Tests of the Universality of the Free-Fall and non-relativistic QED with cold antiatoms

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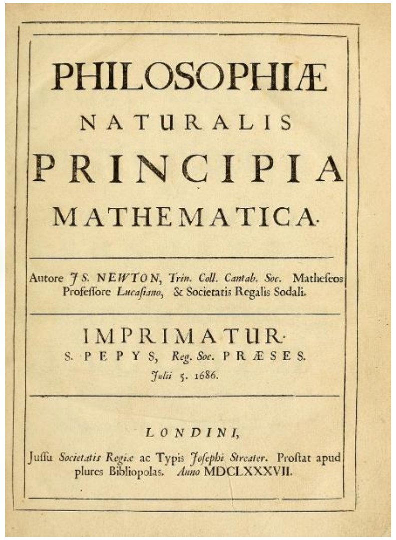
The Universality of the Free-Fall

Galileo’s Pisa leaning tower thought experiment ...

«parmi che ben potremo con molto probabil coniettura credere che nel vacuo sarebbero le velocità loro del tutto eguali» [1]

... gave birth to the Universality of the Free-Fall (UFF)
(known before also by S. Stevin and Philoponus)



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, *Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Newton’s Principle of Equivalence

«The quantity of matter (...) arising from its density and bulk conjointly (...) that I mean hereafter under the name of body or mass. And the same is known by the weight of each body, for it is proportional to the weight, as I have found by experiments on pendulums very accurately made» [2]

$$\begin{cases} \mathbf{F} = m_i \mathbf{a} \\ \mathbf{F} = m_g \mathbf{g} \end{cases} \xrightarrow{UFF} m_i = m_g$$

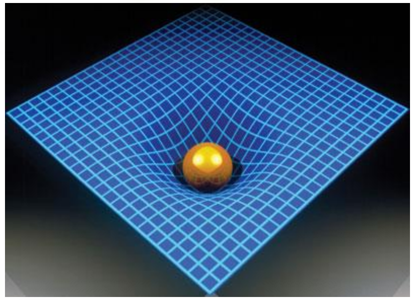
with m_i the inertial mass and m_g the (passive) gravitational mass.

[1] G. Galilei, *Discorsi e dimostrazioni matematiche intorno a due nuove scienze* (1638)
[2] I. Newton, *Philosophiæ Naturalis Principia Mathematica* (1687)

A modern statement of Newton’s (Weak) Equivalence Principle, or WEP

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

Einstein’s Equivalence Principle



Now it came to me: (...) the indepencence of the gravitational acceleration from the nature of the falling substance, may be expressed as follows: in a gravitational field (of small spatial extension) things behave as they do in a space free of gravitation.... This happened in 1908. Why were another seven years required for the construction of the general theory of relativity? The main reason lieas in the fact that it is not so easy to free oneself from the idea that coordinates must have an immediate metrical meaning.[3]

[3] A. Einstein *in Schilpp (1949), pp. 65-67*

(1) WEP is valid (2) the result of any local non-gravitational experiment is independent of the velocity of the free-falling apparatus, and (3) the outcome of any local non-gravitational experiment is independent of where and when in the Universe it is performed.

Will C. M., *Theory and experiment in gravitational physics* (1981)
Misner C. W. , Thorne K. S., Wheeler J. A., *Gravitation* (1973)

Modern form of Einstein's Equivalence Principle

EP := **UFF** (Universality of the Free Fall) + **LLI** (Local Lorentz Invariance)
+ **LPI** (Local Position Invariance)

UFF (Universality of the Free-Fall) $\longleftrightarrow$ $m_i = m_g$ $\longrightarrow$ «free-falling trajectories»

LLI (Local Lorentz Invariance) $\longleftrightarrow$ $g_{\mu\nu} \xrightarrow{\text{locally}} \eta_{\mu\nu}$ $\longrightarrow$ «free-falling Lorentz frames»

LPI (Local Position Invariance) $\longleftrightarrow$ $\forall x^\mu$ $\longrightarrow$ «independently of where and when»

The postulates beyond metric theories of gravity

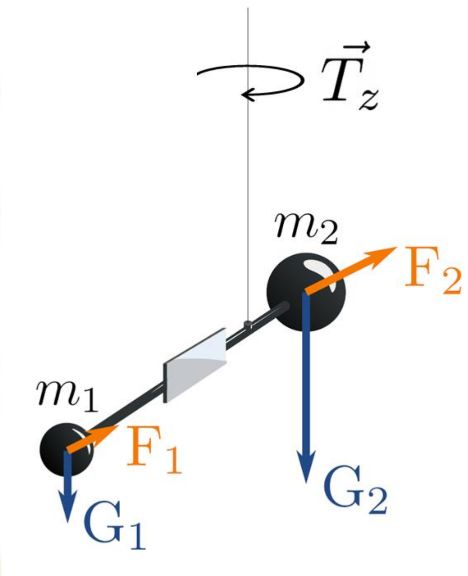
1. Spacetime is endowed with a metric **g** ;
2. The free-fall trajectories (world lines) of test bodies are geodesics of that metric;
3. In local freely falling frames, the nongravitational laws of physics obey special relativity.

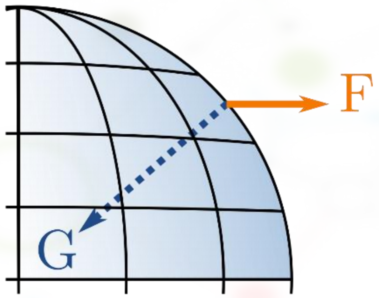
~ the Equivalence Principle is at the heart of <u>any</u> metric theory of gravity ~

~ testing it means both probing our modern paradigm in understanding gravitation ~

Will C. M., *Theory and experiment in gravitational physics* (1981)
Rovelli C., *Relatività Generale* (2021)

Loránd Eötvös' torsion balances





$$T_z = \frac{\left[(\vec{F}_1 + \vec{G}_1) \times (\vec{F}_2 + \vec{G}_2)\right] \cdot \vec{r}_{12}}{\left|(\vec{F}_1 + \vec{G}_1) + (\vec{F}_2 + \vec{G}_2)\right|}$$

$$\Delta a_\perp = -2\frac{\kappa\theta}{m r_{12}} \qquad m_1 \approx m_2$$

Key aspects

1. Direct comparison of test masses with different compositions
2. The balance responds only to a difference in the directions of the external forces, while it is insensitive to their magnitudes.
3. A WEP test can be performed rotating by 180° the balance with respect to the attractor, to remove the arbitrariety in angle.

Eötvös parameter

$$\eta_{12} := \frac{\Delta a_\perp}{g_\perp} = 2\frac{(m_g/m_i)_1 - (m_g/m_i)_2}{(m_g/m_i)_1 + (m_g/m_i)_2} < 2 \cdot 10^{-9}$$

Comparison with pendula

$\eta_{12} < 2 \cdot 10^{-2}$ (Galileo)

$\eta_{12} < 1 \cdot 10^{-3}$ (Newton)

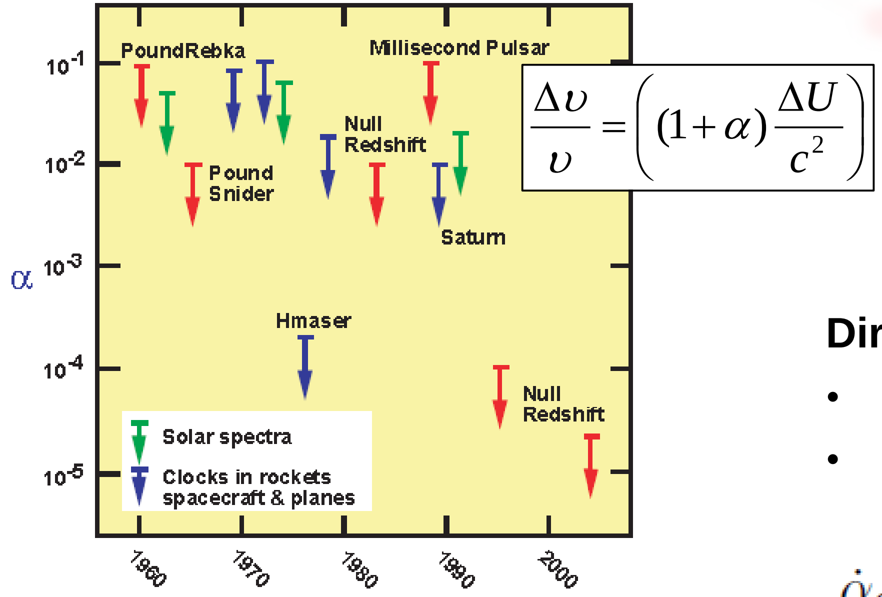
$\eta_{12} < 2 \cdot 10^{-5}$ (Bessel)

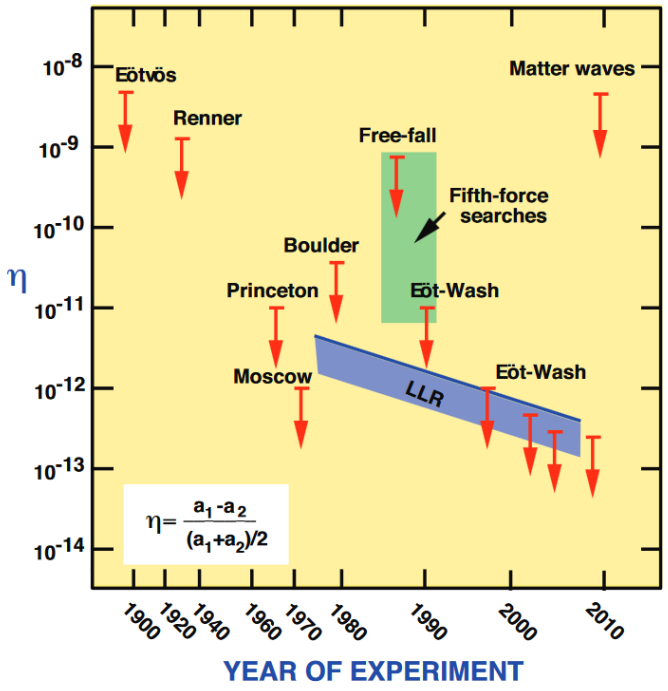
L. Eötvös; Annalen der Physik 68 11 (1922)
Adelberger E. G., Progr. Part. Nucl. Phys. 62 (2009) 102-134

Experimental tests of the Equivalence Principle

Direct tests of the UFF with matter systems

- MICROSCOPE satellite (2 part in 10^{14})
- Eötvös-like torsion balances (2 part in 10^{13})
- Lunar laser ranging (3 part in 10^{4}) (actually, SEP!)
- Cold atoms interferometry (3 part in 10^{8})





Direct tests of the LLI with matter systems

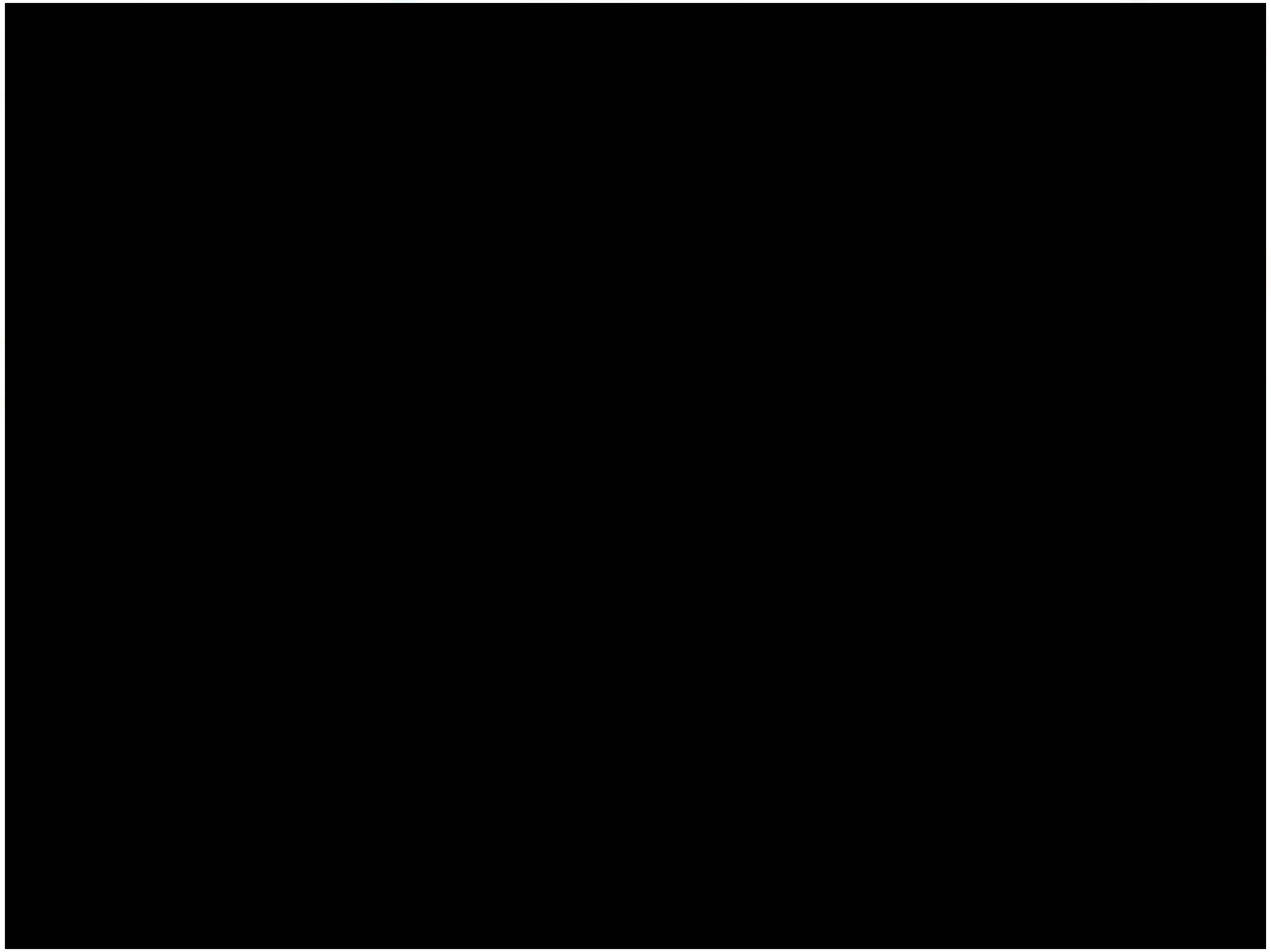
- Gravitational red shift (3 part in 10^{4})
- Time variation of fundamental constants

