EXPANDING HORIZONS

WHAT ARE THE ASTRONOMICAL CHALLENGES OF THE 2040S

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Future perspective for studies of exo-planet formation

Stefano Facchini
University of Milan

Planet formation science has undergone a revolution in the past decade. Millimeter surveys of protoplanetary and debris disks now trace the evolution of planet-forming material across nearby star-forming regions, while high-angular-resolution observations reveal disk substructures and planet–disk interactions beyond 30 au. At optical and infrared wavelengths, high-contrast imaging has delivered the first detections of embedded protoplanets, with spectroscopy probing gas composition and stellar accretion at sub-au scales. Yet we remain far from accessing the formation pathways of Solar System analogues and the bulk of known exoplanets, particularly terrestrial planets, due to fundamental limits in sensitivity and angular resolution — even for ALMA.

Progress now hinges on imaging and resolving the inner ($\lesssim$10 au) disk regions where most planets form, detecting the birth of Jupiter-Saturn analogues, linking disk chemistry to emerging planetary compositions, and capturing the late stages of terrestrial planet formation driven by giant impacts. These goals require simultaneous access to faint continuum emission, key molecular tracers such as water, and gas kinematics at Solar System scales. Such capabilities are enabled by a next-generation sub-mm interferometer, providing a unified and quantitative view of disk physics, chemistry, and planet formation across evolutionary stages.

In synergy with the ELT, which will transform direct imaging of protoplanets near the peak of giant planet occurrence, this facility will place these detections in their full disk context, enabling direct observational constraints on planet–disk co-evolution by linking forming planets to the gas and solid reservoirs that regulate their growth and migration. Together, they will deliver a coherent, multi-scale view of how planetary systems form and evolve across cosmic environments.

Exoplanet Horizons – Detecting and Characterising Exoplanets in the 2040s via Ground-based Facilities

Daniel Bayliss
University of Warwick

The discovery and characterisation of exoplanets has been a major aspect of modern observational astronomy over the past three decades. In this talk I will look at the current facilities that are spearheading this field, and discuss how this might evolve as we move towards the 2040s. I will focus on the interplay between ground-based and space-based facilities, addressing how this might impact the facilities and key enabling technologies required from ESO for the 2040s and beyond.

Tracing the evolution of prestellar cores with H2D+ and D2H+

Silvia Spezzano
Max Planck Institute for Extraterrestrial Physics

H2D+ and D2H+ play a key role in the chemical and dynamical evolution of dense cores. These ions are powerful tracers of the electron fraction, a critical parameter regulating the dynamics of magnetized clouds, and they strongly influence the deuteration and abundances of most molecular species in cold, dense environments. As part of our recent APEX survey (Caselli et al. 2025), we observed o-H2D+ and p-D2H+ towards the ones that showed the largest deuteration in N2H+: the prototypical prestellar core L1544, the bona fide prestellar core Oph178, and the very young (or very low luminosity) stellar object CrA151. In this talk, I will present the first results of this program, highlighting the diagnostic power of the o-H2D+ and p-D2H+ transitions at 372 and 692 GHz, respectively, to probe the physical and dynamical evolution of dense cores. I will show how these lines constrain key parameters such as the ionization fraction and evolutionary stage. Finally, I will discuss the current observational limitations and outline how next-generation submillimeter facilities, such as AtLAST, will enable a transformative view of the coupled dynamical and chemical evolution of prestellar cores.

A Wide-field spectroscopic telescope for understanding the formation of stars in the Milky Way

Germano Sacco
INAF-Osservatorio Astrofisico di Arcetri

Understanding the physical processes regulating the formation of stars at different spatial scales is fundamental to answer some of the main open questions in contemporary astronomy, ranging from the formation of the solar systems to the evolution of Galaxies. Recent studies based on Gaia data and ground-based spectroscopic surveys have unveiled previously unknown young stellar populations spread out across the whole Galactic disc, which in some cases form kpc scale structures of unknown origin. The dynamical evolution of these structures is likely connected with the chemo-dynamical properties of the Galaxy and its satellites and may influence physical processes that lead to the formation and dissolution of young star clusters at smaller scales.

The Vera Rubin Observatory Legacy Survey of Space and Time will allow us to identify millions of young stars across the Milky Way. However, a spectroscopic follow up is fundamental to determine parameters like radial velocities, ages, chemical abundances. In this talk we will discuss how a Wide-field spectroscopic telescope with a large collecting area (10-12 m diameter) is the ideal instrument to follow up the sample of candidate young stars identified by Rubin-LSST with the aim of drawing a complete picture of the star formation process across the Milky Way.

Mass Assembly and Chemical Complexity in the Milky Way

Pamela Klaassen
UK Astronomy Technology Centre

Understanding how the Milky Way assembles mass and builds chemical complexity requires linking physical processes across the full hierarchy of Galactic structure, from diffuse gas to dense star forming regions. Here, we argue that major progress now depends on enhanced sub millimetre capabilities. Sub-mm spectral lines provide comprehensive diagnostics of the interstellar medium: beyond chemical inventories, they reveal the physical conditions, kinematics, ionisation state, and magnetic fields that shape our Galaxy.

Spectrally resolved molecular and atomic lines trace mass assembly and structure formation across scales, charting matter flow through the Galactic ecosystem and how local astrochemical processes connect to the Milky Way's global evolution. This demands wide spectral coverage, high fidelity mapping, and the sensitivity to follow material from large scale flows into the filamentary networks and dense cores where enrichment peaks and stars form.

Expanding ESO's sub mm horizons is therefore essential for a coherent, multi phase view of Galactic mass flow and evolution. Facilities with high survey speeds, broad bandwidths, improved angular resolution, and significantly lower confusion limits will unlock transformative legacy surveys and empower communities working across star formation, astrochemistry, and the ISM in our Galaxy while linking to those nearby. This talk will outline the scientific foundations and strategic motivation for enabling Europe to lead in uncovering how mass and chemical complexity accumulate in the Milky Way.

Future perspective for studies of supernovae and other explosive events

Andrew Levan
Radboud University

A century ago, only a handful of stellar deaths had been observed as supernovae across human history. Today, we are poised to identify a million a year, amongst these stellar deaths are huge numbers of relatively ”common” explosions, such as the core collapse of moderately massive stars or the explosive ends of white dwarfs, as well as much smaller, but still significant, numbers of much rarer but exceptionally valuable explosions — these may include long sought after events that have only never been observed, or have been seen in only small number, including explosion of first generation stars as pair instability supernovae, or the mergers of compact objects in sources which drive gravitational wave detection. In this talk, I will explore questions for the future that can be addressed by both large populations of common events and an in-depth study of rare ones. I will highlight how these observations can be used both to understand the explosions themselves and to address their critical role as probes of key questions in contemporary astrophysics and cosmology more broadly. I will particularly try to identify questions that are likely to remain outstanding beyond the next decade.

From Explosions to Jets: The Transient Millimeter Universe in the 2040s

Karri Koljonen
Norwegian University for Science and Technology

The 2040s will be a golden era for time-domain and multi-messenger astrophysics, but many decisive phases of transient evolution are best seen at millimeter/sub-millimeter (mm/sub-mm) wavelengths, where suitably capable instruments are still lacking. mm/sub-mm uniquely probes early shock and jet emission, penetrate dust-enshrouded environments and reveal magnetic-field geometry providing key information on the physical properties of the sources.

In this talk, I will describe how planned facilities such as the next-generation interferometer ALMA2040 and the wide-field single-dish telescope AtLAST could fill this gap. Wide-field monitoring and rapid tiling of large localization regions from gravitational-wave and neutrino alerts enable efficient counterpart identification. Rapid-response, broadband, full-Stokes interferometric follow-up with large sensitivity gains, simultaneous multi-frequency coverage, long baselines and VLBI compatibility can convert those detections into quantitative constraints on energetics, environments and magnetic structure.

These capabilities will reshape studies of interaction-powered supernovae, novae and stellar mergers, and of engine-driven explosions such as GRBs, fast blue optical transients and tidal disruption events. They will also enable sharper view to jets from X-ray binaries and AGN, and fast coherent transients such as magnetars, pulsars and repeating FRBs. Next-generation mm facilities will make mm/sub-mm time-domain observations a core part of multi-messenger discovery and interpretation in the 2040s, and will deliver legacy datasets that map the transient millimetre sky for decades.

Uncovering the population of compact binary mergers and their formation pathways with gravitational waves through the Einstein Telescope

Irina Dvorkin
Institut d'Astrophysique de Paris

Ground-based gravitational-wave (GW) observatories have transformed our view of compact-object mergers, yet their reach still limits a comprehensive reconstruction of the processes that generate these systems. Only next-generation observatories, with order-of-magnitude improvements in sensitivity and access to lower frequencies, will be capable of radically extending this detection horizon. GW observations will make it possible to detect the complete population of binary black hole (BBH) across cosmic time and enable precise reconstruction of their mass and spin distributions, while for several thousand events the signal-to-noise ratio will surpass 100, enabling precision physics of BHs and neutron stars (NSs). The access to lower frequencies will also open the intermediate-mass window, detecting systems potentially in coordination with multi-band observations from LISA. At higher redshifts, where Population III stars have so far remained beyond reach–even for the James Webb Space Telescope–GW observations by next-generation detectors will routinely provide observations of BH mergers thought to originate from these primordial stellar populations. Such measurements are expected to play a central role in clarifying the early assembly of supermassive black holes. Ultimately, the GW observations will become revolutionary for identifying the physical channels responsible for compact binary formation.

The Time Domain Telescope

Paul Groot
Radboud University

The Time Domain Telescope enables time-critical optical-infrared spectroscopy in an array of ∼100, individually steerable, AO-corrected telescopes of (∼)2 meter diameter. Optical AO at resolutions of ∼0.1" will dilute the sky to ∼26th magnitude. Coupled with read-noise-free detectors per-unit performance will be at $g > 23$, and full-array performance beyond $g > 25.5$. TDT science focuses on 4 areas: "What is the origin of the elements?", "How does accretion power the Universe", "Is the expansion of the Universe isotropic?"; "How does exoplanet and host star variability impact habitability?". In common is the need for time-critical spectra: to catch transients when bright; repeated exoplanets transit spectroscopy; to observe variable stars and binaries during flares or eclipses. The TDT will be proposal-based like current ESO facilities. To make the TDT operationally feasible, and to achieve minute-scale flexibility and turn-around times, the TDT will be fully autonomous, making use of AI Agents. The TDT is complementary to the VLT, ELT and ALMA, and addresses the science needs for time-resolved spectroscopy created by the VRO, Euclid and Roman datasets and concurrent facilities such as LISA, ET and Athena. In partnerships the TDT should expand into a global array. To realise the TDT, key technology developments are needed in robotic optical AO, read-noise-free detectors, (photonic) spectroscopy and the use of AI-enabled agents in operations and scheduling.

