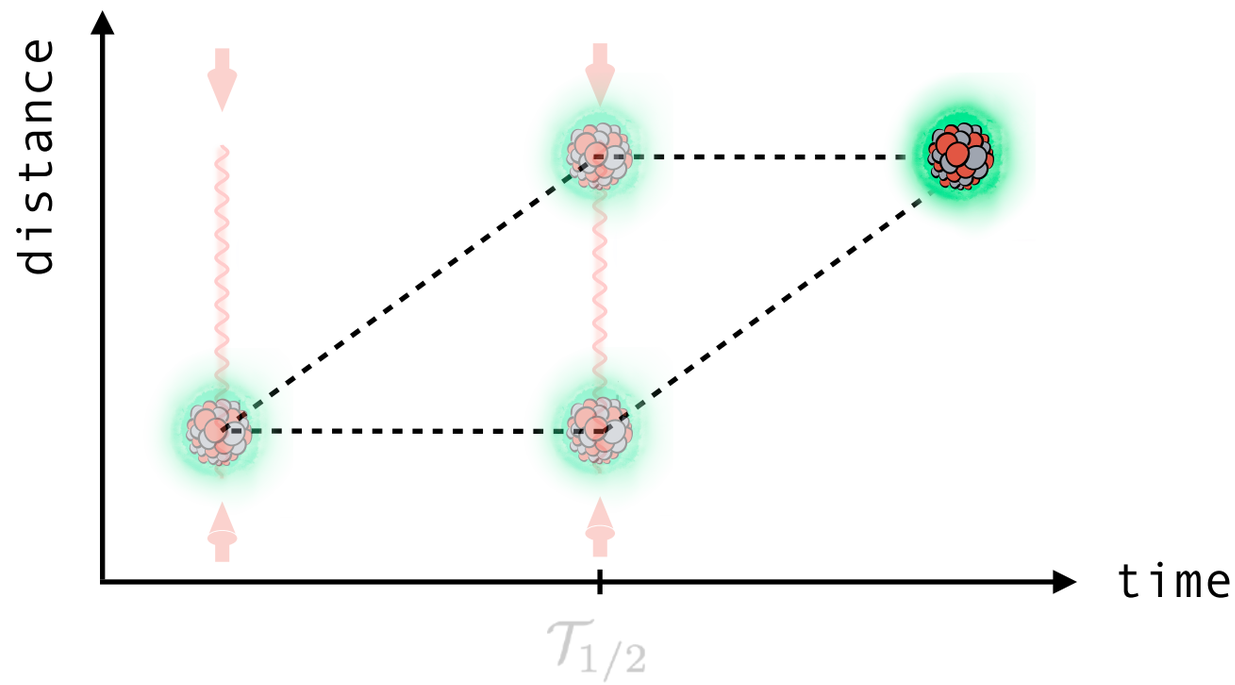


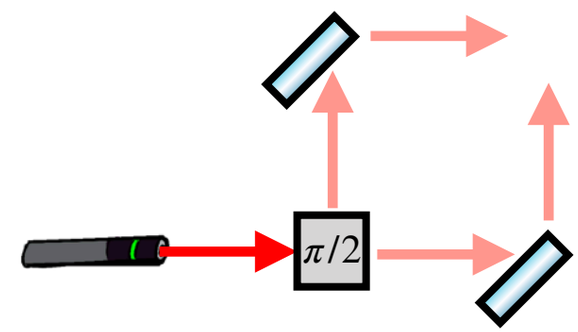
measurement

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

Atom interferometry

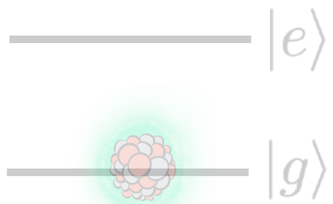
1 atom





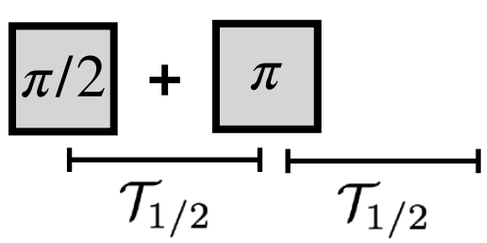
(analogy with light)

state preparation



evolution

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}]$$

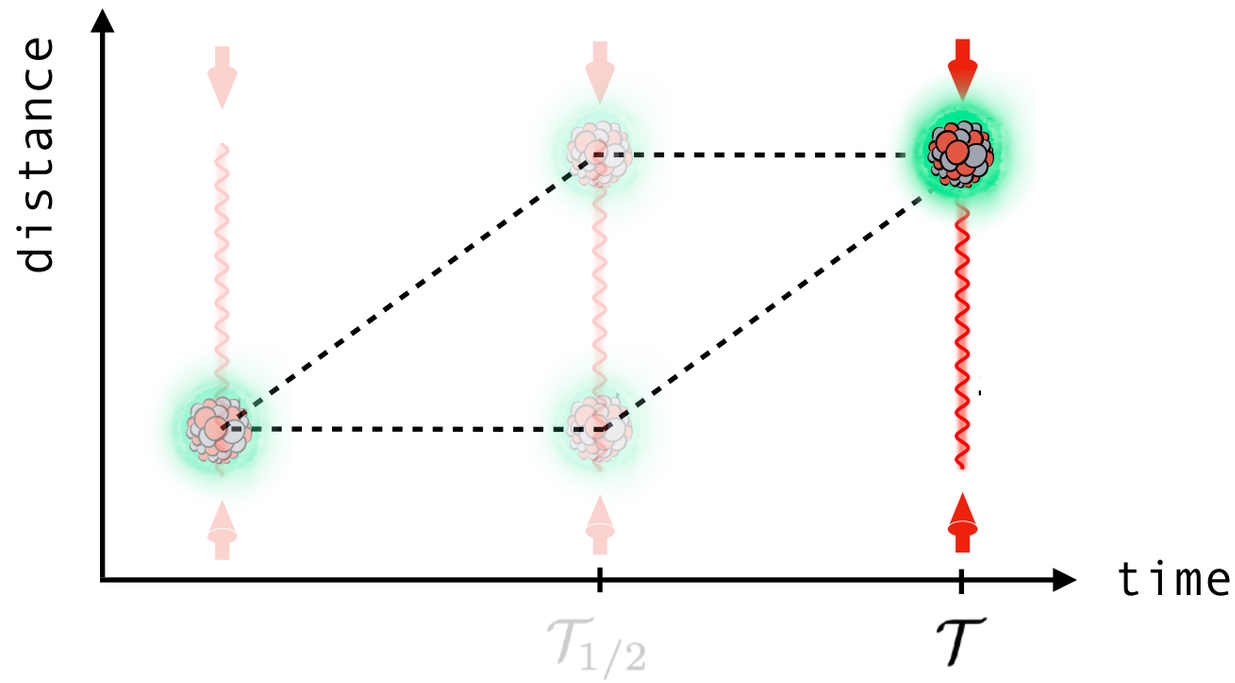


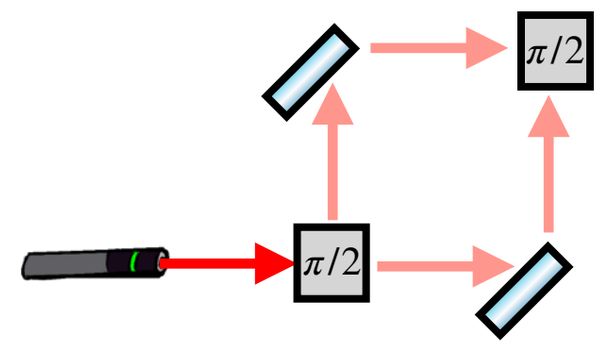
measurement

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

Atom interferometry

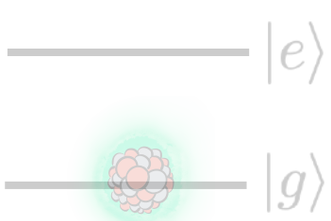
1 atom





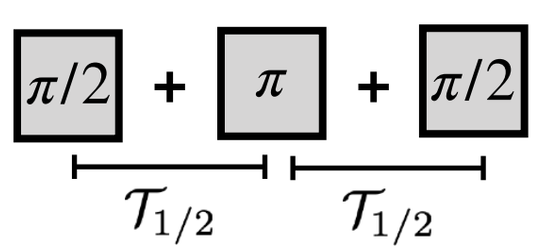
(analogy with light)

state preparation



evolution

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}]$$

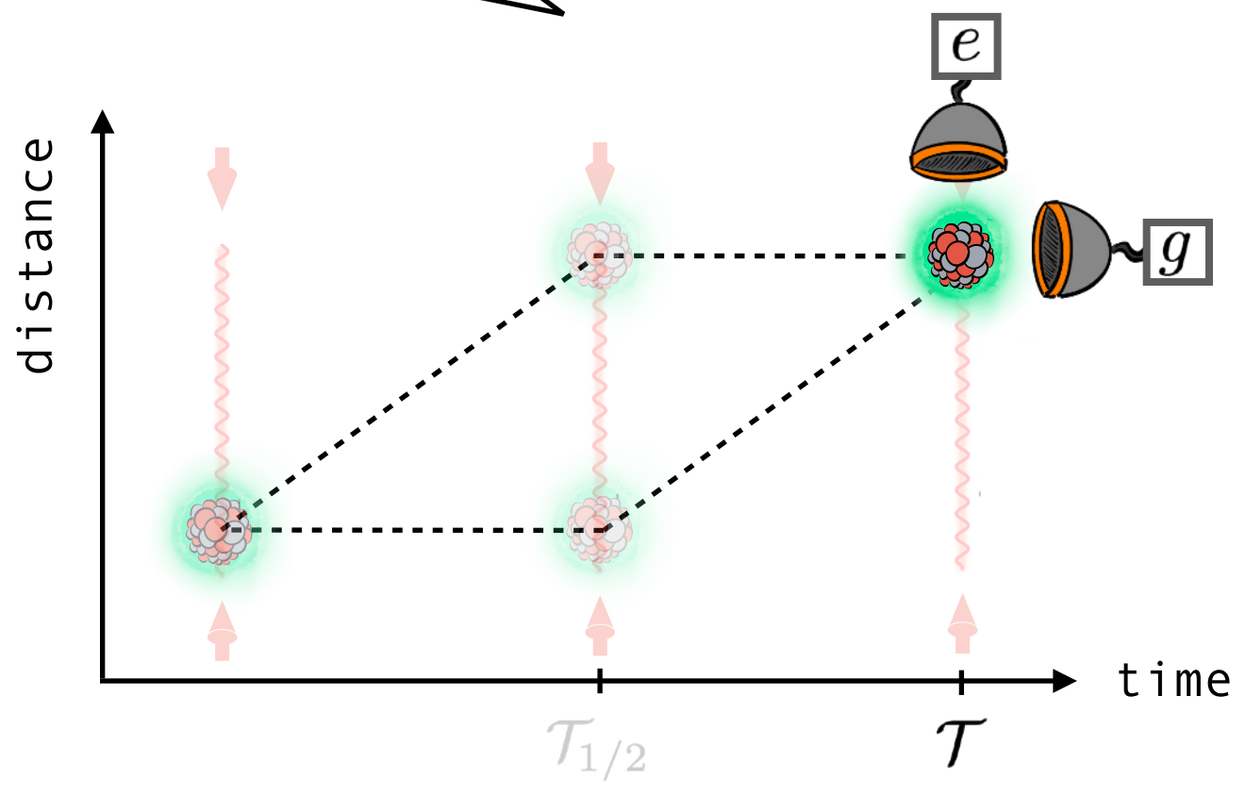


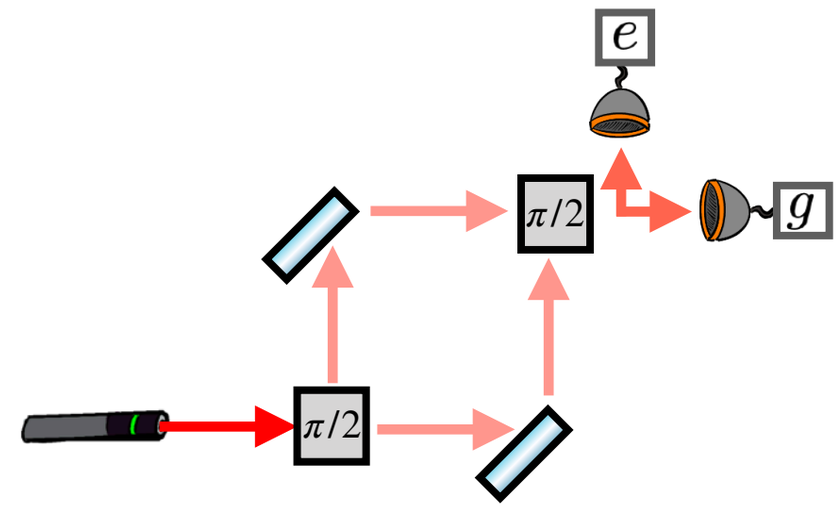
measurement

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

Atom interferometry

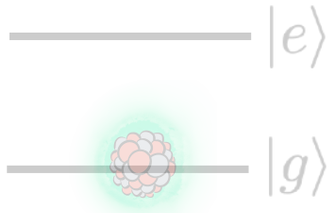
1 atom





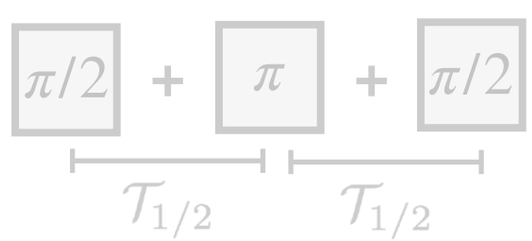
(analogy with light)

state preparation



evolution

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}]$$

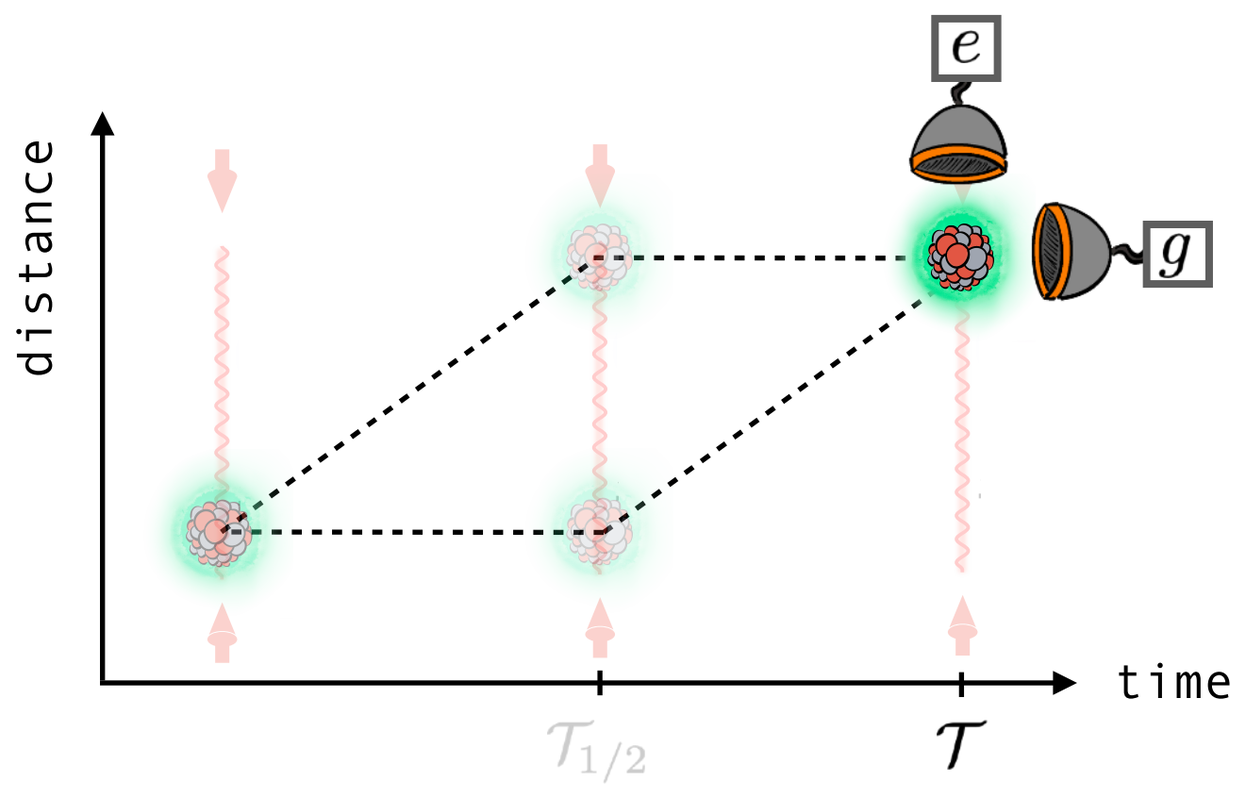


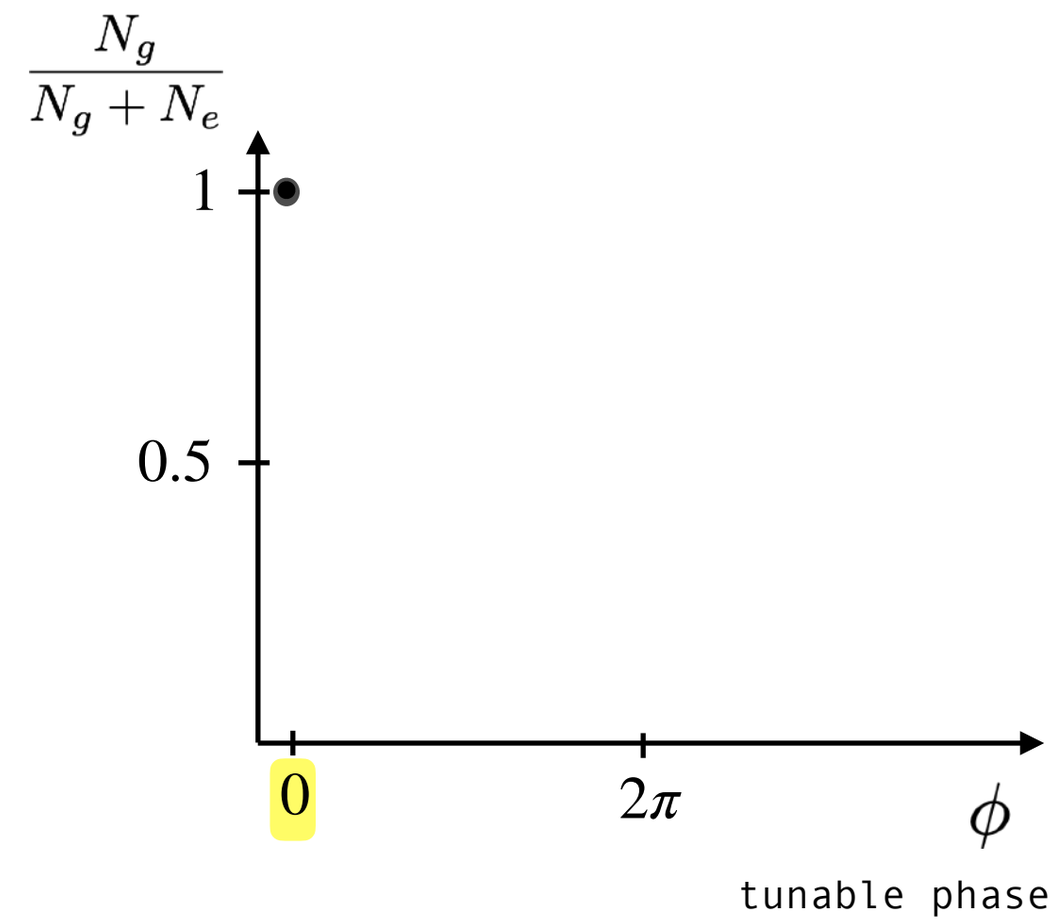
measurement

$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

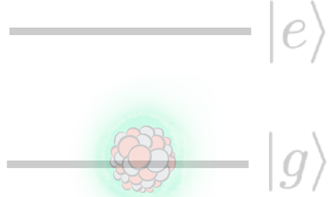
Atom interferometry

1 atom





state preparation



evolution

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$$

$$\underbrace{\boxed{\pi/2} + \boxed{\pi}}_{\mathcal{T}_{1/2}} + \underbrace{\boxed{\pi/2}}_{\mathcal{T}_{1/2}}$$

measurement

$$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(0)$$

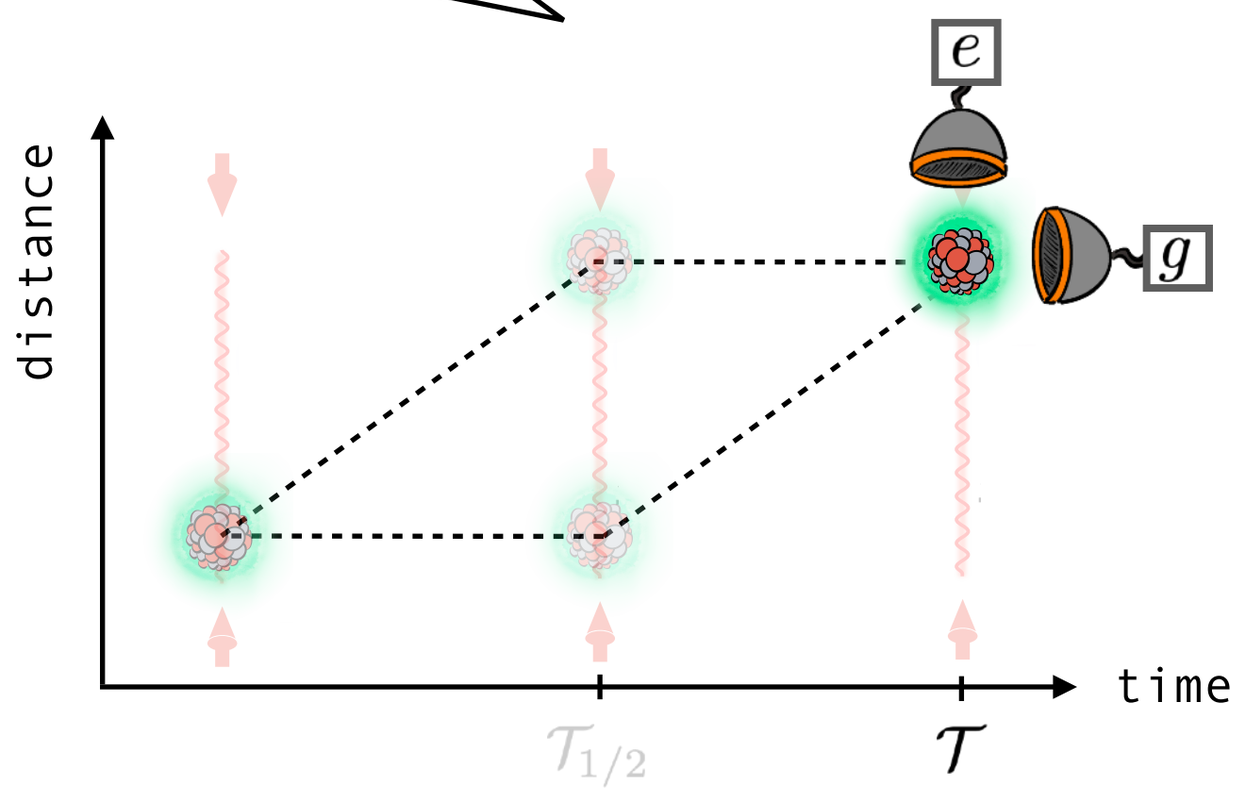
$$\Downarrow$$

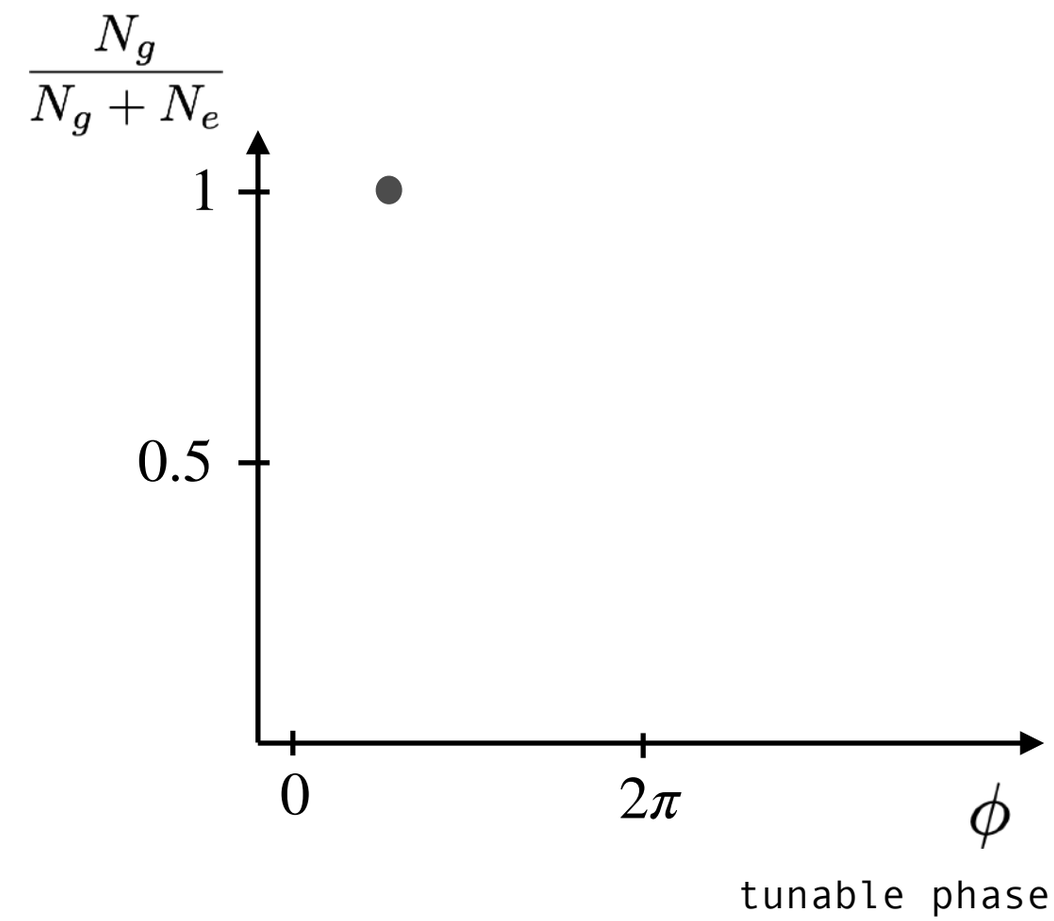
$$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{exp}}(0) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(0)$$

$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{i} \\ -\mathrm{i} & 1 \end{pmatrix}$$

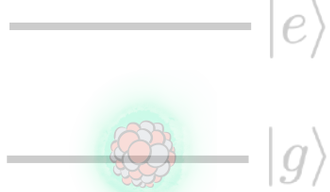
Atom interferometry

1 atom





state preparation



evolution

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$$

$$\underbrace{\boxed{\pi/2} + \boxed{\pi}}_{\mathcal{T}_{1/2}} + \underbrace{\boxed{\pi/2}}_{\mathcal{T}_{1/2}}$$

measurement

$$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\pi/2)$$

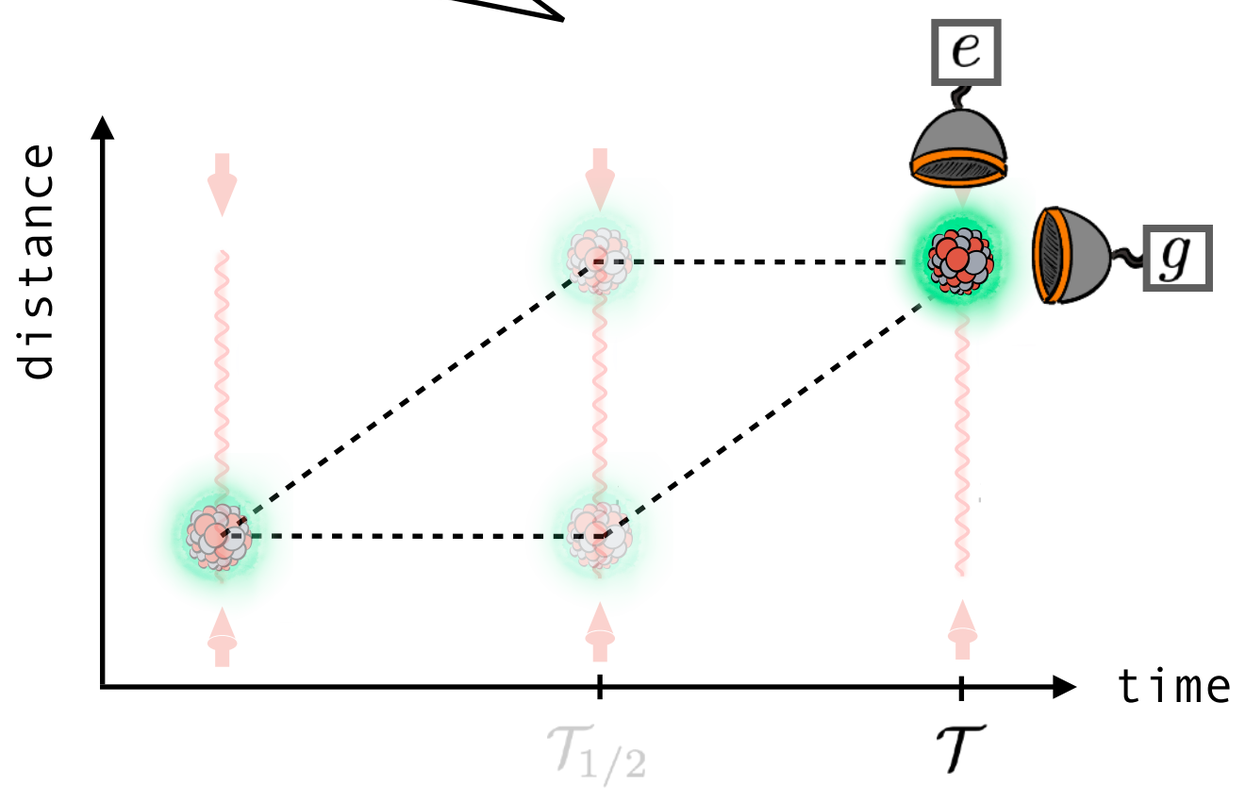
$$\Downarrow$$

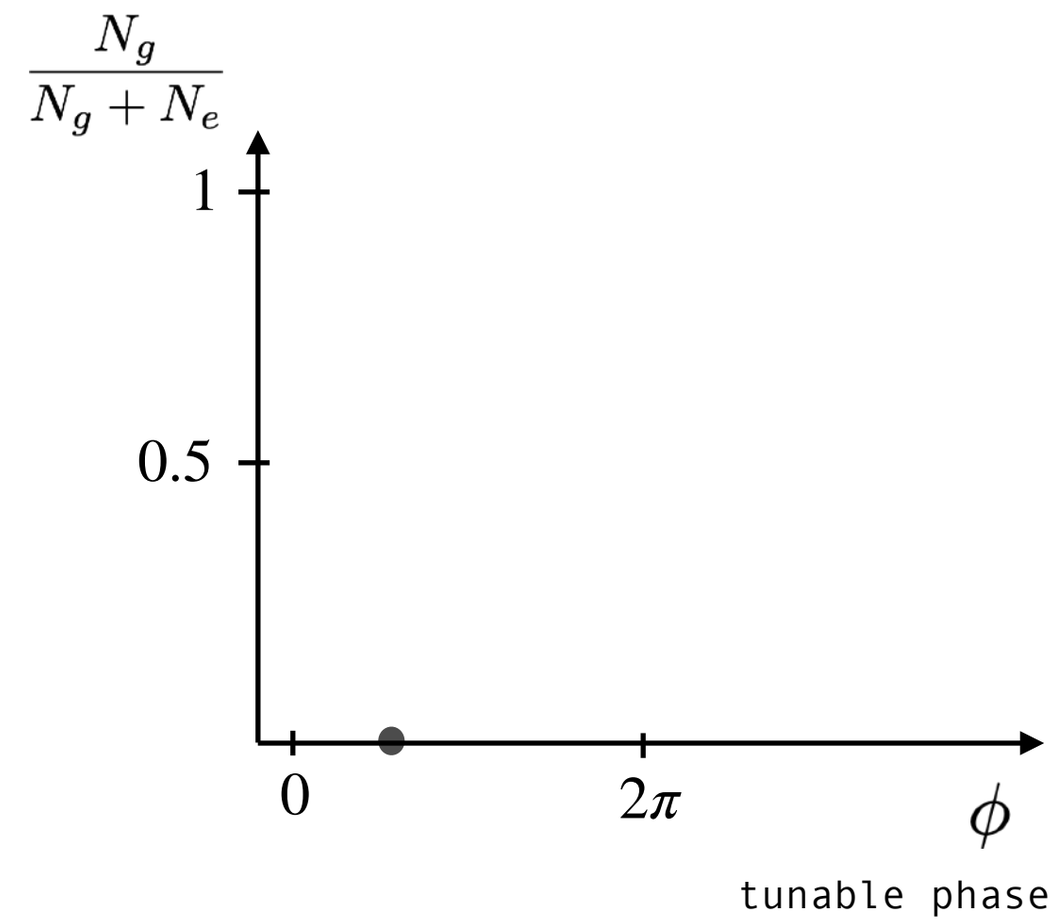
$$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{exp}}(\pi/2) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\pi/2)$$

$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{i} \\ -\mathrm{i} & 1 \end{pmatrix}$$

