KING'S College LONDON

# Light dark matter @ atomic clocks and co-magnetometers


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1810.00889 & 1810.01632

# A growing field…

Physics Beyond Colliders

**Quantum Sensing for High Energy Physics**
Zeeshan Ahmed (SLAC) *et al.*. Mar 29, 2018. 38 pp.
FERMILAB-CONF-18-092-AD-AE-DI-PPD-T-TD
Conference: C17-12-12
e-Print: **arXiv:1803.11306 [hep-ex]** | **PDF**

Quantum Sensors for Fundamental Physics
Oxford, UK

16 October - 17 October 2018
Oxford, UK

+ many new ideas/reviews on the theory side

I will only discuss astrophysical backgrounds

# Fresh view on DM

- ☑ 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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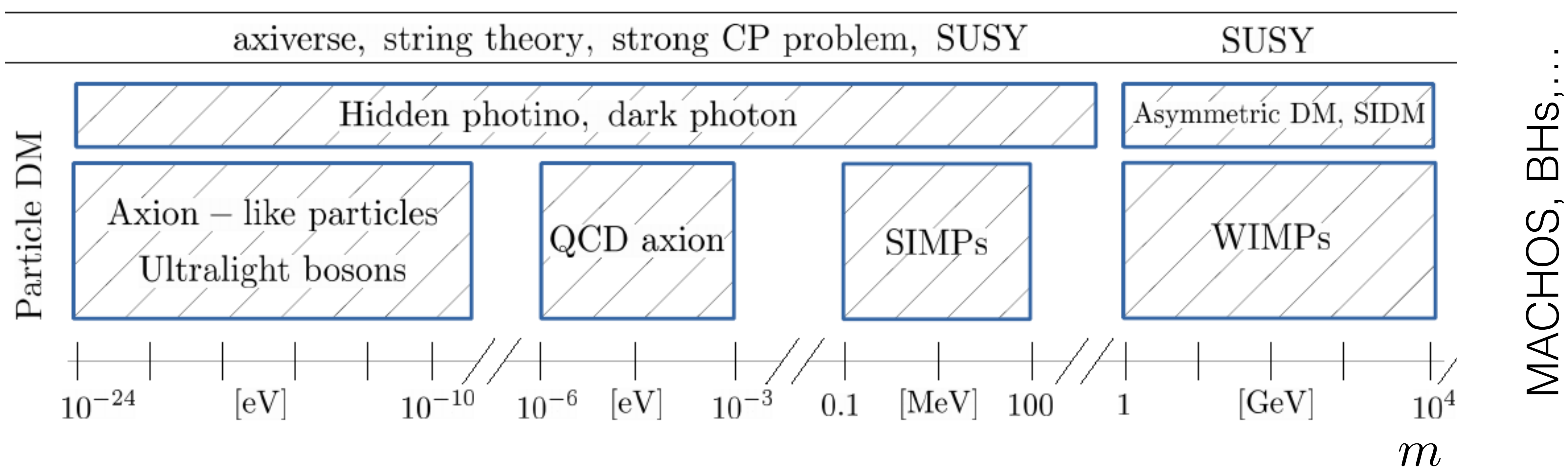
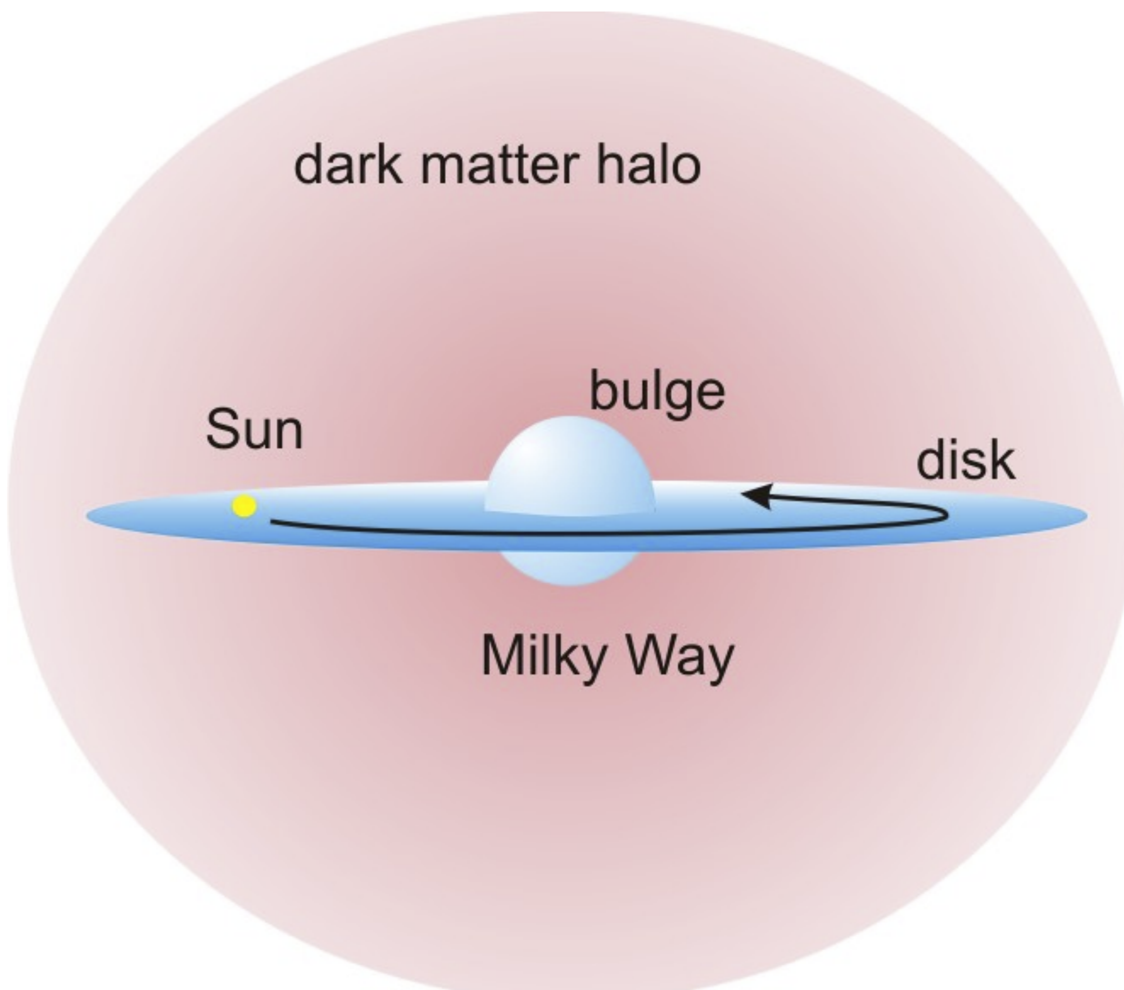


