Snowmass2021 – Letter of Interest

Packed Ultra-wideband Mapping Array (PUMA): Science Opportunities

Thematic Areas:

■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF7) Cosmic Probes of Fundamental Physics
■ (CompF2) Theoretical Calculations and Simulation
■ (TF9) Astro-Particle Physics & Cosmology

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Abstract:

PUMA is a proposal for an ultra-wideband, low-resolution and transit interferometric radio telescope operating at 200 – 1100 MHz. It is designed to address fundamental questions about the nature of the epochs of accelerated expansion the Universe has undergone both before the hot big bang phase (inflation) and now (dark energy). It will study the physics of dark energy and modified gravity by measuring the expansion history and the growth of structure with an exquisite precision up to redshift of $z = 6$. It will study the physics of inlation by constraining primordial non-Gaussianity and features in the primordial power spectrum. It will constrain light relics by measuring the power spectrum shape. In its full configuration, the proposed program has the noise equivalent of a traditional spectroscopic galaxy survey comprised of 2.5 billion galaxies at a comoving wavenumber of $k = 0.5\ h^{-1}$Mpc spanning the redshift range $z = 0.3 - 6$.

We present the Packed Ultra-wideband Mapping Array (PUMA), a design for an ultra-wide band, high-sensitivity and low-resolution radio telescope array operating at 200–1100 MHz. The system is optimized for cosmology with $21\,\mathrm{cm}$ intensity mapping in the post-reionization era, $z \lesssim 6$, but also addresses other science goals enabled by such observations, including Fast Radio Bursts (FRBs), pulsar monitoring and transients as a part of multi-messenger observations. The PUMA concept is the result of a three-year exploratory effort by the $21\,\mathrm{cm}$ subgroup of the Department of Energy Cosmic Visions Dark Energy working group. Following a general call for a Stage II 21 cm experiment [1], the concept evolved into a concrete proposal that culminated in the submission of an APC project to the Decadal Survey on Astronomy & Astrophysics [2] and response to the Request for Information [3].

PUMA will measure the structure in the Universe using intensity mapping of the redshifted $21\,\mathrm{cm}$ emission line from neutral hydrogen; the field of observation will stretch from our local cosmological neighborhood ($z \sim 0.3$) to just after reionization ($z \sim 6$). All of these measurements will be performed with a single instrument, a very large interferometric radio telescope composed of 6-m dishes arranged on a hexagonal lattice with a 50% fill factor. Our full instrument contains 32,000 dishes (called PUMA-32K), while a smaller version with 5,000 dishes (called PUMA-5K) can act as a useful stepping stone while still delivering compelling and scientifically competitive science.

PUMA has been designed around six science goals, of which four are relevant for the Cosmic Frontier of the Office of Science, Department of Energy Mission. By mapping the Universe at redshifts $z > 2$, the instrument naturally fits into the science case presented in [4] for Large Scale Structure observations at high-redshift. In terms of dark energy and modified gravity, PUMA will:

A. *Characterize the expansion history in the pre-acceleration era.* By the time PUMA becomes operational, multiple experiments will have measured the expansion history close to the sample-variance limit out to redshift $z \sim 1.5$ and with some precision to $z \sim 3$. PUMA will enable nearly sample-variance limited Baryon Acoustic Oscillations measurements all the way to $z \sim 6$ and complete the challenge of characterizing the expansion history across the cosmic ages [5]. Use of the full-shape of the power spectrum could tighten constraints even further.

B. *Characterize structure growth in the pre-acceleration era.* Measuring the growth of structure over the same redshift-range as the expansion history allows fundamental tests of general relativity [5]. If general relativity is correct, then the growth of structure is uniquely determined by the expansion history. A disagreement between the two measurements would be a smoking gun of modified gravity and PUMA is one of the most promising probes to detect it. PUMA will measure growth by relying on the weakly non-linear regime where the degeneracy between bias and growth can be broken by the shape of the power spectrum [6].

PUMA will also address fundamental questions about inflation, the Universe's early epoch of accelerated expansion. It will:

C. *Constrain or detect primordial non-Gaussianity.* Primordial non-Gaussianity is one of the few handles that we have on the physics of inflation [7]. A detection of non-Gaussianity would provide evidence for non-minimal models of inflation which would imply either multiple fields or deviations from slow roll. It would be a monumental discovery, potentially probing physics up to the grand unification scale.

D. *Constrain or detect features in the power spectrum.* Features in the primordial power spectrum are another, often overlooked, handle on the physics of inflation [8]. There are two main mechanisms for their production. In one case features can be produced early during the inflationary phase and are generic in a wide class of models of inflation and its alternatives. Primordial features could provide hints about the shape of the inflationary potential and, if detected, would have a profound impact on our understanding of inflation. Alternatively, they can result from a brief period in the early Universe where non-standard components affect the expansion history of the universe, modifying the power spectrum [9–11].

