New test of Lorentz invariance using the MICROSCOPE space mission

Hélène Pihan-Le Bars[1], Christine Guerlin[1,2], Aurélien Hees[1], Romain Peaucelle[1,5], Jay Tasson[4], Quentin Bailey[3], Geoffrey Mo[4], Pacôme Delva[1], Frédéric Meynadier[1,6], Pierre Touboul[7], Gilles Métris[8], Manuel Rodrigues[7], Joël Bergé[7], and Peter Wolf[1]

ACES workshop, Paris, Oct. 28-29, 2019

[1] SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, France
[2] LKB, ENS, Université PSL, CNRS, Sorbonne Université, Collège de France, France
[3] Department of Physics and Astronomy, Embry-Riddle Aeronautical University, Arizona, USA
[4] Department of Physics and Astronomy, Carleton College, Minnesota, USA
[5] Ecole Supérieure des Techniques Aéronautiques et de Construction Automobile (ESTACA), France
[6] Bureau International des Poids et Mesures, France
[7] DPHY, ONERA, Université Paris Saclay, France
[8] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur, France

[Phys. Rev. Lett., accepted, Oct. 2019]

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

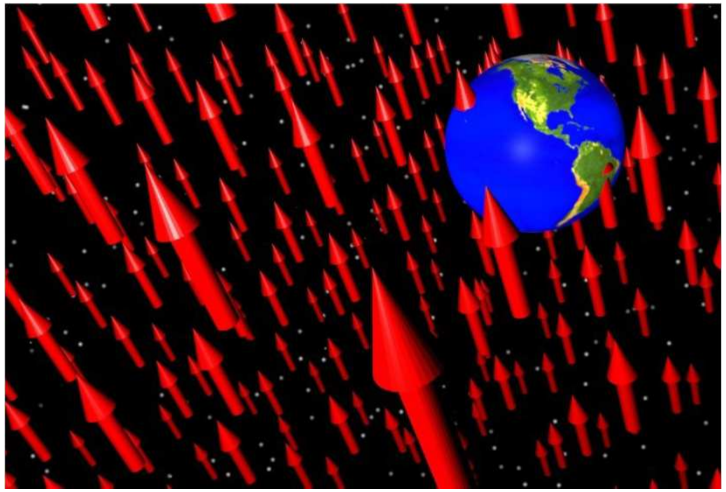
Menu

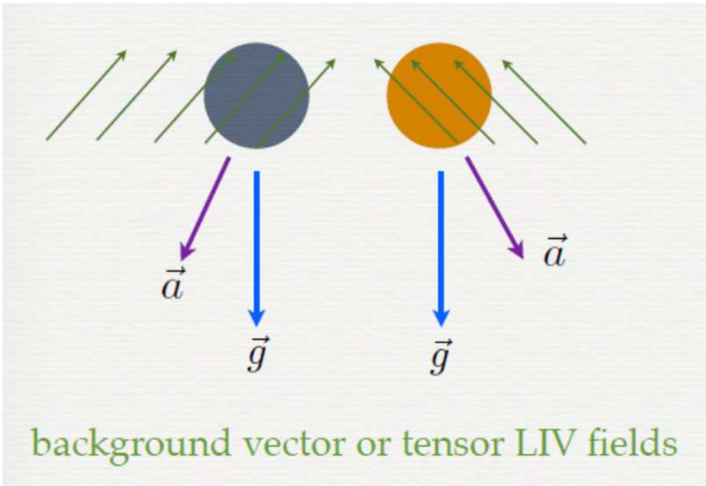
- Introduction
- The Lorentz Violating SME
- The SME signal in the Microscope data
- Analysis Method
- Data
- Comparison to independent analysis
- Final Results
- Conclusion

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

Introduction

- Analysis of the MICROSCOPE data have so far been restricted to “standard WEP” models, i.e. a possible differential acceleration of test masses along the local gradient of the Newtonian potential ***g***.
- The Lorentz violating Standard Model Extension (SME) developed since the late 1990s by Kostelecky and co-workers leads to a different, richer, phenomenology.
- It allows for additional modulations of the signal, related to background fields in an inertial frame (SCF)

