Astro2020 Science White Paper

Inflation and Dark Energy from spectroscopy at $z > 2$

Thematic Areas:
- ☐ Planetary Systems
- ☐ Star and Planet Formation
- ☐ Formation and Evolution of Compact Objects
- ☑ Cosmology and Fundamental Physics
- ☐ Galaxy Evolution
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Principal Authors:

Name: Simone Ferraro
Institution: Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA
Email: sferraro@lbl.gov

Name: Michael J. Wilson
Institution: Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA
Email: mjwilson@lbl.gov

Co-authors / Endorsers:

The University of Oxford, Oxford OX1 3RH, UK
Department of Physics, Lower Mountjoy, South Rd, Durham DH1 3LE, United Kingdom
Lawrence Livermore National Laboratory, Livermore, CA, 94550
Korea Astronomy and Space Science Institute, Daejeon 34055, Korea
Harvard-Smithsonian Center for Astrophysics, MA 02138
SISSA - International School for Advanced Studies, Via Bonomea 265, 34136 Trieste, Italy
IFPU - Institute for Fundamental Physics of the Universe, Via Beirut 2, 34014 Trieste, Italy
INFN – National Institute for Nuclear Physics, Via Valerio 2, I-34127 Trieste, Italy
CSEE, West Virginia University, Morgantown, WV 26505, USA
Center for Gravitational Waves and Cosmology, West Virginia University, Morgantown, WV 26505, USA
Cornell University, Ithaca, NY 14853
National Center for Nuclear Research, Ul.Pasteura 7, Warsaw, Poland
ICC, University of Barcelona, IEEC-UB, Martí i Franquès, 1, E08028 Barcelona, Spain
Dept. de Física Quàntica i Astrofísica, Universitat de Barcelona, Martí i Franquès 1, E08028 Barcelona, Spain
Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth PO1 3FX, UK
Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
The Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA
Institute of Physics, Laboratory of Astrophysics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland
The Ohio State University, Columbus, OH 43212
National Optical Astronomy Observatory, 950 N. Cherry Ave., Tucson, AZ 85719 USA
Lawrence Berkeley National Laboratory, Berkeley, CA 94720
Department of Astronomy/Steward Observatory, University of Arizona, Tucson, AZ 85721
Fermi National Accelerator Laboratory, Batavia, IL 60510
Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom
Perimeter Institute, Waterloo, Ontario N2L 2Y5, Canada
Astronomy Centre, School of Mathematical and Physical Sciences, University of Sussex,
Brighton BN1 9QH, United Kingdom
28 University of California at Santa Cruz, Santa Cruz, CA 95064
29 Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans, s/n, 08193 Barcelona, Spain
30 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
31 HEP Division, Argonne National Laboratory, Lemont, IL 60439, USA
32 Department of Physics, University of California Berkeley, Berkeley, CA 94720, USA
33 Sorbonne Université, Université Paris Diderot, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies, LPNHE, 4 Place Jussieu, F-75252 Paris, France
34 IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
35 Space Sciences Laboratory, University of California Berkeley, Berkeley, CA 94720, USA
36 Institute of Astronomy, University of Cambridge, Cambridge CB3 0HA, UK
37 Kavli Institute for Cosmology, Cambridge, UK, CB3 0HA
38 Department of Physics, McWilliams Center for Cosmology, Carnegie Mellon University
39 Department of Physics, Harvard University, Cambridge, MA 02138, USA
40 University of New Mexico, Albuquerque, NM 87131
41 Stanford University, Stanford, CA 94305
42 University of Utah, Department of Physics and Astronomy, 115 S 1400 E, Salt Lake City, UT 84112, USA
43 Laboratoire Astroparticule et Cosmologie (APC), CNRS/IN2P3, Université Paris Diderot, 10, rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France
44 Département d’Astrophysique, CEA Saclay DSM/IRfu, 91191 Gif-sur-Yvette, France
45 Department of Physics and Astronomy, University of Rochester, 500 Joseph C. Wilson Boulevard, Rochester, NY 14627, USA
46 Boston University, Boston, MA 02215
