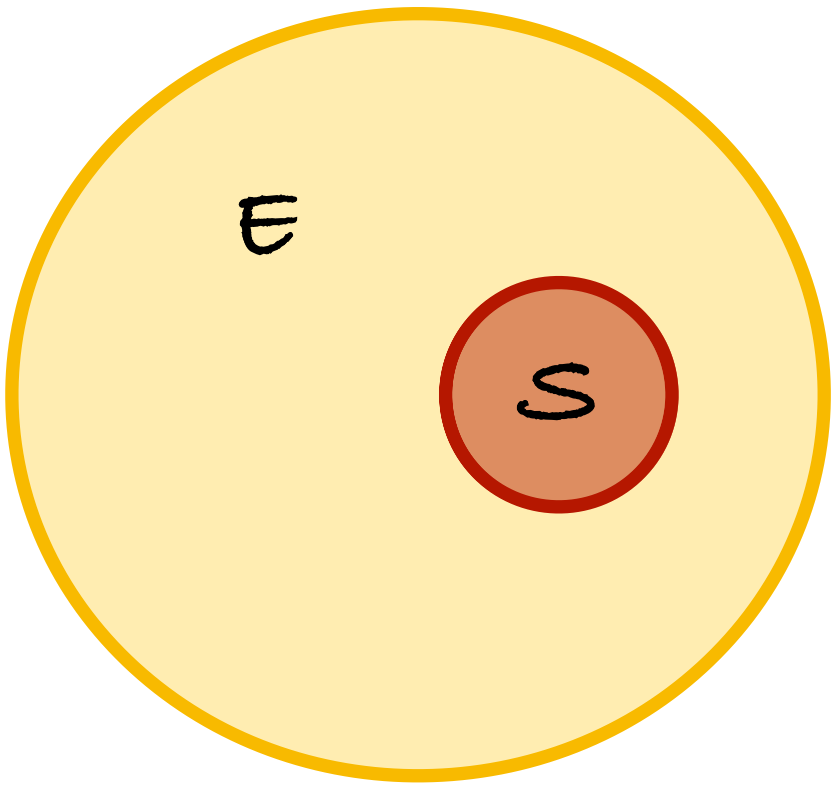
Direct detection of particle-scattering via atom interferometry

Clara Murgui (CERN)



MITP workshop — Open quantum systems — April 22nd 2026

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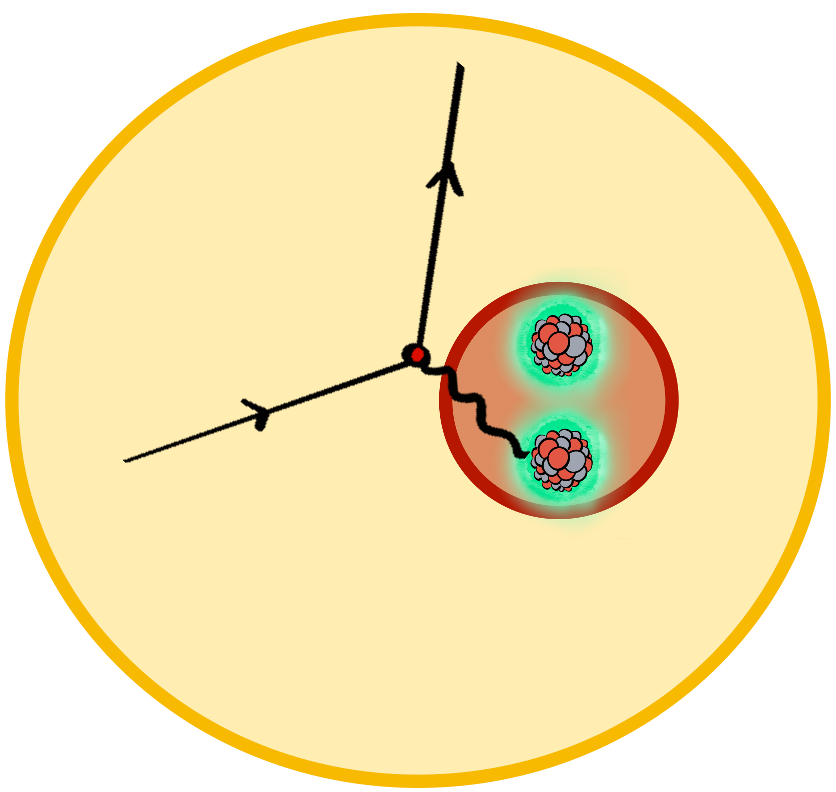

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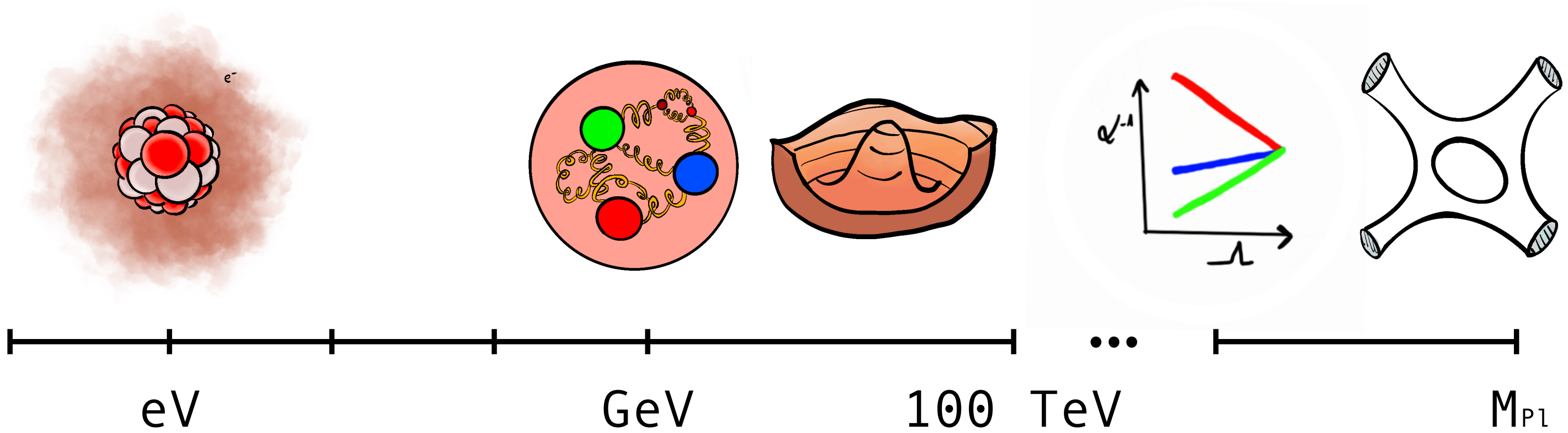
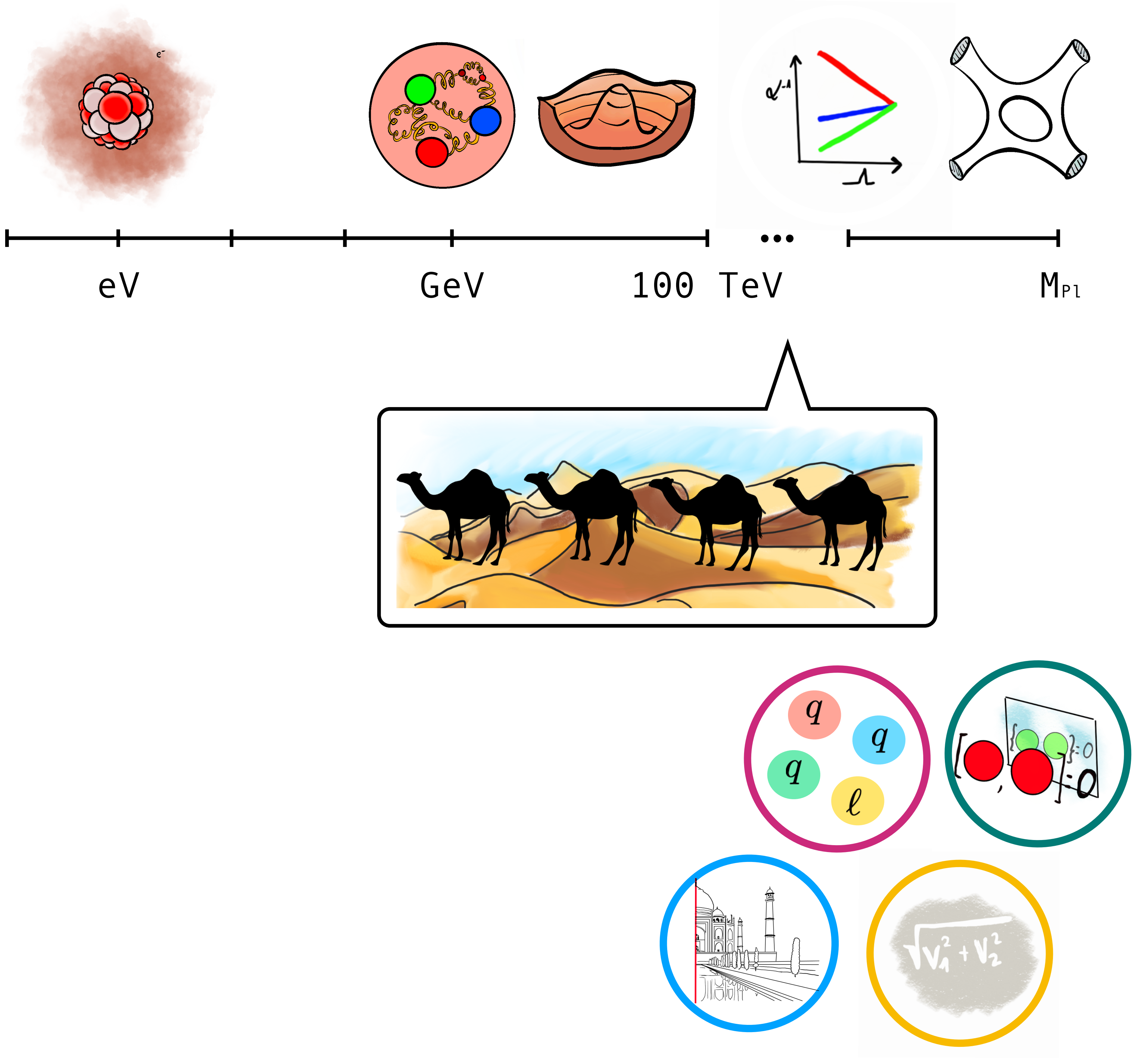
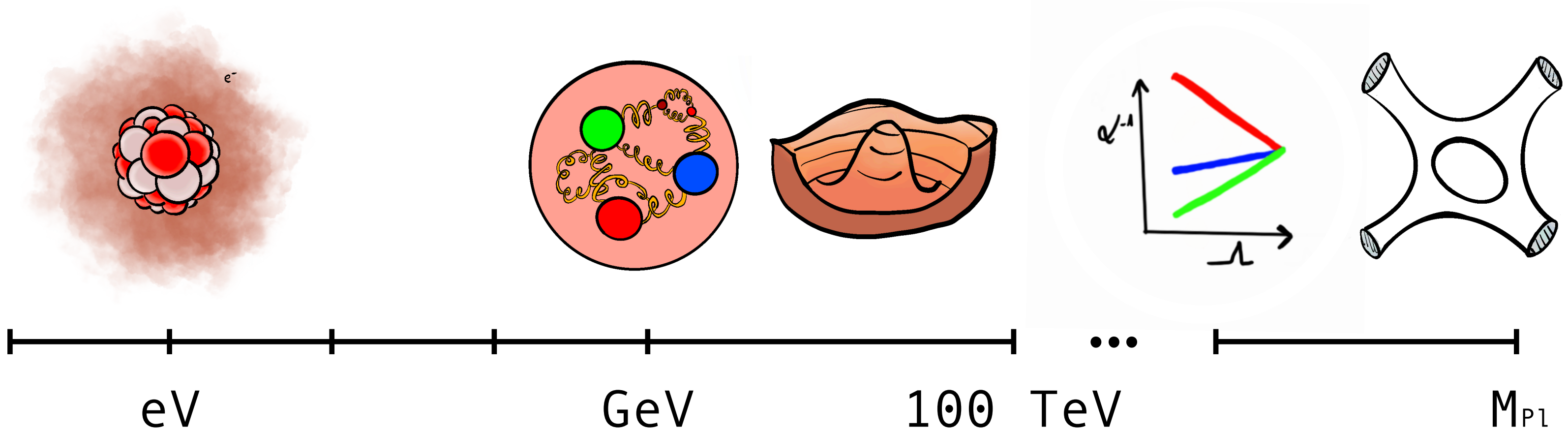
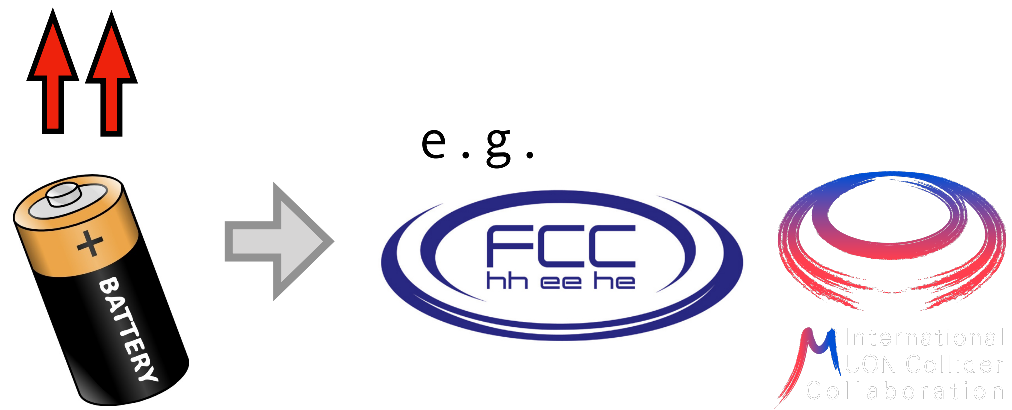
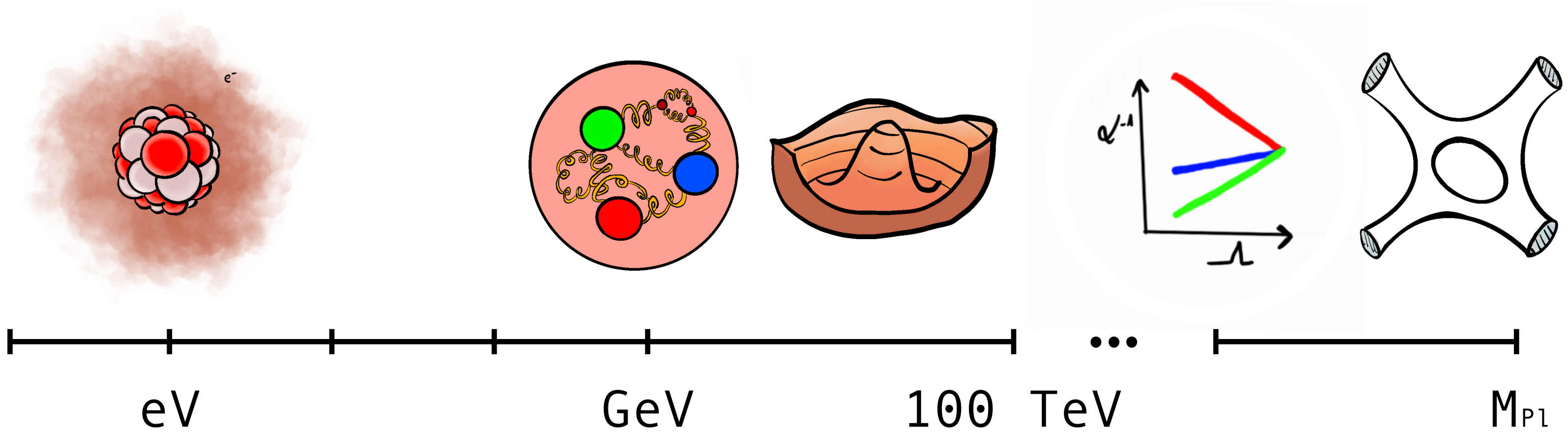

eV
GeV
100 TeV
MPl

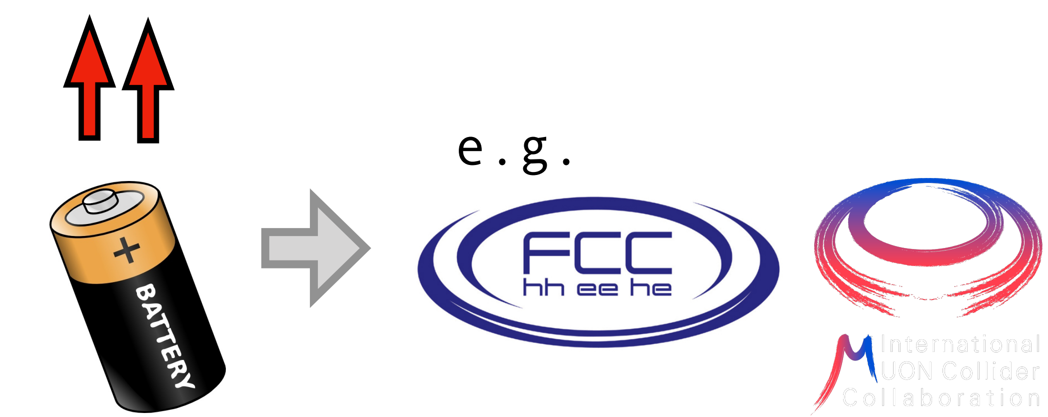

eV
GeV
100 TeV
M_Pl
q
q
q
ℓ





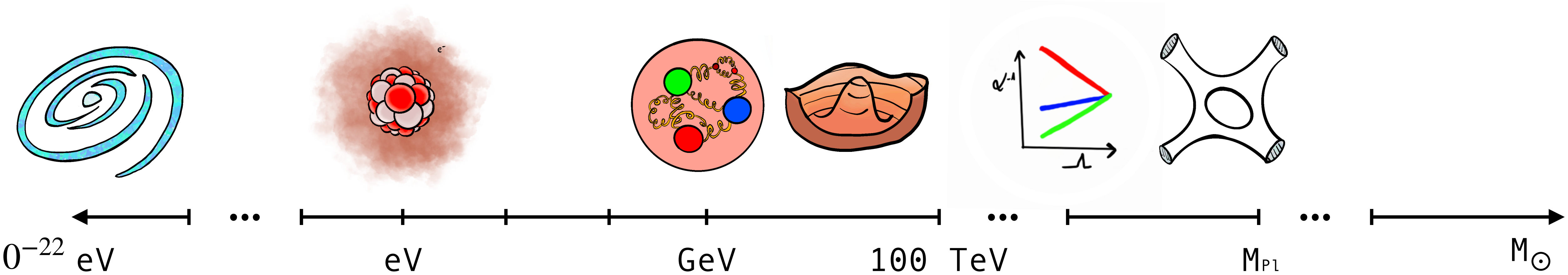
$$\mathcal{L} = \mathcal{L}^{\mathrm{d}\leq 4} + \sum_{d=5}^{\infty} \frac{\mathcal{O}_d}{\Lambda_{\mathrm{NP}}^{d-4}}$$

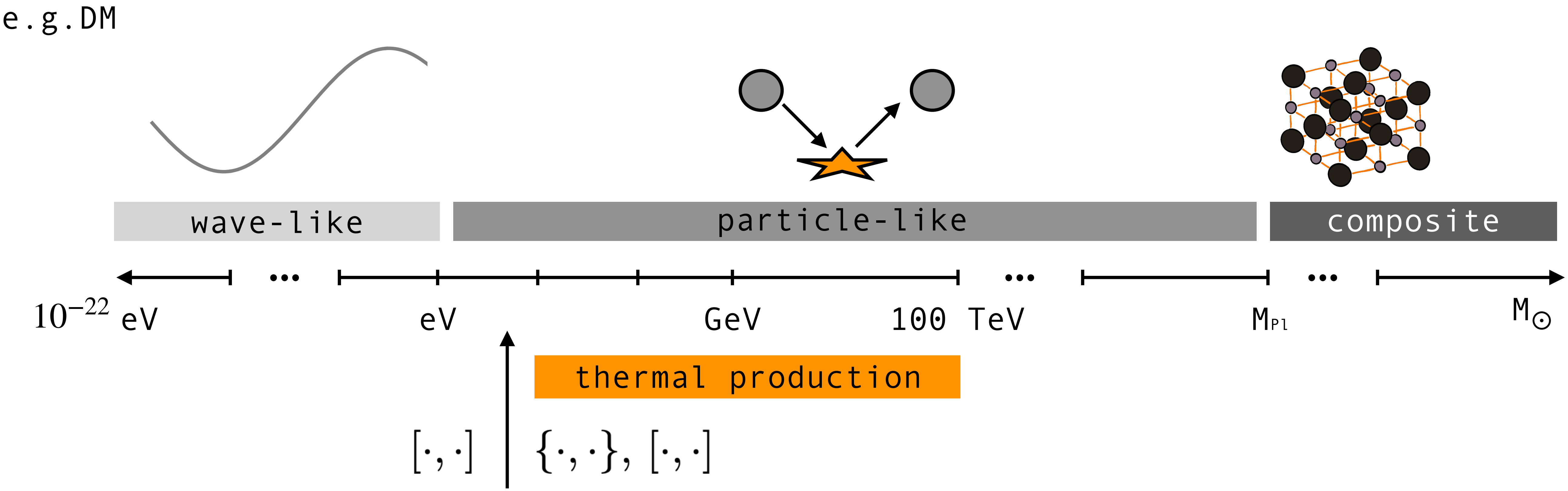




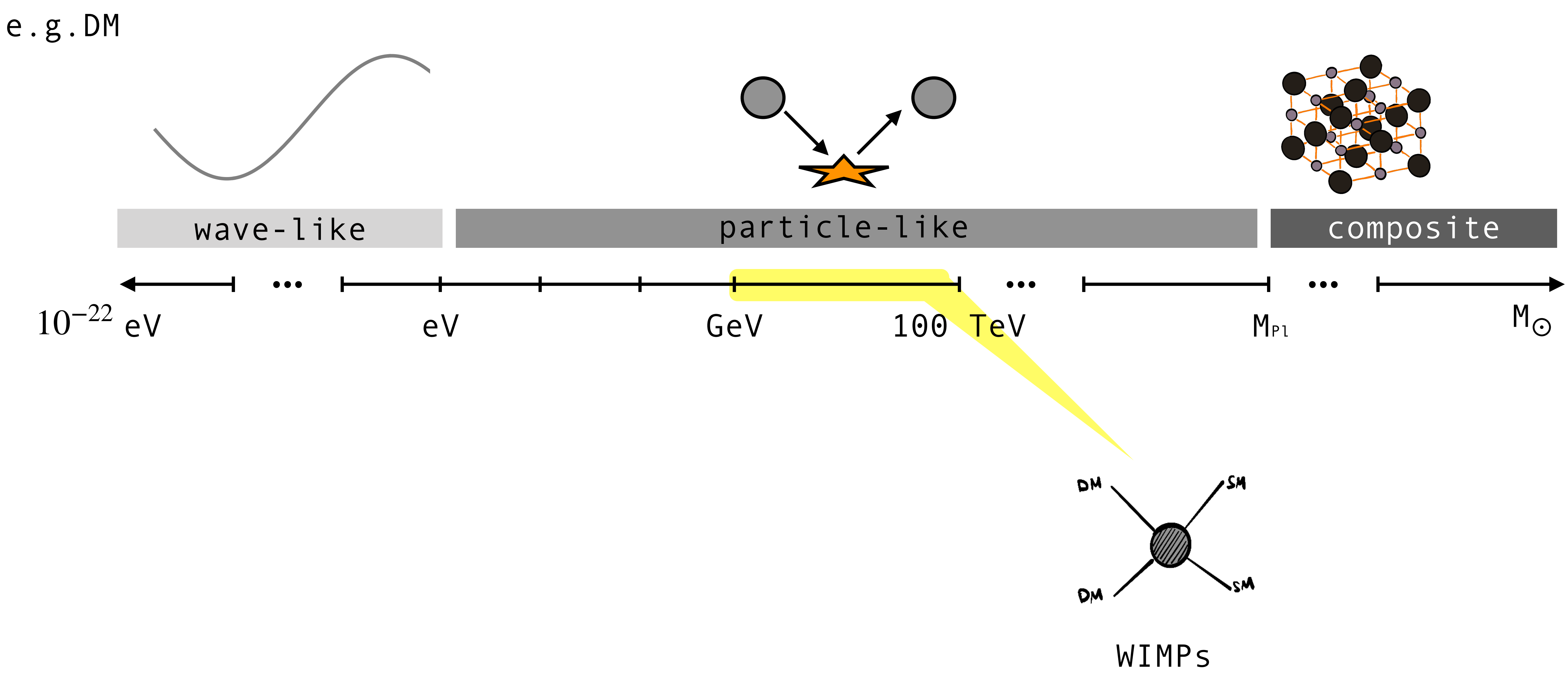
$$\mathcal{L} = \mathcal{L}^{\mathrm{d}\leq 4} + \sum_{d=5}^{\infty} \frac{\mathcal{O}_d}{\Lambda_{\mathrm{NP}}^{d-4}}$$

e.g.DM



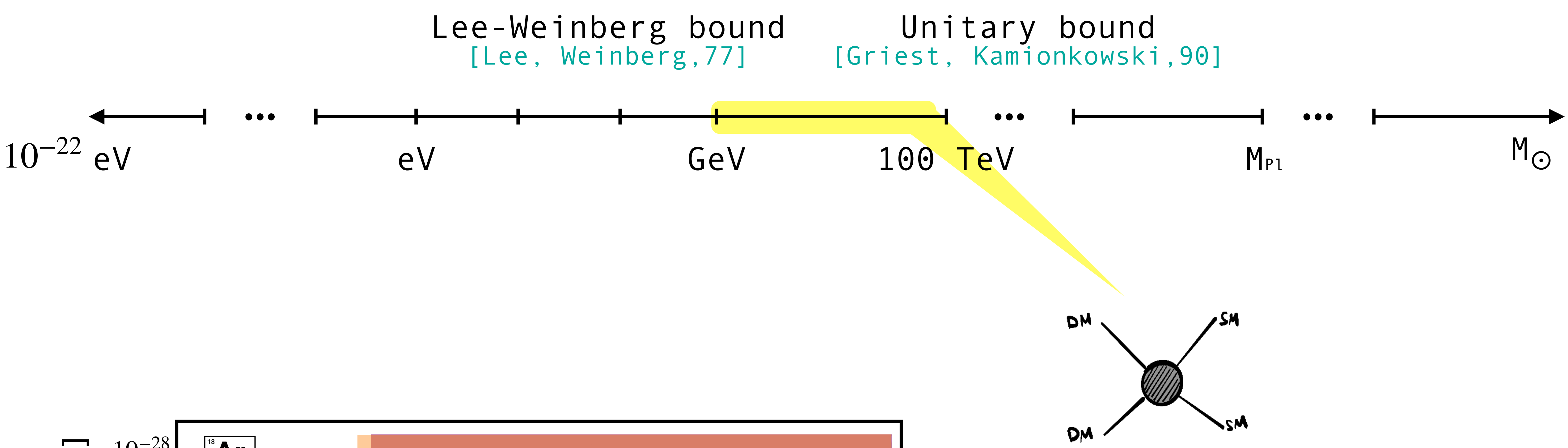


e.g.DM
wave-like
particle-like
composite
10^{-22} eV
eV
GeV
100 TeV
M_{Pl}
$M_{\odot}$
thermal production
$[\cdot,\cdot]$
$\{\cdot,\cdot\}, [\cdot,\cdot]$

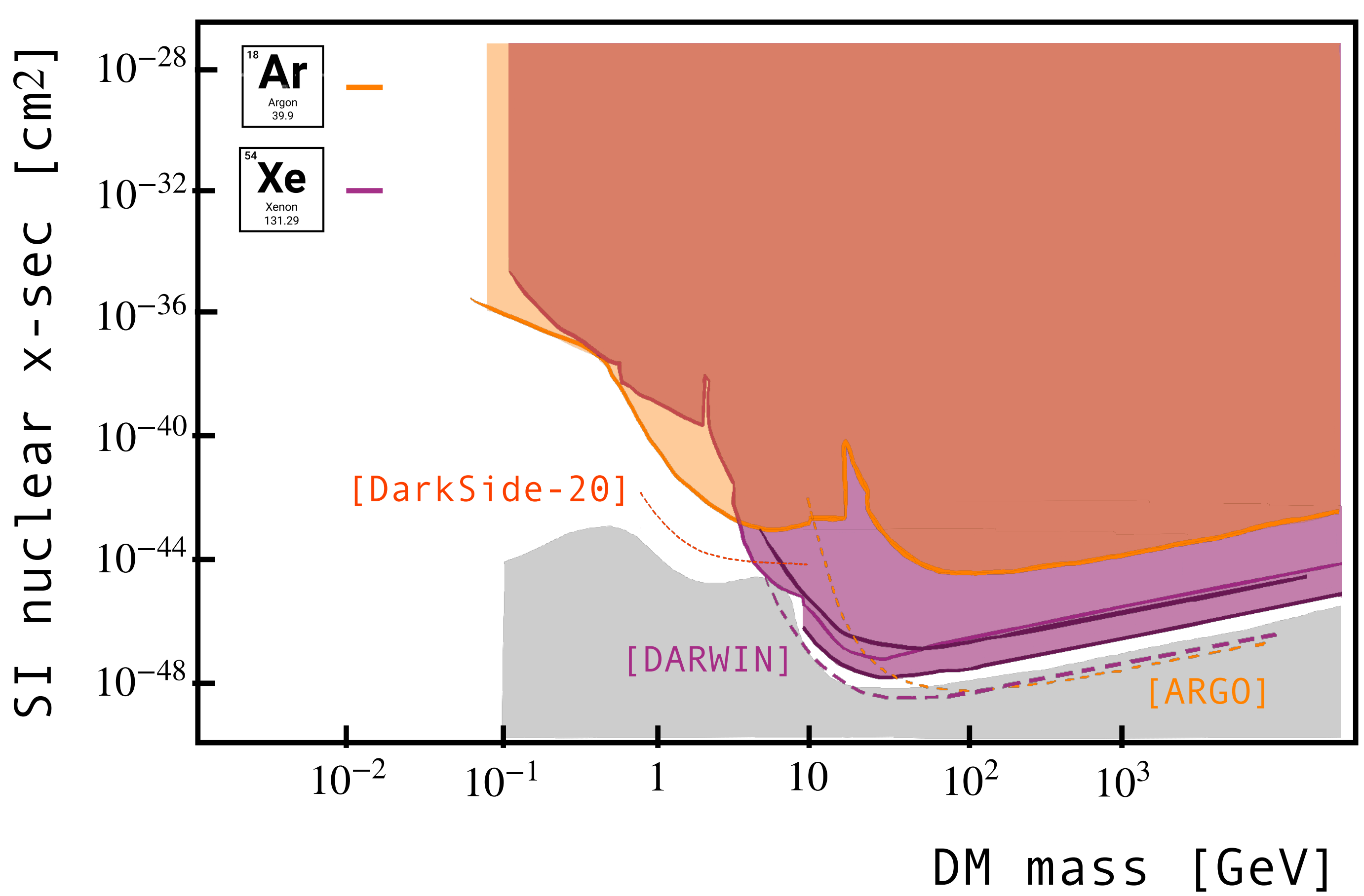

e.g.DM
wave-like
particle-like
composite
10^{-22} eV
eV
GeV
100 TeV
M_{Pl}
$M_{\odot}$
DM
SM
DM
SM
WIMPs

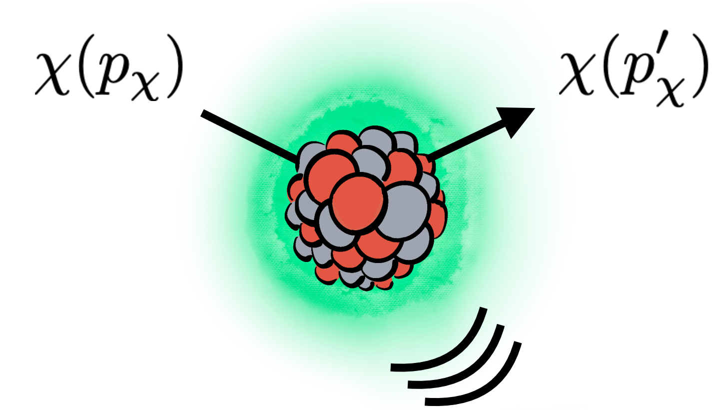
“Traditional” direct detection

Nuclear recoils



WIMPs [2 x miracle]

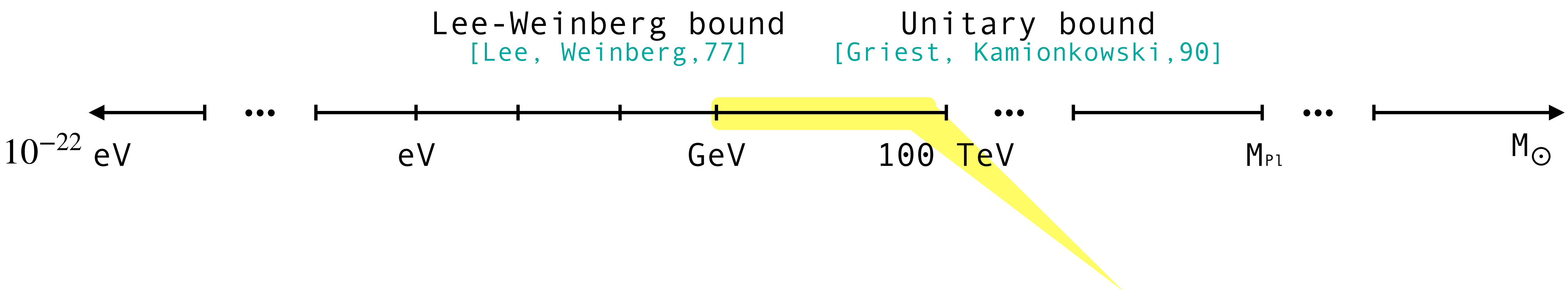


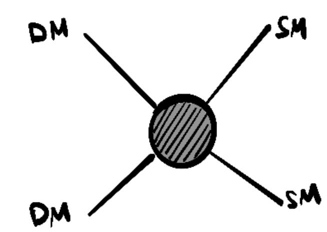


$$E_{\rm rec}^{\rm max} = \frac{q_{\rm max}^2}{2(A\ {\rm GeV})} > {\rm keV}$$

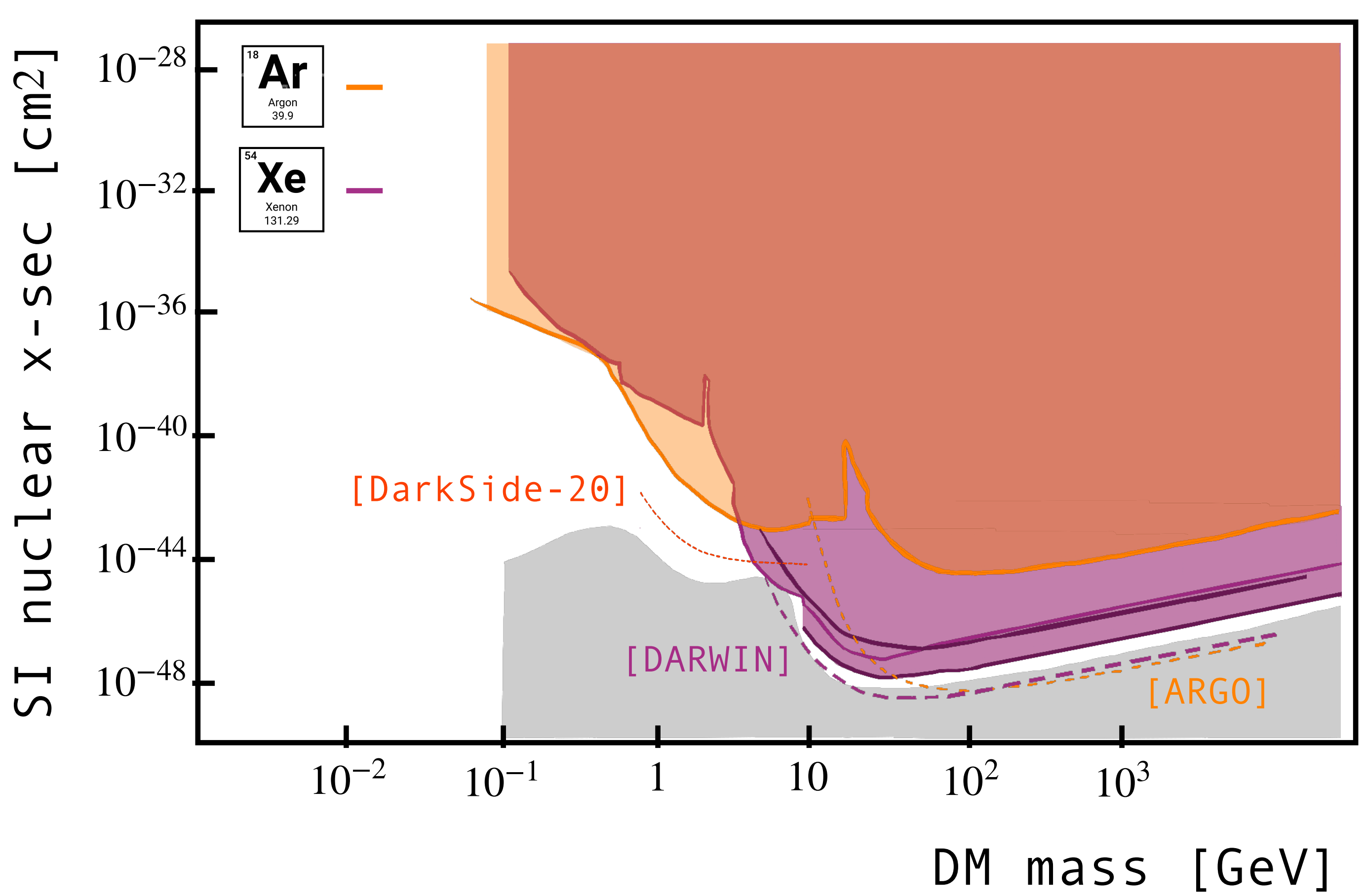
“Traditional” direct detection

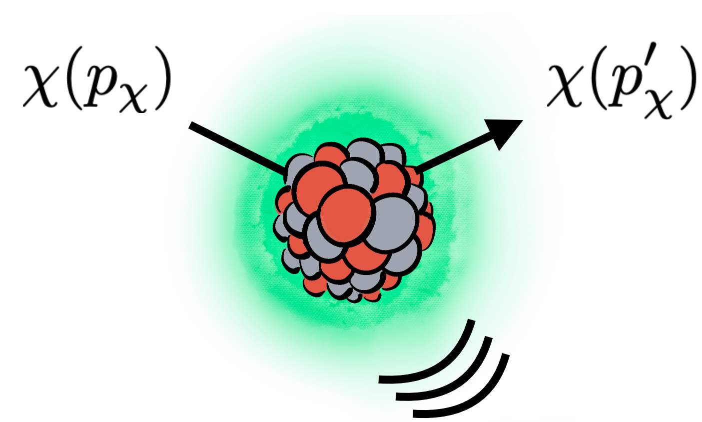
Nuclear recoils



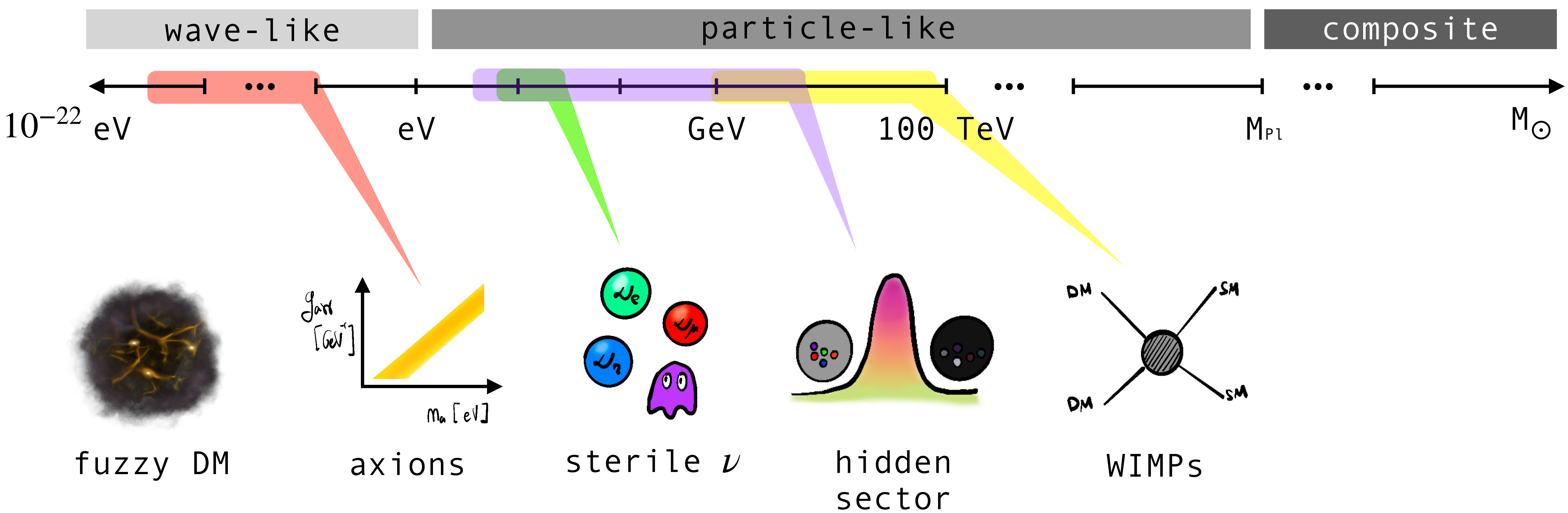


WIMPs [2 x miracle]

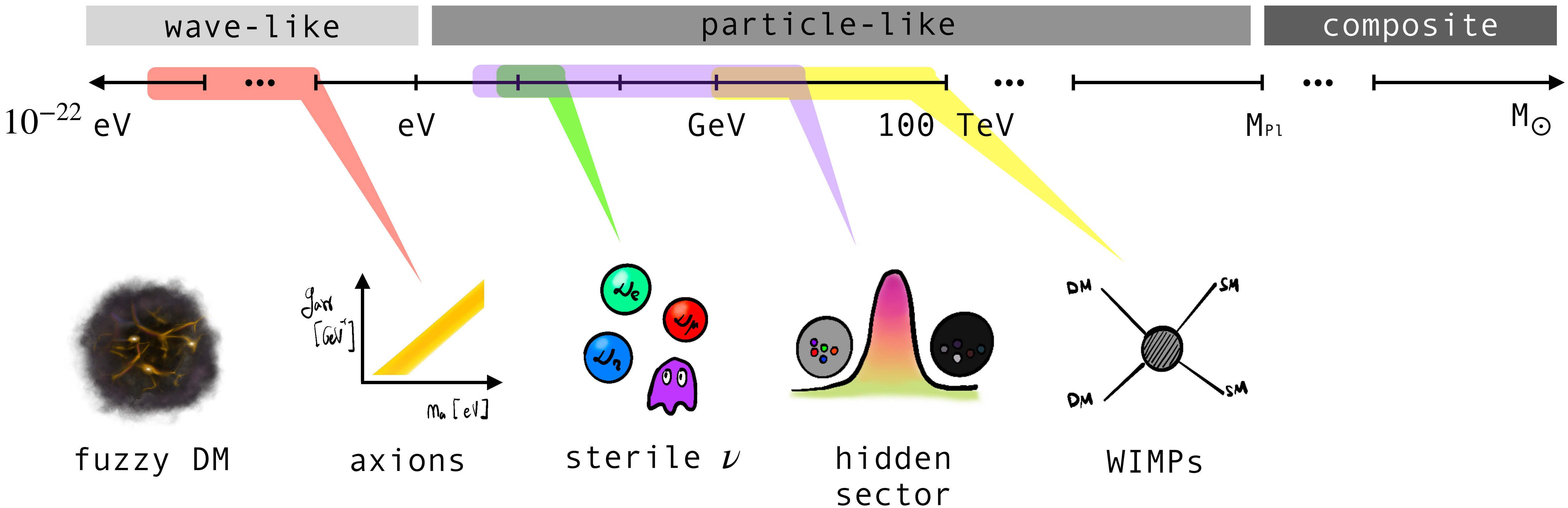


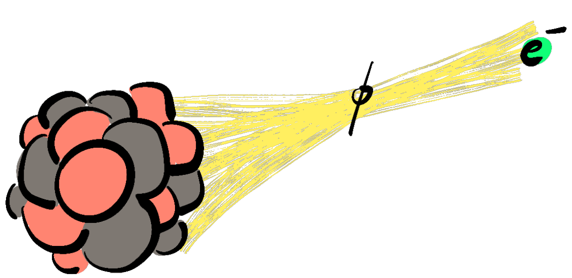


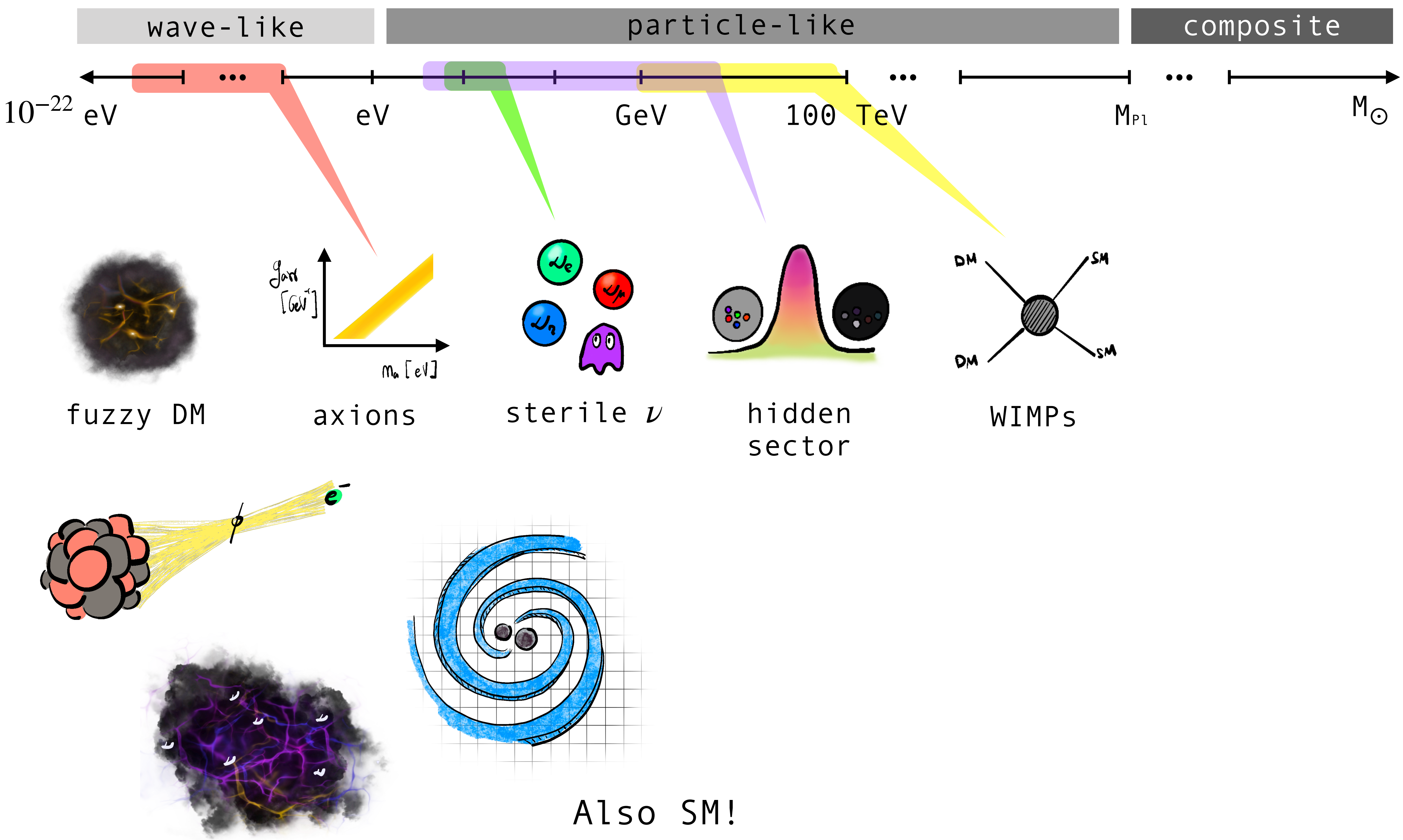
$$E_{\rm rec}^{\rm max} = \frac{4m_\chi^2 v_\chi^2}{2(A\ {\rm GeV})} > {\rm keV}$$

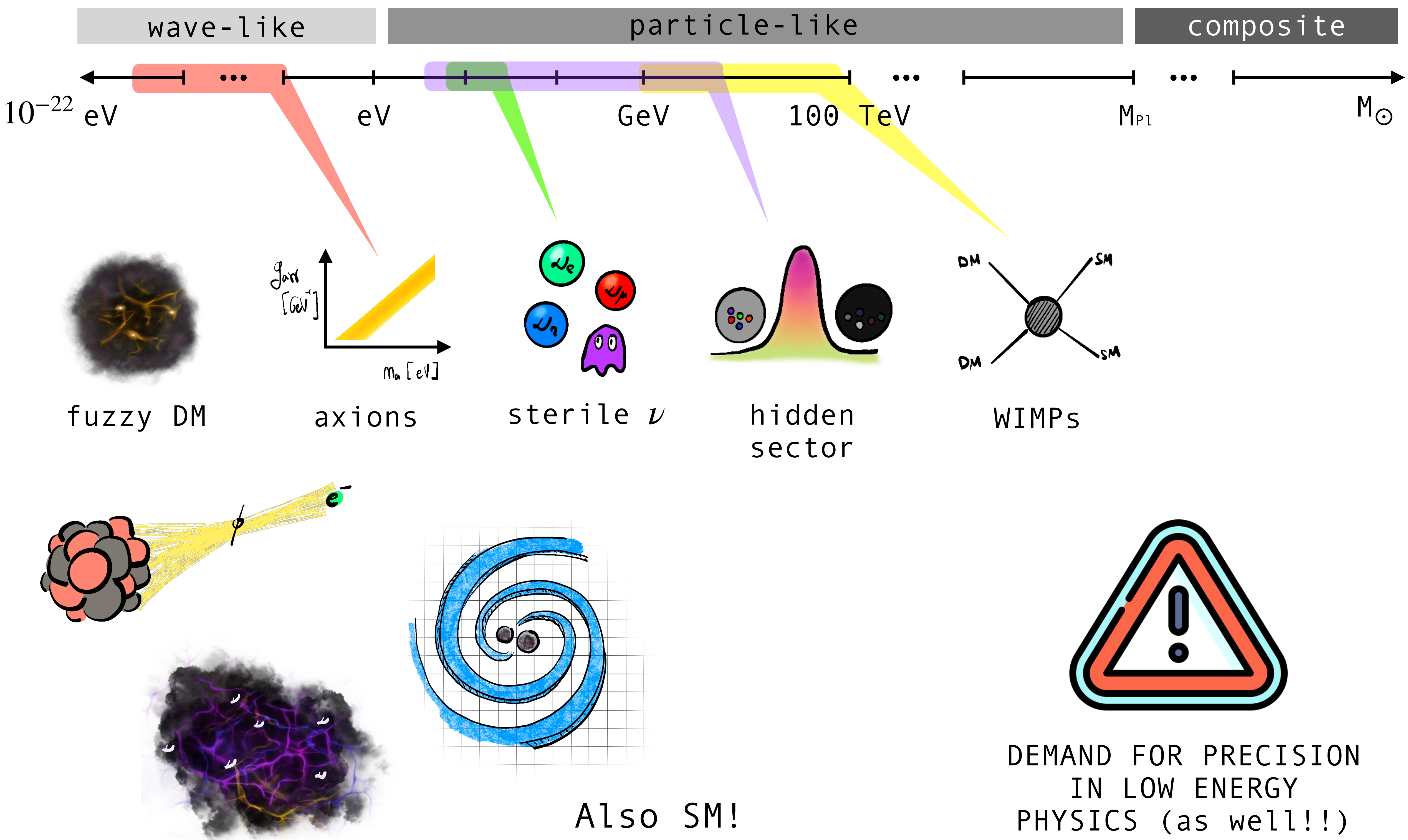


wave-like
particle-like
composite
10^{-22} eV
eV
GeV
100 TeV
M_{Pl}
$M_\odot$
fuzzy DM
axions
sterile ν
hidden sector
WIMPs
DM
DM
SM
SM


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


ϕ
e^-

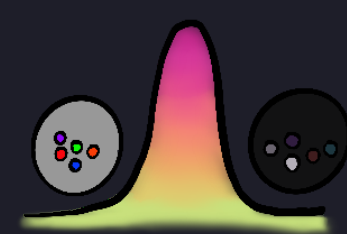

wave-like
particle-like
composite
10^{−22} eV
eV
GeV
100 TeV
M_Pl
M_⊙
fuzzy DM
axions
sterile ν
hidden
sector
WIMPs
DM
SM
DM
SM
e⁻
Also SM!



wave-like
particle-like
composite
10−22 eV
eV
GeV
100 TeV
MPl
M⊙
fuzzy DM
axions
sterile ν
hidden sector
WIMPs
DM
SM
DM
SM
Also SM!
DEMAND FOR PRECISION IN LOW ENERGY PHYSICS (as well!!)

