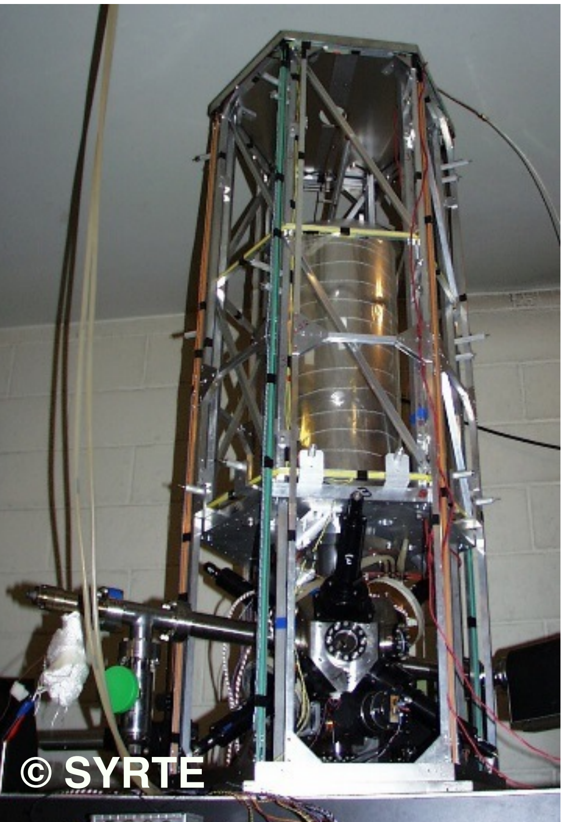
Searching for UltraLight Dark Matter with laboratory experiments

J. Gué, A. Hees, P. Delva, P. Wolf

LNE-SYRTE, CNRS,Paris Obs., Université PSL, Sorbonne Univ.



Journées scientifiques du PN-GRAM
8 Novembre 2023

l'Observatoire de Paris | SYRTE

Systèmes de Référence Temps-Espace

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, …)

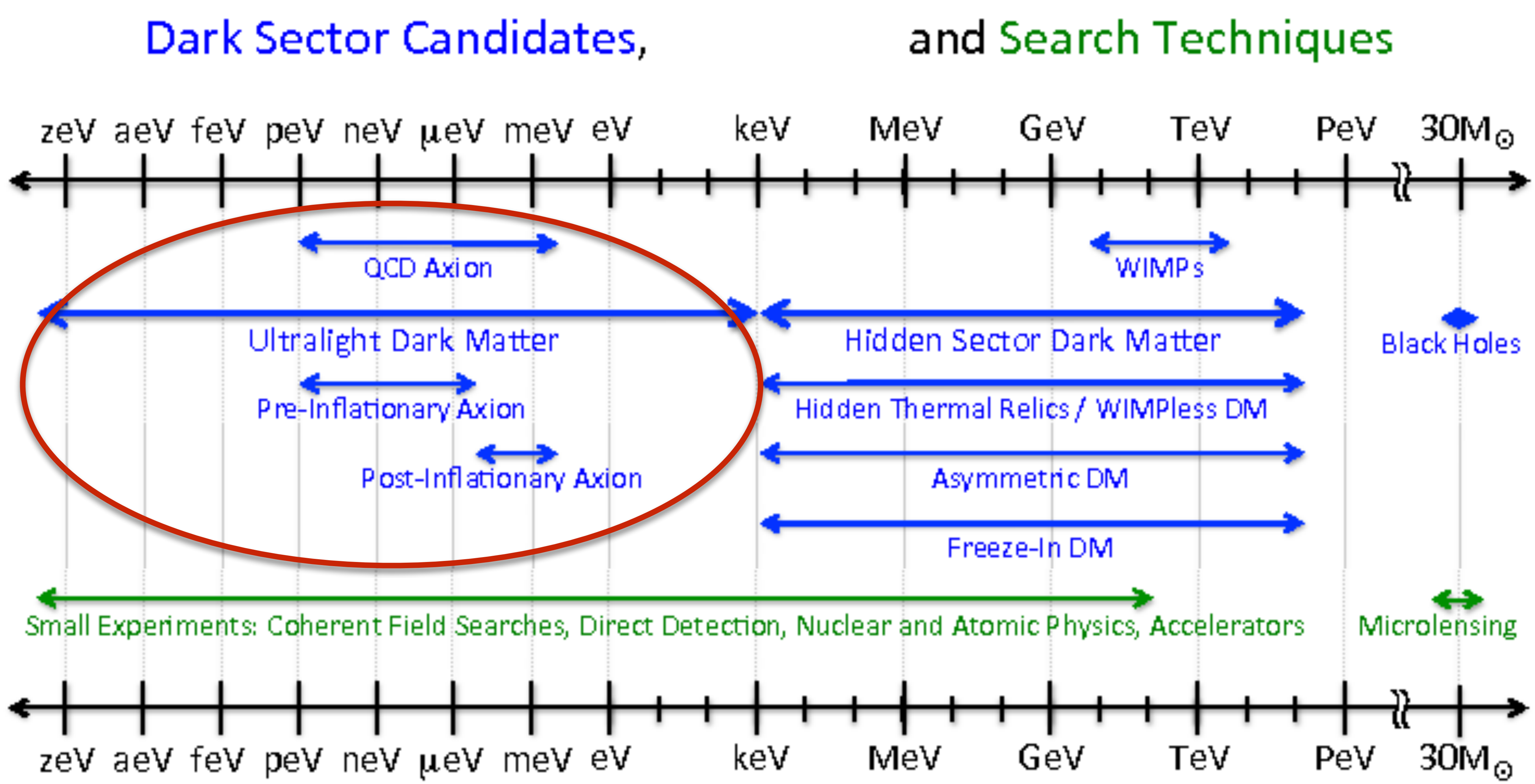


Fig. from *US cosmic vision: new idea for Dark Matter*, 2017, arXiv:1707:04591

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

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

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

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

- In our Galaxy $\rho_{\rm DM} \approx 0.4 {\rm GeV/cm}^3$

- 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)

Mainly two phenomenological signatures explored so far

1. Oscillatory behaviour of the additional field

see Arvanitaki et al, PRD, 2015

   - oscillation with stochastic amplitude
   - oscillation with amplitude depending on location (screening/ scalarization possible)

2. Topological defect: domain wall, …

see Roberts et al, Nature Com., 2017

   - search for transients signatures in the data
   - Search using fiber-link comparison of clocks or using GNSS Galileo data (+ dedicated SLR campaign)

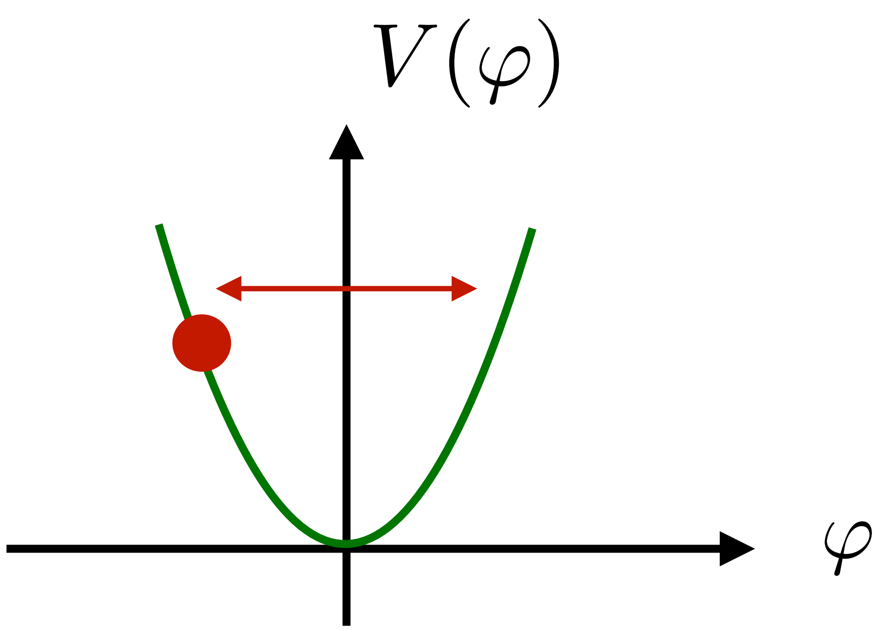
see Roberts et al, New. Journal of Phys. 2020
Bertrand et al, submitted to ASR, 2023

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

- A massive scalar field φ
- A massive vector field X_μ

- When $H \ll m^2$ (H=Hubble constant):

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



If the new field makes DM, its oscillation amplitude is related to the DM energy density

- A massive scalar field φ
- A massive vector field X_μ

- Oscillates at Compton frequency

$$\varphi = \varphi_0 \cos mt$$

$$\vec{X} = \vec{X}_0 \cos mt$$

- The averaged stress-energy tensor

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

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

$$p_{ij} \sim \langle T^i_j \rangle = 0$$

- The scalar/vector field can be identified as a pressureless fluid

⇒ a possible Dark matter candidate!

In experimental searches, we look for interactions between this new fields and SM

- Different couplings for different fields:
  - scalar: dilaton couplings d_i (to EM, fermions, QCD): constants of Nature (α, fermion masses) depend on space/time [atomic clocks, UFF experiments, …]

    see Damour and Donoghue, PRD, 2011

  - Axion (pseudo-scalar): coupling to pseudo scalar Lagrangian density (EM, QCD, fermion). Recent result: mass of pions depend quadratically to the axion field [UFF violation]

    see Kim and Perez, arXiv 2023

  - Vector/Dark photon: kinetic mixing to EM χ [modification of EM, …], coupling to the fermonic currents [B, B-L couplings, leading to a UFF violation]

    see Horns, JCAP, 2011
    P. Fayet, PRD, 2018

Vector Ultra Light Dark Matter: A Dark Photon/Hidden Photon

A vector DM will interact with electromagnetism

- An effective Lagrangian for the vector-matter coupling

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

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

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

An oscillating DM vector field will generate a small electric field

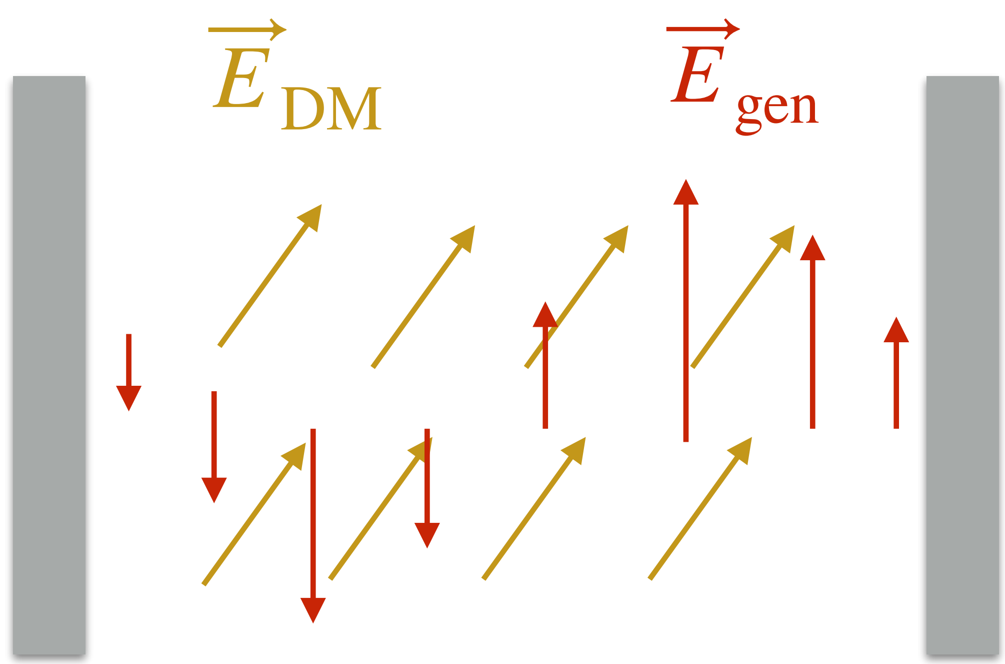
- Oscillating DM vector field $\vec{X} = \vec{X}_0 \cos mt$ will generate an EM field

