Exploring the dark matter landscape with matter-wave interferometry

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IDM 2026, Zaragoza
June 4, 2026

Original plan for the talk

Part I	***Part II***	***Part III***
Gravitational signatures	***Electromagnetic couplings***	***Unified framework***
Proposed ***space-based atom gradiometer*** experiments may be sensitive to DM clumps and small ULDM overdensities via gravitational interactions	**Trapped-ion interferometers** could detect small B-fields sourced by kinetically-mixed dark photon and ALP DM.	Novel computational framework for computing leading order DM signatures in MWIs around the wave-particle boundary.
PRD '25 [LB, Du, Lee, Wang, Zurek]	*PRD '26 [LB, Blas, Ellis, Ellis]*	**2606.00237 [LB, Zurek]**

Actual plan for the talk

Part I	***Part II***	***Part III***
	Ask me later/offline	Ask me later/offline
Gravitational signatures	***Electromagnetic couplings***	***Unified framework***
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PRD '25 [LB, Du, Lee, Wang, Zurek]	*PRD '26 [LB, Blas, Ellis, Ellis]*	**2606.00237 [LB, Zurek]**

Detecting gravitational signatures of dark matter with atom gradiometers

Based on PRD '25
[LB, Du, Lee, Wang, Zurek]

Gravitational searches of DM

Idea: *DM gravitates and therefore distorts spacetime → observable effects on test masses and photon propagation.*

*This is **model-independent:** no need to assume non-gravitational coupling to SM fields [equivalently, this is the "worst-case scenario" for DM direct detection]*

Ultralight DM

Oscillating energy density/pressure
→ oscillating metric perturbation at frequency 2m

Compact DM clumps

Transient fly-by
→ time-varying acceleration on test masses

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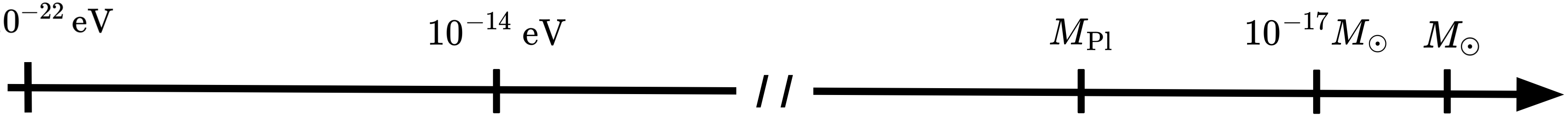

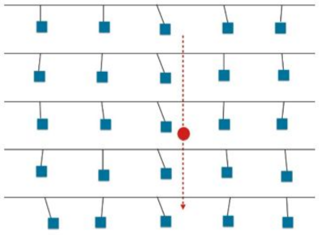

Mechanical sensors

PRD '20 [Carney et al.],
QST '21 [Carney et al.]
Windchime Project [2021]
...

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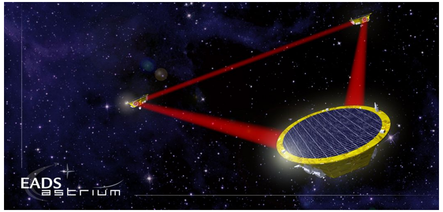
Laser interferometers (LIs) *

JCAP '23 [Kim]



**best probe of DM overdensities*

Mechanical sensors

LIs

PRD '04 [Seto et al.],
PRD '22 [Baum et al.]
PRD '23 [Lee et al.]
...

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10^{-22} eV — 10^{-14} eV — // — $M_{\rm Pl}$ — $10^{-17} M_\odot$ — $M_\odot$

Pulsar timing arrays (PTAs)

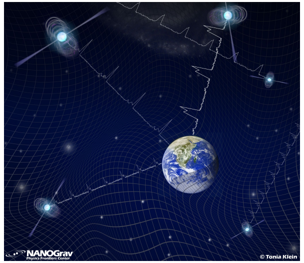
Laser interferometers (LIs) *

Mechanical sensors

LIs

PTAs

JCAP '14 [Khelmitsky et al.]
PRD '24 [Kim et al.]



MNRAS '07 [Siegel et al.],
PRD '19 [Dror et al.]
...

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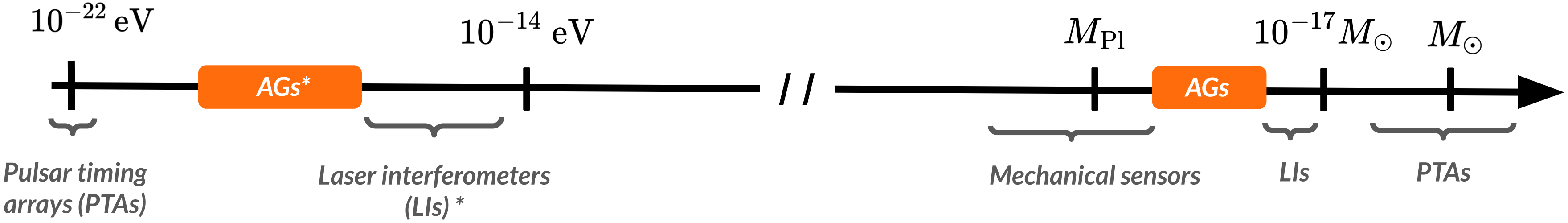
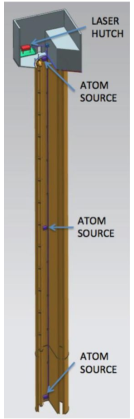


Atom gradiometers (AG) experiments proposed for mid-frequency (10^{-3} -1 Hz) GW searches

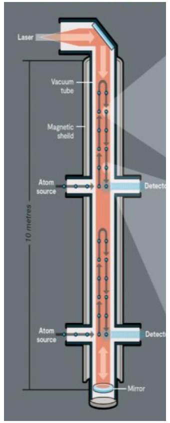
**best probe of DM overdensities*

An overview of the (future) experimental landscape

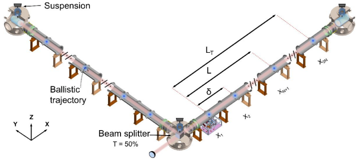
Several experiments have been proposed to search for GW seaches and linearly-coupled ULDM



MAGIS-km
[QST '21]

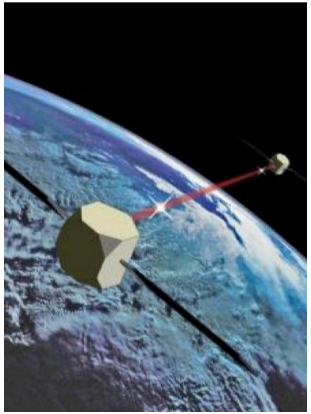


AION-km
[JCAP '20]



ELGAR
[CQG '19]

ZAIGA
[IJPD '20]



AEDGE/AEDGE+
[EPJ Quant '20]

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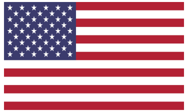
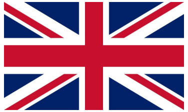
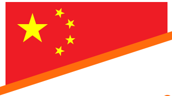
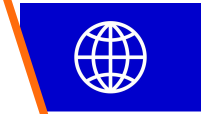
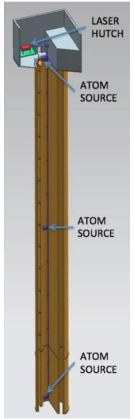



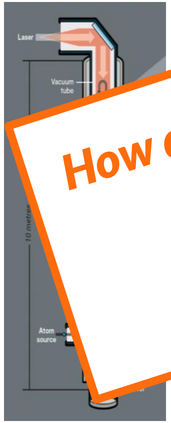



How do atom gradiometers/interferometers work?

How can they detect gravitational perturbations?



MAGIS-km
[QST '21]



AION-km
[JCAP '20]

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[CQG '19]

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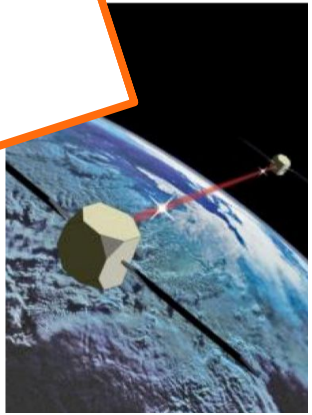


AEDGE/AEDGE+
[EPJ Quant '20]

Light-pulse atom interferometry: the theoretical minimum

Two-level atomic system:
ground state $|g\rangle$ *and excited state* $|e\rangle$,
with energy splitting ω_A .
(e.g. for the clock transition in Sr-87, $\omega_A \simeq 1\ \mathrm{eV}$ *)*

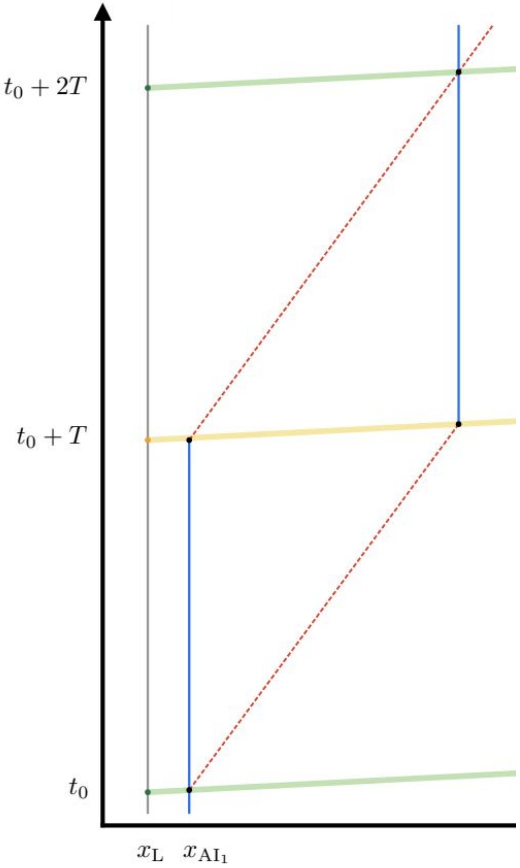
Motional (c.o.m.) *and* ***internal dofs*** *coupled via* ***atom-light interactions (Rabi oscillations)***

Laser pulses act as
beamsplitters (π/2) *and* ***mirrors (π)****:*
$\longrightarrow$ ***π/2-pulses*** *create spatial superpositions of atomic wavepackets and impart a relative kick*
$\longrightarrow$ ***π-pulses*** *redirect spatial superposition of atomic wavepackets and change their internal state*

The atomic wavepackets traverse different regions of spacetime, thereby accruing a
non-vanishing relative gravitational phase

$$\Delta\phi \simeq \int_C m d\tau$$

A theorist's sketch: "spacetime" diagrams



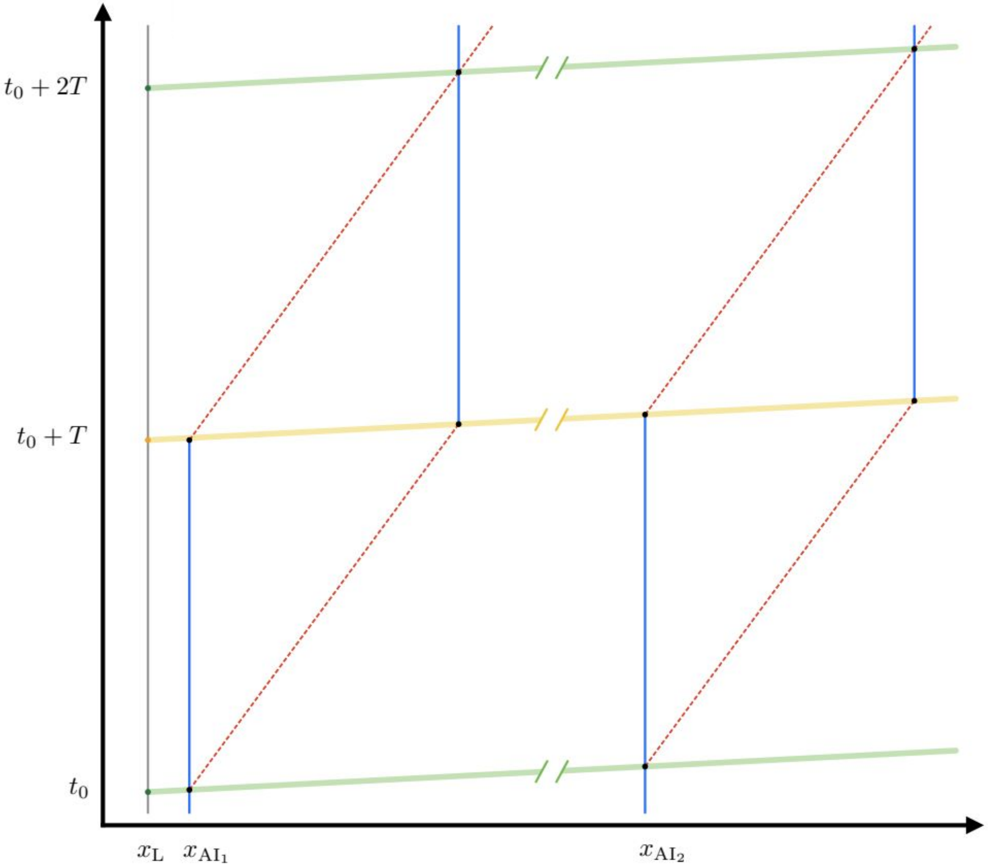
π/2–π–π/2 sequence (1+1 dimensions):

1. t_0: beamsplitter (π/2 pulse)⟶ superposition of $|g\rangle$ and $|e\rangle$, and the excited state recoils with momentum ω_A
2. t_0 + T: mirror π pulse ⟶ swaps atomic states, reverses relative momentum
3. t_0 + 2T : beamsplitter π/2 pulse ⟶ recombines paths for measurement in the qubit basis.