Lowering the threshold

There is plenty of room at the bottom!

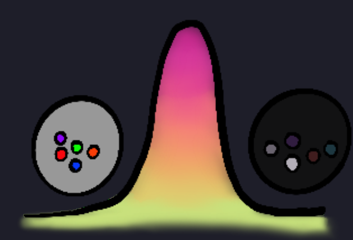


WIMPs

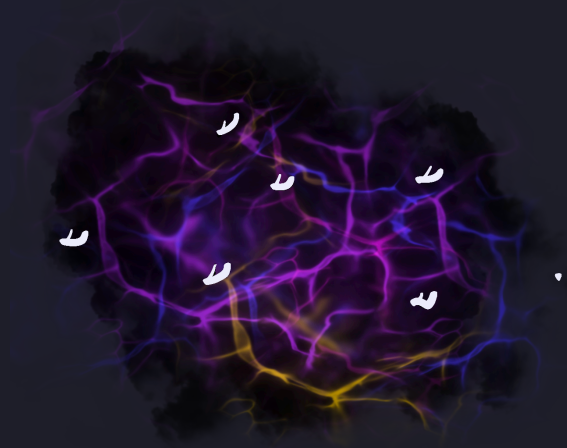
How do we “direct-detect” elusive particles?

Lowering the threshold

There is plenty of room at the bottom!



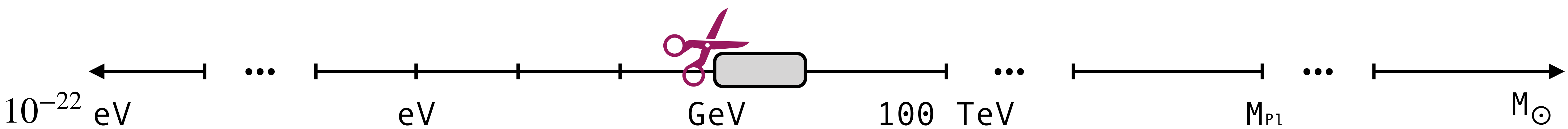
WIMPs



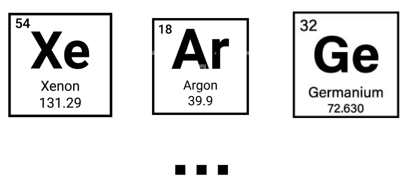
How do we “direct-detect” elusive particles?

Lowering the threshold

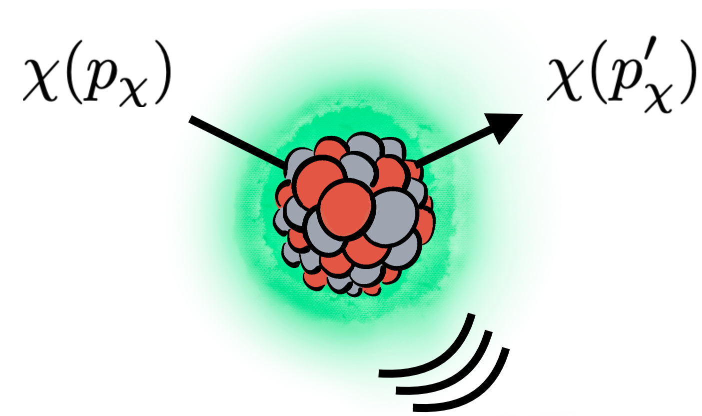
Direct detection



Nuclear recoil
PTM exp.



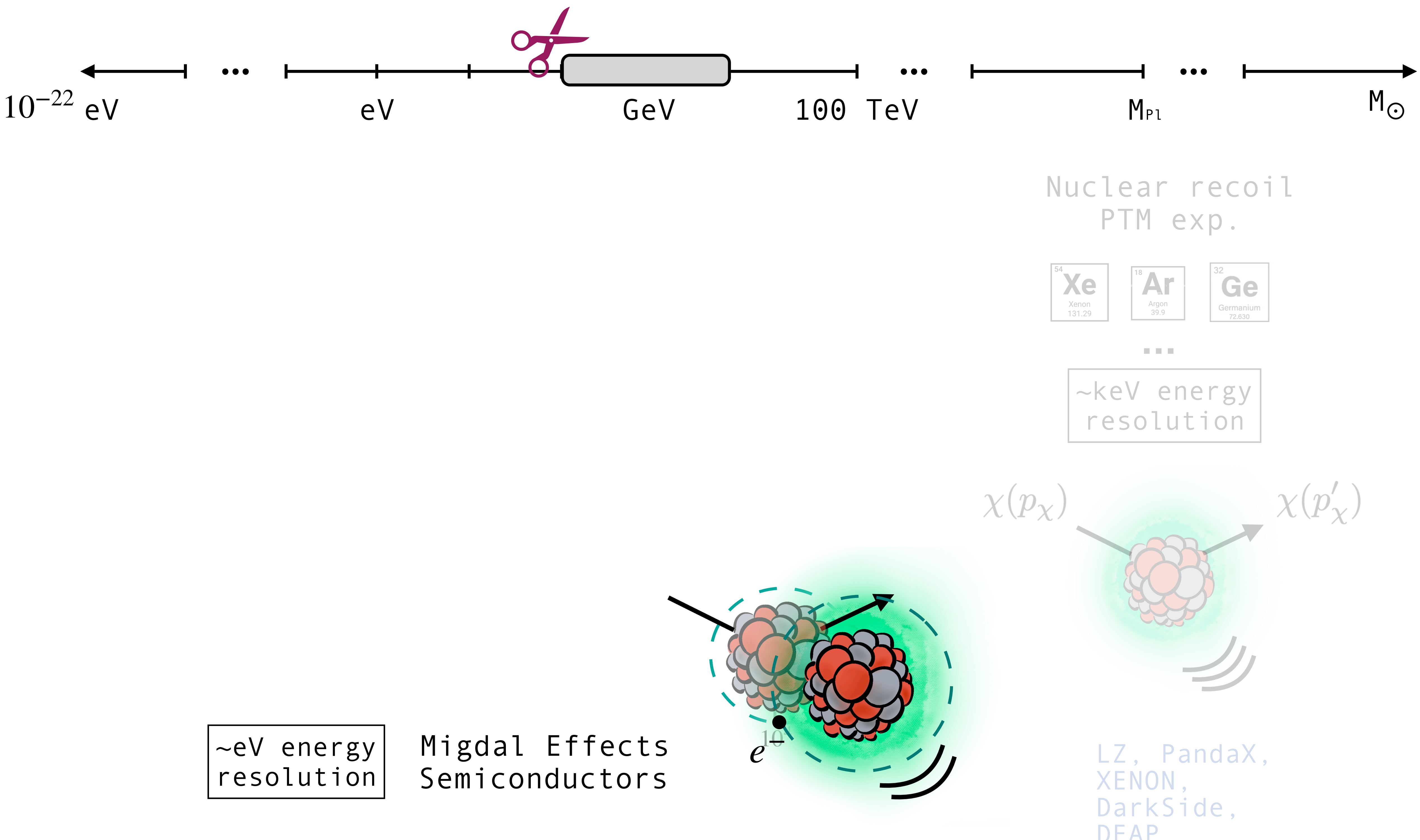
~keV energy resolution



LZ, PandaX, XENON, DarkSide, DEAP…

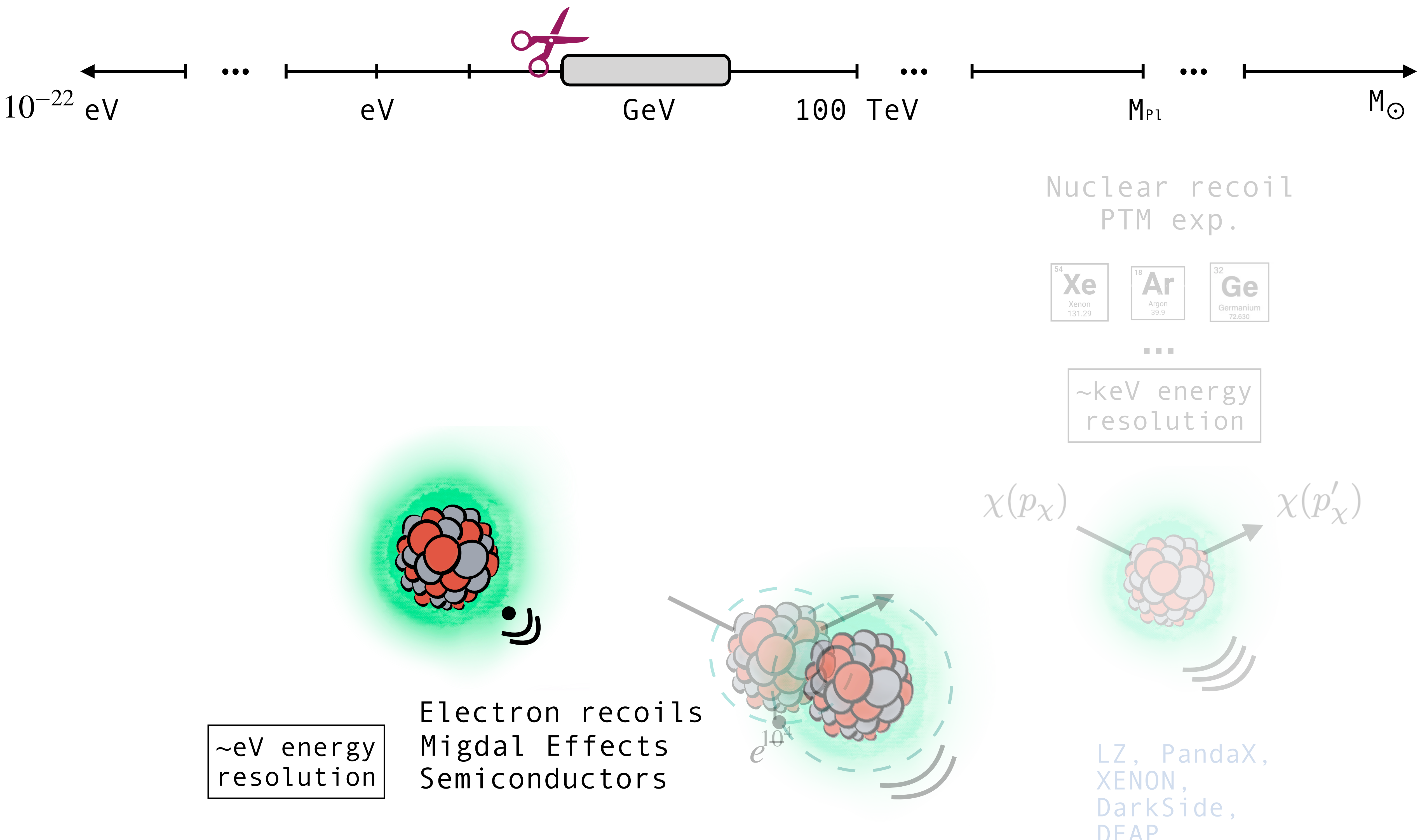
Lowering the threshold

Direct detection



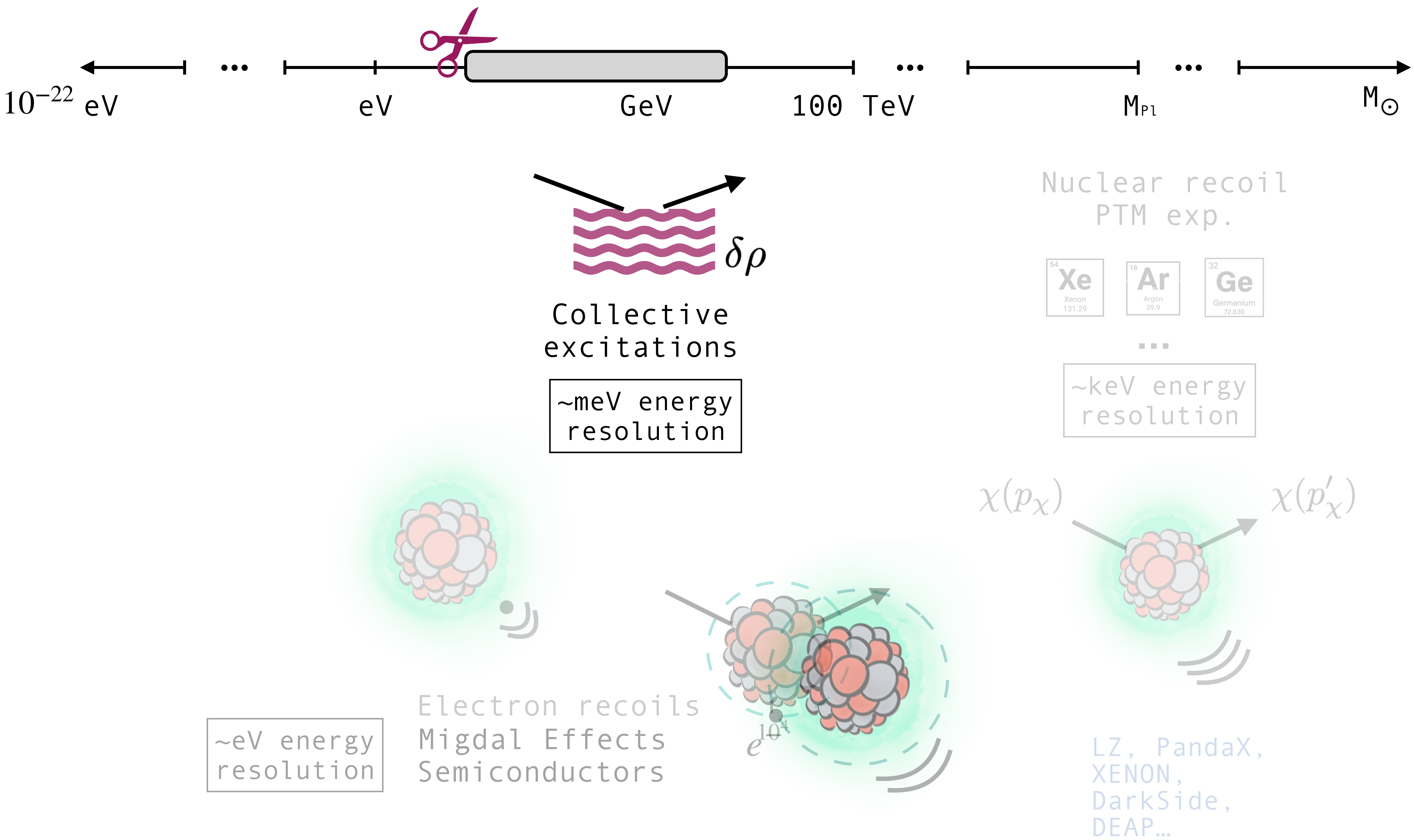
Lowering the threshold

Direct detection



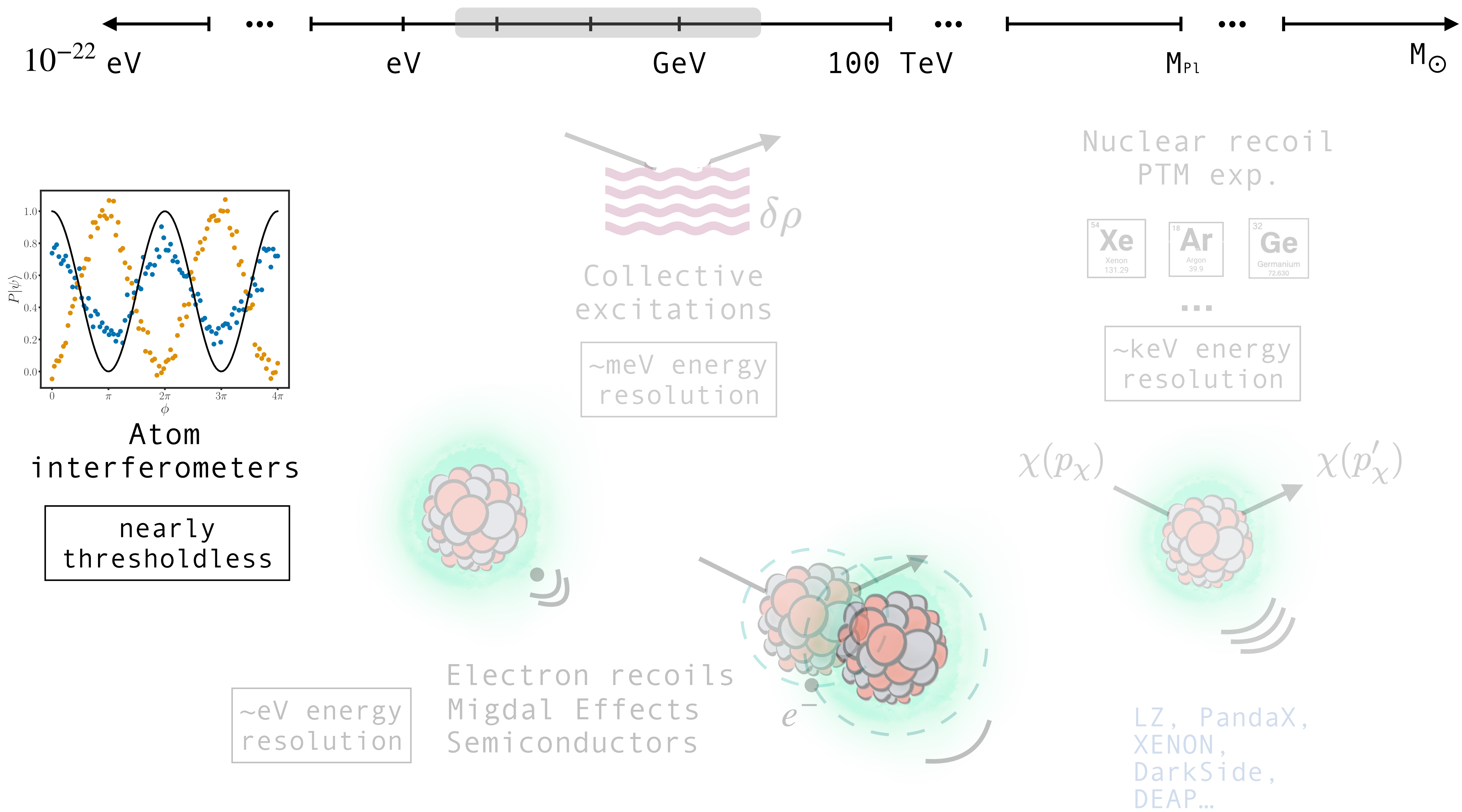
Lowering the threshold

Direct detection



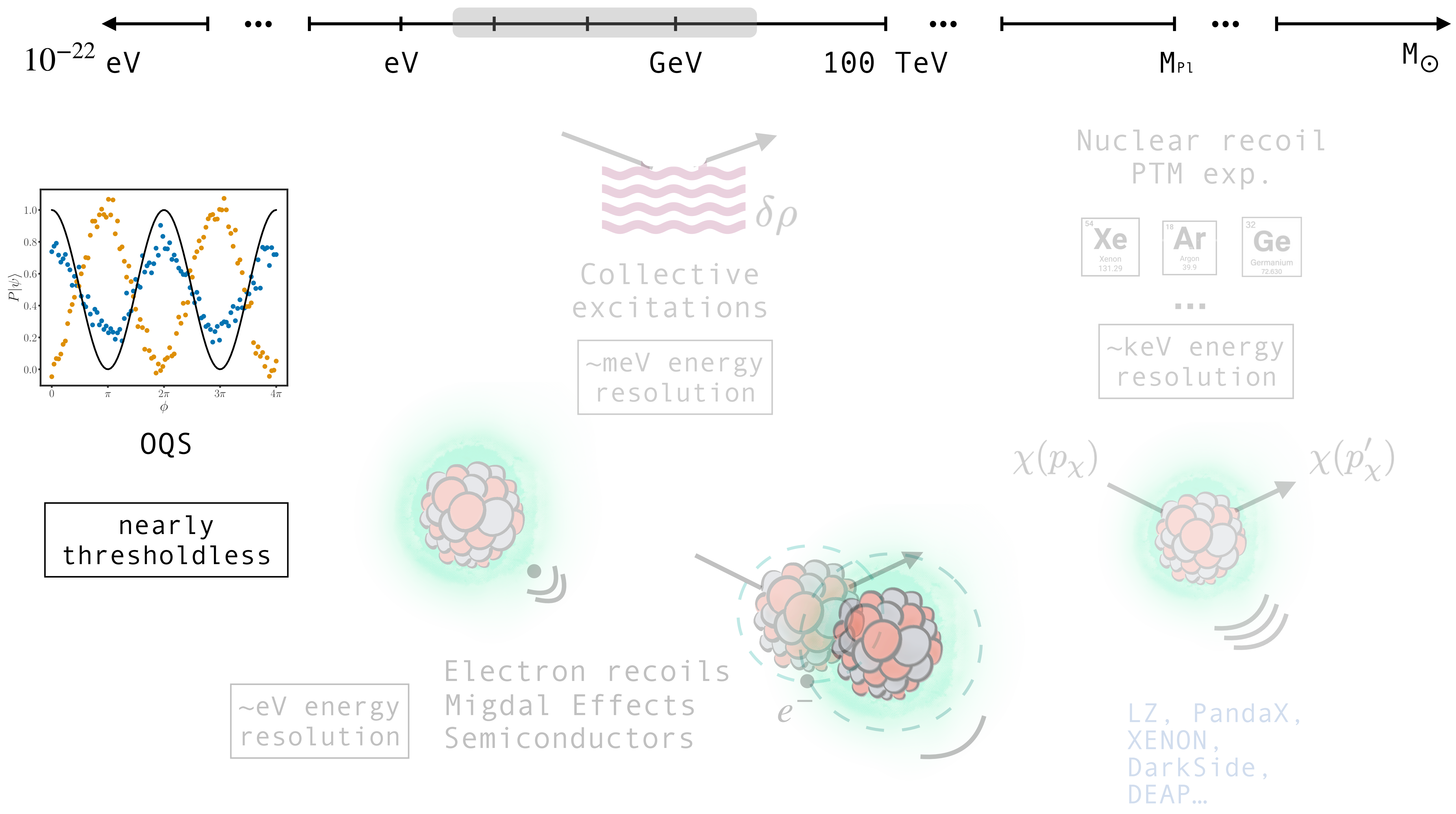
Lowering the threshold

Direct detection



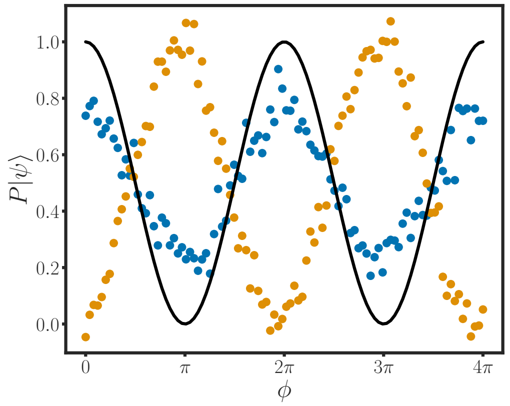
Lowering the threshold

Direct detection



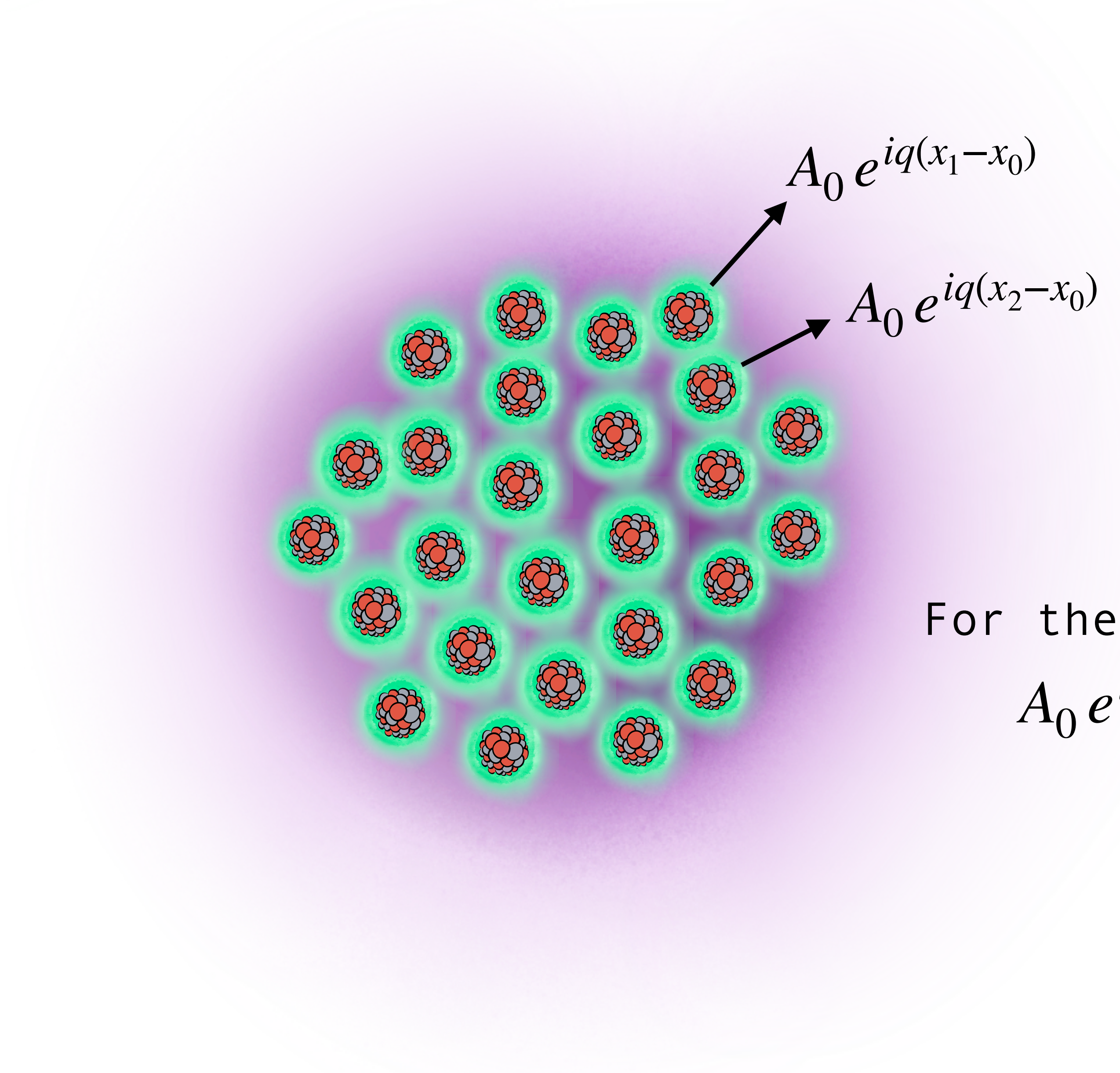
Advantages of low threshold detectors

1 coherent enhancements



OQS

nearly thresholdless



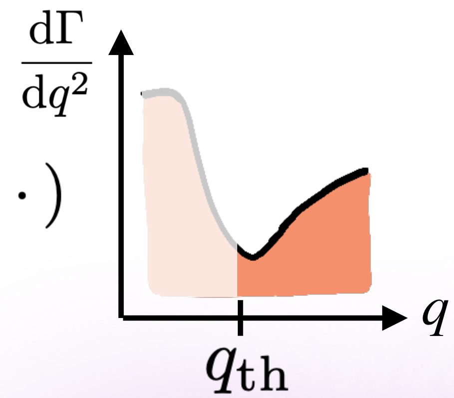
For the ith atom,

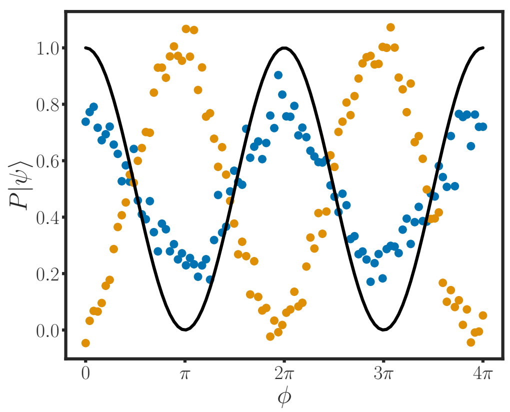
$A_0\, e^{iq(x_i - x_0)}$

Advantages of low threshold detectors

1 coherent enhancements

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

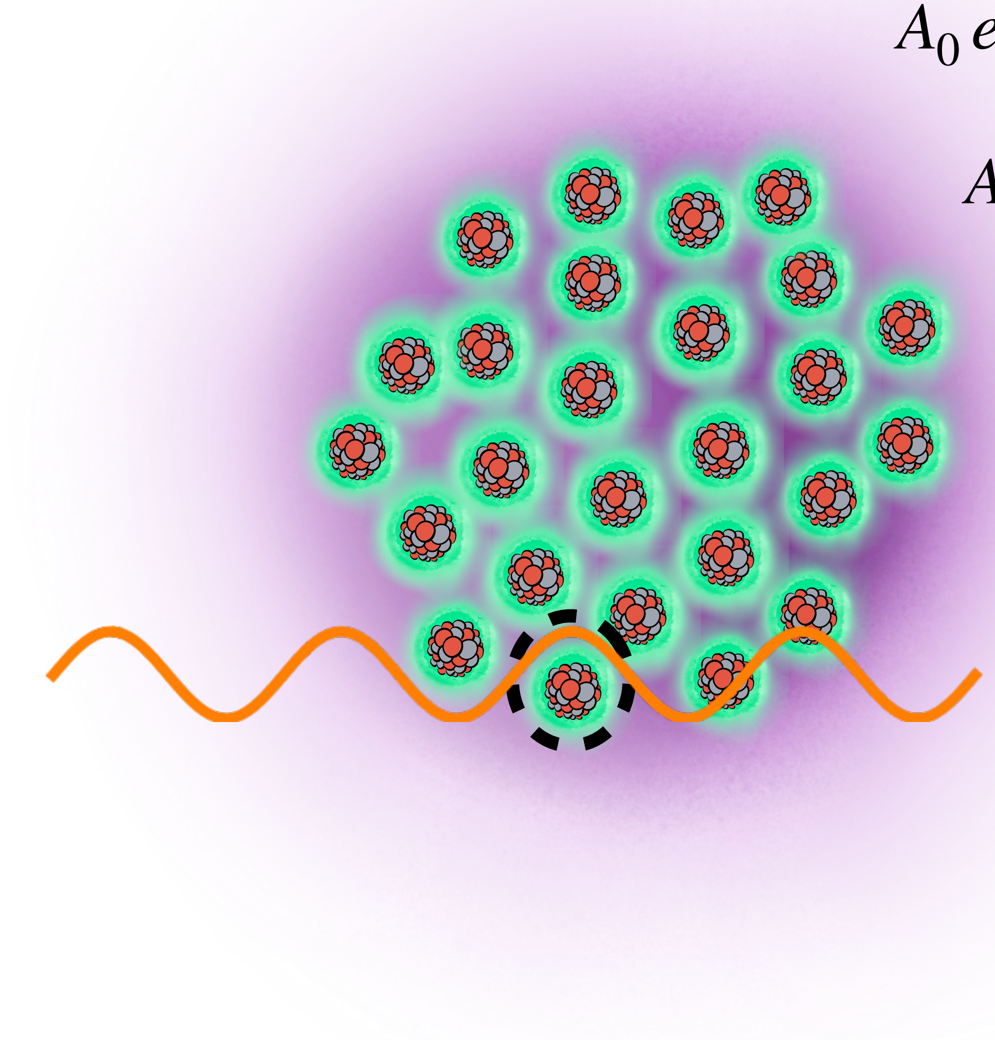




OQS

nearly thresholdless

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



$A_0\, e^{iq(x_1 - x_0)}$

$A_0\, e^{iq(x_2 - x_0)}$

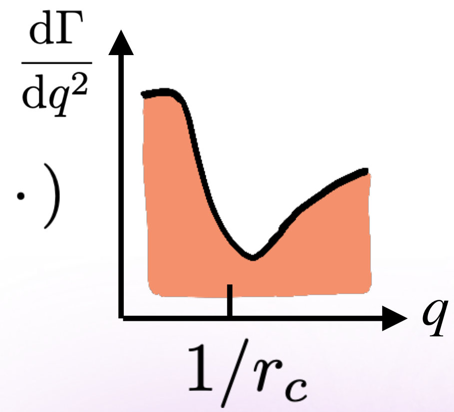
$A_0\, e^{iq(x_i - x_0)}$

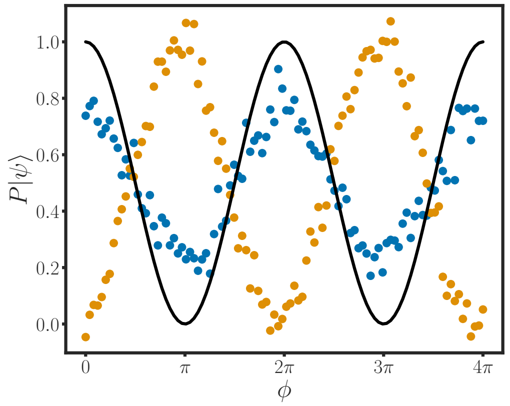
$$\lambda < \frac{2\pi}{q_{\mathrm{th}}}$$

Advantages of low threshold detectors

1 coherent enhancements

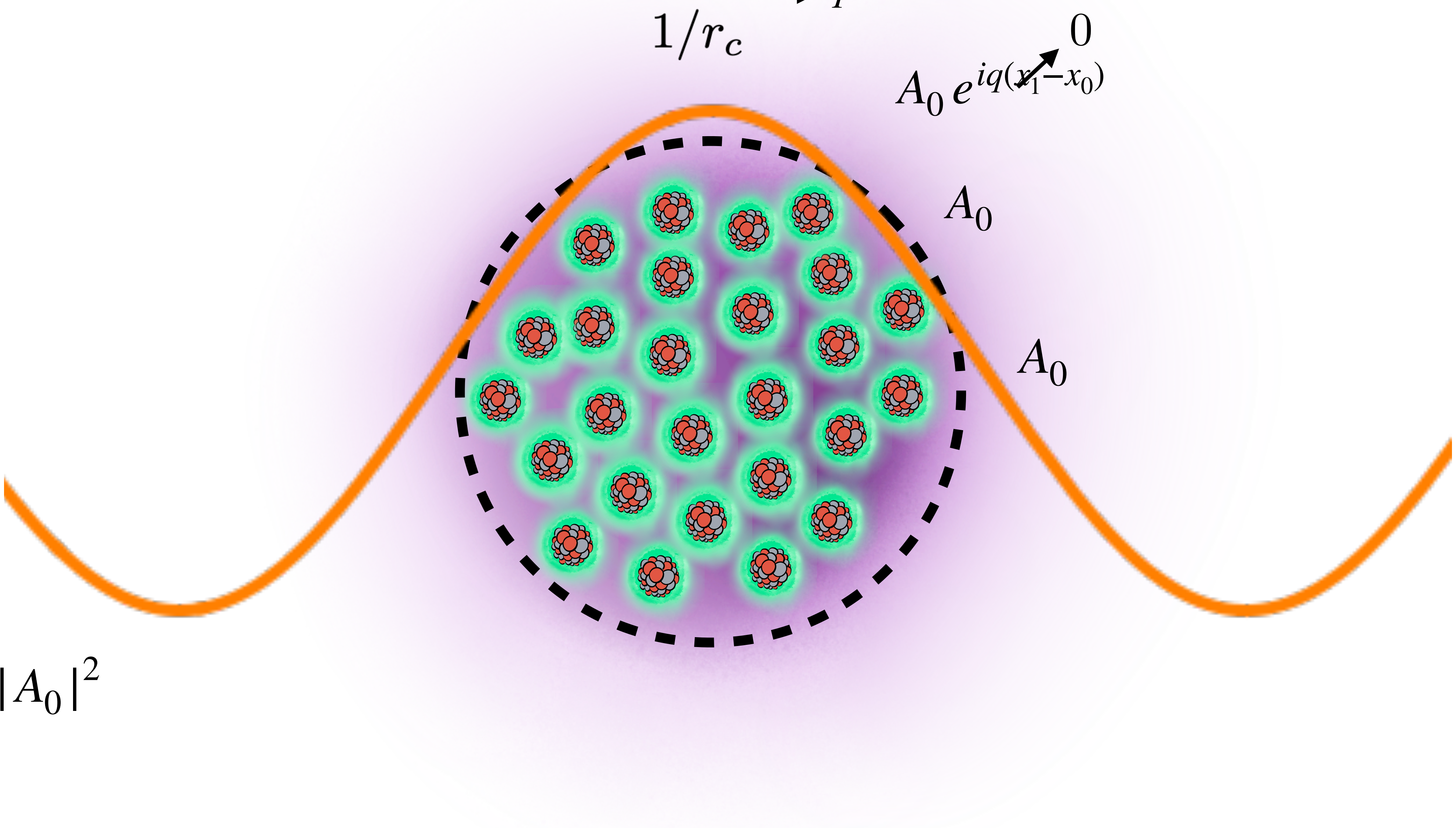
$$\Gamma \propto \int_0^{q_{\max}} dq^2 \, (\cdots)$$





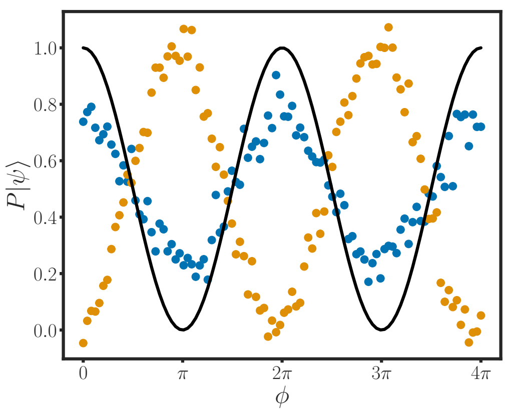
OQS

nearly thresholdless



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

Advantages of low threshold detectors



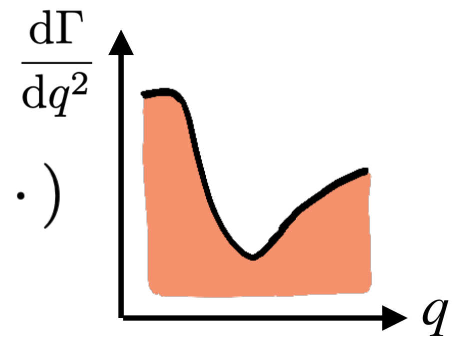
OQS

nearly thresholdless

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

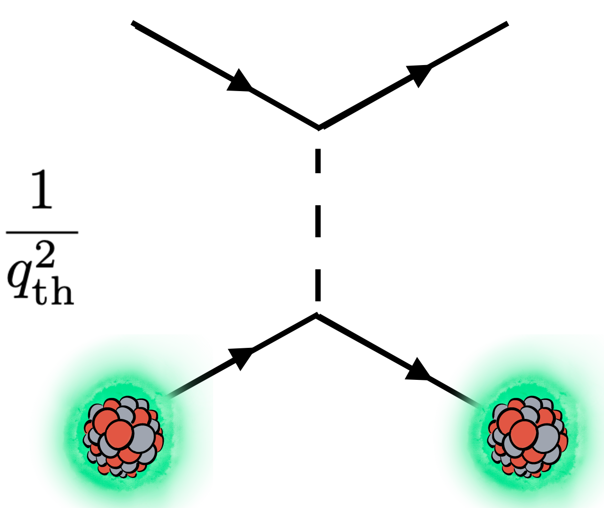
1 coherent enhancements

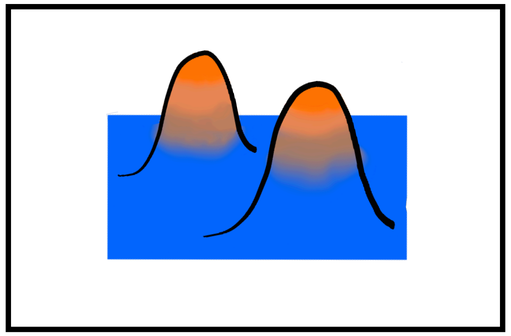
$$\Gamma \propto \int_0^{q_{\max}} \mathrm{d}q^2 \, (\cdots)$$



2 boosted rates

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





Atom interferometers

Atom interferometry

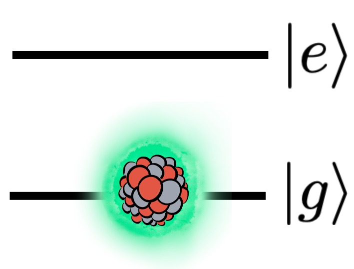
1 atom

(analogy with light)

state preparation

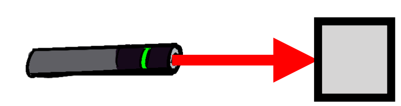
evolution

measurement



Atom interferometry

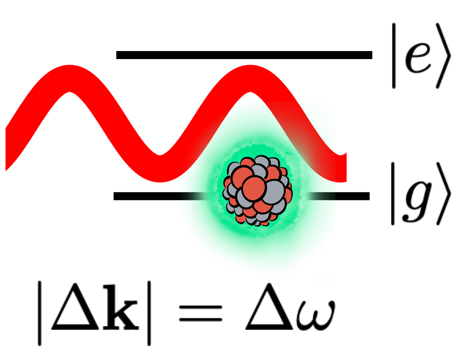
1 atom



state preparation

evolution

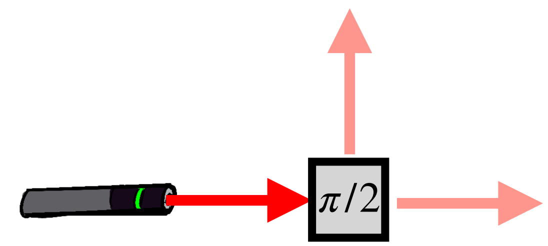
measurement



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

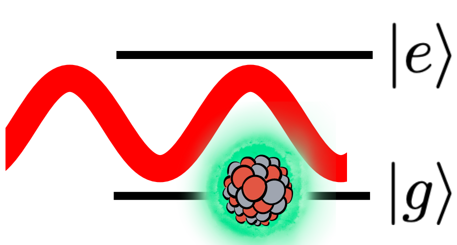
Atom interferometry

1 atom



(analogy with light)

state preparation   evolution   measurement

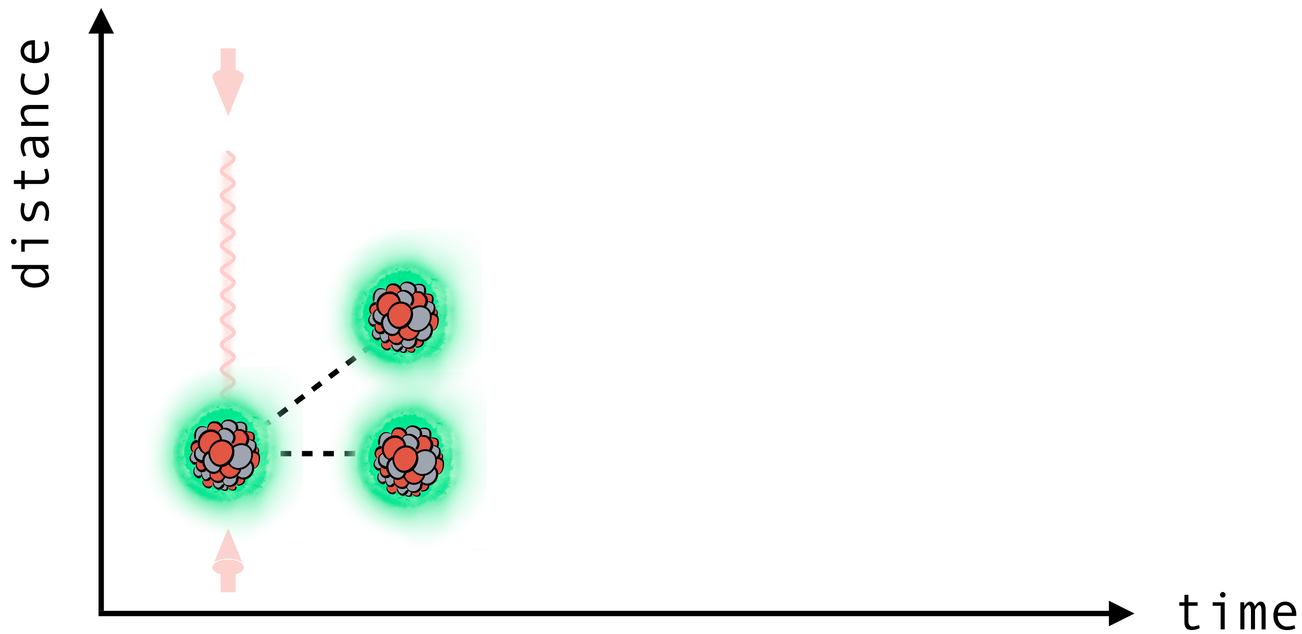


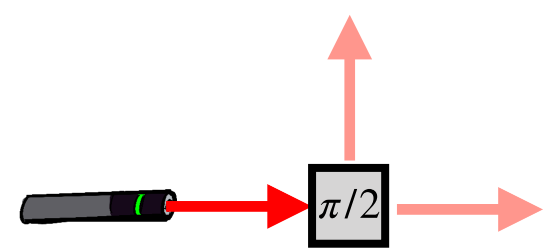
$$|\Delta \mathbf{k}| = \Delta\omega$$

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

Atom interferometry

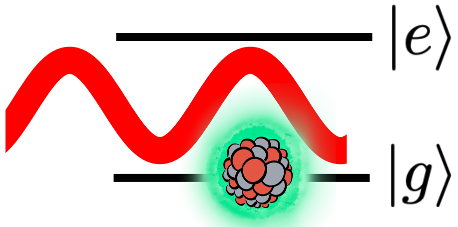
1 atom





(analogy with light)

state preparation   evolution   measurement



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

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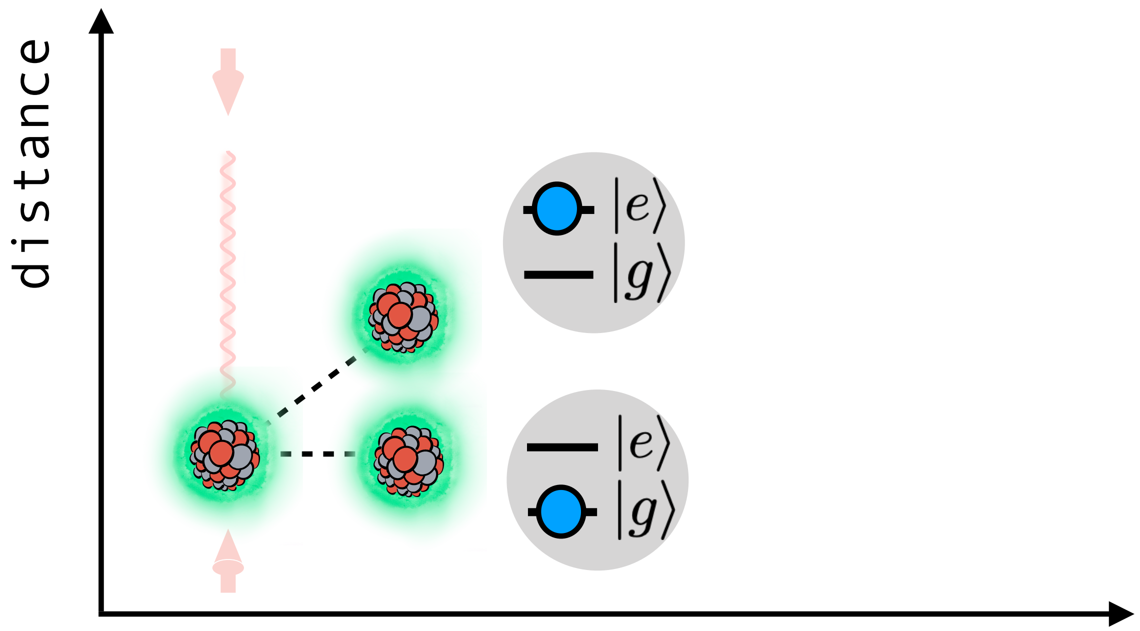
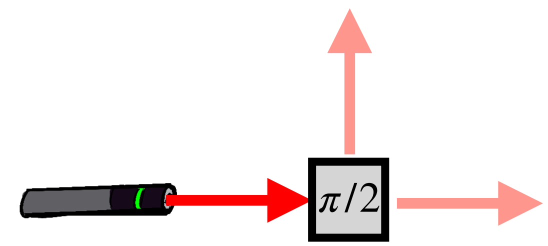
Atom interferometry

