On the Stability of Fundamental Couplings in the Galaxy

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Relevant references:

- **Truppe et al. Nature Communications 4, 2600 (2013), ArXiv: 1308.1496**
- **Levshakov et al. A. & A. 559, A91 (2013), ArXiv: 1310.1850**
- **Vianez et al. submitted to Phys. Rev. D (2014)**

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Outline

- Motivation
  - Fundamental Scalar Fields;
  - Fundamental couplings and their eventual variation;
  - Low *redshifts* studies;
- What was done
  - Results and experimental method;
- What we did
  - Simultaneous variations;
  - Breaking the degeneracy;
  - Alternative models.
- Conclusions and future perspectives

Fundamental Scalar Fields

- We now know that fundamental scalar fields are part of Nature’s building blocks.

- Scalar fields play a key role in most paradigms of modern cosmology, yielding *inter alia*
  - Exponential expansion of the early universe (inflation);
  - Cosmological phase transitions & their relics (cosmic defects);
  - Dynamical dark energy powering current acceleration phase;
  - Varying fundamental couplings.
- More importante than each of these is the fact that they don’t occur alone: this allows for key consistency tests to be made.

Fundamental Scalar Fields

- We all know that fundamental couplings run with energy.
- Moreover, in many (or arguably most?) models they will equally naturally *role* in time and *ramble* in space.
- Therefore astrophysical (and local) tests of their stability provide us with optimal probes of fundamental cosmology.

