Light dark matter @ atomic clocks and co-magnetometers

Diego Blas

w./ R. Alonso (IPMU) and P. Wolf (Paris Observatory)

1810.00889 & 1810.01632

A growing field

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

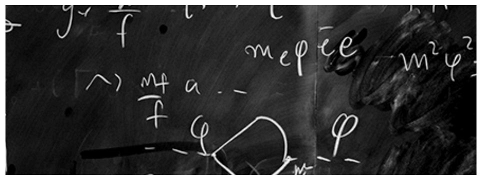
First AION Workshop
at Imperial College London
March 25/26 2019

REVIEWS OF MODERN PHYSICS
Search for new physics with atoms and molecules

M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson Kimball, A. Derevianko, and Charles W. Clark
Rev. Mod. Phys. **90**, 025008 – Published 29 June 2018

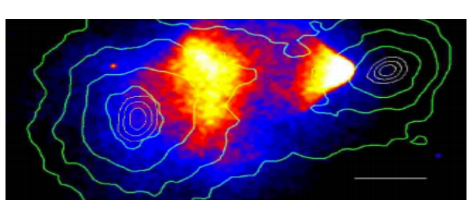
I will only discuss astrophysical backgrounds

Faint astrophysical backgrounds



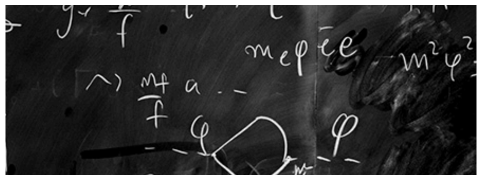
Gravitational waves (SM + BSM)

Cosmic neutrinos (SM)



Dark matter (BSM)

Faint astrophysical backgrounds



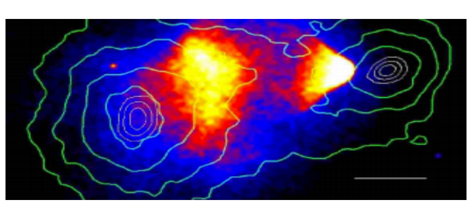
Gravitational waves (SM + BSM)

Produced in many astrophysical situations

in particular in theories BSM

but *weakly interacting* and *low frequency*

Cosmic neutrinos (SM)



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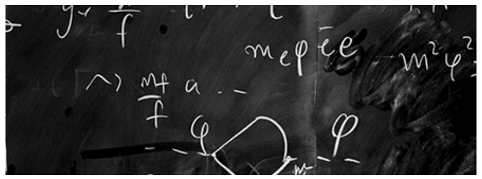


Gravitational waves (SM + BSM)

Produced in many astrophysical situations

in particular in theories BSM

but *weakly interacting* and *low frequency*

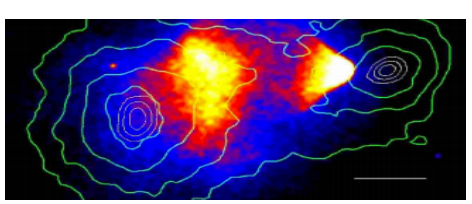
Cosmic neutrinos (SM)

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

$$0.06\,\mathrm{eV} < \sum_i m_{\nu_i} < 0.2\,\mathrm{eV}$$ **(BSM?)**

$10^{12}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ $\qquad T_{today} \sim 10^{-4}\,\mathrm{eV}$

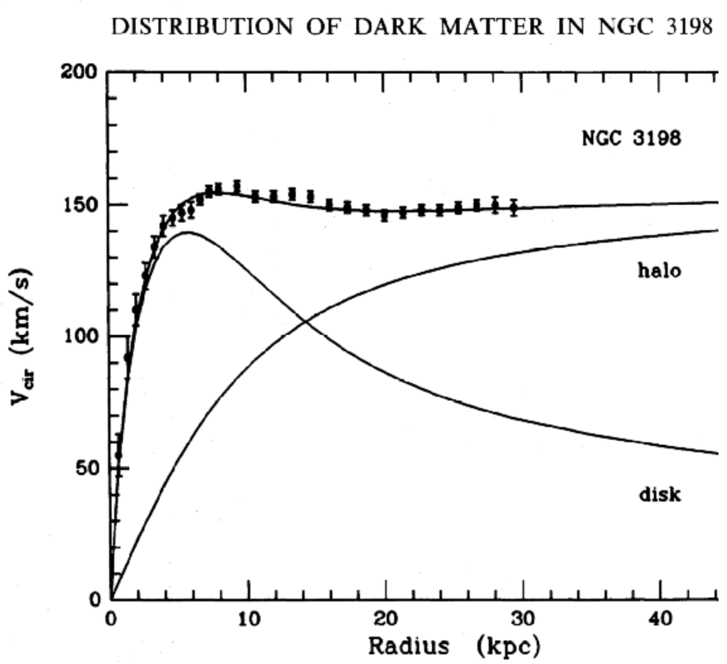
weakly interacting and *low momentum*

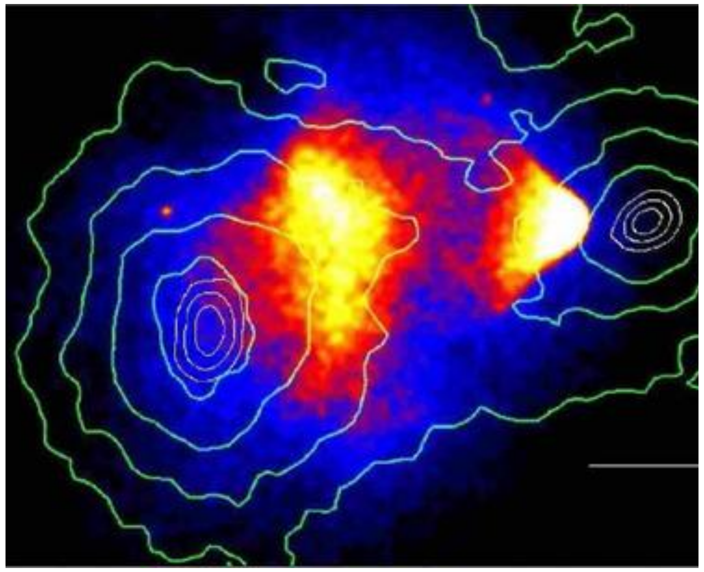


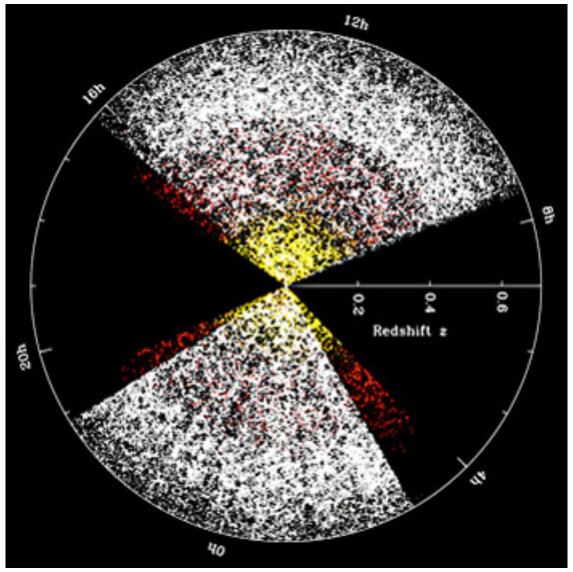
Dark matter (BSM)

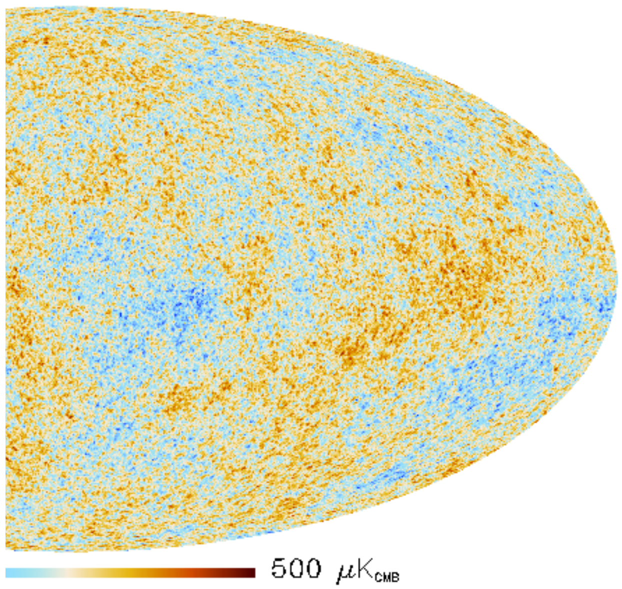
Dark matter evidence

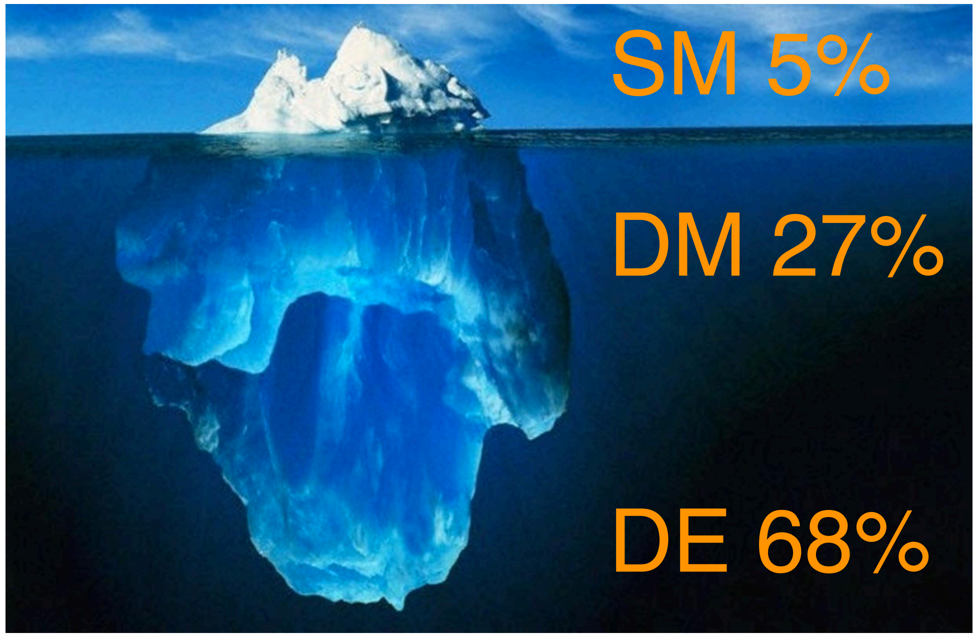
Rotation curves | Clusters lensing | Structure formation | CMB





