

 $\mathbf{e}^{-}$ 

μ









### Anna Soter



### What happens when LEptons in Muonium INteracting with Gravity?

# Standard Model and beyond

CPT

Why three generations?

CLFv?

Many free parameters

. . .

Neutrino oscillation



### Not enough antimatter in the Universe:

### Baryon Asymmetry

### **Dark Matter?**

Dark Energy?

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# Fundamental physics using muonium atoms

- Purely leptonic, exotic atom
- No finite size / hadronic effects



1s-2s and HFS Spectroscopy: MuMASS @ PSI

- $\blacktriangleright$  Fundamental constants (m\_{\mu} , \mu\_{\mu} , R\_{\infty})
- ▶ Test of QED and fundamental symmetries ( $q_{\mu}/q_{e}$ )
- Effects many precision measurements, like muon g-2





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Prospects of measuring muonium gravity

Testing the weak equivalence with and elementary, second generation (anti)lepton

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#### Foundation of GR. Many formulations since Galilei:

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Usually describing that he outcome of any local experiment conducted in gravitational field (local g acceleration) must be the same than in an accelerating lab, where a=g.



▶ Needs to be tested in different experiments sensitive to one of the above!

# Various experimental

▶ Universality of free fall:  $\eta(1,2) = 2 \frac{|g_1 - g_2|}{|g_1 + g_2|}$ 

Local Lorentz invariance

Local position invariance: universality of clocks, lack of variation of fundamental constants



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# Torsion pendulaImage: Strain Stra

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Phys. Rev. Lett. 100, (2008)

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#### Satellite experiments



 $\eta(\text{Ti,Pt}) = [-1.5 \pm 2.3(\text{stat}) \pm 1.5(\text{syst})] \times 10^{-15}$ 

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#### Tests on the largest and smallest scales



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▶ Universality of free fall:  $\eta(1,2) = 2 \frac{|g_1 - g_2|}{|g_1 + g_2|}$ 

▶ Local Lorentz invariance

Local position invariance: universality of clocks, lack of variation of fundamental constants

 $\eta(^{85}\text{Rb},^{87}\text{Rb}) = [1.6 \pm 1.8(\text{stat}) \pm 3.4(\text{syst})] \times 10^{-12}$ Phys. Rev. Lett. 125, 191101, 2020

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Neutral exotic probes to test the WEP with a free fall experiment?



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Neutral exotic probes to test the WEP with a free fall experiment?



▶ **p**-composite antimatter, ~99% of rest mass is from binding energy ▶ The only stable candidate, but hard to produce them cold. 'Indirect' tests (redshift) exists At CERN: ALPHA-g, AEgIS, GBAR







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# Neutral exotic probes to test the WEP with a free fall experiment?

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#### First generation (anti)leptons

 $e^+$ 

 Short lifetime (~140 ns) on the ground state - excited states are needed.
Challenge to get the numbers
Experiments proposed: UCL, ETHZ, Bern, Milano...







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**p**-composite antimatter, ~99% of rest mass is from binding energy ▶ The only stable candidate, but hard to produce them cold. 'Indirect' tests (redshift) exists At CERN: ALPHA-q, AEqIS, GBAR

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Elementary (anti)leptons

▶ No mass shift from strong interaction

Unique gravitational probe of a different SM sector: second generation charged leptons

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### (Personal) disclaimer on "exotic gravity"

Analogy of exotic gravity experiments: checking for monsters under your kid's bed (you would be the most surprised to find one...)



- As of the possible theories, the case of **antihydrogen** was discussed in most details (arXiv:2002.09348)
- Many **indirect constrains** exist, especially concerning hadrons (kaon oscillations, gravitational redshift)
- ▶ Unclear what are the "ultimate" tests of the weak equivalence principle. (Tests that unambiguously exclude any new physics)
- ▶ The clock / redshift measurements may exhaust some new physics, but not all, hence formulation of WEP-ff or WEP-c (free fall / clock tests) in some literature. Short summary: A. Soter and A. Knecht: SciPost Phys. Proc. 5, 031 (2021)
- **No constrains exist yet with muons** or in general pure leptons in the absence of strong binding energies

- 10% precision on g of M <u>arXiv:2206.10808</u>
- dependent hierarchy  $\Lambda_{\mu} \ll \Lambda_{e} \ll \Lambda_{\text{other}}$



