First Laboratory Constraints on Ultra-Light Dark Photon Dark Matter from Precision Atomic Spectroscopy

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Light Dark World 2022.
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Based on work with Joshua Berger
(arXiv:2206.06364)

Overview

1. **Introduction & Motivations for ultralight dark matter.**

2. **Dark Photons.**

3. **Searching for ultralight dark photons using High Precision Atomic Spectroscopy.**

4. **Results**

5. **Future Directions.**

INTRODUCTION

Introduction: Landscape of dark matter models

Wide range of possible dark matter masses.

Focus of this talk!

Ultralight (Boson)	WIMP - (like)	Super Heavy & Composite

10^{-22} eV — 30 eV — 10^{5} TeV — 10^{57} GeV

WIMPs:

Weak scale thermal relic.

Motivated from other puzzles in particle physics - example hierarchy problem.

Super Heavy & Composites:

Non thermal relic.

Primordial black hole or dark fermionic nuggets.

Introduction: “Hints” for ultra-light dark matter

(I) CORE CUSP PROBLEM

CDM N Body Simulations predict $\rho_{DM} \sim 1/r$ but flat profiles inferred from galactic rotation curves.

(II) MISSING SATELLITES PROBLEM

CDM predictions for sub-halos conflict with dwarf galaxy observations.

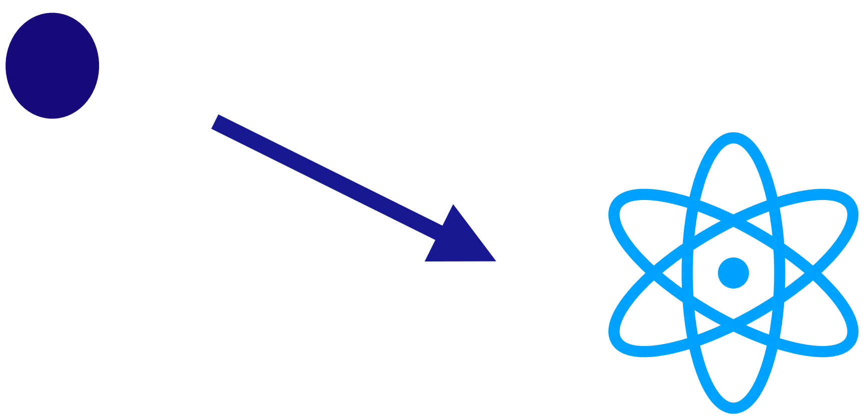
(III) TOO BIG TO FAIL

CDM predicts bright satellite galaxies.

Introduction: Properties of ultra-light dark matter

$$n_{DM} = \rho_{DM}/m_{DM} \simeq \frac{3 \times 10^8}{m\ (eV)}\ cm^{-3}$$

WIMP (TeV mass)



Low number density ~ 10 $^{-4}$ cm^{-3}

Single particle deposits small amount of energy to atom or nucleus

Low threshold detectors

ULDP (10^{-15} eV mass)

High number density ~ 10 ^{23} cm^{-3}

de Broglie wavelength overlap: coherent source

Energy deposit too small to trigger even low threshold detectors

ULTRA-LIGHT DARK PHOTON: MOTIVATIONS & MODEL

Introduction: (III) Ultra-light dark photon dark matter

Extend Standard Model by a massive U(1) gauge boson

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2 A'_\mu A'^\mu - \frac{e}{(1+\epsilon)^2}(A_\mu + \epsilon A'_\mu)J^\mu_{\rm EM},$$

“Dark” Electromagnetism with a massive photon

Stable DM candidate for $m \ll 2m_e$

Introduction: ULDP as a background EM field

Need new detection techniques that exploit coherent nature of ULDP

Can think of ULDP as a background Electromagnetic Field

$$\mathbf{E} \simeq \sqrt{2\rho_{DM}}\epsilon \sin\left(\frac{m_{\gamma'} c^2 t}{\hbar} + \phi_0\right)\hat{\mathbf{n}}$$

Time varying Stark shift in atoms

Time varying Zeeman shift in atoms

$$\mathbf{B} \simeq v\sqrt{2\rho_{DM}}\ \epsilon \sin\left(\frac{m_{\gamma'} c^2 t}{\hbar} + \phi_0\right)\hat{\mathbf{n}}'$$

$\rho_{DM} \simeq 0.3$ **GeV cm^{-3} DM energy density**

$v \simeq 10^{-3}\ c$ **DM velocity**

Introduction: ULDP as a Electric Field

Typical strength in terrestrial laboratory

$$|\mathbf{E}| \simeq 3.3 \times \epsilon \ \mathbf{kVm^{-1}}$$

Typical home appliance about 100 $\mathrm{Vm^{-1}}$

Energy shift in atoms depends on electric dipole polarizability

$$\alpha_D = -\frac{1}{2\pi a_0^3} \sum_{K \neq N} \frac{\langle N | (e\,\hat{z}) | K \rangle \langle K | (e\,\hat{z}) | N \rangle}{E_N - E_K}, \quad |\Delta E| \simeq \alpha_D \times 2\rho_{DM} \times \epsilon^2$$

Introduction: ULDP as a Magnetic Field

Typical strength in laboratory

$$|\mathbf{B}| \simeq 10^{-4} \times \epsilon \ \mathbf{G}$$

Earth's magnetic field about 0.1 G

First order Zeeman shift exists in principle

$$\Delta\nu_Z \sim \langle v \rangle \sqrt{2\rho_{DM}} \times \epsilon$$

DM velocity suppression ($\langle v \rangle$)

Linear sensitivity (ϵ)

