PROBING RAPIDLY OSCILLATING ULTRALIGHT DARK MATTER

Super-resolution in Physics Workshop

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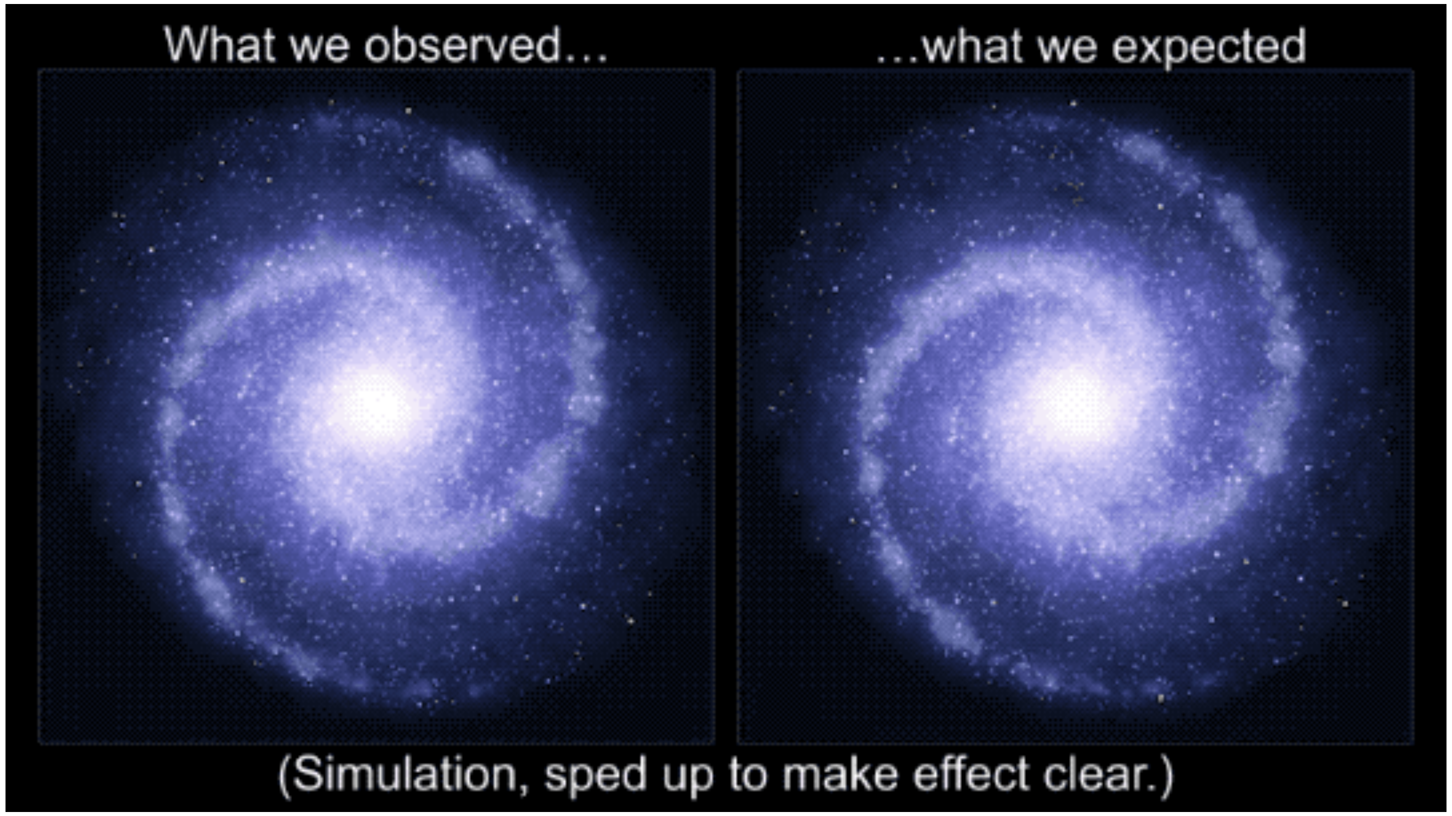
07.02.21

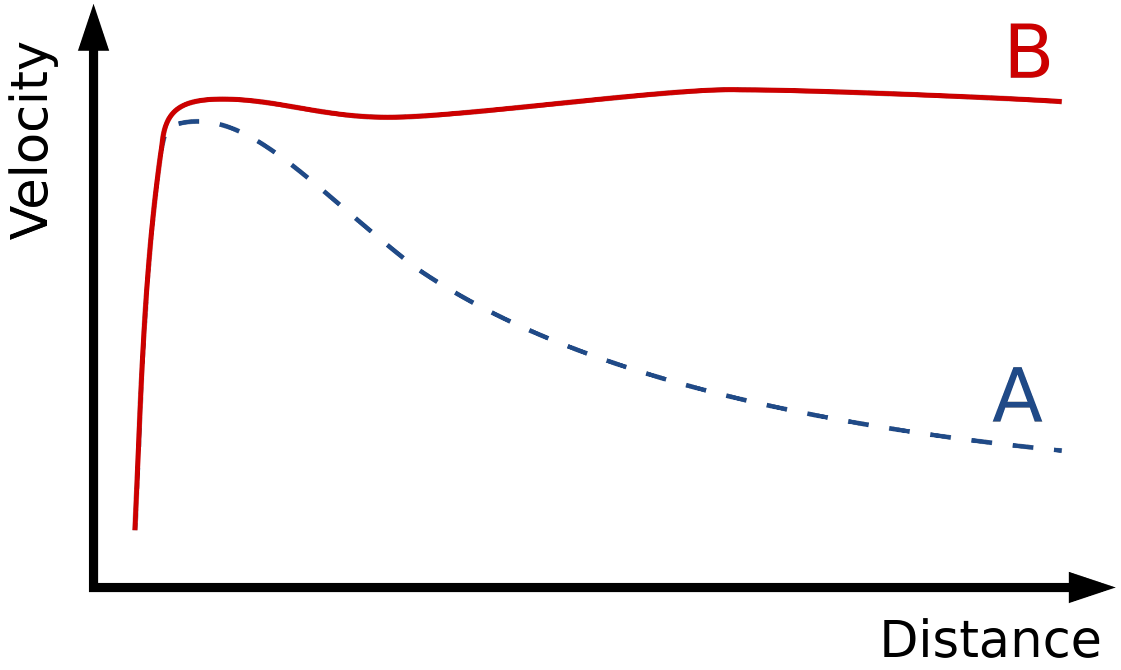
OUTLINE

- Dark matter
- Ultralight Dark Matter
- Atomic probes of Ultralight Dark Matter
- Rapidly oscillating Ultralight Dark Matter
- Super-resolution?

DARK MATTER

- **The missing mass problem** - the discrepancy between the amount of visible (baryonic) matter, and the expected amount of gravitationally interacting matter in the universe.
- Supported by various astronomical and cosmological observations such as: galaxy rotation curves, structure formation, CMB data and more…

