Oscillating dark matter: experiments and data analysis at SYRTE

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with valuable help from FOP + FMO teams and electronics + IT services

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Menu

- Dark matter (DM) overview
- Ultralight dark matter and time/frequency metrology
- DM interacting with standard model spins
- Non-universally coupled scalar field, variation of constants
- Atomic spectroscopy and optical cavities
- Experiments at SYRTE
- Towards axion searches
- Conclusion

[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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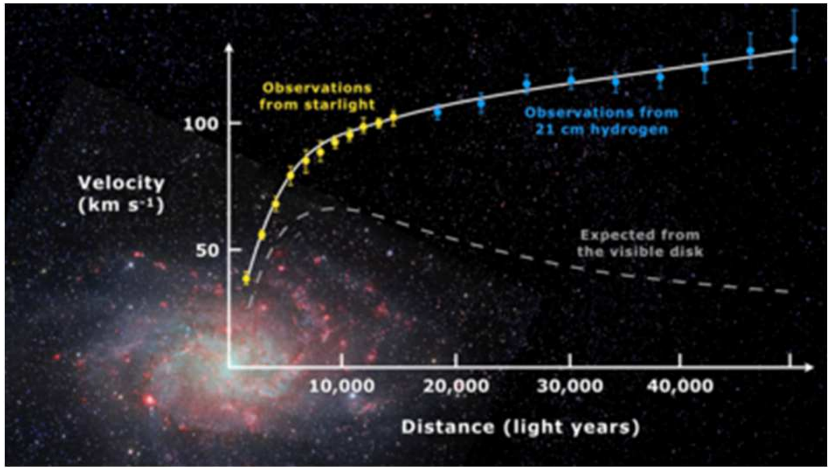
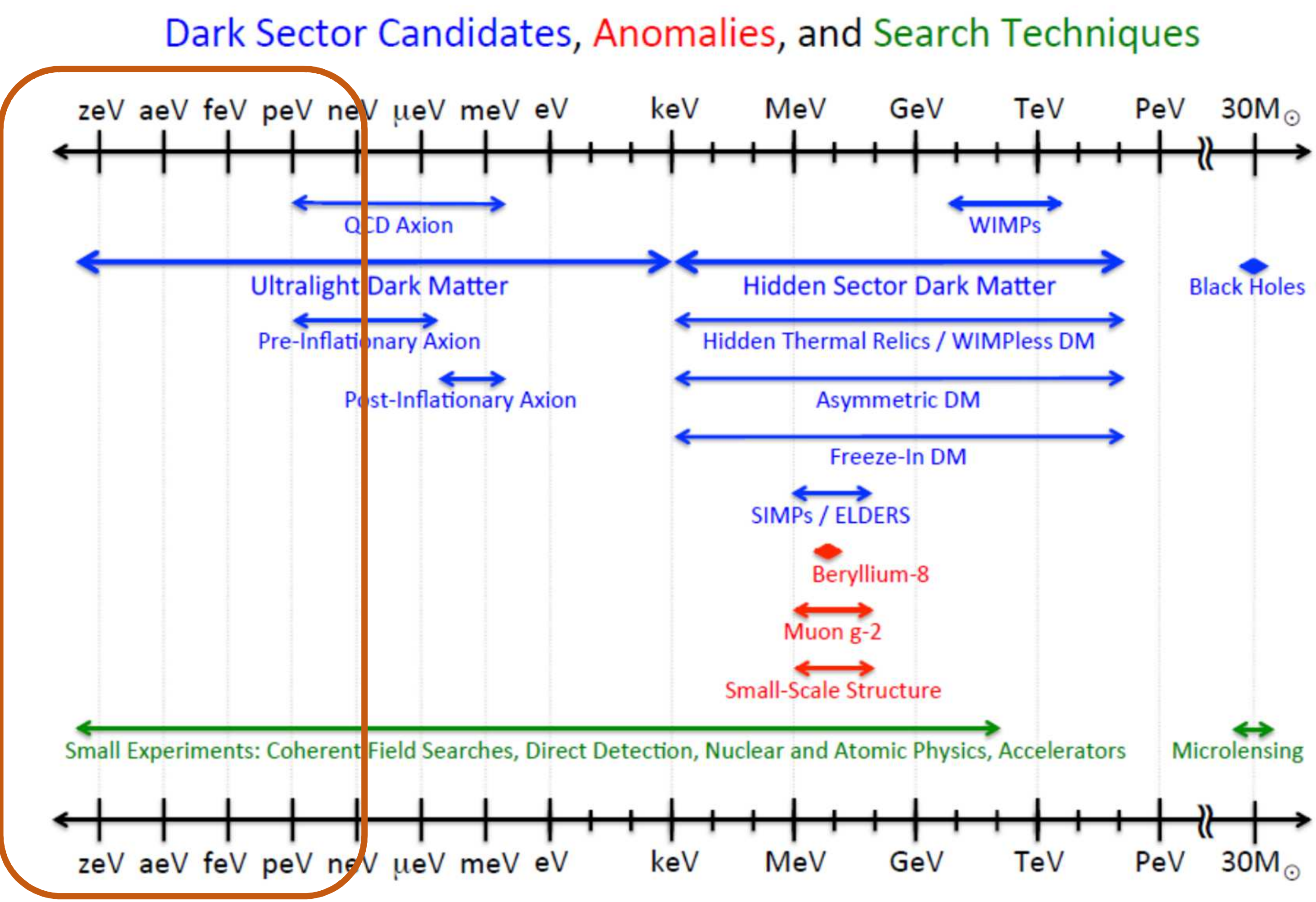
Dark Matter (1)

- "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 $d_x^{(i)}$

Variation of constants

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

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

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

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

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]

