Laying the Groundwork for Cluster Studies: The Long Wavelength Array Response to the Dark Energy Task Force Call for White Papers:

Tracy Clarke[1], Joseph Lazio[1], Greg Taylor[2], Craig Sarazin[3], & Namir Kassim[1]

1. Project Overview

We describe a project utilizing low radio frequency ($<$ 100 MHz) observations to determine the dynamical state of clusters of galaxies (relaxed vs. merging). These determinations will then be used to inform and improve upon various cluster-determined (e.g., cluster gas mass fraction, Sunyaev-Zeldovich) cosmological model measurements by removing an important systematic effect.

The project will make use of the *Long Wavelength Array*[4] (LWA), a telescope operating in the 20–80 MHz (15–3.75 m wavelength) band. Low-frequency observations have already demonstrated that some merging clusters display *halo* and *relic* emission, large regions ($\gtrsim$ 500 kpc) of diffuse synchrotron emission related to shocks produced during a cluster merger. With unparalleled sensitivity to these structures, the LWA will observe clusters being used for cosmological model measurements. The current design goals are that the LWA will obtain a surface brightness sensitivity of $S_{74} = 0.12$ mJy/beam at a fiducial frequency of 74 MHz (4 m wavelength) in 8 hours. This survey will allow those clusters not in a dynamically relaxed state to be "flagged" or, potentially, measured parameters from them (e.g., L_X, T, and M) to be corrected for the effects of the merger.

The LWA will be an interferometer consisting of approximately 50 "stations," with each station serving as the equivalent of an antenna in higher frequency interferometers (e.g., the Very Large Array). Each station will consist of 256 dipoles phased together. The LWA will have maximum station separations approaching 400 km, allowing arcsecond resolution in its frequency band.

The LWA is being developed by the Southwest Consortium (SWC). Member institutions (and the PI at each institution) are the Naval Research Laboratory (Namir Kassim), the University of New Mexico (Greg Taylor), the Applied Research Laboratory of the University of Texas, Austin (Thomas Gaussiran III), and the Los Alamos National Laboratory (William Junor). The LWA is being constructed in phases. Phase I consists of a single station to operate in conjunction with the 74 MHz system on the Very Large Array and is being developed for deployment later this year. Phase II marks the construction of multiple ($\sim$ 7) stations and is expected to commence in 2006, with the full LWA (Phase IV) being operational around 2010. Initial work on the LWA is being funded through the Department of Defense (via the NRL).

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[1]Naval Research Laboratory, Code 7213, 4555 Overlook Ave. SW, Washington, DC 20369

[2]Univ. of New Mexico, Dept. of Physics & Astronomy, MSC 07 4220, 800 Yale Blvd NE, Albuquerque, NM 87131

[3]Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA, 22903

[4]http://lwa.nrl.navy.mil/, http://lwa.unm.edu/

2. Baseline Project

The effects of Dark Energy (DE) are seen through studies of the global geometry as well as through the growth of the largest structures in the Universe. As the largest gravitationally bound objects in the Universe, clusters of galaxies can be used to study DE through both the geometry and structure formation methods. The material within the gravitational potential of clusters is thought to provide a fair sample of the matter distribution of the Universe (Eke et al. 1998). In particular, the most massive, hottest clusters provide the most sensitive cosmological probes. The confidence regions for cosmological parameters outlined by clusters are nearly orthogonal to those of the cosmic microwave background (CMB) and Type Ia supernovae (SNe) (Bahcall et al. 1999) making them an important complimentary technique to the other studies. For example, using a sample of $\sim$26 X-ray luminous clusters in the redshift range $0.1 < z < 0.5$, Allen et al. (2004) have demonstrated how cluster X-ray gas mass fraction can be used to extract cosmological parameters, including Ω_Λ and w. They found $\Omega_\Lambda = 0.94^{+0.21}_{-0.23}$ in a standard ΛCDM model and $w = -1.26 \pm 0.24$ in an extended model. While this is an important step, clearly the ultimate goal of studies utilizing clusters is to extend both the total number of clusters used as well as their redshift distribution.