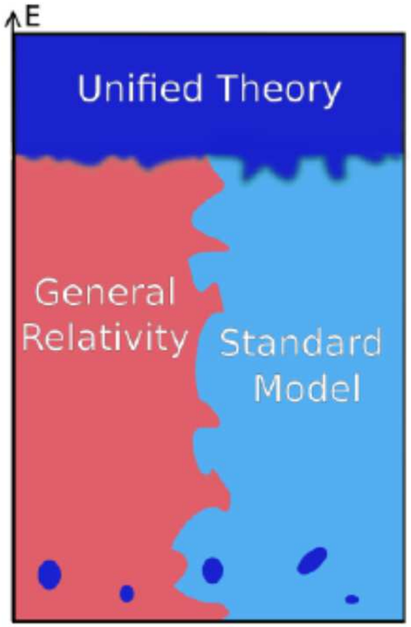




The Lorentz Violating SME

What is SME?

- Effective field theory built from SM fields & in curved spacetime
- General framework describing low-energy effects of a spontaneous LV occurring at Planck scale



Main features

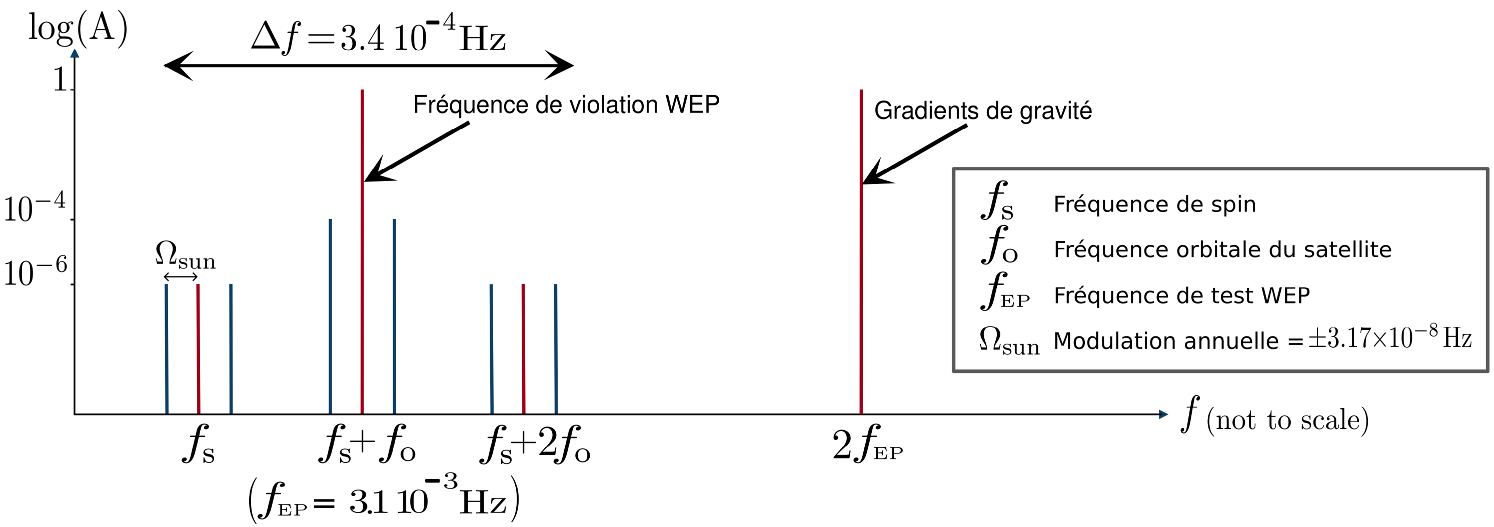
- Includes all possible observer-independent LV built from SM fields and background coefficients in the Lagrangian
- These coefficients vanish if the symmetry is preserved
- LV terms are expected to be strongly suppressed compared with non violating terms
- Phenomenological, not quantitatively predictive
- Enables the derivation of experimental observables