Mezzocielo Telescope: Catching the Earliest Phases of Multimessenger Transients

Nancy Elias-Rosa
INAF – Astronomical Observatory of Padua

The study of transient phenomena in a multimessenger context will remain a major area of astrophysics. Events such as supernovae, kilonovae, black hole formation and GRBs link electromagnetic emission to gravitational waves, neutrinos and high-energy radiation in their earliest phases. However, the physics linking these messengers operates on timescales of minutes to hours, while most surveys revisit the same sky region every few days, missing the onset of these events.

Current facilities are highly effective at determining what happened and how often, but are less sensitive to how these events begin and connect across messengers. Mezzocielo-like wide-field monitoring with continuous, minute-cadence coverage of large sky areas offers a way forward, allowing direct detection of the earliest phases. We need to move from follow-up observations to discovery at the time of the event, complementing and in some cases replacing the traditional strategy in which gravitational-wave or neutrino alerts trigger electromagnetic observations.

Meeting this challenge in the 2040s will require facilities combining wide sky coverage, minute-scale cadence, and real-time processing. In the Einstein Telescope era, such capabilities will allow identification of electromagnetic counterparts and enable targeted searches for otherwise undetectable signals. This requires tight integration between observational and computational infrastructures, including low-latency pipelines and multimessenger correlation.

Future perspective for studies of exo-planet atmospheres

Jayne Birkby
University of Oxford

Over the last two decades, exoplanet characterisation has advanced from mere detection of atmospheres to quantifying their detailed composition and 3D atmospheric dynamics, from global winds and jets to the magnetic fields they induce and mapping the distribution of storms passing across them. However, so far this is largely in the giant exoplanet planet domain, for much hotter and stranger systems than Solar system analogues. As we enter the era of the ELT in the 2030s, the smaller, cooler planets, and true Jupiters become accessible, opening a whole new regime of planetary information. Exoplanet characterisation has advanced thanks to innovative and novel instrumentation and observational strategies, using time-, spectral-, and spatial-resolution to reveal worlds from a single pixel. In this talk I will highlight a few of the most recent and astounding discoveries in exoplanet atmospheres from cutting edge instrumentation and methods, before turning to near term future perspectives on studying rocky exoplanets with the ELT in synergy with space-based missions, and what we will still need beyond the 2030s to truly understand the incredible diversity of rocky exoplanet atmospheres and their potential habitability.

Optical Interferometry for Exoplanet Science in the 2040s: Toward an Upgraded VLTI

Sylvestre Lacour
Paris Observatory

Direct detection of exoplanets will be a key technique to address the major questions of exoplanet science: how they form, how they evolve, and what their physical and chemical properties are. Optical interferometry has recently demonstrated its unique potential in this domain, enabling high-angular-resolution, high-contrast detections, spectroscopic characterization, and precise orbital monitoring. Upgrading the Very Large Telescope Interferometer with additional telescopes, longer baselines, and improved sensitivity would open a new parameter space for exoplanet studies. Such a facility could enable imaging of exoplanet atmospheres and surfaces, characterization of accretion processes, and the detection of mature planets through reflected light. In the 2040s, optical interferometry could thus become a cornerstone of exoplanet science, providing capabilities complementary to extremely large telescopes and future space missions.

How do the first galaxies assemble? Revealing the cold Universe at cosmic dawn with a next-generation sub-millimeter array

Tom Bakx
Chalmers

JWST has transformed our view of the early Universe, uncovering thousands of star-forming galaxies within the first billion years of cosmic history, yet we remain largely ignorant of the cold interstellar medium, dust reservoirs, and obscured star formation that together drive galaxy assembly at the highest redshifts. A next-generation submillimeter interferometer will be essential to close this gap. A five-fold increase in collecting area beyond ALMA, combined with extended baselines delivering ELT-like angular resolution, would constitute the single most transformational leap in early galaxy science in the 2040s. Such a facility would detect [C II] and [O III] emission from thousands of galaxies at $z > 10$, i.e., 480 Myr after the Big Bang, where only several tens of galaxies have been spectroscopically confirmed with the JWST due to its fundamental instrumental limitations. With our current redshift horizon at $z = 14.4$, a future submillimeter interferometer would be able to push our spectroscopic redshift frontier to beyond $z > 20$, just 180 Myr after the Big Bang. This future array would also enable spatially-resolved spectroscopy of the multiphase ISM at cosmic dawn, and reveal the obscured star formation across 99% of cosmic history. Together with ELT, SKA, and ngVLA, a next-generation submillimeter array would complete the multiwavelength picture that JWST has so tantalizingly begun, transforming our view on the earliest formation of galaxies, and delivering a comprehensive picture of the cold Universe in full.

Outlook for gravitational wave astronomy towards the 2040s

Valeriya Korol
SRON Space Research Organisation Netherlands

Gravitational-wave astronomy will undergo a transformation in the 2030s as space-based observatories open access to the millihertz frequency regime. The European Space Agency's flagship Laser Interferometer Space Antenna (LISA), planned for launch in 2035, together with a growing landscape of mission concepts beyond 2040, will enable studies of astrophysical and cosmological phenomena that are not directly accessible by electromagnetic means.

In this talk, I will outline multi-messenger opportunities with the LISA mission. I will show that LISA sources are long-lived, allowing electromagnetic observatories to monitor them as their signals strengthen and their properties are determined with increasing precision. I will discuss two key cases identified for the ESO Expanding Horizons call. First, electromagnetic counterparts to massive black hole mergers (arXiv:2512.21359) will provide unique insight into their astrophysical environments and the behaviour of magnetised plasmas in dynamical strong-field spacetimes. Second, electromagnetic characterisation of millihertz gravitational-wave sources in the Milky Way (arXiv:2512.12075)–dominated by compact stellar-remnant binaries–will be crucial for interpreting their population properties, testing Type Ia supernova progenitor channels, and leveraging them as tracers of Galactic structure and evolution.

Multi-messenger science opportunities with third generation gravitational wave detectors

Susanna Vergani
CNRS - Paris Observatory

The next generation of gravitational wave detectors will search for sources across a volume ≫1000 times larger than possible today. They will discover millions of compact-object mergers, along with the first detections of gravitational waves from other sources, including nearby supernovae and rotating neutron stars. Multi-messenger signals will occur when gravitational waves arise in tandem with another messenger. Such observations offer spectacular new capabilities to answer many open questions on stellar and binary evolution, the formation and physics of compact objects, the chemical enrichment of galaxies, cosmological constants, and even have implications for where and when in the Universe complex life may be possible.

The critical path enhancing the returns of multi-messenger astronomy is to increase the number of detected gravitational-wave sources. To achieve this, third-generation detectors such as the Einstein Telescope should be the field's top instrumentation priority. ESO facilities can play a crucial role in multi-messenger observations, both in the precision localisation and identification of EM counterparts with VLT-like apertures, through to detailed follow-up of signals with the E-ELT.

A comprehensive ESO program focused on multi-messenger astronomy and spearheaded by a next generation gravitational wave detector could transform our understanding of astronomy, providing a direct link between GW detection and characterisation and rapid EM observations. It would enable a once-in-a-century revolution with comparable impact to the birth of multi-wavelength astronomy.

From detection to identification of electromagnetic counterparts: spectroscopy for gravitational-wave multi-messenger astronomy in the 2040s

Sofia Bisero
IRFU, CEA-Saclay

The discovery of GW170817 and its electromagnetic (EM) counterparts initiated gravitational wave (GW) multi-messenger (MM) astrophysics, with major implications across many fields, from r-process elements nucleosynthesis to cosmology. These joint GW-EM observations remain unique to date.

In the 2040s, third-generation (3G) GW observatories such as the Einstein Telescope will bring a quantum leap in GW detection rates, with the main bottleneck shifting from GW detection to EM counterpart identification. Wide-field photometric facilities, such as the Vera Rubin Observatory, will deliver unprecedented numbers of transient candidates within large GW localization regions, while EM counterparts will be faint and rapidly evolving, pushing current search strategies to their limits. Spectroscopy will be key, enabling robust classification, redshift determination, and insight into ejecta physics and composition. However, existing facilities lack the sensitivity, field of view, and multiplexing needed to efficiently identify counterparts in the 3G detectors era.

With large samples of GW-EM events, it will be possible to assess the role of compact object mergers in chemical enrichment, probe binary evolution, and provide independent measurements of the Hubble constant.

Using extensive simulations, I will illustrate how a next-generation wide-field spectroscopic facility can address the challenges ahead, enabling rapid identification and deeper follow-up with facilities such as the ELT. Furthermore, I will highlight multi-messenger synergies with next-generation high-energy neutrino telescopes.

Einstein Telescope and Fundamental Physics

Costantino Pacilio
INFN Roma 1, Sapienza University of Rome

Under ordinary conditions, gravity is the weakest fundamental interaction and, in many ways, remains the least settled. It shapes everything from falling objects to galaxies, yet it also sits at the boundary of our current knowledge: it features singularities, and still resists a complete reconciliation with quantum physics. Einstein's general relativity has passed all tests so far, but for decades these have probed weak, slowly varying fields. Gravitational-wave astronomy has changed the terms of the debate. For the first time, we can listen to spacetime itself as it is driven into its most extreme dynamics: black holes and neutron stars merging and producing detectable signals. Current detectors like LIGO, Virgo, and KAGRA have already observed and used such signals to test gravity at the extreme, but are limited by sensitivity and by the relatively modest signal-to-noise ratios of many events. Next-generation observatories, such as the Einstein Telescope, aim to improve sensitivity by an order of magnitude and extend observations to lower frequencies, down to 2 Hz. This will transform rare detections into precise measurements and turn the Universe into a high-precision laboratory, enabling unprecedented tests of gravity, the nature of spacetime, and strongly-interacting matter in regimes no other experiment has ever achieved before. Any persistent inconsistency would point either to new fundamental interactions or to entirely new classes of compact objects.

Probing the fast optical/IR sky: from millisecond pulsars to sub-millisecond transients

Arianna Miraval Zanon
Italian Space Agency

Sub-millisecond time resolution is essential for unveiling relativistic compact objects and explosive phenomena like Fast Radio Burst (FRBs). While high-cadence observations are standard in radio and high-energy astronomy, progress in the visible band has been slower. However, fast photometers like SiFAP2 are now probing the optical sky at sub-ms scales with impactful results.

The recent detection of unexpectedly bright optical pulsations from 3 millisecond pulsars (MSPs) has opened a new window into relativistic particle acceleration and its interaction with accretion disks and intrabinary winds. These discoveries revealed diverse emission mechanisms, with optical efficiencies significantly exceeding predictions from rotation-powered models. Key questions remain regarding the universality of MSP optical pulsations and the processes driving fast variability challenges that require high-time-resolution optical/IR observations.

