TOWARDS NOVEL QUANTUM APPLICATIONS OF ULTRAFAST PHYSICS (TOWARULTRA)

1. Excellence

1.1 Long-term vision

TOWARULTRA aims to develop novel quantum light sources and their diagnostics at a new frontier in physics and technology, enabling unprecedented access to ultrafast quantum electrodynamics phenomena and novel ultrafast spectroscopies of correlated quantum matter.

Specifically, TOWARULTRA aims at using high harmonic generation (HHG) [KSK92,Cor93,LBI94] to generate *massive quantum states (MQS) of light* with controllable quantum features, with pulse durations in the attosecond (as) to femtosecond (fs) range, carrying $10^{7\text{-}10}$ photons per pulse, and with multimode entanglement across 20 frequency modes from the IR to XUV. We also aim to develop *diagnostics* for these light sources with unprecedented temporal precision and spectral broadness from IR to XUV. This defines a new paradigm: such states of light have never been created before, and their potential applications have not been explored. What is more, the highly non-equilibrium, nonlinear-optical response of matter used to generate such pulses imprints the underlying matter dynamics onto the quantum properties of the generated light, opening a new field of *ultrafast quantum optical spectroscopy,* far beyond the current state-of-the-art technology.

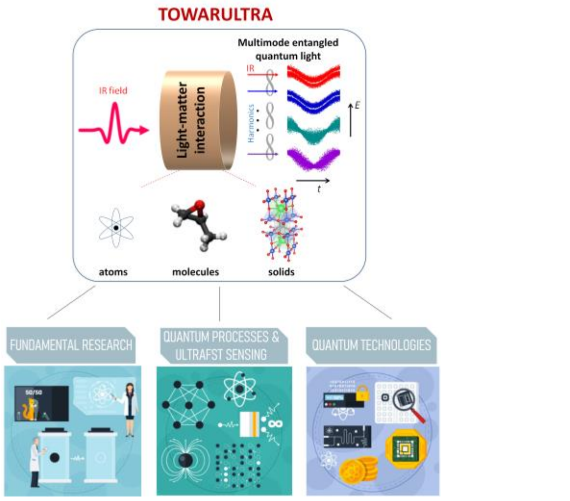

Fig. 1.1.1. *Vision of TOWARULTRA showing the core schemes (top) underlying investigations*

TOWARULTRA is directly related to the fast-expanding research area at the cutting edge of quantum optics, quantum technologies, and ultrafast science, driven by the pioneering work of its partners [LCP21,ABB22,TJP24,YKB25] (for reviews see [BLM23,SRM23,STR26,LSR25]), and other groups [BTB25,Moi24,TCS24,TBG23,LJP205,LHM24, LMw25, GLM25,LHM25]. It explores a new frontier arising from linking quantum optics and quantum information science with strong-field physics and ultrafast science, research fields that have produced major breakthroughs, from Nobel Prize-winning experiments [Mou19,Str19,Ago23, Kra23,Lhu23] to significant interdisciplinary advances in both fundamental research and technology. To achieve its goals, TOWARULTRA will develop and exploit ultrafast physics at the fully quantized level, far beyond the "conventional" results and ultrafast technologies developed so far.

Its key research thrusts are: **(I) development of methods for the generation and characterization of a novel class of high photon number, ultrafast, multimode entangled quantum light sources with controllable quantum features and frequencies spanning from the far-infrared (IR) to extreme-ultraviolet (XUV); (II) establishment of new ultrafast optical spectroscopy at the fully quantized level; and (III) formulation of approaches to shape ultrafast dynamics of quantum matter with unprecedented temporal precision, including the detection and control of topology. Collectively, these research thrusts address long-standing challenges ranging from fundamental tests of quantum theory to ultrafast quantum technologies, quantum light engineering, diagnostics, and sensing (see Fig.1.1.1).**

TOWARULTRA partners have produced major theoretical and experimental advances in recent years. For instance, we have shown: (I) that strong laser–matter interactions can produce high-photon-number, highly entangled non-classical light states such as optical Schrödinger "cat" and squeezed states, with tunable quantum properties across a broad spectral range from the far-infrared (IR) to the extreme-ultraviolet (XUV) [LCP21,TCS24,YKB25]; (II) how intense quantum light propagates through highly nonlinear media [RKS26]; (III) how such states can be harnessed for advanced sensing applications [SML24]; (IV) how quantum correlations in many-body systems can be mapped onto the quantum features of the emitted light [ABB22,TZV25,ZTV25,BAD23, DAB24,Dab26] (V) how the robustness of high-Tc superconducting quantum states under intense optical fields enables the transfer of material entanglement to emitted radiation [ABB22,TZV25,ZTV25,BAD23,DAB24,Dab26] (see also [GLM25,LHM24,LHM25,LM25]); and (VI) how treating quantum harmonic light as a measurable observable makes it possible to characterize multimode entanglement in nonlinear optical responses [TCS24,THC24,LJP25,BTB25]; VII) how ultrafast high harmonic spectroscopy can be used to study strongly correlated many-body systems [SJA19];

and VIII) how ultrafast strong laser fields can be used to control the topological properties of 2D materials, relevant to valleytronics devices [JSS20,TJP24]**.** These and other advances are summarized in recent review articles [BLM23,SRM23,STR26,LSR25]. Thus, the consortium has the experience and expertise to develop radically new technology in the field of ultrafast science.

The scientific excellence of the TOWARULTRA direction is supported not only by the strong publication record of the partners, including numerous articles in high-visibility, high-impact scientific journals, but also by recognitions by the Institute of Physics (IOP), which described the work as "*The research that shaped atomic and molecular physics in 2025*." **Thus, TOWARULTRA is grounded in a clearly defined and forward-looking research vision that aims to advance and explore new directions in both basic research and technology, consolidating progress into a transformative field.**

1.2 Towards technology breakthrough

Fundamentals and challenges of current quantum technologies. Quantum technologies rely on fully quantized light-matter interactions under conditions of negligible decoherence. Key developments include the engineering of **I)** quantum light sources (such as squeezed, Fock, optical Schrödinger "cat" states and entangled photon sources) [LCP21,SRM24,TSC24] which can provide reduced noise and the notable degree of quantum correlations; **II)** isolated quantum systems (such as ion traps, cold atoms etc.) exhibiting pronounced and detectable quantum features at long time scales (micro-millisecond range); and **III)** the development of diagnostics including quantum state characterization approaches (e.g. photon correlation measurements, quantum state tomography, etc.) [LRS25,SML24,SRC26] and entanglement certification protocols [Sta22,RPL26]. Yet, in spite of the remarkable progress, the existing technologies do not yet provide access to: **(I)** sources capable of delivering high–photon-number, massively entangled quantum light states across broad spectral range; **(II)** characterization of light generated by such sources, and **(III)** diagnostics of highly correlated states of non-isolated quantum many-body systems, including ultrafast sensing of their phases and phase transitions. These challenges can be addressed by combining quantum optics with ultrafast technologies, defining a new frontier addressed by TOWARULTRA.

The scientific and technological breakthroughs of the TOWARULTRA project arise in the areas of **(I) quantum light engineering,** and **(II) diagnostics and sensing.**

I) Engineering a new class of novel quantum light sources: We will develop quantum light sources capable of delivering massively entangled (≈20 frequency modes) quantum light states with high mean photon numbers (up to 10^10 photons), spanning frequencies from the IR to the XUV spectral range. The approach builds on recent theoretical and experimental advances by the partners of the TOWARULTRA project [LCP21,ABB22,TJP24, YKB25], which rely on the highly nonlinear process of harmonic generation induced by the interaction of intense femtosecond (fs) IR light fields with matter (top panel in Fig. 1.1.1). Using this process in atoms, molecules, and solids combined with conditioning schemes in non-depleted media [LCP21,RLP25], without conditioning schemes in depleted media [SRL22,SRM24], without conditioning schemes in quantum correlated non-depleted media [YKB25,RSM24a], and wave mixing schemes in the harmonic generation process [KBS25], it has been demonstrated that high–photon-number, massively entangled states of many harmonics, as well as optical Schrödinger "cat" states and squeezed light states of *fs* duration can be generated, with controllable quantum features and frequencies spanning the far-IR to XUV range. Fig.1.2.1(b) shows an example of the experimentally produced optical "cat" states in the near-IR range [LCP21, LSR25]. This source has been employed in nonlinear optics [LRS25], where the emitted second harmonic (400 nm) exhibits optical "cat" state characteristics. Importantly, these states are robust against photon losses [SFL24], enabling metrological applications. While the fundamental principles of the other schemes have been established theoretically, experimental realization requires further investigation, with emphasis on laser-driven semiconductors for delivering massively entangled light states from IR to VUV [RSM24,NRF25].

II) Development of novel diagnostic and sensing approaches: This involves **a**) the development of methods for quantum state characterization of high photon number light states, **b)** the development of ultrafast quantum metrology for tracing ultrafast quantum electrodynamics of many-body systems, and **c)** the development of protocols for multimode entanglement certification. Most of these developments build on recent theoretical and experimental advances by the partners of the TOWARULTRA project (see references mentioned above). Below we provide additional information concerning the developments **a)** to **c)**:

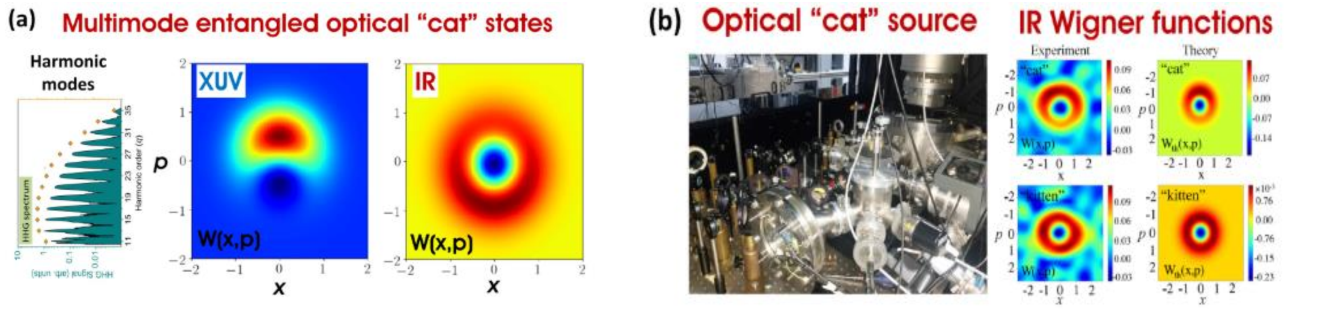

***Fig. 1.2.1. (a)** Theoretically calculated Wigner functions of the multimode entangled optical cat states from IR to XUV (harmonic modes) spectral range. Figures from Ref.* [LCP21]. ***(b)** Left panel: A photo of the IR optical "cat" state source. Right panel. Wigner functions of the measured and calculated IR optical "cat" and "kitten" states depicting the controllable quantum features. Figure from Ref. [LSR25].*

a) Characterization of high photon number quantum light states: Standard characterization methods (quantum tomography, photon correlations [LRS25, RPL26, SRC26]) face challenges at high photon numbers. Leveraging our quantum light sources, we can now develop tools for probing quantum features of such states. We have already demonstrated a scheme for characterizing high-photon-number optical "cat" states [LRS25] (Fig. 1.2.2).