$$\dot{\alpha}_{\rm em}/\alpha_{\rm em} = (-1.6 \pm 2.3) \times 10^{-17} {\rm yr}^{-1}.$$

Will C. M., Living Rev. Rel. 9 (2006) 3
Adelberger E. G., Progr. Part. Nucl. Phys. 62 (2009) 102-134

Very little is known about antimatter bodies

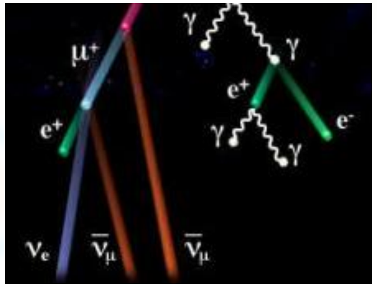
An example of direct test of the LPI ...

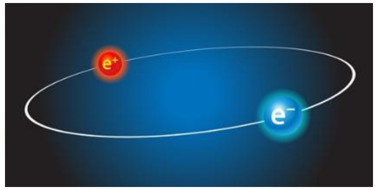


National Aeronautics and Space Administration, Apollo 15 mission footage (1971)

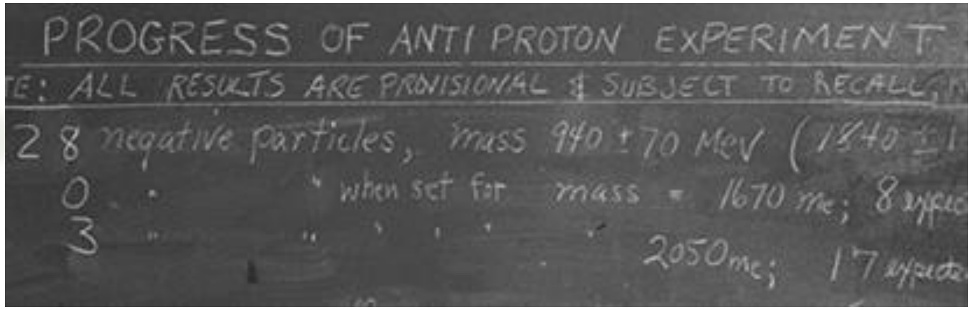
The long journey of antimatter research

(worth so far at least 5 Nobel prizes)





- 1928: P. Dirac hypothesizes the existence of **antiparticles**
- 1932 : C. Anderson discovers **positrons** in cosmic rays (Caltech)
- 1951 : M. Deutsch discovers **positronium** (MIT)
- 1954 : E. Segré discovers the **antiproton** (Bevatron)
- 1965 : A. Zichichi, L. Lederman discover **antimatter nuclei** (CERN)
- 1975-1985 : S. van der Meer stochastically **cools and stores antiprotons** for C. Rubbia's pbar-p collider to discover W and Z at UA1 (CERN)
- 1985-1990 : C. Surko builds the **buffer-gas positron trap** (Bell labs)
- 1995 : first **antihydrogen** atoms are produced at LEAR (CERN)
- 1999 : the **antiproton decelerator** experiments begin operation (CERN)
- 2021 : the **ELENA** antimatter physics experiments begin operation (CERN)



From the theoretical point of view, is there any room for anti-gravity?
(*my collection of arguments against it, despite some «observed» controversy)*

1. Morrison's argument: *antigravity would violate conservation of energy*
2. Schiff's (Dvali's) argument: *Standard Model and gravitational repulsion are incompatible*
3. Good's argument: *antigravity would cause an unobserved CP violation in kaons oscillations*
4. Karshenboim's argument: *no way to keep EP valid for light, matter and antimatter at the same time in case of antigravity, so WEP has to be valid at the level we can verify deflection of light in GR*

Smaller effects pinpointing to new Physics are possible, and yet unconstrained by experiments

What classes models are constrained by EP tests with antimatter?

New scalar and vector fields, allowed for instance in some fifth force models, may mediate interactions violating the Equivalence Principle:

attractive/repulsive vector gravitons

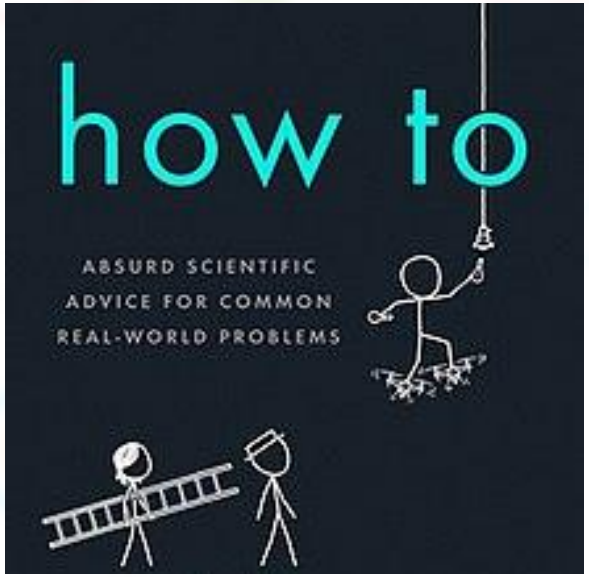
attractive scalar gravitons

$$V = -\frac{G_\infty}{r} m_1 m_2 (1 \mp a e^{-r/v} + b e^{-r/s})$$

with cancellation effects occuring in matter experiments if a ~ b and v ~ s.

Karshenboim, S. G., talk to 2° Workshop on Antimatter and Gravity (2013)
M. Nieto and T. Goldman, Phys. Rep. 205,5 221-281 (1992)
Phys. Rev. D 33 (1986) 2475
Fayet P., Phys. Rev. D 99 (2019) 055043
Fischbach E. et al. (2020), arXiv:2012.02862v1
Caldwell, A. Dvali G. (2019), arXiv:1903.09096

Testing the EP with antimatter: possible approaches



1. **Shapiro delay of neutral cosmic antiparticles**
   - Take a naturally pulsed source of neutral antiparticles
   - wait for them pass in a gravitational field …
   - … and observe their Shapiro delay compared to light
2. **Dropping charged antiparticles**
   - Take some artificial cold charged antiparticles
   - Drop them
   - Measure their free-fall in a field-free environment.
3. **Comparison of particle/antiparticle clocks**
   - Take some artificial cold charged antiparticles
   - Build with them very precise clocks
   - Compare their frequencies while gravitationally redshifting
4. **Dropping neutral antiatoms**
   - Form a neutral antiatom by combining the charged constituents
   - Drop it before it self-annihilates
   - Measure its free-fall

Shapiro delay of neutral cosmic antiparticles

Supernova SN1987A

- 11 (Kamiokande II) + 8 (IMB)+ 5 (Baksan) = 24 (anti)neutrino events
- Burst duration of 13 sec, $T_{light} - T_{neutrinos}$ = 6 hours
- Shapiro delay generated by the field in our Galaxy: 4.8 months
- Neutrinos and light experience the same time delay 6 h/4.8 months

If there was at least one neutrino detected then v and anti-v satisfy the WEP within 13 sec/4.8 months, then $\eta_{\nu-\bar{\nu}} < 1.6 \cdot 10^{-6}$

S. Pakvasa et al., Phys. Rev. D 39, 6, 1989

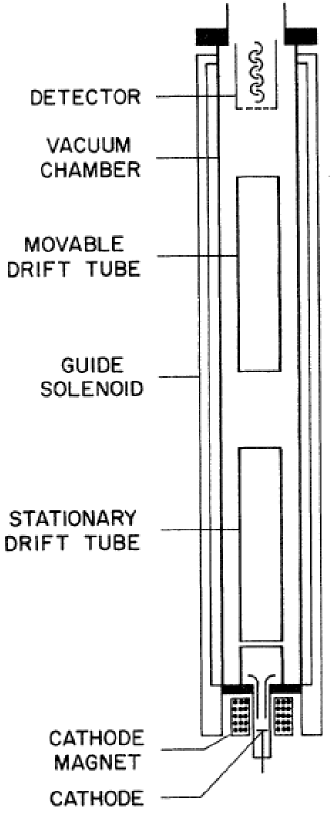
However, anti-v are ultra-relativistic …

FALLING RIGHT WHILE MOVING SLOW: TRUE TESTS OF THE WEAK EQUIVALENCE PRINCIPLE FOR ANTIPARTICLES*

A significant question in experimental gravity is the nature of free fall of antiparticles under gravity and elaborate preparations are underway to directly test this with cold antihydrogen. Earlier, the Shapiro delay of supernova 1987A neutrinos was interpreted as testing the weak equivalence principle (WEP). We establish the surprising result that the Shapiro delay of relativistic particles does not test WEP for intrinsic properties or quantum numbers of particles or antiparticles. This is because essentially the entire gravitational mass of the relativistic neutrinos is contributed by kinetic energy, diluting to insignificance any EP violating contribution from intrinsic properties, by the relativistic factor. The crucial message here is that a true test of the WEP involving intrinsic properties of matter or antimatter — the foundation of relativistic gravity — necessarily requires nonrelativistic "cold" matter and antimatter.

C. S. Gillies G.T., Class. Quantum Grav. **29** (2012) 232001
Unnikrishnan, C. S. Gillies G.T., Int. Journ. Mod. Phys. D 21 11 (2012) 1242016

