Searching for UltraLight Dark Matter: from the lab to space

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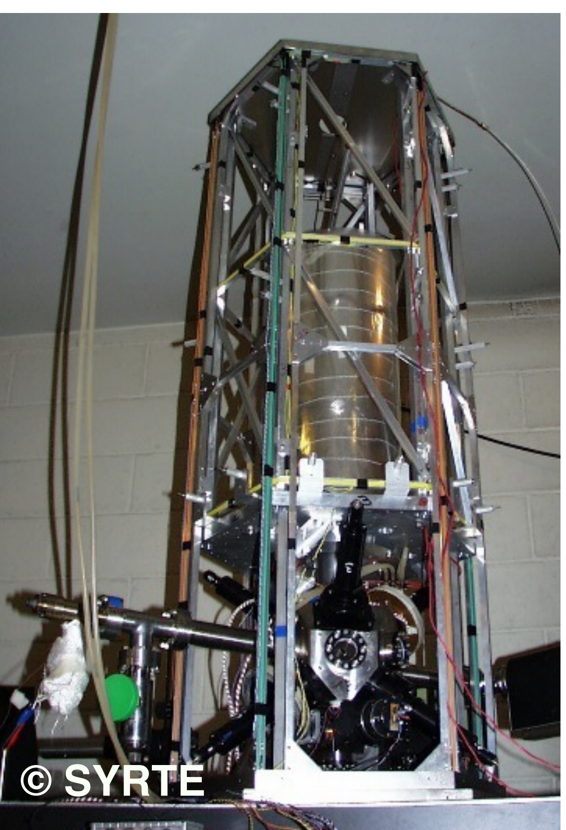
LNE-SYRTE, CNRS,Paris Obs., Université PSL, Sorbonne Univ.
ex PhD students (now at IFAE, Barcelona and at CEA respectively)



Atelier Théorie, Univers, Gravitation
Annecy, November 7th, 2024

in collaboration with

- SYRTE: M. Abgrall, S. Bize, E. Cantin, F. Florian, R. Le Targat, J. Lodewyck, P-E. Pottie, …
- CEA: P. Brun, L. Chevalier, H. Deschamps, P. Polovodov, E. Savalle
- CSM and OCA: O. Minazzoli
- OCA/Grasse Station: J. Chabé, C. Courde
- ROB: B. Bertrand, P. Defraigne
- U. Sidney: Y. Stadnik
- U. Queensland: B. Roberts
- …

DM needed to explain astro/cosmo observations but not direct detection so far

- DM needed at: galactic scales (rotation curves, …), galaxy cluster (bullet cluster, …), cosmo (CMB, structure formation, …)

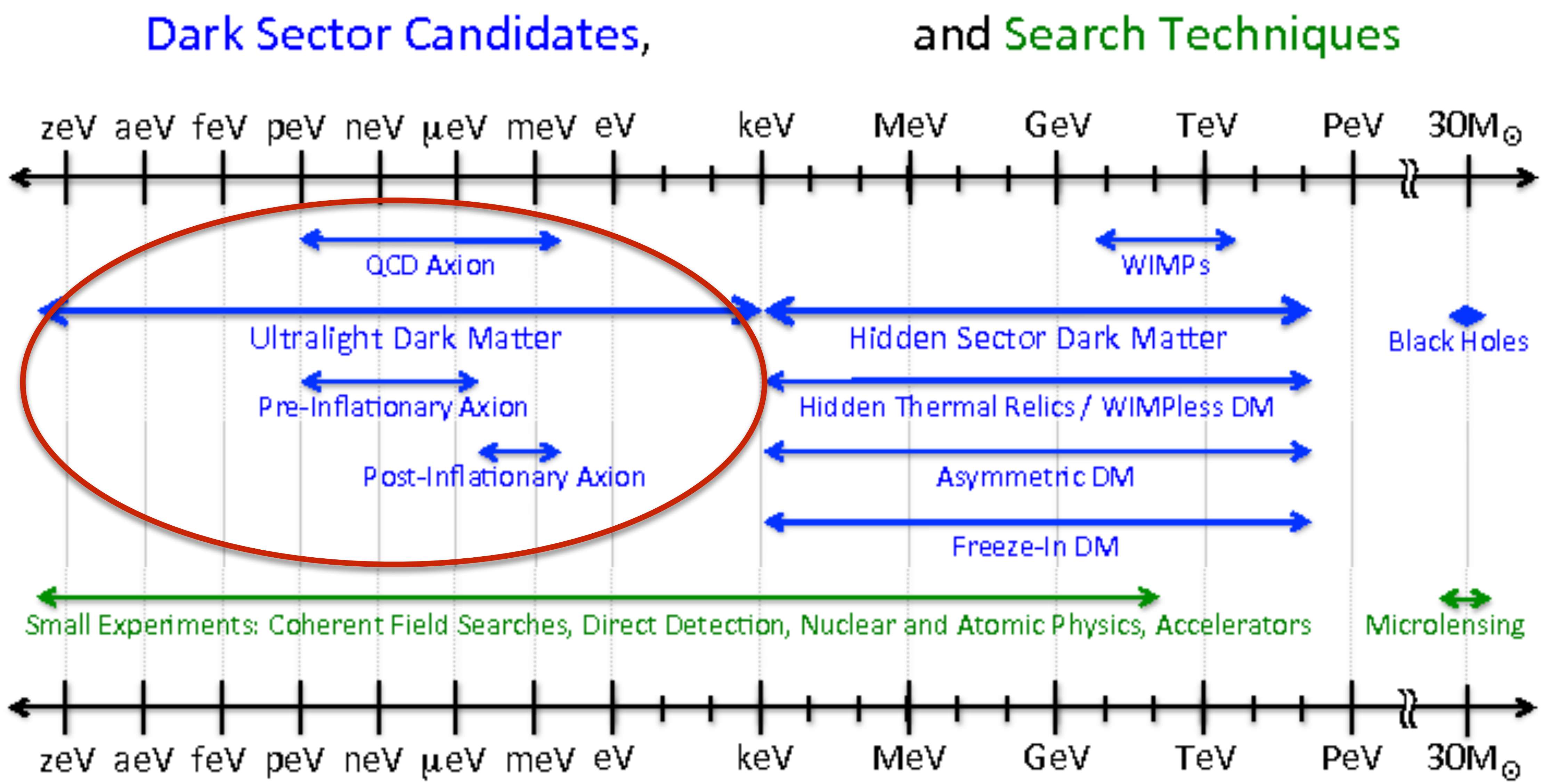


Fig. from *US cosmic vision: new idea for Dark Matter*, 2017

see also presentation from Silvia Manconi

UltraLight Dark Matter needs to be a boson and it behaves classically

- Occupation number (number of particles per volume of phase-space)

$$\frac{n}{n_k} \sim \frac{6\pi^2\hbar^3\rho_{\rm DM}}{m^4c^2v_{\rm max}^3}$$

Calculation inspired from Tourrenc et al, arXiv:quantum-ph/0407187, 2004

- Around the Sun $\rho_{\rm DM} \approx 0.4{\rm GeV/cm}^3$

- This occupation number is larger than 1 if the DM mass is lower than ~ 10 eV: Dark Matter lighter than 10 eV can only be made of boson

  - a bosonic scalar particle (i.e. a scalar field)
  - a bosonic pseudo-scalar particle (i.e. an axion)
  - a boson vector particle (i.e. a hidden photon)

- For m << eV: the occupation number is huge and such a bosonic field can be treated classically (no quantization)

A massive scalar field or a massive vector field oscillates at its Compton frequency

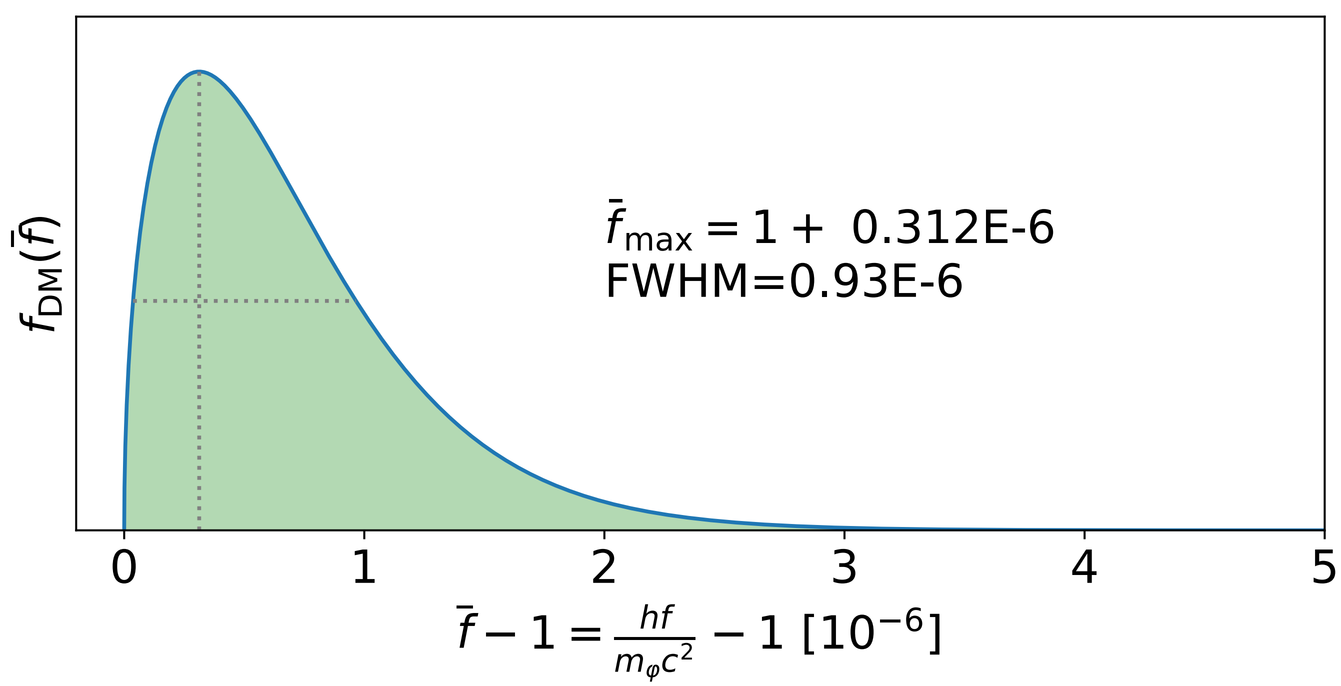
- Cosmological evolution

$$\varphi, X^i \sim \cos mt$$

- The averaged stress-energy tensor:

$$\rho \sim \langle T^0_0 \rangle = \frac{m^2\varphi_0^2}{2} \qquad p_{ij} \sim \langle T^i_j \rangle = 0$$

- The galactic DM distribution: specific spectral distribution
  - complex data analysis (for long dataset, the oscillation is not coherent)
  - use to distinguish from systematics
  - stochastic evolution: allows to probe large masses with low freq. searches



see G. Centers et al, Nat. Comm., 2021
E. Savalle et al, PRL, 2021
V. Flambaum and Samsonov, PRD, 2023

A scalar DM is expected to break the equivalence principle

- An effective Lagrangian for the scalar-matter coupling

$$\mathcal{L}_{\text{mat}}\left[g_{\mu\nu},\Psi,\varphi\right]=\mathcal{L}_{SM}\left[g_{\mu\nu},\Psi\right]+\varphi^i\left[\frac{d_e^{(i)}}{4e^2}F_{\mu\nu}F^{\mu\nu}-\frac{d_g^{(i)}\beta_3}{2g_3}F^A_{\mu\nu}F^{\mu\nu}_A-\sum_{j=e,u,d}\left(d^{(i)}_{m_j}+\gamma_{m_j}d_g^{(i)}\right)m_j\bar{\psi}_j\psi_j\right]$$

see Damour and Donoghue, PRD, 2010

- Couplings usually considered:
  - linear in φ: lowest order expansion (cfr Damour-Donoghue)
  - quadratic in φ: lowest order if there is a Z_2 symmetry (cfr Stadnik et al)

- This leads to a space-time dependance of some constants of Nature to the scalar field

$$\alpha(\varphi)=\alpha\left(1+d_e^{(i)}\varphi^i\right)$$

$$m_j(\varphi)=m_j\left(1+d_{m_j}^{(i)}\varphi^i\right)\qquad\text{for } j=e,u,d$$

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

Can be interpreted as a signature of a violation of the Einstein Equivalence Principle: oscillations of the constants of Nature!

see also Arvanitaki et al, PRD 2015, Hees et al, PRD, 2018

Axion and ALP are effectively leading to quadratic couplings

- At tree level, the axion/ALP couples through terms like

$$\sim \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \quad \text{or} \quad \sim \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

BUT

- the axion-gluon coupling induces a quadratic coupling to the pion mass

$$\frac{\delta m_\pi^2}{m_\pi^2} = -\frac{m_u m_d}{2\left(m_u + m_d\right)^2} \left(\frac{a}{f_a}\right)^2$$

see H. Kim and G. Perez, PRD, 2024

=> induces a dependency on atom rest-mass and atomic transitions

see J. Gué, etl al, PRD, 2024

- the axion-gluon coupling induces a quadratic coupling to EM at 1-loop

$$\frac{\delta\alpha}{\alpha} = c_{F^2} \frac{\alpha}{4\pi^2} \left(\frac{a}{f_a}\right)^2$$

see C. Beadle et al, PRD, 2024
H. Kim et al, PRD, 2024

Various experimental signatures can be searched for

1. Atomic clocks: sensitive to the evolution of the constant of Nature, i.e. to φ (linear coupling) or φ^2 (quadratic coupling)

   see A. Hees et al, PRD 2018

2. Universality of Free Fall (UFF) test: sensitive to the gradient of φ^i, i.e. to $\nabla\varphi$ (linear coupling) or $\varphi\,\nabla\varphi$ (quadratic coupling)

   see A. Hees et al, PRD 2018

3. Atom Interferometry (AI): sensitive to a combination of both $\int\varphi^i$ and φ^i and $\nabla\varphi^i$ depending on specific AI scheme

   see A. Geraci and Derevianko, PRD, 2016
   P. Graham et al, PRD, 2016
   J. Gué et al, PRD, 2024

4. LISA interferometer: sensitive to $\nabla\varphi^i$

   see J-C Yu et al, PRD, 2023
   J. Gué et al, in prep

5. etc…

Scalar field for a linear coupling

$$\Box\varphi + m^2\varphi = -\frac{4\pi G}{c^2}\alpha_A\rho_A$$

Source term

- α_A depends on the scalar coupling d_i and on the composition of body A
- "Easy" to solve (existence of a Green function)