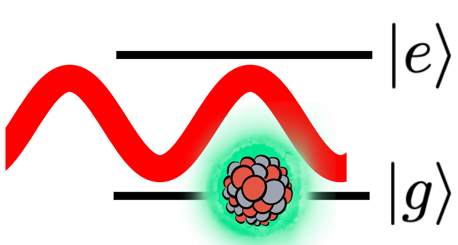
1 atom





(analogy with light)

state preparation evolution measurement

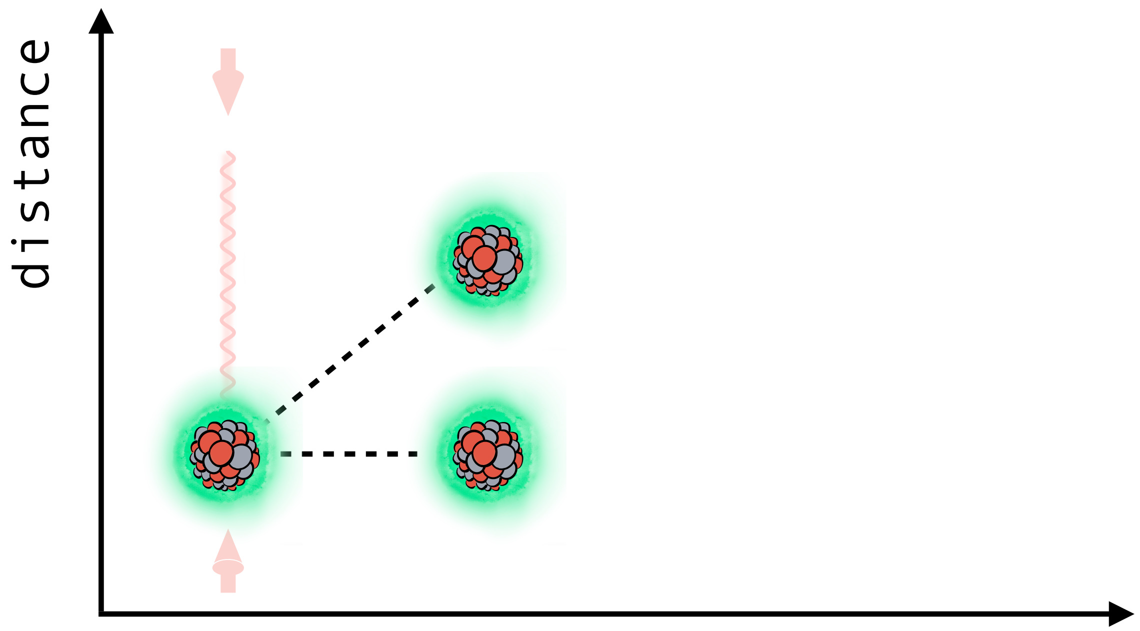


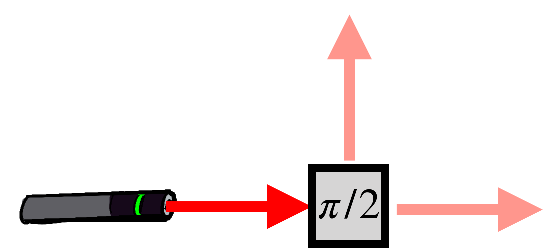
$$|\Delta \mathbf{k}| = \Delta\omega$$

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

Atom interferometry

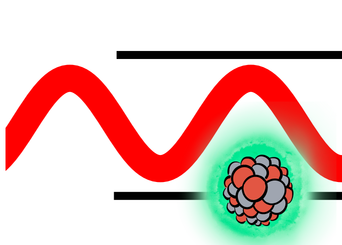
1 atom





(analogy with light)

state preparation evolution measurement

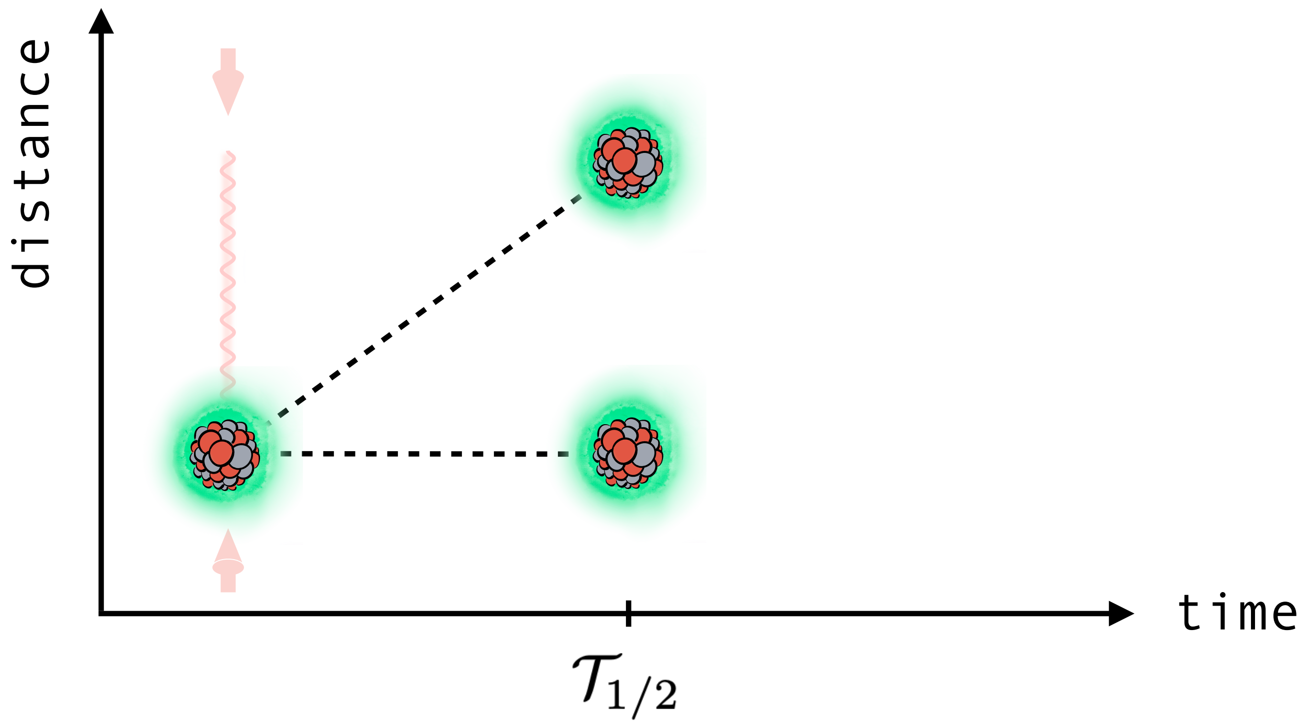


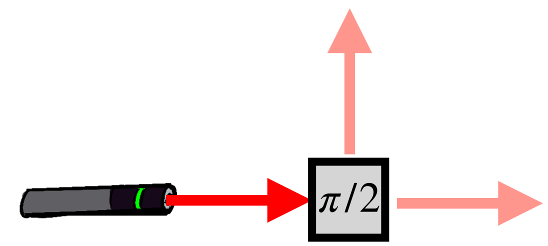
$$|\mathbf{\Delta k}| = \Delta\omega$$

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

Atom interferometry

1 atom



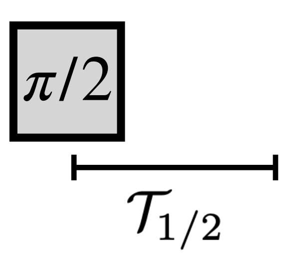


(analogy with light)

state preparation

evolution

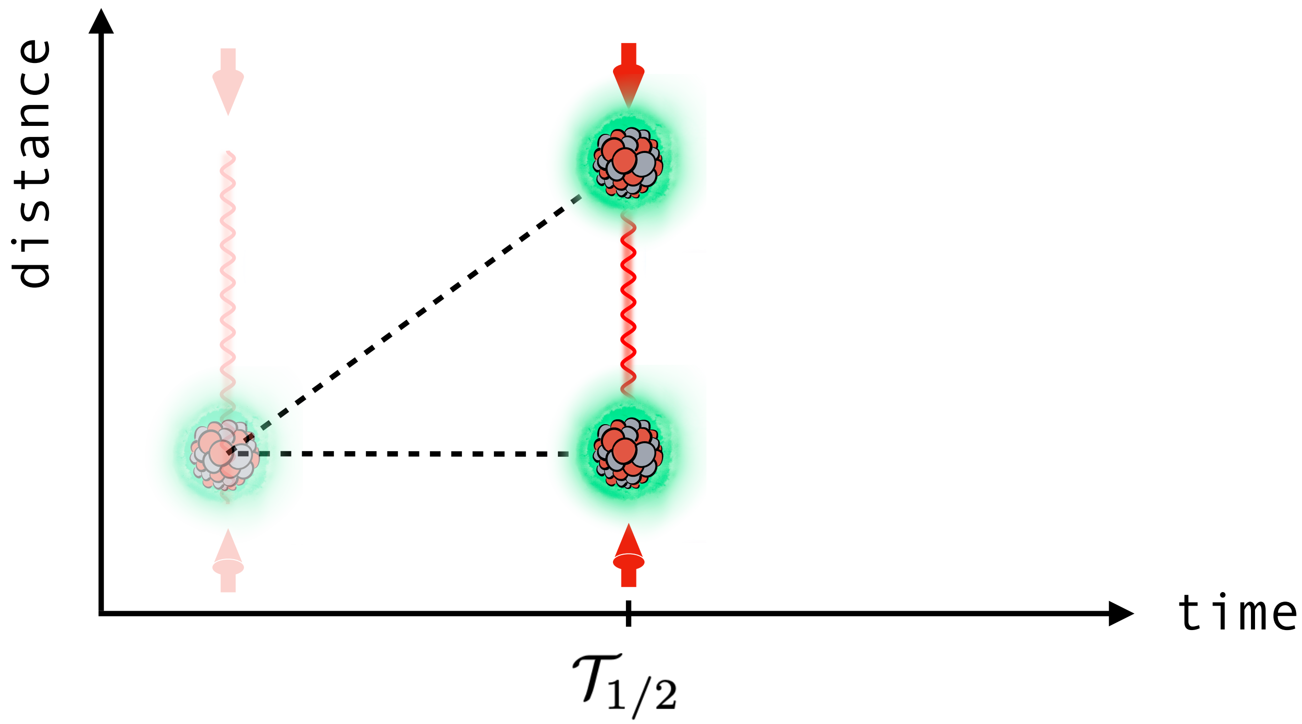
$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$$

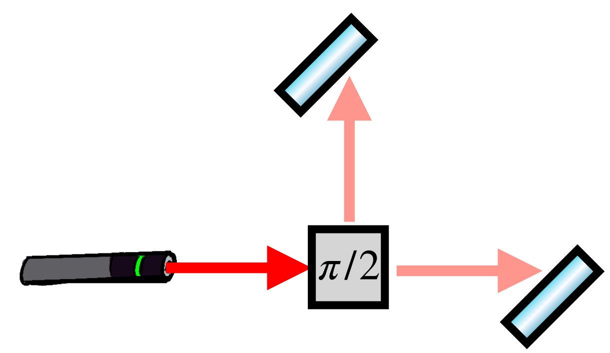


measurement

Atom interferometry

1 atom



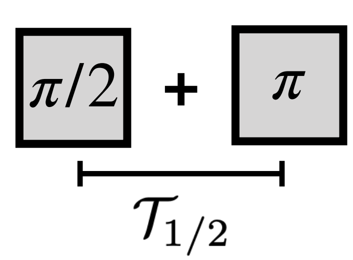


(analogy with light)

state preparation

evolution

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

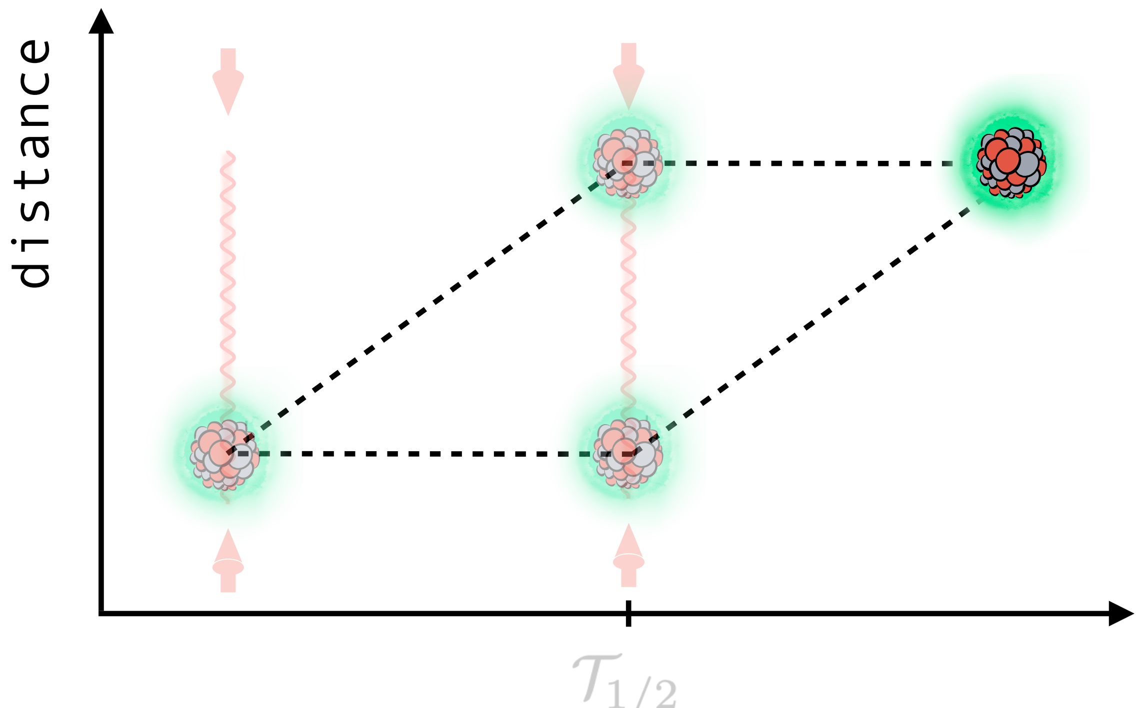


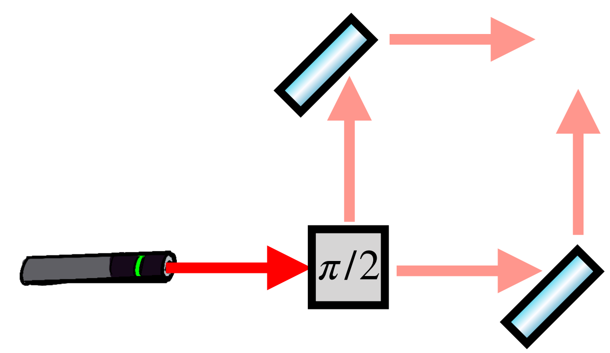
measurement

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

Atom interferometry

1 atom



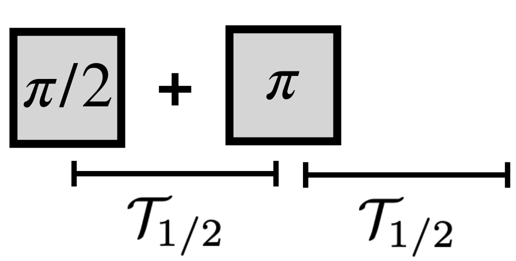


(analogy with light)

state preparation

evolution

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

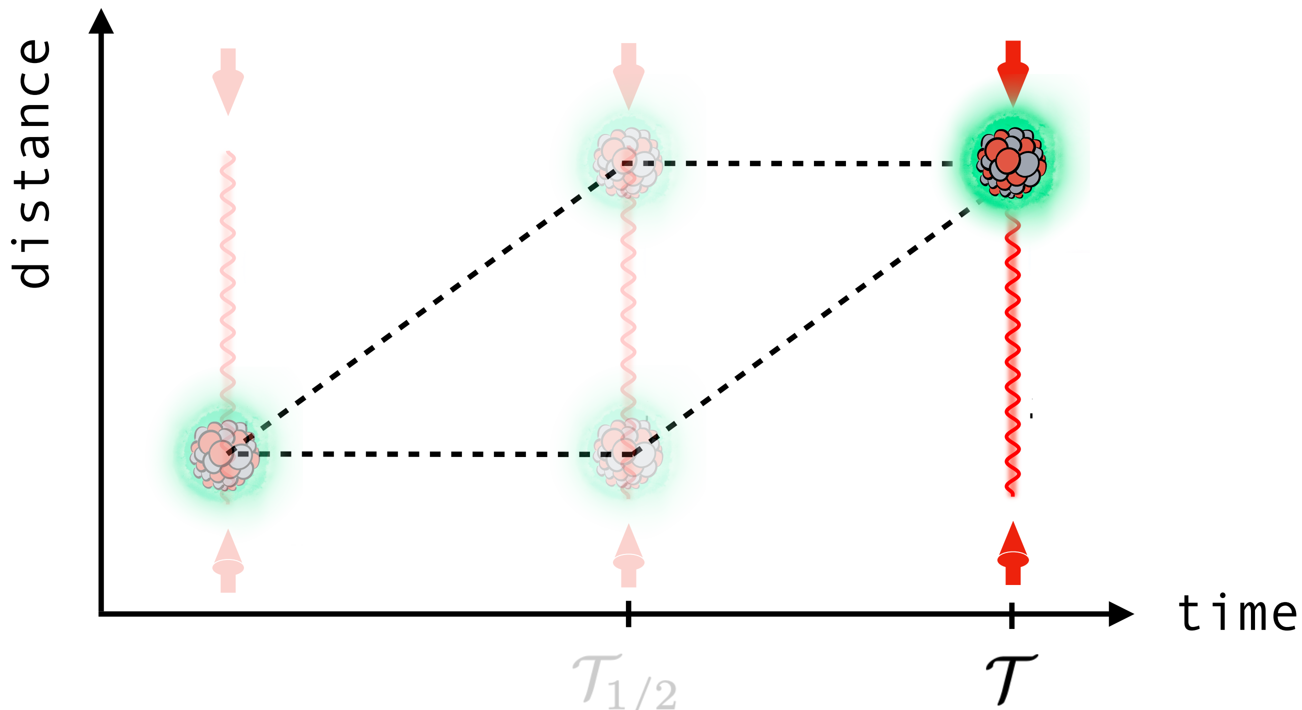


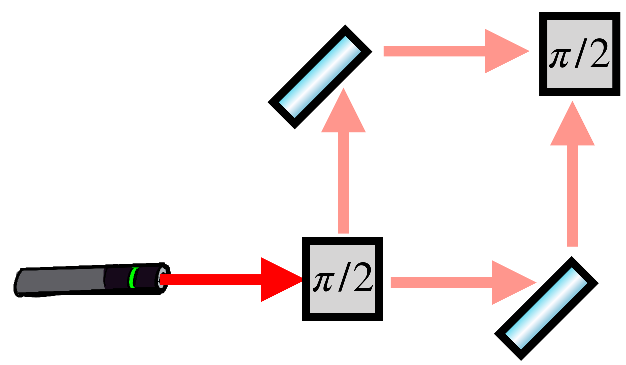
measurement

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

Atom interferometry

1 atom





(analogy with light)

state preparation

evolution

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

$$\boxed{\pi/2} + \boxed{\pi} + \boxed{\pi/2}$$

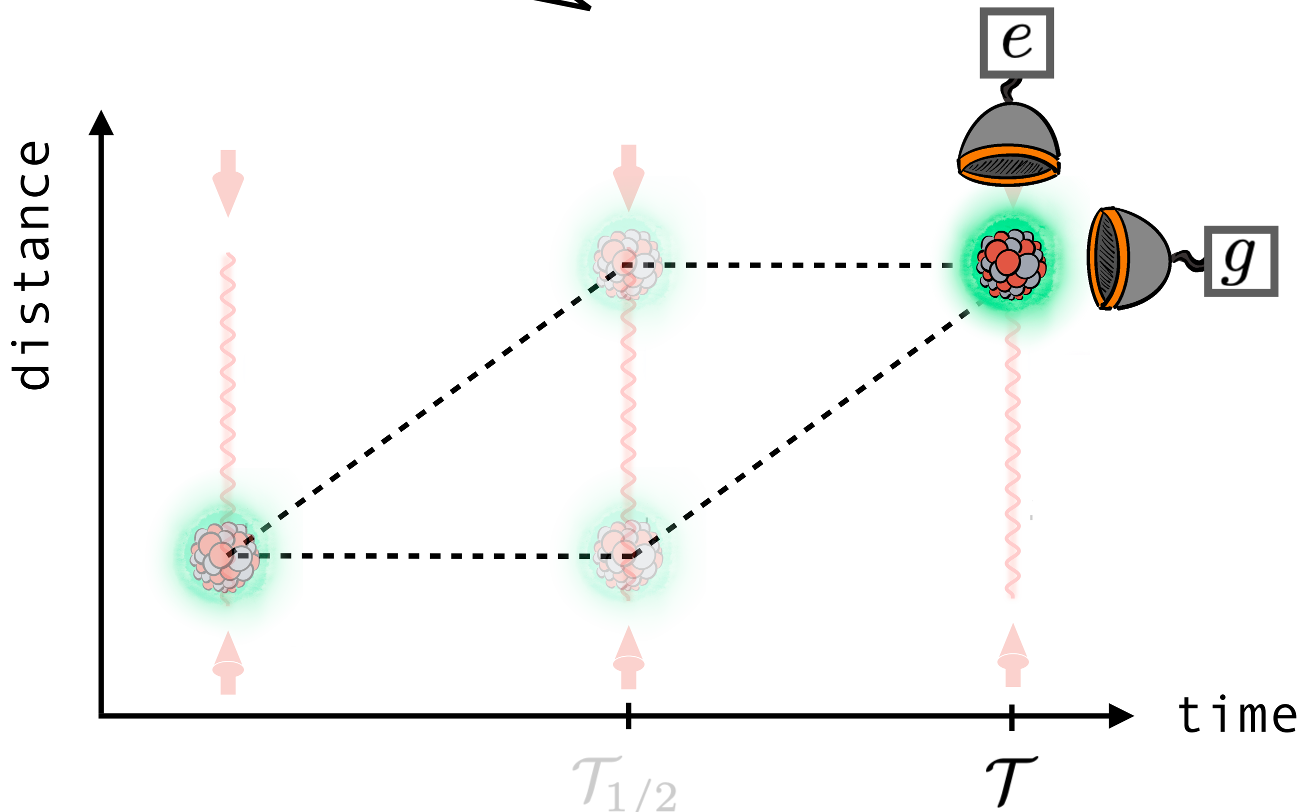
$\mathcal{T}_{1/2}$ $\mathcal{T}_{1/2}$

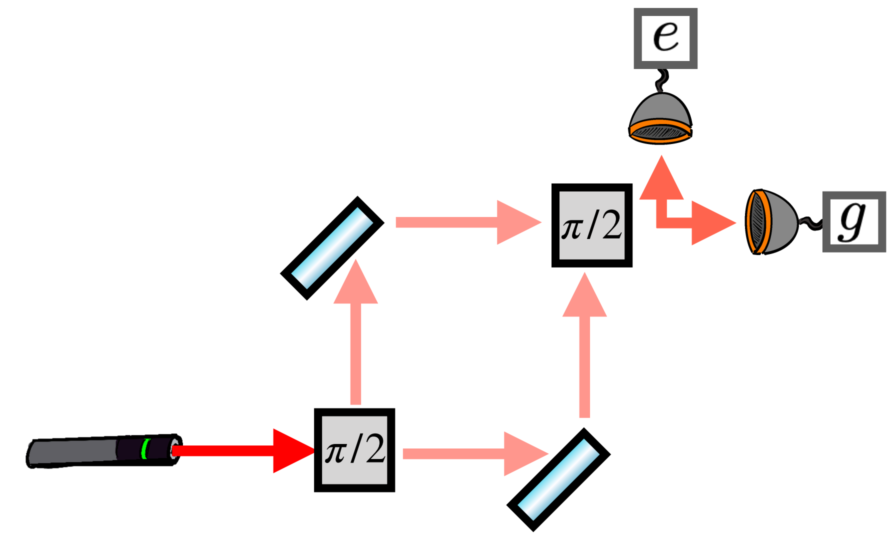
measurement

Atom interferometry

1 atom

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



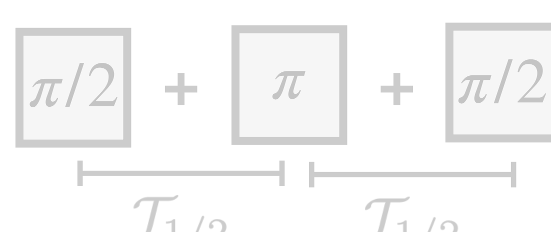


(analogy with light)

state preparation

evolution

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

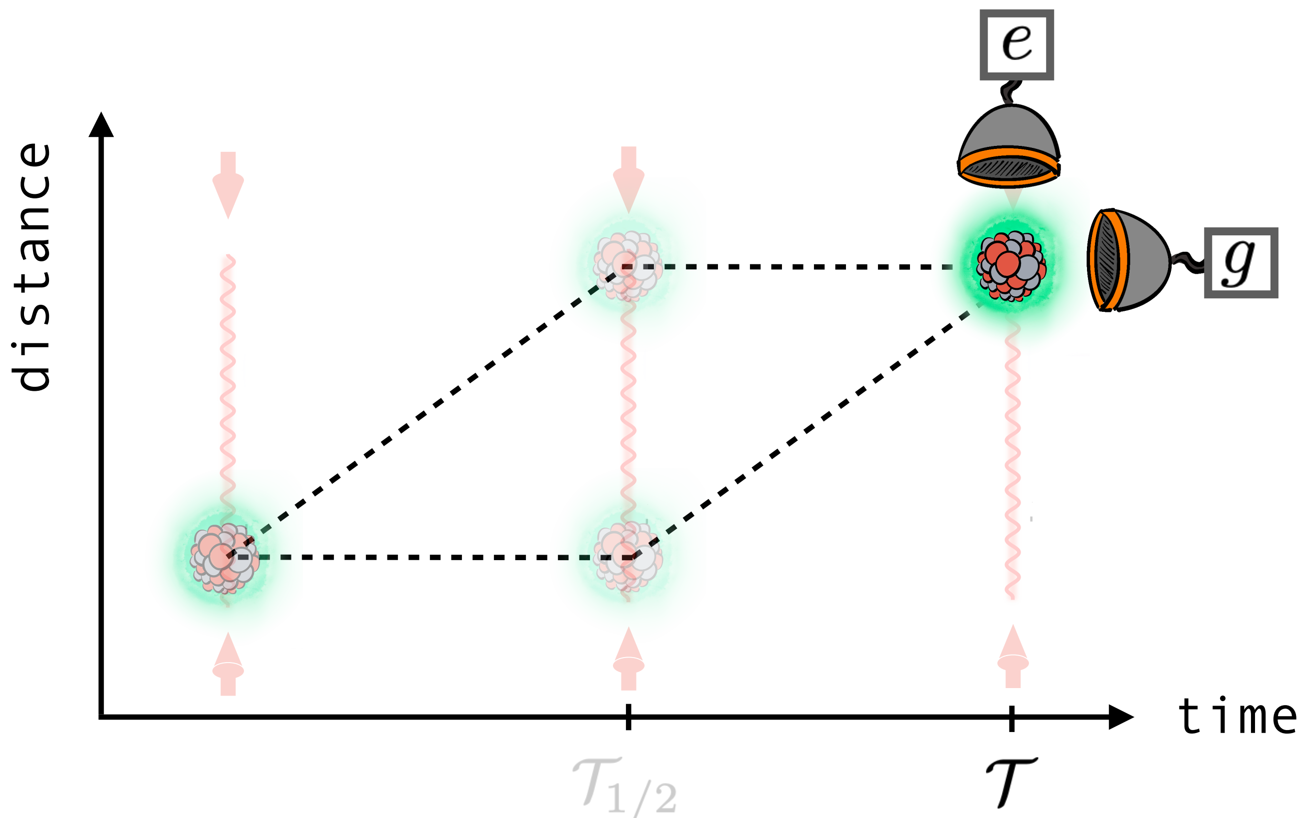


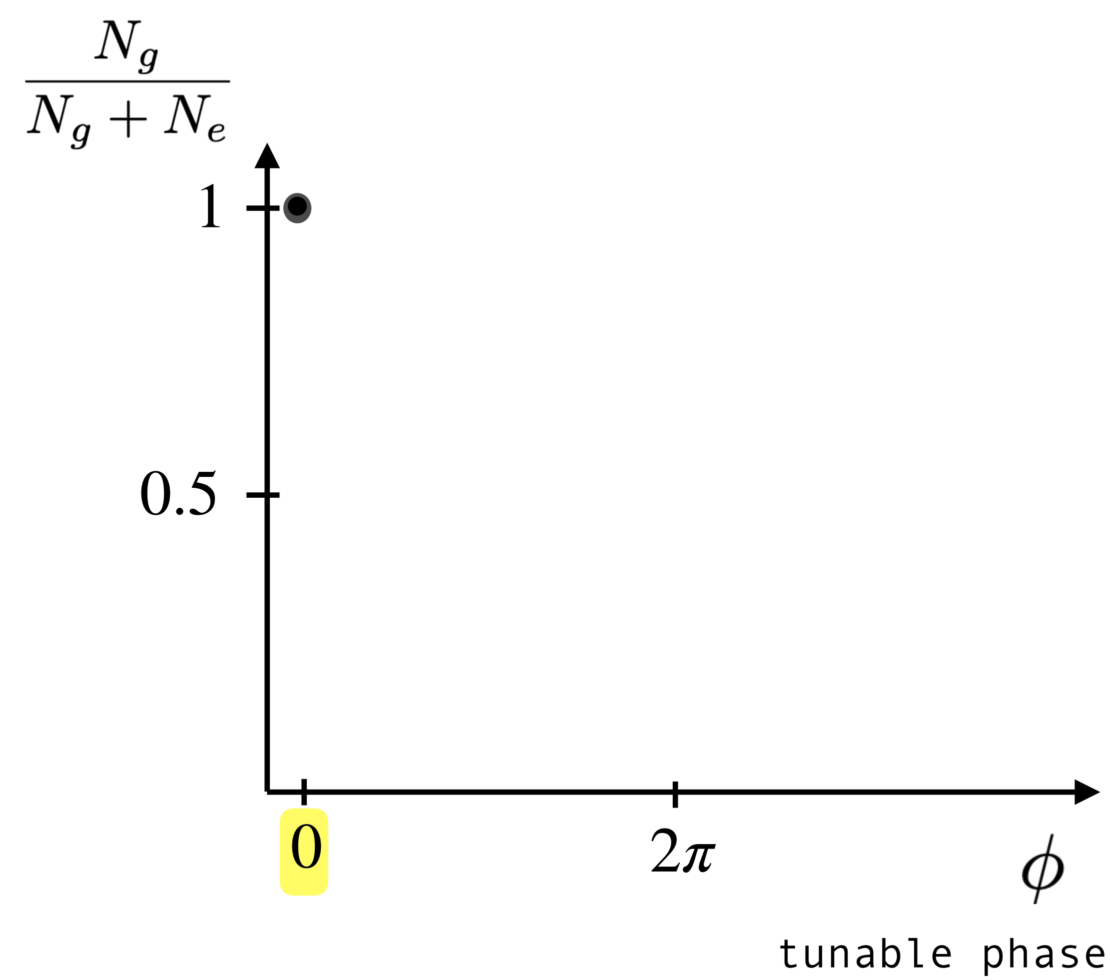
measurement

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

Atom interferometry

1 atom



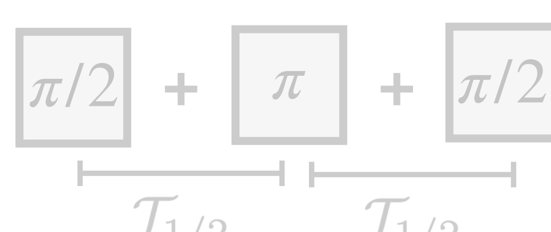


state preparation

$$|e\rangle \qquad |g\rangle$$

evolution

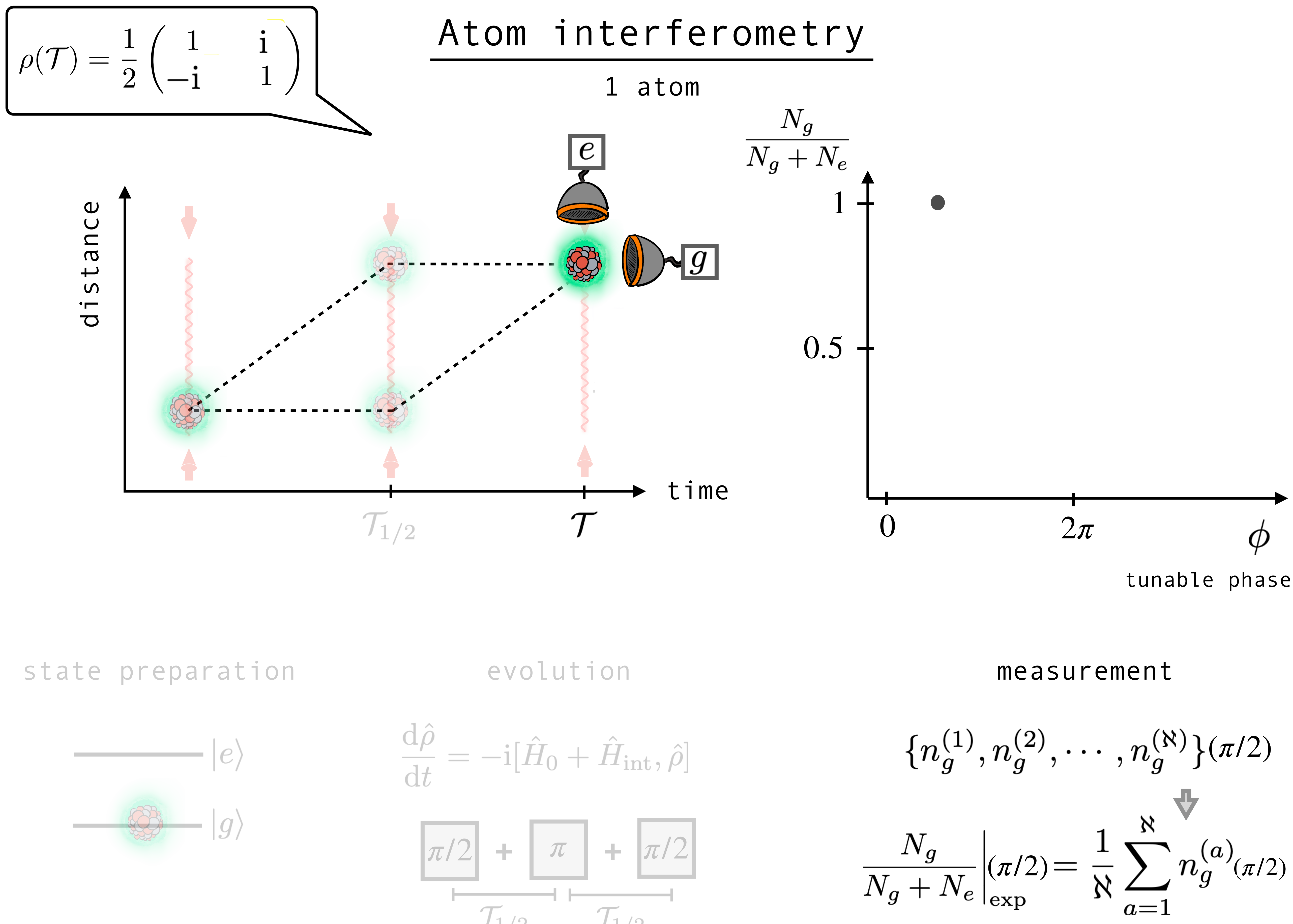
$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$$



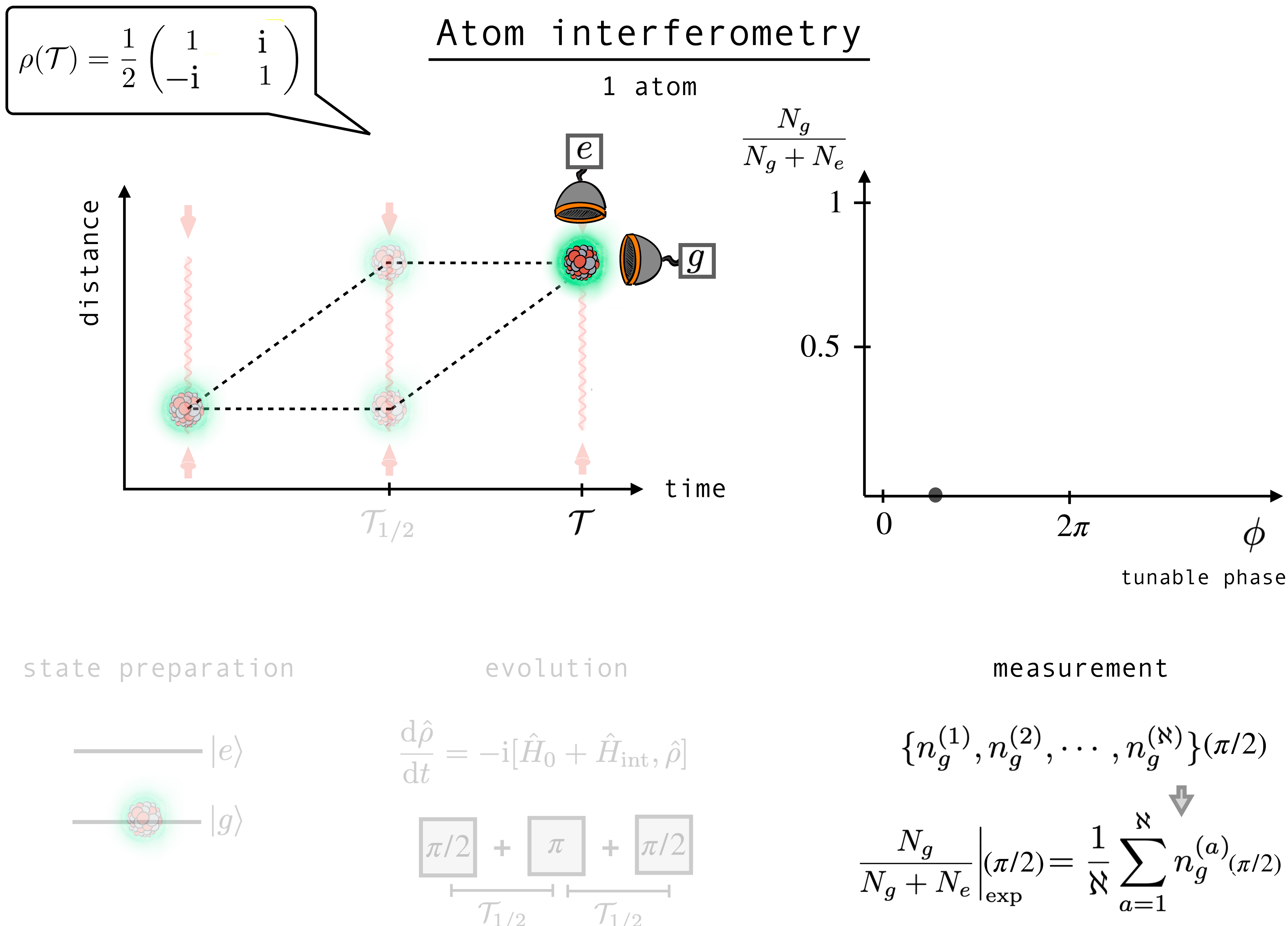
measurement

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

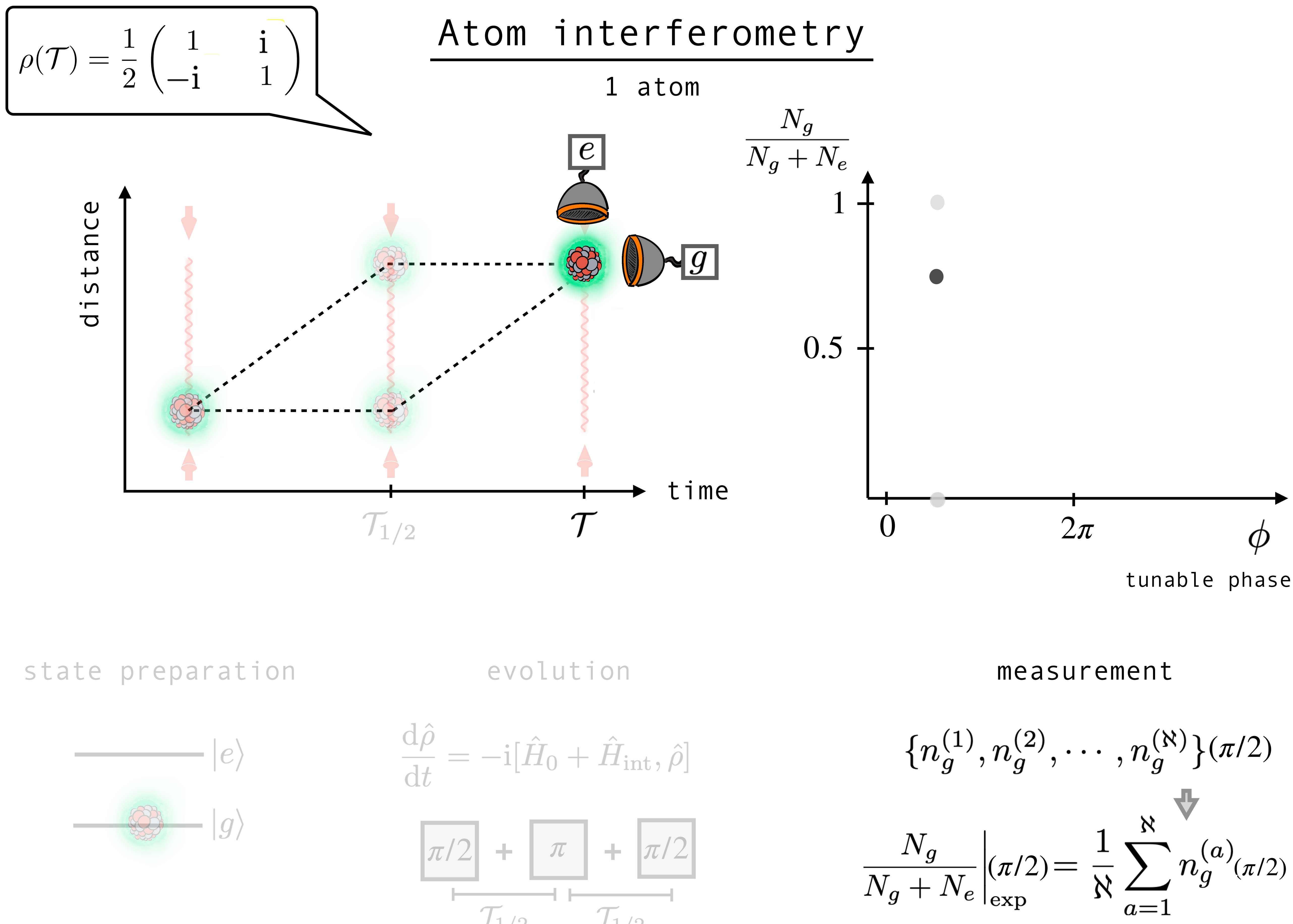
$$\left.\frac{N_g}{N_g+N_e}\right|_{\mathrm{exp}}(0) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(0)$$



