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A Multimessenger View of Galaxies and Quasars From Now to Mid-century

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In the next 30 years, a new generation of space and ground-based telescopes will permit to obtain multi-frequency observations of faint sources and, for the first time in human history, to achieve a deep, almost synoptical monitoring of the whole sky. Gravitational wave observatories will detect a Universe of unseen black holes in the merging process over a broad spectrum of mass. Computing facilities will permit new high-resolution simulations with a deeper physical analysis of the main phenomena occurring at different scales. Given these development lines, we first sketch a panorama of the main instrumental developments expected in the next thirty years, dealing not only with electromagnetic radiation, but also from a multi-messenger perspective that includes gravitational waves, neutrinos, and cosmic rays. We then present how the new instrumentation will make it possible to foster advances in our present understanding of galaxies and quasars. We focus on selected scientific themes that are hotly debated today, in some cases advancing conjectures on the solution of major problems that may become solved in the next 30 years.

Keywords: galaxy evolution, quasars, cosmology, supermassive black holes, black hole physics

1. INTRODUCTION: TOWARD MULTIMESSENGER ASTRONOMY

The development of astronomy in the second half of the twentieth century followed two major lines of improvement: the increase in light gathering power (i.e., the ability to detect fainter objects), and the extension of the frequency domain in the electromagnetic spectrum beyond the traditional optical domain. Around 40 optical, ground based, reflecting telescopes of diameter larger than 3 m are operational at the time of writing: only eleven of them became operational before 1990, which means that 3/4 of the largest telescopes have been built in the last 25 years. The 14 telescopes of the 8–10 m class (counting 2 for the Large Binary Telescope, LBT, and 4 for the Very Large Telescope, VLT) all became operational around the year 2000 or afterwards, with the exception of the first Keck telescope (at Keck science observations began in 1993). Telescopes of the 6–10 m class in space and telescopes of the 30–40 m class on the ground belong to the near future: the James Webb Space Telescope (JWST) will be soon launched and the ground-based telescopes that are under construction are the ESO Extremely Large Telescope (E-ELT) and the Giant Magellan Telescope (GMT). The light gathering power is steadily increasing and will benefit spectroscopic studies of distant quasars, galaxies, and supernovae.

The second line of development involved the extension over unexplored frequency domains of the electromagnetic radiation: from the tiny optical range from 3,700 to 8,000 Å, ground and space

based instrumentation now yields the ability to cover the electromagnetic spectrum from meter wavelengths to the γ -ray domain. If there is a safe prediction is that the progress will follow along the line of a deeper, wider and faster coverage of cosmic sources at all accessible wavelengths of the electromagnetic spectrum.

A third line—the increase in resolving power (i.e., the ability to resolve finer details of distant objects¹)—has somehow lagged behind due to the formidable technical challenges at the typical wavelengths of the electromagnetic radiation in the visual and UV bands. This third line of instrumental development is based on reaching diffraction limit performances for single dish telescopes and on interferometry, from ground and space. In April 2016 *Physics Today* challenged its readers to write a fictional news story about a discovery made in 2116. Robert Austin's winning entry describes a huge space telescope fashioned from laser-machined asteroids (Austin, 2016), the Asteroid Belt Astronomical Telescope (ABAT). Even if this idea is perhaps too far-fetched to become true even one century from now, we can expect substantial developments in interferometry from ground and space. For instance, right at the time of writing, the new instrument MATISSE, an interferometric imaging spectrograph working in the L, M, and N bands in the mid-infrared region (3–13 μm), is becoming operational at the Very Large Telescope Interferometer (VLTI) (Lopez et al., 2014) and is expected to reach a spatial resolution of 0.01 arcsec, comparable to the Hubble Space Telescope (HST), the 1.54m telescope orbiting our Earth since 1990.

There is however a most exciting development that will break the almost complete monopoly of electromagnetic radiation as carrier of information from extragalactic sources. The detection of *gravitational waves* is probably the achievement of the century. Much of frontiers astrophysics will be devoted not only to expand and create new gravitational observatories, but also at conventional electromagnetic studies of counterparts of gravitational wave sources, following the first positive identification just a few months ago (Abbott et al., 2017).

At the same time new types of telescopes and instruments will be soon in operation for the detection of neutrinos and cosmic rays. All these endeavors contribute to *multi-messenger astronomy*: the new magic word under which all future researchers will operate. We would try below to summarize the main aspects of such future instrumental developments.

2. THE MAIN INSTRUMENTAL DEVELOPMENTS

An eminent physicist foresaw that we will be able to have a complete account of the reality, from the Big Bang to humans, in physical and chemical terms, within this century. Although this idea is perhaps too optimistic, it is reasonable to presume that we will have a reasonably complete view of the constituents of the

visible Universe and of its evolution from the dark ages (beyond $z \approx 6$, currently sampled up to $z \approx 10 - 12$) until the present cosmic epoch.

Once an overall physical understanding will be reached, we expect that science will progress toward the explanation and modeling of finer physical details. This has been the case for the study of stars in the twentieth century. The stellar evolution theory provides a detailed general physical framework with predictive power, although there are still many challenging aspects in the physics of stellar atmospheres and stellar structure (magnetic reconnection, flares, internal oscillation, internal turbulence) that are at the frontiers of present-day research. In this sense, we may hope to reach a global understanding of the nature of the active galactic nuclei² (AGN), and of their connection with host galaxy across cosmic times, but this will open a new order of very complex problems concerning the spatial and temporal modeling of the nuclear activity and its interplay with the host galaxies involving turbulence, chemical evolution, dust physics and magnetic fields. All areas of investigations where spatial resolution is crucial (such as the study of nuclear feedback in galaxies, which are now in their infancy, as outlined below) will benefit from the advancements expected in active optics, and ground- and space-based interferometry.

Several developments expected in the next 30–40 years are not so difficult to foresee, not last because the new astronomical instruments require careful planning that may imply at least a 10-year lapse between early proposals and first light at the facility. We will first review the major observational projects that are ongoing or planned and are expected to have frontier capability³, and then discuss their impact on several present-day scientific themes of extragalactic astronomy, in particular for galaxies and quasars (section 3).

2.1. Full-Sky Coverage Across the Electromagnetic Spectrum

Generally speaking, the most modern ground-based telescopes and even more so the forthcoming ones are best suited for spectroscopy to deep limits (currently 25.6 AB mag in the Z-band in 3 h exposure at LBT) or high spectral resolution ($R \sim 10,000 - 100,000$). They can also provide wide-field coverage (up to ≈ 1 deg) and spectroscopic multiplexing ($\sim 10^3$ sources per fields, Dalcanton et al., 2015). These capabilities make it possible to observe large samples of sources. For example, the Dark Energy Spectroscopic Instrument (DESI) is an optical spectrograph capable of performing highly-multiplexed observations to measure the BAOs (5,000 robotized fibers can be distributed in an 8.0 square degree field, Levi et al., 2013).

¹The angular resolutions is defined by the angular radius of the Airy disk which is given as $\theta \approx 0.025\lambda_{1\mu\text{m}}/D_{1\text{m}}$ seconds of arc, where the radiation wavelength is in units of microns and D (either the disk diameter of the interferometer baseline) is in meters.

²In the following we will use the term AGN to indicate all accretion-powered black holes, and “quasars” to indicate mainly high luminosity AGN. However, it is important to stress that there isn't any critical luminosity divide.

³Even if some of the proposed projects may not be completed, or developed as assumed here, we are confident that instrumentation with similar technical specifications will become operational over the next decades.

Ground-based telescopes equipped with adaptive optics systems have also made great advances in high-resolution near-IR imaging. For example, GRAVITY, a VLT-based imaging IR interferometer is expected to reach resolving power of three milliarcsec (Eisenhauer et al., 2011). GRAVITY will yield an unprecedented view of the nuclei of most nearby galaxies. Adaptive optics (AO) systems are expected to improve, although not beyond ≈ 1 arcmin fields and not at the shortest wavelengths. However, multi-Conjugate Adaptive Optics systems can in principle yield diffraction-limited images of a relatively wide field (30 arcsec across), meaning a resolution of 20 milli arcsec in the V band at one of the VLT telescopes (Esposito et al., 2016). The Multi-conjugate Adaptive Optics RelaY for ELT (MAORY) (Fiorentino et al., 2017) may reach a 5σ detection limit of a point source in $J_{AB} \approx 29$ with an exposure time of 5 h (Bellazzini, 2016).

Space-based telescopes provide complementary capabilities. Since backgrounds are 10–100 times lower than at the ground, space offers a stable operating environment. Space-based observations reach the same broadband imaging depths of ground-based observations up to 100 times faster, achieve fainter magnitude limits with the next generation instruments ($AB \sim 32$ – 34 mag), and extend stable diffraction-limited PSFs to larger fields of view (3–4 arcmin) and visual and UV wavelengths (Dalcanton et al., 2015). Foreseeable space astrometric missions [for example the future ESA mission “Theia” (The Theia Collaboration et al., 2017), on the path of the hugely successful Hipparcos and Gaia missions] may eventually achieve sub- μ arcsec precision in astrometric measurement (Vallenari, 2018). The return would be, for the first time in history, the ability to detect proper motions in extragalactic sources through angular displacements and not only by radial velocity differences with respect to a reference frame.

Space telescopes also uniquely cover the information-rich UV, FIR, and sub-mm spectra that are blocked by Earth's atmosphere. Planned projects such as LUVOIR (France et al., 2017) can provide ~ 10 milliarcsec resolution in the visual and UV bands that may be unobtainable for the ELT if it reaches diffraction limited capabilities only at wavelength longer than $0.5 \mu\text{m}$ (Figure 1).

2.1.1. NIR-Optical-UV

A most notable advancement should be the building of fully steerable 40m class telescopes in the optical and near infrared: the GMT and the ESO ELT. The first will consist of seven 8.4 m diameter segments with the collecting area equivalent to a 22.0 m single-mirror telescope (McCarthy, 2006). The E-ELT is a 40-m class with included adaptive optics (Hook et al., 2009). Both will be equipped with integral field units for spatially-resolved spectroscopy (ESO, 2018).

The James Webb Space Telescope (JWST) is expected to be another milestone, providing a ten fold improvement in sensitivity and in spatial resolution with respect to the Hubble Space Telescope (HST, Gardner et al., 2006). The JWST being optimized for optical and infrared, the UV domain (not accessible from ground) needs to be covered by a new generation of space based observatory. At present WSO-UV and LUVOIR

may have some chances to become operational in the 2020s (France et al., 2017; WSO-UV Consortium, 2018). It is difficult to undermine the importance of these new developments. The present danger is that the UV range may not be any more accessible after the decommissioning of HST, a loss without precedent, since the UV has been accessible since the late 1978 after the launch of the International Ultraviolet explorer (Macchetto and Penston, 1978). The perspective is on the converse to have instruments with unprecedented resolving power and sensitivity, able to yield a full map star cluster and dwarf galaxies in the local Universe (apart from the heavily-extinguished regions in the Galactic plane).

The Euclid space mission, designed to study the baryonic acoustic oscillations (BAOs) from the large scale distribution of galaxies and quasars (see section 3.2.8 for a brief discussion) is expected to yield millions of moderate-resolution quasar spectra over the visual wavelength range (ESA, 2018). The Euclid spatial resolution of 0.2 arcsec is comparable to the Hubble Space Telescope and should provide an accurate redshift for the majority of the new sources identified by future imaging observatories, from radio to X-rays, at $z \lesssim 2$. The Euclid output is especially welcome as ground-based survey telescopes such as the Large Synoptic Survey Telescope (LSST) will make it possible to discover millions of quasar candidates. LSST telescope will have an 8.4 m (6.5 m effective) primary mirror, a 9.6 square-degree field of view, and a 3.2 Gigapixel camera. This system can image about 10,000 square degrees of sky in three clear nights using pairs of 15-s exposures twice per night, with typical depth for point sources of $r \approx 24.5$ (AB) (Ivezić, 2017). About 90% of the LSST time will be devoted to a deep-wide-fast survey mode which will uniformly observe a $18,000 \text{ deg}^2$ region about 800 times (summed over six photometric bands). For 10 years of operations, the stacked observations will yield a coadded map up to a limiting magnitude $r \lesssim 27.5$. These data will result in databases including 20 billion galaxies and a similar number of stars (Ivezić, 2017). Most of the candidate quasars identified by LSST will be too faint for spectroscopic studies with 4m class telescope, yielding only a handful of telescopes from which spectroscopy could be obtained. The SDSS V should offer the equivalent to LSST in terms of spectroscopic monitoring: all-sky, multi-epoch spectroscopic survey of over six million objects (Kollmeier et al., 2017), able to reveal spectral changes on timescales from 20 min to 20 years. It will be based on two 2.5 m telescopes that should yield a sky-survey rate of $\approx 40^\circ^2$ per hour, and complement high-energy surveys in the soft- and hard-X domains (eROSITA and Athena, introduced below), at least for the brightest sources, $i \lesssim 20$.