In this talk, we discuss the potential of future facilities for a systematic exploration of the fast-varying

sky. We present a pipeline to identify and characterize transients on sub-ms timescales. This tool has already uncovered a large population of fast optical events, demonstrating its versatility in searching for counterparts of FRBs and magnetar bursts, as well as tracking satellites and space debris. A major future challenge will be discerning astrophysical transients from anthropogenic objects, a crucial step for next-generation time-domain surveys.

Overview of the Wide Field Spectroscopic Telescope

Roland Bacon
CRAL

The WST project aims to design and construct an innovative 12-metre wide-field spectroscopic survey telescope (WST) in the southern hemisphere. It will feature the parallel operation of two cutting-edge instruments: a high-multiplex (30,000), large field-of-view (3 square degrees) multi-object spectrograph (MOS), operating in both low- and high-resolution modes, and a giant panoramic integral field spectrograph (IFS). WST's ambitious top-level requirements place it well ahead of all existing and planned spectroscopic facilities, enabling transformative science across a wide range of astrophysical domains.

In this talk, I will present an overview of the facility as a reference framework for the scientifically focused contributions proposed in this workshop.

Unlocking the Dynamic Universe: The Case for a Spectroscopic Time-Domain Machine

Paula Sanchez Saez
ESO

The dynamic universe is one of the defining scientific frontiers of the coming decades, yet our ability to fully explore it is fundamentally constrained by a spectroscopic bottleneck that will only deepen in the 2040s. Photometric surveys such as LSST and Gaia, and multi-messenger observatories including gravitational-wave detectors, will deliver unprecedented volumes of transient discoveries, but they can only tell part of the story. Photometric classification remains ambiguous, gravitational-wave localizations are coarse, and neither can unlock the physical information encoded in spectra. Answering the key scientific questions of the 2040s, spanning Solar System bodies, stellar formation and evolution, variable and transient events, black hole demographics from stellar-mass to supermassive, AGN activity across cosmic time, and the electromagnetic characterization of gravitational-wave sources, demands a massively multiplexed wide-field spectroscopic facility designed with time-domain operations at its heart. A critical component of such a facility must be a spectroscopic alert system: one capable of ingesting photometric and multi-messenger alert streams, autonomously classifying and prioritizing targets, triggering alerts when spectroscopic variations are detected, and delivering science-ready spectra in near real time. Far from being simply a more efficient follow-up machine, a facility equipped with such capabilities opens an entirely new observational window. The ability to obtain spectra of large numbers of variable and transient events immediately and without prior photometric selection breaks the classification bias inherent to all current approaches, creating the conditions for discovering entirely new classes of phenomena.

Serendipity, in this regime, becomes systematic. In this talk, I will present the science cases that define the requirements for such a facility, and argue that the development of spectroscopic alert capabilities must be a central technological priority for transformational ground-based astronomy in the 2040s.

Embedding sustainability in the next ground-based facility

Laurane Fréour
University of Vienna

The environmental impact of ground-based observatories is a consequent challenge for current and future facilities. To minimise this impact, measures should be taken as early as the design phase of research infrastructures. How best to address and mitigate this impact can only be tackled efficiently by the astronomical community as a whole. The Expanding Horizon workshop, therefore, represents a unique opportunity to discuss this challenge.

A significant portion of this footprint arises from how scientific activities are conducted, including travel to conferences, the use of energy-intensive supercomputers, and the construction and operation of increasingly complex telescopes that require substantial resources. In this talk, we aim to provide an overview of the carbon footprint associated with astronomical research, with a specific focus on research infrastructures. We will examine different types of environmental impacts, share examples, and explore solutions that ESO can use to help make the field and the next facility more sustainable.

Future perspective for studies of the gas content of galaxies

Leindert Boogaard
Leiden Observatory

The cold gas content of galaxies plays a fundamental role in the assembly of stars and growth black holes through cosmic time. The last decades have seen incredible progress in quantifying the gas content of galaxies; from identifying, resolving to physically and chemically characterizing the gas in galaxies in the local universe, out to the highest redshifts. In this talk, I will try to provide an overview of our current understanding of the gas content of galaxies through cosmic time, reflecting on some of the lessons learnt from assembling this picture, and provide future perspectives for breakthroughs in our understanding of the gas content of galaxies towards the 2040's.

Extended Molecular Gas in Protoclusters: A Science Case for AtLAST

Helmut Dannerbauer
Instituto de Astrofísica de Canarias

The Atacama Large Aperture Submillimeter Telescope (AtLAST) will open a new window on the cold molecular gas content of galaxies across cosmic time. With its wide-field mapping, high surface-brightness sensitivity, and ability to detect low-J CO emission, AtLAST will trace diffuse, extended molecular gas in dense environments at high redshift. This is key to understanding how environmental processes shape galaxy evolution and revealing the origin of the intracluster medium.

We demonstrate the feasibility of this approach using deep CO(1–0) observations with the Australian Telescope Compact Array (ATCA). In the Spiderweb protocluster ($z = 2.2$), we discovered massive ($>$40 kpc), extended molecular gas reservoirs in star-forming galaxies - unexpected given predictions of environmental suppression.

Within our ATCA Large Program COALAS, we obtained 475 hours of observations, identifying such reservoirs in a significant fraction of galaxies and assembling the largest sample to date. These reservoirs likely trace early stages of the proto-intracluster medium, indicating that dense environments at $z = 2$ host diffuse molecular gas.

Such detections remain observationally challenging. AtLAST will overcome these limitations through sensitive, large-area surveys, enabling statistical studies across environments. This will allow us to quantify how environment affects gas content, morphology, and star formation, and trace the emergence of the proto-intracluster medium in the early Universe.

Tracking the flow of interstellar gas across scales: from galaxies to star clusters

Ana Duarte Cabral
Cardiff University

Much of the evolution of galaxies across cosmic time is driven by star formation, and thus tightly coupled to the physics of the interstellar medium, which is continuously evolving between a diffuse ionized medium, a warm atomic phase, and a much colder and denser molecular phase, which gradually concentrates and fragments into star-forming cores. This cascade of energies and gas flows relies on the interplay of processes such as turbulence, gravity, feedback, and magnetic fields, all concurring within complex systems – their host galaxies. Still, unraveling the physical processes driving the evolution of the interstellar medium remains an unsolvable challenge with present-day observing facilities, which are unable to map entire galactic ecosystems down to the scales of individual star-forming clumps. Only a next generation millimetre/submillimetre interferometer, combining a true step-change in increased sensitivity, with exquisite resolution and image fidelity, would allow, for the first time, the mapping of entire (tens-of-kpc) galactic systems in the nearby Universe, resolved down to the small (pc) scale physics of star formation. This would finally enable tracking the flows of matter and energy across a vast range of interacting and evolving environments, a critical missing piece for addressing the long-standing question of what regulates star formation across cosmic time.

Imaging the Cosmic Web in Lyα emission: from MUSE to WST

Davide Tornotti
University of Milano-Bicocca

Within the current cosmological paradigm, matter on large scales is organized in a network of filaments connecting galaxies, known as the cosmic web. Far from being a passive backbone, these filaments provide the fuel necessary for galaxies to form stars and evolve. However, direct imaging of these filaments remained elusive until the advent of large-format integral field spectrographs such as the Multi Unit Spectroscopic Explorer (MUSE) at the Very Large Telescope.

In this talk, I will present recent breakthroughs in the direct detection of cosmic web filaments in Lyα emission, enabled by ultradeep ($>$140-hour) MUSE observations. I will introduce a unique sample of large-scale Lyα-emitting structures across diverse overdensities – including a bright quasar pair – at $2.8 < z < 5$, spanning scales from 3 cMpc to 5 cMpc. These observations enable the direct characterization of filament properties, including morphology, surface brightness profiles, and the transition between the circumgalactic and intergalactic media, while providing statistical constraints on the distribution of Lyα-emitting gas comparable to absorption studies.

Key open questions remain: are gaseous filaments distributed as predicted by cosmological models? How is gas accreted onto galaxies within these structures, and how does this depend on environment?

Looking toward the 2040s, I will discuss the transformative role of the Wide-Field Spectroscopic Telescope (WST) in addressing these questions. The next challenge is to move from individual detections to systematic three-dimensional mapping of the IGM over cosmological volumes. With its wide field of view, WST will shift the field beyond discovery mode, turning the cosmic web into a statistical laboratory to probe gas accretion and galaxy co-evolution.

Stellar atmospheres/abundances into the 2040s

Maria Bergemann
Max Planck Institute for Astronomy

Stellar physics at sub-nanoradian angular resolution

Prasenjit Saha
University of Zurich

Many stars — if they could be imaged with enough angular resolution — would exhibit features expected from theory but not possible to extract from spectra. We may group these by increasing complexity as follows. First, smooth variations in brightness across the surface, resembling solar limb darkening but much more prominent and involving more processes in stars with fast spin or external tides. Next, there are periodic features: not only oscillations, but also convective cells and starspots, which appear to transit across a star as its spins, and exoplanets that really do transit across the star. Then, there are transients like flares.

Current optical interferometers provide synthetic apertures of a few hundred metres and angular resolutions down to about nanoradian (about 0.2 milliarcsecond), enough to resolve some of the above features on the nearest upper main-sequence stars, giants and supergiants. Ongoing projects aims to km-scale synthetic apertures, enough to measure the radius of the nearest white dwarf. This presentation will discuss what could be observed with synthetic apertures over 20 km — resolving detail on white dwarfs at the level currently possible on supergiants.

Precision spectroscopy to uncover the origin of the elements

Rodolfo Smiljanic
Nicolaus Copernicus Astronomical Center

Our understanding of how most elements form has improved greatly in recent decades, but key questions remain. Here we focus on two issues that will remain open into the 2040s: (i) identifying all astrophysical sources of neutron-capture elements and (ii) quantifying the output of all subclasses of type Ia supernovae (SNIa). For the first topic, we know of one confirmed r-process source: neutron star mergers (NSMs). However, they are likely not the only Galactic r-process source. Large-scale chemical abundance studies of light and heavy r-process elements are needed to clarify r-process nucleosynthesis and its astrophysical origins. For the second topic, the main progenitor of SNIa is still unknown but will likely be identified by the 2040s. What will still be lacking are observational constraints to quantify the output and relative importance of each subtype in the galactic context. A fundamental breakthrough on these questions requires abundances measured to better than 0.05 dex, which is achievable only with high signal-to-noise ratio, high-resolution spectra (R $\sim$ 40 000). Disentangling the contribution of multiple nucleosynthesis sources requires a survey of a large number of stars, formed in a range of environments at distinct epochs. Current surveys miss crucial elements (e.g. Zn and Th) needed for these science cases, many of which are only found in blue wavelengths (380–390 nm). No precision spectroscopy survey with these characteristics is planned before the 2040s.

