Cosmic backgrounds @ atomic clocks and co-magnetometers

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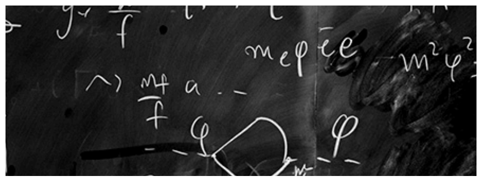
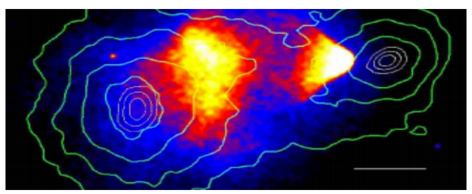
w./ R. Alonso and P. Wolf

1810.00889 & 1810.01632

Astrophysical backgrounds in the lab



Gravitational waves (SM + BSM)



Dark matter (BSM)

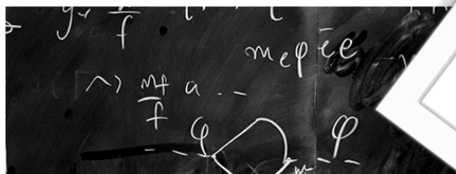
Cosmic neutrinos (SM)

e.g. those produced at the Big Bang,

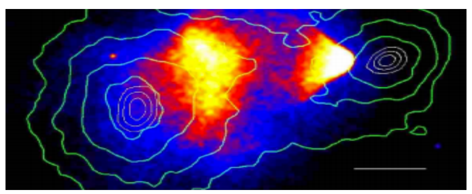
$10^{12}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ *weakly interacting* and *low momentum*

5th forces / Dark Energy (BSM)

Astrophysical backgrounds in the lab



…al waves (SM + BSM)



Dark m…

Cosmic neutrinos (…

e.g. those produced at t…

$10^{12}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ *weakly interac… …entum*

5th forces / Dark Energy (BSM)

Perfect cases for interferometry (sensitivity to small q)

Fresh view on DM

- [x] Candidate should be a cold gravitating medium
- [ ] Production mechanism and viable cosmology
- [ ] Motivation from fundamental physics
- [ ] Possibility of (direct or indirect) detection

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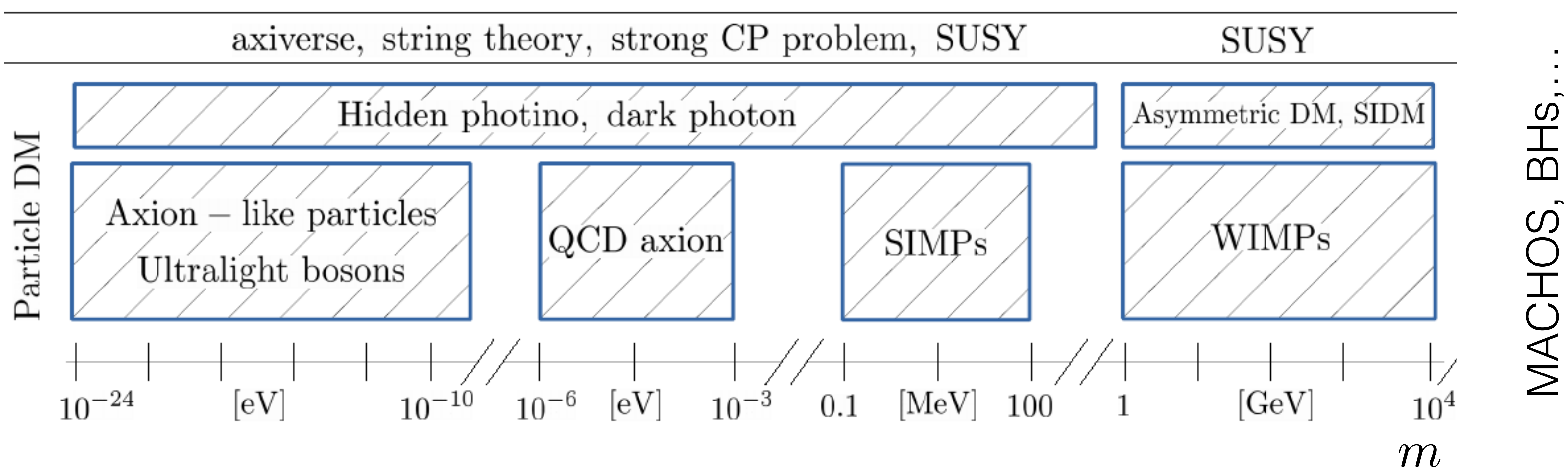