A key aspect of most studies using clusters for cosmological parameter determination is the accurate measurement of the temperature or total cluster mass. Cluster temperatures can be directly determined from X-ray spectroscopic observations but these studies require very deep X-ray observations and are interpreted under the assumption of hydrostatic equilibrium. The only direct method to measure the total mass is from gravitational lensing studies and this is only possible for a small number of clusters. Studies using larger samples of clusters must rely on empirical or semi-empirical relationships between observables such as the cluster X-ray luminosity (L_X) and temperature (T) and the luminosity and total cluster mass (M). More precisely, DE studies require observables that can be used to study the cluster mass over a large range of redshifts. The standard observational correlations between X-ray luminosity and temperature ($L_X - T$) or temperature and mass ($T - M$) may be redshift dependent. Further, the determination of the cluster mass from the observables is generally undertaken under the assumption of hydrostatic equilibrium (i.e. relaxed clusters). Systematic offsets in the relations and/or significant scatter in the relations will dominate the errors in cosmological parameter determination.

The scaling relations between X-ray luminosity, temperature, and cluster mass will be influenced by cluster mergers. Simulations show that two merging clusters of comparable mass will result in a significant boost in L_X and T (Ricker & Sarazin 2001). If a cluster is observed during a period of boosted L_X and T, the inferred mass from the empirical relations will biased too high compared to the true cluster mass. Due to the small number of high mass clusters, the merger boost effect will be most evident as an overabundance in the inferred number of high mass clusters (Randall et al. 2002). As pointed out above, it is the paucity of massive, hot clusters that provides the strongest sensitivity to cosmological parameters. The most luminous clusters (whether intrinsically or boosted) are preferentially detected by X-ray flux-limited studies, thus even a slight bias in these numbers can result a large effect on the inferred cosmology. Mergers will also boost the Sunyaev-Zeldovich (SZ) microwave decrement from clusters but this effect will be smaller than the X-ray boost (Randall et al. 2002). It is clear that cosmological studies with clusters require a method to identify merging systems and preferably correct the observables for the effects of the merger.

X-ray signatures of cluster mergers can be traced with detailed temperature mapping which requires deep X-ray observations of each system or detailed imaging of the X-ray surface brightness. These merger tracers are not independent of orientation and thus merging clusters can be overlooked. Similarly optical cluster studies also suffer from orientation problems in identifying merging systems. Ideally one would like to use a method that is independent of X-ray, SZ, or lensing measurements to determine the merging state of systems. This would avoid a bias which could be introduced by using the observations to both identify merger signatures as well as measure cosmological parameters.

A powerful (independent) technique to investigate the dynamical state of clusters is the use of low frequency radio observations to detect diffuse synchrotron emission characteristic of merging systems. Radio observations of galaxy clusters reveal a number of systems that contain large regions ($\gtrsim$ 500 kpc) of diffuse synchrotron emission that is not associated with individual active galaxies (Figure 1). This emission is characterized observationally as *halo* or *relic* emission depending on the location (core vs. periphery), morphology (symmetric vs. elongated), and polarization properties (weakly polarized vs. highly polarized). Both types of diffuse emission have steep radio spectral indices, so that these sources are brighter at lower radio frequencies. Both halo and relic emission are found *only* in clusters displaying signatures of recent or on-going merger activity (Feretti 2005; Buote 2001). The energy released into the intracluster medium during a cluster merger is expected to drive shocks into the cluster, that in turn accelerate relativistic particles and compress magnetic fields, thereby creating the diffuse radio relic emission (Ensslin et al. 1998). The remnant turbulence in the cores of clusters immediately following merger activity is responsible for the diffuse radio halo emission (Brunetti 2002). The key issue for Dark Energy studies is that radio halos and relics serve as signposts for clusters that are out of equilibrium and not suitable to hydrostatic equilibrium assumptions (e.g. studies such as that of Allen et al. 2004). Most significantly for DE studies, these radio signatures are independent from the data being used for the cosmology parameter studies and they are independent of the orientation of the merger. With their steep radio spectral indices and large angular scales, halo and relic emission can be identified easily by low frequency radio interferometric observations.

Beyond the detection of non-equilibrium systems, radio observations may also be a powerful tool to correct the X-ray and SZ measurements. The diffuse radio luminosity of clusters is observationally correlated with the bolometric X-ray luminosity of the host cluster (Liang et al. 2000). Based on the formation scenarios, the radio luminosity is tied to the energy input from the merger and thus merger strength, therefore radio observations combined with detailed simulations could be used to correct the X-ray measurements for the merger boost in observations of L_X and T. Diffuse radio halo emission in cluster centers will also cause an impact on measurements of the

SZ decrement in clusters by filling in the decrement with excess emission. These sources generally do not contain significant small scale structure and are easily missed in interferometric observation designed to remove point source populations from millimeter SZ studies. Reese et al. (2002) showed that the radio halo in Abell 2163 (Figure 1) has a $\sim 10\%$ effect on the measurements of the central SZ decrement in this system. Accurate flux and spectral index measurements of halos from radio observations can be used to determine and remove their contribution from the SZ decrement observations.