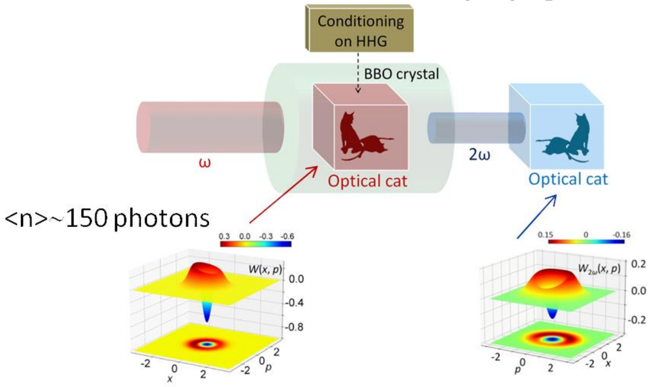

***Fig. 1.2.2.** A schematic showing the operation principle used in the experiment [LRS25] for implementing intense IR optical "cat" states in non-linear optics. An intense IR optical "cat" state of frequency ω (created via conditioning on HHG, not shown here) was used to drive the second harmonic (2ω) generation in a BBO crystal. The 2ω also depicts the quantum features of an optical "cat" state. Lower left: Wigner function of the driving ω field. Lower right: Wigner function of the generated 2ω field. Figure from Refs [LRS25].*

In TOWARULTRA, we will extend this to higher photon-number regimes via higher-order nonlinear processes. We will use wave-mixing of intense conventional light with weak quantum light [TMY25] to map the properties of our IR quantum sources from the IR to the XUV range. Beyond the demonstrated IR feasibility, TOWARULTRA will develop diagnostics in the VUV and XUV – a technology that currently does not exist.

b) Ultrafast quantum optical metrology: This development builds on our recent theoretical investigations conducted using interactions of ultrafast light pulses with atoms [YKB25], molecules [RSM24a], solids [RSM24], and correlated systems [KI25], see also [GLM25,LHM24,LHM25,LM25]. All-optical imaging using nonlinear optics and ultrafast light generation is central to understanding matter far from equilibrium. Non-linear optical conversion offers some of the most versatile methods for probing ultrafast dynamics, from chemical bond breaking to charge density waves in correlated solids and light-harvesting complexes. However, most ultrafast spectroscopies have focused on classical properties of the optical response: spectral intensity and phase. Analysis of the photon statistics of the generated light has not yet entered the standard toolbox of ultrafast spectroscopy. Yet, our preliminary studies show how non-equilibrium quantum dynamics involving multiple light-driven states (e.g., state superpositions in atoms and molecules, multiple correlated states in solids) tailor the quantum state of the material's nonlinear optical response. Introducing quantum-state analysis of light generated by classically driven quantum materials is the key breakthrough this project aims to achieve, offering a new window into the formation of correlated states in quantum matter.

Example #1: The potential of the ultrafast quantum optical spectroscopy is demonstrated by an illustrative example in Fig. 1.2.3 which shows the development of quantum correlations between 10 pseudospins placed inside a resonant waveguide and driven by an external resonant classical field (Ω_{Rabi}/ω_0=0.01). The pseudospins interact with each other via (real or virtual) photon absorption and emission. The development of many-body correlations is illustrated by parameter J, which would reach unity for a fully entangled state. The evolution of the Husimi representation of the generated light, shown in the insets, exhibits clear deviations from the minimum-uncertainty Glauber coherent state (round image at early times). Rapid growth of many-body correlations is accompanied by clear quantum-optical signatures in the generated light: emergence of the banana-like shape in the Husimi function.

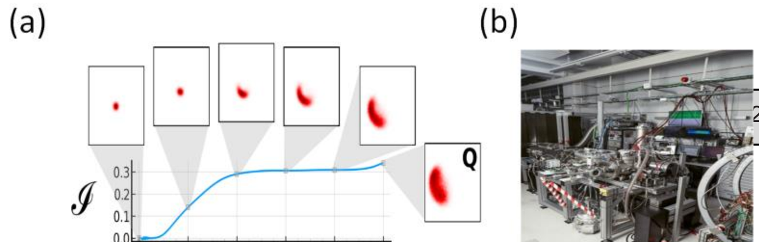

***Fig. 1.2.3. (a)** Time-resolved quantum-*

optical spectroscopy of many body correlations (see text for details). ***(b)*** *ICFO Beamline (Biegert) for ultrafast quantum metrology in solids.*

Example #2: Fig. 1.2.4 shows another example [RSM24] of the importance of ultrafast quantum-optical diagnostics and the viability of quantum-optical metrology for imaging ultrafast quantum electrodynamics (QED) of many-body systems. It shows how ultrafast dephasing in HHG by laser-driven semiconductors affects the Wigner function of an IR optical "cat" state. The development of this metrology is driven by the unique features of our new class of quantum light states, including the robustness of the "cat" states against photon losses [SFL24].

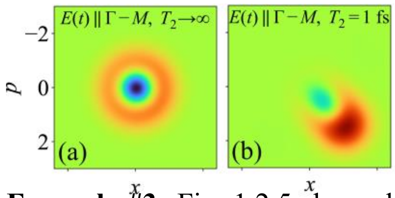

Fig. 1.2.4. *Calculated Wigner function of the optical "cat" states produced in laser driven semiconductors for dephasing times (T2) (a) T2=infinity and (b) T2=1 fs. Figure from Ref. [RSM24].*

Example #3: Fig. 1.2.5 shows light control over selective valley excitation in an *inversion-symmetric multilayer* hexagonal Transition Metal Dichalcogenide (TMDC) material MoS_2 induced by a polarization-tailored "trefoil" light field. This light can switch topological properties of light-driven solids faster than electronic dephasing times at room temperature [TJP24]. The light-induced topology and quantum dynamics during the topological phase transition can be traced by measuring the quantum properties of light (including both the fundamental driving field and its harmonics) after the interaction with the 2D material.

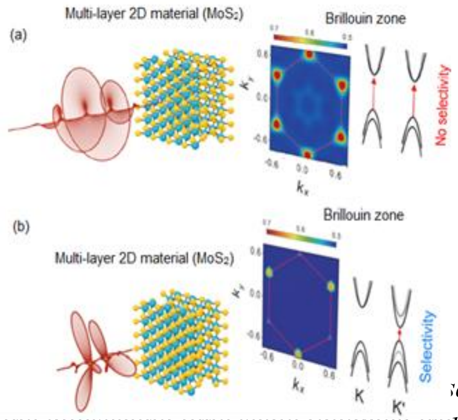

Fig. 1.2.5. *Light control of topology in inversion-symmetric multilayer of the 2D Transition Metal Dichalcogenide (TMDC) MoS_2. In TMDC monolayers with broken inversion symmetry, circularly polarized light tuned on resonance with the bandgap generates valley-selective excitations by matching light circularity to the Berry curvature, which is opposite in the K and K' valleys. In multi-layer materials with restored inversion symmetry, this method fails (panel a). However, a topological optical field created by combining counter-rotating fundamental and second harmonic with attosecond precision restores valley selectivity even in inversion-symmetric multi-layer materials (panel b). Valley selection is achieved by inducing nontrivial material topology with this light, which ...al symmetry. The topology is controlled by controlling the two-color delay on the attosecond time scale (adapted from [TJP24]).*

c) Multimode entanglement certification protocols: High harmonic generation can yield entangled quantum states of light, with multimode squeezed states arising particularly naturally. These are relatively straightforward to classify and characterize, as their quasi-probability distributions are given by the multidimensional Gaussian function. The information needed to characterize their quantum features is captured by the *covariance matrix* γ, the matrix of bilinear correlations between the fluctuations of the components. The overview of "classical" results on bi-partite entanglement of the Gaussian states can be found, for instance, in [GKD01] and references therein. Criteria based on the covariance matrix can still be used for non-Gaussian states, where they are, however, only necessary but not sufficient. These methods apply to a stationary (time-independent) covariance matrix. In the context of attoscience, these methods will need to be extended to short signal durations. A powerful entanglement witness that we will implement is the measurements of second- and higher-order intensity correlations for each harmonic and between harmonics, allowing us to measure the violation of the Cauchy-Schwarz inequality [TCS24] for multiple harmonic pairs. Another pioneering approach that we will pursue is based on mapping continuous variables to qubits, or qudits, using novel mapping techniques [CPR26].

Table 1.2.1: *TRL progression of the TOWARULTRA project*

Current status

TRL1	Basic principles	**On the quantum light sources and light-matter states:** The partners have demonstrated the basic principles concerning the generation of high photon number (massive) quantum states of light and light-matter. **On the diagnostics and sensing:** The partners have demonstrated the basic principles of **a)** characterization of high photon number quantum light states in the IR spectral region, and **b)** ultrafast quantum sensing.
TOWARULTRA project		
TRL1 (2027-2028)	Basic principles.	**On the diagnostics and sensing:** In TOWARULTRA we aim to develop methods for **a)** quantum light state characterization in the VUV-XUV spectral regions, and **b)** protocols for multimode entanglement certification of light and light-matter.
TRL2 (2027-2029)	Formulation of a technological concept	**On the quantum light sources:** We aim to develop robust beamlines delivering ultrafast high photon numbers massively entangled quantum light states from far-IR to XUV and resources for creating MQS of light-matter. These will include the relevant quantum state diagnostics. **On the diagnostics and sensing:** We aim to develop robust diagnostic and ultrafast sensing approaches that can be adapted to quantum light sources for tracing ultrafast quantum electrodynamics (including multimode entanglement) in atoms, molecules, and solids.
TRL3 (2029-2030)	Proof of Concept	**On the quantum light sources:** We aim to confirm the reliable operation of the developed quantum light sources. **On the diagnostics and sensing:** We aim to confirm the reliable operation of the developed diagnostic end sensing methods.
10 years vision after the end of TOWARULTRA project		
TRL4-6	Validation of the technology as prototype.	Our vision is the development of a complete and reliable beamline which includes a high photon number massively entangled quantum light sources and the diagnostics for characterizing quantum states of light and light-matter, multimode entanglement, tracing the ultrafast QED in all states of matter.
TRL7-8	Demonstration of prototype	Our vision is to develop a robust, commercially available system that can serve as a unique resource for advancing new technologies.

