KING'S College LONDON

Light dark matter @ atomic clocks and co-magnetometers

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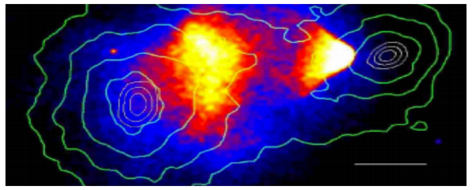
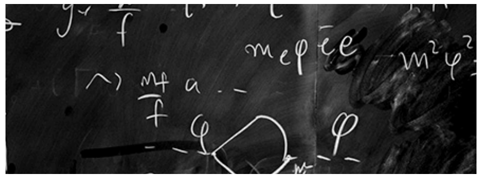
1810.00889 & 1810.01632

To-be-detected astrophysical backgrounds

Cosmic neutrinos (SM)



Dark matter (BSM)



Gravitational waves (SM + BSM)

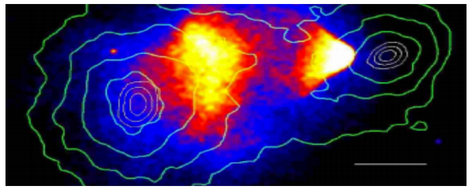
To-be-detected astrophysical backgrounds

Cosmic neutrinos (SM)

Produced at the Big Bang, $T \sim \mathrm{MeV}$ ($T_{CMB} \sim 0.1\,\mathrm{eV}$)

$$0.06\,\mathrm{eV} < \sum_i m_{\nu_i} < 0.2\,\mathrm{eV} \qquad T_{today} \sim 10^{-4}\,\mathrm{eV}$$

$10^{12}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ but *weakly interacting* and *low momentum*



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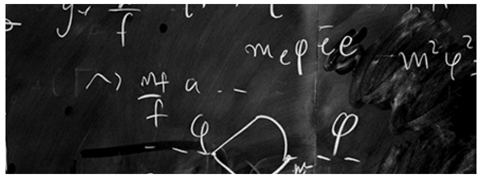

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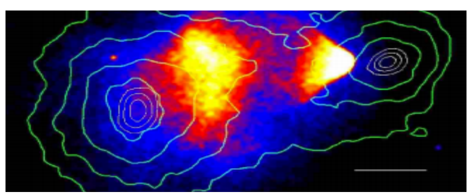


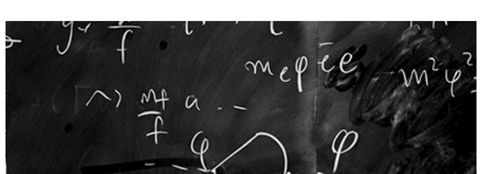
Dark matter (BSM)

Required by multiple observations but no detection in the lab

a new boson? $10^{-21}\,\mathrm{eV} < m_\chi < \Lambda\,(\mathrm{e.g.}\ 10^2\,\mathrm{GeV})$

$10^{10}\left(\frac{\mathrm{MeV}}{m_\chi}\right)\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ *weakly interacting* and

$m_\chi \langle v_\odot \rangle \sim 10^{-3} m_\chi c$ *too low* for nuclear recoils if $m_\chi \lesssim \mathrm{MeV}$



Gravitational waves (SM + BSM)

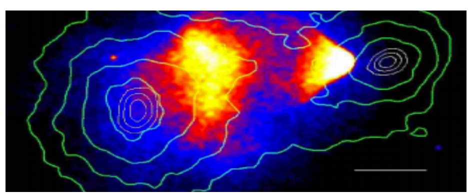
To-be-detected astrophysical backgrounds

Cosmic neutrinos (SM)

Produc… …ang, $T \sim \text{MeV}$ ($T_{CMB} \sim 0.1\,\text{eV}$)