Large samples of galaxy clusters are currently being obtained over wide redshift ranges from the current generation of surveys: the XMM Large Scale Structure Survey is expected to find about 10^3 clusters up to redshift of one (Regregier et al. 2000), the Sloan Digital Sky Survey is expected to identify about 5×10^5 clusters out to redshift $z = 1.2$ (Bartelmann & White 2002), and Sunyaev-Zeldovich observations with *Planck* should find about 10^4 clusters over a similar redshift range (Geisbuesch et al. 2005). The Dark Universe Observatory (DUO; Griffiths et al. 2004) predicts that with 10^4 clusters it will be possible to measure w to an accuracy of $\pm$ 0.05 when WMAP (Bennett 2003) priors are used, while Ω_M can be measured to an accuracy better than 0.01, and Ω_Λ to an accuracy better than 0.1.

Below we describe the *Long Wavelength Array* (LWA) in more detail. Its strength is its extreme sensitivity and its high (arcsecond) resolution, even at wavelengths (3–30 m) not normally associated with high sensitivity. Operating expenses for the LWA to carry out a cluster survey will be a small fraction of the costs of the space-based missions. The LWA is anticipated to have at least 4 simultaneous science beams, one of which could be completely devoted to cluster surveys. Using the conservative radio halo luminosity function model of Enßlin & Röttgering (2002) and assuming a radio spectral index of $\alpha = -1.5$ ($S_\nu \propto \nu^\alpha$) for the halos, the LWA will be able to detect 10^4 clusters in roughly 1.2 years of observing time. Approximately 3×10^3 of these clusters will be at redshifts of $z > 0.3$. Assuming a \$5M/yr operating budget (roughly 10% of the construction costs), this would amount to \$1.5M to survey 10^4 clusters. Similar assumptions of yearly operating costs of 10% of construction for DUO would amount to roughly \$30M for the two year baseline mission to study 10^4 clusters.

3. Precursor Observations

While it is clear that mergers play an important role in producing halos and relics (Giovannini & Feretti 2000; Feretti 2003), current observations would suggest that mergers are not *ipso facto* sufficient. The current census of halos and relics (combined) numbers roughly three dozen (Giovannini et al. 1999; Feretti 2003), no more than about 10% of the total cluster population. However, there have been significant selection effects in the detection of halos and relics, the most notable being their steep spectra. Halos and relics should be identified most naturally at low frequencies, but, until recently, low frequency observations have not been particularly sensitive so searches have focused on higher frequencies, e.g., 1400 MHz (Giovannini et al. 1999). In turn, this bias toward higher frequencies means only the halos and relics with the strongest radio emission will be detected. Necessarily, these will be only the most energetic mergers in relatively nearby clusters. Indeed, the current census is exclusively extremely massive ($> 10^{14}$ M$_\odot$), nearby ($z \sim 0.1$) clusters (Feretti 2003).

Thus, a key set of (on-going) precursor observations is to obtain higher sensitivity low-frequency radio observations of merging systems (e.g., with the Very Large Array at 74 and 330 MHz and the Giant Metrewave Radio Telescope at 150 and 330 MHz). The aim of these precursor observations is two-fold. First, we are exploring the extent to which halos and relics serve as useful proxies for determining whether a cluster is in hydrostatic equilibrium. Is it the case that all merging systems produce diffuse synchrotron emission but sensitivities of previous observations have been insufficient, or is there an additional aspect of a merging system required to produce diffuse synchrotron emission? Second, presuming that all merging systems do produce diffuse synchrotron emission, the radio observations will be combined with X-ray observations to determine the appropriate correction factors for L_X and T to account for the merger boost.

4. Error Budget

The goal of this project is to reduce the error budget of cluster-determined cosmological model parameters, particularly that portion arising from systematic effects.

The radio observations themselves may have two dominant sources of error. The first relates to the success of determining the relationship between merger activity and the presence of relic or halo emission. A quantitative estimate of the actual relationship, and therefore the eventual success of the anticipated radio observations, is difficult to assess because of the significant selection effects described in §3.