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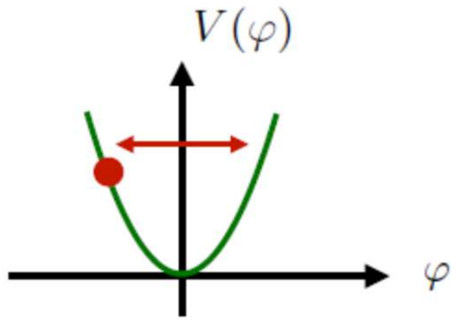
Evolution of the galactic scalar field (2)

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

- 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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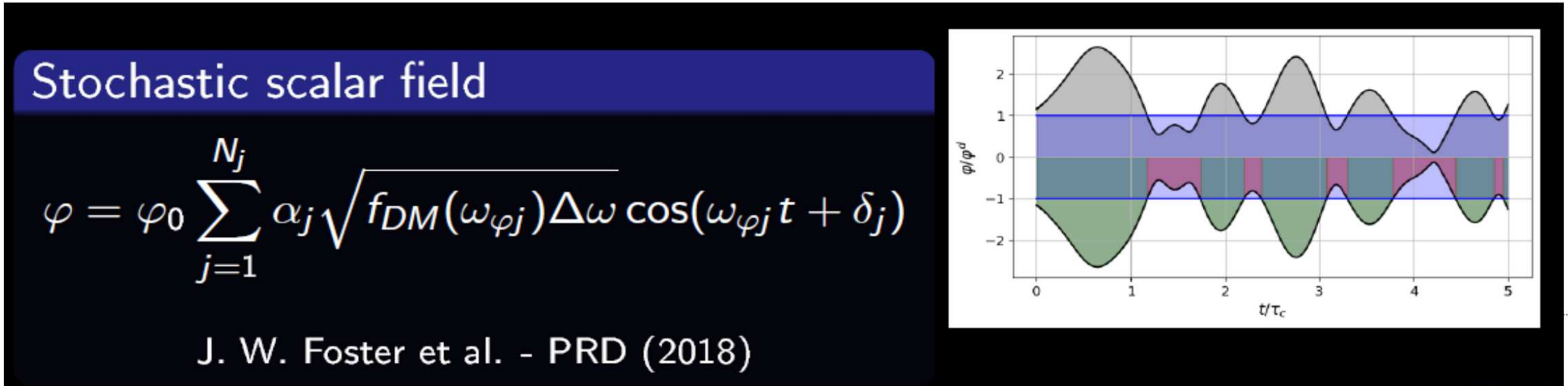
Evolution of the galactic scalar field (2)

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

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

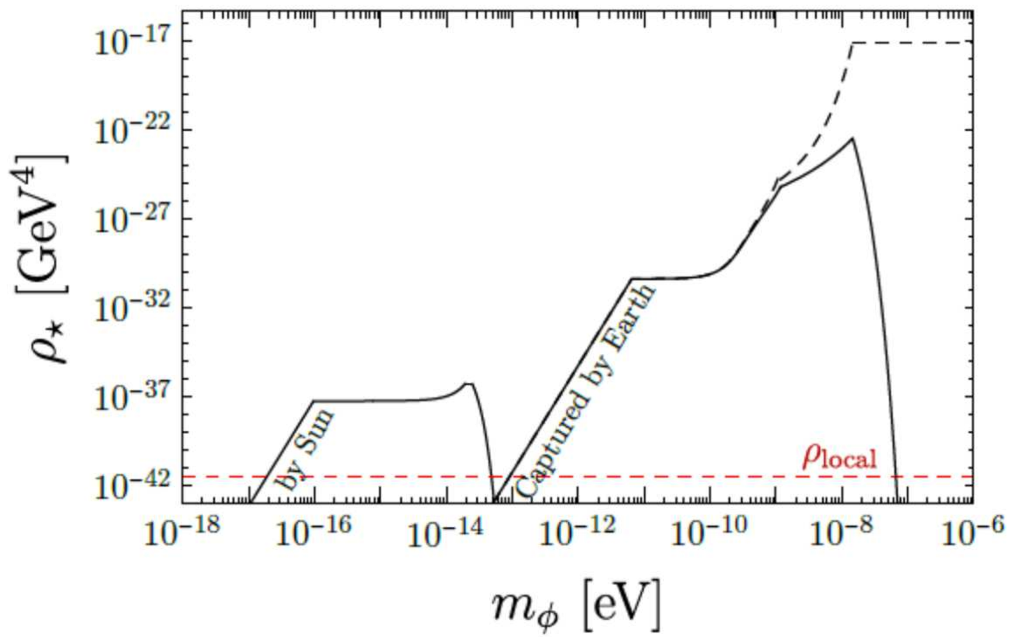
- In our Cs/Rb experiment [Hees et al. 2016] ($f < 5.7 \times 10^{-4}$ Hz) this gives τ_{coh} > 55 years.
- In the DAMNED experiment [Savalle et al. 2021] ($f = [10{:}200]$ kHz) this gives τ_{coh} = [5:100] s.

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.



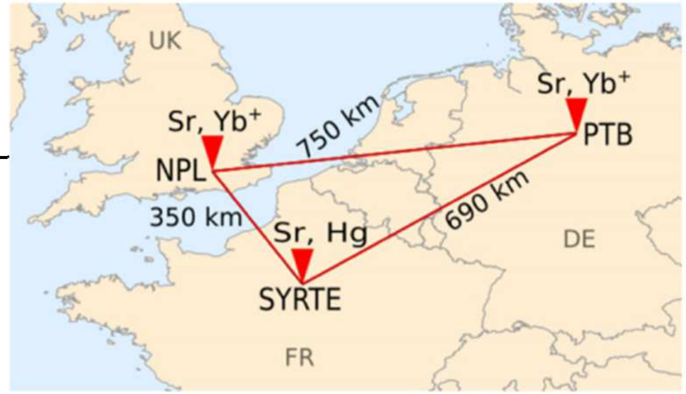
Scalar field transient "clumps" (2)