1.3 Objectives

Below we describe 3 project objectives, first qualitatively and then in a more specific way. For each objective, we propose a novel and ambitious science-to-technology breakthrough beyond the current state of art.

O1) Controlled generation, characterization, and application of massive quantum states (MQS) of light. This objective involves not only the generation and diagnostics of MQS of light but also its applications in ultrafast nonlinear optics and ultrafast quantum metrology and sensing. HHG-based methods for creating MQS will involve three extremes: intense laser fields, ultra-fast time scales, and ultrabroad spectra from IR to XUV, with applications in quantum light sources, nonlinear optics, quantum metrology, and quantum communications. The key new component compared with conventional HHG is the use of (i) available quantum light sources in IR, (ii) controlled quantum matter dynamics achieved by tailoring driving laser fields, and (iii) application of post-selection protocols developed by the consortium. **The measurable science-to-technology breakthrough** is to make MQS generation and exploitation as routine as the conventional high harmonic generation has become routine today. Achieving this breakthrough will require optimization of both the driving light sources and quantum matter.

O2) Interfacing quantum light and quantum materials. Modern photonics technology opens unique opportunities at the interface of ultrafast photonics and two-dimensional (2D) materials: sub-cycle shaped light can tailor and switch quantum properties of light-driven solids faster than electronic dephasing times at room temperature. We aim to extend this control into the quantum optical domain by i) using polarization-tailored light to induce and control topology in 2D transition metal dichalgogenides (TMDC), ii) detecting quantum properties of the generated light, in particular as a sensor of their topology, (iii) tailor the quantum properties of the generated harmonic light by tailoring incident quantum light to control dynamics in TMDC materials. **The measurable science-to-technology breakthroughs** will include (i) achieving quantum light-quantum valley entanglement, (ii) frequency up-conversion of entangled photons, and (iii) quantum optical spectroscopy of light-induced topology.

O3) Quantum high harmonic spectroscopy of quantum phases in strongly correlated materials. Our main goals here are to establish robust fingerprints of correlated quantum phases in the nonlinear optical response of matter driven by (i) classical coherent light and (ii) bright squeezed vacuum light, while using quantum metrology to detect fluctuations and possible light–matter entanglement. This objective will transform HHG spectroscopy of strongly correlated materials from a scientific demonstration into a quantum-metrological diagnostic technology. Building on our demonstration [ALC22] of optical detection of quantum phases in YBCO, we will generalize from superconductors and charge-density waves [TYU25] to broader material classes. The key breakthrough is to move beyond identifying phases through nonlinear optical fingerprints, towards routine quantum-state-resolved readout using ultrafast-light-field tools. We will compare HHG driven by classical coherent light with HHG driven by bright squeezed vacuum light to determine how quantum fluctuations and entanglement are exchanged between the optical field, the correlated electronic system and the emitted harmonics. This introduces quantum metrology as a new layer in HHG spectroscopy. We will relate these studies to laser-induced phase transitions, with the prospect of steering correlated materials into regimes where they act as sources of non-classical radiation. Currently, HHG spectrometry of correlated materials remains largely unexplored, and a predictive description is still missing. TOWARULTRA will address this gap by combining ultrafast spectroscopy, quantum light sources, quantum metrology and theory to establish a transferable methodology for detecting hidden quantum order, characterizing non-equilibrium quantum phases, and quantifying light–matter entanglement.

All of the described objectives are beyond the state of art in terms of technological progress and applications. Achieving them will require the consortium to navigate serious technical challenges, following the old Latin saying *per aspera ad astra*. Still, the proposed objectives are specific, clearly measurable as outlined in the list of tasks shown in Section 3.1, and achievable as they are based on solid preliminary results. The corresponding tasks, deal with “3xULTRA” regime – ultrahigh nonlinearities, ultrashort time scales, and ultrabroadband spectra from IR to XUV.

TOWARULTRA is a **high-risk** project, but it opens the path to achieving **high-gain objectives**, such as new patents and licenses, and a significant increase in TRL. The **overall methodology**, including the concepts, models, and assumptions, has been very broad; thus, we can always seek alternative approaches to overcome obstacles and to realize the project’s objectives efficiently.

During the societal engagement activities planned in WP7 and other WPs, gender will be a relevant factor in the recruitment of citizens and stakeholders. To ensure an equal representation of genders, we will place significant effort on recruiting women for these activities, as our experience has shown that women are less likely to sign up to technically focused events. For this reason, the events’ programs will be framed with an emphasis on the green agenda, as well as local livelihood issues aligned with TOWARLUTRA’s objectives, as these topics are more likely to engage participants of all genders. Effort will be placed on identifying and personally inviting stakeholder representatives of both genders. When targeting potential users of the TOWARULTRA technology and in regards to eventual testing of specific appliances of the technology, effort will be placed on making sure of equal representation of genders in mapped target groups and testing groups. During the public engagement activities planned in WPs, gender will be a relevant consideration in the recruitment of citizens and stakeholders. To ensure a gender-balanced representation, we will place significant effort on recruiting women for these activities, as our experience has shown that women are less likely to sign up to technically focused events. For this reason, the event agendas will be framed with an emphasis on the green agenda, as well as local livelihood issues aligned with TOWARULTRA’s objectives, as these topics are more likely to engage participants of all genders. Moreover, we will place substantial effort when identifying stakeholders, personally inviting them, to ensure a gender-balanced representation. Finally, when targeting potential users of TOWARULTRA’S technology and in regard to eventual testing of specific applications, we will map target and testing groups equal representation of genders for this end.

Open science practices TOWARULTRA starts at TRL 1 and addresses validation to TRL 3-4. Given the low starting TRL, a fully open-science approach is key. At more advanced TRL, exploitation plans will be considered in line with the consortium’s IP strategy (n2-Photonics GmbH). The approach will align with EU objectives on Open Science and Knowledge sharing. Key actions are described below: ***Early and Open Access sharing:*** The decision to publish the data or to seek first IP protection will be discussed among the consortium members according to the protocols outlined in the Consortium Agreement. All scientific publications, including monographs and books, will be open to access at the time of publication and will comply with EU guidelines. Manuscripts will be deposited in trusted repositories, and pre-prints will be shared when journal policies allow. Authors will retain copyrights and grant nonexclusive licenses to publishers. The **experimental data** needed to validate and reproduce the results from the scientific publications will be provided and properly archived in open-access data repositories (we will use Zenodo, and similar ones)..When possible, open peer review will be preferred over traditional ('blind' or 'closed' peer review. ***Citizen, civil society, and end-user engagement:*** Findings will be disseminated through social media, press releases, workshops, and webinars, and incorporated into existing outreach activities such as Science Open Days at ICFO.

Research data management (RDM) Research data will be managed according to FAIR principles, with dedicated team members at each beneficiary and oversight by ICFO's Data Committee. A complete **Data Management Plan** (DMP) will be produced in Month 6 and updated throughout the project lifetime. An initial data identification is provided in Table 1.3 below:

Table 1.3 Data management

Type of data that TOWARULTA will generate/collect	ICFO	FORTH	MBI	n_2-Photonics
Experimental: data captured by lab equipment	Multimodal measurements of absorption, reflection and correlations like g(2) and higher.	Harmonic spectra, photon statistics, photon correlations homodyne traces, and Wigner functions.	No experimental data	Performance data of the IR laser system
Simulation: data generated from numerical models	Simulation data of HHG and its quantum optical properties	No simulation data	Simulations data of HHG and its quantum optical properties	No simulation data
Dissemination Communication & Outreach material	Public deliverables, peer-reviewed journals, conference proceedings, social media content, infographics, videos, press releases, etc			
Persistent identifiers to be used	Data and metadata will be stored according to the internal management procedures of all partners. Processed data included in publications will be made available through a DOI in trusted repositories. And all researchers will be identified with an ORCID code.			
Accessibility of data/research outputs	IPR will be evaluated prior to publication and if a publication cannot be open access, thorough reasoning will be given.			
Interoperability of data/research outputs	Data standards such as the recommended by the Library of Congress at https://www.loc.gov/preservation/resources/rfs/TOC.html, that are open or under a liberal BSD-like license, will be used as a rule. When published, a set of keywords may be used to describe it and allow for interoperability.			
Reusability of data	Use of data licenses that encourage their re-use. Those include, e.g., the creative commons licenses (CCO).			
Preservation of data	One person per partner will be designated to manage the data. Provisions for data security will be put in place and also for long-term storage.			

1.4 Interdisciplinarity

Interdisciplinarity is at the heart of TOWARULTRA. To achieve the expected breakthrough, the project must combine traditionally distant disciplines: a) Atomic, Molecular, and Optical Physics, including Ultrafast Laser Physics, Atto-science, Quantum Optics; b) Solid State and Condensed Matter Physics, including Optics of simple and complex materials, Atto-sciences of topological and correlated materials; c) Quantum Information Science, d) Machine Learning. A combination of disciplines has already led to new scientific collaborations on these topics, cf. with C. Faria (UCL), M. Hassan (UoA, Tuscon), O. Cohen/I.Kaminer (Techion), M. Nisoli/C. Rizzi (POLIMI), M. Maska (Politechnika Wroclawska), H. Merdji (EPoly), M. Chekhova (MPI Erlangen), N. Dudovich (Weizmann).

2. Impact

2.1 Long-term impact

TOWARULTRA will establish scientific and technological foundations for a new generation of engineered quantum light states and diagnostic tools, enabling unprecedented access to ultrafast quantum electrodynamics phenomena. By moving beyond conventional light–matter interaction regimes and developing tailored ultrashort quantum states of light with non-classical and massive correlations, the project has the potential to redefine how electromagnetic interactions are probed, controlled, and ultimately exploited.

Scientific impact: The project will open new directions in ultrafast quantum science by bridging quantum optics, strong-field physics, and attosecond science, enabling exploration of previously inaccessible QED processes and positioning Europe at the forefront of next-generation quantum electrodynamics research.

