Fun(DAMENTAL PHYSICS) with Spin Sensors

Sebastian A. R. Ellis

King's College London

What are we hoping to achieve?

We want to detect new physics with small energy deposition

Quantum sensors characterised by a qubit/bosonic system with manipulable states

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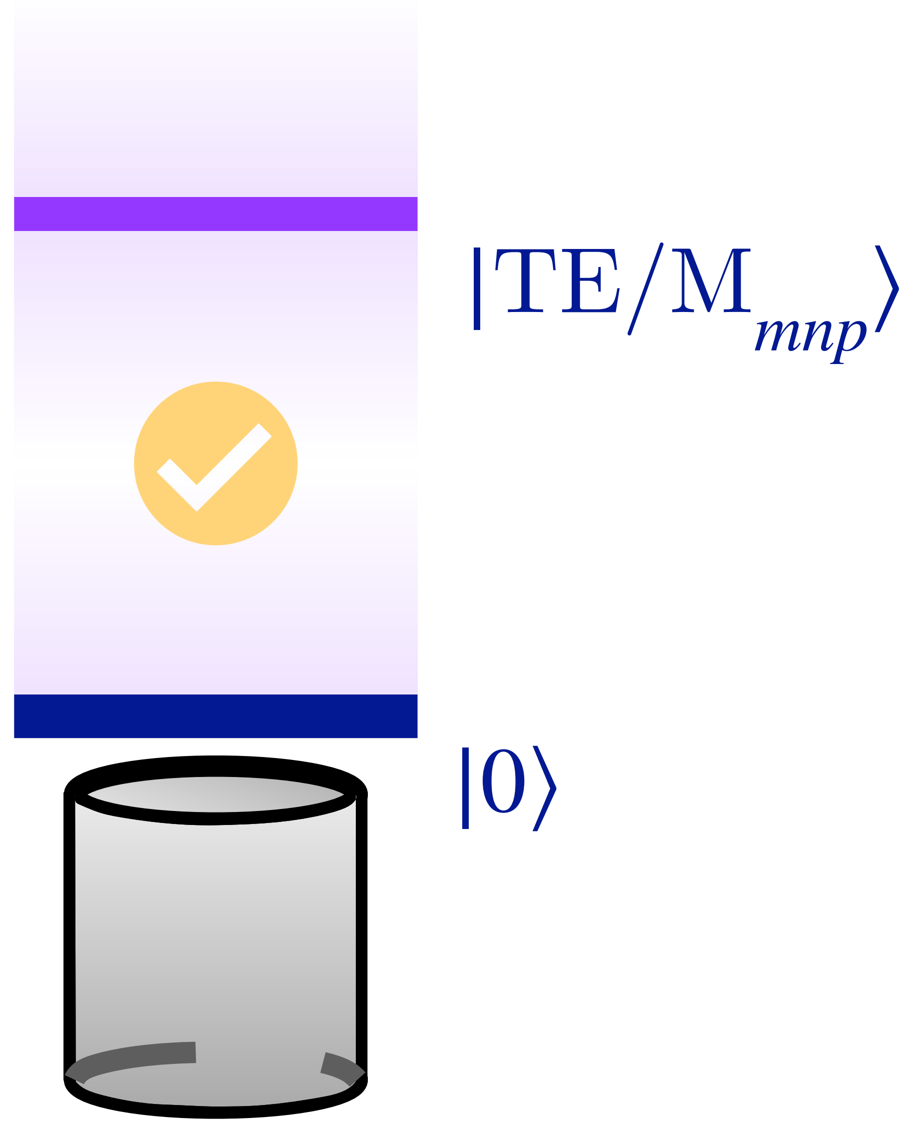

Resonant Cavity

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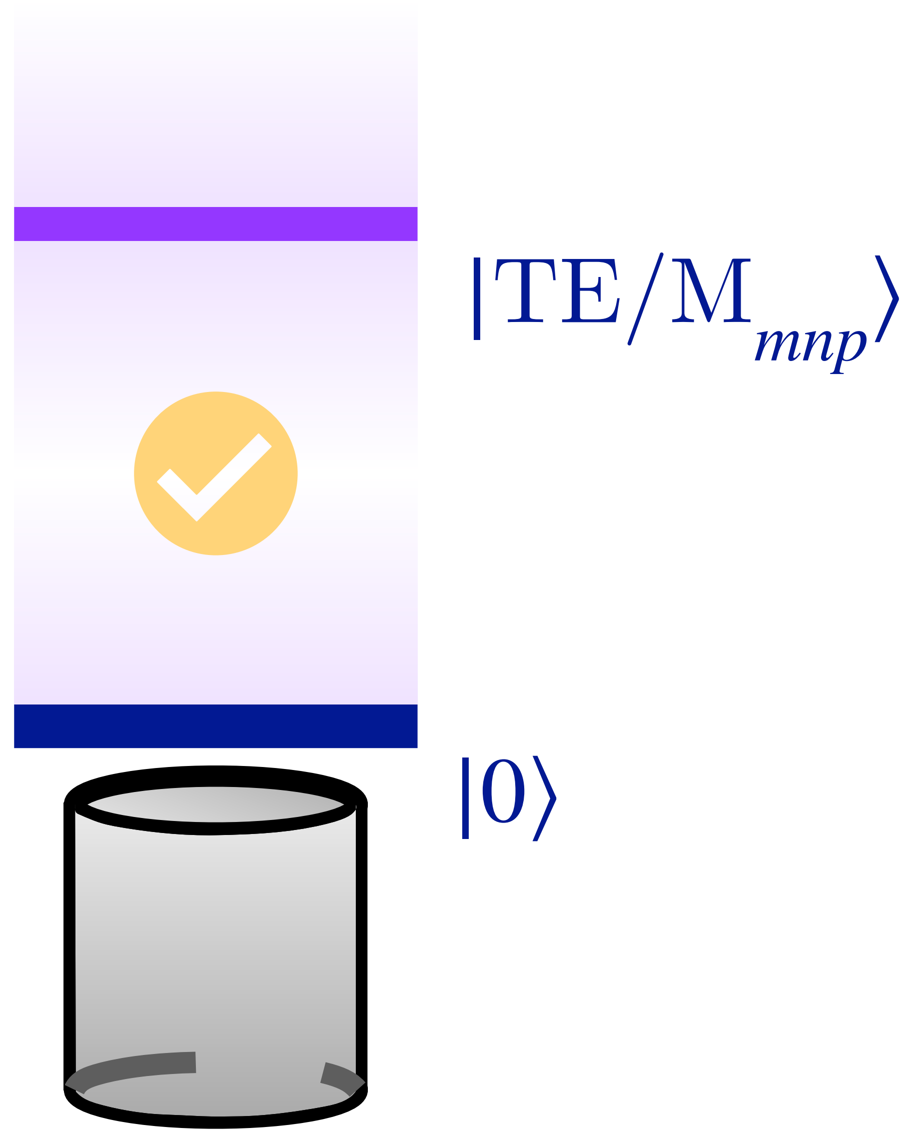

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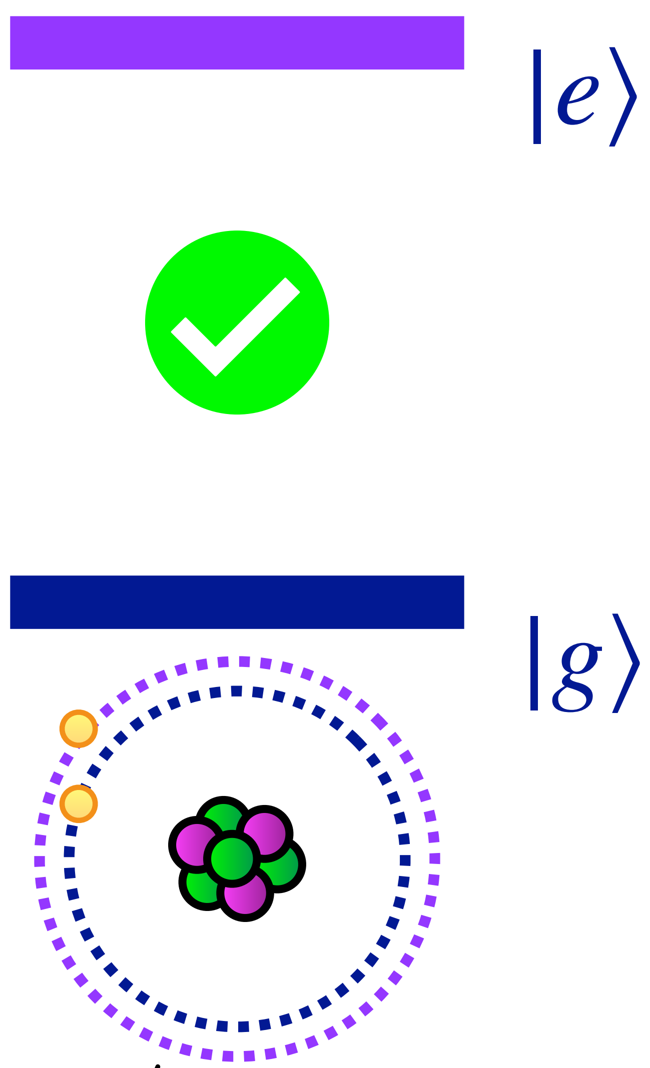

Atomic/Nucl. Clock

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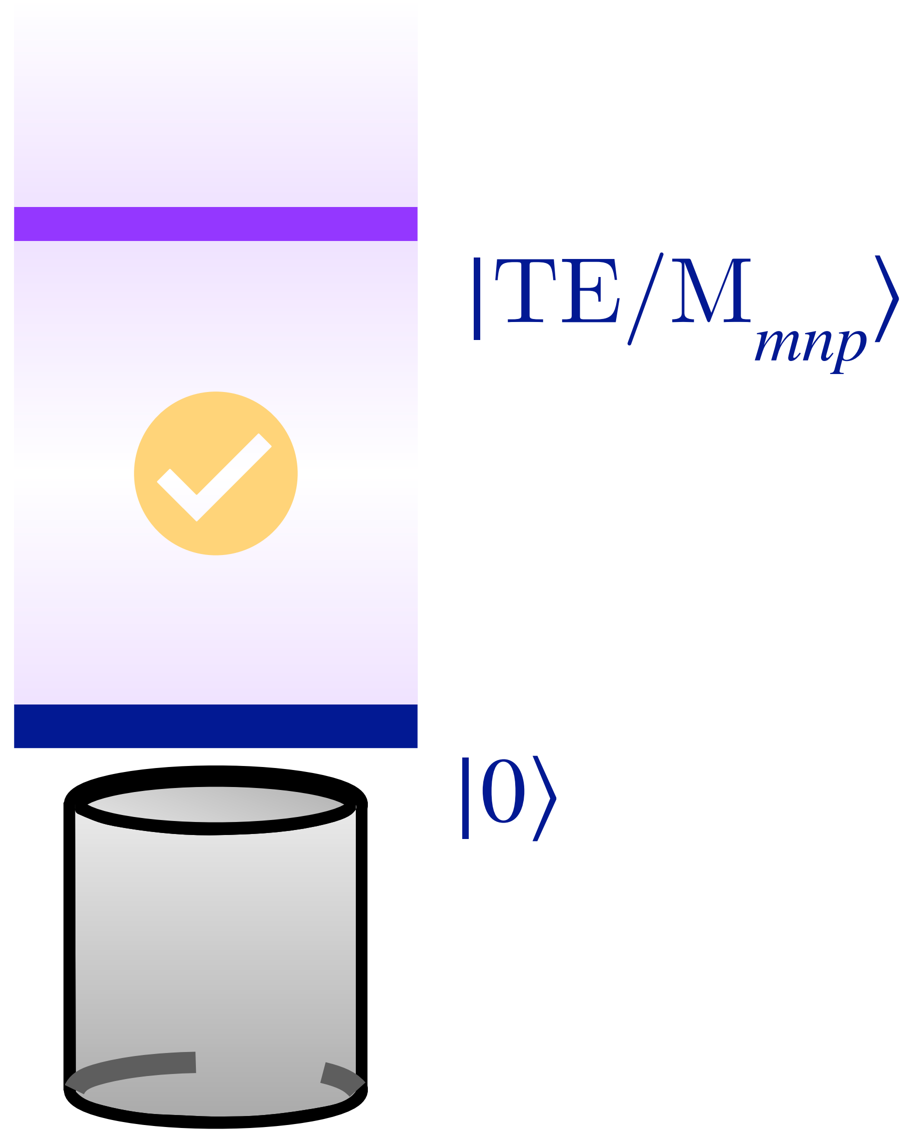

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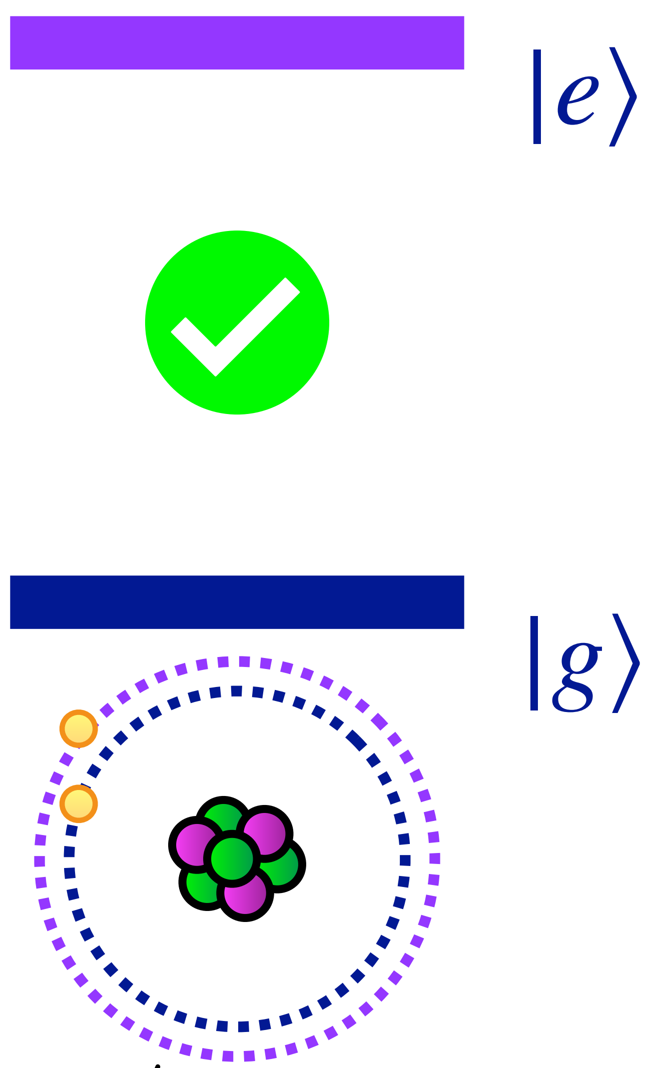

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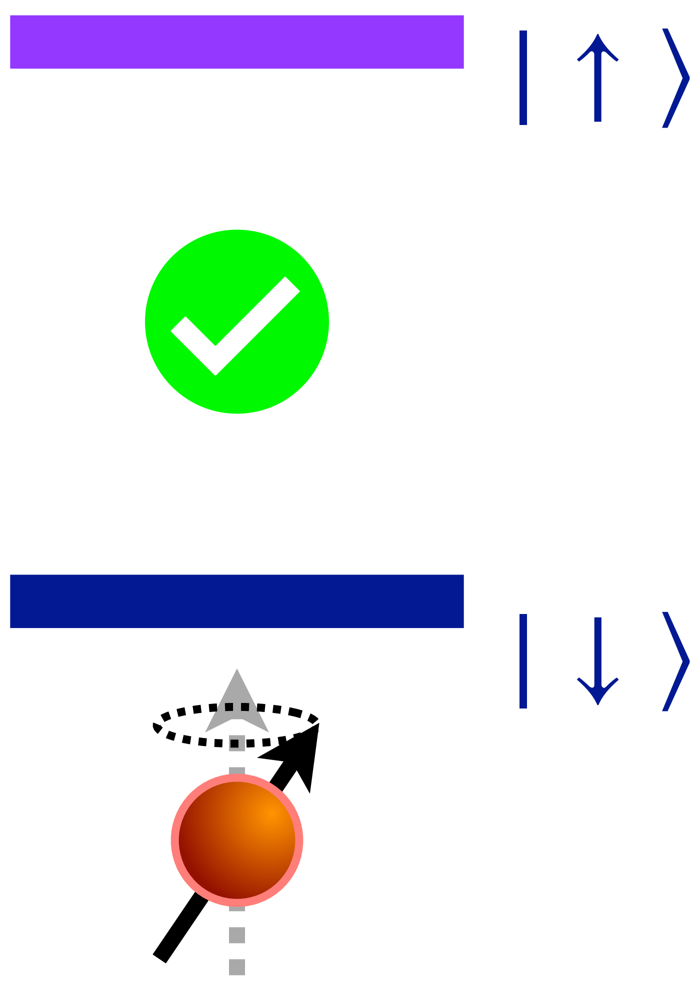

NMR

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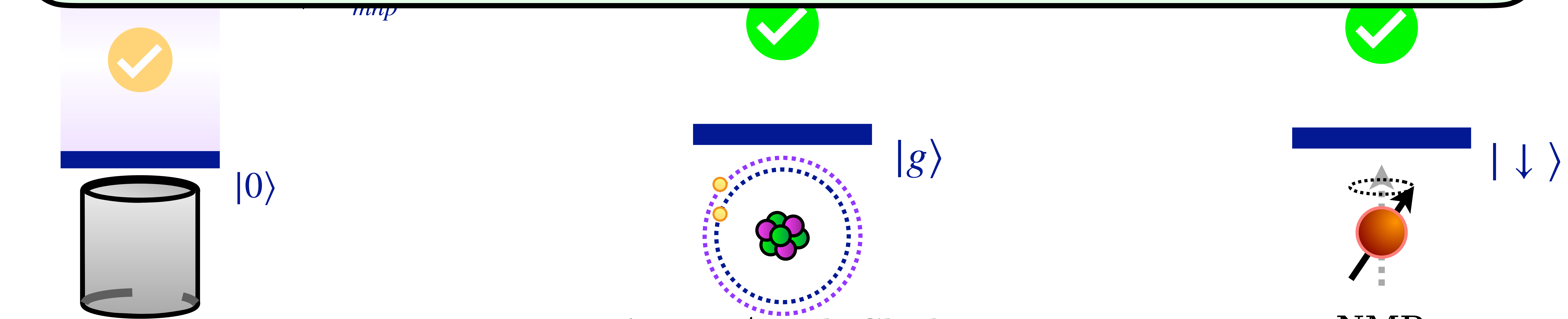
Many more not shown here...



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Many experiments using a variety of quantum-limited sensors operating already

Can we maximise the use-case of those sensors?

Can we kick-start development towards large-scale devices?

Quantum Sensor Zoology

What does your BSM target couple to? $\hat{H}_{\text{int}}$

$$\hat{H}_{a\gamma} = g\int_V a\mathbf{E}\cdot\mathbf{B} \qquad \hat{H}_{AA'} = \epsilon m_{A'}^2\int_V \mathbf{A}\cdot\mathbf{A}' \qquad \hat{H}_{SB} = -\mu\,\hat{\mathbf{S}}\cdot\mathbf{B}$$

What is the sensor? $\hat{H}_{\text{sensor}}$

$$\hat{H}_{\text{EM}} = \frac{1}{2}\int_V \mathbf{B}\cdot\mathbf{B} + \mathbf{E}\cdot\mathbf{E} + \mathbf{J}\cdot\mathbf{A} \qquad \hat{H}_{\text{mech}} = \frac{\hat{p}^2}{2M} + \frac{1}{2}M\omega^2\hat{x}^2 \qquad \hat{H}_{\text{spin}} \supset \hbar\omega_0\hat{S}_z$$

How do you read out the sensor? $\hat{H}_{\text{readout}}$

$$\hat{H}_{\text{I/O}} \simeq i\hbar\int_{-\infty}^{\infty} d\omega\,\kappa(\omega)\left[\hat{b}_\omega^\dagger\hat{a} - \hat{b}_\omega\hat{a}^\dagger\right] \qquad \hat{H}_{\text{optomech.}} \simeq g\hat{x}\left(\hat{a}^\dagger + \hat{a}\right) \qquad \hat{H}_{\text{JC}} \simeq g'\left(\hat{a}^\dagger + \hat{a}\right)\left(\hat{S}_+ + \hat{S}_-\right)$$

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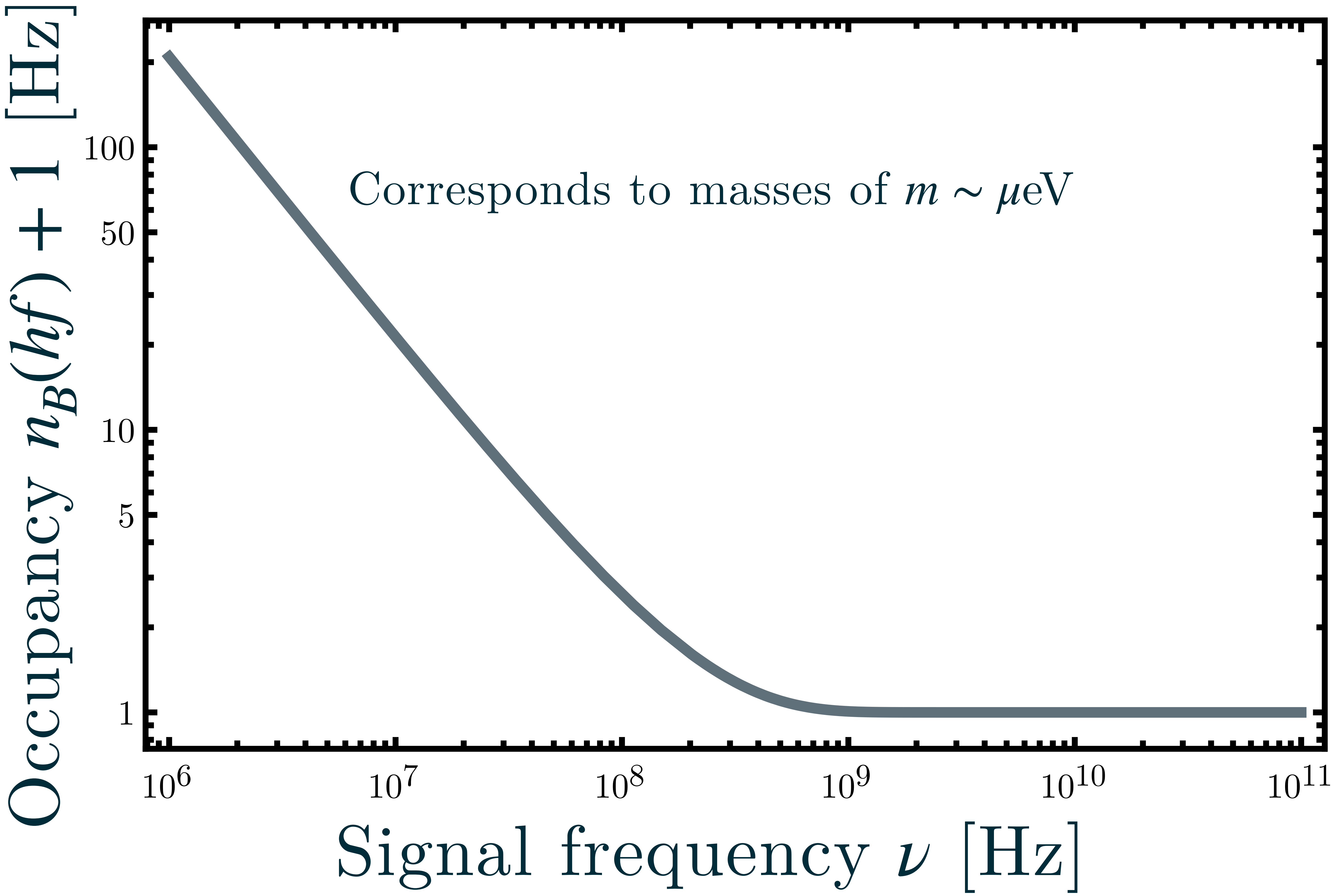
Quantum Noise

Cooling below about $T \sim 0.01$K difficult for macroscopic systems



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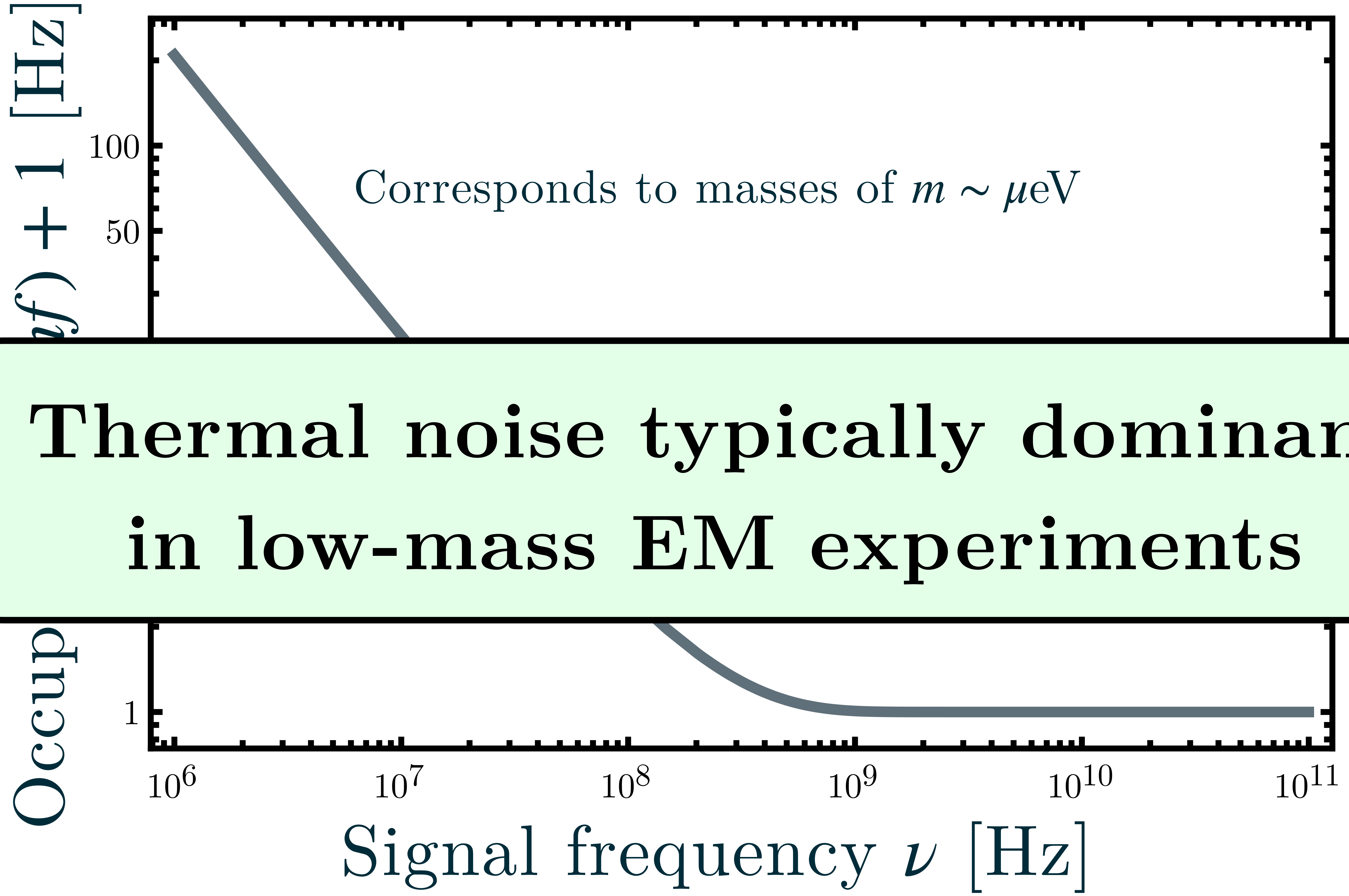

Thermal noise typically dominant in low-mass EM experiments

Spin Sensor Noise

Exception to the previous statement is spin systems

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Macroscopic spin systems with B-field applied:

$$\langle M_x^{\text{s.p.}}(t)^2\rangle \simeq \frac{J(J+1)n\gamma^2}{6V}\frac{1}{1+T_2^2(\omega-\omega_0)^2}$$

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Spin projection noise (QM origin) independent of T_s

Spin Signals

Spin signals from an interaction $\hat{H}_{\rm int} = \gamma \hat{S}_z B(t)$

What is the signal $B(t)$ here?

