HERA: Illuminating Our Early Universe

For the Mid-Scale Science Projects category of the Mid-Scale Innovations Program

The major stages in the history of our Universe are written in the phases of hydrogen. The Hydrogen Epoch of Reionization Arrays (HERA) roadmap is a staged program that uses the unique properties of the 21 cm line from neutral hydrogren to probe the evolution of the intergalactic medium (IGM) during the Epoch of Reionization (EoR) and the preceding Dark Ages. Cosmic reionization corresponds to the epoch when the first stars and black holes reionize the neutral IGM that pervaded the Universe following cosmic recombination, roughly 0.5 Gyr to 1 Gyr after the Big Bang. Direct observation of the evolution of large scale structure via the HI 21 cm line will have a profound impact on our understanding of the birth of the first galaxies and black holes, their influence on the IGM, and cosmology.

HERA was given the "top priority in the Radio, Millimeter, and Sub-millimeter category of recommended new facilities for mid-scale funding" as part of the *New Worlds, New Horizons of Astronomy and Astrophysics* decadal survey, (Comm. for a Decadal Survey of A&A; NRC 2010; hereafter NWNH). The HERA roadmap envisioned a series of radio interferometers constructed throughout the decade, starting with the PAPER and MWA instruments (Donald C. Backer Precision Array for Probing the Epoch of Reionization; Murchison Widefield Array) aimed at characterizing foregrounds and a first effort to detect the Epoch of Reionization (EoR) power spectrum, a second-generation instrument to measure the EoR power spectrum in detail and reveal how early structure in the universe formed, and a third-generation instrument late in the decade to image the EoR. Using the advances spearheaded by the MWA and PAPER experiments, we propose a staged build out of HERA, observing in the 50MHz to 250MHz band, through arrays of 127, 331, and 568 elements, all stages of which will produce deepening levels of understanding of the HI 21cm signal from reionization. This program not only fulfills.

we are proposing to build a 568-element HERA instrument, observing in the 50–250 MHz band, that not only fulfills the goal of detailed power spectrum characterization as a second-generation instrument, but in its late stages is also capable of imaging the EoR, a task previously considered possible only for third-generation instruments.

1. Scientific Justification

The last unexplored phase in the evolution of luminous structures in the Universe begins with the birth of the first stars and culminates with the full ionization of the IGM $\sim$500 Myrs later. Whether during the Dark Ages (z$\geq$15) or the Epoch of Reionization (z$\sim$15–6), a wealth of astrophysical and cosmological phenomena are at play. The precise properties of the IGM depend on the nature and distribution of the first luminous sources (eg. typical masses, UV escape fractions, biased structure formation), the efficiency and abundance of heating sources (eg. X-ray binaries, shocks, or even dark matter annihilations), the formation of the first supermassive black holes, and the relative velocity of baryonic matter and dark-matter halos, among other effects. Exploration of the Dark Ages and EoR and the evolution of the IGM during these epochs has been called-out as one of the top three "priority science objectives chosen by the [NWNH] survey committee for the decade 2012-2021."

Thus far, a number of indirect probes have been used to understand cosmic reionization. These include observations of Gunn-Peterson attenuation by the IGM toward the most distant quasars (Fan et al. 2006; Bouwens et al. 2010), kinetic Sunyaev-Zel'dovich features in the CMB

