Spin dependent EP tests
(and other gravity tests using atom interferometry)

Guglielmo M. Tino

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Istituto Nazionale di Fisica Nucleare, Sezione di Firenze

http://coldatoms.lens.unifi.it/
Atom interferometry and gravity
Atom interferometry and gravity

Interference fringes – Firenze 2006
Why atoms?

- Extremely small size
- Well known and reproducible properties
- Quantum systems
- Precision gravity measurement by atom interferometry
- Potential immunity from stray fields effects
- Different states, isotopes,…
• Measure $g$ by atom interferometry
• Add source masses
• Measure change of $g$

➢ Precision measurement of $G$
➢ Test of Newtonian law

$$F(r) = G \frac{M_1 M_2}{r^2}$$
Measurements of the Newtonian gravitational constant $G$

$G \approx 6.673 \pm 0.004 \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$

Measurements:
- NIST-82: torsion balance
- TR&D-96: torsion balance
- LANL-97: torsion balance
- CODATA 1998
- UWash-00: torsion balance
- BIPM-01: torsion balance
- UWup-02: simple pendulum
- CODATA 2002
- MSL-03: torsion balance
- HUST-05: torsion balance
- UZur-06: beam balance
- CODATA 2006
- HUST-09: torsion balance
- JILA-10: simple pendulum
- CODATA 2010
- BIPM-13: torsion balance
Measurements of the Newtonian gravitational constant $G$

$G = 6.67384 \pm 0.00080 \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$

**Raman interferometry in an atomic fountain**

Phase difference between the paths:

\[ \Delta \Phi = k_e [z(0) - 2z(T) + z(2T)] + \Phi_e \]

with \( z(t) = -g t^2/2 + v_0 t + z_0 \) \& \( \Phi_e = 0 \) \( \Rightarrow \Delta \Phi = k_e g T^2 \)

\[ g = \Delta \Phi / k_e T^2 \]

Final population:

\[ N_a = N/2 \ (1 + \cos[\Delta \Phi]) \]

- 10^6 Rb atoms
- S/N = 1000
- T = 150 ms \( \Rightarrow 2\pi = 10^{-6} g \)

**Sensitivity** \( 10^{-9} \) g/shot

---


Atom gravimeter + source mass

Sensitivity $10^{-9}$g/shot

one shot $\Rightarrow \Delta G/G \approx 10^{-2}$

Peak mass acceleration $a_G \approx 10^{-7}$g

500 kg tungsten mass

10000 shots $\Rightarrow \Delta G/G \approx 10^{-4}$
**Gravity gradiometer**

\[ \Delta \Phi = k_e g T^2 \]

- T = 5 ms
  - resol. = \(2.3 \times 10^{-5}\) g/shot

- T = 50 ms
  - resol. = \(1.0 \times 10^{-6}\) g/shot

- T = 150 ms
  - resol. = \(3.2 \times 10^{-8}\) g/shot


MAGIA: From proof-of-principle to the measurement of $G$

**Sensitivity**
- 15-fold improvement of the instrument sensitivity from 2008 to 2013
- integration time for the target 100 ppm reduced by more than a factor 200

**Accuracy**
- systematic uncertainty reduced by a factor $\sim$10 since 2008, mostly due to
  - better characterization of source masses
  - control & mitigation of Coriolis acceleration
  - excellent control of atomic trajectories

**Data analysis**
- developed a reliable model accounting for all of the relevant effects
  - gravitational potential generated by source masses along atomic path
  - quantum mechanical phase shift of atomic probes
  - detection efficiency
- measured data compared with a Montecarlo simulation
MAGIA: increasing sensitivity

Current sensitivity to differential acceleration: $3 \times 10^{-9}$ g @ 1s (=QPN for $4 \times 10^5$ atoms)

MAGIA: Final sensitivity

- Repetition period of experimental cycle: 1.9 s
- Number of points per ellipse: 720 (23 min)
- Number of launched atoms: \(\sim 10^9\) per cloud
- Number of detected atoms: \(\sim 4 \times 10^5\) per cloud
- Sensitivity to ellipse angle: \(\sim 9\) mrad/shot
- Sensitivity to differential gravity: \(3 \times 10^{-9} \text{ g} / \sqrt{\text{Hz}}\)
- Sensitivity in \(G\) measurements: \(5.7 \times 10^{-2} / \sqrt{\text{Hz}}\)
- Integration time to \(G\) at \(10^{-4}\): 100 hours
(July 2013)

