Exploring light dark matter @ atomic clocks and co-magnetometers

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w./ R. Alonso (IPPP, Durham) and P. Wolf (Paris Observatory)

1810.00889 (JHEP) & 1810.01632 (PRD)

On boundaries of the DM landscape

- ☑ 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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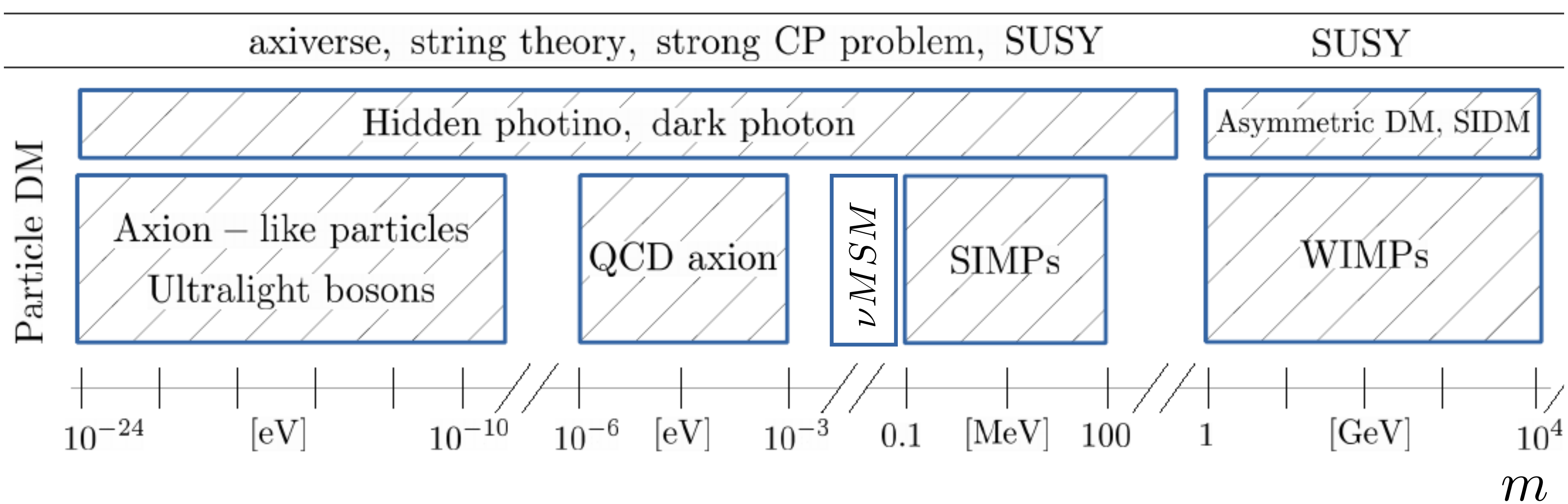
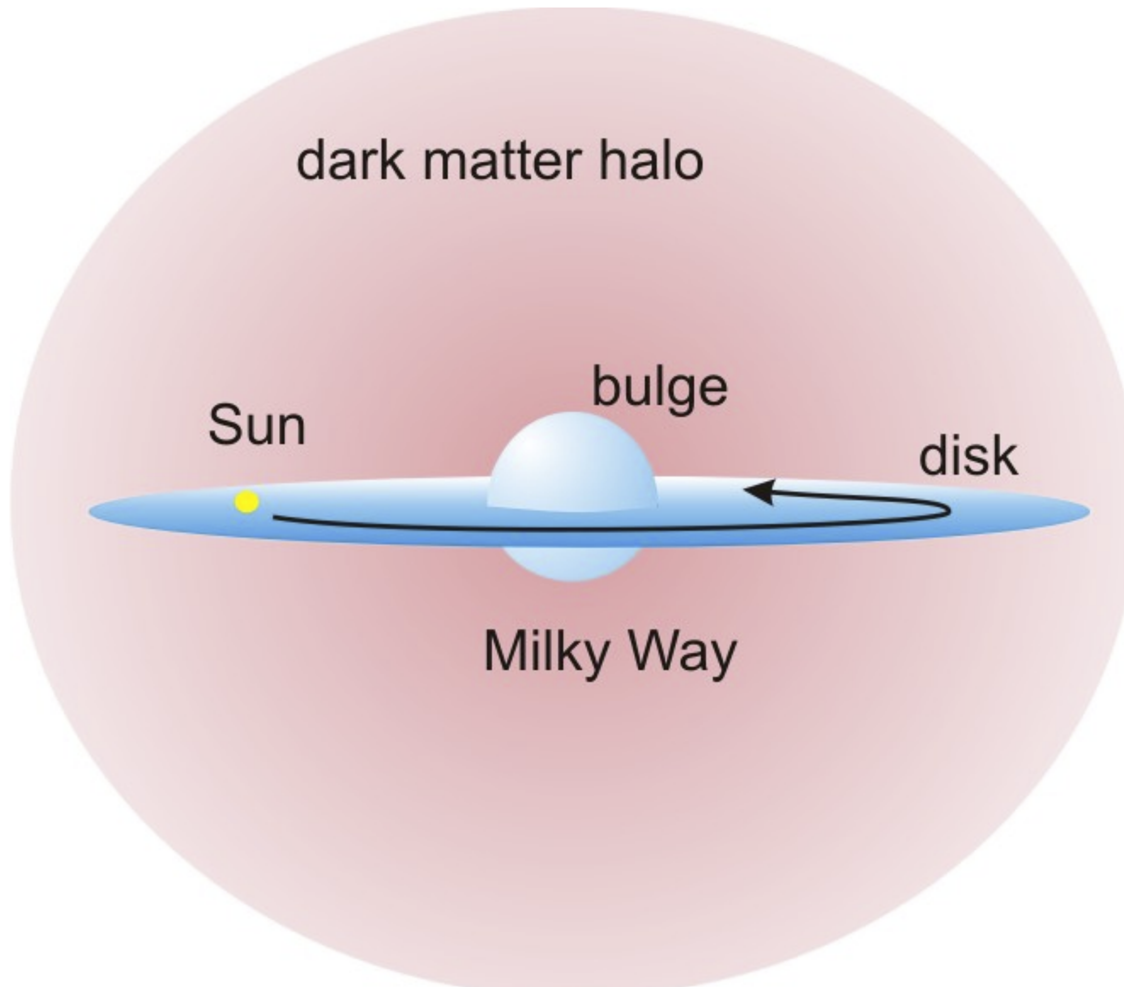


MACHOS, BHs,...

'Knowns' about DM in the Milky Way

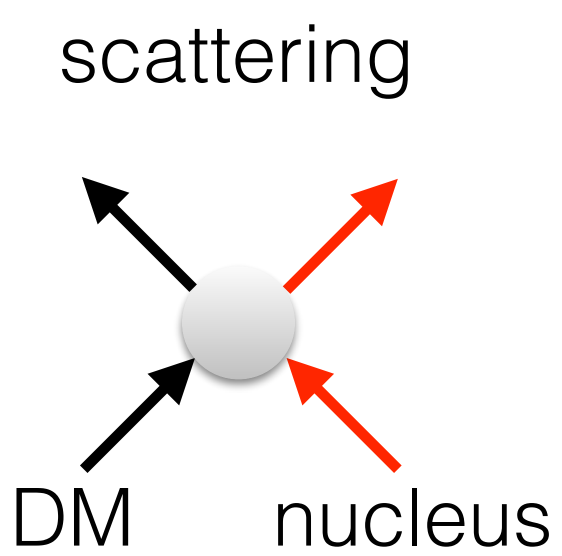


expectation in the Solar system

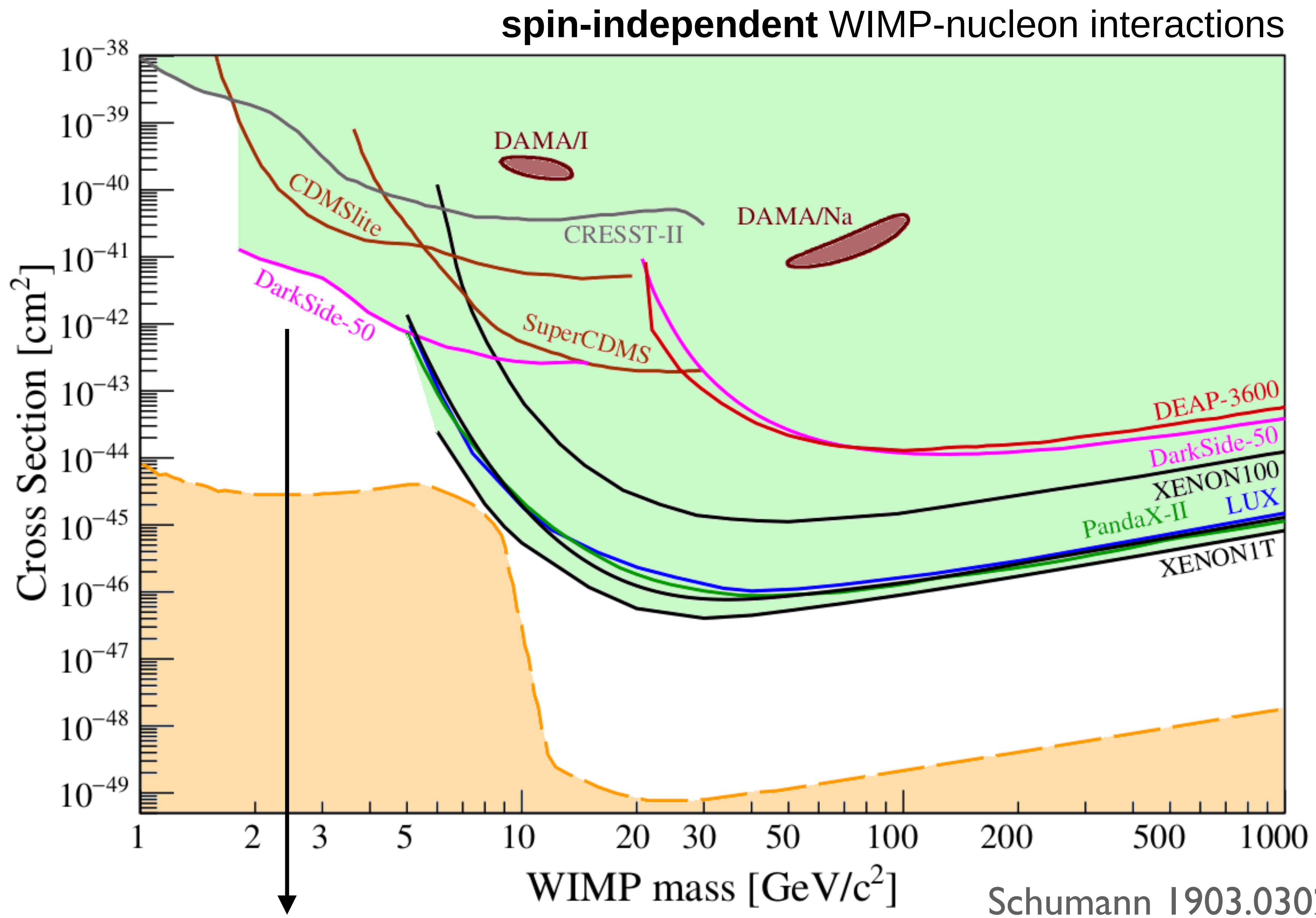
$$\begin{cases} \rho_\odot \sim 0.3\,\mathrm{GeV/cm^3} \\ m_\chi \langle v_\odot \rangle \sim 10^{-3} m_\chi \end{cases}$$

