Imaging the cool gas, dust, star formation, and AGN in the first galaxies

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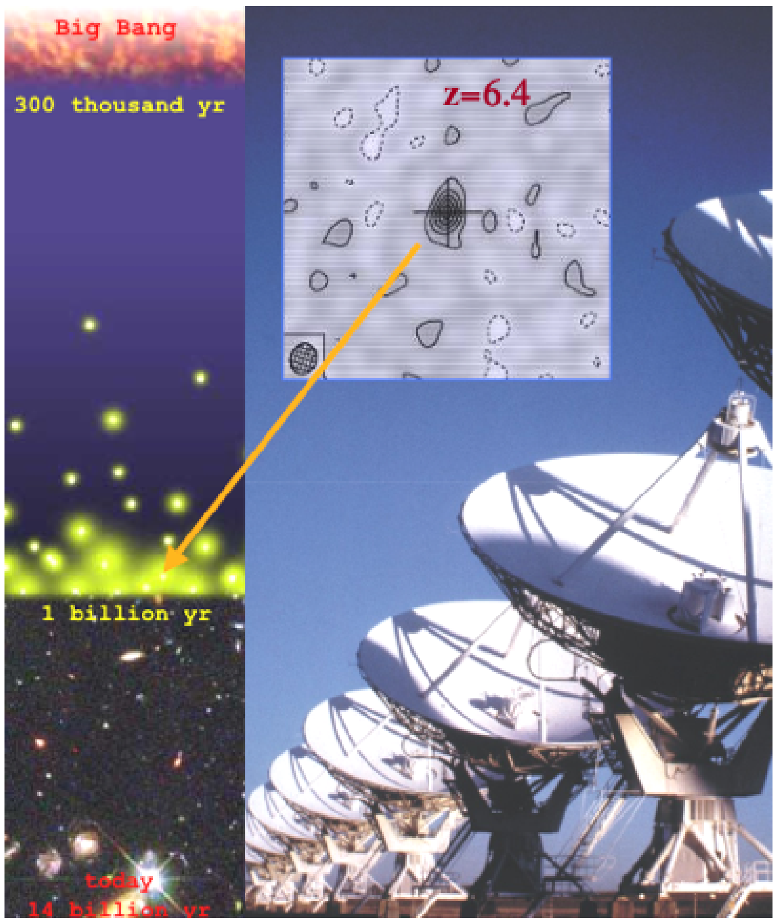

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Abstract: When, and how, did the first galaxies and supermassive black holes (SMBH) form, and how did they reionization the Universe? First galaxy formation and cosmic reionization are among the last frontiers in studies of cosmic structure formation. We delineate the detailed astrophysical probes of early galaxy and SMBH formation afforded by observations at centimeter through submillimeter wavelengths. These observations include studies of the molecular gas (= the fuel for star formation in galaxies), atomic fine structure lines (= the dominant ISM gas coolant), thermal dust continuum emission (= an ideal star formation rate estimator), and radio continuum emission from star formation and relativistic jets. High resolution spectroscopic imaging can be used to study galaxy dynamics and star formation on sub-kpc scales. These cm and mm observations are the necessary compliment to near-IR observations, which probe the stars and ionized gas, and X-ray observations, which reveal the AGN. Together, a suite of revolutionary observatories planned for the next decade from centimeter to X-ray wavelengths will provide the requisite panchromatic view of the complex processes involved in the formation of the first generation of galaxies and SMBHs, and cosmic reionization.

1 The formation of the first galaxies and SMBH

Study of the formation of the first galaxies and super-massive black holes is a key science driver for essentially all large area telescopes, at all wavelengths, under construction or design. Deep near-IR surveys have revolutionized our understanding of early galaxy formation by revealing star forming galaxies and SMBH back to the near-edge of cosmic reionization, $z \sim 6$ to 7 (Ellis 2007, Saas Fe Advanced Course 36 astroph/070124; Fan et al. 2006, ARAA, 44, 414). Reionization sets a fundamental benchmark in cosmic structure formation, corresponding to the epoch when the first luminous sources (galaxies, quasars) reionize the neutral IGM.

