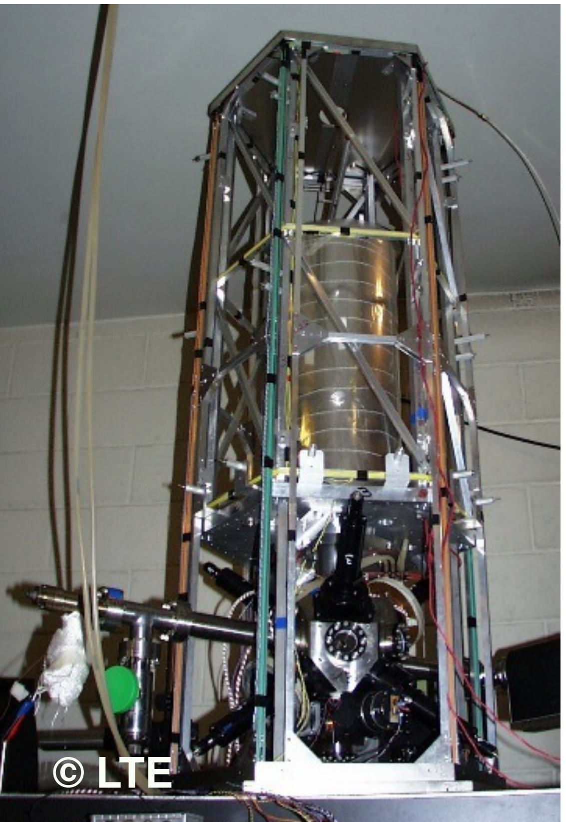
LTE Observatoire de Paris | PSL

Searching for UltraLight Dark Matter: from the lab to our Galactic Center

J. Gué, E. Savalle, A. Hees, P. Wolf and many other collaborators

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



Workshop: ULDM and observable phenomena
IFPU, Trieste, Oct. 1st 2025

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, …)

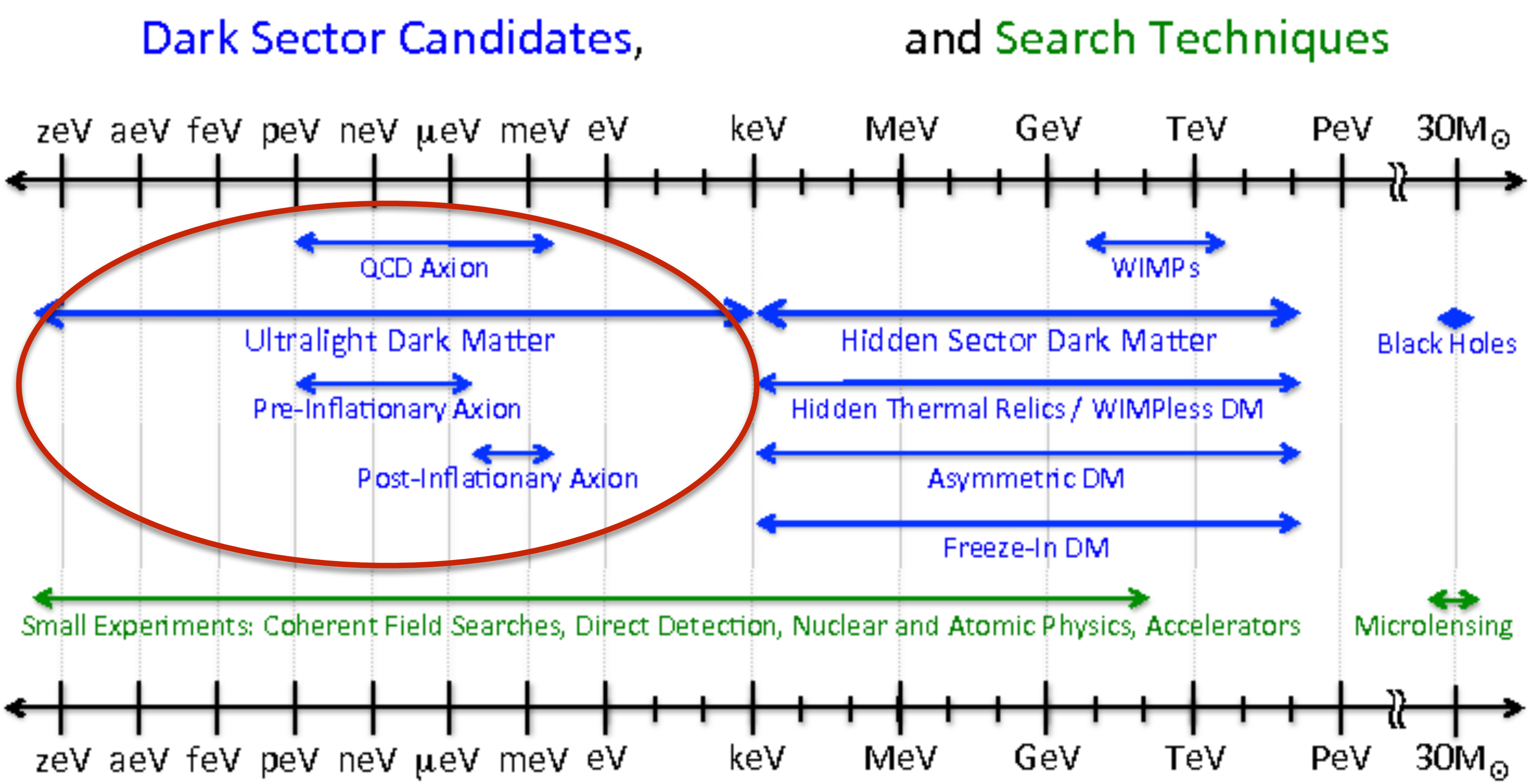


Fig. from *US cosmic vision: new idea for Dark Matter*, 2017

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:

$$\rho \sim \langle T_0^0 \rangle = \frac{m^2 \varphi_0^2}{2}$$

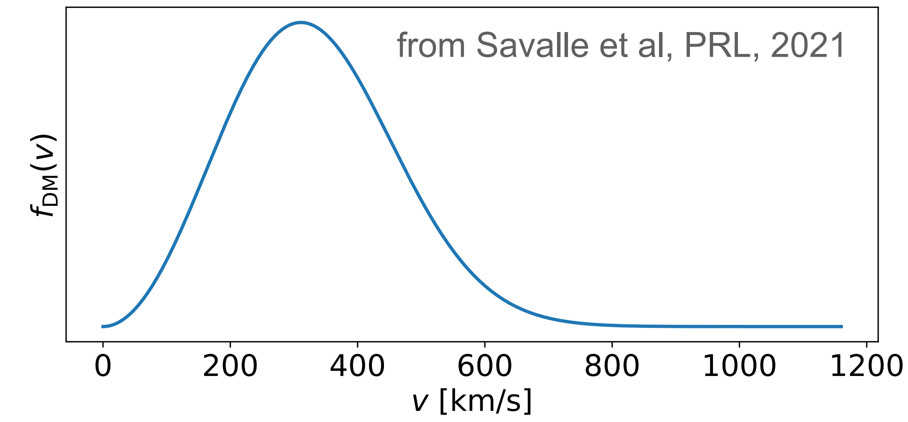
$$p_{ij} \sim \langle T_j^i \rangle = 0$$