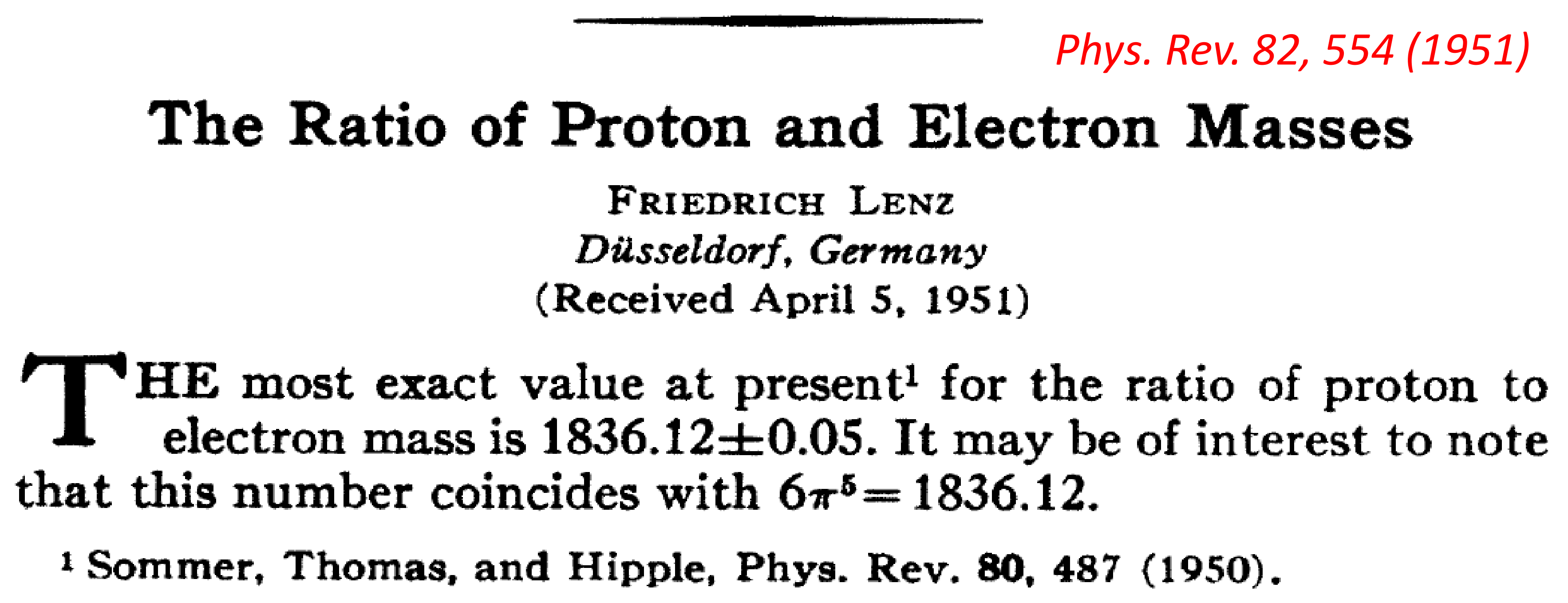
The Constants of Nature

- Nature is characterized by a set of physical laws and fundamental dimensionless couplings, which historically we have assumed to be spacetime-invariant.
  - For the former, this is a cornerstone of the scientific method;
  - For the latter, a simplifying assumption without further justification.

- These couplings determine the properties of atoms, cells, planets and the universe, yet we have no theory for them.

The Constants of Nature

- Improved null results are important and useful; however, a detection would be revolutionary.
  - The natural scale for cosmological evolution would be Hubble time, but current bounds are six orders of magnitude stronger;
  - Varying non-gravitational constants imply a violation of the Einstein Equivalence Principle, a 5th force of nature, etc.



Phys. Rev. 82, 554 (1951)

The Ratio of Proton and Electron Masses

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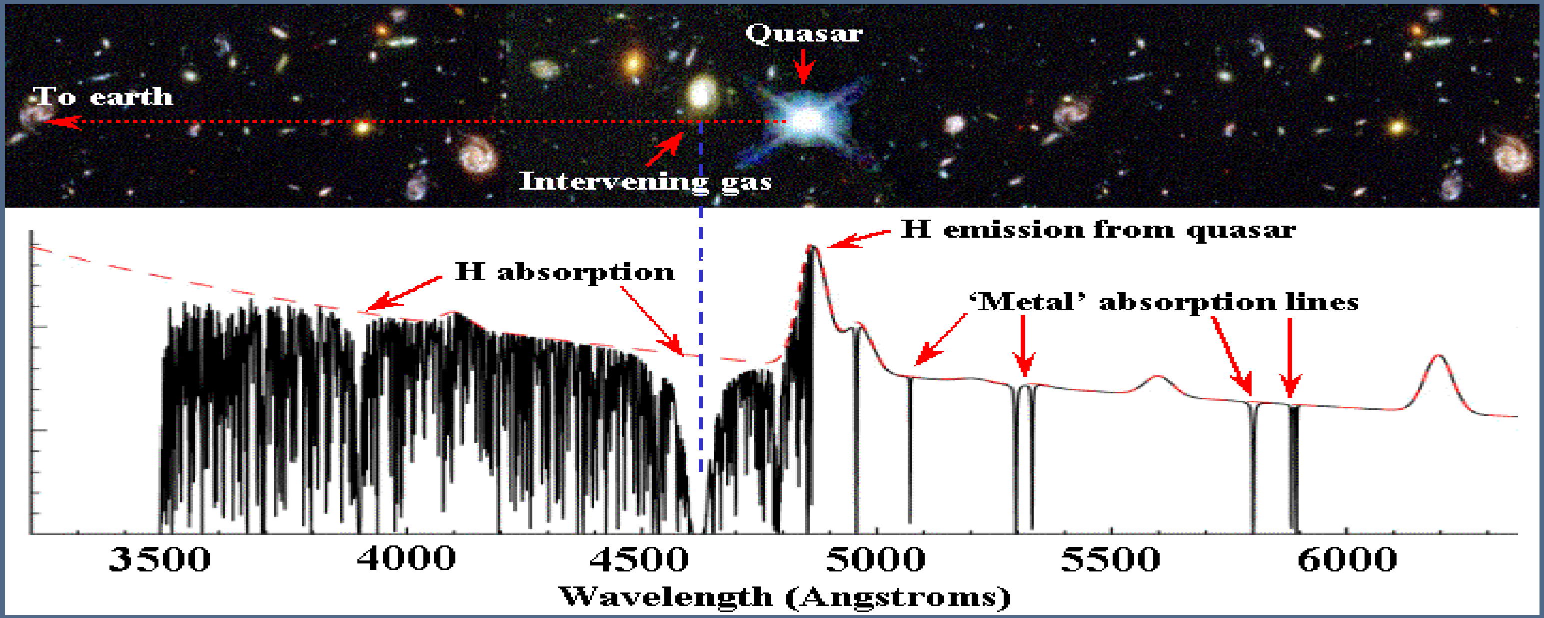
(Received April 5, 1951)