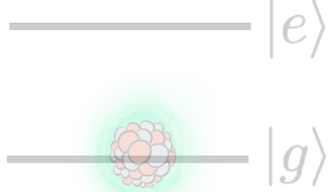
Atom interferometry

1 atom





state preparation



evolution

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$$

$$\underbrace{\boxed{\pi/2} + \boxed{\pi}}_{\mathcal{T}_{1/2}} + \underbrace{\boxed{\pi/2}}_{\mathcal{T}_{1/2}}$$

measurement

$$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\pi/2)$$

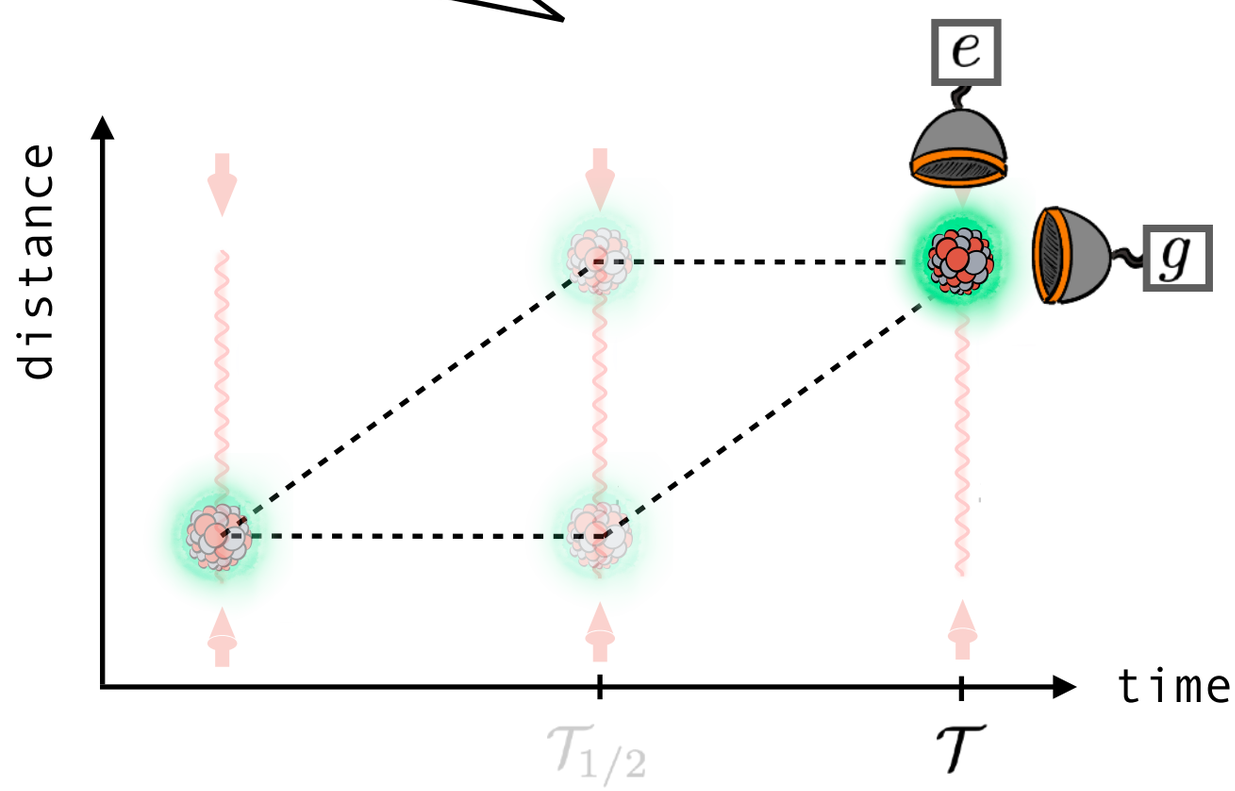
$$\Downarrow$$

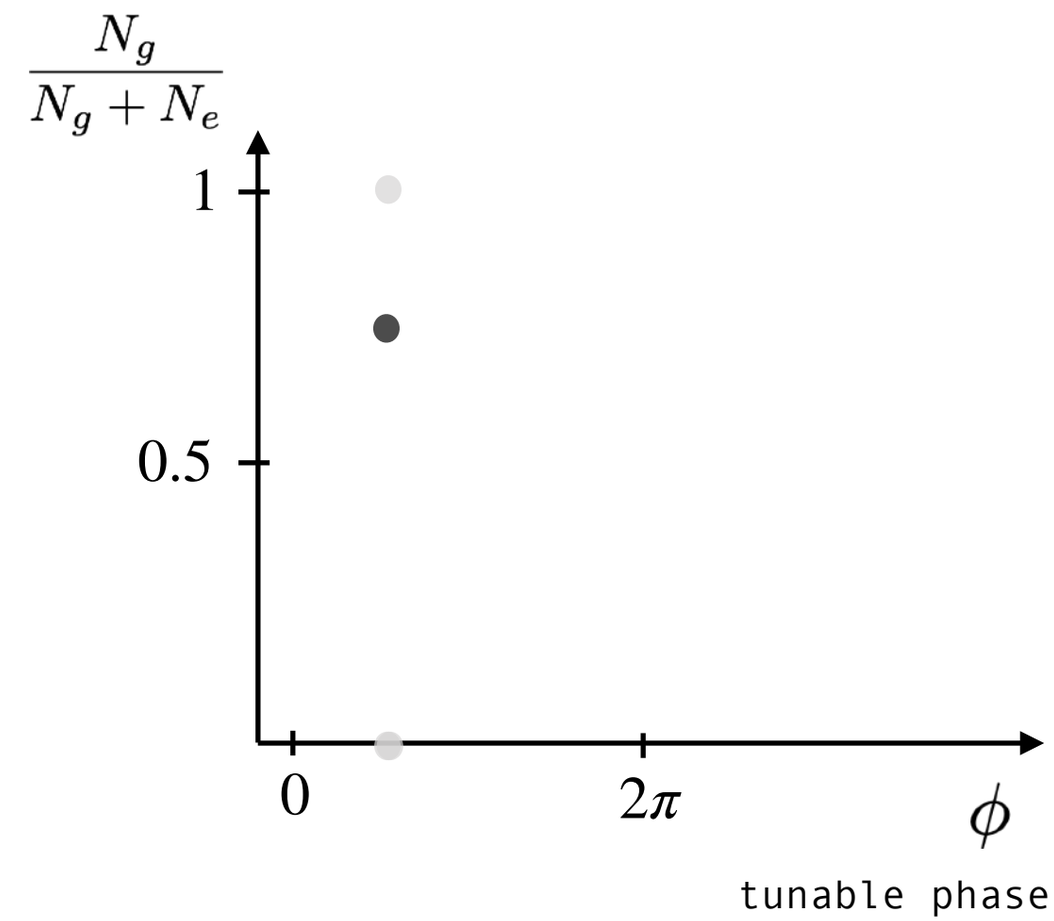
$$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{exp}}(\pi/2) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\pi/2)$$

$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{i} \\ -\mathrm{i} & 1 \end{pmatrix}$$

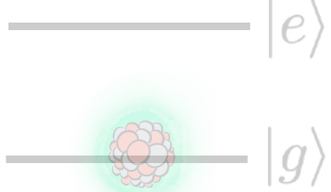
Atom interferometry

1 atom





state preparation



evolution

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$$

$$\underbrace{\boxed{\pi/2} + \boxed{\pi}}_{\mathcal{T}_{1/2}} + \underbrace{\boxed{\pi/2}}_{\mathcal{T}_{1/2}}$$

measurement

$$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\pi/2)$$

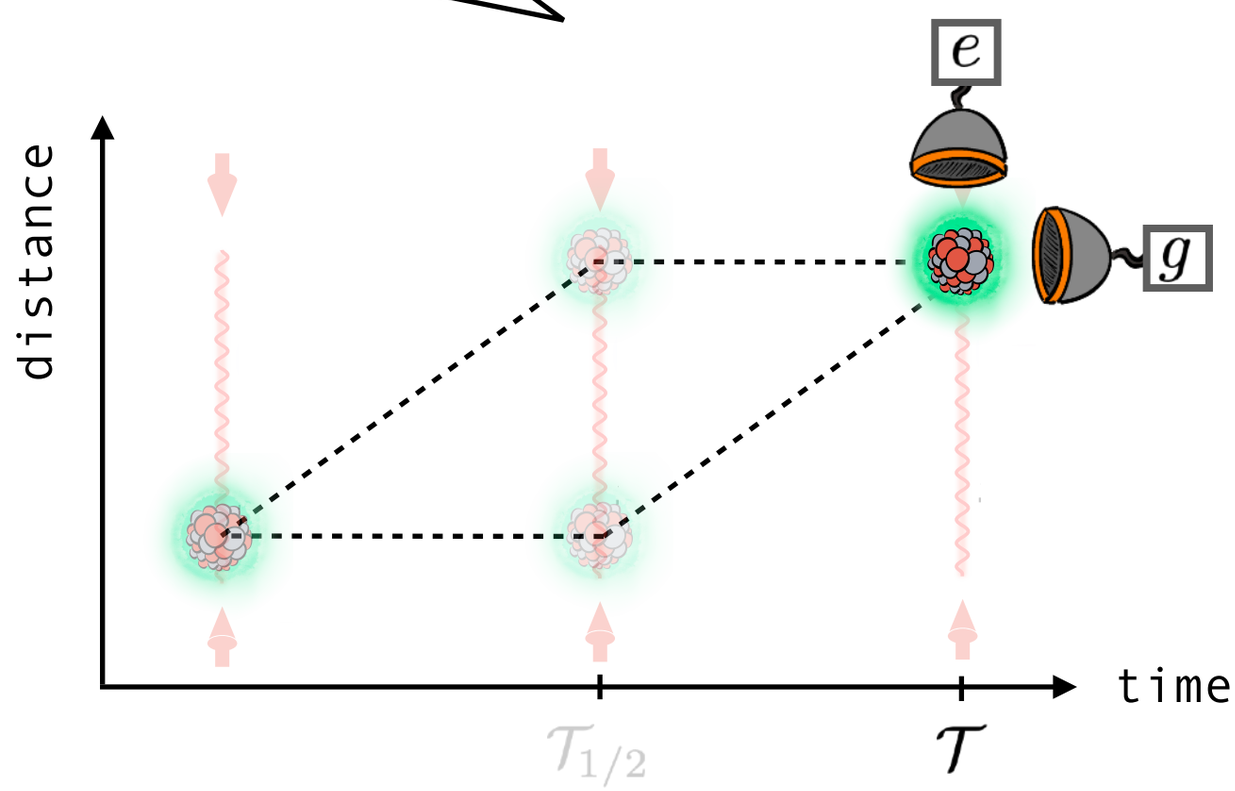
$$\Downarrow$$

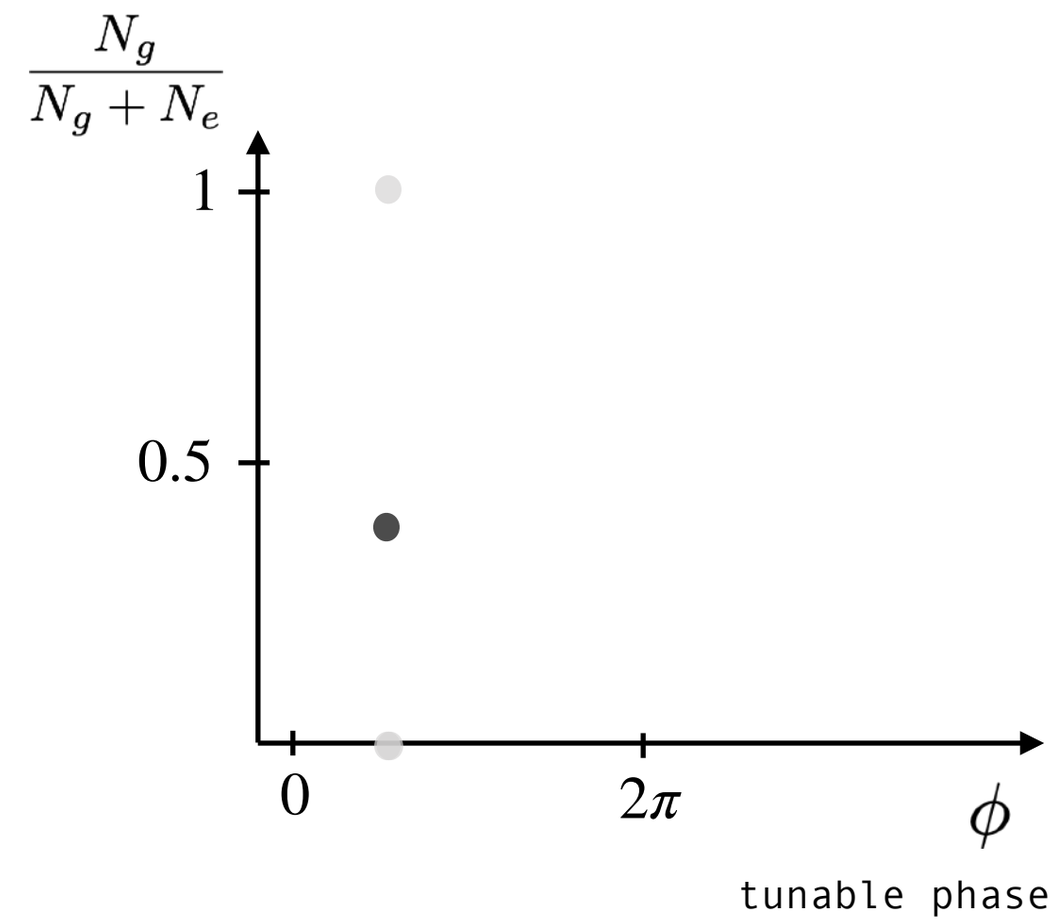
$$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{exp}}(\pi/2) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\pi/2)$$

$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{i} \\ -\mathrm{i} & 1 \end{pmatrix}$$

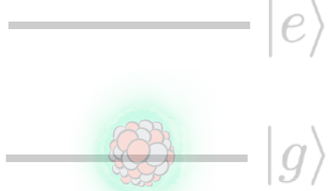
Atom interferometry

1 atom





state preparation



evolution

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$$

$$\underbrace{\boxed{\pi/2} + \boxed{\pi}}_{\mathcal{T}_{1/2}} + \underbrace{\boxed{\pi/2}}_{\mathcal{T}_{1/2}}$$

measurement

$$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\pi/2)$$

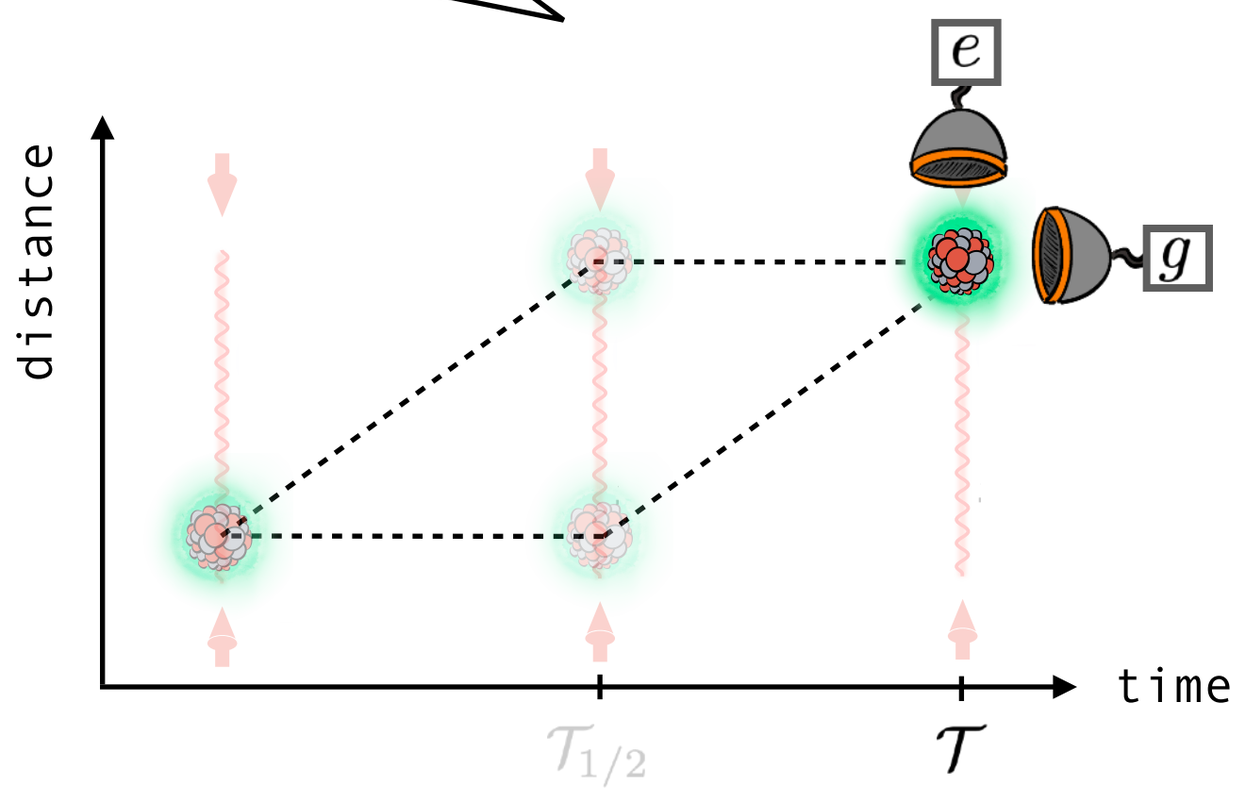
$$\Downarrow$$

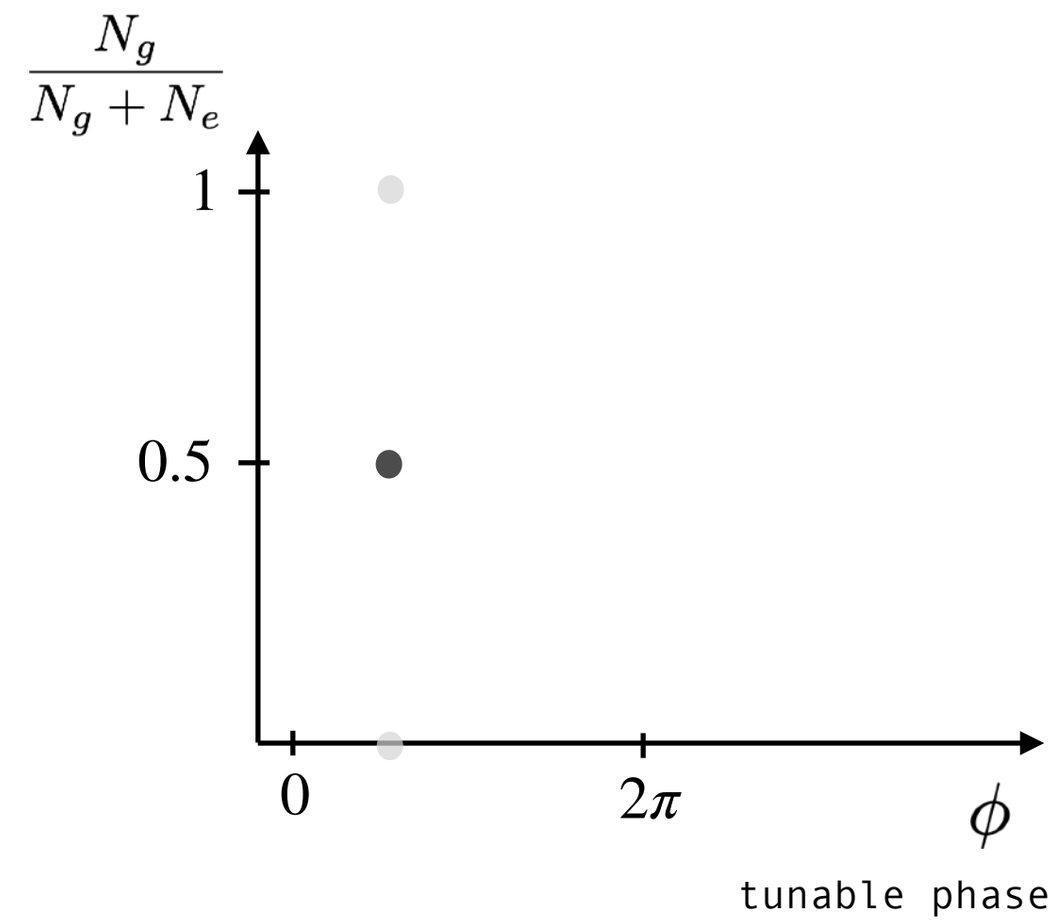
$$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{exp}}(\pi/2) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\pi/2)$$

$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{i} \\ -\mathrm{i} & 1 \end{pmatrix}$$

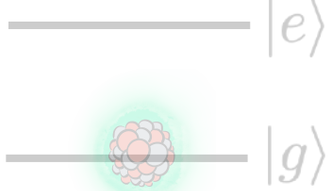
Atom interferometry

1 atom





state preparation



evolution

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$$

$$\underbrace{\boxed{\pi/2} + \boxed{\pi}}_{\mathcal{T}_{1/2}} + \underbrace{\boxed{\pi/2}}_{\mathcal{T}_{1/2}}$$

measurement

$$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\pi/2)$$

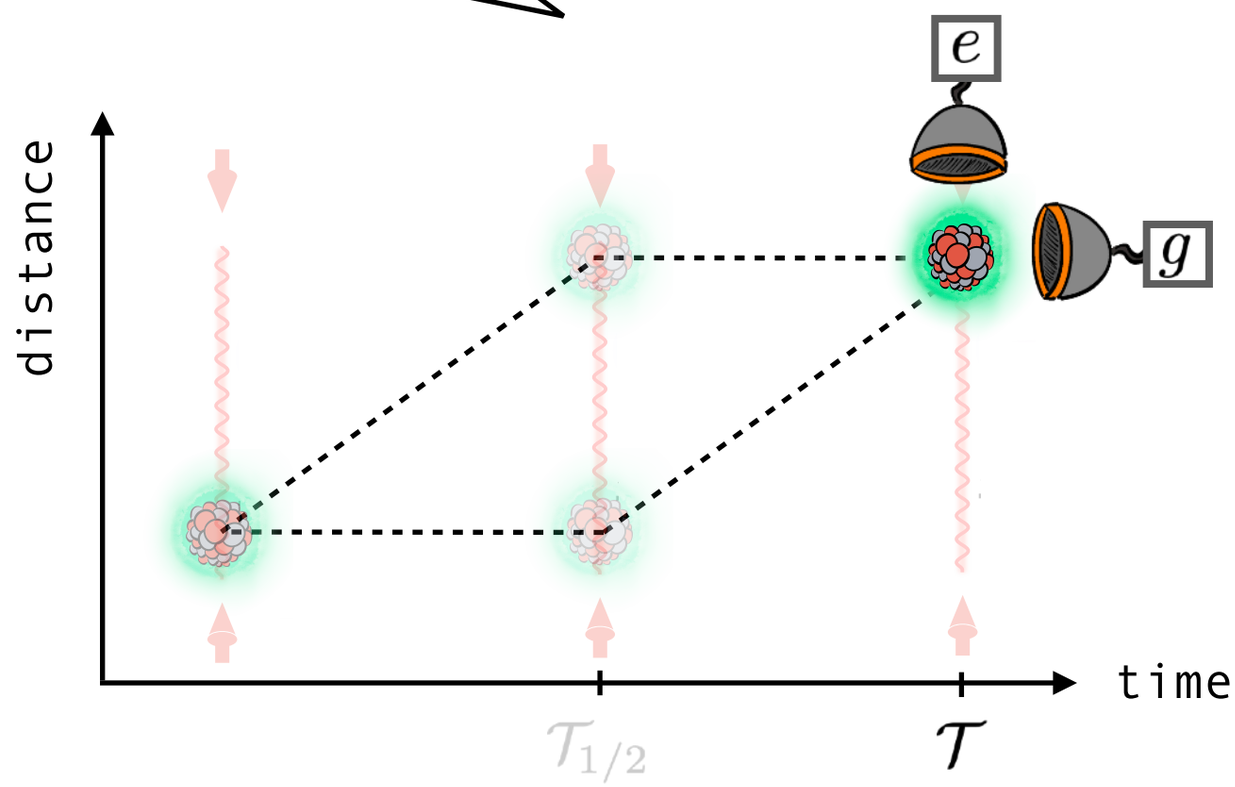
$$\Downarrow$$

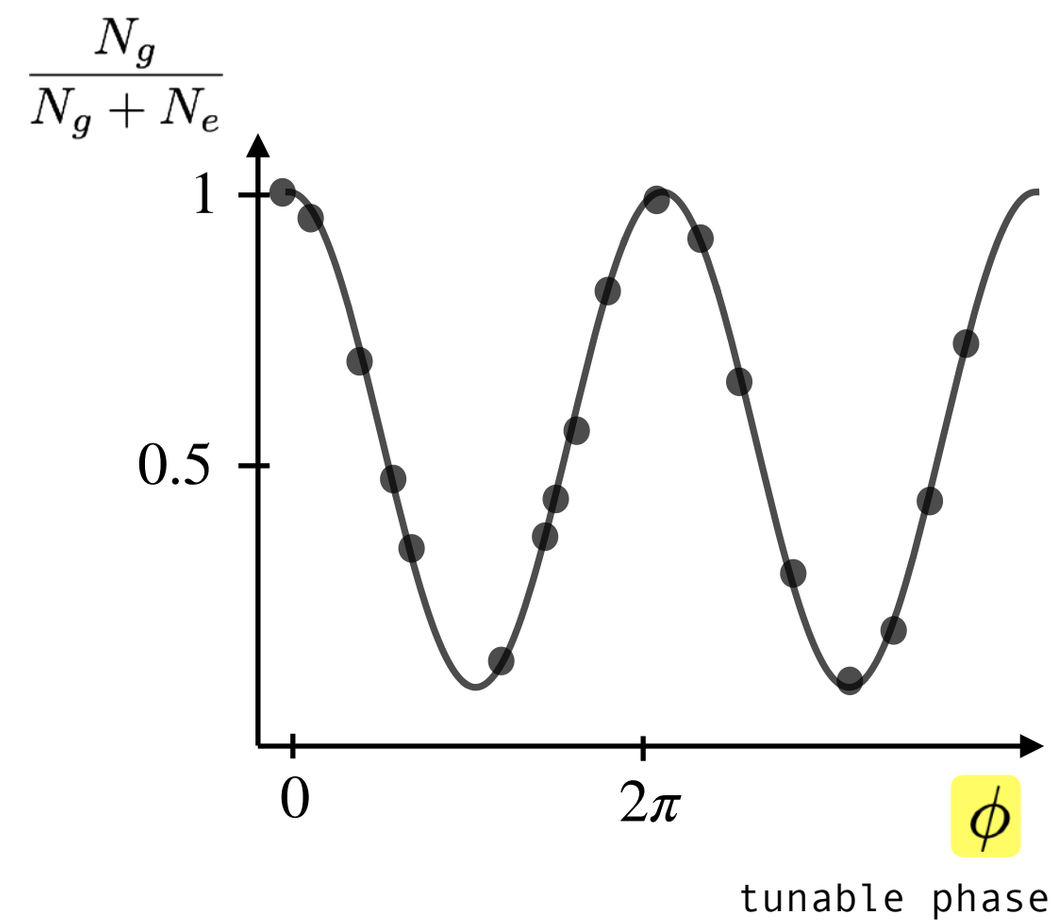
$$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{exp}}(\pi/2) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\pi/2)$$

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

Atom interferometry

1 atom





state preparation

$|e\rangle$

$|g\rangle$

evolution

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}]$$

$\pi/2$ + π + $\pi/2$

$\mathcal{T}_{1/2}$ $\mathcal{T}_{1/2}$

measurement

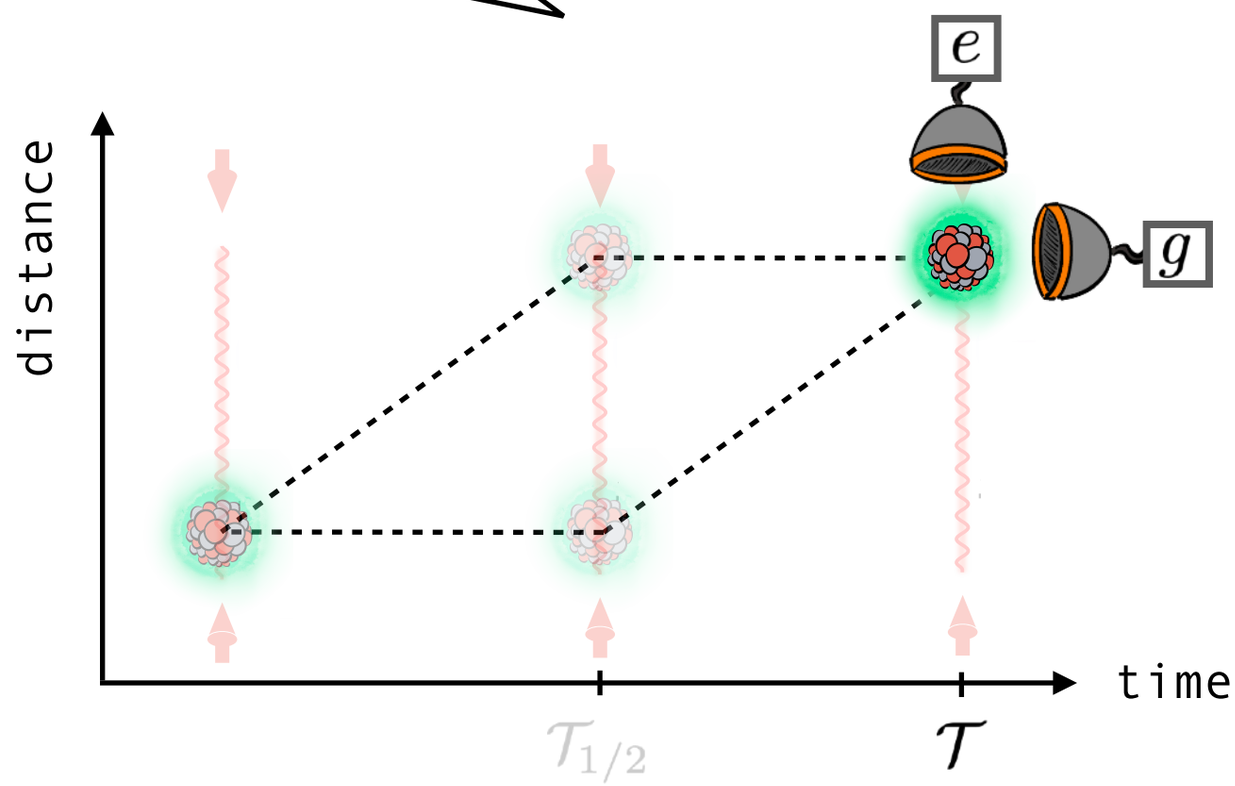
$$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\phi)$$

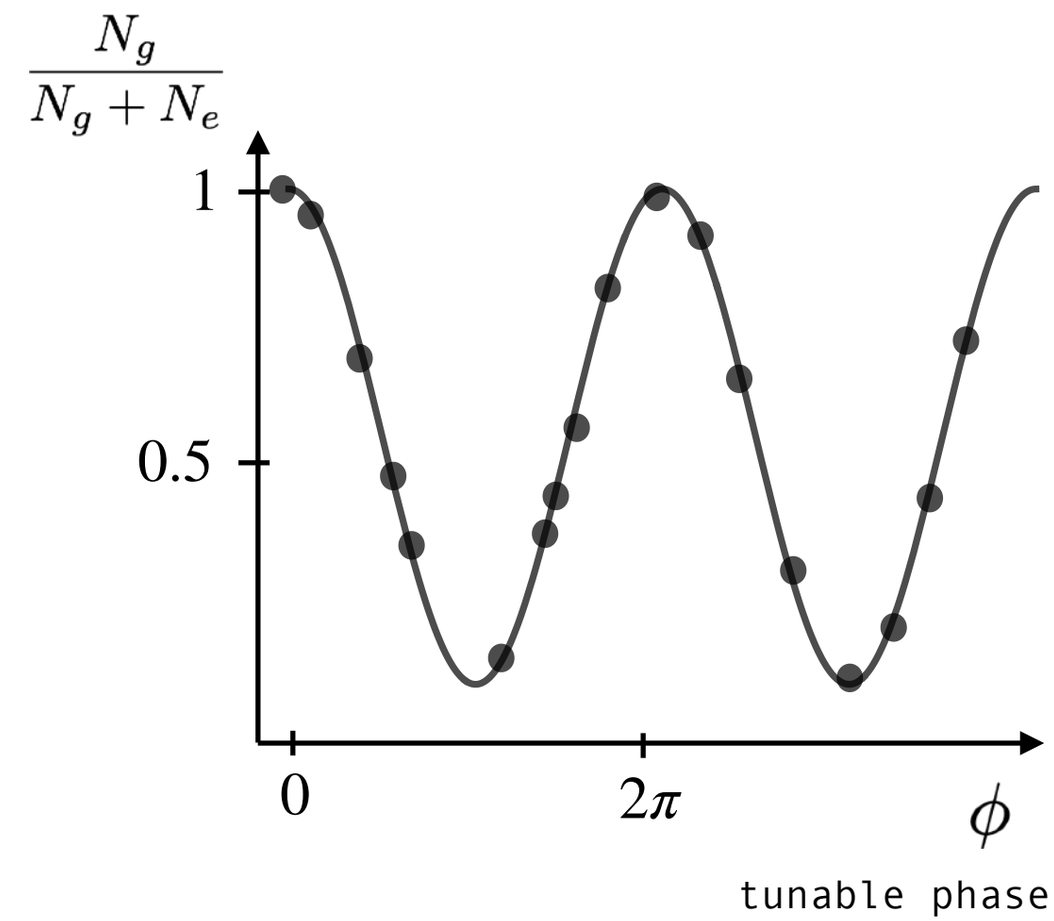
$$\frac{N_g}{N_g + N_e}\Big|_{\text{exp}}(\phi) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\phi)$$

