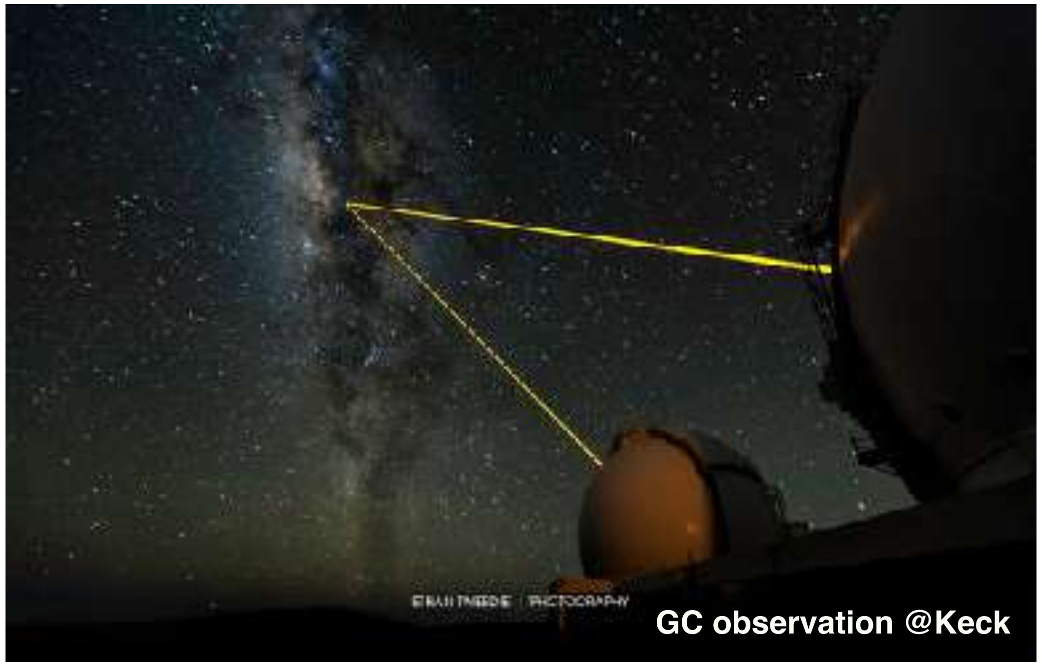
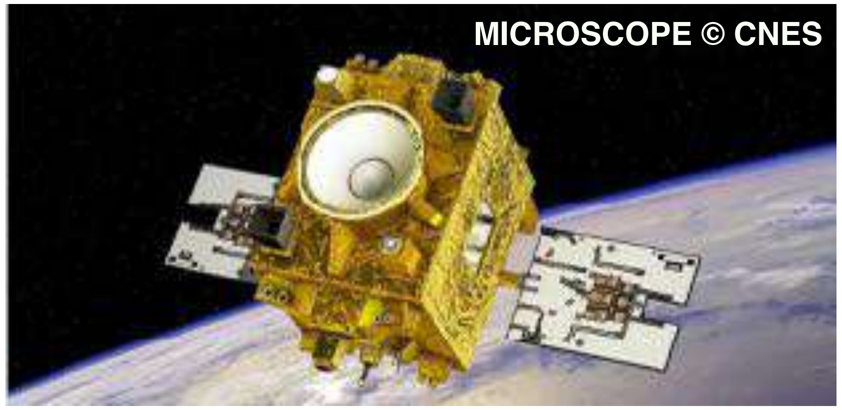
Exploring fundamental physics with tests of the equivalence principle from the lab to the Galactic Center

A. Hees, SYRTE, Paris Observatory





l'Observatoire de Paris | SYRTE

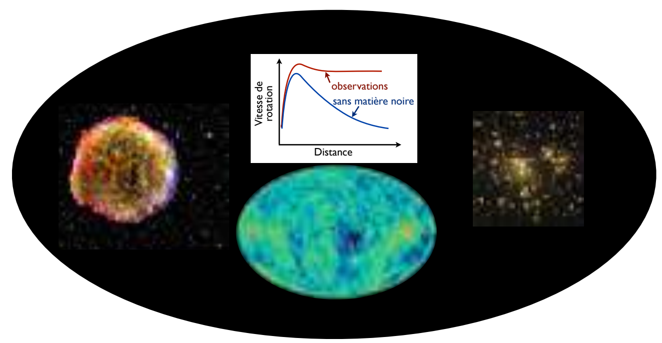
Systèmes de Référence Temps-Espace

LUTH Seminar
December 3, 2020

cnrs

Global picture & motivations

- Some of the "greatest challenges" in theoretical physics:
  - what are Dark Matter and Dark Energy ?
  - how can we develop a quantum theory of gravity and/or unify it with the Standard Model of particles ?

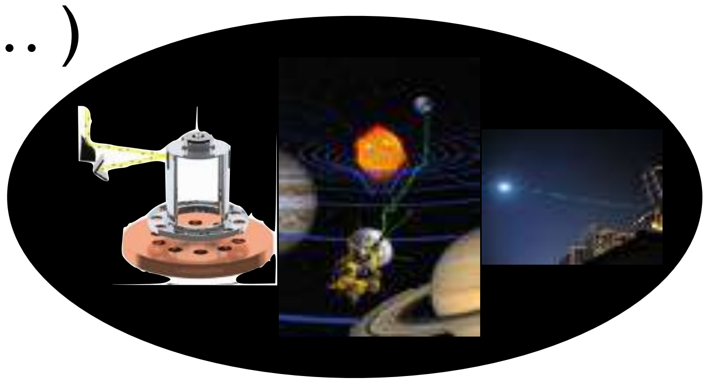


Astronomy & cosmology

(Grav. waves, SNIa, CMB, structure formation, galactic dynamics, …)

Local physics

(Solar System, lab tests, GNSS, …)



Quantum Gravity

Unification

DM and DE

High energy

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

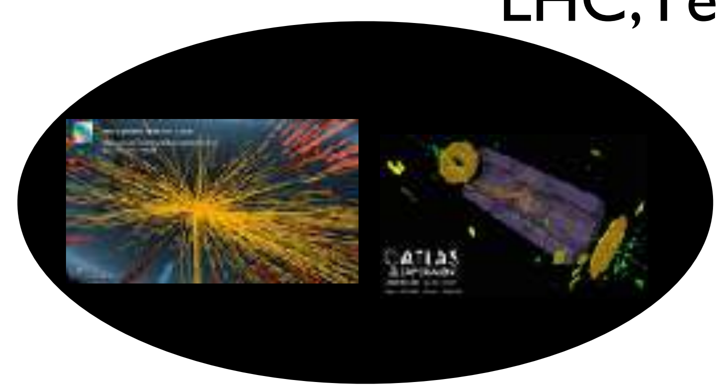


Figure inspired by Altschul et al, Adv, in Space Res. 55, 501, 2015

General Relativity

Einstein Equivalence Principle

Effects of gravitation ⟷ Space-time geometry

$$g_{\mu\nu}$$

see K. Thorne et al, PRD, 1972

$$S_{\rm mat} = \int d^4x \sqrt{-g}\mathcal{L}_{\rm mat}(g_{\mu\nu}, \Psi)$$

- All types of mass-energy are coupled universally to gravitation (anomalous compared to other interactions)
- Governs the motion of test-particles, light ray, gyroscope, etc… from a given metric

see C. Will, 1993

Einstein Field Equations

Space-time geometry ⟷ Energy/Matter content

$$S_{\rm grav} = \frac{1}{2\kappa}\int d^4x \sqrt{-g} R$$

- Contains the dynamics of the space-time metric: how is space-time curved?
- Light deflection, GW propagation, orbital dynamics, …

see C. Will, 1993

Why search for a breaking of the EEP?

- Since the "universal" character of gravitation seems "anomalous" the question should rather be: why is the EEP satisfy? [does not rely on any fundamental symmetry] see the discussion in Damour, CQG, 2012

- The SM of particles contains several arbitrary constants: this seems rather unsatisfactory ⇒ introduction of dynamical fields that replace the constants and explain their values see the discussion in Damour, CQG, 2012

- Several models of DM break the EEP see e.g. Arvanitaki et al, PRD, 2015

- Several models of Dark Energy also break the EEP see Damour and Polyakov, Gen. Rel. Grav., 1994

- Several unification scenarios and most attempts to develop a quantum theory of gravity break the EEP see e.g. refs in Altschul et al, 2015

Searching for a breaking for the EEP seems promising and can shed light on new physics

see the ESA Voyage 2050 white paper: arXiv1908.11785

Where to search for new physics?

1) Improving "standard tests" of the EEP.

2) consider other frameworks and use existing data to search for new signatures. Example: model of ultralight Dark Matter

3) consider new regimes unexplored so far. Example: S-stars around our Galactic Center

EEP implies Universality of Free Fall

If any uncharged test body is placed at an initial event in space-time and given an initial velocity there, then its subsequent trajectory will be independent of its internal structure and composition

$$\eta = \frac{\Delta a}{a}$$

2 different bodies are sensitive to the same space-time geometry

MICROSCOPE

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

- 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

- So far, only 1 scientific session is published (120 orbits, ~ 8 days)

$$\eta = (-1 \pm 9[\mathrm{stat}] \pm 9[\mathrm{syst}]) \times 10^{-15}$$

Touboul et al, PRL, 2017

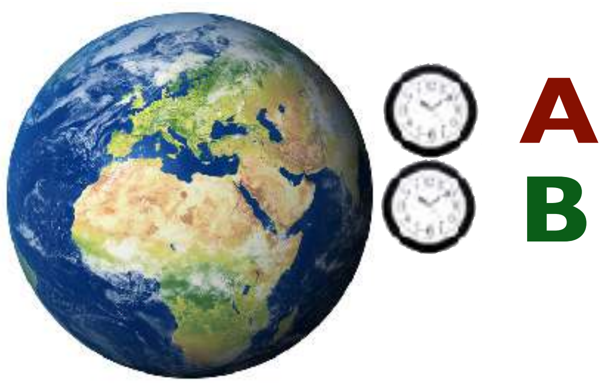
- Independent analysis in the time domain @SYRTE: verification + very modular: other scientific objectives (Lorentz invariance)

Pihan-Le Bars et al, PRL, 2019

- 1 order of magnitude improvement expected for the final results

EEP implies that the constants of Nature are constant (Local Position Invariance)

for a review, see J.P. Uzan, LRR, 2011



Constancy of the fine structure constant, mass of fermions, etc…

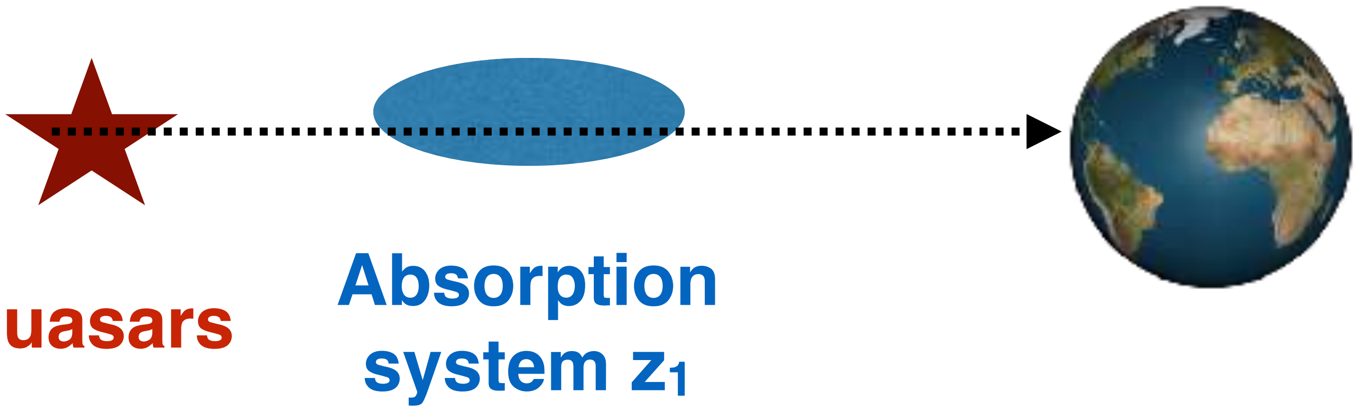
$$\frac{\dot{\alpha}}{\alpha} < 10^{-17}\mathrm{yr}^{-1} \qquad \frac{d\ln\alpha}{dU/c^2} < 10^{-7}$$

- Measurements performed using atomic clocks on Earth
- Improves relatively quick

2 different atomic transitions/frequencies are sensitive to the same space-time geometry

Are the constants of Nature constant on astrophysical scales?

