DM research at SYRTE: an overview

SYRTE, Observatoire de Paris, Université PSL, CNRS,
Sorbonne Université, LNE, France

Paris-Tokyo seminar, March 5, 2021

A. Hees, E. Savalle, B. Roberts, P. Delva, R. Alonso, D. Blas, P. Wolf

M. Abgrall, S. Bize, E. Cantin, L. Cros, F. Frank, J. Guéna, P-E Pottie, B. McAllister, O. Minazzoli, M. Tobar, Y. Stadnik

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Systèmes de Référence Temps-Espace

Menu

- Dark matter (DM) overview
- Ultralight dark matter and time/frequency metrology
- DM interacting with standard model spins
- Non-universally coupled scalar field
- Atomic spectroscopy optical cavities and Universality of free fall
- Experiments at SYRTE and friends
- Conclusion and Outlook

[Hees, Guéna, Abgrall, Bize, Wolf, PRL **117**, 061301, 2016]
[Hees, Minazzoli, Savalle, Stadnik, Wolf, PRD **98**, 064051, 2018]
[Alonso, Blas, Wolf, JHEP **69**, 2019]
[Wolf, Alonso, Blas, PRD **99**, 095019, 2019]
[Roberts, et al., NJP **22**, 093010, 2020]
[Savalle E. et al., PRL **126**, 051301, 2021]

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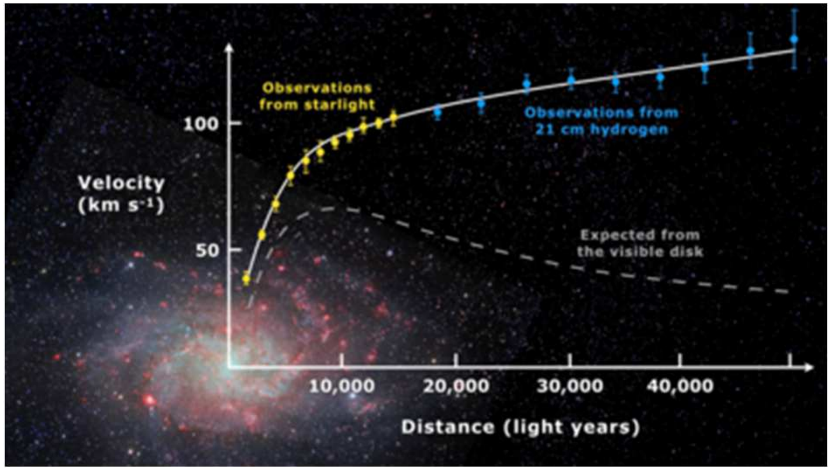
Dark Matter (1)

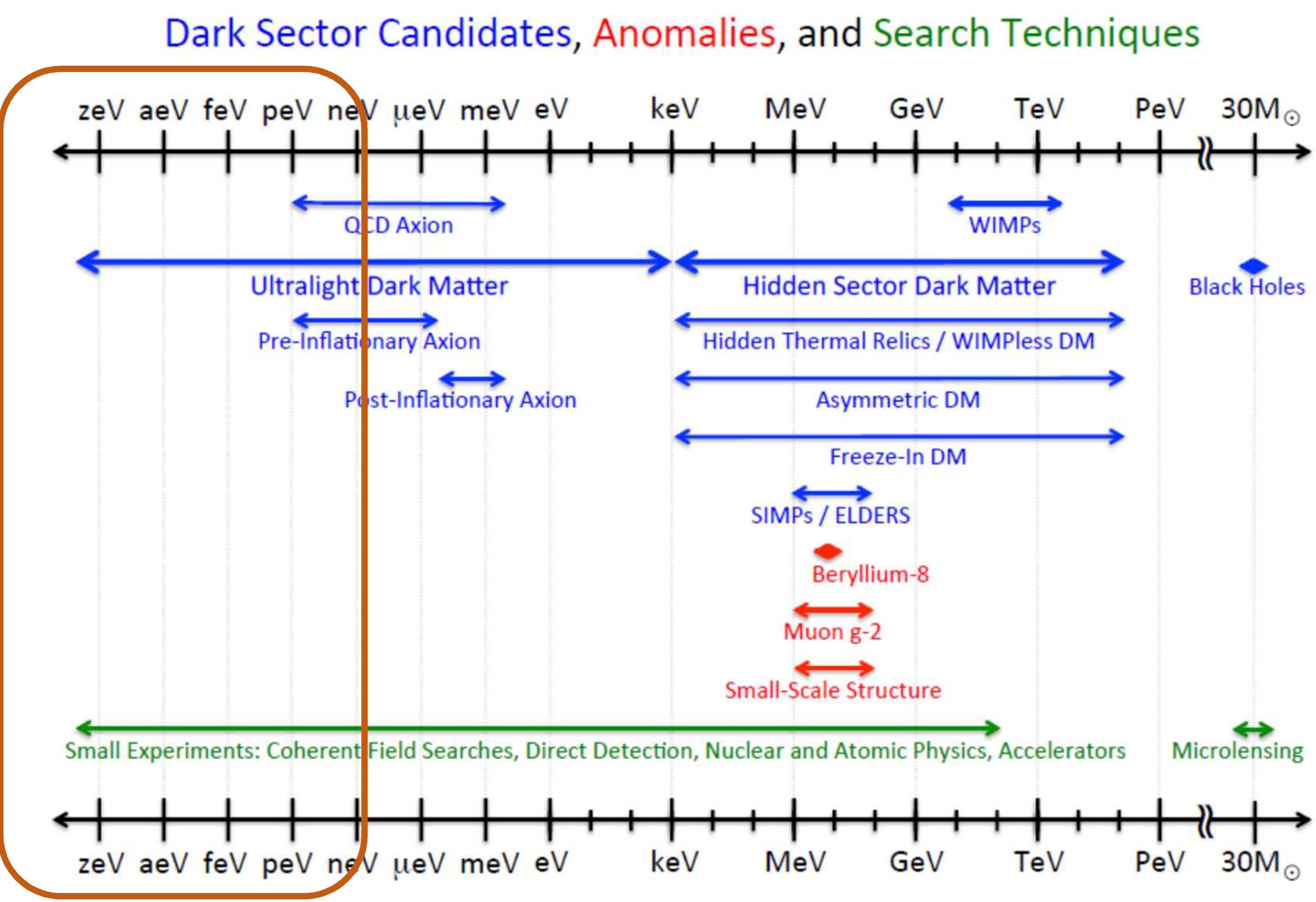
- “Evidence” for DM is purely gravitational, but of several types e.g.:
  - Galaxy rotation curves
  - Gravitational lensing
  - Cosmic Microwave Background
  - Structure formation
  - …



- We “know” that:
  - It is cold ($v << c$)
  - Forms a galactic halo
  - Has virialized in the galaxy ($\delta v \approx 10^{-3}\,c$, $\langle v \rangle \approx 0$)
  - It’s energy density in the solar system is ≈ 0.4 GeV/cm^3 and $\langle v \rangle \approx 10^{-3}\,c$

- We hope that:
  - More gravitational evidence will be obtained to constrain its properties
  - DM interacts other than gravitationally with standard model fields
  - Someone will detect it locally
  - New physics will be learned

Dark Matter (2)



From "US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report" arXiv:1707.04591

- Spans 90 orders of magnitude in mass !
- Here we will concentrate on low masses.
- In that region standard collisional (recoil based) detection techniques fail.

Ultralight DM

$$N_{occ} = \frac{n}{n_{\delta v}} \simeq \frac{3\pi^2\hbar^3\rho}{4m^4\delta v^3}$$

N_{occ} = 1 in our galaxy for m ≈ 10 eV.

- For N_{occ} > 1 the DM field can be treated as a classical field.
- It is likely to oscillate at its Compton frequency $\omega = mc^2/\hbar$.
- It may form "clumps" e.g. topological defects or relaxion stars/halos.
- For N_{occ} < 1 it must be quantized i.e. treated as a particle.
- Fermions cannot have $N_{occ} > g$ (g = number of internal degrees of freedom).
- Fermionic DM mass must be > eV.
- Bosonic DM can be treated as a classical field for mass below 10 eV or so.

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Observable effects

1. DM fields interacting with the spin of the electrons or nuclei in the atoms.
$\Rightarrow$ Effect on spin dependent atomic transition frequecies (Hyperfine transitions, Zeeman states, …).

2. DM scalar field with non-universal scalar couplings to SM fields.
$\Rightarrow$ Apparent violations of the equivalence principle
$\Rightarrow$ Space-time variation of fundamental constants
$\Rightarrow$ Change of atomic transition frequencies
$\Rightarrow$ Change of Bohr-radius = length of solids

Non-universally coupled scalar fields

[Damour & Donoghue 2010]
[Stadnik & Flambaum 2014,2015]

$$S = \frac{1}{c}\int d^4x \frac{\sqrt{-g}}{2\kappa}\left[R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right] + \frac{1}{c}\int d^4x\sqrt{-g}\left[\mathcal{L}_{\rm SM}(g_{\mu\nu},\Psi) + \mathcal{L}_{\rm int}(g_{\mu\nu},\varphi,\Psi)\right]$$

$$\mathcal{L}_{\rm int} = \frac{\varphi^i}{i}\left[\frac{d_e^{(i)}}{4\mu_0}F^2 - \frac{d_g^{(i)}\beta_g}{2g_3}\left(F^A\right)^2 - c^2\sum_{w=e,u,d}\left(d_{m_w}^{(i)} + \gamma_{m_w}d_g^{(i)}\right)m_w\bar{\psi}_i\psi_i\right]$$

- i = 1,2 for linear or quadratic coupling
- With five dimensionless coupling constants $d_x^{(i)}$

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Variation of constants

$$\mathcal{L}_{eff}^{EM} = \underbrace{-\frac{e^2 c}{16\pi\hbar\alpha}F^2}_{\text{Electromagnetism from Standard Model}} \underbrace{+ d_e\varphi\frac{e^2 c}{16\pi\hbar\alpha}F^2}_{\text{Electromagnetism from scalar field}} \simeq \frac{-e^2 c}{16\pi\hbar\alpha(1+d_e\varphi)}F^2$$

$$\alpha_{EM}(\varphi) = \alpha_{EM}(1 + d_e^{(i)}\frac{\varphi^i}{i})$$

$$m_w(\varphi) = m_w(1 + d_{m_w}^{(i)}\frac{\varphi^i}{i})$$

$$\Lambda_3(\varphi) = \Lambda_3(1 + d_g^{(i)}\frac{\varphi^i}{i})$$

i = 1,2

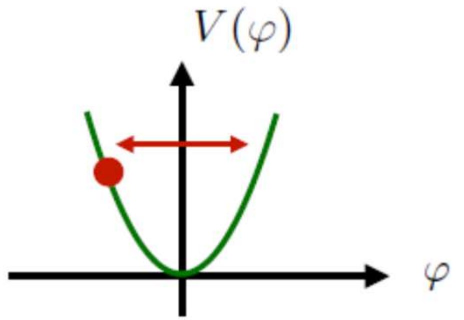
- Fundamental constants (α, Λ_3, m_i) are functions of φ, and vary if φ varies.
- Different atomic transitions depend differently on fundamental constants and thus their relative frequency varies with φ.
- The length of solids (e.g. optical cavities) is proportional to the Bohr radius ($\propto 1/(m_e\alpha)$) and thus varies with φ.
- Light speed is unchanged (in geometric optics approximation)

[Damour & Donoghue 2010]
[Stadnik & Flambaum 2014,2015]