Current cm and mm facilities are providing the first glimpse into the cool gas, dust, and (obscuration-free) star formation in very early (massive) galaxies. In this white paper we describe the key contributions that will be made in the next decade to the detailed study of the first galaxies and SMBH with the powerful suite of large centimeter (cm) and millimeter (mm) interferometers and single dish telescopes. We delineate a key science program on first galaxy formation involving observations from cm through near-IR wavelengths, along with the instrumentation development for the cm and mm facilities that will leverage the major infrastructure investment for dramatic science return.

2 Probing the era of first galaxies

While progress in the field of very high z galaxy formation has been impressive, near-IR studies of the earliest galaxies are fundamentally limited in two ways: *(i)* obscuration of rest-frame UV emission by dust, and Lyα scattering in the neutral intergalactic medium, may lead to a biased view of galaxy formation, and *(ii)* near-IR studies reveal only the stars and ionized gas, thereby missing the evolution of the cool gas in galaxies, the fuel for star formation. Line and continuum studies in the centimeter (cm) and millimeter (mm) and submillimeter (submm) wavelength windows address both these issues, by probing deep into the earliest, most active, and dust obscured, phases of galaxy formation, and by revealing the molecular and cool atomic gas.

Molecular gas: Molecular gas constitutes the fuel for star formation in galaxies, and hence is a crucial probe of galaxy formation. The key physical diagnostics of such studies include:

- CO rotational transitions: Emission from CO is the strongest of the mm molecular lines from galaxies, and is the best tracer of the total molecular gas mass, and of physical conditions via excitation studies (Solomon & vanden Bout 2007, ARAA, 43, 677). Such studies require observation of low to high order transitions, necessitating observations at cm to mm wavelengths for high z galaxies.
- Dense gas tracers: Emission from high dipole moment molecules, such as HCN and HCO+, trace the dense gas ($> 10^5$ cm^{-3}) directly associated with star forming clouds (Gao et al. 2007, ApJ, 660, L93). The higher order transitions may be sub-thermally excited due to their very high critical densities ($> 10^7$ cm^{-3}), accentuating the need for cm observations.
- Gas dynamics: high resolution, spectroscopic imaging of the cool gas is the most effective way to study the dynamics, and dark matter content, of the first galaxies (Riechers et al. 2008, ApJ, 686, L9). Such observations provide unique probes into key questions on the evolution of the Tully-Fisher relation and the black hole mass to bulge mass relation.

Fine structure lines (FSL): Fine structure line emission from galaxies provide critical diagnostics of ISM physics and energetics (Stacey et al. 1991 ApJ, 373, 423), including:

- Emission lines from lower ionization species such as [CII] 158μm and [OI] 63, 145μm, are the dominant coolant in neutral interstellar gas (Spitzer 1978, 'Physical Processes in the ISM'). The [CI] 370 and 609 μm line ratio is a key ISM temperature probe (Weiss et al. 2003, A& A, 409, L41).
- Higher ionization species such as [OIII] 52, 88 μm and [NIII] 57 μm, trace the ionized ISM (Malhotra et al. 2001, ApJ 561, 766; Brauher et al. 2008 ApJS, 178, 280).
- Studies of line ratios and their relationship to the FIR luminosity and color can be used to derive gas temperature and density, the interstellar radiation field (ISRF), and to constrain gas heating and cooling (Brauher et al. 2008; Malhotra et al. 2001).