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PRL 134 (2025) 23, 231401
V. Domcke **SARE,** N. L. Rodd

Spin Signals — Importance of the Box

Standard conductive shielding used in typical experiments has $\sigma \gtrsim 10^6\,\mathrm{S/m} \sim 100\,\mathrm{eV}$

Skin depth of a signal at frequency ω in terms of DC conductivity is $\delta_s = \sqrt{\frac{2}{\omega\mu\sigma}}$

Which boundary is relevant in an experiment will depend on shielding factor $\eta \simeq \frac{|\boldsymbol{B}_{\text{in}}|}{|\boldsymbol{B}_0|}$

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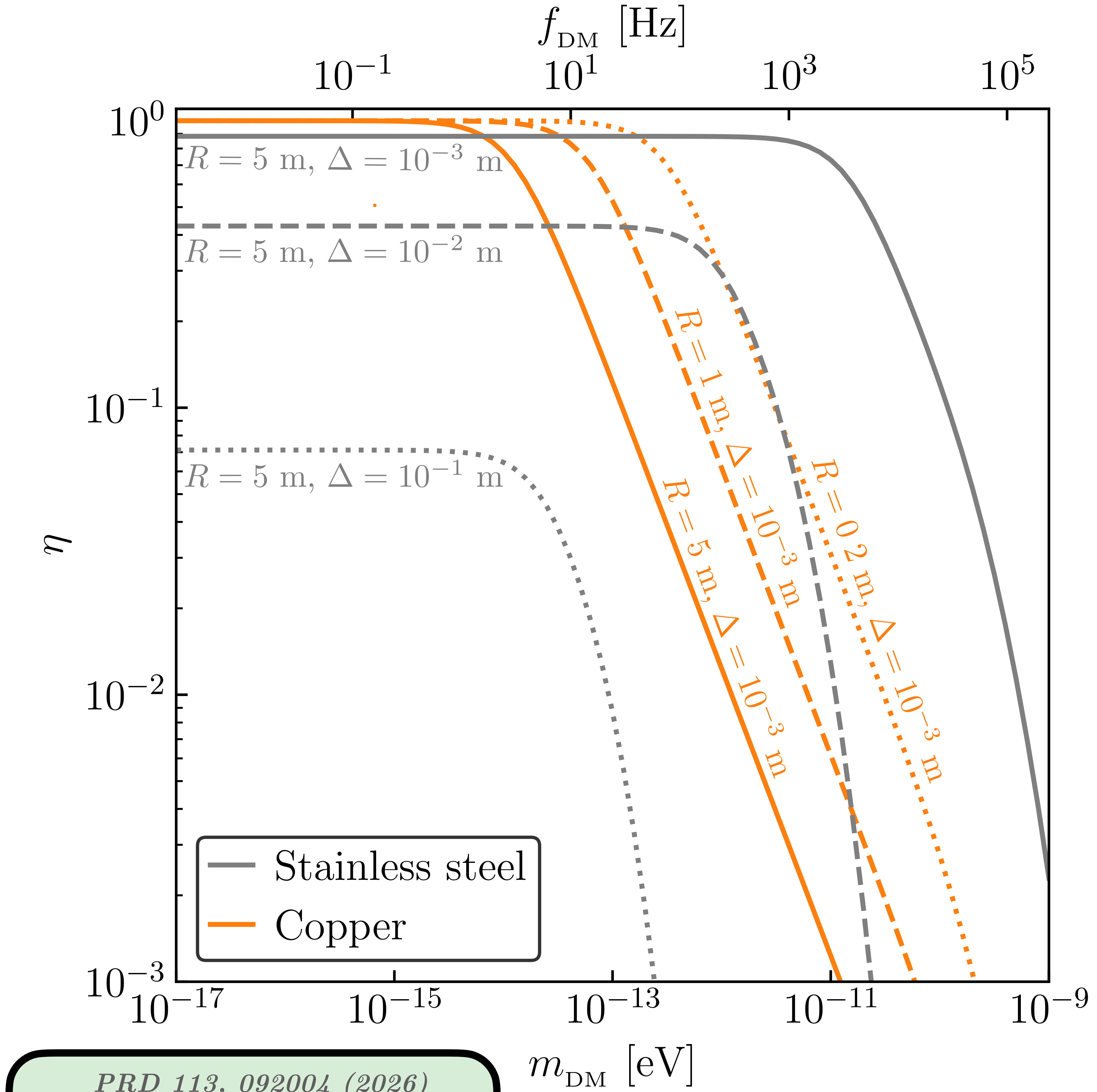
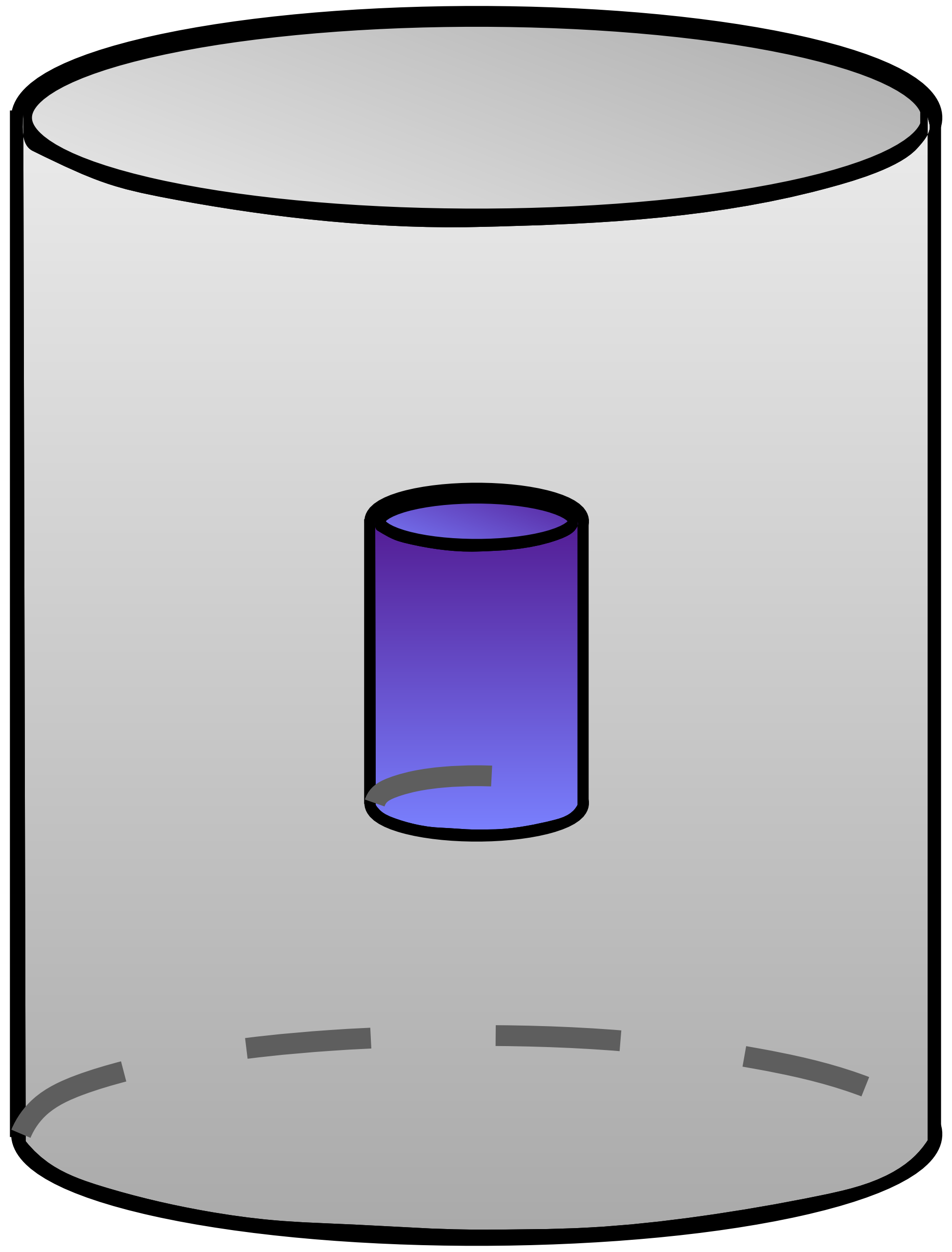
For $m_{\rm DM} \gtrsim 10^{-10}\,$eV, a copper shield ensures the box provides the relevant BCs.

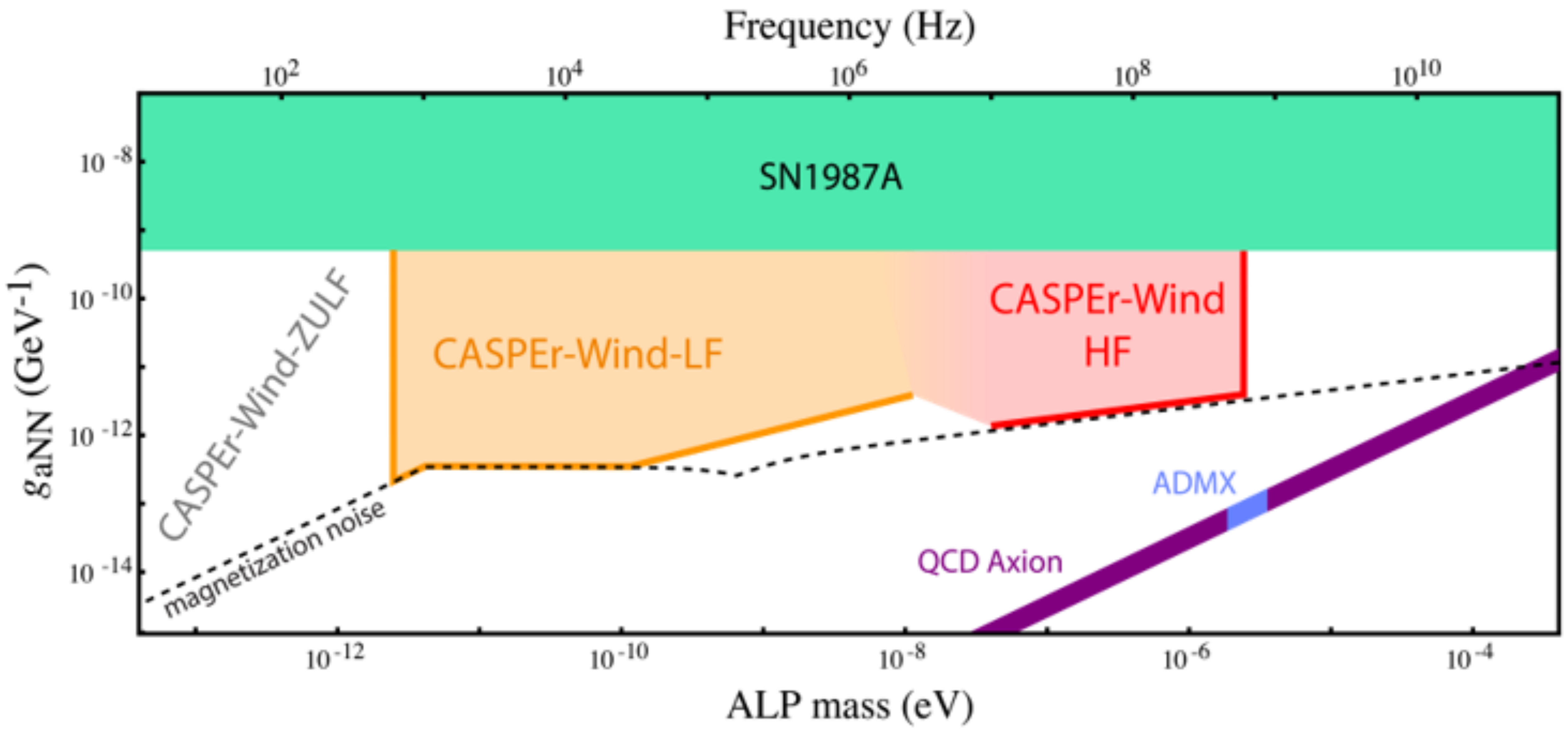


PRD 113, 092004 (2026)
L. Badurina, D. Blas, J. Ellis, **SARE**

The box is the Box: CASPEr



CASPEr-wind searches for $\hat{H}_{\rm int} = -2\, g_N \nabla a \cdot \hat{\boldsymbol{S}}$
with a hyper-polarised spin sample in a box



P. Graham and S. Rajendran (2013)
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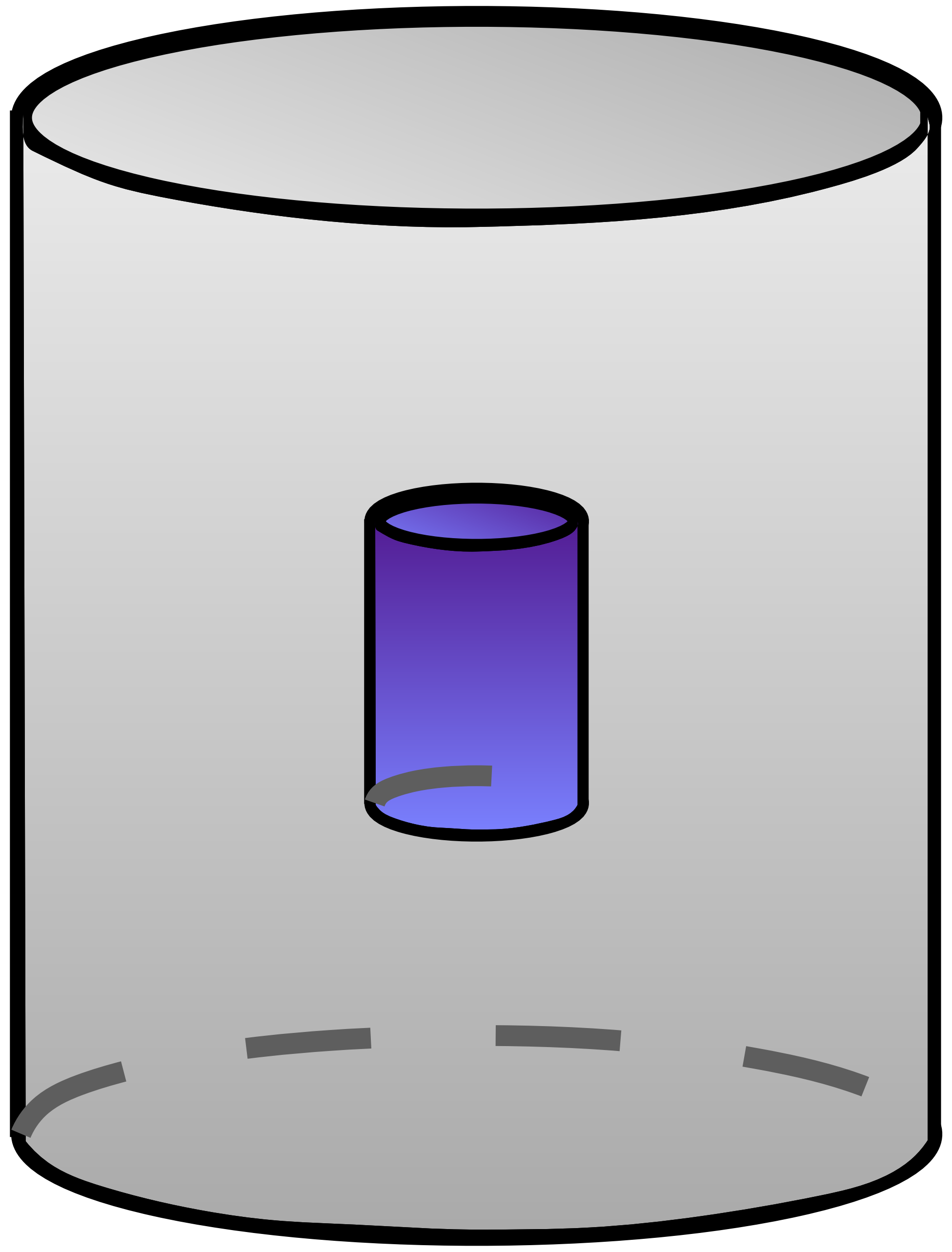

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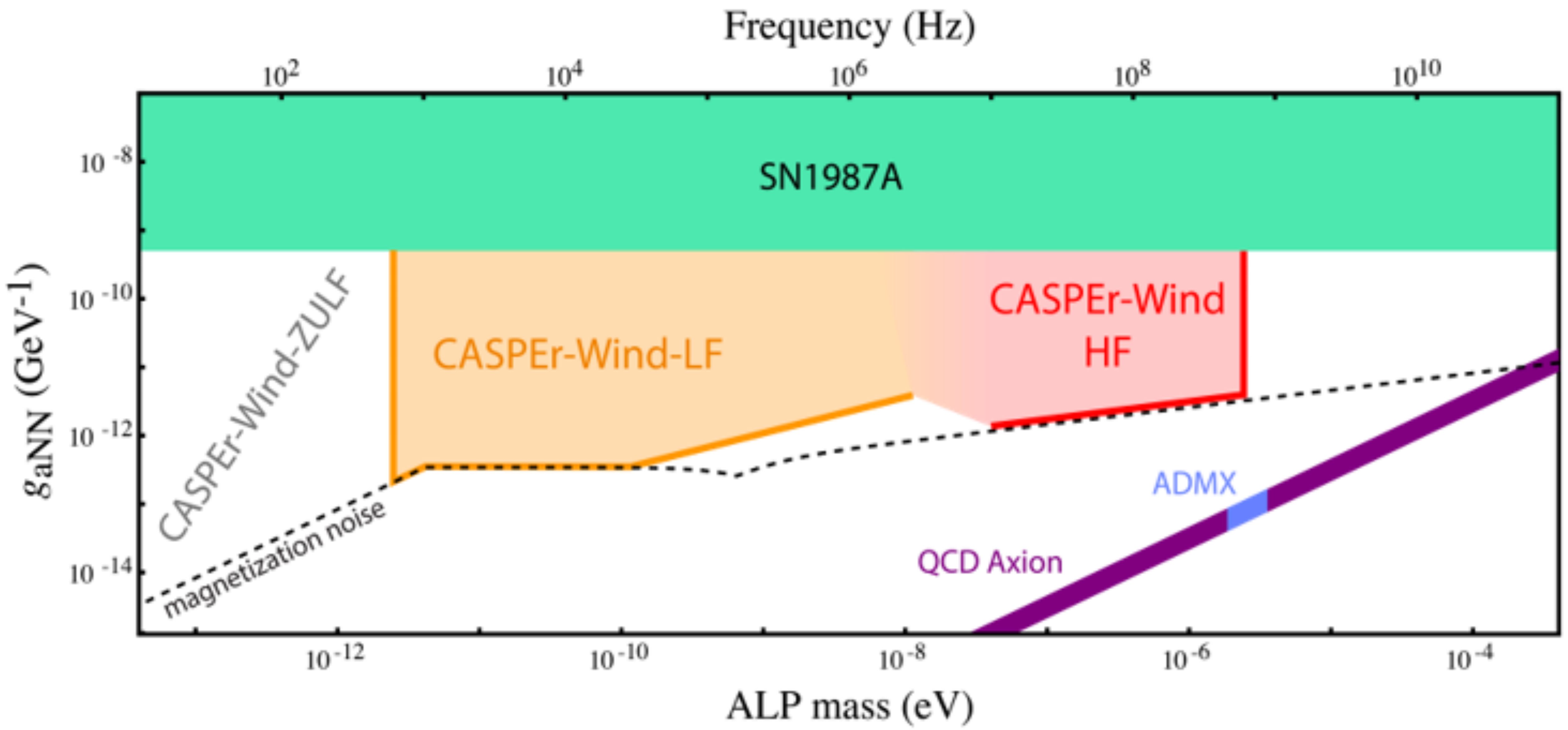

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Hyper-polarisation achieved by applying a big magnetic field...

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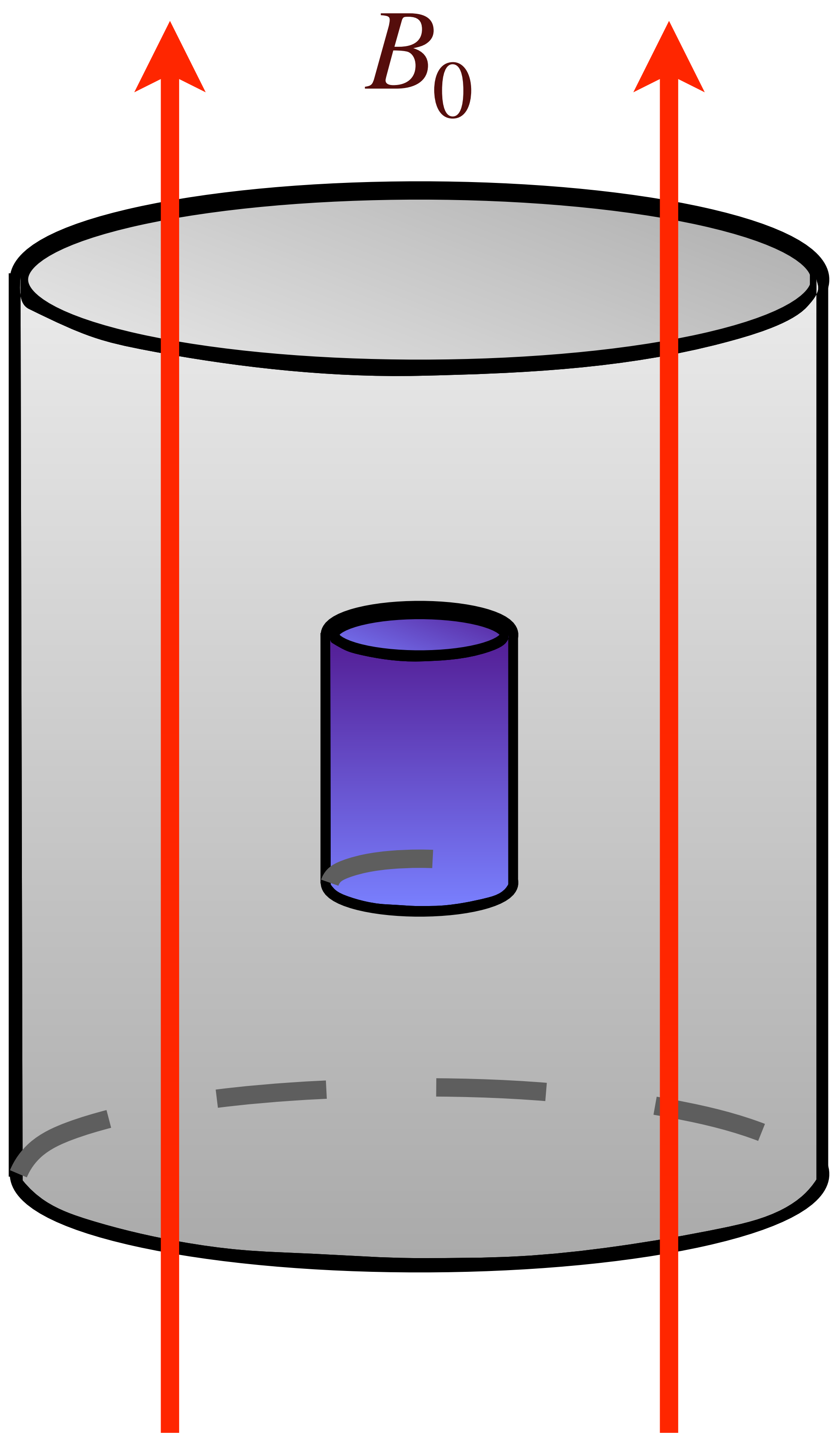

Box acts as a driven cavity, whose EoMs are

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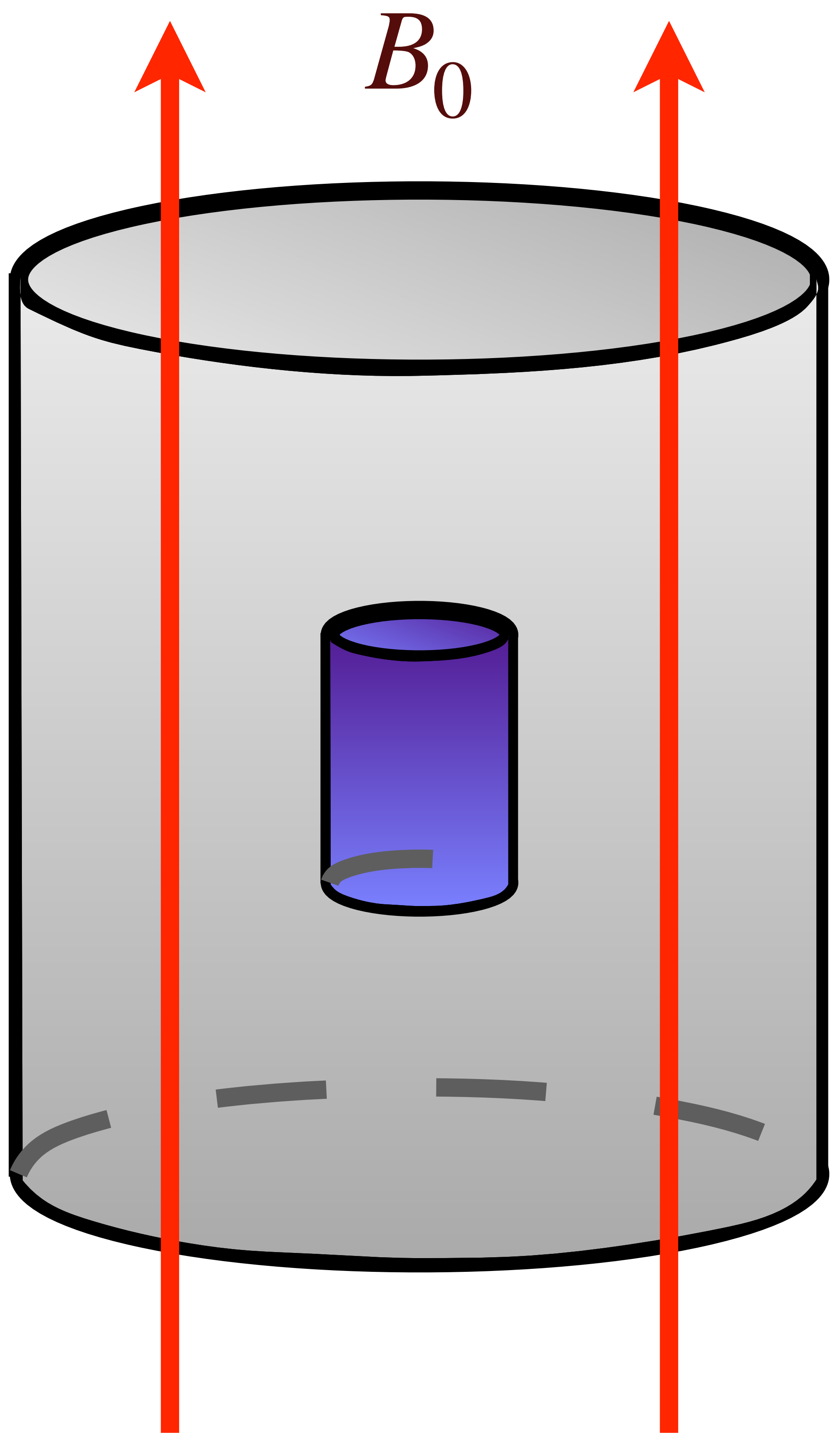

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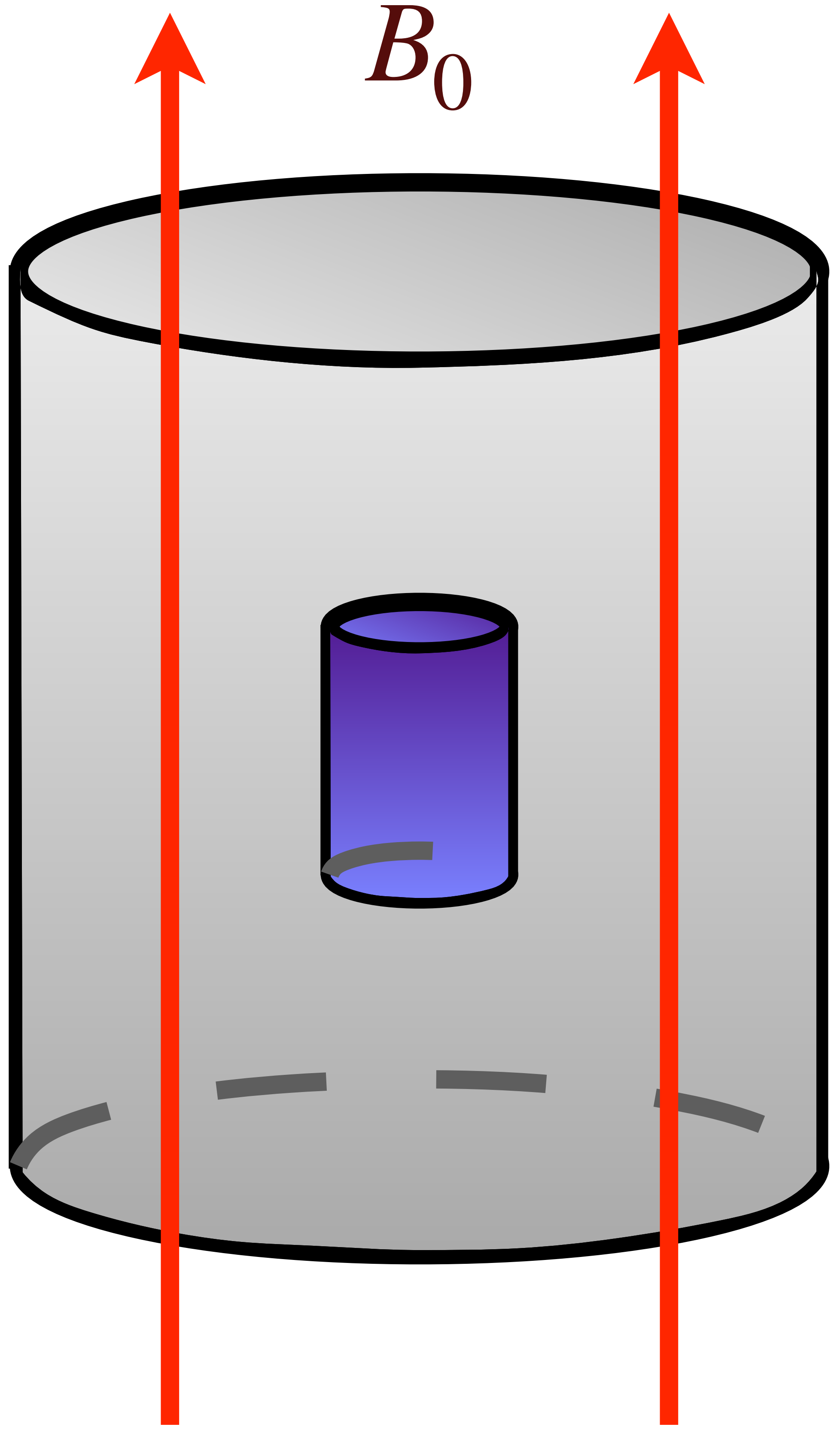