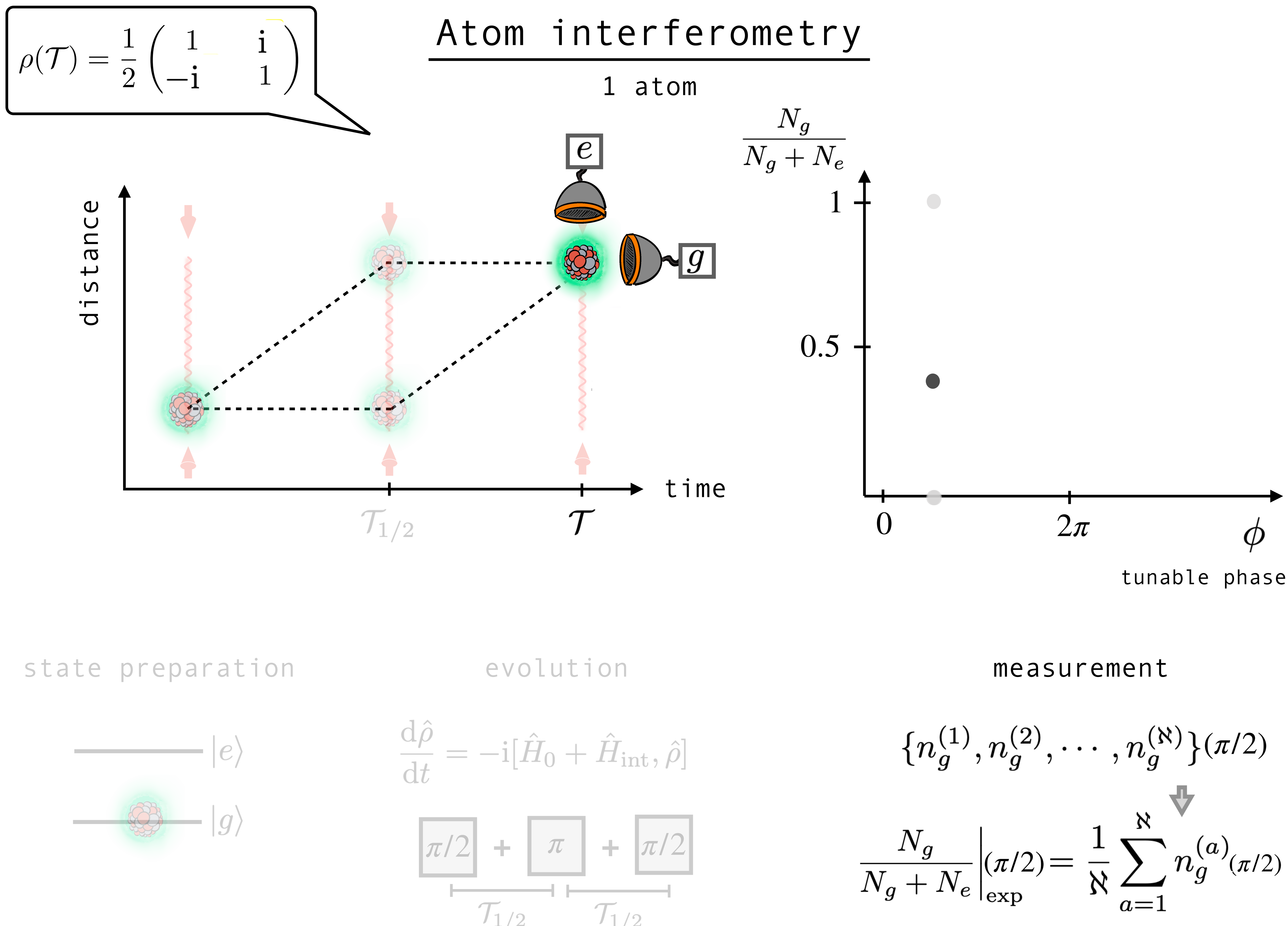
$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{i} \\ -\mathrm{i} & 1 \end{pmatrix}$
Atom interferometry
1 atom
distance
e
g
time
$\mathcal{T}_{1/2}$
$\mathcal{T}$
$\frac{N_g}{N_g + N_e}$
1
0.5
0
2π
ϕ
tunable phase
state preparation
$|e\rangle$
$|g\rangle$
evolution
$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$
$\pi/2$ + π + $\pi/2$
$\mathcal{T}_{1/2}$ $\mathcal{T}_{1/2}$
measurement
$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\pi/2)$
$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{exp}}(\pi/2) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\pi/2)$



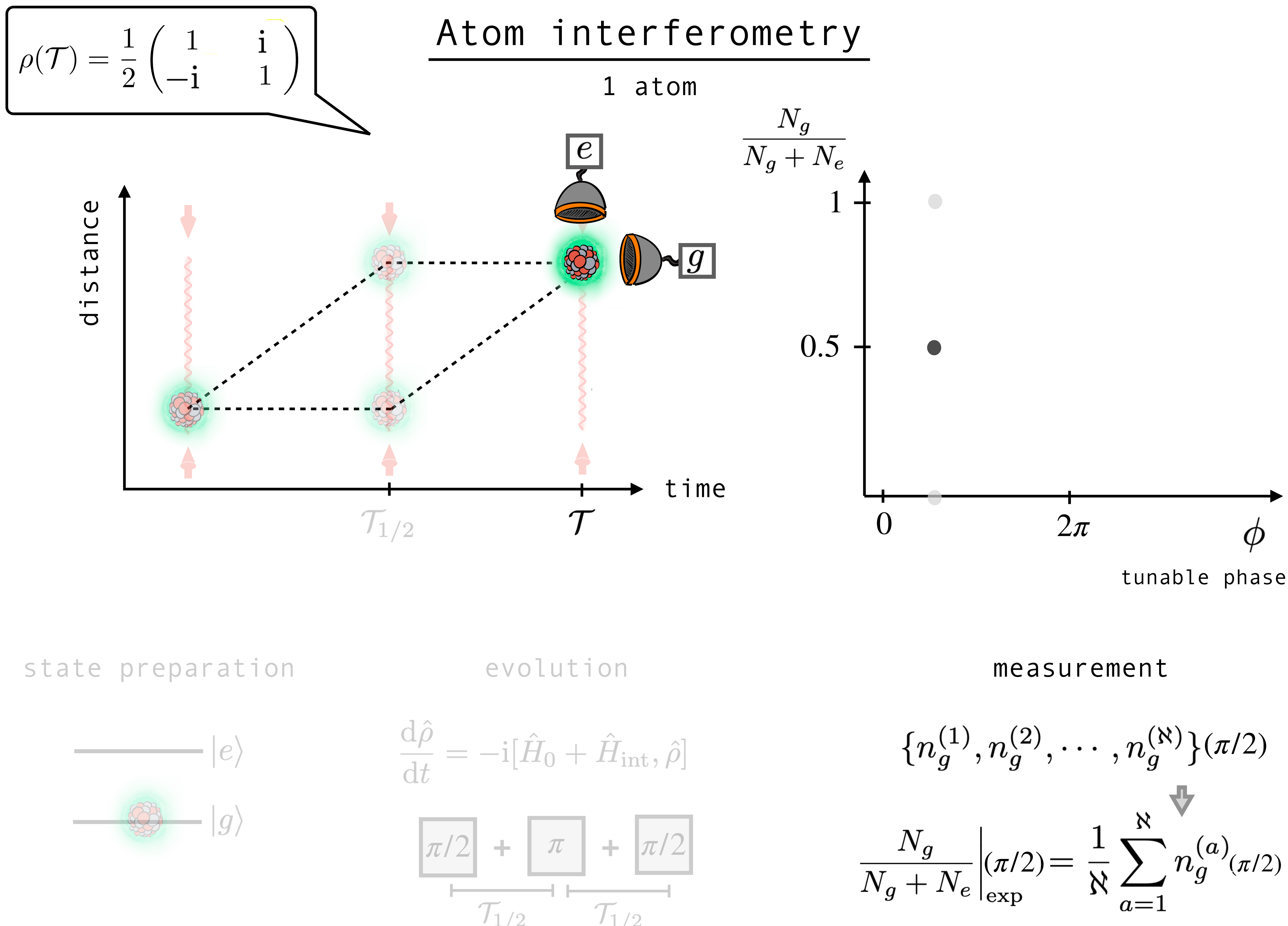
$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{i} \\ -\mathrm{i} & 1 \end{pmatrix}$
Atom interferometry
1 atom
distance
time
$\mathcal{T}_{1/2}$
$\mathcal{T}$
e
g
$\frac{N_g}{N_g + N_e}$
1
0.5
0
2π
ϕ
tunable phase
state preparation
$|e\rangle$
$|g\rangle$
evolution
$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$
$\pi/2$ + π + $\pi/2$
$\mathcal{T}_{1/2}$
$\mathcal{T}_{1/2}$
measurement
$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\pi/2)$
$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{exp}}(\pi/2) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\pi/2)$



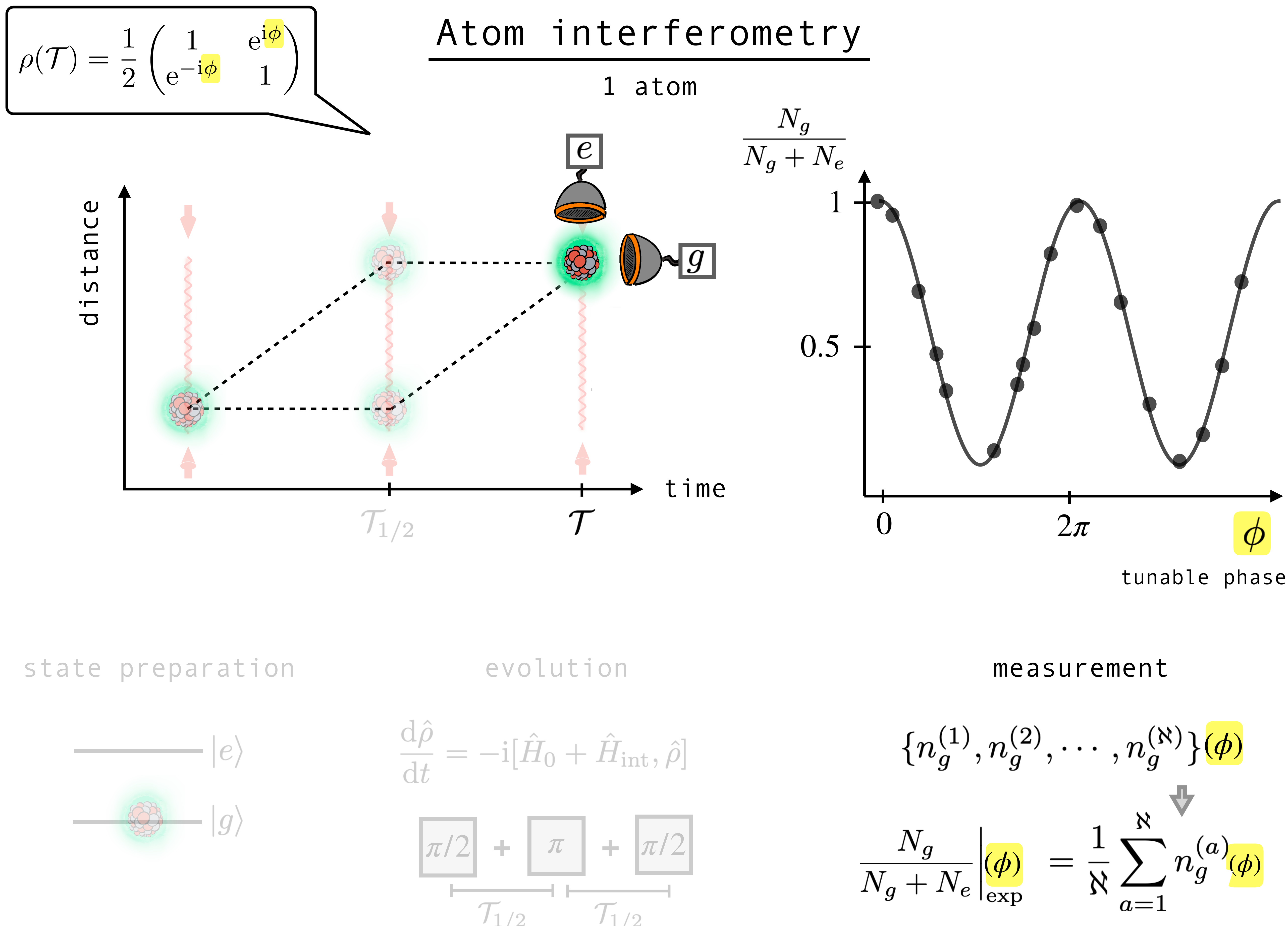
Atom interferometry
1 atom
$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{i} \\ -\mathrm{i} & 1 \end{pmatrix}$
distance
time
$\mathcal{T}_{1/2}$
$\mathcal{T}$
e
g
$\frac{N_g}{N_g + N_e}$
1
0.5
0
2π
ϕ
tunable phase
state preparation
$|e\rangle$
$|g\rangle$
evolution
$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$
$\pi/2$ + π + $\pi/2$
$\mathcal{T}_{1/2}$ $\mathcal{T}_{1/2}$
measurement
$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\pi/2)$
$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{exp}}(\pi/2) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\pi/2)$



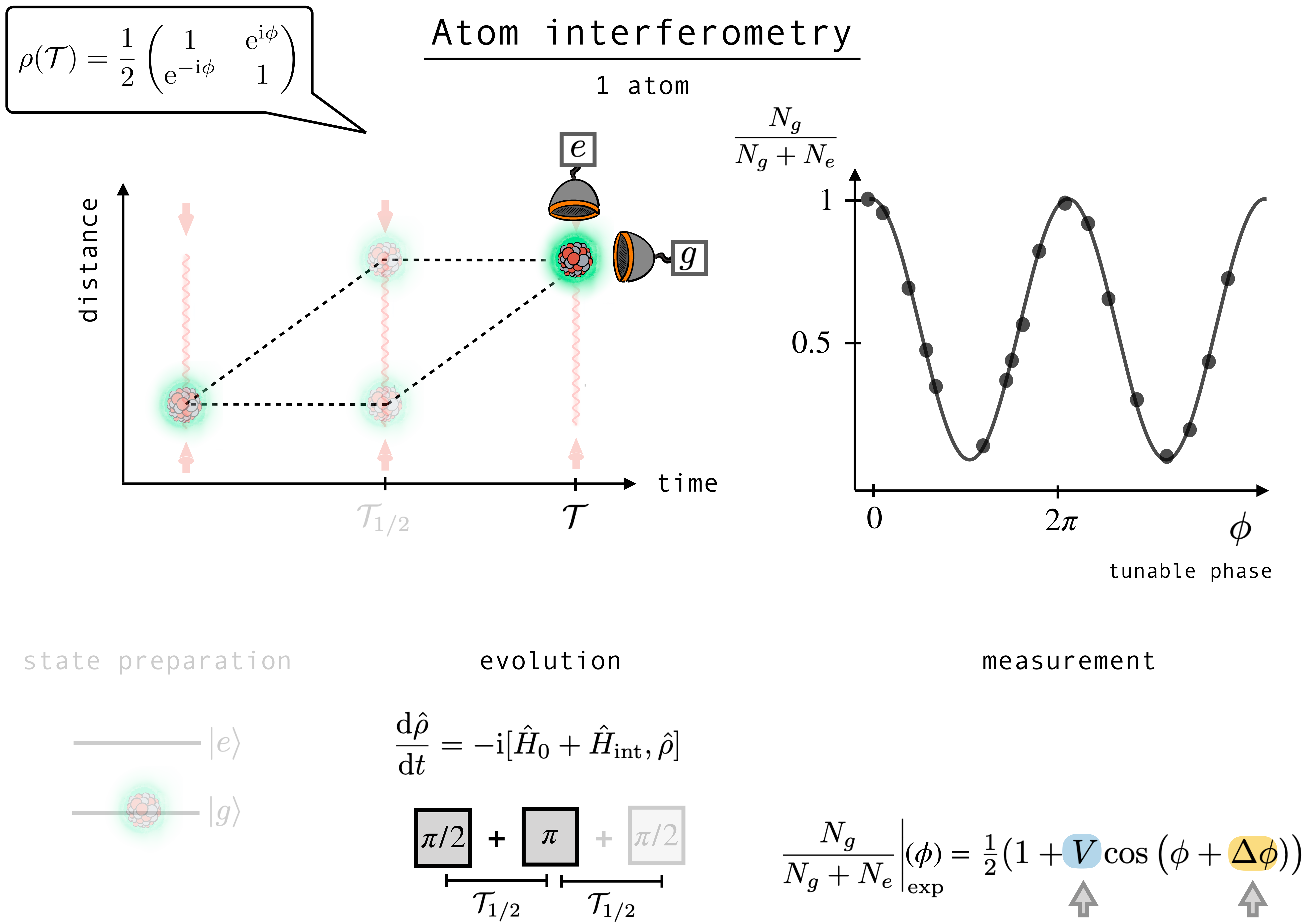
Atom interferometry
1 atom
$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{i} \\ -\mathrm{i} & 1 \end{pmatrix}$
distance
time
$\mathcal{T}_{1/2}$
$\mathcal{T}$
e
g
$\frac{N_g}{N_g + N_e}$
1
0.5
0
2π
ϕ
tunable phase
state preparation
$|e\rangle$
$|g\rangle$
evolution
$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$
$\pi/2$ + π + $\pi/2$
$\mathcal{T}_{1/2}$ $\mathcal{T}_{1/2}$
measurement
$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\pi/2)$
$\frac{N_g}{N_g + N_e}\Big|_{\mathrm{exp}}(\pi/2) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\pi/2)$



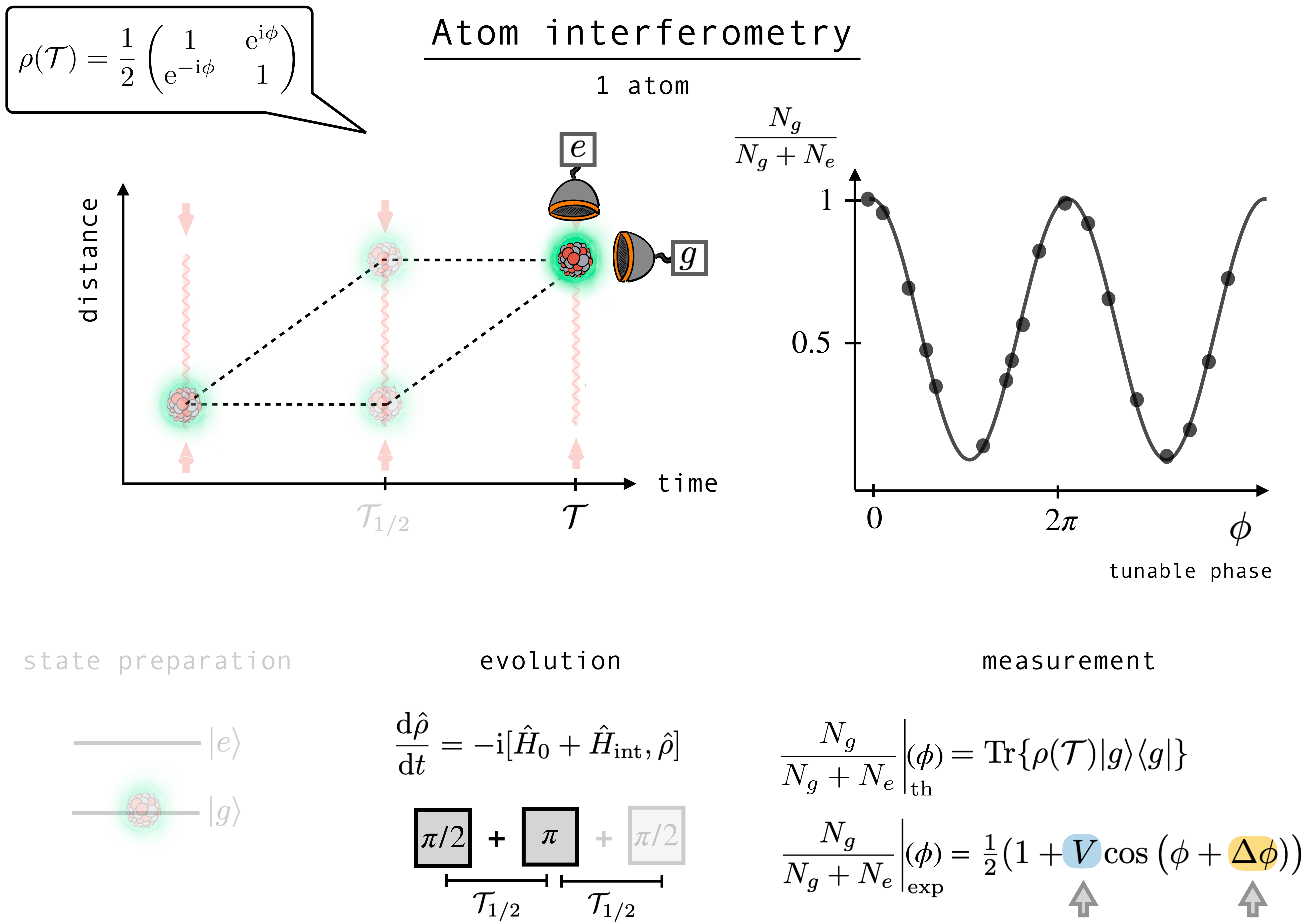
Atom interferometry
1 atom
$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{i} \\ -\mathrm{i} & 1 \end{pmatrix}$
distance
time
$\mathcal{T}_{1/2}$
$\mathcal{T}$
e
g
$\frac{N_g}{N_g + N_e}$
1
0.5
0
2π
ϕ
tunable phase
state preparation
$|e\rangle$
$|g\rangle$
evolution
$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$
$\pi/2$ + π + $\pi/2$
$\mathcal{T}_{1/2}$ $\mathcal{T}_{1/2}$
measurement
$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\pi/2)$
$\frac{N_g}{N_g + N_e}\Big|_{\mathrm{exp}}(\pi/2) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\pi/2)$



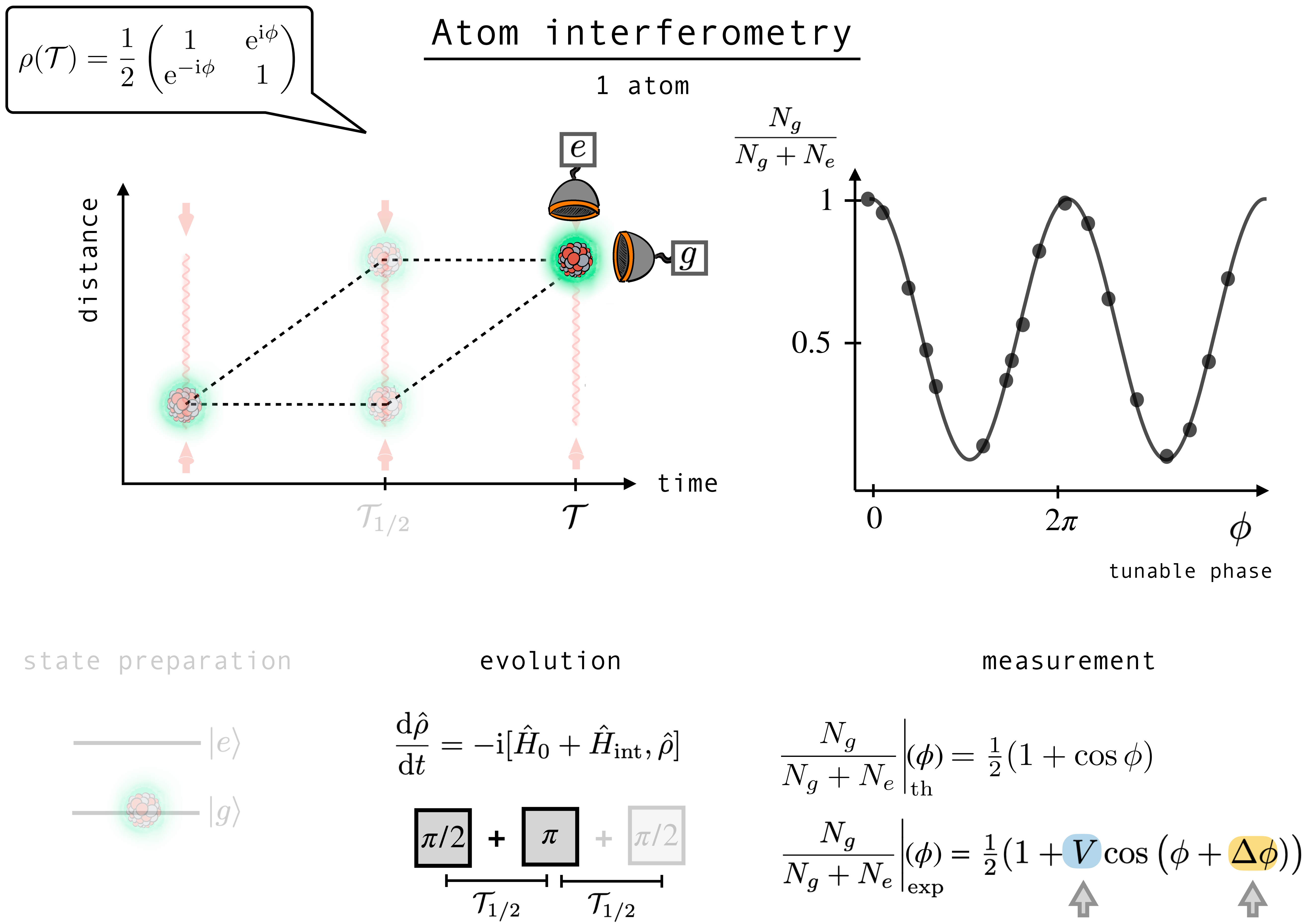
Atom interferometry
1 atom
$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{pmatrix}$
distance
time
$\mathcal{T}_{1/2}$
$\mathcal{T}$
e
g
$\frac{N_g}{N_g + N_e}$
1
0.5
0
2π
ϕ
tunable phase
state preparation
$|e\rangle$
$|g\rangle$
evolution
$\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}t} = -\mathrm{i}[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$
$\pi/2$ + π + $\pi/2$
$\mathcal{T}_{1/2}$ $\mathcal{T}_{1/2}$
measurement
$\{n_g^{(1)}, n_g^{(2)}, \cdots, n_g^{(\aleph)}\}(\phi)$
$\left.\frac{N_g}{N_g + N_e}\right|_{\mathrm{exp}}(\phi) = \frac{1}{\aleph}\sum_{a=1}^{\aleph} n_g^{(a)}(\phi)$



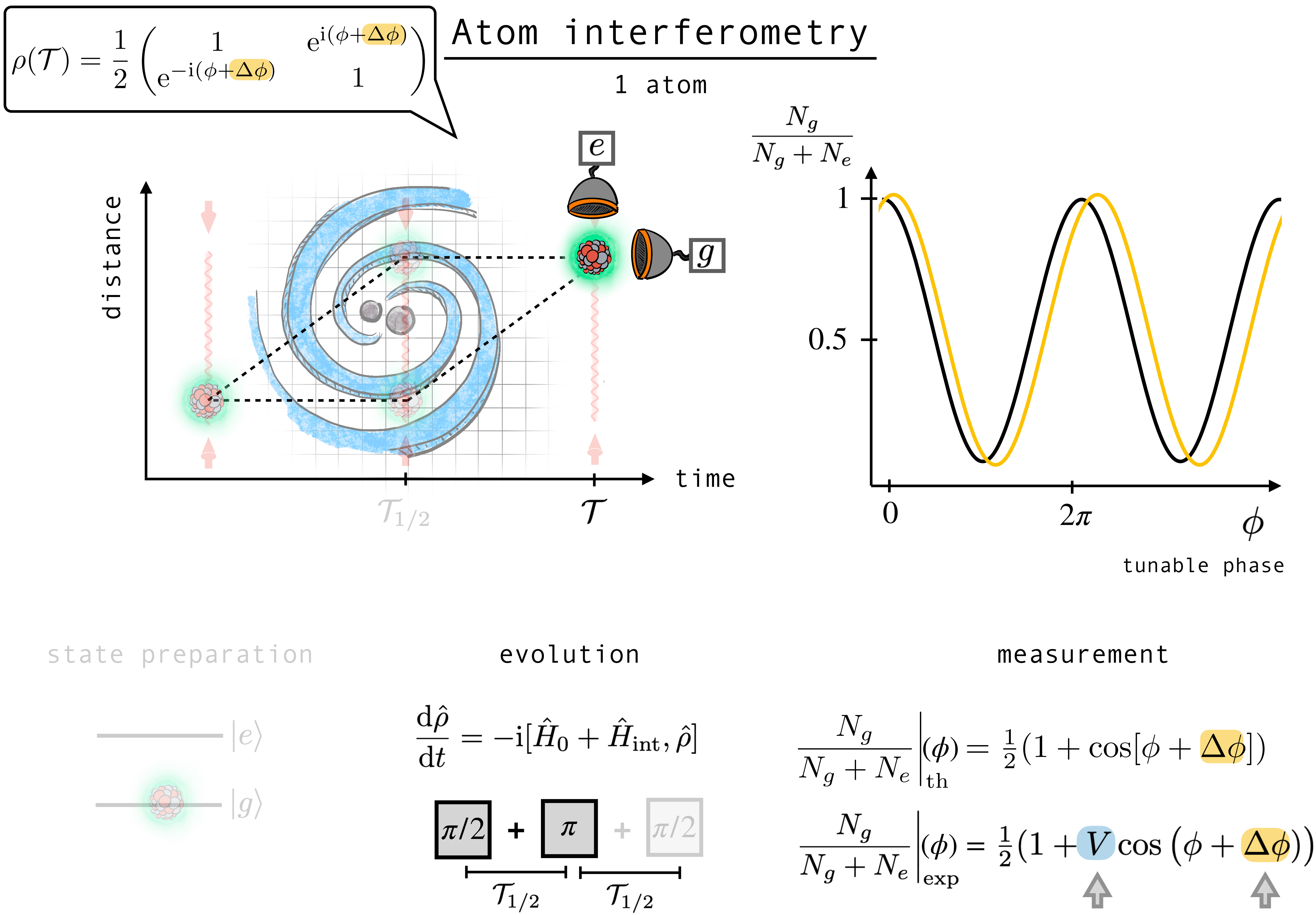
Atom interferometry
1 atom
$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{pmatrix}$
distance
time
e
g
$\mathcal{T}_{1/2}$
$\mathcal{T}$
$\frac{N_g}{N_g + N_e}$
1
0.5
0
2π
ϕ
tunable phase
state preparation
$|e\rangle$
$|g\rangle$
evolution
$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{int}, \hat{\rho}]$
$\pi/2$ + π + $\pi/2$
$\mathcal{T}_{1/2}$
$\mathcal{T}_{1/2}$
measurement
$\left.\frac{N_g}{N_g + N_e}\right|_{exp}(\phi) = \frac{1}{2}\left(1 + V\cos\left(\phi + \Delta\phi\right)\right)$



Atom interferometry
1 atom
ρ(𝒯) = 1/2 (1 e^{iϕ}; e^{−iϕ} 1)
distance
time
𝒯_{1/2}
𝒯
e
g
N_g / (N_g + N_e)
1
0.5
0
2π
ϕ
tunable phase
state preparation
|e⟩
|g⟩
evolution
dρ̂/dt = −i[Ĥ_0 + Ĥ_int, ρ̂]
π/2 + π + π/2
𝒯_{1/2} 𝒯_{1/2}
measurement
N_g/(N_g + N_e)|_th (ϕ) = Tr{ρ(𝒯)|g⟩⟨g|}
N_g/(N_g + N_e)|_exp (ϕ) = 1/2(1 + V cos (ϕ + Δϕ))



Atom interferometry
1 atom
$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & e^{i\phi} \\ e^{-i\phi} & 1 \end{pmatrix}$
distance
time
$\mathcal{T}_{1/2}$
$\mathcal{T}$
e
g
$\frac{N_g}{N_g + N_e}$
1
0.5
0
2π
ϕ
tunable phase
state preparation
$|e\rangle$
$|g\rangle$
evolution
$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{int}, \hat{\rho}]$
$\pi/2$ + π + $\pi/2$
$\mathcal{T}_{1/2}$ $\mathcal{T}_{1/2}$
measurement
$\left.\frac{N_g}{N_g + N_e}\right|_{th}(\phi) = \frac{1}{2}(1 + \cos\phi)$
$\left.\frac{N_g}{N_g + N_e}\right|_{exp}(\phi) = \frac{1}{2}(1 + V\cos(\phi + \Delta\phi))$



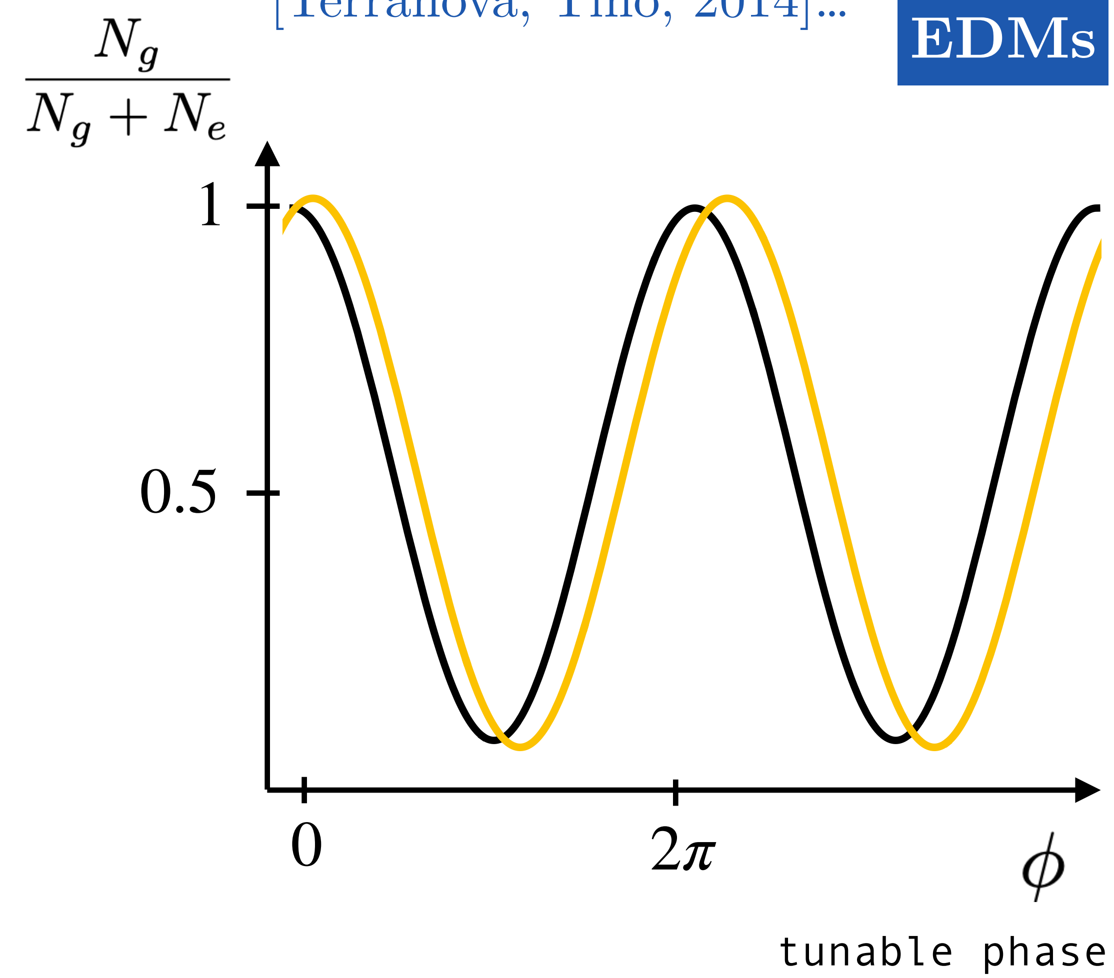
$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & e^{i(\phi+\Delta\phi)} \\ e^{-i(\phi+\Delta\phi)} & 1 \end{pmatrix}$
Atom interferometry
1 atom
distance
time
$\mathcal{T}_{1/2}$
$\mathcal{T}$
e
g
$\frac{N_g}{N_g+N_e}$
1
0.5
0
2π
ϕ
tunable phase
state preparation
$|e\rangle$
$|g\rangle$
evolution
$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{\mathrm{int}}, \hat{\rho}]$
$\pi/2$ + π + $\pi/2$
$\mathcal{T}_{1/2}$
$\mathcal{T}_{1/2}$
measurement
$\left.\frac{N_g}{N_g+N_e}\right|_{\mathrm{th}}(\phi) = \frac{1}{2}(1+\cos[\phi+\Delta\phi])$
$\left.\frac{N_g}{N_g+N_e}\right|_{\mathrm{exp}}(\phi) = \frac{1}{2}(1+V\cos(\phi+\Delta\phi))$

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

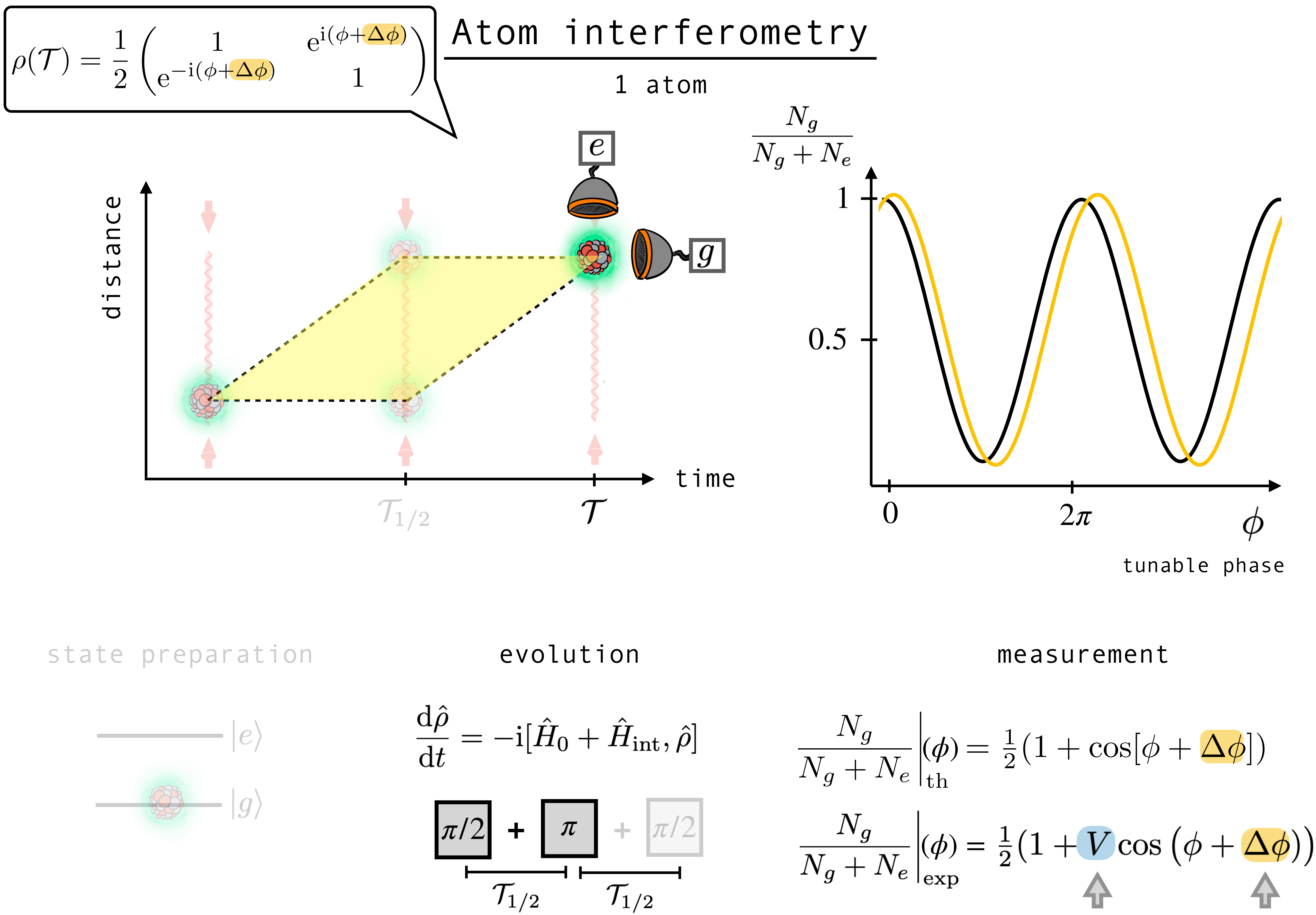


[Graham, Kaplan, et al. 2016] [Arvanitaki, Graham, et al. 2018] [Kolb, Weers, et al. 2018] [Antypas, Banerjee, 2022] [Badurnina, Gipson, et al. 2022] [Badurnina, Beniwal, et al. 2023] ...

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]

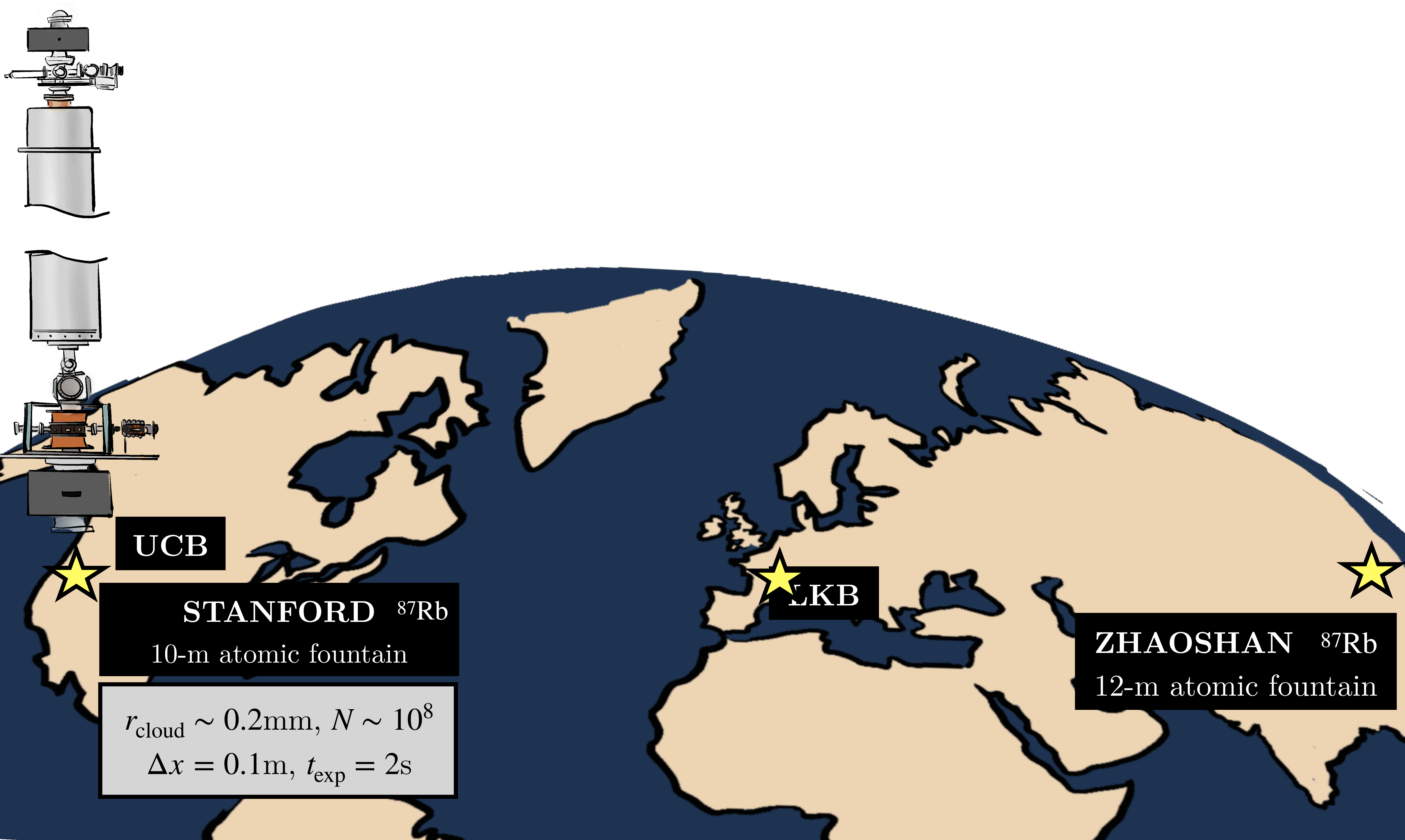
GWs



Atom interferometry
1 atom
$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & e^{i(\phi+\Delta\phi)} \\ e^{-i(\phi+\Delta\phi)} & 1 \end{pmatrix}$
distance
time
$\mathcal{T}_{1/2}$
$\mathcal{T}$
e
g
$\frac{N_g}{N_g+N_e}$
1
0.5
0
2π
ϕ
tunable phase
state preparation
$|e\rangle$
$|g\rangle$
evolution
$\frac{d\hat{\rho}}{dt} = -i[\hat{H}_0 + \hat{H}_{int}, \hat{\rho}]$
$\pi/2$ + π + $\pi/2$
$\mathcal{T}_{1/2}$
$\mathcal{T}_{1/2}$
measurement
$\left.\frac{N_g}{N_g+N_e}\right|_{th}(\phi) = \frac{1}{2}(1+\cos[\phi+\Delta\phi])$
$\left.\frac{N_g}{N_g+N_e}\right|_{exp}(\phi) = \frac{1}{2}(1+V\cos(\phi+\Delta\phi))$

Atom interferometry

Examples – earth based



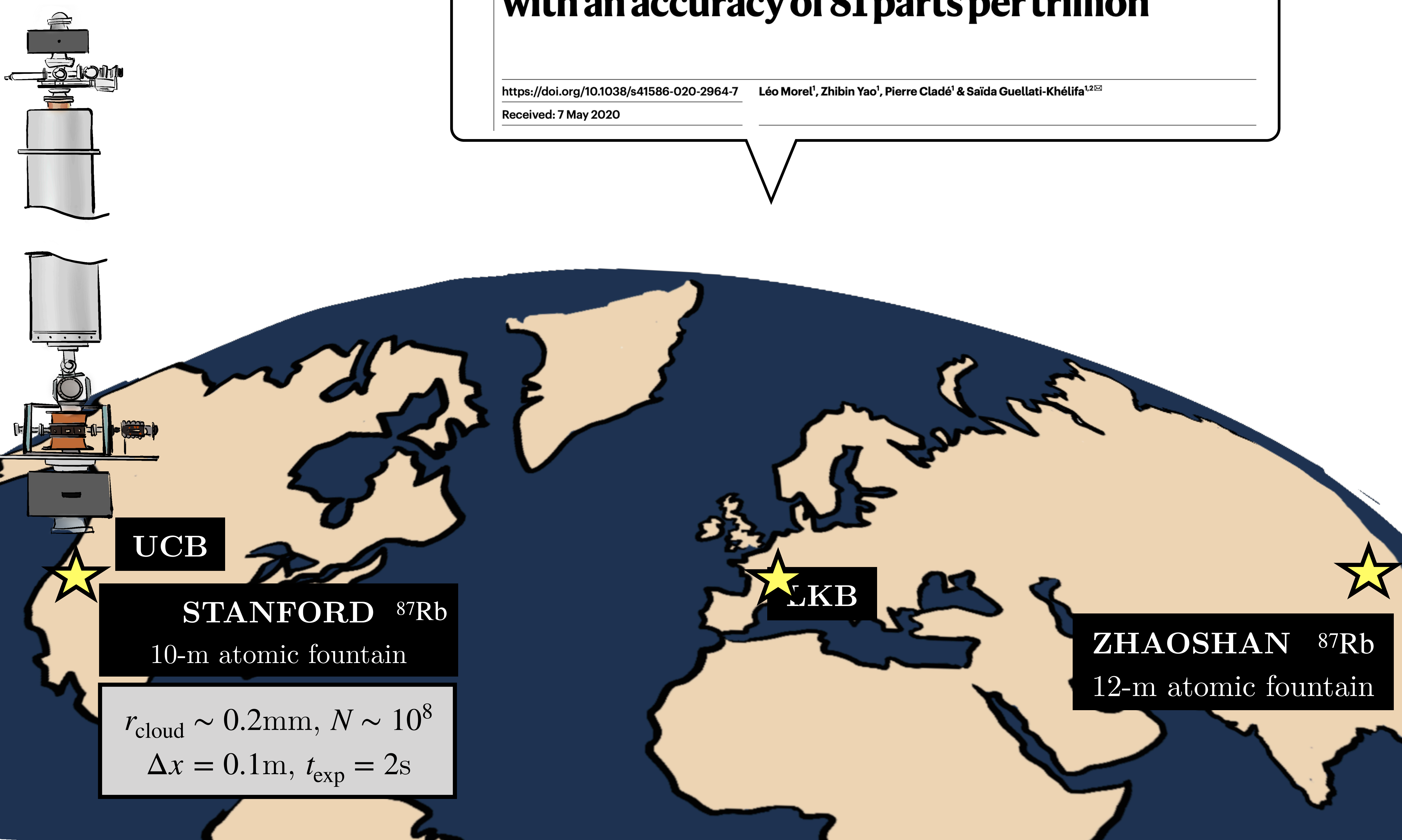
Atom interferometry

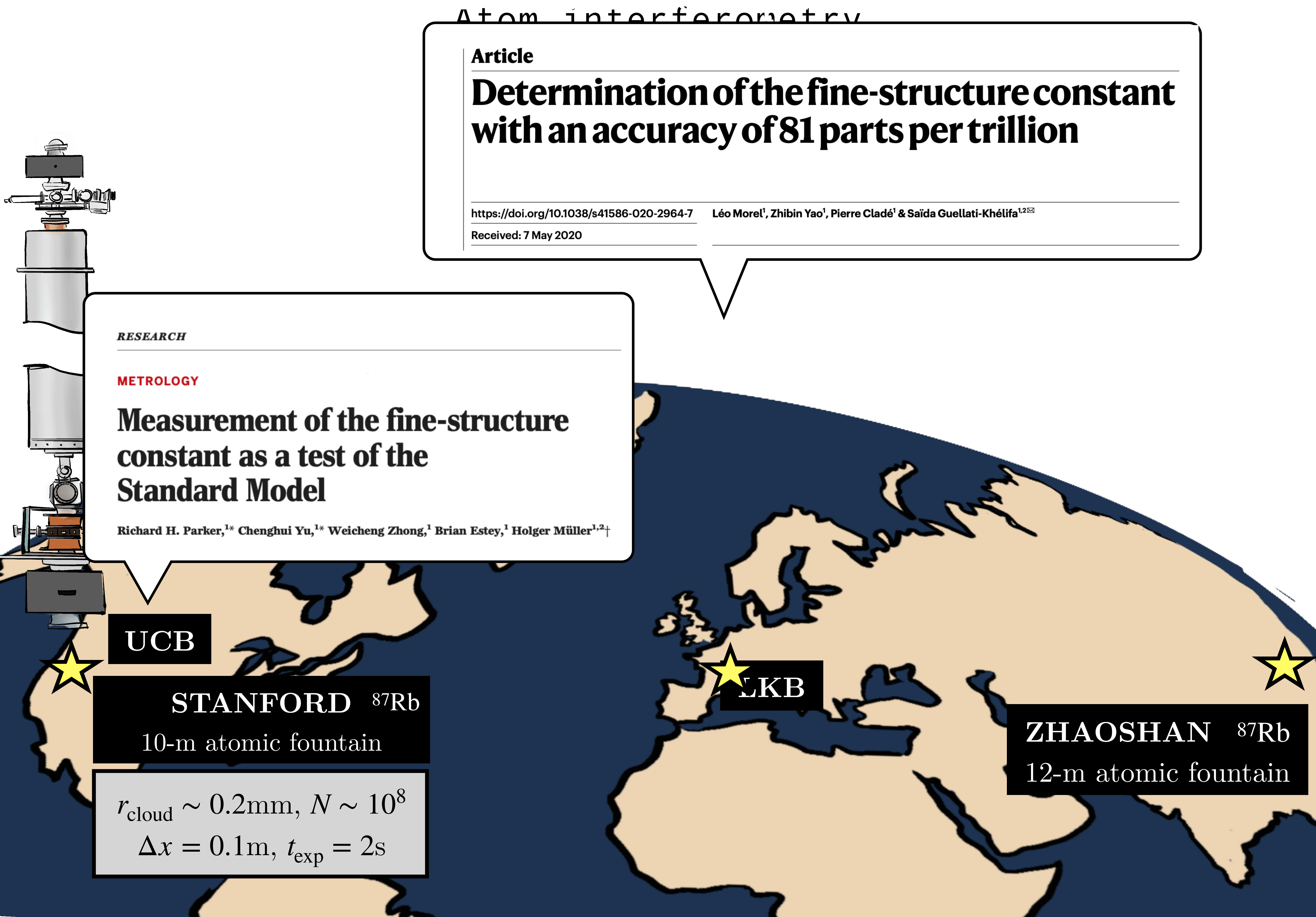
Article

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]✉





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]
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]†
UCB
STANFORD ^{87}Rb
10-m atomic fountain
$r_{\text{cloud}} \sim 0.2\text{mm},\ N \sim 10^8$
$\Delta x = 0.1\text{m},\ t_{\text{exp}} = 2\text{s}$
LKB
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Atom interferometry

Article

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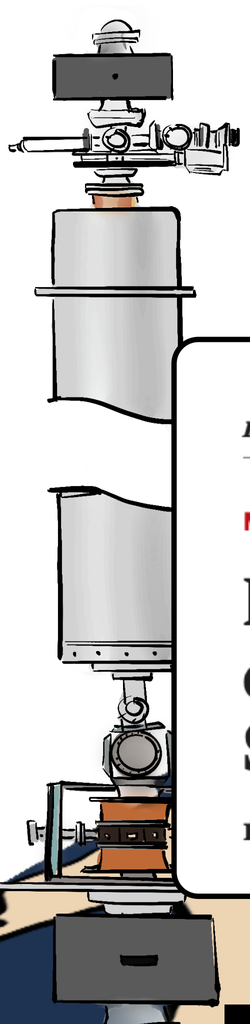


RESEARCH

METROLOGY

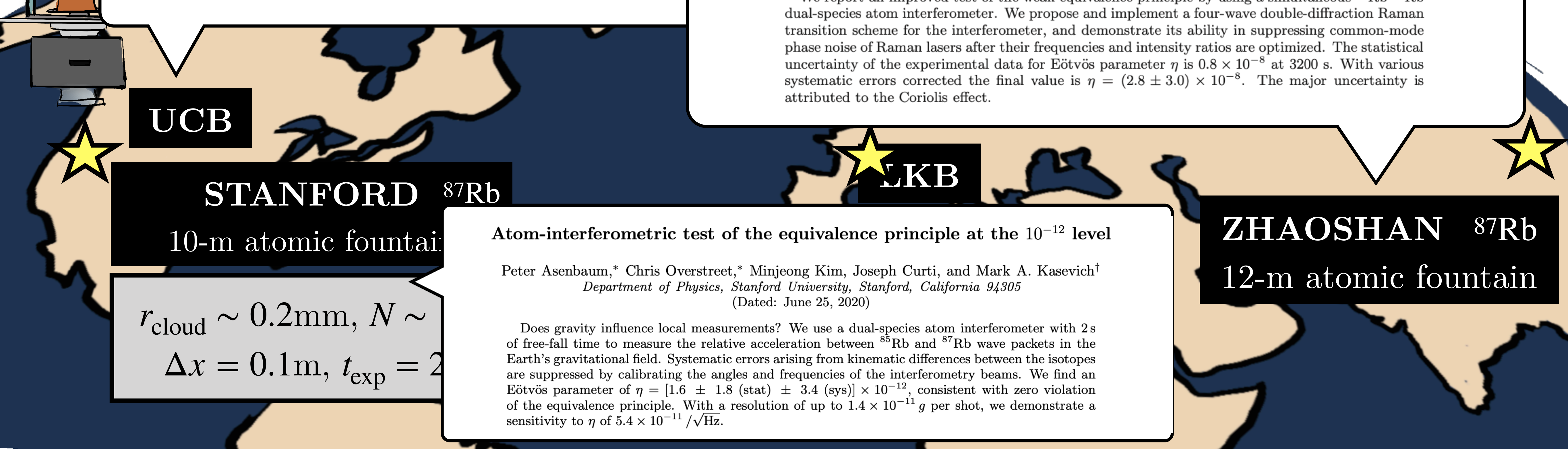
Measurement of the fine-structure constant as a test of the Standard Model

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.