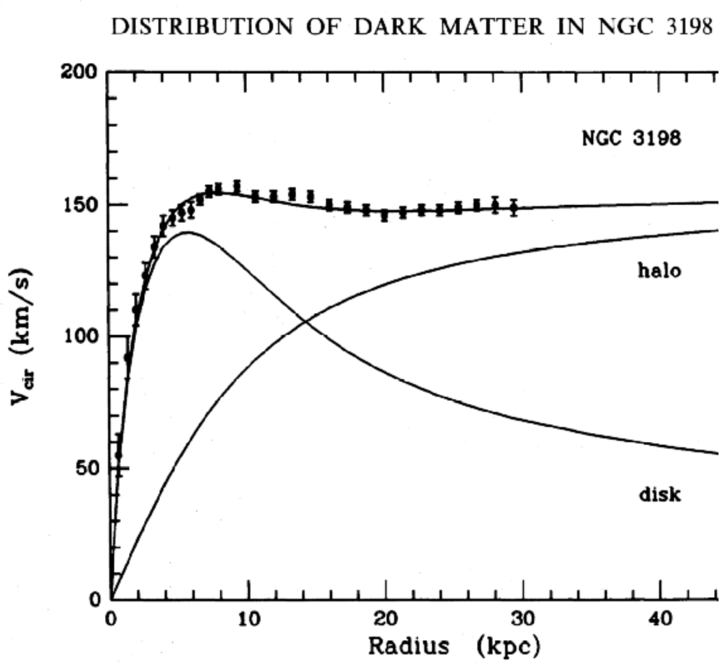


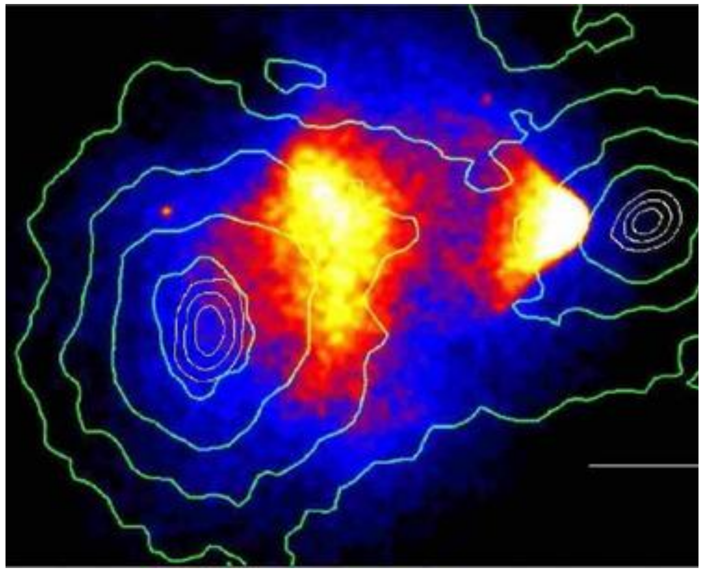


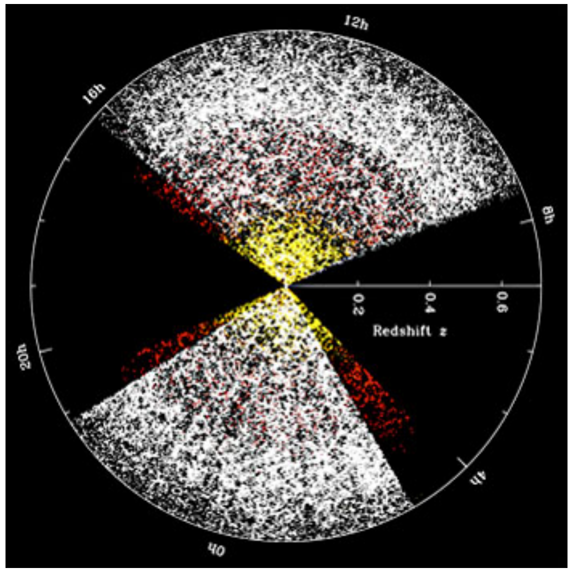


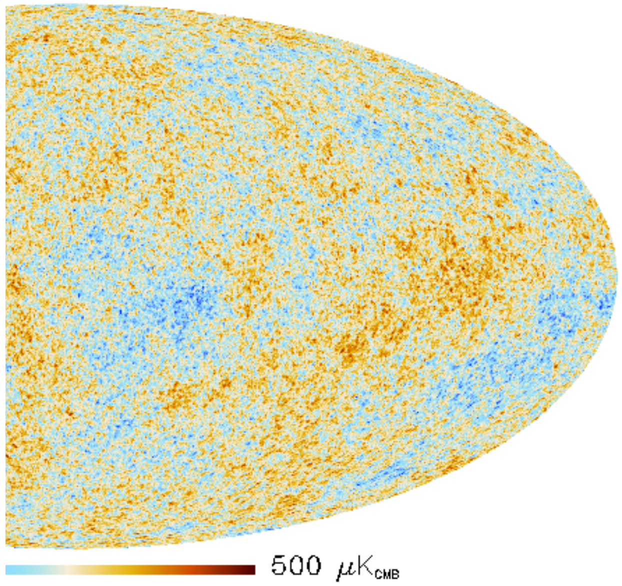
Dark matter evidence

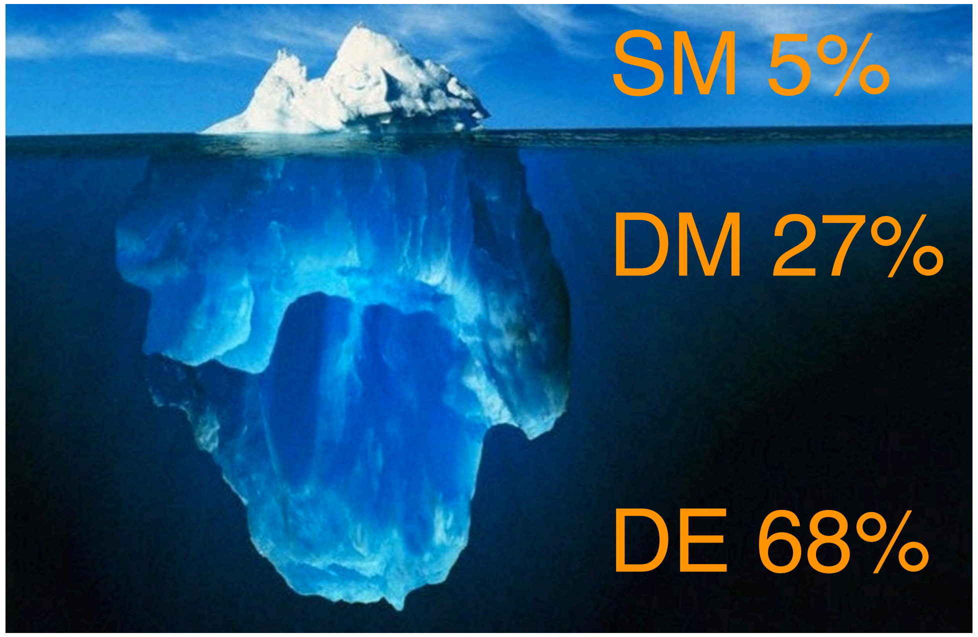
Rotation curves | Clusters lensing | Structure formation | CMB









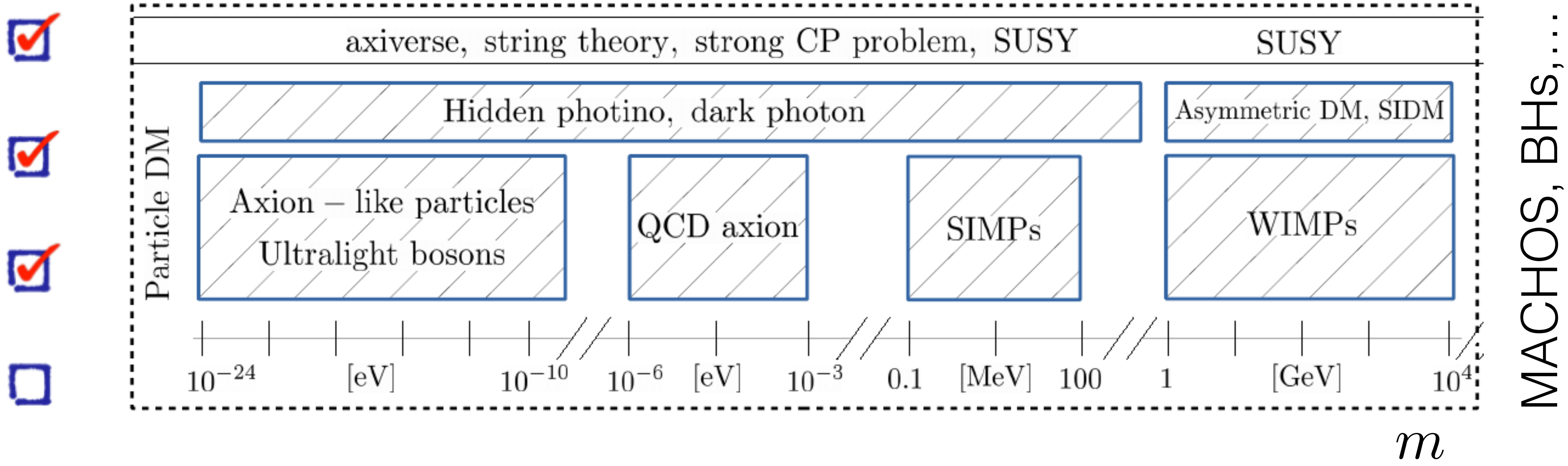


Do we know **anything** fundamental about DM?