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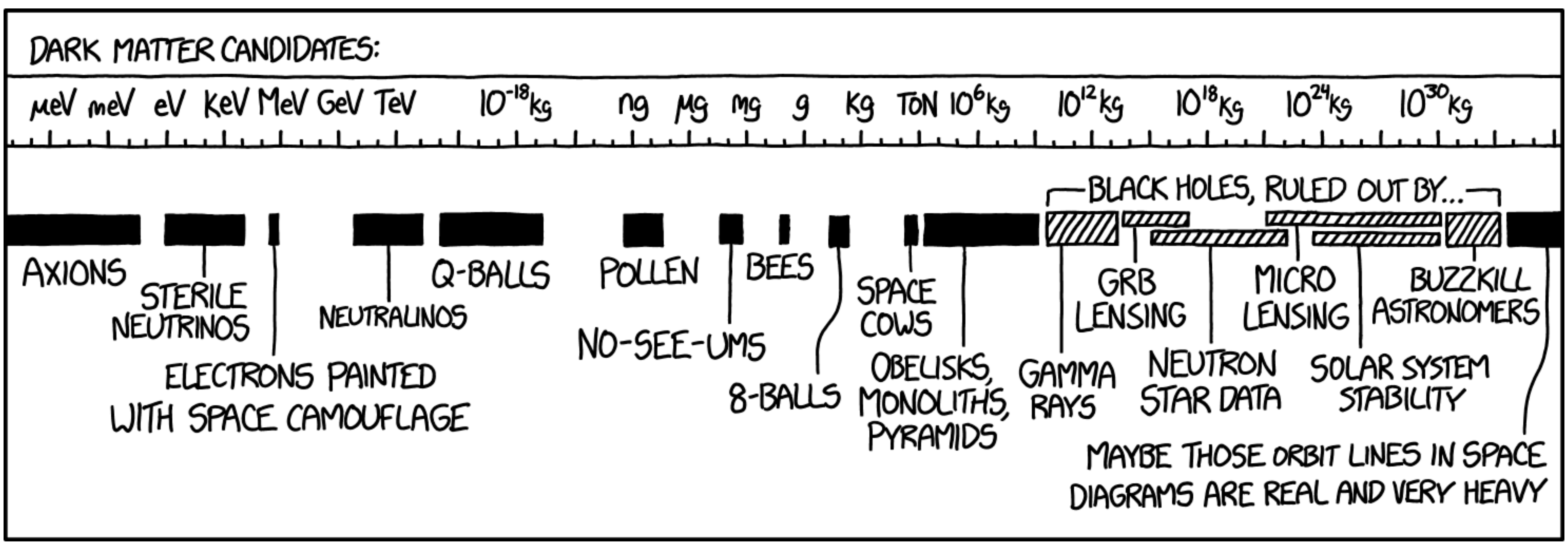
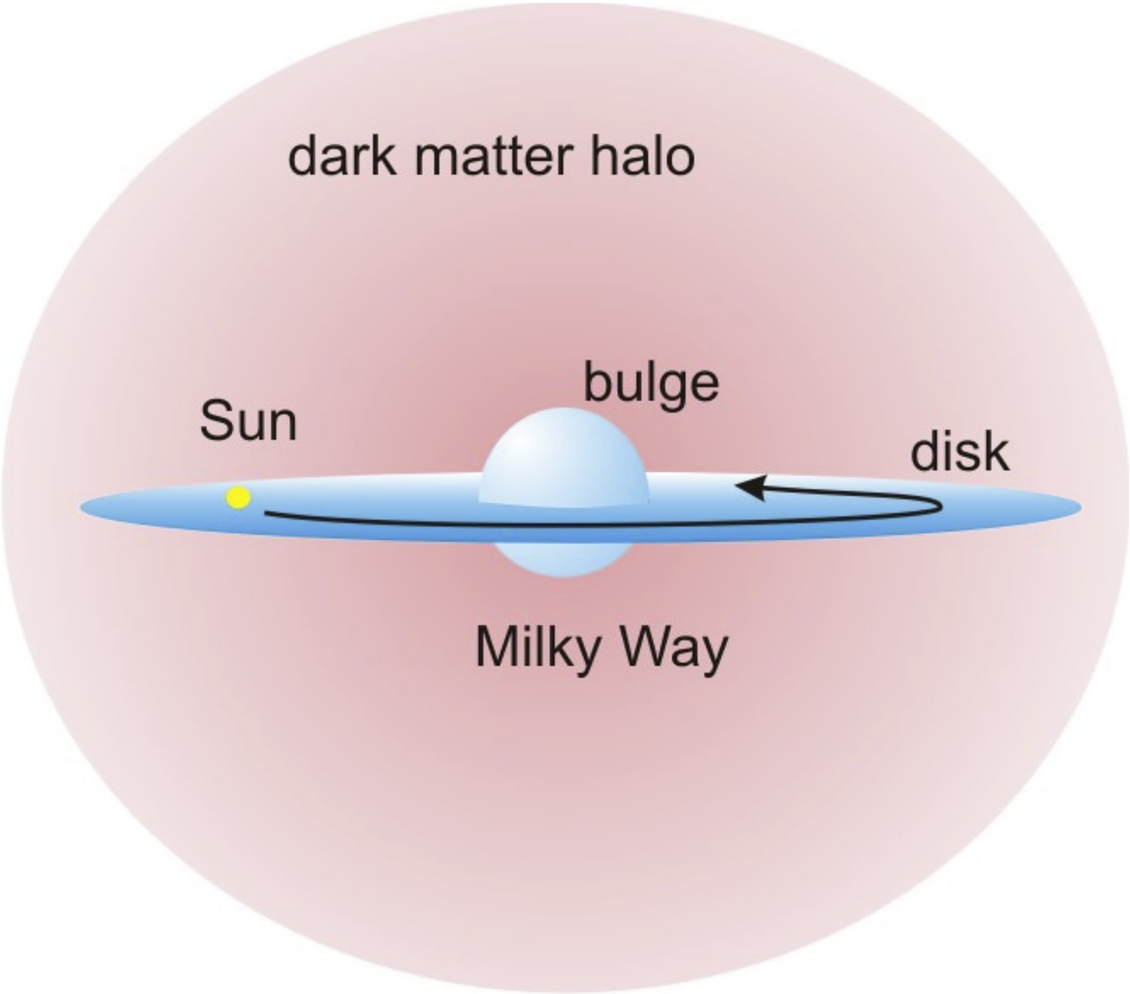


@xkcd

DM in the Milky Way



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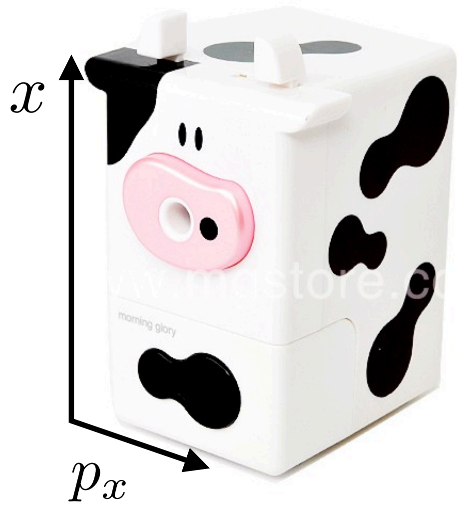


virial equilibrium in the Milky Way (MW) halo:

i) scape velocity $\sim 2 \times 10^{-3} c$
ii) size 100 kpc

$$N_s \sim \left(\frac{0.1 \text{ kpc}\, mc}{\hbar} \right)^3 \rightarrow N_p = \frac{M_{MW}}{N_s m} \sim 10^3 \left(\frac{\text{eV}}{m} \right)^4$$

This logic tells us that 100% of DM can't be fermionic for mass $\lesssim \text{keV}$

For high occupation number and arbitrary phases → classical field description

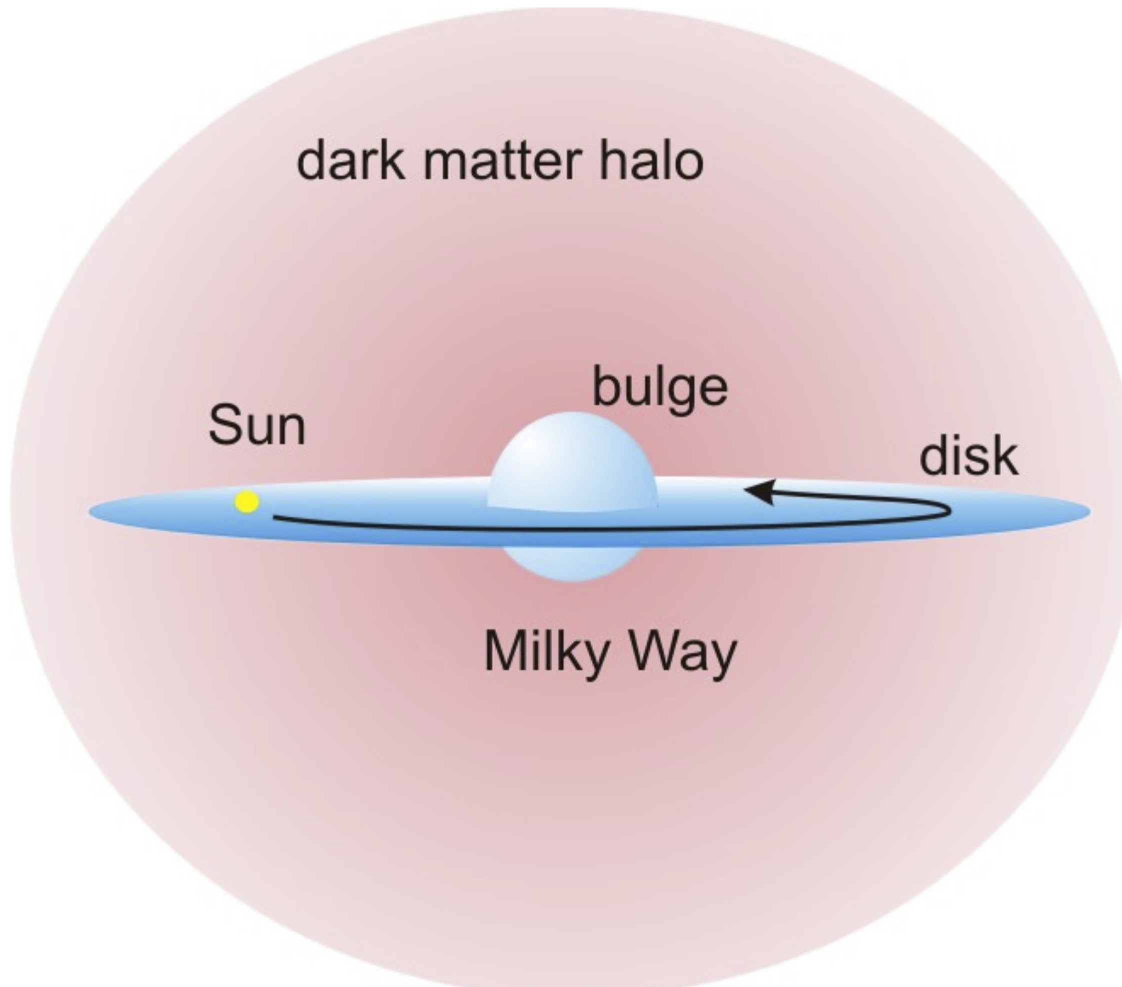
identical argument to use classical EM, GWs, etc

