

Astro2020 Science White Paper

Dark Energy and Modified Gravity

Thematic Areas: Cosmology and Fundamental Physics

Principal Author:

Name: Anže Slosar

Institution: Brookhaven National Laboratory

Email: anze@bnl.gov

Phone: (631) 344 8012

Co-authors: See next page.

Endorsing Collaborations: The surveys designed to carry out dark energy and cosmology investigations in the next decade have attracted large collaborations, organized to facilitate many diverse science goals and broad participation within unified data sets. The following collaborations involving over a thousand people are co-signing this white paper to endorse its content, having reviewed it following their respective internal management processes:

- The Dark Energy Spectroscopic Instrument Collaboration (DESI),
- The Euclid Consortium,
- The LSST Dark Energy Science Collaboration (LSST-DESC),
- The Simons Observatory Collaboration (SO),
- The WFIRST Cosmology Science Investigation Teams

Abstract:

Despite two decades of tremendous experimental and theoretical progress, the riddle of the accelerated expansion of the Universe remains to be solved. On the experimental side, our understanding of the possibilities and limitations of the major dark energy probes has evolved; here we summarize the major probes and their crucial challenges. On the theoretical side, the taxonomy of explanations for the accelerated expansion rate is better understood, providing clear guidance to the relevant observables. We argue that: i) improving statistical precision and systematic control by taking more data, supporting research efforts to address crucial challenges for each probe, using complementary methods, and relying on cross-correlations is well motivated; ii) blinding of analyses is difficult but ever more important; iii) studies of dark energy and modified gravity are related; and iv) it is crucial that R&D for a vibrant dark energy program in the 2030s be started now by supporting studies and technical R&D that will allow embryonic proposals to mature. Understanding dark energy, arguably the biggest unsolved mystery in both fundamental particle physics and cosmology, will remain one of the focal points of cosmology in the forthcoming decade.

arXiv:1903.12016v1 [astro-ph.CO] 28 Mar 2019

Co-authors / Endorsers: Kevork N. Abazajian¹, Zeeshan Ahmed², David Alonso³, Mustafa A. Amin⁴, Behzad Ansarinejad⁵, Robert Armstrong⁶, Jacobo Asorey⁷, Arturo Avelino⁸, Santiago Avila⁹, Carlo Baccigalupi^{10,11,12}, Mario Ballardini¹³, Kevin Bandura^{14,15}, Nicholas Battaglia¹⁶, Amy N. Bender¹⁷, Charles Bennett¹⁸, Bradford Benson^{19,20}, Florian Beutler²¹, F. Bianchini²², Maciej Bilicki²³, Colin Bischoff²⁴, Andrea Biviano²⁵, Jonathan Blazek^{26,27}, Lindsey Bleem^{17,20}, Adam S. Bolton²⁸, J. Richard Bond²⁹, Julian Borrill³⁰, Sownak Bose⁸, Alexandre Boucaud³¹, François R. Bouchet³², Elizabeth Buckley-Geer¹⁹, Philip Bull³³, Zheng Cai³⁴, John E. Carlstrom^{35,20,17}, Francisco J Castander³⁶, Emanuele Castorina³⁷, Anthony Challinor^{38,39,40}, Tzu-Ching Chang⁴¹, Jonás Chaves-Montero¹⁷, Nora Elisa Chisari³, Douglas Clowe⁴², Johan Comparat⁴³, Asantha Cooray¹, Rupert A. C. Croft⁴⁴, Francis-Yan Cyr-Racine^{45,46}, Guido D'Amico⁴⁷, Tamara M Davis⁴⁸, Kyle Dawson⁴⁹, Marcel Demarteau¹⁷, Arjun Dey²⁸, Olivier Doré⁴¹, Yutong Duan⁵⁰, Joanna Dunkley⁵¹, Cora Dvorkin⁴⁵, Alexander Eggemeier⁵, Daniel Eisenstein⁸, John Ellison⁵², Alexander van Engelen²⁹, Stephanie Escoffier⁵³, Giulio Fabbian⁵⁴, Simone Ferraro³⁰, Pedro G. Ferreira³, Andreu Font-Ribera⁵⁵, Simon Foreman²⁹, Pablo Fosalba³⁶, Oliver Friedrich⁴⁰, Juan García-Bellido^{9,56}, Martina Gerbino¹⁷, Mandeep S.S. Gill^{57,47,2}, Vera Gluscevic⁵⁸, Satya Gontcho A Gontcho⁵⁹, Krzysztof M. G'orski⁴¹, Daniel Gruen^{57,47}, Jon E. Gudmundsson⁶⁰, Nikhel Gupta²², Julien Guy³⁰, Shaul Hanany⁶¹, Will Handley^{40,62}, César Hernández-Aguayo⁶³, J. Colin Hill^{64,65}, Christopher M. Hirata²⁷, Renée Hložek^{66,67}, Gilbert Holder⁶⁸, Dragan Huterer⁶⁹, Mustapha Ishak⁷⁰, Tesla Jeltema^{34,71}, Saurabh W. Jha⁷², Johann Cohen-Tanugi⁷³, Bradley Johnson⁷⁴, Marc Kamionkowski¹⁸, Kirit S. Karkare^{35,20}, Ryan E. Keeley⁷, Rishi Khatri⁷⁵, David Kirkby¹, Theodore Kisner³⁰, Jean-Paul Kneib²⁶, Lloyd Knox⁷⁶, Savvas M. Koushiappas⁷⁷, Ely D. Kovetz⁷⁸, Kazuya Koyama²¹, Elisabeth Krause⁷⁹, Benjamin L'Huillier⁷, Ofer Lahav⁵⁵, Massimiliano Lattanzi⁸⁰, Danielle Leonard⁴⁴, Michael Levi³⁰, Michele Liguori⁸¹, Anja von der Linden⁸², Marilena Loverde⁸², Zarija Lukić³⁰, Axel de la Macorra⁸³, Mathew Madhavacheril⁵¹, Andrés Plazas⁵¹, Alessio Spurio Mancini⁴⁰, Marc Manera⁸⁴, Adam Mantz⁴⁷, Paul Martini²⁷, Kiyoshi Masui⁸⁵, Jeff McMahon⁶⁹, P. Daniel Meerburg^{40,39,86}, James Mertens^{87,88,29}, Joel Meyers⁸⁹, Surhud More⁹⁰, Pavel Motloch²⁹, Suvodip Mukherjee³², Julian B. Muñoz⁴⁵, Adam D. Myers⁹¹, Johanna Nagy⁶⁶, Nathalie Palanque-Delabrouille⁹², Laura Newburgh⁹³, Jeffrey A. Newman⁹⁴, Michael D. Niemack¹⁶, Gustavo Niz⁹⁵, Andrei Nomerotski⁹⁶, Paul O'Connor⁹⁶, Lyman Page⁵¹, Antonella Palmese¹⁹, Mariana Penna-Lima⁹⁷, Will J. Percival^{98,99,88}, Francesco Piacentini^{100,101}, Matthew M. Pieri⁵³, Elena Pierpaoli¹⁰², Levon Pogosian¹⁰³, Abhishek Prakash¹⁰⁴, Clement Pryke⁶¹, Giuseppe Puglisi^{47,57}, Radek Stompor³¹, Marco Raveri^{20,35}, Christian L. Reichardt²², Jason Rhodes⁴¹, Steven Rodney¹⁰⁵, Benjamin Rose¹⁰⁶, Ashley J. Ross²⁷, Graziano Rossi¹⁰⁷, John Ruhl¹⁰⁸, Benjamin Saliwanchik⁹³, Lado Samushia¹⁰⁹, Javier Sánchez¹, Misao Sasaki¹¹⁰, Emmanuel Schaan^{30,37}, David J. Schlegel³⁰, Marcel Schmittfull⁶⁴, Michael Schubnell⁶⁹, Douglas Scott¹¹¹, Neelima Sehgal⁸², Leonardo Senatore⁵⁷, Hee-Jong Seo⁴², Arman Shafieloo⁷, Huanyuan Shan¹¹², Blake D. Sherwin^{39,40}, Feng Shi⁷, Sara Simon⁶⁹, Anže Slosar⁹⁶, Suzanne Staggs⁵¹, Glenn Starkman¹⁰⁸, Albert Stebbins¹⁹, Aritoki Suzuki³⁰, Eric R. Switzer¹¹³, Peter Timbie¹¹⁴, Andrew J. Tolley¹¹⁵, Matthieu Tristram¹¹⁶, Mark Trodden¹¹⁷, M. A. Troxel¹¹⁸, M. A. Troxel¹¹⁹, Cora Uhlemann³⁹, Caterina Umiltà²⁴, L. Arturo Ureña-López⁹⁵, Eleonora Di Valentino¹²⁰, M. Vargas-Magaña⁸³, Abigail Viereggs³⁵, Christopher W. Walter¹¹⁹, Yi Wang¹²¹, Scott Watson¹²², Martin White^{123,30}, Nathan Whitehorn¹²⁴, W. L. K. Wu²⁰, Weishuang Xu⁴⁵, Siavash Yasini¹⁰², Matias Zaldarriaga⁶⁴, Gong-Bo Zhao^{125,21}, Yi Zheng¹²⁶, Hong-Ming Zhu^{37,30}, Ningfeng Zhu¹¹⁷, Joe Zuntz¹²⁷,