The second potential source of error will be important only if there is a clear relationship between merger activity and relic or halo emission. If there is a link, then we aim to derive correction factors for various X-ray determined properties. Naively, we expect that these uncertainties will scale with the total number of clusters surveyed. With current estimates for the number of clusters ($\gtrsim 10^4$) and the number of relics and halos ($\gtrsim 10^3$), we expect that we would be able to determine such correction factors to a few percent or better.

5. Impact on Dark Energy Studies

Low frequency interferometric radio observations of large samples of galaxy clusters over a wide range of redshifts provide a means to identify and characterize merging clusters. The presence of diffuse radio emission provides a signpost of a dynamically complex cluster which can be removed from DE studies. Alternatively, combined with simulations of cluster mergers, the radio signatures can be used to apply a "correction" to the observed clusters properties such as L_X, T, or the SZ decrement.

6. Risks and Strengths

The key scientific risk is addressed in §4, namely that the radio observations will yield little insight in the dynamical properties of clusters. Consequently, cluster-determined cosmological model parameters could contain a significant systematic bias.

The key technical risk, which is addressed in more detail in §7, is that the long wavelength observations required to assess the dynamical states of the clusters will prove much more difficult to obtain than it appears currently.

The key strength of the technique that we describe is that they impact cluster determinations of cosmological model parameters. In general, as Figure 2 shows, the uncertainty ellipse in the $(\Omega_m, \Omega_\Lambda)$ plane, as derived from cluster observations, is nearly orthogonal to the uncertainty ellipses as derived from Type Ia SNe and CMB determinations.

The key technical/programmatic strength of this program is that the required investment is relatively low. For instance, the hardware costs associated with a single LWA station, on the basis of Phase I development efforts, are estimated to be no more than \$0.5M. Overall costs for the LWA are estimated currently to be around \$50M, which is only a modest fraction of many proposed space missions.

7. Required R&D

Much of the required R&D for the LWA is in progress as part of Phase I. These tasks focus largely on developing wide-bandwidth dipoles and receivers (3:1 or better) but which are sufficiently sensitive that the dominant contribution to the system noise is provided by the Galactic synchrotron background. With deployment of the first station on schedule for later this year, no significant obstacles are foreseen.

The remaining R&D is largely algorithmic. The most difficult aspect of low-frequency observations is correcting for phase distortions introduced across the wavefront. In contrast to optical observations, where the phase distortions are introduced by the troposphere, for radio observations they are introduced by the ionosphere. Just a few years ago, these phase distortions were thought to be so severe that high-resolution, high-sensitivity observations at low frequencies were considered impossible. In particular, for the field of view anticipated for the LWA ($\approx 3^\circ$), it is likely that it will contain multiple isoplanatic patches; previous low-frequency observations had operated in a regime in which the field of view was smaller than the isoplanatic patch, but with the consequence that source confusion limited the system sensitivity.

Utilizing a series of observations with the 74 MHz system on the Very Large Array (an observing system developed jointly by NRL and the National Radio Astronomy Observatory), a number of methods have been demonstrated to be able to compensate for these ionospheric phase fluctuations. These methods have demonstrated that wavefront correction of ionospheric phase distortions is possible on antenna separations (or synthetic aperture sizes) of order 10–50 km.

One of the goals of the LWA Phase II, which is scheduled to start next year (2006), is to test the applicability of these methods to fields of view and ionospheric conditions that the full LWA is expected to confront (and/or to develop new methods relevant to the full LWA).

8. Access to Facilities

The project described here is designed to target the large samples (10^3–10^5) of clusters that are being identified currently. Radio observations would be used to identify the subset of clusters in equilibrium, and potentially to provide correction factors for L_X, T, and M resulting from the effects of mergers. The primary radio facility envisioned is the LWA, the timeline for which is described in §9.

9. Timeline

The crucial instrumental aspect needed for full application of this technique is a sensitive long-wavelength interferometer. Table 1 presents the timeline for the LWA.

The LWA is envisioned as developing in a phased manner. Phase 0 is in operation currently and being used to develop the technical experience necessary to construct the larger instrument. The deployment of Phase I is on schedule for later this year. Operating in conjunction with the existing Phase 0 instrument, it will yield an immediate factor of 2 improvement in resolution and open a new low frequency window below 74 MHz allowing the relationship between merging systems and the presence of relics and halos to be explored more fully.

In Phase II we will see a doubling of the angular resolution. The most significant progress will occur in Phases III and IV. These phases will improve the overall sensitivity and the surface brightness sensitivity specifically. These phases will allow for the dynamical state of large numbers of mergers to be assessed in a rapid and efficient manner.