47 University College London, WC1E 6BT London, United Kingdom
48 Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada
49 Instituto de Fisica Teorica UAM/CSIC, Universidad Autonoma de Madrid, 28049 Madrid, Spain
50 Universidad Autónoma de Madrid, 28049, Madrid, Spain
51 University of Florida, Gainesville, FL 32611
52 University of California San Diego, La Jolla, CA 92093
53 University of Minnesota, Minneapolis, MN 55455
54 Astrophysics Group, Cavendish Laboratory, J.J.Thomson Avenue, Cambridge, CB3 0HE, UK
55 Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
56 Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham, DH1 3LE, UK
57 Dunlap Institute for Astronomy and Astrophysics, University of Toronto, ON, M5S3H4
58 Department of Astronomy and Astrophysics, University of Toronto, ON, M5S3H4
59 University of Michigan, Ann Arbor, MI 48109
60 University of Texas at Dallas, Texas 75080
61 Johns Hopkins University, Baltimore, MD 21218
62 Dipartimento di Fisica e Astronomia “G. Galilei”, Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy
Southern Methodist University, Dallas, TX 75275
Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005 India
Department of Physics, Ben-Gurion University, Be‘er Sheva 84105, Israel
Department of Astronomy, University of California Berkeley, Berkeley, CA 94720, USA
IFUNAM - Instituto de Física, Universidad Nacional Autónoma de México, 04510 CDMX, México
Princeton University, Princeton, NJ 08544
Texas A&M University, College Station, TX 77843
Massachusetts Institute of Technology, Cambridge, MA 02139
Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands
International Centre for Theoretical Physics, Strada Costiera, 11, I-34151 Trieste, Italy
Siena College, 515 Loudon Road, Loudonville, NY 12211, USA
Department of Physics and Astronomy, University of Wyoming, Laramie, WY 82071, USA
Department of Physics, Yale University, New Haven, CT 06520
University of Pittsburgh and PITT PACC, Pittsburgh, PA 15260
División de Ciencias e Ingenierías, Universidad de Guanajuato, León 37150, México
ETH Zurich, Institute for Particle Physics, 8093 Zurich, Switzerland
Centre for Astrophysics, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
Department of Physics and Astronomy, University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1, Canada
Dipartimento di Fisica, Università La Sapienza, P. le A. Moro 2, Roma, Italy
Istituto Nazionale di Fisica Nucleare, Sezione di Roma, 00185 Roma, Italy
California Institute of Technology, Pasadena, CA 91125
Department of Physics and Astronomy, Sejong University, Seoul, 143-747, Korea
Kansas State University, Manhattan, KS 66506
Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, 277-8583 Kashiwa, Japan
Institute for Advanced Study, Princeton, NJ 08540
Stony Brook University, Stony Brook, NY 11794
Kavli Institute for Particle Astrophysics and Cosmology, Stanford 94305
Department of Physics and Astronomy, Ohio University, Clippinger Labs, Athens, OH 45701, USA
Shanghai Astronomical Observatory (SHAO), Nandan Road 80, Shanghai 200030, China
Brookhaven National Laboratory, Upton, NY 11973
Goddard Space Flight Center, Greenbelt, MD 20771 USA
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
Jodrell Bank Center for Astrophysics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester, M13 9PL, UK
The Hong Kong University of Science and Technology, Hong Kong SAR, China
Syracuse University, Syracuse, NY 13244
National Astronomical Observatories, Chinese Academy of Sciences, PR China
School of Physics, Korea Institute for Advanced Study, 85 Hoegiro, Dongdaemun-gu, Seoul 130-722, Korea
The expansion of the Universe is understood to have accelerated during two epochs: in its very first moments during a period of ‘Inflation’ and much more recently, at \( z < 1 \), when an unknown element known as Dark Energy drives cosmic acceleration. The undiscovered mechanism behind these two epochs represent some of the most important open problems in fundamental physics.