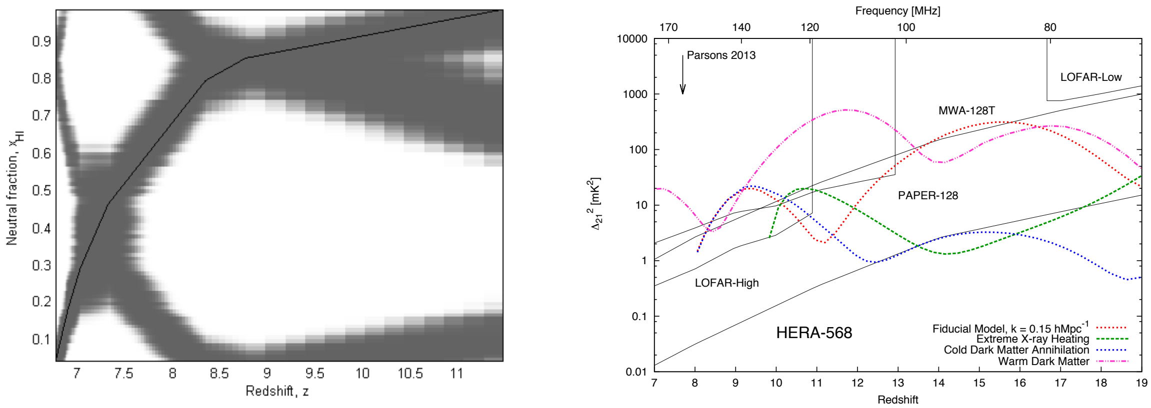

Fig. 1.— Left: A theoretical model from Robertson et al. (2013) that fits the existing constraints for reionization. Existing measurements and limits are indicated, along with the simulated measurements HERA would provide by constraining the rise and fall of the 21 cm power spectrum (see Figure 2). Right: HERA's ability to observe at relatively high sensitivity even at low frequencies opens a window to higher redshift pre-reionization physics. Shown here is the amplitude of the power spectrum as a function of redshift (at $k = 0.15$ hMpc^{-1}) for a variety of theoretical models with different IGM heating mechanisms.

(Zahn et al. 2012), CMB anisotropy and polarization (Page et al. 2007; Planck Collaboration et al. 2013), and the demographics of Lyα emitting galaxies (Treu et al. 2013), as summarized in Figure 1a. Unfortunately, these ground-breaking results have limited reach: the Gunn-Peterson effect and related phenomena saturate at low neutral fractions, and the CMB provides only an integral measure of the optical depth back to recombination. Moreover, many of these indirect observations are in tension with one another, underscoring both the difficulty in interpreting their results and the fact that reionization was a complex process.

The 21 cm hyperfine transition has been recognized as potentially the most powerful probe of the evolution of the IGM during cosmic reionization, and into the preceding Dark Ages (Morales and Wyithe 2010; Furlanetto et al. 2006). The HERA program follows a staged buildout, starting with a 37 antenna prototype followed by annual upgrades to 127, 331, and 568 antennas to unlock additional scientific capability (see project description in §3, and power spectrum sensitivity Figure 2a). This staged buildout will enable:

- **FY 2017** HERA 127 will measure the rise and fall of the EoR power spectrum, constraining the timing and duration of reionization.
- **FY 2018** HERA 331 will measure the shape of the power spectrum over a significant range in wavenumber, determining the features and distribution of the first galaxies that dominate cosmic reionization. Figure 1a shows the direct constraints on reionization HERA 331 will be able to provide.
- **FY 2019** HERA 568 will extend precision power-spectrum observations into the dark ages and start direct imaging of the IGM during reionization. Imaging will be particularly important for providing environmental context for JWST observations and comparison with large scale galaxy surveys .

Detection of the 21 cm signal will have an impact comparable to the discovery of the CMB, and study of the three-dimensional evolution of large scale structure in the IGM via the HI 21 cm