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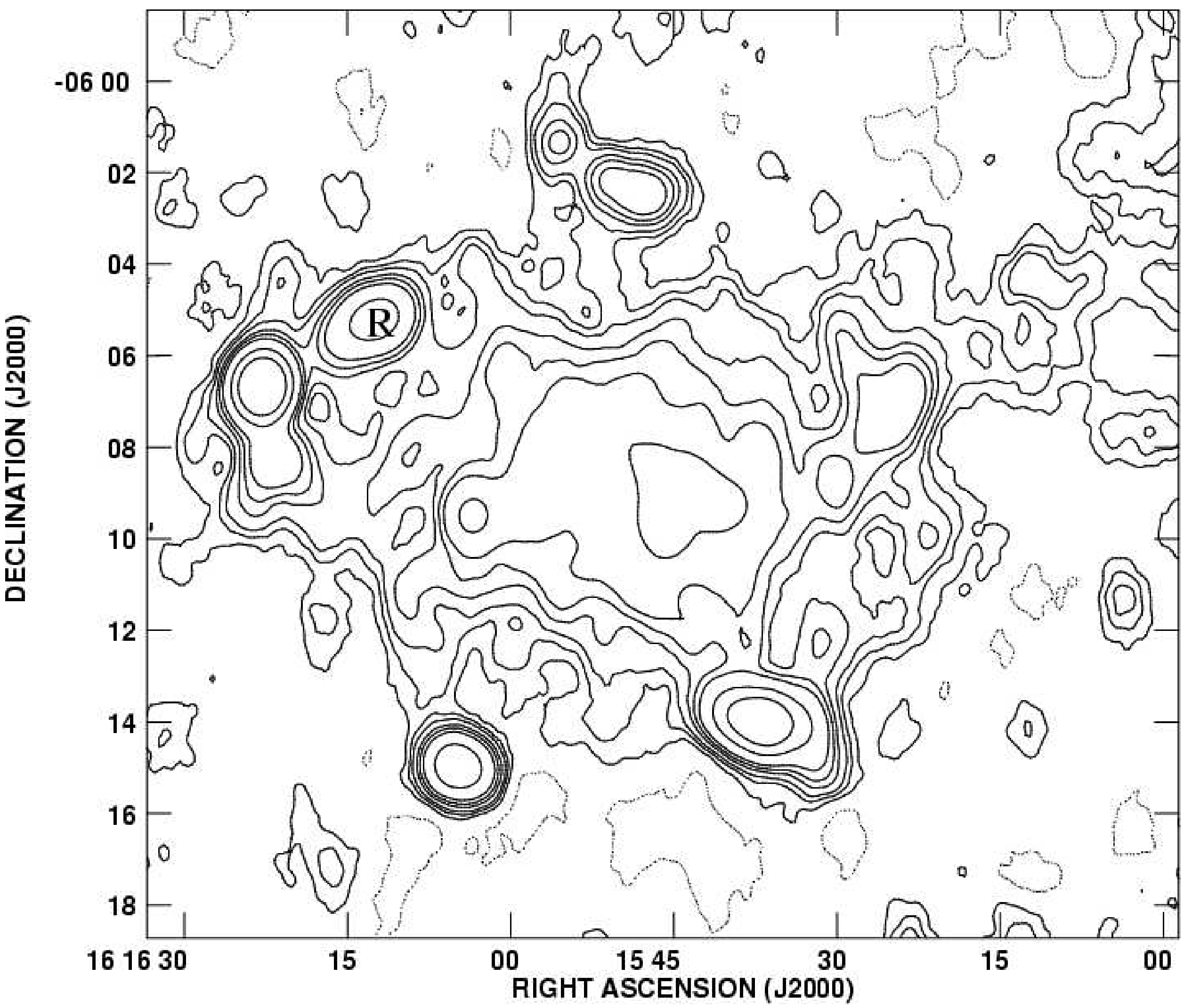

Fig. 1.— An example of diffuse radio halo emission in Abell 2163. The image is from Feretti et al. (2004) and shows radio contours at 330 MHz of the diffuse radio halo emission covering the majority of the image (largest linear size ~ 2.2 Mpc). Also visible are a number of more compact radio sources embedded in the diffuse emission. Abell 2163 is one of the hottest and most X-ray luminous clusters and shows signatures of merger activity.