Extensive studies of FSL line emission in nearby galaxies, using predominantly the [CII] 158 μm line, show a decrease of the [CII]/FIR ratio with increasing FIR 'color temperature' (and FIR luminosity), suggesting less efficient gas heating by photoelectron ejection from dust grains due to positive grain charge induced by a high UV ISRF (Malhotra et al. 2001). However, these studies are hampered by the low resolution available in the FIR, and hence typically consider integrated properties of galaxies. At high redshift, these FSLs redshift into the 200–800 GHz submm bands and can be imaged at sub-arcsecond resolution using ground-based interferometers.

A crucial research goal for understanding the high-redshift universe is to determine how the observed neutral-gas in damped Lyman Alpha absorption systems (DLAs) eventually fuels star formation. Detection of the [C II] 158μm in galaxies associated with DLAs is crucial as it is an excellent tracer of neutral gas, is known to be present as shown by the detection of CII* 1335.7 absorption in a significant fraction of high-z DLAs, and, as the dominant gas coolant, provides insight into FUV emission from young stars that heat the gas.

Submillimeter continuum: The well documented "inverse K correction" in the Rayleigh-Jeans submm spectrum of thermal emission from warm dust implies a distance independent means of studying galaxies from $z \sim 0.5$ to $z \sim 10$ (Blain et al. 2002, Phys. Rep. 369, 111). Imaging of this thermal emission is vital to galaxy formation studies in a number of ways:

- Thermal emission from warm dust provides the one of cleanest method for deriving total star formation rates in galaxies (Dale & Helou 2002, ApJ, 576, 159).
- High resolution submm imaging reveals the distribution of star formation, unhindered by obscuration. For the first galaxies, the peak in the FIR emission is shifted to the submm, allowing the use of interferometers to perform sub-kpc resolution imaging. Combining high resolution images of the rest-frame FIR emission with images of the molecular gas presents a unique opportunity to study the evolution of the Schmidt relation back to the epoch of reionization (Krumholz & Thompson 2007, ApJ, 669, 289).
- Study of the dust SED yields a dust temperature and mass.

A particularly interesting problem is the formation of dust within 1 Gyr of the Big Bang, since the standard method of cool winds from AGB stars takes too long. Numerous groups are considering alternate dust formation mechanisms in the early Universe, likely associated with massive star formation, eg. dust formation in primordial SNe (Maiolino et al. 2004 Nature, 431, 533; Nozawa et al. 2009 arXiv:0812.1448).

Radio continuum: Radio continuum studies are routinely reaching detection limits of ~ 20 to 30 μJy at 1.4 GHz. Such studies probe the first galaxies in a number of ways:

- Radio emission from relativistic jets in AGN can be imaged to milliarcsec resolution using VLBI (Momjian et al. 2008, AJ, 136, 344). Jets likely play an important role in galaxy formation through hydrodynamic feedback on the ISM (Zirm et al. 2005, ApJ, 630, 68).
- The synchrotron continuum emission provides an obscuration-free measure of the massive star formation rate, via the well-quantified radio-FIR correlation for star forming galaxies (Condon 1992). Alternatively, deep cm and mm data can be used to test the evolution of this relation back to the first galaxies.

3 The First Gyr — coeval formation of galaxies and SMBH

The power of submm, mm and cm observations to probe the most distant galaxies is demonstrated by recent results on the host galaxy of the most distant SDSS quasar, J1148+5251, at $z = 6.42$. The SDSS observations, Keck spectroscopy, and HST imaging (White et al. 2005, AJ, 129, 2102; White et al. 2003, AJ, 126, 1), reveal a SMBH of $\sim 2 \times 10^9$ $M_\odot$. The host galaxy has been detected in thermal dust, non-thermal radio continuum, CO line, and [CII] 158 μm emission (Figure 1). High resolution imaging of the CO emission reveals a massive reservoir of molecular gas, 2×10^{10} $M_\odot$, distributed on a scale of