The SDSS V should still leave the faint end of the quasar luminosity function sampled by LSST. It may however serve as a testing experiment for dedicated, larger aperture telescopes. The need to cover spectroscopically faint sources ($i \gtrsim 21$) is already felt (see section 3.2.2 and e.g., the discussion by Sulentic et al., 2014), and will be even more felt in the next decades. It may become a major drive toward the development of more 30 m class and even larger aperture telescopes. Apart from costs, a 100 m telescope is already technologically feasible, and a phase I study for an “Overwhelmingly Large Telescope” was completed at ESO

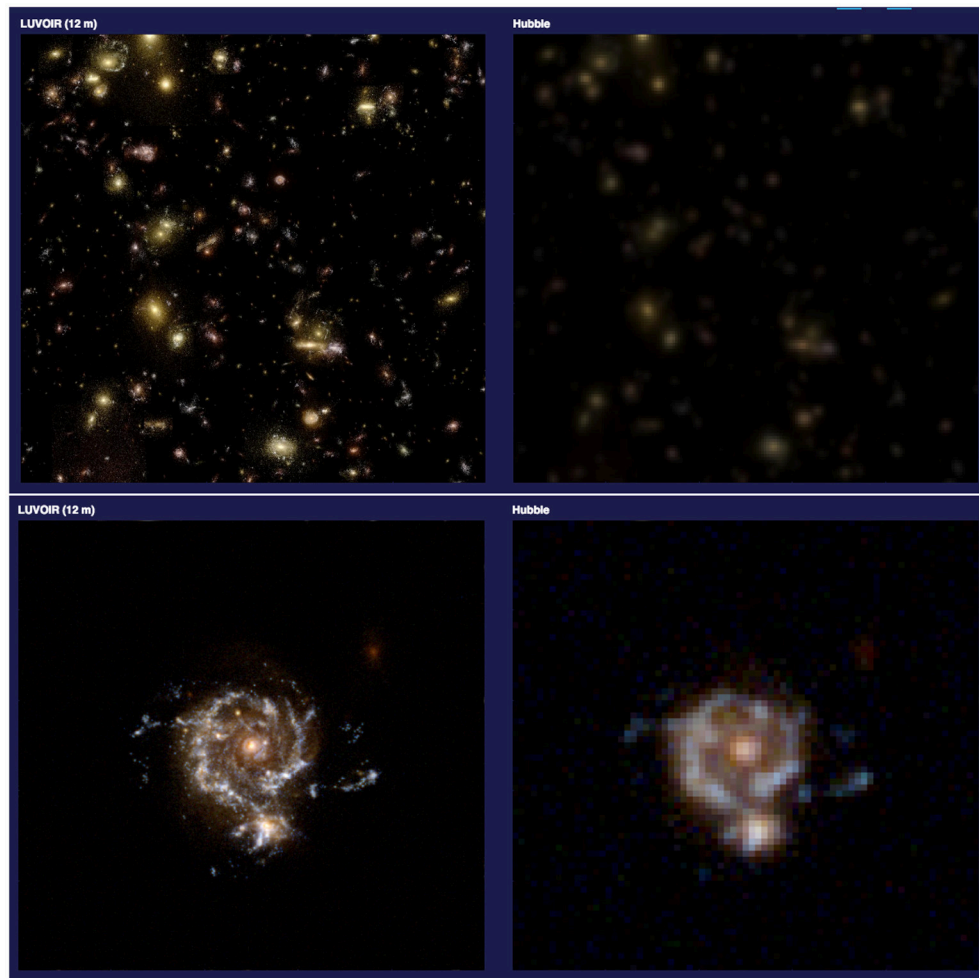


FIGURE 1 | Comparison between expected performance of LUVOIR, an optical space based telescope of 12m aperture (**Left**), and HST (**Right**), for a deep field (**Top**) and for the morphology of a galaxy at redshift ≈ 2 (**Bottom**). Credit: LUVOIR, image comparison page, at <http://luvoir.stsci.edu>.

(ESO, 2006). A 100 m telescope working at diffraction limit of 1 milli-arcsec can reach $V \approx 37$. This means the ability to sample and study objects in the Universe at the epoch of reionization with high efficiency. We are confident that one or more telescopes of the 100 m class will be eventually built around the 2050s.

2.1.2. X-ray/ γ -ray

The obscured Universe is an important part of extra-galactic studies. The word “obscured” refers here to the optical/UV domain that is subject to extinction by interstellar dust⁴. At present, astronomers looking at an all sky survey in the soft-X-ray domain have to rely on the ROSAT All Sky Survey (RASS) carried out over 6 months between 1990 and 1991. The RASS was tremendously successful and detected more than 60,000 X-ray sources over the whole celestial sphere. There is no all-sky survey in the hard X-ray domain above 2 keV presently available,

even if archival observations with XMM and Chandra now include several hundred thousands of exposures. New-generation instruments should be able to probe obscured sources (among them most quasars) in the next decades. eROSITA (extended ROentgen Survey with an Imaging Telescope Array) is expected to perform a deep survey of the entire X-ray sky. In the soft X-ray band (0.5–2 keV) eROSITA is expected to be about 20 times more sensitive than the ROSAT all sky survey with a resolution of 15–30 arcsec with a field of view of 0.8 deg^2 , while in the hard band (2–10 keV) it would provide the first ever true imaging survey of the sky at those energies (Predehl et al., 2010). Athena (over two orders of magnitude more powerful than current facilities) should also provide imaging capabilities in the 0.2–15 keV energy band over a 40 arcmin^2 field of view with angular resolution of 5 arcsec on-axis, simultaneously with spectrally and time-resolved photon counting (Guainazzi and Athena Study Team, 2017; Rau et al., 2017). The NuSTAR (Nuclear Spectroscopic Telescope Array) focuses light in the hard X-ray domain (3–79 keV) with an angular resolution of $\approx 1'$ (HPD) (Harrison et al.,

⁴Dark is used to indicate an early cosmic age at $z \gtrsim 6$ when the Universe was still at least in part opaque to the Lyman continuum radiation i.e., before reionization epoch.

2013). It is conceivable that angular resolution will be improved in forthcoming missions.

A powerful (albeit costly) strategy is to detect the track of γ -rays (as well as cosmic rays) through dedicated arrays of telescopes sensitive to the Cerenkov radiation emitted in the earth atmosphere. The Cerenkov Telescope Array (CTA), based on this approach, is expected to detect Cerenkov radiation from very high-energy (VHE) cosmic rays and γ -rays. The CTA, an array of ~ 100 built-for-purpose optical telescopes, should be able to cover a huge range in photon energy from 20 GeV to 300 TeV, and be a factor $\sim 10^3$ more sensitive on hour timescales than the space-based Fermi Large Area Telescope (LAT) at 30 GeV. The angular resolution of CTA will approach 1 arc-minute allowing detailed imaging of a large number of γ -ray sources. CTA will be the first VHE observatory that will reach the angular resolution needed for easy cross-identification of optical counterparts (Cherenkov Telescope Array Consortium et al., 2017).

2.1.3. FIR/mm/Radio

The Atacama Large Millimeter/submillimeter Array (ALMA) is an aperture synthesis array with 66 radio telescopes for sub-/millimeter astronomy. ALMA bands cover from 30 to 1,000 GHz (300 μ m), with typical resolutions of a few hundredths of arcsec (Testi and Walsh, 2013). The telescope has been operational since 2011, and it will remain operational in the next decades, providing an unprecedented view of the cold Universe. Some of the ongoing and potential research will be described in the next sections. After the huge success of the FIR/mm space observatories (ISO, WISE, Spitzer, Herschel), the future might involve new telescopes for surveys such as WFIRST or mainly dedicated for spectroscopy, for example SPICA (Space Infrared Telescope for Cosmology and Astrophysics) is targeted for launch in the late 2020s. With SPICA, the goals are to reveal “metal and dust enrichment through galaxy evolution” (Spinoglio, 2016) through low-to-high resolution capabilities in the MIR/FIR spectral range. Planned FIR observatories are single dish although it is conceivable that an ALMA-like heterodyne interferometer could eventually become in part space-based.

Currently, the Very Large Array-based FIRST (Becker et al., 1995) is the main radio survey of the Northern hemisphere carried out with a resolution of about ≈ 5 arcsec. Its catalog is overwhelmingly dominated by AGNs (at a detection limit of ≈ 1 mJy), and only a small fraction of sources are star-forming galaxies. At radio wavelengths, advances in digital signal processing and cost reductions are making it possible to build arrays composed of a large number of relatively small antenna elements, giving large fields of view with large collecting areas. Most sources detectable by the next-generation surveys (which will reach sensitivities of the order of 10μ Jy) are expected to be star-forming galaxies, so that these surveys are dominated by the same galaxies that are studied by optical and infrared (IR) surveys (Padovani, 2017). The Square Kilometer Array (SKA) with its unprecedented collecting area and baseline, will offer improvements over the JVLA, LOFAR, for resolving power (5 milliarcsec at 6cm for the widest array configuration, 3,000 km

s^{-1}), sensitivity and survey speed due to its relatively large field of view.

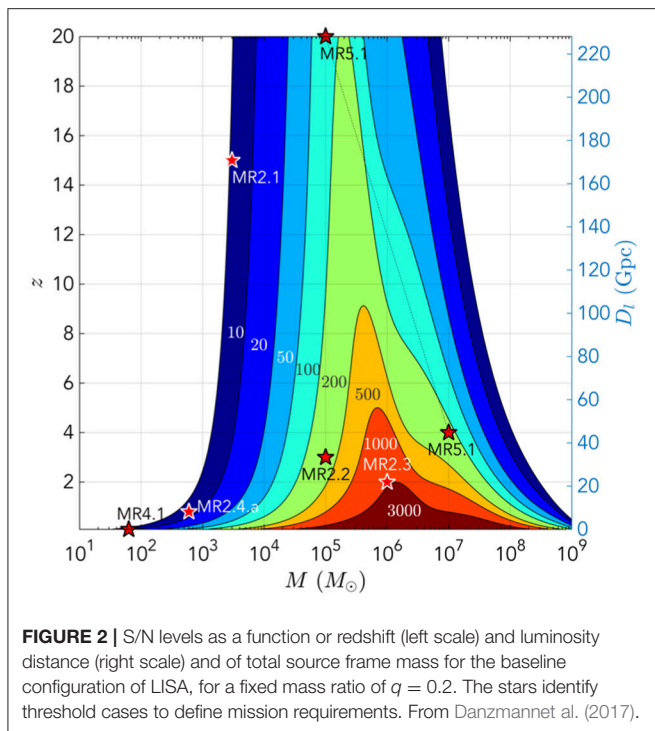
The RadioAstron telescope is an array of ground based telescopes with an antenna of 10m diameter in space (with a baseline of 350,000 km) that achieved the unprecedented spatial resolution of $\approx 35\mu$ arcsec at 6cm. RadioAstron is a successful effort that demonstrated the feasibility of VLBI with space antennae. It is reasonable to think that by 2050 more sensitive arrays with more antennae in space will be operational. Space based radio-antennae obviously yields an extension of the baseline, but can also take advantage of a much lower background noise that allows for a much wider dynamic range (especially helpful when trying to map a boosted jet and much fainter unboosted, extended features, a typical condition in extragalactic radio sources).

A poorly sampled radio frequency domain corresponds to the meter wavelength domain. There are several radio telescopes operating at low frequency, among them the Giant Metrewave Radio Telescope (Ananthakrishnan, 2005) that covers several bands between 50 and 1420 MHz, and the Murchison Widefield Array that covers the frequency range 80–300 MHz. The GMRT completed a survey at 150 MHz with resolution ~ 25 arcsec and noise level $\lesssim 5$ mJy (Intema et al., 2017). The VLA Low-Frequency Sky Survey Redux (VLSSr) provides a Northern view at 74 MHz with resolution about $80''$ and sensitivity 0.1 Jy rms (Cohen et al., 2007; Lane et al., 2012). With LOFAR and SKA low-frequency arrays of unprecedented sensitivity and resolution will become operational (≈ 0.1 arcsec at 100 MHz with SKA2 and ≈ 10 arcsec for LOFAR). LOFAR exploits an array of simple omni-directional antennas in place of a dish antenna (van Haarlem et al., 2013). A space interferometer would allow to extend the frequency range down to about 0.3 MHz, a frequency domain where earth's ionosphere opacity makes ground-based observations unfeasible (Basart et al., 1997).

2.2. Multimessenger

2.2.1. Gravitational Waves

Since spatial changes induced by gravitational waves occur with opposing sign for orthogonal directions, a Michelson interferometer has a well-suited geometry to maximize the tiny effect on the detector. Laser interferometry is employed for motion sensing (Hough et al., 2005). The next generation of ground-based gravitational observatories will be more than ten times more sensitive than Advanced LIGO that made possible the first detection of gravitational waves ever. Several laser-interferometric telescopes are under development or planned. Of them, the third-generation Einstein telescope in Germany has the potential to dramatically increase the detection rate of gravitational wave sources. The current design posits two independent interferometers located underground with vertices separates by 10 km in a triangular configuration. With this baseline the interferometer may detect merging of intermediate mass black holes, below the smallest masses that are found in the nearest AGN, $\sim 10^6 M_{\odot}$. Some of them may however be detected in the nuclei of non-active galaxies and be precursors of more massive BHs detected as AGN. LISA is expected to adopt a triangular configuration in space but the separation is planned to



be 2.5 million km, making the instrument unique to cover a low-frequency domain not accessible from the ground (Figure 2). It will be necessary to wait even beyond the first generation of space-borne observatories such as LISA to detect merging super massive black holes (SMBH $\gtrsim 10^9 M_{\odot}$, see Figure 2).

A complementary technique to detect low-frequency gravitational waves is to consider an array of millisecond pulsars and measure the pulse arrival times. Differences in arrival times (the timing residuals) should be correlated if produced by gravitational waves (Hobbs et al., 2010). Pulsar timing observations are used to place constraints on the rate of coalescence of supermassive black-hole (SMBH) binaries as a function of mass and redshift from the GW background in the nHz domain (Wen et al., 2011). At present the very existence of SMBH binaries is established in only a handful of cases. Larger pulsar timing arrays (i.e., involving a larger number of pulsar and a long temporal baseline will allow for the detection of a SMBH binary in a nearby galaxy, provided that the gravitational wave background can be adequately subtracted (Mingarelli et al., 2017).