Evolution of the galactic scalar field (2)

$$V(\varphi) = 2\frac{c^2}{\hbar^2} m_\varphi^2 \varphi^2$$

- Assume a quadratic potential for φ.
- Varying Lagrangian with respect to φ gives a KG equation:



$$\frac{1}{c^2}\ddot{\varphi}(t,\boldsymbol{x}) - \Delta\varphi(t,\boldsymbol{x}) = -\frac{4\pi G}{c^2} f(d_j^{(i)}) \rho_A(\boldsymbol{x}) \varphi(t,\boldsymbol{x})^{i-1} - \frac{c^2 m_\varphi^2}{\hbar^2}\varphi(t,\boldsymbol{x})$$

$$\varphi^{(1)}(t,\boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta) - s_A^{(1)} \frac{GM_A}{c^2 r} e^{-r/\lambda_\varphi}$$

$$\varphi^{(2)}(t,\boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta) \left[1 - s_A^{(2)} \frac{GM_A}{c^2 r}\right]$$

- The solutions for a spherically symmetric mass distribution oscillate at $\omega = m_\varphi c^2/\hbar$
- The Yukawa term has range $\lambda_\varphi = \hbar/(m_\varphi c)$
- s_A are functions of d_j and the central body (GM_A/R_A)
- Linear (i=1) solution is well known
- Quadratic (i=2) solution is less common and has interesting phenomenology

[Hees, Minazzoli, Savalle, Stadnik, Wolf, PRD **98**, 064051, 2018]

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Link to Dark Matter

$$\rho_{\tilde{\varphi}} = \frac{c^2}{4\pi G}\frac{\omega^2\varphi_0^2}{2} = \frac{c^6}{4\pi G\hbar^2}\frac{m_\varphi^2\varphi_0^2}{2}$$

- The cosmological density (+) and pressure (-) of φ are given by $\frac{c^2}{8\pi G}\left(\dot{\varphi}^2 \pm \frac{V(\varphi)c^2}{2}\right)$.
- The oscillating part of $\varphi(t)$ has zero average pressure and is therefore a candidate for Dark Matter.
- Equating its average density at spatial infinity with the DM density (≈ 0.4 GeV/cm^3) fixes the amplitude φ_0.
- The oscillation translates into an oscillation of the fundamental constants that can be searched for in a 6 parameter space (m_φ, d_x).
- The mass m_φ is given by the frequency of oscillation, the coupling constants d_x by the amplitude.

[Stadnik & Flambaum 2014, 2015]
[Arvinataki, Huang, Van Tilburg 2015]

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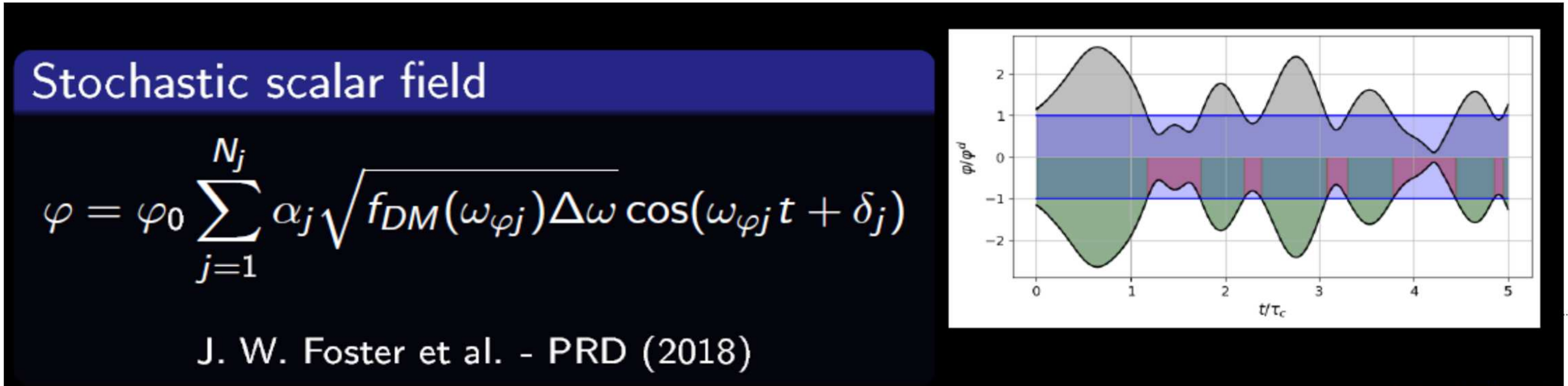
Evolution of the galactic scalar field (2)

Coherence time: $\hbar\omega = mc^2 + \frac{mv^2}{2} \Rightarrow \frac{\delta\omega}{\omega} \approx \frac{v\delta v}{c^2} \approx 10^{-6}$ for $\delta v \approx v \approx 10^{-3}$ c in the virialized galaxy

$$\delta\omega\,\tau_{coh} = 2\pi$$

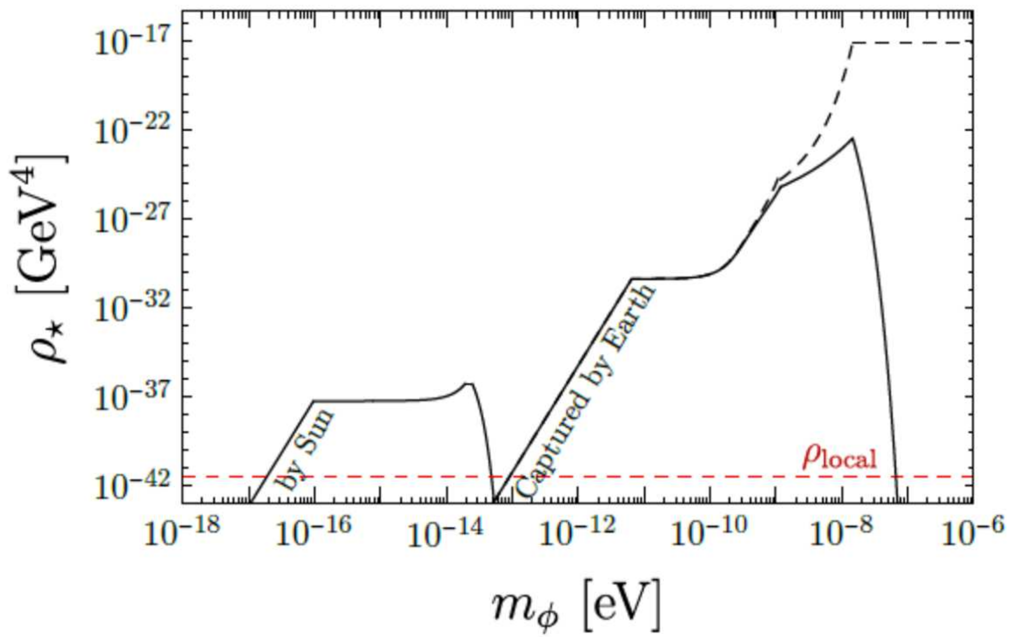
- In our Cs/Rb experiment [Hees et al. 2016] ($f < 5.7 \times 10^{-4}$ Hz) this gives τ_{coh} > 55 years.
- In the DAMNED experiment [Savalle et al. 2021] ($f = [10{:}200]$ kHz) this gives τ_{coh} = [5:100] s.

The velocity distribution is stochastic and that needs to be taken into account either by decreased sensitivity [Centers et al. arXiv:1905.13650] or by modelling the full stochastic evolution.



Scalar field transient “clumps” (2)

- Other self potentials than quadratic are possible.
- The scalar field may form objects (boson stars) or halos around standard matter objects (e.g. Earth, Sun), or topological defects (e.g. domain walls)
- The resulting field may still oscillate at its Compton frequency ($\omega = m_\varphi c^2/\hbar$).
- This could lead to an overdensity around massive objects like the Earth, or to transient local variations of the scalar field.
- It may also modify the coherence properties of the field (e.g. much longer coherence time)



[Derevianko, A. & Pospelov, M., Nature Physics, **10**, 933, 2014]
[Banerjee, A.; Budker, D.; Eby, J.; Kim, H. & Perez, G., Communications Physics **3**, 1, 2020]

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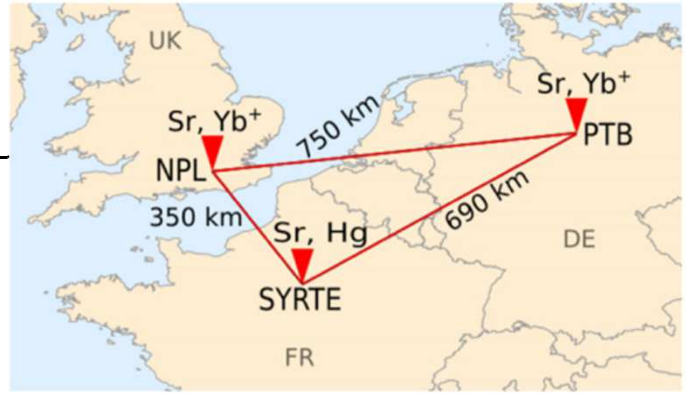
Dark activities at SYRTE

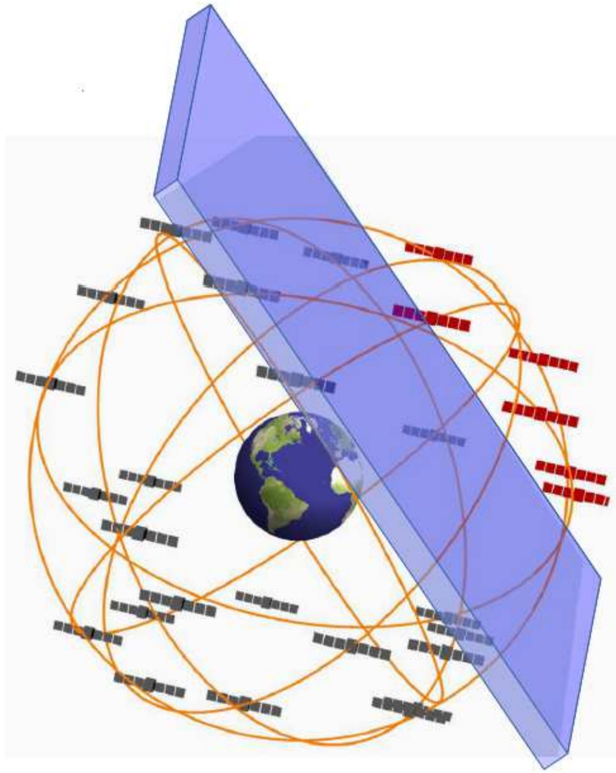


Theory:

- Extensive study/review of equivalence principle violating scalar DM, scalar coupling, atomic transitions/free fall tests [Hees 2018]
- Study of interactions with atomic spins: scalar/fermion/vector boson DM, with axial/tensor coupling, contact interaction/mediator. Effect in atomic cocks and co-magnetometers [Alonso 2019, Wolf 2019].

Experiments:

- Rb/Cs dual cold atom clock, long term comparison [Hees 2016]
- The DAMNED experiment [Savalle 2021]… see Etienne's talk
- Europe-wide comparison of optical clocks to search for transients [Roberts 2020]
- The GASTON project (GAlileo Survey of Transient Objects Network), searching for transients using the clocks on board the Galileo satellite constellation [ESA contract, ongoing].