Interrogation time T sets the sensitivity:

longer T ⟶ larger enclosed spacetime area ⟶ larger phase shift from gravity

A theorist's sketch: the Mach-Zehnder atom gradiometer



Two atom interferometers *separated by baseline L,*
driven by common laser pulses

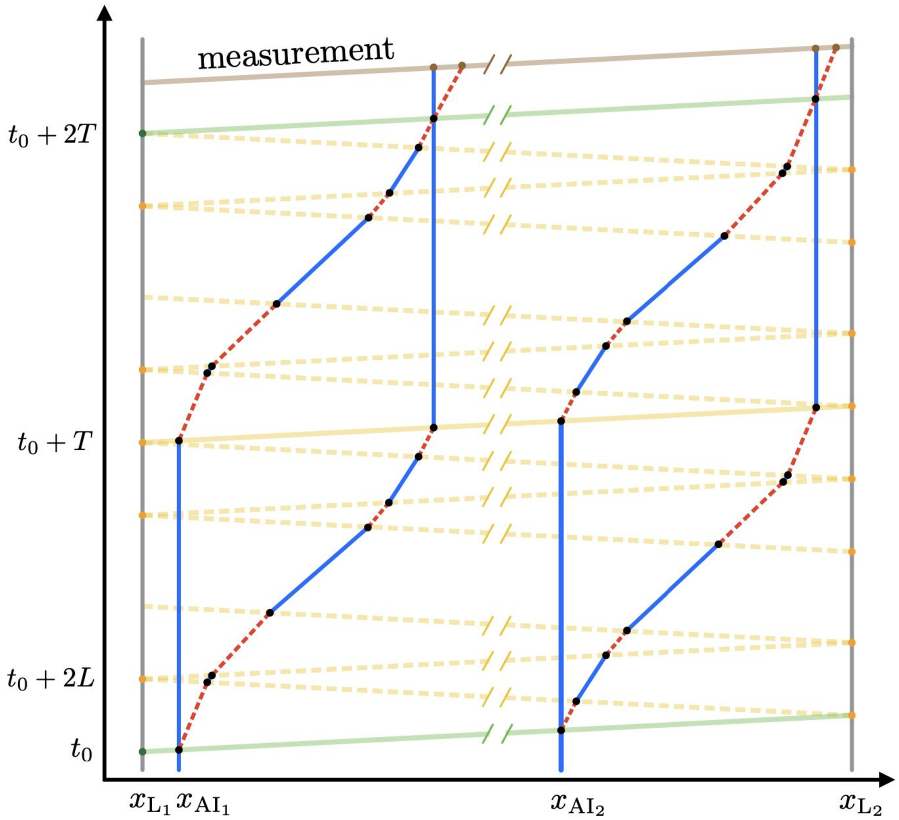
Differential measurement:

$$\Delta\phi_{\mathrm{grad}} = \Delta\phi_1 - \Delta\phi_2$$

✓ *Sensitive to* ***differential (tidal) effects***
✓ ***Laser phase noise cancels*** $\rightarrow$
Can operate at the ***atom shot-noise limit***

Analogous to a single-arm laser interferometer,
but with the atoms playing the role of mirrors/beamsplitters

Large-momentum transfer: boosting sensitivity



***Idea**: use n photon kicks to increase the spatial separation between arms*
[Graham et al., PRL '13]

$k_{\mathrm{eff}} = n\omega_a$ *: effective momentum transfer*

LMT sequence (4n − 1 pulses):

1. *Beamsplitter sequence: π/2 + (n − 1) π-pulses incrementally kick one arm*
2. *Mirror sequence: (2n − 1) π-pulses redirect the wavepackets at ~ t_0 + T*
3. *Final beamsplitter sequence: recombine the arms*

Phase shift scales as $\Delta\phi_{\mathrm{grad}} \propto k_{\mathrm{eff}} T^2$.
⇒ sensitivity ∝ n

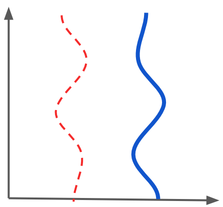
How does gravity affect the AG observable*?

*Dramatically simplifies existing framework [Dimopolous et al. '08]

A small metric perturbation $h_{\mu\nu}$ affects the gradiometer phase through three channels:

[LB, Du, Lee, Wang, Zurek, PRD '25]

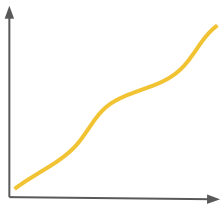
Doppler phase shift



Tidal displacement of atoms along the baseline

$$\Delta\phi_{\mathcal{D}} \propto \nabla h_{00}$$

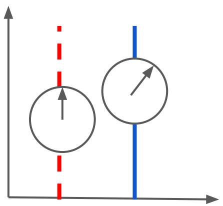
Shapiro phase shift



Delay in photon arrival time between AIs in the AG

$$\Delta\phi_{\mathcal{S}} \propto h_{00} + h_{ij}$$

Einstein phase shift



Difference in the gravitational redshift measured by the AIs

$$\Delta\phi_{\mathcal{E}} \propto h_{00}$$

$$\boxed{\Delta\phi_{\text{grad}} = \Delta\phi_{\mathcal{D}} + \Delta\phi_{\mathcal{S}} + \Delta\phi_{\mathcal{E}} + \mathcal{O}\left(h\frac{\omega_a^2}{m_a^2}\right)}$$

Each term is NOT diffeo-invariant, but their sum is, as desired.

Atom gradiometers vs laser interferometers

	Atom gradiometers (AGs)	Laser interferometers (LIs)
Doppler (tidal displacement)	✓	✓
Shapiro (photon time delay)	✓	✓
Einstein (gravitational redshift)	✓	✗

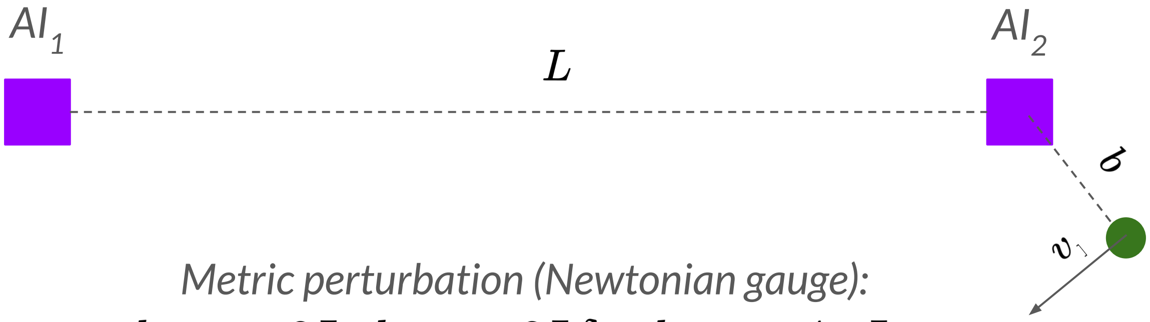
$$\boxed{\Delta\phi_{\mathrm{AG}} \supset \Delta\phi_{\mathrm{LI}}}$$

[Rakhmanov PRD '05]
[Lee, Zurek, PRD '25]

This extra channel will be decisive for ultralight DM searches

Dark clumps: the physical picture

A compact DM clump of mass M flies by with impact parameter b and velocity v



Metric perturbation (Newtonian gauge):

$$h_{00} = -2\Phi,\ h_{ij} = -2\Phi\delta_{ij},\ h_{0i} = -4v_i\Phi,$$

where Φ is the Newtonian potential

Key scales:

Signal duration: ~ b/v

Cutoff frequency: ω ~ v/b

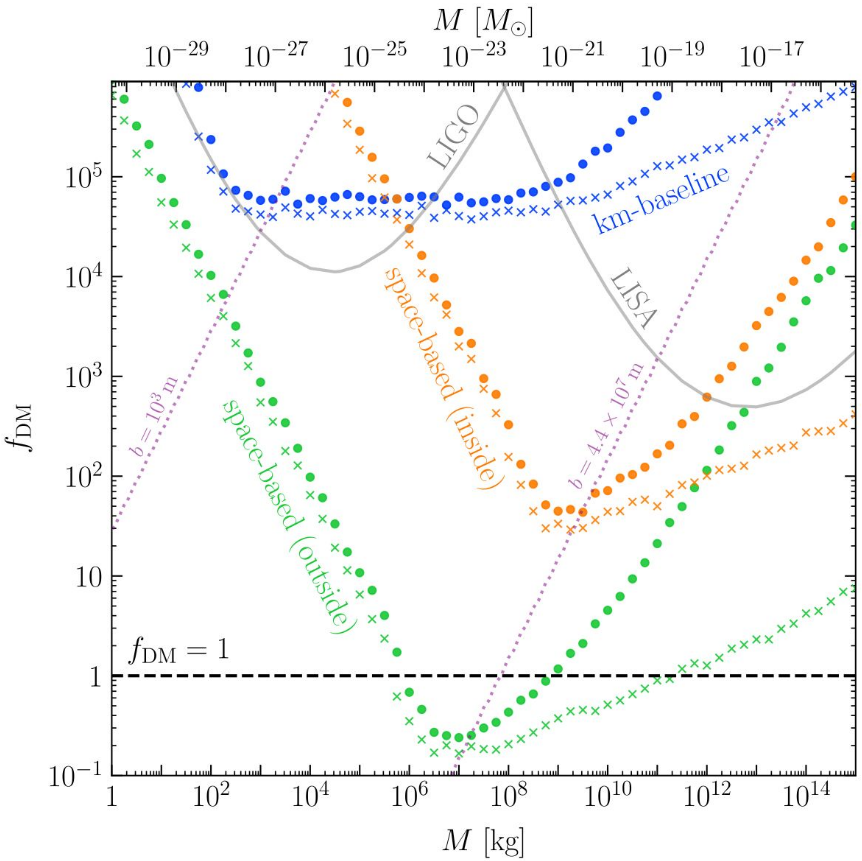
[NB the detector is a low-pass filter, so frequencies above 1/T are suppressed]

[Fourier transform of the potential is flat for ω ≪ v/b, and exponentially suppressed for ω ≫ v/b]

Dark clumps: projected sensitivity

Signal dominated by Doppler phase shift (confirming Newtonian intuition)

AEDGE+ might be able to probe a DM subcomponent via purely gravitational interactions!



AION-km/MAGIS-km

$L = 1$ km
$n = 2500$
$T = 1.7$ s
$\delta\varphi = 10^{-5}\ \mathrm{Hz}^{-1/2}$

AEDGE

$L = 4.4 \times 10^7$ m
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AEDGE+

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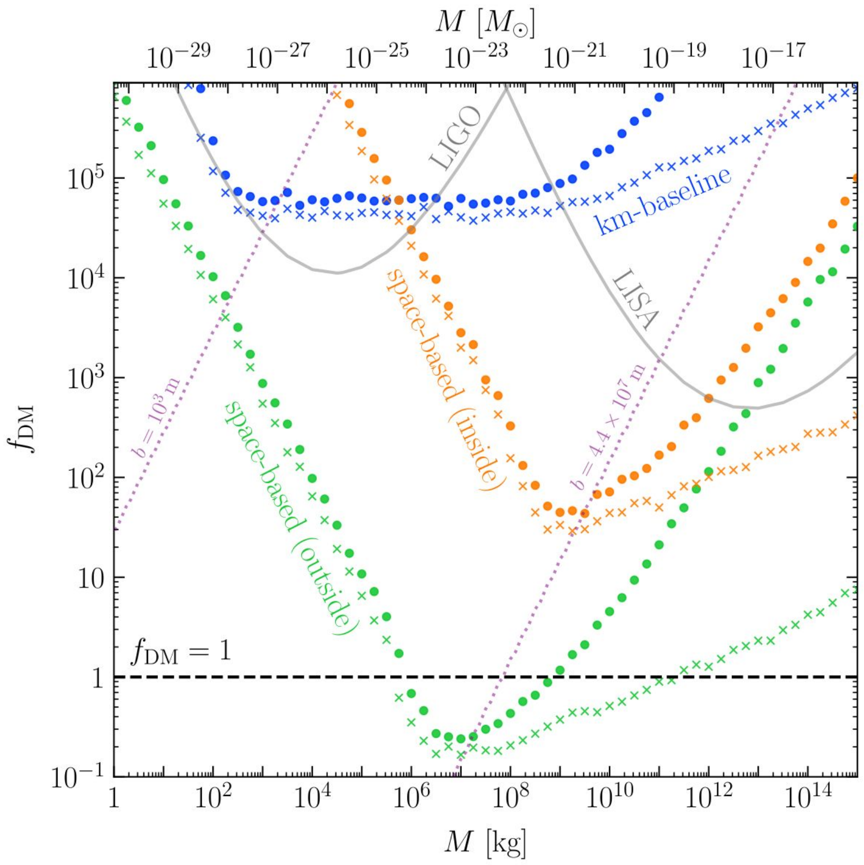

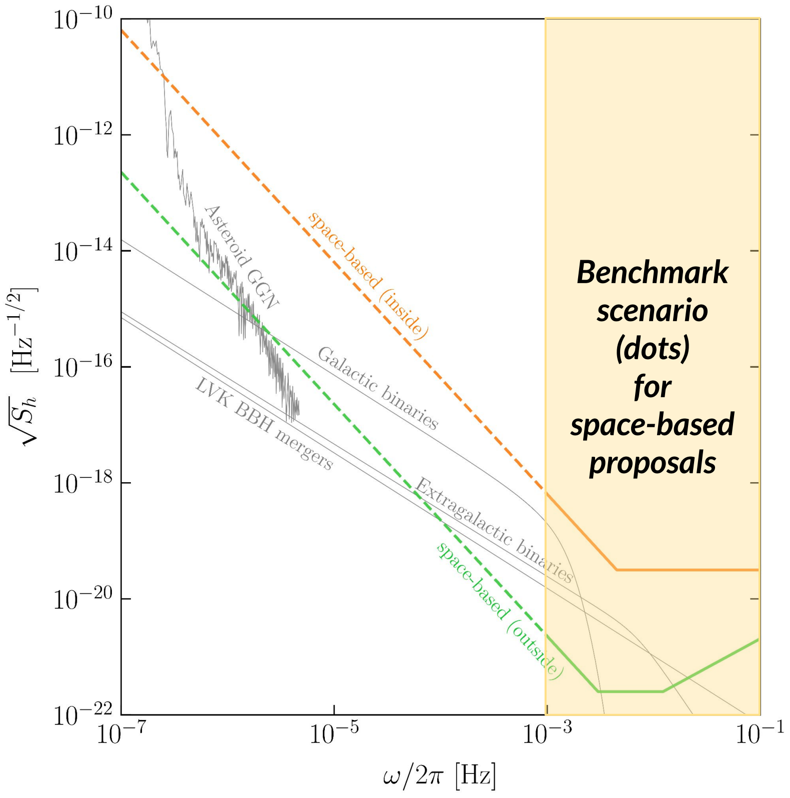

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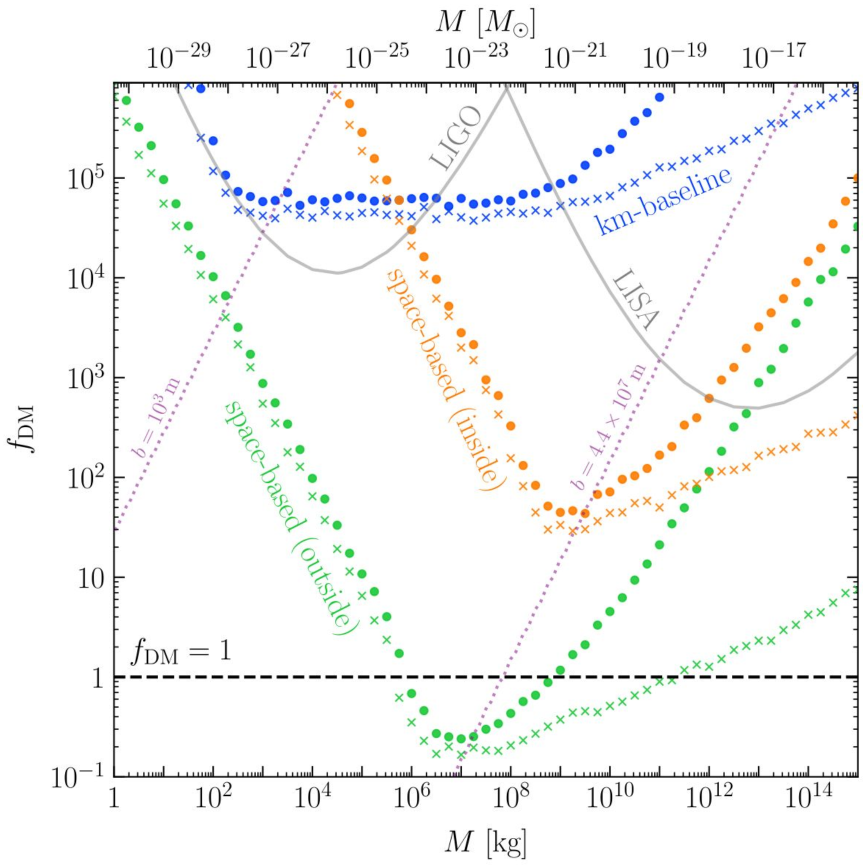
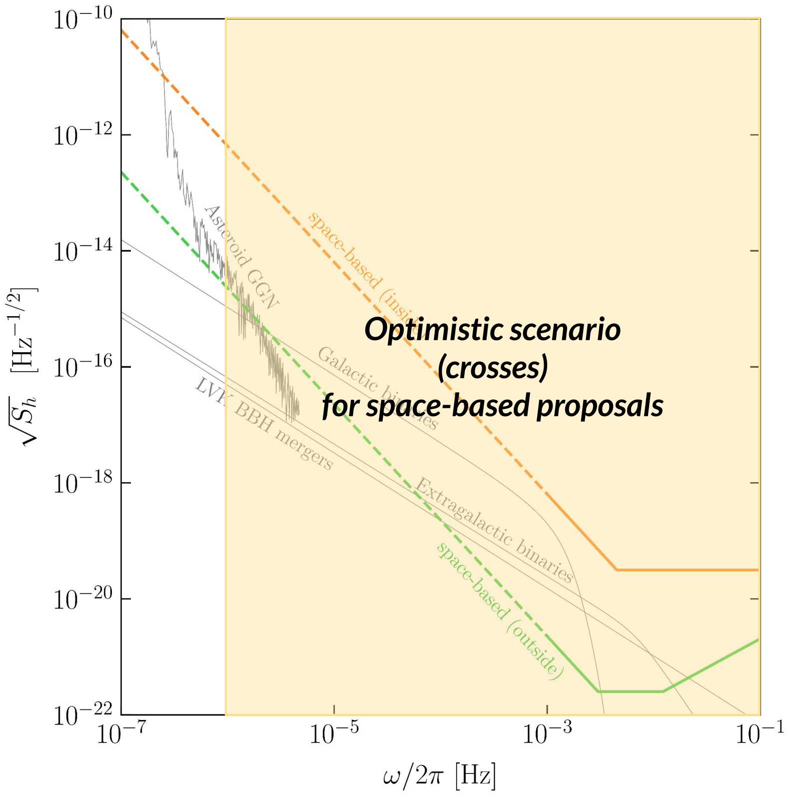