- 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]

Dark activities at SYRTE

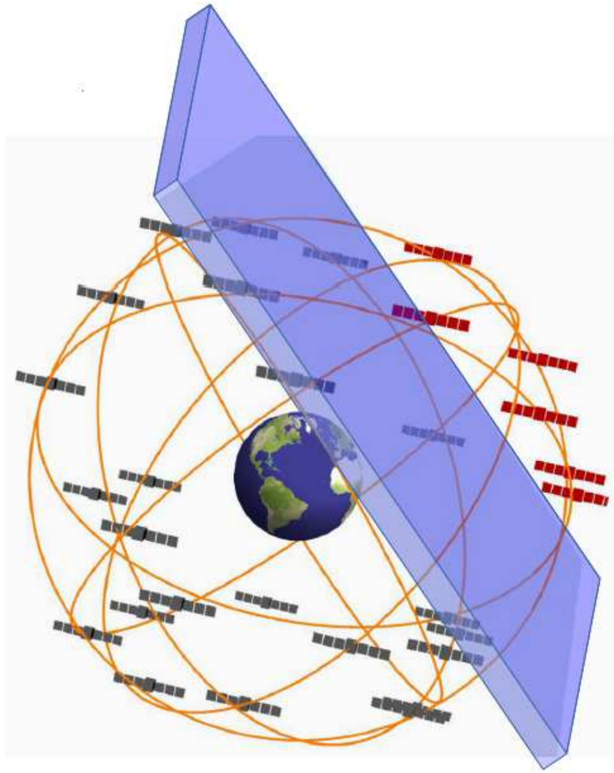


Theory:

- 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:

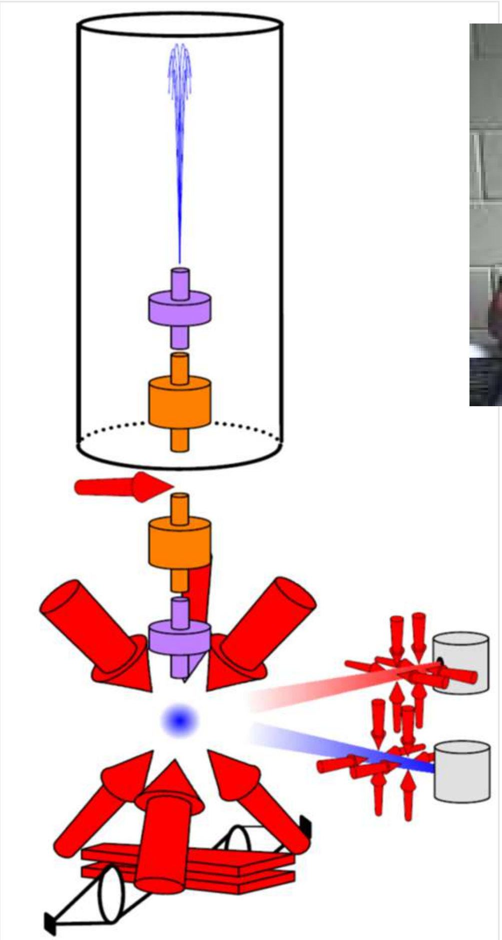
- Rb/Cs dual cold atom clock, long term comparison [Hees 2016]
- The DAMNED experiment [Savalle 2021]
- Europe-wide comparison of optical clocks to search for transients [Roberts 2020]
- The GASTON project (GAlileo Survey of Transient Objects Network), searching for transients using the clocks on board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

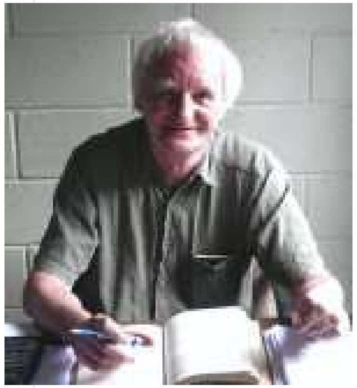


Collaborations:

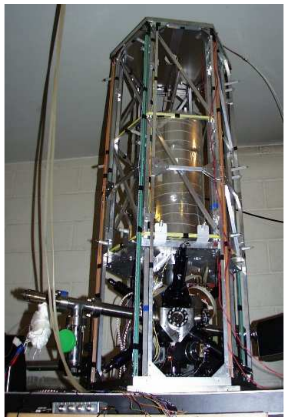
- Collaboration with CEA-IRFU, SHUKET and G-LEAD experiments.
- Common monthly seminars with Univ. Tokyo DM team.

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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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 $\varphi(t, \boldsymbol{x})$.

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

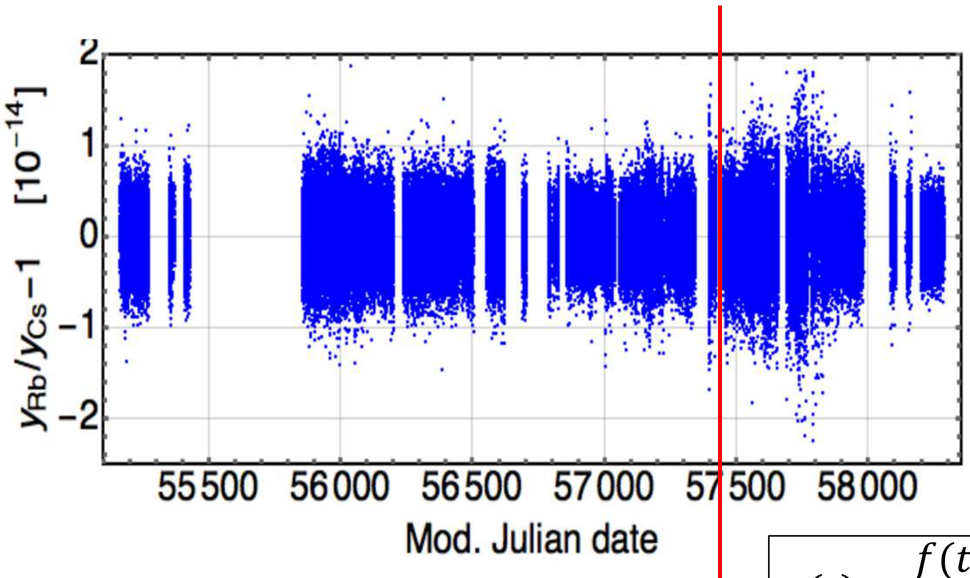
The sensitivity coefficients $\kappa_X^{(i)}$ involve the coupling constants $d_j^{(i)}$ and are obtained from atomic and nuclear structure calculations (Flambaum and co-workers [2006, 2008, 2009]).