[Kostelecky *et al.*, PRD 51, 1995], [Kostelecky *et al.*, PRD 58, 1998]

The SME signal in the MICROSCOPE data

$$S^B \simeq \int d\lambda(-m^B c\sqrt{-g_{\mu\nu}u^\mu u^\nu} - (a^B_{\text{eff}})_\mu u^\mu / c)$$

SME-coefficient: 4-vector



The SME signal in the MICROSCOPE data

$$\gamma_{\hat{x}} = b + S_{\hat{x}\hat{x}}\Delta_{\hat{x}} + (S_{\hat{x}\hat{y}} + \dot{\Omega}_z)\Delta_{\hat{y}} + (S_{\hat{x}\hat{z}} - \dot{\Omega}_y)\Delta_{\hat{z}} + 2g_{\hat{x}}\left[\alpha(\bar{a}^{(\mathrm{d})}_{\mathrm{eff}})_T + \beta_X\alpha(\bar{a}^{(\mathrm{d})}_{\mathrm{eff}})_X + \beta_Y\alpha(\bar{a}^{(\mathrm{d})}_{\mathrm{eff}})_Y + \beta_Z\alpha(\bar{a}^{(\mathrm{d})}_{\mathrm{eff}})_Z\right]$$
$$-\frac{6GM_\oplus R_\oplus^2}{5cr^5}\left(R_{\hat{x}\tilde{x}}\tilde{x}^{\mathrm{orb}} + R_{\hat{x}\tilde{y}}\tilde{y}^{\mathrm{orb}} + R_{\hat{x}\tilde{z}}\tilde{z}^{\mathrm{orb}}\right)\left[\tilde{x}^{\mathrm{orb}}\alpha(\bar{a}^{(\mathrm{d})}_{\mathrm{eff}})_Y - \tilde{y}^{\mathrm{orb}}\alpha(\bar{a}^{(\mathrm{d})}_{\mathrm{eff}})_X\right]\omega_{\tilde{z}}$$
$$+\frac{2GM_\oplus R_\oplus^2}{5cr^3}\left[\alpha(\bar{a}^{(\mathrm{d})}_{\mathrm{eff}})_Y R_{\hat{x}\tilde{x}} - \alpha(\bar{a}^{(\mathrm{d})}_{\mathrm{eff}})_X R_{\hat{x}\tilde{y}}\right]\omega_{\tilde{z}}\,,$$

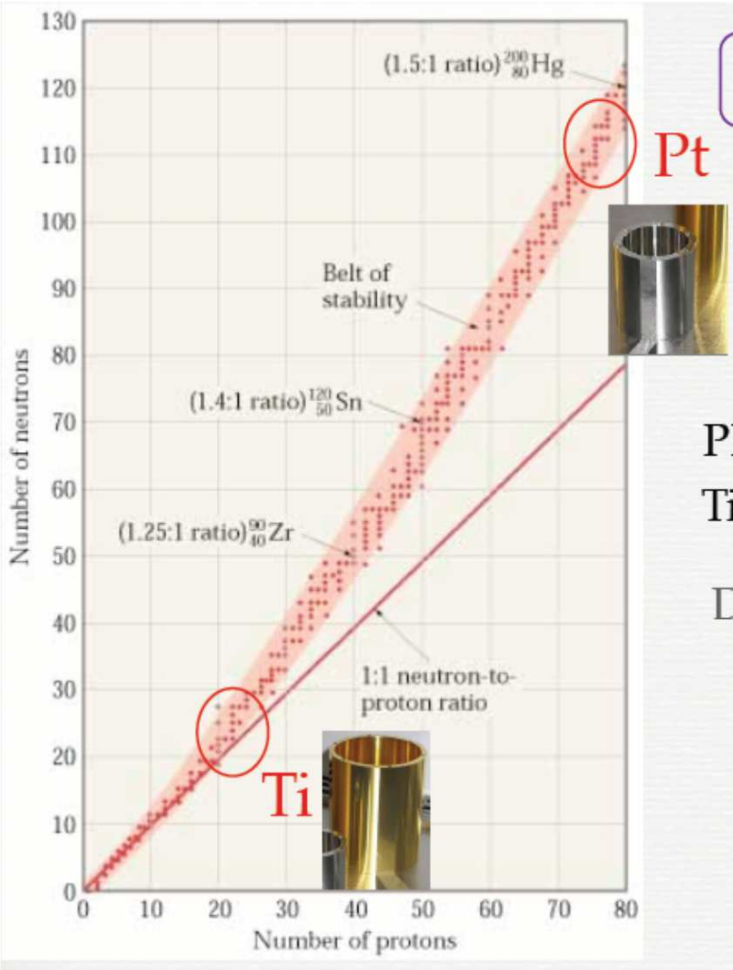
Mission data
SME-coeff. + technical parameters