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

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

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)

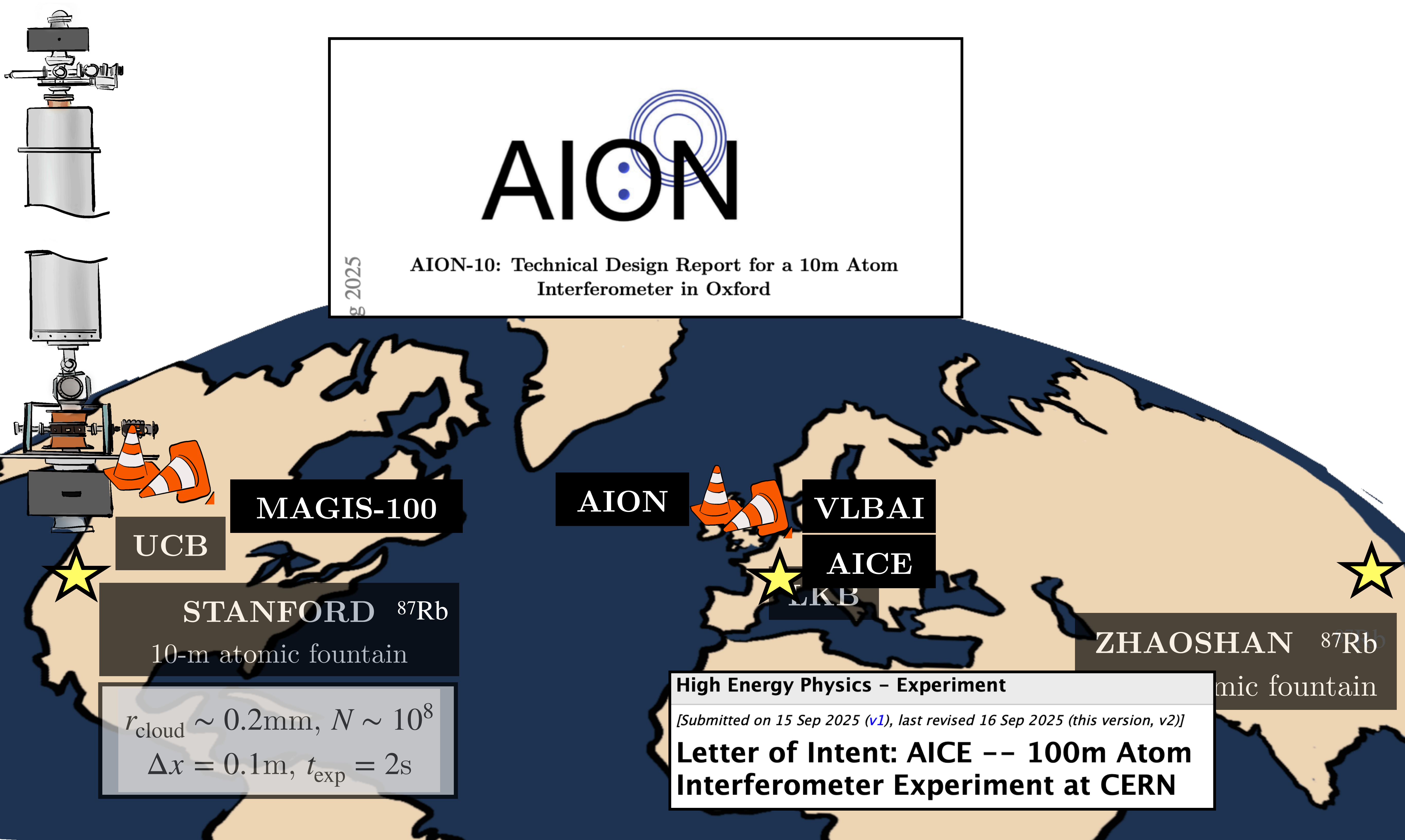
Does gravity influence local measurements? We use a dual-species atom interferometer with 2 s of free-fall time to measure the relative acceleration between ^{85}Rb and ^{87}Rb wave packets in the Earth's gravitational field. Systematic errors arising from kinematic differences between the isotopes are 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 $5.4 \times 10^{-11}\ /\sqrt{\text{Hz}}$.

Atom interferometry

Examples – earth based

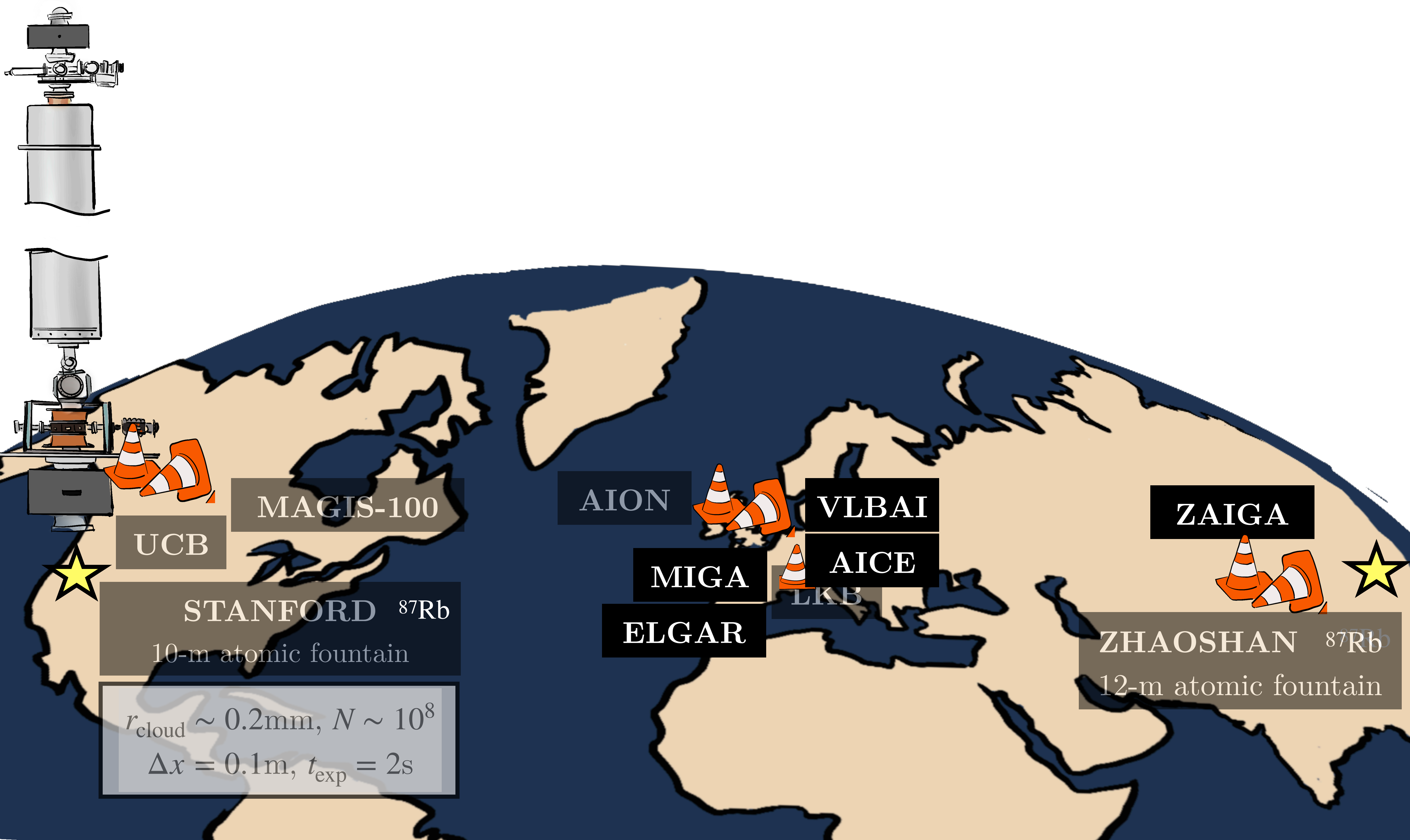
Atom interferometry

Examples – earth based



Atom interferometry

Examples – earth based




Atom interferometry
Examples — space missions
MAGIS-100
UCB
STANFORD ^{87}Rb
10-m atomic fountain
$r_{\text{cloud}} \sim 0.2\text{mm}$, $N \sim 10^8$
$\Delta x = 0.1\text{m}$, $t_{\text{exp}} = 2\text{s}$
AION
VLBAI
MIGA
AICE
LKB
ELGAR
ZAIGA
ZHAOSHAN ^{87}Rb
12-m atomic fountain

Atom interferometry
Examples – space missions
BECCAL
BECCAL
BOSE-EINSTEIN CONDENSATE AND COLD ATOM LABORATORY
NASA
DLR
MAGIS-100
UCB
STANFORD ^{87}Rb
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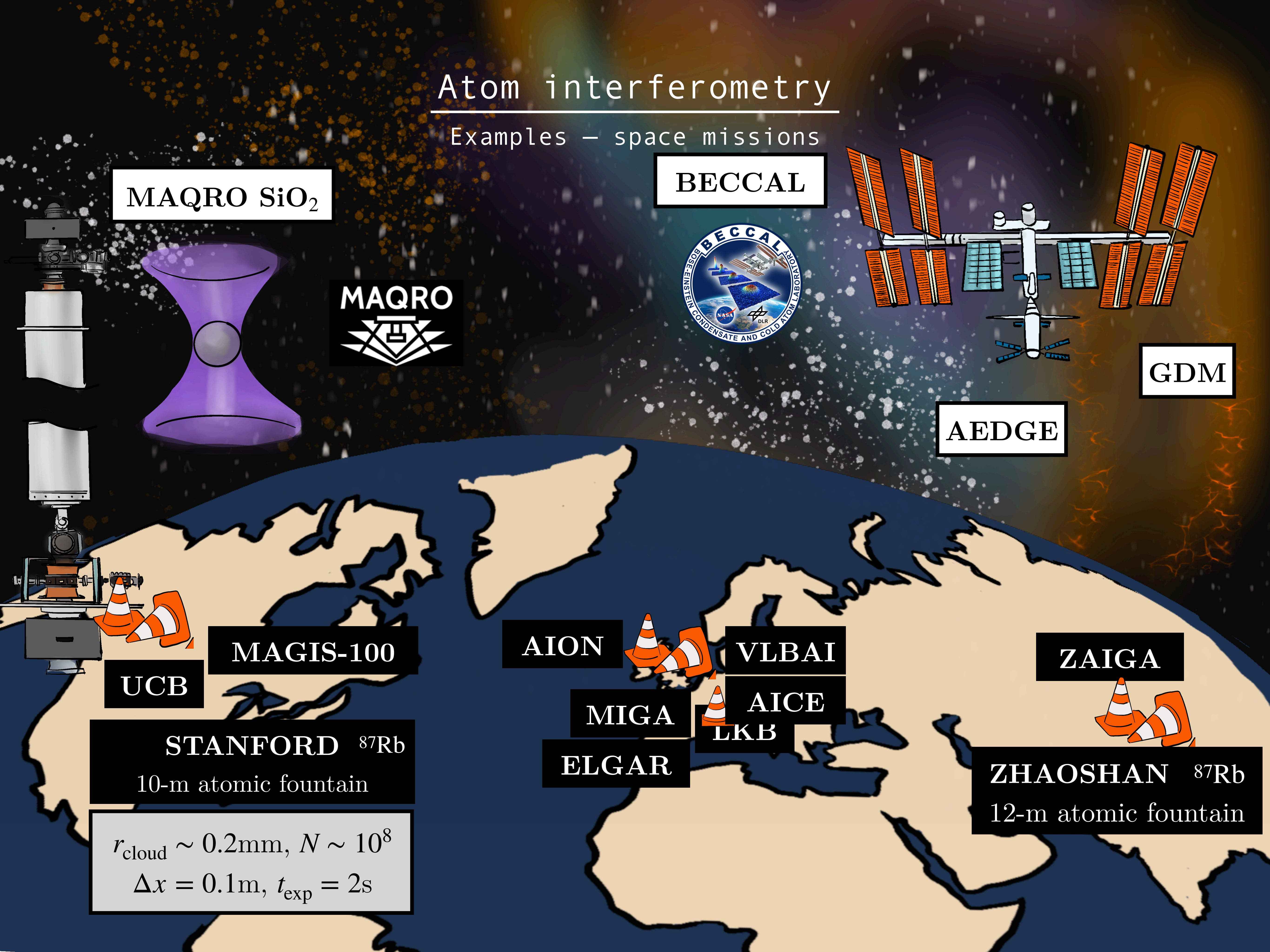
Atom interferometry
Examples – space missions
MAQRO SiO_2
MAQRO
BECCAL
BECCAL
BOSE-EINSTEIN CONDENSATE AND COLD ATOM LABORATORY
NASA
DLR
GDM
AEDGE
MAGIS-100
UCB
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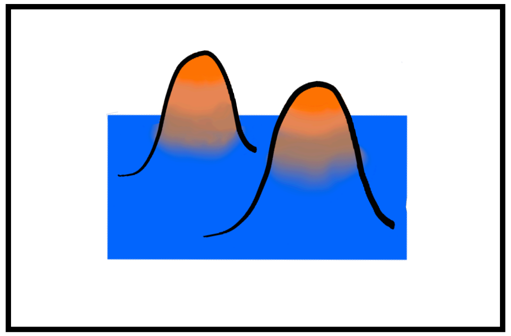
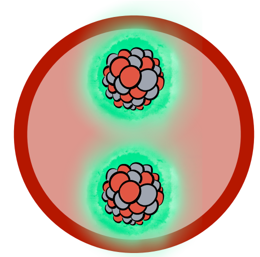


Atom interferometers
as open quantum systems

[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

Worked out the effect of particle scattering on a **single object** (e.g. atom) spatial quantum superposition.



Internal state (energy, spin…)

$$|\Psi\rangle_S = \frac{1}{\sqrt{2}}\left(|s,\mathbf{x}\rangle + \mathrm{e}^{\mathrm{i}\phi}|s',\mathbf{x}'\rangle\right)$$

interferometer's path

time

[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

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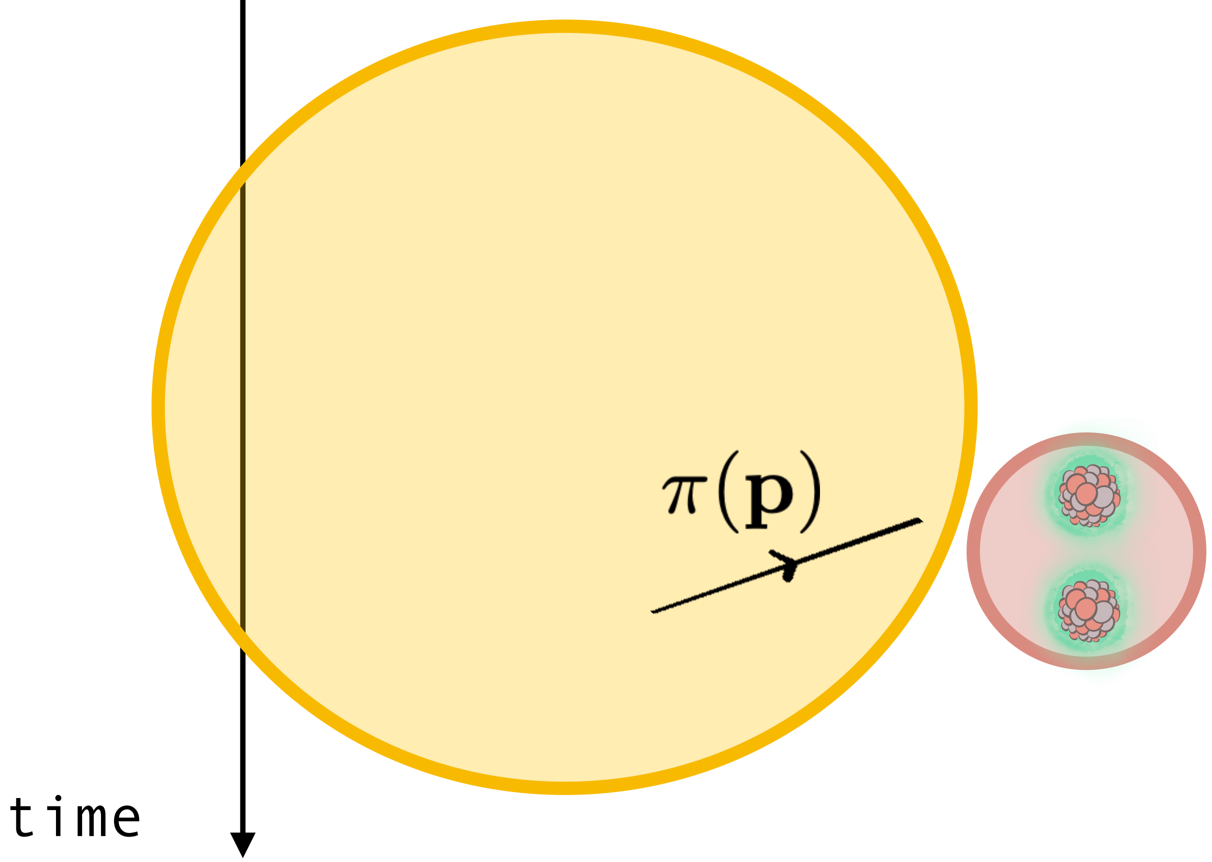

$$|\Psi\rangle_S = \frac{1}{\sqrt{2}}\left(|s, \mathbf{x}\rangle + \mathrm{e}^{\mathrm{i}\phi}|s', \mathbf{x}'\rangle\right)$$

$$\frac{\mathrm{d}^2\Phi}{\mathrm{d}p\,\mathrm{d}\Omega_p}$$

⇨ stationary background

[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

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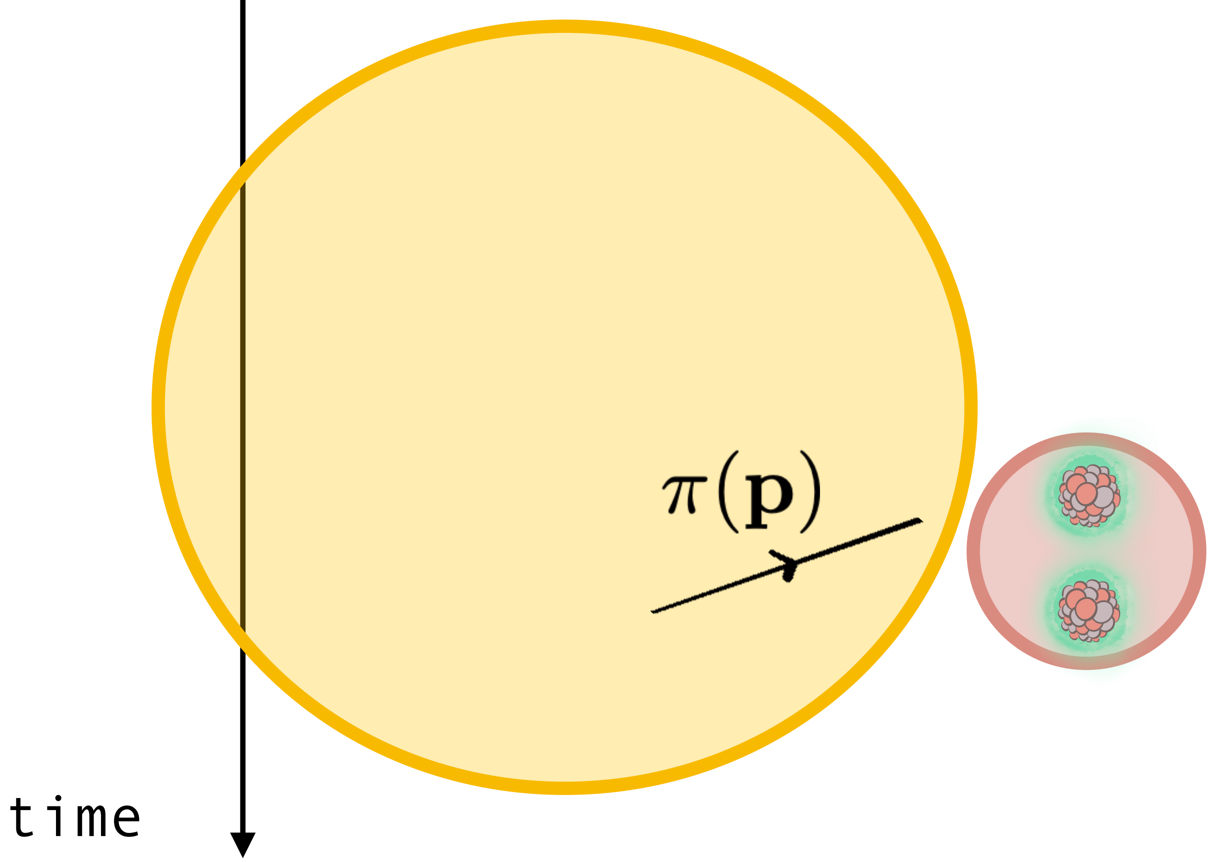

$$|\Psi\rangle_S \otimes |\mathbf{p}\rangle$$

$$|\Psi\rangle_S = \frac{1}{\sqrt{2}}\left(|s, \mathbf{x}\rangle + \mathrm{e}^{\mathrm{i}\phi}|s', \mathbf{x}'\rangle\right)$$

- system & environment initially uncorrelated
- stationary background

$$\frac{\mathrm{d}^2\Phi}{\mathrm{d}p\,\mathrm{d}\Omega_p}$$

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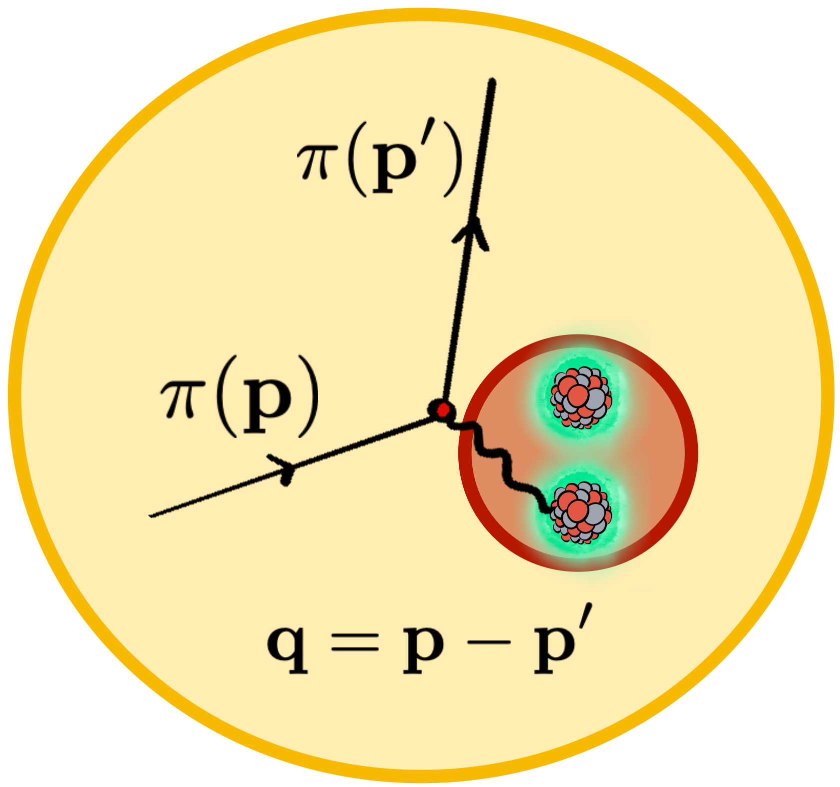

$$S(|\Psi\rangle_S \otimes |\mathbf{p}\rangle)$$

time

- system & environment initially uncorrelated
- stationary background
- Markovian regime

[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

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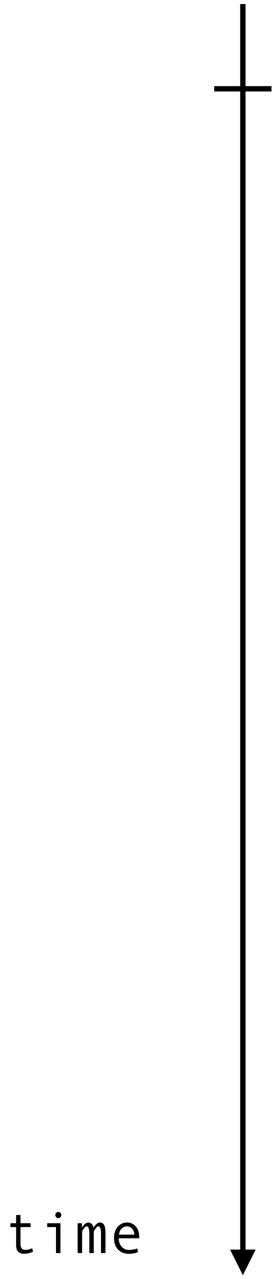
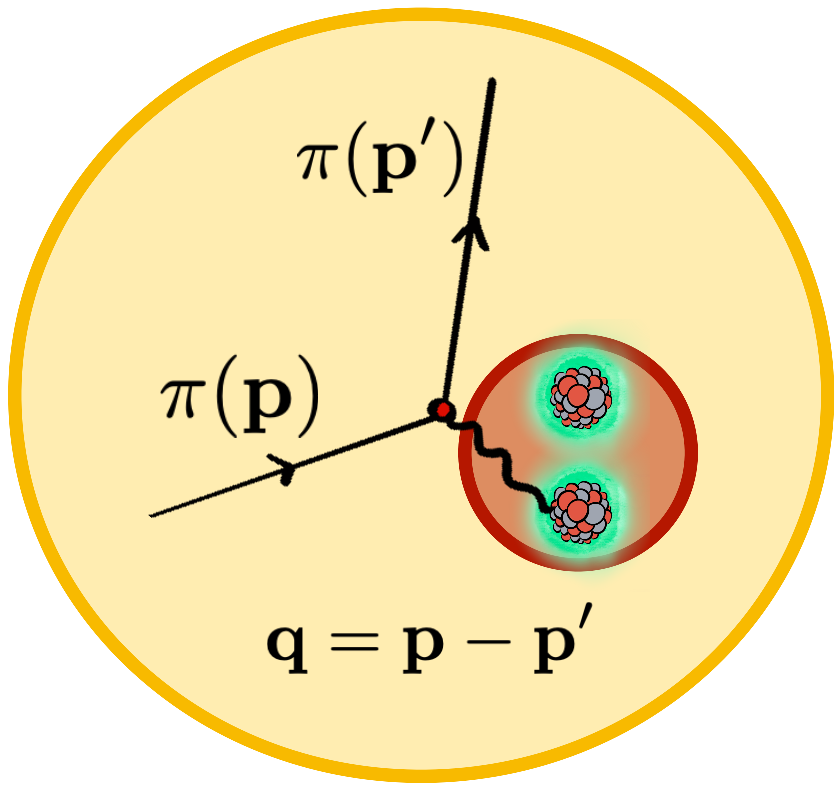




$$S(|\Psi\rangle_S \otimes |\mathbf{p}\rangle) = |\Psi\rangle_S \otimes S_{\mathbf{x}}|\mathbf{p}\rangle$$

- system & environment initially uncorrelated
- stationary background
- Markovian regime
- Recoiless regime

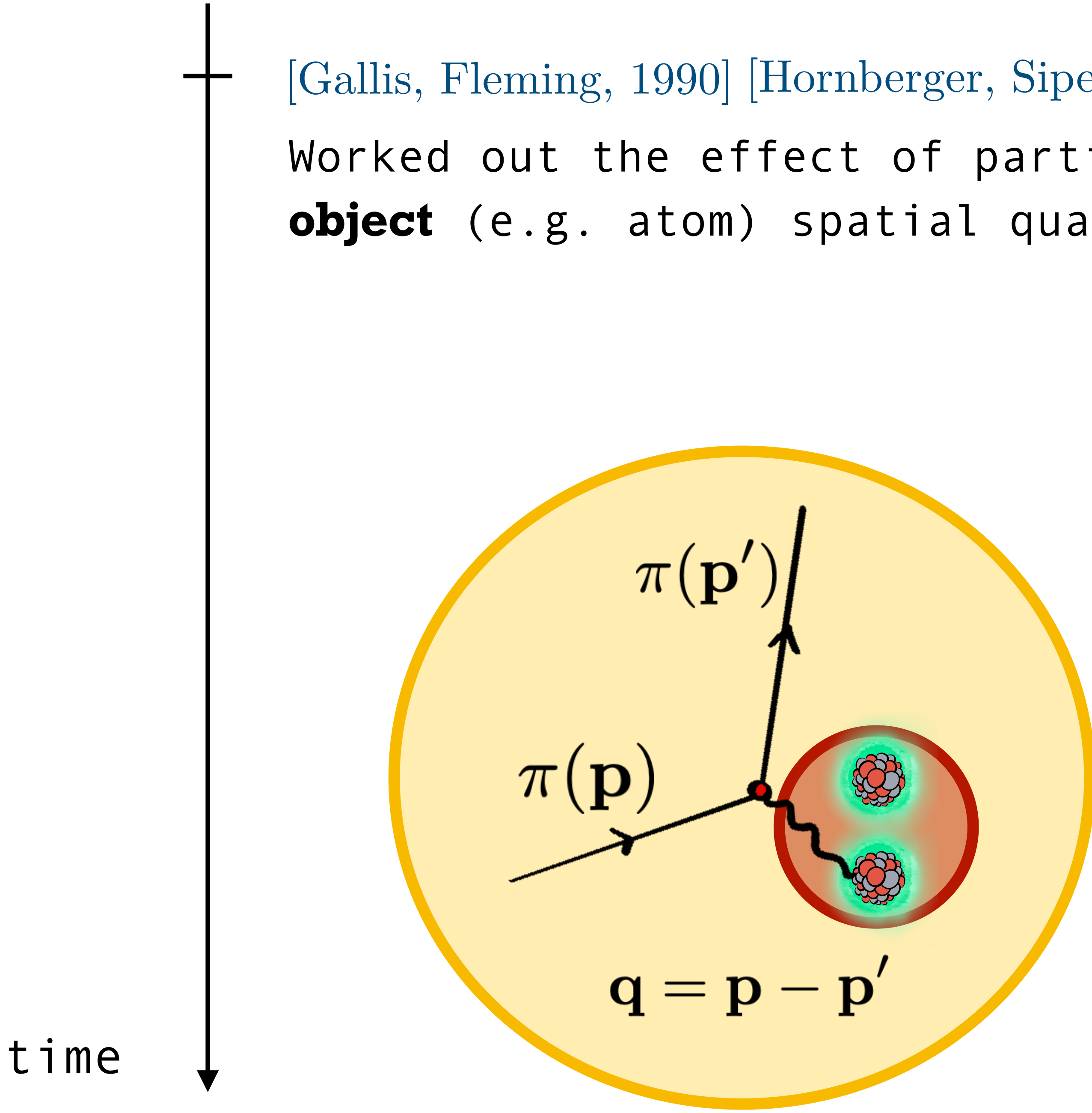
[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

Worked out the effect of particle scattering on a **single object** (e.g. atom) spatial quantum superposition.

$$S = \mathbb{I} + \mathrm{i}T$$

$$S(|\Psi\rangle_S \otimes |\mathbf{p}\rangle) = |\Psi\rangle_S \otimes S_{\mathbf{x}}|\mathbf{p}\rangle$$

$$\langle \mathbf{p}'|T_{\mathbf{x}}|\mathbf{p}\rangle = (2\pi)\delta(E' - E)\mathcal{M}_{\mathbf{x}}(\mathbf{p}', \mathbf{p})$$



[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

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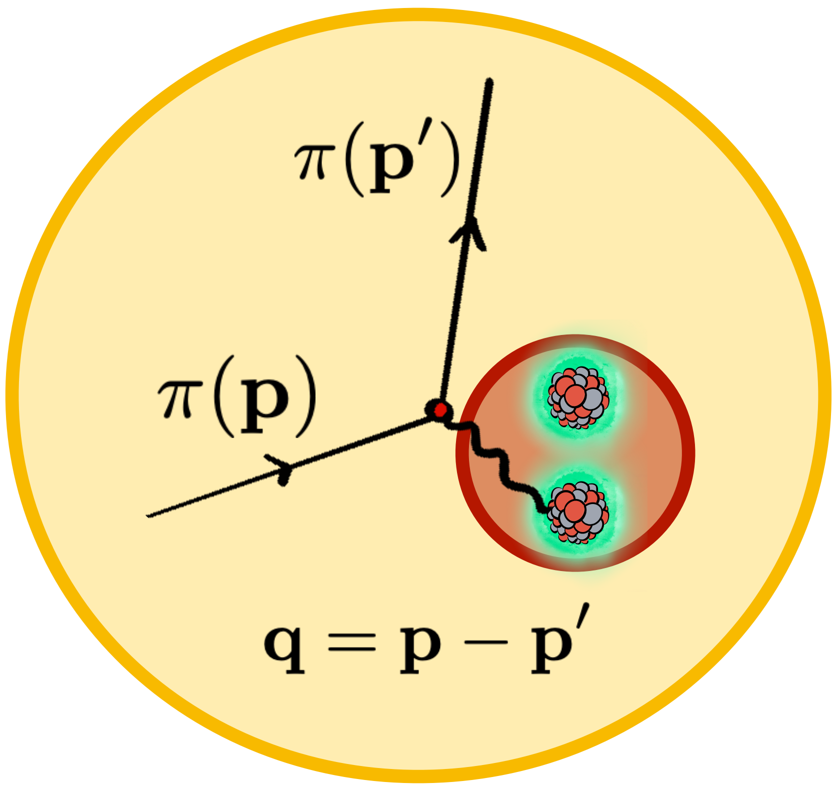
$$T = gT^{(1)} + g^2 T^{(2)} + \mathcal{O}(g^3) \qquad S = \mathbb{I} + \mathrm{i}T$$

$$S(|\Psi\rangle_S \otimes |\mathbf{p}\rangle) = |\Psi\rangle_S \otimes S_{\mathbf{x}}|\mathbf{p}\rangle$$



$$\langle \mathbf{p}'|T_{\mathbf{x}}|\mathbf{p}\rangle = (2\pi)\delta(E' - E)\mathcal{M}_{\mathbf{x}}(\mathbf{p}', \mathbf{p})$$

$$n\,a^3 \ll 1 \qquad \mathcal{M}^{(1)}_{\mathbf{x}}(\mathbf{p}', \mathbf{p}) = \tilde{V}(\mathbf{q})\mathrm{e}^{\mathrm{i}\mathbf{q}\cdot\mathbf{x}}$$

dilute Born approximation

time

[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

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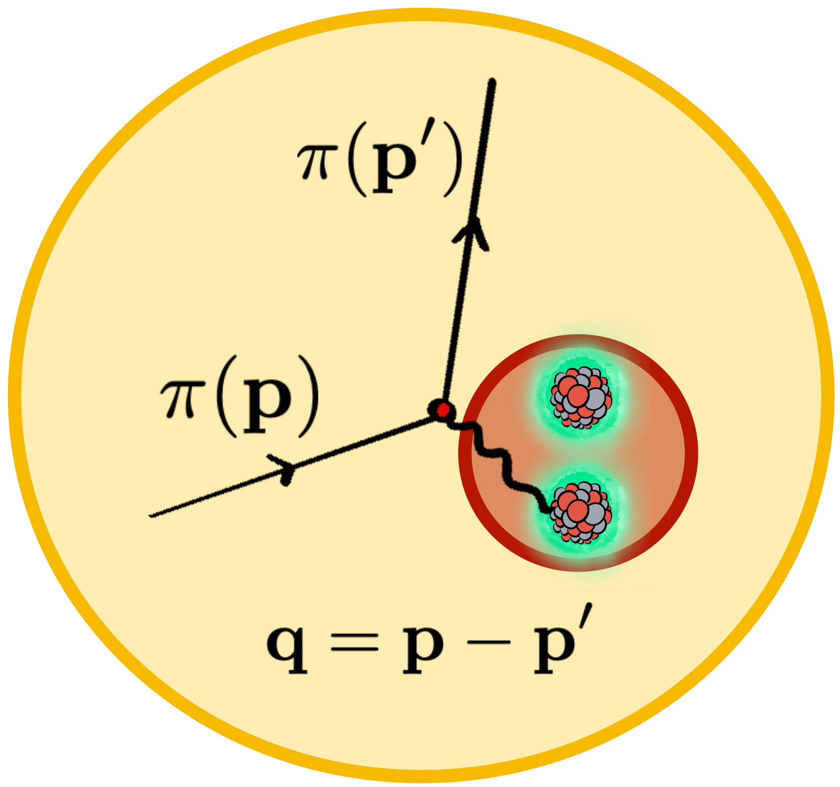

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dilute Born approximation

$$\hat{T}_{\mathbf{x}} = \mathrm{e}^{-\mathrm{i}\hat{\mathbf{k}}\cdot\mathbf{x}}\, \hat{T}_0\, \mathrm{e}^{\mathrm{i}\hat{\mathbf{k}}\cdot\mathbf{x}}$$

time

[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

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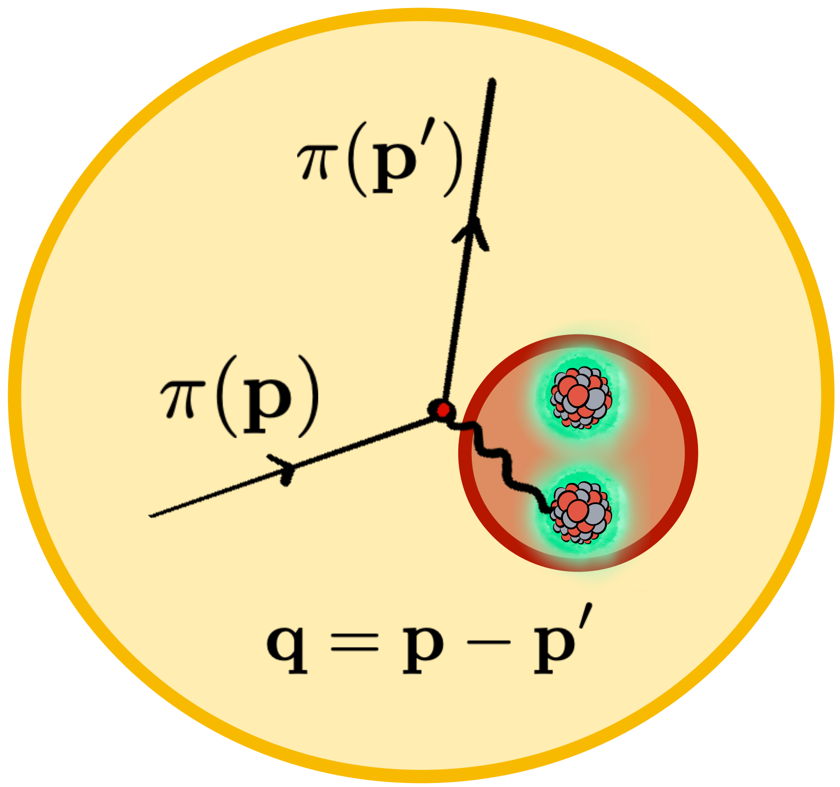

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`time`

$$\rho \to \rho' = S\,\rho\,S^{\dagger}$$

$$\Delta\rho = \tfrac{\mathrm{i}}{2}\left[T + T^{\dagger}, \rho\right] + \tfrac{\mathrm{i}}{2}\left\{T - T^{\dagger}, \rho\right\} + T\rho T^{\dagger}$$

[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

Worked out the effect of particle scattering on a **single object** (e.g. atom) spatial quantum superposition.