- Amplitude of oscillation $$\varphi_0 \propto \sqrt{\rho}/m$$

see the talk from T. Ferreira Chase

Locally, the ULDM field is stochastic

$$\varphi = \varphi_0 \cos\left(\omega t - \vec{k}\cdot\vec{x}\right)$$

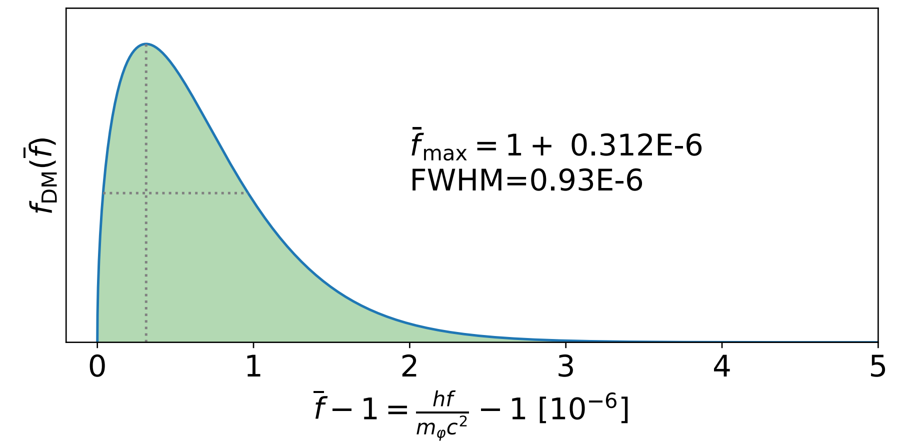


- Within our Galaxy, DM has a velocity distribution
- The dispersion relation

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

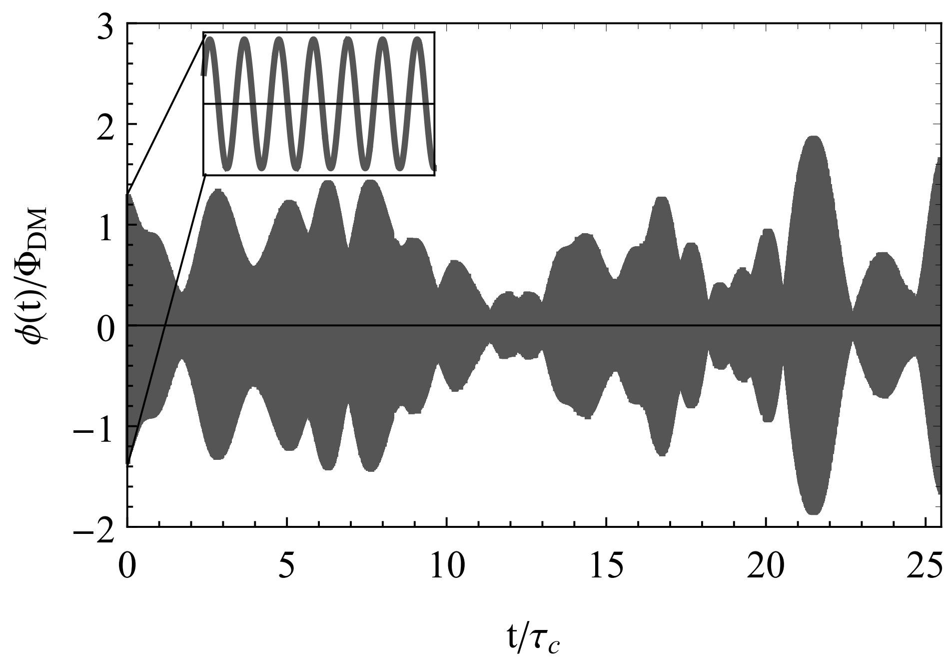
$\Rightarrow$ Non trivial frequency distribution!

see A. Derevianko, PRA, 2018



- Coherence time ~ 10^6 oscillations

- Some consequences for « local » ULDM searches
  - for « short » dataset, the field amplitude is Rayleigh distributed
  - « complex » data analysis for long dataset
  - spectral shape used to distinguish ULDM signal from systematics
  - search for slow stochastic evolution => probe large ULD masses



from Centers et al, Nat. Com, 2021

see G. Centers et al, Nat. Comm., 2021
J. Foster, et al, PRD, 2018
V. Flambaum and Samsonov, PRD, 2023

DM can be searched through:

- its gravitational interaction with standard matter

- its direct interaction with standard matter

- if we want to understand the microscopic nature of DM, a direct detection would be more satisfactory (my opinion)

- if a new field exists, there is no reason (except if forbidden because of a symmetry) why it would not couple to all other known fields

Consider couplings between ULDM and Standard Model (SM)

Some ULDM couplings to Standard Model

A scalar DM is expected to break the equivalence principle

- An effective Lagrangian for the scalar-matter coupling (i=1,2)

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

see Damour and Donoghue, PRD, 2010

- Couplings usually considered:
  - linear in φ: lowest order expansion
  - quadratic in φ: lowest order if there is a Z_2 symmetry

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

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

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

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

see A. Ejlli's talk

- 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, et 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

Phenomenology from quad. coupled scalar field applies to axions

Some scalar field solutions in the presence of standard matter

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)