- ¹ University of California, Irvine, CA 92697
- ² SLAC National Accelerator Laboratory, Menlo Park, CA 94025
- ³ The University of Oxford, Oxford OX1 3RH, UK
- ⁴ Department of Physics & Astronomy, Rice University, Houston, Texas 77005, USA
- ⁵ Department of Physics, Lower Mountjoy, South Rd, Durham DH1 3LE, United Kingdom
- ⁶ Lawrence Livermore National Laboratory, Livermore, CA, 94550
- ⁷ Korea Astronomy and Space Science Institute, Daejeon 34055, Korea
- ⁸ Harvard-Smithsonian Center for Astrophysics, MA 02138
- ⁹ Universidad Autónoma de Madrid, 28049, Madrid, Spain
- ¹⁰ SISSA - International School for Advanced Studies, Via Bonomea 265, 34136 Trieste, Italy
- ¹¹ IFPU - Institute for Fundamental Physics of the Universe, Via Beirut 2, 34014 Trieste, Italy
- ¹² INFN – National Institute for Nuclear Physics, Via Valerio 2, I-34127 Trieste, Italy
- ¹³ Department of Physics & Astronomy, University of the Western Cape, Cape Town 7535, South Africa
- ¹⁴ CSEE, West Virginia University, Morgantown, WV 26505, USA
- ¹⁵ Center for Gravitational Waves and Cosmology, West Virginia University, Morgantown, WV 26505, USA
- ¹⁶ Cornell University, Ithaca, NY 14853
- ¹⁷ HEP Division, Argonne National Laboratory, Lemont, IL 60439, USA
- ¹⁸ Johns Hopkins University, Baltimore, MD 21218
- ¹⁹ Fermi National Accelerator Laboratory, Batavia, IL 60510
- ²⁰ Kavli Institute for Cosmological Physics, Chicago, IL 60637
- ²¹ Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth PO1 3FX, UK
- ²² School of Physics, The University of Melbourne, Parkville, VIC 3010, Australia
- ²³ Center for Theoretical Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668, Warsaw, Poland
- ²⁴ University of Cincinnati, Cincinnati, OH 45221
- ²⁵ INAF - Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, 34143 Trieste, Italy
- ²⁶ Institute of Physics, Laboratory of Astrophysics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland
- ²⁷ The Ohio State University, Columbus, OH 43212
- ²⁸ National Optical Astronomy Observatory, 950 N. Cherry Ave., Tucson, AZ 85719 USA
- ²⁹ Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada
- ³⁰ Lawrence Berkeley National Laboratory, Berkeley, CA 94720
- ³¹ Laboratoire Astroparticule et Cosmologie (APC), CNRS/IN2P3, Université Paris Diderot, 10, rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France
- ³² Institut d'Astrophysique de Paris (IAP), CNRS & Sorbonne University, Paris, France
- ³³ Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom
- ³⁴ University of California at Santa Cruz, Santa Cruz, CA 95064
- ³⁵ University of Chicago, Chicago, IL 60637
- ³⁶ Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans, s/n, 08193 Barcelona, Spain
- ³⁷ Department of Physics, University of California Berkeley, Berkeley, CA 94720, USA
- ³⁸ Institute of Astronomy, University of Cambridge, Cambridge CB3 0HA, UK
- ³⁹ DAMTP, Centre for Mathematical Sciences, Wilberforce Road, Cambridge, UK, CB3 0WA
- ⁴⁰ Kavli Institute for Cosmology, Cambridge,