which DM? e.g. **massive scalar case**

$$\Box \phi(x,t) + m^2 \phi(x,t) = 0$$

(+ i.c. or extra conditions)

DM in the Milky Way



expectation in the Solar system

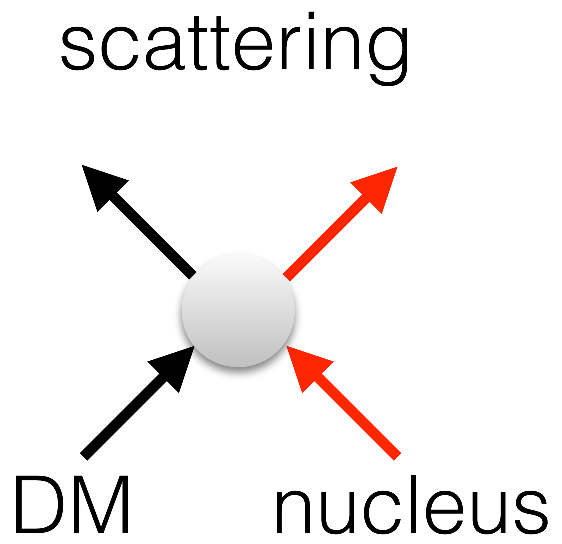
$$\begin{cases} \rho_\odot \sim 0.3\,\mathrm{GeV/cm^3} \\ m_\chi \langle v_\odot \rangle \sim 10^{-3} m_\chi c \end{cases}$$

$$f(v) \propto e^{-v^2/\sigma_0^2}$$

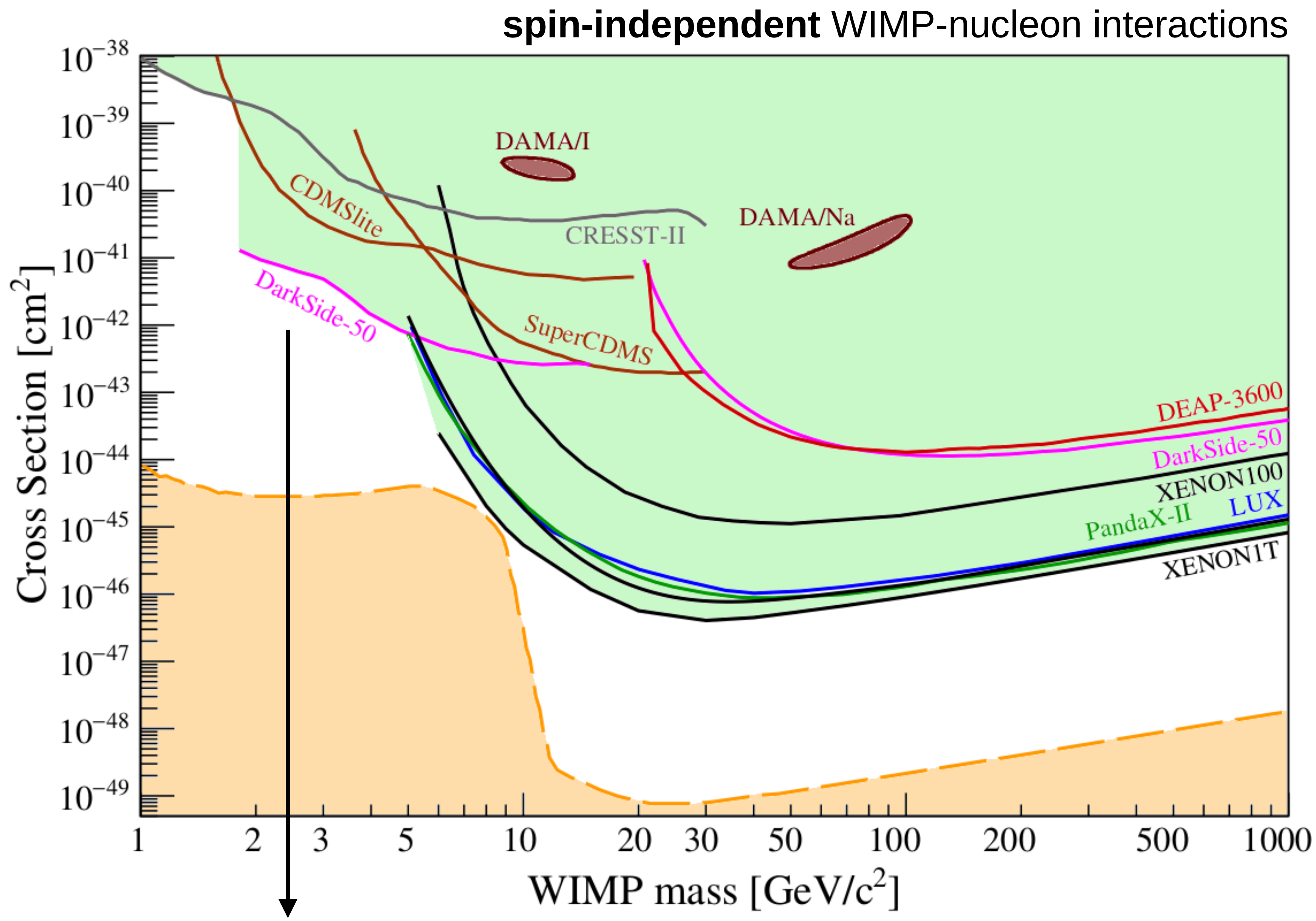
$$\sigma_0 \sim 10^{-3} c$$

flux: $10^{10} \left(\frac{\mathrm{MeV}}{m_\chi} \right) \mathrm{cm^{-2} s^{-1}}$

‘Traditional’ Direct Detection



$$E_R^{\max} \sim \left(\frac{m_\chi}{\mathrm{GeV}}\right) \mathrm{keV}$$



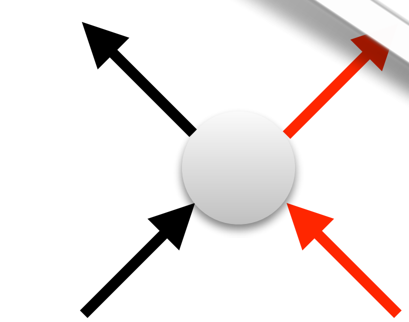
low-energy threshold

dramatic loss of sensitivity at low mass (still ‘high’ mass)