Technological impact: The project lays down the groundwork for new innovations in quantum photonics and sensing. The quantum light sources and diagnostics could evolve into enabling technologies for ultrahigh-precision measurements surpassing classical limits, with long-term applications in ultrafast spectroscopy, imaging, and next-generation metrology platforms.

Economic impact: The project seeds future deep-tech value chains in ultrafast quantum photonics, creating opportunities for commercialization through spin-offs and industry partnerships, aligned with Europe's ambition to lead in quantum technologies.

Social impact: From a societal perspective, the long-term outcomes of TOWARULTRA may contribute to advances in medical diagnostics, environmental monitoring, and secure communication through improved measurement and control at the quantum level.

Impact on human capital: TOWARULTRA will train researchers at the interface of quantum optics, ultrafast science, and photonic engineering, creating a new generation of scientists and strengthening European research networks.

Impact on gender balance: The project will promote gender balance through equitable recruitment, transparent selection procedures, and targeted mentoring for female researchers. Efforts in this area are already supported by Olga Smirnova from MBI (co-PI in TOWARULTRA), as well as by the participation of the partner groups, where female representation averages around 25%. Strong emphasis will be placed on further increasing this representation, while the EU gender balance policy has already been adopted by all institutes within the consortium. Additionally, the gender dimension does not apply to the research content of this proposal. The proposed research is not influenced by sex or gender-related variables. Consequently, scientific methodology and expected outcomes are independent of gender considerations. In summary, the project's long-term impact lies in establishing a new paradigm for generating and exploiting quantum light in extreme regimes, enabling transformative technologies for quantum science in Europe and beyond.

2.2 Innovation potential

Disruptive Innovation and Market Creation: TOWARULTRA targets three innovations with genuinely disruptive potential, each addressing a capability gap that existing technology cannot bridge: *(i) ultrafast massively entangled quantum light sources spanning the IR to XUV*, defining a product category that does not yet exist; *(ii) quantum-optical diagnostics for high-photon-number states in the VUV–XUV range*, for which no characterization tools currently exist; and *(iii) quantum-state-resolved ultrafast spectroscopy of correlated matter*, introducing photon statistics and light-matter entanglement as experimentally accessible observables.

These advances will open new market segments in ultrafast quantum photonics instrumentation, attosecond-range quantum state characterization, and quantum-enhanced materials diagnostics. Concrete application pathways include quantum-enhanced sensing of light-induced topological phases, attosecond quantum spectroscopy of strongly correlated systems, and high-harmonic-generation-based fingerprints for phase-resolved materials diagnostics (e.g. charge density waves). These capabilities extend beyond incremental improvements and enable new classes of measurement and sensing technologies.

Exploitation Measures and Translation Pathway: Both licensing and spin-off options will be assessed as technical maturity develops. The project includes early engagement with industry, particularly n2Photonics, to align developments with commercial roadmaps and system-level integration requirements. Technology transfer pathways, including follow-on support through European and national innovation instruments, will be pursued to transition results toward pre-commercial prototypes, with exploitation prioritized within the European ecosystem.

Intellectual Property Strategy: TOWARULTRA anticipates intellectual property emerging from the core innovations described above, with protection focused on their key enabling components and implementation methods. These include: *(i) source architectures and control schemes for generating ultrafast massively entangled quantum light*, including bright squeezed vacuum generation and conditioning approaches; *(ii) diagnostic and*

metrology techniques for characterizing high-photon-number quantum states in the VUV–XUV range; and *(iii) quantum-light-driven nonlinear optical processes and spectroscopy protocols enabling quantum-state-resolved measurements in correlated and low-dimensional materials*. These domains focus on protectable implementations rather than broad platform claims, ensuring clear pathways for exploitation.
The consortium will protect results at appropriate stages through coordinated IP management involving institutional technology transfer offices. Foreground ownership, access rights, and licensing strategies will be defined in the Consortium Agreement. Continuous monitoring of the IP landscape will ensure strategic positioning and freedom to operate, while balancing protection with open scientific dissemination.
Regulation, Certification, and Standardization: Although operating at a pre-commercial stage, TOWARULTRA anticipates future regulatory and standardization needs, particularly in sensing and quantum photonics instrumentation. As the technology matures, relevant certification frameworks and links to standardization bodies will be explored to ensure compatibility with emerging quantum technology standards.
Empowering Key Actors and Young Researchers: TOWARULTRA builds innovation capacity by embedding early-career researchers in interdisciplinary R&D, IP strategy, and industry collaboration, ensuring they develop both scientific excellence and the ability to translate breakthroughs into technological applications.
Inclusion and Equality Actions and Disability Measures: TOWARULTRA ensures inclusive recruitment, equal access to opportunities and decision-making, and full participation through accessibility measures aligned with the EU Disability Rights Strategy 2021–2030.

2.3 Communication and Dissemination

The project will implement a coherent and integrated strategy for **dissemination, exploitation, and communication**, designed to maximize scientific impact, enable future acceptance of the results, and ensure broad visibility among relevant stakeholders (Figure 2.3). The strategy balances open knowledge sharing with the protection of results that have potential for future valorization.

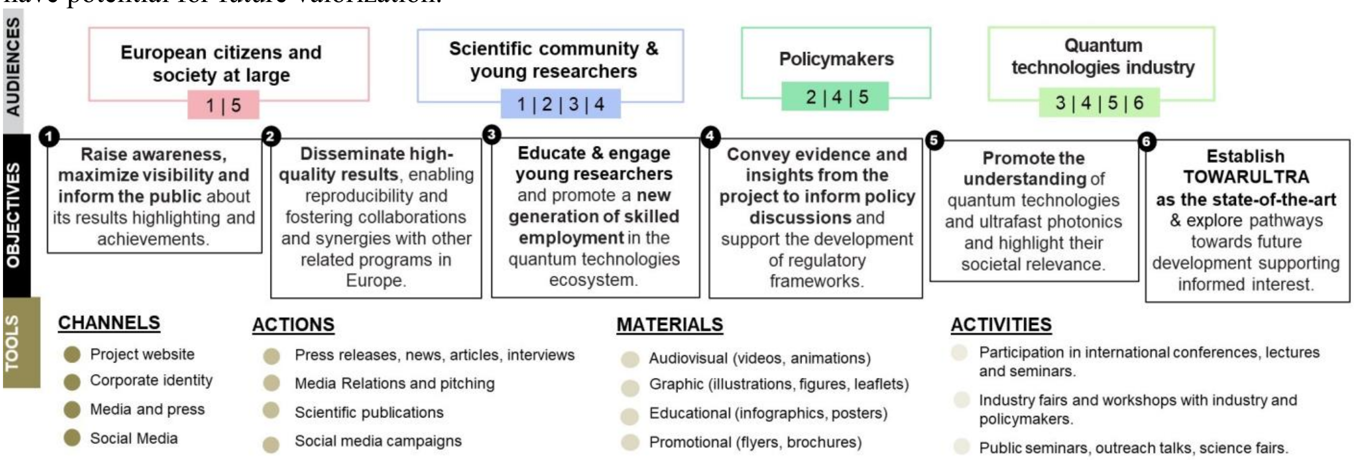

Fig 2.3 *First version of the communication, dissemination, and exploitation plan.*

Dissemination: The consortium will publish in high-impact peer-reviewed journals and present at leading international conferences. Open science practices will be adopted, including open access publications and sharing of data and methods. *KPIs (over 48 months):* ≥16 peer-reviewed publications (≥50% open access; ~4 per year); ≥32 presentations in international conferences/workshops/schools (~8 per year); ≥4 invited/keynote talks; Organization of 1 international conference (M46) and 3 workshops (M18, M30, M46).
Exploitation: Exploitation will follow a planned approach, identifying and protecting results with innovation potential. Clear ownership and access rights will be defined per the Consortium Agreement. Pathways, including follow-up funding, industrial collaboration, and spin-off creation, will be explored via a dynamic exploitation roadmap. *KPIs (over 48 months):* ≥3 invention announcements (~1 per year); ≥2 patent applications where justified (M24–M48); ≥3 industry engagement actions (e.g., workshops or targeted meetings at M24, M36, M48); annual exploitation roadmap updates (4 versions); ≥3 follow-up funding applications submitted (at least 1 by M36 and 2 by M48); 1 feasibility study for a spin-off company (M42–M48).
Communication: A communication plan will target European citizens, the scientific community, policymakers, and industry through a dedicated website, press releases, social media campaigns, videos, infographics, and public events. *KPIs (over 48 months):* A project website (M4), with regular updates and technical maintenance beyond the end of the project; ≥20 posts in social media and ≥2 dedicated campaigns; ≥3 outreach events (science fairs, webinars, public talks ~1–2 per year); ≥4 educational engagement activities. All KPIs will be regularly monitored at 6-month intervals

to ensure progress and allow for adaptive improvements. This structure ensures that the project maximizes its scientific visibility, innovation potential, and societal outreach over its full 48-month duration. For the last 5 years, ICFO has conducted a communication/outreach program devoted to the sonification of quantum processes, including those in strong-field physics. We participate in music festivals, organize conferences, symposia, and presentations with concerts, and publish scientific papers [YRP24,TPL26].

3. Quality and efficiency of the implementation

3.1 Work plan and allocation of resources.

The project is centered on 3 objectives: **O1) Generating MQS of light and light-matter; O2) Interfacing quantum light and quantum materials; O3) Quantum high harmonic spectroscopy of quantum phases in strongly correlated materials.** Each objective includes the 2 work packages: an initial and a final one. Each WP includes 2-3 concrete tasks, around which the work will be organized. These in turn determine deliverables, and define milestones, with the corresponding challenging, but doable timeline (see : 0- Gantt_draft.xlsx). Each task is related to its own risk and appropriate risk mitigation.