UK, CB3 0HA

⁴¹ Jet Propulsion Laboratory, California
Institute of Technology, Pasadena, CA, USA

⁴² Department of Physics and Astronomy,
Ohio University, Clippinger Labs, Athens, OH
45701, USA

⁴³ Max-Planck-Institut für extraterrestrische
Physik (MPE), Giessenbachstrasse 1, D-85748
Garching bei München, Germany

⁴⁴ Department of Physics, McWilliams Center
for Cosmology, Carnegie Mellon University

⁴⁵ Department of Physics, Harvard University,
Cambridge, MA 02138, USA

⁴⁶ University of New Mexico, Albuquerque,
NM 87131

⁴⁷ Stanford University, Stanford, CA 94305

⁴⁸ The University of Queensland, School of
Mathematics and Physics, QLD 4072,
Australia

⁴⁹ University of Utah, Department of Physics
and Astronomy, 115 S 1400 E, Salt Lake City,
UT 84112, USA

⁵⁰ Boston University, Boston, MA 02215

⁵¹ Princeton University, Princeton, NJ 08544

⁵² University of California at Riverside,
Riverside, CA 92521

⁵³ Aix Marseille Univ, CNRS/IN2P3, CPPM,
Marseille, France

⁵⁴ Astronomy Centre, School of Mathematical
and Physical Sciences, University of Sussex,
Brighton BN1 9QH, United Kingdom

⁵⁵ University College London, WC1E 6BT
London, United Kingdom

⁵⁶ Instituto de Fisica Teorica UAM/CSIC,
Universidad Autonoma de Madrid, 28049
Madrid, Spain

⁵⁷ Kavli Institute for Particle Astrophysics and
Cosmology, Stanford 94305

⁵⁸ University of Florida, Gainesville, FL 32611

⁵⁹ Department of Physics and Astronomy,
University of Rochester, 500 Joseph C. Wilson
Boulevard, Rochester, NY 14627, USA

⁶⁰ Oskar Klein Centre for Cosmoparticle
Physics, Stockholm University, AlbaNova,
Stockholm SE-106 91, Sweden

⁶¹ University of Minnesota, Minneapolis, MN
55455

⁶² Astrophysics Group, Cavendish Laboratory,
J.J.Thomson Avenue, Cambridge, CB3 0HE,
UK

⁶³ Institute for Computational Cosmology,
Department of Physics, Durham University,
South Road, Durham, DH1 3LE, UK

⁶⁴ Institute for Advanced Study, Princeton, NJ
08540

⁶⁵ Center for Computational Astrophysics, 162
5th Ave, 10010, New York, NY, USA

⁶⁶ Dunlap Institute for Astronomy and
Astrophysics, University of Toronto, ON,
M5S3H4

⁶⁷ Department of Astronomy and
Astrophysics, University of Toronto, ON,
M5S3H4

⁶⁸ Department of Physics, University of
Illinois at Urbana-Champaign, Urbana, Illinois
61801, USA

⁶⁹ University of Michigan, Ann Arbor, MI
48109

⁷⁰ University of Texas at Dallas, Texas 75080

⁷¹ University of California at Santa Cruz,
Santa Cruz, CA 95064

⁷² Department of Physics and Astronomy,
Rutgers, the State University of New Jersey,
136 Frelinghuysen Road, Piscataway, NJ
08854, USA

⁷³ Laboratoire Univers et Particules de
Montpellier, Univ. Montpellier and CNRS,
34090 Montpellier, France

⁷⁴ Columbia University, New York, NY 10027

⁷⁵ Tata Institute of Fundamental Research,
Homi Bhabha Road, Mumbai 400005 India

⁷⁶ University of California at Davis, Davis, CA
95616

⁷⁷ Brown University, Providence, RI 02912

⁷⁸ Department of Physics, Ben-Gurion
University, Be'er Sheva 84105, Israel

⁷⁹ Department of Astronomy/Steward
Observatory, University of Arizona, Tucson,
AZ 85721

⁸⁰ Istituto Nazionale di Fisica Nucleare,

Sezione di Ferrara, 40122, Italy

⁸¹ Dipartimento di Fisica e Astronomia “G. Galilei”, Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy

⁸² Stony Brook University, Stony Brook, NY 11794

⁸³ IFUNAM - Instituto de Física, Universidad Nacional Autónoma de México, 04510 CDMX, México

⁸⁴ Institut de Física d’Altes Energies, The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain

⁸⁵ Massachusetts Institute of Technology, Cambridge, MA 02139

⁸⁶ Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

⁸⁷ Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada

⁸⁸ Perimeter Institute, Waterloo, Ontario N2L 2Y5, Canada

⁸⁹ Southern Methodist University, Dallas, TX 75275

⁹⁰ The Inter-University Centre for Astronomy and Astrophysics, Pune, 411007, India

⁹¹ Department of Physics and Astronomy, University of Wyoming, Laramie, WY 82071, USA

⁹² IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

⁹³ Department of Physics, Yale University, New Haven, CT 06520

⁹⁴ University of Pittsburgh and PITT PACC, Pittsburgh, PA 15260

⁹⁵ División de Ciencias e Ingenierías, Universidad de Guanajuato, León 37150, México

⁹⁶ Brookhaven National Laboratory, Upton, NY 11973

⁹⁷ Instituto de Física, Universidade de Brasília, 70919-970, Brasília, DF, Brazil

⁹⁸ Centre for Astrophysics, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

⁹⁹ Department of Physics and Astronomy, University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1, Canada

¹⁰⁰ Dipartimento di Fisica, Università La Sapienza, P. le A. Moro 2, Roma, Italy

¹⁰¹ Istituto Nazionale di Fisica Nucleare, Sezione di Roma, 00185 Roma, Italy

¹⁰² University of Southern California, CA 90089

¹⁰³ Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6

¹⁰⁴ California Institute of Technology, Pasadena, CA 91125

¹⁰⁵ The University of South Carolina, Columbia, SC 29208

¹⁰⁶ Space Telescope Science Institute, Baltimore, MD 21218

¹⁰⁷ Department of Physics and Astronomy, Sejong University, Seoul, 143-747, Korea

¹⁰⁸ Case Western Reserve University, Cleveland, OH 44106

¹⁰⁹ Kansas State University, Manhattan, KS 66506

¹¹⁰ Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, 277-8583 Kashiwa, Japan

¹¹¹ University of British Columbia, Vancouver, BC V6T 1Z1, Canada

¹¹² Shanghai Astronomical Observatory (SHAO), Nandan Road 80, Shanghai 200030, China

¹¹³ Goddard Space Flight Center, Greenbelt, MD 20771 USA

¹¹⁴ Department of Physics, University of Wisconsin - Madison, Madison, WI 53706

¹¹⁵ Theoretical Physics, Blackett Laboratory, Imperial College, London, SW7 2AZ, U.K.

