The “Billion Galaxy” Cosmological HI Large Deep Survey (BiG-CHILDS)

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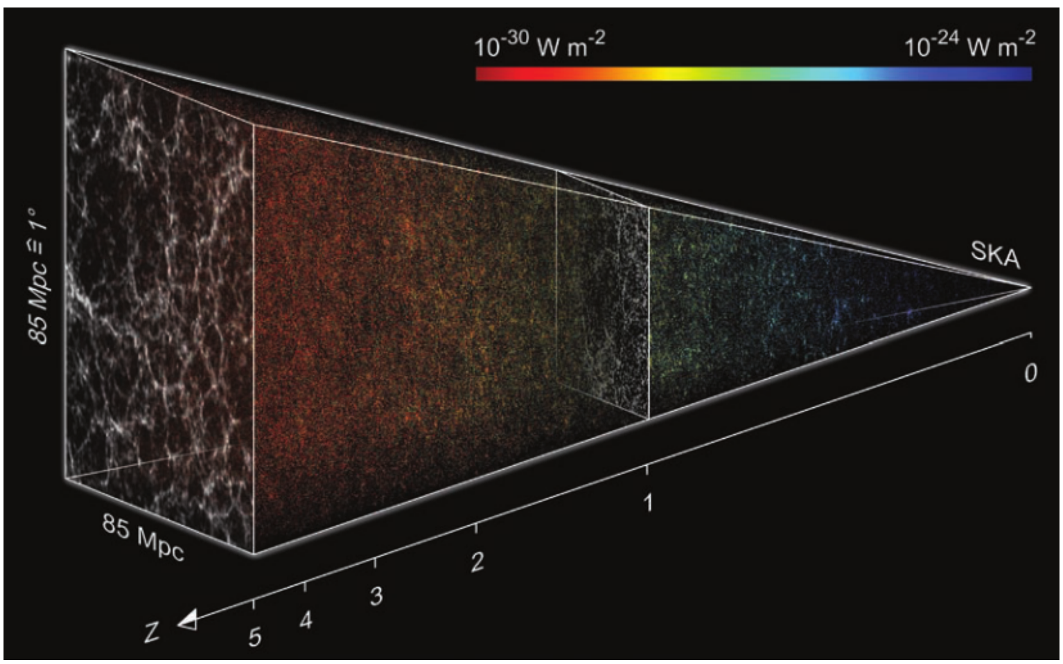

Simulated SKA observing cone, courtesy D. Obreschkow (Oxford), SKADS, and the SKA project.

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The Billion Galaxy Cosmological HI Large Deep Survey

Abstract: We outline the case for a comprehensive wide and deep survey ultimately targeted at obtaining 21-cm HI line emission spectroscopic observations of more than a billion galaxies to redshift $z > 1.5$ over half the sky. This survey provides a database of galaxy redshifts, HI gas masses, and galaxy rotation curves that would enable a wide range of science, including fundamental cosmology and studies of Dark Energy. This science requires the next generation of radio arrays, which are being designed under the umbrella of the "Square Kilometer Array" (SKA) project. We present a science roadmap, extending to 2020 and beyond, that would enable this ambitious survey. We also place this survey in the context of other multi-wavelength surveys.

The first decade of the 21st century has seen cosmology build upon the successes of the pioneering cosmic microwave background and galaxy surveys and build a cohesive "standard model" for the Universe. In this model, Dark Energy and Dark Matter are the primary constituents, and their densities and properties govern the evolution of the expansion rate (Hubble constant) and the growth of structure in the cosmic web. As we head into the next decade, the focus is on probing the physics of the components of the model and testing the limits of our understanding. Is dark energy a quintessence fluid or is it a failure of general relativity? Did inflation really set up the initial conditions? What is the mass of the neutrino? Current data is insufficient to answer fundamental questions such as these, but next-generation cosmological surveys across the observable electromagnetic spectrum are the necessary next steps in this enterprise as set forth in nationally recognized documents such as [1] and [2]. This Science White Paper focuses on the exploitation of the 21-cm wavelength HI line emission from gas in galaxies as a probe of the Universe from the present epoch back to a redshift $z > 1.5$ through a "billion galaxy" Cosmological HI Large Deep Survey (BiG-CHILDS) as a key science project for future radio astronomical facilities.

