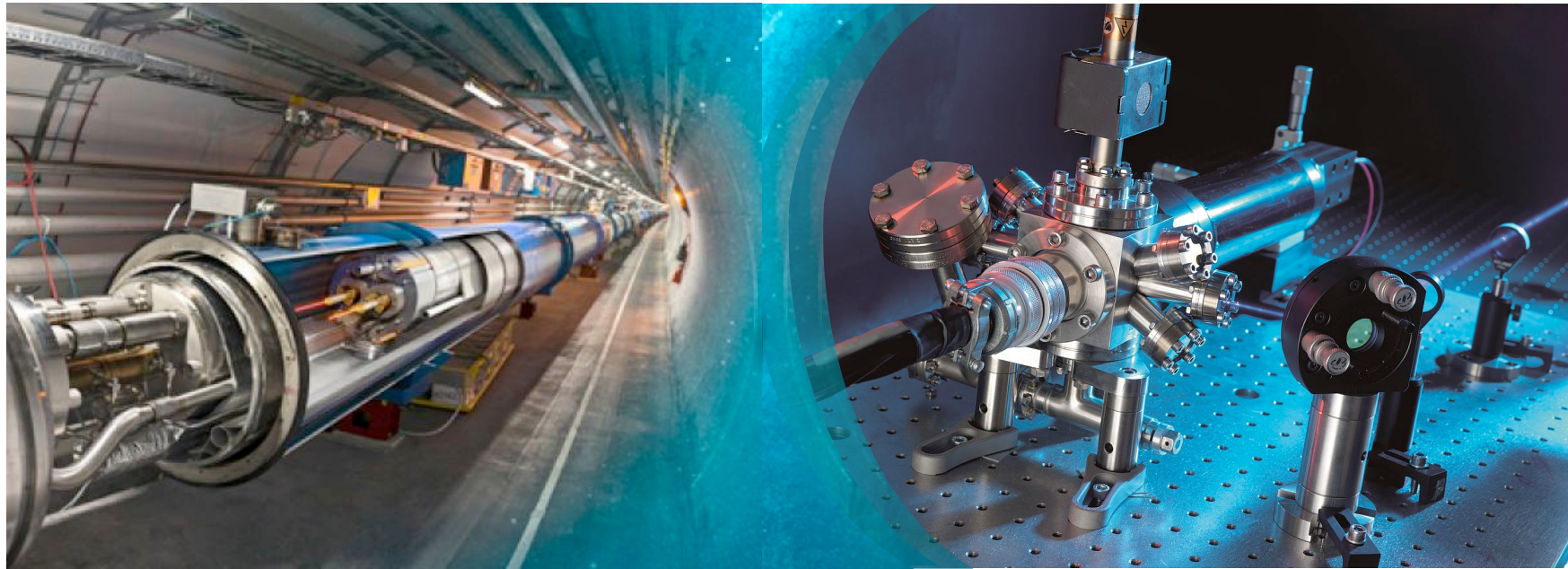


Nuclear Physics and ultralight dark matter



Sreemanti Chakraborti, FLF PDRA
Jonas Spinner, Feodor-Lynen PDRA

Alex Eberhart, STFC PhD
Ekrem Demiray, AM DIRAC fellow, PhD
Harry Graham, AM DIRAC fellow, PhD

Martin Bauer



Future
Leaders
Fellowships



Science & Technology
Facilities Council

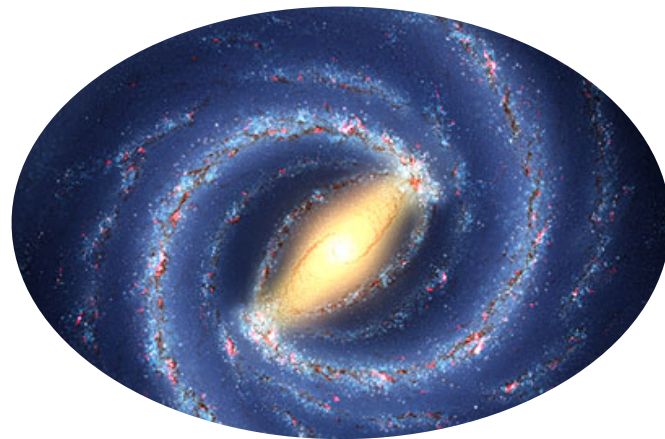


Durham
University

Dark Matter

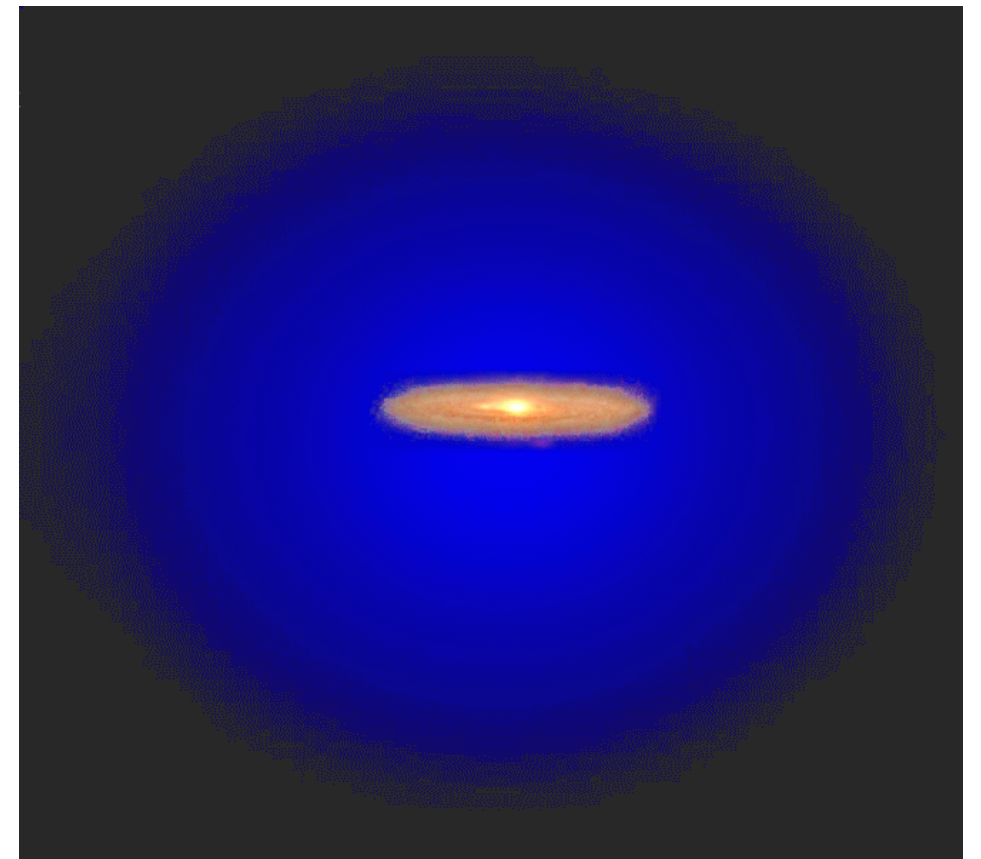
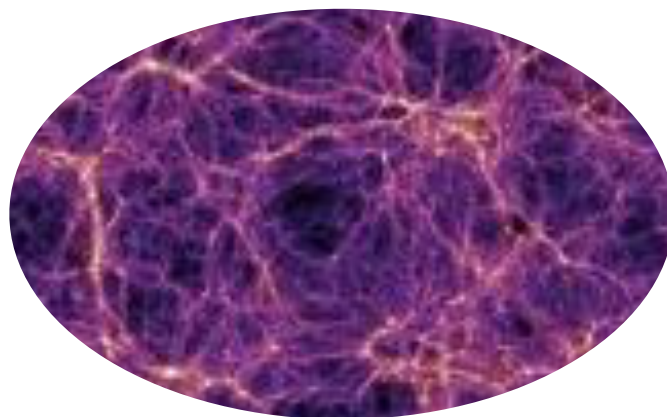
Evidence for dark matter appear at scales from the size of galaxies to the entire Universe