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

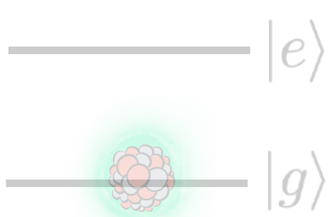
Atom interferometry

1 atom



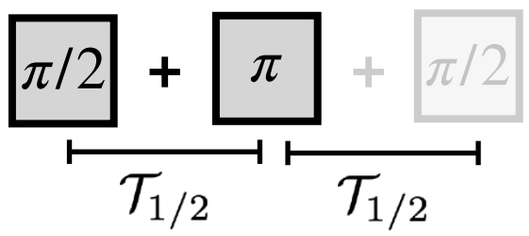


state preparation



evolution

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}]$$



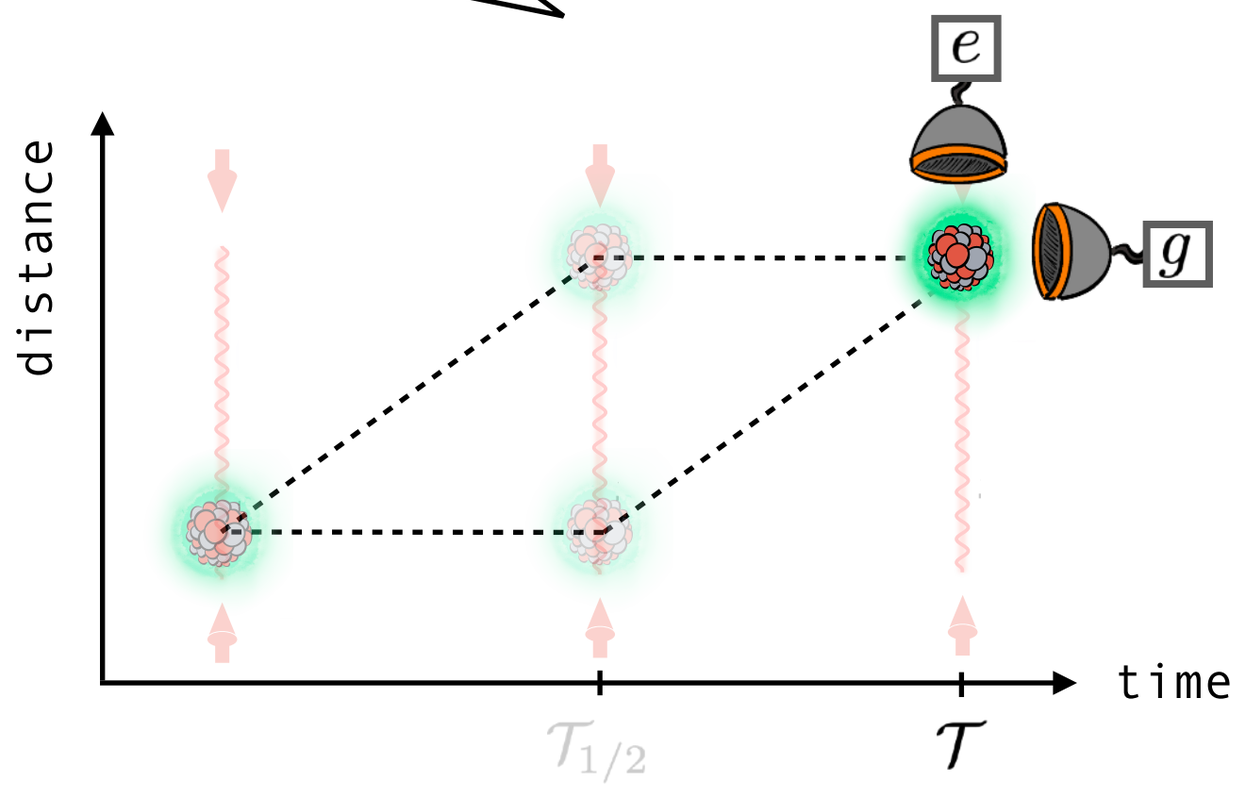
measurement

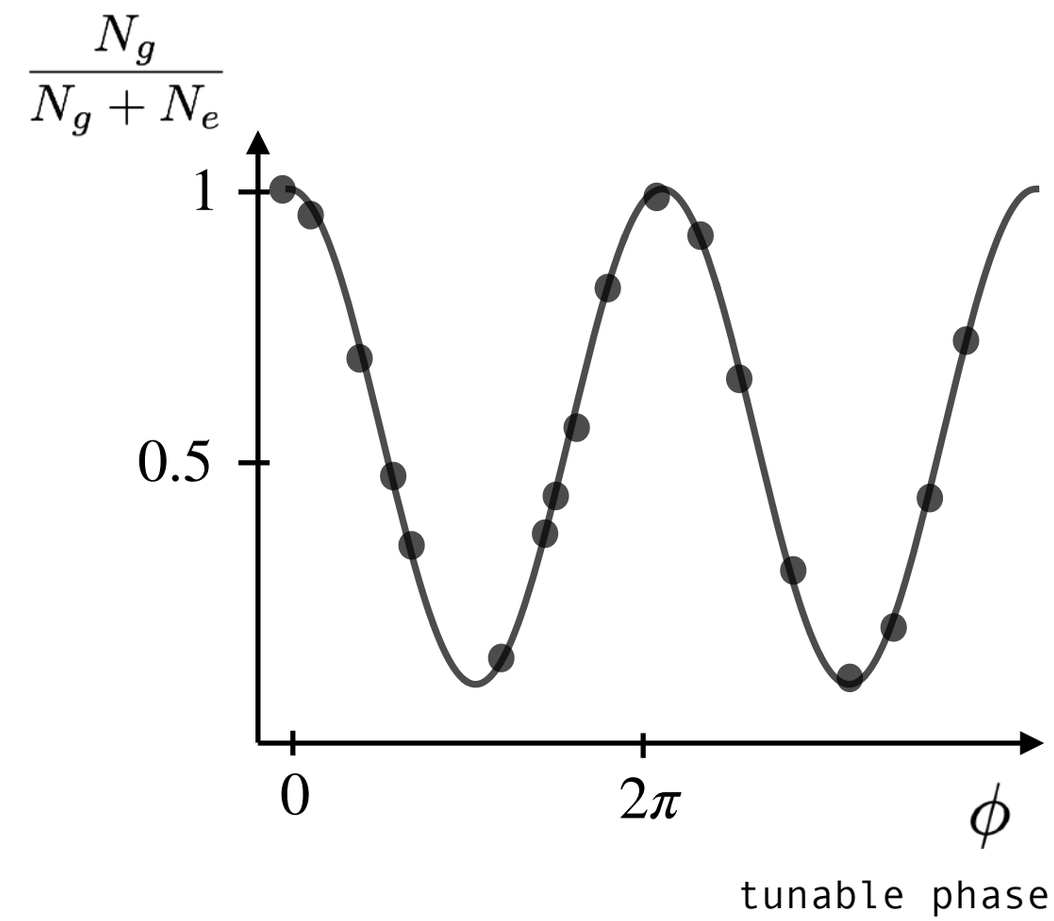
$$\left.\frac{N_g}{N_g + N_e}\right|_{\text{exp}}(\phi) = \frac{1}{2}\left(1 + V\cos\left(\phi + \Delta\phi\right)\right)$$

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

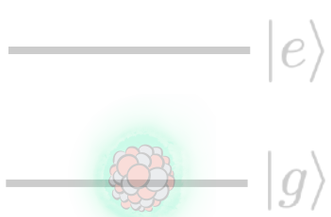
Atom interferometry

1 atom



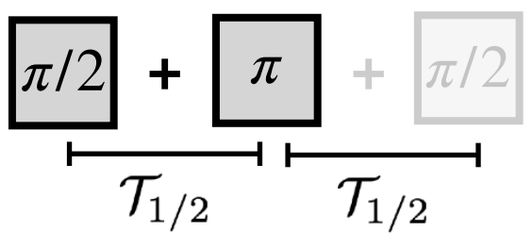


state preparation



evolution

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}]$$



measurement

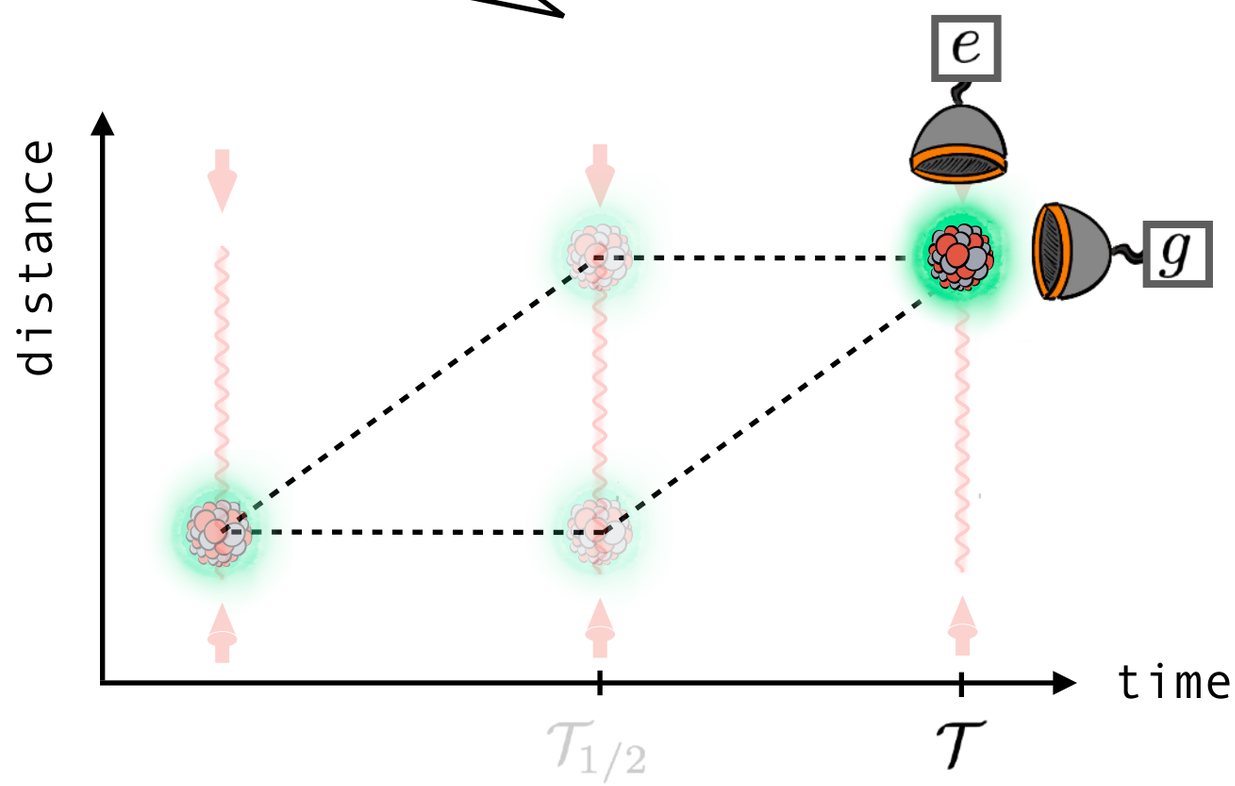
$$\left.\frac{N_g}{N_g + N_e}\right|_{\text{th}}(\phi) = \text{Tr}\{\rho(\mathcal{T})|g\rangle\langle g|\}$$

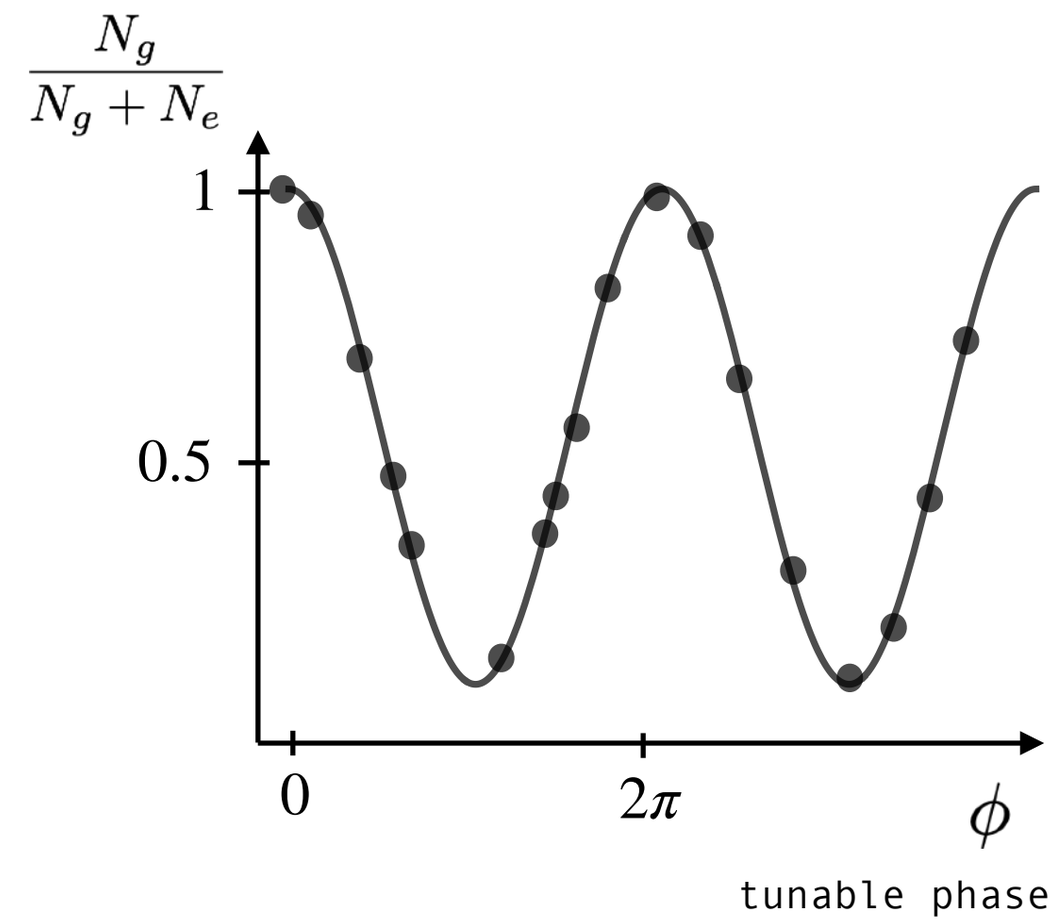
$$\left.\frac{N_g}{N_g + N_e}\right|_{\text{exp}}(\phi) = \frac{1}{2}\left(1 + V\cos\left(\phi + \Delta\phi\right)\right)$$

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

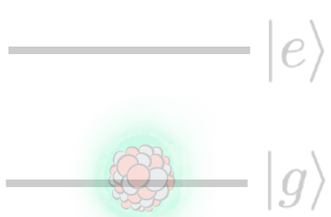
Atom interferometry

1 atom



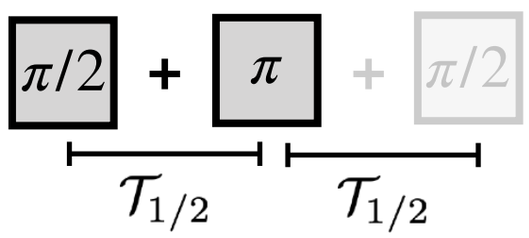


state preparation



evolution

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}]$$



measurement

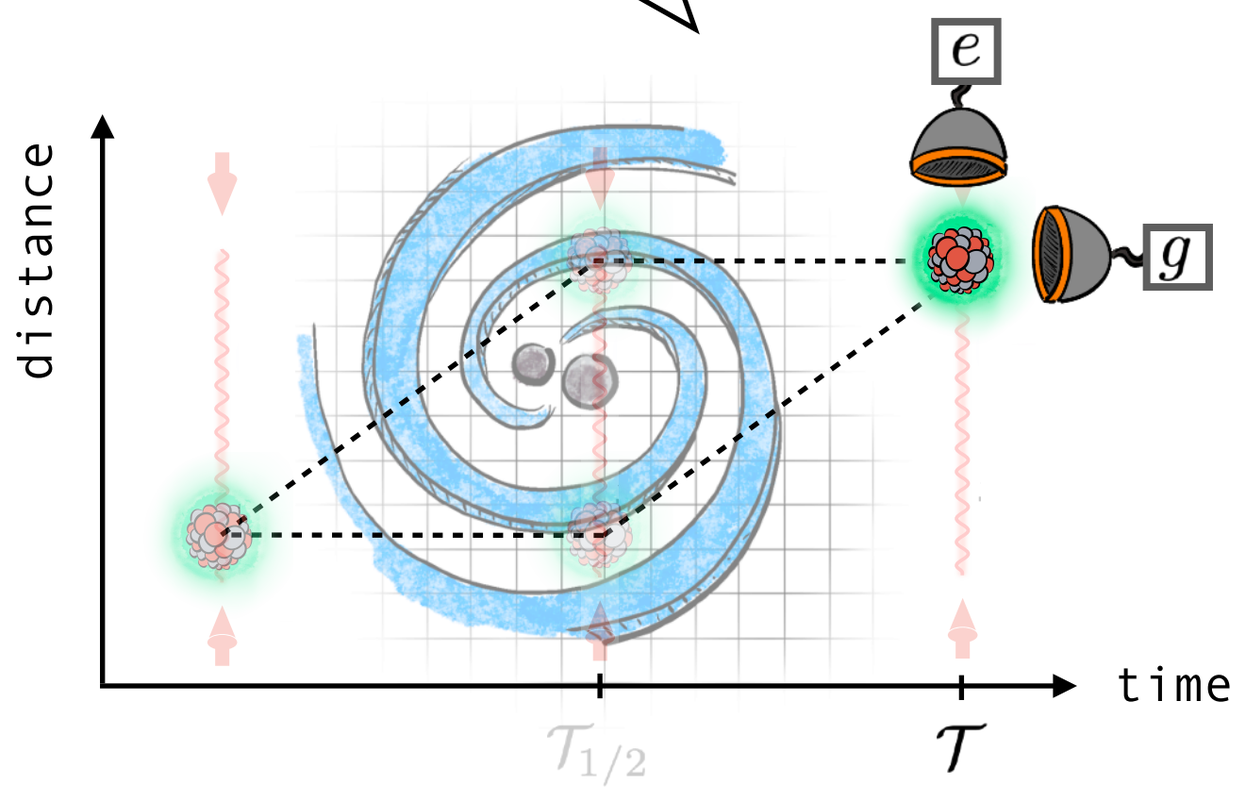
$$\left.\frac{N_g}{N_g + N_e}\right|_{\text{th}}(\phi) = \tfrac{1}{2}(1 + \cos\phi)$$

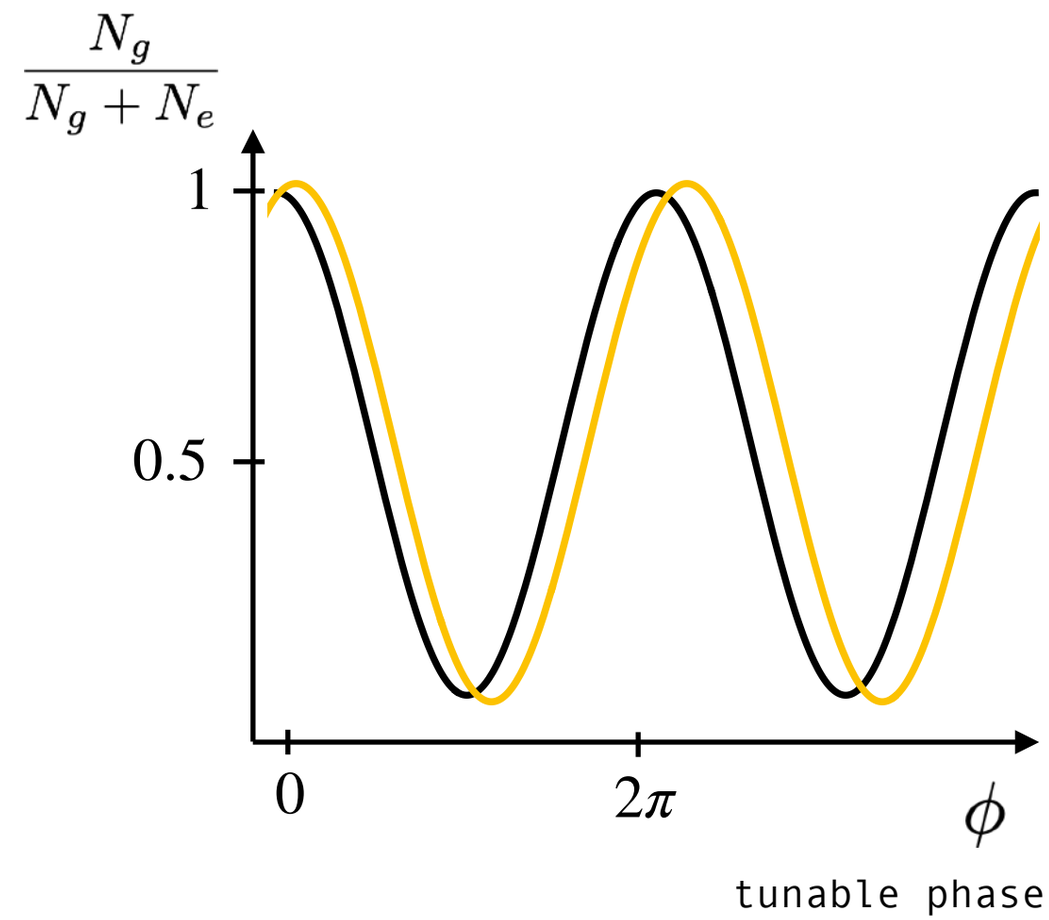
$$\left.\frac{N_g}{N_g + N_e}\right|_{\text{exp}}(\phi) = \tfrac{1}{2}(1 + V\cos(\phi + \Delta\phi))$$

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

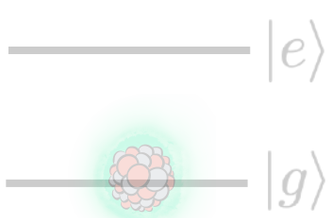
Atom interferometry

1 atom





state preparation



evolution

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}]$$

$$\underbrace{\boxed{\pi/2} + \boxed{\pi}}_{\mathcal{T}_{1/2}} \underbrace{+ \boxed{\pi/2}}_{\mathcal{T}_{1/2}}$$

measurement

$$\left.\frac{N_g}{N_g+N_e}\right|_{\text{th}}(\phi) = \tfrac{1}{2}(1+\cos[\phi+\Delta\phi])$$

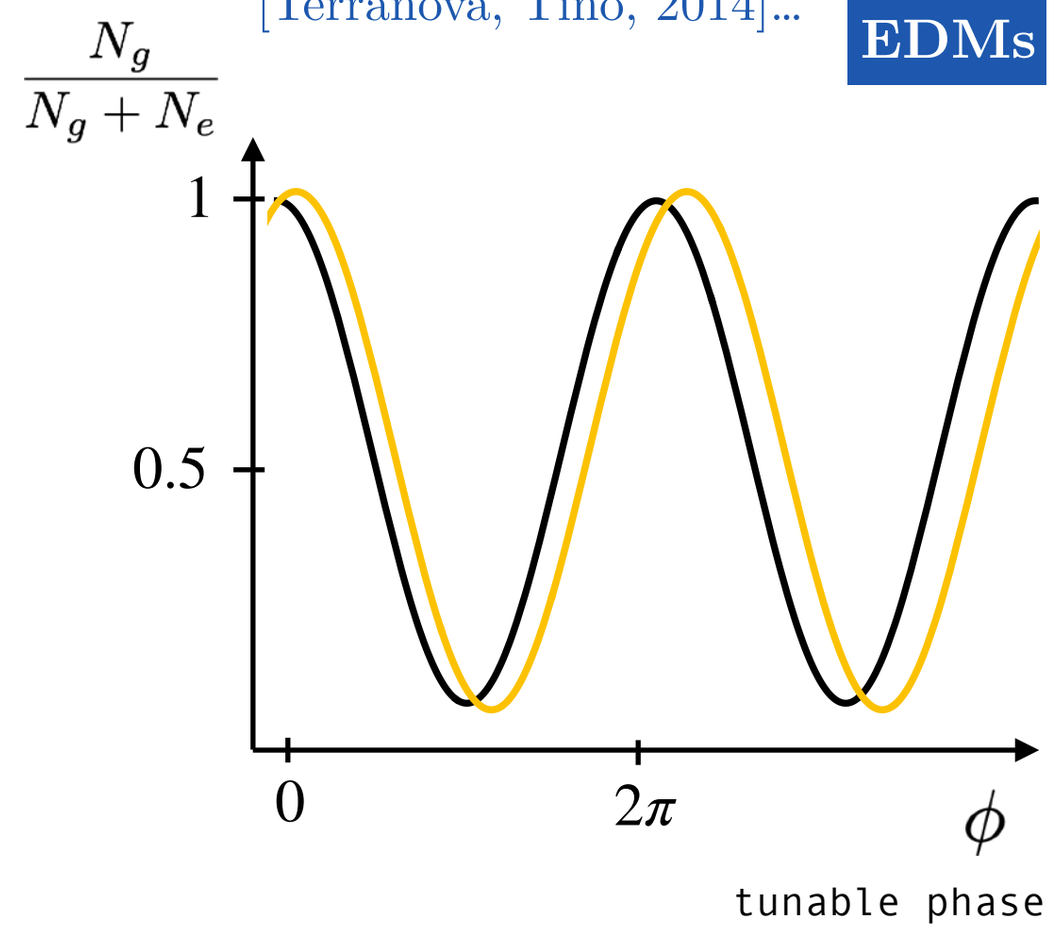
$$\left.\frac{N_g}{N_g+N_e}\right|_{\text{exp}}(\phi) = \tfrac{1}{2}(1+V\cos(\phi+\Delta\phi))$$

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



[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

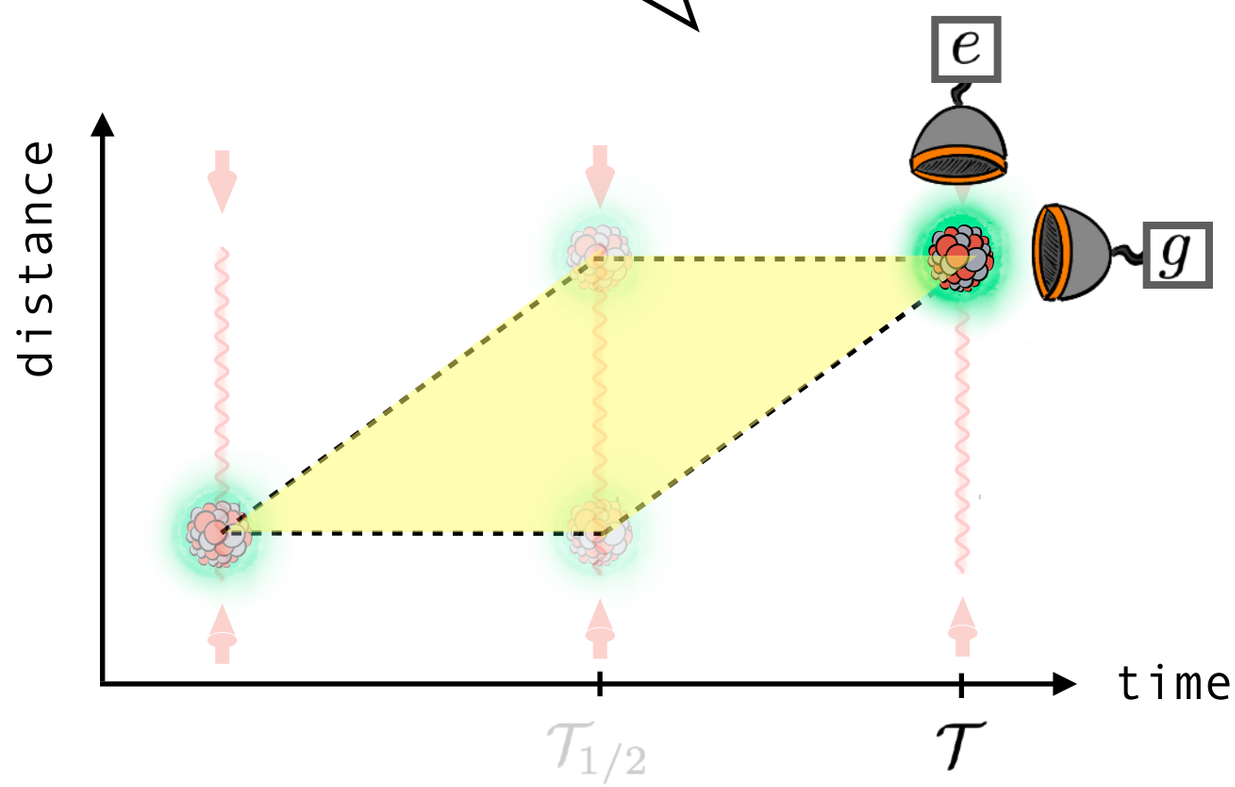
[Dimopoulos, Graham, et al. 2008] [Hogan, Johnson, et al . 2011], [Yu, Tinto, 2011] [Graham, Hogan, 2013], [Canuel, Bertoldi, et al. 2018] [Canuel, Abend, et al. 2020] [Kolkowitz, Pikovski, et al., 2016] [Zhan, Wang, et al. 2020] [El-Neaj, Alpigiani, et al. 2020] [Badurina, Bentine, et. Al. 2020] [Graham,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

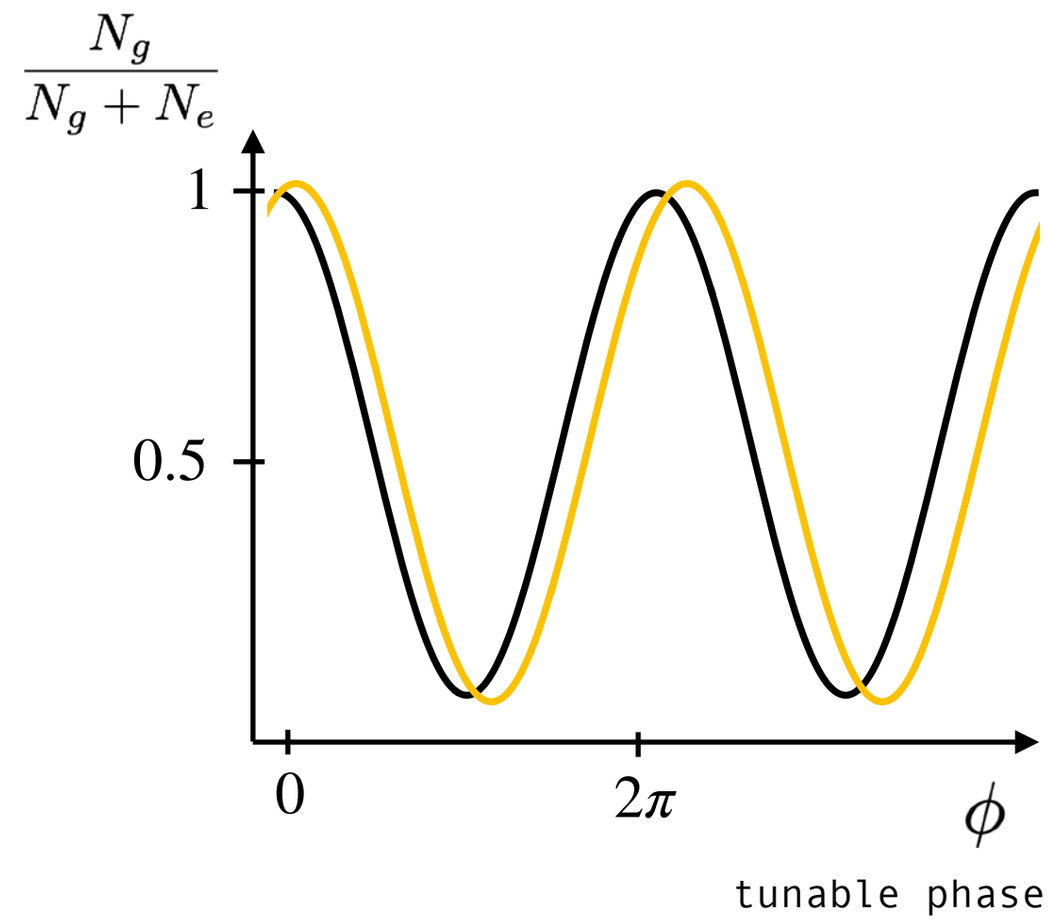
GWs

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

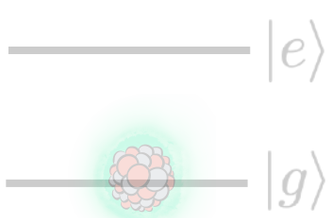
Atom interferometry

1 atom





state preparation



evolution

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}]$$

$\pi/2$ + π + $\pi/2$

$\mathcal{T}_{1/2}$ $\mathcal{T}_{1/2}$

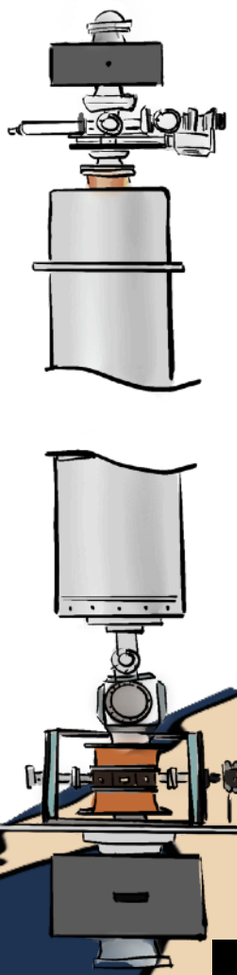
measurement

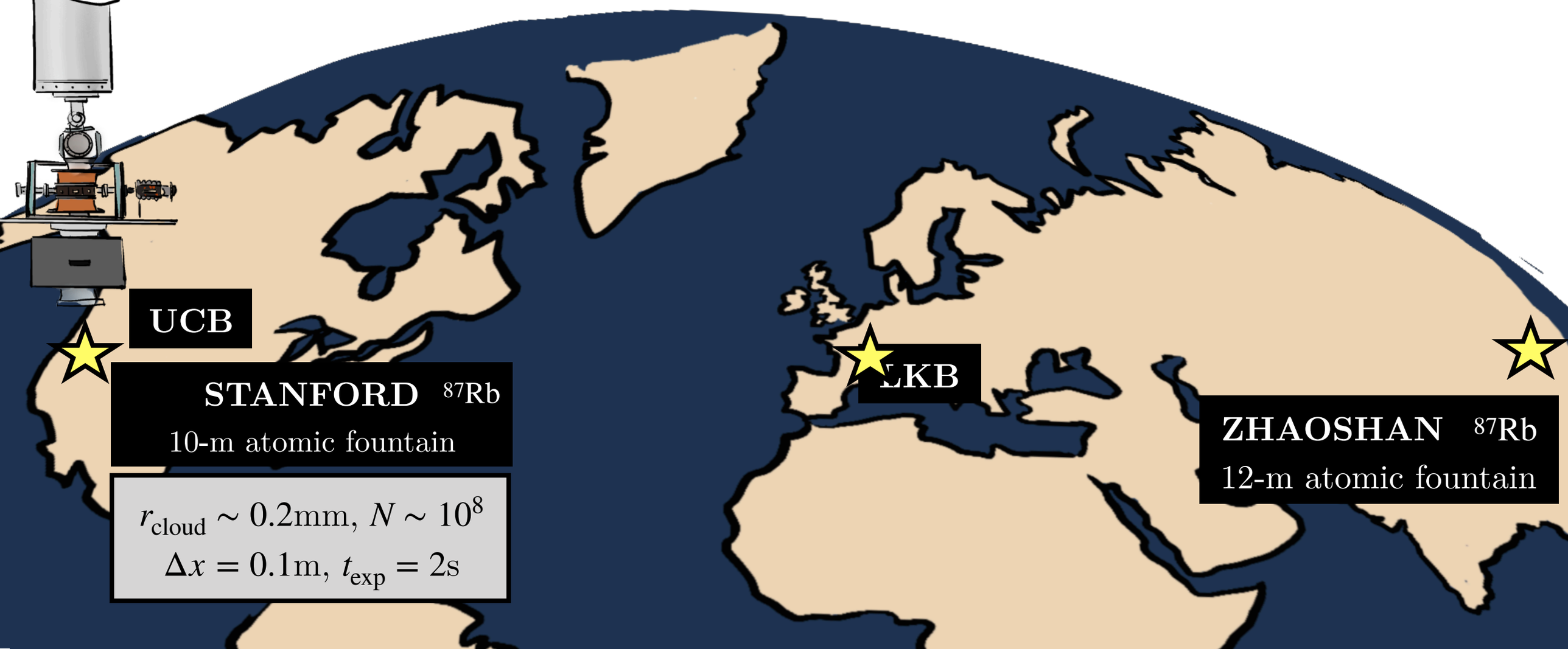
$$\left.\frac{N_g}{N_g + N_e}\right|_{\text{th}}(\phi) = \frac{1}{2}(1 + \cos[\phi + \Delta\phi])$$