THE most exact value at present[1] for the ratio of proton to electron mass is 1836.12 ± 0.05. It may be of interest to note that this number coincides with $6\pi^5 = 1836.12$.

[1] Sommer, Thomas, and Hipple, Phys. Rev. **80**, 487 (1950).

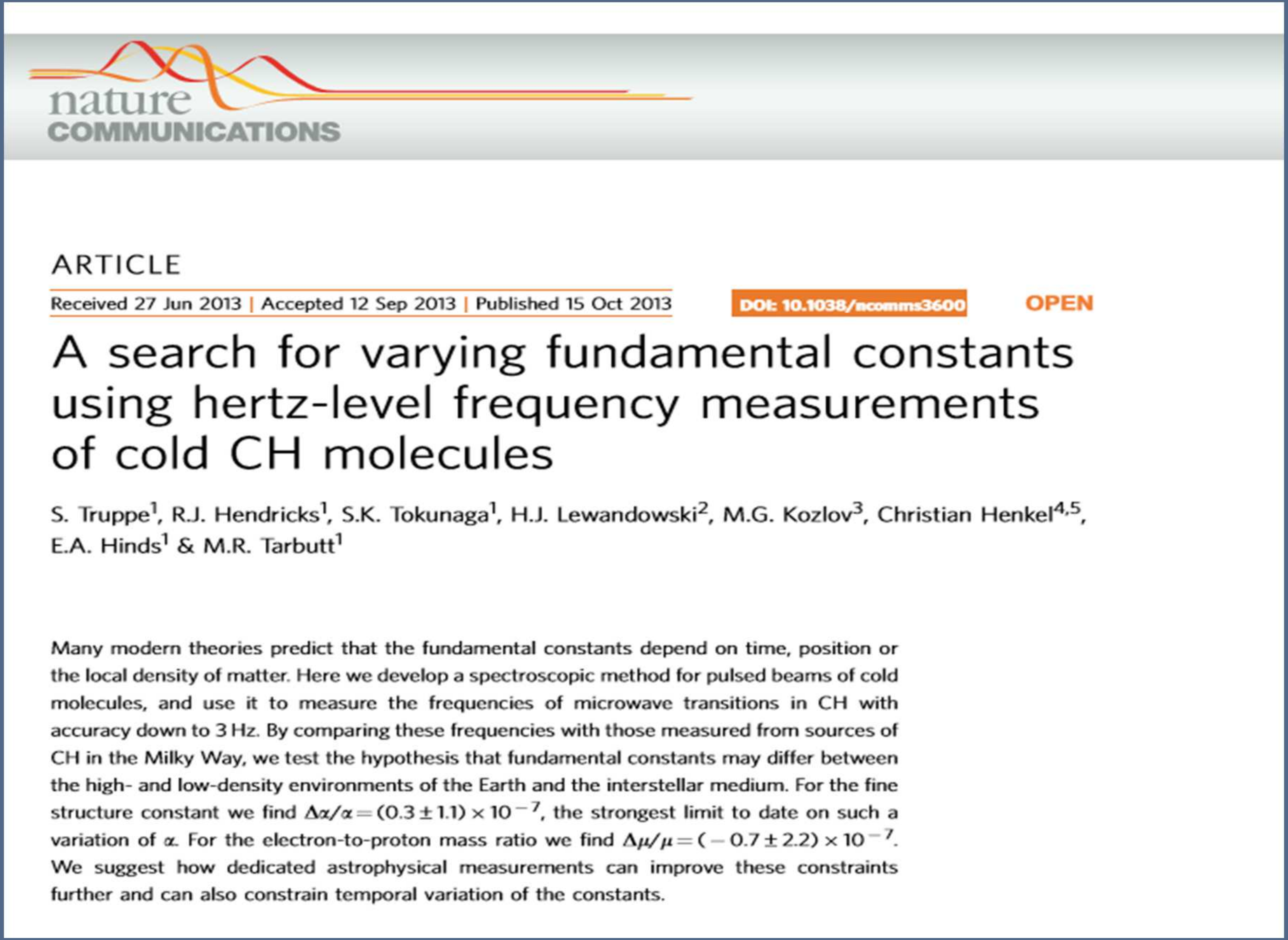
Constraints from Absorption Lines

- α_{em}: Fine-structure doublet
- $\mu = m_p/m_e$: Molecular Rotational *vs.* Vibrational modes
- $\alpha_{em}^2 g_p$: Rotational modes *vs.* Hyperfine H
- $\alpha_{em} g_p \mu$: Hyperfine H *vs.* Fine-structure
- $\alpha_{em}^2 g_p \mu$: Hyperfine H *vs.* Optical
- …



Low-redshift Constraints

- Atomic clocks: sensitivity of fewx10^{-17}/yr [Rosenband et al. 2008]
  - Future: molecular & nuclear clocks, ~10^{-21}/yr (?)
- Compact objects used to constrain environmental dependencies; limiting factor usually from nuclear physics uncertainties
  - Population III *'s [Ekstrom et al. 2010], sensitivity ~10^{-5}
  - Neutron *'s [Pérez-García & Martins 2012], sensitivity ~10^{-4}
  - Solar type *'s [Vieira et al. 2012], sensitivity ~10^{-4} (?)
  - White dwarfs [Berengut et al. 2013], sensitivity ~10^{-4} (?)
- Oklo (natural nuclear reactor, z~0.14): nominal sensitivity of fewx10^{-18} [Gould et al. 2006]; but not a "clean" measurement
  - Assumptions somewhat simplistic; effectively constrains α_s
- Clusters of galaxies (z<1): compare SZ and X-ray observations: 0.8% sensitivity[Galli 2013]
  - Promissing with larger numbers of clusters