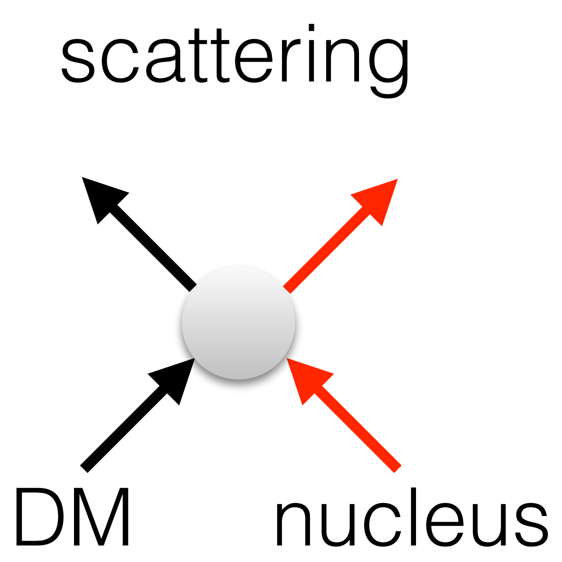
# For the Milky Way




expectation in the Solar system $\left\{ \begin{array}{l} \rho_\odot \sim 0.3\,\mathrm{GeV/cm^3} \\ m_\chi \langle v_\odot \rangle \sim 10^{-3} m_\chi c \end{array} \right.$

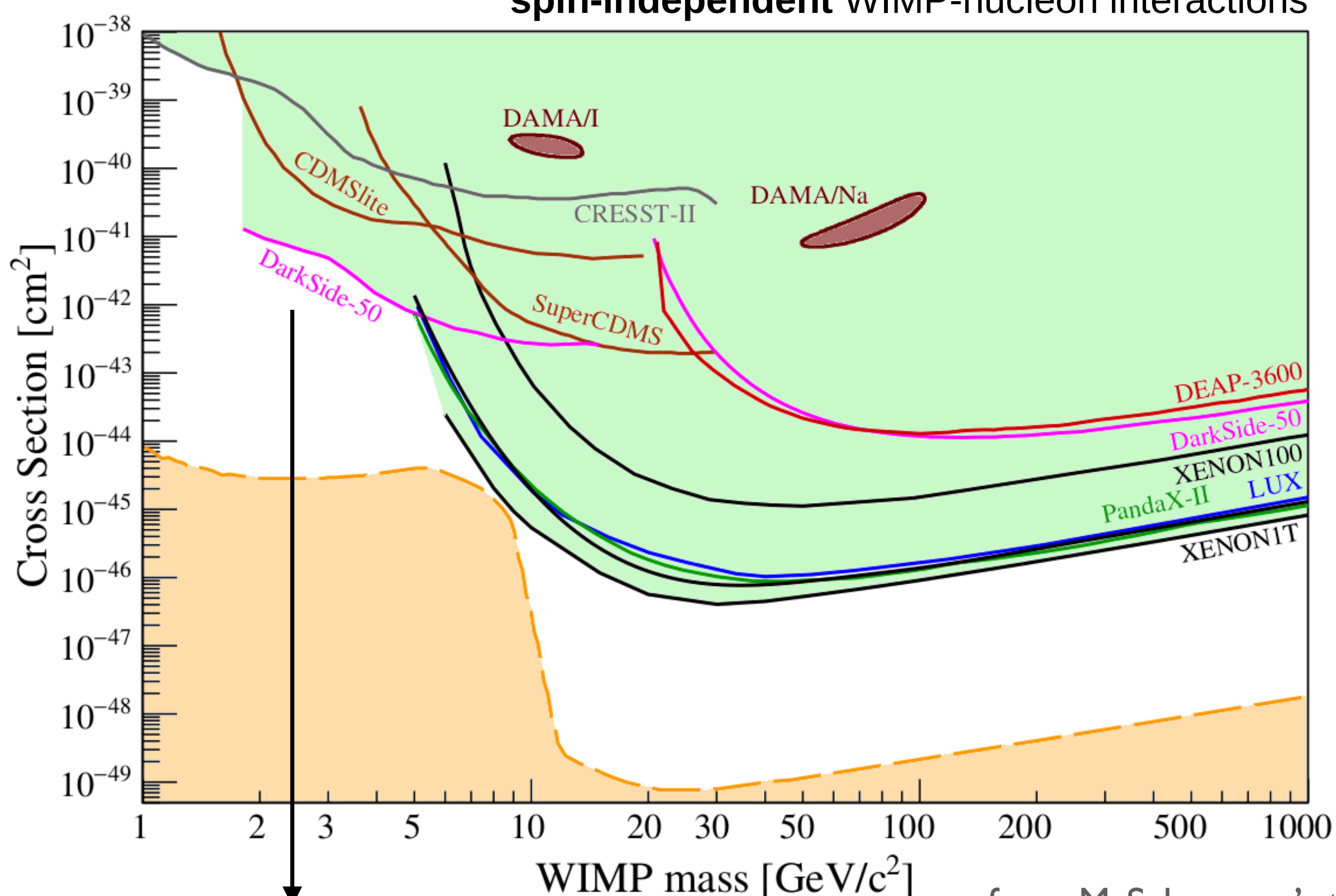
flux: $$10^{10} \left( \frac{\mathrm{MeV}}{m_\chi} \right) \mathrm{cm^{-2} s^{-1}}$$