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

Atom interferometry

Examples – earth based





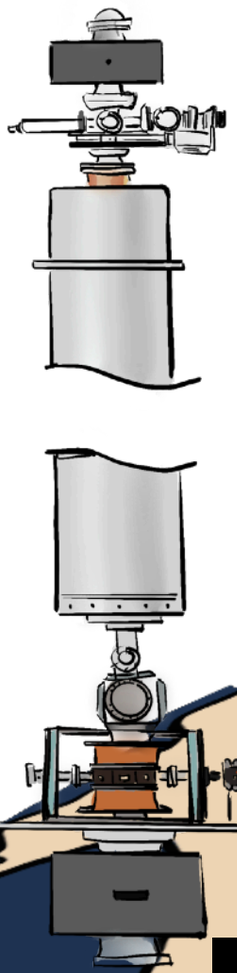
Atom interferometry

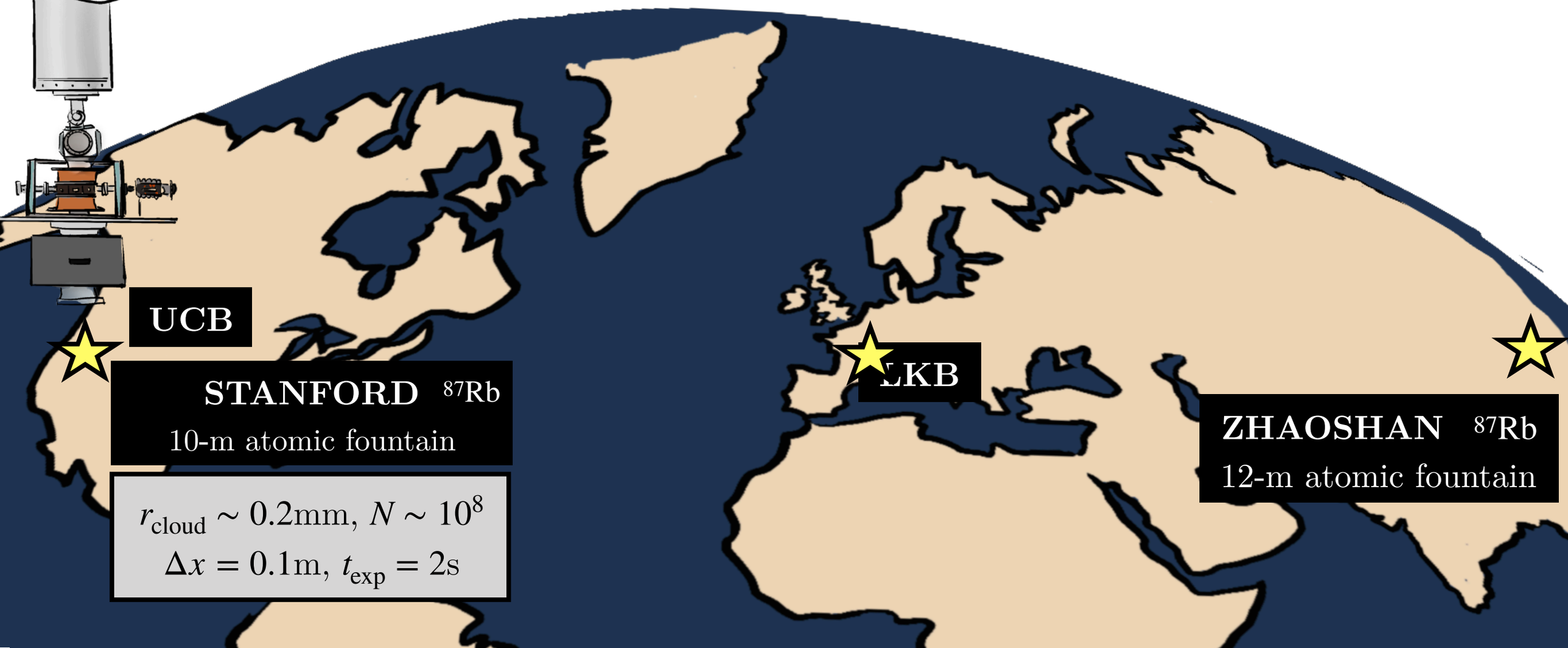
Article

Determination of the fine-structure constant with an accuracy of 81 parts per trillion

https://doi.org/10.1038/s41586-020-2964-7
Received: 7 May 2020

Léo Morel[1], Zhibin Yao[1], Pierre Cladé[1] & Saïda Guellati-Khélifa[1,2]✉





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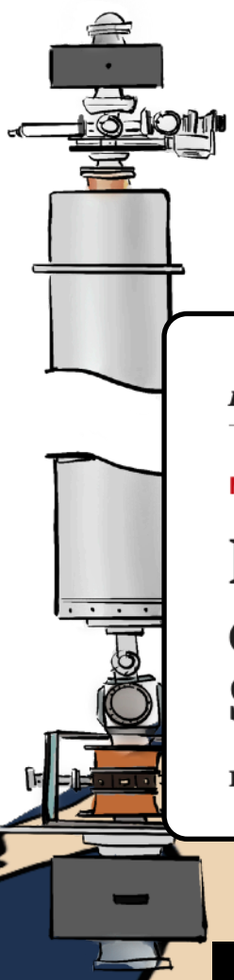
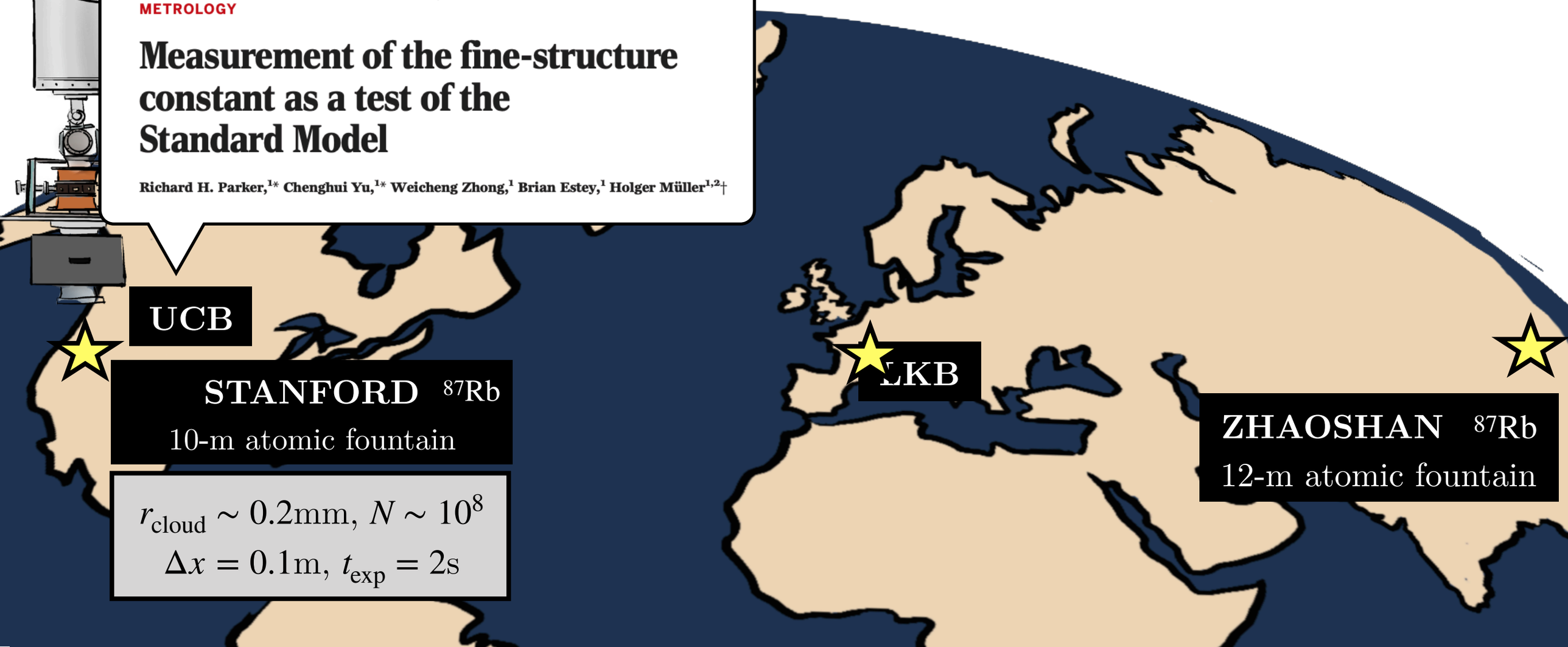


RESEARCH

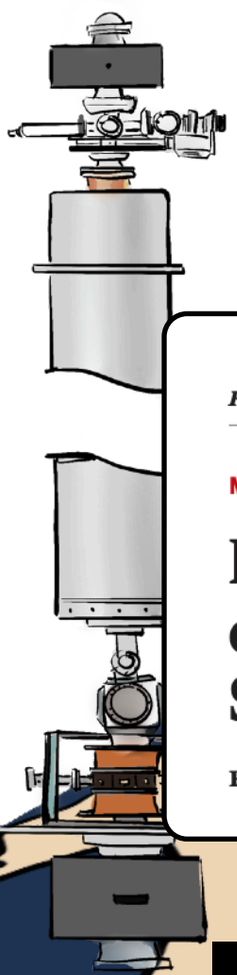
METROLOGY

Measurement of the fine-structure constant as a test of the Standard Model

Richard H. Parker,[1*] Chenghui Yu,[1*] Weicheng Zhong,[1] Brian Estey,[1] Holger Müller[1,2]†



Atom interferometry



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RESEARCH

METROLOGY

Measurement of the fine-structure constant as a test of the Standard Model

Richard H. Parker,[1*] Chenghui Yu,[1*] Weicheng Zhong,[1] Brian Estey,[1] Holger Mül

Test of Equivalence Principle at 10^{-8} Level by a Dual-species Double-diffraction Raman Atom Interferometer

Lin Zhou,[1,2] Shitong Long,[1,2,3] Biao Tang,[1,2] Xi Chen,[1,2] Fen Gao,[1,2] Wencui Peng,[1,2] Weitao Duan,[1,2,3] Jiaqi Zhong,[1,2] Zongyuan Xiong,[1,2] Jin Wang,[1,2,*] Yuanzhong Zhang,[4] and Mingsheng Zhan[1,2,†]
[1] *State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China*
[2] *Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China*
[3] *University of Chinese Academy of Sciences, Beijing 100049, China*
[4] *Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*
(Dated: March 3, 2015)

We report an improved test of the weak equivalence principle by using a simultaneous ^{85}Rb-^{87}Rb dual-species atom interferometer. We propose and implement a four-wave double-diffraction Raman transition scheme for the interferometer, and demonstrate its ability in suppressing common-mode phase noise of Raman lasers after their frequencies and intensity ratios are optimized. The statistical uncertainty of the experimental data for Eötvös parameter η is 0.8×10^{-8} at 3200 s. With various systematic errors corrected the final value is $\eta = (2.8 \pm 3.0) \times 10^{-8}$. The major uncertainty is attributed to the Coriolis effect.

UCB

STANFORD ^{87}Rb
10-m atomic fountai

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

LKB

Atom-interferometric test of the equivalence principle at the 10^{-12} level

Peter Asenbaum,* Chris Overstreet,* Minjeong Kim, Joseph Curti, and Mark A. Kasevich†
Department of Physics, Stanford University, Stanford, California 94305
(Dated: June 25, 2020)

Does gravity influence local measurements? We use a dual-species atom interferometer with 2 s of free-fall time to measure the relative acceleration between ^{85}Rb and ^{87}Rb wave packets in the Earth's gravitational field. Systematic errors arising from kinematic differences between the isotopes are suppressed by calibrating the angles and frequencies of the interferometry beams. We find an Eötvös parameter of $\eta = [1.6 \pm 1.8\ (\text{stat}) \pm 3.4\ (\text{sys})] \times 10^{-12}$, consistent with zero violation of the equivalence principle. With a resolution of up to $1.4 \times 10^{-11}\, g$ per shot, we demonstrate a sensitivity to η of $5.4 \times 10^{-11}/\sqrt{\text{Hz}}$.

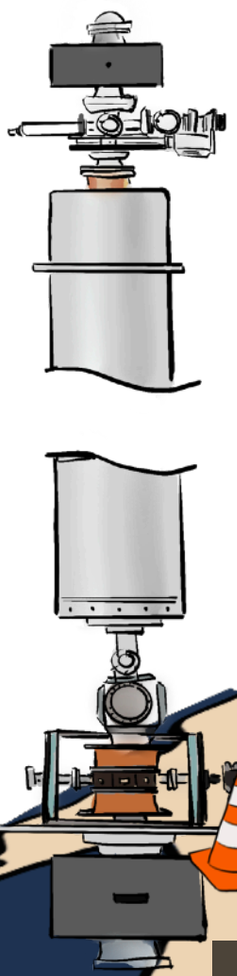
ZHAOSHAN ^{87}Rb
12-m atomic fountain

Atom interferometry

Examples – earth based

Atom interferometry

Examples – earth based



AION-REPORT/2023-10

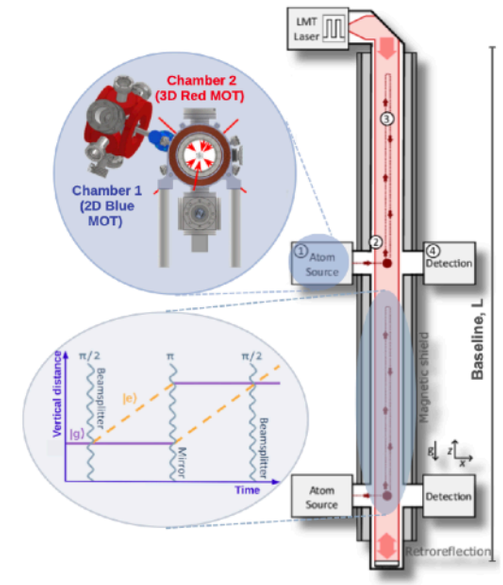
Progress towards ultracold Sr for the AION project – sub-microkelvin atoms and an optical-heterodyne diagnostic tool for injection-locked laser diodes

E. Pasatembou,[1] C. F. A. Baynham,[1] O. Buchmüller,[1, a)] D. Evans,[1] R. Hobson,[1] L. Iannizzotto-Venezze,[1] and A. Josset[1]

Department of Physics, Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, U.K.

(*Electronic mail: c.baynham@imperial.ac.uk)

(Dated: 13 October 2023)



MAGIS-100

UCB

AION

LKB

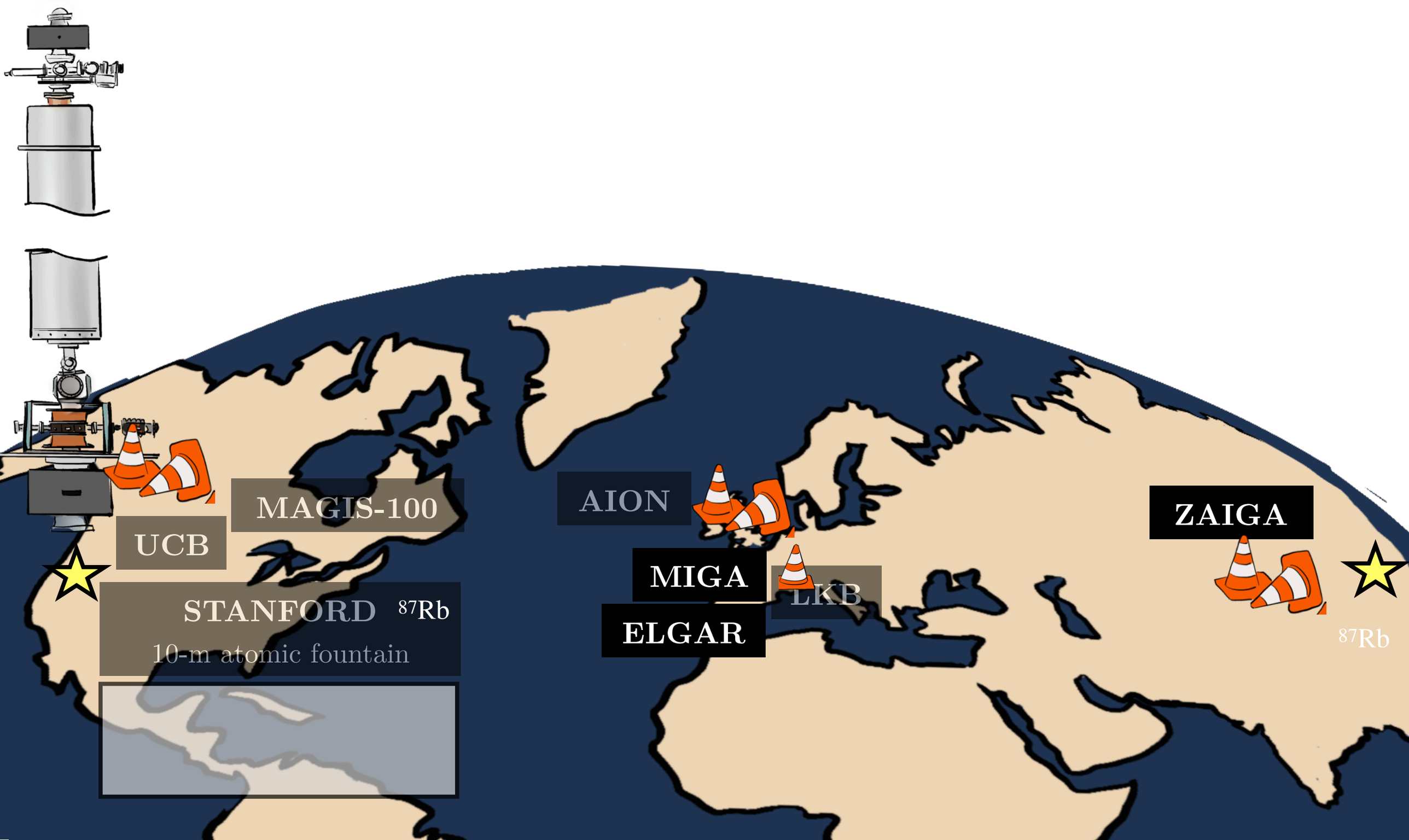
STANFORD ^{87}Rb

10-m atomic fountain

^{87}Rb

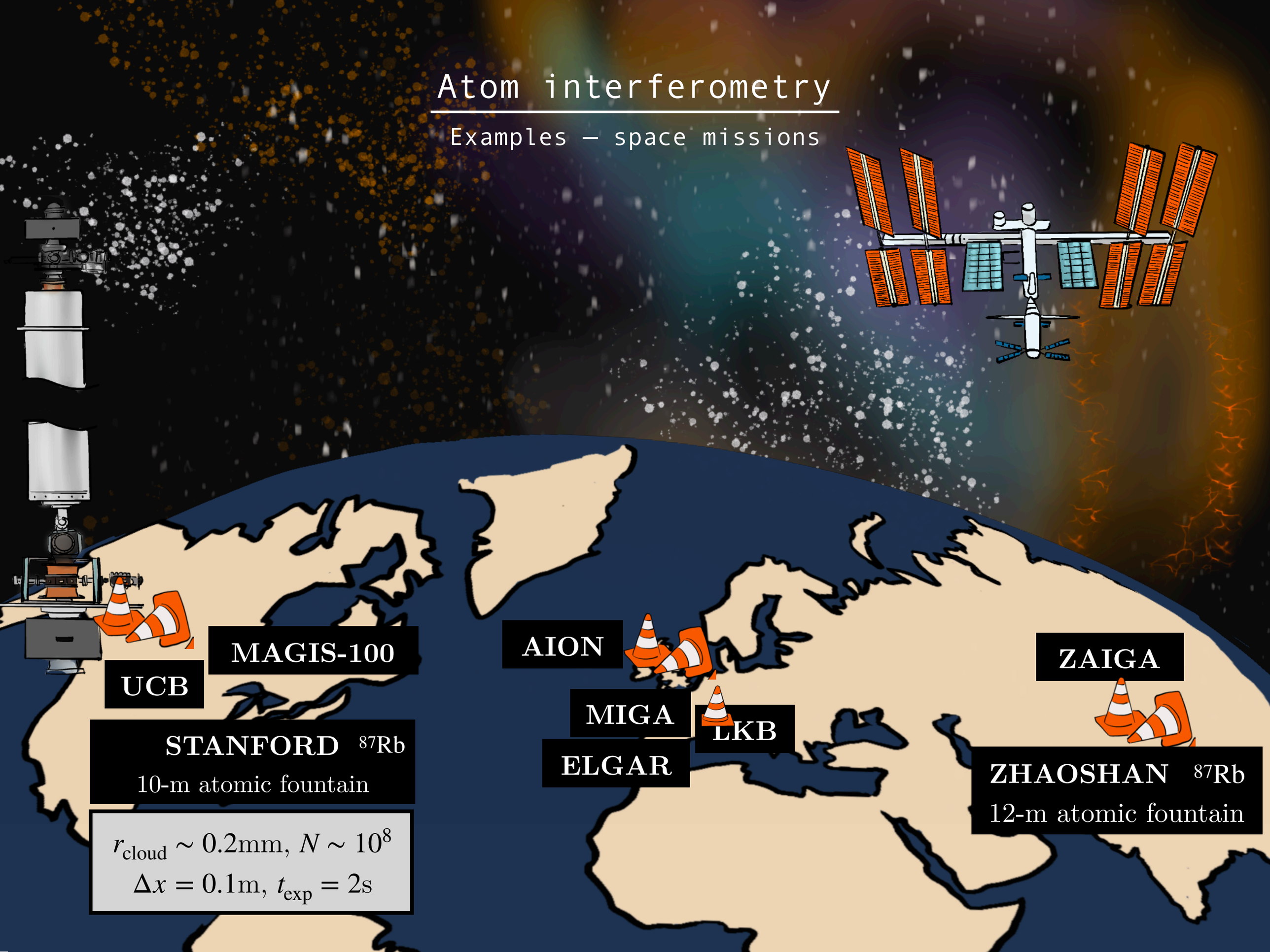
Atom interferometry

Examples – earth based



Atom interferometry

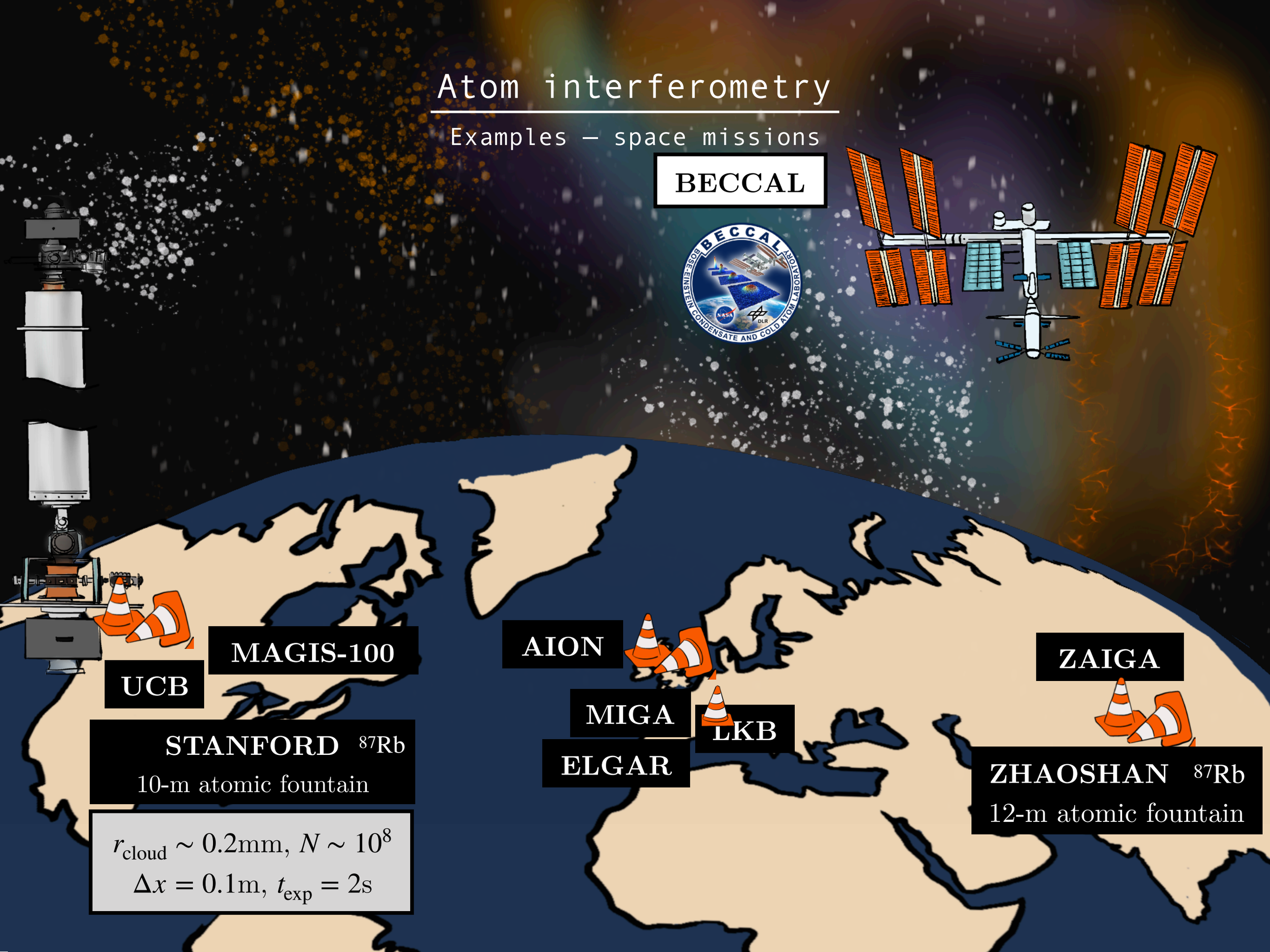
Examples – space missions



Atom interferometry

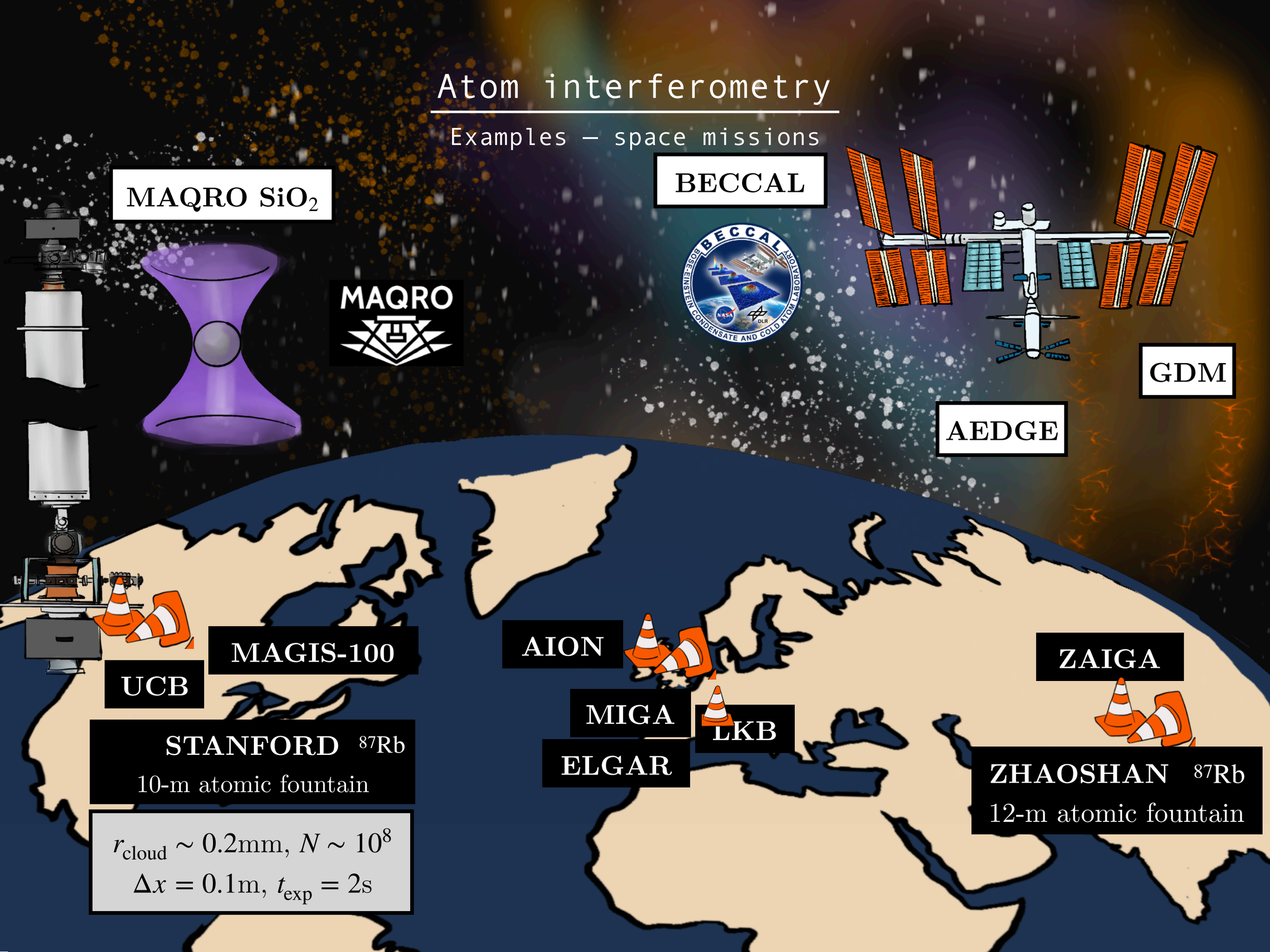
Examples – space missions

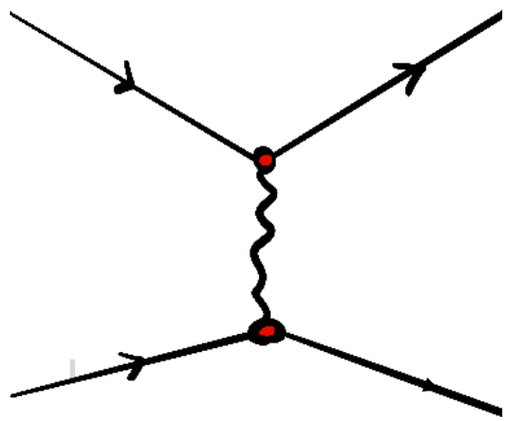
BECCAL



Atom interferometry

Examples – space missions



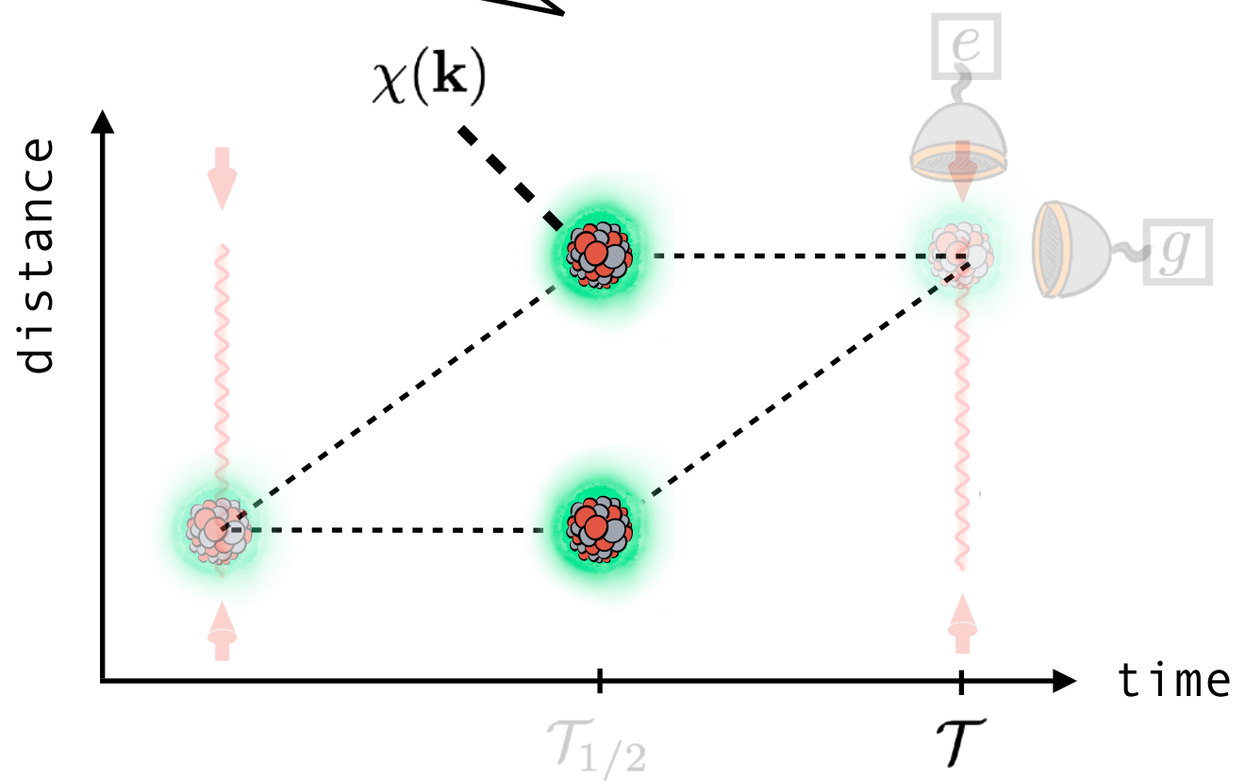


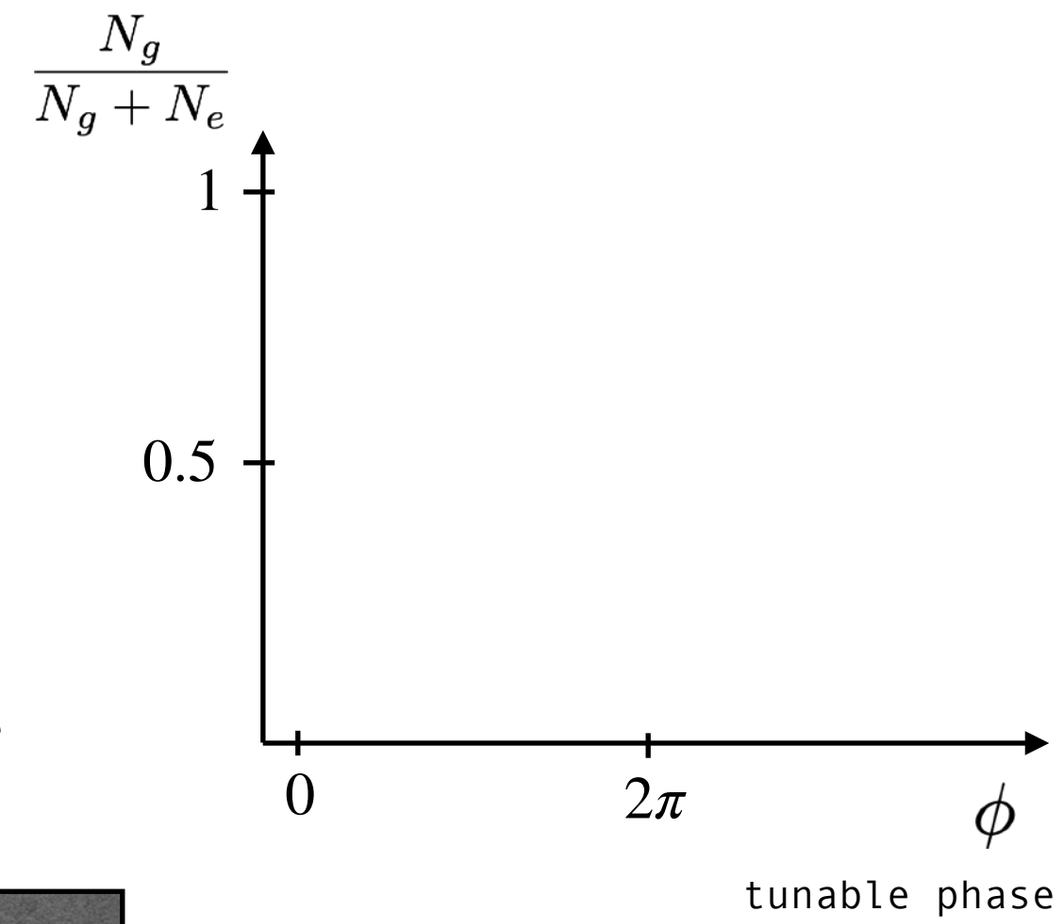
How can we detect particles with them?