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ARTICLE

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A search for varying fundamental constants using hertz-level frequency measurements of cold CH molecules

S. Truppe[1], R.J. Hendricks[1], S.K. Tokunaga[1], H.J. Lewandowski[2], M.G. Kozlov[3], Christian Henkel[4,5], E.A. Hinds[1] & M.R. Tarbutt[1]

Many modern theories predict that the fundamental constants depend on time, position or the local density of matter. Here we develop a spectroscopic method for pulsed beams of cold molecules, and use it to measure the frequencies of microwave transitions in CH with accuracy down to 3 Hz. By comparing these frequencies with those measured from sources of CH in the Milky Way, we test the hypothesis that fundamental constants may differ between the high- and low-density environments of the Earth and the interstellar medium. For the fine structure constant we find $\Delta\alpha/\alpha = (0.3 \pm 1.1) \times 10^{-7}$, the strongest limit to date on such a variation of α. For the electron-to-proton mass ratio we find $\Delta\mu/\mu = (-0.7 \pm 2.2) \times 10^{-7}$. We suggest how dedicated astrophysical measurements can improve these constraints further and can also constrain temporal variation of the constants.

[1] S. Truppe, R. J. Hendricks, S. K. Tokunaga, H. J. Lewandowski, M. G. Kozlov, C.Henkel, E. A. Hinds, and M. R. Tarbutt, Nature Communications 4, 2600 (2013), 10.1038/ncomms3600, arXiv:1308.1496 [physics.atom.-ph].