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

Interpreted as DM

Oscillations of fundamental constants

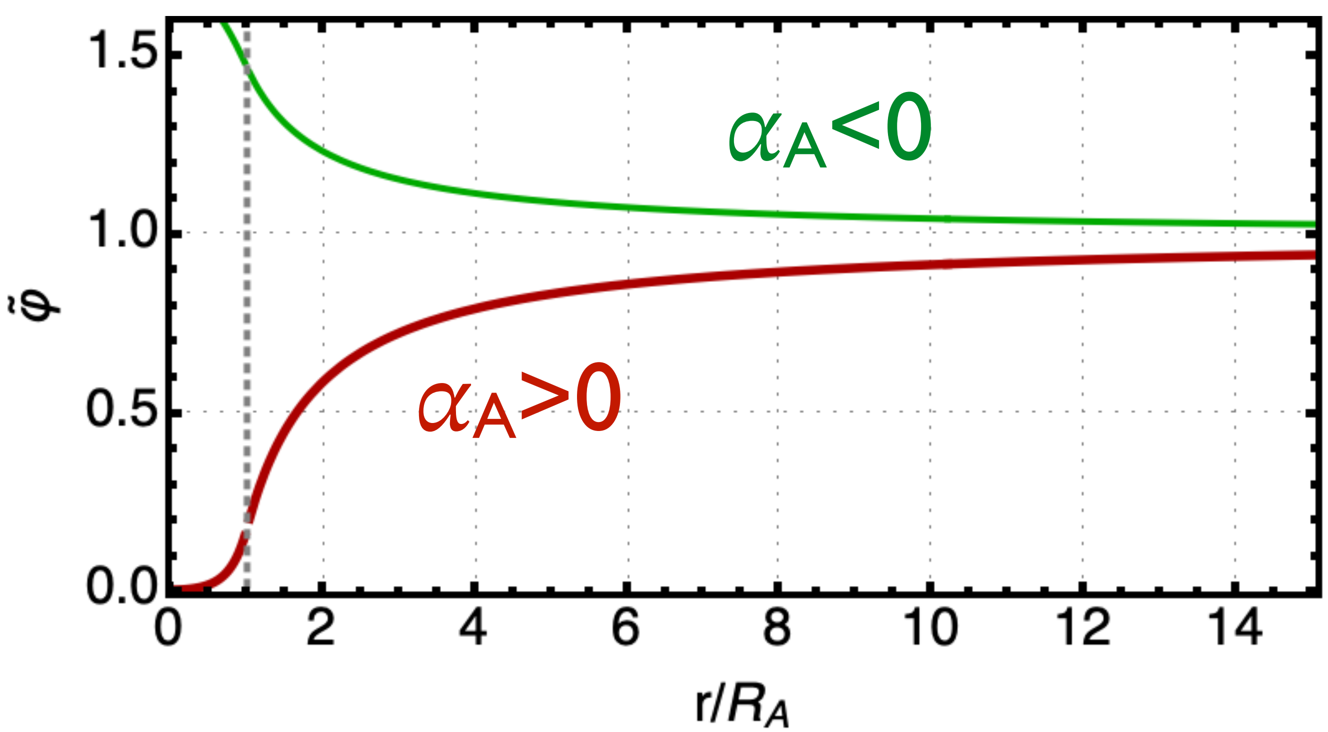
Independent of the DM interpretation

Modification of 2 body interactions (fifth force)

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



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

Rich phenomenology

Screening for positive couplings and scalarization for negative couplings!

see C. Burrage's talk

see A. Hees et al, PRD, 2018
generalised recently in A. Barnerjee et al, arXiv:2502.04455, Y. Garcia del Castillo, et al arXiv:2502.04456

Some experiments:
A. Oscillations of fundamental constants

Induce oscillations of:

- atomic rest masses
- atomic transition frequencies
- size of solid bodies (due to oscillation of Bohr radius)
- refractive index
- …

A. Some experiments searching for oscillations of fundamental constants

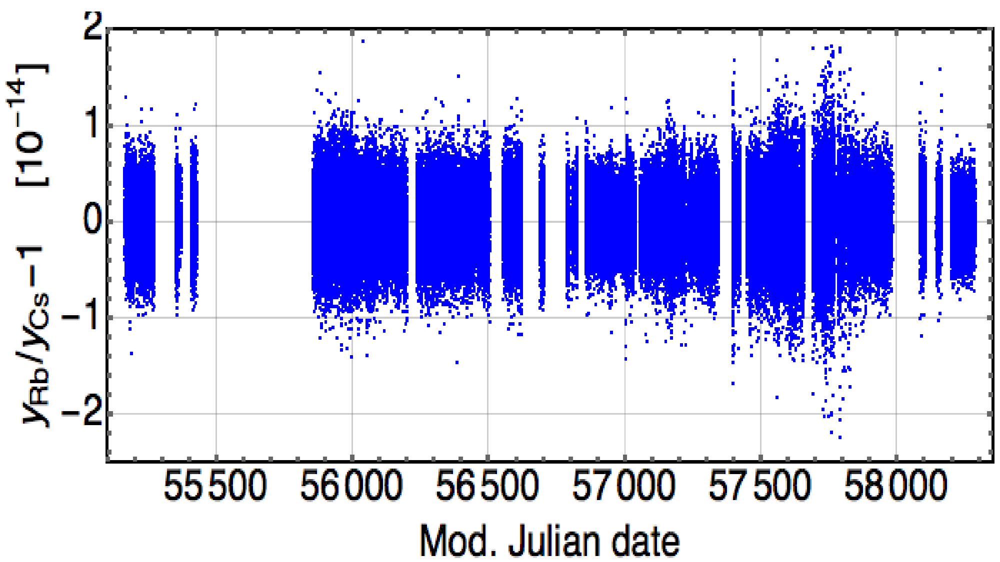
1. Comparison of colocated atomic clocks
   Experiments run in every metrology institute: LTE (Fr), PTB (Ge), NIST (USA), NPL (UK), …

Search for a periodic signal in clocks comparison

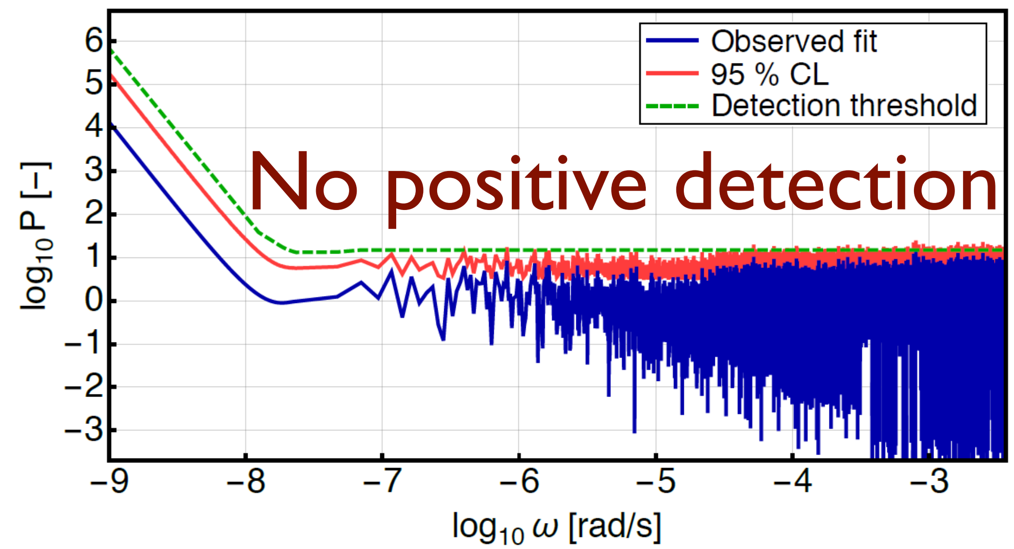
- Cs/Rb FO2 atomic fountain data from LTE, Paris Observatory: high accuracy and high stability, data used from 2008

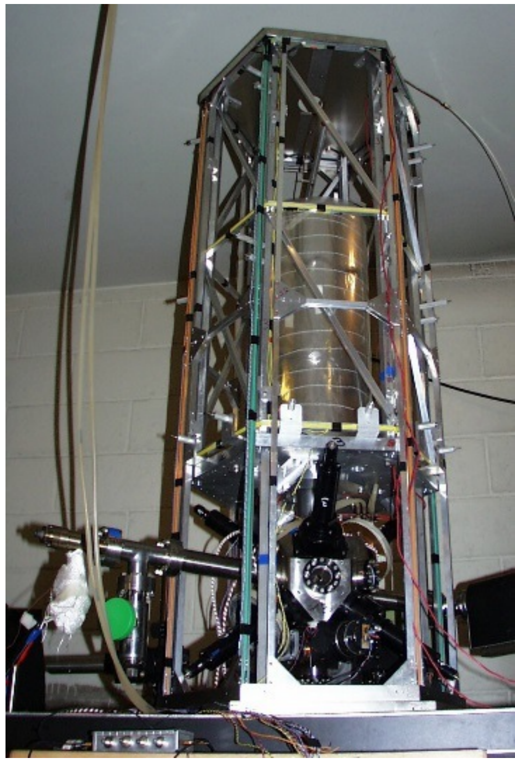
  see J. Guéna et al, Metrologia, 2012 and J. Guéna et al., IEEE UFFC, 2012