Relative uncertainty ~ 116 ppm (statistical)
**LETTER**

**Precision measurement of the Newtonian gravitational constant using cold atoms**

G. Rosi¹, F. Sorrentino¹, L. Cacciapuoti², M. Prevedelli³ & G. M. Tino⁴

About 300 experiments have tried to determine the value of the Newtonian gravitational constant, $G$, so far, but large discrepancies in the results have made it impossible to know its value precisely. The weakness of the gravitational interaction and the impossibility of shielding the effects of gravity make it very difficult to measure $G$ while keeping systematic effects under control. Most previous experiments performed were based on the torsion pendulum or torsion balance scheme as in the experiment by Cavendish in 1798, and in all cases macroscopic masses were used. Here we report the precise determination of $G$ using laser-cooled atoms and quantum interferometry. We obtain the value $G = 6.67191(99) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ with a relative uncertainty of 150 parts per million (the combined standard uncertainty is 150 ppm). A possible source of spurious effects was obtained by reversing the direction of the two-photon recoil used to split and recombine the wave packets in the interferometer. Efforts were devoted to the control of systematic effects related to atomic trajectories, the positioning of the atoms and effects due to stray fields. The high density of tungsten was instrumental in maximizing the signal and in compensating for the Earth's gravitational gradient in the region containing the atom interferometers, thus reducing the sensitivity of the experiment to the vertical position and size of the atomic probes.

The atom interferometer is realized using light pulses to stimulate $^{87}$Rb atoms at the two-photon Raman transition between the hyperfine levels $|F=2, m_F=2\rangle$ and $|F=1, m_F=1\rangle$. The relevant gravitational signal. An additional cancellation of common-mode spurious effects was obtained by reversing the direction of the two-photon recoil used to split and recombine the wave packets in the interferometer.
Determination of \( G \)

\[
G = 6.674 \pm 0.003 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}
\]

\( G \) values from various experiments:
- NIST-82 torsion balance
- TR&D-96 torsion balance
- LANL-97 torsion balance
- CODATA 1998
- UWash-00 torsion balance
- BIPM-01 torsion balance
- UWup-02 simple pendulum
- CODATA 2002
- MSL-03 torsion balance
- HUST-05 torsion balance
- UZur-06 beam balance
- CODATA 2006
- HUST-09 torsion balance
- JILA-10 simple pendulum
- CODATA 2010
- BIPM-13 torsion balance
- THIS WORK atom interferometry

G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli & G. M. Tino,
*Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms*
*NATURE* vol. 510, p. 518 (2014)
## MAGIA error budget

<table>
<thead>
<tr>
<th>Effect</th>
<th>Uncertainty</th>
<th>Correction to $G$ (ppm)</th>
<th>Relative uncertainty $\Delta G/G$ (ppm)</th>
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<tbody>
<tr>
<td>Air density</td>
<td>10 %</td>
<td>60</td>
<td>6</td>
</tr>
<tr>
<td>Apogee time</td>
<td>30 $\mu$s</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Atomic clouds horizontal size</td>
<td>0.5 mm</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Atomic clouds vertical size</td>
<td>0.1 mm</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td>Atomic clouds horizontal position</td>
<td>1 mm</td>
<td></td>
<td>37</td>
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<tr>
<td>Atomic clouds vertical position</td>
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<td></td>
<td>5</td>
</tr>
<tr>
<td>Atoms launch direction change C/F</td>
<td>8 $\mu$rad</td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>Cylinders density inhomogeneity</td>
<td>$10^{-4}$</td>
<td>91</td>
<td>18</td>
</tr>
<tr>
<td>Cylinders radial position</td>
<td>10 $\mu$m</td>
<td></td>
<td>38</td>
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<tr>
<td>Ellipse fitting</td>
<td>-13</td>
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<tr>
<td>Size of detection region</td>
<td>1 mm</td>
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<tr>
<td>Support platforms mass</td>
<td>10 g</td>
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<tr>
<td>Translation stages position</td>
<td>0.5 mm</td>
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<td>6</td>
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<tr>
<td>Other effects</td>
<td>&lt;2</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Systematic uncertainty</td>
<td></td>
<td></td>
<td>92</td>
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<tr>
<td>Statistical uncertainty</td>
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<td></td>
<td>116</td>
</tr>
<tr>
<td>Total</td>
<td>137</td>
<td>148</td>
<td></td>
</tr>
</tbody>
</table>