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

Atomic clocks are more sensitive

Oscillations can be interpreted as DM

A fifth force generated by a body (more common in the modified gravity community)

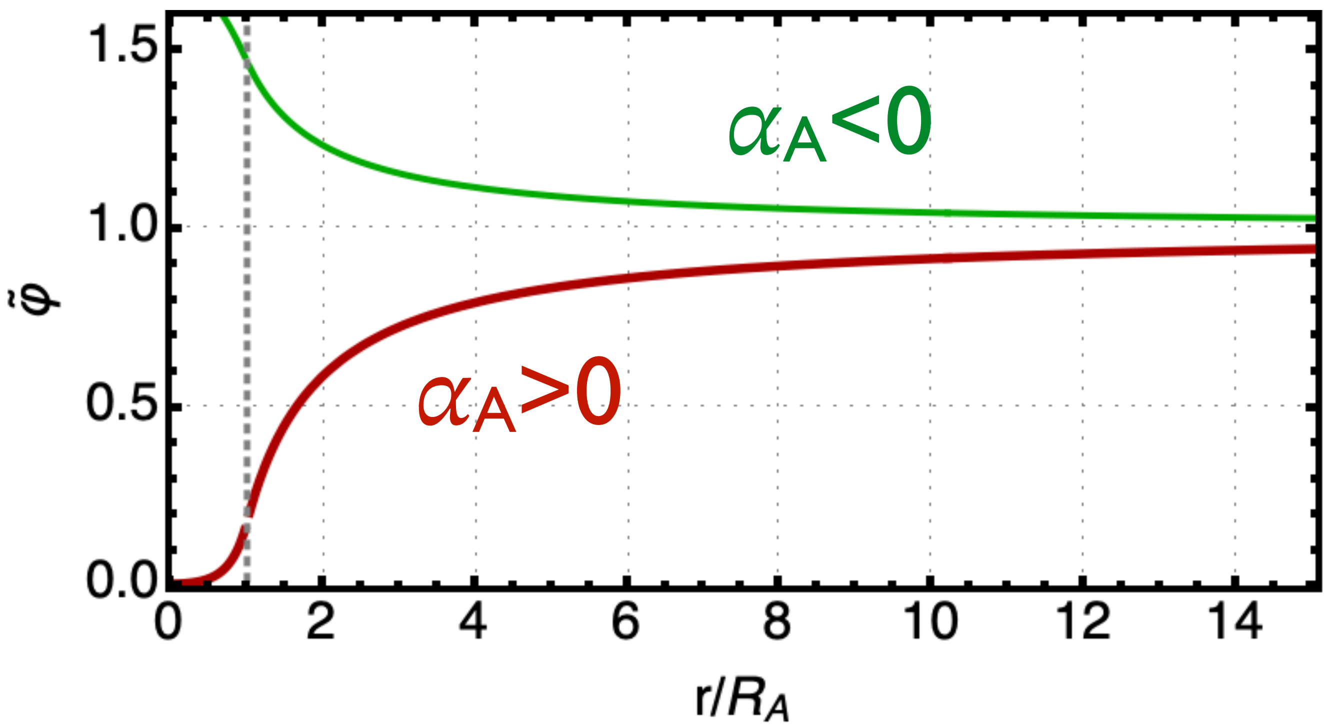
UFF measurements are more sensitive

Independent of the DM interpretation

Scalar field for a quadratic coupling

$$\Box\varphi + \left(m^2 + \frac{4\pi G}{c^2}\alpha_A \rho_A\right)\varphi = 0$$

No source term (no fifth force) but effective mass that depends on the local matter density



$$\varphi = \tilde\varphi(r)\varphi_0 \cos mt$$

<u>Screening</u> for positive couplings and <u>scalarization</u> for negative couplings!

In case of screening: space observations are highly favoured!

see A. Hees et al, PRD, 2018

similar mechanism as the one studied by G. Esposito-Farèse and T. Damour, PRL, 1993

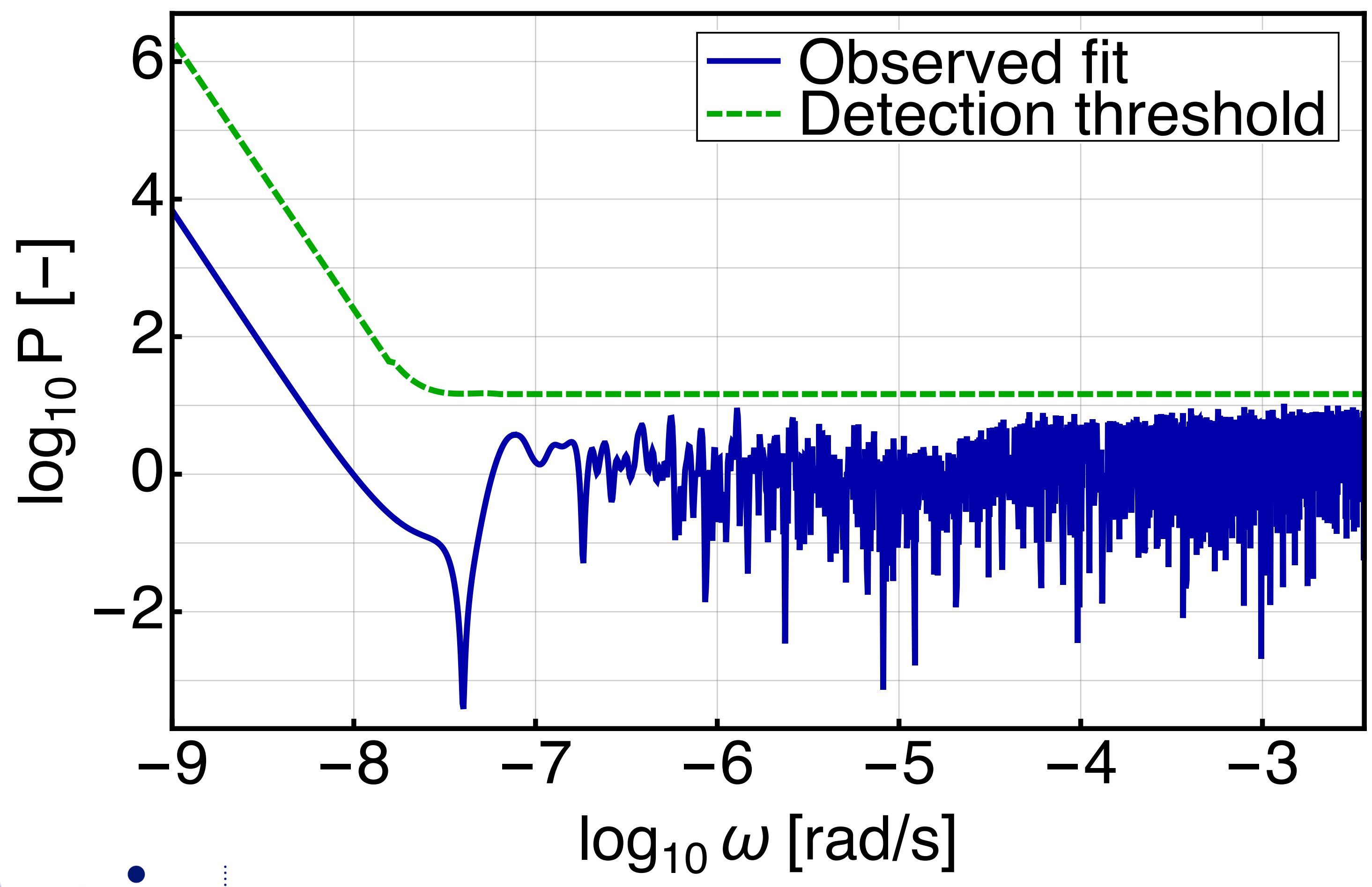
Two experiments developed at SYRTE

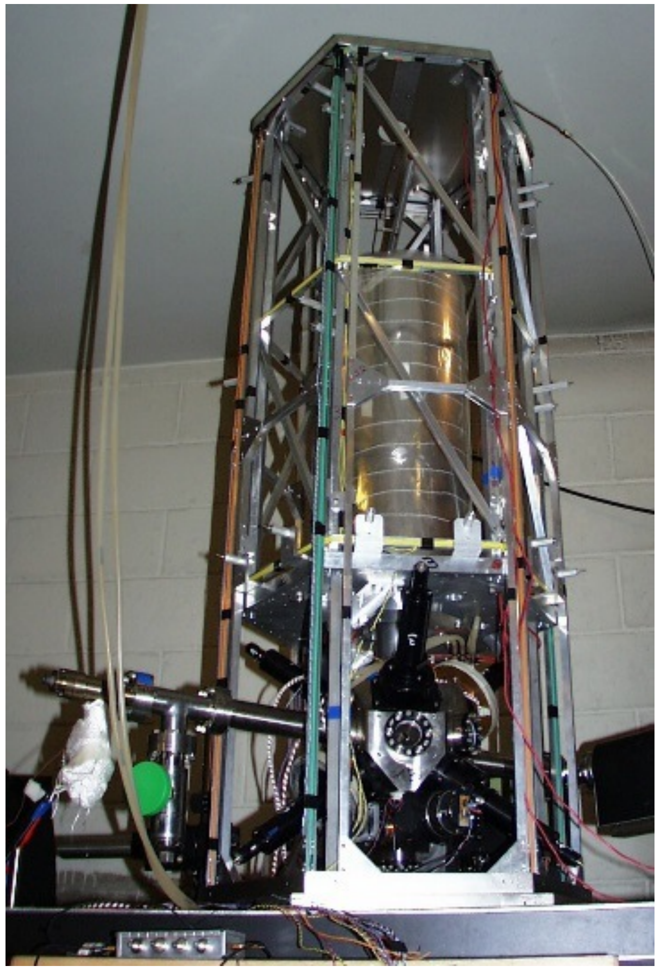
Search for a periodic signal in Cs/Rb comparison

- Cs/Rb FO2 atomic fountain data from SYRTE: high accuracy and high stability, data used from 2008

see J. Guéna et al, Metrologia, 2012 and J. Guéna et al., IEEE UFFC, 2012

- Search for a periodic signal in the data using Scargle's method, see Scargle ApJ, 1982





l'Observatoire de Paris | SYRTE

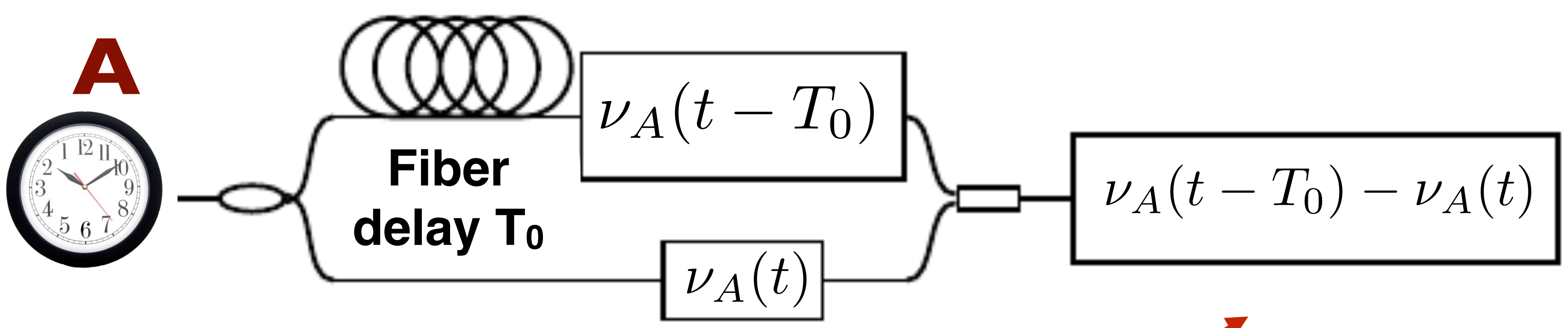
Systèmes de Référence Temps-Espace

No positive detection ☹

A. Hees, J. Guéna, M. Abgrall, S. Bize, P. Wolf, PRL, 2016

Search for a periodic signal in a Mach-Zender interferometer

- New type of experiment proposed. Simplified principle:



$$\frac{\Delta\nu_A}{\nu_A} = \kappa_A^{(i)}\varphi^i$$

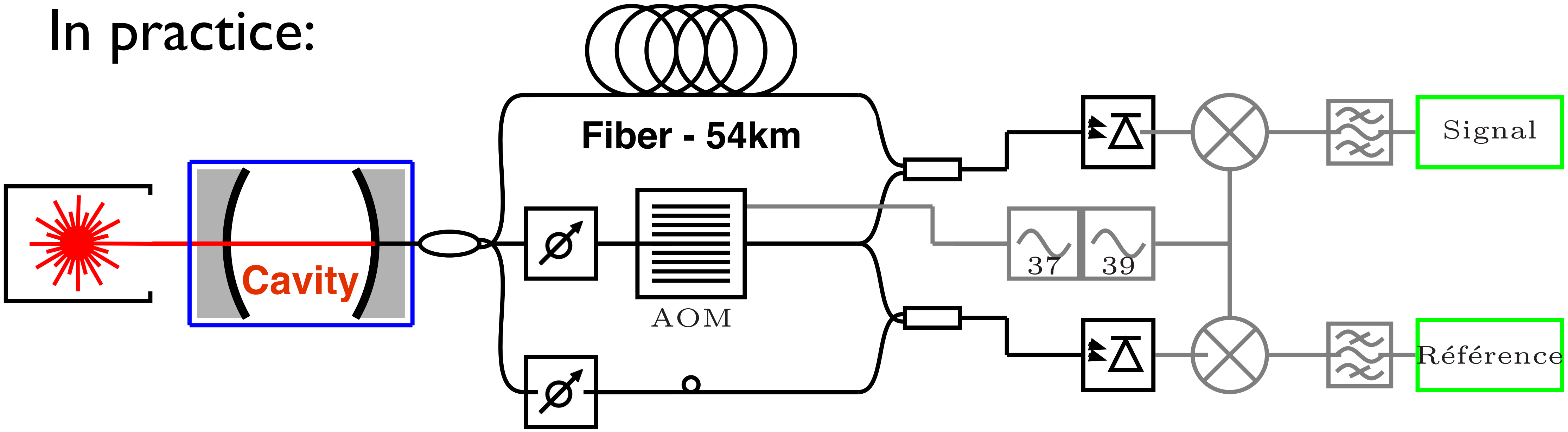
Oscillations of the scalar field

- Interpretation: comparison of an atomic frequency with itself in the past
- Main advantage: explored frequency range ~ kHz-MHz while standard clocks are limited to 100 mHz

see Savalle et al, PRL 2021

The DAMNED experiment (DArk Matter from Non Equal Delays)