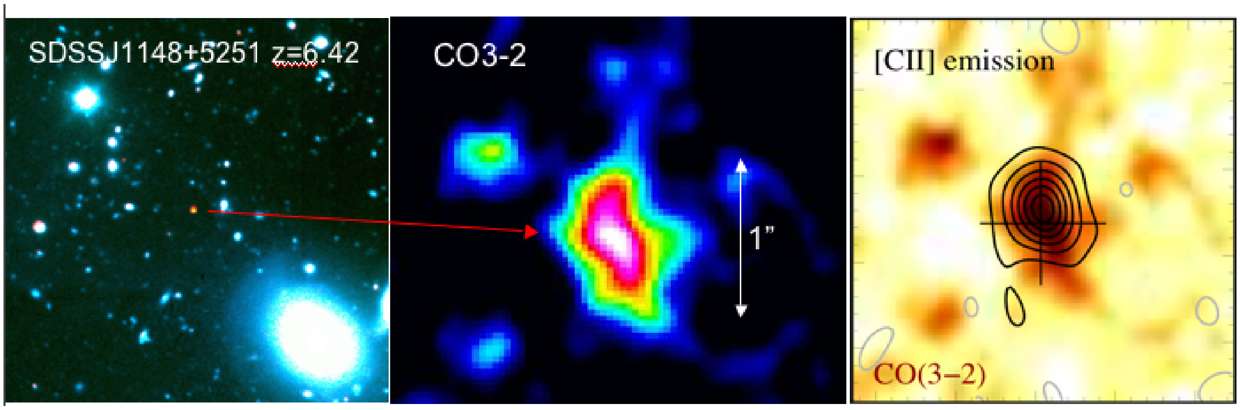

Figure 1: Images of SDSS J1148+5251 at $z = 6.42$. Left is a Keck true-color image (Djorgovski, Mahabal, and Bogosavljevic priv. comm.). Center is the VLA image of CO 3-2 emission (Walter et al. 2004). Right is the PdBI [CII] 158 μm image (Walter et al. 2009).

~ 6 kpc in the host galaxy (Walter et al. 2004). The broad band SED of J1148+5251, shows a clear FIR excess, consistent with 50K dust emission and with the radio-FIR correlation for star forming galaxies (Wang et al. 2008, ApJ, 687, 848). The high CO excitation in J1148+5251 (Bertoldi et al. A& A, 406, L55) is comparable to that seen in starburst nuclei implying a predominantly dense ($\sim 10^5$ cm^{-3}), warm ISM. Recent high resolution imaging of the [CII] emission in the host galaxy of J1148+5251 reveals an extreme starburst region with a diameter of $\sim$ 1.5kpc (Walter et al. 2009, Nature, 475, 699), forming stars at the 'Eddington limited' rate of ~ 1000 M$_\odot$ year^{-1} kpc^{-2} (Thompson et al. ApJ, 630, 167). Such a high surface density of star formation is seen in the starburst nuclei of low z ULIRGs, such as Arp 220, although on a much smaller scale (< 100pc).

These results, and results on similar $z \sim 6$ quasar host galaxies, are consistent with the co-eval formation of massive galaxies, and SMBH, at the earliest epochs. Cosmological numerical simulations have been used to elucidate such systems (Li et al. 2007. ApJ, 665, L187) who find that the SMBH forms through Eddington limited accretion and BH mergers, while the host galaxy experiences vigorous star formation ($\sim 10^3$ M$_\odot$ year^{-1}) during a series of major gas rich mergers, starting at $z \sim 14$. These systems are destined to become giant elliptical galaxies at the centers of rich clusters.

4 Key Science Program: First Galaxies 2010–2020

In this section, we outline a science program to find and exploit the first galaxies.