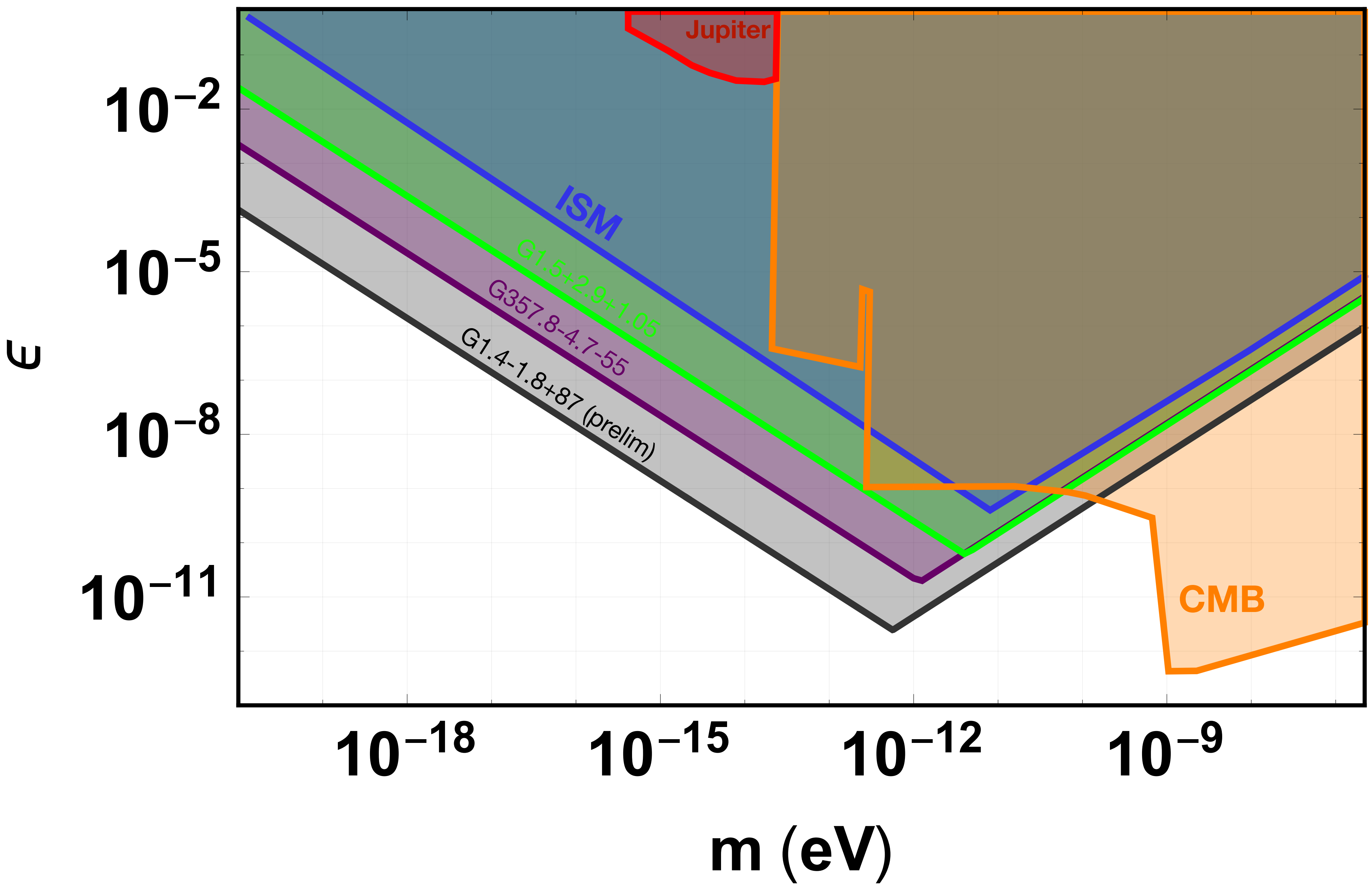
Nelson & Scholtz used this to set constraints on ULDP using Cs clock.

arXiv:1105.2812

Unfortunately Cs clock has no first order Zeeman sensitivity!

Introduction: Current constraints on ULDP

Source: Bhoonah et al Phys. Rev. D 100 (2019) 2, 023001 & Pjys. Rev. Lett 121 (2018) 13, 131101

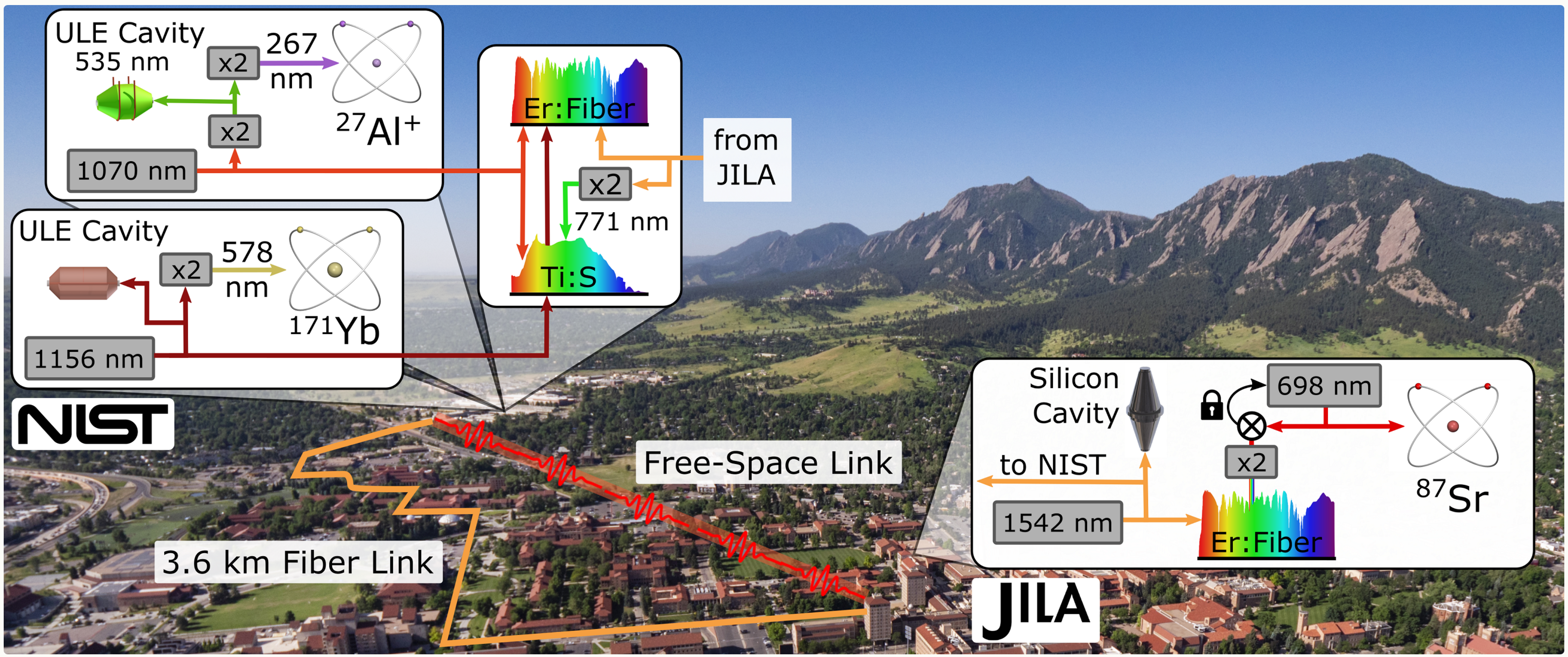


All indirect constraints from astrophysics and cosmology!

SEARCHING FOR ULTRA-LIGHT DARK PHOTONS USING HIGH PRECISION ATOMIC SPECTROSCOPY

High Precision Atomic Spectroscopy: Optical Clocks

Three atomic clocks at NIST/JILA in Boulder.



High Precision Atomic Spectroscopy: Optical Clocks

Three atomic clocks at NIST/JILA Boulder.

Atom	Transition	Energy (eV)	Ground state α_D (a.u.)	Excited state α_D (a.u.)
Al^+	$3s^2\ {}^1S_0 — 3s3p\ {}^3P_0$	4.643	23.780	24.175
Sr	$5s^2\ {}^1S_0 — 5s5p\ {}^3P_0$	1.776	193	410
Yb	$4f^{14}6s^2\ {}^1S_0 — 4f^{14}6s6p\ {}^3P_0$	2.145	139	257

Larger α_D (dipole polarizability) : greater sensitivity to electric field.

MOTIVATIONS

Achieve $\Delta\nu/\nu < 10^{-18}$ to replace Cs clock (microwave)

Optical transition ~ 100 nm. Better fractional uncertainty

High Precision Atomic Spectroscopy

AMO Experiments: Stark and Zeeman Shifts are unwanted background.