# ‘Traditional’ Direct Detection




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

**spin-independent** WIMP-nucleon interactions



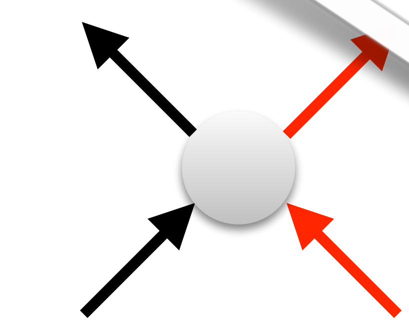

from M. Schumann’s talk

low-energy threshold

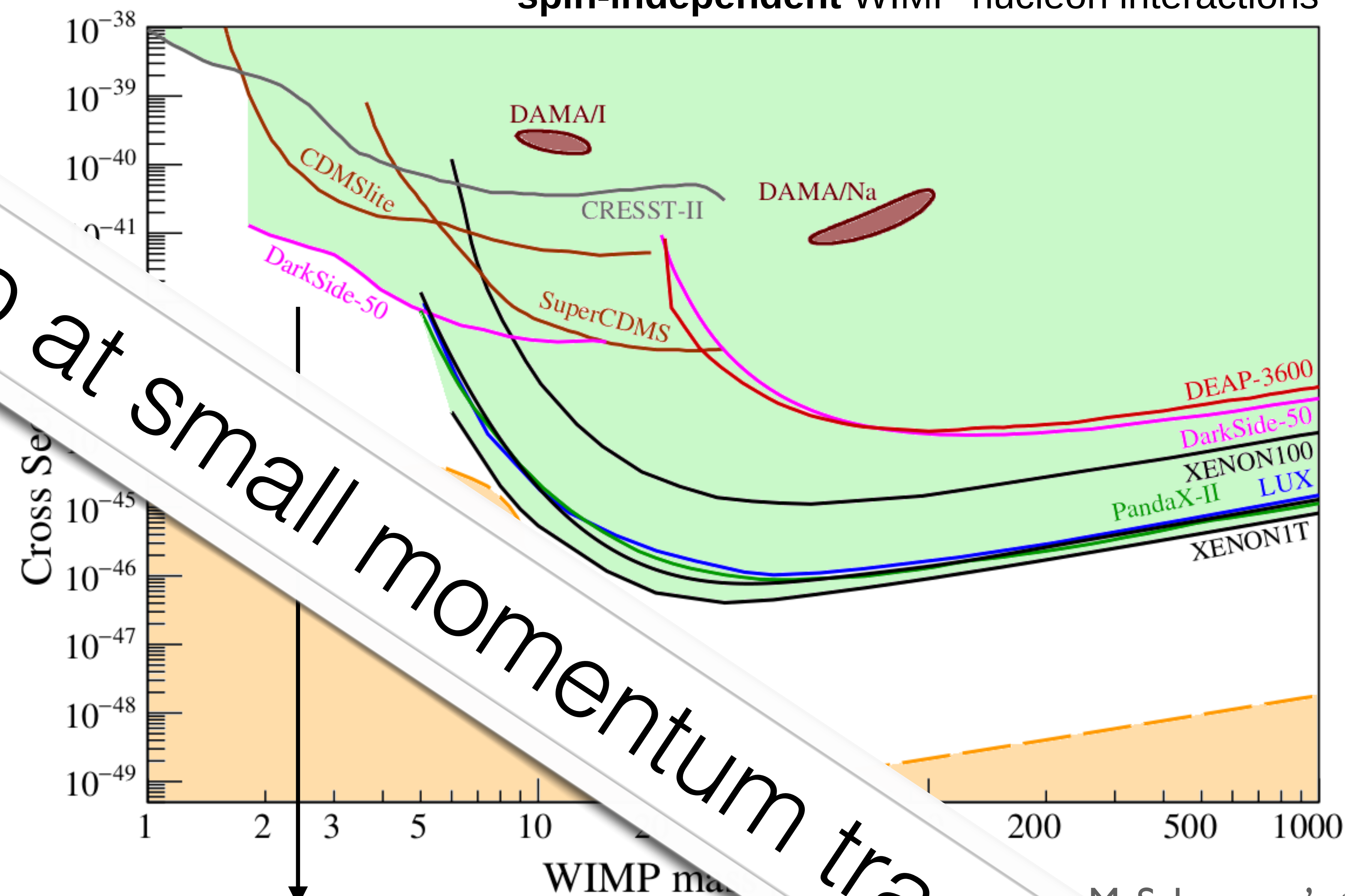
dramatic loss of sensitivity at low mass (still ‘high’ mass)

# ‘Traditional’ Direct Detection

sca




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




M. Schumann’s talk

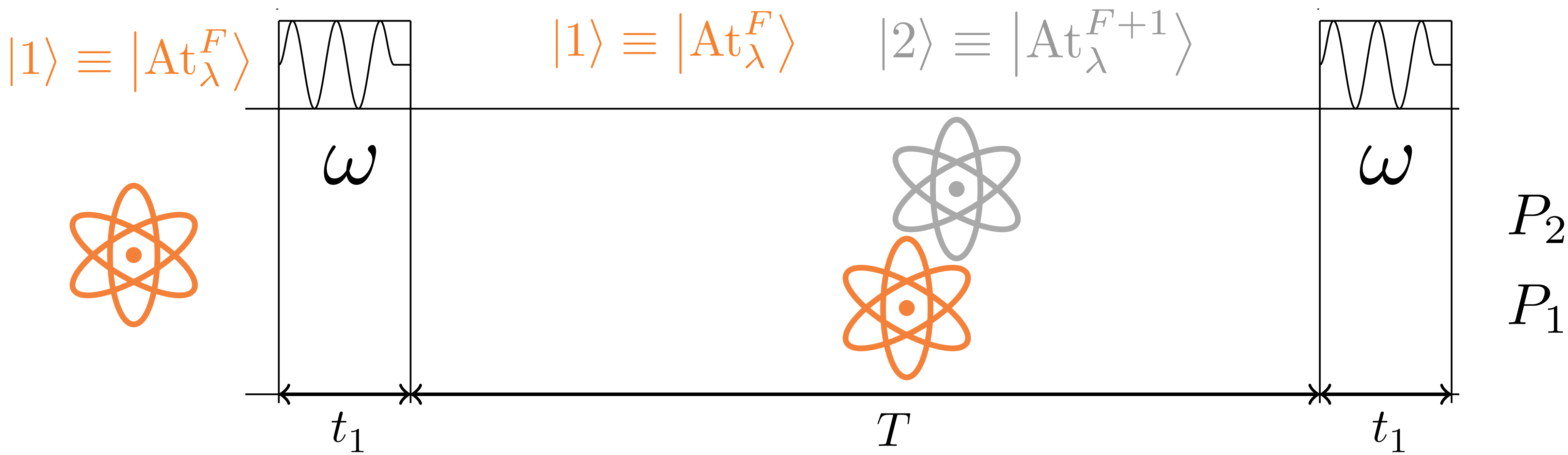
low-energy threshold

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

what to do at small momentum transfer?

# Measuring at $q = 0$: Ramsey sequence

(atomic clock basics)




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

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

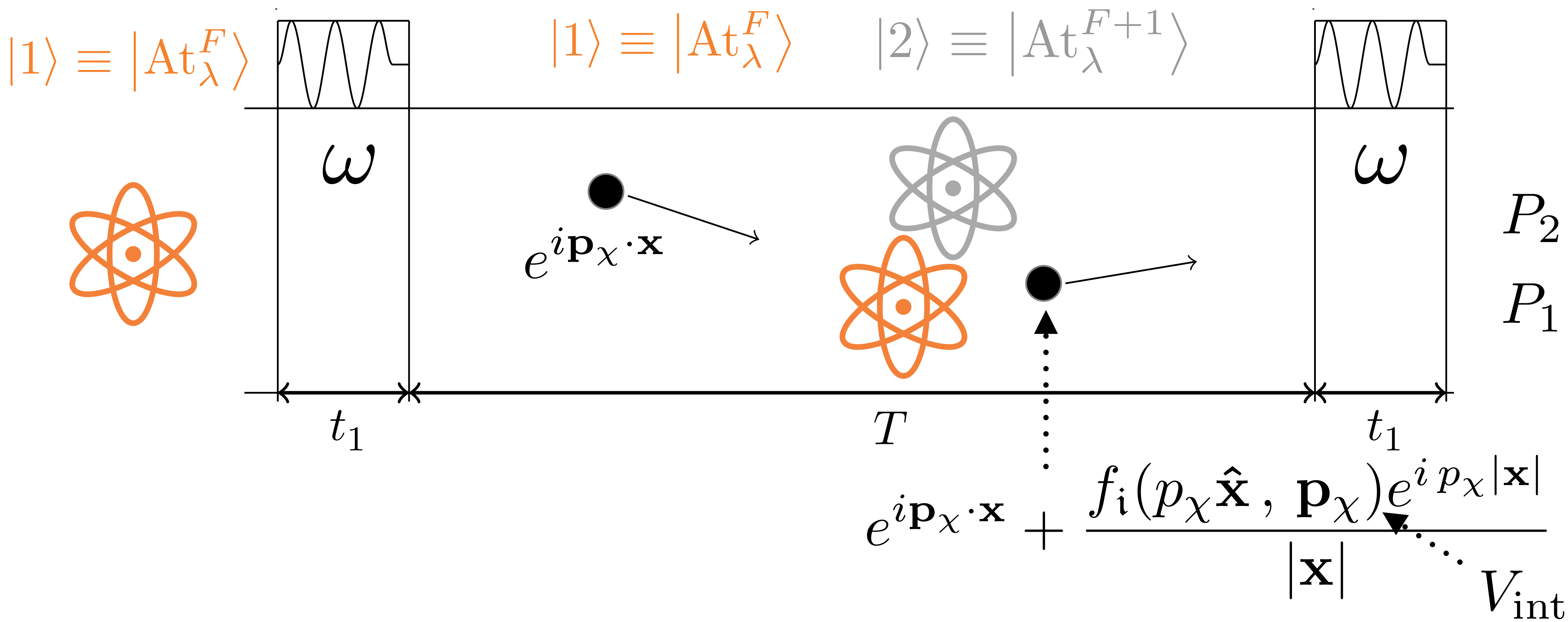
$\partial P_2 = 0$ ➡ $\omega_{\rm max} = \Delta E$