- Develop for metrology (TAI), systematics corrected during operation



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





- Infer upper limits on the ULDM coupling constants d_i (here d_e, d_g, d_{mu}, d_{md})
- Atomic clocks working with different atomic transitions sensitive to different d_i
- Current best clocks @10^{-18}: optical clocks, sensitive only to d_e (electromagnetism)

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A. Some experiments searching for oscillations of fundamental constants

1. Comparison of colocated atomic clocks
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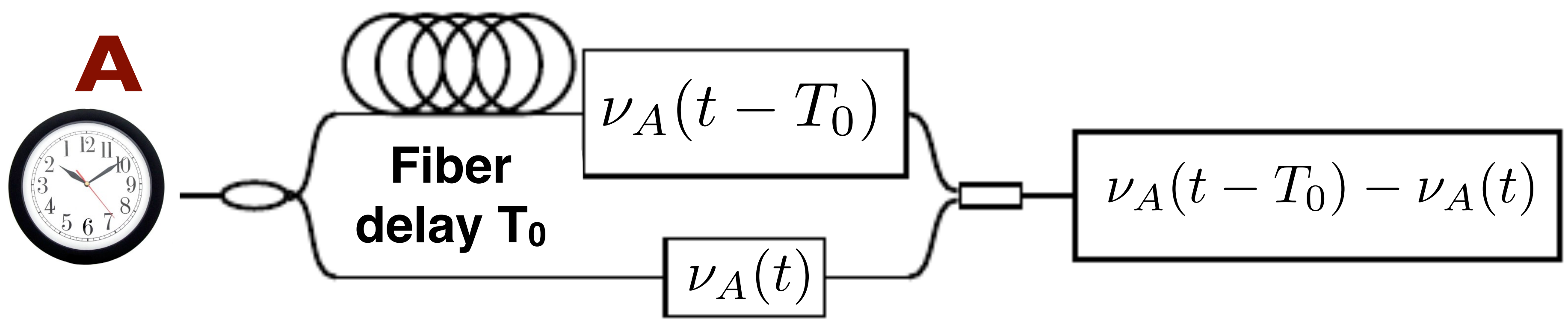
2. Cavity, fibre links, …
   Example: the DAMNED experiment

The DAMNED experiment (DArk Matter from Non Equal Delays)

- Main idea:



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

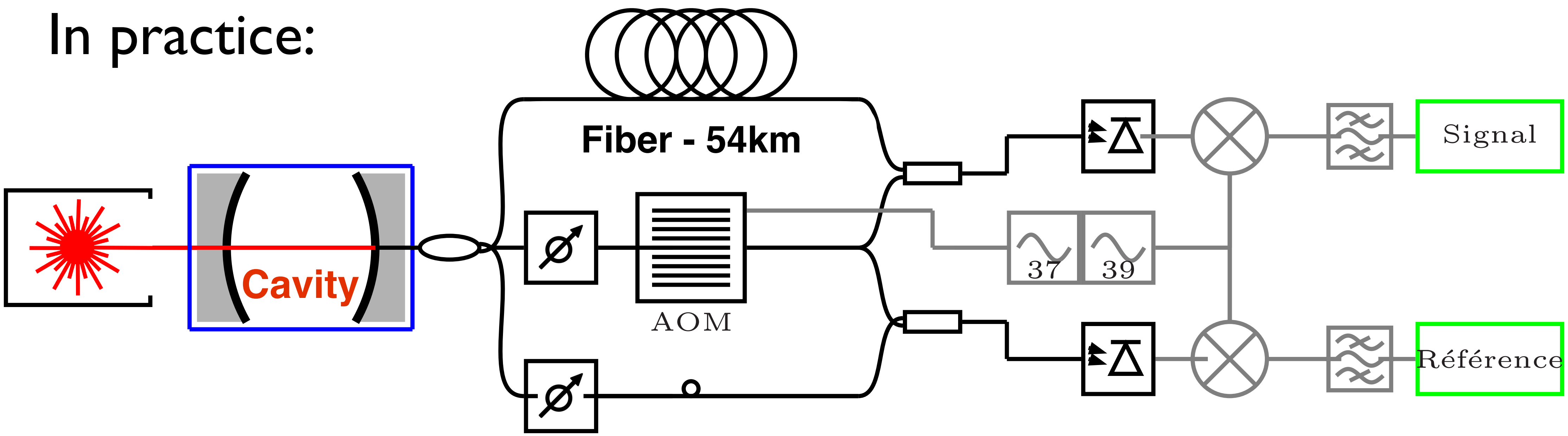
Oscillations of the scalar field

- Interpretation: comparison of an atomic frequency with itself in the past
- Main advantage: explored frequency range ~ kHz-MHz while standard clocks are limited to 0.1 Hz

see Savalle et al, PRL, 2021

The DAMNED experiment (DArk Matter from Non Equal Delays)

- In practice:

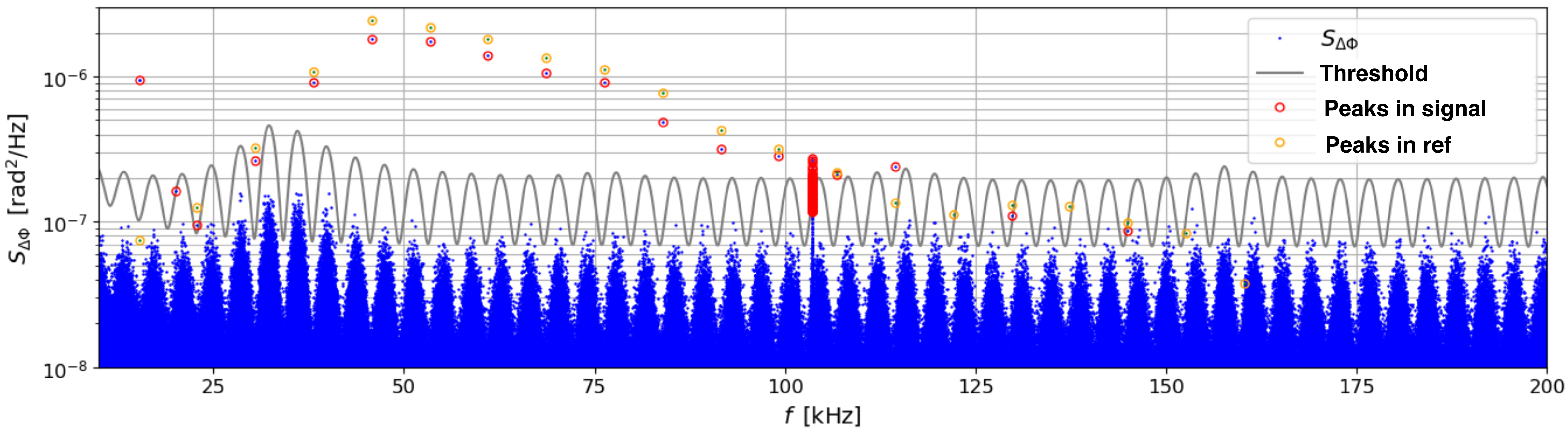


  - the "clock" is a laser cavity (both length and laser frequency oscillate)
  - the length of the fiber oscillates
  - the refractive index of the fiber oscillates
- First experiment built @LTE (E. Savalle's PhD) and data analyzed taken into account the stochasticity of the signal

C

The DAMNED experiment (DArk Matter from Non Equal Delays)

- Results



- limited by the cavity noise
- Peaks: excluded thanks to reference arms, correlation with temperature or by changing the cavity
- Infer upper limits on the ULDM coupling constants d_i (here d_e, d_{me}, d_g, d_{mu}, d_{md})