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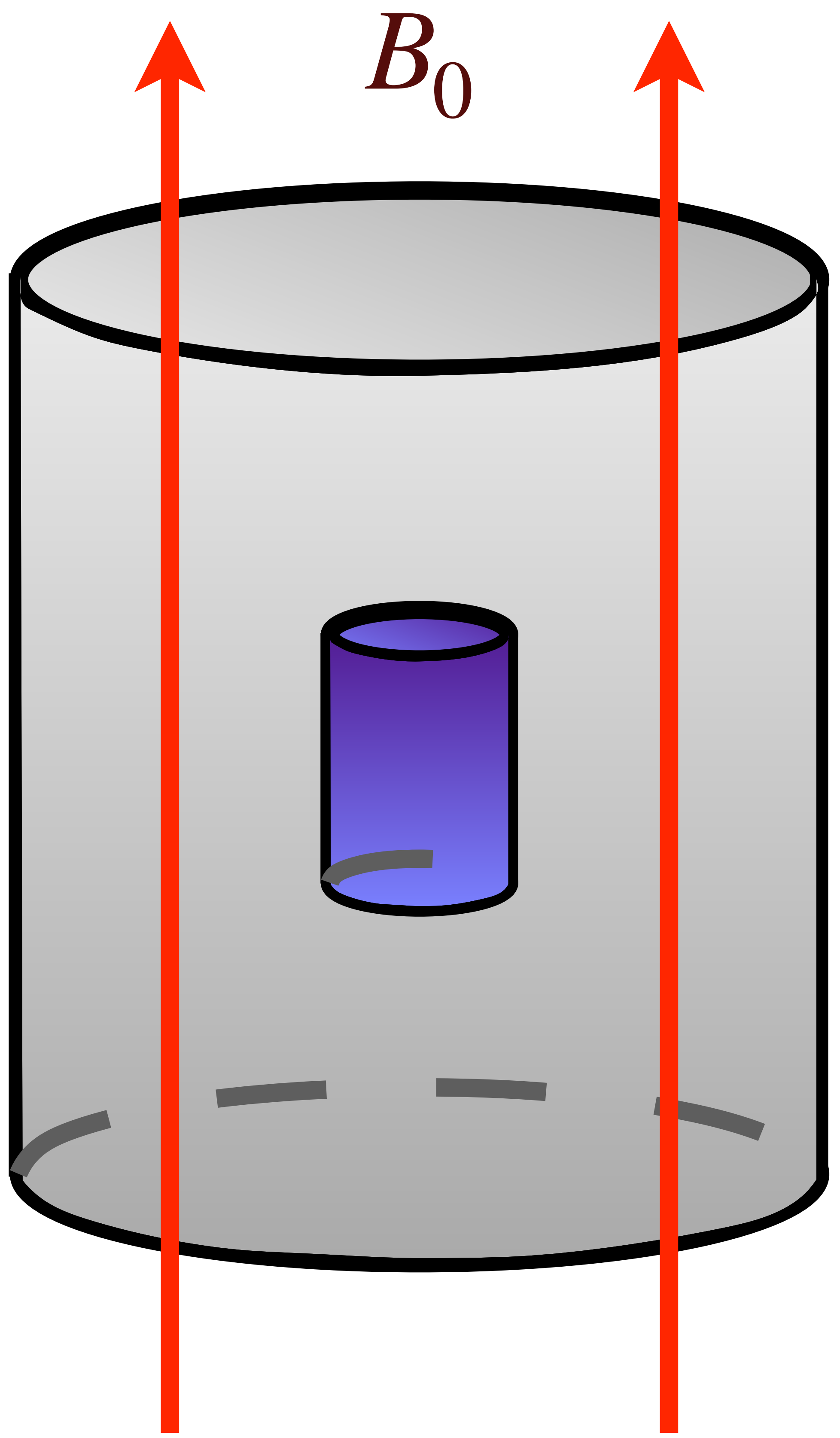

General solution for **electric** fields:

$$\mathbf{E}(\mathbf{x}, t) = \int \frac{d\omega}{2\pi}\, e^{-i\omega t} \sum_\ell c_\ell(\omega)\, \mathbf{E}_\ell(\mathbf{x}).$$

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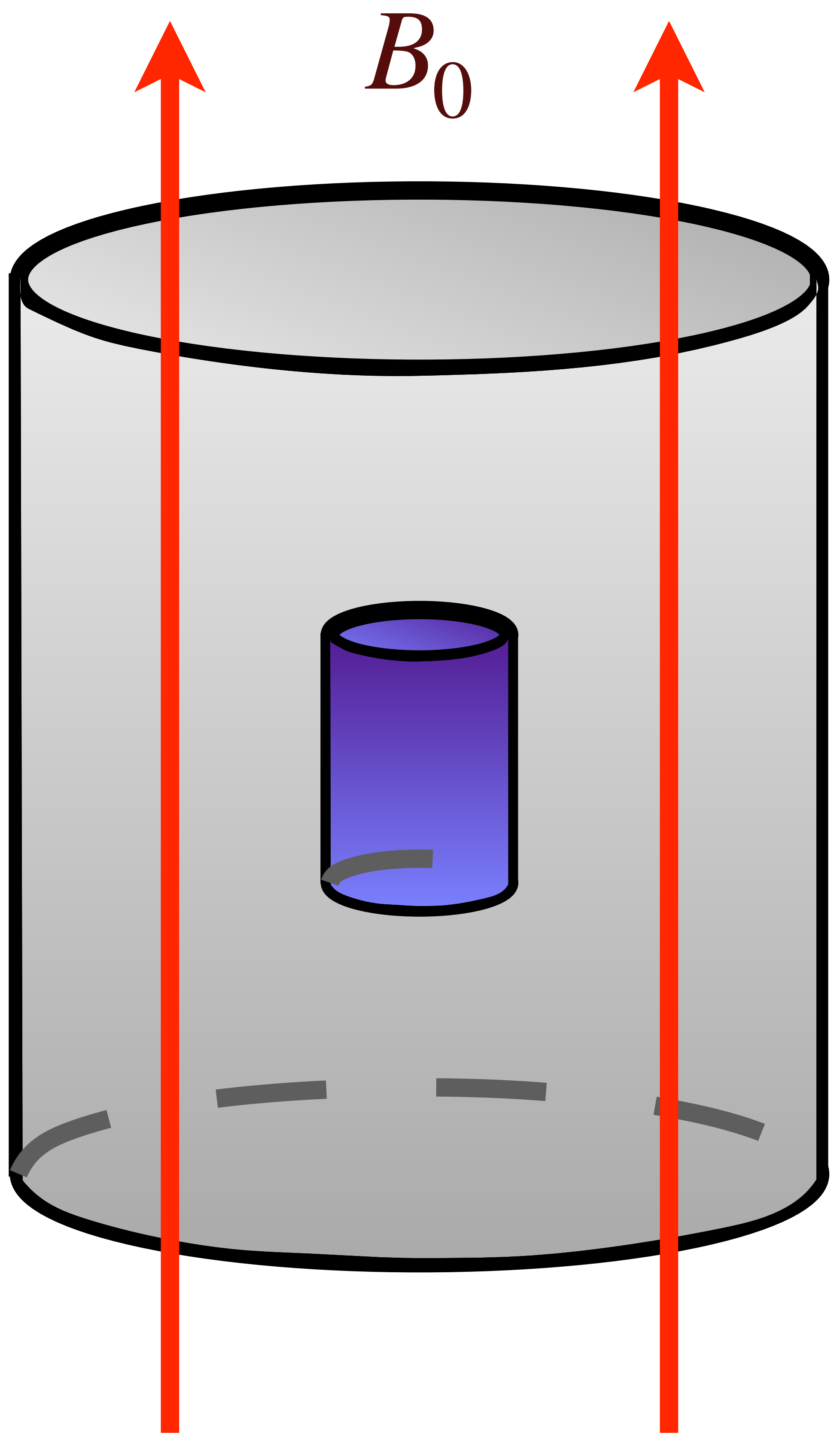

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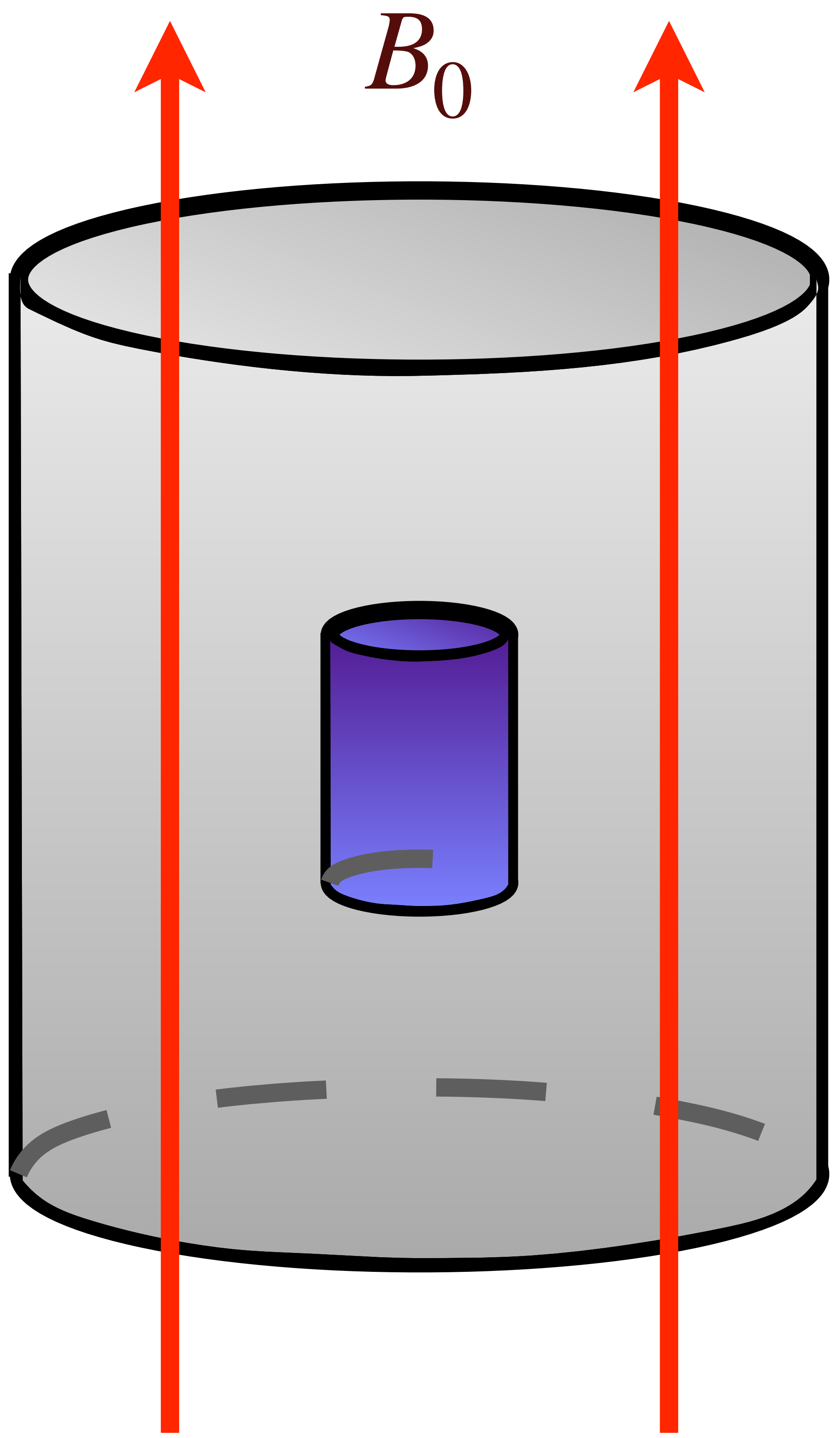

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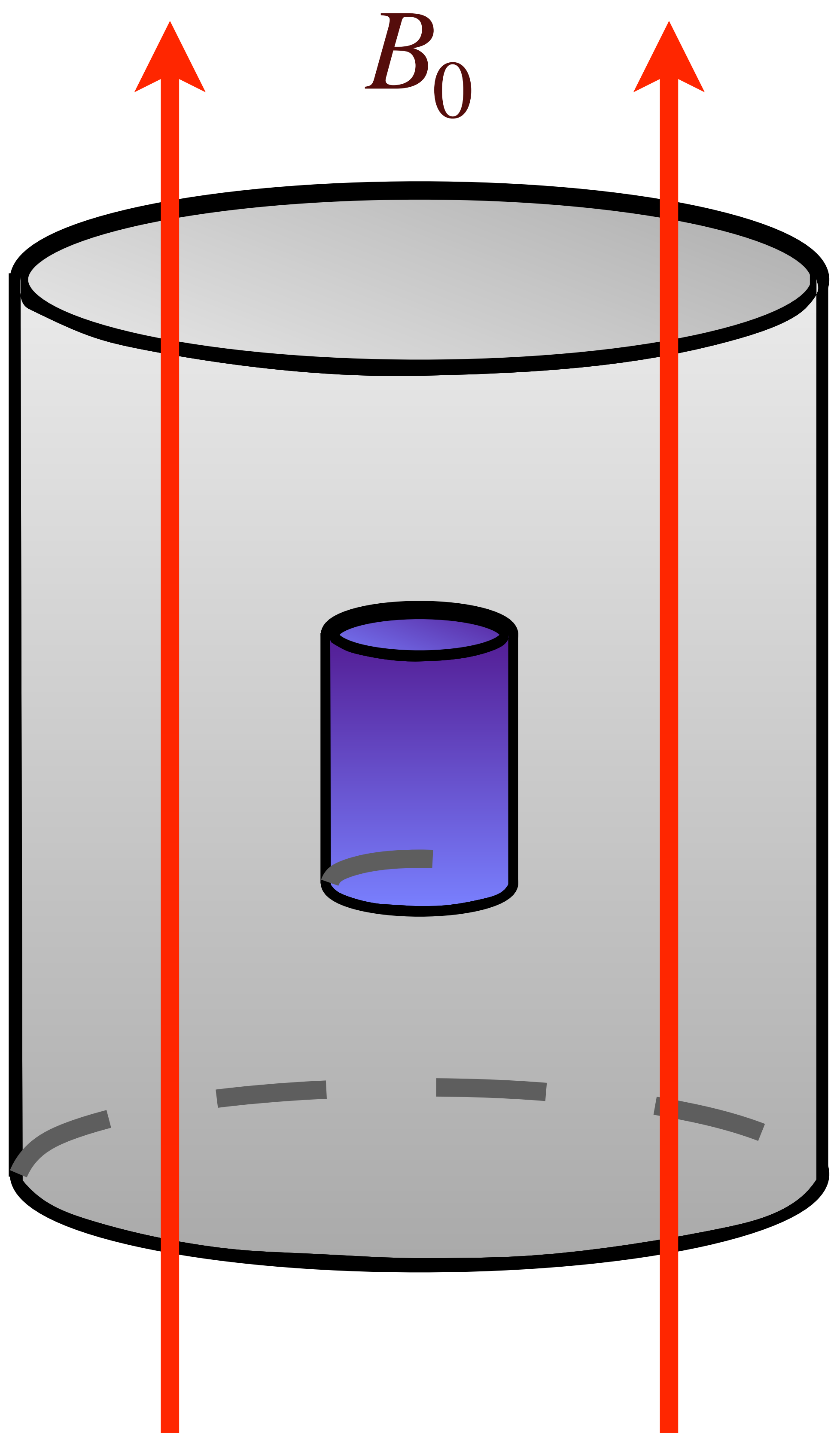

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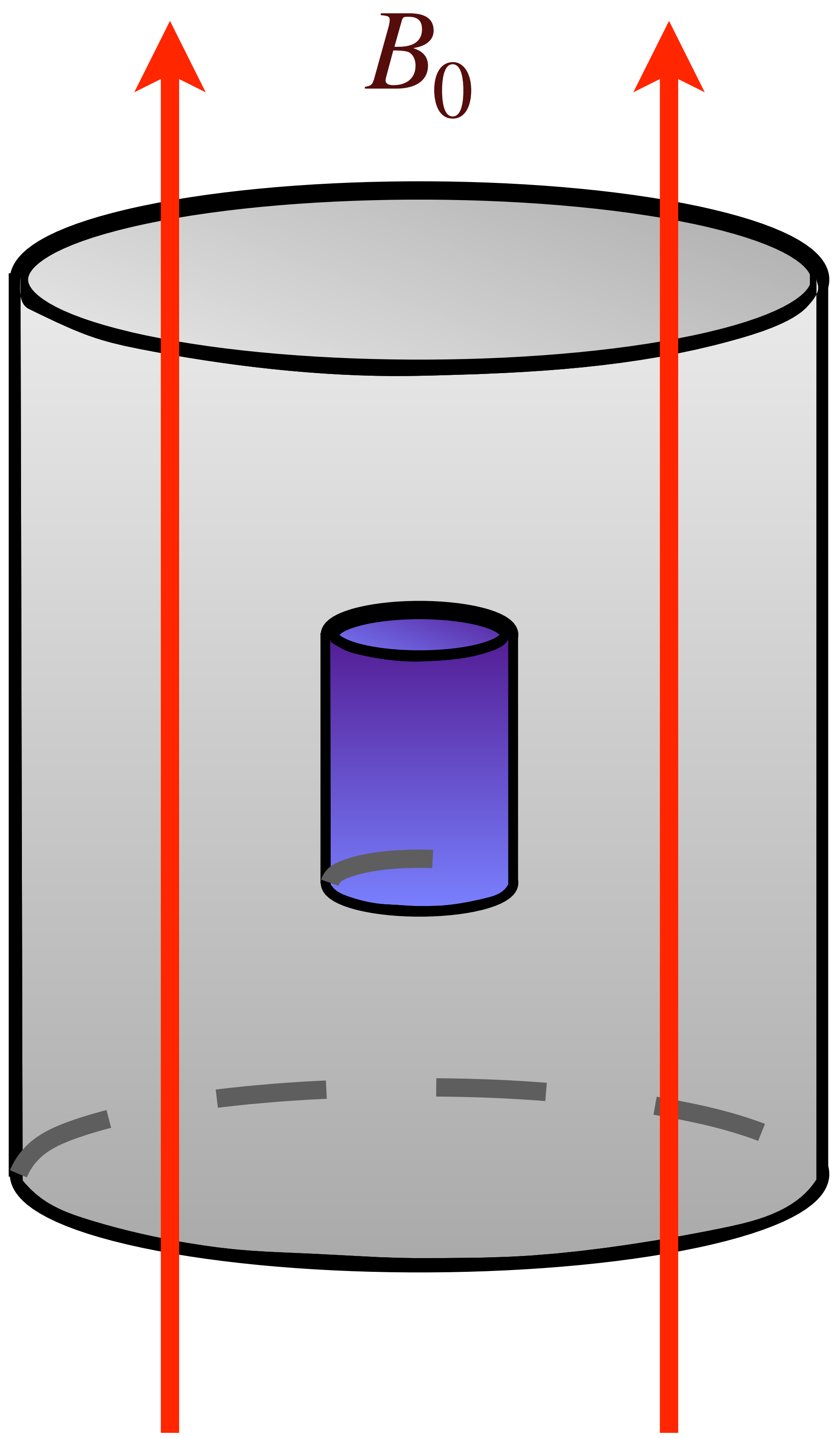
Magnetic field larger by $\omega_\ell/\omega \gg 1$

P. Graham, J. Mardon, S. Rajendran, Y. Zhao (2014)
S. Chaudhuri et al (2015)

Spin Signals — the box is the Box: CASPEr



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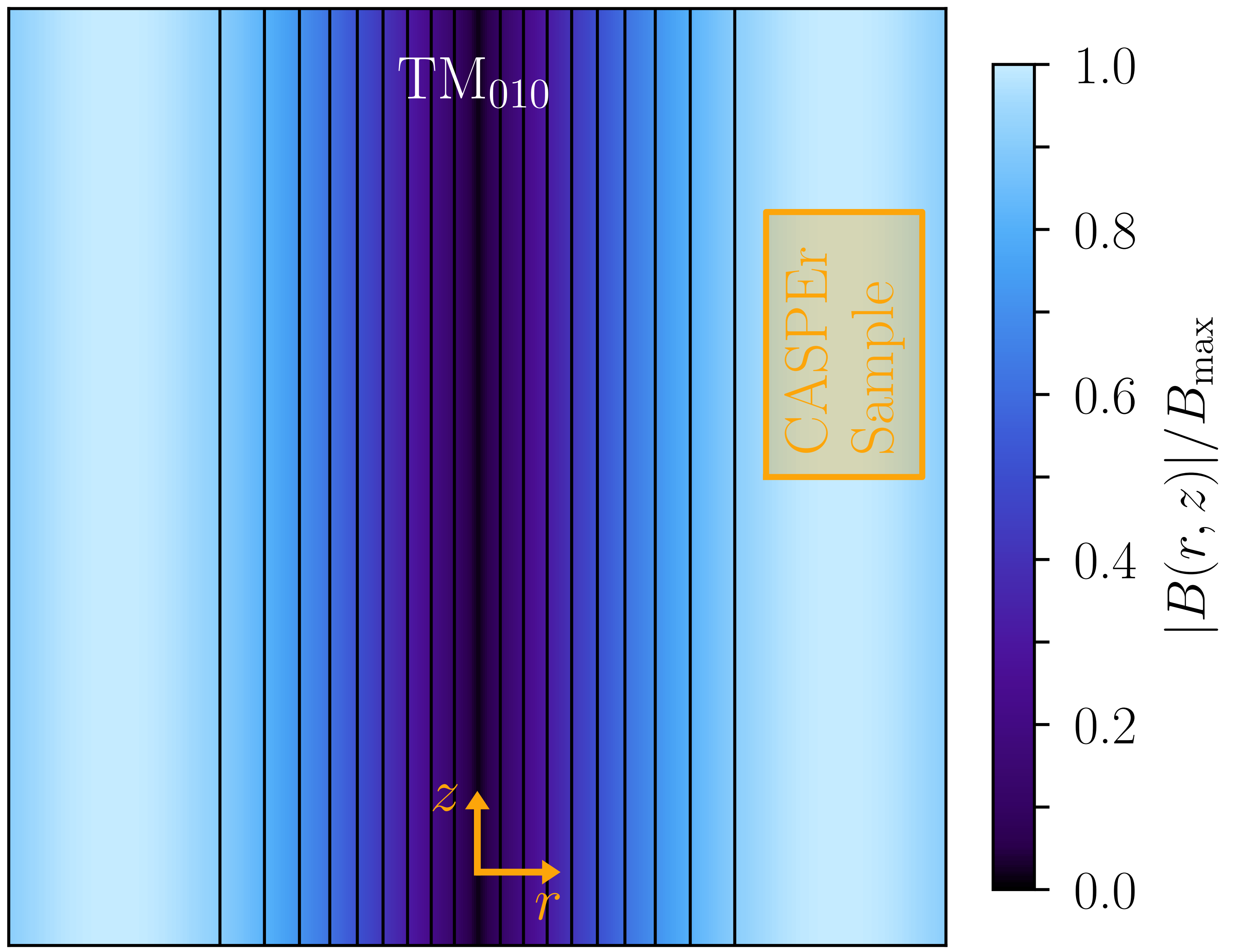

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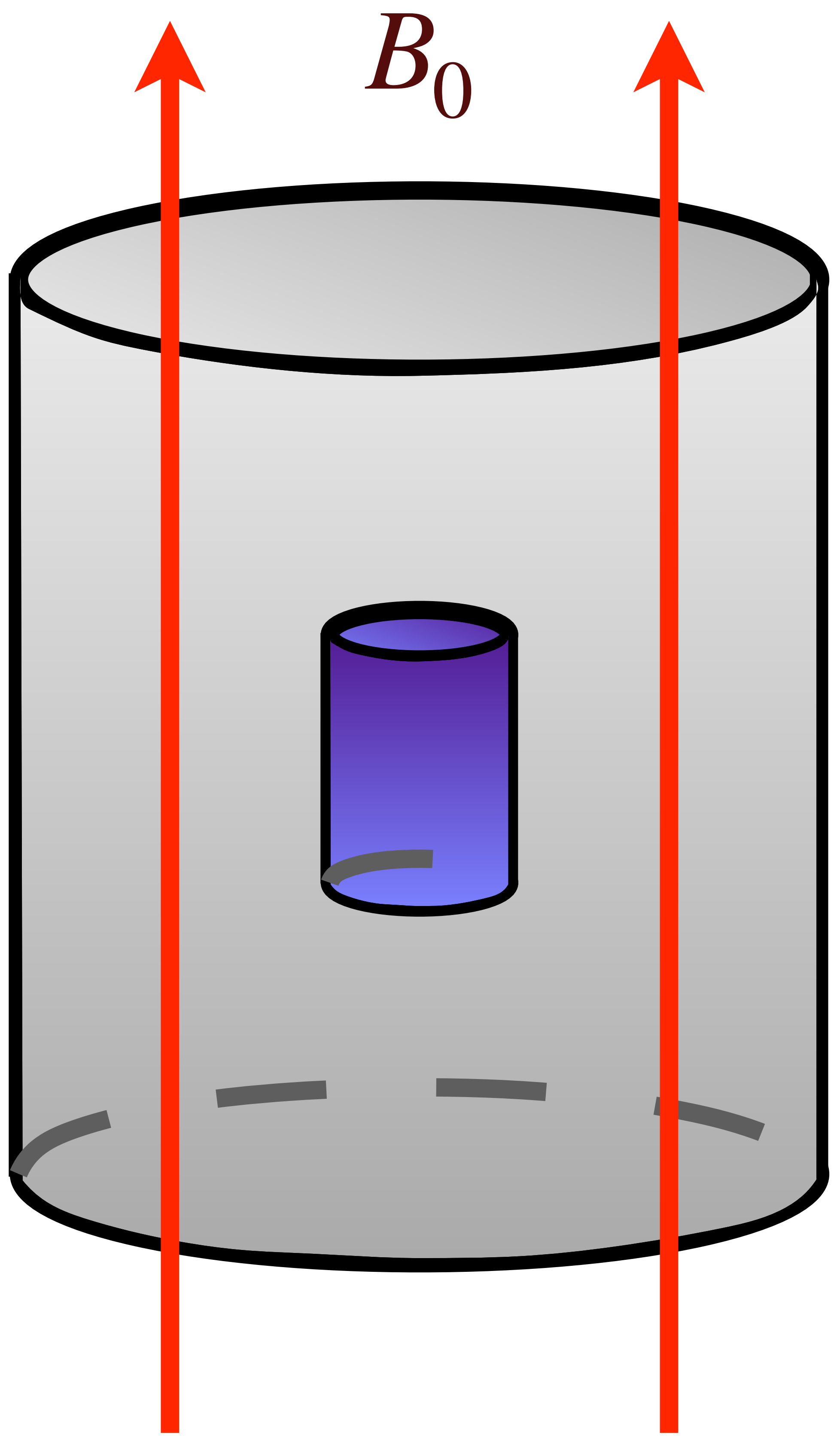