For ULDP search, Stark and Zeeman Shifts are signal!

$^1S_0 \rightarrow {}^3P_0$ **has no first order Stark shift.**

$^1S_0 \rightarrow {}^3P_0$ **use $m_F = 0$ states by averaging:**

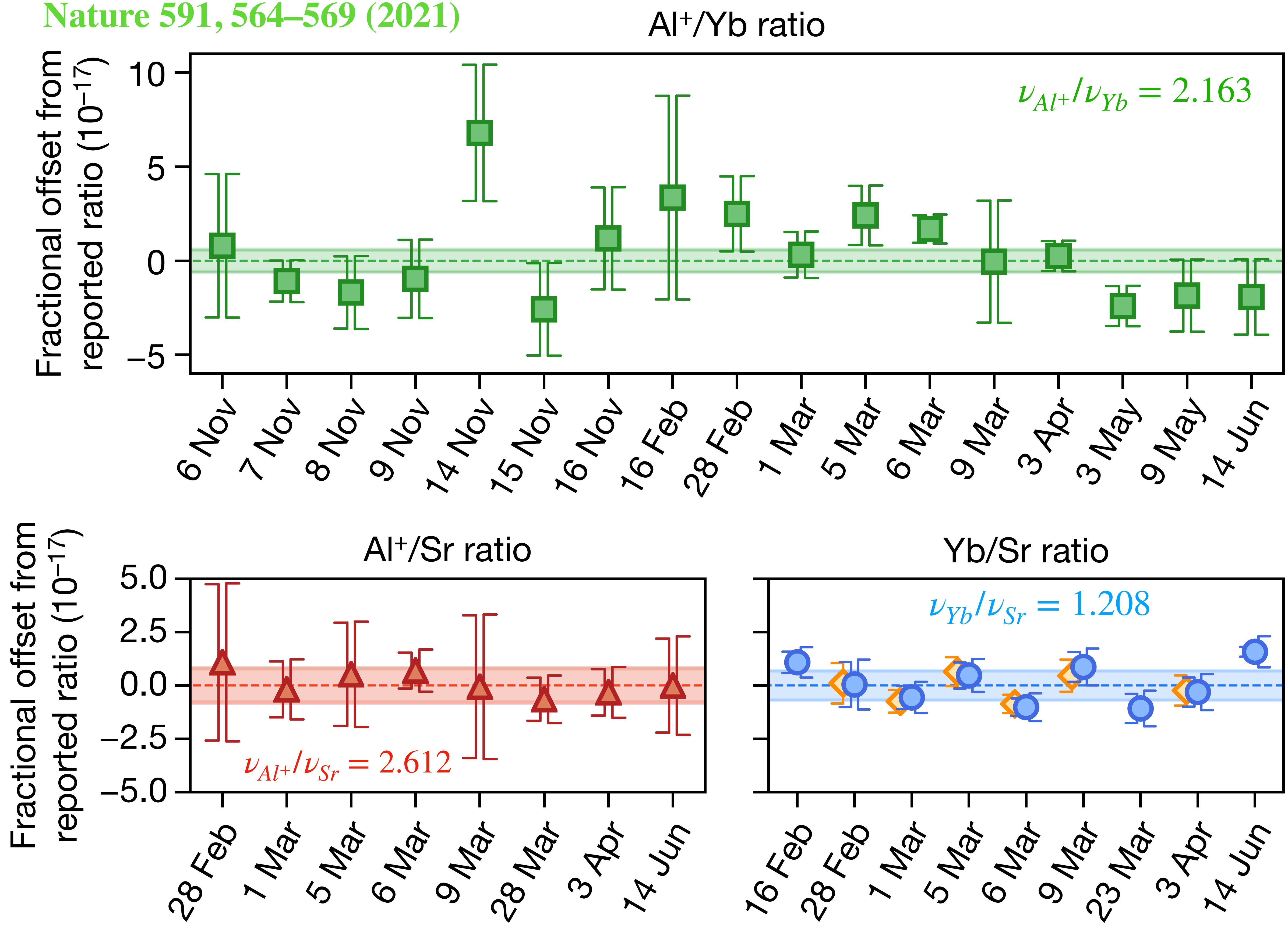
$$\nu_{m_F=0} \simeq \frac{1}{2}\left[\nu_{+m_F} + \nu_{-m_F}\right] + \mathcal{O}\left(|B^2|\right)$$

First order Zeeman shift cancels.

Second order Stark shift is the dominant effect.

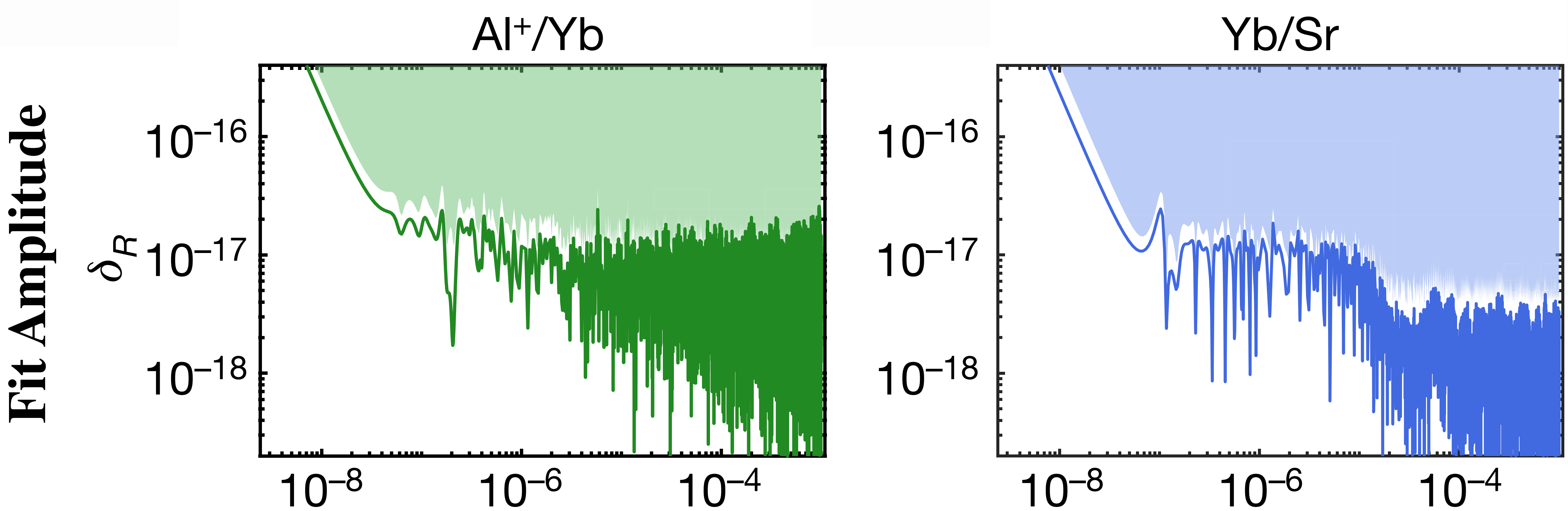
High Precision Atomic Spectroscopy: Time Series Ratio Data

Nature 591, 564–569 (2021)