Most of the processes involved during Inflation impact observations on the very largest spatial scales \([1, 2]\). Traditionally, these have been accessed through observations of the Cosmic Microwave Background (CMB). While very powerful, the CMB originates from a 2D surface and the finite number of modes that it contains will largely be measured by experiments over the next decade\(^1\). Observations of large 3D volumes with large-scale structure (LSS) access similar scales and will dramatically increase the number of available modes. For example, LSS observations in the range \( 2 \lesssim z \lesssim 5 \) can more than triple the volume surveyed at \( z \lesssim 2 \), and, together with the sufficiently high galaxy number in this interval, strongly motivates a future spectroscopic survey that exploits this opportunity. In addition, tomography allows a mapping of the growth of structure with redshift, which provides robust constraints on Dark Energy and neutrino masses, while relaxing restrictive assumptions such as a power-law primordial power spectrum \([7]\).

Finally, cross-correlation with external tracers, such as CMB lensing, Intensity Mapping or the Lyman-\( \alpha \) forest, immunises the constraints to the systematics that make measurement challenging and further improves the precision through ‘sample variance cancellation’ \([8, 9, 10]\) and degeneracy breaking.

1 Science Case

*Inflation* Simple theories of inflation, involving a single non-interacting field, predict that the primordial fluctuations are extremely close to Gaussian distributed \([11, 12]\). However, very large classes of inflationary models produce levels of non-Gaussianity that are detectable by the next generation of spectroscopic surveys \([1]\). Measurements of primordial non-Gaussianity probe the dynamics and field content of the very early Universe, at energy scales far above particle colliders. Deviations from Gaussianity leave a particular imprint on the galaxy three-point correlation function or bispectrum \([13]\) (and of the CMB), and can also produce a characteristic scale-dependence in the galaxy bias \([14]\). Depending on the physical process responsible for these deviations from Gaussianity, different configurations in the three-point function are generated. These are typically described by a number of dimensionless parameters, \( f_{NL} \) \([15]\), and common examples include the local, equilateral and orthogonal types. The local type is generically produced in multi-field inflation, while the equilateral type often indicates self-interaction of the inflaton.

Pushing the observational frontier to the threshold typically expected from ‘non-minimal’ inflation \( (f_{NL} > 1, \text{see}\ [2]) \) provides a compelling opportunity for future large-scale structure surveys. In summary, capturing the full picture of inflation requires measuring primordial non-Gaussianity to an unprecedented level, complementing the search for primordial gravitational waves and informing us about the Universe’s first moments.

\(^1\)Cosmologically relevant modes of CMB temperature have been measured to the cosmic-variance limit by Planck \([3]\) and upcoming or proposed experiments will achieve the same for polarization \([4, 5, 6]\).
**Dark Energy** A large number of theories have been put forward to explain the late time cosmic acceleration. They range from a cosmological constant, to some dynamical forms of Dark Energy or modification to General Relativity on large scales [16, 17]. By mapping expansion and growth at $z > 1.5$ – deep into matter domination – we can ease parameter degeneracies, better constrain potential theories of Dark Energy, and test posited modifications to General Relativity, e.g. by comparing measurements of growth to the amplitude of gravitational lensing of the CMB.

**Curvature** A measurement of the global value of the Universe’s curvature can potentially have important implications for Inflation. Slow-roll eternal inflation predicts $|\Omega_K| < 10^{-4}$, while false-vacuum models would be ruled out by a measurement of $\Omega_K < -10^{-4}$ [18, 19]. Moreover, the current bound $\Omega_K < 2 \times 10^{-3}$ [3] relies on the strong assumption that Dark Energy is a cosmological constant. If this is relaxed, large degeneracies with the time evolution of Dark Energy arise, significantly degrading the constraints on both. Measurements at high redshift can break this degeneracy and, at the same time, approach the threshold $\sigma(\Omega_K) \approx 10^{-4}$ that is crucial for a better understanding of Inflation [20].