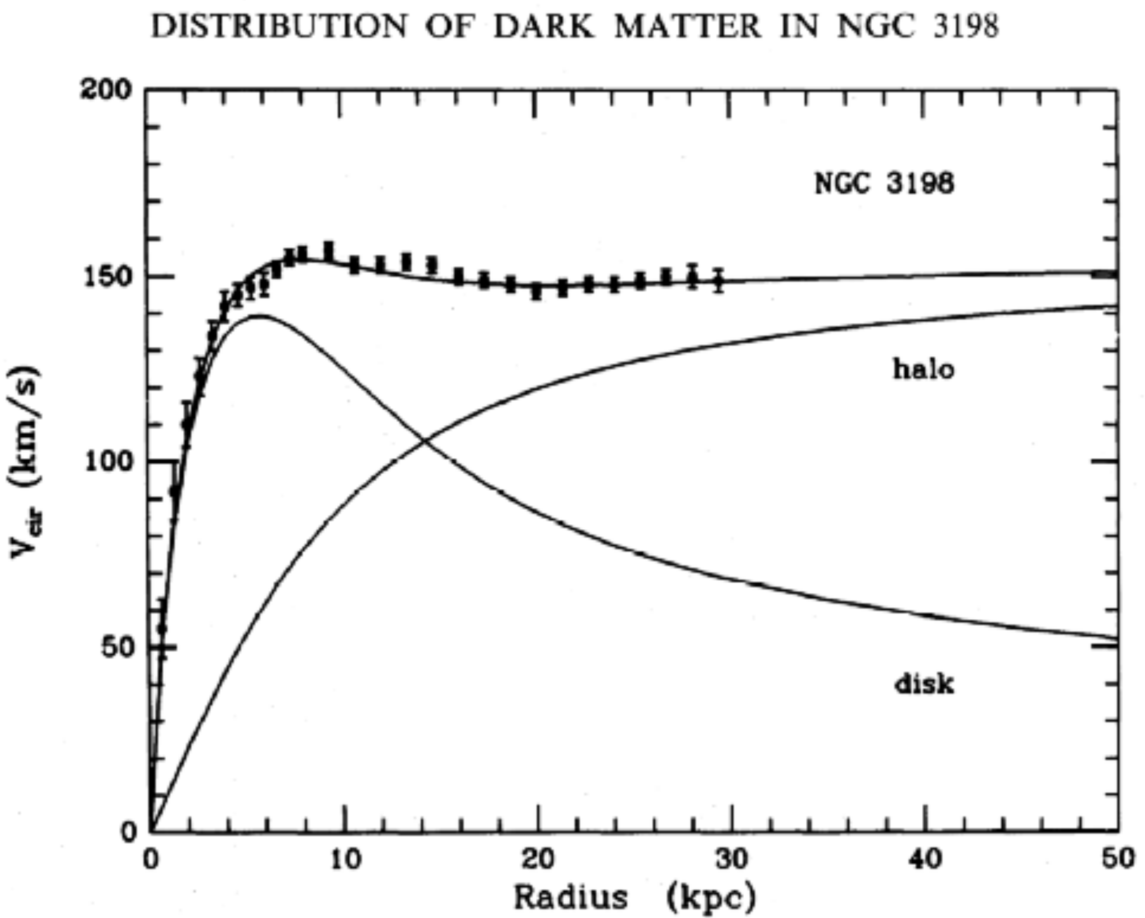




http://nasa.tumblr.com, simulation by ESO/L. Calçada.

DARK MATTER

- **The missing mass problem** - the discrepancy between the amount of visible (baryonic) matter, and the expected amount of gravitationally interacting matter in the universe.
- Supported by various astronomical and cosmological observations such as: galaxy rotation curves, structure formation, CMB data and more…
- **Dark matter** -
  - a “new” type of matter
  - has gravitational interactions, but only very weak (or no) interactions with light.



ULTRALIGHT SCALAR DARK MATTER

- DM number density in the galaxy $n_\phi = \rho_{DM}/m_\phi$
- De-Broglie length $\lambda_{DB} = h/(m_\phi v)$
- **Ultralight DM (m<0.1 eV) - many particles within a De-Broglie cube**

$$N = n \cdot \lambda_{dB}^3 = \frac{\rho_{DM}}{m^4 v^3} \approx \left(\frac{\rho_{DM}}{0.3GeV/cm^3}\right)\left(\frac{0.1eV}{m}\right)^4$$

- Cannot be treated as individual particles, but rather as a **macroscopic coherent field** (much like a laser/BEC/superfluid)
- **Ultralight scalar DM is a field the coherently oscillating**

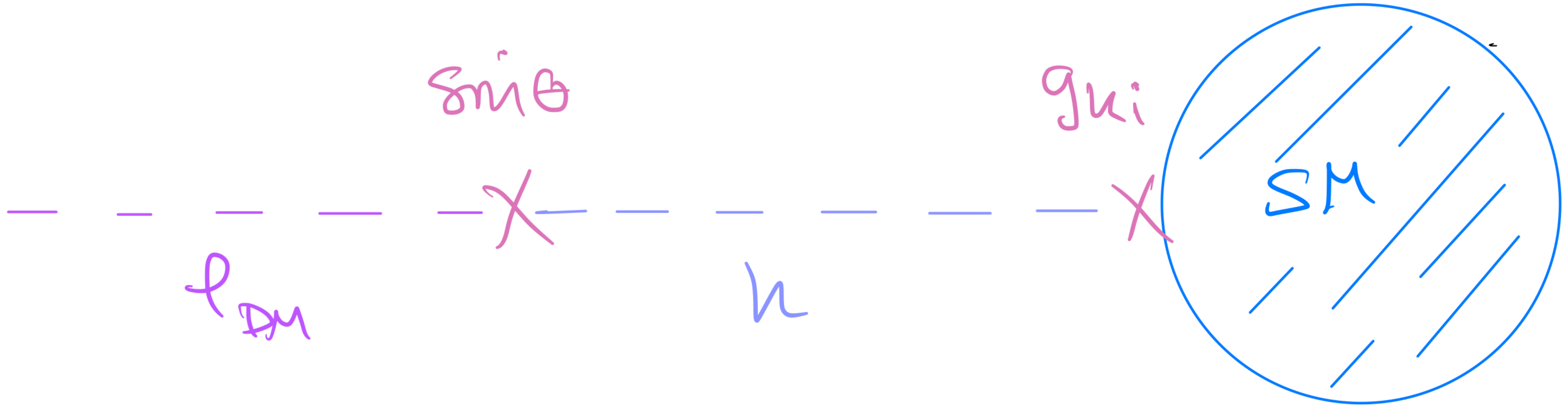
$$\boxed{\langle \phi\,(t) \rangle \simeq \frac{\sqrt{2\rho_{DM}}}{m_\phi} \cos(m_\phi t)}$$

A. Khmelnitskya and V. Rubakov, 1309.5888

ULTRALIGHT DM COUPLING TO THE SM

- The DM field can be searched for through its interactions with "ordinary" (Standard Model) particles.
- e.g. *Higgs-portal* models, in which the DM couples to the SM through its mixing with the Higgs, inheriting its interactions.

$$g_{\phi i} = g_{hi} \sin\theta$$



B. Patt, F. Wilczek, [0605188]

ULTRALIGHT DM COUPLING TO THE SM

- If the DM field is coupled to electrons and/or photons

$$\mathscr{L}_{int} \supset -g_{\phi e} m_e \phi \bar{e} e + \frac{g_{\phi\gamma}}{4} \phi F^{\mu\nu} F_{\mu\nu}$$

- The DM background field would appear to "give mass" to the electrons (similarly to the Higgs), and/or modify the field strength of EM fields.

- **Temporal oscillations of** m_e, α **at a frequency determined by the mass of the field.**

$$\delta m_e = g_{\phi e} m_e \langle \phi(t, \overrightarrow{x}) \rangle \,, \qquad \delta\alpha = g_{\phi\gamma} \langle \phi(t, \overrightarrow{x}) \rangle \alpha^{SM} \qquad \langle \phi\left(t, \overrightarrow{x}\right) \rangle \simeq \frac{\sqrt{2\rho_{DM}}}{m_\phi} \cos(m_\phi t) \,,$$

TEMPORAL VARIATIONS OF FUNDAMENTAL CONSTANTS

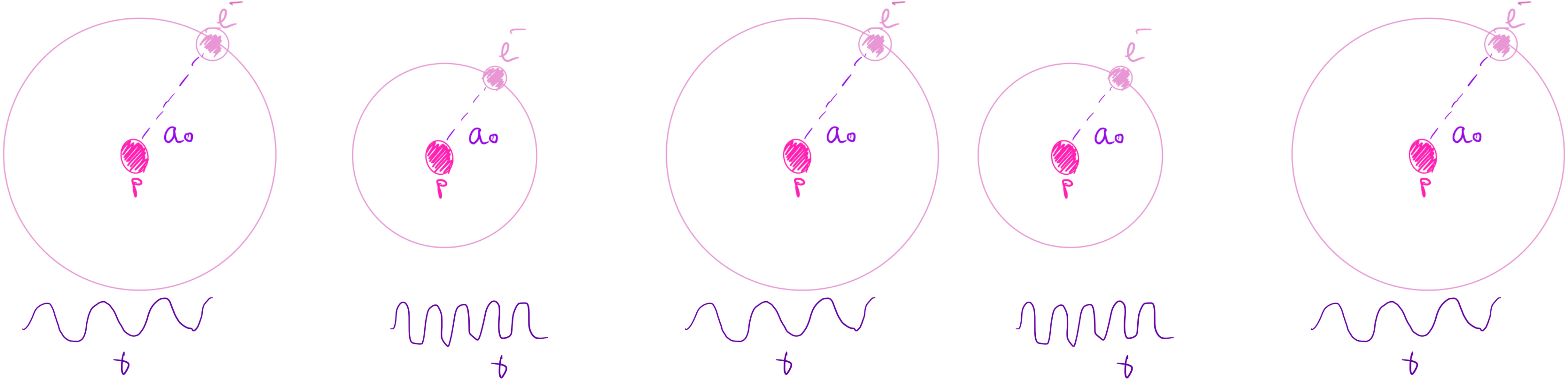
- Oscillations of the DM field induce oscillations of m_e, α

$$\delta m_e = g_{\phi e} m_e \langle \phi(t, \vec{x}) \rangle , \qquad \delta \alpha = g_{\phi\gamma} \langle \phi(t, \vec{x}) \rangle \alpha^{SM} \qquad \langle \phi\left(t, \vec{x}\right) \rangle \simeq \frac{\sqrt{2\rho_{DM}}}{m_\phi} \cos(m_\phi t) ,$$