‘Traditional’ Direct Detection

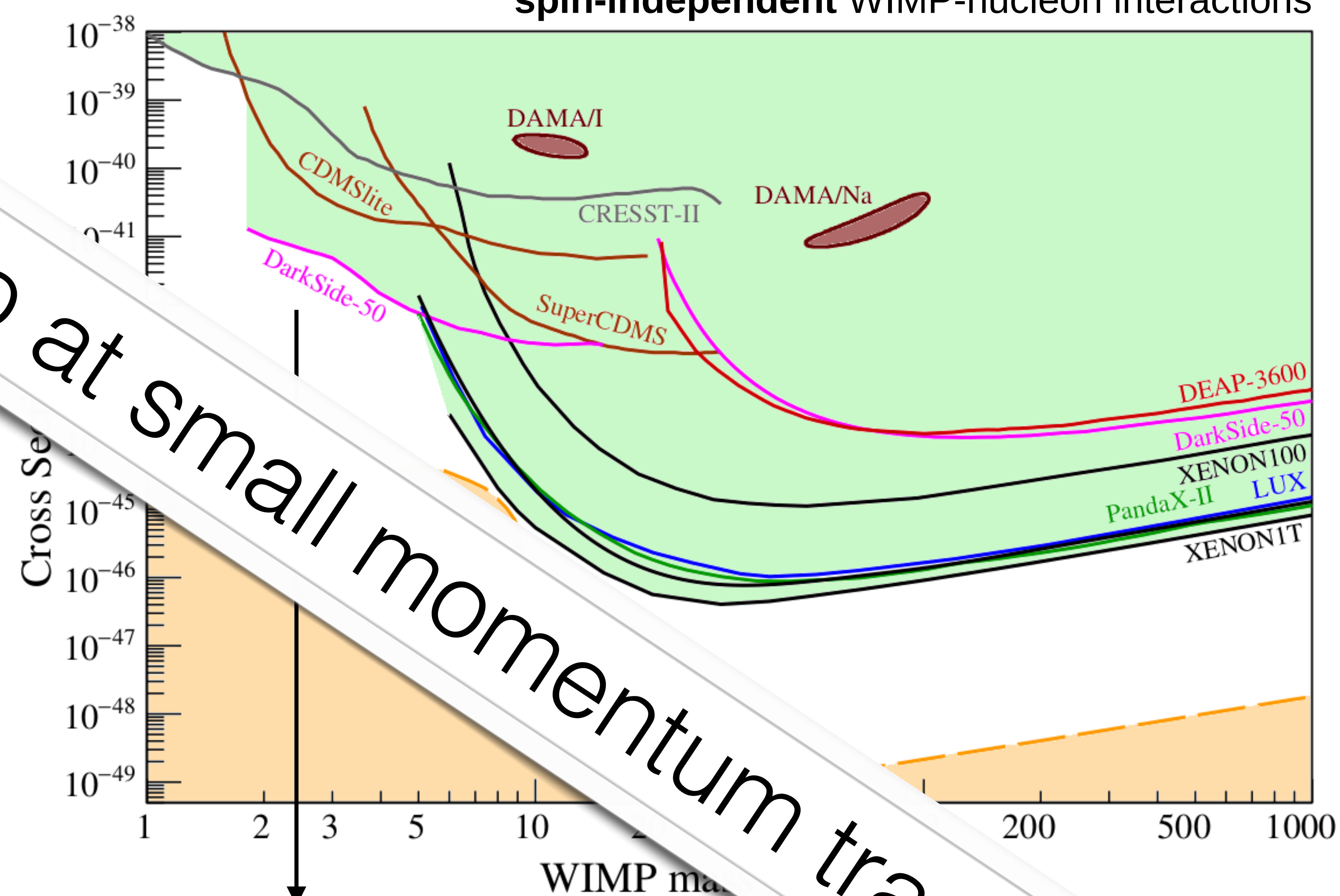
what to do at small momentum transfer?

sca



$$E_R^{\max} \sim \left(\frac{m_\chi}{\text{GeV}}\right) \text{keV}$$

spin-independent WIMP-nucleon interactions



low-energy threshold

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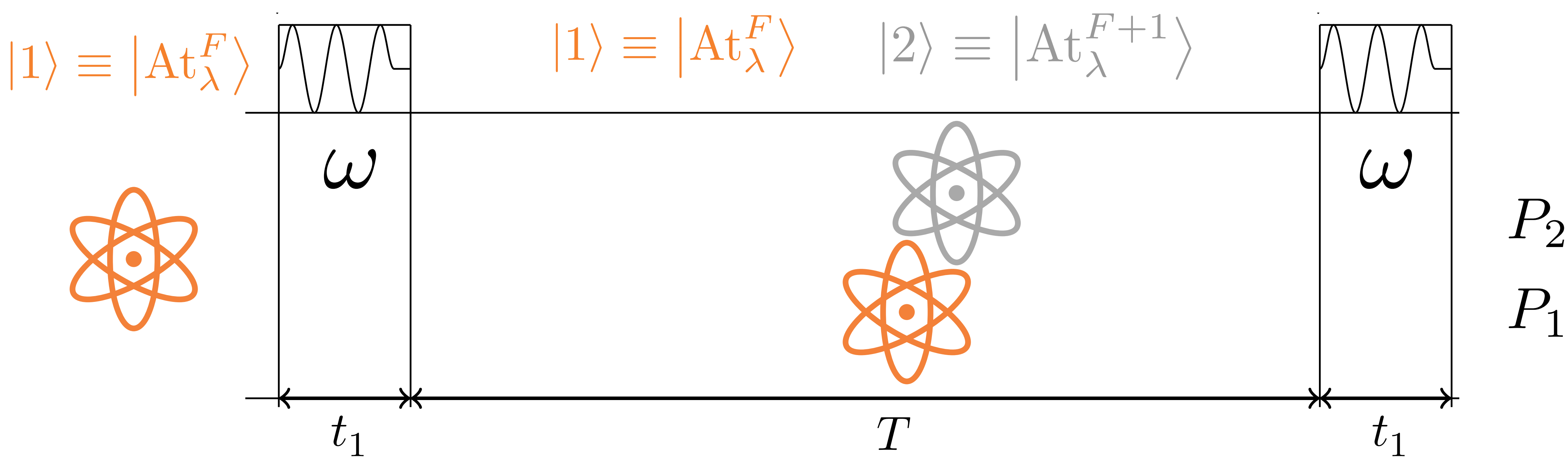
Measuring at $q = 0$: Ramsey sequence

(atomic clock basics)



$$P_2 = \cos[\Delta\omega\, T/2]^2$$

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

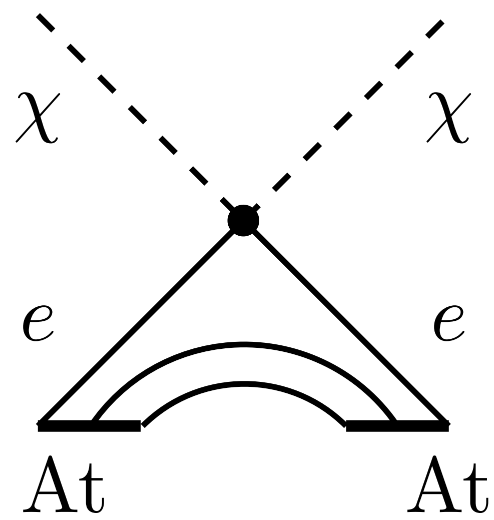
$$\partial P_2 = 0 \quad \Rightarrow \quad \omega_{\max} = \Delta E$$