- Quasar measurements: each absorption line acts as a "clock"



$$\sigma_{\Delta\alpha/\alpha} \sim 10^{-4} - 10^{-6}$$

  - 338 absorption systems up to redshift 7
  - Spatial variation of α reported at the level of 3.9 σ

see King et al, MNRAS 2012
Wilczynska et al, Sciences Ad. 2020

- White dwarf (G191-B2B): Fe absorption lines from the white dwarf atmosphere
  - "Strong" gravitational potential $\phi \sim \frac{GM}{c^2 R} \sim 5 \times 10^{-5}$

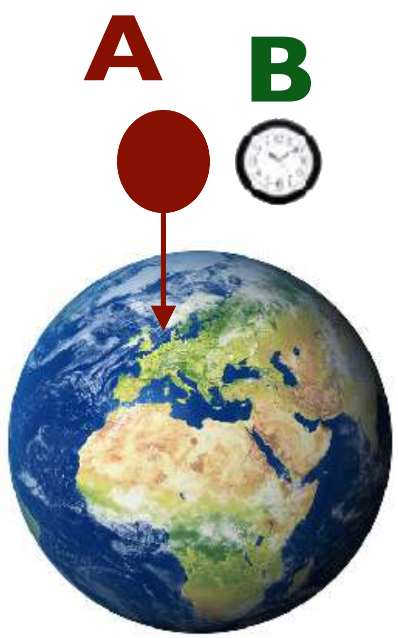
see Berengut et al, PRL, 2013
Hu et al, MNRAS, 2020

$$\frac{\Delta\alpha}{\alpha} = (6.36 \pm 0.35_{\rm stat} \pm 1.84_{\rm sys}) \quad \text{and} \quad \frac{\Delta\alpha}{\alpha} = (4.21 \pm 0.48_{\rm stat} \pm 2.25_{\rm sys})$$

  - variation of α in strong gravitational field reported at the level of 1.5-3 σ

Independent measurements from other systems with other lines needed to confirm (or infirm) these results

EEP implies the GR gravitational redshift (Local Position Invariance)



$$\boldsymbol{a}_A = -\boldsymbol{\nabla} U$$

$$\left[\frac{\Delta\nu}{\nu}\right]_{B,\mathrm{grav}} = \frac{U}{c^2}$$

A free falling body and an atomic transition are sensitive to the same space-time geometry

- The best redshift test uses 2 misplaced Galileo satellites

$$\left[\frac{\Delta\nu}{\nu}\right]_{\mathrm{grav}} = (1+\alpha_{\mathrm{redshift}})\frac{U}{c^2}$$

$$\alpha_{\mathrm{redshift}} = (0.19 \pm 2.48) \times 10^{-5}$$

See Delva et al, PRL, 2018 and Herrman et al, PRL 2018

Where to search for new physics?

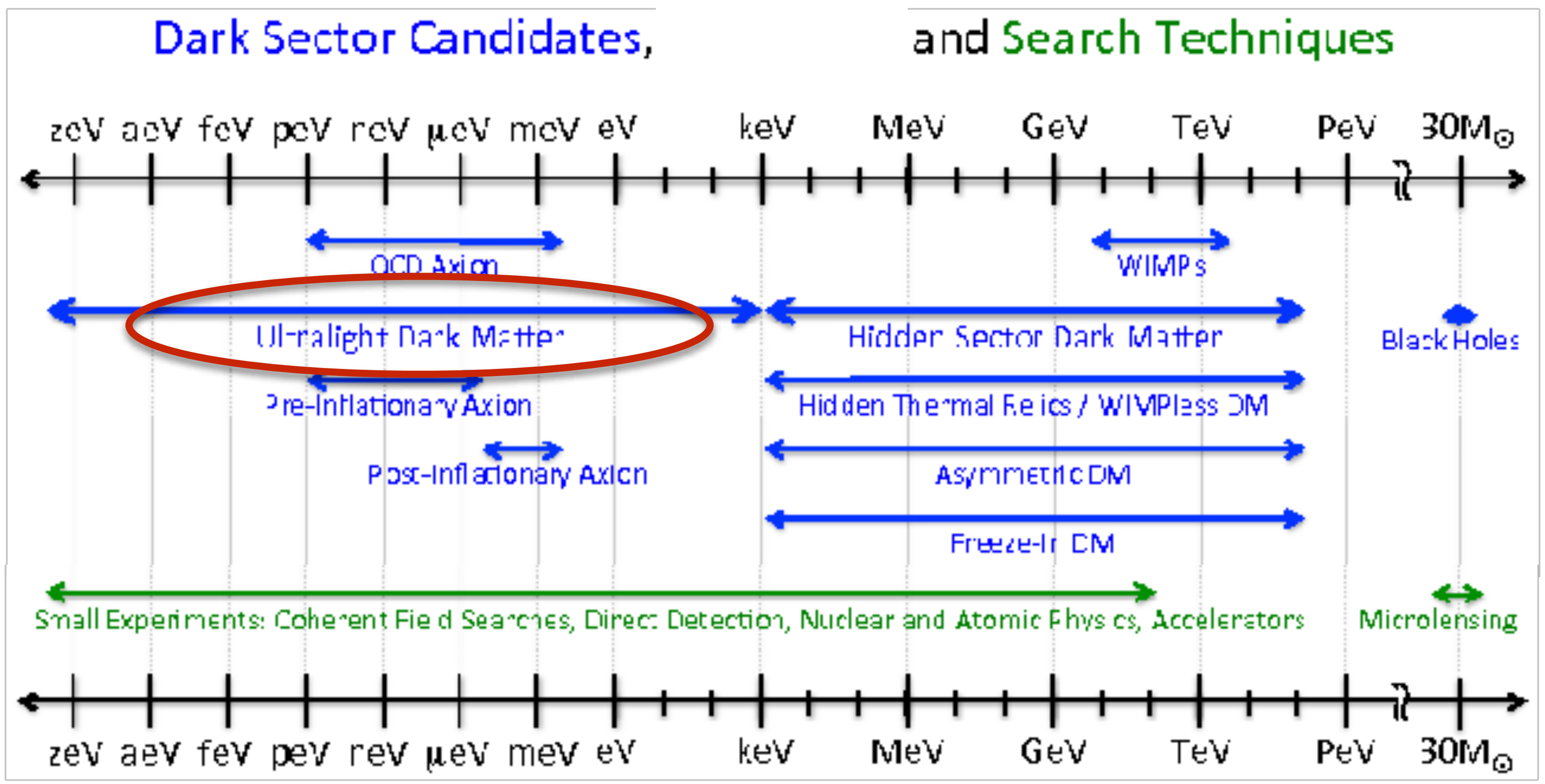
1) Improving "standard tests" of the EEP.

2) consider other frameworks and use existing data to search for new signatures. Example: model of ultralight Dark Matter

3) consider new regimes unexplored so far. Example: S-stars around our Galactic Center

Motivations: Dark Matter?

- Required to explain several astro/cosmo observations: CMB, galactic rotation curves, lensing, structures formation, …
- So far: Not directly detected at high energy



Dark Matter can be made out of bosonic scalar particles

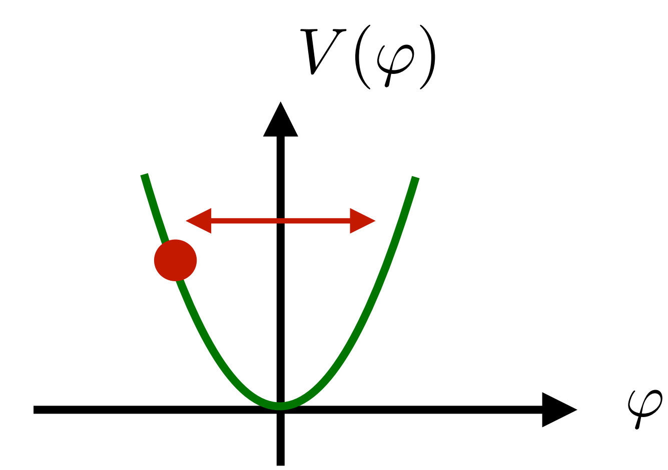
Fig. from *US cosmic vision: new idea for Dark Matter*, 2017, arXiv:1707:04591

A light scalar Dark Matter model

- A massive scalar field (sometimes called dilaton)

$$S = \frac{1}{c}\int d^4x \frac{\sqrt{-g}}{2\kappa}\left[R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right] + S_{\mathrm{mat}}\left[g_{\mu\nu}, \varphi\right]$$

$$V(\varphi) \propto m^2\varphi^2$$



- will oscillate at the cosmological level

$$\varphi \sim \varphi_0 \cos\left[\frac{mc^2}{\hbar}t\right]$$

- similar to a cosmo pressure-less fluid with $\rho \propto m^2\varphi_0^2$

see e.g. Arvanitaki et al PRD, 2015 or Stadnik and Flambaum, PRL 2015

Some properties of this ultralight DM candidate

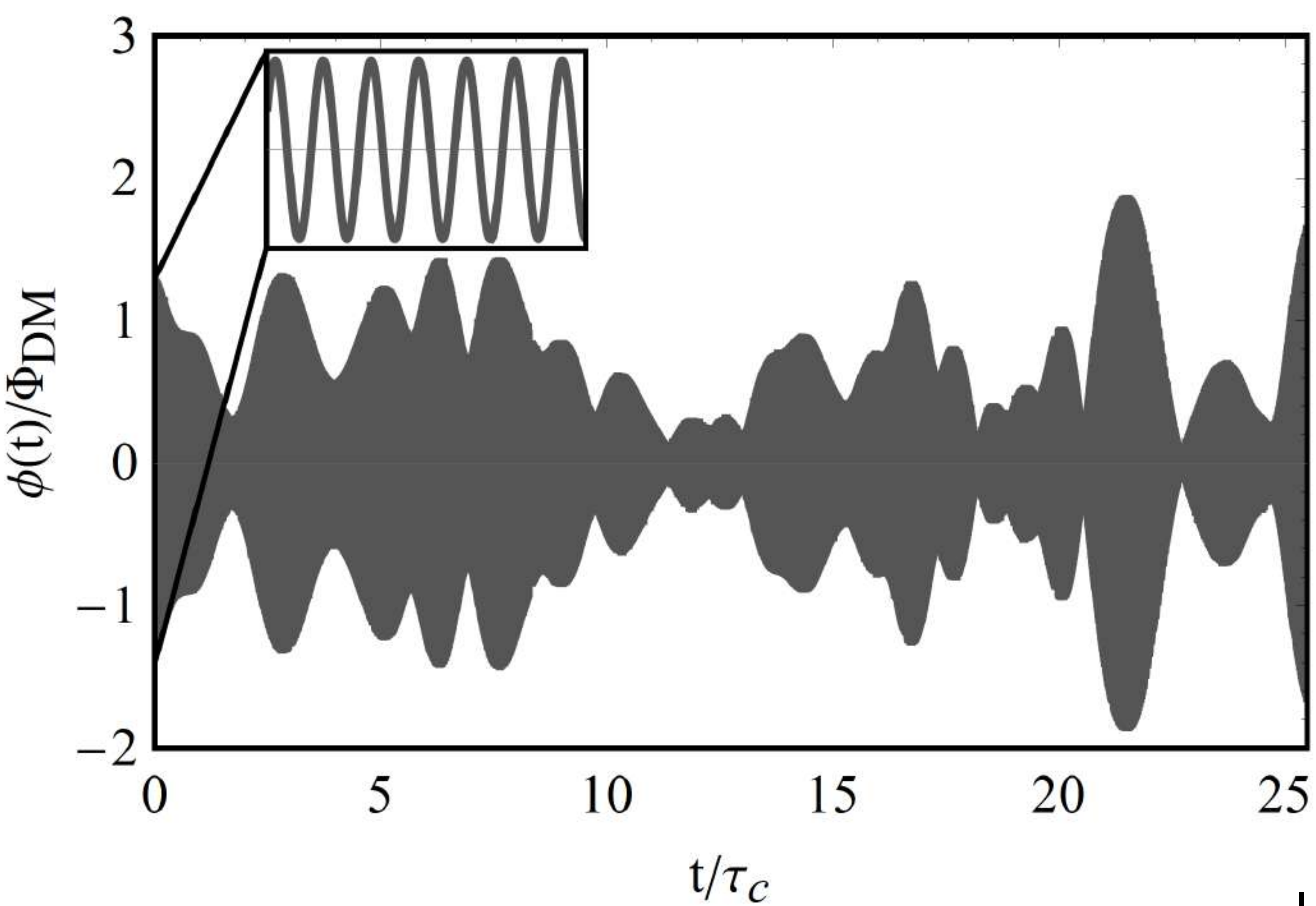
- For low masses (m < 10 eV), it behaves as a classical field

see Derevianko, PR A, 2018 for a detailed derivation

- Around 10^{-22} eV, nice large scales properties

see e.g. Marsh, Phys. Reports, 2016

- oscillation coherent over 10^6 oscillations only (due to DM velocity distribution): complex data analysis for long dataset (or high frequency)



see Centers et al, arXiv:1905.13650

ULDM induces a space/time variation of constants of Nature

- 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

- Most usual couplings: linear (cfr Damour-Donoghue) or quadratic (cfr Stadnik et al) in φ
- This leads to a space-time dependance of some constants of Nature to the scalar field