			Year 1				Year 2				Year 3				Year 4			
No	Workpackages and Tasks	Task		6		12		18		24		30		36		42		48
1	Generating MQS of light and light-matter and diagnostics	1.1				D1.1												
		2.2				D1.2												
2	Generating MQS of light and light-matter and diagnostics II	2.1								D2.1								
		2.2												D2.2				
3	Quantum sensing of light-induced topology in multilayer TMDCs	3.1				D3.1				D3.2 D3.3								
4	Quantum optical properties of harmonic generation in quantum light driven TMDCs	4.1												D4.1				
5	Strongly correlated materials with HHG spectroscopy I	5.1				D5.1												
		5.2																
6	Strongly correlated materials with HHG spectroscopy II	6.1												D6.1				
		6.2																D6.2
7	MNG, C&D AND EXPLOITATION	6.1	D7.1															
		6.2		D7.2														D7.2
		6.3		D7.3								D7.3						D7.3
		6.4												D7.4				
		6.5																D7.5
	Milestones					1				2		3		4				

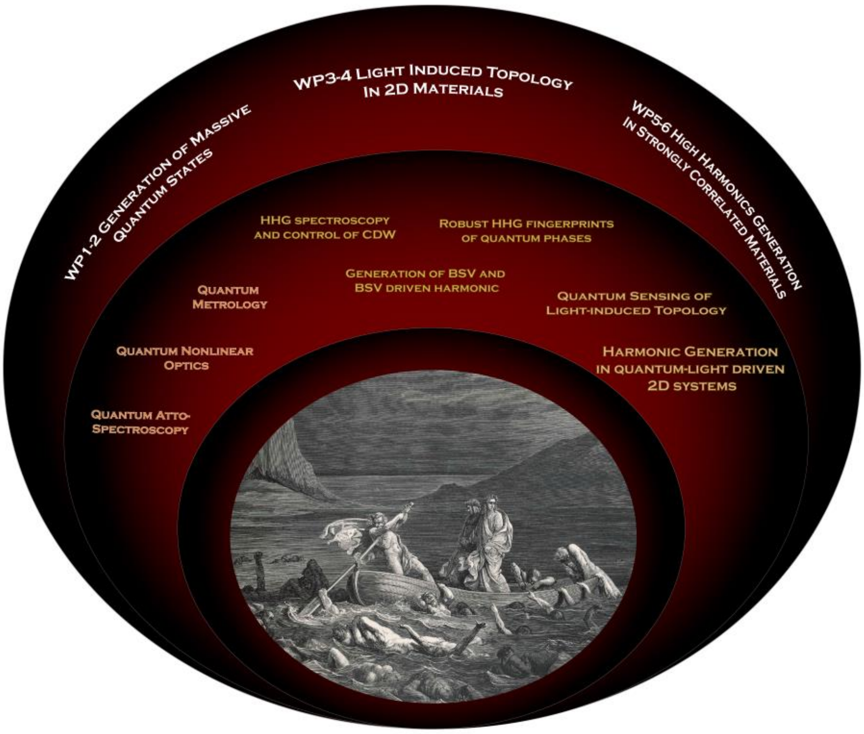

***Fig 3.1.2** PERT chart inspired by Dante Alighieri's Inferno: i) the first circle of fundamentals; ii) the second circle of applications; iii) the central painting symbolizes the challenges in exploitation and innovation (La Traversée du Styx by Gustav Doré, from his series Inferno Canto based on the Divine Comedy, CC0 - public domain).*

Table 3.1a: List of work packages

WP No	Work package Title	Lead No	Lead Short Name	Name & surname of WP leader	Gender of WP leader	Start Month	End month
WP1	Generating MQS of light and light-matter and diagnostics I	2	FORTH	Paraskevas Tzallas	M	1	12
WP2	Generating MQS of light and light-matter and diagnostics II	2	FORTH	Paraskevas Tzallas	M	12	36
WP3	Quantum sensing of light-induced topology in multilayer TMDCs	3	MBI	Olga Smirnova	F	1	24
WP4	Quantum optical properties of harmonic generation in quantum light driven TMDCs	3	MBI	Olga Smirnova	F	12	36
WP5	Strongly correlated materials with HHG spectroscopy I	4	ICFO	Jens Biegert	M	1	12
WP6	Strongly correlated materials with HHG spectroscopy II	4	ICFO	Jans Biegert	M	24	48
WP7	Project Management Communication, Dissemination and Exploitation	1	ICFO	Judith Salvador Herena	F	1	48

Table 3.1b: Work package description

Work package number	**WP1** (lead partners **ICFO/FORTH**)
Work package title	Generating MQS of light and light-matter and development of diagnostics I

Objectives: We aim to develop methods and diagnostics for the generation and characterization of MQS of light and light-matter for future applications in quantum attosecond spectroscopy that utilize photonic effects.

Description of work:

T1.1: Generation of MQS of light and light-matter: To generate MQS of light and light-matter, we will use harmonic generation processes that occur when intense fs IR light interacts with atoms (Argon, Xenon, Helium), simple molecules (H2+), and solids, including semiconductors (such as ZnO crystals), and high Tc superconductors YBCO [ABB22]. Although a 1kHz repetition rate Ti:sapphire fs IR (800nm) laser system is available in FORTH laboratory, a higher repetition rate (>1kHz) laser system that delivers fs IR(1μm) pulses with ultrahigh shot to shot energy stability (<0.5%) over long experimental runs (12h) and pulse energies in the hundreds of μJ, is highly required for I) generating high harmonics in gases and solids, and II) obtaining high quality statistical measurements. This laser source will be developed in collaboration with n2-photonics. We will explore conditioning schemes in non-depleted media and setups without conditioning in depleted and quantum-correlated media, plus wave-mixing during harmonic generation. Based on TOWARULTRA predictions (see Section 1.2), we expect MQS light with >10^10 photons, ~20 entangled modes, fs durations, tunable properties, spanning IR–XUV. Optical "cat" states already exist in IR via conditioning; we will improve control and create more complex states following Ref. [RLP25]. For the generation of light-matter MQS, we will follow the theoretical predictions of Refs. [RSM22,RLP22,RSM24,RSM24a]. Conditioning techniques will be applied to electrons produced by Above-Threshold Ionization (ATI), while excited H2+ molecules will be studied without conditioning schemes. Additionally, for the generation of light–matter MQS, we will follow the theoretical predictions of Ref. [ABB22] in strongly quantum correlated high Tc superconductors, exploring both conditioning and non-conditioning approaches.

T1.2: Characterization of MQS of light and light-matter: Characterizing high-photon-number, entangled light (IR-XUV) is challenge. It requires (i) high-repetition-rate (>1 kHz), ultra-stable laser with high-dynamic-range multichannel data acquisition (DAQ) system, and (ii) detectors with quantum efficiency >0.6. Achieving spectrally flat efficiency across Vis-VUV-XUV remains challenging; ongoing discussions with industrial partners target detectors optimized for narrower spectral bands. For low photon numbers, g^(n) correlation measurements and homodyne/tomography will be used. For high-photon-number light states, efforts will focus mostly on the IR states (without excluding the XUV). To achieve this goal, TOWARULTRA partner methods will be applied in the IR range (Section 1.2), including higher-order nonlinear interactions and IR+XUV wave mixing. Light–matter MQS diagnostics for ultrafast sensing will measure the quantum properties of emitted light ($g^{(n)}$, quantum tomography) after interaction with matter. We will study their dependence on many-body properties (e.g., decoherence, temperature in high-Tc superconductors) and time delay after coherent state preparation, using a pump–probe scheme for time-resolved dynamics. In addition, multimode photon-correlation measurements will be performed to detect potential violations of the Cauchy-Schwarz inequality.

Work distribution: The theory groups of M. Lewenstein (**ICFO**), M. Ivanov & O. Smirnova (**MBI**) will lead all the theoretical investigations of this WP. The experimental group of P. Tzallas (**FORTH**) will lead the experimental part of the work in concerning the interactions with gas phase media. The experimental group of J. Biegert (**ICFO**) will lead the experimental work on high Tc superconductors. The experimental groups of P. Tzallas (**FORTH**) and J. Biegert (**ICFO**) will lead the experimental part work on interactions with semiconductors. The laser company (**n2-photonics**) will contribute to the development of the primary IR laser fs source and investigations towards potential commercialization of the research findings.

Deliverables: D1.1: Report on the development of the laser system and on generation of MQS of light and light-matter (M12); **D1.2:** Report on characterization of MQS of light and light-matter (M12).

Work package number	**WP2** (lead partners **ICFO/FORTH**)
Work package title	Generating MQS of light and light-matter and development of diagnostics II

Objectives: In this WP we aim to justify the novelty of the MQS and diagnostics produced in WP1, by utilizing them in breakthrough investigations in nonlinear optics and ultrafast quantum metrology and sensing.

Description of work:

T2.1: Applications in ultrafast non-linear optics: Introducing quantum light into nonlinear optics is considered a breakthrough, as it opens the way to a wide range of investigations in ultrafast science and quantum technologies, including quantum light engineering. Here, we aim to demonstrate this capability by using the quantum light sources developed in WP1 as a primary source to engineer quantum light driven in deferent spectral regions. As described in Section 1.2, we have already demonstrated that quantum light states can serve as primary sources for engineering quantum light in different spectral regions via frequency up-conversion processes [LRS25]. Building on this demonstration for IR optical "cat" states via 2nd-harmonic generation in BBO, we will extend to higher-order nonlinear processes generating quantum light in the UV (3rd harmonic), VUV (5th/7th), and XUV (high-

order harmonics > 9th) by focusing intense IR "cat" states into Xenon gas. WP1 diagnostics will characterize the resulting states.
T2.2: Applications in ultrafast quantum metrology and sensing: A groundbreaking and straightforward application in ultrafast quantum metrology and sensing is to trace the ultrafast dephasing times in the HHG process in semiconductors. As shown in Section 1.2, we have already conducted theoretical investigations of this topic [RSM24], using conditional measurements on ZnO-driven harmonics where the dephasing time is encoded in the Wigner function of the IR field (Fig. 1.2.4). We aim to demonstrate this experimentally. Additionally, we will track ~1 fs dynamics in coherently excited H2+ molecules via pump-probe Wigner-function measurements, in line with predictions in Ref. [RSM24a]. In a similar context, experiments will also be conducted using coherently excited atoms, guided by the theoretical frameworks developed in Refs. [YBK25,RSM24a].
Work distribution: The theory groups of M. Lewenstein (**ICFO**), M. Ivanov & O. Smirnova (**MBI**) will lead all theoretical investigations of this WP. The experimental group of P. Tzallas (**FORTH**) will lead the experimental part of the work concerning the T2.1 and the investigations using the H2+ molecule and resonant atoms in T2.1. The experimental groups of P. Tzallas (**FORTH**) and J. Biegert (**ICFO**) will lead the experimental part of the work related to the investigations of dephasing times in semiconductors in T2.2. The laser company (**n2-photonics)** will contribute to the development of the primary IR laser fs source and investigations towards potential commercialization of the research findings.

Deliverables: D2.1: Report on applications of quantum light into non-linear optics (M24); **D2.2:** Report on applications in ultrafast quantum metrology and sensing (M36).