¹¹⁶ Université Paris-Sud, LAL, UMR 8607, F-91898 Orsay Cedex, France & CNRS/IN2P3, F-91405 Orsay, France

¹¹⁷ Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

¹¹⁸ Duke University and Triangle Universitites
Nuclear Laboratory, Durham, NC 27708

¹¹⁹ Department of Physics, Duke University,
Durham, NC 27708, USA

¹²⁰ Jodrell Bank Center for Astrophysics,
School of Physics and Astronomy, University
of Manchester, Oxford Road, Manchester,
M13 9PL, UK

¹²¹ The Hong Kong University of Science and
Technology, Hong Kong SAR, China

¹²² Syracuse University, Syracuse, NY 13244

¹²³ Department of Astronomy, University of

California Berkeley, Berkeley, CA 94720,
USA

¹²⁴ University of California at Los Angeles,
Los Angeles, CA 90095

¹²⁵ National Astronomical Observatories,
Chinese Academy of Sciences, PR China

¹²⁶ School of Physics, Korea Institute for
Advanced Study, 85 Hoegiro,

Dongdaemun-gu, Seoul 130-722, Korea

¹²⁷ University of Edinburgh, EH8 9YL
Edinburgh, United Kingdom

1 Introduction

Twenty years since the discovery of cosmic acceleration, the laws of physics on the largest scales remain an enigma. The phenomenon continues to drive us to consider bold transformations in our understanding of cosmic forces. Broadly speaking, theories of dark energy fall into three major classes. The first and simplest class is the cosmological constant, which fits all the available data but which is theoretically unsatisfactory because it is fine-tuned and sensitive to the UV completion of gravity. This implies that any fundamental theory that could give rise to a stable value must have some new physics associated with it [1, 2].

The second class of models includes quintessence-type theories where dark energy is a component with novel properties, typically explained in terms of a scalar field. These models of dark energy are the simplest dynamical models of dark energy and are a low-redshift equivalent of inflation [3]. They have recently been discussed within a somewhat controversial debate about the swampland conjecture, which states that theories that can produce a slowly rolling $w \simeq -1$ universe like the one we observe do not have consistent UV completions within string theory ([4], but see also [5]). This conjecture severely constrains the space of string-theory compatible models [6, 7].

The third class of models includes modified-gravity theories in which cosmic acceleration is caused by some extension of the gravitational sector. These theories have been significantly constrained after the discovery of gravitational wave source GW170817 for which the optical counterpart has been discovered, which constrained the speed of tensor mode propagation $c_t = c$ with a fractional accuracy of 10^{-15} . Nevertheless, there are significant caveats: i) the cosmic acceleration and the LIGO event are separated by twenty orders of magnitude in energy scales and the effective theories can be very different [8], and ii) modified-gravity theories can predict significant time dependence, so a single event cannot completely constrain the underlying physics. Significant parts of parameter space thus remain open. Finally, there are somewhat more exotic theoretical paths towards generating accelerated expansion, like novel coupling between baryons and dark matter [9] or involving neutrino physics [10, 11].

The main observables that will help us distinguish between these scenarios are the precise characterization of the *expansion history*, the *gravitational slip* ($\eta = \Phi/\Psi$, where Φ and Ψ are gravitational potentials in the time and space perturbations of the metric) and the *effective large-scale Newton's constant* G_{eff} [12]. Both η and G_{eff} are unity in the standard GR, but can be time- and scale-dependent quantities in modified-gravity theories. This has led to renewed interest in measuring the growth of structure and the combination of datasets with the explicit purpose of constraining these two parameters [13–21]

Faced with this compelling mystery, astrophysicists have mounted an ambitious multi-faceted campaign to study the behavior of the Universe on the large scales. This program has been undeniably successful: data quality has improved radically over the past decade, with new leaps expected early in the 2020s from the upcoming facilities. There have been major improvements in parameter constraints: for a simple equation of state $w(z) = p/\rho c^2$, we have measured a constant w to be consistent with the cosmological constant ($w = -1$) to about ± 0.05 . And while there is consistency in many aspects of the results, there are also active disagreements in other parts, such as the value of the Hubble constant and perhaps the amplitude of late-time matter clustering [22–27].

2 Entering the decade of precision dark energy science

There is a rich portfolio of observational methods that we expect will drive the study of cosmic acceleration in the coming decade. We stress that the whole is more than the sum of the parts. The methods reinforce each other both in terms of statistical leverage and control of systematic uncertainties. Cross-correlations and data combination have emerged as indispensable tools for both controlling systematic uncertainties and isolating particularly informative aspects of theories. During this decade, use of blinded analysis has become the norm for most measurements of cosmic acceleration, so as to avoid confirmation bias; developing methods for blinded analysis that will work for surveys at the next level of precision will be important as the field moves forward. For all of these methods, marginalizing over systematic uncertainties has resulted in expanded parameter spaces, and the field continues to work on building and validating models for major systematic uncertainties that will work at the level needed for upcoming surveys.

There are two main classes of methods to study dark energy. The first measures the *expansion history*, particularly through the study of the distance-redshift relation. The second class measures the *growth* of matter density fluctuations, which is impacted by the large-scale gravitational forces. Because dark energy is typically smooth, it slows the growth of fluctuations and decreases the number of dark matter halos of a given mass. However, growth measurements offer more than an increase in statistical precision; they provide an important consistency check. In a broad class of quintessence theories, the expansion history predicts the behavior of the growth of fluctuations, so any evidence for inconsistency there would necessarily imply some non-standard physics in the gravitational sector.

We now briefly summarize what we see as the major methods for the coming decade.

Expansion history

Baryonic Acoustic Oscillations (BAOs): Description: The BAO peak is a feature in the correlation function of a tracer of large-scale structure, acting as a standard ruler and thus allowing measurements of distances and expansion rates as a function of redshift. Status: Numerous experiments have measured BAOs with high precision in the past decade, including 2dFGRS, 6dFGS, WiggleZ, SDSS II, BOSS and eBOSS, using both galaxies and the Lyman- α forest as tracers. In the 2020s, DESI, PFS, and Euclid will carry out high precision galaxy BAO measurements to $z \sim 2$ with DESI Lyman- α , HETDEX, and WFIRST galaxy surveys reaching $z \sim 3$. Future challenges: The main future challenge lies in obtaining sufficiently large spectroscopic samples at ever increasing volumes. At redshifts beyond 2, non-galaxy tracers such as the Lyman- α forest and 21 cm could be optimal. Unique selling points: BAO is arguably the most mature method and is theoretically and experimentally well understood.