1 Science with a Billion Galaxy HI Survey

To enable the precise and accurate determination of the fundamental cosmological parameters, observations must cover a large volume of the Universe (to defeat sample variance). A number of complementary approaches have been proposed to meet this challenge. For example, the exploitation of the Baryon Acoustic Oscillation (BAO) signature in the galaxy angular power spectrum is a particularly promising line of attack for dark energy studies (e.g. [3, 2]). Other approaches include the measurement of weak gravitational lensing distortions in galaxy shapes, the growth rate of structure in the Universe, and the use of standard candles (SNe) and rulers (maser disks) in the determination of the distance scale.
Big Questions + Compelling Opportunities: A CHILD Survey would enable astronomical observations to address key questions in cosmology such as — **How does rate of cosmic expansion evolve, and what physical phenomena control this expansion? What is Dark Matter? What is the nature of Dark Energy? What are the masses of the neutrinos, and how have they shaped the evolution of the Universe?** A suite

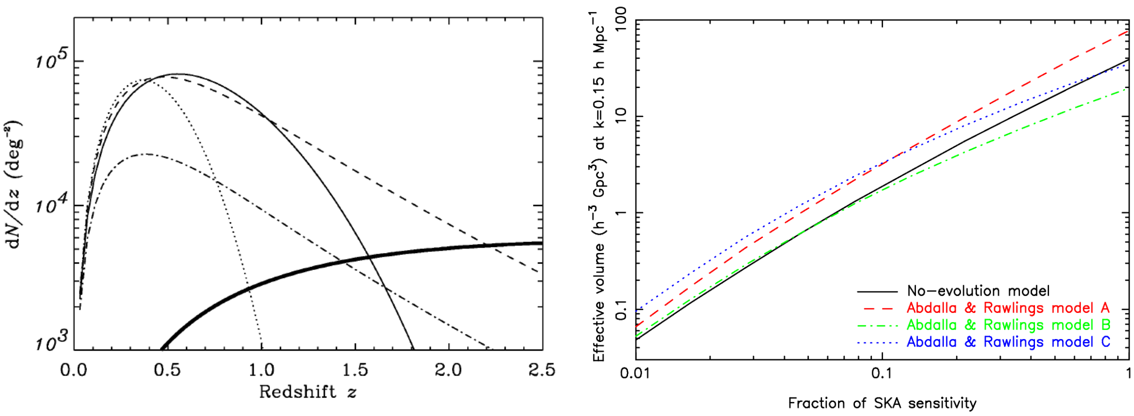

Figure 1: (a) *Left:* CHILD Survey yields for various HIMF models, reproduced from Figure 5 from [4]. The thin solid line is the favored model "C", which lies intermediate to models with no evolution (dashed) and evolution following dark matter haloes (dotted). The thick solid line shows the yield threshold needed to exceed cosmic variance, which for model C and a BiG-CHILD survey encompasses a cosmic volume out to $z \sim 1.5$. (b) *Right:* The equivalent volume on scales relevant for the BAO signature for a large CHILD surveys as a function of sensitivity (in units of a fiducial full SKA). The curves are for the models in the left panel (with different lines, see legend). Note that a 10% SKA produces a survey roughly equivalent to O/IR surveys projected to 2015.

of cosmological surveys spanning the electromagnetic spectrum are needed to address fundamental questions such as these. Furthermore, the next decade will see the fruition of key techniques and technologies necessary to build on the pioneering cosmological surveys such as SDSS and provide the opportunity to mine the cosmos and make precision measurements using truly large and robust samples of galaxies and AGN.

Why CHILDS? A CHILD survey as proposed in this white paper provides the measurement of redshifts, HI masses, and velocity profiles for a large sample of galaxies in the 21-cm line of neutral hydrogen (HI) to $z \sim 1.5$ over a wide area of sky. The use of a HI survey in the context of cosmological parameter measurement was presented in the Dark Energy Task Force (DETF) report as a "Stage IV" candidate project. The high level of performance of a BiG-CHILD BAO survey in comparison with other DETF motivated surveys is presented in [4, 5, 6].

The future large optical/infrared (O/IR) DE surveys are overwhelmingly photometric in approach. Spectroscopic surveys such as BiG-CHILDS have a key role in the coming decade because they are particularly rich in astrophysical and cosmological information. For example: (1) the BAO signature provides robust cosmic distances and expansion rates ($H(z)$), (2) redshift-space distortions and higher-order clustering statistics measure the growth rate of structure, which can be combined with the cosmic expansion history to constrain models of dark energy and/or modified gravity, (3) higher-order clustering and topological measures are tests of Gaussianity of the seeds of large-scale structure and therefore the predictions of inflation-inspired models, (4) the shape of the galaxy power spectrum contains information on detailed physics such as the neutrino mass, (5) spectroscopic velocities and widths can be used to determine Tully-Fisher distances and to measure peculiar and bulk motions that are inaccessible to purely photometric surveys, and (6) spectroscopic redshifts are needed to calibrate photo-z utilized in purely photometric surveys.