Rotation curves



Grav Lensing

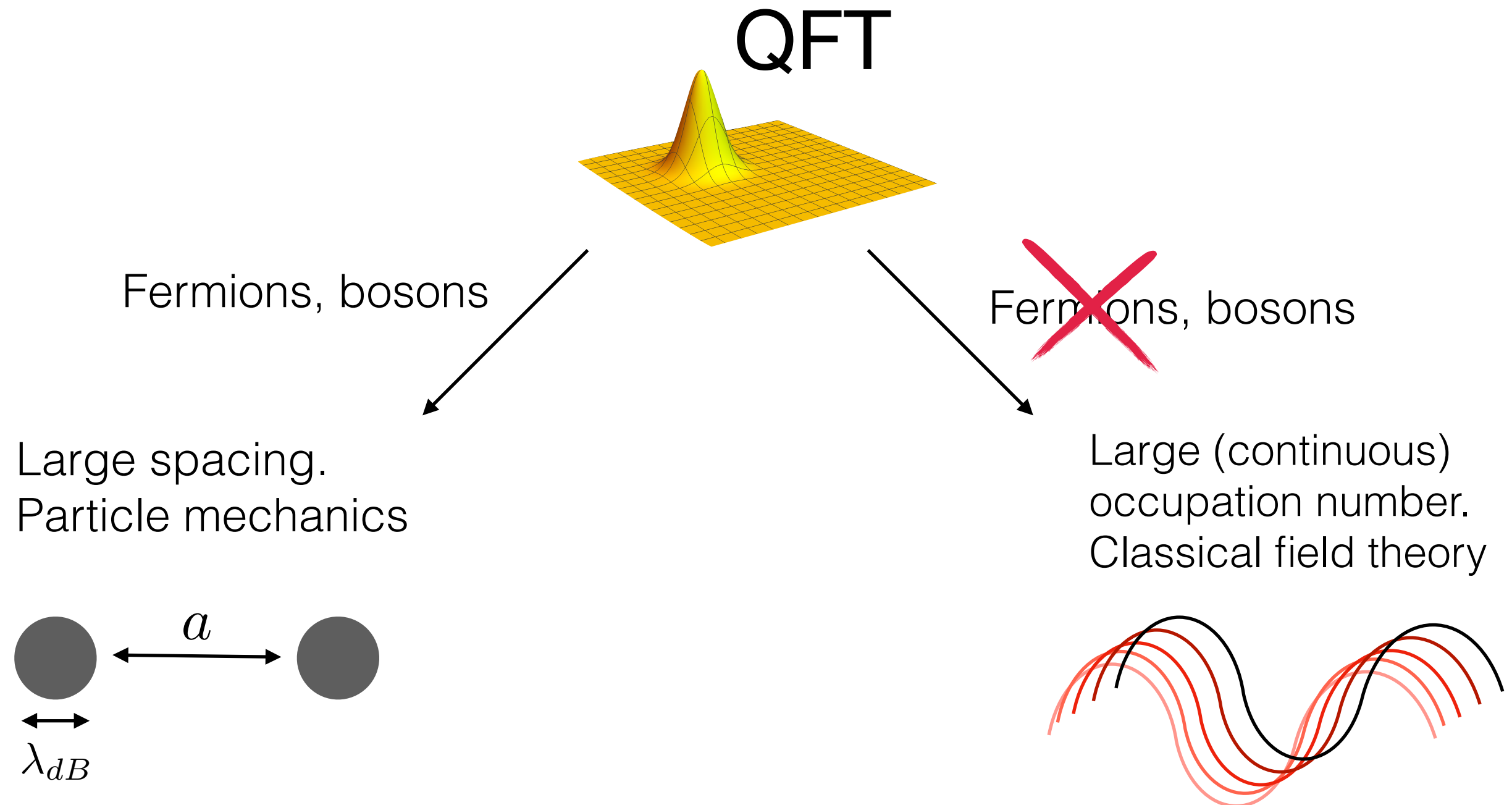
Large scale structure



We know where it is, but not what it is

Dark Matter

If dark matter is described by a quantum field theory, there are two different non-relativistic limits

