Dwarf galaxies yesterday, now and tomorrow

In the past 20 years, the discovery and characterization of the smallest galaxies have pushed the edges of observational endeavours and theoretical advancements alike, and they will continue to be at the forefront of this field for years to come.

Denija Crnojević and Burçin Mutlu-Pakdil

Impressive technological improvements in observational facilities have allowed the community to transform our understanding of dwarf galaxies, historically viewed as a handful of 'boring' Milky Way satellites, and now recognized to constitute the largest and, arguably, most intriguing population of galaxies in the Universe. Increasingly high-resolution simulations, coupled with a careful inclusion of baryonic physics, have further asserted the unsuspected and complex central role of dwarfs in our investigation of the physics of star formation, stellar feedback, gas dynamics, tidal/ram pressure stripping, dark matter and cosmic reionization, to name a few. To get a perspective on the milestones reached over the past two decades, on the current transformational results in dwarf galaxy research and on what exciting prospects the future holds, we have taken the pulse of the community by asking the opinions of a number of experts on these topics.

The largest satellites of the Milky Way, the Large Magellanic Cloud and the Small Magellanic Cloud, are easily visible to the naked eye in the Southern Hemisphere, and have thus been known since ancient times. In 1938, the discovery of Sculptor motivated the search for faint dwarf galaxies around the Milky Way. Before 1990, a dozen so-called classical Milky Way satellites were discovered as a result of visual searches in photographic survey data. Dwarf galaxies were not deemed particularly exciting targets for a long time, until in the late 1990s advances on both the observational and theoretical fronts revealed their true potential. On the one hand, simulations started to pose the long-standing and puzzling 'missing satellites' problem[1], predicting an order of magnitude more dark matter subhaloes than the number of observed dwarfs around the Milky Way; on the other hand, deep photometric observations started to bring up low surface brightness stellar overdensities in the Galaxy halo, which turned out to be the remnants of disrupting satellites (for example, the Sagittarius stream). The latter represented the tip of the iceberg of a lurking population that initiated the renaissance era of dwarf galaxies: in 2005, the first 'ultra-faint' dwarfs were identified in the wide-field Sloan Digital Sky Survey (SDSS)[2], and have since increased the census of Local Group galaxies by more than an order of magnitude (Fig. 1).

Within two years, the SDSS had doubled the known population of Milky Way satellite galaxies. This trend has continued ever since, with the Dark Energy Survey (DES; for example, refs. [3,4]), other DECam surveys (for example, SMASH[5], MagLiteS[6] and DELVE[7]), Pan-STARRS1 (for example, ref. [8]), ATLAS (for example, ref. [9]) and Gaia (for example, ref. [10]), further bringing the number of confirmed and candidate satellites to more than 60. In parallel with these Milky Way discoveries, a similar population of faint dwarfs has been uncovered around M31 (for example, ref. [11]).