Milky Way Disc and Bulge in-situ populations with WST telescope

Maria Bergemann
Max Planck Institute for Astronomy

In this talk, I will present the WST Galactic Disc/Bulge program. The planned WST is unique among available facilities as a 10-m class telescope combining high spectral resolution with massive multiplexing capability. This program represents a major step for Galactic archaeology, enabling the first truly homogeneous Galaxy-scale view of stellar kinematics and chemical composition for tens of millions of

stars.

The survey will probe the Galactic disc, bulge, and bar with unprecedented precision and depth, significantly extending the accessible spatial volume - by more than 10 kpc compared to surveys such as 4MOST and WEAVE. It will enable us to study the key processes that shaped the Milky Way, its detailed chemical evolution (through measurements of over 30 chemical elements of all nucleosynthesis channels), earliest star formation, and secular evolution processes.

I will also highlight the strong synergies between the WST Disc/Bulge program and upcoming facilities such as PLATO and the ELT, but also proposed missions Gaia-NIR and HAYDN. WST will provide the essential spectroscopic follow-up required to fully exploit these missions scientifically. In addition, its synergy with extragalactic surveys will place the Milky Way in a cosmological context, linking resolved stellar populations in our Galaxy to high-redshift disc-like analogues observed with JWST and ALMA. With a potential near-infrared upgrade, WST will open a window into the most obscured regions of the inner Galaxy, offering new insights into the bar, bulge, and nuclear structures.

Taken together, this program will not only resolve long-standing questions about the formation of the Milky Way, but also establish it as the key reference for disc galaxy evolution studies in the coming decades.

Toward the time-domain spectroscopic study of the dynamic life of stars: from accretion to magnetic activity

Fatemeh Zahra Majidi
INAF-OACN

Young stellar objects (YSOs) are multi-component systems: a forming central object, a circumstellar disk mediating accretion, and supersonic bipolar jets interacting with the surrounding medium. Each component imprints diagnostic spectral signatures over a wide wavelength range, and the governing physical processes are strongly time-variable, from hour-day stochastic accretion to rotational modulation and magnetic variability on week-month scales, up to secular evolution over years. Progress therefore demands systematic spectroscopic monitoring that simultaneously captures both rapid variability and long-term evolution. A wide-field, high-multiplex ground-based spectroscopic facility such as WST uniquely enables this approach. Its ability to perform repeated observations over large sky areas with flexible cadence strategies provides the long-baseline time-domain coverage required to disentangle accretion, ejection, disk evolution, and stellar activity across entire star-forming populations.

I will summarize our contributions to the ESO's Expanding Horizons 2025 Call in the context of the science cases for WST, a concept facility for the 2040s. I address which fundamental questions and long-standing dilemmas in star formation can only be answered with WST, the star-forming regions we will observe, the observational strategies, and the approximate sample sizes required for statistically meaningful studies of variability and evolution in young stellar populations.

ALMA2040: Resolving the cold Universe in 2040s

Jacqueline Hodge
Leiden Observatory

In the last 15 years, the Atacama Large Millimeter/submillimeter Array (ALMA)—one of ESO's flagship facilities—has revolutionized astrophysics with its high-definition view of the cold Universe. However, looking ahead another 15 years to the 2040s, many of the most transformative questions will demand a step change in sensitivity and angular resolution at these critical wavelengths.

Key science drivers span galaxy and black hole growth from cosmic dawn ($z \sim 20$), the evolution of the cosmic baryon cycle, and the formation of planetary systems and complex chemistry. In parallel, the physics of the extreme Universe—including transients, gravitational-wave follow-up, and event horizon-scale black hole imaging—is a major frontier in the era of time-domain and multi-messenger astronomy.

To address these challenges, the community-led ALMA2040 initiative has developed a science-driven reference design for a next-generation interferometric facility that builds on ALMA's legacy while opening entirely new discovery space. ALMA2040 combines high-fidelity imaging across a vast range of spatial scales with transformative gains in sensitivity and operational flexibility, enabling a fundamental leap in our understanding of the cold Universe.

The science driving the specifications and capabilities of AtLAST

Stephen Molyneux
University of Oslo

In recent years the need for a large single dish (sub-)mm telescope has been debated within the community, in particular a facility that has the capability to operate at the full (sub-)mm frequency range (30–950 GHz). In doing so, such a facility will not only be complementary to current interferometers such as ALMA, but will also fill a vital gap in our observations. AtLAST will be one such facility and in this talk I will present the technical specifications for AtLAST and the science cases that have motivated these choices. Briefly, thanks to its large collecting area (50m diameter dish) AtLAST will greatly improve our ability to observe the diffuse, extended gas in ISM/IGM that is often missed by our current suite of facilities. AtLAST will also open the window to time domain science at (sub-)mm wavelength, which will be facilitated by the fast scanning speeds (on the order of 3 degrees per second). Finally, the 2 degree field of view will allow AtLAST to be an excellent survey telescope, as well as giving us the ability to capture large areas of the sky in one shot. For example, AtLAST could observe the entire surface of the Sun at once, significantly improving our understanding of solar phenomena and their consequences for global communication systems and power grids on Earth. With these capabilities AtLAST will be able to drive forwards several scientific fields making it an invaluable facility for decades to come.

The ALMA view of the feeding/feedback cycle of the gas in nearby AGN

Santiago Garcia-Burillo
Observatorio de Madrid (OAN-IGN)

High-resolution images of the distribution and kinematics of molecular gas in the circumnuclear disks of nearby active galactic nuclei (AGN) are essential for understanding the mechanisms that control the feeding and feedback cycles of gas in active galaxies. AGN appears to be a phase in a galaxy's lifecycle. Our understanding of the obscuring medium that affects the observed properties of AGNs has also evolved, and we now have a physical grasp of the connection between fuelling and feedback from AGN central engines. Using high-resolution ALMA images from an expanding sample of nearby AGN, we have revealed the 'relic' imprint left by AGN feedback on the nuclear-scale distribution of molecular gas. In this talk we also present new results from high-spatial-resolution observations of six nearby Seyfert galaxies from the GATOS sample, obtained by ALMA in Bands 7 and 8. These observations have enabled us to spatially resolve the tori in our targets down to $r = 1.5$ pc for the first time, allowing us to study detailed changes in their internal properties. Our findings indicate that AGN feedback can leave a distinct imprint on the internal properties of the molecular gas and dust in the tori of our targets, reflecting the different evolutionary stages of the interstellar medium (ISM) around their central engines. Future ALMA2040 developments will allow us to fully resolve the tori and their surrounding nuclear regions in much larger AGN samples, including QSOs.

ALMA2040: Concept and Enabling Technologies for a Next-Generation Interferometer

Gie Han Tan
Eindhoven University of Technology

The ALMA2040 initiative is developing a science-driven concept for a next-generation millimeter/submillimeter interferometric facility designed to deliver a step change in sensitivity and angular resolution—capabilities not achievable with current or planned facilities. Cost, operational efficiency, and sustainability are treated as core design requirements from the outset.

These advances are enabled by a combination of increased collecting area and major developments in receiver technology, including multi-band operation, substantially broader instantaneous bandwidth, and improved receiver noise temperature. This will allow full receiver bands to be observed simultaneously, enabling highly efficient spectral surveys and transformative gains in line sensitivity and observing efficiency beyond the ALMA Wideband Sensitivity Upgrade.

While many of the required technologies already exist, their implementation at the necessary scale remains cost-prohibitive. The ALMA2040 concept therefore builds on a set of emerging technologies—expected to mature over the next decade—that will enable a technically feasible and financially viable facility.

The development of this concept brings together expertise across instrumentation, engineering, and operations within the ALMA2040 technical working groups, ensuring a coherent and realistic path toward a next-generation facility.

Instrumentation for the Atacama Large Aperture Submillimeter Telescope (AtLAST)

Eelco van Kampen
ESO

We review the various classes of instrumentation that will help achieve the science goals and sensitivity requirements of the Atacama Large Aperture Submm Telescope (AtLAST). We consider technologies pertinent to the front end receivers, cameras, and direction spectrometers, and we outline the back end spectrometers and readouts that couple to these front ends. We attempt to extrapolate today's technologies to AtLAST's first and second generation instrumentation, including capabilities, power demands, and cooling requirements. We discuss key areas of technological development necessary to achieve the technology readiness level required. Many of the groups leading such developments are working in ESO member states, so the present AtLAST consortium efforts to build large-scale instrumentation for AtLAST would fit perfectly within the way ESO conducts its instrumentation projects in partnership with its member states.

Unveiling the Cosmic Dust Cycle: Astronomical Challenges and Future Perspectives

Ciska Kemper
ICE-CSIC / ICREA / IEEC

The cosmic life cycle of dust describes the formation of dust in stellar winds and supernova ejecta, its processing in the interstellar medium (ISM) and the role it plays in the process of star formation. Understanding the physical mechanisms and chemical pathways governing dust formation and processing is essential for both galaxy evolution across cosmic time and the local building blocks of planetary systems. ESO's Expanding Horizons Programme presents a unique opportunity to address these fundamental topics.

I will explore the future perspectives of dust physics across the breadth of concepts emerging from the community. Next-generation submillimeter interferometric upgrades promise unprecedented spectral-line sensitivity to trace faint molecular reservoirs harboring the species out of which dust forms, while facilities accessing the near-infrared will probe dust formation and processing in circumstellar environments.

I will balance these concepts against a highly compelling alternative: a next-generation, large-aperture single-dish submillimeter facility. Equipped with wide field-of-view and high resolution spectrometers, such a facility would address an obvious knowledge gap by rapidly mapping cold ISM chemistry over entire galaxies, cosmological deep fields and the Galactic Plane, allowing us to obtain a global view of the formation, composition and evolution of dust in galaxies across cosmic time, and the role it plays in galaxy evolution.

Resolving the Cosmic Infrared Background: Tracing Star Formation from the Dawn of Galaxies to Today

Benjamin Magnelli
CEA Paris-Saclay

Dust absorbs the UV/optical light emitted by young stars and re-emits it in the far-infrared (FIR) and submillimeter (submm), producing the cosmic infrared background (CIB), which contains about half of the total energy released by galaxies across cosmic history. Resolving the CIB into individual galaxies is therefore essential. Yet, at $>$250 µm, only $\sim$20-40% of the CIB has been resolved into individual galaxies, due to the confusion limit of Herschel's 3.5-m mirror and the strong cosmic variance affecting ALMA's pencil-beam surveys. This lack of information is critical, as the CIB at these wavelengths (350 µm – 2 mm) is dominated by high-redshift galaxies. Deep, wide-area continuum and spectroscopic surveys are required to obtain an unbiased census of star-forming galaxies in the early Universe, their connection to the cosmic web, and the properties of their gas and dust. Such surveys are inaccessible to current or planned facilities and require a 50-m-class single-dish submm (350 µm – 2 mm) telescope with large multiplexing capability. In this talk, I will explore how the observing capabilities of such 50-m-class sub telescope will enable the pursuit of these major scientific goals. I'll start by estimating how the photometric and source criterion confusion limits will constrain such telescope in its various bands, and compare them to the most modern current facilities. Next, I'll examine how various realistic survey designs will compare to these confusion limits, what fraction of the cosmic infrared background they will resolve, and how these various surveys will compare to the constraints obtainable by current or future far-infrared facilities. Finally, I'll conclude by explaining how such optimized large-area ($>$1 deg^2) spectroscopic and continuum surveys will transform our view of galaxy evolution, and particularly the role of environment (voids, filaments, groups, clusters) while providing key synergies with current or forthcoming optical, near-infrared, and radio surveys (e.g., Euclid, LSST, Roman, SKA). Together, these efforts will usher in the era of deep and large extragalactic surveys.