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

Atom interferometry

1 atom





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

AI

env

measurement

$$\left.\frac{N_g}{N_g + N_e}\right|_{\text{th}}(\phi) = \mathrm{Tr}\{\rho(\mathcal{T})|g\rangle\langle g|\}$$

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

evolution

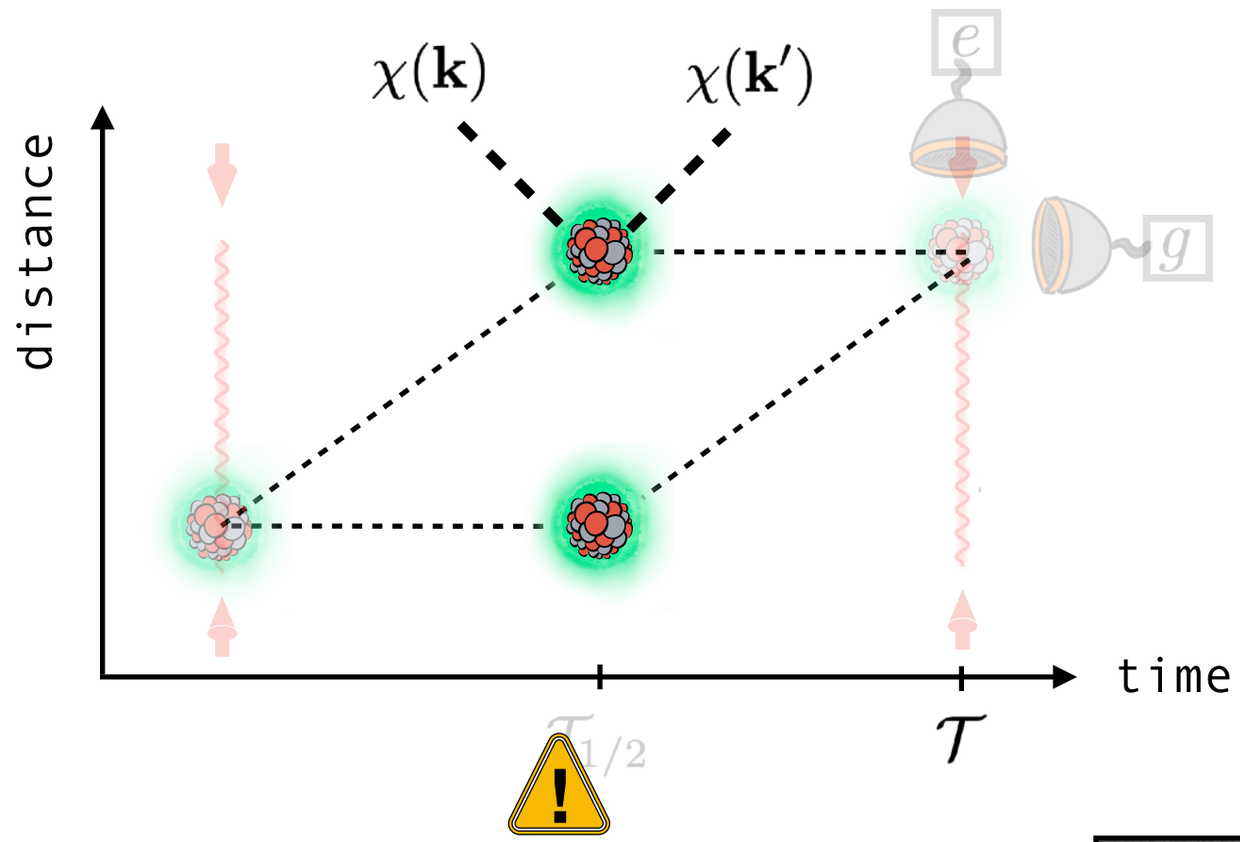
$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}]$$

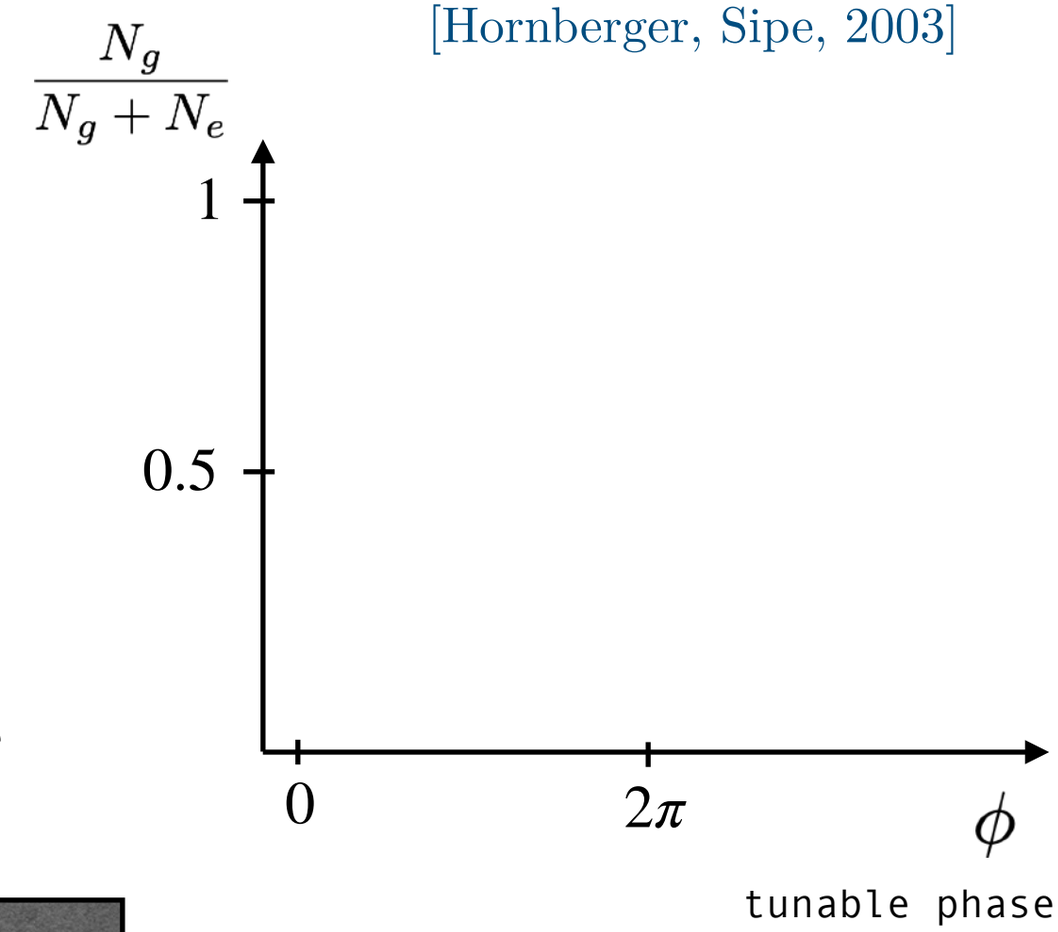
$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & \end{pmatrix}$$

Atom interferometry

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

1 atom





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

AI env

measurement

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Atom interferometry

[Joss, Zeh, 1985]
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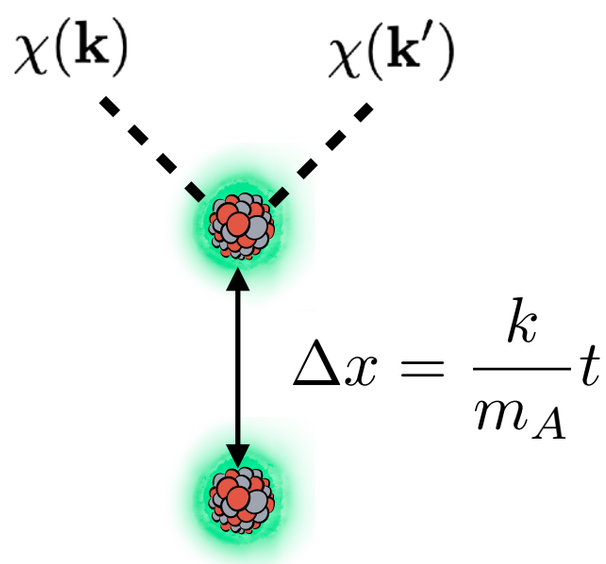
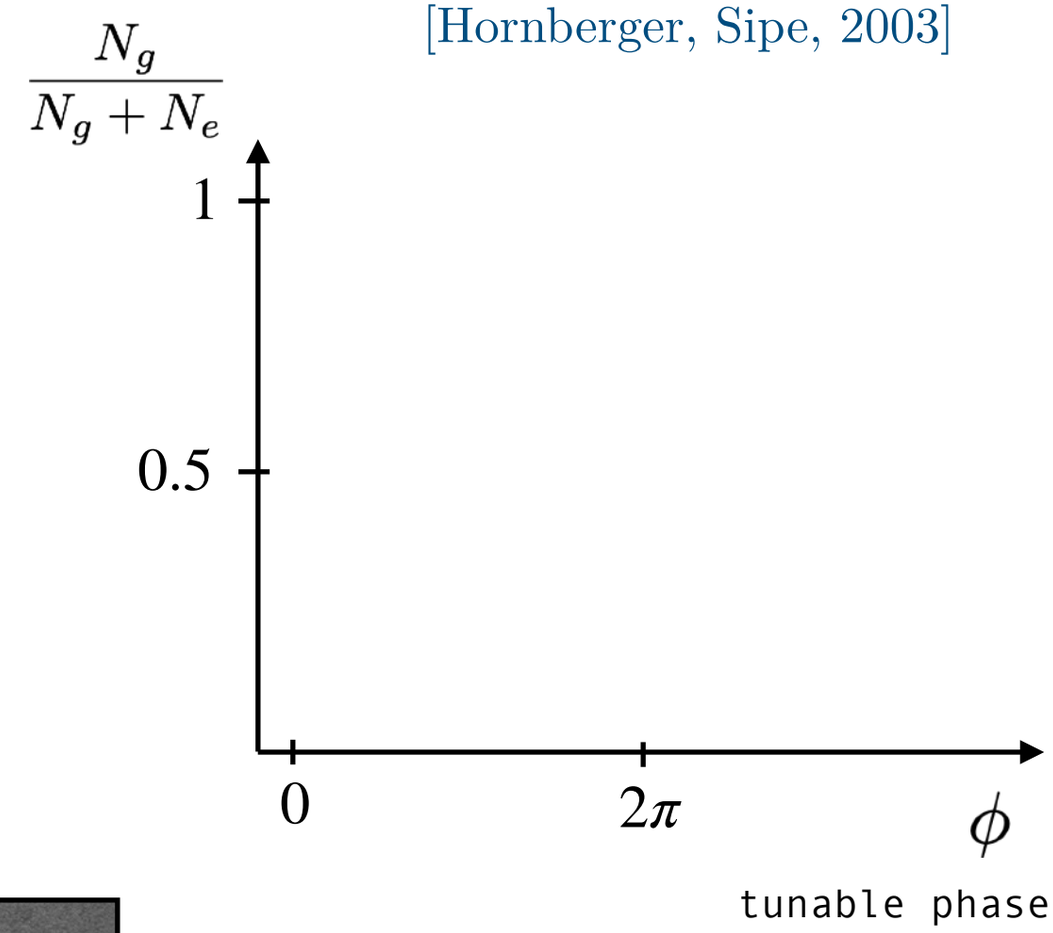
1 atom





$$\ln \gamma = -\int_t \int_0^{q_{\max}} \mathrm{d}q^2 \frac{d\Gamma}{dq^2} \mathcal{F}_{\mathrm{decoh}}(\mathbf{q})$$

Decoherence Kernel

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

measurement

$$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{th}}(\phi) = \mathrm{Tr}\{\rho(\mathcal{T})|g\rangle\langle g|\}$$

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Atom interferometry

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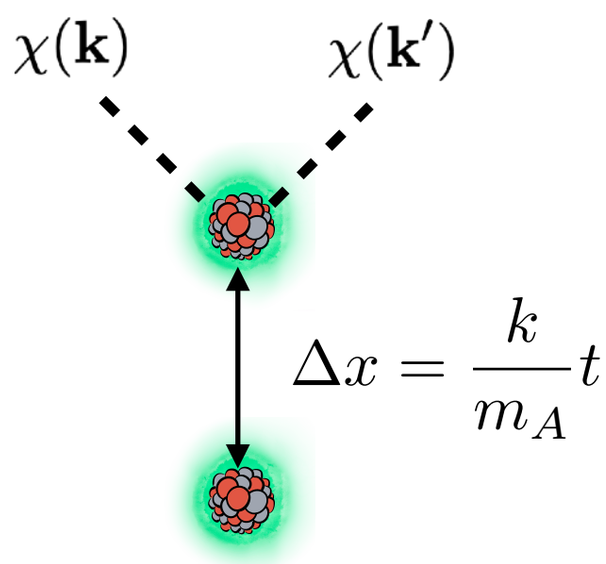

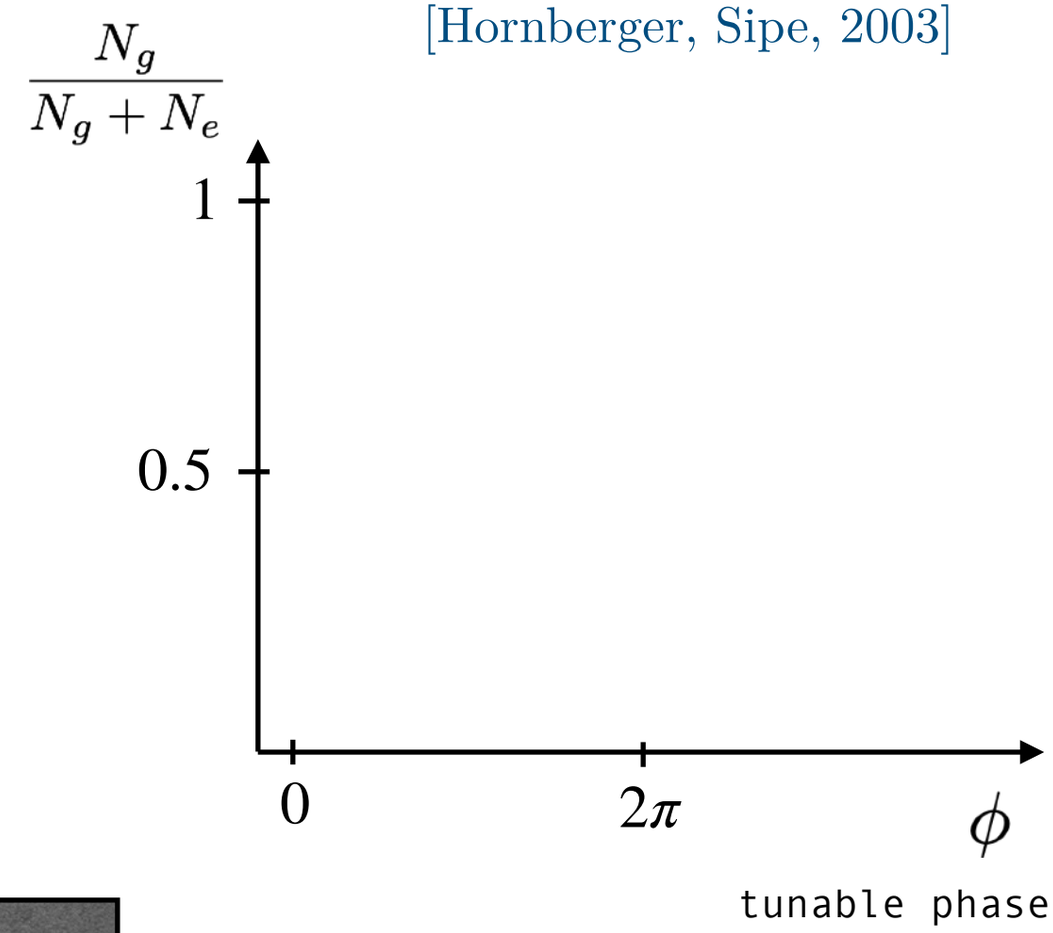

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Decoherence Kernel

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Atom interferometry

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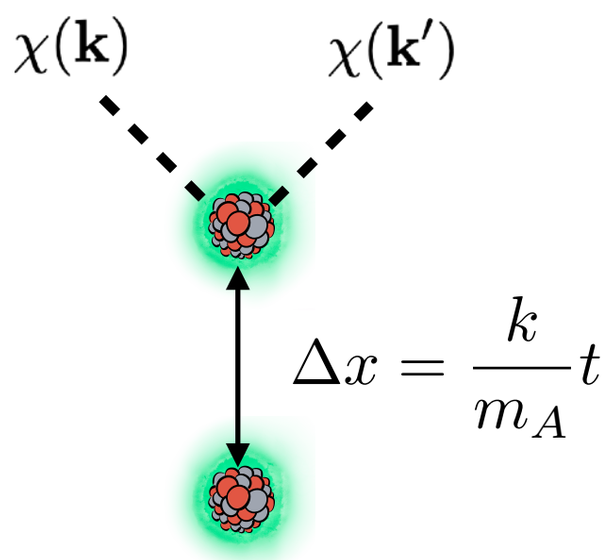

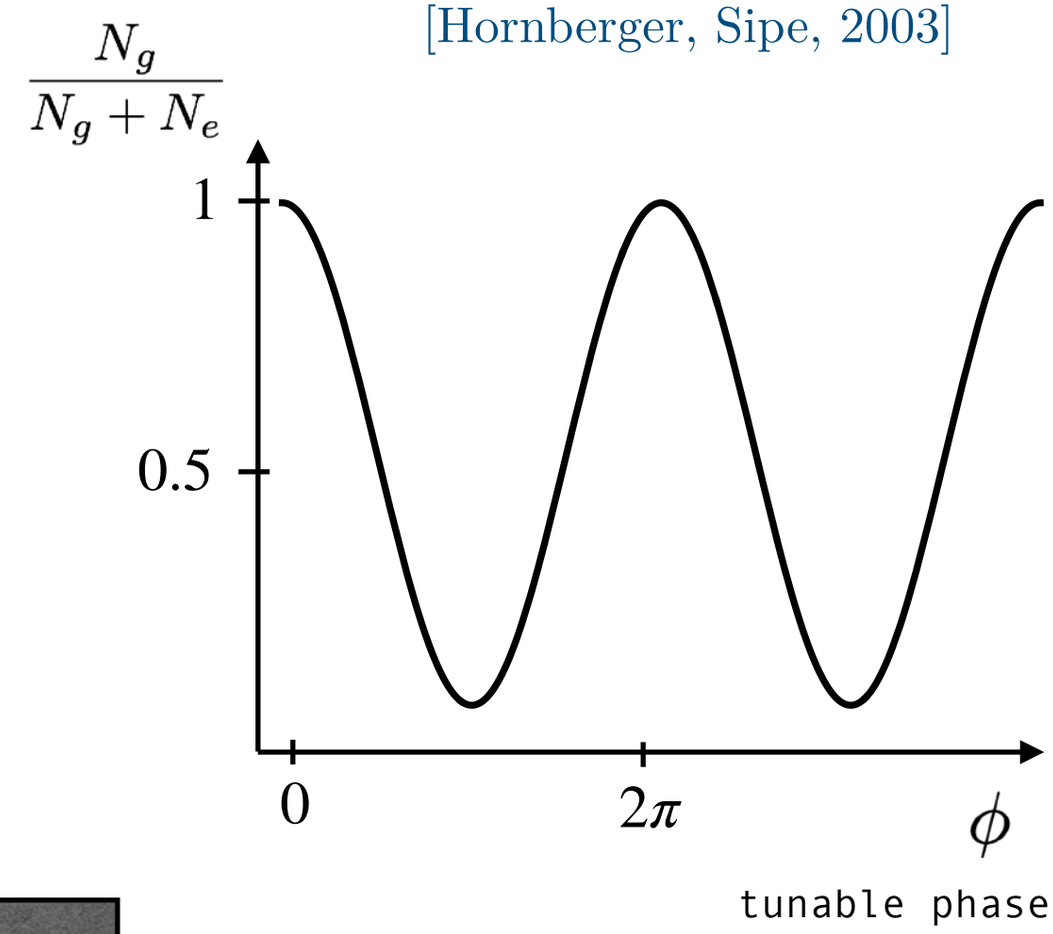

1 $\Gamma \to 0$

$$\ln \gamma = -\int_t \int_0^{q_{\max}} \mathrm{d}q^2 \frac{d\Gamma}{dq^2} \mathcal{F}_{\mathrm{decoh}}(\mathbf{q})$$

Decoherence Kernel

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

measurement

$$\frac{N_g}{N_g + N_e}\Big|_{\mathrm{th}}(\phi) = \tfrac{1}{2}\Big(1 + \underbrace{e^{-\int_q \Gamma(\mathbf{q})(1-\cos[\mathbf{q}\cdot\mathbf{\Delta x}])}}_{\to 0} \cos\Big[\phi + \underbrace{\int_q \Gamma(\mathbf{q}) \sin[\mathbf{q}\cdot\mathbf{\Delta x}]}_{\to 0}\Big]\Big)$$

evolution

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}] + \hat{T}\hat{\rho}\hat{T}^\dagger - \tfrac{1}{2}\{\hat{T}^\dagger\hat{T}, \hat{\rho}\}$$

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Atom interferometry

1 atom

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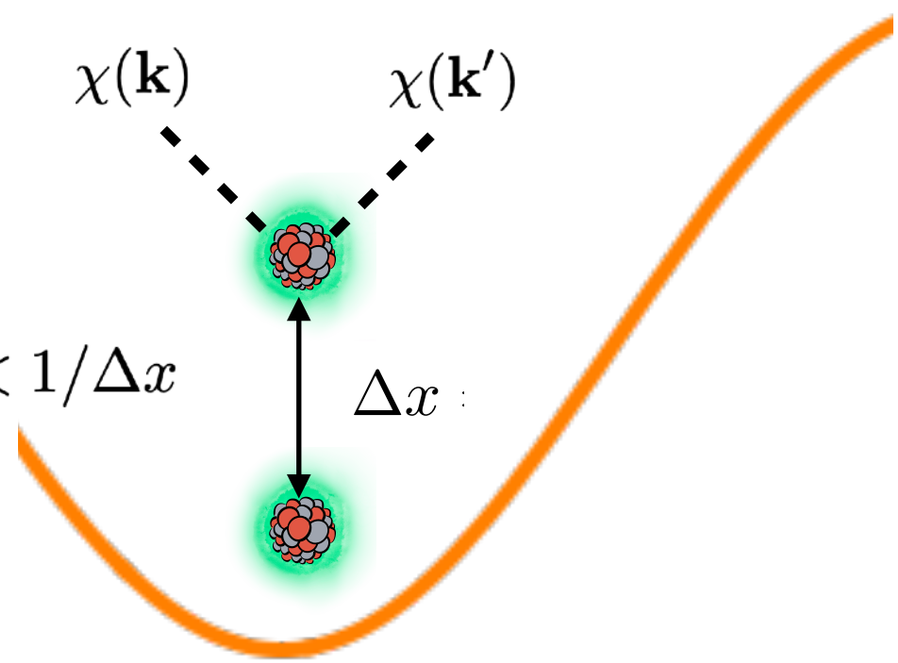
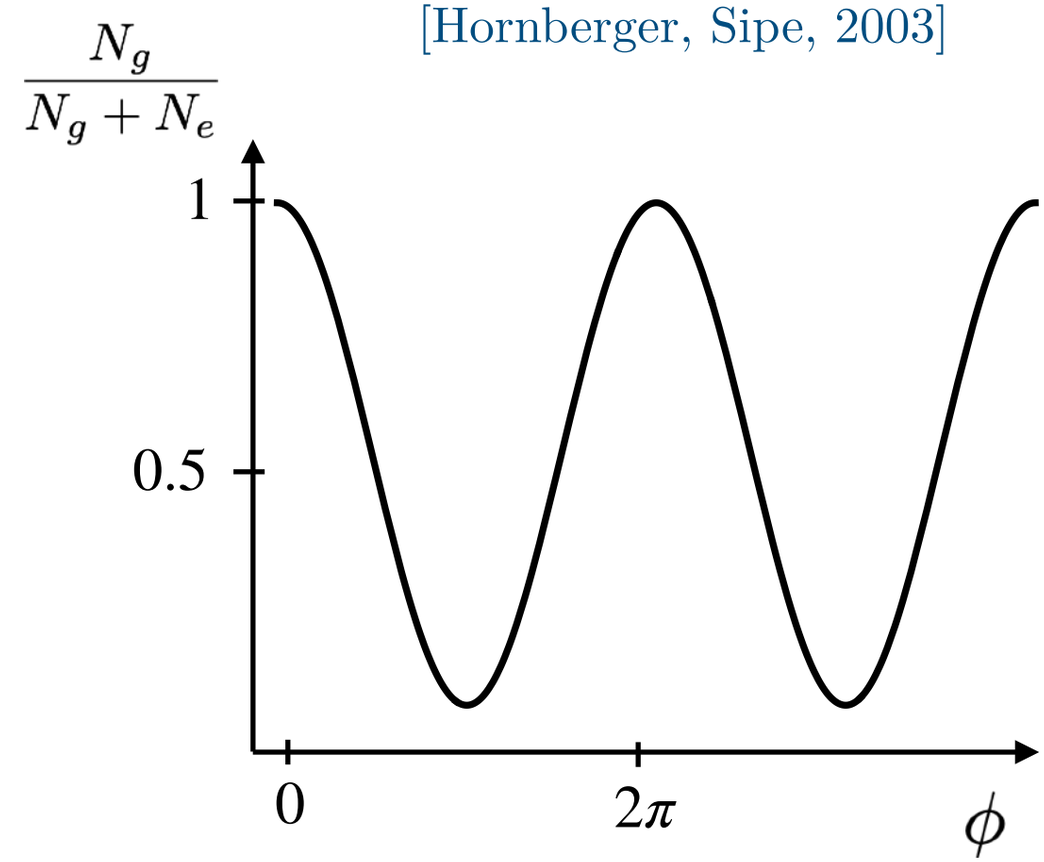


1 $\Gamma \to 0$

2 $\Gamma \neq 0,\ q \ll 1/\Delta x$

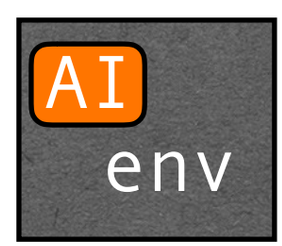


tunable phase

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

Decoherence Kernel

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



measurement

$$\left.\frac{N_g}{N_g + N_e}\right|_{\text{th}}(\phi) = \tfrac{1}{2}\left(1 + e^{-\int_q \Gamma(\mathbf{q})(1-\cancelto{0}{\cos[\mathbf{q}\cdot\mathbf{\Delta x}]})} \cos[\phi + \cancelto{0}{\textstyle\int_q \Gamma(\mathbf{q})\sin[\mathbf{q}\cdot\mathbf{\Delta x}]}]\right)$$

evolution

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\text{int}}, \hat{\rho}] + \hat{T}\hat{\rho}\hat{T}^\dagger - \tfrac{1}{2}\{\hat{T}^\dagger\hat{T}, \hat{\rho}\}$$

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Atom interferometry

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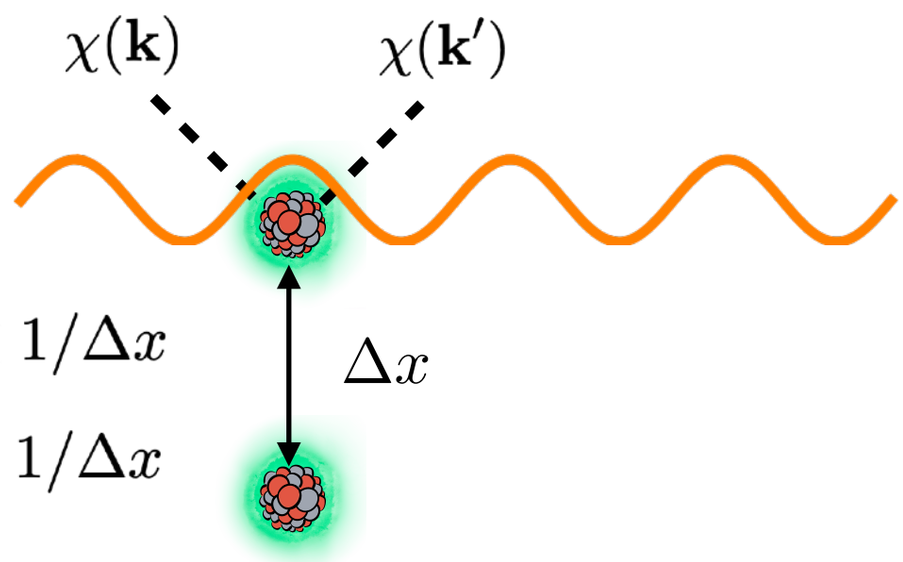
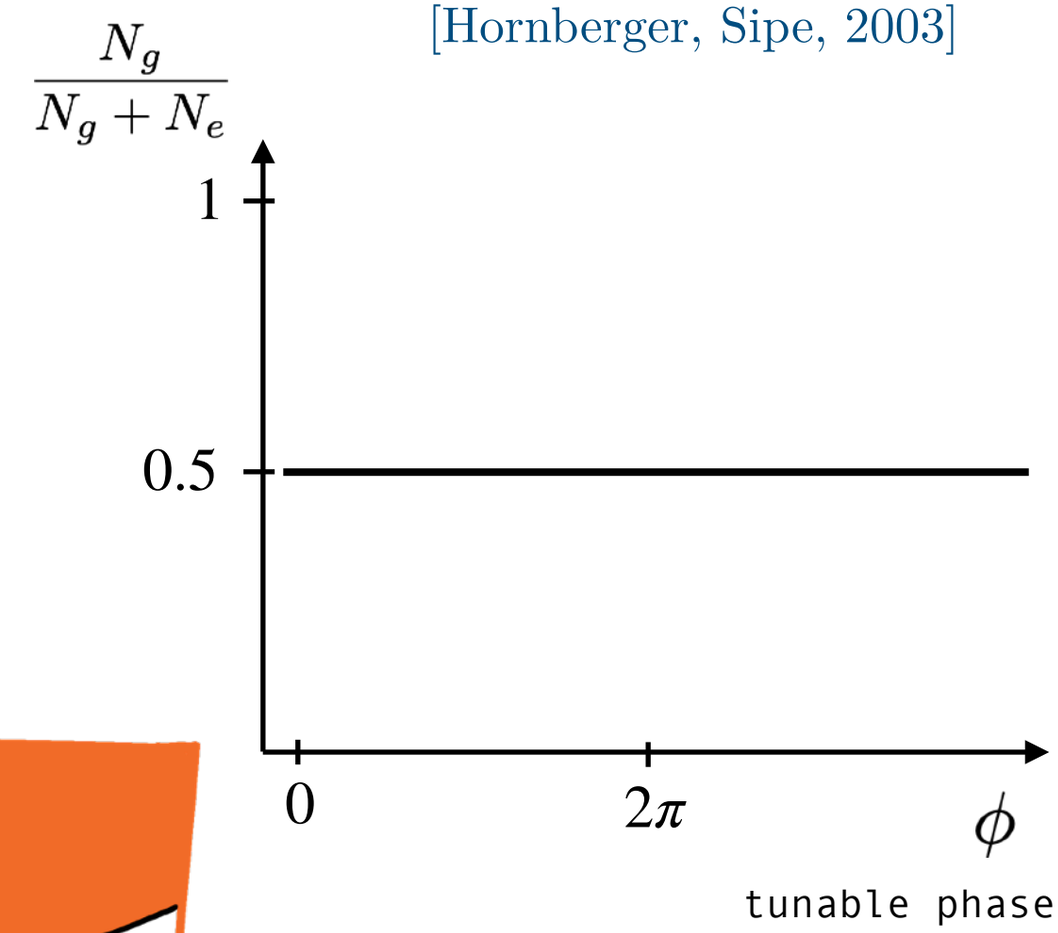