- Temporal oscillations of atomic frequencies

  Y. V. Stadnik and V. V. Flambaum, [1412.7801]

  - Rydberg energy levels $R_\infty \propto \alpha^2 m_e$
  - cavity modes frequencies $a_0 \propto (\alpha m_e)^{-1}$
  - H hyperfine transition $\omega_{HF} \propto \alpha^4 m_e^2$

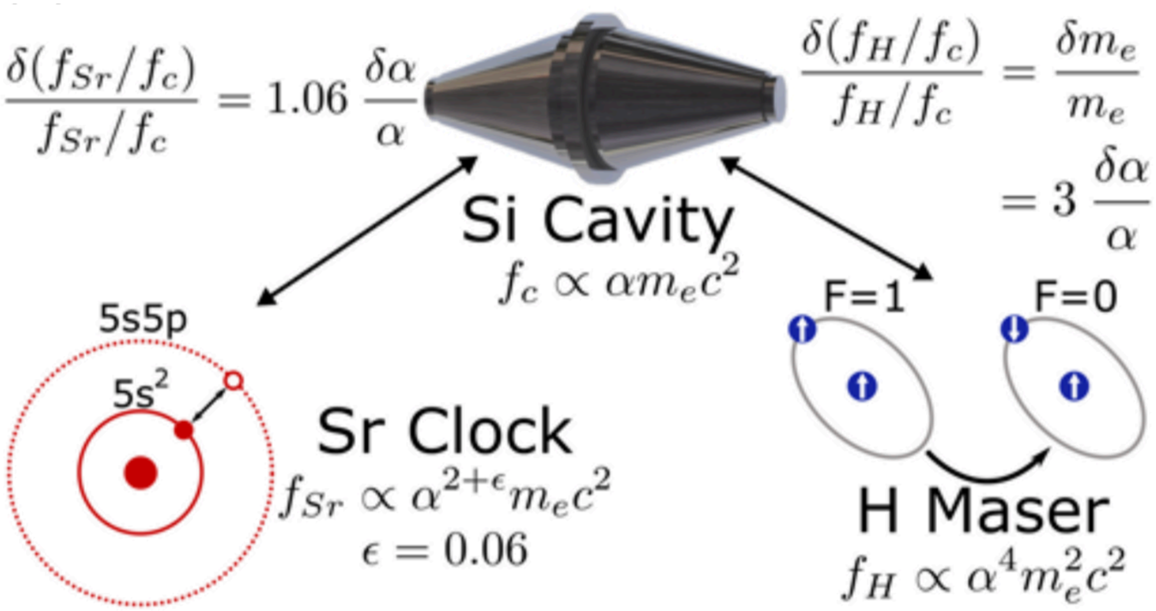


SEARCHING FOR ULDM WITH ATOMIC CLOCKS

- **Goal** - measure oscillations of fundamental constants induced by ULDM.

1. Compare two atomic clocks with clock frequencies that depend differently on α, m_e

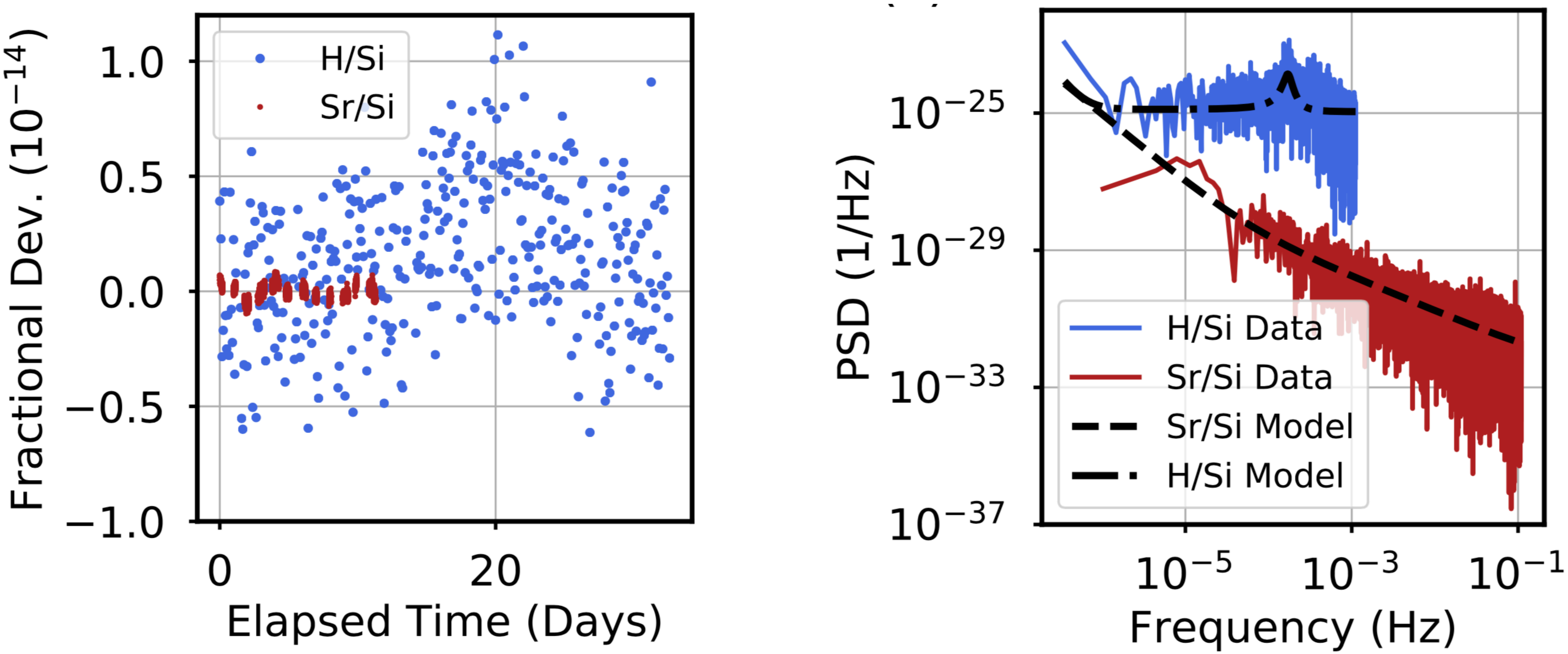
$$\boxed{\frac{\delta(f_A/f_B)}{f_A/f_B} = \frac{\delta f_A}{f_A} - \frac{\delta f_B}{f_B} \approx \Delta n^{\alpha}_{A,B}\frac{\delta\alpha}{\alpha} + \Delta n^{m_e}_{A,B}\frac{\delta m_e}{m_e}}$$



C.J. Kennedy et al., arXiv:2008.08773

SEARCHING FOR ULDM WITH ATOMIC CLOCKS

2. Sample the deviations $\frac{\delta(f_A/f_B)}{f_A/f_B}$ over time
3. Obtain the power spectrum (periodogram)
4. Compare to known noise model (e.g. clock stability)