2.2.2. Cosmic Rays

The CTA will detect Cerenkov photons emitted by the cosmic rays before their first interaction with the atmosphere. While the CTA will remain state-of-the-art in the next decades for atmospheric Cerenkov CR detection, it is expected that other type of CR detectors may undergo significant developments. For instance, a large collecting area can be obtained exploiting Cerenkov radiation emitted in dense media. In this case, the detection of Cerenkov flashes is achieved by using

photomultipliers submerged in water tanks over a large surface area, as in the case of “HAWC” (Carramiñana and HAWC Collaboration, 2017). Extensive air shower (EAS) arrays presently employ a variety of detecting techniques, according to the energies of the air shower particles that may include, drift chambers, scintillators and Geiger tubes, and other devices. The Auger Observatory employs a hybrid technique monitoring the sky with a fast UV-sensitive camera able to record the track of fluorescent emission (a near-UV line of sodium) associated with the interaction between the atmosphere and particle showers induced by CRs, in addition to water tanks for monitoring Cerenkov flashes.

Cosmic ray detection from extra-galactic sources has been a serious problems in the past decades. Low energy ($\lesssim 1$ GeV) cosmic rays are frequent (1 event/s/m²) and their detection straightforward with fog chambers. The cosmic ray energy spectrum (Beringer et al., 2012) is a power law that shows a steepening (a “knee”) at energy ~ 1 PeV, and then a flattening (an “ankle”) at ~ 1 EeV (in the domain of ultra-high energy cosmic rays, UHECRs). Acceleration from supernovae to energies ~ 1 EeV is ruled out. Around and above this energy the UHECR energy distribution is believed to be dominated by extra-galactic CRs. Since the spectral energy distribution of CRs is a steep power law, events due to extra-galactic CRs are exceedingly rare (at energies of the order of ~ 1 PeV, the expected flux is just 1 event/yr/m²). A major driver in the development of detectors with large collecting areas is therefore the nature of the CR with energies $\gtrsim 1$ PeV whose acceleration mechanism is unclear but believed to be at the heart of the inner working of radio jet acceleration.

2.2.3. Neutrinos

Neutrinos offer a unique diagnostic of extremely high energy processes, and they can, unlike cosmic rays, travel unimpeded across the magnetic field of the Galaxy. Given the weak interaction of neutrinos with matter, large masses are needed to reveal neutrinos. Mechanisms for the production of high energy neutrinos will also produce γ rays of similar energies. γ -ray telescopes such as CTA are expected to achieve precision pointing and sensitivity to identify populations of accelerators.

A common type of design of a neutrino observatory involves an array of photomultiplier tubes housed in transparent containers which are suspended within a large tank of pure water or ice (or other suitable materials) and aimed at the detecting the Cerenkov radiation due to leptons (typically muons) or to other decay products induced by the interaction with the neutrinos. Over the years, neutrino observatories have employed larger and larger volumes placed underground, to improve the detection rate and lower the background. The IceCube Neutrino Observatory is a cubic-kilometer detector that uses ice as a medium which detects Cerenkov radiation through an array of photomultipliers. At present, IceCube has detected $\lesssim 100$ PeV neutrinos of astrophysical origin. The PeV detections of IceCube might be substantially increased by a second-generation observatory, IceCube-Gen2 which should be based on a 10 km³ volume of ice at the South Pole (IceCube-Gen2 Collaboration et al., 2014). The large collecting volumes are needed in order

to detect extra-galactic neutrinos in the PeV energy domain. They are extremely rare and likely the ones produced in active nuclei. The neutrinos detected using reconstructed muon tracks, are unambiguous tracers of hadronic acceleration, up to high redshifts and beyond PeV energies. This means that at present, data rest on several tens of neutrino detections, and that larger volumes are needed to have a good statistics of UHE neutrinos to make them of relevance for the study of relativistic jet formation physics (section 3.2.7). A high-energy neutrino background has been revealed by IceCube since 2013 (Icecube Collaboration, 2013), and blazars have been suggested as a likely source (Padovani et al., 2016). Very recently, IceCube detected an ≈ 290 TeV neutrino for which follow up γ -ray observations have made possible, for the first time, the identification with an electromagnetic counterpart, the flaring γ -ray blazar TXS 0506+056 (Icecube Collaboration, 2018).

2.3. Computing Power and Software Development

Increase in computing power cannot follow the Moore's law forever. The Moore's law posits that the surface density of transistors on integrated circuits doubles approximately every 2 years. However, the limiting size of the technology is about 2–3 nm (down from about 14 of today, which may still implying a more than tenfold increase in computing speed), and may be reached around 2025. At present it is not clear what may follow. The clock speed saturated at about 3GHz because faster speeds produce too much heating (Evans, 2014). The increase in speed in the last years has been achieved by building multicore processors. Two hundred petaflops can be obtained in supercomputers that house a large number of cores, and computers reaching the 1,000 petaflops will be build toward the 2030s. These computers are the best hopes for modeling of chaotic astrophysical environments. Quantum computing is still in infancy, and it is not yet clear whether an all-purpose mainframe can be built. However, the potential for contribution to computational astrophysics in the next decades is enormous, even epoch-making (Cross, 2016).

2.4. Artificial Intelligence for Data-Driven Science

Large surveys and simulations will provide data in the order of the petabyte; SKA is expected to store more than 1 petabyte of data per day. These “big data” will require *ad hoc* solutions for storage and data processing and retrieval. The radio interferometric data processing should become especially data intensive, as instrumental configurations such as the one of LOFAR demand special approaches to compensate for the individual antennae lack of directionality. Numerical models of increasing complexity may involve the accretion disk structure as well as the interaction between the accretion disk and other compact objects orbiting the same black hole. Magneto-hydrodynamics simulations in general relativity are needed to provide realistic model of the multi-phase quasar winds at the origin of feedback effects. Large scale cosmological simulations like the Illustris (Springel et al., 2005) still fail to reproduce the diversity in galaxy properties, and treat central BH in a primitive

way. There is a large latitude of improvement for SPH codes that exploit enhanced computing power.

Major surveys are expected to produce huge amounts of reduced data as well as public-domain Virtual Observatory (VO) compliant catalogs of measurements. The analysis of large amounts of data provided by instruments from the new generation of telescopes and numerical experiments is expected to become increasingly cumbersome for human researchers. Ultimately, neural networks and other forms of artificial intelligence may become a necessity to manage the sheer amount of data. Deep machine learning has been considered for applications to astronomy since the late 1980s. A convolutional neural network is a class of deep, feed-forward artificial neural networks that has successfully been applied to analyzing visual imagery. Deep neural networks are being exploited for a host of problems associated with visual morphological classification, a frequent necessity in astronomy. For instance, they proved to be very effective in evaluating galaxy morphology, and extracting morphological parameters such as Sersic index and isophotal magnitudes (Tuccillo et al., 2018), as well as in the classification of radio morphology (Aniyan and Thorat, 2017).

3. EXPECTED PROGRESSES ON SELECTED, PRESENT-DAY SCIENTIFIC THEMES

Summing up the previous discussion of instrumental capabilities, we can say that we can expect the ability to probe much deeper than today with planned instrumentation. Observations with active optics may become commonplace with the largest telescopes, yielding an overall improvement of a factor ~ 10 in resolution for “every night” observations in the optical and NIR domains. The largest telescopes are expected to reach magnitudes ~ 30 , with a more-than-tenfold improvement with respect of today. In ranges where spatial resolution has been poor (low-frequency radio, hard X-ray, γ -ray) improvements are expected to bring the resolution $\sim 1'$. This means that, for example, bright optical extra-galactic sources could be unambiguously identified with their γ counterparts in the wide majority of cases. We can now focus in more detail on the possibilities that the new instrumental capabilities will offer in the study of galaxies and quasars, and nuclear activity in general.

3.1. Galaxies: Studies in the Next 30 Years

Imagining the future of our understanding of galaxies is not an easy task, in particular for researchers who formed their background of astrophysics during the epoch of transition from photographic plates to CCDs, when the only big telescope was the 5m Hale in Palomar and few space missions were already launched (e.g., IUE, Uhuru, Ariel 5) and ROSAT as well as HST were still to come. At that time radio observations already revealed the spiral structure of our Galaxy and the first radio sources were identified with optical counterparts. This is the epoch when computers started the first data reduction of astronomical images and spectra and the most-widely used compiler was Fortran 77. Galaxies were singularly studied through deep CCD images or

photographic plates (micro-densitometers were still largely used) with optical filters (B and V Johnson) or long slit spectra, and the first numerical models started to appear in the astronomical literature.

The progress in all fields of astronomy has been so far-reaching during these 30 years that a single researcher could not be up-to-date of the whole literature with the exception of his/her specific interests. When we think that only 100 years ago the humankind was not aware of the existence of galaxies, we are legitimate to feel very happy of being part of such a fantastic development of our field.

Coming back to the theme of this review, the first step to imagining the future of the study of galaxies is to keep in mind first why we study galaxies. The second step is to make a list of the hottest research topics in this field. The first item is necessary because it acts as the helm of a ship. Remembering why we study galaxies it is important to stay on course, to follow the aims of our projects. The second item is fundamental because we plan today our future researches and this implies to know many things, last but not least how much they cost in terms of economical resources.

Why do we study galaxies? Galaxies are the largest gravitational bound systems where stars are “organized” to trace the baryonic matter in the Universe. If our aim is to reconstruct the history of the Universe, we must understand how such organization of stars in galaxies changed during the cosmic epochs. This means to examine how stars are distributed at all spatial scales, how and when galaxies and stars formed and in which way the population of stars evolved. With such motivation, we can easily predict that the focus of our future researches will be to understand the origin of galaxies. This implies that most of the efforts will be dedicated to the studies of high redshift objects.

When do galaxies emerge from the dark era? Which kind of stars formed first? How long was the epoch of re-ionization of the Universe and what kind of sources contributed to it? Were the first galaxies similar in structure and shape to those we see at low z ? What was the contribution of merging in shaping the galaxies observed at recent cosmic epochs? How did the chemical elements produced by stars contaminate the galactic medium that formed new stars enriching it of metals? What does trigger the star formation (SF) and in which way this phenomenon evolved in the various types of galaxies? These are only a few examples of questions that still have only an approximate answer. They act as a beacon in the night and they will likely remain fundamental questions for many years to come.

Up to now coordinated efforts exploiting multi-wavelength observations have permitted to trace a preliminary picture of the evolution of the star formation in galaxies. In particular we have measured the star formation rate density (SFRD). This is the rate at which stars formed within galaxies in comoving volumes of the Universe. Most of the merits of such achievement can be attributed to space missions like HST, Spitzer, Herschel, and Galex. The surveys carried out with these telescopes permitted to acquire a large database of galaxies observed at different cosmic epochs. We should not forget however the important contribution of the optical surveys at smaller redshifts, like e.g.,

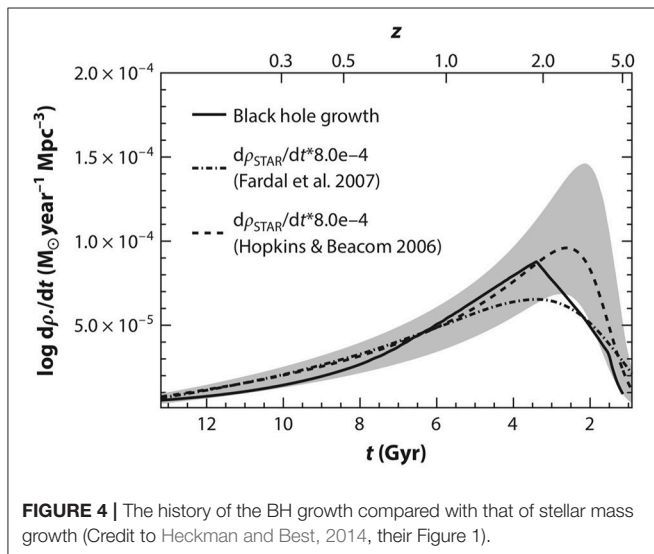
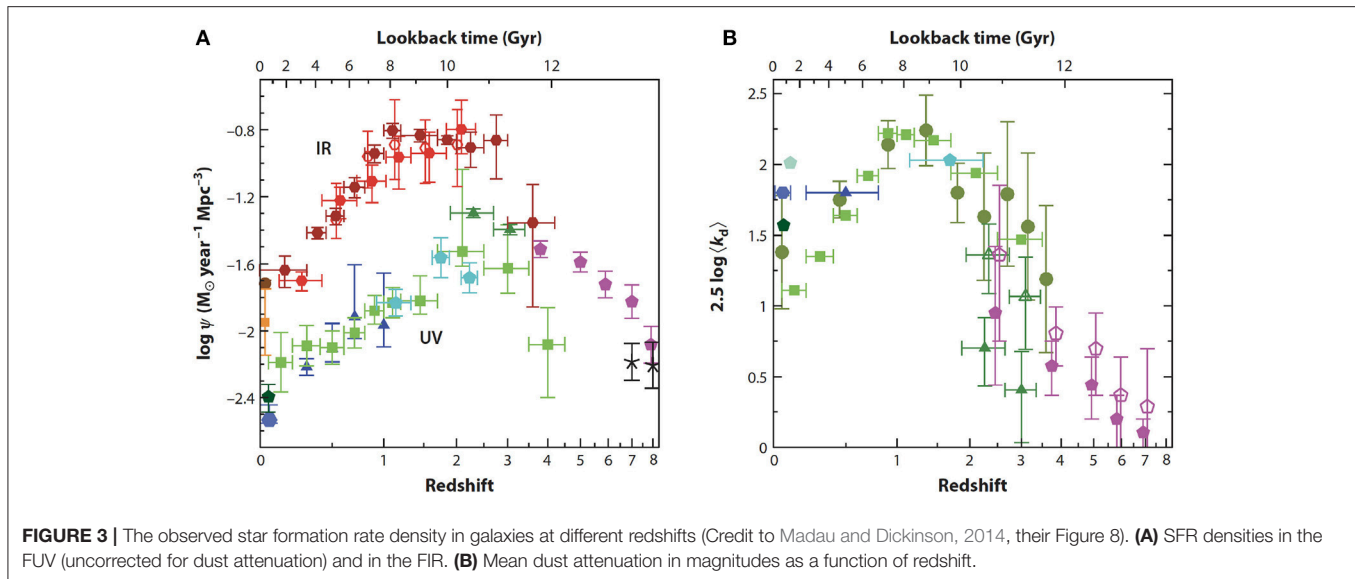
the SDSS. The SDSS sample contains $\sim 300,000$ galaxies brighter than L^* , the turning point of the galaxy luminosity function, within a volume of $\approx 0.05h^{-3} \text{ Gpc}^3$ (Bell et al., 2009).