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

‘Traditional’ Direct Detection



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



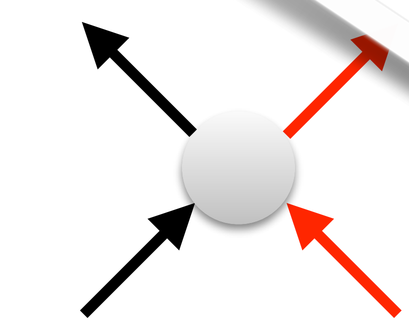
Schumann 1903.03026

low-energy threshold

dramatic loss of sensitivity at low mass
(still ‘high’ mass in the DM landscape)

‘Traditional’ Direct Detection

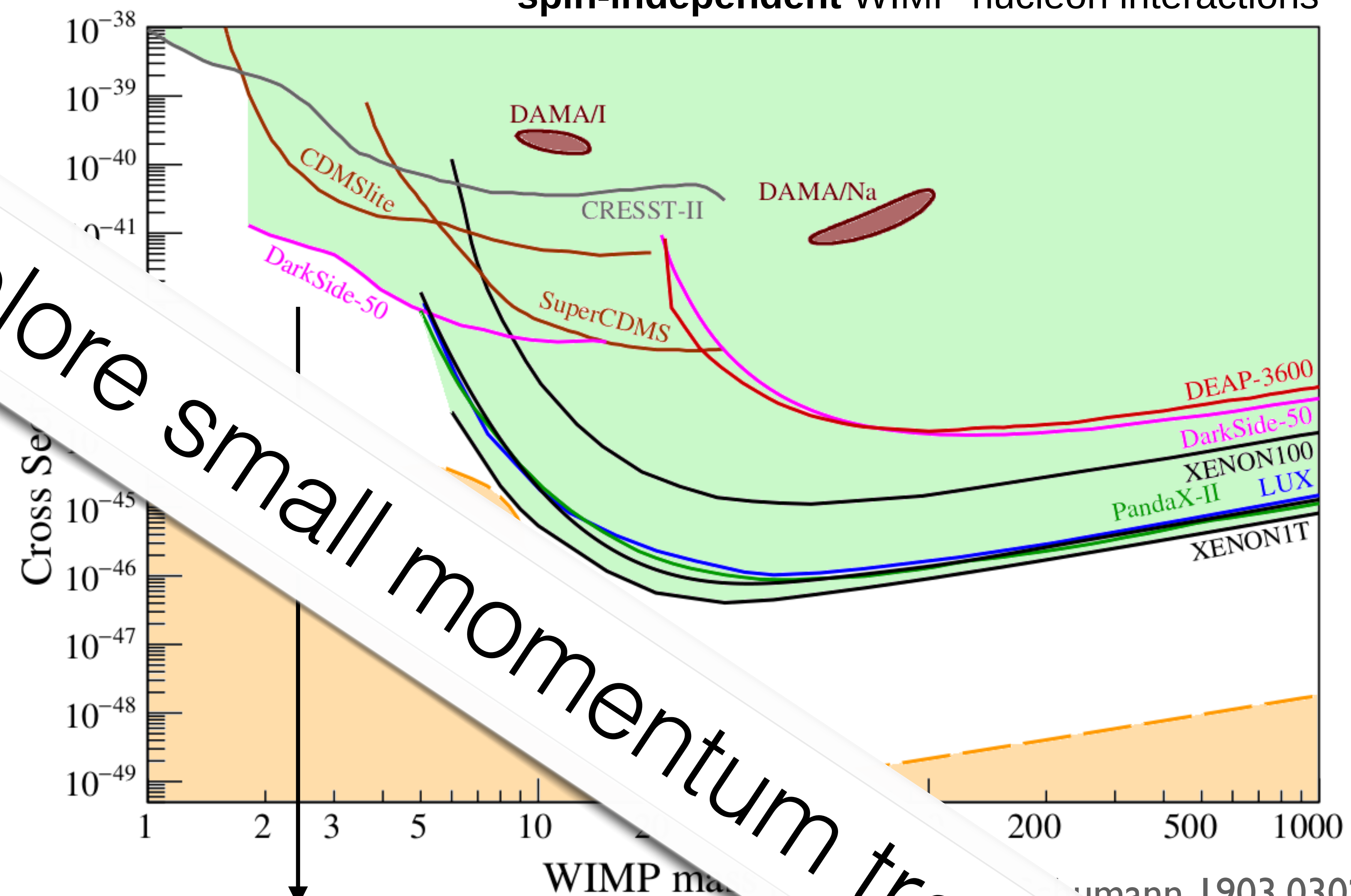
sca...



DM nucleus

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

spin-independent WIMP-nucleon interactions



...umann 1903.03026

how to explore small momentum transfer?

low-energy threshold

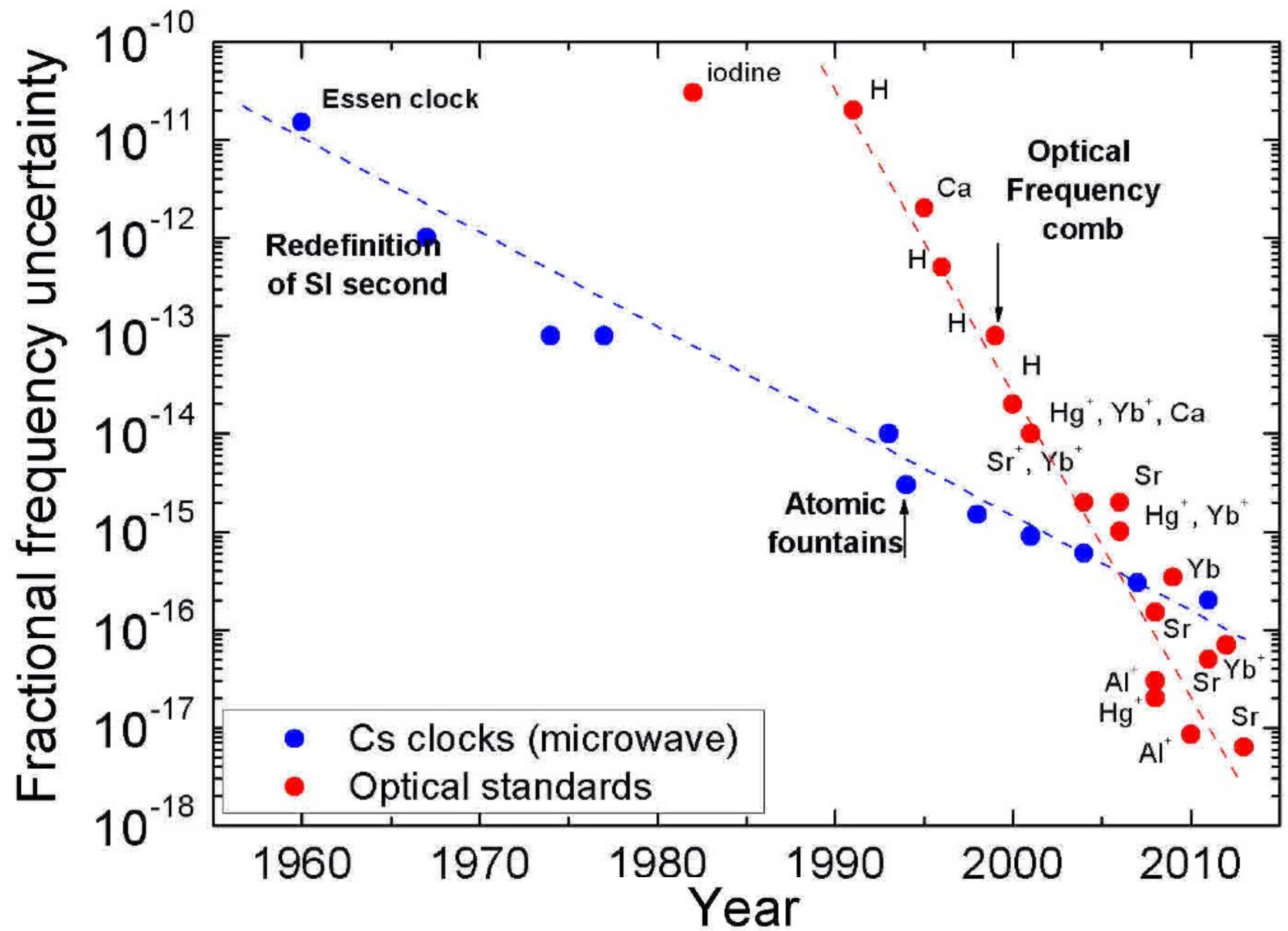
dramatic loss of sensitivity at low mass
(still ‘high’ mass in the DM landscape)