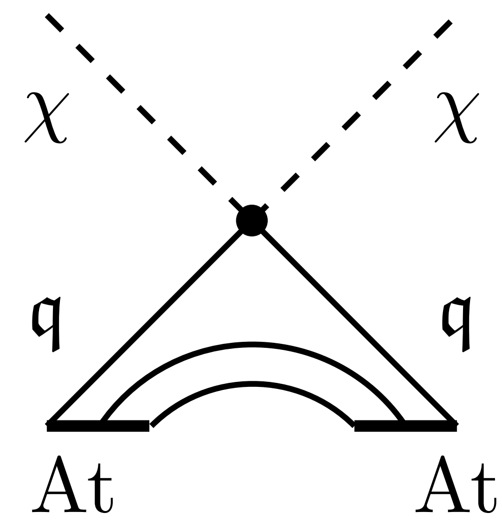
measurement of the phase difference e^{iHT}

will be sensitive to anything of the form $H_i = E_i^{\mathrm{free}} + V_i$

provided $\delta V_i \neq 0$

DM-atom scattering





Fundamental interaction

DM current

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

All possible effective DM-SM interactions

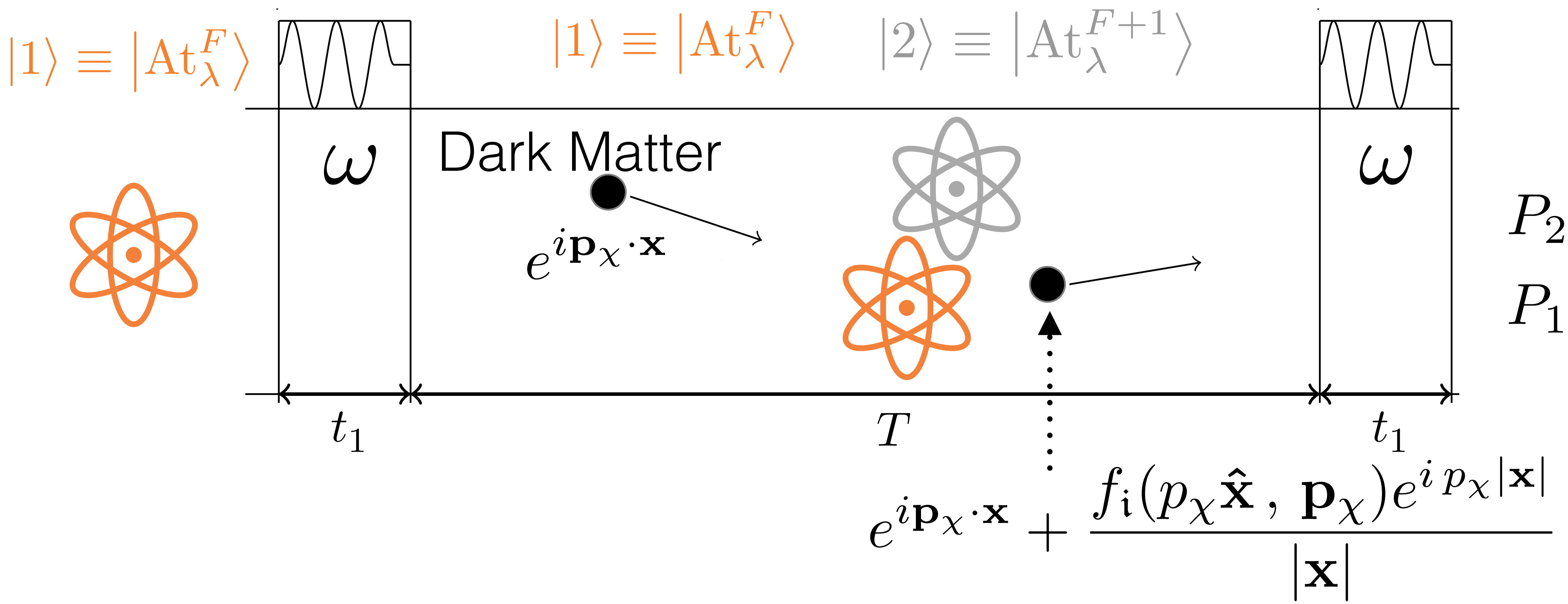
At the practical level

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

$$V_i \supset \vec{S}_e \cdot \vec{v}_\chi\,,\ \vec{S}_e \cdot \vec{S}_\chi\,, \ldots \qquad \vec{S}_N \cdot \vec{v}_\chi$$

we focused on interactions depending on atomic spin since $\Delta F \neq 0$

DM-atom interaction during Ramsey sequence



Interaction potential

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

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

The measured phase can be used to detect the interaction of DM

The ultra-light domain: interaction with atoms

$m_\chi \ll 1\,\mathrm{eV}$

$\bar{\phi}(x,t)$

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

$$H_{\rm int} \propto \quad \vec{S}_e \cdot \vec{v}_\chi,\ \vec{S}_e \cdot \vec{S}_\chi,\ \vec{S}_N \cdot \vec{S}_\chi,\ \ldots.$$

these are now backgrounds!
(linear or quadratic coupling)

for generic couplings this means the
oscillation of 'fundamental constants'

e.g. $(m + g_{\phi ee}\bar{\phi}(t))\bar{e}e$

different effect in different atoms: can be searched for in clocks!

Arvanitaki et al 2015, talks by Bauer and Hogan

The ultra-light domain: galactic configuration

$$\Box\phi(x,t) + m^2\phi(x,t) = 0$$

Virialized distribution: collection of waves
with a Maxwell distribution

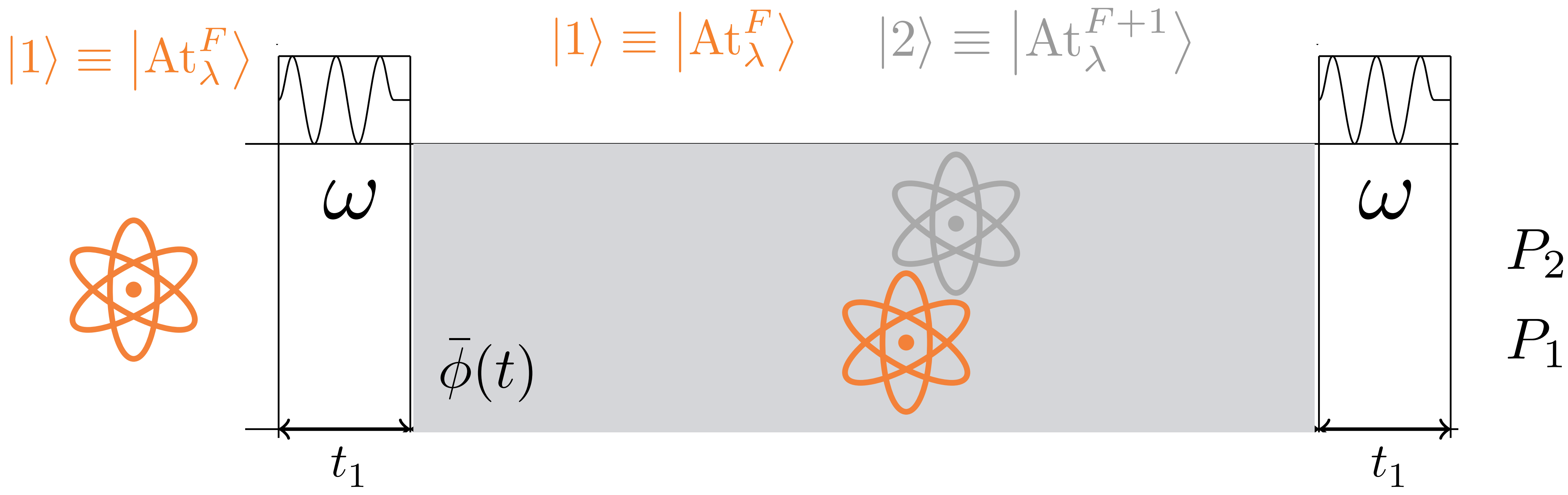
$$\phi \propto \int_0^{v_{max}} \mathrm{d}^3v\, e^{-v^2/\sigma_0^2} e^{i\omega_v t} e^{-im\vec{v}\cdot\vec{x}} e^{if_{\vec{v}}} + c.c.$$

in the MW $\sigma_0 \sim 10^{-3}c$

since $\omega_v \approx m(1+v^2)$, oscillations coherently over

$$t \sim 10^6 \left(\frac{10^{-15}\,\mathrm{eV}}{m}\right)\left(\frac{10^{-6}}{\sigma_0^2}\right) s$$