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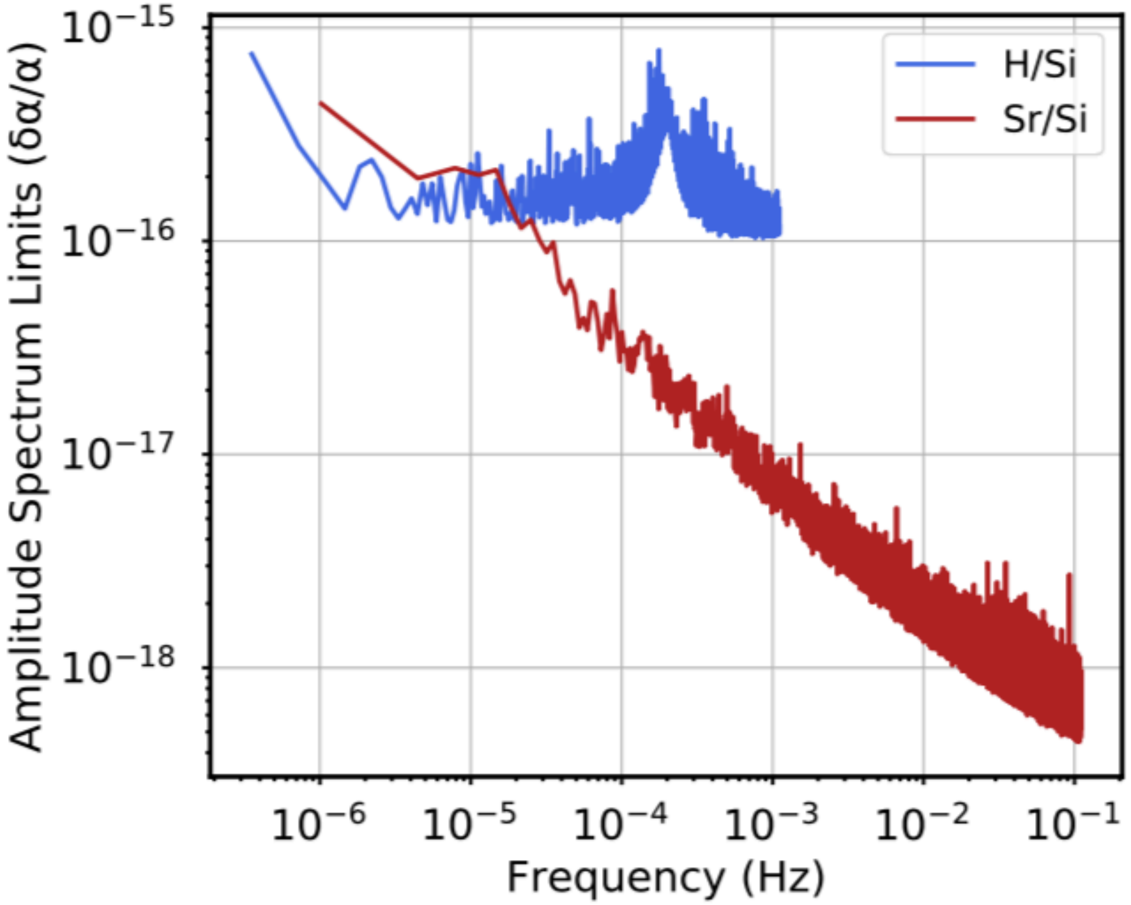
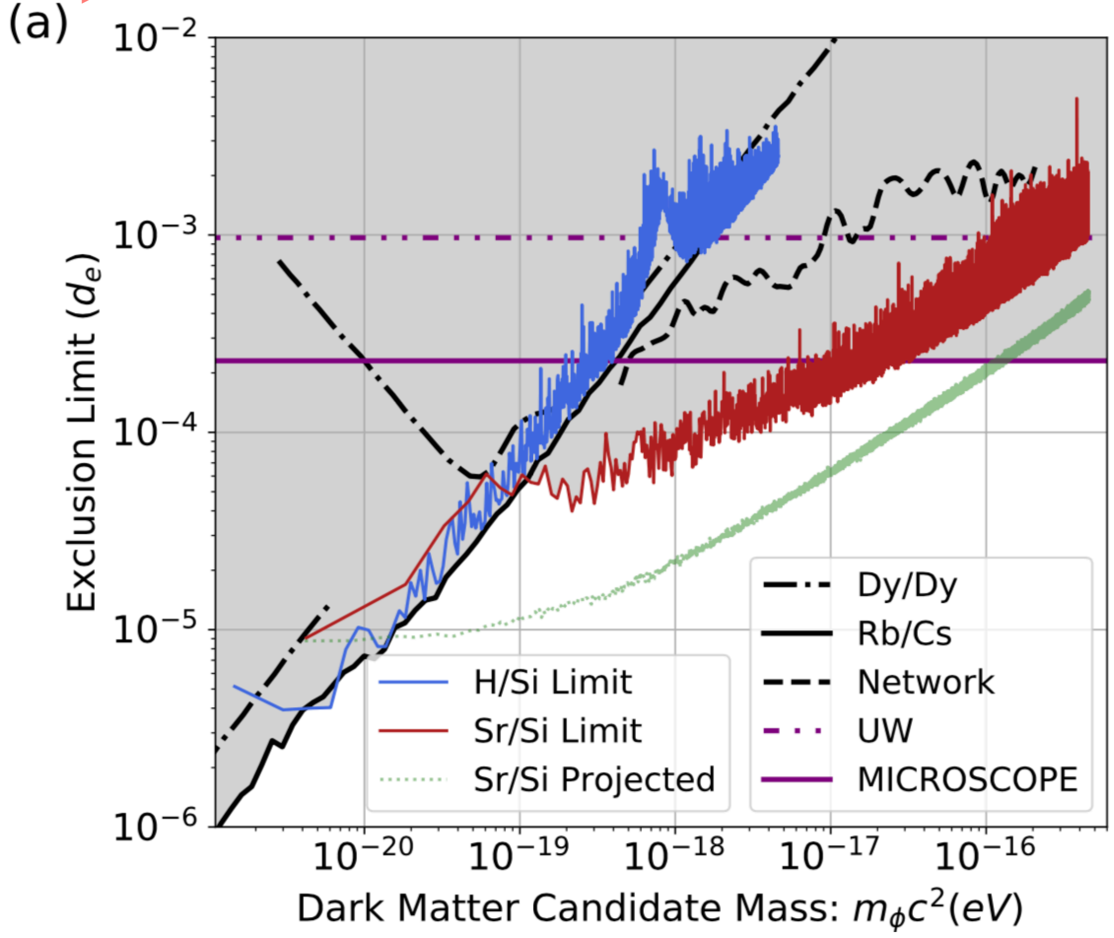
SEARCHING FOR ULDM WITH ATOMIC CLOCKS

- Bounds on variations of fundamental constants translated to bounds on DM couplings to photons and to electrons.

$$\frac{\delta\alpha}{\alpha}(\omega = m_\phi) = -\frac{d_e}{m_\phi}\frac{\sqrt{2\rho_{DM}}}{M_{pl}}$$





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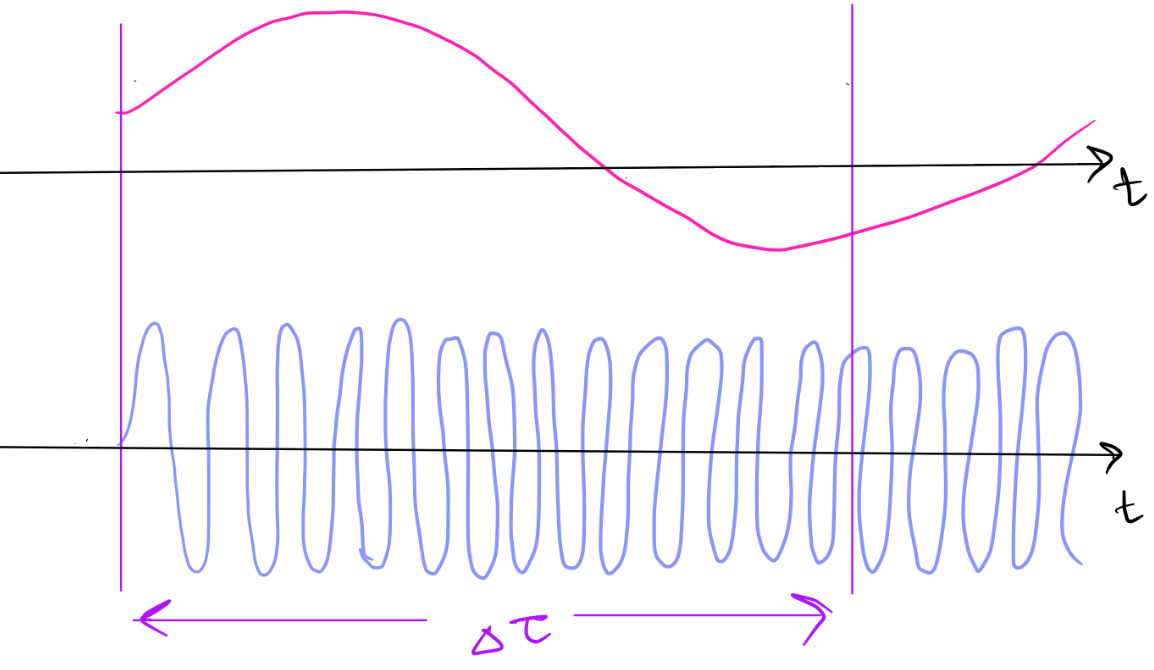
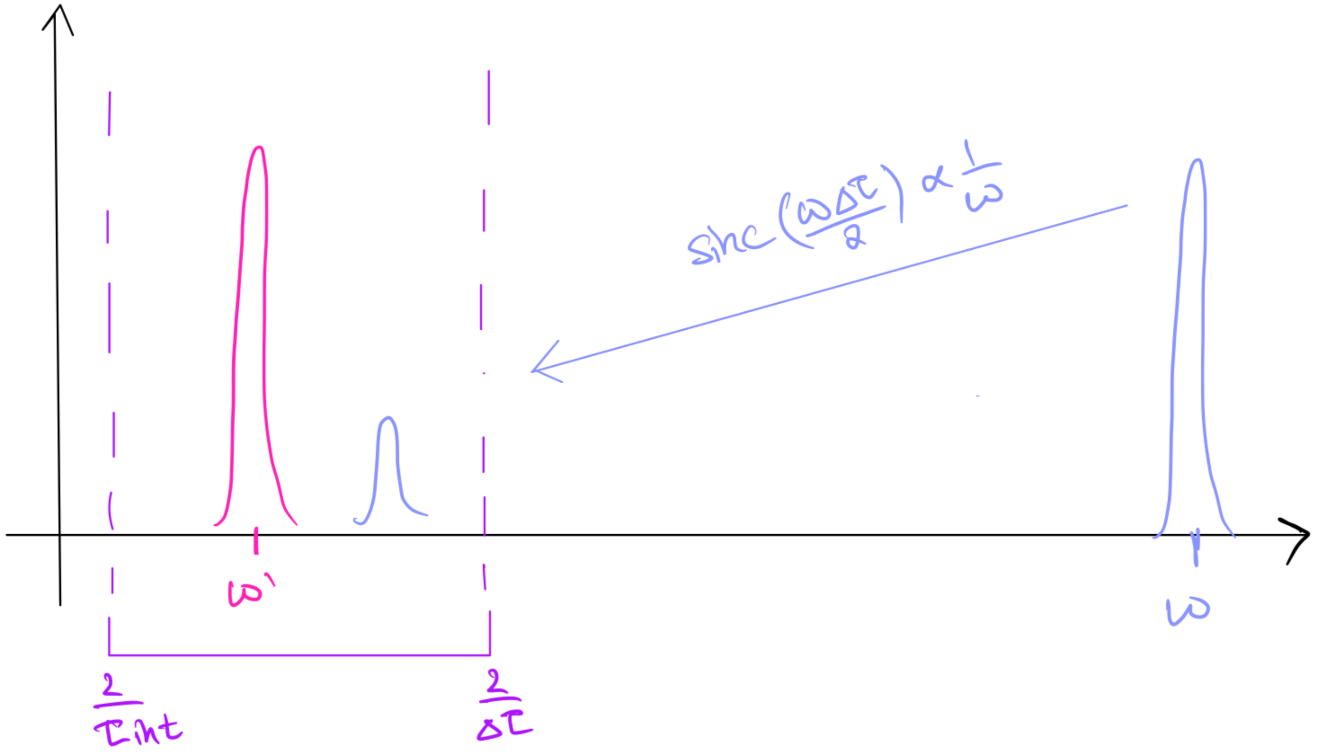
RAPIDLY OSCILLATING DARK MATTER