**Neutrino Masses** Massive neutrinos suppress the growth of structure on small scales in a time-dependent manner [21]. Measuring the amplitude of structure over a long lever-arm in redshift, $z \sim 0 - 5$, better constrains the neutrino masses and breaks important degeneracies with the time evolution of Dark Energy and the primordial power spectrum [22, 23].

### 1.1 High-$z$ Lyman-break galaxies and Lyman-$\alpha$ emitters

Lyman-break galaxies are young, star forming galaxies that comprise the majority population at $z > 1.5$. Their characteristic spectral energy density exhibits a sharp drop in the optical flux blue-wards of the redshifted Lyman limit, $(1 + z) \times 912 \, \text{Å}$, due to absorption by neutral hydrogen, in an otherwise shallow $F_\nu$ spectrum. As such, they are efficiently selected with a search for galaxies bright in a detection band, $m_{UV}$ – chosen to correspond to the rest-frame UV for ease – but otherwise undetected in all bluer filters; See Refs. [24, 25] for reviews. In this manner, convenient target populations (BX, $u$-dropouts, $g$-dropouts and $r$-dropouts) spanning $\Delta z \simeq 1.0$ at $z \simeq 2, 3, 4$ and 5 are obtained by enforcing these criteria for increasingly red detection bands; Selection on photometric redshift largely yields the same ends [26, 27].

While of great interest for providing very large populations at high redshift, to achieve the necessary spectroscopic success rate in a baseline exposure typically requires refinement to those with significant Lyman-$\alpha$ emission (LAEs). This is traditionally achieved with narrow-band selection, but large volumes and sufficient depth are not obtainable in this manner. Accepting some degree of increased contamination or lower completeness, broad-band selection based on the bluer continua of strong emitters has been shown to provide very encouraging results [28, 29, 30]. Alternatively, one may limit oneself to only the brightest galaxies, for which secure absorption line redshifts are also possible.

### 1.2 Survey strategy

We identify two galaxy surveys that we use as a baseline for forecasts of an airmass-limited 14,000 square degree survey. Following Ref. [10], we first consider the idealised $m_{UV} = 24.5$
sample in Table 1. This informs what conclusions may ultimately be drawn for this science case with minimal assumptions on the required facilities and survey details.

Conversely, assuming a next generation survey speed, we posit a fiducial survey to approximate the properties shown in Table 2 – assuming completion of LSST Year 10 by first light; Interim LSST data may suffice depending on the cadence strategy adopted.

\[
\begin{array}{cccc|cccc}
 z & n(z) [10^{-4} h^3 \text{Mpc}^{-3}] & b(z) & z & n(z) [10^{-4} h^3 \text{Mpc}^{-3}] & b(z) \\
 2.0 & 25 & 2.5 & 4.0 & 1.5 & 5.8 \\
 2.5 & 12 & 3.3 & 4.5 & 0.8 & 6.6 \\
 3.0 & 6.0 & 4.1 & 5.0 & 0.4 & 7.4 \\
 3.5 & 3.0 & 4.9 & & & & \\
\end{array}
\]

Table 1: Our ‘idealised’ sample: a \( m_{UV} = 24.5 \) magnitude-limited dropout sample as defined by Ref. [10]. Here \( n(z) \) and \( b(z) \) correspond to the expected number density and linear galaxy bias with redshift.

\[
\begin{array}{cccc|cccc}
 z & n(z) [10^{-4} h^3 \text{Mpc}^{-3}] & b(z) & z & n(z) [10^{-4} h^3 \text{Mpc}^{-3}] & b(z) \\
 2.0 & 9.8 & 2.5 & 4.0 & 1.0 & 3.5 \\
 3.0 & 1.2 & 4.0 & 5.0 & 0.4 & 5.5 \\
\end{array}
\]