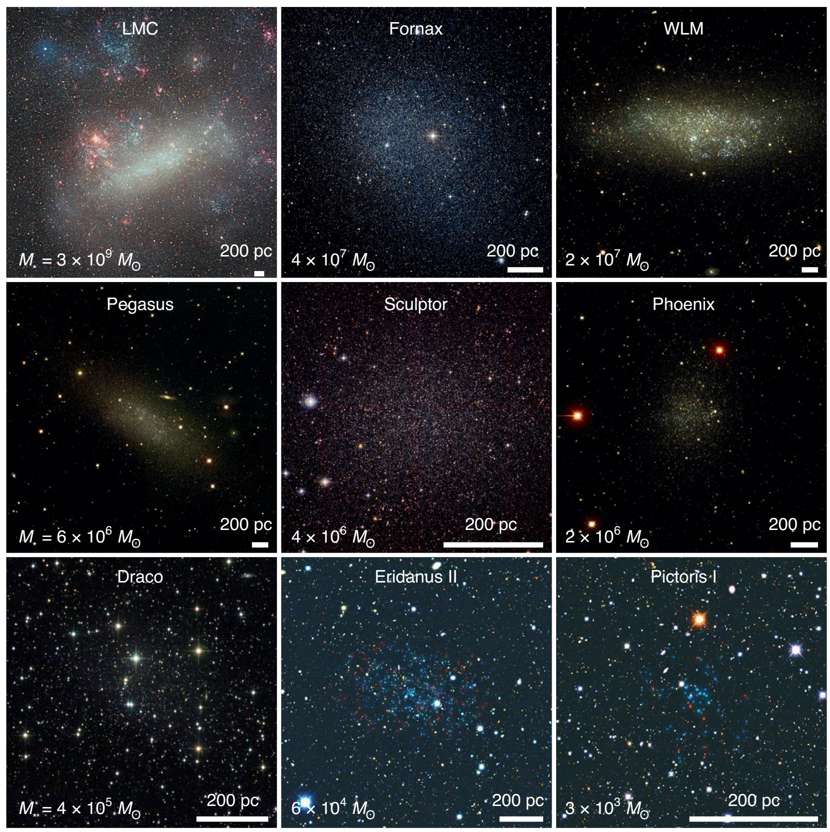

Fig. 1 | Images of a representative sample of Local Group dwarf galaxies, spanning a range of stellar masses and sizes. While the Large Magellanic Cloud (LMC), Wolf–Lundmark–Melotte (WLM) and Pegasus are examples of dwarf irregulars with ongoing star formation, the others are gas-free dwarf spheroidals. Draco is a faint member of Milky Way 'classical' satellites, and Eridanus II and Pictoris I are examples of 'ultra-faint' dwarfs. Stellar masses and sizes are given in the bottom left and right corners of each panel, respectively. Figure reproduced with permission from ref. [1], Annual Reviews. Credit: Eckhard Slawik (LMC); ESO/Digitized Sky Survey 2 (Fornax); ref. [23] (WLM, Pegasus, Phoenix); ESO (Sculptor); Mischa Schirmer (Draco); Vasily Belokurov and Sergey Koposov (Eridanus II, Pictoris I).

The mere discovery of such faint dwarfs represents just the beginning of this exciting quest: their stellar and gas content, their structural parameters, their kinematics, their chemical abundances, and the relation to and interaction with their hosts are all being investigated further to shed light on to their nature (see the other contributions in this Collection). The past two decades have clearly revolutionized our view of the smallest of galaxies, highlighting their key role in our understanding of galaxy evolution: this sheer number of multifaceted discoveries (as highlighted in the 'What was the biggest discovery in the past two decades?' section) has paved the path for a renewed push on the theoretical front as well.

Dwarf galaxies still provide a challenge for the currently widely accepted cold dark matter (CDM) cosmological model[1], with issues related to the dark matter shape in their innermost regions (the 'cusp–core' problem), to the central stellar densities in the most massive satellites (the 'too-big-to-fail' problem) and to the recent discovery of planes of satellites (for example, ref. [12]; see also the dedicated contributions in this issue). The number of intriguing questions related to the extreme nature of this dwarf population keeps increasing, as we obtain a more detailed view of their properties and we find puzzling discrepancies with theoretical expectations. For example, is there a limit for the smallest galaxies? What are their dark matter structures, and do they contain stellar haloes? What is their stellar and gas content, and how do interactions with the surrounding environment regulate them? What is the difference between the smallest/faintest galaxies and star clusters? How can dwarf satellites be distributed along thin planes around their host? How can Local Group satellites guide our understanding of their high-redshift counterparts? These and many other questions have been at the centre of the current observational and theoretical efforts (and debates) in the field (see the 'What is the biggest question/controversy in observations/simulations?' section). Our theoretical dark matter paradigm could still be too simplistic to reproduce what we observe in the Local Group dwarfs, and our observations may be incomplete/biased given the challenging parameter space covered by the faintest and most diffuse of these objects.