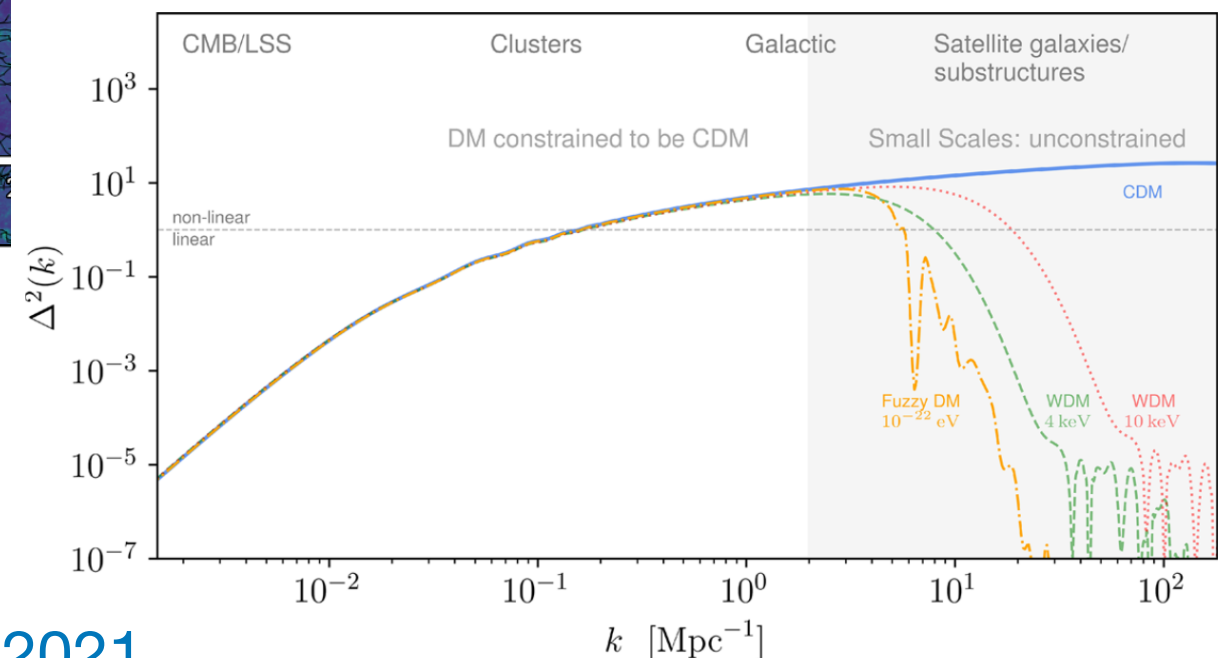
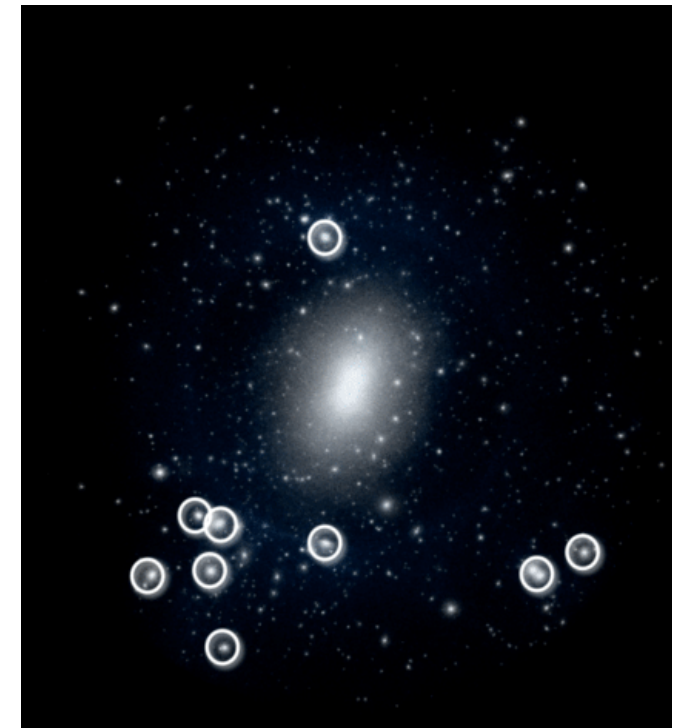
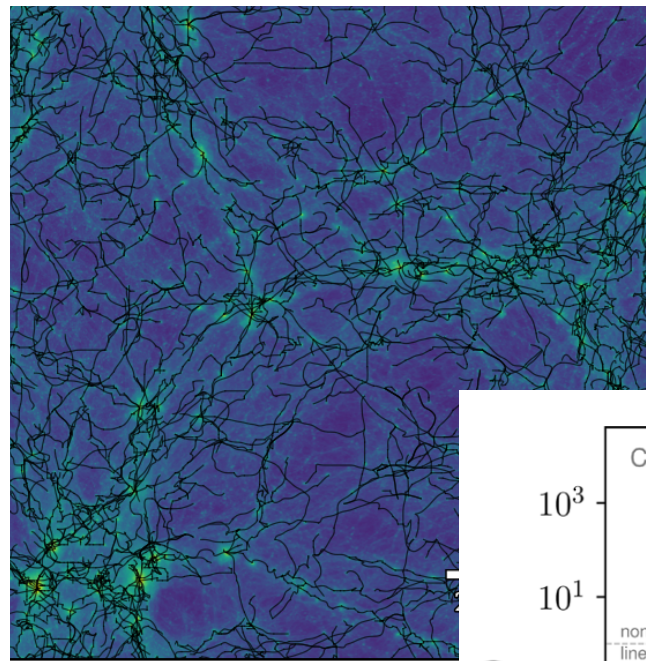
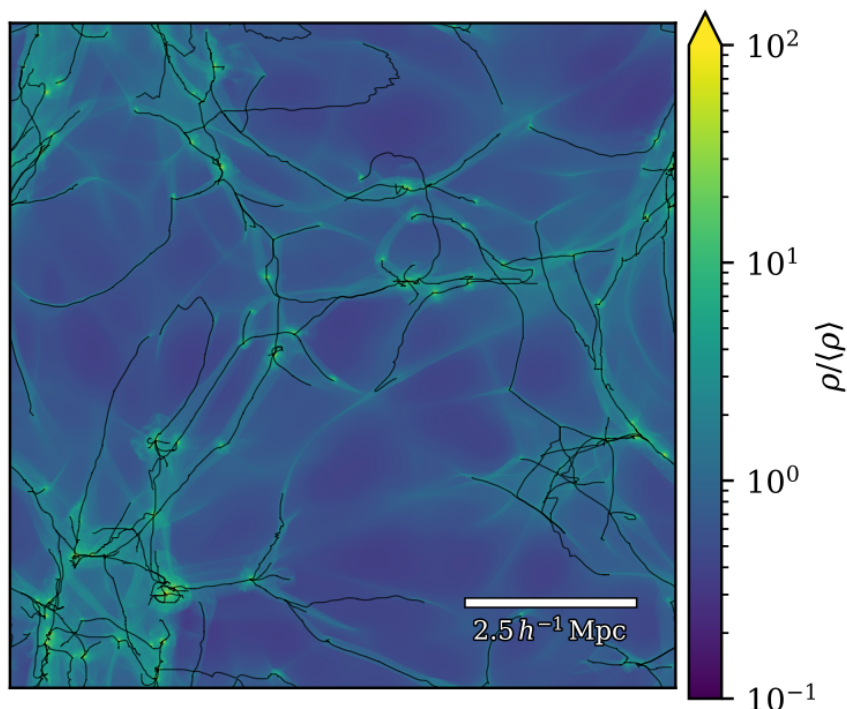