- **“Heavy” ultralight DM** $m_\phi \gtrsim 10^{-12}\, eV, \nu_\phi \gtrsim 100\, Hz$
- Theoretically motivated - relaxion DM. A. Banerjee et al., [1810.01889].
- **Blind spot** for atomic probes of temporal variations of fundamental constants due to rapid oscillations.
- Long averaging times (>1s) significantly lower the sensitivity to signals at frequencies above the Nyquist rate (>1Hz)





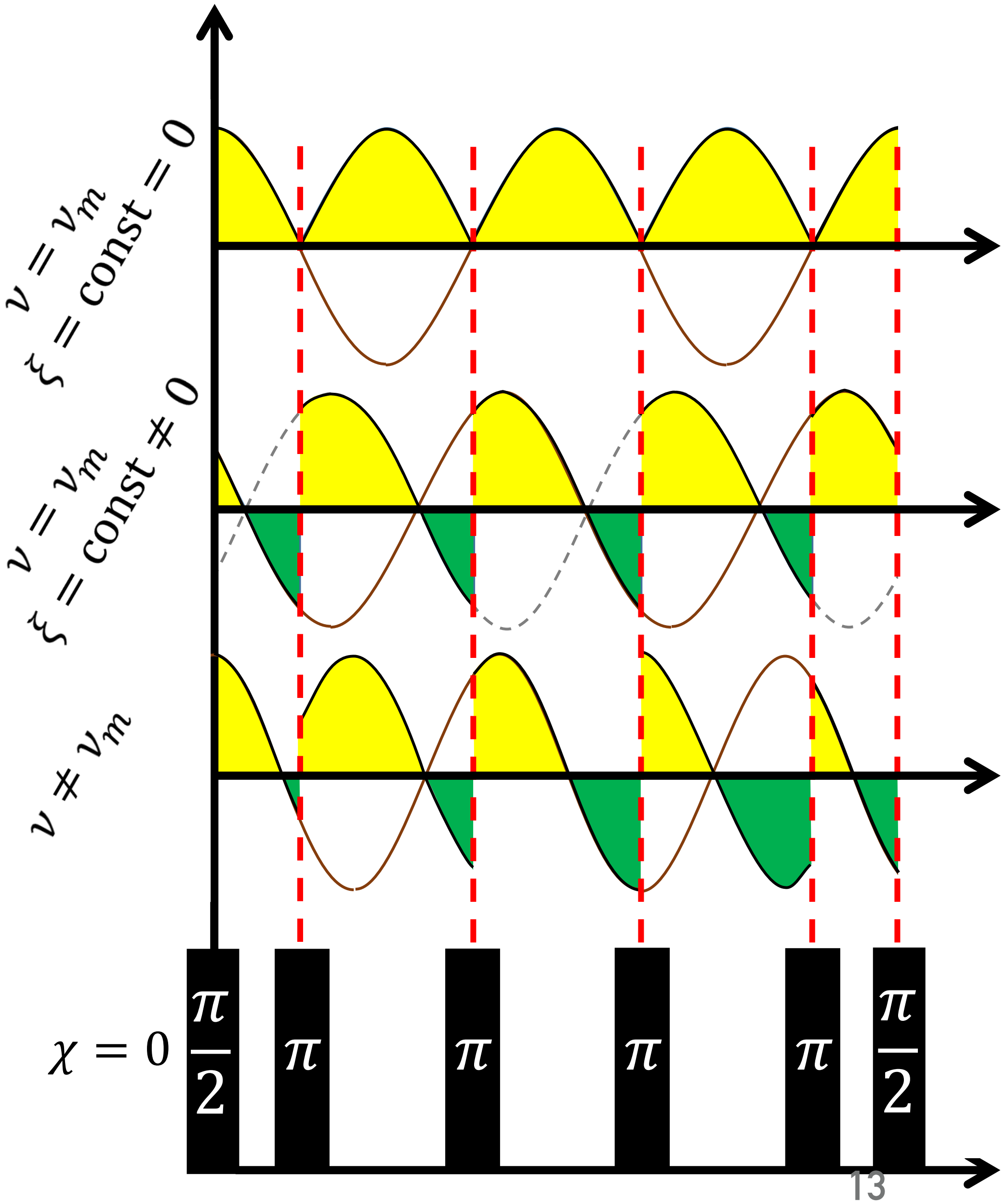
OBSERVING RAPIDLY OSCILLATING DARK MATTER

- **Dynamical Decoupling** - echo pulses applied at $\nu_m \gg \nu_s$
- Effectively - **amplitude modulation** of the signal by an alternating sign

$$\psi\left(\tau, n, \xi\right) = \int_{-\infty}^{\infty} G\left(t, \tau, n\right) \Delta f\left(t, \nu, \xi\right) dt \,.$$

$$G\left(t, \tau, n\right) = rect\left(\frac{t}{2n\tau}\right) \times \left[\Theta\left(t\right) + 2\sum_{k=1}^{\infty}\left(-1\right)^{k}\Theta\left(t - \left(2k-1\right)\tau\right)\right],$$

- Thus, **effects at the modulation frequency are accumulated**, allows for long interrogation times.