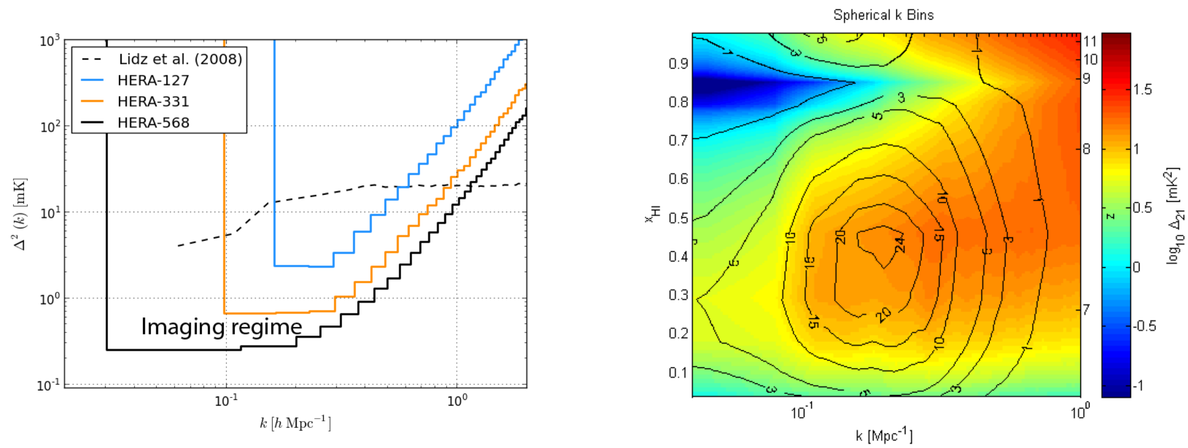

Fig. 2.— Left: Predicted power-spectrum sensitivities for three stages of HERA (solid) relative to a fiducial 50% ionization model (dashed; Lidz et al. 2008). In addition to a staged array size, sensitivity curves follow a staged improvement in analysis software that expands the range of modes that are not corrupted by systematics. Right: The color contours show the rise and fall of the 21 cm power spectrum (Lidz et al. 2008) as a function of ionization fraction x_i (and redshift). The spectrum initially follows the dark matter fluctuations at the upper edge of the plot, falls as the densest regions reionize at $x_i = 0.8$ (inside-out in this model), rises and flattens as galaxies ionize large bubbles in the IGM (x_i 0.6–0.2, $x_i = 0.5$ corresponds to the line in the lefthand panel), before falling again as reionization completes at the bottom of the plot. The contours indicate the predicted significance of HERA 568 observations, which will fully observe the shape and evolution of the EoR power spectrum and start imaging the EoR at large scales. The dashed line dashed line indicates the location of the model used in the left panel.

line has the potential to become 'the richest of all cosmological data sets' (Barkana and Loeb 2005; Loeb and Zaldarriaga 2004)). As emphasized in NWNH: "The panel concluded that to explore the discovery area of the epoch of reionization, it is most important to develop new capabilities to observe redshifted 21 cm HI emission, building on the legacy of current projects and increasing sensitivity and spatial resolution to characterize the topology of the gas at reionization." As a high sensitivity instrument with broad frequency coverage, HERA would be capable of painting a consistent and uninterrupted picture of not just the EoR, but also into the preceding Dark Ages.

Theorists have devoted considerable effort to modeling the complex astrophysics of reionization. [XXX Some good refs Steve?]. but bridging the enormous scale difference between the self-shielding regions that are the primary sinks of ionizing photons and volumes required for statistically representative samples of cosmic structures remains an open problem. However, basic constraints on theoretical models remain rudimentary, and the most fundamental questions remain concerning the process of reionization: when did reionization occur, and over what timescale? what objects dominated the radiation field? how were the objects distributed? did the first generation of stars enhance or suppress the formation of subsequent stars in the original halo and smaller nearby halos? are all open questions. Without HERA's measurements, further progress on understanding first galaxy formation and cosmic reionization remains problematic.

2. Foregrounds & Lessons Learned from PAPER and MWA

The challenge of 21 cm cosmology is isolating the faint EoR signal from astrophysical foregrounds that are 4–5 orders-of-magnitude brighter, as seen in the lefthand panel of Figure 3. The major breakthrough in 21 cm cosmology—what enables us to propose HERA now—is the discovery of the EoR Window.

21 cm cosmology observations and foreground isolation are best understood in the three dimensional wavenumber space $\mathbf{k}$. Because the HI emission is a narrow spectral line, the observed frequency of the emission can be mapped to redshift or line-of-sight distance to provide an observed volume $\{x, y, z\}$ in cMpc. This observed volume is Fourier transformed into a three dimensional wavenumber cube $\{k_x, k_y, k_z\}$. For graphical simplicity the angular wavenumbers are typically averaged ($\{k_x, k_y\} \to k_\perp$) to produce line-of-sight wavenumber $k_\|$ vs. angular $k_\perp$ figures. Spatial isotropy allows measurements within the 3D wavenumber space to be squared and averaged in shells to produce the spherical power spectrum presented in Figure 2.

The astrophysical foreground emission is spectrally very smooth (synchrotron & Bremsstrahlung emission) or at known editable frequencies (radio recombination lines). The advance in 21 cm cosmology has been understanding how this foreground emission interacts with the instrument to produce the EoR Window. Through a concerted theoretical and observational campaign (Morales et al. 2012; Parsons et al. 2012; Vedantham et al. 2012; Datta et al. 2010; Hazelton et al. 2013; Pober et al. 2013; Parsons et al. 2013; Dillon et al. 2013) we now understand that the foreground contamination is confined to a 'wedge' in $k_\|$ vs. $k_\perp$, as demonstrated by the PAPER observations in the righthand panel of of Figure 3. This wedge is the result of the smooth spectrum foregrounds (low $k_\|$) interacting with the inherent chromaticity of an interferometer. This leaves the region above isolated from the foreground emission—a window through which we can observe the EoR.