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Atomic Spectroscopy

- Different atomic transition frequencies depend differently on fundamental constants.
- Comparison of two atomic transition frequencies ($Y=X_A/X_B$) is a direct measure of the scalar field. Can be used to search for the space-time variation of $\varphi(t,\boldsymbol{x})$.

$$\frac{Y(t,\boldsymbol{x})}{Y_0} = K + \left(\kappa_{X_A}^{(i)} - \kappa_{X_B}^{(i)}\right)\varphi^i(t,\boldsymbol{x})$$

The sensitivity coefficients $\kappa_X^{(i)}$ involve the coupling constants $d_j^{(i)}$ and are obtained from atomic and nuclear structure calculations (Flambaum and co-workers [2006, 2008, 2009]).

$$\varphi^{(1)}(t,\boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta) - s_A^{(1)} \frac{GM_A}{c^2 r} e^{-r/\lambda_\varphi}$$

$$\varphi^{(2)}(t,\boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta) \left[1 - s_A^{(2)} \frac{GM_A}{c^2 r}\right]$$

Can search for both, oscillations and spatial dependence in the field of body A (e.g. Earth)

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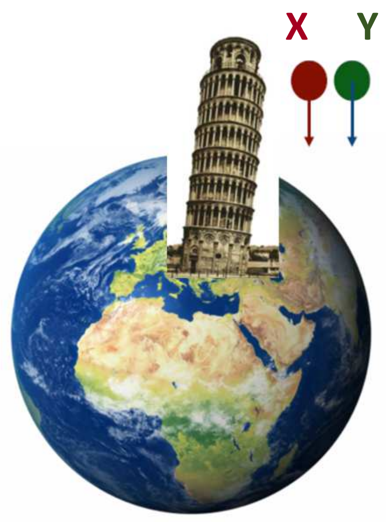
Tests of the Universality of Free Fall

- Two bodies of different composition will couple differently to $\varphi(t, \boldsymbol{x})$.
- They will experience a differential acceleration as a function of $\varphi(t, \boldsymbol{x})$:

$$[\Delta \boldsymbol{a}]_{X-Y} = -\left(\alpha_X^{(i)} - \alpha_Y^{(i)}\right) \varphi^{i-1} \left[c^2 \boldsymbol{\nabla}\varphi + \boldsymbol{v}\dot{\varphi}\right]$$

The sensitivity coefficients $\alpha_X^{(i)}$ are composition dependent and involve the coupling constants $d_j^{(i)}$. They are derived in [Damour & Donaghue 2010].



$$\varphi^{(1)}(t, \boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta) - s_A^{(1)} \frac{GM_A}{c^2 r} e^{-r/\lambda_\varphi}$$

$$\varphi^{(2)}(t, \boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta) \left[1 - s_A^{(2)} \frac{GM_A}{c^2 r}\right]$$

Can search for both, oscillations and spatial dependence in the field of body A (e.g. Earth)

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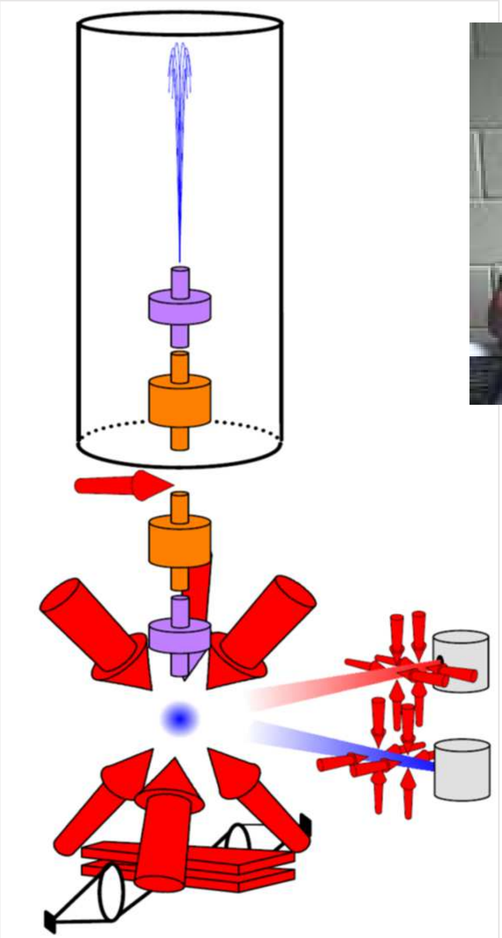
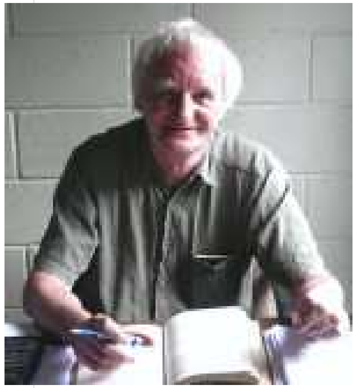
Summary so far

- If light (m_φ< 10 eV) a massive scalar field will behave classically and oscillate at frequency $f = m_\varphi c^2/h$
- It could be coupled to SM fields (standard matter) in which case it will lead to a violation of the equivalence principle. This can be searched for by:
  - atomic spectroscopy
  - tests of the universality of free fall

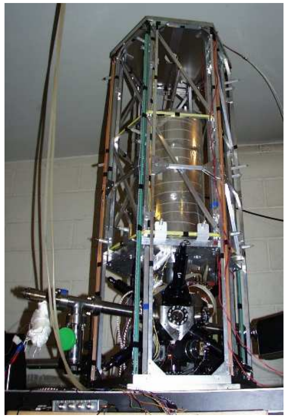
- In both cases the phenomenology includes oscillations related to DM and spatial dependence due to the presence of e.g. the Earth.

The SYRTE dual Rb-Cs fountain FO2





André Clairon
1947 - 2015



- Built in early 2000s by André Clairon and co-workers.
- Operates simultaneously on laser cooled (μK) ^{87}Rb and ^{133}Cs since 2008 (common mode systematics).
- Most accurate and stable Rb/Cs frequency ratio measurement world-wide (and longest duration).
- Contributes continuously to TAI with both Rb and Cs
- Previously used to constrain linear drifts of fundamental constants, and variations proportional to U/c^2 i.e. annual variations [Guéna, PRL 2012]+*updates*.
- All systematics are evaluated and corrected during operation.

[Guéna et al. 2010, 2012, 2014]

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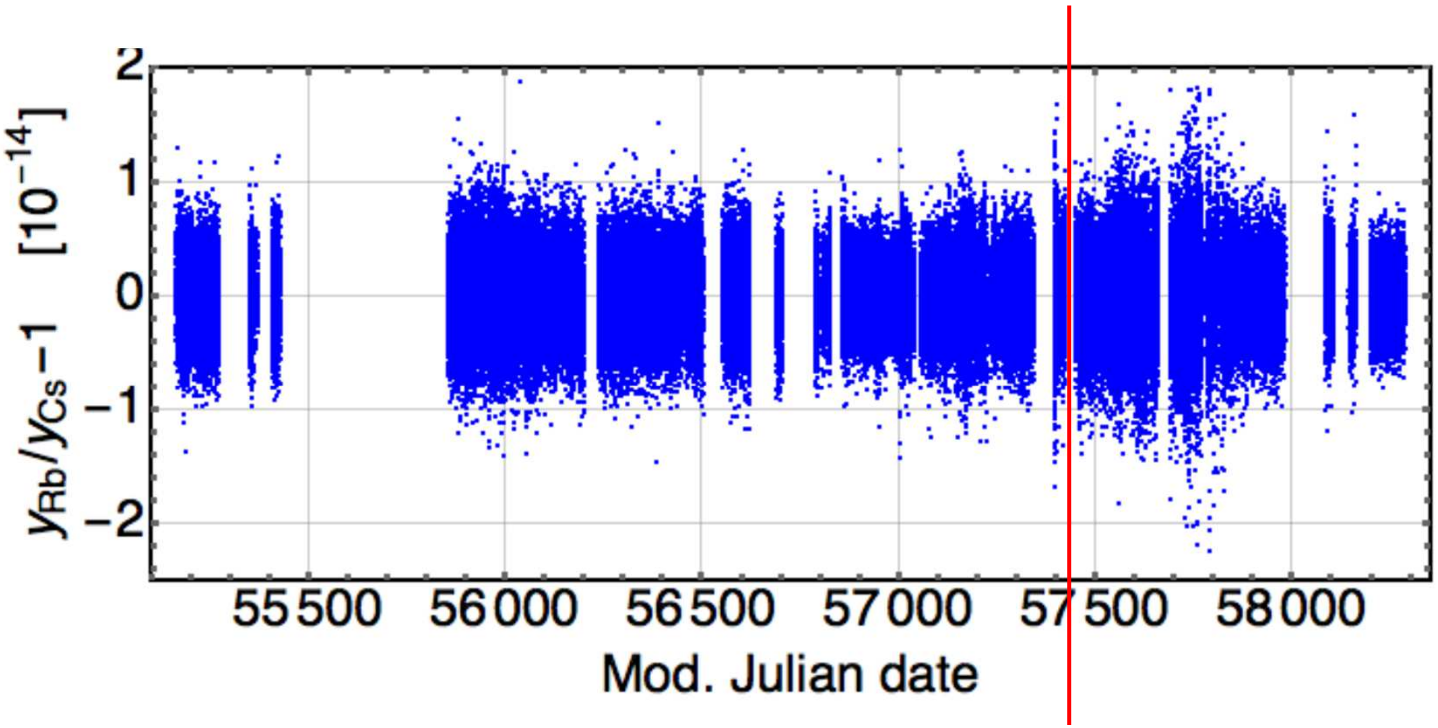
FO2 Rb/Cs raw data



- Nov 2009 – May 2018
- Averaged to 100 points/day
- 144000 points in total
- ≈ 45% duty cycle with gaps due to maintenance and investigation of systematics
- Standard deviation = 3×10^{-15}

$$y(t) = \frac{f(t)}{f_0}$$

Update of [Hees, Guéna, Abgrall, Bize, Wolf, PRL **117**, 061301, 2016]

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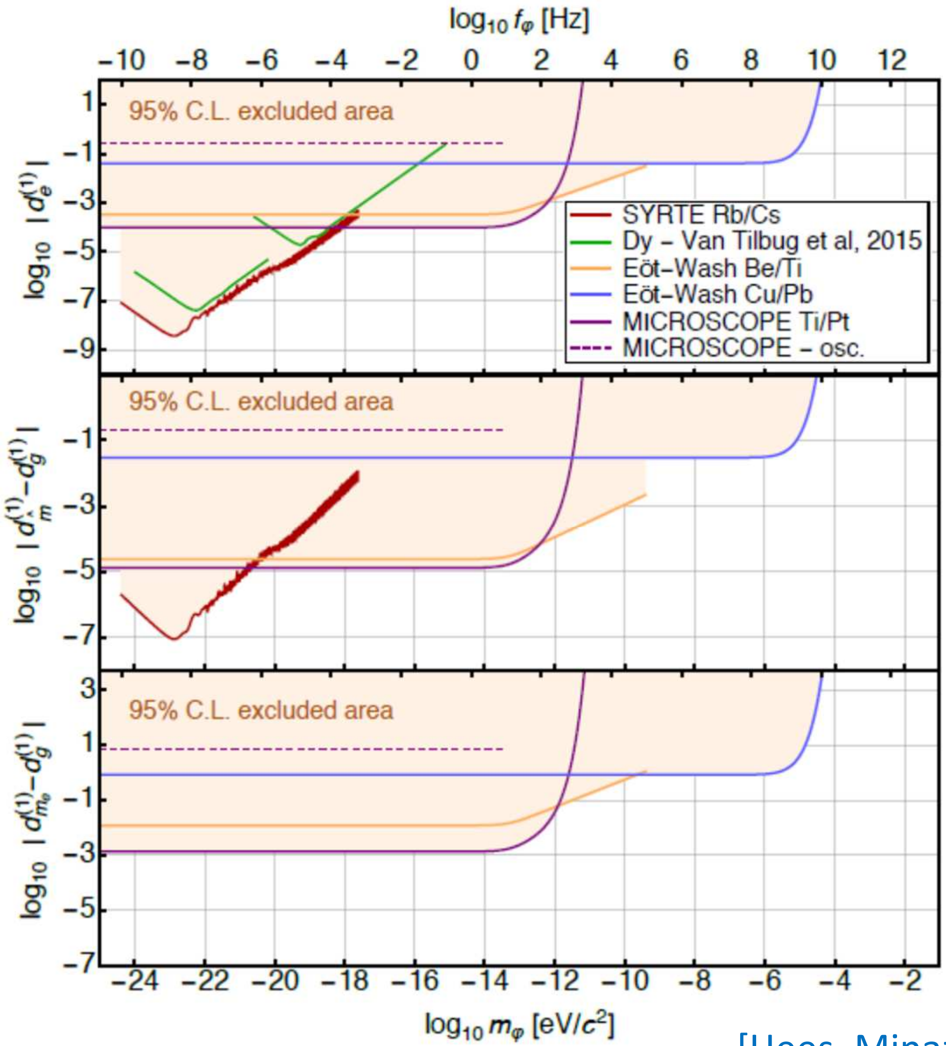
Constraints for linear coupling