- Similar expressions for acceleration along *y* and *z* in the instrument frame.
- Derived from [Kostelecky & Tasson, 2011]. Cross checked independently by J. Tasson and Q. Bailey.
- Need to determine the 4 components of the differential SME vector coefficient $\alpha(\bar{a}^{(\mathrm{d})}_{\mathrm{eff}})$.

$$(\bar{a}^{(\mathrm{d})}_{\mathrm{eff}})_\mu = \frac{(\bar{a}^{\mathrm{Pt}}_{\mathrm{eff}})_\mu}{m^{\mathrm{Pt}}c^2} - \frac{(\bar{a}^{\mathrm{Ti}}_{\mathrm{eff}})_\mu}{m^{\mathrm{Ti}}c^2} = \sum_{w=n,p,e}\left(\frac{N^{\mathrm{Pt}}_w}{m^{\mathrm{Pt}}c^2} - \frac{N^{\mathrm{Ti}}_w}{m^{\mathrm{Ti}}c^2}\right)(\bar{a}^w_{\mathrm{eff}})_\mu$$

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

The SME signal in the MICROSCOPE data



$$\alpha(\overline{a}^{(\mathrm{d})}_{\mathrm{eff}})_\mu = A \cdot \alpha(\overline{a}_{\mathrm{eff}})^{\mathrm{n}}_\mu + C \cdot \alpha(\overline{a}_{\mathrm{eff}})^{(\mathrm{e+p})}_\mu$$

$$A \approx \Delta\left(\frac{N_n}{N_n+N_p}\right)\ \mathrm{GeV}^{-1} \qquad C \approx \Delta\left(\frac{N_p}{N_n+N_p}\right)\ \mathrm{GeV}^{-1} \approx -A$$

