

**GRUPPO DI RICERCA: Atoms, Molecules and Precision measurements (AMP) –  
Atomi, Molecole e misure di Precisione (AMP)**

**1. DATI IDENTIFICATIVI DEL GRUPPO DI RICERCA**

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| <p><b>Categorie ERC</b></p>                        | <p>PE2_10 Atomic, molecular physics<br/>PE2_12 Optics, non-linear optics and nano-optics<br/>PE2_14 Lasers, ultra-short lasers and laser physics<br/>PE2_17 Metrology and measurement</p>   |
| <p><b>Settore Scientifico<br/>Disciplinare</b></p> | <p>PHYS-03/A, FISICA SPERIMENTALE DELLA MATERIA E APPLICAZIONI.</p>   |
| <p><b>Parole Chiave (Keywords)</b></p>             | <ul style="list-style-type: none"> <li>• Laser spectroscopy</li> <li>• Fundamental tests and measurements</li> <li>• Cavity enhanced spectroscopy</li> <li>• Cavity ring-down spectroscopy</li> <li>• Trace gas detection</li> <li>• Nonlinear optics</li> <li>• Nonlinear spectroscopy</li> <li>• Optical frequency combs</li> <li>• Waves in complex media</li> </ul> |

**2. COMPOSIZIONE E COORDINAMENTO**

**Responsabile Scientifico / Coordinatore:**

- **Nome e Cognome:** Livio Gianfrani
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### Componenti del Gruppo:

1. **Antonio Castrillo** – Associate Professor, <https://orcid.org/0000-0002-1253-9172>
  2. **Eugenio Fasci** – Associate Professor, <https://orcid.org/0000-0003-1722-5831>
  3. **Stefania Gravina** – Researcher, <https://orcid.org/0000-0003-2783-7049>
  4. **Luigi Moretti** – Associate Professor, <https://orcid.org/0000-0003-3908-4689>
  5. **Vittorio D'Agostino** – PhD student, <https://orcid.org/0009-0003-3475-7351>
  6. **Simona Di Bernardo** – PhD student, <https://orcid.org/0009-0003-5694-9792>
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### 3. ATTIVITÀ SCIENTIFICA E NETWORK

The AMP Group is active in the field of light-matter interaction, ultrasensitive laser spectroscopy and high-precision studies on atomic and molecular systems. It boasts a long-standing and well-recognized expertise in precision spectroscopic measurements, cavity-enhanced techniques, nonlinear optics and spectroscopy, trace gas detection.

Nowadays, precisely controlled lasers enable deep communication with the quantum world of atoms and molecules. By using probe lasers with the highest coherence properties, often combined with the optical frequency comb technology, the AMP group is highly motivated to perform fundamental tests and measurements, also providing high-quality spectroscopic data for atoms and molecules of particular interest for terrestrial and planetary atmospheric sciences, astronomy and astrophysics, plasma physics.

The main research activities are described hereafter.

#### 3.1 Fundamental tests and measurements

The AMP Group conducts high-precision experiments on atoms and molecules, designed to probe the fundamental laws of physics, test quantum electrodynamics, and search for new physics beyond the Standard Model. Past activities included the measurement of the near-infrared spectrum of HD by using comb-locked cavity ring-down spectroscopy. It is worth noting that deuterated molecular hydrogen is the simplest heteronuclear (and neutral) diatomic molecule, which is considered a benchmark system to test QED in chemically bound atoms.

Recently, refined experimental studies have been performed on atomic mercury vapours. more specifically, isotope shift spectroscopy in the deep-UV region has allowed the Group to observe a King-plot nonlinearity for Hg isotopes with spin-zero nuclei. An upper limit to the strength of a hypothetical fifth interaction, mediated by a protophobic light boson, has been provided, thus setting a useful constraint for a new physics scenario beyond the Standard Model.