Work package number	**WP3** (lead partner **MBI**)
Work package title	Quantum optics of topological phases in TMDC materials

Objectives. Characterizing quantum properties of HHG near light-induced topological phase transition

Description of work:
T3.1: Quantum sensing of light-induced topology in multilayer TMDCs: In TMDC *monolayers*, opposite Berry curvatures in K and K' valleys of the Brillouin zone enable valley-selective opto-electronics for information processing [SYC16,VNV18]. However, *standard multilayer* TMDCs maintain inversion symmetry, thereby nullifying the Berry curvature, losing the potential for related topological effects, and seemingly disabling valley-selective opto-electronics. Our recent work [TJP24] has overcome these challenges, using light with attosecond-shaped polarization to break both inversion and time-reversal symmetries. Here, we will take advantage of this light-induced topology to tune the quantum properties of nonlinear optical response. Theory will (i) develop framework for quantum optical response of light-driven TMDC materials; (ii) perform simulations for the nonlinear quantum-optical response of excited TMDC materials far away and near a topological phase transition; (iii) establish how topological phase transition affects the quantum optical properties of the generated harmonics when the material is driven by classical light. Experiments will (i) Set up two-colour "trefoil" light pulses (Fig. made of counter-rotating fundamental and second-harmonic fields with controlled delay; (ii) Apply it to multilayer MoS_2/WS_2 to induce valley-selective excitation and trigger light-induced topological phase transitions, (iii) Measure intensity-intensity correlation functions for individual harmonics and between harmonics as a function of the intensity and orientation of the driving trefoil field, which controls the light-induced topology.
Work distribution: The theory groups M. Ivanov & O. Smirnova (**MBI**), and M. Lewenstein (**ICFO**) will lead the theoretical investigations of this task. The experimental groups of P. Tzallas (**FORTH**) and J. Biegert will lead the experimental part of the work concerning the interactions with solids. The company **n2-photonics** will will provide the knowhow on laser pulse technology and fs pulse characterization and will contribute to investigations towards potential commercialization of the research findings.

Deliverables: D3.1: Report on theoretical framework for QED description of harmonic generation in TMDC materials driven by classical light (M12); **D3.2:** Report on numerical simulations of quantum optical response in trefoil-driven TMDC (M24); **D3.3:** Report on experimental measurements of $g^{(2)}(0)$ correlation functions for individual harmonics and between harmonics as a function of the trefoil field intensity and orientation (M24).

Work package number	**WP4** (lead partner **MBI**)
Work package title	Quantum optics of HHG in TMDC materials driven by quantum light

Objectives Development of methods, diagnostics, and control of the light-induced topological effects

Description of work:
T4.1: Quantum-optical properties of harmonic generation in quantum-light driven TMDC. In contrast to Task 3.1, here we will focus on the quantum-optical properties of harmonics from TMDCs driven by quantum light.

We will analyze the possibility of generating frequency-upconverted, polarization-entangled bi-photons in monolayer TMDC (WS_2 or MoS_2) driven by a bi-photon BSV source [RCB24], extending our method [SIJ22,GMR26] to quantum information processing via entangling K and K' valleys. First, we will consider driving by linearly polarized single-color BSV field, which populates both K and K' valleys. Our goal is to see if the harmonics are generated as polarization-entangled bi-photons from K and K' valleys. We will detect not only the emission spectra, but also photon statistics, $g^{(2)}(0)$, and higher-order correlations. To show that harmonic photons are emitted as polarization-entangled pairs, we will use polarization-resolved photon statistics, focusing on polarizations parallel and perpendicular to the driver. Second, we will extend these measurements to the TMDC driven by trefoil BSV and measure photon statistics and harmonic correlations as a function of attosecond delay between the two BSV fields. This task takes full advantage of the dramatically increased damage thresholds when the BSV driver is applied [RCB24].

Work distribution among the partners: The theory groups M. Ivanov & O. Smirnova (**MBI**), and M. Lewenstein (**ICFO**) will lead the theoretical investigations of this task. The experimental groups of P. Tzallas (**FORTH**) and J. Biegert (**ICFO**) will lead the experimental part of the work concerning the interactions with solids and semiconductors. The laser company (**n2-photonics)** will provide the knowhow in short laser pulse technology and fs pulse characterization and will contribute to investigations towards potential commercialization of the research findings.

Deliverables:D4.1: Report on quantum-optical properties of HHG from BSV-driven TMDC material (M36)

Work package number	**WP5** (lead partner **ICFO**)
Work package title	Strongly correlated materials with HHG spectroscopy I

Objectives Establish robust HHG fingerprints of correlated quantum phases in YBCO and $TiSe_2$ driven by classical coherent light, develop the supporting theoretical framework, and construct the BSV light source required for the quantum-metrological extensions in WP6.

Description of work:

T5.1: Robust HHG fingerprints of correlated quantum phases using classical coherent light.

We will establish reliable, experimentally accessible HHG fingerprints of two prototypical strongly correlated material systems: the high-temperature superconductor YBCO and the charge-density-wave material $TiSe_2$. Building on the consortium's prior demonstration of optical detection of quantum phases in YBCO [ABB22], we will conduct systematic HHG measurements across known phase transitions in both materials, tracking observables including harmonic yield, spectral shape, polarization dependence, and temperature dependence, as well as pump-induced changes that allow non-equilibrium phase dynamics to be followed in real time. For YBCO, measurements will focus on how the superconducting condensate and its order parameter are encoded in the nonlinear optical response, seeking fingerprints that are robust across driving conditions and can serve as reliable phase diagnostics. For $TiSe_2$, we will map the HHG response across the CDW transition, establishing a spectroscopic baseline that will underpin the more detailed mechanistic study in WP6-T6.2. Theory will develop microscopic models of the strong-field nonlinear optical response, enabling quantitative interpretation of measured harmonic spectra and identification of spectral features sensitive to the nature and strength of the correlated order parameter. This theoretical framework will also guide the experimental design in WP6.

T5.2: Construction/characterization of the BSV source. To enable quantum-metrological HHG experiments in WP6-T6.1, we will design, construct, and characterize a bright squeezed-vacuum source for driving strong-field interactions in correlated solids under cryogenic conditions. The BSV source is based on an OPA scheme in which a 1.5 µm pump drives spontaneous parametric down-conversion to generate photon pairs at 3 µm, well matched to the strong-field driving conditions of our existing HHG beamline for correlated materials. Characterization will be based on: photon-correlation measurements will verify the super thermal photon number distributions characteristic of a genuine BSV state, and homodyne detection will confirm squeezing. Crucially, characterization will be performed not only at the OPA output but also at the sample position, since optical losses through the beam delivery chain — including vacuum windows and cryostat interfaces required for measurements on YBCO and $TiSe_2$ — can degrade squeezing and modify photon statistics. The beam delivery and focusing geometry will be designed to minimize the use of lossy elements, and active OPA stabilization will ensure the shot-to-shot stability required for reliable photon statistics measurements. The BSV source will be fully operational and integrated with the cryogenic sample environment by the end of month 12.

Work distribution: J. Biegert (**ICFO**) leads all experimental work. P. Tzallas (**FORTH**) will participate in the experiment, transferring the knowhow acquired from WP1,2. Theory co-led by M. Lewenstein (**ICFO**), M. Ivanov & O. Smirnova (**MBI**). The laser company (**n2-photonics)** will provide the knowhow in short laser pulse technology and fs pulse characterization and will contribute to investigations towards potential commercialization

of the research findings.	
Deliverables: D5.1: Report on HHG fingerprints of correlated quantum phases in YBCO and $TiSe_2$ using classical coherent light, and on BSV source construction (M12)	
Work package number	**WP6** (lead partner **ICFO**)
Work package title	Strongly correlated materials with HHG spectroscopy II

Objectives D Extend HHG spectroscopy of YBCO and $TiSe_2$ into the quantum-metrological regime using the BSV source constructed in WP5, and develop a mechanistic understanding of CDW formation in $TiSe_2$ including electron–phonon coupling, with the goal of establishing spectroscopic control of CDW order.

Description of work:
T6.1: BSV-driven HHG and quantum metrology of correlated phases. Using the BSV source delivered in WP5-T5.2, we will replace the classical coherent driving field with bright squeezed vacuum light to probe the quantum character of the strong-field interaction with YBCO and $TiSe_2$. By comparing HHG spectra and quantum-optical observables under coherent versus BSV excitation, we will quantify how quantum fluctuations and correlations in the driving field are modified or amplified by the correlated electronic system. Experimentally, we will measure photon statistics, phase-sensitive noise, squeezing degradation or enhancement, and higher-order photon correlations ($g^{(2)}$ and beyond) in the emitted harmonic radiation as a function of material phase, temperature, and driving conditions. This introduces quantum metrology as a new layer in HHG spectroscopy, enabling the detection of fluctuations and possible light–matter entanglement invisible to classical driving. A goal is whether high-Tc superconductors, whose correlated quantum states have been shown to survive intense optical driving [ABB22,TZV25], can act as material-based sources of non-classical radiation when driven by BSV fields. Theory will model how quantum fluctuations in the BSV field propagate through the correlated electronic system and are imprinted on the emitted harmonics, building directly on WP5-T5.1.
T6.2: HHG spectroscopy and control of CDW order in $TiSe_2$: role of electron–phonon coupling. The microscopic origin of CDW formation in $TiSe_2$ remains contested, with electronic instabilities and electron–phonon coupling proposed as competing driving mechanisms. We will address this by extending the mean-field theoretical framework of [TZV25,ZTV25] to include electron–phonon coupling explicitly, enabling identification of phonon-specific signatures in the HHG spectrum that can distinguish between the two mechanisms experimentally. Different order-parameter arrangements give rise to distinct symmetry-breaking patterns; we will study how nematic ordering and possible chirality of CDW domains manifest in the polarization dependence and spectral structure of harmonic emission. Experimentally, building on the CDW baseline established in WP5-T5.1, we will measure HHG spectra across the CDW transition as a function of temperature, pump fluence, and driving field polarization, seeking signatures that discriminate electronic from phononic CDW mechanisms. We will further explore whether tailored ultrafast light fields can be used to control CDW domain structure and ordering, using polarization-resolved pump–probe HHG measurements.
Work distribution: J. Biegert (**ICFO**) leads all experimental work. P. Tzallas (**FORTH**) will participate in the experiment, transferring the knowhow acquired from WP1,2. Theory co-led by M. Lewenstein (**ICFO**) and M. Ivanov & O. Smirnova (**MBI**), with CDW theory extension led from ICFO. The laser company (**n2-photonics)** will contribute to investigations towards potential commercialization of the research findings.