1 $\Gamma \to 0$

2 $\Gamma \neq 0,\ q \ll 1/\Delta x$

3 $\Gamma \neq 0,\ q \gg 1/\Delta x$



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Decoherence Kernel

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Atom interferometry

1 atom

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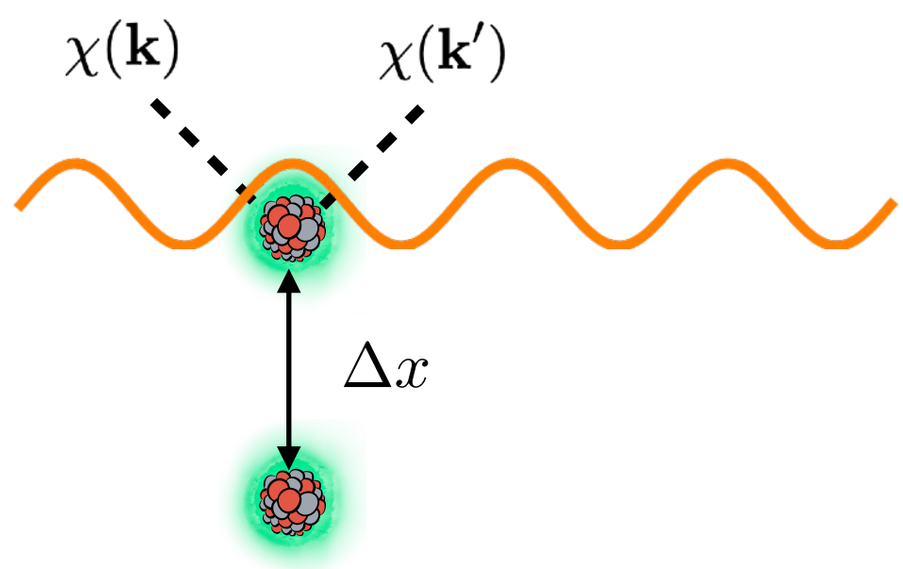

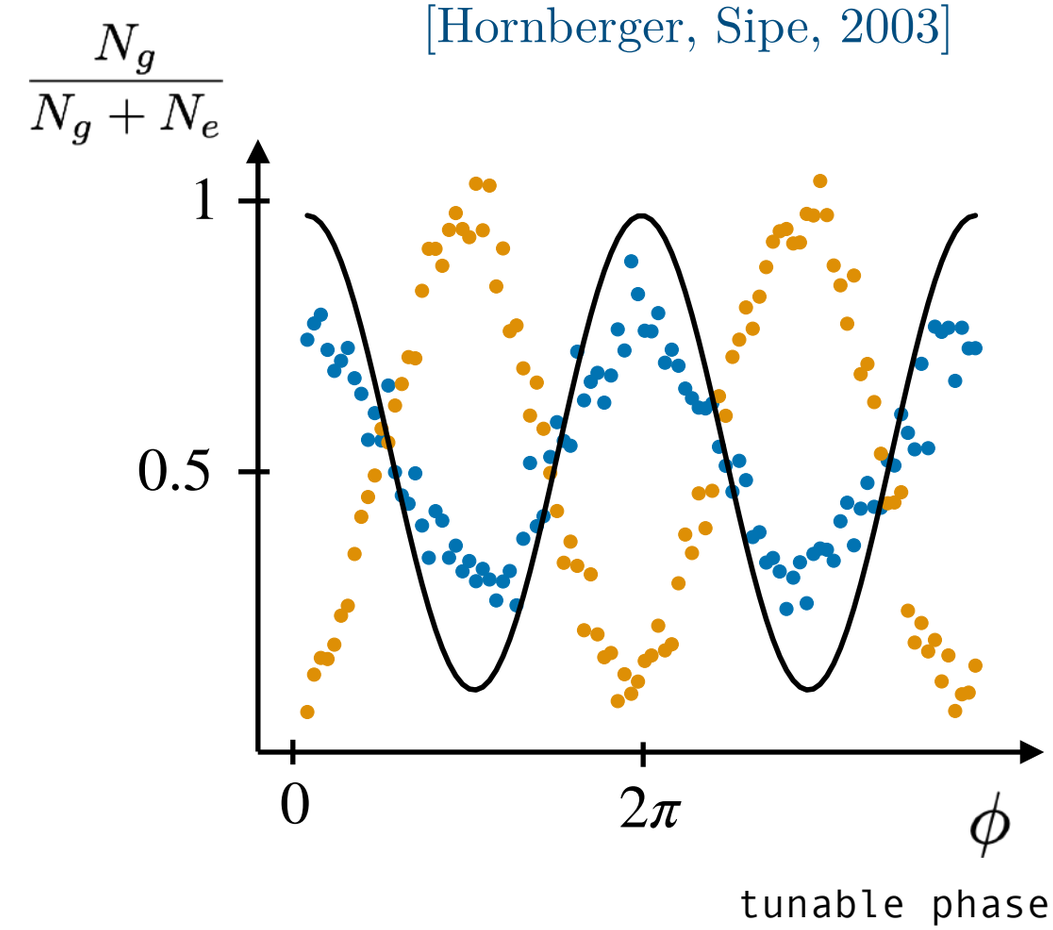

$$\ln \gamma = -\int_{q,t} R(\mathbf{q}) \mathcal{F}_{\text{decoh}}(\mathbf{q})$$

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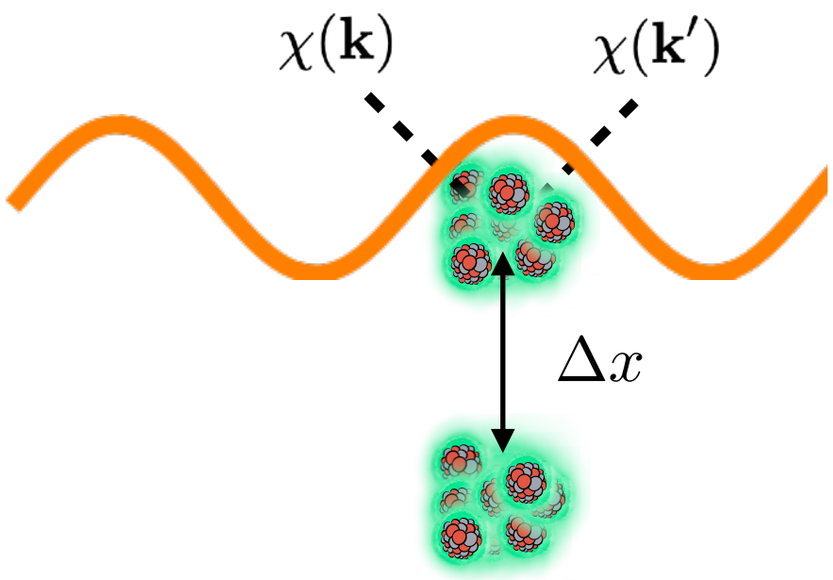
$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & \end{pmatrix}$$

Atom interferometry

N atoms



Statistics

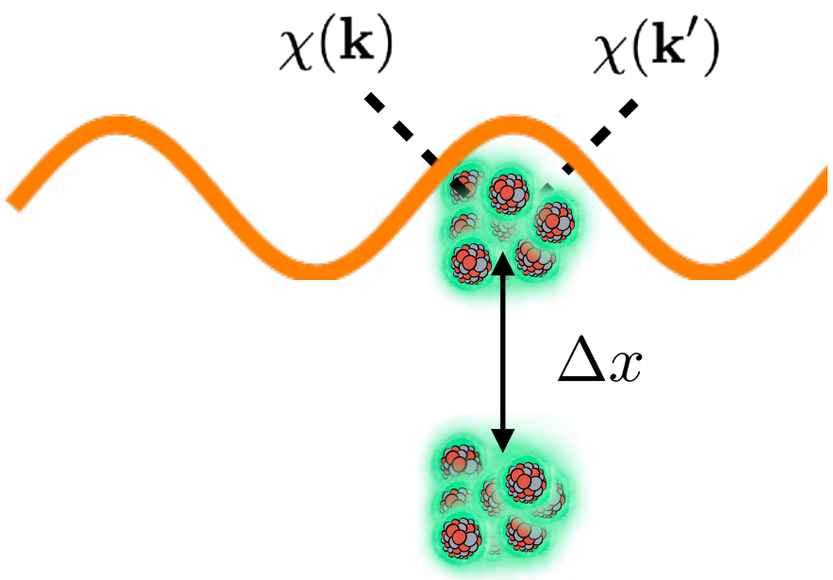
$$\delta\phi|_{\text{shot}} = 1/\sqrt{N}$$

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

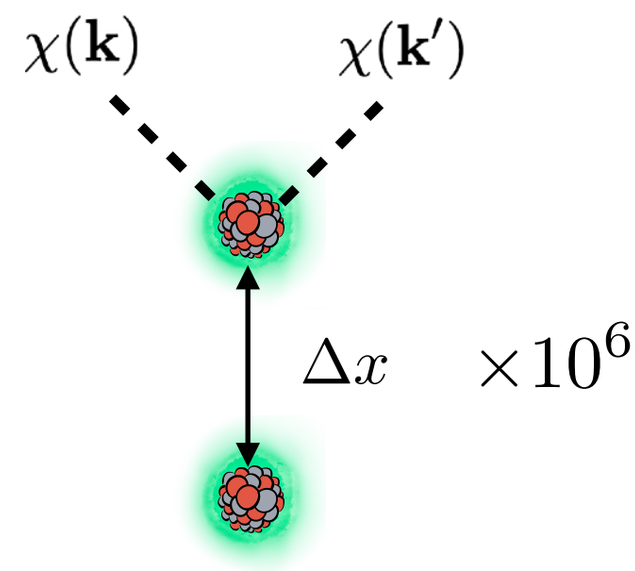
$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & \end{pmatrix}$$

Atom interferometry

N atoms



$\overset{?}{\equiv}$



$\times 10^6$

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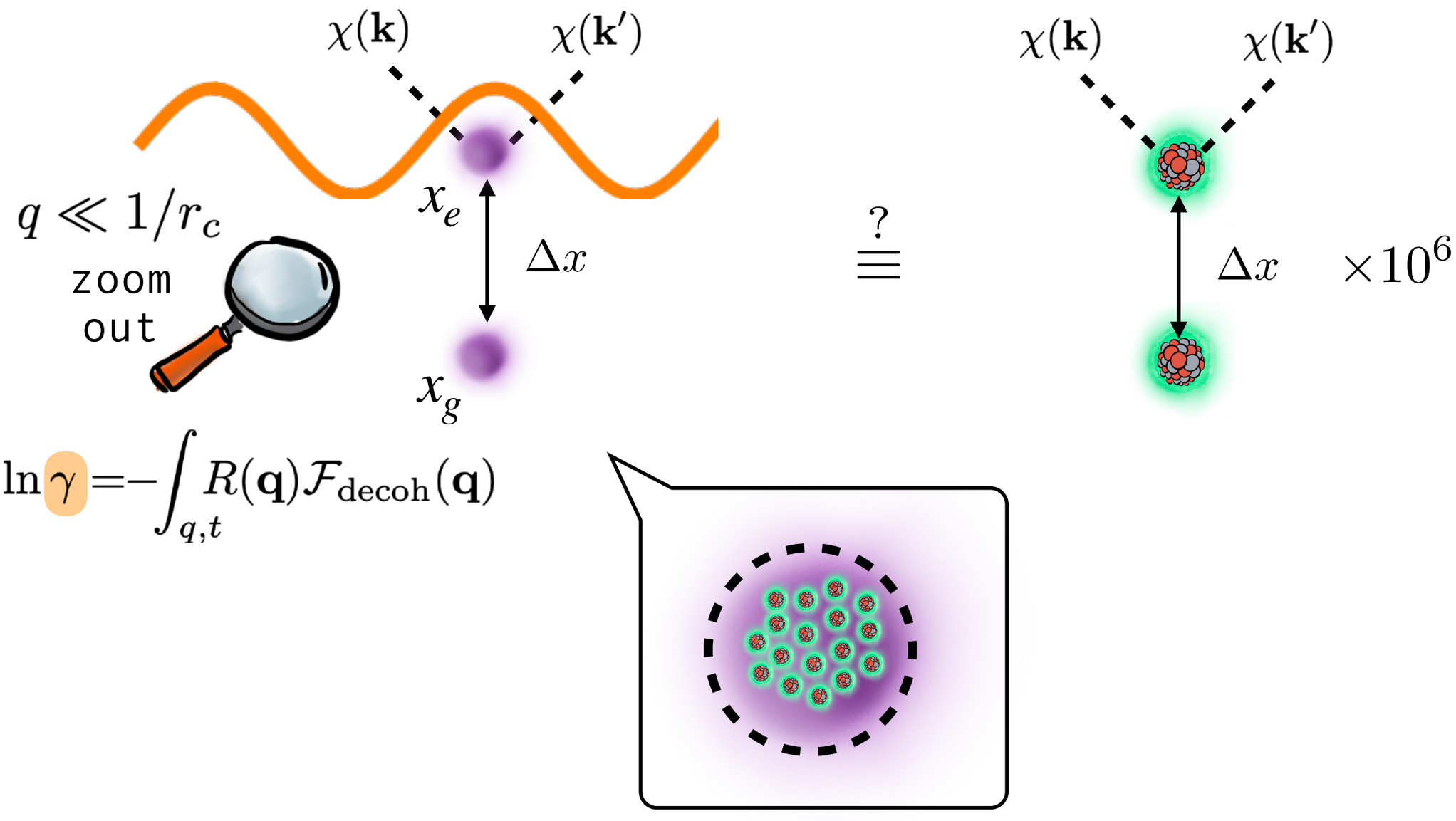
$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & \end{pmatrix}$$

Atom interferometry

N atoms

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



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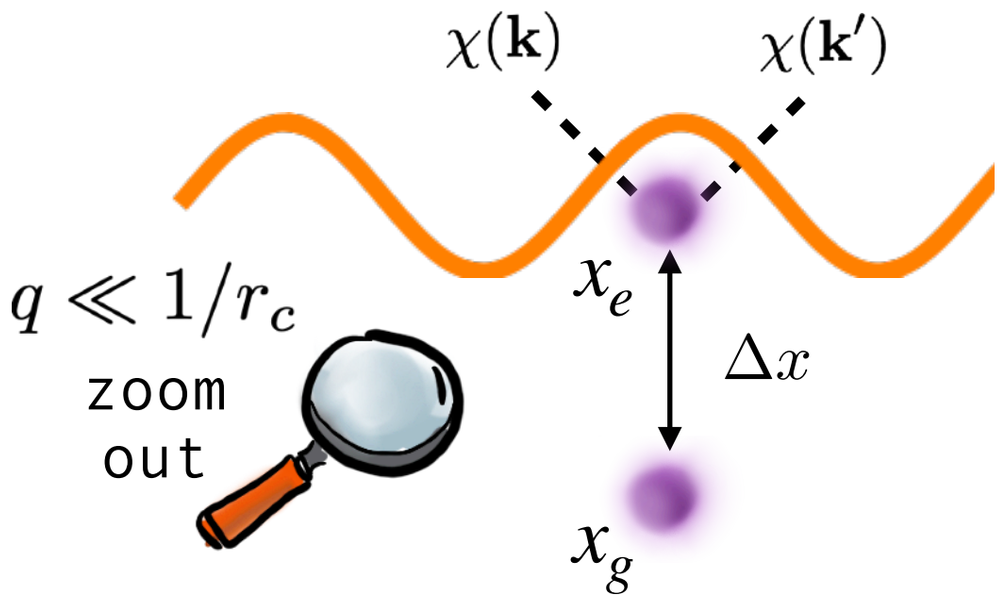
Atom interferometry

N atoms

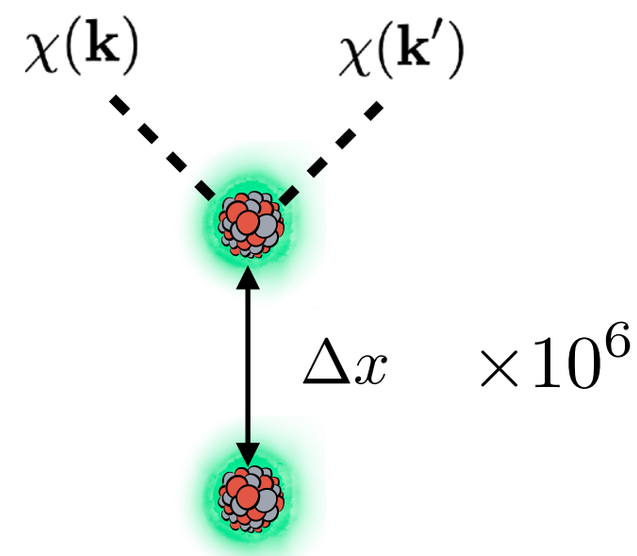
[Badurina, **CM**, Plestid, 2024]

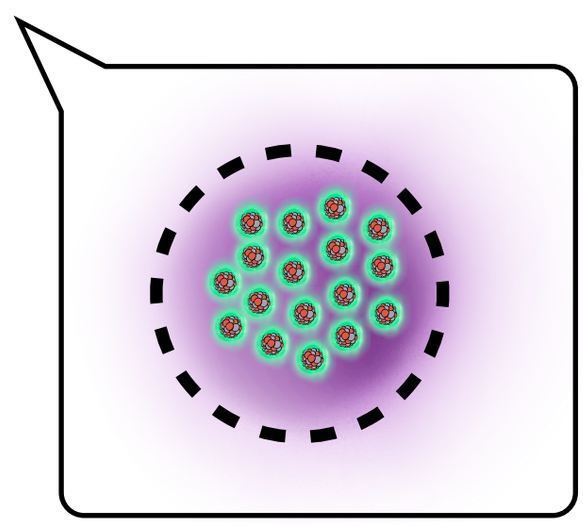


$$\ln \gamma = -\int_{q,t} R(\mathbf{q}) \mathcal{F}_{\rm decoh}(\mathbf{q})$$

$$|\Psi\rangle = \frac{1}{2^{N/2}} \prod_{i=1}^{N} (|g\rangle + e^{i\phi}|e\rangle)$$

$\overset{?}{\equiv}$





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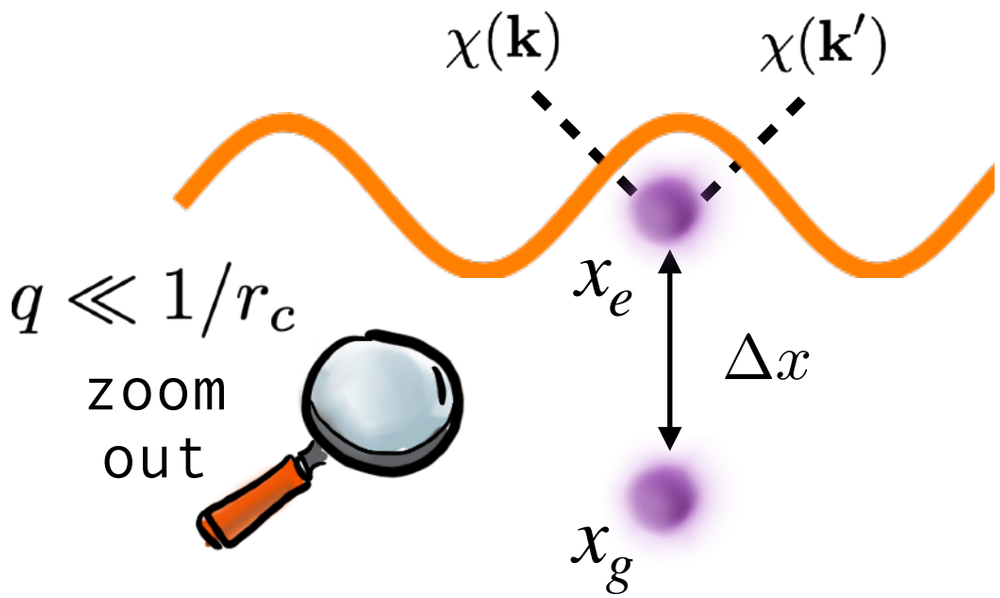
Atom interferometry

N atoms

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



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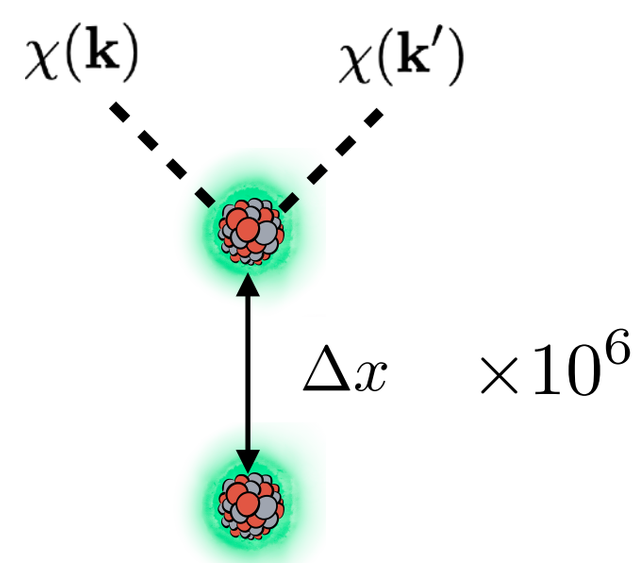
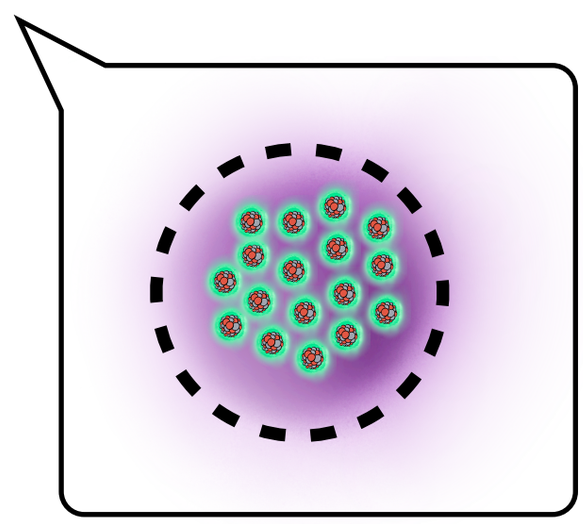


$$\ln \gamma = -\int_{q,t} R(\mathbf{q}) \mathcal{F}_{\rm decoh}(\mathbf{q})$$



$$|\Psi\rangle = \frac{1}{2^{N/2}} \prod_{i=1}^{N} (|g\rangle + e^{i\phi}|e\rangle)$$

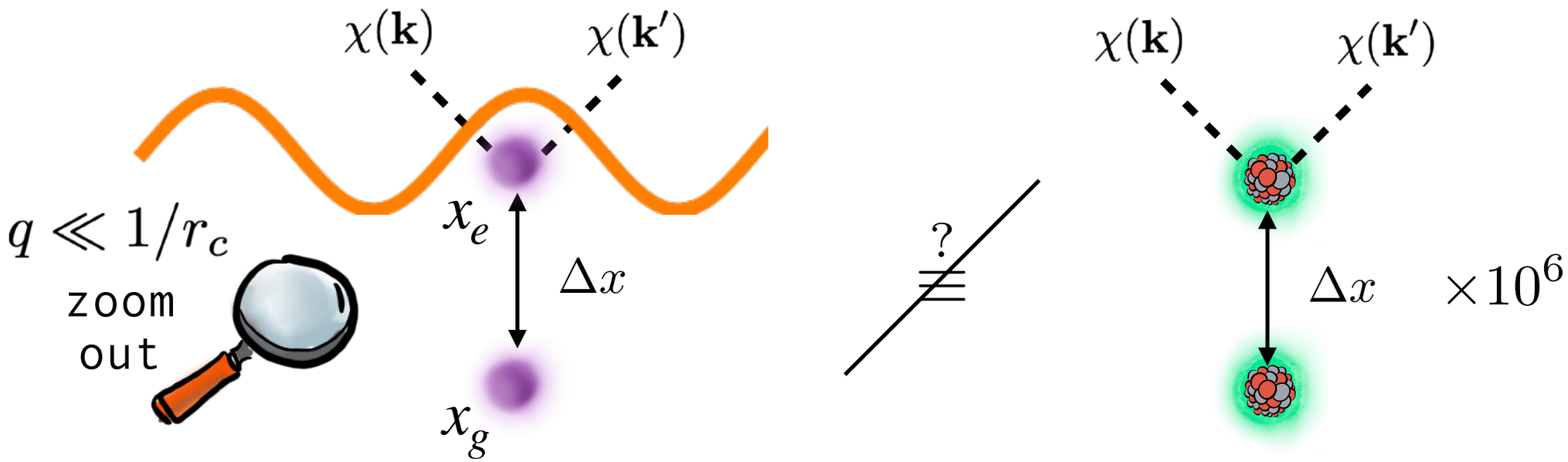
$$= \frac{1}{2^{N/2}} \sum_{m=0}^{N} \binom{N}{m} |g_1 \cdots g_m e_{m+1} \cdots e_N\rangle$$

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

Atom interferometry

N atoms

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



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

HUGE ENHANCEMENT!

Decoherence Kernel 1-body

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

measurement

$$\left.\frac{N_g}{N_g+N_e}\right|_{\rm th}(\phi) = \tfrac{1}{2}\left(1 + e^{-\int_q \Gamma(\mathbf{q})(1-\cos[\mathbf{q}\cdot\mathbf{\Delta x}])}\cos[\phi + \int_q \Gamma(\mathbf{q})\sin[\mathbf{q}\cdot\mathbf{\Delta x}]\right)$$

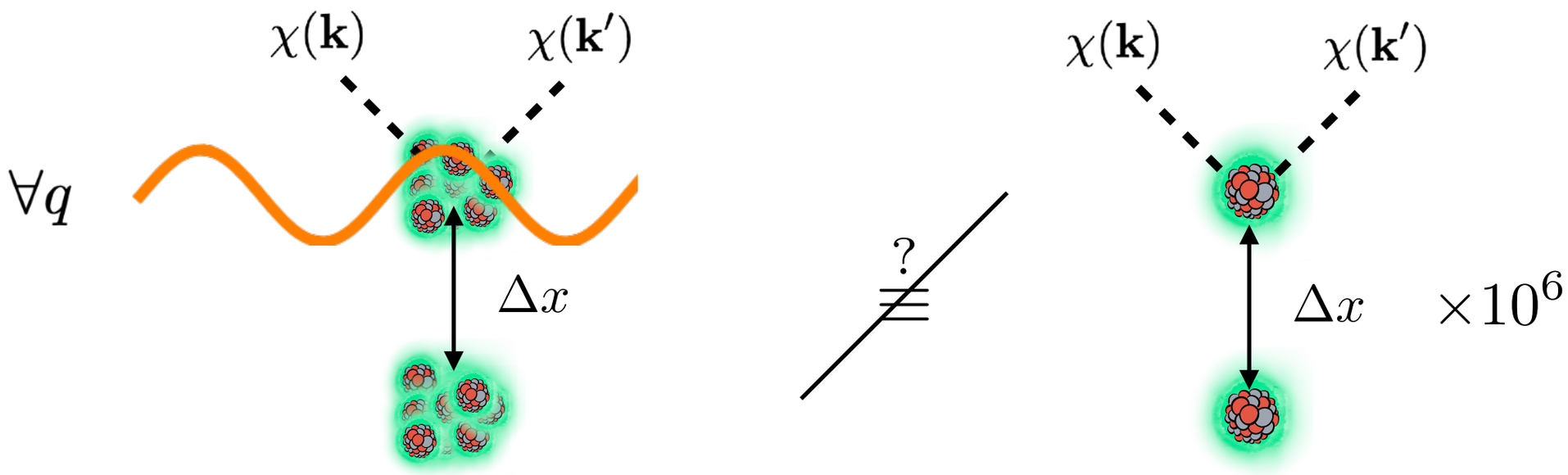
$$\left.\frac{N_g}{N_g+N_e}\right|_{\rm exp}(\phi) = \tfrac{1}{2}\left(1 + V\cos\left(\phi + \Delta\phi\right)\right)$$

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

Atom interferometry

N atoms

[Badurina, **CM**, Plestid, 2024]
[**CM**, Plestid, 2025]



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

Decoherence Kernel 1-body

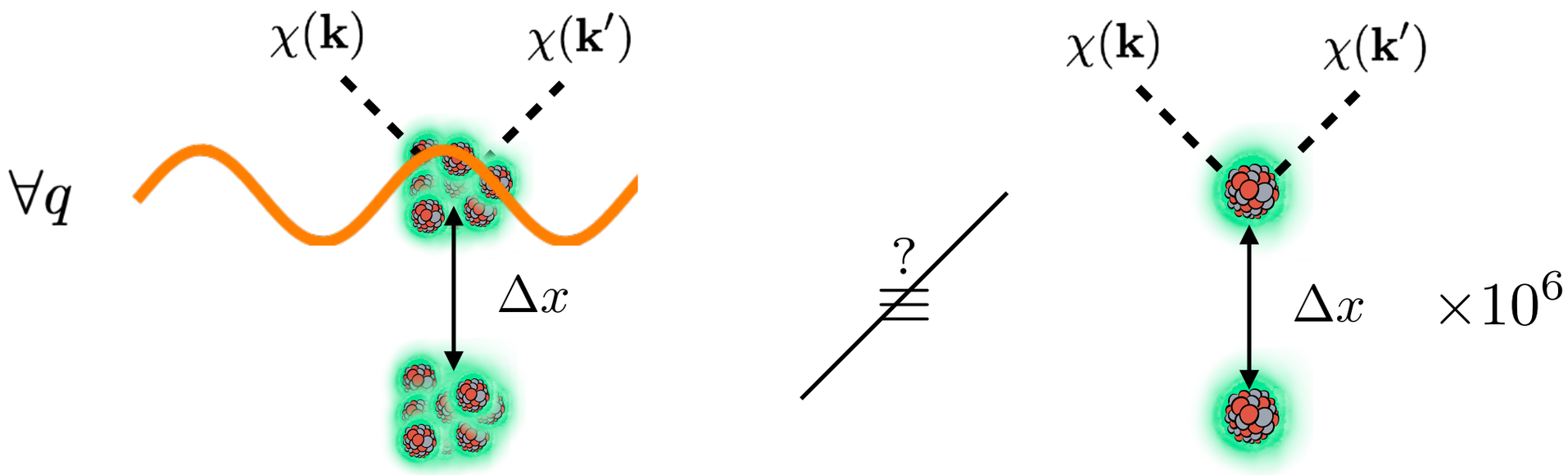
$$\mathcal{F}_{\text{decoh}}(\mathbf{q}) = G(\mathbf{q})\big(1 - \cos[\mathbf{q}\cdot\mathbf{\Delta x}] - iN\sin[\mathbf{q}\cdot\mathbf{\Delta x}]\big) + (1 - G(\mathbf{q}))\big(1 - \cos[\mathbf{q}\cdot\mathbf{\Delta x}] - i\sin[\mathbf{q}\cdot\mathbf{\Delta x}]\big)$$

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

Atom interferometry

N atoms

[Badurina, **CM**, Plestid, 2024]
[**CM**, Plestid, 2025]



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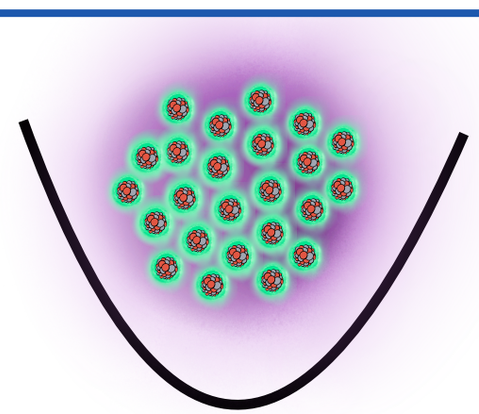
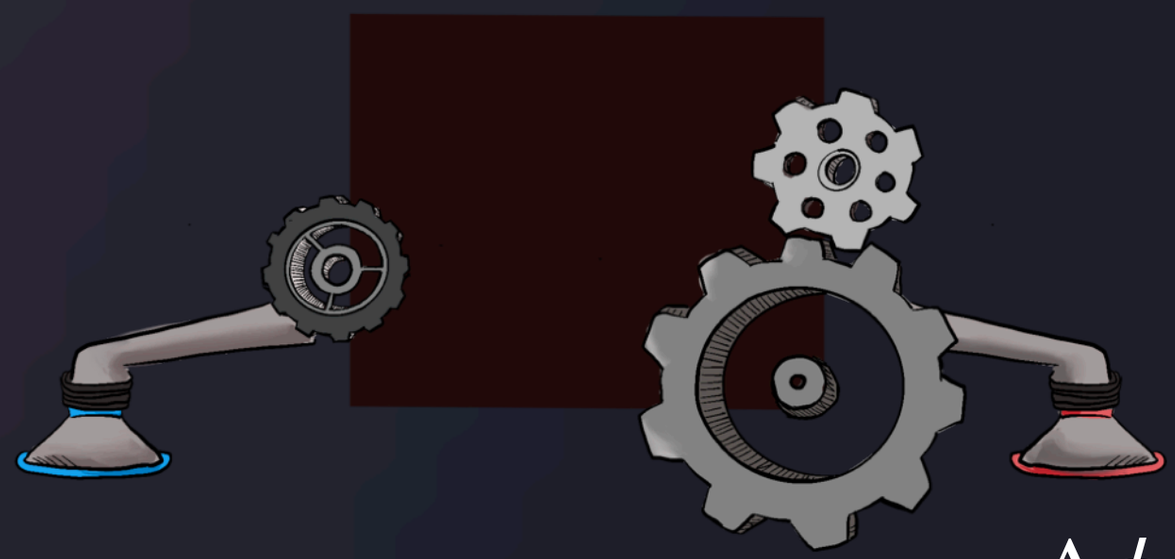