Precise observations of the shape of the mercury intercombination line paves the way to a new implementation of Doppler-broadening thermometry. The AMP team is widely recognized as the world-leading group in this field. Past work on the spectroscopic determination of the Boltzmann constant is particularly well known. The scientific goal in this case is the practical realization of

the new kelvin definition (in force since 2019), pursuing an experimental accuracy at the part-per-million level.

### **3.2 Experimental tests of quantum chemistry calculations in simple polyatomic molecules**

Atmospheric monitoring applications often require high quality spectroscopic data for a variety of molecules. This is particularly true for greenhouse gases, such as carbon dioxide and nitrous oxide, and for molecules that can be found in exoplanets' atmospheres, such as acetylene. As widely experienced in many laboratories worldwide, measuring molecular parameters with low uncertainty is not an easy task. Accurate experimental studies, however, are usually limited to a small number of vibration-rotation lines. On the theory side, an accurate theoretical solution to the problem of line intensity determinations has been found, using *ab initio* quantum chemistry calculations. Extensive line lists are currently being produced for many molecules of special interest for spectroscopic studies of Earth and planetary atmospheres, exoplanets and other astronomical bodies. Theoretical datasets may include, besides the transition strengths, centre frequencies, partition functions, spontaneous emission Einstein coefficients, temperature-dependent cross sections, pressure-broadening parameters. Experimental validations of these calculations are of the utmost importance to quantify the achievable level of accuracy. The AMP group is active in this field since long time, also giving significant contributions in the development of innovative spectroscopic methods and spectral analysis strategies.

### **3.3 Ultra-sensitive cavity ring-down spectroscopy**

Cavity ring-down spectroscopy (CRDS) is a highly sensitive laser absorption technique that finds wide use in molecular spectroscopy since its invention in 1988, for fundamental studies and applications. CRDS relies on the measurement of the decay rate of the coherent radiation trapped in a high finesse optical cavity. The intracavity absorption coefficient is retrieved from the variation of the ring-down time when the cavity is empty and filled with an absorbing gas sample. Thanks to the very long achievable pathlength (up to hundreds of km), the minimum detectable absorption coefficient can be as low as  $10^{-13} \text{ cm}^{-1}$ , thus making CRDS particularly suitable for studies of weak lines, rare isotopologue detection, or trace gas measurements. The AMP group has contributed significantly to the progress in this field, also developing other cavity-based techniques, such as Noise Immune Cavity Enhanced Optical Heterodyne Molecular Spectroscopy, Optical-Feedback Cavity Enhanced Absorption Spectroscopy (OF-CEAS) and OF-CRDS. Recently, the AMP group has specialized in precision spectroscopic measurements in weakly absorbing gases, combining CRDS with the technology of optical frequency combs. Current activities in this field include detection and measurements of selected molecular species in ultra-high purity gases and ultra-high vacuum environments, the latter being of special interest for the planned third-generation European gravitational wave observatory, known as Einstein Telescope.

### **3.4 Precision spectroscopy of muonic hydrogen**

The AMP Group contributes to the FAMU (Fisica degli Atomi MUonici) collaboration, within the framework of a national project funded by INFN, the National Institute for Nuclear Physics. The collaboration is aimed to perform the first hyperfine splitting measurement of the muonic hydrogen ground state at the muon beam facility of the Rutherford-Appleton Laboratory, in Didcot

(UK). FAMU intends to determine the proton Zemach radius (from which the proton size can be inferred) with higher precision (<1%) than previously possible, disentangling discordant theoretical values and quantifying any discrepancy that may exist between values as extracted from normal and muonic hydrogen atoms. After extensive data acquisition campaigns between 2023 and 2025, the FAMU collaboration is currently working on the data analysis. In this framework, the AMP Group was responsible for the development, optimization and use of a multipass optical cavity, expressly designed to enhance the strength of the signal resulting from laser excitation. Over the years, the activities have been extended to the optimization of the pulsed laser system operating at 6.78  $\mu\text{m}$  and to the development of a strategy for the absolute frequency calibration of the FAMU experiment, characterized by an effective traceability to the primary frequency standard. This latter activity is currently being performed within a national project entitled MENPHYS (within the PRIN2022 program).