Madau and Dickinson (2014) provided a comprehensive review of the history of star formation across cosmic epochs. Their most famous figure is reproduced here in **Figure 3**. The data indicate that the SFRD peaked at $z \sim 2$, i.e., approximately 3.5 Gyrs after the Big Bang and that nearly half of the stellar mass observed today was already in place at $z \sim 1.3$. The Universe was very active in forming stars in the past, with a rate much larger than what we measure today, while at the present epoch the SFR is very low.

The observed trend and the well-known $\text{SFR} - M^*$ relation between SFR and stellar mass, suggest that such behavior is due to a balance between the accretion of gas and the feedback effects from SNe and active galactic nuclei. It seems that the stochastic events provided by mergers do not play a significant role. This might appear in contrast with the widely accepted view that we live in a hierarchical Universe, where structures form by subsequent merging events, but it is clearly a symptom of our still poor knowledge of the processes that occurred in galaxies at different cosmic epochs. The most recent numerical simulations running in the cosmological framework are in fact able to reproduce many observed features of present day galaxies (see below).

In this respect the recent work by Chiosi et al. (2017) provides one possible theoretical explanation of the trend seen in **Figure 3** which is due to a combination of effects: the number of galaxies of a given mass at each redshift (regulated by the hierarchical structure of our Universe), and the time-delayed star formation of galaxies. The star formation in galaxies starts at a low rate, grows to a maximum and then declines. Within the formalism of the infall models, the gas is gradually converted into stars ($\dot{M}_s \propto (t/\tau)\exp(-t/\tau)$). This kind of behavior is different for galaxies of different masses. While massive objects have a rapid increase to a maximum SFR followed by a prolonged decline, smaller systems have a slow progressive increase of the SFR followed by episodic events. In their models the large feedback effects from AGN (section 3.2.3) do not seem to be relevant. This is in contrast with the conclusions of Tescari et al. (2014) and Katsianis et al. (2017) who found that the key factor for reproducing the SFRD is the combination of feedback effects. Interestingly, a very similar trend is observed when we look at the growing history of the super-massive black holes (**Figure 4**), suggesting a close connection between the two physical phenomena (see e.g., Heckman and Best, 2014).

The idea about the formation and evolution of galaxies is that stellar systems grow primarily for the accretion of gas from the cosmic web. Major mergers of gas-rich systems happen and provide strong bursts of star formation, but do not seem to contribute to the bulk of star formation (they might do so for $\sim 10\%$). This seems consistent with numerical simulations and with observations of the star-forming galaxies (see e.g., Dekel et al., 2009; Wuyts et al., 2011; Lilly et al., 2013). In an analogous way, the accretion of SMBHs must be related to the growth of the inner region of galaxies. The efficiency of the two processes are



different, but both rates reflect the way in which gas is accreted and transformed.

Clearly the possibility of making significant progresses in this area is closely linked to our ability of planning new powerful telescopes for the ground and space. Among the various projects that will have a big impact on the next 20 years we should mention the JWST and the ELT whose construction has started in the Chilean desert. The ground-based telescopes will in fact largely benefit of the progresses made in adaptive optic systems, like e.g., MAORY.

In the next decade high redshift observations would likely permit to formulate a coherent picture of galaxy evolution linking the data available for the different cosmic epochs. What is important is to establish which physical processes play the major effects and are responsible of the major transformation observed in size, morphology and stellar population content.

By studying the earliest galaxies JWST and ELT will contribute to understand how galaxies grow and evolve. These telescopes will gather data on the types of stars that populated the very early objects. The spectroscopic follow-up observations will help to clarify how elements heavier than hydrogen formed and built galaxies through the cosmic ages. These studies would also contribute to understand the role of merging among galaxies and to have a much better knowledge of the mechanisms of feedback from supernovae (SNe) and AGN.

The AGN feedback has characterized the evolution of galaxies in particular during the epoch of major interest for the stellar population evolution in galaxies at $z \sim 2 - 3$. The galaxies we see today around us have already experienced the turbulent period that characterize the first structures. Their SF is almost null or very small and the enormous feedback effects are no more present. So, the Universe we are going to discover in the new decades contains galaxies at their infancy and we know that this is a turbulent period not only for galaxies. The new generation of astronomers will face and will be called to explain all the processes that galaxies have experienced during their lifetime.

A further step forward requires the analysis of data coming from large optical and spectroscopic near infrared surveys. In particular it will be extremely important to address the nature of galaxies fainter than L^* at the redshift were these objects assembled, i.e., around $z = 2 - 3$ (where we observe the peak of star formation density and black hole accretion activity) (Madau and Dickinson, 2014).

The first galaxies with redshift larger than 1 were discovered with a color selection technique (see Steidel et al., 1999) and called Lyman Break Galaxies (LBGs). These are galaxies with moderate masses ($10^9 - 10^{10} M_\odot$) and metallicities (~ 0.3 solar), characterized by a rapid SF and significant outflows from SN winds. Later on a class of distant red galaxies (DRGs) was discovered (see Franx et al., 2003). These objects cannot be isolated through the color selection technique. They are generally more massive and red than LBGs. Some of them suffer a

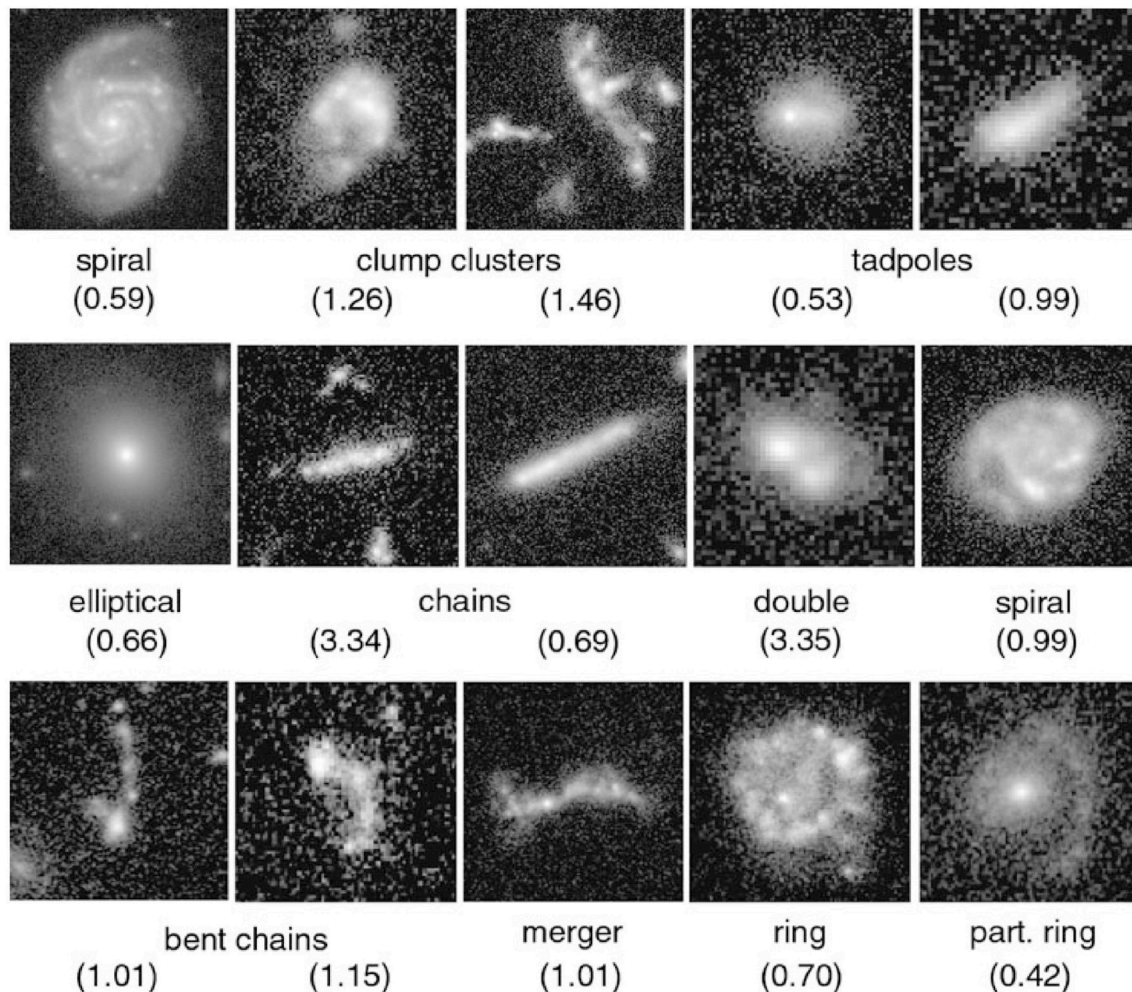


FIGURE 5 | Morphology of galaxies at intermediate and high redshift. Redshift is given by numbers in parentheses. (Credit to Buta, 2013, his Figures 1–46, from Planet and Stellar Systems).

conspicuous obscuration by dust. This the class of high redshift galaxies increased in number since new telescopes were able to detect more objects at $z = 2 - 3$. We have now a zoo of galaxy types (see e.g., **Figure 5**). This clearly reflects that we are at the beginning of a new era, very similar to that of 100 years ago, when galaxies were discovered as isolated “island universes.” A lot of work is therefore needed to assemble a coherent picture, to classify the galaxy types and to understand the transformations that have produced the objects we see today.

The morphological transformation of galaxies is generally accompanied by an evolution in size of stellar systems. Galaxy size is typically measured through the effective radius R_e , the radius of the circle enclosing half the total luminosity. Observations have shown that both local early-type and late-type galaxies follow a direct relation between size and stellar mass M^* (see e.g., Shen et al., 2003; Valentinuzzi et al., 2010; Cappellari et al., 2013; Li et al., 2018). The distribution of galaxies in the mass-size plane appreciably vary with velocity dispersion, age,

metallicity and stellar mass-to-light ratio (Cappellari et al., 2013; Lange et al., 2015). This behavior confirms that there is a fine-tuning between the stellar population that each galaxy forms and its structural shape and dynamics. The same mechanism is likely at the origin of the Fundamental Plane, the scaling relation involving size, effective surface brightness and velocity dispersion (see e.g., D'Onofrio et al., 2017). The existence of a fine-tuning implies that the dynamical condition of a galaxy have an active role in determining the amount of star formation of each system and the epoch of its occurrence. This is surprising being the SF a local phenomenon triggered by the local density of gas and dust.

At high redshift the observed quiescent early-type galaxies have more compact sizes (by a factor of 3–5) than local objects (Daddi et al., 2005; Trujillo et al., 2006; van Dokkum et al., 2008; Straatman et al., 2015; Belli et al., 2017). The kinematical studies measured increasingly larger stellar velocity dispersions and smaller sizes up to redshifts $z \sim 2$ (Newman et al., 2015; Belli et al., 2017).

The questions posed by these observations are therefore: how massive and compact systems could be already in place at early cosmic epochs in a hierarchical Universe where the large structures are the last to form, and what are their progenitors? What processes drive the evolution of these systems and the quenching of star formation? All these questions will find in the future planned sky surveys from ground and space, with billion of new data, the possibility of being answered.

Before the consolidation of the so-called “precision cosmology” that is today represented by the Λ -CDM model, according to which the Universe consists of 70% of dark energy (DE), 25% of dark matter (DM) and 5% of ordinary matter, galaxies were the main objects that enclosed the information on the cosmological parameters. Constraints on Ω and H_0 were often derived by studying galaxies at different redshifts, determining their distances, metal abundances, masses and ages. Today the works on the cosmic microwave background (CMB), the SNe as distance indicators, the Sunayen-Zeldovic effect on galaxy clusters, the gravitational lensing, the quasars and the large scale structure of the Universe have largely eclipsed the importance of the stellar population studies at high redshifts for the measurement of the cosmological parameters. However, once galaxies will fill the gap due to the lack of a coherent picture of their stellar populations at redshift $z = 2 - 3$, they could contribute very important information. We should remember that stellar evolution is a natural clock that we can use to measure the age of systems in the Universe. So when we will have a much clear view of the stellar populations that dominate at large redshifts, we could be in the position of linking descendants and progenitors simply on the base of the prediction of stellar evolution.

A still open problem is that we do not know the nature of DM, although we can constrain its distribution through dynamical studies of clusters and satellite systems, working on the intergalactic absorption visible in the spectra of high redshift objects, and studying gravitational lenses.