neutron ratio

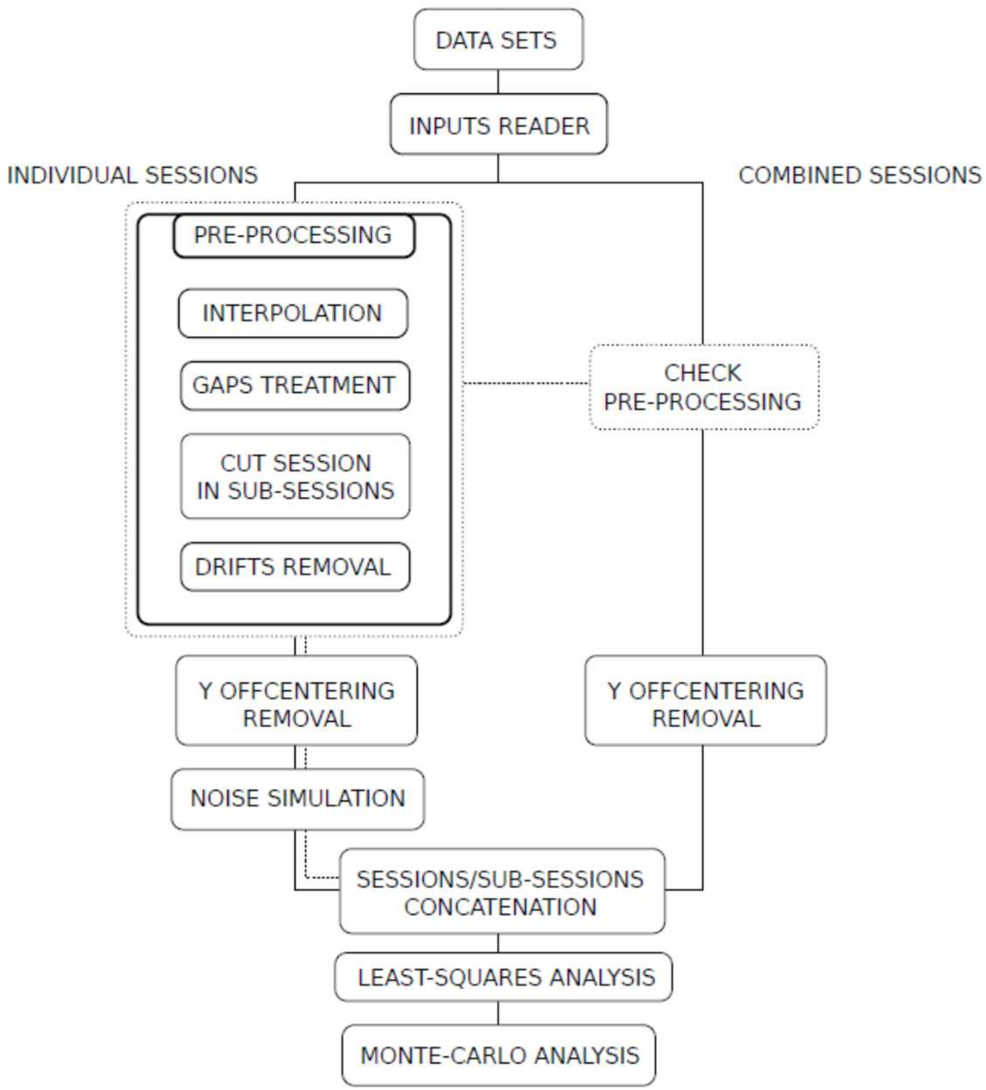
Platinum	0.6
Titanium	0.54
Difference	0.06

Need to take isotopic composition and alloys into account: 9Pt:1Rh and 9Ti:0.6Al:0.4Va).