Archaeological investigation of galaxies' evolutionary history in the cosmic middle ages

Laura Scholz-Diaz
INAF - O. A. Arcetri

The last 10 billion years of cosmic history mark a pivotal transition: star formation declines pervasively, passive systems come to dominate, and the cosmic web reaches maturity. Disentangling internal and external drivers of galaxies' transformations during this cosmic "middle ages" (0.3 $< z <$ 1.5) requires a wealth of physical properties for large, representative galaxy samples.

Stellar populations at these intermediate redshifts offer a unique window into this history, from both a look-back time and an archaeological perspective. Their chemical composition, age, and kinematics encode integrated star-formation and assembly histories. Their scaling relations and scatter with mass, SFR, structure and environment constrain star formation and quenching paths across cosmic time. Their gradients and spatial variations reveal the role of local and global physical drivers and the imprint of assembly processes. This information is only accessible through deep, high-S/N rest-frame optical MOS+IFU spectroscopy.

Only by tracing the volume-weighted distribution of galaxies across mass, redshift and environment can we make a statistical yet physical connection between progenitors and descendants. This demands surveys of unprecedented scale not in reach in the 2030s landscape: large statistics ($\sim 10^6$ galaxies) of volume-representative samples complete to 10^9 $M_\odot$, with uniform redshift coverage, accurate integrated and spatially resolved physical parameters, and dense spatial sampling across diverse environments. Such a survey requires a dedicated large-collecting-area facility with wide-area high-multiplex MOS and large-FoV IFU, and would establish a transformative legacy for our understanding of galaxy evolution.

Mapping Galactic Ecosystems: from the ISM to the IGM

Francesco Belfiore
ESO Garching

Galaxies are highly dynamic ecosystems, whose evolution is driven by interconnected cycles of matter and energy. On the scale of megaparsecs this 'large scale' cycle of baryons links galaxies to the circum- and intergalactic medium via gas inflows and feedback-driven outflows. On small scales, within galactic discs, stellar feedback drives the cycling of matter between the different phases of the interstellar medium (ISM), induces gas flows and turbulence, and determines the physical conditions for future star formation. A key challenge in understanding how galaxies evolve is to connect the small-scale physics of the matter and energy cycle to its large-scale impact on the properties of galaxies.

In the 2040s, wide-area imaging from LSST, Roman and Euclid, coupled with the extensive view of the radio sky provided by SKA, will provide information for millions of galaxies. However, a full accounting of the baryon cycle requires mapping of the tenuous gas component between galaxies, in the circum- and intergalactic medium (CGM & IGM). In this talk I will argue that meeting this goal requires a large-aperture, highly multiplexed spectroscopic facility equipped with a panoramic IFU. Such a facility would uniquely probe the matter cycle across scales (from the ISM to the CGM) and allow to draw a direct connection between galaxies and their environment across a wide range of redshifts, from the local Universe to the Epoch of Reionization.

Future perspective for studies of galaxies as stochastic systems

Sandro Tacchella
University of Cambridge

Galaxy evolution is an inverse statistical problem: each galaxy is observed only once, yet its present state encodes a history of gas accretion, star formation, feedback, enrichment, quenching, and black-hole growth. I will argue that the next step is to move beyond mean scaling relations and treat galaxies as stochastic physical systems, whose amplitudes, duty cycles, memory, and correlation timescales encode the physics of baryon cycling. By the late 2030s, JWST, Euclid, Roman, Rubin, DESI, 4MOST, and MOONS will have transformed the field, but will also expose its next limitation: our ability to infer the underlying histories, transition rates, and physical couplings of galaxies across mass, environment, and cosmic time. I will outline where progress may become limited without significant new facilities or major new instrument concepts, and why turning galaxy evolution into a predictive theory will require deep, wide, homogeneous spectroscopy, moving from millions to tens or hundreds of millions of rest-UV/optical spectra.

Future perspectives for cosmology

Ofer Lahav
University College London

After more than a quarter of a century as the standard model of cosmology, the Λ Cold Dark Matter (ΛCDM) paradigm is facing increasingly stringent tests from a combination of observational probes, including galaxy clustering, weak gravitational lensing, Type Ia supernovae, and the cosmic microwave background. Other major ”known unknowns” in cosmology include the sum of neutrino masses, the physics of inflation, and the possible presence of primordial non-Gaussianity.

In this talk, I will discuss what we have learned so far from the Dark Energy Survey (DES) and the Dark Energy Spectroscopic Instrument (DESI) regarding the relative merits of the ΛCDM model and dynamical dark energy alternatives. I will then review the prospects for the current generation of Stage-IV facilities—including Euclid, the Vera C. Rubin Observatory LSST, and the Nancy Grace Roman Space Telescope—and discuss how future Stage-V projects such as WST, Spec-S5, and MUST could address some of the most fundamental questions in cosmology over the coming decades.

A high-dynamic-range view of the growth of structure and the warm/hot Universe

Luca Di Mascolo
Kapteyn Astronomical Institute

As baryons accrete onto massive overdensities — galaxies, groups, clusters, and filaments — they are heated to temperatures exceeding 10^5 K, becoming ionized and optically transparent. Deep millimeter-wave observations with facilities such as ALMA have begun to probe a small number of massive systems at redshifts $z \sim$ 2-4, while wide-field mm-wave surveys have detected thousands of objects at arcminute resolution out to $z \sim 2$. However, charting the evolution of large-scale structure by mapping the warm-hot ionized gas distribution out to the epoch of its formation demands a transformative leap in observational capability. In this talk, I will present the case for the Atacama Large Aperture Submillimeter Telescope (AtLAST), a large-aperture single-dish (sub-)millimeter telescope capable of delivering several orders of magnitude improvement in mapping speed over current facilities, while maintaining the few-arcsecond angular resolution necessary to image the gas and disentangle contaminating radio and thermal dust emission across the full (sub-)mm wavelength range. I will also discuss the key scientific drivers and technical requirements for such an instrument.

SHARP: Beyond JWST - Revealing the birth and growth of galaxies with the resolution of the ELT

Paolo Saracco
INAF - Osservatorio Astronomico di Brera

Understanding the life-cycle of massive galaxies requires deciphering the mechanisms regulating star formation (SF) and its abrupt shutdown (quenching). Key unsolved issues include what triggers and sustains quenching despite large gas reservoirs, and how galaxies interact with the surrounding Circumgalactic and Intergalactic Medium (CGM/IGM). Addressing these questions requires resolving physical scales comparable to giant molecular clouds (GMCs). These are the primary drivers of star formation and chemical enrichment, the fundamental building blocks of galaxies, and the scales at which quenching mechanisms must operate.

To study these processes homogeneously up to high redshift, we must move beyond current observational limits. SHARP is a concept study for a near-IR (0.95–2.45 μm) spectrograph designed to fully exploit the MCAO-assisted ELT. Featuring multi-object slit and multi-IFU spectroscopy, SHARP will achieve angular resolutions of ∼30 mas, three times better than NIRSpec@JWST (∼100 mas). This sharpness will allow us to directly resolve these sub-galactic units, ultimately reconstructing the complete life-cycle of early galaxies. This presentation will provide a brief overview of the science behind SHARP and of its main characteristics.

Emerging technologies for future astronomical detectors

Naidu Bezawada
European Southern Observatory

The ESO detector group has been working with the state-of-the-art optical and infrared detectors for the current and planned instruments for both VLT and ELT as well as evaluating the new detector technologies for future instruments. We have been characterising very large format NIR and SWIR detectors for the ELT instruments and preparing to evaluate the performance of emerging large format e-APD detectors to see if they are a real competitor to the ubiquitous H2RG / H4RG devices. We are also evaluating the potential and working with manufacturers for curving large format visible CMOS detectors for future instruments. We will present some of the performance results of the above detectors from our detector characterisation program and provide an overview of the emerging technologies for future astronomical detectors.

Curved sensors for the future of astronomical instrumentation

Emmanuel Hugot
Laboratoire d'Astrophysique de Marseille

The emergence of curved CMOS detectors certainly represents the major disruptive technology for imaging systems that will come up in a near future. Such a breakthrough device has a very high potential impact for astronomy. The curvature of focal plane arrays leads to a drastic simplification of the optical systems by directly correcting the field curvature in the focal plane of wide field instruments and telescopes. It results in an increase of transmitted flux and a reduction of the exposure time by a significant factor (a gain of 30% is demonstrated). Less optics means less misalignments and instrumental errors, obvious increase of the stability of instruments and PSF homogeneity (key point for applications such as astrometry or galaxy morphology study), less calibration time, less dependence to the environmental condition. In addition, the volume of the instruments shrinks by a third, positively impacting all these performance parameters and allowing a drastic reduction of the cost.

We will present the recent advances for the development of robust manufacturing process through two programs funded by the European Space Agency, and the development of the CASTLE observatory using a large CMOS sensor. We will discuss the challenges posed by ESO for the development of large format curved CMOS sensors in the perspective of WST.

Key technology development for the Time Domain Telescope

Kieran O'Brien
Durham University

The Time-Domain Telescope is a planned spectroscopic facility consisting of a large number of medium size telescopes which can either operate as individual telescopes or be incoherently combined to a single large collecting area telescope. The current baseline is for 100 unit telescopes, each with a 2-m aperture, but this could be expandable and distributed across multiple sites. The baseline design would enable 100 individual objects to be monitored simultaneously anywhere in the sky, or focus the entire array onto a single object, recreating the collecting area a 20m aperture telescope. This is enabled by using noise-free and ideally photon-counting detectors. The photon events are collected at high spectral and temporal resolution and then rebinned and combined from multiple telescopes without penalty. The TDT would be the first software telescope in the optical/IR. Each unit telescope of the TDT will send light to an instrument cluster that will house the various spectroscopic instruments. In order to maximise the sensitivity for faint sources, the TDT will use laser guide star adaptive optics in the visible and IR to increase the encircled energy for the fiber-fed instruments. The science cases for the TDT will be presented elsewhere. In this talk, I will focus on the concept and the key technological developments needed to make the TDT a reality.