The Debye-Waller factor (cloud form factor squared)

$$G(\mathbf{q}) = \int_y \varrho_y(\{\mathbf{y}\},\{\mathbf{y}\})e^{i\mathbf{q}\cdot(\mathbf{y}_i - \mathbf{y}_j)} = e^{-q^2 r_c^2/2}$$

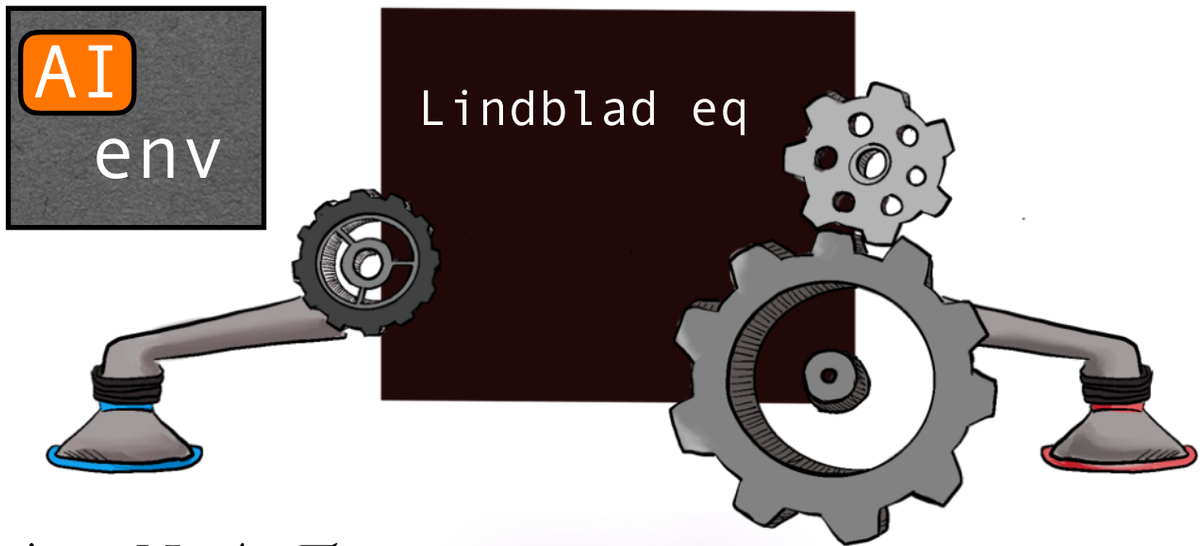


$$\Delta\phi = \phi + \gamma_0 + N\gamma$$

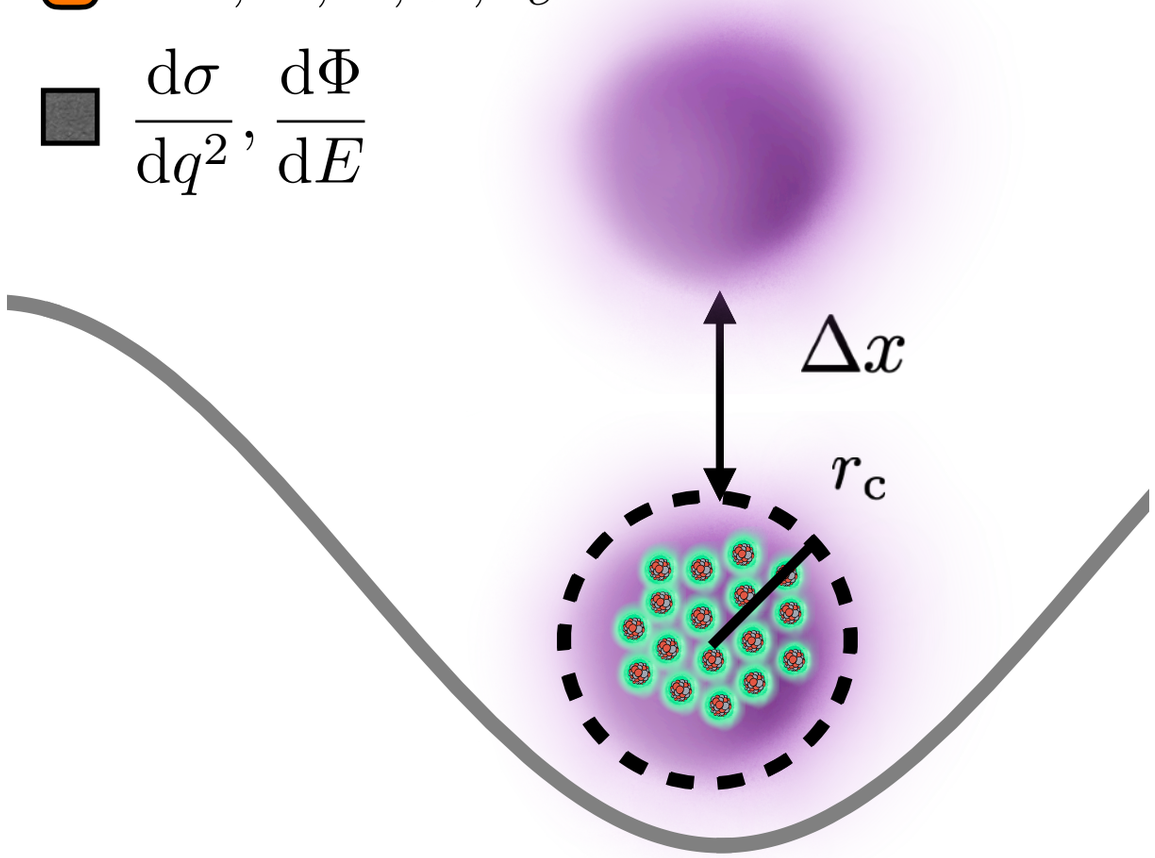
How do we test the “coherenctly enhanced decoherence” at the lab?

Enhanced phase-shift

How do we test it?

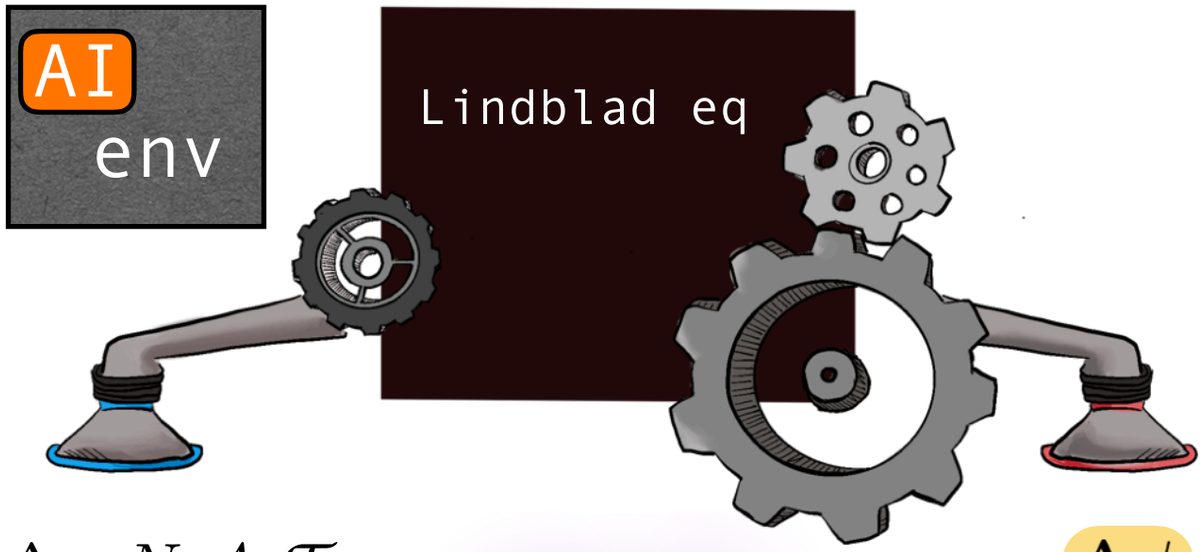


- $\Delta x, N, A, \mathcal{T}, r_c$
- $\dfrac{\mathrm{d}\sigma}{\mathrm{d}q^2}, \dfrac{\mathrm{d}\Phi}{\mathrm{d}E}$



Enhanced phase-shift

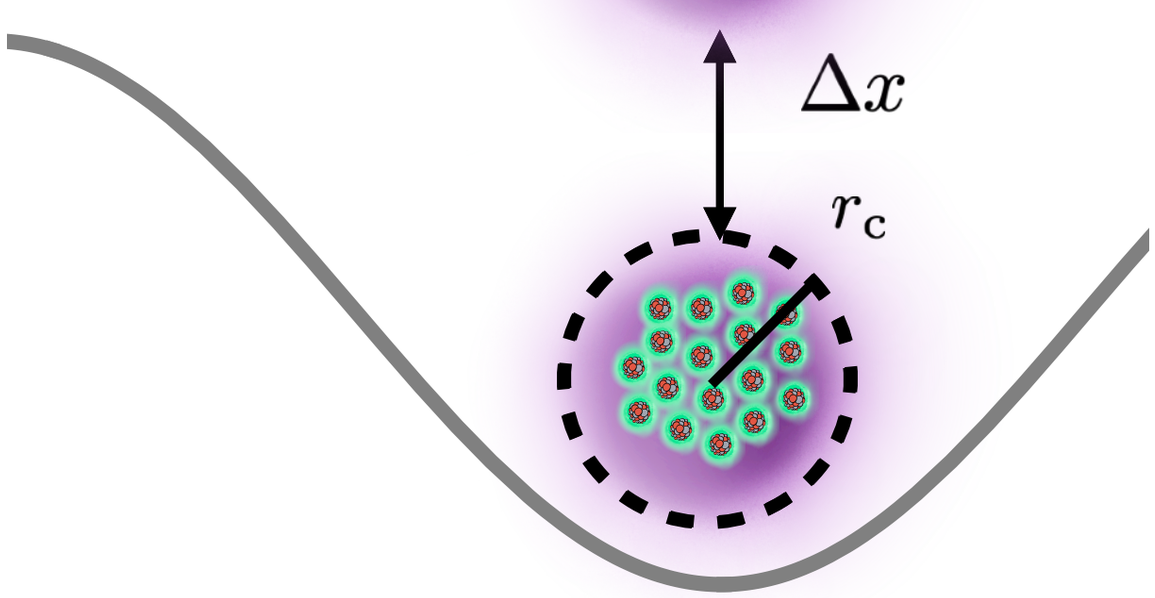
How do we test it?



- $\Delta x, N, A, \mathcal{T}, r_c$
- $\dfrac{\mathrm{d}\sigma}{\mathrm{d}q^2}, \dfrac{\mathrm{d}\Phi}{\mathrm{d}E}$

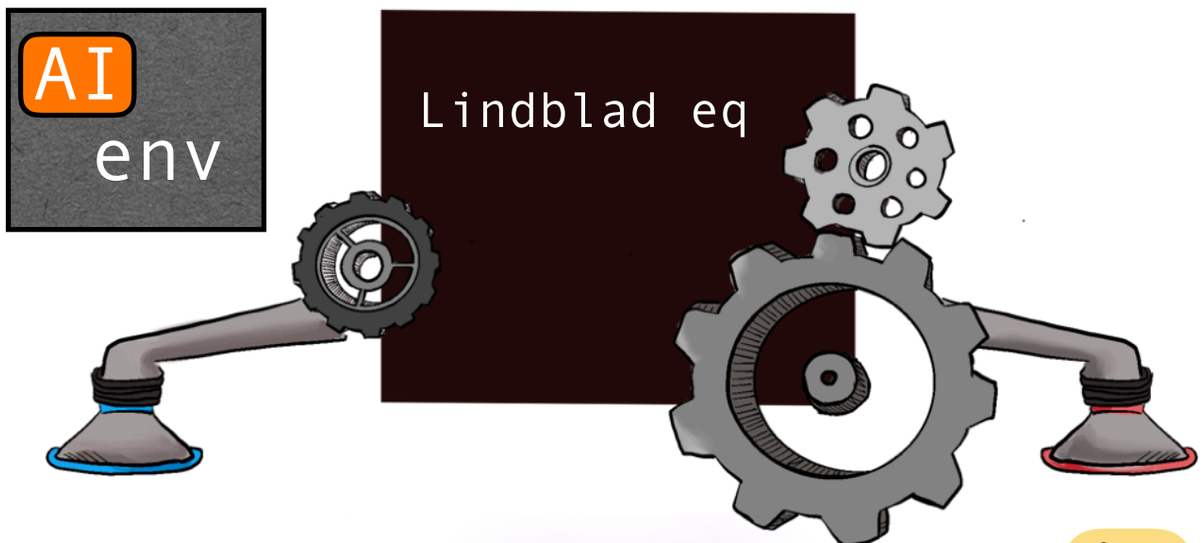
$$\Delta\phi = \phi + \gamma_0 + N\gamma$$

tunable phase

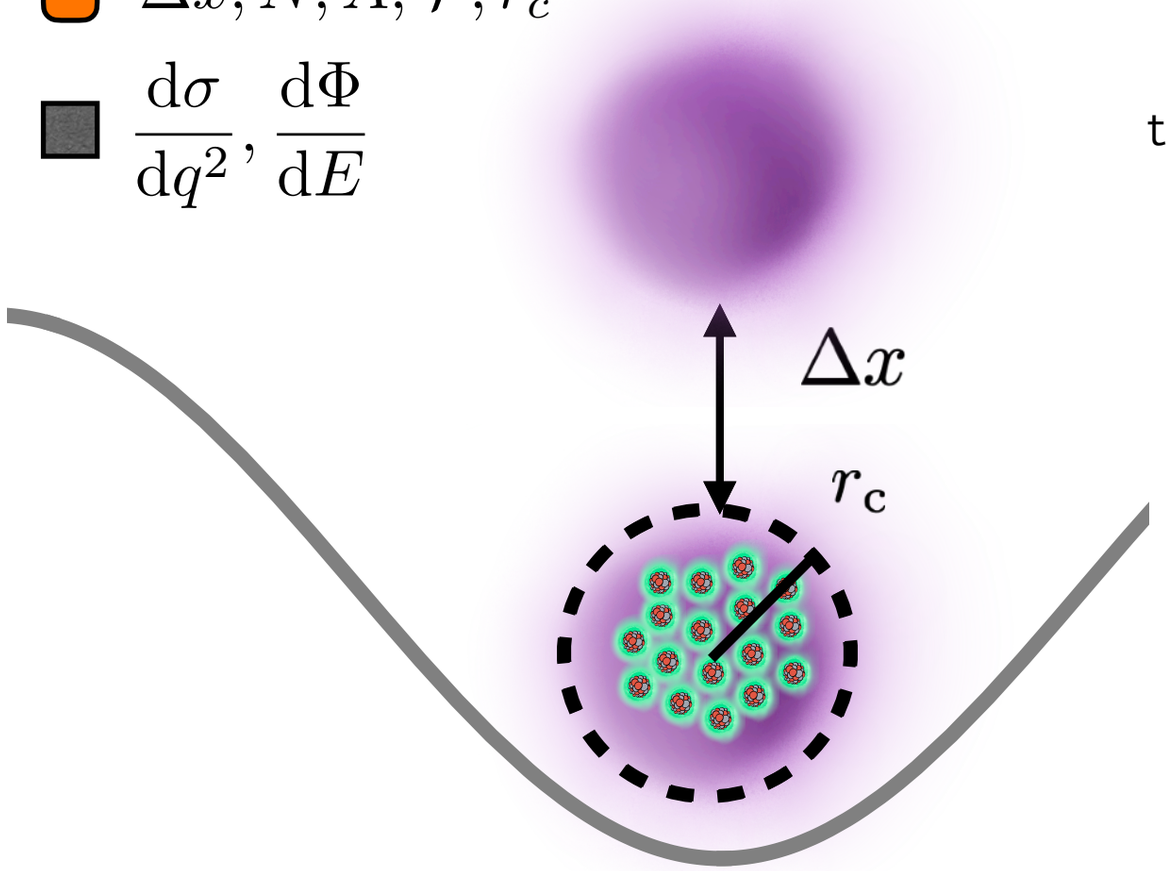


Enhanced phase-shift

How do we test it?



- $\Delta x, N, A, \mathcal{T}, r_c$
- $\dfrac{\mathrm{d}\sigma}{\mathrm{d}q^2}, \dfrac{\mathrm{d}\Phi}{\mathrm{d}E}$



$$\Delta\phi = \phi + \gamma_0 + N\gamma$$

tunable phase

Incoherent-decoherence

$$\gamma_0 = \int_q \Gamma(\mathbf{q})[1 - G(\mathbf{q})]\sin(\mathbf{q}\cdot\mathbf{\Delta x})$$

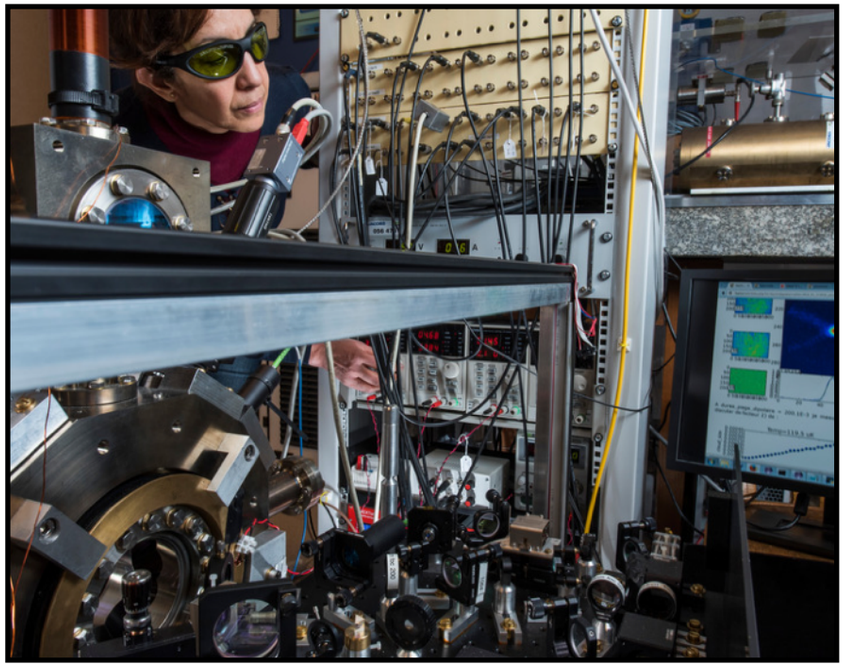
Coherent-decoherence

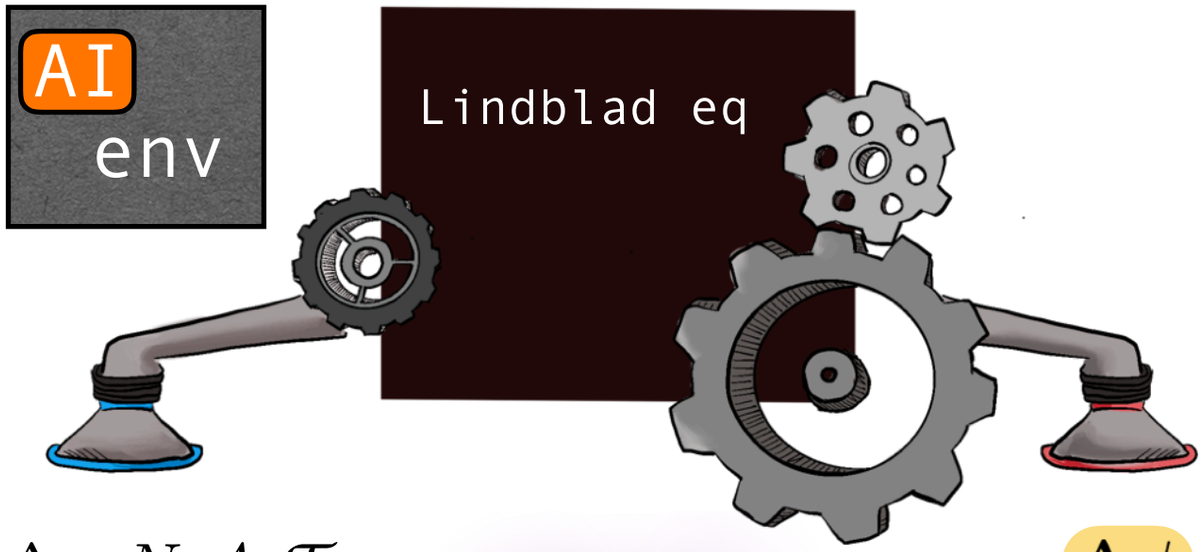
$$\gamma = \int_q \Gamma(\mathbf{q})\, G(\mathbf{q})\sin(\mathbf{q}\cdot\mathbf{\Delta x})$$

Enhanced phase-shift

How do we test it?

e.g. Kastler Brossel Lab





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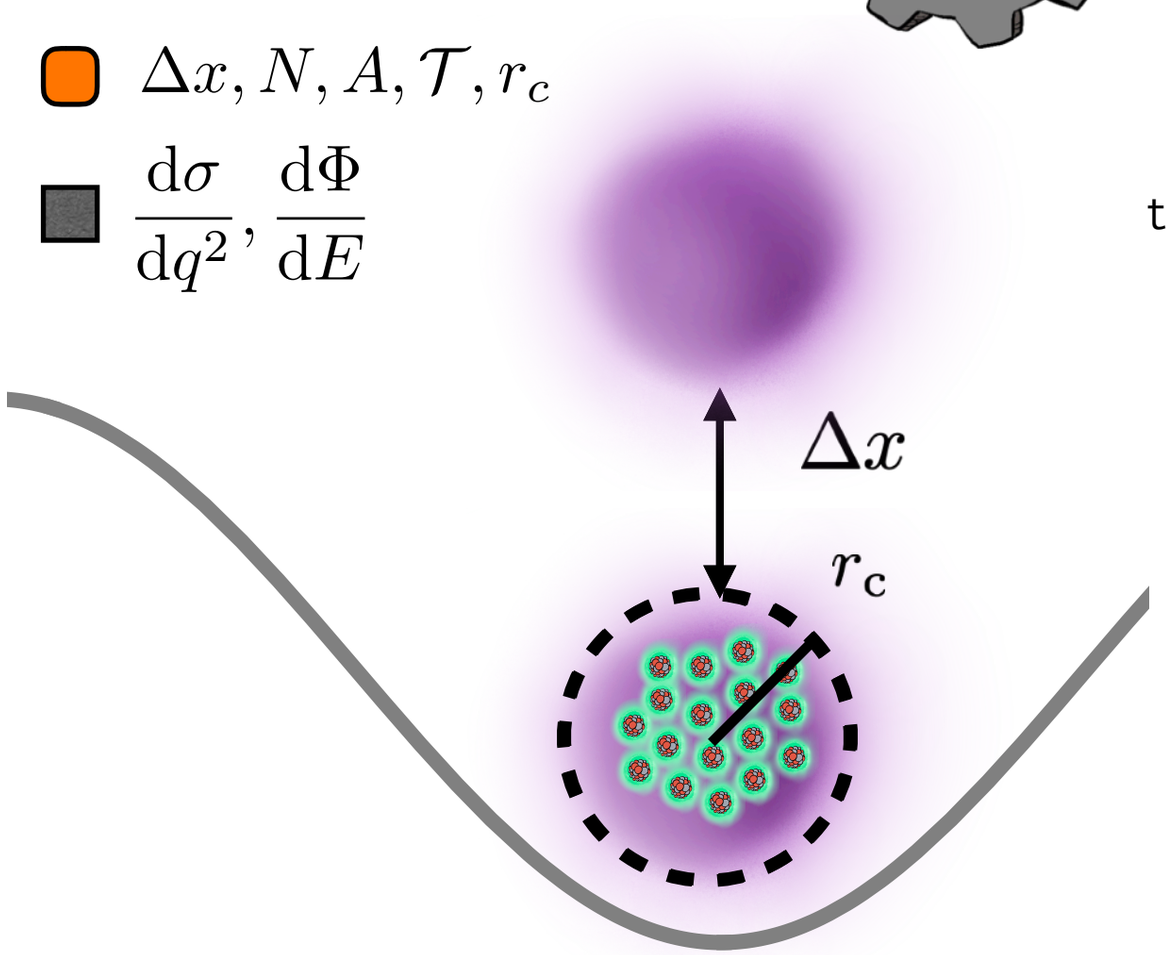

$$\Delta\phi = \phi + \gamma_0 + N\gamma$$

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$$\gamma_0 = \int_q \Gamma(\mathbf{q})[1 - G(\mathbf{q})]\sin(\mathbf{q}\cdot\mathbf{\Delta x})$$

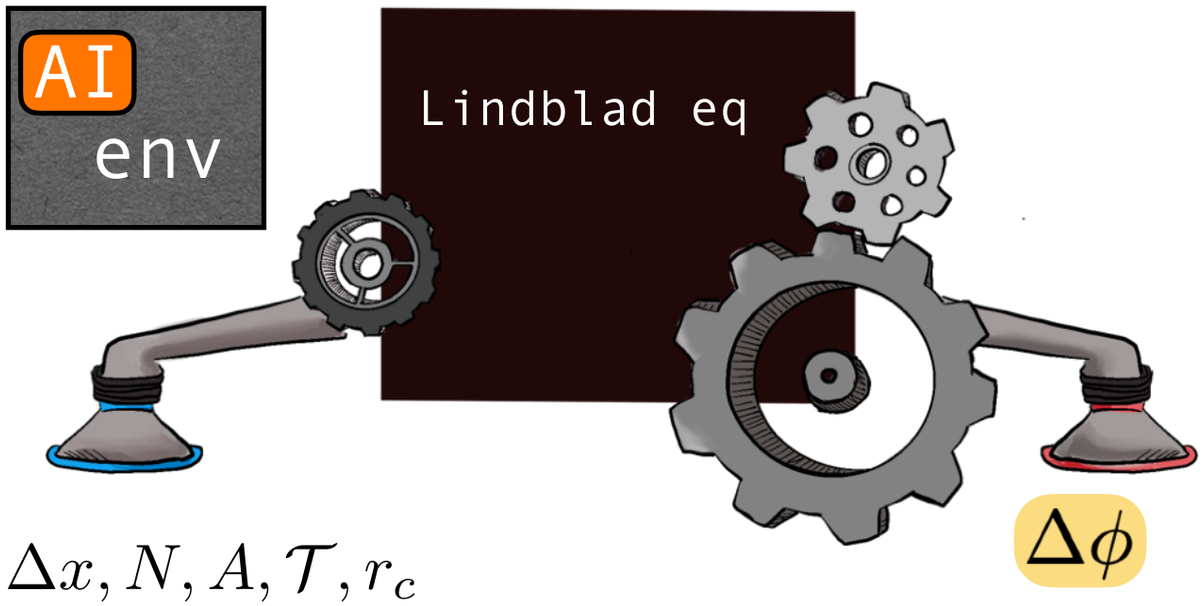
Coherent-decoherence

$$\gamma = \int_q \Gamma(\mathbf{q})\, G(\mathbf{q})\sin(\mathbf{q}\cdot\mathbf{\Delta x})$$

Enhanced phase-shift @ the lab

[**CM**, Plestid, 2025]

Via an IR-lamp

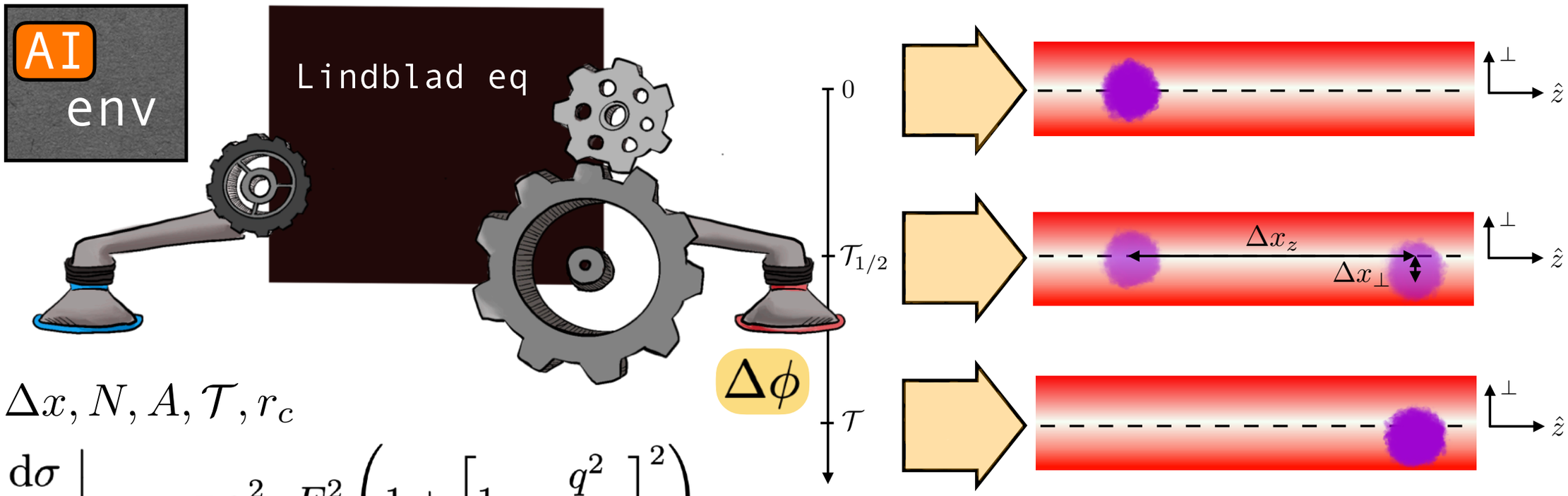


- $\Delta x, N, A, \mathcal{T}, r_c$
- $\left.\dfrac{\mathrm{d}\sigma}{\mathrm{d}q^2}\right|_{\mathrm{IR-lamp}} = \pi\,\alpha_{\mathrm{pol}}^2 E^2 \left(1 + \left[1 - \dfrac{q^2}{2E^2}\right]^2\right)$

Enhanced phase-shift @ the lab

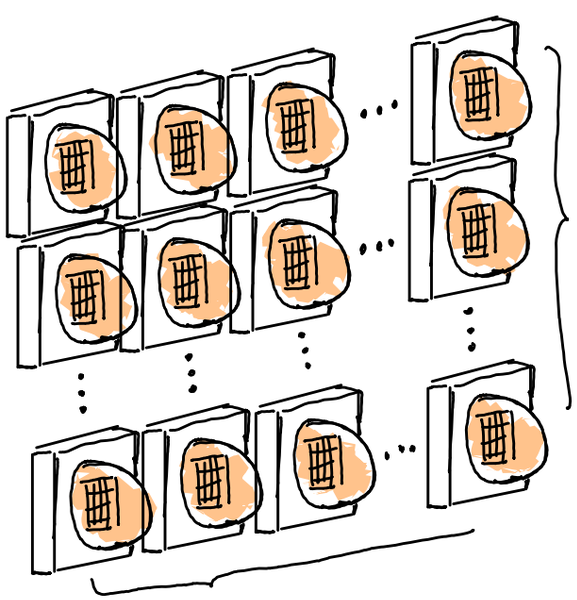
[CM, Plestid, 2025]

Via an IR-lamp



$\Delta x, N, A, \mathcal{T}, r_c$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}q^2}\right|_{\mathrm{IR-lamp}} = \pi\,\alpha_{\mathrm{pol}}^2 E^2 \left(1 + \left[1 - \frac{q^2}{2E^2}\right]^2\right)$$

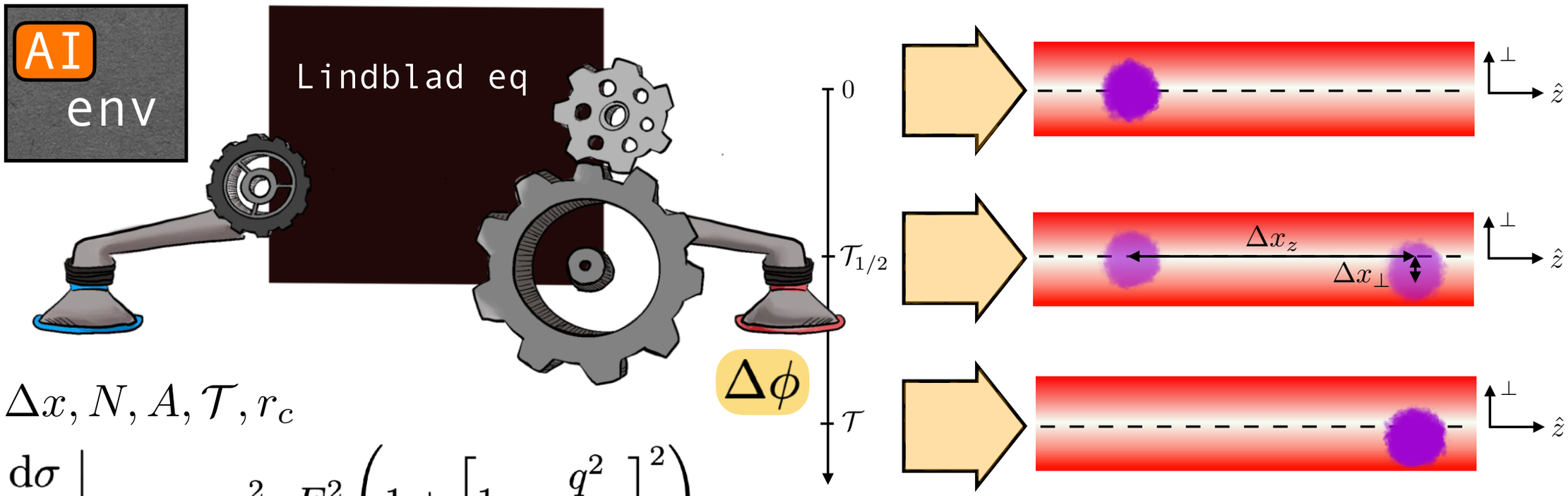


10x10 1mm^2 LED IR lamps
1€ each

Enhanced phase-shift @ the lab

[**CM**, Plestid, 2025]