Witteborn and Fairbank experiment

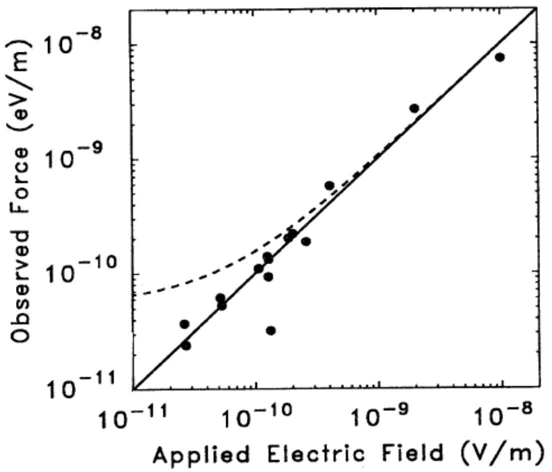


- Launch e^-/e^+ from cathode upwards towards a detector
- Shield the charged particles from all external fields to a level lower than gravity by "drift tube"
- Measure g from time of flight distributions

$$t_{max} = \sqrt{\frac{2mh}{|mg + qE_{env} + qE_{app}|}}$$

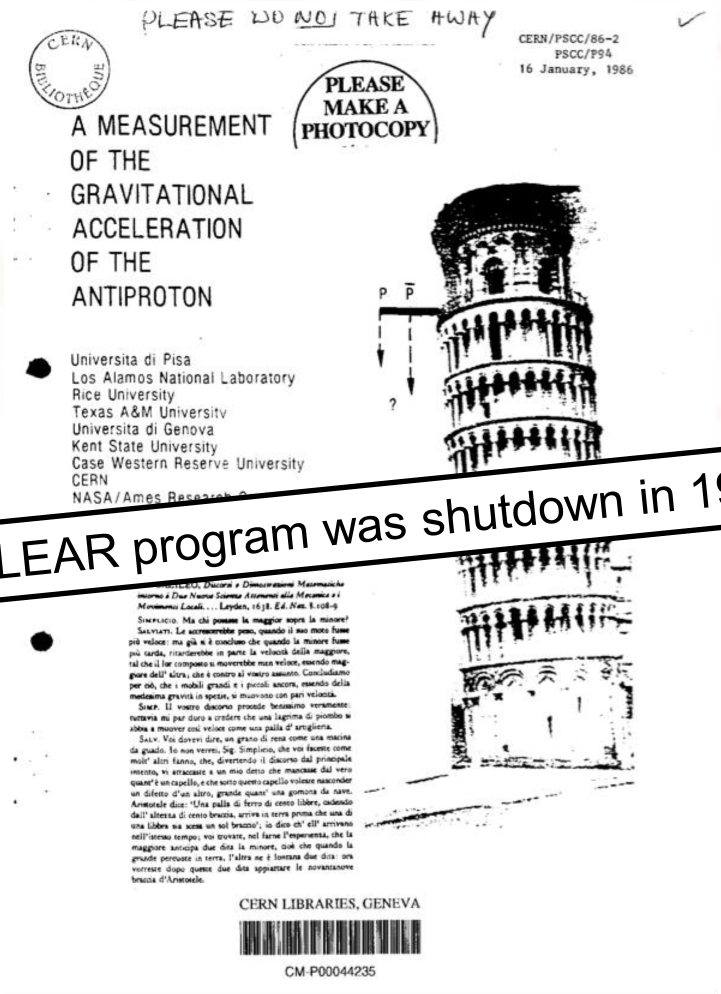
Gravity effect was not observed, most likely due to sagging of free electron gas (Schiff-Barnhill effect)

(+ other possible difficulties from electric patches and magnetic fields)



Witteborn F. C. and Fairbank, W. M, Nature **220** (1968)
Holzscheiter, M., talk to 3° Workshop on Antimatter and Gravity (2015)

PS200 at LEAR (1986)



PLEASE DO NOT TAKE AWAY

CERN/PSCC/86-2
PSCC/P94
16 January, 1986

CERN BIBLIOTHEQUE

PLEASE MAKE A PHOTOCOPY

A MEASUREMENT OF THE GRAVITATIONAL ACCELERATION OF THE ANTIPROTON

Universita di Pisa
Los Alamos National Laboratory
Rice University
Texas A&M University
Universita di Genova
Kent State University
Case Western Reserve University
CERN
NASA/Ames Research [illegible]

[illegible]LILEO, *Discorsi e Dimostrazioni Matematiche intorno à Due Nuove Scienze Attenenti alla Mecanica & i Movimenti Locali*. . . . Leyden, 1638. *Ed. Naz.* 8.108-9

SIMPLICIO. Ma chi possano la maggior sopra la minore?

SALVIATI. Le accrescerebbe peso, quando il suo moto fusse più veloce: ma già si è concluso che quando la minore fusse più tarda, ritarderebbe in parte la velocità della maggiore, tal che il lor composto si moverebbe men veloce, essendo maggiore dell' altra; che è contro al vostro assunto. Concludiamo per ciò, che i mobili grandi e i piccoli ancora, essendo della medesima gravità in spetie, si muovono con pari velocità.

SIMP. Il vostro discorso procede benissimo veramente: tuttavia mi par duro a credere che una lagrima di piombo si abbia a muover così veloce come una palla d' artiglieria.

SALV. Voi dovevi dire, un grano di rena come una macina da guado. Io non vorrei, Sig. Simplicio, che voi faceste come molt' altri fanno, che, divertendo il discorso dal principale intento, vi attaccaste a un mio detto che mancasse dal vero quant' è un capello, e che sotto questo capello volesse nasconder un difetto d'un altro, grande quant' una gomona da nave. Aristotele dice: 'Una palla di ferro di cento libbre, cadendo dall' altezza di cento braccia, arriva in terra prima che una di una libbra sia scesa un sol braccio'; io dico ch' ell' arrivano nell' istesso tempo; voi trovate, nel farne l'esperienza, che la maggiore anticipa due dita la minore, cioè che quando la grande percuote in terra, l'altra ne è lontana due dita: ora vorreste dopo queste due dita appiattare le novantanove braccia d'Aristotele.

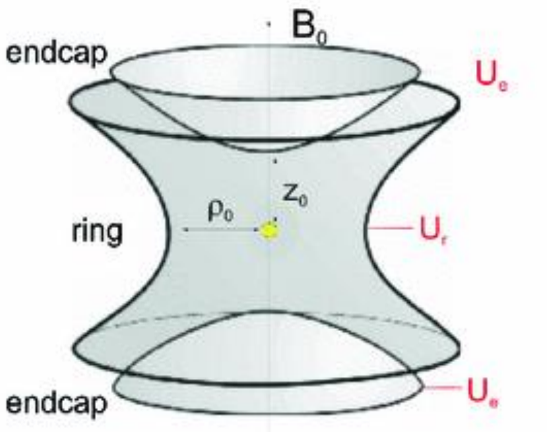
CERN LIBRARIES, GENEVA
CM-P00044235

Untimely – the LEAR program was shutdown in 1996 in favour of AD

Holzscheiter, M., talk to 2° Workshop on Antimatter and Gravity (2015)

Gabrielse's argument: an accurate frequency comparison, such as that done by TRAP …

Cyclotron frequency of single protons and antiprotons in a Penning trap



$$\omega_c = \frac{qB}{m} \approx 15\ \mathrm{MHz\,T^{-1}} \qquad \left|\frac{\omega_c - \bar{\omega}_c}{\omega_c}\right| < 9 \cdot 10^{-11}$$

… can be re-interpreted as an indirect WEP test, if

1) Protons do not violate the Equivalence Principle
2) EEP violation for antiprotons parametrized by α
3) At "infinity" by CPT symmetry $\omega_c^\infty = \bar{\omega}_c^\infty$

$$\frac{\omega_c - \bar{\omega}_c}{\omega_c} = (3\alpha - 1)\frac{U}{c^2}$$

the absolute gravitational potential!

$$U/c^2 \approx 3 \cdot 10^{-5} \longrightarrow \alpha < 3 \cdot 10^{-6}$$

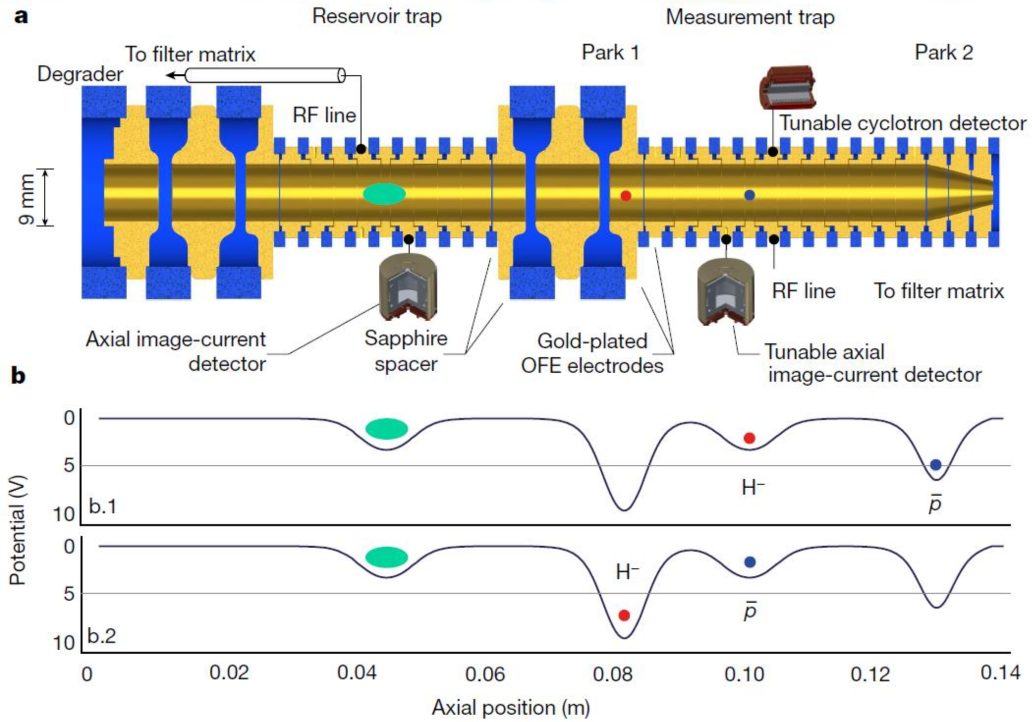
This approach has been discussed controversially[39], since the imposed clock shift depends on the absolute value of the gravitational potential, and a WEP-violating force might have a finite range, which would modify the chosen potential.

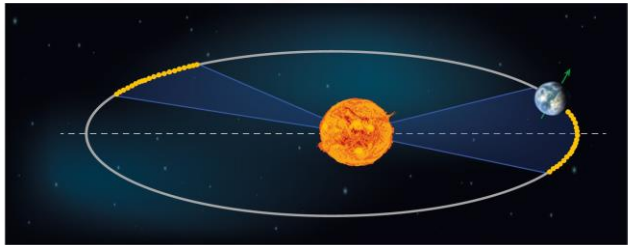
Gabrielse G. et al., Phys. Rev. Lett. 82 (1999) 3198
Gabrielse G. et al., Phys. Rev. Lett. 63 (1989) 1360

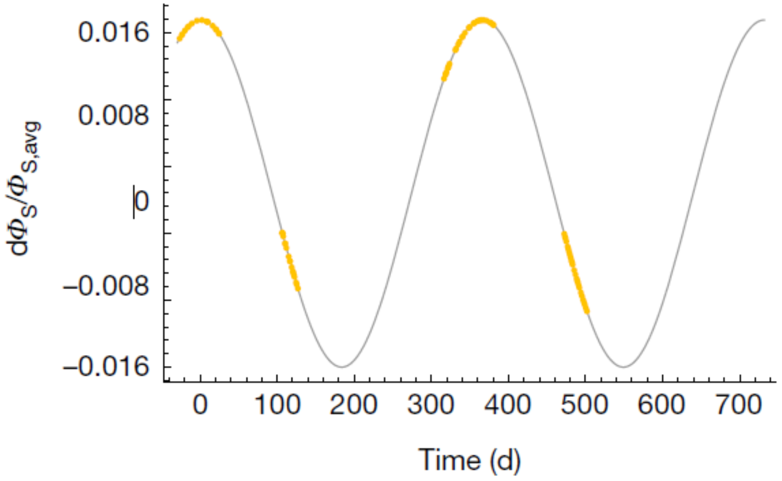
The absolute potential problem has now been addressed at Solar system scale

Article

A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio





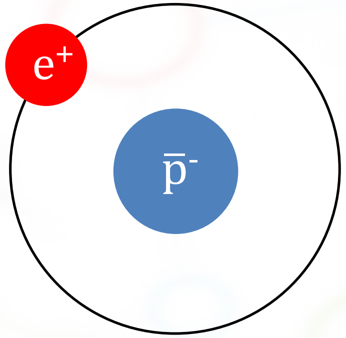


$$\frac{\Delta R(t)}{R_{avg}} = \frac{3GM_{sun}}{c^2}(\alpha_{g,D}-1)\left(\frac{1}{O(t)} - \frac{1}{O(t_0)}\right),$$

$$O(t) = D_p(1-\varepsilon^2)/[1+\varepsilon\cos((2\pi/t_{sid})t)]$$

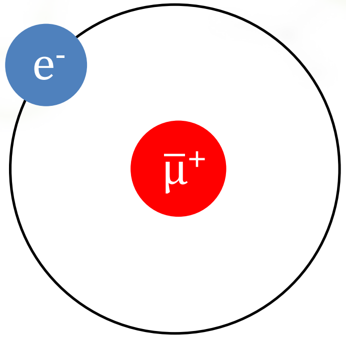
First indirect measurement: no gravitational signal is in fact detected; its absence puts a limit to WEP violations to: $|\alpha_{g,D}-1| < 0.03.$

Dropping neutral antiatoms: possible options



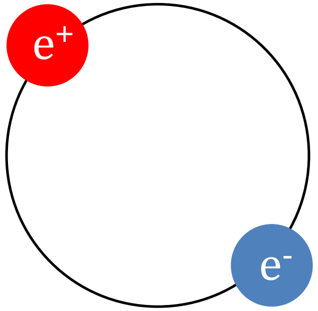
Antihydrogen ($\bar{H}$) Option 1

- only stable candidate
- 99.95% mass is in form of QCD binding E
- first generation, non-elementary system
- produced in small amounts only @ CERN