M. Prevedelli, L. Cacciapuoti, G. Rosi, F. Sorrentino and G. M. Tino,
*Measuring the Newtonian constant of gravitation $G$ with an atomic interferometer*,
Measurement of the Gravity-Field Curvature by Atom Interferometry

Measurement of the Gravity-Field Curvature by Atom Interferometry

\[ x(\theta) = A + B \sin \theta, \]
\[ y(\theta) = C + D \sin(\theta + \varphi_1), \]
\[ z(\theta) = E + F \sin(\theta + \varphi_1 + \varphi_2) \]
Ultracold Sr - Experiments in Firenze

- Optical clocks using visible intercombination lines
- New atomic sensors for fundamental physics tests


1992

sub-Doppler laser spectroscopy
of Sr in a hollow cathode discharge
0 -> 1 intercombination line

2003

saturation spectroscopy
of Sr in a thermal atomic beam
0 -> 1 intercombination line

2009

Magnetic field induced spectroscopy
of cold Sr atoms in an optical lattice
0 -> 0 intercombination line

2012

Magnetic field induced spectroscopy
of cold Sr atoms in an optical lattice
0 -> 0 intercombination line


N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino,

Laser cooling of $^{88}\text{Sr}$

- **500 °C vapor from oven**
  - Slow-down
  - $a \sim 5 \times 10^5 \text{ m/s}^2$
- **Zeeman slower**
  - $\lambda = 461 \text{ nm (blue laser)}$
  - $T \sim 1 \text{ mK}$
  - $N \sim 5 \times 10^7$
- **Blue MOT**
  - $\lambda = 689 \text{ nm (red laser)}$
  - $T \sim 1 \mu\text{K}$
  - $N \sim 2 \times 10^6$
- **Red MOT**
  - $\lambda = 532 \text{ nm (Nd:YVO}_4\text{ green laser)}$
  - $T \sim 1 \mu\text{K}$
  - $N \sim 10^5$

### Parameters

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$T_R$</th>
<th>$T_D$</th>
<th>$I_s$</th>
<th>$a_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$461 \text{ nm}$</td>
<td>$1 \mu\text{K}$</td>
<td>$760 \mu\text{K}$</td>
<td>$42 \text{ mW/cm}^2$</td>
<td>$10^5 \times g$</td>
</tr>
<tr>
<td>$689 \text{ nm}$</td>
<td>$460 \text{nK}$</td>
<td>$180 \text{nK}$</td>
<td>$3 \mu\text{W/cm}^2$</td>
<td>$16 \times g$</td>
</tr>
</tbody>
</table>
Bloch oscillations of Sr atoms in an optical lattice

Precision gravity measurement at μm scale

$\nu = m \frac{g \lambda}{2 \hbar}$

Persistent Bloch oscillations

average vertical momentum of the lower peak
width of the atomic momentum distribution

Bloch frequency $v_B = 574.568(3)$ Hz

damping time $\tau = 12$ s

8000 photon recoils in 7s

$g_{\text{meas}} = 9.80012(5) \text{ ms}^{-2}$

Modulation of optical lattices

**Phase modulation**

\[ \Delta z = z_0 \sin(\omega_M t) \]

**Amplitude modulation**

\[ \mathcal{H}_0 = \frac{p^2}{2m} - \frac{U_0}{2} \cos\{2k_L[z - z_0 \sin(\omega_M t)]\} + mgz \]

\[ \mathcal{H}_0 = \frac{p^2}{2m} - \frac{U_0}{2} \cos(2k_L z)[1 + \alpha \sin(\omega_M t)] + mgz \]


Objective: $\lambda = 1-10 \, \mu m$, $\alpha = 10^3-10^4$

Accessible region with atomic probes

- Newton+Yukawa potential

\[ V(r) = -G \frac{M_1 M_2}{r} \left[ 1 + \alpha e^{\frac{r}{\lambda}} \right] \]

- Exchange of a boson with \( m = \frac{\hbar}{\lambda c} \)
- Extra dimensions
Atom elevator

Vertical size of the atomic sample: 15 µm

Atom elevator:
- upward acceleration (1.35 g) for 10 ms
- uniform velocity (133 mm/s) for variable time
- downward acceleration (-1.35 g) for 10 ms
- rest for 470 ms
- reverse motion back to the starting point