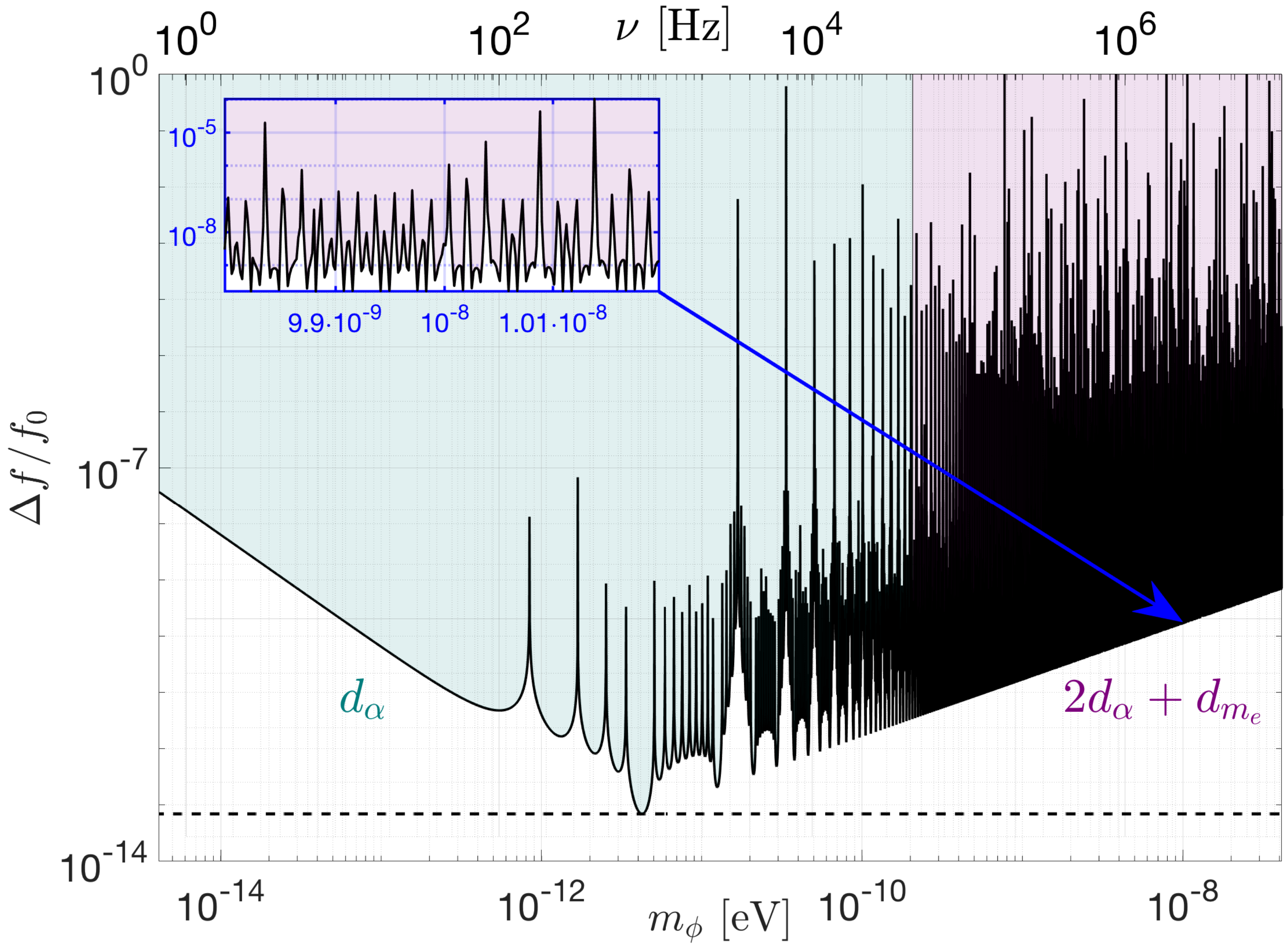


R.Shaniv and R. Ozeri, [1602.08645].

S. Aharony et al., [1902.02788].

PROBING RAPIDLY OSCILLATING DM USING DD

$$\frac{\Delta f(\nu)}{f_0} = \frac{\delta f_{\rm ion}(\nu) - \delta f_{\rm laser}(\nu)}{f_0} = \left(2 - F(\nu)\right)\frac{\delta\alpha}{\alpha} + \left(1 - F(\nu)\right)\frac{\delta m_e}{m_e}$$



First model independent bounds on variations of α, m_e up to MHz frequencies.

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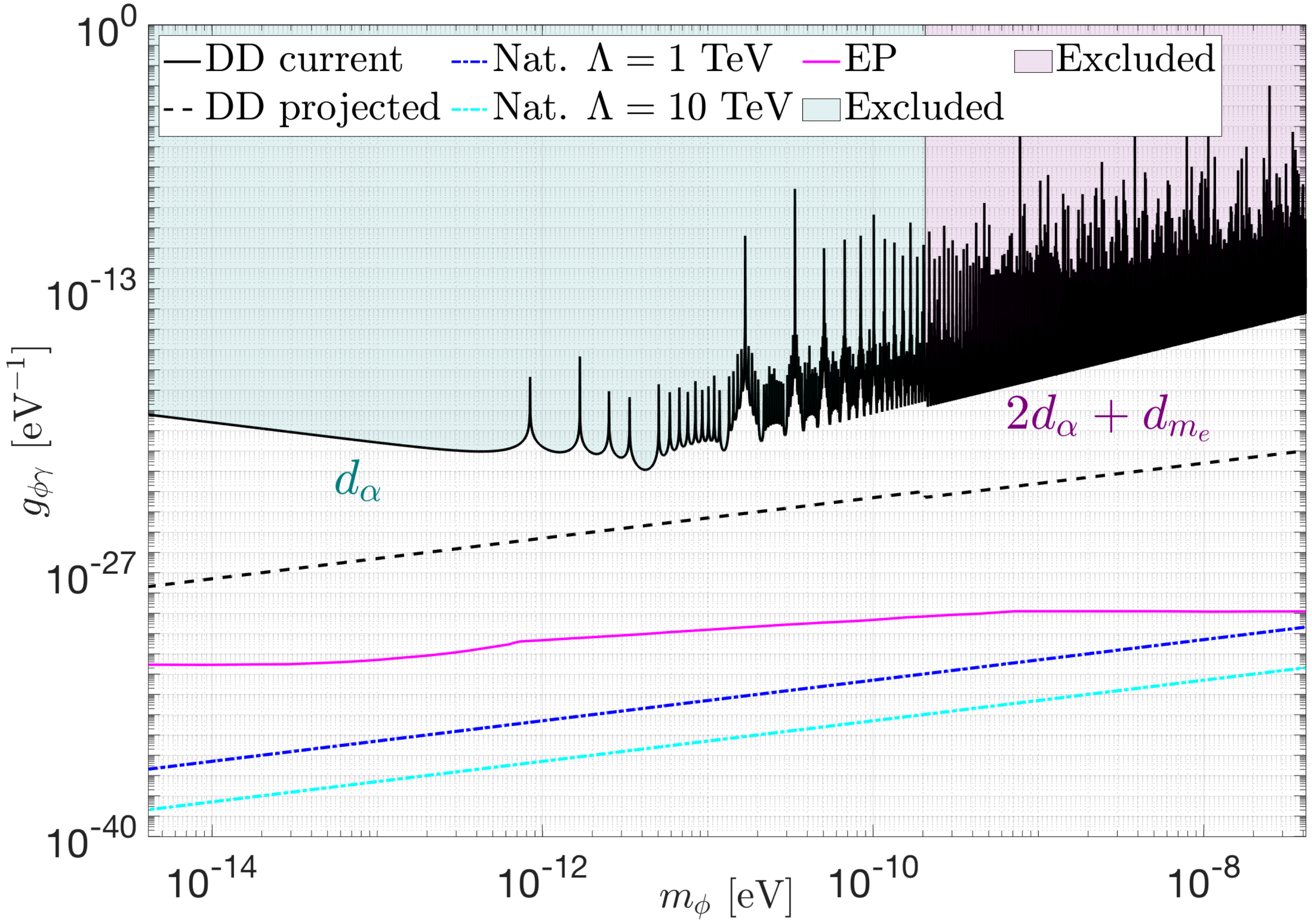

First model independent bounds on variations of $\alpha\,, m_e$ up to MHz frequencies.

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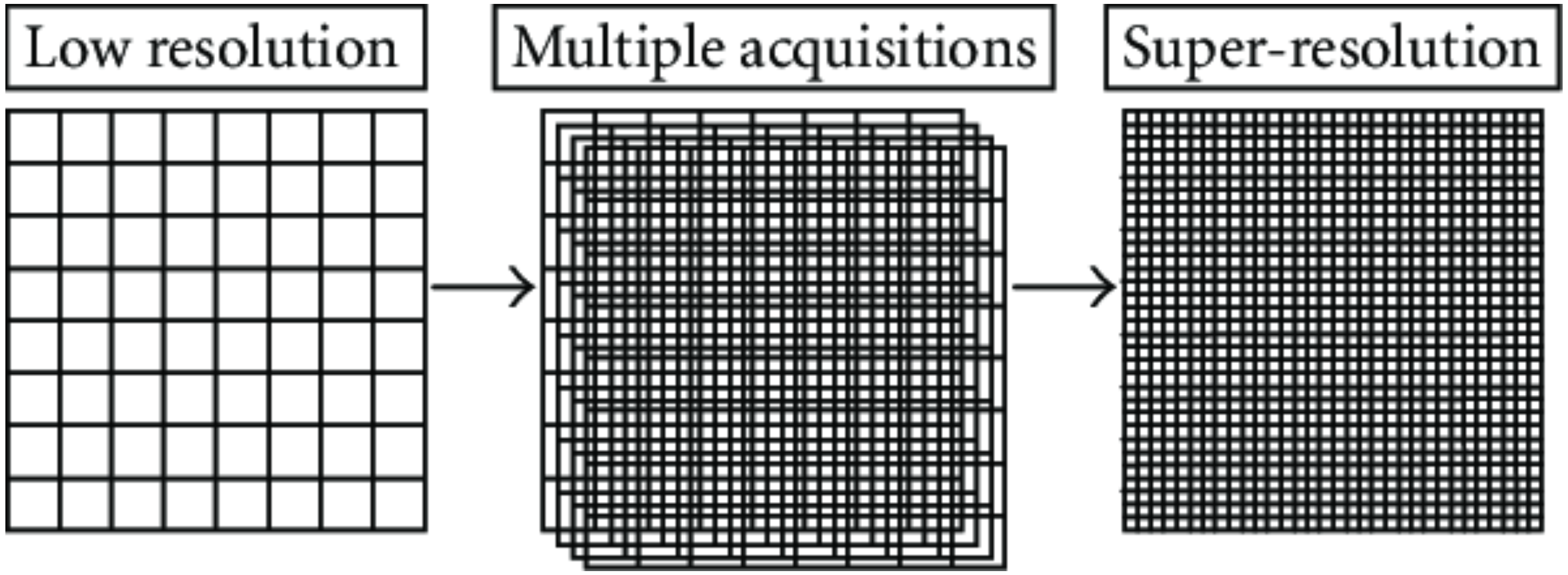
CAN WE DO BETTER?