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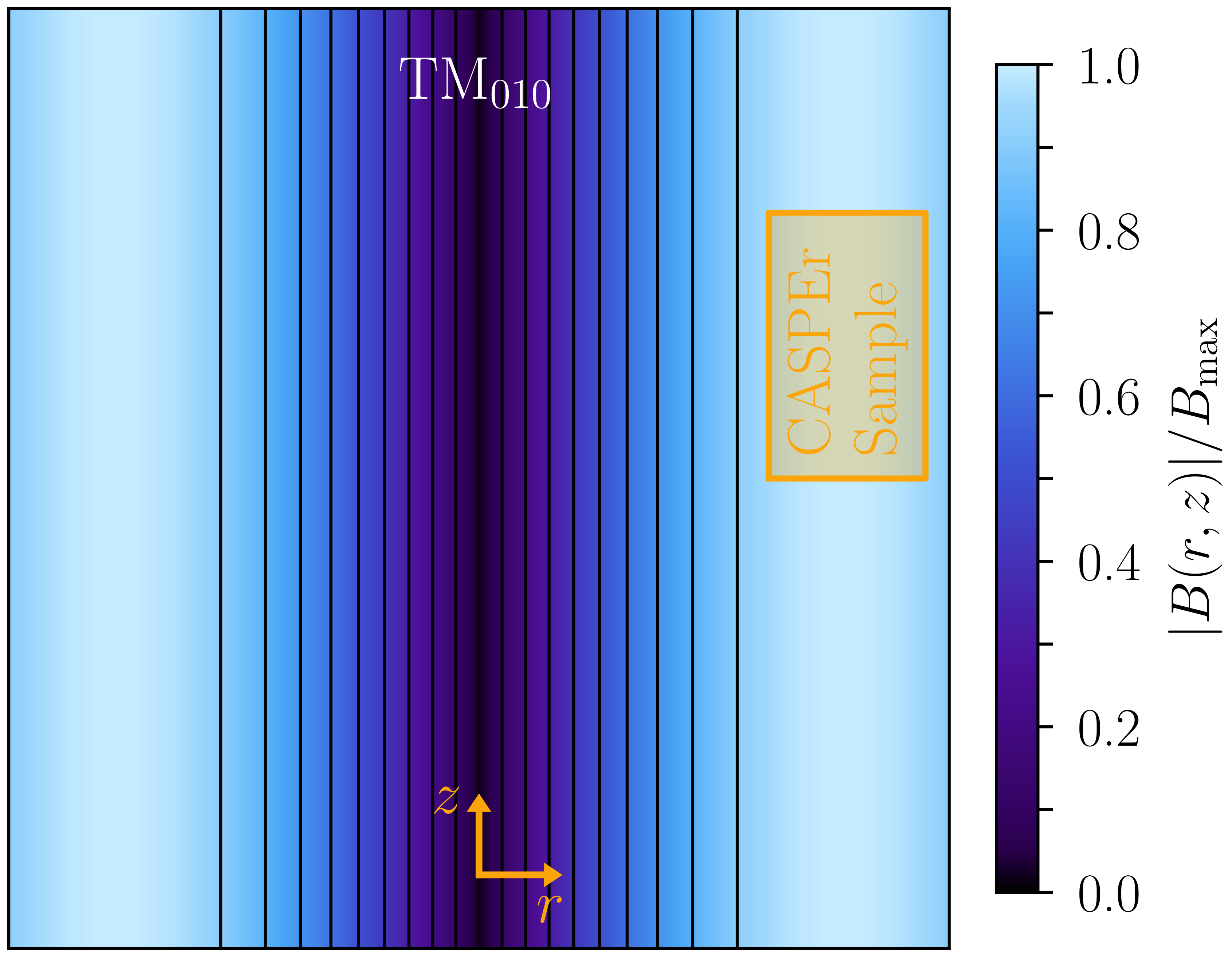
Dark matter is ~uniform across the box

$$c_\ell \propto \mathbf{J}_{\text{eff}} \cdot \int_V dV\, \mathbf{E}^*_\ell$$



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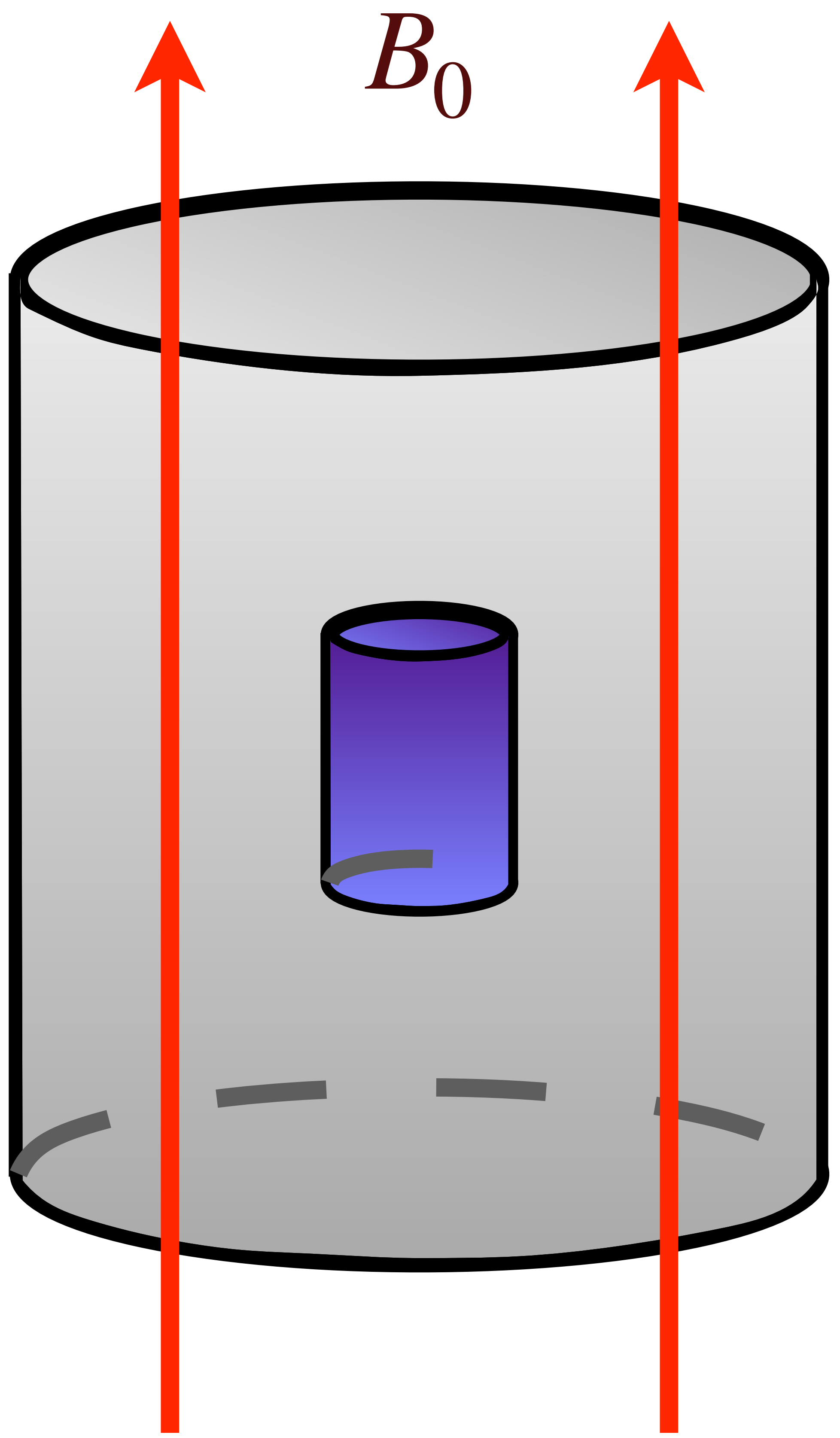

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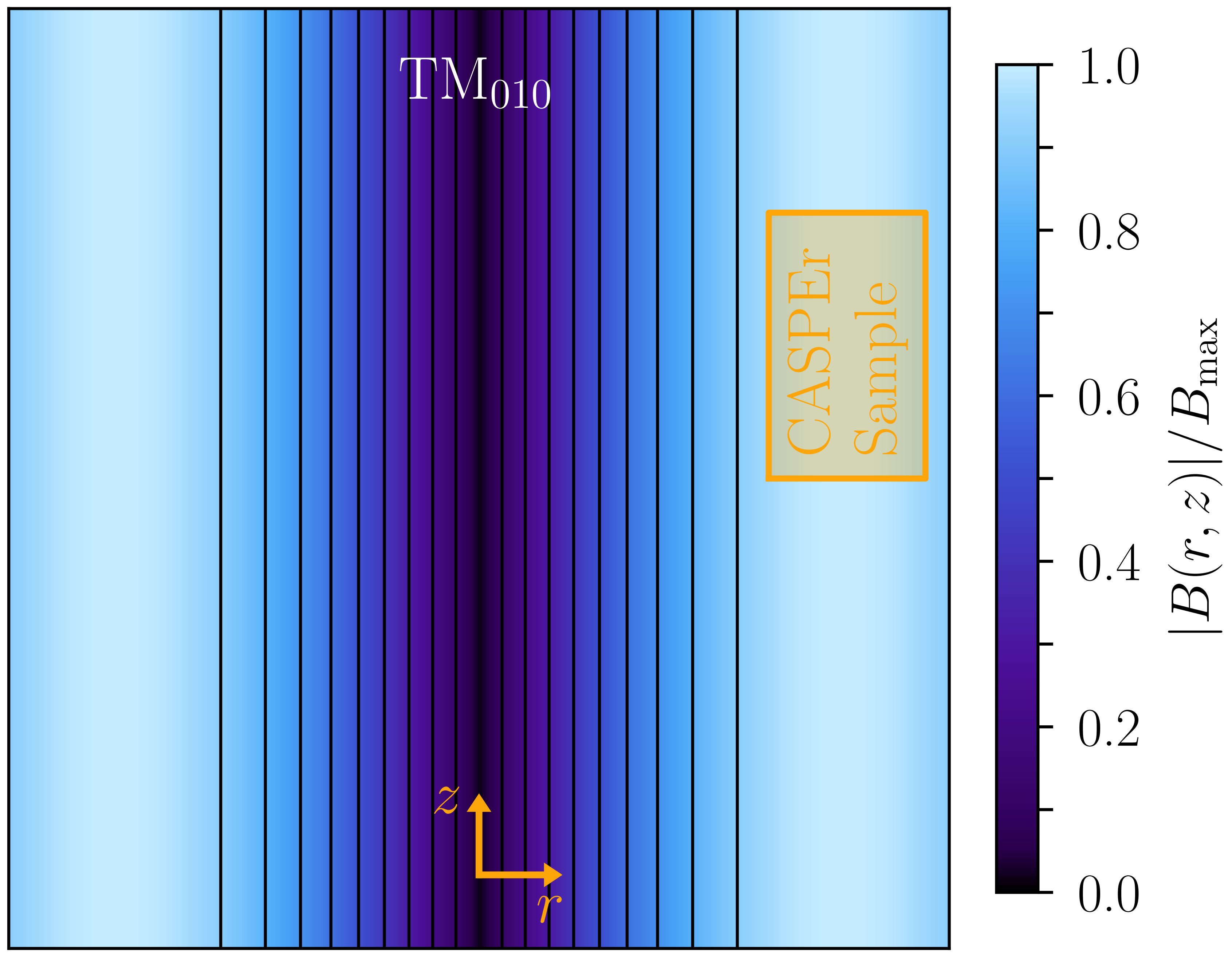
For Transverse Magnetic modes:

$$\int dV\, \mathbf{E}^*_{0n0,M} = (-1)^{n+1} \frac{2}{j_{0n}} \sqrt{V}$$



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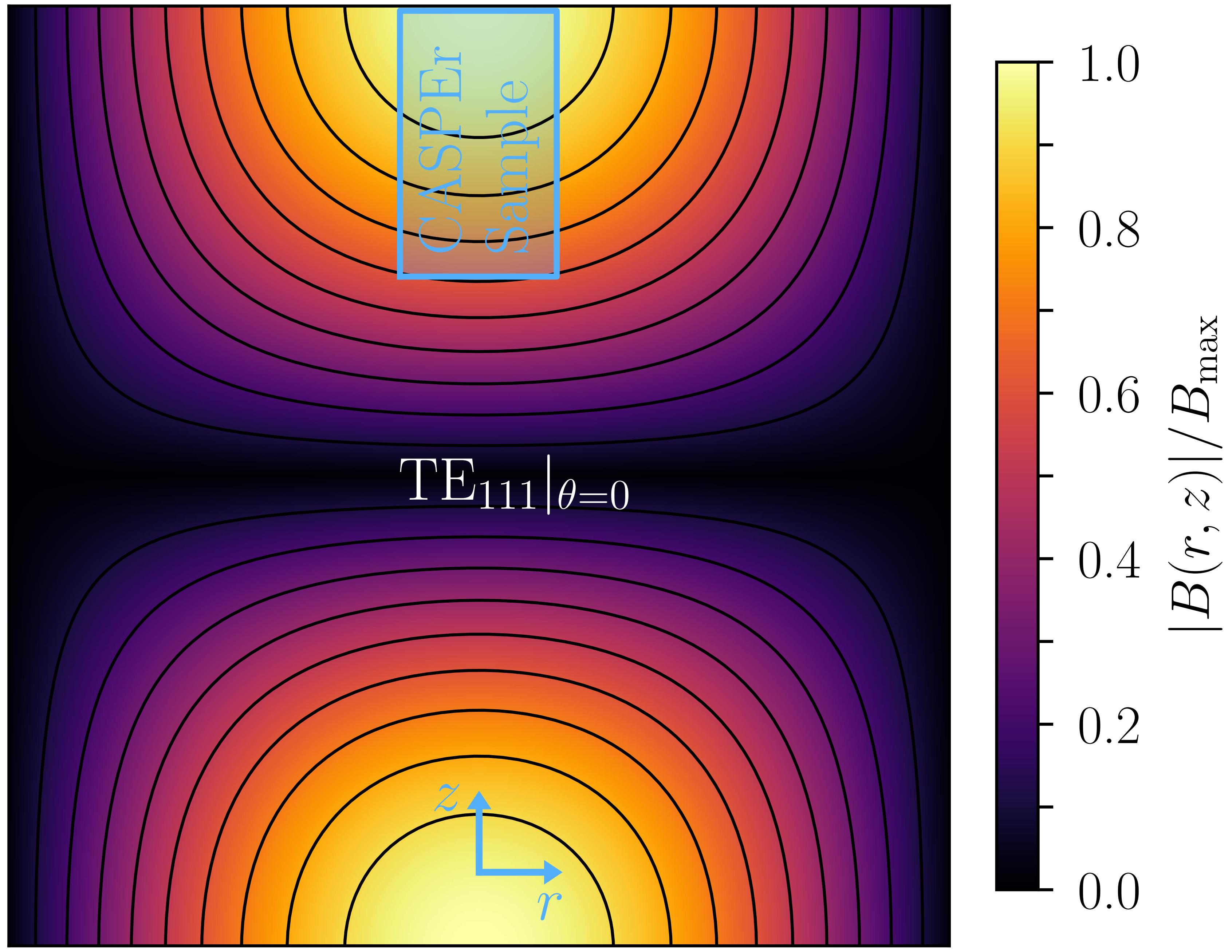
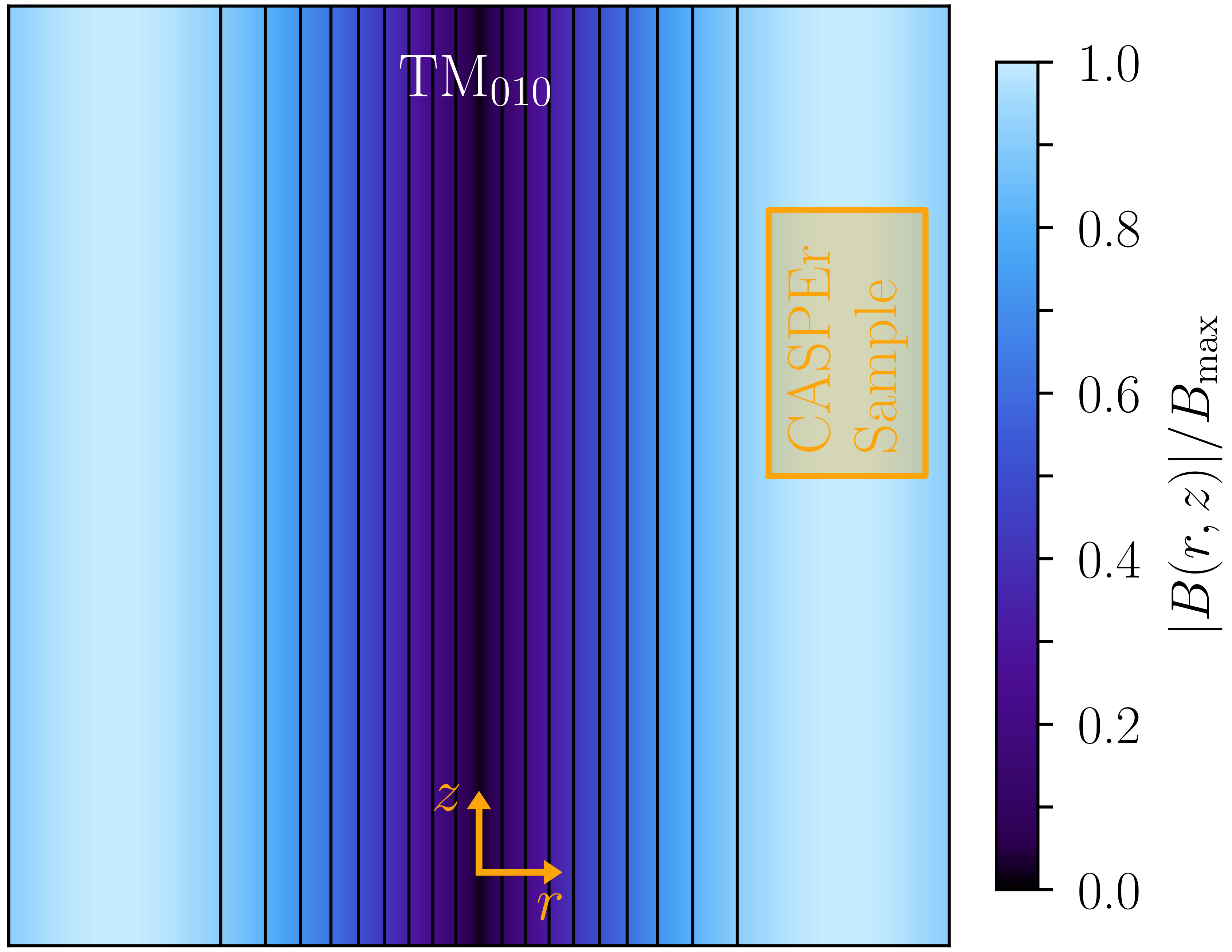


Dark Photon and Axion signals can be disentangled by where the signal appears

	TE modes	TM modes
Axion	💀	✅
Dark Photon	✅	✅



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Sensitivity for CASPEr-Wind is easily estimated from axion gradient sensitivity

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Compare sensitivity to $\mathbf{B}_{\rm grad} \sim g_N (2/\gamma) \nabla a$ with: $$g_N \equiv c_N \frac{m_{\rm DM}}{m_\pi f_\pi}$$

$$\mathbf{B}_{\rm DP} \sim \epsilon m_{A'}^2 L \mathbf{A}' \quad \text{or} \quad \mathbf{B}_{a\gamma} \sim g_{a\gamma\gamma} \mathbf{B}_0 L (\partial_t a)$$

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Arrive at

$$\epsilon \sim 10^{-16} c_N \left(\frac{\gamma_{\rm He}}{\gamma}\right)\left(\frac{10\,\mathrm{cm}}{L}\right) \qquad\qquad c_\gamma \sim c_N \left(\frac{10\,\mathrm{T}}{B_0}\right)\left(\frac{\gamma_{\rm He}}{\gamma}\right)\left(\frac{10\,\mathrm{cm}}{L}\right)$$

$$g_{a\gamma\gamma} \equiv c_\gamma \frac{\alpha_{\rm EM}\, m_{\rm DM}}{2\pi\, m_\pi f_\pi}$$

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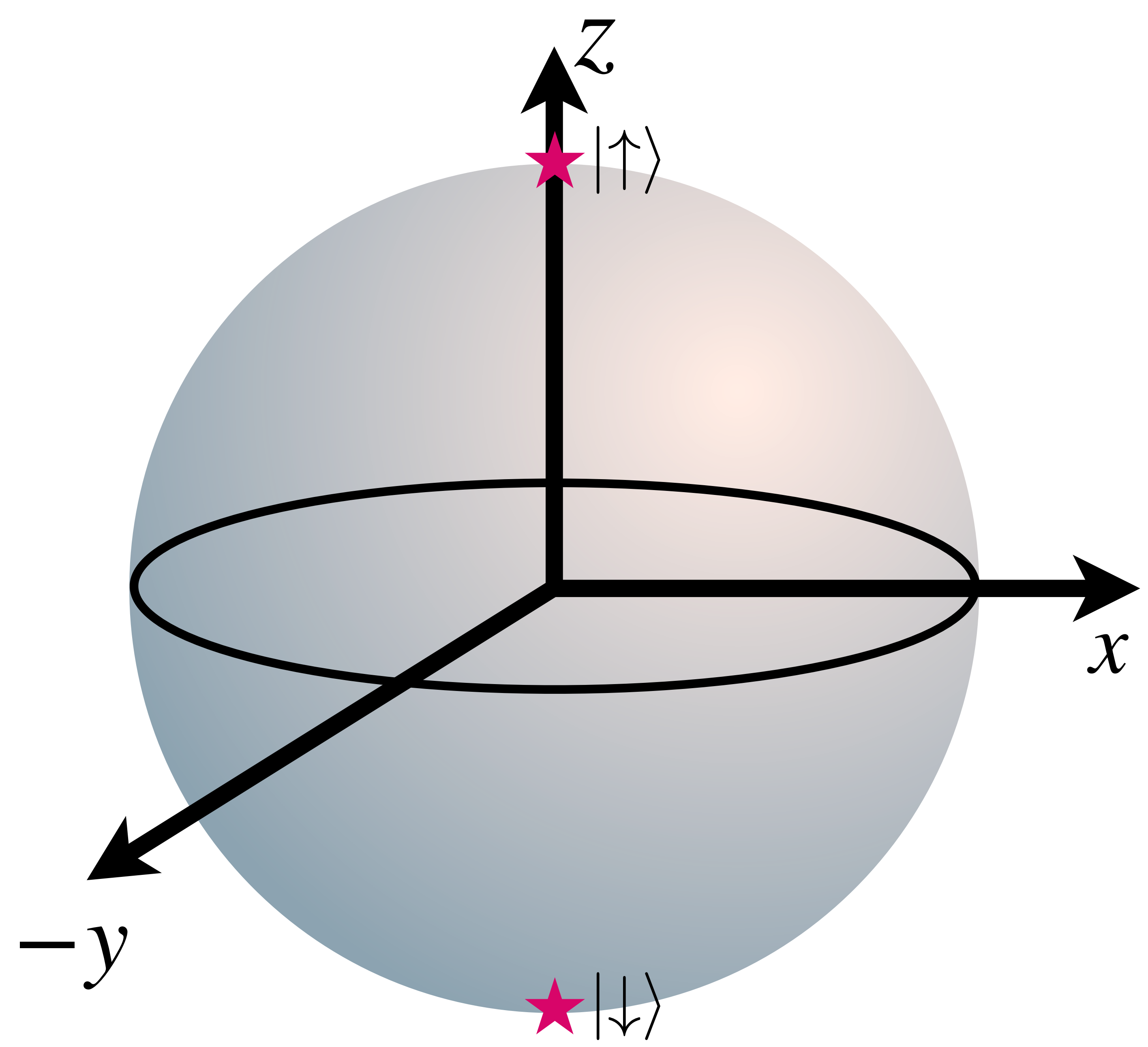
More careful analysis requires solving the Bloch equations

$$\dot{\mathbf{M}} = \mathbf{M} \times \gamma \mathbf{H} - \frac{M_x \hat{\mathbf{x}} + M_y \hat{\mathbf{y}}}{T_2} - \frac{(M_z - M_0)\hat{\mathbf{z}}}{T_1}$$



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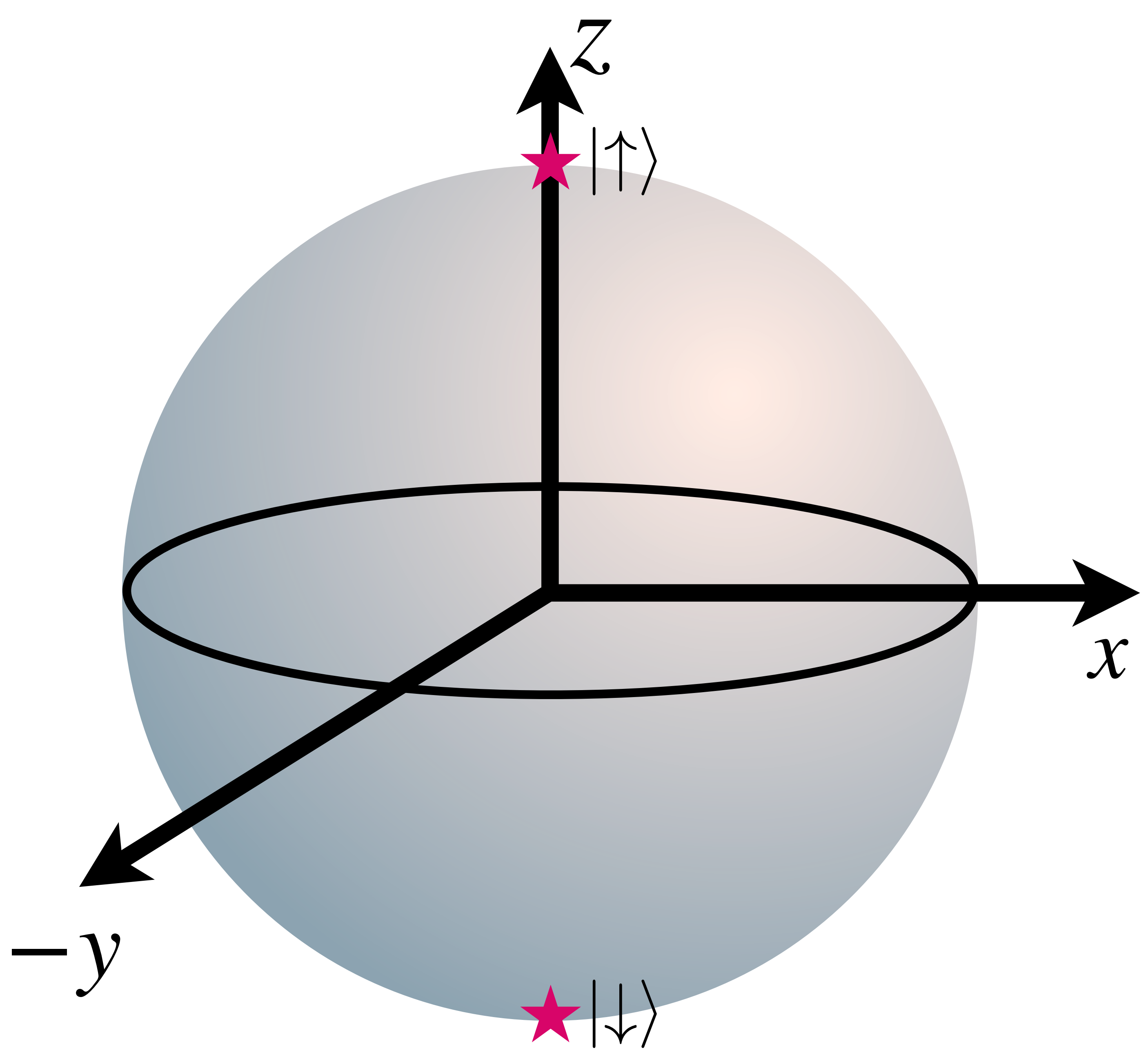
x and y directions coupled, so work in $M_\pm = \frac{1}{\sqrt{2}}\left(M_x \pm iM_y\right)$ basis



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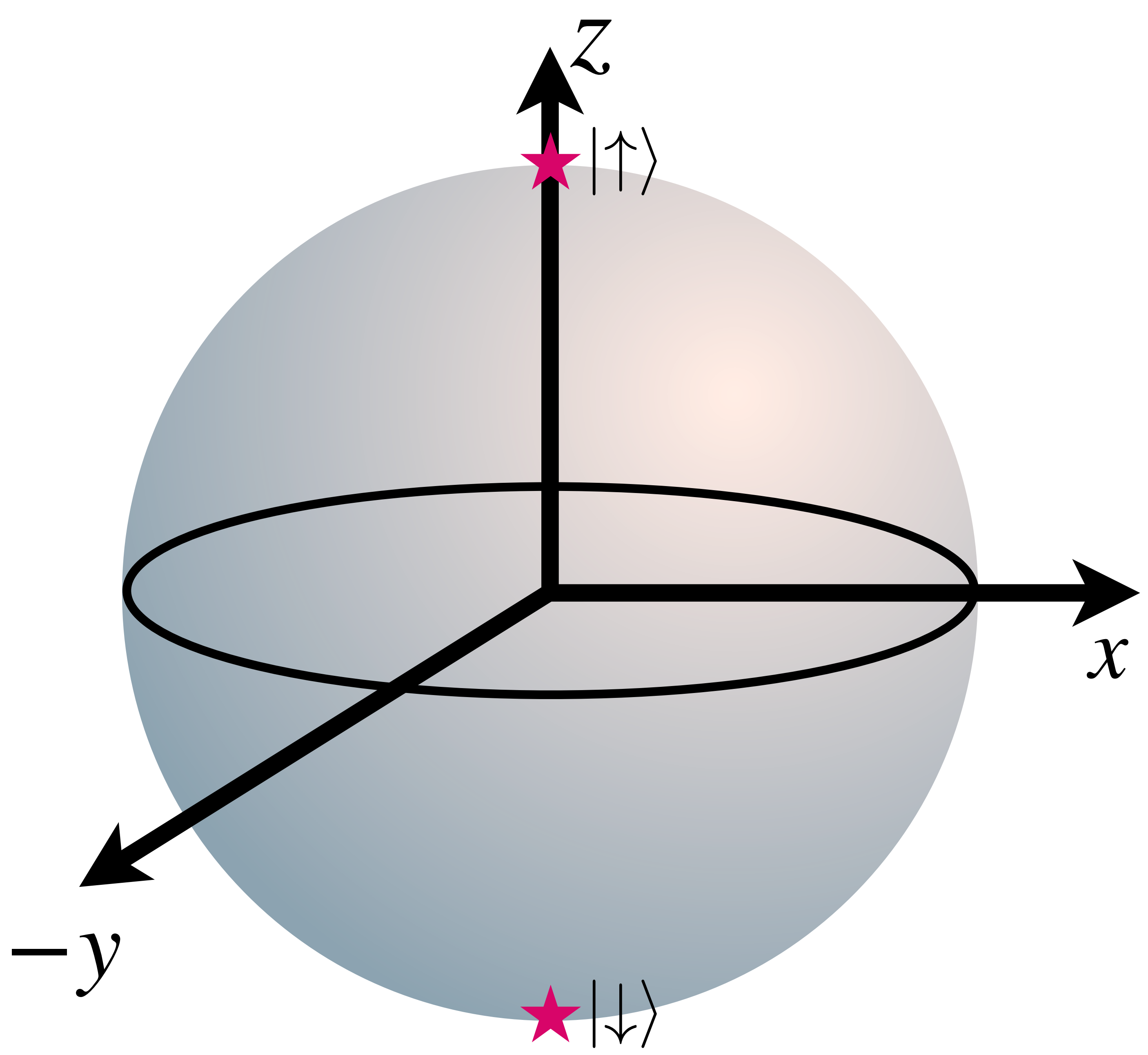
Time domain solution is simple: $M_+(t) = i\gamma M_0 \int_0^t dt'\, e^{-(t-t')/T_2} e^{-i\omega_0 (t-t')} H^+_{\rm DM}(t')$



The box is the Box: CASPEr

Signal 2-pt function is non-zero for DM signals

$$\langle M_+(t)^2 \rangle \propto (\gamma M_0 T_2)^2 \langle H^+_{\rm DM}(t)^2 \rangle$$

SNR comes from comparing this signal to spin-projection noise

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Dark Photons $H_{\rm DM} \sim \epsilon m_{A'} L \sqrt{\rho_{\rm DM}}$

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Dark Photons $H_{\mathrm{DM}} \sim \epsilon m_{A'} L \sqrt{\rho_{\mathrm{DM}}}$

Axions $H_{\mathrm{DM}} \sim g_{a\gamma\gamma} B_0 L \sqrt{\rho_{\mathrm{DM}}}$

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Usual spin state is $|\uparrow\rangle^{\otimes N}$, held fixed by an applied magnetic field