Vertical position fluctuations: 3 µm rms

• Vertical size reduced to 4 µm with an optical tweezer

Short-distance measurements

- **Optical elevator** to bring atoms close to a sample surface: trying to measure Casimir-Polder force

⇒ AM measurement close to the surface (preliminary)

Getting closer:
Test of the equivalence principle with atoms

**atom vs macroscopic mass**

**different atoms**
A.E. Charman, et al. (ALPHA collaboration), Nat. Commun. 4, 1785 (2013)

$^{133}$Cs atoms vs classical gravimeter

$^{87}$Rb atoms vs classical gravimeter

$^{88}$Sr atoms vs classical gravimeter

$^{87}$Rb vs $^{85}$Rb

$^{87}$Rb vs $^{85}$Rb

$^{87}$Rb vs $^{39}$K

$^{87}$Sr vs $^{88}$Sr

H vs anti-H
Precision measurement of gravity with cold atoms in an optical lattice and comparison with a classical gravimeter

Precision measurement of gravity with cold atoms in an optical lattice and comparison with a classical gravimeter

$g_{\text{atom}} = 9.8049232(14) \text{ m/s}^2$

$g_{FG5} = 9.804921609(84) \text{ m/s}^2$

140 ppb relative uncertainty

Test of the equivalence principle for 0-spin and half-integer-spin atoms: Search for spin-gravity coupling effects

Test of EP with two isotopes of strontium atom:

\[ ^{88}\text{Sr} \]
- Boson
- Total spin \( I = 0 \)

\[ ^{87}\text{Sr} \]
- Fermion
- Total spin \( \equiv \) nuclear spin \( I = 9/2 \)

Comparison of the acceleration of \(^{88}\text{Sr}\) and \(^{87}\text{Sr}\) under the effect of gravity by measuring the respective Bloch frequencies in a vertical optical lattice

Suitable system to search for EP violations due to spin-gravity coupling effects
Test of the equivalence principle with $^{88}\text{Sr}$ and $^{87}\text{Sr}$ atoms

- Atomic beam from an oven at 430°C
- Zeeman-slowed down to 50 m/s
- Two cooling stages sequence in MOT
  - Broad transition 461 nm, $\gamma = 32$ MHz
  - Narrow transition 689 nm, $\gamma = 7$ kHz

Loaded alternately in a vertical OL @ 532 nm
- waist 300 μm
- $U_0 = 6E_R$
- lifetime >10 s

8x$10^6$ atoms
T: 1 μK

1x$10^6$ atoms
T: 1.4 μK
Differential gravity measurements for $^{88}\text{Sr}$ and $^{87}\text{Sr}$ – Equivalence Principle test

Weak Equivalence Principle test with coherent probe masses with and without nuclear spin: $^{88}\text{Sr} (I = 0)$ and $^{87}\text{Sr} (I = 9/2)$

Measuring Eötvös ratio that depends only on Bloch frequencies and mass ratio $R_m = \frac{m_{88}}{m_{87}}$ (*)

$$\eta = \frac{a_{88} - a_{87}}{(a_{88} + a_{87})/2} = \frac{\nu_{88} - R_m \nu_{87}}{(\nu_{88} + R_m \nu_{87})/2}$$

Uncertainty for each point is the quadratic sum of statistical error and systematics uncertainty

Final result: $\eta = (0.2 \pm 1.6) \times 10^{-7}$

Where uncertainty corresponds to the standard error of the weighted mean

(*) known better than $10^{-10}$: Rana et al., PRA 86, 050502 (2012)
Search for spin-gravity coupling

We consider possible EEP violation due to **spin-gravity coupling** generated by a gravitational potential of the form

\[ V_{g,A}(z) = (1 + \beta_A + kS_z) m_A g z \]

- \( m_A \) is the rest mass of the atom
- \( S_z \) is the projection of the spin along gravity direction
- \( k \) is the model-dependent spin-gravity coupling strength

Each \(^{87}\text{Sr}\) spin component \( S_z = l_z \) will feel different gravitational forces due to different spin-gravity coupling. For unpolarized sample → broadening of the resonant tunneling spectra

Deviations \( \Delta \Gamma \) of measured linewidth from Fourier linewidth, corrected by systematics (two-body collisions, residual magnetic field)

→ Upper limit on spin-gravity coupling \( k \)

\[ \Delta \Gamma = 2l_{87}k \nu_{87} \]

\[ \implies k = (0.5 \pm 1.1) \times 10^{-7} \]