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

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

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

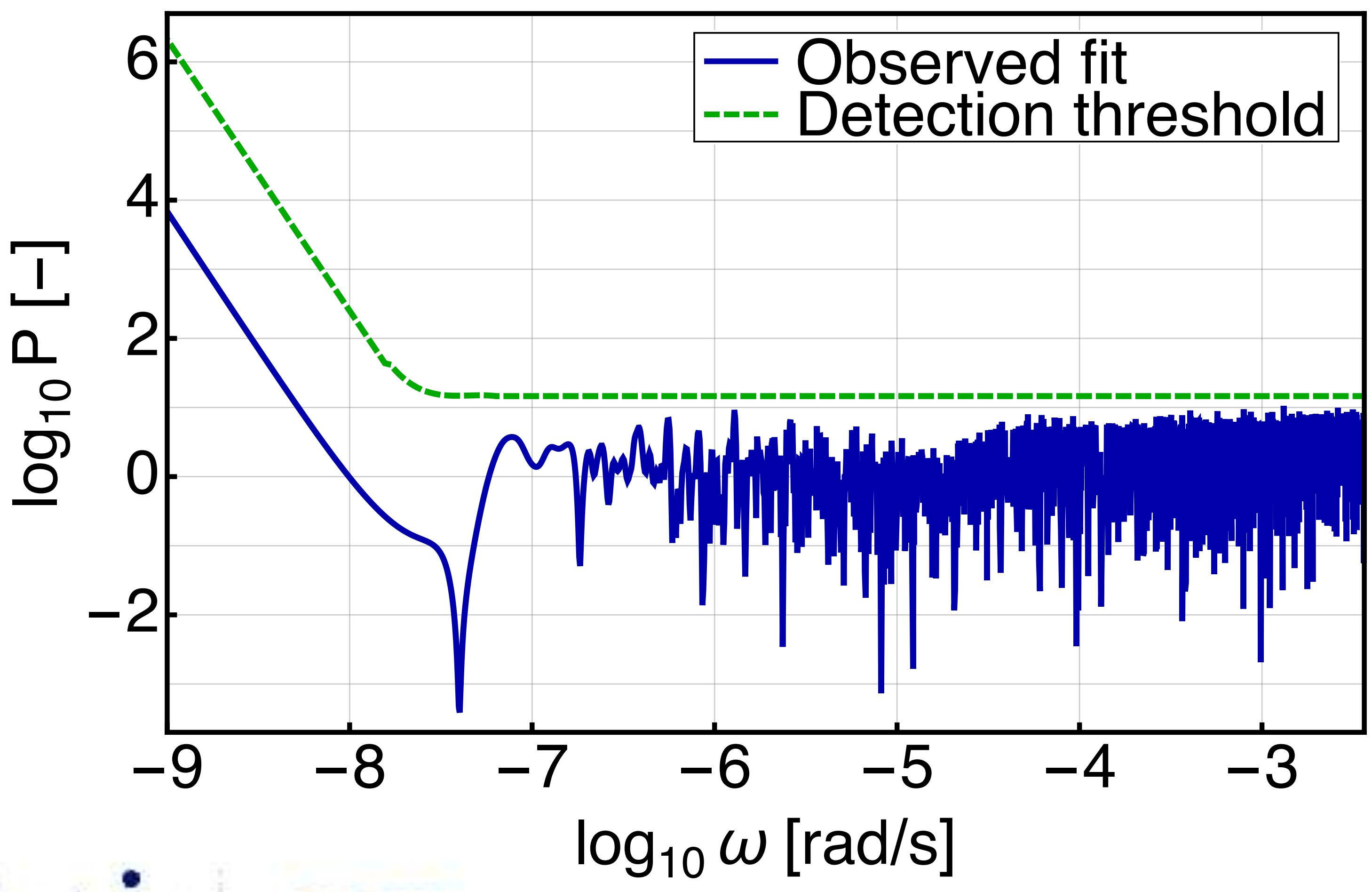
ULDM will induce periodic signals on atomic clocks comparison

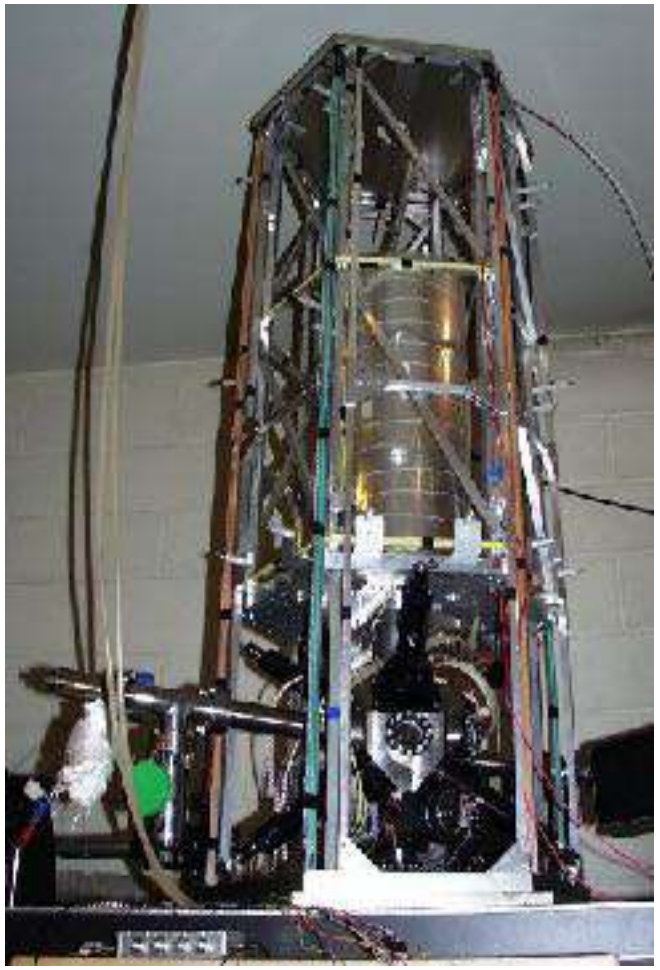
Search for a period signal in Cs/Rb comparison

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

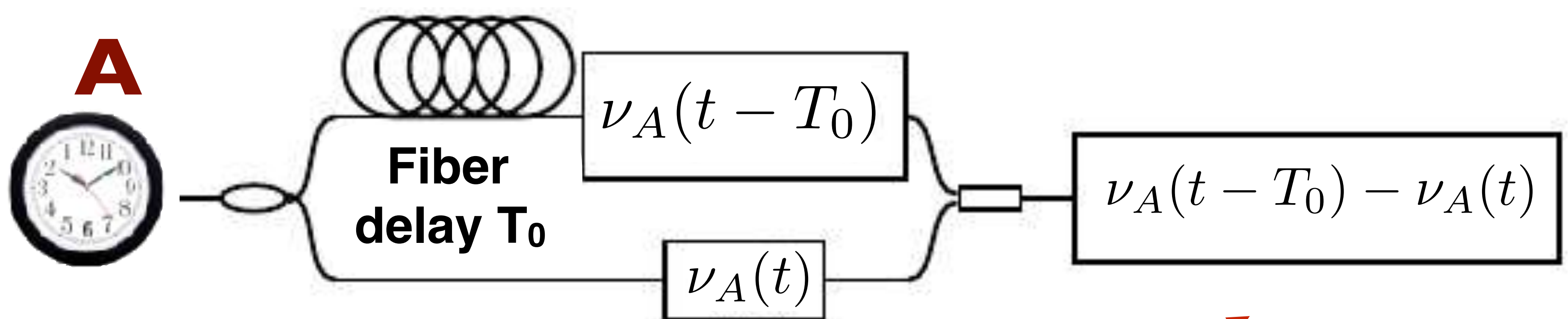
Systèmes de Référence Temps-Espace

No positive detection

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

Search for a period signal in a Mach-Zender interferometer

- New type of experiment proposed by P. Wolf (SYRTE). Simplified principle:



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

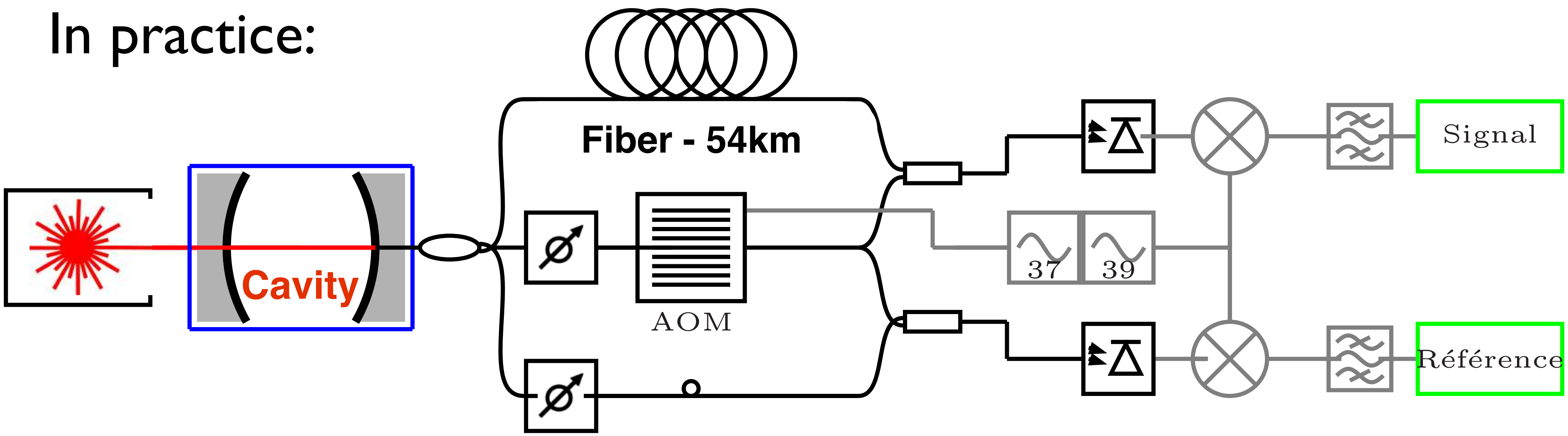
Oscillations of the scalar field

- Main advantage: explored frequency range ~ kHz-MHz while standard clocks are limited to 100 mHz

For the theoretical interpretation, see Savalle et al, arXiv:1902.07192

The DAMNED experiment (DArk Matter from Non Equal Delays)

- In practice:



  - the "clock" is a laser cavity (its length/output frequency oscillate)
  - the length of the fiber oscillates
  - the refractive index of the fiber oscillates

- First experiment built @SYRTE (E. Savalle's PhD) and data analyzed

- A Lomb-Scargle analysis shows that
  no significant periodic signal is detected in the 10-200 kHz frequency band

see Savalle et al, submitted to PRL, arXiv:2006.07055

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

Let's focus on two specific cases: a linear and a quadratic coupling

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

Scalar field for a linear coupling

- "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 sensors are more sensitive