Survey Requirements: The facility described in [4] would carry out a cosmological survey competitive with other O/IR DETF "Stage IV" probes. This requires an array with around a square kilometer collecting area and a field-of-view of FoV $> 10\,\mathrm{deg}^2$. To optimize survey speed[1], one can trade off collecting area A for decreased noise system temperature T_{sys} or for increased field of view. To minimize cosmic variance, a comoving survey volume of $\sim 100\,\mathrm{Gpc}^3$ is needed. Assuming a "standard" LCDM cosmology ($H_0 = 71$ km/s/Mpc, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$) one obtains a comoving volume of $56\,\mathrm{Gpc}^3$ for $\sim 10^4\,\mathrm{deg}^2$ with a depth of $\Delta z = 0.5$ at $z = 1$. The fiducial survey would aim to cover a hemisphere ($\sim 2 \times 10^4\,\mathrm{deg}^2$).

Yields: The counts of galaxies detected in a HI galaxy survey are set by the HI mass function (HIMF), which is usually characterized by an exponential times a power law [2] with a mass M^*_{HI} characteristic of the turn-over into the exponential. For example, [4] used the Parkes multi-beam HIPASS survey HIMF of [7] to normalize the counts at $z = 0$ with $M^*_{HI} = 3 \times 10^9\, M_\odot$, and then explored several evolution models. There is a wide variation in the counts for $z > 1$ between the models due to differences between the M^*_{HI} at high redshift, though $z > 1$ is attainable for all plausible models. Using conservative model "C" [4] estimate a large survey could detect $> 10^5$ galaxies per square degree, giving $> 10^9$ galaxies over 10^4 square degrees (Figure 1a). Thus, we designate a CHILD survey such as this the "Billion Galaxy" Cosmological HI Large Deep Survey (BiG-CHILDS).

Note that the billion galaxy count is not the controlling factor for its utility for precision cosmological studies, but follows from the need to survey a large cosmic volume to the required depth. This requires the sensitivity to detect a sufficient number of galaxies at $z > 1.5$. For a BiG-CHILD-like survey, [6] show that constraints on dark energy models are an order of magnitude better than for other smaller volume surveys (Figure 2).

2 Using the SKA for BiG-CHILDS

The Square Kilometer Array (SKA) [3] program includes a mid-frequency array component [8] that could be designed to meet these requirements. In this context, the cosmology science case has been previously presented by [9, 10, 11] in the SKA Science Book. The use of the SKA for the cosmological observations exemplified by BiG-CHILDS were explored by [4, 6]. This requires a facility that is 40 times faster than a minimal "baseline" SKA design using 3000 15-m antennas with wideband single-pixel feeds of [8][4]. The necessary speedup would be attained through a combination of increasing the survey durattion, operational upgrades for sensitivity and field-of-view above the baseline design, and/or by descoping other options.

[1] speed $\propto$ FoV $\times A^2/T^2_{sys}$

[2] The Schechter mass function is $dN/dz = \phi^*_{HI}\,(M_{HI}/M^*_{HI})^\alpha\, \exp(-M_{HI}/M^*_{HI})$

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

[4] For reference, for a 15-m diameter antenna the "single-pixel" FoV $= 0.73\,\mathrm{deg}^2$ at 1.4 GHz ($z = 0$), scaling as $(1+z)^2$.