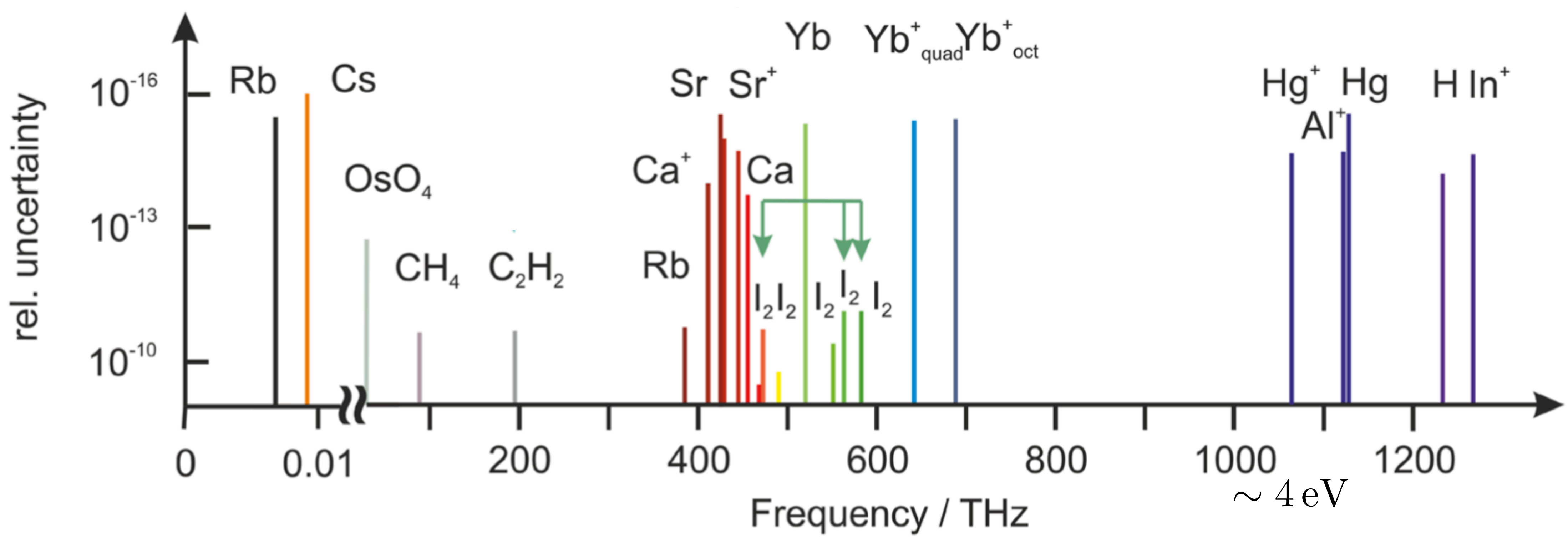
Very active field! See e.g. Alexander et al 1608.08632

Atomic clock achievements

Poli et al. 1401.2378
Safronova et al. 1710.01833
Riehle et al. (CIPM) 2018

$$\frac{\delta(E_2 - E_1)}{E_2 - E_1}$$



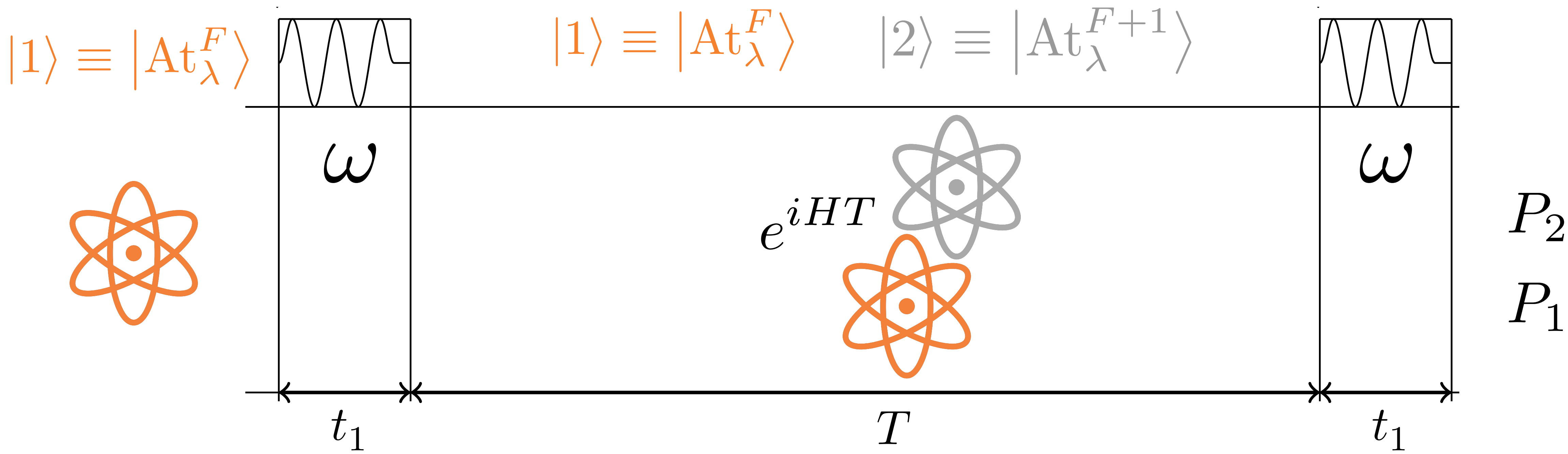


$\sim 4\,\mathrm{eV}$

Measuring at $q=0$: phase shifts in atomic clocks

Ramsey sequence

e.g. Weinberg QM. Sec 6.8



after 'adjusting the device': $P_2 = \cos[\Delta\omega\, T/2]^2$

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

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

measurement of the phase difference e^{iHT}

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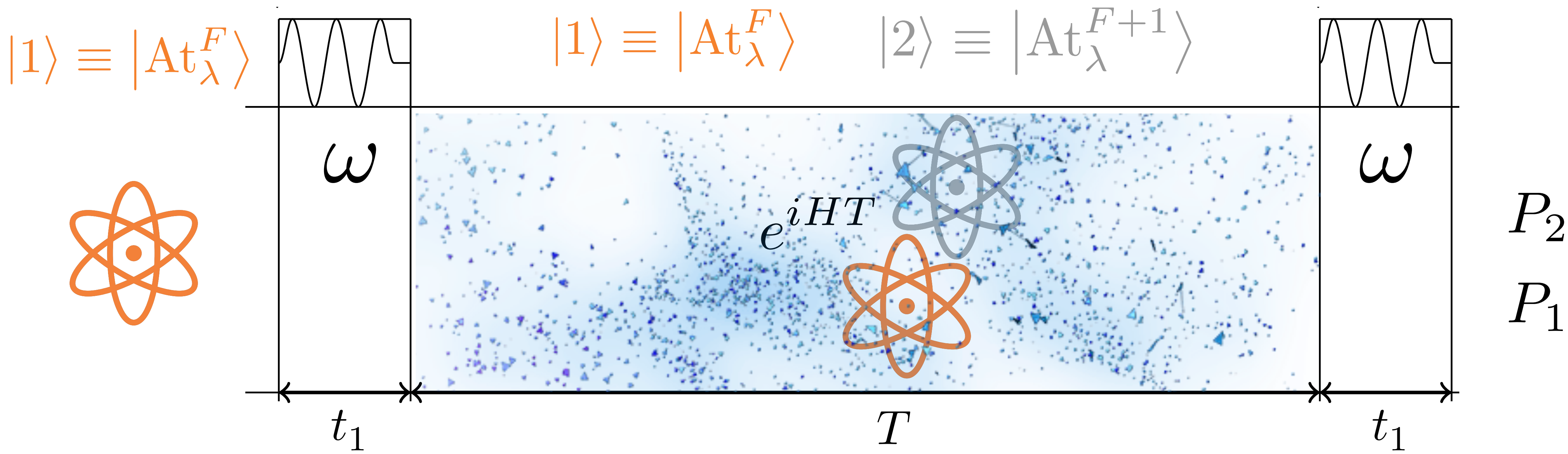

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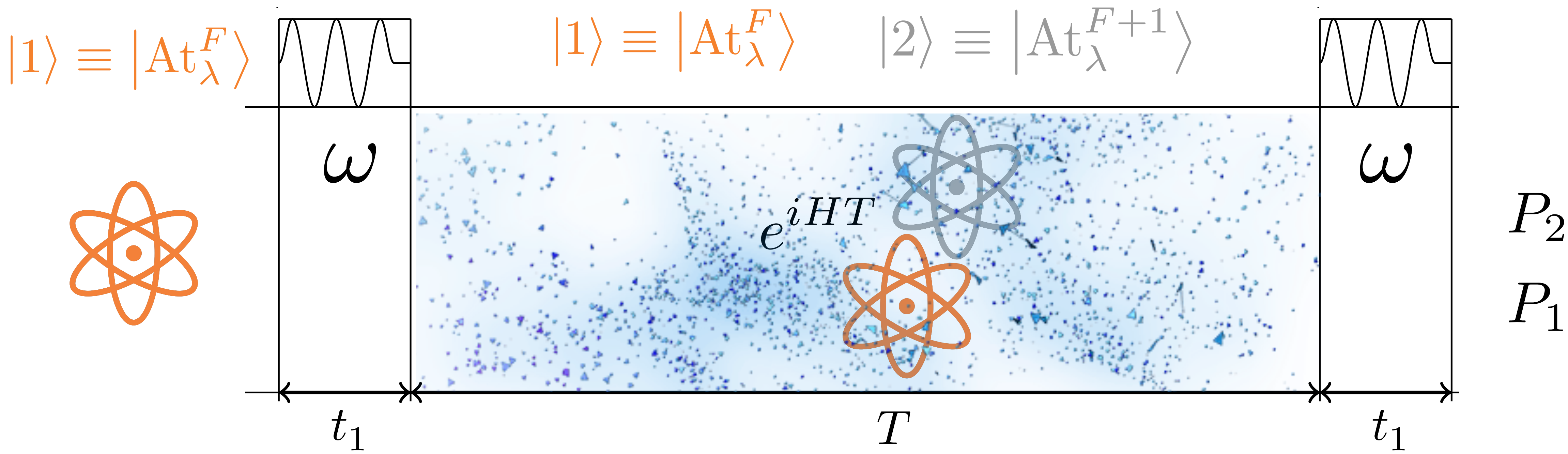