Detecting ULDP using High Precision Atomic Spectroscopy

Fit a sinusoidal signal to time series ratio data. Previously done for dilation DM

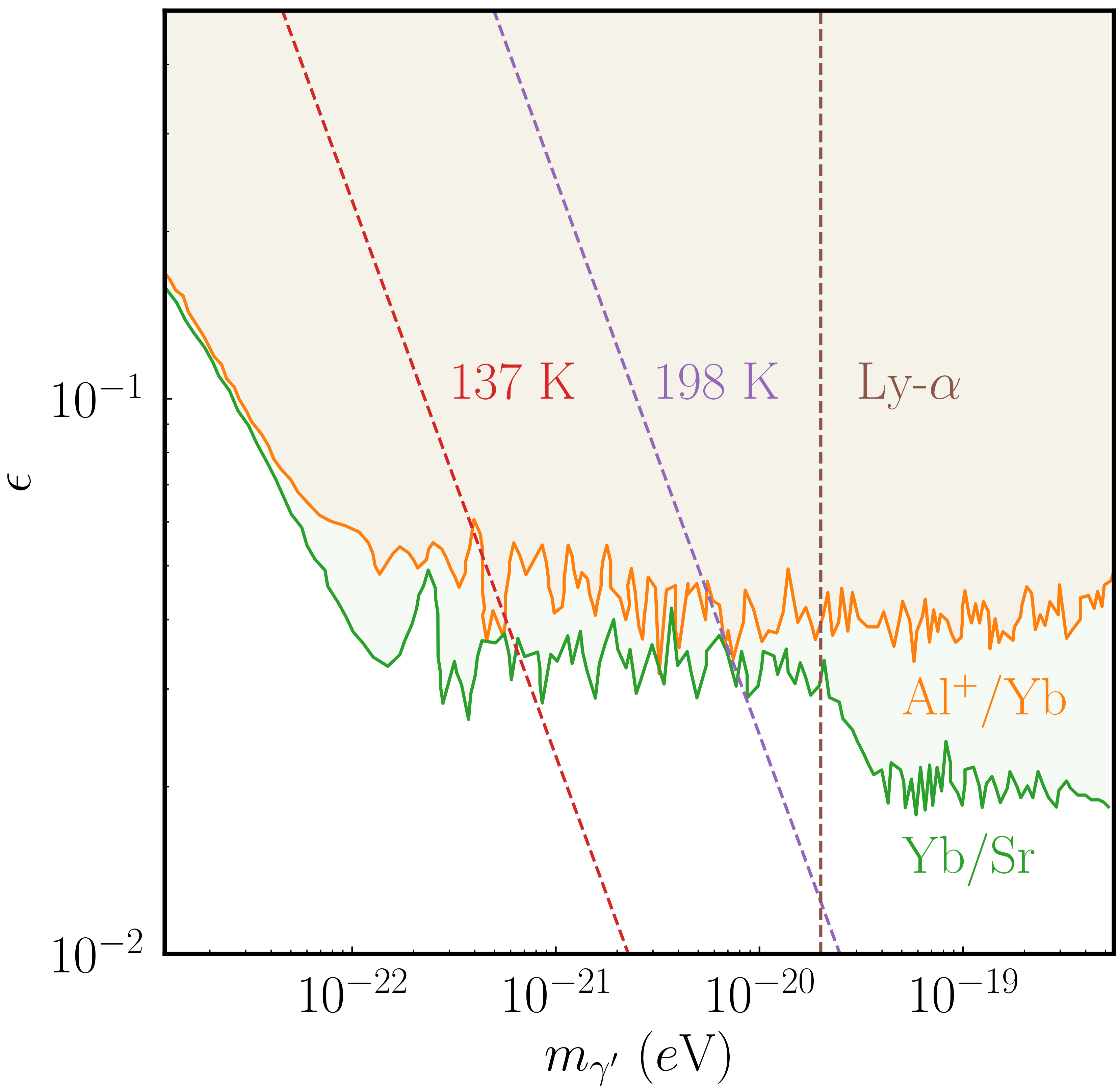


Nature 591, 564–569 (2021)

Fit Frequency: dark photon mass $\sim \sin^2\left(\frac{mc^2 t}{\hbar} + \phi_0\right)$

$$\delta_R = 2\,\pi\,\epsilon^2\,\rho_{\rm DM}\,a_0^3\,\left(\frac{\Delta\alpha_{D,1}}{\hbar\,\omega_1} - \frac{\Delta\alpha_{D,2}}{\hbar\,\omega_2}\right)$$

Results: Ultra-light Dark Photons

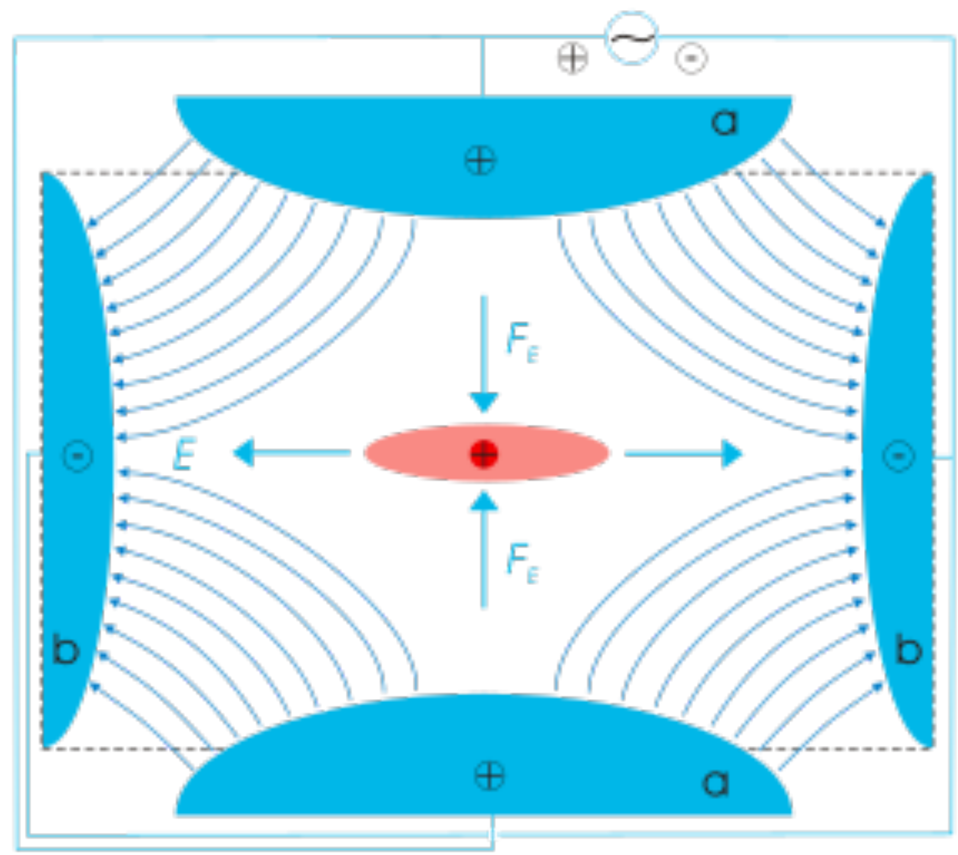


Source: Berger & Bhoonah (arXiv:2206.06364)

FUTURE DIRECTIONS

Future Directions: Excess Micromotion (EMM) in Single Ion Traps

Ion trapped with AC/DC electrodes such that average force zero.