Astrophysical Sources
Measurements inside the Galaxy

- Radio/microwave measurements of these couplings can be perfomed. While they are typically limited to lower *redshifts* than their optical/UV counterparts, their sensitivity is competitive.
  - The experimental setup utilized allowed for improved laboratory results;

- Comparison between measurements obtained inside our Galaxy (efectively at z=0) allow for studies of possible environmental dependences on the variation of fundamental couplings of nature.
  - The transitions used are sensible to both α_{em} and μ

- Each limit was obtained assuming, respectively, that the other didn't vary
  - From the theoretical point of view, this is unatural;
  - Possible motivation: mathematical simplicity; less tight constraints

Astrophysical Sources
Measurements inside the Galaxy

- Laboratory and astrophysical measurements were obtained for transitions in CH and OH molecules.
  - The fractional variation of α can be obtained by comparing two diferent transitions in the same system;

$$\boxed{\omega_{ast} = \omega_{lab}\left[1 + K_{\alpha}\frac{\Delta\alpha}{\alpha} + K_{\mu}\frac{\Delta\mu}{\mu}\right]}$$

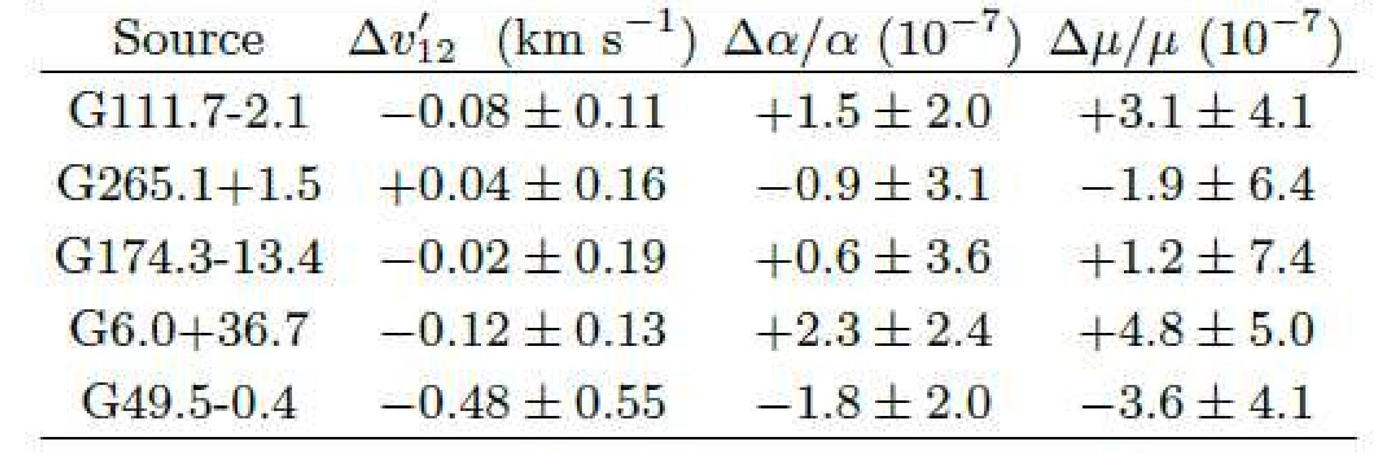
- The sensitivity coefficients utilized are relevant for both couplings [Kozlov (2009), Nijs et al. (2012)]
  - We note that the sensitivity of the first is typically double of that of the second.

$$\boxed{\frac{\Delta\alpha}{\alpha} = \frac{1}{K_{\alpha_2} - K_{\alpha_1}}\frac{\Delta\nu'_{12}}{c}}$$

(analogous expression for μ)