Concept for a Kilometric Baseline Interferometer

Stefan Kraus
University of Exeter

We present the concept for a Kilometric Baseline Interferometer (KBI) designed to open new parameter space in High-Angular Resolution Astronomy in the 2040s. Building on the Paranal infrastructure and the VLTI as compact array, KBI will incorporate an extended array of 8m-class telescopes spread across baselines of at least 4 km, enabling microarcsecond-scale imaging/astrometry of targets ranging from nearby exoplanet systems to compact objects. In this contribution, we outline key design trade-offs around cost, sensitivity, and number of apertures, while highlighting ESO's unique potential for maintaining leadership in this science area in the second half of the 21st century.

Micro to nano arcsecond optical resolution for compact objects, accretion, ejections and explosions

Roland Walter
Department of Astronomy - University of Geneva

We witness the death of stars when they explode in nova, supernova, kilonova or gamma-ray bursts. Gravitational waves rings when matter flows through black-holes horizons. The imaging information, critically essential to improve or confirm our understandings, is however lacking. As a consequence we do not know precisely how rotating black-holes accrete and feed energy to the Universe, nor the physics of matter in extreme conditions. Extremely large telescopes, single photon detectors with picosecond resolution, long distance picosecond synchronisation and synchronous spectrometers bring the key improvements to increase the signal-to-noise of intensity interferometry by a factor of 106 (15 magnitudes) and achieve angular resolutions of micro to nano arcseconds (µas to nas) on faint optical sources, surpassing the capabilities of the Event Horizon Telescope at mm wavelength. These advancements allow to reach optical resolutions of 100 µas with baselines provided by VLT and VISTA today, 10 µas with baselines that will be provided tomorrow by the VLT-ELT system (mV$\sim$15 sensitivity). On the ESO2040 time frame an array of low cost telescopes surrounding the ELT will provide many simultaneous baselines and boost observation efficiency, without the need for variable delay lines. nas (1km on the closest exoplanet) will be obtained combining data from the ELT and other large telescopes spread over the globe.

Future perspectives on astronomical studies of the strong limit of the gravity

Frank Eisenhauer
Max Planck Institute for extraterrestrial Physics

Optical/IR interferometry has revolutionized astronomy at highest angular resolution, and made possible transformational observations of black holes, exoplanets, young stellar objects, stars and binaries, microlenses, and many more. No other technique comes even close to the sharpness of interferometry. Here we present the science perspective for optical interferometry with a kilometer wide array, which will then be even hundred to thousand times sharper than the largest single dish telescopes.

Strong gravitational lensing with a next-generation sub-millimetre/millimetre array: Astrophysical tests of the nature of dark matter in the 2040s

Hannah Stacey
ESO

The nature and characteristics of dark matter are of central importance to the understanding of galaxy formation and cosmology. The Cold Dark Matter model has been successful in describing the formation and distribution of structures in the Universe. However, this model is not unchallenged, particularly at (sub-)galactic scales. Meanwhile, prominent alternative classes of models, such as Warm Dark Matter or Self-Interacting Dark Matter, enjoy similar success in observational cosmology.

A key difference between these dark matter models is how they form structure on small scales, especially in the $\sim 10^{6-7}$ $M_\odot$ range, due to the dramatically different abundance and density profiles between dark matter models. Haloes in this low mass range cannot be directly detected, but can be characterised only through their gravitational influence. Strong gravitational lensing provides a uniquely sensitive probe of mass, independent of whether it is dark or baryonic, and has become a powerful test of dark matter through its ability to reveal low-mass haloes via perturbations in the surface brightness of lensed images.

In this talk, I will demonstrate that the most promising approach to access this key mass regime and infer statistically significant constraints on the nature of dark matter is with a next-generation sub-mm interferometer to succeed ALMA in the 2040s.

The Galactic Center with Kilometer-Baseline Interferometry

Stefan Gillessen
MPE

The Galactic Center is one of the most famous success stories of high angular astronomy, honored with the 2020 Nobel prize. Near-infrared observations of individual stellar orbits have established that the radio source Sgr A* is a massive black hole. The scientific theme has now moved on to testing general relativity in the vicinity of the black hole from these motions, reaching down to few hundreds of Schwarzschild radii. With Kilometer-Baseline Interferometry, we will be able to zoom in even further, resolving the central engine, the innermost accretion zone, at a scale of few Schwarzschild radii, a regime fully dominated by relativistic hydrodynamics. Unlike the global mm-VLBI technique, the infrared allows fine sampling of the dynamical time scale, amounting to around 20 minutes for Sgr A*. This allows using its infrared flares as probes for the structure of space-time. In particular, this would allow testing for a range of black-hole mimickers, such as hypothetical boson stars. Further, the associated ultra-precise astrometry of stellar motions will allow directly measuring effects at the relativistic 2PN order, such as the quadrupole moment of the metric, enabling thereby a test of the fundamental no-hair theorem of general relativity.

Zooming In on the Monster: Revealing Supermassive Black Hole Physics with Kilometre Baseline Interferometry

Taro Shimizu
MPE

GRAVITY at the VLTI has revolutionised our understanding of active galactic nuclei, delivering the first spatially resolved measurements of broad-line region (BLR) kinematics and direct dynamical black hole mass measurements. GRAVITY+ is now extending these capabilities to fainter targets and higher redshift quasars. These breakthroughs, however, are only the beginning. Key physical structures governing black hole accretion and growth remain at or below the resolution limits of current baselines. Kilometre-baseline interferometry with large telescopes has the potential to move from marginally resolved signals to direct imaging, opening a new observational frontier.

In this talk, I will discuss the transformative science enabled by microarcsecond-scale resolution. I will explore how kilometre baselines can directly image the BLR across a significant AGN sample, delivering velocity-resolved maps of the emitting gas and enabling black hole mass measurements independent of reverberation mapping assumptions. I will discuss resolving the thermal structure and temperature profile of accretion disks, allowing direct tests of standard thin-disk models that microlensing and reverberation studies have repeatedly called into question. I will examine the opportunity presented by tidal disruption events, where kilometre baselines could resolve rapidly evolving gas and dust structures, providing real-time constraints on the geometry and energetics of these transients. Finally, I will outline the requirements for each science case and discuss how a future kilometre-baseline facility could work in synergy with time-domain surveys and multi-wavelength observations.

Kilometer Baseline Interferometry: from scientific vision to instrument reality

Guillaume Bourdarot
Max Planck for extraterrestrial Physics

Optical/IR interferometry has revolutionized High Angular Resolution astrophysics. Based on ESO's VLTI and its recent GRAVITY+ upgrade, it has delivered ground-breaking results and is opening a new era in Optical/Infrared astronomy. Extending this capability to large, kilometer interferometric arrays, able to resolve the innermost environment of Black-Holes or map the surface of exoplanets, is a key scientific frontier at the Horizon 2040. In this talk, we focus on the main design requirements in terms of spatial resolution, collecting area, array geometry, and the experimental roadmap towards a kilometer baseline array. Technology is the backbone of this revolution, with key developments coming on segmented telescopes, adaptive optics, photonics, laser guide stars, and even quantum technologies in the next decade. ESO's Paranal, Armazones, and future facilities would offer a unique platform for ground-based astronomy at the highest angular resolution.

Cosmology with Massive Spectroscopic Redshift Surveys in the 2040's

Jean-Paul Kneib
EPFL

Over the past quarter-century, cosmology has transitioned into a precision science, establishing the Lambda-CDM model. With the current DESI results, a new cosmological model advocating for Dark Energy evolution is emerging. Yet, the cosmology model is overall in crisis with: cosmological tensions (Hubble constant, cosmic dipole, S8), major unknown components (Dark Energy and Dark Matter), poorly defined neutrino mass and yet to be constrained inflationary physics.

To go beyond the current Stage-IV experiments (e.g. DESI, Euclid, 4MOST), a future ESO spectroscopic facility operating from 2040, designed to deliver high-density, high-redshift, high-fidelity spectroscopy over large cosmic volumes, will open a new observational window on the early cosmic epochs where these elusive components first emerge and leave measurable imprints.

The proposed Wide-field Spectroscopic Telescope (WST) concept demonstrates how extreme multiplexing, high spectral resolution, and complementary observing modes could be combined within a single facility. WST will address the most fundamental questions in cosmology in the Stage V era, but also open new discovery space through for example Gravitational Wave event follow-up.

ESO is uniquely positioned to lead this ambitious challenge taking advantage of the Southern multiband surveys (LSST, SKAO, Atacama CMB experiments, Euclid Dark Matter maps) and will complement current astronomical facilities (including ESO's) to new uncharted parameter spaces.

Beyond the ΛCDM model: probing the Universe's underlying Physics with Cosmic Void Counts

Sofia Contarini
Max Planck Institute for Extraterrestrial Physics

The increasing precision of modern galaxy surveys has revealed persistent discrepancies between independent cosmological probes, commonly known as cosmological tensions. These may reflect unresolved systematic effects or hint at new physics beyond the standard ΛCDM framework, including modified gravity or an evolving dark energy component. Fully exploiting the information contained in large-scale structure therefore requires complementary observables beyond traditional probes such as galaxy clustering and weak lensing.

Cosmic voids are large underdense regions of the cosmic web, extending over tens to hundreds of megaparsecs. Their interiors contain very few galaxies, which greatly reduces the impact of complex baryonic processes. This makes voids particularly clean environments for probing the gravitational dynamics that drive the growth of cosmic structure. Among the various void observables, the void size function, which describes the abundance of voids as a function of their size, has recently emerged as a powerful statistical probe. With the advent of next-generation wide-field spectroscopic surveys, precise measurements of the void size function will enable transformative tests of dark energy and gravity, establishing void statistics as a key probe of cosmology in the 2040s. Facilities such as the Wide-field Spectroscopic Telescope (WST) will provide the wide-area, high-precision spectroscopic data required to fully exploit this potential.

[Cancelled] Photonic EMARCOT: a modular and photonically-connected telescope architecture for the post-ELT era

Pedro J. Amado
Instituto de Astrofisica de Andalucia-CSIC

Photonic EMARCOT proposes a new approach to future ground-based astronomy through modular telescope architectures connected via photonic technologies. Within the strategic framework of the Calar

Alto Observatory (CAHA, Almeria, Spain), the project aims to provide an order-of-magnitude lower-cost alternative to large monolithic telescopes by linking multiple Optical Telescope Assemblies (OTAs) on a single mount (a module) through a multimode-to-multimode photonic lantern.

As funding becomes available, building additional modules (in our concept, the building block is a 5-m module) enables scalable increases in effective collecting area and long-term adaptability to scientific and technological evolution. The architecture also incorporates a digital twin and an AI-assisted operational framework to support optimisation, predictive maintenance, and intelligent scheduling.