Muonium (Mu) Option 3

- short lifetime in all levels (2.2 us)
- 99.5% of mass is antimatter
- second generation elementary system
- produced in large numbers @ PAUL SCHERRER INSTITUT PSI



Positronium (Ps) Option 2

- short lifetime only in GS (142 ns)
- 50% of mass is antimatter
- first generation elementary syste
- produced in large numbers @

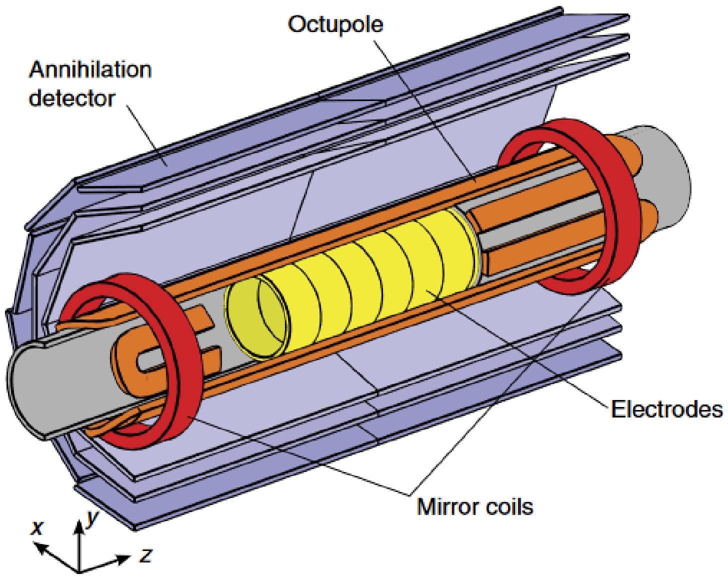
CERN INFN UCL

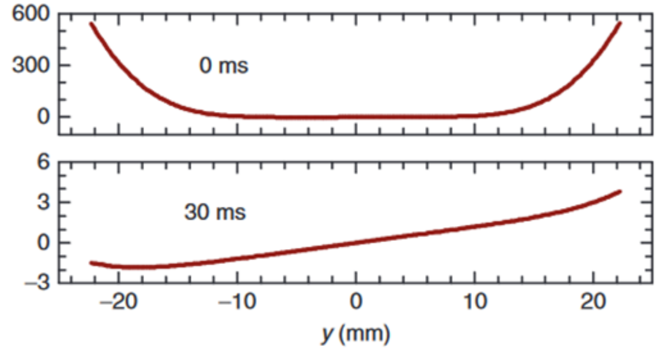
1) http://moriond.in2p3.fr/2019/Gravitation/transparencies/6_friday/1_morning/3_soter.pdf

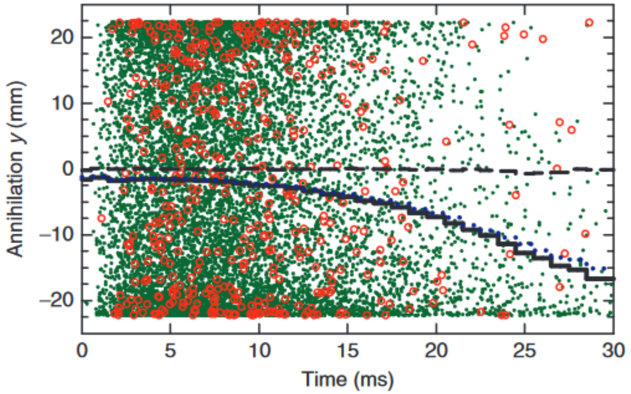
ARTICLE

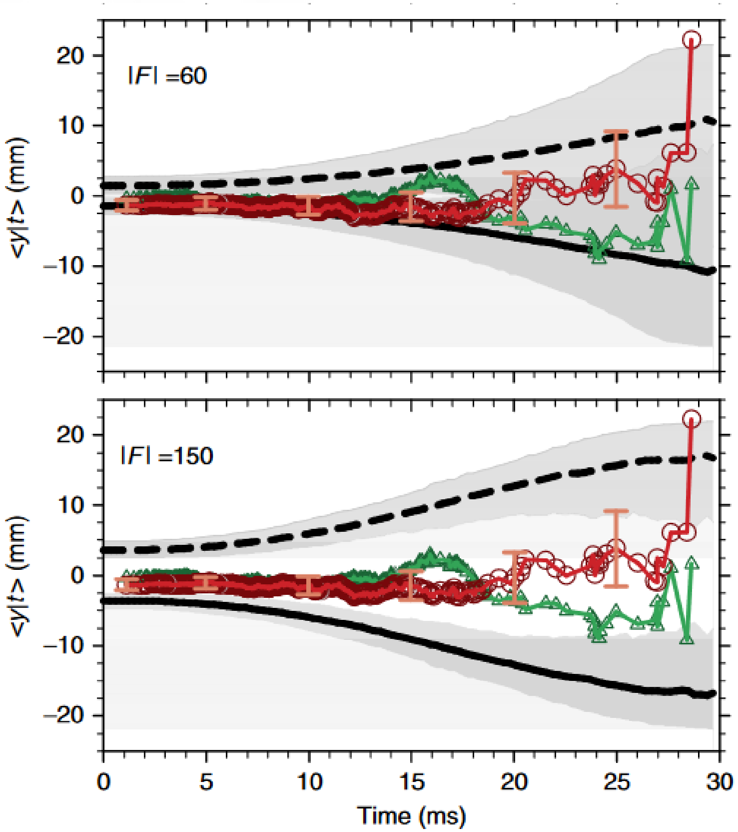
Received 14 Jan 2013 | Accepted 22 Mar 2013 | Published 30 Apr 2013 DOI: 10.1038/ncomms2787 OPEN

Description and first application of a new technique to measure the gravitational mass of antihydrogen









First coarse limit with a sensitivity in the ratio of masses of 75

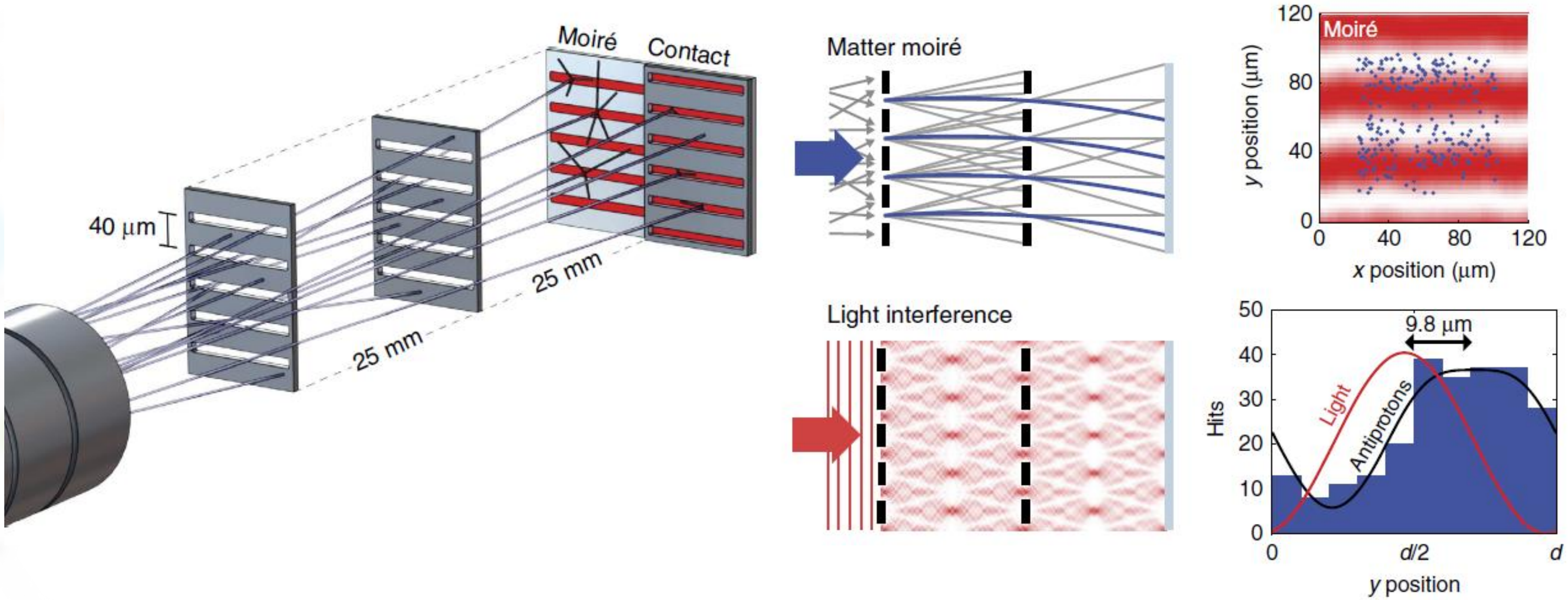
Basis of the method now used by ALPHA-g

Dropping neutral antiatoms: pulsed-produced antihydrogen

ARTICLE

Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014 DOI: 10.1038/ncomms5538 OPEN

A moiré deflectometer for antimatter



- Near-field diffraction of light as a tool for gratings alignment in all three spatial directions
- Atoms' time-of-flight knowledge required

$$\Delta y = \frac{F_{\|}}{m}\tau^2 \longrightarrow F_{min} \approx 5 \cdot 10^{-16}\,\mathrm{N}$$

Basis of the method now used by AEgIS

My research activity

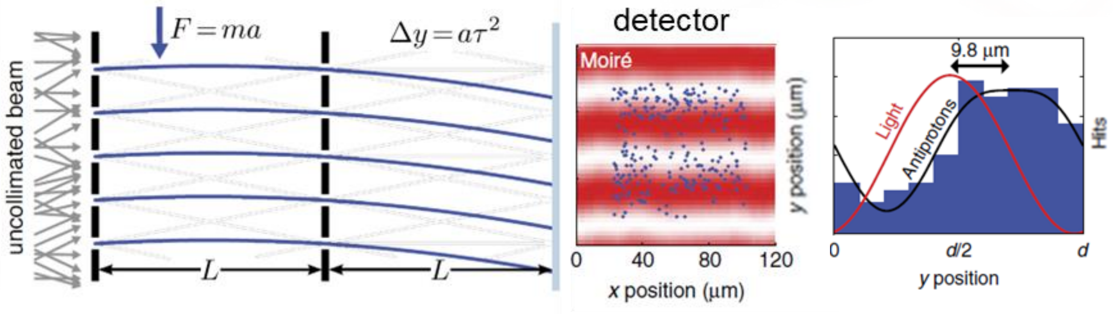
1) testing the Universality of the Free-Fall with Hbar

$$\begin{cases} \vec{F} = m_i\,\vec{a} \\ \vec{F}_g = m_g\,\vec{g} \end{cases} \xrightarrow{\text{UFF}} m_i \equiv m_g$$

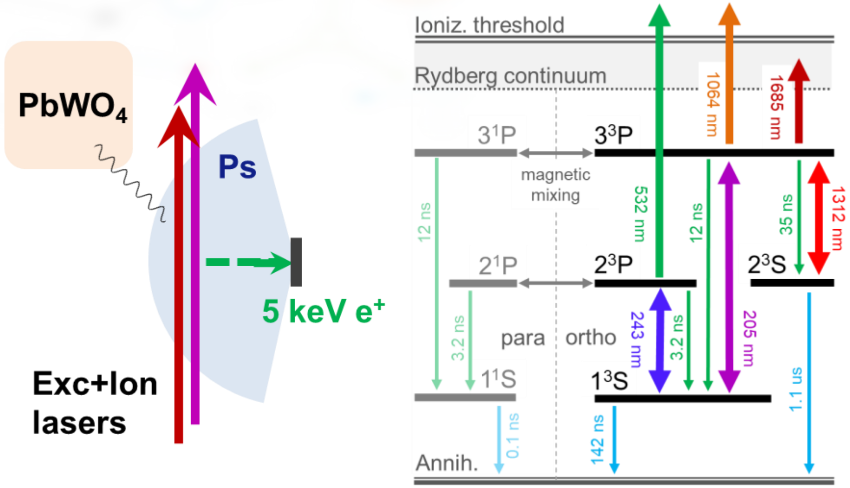
2) testing non-relativistic QED with Positronium

$$E(n,l,s,j) = -\frac{E_{ha}}{2n^2} + \frac{E_{ha}}{4n^3}\alpha^2\left[\frac{11}{8n} - \frac{4}{2l+1} + \delta_{s,1}\left(\delta_{l,0}\frac{14}{3} + \frac{2(1-\delta_{l,0})}{l(2l+1)(l+1)}\begin{cases} -\frac{(l+1)(3l-1)}{2l-1}, & \text{if } j=l-1 \\ -1, & \text{if } j=l \\ +\frac{l(3l+4)}{2l+3}, & \text{if } j=l+1 \end{cases}\right)\right]$$