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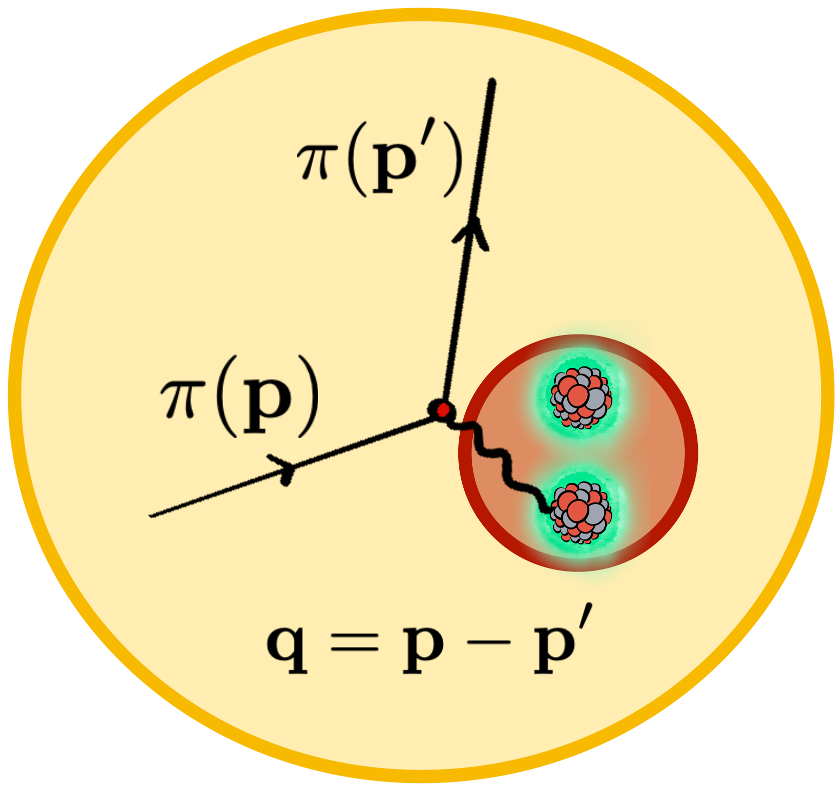

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dilute Born approximation

$$\hat{T}_{\mathbf{x}} = \mathrm{e}^{-\mathrm{i}\hat{\mathbf{k}}\cdot\mathbf{x}}\, \hat{T}_0\, \mathrm{e}^{\mathrm{i}\hat{\mathbf{k}}\cdot\mathbf{x}}$$

time

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$$\begin{aligned} \Delta\rho &= \tfrac{\mathrm{i}}{2}\left[T + T^\dagger, \rho\right] + \tfrac{\mathrm{i}}{2}\left\{T - T^\dagger, \rho\right\} + T\rho T^\dagger \\ &= \tfrac{\mathrm{i}}{2}\left[T + T^\dagger, \rho\right] - \tfrac{1}{2}\left\{T^\dagger T, \rho\right\} + T\rho T^\dagger \,, \end{aligned}$$

[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

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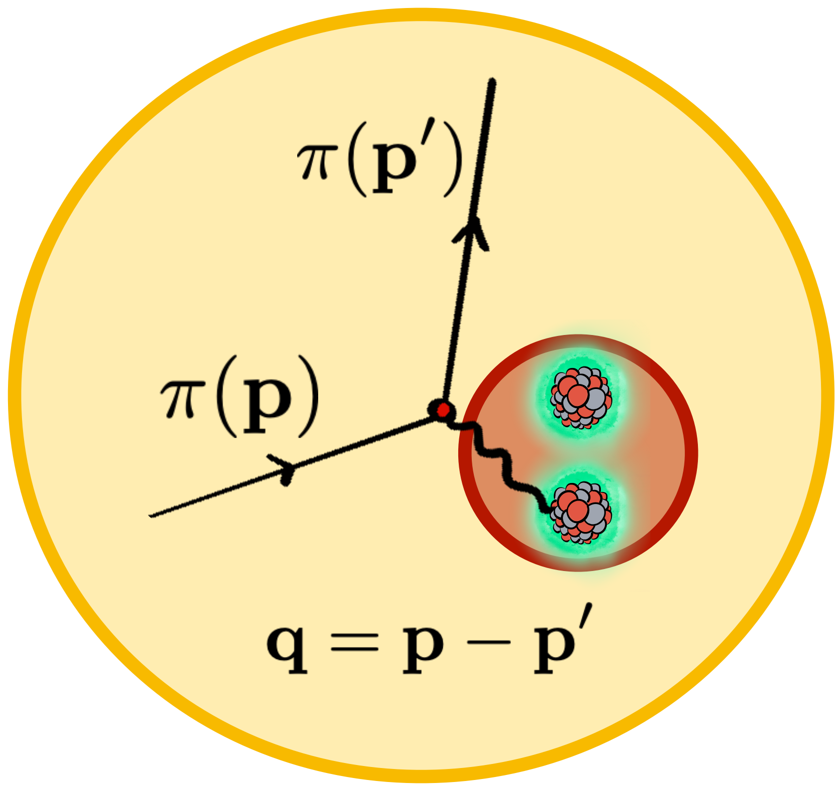

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dilute Born approximation

$$\hat{T}_{\mathbf{x}} = \mathrm{e}^{-\mathrm{i}\hat{\mathbf{k}}\cdot\mathbf{x}}\,\hat{T}_0\,\mathrm{e}^{\mathrm{i}\hat{\mathbf{k}}\cdot\mathbf{x}}$$

time

$$\Delta\rho_A(\{\mathbf{x}\},\{\mathbf{x}'\}) = \rho_A(\{\mathbf{x}\},\{\mathbf{x}'\}) \int \frac{\mathrm{d}^3 p}{(2\pi)^3}\, \rho_\pi(\mathbf{p}) \Big(\tfrac{\mathrm{i}}{2}\langle \mathbf{p}| \big(\cancelto{0}{T_{\{\mathbf{x}\}} + T^\dagger_{\{\mathbf{x}\}} - T_{\{\mathbf{x}'\}} - T^\dagger_{\{\mathbf{x}'\}}}\big)|\mathbf{p}\rangle$$
$$- \tfrac{1}{2}\langle \mathbf{p}| \Big(T_{\{\mathbf{x}\}}T^\dagger_{\{\mathbf{x}\}} + T_{\{\mathbf{x}'\}}T^\dagger_{\{\mathbf{x}'\}}\Big)|\mathbf{p}\rangle$$
$$+ \langle \mathbf{p}| T^\dagger_{\{\mathbf{x}'\}} T_{\{\mathbf{x}\}}|\mathbf{p}\rangle \Big)$$

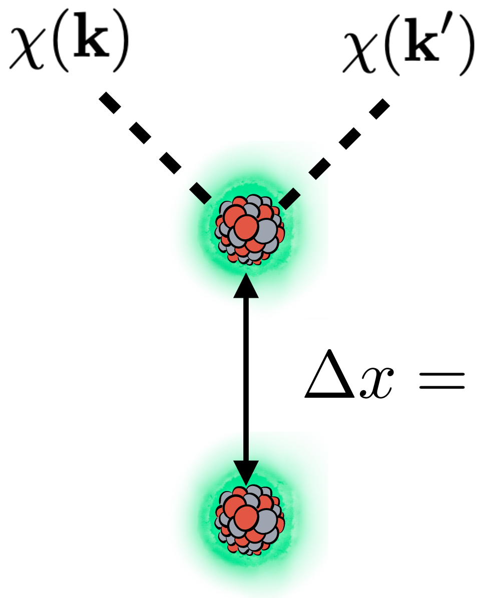
[Badurina, CM, Plestid, 24]

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

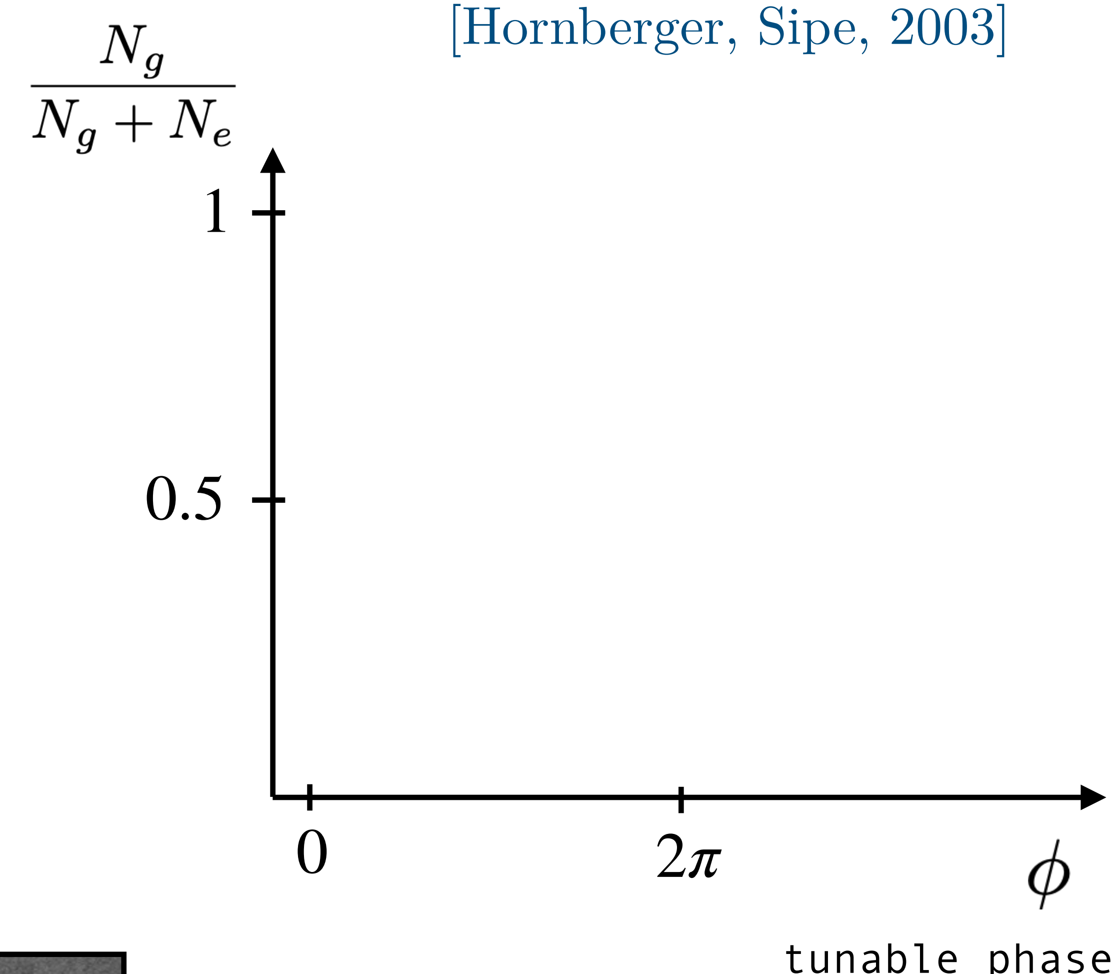
Atom interferometry

1 atom

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



$$\Delta x = \frac{k}{m_A} t$$



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

Decoherence Kernel

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

AI env

method of characteristics

$$\rho(x, x'; s, s'; \mathcal{T}) = \rho(x_0, x_0')\rho_s(s, s')e^{i\tilde{\Phi}(s,s')}\exp\left[-\int_0^{\mathcal{T}} \mathrm{d}t\, \lambda(\mathbf{x_s}(t), \mathbf{x}_{\mathbf{s}}'(t))\right]$$

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

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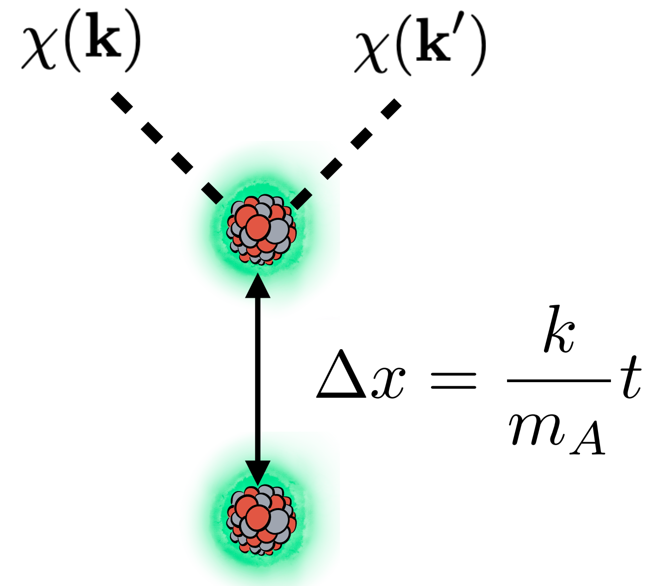

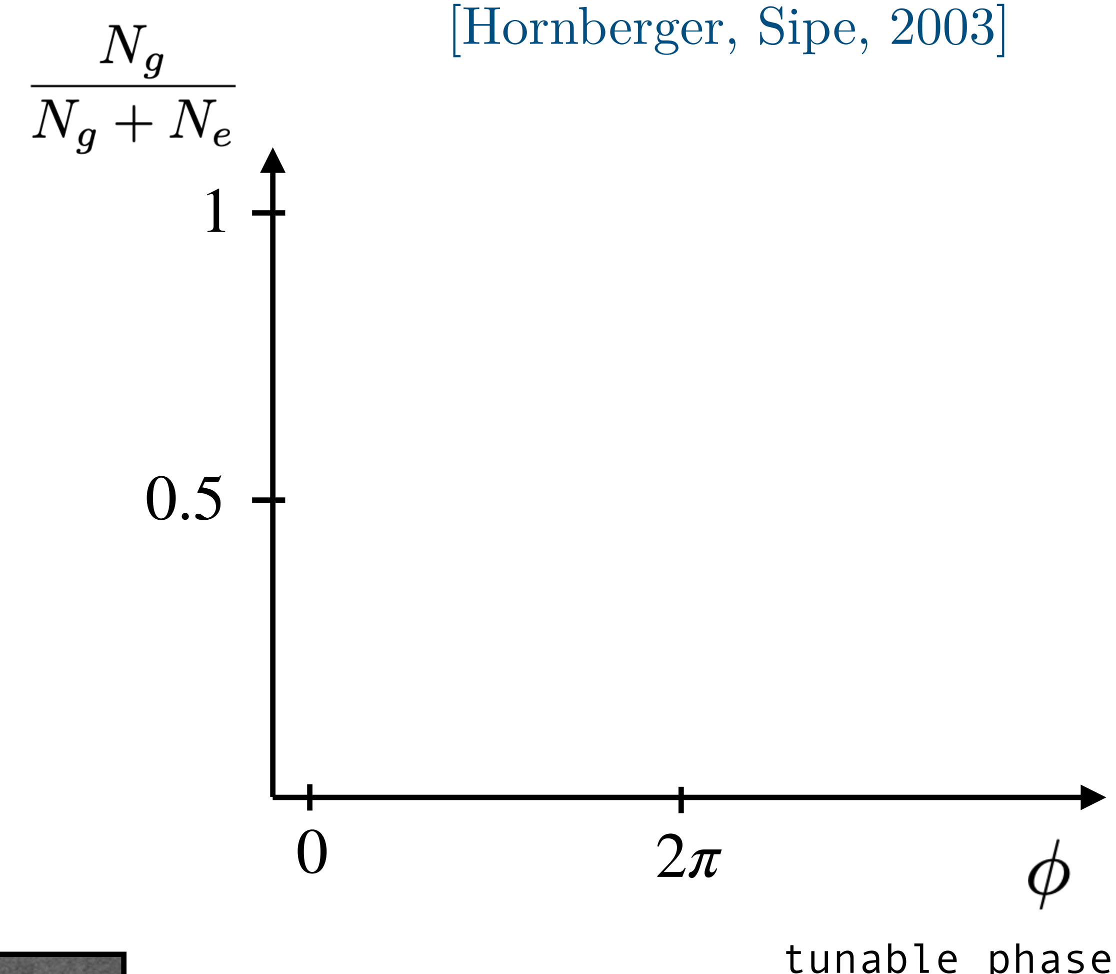

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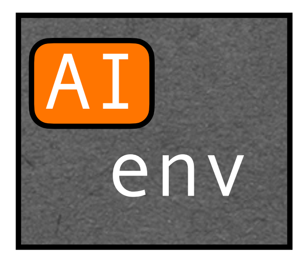

measurement

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

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

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

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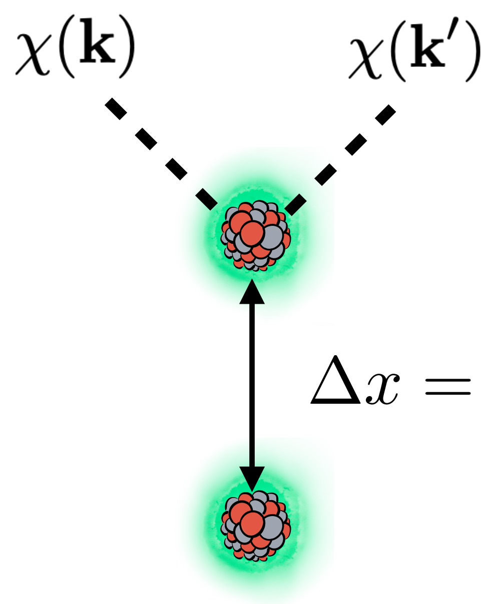

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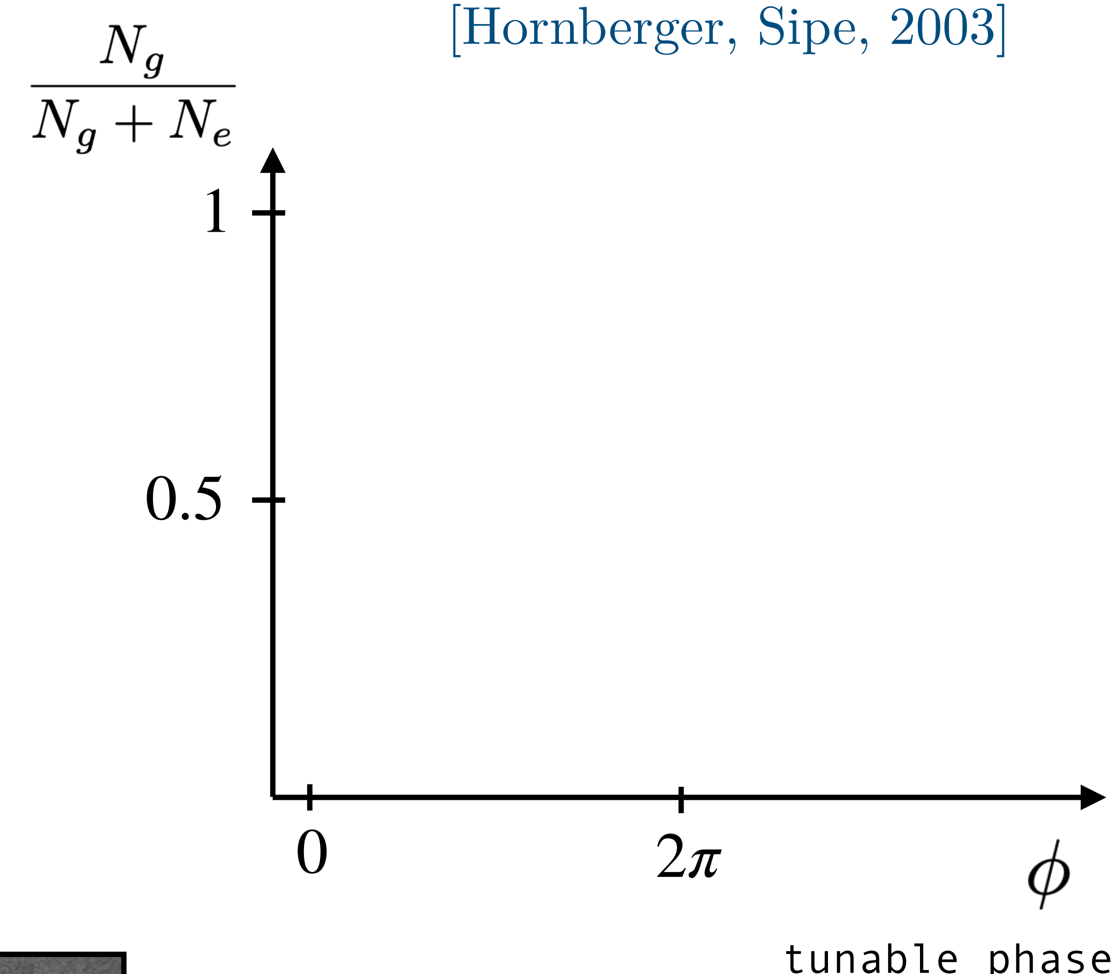

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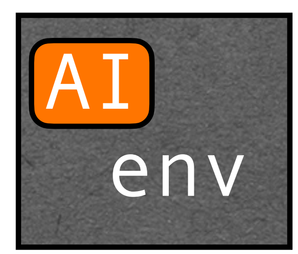
Decoherence Kernel

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



measurement

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

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

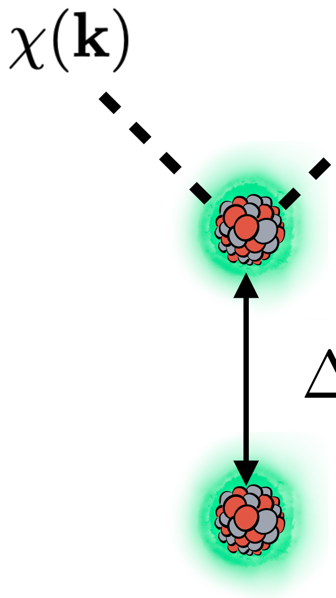
$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix}$$

Atom interferometry

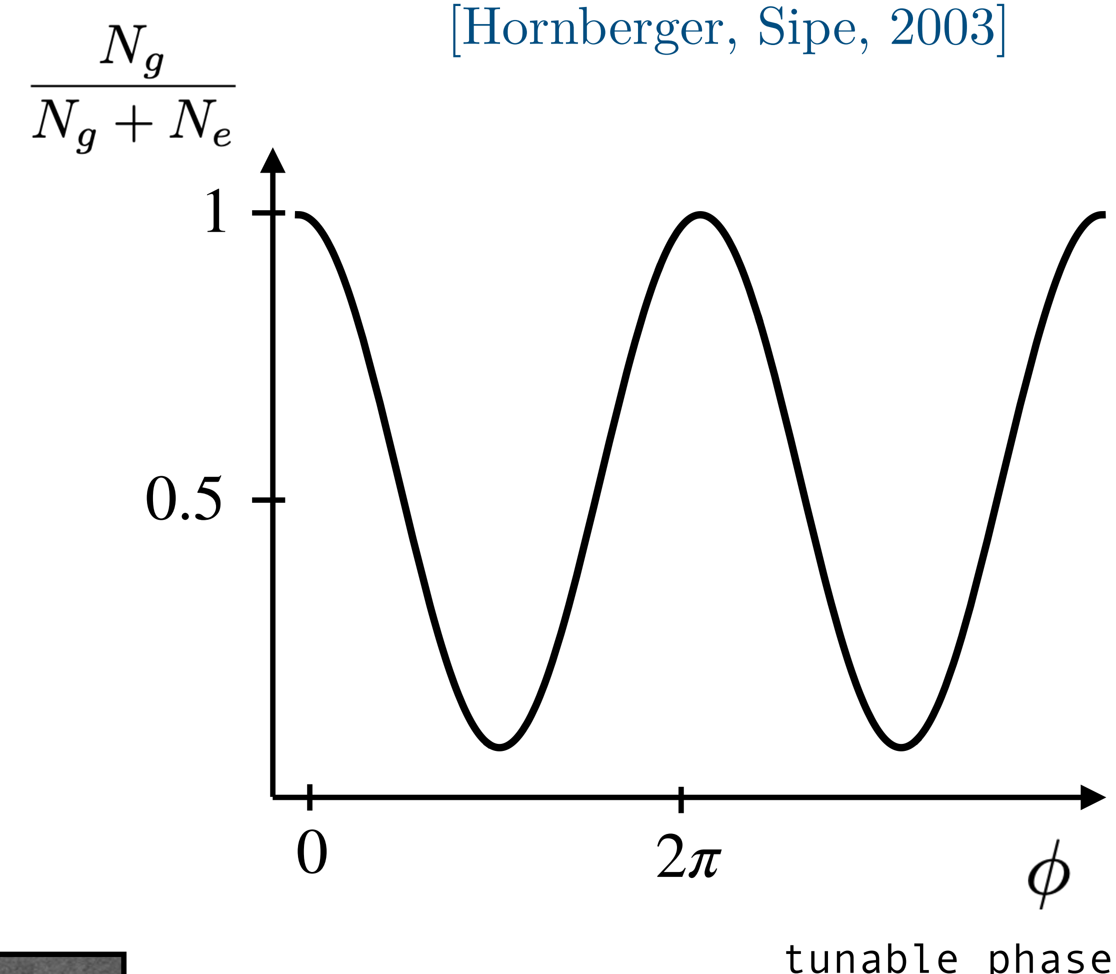
1 atom

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

1 $\Gamma \to 0$



$$\Delta x = \frac{k}{m_A} t$$



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

Decoherence Kernel

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

AI env

measurement

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

0 0

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

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

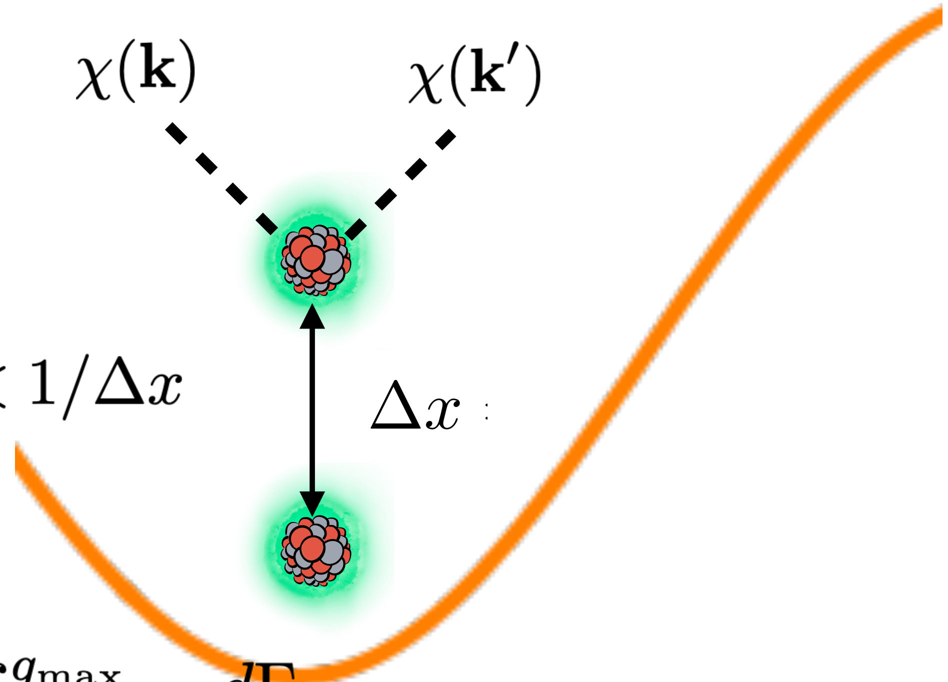
Atom interferometry

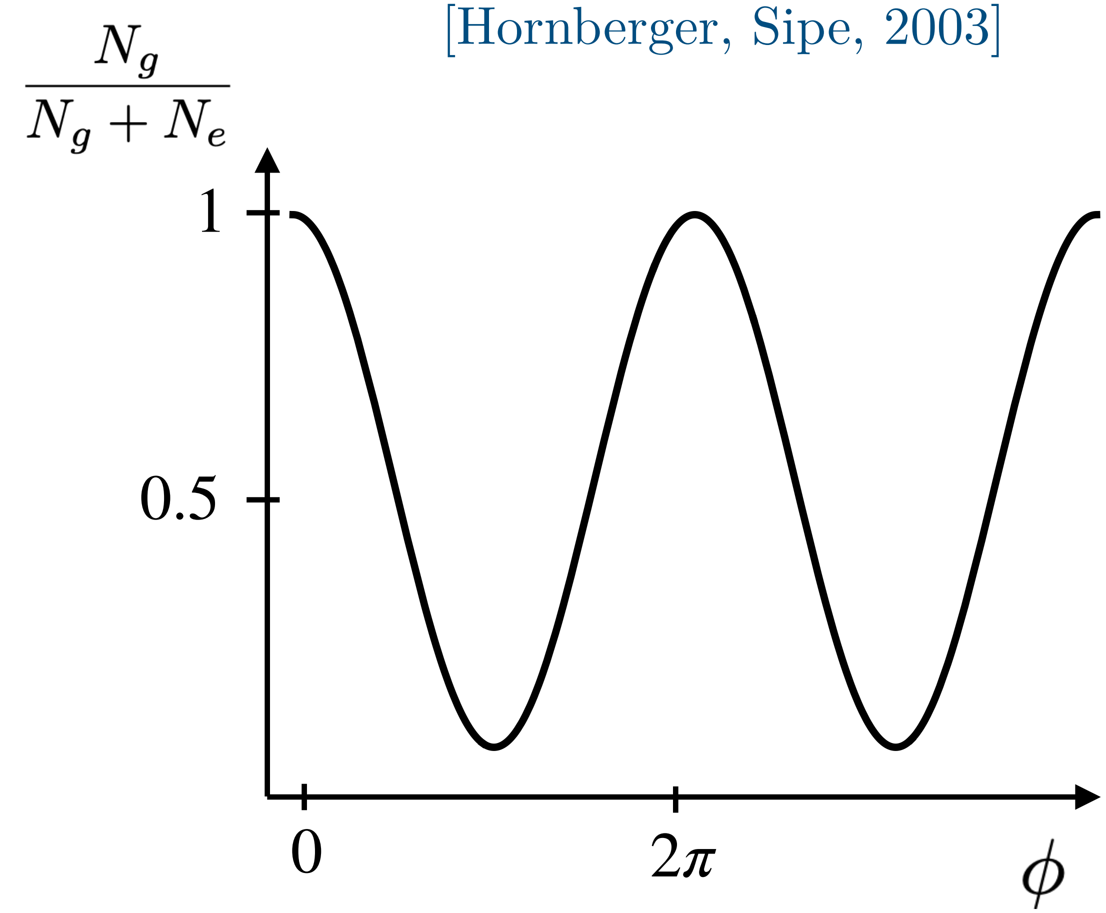
1 atom

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

1 $\Gamma \to 0$

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





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

Decoherence Kernel

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

AI env

measurement

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

0 0

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

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Atom interferometry

1 atom

[Joss, Zeh, 1985]
[Gallis, Fleming, 1990]
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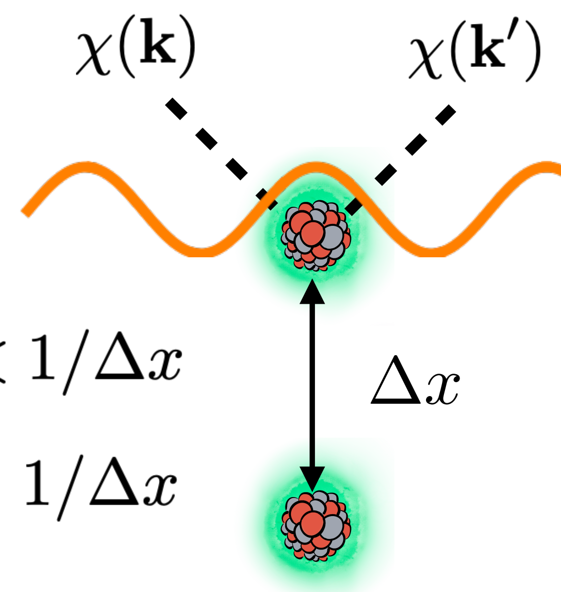
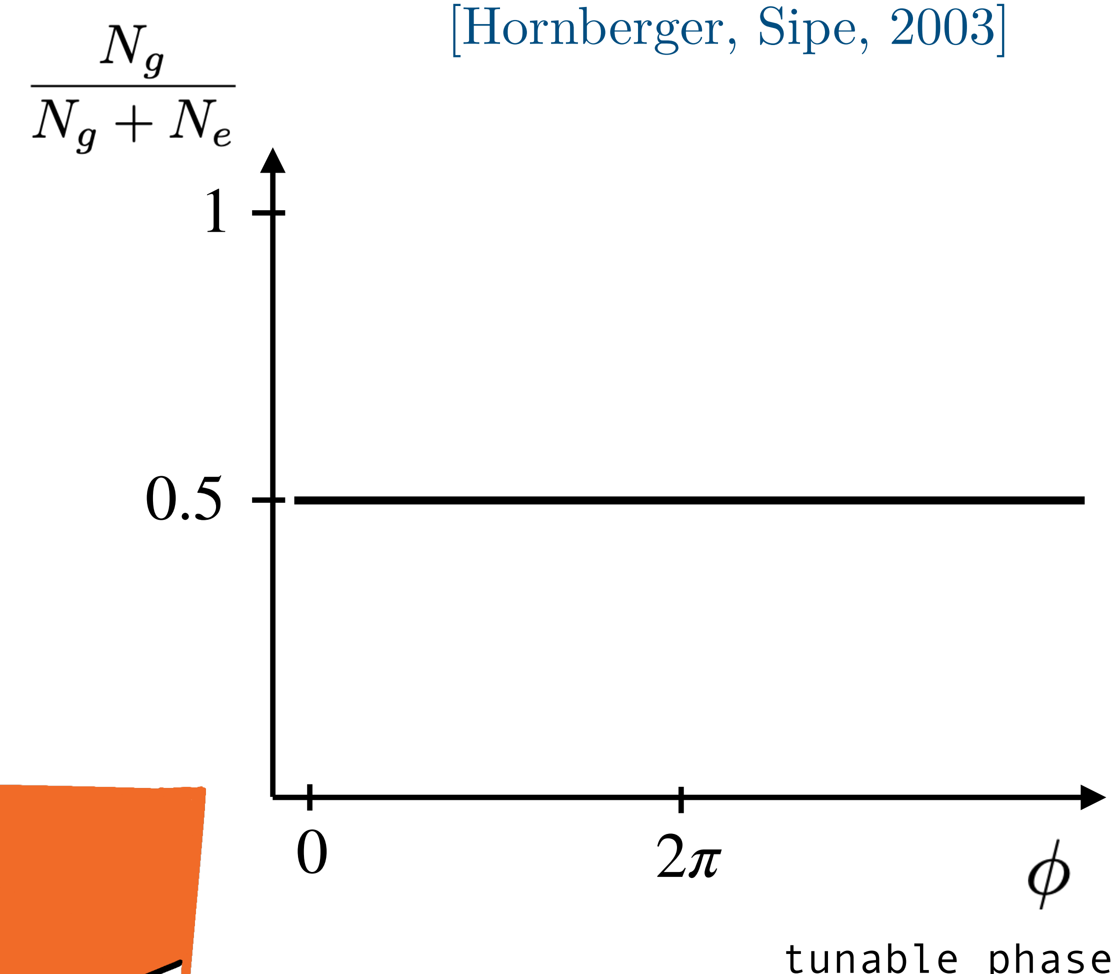
1. $\Gamma \to 0$
2. $\Gamma \neq 0, \ q \ll 1/\Delta x$
3. $\Gamma \neq 0, \ q \gg 1/\Delta x$

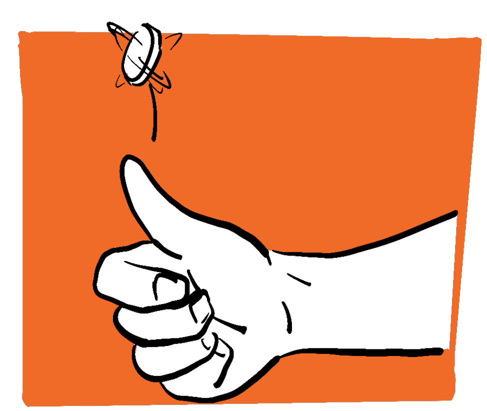




$$\ln\gamma = -\int_t \int_0^{q_{\max}} \mathrm{d}q^2 \frac{d\Gamma}{dq^2} \mathcal{F}_{\mathrm{decoh}}(\mathbf{q})$$

Decoherence Kernel

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



measurement

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

0

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Atom interferometry

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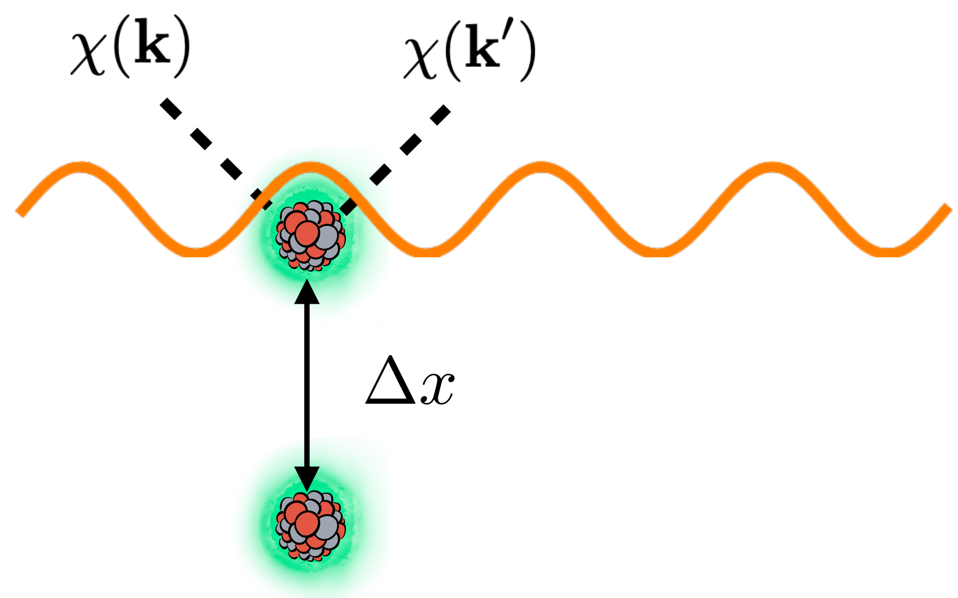

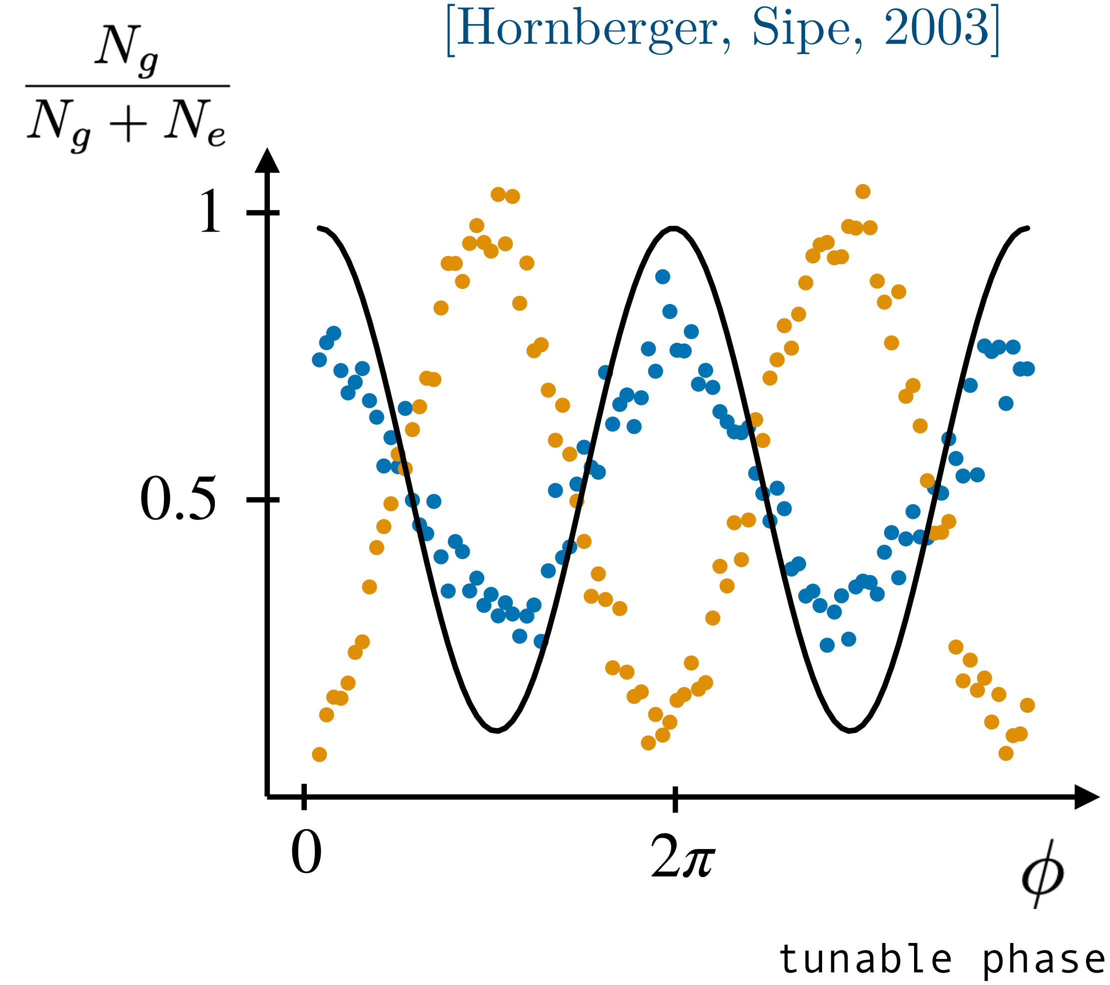

$$\ln \gamma = -\int_t \int_0^{q_{\max}} \mathrm{d}q^2 \, \frac{d\Gamma}{dq^2} \mathcal{F}_{\mathrm{decoh}}(\mathbf{q})$$

Decoherence Kernel

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

measurement

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

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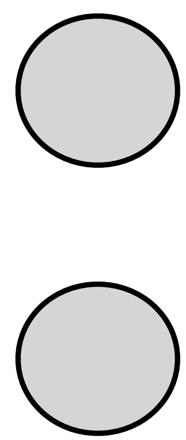
[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

Worked out the effect of particle scattering on a **single object** (e.g. atom) spatial quantum superposition.

[Riedel, 2012], [Riedel, Yavin, 2016]

Propose the use of matter interferometers (still **single object** in spatial quantum superposition) to search for dark matter.



$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|gg\cdots gg, \mathbf{0}\rangle + |ee\cdots ee, \mathbf{k}\rangle)$$

time

Rate of macro object

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

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

Work out the effect of particle scattering on a **collection of objects** (e.g. a cloud of N >> 1 atoms) in a product state

time

[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

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

Work out the effect of particle scattering on a **collection of objects** (e.g. a cloud of N >> 1 atoms) in a product state

time

$$\langle \mathbf{p}'|T_{\mathbf{x}}|\mathbf{p}\rangle = (2\pi)\delta(E'-E)\mathcal{M}_{\mathbf{x}}(\mathbf{p}',\mathbf{p})$$

$$n\,a^3 \ll 1 \quad \mathcal{M}^{(1)}_{\mathbf{x}}(\mathbf{p}',\mathbf{p}) = \tilde{V}(\mathbf{q})\sum_i \mathrm{e}^{\mathrm{i}\mathbf{q}\cdot\mathbf{x}_i}$$

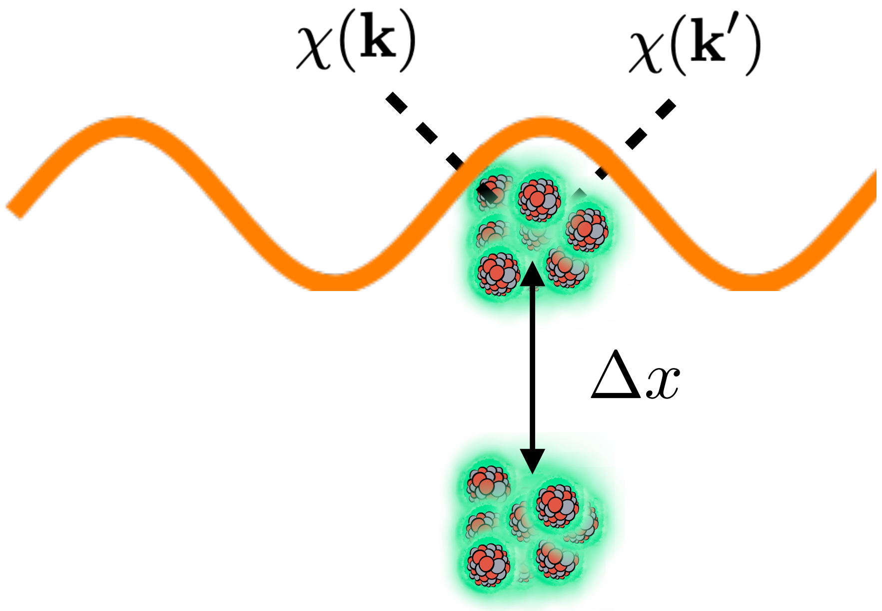
dilute Born approximation

$$\Delta\rho_A(\{\mathbf{x}\},\{\mathbf{x}'\}) = \rho_A(\{\mathbf{x}\},\{\mathbf{x}'\})\int \frac{\mathrm{d}^3p}{(2\pi)^3}\,\rho_\pi(\mathbf{p})\,\Big(\tfrac{\mathrm{i}}{2}\langle\mathbf{p}|\big(T_{\{\mathbf{x}\}}+T^\dagger_{\{\mathbf{x}\}}-T_{\{\mathbf{x}'\}}-T^\dagger_{\{\mathbf{x}'\}}\big)|\mathbf{p}\rangle - \tfrac{1}{2}\langle\mathbf{p}|\Big(T_{\{\mathbf{x}\}}T^\dagger_{\{\mathbf{x}\}}+T_{\{\mathbf{x}'\}}T^\dagger_{\{\mathbf{x}'\}}\Big)|\mathbf{p}\rangle + \langle\mathbf{p}|\,T^\dagger_{\{\mathbf{x}'\}}T_{\{\mathbf{x}\}}\,|\mathbf{p}\rangle\Big)$$

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

Atom interferometry

N atoms



Statistics

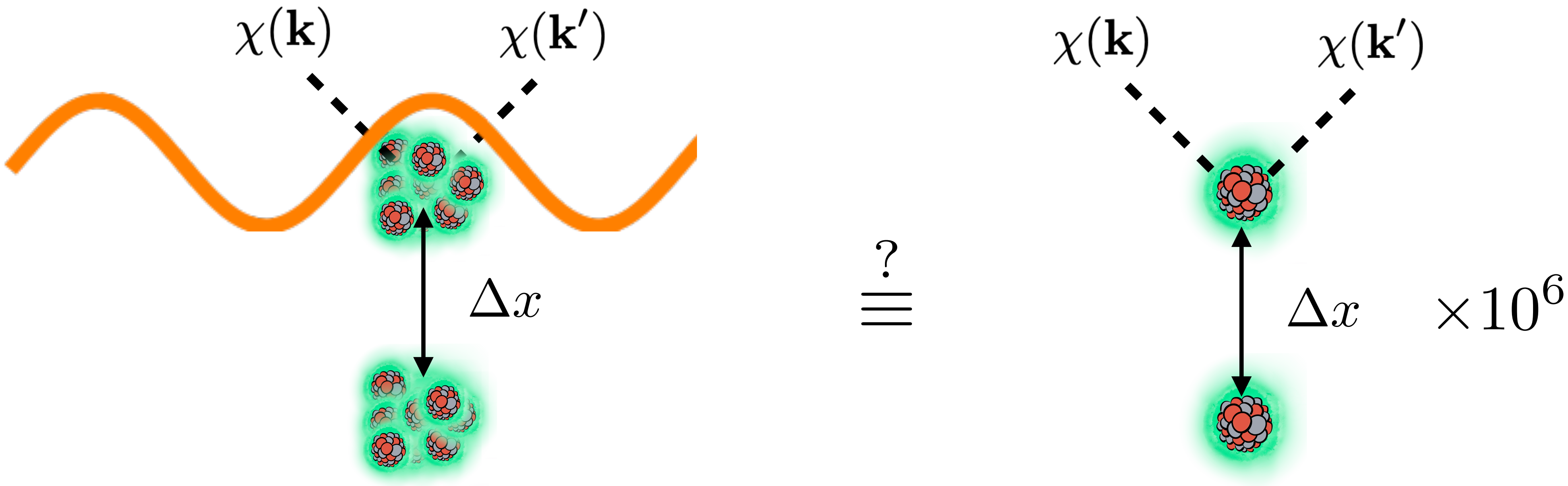
$$\delta\phi|_{\mathrm{shot}} = 1/\sqrt{N}$$

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

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

Atom interferometry

N atoms



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

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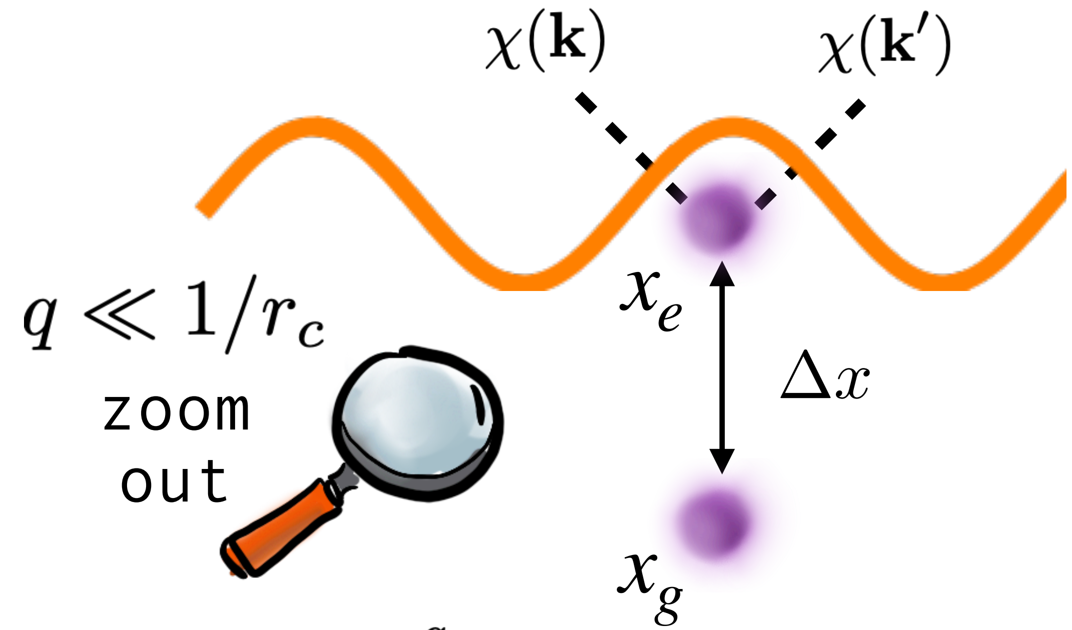
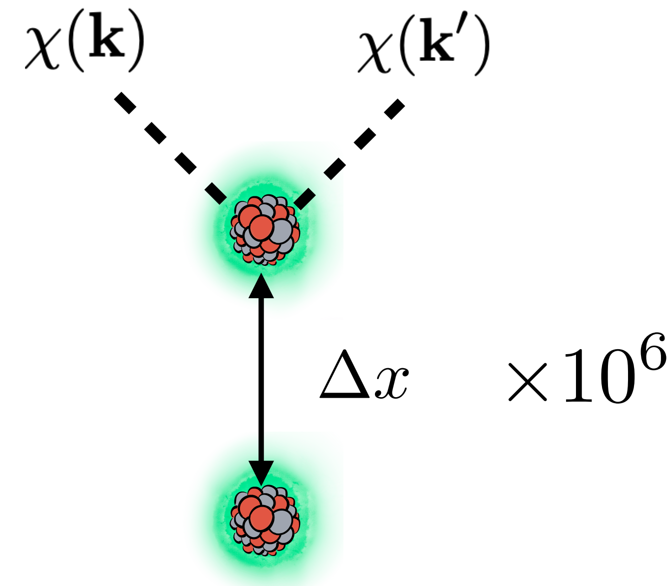
Atom interferometry

N atoms

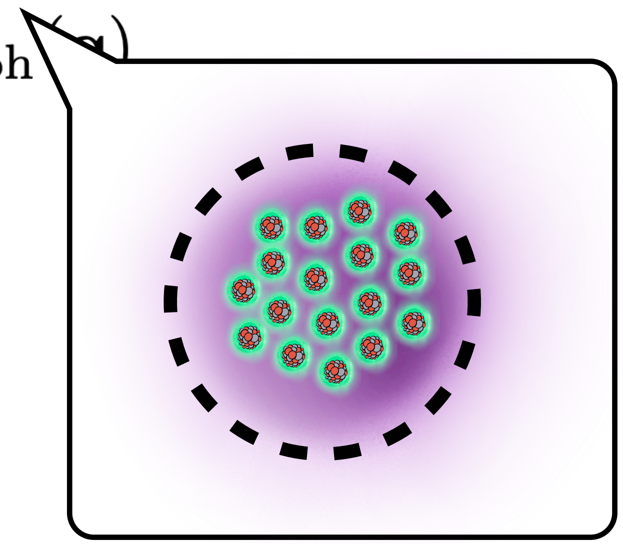
[Badurina, **CM**, Plestid, 2024]