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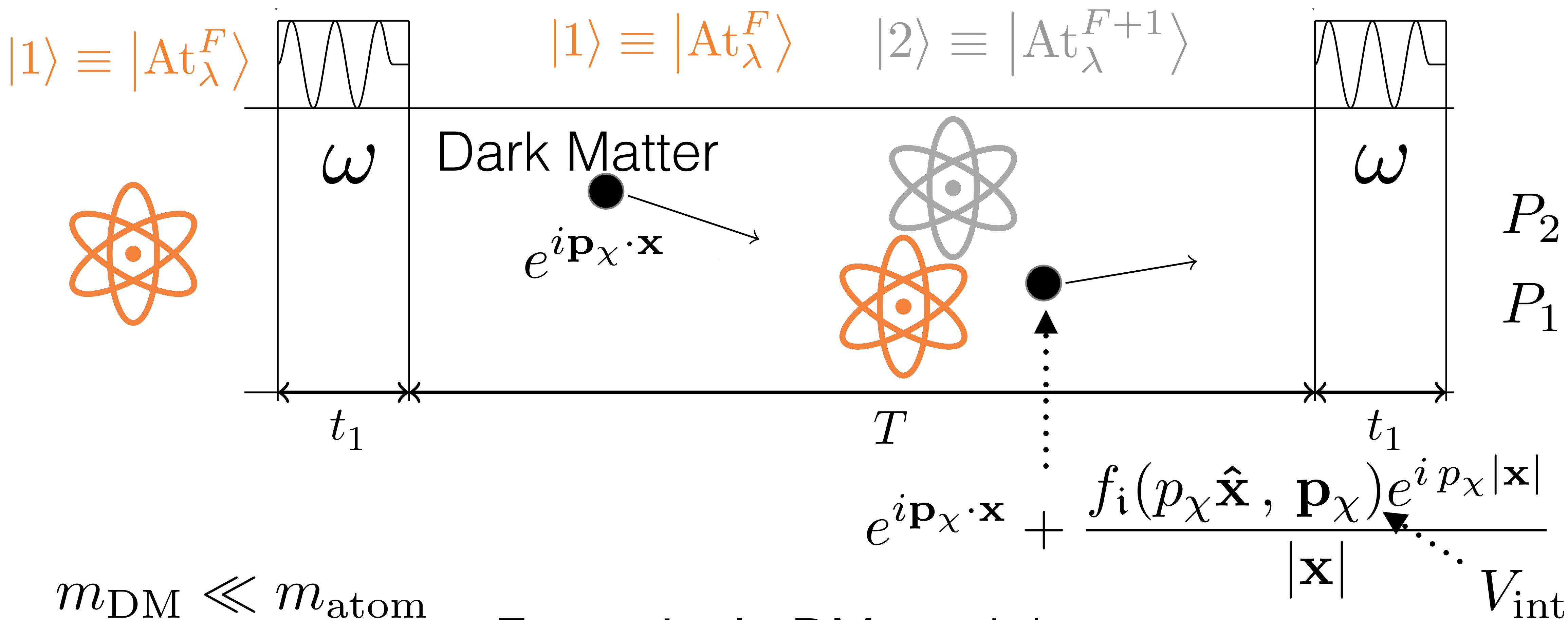
measurement of the phase difference e^{iHT}

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

provided $\delta V_i \neq 0$ (analogy with MSW if useful)

DM-atom interaction during Ramsey sequence

Ramsey sequence



$m_{\mathrm{DM}} \ll m_{\mathrm{atom}}$

For **a single** DM particle

Wolf, Alonso, DB. 1810.01632

$$P_2 \simeq \cos[\Delta\omega T/2]^2 + \frac{1}{2 p_\chi d^2} \mathrm{Re}\left[f_1(0) - f_2(0)\right] \sin[\Delta\omega T/2]$$

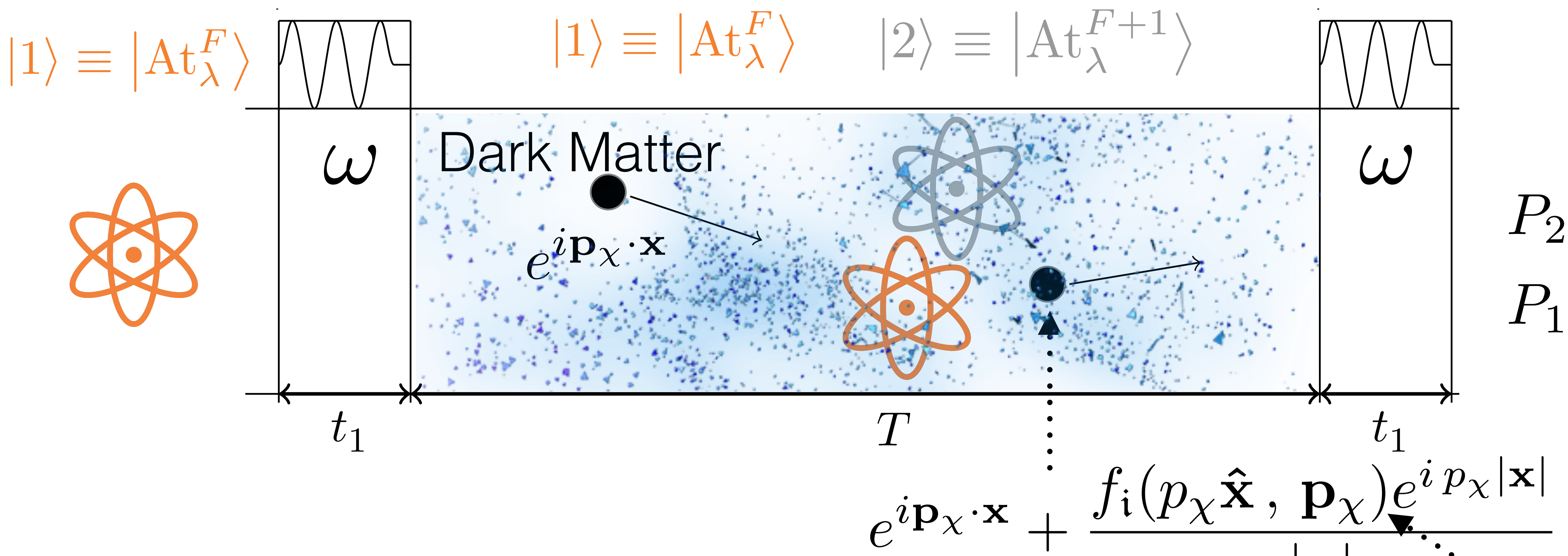
wave-packet size

$$f_i(q=0) \equiv f_i\left(\mathbf{p}_\chi, \mathbf{p}_\chi\right)$$

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

DM-atom interaction during Ramsey sequence

Ramsey sequence



$m_\mathrm{DM} \ll m_\mathrm{atom}$

For **FLUX** of DM

Wolf, Alonso, DB. 1810.01632

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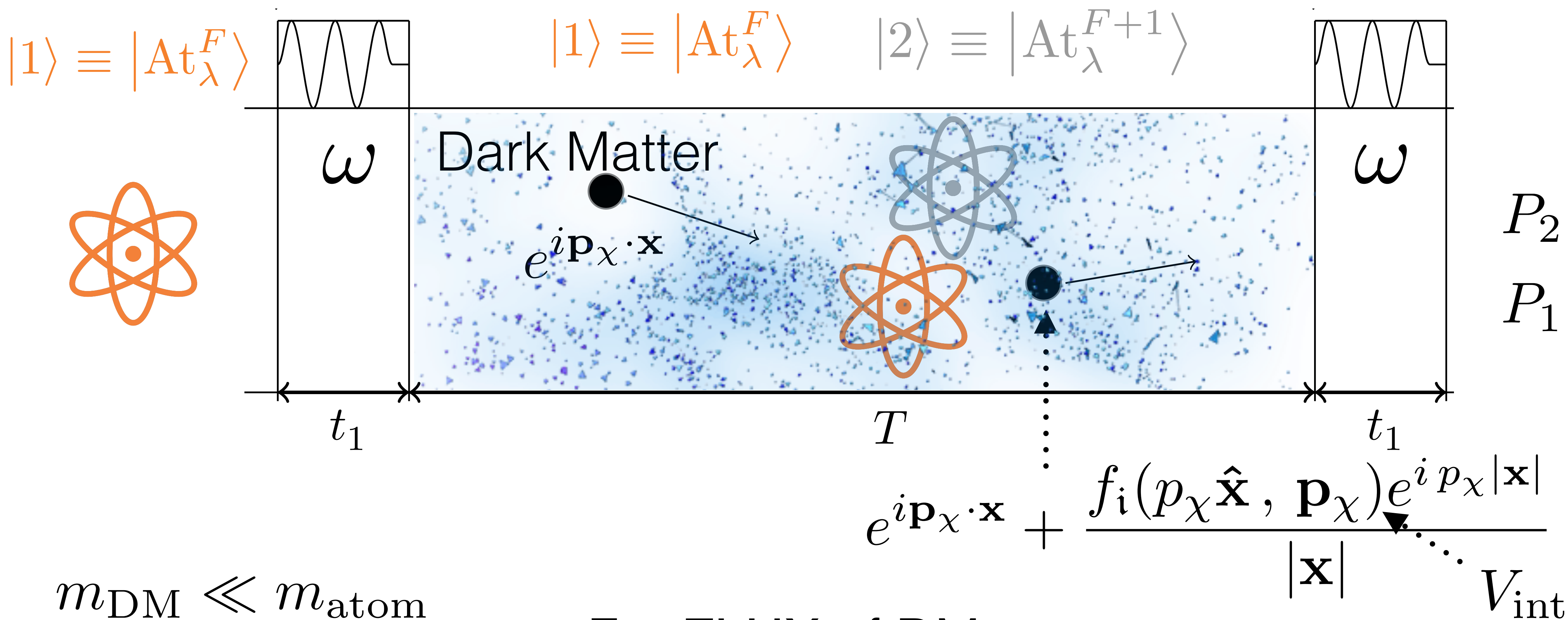
Ramsey sequence