Supernovae Type Ia (SNe Ia): Description: Type Ia supernovae (SNe Ia) are bright standard candles that probe the expansion history of the Universe through calibrating the luminosity distance as a function of redshift. Status: The CfA Supernova program, Carnegie Supernova Program (CSP), SDSS-II SN survey, Supernova Legacy Survey (SNLS), PanSTARRS, DES Supernova program, ESSENCE, GOODS survey, CANDELS/CLASH, Supernova Cosmology Project (SCP) and others have measured SNe Ia over wide range of redshifts. In the 2020's, LSST will deliver $O(10^5)$ photometric SNe Ia, WFIRST will measure SNe Ia in the infrared with the resolution and photometric stability achievable from space, while the Foundation survey will yield many low-redshift SNe. Future challenges: Photometric SNe require very precise

photometric and filter calibrations, spectroscopic characterization and updated light curve models. Unique selling points: SN are the dominant probe of the Hubble diagram at the lowest redshifts, $z < 0.5$, but are also bright enough to be used over a wide range of redshift.

Time delays strong lensing: Description: Time delays measured between the multiple images of the same object provide measurements of the Hubble parameter independently of other distance measures. Status: Dedicated observational programs like H0LiCOW/COSMOGRAIL and STRIDES, which combine ground and space observations of 20 lensed quasar systems, are publishing competitive H_0 constraints. Future surveys like LSST will discover orders of magnitude more systems, with ~ 400 expected to be suitable for dark energy science, and measure hundreds of strongly gravitationally-lensed supernovae, which should enable similar measurement with less monitoring. Future challenges: Mass modeling, external convergence, and correlations between the modeling and the cosmological parameters remain the largest systematic uncertainty.

Unique selling points: This technique is independent from other distance indicators and can achieve precision to constrain dark-energy parameters from a relatively small number of systems.

Standard Sirens: Description: Gravitational waves (GW) from the inspiral of two massive objects are a powerful measure of a source's luminosity distance. Status: The discovery of GWs by Advanced LIGO in 2016 ushered in the era of gravitational wave astrophysics. From one source with an identified optical counterpart, a 7% measurement of the Hubble constant was obtained. The 2020s could see standard sirens providing a 2% determination of H_0 .

Future challenges: As more sources are discovered, selection effects in both the GW surveys and the EM follow-up programs will need to be included in systematic error analyses.

Unique selling points: The amplitude of the standard siren signal is computed from fundamental physics and does not rely on empirical calibration.

Growth

Weak Gravitational Lensing: Description: Measurements of coherent distortions in galaxy shapes due to weak gravitational lensing reveal the distribution of dark matter in the Universe. Status: Dedicated surveys including CFHTLS, KIDS, DES and HSC have achieved statistical precision of a few percent in the amplitude of matter fluctuations at redshift $z \lesssim 1.2$. Lensing surveys in the 2020s from the ground (LSST) and space (WFIRST and Euclid) will cover large sky areas at significant depths. Dedicated space-based observations will enable major advances via high resolution, wavefront stability, and access to the NIR. Future challenges: Photometric redshifts and blending will require further methodological improvements. Another challenge is the theoretical modeling of the signal in the presence of astrophysical systematics (intrinsic alignments and baryonic effects). Unique selling points: Combining tomographic measurements of weak lensing with measurements of the expansion history may be the most effective way to probe GR potentials and distinguish between dark energy and modified gravity.

Cosmic Microwave Background (CMB) lensing: Description: Measuring distortions in the CMB fluctuations can probe weak gravitational lensing to the surface of last scattering. Status: Lensing reconstructions from the Planck satellite currently provide the highest signal-to-noise measurements on the linear amplitude of fluctuations at $z < 6$. Simons Observatory, CMB-S4 and PICO will improve these limits by an order of magnitude in the coming decades.

Future challenges: In order to minimize systematic uncertainties from secondary anisotropies, the CMB lensing will rely on the polarization signal, which is weaker and has its own, yet to be fully understood foregrounds. Unique selling points: CMB lensing provides a long redshift lever-arm

and has fewer observational systematic uncertainties compared to galaxy lensing.

Peculiar Velocities: Description: Peculiar velocities are motions of galaxies not comoving with the expansion of the Universe. They can be measured for individual objects using redshift and a distance indicator. Status: 6dFGS and 2MTF have measured tens of thousands of galaxy peculiar velocities with accuracies of 20%. Supernova surveys have higher precision, but are limited by low numbers. Upcoming surveys like TAIPAN, WALLABY+WNSHS, ZTF and LSST will make large peculiar-velocity catalogs, enabling tight constraints on growth at low redshift.

Future challenges: Proper handling of the asymmetric uncertainties on distance indicators is crucial. Unique selling points: Understanding the local peculiar velocity field constrains dark energy and dark matter directly, and helps with systematic control in other probes by characterizing the local density environment.

Redshift-space distortions (RSDs): Description: Redshift-space distortions are peculiar velocities detected statistically as an apparent anisotropy of the measured correlations in any large-scale structure survey. Status: Spectroscopic galaxy surveys, including 6dFGS, WiggleZ, VIPERS, BOSS and eBOSS, have measured the growth parameter $f\sigma_8$ with 3-10% precision depending on modeling assumptions. In the coming decade DESI, PFS, Euclid and WFIRST will make percent-level measurements at $z < 1.8$ and WFIRST will push to $z \simeq 3$. Future challenges: Theoretical modeling of non-linear effects, and the connection between light and mass, remain the main issue. Unique selling points: One of the most direct ways of measuring the growth rate with the potential to significantly improve signal-to-noise with better modelling.

Kinetic Sunyaev-Zeldovich (kSZ) effect: Description: The kSZ effect is the Doppler shift of CMB photons caused by scattering off the plasma in late-time galaxies and clusters. Status: The first detection of the pairwise kSZ was made in 2012 using data from the Atacama Cosmology Telescope and BOSS galaxy survey. This science will benefit from the large survey area CMB experiments (SO, CMB-S4, PICO), and their cross-correlation with optical galaxy surveys (LSST, DESI). Future challenges: A difficulty in constraining growth using kSZ measurements is the degeneracy with the optical depth in galaxy clusters and groups. Unique selling points: This is an independent probe of the velocity field at low redshift, with different systematics and modelling assumption compared to redshift-space distortions.