$\stackrel{?}{\equiv}$



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

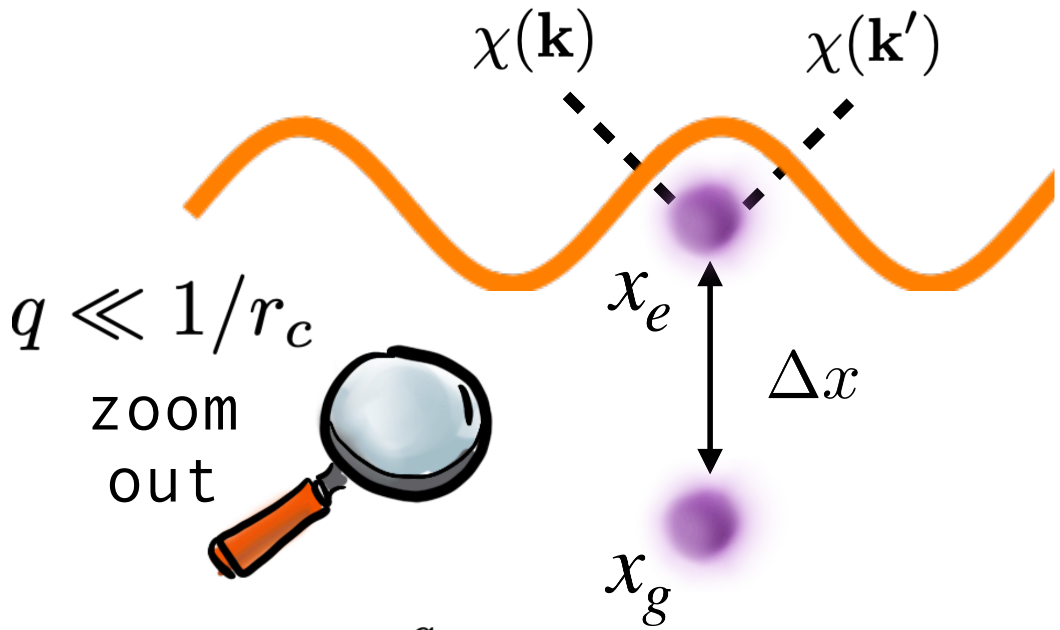


$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & \end{pmatrix}$$

Atom interferometry

N atoms

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



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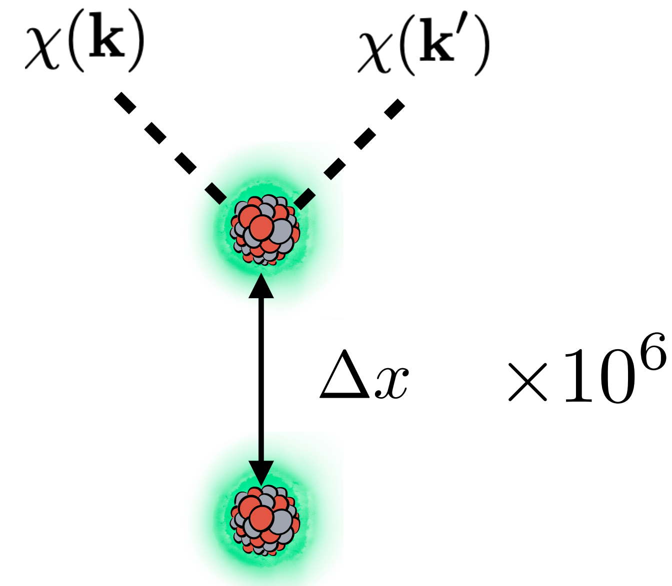
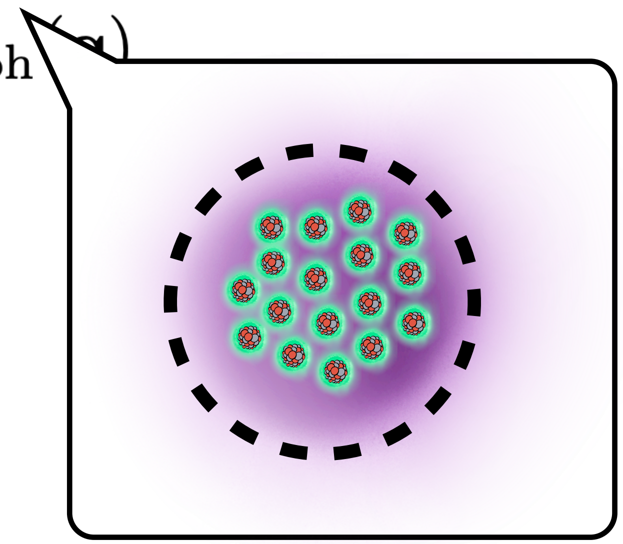


$$\ln \gamma = -\int_t \int_0^{q_{\mathrm{max}}} \mathrm{d}q^2 \frac{d\Gamma}{dq^2} \mathcal{F}_{\mathrm{decoh}}(q)$$



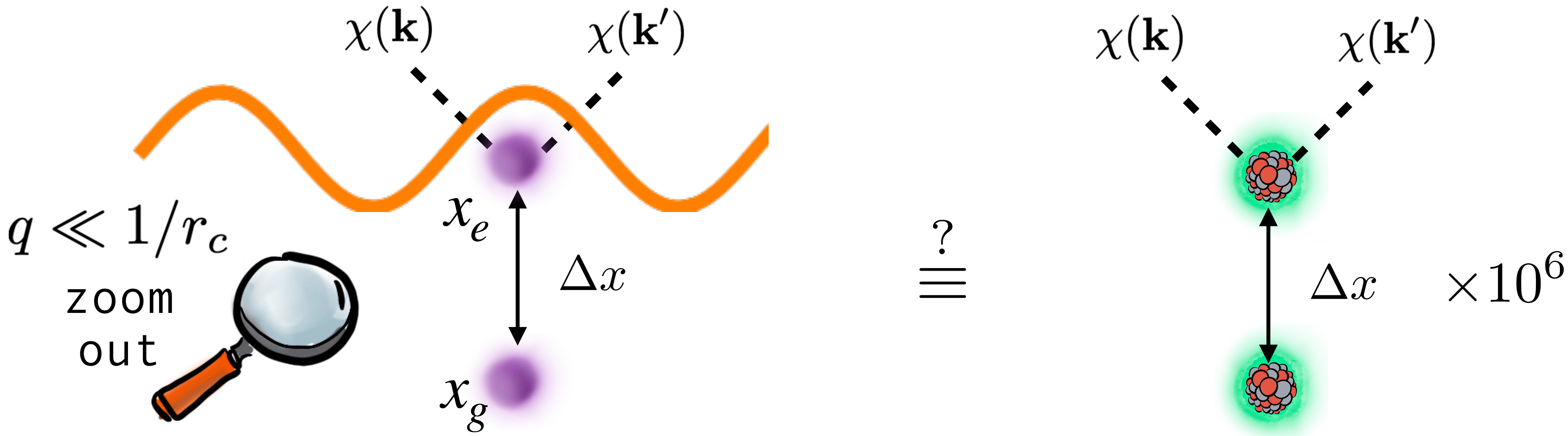
$$|\Psi\rangle = \frac{1}{2^{N/2}} \prod_{i=1}^{N} (|g\rangle + e^{i\phi}|e\rangle)$$

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

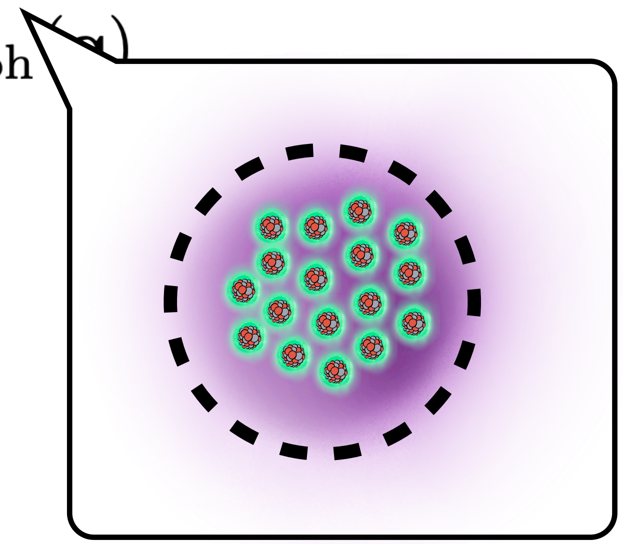
Atom interferometry

N atoms

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



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



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

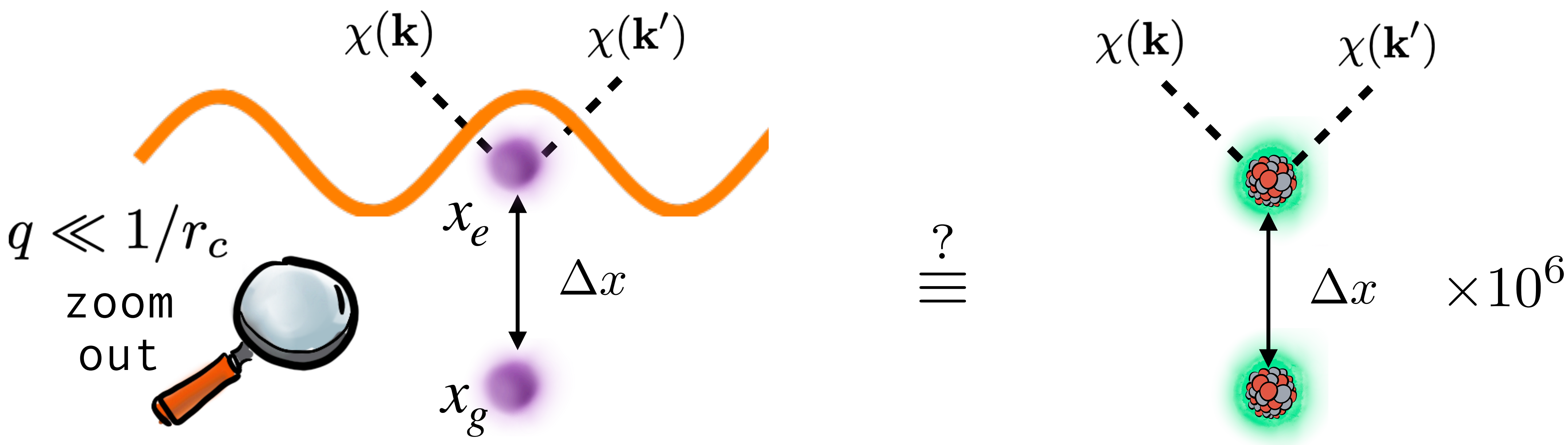
$$= \frac{1}{2^{N/2}} \sum_{m=0}^{N} \binom{N}{m} |g_1 \cdots g_m e_{m+1} \cdots e_N\rangle$$

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

Atom interferometry

N atoms

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



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

$$\rho_A(\{\mathbf{x}\},\{\mathbf{x}'\},t) = \rho_A(\{\mathbf{x}\},\{\mathbf{x}'\}) \times \exp\left[-\int_0^t d\tau \lambda(\{\mathbf{x}\},\{\mathbf{x}'\},\tau)\right].$$

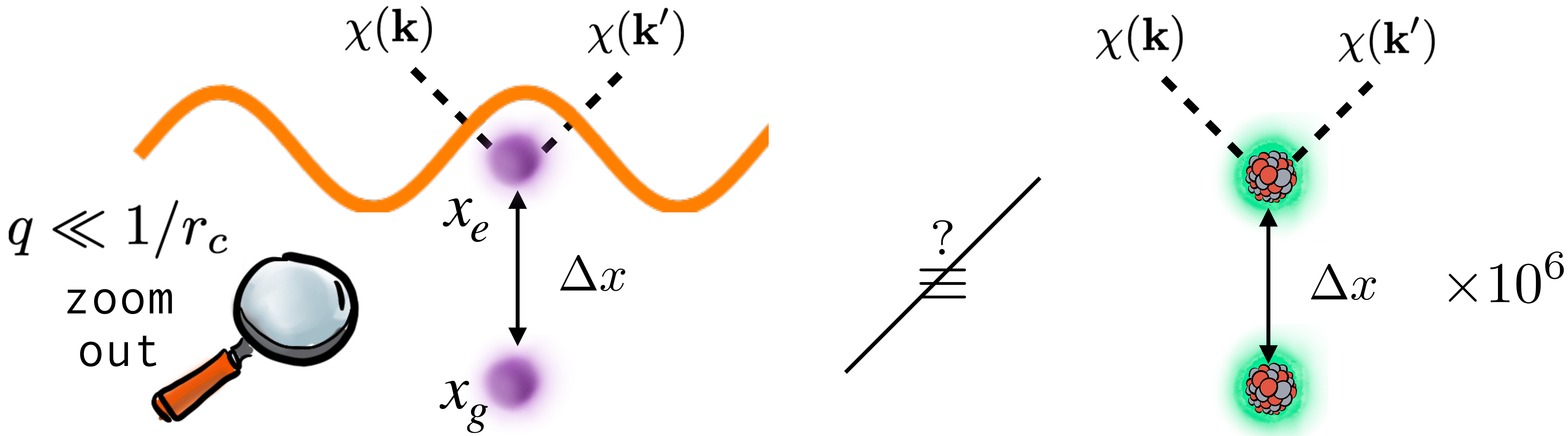
$$\lambda_D = \int \frac{d^3p}{(2\pi)^3}\,\rho_\pi(\mathbf{p}) \int \frac{d^3q}{(2\pi)^3}\,(2\pi)\delta(\Sigma E)|\widetilde{V}(\mathbf{q})|^2 \left[\frac{1}{2}\sum_{ij}^{N} e^{i\mathbf{q}\cdot(\mathbf{x}_i-\mathbf{x}_j)} + e^{i\mathbf{q}\cdot(\mathbf{x}'_i-\mathbf{x}'_j)} - 2e^{i\mathbf{q}\cdot(\mathbf{x}_i-\mathbf{x}'_j)}\right]$$

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

Atom interferometry

N atoms

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



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

HUGE ENHANCEMENT!

Decoherence Kernel 1-body

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

measurement

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

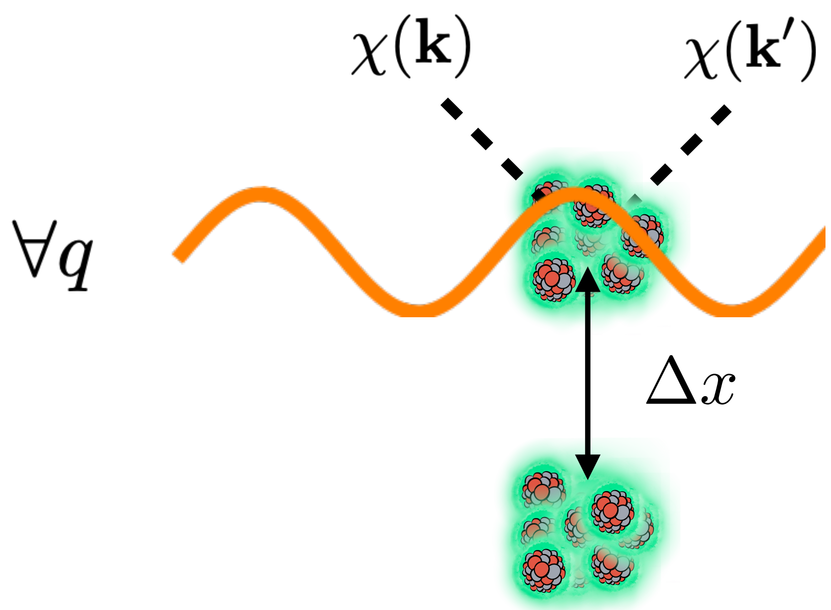
$$\frac{N_g}{N_g+N_e}\bigg|_{\rm exp}(\phi) = \tfrac{1}{2}\big(1 + V\cos\left(\phi+\Delta\phi\right)\big)$$

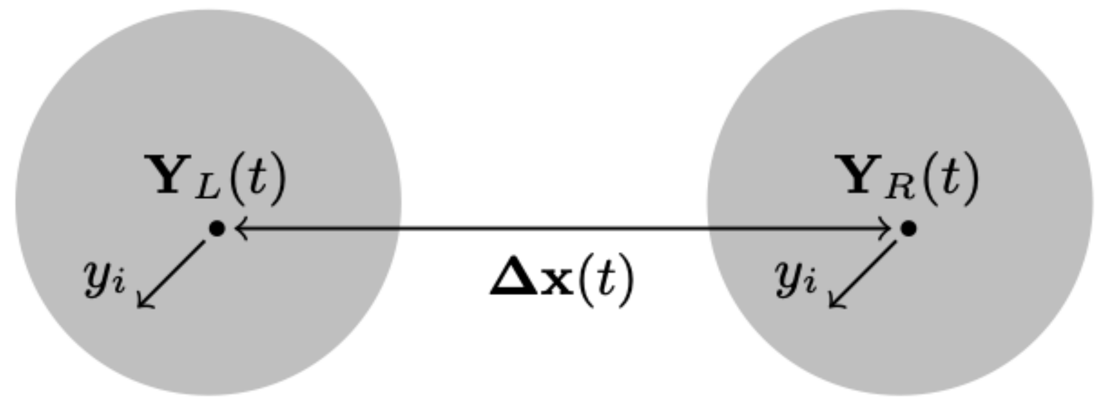
$$\rho(\mathcal{T}) = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & \end{pmatrix}$$

Atom interferometry

N atoms

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





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

$$\mathbf{x}_i = \mathbf{Y}_{\mathcal{P}_i}(t) + \mathbf{y}_i$$

Decoherence Kernel 1-body

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

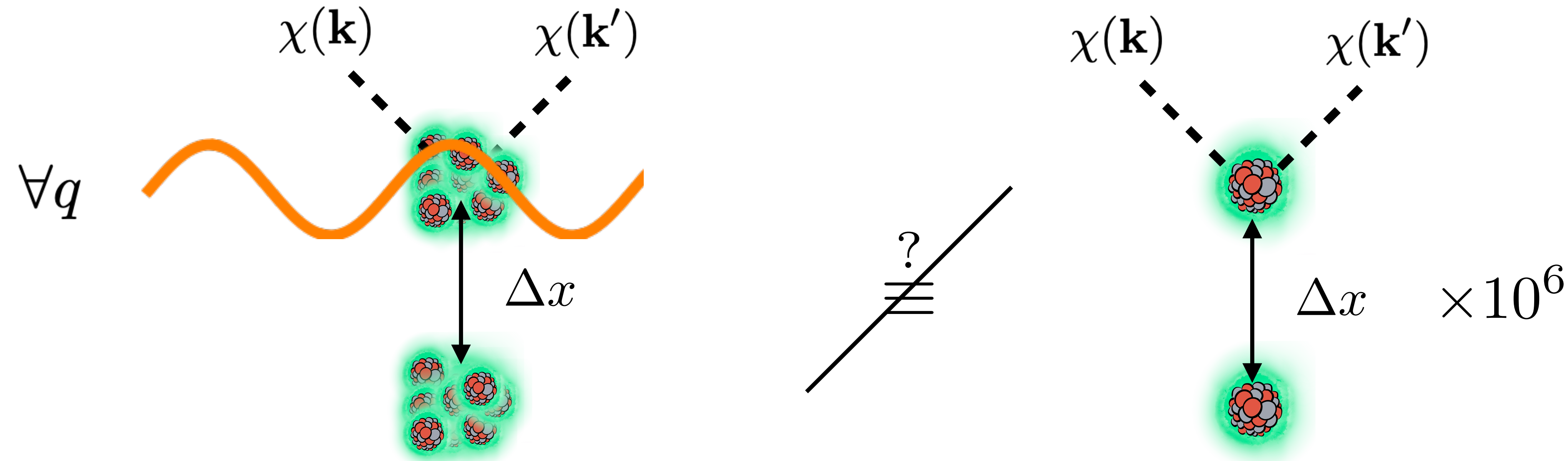
$$\rho(\{\mathbf{x}\},\{\mathbf{x}'\};\{s\},\{s'\};\mathcal{T}) = \varrho_y(\{\mathbf{y}\},\{\mathbf{y}'\})\varrho_s(\{s\},\{s'\})e^{\mathrm{i}\tilde{\Phi}(\{s\},\{s'\})}\exp\left[-\int_0^{\mathcal{T}} \mathrm{d}t\,\lambda(\{\mathbf{x}_s(t)\},\{\mathbf{x}'_{s'}(t)\})\right]$$

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

Atom interferometry

N atoms

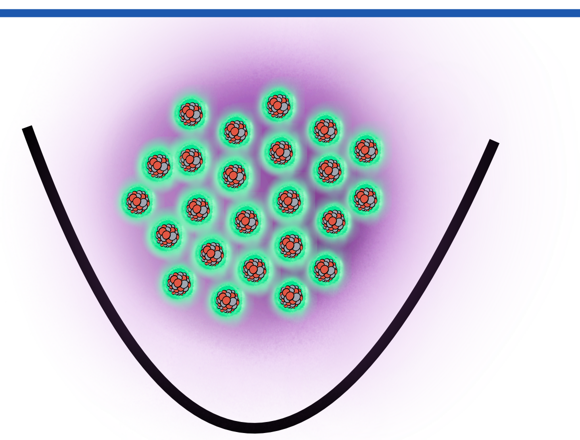
[Badurina, **CM**, Plestid, 2024]
[**CM**, Plestid, 2025]



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

Decoherence Kernel 1-body

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



The Debye-Waller factor (cloud form factor squared)

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

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

Atom interferometry

N atoms

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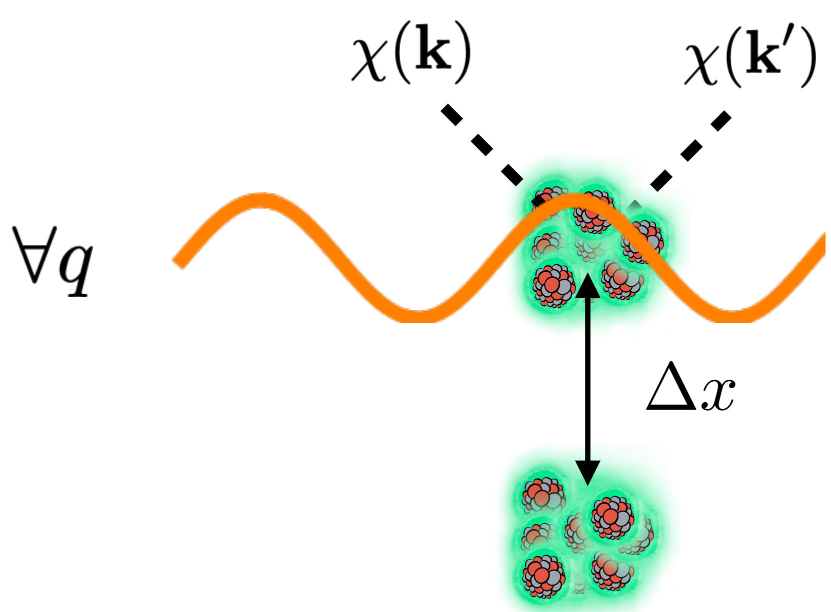
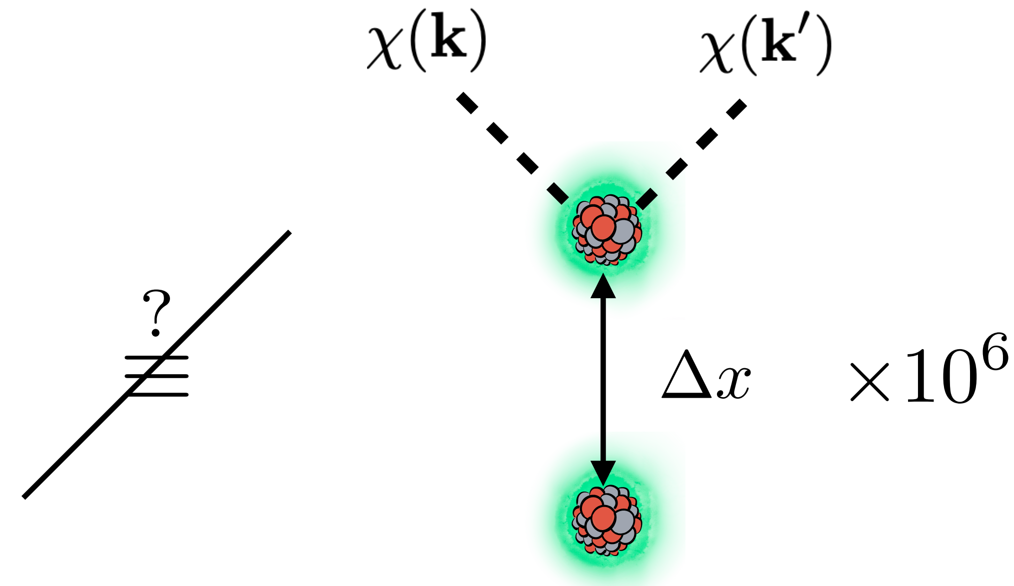
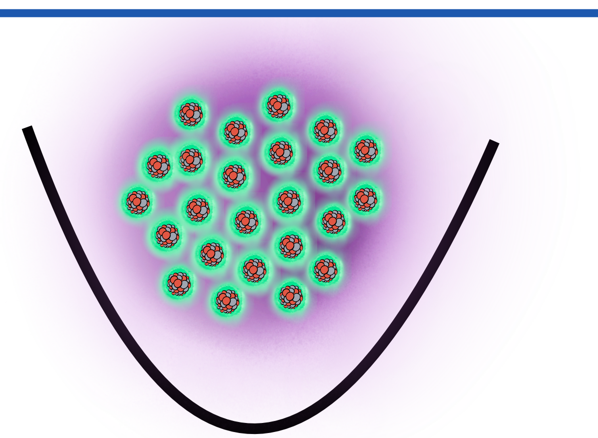




$$\ln \gamma = -\int_t \int_0^{q_{\max}} \mathrm{d}q^2 \frac{d\Gamma}{dq^2} \mathcal{F}_{\mathrm{decoh}}(\mathbf{q})$$

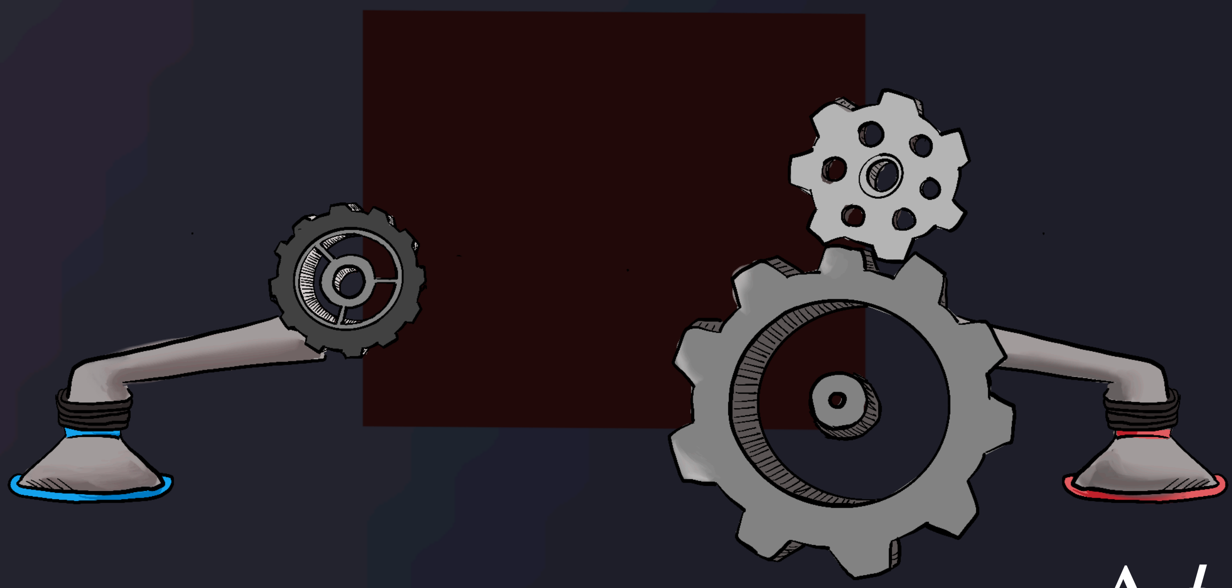
Decoherence Kernel n-body

$$\mathcal{F}_{\mathrm{decoh}}(\mathbf{q}) = G(\mathbf{q})(n^2(1-\cos[\mathbf{q}\cdot\mathbf{\Delta x}]) - inN\sin[\mathbf{q}\cdot\mathbf{\Delta x}])$$
$$+ (1-G(\mathbf{q}))|n|(1-\cos[\mathbf{q}\cdot\mathbf{\Delta x}] - in\sin[\mathbf{q}\cdot\mathbf{\Delta x}])$$



The Debye-Waller factor (cloud form factor squared)

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

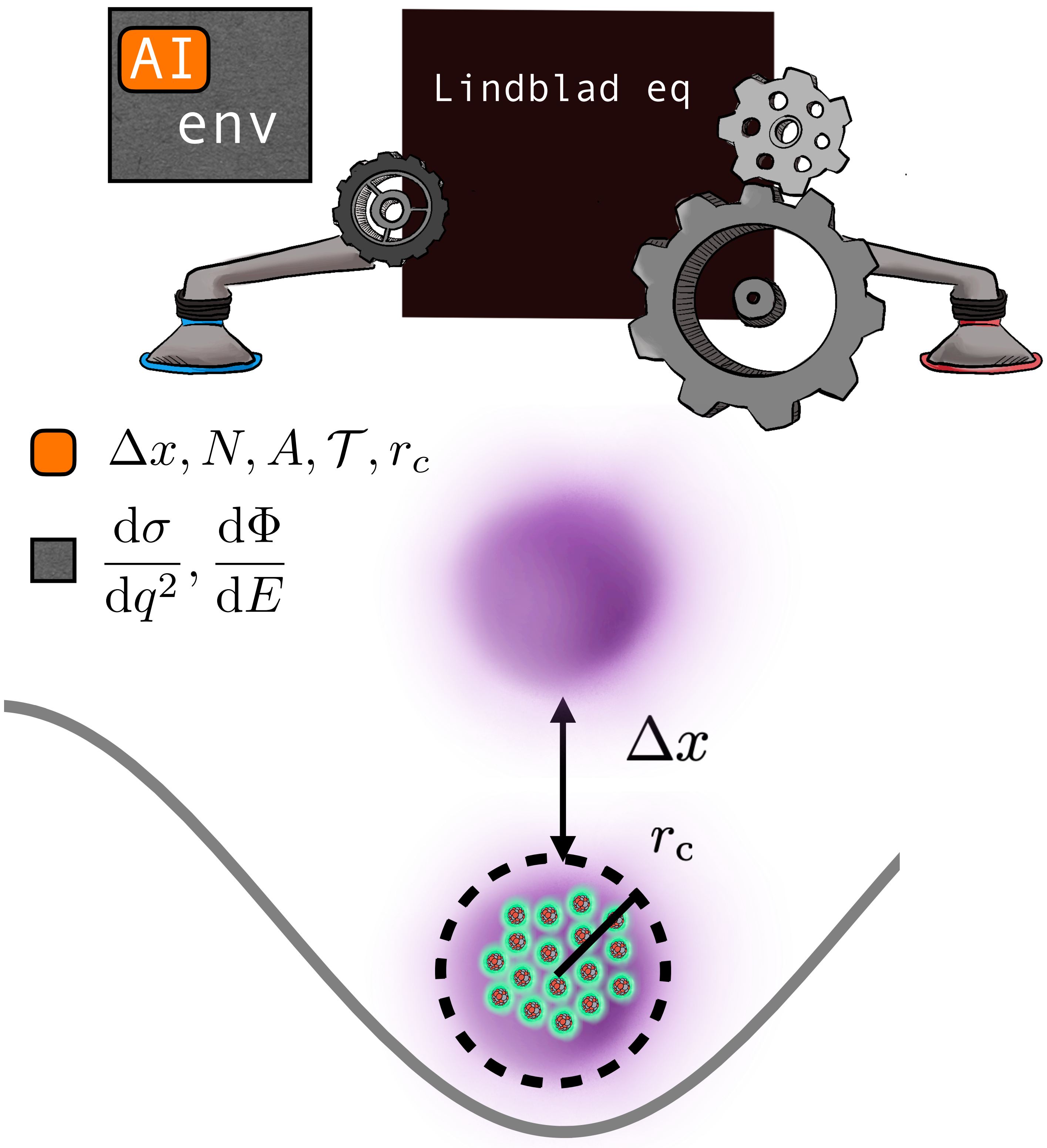


$$\Delta\phi = \phi + \gamma_0 + N\gamma$$

Let's apply it to search for elusive particles!

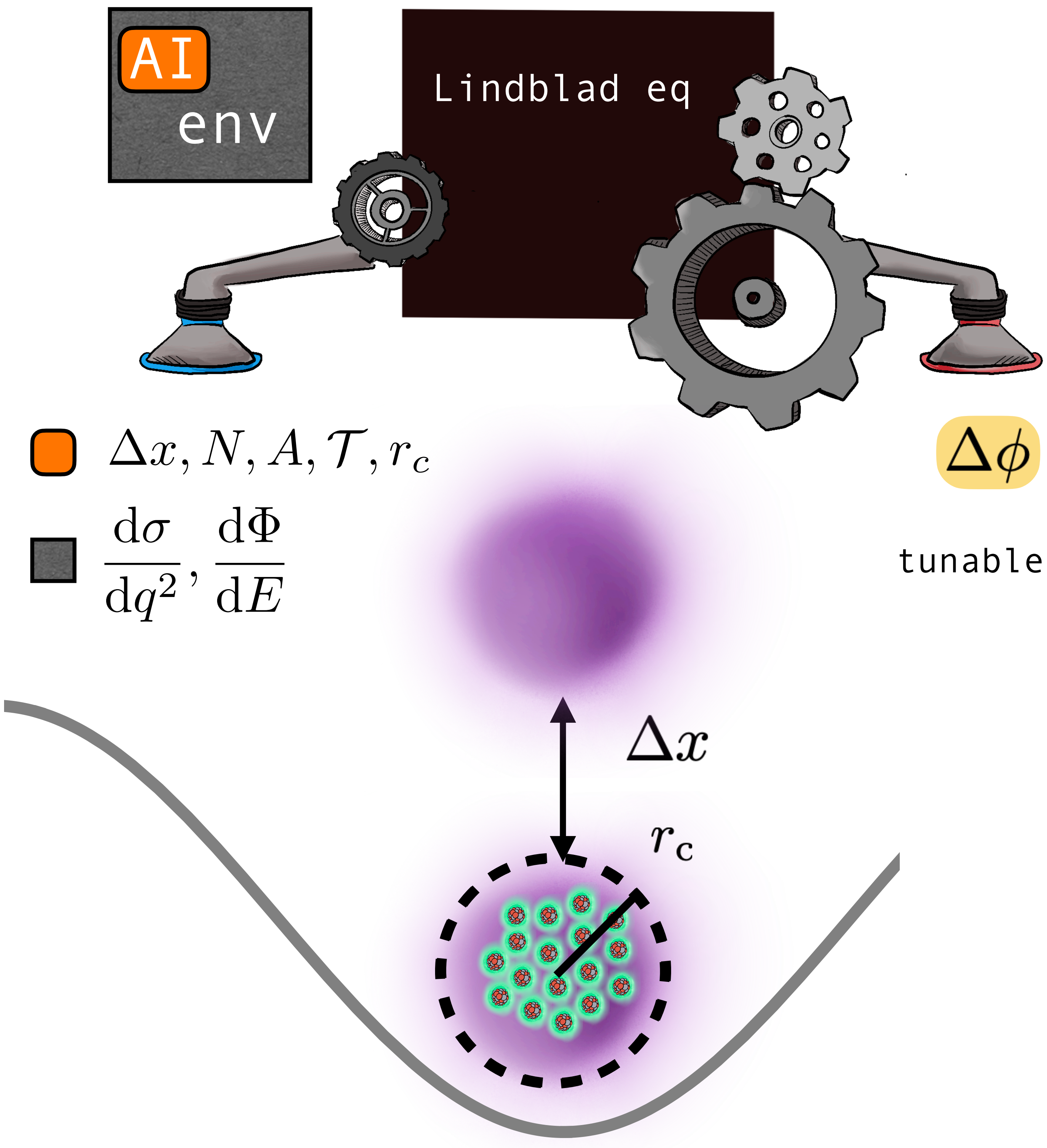
Enhanced phase-shift

Applications



Enhanced phase-shift

Applications

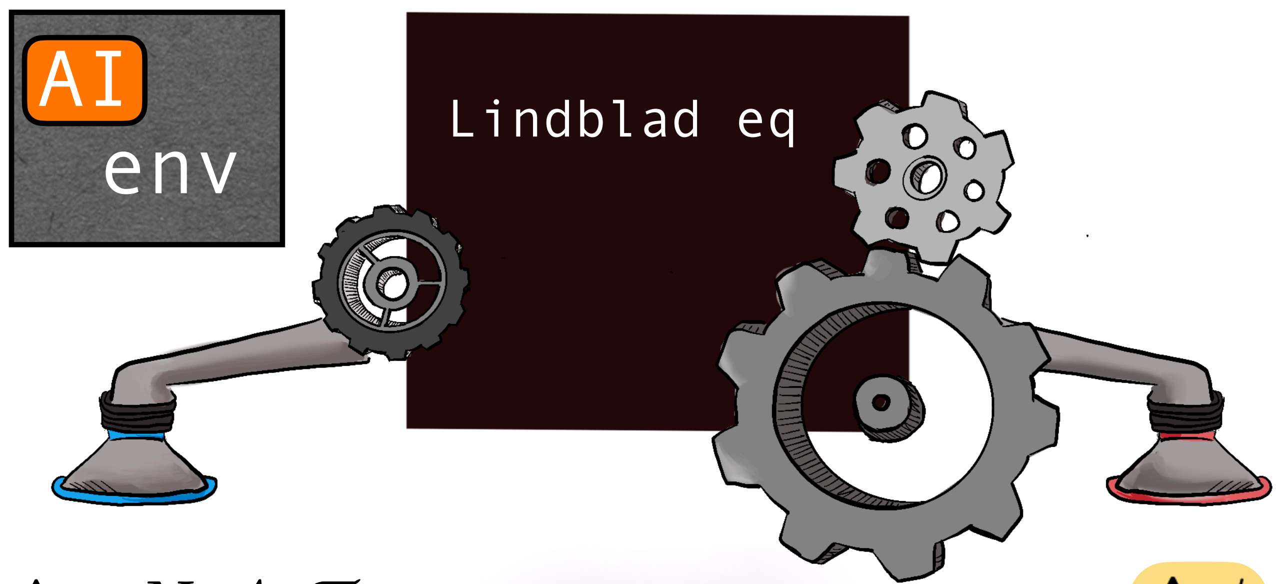


$$\Delta\phi = \phi + \gamma_0 + N\gamma$$

tunable phase

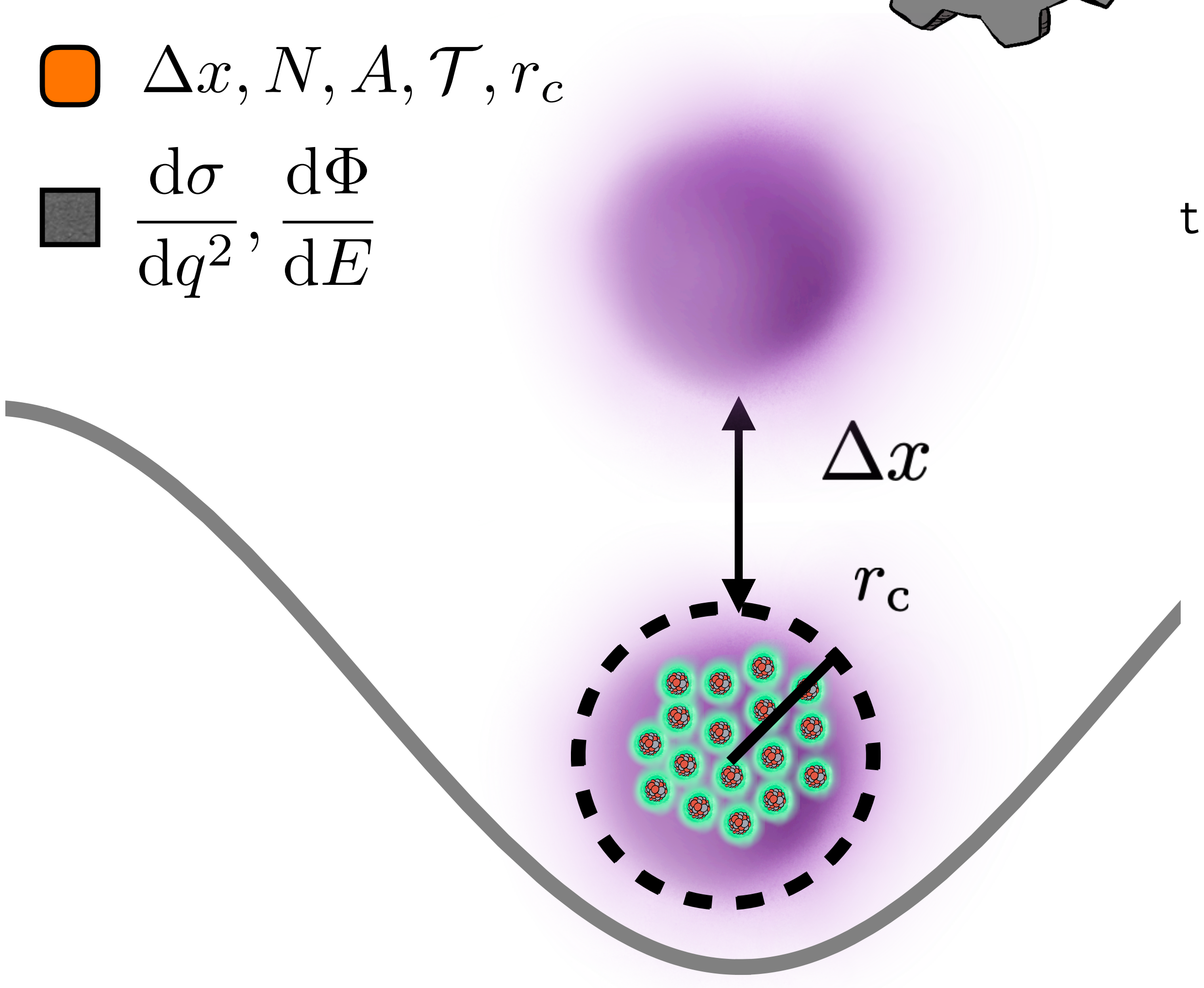
Enhanced phase-shift

Applications



■ $\Delta x, N, A, \mathcal{T}, r_c$

■ $\frac{\mathrm{d}\sigma}{\mathrm{d}q^2}, \frac{\mathrm{d}\Phi}{\mathrm{d}E}$



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

tunable phase

Incoherent-decoherence

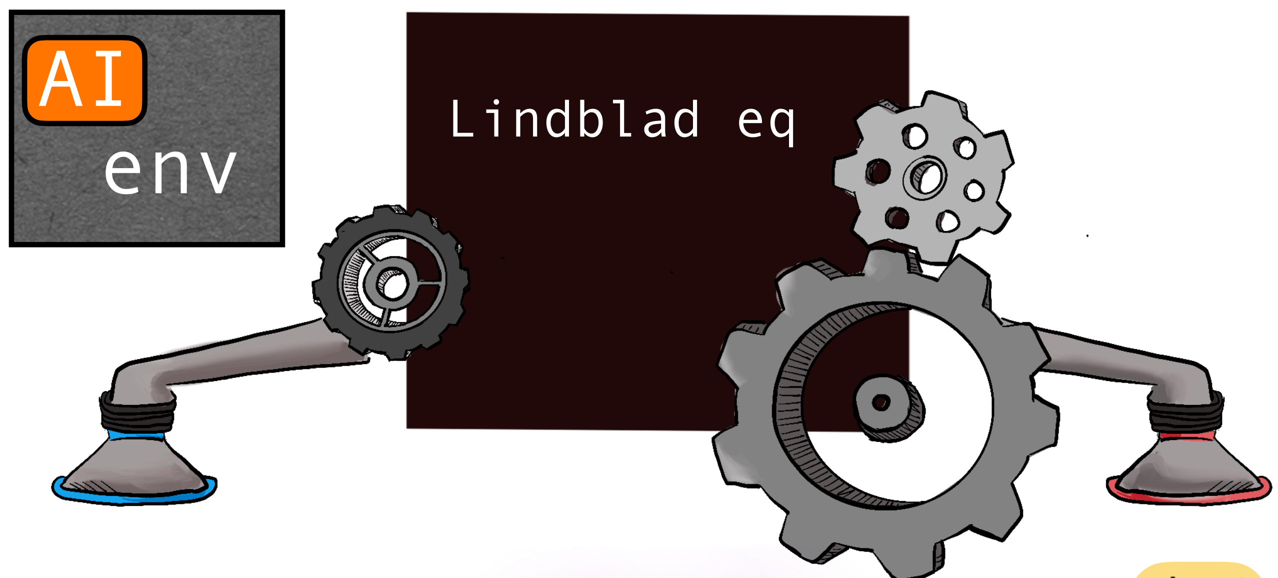
$$\gamma_0 = \int_q \Gamma(\mathbf{q})[1 - G(\mathbf{q})] \sin(\mathbf{q} \cdot \mathbf{\Delta x})$$

Coherent-decoherence

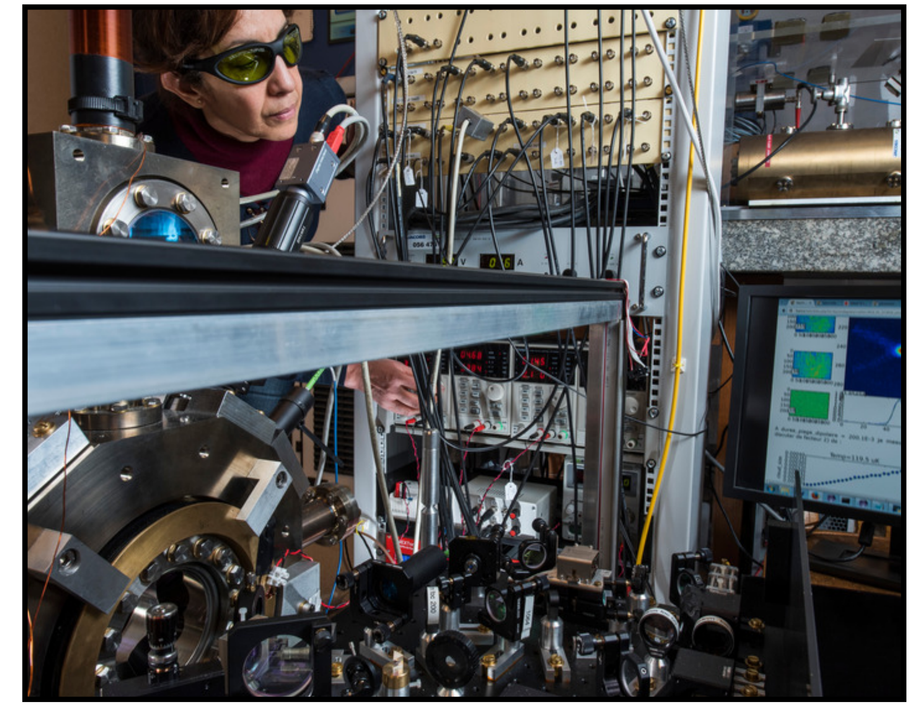
$$\gamma = \int_q \Gamma(\mathbf{q})\, G(\mathbf{q}) \sin(\mathbf{q} \cdot \mathbf{\Delta x})$$