- In practice:



  - the "clock" is a laser cavity (both length and laser frequency oscillate)
  - the length of the fiber oscillates
  - the refractive index of the fiber oscillates

- First experiment built @SYRTE (E. Savalle's PhD with P-E Pottie, F. Franck, E. Cantin) and data analyzed taken into account the stochasticity of the signal

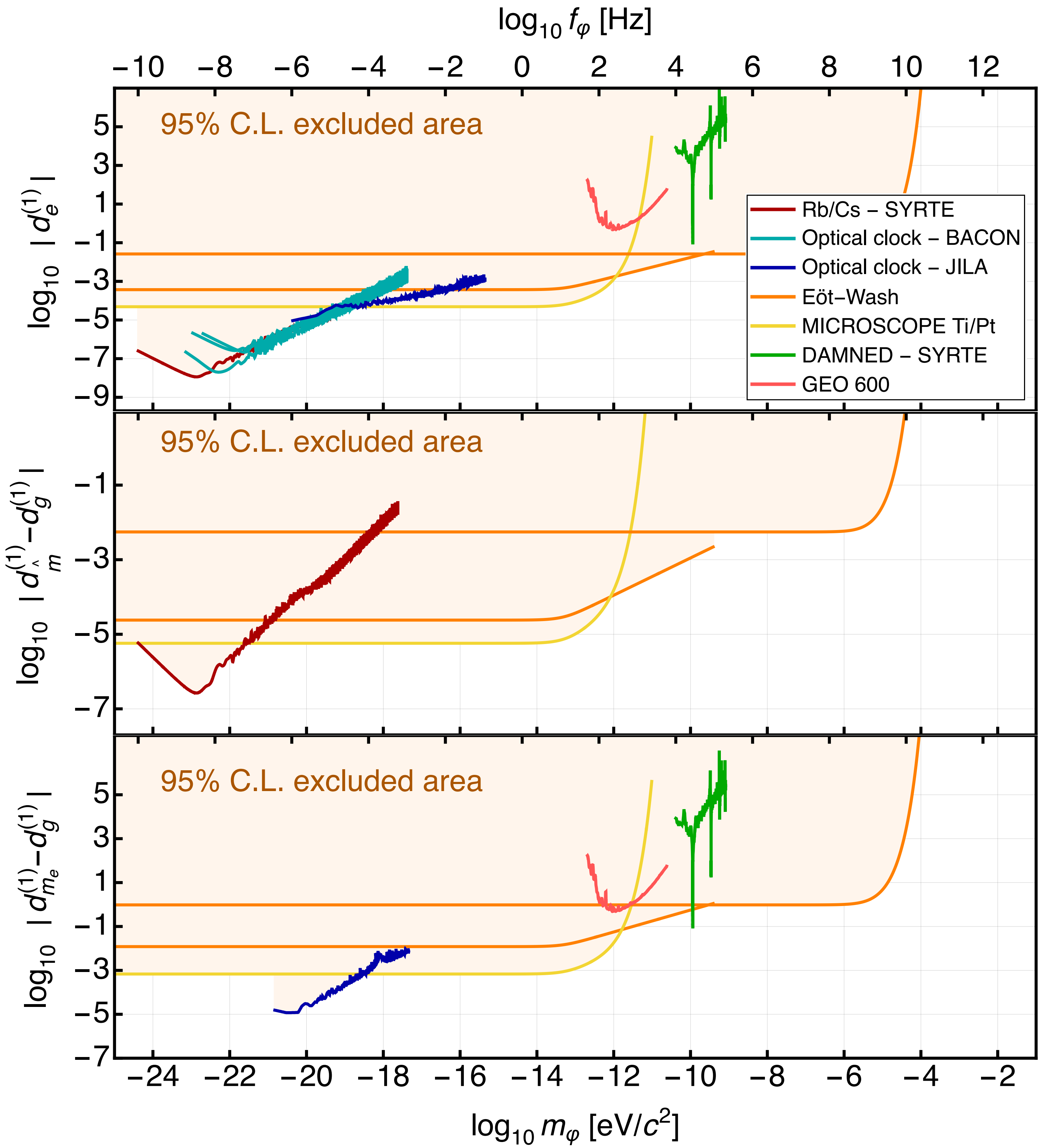
- no significant periodic signal is detected in the 10-200 kHz frequency band

see Savalle et al, PRL, 2021

l'Observatoire de Paris | SYRTE
Systèmes de Référence Temps-Espace

Constraints on the linear couplings

Assuming the DM density to be constant over the whole Solar System (0.4 GeV/cm³)

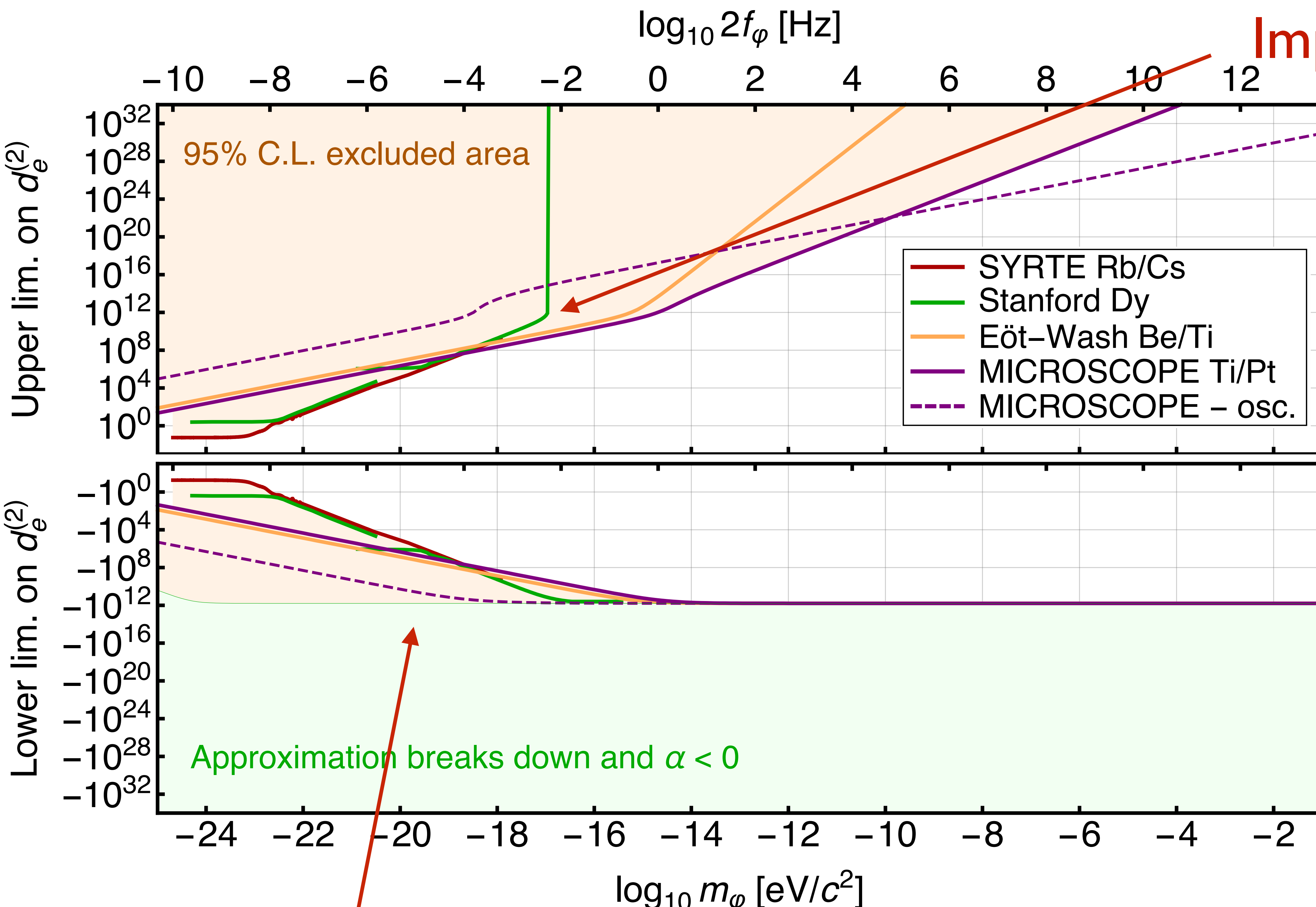


Update from Hees et al, PRD, 2018

Results from:

- Rb/Cs: Hees et al, PRL, 2016
- BACON: Nature, 2021
- JILA: Kennedy et al, PRL, 2020
- Eöt-Wash: Wagner et al, CQG, 2012
- MICROSCOPE: Bergé et al, PRL, 2018
- DAMNED: Savalle et al, PRL 2021
- GEO600: Vermeulen et al, Nature, 2021

Constraints on the quadratic couplings



Impact of screening

Impact of amplification

Being in space is favorable ! Scalar field tends to vanish at the Earth surface

see A. Hees et al, PRD, 2018

Constraints on the quadratic couplings have been reinterpreted as constraints on axion coupling

- the axion-gluon coupling induces a quadratic coupling to EM at 1-loop

$$\frac{\delta\alpha}{\alpha} = c_{F^2}\,\frac{\alpha}{4\pi^2}\left(\frac{a}{f_a}\right)^2$$

see C. Beadle et al, PRD, 2024
H. Kim et al, PRD, 2024

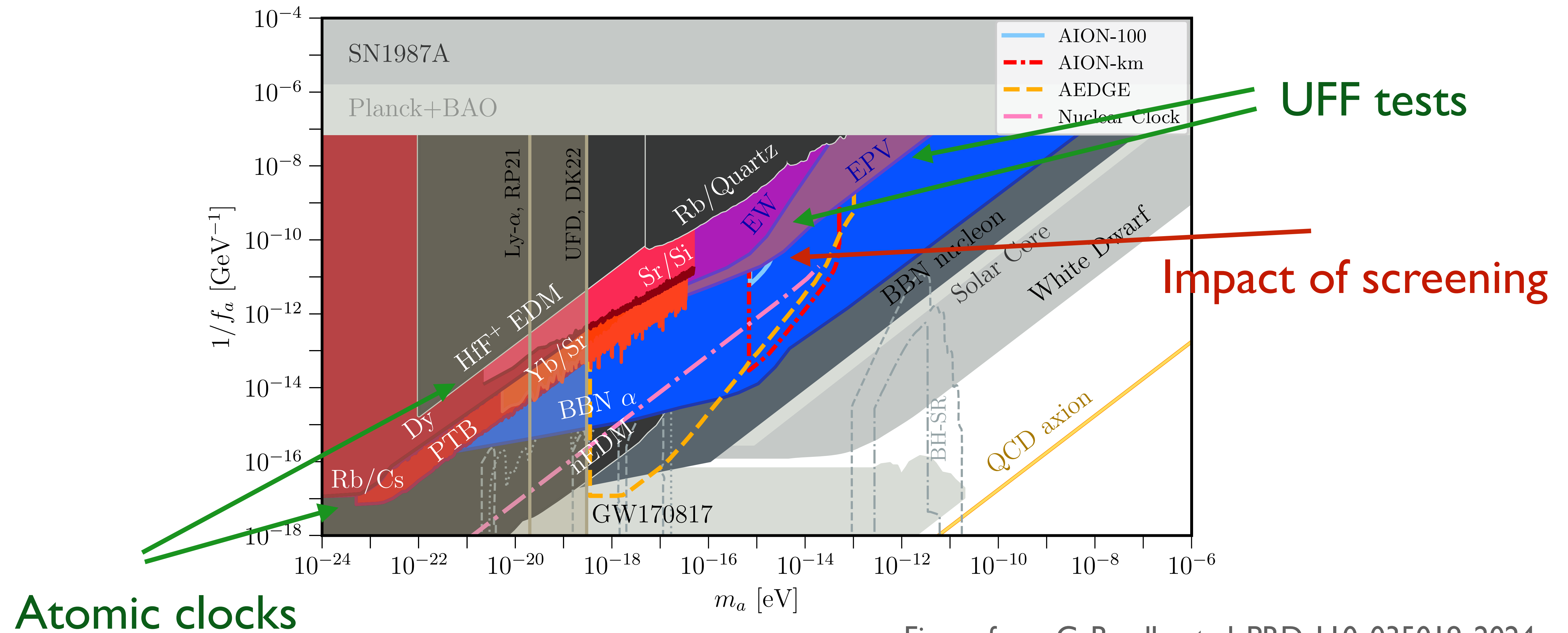
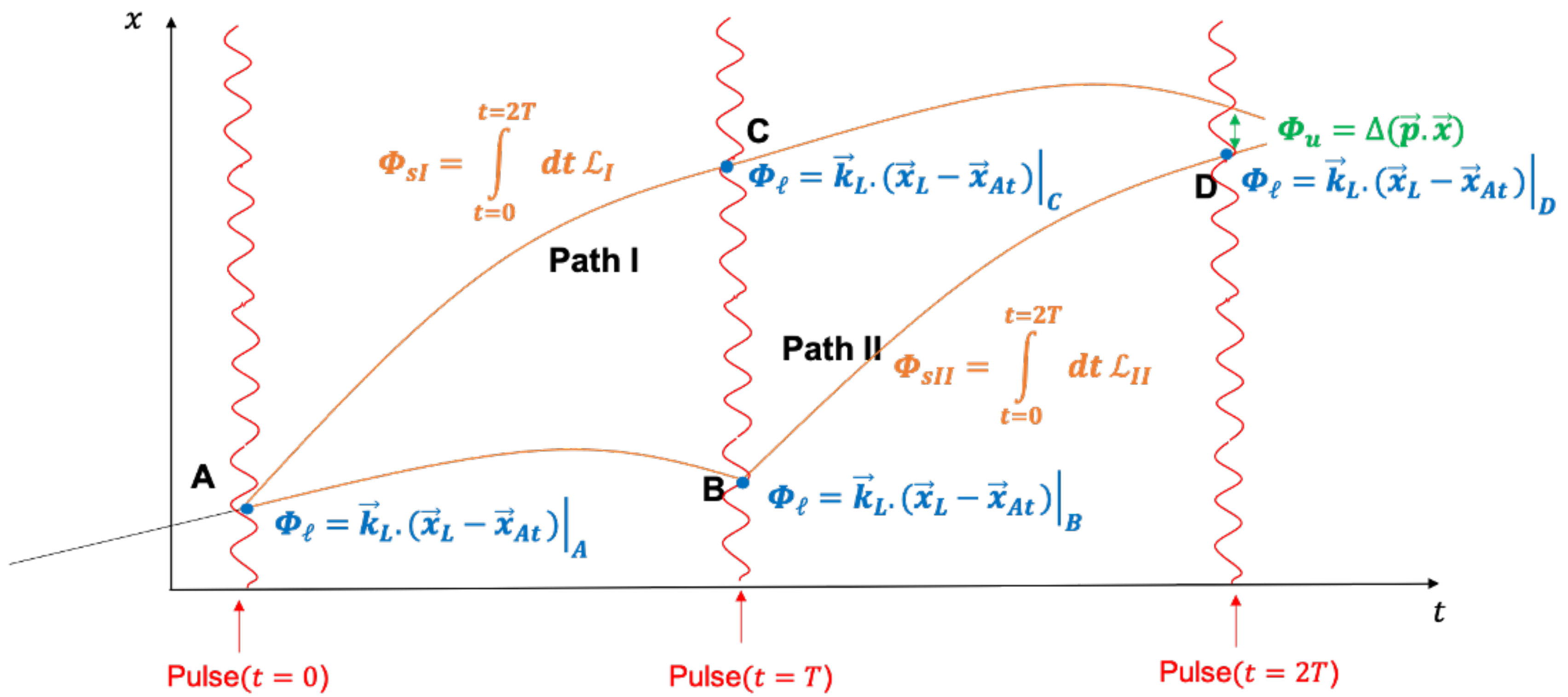