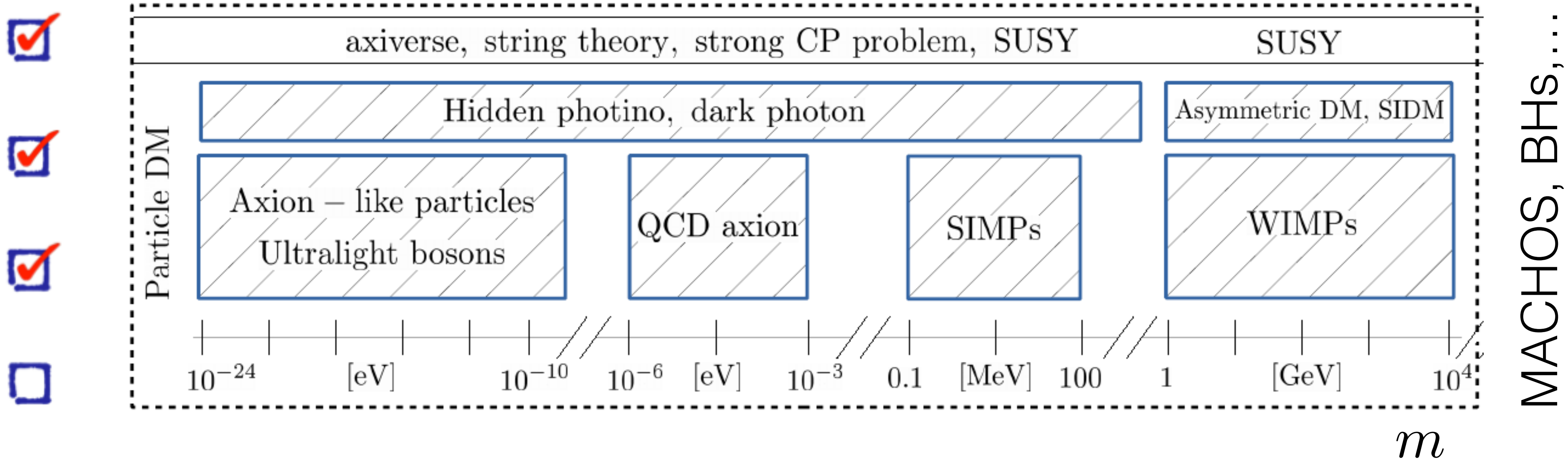
Dark matter wish list

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

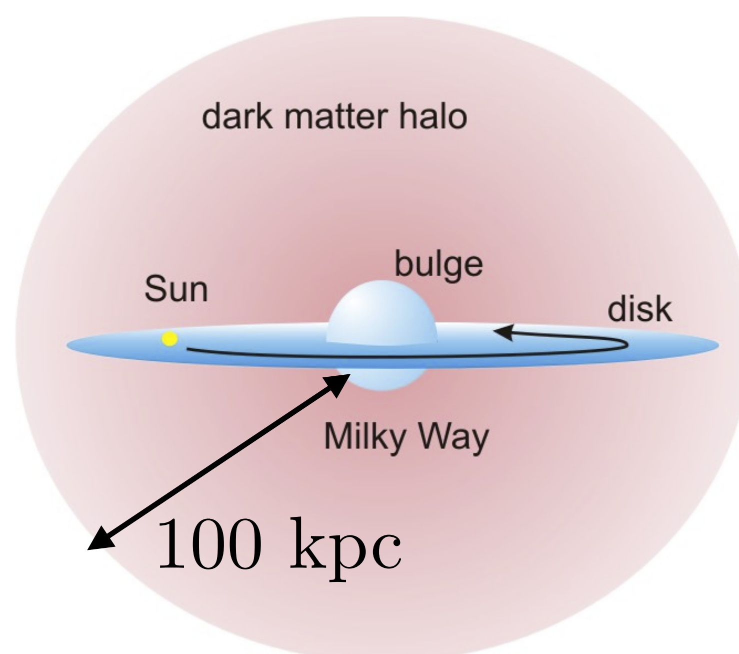
Particle dark matter properties



Particle dark matter properties



'local' distribution



$$\rho_\odot \sim 0.3\,\mathrm{GeV/cm^3}$$

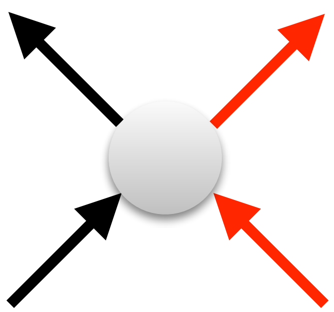
$$10^{10}\left(\frac{\mathrm{MeV}}{m_\chi}\right)\,\mathrm{cm^{-2}s^{-1}}, \quad m_\chi\langle v_\odot\rangle \sim 10^{-3} m_\chi c$$