These are particularly promising since future large scale imaging surveys will likely increase the number of strong lensing candidates. These objects are difficult to find, but great results are expected from the automated search methods in rapid development (see e.g., Alard, 2007; Seidel and Bartelmann, 2007; Gavazzi et al., 2014; Joseph et al., 2014; Bom et al., 2017). A strong gravitational lens occurs when a distant galaxy or quasar is aligned with a foreground galaxy or cluster of galaxies whose gravitational field might create multiple, highly distorted images of the background object. Strong lensing could also magnify the brightness of a source. General relativity has permitted a profound understanding of the lensing phenomenon enabling their use for the study of the dark matter distribution around galaxies and clusters (see e.g., Koopmans and Treu, 2003; Wayth et al., 2005; Vegetti and Koopmans, 2009; Tessore et al., 2016). Lenses have also been used to measure the Hubble constant and the cosmological parameters (e.g., Blandford and Narayan, 1992; Witt et al., 2000; Suyu et al., 2013; Treu and Marshall, 2016). This can be better accomplished when the constraints from strong lenses are coupled with those coming from weak lenses (see e.g., Bartelmann et al., 2002). This definitely more

important at larger scales. The weak lens from galaxy clusters might distort the shape of background galaxies and affect their apparent brightness. This phenomenon may then permit the determination of the primordial power spectrum of the DM distribution through measurements of the shear on large angular scales (see e.g., Maturi et al., 2011).

The SKA, LSST and the Euclid space telescope will likely increase the number of lenses by orders of magnitude (see e.g., Oguri and Marshall, 2010; Collett, 2015). Estimates give $\sim 200,000$ observable galaxy-galaxy lenses from Euclid. A big jump considering that up to now less than a thousand lenses have been discovered across many heterogeneous surveys.

Today, despite the past efforts, there is still a large uncertainty latitude concerning the mass of the DM halos (see the contribution of P. Kroupa in D'Onofrio et al., 2016), especially for the smallest galaxies whose mass merges with the mass distribution of globular clusters; in such cases, DM halos might be completely absent (van Dokkum et al., 2018).

The situation is promising in particular because astronomers have learned how to model the behavior of the DM component with N-body simulations on large computers. Unfortunately, the behavior of the baryonic component is complex. This will be a key question for the future. The problem is the large dynamic range of the baryon interactions, from the scale of stars to that of galaxies. What we know is that baryons collapse in the DM halos forming the first stars and that the gas often feed large super-massive BH at the center of galaxies, originating enormous feedback effects in terms of energy and matter moved all across the galaxy body.

The future astrometric mission Theia is aimed at probing the dark matter distribution in galaxies and the power spectrum of density perturbations. Theia could permit a detailed study of the shape of the dark matter profiles (core or cuspy) that are known to depend on different processes induced by the baryon physics, such as star formation, self-interaction, BH growth, etc. (Read et al., 2016). At the same time the sub-micro-arcsec astrometry of Theia should permit for the first time high-precision proper motion measurements (even of nearby galaxies) that could remove the degeneracy between radial dark matter profile and orbital anisotropy, clarifying the nature of DM particles.

The standard hierarchical model of galaxy formation and evolution has permitted up to now to follow the evolution of the cosmic structures, to observe the creation of the first galaxies up to the appearance of the galaxies we see today. The “Illustris” project is one of these large-scale cosmological simulations (see e.g., Springel, 2005; Springel et al., 2005; Vogelsberger et al., 2014; Sijacki et al., 2015). The model tracks the expansion of the Universe, the effects of gravity and the hydrodynamics of the gas, as well as the formation of stars and black holes. The simulation starts from very initial cosmological conditions and maps the evolution of a big volume of the Universe up the present epoch. A wide range of masses, rates of star formation, shapes, sizes of the galaxies we see today are reproduced.

Despite the success of these simulations a number of severe problems still affect galaxies and the structures that are reproduced. One is that it is difficult to form realistic disk structures (the so-called angular momentum catastrophe). Another one is that the amount of stars that can be predicted with

a simple physical receipt is largely overabundant with respect to what observations tell us. There are today a number of tensions between theory and observation that will likely characterize the future epoch. Probably many of these are due to the fact that we do not know so well the complex physics of baryons.

In any case the enormous growth of numerical simulations will likely characterize the years to come. At present we are still testing the power of simulations in representing reality. The complexity of the problem does not permit to numerical calculations to fully capture the correct answer across all scales of space and time. The finite resolution, i.e., the size of the smallest details that can be reproduced implies that some processes, such as the birth of individual stars, cannot be followed by cosmological simulations. As a consequence many physical approximations are necessary to accomplish the whole simulation.

The expected increase in computing power will certainly help numerical simulations and will be particularly useful, when managing the enormous databases of galaxies at different redshift that the various projects have in program. New statistical approaches to the data should be adopted to extract the driving processes of galaxy evolution. It is well-known in fact that galaxy properties are mutually correlated: e.g., mass correlates with color, morphology, metallicity, SF rate, gas content, etc. and that galaxy environment also plays a role. It is therefore far from being simple to recognize the paths of evolution. In this respect the cladistic approach (see Fraix-Burnet et al., 2017) seems promising. The phylogenetic approach, also adopted in biology, try to establish a relationship among different species by minimizing the total evolutionary cost. The tree that results from cladistic analysis is not a genealogical tree, in the sense that it does not show ancestors and descendants (i.e., the ontogeny of individual galaxies), but the phylogenetic tool can take correctly into account the evolution of populations of objects. This technique requires an enormous amount of computing time (Fraix-Burnet et al., 2015).

The phylogenetic analysis provides information equivalent to that of “scaling relations,” but in a larger space defined by the number of parameters. The classical 2D or 3D scaling relations, that identify some paths of evolution. For example the mass-metallicity relation constrains the amount of gas inflow and outflow during the cosmic epochs (see e.g., Hartwick, 2017; Torrey et al., 2017; Lian et al., 2018; Truong et al., 2018) and the mass-size relation constrains the epoch and location of star formation (see e.g., Zanella et al., 2016; Sweet et al., 2017; Li et al., 2018). The phylogenetic analysis offers the possibility of testing some ancestral hypothesis by rooting the phylogenetic tree on a physical or observational parameter. We are confident that the method has a high scientific potential also in the field of galaxies and quasars.

Figure 6 shows an example of such analysis applied to the data of the WINGS survey (see e.g., Fraix-Burnet et al., 2017). The colored lines mark the families of objects sharing similar properties according to a pre-clustering analysis (computing power was not sufficient to consider individual galaxies). **Figure 6** shows the cladistic tree of 300 pre-clusters of the WINGS sample of 1,494 galaxies. Lower masses are at the

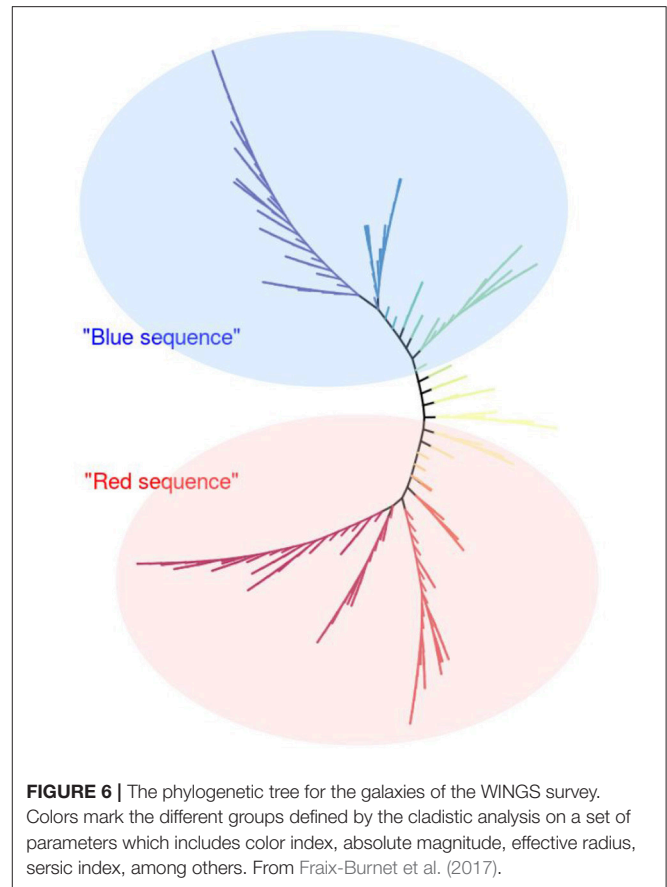


FIGURE 6 | The phylogenetic tree for the galaxies of the WINGS survey. Colors mark the different groups defined by the cladistic analysis on a set of parameters which includes color index, absolute magnitude, effective radius, sersic index, among others. From Fraix-Burnet et al. (2017).

top and each leaf (ending branch) of the tree is one pre-cluster. Each group of galaxies thus corresponds either to a single branch or to a bunch of branches on the tree. The color progression from blue to red grossly matches the increase in mass of galaxies. Interestingly, the morphological type decreases along the tree downward. Even if the tree of **Figure 6** is unrooted, the cladistic analysis is able to reconstruct a phylogenetic sequence that separates the blue and red sequence of galaxies.

A further step forward for our understanding of galaxies will be obtained when we will be able to trace the behavior of the cold neutral and molecular gas up to the first cosmic epochs. The drivers of LOFAR and SKA are the capability to probe deep into the redshift range of the reionization epoch from 6 to 20, mapping the formation of massive galaxies, clusters and black holes using $z \leq 6$ radio and starburst galaxies as probes.

The maps provided by e.g., ALMA and SKA will be important to understand the relation between SF, gas density and kinematics and could contribute to clarify the mechanisms of starburst and AGN activity with the associated feedback processes. The ALMA data for our own Galaxy will also provide the opportunity of resolving the gas transformation in the vicinity of the central BH. The environment around a BH is very poorly known. What we know is that the central region of galaxies are very dense and are dominated by gas cloud collisions and strong magnetic fields. The

knowledge of the chemical enrichment in this region is crucial to understand the origin of BH itself. At the time of writing this contribution, strong molecular outflows have already been measured by ALMA using e.g., the CO lines and other molecular transitions. All these data will provide a significant advance for our understanding of the feedback process and the inter-stellar medium (ISM) enrichment.

For neutral Hydrogen, SKA with its unprecedented sensitivity will certainly contribute to create a better defined picture of the formation and evolution of the first stars and of the galaxies after the Big Bang, and will provide important information on the role of the cosmic magnetism, as well as on the nature of gravity, and possibly even on the existence of life beyond Earth. Hydrogen is the most diffuse element in the Universe and we can exploit its distribution to afford one of the mysteries of the current cosmology: the nature and the role of dark energy. DE is responsible of the observed acceleration of the Universe, but its nature is unknown. The next 50 years will likely be dedicated to solve the puzzle posed by the current cosmological model. SKA should be able to detect the young forming galaxies at very high redshifts, so that HI maps might include million of galaxies. The origin and evolution of cosmic magnetisms will be one of the key researches of the new astrophysics that can change the future of our understanding of galaxies.

The nature of the DE can in principle be constrained by reconstructing the cosmic expansion history and the linear growth of cosmic structures. In this context the future ESA mission Euclid, by mapping billion of galaxies, will be able to provide the geometry of the dark Universe and classical spectroscopy is still mandatory to check for systematics effects in all measurements. Cluster velocity dispersions also require precise spectroscopy to reconstruct their evolution and spectra will be fundamental to test AGN activity and systematic variations in the progenitor properties of SNe (a method that requires a good knowledge of metallicities, SFRs, and dust contents).

The large-scale photometric surveys used for example by BAOs or by the lensing statistics also require a precise spectroscopic calibration. Baryonic Acoustic Oscillations (BAOs) are regular density fluctuations of a fluid of baryonic matter and photons present in the primordial Universe during the clustering of structures. Pressure generated expanding sound waves were imprinted on this fluid. With the expansion of the Universe the expansion of the pressure wave stopped and photons streamed away while BM and DM locked together for gravitational attraction. This gave rise to the acoustic peak visible in the data of the SDSS and 2dFGRS as a characteristic scale bump of galaxy clustering in the power spectrum (Cole et al., 2005; Eisenstein et al., 2005). The position of this bump is a powerful cosmological probe that will be studied in detail by the Euclid mission. The BAOs provide what in cosmology is called a “standard ruler”: Tighter and tighter constraints may be obtained in a not-so-distant future by high resolution spectroscopy on the next generation of large-aperture telescopes. DESI aims at constructing a 3-dimensional map spanning the nearby universe to 3Gpc (Levi et al., 2013). First light is expected in 2019.

3.2. The Next 30 Years (and Beyond) in Quasar Research

3.2.1. Evolving Quasars, the Obscured Universe, and the Dawn of the Present-Day Universe

Figure 7 depicts the early stages in the evolution of quasars from low to high redshift ($0 \lesssim z \lesssim 6$): merging and strong interaction lead to accumulation of gas in the galaxy central regions, inducing a burst of star formation. In this phase, the quasar may remain shrouded by a dense cocoon of gas and dust, opaque to UV and optical radiation. In the most extreme cases, the cocoon may be Compton thick and therefore so opaque that soft-X-ray emission can be blanketed (if the column density of absorbing gas is $N_{\text{c}} \sim 10^{25} \text{ cm}^{-2}$, a source is fully absorbed up to $\sim 10 \text{ keV}$, Comastri, 2004), and even emission at $\sim 10 \text{ KeV}$ is significantly absorbed. These sources are expected to be visible only in the hard X-ray domain, by instrument such as *Nustar*. The “obscured” phase may well occur after the collapse of the first seed black holes at redshift $\gtrsim 10$. Mass loss due to stellar winds and supernova explosions provide a large amount of enriched gas that is accretion fuel for the black hole. The accretion rate is initially expected to be very high, yielding maximum radiative output per unit mass. Radiation force and mechanical energy can then sweep away the dust surrounding the accreting black hole, at least within a cone coaxial with the accretion disk axis. An unobscured (if seen not too far from the cone's axis) quasar is born. This scheme may apply to seed quasars of masses as low as $10^{3-4} M_{\odot}$ in the primordial Universe as well as to low-mass local quasars (local quasars that may be quasi-analogous of highly-accreting seed black holes have been identified since long, Mathur, 2000; Sulentic et al., 2000). In the case of primordial seeds, direct black hole collapse and enormous star formation rates may be associated with the build-up of the protogalaxy (instead of the merging phase depicted in **Figure 7**).