All observations have now confirmed the presence of the EoR Window (Pober et al. 2013; Dillon et al. 2013), including suppression by more than 3 orders-of-magnitude (6 in mK^2 units) to the thermal noise floor of current PAPER observations (Parsons et al. 2013). This is a major advance—we can suppress foregrounds and we understand the instrumental and analysis characteristics needed to perform the EoR measurement. The MWA and PAPER teams have been at the forefront of developing the EoR Window, writing all of the papers in the literature and developing the individual baseline (delay-spectrum) and full power spectrum (imaging) analyses to exploit this insight.

3. HERA

The HERA program a staged build-out to a 568-antenna array in South Africa that incorporates the lessons learned from the first generation EoR observatories. It features a 14 m zenith-pointing dish optimized for sensitivity and spectral smoothness, a dense hexagonal core to enable redundant baseline calibration and delay-spectrum analysis, and a distribution of outrigger antennas to provide complete uv coverage to ∼700 m for foreground imaging and mitigation (see Figure 4). HERA draws on the technical heritage of the MWA, PAPER, EDGES and MITEoR. Specific examples include the antenna feed and correlator of PAPER, receiver node and field digitization from the MWA, absolute radiometric calibration from EDGES, redundant baseline calibration from MITEoR, the delay-spectrum analysis from PAPER, and the precision imaging and foreground removal software from the MWA.

The HERA antenna is an example of this technical heritage. The spectral smoothness and the stability of the antenna response determine the precision to which astrophysical foreground emission can be separated from the cosmological 21 cm emission. HERA uses the PAPER dipole feed—modified slightly for wider bandwidth—suspended over a 14 m parabolic dish (Figure 4a).

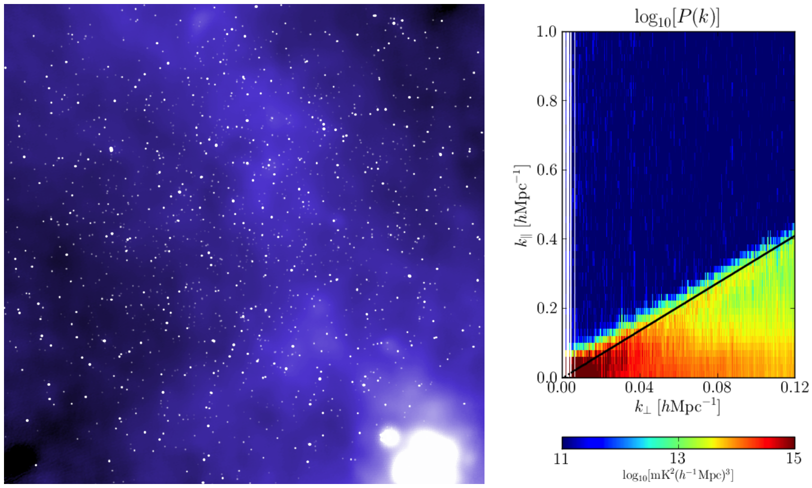

Fig. 3.— The left panel shows foregrounds as imaged with the MWA using the Fast Holographic Deconvolution software package developed by the University of Washington (Sullivan et al. 2012). This image uses 2 minutes of MWA data towards galactic anti-center, spans $\sim$30° with the Vela and Puppis SNRs in the lower righthand corner, and has less than 0.5% polarization leakage across the field. The right hand panel shows the EoR window as observed by PAPER (Pober et al. 2013). While astrophysical foregrounds are very bright as seen in the 'wedge' to the bottom right, their contribution falls by orders-of-magnitude to below the thermal noise in the EoR window as predicted by Morales et al. 2012; Parsons et al. 2012; Vedantham et al. 2012; Datta et al. 2010; Hazelton et al. 2013.

The short ($\sim$5 m) focal height of the dishes is central to limiting the path length of reflections whose time-delay gives rise to chromatic antenna sensitivity. The zenith pointing enhances the stability of the antenna response (PAPER), short cables to in-field digitizers limit the length of cable reflections (MWA), and absolute calibration (EDGES) are all designed to provide an extremely stable and smooth spectral response. Similarly the antenna layout uses the dense core, outriggers, and symmetric configuration of the MWA, combined with redundant baselines within the core (PAPER, MITEoR). Together these advances enable HERA to have the science reach envisioned in the decadal survey while fitting within the MSIP funding envelope.