and *weakly interacting*

‘Traditional’ DM searches

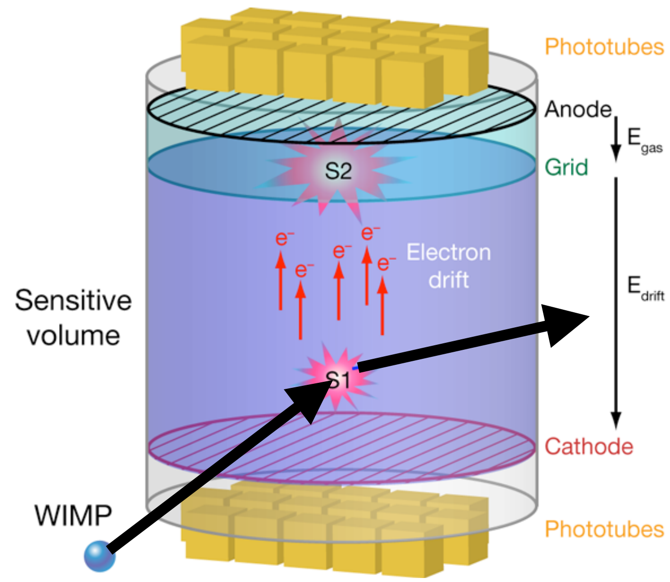
Direct: e.g. Xenon 100

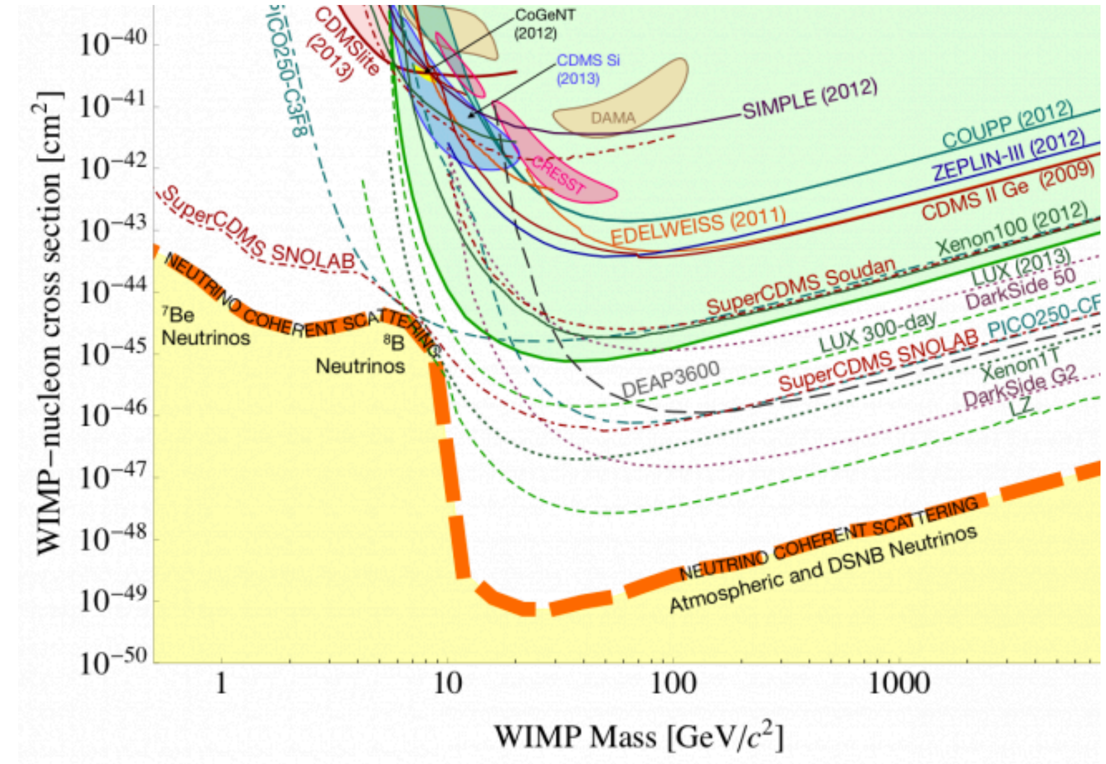
scattering



DM nucleus

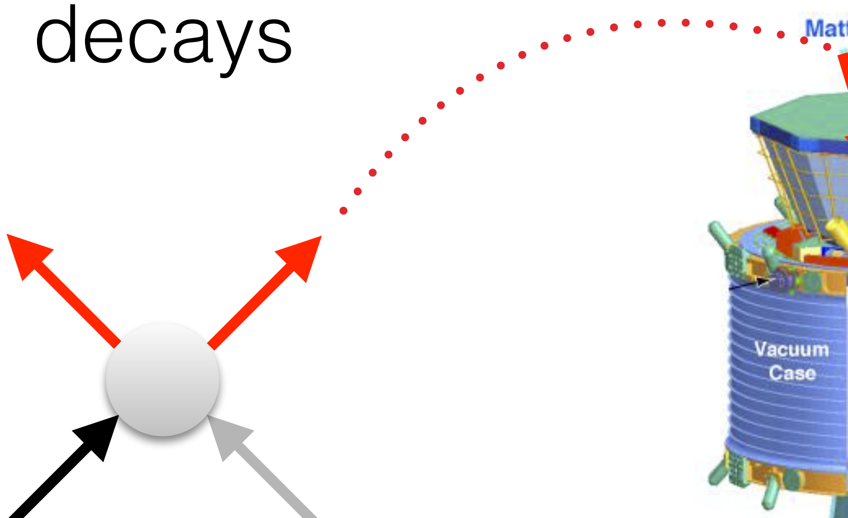
$$E_R^{\max} \sim \left(\frac{m_\chi}{\text{GeV}}\right) \text{keV}$$