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

Oscillations can be interpreted as DM

UFF measurements are more sensitive

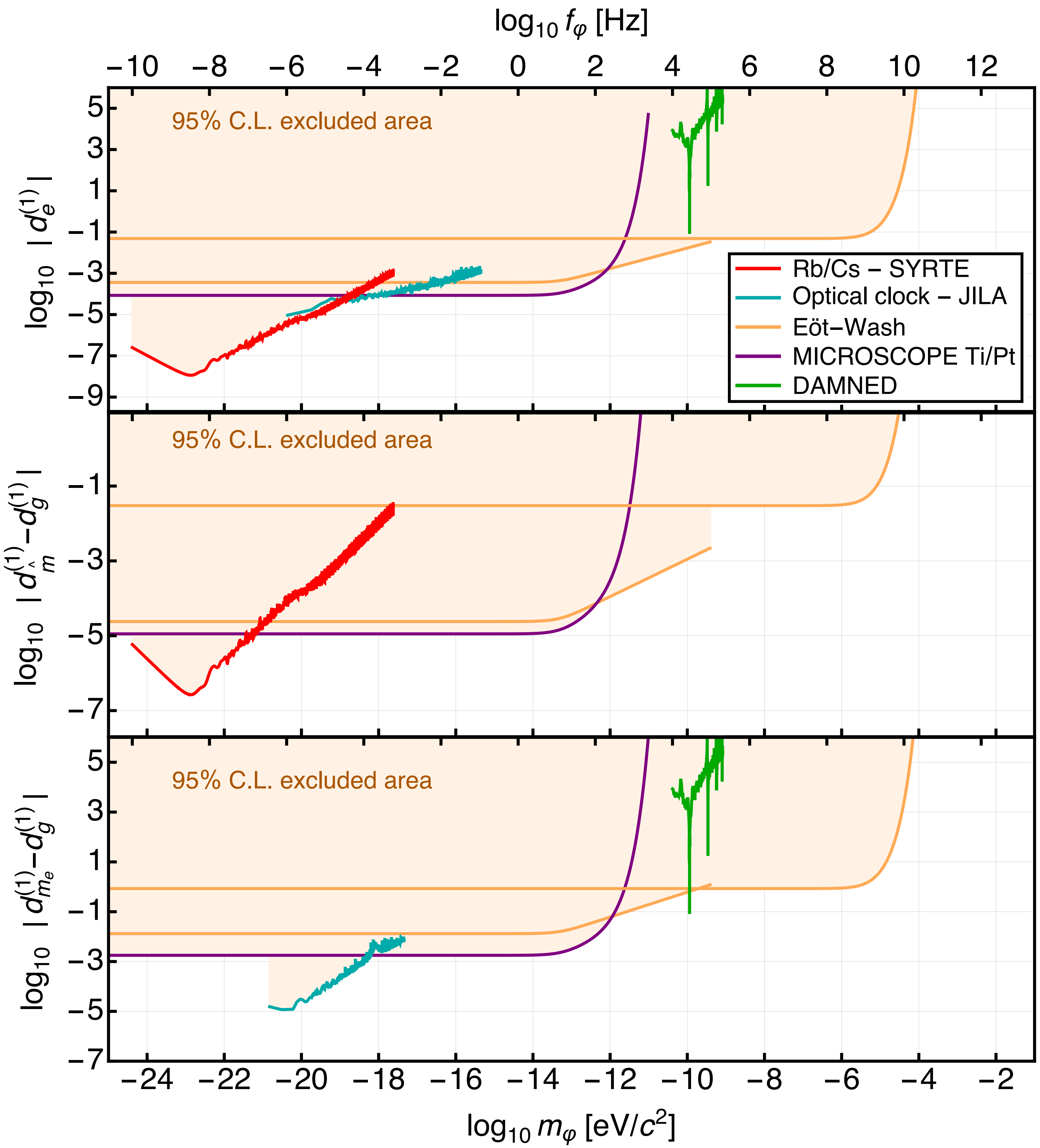
Independent of the DM interpretation

see A. Hees et al, PRD, 2018

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

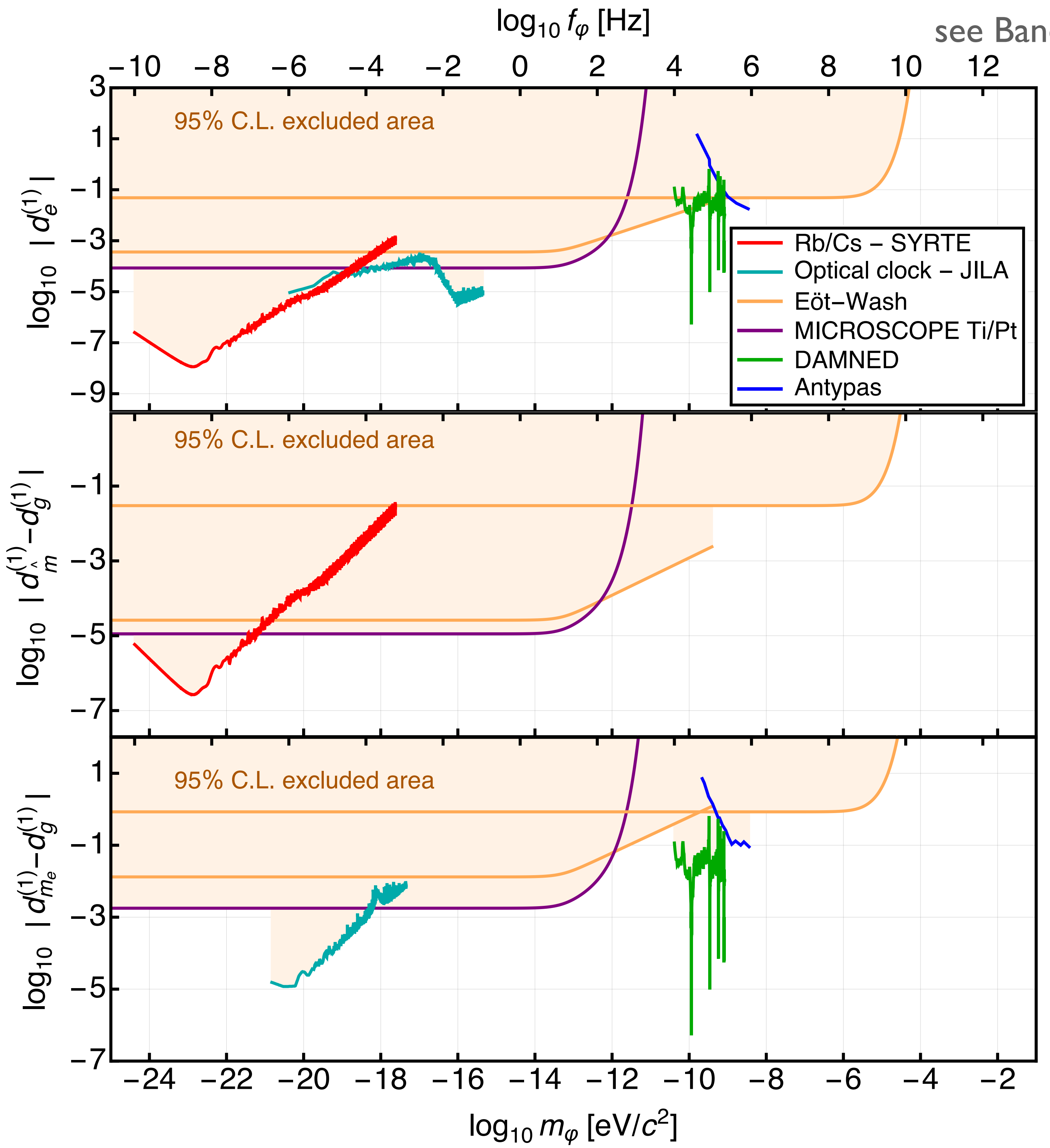


- Rb/Cs: Hees et al, PRL, 2016
- JILA: Kennedy et al, PRL, 2020
- Eöt-Wash: Wagner et al, CQG, 2012
- MICROSCOPE: Bergé et al, PRL, 2018
- DAMNED: Savalle et al, arXiv:2006.07055

Linear couplings for the relaxion halo

Large density of scalar field can be (gravitationally) bound by the gravitational field of the Earth/Sun

see Banerjee et al, Communications Physics, 2020 [and ref. therein]



- Rb/Cs: Hees et al, PRL, 2016
- JILA: Kennedy et al, PRL, 2020
- Eöt-Wash: Wagner et al, CQG, 2012
- MICROSCOPE: Bergé et al, PRL, 2018
- Antypas, PRL, 2019
- DAMNED: Savalle et al, arXiv:2006.07055

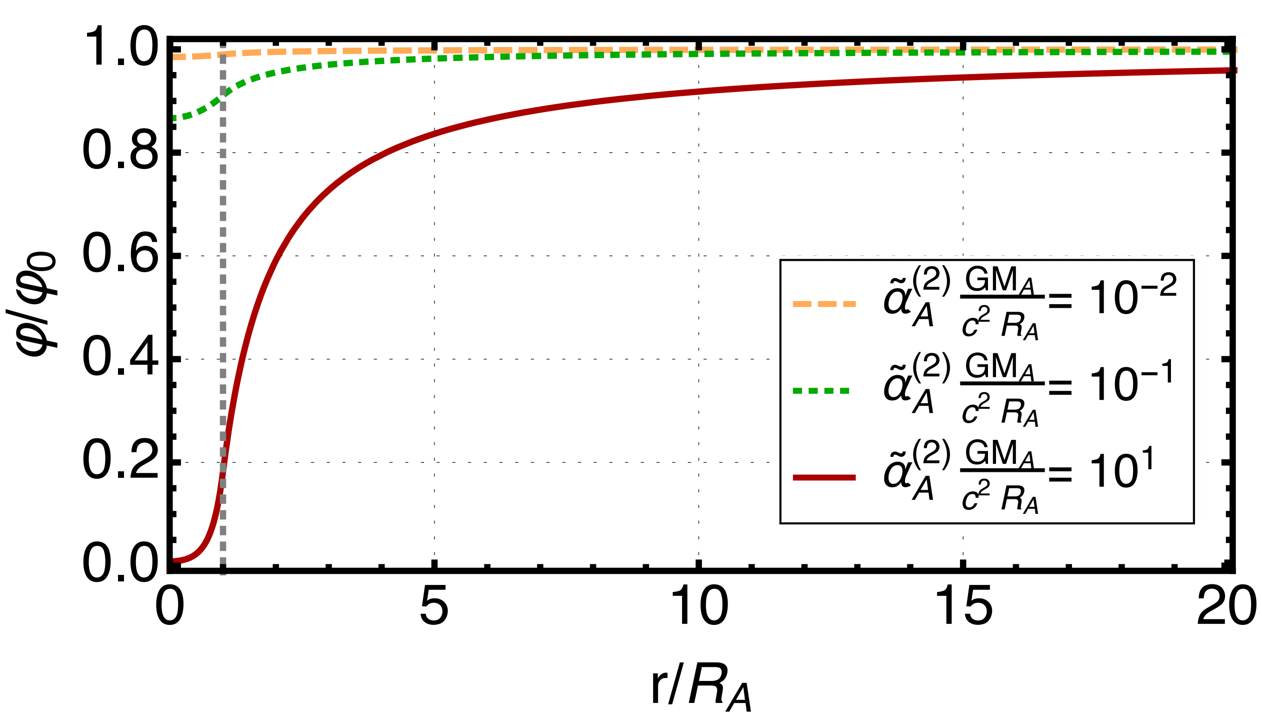
Scalar field for a quadratic coupling

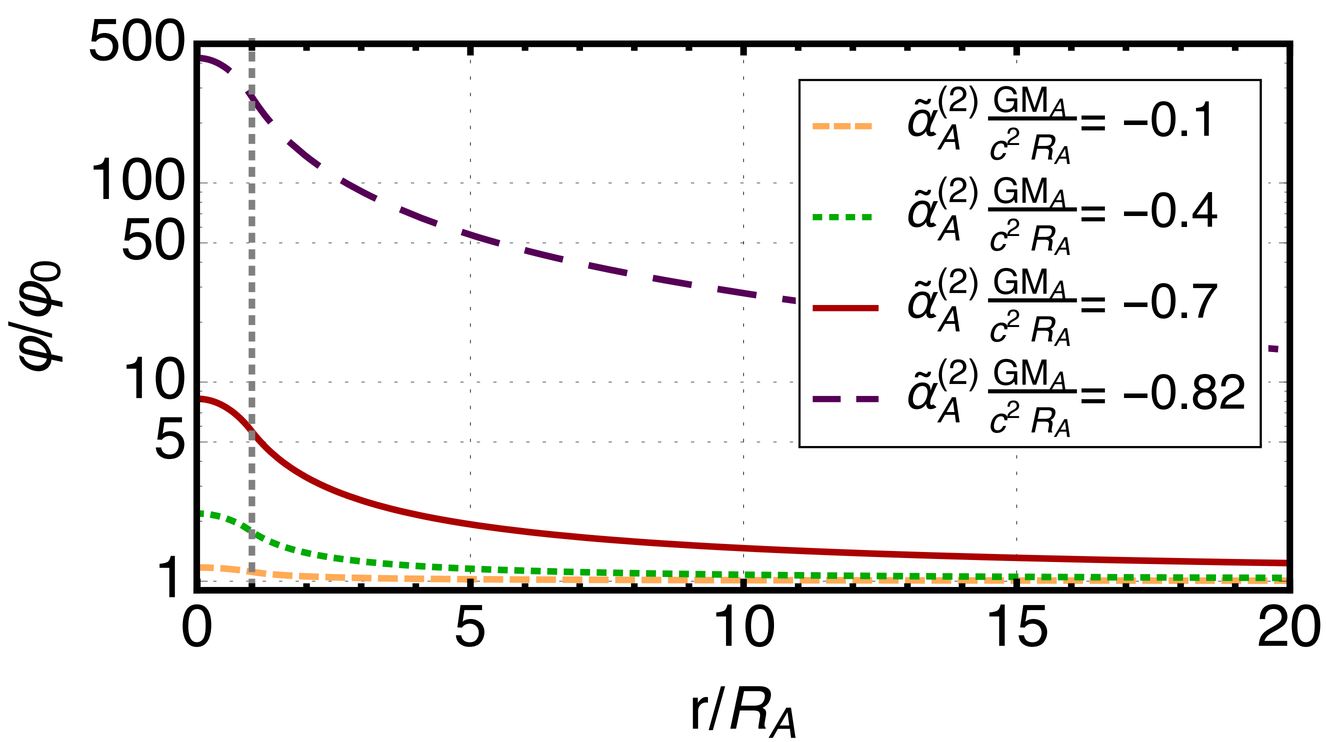
- More difficult to solve

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

see A. Hees et al, PRD, 2018

- No more Yukawa term! And a non-linear dependency for $s_A^{(2)}$





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

Similar to the "scalarization", see Damour and Esposito-Farèse, PRL, 1993

This leads to a rich phenomenology

- Comparison of atomic sensors:

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

Atomic clocks on elliptic orbits?