The sketch of **Figure 7** identifies several key elements that are at the root of the complex physical processes in quasars:

1. The connection between black hole growth and the build-up and evolution of galaxies, which involves the interplay between accretion and star formation. The first side of the issue is what the physical conditions (e.g., fueling mode, triggering mechanism) that initiate major black hole accretion events should be. The second side involves the mechanical and radiative output of the quasar (understood as an accreting black hole). What is the nature of AGN feedback?
2. The accretion process itself. The basic process of accretion is self-similar although it may take different forms as a function of accretion rate, black hole mass, and spin, and these parameters are expected to be not only a function of cosmic epoch, but of environment as well (for example, merging leading to a sizable population of massive black hole binaries).

These issues are addressed by detailed studies of both nearby and distant SMBHs, and will of course benefit from the wide array of instruments providing very high spatial resolution from ground (active optics; interferometers) and space.

ALMA can locate star-formation activity hidden by dust, and identify spectroscopically the cooling of molecular clouds

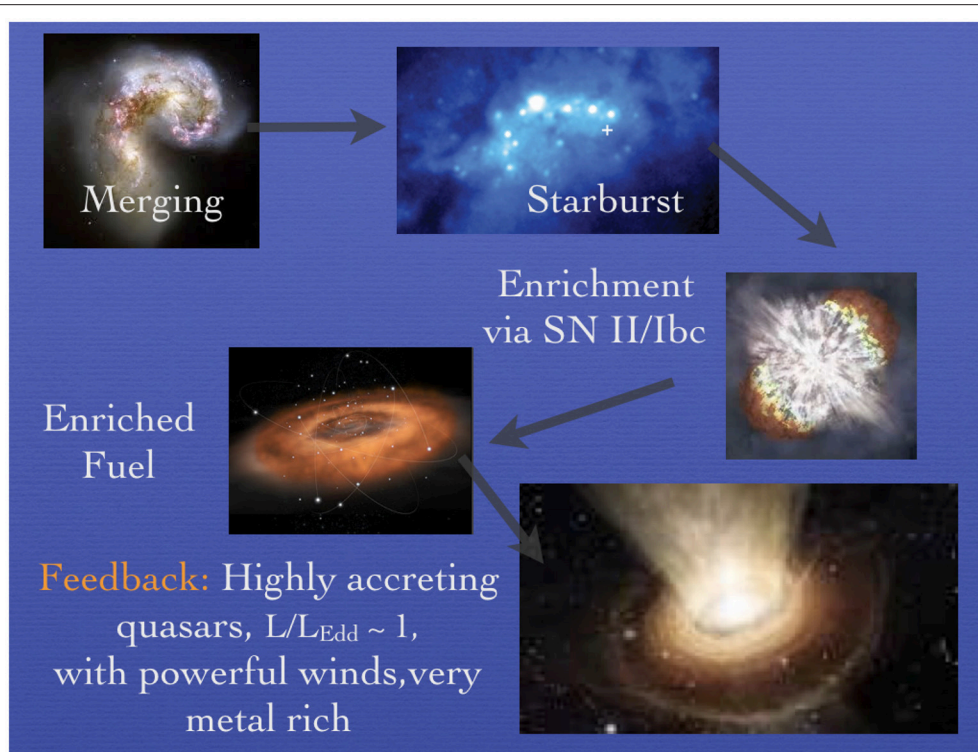


FIGURE 7 | The early stages in the evolution of AGN and quasars: merging and strong interaction lead to accumulation of gas in the galaxy central regions, inducing a burst of star formation (**Top**). Mass loss due to stellar winds and supernova explosions eventually provides accretion fuel for the massive black hole at the galaxy center. Radiation force and mechanical energy can then sweep the dust surrounding the black hole, at least within a cone coaxial with the accretion disk axis from where the radiative and mechanical output is free to escape into the host galaxy ISM (**Bottom**).

with primordial chemical composition. ALMA is a powerful tool with the potential of clarifying the inter-relation between star formation, metal enrichment and SMBH accretion-induced activity. As an example of an application of the ALMA data, we can consider the [CII] $158 \mu\text{m}$ line that is strong in star-forming galaxies, and is the dominant cooling mechanism for cold interstellar gas. Kimball et al. (2015) presented an analysis of an unusual [CII] emission line observed with ALMA of a very luminous quasi-stellar object (QSO) SDSS J155426.16+193703.0 at $z \approx 4.6$. The line is extremely broad, with $\text{FWHM} \approx 700 \text{ km s}^{-1}$ and a flat-topped or double-peaked line profile. These results suggest the presence of a massive rotating disc that may be the ultimate accretion fuel for the SMBH. Findings like these are hinting at the potential of sensitive, high resolution sub-mm spectroscopy for relating gas dynamics and metal content to a quasar dark matter halo also at high redshift. X-ray observatories such as Athena should maximize the synergies with ALMA and reveal hidden nuclear activity in star forming galaxies. The issue of the relation between nuclear activity and circumnuclear star formation may be solved by the synergy of radio, mm, and X observations which circumvent the effect of dust and provide a less biased view of the “obscured” Universe than the one we have now over a broad range of cosmic epochs. Gravitational wave observations from LISA (section 2.2.1) may reveals BHs that are invisible even in the X-ray domain because deeply enshrouded

by a Compton thick cocoon. The Einstein telescope may reveal intermediate mass BHs ($\sim 10^3 M_{\odot}$) that may be the progenitor of more massive BHs, perhaps filling the gap between the stellar mass domain and the massive black hole domain.

The radio surveys with SKA (Diamond, 2008) and the next-generation VLA will play an important role of multi-wavelength studies of galactic evolution, as they will detect sources whose radio emission is associated with stellar evolution processes up to the epoch of reionization ($z \gtrsim 6$; Nyland et al., 2018). The 21 cm line will become detectable up to high redshift: an all-sky survey detecting $\sim 10^9$ galaxies up to redshift ≈ 2 will become feasible with SKA (for comparison, at present there are only few detections beyond $z \approx 0.2$, Abdalla et al., 2015).

3.2.2. Feedback and Reionization at the Redshift Frontiers

The existence of a SMBH (J1342+0928, $M_{\text{BH}} \approx 8 \cdot 10^8 M_{\odot}$) at redshift 7.5 (when the Universe age was just 690 Myr) reinforces black hole growth models that assume seed black holes with significant initial masses ($\lesssim 10^4 M_{\odot}$) and super-Eddington accretion (Lodato and Natarajan, 2007). There is time to build up an M_{BH} that large without challenge the ΛCDM cosmology? Even if there has been a large delay between the previous record-holder and the last one and only ~ 100 quasars are known above redshift 6 (Matsuoka et al., 2018, and references therein),

it is legitimate to surmise that more quasars at $z > 6$ will be discovered in the next decades through dedicated surveys with *ad-hoc* photometric bandpasses. Very high M_{BH} values may turn out to be more challenging for Λ CDM cosmology if they are found at higher redshift. It is not only the high mass, but also the relatively high metal content (especially iron) of the line emitting gas that needs to be accounted for (Juarez et al., 2009). Clearly, metal enrichment in the proximity of a black hole may be decoupled from the host galaxy via circumnuclear star formation. The details of the enrichment process are however still not known.

In the standard big bang cosmology, the Universe baryonic matter, following the hot phase after the big bang, should have undergone a rapid cooling, and have become mostly neutral. It may have remained so until the first accreting black holes and the first shining massive stars may have produced enough radiation to reionize it (Jiang et al., 2016; Yoshiura et al., 2017, and references therein). The evidence of reionization (or better, of the existence of a significant fraction of neutral gas able to absorb Ly α photons from quasars) was associated with a deep, contiguous absorption through leading to zero flux on the blue side of Ly α (Gunn and Peterson, 1965). The first detection of the Gunn-Peterson effect (Becker et al., 2001) started the exploration of the dark ages when the Universe was still partly neutral. We see strong evidence of the quasar Ly α emission line being absorbed by a Gunn-Peterson damping wing from the intergalactic medium, as would be expected if the intergalactic hydrogen surrounding is significantly neutral, indicating that the quasar allows to probe well within the reionization epoch (Bañados et al., 2016). The redshift frontier is now at $z = 9 - 12$, within 500 million years of the Big Bang. Lyman-break galaxies are detected in increasing number from $z = 10$ to $z = 6$, consistently with the predicted mass growth of their parent dark matter halos (Kashikawa et al., 2011). On the converse, Hydrogen Ly α emission from these early galaxies appears to decline rapidly at $z > 6$, which suggests that gas at early epochs is becoming more and more opaque to the Ly α photons (Stark et al., 2011).

Determining the relation of star formation (a Population III of stars) and accretion (onto a direct collapse black hole?) and reionization during early cosmic epochs will connect the first light sources to the processes that assembled galaxies after reionization. Quasars are apparently not enough for the reionization of hydrogen: the number of ionizing photons from the luminosity function of $z \approx 6$ is apparently insufficient to keep the Universe ionized, given also that the soft X-ray background sets limits on accretion power at high redshift (McQuinn, 2016). In a cosmological context, X-rays are essential for addressing the issue, as they uniquely probe AGN at both the early heavily obscured stage and the later blow-out phase. X-rays can identify the “buried” evidence of heavily obscured black hole growth (e.g., the iron K α line at 6.4 keV). Planned large-aperture X-ray observatories will trace the cosmic history back to the time when the first luminous sources ignited, and the subsequent evolution of galaxies and their supermassive black holes (Georgakakis et al., 2013).

Near- and mid IR spectroscopy in addition to X-ray observations (discussed in more detail below) are crucial to

understand the quasar accretion properties. JWST and E-ELT will be suitable instruments to characterize the first luminous sources, in order to reconstruct the ionization history of the early universe, and to analyze how AGN and star formation evolved from the epoch of reionization to the present day (Gardner et al., 2006).

The redshift frontiers depend on luminosity. Relatively low mass black holes radiating at modest Eddington ratio remain undetectable at high z , with the important consequence that our view of nuclear activity evolution suffers from a bias: at intermediate-to-high redshifts ($z \gtrsim 1$), we almost fully miss a population of low-luminosity quasars (Sulentic et al., 2014). The ability to collect moderate dispersion visual spectra down to $V \sim 30$ mag would allow to cover black holes down to $10^6 M_{\odot}$ radiating at low Eddington ratio up to $z \approx 3$. The LSST and the 40m-class telescopes are needed to unveil a much more comprehensive view of nuclear activity than the one available to us until now.

3.2.3. Feedback and the Interplay Black Hole / Host Galaxy

The most important epoch for investigating the relation between accreting black holes and galaxies is the redshift range 1–4, when most black holes gained most of their masses and when most accretion power was released. X-rays are well-suited for studying in detail black hole feedback, although they are only one of the many spectral ranges that need to be covered to get a complete view of the phenomenon. Feedback is a process that ultimately originates in the innermost regions close to the supermassive black hole and is dominated, in terms of energy and mass flow, by material over a wide range of ionization stages. Current studies of the incidence, nature and energetics of AGN feedback are mainly restricted to the local Universe (with only very limited knowledge on the most deeply enshrouded (Compton-thick) black hole population), but systematic studies of AGN feedback to $z \sim 4$ via the identification and measurement of blue-shifted absorption and emission lines in the X-ray, optical and UV domains should become possible. We still have no clear global view of the prevalence and evolution of outflows and their relation to the growth of black holes as well as of their effects on galaxy evolution. Most galaxies host a SMBH at their center, with their mass correlated with that of their host galaxy (Ferrarese and Merritt, 2000; Gebhardt et al., 2000). This correlation may suggest that the evolution of AGN and their galaxy hosts follow a parallel track (at least on a broad temporal average and for massive galaxies), although it says nothing of how this relation is built in physical terms. Some self-regulating process has to connect the growth of the SMBH (accretion-powered) to the growth of the host galaxy (due to star formation) to the point of suggesting coevolution. The observational evidences of such coevolution has been reviewed by Kormendy and Ho (2013) while the theoretical motivation for the link between AGN feedback and galaxy evolution was reviewed by Fabian (2012).

A crucial process is the phase in which quasar winds “invade” the host galaxy (mechanical feedback). According to models, quasar outflow rates may reach thousands of solar masses per year at high z (Barai et al., 2018). A key physical question is:

how are the energy and metals accelerated in winds/outflows transferred and deposited into the circum-nuclear medium? The energy of such powerful AGN-driven winds is deposited into the host galaxy ISM, but it is as yet unclear, for instance, under which conditions quasar winds quench or trigger star formation. Fast galactic-scale molecular outflows (e.g., Cicone et al., 2014; Zschaechner et al., 2016) are believed to be ultimately driven by nuclear activity (Morganti, 2017 and references therein). In a spectacular case, a galactic-scale molecular outflow (Feruglio et al., 2015) sweeps away the molecular gas ultimately suppressing star formation, but there are counterexamples in which the quasar outflows trigger star formation (e.g., Ishibashi and Fabian, 2012). The most compelling evidence is now limited to a few case studies, but it is reasonable to expect that consensus on a global view may be reached by the mid of the century. A more general assessment will come from the next generation of imaging spectrographs operating in the optical and near-IR from ground (with active optics) and space, that may reach sub-0.1 arcsec resolution under ordinary observing conditions.