# Exciting preprint of Yevgeny V. Stadnik, assuming

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Effects of virtual ultralight scalar bosons, flavor





Method: free fall of a Mu beam

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# Inherent challenge: Mu lifetime of 2.2 µs $\Delta x < 1 \text{ nm}$























▶High quality muonium beam is needed





Transmission vs 3rd grating position



Measurable acceleration with a phashift on a sinusoidal:

 $\Delta g \approx \frac{1}{2\pi T^2} \frac{a}{C\sqrt{N_0 \epsilon \eta^3 e^{-(t_0+T)/\tau}}}$ 





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Measurable acceleration with a phashift on a sinusoidal:



See e.g. M.K. Oberthaler et al. Phys. Rev. A 54 (1996) 3165. Batelaan, H. et al. Atom interferometry, 85–120 (Elsevier, 1997)

#### **Loss factor:**

- Intrinsic loss from M decay a trade-off with measurement time.
- Other losses should be kept at minimum: large grating transmittance ( $\eta \sim 0.3$ ) and detection efficiency ( $\epsilon$ =0.5), low dead time ( $t_0 < \tau$ )

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### Present state-of-the-art vacuum M sources



- M converting materials with interconnecting nanoscopic pore stucture (silica aerogel, mesoscopic SiO2)
- Large (thermal) energy spread
- ▶ Broad angular distribution ( $\sim \cos\theta$ )
- $\mu \rightarrow$  vacuum M conversion efficiency:  $\eta_{M} = 0.003 0.3$ , depends strongly on diffusion time (implantation depth)

Beer et al, PTEP 2014, 091C01 Beare et al, PTEP 2020, 23C01

Antognini et al, PRL 108, 143401 (2012) K. S. Khaw et al, Phys. Rev. A 94, 022716

Tradeoff between beam intensity (decreases stongly with momentum) and implantation depth



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### Creation and fast diffusion in SFHe

▶ effective mass with VdW core repulsion for all H isotopes ~ 2.5  $M_{He}$ 

This makes M a relatively small impurity: might avoid hydrodynamic losses (vortex creation)

▶ thermalization below the roton gap ( $v \approx 50$  m/s)

▶ Thermal up-scattering: at 0.2 K phonon density is small:

 $n_{ph} = 2 \times 10^{19} T^3 \text{cm}^{-3} \approx 10^{16} / \text{cm}^3$ 

Small density makes scattering unlikely in µs times:  $\frac{1}{-1} \approx 4.8 \times 10^7 T^7 \approx 5/s$ 

Europhys. Lett., 58 (5), pp. 718–724 (2002)

### Boost from chemical potential

- M. Saarela and E. Krotscheck, JLTP 90, 415 (1993) D. Taqqu, Physics Procedia 17 (2011) 216-223
- M atoms are ejected from bulk SFHe with E = 23meV, v = 6300 m/s

Low thermal energy spread (+/- 100 m/s) Narrow angular distribution (~30 mrad)



▶ M and H, D, T chemical potentials: ▶ E/k<sub>B</sub>~ 270 K and 37 K, 14 K , 7 K





# New target concept - M from superfluid helium



▶ Collision-free diffusion (ballistic propagation) may happen with small thermalized impurities like antiprotonic helium - see A. Soter et al., Nature 603, 411-415 (2022)

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# LEWING An (overly simplified) experimental setup for LEMING

### $\mu^+ \rightarrow$ vacuum M conversion

- ▶ efficient M production
- ▶ fast diffusion to surface
- efficient vacuum emission





# **Wing** An (overly simplified) experimental setup for LEMING



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### **VING** An (overly simplified) experimental setup for LEMING





#### An (overly simplified) experimental setup for LEMING ĬŊØ



# Background-free Atomic M

with coincident detection of atomic e-

# Test setup at PSI for creating cold vacuum muonium

SOCION SINDA





# Feasibility studies 2018-2020

### M production in low temperature SFHe

▶ MuSR measurements ▶ >70% muon to muonium conversion



### Indication of M atoms reflecting on SFHe films, 0.5 K



M dephasing/ sticking to aerogel



▶ M precessing in SFHe coated aerogel pores

### Study of M scattering in He gas

- ▶ Tracking of M atoms in room temperature chambers
- ▶ Realization that T < 0.3 K is needed dilution refrigerator





#### Cryogenic detector developments



▶ SiPM-based scintillator detectors reliably operate at min. temp: T<0.2 K





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### First M extraction from SFHe, 2021 - Setup