Nuclear Physics and ultralight dark matter

If dark matter is made from extremely light bosons, its best described by an oscillating wave

$$\phi(t) = \frac{\sqrt{2\rho_{\text{DM}}}}{m_\phi} \cos \omega t$$

There are interesting astrophysical implications



Nuclear Physics and ultralight dark matter

If dark matter is made from extremely light bosons,

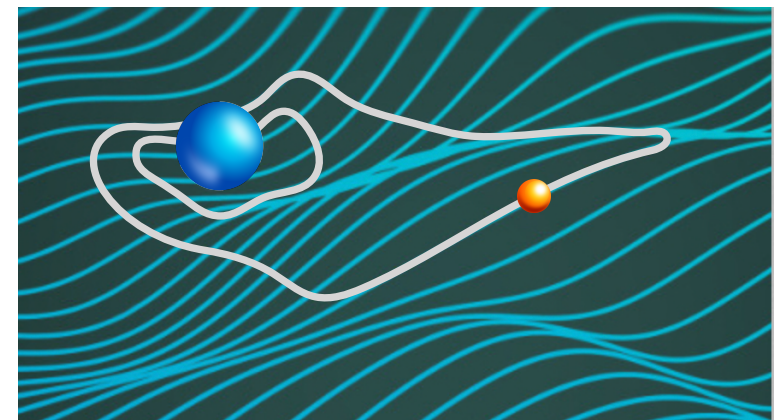
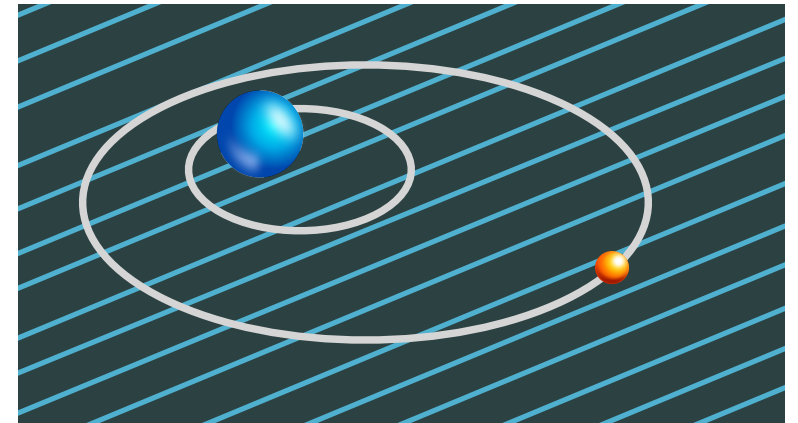
$$\phi(t) = \frac{\sqrt{2\rho_{\text{DM}}}}{m_\phi} \cos \omega t$$

and has tiny interactions with matter

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{\phi}{\Lambda} F_{\mu\nu} F^{\mu\nu} \\ &= -\frac{1}{e^2} \frac{1}{1 + \phi/\Lambda} F_{\mu\nu} F^{\mu\nu} + \mathcal{O}(\phi^3/\Lambda^3) \end{aligned}$$

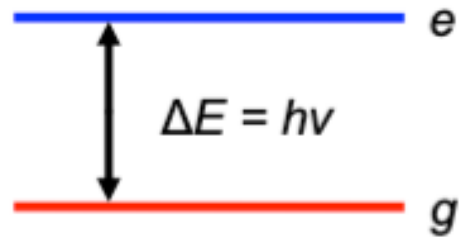
it induces oscillating fundamental constants