First galaxy candidates: Candidates $z > 6$ can be identified in deep, wide area surveys in the near-IR, radio, and submm. For example, near-IR deep survey instruments such as Hyper-Suprime-Cam at Subaru and Vista at ESO will reveal thousands of Lyman break (LBG) and Lyman alpha (LAE) galaxy candidates at $z > 6$, while wide field surveys such as Pan-STARRS and LSST will discover $z \sim 7$ quasar candidates. Multi-wavelength, large format bolometer cameras on single dish mm telescopes such as the GBT, LMT, and CCAT, along with deep EVLA radio surveys at 1.4 GHz, will identify similar numbers of distant, dusty star forming galaxies, with redshift estimates based on the broad-band SEDs.

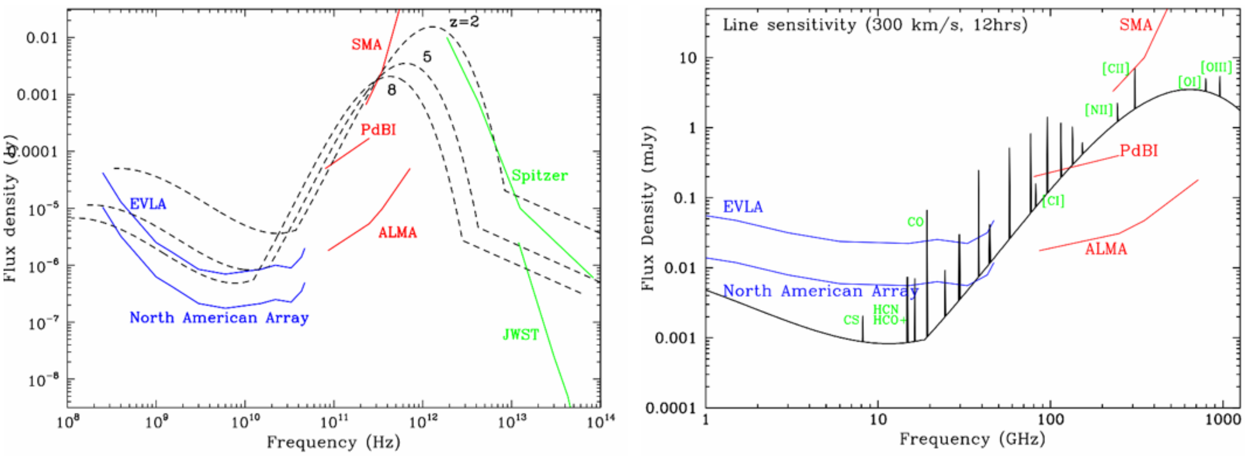

Figure 2: **Left:** The solid curves show the (1σ) sensitivity to continuum emission for select current and future cm and mm interferometers, as well as for space IR telescopes, in 12 hours. The dashed curves are the continuum spectra for Arp 220, at $z = 2$, 5, and 8. **Right:** The colored curves show the (1σ) sensitivity to spectral line emission in 12 hours for a 300 km s^{-1} line width. The solid curve is the spectrum, including molecular and atomic fine structure lines, for Arp 220 at $z = 5$.

Spectroscopic confirmation: Follow-up wide-band spectroscopy can then be done in the mm and near-IR to determine spectroscopic redshifts and the global properties of the galaxies. As there will be large numbers of candidates fed in by the surveys, a key role will be played in these studies by very wide-band spectrometers on large mm telescopes.

High Resolution Imaging and spectroscopy: Once identified, high resolution spectroscopic imaging with ALMA and the EVLA will delineate the gas, dust, star formation, and AGN at sub-kpc spatial resolution (< 0.2"), as described in the sections above. In parallel, the JWST and TMT will provide ultra-sensitive spectroscopy and imaging of the stars, ionized gas, and AGN.

Figure 2a shows the continuum sensitivities of current and future telescopes, along with the radio through near-IR SED of an active star forming galaxy, Arp 220 (star formation rate ~ 100 $M_\odot$ $year^{-1}$) at $z = 2, 5$, and 8. Current telescopes, such as Spitzer, the Plateau de Bure, and, soon, the EVLA, are able to detect such active star forming galaxies into cosmic reionization. The increased sensitivity of JWST and ALMA will push down to "normal" star forming galaxies, e.g. LAE and LBGs, with star formation rates ≤ 10 $M_\odot$ $year^{-1}$.