---

$^{88}\text{Sr}$ free falling Mach-Zehnder interferometer with Bragg pulses

- Single ground state: Raman transitions are not present
- Bragg laser detuned 8 GHz from allowed 461 nm line
- Direct launch from MOT with high efficiency Bragg pulses

Simultaneous detection of the two output ports with absorption imaging or fluorescence detection
Gravimeter best performances so far achieved with:

- $T = 30$ ms
- $n = 1$

Contrast around 50%

- Phase noise limited by vibrations of the retroreflecting mirror

\[
\frac{\Delta g}{g} \sim 6 \times 10^{-8} \quad @ \quad 500\ s
\]

See poster presented by Nicola Poli
Large Momentum Transfer
Bragg interferometer

Phase of the Mach-Zehnder interferometer

\[ \phi = n(k_{eff} \cdot g - 2\pi \alpha)T^2 + n\phi_L \]

Phase sensitivity

- Scales quadratically with interferometer time \( T \)
- Sensitivity scales linearly with order of Bragg diffraction \( n \) corresponding to \( 2n\hbar k \) transferred momentum

- Main limitation to contrast coming from beam intensity inhomogeneity and atomic transvers velocity
- The effect is stronger for higher orders

See poster presented by Nicola Poli
Rb LMT atom gradiometer

- Experimental condition: 3° Bragg order, T=80 ms, state F=1, detuning 4.8 GHz, Gaussian pulses (sigma=12 us), vertical velocity spread 0.15 hk, peak intensity 0.2 W/cm²

Problems to address:
- Increasing the order n => losing in contrast at large T
- Bragg transitions need narrow vertical (0.1 hk) momentum spread => severe velocity selection => low atomic flux
- Same internal state at the interferometer output => fluorescence detection makes difficult to distinguish between interferometer outputs
New large-scale atomic fountain apparatus

EP Tests, GW detection, ...
Special issue on

Gravitational Waves Detection with Atom Interferometry

G.M. Tino, F. Vetrano, C. Laemmerzahl Editors,

General Relativity and Gravitation 43, 1901 (2011)
Application to Gravitational Wave Detection

$h k_{\text{eff}} = 100 h k$

\[ \delta \phi = 10^{-4} \text{ rad}/\sqrt{\text{Hz}} \]

\[ T = 100 \text{ s} \]

\[ L = 1000 \text{ km} \]

(a) $10^3 M_\odot$, $1 M_\odot$ intermediate mass black hole binaries at 10 kpc

(b) $10^5 M_\odot$, $1 M_\odot$ massive black hole binaries at 10 Mpc

(c) white dwarf binaries at 10 kpc

(d) $10^3 M_\odot$, $1 M_\odot$ intermediate mass black hole binaries at 10 Mpc

From M. Kasevich, ICAP 2014


Space Optical Clock & Atom Interferometer + GW detector with Sr atoms?
Constraining the Energy-Momentum Dispersion Relation with Planck-Scale Sensitivity Using Cold Atoms

Giovanni Amelino-Camelia,1 Claus Laemmerzahl,2 Flavio Mercati,1 and Guglielmo M. Tino3

1Dipartimento di Fisica, Università di Roma “La Sapienza” and Sezione Roma1 INFN, Piazzale Moro 2, 00185 Roma, Italy
2ZARM, Universität Bremen, Am Fallturm, 28359 Bremen, Germany
3Dipartimento di Fisica and LENS, Università di Firenze, Sezione INFN di Firenze, Via Sansone 1, 50019 Sesto Fiorentino, Italy

(Received 22 June 2009; published 21 October 2009)

We use the results of ultraprecise cold-atom-recoil experiments to constrain the form of the energy-momentum dispersion relation, a structure that is expected to be modified in several quantum-gravity approaches. Our strategy of analysis applies to the nonrelativistic (small speeds) limit of the dispersion relation, and is therefore complementary to an analogous ongoing effort of investigation of the dispersion relation in the ultrarelativistic regime using observations in astrophysics. For the leading correction in the nonrelativistic limit the exceptional sensitivity of cold-atom-recoil experiments remarkably allows us to set a limit within a single order of magnitude of the desired Planck-scale level, thereby providing the first example of Planck-scale sensitivity in the study of the dispersion relation in controlled laboratory experiments.