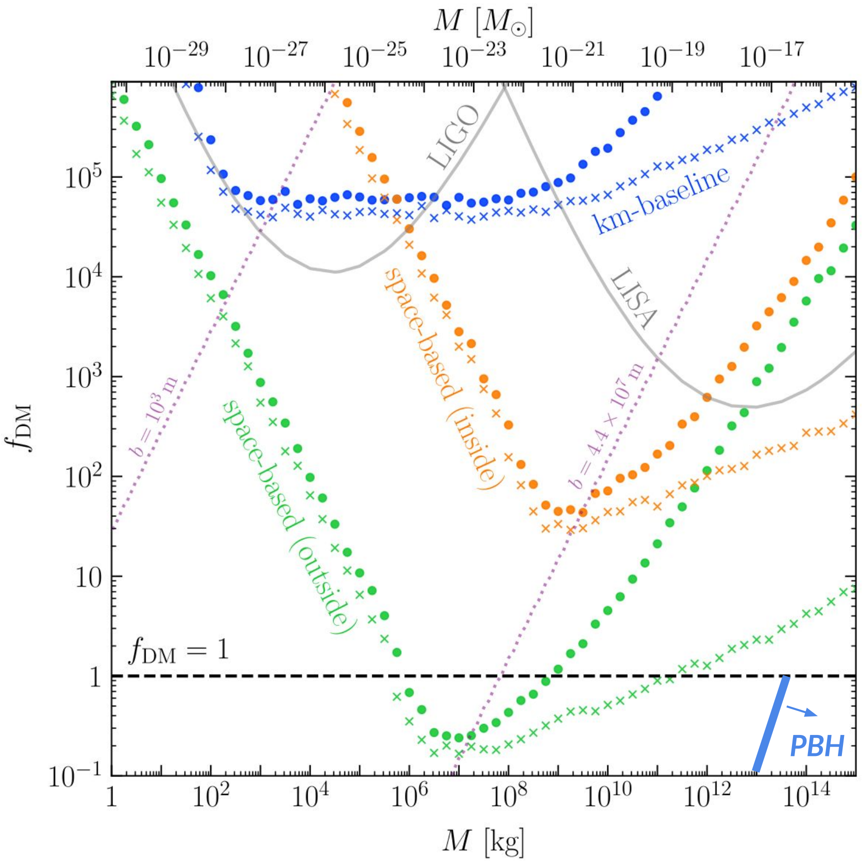
Dark clumps: projected sensitivity

Full GR calculation confirms heuristic estimate

AEDGE+ might be able to probe a DM subcomponent via purely gravitational interactions!

What DM candidate could this be?

Not PBHs…
Not DM sub-structure,
DM bound state



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Ultralight dark matter (ULDM): the gravitational signal

***ULDM**: oscillating classical field,*

$$\phi = \phi_0 \cos(mt - \mathbf{k}\cdot\mathbf{x} + \theta)$$

with

$$\langle \phi_0^2 \rangle = 2 f_{\rm DM} \rho_{\rm DM}/m^2$$

Energy density and pressure contain a piece fluctuating at frequency 2m:

$$T_{\mu\nu} \supset \partial_\mu \phi \partial_\nu \phi \propto \cos(2mt - 2\mathbf{k}\cdot\mathbf{x})$$

*Solve linearized Einstein equations → metric perturbation in **Newtonian gauge**:*

$$h_{00} = \pi G \phi_0^2 \cos(2mt - 2\mathbf{k}\cdot\mathbf{x}), \quad h_{ij} = -\pi G \phi_0^2 \cos(2mt - 2\mathbf{k}\cdot\mathbf{x})\delta_{ij}$$

Key observation:

Phase-coherent signal within a coherence length/time "similar" to a transient GW at frequency 2m.

$$h_{\mu\nu} = \Phi \eta_{\mu\nu} \qquad \tau_c \sim 1/mv^2 \; \lambda_c \sim 1/mv.$$

ULDM: effect on test particles

Gravity couples to test particles via:

$$h_{\mu\nu}T^{\mu\nu} = \Phi\eta_{\mu\nu}T^{\mu\nu} = \Phi T^{\mu}_{\mu}$$

What is the trace of the energy-momentum tensor for test particles in the experiment?

Atoms *(massive particles)*

$$T^{\mu}_{\mu} \propto m$$

⇒ Atoms feel the ULDM field through the Einstein and Doppler time delay/phase shift

Photons *(massless)*

$$T^{\mu}_{\mu} = 0$$

(classically)

⇒ Photons are blind to the ULDM field and the Shapiro delay exactly vanishes

Shapiro term is exactly zero for ULDM in Newtonian gauge

ULDM: AGs vs LIs

Atom gradiometers

***Einstein**: $\Phi \sim O(v^0)$ ✓*
Dominant.
***Doppler**: $\nabla\Phi \sim O(v)$ (subdominant)*
***Shapiro**: exactly zero*

⇒ Signal unsuppressed

Laser interferometers

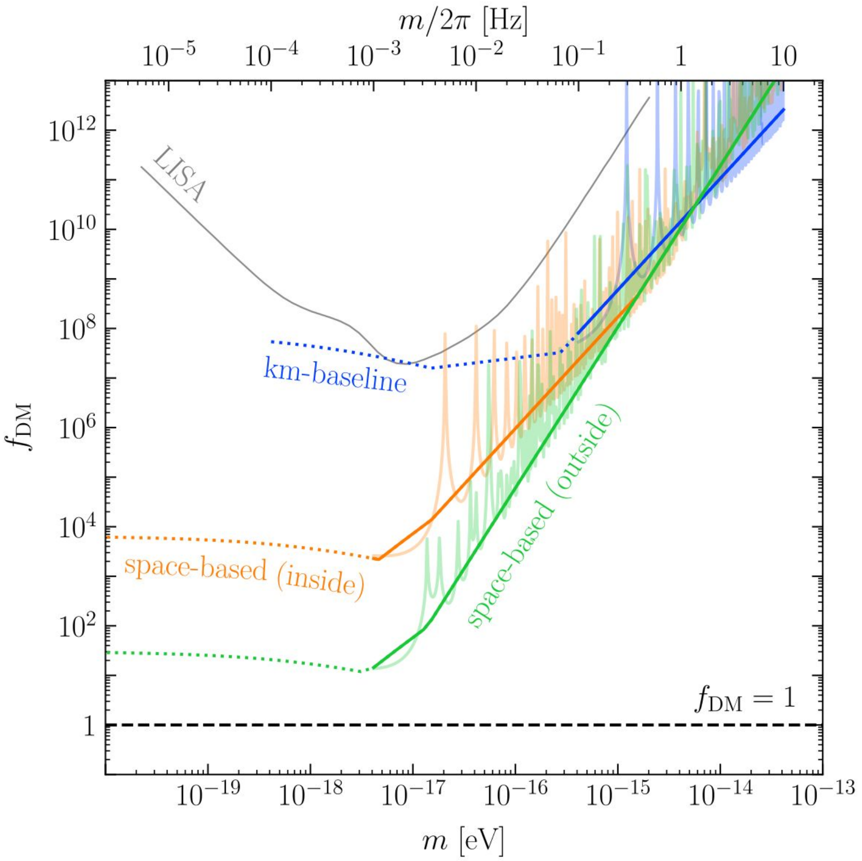
***Einstein**: N/A* ×
Mirrors have no clock d.o.f.
***Doppler**: $\nabla\Phi \sim O(v)$ (dominant)*
Suppression from tidal displacement $L/\lambda \ll 1$
***Shapiro**: zero (same reason)*

⇒ Signal velocity-suppressed

AGs are parametrically more sensitive to ULDM than LIs with comparable strain sensitivity

ULDM: projected sensitivity

The most ambitious space-based experiment would be the best probe of DM overdensities in this mass range [Planetary ephemerides: $f \lesssim 10^4$]



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ULDM: projected sensitivity

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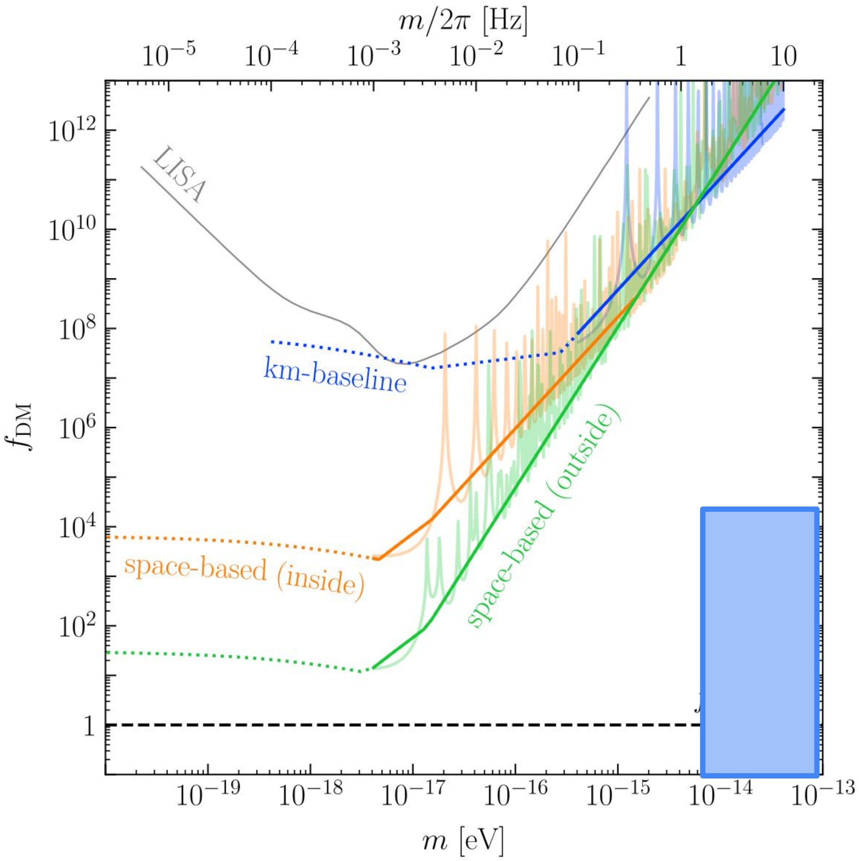
Do we expect a O(10) overdensity?

DM self-interactions + gravitational focusing [Budker et al., JCAP '23]?

Model building required (see J. Carlton's talk)



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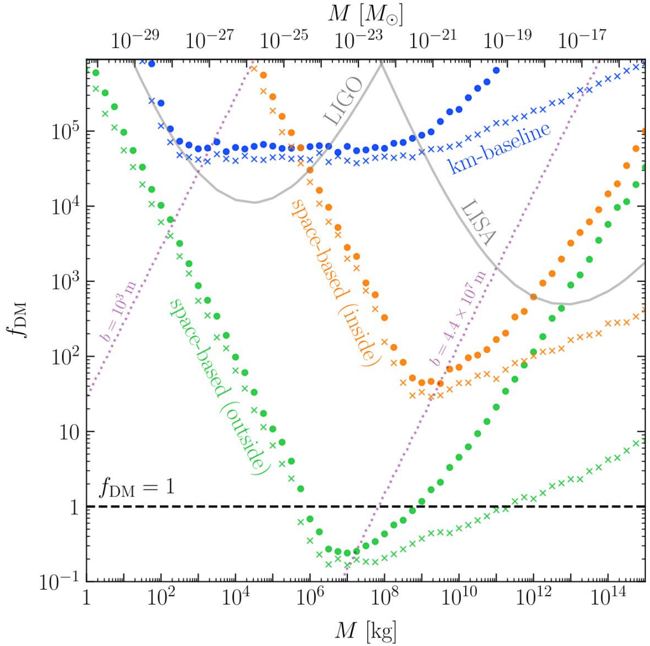
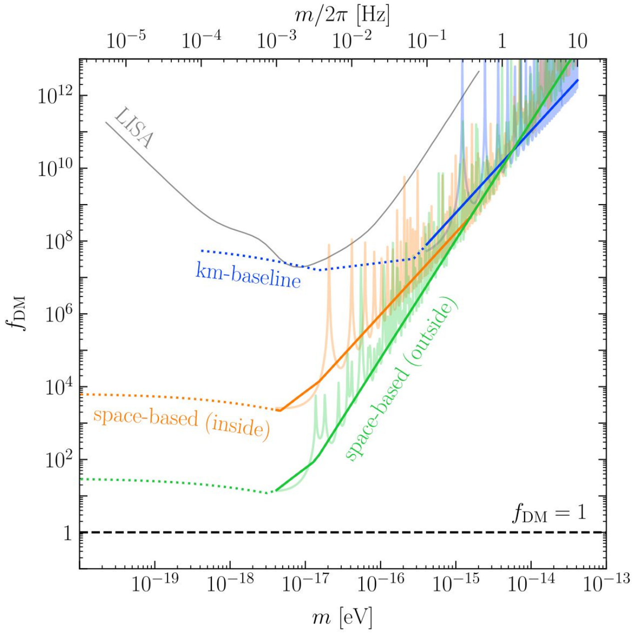
Summary