Experimental implementations



$$a_{\min} = \underbrace{\frac{d}{2\pi\,\mathcal{V}\,\eta\,r}}_{\text{gratings}} \cdot \underbrace{\frac{2(L_{1\text{st}} + 2L)}{L^2}}_{\text{geometry}} \cdot \underbrace{\beta}_{\text{boost}} \cdot \underbrace{\frac{2k_bT}{m}\frac{1}{\sqrt{N_{\text{prod}}}}}_{\bar{\text{H}}\text{ source}}$$



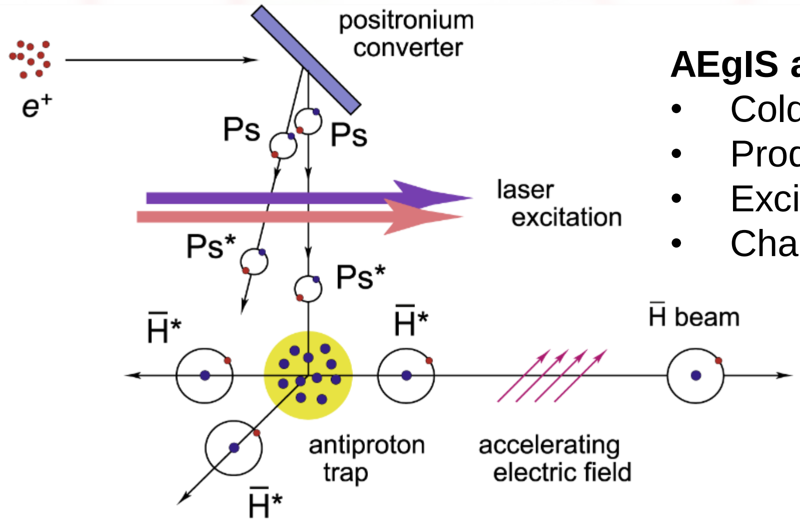
Main challenge: develop the manipulation technologies to build the sources

Pulsed production of a beam of antihydrogen

Positronium precise spectroscopy

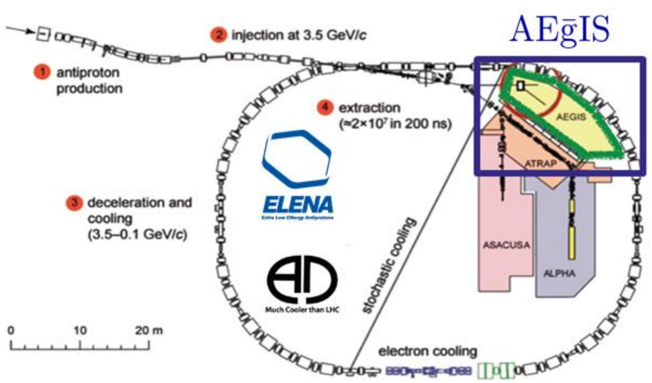
Positronium laser cooling

Pulsed production of a beam of antihydrogen (1/3)

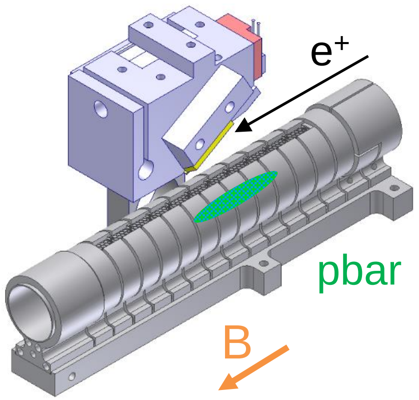


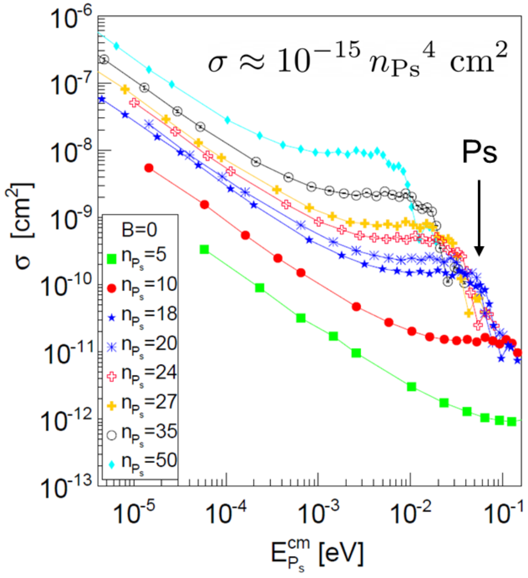
AEgIS antihydrogen source

- Cold trapped antiprotons
- Production of Positronium (Ps)
- Excitation to Rydberg levels (Ps*)
- Charge-exchange reaction



Malmberg-Penning trap





$$N_{\bar{H}} = \sigma \frac{L_{int}}{V_{\bar{p}}} N_{\bar{p}} N_{Ps}$$

$$\approx 0.05\ \text{cycle}^{-1}$$

$n_{Ps} \approx 17\ (32)$

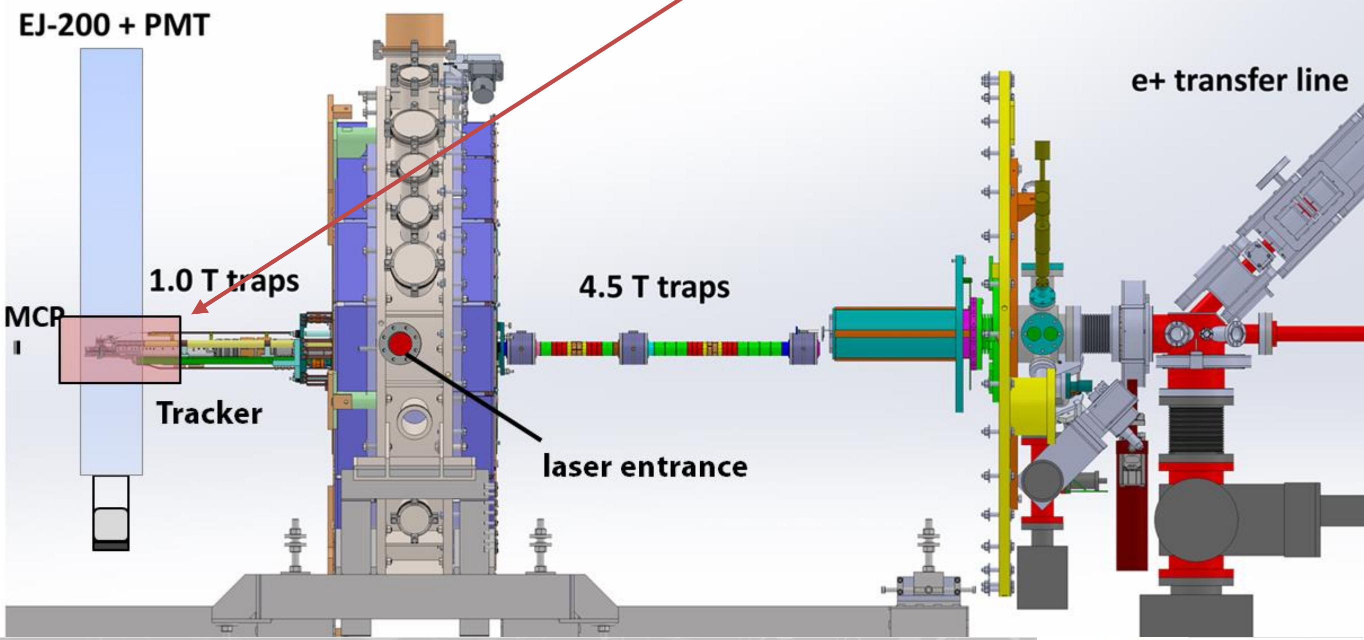
$L_{int} \approx 2\,\text{mm}\ (15\,\text{mm})$

$V_{\bar{p}} \approx 250\,\text{mm}^3$

$N_{\bar{p}} \approx 8 \cdot 10^5\ (3.0 \cdot 10^7)$

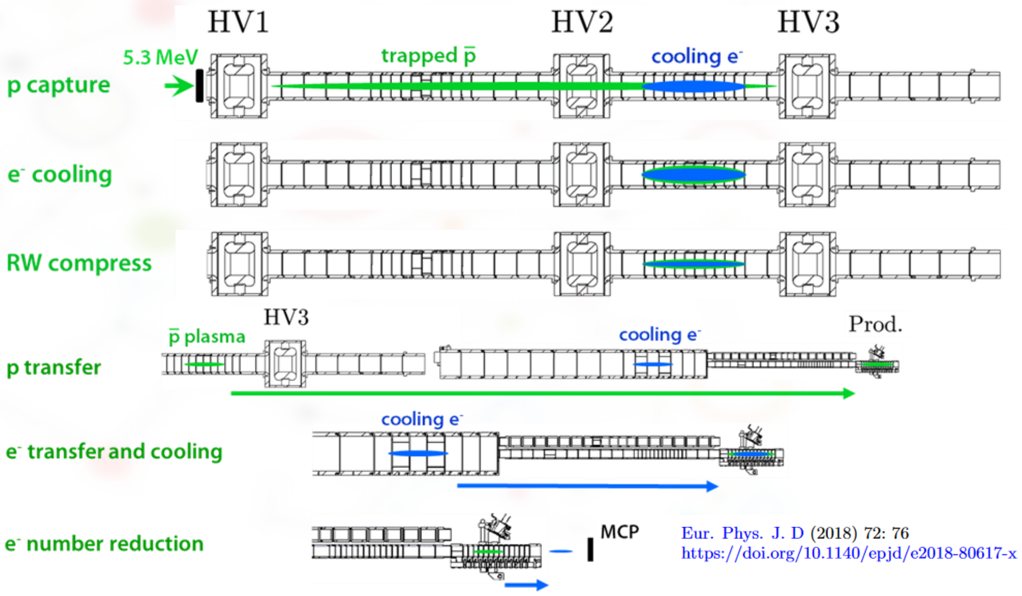
$N_{Ps} \approx 1500\ (10000)$

*in parenthesis, the numbers from the AEgIS-2 collinear scheme

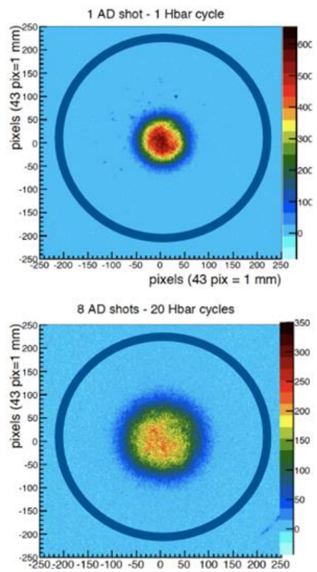


Ingredients preparation - my contributions

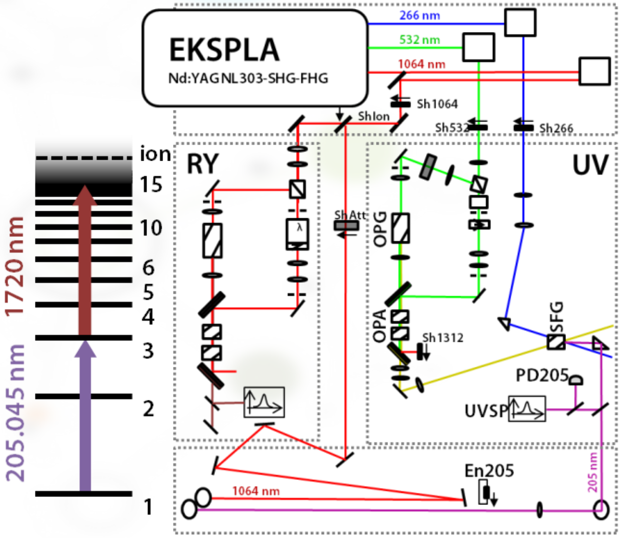
- Antiproton trapping, cooling, plasma manipulations and transfer to 1 T prod. trap – meas. temperature and expansion rate in asym. trap.
- Development of the excitation laser system and first Ps excitation
- Design of Ps target structure
- Technique for Rydberg Ps imaging on MCP based on the Motional Stark effect