$$A \simeq 0.06\ \mathrm{GeV}^{-1},\ C \simeq -0.06\ \mathrm{GeV}^{-1}$$

l'Observatoire de Paris | SYRTE

Systèmes de Référence Temps-Espace



Analysis Method

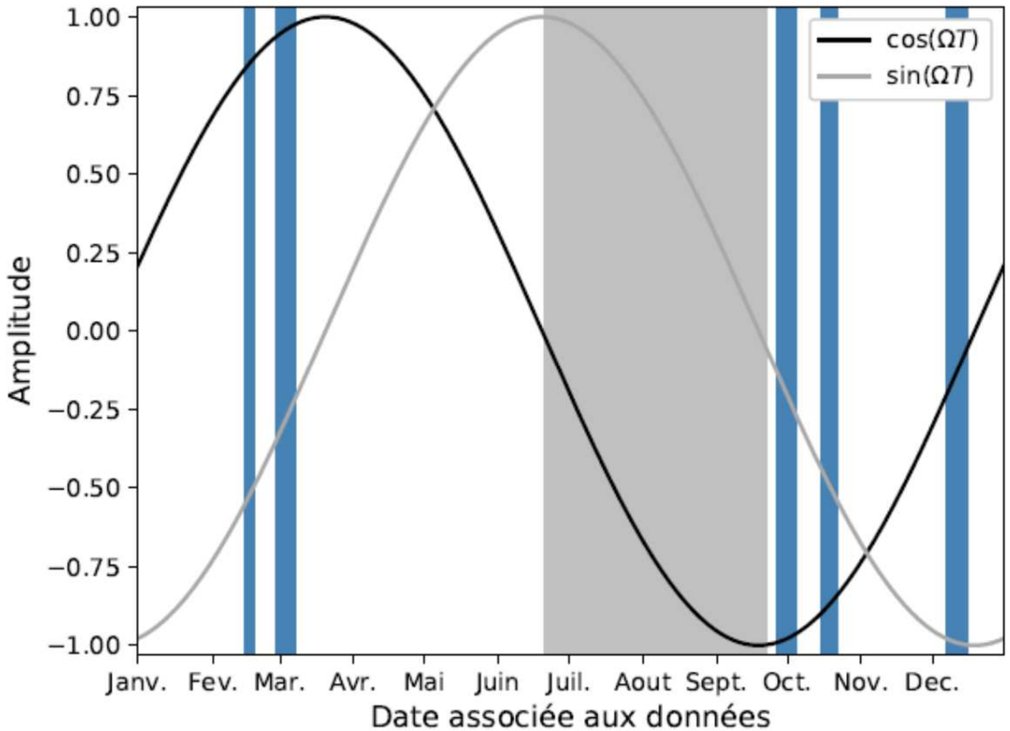
- We use a MCLS method, already successfully applied to Galileo data, and simulated ACES data.
- Determine parameters from an ordinary LS fit to data.
- Determine their uncertainties and covariances by generating N synthetic data sets with same noise properties, gaps, non-stationarity, etc… and do statistics on the N sets of fitted parameters.
- Apply exactly the same analysis to temperature data, in order to obtain systematic effect on each parameter (using sensitivity coefficient given in Touboul et al. 2017).

l'Observatoire de Paris — SYRTE

Systèmes de Référence Temps-Espace

Data

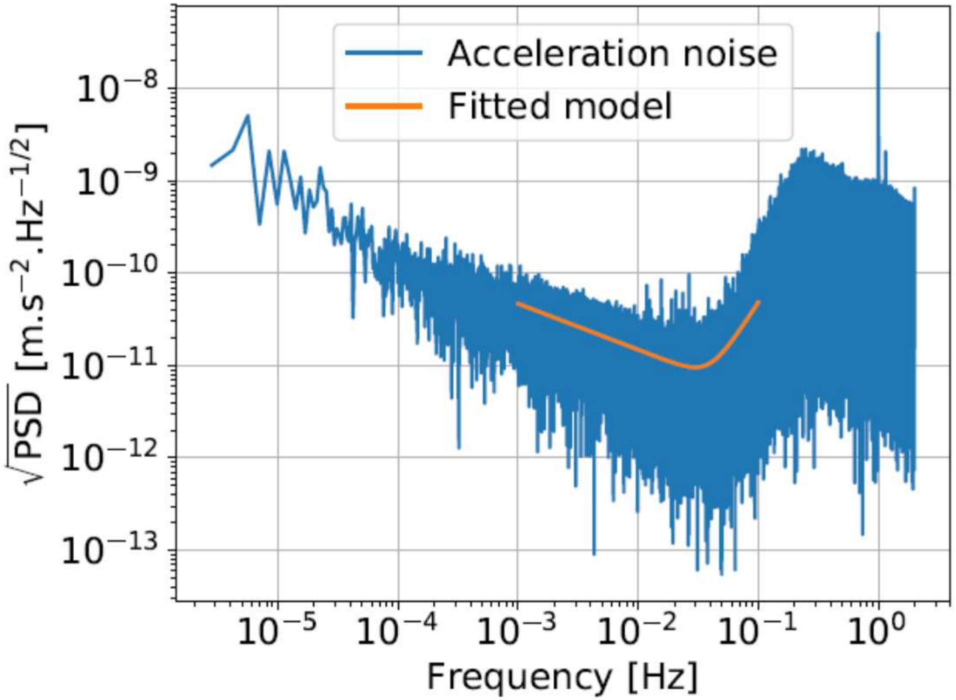
n° session	Durée en nombre d'orbites	Date de début et de fin	Pourcentage de données manquantes
210	50	2017/02/14 - 2017/02/18	7.6×10^{-4}
218	119	2017/02/28 - 2017/03/08	2.8×10^{-4}
326	101	2017/09/27 - 2017/10/04	3.7×10^{-4}
358	91	2017/10/14 - 2017/10/21	5.2×10^{-4}
404	119	2017/12/07 - 2017/12/15	4.9×10^{-4}