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

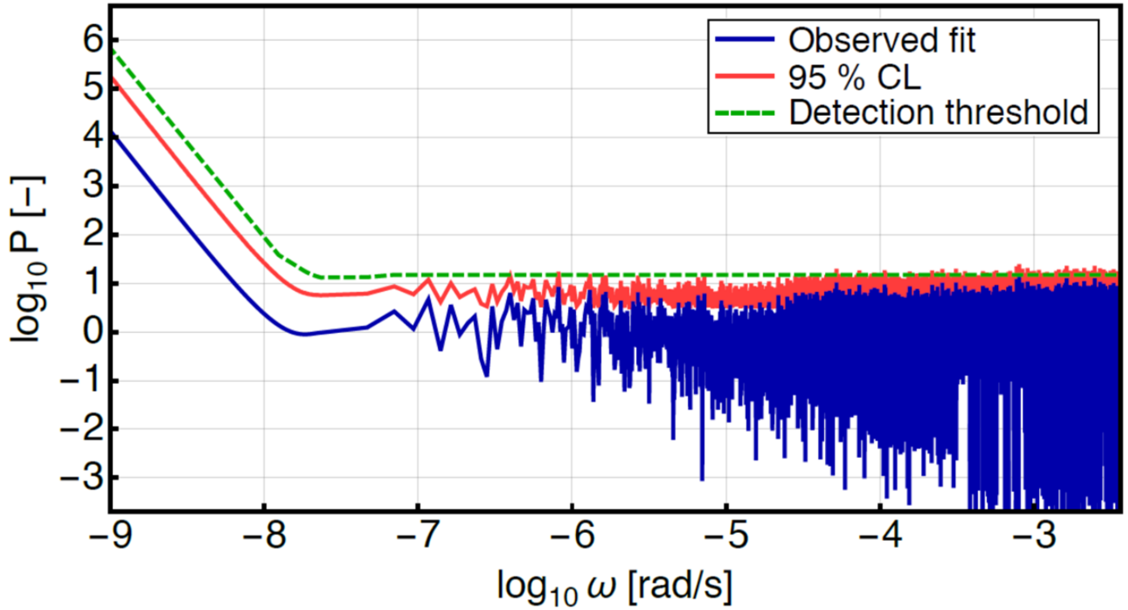
$$\varphi^{(2)}(t,\boldsymbol{x}) = \varphi_0 \cos(\omega t + \delta) \left[1 - s_A^{(2)} \frac{GM_A}{c^2 r}\right]$$