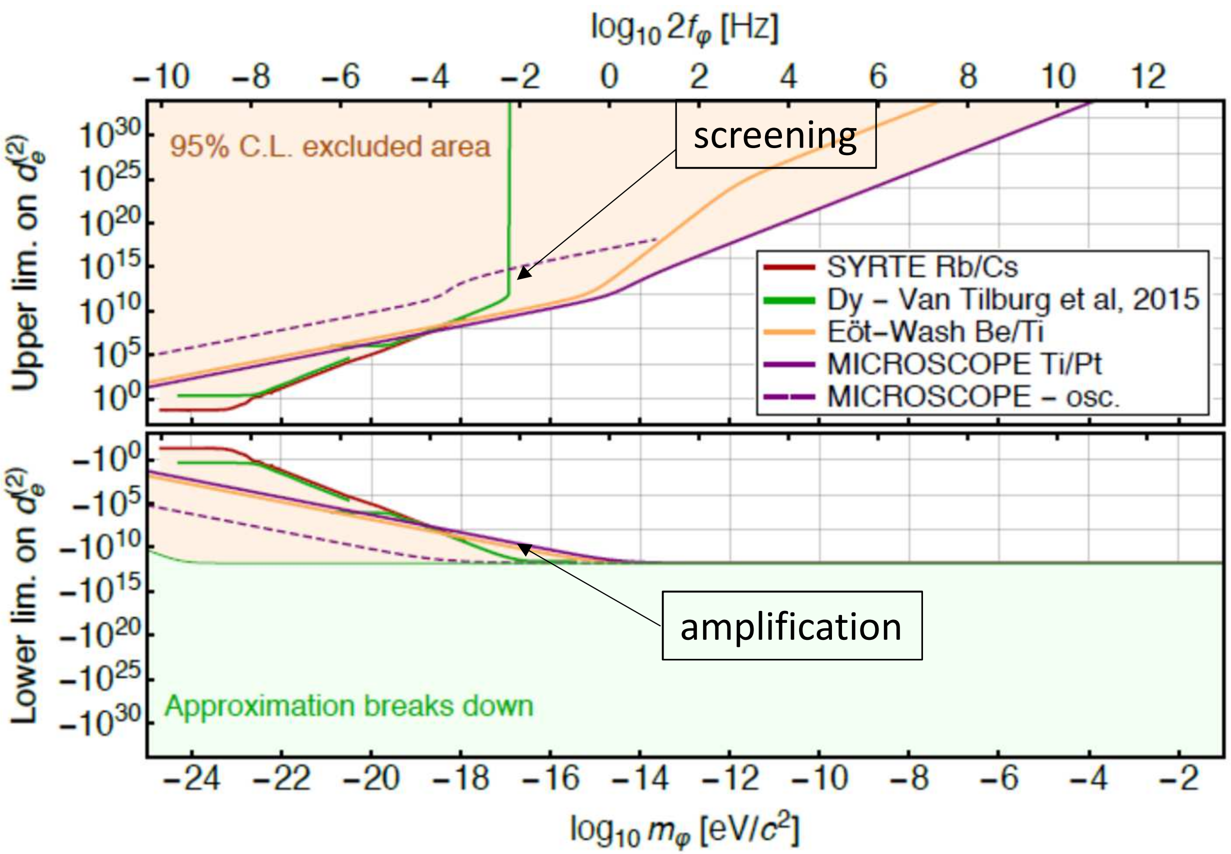


- Here we compare bounds assuming that “all other coefficients = 0”.
- UFF tests are more sensitive at higher masses, spectroscopy at lower masses.
- UFF are limited by Yukawa range for higher masses.
- Could also search for harmonic signal in UFF (limited by sampling rate).
- Generally, one could imagine varying distance (satellite tests) to better explore the spatial dependence.

$$\varphi^{(1)}(t,\boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta) - s_A^{(1)} \frac{GM_A}{c^2 r} e^{-r/\lambda_\varphi}$$

[Hees, Minazzoli, Savalle, Stadnik, Wolf, PRD **98**, 064051, 2018]

Constraints for quadratic coupling



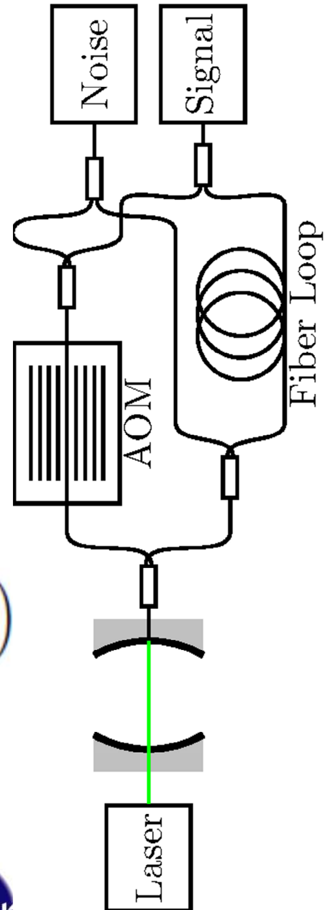
- Only d_e here. Graphs for other coefficients look similar.
- Constraints are much less stringent. They are compatible with “natural” values (whatever that means….).
- Either “screening” or “amplification” by the central mass can occur.

$$\varphi^{(2)}(t, \boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta) \left[1 - s_A^{(2)} \frac{GM_A}{c^2 r}\right]$$

[Hees, Minazzoli, Savalle, Stadnik, Wolf, PRD **98**, 064051, 2018]

DArk Matter from Non Equal Delays (DAMNED)

- Presently running and being optimized at SYRTE – Paris Observatory
- Based on ultra-stable optical cavity
- Aiming at high frequency (10-100 kHz i.e. DM mass around 10^{-10} eV)
- Shot noise limited just above the cavity noise.



$$\Delta\phi(t) = \omega_0 T_0 + 2\frac{\omega_0}{\omega_m}\left(\frac{\delta T}{T_0} + \frac{\delta\omega}{\omega_0}\right)\sin\left(\frac{\omega_m T_0}{2}\right)\sin\left(\omega_m t + \Phi\right)$$

$$\left(\frac{\delta T}{T_0} + \frac{\delta\omega}{\omega_0}\right) \simeq \frac{\omega_0}{n_0}\frac{\partial n}{d\omega}\left(d^{(1)}_{m_e} - d^{(1)}_e - \frac{1}{2}\left(d^{(1)}_{m_e} - d^{(1)}_g\right) + 0.024\left(d^{(1)}_{m_q} - d^{(1)}_g\right)\right)\varphi_0 + \mathcal{O}\left(10^{-4}\varphi_0 d^{(1)}_i\right)$$

$\approx 10^{-2}$

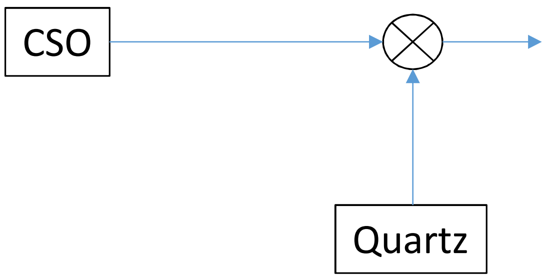
Fibre delay

Cavity frequency

[Braxmaier et al., PRD **64**, 042001, 2001]
[Pasteka et al., arXiv:1809.02863, 2018]

Quartz vs Cryogenic-Cavity

- Presently being set up at UWA.
- Based on high performance quartz crystal and cryogenic sapphire resonator.
- Aiming at high frequency (10-100 kHz and above i.e. DM mass ≥ 10^{-10} eV).



$$\propto \left(\frac{\delta\alpha}{\alpha} + \frac{1}{2}\frac{\delta(m_e/\Lambda_3)}{m_e/\Lambda_3} - 0.024\frac{\delta(m_q/\Lambda_3)}{m_q/\Lambda_3} \right) \sin\left(\omega_m t + \Phi\right)$$

$$\propto \left(d_e^{(1)} + \frac{1}{2}\left(d_{m_e}^{(1)} - d_g^{(1)}\right) - 0.024\left(d_{m_q}^{(1)} - d_g^{(1)}\right) \right) \varphi_0 \sin\left(\omega_m t + \Phi\right)$$

Conclusion and Outlook

Conclusion:

- Ultralight (10^{-23} – 10^4 eV) dark matter is a an active field, both theoretically and experimentally
- Could be detected in high precision atomic devices (clocks, magnetometers, ….)
- More generally, if DM interacts with SM fields you might have effects in many high precision experiments (e.g. equivalence principle tests, time/frequency metrology, ….).

Outlook:

- New experiments are being designed targeting specific regions of parameter space
- Theoretical work develops new models, and helps identifying potential effects on high precision experiments
- This seems just the beginning…

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Thank you for your attention!

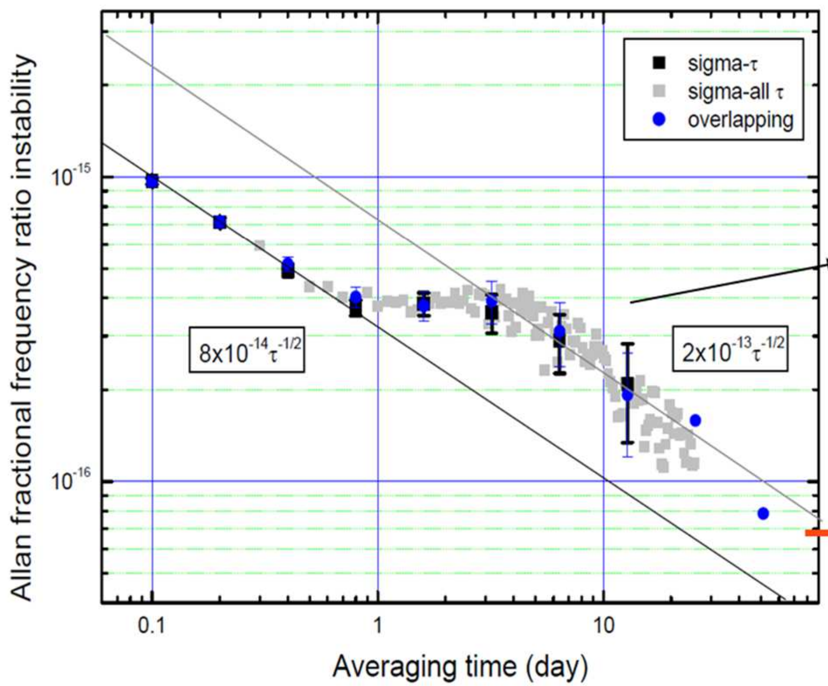
Backup Slides

Noise model

FO2-Rb/Cs comparison over 6 months

Allan standard deviation of the Rb/Cs frequency ratio

effective duration 130 days



Bump well understood: correction of collision shift by HD/LD measurements interleaved introduce another timescale at 5 days