Dark clumps



Unique mass window, driven by anticipated ***acceleration sensitivity***

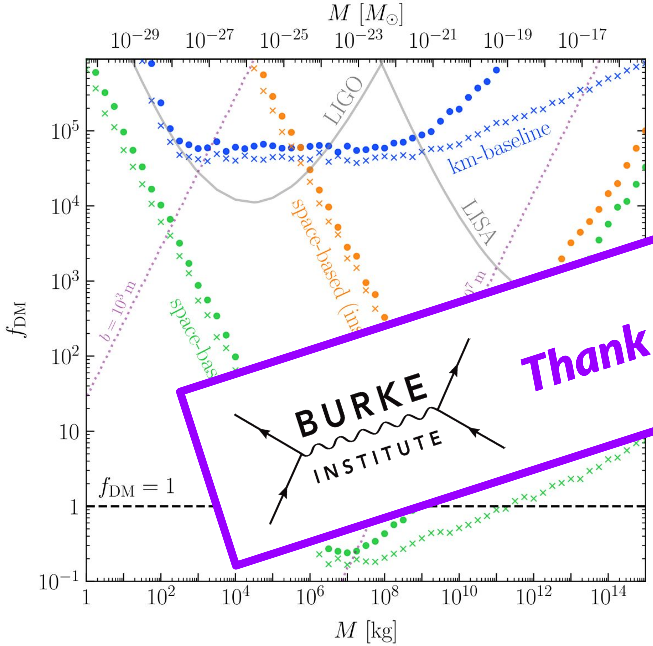
Ultralight dark matter



Parametrically better than LISA, due to ***Einstein time delay*** *sensitivity*

Summary

Dark clumps



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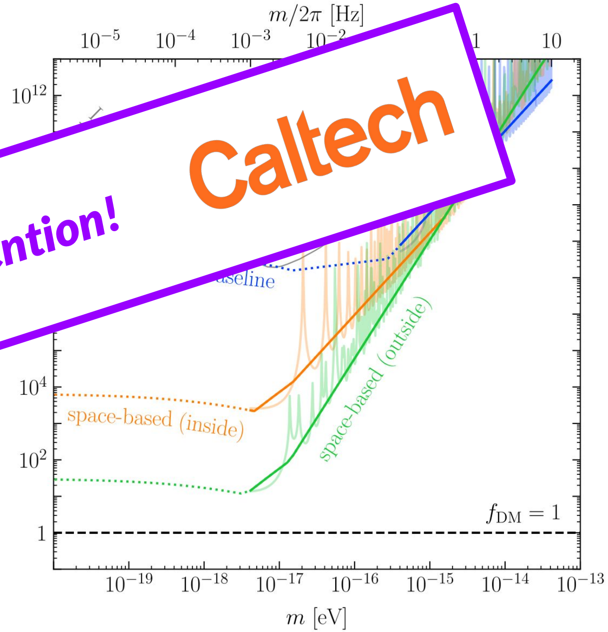

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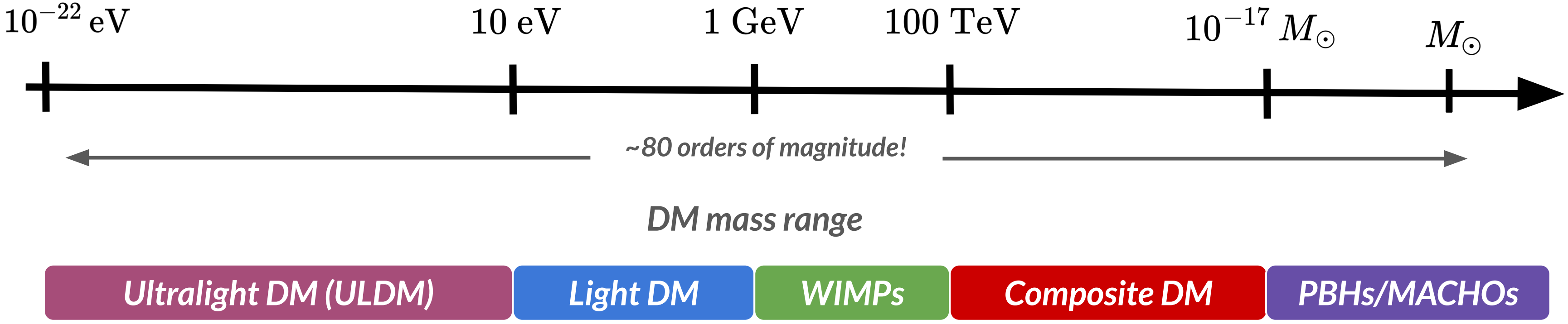
Thank for your attention!

Caltech

BURKE INSTITUTE

Back-up slides

The dark matter landscape



Many models, many possible couplings to the SM

⬇

Many different laboratory (and astrophysical) probes are necessary.

Can we leverage quantum sensing techniques to probe unexplored regions of DM model space with "tabletop" experiments?

Yes, e.g. matter-wave interferometry (MWI)

Dark clumps: signal

Signal is dominated by the Doppler term *(tidal acceleration of atoms)*

Contribution	*Scaling at ω ~ v/b*	*Suppression*
Doppler	$\sim k_{\text{eff}} T^2 \cdot GM/bv$	$-$
Shapiro	$\sim k_{\text{eff}} T^2 \cdot GM\omega L/bvT$	$\times vL/T$
Einstein	$\sim k_{\text{eff}} T^2 \cdot GMv/b$	$\times v^2$

Intuition*: in the lab frame, the dominant effect is simply the Newtonian acceleration GM/b^2 acting on the atoms. Einstein and Shapiro phase shifts are relativistic corrections.*

$$|\Delta\phi_{\text{grad}}| \sim k_{\text{eff}} T^2 \frac{GM}{bv} \min\left(1, \frac{2L}{b}\right)$$

Dark clumps: heuristic reach estimate à la Baum et al. PRD '22

SNR for a shot-noise limited detector:

$$\mathrm{SNR} \sim k_{\mathrm{eff}} T^2 \frac{GM}{bv} \sqrt{\frac{\Delta\omega}{2\pi S_n}} \min\left(1, \frac{2L}{b}\right)$$

Assume a single event in T_{int}~3 years:

$$f_{\mathrm{DM}} \frac{\rho_{\mathrm{DM}}}{M} b^2 T_{\mathrm{int}} v \sim 1$$

$$\Rightarrow \quad b \sim \sqrt{\frac{M}{\rho_{\mathrm{DM}} f_{\mathrm{DM}} v T_{\mathrm{int}}}}$$

Scaling:

$$f_{\mathrm{DM}}^{(\mathrm{min})} \propto \begin{cases} M^{-1} & b \lesssim vT, L \\ M^{-1/3} & vT \lesssim b \lesssim L \\ M^{0} & L \lesssim b \lesssim vT \\ M^{1/5} & b \lesssim vT, L \\ M^{1} & b \sim v/\omega_{\min} \end{cases}$$

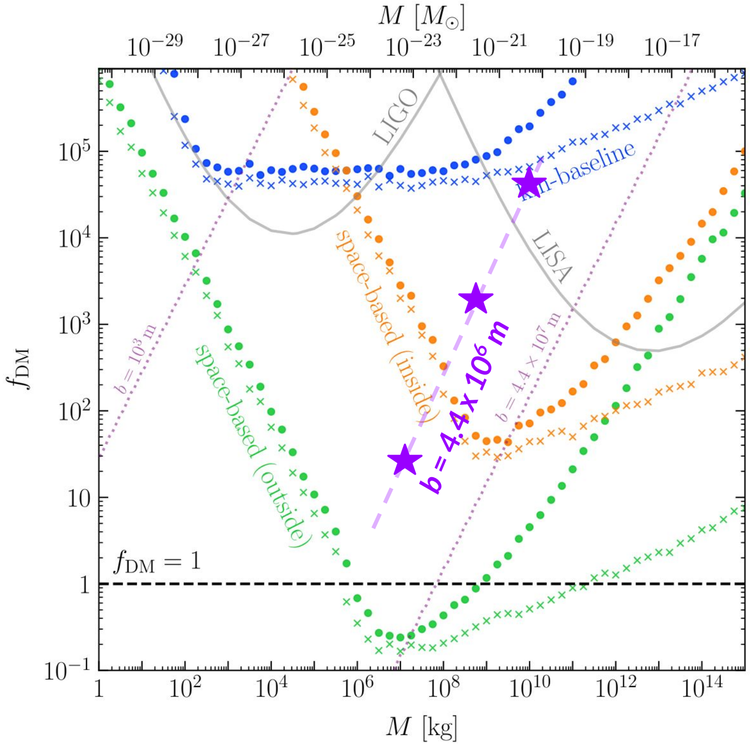
Peak sensitivity (assuming AEDGE+)

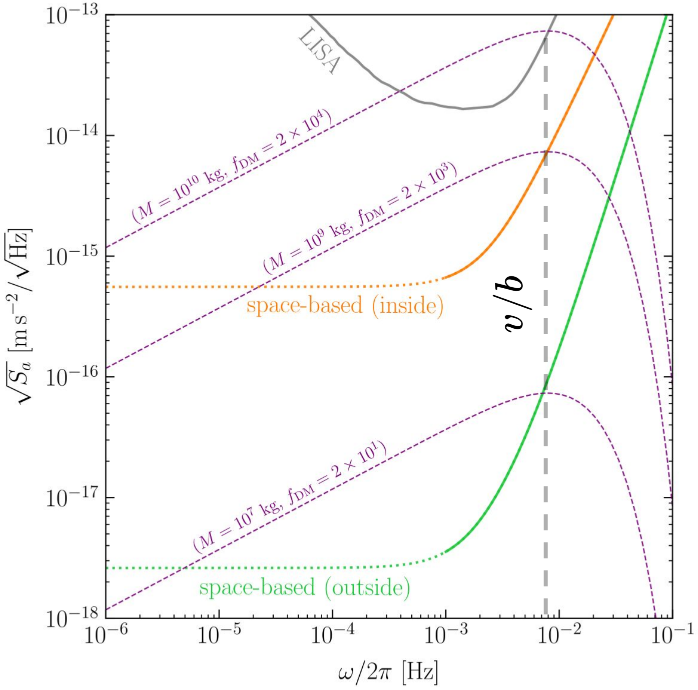
$$b \sim L$$

$$M^{(\star)} \sim \mathcal{O}\left(10^6\ \mathrm{kg}\right)$$

$$f_{\mathrm{DM}}^{(\star)} \sim \mathcal{O}(0.1)$$

Dark clumps: why space-based AGs beat LISA + LIGO





AGs are better accelerometers than LIs operating in the same frequency range because of the $k_{\rm eff}T^2$ *enhancement and small phase noise*

ULDM: signal

Signal amplitude *(Einstein-dominated):*

$$\sqrt{\langle|\Delta\phi_{\rm grad}|^2\rangle} = \frac{4\pi G\omega_a f_{\rm DM}\rho_{\rm DM}}{m^3}\sin(mT)\sin(mnL)\sin(m(T-(n-1)L))$$

Scaling of minimum detectable DM fraction:

$$f_{\rm DM}^{(\rm min)} \propto \begin{cases} m^0 \text{ for } m \lesssim 1/T, 1/nL \\ m^2 \text{ for } 1/T \lesssim m \lesssim 1/nL \\ m^3 \text{ for } m \gtrsim 1/T, 1/nL \end{cases}$$

Peak sensitivity:

$$m^{(\star)} \lesssim 10^{-17}\text{eV}$$

$$f_{\rm DM}^{(\star)} \sim \mathcal{O}(10)$$

for AEDGE+

GW signal in different frames

	Transverse-traceless (TT) frame	Proper detector frame (PD)
Doppler	0	Yes (dominant)
Shapiro	Yes	Yes (subdominant)
Einstein	0	Yes (subdominant)

Sum of 3 contributions is identical in both frames
+
Results agree with, e.g., PRD '08 [Dimopolous et al.]

Beyond gravity: electromagnetic couplings

***Different direction**: some ULDM candidates produce oscillating **electromagnetic fields**.*

Kinetically-mixed dark photon

$$\mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

$\rightarrow$ *effective oscillating current*

$\rightarrow$ *small oscillating B-field at frequency m*

Axion-like particles (ALPs)

$$\mathcal{L} \supset g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

$\rightarrow$ *in external B field (e.g. Earth's field):*

Small oscillating B-field at frequency m

Can we detect these with matter-wave interferometry?

Yes, using a trapped-ion interferometer, through sensitivity to oscillating B-fields via the Aharonov–Bohm effect

Part II:

Ultralight dark matter detection with trapped-ion interferometers

Based on PRD'26, 2507.17825
[LB, Diego Blas, John Ellis, Sebastian Ellis]

Key features of trapped-ion interferometry

Proposal developed by Wes Campbell and Paul Hamilton for rotation sensing [JPB, 2017]

Key features:

Matter-wave interferometry with electrically charged states

Entanglement of spin and motional degrees of freedom

Magnetically-insensitive states -> long coherence times of the excited state

Harmonic and rotationally symmetric potential in 2D

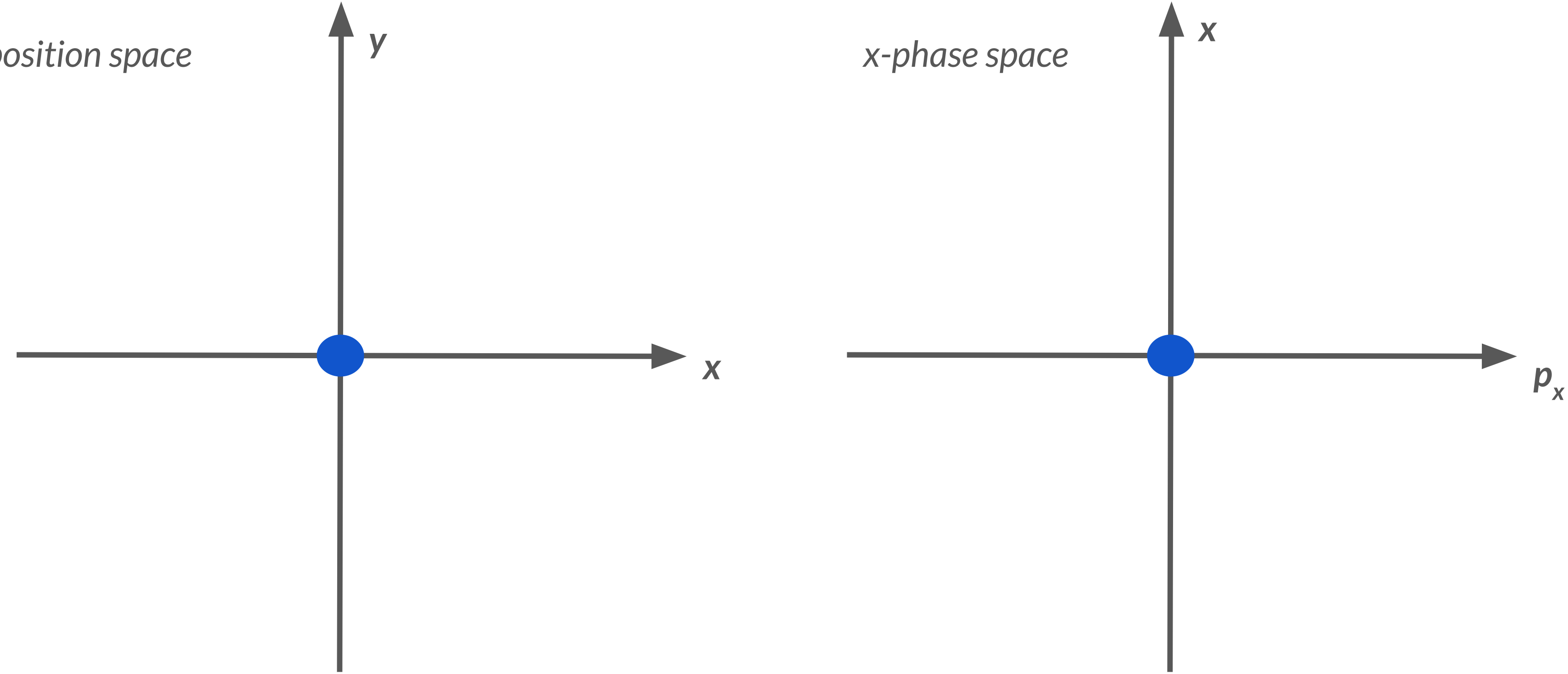
Excellent control over systematics [West, PRA 2019]