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

FO2 Rb/Cs raw data



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



- 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}

Search for a peak in normalized power

$$P_\omega = \frac{N}{4\sigma_0^2(\omega)}(C_\omega^2 + S_\omega^2)$$

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

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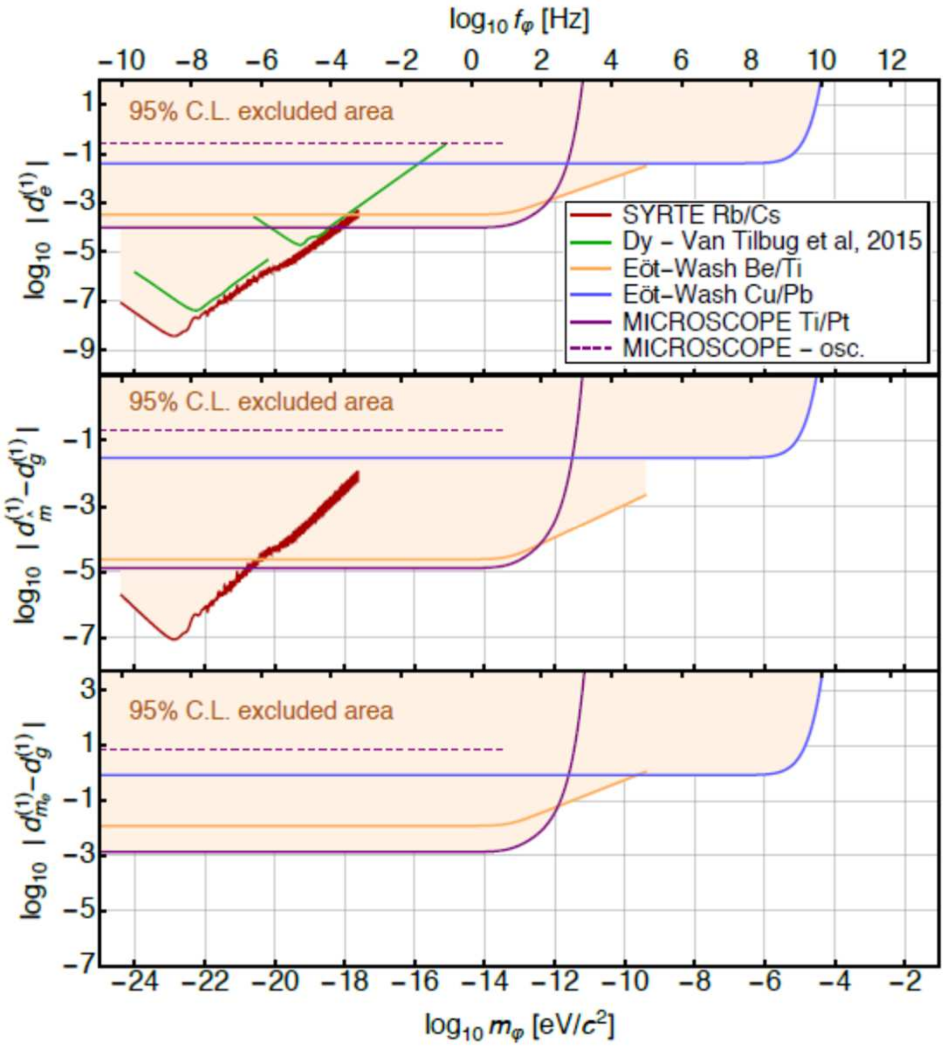
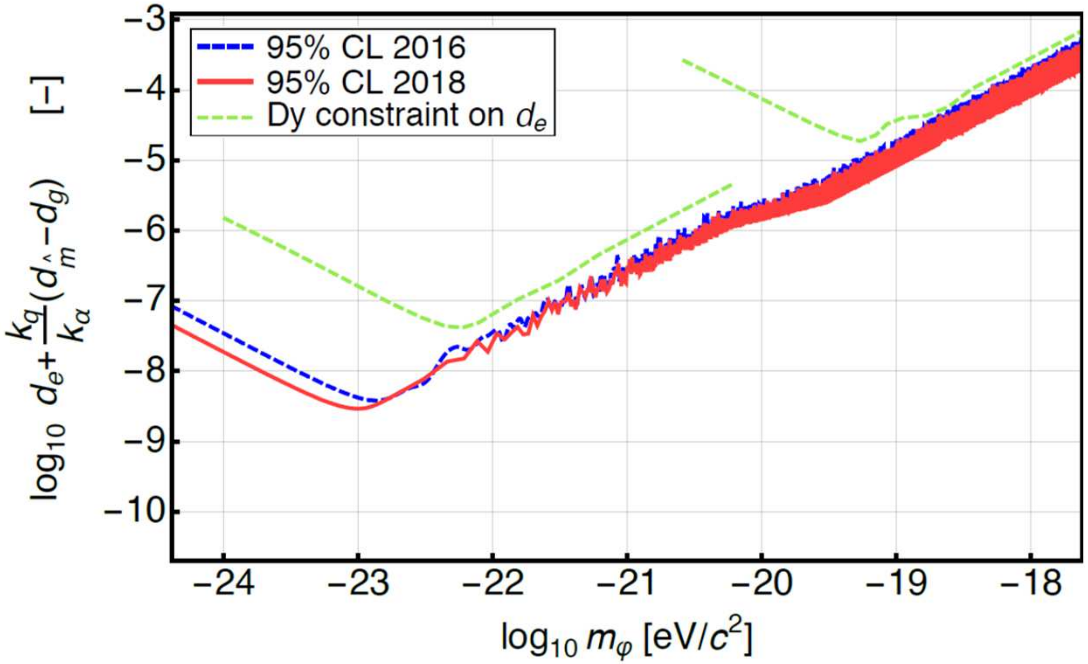
Constraints for linear coupling





[Hees 2016, Hees 2018]

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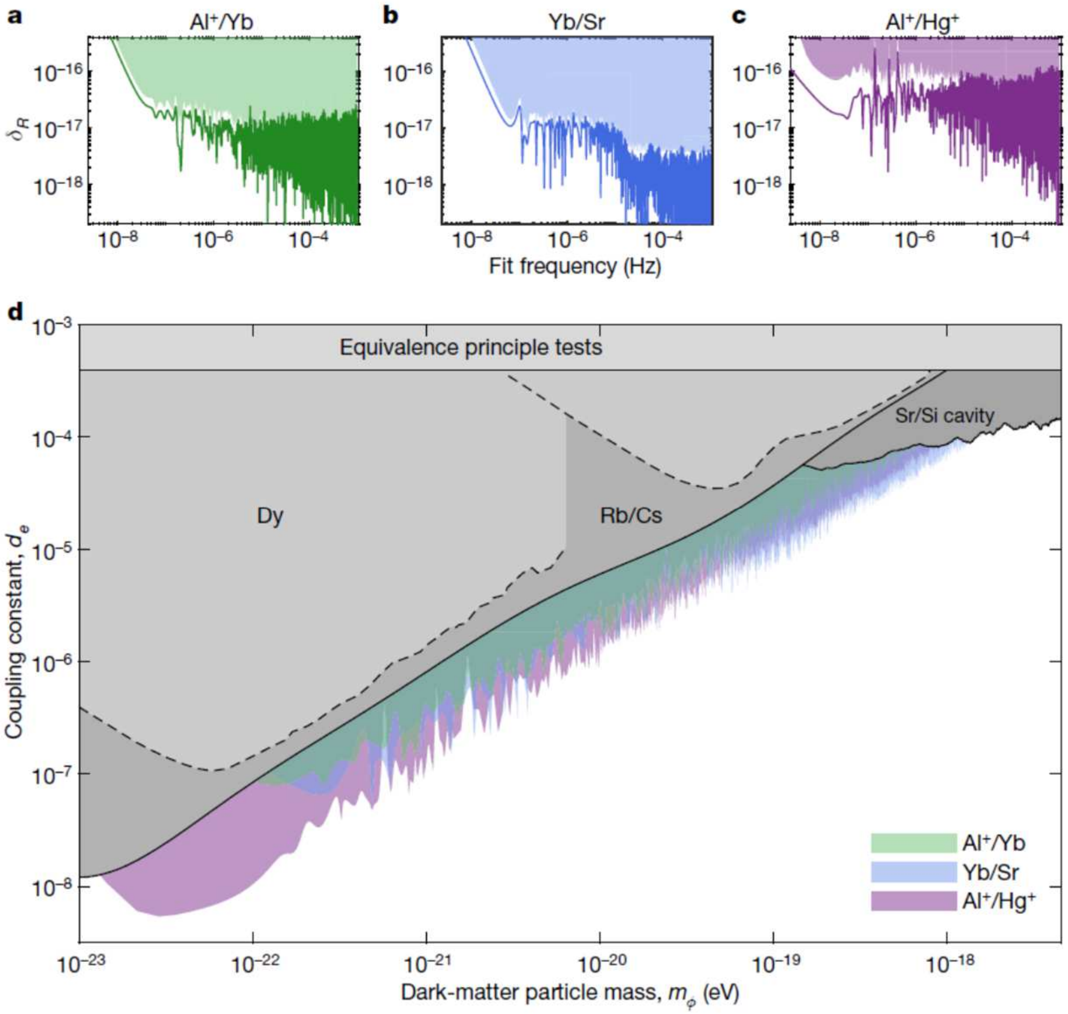
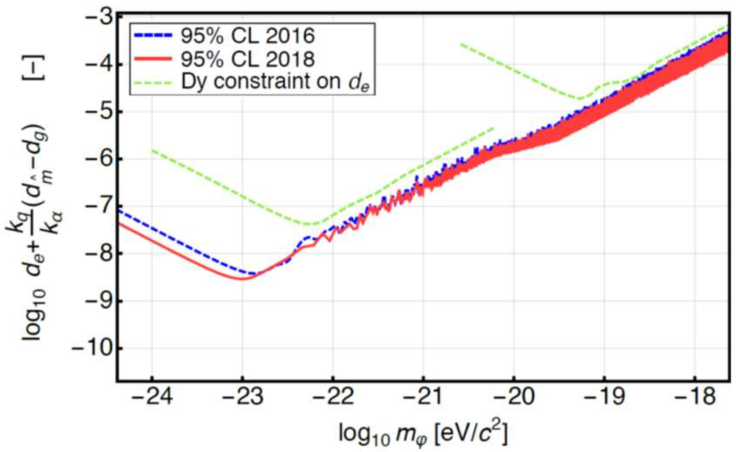
Constraints for linear coupling