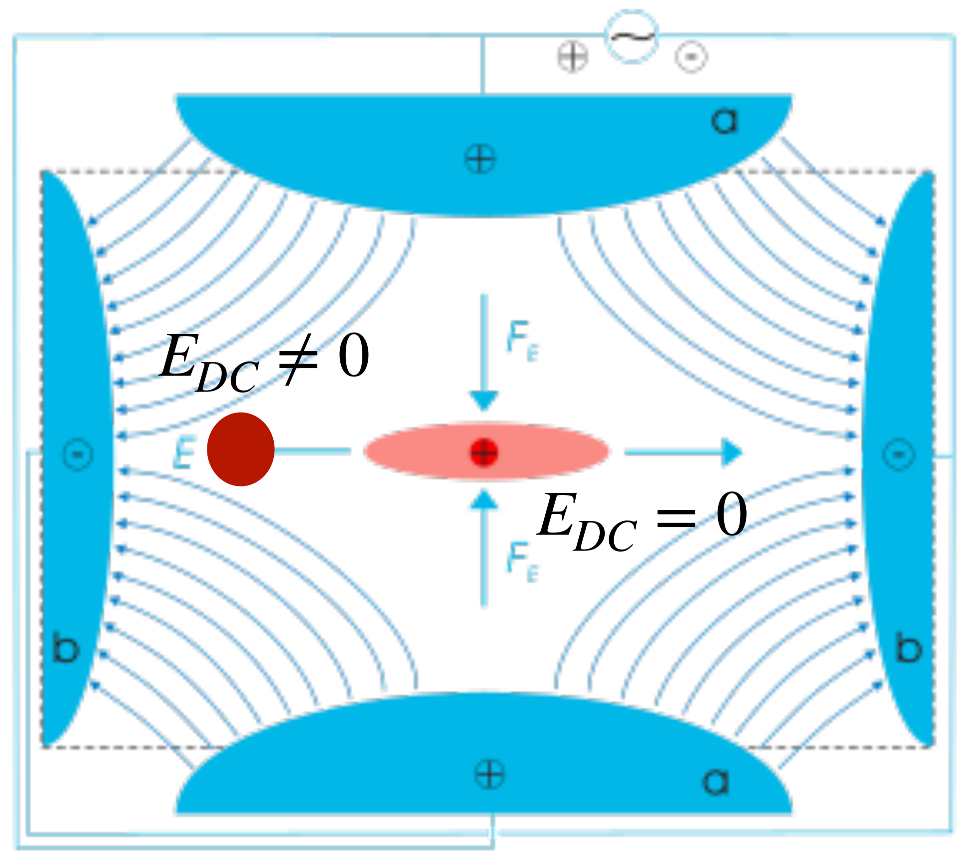


a_i, q_i: **Trap parameters**

$$\frac{d^2 x_i}{dt^2} + \left(a_i + 2q_i \cos(\Omega_{rf} t)\right) \frac{\Omega_{rf}^2}{4} x_i = \frac{Q_{ion} E_{dc}}{m}$$

E_{dc} : **Stray fields (background) and dark photon E-field (signal)**

Future Directions: Excess Micromotion (EMM) in Single Ion Traps



Ideally no Electric field at trap center.

Intrinsic Micromotion: Periodic motion about trap center at *secular frequency*.

DC Electric Field pushes ion away from center where there is an AC Electric Field.

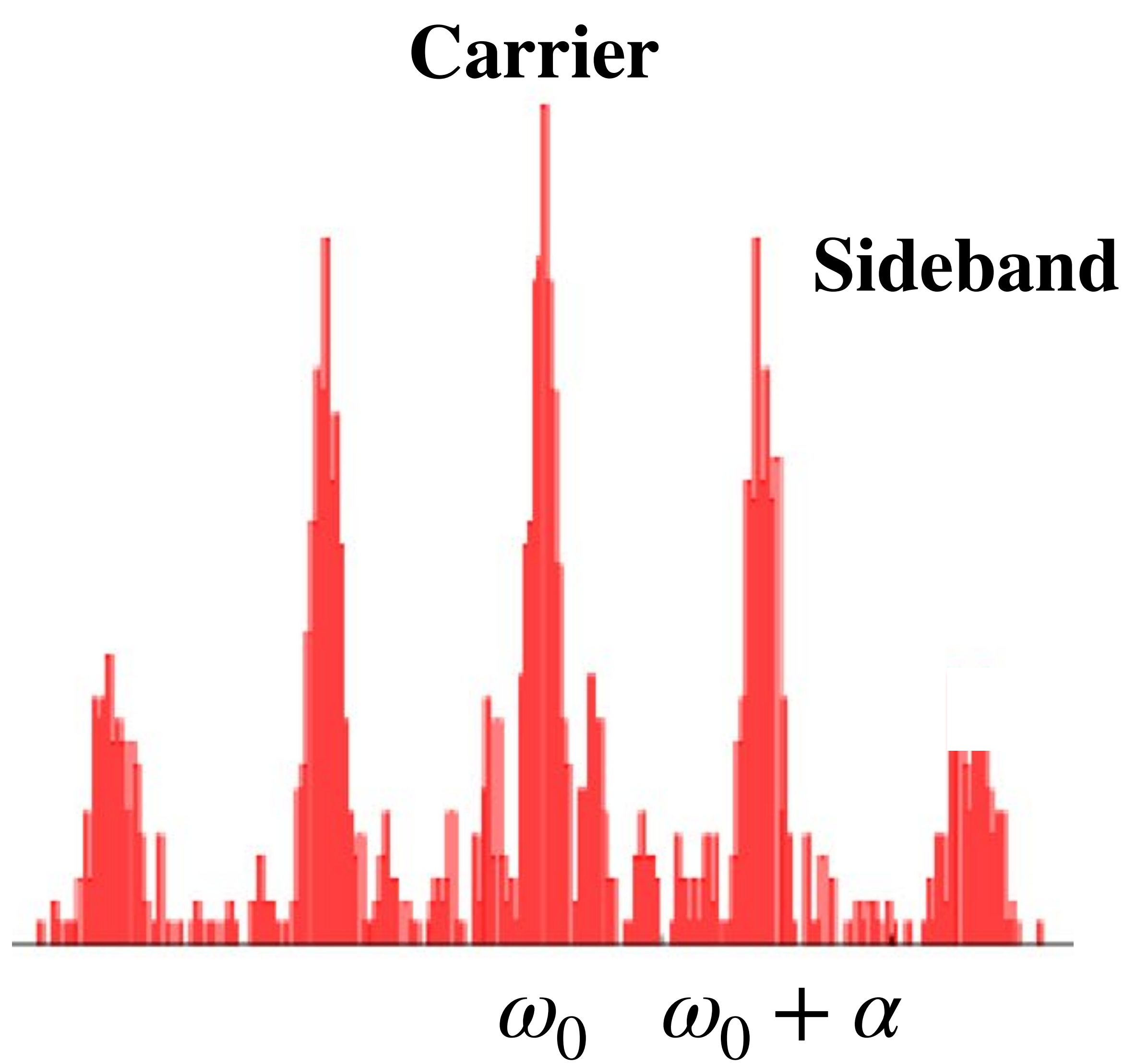
Excess Micromotion: Periodic motion at trap *frequency* Ω_{rf}.