- DD - resonance search, requires scanning over modulation frequency.
- Can we apply super-resolution/sub-Nyquist sampling techniques to enhance the detectability of rapidly oscillating DM?



CAN WE USE SUPER-RESOLUTION/ SUB-NYQUIST SAMPLING?

- Open questions for discussion:
  - Can we use super-resolution techniques to enhance the detectability of rapidly oscillating DM signals?
    - Single probe - different sampling method?
    - Many probes - sub-pixel shifts?
  - Are there better techniques to search for a sinusoidal signal with unknown frequency?
  - What are the experimental factors limiting the sensitivity of super-resolution techniques?

THANK YOU!

BACKUP SLIDES

ULTRALIGHT SCALAR DARK MATTER

- Ultralight DM (m<0.1 eV) - large occupation number in the galaxy

$$N = n \cdot \lambda_{dB}^3 = \frac{\rho_{DM}}{m^4 v^3} \approx \left(\frac{\rho_{DM}}{0.3GeV/cm^3}\right)\left(\frac{0.1eV}{m}\right)^4$$

- Can be described as a macroscopic classical field (much like a laser/BEC/superfluid)

$$\phi(t) = A\cos(m_\phi t)$$

- Energy density

$$\rho_{DM} = T_{00} \approx \frac{1}{2} m_\phi^2 A^2$$

- Ultralight scalar DM is the coherently oscillating as

$$\boxed{\langle \phi(t) \rangle \simeq \frac{\sqrt{2\rho_{DM}}}{m_\phi} \cos(m_\phi t)}$$

A. Khmelnitskya and V. Rubakov, 1309.5888

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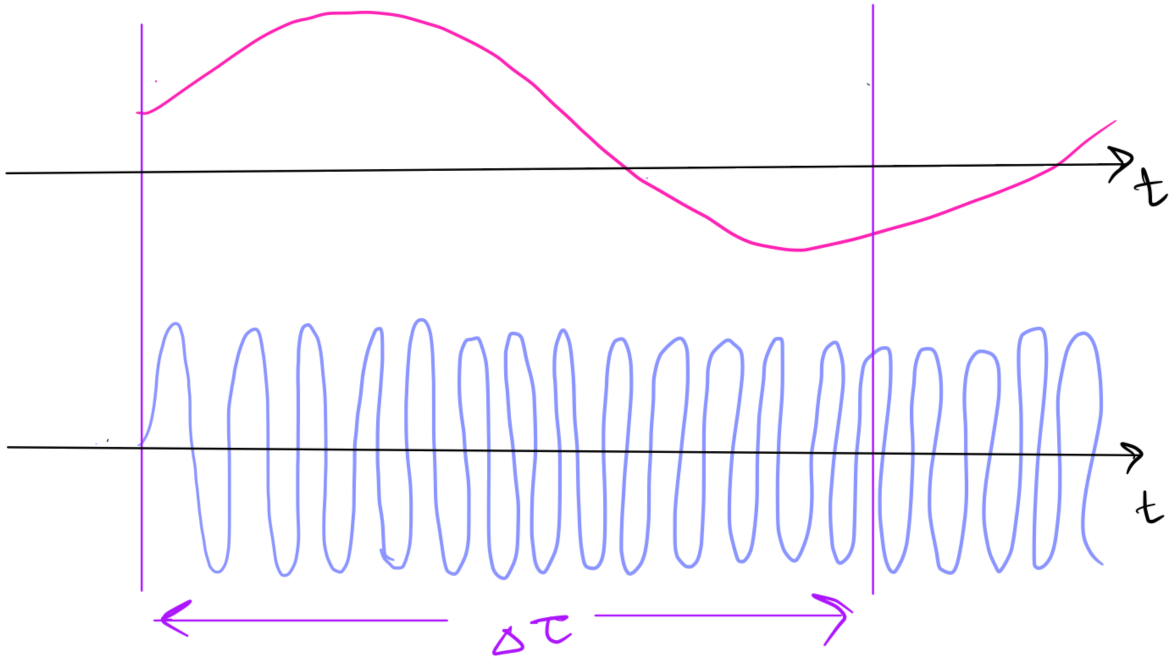
$$= \frac{g\sqrt{2\rho_{DM}}\Delta n_{A,B}}{m_\phi} sinc\left(\frac{m_\phi\Delta\tau}{2}\right)\sin\left(m_\phi t_n\right)$$

$additional\ \frac{1}{m_\phi}\ suppression$

$for\ m_\phi \gg \frac{2}{\Delta\tau}$



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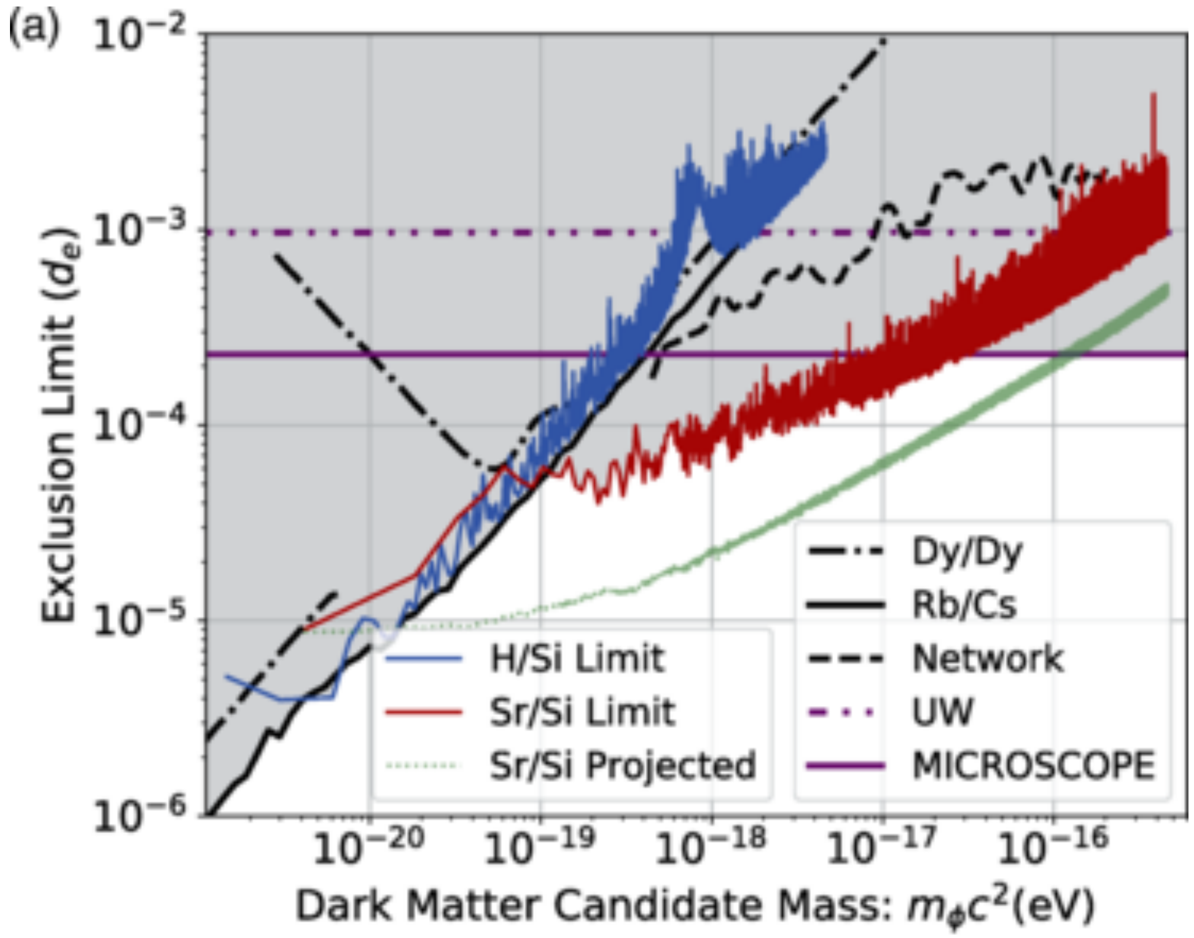
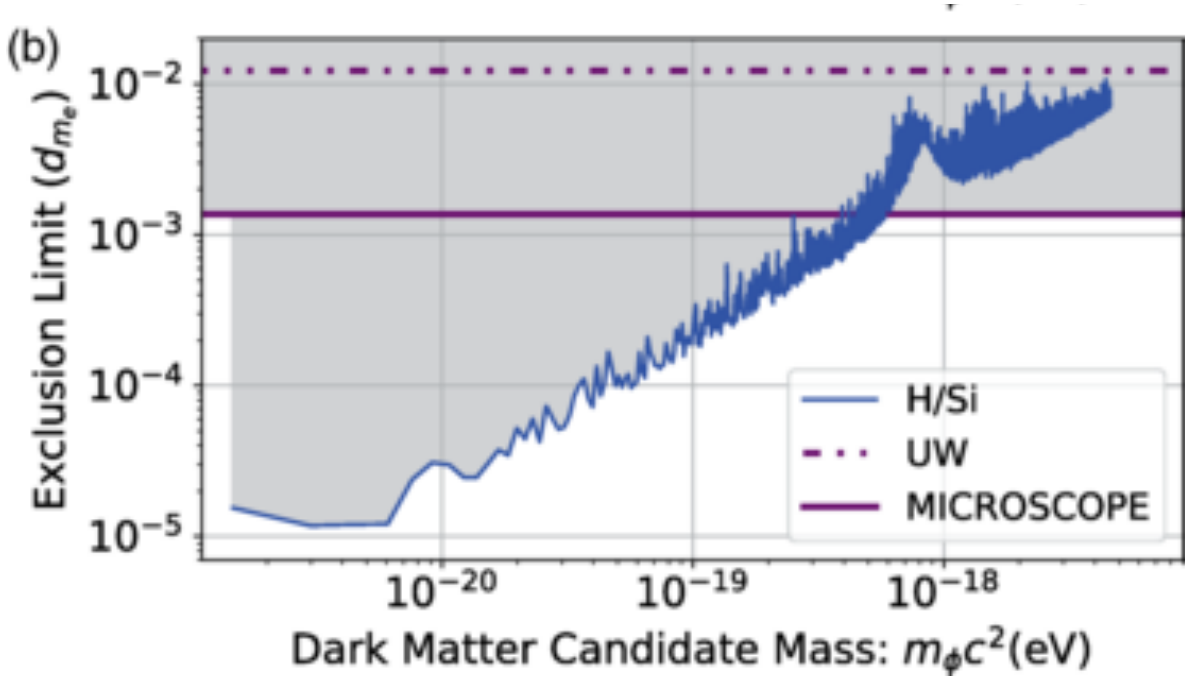
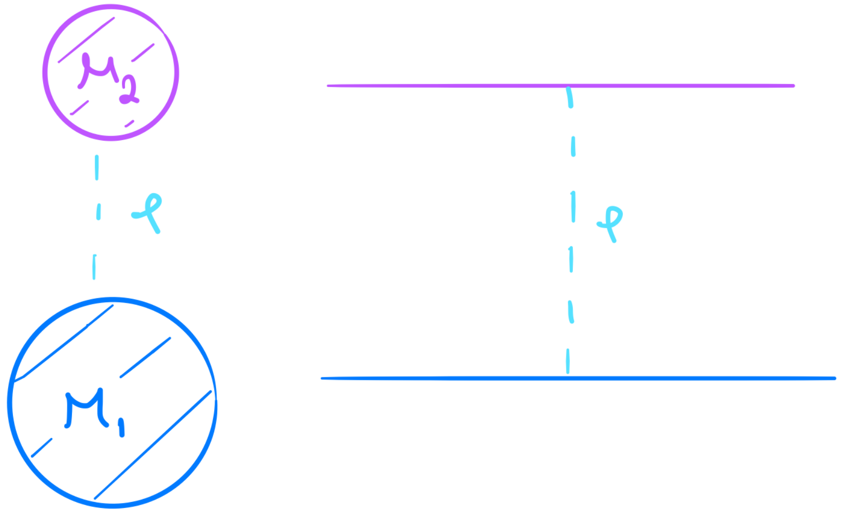