Galaxy Clusters: Description: Galaxy clusters are the most massive, gravitationally bound structures in the Universe, and their abundance provides a sensitive probe of growth. Status: Planned optical/IR (LSST, WFIRST, Euclid), Sunyaev-Zeldovich (SO, CMB-S4, PICO), and X-ray (eROSITA, ATHENA) surveys will provide cluster catalogs over a wide range in mass and out to unprecedentedly high redshifts. Future challenges: The main difficulty is obtaining an accurate absolute cluster mass calibration and precise relative mass estimates. The latter are considerably improved using X-ray data; while eROSITA will provide these at relatively low redshifts, an ongoing source of high-throughput, targeted X-ray observations will be required to fully exploit the high-redshift catalogs provided by thermal SZ surveys. Unique selling points: Galaxy clusters are a statistically sensitive probe of growth with largely independent systematics.

3 Conclusions and Outlook

The coming decade will be an exciting one for dark energy studies, as a new generation of powerful observational facilities comes to fruition. The combination of high-precision data with growth in theoretical models and statistical techniques will allow a great leap in our cosmological

leverage, testing our theories in unprecedented ways and perhaps sharpening the fault lines in present results. As we look toward the coming decade in cosmology and the study of dark energy and modified gravity, we want to highlight the following themes.

Improving statistical and systematic precision on the equation of state is essential. The current statistical precision for the w CDM model is around 5% (1σ). To formally distinguish between a $w = -1$ model and a $-1 < w < 0$ model at 1:100 statistical odds, one would need to achieve sub-percent level precision. Even more importantly, dark energy models with dynamical equations of state remain significantly underconstrained. Understanding dark energy to the percent level in the acceleration era and tens of percent in the high-redshift pre-acceleration era remains one of the long-term programmatic goals of cosmology. This also requires support for further methodological advances to reduce systematic uncertainties.

Multiple methods bring robustness. Characterizing dark energy and modified gravity through as many different methods as possible provides valuable cross-checks and data consistency tests as methods hit systematic floors. We see critical opportunities here both in tests of expansion history (e.g., the current tension in the value of H_0) and growth (e.g., the current concerns within lensing and cluster analysis regarding the value of σ_8).

Multiple observatories bring robustness. If there is evidence of deviations from General Relativity or evidence for dynamical dark energy, it is essential to cross-check results with independent experiments using multiple techniques with careful control of systematic errors.

Cross-correlations are ever more important. Applying similar methods over the same volume brings about numerous cross-correlations that have proven to be very valuable. In order to make maximal use of cross-correlations, it is essential to support simulation and data processing/analysis tools that are compatible across surveys and collaborations.

Blind analysis is desirable but challenging. This is especially true with upcoming complex analyses that involve numerous, often subjective, analysis choices. Executing a blind analyses requires careful methodological planning, extensive support from simulations, and delicate coordination, particularly when combining numerous methods across a broad collaboration.

Studies of dark energy and modified gravity are related. All but the simplest dark energy models predict modifications of gravity, although the two can be distinguished by comparing probes of the background expansion and the growth of structure [16]. Both exhibit deviations from Λ CDM on cosmological scales (e.g. [17,28]) that can be tested with the same probes. They should be studied as one field.

Dark energy science in the 2030s will require technical R&D support. The path forward into the 2030s will require an ongoing investment at the observational frontier. Whether by mapping of huge cosmic volumes or by discovery and characterization of rare transients, improving our view of dark energy will require continued technological ambition. Design and development of a broad technical portfolio in this decade will be needed to achieve the necessary capabilities, both statistically and systematically, in a cost-effective manner.

The field of cosmology has been adept at unifying large teams to produce and optimize state-of-the-art facilities, the products of which have advanced many areas of astrophysics. We believe that the mystery of dark energy and the diverse range of measurements that bear on it remains a compelling driver to motivate this development in the coming decade.

References

- [1] Antonio Padilla. Lectures on the Cosmological Constant Problem. 2015.
- [2] C. P. Burgess. The Cosmological Constant Problem: Why it's hard to get Dark Energy from Micro-physics. In *Proceedings, 100th Les Houches Summer School: Post-Planck Cosmology: Les Houches, France, July 8 - August 2, 2013*, pages 149–197, 2015.
- [3] Sean M. Carroll. The Cosmological Constant. *Living Reviews in Relativity*, 4:1, February 2001.
- [4] Marco Raveri, Wayne Hu, and Savdeep Sethi. Swampland Conjectures and Late-Time Cosmology. *arXiv e-prints*, page arXiv:1812.10448, December 2018.
- [5] Jonathan J. Heckman, Craig Lawrie, Ling Lin, Jeremy Sakstein, and Gianluca Zoccarato. Pixelated Dark Energy. *arXiv e-prints*, page arXiv:1901.10489, Jan 2019.
- [6] Prateek Agrawal, Georges Obied, Paul J. Steinhardt, and Cumrun Vafa. On the Cosmological Implications of the String Swampland. *Phys. Lett.*, B784:271–276, 2018.
- [7] Lavinia Heisenberg, Matthias Bartelmann, Robert Brandenberger, and Alexandre Refregier. Dark Energy in the Swampland. *Phys. Rev.*, D98(12):123502, 2018.
- [8] Claudia de Rham and Scott Melville. Gravitational Rainbows: LIGO and Dark Energy at its Cutoff. *Phys. Rev. Lett.*, 121(22):221101, 2018.
- [9] Lasha Berezhiani, Justin Khoury, and Junpu Wang. Universe without dark energy: Cosmic acceleration from dark matter-baryon interactions. *Phys. Rev. D*, 95:123530, Jun 2017.
- [10] Rob Fardon, Ann E. Nelson, and Neal Weiner. Dark energy from mass varying neutrinos. *Journal of Cosmology and Astro-Particle Physics*, 2004:005, Oct 2004.
- [11] H. Mohseni Sadjadi and V. Anari. Mass varying neutrinos, symmetry breaking, and cosmic acceleration. *arXiv e-prints*, page arXiv:1702.04244, Feb 2017.
- [12] Ippocratis D. Saltas, Luca Amendola, Martin Kunz, and Ignacy Sawicki. Modified gravity, gravitational waves and the large-scale structure of the Universe: A brief report. *arXiv e-prints*, page arXiv:1812.03969, December 2018.
- [13] Reinabelle Reyes, Rachel Mandelbaum, Uros Seljak, Tobias Baldauf, James E. Gunn, Lucas Lombriser, and Robert E. Smith. Confirmation of general relativity on large scales from weak lensing and galaxy velocities. *Nature*, 464:256–258, Mar 2010.
- [14] T. Clifton, P. G. Ferreira, A. Padilla, and C. Skordis. Modified gravity and cosmology. *Phys. Rep.*, 513:1–189, March 2012.
- [15] L. Amendola, M. Kunz, M. Motta, I. D. Saltas, and I. Sawicki. Observables and unobservables in dark energy cosmologies. *Phys. Rev. D*, 87(2):023501, January 2013.