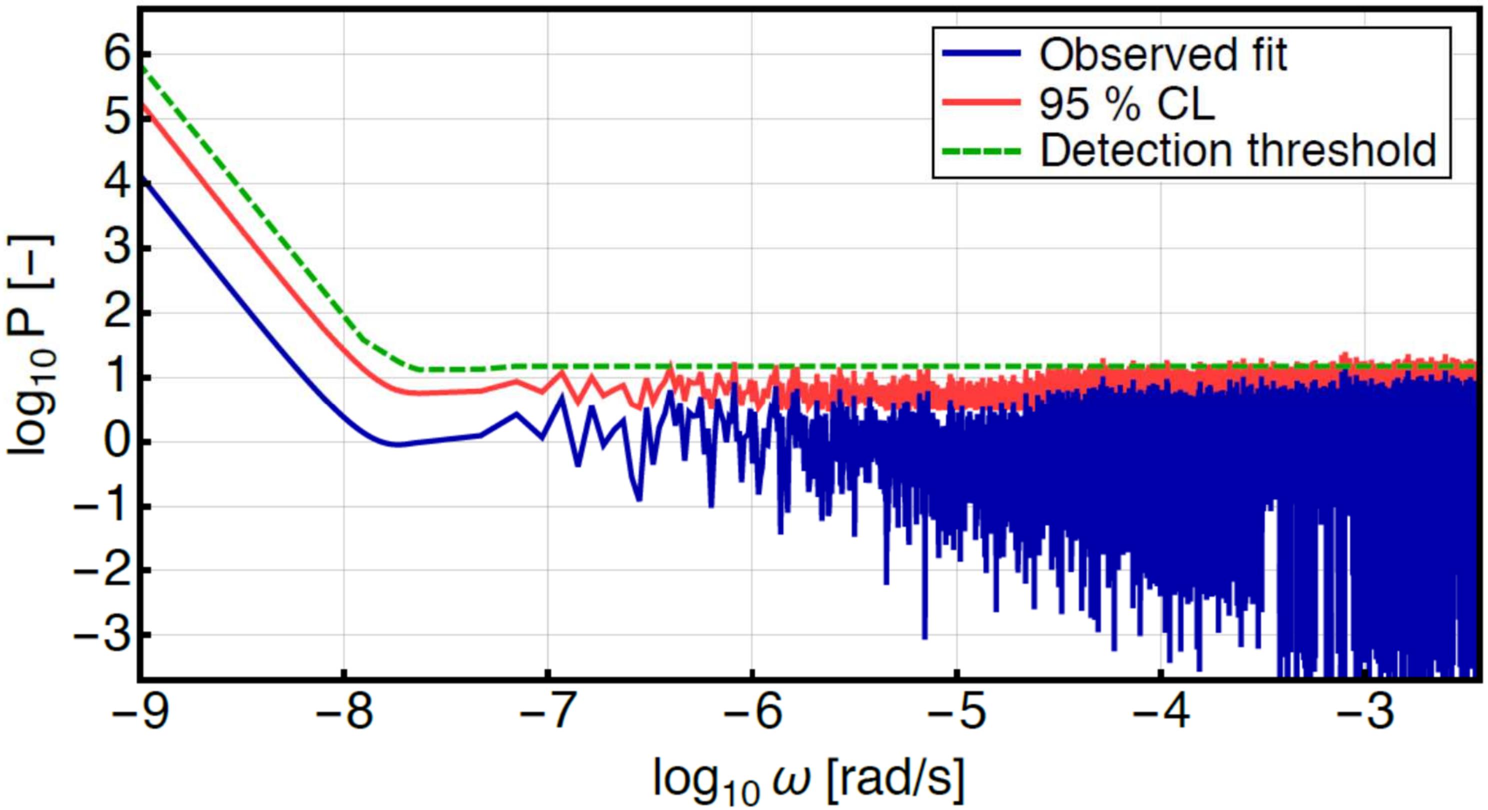
Resolution below 10^{-16}

• Noise level is a function of Fourier frequency:

$$\sigma_o^2(\omega) = 4.6 \times 10^{-29}, \quad \text{for } \omega \leq 9.0 \times 10^{-6} \text{ rad/s}$$
$$\sigma_o^2(\omega) = 9.3 \times 10^{-30}, \quad \text{for } \omega \geq 4.5 \times 10^{-5} \text{ rad/s}$$
$$\sigma_o^2(\omega) = 4.2 \times 10^{-34}/\omega, \quad \text{otherwise,}$$

See Guéna et al., *Metrologia,* **51**, 108, (2014) for details

Normalized power



- Fit $A + C_\omega \cos(\omega t) + S_\omega \sin(\omega t)$ to data for each independent ω.
- Search for a peak in normalized power $P_\omega = \frac{N}{4\sigma_0^2(\omega)}(C_\omega^2 + S_\omega^2)$.
- Use different methods (LSQ + MC, Bayesian MCMC) to determine confidence limits.

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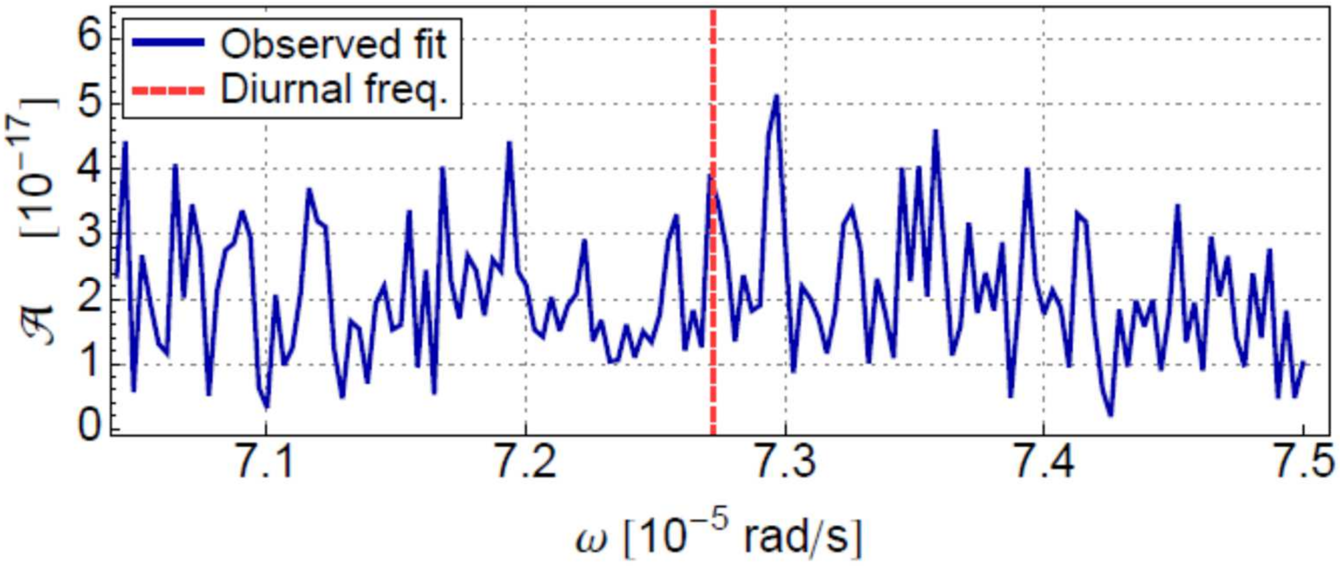
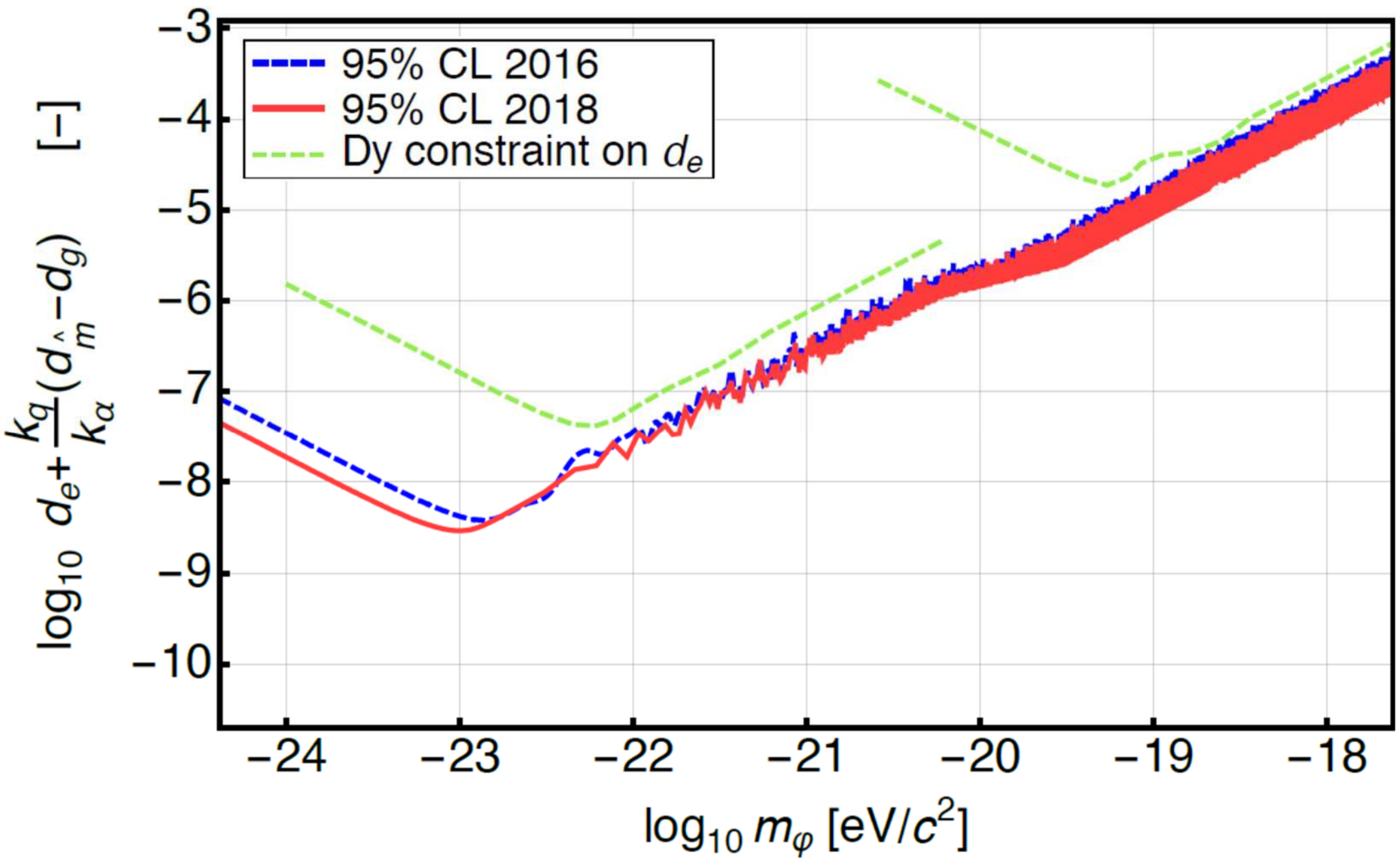
Systematic Effects



• Detailed and repeated analysis of systematic effects (Guéna 2012, 2014) estimates uncertainty on absolute determination of Rb and Cs hyperfine frequency to 3.2×10^{-16} and 2.1×10^{-16}.
• The uncertainty on the difference is expected to be significantly less due to common mode.
• Periodic variations at any frequency are again expected to be below that level.
• No evidence for systematic effect at most likely frequency (diurnal).
$\Rightarrow$ Our results are limited by statistics rather than systematic uncertainties.

Constraints for linear coupling



- Rb/Cs comparison is sensitive to the combination $d_e + 0.043(d_{\hat{m}} - d_g)$.
- Additional data has (40% increase in duration) has only small effect, mainly at low mass.

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Limits on mass range

A lower limit on plausible DM masses is obtained by requiring that $\lambda = h/mv$ < smallest dwarf galaxy (≈ 1 kpc ≈ 3×10^{19} m). With $v \approx 10^{-3}\, c$ this gives a minimum mass of about 10^{-23} eV.

- Our upper limit is due to our data being averaged to 100 points/day, imposing a Nyquist limit at 5.8×10^{-4} Hz corresponding to $m \approx 2.4\times10^{-18}$ eV.
- But our basic measurement cycle time is 2 s, so we will analyze some high frequency data to extend our search up to 10^{-15} eV.
- It is possible to search at even higher masses, at the expense of sensitivity [see e.g. Kalaydzhyan & Yu, PRD 2017]. Limited when DM coherence time = h/mv^2 (assuming virialized DM) becomes shorter than clock cycle (2 s). Then $m \leq 2\times10^{-9}$ eV.