Figure from C. Beadle et al, PRD 110, 035019, 2024

Atom interferometers are sensitive to such DM candidates as well

see J. Gué et al, PRD, 2024

- Calculations performed following method from Storey and Cohen-Tannoudji, J. Phys, 1994. Exemple for a Mach-Zender:



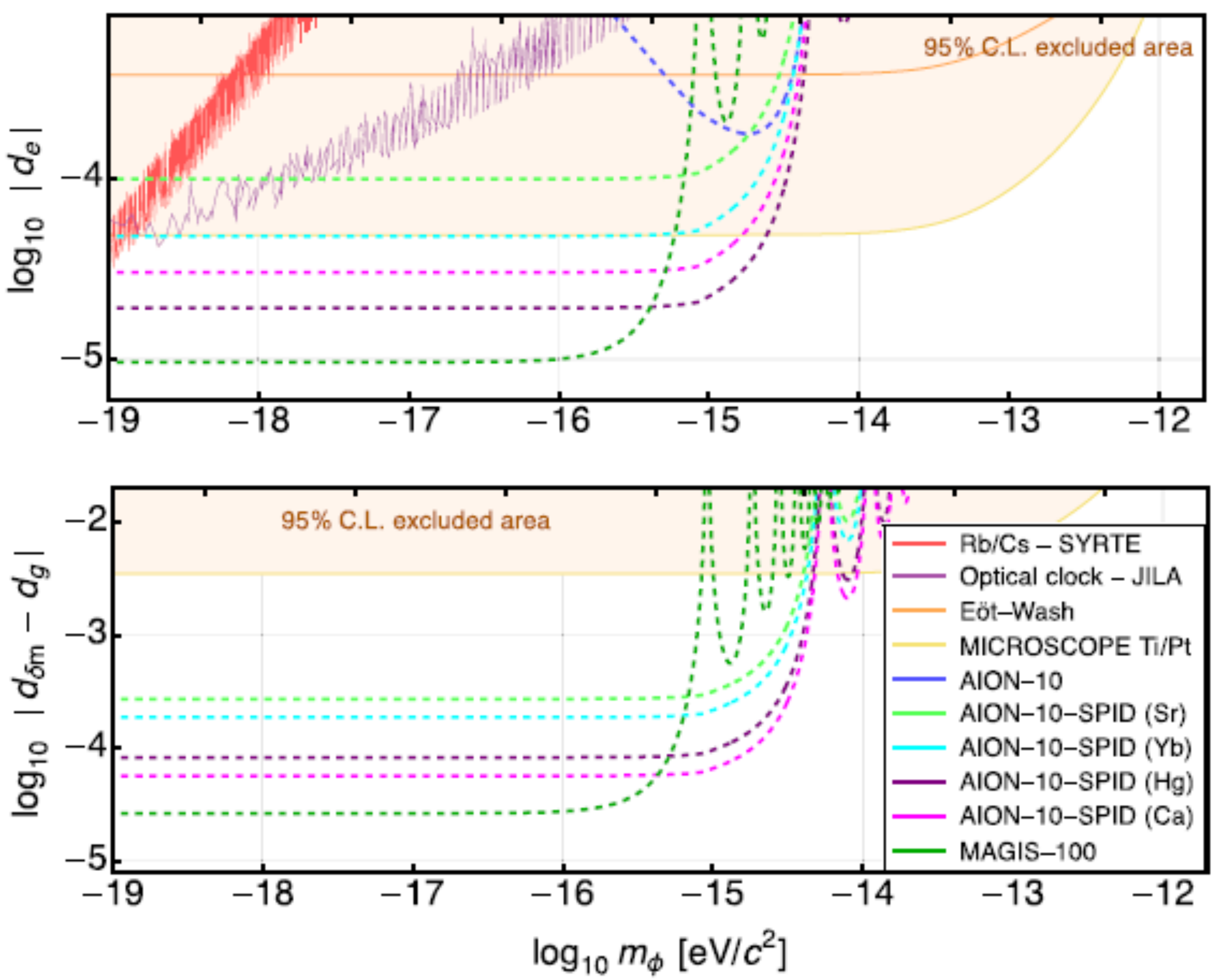
- Dilaton DM field impacts:
  - Classical trajectories of atoms
  - Rest mass/transition energy (Lagrangian + recoil velocity kick)
  - Laser frequency

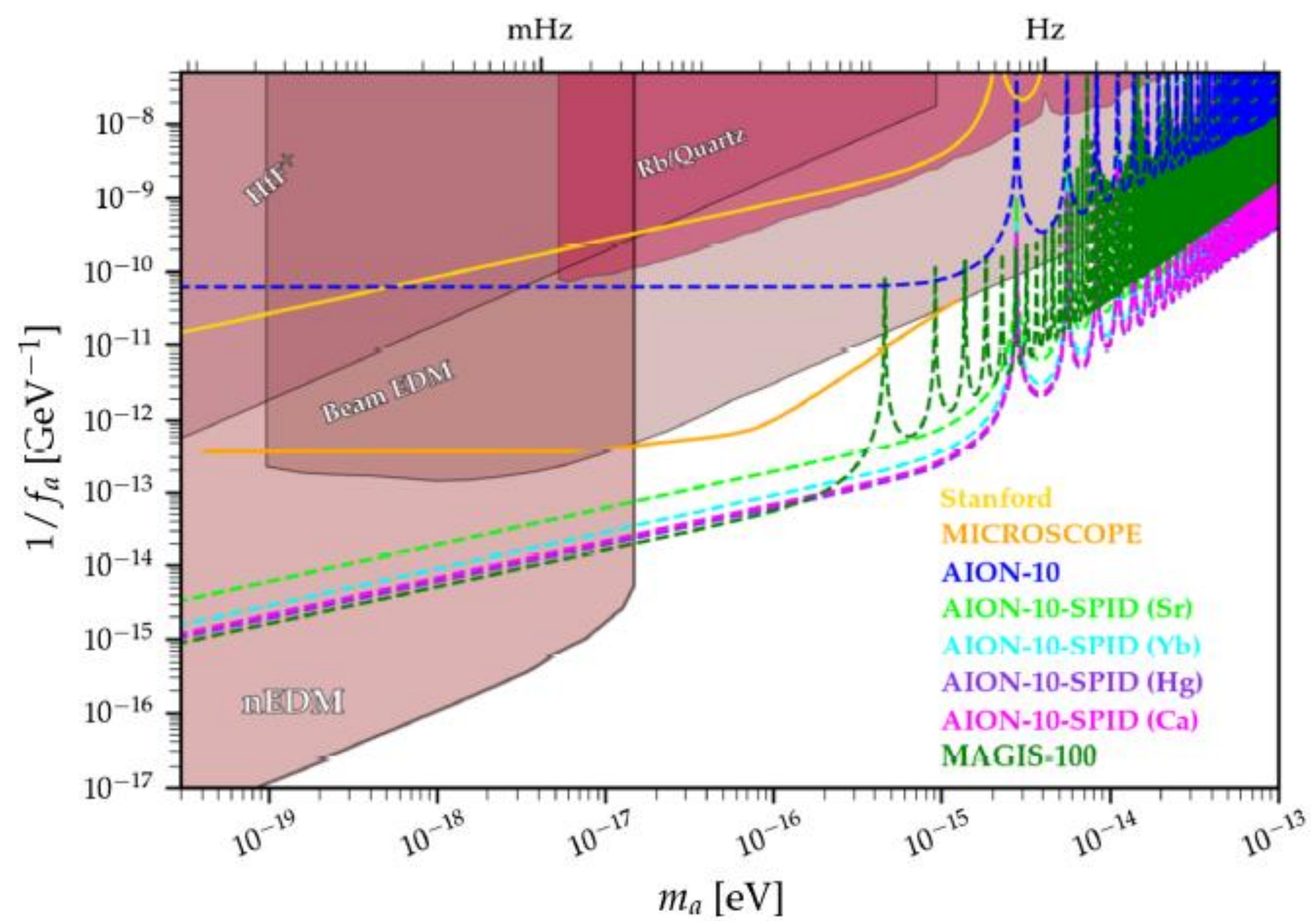
Extends previous calculations

see A. Geraci and A. Derevianko, PRD 2016
P. Graham et al, PRD 2016
L. Badurina et al, PRD 2022