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see Savalle et al, PRL, 2021

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3. Oscillations of properties/size of optical elements used in laser interferometers: Example GEO 600, LVK, QUEST experiment, …

see L. Aiello's talk

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   Example: AION, MAGIS, …

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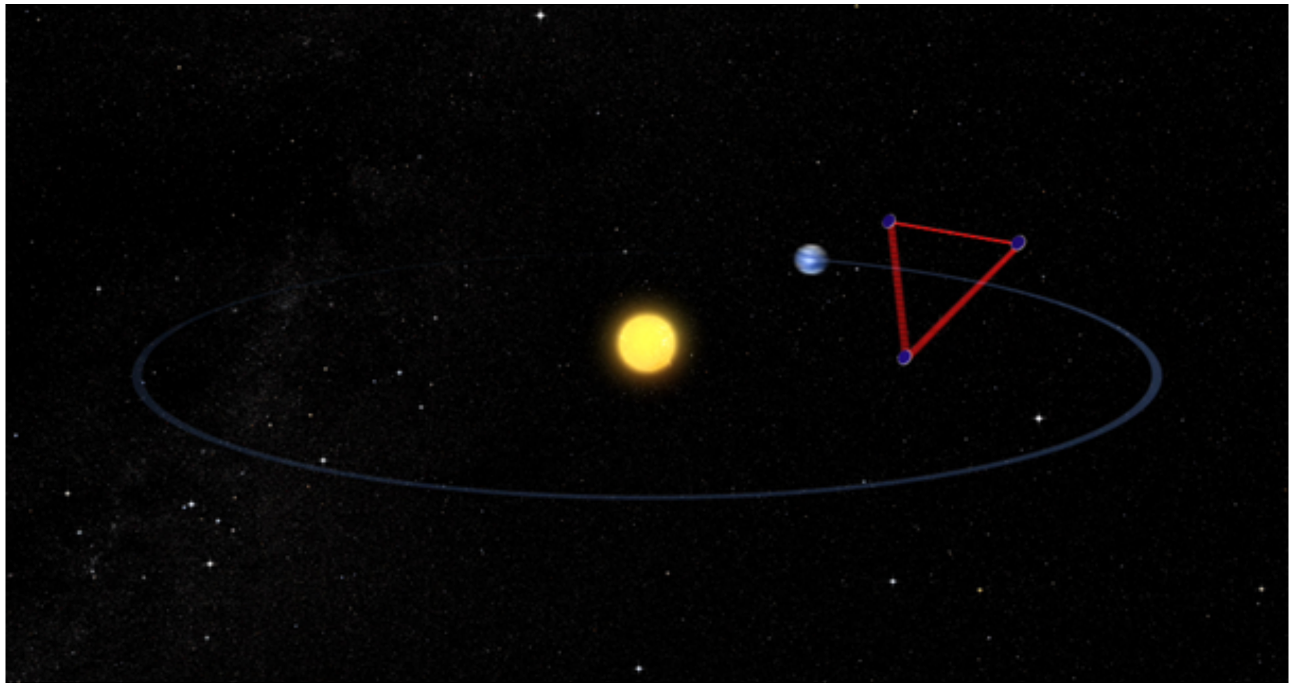
5. Space-based GW detectors: LISA

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

- Oscillating rest masses ⇒ oscillating acceleration ⇒ oscillating trajectory for free falling bodies.

$$\vec{a} \propto \vec{v}_{\rm DM}\omega\varphi_0 \sin\left(\omega t - \vec{k}\cdot\vec{x}\right)$$

- LISA: measures precisely the distance between freely falling test masses (2.5E6 km apart) in the mHz regime



$$\frac{\delta L}{L} \sim 10^{-21}$$

⇒ expected signature in LISA data.

see e.g. Yu, et al, PRD, 2023

- Will LISA be able to discriminate ULDM from GW signal? Yes

  - analytical arg.: polarisation of spin 0 and spin 2 produces different modulations

  - numerical arg.: simulation of realistic LISA data with ULDM or GW signal and data analysis recovers the correct model.

see e.g. J. Gué, et al, arXiv, 2025 (submitted to PRD)

A. Some experiments searching for oscillations of fundamental constants

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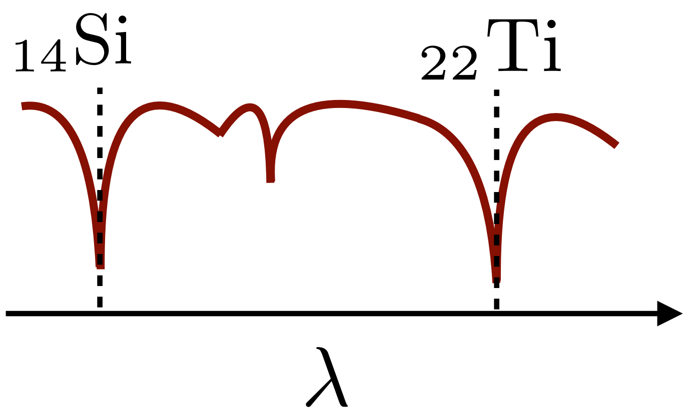
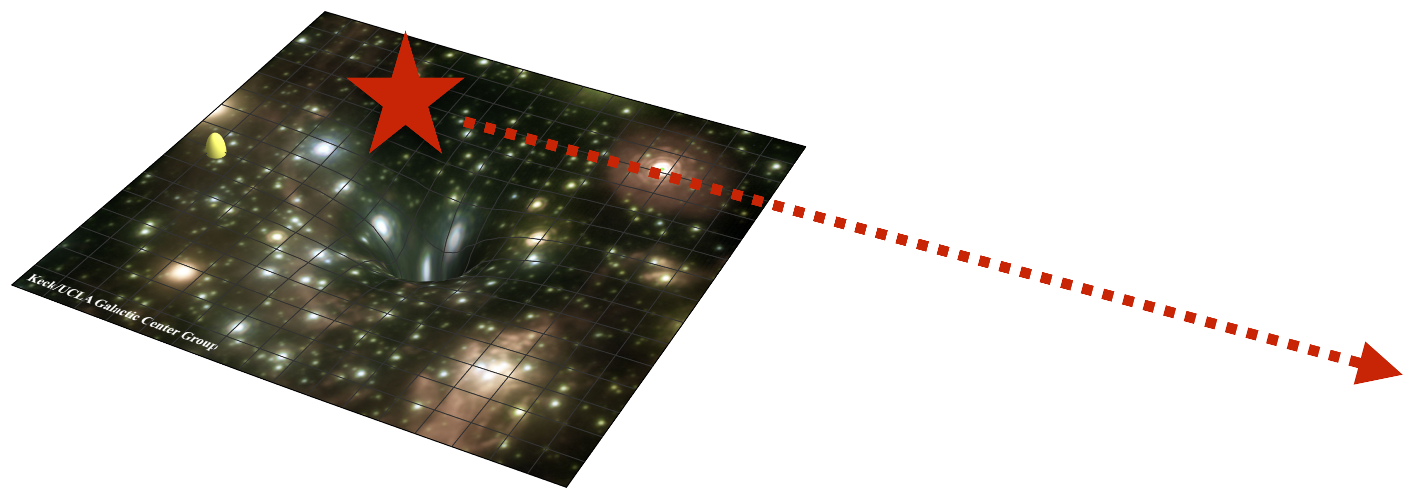
6. Spectroscopic observations of stars around our Galactic Center