$0.06\,\text{eV} < \sum_i$ … $T_{today} \sim 10^{-4}\,\text{eV}$

$10^{12}\,\text{cm}^{-2}\text{s}^{-1}$ bu… …ing and *low momentum*



Dark m…

Required by multiple observation… …in the lab

a new boson? $10^{-21}\,\text{eV} < m_\chi$ … $^2\,\text{GeV})$

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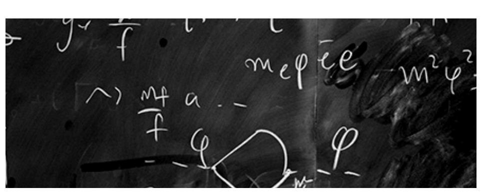
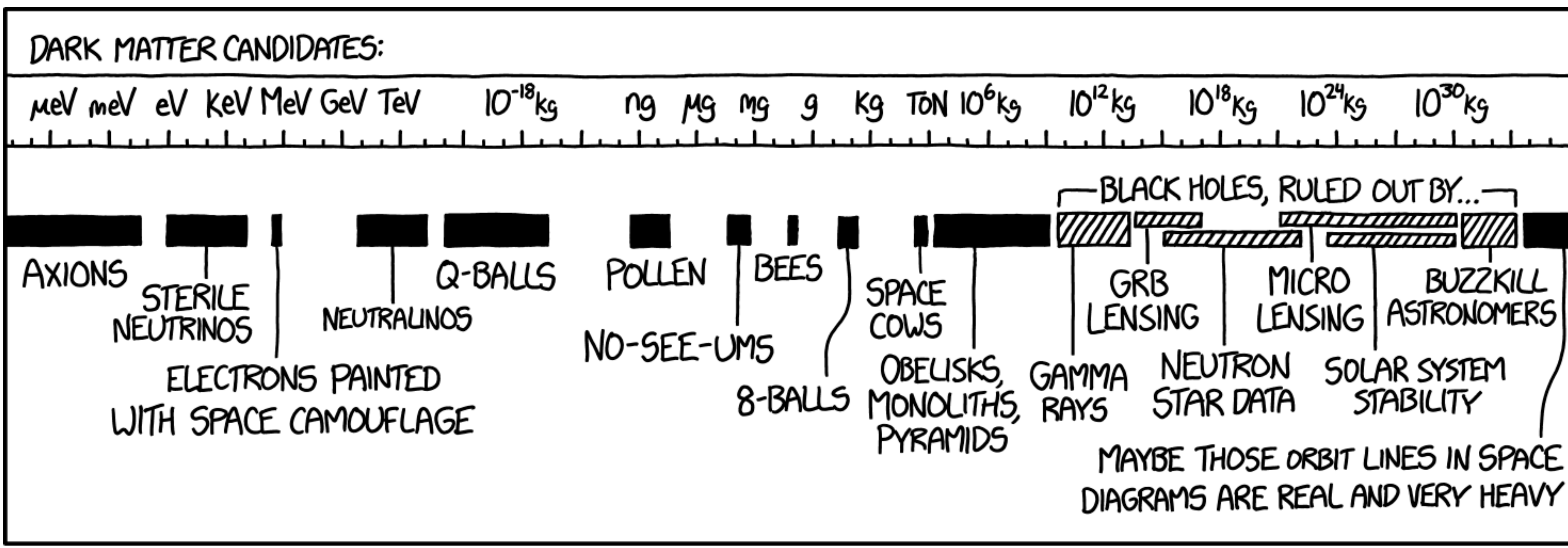


Gravitational waves (SM + BSM)