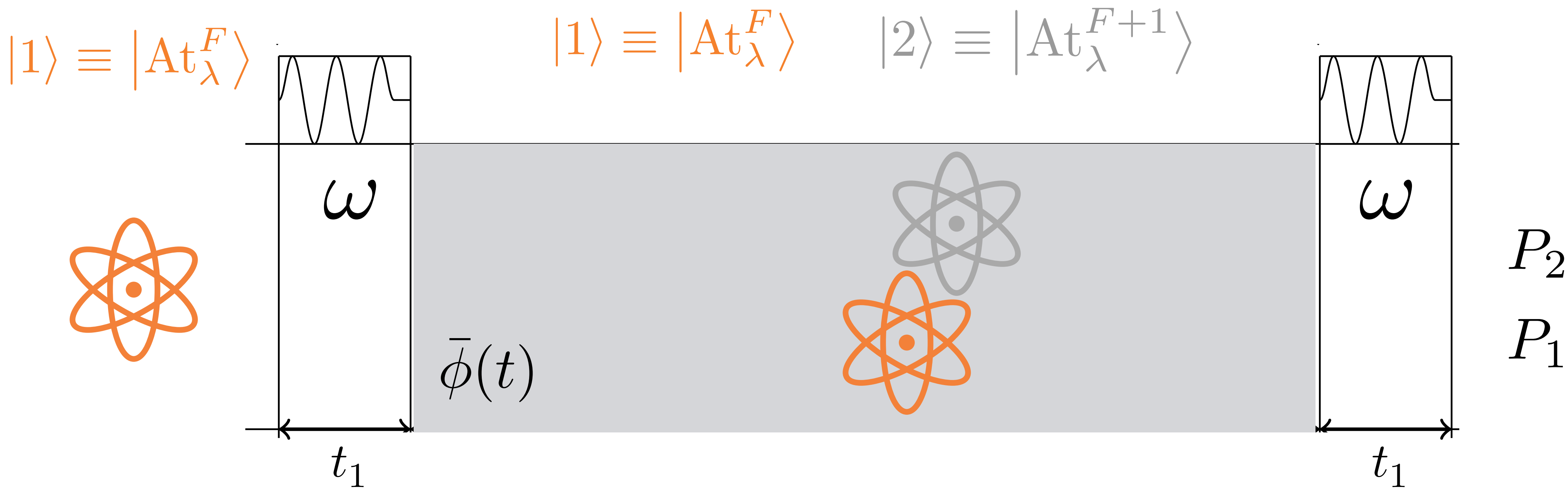
Ultra-light case



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

$$V_2 - V_1 \neq 0$$

Ultra-light case



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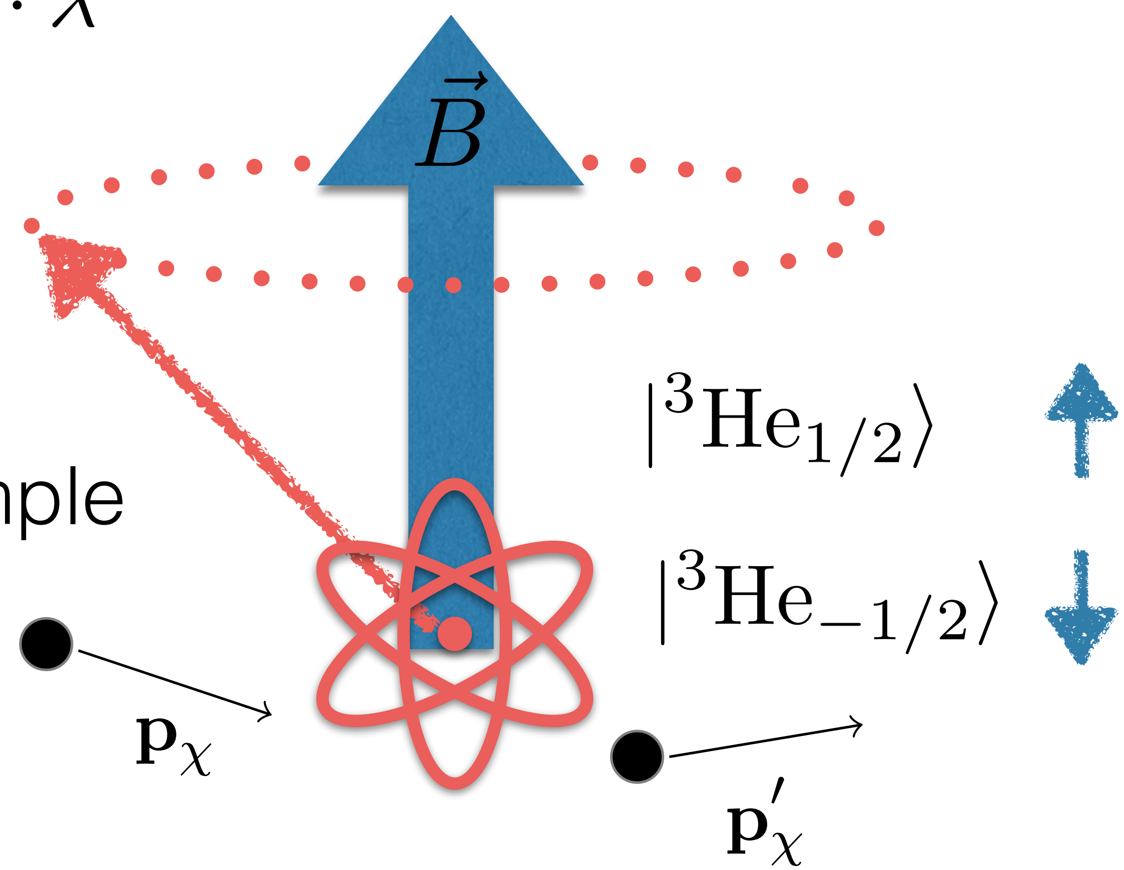
DM-atom interaction in co-magnetometers

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

polarized sample



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

Which DM-atom interactions?