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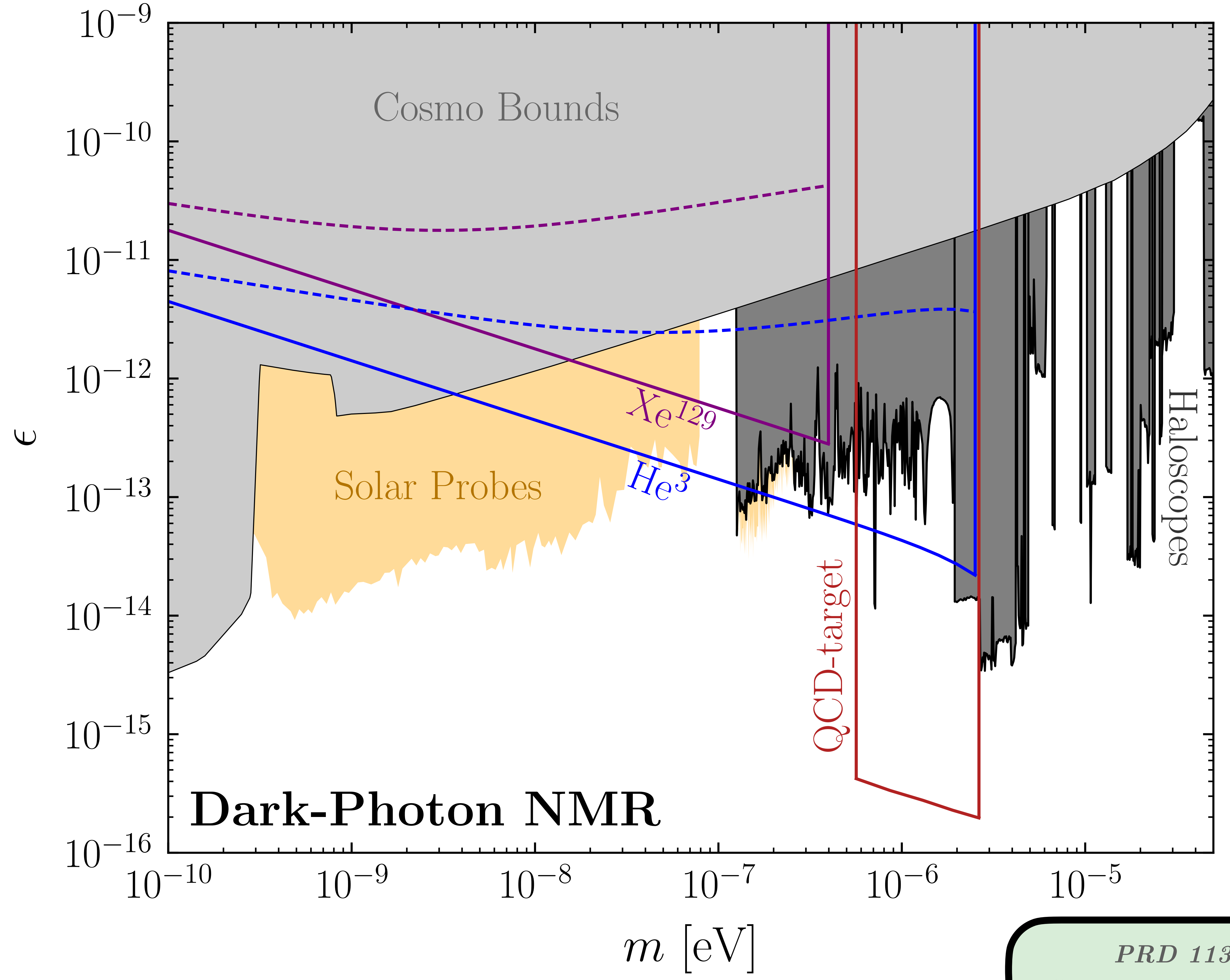
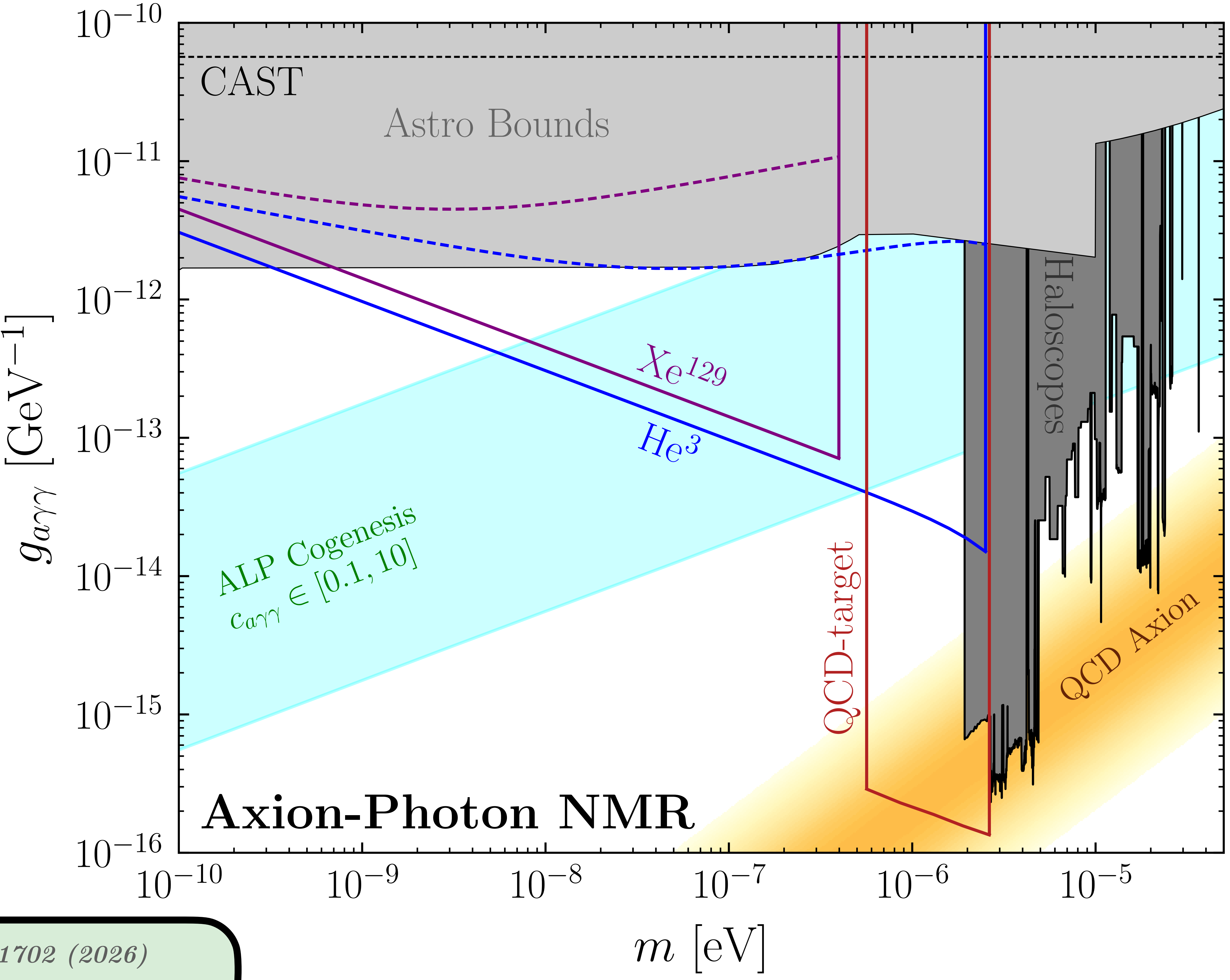
Recall $MV = \sum_i \gamma s_i \sim N\gamma$

Compare the above with the previous slide: $H_{\mathrm{DM}} \propto n^{-1/2}\gamma^{-1}$ — **S**tandard **Q**uantum **L**imit scaling

The box is the Box: CASPEr projections

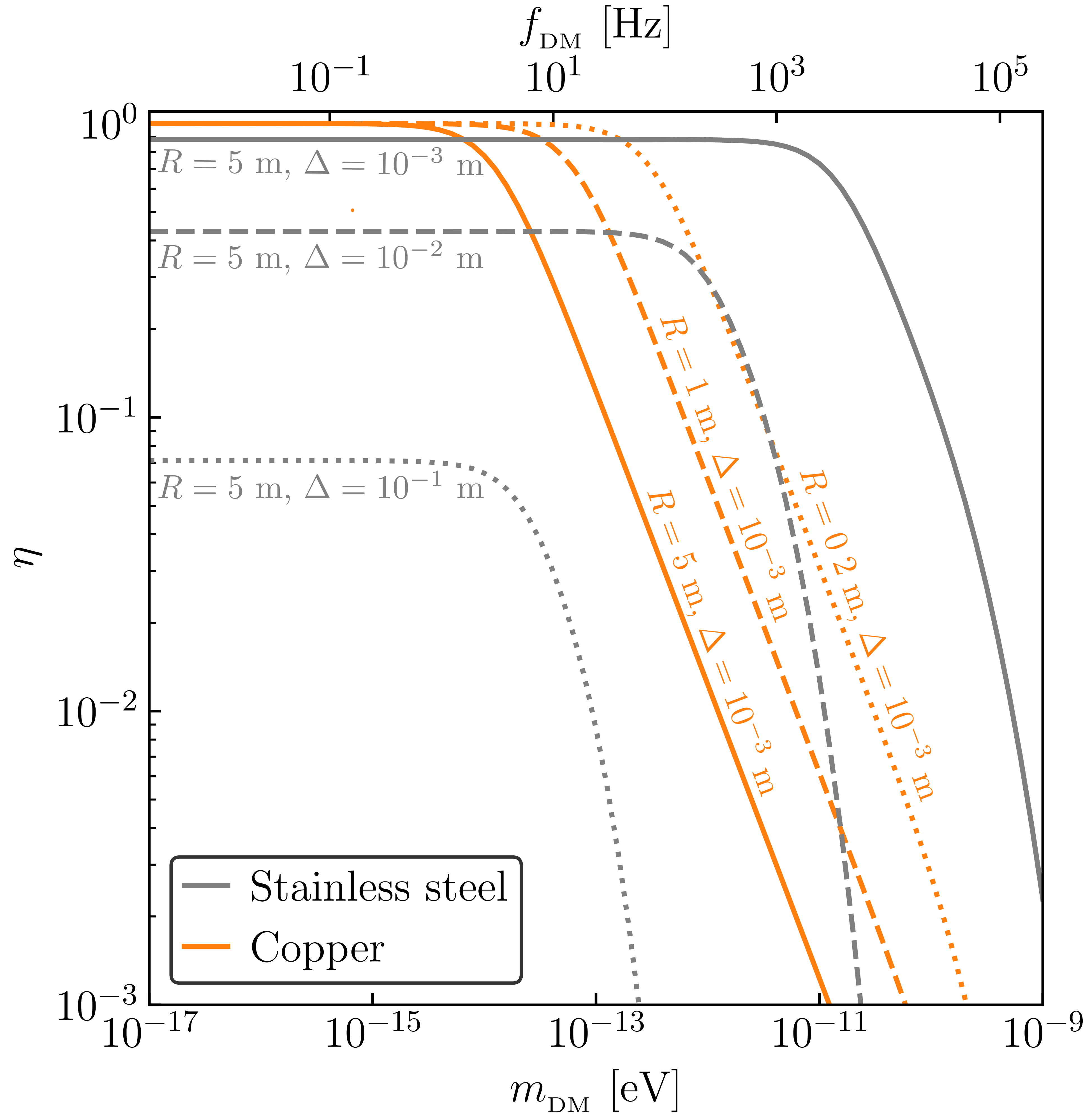




PRD 113, L031702 (2026)
C. Beadle, **SARE,** J. Leedom, N. L. Rodd

The box is NOT the Box: Ion Interferometry

Below $\sim 10^{-13}$ eV, unless you use a material with high magnetic permeability, the box is not the Box



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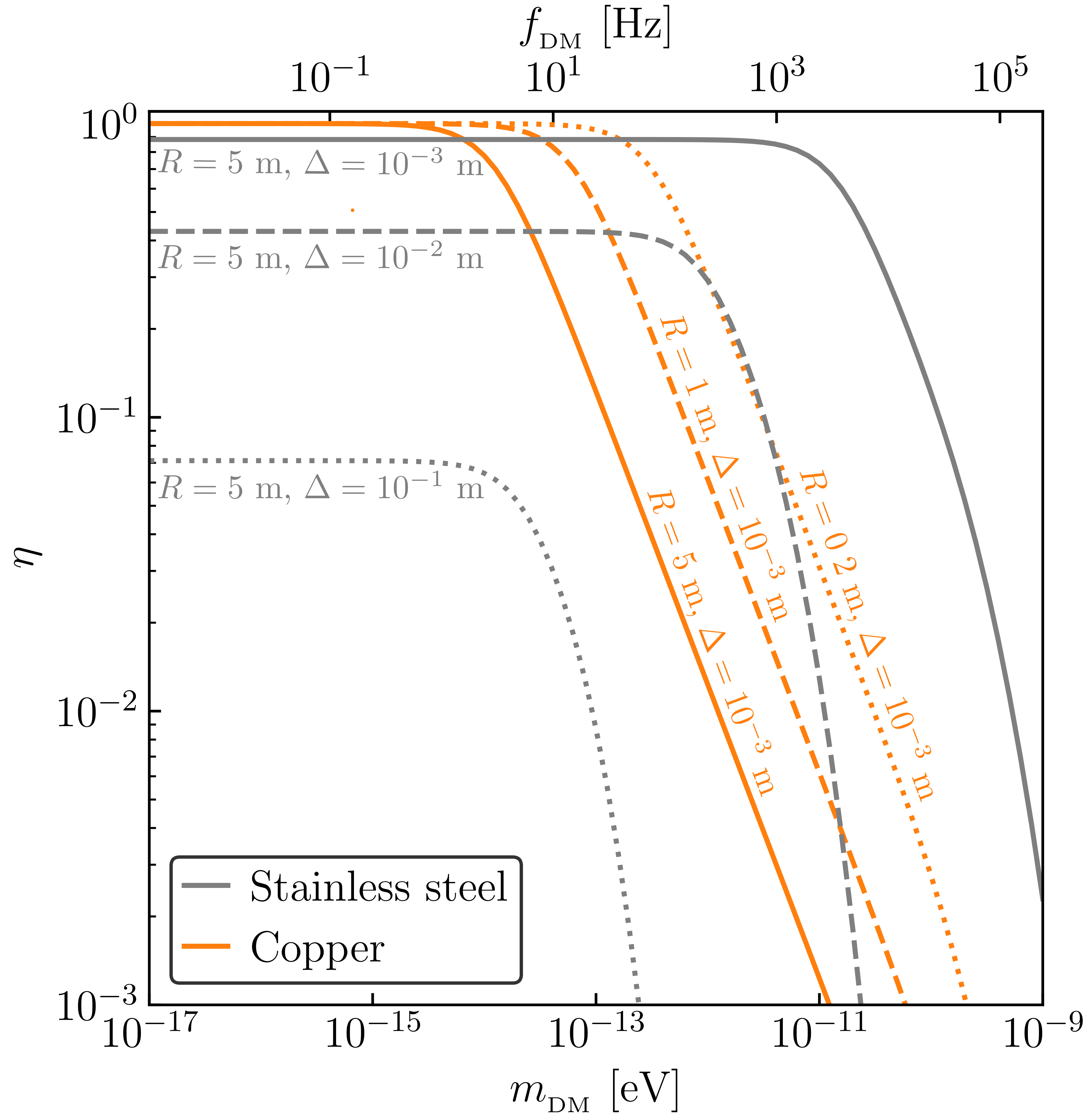

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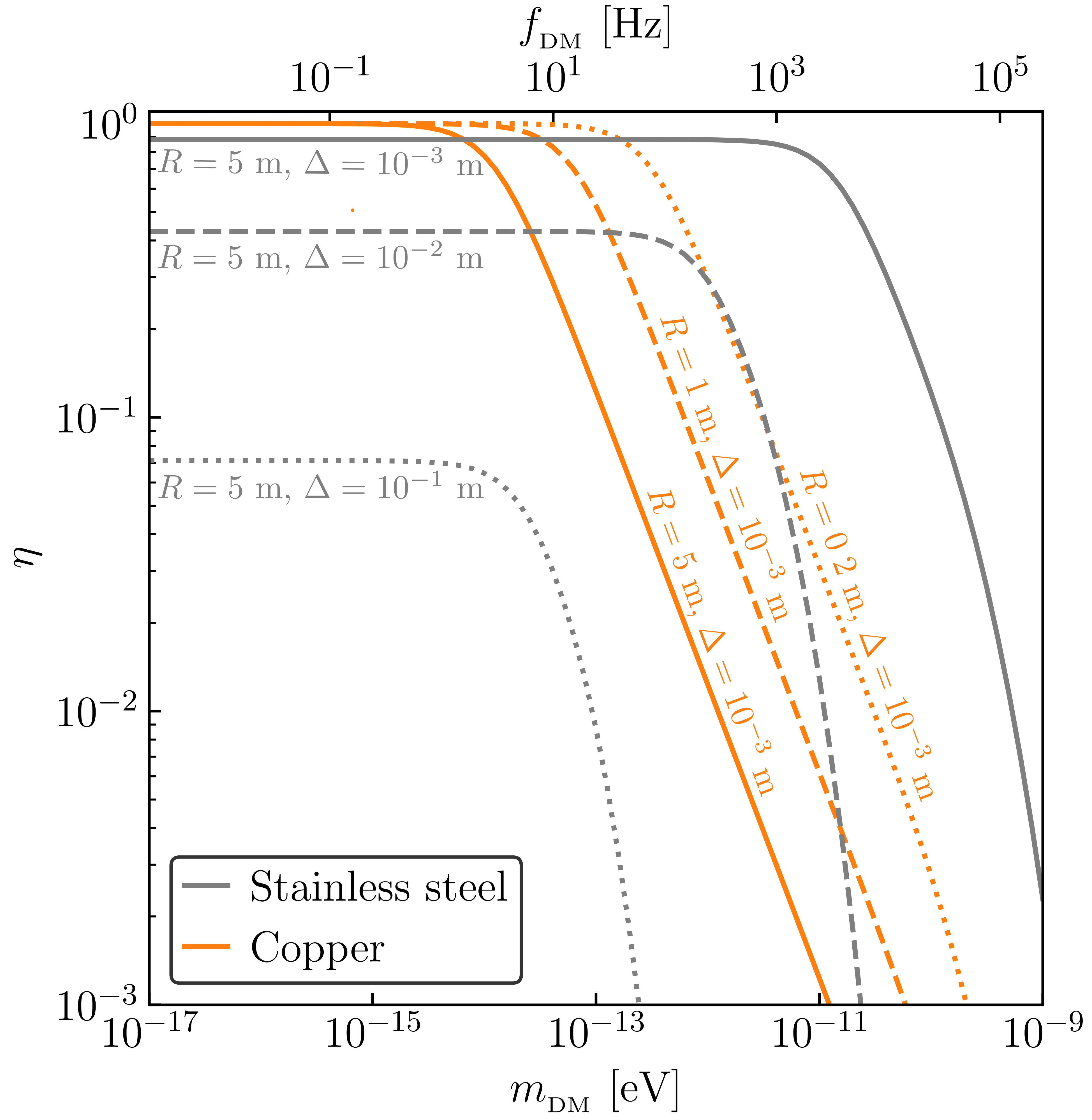

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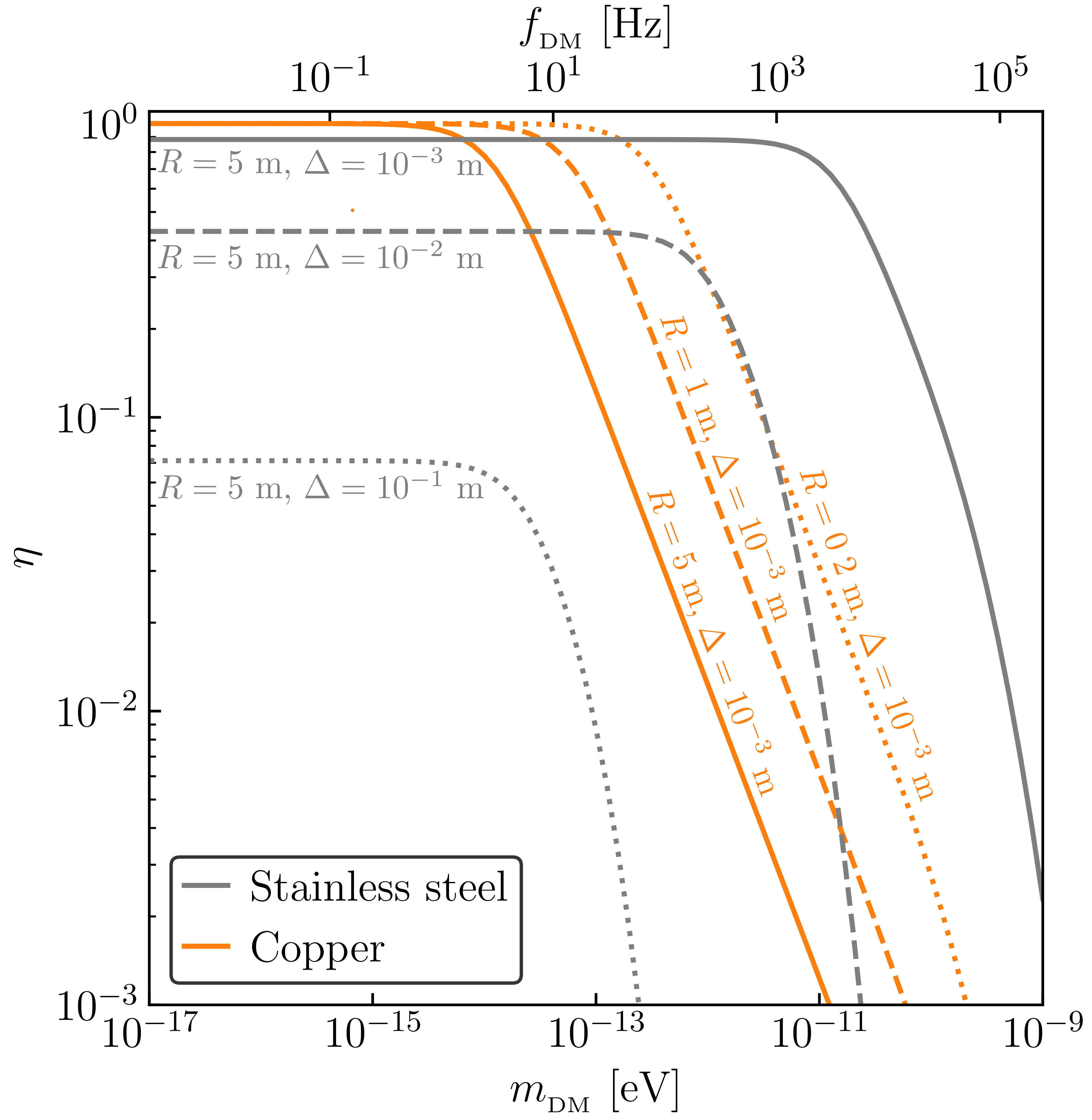
Below 10 Hz, we can treat the Earth-ionosphere Box as concentric spherical conductive boundaries



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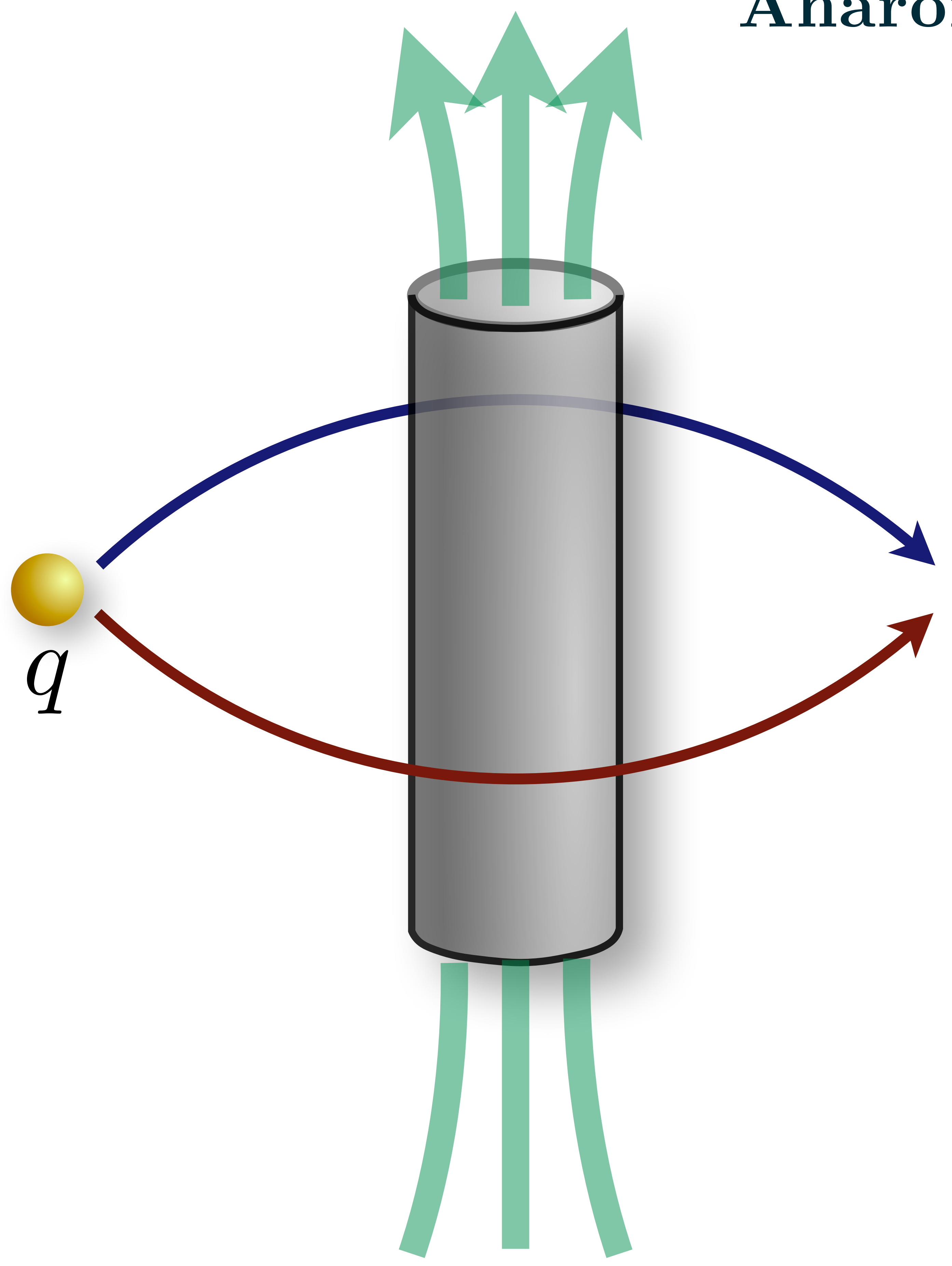
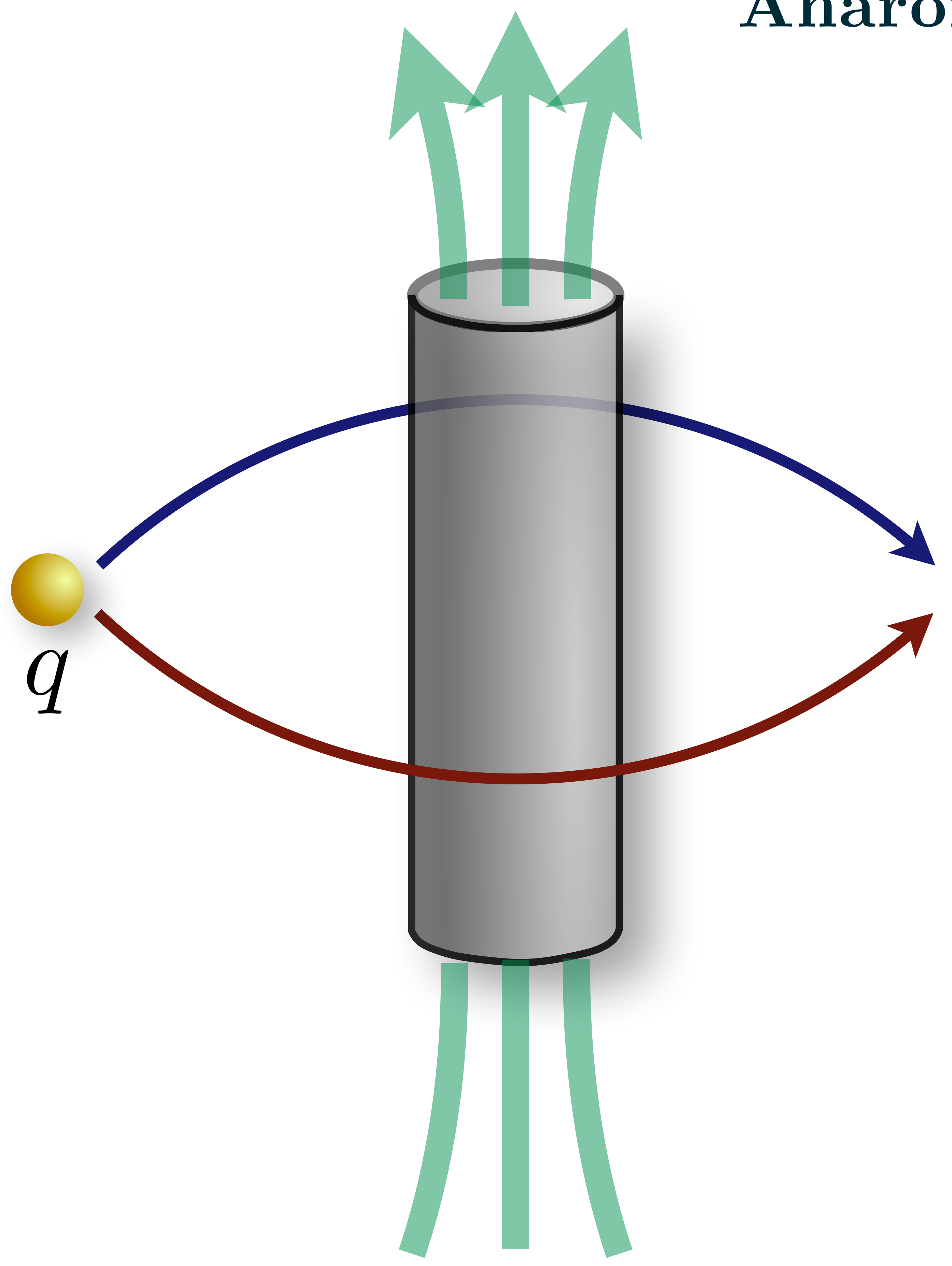