- UFF measurements

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

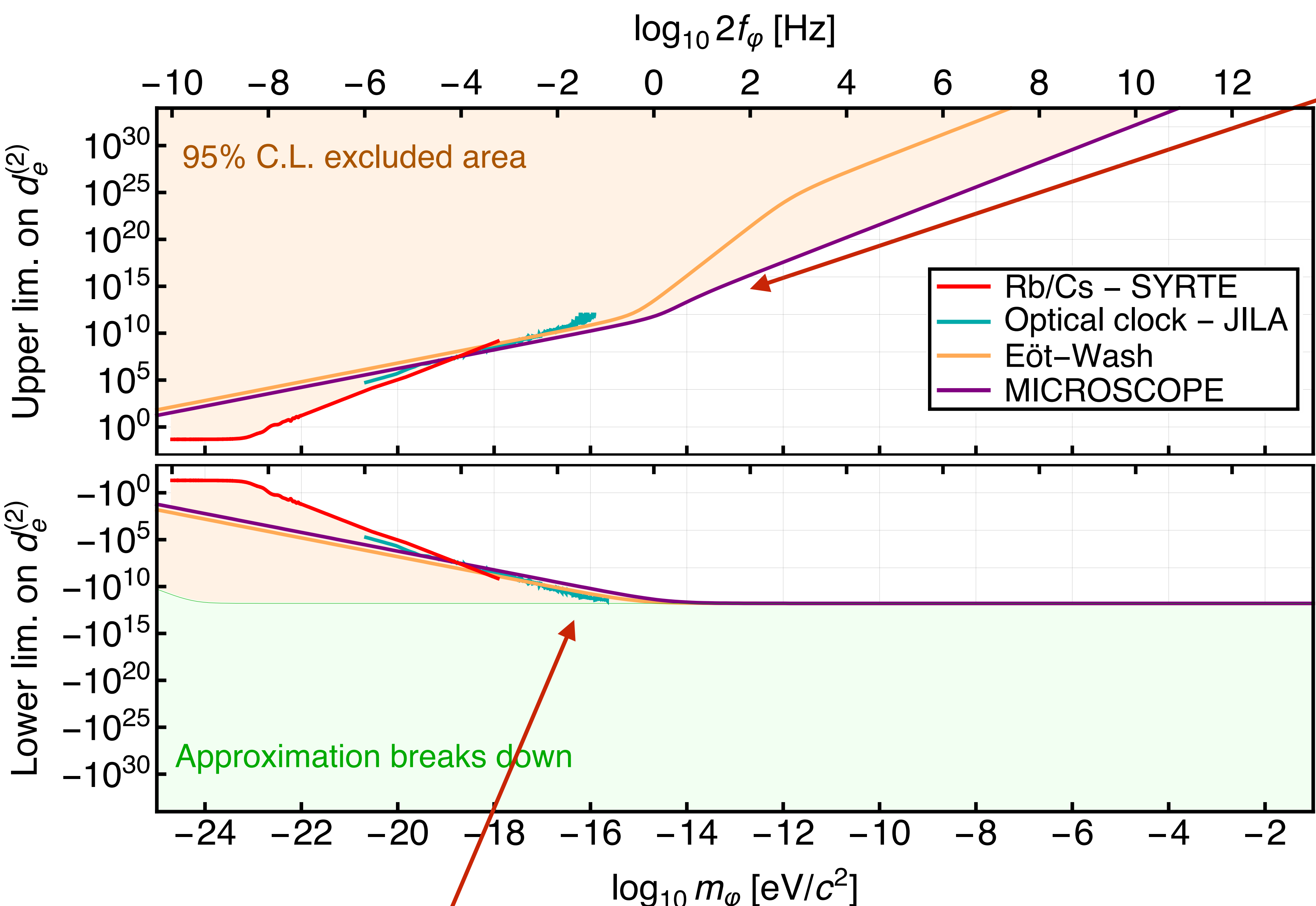
η that depends on r (directly related to Eöt-Wash and MICROSCOPE results)

2 terms that oscillate, amplitude depends on position

See A. Hees et al, PRD, 2018

Constraints on the quadratic couplings

Impact of screening



Impact of amplification

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

see A. Hees et al, PRD, 2018

Where to search for new physics?

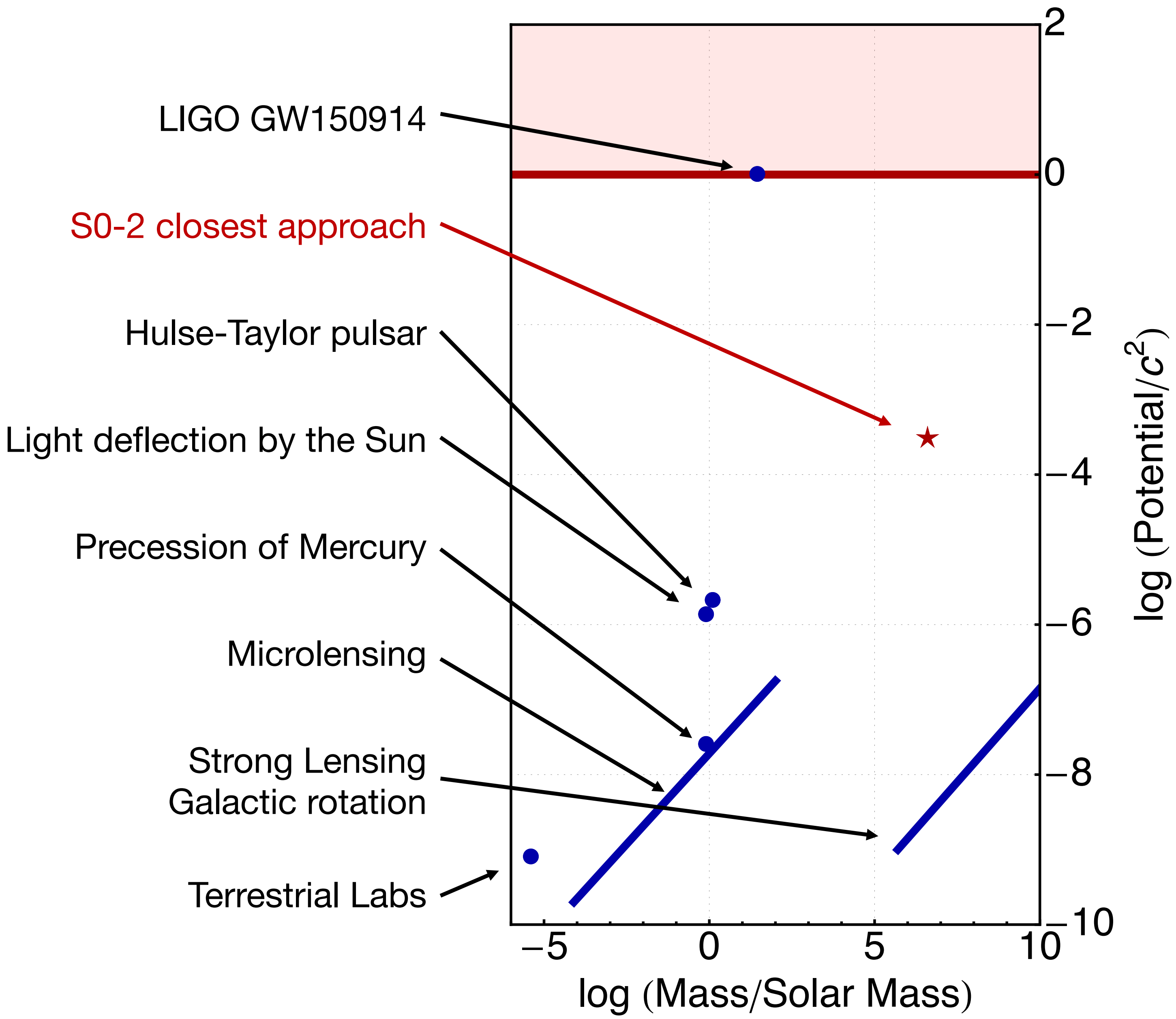
1) Improving standard tests of the Equivalence Principle

2) consider other frameworks and use existing data to search for new signatures. Example: model of ultralight Dark Matter

3) consider new regimes unexplored so far. Example: S-stars around our Galactic Center

work done in collaboration with the UCLA Galactic Center Group (A. Ghez, T. Do, et al)

GC observations probe another region of the parameters space



- strong field effects may show deviations from GR
- deviation "hidden" in some region of space-time ("screening mechanism")
- is gravitation working as expected around BH?

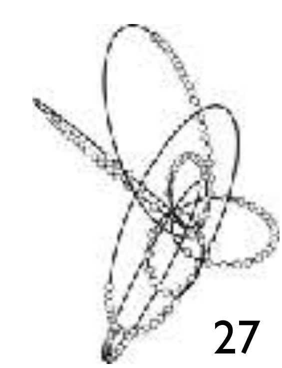
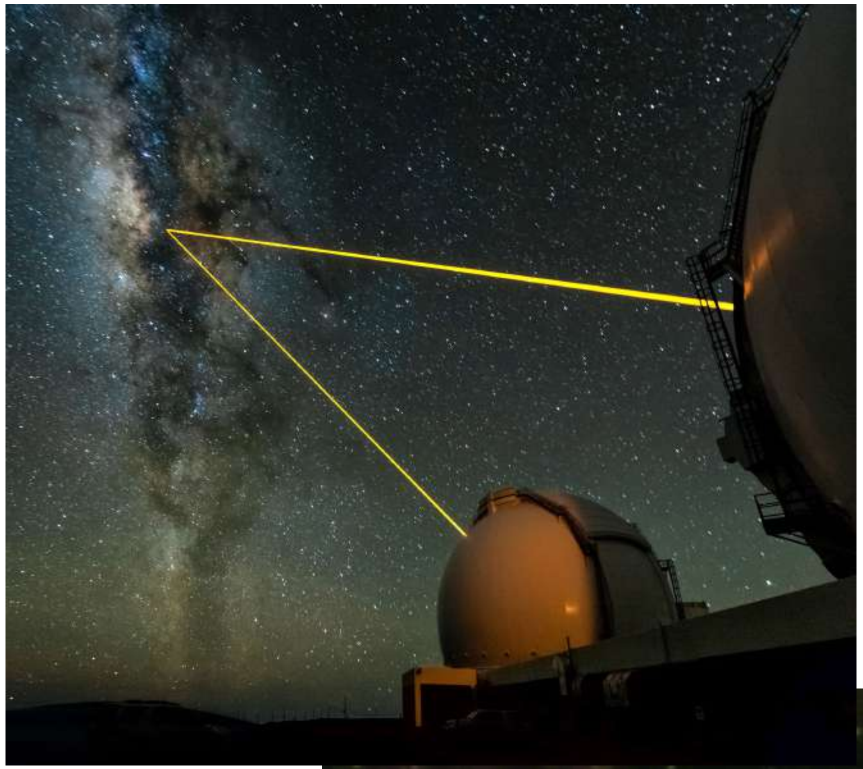