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

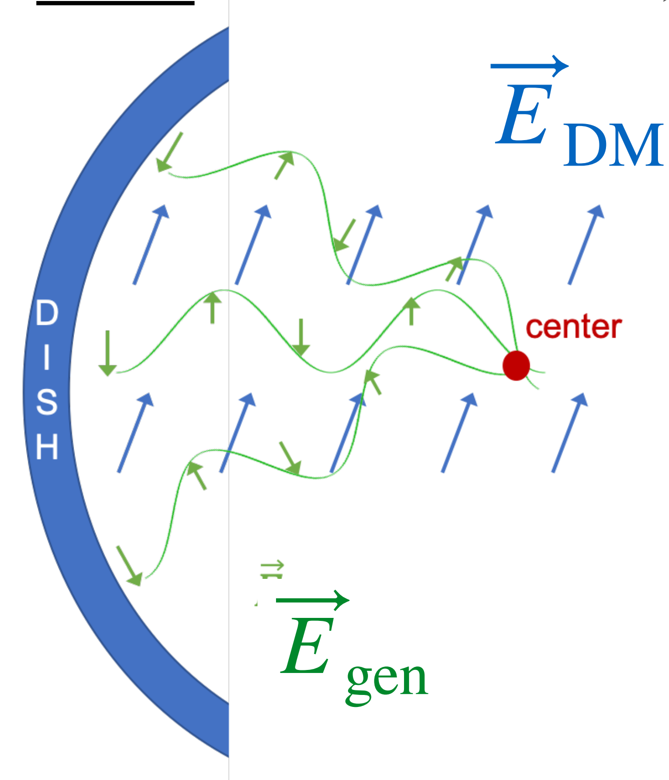
- Reminder: the amplitude is related to the DM density $\rho = \frac{m^2 \left|\vec{X}_0\right|^2}{2}$

- Idea to search for such a DM: amplify this electric field using reflectors (boundary condition: creation of a classical propagating EM field)

<u>Cavity</u> see Gué et al, PRD, 2023



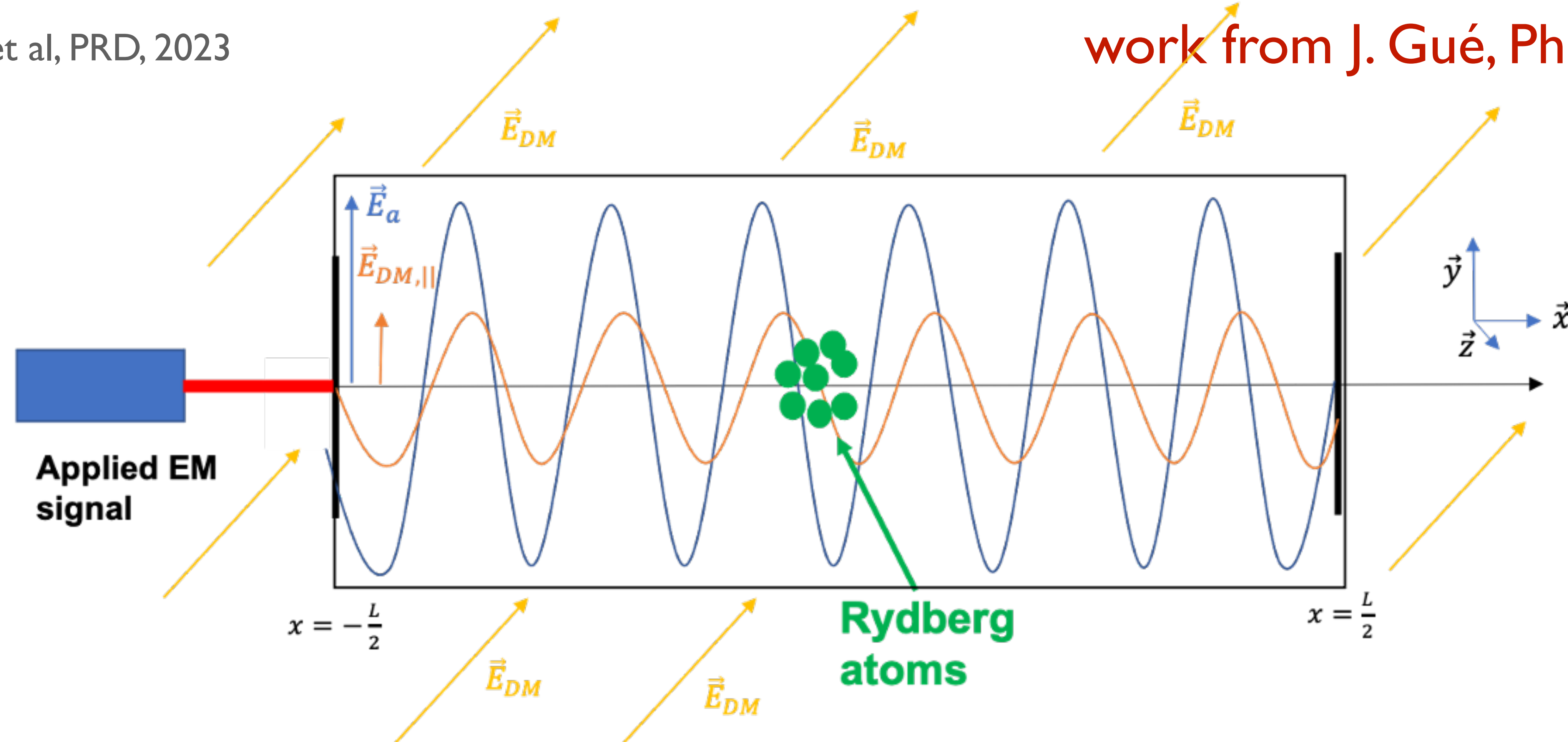
<u>Dish</u> see Horns et al, JCAP, 2013



Use cavity and Rydberg spectro to search for Dark Photon

See J. Gué, et al, PRD, 2023

work from J. Gué, PhD student



- 2 electric fields: (i) an injected field and (ii) the DM induced field
- Detection of E^2 through the Stark effect $\Delta\nu \propto E^2$ using Rydberg atoms

$$E^2 \in \chi \overrightarrow{E}_{in} \cdot \overrightarrow{X}_{\mathrm{DM}} \cos\left(\left(\omega_{\mathrm{DM}} - \omega_{in}\right) t\right) + \ldots$$

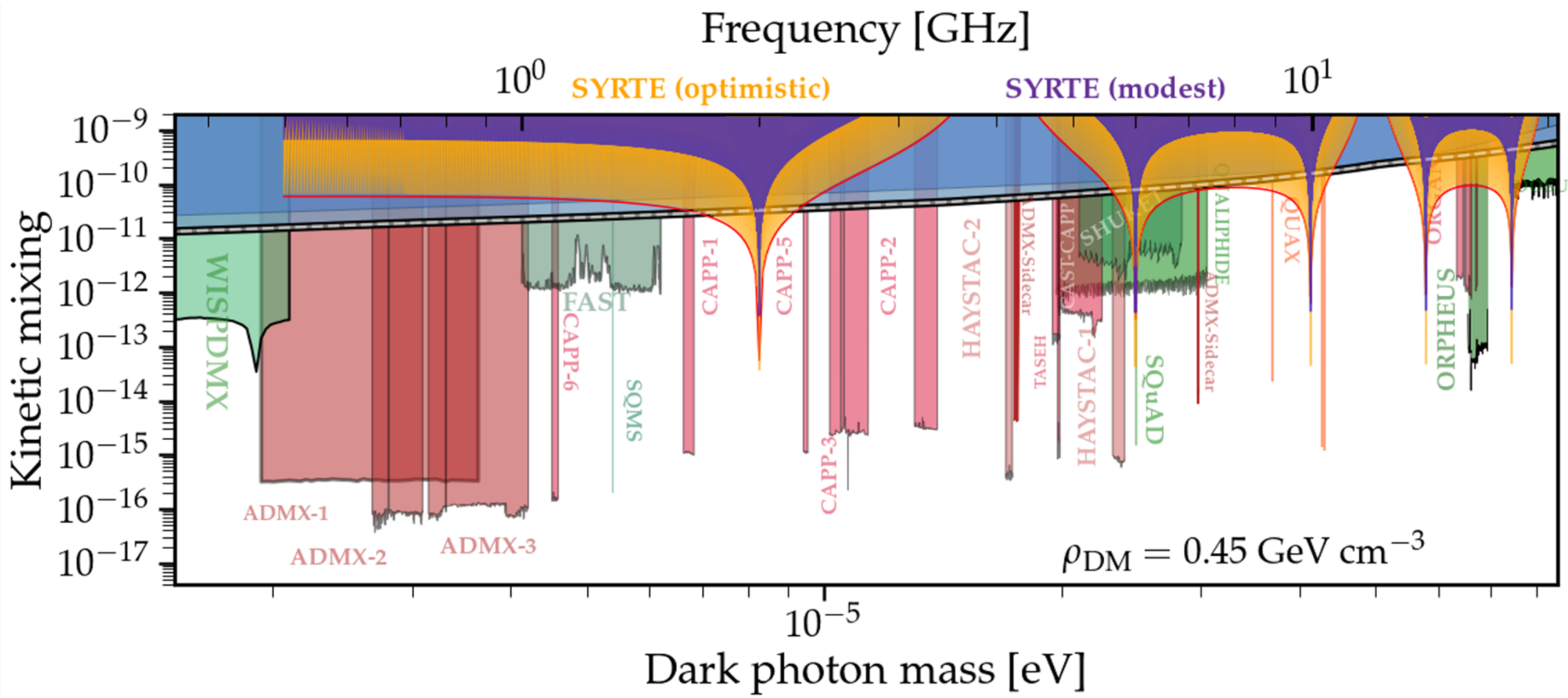
Enhance the signal amplitude

- Slowly evolving signal (detectable)
- Large range of DM mass explorable

Sensitivity analysis

work from J. Gué, PhD student

- Analysis includes: cavity losses (Q-factor), statistical noise (Rydberg), systematic noise (RIN of injected field), …