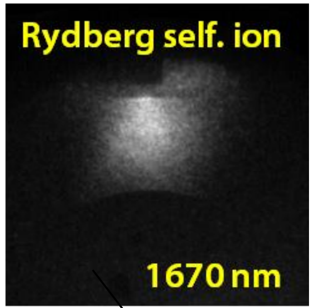


Eur. Phys. J. D (2018) 72: 76
https://doi.org/10.1140/epjd/e2018-80617-x

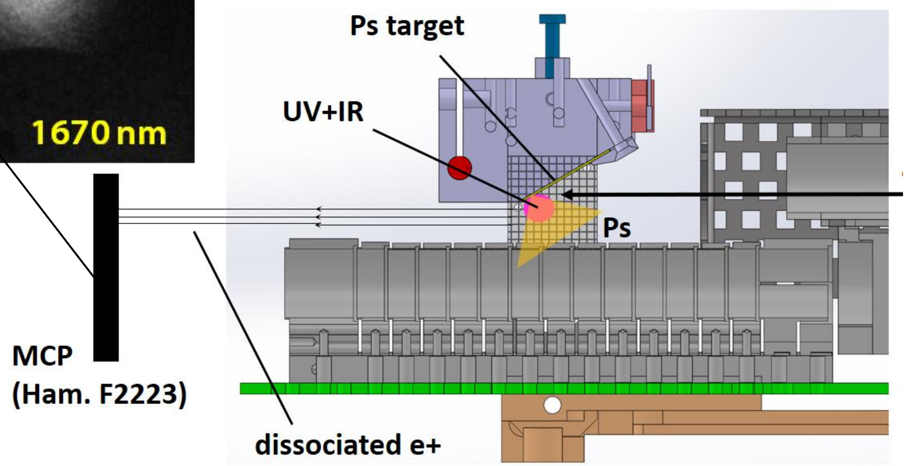


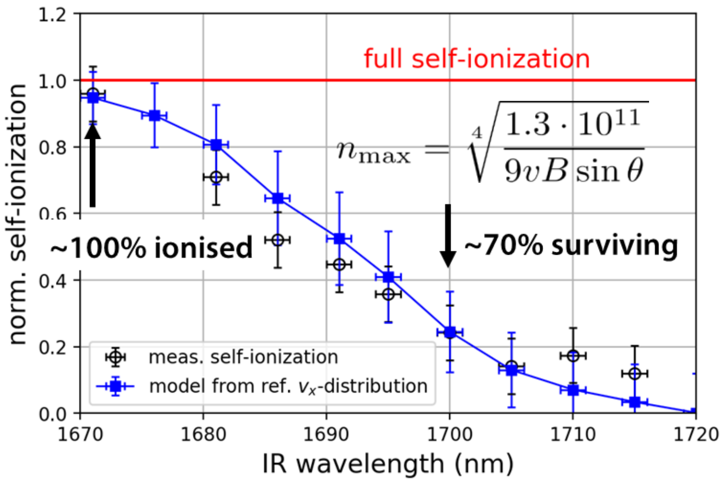
T = 400 K





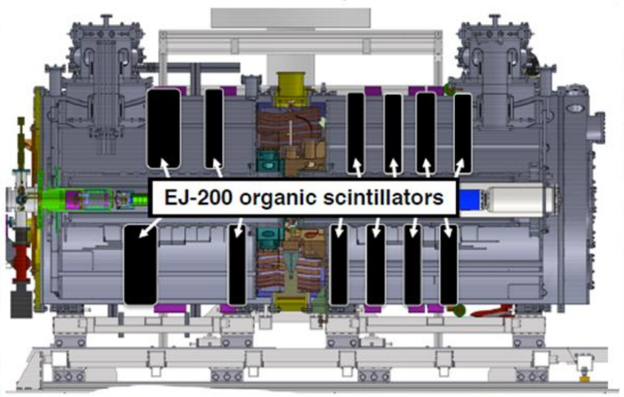
$$\vec{E}_{MS} = \vec{v} \times \vec{B} \qquad E_{1\,\mathrm{GHz}} = \frac{1.3 \cdot 10^6}{9n^4}\ \mathrm{kV\,cm^{-1}}$$

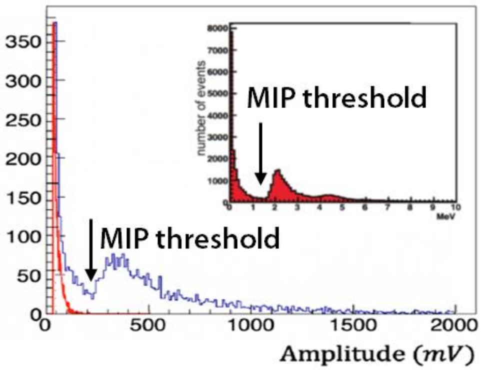


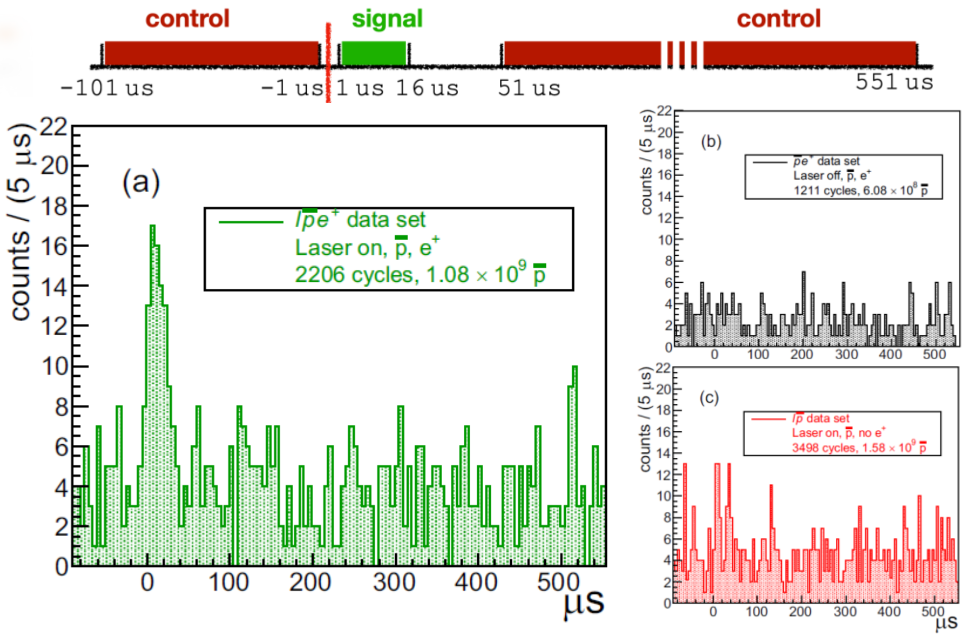


Pulsed production of a beam of antihydrogen (3/3)

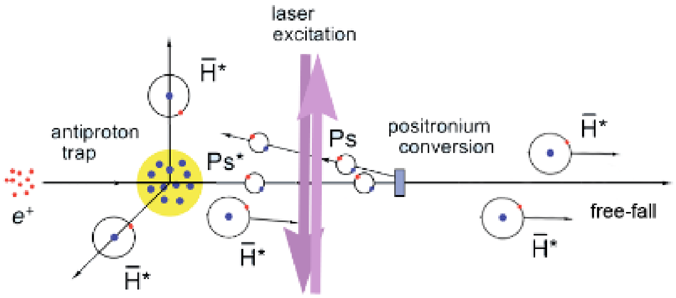
First pulsed Hbar source – my contributions
- Co-author analysis framework in ROOT/C++ (gAn)
- Co-author of analysis and of the article
- Operation of all main systems

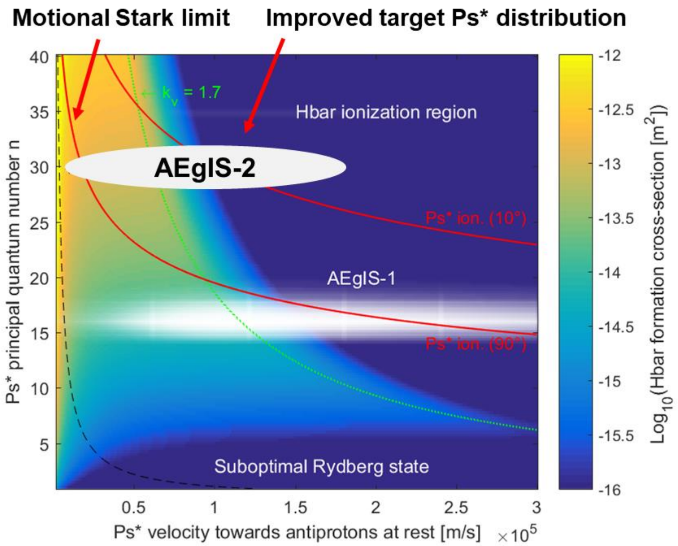


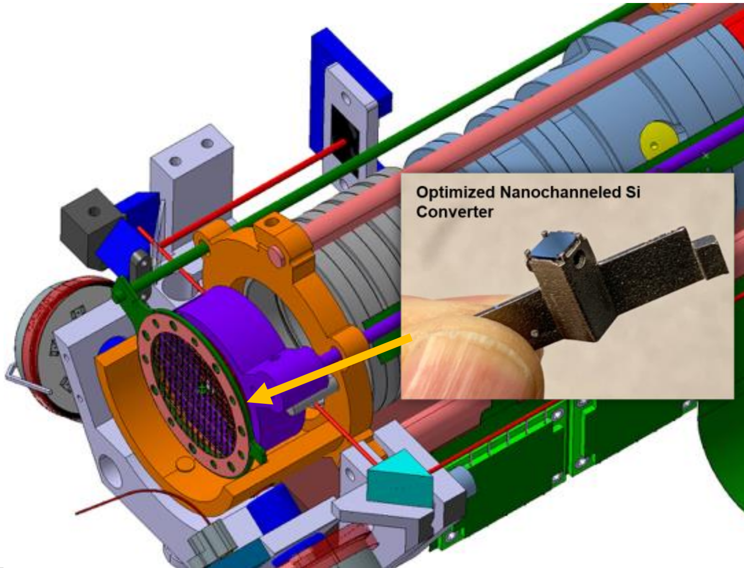




Going beyond the proof of concept (AEgIS-2)
- Layout of new collinear scheme
- Physics-driven redesign of the trap
- Redesign and implementation of the control system (SINARA+ARTIQ)



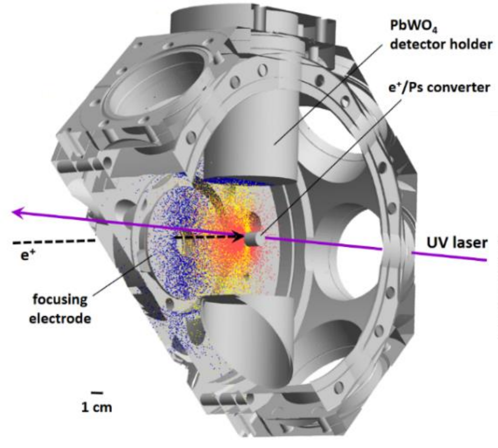




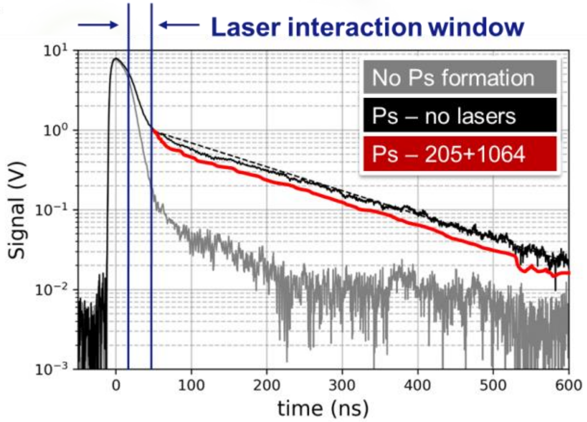
Byproduct: precise spectroscopy of Ps (1/2)

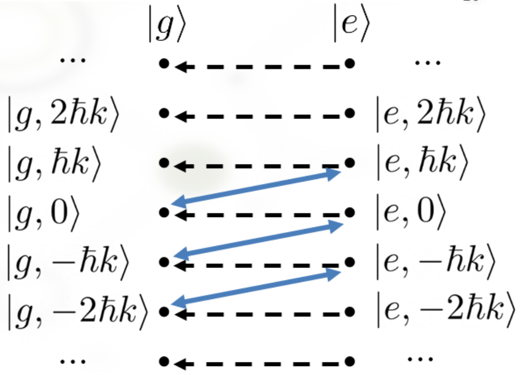
Positronium precise spectroscopy goal: reaching unprecedented experimental accuracies in the determination of the transition frequencies.