HERA follows a staged build-out plan. In each deployment stage improvements are incorporated into the system and new science capabilities are unlocked. This approach has the advantage of providing early access to science and reducing the project risk by testing systems early and changing them incrementally. As shown in Figure 2, each stage of HERA brings an associated improvement in sensitivity that allows key aspects of 21 cm reionization science to be addressed. The timeline of HERA development, along with the associated science products, is outlined below.

Year 1–Infrastructure and First 37 Antennas (FY 2015).

- Infrastructure installation. Using the new 'K3' site approximately 10 km from the current PAPER site at the Karoo Radio Observatory in South Africa. Includes ground leveling, power and basic network connectivity.
- Move existing PAPER-128 antennas, correlator, and EMC container to K3 site.
- Install first 37 HERA antennas and instrument with existing PAPER feeds and electronics.
- Begin development of wider bandwidth HERA baluns, receivers, feeds, and nodes using the PAPER and MWA techical heritage (Bradley et al. 2005; Lonsdale et al. 2009; Tingay et al.

Fig. 4.— [New picture of HERA antenna and core of the array] Left: the HERA antenna which has been optimized for spectral smoothness and stability. Right: the core of HERA 568 in a redundant hexagonal array with outrigger antennas (not shown) for imaging and foreground mitigation.

2013) and the development of in-situ antenna calibration system based on EDGES (Rogers and Bowman 2012). Continue development of delay-spectrum (Parsons et al. 2012), Fast Holographic Deconvolution software (FHD; Sullivan et al. 2012) and automated redundant baseline calibration software (Liu et al. 2010).

Year 2–Hardware Commissioning and Deep Foreground Survey (FY 2016).

- Commissioning observations using a hybrid array of 37 HERA antennas in a close-packed hexagon surrounded by 91 PAPER antennas in an imaging configuration.
- Perform a deep polarized foreground survey using unique hybrid antenna capability of FHD. Will directly determine on-sky beam response of HERA antennas and enable future subtraction of sources in HERA sidelobes.
- Finalize site infrastructure (high-bandwidth optical network, surveying, trenching).
- On-antenna commissioning of new feeds, receivers, nodes, and antenna calibrations systems in Green Bank and South Africa.
- Build out to 127 HERA antennas starts.

Year 3–HERA 127 and Detecting the Rise and Fall of Reionization (FY 2017).

- Construction of HERA 127 completes, and science observations begin in Oct. 2016, again using the PAPER correlator.
- Analysis begins on a dataset capable of constraining the timing and duration of reionization. Analysis focuses on current techniques based on PAPER individual baseline analysis, with exploration of subtracting bright and polarized foreground sources.
- Deployment of HERA 331 begins. Node electronics are installed for all 331 elements, and a new, 331-element GPU-based correlator is installed in the Karoo Array Processing Building (KAPB).
- Additional data storage infrastructure is installed in the KAPB. The UPenn data analysis cluster is upgraded.

Year 4–HERA 331 and Measuring the Evolution of the First Galaxies (FY 2018).

- Construction of HERA 331 completes, and science observations begin in Oct. 2017.

- Science observations with HERA 331 complete in Apr. 2018, and analysis begins on a dataset capable of characterizing the redshift evolution the power spectrum shape—revealing the development of the first galaxies.
- Continued analysis and software development with an emphasis on opening the EoR window (removing contamination at low $k_{\|}$).
- Build out to 568 antennas begins, including outrigger antennas to fascilitate imaging and better foreground removal.
- Pipelines for EoR processing of HERA 568 complete.

Year 5–HERA 568, Imaging Reionization and Constraining the Development of Structure at $z > 11$ (FY 2019).

- Construction of HERA 568 completes, and science observations begin in Oct. 2018.
- Analysis push to enable imaging of the largest structures and extracting the full sensitivity of the instrument (including partially coherent baselines).

The staged buildout of HERA enables cutting edge science at each stage while mitigating risk by allowing the team to learn from experience along the way. HERA 127 will measure the rise and fall of the EoR power spectrum; HERA 331 will characterize the shape of the power spectrum and constrain the development of the first galaxies; and HERA 568 will start to image reionization while pushing power spectrum measurements into the Dark Ages.

4. Broader Impacts

Training Instrumentalists and Developing African Scientists. As a part of the HERA program we will train new instrumentalists and increase the diversity of US graduate programs by preparing South African students for admission to US degree programs.