Spectroscopic observations of stars around our GC: a way to measure variations of fundamental constants





Each measured line acts as a « clock » - atomic frequency

- Using 2 different lines: direct measurements of $\Delta\alpha$ see A. Hees et al, PRL 2020
- Using high cadence observations during one night: search for oscillations of α:
  - oscillations of fund. constants in a region where DM density is higher
  - oscillations of fundamental constants « closer » to a BH (superradiance)
- Current observations: proof of principle and mild constraints.
- Future instrument/Extremely Large Telescope: very promising

see Z. Bai, V. Cardoso, et al, arXiv:2507.07482

Some experiments:
B. Modification of the 2-body interaction

- Linearly coupled scalar field: Yukawa interaction

- Quadratically coupled scalar field: static (position dependent) contribution + oscillating terms

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, cold gas motion and attitude controlled
- Two cylindrical test masses: Pt/Ti. Measurement of the diff. acceleration along the symmetry axis
- Final results published in September 2022

$$\eta = \frac{\Delta a}{a} = (-1.5 \pm 2.3(\mathrm{stat}) \pm 1.5(\mathrm{syst})) \times 10^{-15}$$

Touboul et al, PRL, 2022

MICROSCOPE results can be used to probe ULDM

- The final results can be transposed into a Yukawa constraint and therefore into a constraint on the linear scalar couplings

see e.g. Brax et al, PRL 2018
Hees et al, PRD 2018

- For quadratic scalar couplings, 2 contributions
  - DC contribution can directly be constrained using existing results

    see e.g. Hees et al, PRD 2018
    J. Gué, et al, PRL to appear

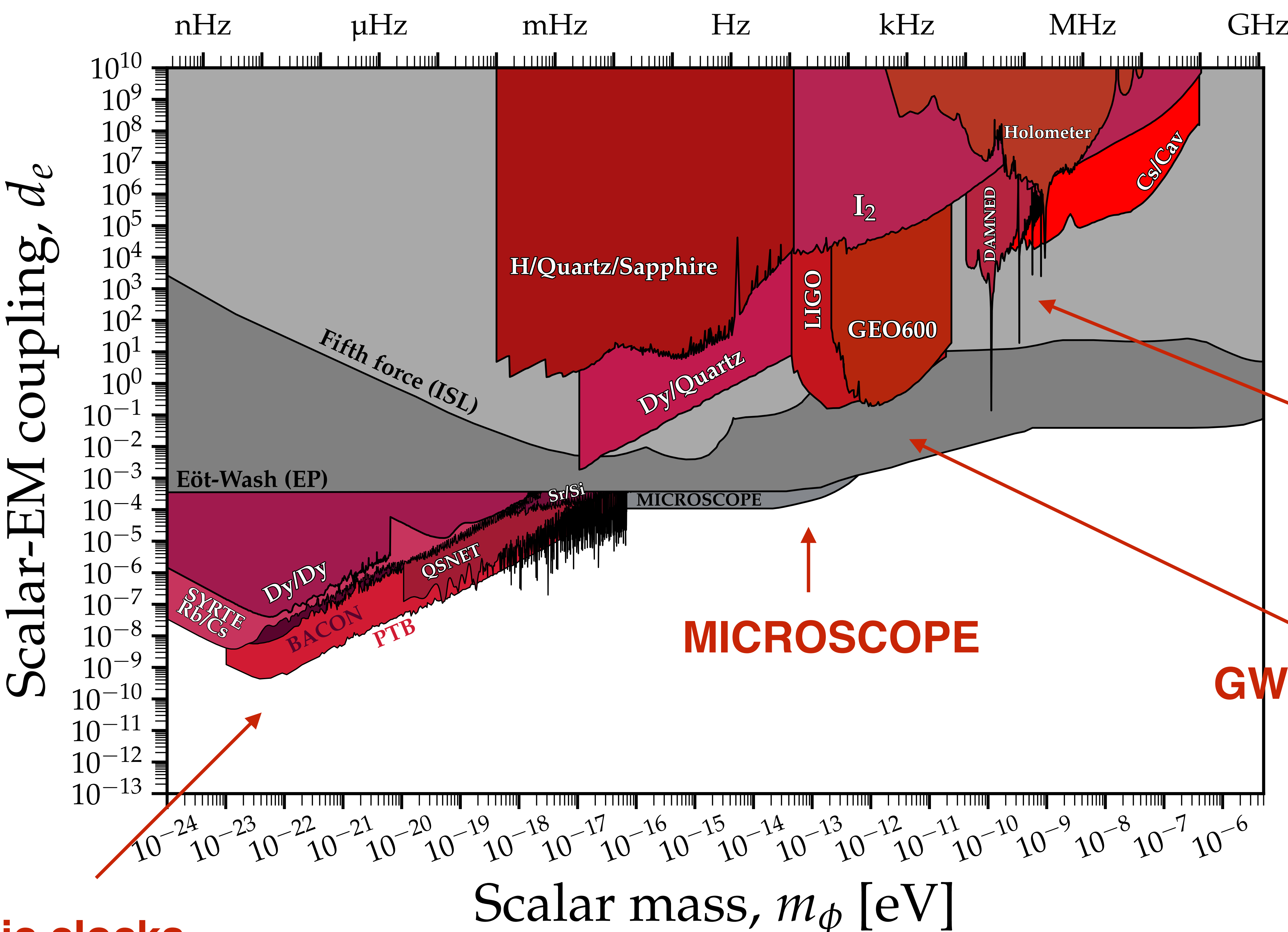
  - Oscillations: needs a proper re-analysis of the raw data. Promising sensitivity analysis