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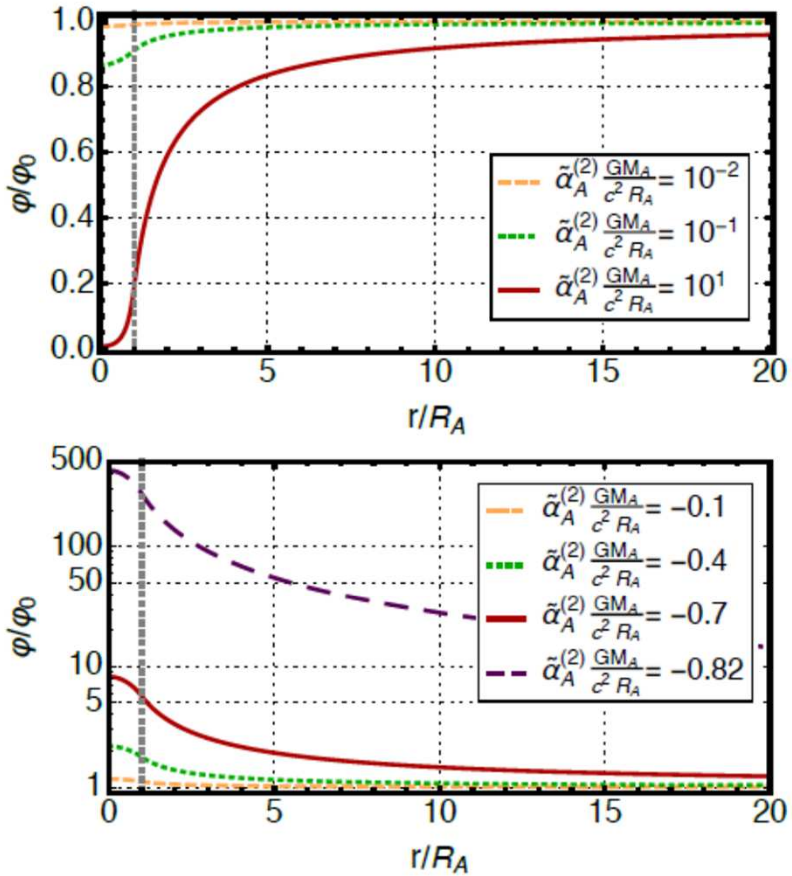


FIG. 2. Evolution of the scalar field around a homogeneous spherically symmetric body. The different curves show the impact of the values of $\tilde{\alpha}^{(2)}$. In particular, in the limit of large positive couplings, the scalar field tends to vanish inside the body and the scalar field diverges for negative values of $\tilde{\alpha}^{(2)}$.

$$\boxed{\varphi^{(2)}(t,\boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta)\left[1 - s_A^{(2)}\frac{GM_A}{c^2 r}\right]}$$

$$s_A^{(2)} = \tilde{\alpha}_A^{(2)} J_{\text{sign}[\tilde{\alpha}_A^{(2)}]}\left(\sqrt{3\left|\tilde{\alpha}_A^{(2)}\right|\frac{GM_A}{c^2 R_A}}\right), \tag{23}$$

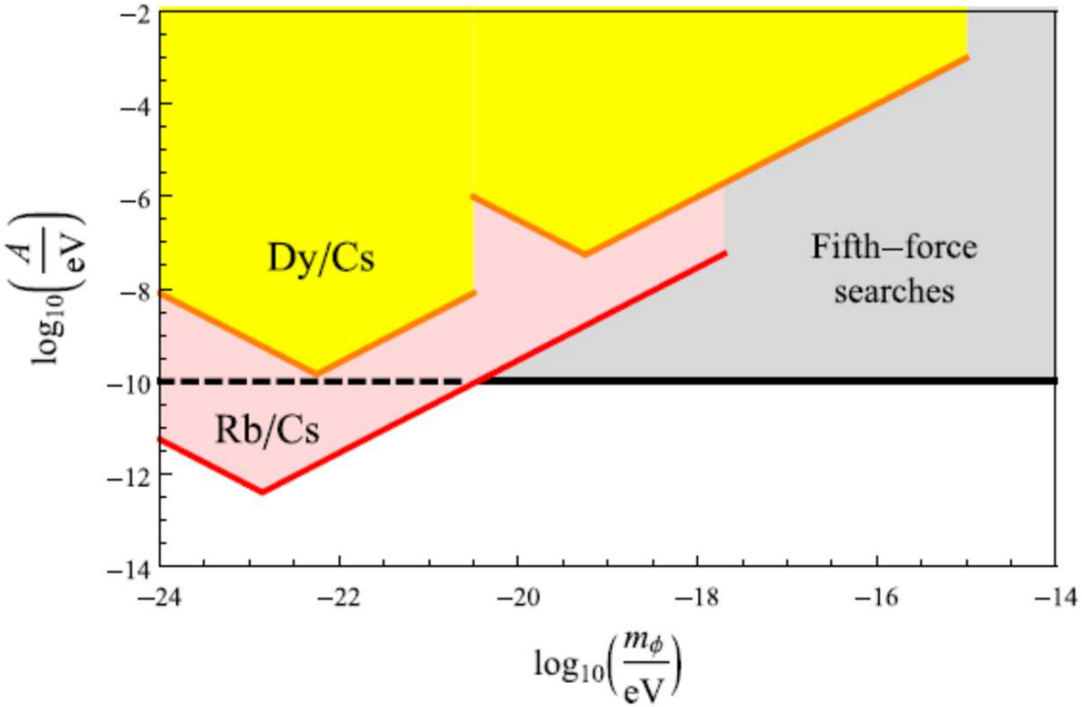
which depends on the sign of $\tilde{\alpha}_A^{(2)}$ through

$$J_+(x) = 3\frac{x - \tanh x}{x^3}, \tag{24a}$$

$$J_-(x) = 3\frac{\tan x - x}{x^3}. \tag{24b}$$

$$\boxed{\lim_{d_j \to +\infty} \varphi^{(2)}(t,\boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta)\left[1 - \frac{R_A}{r}\right]}$$

Higgs portal



$$\mathcal{L}^{\text{Higgs}}_{\text{int,eff}} = \frac{A\langle h\rangle}{m_h^2}\phi\left(\sum_f g_{hff}\bar{f}f + \frac{g_{h\gamma\gamma}}{\langle h\rangle}F_{\mu\nu}F^{\mu\nu}\right), \quad (7)$$

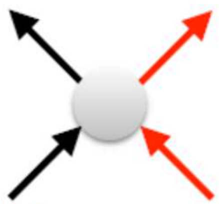
where $m_h = 125$ GeV is the mass of the Higgs boson, $g_{hff} = m_f/\langle h\rangle$ for couplings of the Higgs to elementary fermions (leptons and quarks), $g_{hNN} = bm_N/\langle h\rangle$ with $b \sim 0.2$–0.5 [24] for couplings of the Higgs to nucleons, and $g_{h\gamma\gamma} \approx \alpha/8\pi$ for the radiative coupling of the Higgs to the electromagnetic field

[From Stadnik & Flambaum, PRA **94**, 022111 (2016)]

'Traditional' DM searches

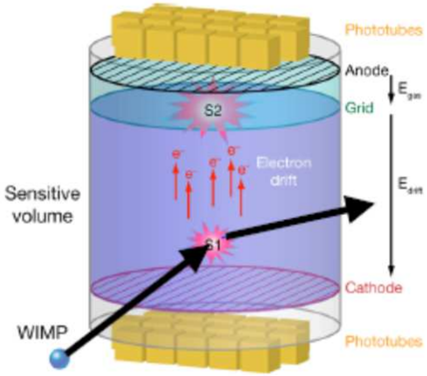
Direct: e.g. Xenon 100

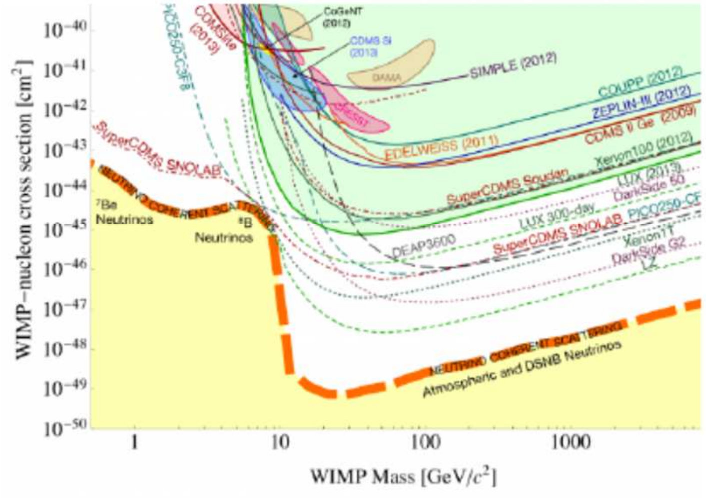
scattering



DM nucleus

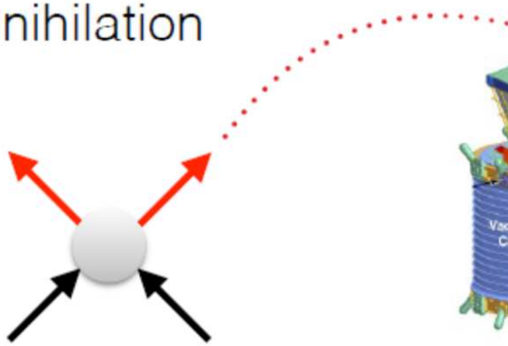
$$E_R^{\max} \sim \left(\frac{m_\chi}{\mathrm{GeV}}\right) \mathrm{keV}$$