Perfect cases for precise devices

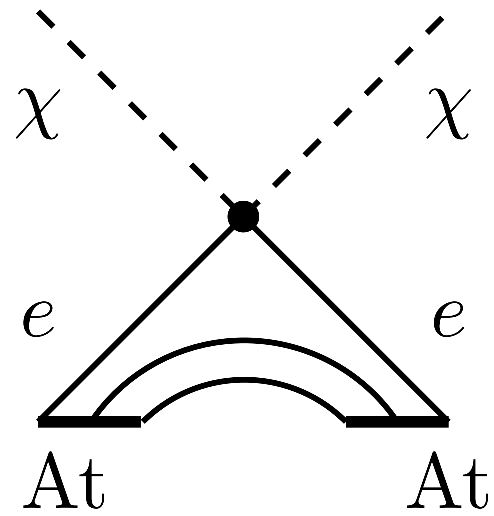
Dark matter: theory landscape

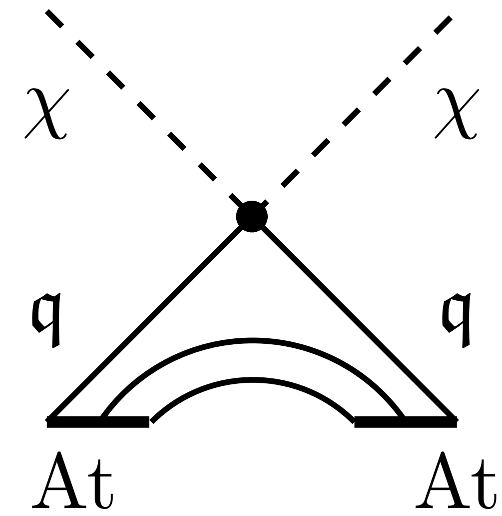
- ☑ Production mechanism in the early universe
- ☑ Motivation from fundamental physics
- ☑ Possibility of (direct or indirect) detection



@xkcd

DM-atom scattering*





DM current

$$L_{\rm int} = -\int \mathrm{d}^3x \left(G_e^{\mathcal{I}} \bar{e}\, \Gamma^{\mathcal{I}} e\, \mathcal{J}_\chi^{\mathcal{I}} + \sum_{\mathfrak{q}=u,d} G_{\mathfrak{q}}^{\mathcal{I}} \bar{\mathfrak{q}}\, \Gamma^{\mathcal{I}} \mathfrak{q}\, \mathcal{J}_\chi^{\mathcal{I}} \right)$$

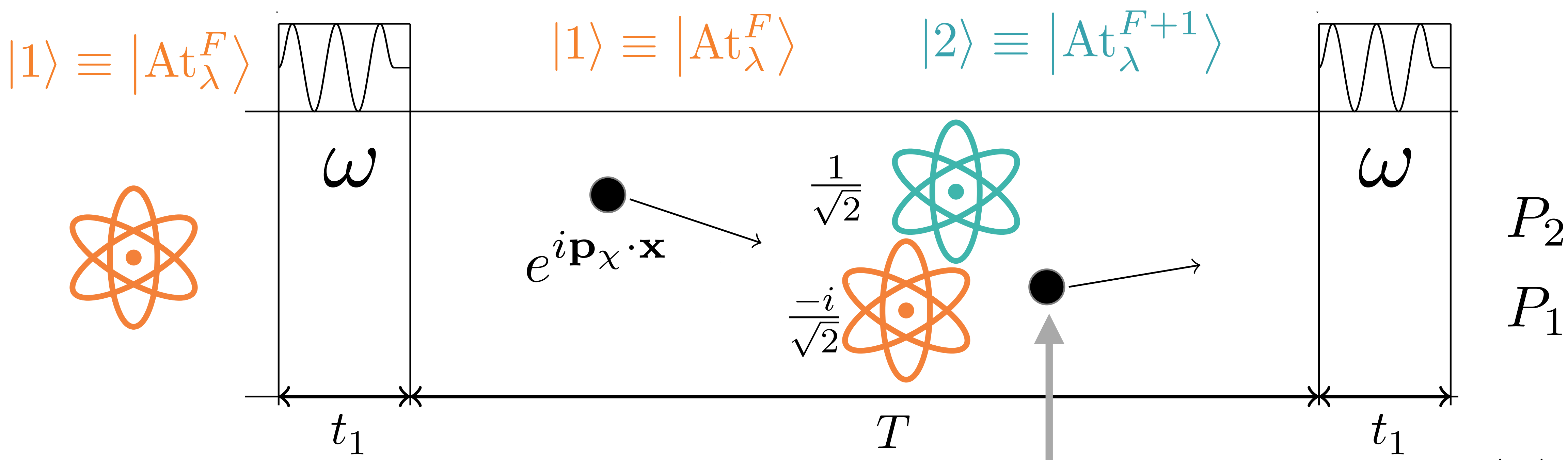
All possible interactions $\quad \vec{S}_e \cdot \vec{v}_\chi,\ \vec{S}_e \cdot \vec{S}_\chi, \ldots.$