$m_{\mathrm{DM}} \ll m_{\mathrm{atom}}$

For **FLUX** of DM

Wolf, Alonso, DB. 1810.01632

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

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

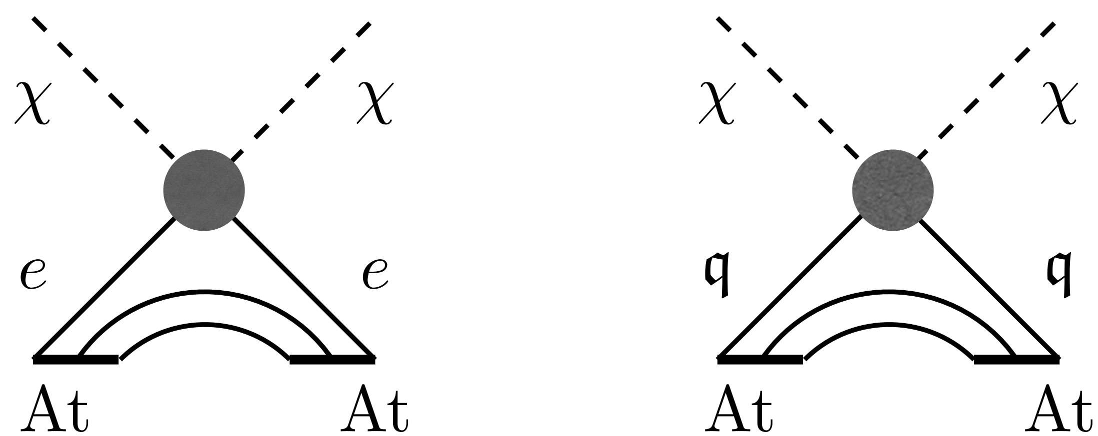
The measured phase can be used to detect the interaction if

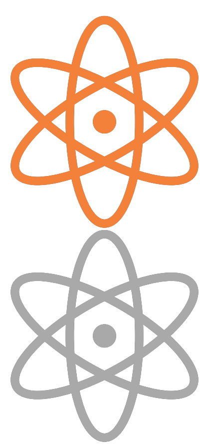
$$f_F(0) - f_{F+1}(0) \neq 0$$

DM-atom scattering: effective vertex

$$f\left(\mathbf{p}',\mathbf{p}\right) = -\frac{\mu}{2\pi}\mathcal{T}\left(\mathbf{p}',\mathbf{p}\right)$$

Born: $$\left\langle \mathbf{P}',\mathbf{p}'\left|H_{\rm int}\right|\mathbf{P},\mathbf{p}\right\rangle = (2\pi)^3\delta^{(3)}\left(\mathbf{P}'-\mathbf{P}\right)\mathcal{T}\left(\mathbf{p}',\mathbf{P}',\mathbf{p},\mathbf{P}\right)$$





$$\left|{\rm Rb}^F_\lambda\right\rangle = \sum_{\lambda_e,\lambda_I}\left|e^{5s}_{\lambda_e}\right\rangle\otimes\left|{\rm Ncl}^I_{\lambda_I}\right\rangle\left\langle 1/2,\,\lambda_e,\,I,\,\lambda_I\left|F,\,\lambda\right.\right\rangle$$

DM current

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

effective vertices: only those for which $f_1(0)-f_2(0)\neq 0$

Spin dependent couplings! e.g. $\left\langle e\left|\bar{e}\gamma^\mu\gamma_5 e\right|e\right\rangle = \left(0,2\vec{S}_e\right)$

Main results

Alonso, DB, Wolf 1810.00889

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

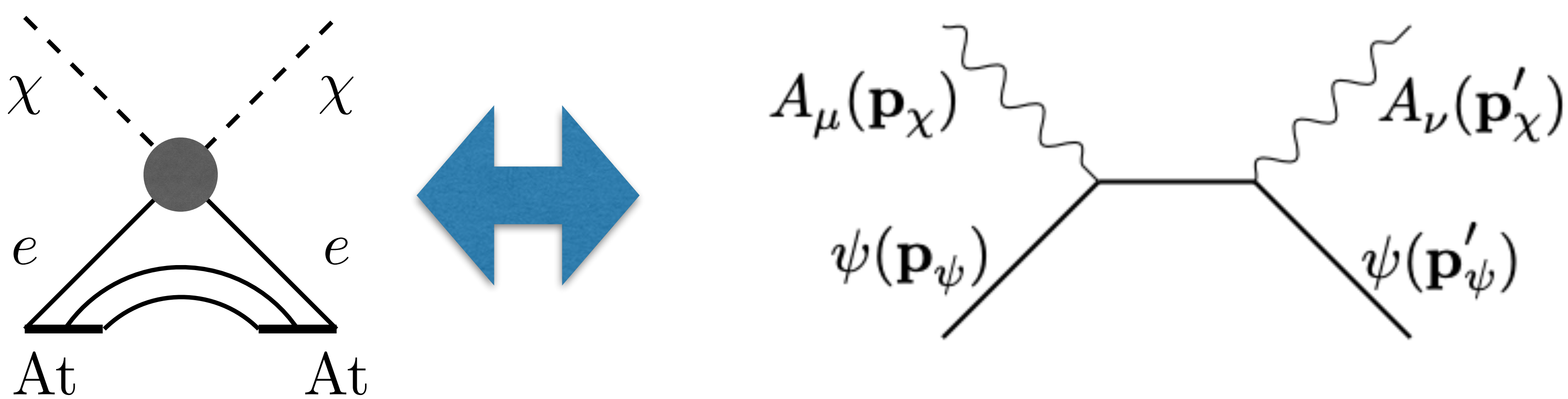
$f_1(0) \to (F, \lambda)$ $\quad$ $f_2(0) \to (F+1, \lambda)$

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

$$\vec{J}^N_{\rm Ncl} = 2\mathfrak{g}^N_{\rm Ncl}\vec{I}$$

nucleon form factors
$G_N(G_u, G_d)$

for scattering with axial vectors $A_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$



$$f_1(0) - f_2(0) = \frac{-1}{\pi m_A}\left(\left(g^A_N\right)^2\mathfrak{g}^N_{\rm Ncl} - \left(g^A_e\right)^2\right)\frac{\vec{\lambda}\cdot\vec{\lambda}_A}{F}$$

(cancels at first order for pseudo-scalars)

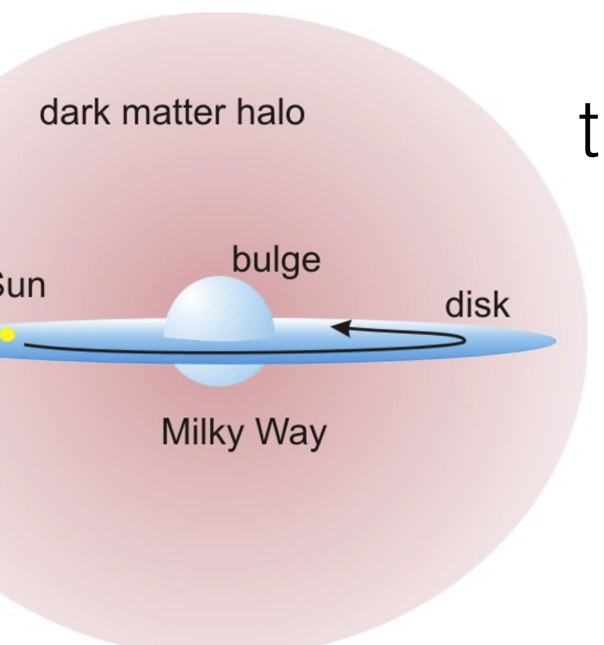
Which DM-atom interactions?

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

We probe *spin-dependent interactions*

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

average effect



the relative velocity contains a **coherent** part

the DM spin is in principle **arbitrary**

$O(1/\sqrt{N})$ suppression (independent scatterings)

but detectable as 'noise'

$$N_{\rm at} \sim 10^6$$
$$l \sim {\rm cm},\; t \sim {\rm s}$$

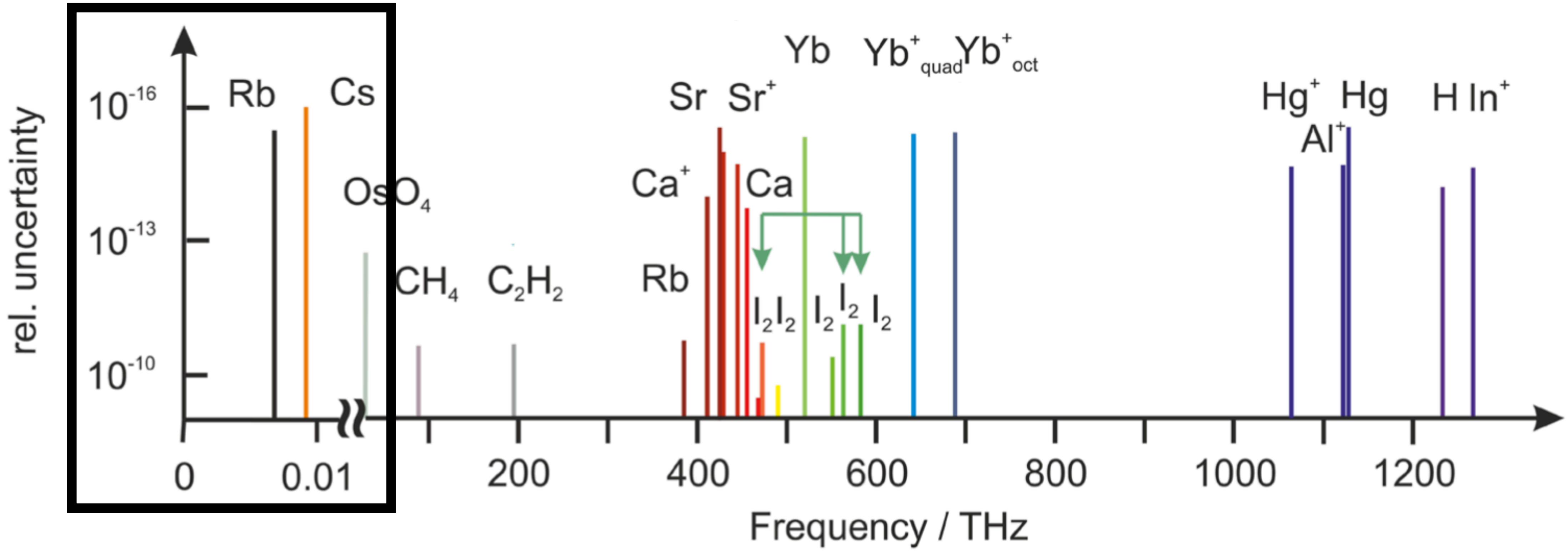
final remark

one needs to make sure that the effect is
not confused with atomic physics/backgrounds
(e.g. use daily modulation, system comparison…)

$$\omega_{\max} = \Delta E + \delta_{\rm DM}$$ → absolute shift

more accurate for **absolute** shifts!