The need for training new instrumentalists has been widely recognized, and was specifically called out by NWNH in creating the MSIP program: "MSIP—would provide first-class science at moderate cost and would address the need to involve and train students in experiment design and instrumentation (NWNH, pg. 225)." The three junior faculty on this proposal were all trained on the MWA, PAPER, and EDGES experiments, and together these experiments have enabled 1 Hubble and 3 NSF postdoctoral fellowships in astrophysics instrumentation. As a university based program that is pushing the state-of-the-art in radio instruments, HERA will naturally train another generation in instrumentation.

The PAPER project has a history of employing South African undergraduate and masters students as part of major deployment activities, and this work applies directly to their academic program as field engineering experience. We will expand our South African outreach program during HERA, by recruiting talented South African undergraduate and masters students for 3 month internships at the HERA partner institutions. Each year one institution will host the SA cohort (cohorts are more culturally appropriate than individual internships), providing an REU-like experience focused on helping commission and operate HERA. This experience will familiarize the students with the US graduate schools, and give them the research experience and letters of recommendation critical for future admission.

Public Data Products. On the HERA timescale a number of new observations will come on line that would benefit from cross-comparison with the power spectra and images produced by HERA. These include providing the reionization environment for JWST and ALMA galaxy and cluster observations; cross-correlation with WFIRST near-IR surveys; and cross-correlation with CMB polarization observations. The HERA measurements will be released to the community after an 18 month proprietary period and hosted at MIT. These data products will include foreground subtracted cubes for cross-correlation, deep images of reionization from HERA 568, compressed visibilities for re-analysis, snapshot continuum images for transient observations, and wide-field maps from the survey made in the first two years.

5. Project Management Plan

This project balances the light-weight management structure of PAPER/MWA activities and the more formal structure required for larger-scale projects. Construction management is centered at UC Berkeley's Radio Astronomy Laboratory (RAL), headed by Aaron Parsons as the Project Director and David DeBoer as Project Manager. They will be assisted by Bob Goeke at MIT as a part-time Project Engineer with a particular emphasis on interfacing with the NE based antenna contractor. A Site Manager will split their time between South Africa and Berkeley and manage the construction activities by local South African contractors. A SKA-SA Liaison will coordinate HERA, Meerkat, and SKA site activities (supported by SKA-SA). Governance will be provided by a Board made of this proposal's senior investigators, and will be operate using super-majority policies.

The scientific capability of HERA and the data analysis and publication will be overseen by the Science Panel, and chaired by the Project Scientist. These positions will rotate as needed expertise changes, and are appointed by the Board. Initial members are Aguirre, Furlanetto, Morales, and Tegmark with Bowman serving as the Project Scientist. As with the MWA and PAPER, observing will be performed remotely with maintenance headed by the Site Manager.

[Can we say even this?] The estimated inherent contingency is $\sim$15%, anticipating that project risk and contingency are handled by reducing build-out with associated de-scoping of science capabilities.

6. Why Now? Why Us?

This HERA proposal follows the vision for 21 cm observations laid out in NWNH. PAPER and the MWA have already succeeded in the primary task envisioned in NWNH—characterizing the astrophysical foregrounds and developing the hardware and analysis advances needed to suppress the contamination. The discovery and characterization of the EoR Window and the development of precision foreground mitigation techniques have shown that foregrounds can be suppressed to the thermal noise (§2; Parsons et al. 2013). While the MWA and PAPER are pushing hard to detect the EoR PS, budget constraints have dictated that a marginal detection is the best these instruments can achieve. HERA will both ensure a high significance detection of the HI 21cm signal, as well as provide powerful constraints on rise and fall of reionization, how early stars and structure formed, and physical processes at the end of the cosmic dark ages (Figures 1 & 2).

As envisioned in NWNH, the US EoR projects (PAPER, MWA, EDGES, MITEoR) have pooled their expertise to develop the second generation HERA observatory. This has created a small collaborative team with a deep well of scientific experience—the majority of papers on EoR observations are authored by members of the HERA team. By leveraging this expertise the HERA design is significantly less expensive than envisioned in NWNH, while having greater scientific reach.

The last few years have been very productive for the EoR community—we understand the foreground contamination and we are pushing the current instruments to their thermal limits. We are now ready to build the HERA instrument envisioned in NWNH and capitalize on the scientific promise of 21 cm cosmology.

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