The next step in the project roadmap is the construction of a dedicated pathfinder for the 5-m module and its connection to the CARMENES-NIR spectrograph, establishing the first operational platform to test modular photonically transported light into an existing high-resolution instrument at CAHA.

The scientific vision of Photonic EMARCOT is to extend observational reach by enabling higher-signal-to-noise observations, improved sensitivity to faint targets, a degree of multiplexing, and the ability to route starlight independently to several instruments or spectral channels. Such capabilities go beyond what is achievable with telescopes with few mutually exclusive focal planes and create opportunities for simultaneous multi-technique or multi-wavelength observations as the array grows, and possibly intensity interferometry.

The project is jointly led by IAA-CSIC (Granada, Spain) and CAHA, with the Leibniz Institute for Astrophysics Potsdam (AIP, Germany) as an initial partner. Its development roadmap foresees a first 5-metre-equivalent module by 2030, followed by a 15-metre-class configuration formed by combining several modules by 2035. This contribution presents the project's current status, scientific motivations, and long-term architectural vision, together with the collaboration framework supporting its development.

Abstracts of posters

Galaxy Spins and the Cosmic Web: a Rosetta Stone for Galaxy Evolution and Weak Lensing Cosmology

Matthew Colless
Australian National University

Galaxies spins are sculpted by the filaments of the cosmic web. Alignments between galaxy angular momentum and large-scale filaments provide both a powerful, physically-motivated tracer of galaxy assembly and a missing link between galaxy evolution and precision cosmology. Simulations and observations reveal a striking mass-dependent transition: low-mass, star-forming disks tend to spin parallel to filaments, while massive, bulge-dominated systems preferentially orient perpendicular to them, reflecting the balance between smooth accretion and merger-driven evolution. These alignments evolve with redshift, encoding how angular momentum is gained, lost, and reoriented across cosmic time. Beyond galaxy physics, spin–filament alignments are intimately connected to intrinsic alignments of galaxy shapes, one of the dominant systematics in weak-lensing surveys measuring dark energy and neutrino mass. Combining spatially-resolved kinematics with sub-Mpc reconstructions of the cosmic web offers a new, physics-driven route to model intrinsic alignments across mass, morphology, environment, and redshift. Realising this vision requires wide-field, high-density MOS and IFS surveys that both resolve the sub-Mpc cosmic web and deliver millions of galaxy spins. Such an observational leap can reveal the physics of angular momentum reorientation across cosmic time, deepening understanding of how galaxies and large-scale structures co-evolve and enabling precision weak-lensing cosmology.

Towards a Predictive Theory of Star Formation: Unlocking the Potential of Extragalactic Astrochemistry

Jakob den Brok
MPIA

Understanding what regulates star formation in galaxies remains a central challenge in astrophysics. Over the past decade, observations beyond the Milky Way have established global scaling relations linking the molecular gas content to star formation. Yet galaxies with similar molecular gas reservoirs can form stars at very different rates, pointing to fundamental variations in the physical and chemical state of the cold interstellar medium (ISM). Uncovering these conditions and their interplay with stellar feedback is the key step toward moving from empirical relations to a predictive theory of star formation. Molecular line emission provides a uniquely powerful probe of the cold ISM, tracing gas density, temperature, and chemical complexity. Recent astrochemical surveys of individual galaxies have already demonstrated the rich diagnostic potential of this approach. A next generation of (sub)millimeter interferometer, with greatly improved sensitivity and angular resolution, will make it possible to extend astrochemical studies across galaxy populations, enabling a comprehensive and physically grounded view of molecular gas and its connection to star formation. Realizing this potential will require parallel advances by the 2040s in theoretical models and simulations, capable of capturing the astrochemical and physical complexity of the ISM and fully exploiting the diagnostic power of astrochemical observations.

Unveiling Low-ionization structures in Planetary nebulae: four decades of discoveries

Lydia Konstantinou
ESO-NOA-UoP

Planetary nebulae (PNe) mark the final evolutionary stage of low to intermediate mass stars meaning that the vast majority of stars will go through the PNe phase. They are major contributors to the enrichment of the interstellar medium with heavy elements and host information regarding the chemical history of the galaxies. PNe are also key laboratories for studying gas dynamic, radiative processes and deepening our understanding on stellar evolution of low-mass stars. Despite the extensive interest around PNe studies major questions remain unanswered regarding their peculiar morphologies, their small-scale structures and their collimated outflows. These features pose challenges to our understanding of the late stages of stellar evolution, but they also offer clues about binary interactions and gas dynamics. However, many of them remain beyond the spatial resolution and sensitivity of current facilities. In this contribution, I review the evolution of microstructure studies from imaging and long-slit spectroscopy to integral-field techniques and the opportunities offered by next-generation observatories. I will also present results from the first multiwavelength long-slit analysis focused on clumps using X-Shooter/VLT data, together with the study of nebular knots based on MUSE observations, aimed at disentangling their physical nature and origin.

The Conceptual Design of the 50-meter Atacama Large Aperture Submm Telescope (AtLAST)

Tony Mroczkowski
Institute of Space Sciences (ICE-CSIC)

Across the spectrum, the landscape of planned European facilities is extensive. Yet facilities to map far-IR through mm wavelengths are missing from the roadmap. The Atacama Large Aperture Submm Telescope (AtLAST) aims to fill this gap. AtLAST is a concept for a next-generation 50-m observatory optimized to cover the same wavelength range as ALMA, providing an unprecedentedly large instantaneous field of view (FoV$\sim$1-2deg, $\sim$500x that of existing large single dish (sub)mm facilities). Observations at submm wavelengths uniquely allow us to study regions of the sky that are either too cold, dusty, distant, or hot and tenuous to be probed in the visible regime – i.e. submm observations reveal the vast, invisible multiphase gas and dust inaccessible to the visible and NIR. From probing the earliest stages of star and planet formation, to studying the evolution of galaxies across cosmic time, submm observations have revolutionized our understanding of astrophysical phenomena. However, as we look to the 2040s, all fields of astrophysics demand a new (sub-)mm facility with an unprecedented combination of sensitivity, resolution, and mapping speed to address fundamental questions that remain beyond our current capabilities and yield a more complete view of the sky. In this talk, I will provide an overview of the AtLAST design, now in its 2nd phase of EU funding, and I will highlight its sustainability, technological maturity, and how ESO can bring this project to fruition.

Detection and characterisation of submm transient sources with a large single-dish telescope

Mike Peel
Imperial College London

The exploration of the time-variable astronomical sky at submm wavelengths is rapidly becoming more feasible with large sky surveys by Cosmic Microwave Background telescopes with tens of thousands of detectors. Observations with the Atacama Cosmology Telescope and South Pole Telescope have already detected some transients, and Simons Observatory and CCAT are expected to detect many more in the near future. These include Gamma-Ray Bursts, Tidal Disruption Events, flaring stars, and many more types of objects where submm observations can provide valuable input into their evolution and origins.

Follow-up observations to characterise these transients, and surveying to uncover fainter populations, will need high sensitivity and large fields of view at submm wavelengths, which could be provided by large single dish telescopes such as AtLAST. Should AtLAST be selected as ESO's next flagship project, it will be the first capable of discovering submm transients, providing a tremendous amount of synergy with the Cherenkov Telescope Array as well as telescopes like ALMA and the ELT that are capable of rapid follow-up and detailed characterization.

Thermal emission from increasing numbers of low earth orbit satellites will present new challenges in the future - both for transient detection, and more widely with future high sensitivity observations through Earth's increasingly crowded orbital environments on the timescales being considered here.

The Extremely Large Telescope Interferometer

Francisco Prada
Instituto de Astrofísica de Andalucía CSIC

The ELTI concept capitalizes on recent breakthroughs in large-format SPAD (Single-Photon Avalanche Diode) imaging sensors, combining them with the unprecedented collecting area and segmented architecture of the ELT to deliver a fundamentally new observational capability for the 2040s: visible-light intensity interferometry with ELT-scale angular resolution and quantum-limited temporal sampling. By uniting three transformative innovations - segmented sub-pupil beam combination, megapixel SPAD arrays with picosecond time resolution, and high-dispersion spectroscopy - ELTI opens an entirely new region of observational parameter space in angular resolution, spectral bandwidth, and temporal precision. This capability enables true milliarcsecond imaging of stellar surfaces, direct probes of extreme-gravity and strong electromagnetic-field environments around compact objects, precision studies of accretion physics, and even the potential detection of Earth-sized exoplanets through minute visibility modulations. ELTI thus positions the ELT as the world-leading facility for ultra-high-resolution optical astronomy in the coming decades.

White Dwarfs in Wide Binary Systems as Reliable Age Calibrators

Alberto Rebassa-Mansergas | Anna Francesca Pala | Roberto Raddi
Universitat Politècnica de Catalunya | ESO | Universitat Politècnica de Catalunya

Stellar ages remain one of the weakest links in Galactic astrophysics, limiting our ability to fully exploit age-dependent relations across the Milky Way. White dwarfs offer a powerful solution: their simple and well-understood cooling makes them reliable cosmic clocks, especially in wide binaries with main-sequence companions. A limitation, however, is the uncertain initial-to-final mass relation, which affects progenitor lifetime estimates. I will present a strategy to bypass this issue by focusing on massive white dwarfs whose progenitor lifetimes are negligible, enabling robust and precise age determinations. In the 2040s, large samples of these intrinsically faint objects will become accessible, opening a new era of precision Galactic archaeology. I will outline the observational challenges and key requirements for next-generation ESO facilities to fully exploit white dwarfs as high-precision age calibrators.

Hunting pre-stellar cores with APEX: high-density tracers and deuteration

Elena Redaelli
ESO

What are the physical and chemical properties of prestellar cores in the nearby galaxy? This is the question that the observational campaign Hunting pre-stellar cores with APEX (Caselli et al. 2025) intends to address. The sample of cores was formed from the Herschel Gould Belt Survey catalogues, selecting those with high central densities and no known associated protostars. We targeted the 40 objects with high-J N2H+ and N2D+ observations with the APEX telescope. In my talk, I will show the initial results from the whole sample in terms of line detection and deuteration levels. Furthermore, I will show preliminary results from the analysis of HDO line serendipitously detected in the sample. Deuterated water represents an important diagnostic tool to follow the inheritance of water from the prestellar stage down to the protoplanetary disc one. I will then discuss how these scientific questions will benefit from future facilities, such as the AtLAST single-dish telescope.