$$\frac{\delta\left(E_2 - E_1\right)}{E_2 - E_1} < 10^{-15}$$



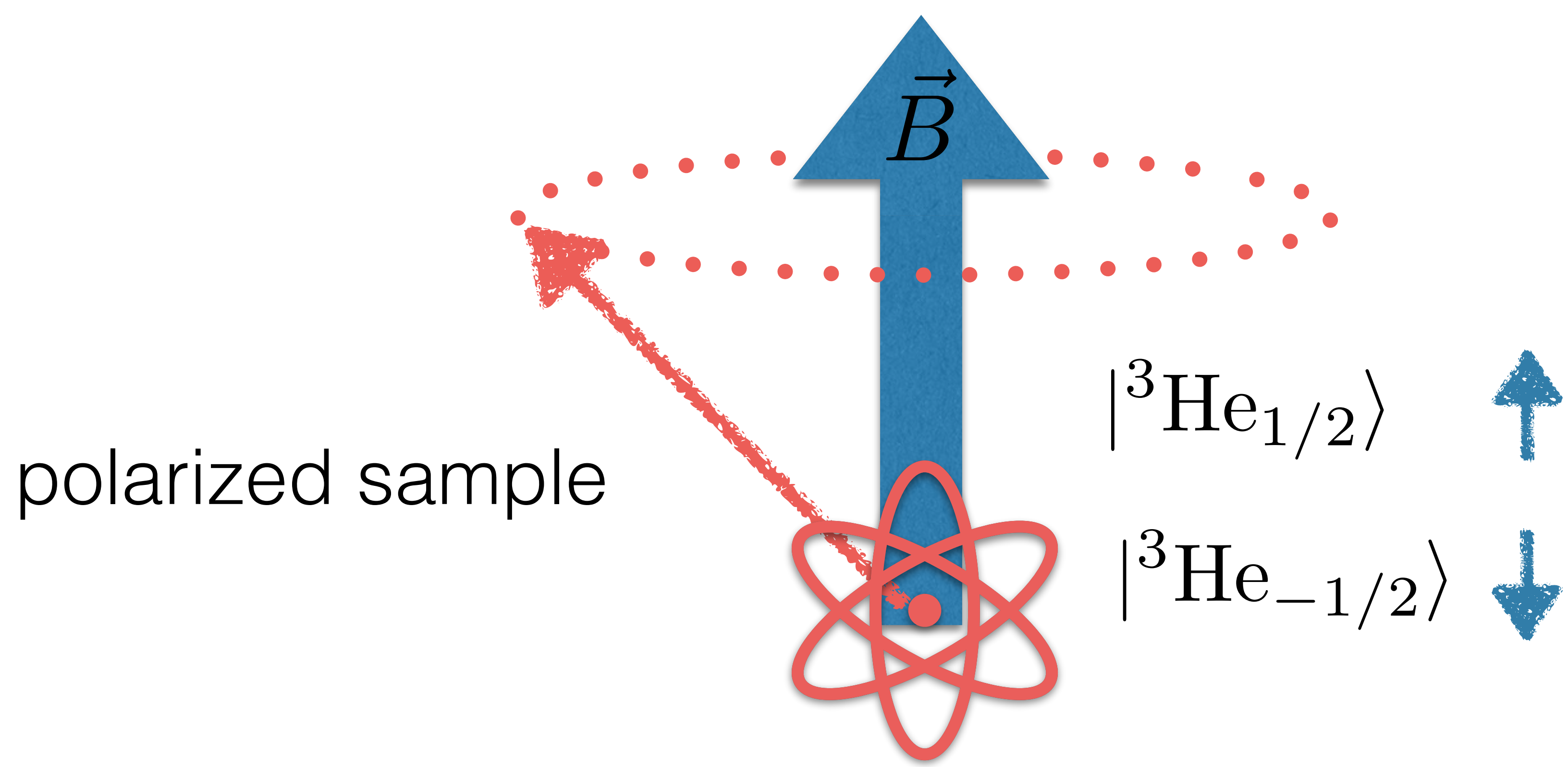
Q: Are atomic clocks the best way to measure differences in absolute energies of levels of different spin?

$$\Delta\omega \lesssim 10^{-15}\omega \sim 10^{-15} \times 10\,\mathrm{GHz} \sim 10^{-5}\,\mathrm{Hz}$$

Atomic magnetometers basics

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

$N_{\rm at} \sim 10^{22}$



same with ^{129}Xe

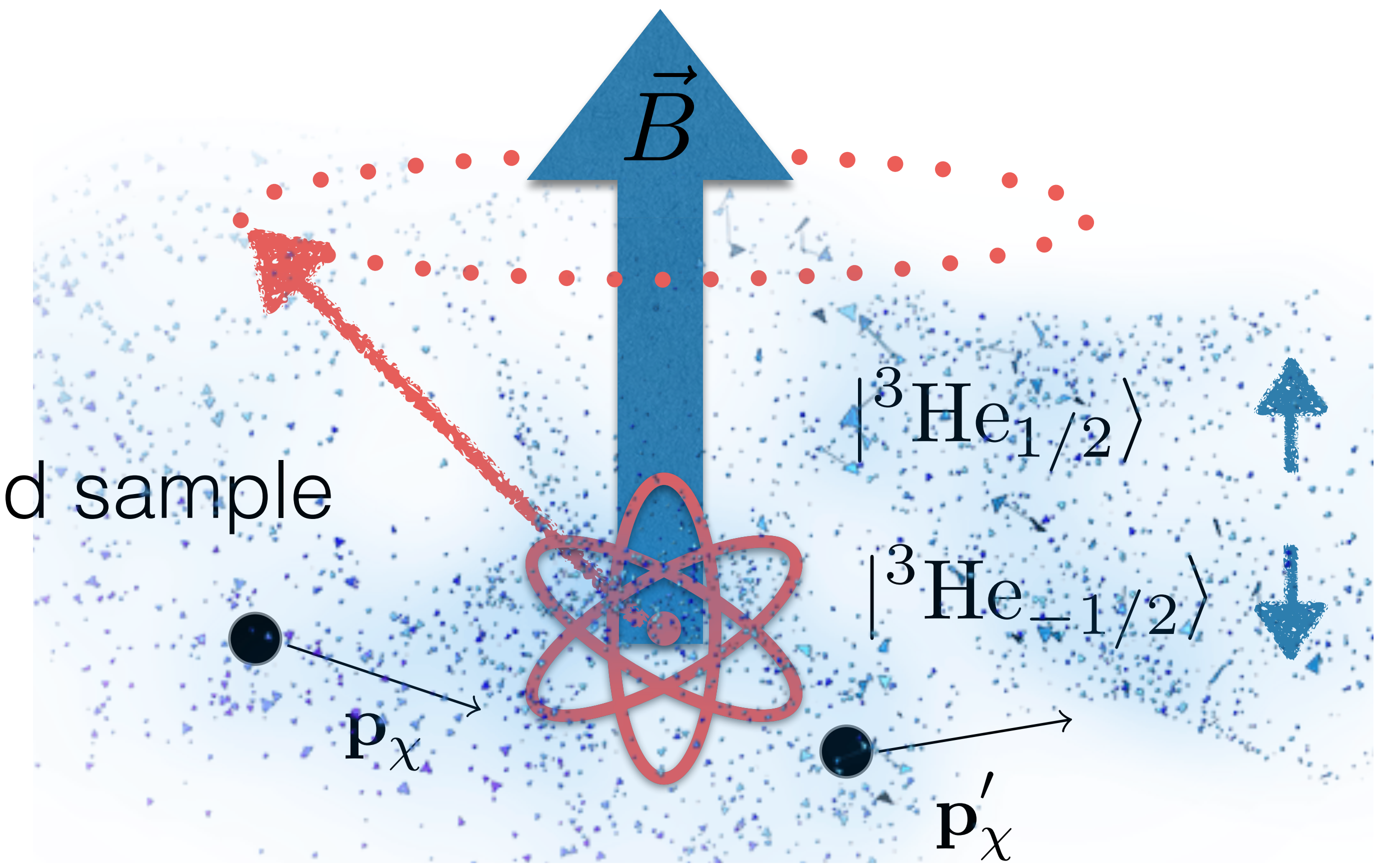
$$\omega \equiv \gamma\beta = \gamma \Big(B \qquad\qquad\qquad\qquad \Big)$$