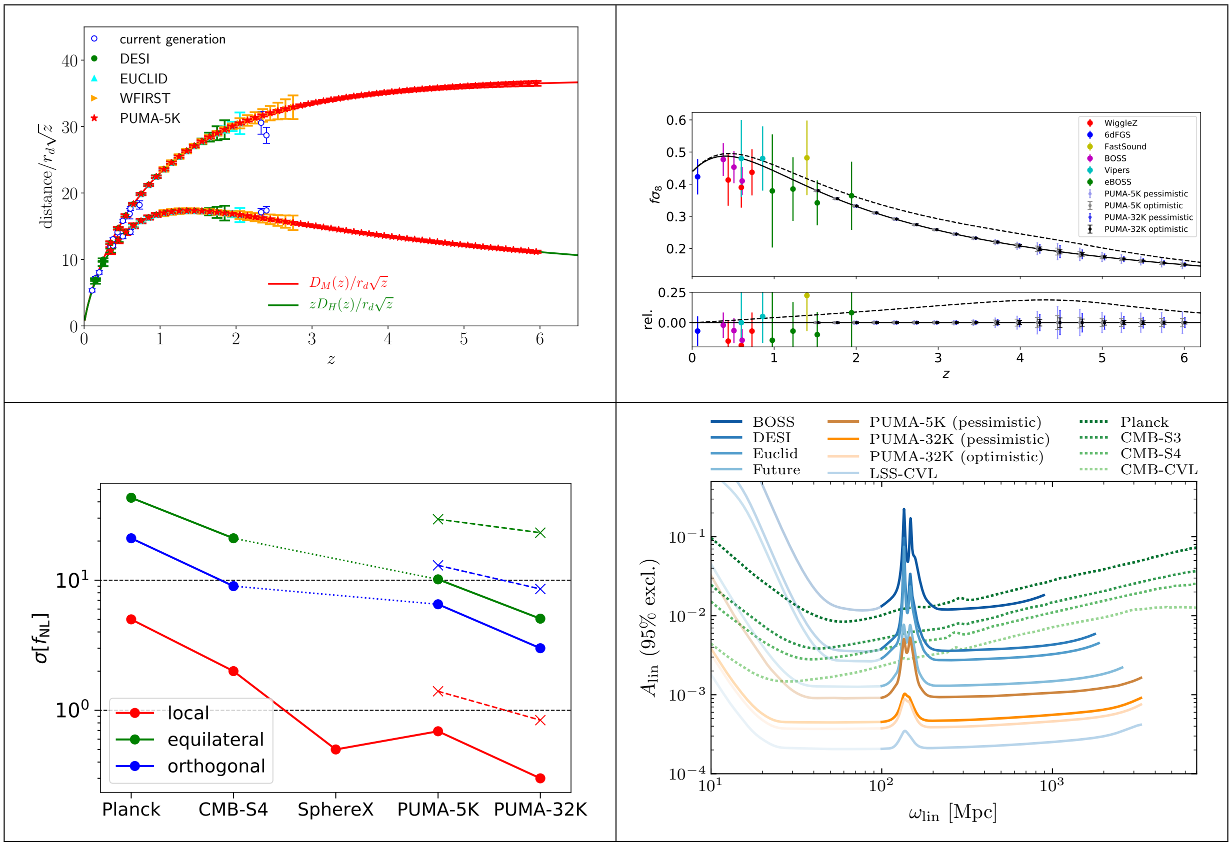

Figure 1: Science reach of PUMA's four main probes: *Upper Left:* Projected Baryon Acoustic Oscillations (BAO) errors; *Upper Right:* Projected sensitivities on growth parameter $f\sigma_8$; *Lower Left:* Error on inflationary non-Gaussianity parameters f_{NL}; *Lower Right:* Projected sensitivity to features in the primordial power spectrum. Adapted from Ref. [3] which should be consulted for a detailed description.

While PUMA will likely be the most cost efficient method of mapping the high-redshift universe, we recognize that it is not a shovel-ready experiment. The 21 cm signal has never been detected using an interferometer. However, the problems are well understood and are associated with purely technical issues of calibration and instrument stability.

Research & Development Need: We propose a robust research and development program that will lead to an instrument design with guaranteed performance. This program will run in conjunction with hardware and facility development as described in a companion document [12]. This research should cover development of a wide-ranging software infrastructure that will allow us to make controlled numerical experiments. In particular, we should be able to (i) make an extensive simulation of the entire system with increasing levels of fidelity in order to establish basic hardware requirements on subsystems like clock distribution, mechanical properties of reflecting elements and phase calibration requirements; (ii) prototype the real-time calibration algorithms that can be tested, validated and characterized *in-silico* to establish requirements on the correlator subsystem; and (iii) enable electromagnetic modelling of both a single isolated dish as well as cluster of dishes in order to assess and model the amount of electromagnetic coupling between elements.

PUMA will enable exciting science that will take Cosmology into the third decade of the twenty-first century. It carries the pioneering work enabled by optical spectroscopy to higher redshift, where it has numerous technical and performance advantages over other techniques.

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