- [16] Dragan Huterer et al. Growth of Cosmic Structure: Probing Dark Energy Beyond Expansion. *Astropart. Phys.*, 63:23–41, 2015.
- [17] David Alonso, Emilio Bellini, Pedro G. Ferreira, and Miguel Zumalacárregui. Observational future of cosmological scalar-tensor theories. *Phys. Rev.*, D95(6):063502, 2017.
- [18] A. Spurio Mancini, R. Reischke, V. Pettorino, B. M. Schäfer, and M. Zumalacárregui. Testing (modified) gravity with 3D and tomographic cosmic shear. *MNRAS*, 480:3725–3738, Nov 2018.
- [19] Robert Reischke, Alessio Spurio Mancini, Björn Malte Schäfer, and Philipp M. Merkel. Investigating scalar-tensor gravity with statistics of the cosmic large-scale structure. *MNRAS*, 482:3274–3287, Jan 2019.
- [20] Alessio Spurio Mancini, Fabian Köhlinger, Benjamin Joachimi, Valeria Pettorino, Björn Malte Schäfer, Robert Reischke, Samuel Brieden, Maria Archidiacono, and Julien Lesgourgues. KiDS+GAMA: Constraints on Horndeski gravity from combined large-scale structure probes. *arXiv e-prints*, page arXiv:1901.03686, Jan 2019.
- [21] Mustapha Ishak. Testing general relativity in cosmology. *Living Reviews in Relativity*, 22:1, December 2019.
- [22] M. Tanabashi et al. Review of Particle Physics. *Phys. Rev.*, D98(3):030001, 2018.
- [23] Adam G. Riess, Stefano Casertano, Wenlong Yuan, Lucas Macri, Jay Anderson, John W. MacKenty, J. Bradley Bowers, Kelsey I. Clubb, Alexei V. Filippenko, David O. Jones, and Brad E. Tucker. New Parallaxes of Galactic Cepheids from Spatially Scanning the Hubble Space Telescope: Implications for the Hubble Constant. *ApJ*, 855:136, Mar 2018.
- [24] Edo van Uitert, Benjamin Joachimi, Shahab Joudaki, Alexandra Amon, Catherine Heymans, Fabian Köhlinger, Marika Asgari, Chris Blake, Ami Choi, Thomas Erben, Daniel J. Farrow, Joachim Harnois-Déraps, Hendrik Hildebrandt, Henk Hoekstra, Thomas D. Kitching, Dominik Klaes, Konrad Kuijken, Julian Merten, Lance Miller, Reiko Nakajima, Peter Schneider, Edwin Valentijn, and Massimo Viola. KiDS+GAMA: cosmology constraints from a joint analysis of cosmic shear, galaxy-galaxy lensing, and angular clustering. *MNRAS*, 476:4662–4689, Jun 2018.
- [25] T. M. C. Abbott, F. B. Abdalla, A. Alarcon, J. Aleksić, S. Allam, S. Allen, A. Amara, J. Annis, J. Asorey, S. Avila, D. Bacon, E. Balbinot, M. Banerji, N. Banik, W. Barkhouse, M. Baumer, E. Baxter, K. Bechtol, M. R. Becker, A. Benoit-Lévy, B. A. Benson, G. M. Bernstein, E. Bertin, J. Blazek, S. L. Bridle, D. Brooks, D. Brout, E. Buckley-Geer, D. L. Burke, M. T. Busha, A. Campos, D. Capozzi, A. Carnero Rosell, M. Carrasco Kind, J. Carretero, F. J. Castander, R. Cawthon, C. Chang, N. Chen, M. Childress, A. Choi, C. Conselice, R. Crittenden, M. Crocce, C. E. Cunha, C. B. D’Andrea, L. N. da Costa, R. Das, T. M. Davis, C. Davis, J. De Vicente, D. L. DePoy, J. DeRose, S. Desai, H. T. Diehl, J. P. Dietrich, S. Dodelson, P. Doel, A. Drlica-Wagner, T. F. Eifler, A. E. Elliott, F. Elsner, J. Elvin-Poole, J. Estrada, A. E. Evrard, Y. Fang, E. Fernandez, A. Ferté, D. A. Finley, B. Flaugher, P. Fosalba, O. Friedrich, J. Frieman, J. García-Bellido, M. Garcia-Fernandez,