DM-atom interaction in co-magnetometers

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

$N_{\text{at}} \sim 10^{22}$

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

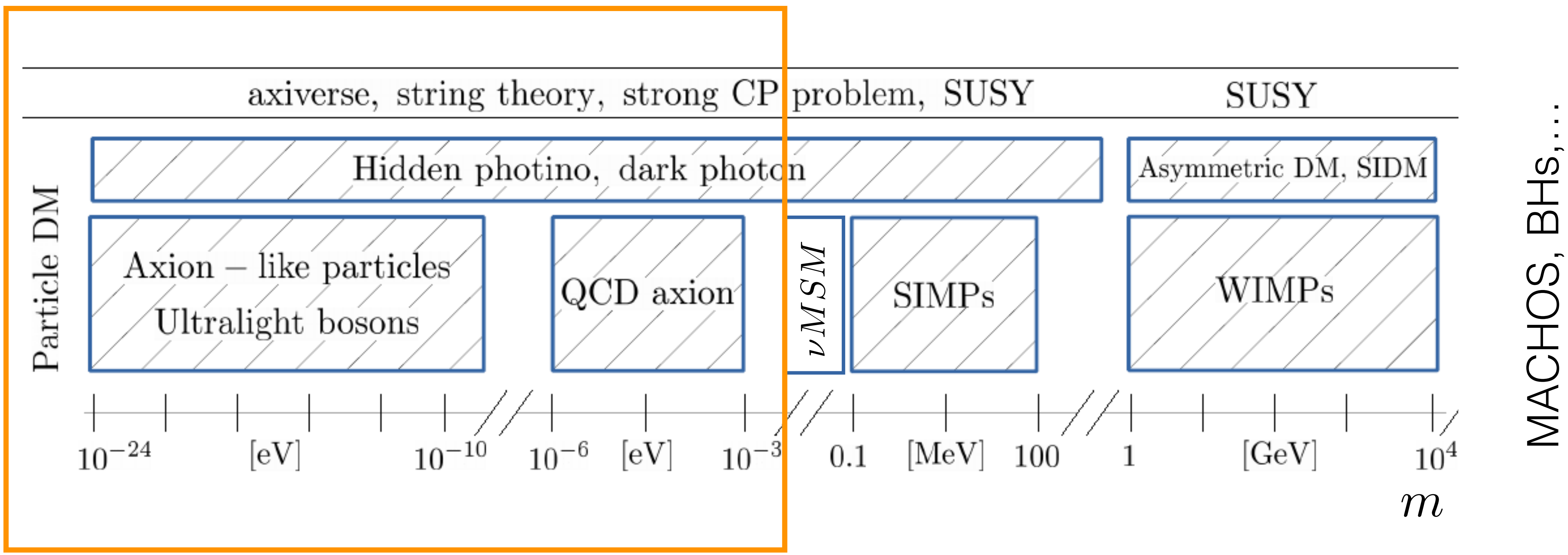
Can be also understood as a phase difference

Co-magnetometer: eliminates *B*

$\Delta\omega \lesssim 10^{-9}\,\text{Hz}$ Brown et al. 2010

New effects of the ultra-light domain

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



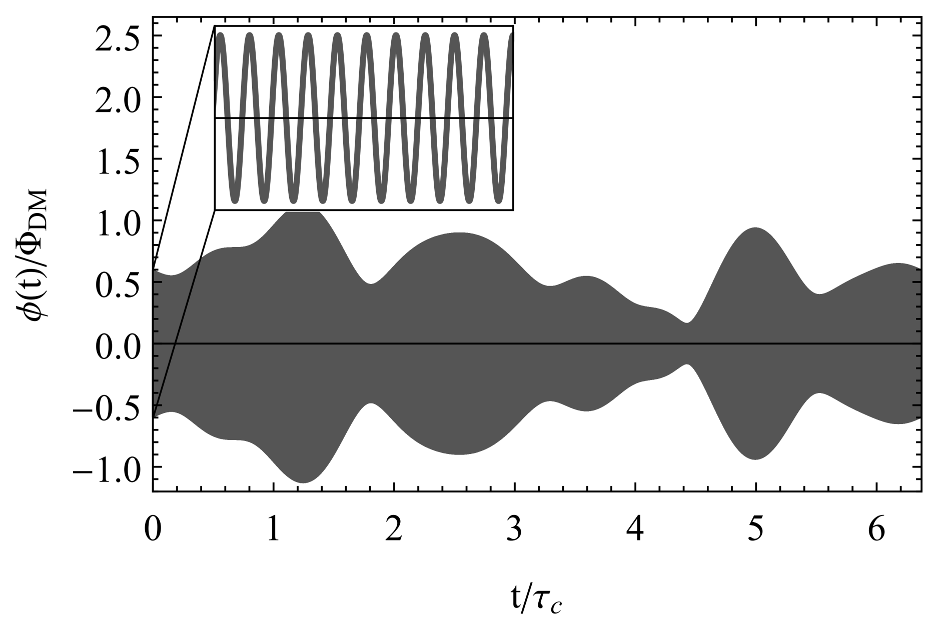
'Coherent' effects of ULDM in the MW

Virialized collection of waves

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

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

since $v \sim \sigma_0 \ll 1$ ➔ $\omega_v \approx m(1+v^2)$ ➔ $\phi \propto \phi_0 \cos(mt + f)$



Centers et al 1905.13650

$$\tau_c \sim 8\,\mathrm{months} \left(\frac{10^{-3}}{V_0}\right)^2 \left(\frac{10^{-15}\mathrm{eV}}{m_\Phi}\right)$$

The ultra-light domain: interaction with atoms

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

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

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

these are now 'oscillating' backgrounds!

Graham et al 1709.07852

• •

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!

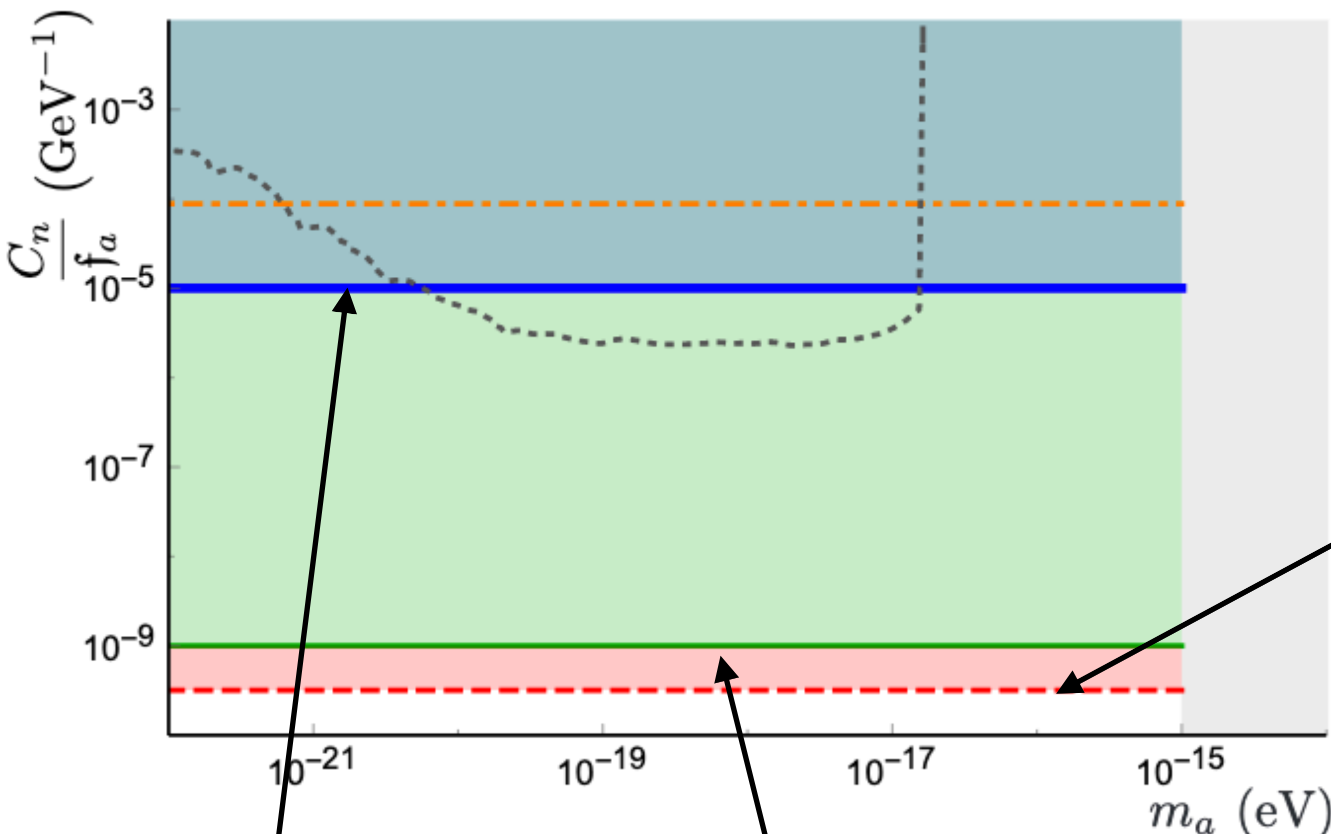
Arvanitaki et al 1405.29205
+ Stadnik and Flambaum 16 + Hess et al 16 + Derevianko and Pospelov 13

Estimates: three examples

Graham et al 1709.07852
Alonso, DB, Wolf 1810.00889

axionic DM

$$\frac{-C_\psi}{2\mathfrak{f}_a}\int \mathrm{d}^3x\bar{\psi}\gamma_\mu\gamma_5\psi\partial^\mu a \quad \blacktriangleright \quad \vec{S}_n\cdot\vec{v}_\chi$$