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# First M extraction from SFHe, 2021 - Setup



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#### Dilution cryostat with SFHe target at 170 mK



#### Cryogenic SiPM detection system

(C)



# $E_{\text{EQING}}$ First detection of a cold atomic M beam from SFHe





- Passing-by of the atoms are detected in the positron trackers
- Main parameter could be determined in a modelindependent way: v~2200 m/s

distance from floor [mm]

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time [µs]

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e<sup>+</sup>

LF

3 00

10 mm

### **Conversion efficiency**

A lower limit on the stopped muon to vacuum M conversion efficiency: 19%

Leaving of M atoms can be detected by looking for trajectories originating from the target

Atomic

Μ

RC

SFHe

RF

LC



# Average depth of implantation: 40-50 um

# LEMonte Carlo simulations - thermal and directed atomic M beam

8000

10000 t [ns]



- Simulations seem to verify a directed beam vs. other conceivable solutions
- But: no sensitivity yet in the transverse direction



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### The superthermal beam vs thermal sources

Broadening in time after muon arrival is mainly from the diffusion time in the liquid Location of atoms after muon arrival: compact, ~2-3 mm wide cloud



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### Interferometer - what kind of interferometry are we doing?



regime

- d ~ spacing of slits
- L ~ length of the apparatus
- ▶  $\lambda$  ~ de Broglie wavelength

$$\lambda = \frac{h}{mv} = \frac{hc}{pc} = \frac{1239.84 \; [\mathrm{nm} \cdot \mathrm{eV}]}{P \; [\mathrm{eV/c}]}$$

- ▶ w<sub>0</sub> ~ beam width
- $\triangleright$   $\ell_0 \sim$  transverse coherence length

- ▶ Mu from SF: λ ~ 1.6 nm (v=2200 m/s)
- ▶ d ~ 100 nm, L<sub>T</sub> ~ 6.2 µm
- few 7-8 us interaction ~ 10 mm between gratings
- ▶ => we are in the 'quantum regime,' and in the 'aperture near field', but several hundreds Talbotlength away





- Model: using mutual intensity functions from statistical optics
- Calculations assume a Gaussian Schellmodel beam

 $w_0 \sim beam width (aperture)$  $\ell_0 \sim \text{transverse coherence length}$ 

 $\ell_0$  relates to the angular spread ( $\alpha$ ) of the atoms (via the Cittert-Zernike theorem) as:

 $\ell_0 \approx \frac{\lambda}{\alpha} \approx \frac{1.6 \text{ nm}}{50/2200} = 70 \text{ nm}$ 

 $\alpha$  ~ 22 mrad, and  $\ell_0$  ~ 70 nm - close to the grating pitch size

Contrast ~ 0.3 

Given there is enough high quality M atoms, might be feasible!

model based on: McMorran et al., PRA 78 (2008)





### Sensitivity with high intensity muon beams



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- ▶ We are producing about the same amount of cold M than the best room temperature sources, in a small, directed beam
- Small spotsize would offer high ionization efficiencies, as a viable way to produce low energy muons, especially for pulsed sources
- The large yield of slow atoms mean that 1s-2s spectroscopy can benefit a lot small spotsize, slow atoms





### **Ongoing developments**

### Vertical targets





▶ Posters at PSI'22: R. Waddy and J. Zhang

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### Cryogenic detectors

Fast transition edge type detectors (superconducting nanotubes)





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# Thank you!

### LEMING: A next generation atomic physics and gravity experiment using muonium (M) atoms

A. Antognini<sup>\*</sup>, P. Crivelli, I. Cortinovis<sup>‡</sup>, M. Heiss, K. Kirch<sup>\*</sup>, D. Goeldi, A. Soter<sup>†</sup>, D. Taqqu, R. Waddy<sup>‡</sup>, P. Wegmann<sup>§</sup>, J. Zhang <sup>‡</sup> Institute for Particle Physics and Astrophysics, ETH Zurich, 8093 Zurich, Switzerland

> M. Bartkowiak, A. Knecht, J. Nuber<sup>‡</sup>, A. Papa,<sup>¶</sup> R. Scheuermann Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland

F. Wauters Johannes Gutenberg University of Mainz, 55122 Mainz, Germany



+ others above! :)



with Gravity:



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### Approved in 2022 January

### The expected experimental outcome when LEptons in Muonium INteracting