measurement of the phase difference $e^{iHT}$

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

provided $\delta V_i \neq 0$

# DM-atom interaction during Ramsey sequence



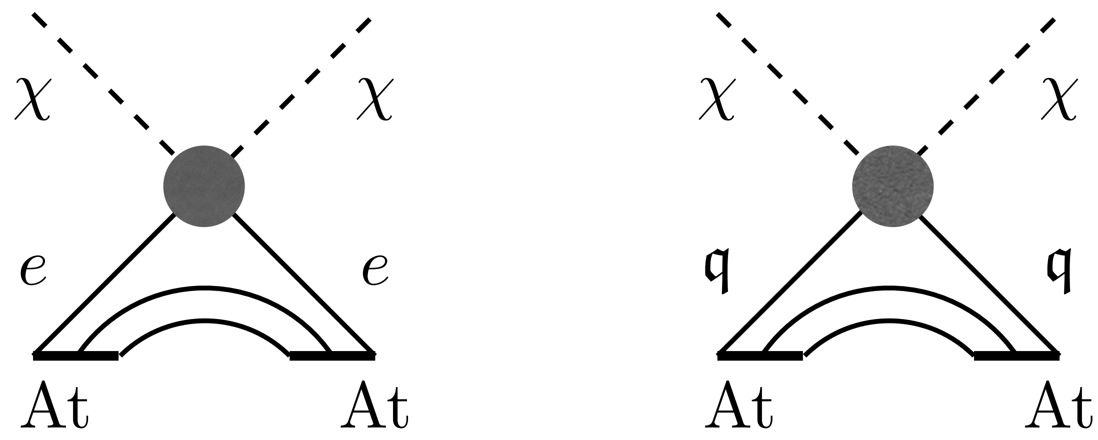

for low masses (all the atoms stay in the clock) & small coupling

forward scattering

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

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

# DM-atom scattering: effective vertex




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

$$\text{“}\sum_{n,p} |N\rangle\text{”}$$

DM current

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

(to nucleon form factors)

At the level of *e, N*: $\vec{S}_e \cdot \vec{v}_\chi\,,\ \vec{S}_e \cdot \vec{S}_\chi,\ \vec{S}_N \cdot \vec{S}_\chi\,,\ \ldots.$

# Main results

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

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

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

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

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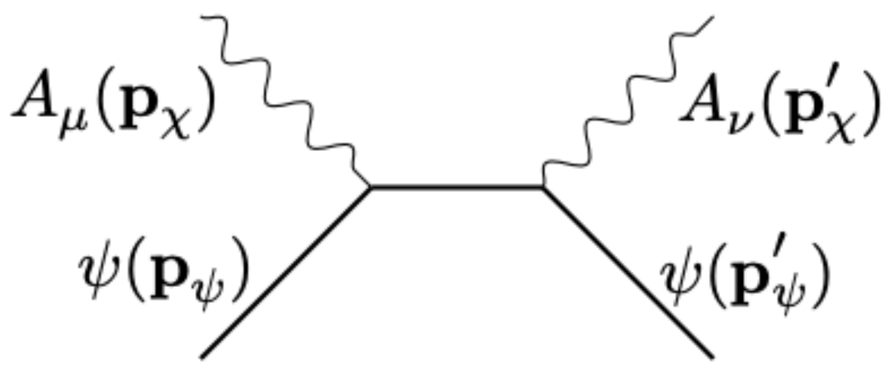
for scattering with axial vectors




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

(cancels at first order for axions)

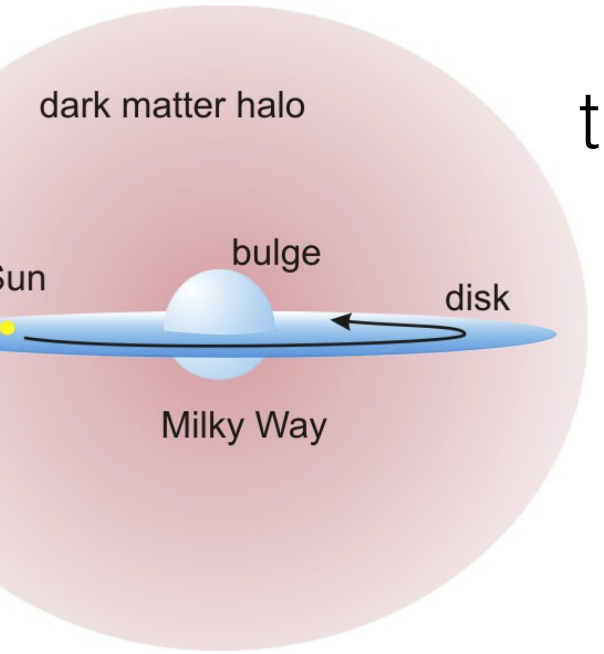
# Which DM-atom interactions?

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

The two states have different *spin*
We easily 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**