Pillar 1. SSPALS measurement technique + minimization of external E and B fields for e^+ transport (fully electrostatic Ps setup with ns switchable fields)



$$S = \frac{A_{on} - A_{off}}{A_{off}}$$





$$\frac{dN_e(t)}{dt} = -A_{eg}N_e - u_{\vec{k}}(\omega_{eg})B_{eg}(N_e - N_g) + \sigma_I N_e$$

$$\frac{dN_g(t)}{dt} = -\gamma_g N_g + A_{eg}N_e + u_{\vec{k}}(\omega_{eg})B_{eg}(N_e - N_g)$$

A_{eg} $|e,0\rangle \longrightarrow |g,0\rangle + \gamma$

B_{eg} $|g,0\rangle + \gamma \longrightarrow |e,\hbar k\rangle$, $|e,0\rangle + \gamma \longrightarrow |g,-\hbar k\rangle + 2\gamma$

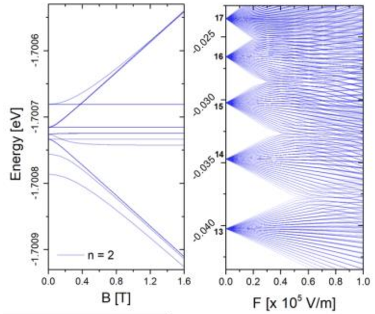
Pillar 2. Calculate non-perturbatively Ps levels and Einstein coefficients in arbitrary E and B fields to estimate systematic effects/calculate corrections at the same degree of precision of energy levels in vacuum (α^{6+}, or 0.01 MHz)

$$H = H_0 - e\vec{r}\cdot\left(\vec{E} + \vec{v}\times\vec{B}\right) + \mu_B\,\vec{B}\cdot(\vec{\sigma}_e - \vec{\sigma}_p) - \frac{e^2}{4m_e}(\vec{r}\times\vec{B})^2$$

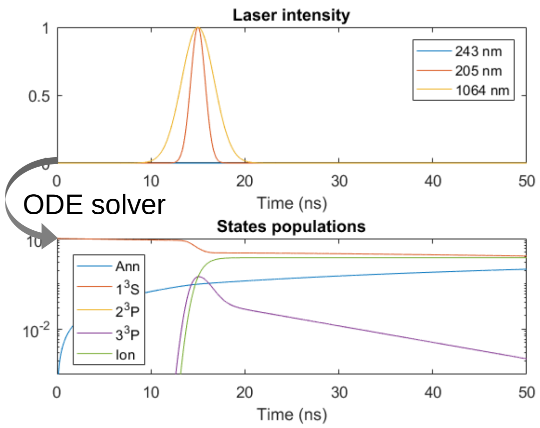
$$\longrightarrow \langle n,l,s,j,m|\,H_Z\,|n',l',s',j',m'\rangle = 2\mu_B\,B\,\delta_{nn'}\,\delta_{ll'}\,\delta_{mm'}\,\delta_{s,1-s'}\,(-1)^{2j+l'-s+s'+m} \cdot \sqrt{3(2j+1)(2j'+1)}\begin{pmatrix} j & 1 & j' \\ -m & 0 & m' \end{pmatrix}\begin{Bmatrix} s & l & j \\ j' & 1 & s' \end{Bmatrix}$$

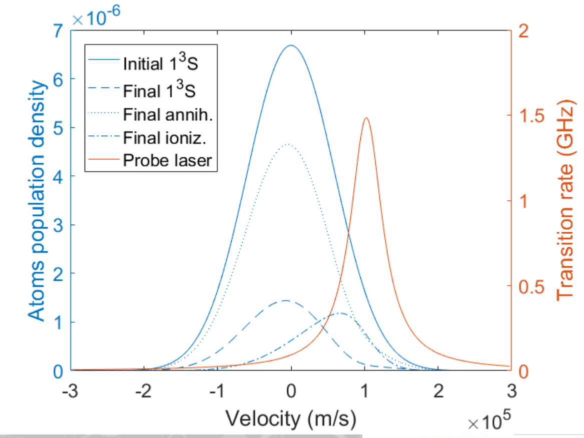
$$\longrightarrow f(j) = \begin{pmatrix} j & j_2 & j_3 \\ -m_2-m_3 & m_2 & m_3 \end{pmatrix} \longrightarrow X(j)\,f(j+1) + Y(j)\,f(j) + Z(j)\,f(j-1) = 0$$

$$Z(j) = (j+1)\sqrt{j^2-(j_2-j_3)^2}\sqrt{(j_2+j_3+1)^2-j^2}\times\sqrt{j^2-(m_2+m_3)^2}$$
$$Y(j) = (2j+1)[(m_2+m_3)\{j_2(j_2+1)-j_3(j_3+1)\}-(m_2-m_3)j(j+1)]$$
$$X(j) = j/(j+2)\,Z(j+1)$$

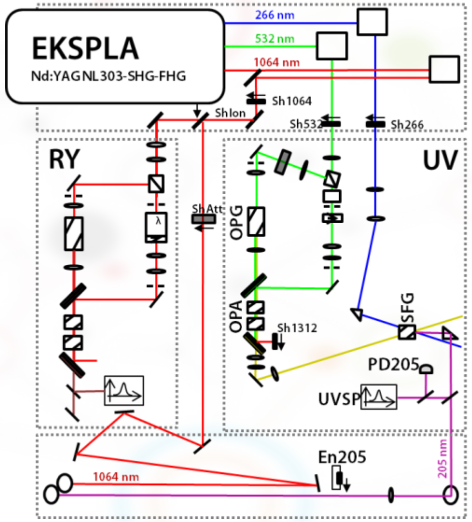


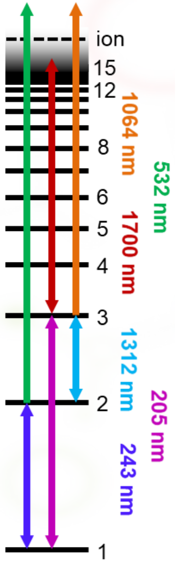
Pillar 3. A rate-equations code to model incoherent laser excitation including the atoms' external degrees of freedom to account for the motional Stark and recoil effects (relevant for Ps due to the small mass: 6.1 GHz at 243 nm)



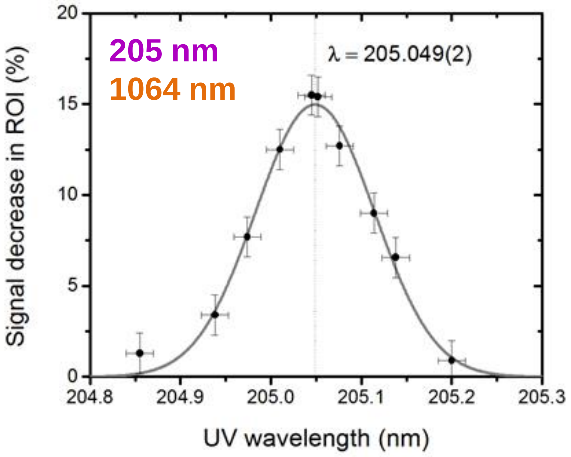


Byproduct: precision spectroscopy of Ps (2/2)

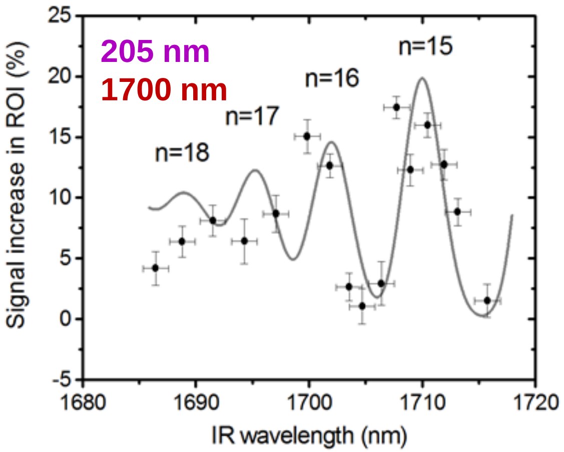




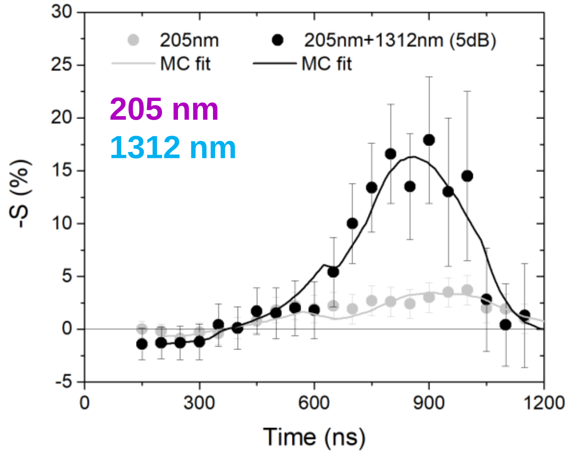
Spectroscopy 1S-3P in 250 G



Spectroscopy 3P-Ry in 250 G

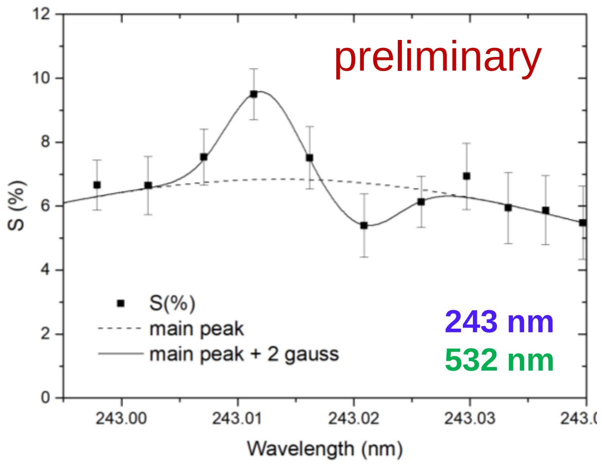


De-excitation 3P-2S in 150 G

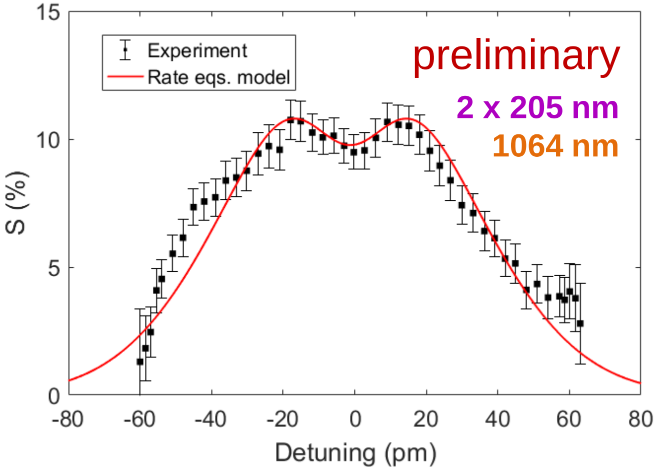


$$\lambda_3^{\mathrm{exp}} = 205.050 \pm 0.02_{\mathrm{sys}} \pm 0.005_{\mathrm{stat}}\ \mathrm{nm} \qquad \lambda_3^{\mathrm{the}} = 205.0474\ \mathrm{nm}$$

GS HFS via 1S-2P spectroscopy



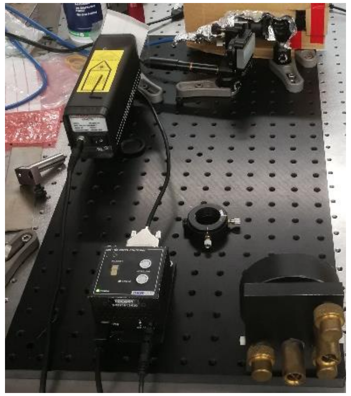
Sat. Absorp. Spectr. 1S-3P



Challenges

- Obtaining a ultra-high resolution spectrometer in the UV range with a resolving power of >100.000
- Current limit: absolute calibration lines. Candidates: H (1s-2s, 1s-3s), tin (242.169 nm, 242.959 nm).
- First order Doppler effect from the velocity spread of Ps: need a colder Ps source.

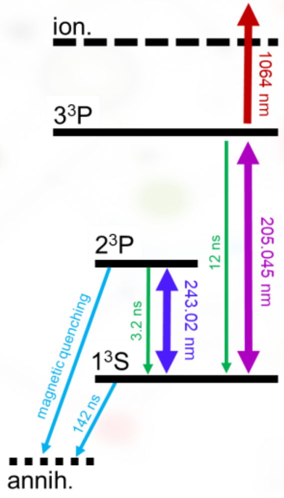
Echelle spectrometer

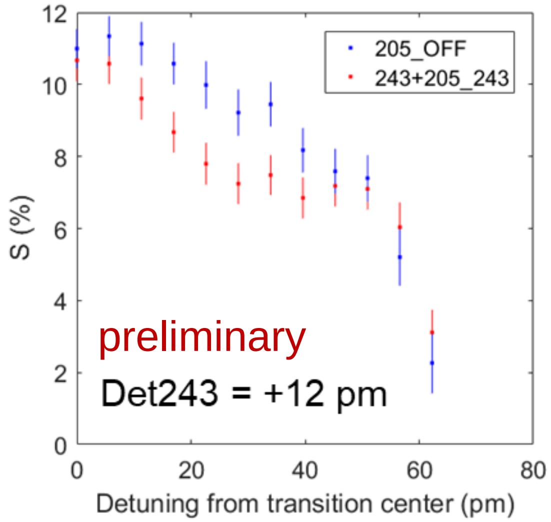


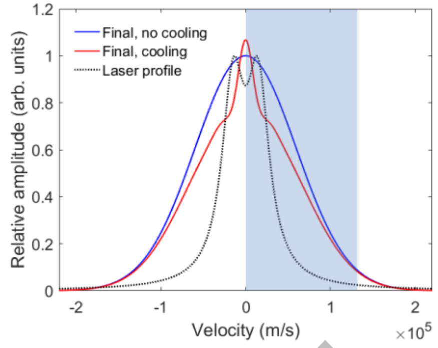
The key technologies for the future: positronium laser cooling

Doppler-cooled Ps sources: the real challenge to next-gen. high resolution spectroscopy to overcome the Doppler effect. Major technical breakthrough.