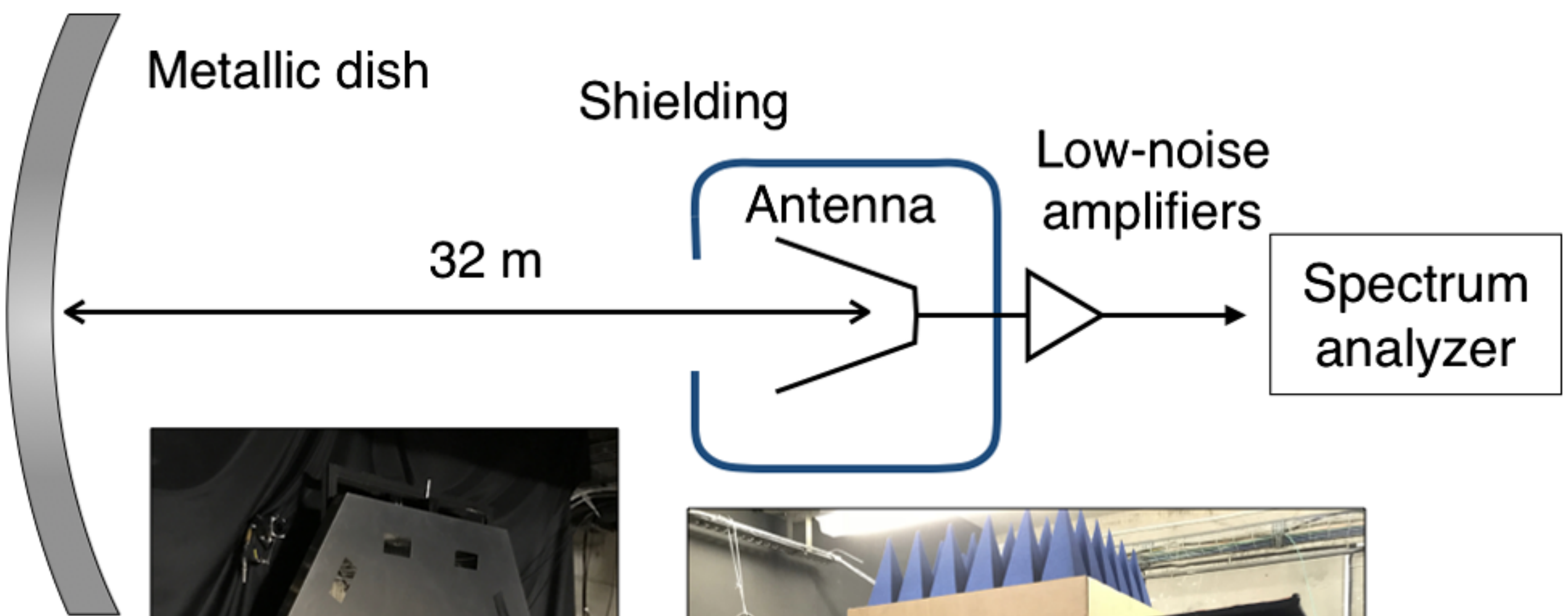
New proposal of experiment: cavity can be used to search for Dark Photons

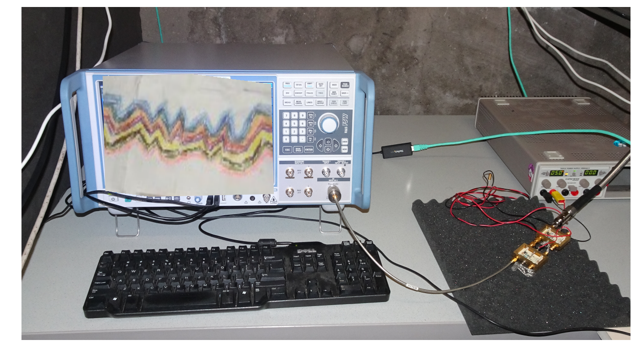
(acts as a narrow band resonant detector)

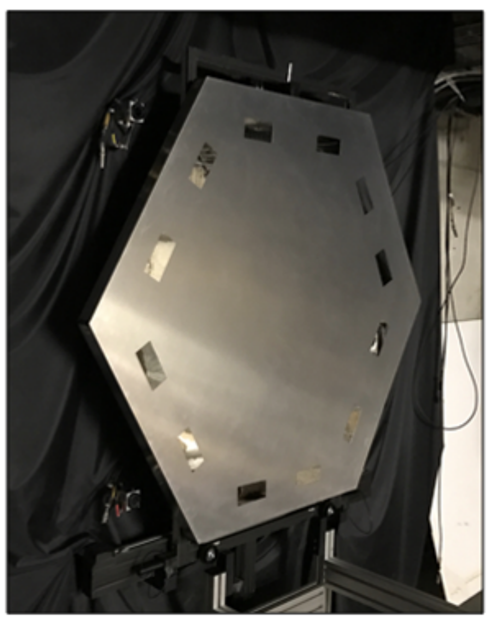
More details in J. Gué, PRD, 2023

The SHUKET experiment at CEA

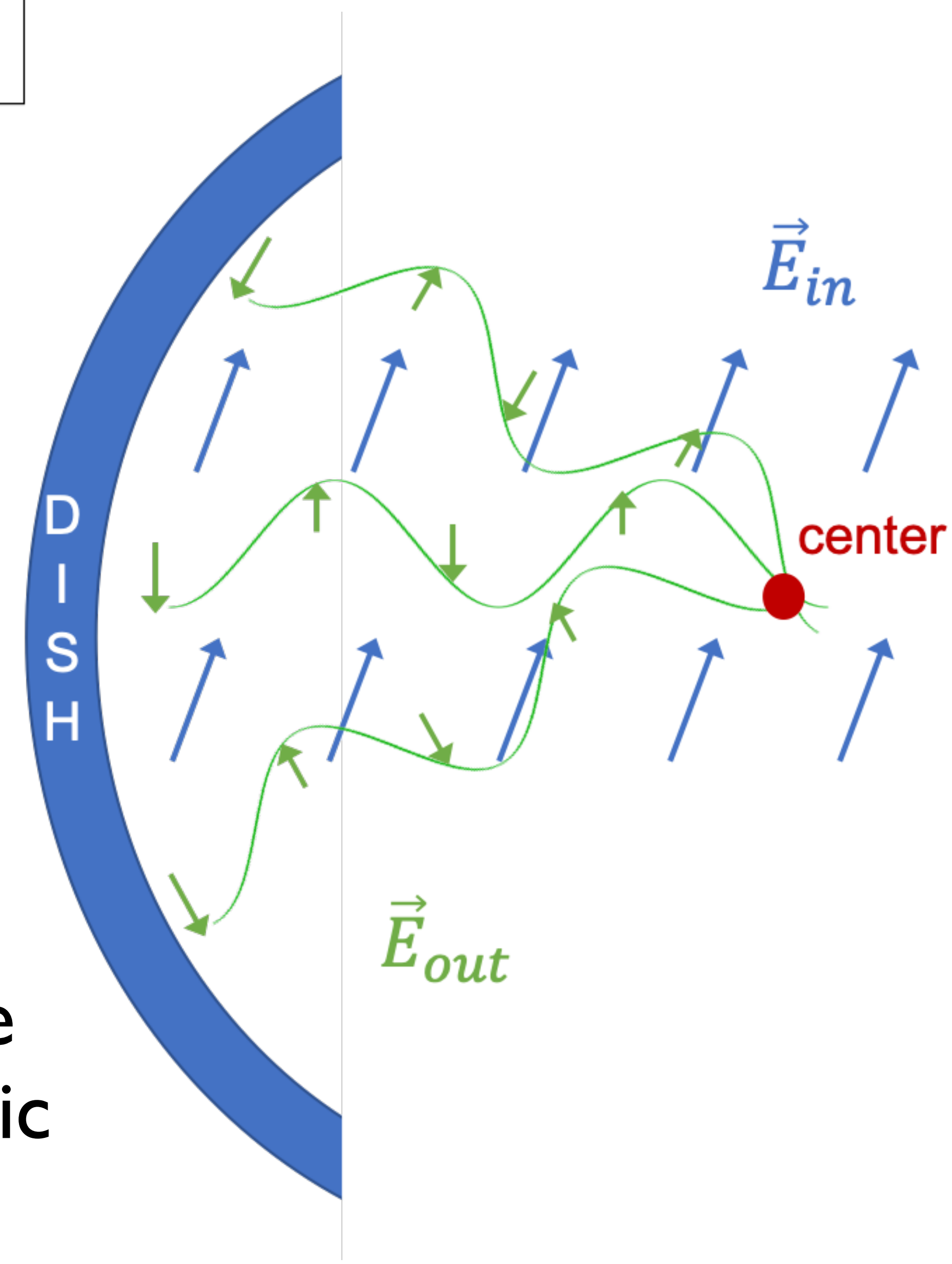
SearcH for U(1) darK matter with an Electromagnetic Telescope





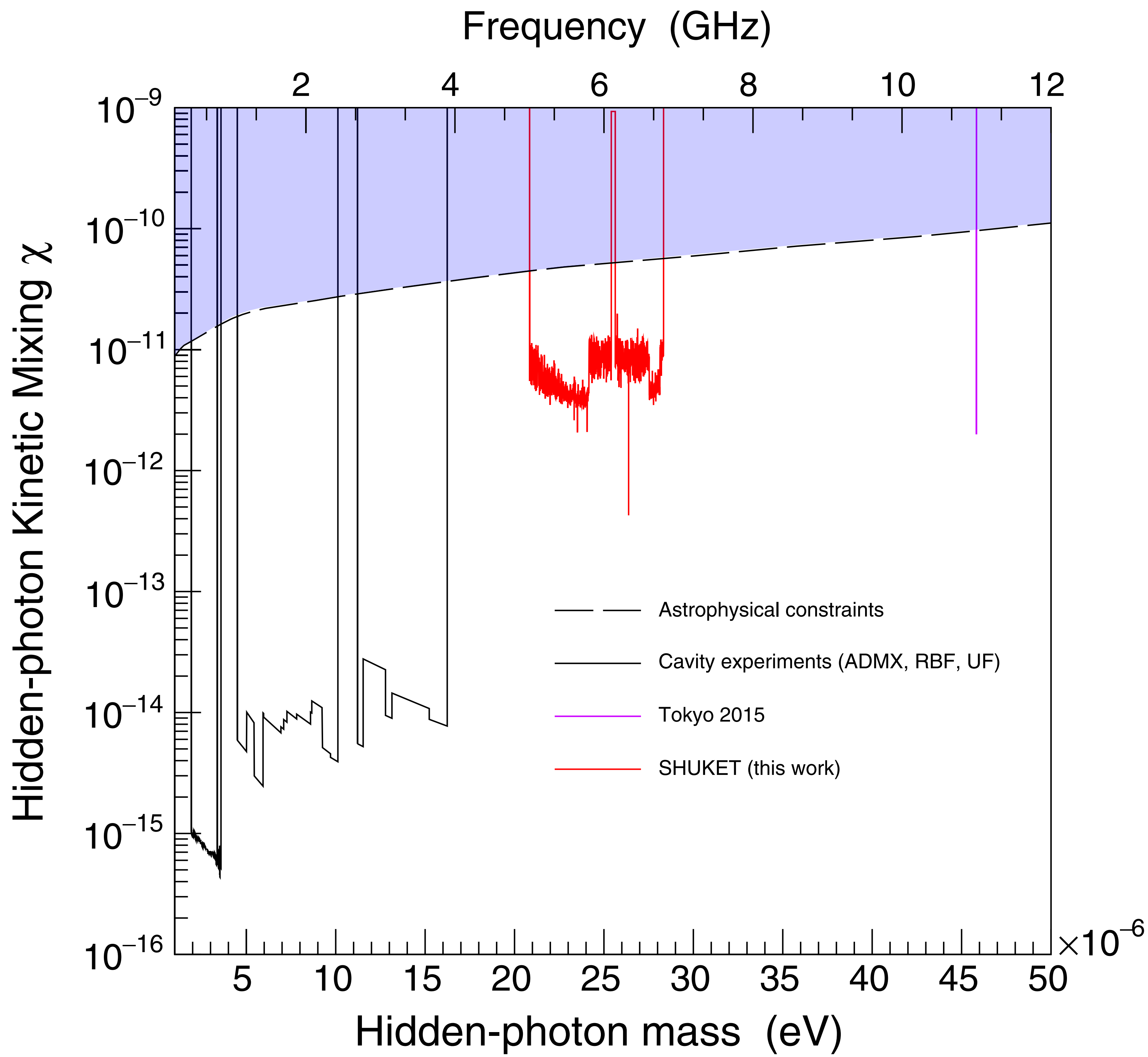


Pictures from P. Brun et al, PRL, 2019



- For a spherical dish, the electric field will be focused at the center + non-relevant electric field will be focused at the focal point

First result: SHUKET puts a stringent constraint on the kinetic mixing parameter



from P. Brun et al, PRL, 2019

Recent update from CEA-SYRTE collaboration

work from J. Gué, PhD student

- Improved data analysis considering signal stochasticity: improves slightly the constraints

  based on a methodology presented in E. Savalle et al, PRL, 2021

- Improved modelling of the experiment including
  - Diffraction of the EM field emitted by the dish
  - matching with the EM mode of the antenna

This improved realistic modelling leads to ~ 1 order of magnitude loss of sensitivity (unfortunately).