A second key question is: how do accretion disks around black holes launch winds/outflows, and how much energy do these carry? The answer to this question suffers because of the poor understanding of the structure and dynamics of the broad line emitting regions, within 10^4 gravitational radii from the central black hole. Certainly, not all quasars show powerful winds able to influence the global evolution of their hosts. Some authors distinguish between wind- and disk-dominated quasars (Richards et al., 2011), a separation that is consistent with the one between high- and low- Eddington ratio quasars (Pop. A and B respectively, Sulentic et al., 2000). The observational results point toward an origin very close to the SMBH for X and UV outflows alike. Measurements in the optical and UV rest frame of the quasars are important tracers of the outflow, but they are only part of the story. In the X-ray bands we observe narrow absorption lines outflowing with moderate velocity of hundreds to few thousands km/s (Halpern, 1984; Longinotti et al., 2015). The *warm absorber* is detected in $\approx 50\%$ of AGN (Reynolds, 1997; Piconcelli et al., 2005). In the UV band, narrow-absorption lines may be associated with the warm absorber and broad absorption lines are seen in $\sim 20\text{--}40\%$ of AGN, and may be present with extreme properties (terminal velocity $0.1\text{--}0.2\ c$) in most Population A AGN (Sulentic et al., 2006; Trump et al., 2006; Scaringi et al., 2009), but detected only if the outflowing material intercepts the line of sight. They probably arise in a radiation driven wind from the accretion disk (Elvis, 2000; Proga and Kallman, 2004) that seems to be a widespread and powerful phenomenon at least among Population A sources (e.g., Sulentic et al., 2007). However, most impressive outflows may appear from gas so highly ionized that the only bound transitions are for Hydrogen- and Helium-like iron. These X-ray winds are relatively frequent at low- z , with a prevalence $\approx 30\text{--}40\%$ of local AGN, and outflow velocities reaching $0.3c$ [Ultra-Fast Outflows (UFOs); Tombesi et al., 2010]. The evidence supporting UFOs has been growing (e.g., Longinotti et al., 2015). Originally it was based on faint absorption features of unclear identification, and UFO phenomenology is as yet poorly known, but the point here is that the mechanical feedback effect from the SMBH involve gas

in widely different physical conditions. A multifrequency analysis involving data from sub-mm to the soft and hard X-ray domain is needed to gain a full understanding of a multi-phase, likely highly-turbulent medium.

Even if there is agreement about the existence of an accretion disk and convincing evidence of outflows, the launching mechanism and the physical processes involved are only crudely understood today. Significant progress should come not only from multi-frequency simultaneous observations (optical, UV, and X) but also from SPH hydrodynamics simulations that are expected to improve in numerical sophistication and in the treatment of physical processes (see e.g., Sądowski et al., 2014; Liska et al., 2018).

3.2.4. Monitoring and Reverberation Mapping on “Industrial Scales”

Variability at all wavelengths is one of the defining properties of AGN. The most rapid variations in γ -rays are on the scale of only a few minutes. The very rapid variability of flares puts strong constraints on the size of the emitting region and its bulk velocity due to light crossing-time arguments. However a fundamental question such as: “what causes the observed variability in AGN from time scales of a few years down to a few minutes?” remains without convincing answers at present. As for the analysis of single-epoch spectra of individual quasars, the potential of spectral variability to constrain quasar models has not been sufficiently explored. The planned “panoptic” SDSS-V is intended to exploit this potential on wide scales. The SDSS-V plans to do spectroscopic reverberation mapping sampling hundreds of epochs for $\sim 10^3$ quasars ($0.1 < z < 4.5$) and $L_{\text{bol}} \sim 10^{45} - 10^{47}$ erg/s. This is a 10-fold increase in the number of sources monitored until now. With a more modest number of epochs (a few to a dozen per target), the SDSS-V will also characterize the optical spectral variability of approximately 25,000 quasars. Implications on the SMBH accretion disks, dynamical structure in the broad line region (BLR) including the optical UV outflows, and especially on signatures of binary BHs might be far reaching, perhaps yielding predictive ability on spectral variations of AGN, from broad band luminosity to emission line profiles. Optical spectrographs planned at major telescopes should bring similar scales to other spectrographic surveys.

Changing-look AGN, in which the broad lines in the AGN spectra either appear or disappear (i.e., passing from type-1 to type-2, or viceversa), an extreme case of line profile variability (LaMassa et al., 2015; Yang et al., 2017) may pose that challenges to standard accretion disk theory (Lawrence, 2018). In this respect, the most interesting sources are the ones hinting at a periodic behavior that in turn may suggest the presence of a sub-pc SMBH binary (Bon et al., 2012; Graham et al., 2015). We are forced the word “hint” for both the observational data and inferences, as the temporal baseline is still not long enough to confirm the periods excluding the “red noise” typical of nearby AGN light curves (Vaughan et al., 2016, note that the “red noise” behavior may not be stochastic but due to processes occurring on timescales comparable to the monitoring temporal baseline). The inference of a SMBH binary is bound by several assumptions at present rather *ad hoc* (Li et al., 2016).

The new capabilities offered by multiplexing spectrographs as well as a significantly longer temporal baseline for the monitoring (periods—often corresponding to the dynamical timescale of the BLR—are of the order of tens of years) will likely lead to an assessment of the prevalence of supermassive binary black holes in the local and in the remote Universe, as well as of the interplay magnetic fields/viscosity/turbulence in accretion disk. Astrometric measurements with resolution $\sim 1\mu\text{arcsec}$ have the potential to resolve sub-pc binary black hole systems up to high redshifts.

3.2.5. Accreting Black Hole Physics Close to the Event Horizon

The gas in the accretion disk may lose up to almost half of its energy within 1,000 gravitational radii, resulting in powerful UV and X-ray emission. The strong gravity field implies that general and special relativity effects are detectable from the emitted radiation not only in the hard X-ray domain but in the optical and UV as well. The close proximity to the event horizon is where differences in the spacetime metric due to the black hole rotation become appreciable. Lense-Thirring precession may be at the origin of warped disks in the case the angular momentum of the accreting material is misaligned with the spin angular momentum of the black hole (Bardeen and Petterson, 1975). Effects on optical and UV emission line profiles are expected (Bachev, 1999) although their assessment requires large samples of high-quality spectroscopical data. The DR 14 of the SDSS now lists over half a million quasars (Pâris et al., 2017) and millions of quasars are expected to be discovered and observed by Euclid. The potential of large samples of spectroscopic data are largely unexploited. From single-epoch spectra a wealth of information can be retrieved considering the trends along the quasar “main sequence” (Sulentic et al., 2000), including an estimate of the BLR size, physical and dynamical conditions, and chemical composition of the BLR gas (Negrete et al., 2012, 2013). The methods are in place but still not widely applied also because of the lack of high S/N data that are however expected to grow in availability in the next decades. We expect that the synergy between reverberation mapping and systematic inter-comparison of optical and UV emission lines coming from ionic species of low- and high-ionization potential for large samples of individual spectra organized along the main sequence yields contextualized inputs leading to full physical and dynamical models of the broad line emitting region, as a function of black hole mass, Eddington ratio, spin, and environment (Marziani et al., 2018). This issue—conceptually analogous to the definition and interpretation of the stellar Hertzsprung-Russell diagram—has been an unrelenting problem of quasar research that has remained basically unsolved since quasar discovery (see D'Onofrio et al., 2012; Sulentic et al., 2012).

The ISCO of the accreting gas also depends on the black hole spin, being closest to the black hole for maximally rotating black holes. In other words, the determination of the ISCO is a key endeavor because it is an indirect measurement of the black hole spin. This has important consequences for the radiation emitted by the accretion disk which is hotter in the case of high spin (Wang et al., 2014a). It is hard to conceive a black hole

that is not spinning at all (everything in the Universe spins, even cometary nuclei or asteroids!), but how many are spinning close to the maximally rotating case? How does the spin evolves with cosmic time? We think these questions are going to find an answer as the next generation of X-ray observatories will be launched. Much is needed even after successful missions such as XMM. $K\alpha$ line profile—associated with reflection from the accretion disk—remains to be observed in most quasars. While ASCA detected the extended wing in the $K\alpha$ profile associated with gravitational and transverse redshift (Tanaka et al., 1995), XMM spectra are revealing additional complexity in the $K\alpha$ profiles that may not be associated with relativistic effects. Several methods have been proposed to estimate the ISCO; the one that has proved viable at least in a large fraction of cases is the $K\alpha$ profile modeling, but other methods are possible as well: for example, if quasi periodic oscillations are associated with the ISCO angular frequency (Brenneman, 2013). X-ray observatories that are expected to be in service after 2025 may provide a view of the spin and ISCO distributions for supermassive black holes over a broad range of z .

LISA design is suited to detect the signal for coalescing black holes with masses $\lesssim 10^6 M_\odot$ in the source frame up to $z \approx 9$, and to enable the measurement of the dimensionless spin of the largest M_{BH} with an absolute error better than 0.1. It would allow the detection of spin misalignment with the orbital angular momentum with a precision better than 10 degrees (Danzmann et al., 2017). These multimessenger abilities should give an unprecedented view of the obscured populations well within the dark ages that preceded full reionization i.e., beyond redshift ≈ 6 . Within reach in the next 30–40 years (after LISA) is even the detection of SMBH merging with space-based interferometry (a feat that could be obtained even earlier with the pulsar timing arrays, Mingarelli et al., 2017).

3.2.6. Zooming Closer to the Innermost Stable Circular Orbit (ISCO)

In radio-quiet quasars, X-rays are produced by Comptonization of thermal disk photons in a hot corona. Among radio-loud quasars, photons from the radio jet also contribute as seeds in the inverse Compton scattering process (Pian et al., 1999; Böttcher et al., 2013; Bottacini et al., 2016). Part of the resulting power-law continuum illuminates the disk, where it is reprocessed and reflected, both in the soft and hard X-ray domain, yielding a Compton hump peaking at energy $\epsilon \approx 40$ keV and Fe $K\alpha$ emission at 6.4 KeV. The disk may not always extend down to the ISCO; in the Magnetically Arrested Disk (MAD) configuration, the disk is truncated and the truncation makes it possible to launch relativistic jets (Punsly et al., 2009; Rusinek and Sikora, 2017). The next generation of X-ray observatories should enable measurements of reflection features (Compton hump and $K\alpha$ line), and allow us to measure the ISCO and spin (from the ISCO) of black holes much beyond the local Universe. This feat should be achieved by measuring the general relativistic effects predicted on the $K\alpha$ line profile, most notably the gravitational redshifting of the line base that is sensitive to the ISCO value.

It is not clear what the hot corona might actually be: a compact “sphere” (as it is often modeled) or clumps above the

disk that illuminate the disk? How does the corona depend on the accretion status of the SMBH? The time lag between changes in primary radiation emission from the corona and the reprocessed emission from the disk provides a tool to measure the distance between corona and illuminated disk, as in the case of optical and UV reverberation mapping. Results on the $K\alpha$ response of several nearby AGN are already available (Kara et al., 2016) and is presumable that they will be extended in the coming decades. The determination of the disk-corona geometry via transfer function fitting requires data of much better quality than presently available (Dovciak et al., 2013). This is a task meant for X-ray observatories such as Athena, with the possibility of long uninterrupted observations on its orbit at L2. Athena should maximize the synergies with the LISA gravitational wave observatory, notably in locating the mergers of massive and seed black holes expected to be detected by LISA.

The radio source Sgr A* at the center of the Galaxy, and interpreted as the radio emission from a supermassive black hole, shows a compact and diffuse morphology at high radio frequencies above 200 GHz. The prediction is that a global VLBI array of radio telescopes, the global Event Horizon Telescope, could detect the shadow of the event horizon (Falcke, 2017). Ultimately, a space array at THz frequencies, the Event Horizon Imager, could produce much more detailed images of black holes that may allow for a measurement of the ISCO (and hence of the black hole spin). There is no doubt about the large concentration of mass in a restricted volume of space (e.g., Peterson and Wandel, 1999), but the existence of an event horizon has been questioned also on theoretical grounds in the context of quantum gravity. Gravitational wave detections from black hole merging events may finally distinguish between black holes and two main competitors: gravastar (Mazur and Mottola, 2004) and dark-energy stars (Chapline, 2005), classes of compact objects that are innerly sustained by the negative pressure of dark energy, and that avoid some of the paradoxes associated with the black hole singularity and event horizon.

3.2.7. What Is the Origin of Very High Energy Processes?

Radio-loud AGN are producing collimated relativistic outflows by a still poorly-understood process. Acceleration occurs extremely close to the SMBH (to explain remarkably short variability timescales), within a few tens gravitational radii, but what are the sufficient conditions for an efficient accelerations to ultra-relativistic speed (Lorentz factors $\gtrsim 10 - 100$)? This may indicate indicate a Lorentz factor much larger than previously thought, or hadronic acceleration. Very and ultra high energy (VHE and UHE) observations are the best tool to probe the physics of jet formation and the interaction of the black-hole magnetosphere with the accretion disk corona.