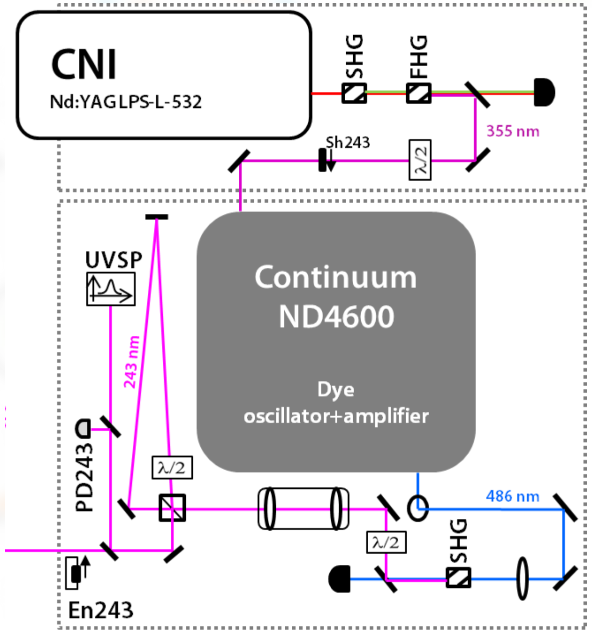
Approach:
- Laser cool along 1S-2P, each recoil 6 GHz, but only ~150 ns available
- Probe along 1S-3P with 1S-3P laser at 205 nm



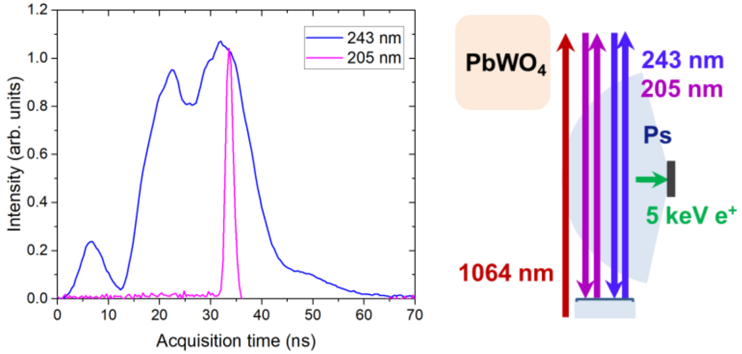


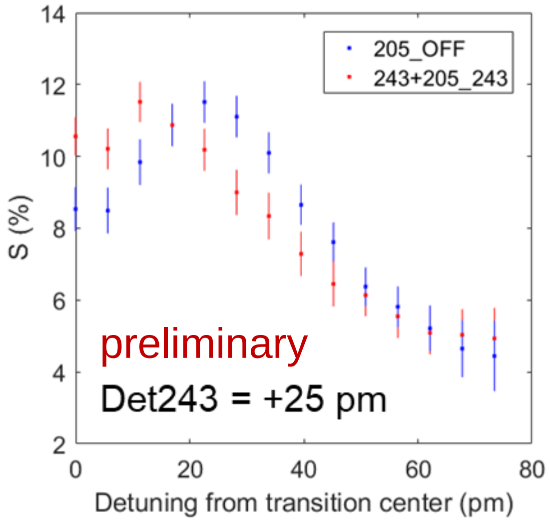


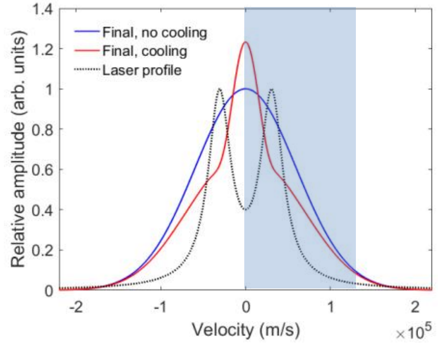
$$\delta v = (c/\lambda)\,\delta\lambda$$



Challenges:
- Long-pulse intense 243nm laser
- Demonstrate the simultaneous excitation and probing
- Transport e^+ without magnetic field







Tentative signal but rather small effect and the experiment requires further consolidation

The key technologies for the future: (anti)-atom interferometry

J. Rodewald, N. Dörre, A. Grimaldi, P. Geyer, L. Felix, M. Mayor, A. Shayeghi, and M. Arndt, *Isotope-selective high-order interferometry with large organic molecules in free fall*, New J. Phys. 20, 033016 (2018)

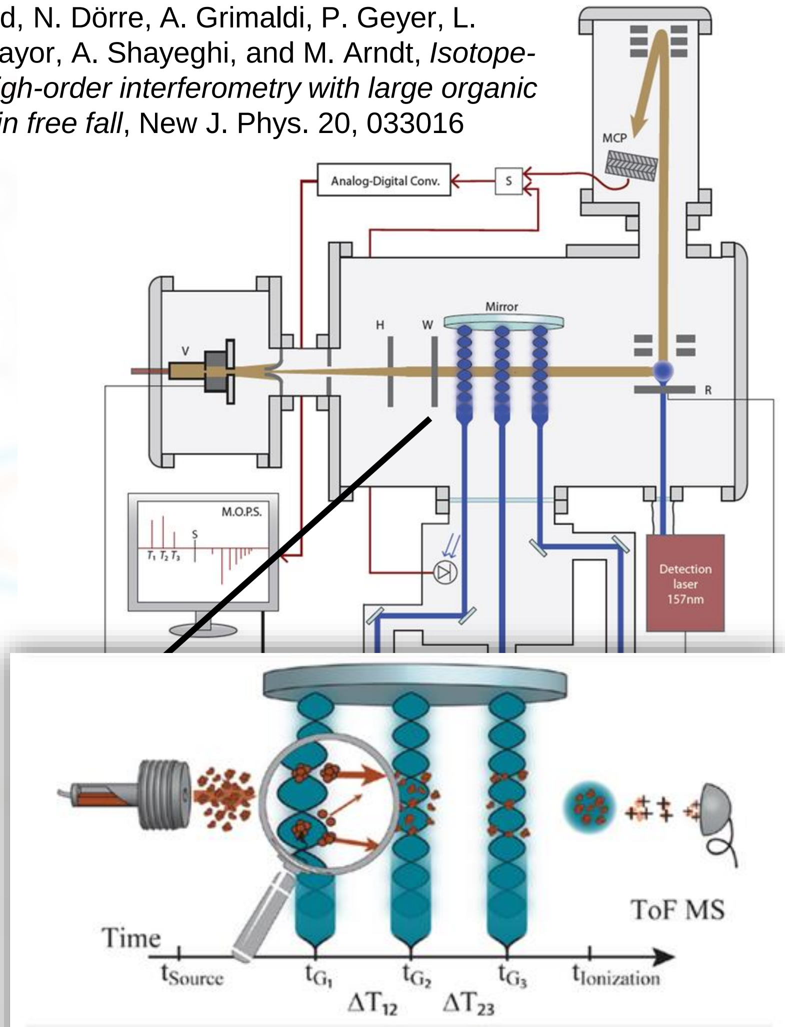
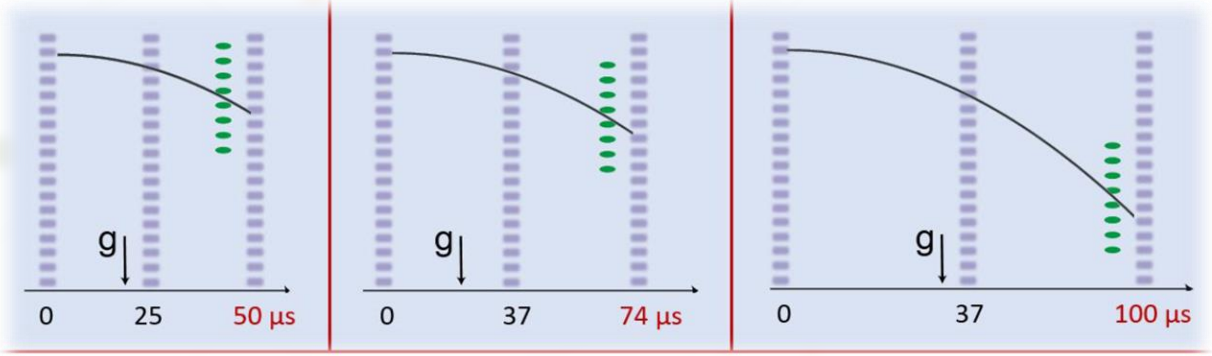
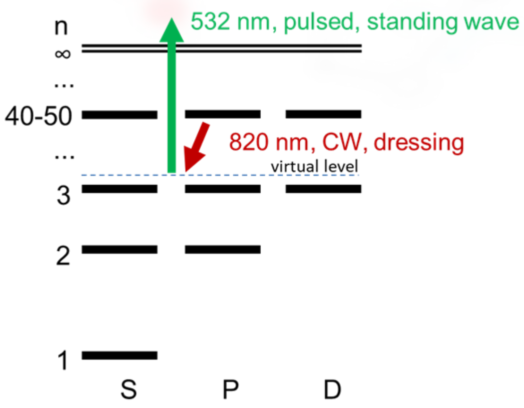
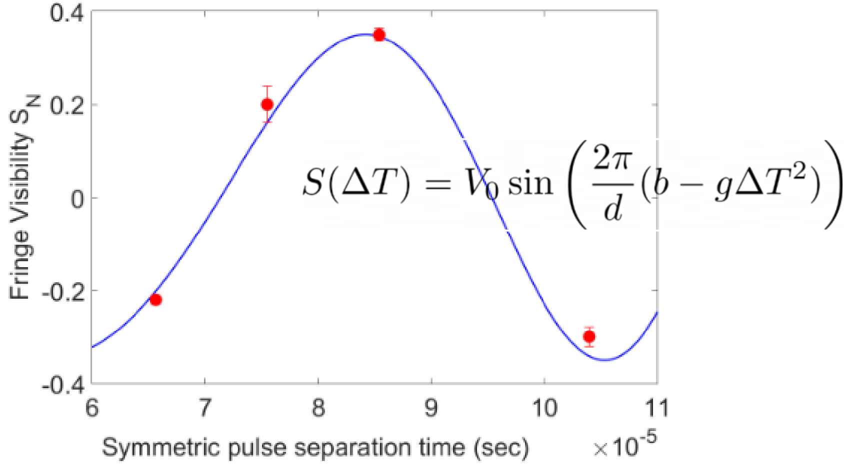


Figure 3: Talbot-Lau-interferometer OTIMA with three pulsed standing laser waves [4].







Much higher sensitivities can be obtained thanks to the ~200 nm periodicity of light gratings. dg/g of 10% reachable with 400 detected atoms and a 532 nm time-domain interferometer.

Future outlook

LS2 | **LS3**

Immediate future (1 year) → **Mid-next future (5 years)** → **Longer term outlook ...**

Immediate future (1 year)

Consolidating source technologies

- Establishing of Ps laser cooling
- Realization of the first intense **beam of antihydrogen**
- Design of first **atom interferometer** employing **antimatter**
- Design of a portable antiproton traps based on a new concept (*hot storage* vs *cold storage*)
- Proposal and design of 2° gen. precision spectroscopy measurements (1s-3s, 1s-3p, HFS on n=2 and n=3, 1s-Ry)

Mid-next future (5 years)

First Physics results

- First **test** of the **Universality of the Free-Fall**
- Precision **spectroscopy of Ps** at the **MHz** level
- Realization of atom interferometry with antimatter
- Validation of the *hot storage* technique to transport antiprotons in precision atomic physics laboratories

Longer term outlook ...

Fundamental Physics questions

- Precision tests of the Universality of the Free-Fall – constraining theoretical models of modified gravity
- Precision tests of bound-state QED with Positronium, possibly detecting the gravitational redshift of the 1s-2s and 1s-3s transitions at the 0.1 MHz level