Future AI setup will be very competitive to search for scalar DM candidates

work from J. Gué, ex PhD student



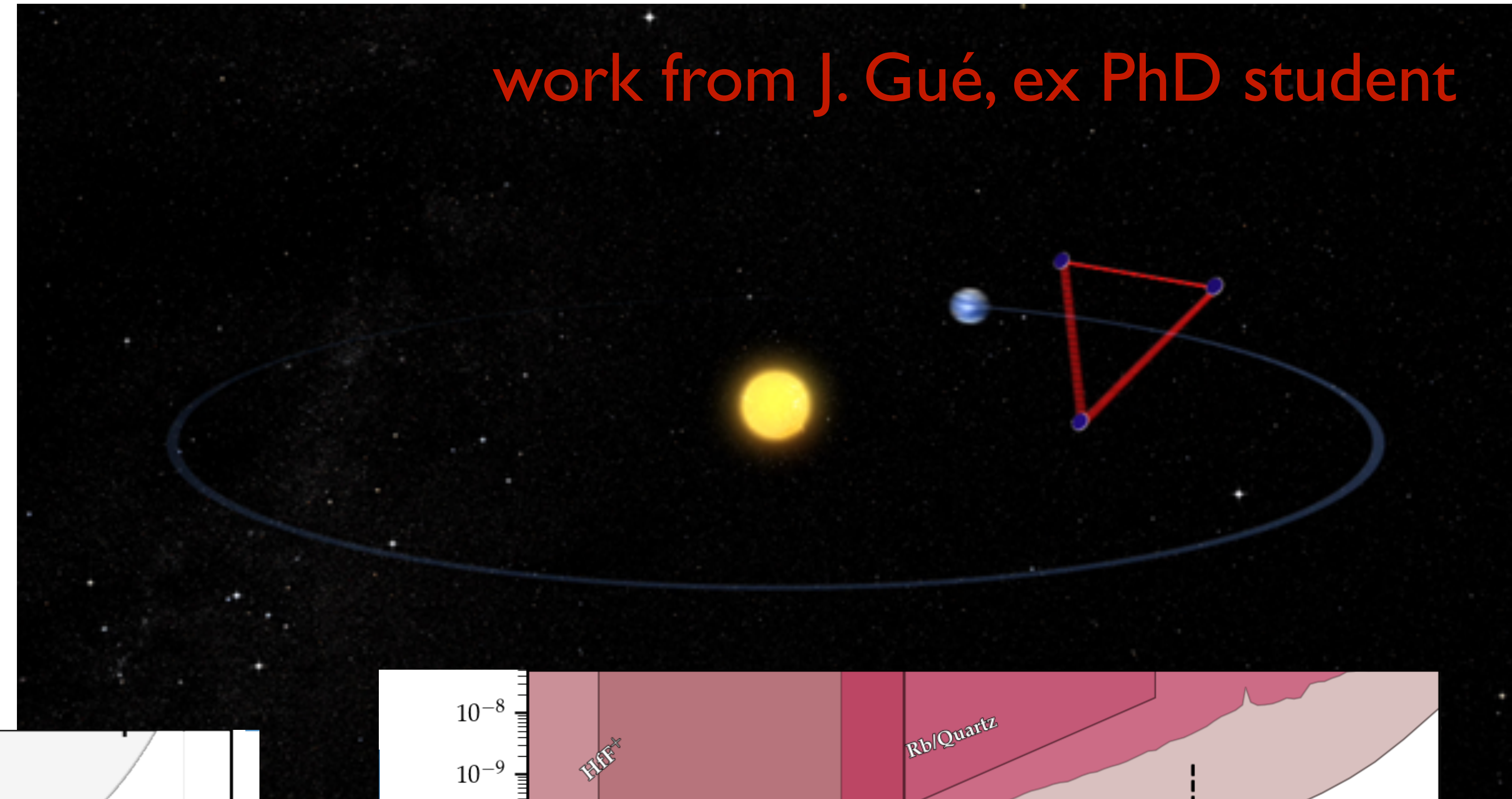


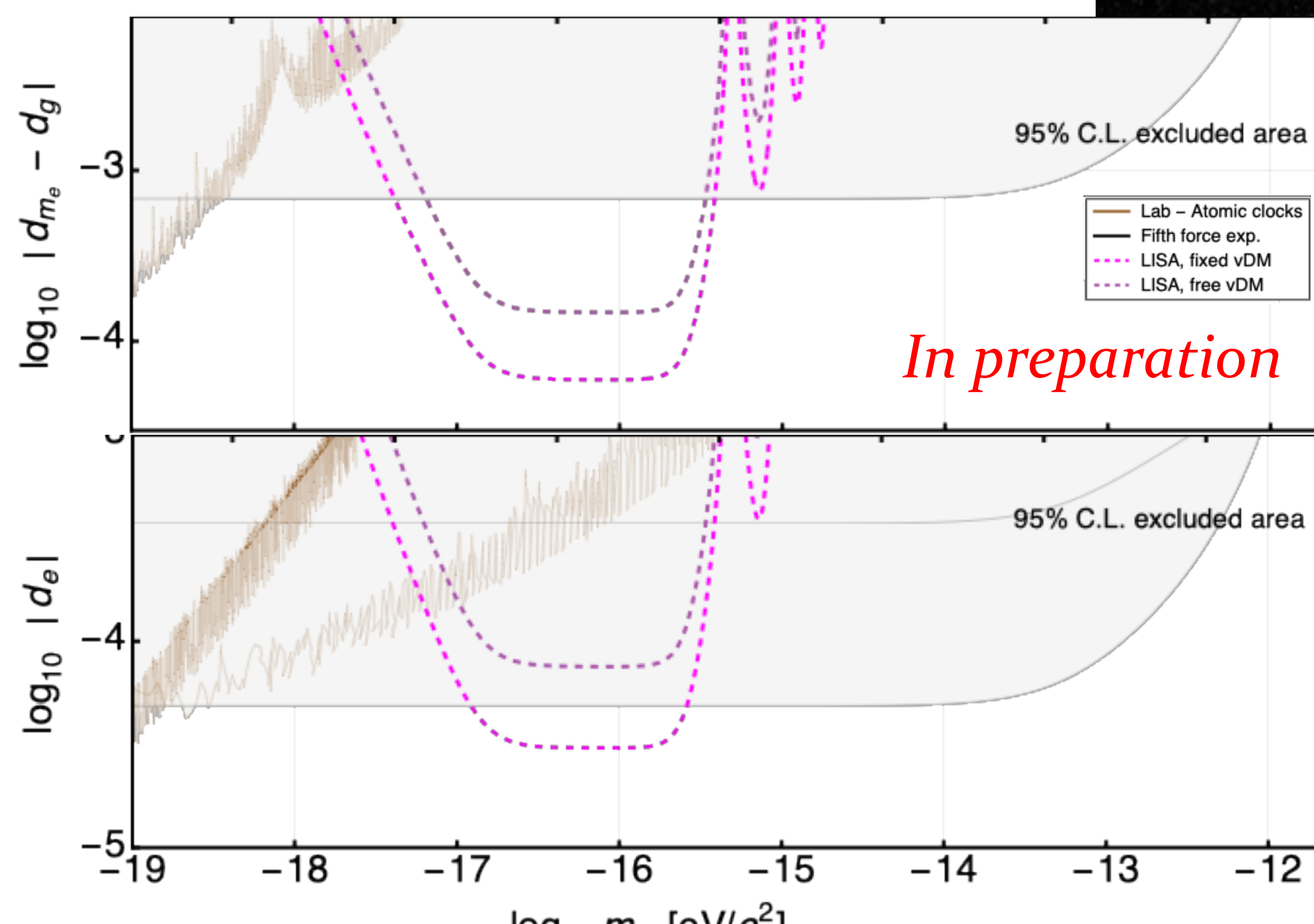
Axion

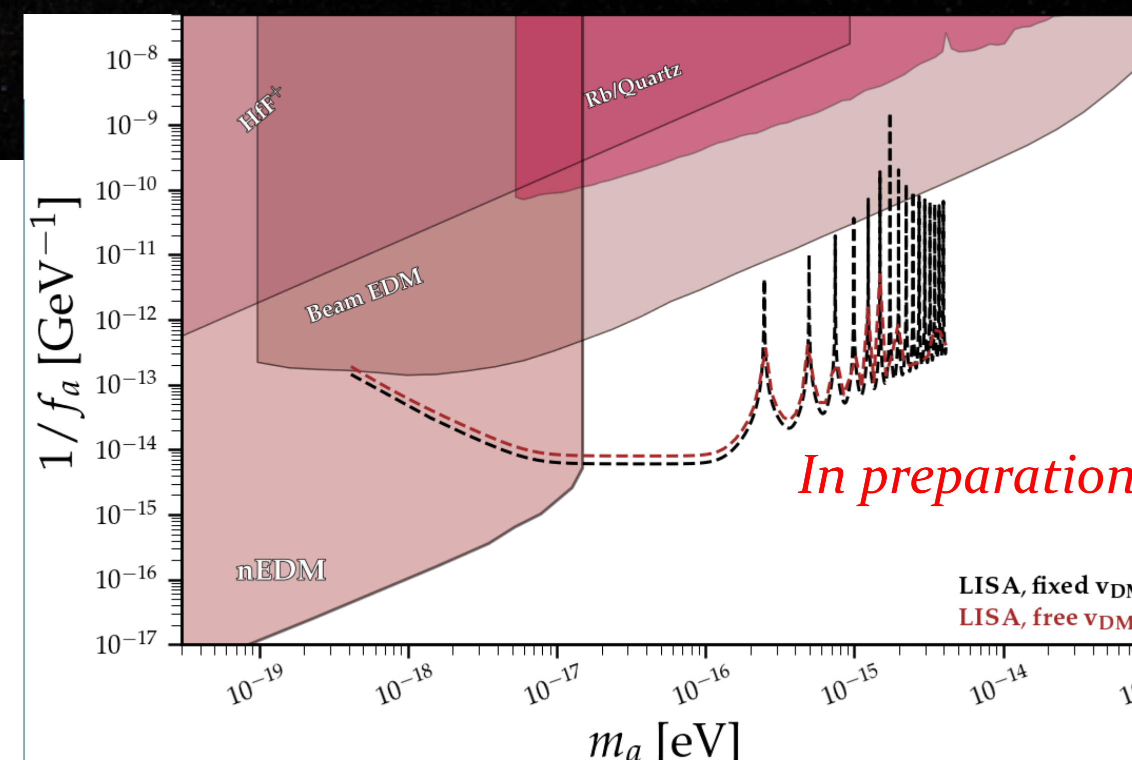
- SPID = Single Photon Isotope Differential (variation of AION more sensitive to scalar DM or axion)

Space-based GW detectors (LISA) will also be very competitive to search for ULMD

- Monitor the distance between 3 free falling test masses 2.5E6 km apart
- ULDM will make the position of these masses oscillate with time





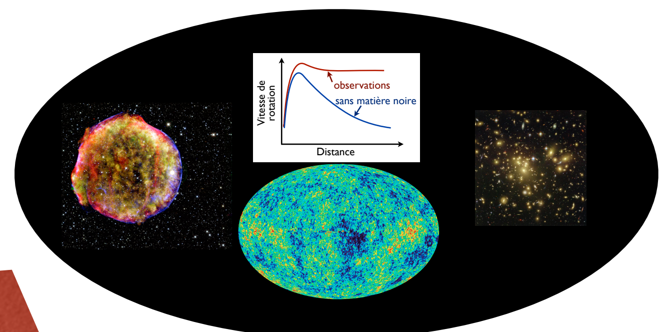


- Preliminary: it is possible to disentangle a possible ULDM signal from GWs

Conclusion

- Nature of Dark Matter remains one major challenge of modern physics
- In recent years (2015+): precision metrology has pushed the search for Dark Matter of mass < 1 eV (bosonic)
- Several models exist: scalar field, axion, dark photon, … with different phenomenology: oscillations (possible screening), topological default, …
- In this talk: some results on scalar ULDM and axions
- Others and on-going: work
  - search for Dark Photon/axions with dish antenna (CEA - P. Brun)
  - search for Dark Photon using cavities and Rydberg atoms
  - re-interpretation of MICROSCOPE in light of axions (pions mass)
  - exploration of LISA to search for such DM candidates
  - space test of UFF: STE-QUEST mission?
  - astrophysical searches (stars around SgrA*)
  - …
- Hunt for new ideas inspired by experimental progress and possibilities, led by theoretical models and plausibility

Can laboratory experiments and space-based experiments help in understanding DM?



Astronomy & cosmology

(gravitational waves, SNIa, CMB, structure formation, galactic dynamics, …)

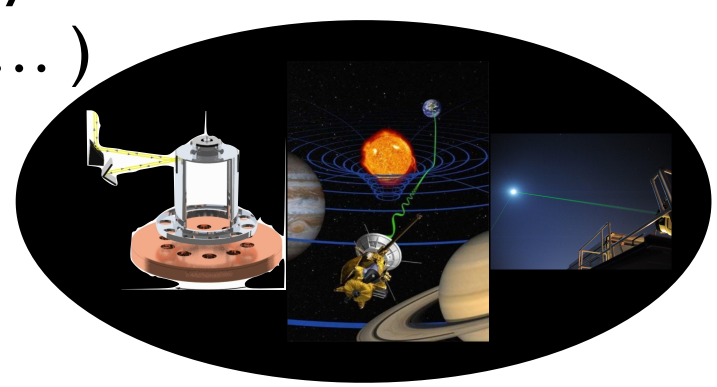
Quantum Gravity

Unification

DM and DE

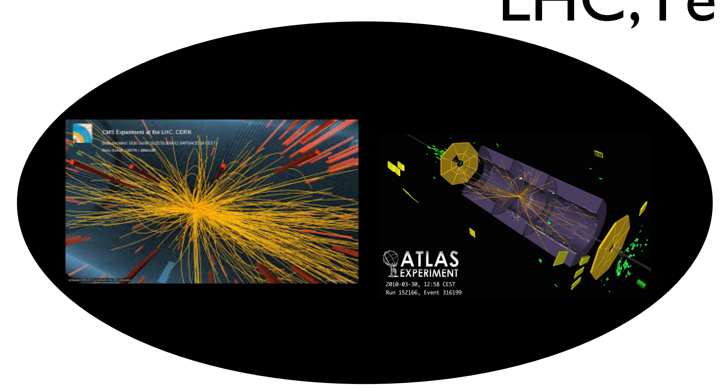
Local physics

(Solar System, **lab tests**, GNSS, …)



High energy

(particle physics: CERN-LHC, Fermilab, DESY, …)



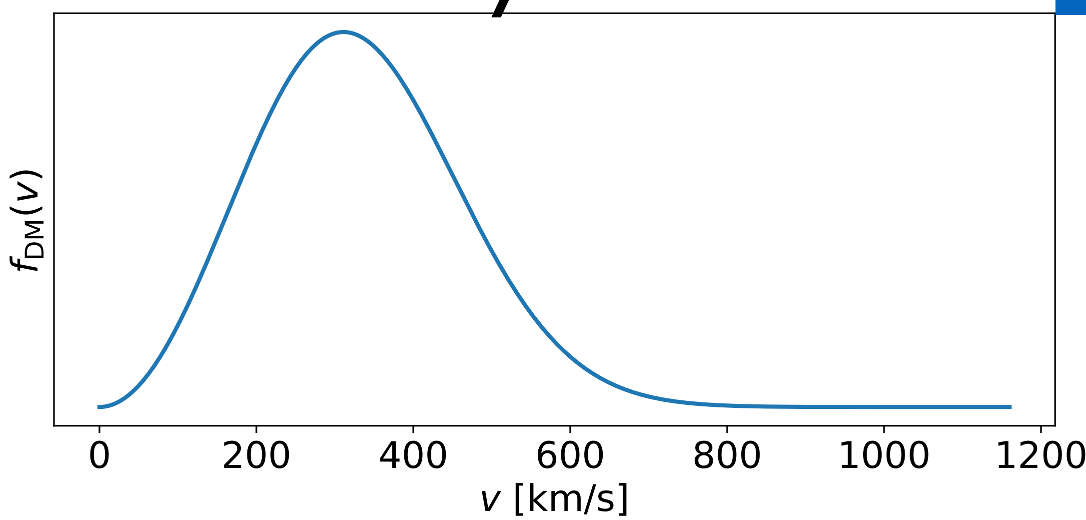
Picture inspired by Altschul et al, Adv, in Space Res. 55, 501, 2015

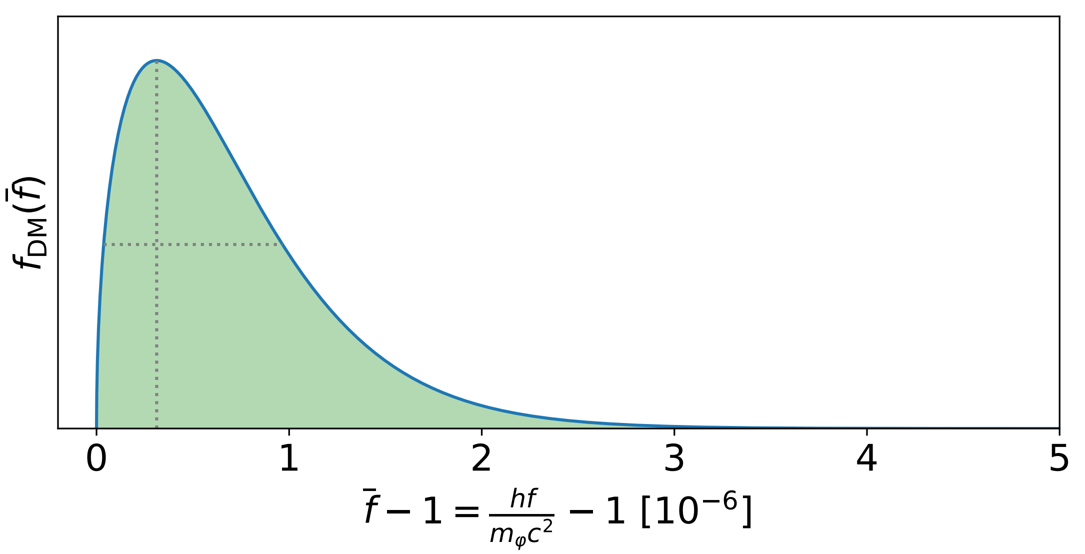
The field has a frequency distribution due to the DM velocity distribution