Future Directions: Detecting EMM through sideband spectroscopy

Laser to excite transition. AC laser field $E_{laser} = E_0 \sin(\omega_L t)$

Time dependent perturbation - time dependent energy!

$$\alpha = \frac{\alpha_D |E_0|^2}{4\omega_0\omega_L}$$

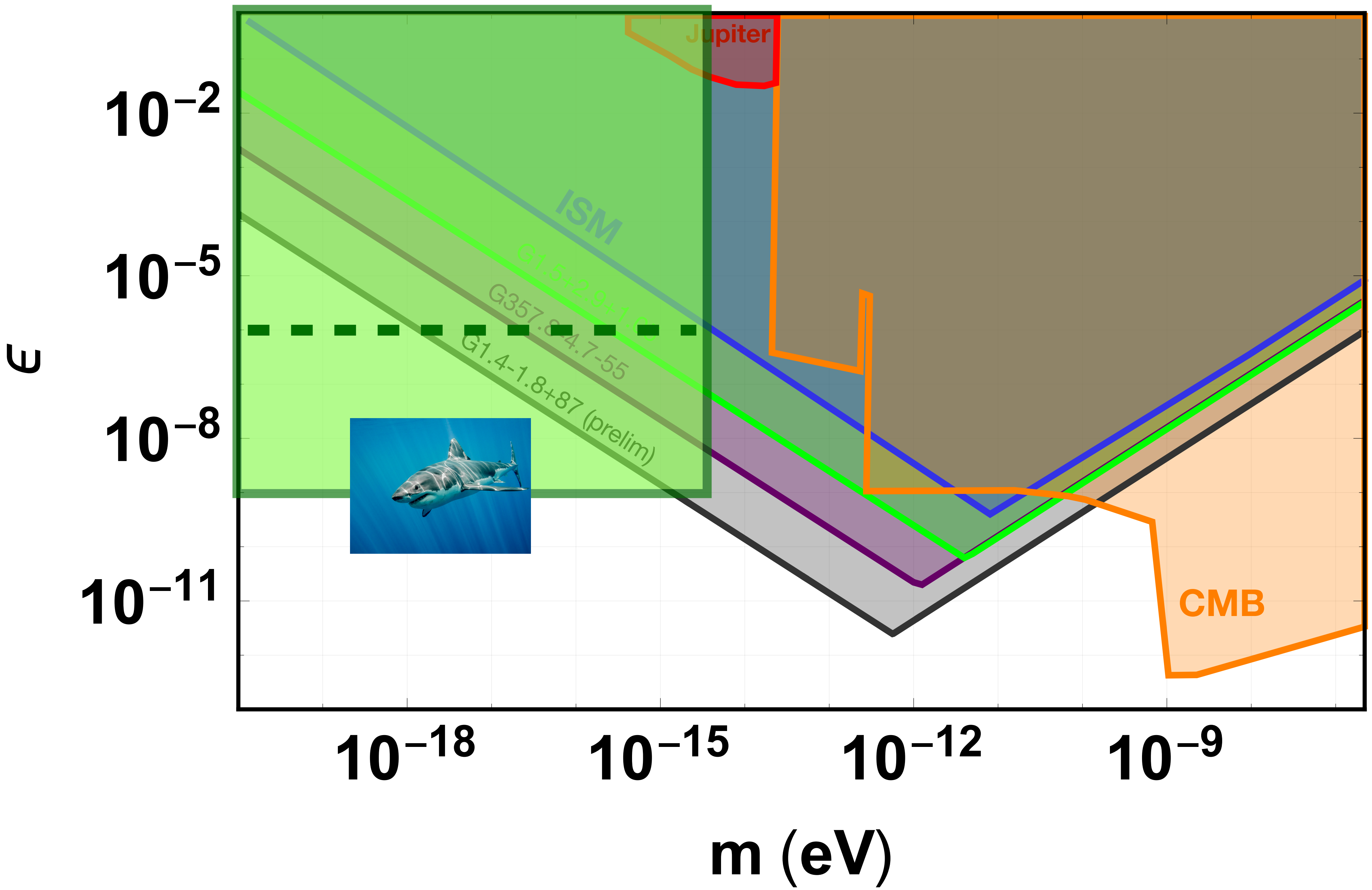


Sidebands appear with probability $|J_n(\alpha)|^2$.

EMM phase modulates laser E-Field - sideband modulation.

Future Directions: Detecting EMM through sideband spectroscopy

Optimistic scenario: constrain $\mu V/m$ Electric Fields at low frequency.



Future Directons: Stochastic Fluctuations

DM velocity corrections to Electric and Magnetic Field.

$$\mathbf{E} \simeq \sqrt{2\rho_{DM}}\epsilon \sin\left(\frac{m_{\gamma'}c^2 + \frac{1}{2}m_{\gamma'}v^2 c^2 t}{\hbar} + \phi_0\right)\hat{\mathbf{n}}$$

Phase coherence time $\tau_C \sim \frac{1}{2}m_{\gamma'}v^2$**.**

$T_{exp} < \tau_C$ **signal can be assumed coherent.**

$T_{exp} > \tau_C$ **full stochastic nature must be taken into account.**

Extra Time Sensitivity

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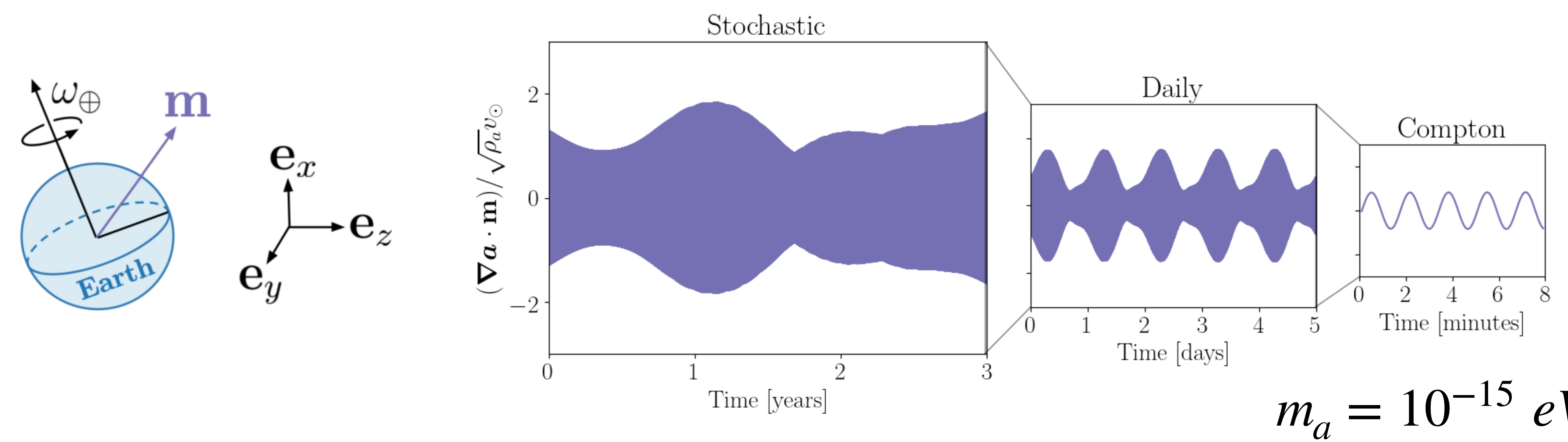

$m_a = 10^{-15}\ eV$

Lisanti, Moschella, Terrano: PRD 104, 055037 (2021)

- Modulation strongly affects $\mathbf{B}_{\text{eff}} \propto \mathbf{v}$
- Barely affects $\mathbf{E}_{\text{eff}}$

Conclusions

Ultralight dark photons are a well motivated model of dark matter.