Enhanced phase-shift

Applications



e.g. Kastler Brossel Lab



■ $\Delta x, N, A, \mathcal{T}, r_c$

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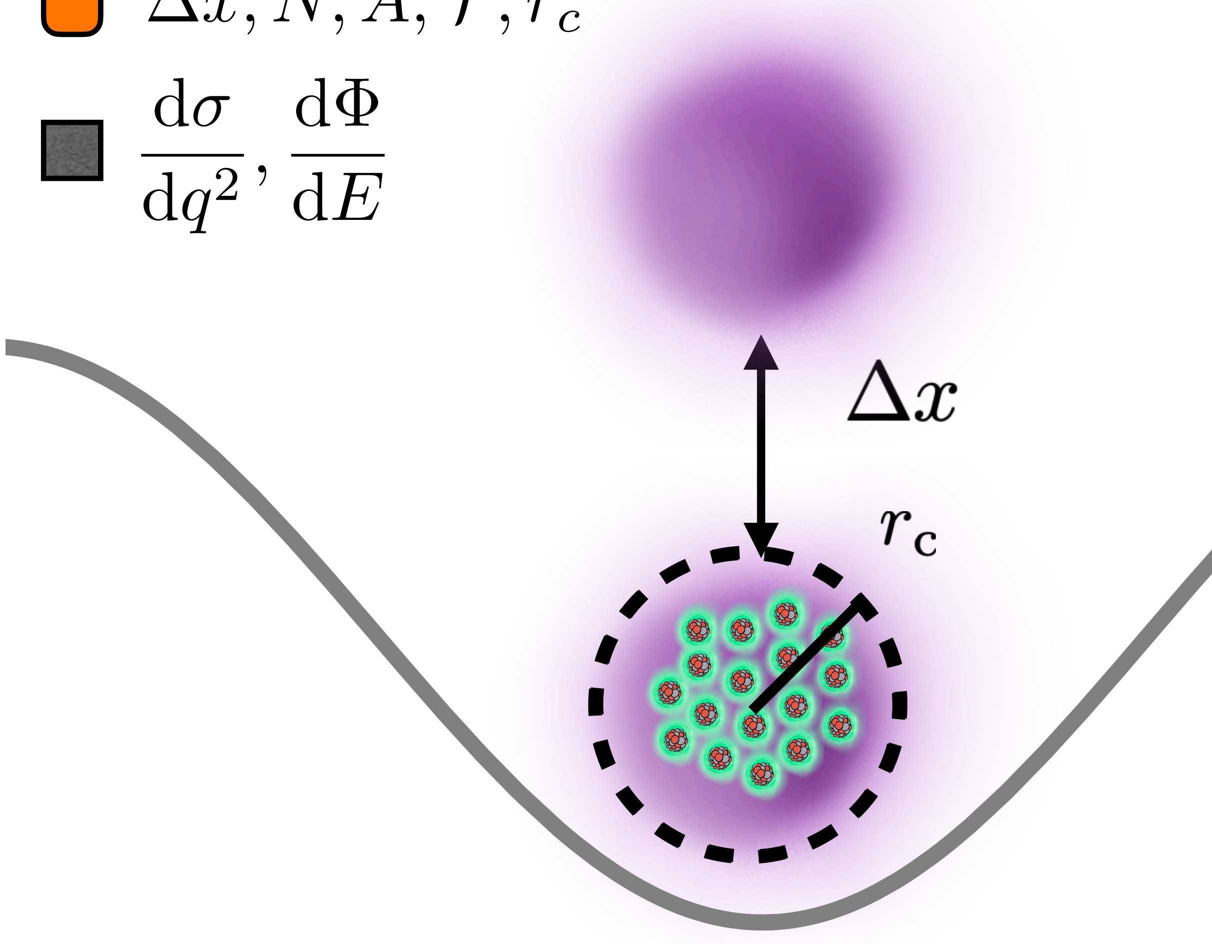

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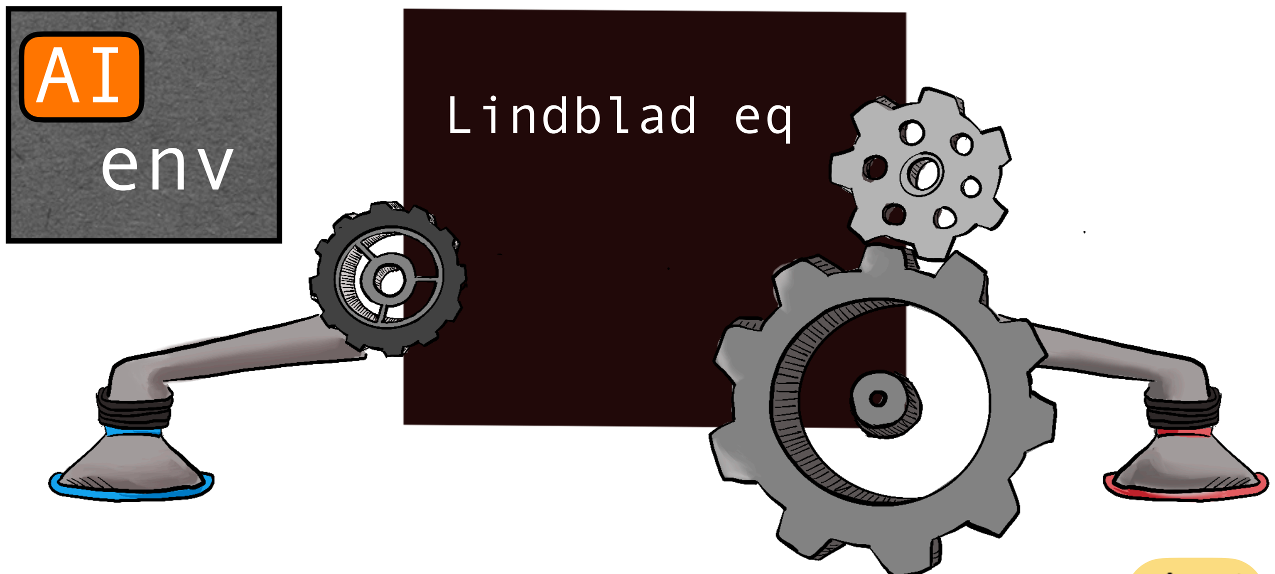
Dark matter inprints



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

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

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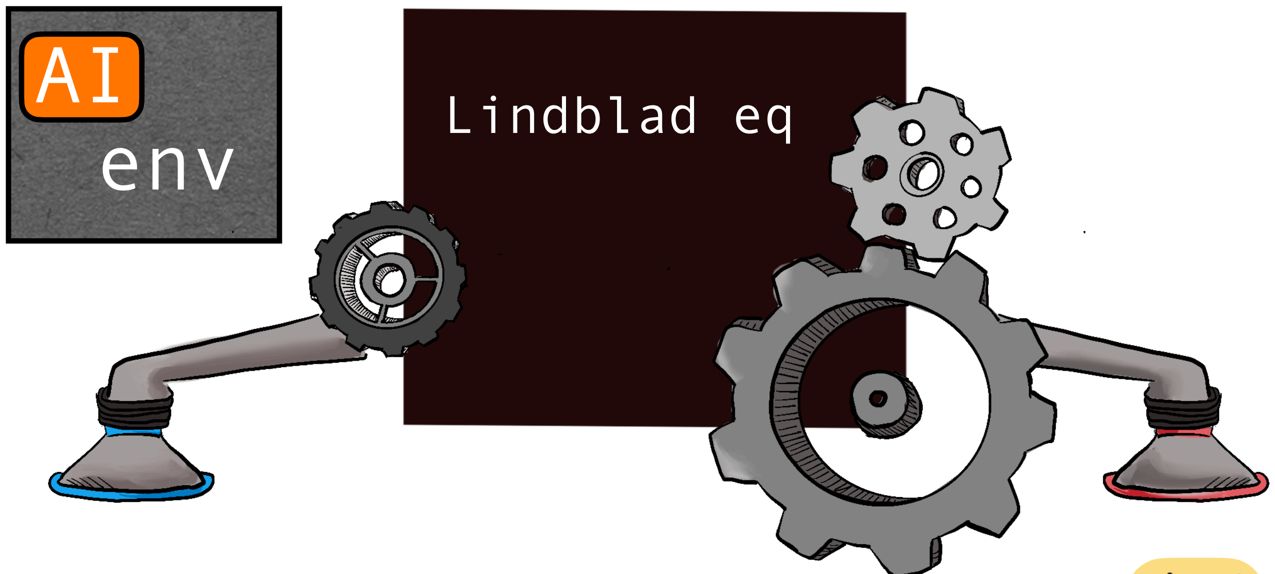
Dark matter inprints

[Riedel, 2013]

[Riedel, Yavin, 2017]

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

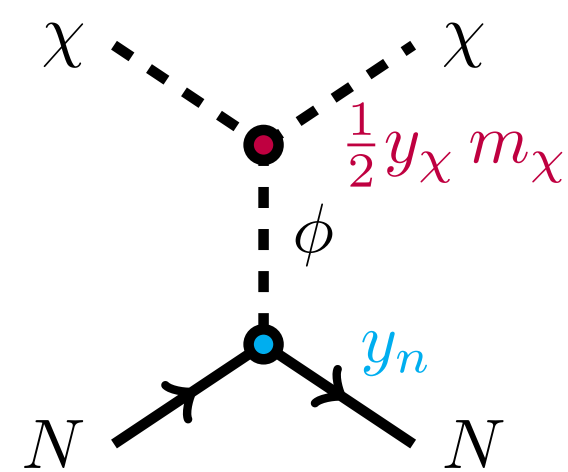
[**CM**, Plestid, 2025]



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

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

$\Delta\phi$



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

Dark matter inprints

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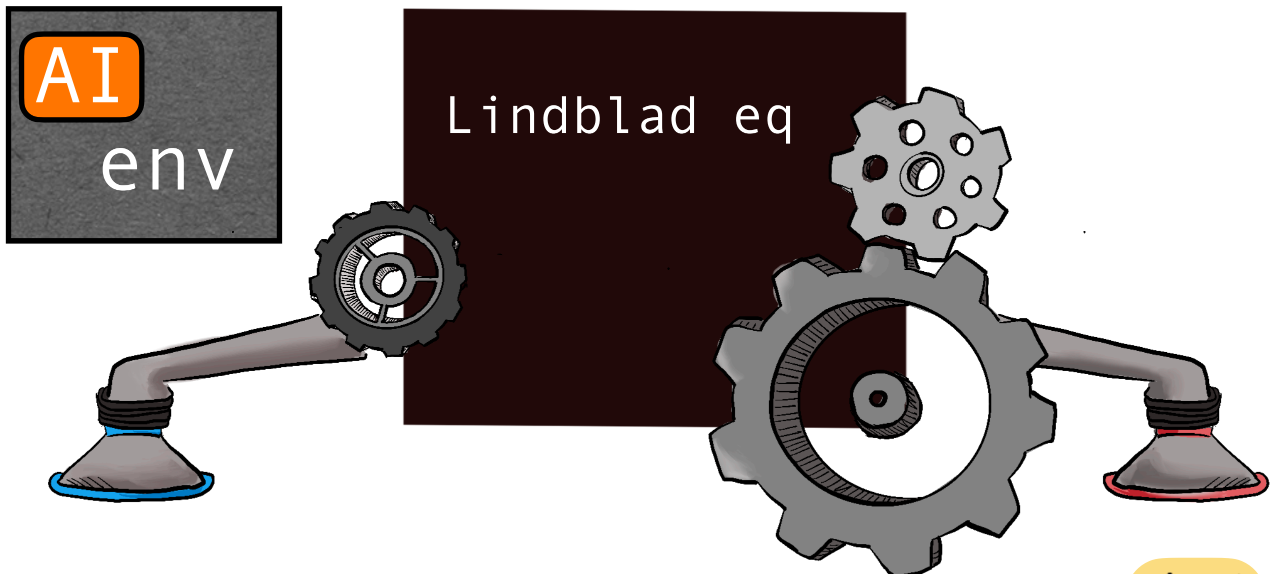
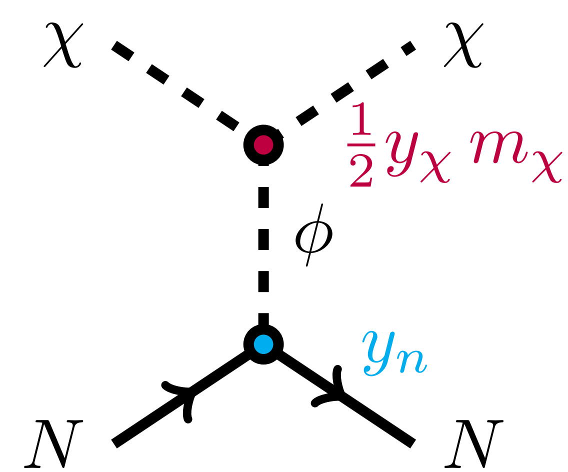


$\Delta\phi$

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

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



coherent decoherence dominates

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

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

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

Dark matter inprints

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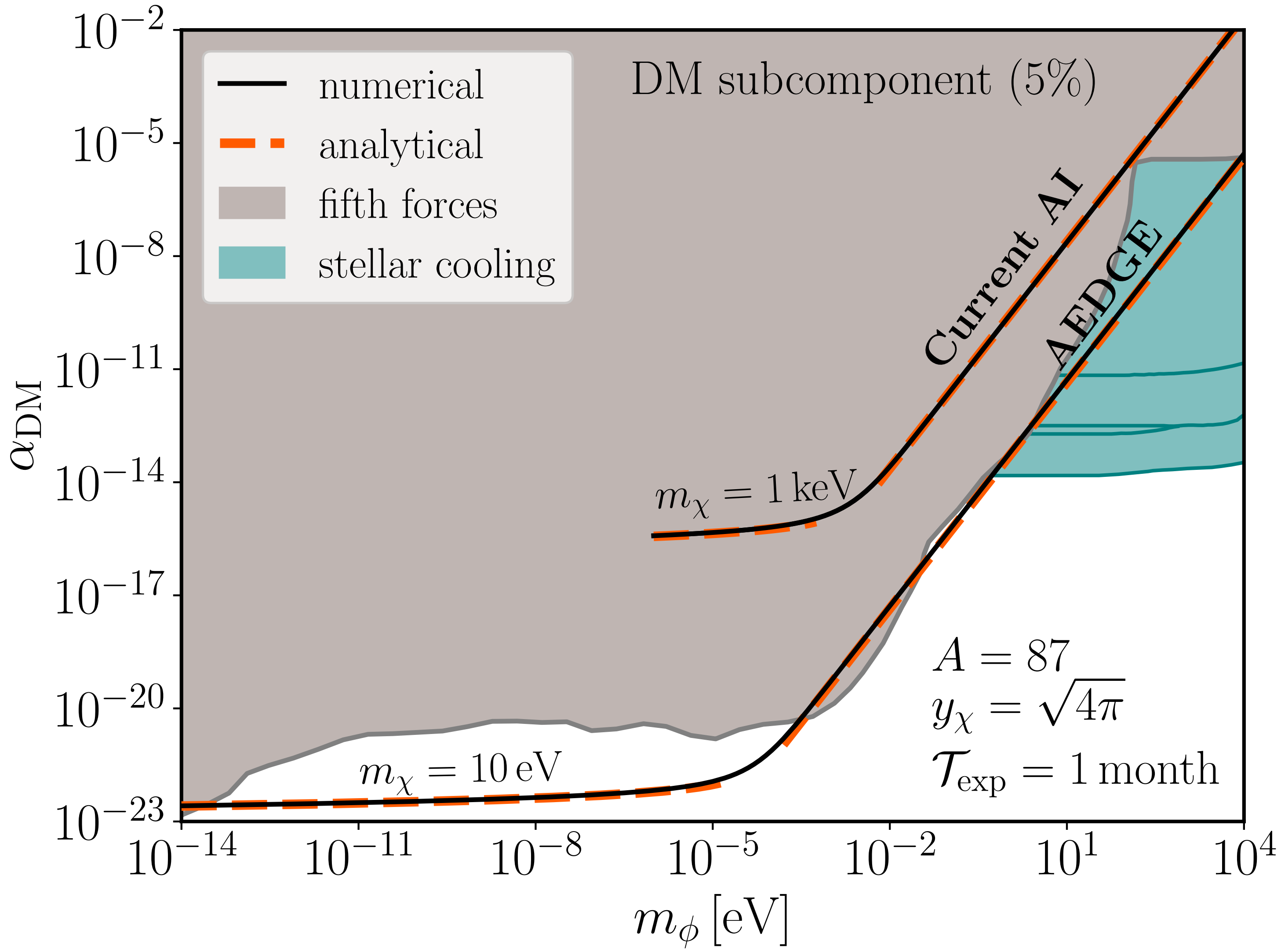

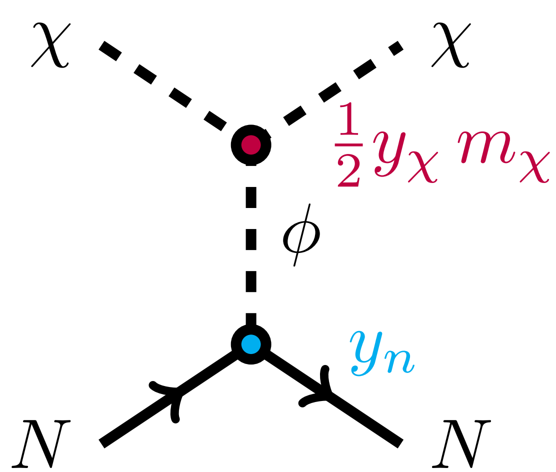

coherent decoherence dominates

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

[Gallis, Fleming, 1990] [Hornberger, Sipe, 2003]

Worked out the effect of particle scattering on a **single object** (e.g. atom) spatial quantum superposition.

[Riedel, 2012], [Riedel, Yavin, 2016]

Propose the use of matter interferometers (still **single object** in spatial quantum superposition) to search for dark matter.

[Badurina, CM, Plestid, 2024]

Work out the effect of particle scattering on a **collection of objects** (e.g. a cloud of N >> 1 atoms) in a product state

[CM, Plestid, 2026]

Propose a **new observable** in atom interferometry (anomalous fluctuations) that is enhanced by the number of atoms

time

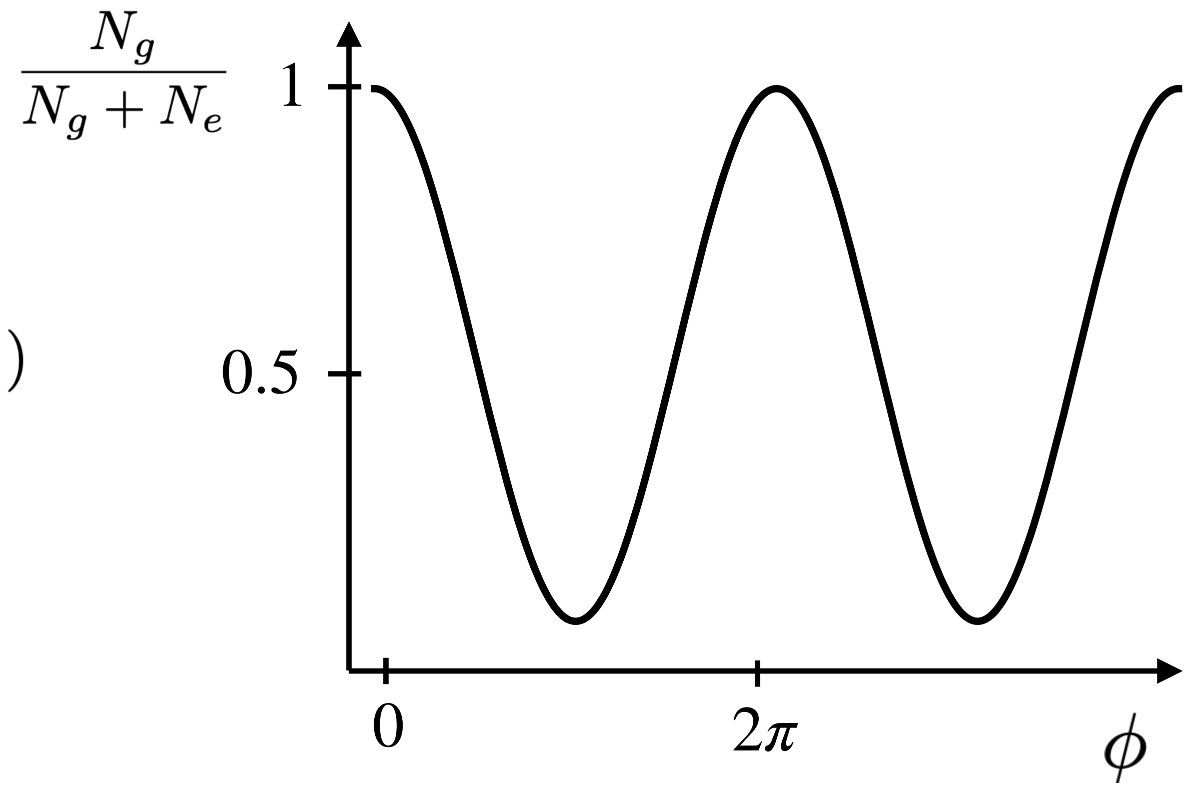
Alternative observables?

[**CM**, Plestid, 2026]

The mean

$$\langle \mathcal{O}_+ \rangle = \mathrm{Tr}\{\rho \mathcal{O}_+\} = \frac{N}{2}(1 + \mathrm{Re}[\text{[redacted]}_1])$$

$$\rho_1 = \frac{1}{2}\begin{pmatrix} \circ & \text{[redacted]} \\ \text{[redacted]} & \circ \end{pmatrix}$$



Anomalous (enhanced) fluctuations

[**CM**, Plestid, 2026]

The mean

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

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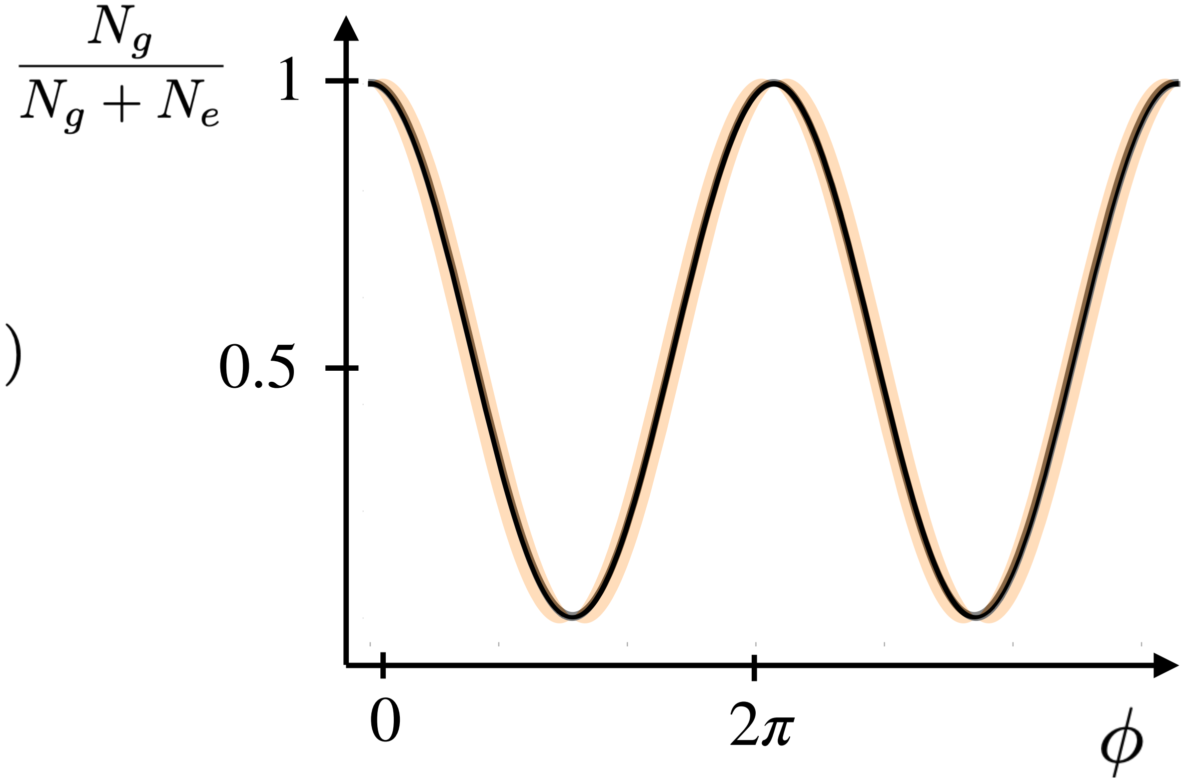


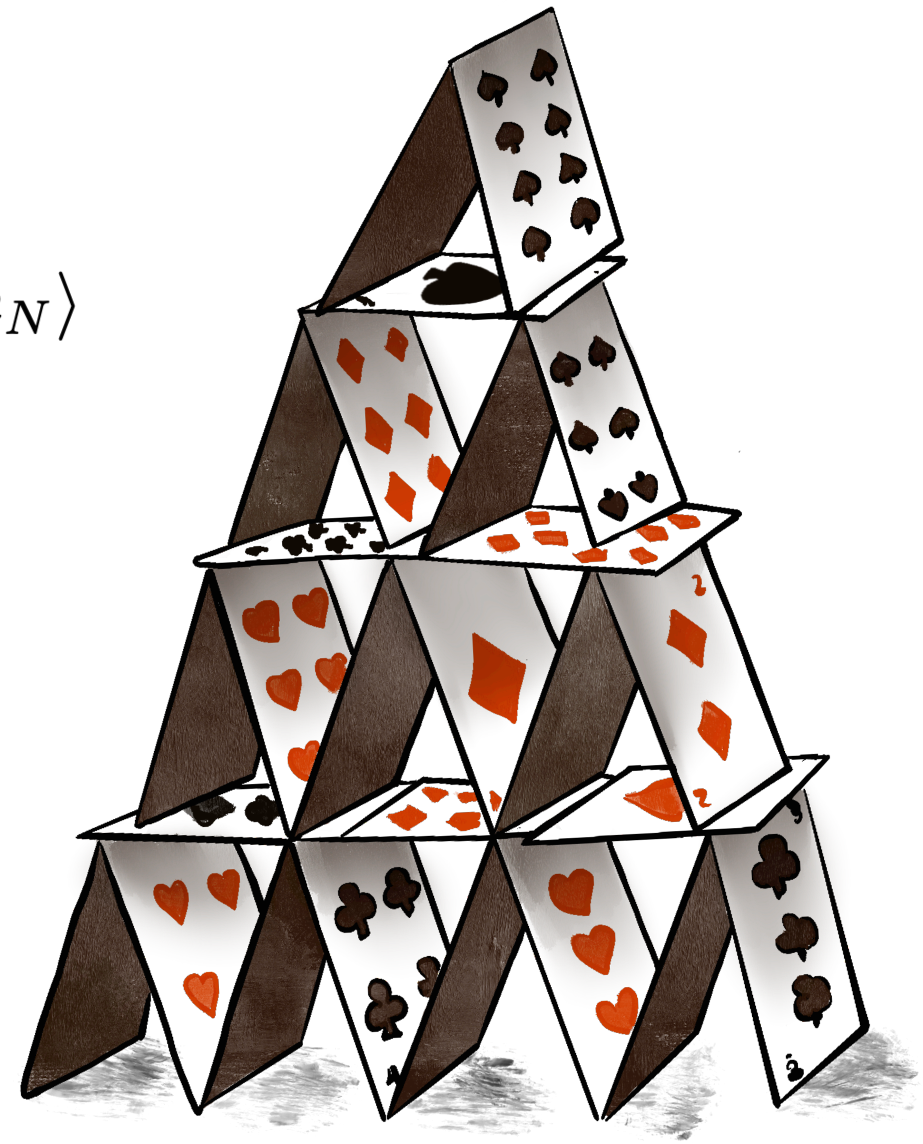
Higher statistical moments!

The weirdos: product states

[**CM**, Plestid, 2026]

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

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



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[**CM**, Plestid, 2026]

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Pure product state

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

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

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[**CM**, Plestid, 2026]

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Fully decohered $e^{-(s+s_0)}$ → 0

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

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The weirdos: product states

[**CM**, Plestid, 2026]

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The variance

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

$$\rho_2 = \frac{1}{4}\begin{pmatrix} \circ & \blacksquare & \blacksquare & \bigstar \\ \blacksquare & \circ & \circ & \blacksquare \\ \blacksquare & \circ & \circ & \blacksquare \\ \bigstar & \blacksquare & \blacksquare & \circ \end{pmatrix}$$

The weirdos: product states

[**CM**, Plestid, 2026]

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The weirdos: product states

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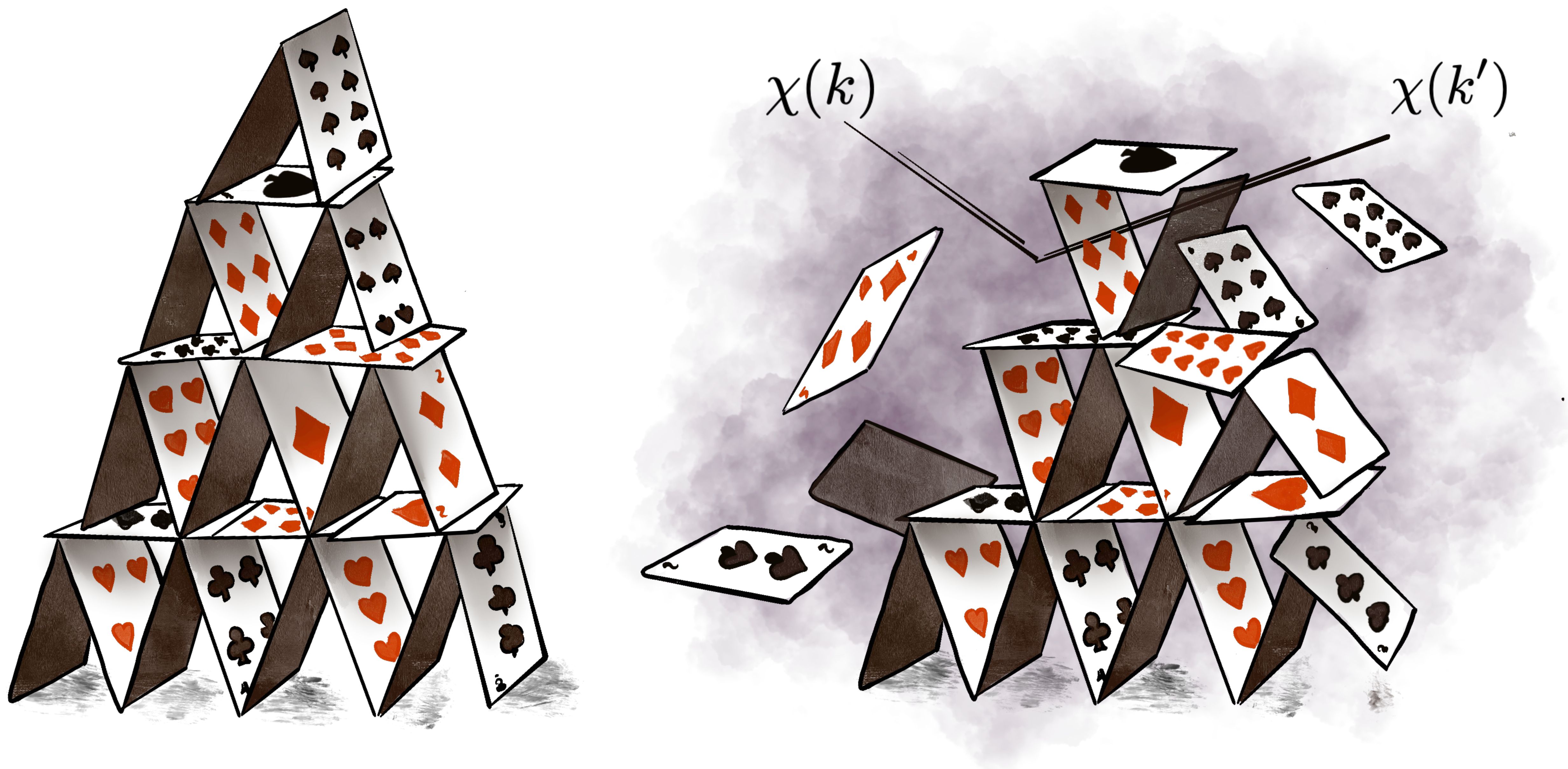
The weirdos: product states

[**CM**, Plestid, 2026]



New observable: super-binomial fluctuations

[**CM**, Plestid, 2026]

Applies to incoherent interactions

New observable: super-binomial fluctuations

[**CM**, Plestid, 2026]

Applies to incoherent interactions

Applies to isotropic interactions

New observable: super-binomial fluctuations

[**CM**, Plestid, 2026]

Applies to incoherent interactions

Applies to isotropic interactions

Sensitive to the full cross-section (no upper bound in $1/r_c$)

$$s_0 \simeq \Phi \mathcal{T} \sigma$$

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A 95%-CL, $\sigma^2_{\text{pred}}(s, s_0) - \sigma^2_{\text{obs}} \leq 2\sqrt{\text{var}(\sigma_0^2)/\aleph}$

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New observable: super-binomial fluctuations

[**CM**, Plestid, 2026]

$$s_0 \leq \frac{8\sqrt{2}}{N} \frac{1}{\sqrt{\aleph}} \bar{p}$$

$$s_0 \simeq \Phi \mathcal{T} \sigma$$

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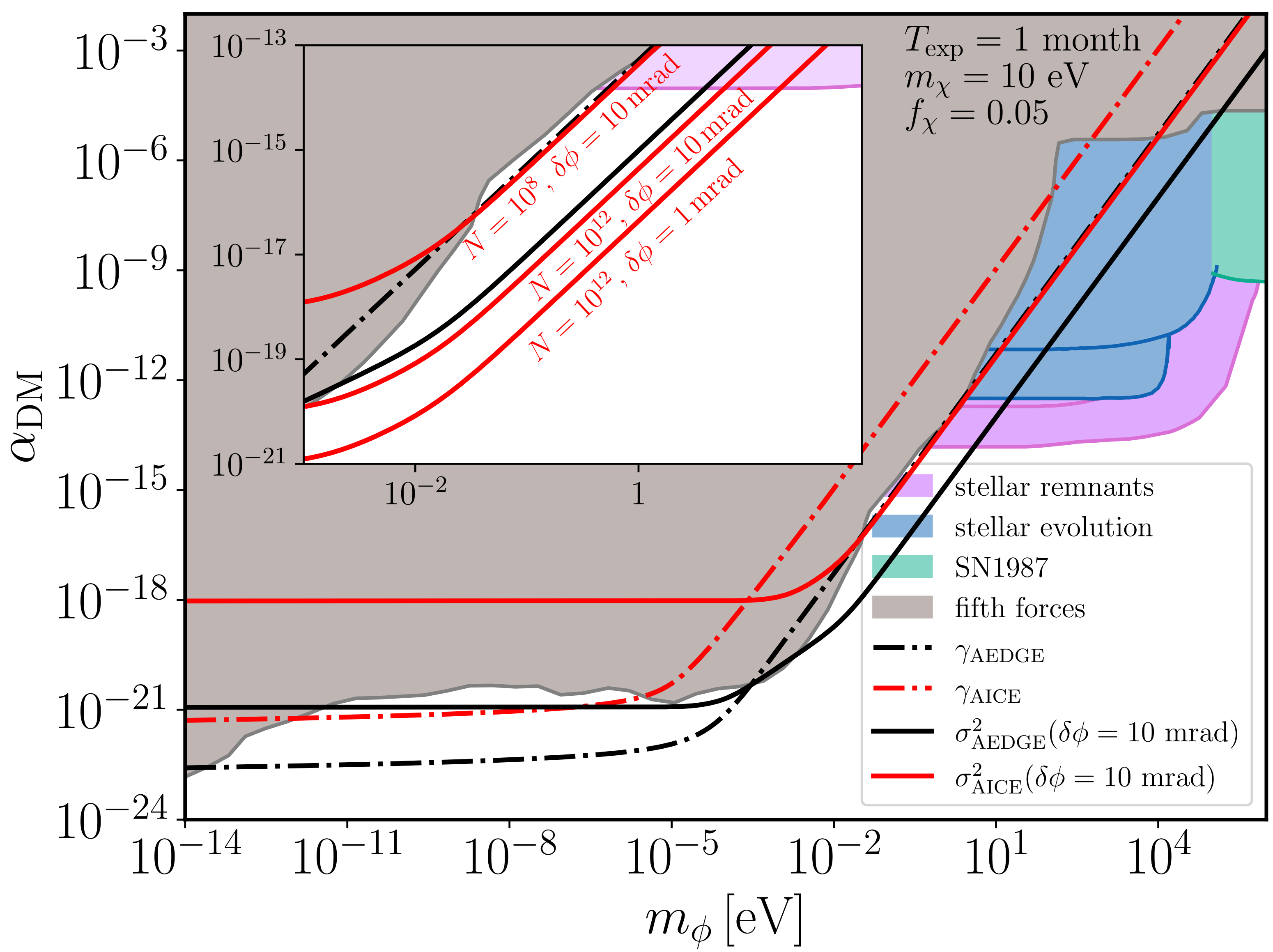
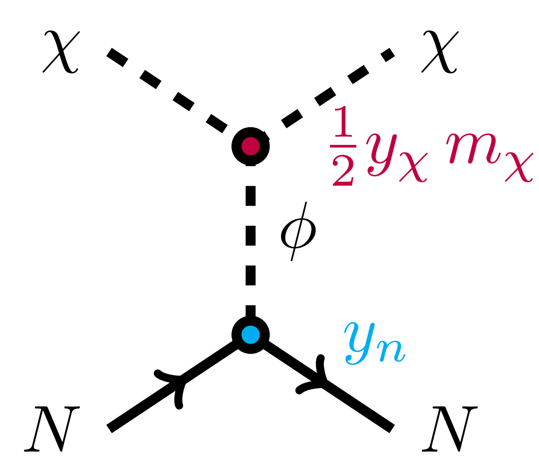


Long-range dark matter

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



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

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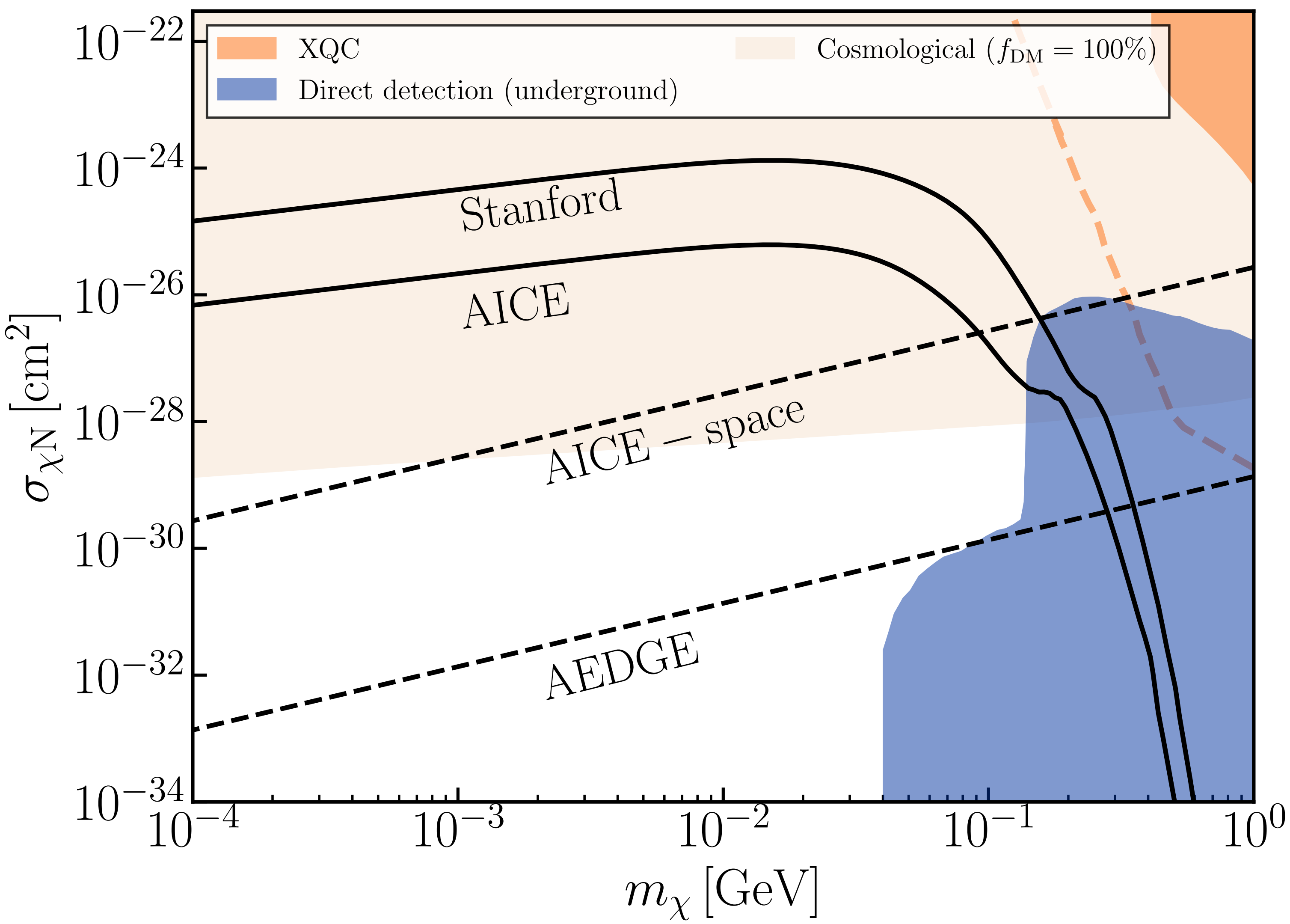
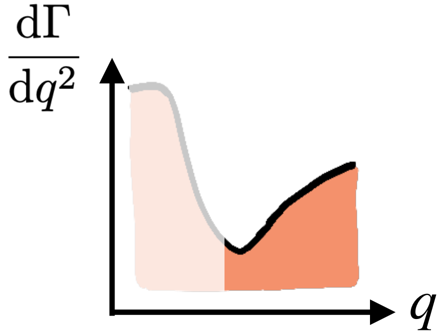


Strongly Interacting Dark Matter

Future steps

Conclusions

Atom interferometers open ("THE") parameter space.



Conclusions

Atom interferometers open (“THE”) parameter space.

These experiments exist! Many funded already. Parasitic searches.

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

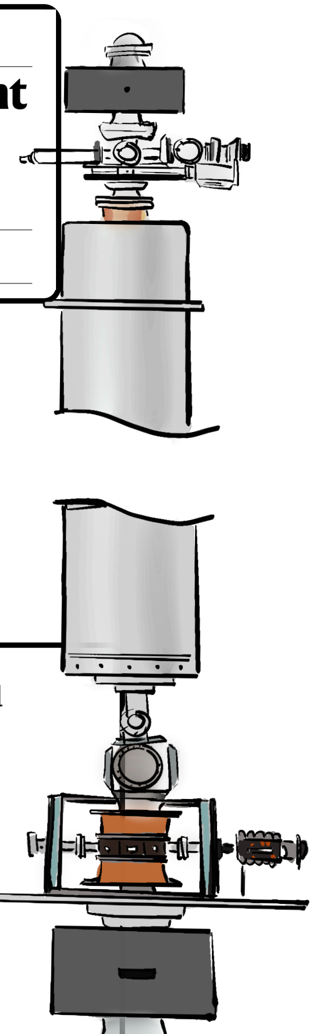
Léo Morel[1], Zhibin Yao[1], Pierre Cladé[1] & Saïda Guellati-Khélifa[1,2]

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

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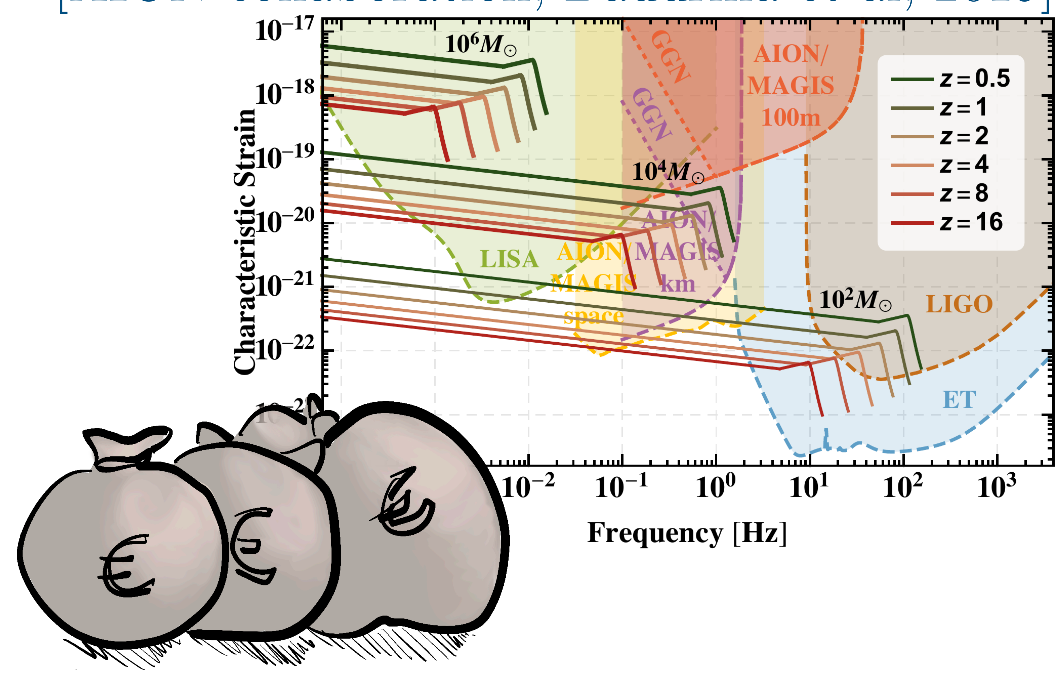
(Dated: June 25, 2020)

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 $5.4 \times 10^{-11}/\sqrt{\text{Hz}}$.

[AION collaboration, Badurina et al, 2019]



High Energy Physics – Experiment

[Submitted on 15 Sep 2025 (v1), last revised 16 Sep 2025 (this version, v2)]

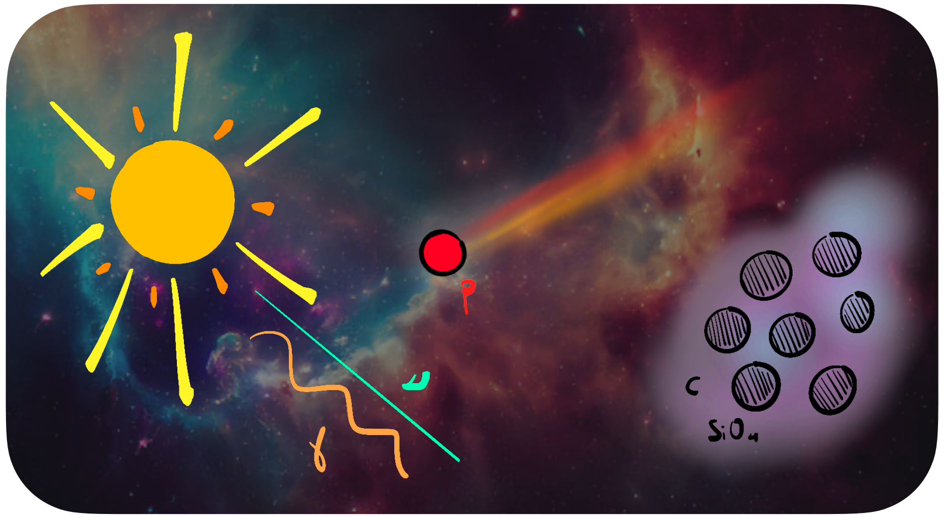
Letter of Intent: AICE -- 100m Atom Interferometer Experiment at CERN

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]

Conclusions

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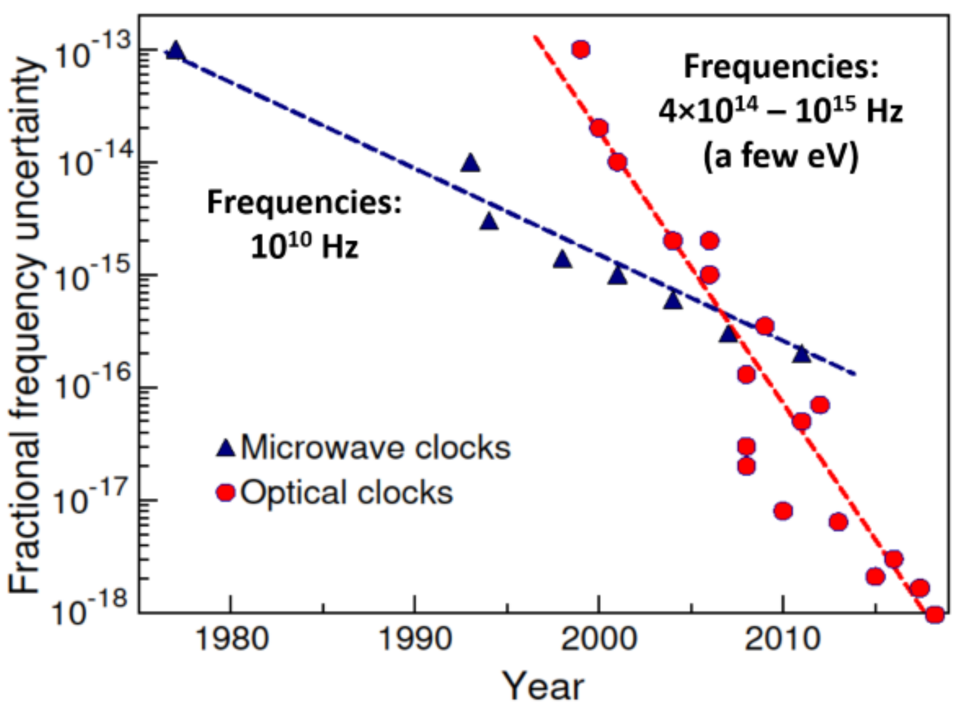
Boundaries not reached yet!
The line between science fiction and science fact vanishes quickly.




THIS IS WHERE YOU LOST YOUR WALLET?
NO, I LOST IT IN THE PARK. BUT THIS IS WHERE THE LIGHT IS.

THANK YOU!