J. Gué, paper to be submitted soon

- Using this realistic modelling: optimization of the experiment: work in progress

- New runs in the 10-20 GHz frequency range performed at CEA

- Improvements:
  - new low-noise amplifiers
  - new spectrum analyses

Scalar Ultra Light Dark Matter: the dilaton

Remark: the QCD coupling of the axion implies that the pions mass depends quadratically on the axion.

see Kim and Perez, arXiv 2023

⇒ Part of the following discussion can be extended to the axion

A scalar DM is expected to break the equivalence principle

- An effective Lagrangian for the scalar-matter coupling

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

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

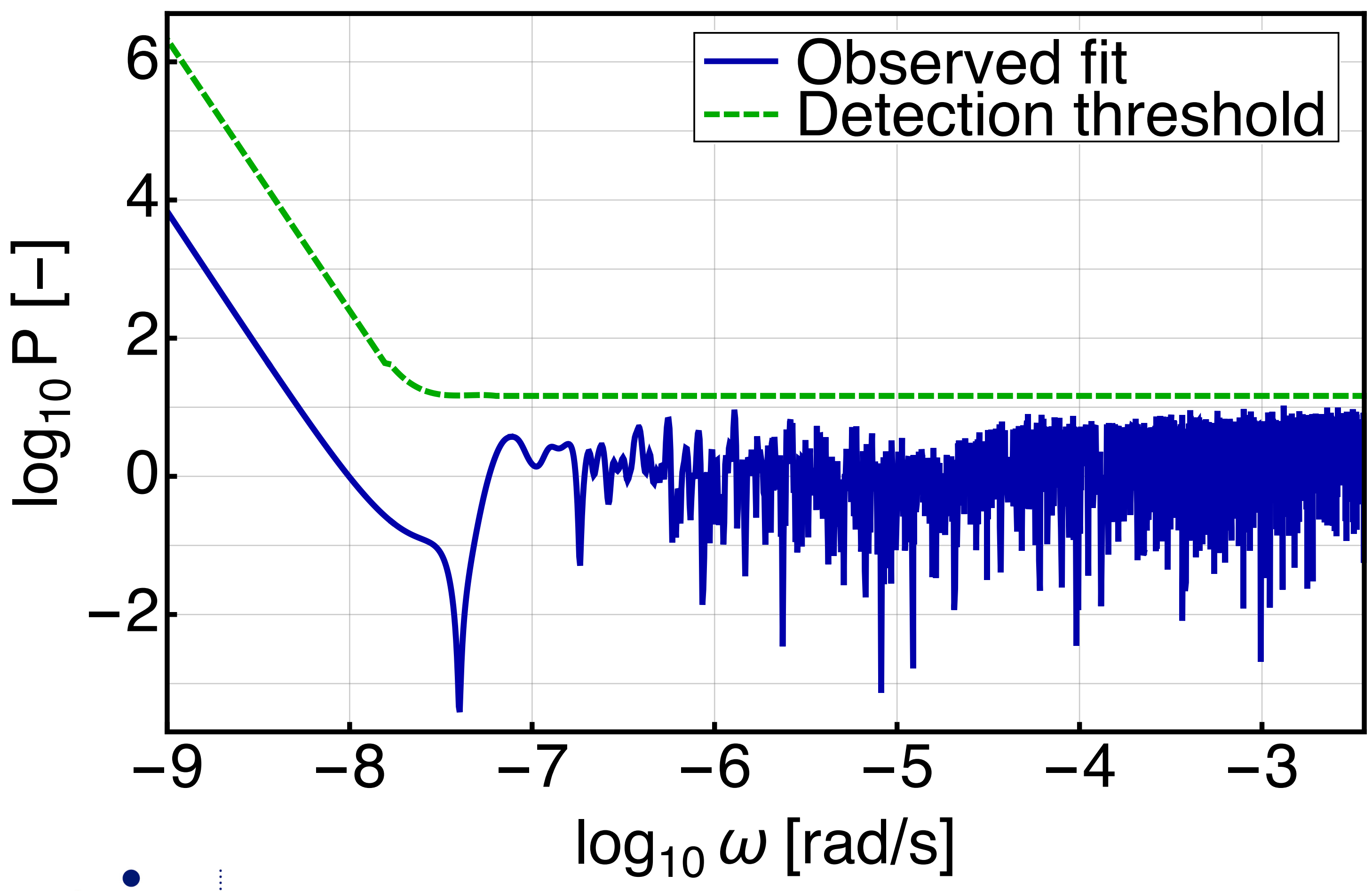
Two experiments developed at SYRTE

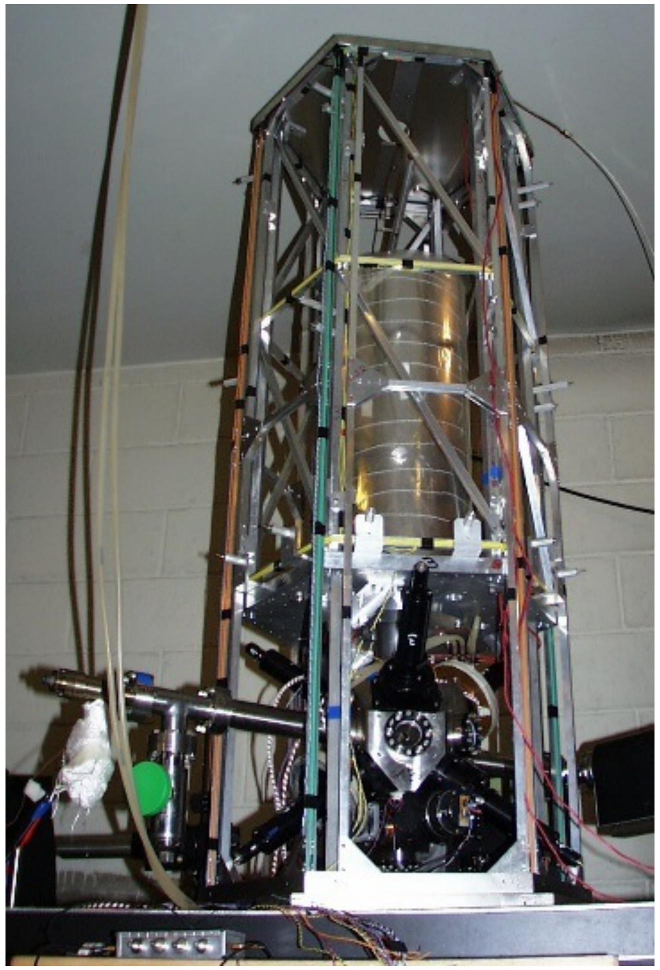
Search for a periodic signal in Cs/Rb comparison

- 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

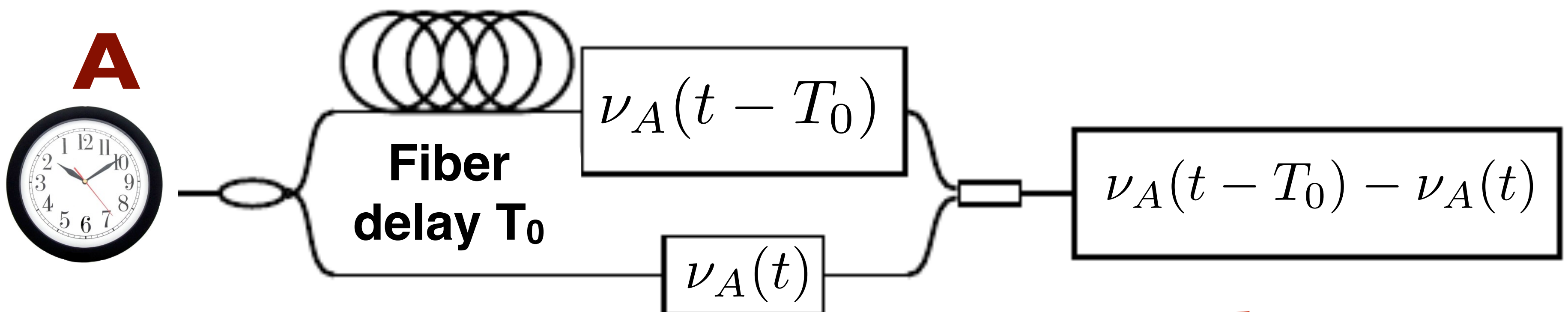
Systèmes de Référence Temps-Espace

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:



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

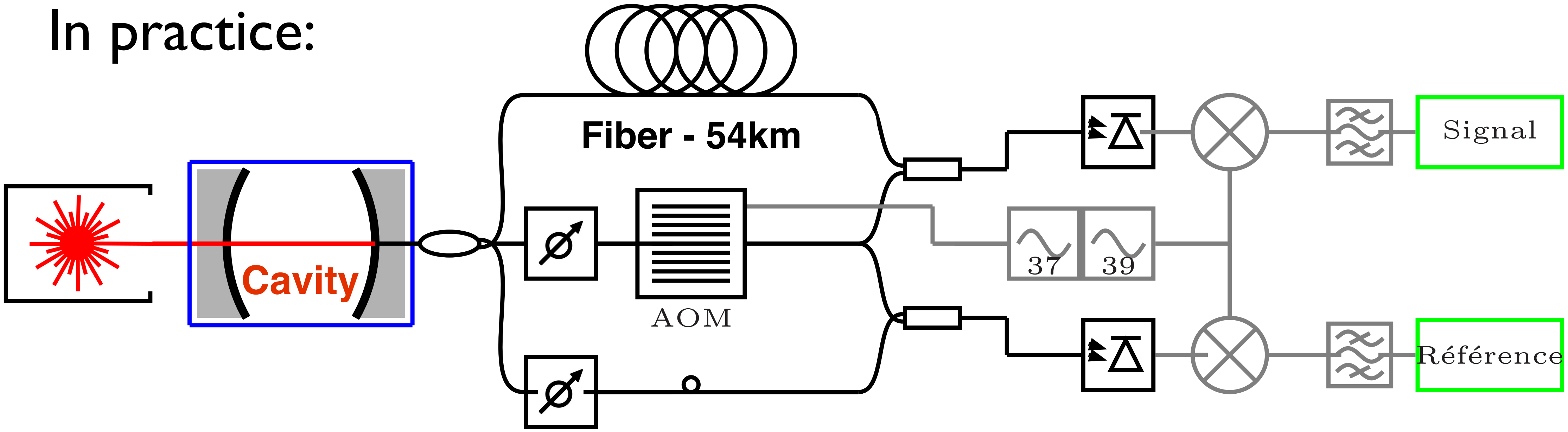
Oscillations of the scalar field

- 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

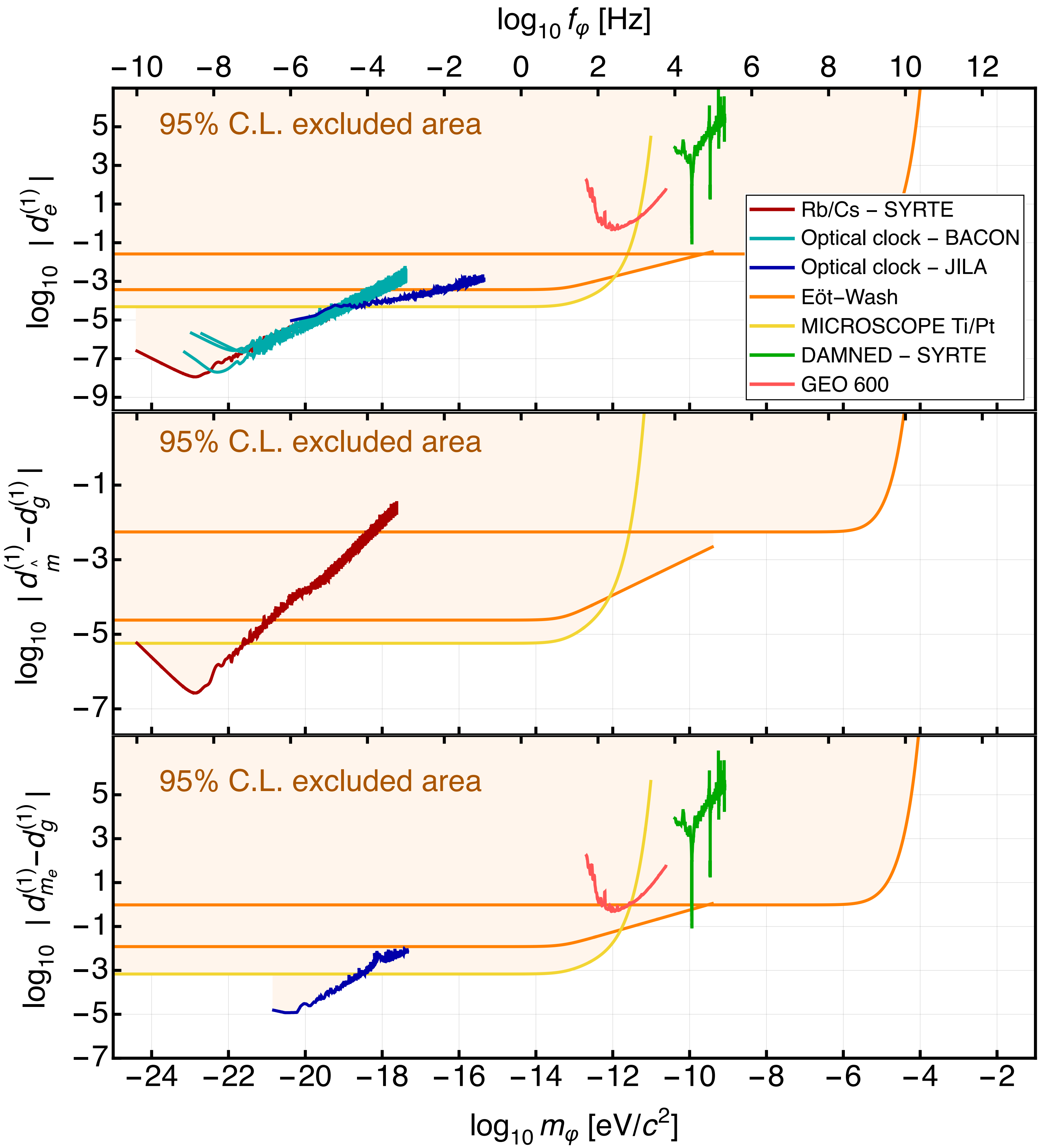
see Savalle et al, PRL, 2021

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



Quadratic couplings or relaxion model leads to different constraints

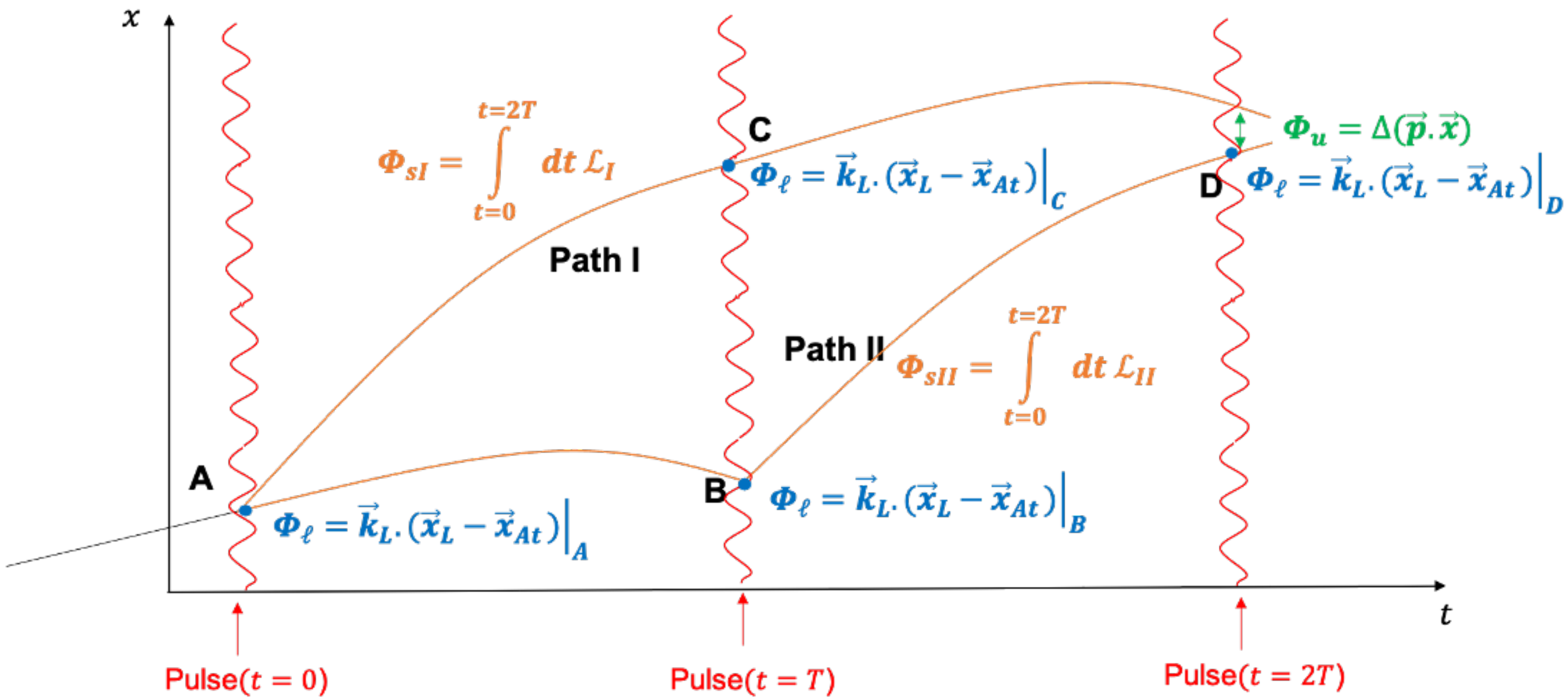
Results from:

- 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

Atom interferometers are sensitive to such DM candidates as well

work from J. Gué, PhD student

- 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 + kick velocity)
  - Laser reference and frequency