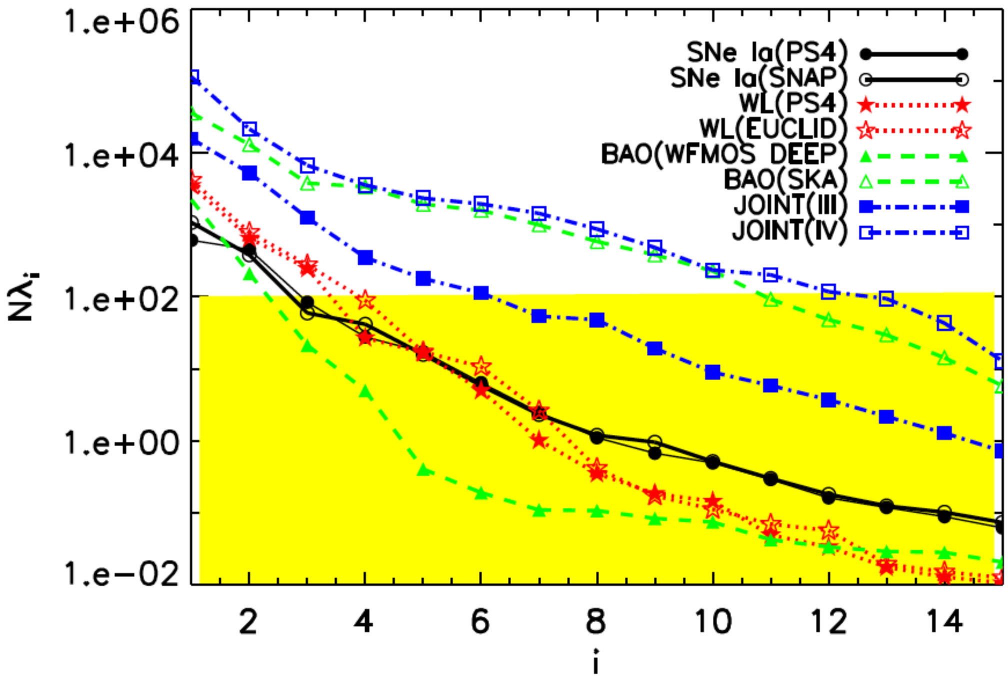

Figure 2: Dark Energy survey capabilites reproduced from Figure 19 from [6]. Shown are the eigenvalues of the Fisher matrix as a proxy for signal-to-noise ratio on dark energy parameterizations. The SKA (BiG-CHILD) survey provides superior sensitivity by having redshifts for a much larger sample of galaxies than other Stage III and IV experiments, allowing more complex Dark Energy parameterizations and equations of state to be explored.

The cosmology science case is clearly a driver for setting the goal for facility requirements, and the SKA project is focusing design and development in this area to deal with the risk. Note that maximizing the astronomical utility of the survey (e.g. for dynamical studies, accurate position determination) requires substantial sensivity at higher resolution ($\sim 1''$). Thus the baseline design for SKA of [8] includes longer baselines in its proposed configuration for this reason.

CHILDS would be a nested series of 21-cm line surveys of the sky to various depths, for which the ultimate stage would be BiG-CHILDS. This would be carried out commensally with other surveys for continuum emission from these and other galaxies, and a transient source discovery and monitoring survey. This program is intended as a next generation astronomical survey with wide application beyond cosmology, much like SDSS and its successors. For example, another science case for CHILDS is that of tracking Galaxy Evolution and structure formation, e.g. [12]. This has less stringent requirements on survey speed than precision cosmology, because smaller galaxy samples from smaller volumes can be used. For example, assuming the HIMF evolution model "C" favored by the authors, a five year small-CHILD Survey with the baseline SKA would yield 1 million $z > 1$ galaxies over 800 deg^2. Thus, galaxy evolution studies would have extensive samples to work with, and there would be 30–50 million $z < 1$ galaxies as well.

3 A Science Roadmap

It is important to the health of astronomy that our current and upcoming instruments be fully exploited to reach their science goals, as well as to lay the groundwork for future facilities.

Instrumenting the Roadmap: A comprehensive HI galaxy survey is a major endeavor, with capital and operating costs for the required facility comparable to and likely greater than that of ALMA. A large ground-based instrument such as the SKA will not just appear one day, fully operational and at ultimate science capability. Therefore, a comprehensive build-up and build-out plan that is plausible, affordable, and above all scientifically compelling must be developed. This plan must involve a large cross-section of the astronomical (not just radio) community with a well-supported staged scientific program using the instruments of today through to the frontiers of the next decade and beyond.

Science Precursors: The Arecibo ALFALFA survey[5] [13]) will supplant the HIPASS survey in anchoring the local HIMF. Dedicated use of the EVLA[6], a low-end enhanced ALFA, and a full ATA[7] with optimal performance below 1 GHz would allow us to characterize the HIMF beyond $z = 0.1$ in the coming decade. This program, in conjunction with the pathfinders (see below), would lead to the HI equivalent of the SDSS.

Pathfinders: There are mid-frequency SKA pathfinders and demonstrators underway in various locales (e.g. ASKAP, APERTIF, ATA, MeerKAT). There is also a US-SKA Technical Development Program[8] funded by the NSF. All of these are important to prove technology and gain experience running SKA-like instruments. The one that is most accessible to the US community is the ATA. An important goal for pathfinder science programs is a more accurate measurement of the $z < 0.2$ HIMF, and the detection of extreme HI galaxies and also constraint on the HIMF (e.g. through stacking) out to $z \sim 0.5$.