ULDPs can be searched for using high precision atomic spectroscopy.

Single ion traps can be even more sensitive to ULDPs.

To explore a broader range of ULDP mass, need to characterize the full stochastic signal

AMO systems can probe dark matter models that, until now, had only been probed indirectly through astrophysics and cosmology.

THANK YOU!

EXTRA SLIDES

Introduction: Ultra-light dark matter

$$n_{DM} = \rho_{DM}/m_{DM} \simeq \frac{3 \times 10^8}{m\ (eV)}\ \ cm^{-3}$$

$$\Delta x \approx n_{DM}^{-\frac{1}{3}} \qquad \lambda_{dB} = \frac{2\pi}{m_{DM}\langle v \rangle}$$

Overlap for $\frac{\Delta x}{\lambda_{dB}} \lesssim 1$ **or** $m_{DM} \lesssim 30$ **eV**

$m_{DM} \lesssim 30$ **eV will exhibit wave-like behaviour!**

E-B Correlations

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- We saw $|\mathbf{E}_{\text{eff}}|/|\mathbf{B}_{\text{eff}}| \sim 10^3\, c$
- Moreover: longer scale time variations in $\mathbf{B}_{\text{eff}}$
- Daily modulation and annual modulation

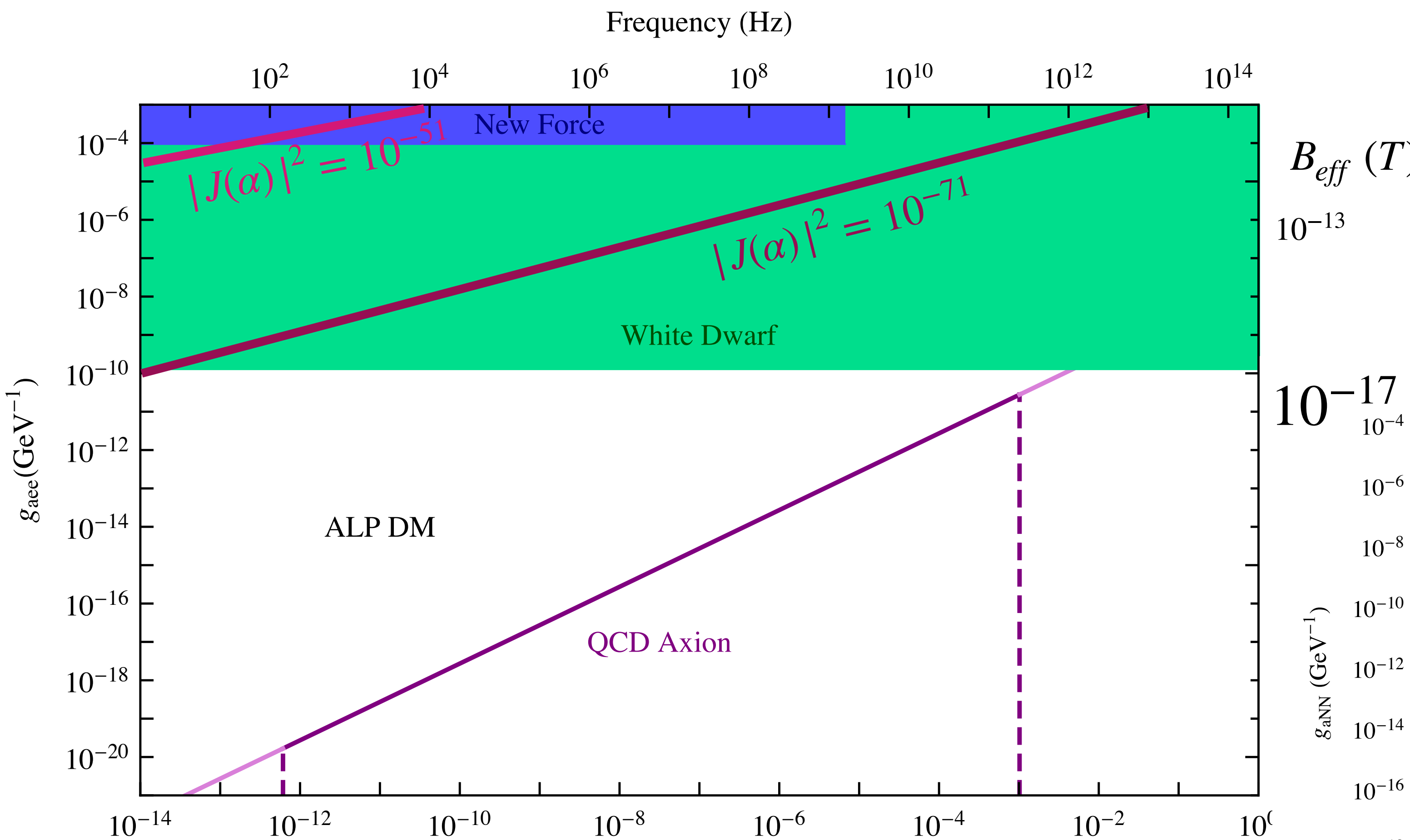
$$\mathbf{v} = \mathbf{w} + \mathbf{v}_{\odot} + \mathbf{v}_{\oplus}$$

$$|\mathbf{v}_{\oplus}| \sim 10^{-6}\, c, |\mathbf{v}_{\odot}| \sim 10^{-4}\, c$$