$O(1/\sqrt{N})$ 'noise'*

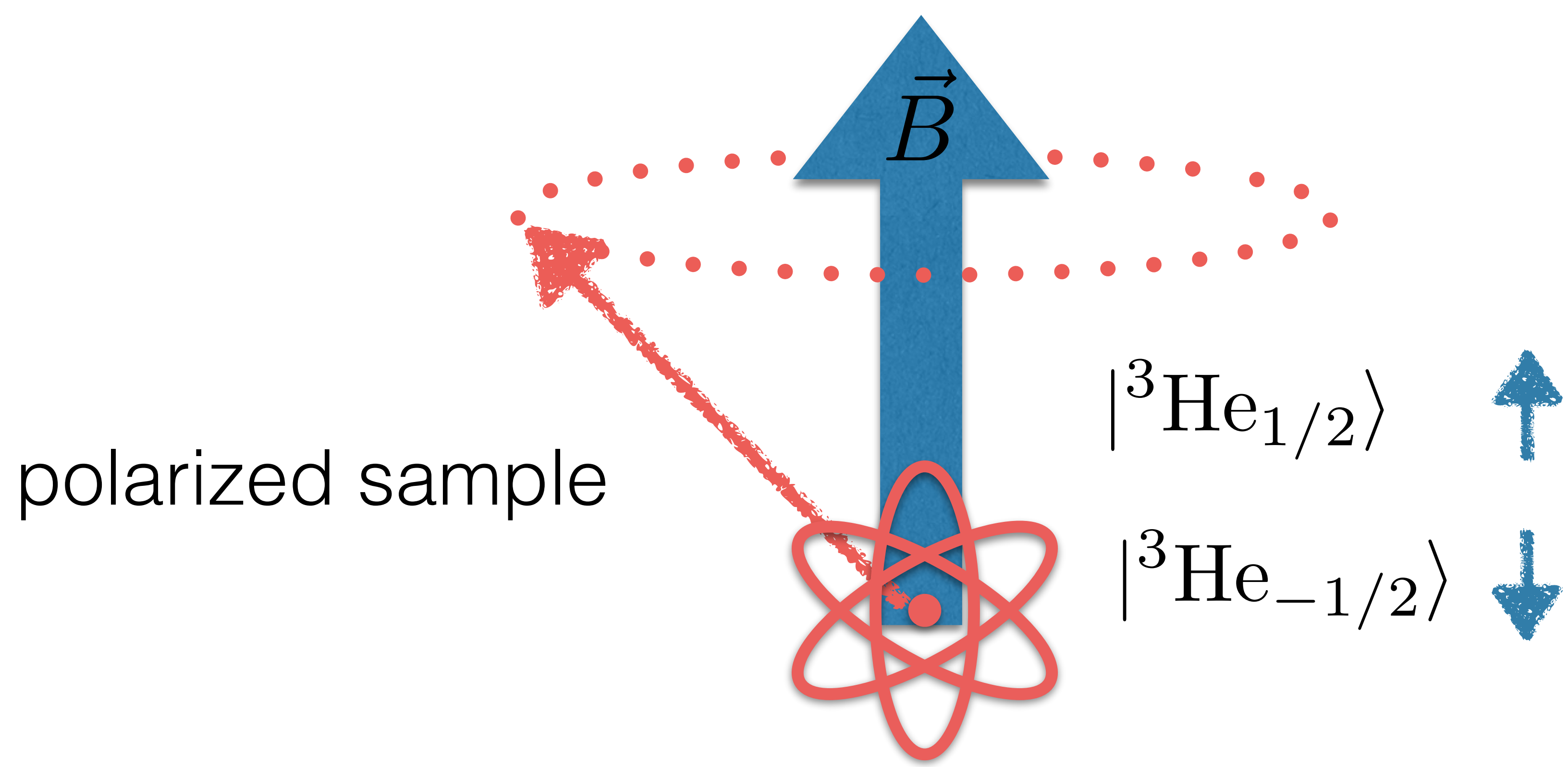
* depends on $N_{\rm at}^{\chi}$

final remark

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

# Atomic magnetometers basics

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



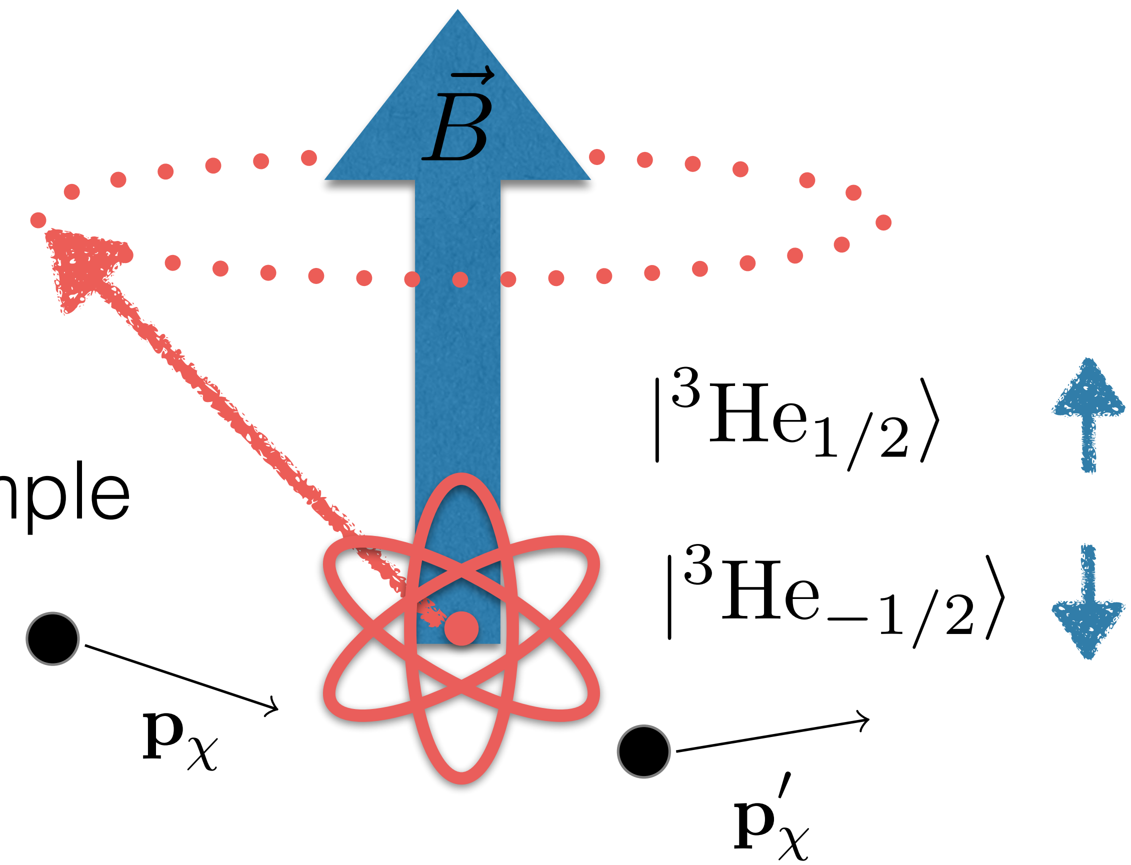

same with $^{129}\mathrm{Xe}$

$$\omega \equiv \gamma \beta = \gamma \left( B \qquad\qquad\qquad\qquad \right)$$

# DM-atom interaction in co-magnetometers

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

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*

# The ultra-light domain: galactic configuration

For $m \lesssim 10\ \mathrm{eV}$ high occupation numbers in the MW (similar to classical EM)

Collection of virialized waves

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

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

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

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

# The ultra-light domain: interaction with atoms

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

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

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

these are now 'oscillating' backgrounds!

Graham et al 17

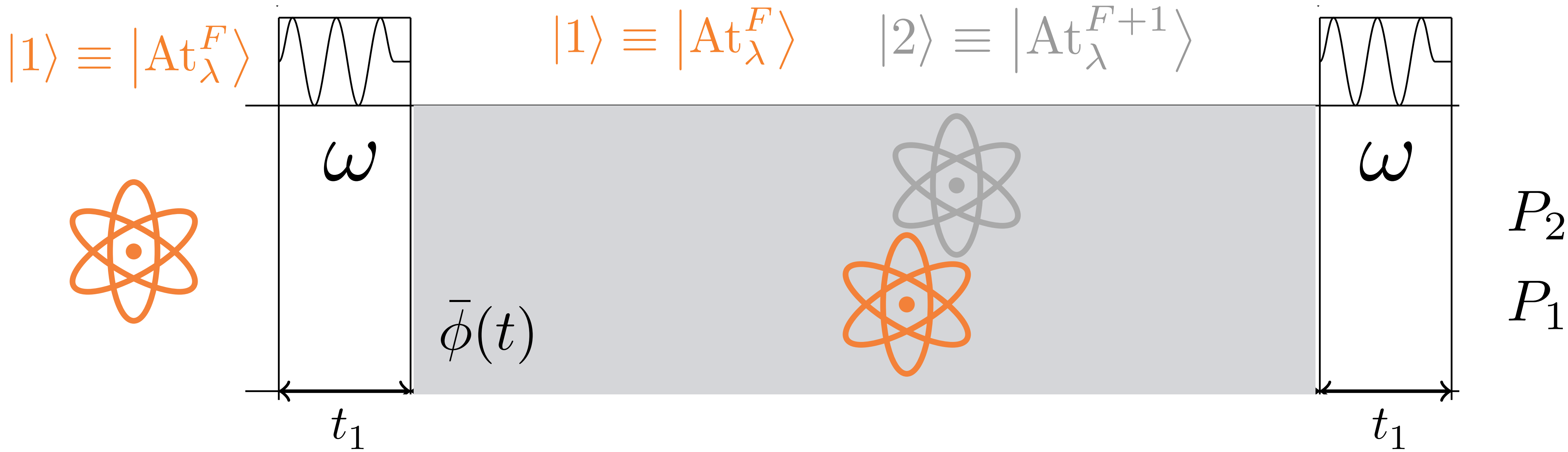
for generic couplings this means the
**oscillation of 'fundamental constants'**