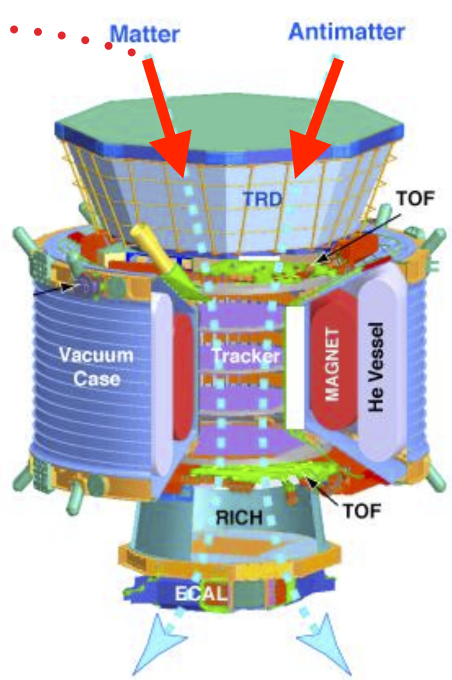


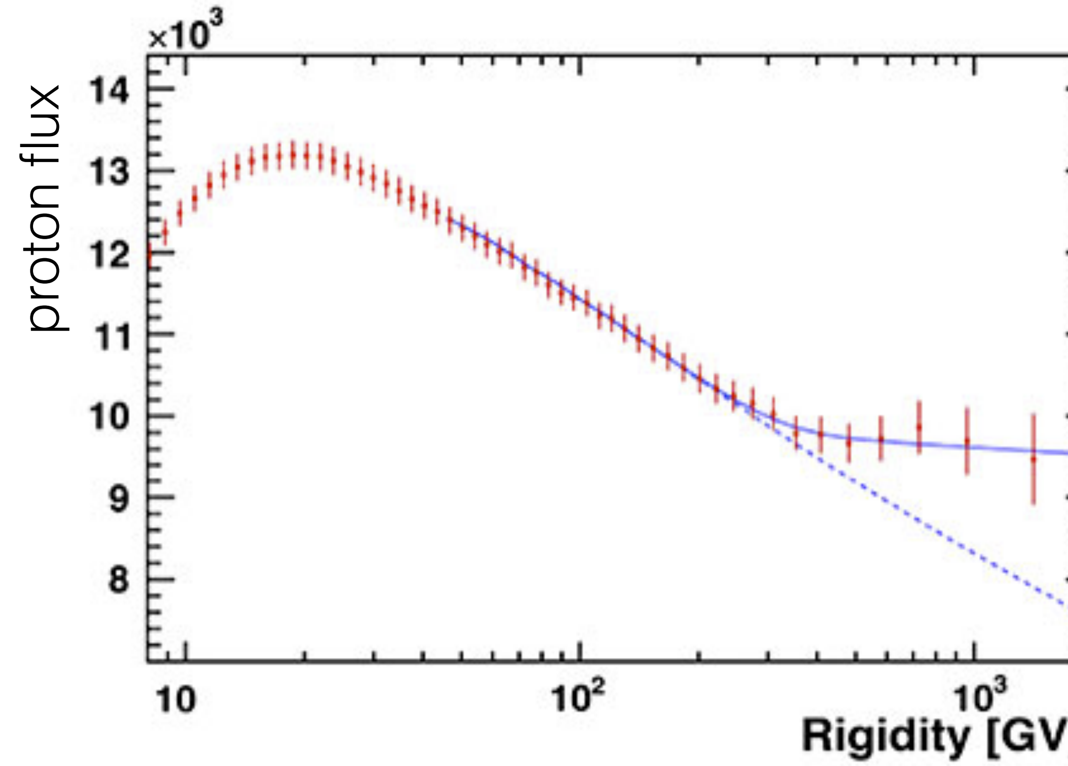
Indirect: e.g. AMS02

decays



DM DM

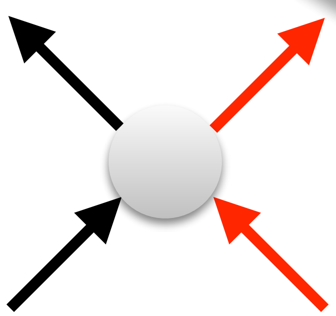




‘Traditional’ DM searches

LOSS OF SENSITIVITY AT LOW MASS

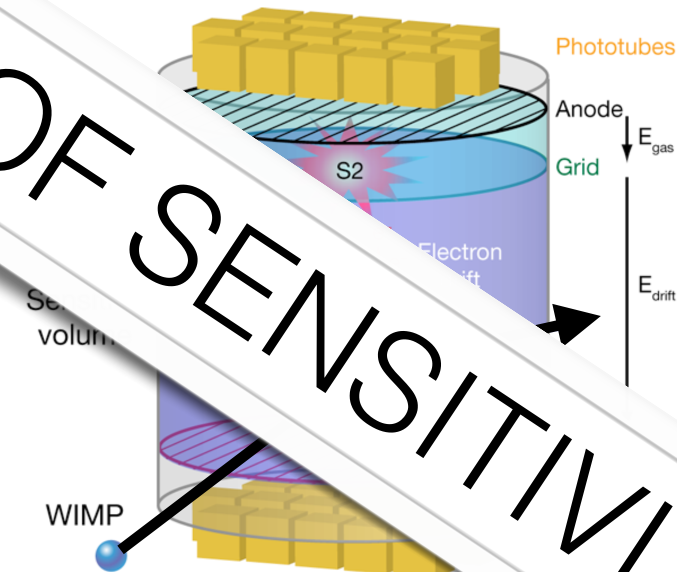
scatter

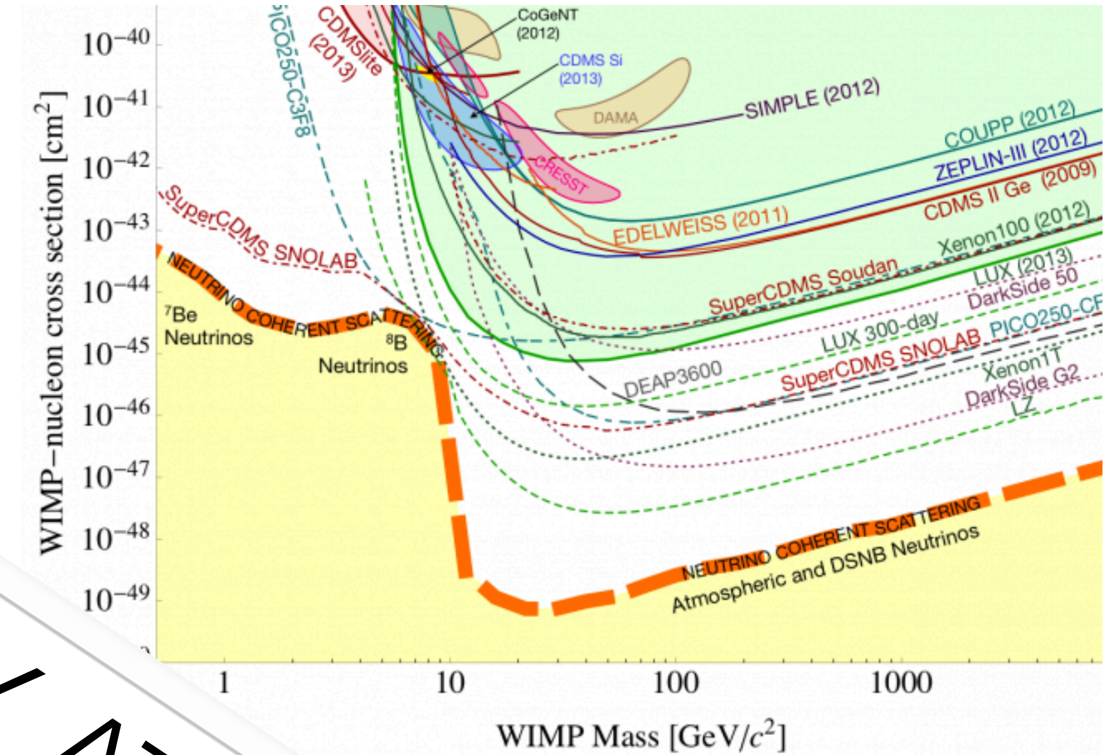


DM nucleus

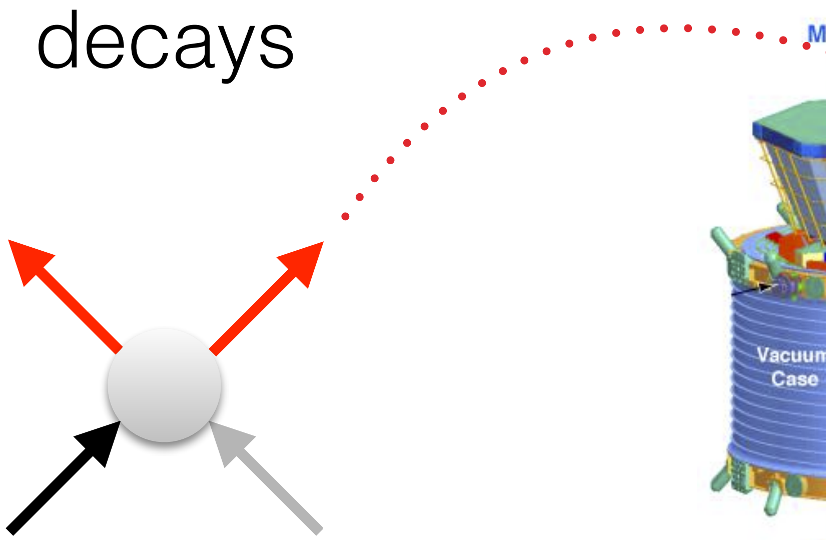
$$E_R^{\max} \sim \left(\frac{m_\chi}{\text{GeV}}\right)\,\text{keV}$$

Direct: e.g. Xenon 100



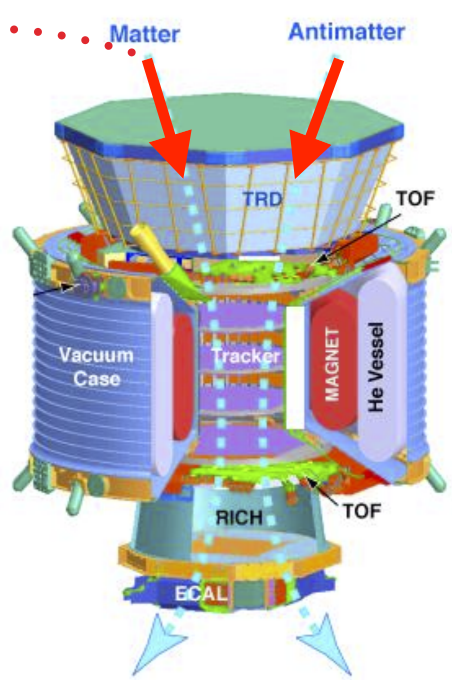


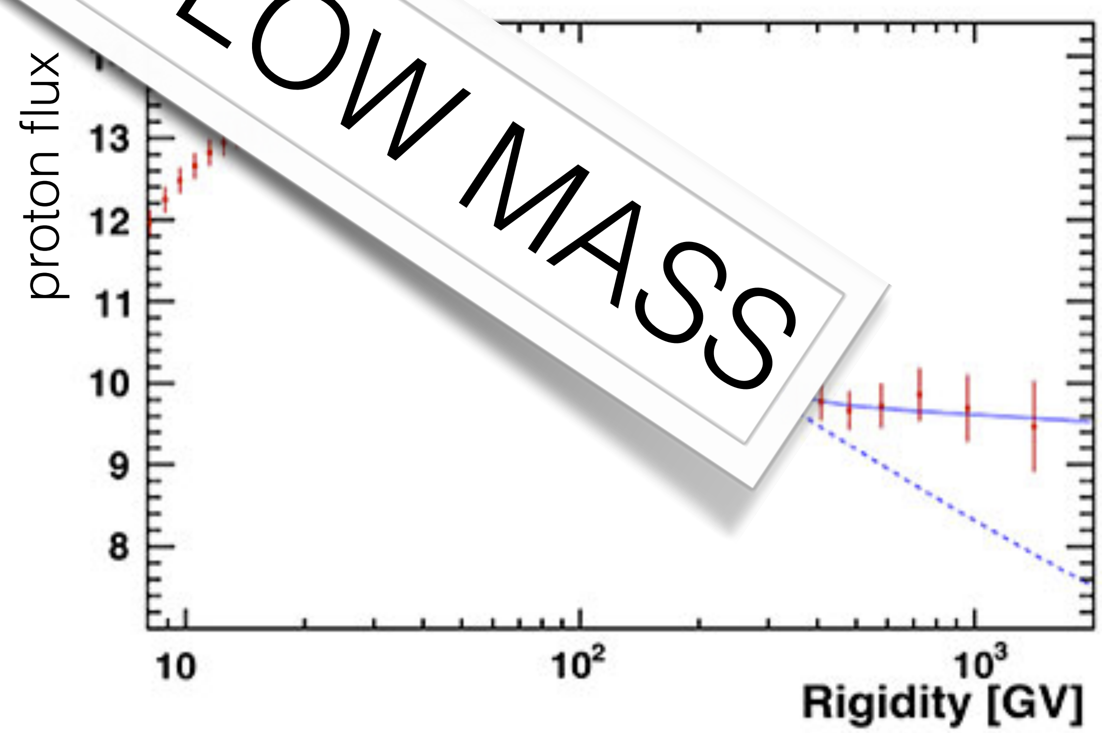
decays



DM DM

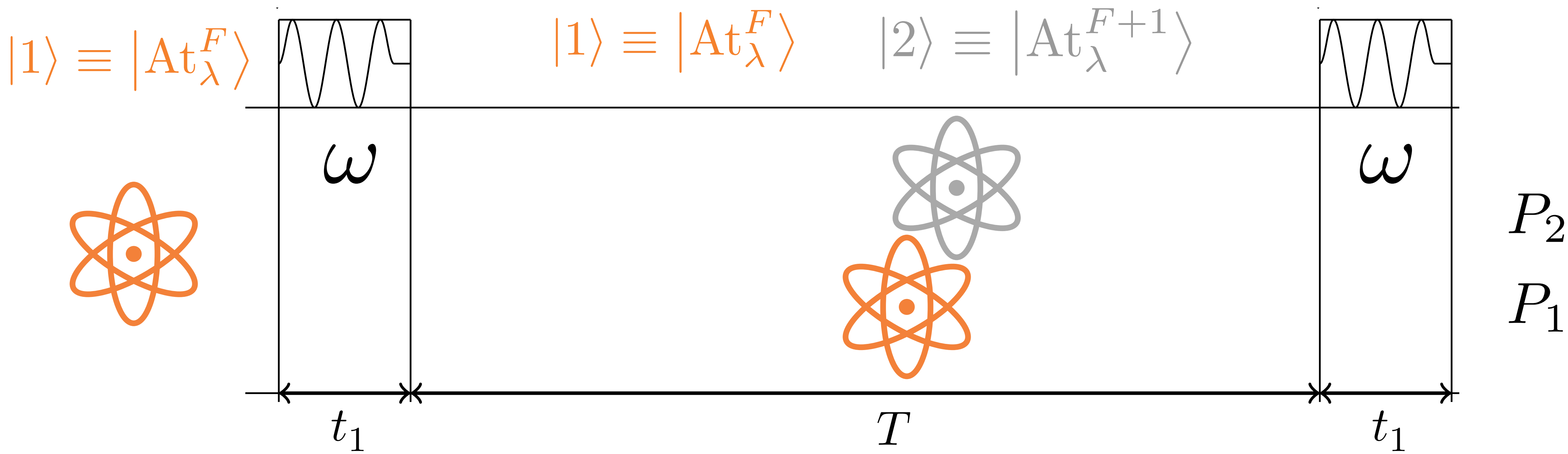
Indirect: e.g. AMS02





Measuring at $q = 0$: Ramsey sequence

(atomic clock basics)