A sketch of trapped-ion interferometry

Step 1: ion is prepared in the spin down state and placed at the centre of the trap

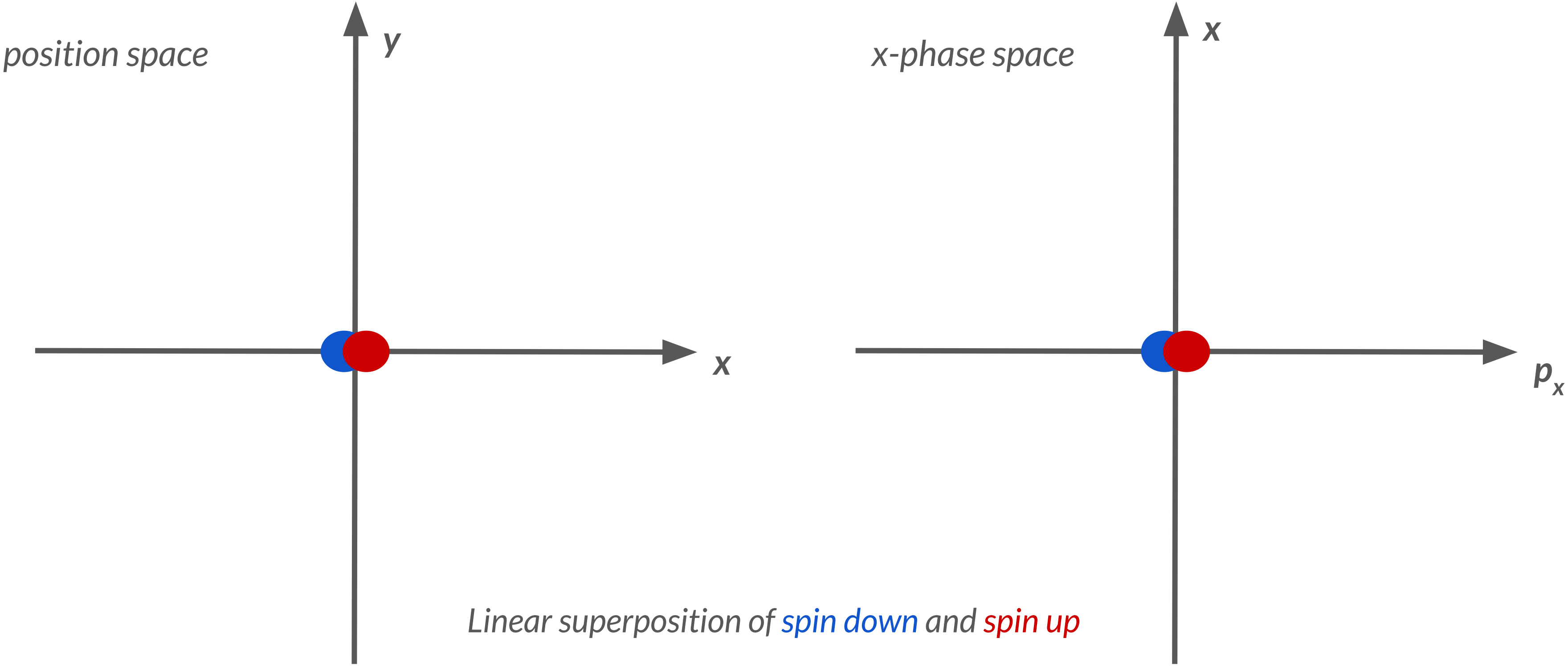
position space

x-phase space



A sketch of trapped-ion interferometry

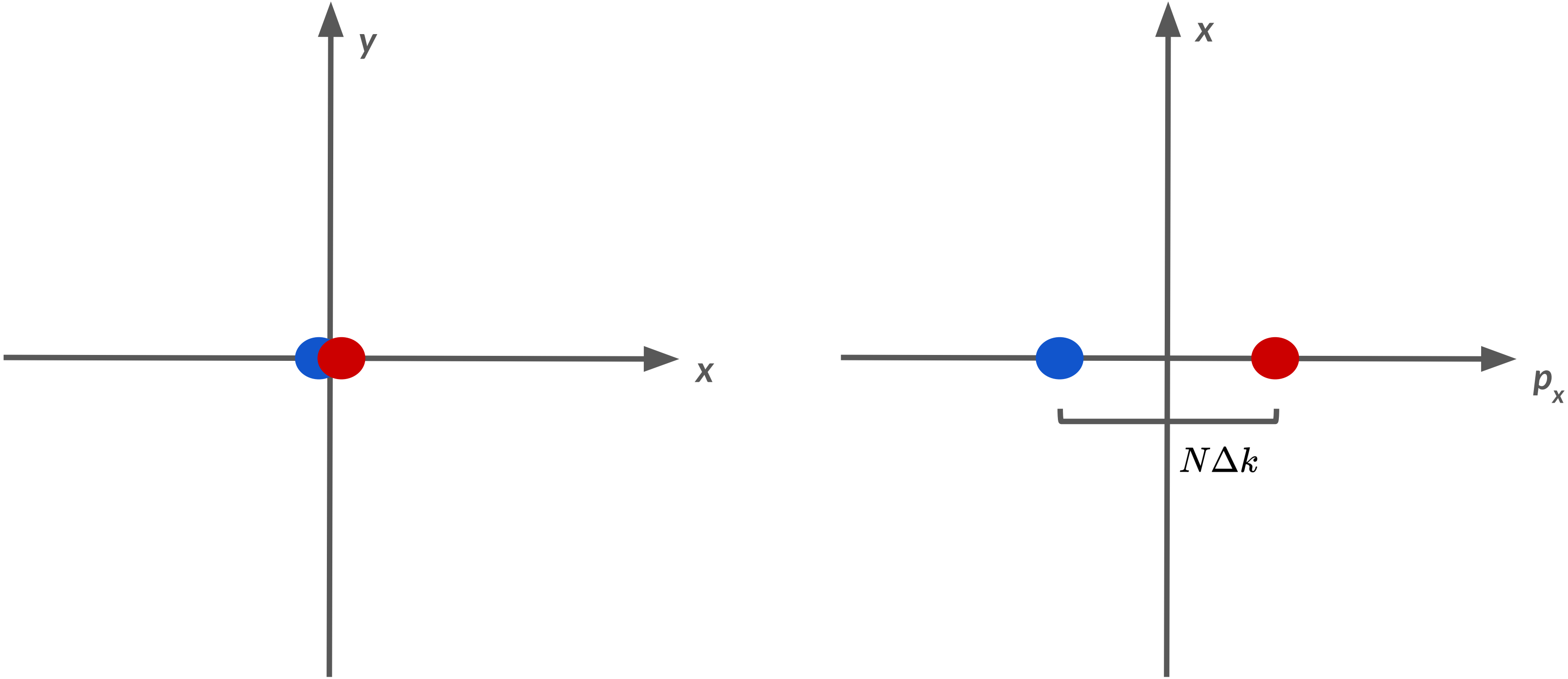
Step 2: apply a beam-splitter pulse



Linear superposition of spin down and spin up

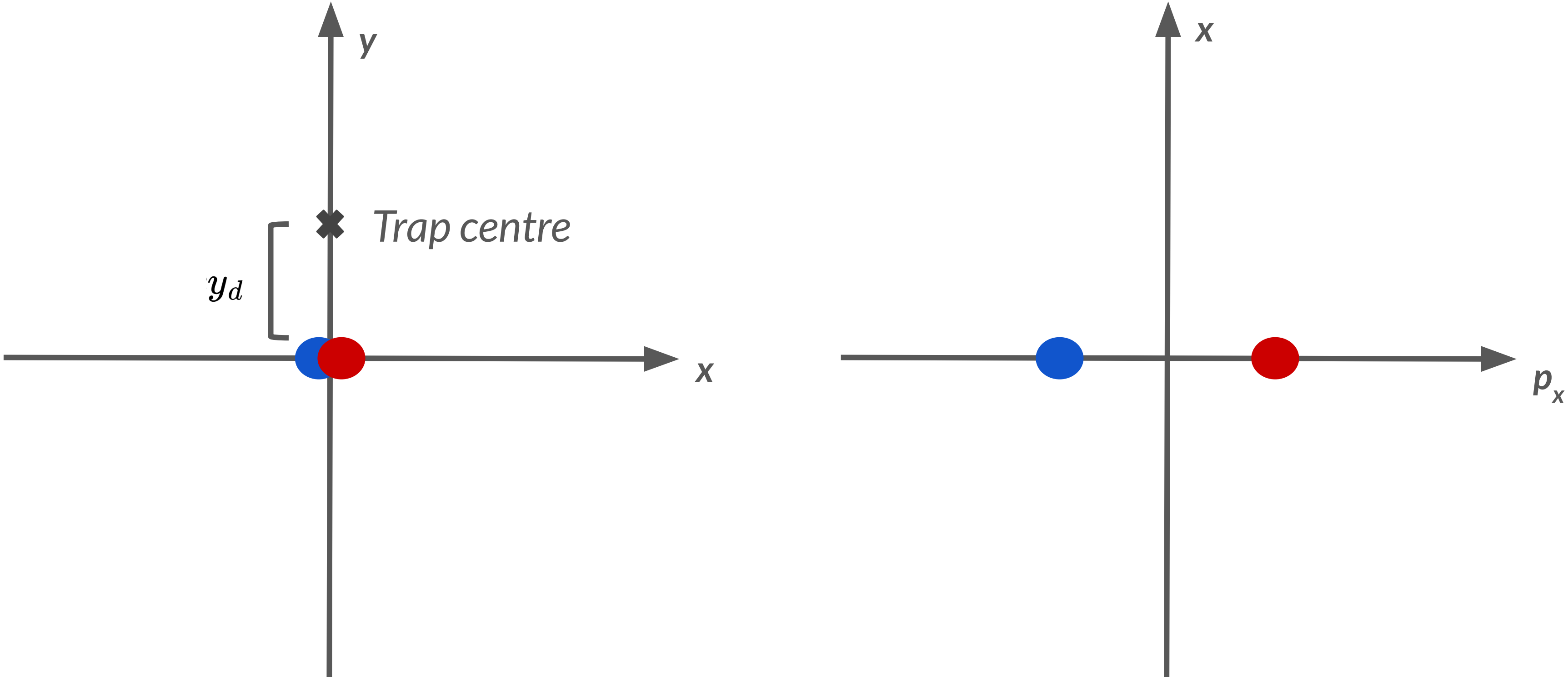
A sketch of trapped-ion interferometry

Step 3: apply N successive spin-dependent laser kicks (SDKs) in the x-direction



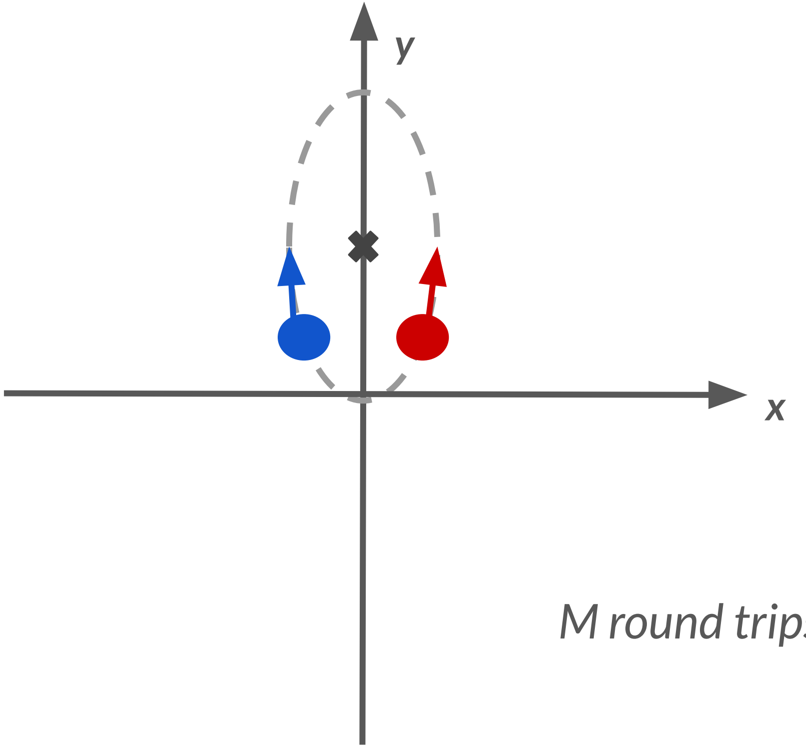
A sketch of trapped-ion interferometry

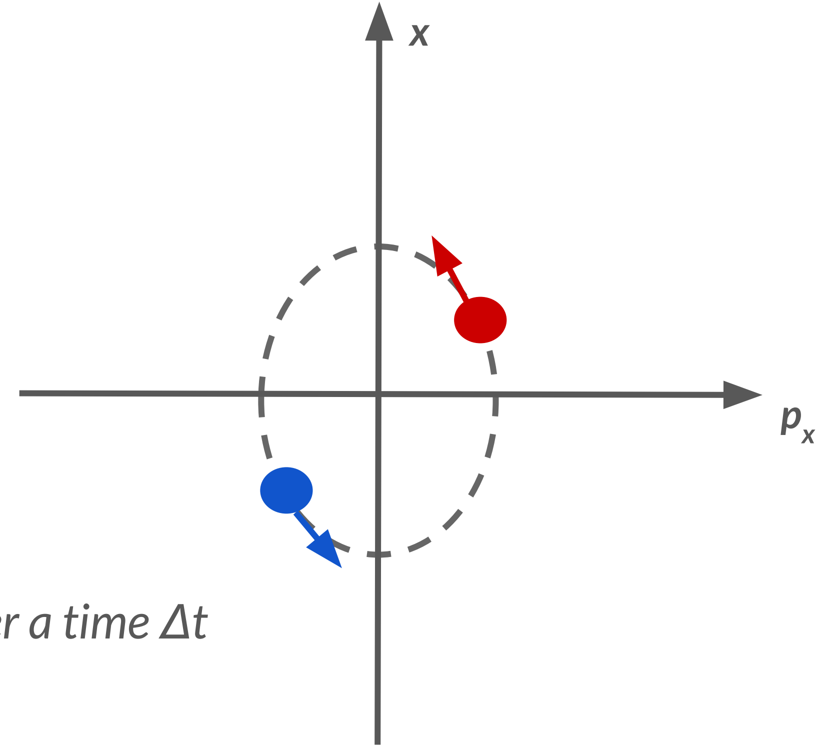
Step 4: non-adiabatic displacement of the trap centre in the y-direction