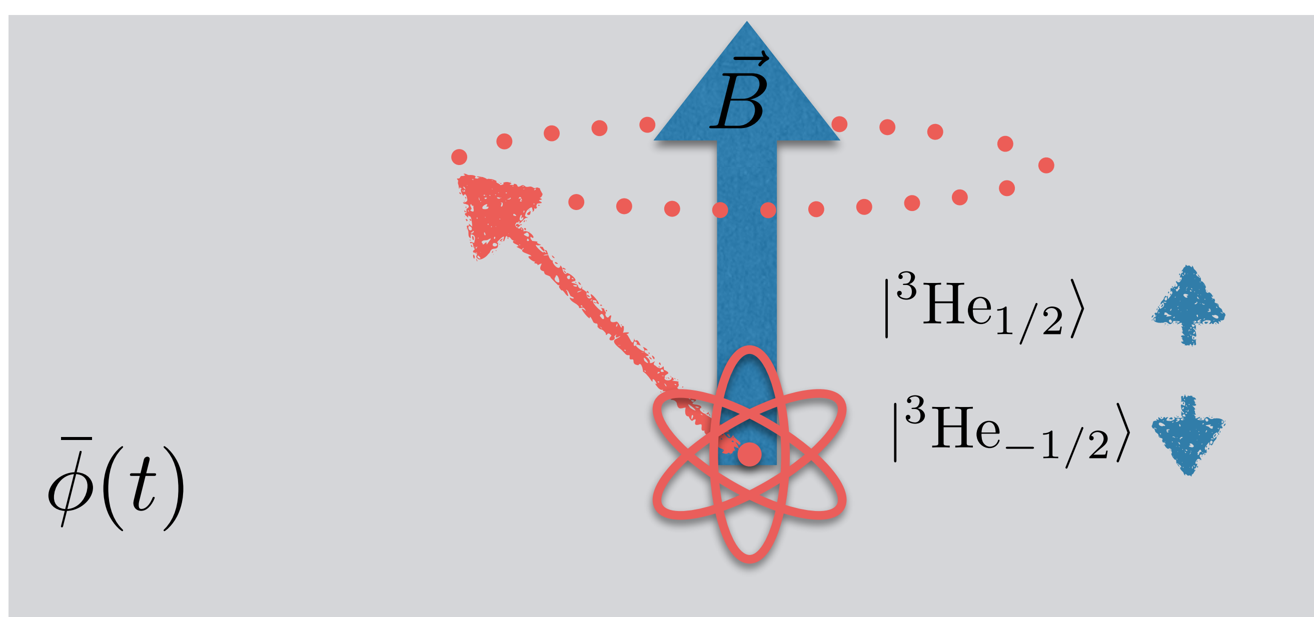
e.g. $(m + g_{\phi ee}\bar{\phi}(t))\bar{e}e$