$$\left|\mathrm{Rb}_\lambda^F\right\rangle = \sum_{\lambda_e, \lambda_I} \left|e_{\lambda_e}^{5s}\right\rangle \otimes \left|\mathrm{Ncl}_{\lambda_I}^I\right\rangle \langle 1/2,\, \lambda_e,\, I,\, \lambda_I\,|F,\, \lambda\rangle$$

$$\sum_{n,p} |N\rangle \quad + \quad \langle N|\bar{\mathfrak{q}}\, \Gamma^{\mathcal{I}} \mathfrak{q}|N\rangle$$ (known)

* see the papers for more possibilities

DM-atom interaction during Ramsey sequence



$$\Delta\omega \equiv \omega - (E_2 - E_1)$$

$$e^{i\mathbf{p}_\chi\cdot\mathbf{x}} + \frac{f_\mathrm{i}(p_\chi\hat{\mathbf{x}}\,,\,\mathbf{p}_\chi)e^{i\,p_\chi|\mathbf{x}|}}{|\mathbf{x}|}$$

L_int

for low masses (all the atoms stay in the clock) at first order

$$P_2 = \cos[\Delta\omega\,T/2]^2 + \frac{\pi n_\chi v\,T}{p_\chi}\mathrm{Re}[\bar{f}_1(0) - \bar{f}_2(0)]\sin[\Delta\omega T]$$