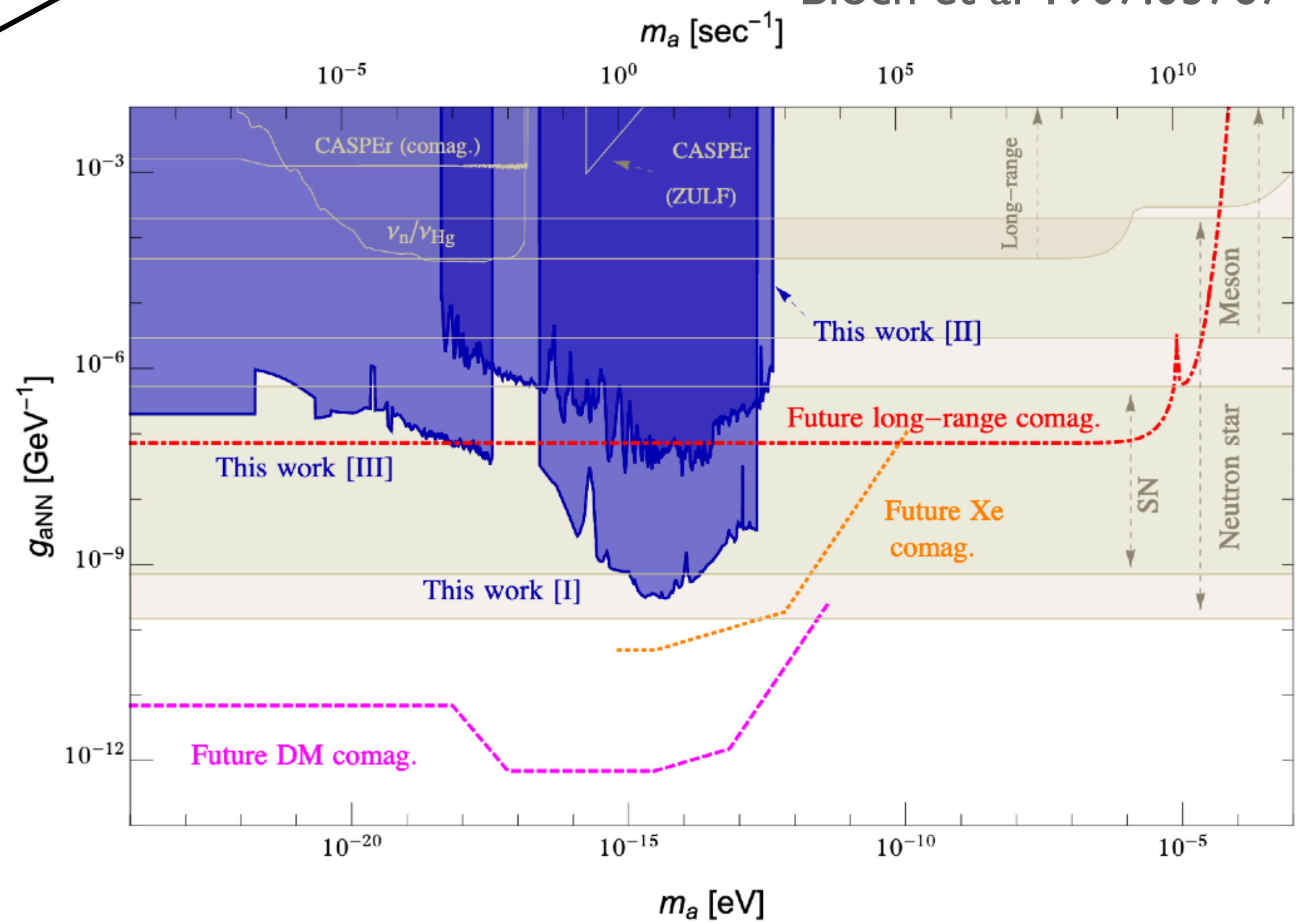


previous bounds
(astrophysics)

clocks estimates
(data Guena et al 2014)

magnetometer estimates
(data Brown et al. 2010)

Bloch et al 1907.03767



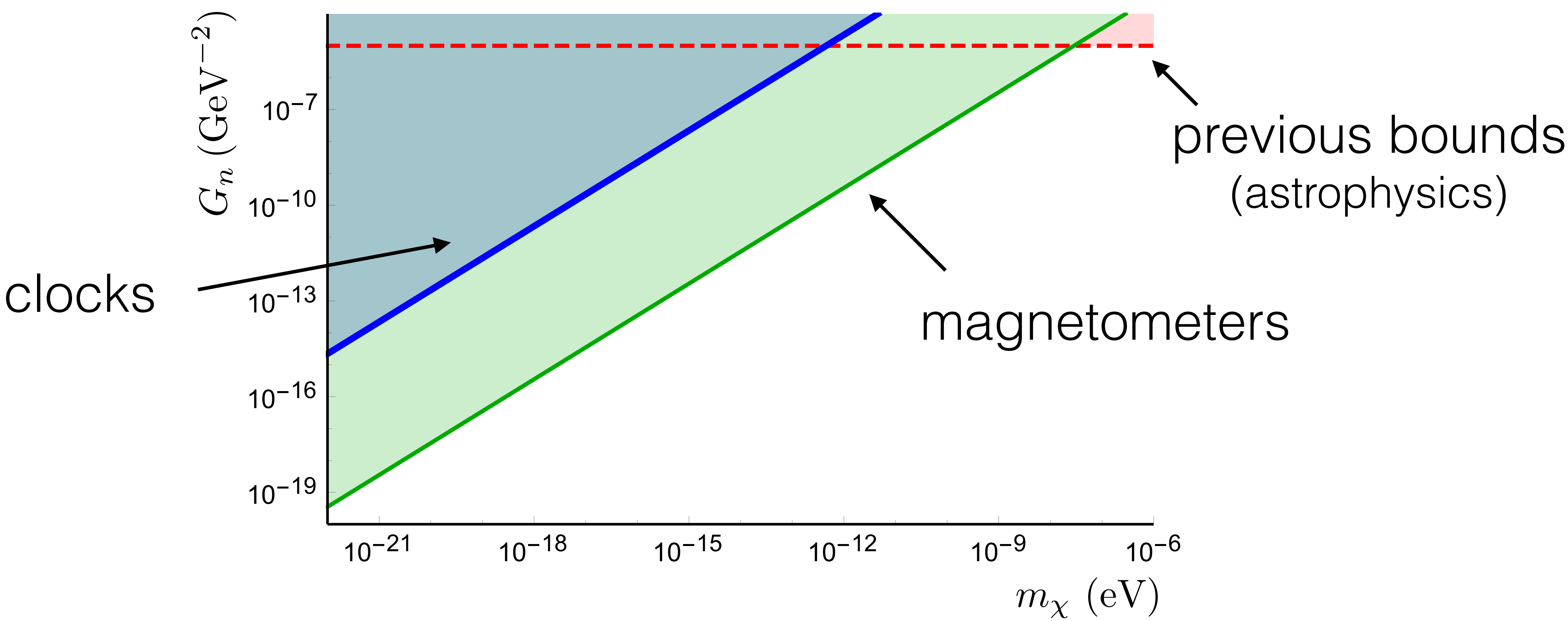
Estimates: three examples

Alonso, DB, Wolf 1810.00889

complex scalar DM

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

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



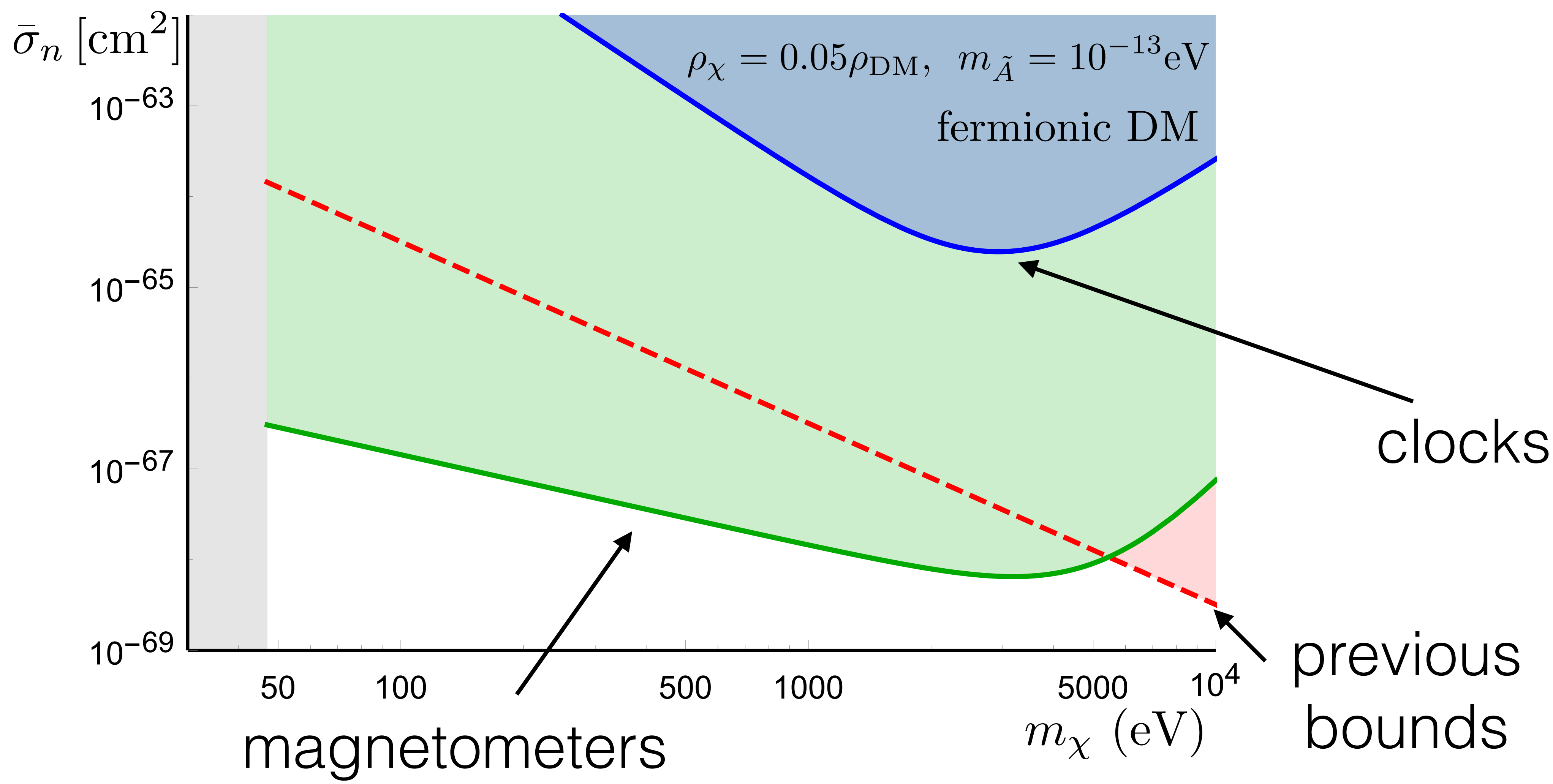
Estimates: three examples

Alonso, DB, Wolf 1810.00889

fermionic DM with light mediator

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

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



Summary and Conclusions

- Precise (quantum) devices perfect for small momentum transfer (typical of low mass DM)

- **Standard operation** of **atomic clocks/magnetometers** yields new bounds on some DM-SM couplings

- New possibilities to explore!

Future

- More complete cosmology framework for some models
- Other operators (e.g. momentum dependent couplings)

  when $\bar{f}(0)_1 - \bar{f}(0)_2 \neq 0$ (optical/nuclear clocks?)
- Neutrinos? (CnB seems out of reach) Alonso, DB, Wolf 1810.00889
- Devices close to beams for large fluxes of small *m* particles?
- Other precise devices…atom interferometry?