Deliverables: D6.1: Report on BSV-driven HHG and quantum-metrological observables in YBCO and $TiSe_2$ (M36); **D6.2:** Report on HHG spectroscopy and light-field control of CDW order in $TiSe_2$ (M48)

Work package number	**WP7** (lead partner **ICFO**)
Work package title	Project Management, Communication, Dissemination and Exploitation

Objectives

O7.1: To ensure the effective progress and management of the project by fostering clear communication both internally (among partners) and externally (with the European Commission), while fulfilling all obligations towards the European Commission (EC) to support smooth project progression.
O7.2 To effectively communicate and exploit the project results and raise awareness about the project's achievements and its impact on society. To ensure efficient coordination, and project management.

Task 7.1 Coordination: ICFO with the commitment and collaboration of all partners, will coordinate the implementation of all objectives by monitoring tasks, milestones, and progress across work packages, while compiling scientific reports. This task also includes efficient administrative, legal, and financial management, as well as good communication between partners and through the European Commission. (ICFO, all) M1-48
Task 7.2 Data Management: A Data Management Plan (DMP) will be delivered by Month 6 and regularly updated throughout the project, ensuring data follows FAIR principles and Open-Access requirements, but also planning

for potential data business readiness. (ICFO, all) M1-48
Task 7.3 IP monitoring:
Task 7.4 Exploitation, incl. a Market research report:
Create a plan for IP and innovation management to maximize the protection of the project's new results and start with the design of an exploitation plan to maximize the economic and societal value generated from the project's results (D7.4, month 12). Monitor new innovations/assess their potential for IP protection and further development into viable products, evaluate markets for the adoption of new results and create the exploitation plan to maximize economic/societal value generated from the project's results (update of D7.4, month 42).
Task 7.4 Communication and dissemination strategy: A thorough strategy will be developed and implemented to raise awareness about the project and make its impact visible to Europe and beyond, detailed in D7.6 (M6, updated in 48), identifying target groups and specifying clear actions to reach them. A set of audio-visual materials (e.g. presentations, videos) explaining the technology and impact will be designed and distributed across all available channels. Partners will join industry fairs, international academic conferences or relevant events to further disseminate project outcomes and results. (ICFO, all) M1-48

Deliverables: D7. 1: Project handbook (M3); **D7.2:** Communication, dissemination & exploitation plan (M6, M48); **D7.3** Data Management Plan (M6, M30, M48); **D7.4**: IP management and Exploitation plan (M12-M42); **D7.5:** Communication, dissemination & exploitation plan update (M48)

Table 3.1c: List of Deliverables

Number	Deliverable name	Short description	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date (in months)
D1.1	Laser system for generation of MQS of light and light-matter	Report on laser system for generation and charac-terization of MQS of light and light-matter.	WP1	FORTH /n2-Photonics	R	SEN	M12
D1.2	Characterization of MQS of light and light-matter	Diagnostics for the characterization of MQS of light and light-matter.	WP1	FORTH	R	SEN	M12
D2.1	Applications of quantum light in non-linear optics.	Justification of novelty and diagnostics of MQS in nonlinear optics.	WP2	FORTH ICFO	R	SEN	M24
D2.2	Applications in ultrafast quantum metrology and sensing.	Justification of the novelty and diagnostics of MQS by utilizing them in ultrafast quantum metrology	WP2	FORTH ICFO	R	SEN	M36
D3.1	Theory of QED of HHG in TMDC materials in classical light	Theory to design the experiments on the control of valley polarization and topological effects	WP3	MBI	R	SEN	M12
D3.2	Simulations of quantum optical response in trefoil driven TMDC.	Simulations in trefoil driven TMDC in trivial and topological phases and near the	WP3	MBI	R	SEN	M24

		phase transition point					
D3.3	Measurements of $g^{(2)}(0)$ for indivi-dual/between harmonics	Measurements of $g^{(2)}(0)$ as a function of the intensity/ orientation of the driving trefoil field correlated to the light-induced topology	WP3	MBI	R	SEN	M24
D4.1	Report on HHG in BSV-driven TMDC material	Report/publication on novel applications of BSV for TMDC materials	WP4	MBI	R	SEN	M36
D5.1	Report on HHG fingerprints of correlated quantum phases	Report preparing a paper on HHG fingerprints of correlated quantum phases in broader material classes	WP5	ICFO	R	SEN	M12
D6.1	Report on BSV-driven HHG and metrology in qua-ntum materials	Report preparing a paper on fingerprints of correlated quantum phases using bright squeezed vacuum	WP6	ICFO	R	SEN	M36
D6.2	Report on harmo-nic spectroscopy and light-field control of CDW	Report preparing a paper on HHG use for control of CDW	WP6	ICFO	R	SEN	M48
D7.1	Project handbook	Project management handbook	WP1	ICFO	R	PU	M3
D7.2	Communication, dissemination and exploitation plan	Continuous plan for dissemination, exploitation including communication activities	WP1	ICFO	R	SEN	M6, M48
D7.3	DMP	Data Management Plans	WP1	ICFO	R	SEN	M6, M30, M48
D7.4	IP and Exploitation Plan	IP management and Exploitation Plan	WP7	n2-photonics	R	SEN	M12-M40

Table 3.1d: List of milestones

Milestone number	Milestone name	Related work package(s)	Due date (in month)	Means of verification
MS1	Project website	WP7	4	Available project website for the project
MS2	Development of the optical arrangement, laser system and	WP1, WP2	12	Report

	electronics			
MS3	Progress on topology control with quantum light	WP3,WP4	24	Report
MS4	Progress in studies of fingerprints of strong correlations in various systems	WP5, WP6	36	Report

Table 3.1e: Critical risks for implementation

Description of risk (indicate level of (i) likelihood, and (ii) severity: Low/Medium/High)	Work package(s) involved	Proposed risk-mitigation measures
Unstable two-colour BSV fields (M)	WP2	Classical pre-alignment; active delay stabilization; phase feedback
Weak valley selectivity (L)	WP2	lattice-field angle control; polarization optimization; monolayer/bilayer controls
Fast exciton dephasing (M)	WP2	low temperature; hBN encapsulation; time-gated detection; quality samples
Technical noise masks quantum signals (M)	WP2/WP3	shot-noise calibration; balanced detection; background subtraction; reference arm
No entanglement witness (M)	WP3	higher-order correlations; squeezing transfer; covariance analysis; alternative non-classicality metrics
Sample damage / heating (M)	WP3	Fluence map; cryo cooling; pulse shaping; low-duty cycle
Broadband (Vis-UV-XUV) photon detector's spectral flatness/low efficiency (H/M)	WP1	Detectors optimized for narrower spectral bands in the Vis-VUV–XUV range
Shot to short energy instabilities of the IR laser sources (L)	WP1-6	Tagging of the measurements at <0.1% of the mean of the IR laser energy fluctuations
>0.5 fs time delay instabilities of the interferometer used for quantum tomography (L)	WP1,2	active delay stabilization; phase feedback
Theory method fails (M)	All WPs	Choose an alternative method, apply approximations, simplify the underlying model
Squeezing degradation through cryogenic beam delivery chain reduces BSV state fidelity at sample position (M/M)	WP5,6	Minimize lossy optical elements; AR-coated vacuum windows optimized for 3 μm; end-to-end quantum-optical characterization at sample position; loss budget modeling prior to construction
OPA instability at 3 μm prevents reliable photon-pair generation for BSV-driven HHG experiments (M/H)	WP5,6	Active power and pointing stabilization; shot-tagging to reject unstable shots; fallback to coherent 3 μm driving to maintain experimental progress on HHG fingerprints while BSV source is optimized
HHG signal too weak in cryogenic correlated material to distinguish quantum-optical signatures from noise (M/H)	WP5,6	Optimize sample geometry and thickness; increase repetition rate; balanced detection with reference arm; cross-validate with room-temperature measurements before cryogenic runs
CDW domain structure in $TiSe_2$ varies between samples, Preventing reproducible HHG fingerprints (M/M)	WP5,6	Systematic sample screening with complementary characterization (X-ray, transport); multiple samples from Different growth batches; temperature cycling protocols to control domain ordering

Table 3.1f: Summary of staff effort

	WP1	WP2	WP3	WP4	WP5	WP6	WP7	Total Person-Months per Participant
1/ ICFO	24+2	24+2	24	24	24+2	24+2	4	156
2/ FORTH								
3/ MBI	X	X	X	X	X			
4/ n2-Photonics	X						X	
Total Person Month								

Table 3.1g: ‘Subcontracting costs’ items

1/ ICFO		
	Cost (€)	**Description of tasks and justification**
Subcontracting	225.000	**Prototype ultrafast laser system (150k€):** The BSV source in WP5-T5.2 requires 2 MHz repetition rate, 100 fs pulses, and <0.1% rms stability-specifications unavailable in any commercial system. A prototype is subcontracted to a specialist ultrafast laser manufacturer. No commercially available equipment provides this capability. **Multi-channel detection system (75k€):** A thermo-electrically cooled, multi-stage, custom laser-etched broadband balanced detector for simultaneous measurement of photon statistics and inter-harmonic $g^{(2)}$ and higher-order correlations in WP5-T5.2 and WP6-T6.1. A prototype is subcontracted to a specialist metrology equipment manufacturer. No commercially available equipment provides this capability.

Table 3.1h: ‘Purchase costs’ items (major equipment costs)

2/ FORTH		
	Cost (€)	**Justification**
Equipment	250.000	**kHz-MHz repetition rate harmonic generation laser driver (190000€)**: Ultra stable (< 0.5% rms 12h) high repletion rate (tuneable up to 1MHz) laser system, delivering <100 fs pulses at 1μm carrier wavelength and energy in the range of hundreds-μJ per pulse-sufficient to generate harmonics in the XUV. The price includes optics for beam shaping and delivery. Such high rep. rate stable light sources are crucial for conducting HHG experiments and high-quality photon statistics measurements. **Detectors/DAQ system (60000€):** Balanced detector for IR, UV-VIS, XUV. Balancing circuits timing electronics with CFD and analog logic. Parallel multi-channel DAQ system. This system is required for the quantum light state characterization in the aforementioned spectral regions.
1/ICFO		
	Cost (€)	**Justification**
Equipment	35.000	**Multi-channel DAQ system (35k€):** Picosecond timing electronics with CFDs and parallel 4-channel acquisition, synchronized with the laser and cryogenic environment, are required for shot-resolved photon correlation measurements in WP5-T5.2 and WP6-T6.1.
4/n2-photonics GmbH		
	Cost (€)	**Justification**
Equipment	80.000	**Spectrometer:** Brief description of the equipment and explanation how will be used in the project.