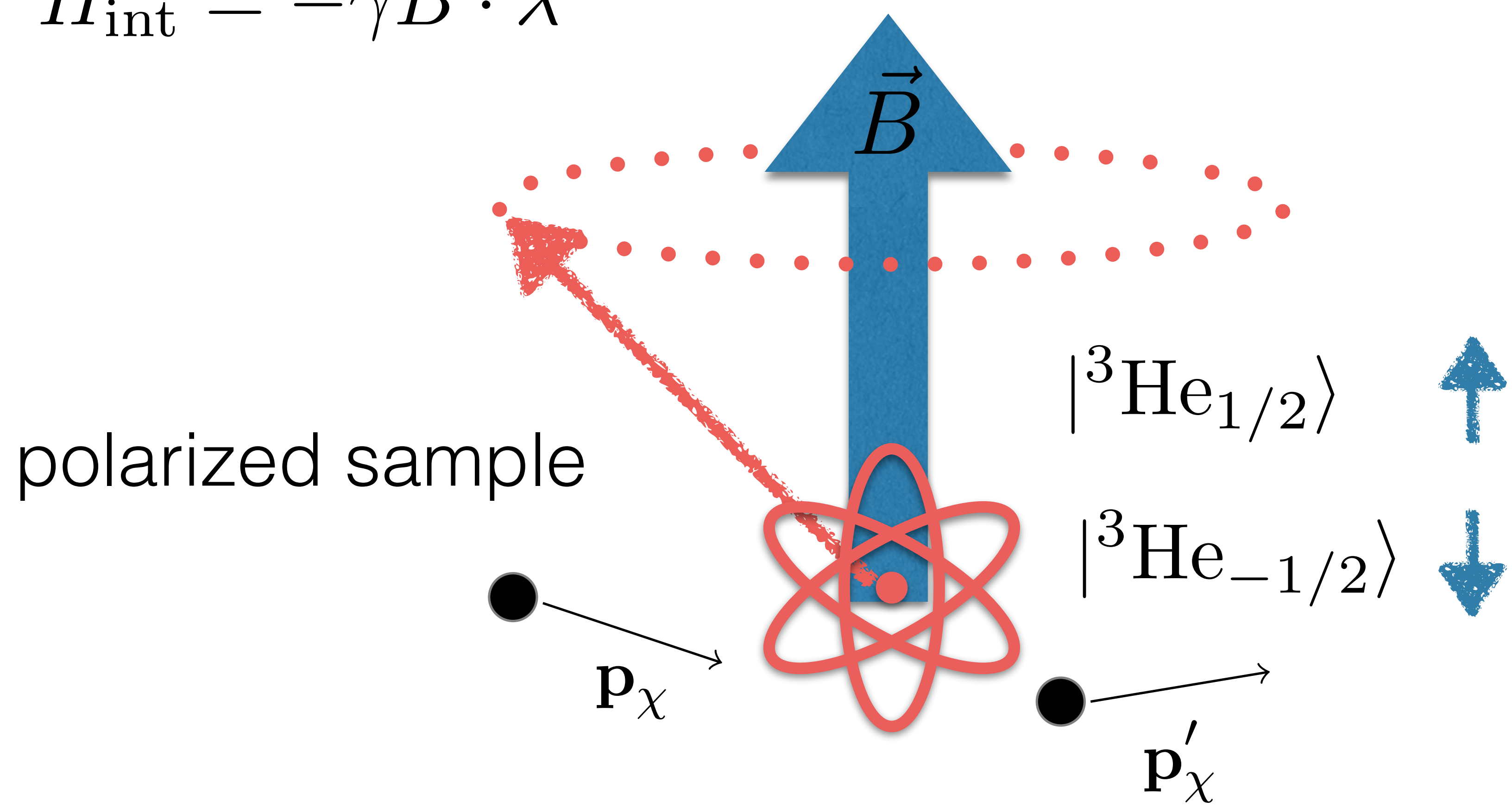
standard result

The states have different *spin*

$$\partial P_2 = 0 \;\Rightarrow\; \omega_\mathrm{max} = \Delta E + \delta_\mathrm{DM}$$

DM-atom interaction in co-magnetometers

$$H_{\text{int}} = -\gamma \vec{B} \cdot \vec{\lambda}$$



same with ^{129}Xe

$$\omega \equiv \gamma\beta = \gamma \left(B + \frac{2\pi n_\chi}{m_\chi \gamma} \left(\bar{f}(0)_1 - \bar{f}(0)_2 \right) \right)$$

Modified Larmor frequencies

Can be also understood as a phase difference

Co-magnetometer: eliminates *B*

DM-atom interactions: extra info

$$\bar{f}(0)_1 - \bar{f}(0)_2$$

The two states have different *spin*
We thus probe *spin-dependent interactions*

$$\vec{S}_e \cdot \vec{v}_\chi\,,\ \ \vec{S}_e \cdot \vec{S}_\chi\,,\ \ldots.$$

may contain a coherent part ($O(1)$ e.g. relative velocity)
or a non-coherent part ($O(1/\sqrt{N})$ e.g. DM spin)

The ultralight case ($m_\chi \lesssim 10\,\mathrm{eV}$, field description)
yields similar results