Astrophysical Sources

Measurements inside the Galaxy



Source	$\Delta v'_{12}$ (km s^{-1})	$\Delta\alpha/\alpha$ (10^{-7})	$\Delta\mu/\mu$ (10^{-7})
G111.7-2.1	-0.08 ± 0.11	$+1.5 \pm 2.0$	$+3.1 \pm 4.1$
G265.1+1.5	$+0.04 \pm 0.16$	-0.9 ± 3.1	-1.9 ± 6.4
G174.3-13.4	-0.02 ± 0.19	$+0.6 \pm 3.6$	$+1.2 \pm 7.4$
G6.0+36.7	-0.12 ± 0.13	$+2.3 \pm 2.4$	$+4.8 \pm 5.0$
G49.5-0.4	-0.48 ± 0.55	-1.8 ± 2.0	-3.6 ± 4.1

Table I. Data from the five interstellar sources used by (and reproduced from) [1]. Both the velocity diferences and the fractional variations are given with one sigma uncertainties. Note that our definition of μ differs from that of [1].

Astrophysical Sources

Measurements inside the Galaxy

- We obtained:

$$\boxed{\left(\frac{\Delta\alpha}{\alpha}\right)_{Truppe} = (0.32 \pm 1.08) \times 10^{-7}}$$

$$\boxed{\left(\frac{\Delta\mu}{\mu}\right)_{Truppe} = (0.68 \pm 2.23) \times 10^{-7}}$$

- One generically expects that the two couplings will vary simultaneously with the relative size of the variations being highly model-dependent.

Is it plausible to assume independent variations?

- In a broad class of unification scenarios, recently tested agaisnt extragalatic measurements, the two variations are related by [Ferreira et al. (2014)]
  - R and S are true dimensionless fundamental couplings (meaning that they are spacetime-invariant)
  - The former is related to Quantum Chromodynamics and the latter to the Electroweak sector of the underlying theory

$$\frac{\Delta\mu}{\mu} = [0.8R - 0.3(1+S)]\frac{\Delta\alpha}{\alpha}$$

- The molecular transitions being used are sensitive to changes of both α_{em} and μ

$$\frac{\Delta(\alpha^2\mu)}{(\alpha^2\mu)} = (0.68 \pm 2.23) \times 10^{-7}$$

What we did…

- Allowing for generic simultaneous variations of both couplings we obtained:

- This shows that the bounds previously shown are misleading
  - There's an infinite number of models (i.e. choices of R and S) that can be consistent but nevertheless have α and μ variations larger than those given