Figure 2b shows the line intensity of Arp 220 at $z = 5$, along with the rms line sensitivity of current and future radio interferometers. Centimeter telescopes study the low order molecular line transitions, while in the mm, higher order molecular line transitions, as well as the atomic FSL, are observed.

5 Instrumenting for First Galaxy Science

Galaxy formation is a complex process, and it is clear that a panchromatic approach is required to understand the myriad processes involved in early galaxy formation. In this white paper, we call particular attention to large radio, millimeter, and submillimeter facilities that

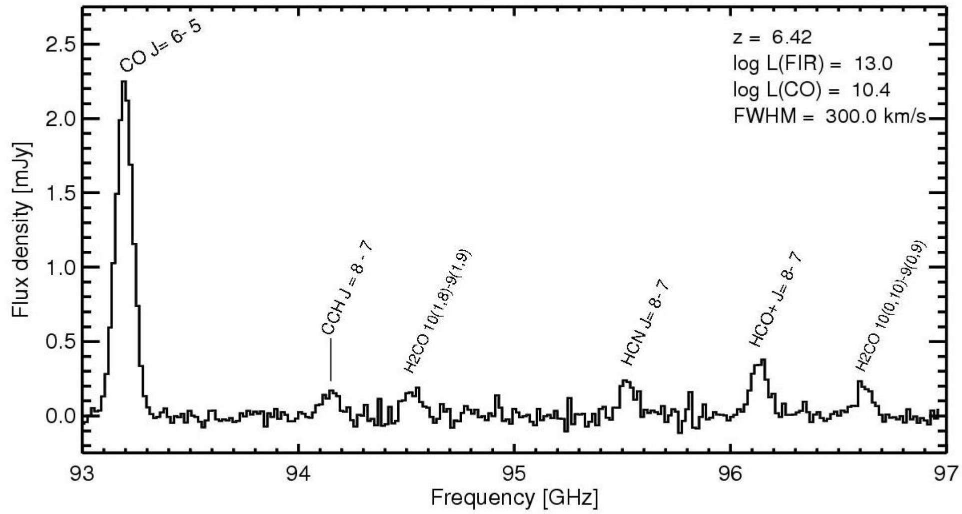

Figure 3: A simulated spectrum at 93GHz of J1148+5251 ($z = 6.42$) for a 24hr exposure on ALMA. This is only one of the two 4 GHz sidebands.

will play a crucial and complimentary role in the field over the coming decade.

Survey Telescopes: Large-aperture millimeter and submillimeter telescopes such as CCAT, GBT, and LMT equipped with large wide-field bolometer cameras and wide-band spectroscopic receivers will be able to carry out the key surveys that form the basis of the follow-up detailed studies. Ultra-sensitive, multiwavelength continuum surveys can be used to identify candidate $z > 6$ galaxies, while very wide band spectroscopy ($\geq$ 32GHz) can be used to determine redshifts from molecular and fine structure lines.

ALMA: The Atacama Large Millimeter Array (ALMA)[2] will do the heavy-lifting for detailed studies of the cool gas, dust, and star formation in early galaxies. ALMA will have close to two orders of magnitude improved sensitivity, spatial resolution, and spectral capabilities over existing (sub)mm interferometers. As a concrete example, a $z \sim 7$ galaxy with a ~ 10 $M_\odot$ year^{-1} star formation rate has an expected peak [CII] 158 μm line (redshifted to 240 GHz) flux density $\sim$ 0.5mJy and width $\sim$ 200 km s^{-1}, which could be detected by ALMA at 5σ in 1 hour. Longer exposures can be used for detailed imaging at sub-kpc resolution, as well as to look for other key diagnostic FSL, such as redshifted [OI] 63μm and [OIII] 52 μm lines. Figure 3 shows the predicted 93GHz ALMA spectrum of J1148+5251 at $z = 6.42$. Future large area mm telescopes allow for true multi-line spectroscopy, comparable to optical spectra.