### **3.5 Advanced photonics: wave propagation in complex media, random lasers, and photodetector innovations**

Electromagnetic propagation in complex media addresses how light travels through disordered or heterogeneous materials where multiple scattering dominates the transport properties. Beyond fully random systems, aperiodic structures—such as quasicrystalline or deterministic aperiodic structures—introduce long-range order without translational symmetry, leading to unusual band structures and critical modes. The aperiodic multilayers band structures can be used to design omnidirectional mirrors exploiting tailored refractive index profiles to achieve broadband, angle-insensitive reflection. On the other hand, disordered aperiodic media, combining deterministic correlations with randomness, gives rise to hybrid localization and anomalous transport regimes. Random lasers emerge as a striking manifestation of these phenomena: the optical feedback is provided by multiple scattering in a gain medium with structural disorder. The interplay between amplification and disorder leads to threshold behavior, spectral narrowing, and rich spatiotemporal dynamics. Understanding these mechanisms enables control of light in materials and supports applications in optoelectronic devices, sensing, and novel light sources. In parallel, graphene–silicon photodetectors with enhanced responsivity leverage strong light–matter interaction and efficient carrier separation to enable sensitive detection across a broad spectral range.

#### **Collaborazioni Nazionali ed Internazionali:**

- **Nazionali:** Istituto Nazionale di Ricerca Metrologica (INRIM); Istituto Nazionale di Ottica, INO-CNR, Sezioni di Napoli e Firenze; LENS – European Laboratory for Nonlinear Spectroscopy, Firenze; Istituto Nazionale di Fisica Nucleare; Dipartimento di Fisica del Politecnico di Milano; Istituto di Fotonica e Nanotecnologie, IFN-CNR, Milano; Istituto di Scienze Applicate e Sistemi Intelligenti, ISASI-CNR; Università di Perugia.
- **Internazionali:** Institute of Physics, Nicolaus Copernicus University in Torun (PL); Laboratoire de Physique des Lasers, Université Sorbonne Paris Nord (F); Experimental

Physics V: Spectroscopy of Atoms and Molecules by Laser Methods, Faculty of Physics and Astronomy, Ruhr University Bochum (D); Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Berlin (D); Physikalisch-Technische Bundesanstalt (PTB), Branschweig (D); Department of Physics and Astronomy, University College London (UK); AMOLF - Physics of functional complex matter, Amsterdam (NL).

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#### 4. PROGETTI, BREVETTI E PUBBLICAZIONI

##### Principali Progetti di Ricerca e Brevetti:

- **Primary spectrometric thermometry for gases** – EURAMET, European Partnership Program – Funded Partner, 2023-2026, <https://www.prispectemp.ptb.de/home>.
- **Einstein Telescope Infrastructure Consortium (ETIC)** – PNRR – Funded Partner, 2023-2026, <https://www.researchitaly.mur.gov.it/en/2023/02/07/gravitational-waves-italy-bidding-to-host-the-einstein-telescope-with-the-etic-project/>.
- **MEtrology and Nonlinear optics for Precision muonic HYdrogen physicS (MENPHYS)** – PRIN 2022 – Coordinating Unit, 2023-2026.
- **Fisica degli Atomi MUonici (FAMU)** – INFN – Funded Partner, <https://web.infn.it/FAMU/>.
- **Detector Innovation and custOM Electronics for DEcay Spectroscopy (DIOMEDES)** – INFN - Funded Partner, 2026-2028.