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

Arvanitaki et al 14

# Ultra-light case

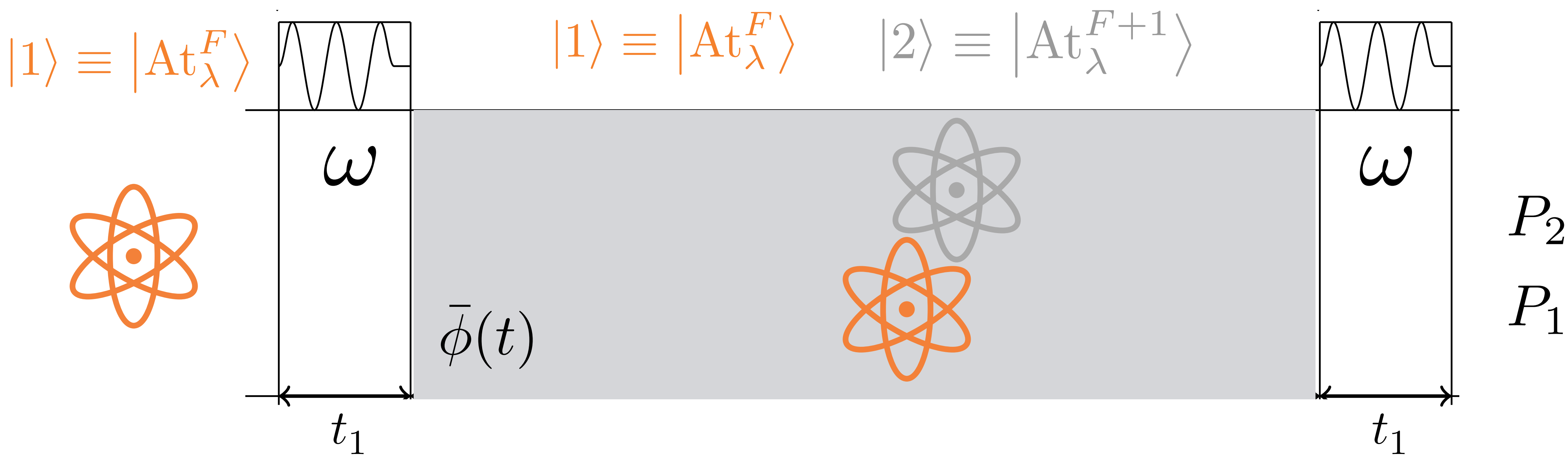


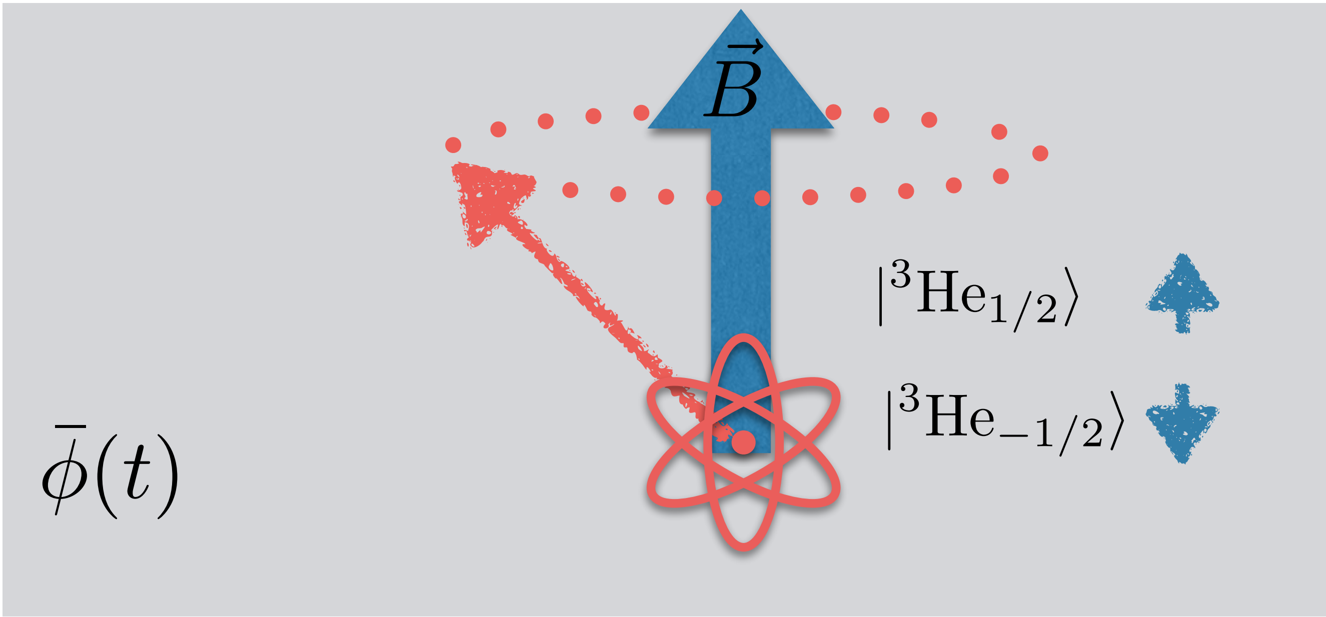




The atoms live in a background with some coherent features and for certain dark matter models

$$V_2 - V_1 \neq 0$$

# Ultra-light case




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

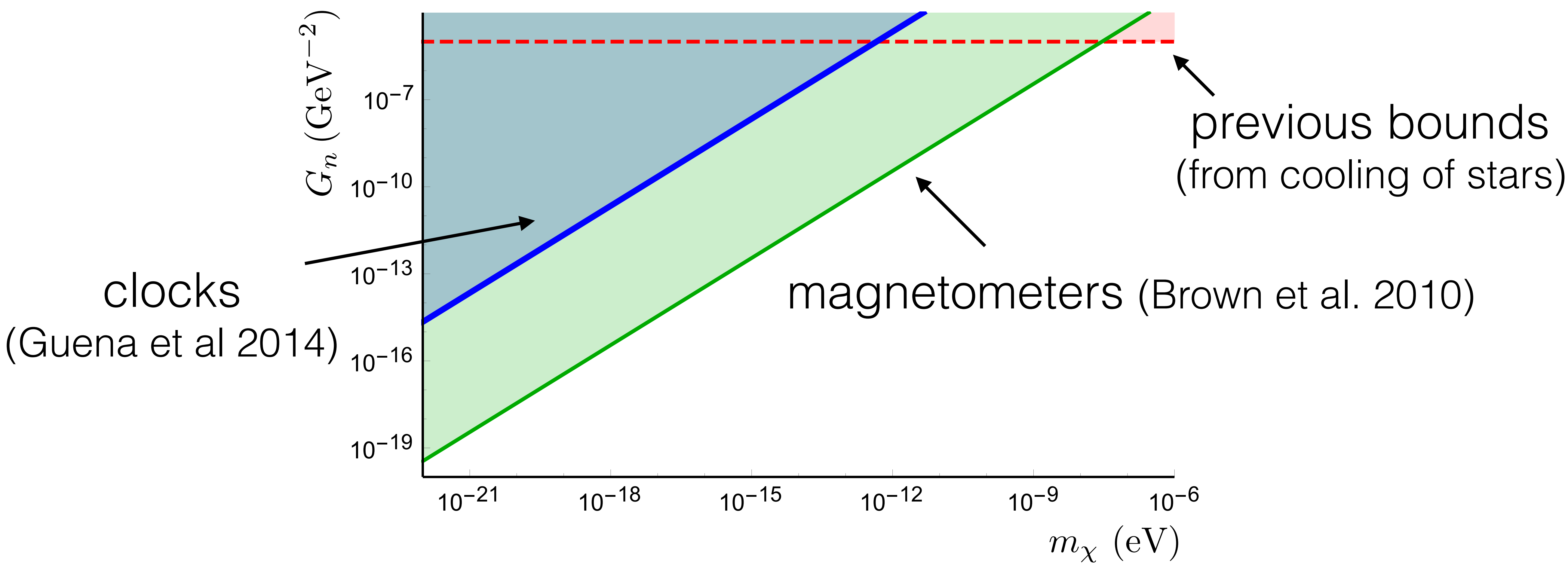
$$V_2 - V_1 \neq 0$$

# Constraints: three examples

scalar DM

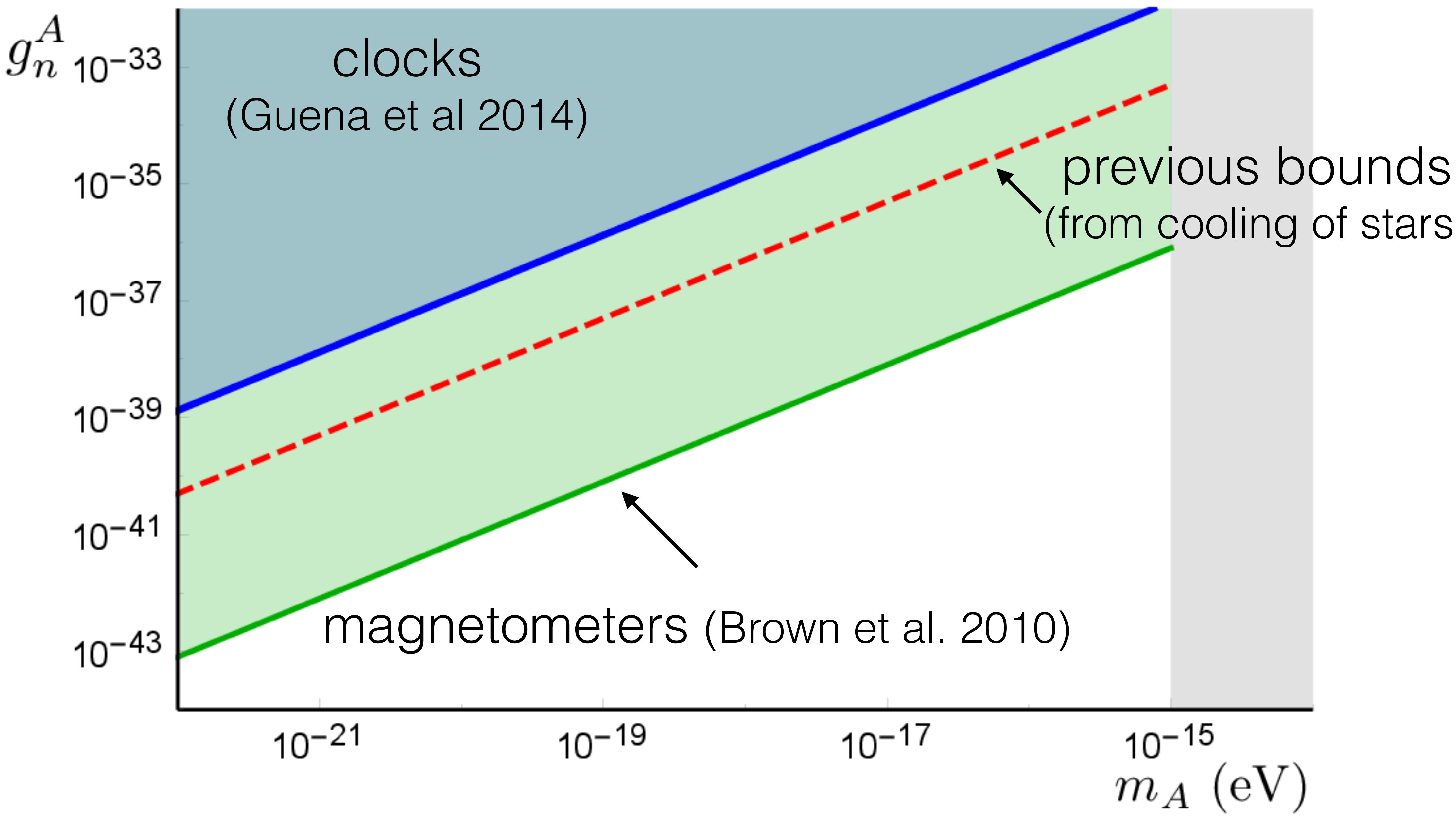
$$L_{\rm int} = -G_n \int \mathrm{d}^3x\,(\bar{n}\gamma^\mu\gamma_5 n)\,(i\chi^\dagger\partial_\mu\chi + \mathrm{h.c.})$$