- The oscillation frequency depends on the velocity

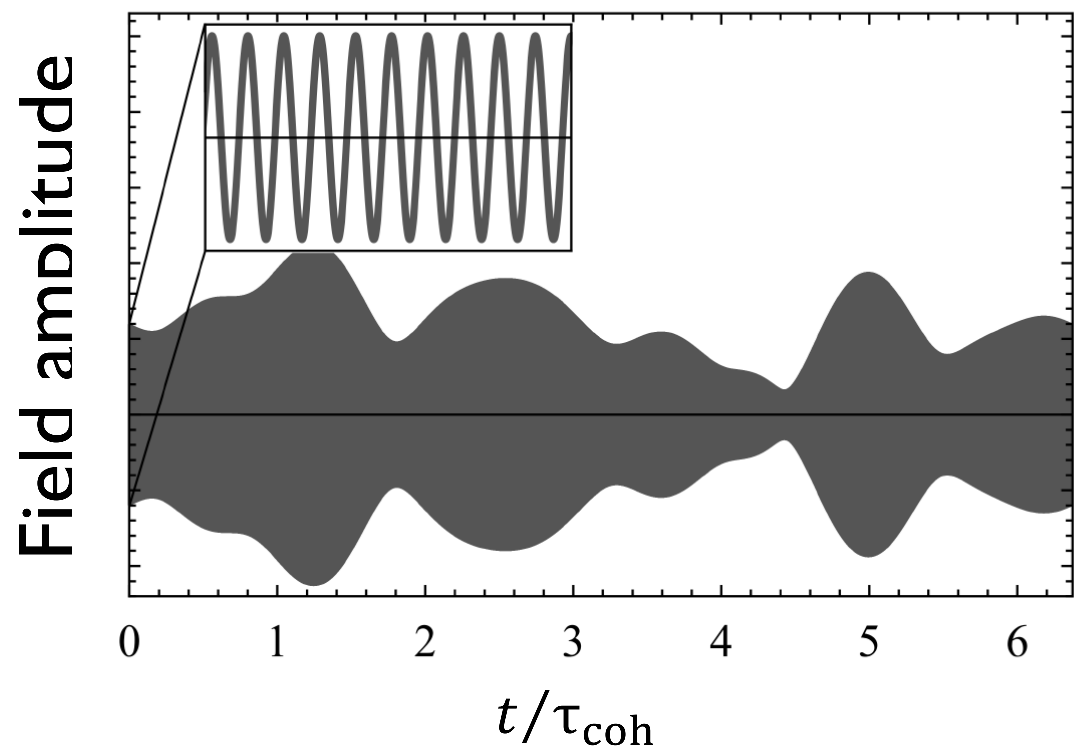
$$\omega = 2\pi f = \frac{mc^2}{\hbar}\left(1 + \frac{v^2}{2c^2}\right)$$

- DM velocity distribution





- Stochastic distribution
- Coherence time ~ 10^6 osc.



Stochastic modelling important for the data analysis

See Centers et al, arXiv1905.13650 and Foster et al, PRD, 2018
Savalle et al, PRL 2021

MICROSCOPE

collaboration between CNES,
ONERA, CNRS, ESA, ZARM, PTB

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- Launched on April 25th, 2016 ; life-time: ~ 2 yr (12% of the time used for UFF tests)
- Drag-free satellite, two cylindrical test masses: Pt/Ti. Measurement of the diff. acceleration along the symmetry axis
- Final results published in September 2022

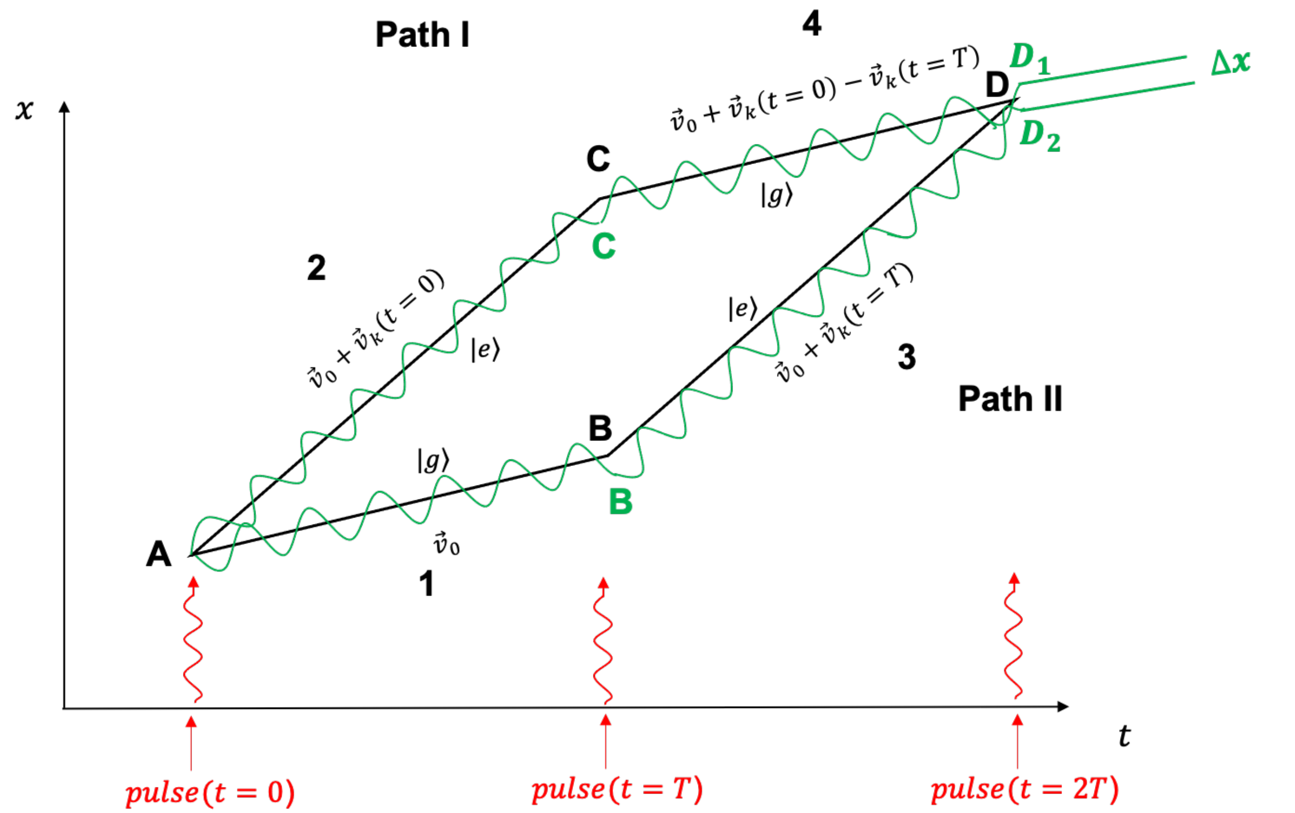
$$\eta = (-1.5 \pm 2.3\ [\mathrm{stat}] \pm 1.5\ [\mathrm{syst}]\ ) \times 10^{-15}$$

Touboul et al, PRL, 2022

- Independent analysis in the time domain @SYRTE: verification + other scientific objectives (Lorentz invariance "Standard Model Extension": search for a preferred frame UFF violation)

Pihan-Le Bars et al, PRL, 2019

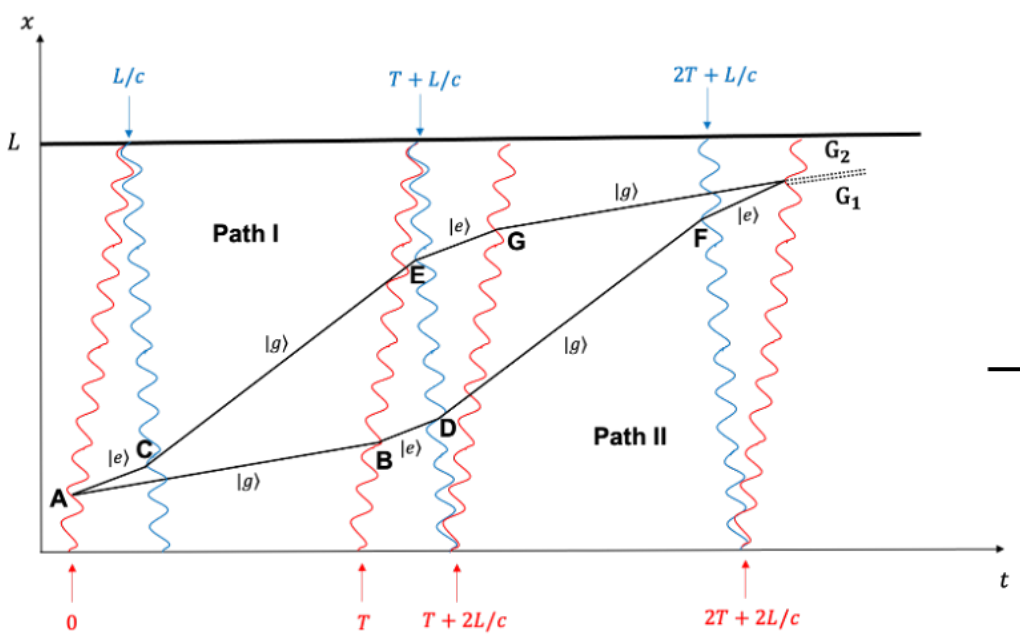
Expected phase shift in Mach-Zehnder AI



The oscillating acceleration implies a modification of the atom EoM → the atom oscillates in the interferometer
The differential phase shift between two atoms A and B at the end of the sequence is

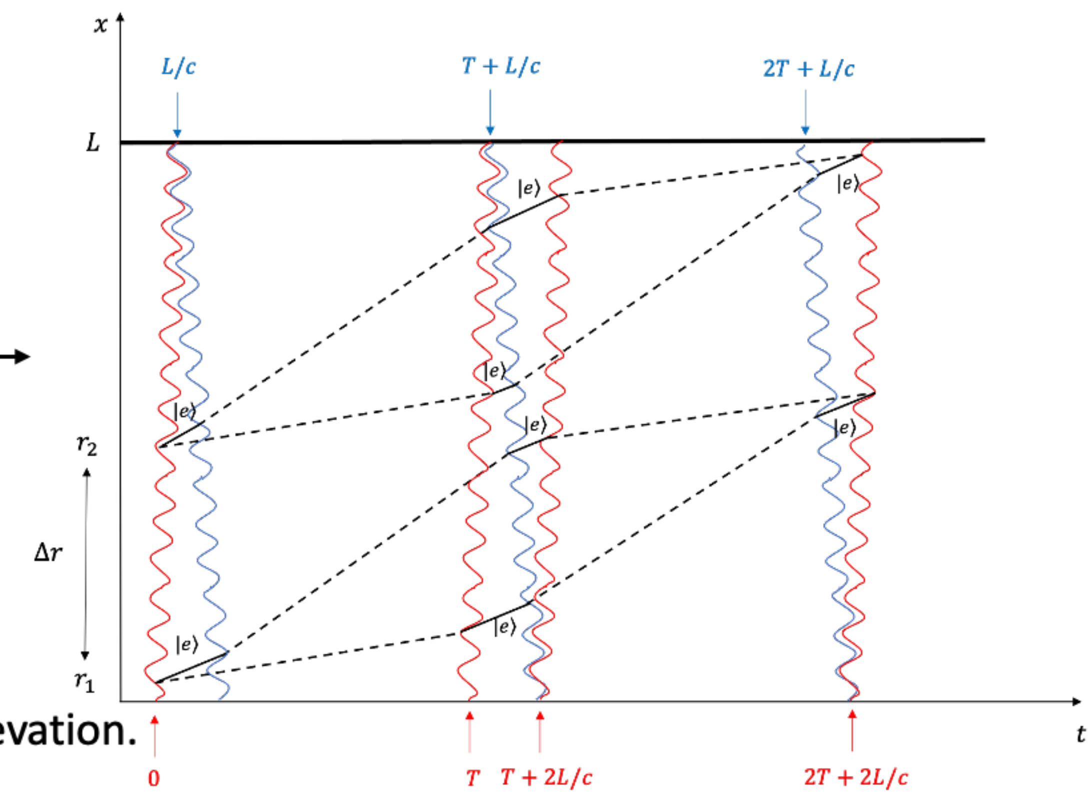
$$\begin{cases} \Delta\phi_{AB}^{MZ} \propto \frac{\rho_{DM} v_{DM}}{\omega_a^3}\left(k_{eff}^A\left(\left[Q_M^{\mathrm{A}}\right]_a - \left[Q_M^{\mathrm{M}}\right]_a\right) - k_{eff}^B\left(\left[Q_M^{\mathrm{B}}\right]_a - \left[Q_M^{\mathrm{M}}\right]_a\right)\right)\sin^2(\omega_a T) \\ \Delta\phi_{AB}^{MZ} \propto \frac{\sqrt{\rho_{DM}} v_{DM}}{\omega_\phi^2}\left(k_{eff}^A\left(\left[Q_M^{\mathrm{A}}\right]_\phi - \left[Q_M^{\mathrm{M}}\right]_\phi\right) - k_{eff}^B\left(\left[Q_M^{\mathrm{B}}\right]_\phi - \left[Q_M^{\mathrm{M}}\right]_\phi\right)\right)\sin^2\left(\frac{\omega_\phi T}{2}\right) \end{cases}$$