Aharonov-Bohm: a specific version of a Berry phase

The box is NOT the Box: Ion Interferometry



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Accumulated phase is $\Delta\phi = 2e\oint \mathbf{A}\cdot d\mathbf{x}$

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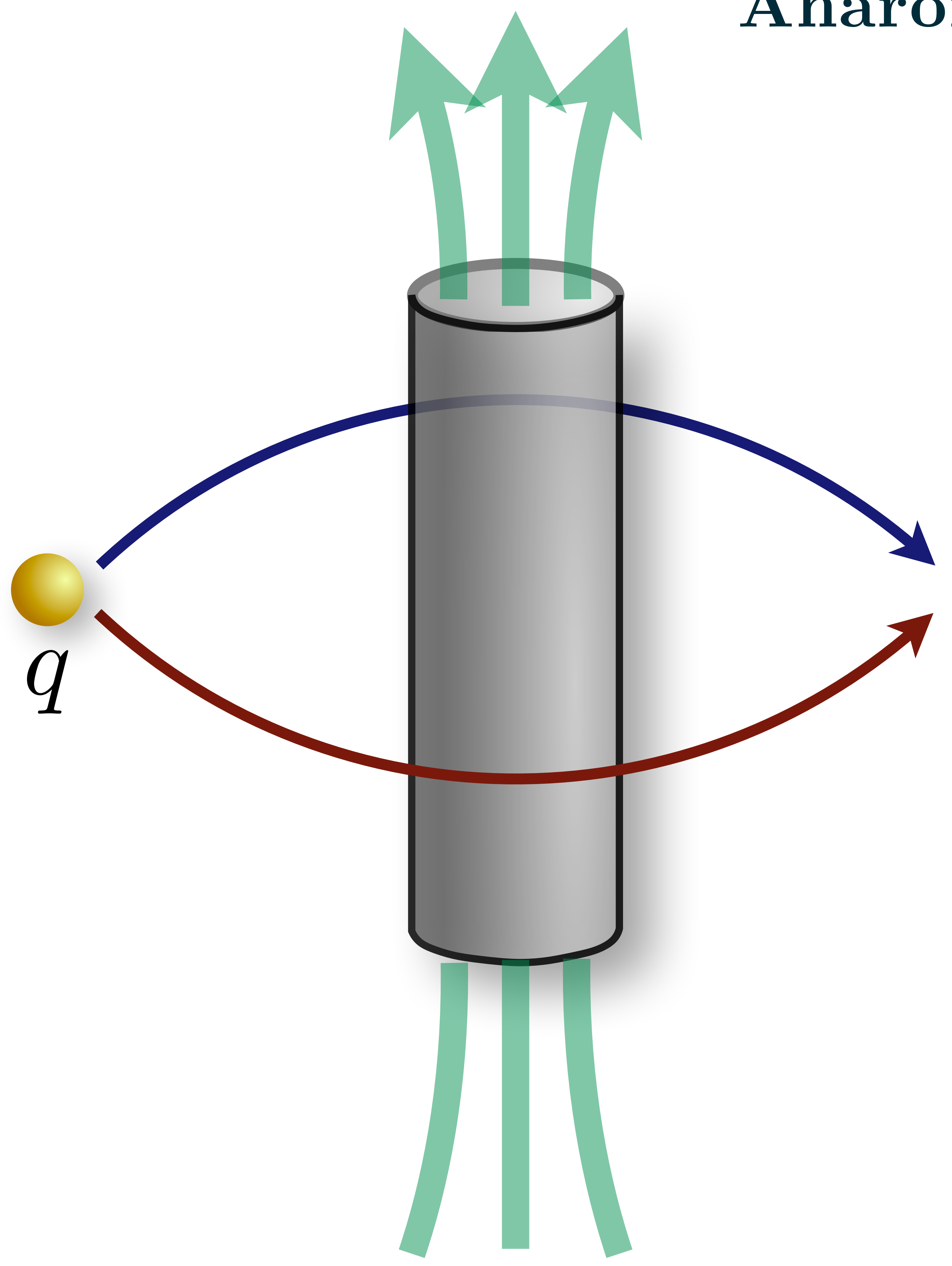

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By Stokes' theorem, relate to area as $\Delta\phi = 2e\int_0^T \mathbf{B}\cdot\frac{d\mathbf{S}}{dt}dt$

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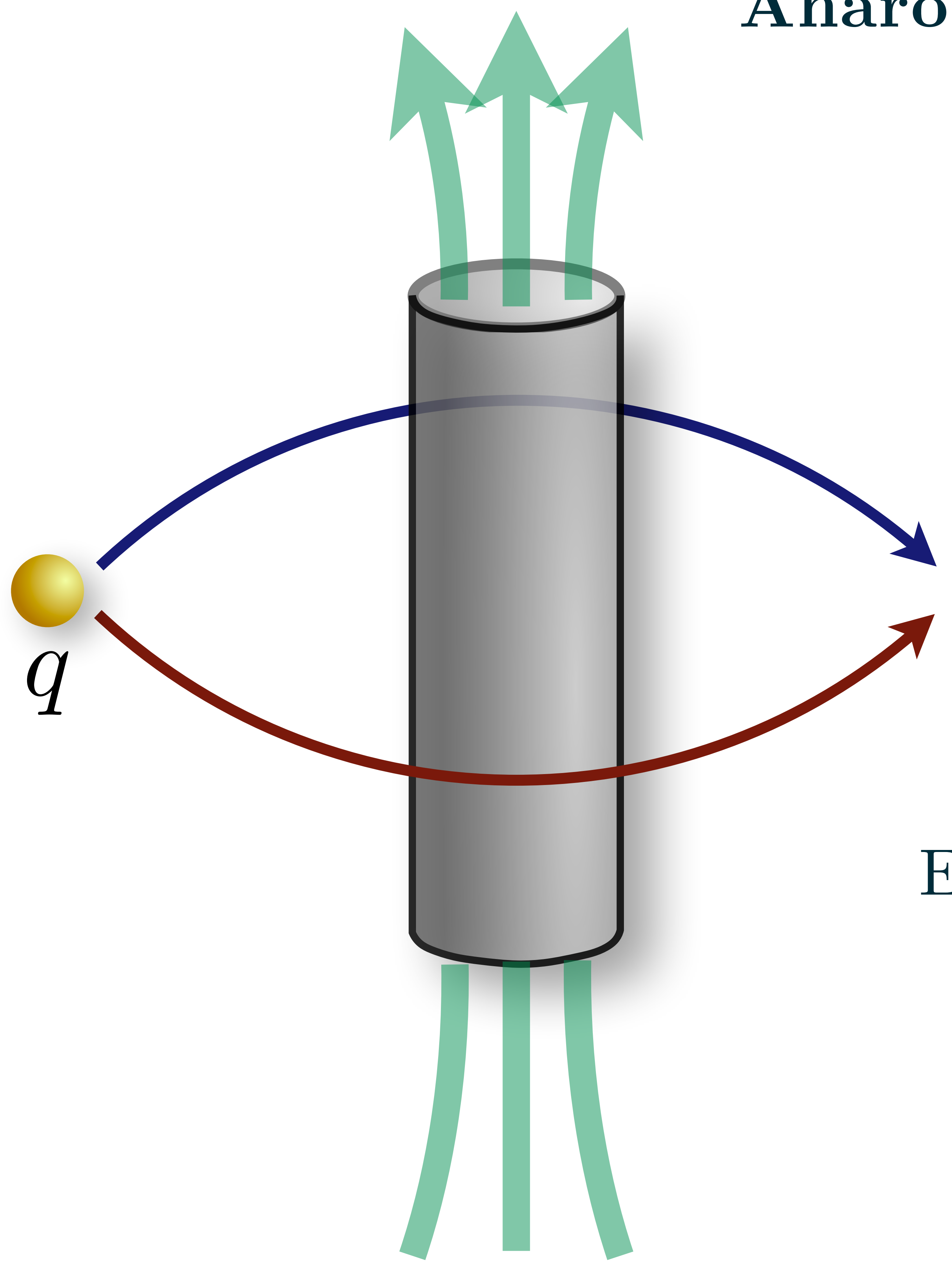

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Engineer a system where $\frac{d\mathbf{S}}{dt}$ is large using quantum techniques?

Ion Interferometry with Cat States

Leverage proposal for rotation sensing made by W. Campbell & P. Hamilton (2017)

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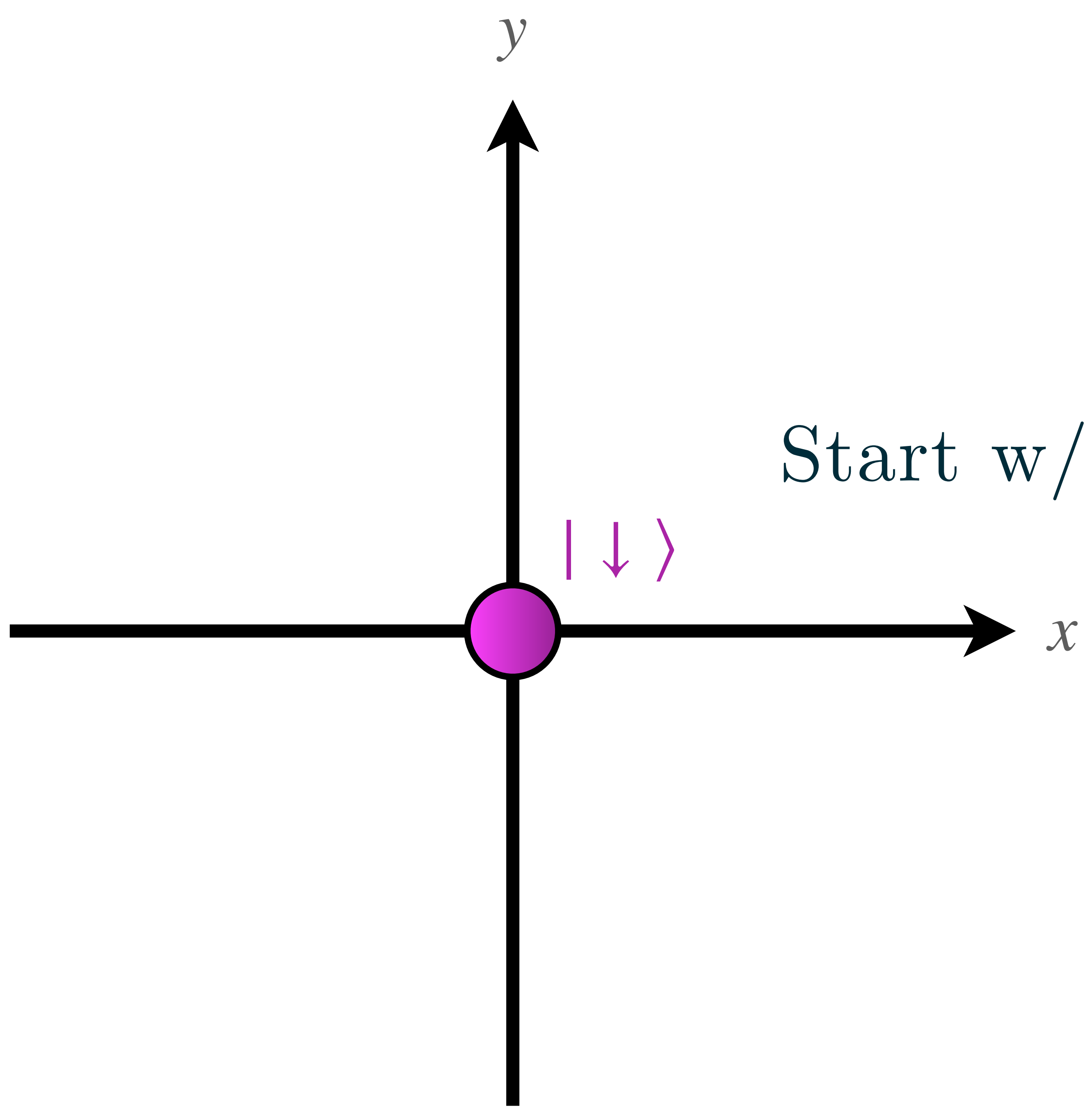
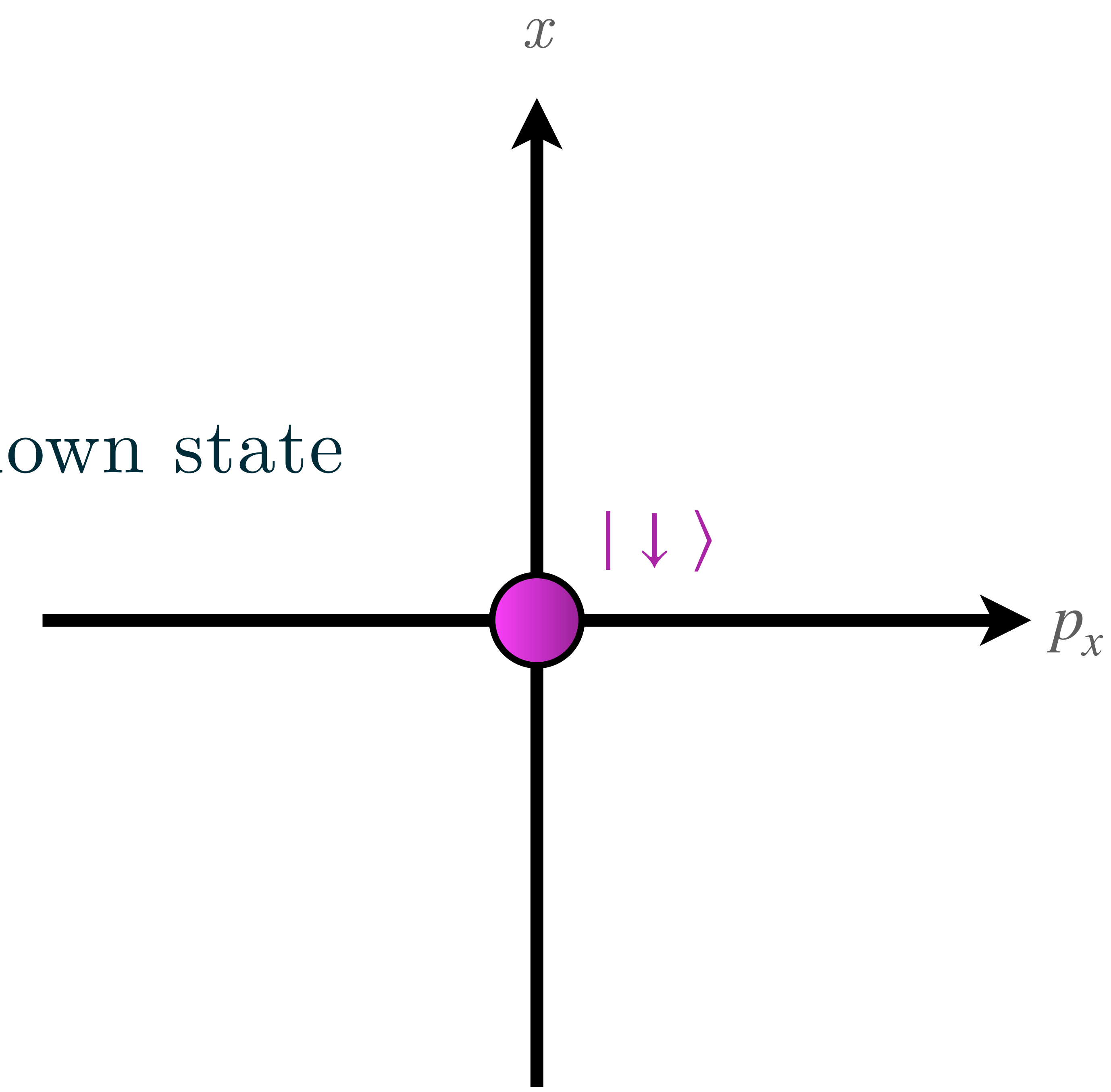


Start w/ *single trapped ion* in down state



Ion Interferometry with Cat States

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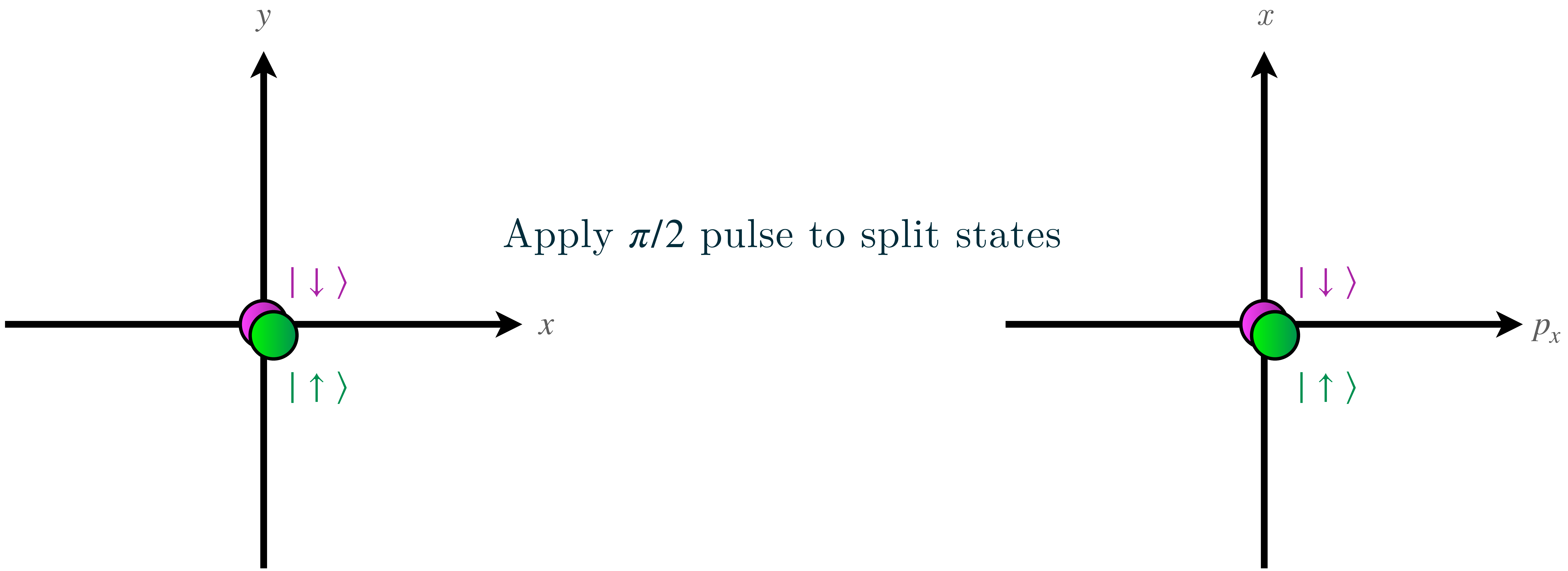

Apply $\pi/2$ pulse to split states

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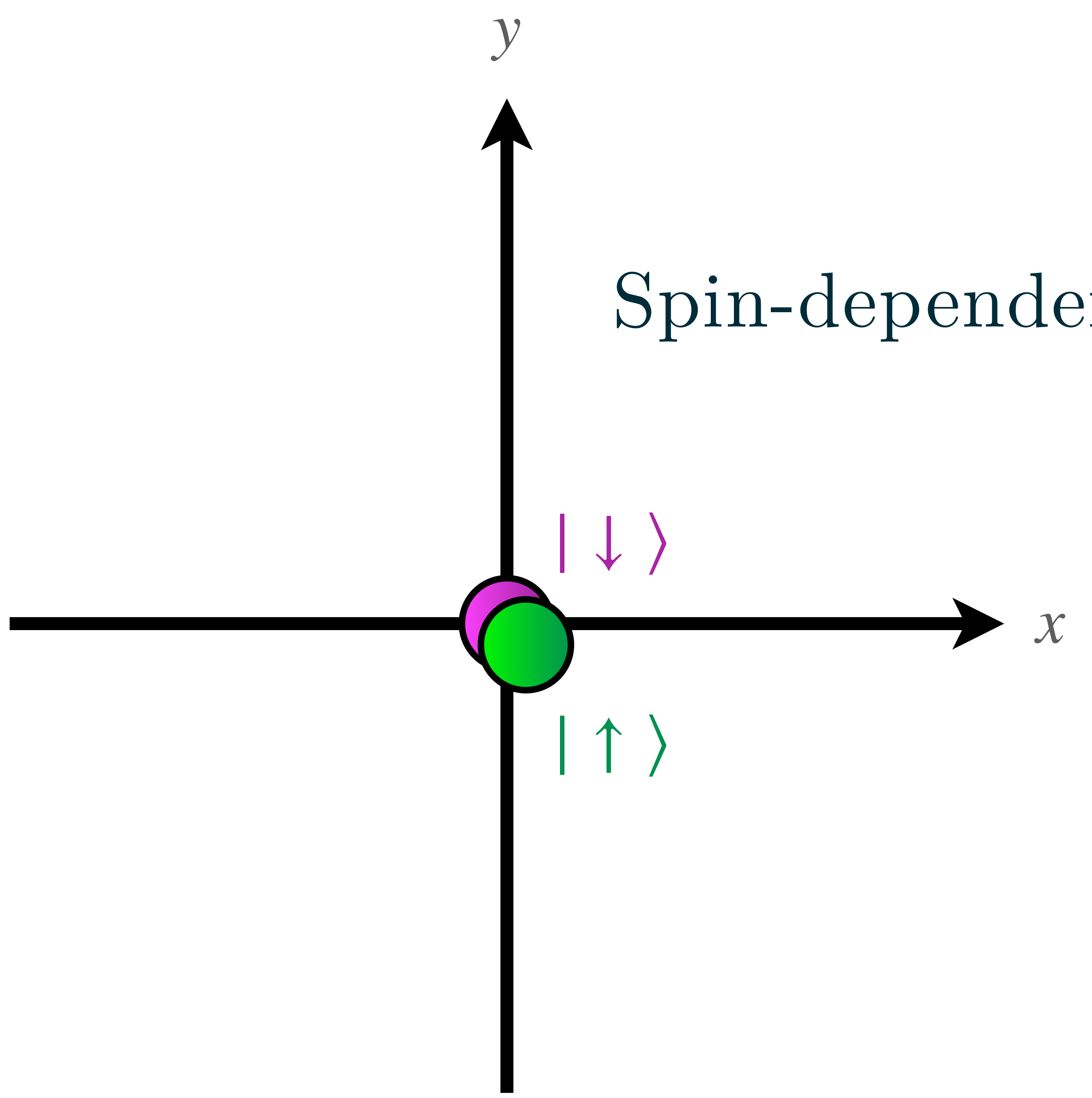
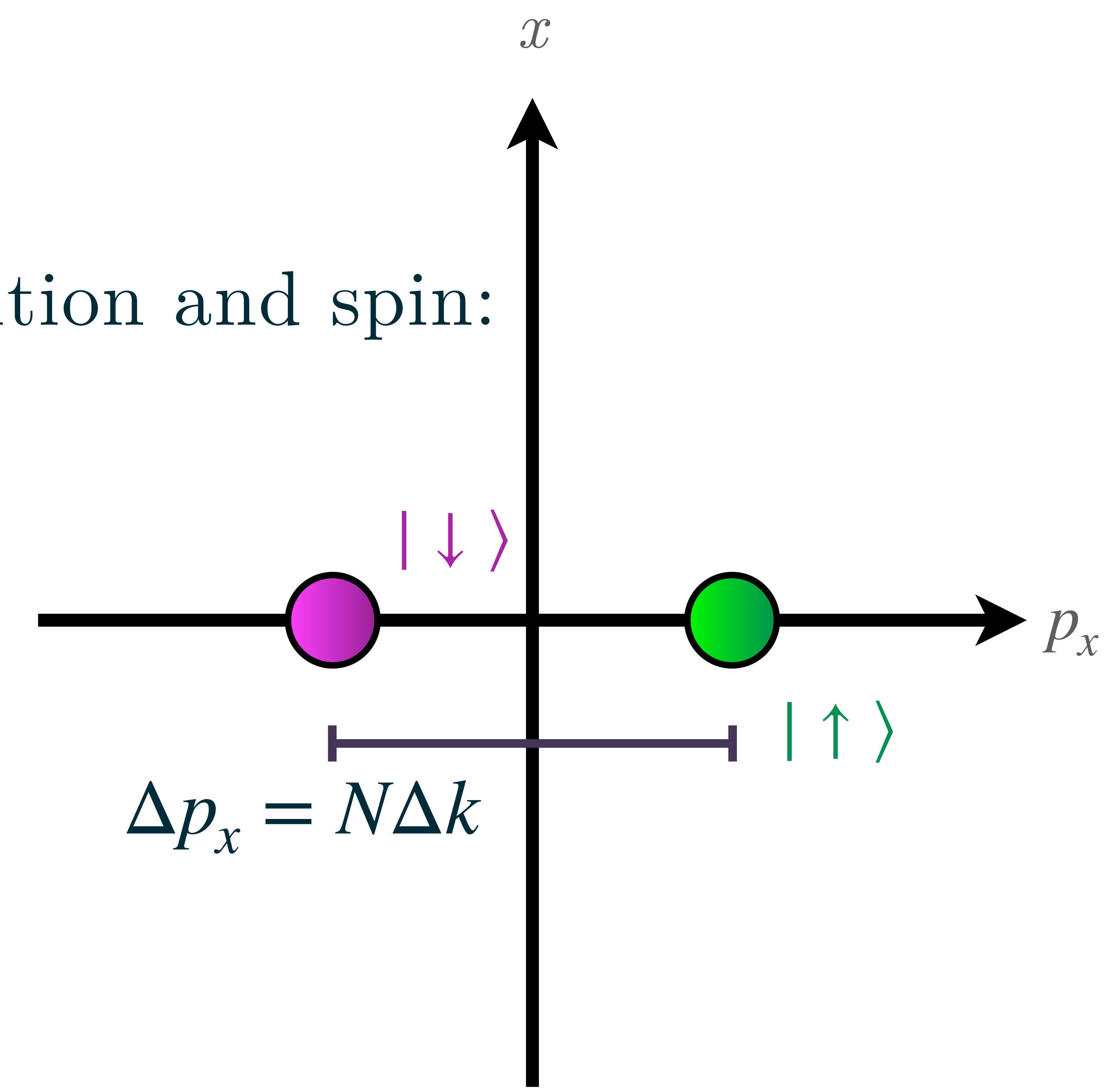