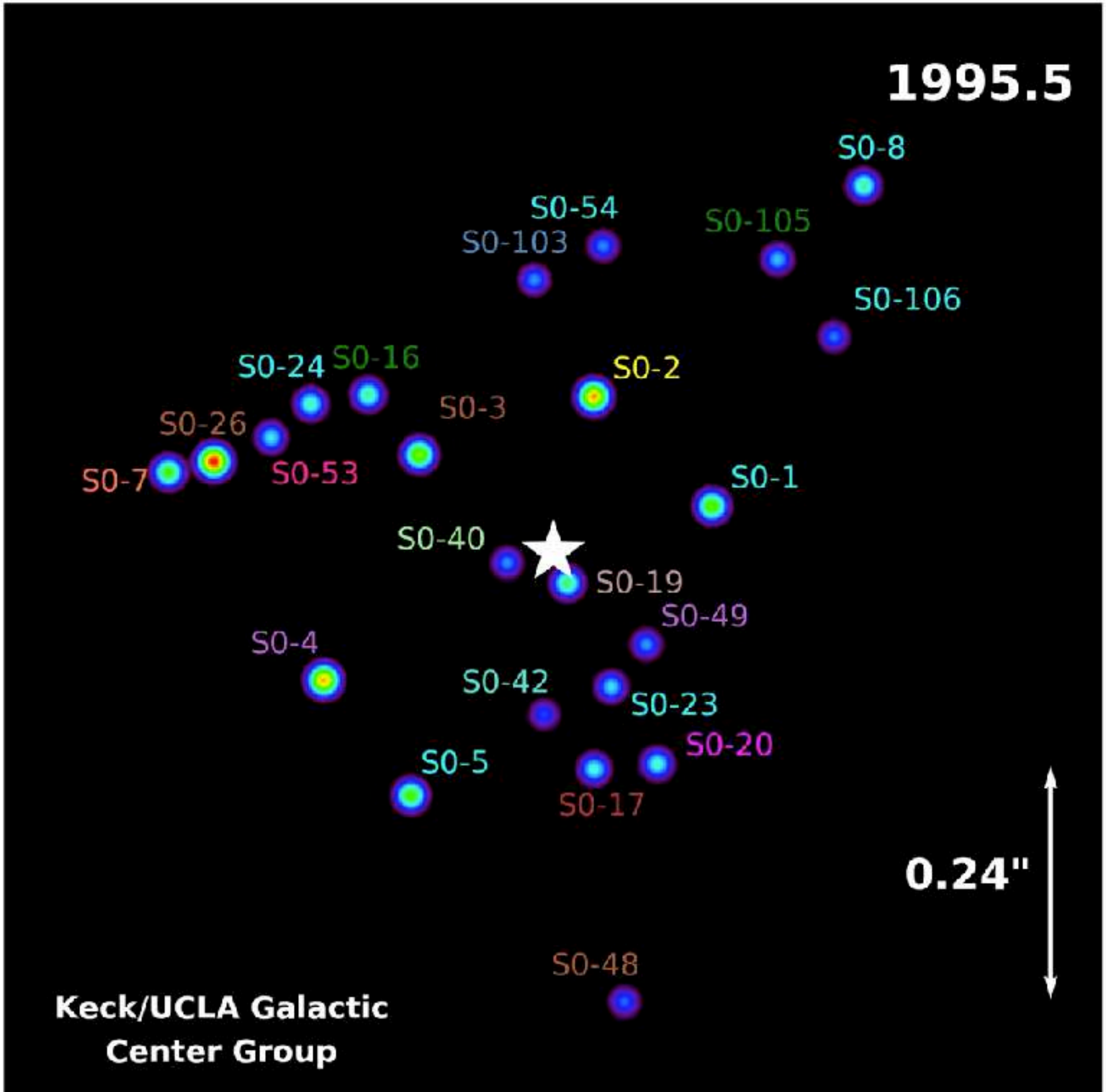
Figure inspired by D. Psaltis, 2004

Stars orbiting the GC have been observed since 1995

- Keck Observatory:
  - Speckle and Adaptive Optics **imaging**. *Accuracy @0.15 mas*
  - ***Spectroscopic*** measurements. *Accuracy @20 km/s*
- The motion of ~ 100ish stars is tracked:
  - construction of an absolute reference frame
  - the central arc second: Keplerian motion
- Similar observations have been taken @VLT

See Sakai et al, ApJ, 2019
Jia et al, ApJ, 2019

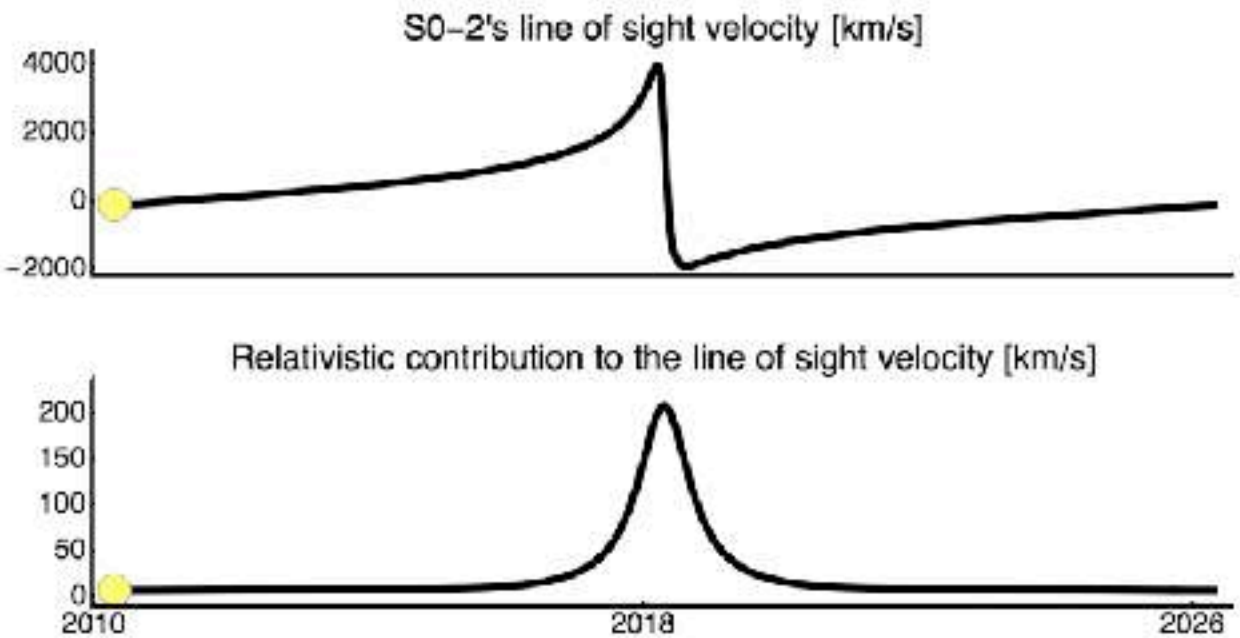


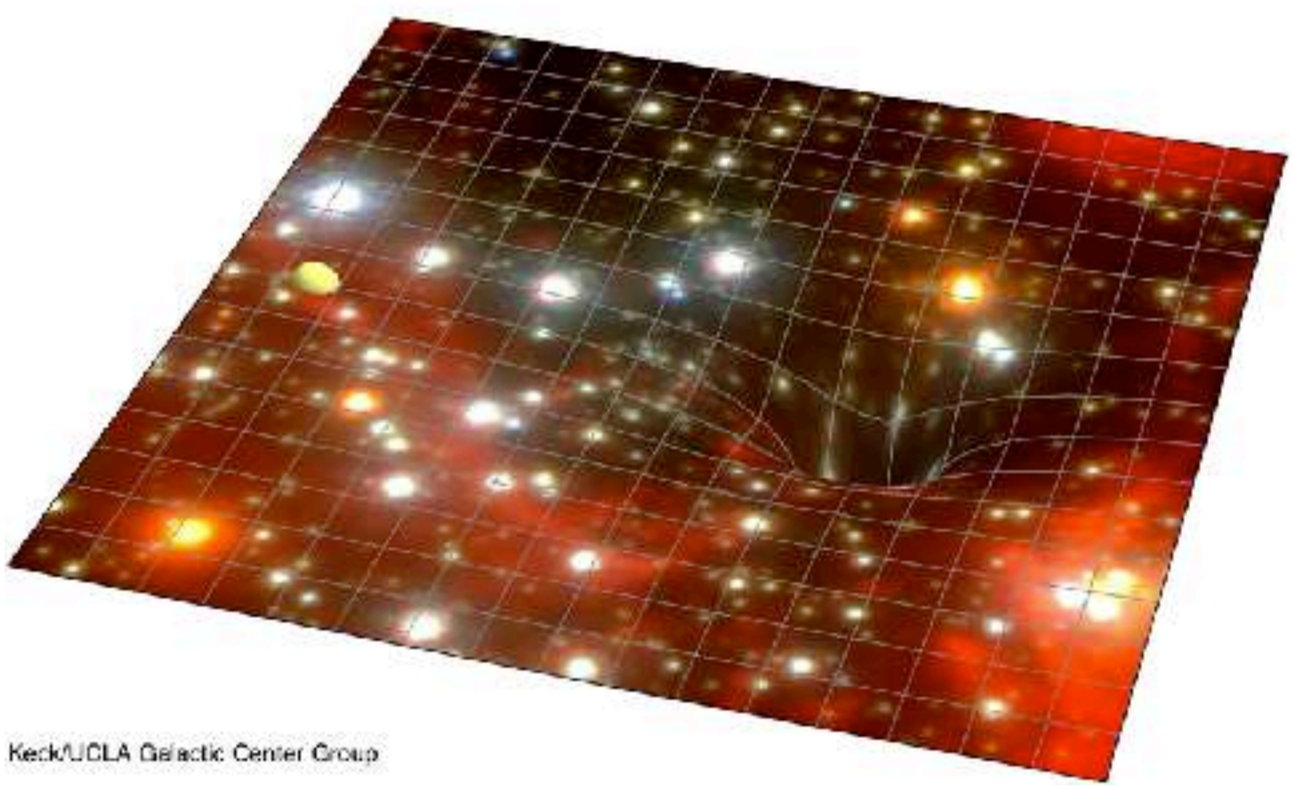

1995.5
S0-8
S0-54
S0-105
S0-103
S0-106
S0-24
S0-16
S0-2
S0-26
S0-3
S0-53
S0-7
S0-1
S0-40
S0-19
S0-49
S0-4
S0-42
S0-23
S0-20
S0-5
S0-17
0.24"
S0-48
Keck/UCLA Galactic
Center Group

Can these observations be used to probe fundamental physics?

Is the Equivalence Principle valid around a SMBH?

Measurement of the relativistic redshift during S0-2/S2's closest approach in 2018





- Relativistic redshift (eq. principle)

$$[RV]_{\mathrm{rel}} = \frac{v^2}{2c} + \frac{GM}{rc}$$

peak @ ~ 200 km/s

- S0-2/S2 was followed very closely at Keck and at the VLT in 2018

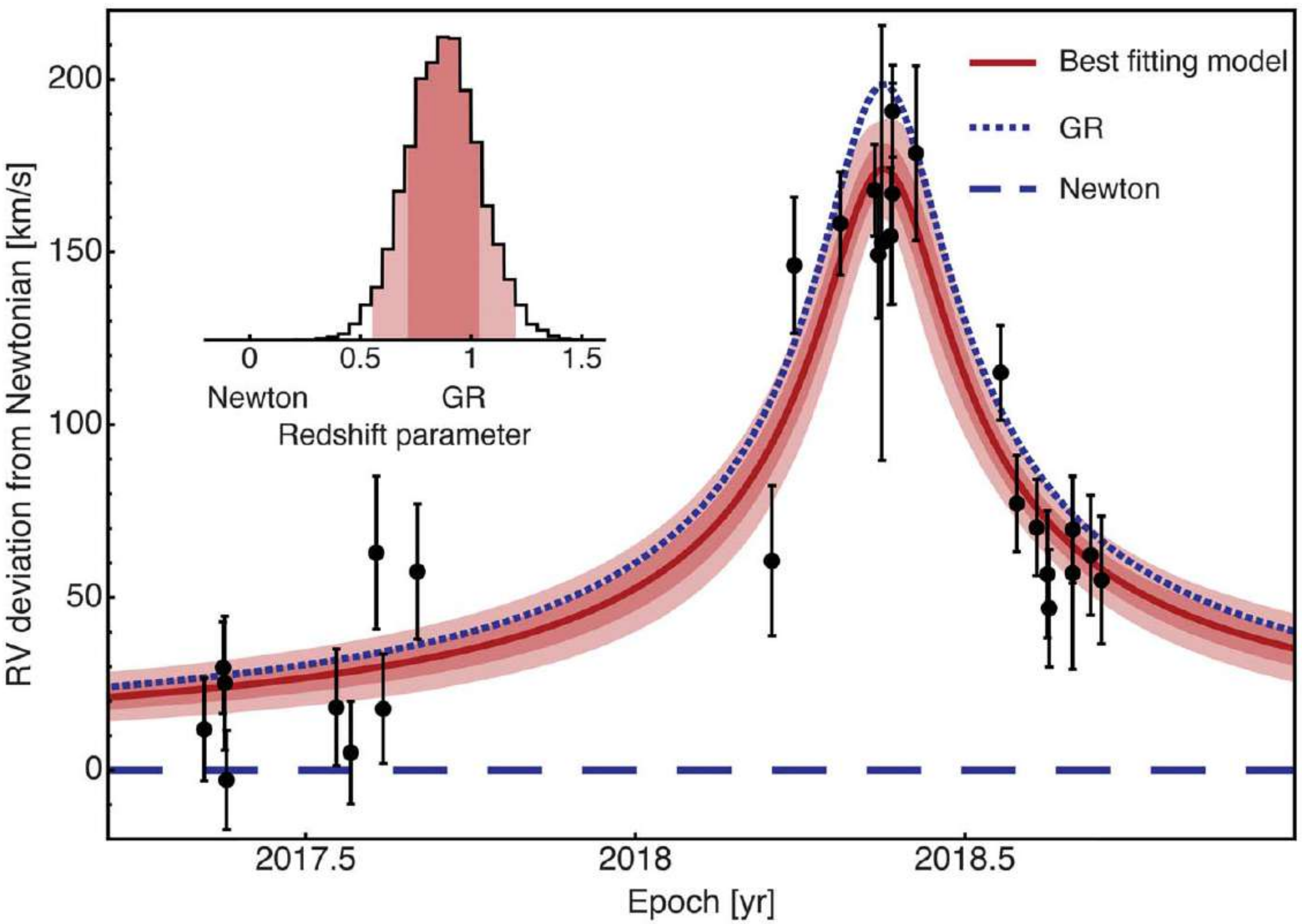
Measuring the redshift requires a careful analysis