TESTS OF FIFTH-FORCE AND EP

- New scalar mediates a force (interaction) between neutral masses



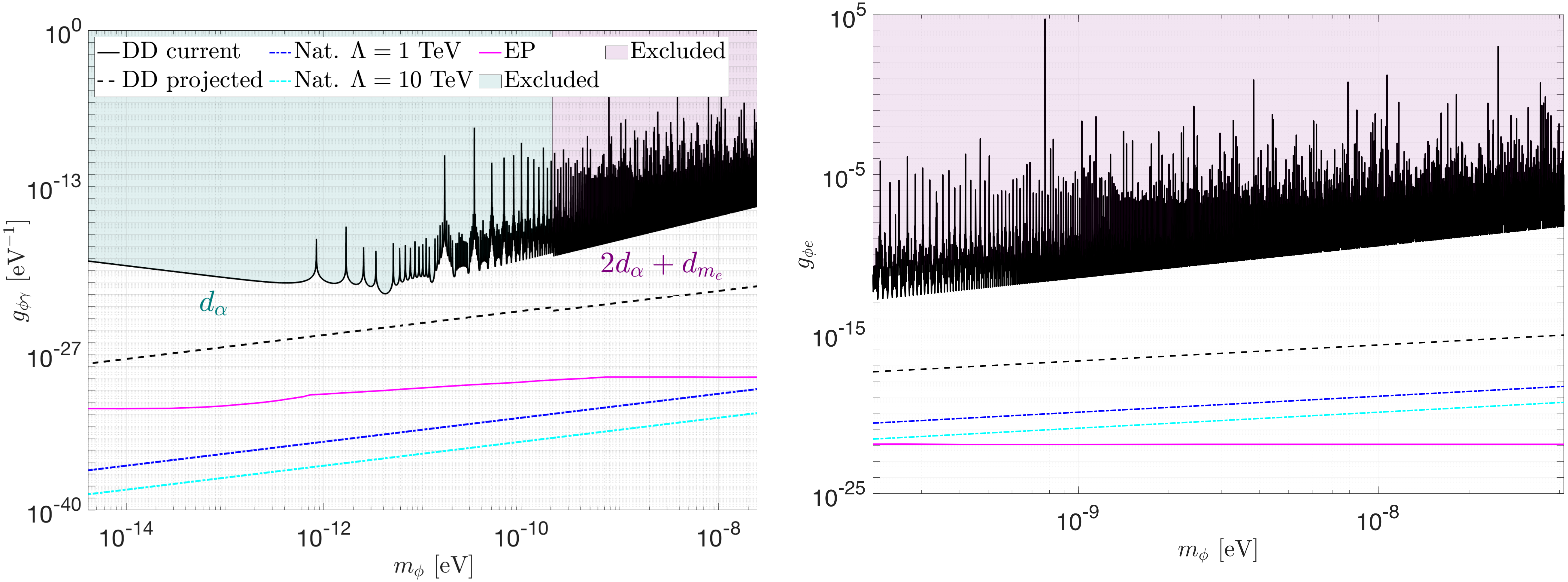
- **Searches for deviations from gravity**
  - massive force carrier - Yukawa potential

$$\boxed{V_\phi \propto \frac{e^{-m_\phi r}}{r}}$$

  - Non-universal couplings to masses of different compositions - **violation of the universality of free-fall** (Einstein's Equivalence Principle)

$$\boxed{\eta = \frac{a_A - a_B}{a_A + a_B} \propto \frac{1}{G}\left(g_{\phi e} Q^C_{m_e} + g_{\phi\gamma} Q^C_e\right)\left(g_{\phi e}\left(Q^A_{m_e} - Q^B_{m_e}\right) + g_{\phi\gamma}\left(Q^A_e - Q^B_e\right)\right)}$$

COMPARISON – FIFTH FORCE VS. FUND. CONSTANTS



QUADRATICALLY COUPLED DM

- Higher order interactions of the DM candidate with the SM

$$\mathscr{L} = g_{\phi^2 e}\phi^2 m_e \bar{e}e$$

- **Variations of** $\boldsymbol{m_e}$

$$\boxed{\frac{\delta m_e}{m_e} = g_{\phi^2 e}\frac{\rho_{DM}}{m_\phi^2}\cos(2m_\phi t)}$$

- **5F/EP -** gains DM density sensitivity, different r-dependance

$$\boxed{V(r) \propto \phi^2 \sim \frac{\rho_{DM}}{m_\phi^2}\left(1 - s_A\frac{GM_A}{r}\right)^2}$$

$$\boxed{\eta = \frac{a_A - a_B}{a_A + a_B} \propto \frac{\rho_{DM}}{Gm_\phi^2}\left(g_{\phi^2 e}Q^C_{m_e} + g_{\phi^2\gamma}Q^C_e\right)\left(g_{\phi^2 e}\left(Q^A_{m_e} - Q^B_{m_e}\right) + g_{\phi^2\gamma}\left(Q^A_e - Q^B_e\right)\right)}$$

A. Hees et al, 1807.04512

COMPARISON – QUADRATICALLY COUPLED DM