    see e.g. J. Gué, et al, PRD, 2024

Some constraints

Linearly coupled ULDM

Figure from C. O'Hare, Zenodo 3932430



DAMNED

MICROSCOPE

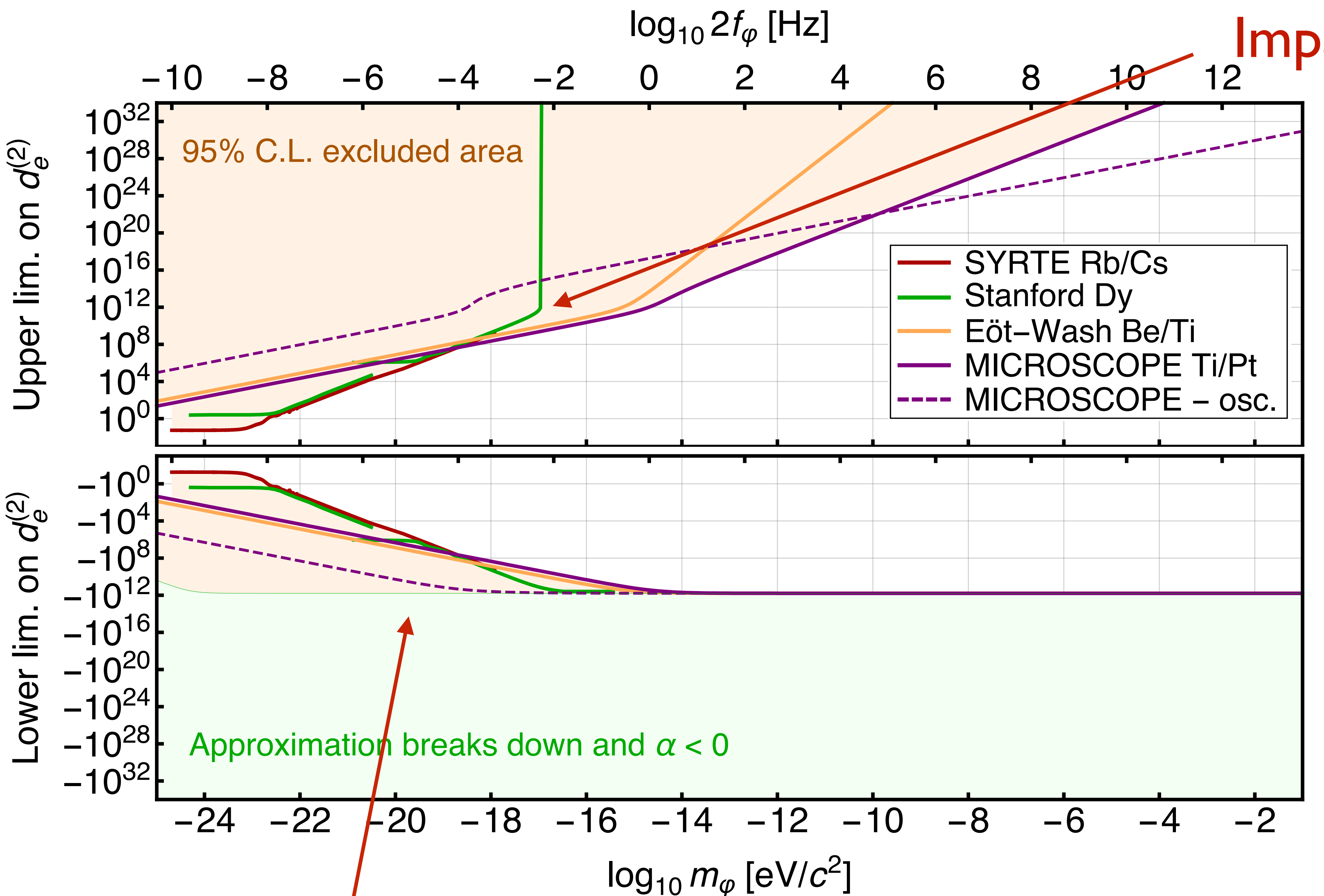
GW detectors

Atomic clocks

Similar exclusion plots exist for the other couplings

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

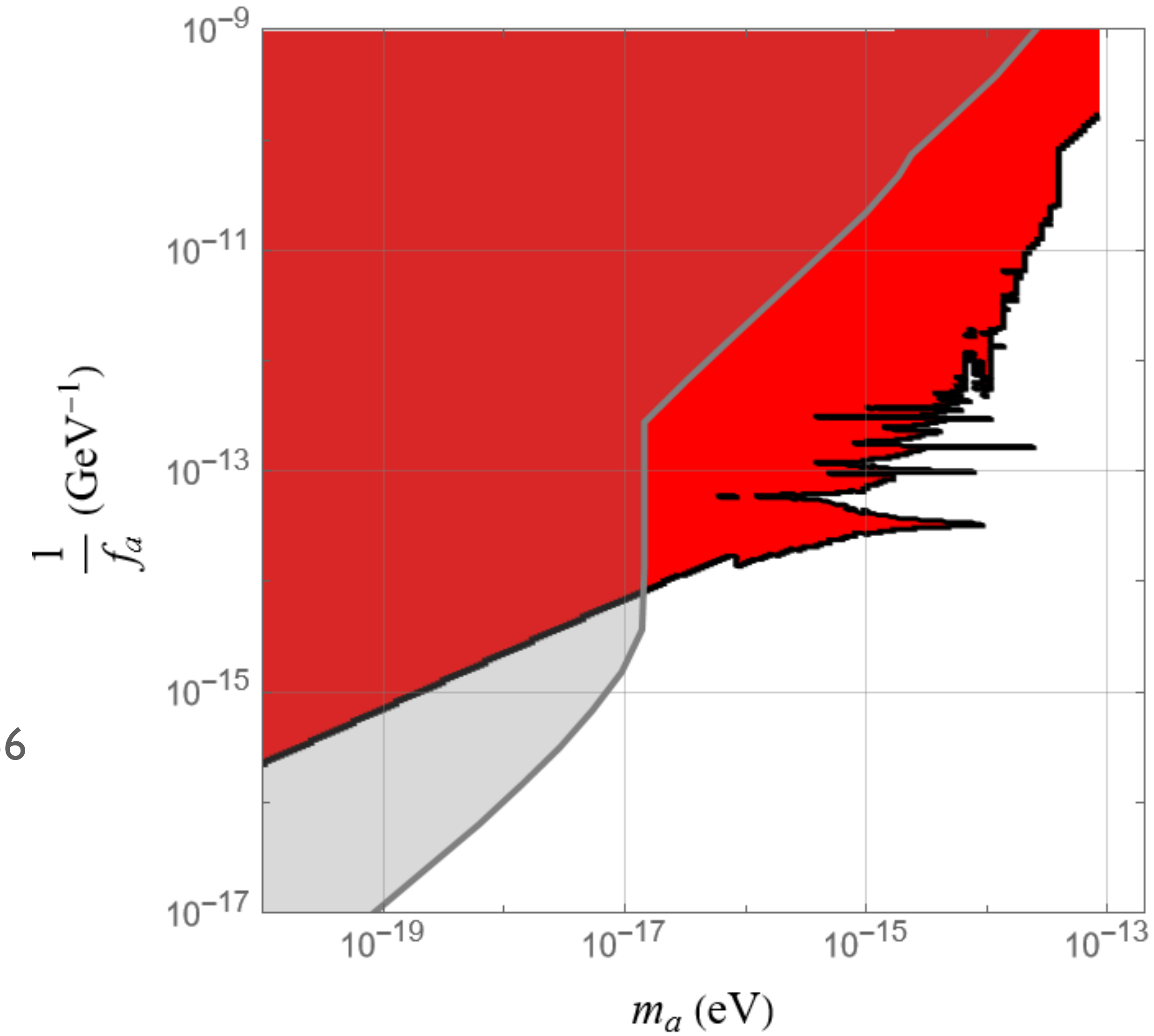
Re-interpretation of MICROSCOPE data to search for axion

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

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

- Stochasticity of the axion properly accounted for
- Recently derived axion field solution accounting for correction due to axion propagation: presence of resonances for certain coupling