$$\alpha^{\text{eff}} = \alpha(1 + \phi(t)/\Lambda)$$

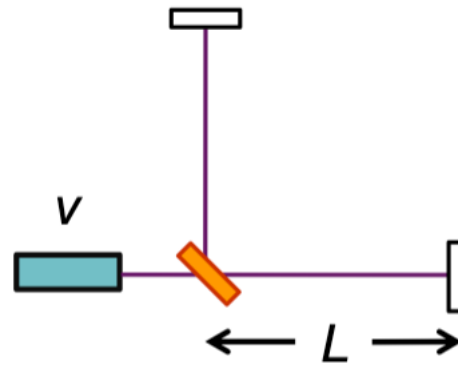


Nuclear Physics and ultralight dark matter

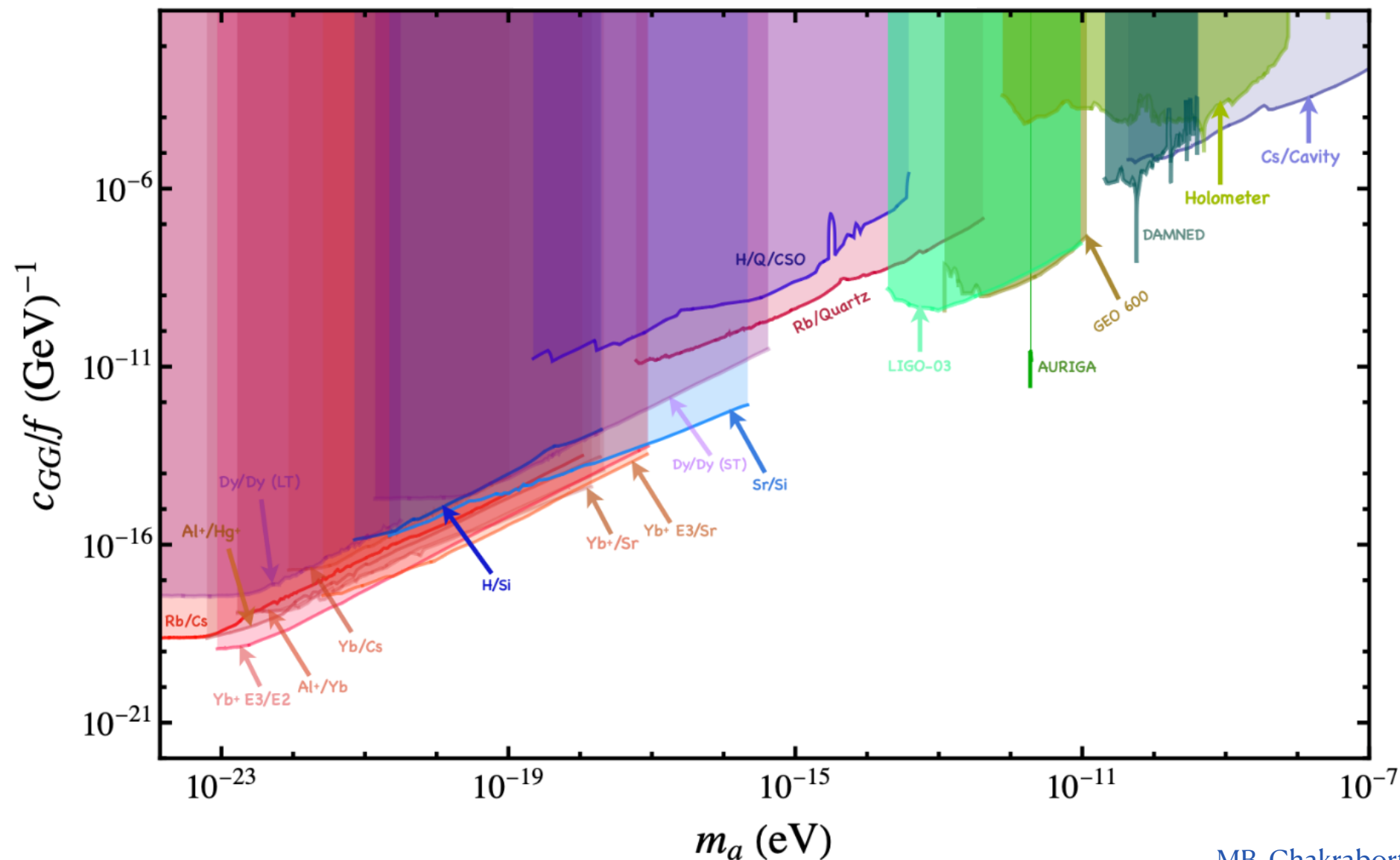
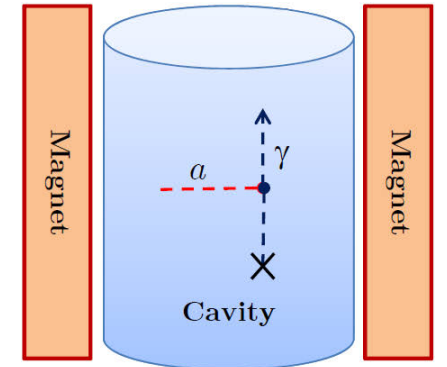
Atomic clocks