Expected phase shift in gradiometers



*P. Graham et al. PRL **110** 171102 (2013)*

Gradiometers (AION-10) →



*L. Badurina et al. PRD **105** 023006 (2022)*

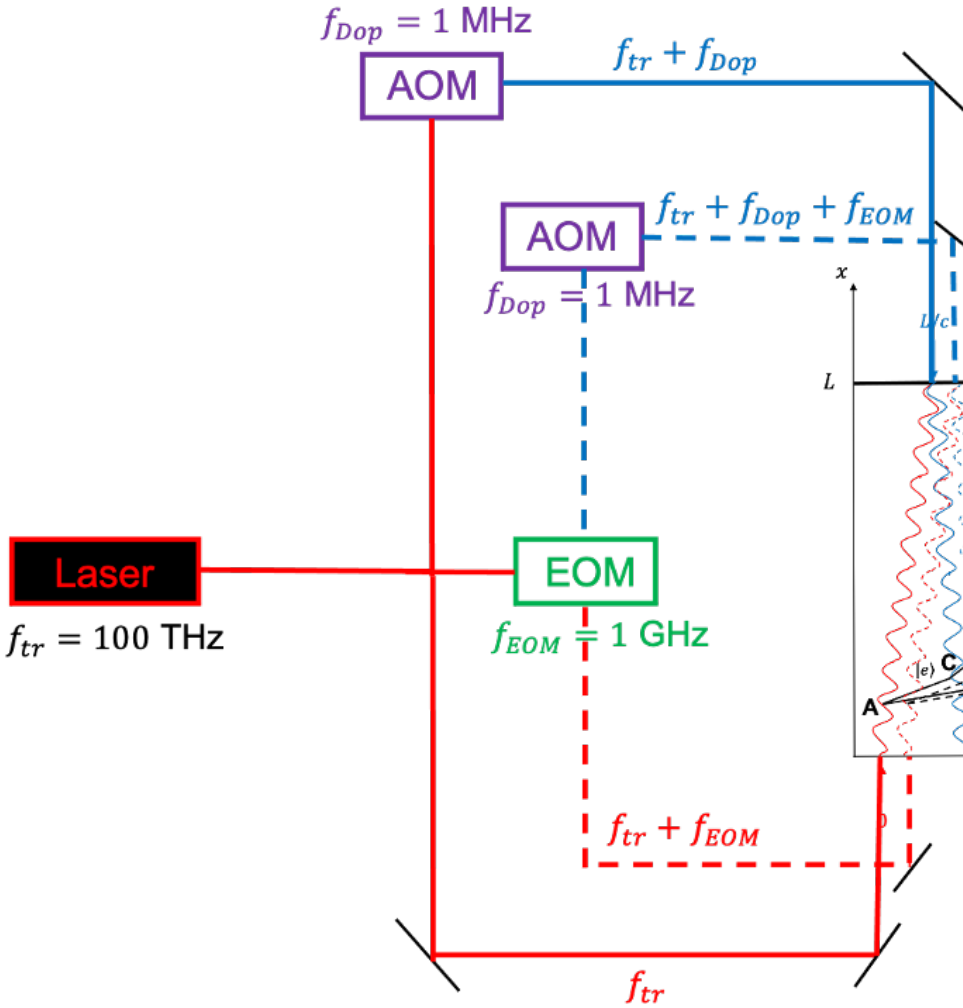
Same atom species undergoes the same AI sequence with different elevation.
Same lasers interact with both AI → **NO** laser phase noise
The differential phase shift between two atoms A and B at the end of this sequence is

Number of "Large Momentum Transfer" (LMT) kicks → n

$$
\begin{cases}
\Delta\phi_A^{Grad} \propto \dfrac{n\,\Delta r\,\rho_{DM}}{\omega_a^2}\left[Q_\omega^{\mathrm{A}}\right]_a \sin^2(\omega_a T) \\
\Delta\phi_A^{Grad} \propto \dfrac{n\,\Delta r\sqrt{\rho_{DM}}}{\omega_\phi}\left[Q_\omega^{\mathrm{A}}\right]_\phi \sin^2\left(\dfrac{\omega_\phi T}{2}\right)
\end{cases}
$$

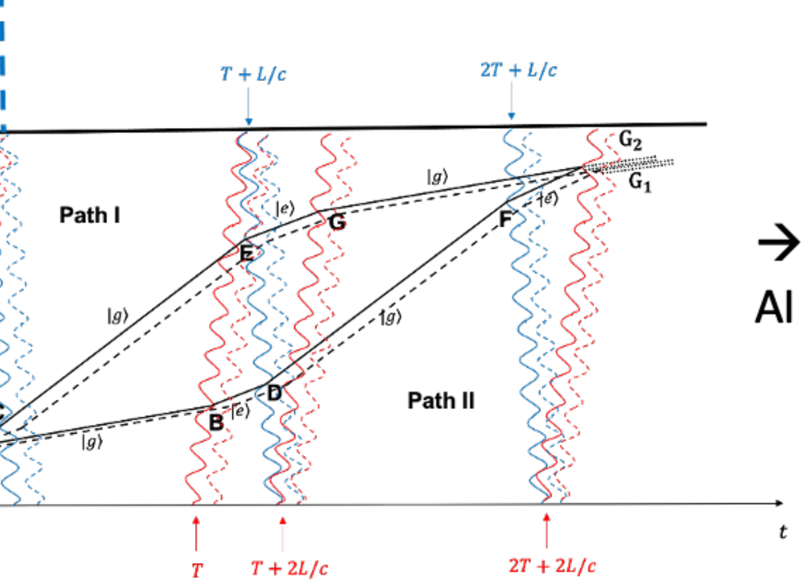
Signal is limited by the small time the atom lasts in the excited state ($\sim\omega L/c \ll 1$) (+ sensitivity to Q_M^{A} at 2nd order in $\omega L/c$)

Can we do better ? Modified AI setup proposal



Use of two isotope species with sequence based on LMT AI **at same elevation**

Addition of EOM to account for isotope shift $\Delta\omega \sim 10^{-6}\,\omega_0$



→ This experiment is a sort of Mach-Zehnder AI with n (≫ 1) single photon transition

The differential phase shift between two atoms A and B is

$$\begin{cases} \Delta\phi_{AB}^{New} \propto \dfrac{n\,\omega_0\,\rho_{DM} v_{DM}}{\omega_a^3}\left(\left[Q_M^A\right]_a - \left[Q_M^B\right]_a\right)\sin^2(\omega_a T) \\ \Delta\phi_{AB}^{New} \propto \dfrac{n\omega_0\,\sqrt{\rho_{DM}}\,v_{DM}}{\omega_a^2}\left(\left[Q_M^A\right]_\phi - \left[Q_M^B\right]_\phi\right)\sin^2\left(\dfrac{\omega_\phi T}{2}\right) \end{cases}$$

→ **Signal not limited anymore by small factor $\omega L/c$**

However, EOM comes with an additional noise…

Phase shift induced by DM in various AI setup and sensitivity of various experiments

work from J. Gué, PhD student

- Standard Mach-Zender: used in Standford with ^{85}Rb and ^{87}Rb and for a gravimeter in Wuhan using ^{87}Rb

  see P. Asenbaum et al, PRL, 2020 for standford and Z. Hu et al, PRA, 2020 for Wuhan

- Future AION10 gradiometer: 2 Mach-Zender with Large Momentum Transfer stacked at different elevations

  see e.g. Badurina et al, PRD, 2022

- Future MAGIS-like experiment: 2 colocated Mach-Zender with Large Momentum Transfer using 2 isotopes: advantageous for UFF tests

  see e.g. Abe et al, Quantum Sc. and Tech., 2021

Linear and quadratic couplings have a different phenomenology

- Linear coupling

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

DM, atomic sensors are more sensitive

A fifth force generated by a body - UFF tests are more sensitive

- Quadratic coupling: no more Yukawa interaction, richer phenomenology

Can be screened or enhanced (scolarisation)

Both atomic sensors and UFF tests are sensitive to this behaviour

see A. Hees et al, PRD, 2018

Linear and quadratic couplings have a different phenomenology

- Linear coupling

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

DM, atomic sensors are more sensitive

A fifth force generated by a body - UFF tests are more sensitive

- Quadratic coupling: no more Yukawa interaction, richer phenomenology

$$\varphi = \tilde{\varphi}(r)\varphi_0 \cos mt$$

Can be screened or enhanced (scolarisation)

Both atomic sensors and UFF tests are sensitive to this behaviour

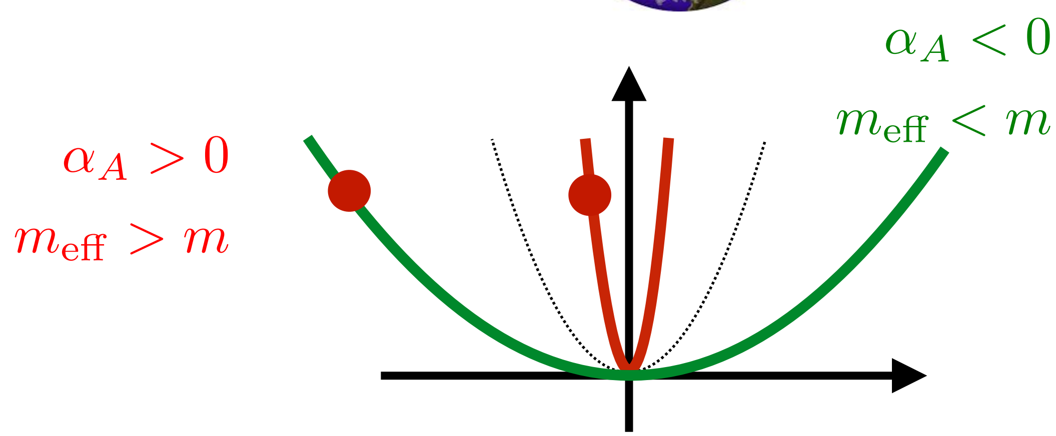
see A. Hees et al, PRD, 2018

Scalar field for a quadratic coupling

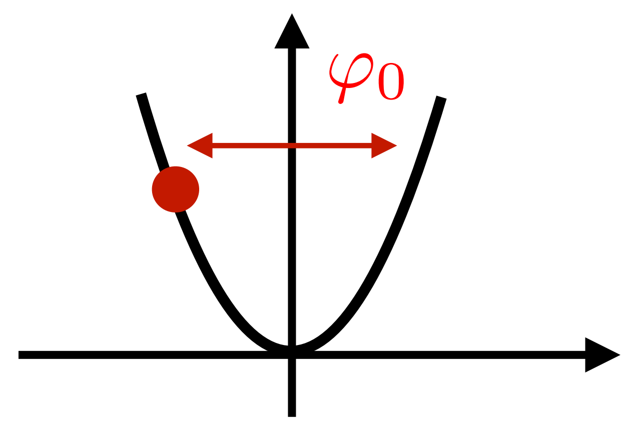
$$\Box\varphi + \left(m^2 + \frac{4\pi G}{c^2}\alpha_A \rho_A\right)\varphi = 0$$

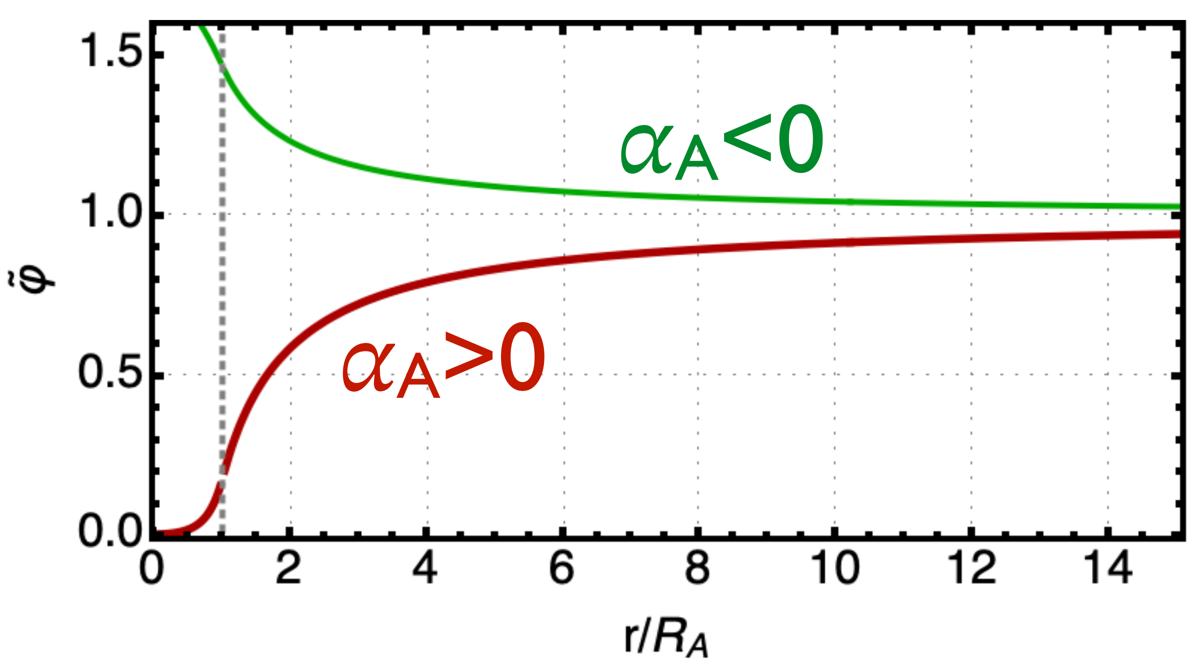
No source term (no fifth force) but effective mass that depends on the local matter density

V(φ) in



V(φ) in a vacuum





$$\varphi = \tilde{\varphi}(r)\varphi_0 \cos mt$$

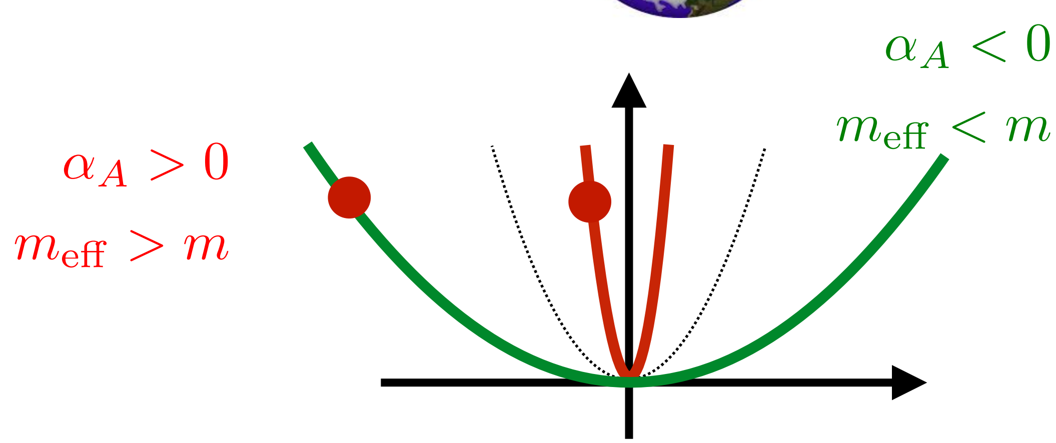
see A. Hees et al, PRD, 2018

Scalar field for a quadratic coupling

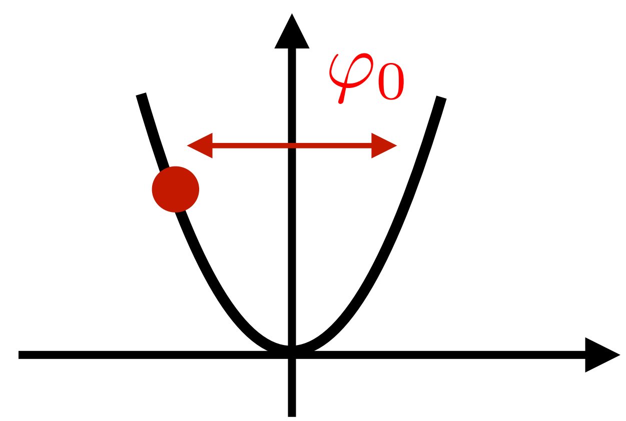
$$\Box\varphi + \boxed{\left(m^2 + \frac{4\pi G}{c^2}\alpha_A \rho_A\right)\varphi} = 0$$