##### Principali Pubblicazioni Recenti:

1. S. Gravina, A. Castrillo, and L. Gianfrani, *Isotope Shift Spectroscopy in Mercury Vapors: A Promising Alternative to Ytterbium for New Physics Search*, **Physical Review Letters**, 2026. DOI: <https://doi.org/10.1103/2qwx-y8df>.
2. V. D'Agostino, E. Tofani, S. Gravina, E. fasci, A. Grado, A. Castrillo, and L. Gianfrani, *Linear optical-feedback cavity ring-down spectroscopy using an interband cascade laser at 3- $\mu$ m wavelength*, **Optics Express**, 2026. DOI: <https://doi.org/10.1364/OE.581115>.
3. M. Asad Khan, V. D'Agostino, S. Gravina, L. Gianfrani, A. Castrillo, Comb-locked cavity ring-down spectroscopy of CO<sub>2</sub> at 2- $\mu$ m wavelength, **Journal of Quantitative Spectroscopy and Radiative Transfer**, 2026. DOI: <https://doi.org/10.1016/j.jqsrt.2026.109887>.
4. P. Wcisło, N. Stolarczyk, M. Stowiński, H. Józwiak, D. Lisak, R. Ciuryło, A. Cygan, F. Schreier, C.D. Boone, A. Castrillo, L. Gianfrani, Y. Tan, S.-M. Hu, E.M. Adkins, J.T. Hodges, H. Tran, H.N. Ngo, J.-M. Hartmann, S. Beguier, A. Campargue, R.J. Hargreaves, L.S. Rothman, I.E. Gordon, *New beyond-Voigt line-shape profile recommended for the HITRAN database*, **Journal of Quantitative Spectroscopy and Radiative Transfer**, 2025. DOI: <https://doi.org/10.1016/j.jqsrt.2025.109596>.

5. T. Crisci, L. Moretti, C. Russo, M. Gioffrè, M. Iodice, G. Coppola, M. Casalino, *Unveiling high responsivity in on-chip photodetectors with graphene interposed between amorphous and crystalline silicon*, **CARBON**, 2025. DOI: <https://doi.org/10.1016/j.carbon.2024.119837>.
6. S. Pourmasoud, P. Falcone, L. Moretti, *Omnidirectional mirror based on the aperiodic and hybrid-order aperiodic-periodic chirped multilayers*, **OPTICAL MATERIAL EXPRESS**, 2024, <https://doi.org/10.1364/OME.505558>.
7. A. Adamczak, D. Bakalov, G. Baldazzi, M. Baruzzo, R. Benocci, R. Bertoni, M. Bonesini, S. Capra, D. Cirrincione, M. Clemenza, L. Colace, M. Danailov, P. Danev, A. de Bari, C. De Vecchi, D. Di Ferdinando, E. Fasci, R. Gaigher, L. Gianfrani, A. D. Hillier, K. Ishida, J. S. Lord, A. Menegolli, E. Mocchiutti, S. Monzani, L. Moretti, G. Morgante, C. Pizzolotto, A. Pullia, M. Pullia, R. Ramponi, H. E. Roman, M. Rossella, R. Rossini, A. Sbrizzi, M. Stoilov, J. J. Suárez-Vargas, G. Toci, L. Tortora, E. Vallazza, K. Yokoyama, A. Vacchi, *First operation of the FAMU experiment at the RIKEN-RAL high intensity muon beam facility*, **European Physical Journal A**, 2025. DOI: <https://doi.org/10.1140/epja/s10050-025-01758-4>.
8. V. D'Agostino, E. Fasci, M. Asad Khan, S. Gravina, L. Gianfrani, A. Castrillo, *Cavity ring-down spectroscopy at 2- $\mu$ m wavelength assisted by a comb-locked optical parametric oscillator*, **Optics Letters**, 2025. DOI: <https://doi.org/10.1364/OL.563855>.
9. S. Gravina, N.A. Chishti, A. Castrillo, L. Gianfrani, A. Sorigi, P. Cancio Pastor, C. Clivati, F. Bertiglia, G. Lopardo, F. Levi, G. Galzerano, *Comb-locked deep-ultraviolet laser system for precision mercury spectroscopy*, **Physical Review A**, 2024. DOI: <https://doi.org/10.1103/PhysRevA.109.022816>.
10. A. Castrillo, M. Asad Khan, E. Fasci, V. D'Agostino, S. Gravina, and L. Gianfrani, *Demonstration of record sensitivity for water vapor detection by means of comb-locked cavity ring-down spectroscopy*, **OPTICA**, 2024. DOI: <https://doi.org/10.1364/OPTICA.531464>.
11. M. Baruzzo, J.J. Suárez-Vargas, L. I. Stoychev, H. Cabrera, K.S. Gadedjisso-Tossou, G. Toci, L. Moretti, E. Fasci, L. Gianfrani, C. Pizzolotto, E. Mocchiutti, M. B. Danailov, A. Vacchi, *A mid-IR laser source for muonic hydrogen spectroscopy: The FAMU laser system*, **Optics and Laser Technology**, 2024. DOI: <https://doi.org/10.1016/j.optlastec.2024.111375>.
12. L. Gianfrani, S.-M. Hu, and W. Ubachs, *Advances in cavity-enhanced methods for high precision molecular spectroscopy and test of fundamental physics*, **La Rivista del Nuovo Cimento**, 2024. DOI: <https://doi.org/10.1007/s40766-024-00054-z>.
13. S. Gravina, N. A. Chishti, S. Di Bernardo, E. Fasci, A. Castrillo, A. Laliotis, and L. Gianfrani, *Comb-Referenced Doppler-Free Spectrometry of the  $^{200}\text{Hg}$  and  $^{202}\text{Hg}$  Intercombination Line at 254 nm*, **Physical Review Letters**, 2024. DOI: <https://doi.org/10.1103/PhysRevLett.132.213001>.
14. P. Falcone, L. Moretti, *Statistics of Lyapunov exponent in random Fibonacci multilayer*, **Journal of Optics**, 2024. DOI: <https://doi.org/10.1088/2040-8986/ad699d>.
15. A. Castrillo, E. Fasci, T. Furtenbacher, V. D'Agostino, M.A. Khan, S. Gravina, L. Gianfrani and A.G. Csaszar, *On the  $^{12}\text{C}_2\text{H}_2$  near-infrared spectrum: absolute transition frequencies and an improved spectroscopic network at the kHz accuracy level*, **Physical Chemistry Chemical Physics**, 2023. DOI: <https://doi.org/10.1039/D3CP01835K>.
16. E. Fasci, M. Asad Khan, V. D'Agostino, S. Gravina, V. Fericola, L. Gianfrani, and A. Castrillo, *Water vapor concentration measurements in high purity gases by means of*