3.2 Quality of the consortium

Capacity and role of each participant and consortium expertise: TOWARULTRA aims to develop novel quantum light sources and diagnostics at the frontier of quantum optics, strong-field physics and ultrafast science. Each consortium member (ICFO, MBI, FORTH & n2-Photonics GmbH) brings distinct expertise. The consortium combines complementary partners covering all key disciplines, with strong track records evidenced by high-impact publications and competitive projects. Academic members provide scientific and methodological expertise, while the industry partner contributes capabilities in validation and prototyping. All partners have the infrastructure, facilities, and skilled personnel needed to implement their tasks. The coordinator (ICFO) brings extensive EU project experience, supported by clear governance and defined roles.

Quality of the partnership:

- **ICFO - The Institute of Photonic Sciences:** ICFO is one of the world's leading photonic sciences institutes, with a mission to conduct frontier research, train the next generation of scientists, and promote knowledge and technology transfer. It is internationally recognized in quantum technologies and ultrafast photonics. Founded in 2002, ICFO is a Severo Ochoa Center of Excellence and hosts ca. 550 researchers from 60 countries, providing a stimulating international environment with extensive networking and training opportunities. ***The core members of ICFO in TOWARULTRA are:*** **Prof. Maciej Lewenstein (PI)** (Researcher unique identifier: https://scholar.google.com/citations?user=ObF-4tYAAAAJ&hl=en): M. Lewenstein earned an MSc from Warsaw University (1978) and a PhD from Universität Essen (1983). After positions at Harvard, CEA Saclay, JILA Boulder, the Centre for Theoretical Physics in Warsaw, and Leibniz University Hannover, he moved to ICFO in 2005 as ICREA Research Professor. His interests include quantum optics, quantum information, attosecond science, and statistical physics. He published over 800 papers, has been cited nearly 88000 times (h-index 137), is a recipient of 3 ERC AdGs, and is nearly 88000 times (h-index 137), is a recipient of 3 ERC AdGs, and a Highly Cited Researcher 2014-2025; **Prof. Jens Biegert (PI)** (Researcher unique identifier: https://scholar.google.com/citations?user=QKtLfo8AAAAJ&hl=en): J. Biegert is an ICREA Professor of Attoscience and Ultrafast Optics at ICFO. He received his PhD from the Technische Universität München and pursued his habilitation at ETH Zürich. His research focuses on generation, control, and application of ultrashort laser pulses to probe matter on electronic and atomic timescales. Since joining ICFO, Biegert has pioneered mid-infrared photonics and attosecond soft X-ray science. His research has enabled new approaches to imaging chemical reactions, tracking electron dynamics, and observing carrier motion in quantum systems.Biegert serves in leadership roles in the international photonics community, including coordinator of a European Commission FET consortium and Guest Professor at the Fritz Haber Institute. He served as Executive Director of Laserlab-Europe and on Optica's Board of Directors. He is a Fellow of Optica and APS. Recent distinctions include the C.E.K. Mees Medal, the Allen Prize, the Humboldt Bessel Prize, and an ERC AdG. He published ≈150 papers, cited ≈13000 times (h-index 62); ***Additional members of ICFO in TOWARULTRA are:*** **Dr. Fernando Ardana-Lamas** (Staff Researcher): Staff Researcher at ICFO with PhD from EPFL. Expert in attoscience and ultrafast optics, contributing to breakthroughs including 19.2-attosecond soft X-ray pulses (1900 citations). **Ms. Zoé de Bigault de Granrut** is a PhD student in the group, with an MSc from the University of Strasbourg, conducting research in ultrafast optics and attoscience. **Ms. Arti Gaharwar** (PhD)**, Ms. Lidija Petrovic** (PhD)**,** both working in the field directly relevant to TOWARULTRA. **Additional staff of ICFO** (including early-stage and experienced researchers, technicians, administration, and management) will also support TOWARULTRA.
- **MBI-Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy:** MBI conducts basic research in nonlinear optics and ultrafast dynamics of matter with laser light. MBI includes the Theory Department with 3 full professors and about 25 postdocs and PhD students. The Department has developed a unique set of tools for attosecond science and ultrafast spectroscopy, including microscopic and macroscopic nonlinear optical response. The department invests about 100K Euro annually to maintain its high-performance computing facility. ***The core members of MBI in TOWARULTRA are:*** **Prof. Misha Ivanov (PI)** (Researcher unique identifier: https://scholar.google.com/citations?user=Ncu-IYYAAAAJ&hl=de): M. Ivanov graduated from Moscow State University (1987), defended PhD at the General Physics Institute (1989). After positions at the NRC Canada, Imperial College London (Attosecond Chair, 2008), he moved to the Max Born Institute in 2012, where he leads the Theory Department and holds a Professorship at Humboldt University. Recipient of the Rutherford medal of the Royal Society of Canada and the Humboldt Bessel prize, and member of the Academia Europea. His h-index is 84, with over 42000 citations to his over 260 papers; **Prof. Olga Smirnova (PI)** (Researcher unique identifier: https://scholar.google.com /citations?user=wsyVUeMAAAAJ&hl=en): O. Smirnova graduated from Moscow State University (1996, PhD 2000). After a Lise-Meitner Fellowship at Vienna University of Technology and a position at the NRC Canada, she moved to the Max Born Institute in 2009 to establish her Strong Field Theory group. Since 2016 she holds a full professorship at TU Berlin. Awards include the Karl-Scheel-Preis, Ahmed Zewail Award (2020), and Mildred Dresselhaus Prize (2022). Her research focuses on ultrafast electron dynamics, supported by an ERC advanced grant. H-index 61, over 14000 citations to over 150 papers; ***Additional members of MBI in TOWARULTRA are:*** **Dr. Serguei Patchkovskii** (Researcher unique identifier: https://scholar.google.com/citations?user=ZfntG90AAAAJ&hl=en): Dr. S. Patchkovskii (PhD, Univ. Zürich, 1997) joined MBI in 2014 after positions at the Univ. of Calgary and NRC Canada. His focus is on quantum chemistry methods and computational

techniques for intense-field light-matter interactions (h-index 67, over 15800 citations). **Dr. Felipe Morales** (Researcher unique identifier: https://scholar.google.com/ citations?user=FcxICxIAAAAJ&hl=en): His research interests are strong field and attosecond physics, numerical and parallelization schemes applied to light- matter interaction both at the microscopic and macroscopic level. His h-index is 29, with over 3700K citations. **Mr Nikolai Klimkin (PhD student)** (Researcher unique identifier: https://scholar.google.com/citations?user=ZfntG90AAAAJ&hl=en): His research interests are in AMO physics, strong field, attosecond science, quantum optics and machine learning. His h-index is 4, with ≈300 citations. **Additional MBI staff** (including dedicated high performance computing technician and the EU projects management team) will also support TOWARULTRA.

- **FORTH-Foundation for Research and Technology - Hellas:** FORTH is the largest research center in Greece with ten research institutes. IESL, directly related to TOWARULTRA, has pioneered quantum light and quantum technologies. FORTH has established the "Quantum Light and Technologies (Q-Light)" and the Center for Quantum Science and Technologies (FORTH-QuTech). The Q-Light and Attosecond Science and Technology activities, both led by P. Tzallas, focus on atto-science and quantum light engineering. ***Core members of FORTH in TOWARULTRA are:*** **Dr. Paraskevas Tzallas (PI)** (Researcher unique identifier https:// scholar. google.gr/citations?user=QsFJe7AAAAAJ&hl=en): P. Tzallas earned his PhD in physics in 2002. He continued his PostDoc at the Max Planck Institute for Quantum Optics (MPQ) in Garching, Germany. Currently, he is Research Director at the Institute of Electronic Structure and Laser (IESL) of the Foundation for Research and Technology – Hellas (FORTH), Greece, and head of the "Quantum Light and Technologies" and "Attosecond Science and Technology" activities at FORTH. He is also Coordinator of the Center of Quantum Science and Technologies of FORTH (FORTH-QuTech) and Scientific Advisor of secondary sources at Extreme Light Infrastructure-Attosecond Light Pulse Source (ELI-ALPS), Szeged, Hungary. His research focuses on strong laser-field physics, attosecond science, quantum optics, and pioneering work on non-classical light states, including optical “cat” states. He published ≈100 papers (h-index 41, ≈5500 citations); ***Additional members of FORTH team in TOWARULTRA are:*** **Dr Nikolaos Tsatrafyllis** (Researcher unique identifier: https://scholar.google.com/ citations?user=jOYdQxoAAAAJ&hl=el): He earned his PhD in AMO physics from the Univ. of Crete & FORTH-IESL in 2018. Currently, he is a PostDoc researcher at the Q-Light activity of FORTH-IESL. He is experienced in quantum optics and technologies with novel contributions on the development of conditioning measurements and the generation of optical "cat" states. His h-index is 7, with ≈420 citations. **Dr. Deeksha Kanti**: She earned her PhD in AMO physics from the Univ. of Warsaw in 2025. Currently, she is a PostDoc researcher at the Q-Light activity of FORTH-IESL, conducting her research in AMO physics and quantum optics. **Mr Sannik Acharya**: He is a PhD student conducting his research at the Q-Light activity of FORTH-IESL in a topic that is directly connected with TOWARULTRA. **Mr Y. Lamprakis**: He is a technical scientist at FORTH-IESL and member of the Q-Light group and experienced in laser technology. **Dr. Georgina Kaklamani:** Dr. Kaklamani is a member of the Central Administration of FORTH. In the proposed Pathfinder project, Dr. Kaklamani will serve as Core Management Team member from the FORTH side on management issues; **Additional staff of FORTH** (including early-stage and experienced researchers, technicians, administration, and management), specialized in AMO physics, laser technology and computer science will support TOWARULTRA.
- **n2-Photonics GmbH:** n2-Photonics GmbH is a high-tech SME specializing in nonlinear pulse compression of ultrafast laser systems, generating few-cycle pulses with high peak power via gas-filled multipass-cells. Their modular platforms support applications such as HHG and attosecond science. Within TOWARULTRA, n2-Photonics contributes expertise in ultrafast laser engineering and system integration for the development of robust, scalable light sources.

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