Laser interferometers

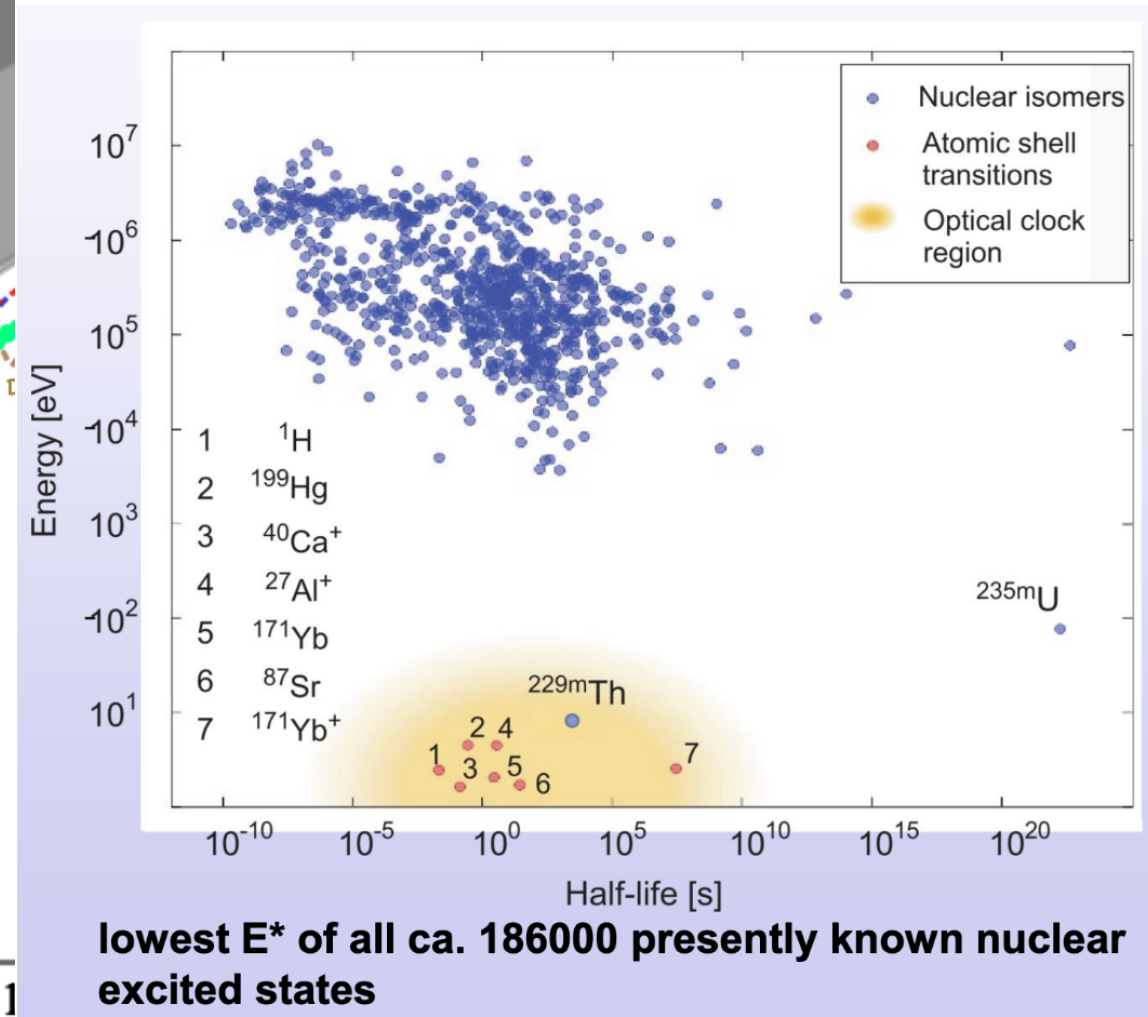
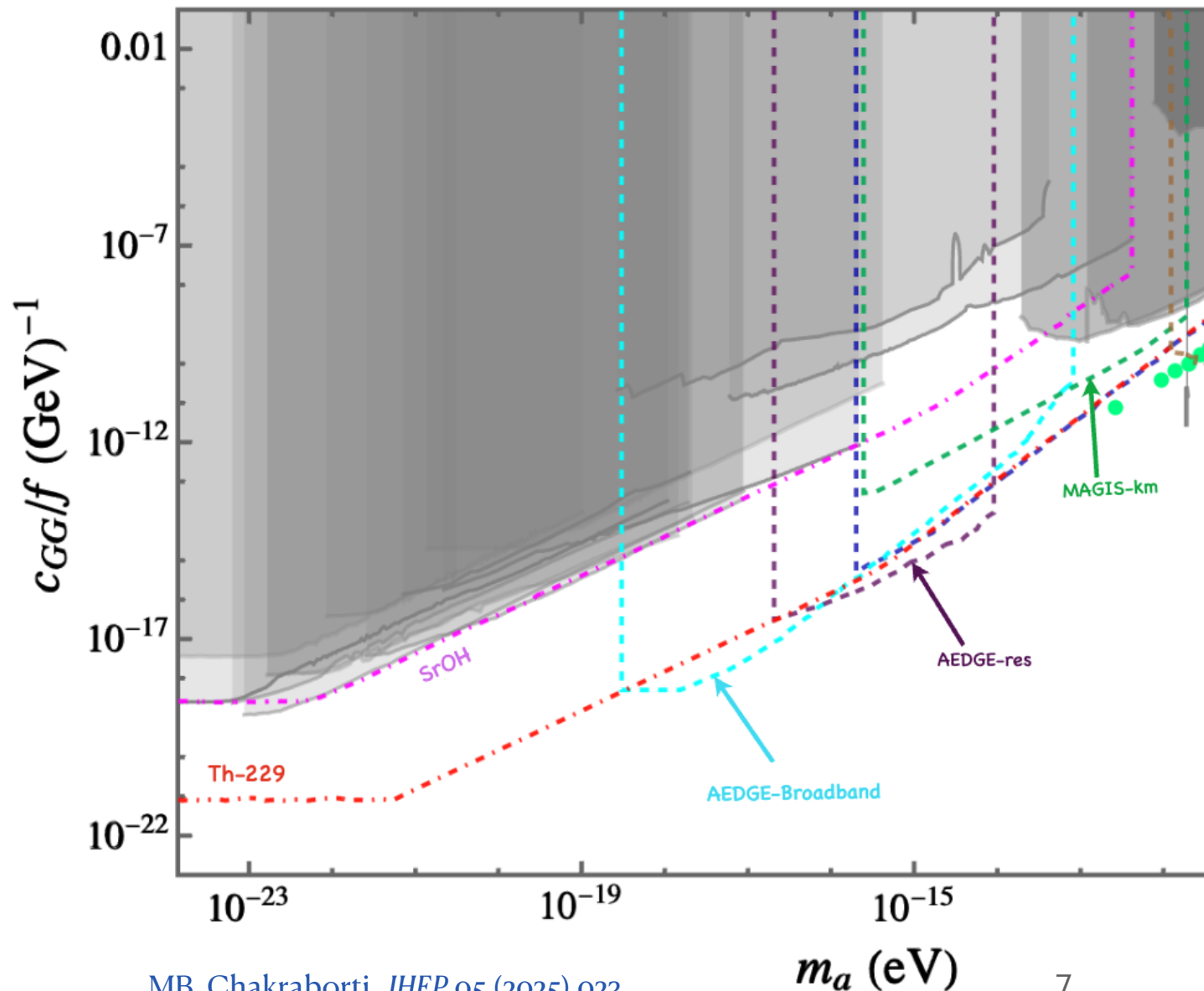
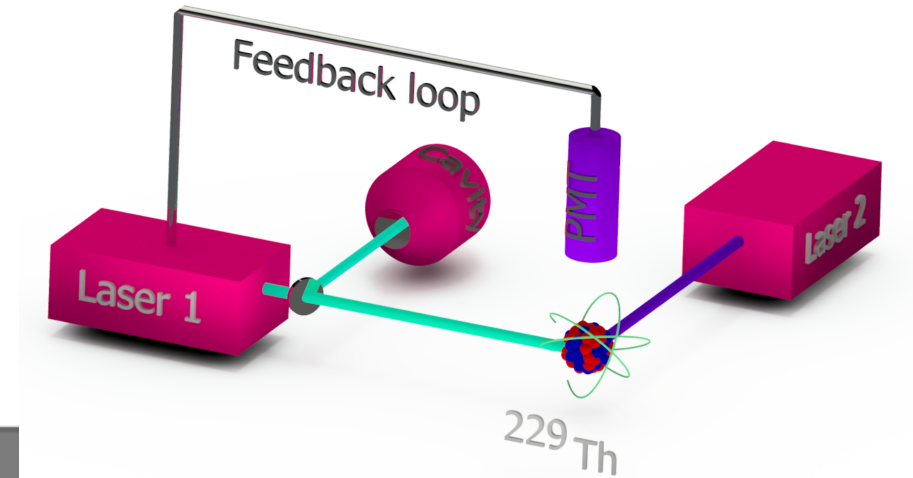