- NIST-JILA optical clocks.
- All clock constraints « rescaled » to account for stochastic DM fluctuations.
- Improvement mostly due to α sensitivity.
- Optical clocks couple only to α but not to quark masses => continue using hyperfine transitions.

[Beloy et al., 2021]

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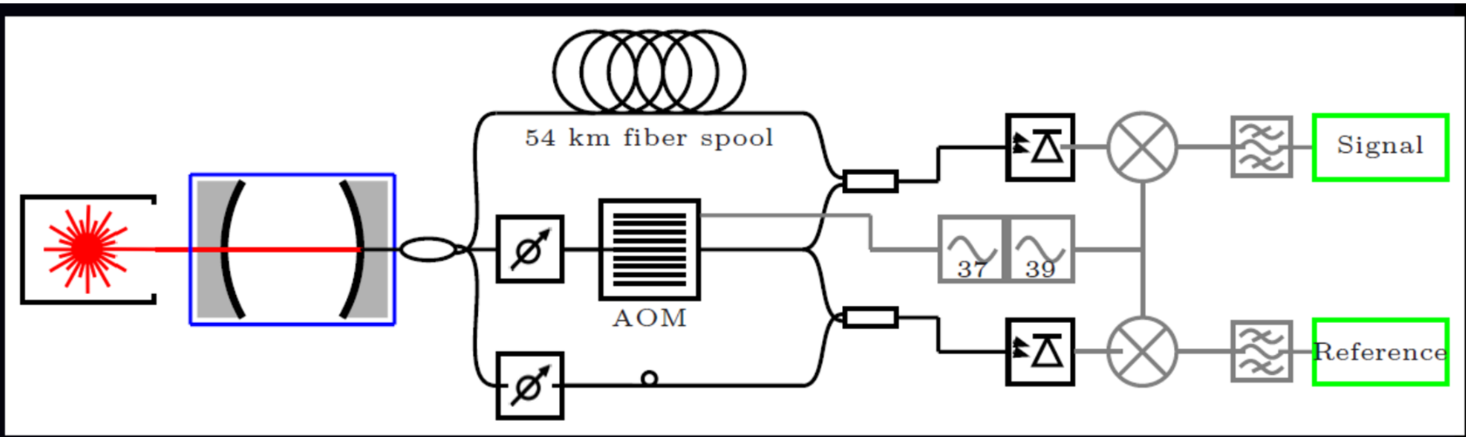
DArk Matter from Non Equal Delays (DAMNED)



Source

1542 nm laser source stabilized on an ultra stable cavity, unevenly distributed in three arms.

Delay

Long delay line of
50 → 125 km
Short delay line of 1 m
AOM for detection

Detection

Beatnotes
Self-heterodyne
Photodiodes
Ettus X310

- Based on ultra-stable optical cavity and fibre delay line
- Variation of fundamental constants leads to variation of cavity/fibre length (Bohr radius) and fibre refractive index.
- Aiming at high frequency (10-100 kHz i.e. DM mass around 10^{-10} eV).