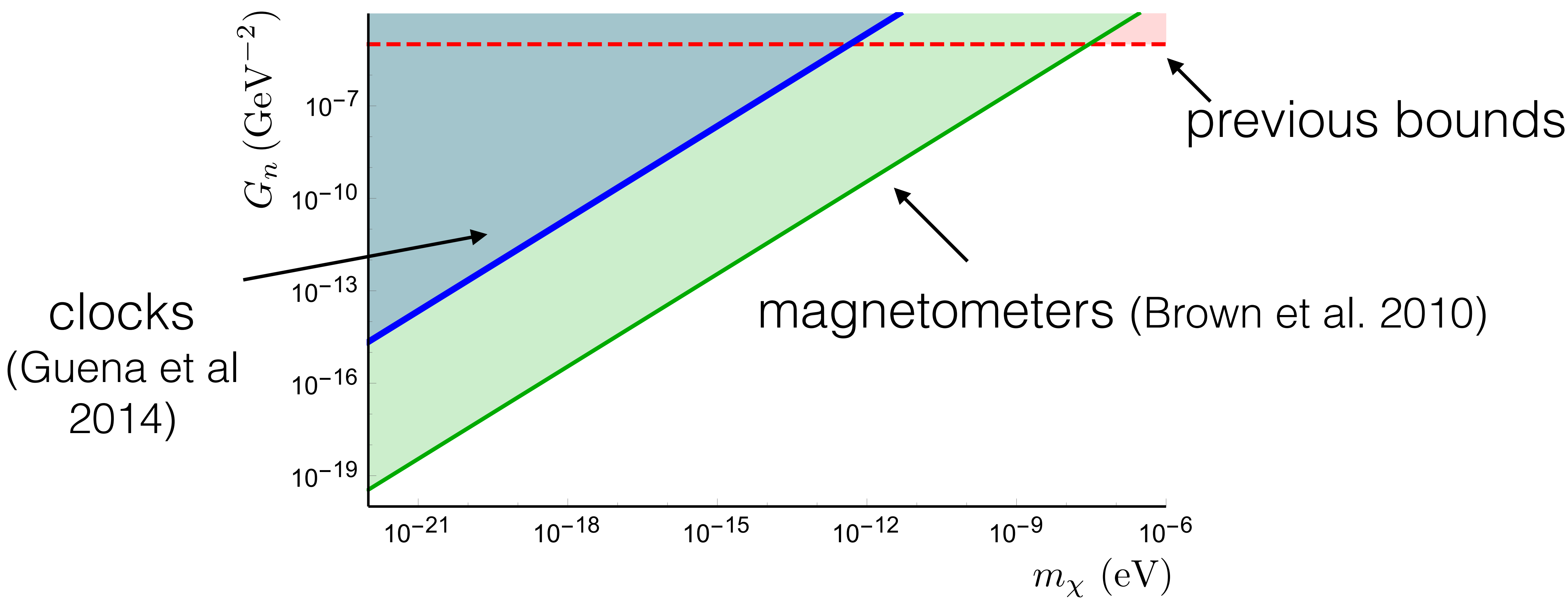
one needs to make sure
that the effect is not confused with
atomic physics/backgrounds

Constraints: two examples

scalar DM

$$L_{\rm int} = -G_n \int \mathrm{d}^3x \, (\bar{n}\gamma^\mu\gamma_5 n)\left(i\chi^\dagger\partial_\mu\chi + \mathrm{h.c.}\right)$$