Table 2: Our ‘fiducial’ sample achievable with next generation facilities. The number density and galaxy bias estimates derive from Refs. [10, 30, 31, 32, 33] and [34]. Note this is significantly less dense than that in Table 1 at lower redshift; We find the limiting factors are efficient pre-selection of LAEs based on broad-band imaging, LSST \( u \)-band depth and our posited survey speed for \( z = 2, 3 \) and 4 respectively.

## 2 Forecasts

### 2.1 Primordial non-Gaussianity

We follow Ref. [13] in order to forecast the constraints on primordial non-Gaussianity achievable with these samples. The results are shown in Table 3 when including both the power spectrum and bispectrum. We find that local \( f_{NL} \) sees the largest improvement, achieving \( \sigma(f_{\text{local}}^{f_{NL}}) \approx 0.1 \) for the fiducial sample. This represents a factor of \( \approx 50 \) improvement over current surveys and achieves the precision necessary for a paradigm shift in our understanding of the early Universe. No planned survey can deliver this at such a redshift, which would be entirely complementary to lower \( z \) studies [35]. When including the external CMB and LSS data expected to be available by first light, the constraints on equilateral and orthogonal \( f_{NL}^{f_{\text{local}}} \) see additional improvements of \( \sim 2 \) and 3 over current estimates. Given this achievable precision, the measurement will likely be systematic dominated and the survey should be designed accordingly.

The competitiveness of spectroscopy is clear from the sharp degradation in constraints – a factor of 3 for both local and orthogonal, and a factor of 4 for equilateral – if only photometric redshifts are available.

### 2.2 Dark Energy

The galaxy power spectrum yields measures of the expansion and growth rates. In turn, these can be used to infer the energy content at a particular redshift. In Figure 1, we show
Table 3: Constraints on $f_{NL}$ for the two samples considered. $P$ denotes those derived from the power spectrum, while $+B$ includes additional constraints from the bispectrum. External datasets include constraints on $f_{NL}$ coming from Planck [36], DESI [37] and Simons Observatory [4], which are expected to complete by our first light. In the last column, we illustrate a photo-$z$ degradation corresponding to $\sigma(z)/(1+z) = 2 \times 10^{-2}$.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma(f_{NL})$</th>
<th>$P$</th>
<th>$+B$</th>
<th>$+\text{External}$</th>
<th>Current (Planck)</th>
<th>Photo-$z$ degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial / Idealised</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local</td>
<td>0.75 / 0.63</td>
<td>0.11 / 0.073</td>
<td>0.11 / 0.073</td>
<td>5</td>
<td></td>
<td>$\times 3$</td>
</tr>
<tr>
<td>Equilateral</td>
<td>–</td>
<td>43 / 23</td>
<td>23 / 18</td>
<td>43</td>
<td></td>
<td>$\times 4$</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>50 / 33</td>
<td>8.8 / 5.0</td>
<td>7.5 / 4.7</td>
<td>21</td>
<td></td>
<td>$\times 3$</td>
</tr>
</tbody>
</table>

that both potential surveys constrain the fraction of Dark Energy to one percent, or even sub-percent, precision to $z \sim 5$. This would represent a tremendous increase in precision over DESI, especially for $z > 3$. In the standard parametrization, these correspond to a Dark Energy Figure of Merit (FoM) of 398 and 441 for the fiducial and idealised samples respectively. This is an improvement of a factor of 2.7 over DESI [37] when combined with the current Planck constraints. Spectroscopy is essential in this respect, with a degradation of over $\sim 60\%$ for photometric redshifts ($\sigma(z)/(1+z) = 0.01$).