\[ E = \sqrt{p^2 + m^2 + \Delta_{QG}(p, m, M_P)} \]

\[ E \approx m + \frac{p^2}{2m} + \frac{1}{2M_P} \left( \xi_1 mp + \xi_2 p^2 + \xi_3 \frac{p^3}{m} \right) \]

\[ |\xi_1| \sim 1 \text{ to } |\xi_1| \sim 10^3 \]

\[ -6.0 < \xi_1 < 2.4, \quad |\xi_2| \lesssim 10^9 \]
The Fourteenth Marcel Grossmann Meeting on Recent Developments in Theoretical and Experimental General Relativity, Gravitation, and Relativistic Field Theory will take place at the University of Rome Sapienza July 12 - 18, 2015, celebrating the 100th anniversary of the Einstein equations as well as the International Year of Light under the aegis of the United Nations.

For the first time, in addition to the main meeting in Rome, a series of satellite meetings to MG14 will take place. The registration to MG14 will also cover participation in one additional satellite meeting.

Preregistration will take place Sunday afternoon July 12, and the official opening of the meeting Monday morning, July 13.
### Precision Tests

<table>
<thead>
<tr>
<th>Test (PT)</th>
<th>Description</th>
<th>Contacts</th>
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</thead>
<tbody>
<tr>
<td>PT1</td>
<td>Tests of gravity with atom interferometers and clocks</td>
<td>Guglielmo Tino</td>
</tr>
<tr>
<td>PT2</td>
<td>Theory of light propagation in gravitational fields</td>
<td>Perlick Volker</td>
</tr>
<tr>
<td>PT3</td>
<td>Experimental Gravitation</td>
<td>Claus Lämmerzahl, Angela Di Virgilio</td>
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<td>PT4</td>
<td>Variation of Fundamental Constants</td>
<td>Victor Flambaum, Julian Berengut</td>
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<td>PT5</td>
<td>GR in the Solar System</td>
<td>Roberto Peron, Agnes Fienga</td>
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<tr>
<td>PT6</td>
<td>Dynamics of extended test objects -- equations of motion and their solution</td>
<td>Eva Hackmann, Dirk Puetzfeld</td>
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</tbody>
</table>
G. Tino team members

Nicola Poli, Researcher, Università di Firenze
Fiodor Sorrentino, Post-doc, LENS (now at INFN - Genova)
Quentin Bodart, Post-doc, Università di Firenze
Gabriele Rosi, Post-doc, Università di Firenze
Marco Tarallo, Post-doc, LENS (now at Columbia University)
Xian Zhang, Post-doc, LENS/ICTP
Tommaso Mazzoni, PhD student, LENS
Leonardo Salvi, PhD student, Università di Firenze
Ruben del Aguila, PhD student, Università di Firenze
Giulio D’Amico, Diploma student, Università di Firenze
Jacopo Grotti, Diploma student, Università di Firenze (now at PTB)
Marco Marchetti, Diploma student, Università di Firenze
Marco Menchetti, Diploma student, Università di Bologna (now at NPL)

Previous members and visitors

Andrea Alberti, PhD student
Andrea Bertoldi, Post-doc
Sergei Chepurov, Institute of Laser Physics, Novosibirsk, visitor
Robert Drullinger, NIST, Long term guest
Marco Fattori, PhD student
Gabriele Ferrari, Researcher, INFN/CNR
Antonio Giorgini, PhD and Post-doc
Vladyslav Ivanov, Post-doc
Marion Jacquey, Post-doc
Giacomo Lamporesi, PhD student
Yu-Hung Lien, Post-doc
Chris Oates, NIST, visitor
Torsten Petelski, PhD student
Marco Schioppo, Post-doc, LENS
Juergen Stuhler, Post-doc
Denis Sutyrin, Post-doc
Fu-Yuan Wang, Post-doc

Support and funding

- Istituto Nazionale di Fisica Nucleare (INFN)
- European Commission (EC)
- ENI
- Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR)
- European Laboratory for Non-linear Spectroscopy (LENS)
- Ente Cassa di Risparmio di Firenze (CRF)
- European Space Agency (ESA)
- Agenzia Spaziale Italiana (ASI)
- Istituto Nazionale per la Fisica della Materia (INFM)
- Istituto Nazionale Geofisica e Vulcanologia (INGV)

Collaborators

Nicola Poli
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Marco Marchetti
Marco Menchetti
Luigi Cacciapuoti
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Marco Prevedelli
http://coldatoms.lens.unifi.it/