- 45 astrometric measurements (from two instruments) and 115 radial velocity (RV) measurements (from 6 instruments - 4 telescopes: Keck, VLT, GEMINI and SUBARU)
- Combined in an orbital fit that includes: SMBH mass, SMBH position/velocity, orbital parameters, + parameters for systematics
- Thorough analysis of systematics:
  - Additional systematic uncertainty
  - Correlation within the astrometric dataset
  - Offset between instruments
  - Use of different telescope to check for possible systematics
  - Measurement of RV standards to check for systematics
  - …

see Do et al, Science, 2019

S0-2's relativistic redshift is consistent with GR

Υ is a parameter that encodes a deviation from relativistic redshift (=1 in GR, =0 in Newton)



$$RV = [RV]_{\rm Newton} + \Upsilon \left[\frac{v^2}{2c} + \frac{GM}{rc} \right]$$

$$\Upsilon = 0.88 \pm 0.17$$

see Do et al, Science, 2019

1σ agreement with GR and Newton excluded @5σ

- A similar result has been obtained by GRAVITY

$$\Upsilon = 0.9 \pm 0.06(\text{stat}) \pm 0.15(\text{syst})$$

see GRAVITY coll. , A & A, 2018

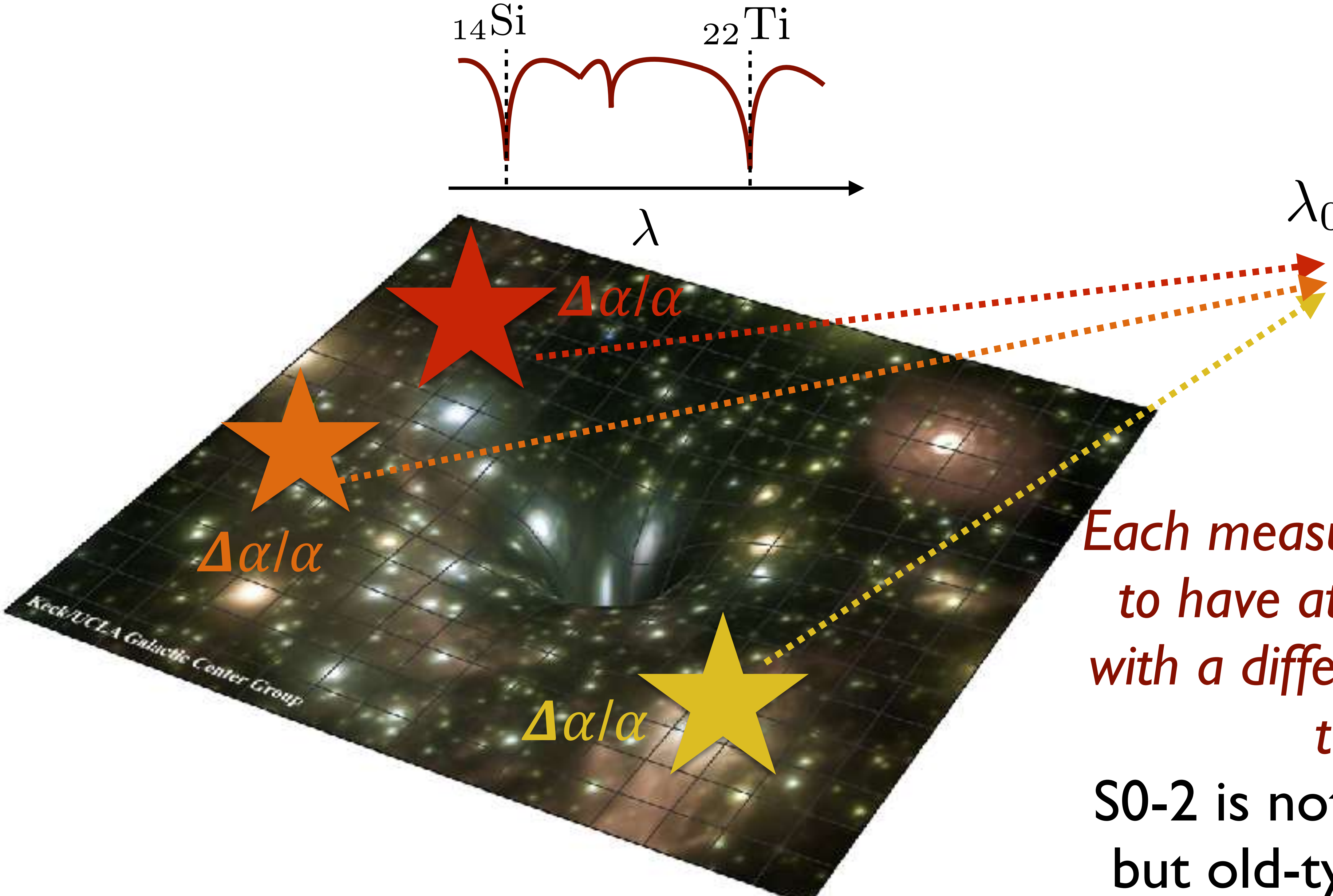
First test of the equivalence principle around a BH

- This result is 4 orders of magnitude less stringent than solar system measurements but this is the first redshift test around a BH

see Do et al, Science, 2019
GRAVITY coll.,A & A, 2018

- Another way to test the equivalence Principle is to search for a variation of the constants of Nature around the SMBH
$\rightarrow$ particularly interesting considering the recent results reporting a varying α around a white dwarf and with quasars

Spectroscopy measurements in the GC can be used to search for variations in α



Each measurement needs to have at least 2 lines with a different sensitivity to α.

S0-2 is not appropriate but old-type stars are appropriate

Six old-type stars have been identified as promising

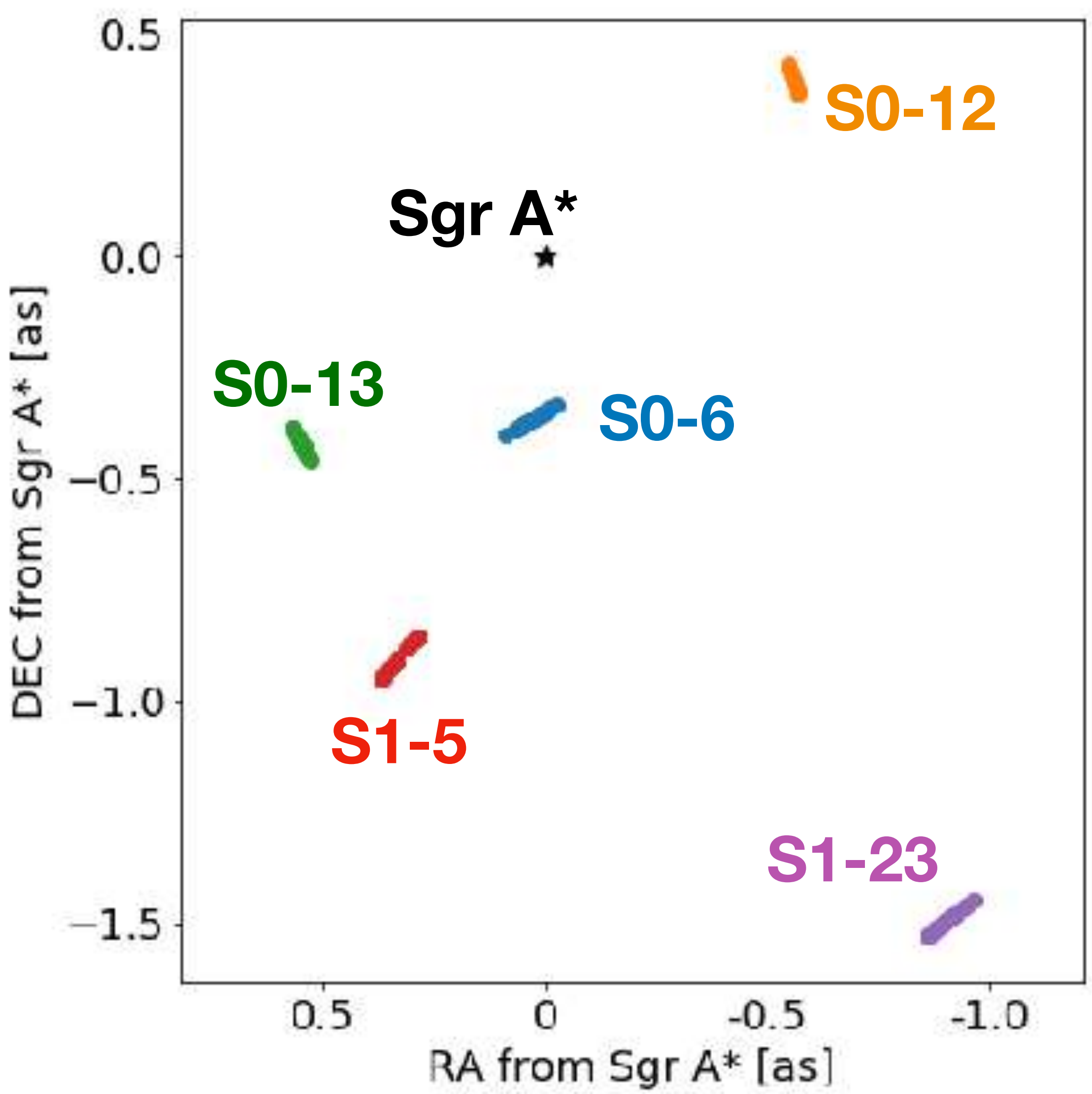
- Needs a lot of spectral lines (with different sensitivities to α): old-type stars
- Bright, to ensure a high SNR. Magnitude < 15
- Sufficiently in the central region: existence of measurements and probe of α "close" to the BH

- S0-6 - Mag: 14.1
- S0-12 - Mag: 14.3
- S0-13 - Mag: 13.3
- S1-5 - Mag: 12.7

measured by NIFS in 2018

- S1-23 - Mag: 12.7

measured by NIRSPEC in 2016



see Hees et al, PRL, 2020

Conceptually easy to infer a mapping of α in the GC

- For each spectrum (i.e. one star at one epoch t_i), we extract N lines (j) independently
- Lines need to be isolated enough to be extracted alone: 15 lines identified