The SED of bright blazars is well explained by leptonic emission scenarios, where the radiative output throughout the electromagnetic spectrum is assumed to be dominated by electrons and possibly positrons (Celotti and Ghisellini, 2008). Radio-astron observation of the jet base of powerful radio sources (Kardashev et al., 2015) with resolution of $20\mu\text{arcsec}$ isolated the “nozzle” at a brightness temperature $T \sim 10^{15}$ K, a very

high temperature in excess to the Compton temperature. A very rapid variability of the high-energy flux (on timescales of a few minutes) as well as the temperature revealed by RadioAstron require extremely high Lorentz factors which are challenging for leptonic models (Böttcher et al., 2013). In hadronic models, both primary electrons and protons are accelerated and produce VHE photons in the γ domain. Protons however exceed the threshold for $p\text{-}\gamma$ photo-pion production, leading to high-energy emission due to several processes involving synchrotron and Compton emission decay products of pions which include the highest energy neutrinos (Kun et al., 2018), among other particles. The synergy between γ -ray such as CTA and neutrino observatories should yield insight on this issue, which is ultimately about the workings of the mechanism that is extracting energy from the black hole spin (Blandford and Znajek, 1977). Alternatively, the energy could be extracted by the rotating accretion disk (Blandford and Payne, 1982). In both cases, it is not clear how an ordered magnetic field can be transported down to a few tens of gravitational radii. The increase in computing power as well as the improved constraints on jet acceleration (a proton component? is the jet heavy?) from γ -ray and neutrino observation may lead to a more detailed description of magnetic field transport over a broad range of spatial scale and of the ultimate energy source of relativistic ejecta. Understanding the momentum flow of relativistic ejecta is related to the effects that they may have on the host galaxy. And CTA may unveil that γ -ray sources are much more frequent than inferred from present detection rates (Costamante et al., 2018).

Radio-loud quasars are one of the likely sites of the acceleration of UHE CRs, with energies up to around 100 EeV. γ -ray and neutrino observations also allow to search for UHECRs. γ -ray imaging observatories such as the CTA are expected to explore with unprecedented sensitivity the γ rays in the energy range from 50 keV-2 MeV which are the best tracers of CRs: low event statistics and deviation of charged particles in extra-galactic and Galactic magnetic fields make it difficult to direct search for UHECR sources. The γ -ray observations are expected to identify beacons (the γ RL quasars) that track the cosmological evolution of black holes down to the epochs of galaxy formation. Gravitational wave, γ and hard X-ray observations could provide a solution of the long standing problem of the energy source of reionization, and of the role of accreting black holes in the formation of protogalaxies.

3.2.8. Quasars and Observational Cosmology

The quasars spatial distribution has been used as a tracer of large scale structures and BAOs (e.g., Zarrouk et al., 2018, and references therein). The array of optical/IR instruments described in section 2 should provide an enormous gain in statistics (at least two orders of magnitude) of optical SN Ia measurements, allowing the extension of the SN Ia Hubble diagram, but only up to $z \approx 1.5$ (Hook, 2013). Also the DESI instruments may not go beyond 3 Gpc. Therefore, a large fraction of the early cosmic epochs will be left uncharted.

Quasars have a tremendous potential for cosmology, but their potential is as yet unexploited since they are not standard candles in conventional terms. Early efforts to establish correlations

TABLE 1 | Table illustrating the foundations of several methods that have been proposed to exploit quasars as distance indicators.

Sources	Parameters	Basic relation	References	Notes
Extremely radiating quasars (xA)	Hard-X-ray slope	$d_L \propto [l_0 (1 + a \ln \dot{m}) R_0]^{1-\alpha} \frac{FWHM^{1-\alpha}}{f_{5100}^{1/2}}$	Wang et al., 2013	xA, V
Extremely radiating quasars (xA)	velocity dispersion			
Extremely radiating quasars (xA)	Virial velocity dispersion	$L \propto FWHM(\beta)^4$	Marziani and Sulentic, 2014	xA, V
General quasar population	$FWHM(H\beta)$, $L/L_{Edd} = const.$			
General quasar population	X-ray variability, velocity dispersion	$\log L + 4 \log FWHM = a \log \sigma^2 + b$	La Franca et al., 2014	V
Mainly quasars at $z \lesssim 1$	Reverberation mapping	$d_L \propto \frac{\tau}{\sqrt{f_{5100}}}$	Watson et al., 2011	
General quasar population	time delay τ		Czerny et al., 2013	
General quasar population	Non-linear UV-X relation	$\log d_L \propto \log f_X - \gamma \log f_{UV}$	Risaliti and Lusso, 2015	

All methods have been developed in the last decade. d_L indicates the luminosity distance, f the fluxes observed at 5100, and in the UV and X ray ranges, $\dot{m}$ the dimensionless accretion rate, σ the excess variance in X ray fluxes. xA, extreme Population A sources following Sulentic et al. (2000); V, use of a virial broadening estimator (i.e., the FWHM of a suitable low-ionization line such as $H\beta$ or $P\alpha\lambda$ of Hydrogen).

between luminosity and one or more parameters (for example, the equivalent width of high-ionization lines, the so-called Baldwin effects, Baldwin et al., 1978) did not live up to cosmological expectations (some early and some recent attempts are reviewed in the Chapter by Bartelmann et al., 2009 D'Onofrio and Burigana, 2009). Nonetheless, in the last few years several methods have been proposed for the use of quasars as redshift-independent distance indicators, or as standard rulers. Four methods are summarized in **Table 1**, and some of them are widely discussed by Czerny et al. (2018). Their aims are to provide independent measures of the cosmic density of matter and dark energy Ω_M and Ω_Λ , as well as to gain constraints on the equation of state of dark energy, and to test alternative cosmological scenarios. Perhaps an accelerating Universe is not anymore an issue, but the nature of dark energy yielding a non-zero Ω_Λ is still mysterious. We choose to focus on these methods since they represent novel lines of investigations which rely on an improved understanding of quasar inner structure and all have the potential to constrain the geometry of the Universe in the redshift range $2 \lesssim z \lesssim 4$, a still-uncharted territory. Needless to say, these methods still need years of testing before they may provide useful data, and not all of them may turn out to be feasible. The main parameters, the basic relations and the sources for which the methods are applicable are summarized in **Table 1**.

At very high accretion rate, the luminosity-to-black hole mass ratio ($L/M_{BH} \propto L/L_{Edd}$) tends toward a well-defined value (more precisely it grows with the logarithm of the mass accretion rate). The resulting “slim” accretion disk is expected to emit a steep soft and hard X-ray spectrum, with hard X-ray photon index (computed between 2 and 20 KeV) converging toward $\Gamma_{hard} \approx 2.5$. The steep slope of their hard X-ray spectrum allows for the identification of super-Eddington accretors (Wang et al., 2013, 2014b). A challenge in this case is the sample size, but the next generation of X-ray instruments could make possible to identify sizable sample of extremely accreting quasars.

Highly accreting quasars can be considered as “Eddington standard candles.” $L/L_{Edd} \propto L/M_{BH}$, so that, if M_{BH} can be retrieved under the virial assumption, an estimate of the

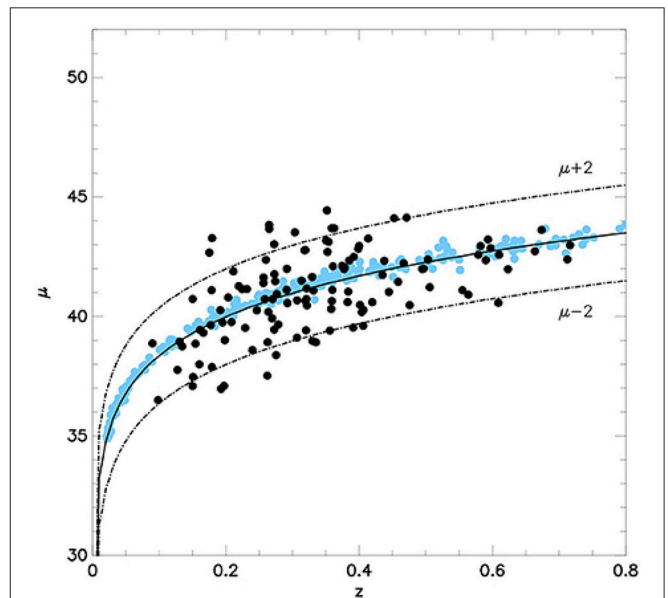


FIGURE 8 | Distance modulus of the “extreme sample” of Negrete et al. (black dots) and the Kessler et al. (2009) SDSS-II SN sample (cyan dots) as a function of redshift. The solid curve is the expected distance modulus μ for concordance cosmology. The dotted-dash lines delimit the area with $|\delta\mu| \leq 2$ magnitudes with respect to the concordance model. From Negrete et al. (2017).

luminosity becomes possible (La Franca et al., 2014; Marziani and Sulentic, 2014, **Table 1**). This approach is conceptually analogous to the use of the link between the rotational velocity of virialized systems such as the disks of spiral galaxies and their luminosity (Tully and Fisher, 1977): in both cases, $L \propto \delta v^4$. In the case of quasars, δv is provided by the FWHM of $H\beta$ or $P\alpha\lambda$. An explorative analysis confirms the conceptual validity of the quasar “virial luminosity” estimates, although the scatter on the distance modulus is still too large to draw meaningful inferences for cosmology (Negrete et al., 2017). **Figure 8** shows that the scatter

is no match for supernovae, being around 0.3 dex rms. A deeper understanding of the dynamics and physical conditions of the BLR of extremely accreting quasars may yield models of line broadening that may in turn improve the accuracy and precision for cosmology.

The BLR size has been suggested as standard ruler, in a way that is conceptually analogous to the BAOs. The cross-correlation function between the continuum and the emission line light curve measures a time lag τ , meaning that the distance of the BLR from a central continuum source can be written as: $r_{\text{BLR}} = c\tau$. If $r_{\text{BLR}} = c\tau \propto \sqrt{L}$ (Bentz et al., 2013, and references therein; see also Kaspi et al., 2005), the ratio $\tau/\sqrt{f_{5100}}$ (where f_{5100} is the continuum flux at 5100 Å) is proportional to the luminosity distance that depends on the cosmological parameters H_0 , Ω_M , Ω_Λ (Watson et al., 2011; Czerny et al., 2013; Melia, 2015). This method may yield important results in the next decades thanks to the SDSS-V and to other reverberation mapping campaigns that exploit the increasing multiplexing and wide field coverage of the forthcoming generation of spectrographs.

The non-linear relation between soft X-ray and UV has also been used to build a Hubble diagram (Risaliti and Lusso, 2015). Much is dependent on our understanding of high-energy continuum emission in quasars that is, as outlined above, not yet satisfactorily modeled. However, the data coming from the next surveys and advancements in our understanding in quasar structure may yield significant constraints for cosmology that are independent from all methods used to-date.

4. CONCLUSION

For the first time in human history, the next decades will see the ability to cover the sky in a panchromatic fashion, with a resolution clearly variable across the electromagnetic spectrum, but sufficient to resolve at least the brightest extragalactic sources from the low-frequency radio to the γ -ray domain. This ability will be enhanced by “synoptical monitoring” capabilities, at least in the visual bands. Optical sky surveys will make data available for sources down to ≈ 28 mag, and for brighter but still very faint sources ($i \lesssim 21$) in the X-ray domain. If the surveys that have been carried out in the 1990s and 2000s (or even earlier) are of any help, astronomers will have a treasure trove that will require decades to be fully exploited (IRAS data collected in the 1980s are still used today!). Multimessenger astronomy is literally still “in the making,” but its revolutionary potential may well go beyond our expectations, revealing a population of massive black holes that we are almost completely missing today.

We are confident that several of the main issues that are hotly debated and that need observational and computational improvement will become if not fully settled, at least better understood: (1) the role of nuclear activity on the host galaxy evolution, over a broad range of redshift. This fundamental issue will benefit from the ability to trace nuclear activity phenomena in obscured source of radio, mm, X-ray and gravitational wave observatories; (2) the reionization main players at the redshift frontier; (3) the inner structure of quasars involving the emission

line region physics and dynamics, including the disk wind physics and modelization; (4) the real nature of the massive compact object in the nuclei of galaxies. We may obtain a final answer to the question: is it really a black hole? (5) The origin of the relativistic radio jets and the mysterious high-energy phenomena occurring in AGN should become more constrained by the radio, X and γ ray observational developments. (6) Last, the possibility that quasars may be exploited as distance indicator will be certainly explored by several groups.

The same could be said for what concern our understanding of galaxies and clusters. Multi-messenger data will likely allow to map the star formation history of galaxies down to the first epochs, in close connection with the development of SMBHs. Most of the questions outlined before will find possible answers. Thanks to the enormous mass of data for billion of galaxies we will also have in a nearby future a much better understanding of the large scale structure of the Universe and in close connection with this, it will be likely possible to clarify which is the nature of DM and DE.

We should not be oblivious that many of the advancements hypothesized in the previous sections depend on the preservation of the social and economic conditions that should make possible for science to progress. They shall also imply vast educational efforts. However, if the advancements progress as expected, the amount of data and model sophistication may appear overwhelming. Large size elite collaboration may monopolize the frontiers fields of astronomical research, with costly dedicated instruments. Will there still be a place for the work of amateur astronomers and of citizen scientists?

We may even ask whether there will be anything left to discover? Will astronomers be reduced to priestesses and priests of a static wisdom, just monitoring that nothing unexpected or unpredicted by models is happening? We believe there is a chance that this might happen, although not in the next 30 years and perhaps not even before the end of the century. As the boundary of humankind is going to spread beyond our home planet Earth in the next decades, we will be able to see further and further developments, and interferometers with longer and longer baselines, probing deeper and deeper into the dark ages at the cosmic frontiers. There will be still fainter sources that will escape detection, and spatial details that we will not be able to resolve. As well as intrinsically stochastic processes that will be impossible to predict or model. And we may still face challenging aspects related to the inability to see beyond the cosmic horizon, if we attempt to analyze the global topology of the Universe (Luminet, 2016).

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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