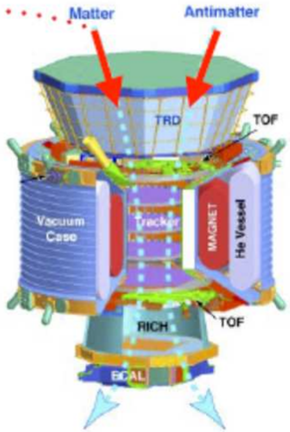


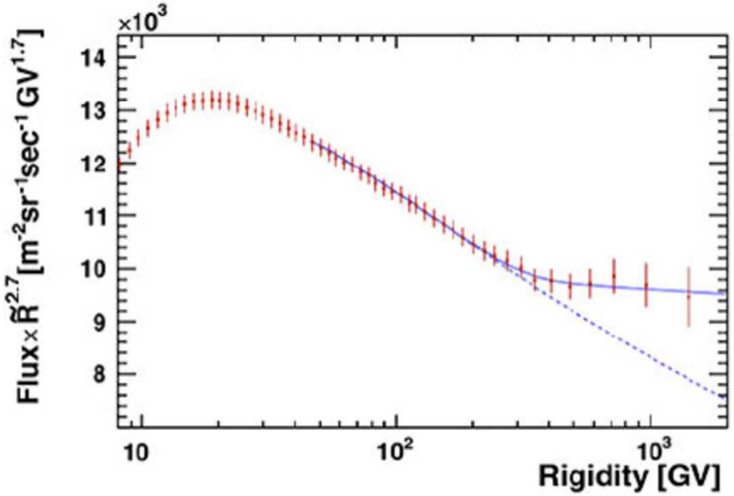
Indirect: e.g. AMS02

annihilation

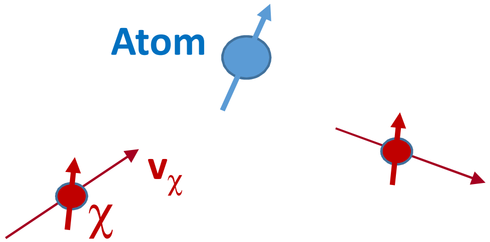


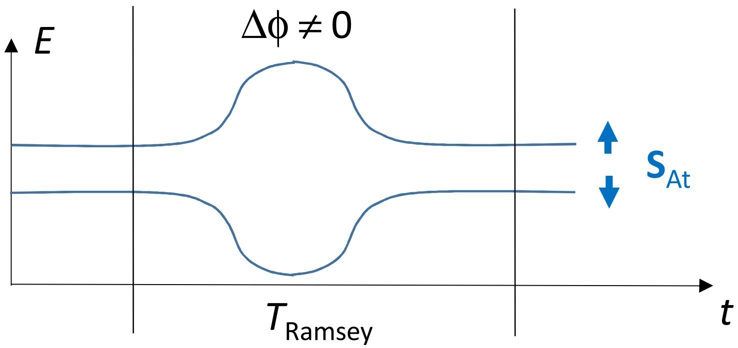
DM DM



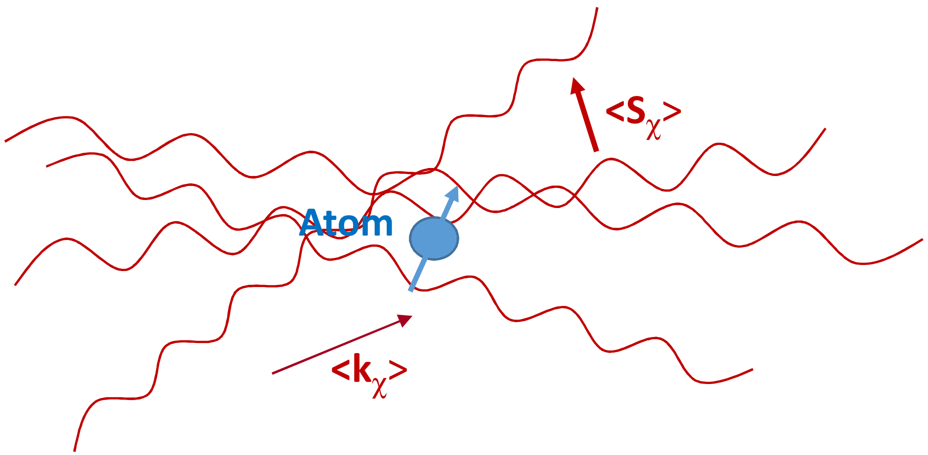


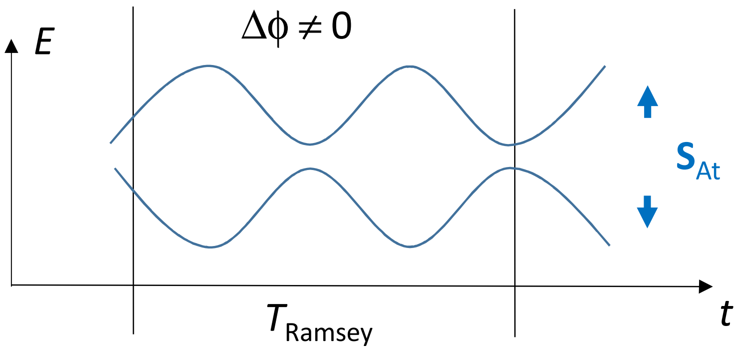
DM interacting with SM spins



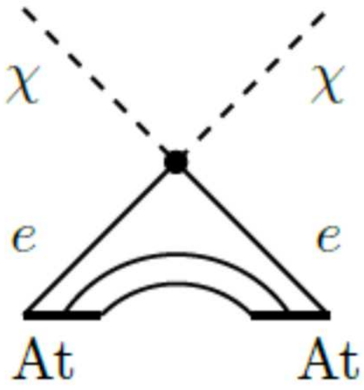


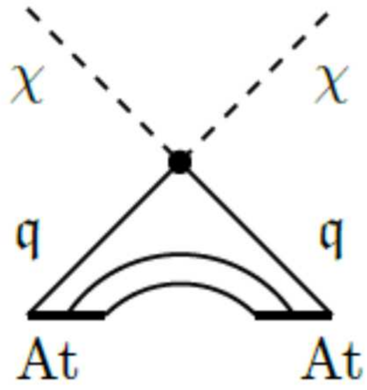
- $m_\chi << m_{At} \Rightarrow$ no momentum exchange
- "See" effects proportional to $\mathbf{S}_{At}.\mathbf{S}_\chi$ or $\mathbf{S}_{At}.\mathbf{v}_\chi$
- When varying $\mathbf{S}_{At}$ (e.g. using a magnetic field) the effect is modulated





Interaction types





- Example: EFT model with contact interaction
- Generalized to a model with a dynamical mediator.
- Also considered 3-point interactions with axial scalar (axion) or axial vector boson.

see [Alonso, Blas, Wolf, arXiv:1810.00889] for details.

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

Leads to $\mathbf{S}_{At}.\mathbf{S}_\chi$ or $\mathbf{S}_{At}.\mathbf{v}_\chi$

$\mathcal{I}$	$\psi = e, u, d$		DM	Scalar	Fermion	Vector Boson
Ax. vector	$\mathcal{J}_\psi$:	$\bar{\psi}\gamma^\mu\gamma_5\psi$	$\mathcal{J}_\chi$:	$i\chi^\dagger\partial_\mu\chi$+h.c.,	$\bar{\chi}\gamma_\mu\chi$, $\bar{\chi}\gamma_\mu\gamma_5\chi$,	$i\chi_\nu^\dagger\partial_\mu\chi^\nu$+h.c.
Tensor	$\mathcal{J}_\psi$:	$\bar{\psi}\sigma^{\mu\nu}\psi$	$\mathcal{J}_\chi$:	–	$\bar{\chi}\sigma^{\mu\nu}\chi$,	$\chi_\alpha^\dagger(\Sigma_{\mu\nu})^\alpha{}_\beta\chi^\beta$.

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Observables (ex. hyperfine atomic clock)

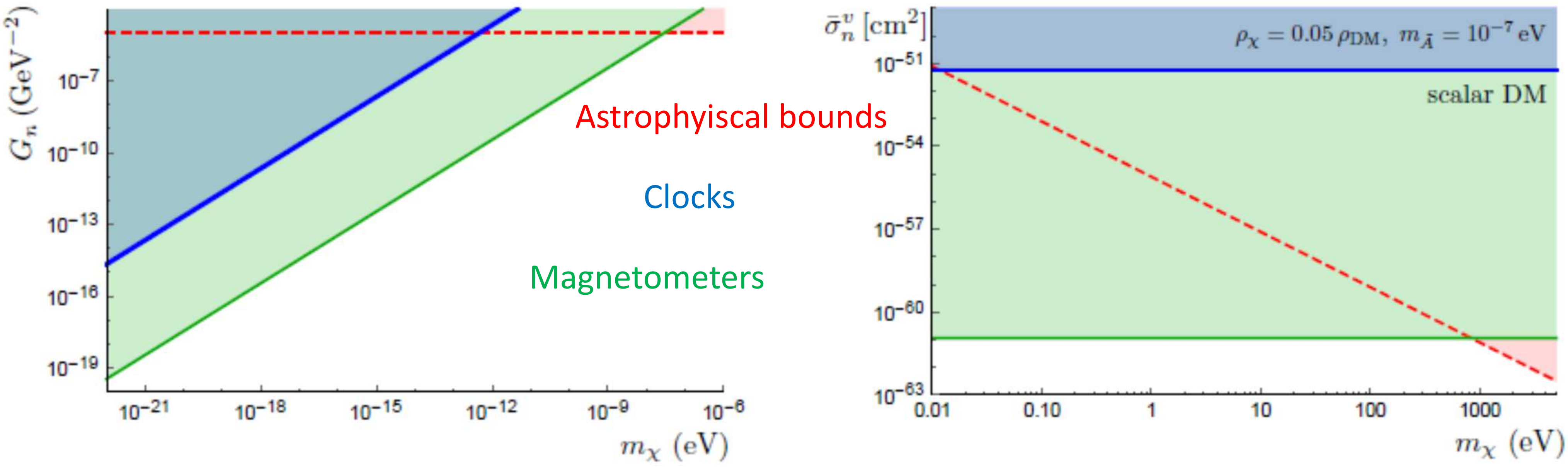
Consider hyperfine transition in Rb or Cs clocks. The effect is akin to frequency shifts due to collisions with background gases [Gibble, PRL **110**, 180802, 2013]. For a detailed derivation see [Wolf, Alonso, Blas, arXiv:1810.01632]:

$$\delta\omega \simeq \frac{2\pi\rho_\chi \hbar}{m_\chi^2}\mathrm{Re}\left[f_1(0) - f_2(0)\right]$$

$f_i(0)$ = forward scattering amplitudes in the two clock states $|1\rangle$ and $|2\rangle$:

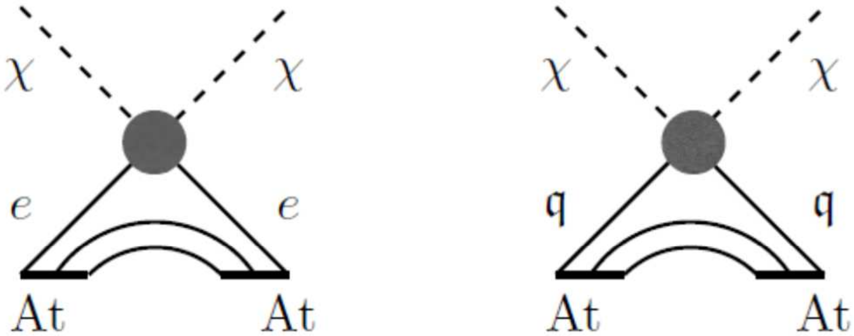
- $f_1(0)$- $f_2(0)$ depends **linearly** on $G_{e/q}\mathbf{S}_{At}.\mathbf{S}_\chi$ or $G_{e/q}\mathbf{S}_{At}.\mathbf{v}_\chi$
- When operating the clock on spin polarized states (using a quantization magnetic field B) the frequency shift varies as the orientation of **B** varies.
- Additionally, may have modulations at Compton frequency of m_χ.
- To control magnetic field fluctuations use differential measurement between different species e.g. Rb and Cs in clocks (see later) or He and Xe in magnetometers.

Sensitivity estimate examples



- Coupling to neutron.
- Sensitivity estimates, not bounds!
- Assume μHz uncertainty for Rb/Cs hyperfine clocks, sub-nHz for He/Xe magnetometers.
- Provides an indication of parameter space that can be explored.