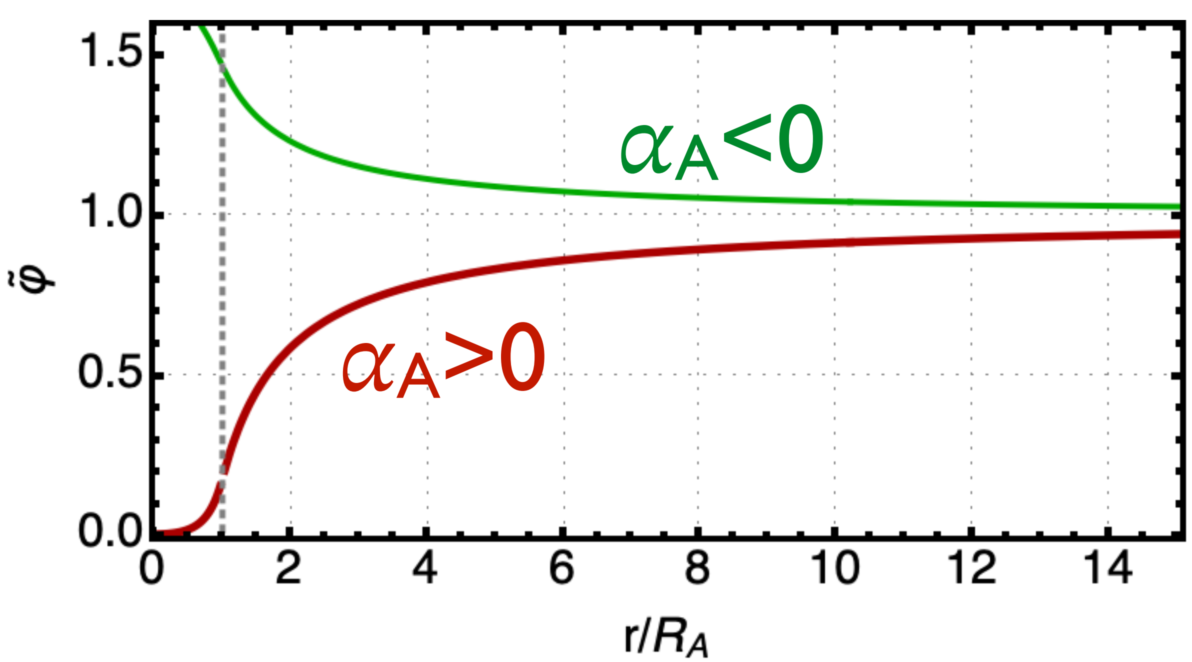
No source term (no fifth force) but effective mass that depends on the local matter density

V(φ) in 



V(φ) in a vacuum





$$\varphi = \tilde{\varphi}(r)\varphi_0 \cos mt$$

see A. Hees et al, PRD, 2018

<u>Screening</u> for positive couplings and <u>scalarization</u> for negative couplings!

This leads to a rich phenomenology

- Comparison of atomic frequencies:

$$Y(t,\boldsymbol{x}) = K + \Delta\kappa^{(2)}\frac{\varphi_0^2}{2}\left(1 - s_A^{(2)}\frac{GM_A}{c^2 r}\right)^2 + \Delta\kappa^{(2)}\frac{\varphi_0^2}{2}\cos\left(2\omega t + 2\delta\right)\left(1 - s_A^{(2)}\frac{GM_A}{c^2 r}\right)^2$$

Position dependent: clocks on elliptic orbit? Comparison clock in space versus clock on ground?

oscillation, amplitude depends on position

- UFF measurements

$$[\Delta\boldsymbol{a}]_{A-B} = \Delta\bar{\alpha}^{(2)}\frac{\varphi_0^2}{2}\left(1 - s_C^{(2)}\frac{GM_c}{c^2 r}\right)\left[-\frac{GM_c}{r^3}\boldsymbol{x}\, s_C^{(2)} - \frac{GM_c}{r^3}\boldsymbol{x} s_C^{(2)}\cos\left(2\omega t + 2\delta\right) + \left(1 - s_C^{(2)}\frac{GM_c}{c^2 r}\right)\omega\boldsymbol{v}\sin\left(2\omega t + 2\delta\right)\right]$$

η that depends on r (directly related to Eöt-Wash and MICROSCOPE results)

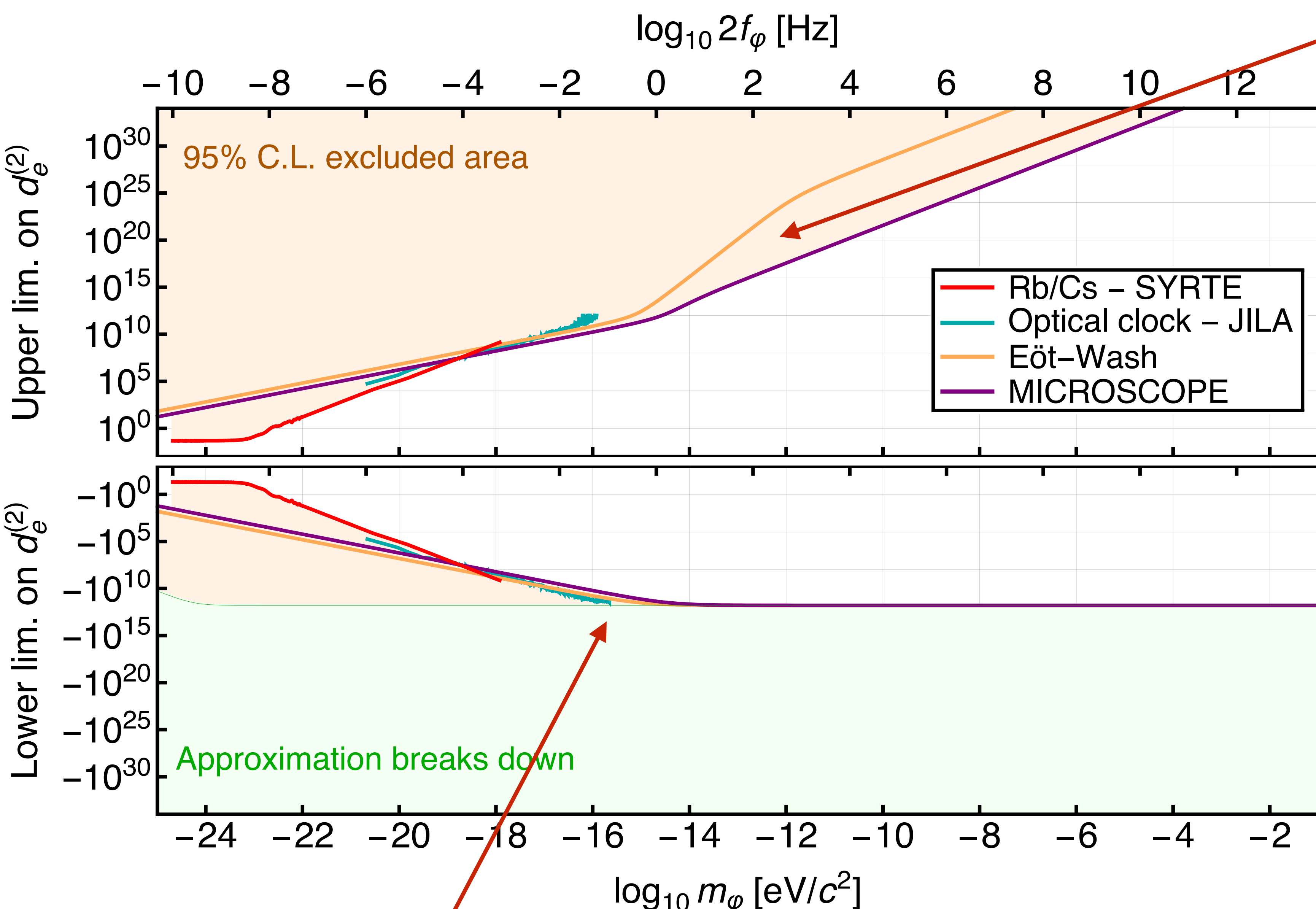
2 terms that oscillate, amplitude depends on position

See A. Hees et al, PRD, 2018

They are all sensitive to screening/scalarization

Constraints on the quadratic couplings

Impact of screening



Impact of scalarization

Being in space is favorable ! Scalar field tends to vanish at the Earth surface

see A. Hees et al, PRD, 2018

A vector DM will interact with electromagnetism

- An effective Lagrangian for the vector-matter coupling

$$\mathcal{L}_{\rm mat}\left[\Psi, g_{\mu\nu}, X_\mu\right] = \mathcal{L}_{\rm SM}\left[\Psi, g_{\mu\nu}\right] - \frac{\chi}{2} F^{\mu\nu} X_{\mu\nu} + \dots$$

see Horns et al, JCAP, 2013 and references therein

- Kinetic mixing coupling χ characterises the coupling with EM

- Other couplings with matter can be considered like to the B-L current: leads to a violation of the UFF

see e.g. Fayet, PRD, 2018

- The hidden photon X^μ will mix with the usual photon A^μ

$$\Box A^\mu = -\chi \Box X^\mu$$

$$\Box X^\mu + m^2 X^\mu = -\chi \Box A^\mu$$

A hidden photon field will generate a small EM field and vice versa

An oscillating DM vector field will generate a small electric field

- Oscillating DM vector field $\vec{X} = \vec{X}_0 \cos mt$ will generate an EM field

$$\vec{A} = -\chi \vec{X}$$

and in particular a small electric field

$$\vec{E}_{\rm DM} = -\partial_t \vec{A} = -m\chi \vec{X}_0 \sin mt$$

- As a reminder: the amplitude of oscillation is related to the DM energy density

$$\rho = \frac{m^2 \left|\vec{X}_0\right|^2}{2}$$

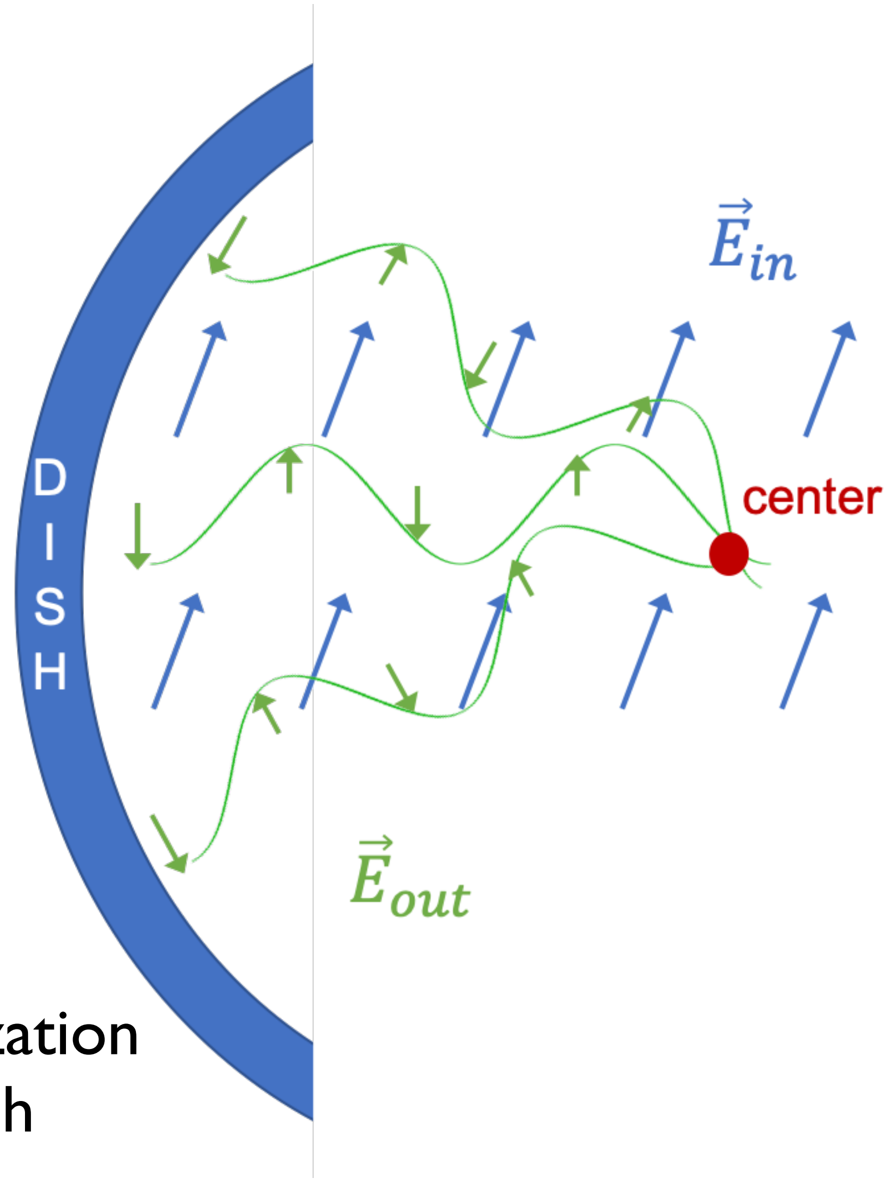
see Horns et al, JCAP, 2013 and references therein

In a DM vector field, a dish antenna will generate an EM field that will be focused in its center

- the electric field // to a conductor surface vanishes (boundary condition)
- The surface of the dish will generate a propagating electric field to vanish the DM electric field
- For a spherical dish, the electric field will be focused at the center + non-relevant electric field will be focused at the focal point
- Sensitivity

$$\chi_{\rm sens} = 4.5 \times 10^{-14} \left(\frac{P_{\rm det}}{10^{-23}\,{\rm W}}\right)^{\frac{1}{2}} \left(\frac{0.3\,{\rm GeV/cm^3}}{\rho_{\rm CDM,halo}}\right)^{\frac{1}{2}} \left(\frac{1\,{\rm m^2}}{A_{\rm dish}}\right)^{\frac{1}{2}} \left(\frac{\sqrt{2/3}}{\alpha}\right)$$

coeff. characterising the polarization of the DM field wrt the dish



see Horns et al, JCAP, 2013 and references therein