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

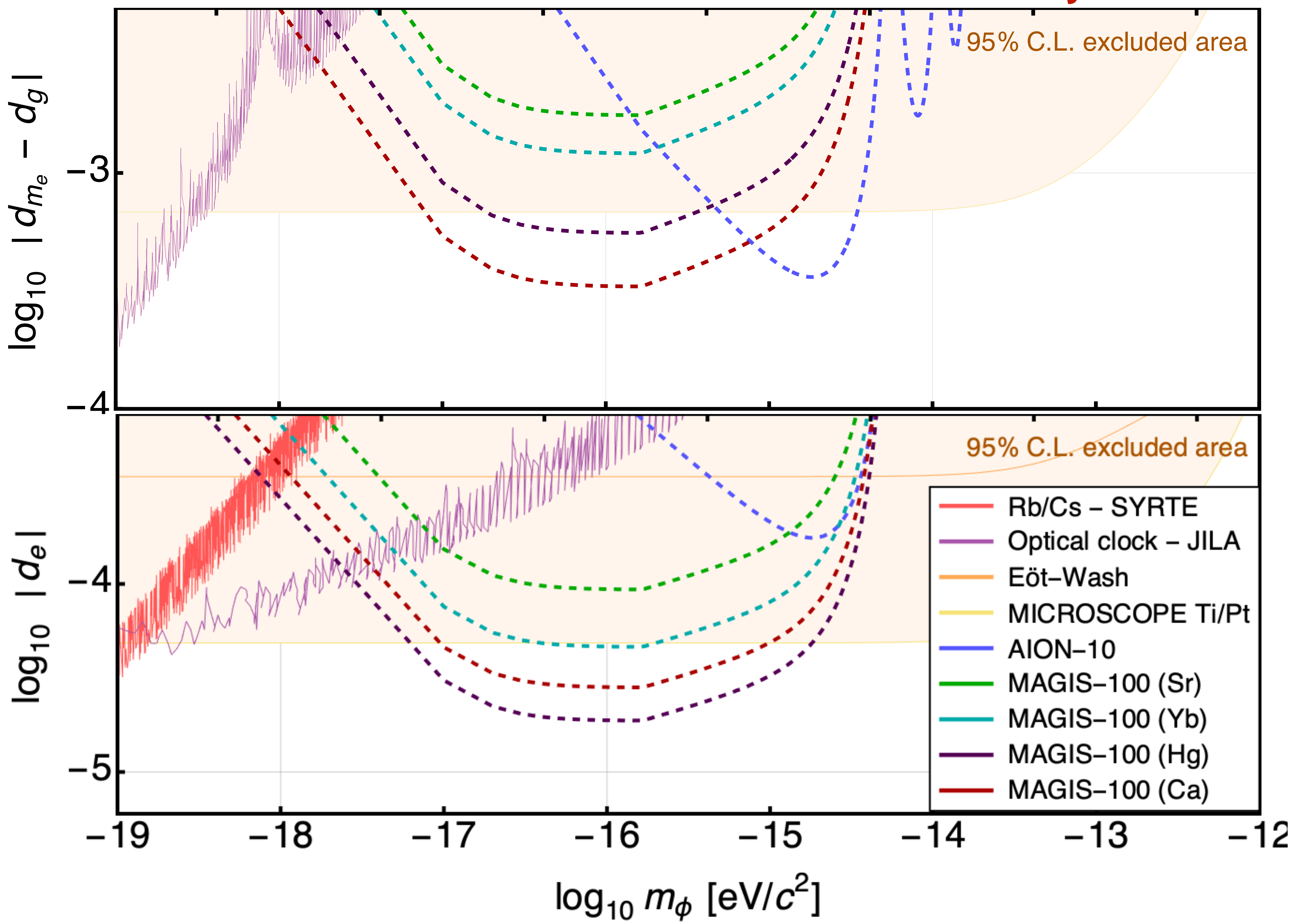
  see e.g. Badurina et al, PRD, 2022

- 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

Results: search for dilaton

work from J. Gué, PhD student



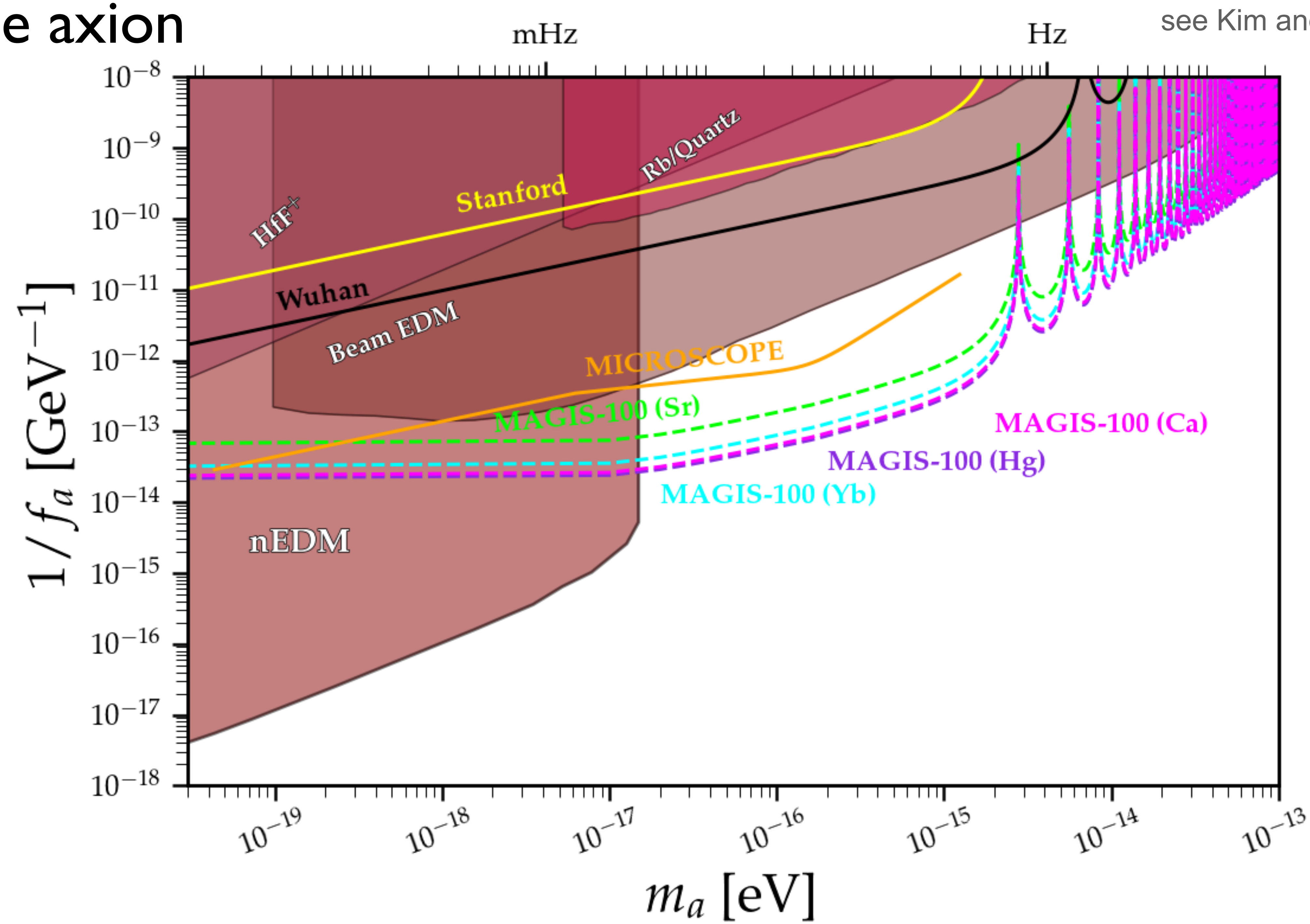
Low sensitivity from Stanford and Wuhan, good sensitivity of AION10 and even better with MAGIS-like scenario

Results: search for axion

work from J. Gué, PhD student

- The mass of the pion oscillate due to the QCD coupling of the axion

see Kim and Perez, arXiv 2023



Low sensitivity from Stanford and Wuhan, good sensitivity of AION10 and even better with MAGIS-like scenario

Conclusion

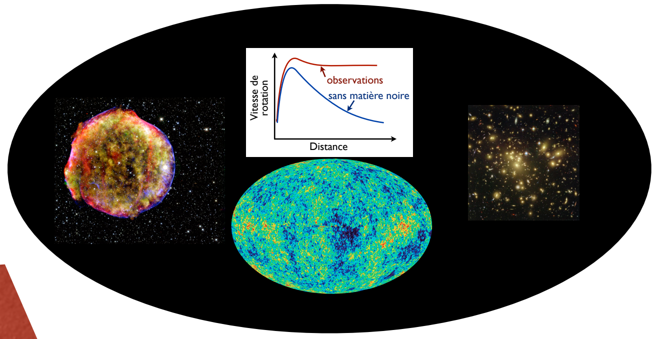
- Searches for Dark Matter of mass < 1 eV (bosonic) is very active
- Several models exist: scalar field, axion, dark photon, … with different phenomenology: oscillations (possible screening), topological default, …
- We (SYRTE + collaborations) are involved in:
  - theoretical exploration, predictions of such models
  - proposition of new experiments
  - accurate modelling, optimization of existing experiments
  - perform some experiments
  - dedicated data analysis (sometimes tricky: stochasticity of signal)
- Very recent results: - new proposal for an experiment to search for DP

  - modelling/optimisation of SHUKET (DP)

  - impact of dilatons/axions on UFF measurements and AI

  - GASTON: search for transient DM candidate with Galileo

Are there other signatures to be searched in lab data that can help constraining DE models?



Astronomy & cosmology

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

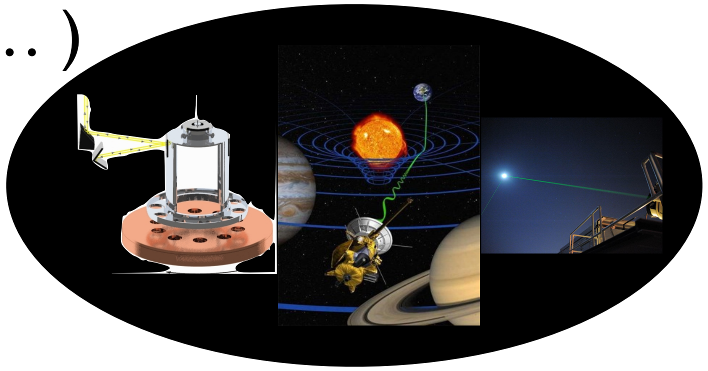
Quantum Gravity

Unification

DM and DE

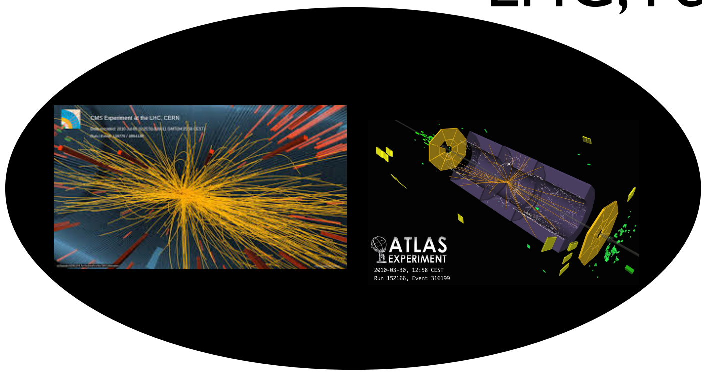
Local physics

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



High energy

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



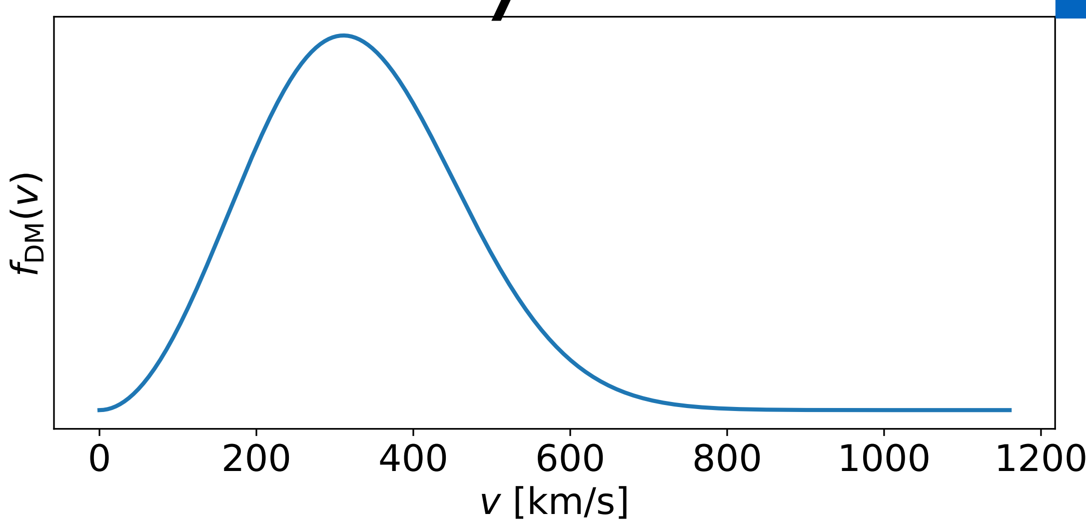
Picture inspired by Altschul et al, Adv, in Space Res. 55, 501, 2015

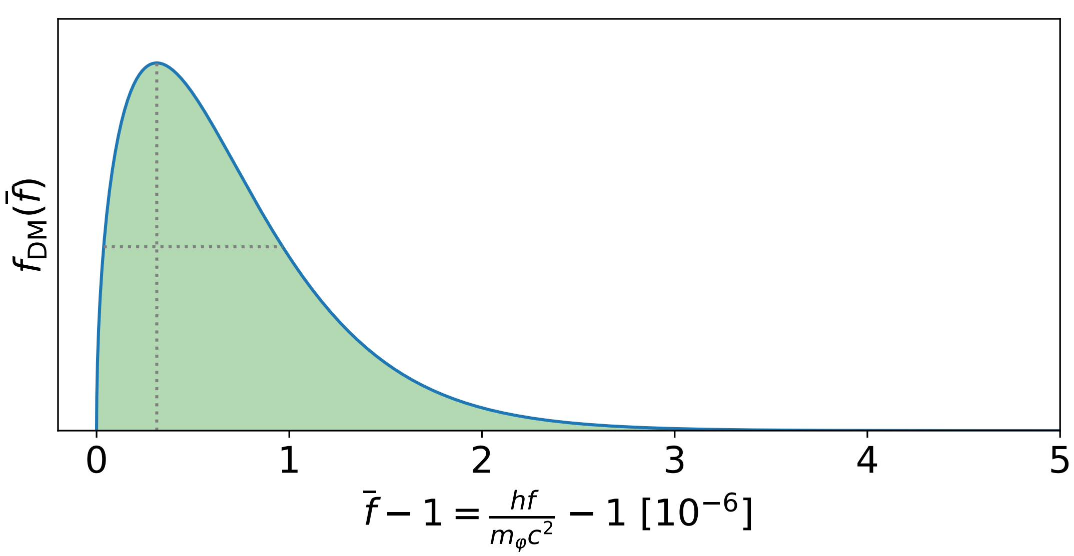
The field has a frequency distribution due to the DM velocity distribution