$$\vec{S}_n \cdot \vec{v}_\chi$$

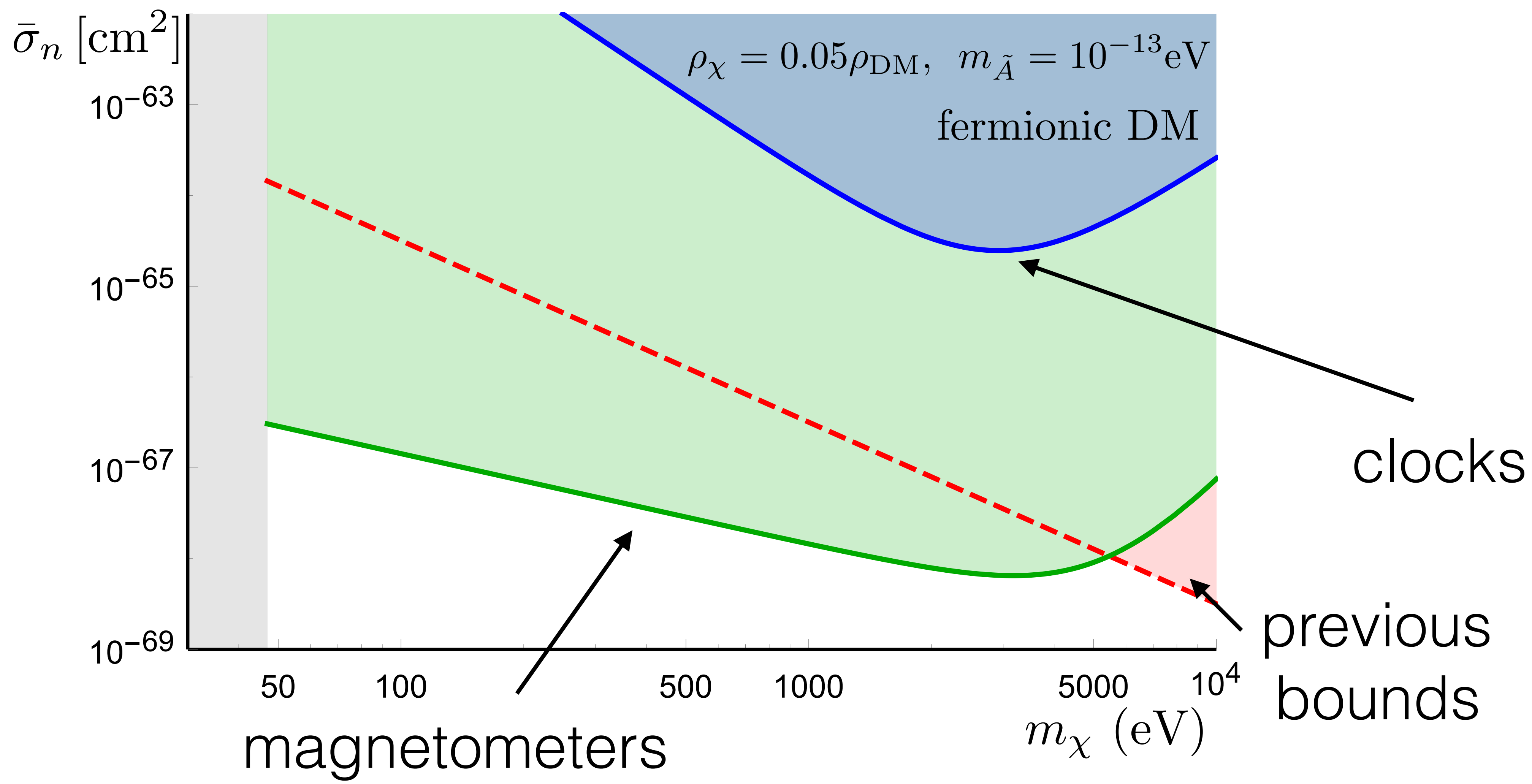


Constraints: two examples

fermionic DM with light mediator

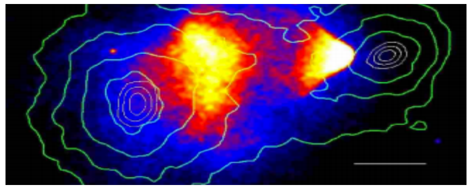
$$L_{\rm int} = -g_{\tilde{A}} g_\chi \int {\rm d}^3x \, (\bar{n}\gamma^\mu\gamma_5 n) \, \frac{1}{m_{\tilde{A}}^2 + \Box} \, (\bar{\chi}^\dagger \gamma^\mu \gamma_5 \chi)$$