Chemical complexity from molecular clouds to star-forming cores

Peter Schilke
Institute for Astrophysics, University of Cologne

The study of the molecular feedstock of star-forming regions is pivotal for understanding the physical and chemical conditions that govern the formation of stars and planetary systems from their natal clouds, and its potential to provide ingredients for the emergence of life. The chemical composition gives important insights into the present and past conditions of specific objects, tracing important properties like UV or cosmic ray fluxes, but also the effect of metallicity, or the influence of shocks and turbulence and, through chemical memory effects, the origin of the building blocks. Also, chemistry plays an active role in determining heating and cooling rates, and thus deeply influences the star formation process. This transcends scales from large, tracing the earlier stages of molecular clouds, down to protoplanetary disks. Studies of this kind are also necessary to understand the process in extragalactic systems. Instruments such as JWST or SPHERx provide important input data for these studies, but most of the material relevant for these processes is cold and thus inaccessible for IR studies, hence requires complementary instruments.

Only a new generation (sub)millimeter interferometer with a 10x enhancement, in spectral line sensitivity, spatial resolution and wide-field imaging capabilities, will allow us to capture the true extent of chemical diversity (complex prebiotic molecules and rare isotopologues) towards representative samples of sources, and to follow its emergence, evolution and variations locally and at Galactic scales.

Exploiting Light Coherence in Astrophysics using ELT

Vitalii Sliusar
University of Geneva

The Hanbury Brown–Twiss (HBT) effect, discovered in the 1950s and further developed in the 1960s, exploits photon bunching in incoherent light to estimate stellar radii via intensity interferometry and has played a foundational role in the development of quantum optics.

When two detectors are co-located using a beamsplitter, one can measure the zero-baseline intensity correlation. After correcting for detector response, this yields the temporal part of the second-order coherence function, $g^{(2)}$. Unlike standard interferometry, this quantity is independent of source geometry and directly probes photon statistics, enabling discrimination between thermal, synchrotron, bremsstrahlung, and stimulated emission. Changes in emission processes are reflected in the evolution of $g^{(2)}$.

The second-order coherence function can thus serve as a complementary "messenger," carrying intrinsic information about the source emission process. ESO's Extremely Large Telescope (ELT), equipped with SPAD detectors, could measure photon statistics of faint astrophysical sources (accretion disks, jets, white dwarfs, et al.) and constrain their emission mechanisms and study their evolution. Measurements of the temporal component of $g^{(2)}$ are complementary to standard intensity interferometry and can be obtained simultaneously by doubling detectors without loss of optical efficiency.

The evolution of obscured AGN across cosmic time – A large quasar survey for the 2040s

Tanya Urrutia
Leibniz Institut für Astrophysik, Potsdam

We propose a large quasar demographic optical multi-object spectroscopic (MOS) survey targeting over 50 million AGN candidates up to the highest redshifts possible in the optical ($z \sim 6.5$), with repeat visits, using a variety of selection criteria available by 2040. A large MOS survey combining all AGN selection methods is the only way to unify a diverse range of different obscured AGN populations within a single, variability- and spectroscopy-based framework, rather than as disjoint classes selected by different methods.

Hunting exomoons with a kilometric baseline interferometer

Thomas Winterhalder
Leiden Observatory

Despite numerous search campaigns based on a diverse set of observational techniques, exomoons - prospective satellites of extrasolar planets - remain an elusive and hard-to-pin-down class of objects. Yet, the case for intensifying this search is compelling: as in the Solar System, moons can act as proxies for studying planet formation and evolution, provide direct clues as to the migration history of the planetary hosts and, in favourable cases, offer potentially habitable environments. Here, we present an investigation into how the search for exomoons would benefit from a new interferometric facility operating in the optical wavelength domain and leveraging baselines substantially longer than the ones the VLTI is currently equipped with. We find that an interferometer providing an astrometric precision of 1 μas would be able to robustly detect Earth-mass and sub-Earth-mass exomoons on dynamically stable orbits around Jupiter-like planets at distances between 50 and 200 pc. This talk is related to our recent ESO Expanding Horizons White Paper.

Long-baseline far-infrared interferometry on the Moon

Hans Zinnecker
Universidad Autonoma de Chile

We are making a case for ESO entering far-infrared astronomy in the long-term future, possibly in cooperation with ESA or NASA (post-Artemis). Far-infrared astronomy is the only wavelength range (30-300 micron) in the electromagnetic spectrum that is currently (and in the foreseeable future) not covered, but is of fundamental importance to study the cold universe (100-100K), especially the interstellar medium (molecular clouds) and star and planet formation (astrochemistry) at high spatial resolution. Ideally, this would complement both JWST (mid-IR) and ALMA (sub-mm and mm).

Far-infrared astronomy cannot be carried out on Earth due to the lack of atmospheric transparency, therefore we boldly suggest to consider going to the Moon which has no atmosphere and which has the advantage of building an array of small telescopes to perform long-baseline interferometry to obtain the necessary high spatial resolution in the far-infrared (up to 2 mas for 10 km baselines at 100 micron). Interferometry on the Moon may be difficult, but is a clear alternative to free-flying space interferometry that has been proposed (see Helmich & Ivison 2009 and Linz et al. 2021).

Testing quantum systems in space with advanced intensity interferometers

Andreas Zmija
Institute de Physique de Nice, Université Côte d'Azur

Stellar Intensity Interferometry is a rapidly developing technique of interferometric measurements, enabling observations at in principle arbitrarily large interferometric baselines, and at optical wavelengths that are challenging - if not out of reach - by state-of-the-art amplitude interferometers. Therefore it can complement the field of high-angular resolution astronomy particularly for hot stellar targets. As an additional science case from a quantum optics perspective, intensity interferometers measure the photon statistics of the observed targets, able to distinguish thermal and non-thermal emission processes.

One currently running ERC-funded project - IC4Stars - makes use of both of these possibilities, in order to study quantum systems in space. By aiming to measure the diameter of the white dwarf Sirius B, it will probe the predictions of quantum mechanics for a planet-sized quantum object. The second aspect is the search of stimulated emission processes, in particular natural lasing lines in astrophysical systems, which are predicted by a multitude of spectral observations, but impossible to be confirmed by any other observational technique but the measurement of second-order photon correlations provided by an intensity interferometer.

In this contribution we highlight the scientific impact potential of both objectives. In addition, we describe the technical development of these interferometers, making use of state-of-the-art technology in the context of ultra-high time resolution electronics, synchronization between telescopes at the picosecond level, spectral multiplexing designs to boost signal-to-noise, optical interferometric baselines on the kilometer-scale, and modern photo-detectors, such as superconducting nanowire single photon detectors. All of these aspects are key developments, paving the way towards future intensity interferometry instruments.

Hands-On Exploration of Quantum Optics through the Hanbury Brown–Twiss Effect with Picosecond Photon Detection

Gilles Koziol
Observatory of Geneva

The Hanbury Brown–Twiss (HBT) effect is a foundational phenomenon in quantum optics, revealing the statistical nature of light through intensity correlations. This session highlights its impact, from early stellar interferometry to modern studies of photon coherence and quantum statistics enabled by picosecond-resolution detectors.

Along with explanatory poster, we'll demonstrate the HBT effect live: two single-photon avalanche diode (SPADs) detectors and a high-precision time-to-digital converter (TDC) will be used to show photon-bunching effect on a scales of few tens of picoseconds – intensity correlations. This experiment would highlight how the advances in fast photon detection and multi-channel spectrometry significantly enhance signal-to-noise ratios, enabling applications that extend from laboratory to astronomical targets.

The demo setup realizes a zero-baseline setup, a photometer, where a spectral lamp light (a single spectral line) is split by a beamsplitter. On the actual telescopes the same detectors instead are placed on two separated telescopes comprizing an intensity interferometer with a baseline related to the distance between the telescopes and position of the target in the sky. Resolution of such intensity interferometry setup scales with the baseline, few tens of kilometers baseline could yield nano to pico degrees resolution.

Picosecond Intensity Interferometry with Auxiliary Telescope Arrays around the ELT

Gilles Koziol
Observatory of Geneva

Recent developments in picosecond single-photon avalanche diode (SPAD) detectors paired with a multi-channel spectrometer, enable significant improvements in sensitivity in comparison with the pioneering experiment of Hanbury Brown and Twiss (1956), making it possible to resolve faint and compact astrophysical sources, like accretion disks or cataclysmic variables.

In this work, we explore the feasibility and scientific benefits of deploying an array of small (10 sq. meters each) and low-cost telescopes around ELT. Beyond increasing the total collecting area, such an array also expands the number of interferometric baselines, enhancing the uv-plane coverage and thereby allowing better constraints on more complex models of source geometry.

Our results reveal great potential and emphasize the importance of further developments of intensity interferometry techniques in conjunction with the ESO's VLTs, and the ELT.

WST Multi-Object Spectrograph Fiber Positioners: Development of a 32,000-Unit Precision Robotic System

Sébastien Pernecker | Jean-Paul Kneib
Observatory of Geneva | EPFL

The Wide-field Spectroscopic Telescope Multi-Object Spectrograph requires an unprecedented fiber positioning system comprising 30,000 low-resolution and 2,000 high-resolution positioners across a 3.1 deg^2 field of view. Each robotic positioner must achieve 5 µm RMS positioning accuracy in a densely packed focal plane, representing a more than sixfold scale increase over current instruments like 4MOST and DESI. To mitigate risks associated with industrial-scale production of 32,000 precision mechanisms, WST is pursuing a multi-concept development strategy. Four distinct positioner architectures are being prototyped and tested by an international collaboration (EPFL, AIP, UKATC, AAO) using 6.2 mm pitch triangular modules of 63 units each or a new inline modular concept. Performance metrics including positioning accuracy, repeatability, reconfiguration speed, collision avoidance, and manufacturability are being systematically evaluated. Down-selection to one or two concepts is planned for 2026-2027 during the HORIZON Europe-funded conceptual study phase. Current prototype testing demonstrates feasibility of meeting specifications, supporting WST's path toward first light in the early 2040s as ESO's next major spectroscopic facility.

Wind Characterisation at two sites on the Chajnantor Plateau for the AtLAST Project

Carlos De Breuck
ESO

In the last two decades, the 5000-metre high Chajnantor plateau has become the major sub/mm observatory worldwide. While ALMA is obviously the main driver, other smaller telescopes have benefited from the available infrastructure to share resources and address complementary science parameter space not covered by ALMA, whose strength is sensitive high spatial and spectral resolution studies of relatively small objects. The ultimate and originally planned complement to the ALMA interferometer is a large single dish telescope such as AtLAST to fill the unavoidable hole in the uv-plane, while at the same time opening the era of wide-area sub/mm astronomy thanks to a 2-degree field of view.

In this talk, I will describe the site selection and characterization for this 50-metre telescope, which will be more sensitive to the wind than the 12-metre ALMA dishes. Using dedicated wind towers, we have for the first time identified the vertical wind profile on Chajnantor, which is essential for such a large telescope without a dome. These measurements are fed back into the telescope design to provide actual rather than simulated environmental conditions. Other aspects considered in the site selection included the absence of interference with any current or planned telescope, the accessibility, soil stability and local weather conditions, as well as the possibility to link up with ALMA and other sub/mm telescopes as part of a VLBI network.