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

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

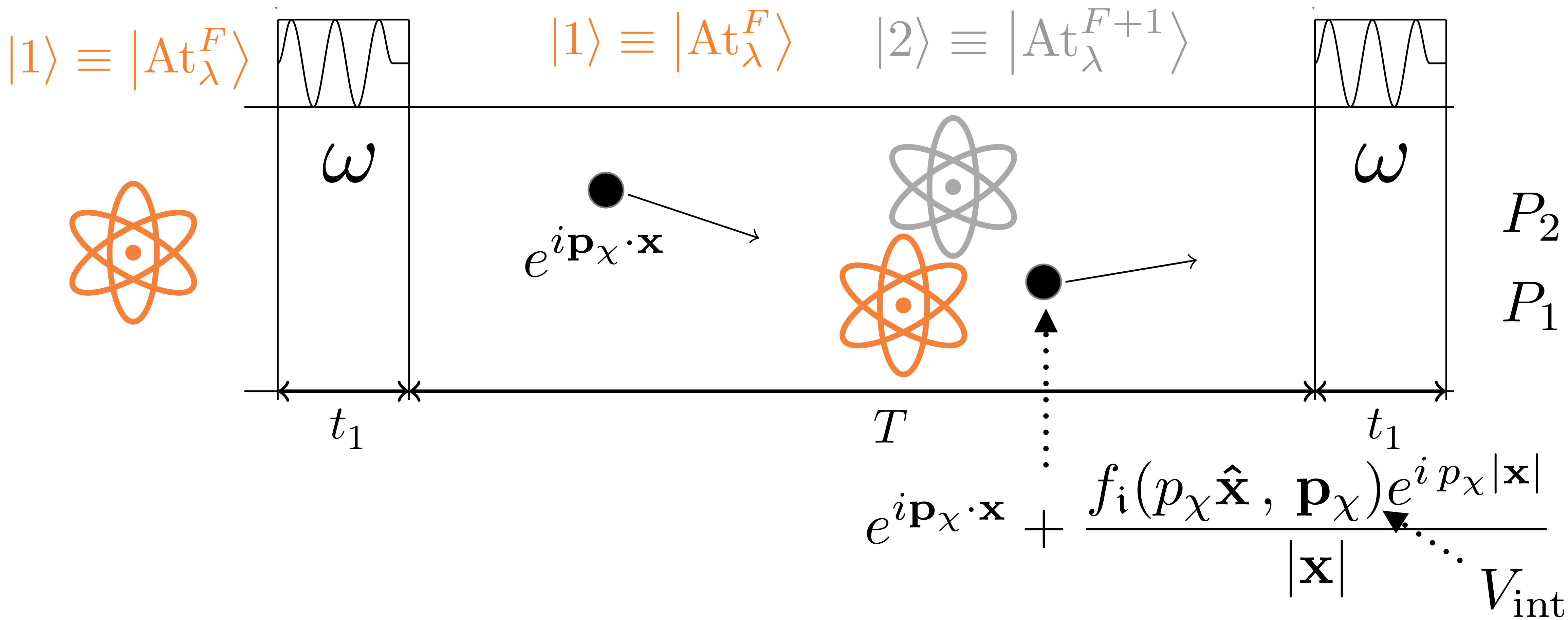
$$\partial P_2 = 0 \quad \Rightarrow \quad \omega_{\max} = \Delta E$$

measurement of the phase difference e^{iHT}

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

provided $\delta V_i \neq 0$

DM-atom interaction during Ramsey sequence



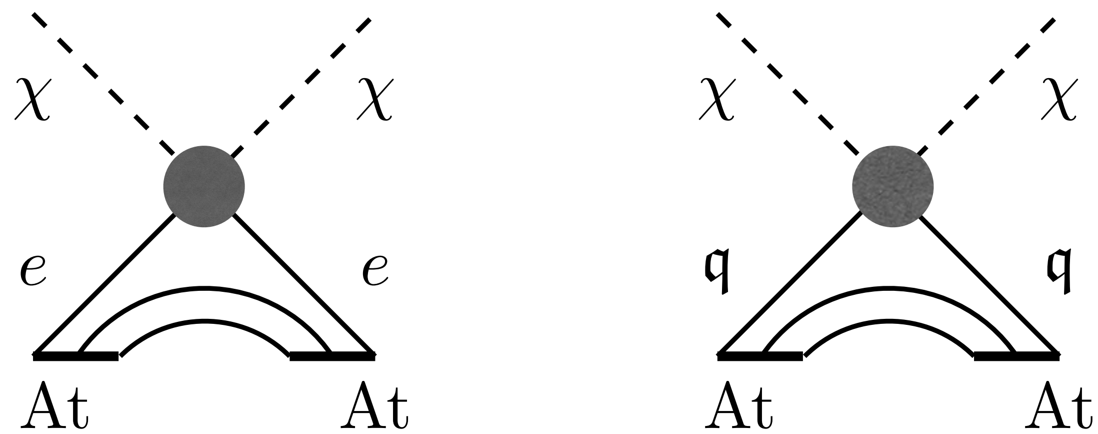
for low masses (all the atoms stay in the clock) & small coupling

forward scattering

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

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

DM-atom scattering: effective vertex



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

$$\downarrow$$

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

DM current

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

$$\downarrow$$

$$\langle N|\bar{\mathfrak{q}}\,\Gamma^{\mathcal{I}}\mathfrak{q}|N\rangle$$ (known)

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

The calculation in a nutshell

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

$$f(\mathbf{p}'_\chi, \mathbf{p}_\chi) = -\frac{m_\chi}{2\pi} \mathcal{T}(\mathbf{p}'_\chi, \mathbf{p}_\chi)$$

Single DM particle-atom interaction

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

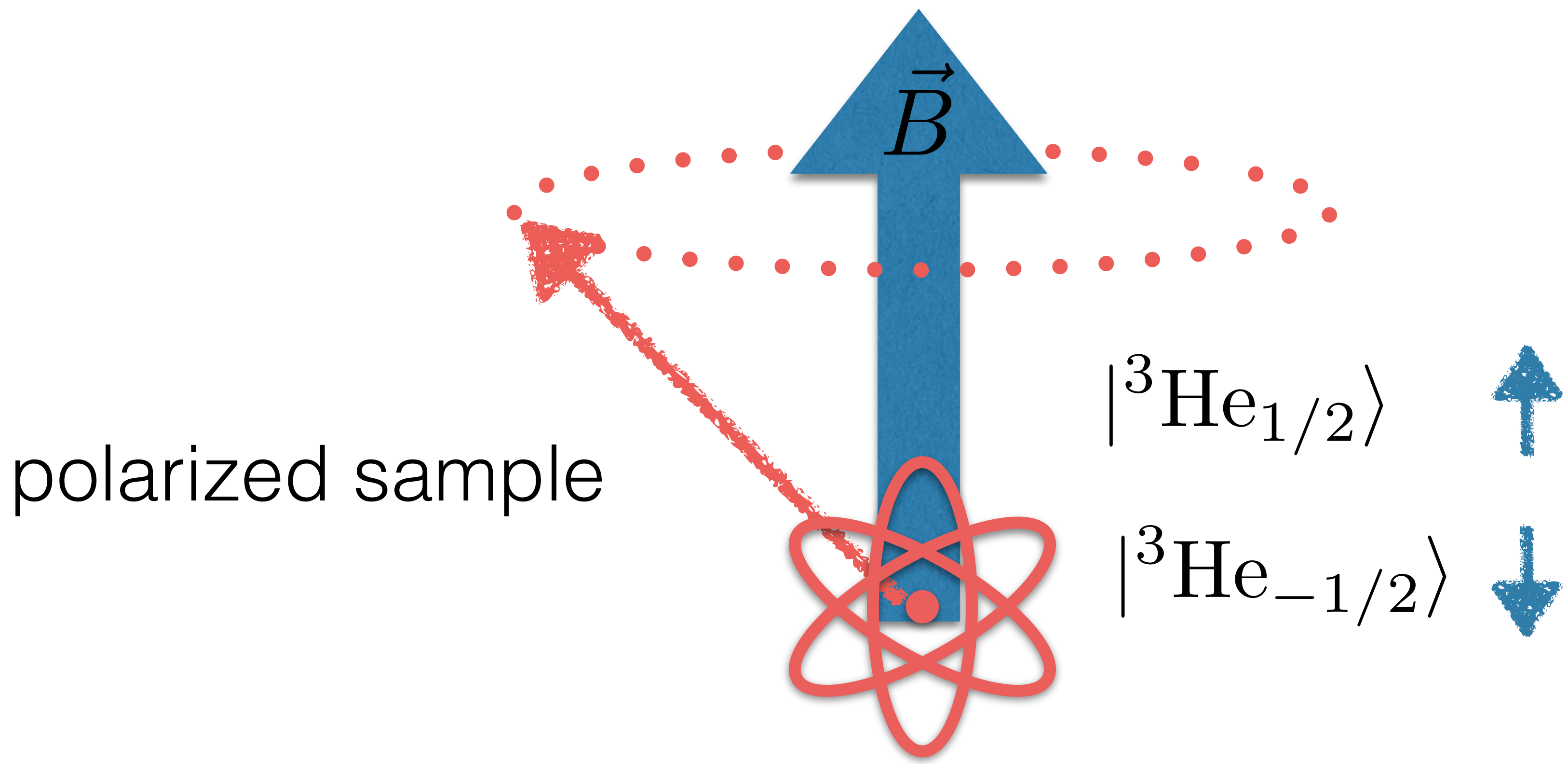
$f_1 \to (F, \lambda)$ $f_2 \to (F+1, \lambda)$