A sketch of trapped-ion interferometry

Step 5: free evolution of the ions in the trap

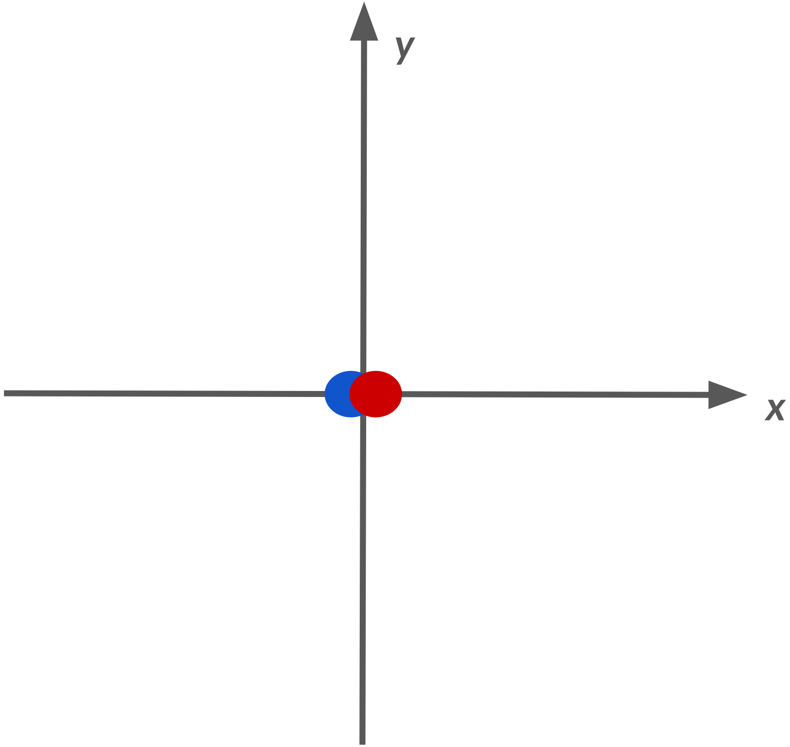


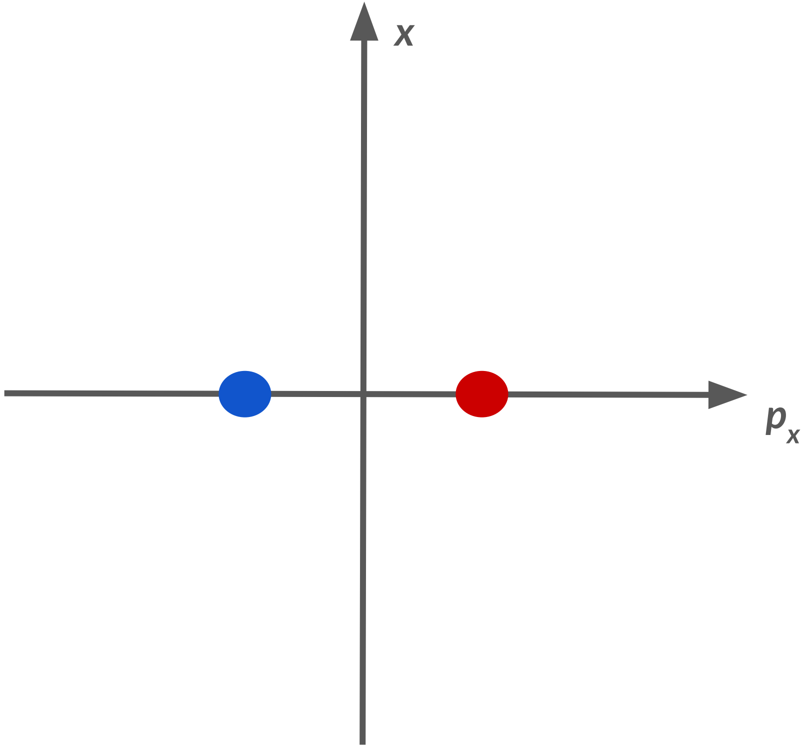


M round trips after a time Δt

A sketch of trapped-ion interferometry

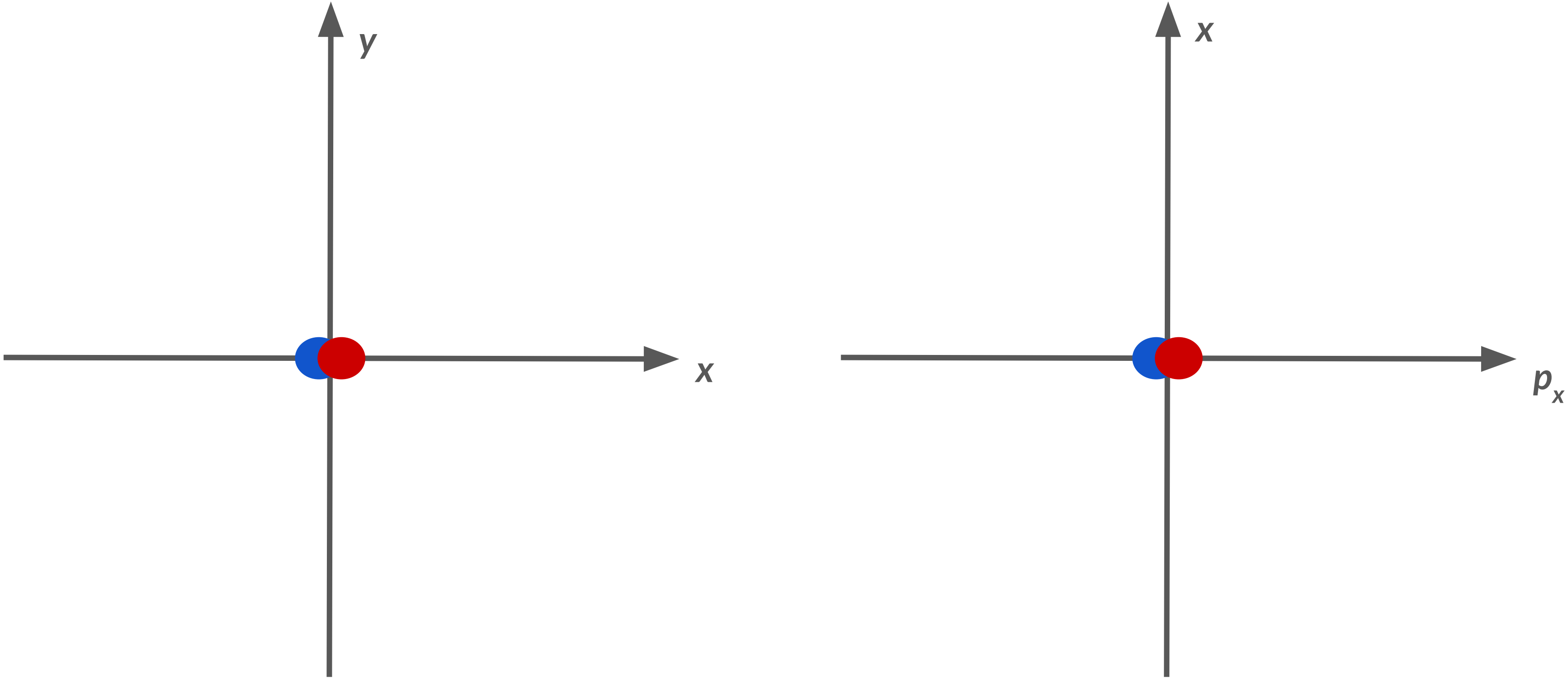
Step 6: reverse trap displacement non-adiabatically





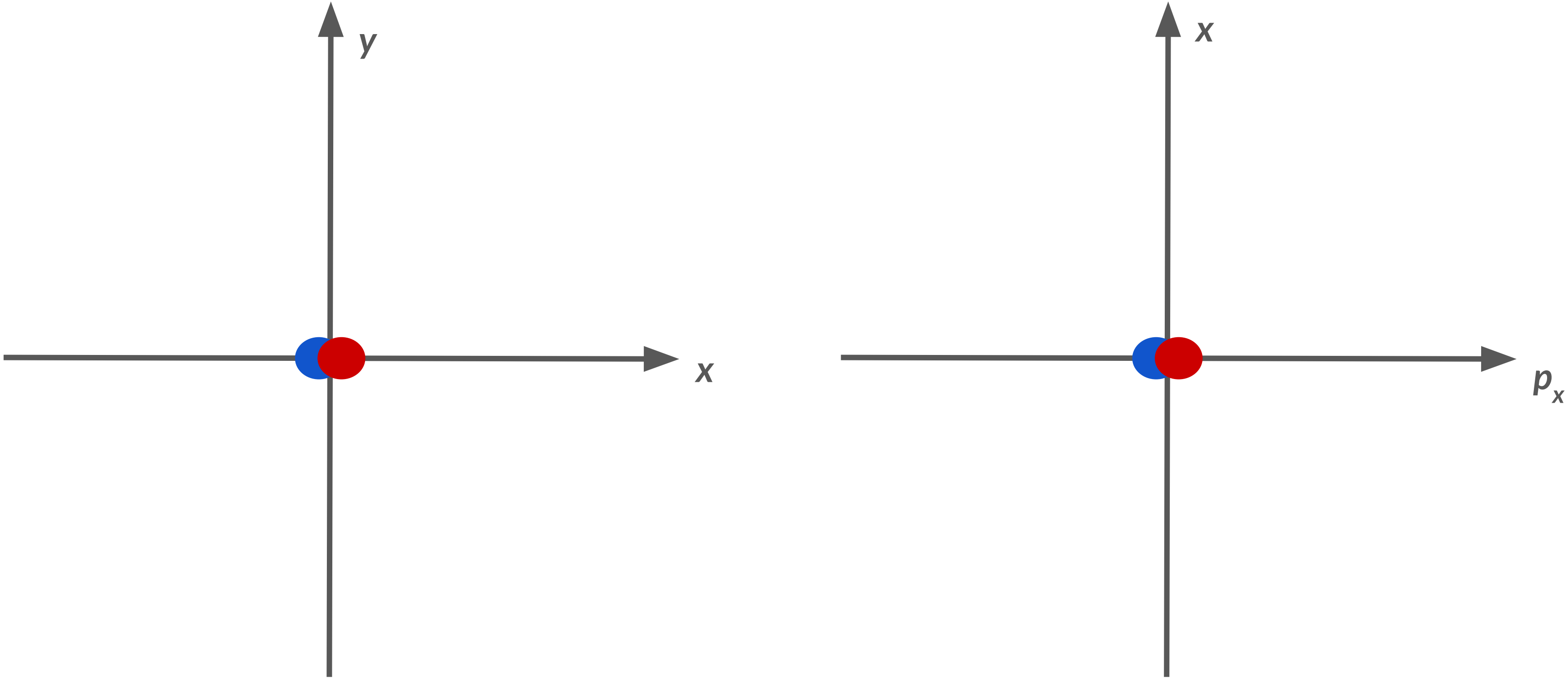
A sketch of trapped-ion interferometry

Step 7: reverse SDKs



A sketch of trapped-ion interferometry

Step 8: measure the ions in the qubit spin states

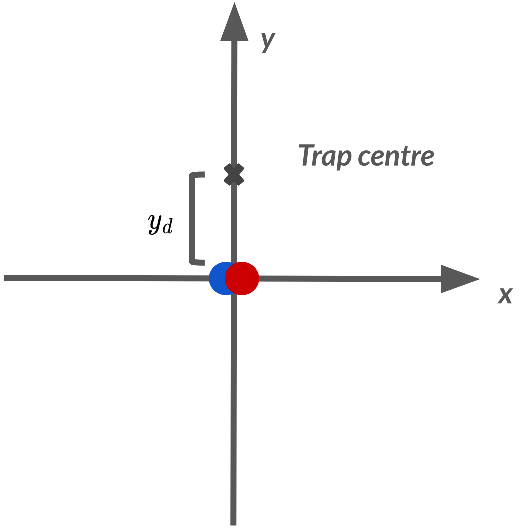


Trapped-ion interferometers as B-field sensors

Ions evolve in counter-propagating orbital motion

⬇

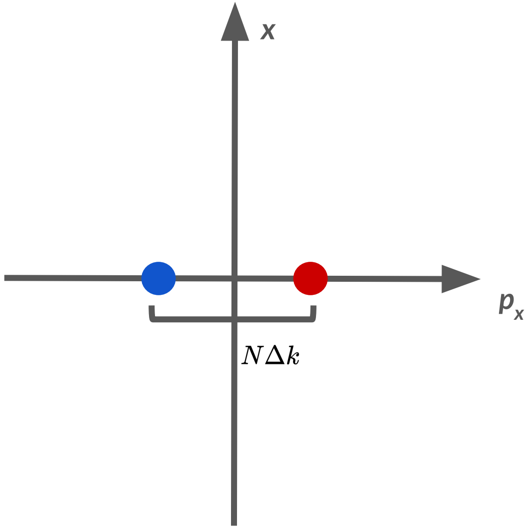
Electromagnetic phase shift only depends on the magnetic vector potential



$$\Delta\phi = 2e\oint \mathbf{A}\cdot d\mathbf{l}$$

$$\simeq 2e\int_0^{\Delta t}\mathbf{B}\cdot\frac{d\mathbf{S}}{dt}dt$$

$$\frac{d\mathbf{S}}{dt}\sim y_d\frac{N\Delta k}{m_{\text{ion}}}$$



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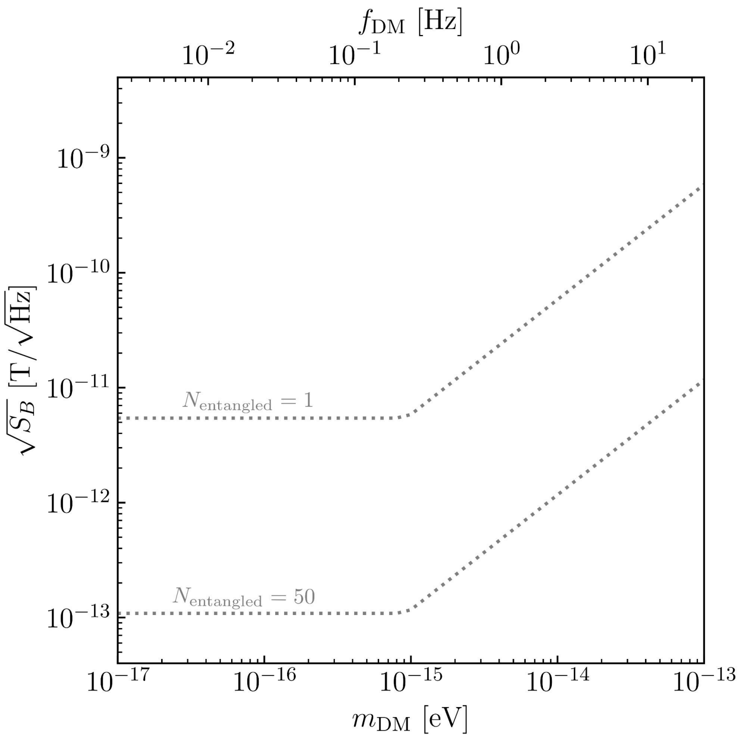
$$\frac{d\mathbf{S}}{dt} \sim y_d \frac{N\Delta k}{m_{\text{ion}}}$$