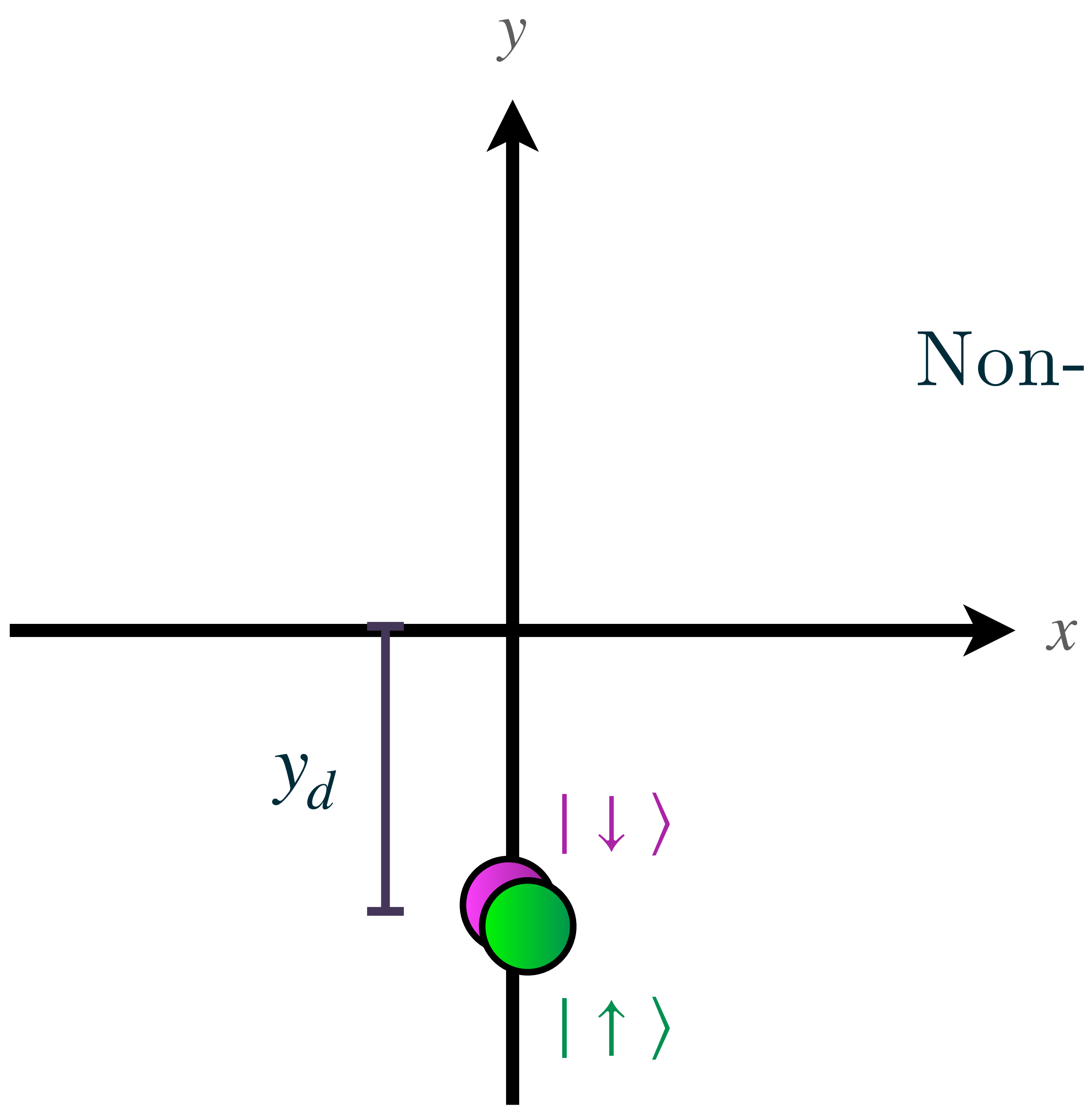
Spin-dependent kicks **entangle** position and spin:

cat state

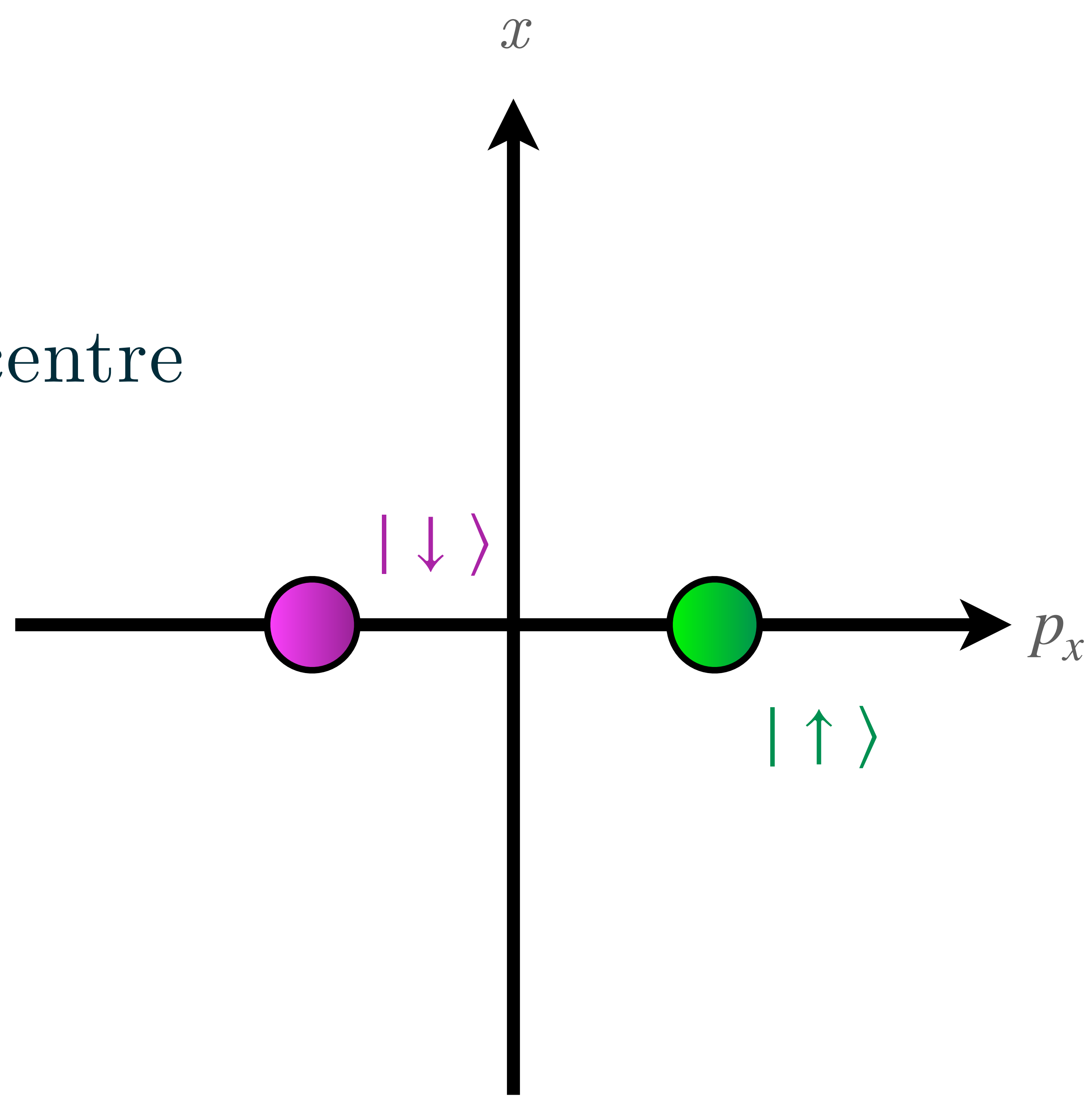


A different spin system

Leverage proposal for rotation sensing made by W. Campbell & P. Hamilton (2017)



Non-adiabatic shift in trap centre



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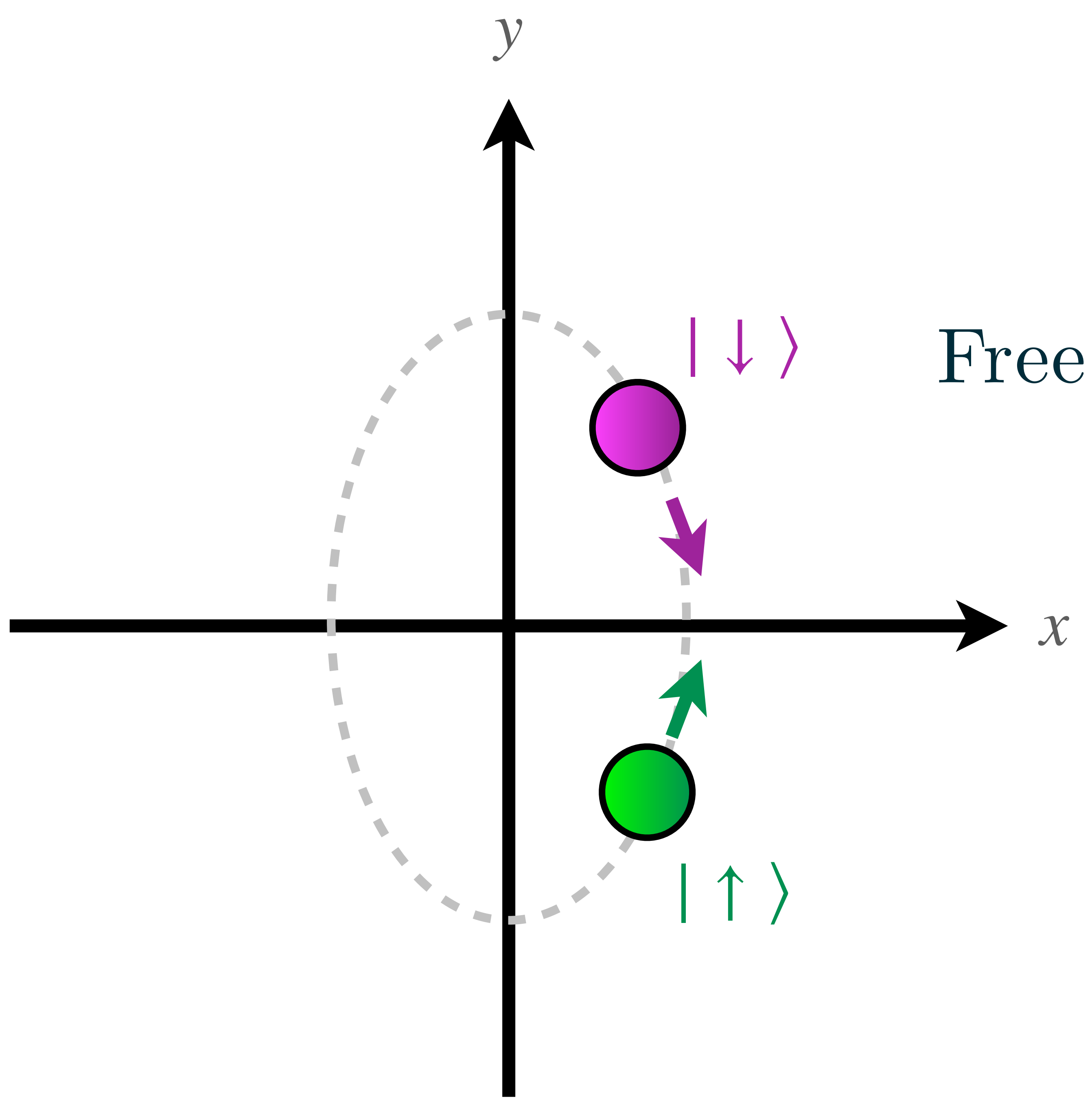
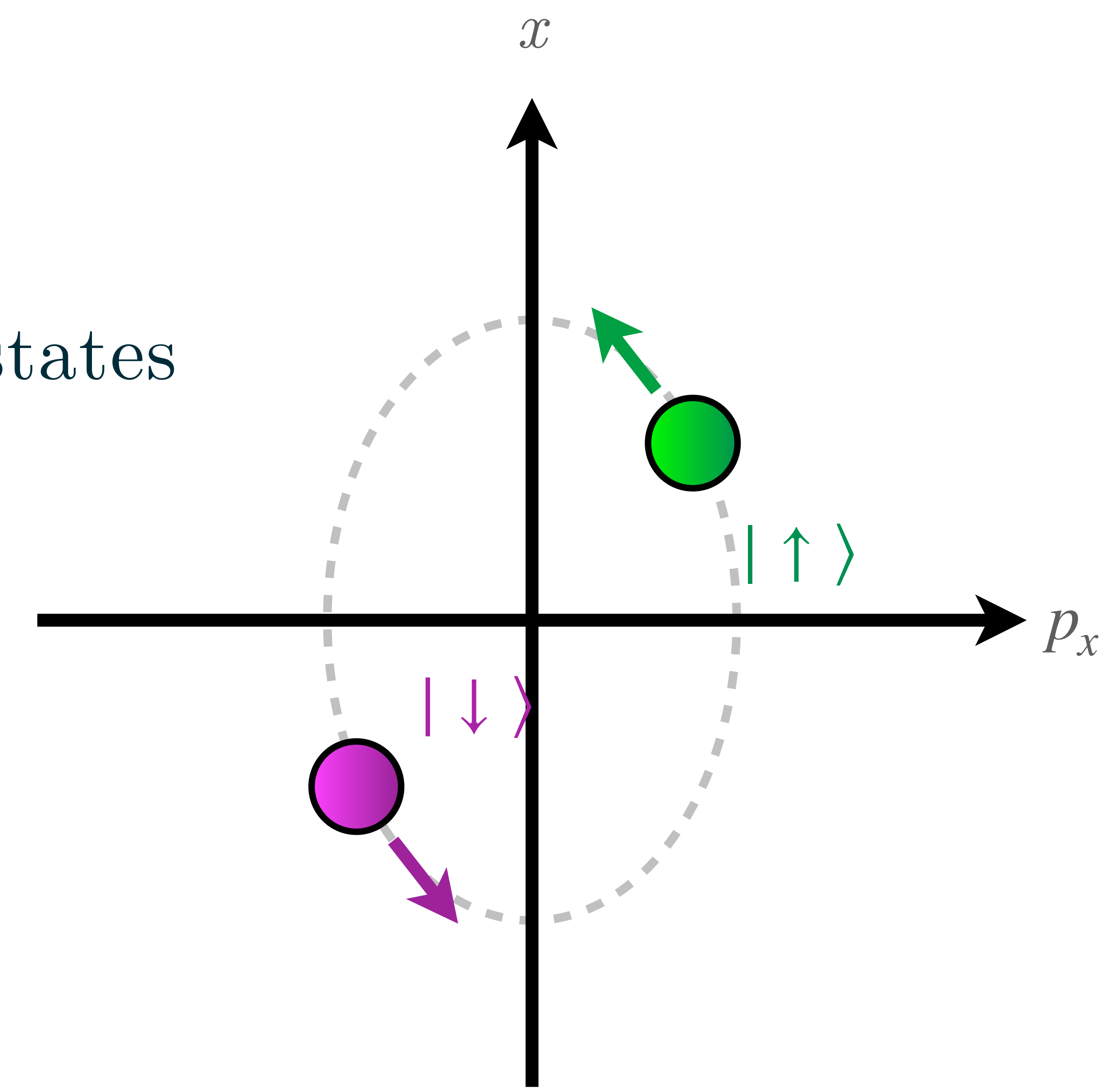


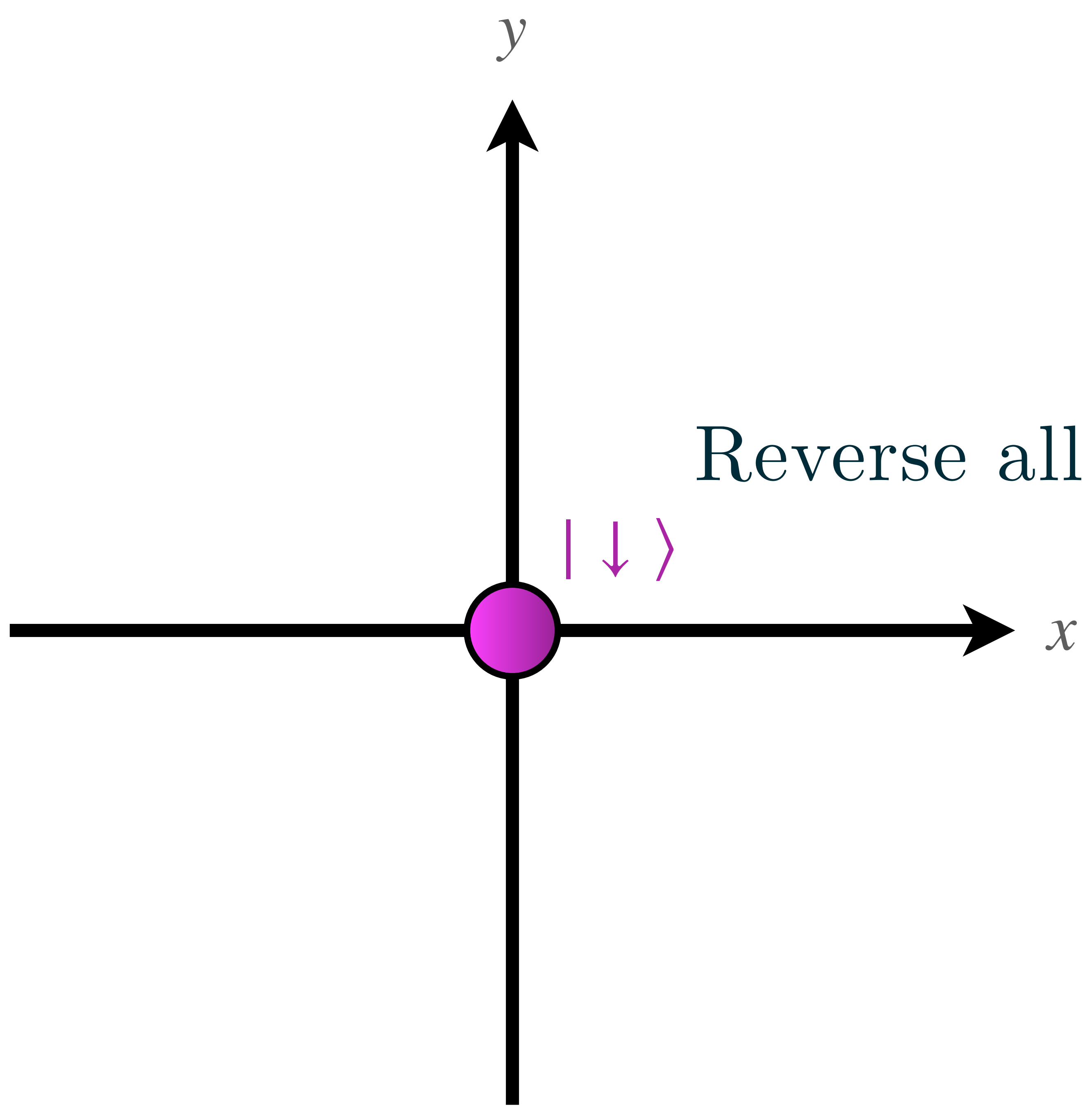
Free evolution of the spin states



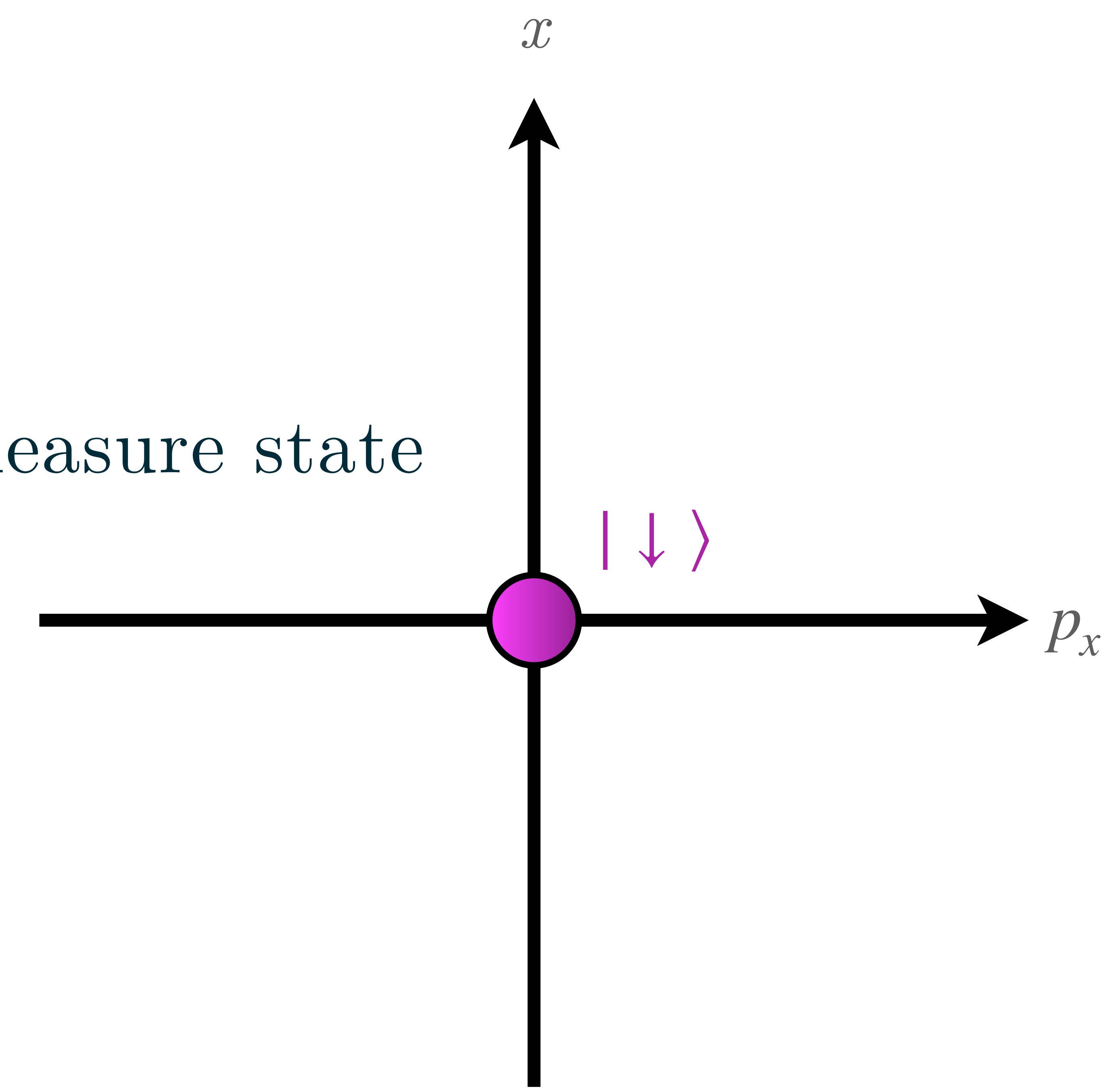
Coherence of states in trap dictates T, and $N_{\text{turns}} \sim \omega_{\text{trap}} T$

Ion Interferometry with Cat States

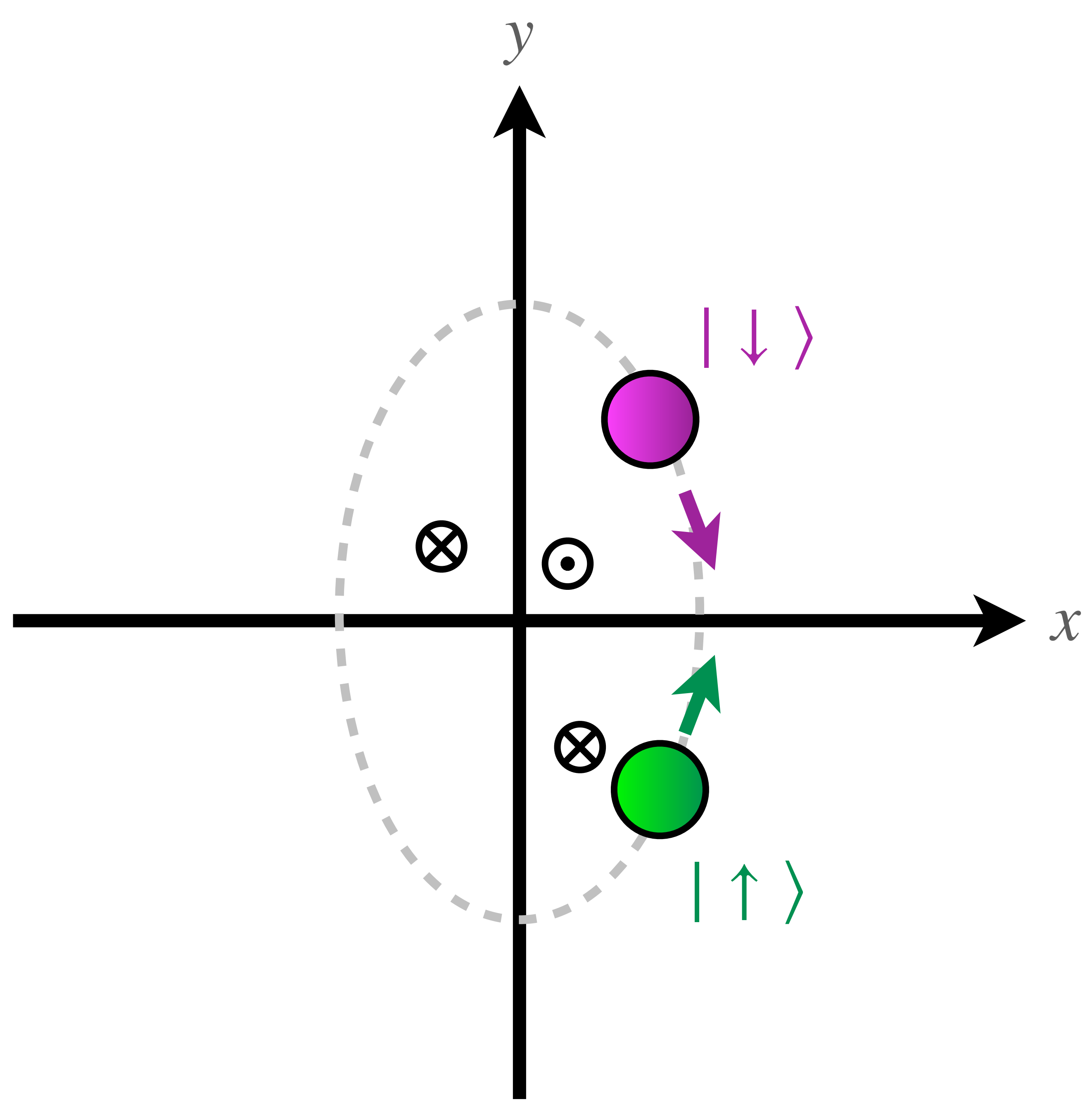
Leverage proposal for rotation sensing made by W. Campbell & P. Hamilton (2017)



Reverse all the above steps and measure state



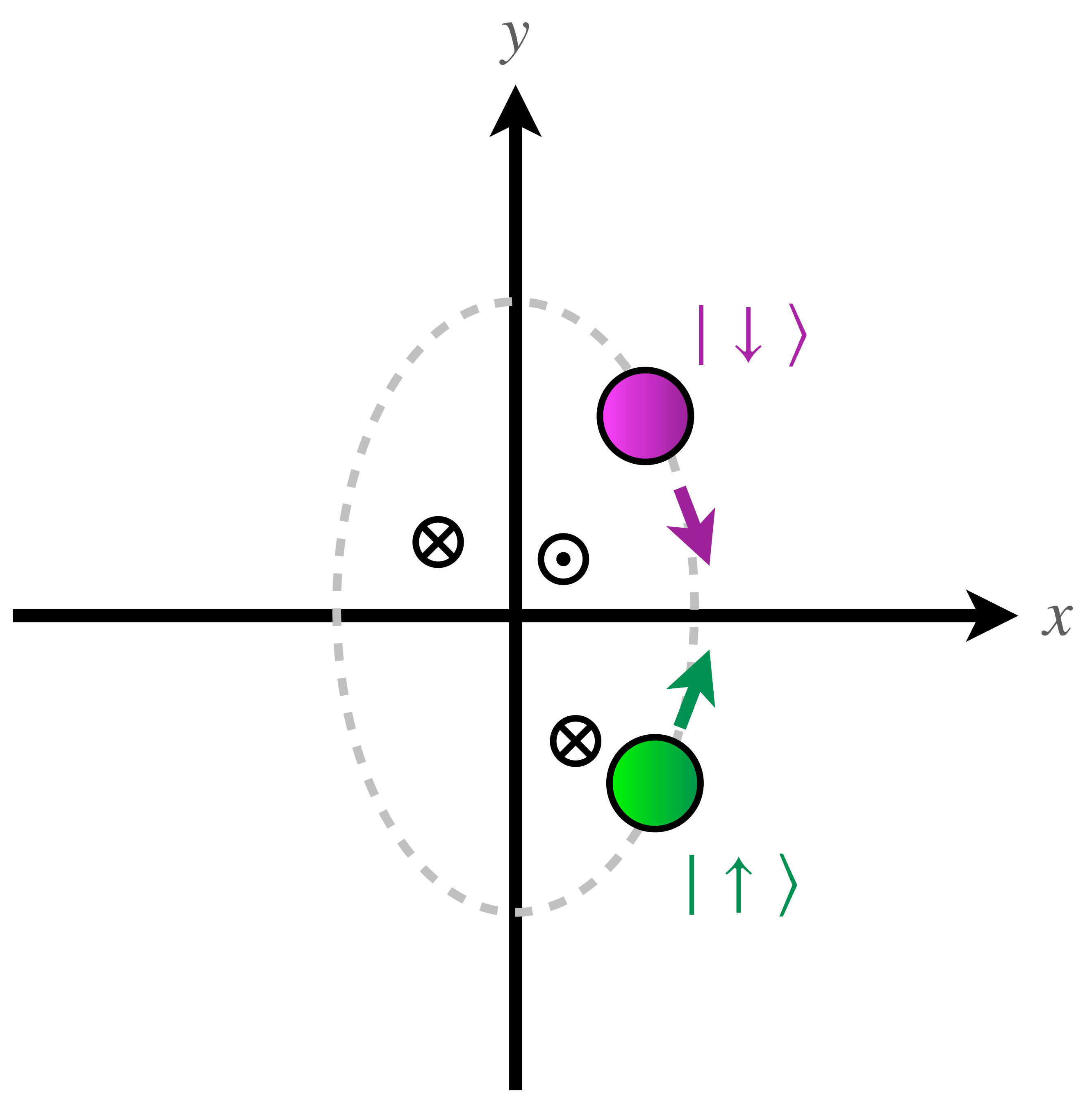
Ion Interferometry with Cat States



PRD 113, 092004 (2026)
L. Badurina, D. Blas, J. Ellis, **SARE**

With one ion, $y_d = 100\,\mu\text{m}$, $N = 100$ and $\Delta k = 4\pi/355\,\text{nm}$, $\mu \sim \mu_B$

Ion Interferometry with Cat States



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Counter-propagation of entangled spin & position state means relative phase of $\varphi_\uparrow - \varphi_\downarrow$ measurable

$$\Delta\phi = 2\int_0^T \frac{d\boldsymbol{S}}{dt}\cdot \boldsymbol{B}\, dt \qquad \frac{d\boldsymbol{S}}{dt} \simeq \frac{y_d N \Delta k}{m_{\text{ion}}}$$