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

$G_N \mathfrak{g}^N_{\rm Ncl} \to$ atomic form factors $G_N(G_u, G_d)$

Atomic magnetometers basics

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



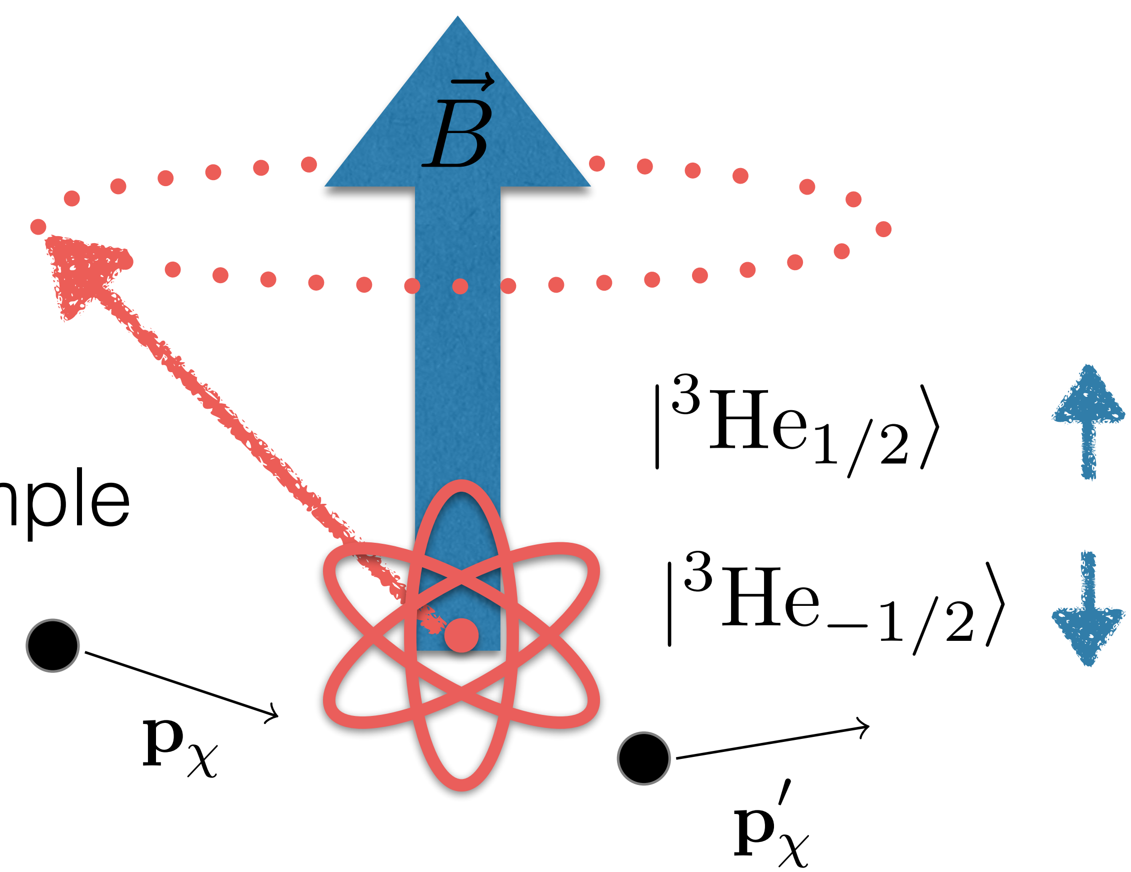
same with $^{129}\mathrm{Xe}$

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

DM-atom interaction in co-magnetometers

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

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*

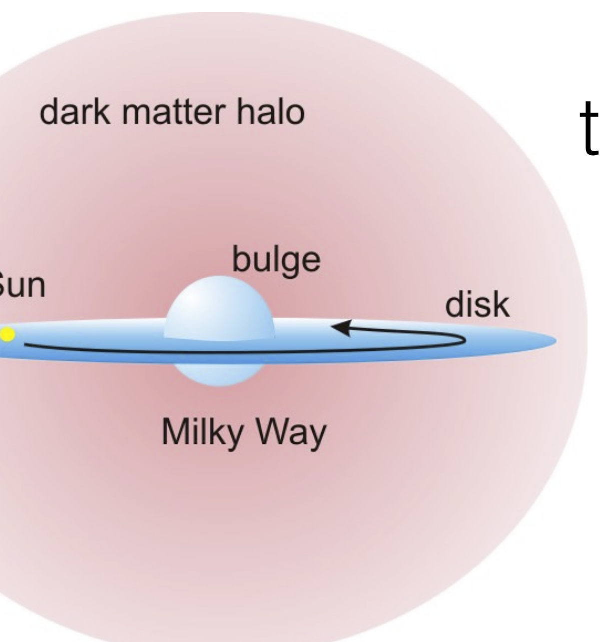
Which DM-atom interactions?

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

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**

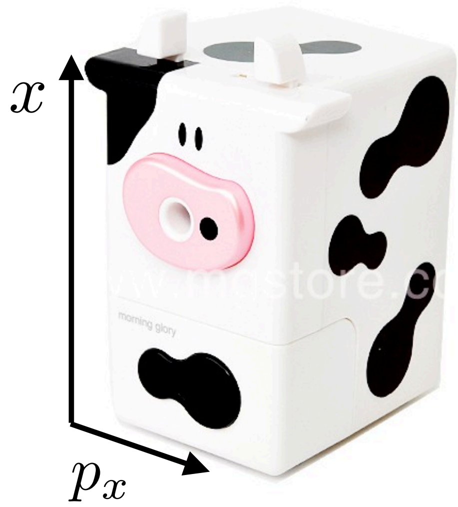
$O(1/\sqrt{N})$ 'noise'*

* 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…)

The ultra-light domain



virial equilibrium in the Milky Way (MW) halo:

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

ii) size 100 kpc

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

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

For high occupation number → field description

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

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

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 (properties from the galaxy)

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

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

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

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

The ultra-light domain: interaction with atoms

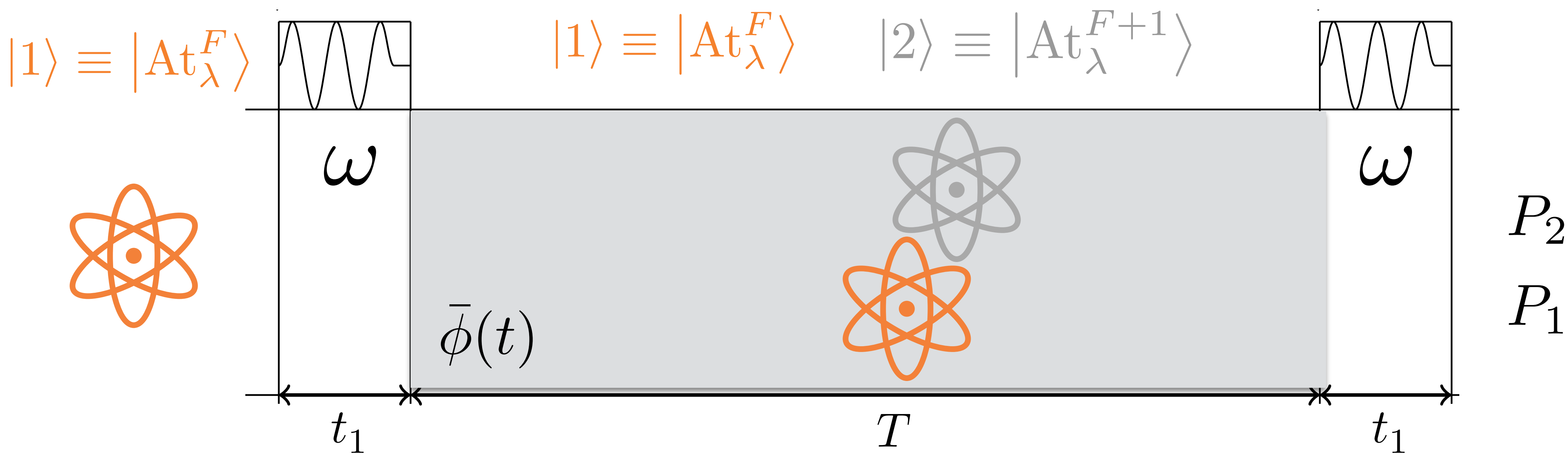
$\bar{\phi}(x,t)$

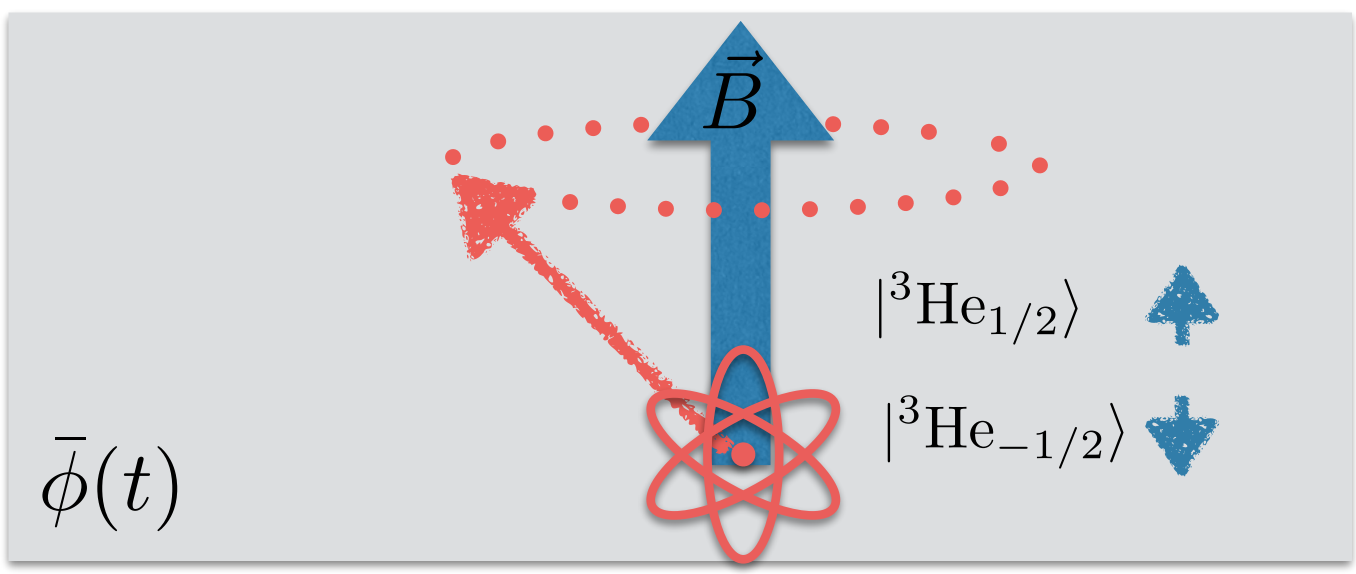
$$L_{\rm int} = -\int \mathrm{d}^3x \left(G_e^{\mathcal{I}} \bar{e}\, \Gamma^{\mathcal{I}} e\, \mathcal{J}_\chi^{\mathcal{I}} + \sum_{\mathfrak{q}=u,d} G_{\mathfrak{q}}^{\mathcal{I}} \bar{\mathfrak{q}}\, \Gamma^{\mathcal{I}} \mathfrak{q}\, \mathcal{J}_\chi^{\mathcal{I}} \right)$$