Dynamical Zeeman shift with (motional) magnetic moment

$$\mu_m \sim \mu_{\text{B}} N \Delta k y_d \frac{m_e}{m_{\text{ion}}}$$

Trapped-ion interferometers as B-field sensors

$$\sqrt{S_B} = 5 \times 10^{-12}\,\mathrm{T}/\sqrt{\mathrm{Hz}} \left|\mathrm{sinc}\left(\frac{\omega \Delta t}{2}\right)\right|^{-1} \left(\frac{1s}{\Delta t}\right)\left(\frac{1}{N_{\mathrm{GHZ}}}\right)$$



$$\mu_m \sim \mu_{\mathrm{B}} N \Delta k y_d \frac{m_e}{m_{\mathrm{ion}}}$$

[Campbell, Hamilton, JPB 2017]

$^{171}\mathrm{Yb}^+$

$$\Delta k = 4\pi/355\ \mathrm{nm}$$
$$N = 100$$
$$\Delta t = 1\ \mathrm{s}$$
$$y_d = 100\ \mu\mathrm{m}$$
$$\delta\phi = 1\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$$

Trapped-ion interferometers as B-field sensors

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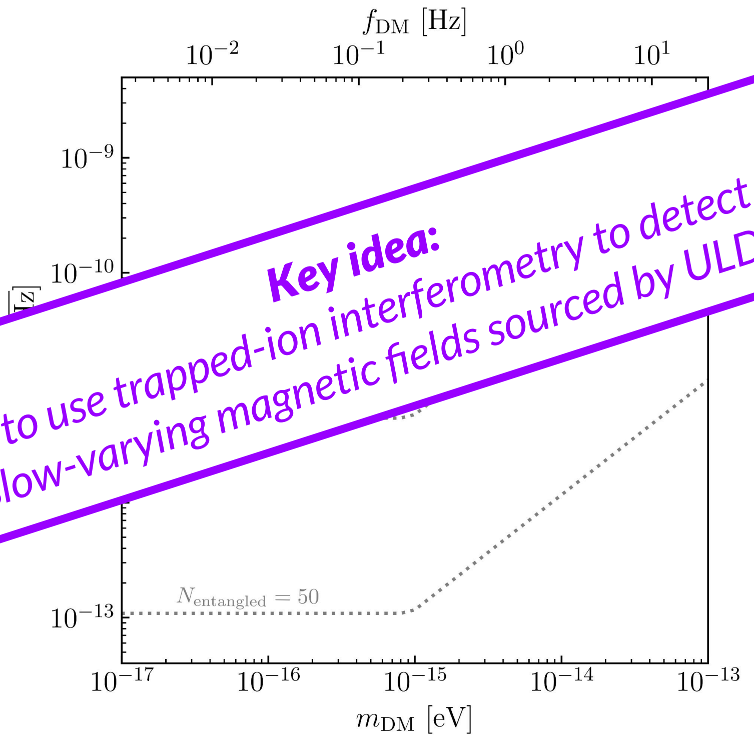


Key idea:
to use trapped-ion interferometry to detect
slow-varying magnetic fields sourced by ULDM

[Campbell, Hamilton, JPB 2017]

$^{171}\mathrm{Yb}^+$

$\Delta k = 4\pi/355$ nm
$N = 100$
$\Delta t = 1$ s
$y_d = 100\ \mu$m
$\delta\phi = 1\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$

Models

Kinetically-mixed DPs

$$\mathcal{L} \supset \epsilon m_{A'}^2 A'_\mu A^\mu$$

$$\boldsymbol{A'} \sim \frac{\sqrt{2\rho_{\rm DM}}}{\sqrt{3} m_{A'}} e^{i m_{A'} t - i \boldsymbol{k}\cdot\boldsymbol{x}} \sum_i \hat{\boldsymbol{n}}_i \, e^{i\varphi_i} \, ,$$

$$\mathbf{J}_{\rm eff} = \epsilon m_{A'}^2 \mathbf{A}'$$

ALPs

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a \widetilde{F}_{\mu\nu} F^{\mu\nu}$$

$$a \sim \frac{\sqrt{2\rho_{\rm DM}}}{m_a} e^{i m_a t - i \boldsymbol{k}\cdot\boldsymbol{x} + i\varphi}$$

$$\mathbf{J}_{\rm eff} = -g_{a\gamma\gamma} \mathbf{B_0} \frac{\partial a}{\partial t}$$

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J}_{\rm eff}$$

ULDM sources e.m. fields with angular frequency m

Models

Kinetically-mixed DPs

$$\mathcal{L} \supset \epsilon m_{A'}^2 A'_\mu A^\mu$$

$$\boldsymbol{A'} \sim \frac{\sqrt{2\rho_{\rm DM}}}{\sqrt{3} m_{A'}} e^{i m_{A'} t - i \boldsymbol{k}\cdot\boldsymbol{x}} \sum_i \hat{\boldsymbol{n}}_i \, e^{i\varphi_i} \,,$$

$$\mathbf{J}_{\rm eff} =$$

ALPs

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a \widetilde{F}_{\mu\nu} F^{\mu\nu}$$

$$\boldsymbol{ik}\cdot\boldsymbol{x} + i\varphi$$

$$\mathbf{J}_{\rm eff} = -g_{a\gamma\gamma} \mathbf{B_0} \frac{\partial a}{\partial t}$$

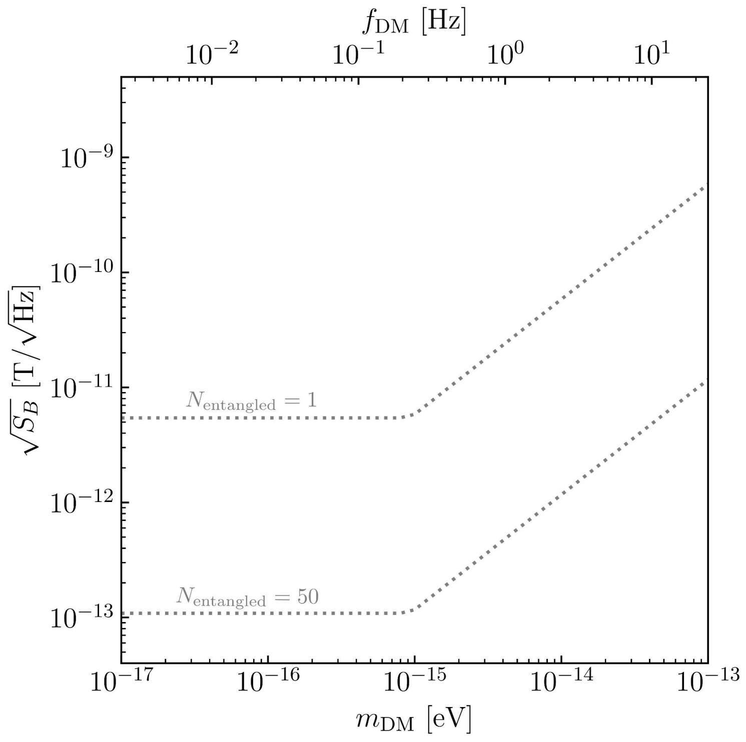
WARNING:
Boundary conditions -> cavity

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J}_{\rm eff}$$

ULDM sources e.m. fields with angular frequency m

Which cavity should we use?

Since Δt > 1 s, a TI would be most sensitive to signals oscillating with frequencies below 1 Hz.

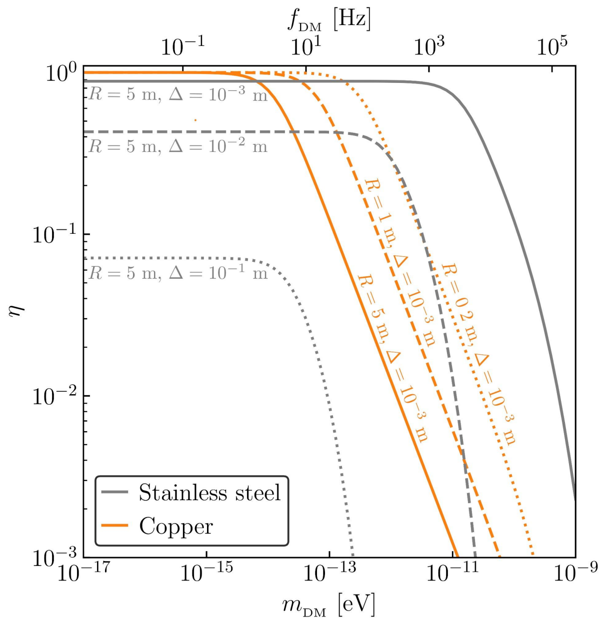


Key point:
Most sensitive to DM with mass $\lesssim 10^{-15}$eV

Which cavity should we use?

Since Δt > 1 s, a TI would be most sensitive to signals oscillating with frequencies below 1 Hz.

We expect that shielding in the lab suppresses high-frequency magnetic fields



Key point:
In the lab, limited sensitivity to DM with mass ≳ 10^{-13}eV

Which cavity? The Earth-ionosphere/IPM!

Well below 10 Hz, the Earth's core and the ionosphere/interplanetary medium act as good concentric spherical conducting boundaries [Fedderke et al., PRD 2021; Arza et al., PRD 2022]

$$h \sim \mathcal{O}(100\,\mathrm{km})$$
$$R_\oplus \approx 6 \times 10^3\,\mathrm{km}$$

Skin depths (frequency-dependent)

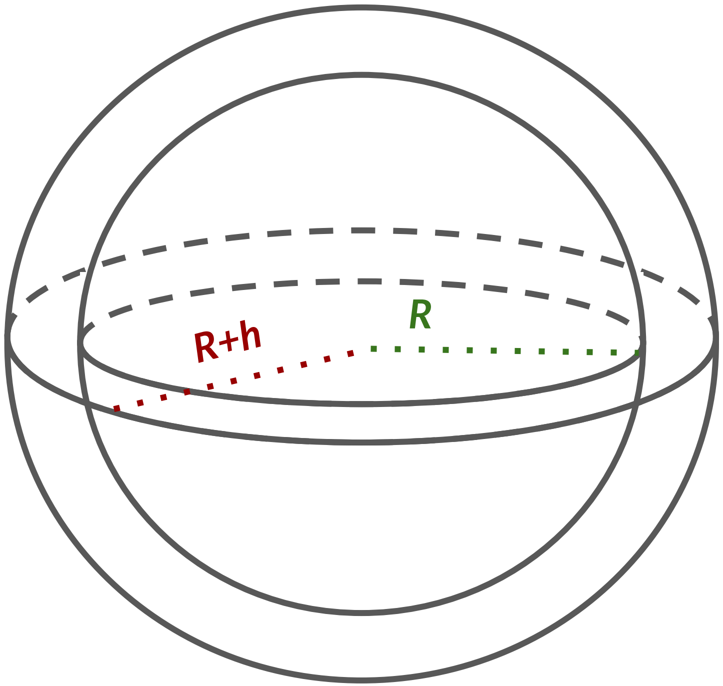
Inner boundary

$$\delta\big|_{\mathrm{core}} \ll h \quad \text{for } m_{\mathrm{DM}} \gtrsim 10^{-18}\,\mathrm{eV}$$

Outer boundary

$$\delta\big|_{\mathrm{ionosphere}} \ll h \quad \text{for } 10^{-13}\,\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 10^{-8}\,\mathrm{eV}$$

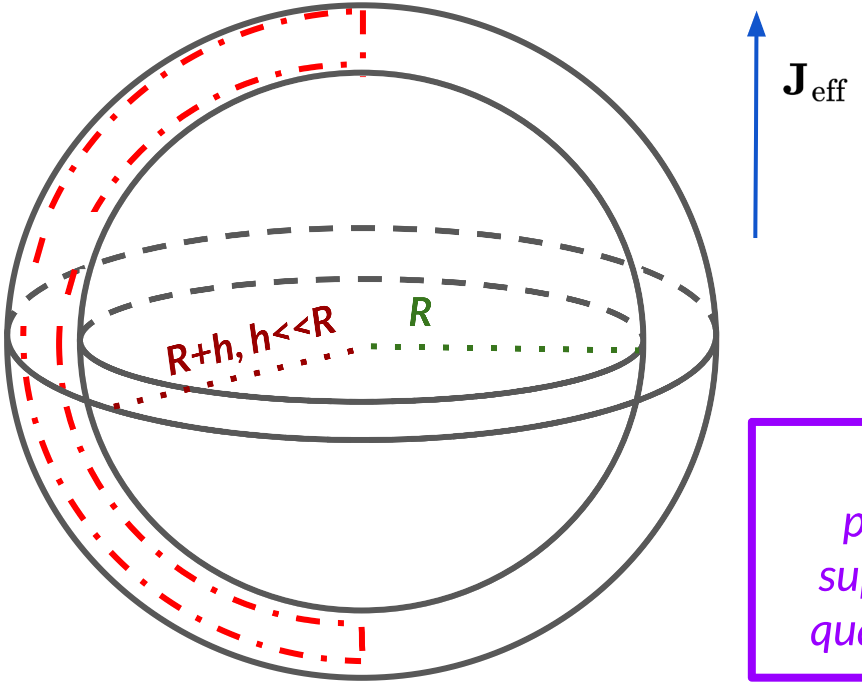
$$\delta\big|_{\mathrm{IPM}} \ll h \quad \text{for } 10^{-22}\,\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 10^{-13}\,\mathrm{eV}$$



Signal in a cavity with concentric spherical boundaries

Boundary conditions

$$\hat{\mathbf{n}} \cdot \mathbf{B} = 0 \quad \hat{\mathbf{n}} \times \mathbf{E} = 0$$



E field is parametrically suppressed in the quasistatic regime

$$\oint \mathbf{E} \cdot d\mathbf{l} = \int (\nabla \times \mathbf{E}) \cdot d\mathbf{S} = \int \partial_t \mathbf{B} \cdot d\mathbf{S} \implies E \sim (m_{\text{DM}} R)\, B$$

Signal in a cavity with concentric spherical boundaries

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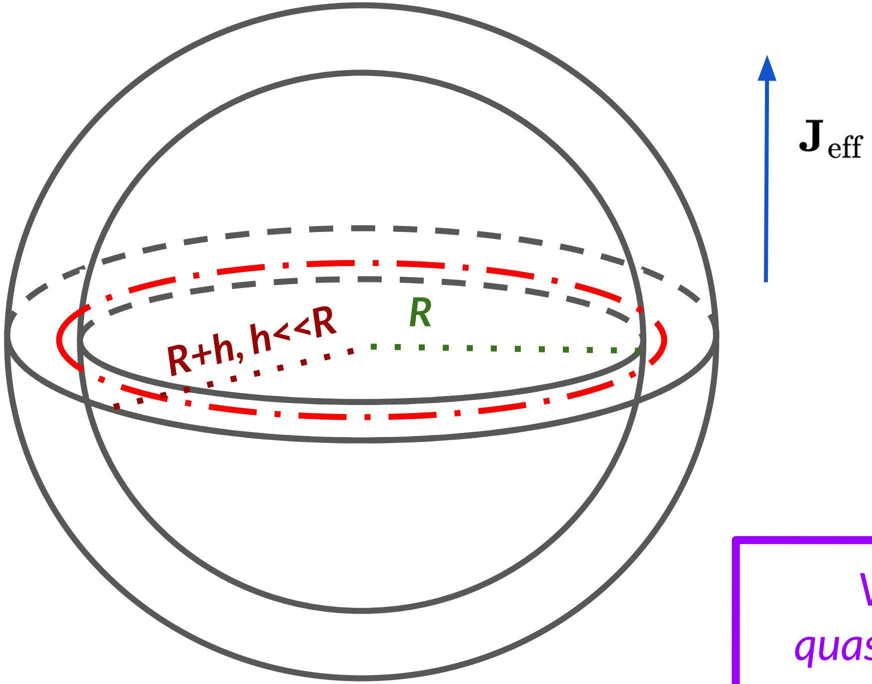