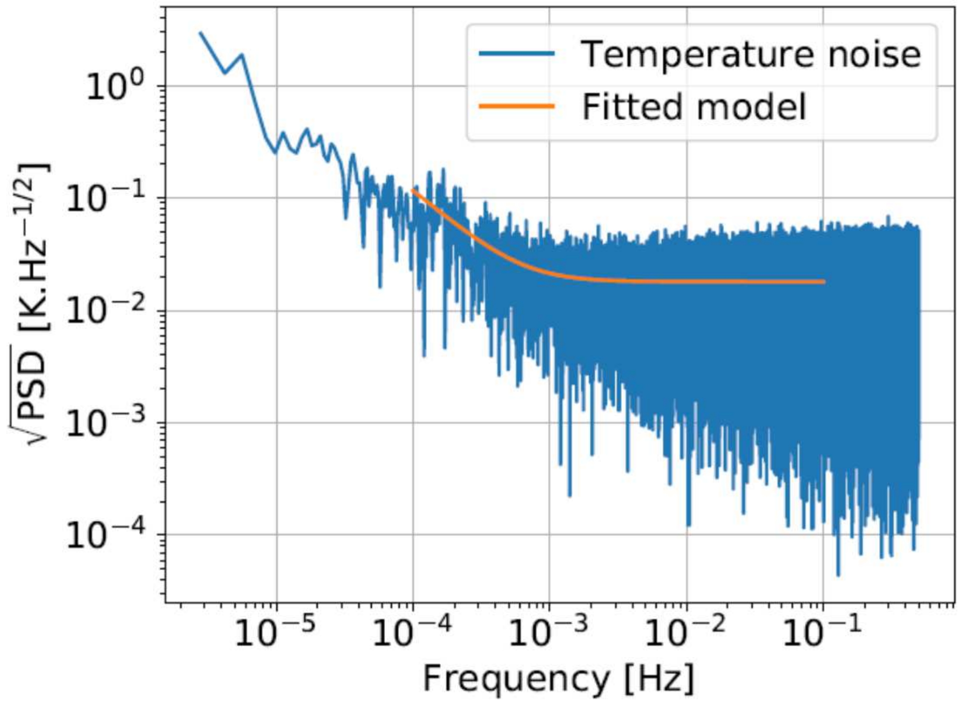


- The data sets cover most of 2017. Allows resolution of annual modulations
- Includes differential acceleration, temperature and all auxiliary data (orbit, attitude, gravity).
- In the following session 404 will be used for illustrating the procedure.

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

Data





- Data gaps are extremely rare (<0.0008%) and all = 0.25 s (one missing point), identified by a (0,1) mask. Removing them can only affect PSD noise estimation, not the fit of the parameters. They are highly unlikely to have a significant effect on the MCLS result.
- We first remove long term drifts by fitting a polynomial of order 5. We checked that fitting it at the same time with all other parameters makes no difference.