Cavities



Nuclear Physics and ultralight dark matter

A future nuclear clock could increase the sensitivity significantly



Nuclear Physics and ultralight dark matter

Atomic clocks set very strong bounds, but a ^{229}Th clock has the potential to be even better

$$\Delta E_{is} = \Delta E_{\text{QCD}} - \Delta E_{\text{EM}}$$

A variation in alpha induces a frequency shift

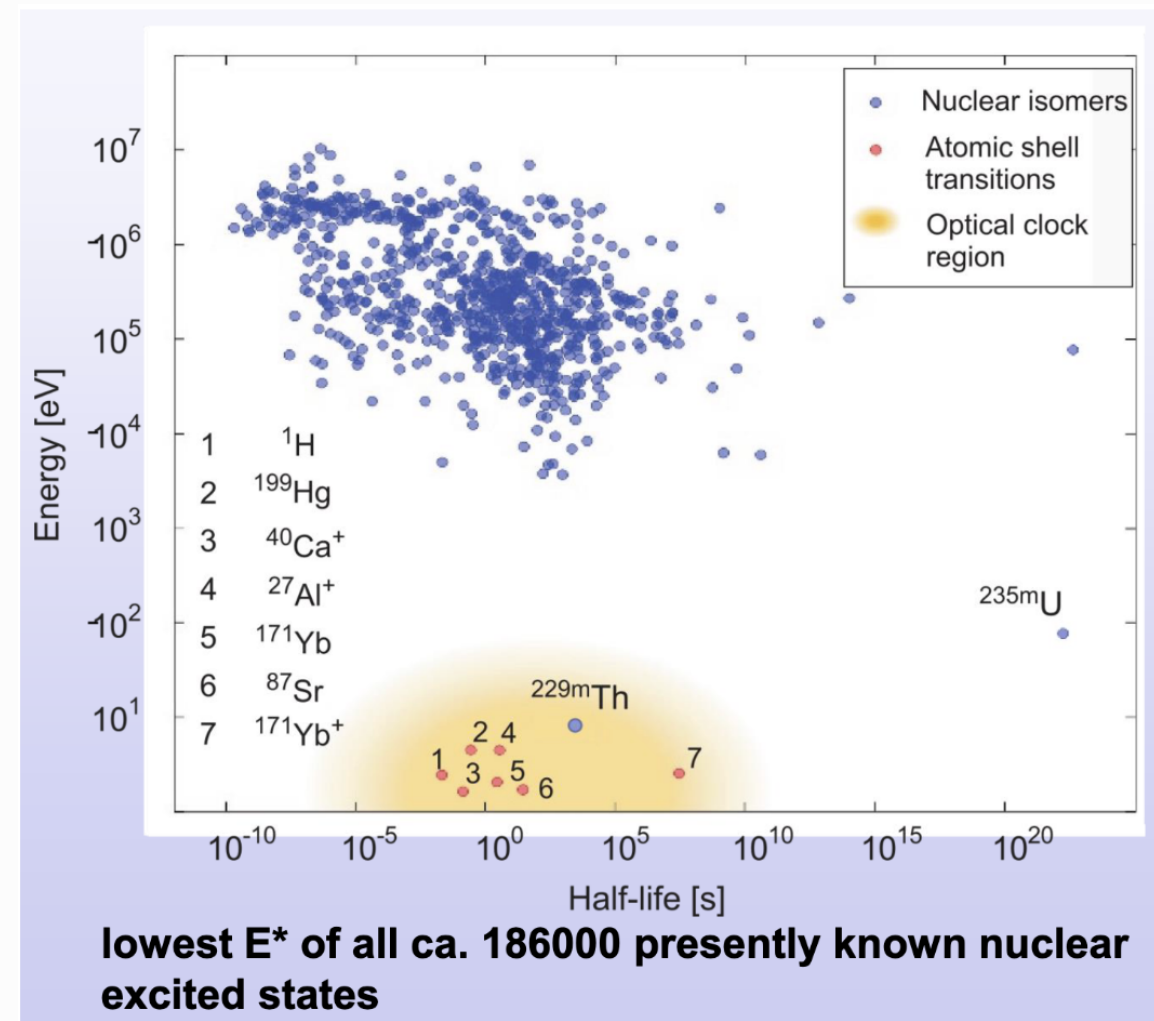
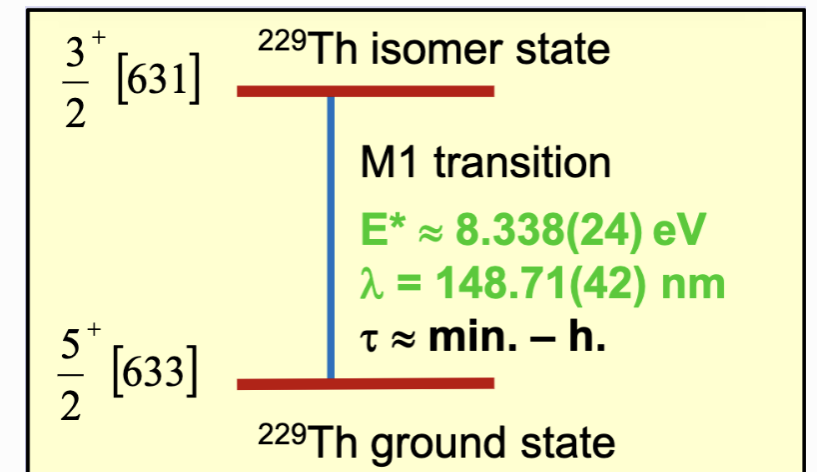
$$\frac{\delta\nu}{\nu} \approx K_\alpha \frac{\delta\alpha}{\alpha}$$

enhanced by $\delta(\Delta E_{\text{EM}}) = \Delta E_{\text{EM}} \frac{\delta\alpha}{\alpha}$

so that

$$K_\alpha = \frac{\partial \ln \Delta E_{is}}{\partial \ln \alpha} \approx -\frac{\Delta E_{\text{EM}}}{\Delta E_{is}} \sim 10^5$$