- The oscillation frequency depends on the velocity

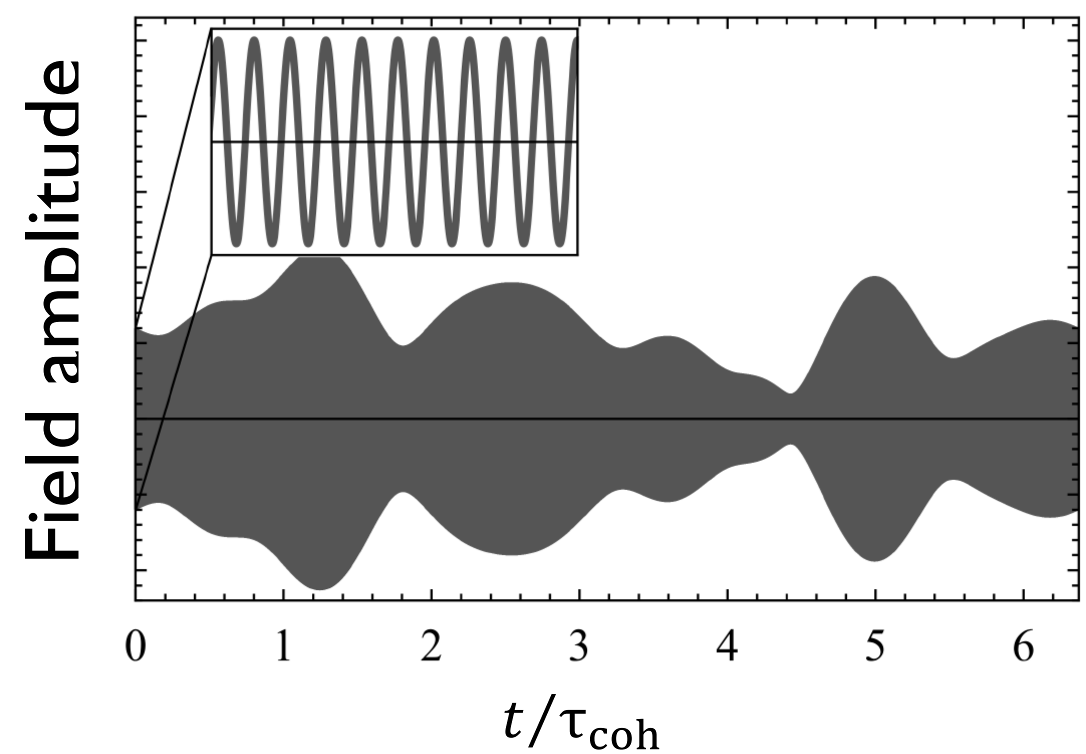
$$\omega = 2\pi f = \frac{mc^2}{\hbar}\left(1 + \frac{v^2}{2c^2}\right)$$

- 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

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

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

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

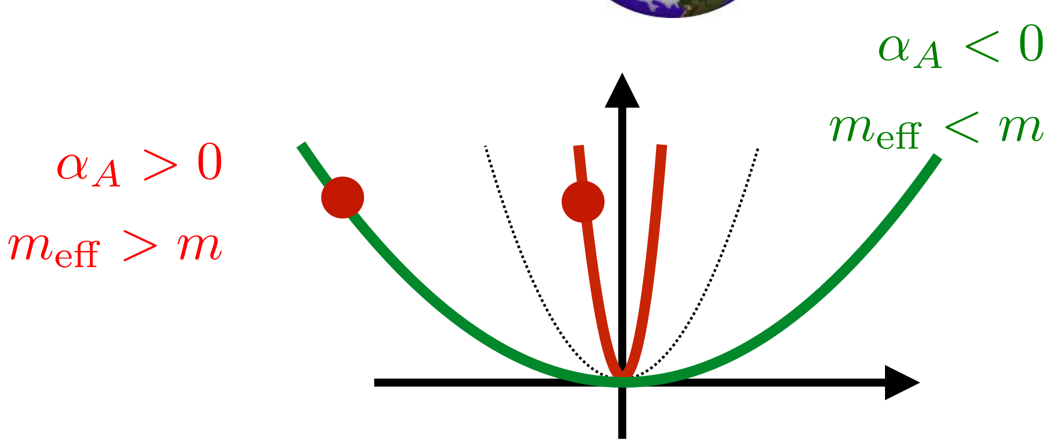
see A. Hees et al, PRD, 2018

Scalar field for a quadratic coupling

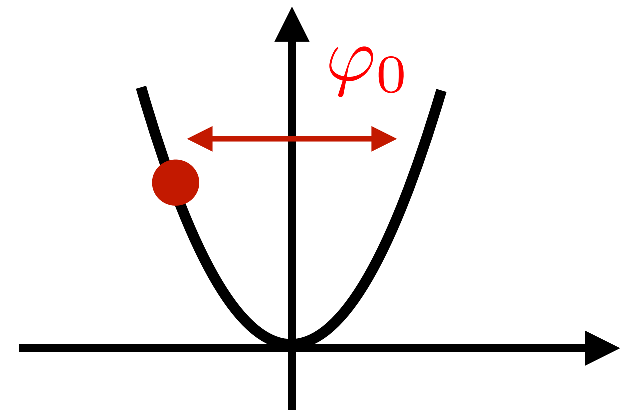
$$\Box\varphi + \left(m^2 + \frac{4\pi G}{c^2}\alpha_A\rho_A\right)\varphi = 0$$

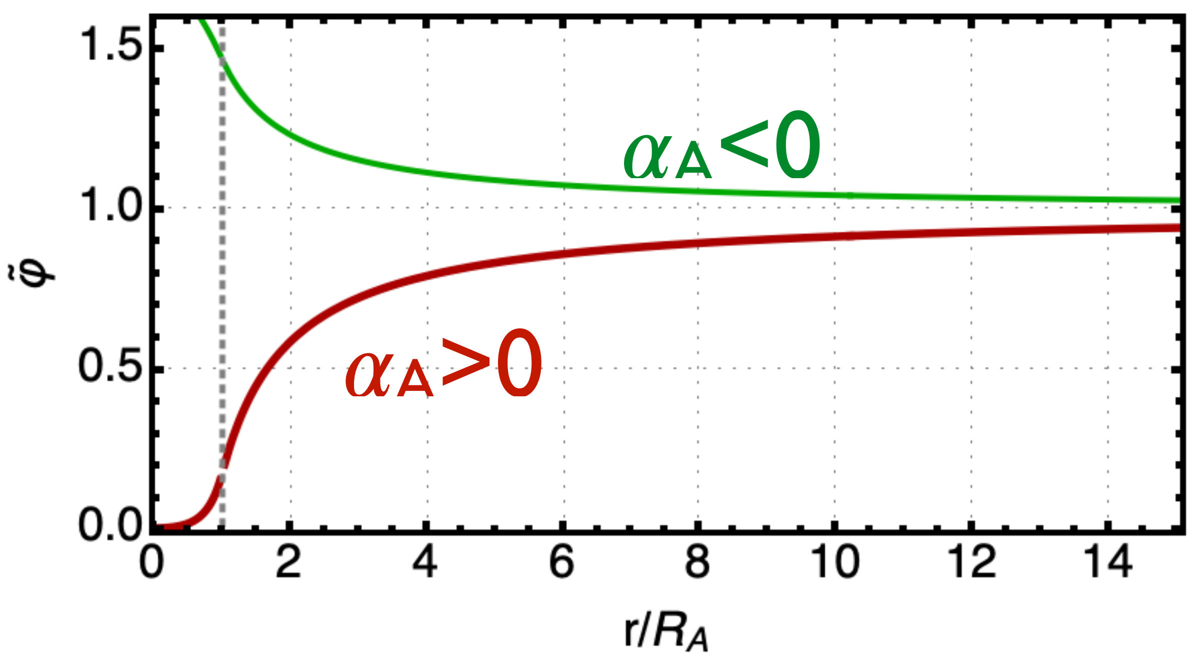
No source term (no fifth force) but effective mass that depends on the local matter density

V(φ) in 



V(φ) in a vacuum





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

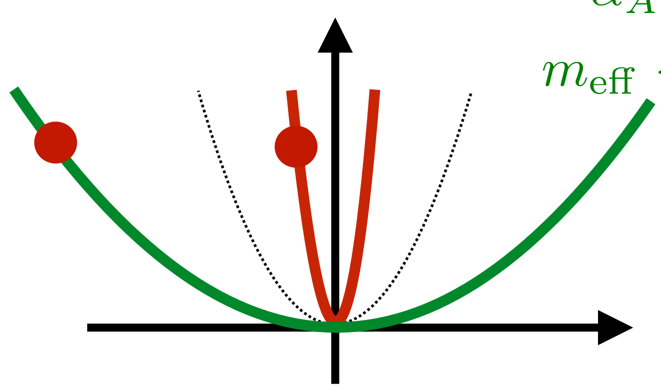
see A. Hees et al, PRD, 2018

Scalar field for a quadratic coupling

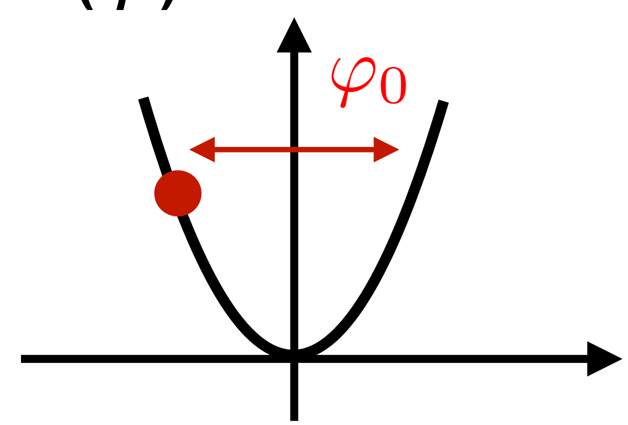
$$\Box\varphi + \left(m^2 + \frac{4\pi G}{c^2}\alpha_A \rho_A\right)\varphi = 0$$

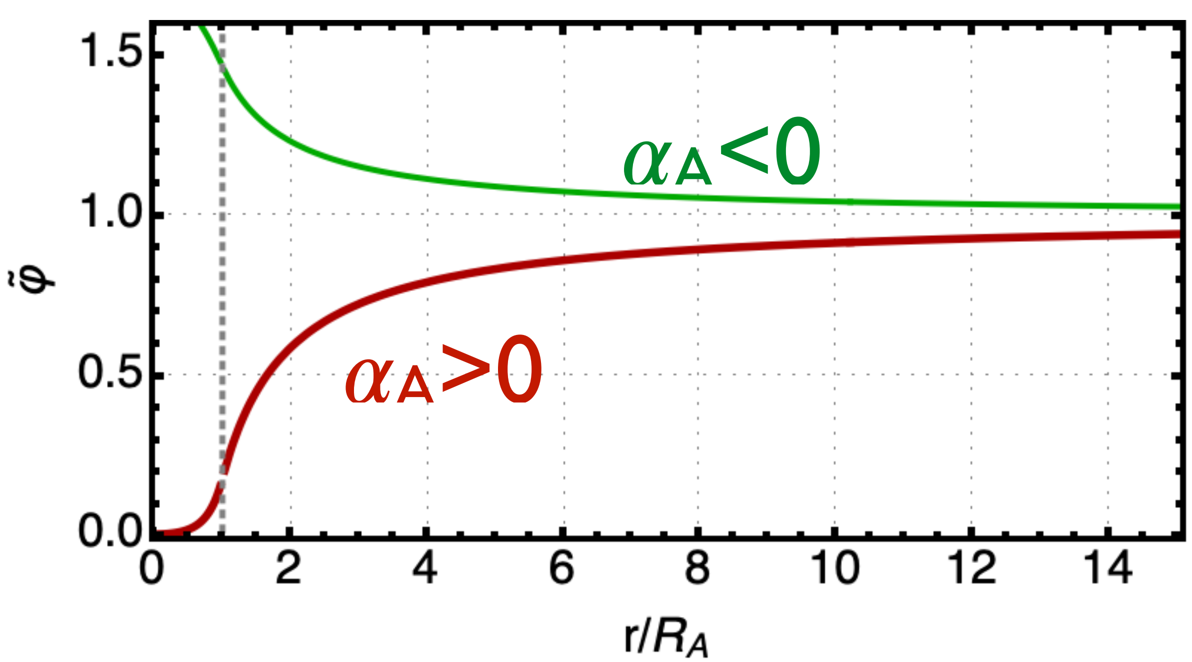
No source term (no fifth force) but effective mass that depends on the local matter density