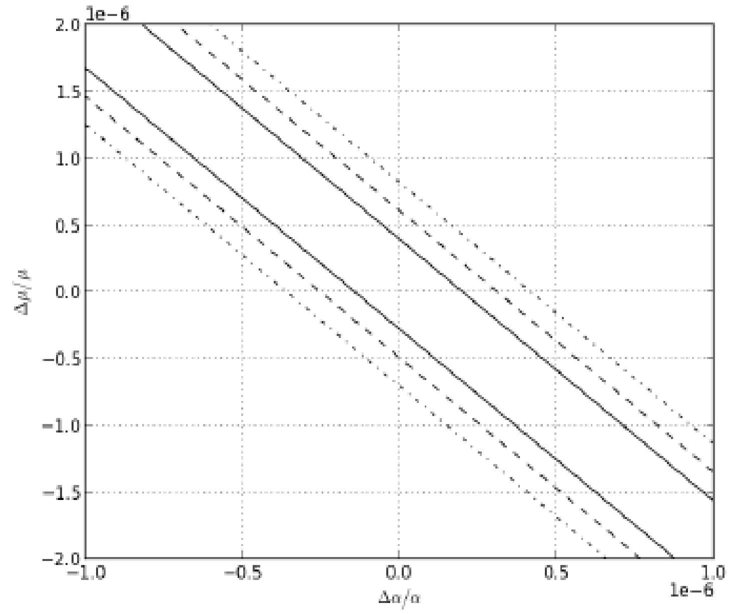
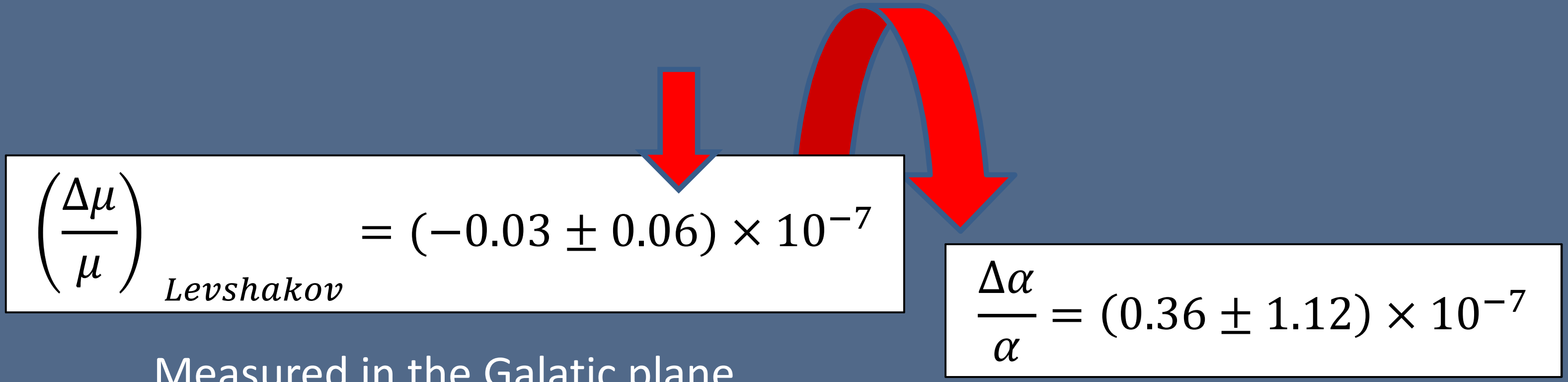


Fig I. Constraints on the α-μ parameter space, obtained from the data of Table I while allowing for generic simultaneous variations of both couplings. One, two and three sigma constraints are respectively indicated by solid, dashed and dash-dotted lines.

How to break the degenerency?

(preferably in a model-independent way)

- **Answer:** Use as external *prior* an independent measurement of one of the two couplings.



$$\left(\frac{\Delta\mu}{\mu}\right)_{Levshakov} = (-0.03 \pm 0.06) \times 10^{-7}$$

Measured in the Galatic plane

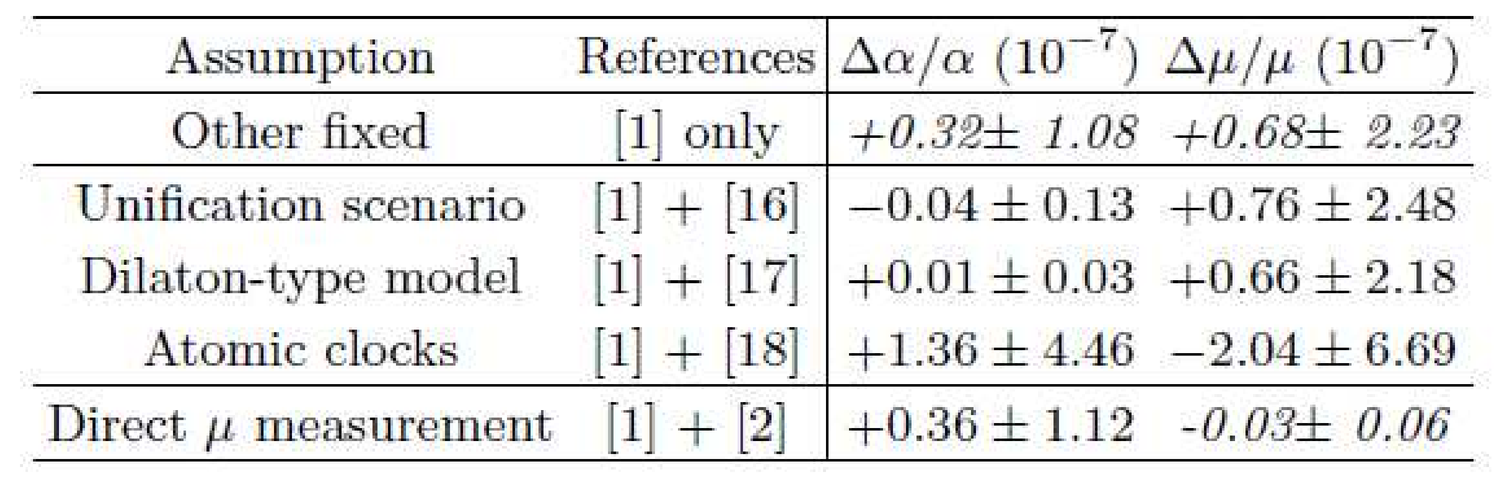
$$\frac{\Delta\alpha}{\alpha} = (0.36 \pm 1.12) \times 10^{-7}$$