DAMNED signal

Cavity frequency oscillation

$$\omega(t) = \omega_0 + \Delta\omega(t) + \delta\omega \sin(\omega_\varphi t)$$

Color code

Nominal value
Noise
Dark matter effect

Fiber delay oscillation

$$T(t) = T_0 + \int_{t-T_0}^{t} \frac{\Delta T(t')}{T_0} \mathrm{d}t' + \delta T \sin\left(\omega_\varphi t - \omega_\varphi \frac{T_0}{2}\right) \operatorname{sinc}\left(\omega_\varphi \frac{T_0}{2}\right)$$

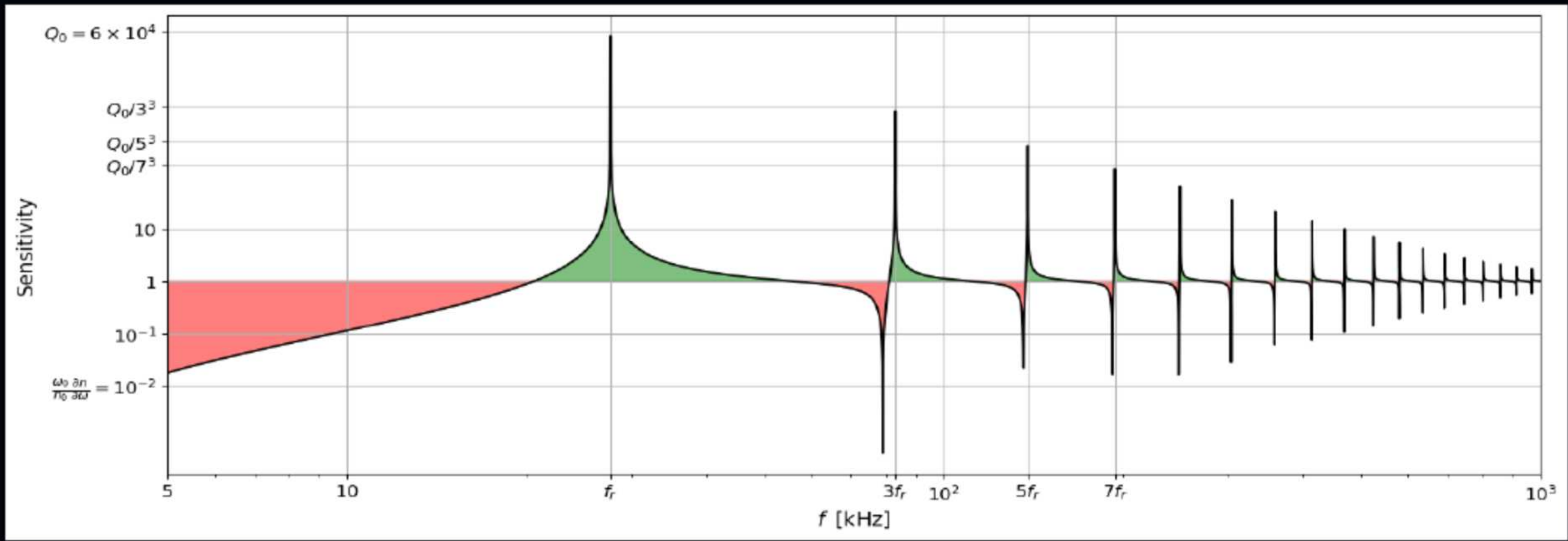
Phase difference between the delayed and non delayed signals

$$\Delta\Phi(t) = \omega_0 T_0 + \omega_0 \int_{t-T_0}^{t} \left(\frac{\Delta T(t')}{T_0} + \frac{\Delta\omega(t')}{\omega_0}\right) \mathrm{d}t'$$
$$+ \omega_0 T_0 \left(\frac{\delta T}{T_0} + \frac{\delta\omega}{\omega_0}\right) \sin\left(\omega_\varphi t - \omega_\varphi \frac{T_0}{2}\right) \operatorname{sinc}\left(\omega_\varphi \frac{T_0}{2}\right)$$

Use two fibre lengths (52 and 56 km) to avoid sensitivity zeros from sinc function.

DAMNED sensitivity

Full sensitivity



Link to the coupling constants

$$\left(\frac{\delta\omega}{\omega_0} + \frac{\delta T}{T_0}\right) \simeq d_e \varphi_0 \text{"Sensitivity"}$$

$$\text{or} \simeq d_{m_e} \varphi_0 \text{"Sensitivity"}$$

Best sensitivity at mechanical resonances of the cavity

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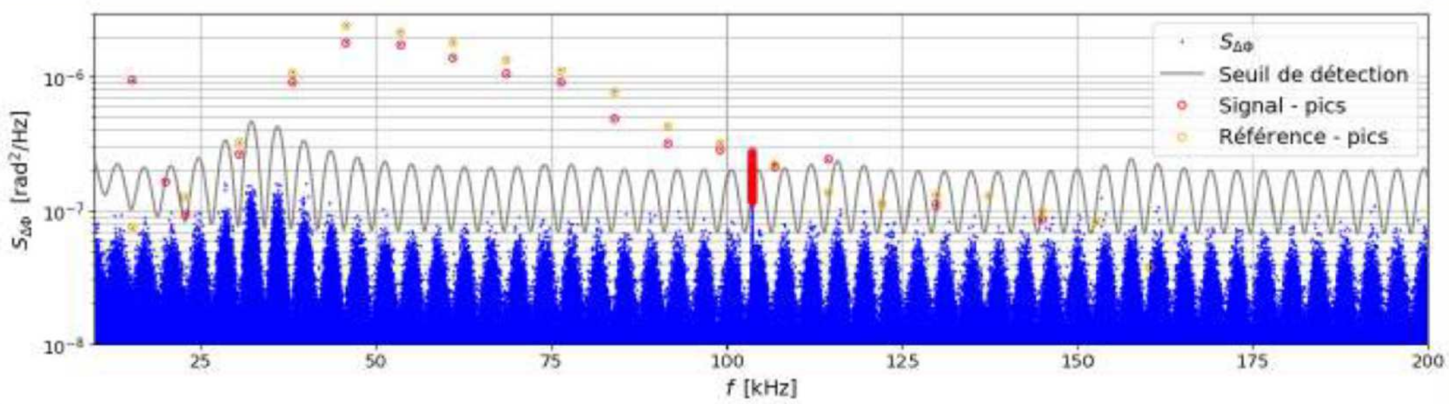
DAMNED data