Risks and Mitigation: The design requirements placed on a SKA in order to attain the sensitivities needed to carry out a BiG-CHILD Survey are extreme compared to other SKA science drivers, and is thus expensive. The detection of cosmological HI is what originally suggested that a square kilometer of collecting area was needed. The SKA project is exploring the options to achieve these goals, including an upgrade path enhancing the field-of-view and sensitivity, or descoping by trading off other aspects (such as upper frequency limit). A more modest small-CHILDS, more on the scale of near-future "Stage III" DETF experiments, would start the SKA on the road to the bigger survey while providing first science. A 10% Phase I SKA, for example, would have the capability to carry out cosmological surveys equivalent to the O/IR surveys projected for 2015 (see Figure 1b).

Survey Science: The concept of a Radio Synoptic Survey Telescope (RSST) [9] has been developed to encapsulate the mid-freqency SKA science case. The proposed CHILD Survey is but one key component of the science opportunities afforded by a SKA as RSST. Even CHILDS itself would provide additional information to the spectroscopic redshift survey, such as very deep continuum polarimetric imaging of galaxies and AGN. For example, galaxy imaging

[5] `http://egg.astro.cornell.edu`

[6] `http://www.aoc.nrao.edu/evla`

[7] `http://ral.berkeley.edu/ata`

[8] `http://usskac.astro.cornell.edu`

[9] `http://www.aoc.nrao.edu/~smyers/rsst/`

could be used as a weak-lensing probe of cosmology and dark energy complementary to the BAO signature (e.g. [11]). Also, detection of HI absorption signatures against higher redshift AGN [14] also provides an important probe of galaxies, much like damped Lyman Alpha absorbers in the O/IR bands. The staged approach would allow the various CHILDren to build upon each other in all these science areas.

Complementarity: The BiG-CHILD Survey is essentially a galaxy redshift survey, and thus will provide a hydrogen-filtered view of the cosmic web. Note that future photometric surveys at other wavelengths, such as those proposed in the O/IR bands for PanSTARRS and LSST, will also yield around a billion galaxies, and cross-correlation with BiG-CHILDS would be of great utility for both cosmology and galaxy studies. For example, BiG-CHILDS galaxies can be used to calibrate the photometric redshifts used in these non-spectroscopic surveys.

Alternatives: The science goal of measuring the BAO signature in the HI galaxy power spectrum could also be approached through a very low resolution high sensitivity interferometer array [15]. This would be much like scaling up proposed HI EOR experiments, at potentially lower cost than a CHILDS-capable SKA. However, unlike BiG-CHILDS, this experiment does not deliver a combined continuum and spectroscopic sample of galaxies that is useful for more general astronomical science.

Timeline: The ultimate facility required to carry out BiG-CHILDS would only be possible in the post-2020 timeframe. However, significant staged CHILDren surveys will be carried out in 2010–2015 through science precursor programs on facilities such as Arecibo, ATA, EVLA, and GBT. In the latter half of the decade, the international SKA pathfinders such as an expanded ATA and ASKAP will take this science to the next stage. Finally, construction on a first phase of the SKA later in the decade could start to yield HI galaxy samples at $z > 0.5$ around 2020.

Uniqueness: The BiG-CHILD survey would be a unique resource for astronomy, astrophysics, and cosmology. It is a simulataneous spectroscopic and photometric (continuum) radio survey. With a yield of more than a billion redshifts, it would be the ultimate ground-based cosmological redshift sky survey, and an important counterpart to space-based spectroscopic missions targeting similar-sized samples. The unprecedented velocity information will enable key tests of GR, redshift space distortion probes of cosmology, large-scale flows, and the nature of initial velocity perturbations. Radio surveys and techniques do have some advantages over O/IR surveys, such inherently wide instantaneous field-of-view ($> 1\,\mathrm{deg}^2$), and insenstitivity to galactic obscuration. However, the greatest science utility comes from the combination of all multi-wavelength surveys, including BiG-CHILDS.

Related Development: In addition to the substantial technology development needed to construct the SKA, significant advances in theory, modeling, and data analysis algorithms and techniques is also required. Extracting a billion-galaxy catalog from the huge raw data volumes that BiG-CHILDS will produce is a daunting challenge. Furthermore, carrying out the cosmological and astrophysical simulations needed as input to model the theoretical part of the parameter extraction will also require development during the decade. The staged science approach will allow this to grow with the CHILDren surveys. Support for next-generation algorithmic and computational infrastructure will be critical to enable the science from surveys such as BiG-CHILDS.

4 Conclusions

The Billion Galaxy Cosmological HI Large Deep Survey, in conjunction with commensal continuum and transient-response surveys on the same instrument, would comprise a truly transformational science program. The BiG-CHILDS key project would provide superb constraints on cosmological parameters such as the dark energy equation of state. A staged survey suite leading from the facilities of today to the SKA beyond 2020 would enable this exciting opportunity.

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