M. Gatti, E. Gaztanaga, D. W. Gerdes, T. Giannantonio, M. S. S. Gill, K. Glazebrook, D. A. Goldstein, D. Gruen, R. A. Gruendl, J. Gschwend, G. Gutierrez, S. Hamilton, W. G. Hartley, S. R. Hinton, K. Honscheid, B. Hoyle, D. Huterer, B. Jain, D. J. James, M. Jarvis, T. Jeltema, M. D. Johnson, M. W. G. Johnson, T. Kacprzak, S. Kent, A. G. Kim, A. King, D. Kirk, N. Kokron, A. Kovacs, E. Krause, C. Krawiec, A. Kremin, K. Kuehn, S. Kuhlmann, N. Kuropatkin, F. Lacasa, O. Lahav, T. S. Li, A. R. Liddle, C. Lidman, M. Lima, H. Lin, N. MacCrann, M. A. G. Maia, M. Makler, M. Manera, M. March, J. L. Marshall, P. Martini, R. G. McMahon, P. Melchior, F. Menanteau, R. Miquel, V. Miranda, D. Mudd, J. Muir, A. Möller, E. Neilsen, R. C. Nichol, B. Nord, P. Nugent, R. L. C. Ogando, A. Palmese, J. Peacock, H. V. Peiris, J. Peoples, W. J. Percival, D. Petravick, A. A. Plazas, A. Porredon, J. Prat, A. Pujol, M. M. Rau, A. Refregier, P. M. Ricker, N. Roe, R. P. Rollins, A. K. Romer, A. Roodman, R. Rosenfeld, A. J. Ross, E. Rozo, E. S. Rykoff, M. Sako, A. I. Salvador, S. Samuroff, C. Sánchez, E. Sanchez, B. Santiago, V. Scarpine, R. Schindler, D. Scolnic, L. F. Secco, S. Serrano, I. Sevilla-Noarbe, E. Sheldon, R. C. Smith, M. Smith, J. Smith, M. Soares-Santos, F. Sobreira, E. Suchyta, G. Tarle, D. Thomas, M. A. Troxel, D. L. Tucker, B. E. Tucker, S. A. Uddin, T. N. Varga, P. Vielzeuf, V. Vikram, A. K. Vivas, A. R. Walker, M. Wang, R. H. Wechsler, J. Weller, W. Wester, R. C. Wolf, B. Yanny, F. Yuan, A. Zenteno, B. Zhang, Y. Zhang, J. Zuntz, and Dark Energy Survey Collaboration. Dark Energy Survey year 1 results: Cosmological constraints from galaxy clustering and weak lensing. *Phys. Rev. D*, 98:043526, Aug 2018.

- [26] Planck Collaboration, N. Aghanim, Y. Akrami, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday, R. B. Barreiro, N. Bartolo, S. Basak, R. Battye, K. Benabed, J. P. Bernard, M. Bersanelli, P. Bielewicz, J. J. Bock, J. R. Bond, J. Borrill, F. R. Bouchet, F. Boulanger, M. Bucher, C. Burigana, R. C. Butler, E. Calabrese, J. F. Cardoso, J. Carron, A. Challinor, H. C. Chiang, J. Chluba, L. P. L. Colombo, C. Combet, D. Contreras, B. P. Crill, F. Cuttaia, P. de Bernardis, G. de Zotti, J. Delabrouille, J. M. Delouis, E. Di Valentino, J. M. Diego, O. Doré, M. Douspis, A. Ducout, X. Dupac, S. Dusini, G. Efstathiou, F. Elsner, T. A. Enßlin, H. K. Eriksen, Y. Fantaye, M. Farhang, J. Fergusson, R. Fernandez-Cobos, F. Finelli, F. Forastieri, M. Frailis, E. Franceschi, A. Frolov, S. Galeotta, S. Galli, K. Ganga, R. T. Génova-Santos, M. Gerbino, T. Ghosh, J. González-Nuevo, K. M. Górski, S. Gratton, A. Gruppuso, J. E. Gudmundsson, J. Hamann, W. Handley, D. Herranz, E. Hivon, Z. Huang, A. H. Jaffe, W. C. Jones, A. Karakci, E. Keihänen, R. Keskitalo, K. Kiiveri, J. Kim, T. S. Kisner, L. Knox, N. Krachmalnicoff, M. Kunz, H. Kurki-Suonio, G. Lagache, J. M. Lamarre, A. Lasenby, M. Lattanzi, C. R. Lawrence, M. Le Jeune, P. Lemos, J. Lesgourgues, F. Levrier, A. Lewis, M. Liguori, P. B. Lilje, M. Lilley, V. Lindholm, M. López-Cañiego, P. M. Lubin, Y. Z. Ma, J. F. Macías-Pérez, G. Maggio, D. Maino, N. Mandolesi, A. Mangilli, A. Marcos-Caballero, M. Maris, P. G. Martin, M. Martinelli, E. Martínez-González, S. Matarrese, N. Mauri, J. D. McEwen, P. R. Meinhold, A. Melchiorri, A. Mennella, M. Migliaccio, M. Millea, S. Mitra, M. A. Miville-Deschênes, D. Molinari, L. Montier, G. Morgante, A. Moss, P. Natoli, H. U. Nørgaard-Nielsen, L. Pagano, D. Paoletti, B. Partridge, G. Patanchon, H. V. Peiris, F. Perrotta, V. Pettorino, F. Piacentini, L. Polastri, G. Polenta, J. L. Puget, J. P. Rachen, M. Reinecke, M. Remazeilles, A. Renzi, G. Rocha, C. Rosset, G. Roudier, J. A. Rubiño-Martín, B. Ruiz-Granados, L. Salvati, M. Sandri, M. Savelainen, D. Scott, E. P. S. Shellard, C. Sirignano, G. Sirri, L. D.

Spencer, R. Sunyaev, A. S. Suur-Uski, J. A. Tauber, D. Tavagnacco, M. Tenti, L. Toffolatti, M. Tomasi, T. Trombetti, L. Valenziano, J. Valiviita, B. Van Tent, L. Vibert, P. Vielva, F. Villa, N. Vittorio, B. D. Wand elt, I. K. Wehus, M. White, S. D. M. White, A. Zacchei, and A. Zonca. Planck 2018 results. VI. Cosmological parameters. *arXiv e-prints*, page arXiv:1807.06209, Jul 2018.

- [27] Chiaki Hikage, Masamune Oguri, Takashi Hamana, Surhud More, Rachel Mandelbaum, Masahiro Takada, Fabian Köhlinger, Hironao Miyatake, Atsushi J. Nishizawa, Hiroaki Aihara, Robert Armstrong, James Bosch, Jean Coupon, Anne Ducout, Paul Ho, Bau-Ching Hsieh, Yutaka Komiyama, François Lanusse, Alexie Leauthaud, Robert H. Lupton, Elinor Medezinski, Sogo Mineo, Shoken Miyama, Satoshi Miyazaki, Ryoma Murata, Hitoshi Murayama, Masato Shirasaki, Cristóbal Sifón, Melanie Simet, Joshua Speagle, David N. Spergel, Michael A. Strauss, Naoshi Sugiyama, Masayuki Tanaka, Yousuke Utsumi, Shiang-Yu Wang, and Yoshihiko Yamada. Cosmology from cosmic shear power spectra with Subaru Hyper Suprime-Cam first-year data. *arXiv e-prints*, page arXiv:1809.09148, Sep 2018.
- [28] Mario Ballardini, Domenico Sapone, Caterina Umiltà, Fabio Finelli, and Daniela Paoletti. Testing extended Jordan-Brans-Dicke theories with future cosmological observations. *arXiv e-prints*, page arXiv:1902.01407, Feb 2019.