Quantity of interest

Measurement of the line j at epoch t_i

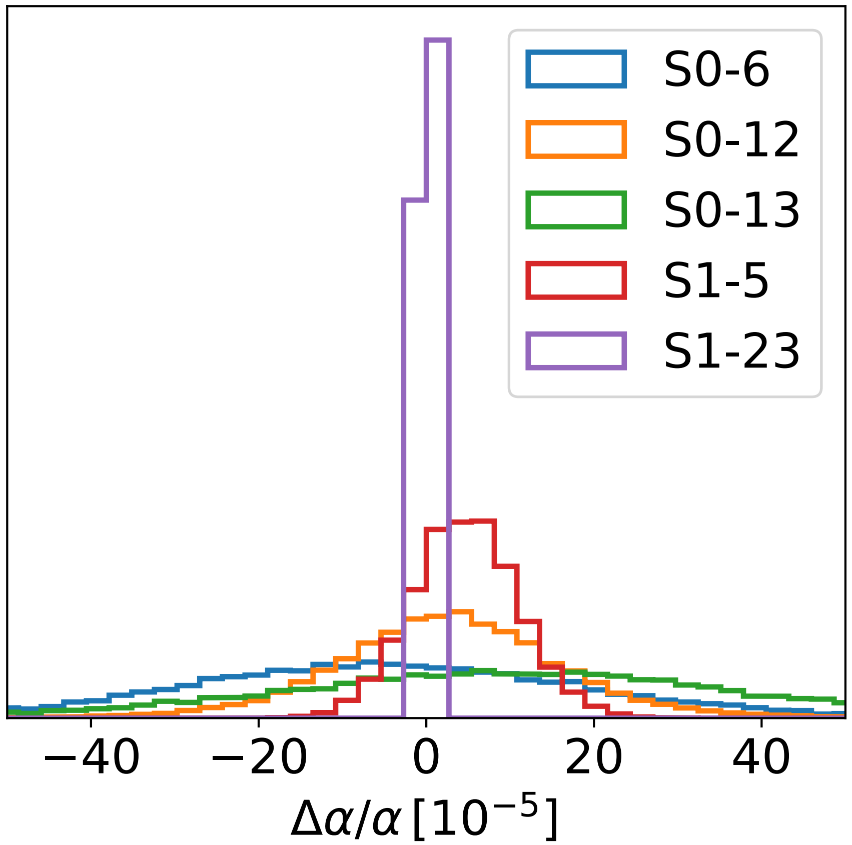
$$\left.\frac{\Delta\lambda_j}{\lambda_j}\right|_{z_i} = z_i - k_{\alpha,j}\frac{\Delta\alpha}{\alpha}$$

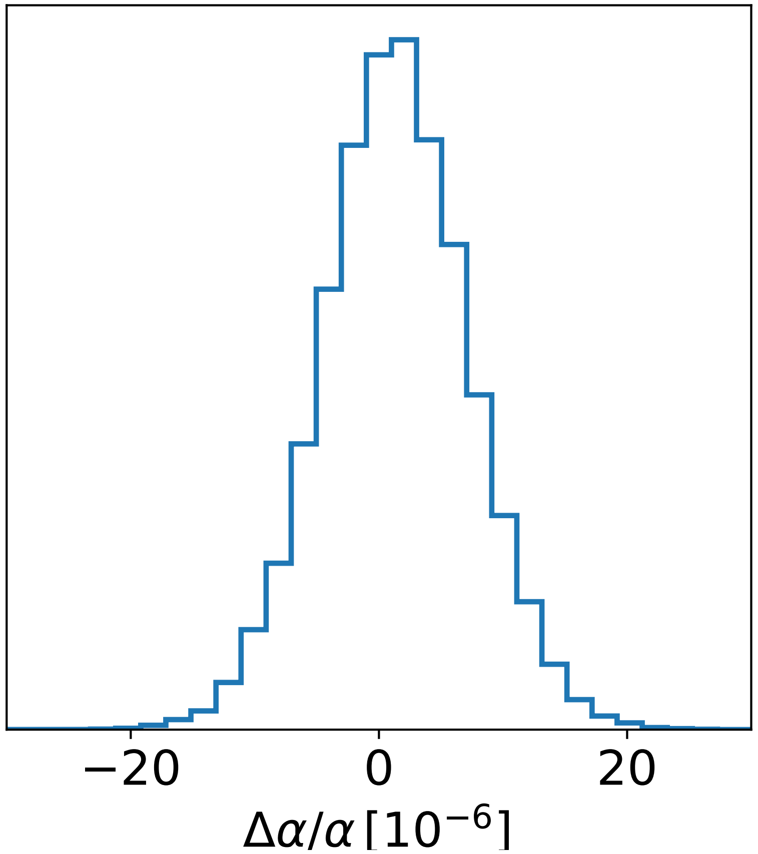
RV + relativistic redshift

Sensitivity of the line j to α: determined by solving the Schrödinger equation (very costly computation)

- Fit with 2 parameters: z_i and $\Delta\alpha/\alpha$

No variations of α detected around Sgr A*





- Variation of the fine structure constant between the GC and Earth constrained

$$\frac{\Delta\alpha}{\alpha} = (1.4 \pm 5.8) \times 10^{-6}$$

- Same order of magnitude as constraints from quasars
- NIRSPEC measurements are the ones the most constraining

see Hees et al, PRL, 2020

Constraint on variations of α with respect to the gravitational potential

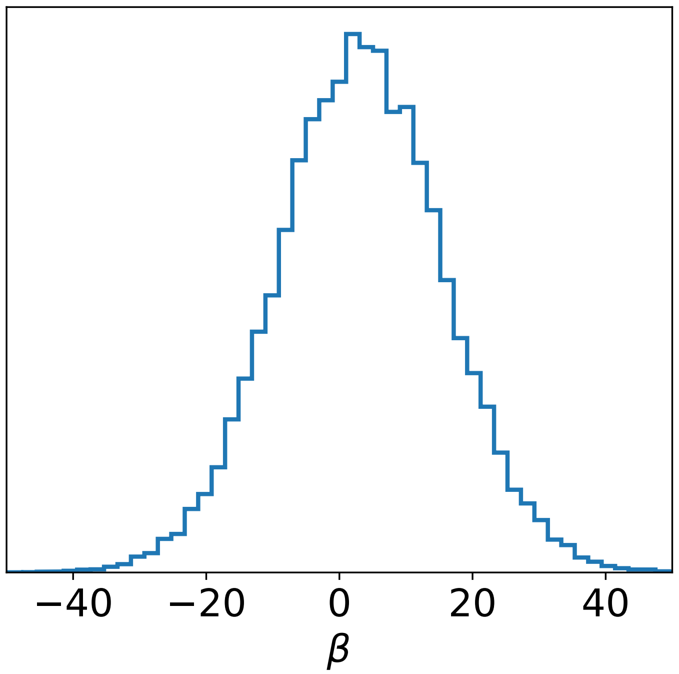
- A parametrization that appears naturally in some tensor-scalar theories of gravitation

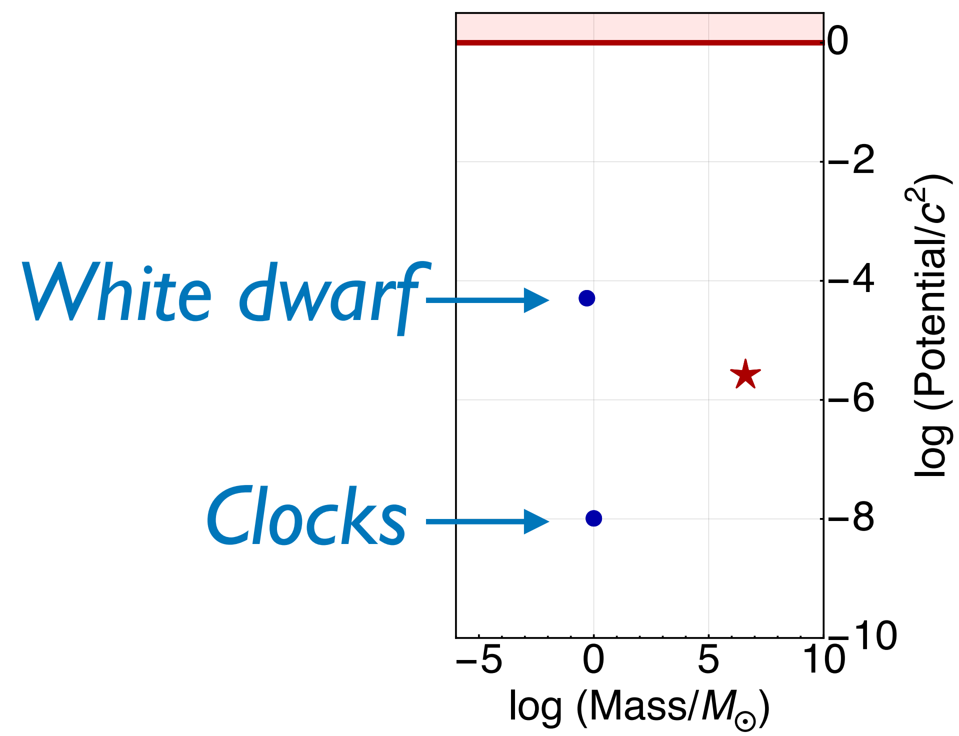
$$\frac{\Delta\alpha}{\alpha} = \beta \frac{\Delta U}{c^2}$$

gravitational potential

fundamental parameter

$\beta = 3 \pm 12$





- 1 order of magnitude less stringent than the white dwarf but for the first time around a BH
- Dedicated measurements can improve this result by 1 order of magnitude

see Hees et al, PRL, 2020

Where to search for deviations from GR?

1) consider new projects with a better accuracy to improve constraints on the "standard" frameworks

2) consider other frameworks and use existing data to search for new signatures

3) consider new regimes unexplored so far or new region in space-time

4) Conclusion

Conclusion

- Searching for violation of the EEP is one promising way to search for new physics: unification theories, Dark Matter/Dark Energy

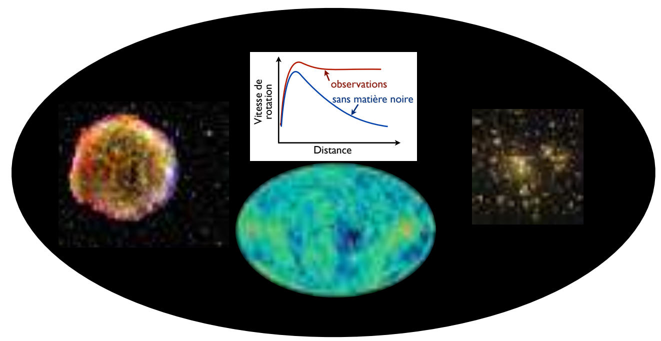
- Challenge

  - theory: construct alternative theories
    1) not suffering from theoretical pathology
    2) able to explain a wide set of observations at different scales
    3) that would solve some of the theoretical problems (quantum gravity, DM/DE…)

  - observations:
    1) searching for "tiny" deviations (UFF with MICROSCOPE)
    2) for new signatures (new Dark Matter signatures)
    3) or in regimes unexplored so far (around a SMBH in our GC)

Improve our fundamental understanding of the gravitation interaction and of physics in general

Thank you for your attention



Astronomy & cosmology

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

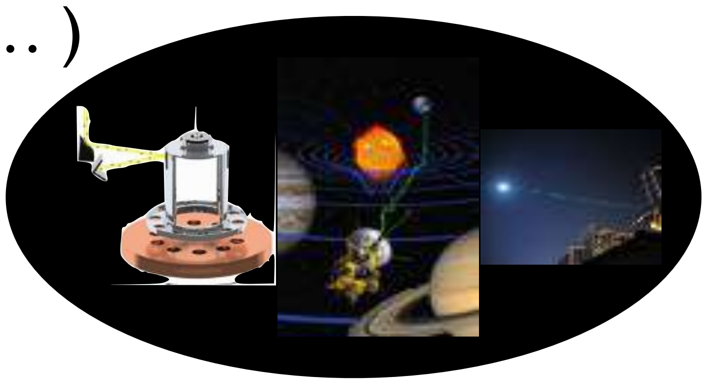
Quantum Gravity

Unification

DM and DE

Local physics

(Solar System, lab tests, GNSS, …)



High energy

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

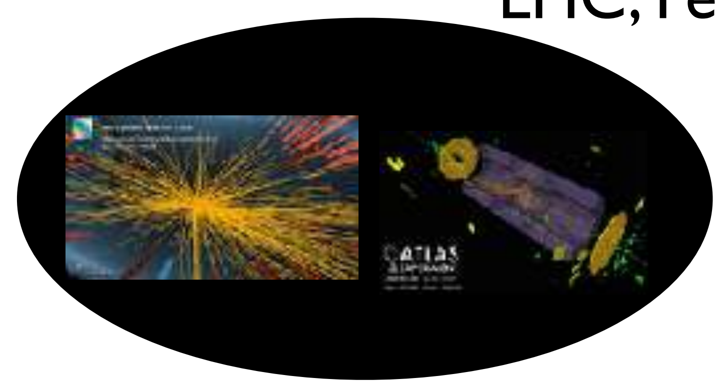


Figure inspired by Altschul et al, Adv, in Space Res. 55, 501, 2015