- comb assisted cavity ring down spectroscopy*, **Sensors and Actuators A**, 2023. DOI: <https://doi.org/10.1016/j.sna.2023.114632>.
17. S. Gravina, C. Clivati, A. Castrillo, E. Fasci, N. A. Chishti, G. Galzerano, F. Levi, and L. Gianfrani, *Measurement of the mercury (6s6p)  $^3P_1$ -state lifetime in the frequency domain from integrated absorbance data*, **Physical Review Research**, 2022. DOI: <https://doi.org/10.1103/PhysRevResearch.4.033240>.
18. E. Fasci, S. Gravina, G. Porzio, A. Castrillo, and L. Gianfrani, *Lamb-dip cavity ring-down spectroscopy of acetylene at 1.4  $\mu\text{m}$* , **New Journal of Physics**, 2021. DOI: <https://iopscience.iop.org/article/10.1088/1367-2630/ac3b6e>.
19. A. Castrillo, E. Fasci and L. Gianfrani, *Doppler-limited precision spectroscopy of HD at 1.4  $\mu\text{m}$ : An improved determination of the R(1) center frequency*, **Physical Review A**, 2021. DOI: <https://doi.org/10.1103/PhysRevA.103.022828>.
20. G. Lopardo, F. Bertiglia, A. Barbone, M. Bertinetti, R. Dematteis, D. Giraudi, L. Gianfrani, *A thermostatic chamber for doppler-broadening thermometry of mercury vapors*, **Measurement**, 2021. DOI: <https://doi.org/10.1016/j.measurement.2020.108594>.
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