There are a number of development projects for ALMA that are being considered that will provide dramatic science return for modest investments, leveraged on the existing infrastructure. These include: (1) completion of the ALMA receiver bands beyond those funded in the construction project, such as 165–210 GHz (ALMA band 5) covering the key ISM cooling [CII] 158μm line for $8 < z < 10.6$, and the Terahertz bands (Bands 10 and 11: 750 to 950GHz, and 1240 to 1520 GHz, respectively) for the lowest order rotational transitions

[2]http://www.almaobservatory.org/

from H_2 at $z > 7$ (rest wavelength 28μm). (2) A second generation correlator for wide-band spectroscopy with 32 GHz bandwidth, improving capabilities for redshift determinations, astrochemistry, and continuum sensitivity. (3) Wide-field upgrades using focal plane arrays to increase survey speed dramatically.

EVLA: The Expanded Very Large Array (EVLA)[3] is a cornerstone of the program for the detailed study of first galaxies. The EVLA upgrade provides complete frequency coverage from 1–50 GHz with 8 GHz of instantaneous bandwidth and 10^4 spectral channels, giving an order of magnitude improvement in continuum sensitivity at the upper end. The EVLA will image the low order molecular lines in the 20–50 GHz bands at sub-arcsecond resolution, and provide unprecedented sensitivity to the radio continuum emission at 1–4 GHz, at arcsecond resolution. Deep and wide field observations will image to ~ 1 μJy levels , adequate to detect active star formation (≥ 50 $M_\odot$ year^{-1}) at $z \sim 6$, with stacking analyses potentially pushing an order of magnitude further for statistical studies.

We note a few of the key EVLA development projects proposed for the coming decade that will greatly benefit studies of first light: (1) A state-of-the-art low frequency system (75 to 350 MHz) would enhance the ability of the EVLA to image steep spectrum (AGN and starburst) radio emission with the resolution (a few arcseconds) needed to avoiding confusion. (2) Real-time interferometric phase correction via water vapor radiometry is being planned to increase the efficiency of observing at the highest frequencies at the EVLA. (3) The 'North American Array' is a technology development program with the long-term goal of increasing the EVLA collecting area and extending baselines to a few hundred kilometers. Such improvements are required to image thermal emission and study the cool molecular gas reservoirs in normal galaxies at the highest redshifts. This is the first step towards a high-frequency component of the Square Kilometer Array[4] program, targeted at exploring the sub-μJy sky in the decade beyond 2020.

6. Conclusions

Cosmic reionization and the formation of the first galaxies and SMBH is among the last frontiers in the study of cosmic structure formation. We envision a clear path for the discovery, and detailed study, of the first galaxies afforded by a powerful suite of telescopes in the next decade. Near-IR telescopes (eg. JWST, TMT) will reveal the stars and ionized gas, while X-ray telescopes (eg. the IXO) will study the AGN. Far-IR telescopes (eg. SPICA, CALISTO) provide views of the rest-frame mid-IR emission, including the molecular hydrogen rotational transitions. The submm, mm, and cm-wave observations discussed in this white paper probe the dust and cool gas, the fuel for star formation, provide an unobscured view of star formation and AGN, and constrain galaxy dynamics on kpc-scales. In parallel, low frequency 'redshifted HI 21cm cosmology' telescopes will image the evolution of the neutral IGM on large scales. Together, this suite of revolutionary observatories will provide the requisite panchromatic view of the complex processes involved in cosmic reionization and the formation of the first generation of galaxies and SMBHs.

[3]http://www.aoc.nrao.edu/evla/

[4]http://www.skatelescope.org