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)

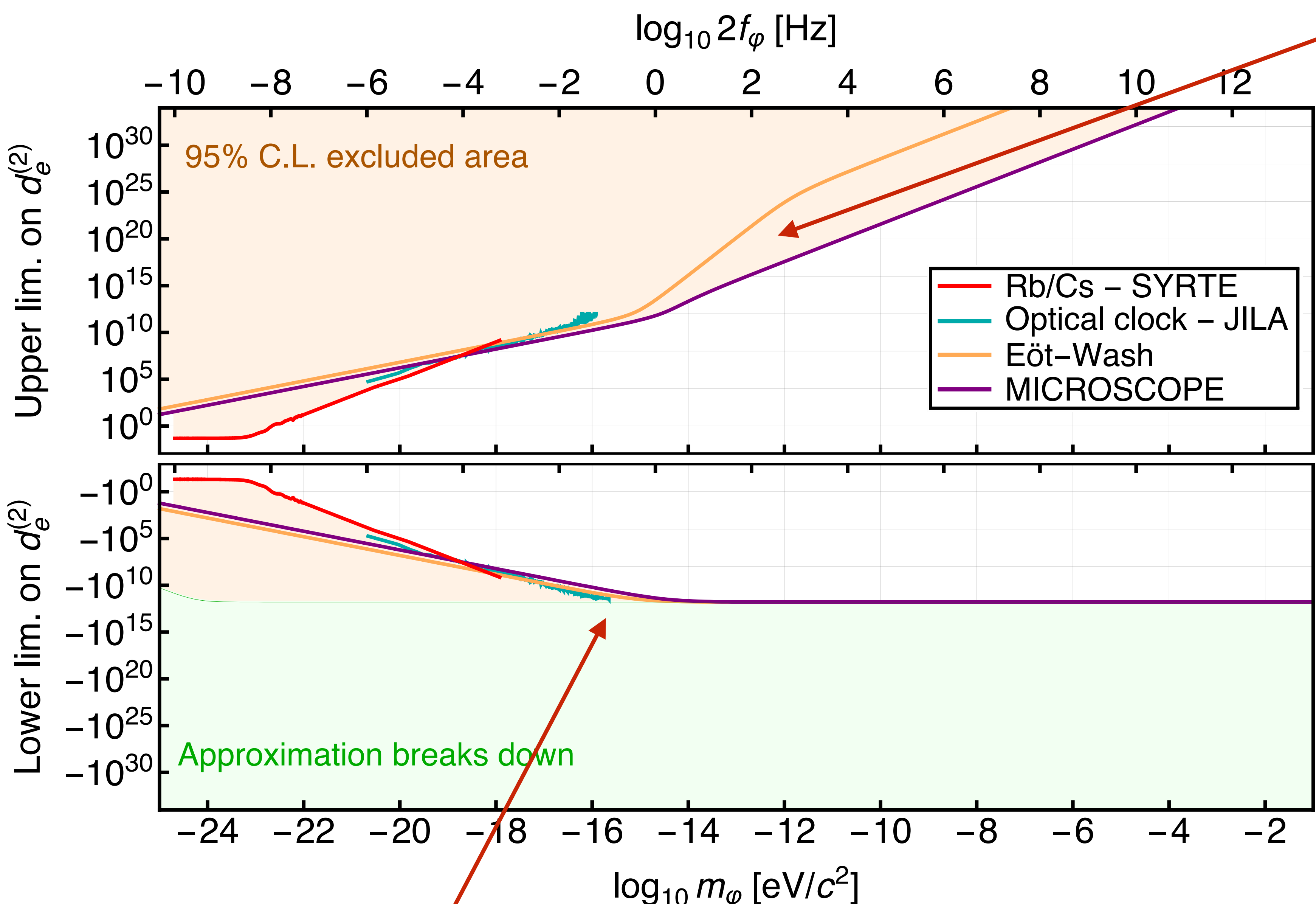
2 terms that oscillate, amplitude depends on position

They are all sensitive to screening/scalarization

See A. Hees et al, PRD, 2018

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

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

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

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

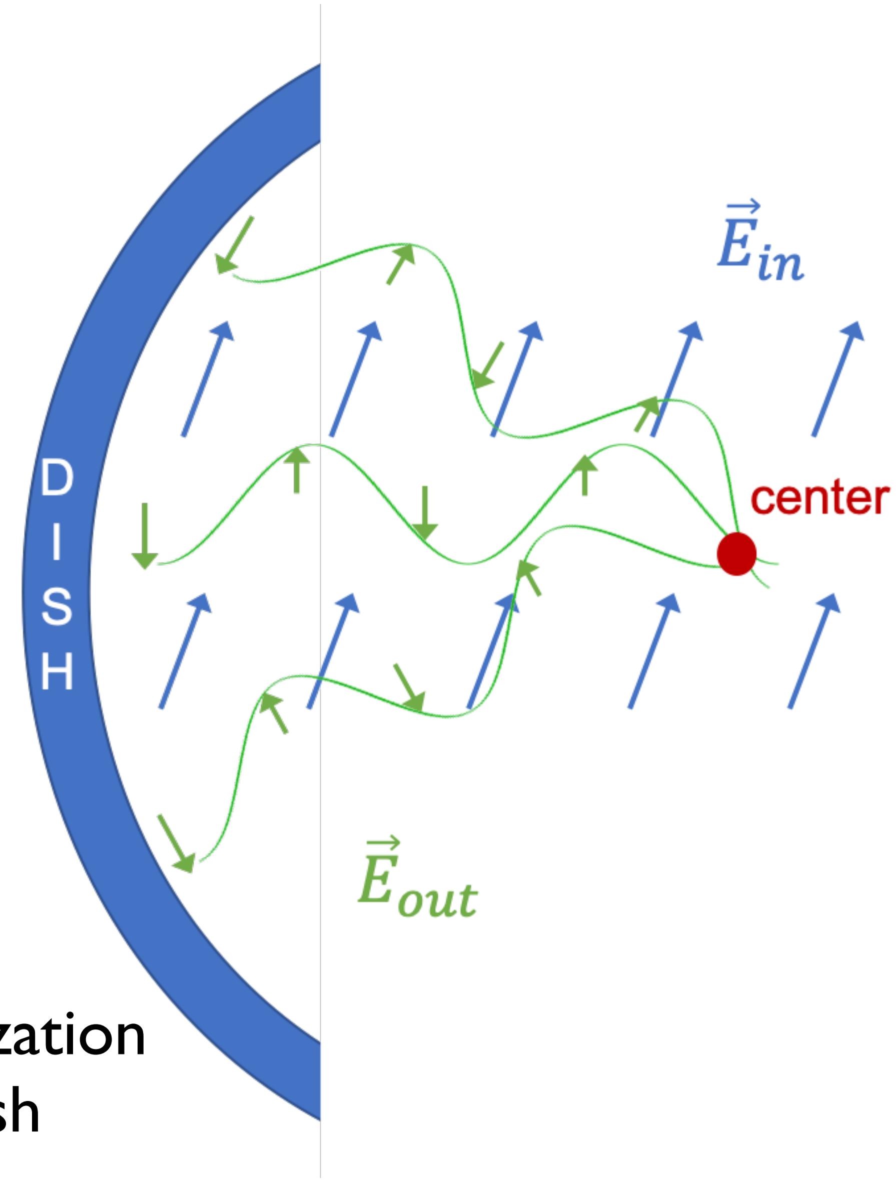
- As a reminder: the amplitude of oscillation is related to the DM energy density

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

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



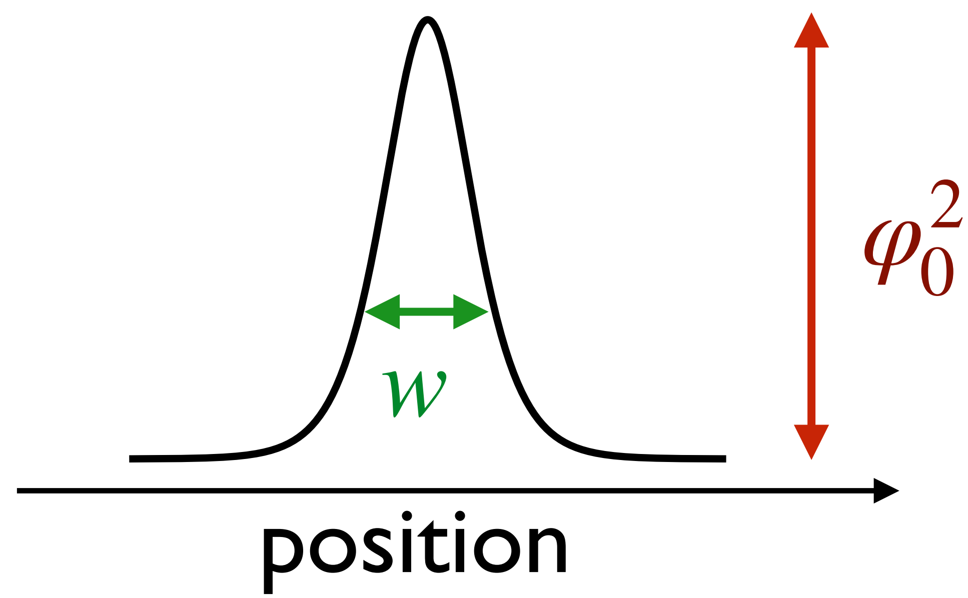
$$\chi_{\text{sens}} = 4.5 \times 10^{-14} \left(\frac{P_{\text{det}}}{10^{-23}\,\text{W}}\right)^{\frac{1}{2}} \left(\frac{0.3\,\text{GeV/cm}^3}{\rho_{\text{CDM,halo}}}\right)^{\frac{1}{2}} \left(\frac{1\,\text{m}^2}{A_{\text{dish}}}\right)^{\frac{1}{2}} \left(\frac{\sqrt{2/3}}{\alpha}\right)$$

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

see Horns et al, JCAP, 2013 and references therein

A scalar field with a quartic potential can form topological defects

- Spatial evolution of φ^2:



- Width related to the mass of the scalar field $w \sim 1/m$

- Amplitude related to DM energy density $\varphi_0^2 \sim \rho_{\rm DM}$

- Cross the Earth with a velocity (DM velocity distribution)