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

We studied *spin-dependent interactions* $\vec{S}_e \cdot \vec{v}_\chi\,,\ \vec{S}_e \cdot \vec{S}_\chi\,,\ \ldots$

clocks at $\lambda_z \neq 0$
worse than magnetometers

$\vec{p}_{\rm at}$ dependent interactions require two samples of

$$\int dt(\vec{p}_{{\rm at},1} - \vec{p}_{{\rm at},2}) \neq 0$$

phase comparison at
different locations/trajectories?
interfering rotating states?

average effect

the velocity contains a **coherent** part
the DM spin is in principle **arbitrary**

$$O(1/\sqrt{N})$$

faster and smaller
devices?

final remark

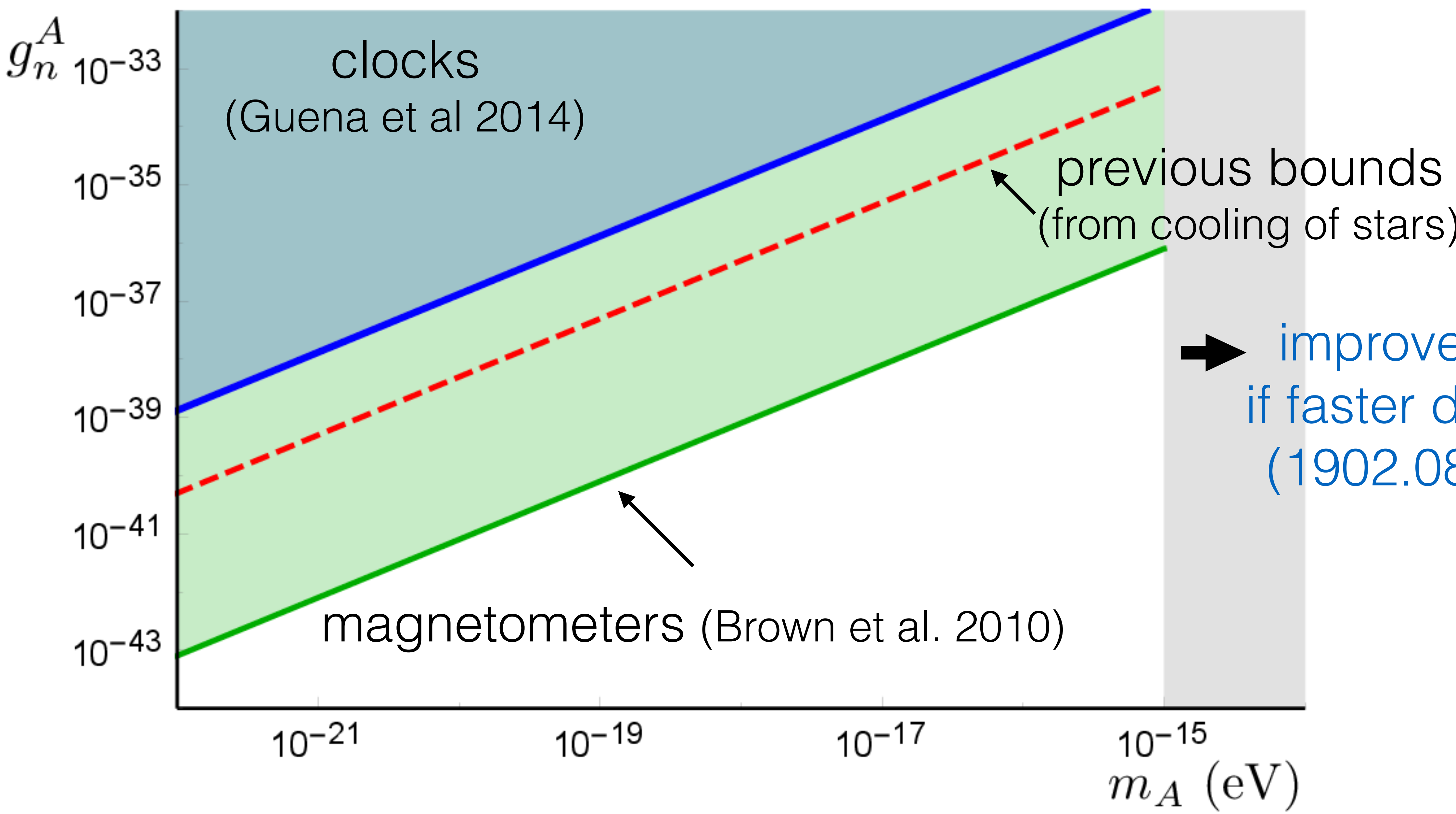
make sure that the effect is
not confused with other physics

different species in
one device

Constraints: examples

ultralight axial vector

$$L_{\rm int} = g_n^A \int \mathrm{d}^3x A^\mu \bar{n}\gamma_\mu\gamma_5 n \quad \blacktriangleright \quad \vec{\epsilon}\cdot\vec{S}\cos(m_A t)$$

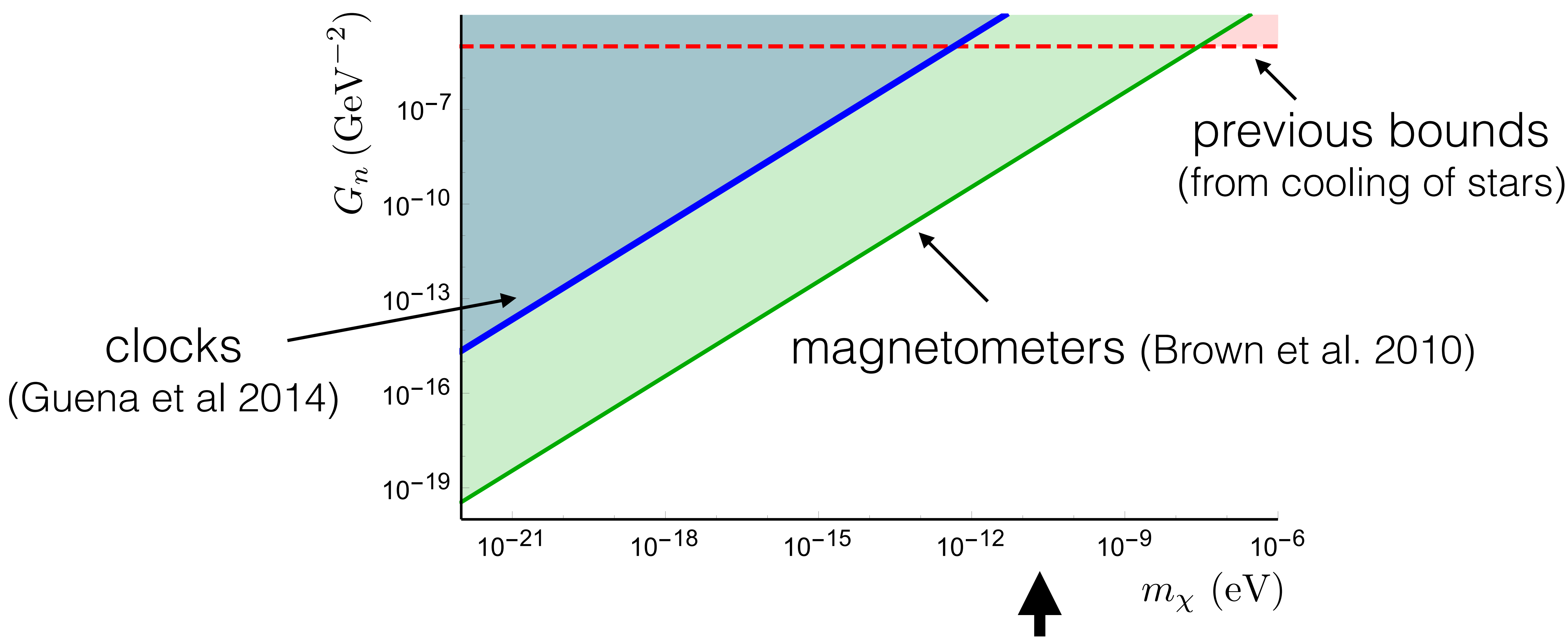


improvement
if faster devices
(1902.08212)