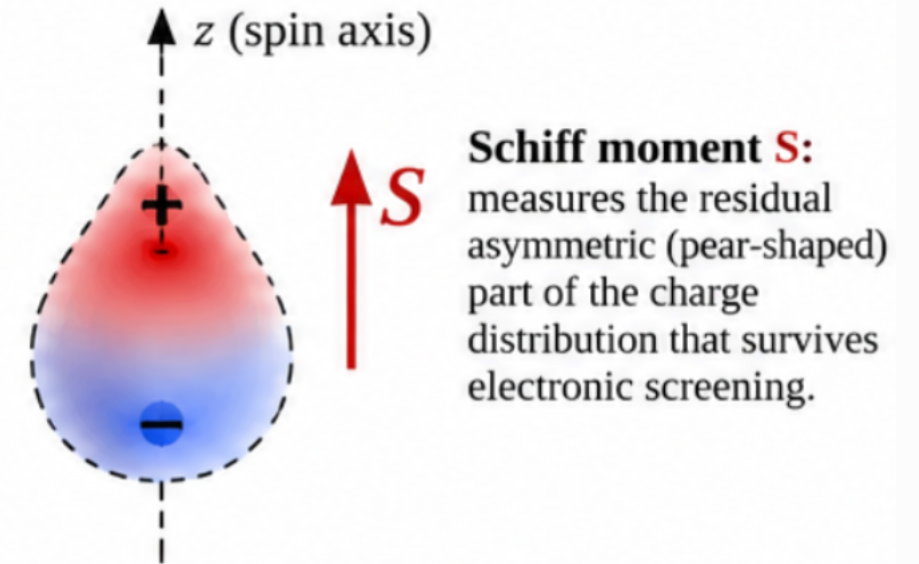
requires calculation of ΔE_{EM} (or ΔE_{QCD})



Nuclear Physics and ultralight dark matter

Fifth force searches are sensitive to nuclear structure, especially when the

$$\mathbf{S} = \frac{1}{10} \int d^3r \rho(\mathbf{r}) \left[r^2 \mathbf{r} - \frac{5}{3} \langle r^2 \rangle \mathbf{r} \right]$$



An oscillating P-violating dark matter field induces oscillating el. dipole moments

$$d_{\text{atom}} = k_S \mathbf{S}, \quad \text{e.g. axions}$$

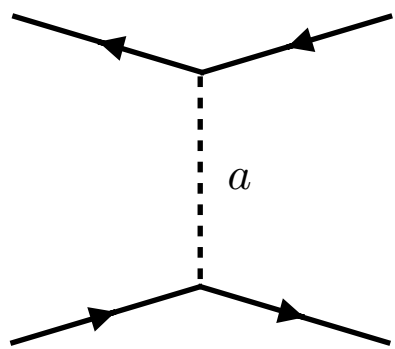
$$\mathcal{L} = \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{m_a^2}{2} a^2 + c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Requires nuclear wavefunctions

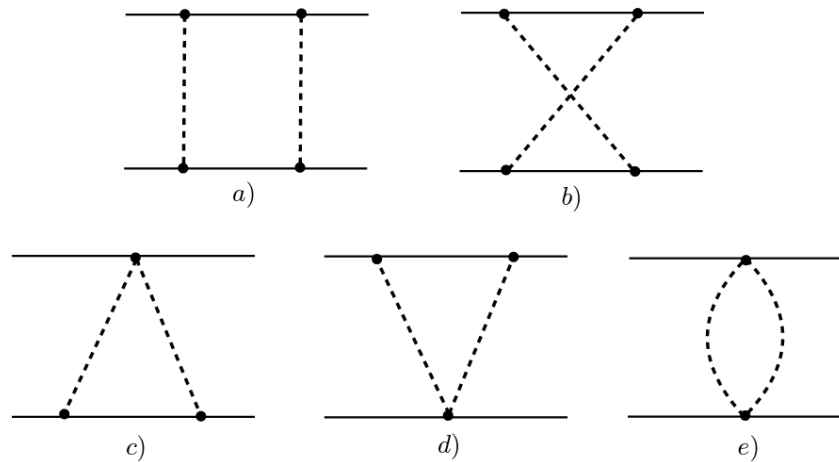
$$S \simeq 2 \sum_n \frac{\langle 0 | \hat{S} | n \rangle \langle n | V_{PT} | 0 \rangle}{E_0 - E_n}.$$

Nuclear Physics and ultralight dark matter

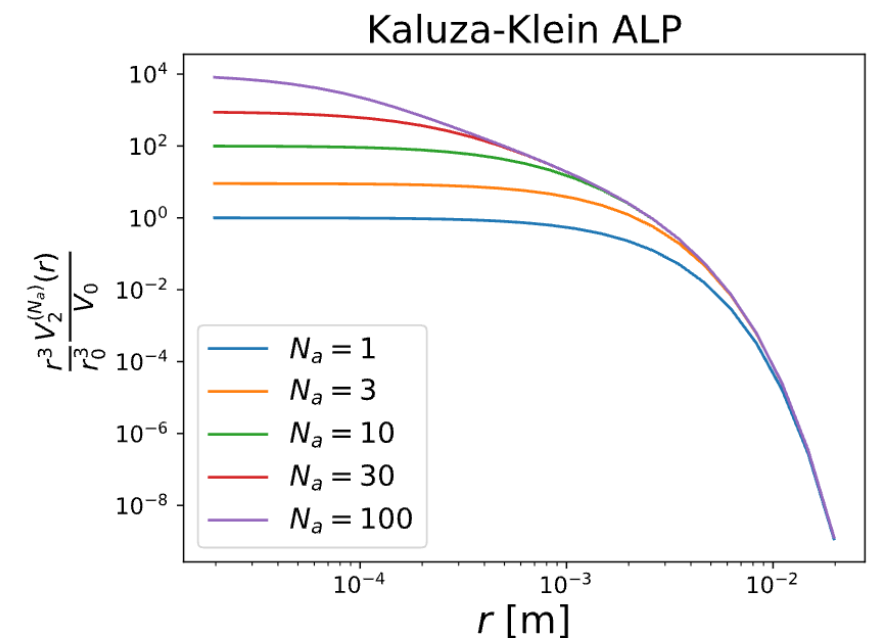
Fifth force searches are sensitive to nuclear structure, especially when pair exchange of new particles induce very singular potentials



$$V(r) \propto \frac{1}{r} e^{-mr}$$



$$V(r) \propto \frac{1}{r^3} e^{-mr}$$



MB, Chada-Day, Eberhart, 2606.06606

Requires accurate proton and neutron density profiles inside the nucleus

$$\Delta E = \int d^3 r_e d^3 r_N |\psi_e(\mathbf{r}_e)|^2 \rho_N(\mathbf{r}_N) V_{eN}(|\mathbf{r}_e - \mathbf{r}_N|)$$

Nuclear Physics and ultralight dark matter

The understanding of nuclear structure underlies many (most) current and future directions in searches for ultralight dark matter, e.g.

- Nuclear clocks
- Schiff moment measurements
- Fifth forces