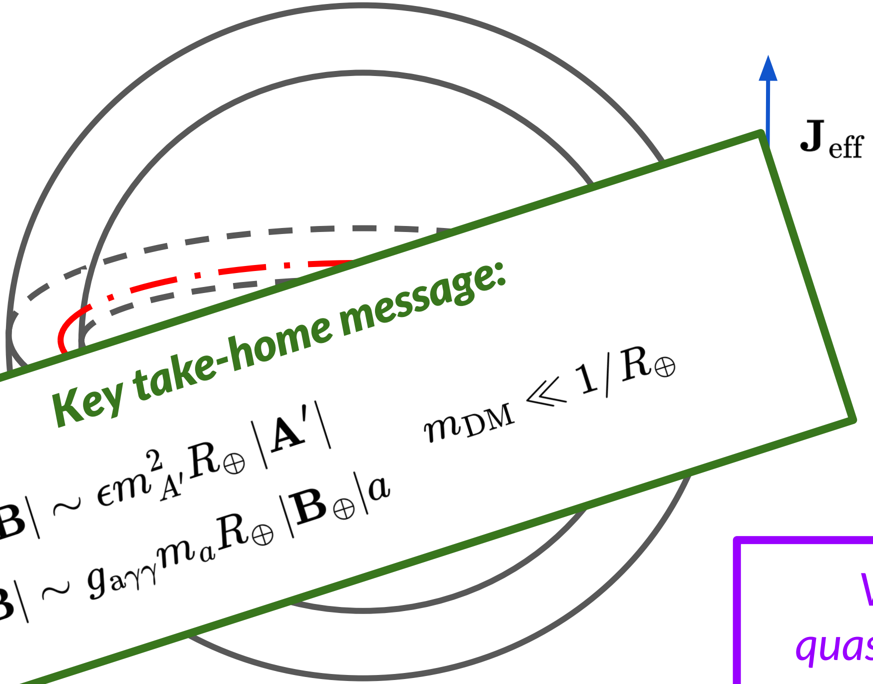
Valid in the quasistatic regime

$$\oint \mathbf{B} \cdot d\mathbf{l} = \int (\nabla \times \mathbf{B}) \cdot d\mathbf{S} = \int \mathbf{J}_{\rm eff} \cdot d\mathbf{S} \implies B \sim R J_{\rm eff}$$

Signal in a cavity with concentric spherical boundaries

Boundary conditions

$$\hat{\mathbf{n}} \cdot \mathbf{B} = 0 \quad \hat{\mathbf{n}} \times \mathbf{E} = 0$$



Key take-home message:

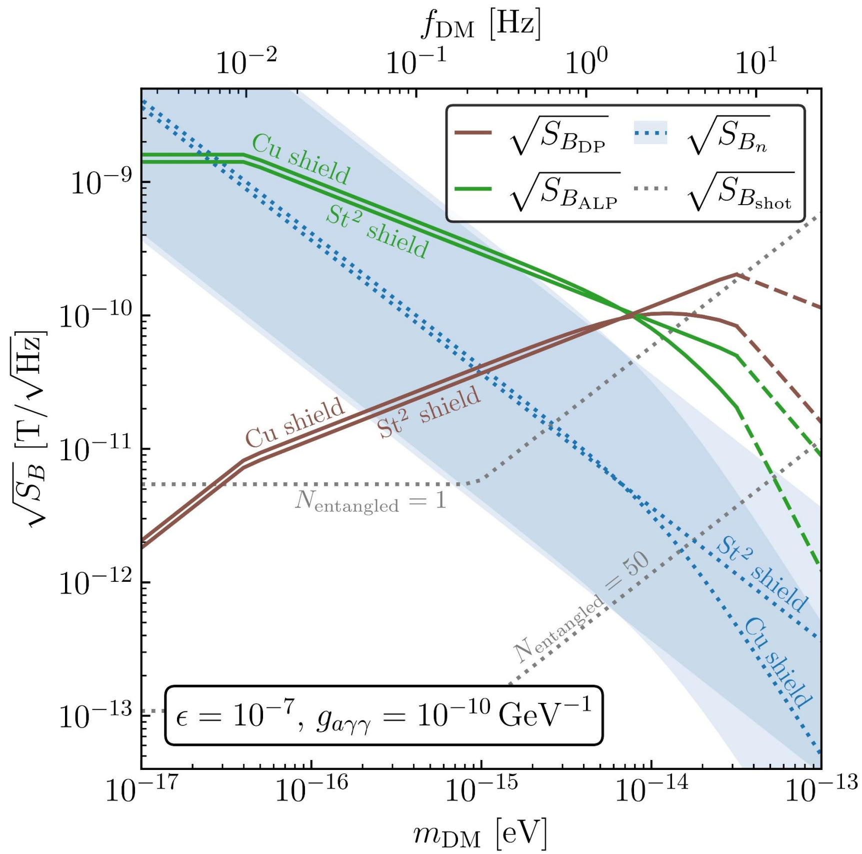
$$|\mathbf{B}| \sim \epsilon m_{A'}^2 R_\oplus |\mathbf{A}'| \qquad m_{\text{DM}} \ll 1/R_\oplus$$

$$|\mathbf{B}| \sim g_{a\gamma\gamma} m_a R_\oplus |\mathbf{B}_\oplus| a$$

Valid in the quasistatic regime

$$\oint \mathbf{B} \cdot d\mathbf{l} = \int (\nabla \times \mathbf{B}) \cdot d\mathbf{S} = \int \mathbf{J}_{\text{eff}} \cdot d\mathbf{S} \implies B \sim R J_{\text{eff}}$$

Noise projections



[Campbell, Hamilton, JPB 2017]

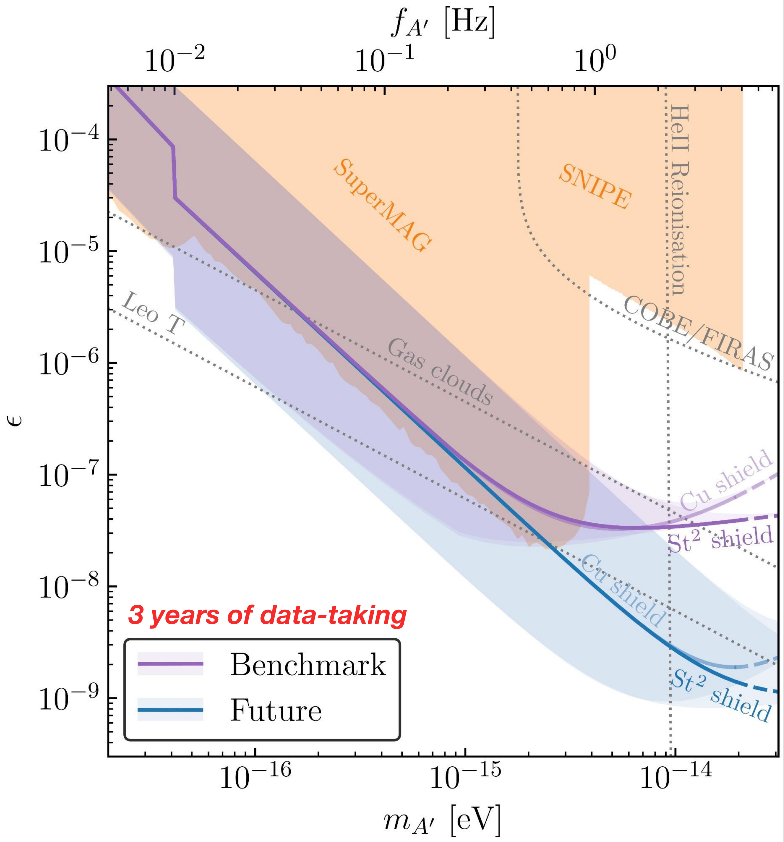
$^{171}\mathrm{Yb}^+$

$$\Delta k = 4\pi/355\ \mathrm{nm}$$
$$N = 100$$
$$\Delta t = 1\ \mathrm{s}$$
$$y_d = 100\ \mu\mathrm{m}$$
$$\delta\phi = 1\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$$

Dominated by ambient magnetic noise

Fullerkrug and Fraser-Smith [2011], Constable and Constable [2023]

Projected sensitivity: DPs



Signal is insensitive to latitude + longitude + trap orientation tangent to the Earth's surface

$$\sqrt{\left\langle \left| \widetilde{\boldsymbol{B}}_{A'}(\omega) \cdot \hat{\boldsymbol{\Sigma}} \right|^2 \right\rangle} = \epsilon m_{A'} R_{\oplus} \sqrt{\frac{\rho_{\mathrm{DM}}}{6}},$$

[Campbell, Hamilton, JPB 2017]

$^{171}\mathrm{Yb}^+$

$$\Delta k = 4\pi/355 \text{ nm}$$
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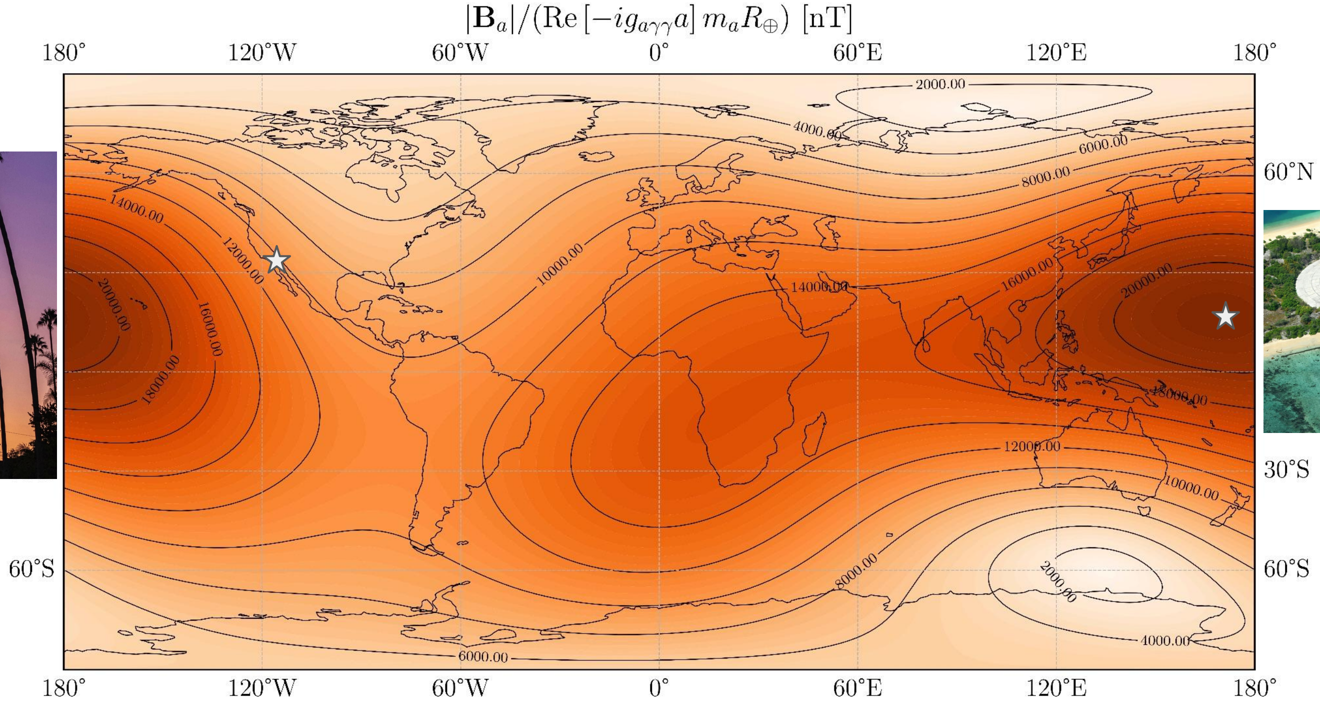
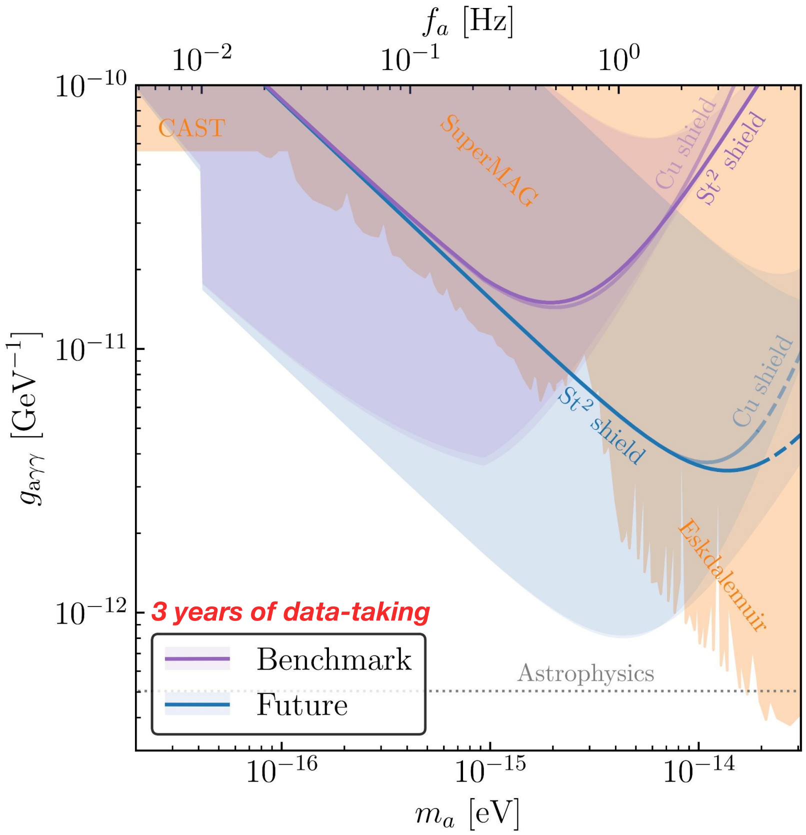
Projected sensitivity: ALPs

Signal is sensitive to latitude + longitude + directionality known a priori (set by the Earth's magnetic field) [IGRF 2021]



Projected sensitivity: ALPs



Signal is sensitive to latitude + longitude + directionality known a priori (set by the Earth's magnetic field)

$$\sqrt{\left\langle\left|\widetilde{\boldsymbol{B}}_a(\omega)\cdot\hat{\boldsymbol{\Sigma}}\right|^2\right\rangle}=\sqrt{\left\langle\left|\widetilde{\boldsymbol{B}}_a(\omega)\right|^2\right\rangle}\approx g_{a\gamma\gamma}R_{\oplus}\sqrt{2\rho_{\rm DM}}\,(0.11\mathrm{G})$$

[Campbell, Hamilton, JPB 2017]

^{171}Yb$^+$

$$\begin{aligned}\Delta k &= 4\pi/355\ \mathrm{nm}\\ N &= 100\\ \Delta t &= 1\ \mathrm{s}\\ y_d &= 100\ \mu\mathrm{m}\\ \delta\phi &= 1\ \mathrm{rad}/\sqrt{\mathrm{Hz}}\end{aligned}$$

Summary

Trapped-ion interferometers are sensitive to small B-fields via the dynamical Zeeman effect.

In light of their promising projected reach, trapped-ion interferometers could probe unexplored regions of ULDM parameter space!