- Decoherence on $\tau_c \sim h/(m\,\sigma_v^2) \sim 10^6\; T$

Future Directions: Axions and Axion Like Particles

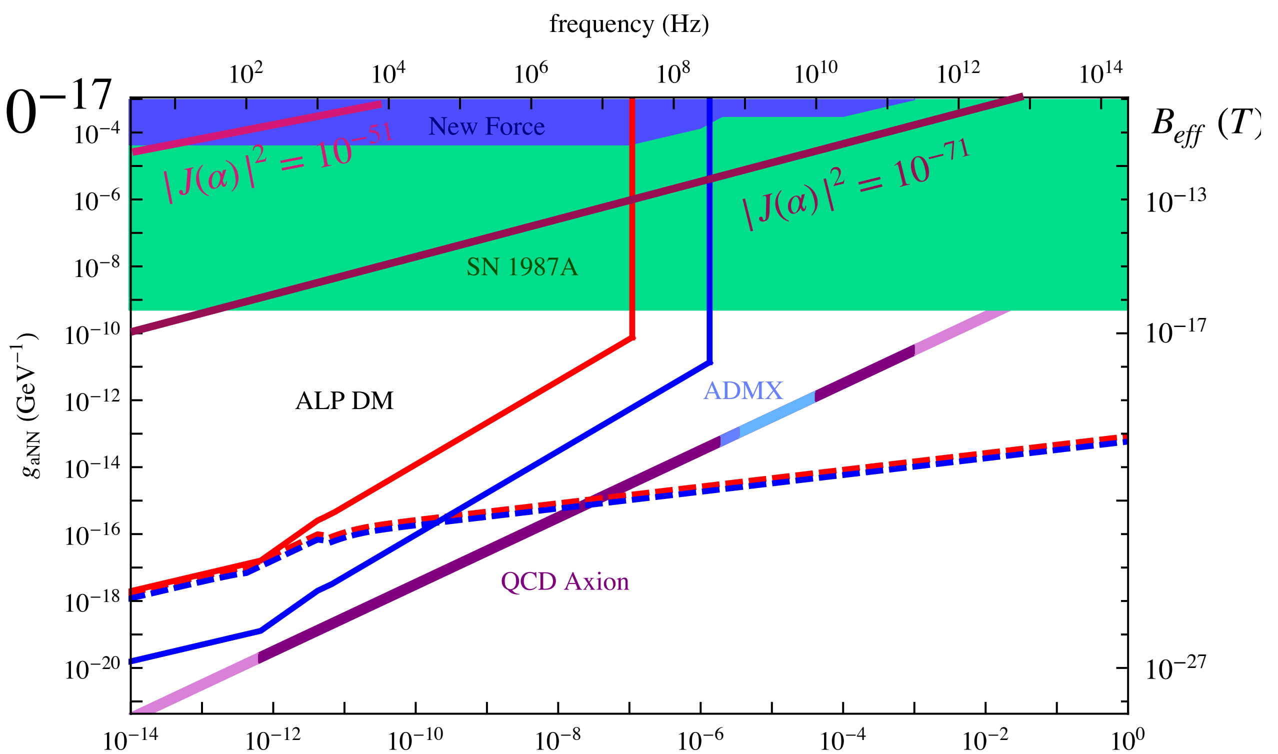
Axion Like Particles have "Zeeman-like" coupling to electrons and nucleons



mass (eV)

Electrons

Nucleons



mass (eV)

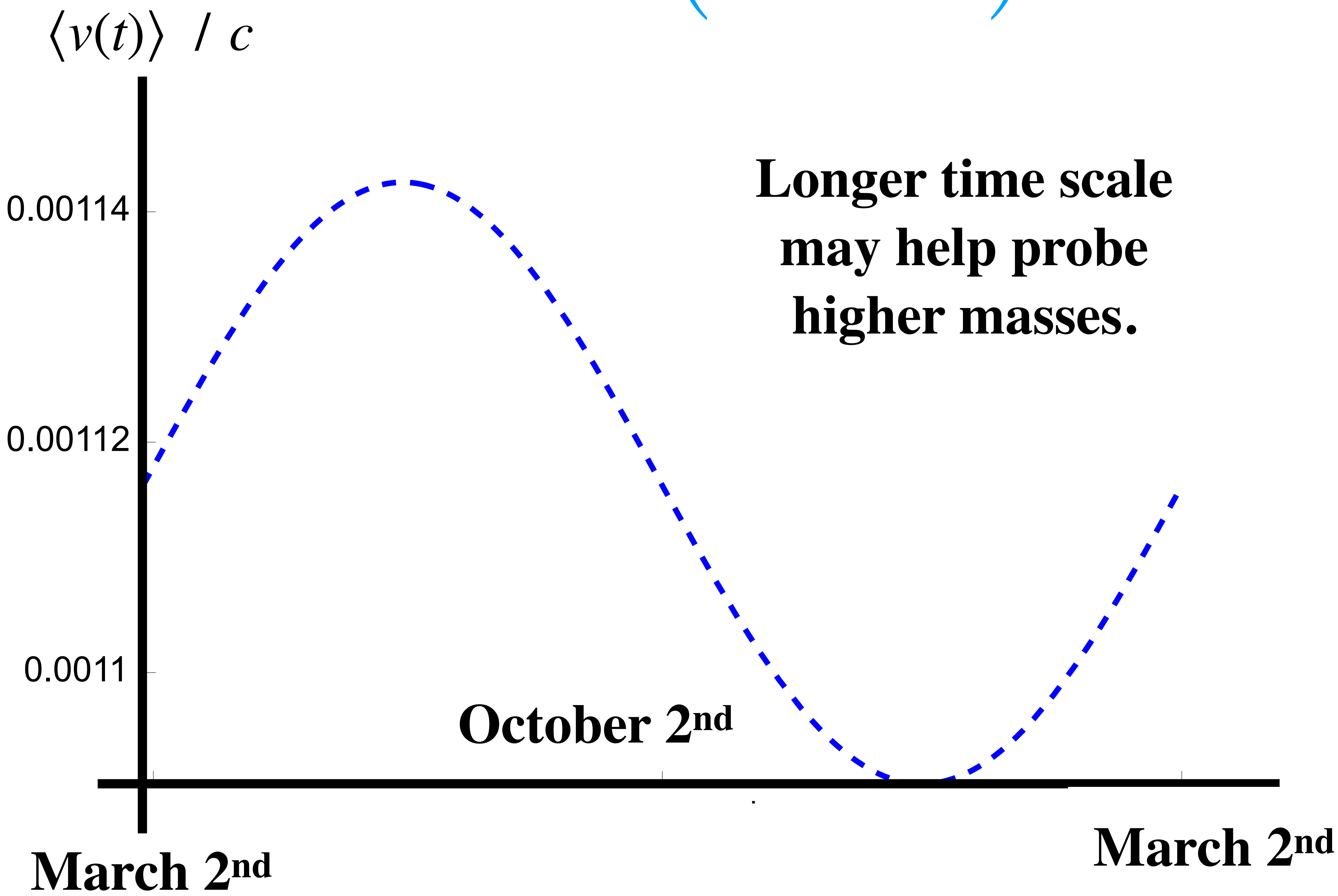
$$H_e = g_{aee} \times \sqrt{2\rho_{DM}} \cos\left(m_a t\right) \mathbf{v} \cdot \sigma_e$$

$$H_n = g_{ann} \times \sqrt{2\rho_{DM}} \cos\left(m_a t\right) \mathbf{v} \cdot \sigma_n$$

Future Directions

Exploiting time evolution of dark matter velocity.

$$\mathbf{B} \simeq \langle v \rangle \sqrt{2\rho_{DM}}\, \epsilon \sin\left(\frac{m_{\gamma'} c^2 t}{\hbar} + \phi_0\right) \hat{\mathbf{n}}'$$



Other Models

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- Stark and Zeeman shifts affect different transitions in different ways from other models
  - Dilaton: K factor
  - Stark: polarizability α
  - Zeeman: magnetic moment & m_F
  - Axion: electron spin

Can we exploit these differences after discovery?

Higher Frequency

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- Here: DC field approximation
- Faster than servo: need different methods
- Astrophysical bounds are stronger
- Other techniques like NMR (CASPER-ZULF)