Constraints: examples

scalar DM

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

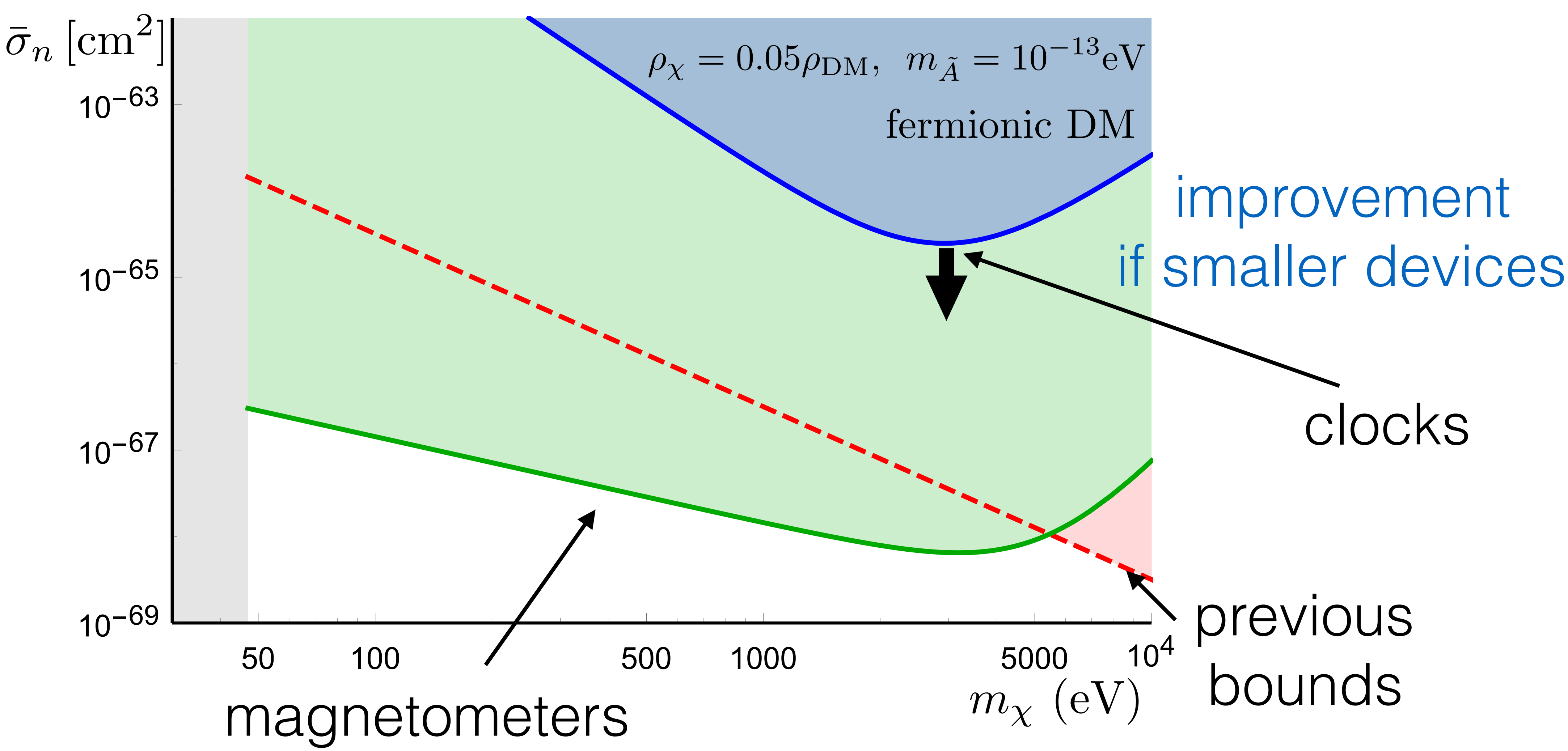


also bounds for high masses (not only ‘coherent’ oscillations)

Constraints: examples

fermionic DM with light mediator

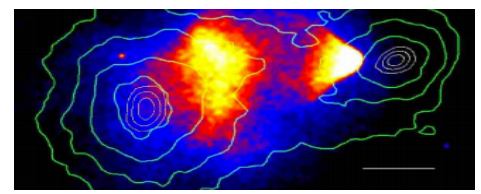
$$L_{\rm int} = -g_{\tilde{A}} g_\chi \int d^3x \, (\bar{n}\gamma^\mu\gamma_5 n) \, \frac{1}{m_{\tilde{A}}^2 + \Box} \, (\bar{\chi}^\dagger \gamma^\mu \gamma_5 \chi) \quad \blacktriangleright \quad \vec{S}_n \cdot \vec{S}_\chi / m_{\tilde{A}}^2$$

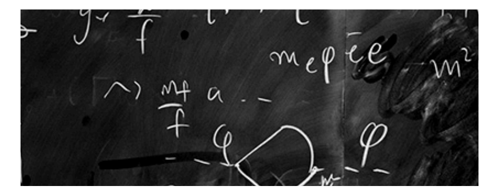


also bounds for high masses (not only 'coherent' oscillations)

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 dark matter models

Future directions

- More complete framework for some models (cosmology)
- Other couplings and other interferometers (AION)

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

populations of different momentum (interfering rotating states?)

- TBD: map of EFT operators to devices! (relatively complete for dimensions 5 operators, axions/dilatons)
- Neutrinos: always out of reach but it's always worth putting the numbers together (also dipole moments?)
- Calibration using beams?

Main results

$$f_1(0) - f_2(0) = \frac{m_\chi}{\pi}\left(G_N \mathfrak{g}^N_{\mathrm{Ncl}} - G_e\right) \vec{J}_\chi \cdot \frac{\vec{\lambda}}{F}$$

$f_1(0) \rightarrow (F, \lambda)$ $\quad$ $f_2(0) \rightarrow (F+1, \lambda)$

$\vec{J}_\chi \rightarrow \vec{v}_\chi, \ \vec{S}_\chi$

$G_N \rightarrow$ nucleon form factors $G_N(G_u, G_d)$

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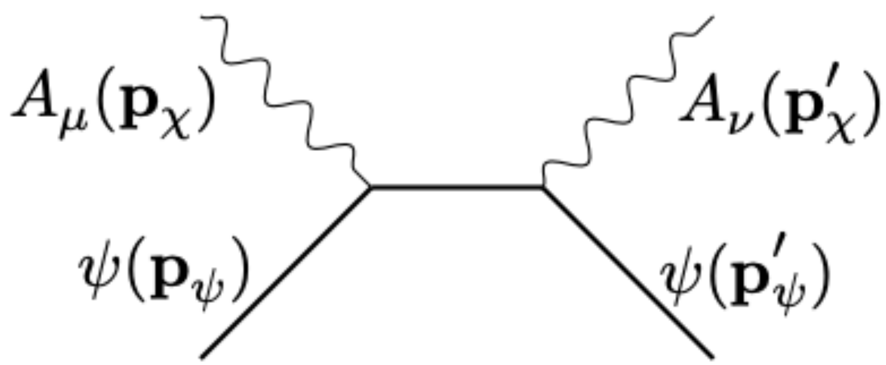
for scattering with axial vectors



$$f_1(0) - f_2(0) = \frac{-1}{\pi m_A}\left((g_N^A)^2 \mathfrak{g}^N_{\mathrm{Ncl}} - (g_e^A)^2\right) \frac{\vec{\lambda}_A \cdot \vec{\lambda}}{F}.$$

(cancels at first order for axions)