Via an IR-lamp



$\Delta x, N, A, \mathcal{T}, r_c$

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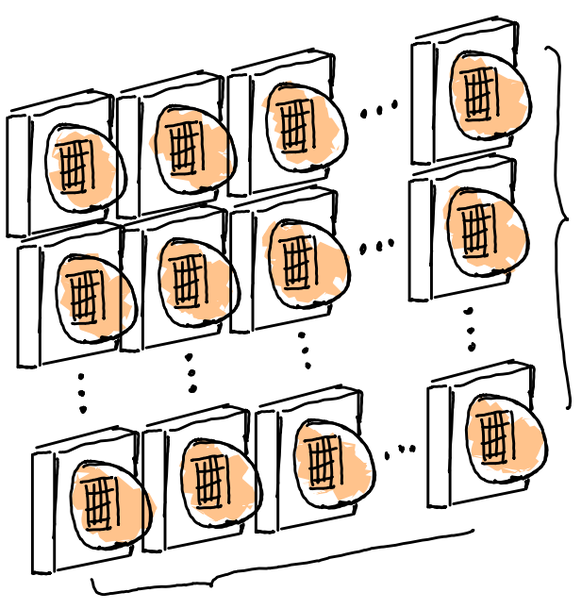


10x10 1mm^2 LED IR lamps
1€ each

$$\delta\phi(\aleph) = \sqrt{\frac{\delta\phi_{\mathrm{shot}}^2}{\aleph} + \delta\phi_{\mathrm{sys}}^2}$$

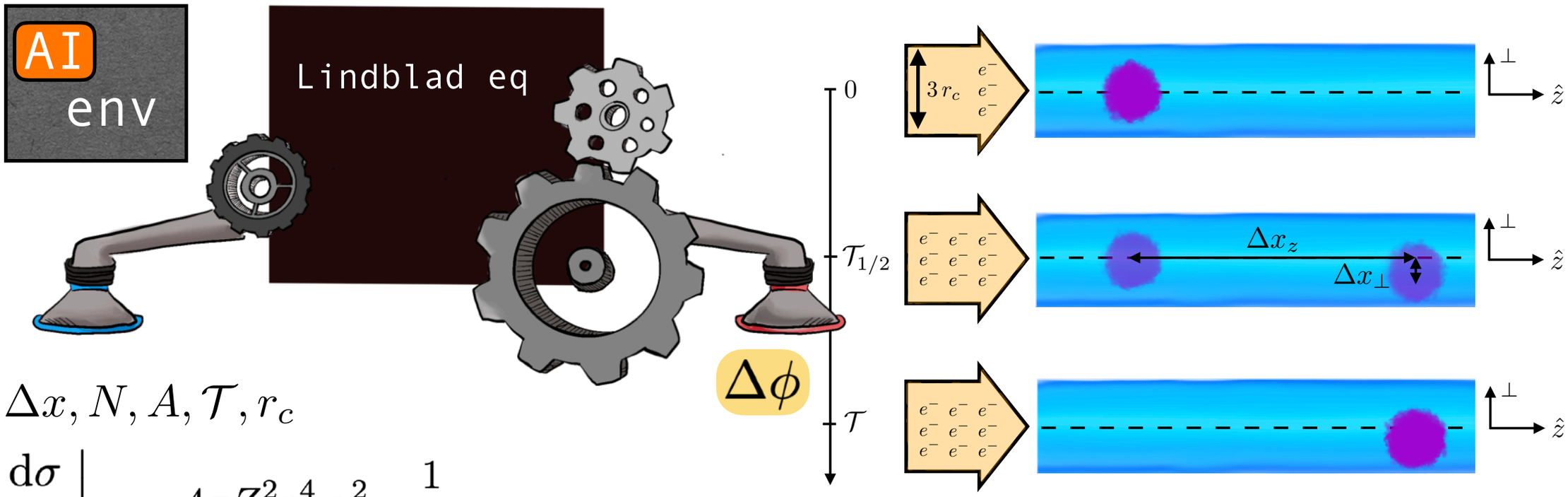
(within a single shot)

$$N\gamma \sim 8\times 10^{-6}\left(\frac{P_{\mathrm{LED}}}{6\,\mathrm{W/mm^2}}\right)\left(\frac{\mathcal{T}_{1/2}}{0.1\ \mathrm{s}}\right)\left(\frac{\Delta x_z}{1\ \mathrm{cm}}\right)\left(\frac{850\ \mathrm{nm}}{\lambda}\right)\left(\frac{N}{10^6}\right)\left(\frac{\alpha_{\mathrm{pol}}}{47.39\mathring{A}^3}\right)^2$$

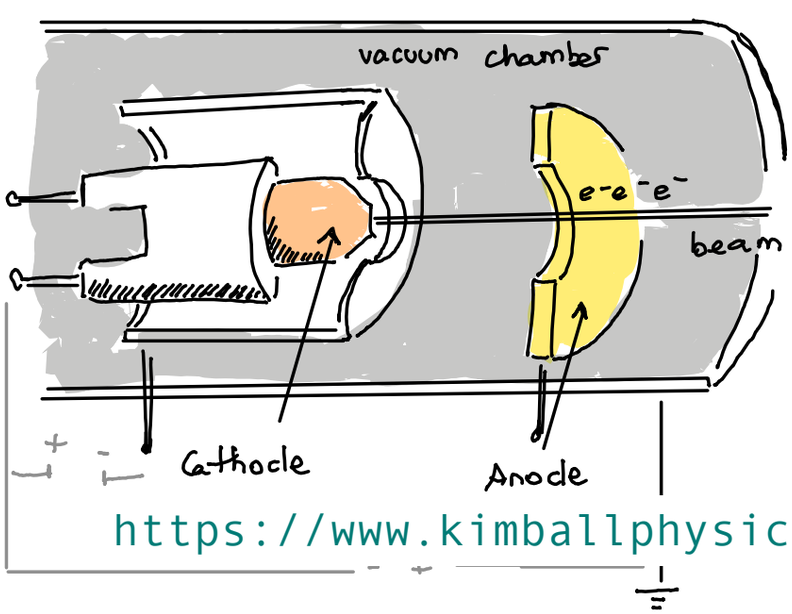
Enhanced phase-shift @ the lab

[CM, Plestid, 2025]

Via an electron gun



- $\Delta x, N, A, \mathcal{T}, r_c$
- $$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}q^2}\right|_{e^- \text{ gun}} = 4\pi Z^2 r_A^4 \alpha_{\rm EM}^2 \frac{1}{\beta_e^2}$$



Within a single shot!

$$N\gamma \simeq 6\times 10^{-3}\left(\frac{\mathcal{T}_{1/2}}{0.1\ \mathrm{s}}\right)\left(\frac{\Delta x}{1\ \mathrm{m}}\right)\left(\frac{I_e}{1\ \mathrm{A}}\right)\left(\frac{0.1\ \mathrm{mm}}{r_c}\right)^6\left(\frac{10^6}{N}\right)$$

$$\gamma_0 \simeq 5\times 10^{-4}\left(\frac{\mathcal{T}_{1/2}}{0.1\ \mathrm{s}}\right)\left(\frac{1\ \mathrm{m}}{\Delta x}\right)\left(\frac{I_e}{1\ \mathrm{A}}\right)\left(\frac{0.1\ \mathrm{mm}}{r_c}\right)^2$$

https://www.kimballphysics.com/learning_center/electron-gun-beam-systems/

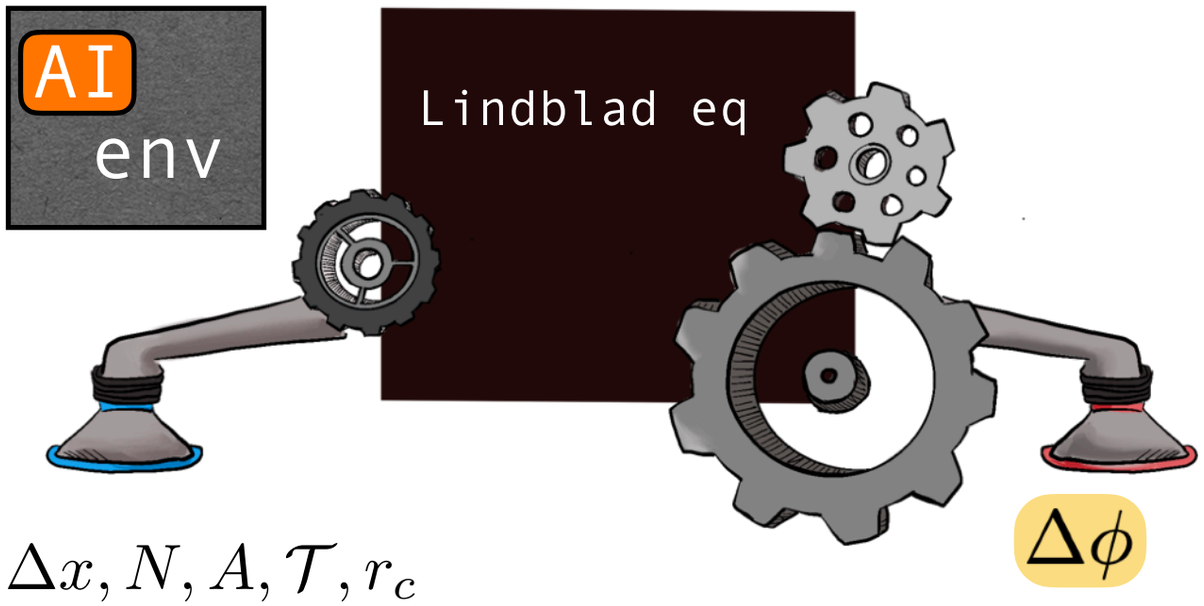
Dark matter inprints

[Riedel, 2013]

[Riedel, Yavin, 2017]

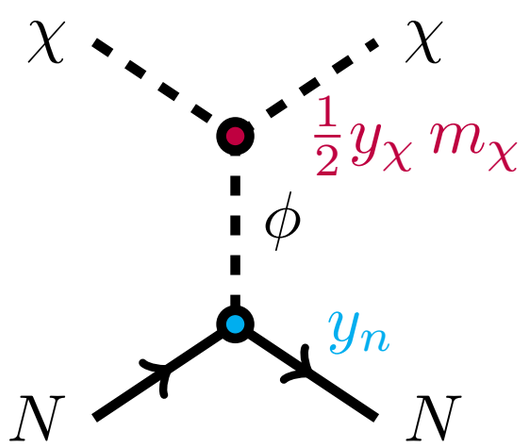
[Du, **CM**, Pardo, Wang, Zurek, 2022]

[**CM**, Plestid, 2025]



$\Delta x, N, A, \mathcal{T}, r_c$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}q^2}\right|_{\mathrm{DM}} = 4\pi A^2 \alpha_{\mathrm{DM}}^2 \frac{1}{u_\chi^2}\left(\frac{1}{q^2 + m_\phi^2}\right)^2$$



coherent decoherence dominates

$$\alpha_{\mathrm{DM}} < 10^{-16}\left(\frac{m_\chi}{10\ \mathrm{eV}}\right)\left(\frac{1\ \mathrm{cm}}{\Delta x}\right)^{\frac{1}{2}}\left(\frac{87}{A}\right)$$

$$\times\left(\frac{0.1\ \mathrm{s}}{\mathcal{T}_{1/2}}\right)^{\frac{1}{2}}\left(\frac{10^6}{N}\right)^{\frac{3}{4}}\left(\frac{1}{\aleph}\right)^{\frac{1}{4}}\left(\frac{1}{f_\chi}\right)^{1/2} 10^2\left[\left(\frac{m_\phi r_c}{10}\right)^2\right]$$

$$\Rightarrow \alpha_{\mathrm{DM}} = y_\chi y_N / 4\pi$$

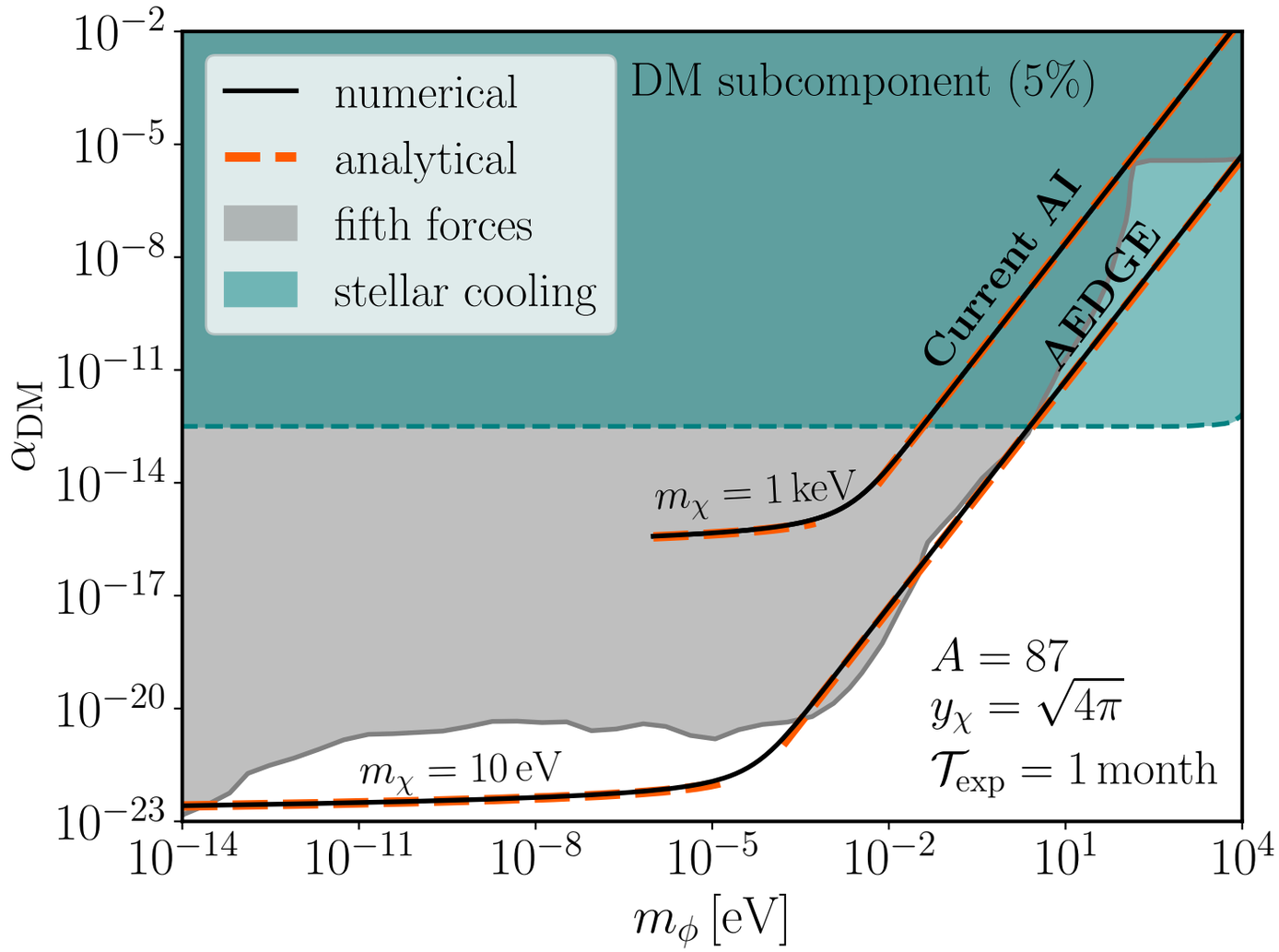
Dark matter inprints

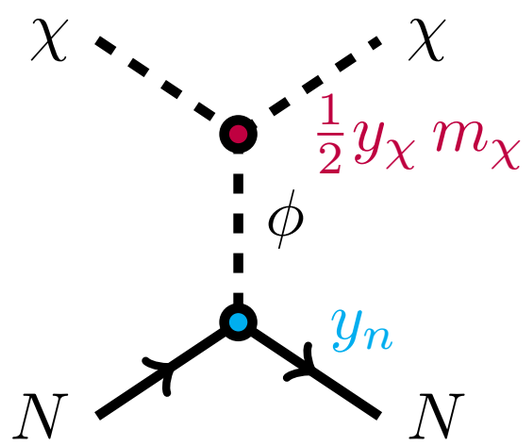
[Riedel, 2013]

[Riedel, Yavin, 2017]

[Du, **CM**, Pardo, Wang, Zurek, 2022]

[**CM**, Plestid, 2025]





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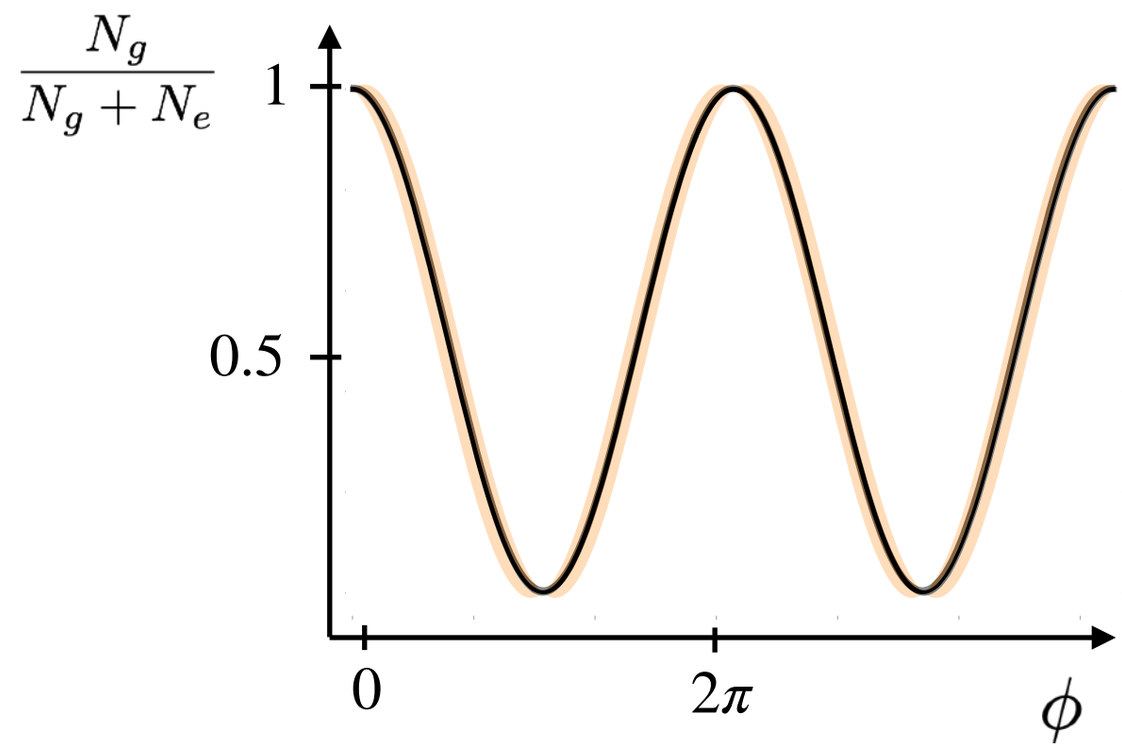
Future steps

Explore new observables

[**CM**, Plestid, 251X.XXXX]



Fluctuations in atom interferometers as a new tool for dark matter

Clara Murgui[1,*] and Ryan Plestid[1,†]

[1] *Theoretical Physics Department, CERN, 1 Esplanade des Particules, CH-1211 Geneva 23, Switzerland*

(Dated: November 18, 2025)

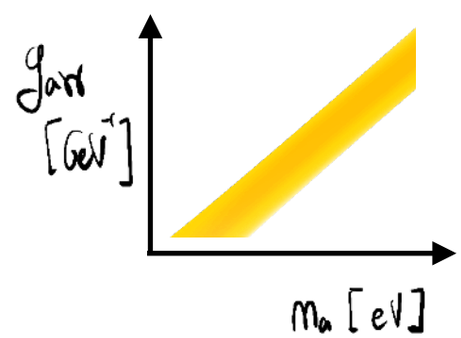
Disadvantages of coherent enhancements

Penalty if the “most prefered” incoming momentum is $\neq \mathcal{O}(1/r_c)$

$$\text{obs} \propto \int dt \int dE \, \frac{d\Phi}{dE} \int dq^2 \, \frac{d\sigma}{dq^2} G(\mathbf{q}, t) \int \frac{d\phi}{(2\pi)^3} \sin(\mathbf{q} \cdot \mathbf{v})$$

Not applicable to spin-dependent interactions (γ_5)

e.g.



The weirdos: coherent states

[Badurina, **CM**, Plestid, 24] [**CM**, Plestid, 251X.XXXX]

The mean

$$\langle \mathcal{O}_+ \rangle = \mathrm{Tr}\{\rho \mathcal{O}_+\} = N \mathrm{Tr}\{\rho_1 |+\rangle\langle +|\} = \tfrac{N}{2}(1 + \mathrm{Re}[\blacksquare_1])$$

$$\langle n_+ \rangle = \frac{1}{\aleph} \sum_{i=1}^{\aleph} n_+^{(a)} \qquad \rho_1 = \frac{1}{2}\begin{pmatrix} \circ & \blacksquare \\ \blacksquare & \circ \end{pmatrix}$$

Pure product state

$\circ = 1 \quad \blacksquare = e^{i\Phi}$

$\langle O_+ \rangle|_{\text{pure}} \propto N$

Fully decohered $e^{-(s+s_0)}$ 0

$\circ = 1 \quad \blacksquare = 0$

$\langle O_+ \rangle|_{\text{decoh}} \propto N$

The weirdos: coherent states

[Badurina, **CM**, Plestid, 24] [**CM**, Plestid, 251X.XXXX]

The mean

$$\langle \mathcal{O}_+ \rangle = \mathrm{Tr}\{\rho \mathcal{O}_+\} = N \mathrm{Tr}\{\rho_1 |+\rangle\langle +|\} = \tfrac{N}{2}(1 + \mathrm{Re}[\blacksquare_1])$$

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$\circ = 1 \quad \blacksquare = e^{i\Phi}$

$\langle O_+ \rangle|_{\text{pure}} \propto N$

Fully decohered $e^{-(s+s_0)}$

$\circ = 1 \quad \blacksquare = 0$

$\langle O_+ \rangle|_{\text{decoh}} \propto N$

The variance

$\cos 2\Phi = 2\cos^2\Phi - 1$

$$\sigma_+^2 = \langle \mathcal{O}_+^2 \rangle - \langle \mathcal{O}_+ \rangle^2 = \tfrac{N}{8}\left[N\left(1 + \mathrm{Re}[\bigstar] - 2\mathrm{Re}[\blacksquare_1]^2\right) + 1 - \mathrm{Re}[\bigstar]\right]$$

$$s = \frac{1}{\aleph} \sum_{a=1}^{\aleph} [n_+^{(a)} - \langle n_+ \rangle]^2 \qquad \rho_2 = \frac{1}{4}\begin{pmatrix} \circ & \blacksquare & \blacksquare & \bigstar \\ \blacksquare & \circ & \circ & \blacksquare \\ \blacksquare & \circ & \circ & \blacksquare \\ \bigstar & \blacksquare & \blacksquare & \circ \end{pmatrix}$$

Pure product state

$\circ = 1 \quad \blacksquare = e^{i\Phi} \quad \bigstar = e^{i2\Phi}$

$\sigma_+|_{\text{pure}} \propto \sqrt{N}$

Fully decohered $e^{-(s+s_0)} \to 0$

$\circ = 1 \quad \blacksquare = 0 \quad \bigstar = 0$

$\sigma_+|_{\text{decoh}} \propto N$

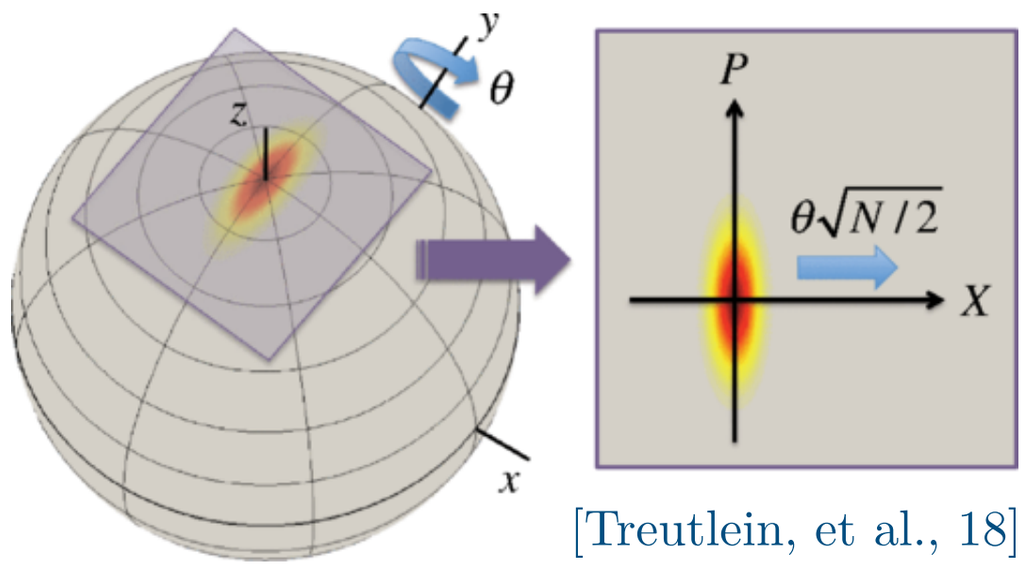
Future steps

Explore new observables

[**CM**, Plestid, 251X.XXXX]

Add more generic configurations to the formalism

⇨ Squeezing



[Treutlein, et al., 18]

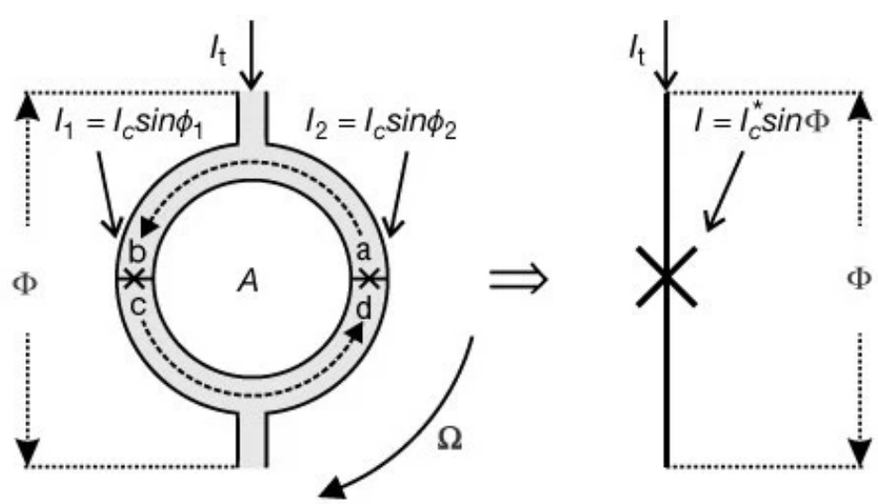
Future steps

Explore new observables

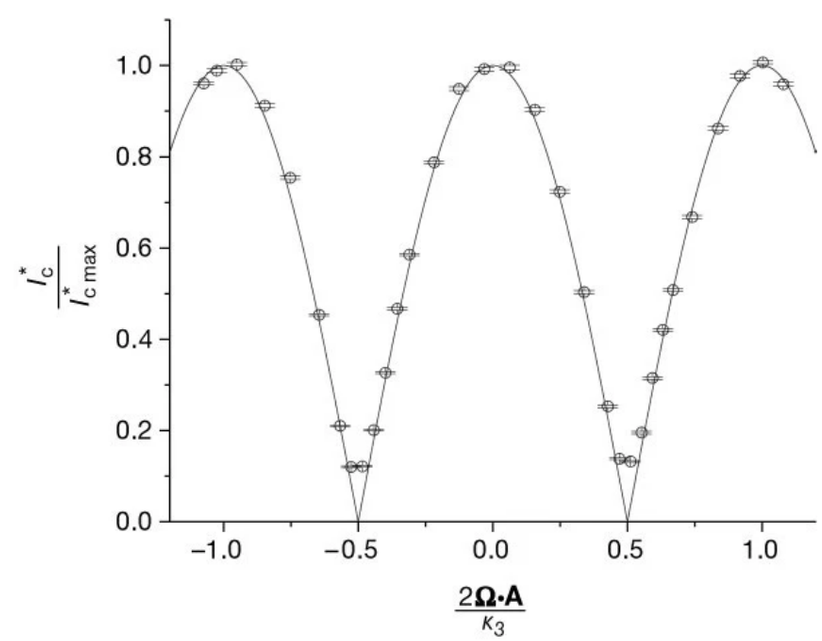
[**CM**, Plestid, 251X.XXXX]

Add more generic configurations to the formalism

- Squeezing
- Liquids



[Simonds et al., 2001, Nature]



Future steps

Explore new observables

[**CM**, Plestid, 251X.XXXX]

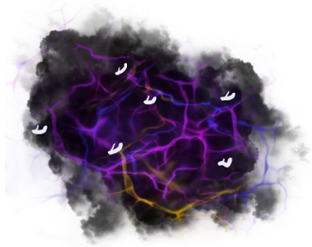
Add more generic configurations to the formalism

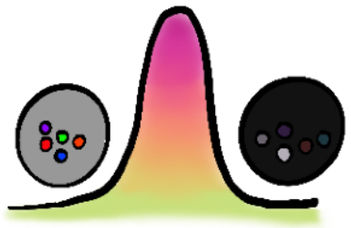
- Squeezing
- Liquids

Convince experimentalists!

Conclusions

Atom interferometers open (“THE”) parameter space

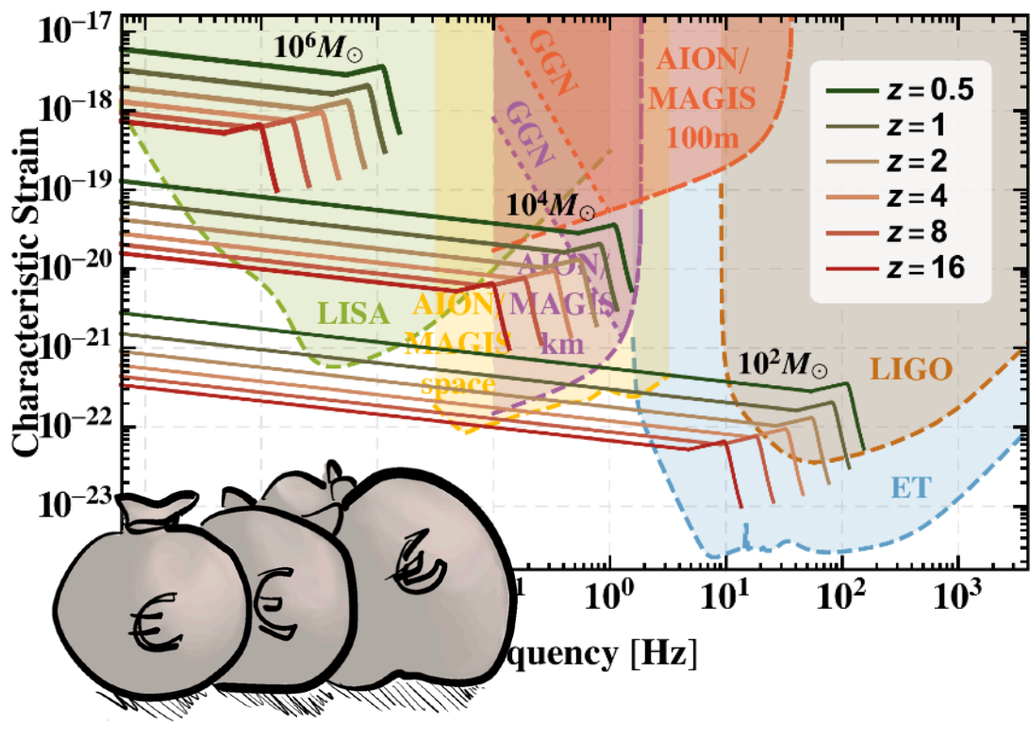




Conclusions

Atom interferometers open (“THE”) parameter space

These experiments exist! Many funded already. Parasitic searches.



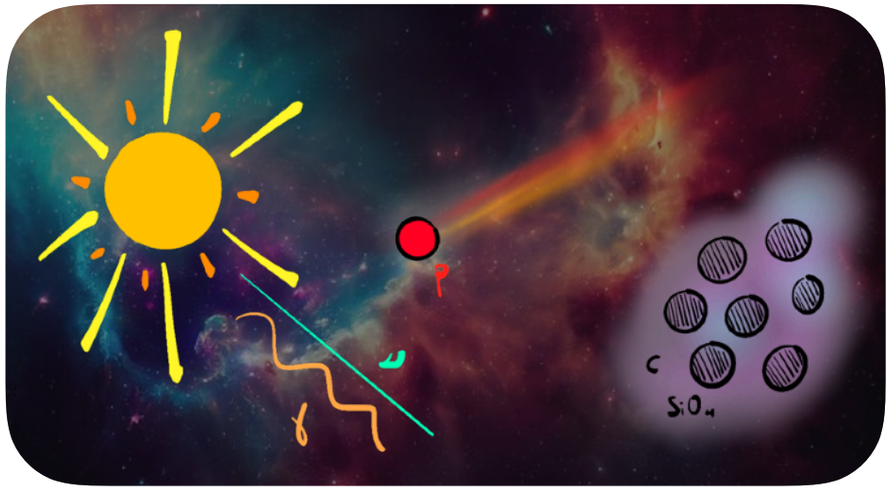
[AION collaboration, Badurina et al, 2019]

Conclusions

Atom interferometers open (“THE”) parameter space

These experiments exist! Many funded already. Parasitic searches

Ambitious projects require controlled backgrounds (SM physics)



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

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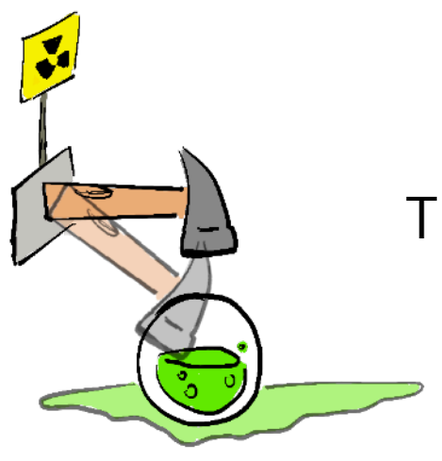

THANK YOU!