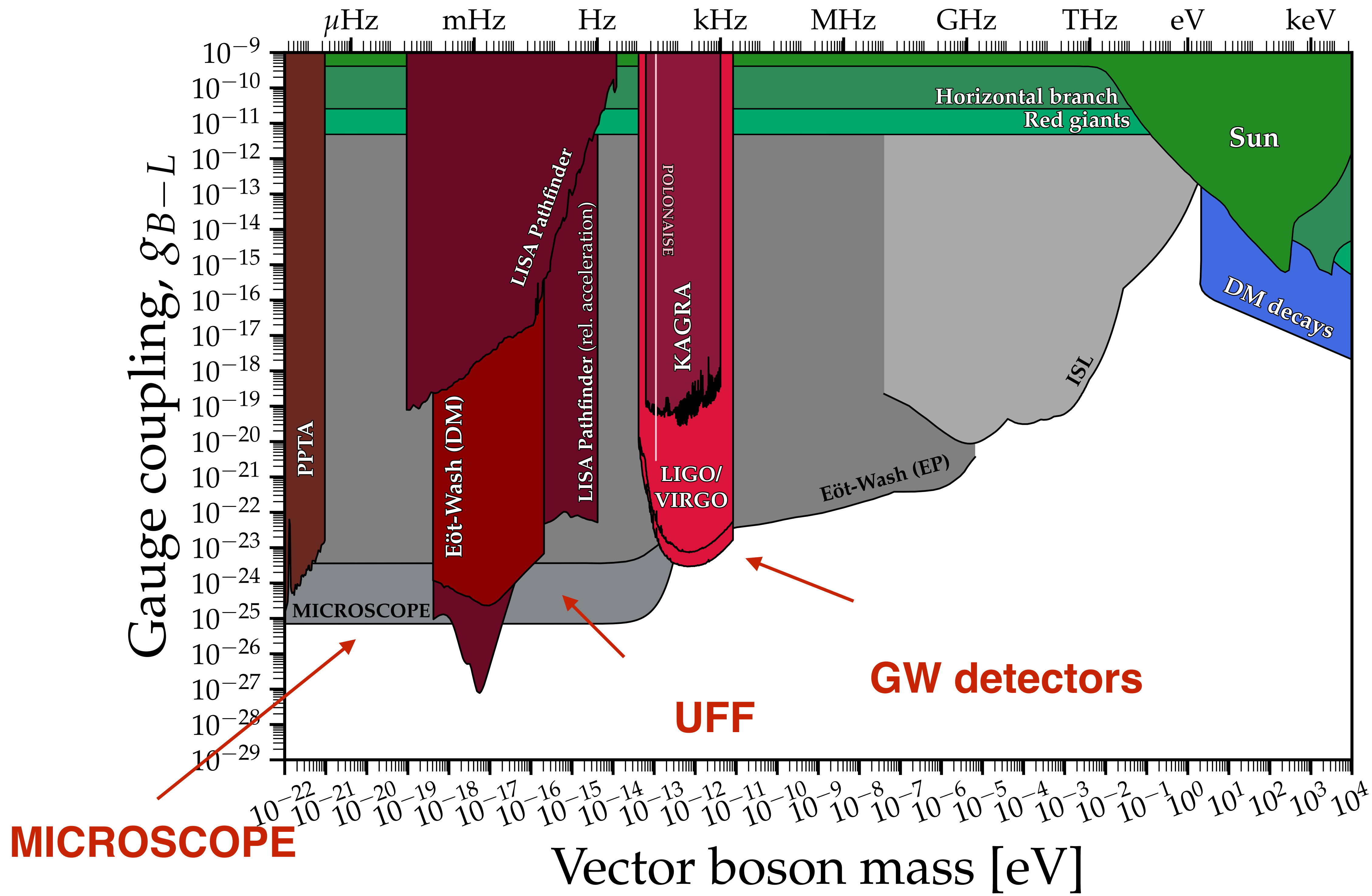
see A. Barnerjee et al, arXiv:2502.04455,
Y. Garcia del Castillo, et al arXiv:2502.04456



see J. Gué et al, to appear PRL, 2025

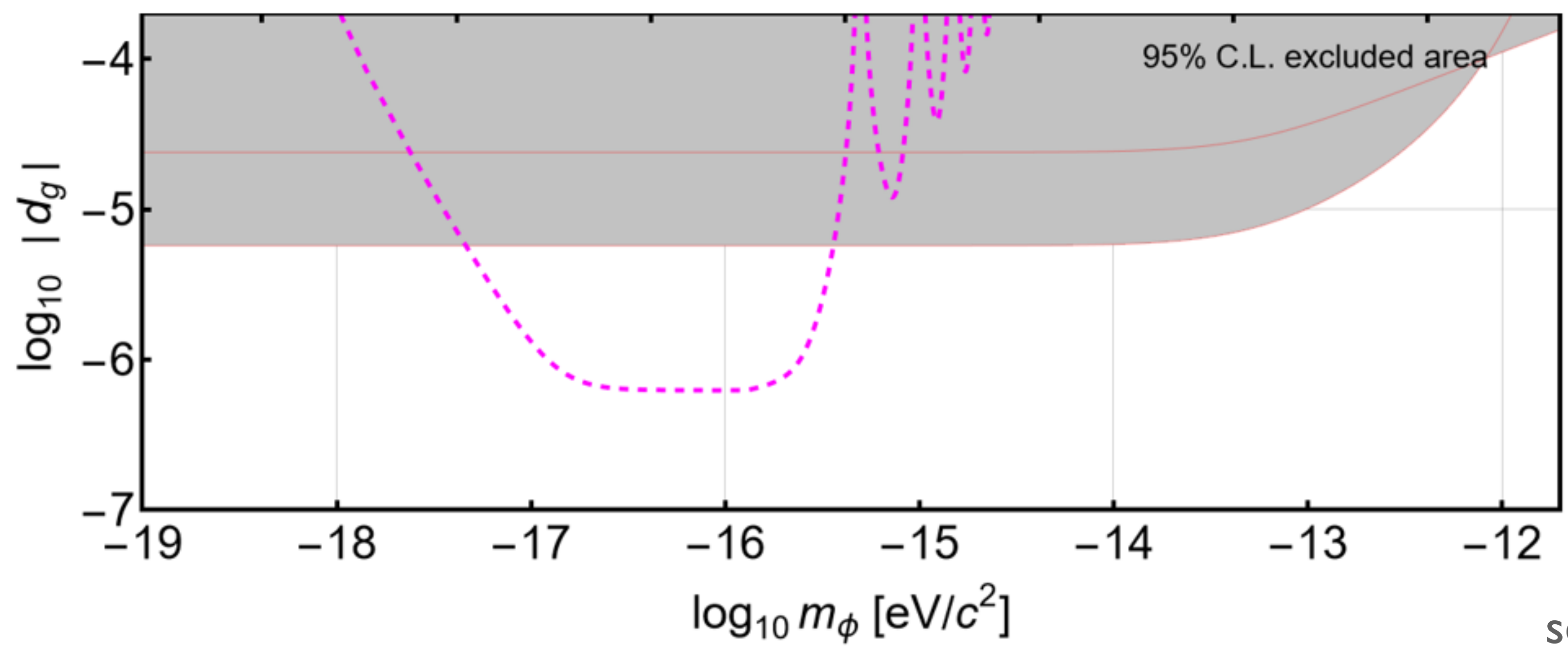
Constraints on spin 1 B-L coupling

Figure from C. O'Hare, Zenodo 3932430



Sensitivity analysis of LISA space mission

- Example of sensitivity analysis done for LISA (linearly coupled scalar field)



see J. Gué et al, arXiv:2508.13847

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), fifth force, …
- I focus on spin-0 ULDM but similar results exist for spin 1 (B-L boson)
- This is a rich playground for experimental searches and a lot of clever ideas have come up in the last decades (usually at a relatively modest cost)

- Hunt for new ideas inspired by experimental progress and possibilities, led by theoretical models and plausibility

- Interactions between both communities (astro and precision metrology) important to avoid flogging a dead horse ! (example: still worth searching at very low masses?) see J. Niemeyer's talk