Figure 1: The absolute error on the fraction of Dark Energy, $\Omega_{DE}$, at a given redshift for the fiducial (left) and idealised (right) samples. This is obtained from a combination of radial Baryon Acoustic Oscillation (BAO) and Redshift-Space Distortions (RSD). If Dark Energy is a cosmological constant, its fraction is forecasted to be 7%, 3%, 2% and 1% at $z = 2, 3, 4, 5$ to a very high degree of accuracy, which motivates facilities capable of challenging this prediction.

Table 4 shows forecasts for the (beyond) Standard Model parameters. In addition to the Dark Energy FoM, large improvements are found for the curvature, $\Omega_K$, (with errors decreasing by over a factor of 2), together with the sum of neutrino masses.

While not explored in great detail here, it has been shown that cross-correlation with the CMB and Intensity mapping experiments can greatly reduce systematics and break several astrophysical and cosmological degeneracies. As an example, Figure 2 shows constraints on the amplitude of fluctuations $\sigma_8(z)$ as a function of redshift by cross-correlating CMB lensing with galaxy surveys. With this potential for synergy with future CMB surveys, we
Table 4: Forecasts on cosmological parameters from our samples, combined with Planck priors. Gravitational slip is defined as the ratio between the two potentials describing the metric, in combination with a CMB experiment with map noise of 1 μK-arcmin.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>σ(parameter) Fid./Ideal.</th>
<th>DESI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curvature Ω_K/10^{-4}</td>
<td>6.6 / 5.2</td>
<td>12.0</td>
</tr>
<tr>
<td>Neutrinos Σ m_ν</td>
<td>0.028 / 0.026</td>
<td>0.032</td>
</tr>
<tr>
<td>Spectral index n_s</td>
<td>0.0026 / 0.0026</td>
<td>0.0029</td>
</tr>
<tr>
<td>Running α_s</td>
<td>0.003 / 0.003</td>
<td>0.004</td>
</tr>
<tr>
<td>Rel. species N_{eff}</td>
<td>0.069 / 0.069</td>
<td>0.078</td>
</tr>
<tr>
<td>Gravitational slip</td>
<td>0.008 / 0.008</td>
<td>0.01</td>
</tr>
<tr>
<td>D.E. FoM</td>
<td>398 / 441</td>
<td>162</td>
</tr>
</tbody>
</table>

Figure 2: Constraints on σ_8(z) from cross-correlation with CMB lensing. ‘S3’ and ‘Future exp.’ refer to CMB experiments with map noise of 7 and 1 μK-arcmin respectively.

can extract sub-percent constraints on the growth that are relatively insensitive to the z < 2 universe and hence a powerful probe of non-standard Physics.

3 Challenges

Further development of efficient pre-selection of LAEs from broad-band photometry is a requirement for this case as presented. The success of this pre-selection will largely determine the necessary facilities and achievable samples. Some of the measurements outlined above – especially local f_{NL} – also require complete understanding of e.g. the parent photometry and the galaxy selection function generally [2, 38, 39]. Percent-level sky subtraction with fibers and exposures approaching an hour, together with mitigation of line confusion, are also technical tasks to be overcome. Potential strategies have already been proposed and are under active study, but future surveys will require careful consideration of these points during any design phase.

4 Conclusions

The colossal, relatively uncharted, volume at z > 2 and known means of efficiently selecting high-z galaxies grants a tremendous opportunity to study the beginning and fate of our Universe, namely Inflation and Dark Energy. We have shown potential surveys can test the early Universe (Gaussianity) up to a factor of ~ 50 better than our current bounds and cross the highly significant threshold of f_{NL} ≈ 1 that would separate single-field from multi-field models of Inflation; Such measurements would be entirely complementary to low-z studies. This is enabled by spectroscopic redshift precision, with photometric redshift precision degrading these constraints by a factor of three or greater.

Such a dataset would leave an important legacy for the science cases we have presented, together with a wealth of opportunities for the field of galaxy formation and many others.
References