DM-atom scattering: effective vertex



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

$$\mathrm{Ncl}^I_{\lambda_I} \downarrow \sum_{n,p} |N\rangle$$

DM current

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

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

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

Making the calculation

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

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

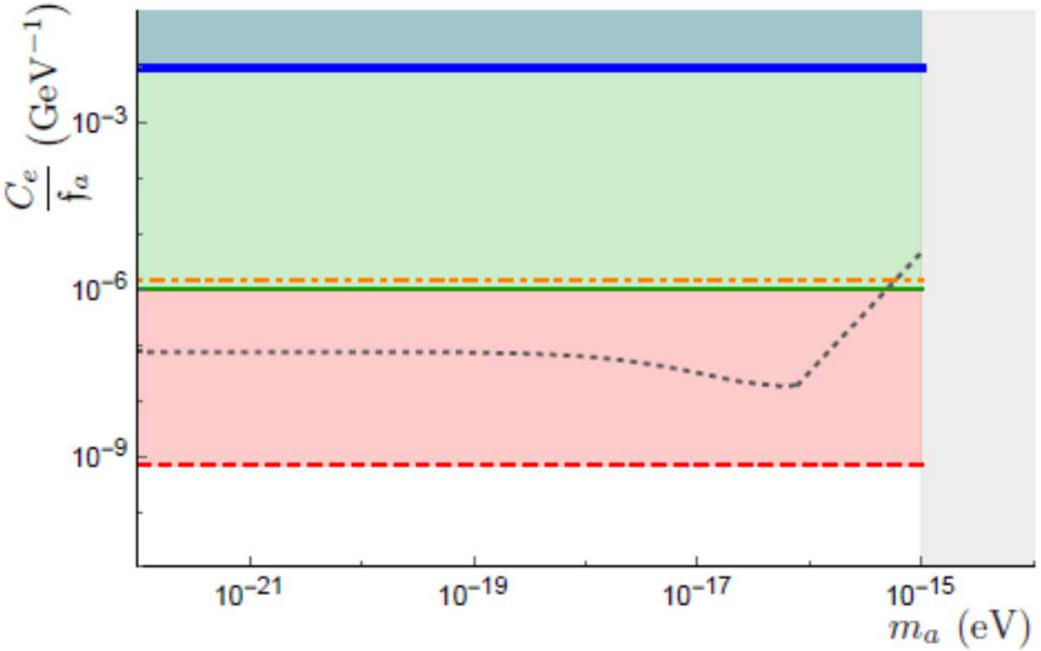
Single DM particle-atom interaction

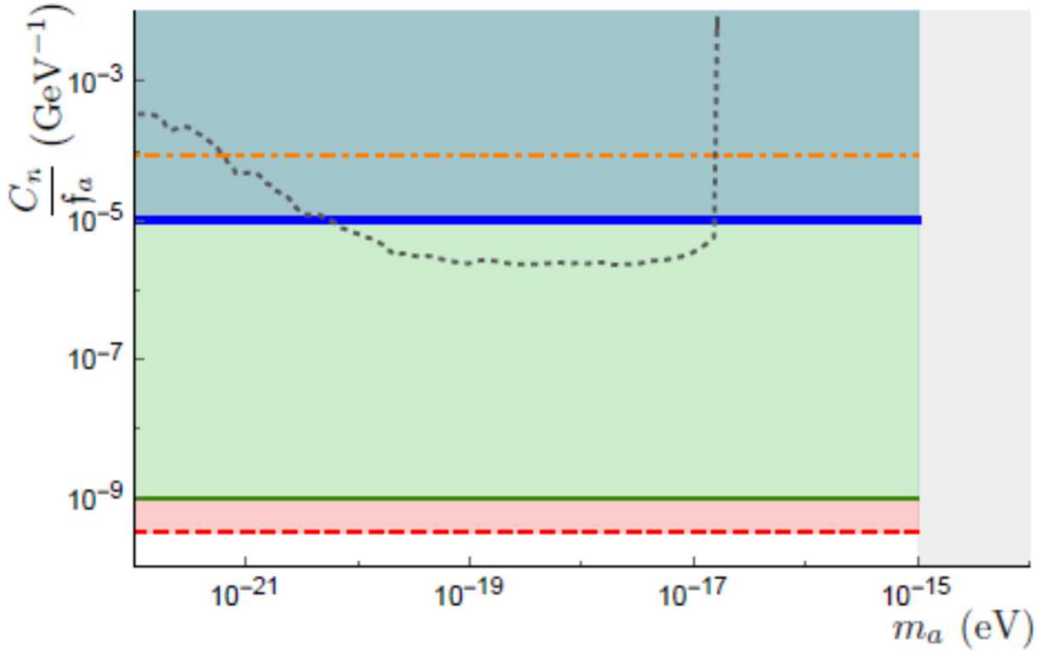
$$f_1(0) - f_2(0) = \frac{m_\chi}{\pi} \left(G_N \mathfrak{g}^N_{\text{Ncl}} - G_e \right) \vec{J}_\chi \cdot \frac{\vec{\lambda}}{F}$$

atomic form factors $\qquad \vec{v}_\chi \qquad \vec{S}_\chi$

Axion field coupling to electron or nucleon

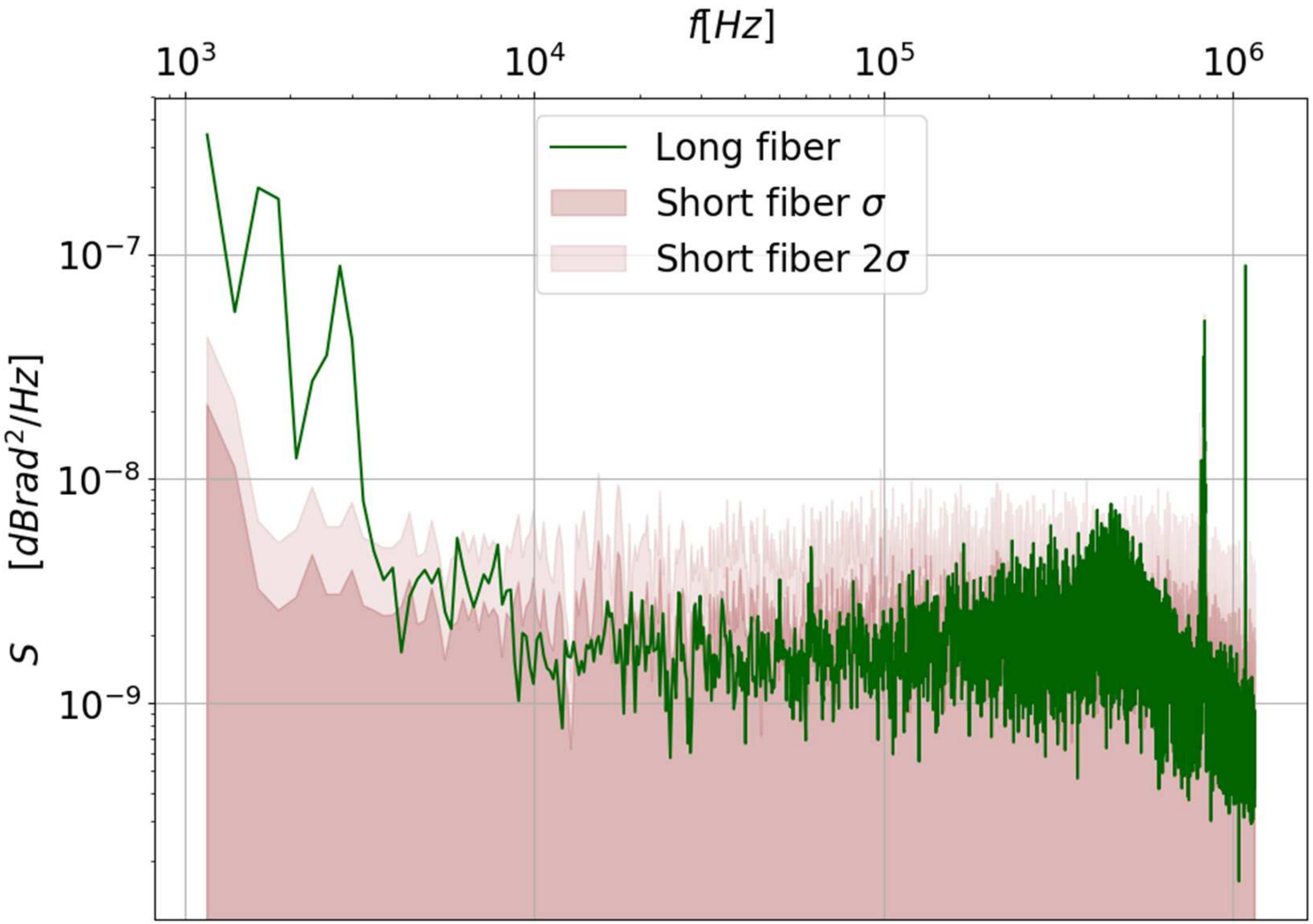
$$H_a = -\frac{C_\psi \sqrt{2\rho_\chi}}{f_a} \vec{\lambda}_\psi \cdot \vec{v} \cos(m_a t + \phi_0)$$

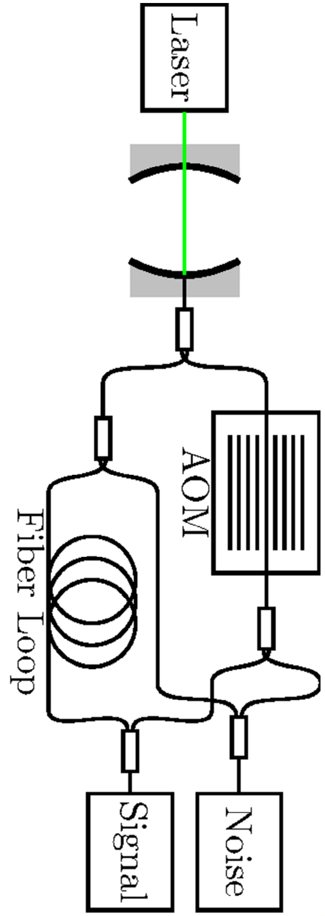




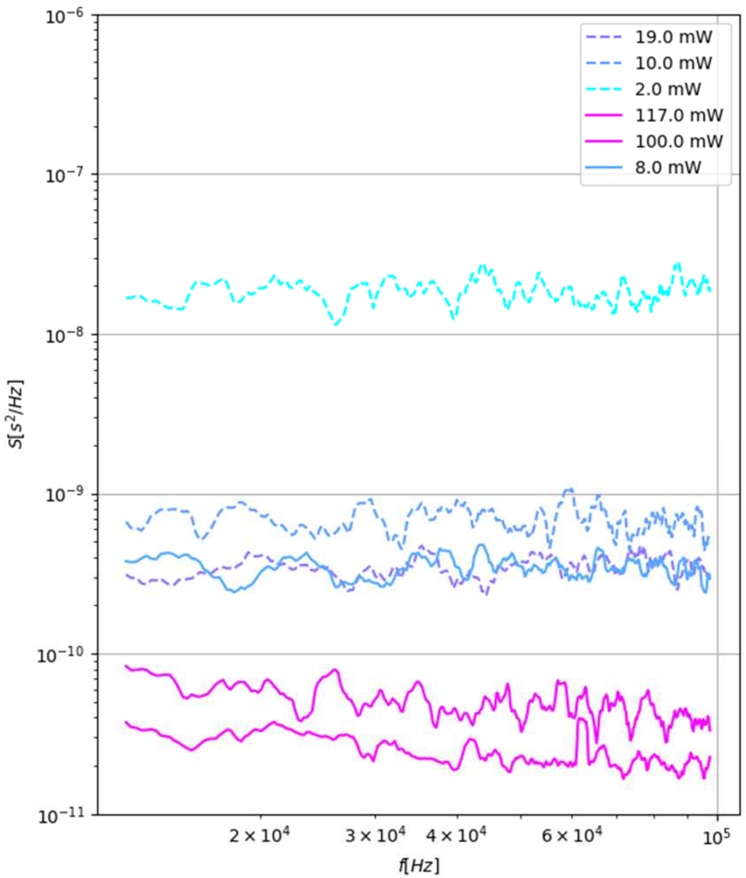
- Much lower mass region than many other axion experiments (e.g. ADMX)
- Not quite able to reach astrophysical (stellar cooling) bounds
- Price to pay is that QCD axion is much lower ($C_n/f_a \approx 10^{-24}$ @ 10^{-15} eV)

DArk Matter from Non Equal Delays (DAMNED)

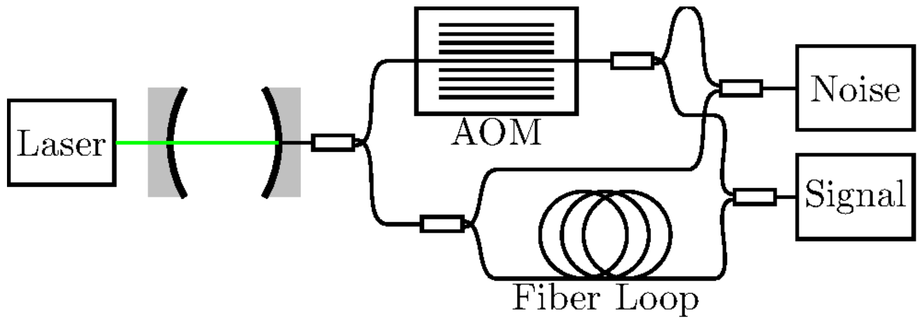




DArk Matter from Non Equal Delays (DAMNED)



Short fibre noise vs. Power on diode



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