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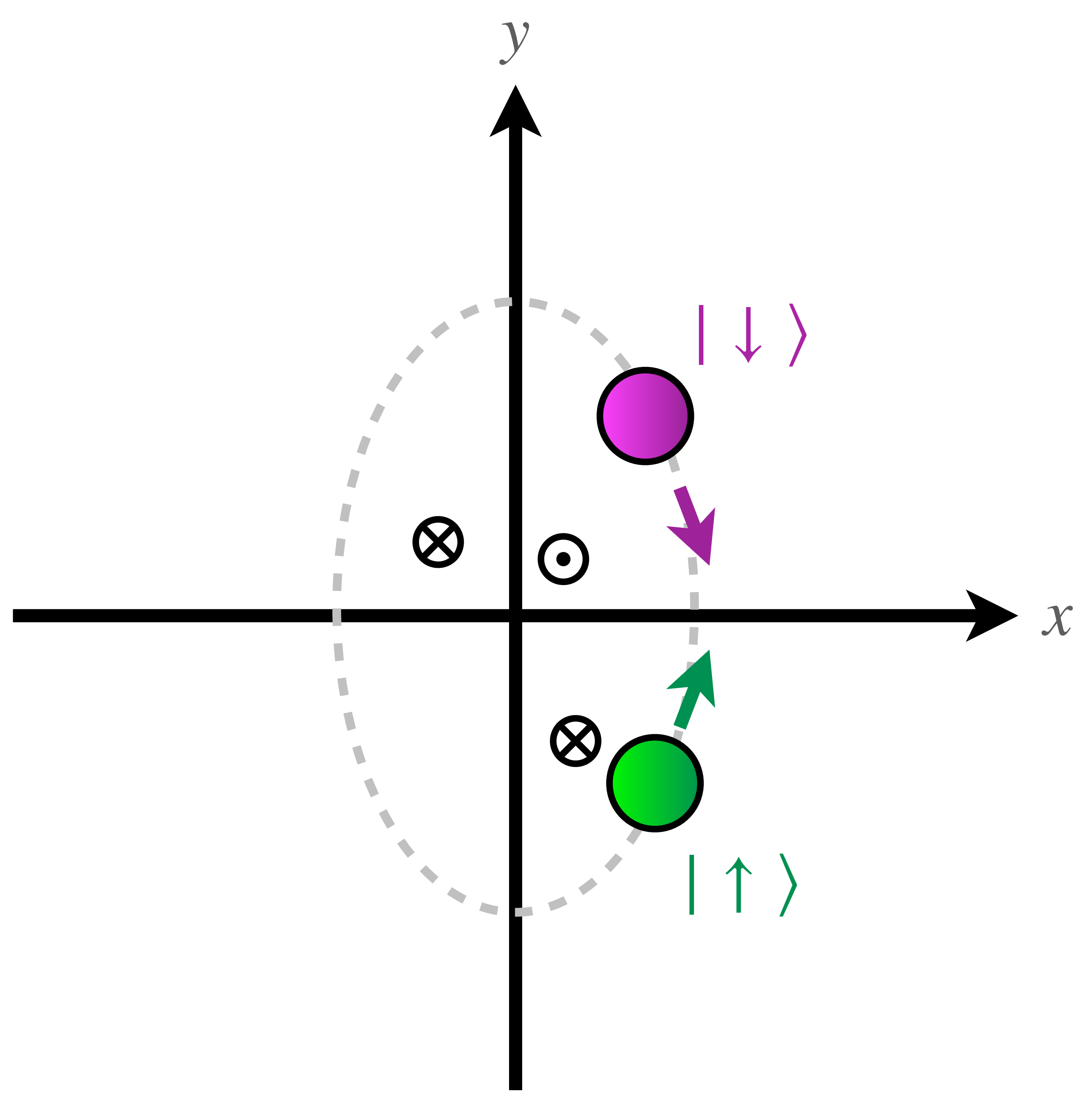

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Morally equivalent to a motional magnetic moment

$$\mu \sim \mu_B y_d N \Delta k \frac{m_e}{m_{\rm ion}}$$

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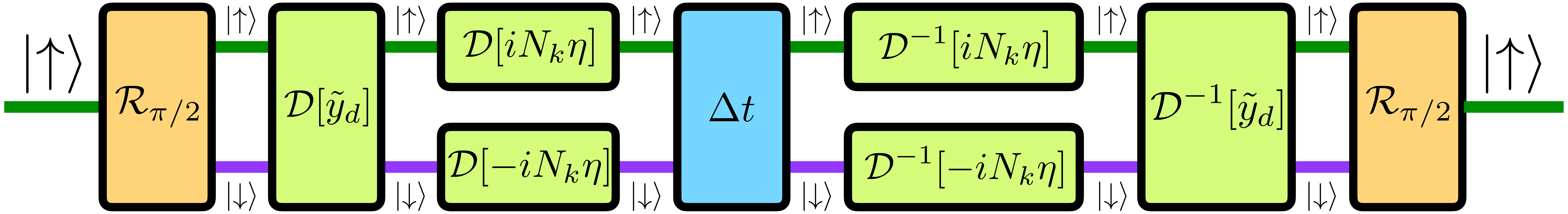
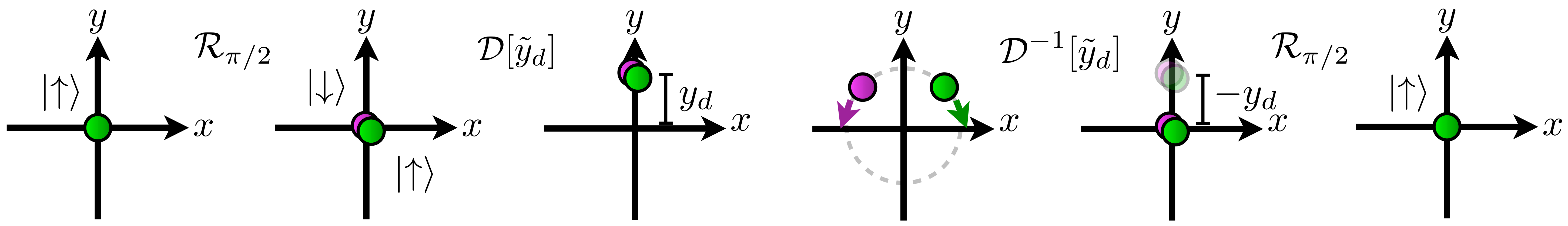
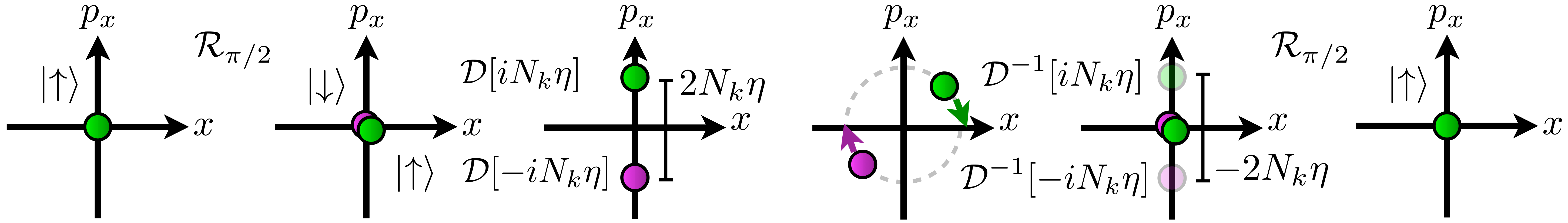
Ion Interferometry with Cat States



Position Space



Momentum Space



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Ion Interferometry with Cat States

During sensing phase $\boldsymbol{\Delta t}$, any real (or effective) magnetic fields will displace spin states

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Ion Interferometry with Cat States

During sensing phase Δt, any real (or effective) magnetic fields will displace spin states

For a real magnetic field due to e.g. Dark Photon or Axion,

$$\mathcal{D}_{\mathrm{AB}} = \exp\left[\frac{i}{\hbar}\beta_z(t)\hat{J}_z\right] \qquad \beta_z(t) = \frac{q}{2M}\int_0^t dt'\, B_{\mathrm{ext}}(t')$$

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A different way in which the Box Matters

For an effective magnetic field, can have same form of displacement operator

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For an effective magnetic field, can have same form of displacement operator with, e.g.

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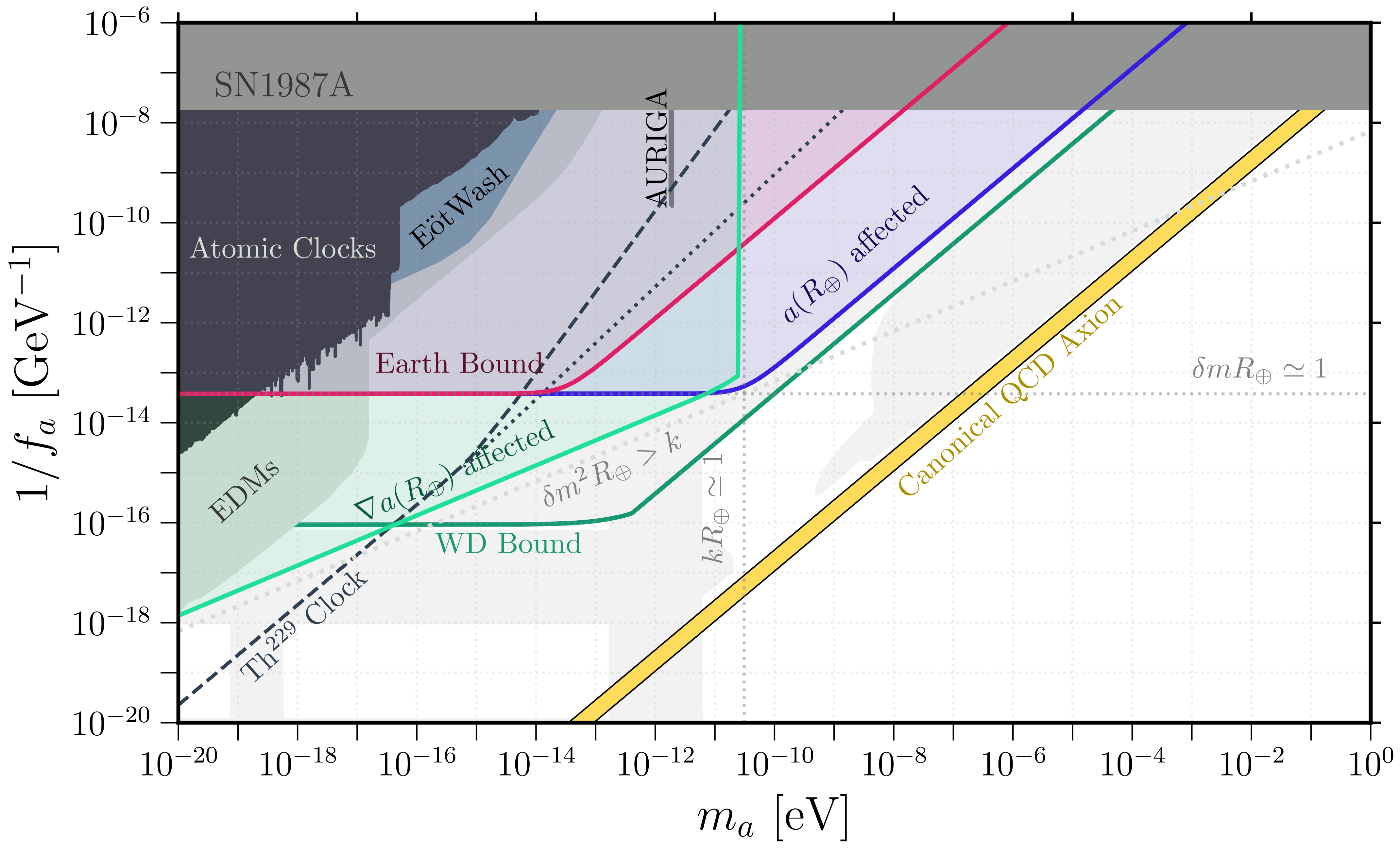

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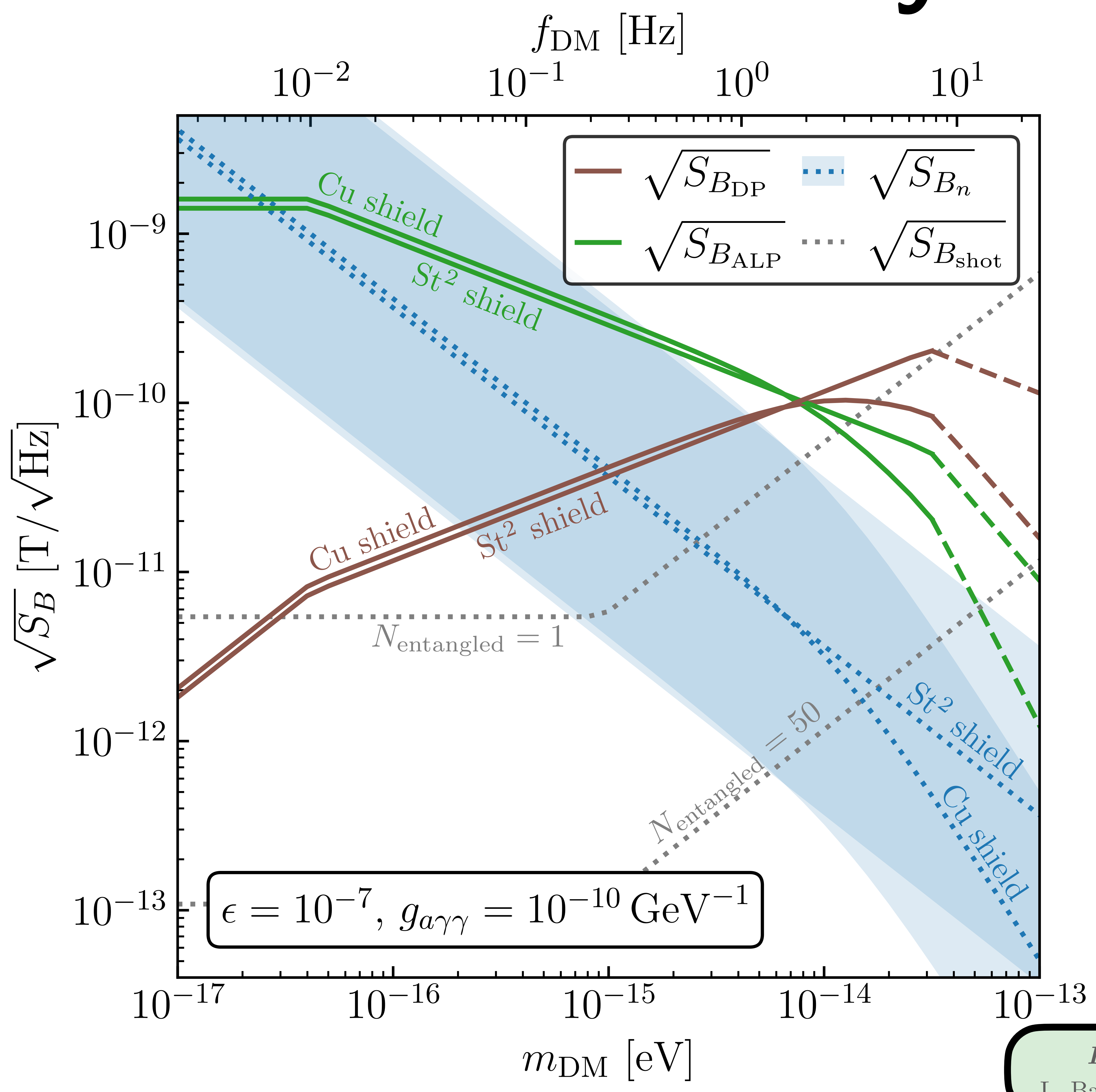
Tuned QCD axions, or ALPs with quadratic couplings to matter, need to account carefully for effect on axion gradient

JHEP **06 (2026) 039**
A. Banerjee, I. Bloch, Q. Bonnefoy, **SARE**, G. Perez, I. Savoray, K. Springmann, Y. Stadnik

Ion Interferometry with Cat States



Shot noise dominant at high frequency $\delta\phi_{\rm shot} \sim 1/\sqrt{\rm Hz}$

Ambient EM noise dominant at low frequency

$$\sqrt{S_B} \sim 10^{-11\pm1} \times \left(\frac{1\,\mathrm{Hz}}{f}\right)\,\mathrm{T}/\sqrt{\mathrm{Hz}}$$

Entangling ions can decrease shot noise like $1/N_{\rm ion}$

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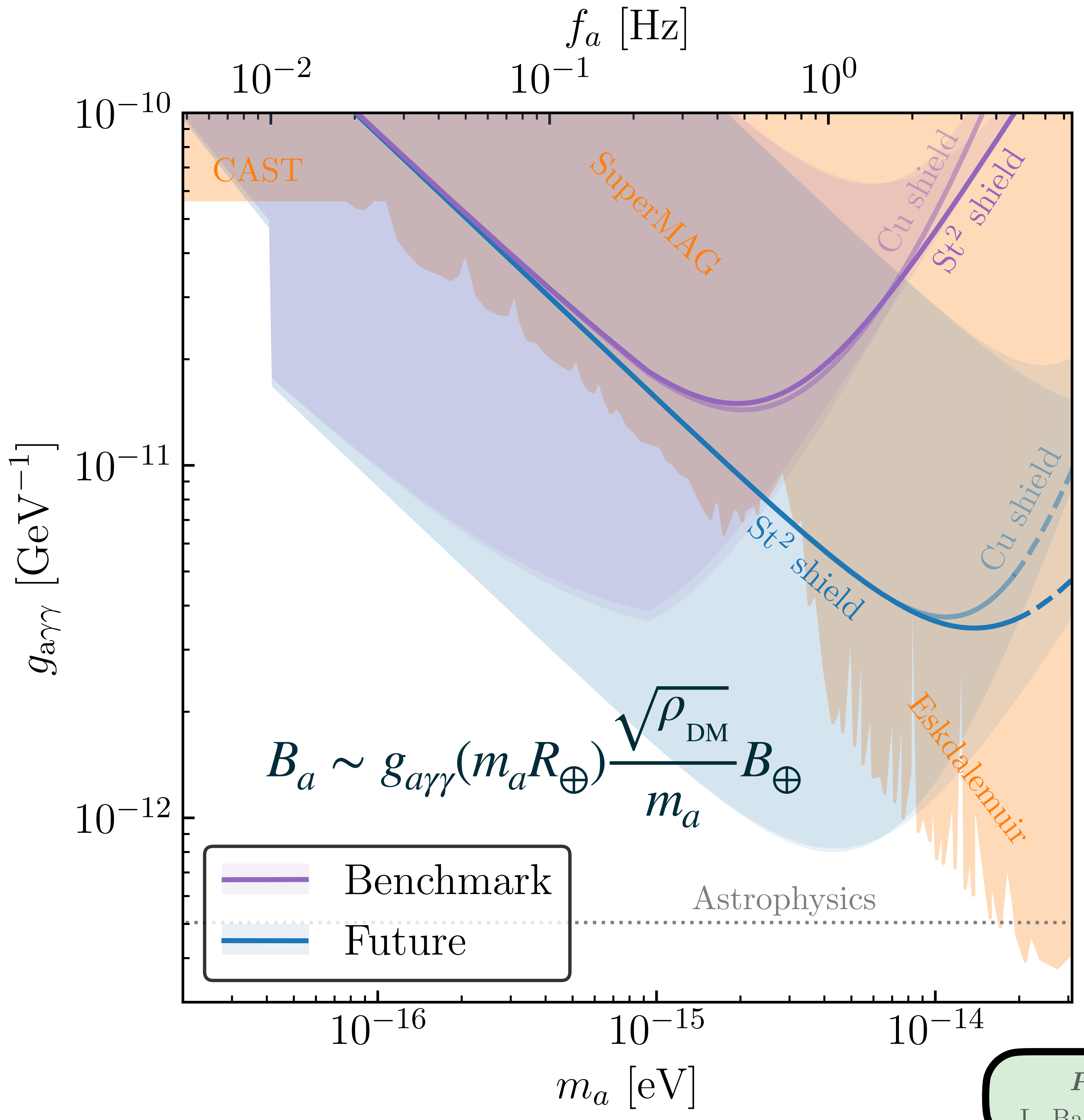

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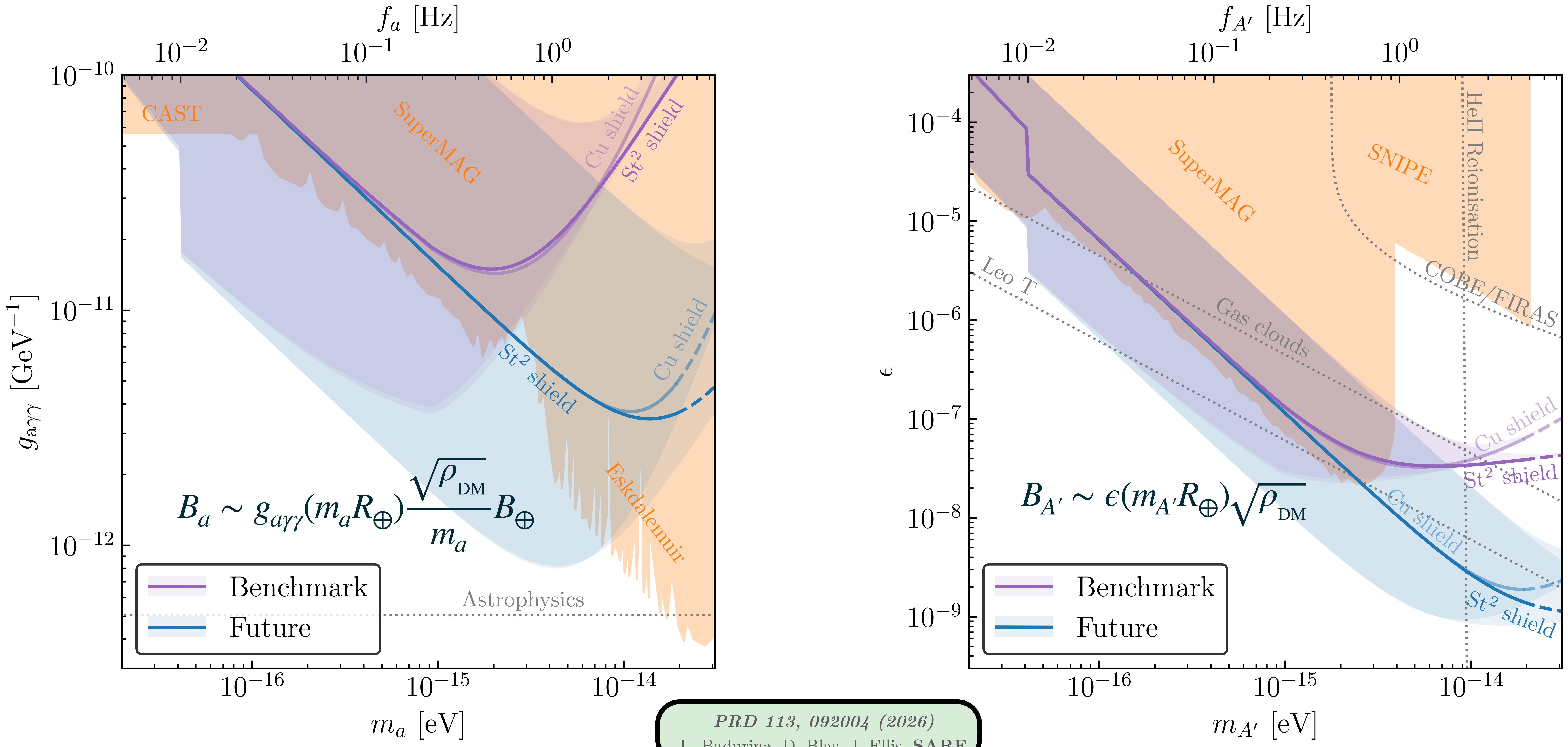
Ion Interferometry with Cat States



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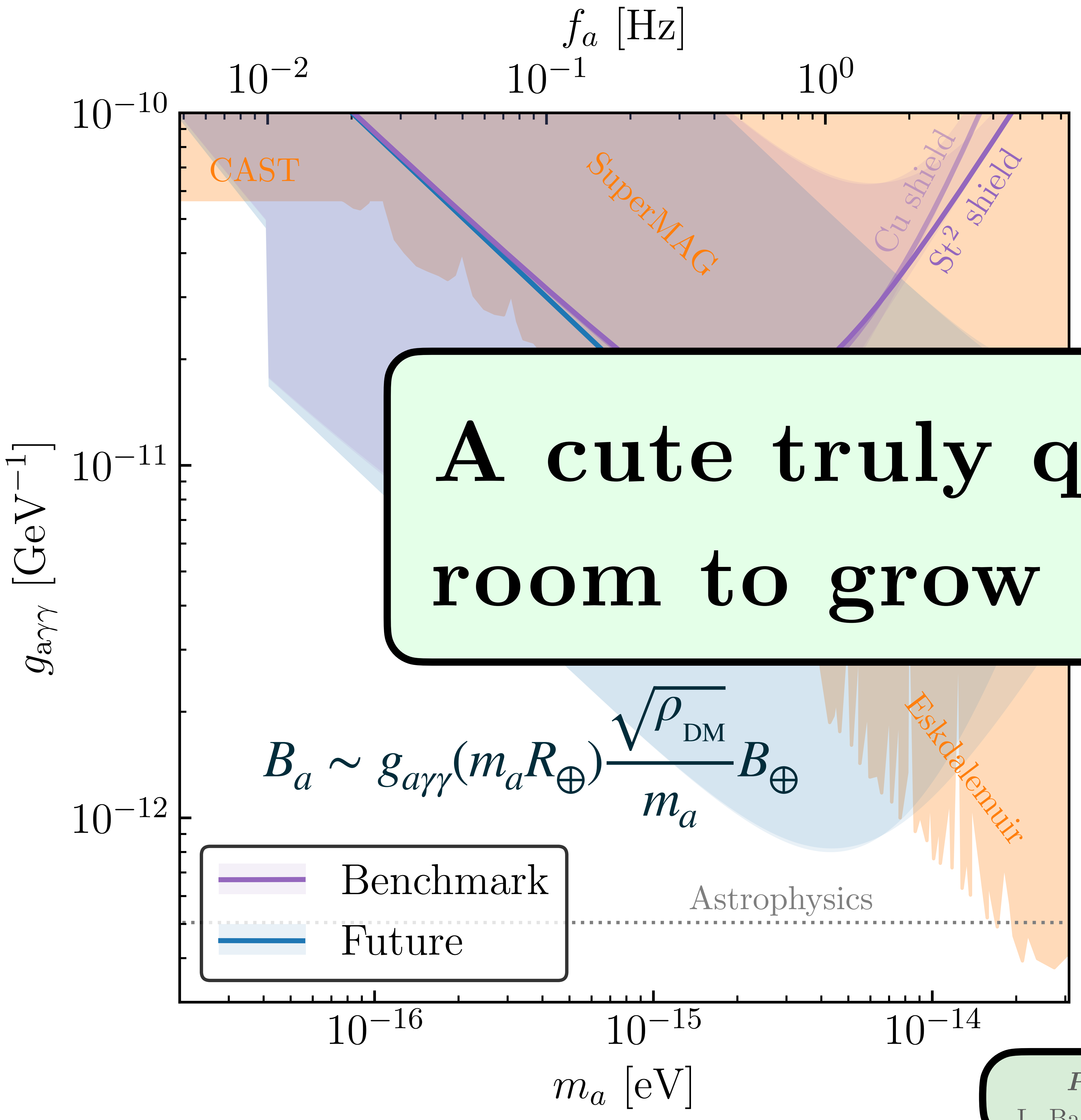

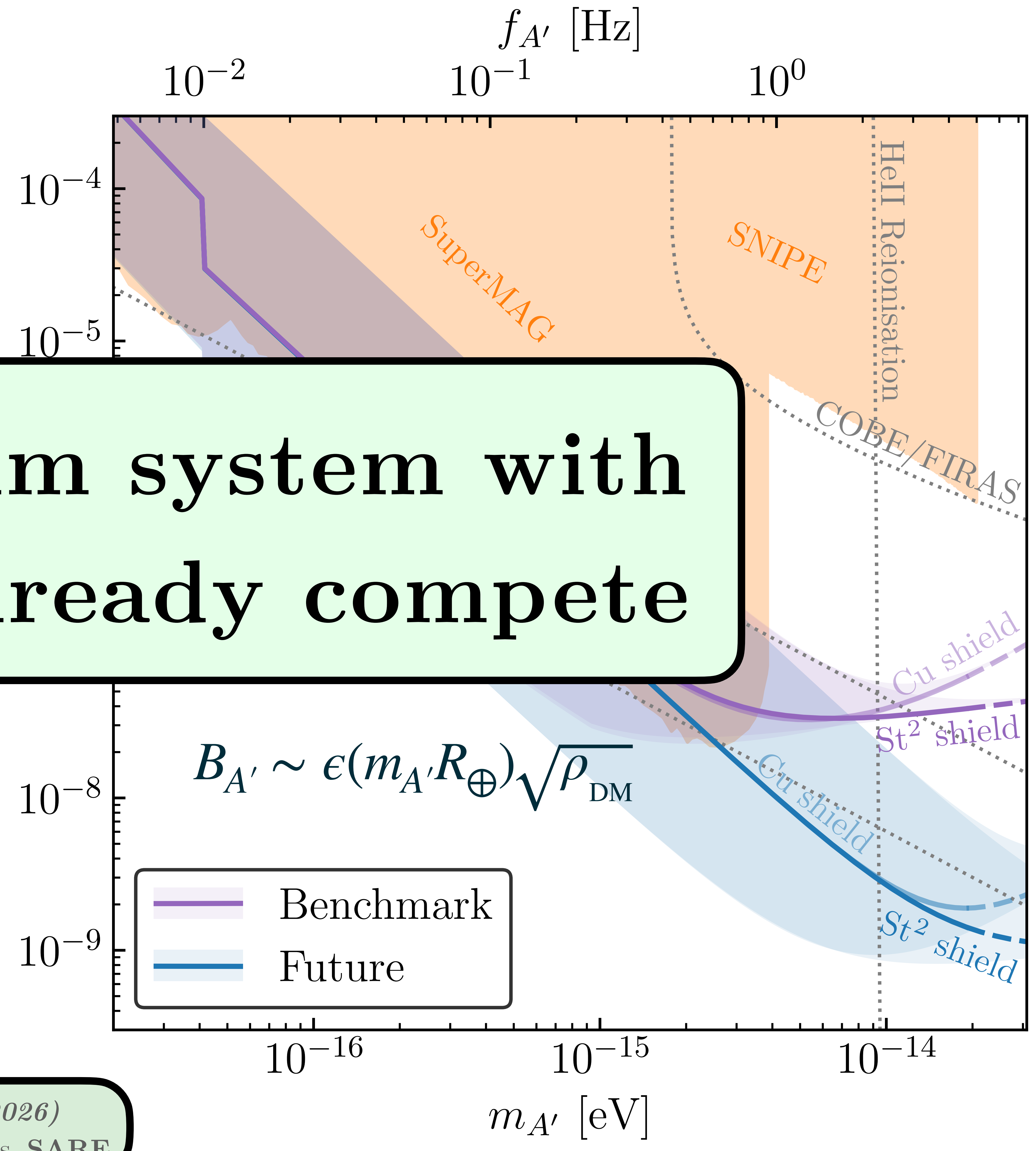

A cute truly quantum system with room to grow can already compete

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Engineering and maintaining special quantum states is not easy

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Conclusions

Spin sensors are nice, manipulable quantum sensors

The **Box** in which the spins are placed **matters**

Most promising avenue for now is large classical ensemble à la CASPEr

Sensitive to more than just the axion wind coupling

At low masses, truly quantum states can compete with classical devices, with potentially great upside