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



# Constraints: three examples

$$L_{\rm int} = g_n^A \int {\rm d}^3x A^\mu \bar{n}\gamma_\mu\gamma_5 n$$

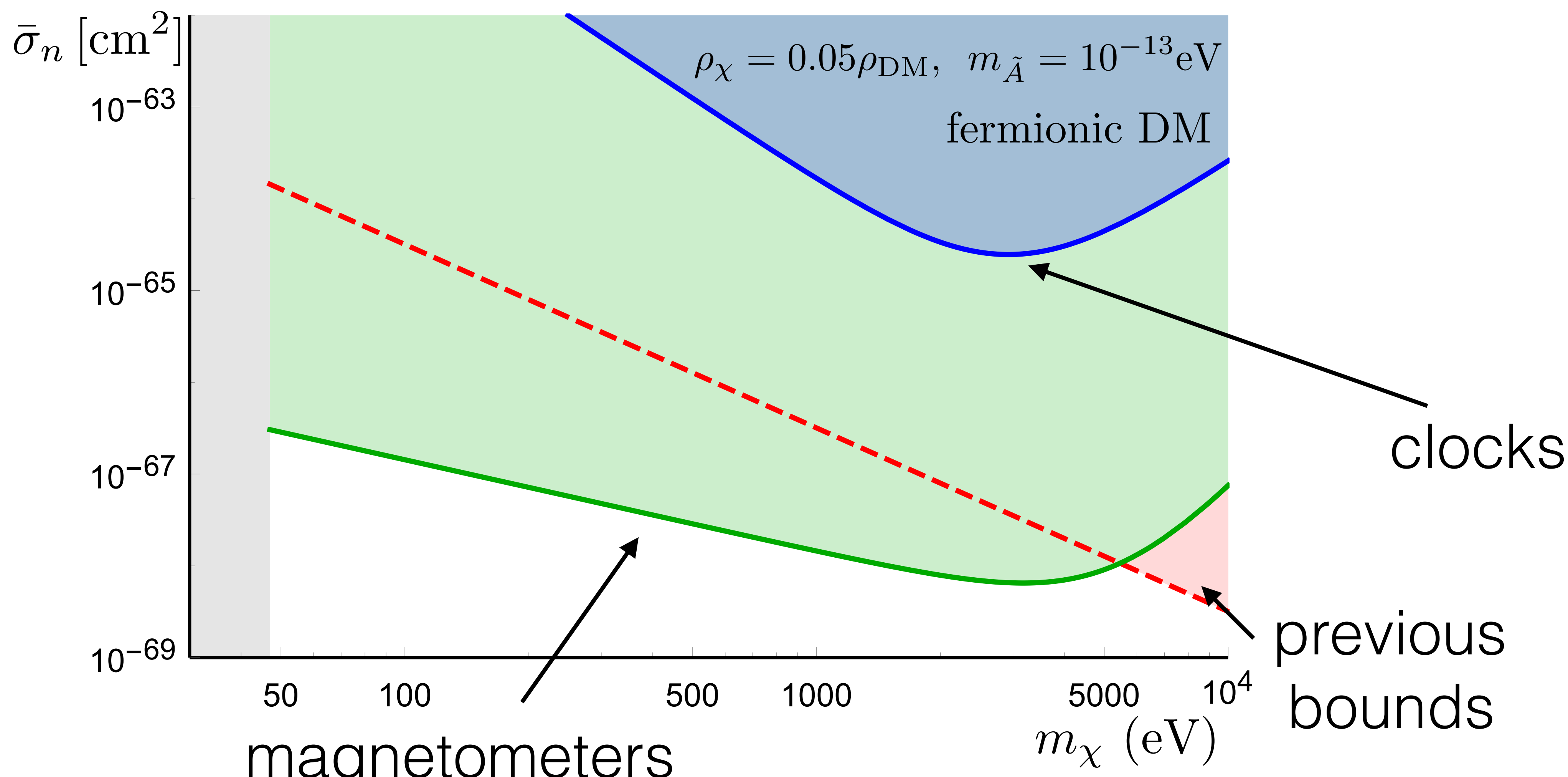


# Constraints: three examples

fermionic DM with light mediator

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

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



# 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 'putative' DM models

- This seems just the beginning…

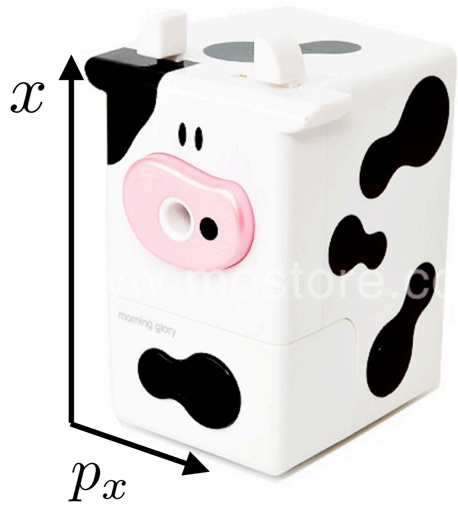
# Future

- 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)

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

- Neutrinos? (CnB seems out of reach) Gravitational waves?
- Devices close to beams? To study coherent scattering?
- Other precise devices…

# The ultra-light domain




virial equilibrium in the Milky Way (MW) halo:

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

ii) size $100\ \mathrm{kpc}$

$$\Delta x \Delta p \gtrsim \hbar \rightarrow N_s \sim 10^{75} \left(\frac{m}{\mathrm{eV}}\right)^3 \rightarrow N_p = \frac{M_{MW}}{N_s m} \sim 10^3 \left(\frac{\mathrm{eV}}{m}\right)^4$$

This logic tells us that DM can't be fermionic for mass $\lesssim \mathrm{keV}$

For high occupation number → field description

e.g. **massive scalar case** $\phi(x,t)$

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