Comparison to independent analysis

- Session 218, same as the one analyzed by OCA/ONERA in Touboul et al., PRL 2017.
- Use a standard WEP model to compare results:

Parameter	Value and uncertainties	Units	PRL 2017
δ	$(4.0 \pm 9.6_{\mathrm{stat}} \pm 13.0_{\mathrm{syst}}) \times 10^{-15}$	–	$(-1 \pm 9_{\mathrm{stat}} \pm 9_{\mathrm{syst}}) \times 10^{-15}$
Δ_x	$(20.2 \pm 0.04) \times 10^{-6}$	m	$(20.1 \pm 0.1) \times 10^{-6}$
Δ_z	$(-5.77 \pm 0.04) \times 10^{-6}$	m	$(-5.6 \pm 0.1) \times 10^{-6}$

- Only statistical uncertainties shown for the offcenterings.
- All correlation coefficients < 0.08.
- Larger systematic uncertainty might be due to OCA/ONERA having used more temperature data than just session 218 [M. Rodrigues, personal communication].

Two very different and completely independent analysis methods give same result ! ☺

Final Results

Coefficient	Value and uncertainties [GeV]
$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_T$	$(6.3 \pm 12)\,(10)(6.0) \times 10^{-14}$
$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_X$	$(0.81 \pm 1.7)\,(1.4)(0.98) \times 10^{-9}$
$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_Y$	$(0.67 \pm 3.1)\,(1.4)(2.7) \times 10^{-7}$
$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_Z$	$(-1.55 \pm 7.1)\,(3.2)(6.3) \times 10^{-7}$

- Combined analysis using all five sessions, weighted according to their individual uncertainties on WEP - δ
- Uncertainties at 68% confidence
- Correlation coefficients are ≈ 0.9 between T and X components, 1 between Y and Z, and≤ 0.02 otherwise.

As we have the full covariance matrix we can determine independent linear combinations:

SME linear combination	Value and uncertainty [GeV]
a_1	$(1.7 \pm 5.5) \times 10^{-14}$
a_2	$(0.85 \pm 1.7) \times 10^{-9}$
a_3	$(0.33 \pm 1.2) \times 10^{-9}$
a_4	$(-1.7 \pm 7.7) \times 10^{-7}$

	$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_T$	$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_X$	$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_Y$	$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_Z$
a_1	1.0	$-6.0\ 10^{-5}$	$4.8\ 10^{-6}$	$2.0\ 10^{-6}$
a_2	$5.9\ 10^{-5}$	0.99	0.11	0.050
a_3	$-1.3\ 10^{-5}$	−0.12	0.91	0.39
a_4	$1.2\ 10^{-9}$	$-4.9\ 10^{-5}$	−0.40	0.92

Final Results

Following SME data tables [Kostelecky and Russel] we give "maximal sensitivities", by assuming only one non-zero coefficient at a time rounding logarithmically the 2σ uncertainty.

Coefficient	Maximal sensitivity [GeV]	Prev. best [GeV]
$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_T$	10^{-13}	10^{-11}
$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_X$	10^{-8}	10^{-8}
$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_Y$	10^{-9}	10^{-8}
$\alpha(\bar{a}_{\text{eff}}^{(\text{n-e-p})})_Z$	10^{-8}	10^{-7}

Torsion balance – reinterpretation [1,2]

Superconducting gravimeters [3], Lunar Laser Ranging [4], Binary Pulsars [5]

Improvements by 1-2 orders of magnitude !

[1] Schlamminger et al., PRL 2008
[2] Kostelecky & Tasson, PRD 2011
[3] Flowers et al., PRL 2017
[4] Bourgoin et al., PRL 2017
[5] Shao, Symmetry 2019

Conclusion and Outlook

- First SME analysis of Microscope data, improving on previous constraints by 1-2 orders of magnitude.
- 5 data sets spread over a year, more to come $\Rightarrow$ expect improvement in the near future.
- Our analysis confirms independently previous results (OCA/ONERA) when using the same data and model ("standard" WEP).
- We are ready to analyze new data and compare to others.
- Our software is "versatile" i.e. any model can be easily tested
  $\Rightarrow$ give us your favorite model, we will test it!

l'Observatoire de Paris | SYRTE

Systèmes de Référence Temps-Espace