Mesure de la phase



Limites

- $<$ 10 kHz, bruit thermique/acoustique des fibres
- $>$ 200 kHz, boucle de stabilisation laser/cavité

Fonction de transfert

$$S_{\Delta\phi}(\omega) = 4\sin^2\left(\frac{\omega T}{2}\right) S_{\phi_c}$$

- 12 days data at 500 kHz sampling
- Limited by cavity noise after air conditioning failure
- Peaks excludes either by ref. arms or shape and e.g. temperature dependence or by using another cavity.
- Use stochastic Bayesian analysis (Derveianko, Hees)

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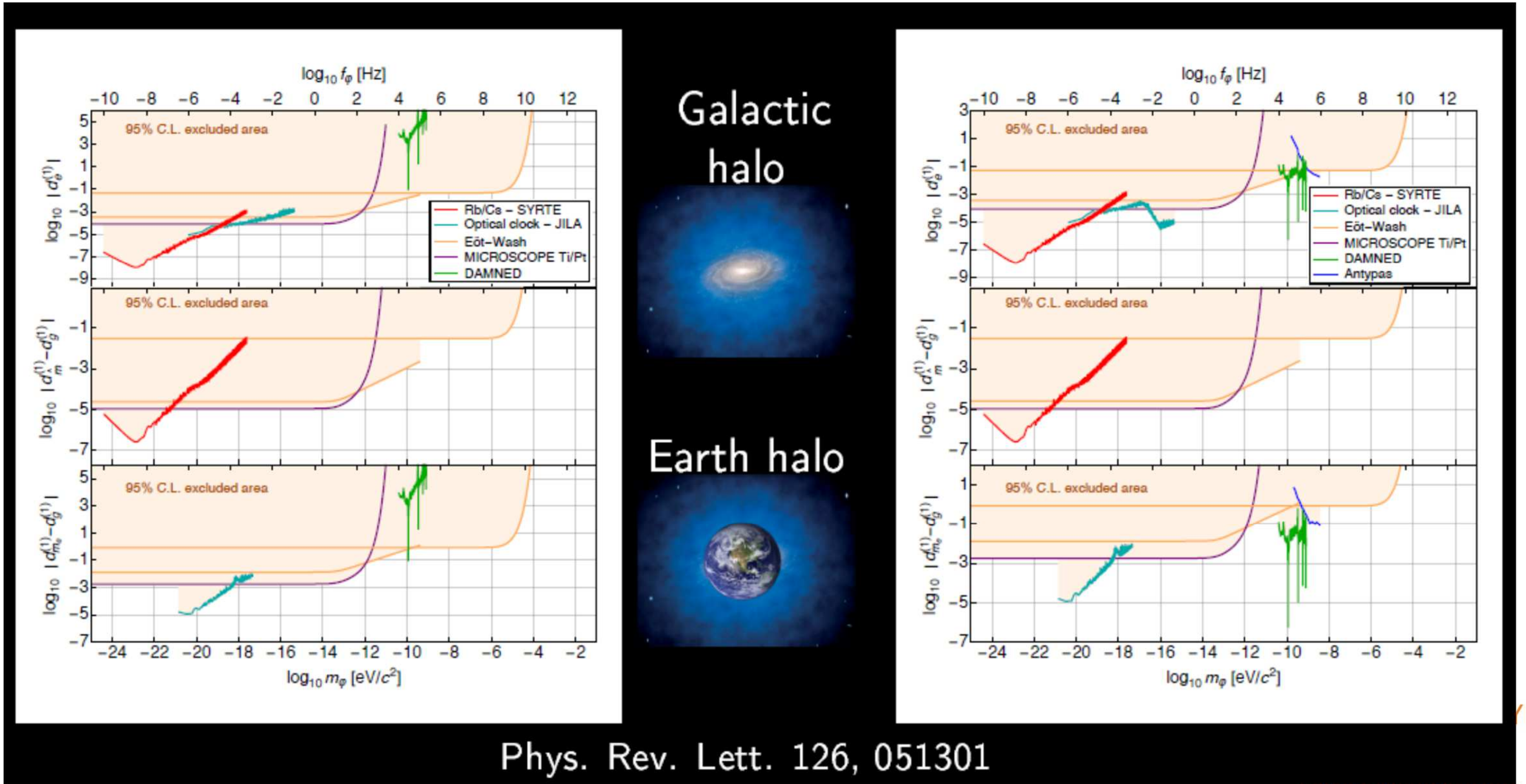
DAMNED results



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Towards Axion searches

- Axions and axion-like particles are “popular” pseudoscalar ultra-light DM candidates
- Initially postulated to solve the “strong-CP” problem in QCD, aka the problem of vanishing electric dipole moment of the neutron
- They have similar distributions as the scalar fields I discussed so far

$\Rightarrow$ Similar data analysis methods

- Generally searched for using strong magnetic fields to induce RF photon emissions. E.g. G-LEAD experiment @ CEA-IRFU.
- They may also induce polarization dependent effects in cavities e.g. DANCE experiment @ Tokyo Univ., or [Goryachev 2019].

PhD thesis of Jordan Gué starting, hopefully, Oct. 2021 to theoretically study and model possible experimental axion searches using the optical cavities at SYRTE.

Conclusion

- Dark matter searches have become a major "application" of the outstanding uncertainty achieved in time/frequency metrology
- SYRTE has contributed significantly in that domain, and is continuing to do so (e.g. GASTON project).
- Unique data acquisition and analysis methods were developed for DAMNED, and are being adapted to other experiments (e.g. axion searches).
- There is still plenty of unexplored parameter space, may be accessible with SYRTE technology and expertise. And who knows what we will find?
- All of this activity relies on the interplay between theory and experimental teams in several groups and services of SYRTE. Thanks to all who make an effort for fruitful collaborations!