[2] S. A. Levshakov, D. Reimers, C. Henkel, B. Winkel, A. Mignano, M. Centurión, and P. Molaro, A. & A. 559, A91 (2013), arXiv:1310.1850 [astro-ph.GA].

Results

- Although nominally this is consistente with the previous result (and indeed very close to it, since the prior on μ has a very small statistical uncertainty compared to that of $\alpha^2\mu$), we emphasize that physically it is a much more robust bound
- Alternatively one may focus on particular models, which will provide specific values of the unification parameters
  - Unification scenarios R~36 e S~160
  - Dilaton- type model R~109,4 e S~0
  - Laboratory comparisons among atomic clocks with diferent sensitivies to these couplings (and also to the proton gyromagnetic factor) allow us to obtain in the R-S plane: $(1+S)-2.7R=-5\pm15$

Summarizing…



Assumption	References	$\Delta\alpha/\alpha$ (10^{-7})	$\Delta\mu/\mu$ (10^{-7})
Other fixed	[1] only	*+0.32± 1.08*	*+0.68± 2.23*
Unification scenario	[1] + [16]	-0.04 ± 0.13	$+0.76 \pm 2.48$
Dilaton-type model	[1] + [17]	$+0.01 \pm 0.03$	$+0.66 \pm 2.18$
Atomic clocks	[1] + [18]	$+1.36 \pm 4.46$	-2.04 ± 6.69
Direct μ measurement	[1] + [2]	$+0.36 \pm 1.12$	*-0.03± 0.06*

- We highlight the fact that derived constraints are highly model-dependent. Moreover, it’s clear that assuming that the other coupling is fixed can lead to erroneously tight constraints.
- A more robust procedure is therefore to combine different datasets or to use external observartional *priors*.
- A possible *caveat* here is that in models where the couplings depend on the environment; combining measurements requires assumptions on the underlying model

  - Instead, one should translate them into bounds on the R-S parameter space, which is expected to be spacetime invariant

…and concluding…

- By considering some representative unification scenarios we find no evidence for variations of α at the 0.4 ppm, and of μ at 0.6 ppm; if one uses μ as *prior* , the α bound is improved to 0.1 ppm.

- Observational data for the expasion of the universe shows that canonical theories in cosmology and particle physics are incomplete, if not incorrect.

- Nothing is varying at ~10^{-5}, a limit already quite significant (stronger than that of Cassini)
  - At 10^{-6} things are less clear.
  - An improvement of 2-3 orders of magnitude is coming…
  - …soon (be patient ☺)

- Instruments dedicated for this studies are being built, allowing for a new generation of precise consistency tests.
  - A new generation of ultra-stable high-resolution spectrographs: EXPRESSO, ELT-HIRES.

Thank you for your attention!

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Questions??