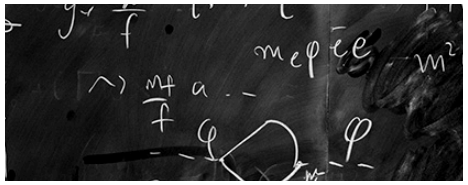
$$\vec{S}_n \cdot \vec{S}_\chi / m_{\tilde{A}}^2$$



Conclusions

- Cosmic neutrinos, low-mass dark matter and grav. waves: **high flux, low momentum and small coupling**





- Precise (quantum) devices perfect place to look for them!

- The effect of dark matter in the **standard operation** of **atomic clocks/magnetometers** yields new (sometimes spectacular) bounds on the dark matter models

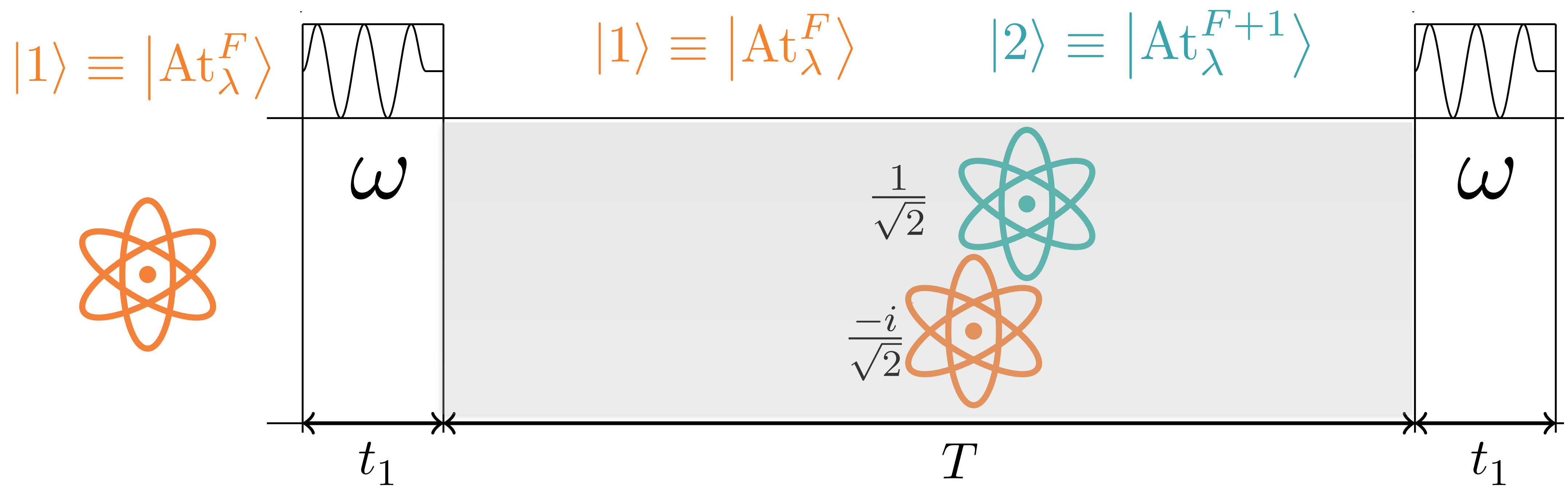
- This seems just the beginning…

Future

- More complete framework for some models (cosmology)
- Perform the atomic clock measurements (at $\lambda \neq 0$)
- Bounds on other operators (may be enhanced by #nucleons)

  provided $\bar{f}(0)_1 - \bar{f}(0)_2 \neq 0$
- Neutrinos? Gravitational waves?
- Can these devices be used as detectors? To study coherent scattering? (they work at zero momentum transfer)
- …

Ultra-light case



The atoms live in a background with some coherent features and for certain dark matter models

$$V_2 - V_1 \neq 0$$