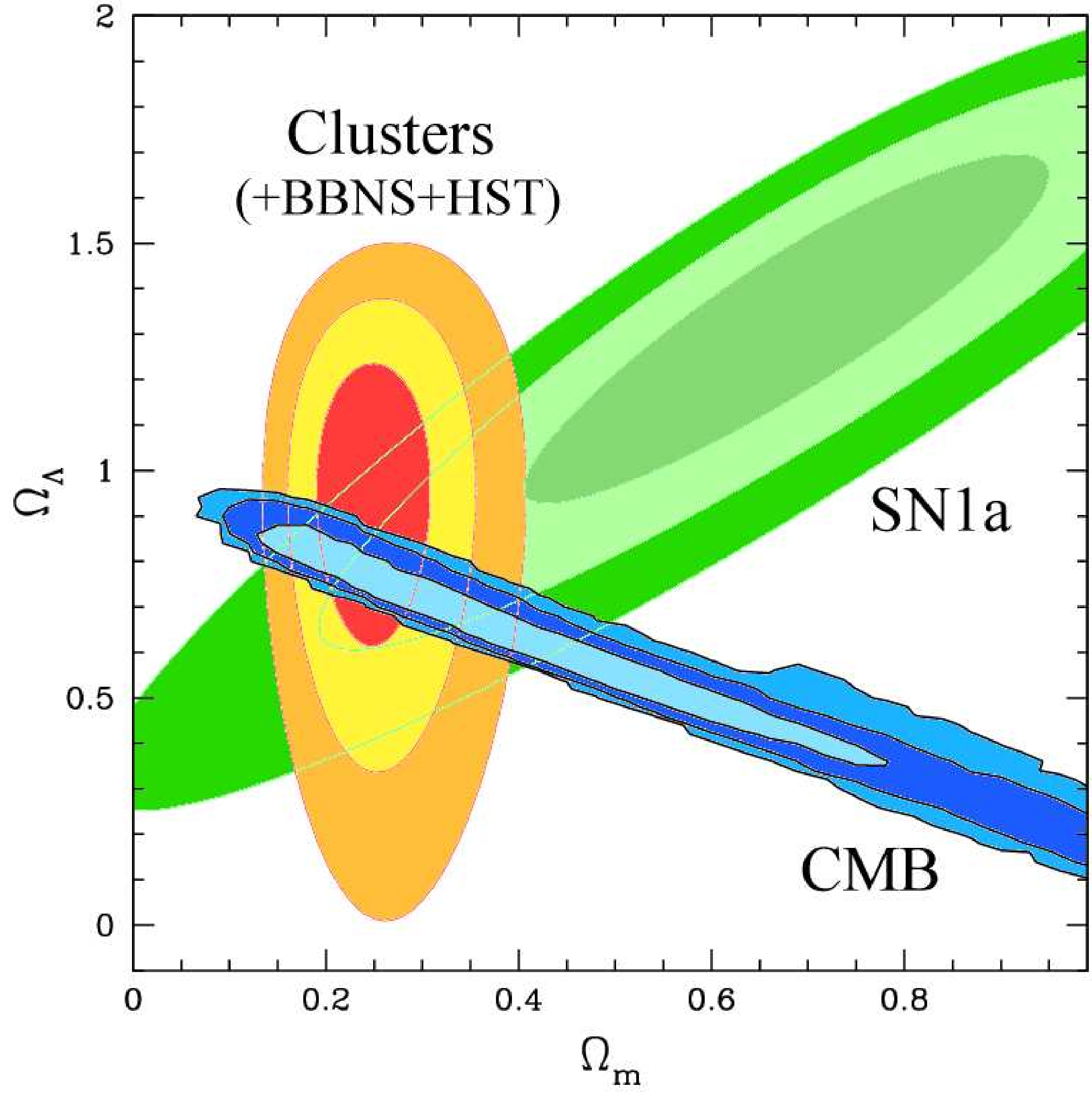

Fig. 2.— Figure from Allen et al. (2004) showing the 1, 2, and 3σ confidence intervals on Ω_Λ from the cluster baryonic mass fraction using priors on $\Omega_b h^2$ from Kirkman et al. (2003) and on h from Freedman et al. (2001). The plot also includes the independent constraints from the CMB data and Type 1a supernovae. Note that the constraints from the cluster baryonic mass fractions are nearly orthogonal to the those from other methods.

Table 1. LWA Timeline

Year	Phase	Description
1998–present	0	Very Large Array 74 MHz system
2005–2006	I	Long Wavelength Development Array
2006–2009	II	LWA Intermediate Array
2008–2010	III	LWA Core
2010–2012	IV	LWA