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

these are now 'oscillating' backgrounds!

Ultra-light case





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

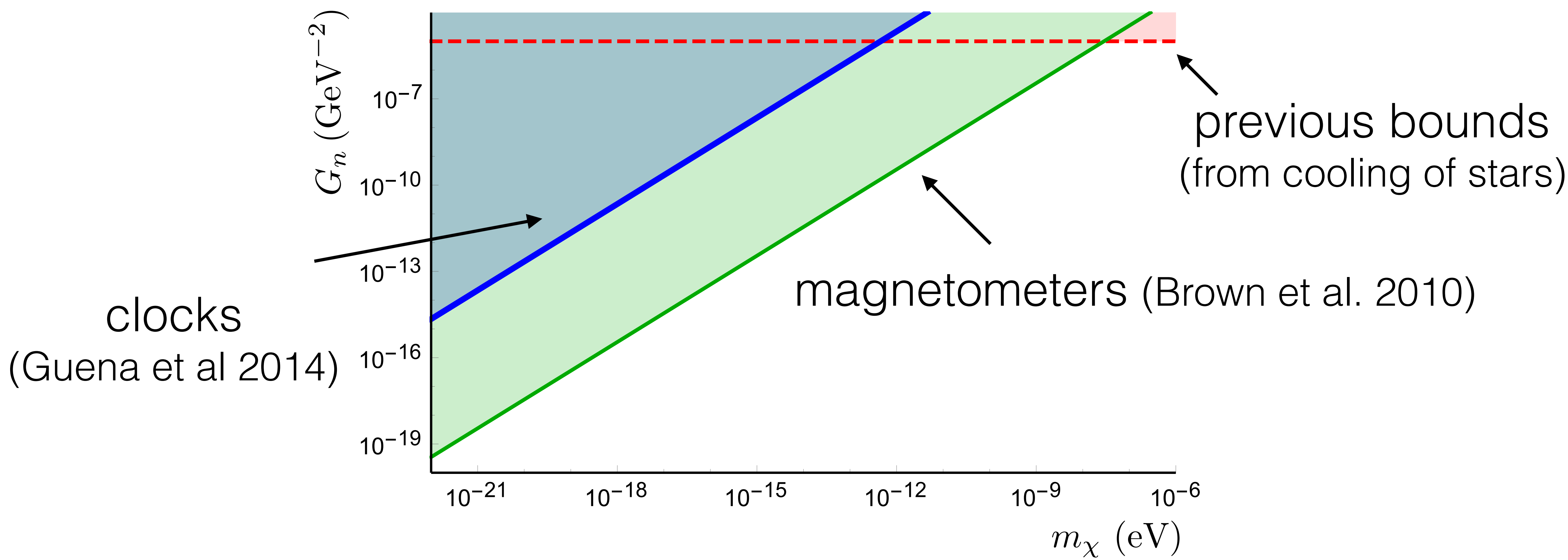
$$V_2 - V_1 \neq 0$$

Constraints: two examples

scalar DM

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

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

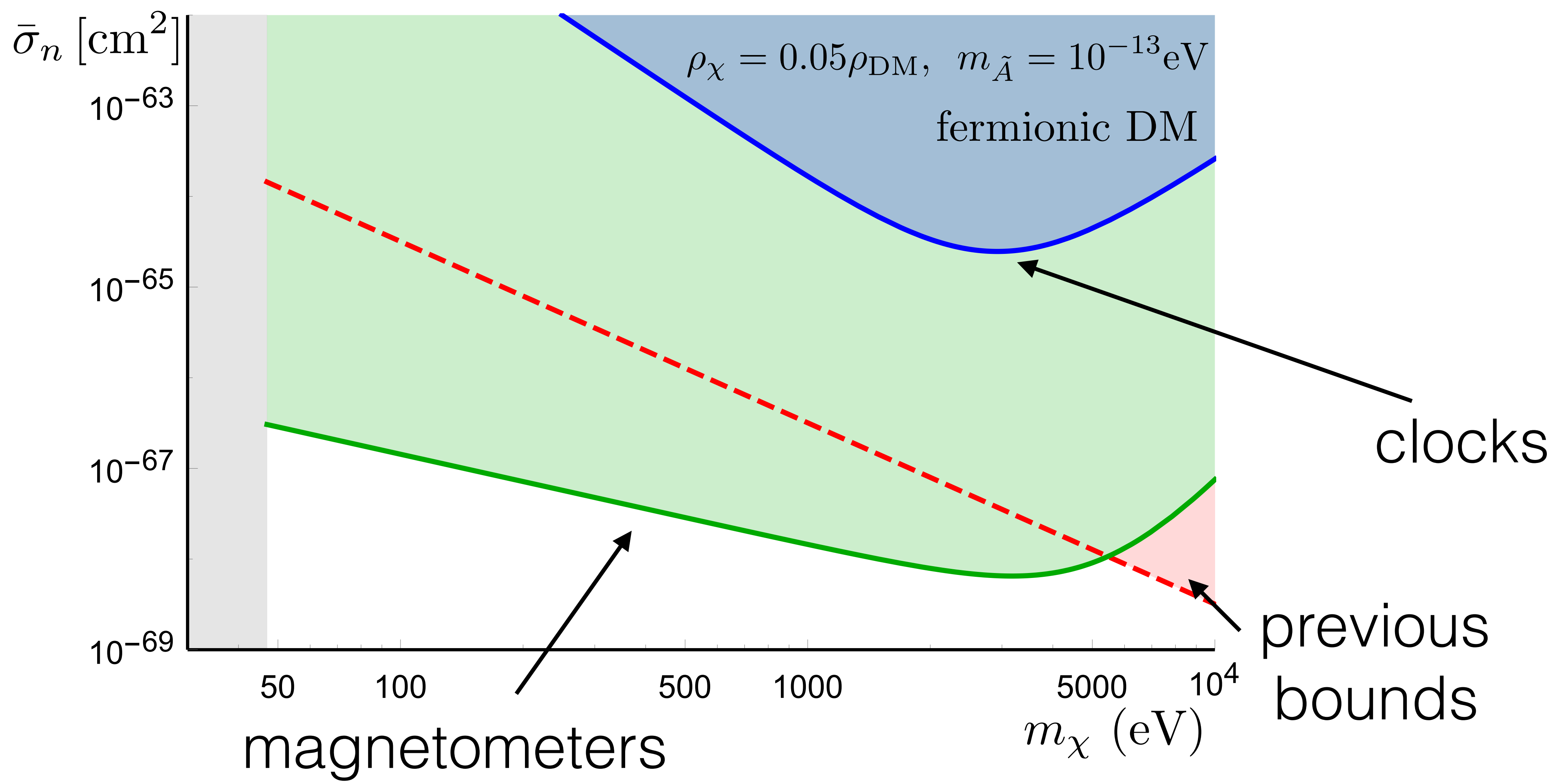


Constraints: two examples

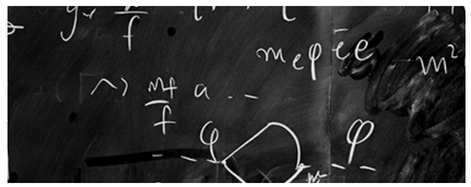
fermionic DM with light mediator

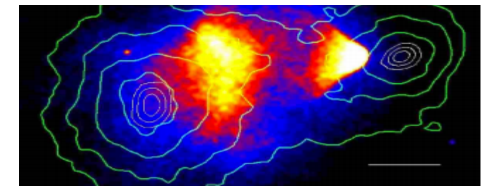
$$L_{\rm int} = -g_{\tilde{A}} g_\chi \int {\rm d}^3x \, (\bar{n}\gamma^\mu\gamma_5 n) \, \frac{1}{m_{\tilde{A}}^2 + \Box} \, (\bar{\chi}^\dagger \gamma^\mu \gamma_5 \chi)$$

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



Summary and Conclusions





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

- Precise (quantum) devices perfect to look for them! $(q = 0)$

- 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)

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

- Neutrinos? Gravitational waves?
- Devices close to beams? To study coherent scattering? (they work at zero momentum transfer)
- …