The Local Group will arguably remain the ultimate testing ground for understanding the faintest dwarf galaxy satellites due to the detail with which they can be studied. However, there is a danger of 'over-tailoring' the models to fit local observations alone. To fully test the CDM model and the astrophysics pertaining to dwarf galaxy formation and evolution, faint satellite systems beyond the Local Group have started to be investigated. Fortunately, in the next decade, it will be possible to push the discovery frontier not just within our own Local Group, but well into the Local Volume (<10–15 Mpc), and thus sample primary haloes with a range of masses, morphologies and environments all the way down to the 'ultra-faint' regime[13]. Successful wide-field searches are already underway using resolved and unresolved imaging (for example, refs. [14,15]), as well as spectroscopic surveys around Milky Way analogues at larger distances (20 Mpc $<D<$40 Mpc; for example, ref. [16]). Dwarf searches in the field are also revealing and characterizing numerous faint dwarf galaxy systems using several complementary techniques (for example, ref. [17]).

The coming decade is going to be rich in discoveries, with missions and surveys such as the James Webb Space Telescope, the Vera Rubin Observatory, the Extremely Large Telescopes and the Nancy Roman Space Telescope, featuring state-of-the-art wide-field optical and infrared imagers in concert with high-resolution spectrographs. Such future facilities will enable the exploration of larger volumes with greater sensitivity, providing a comprehensive, rigorous census of faint galaxies across a wide range of environments, which will ultimately refine our understanding of baryonic physics, galaxy formation and dark matter (as testified by the expert opinions in the 'What will be the biggest discovery or theoretical advancement in the coming decade?' section).

What was the biggest discovery in the past two decades?

Pierre-Alain Duc (Paris Observatory). I would not refer to a specific discovery. Obviously there have been many, including the census of regular or ultra-faint ones in the Local Group and nearby galaxy clusters. I would rather highlight the technical developments that now allow us to characterize the stellar populations, dark matter content and globular cluster content of early-type dwarfs for the first time outside the Local Group, and at the same time constrain their distance. The vast majority of these dwarfs are of low surface brightness. Whereas the detection of their diffuse light is already difficult in deep images, getting their spectra remained extremely difficult for a long time until the advent of a new generation of integral field spectrographs (for example, MUSE on the VLT). A lot of detailed studies of low surface brightness dwarfs outside the Local Group have been triggered by the attention given to the so-called ultra-diffuse galaxies known for a long time, but re-discovered with the availability of modern deep-imaging surveys. The controversy on their nature (deviating or not from the standard scaling relations, dark matter rich or not) convinced the community to make observing proposals targeting this specific 'class' of objects, and the allocation committees to accept them, whereas before they became topical, it would have been extremely difficult to get observing time on the largest telescopes to observe dwarfs.

Marla Geha (Yale University). If you had asked me 'what is the biggest discovery in the past ten years', I would have had to think. The past 20 years requires no thinking: the discovery of the ultra-faint galaxies and their confirmation as dark matter-dominated galaxies has completely changed our field. Before this, the study of dwarf galaxies was not deemed particularly exciting nor relevant to understanding larger questions of cosmology or galaxy formation. The ultra-faints changed this completely. Now, the faintest galaxies are arguably the best place to answer these questions.

Igor Karachentsev (Special Astrophysical Observatory). The biggest discovery in the realm of dwarf galaxies in the past two decades is the measurement of 5%-precise distances to about 400 nearby dwarf galaxies with the Hubble Space Telescope. Being used as test particles, these dwarfs trace the Hubble flow in the 10 Mpc volume with unprecedented accuracy. There are documented departures from Hubble expansion at the scale of the virial radius for 25 Milky Way-like galaxies, at the scale of their infall region radius, as well as peculiar velocities in the field. Mass estimates of the luminous galaxies via external (infall) motions agree well with those derived from internal (virial) motions of dwarf satellites only when the dark energy existence is taken into account. Therefore, it is found that dark energy reveals itself at a 1 Mpc scale, but not only at redshift $z=1$. The kinematics of nearby dwarfs gives clear evidence of the Virgo-centric infall and the Local Void expansion. The observational data on nearby dwarfs accumulated in the past two decades are the reliable basis to test cosmology on small scales.

Alan McConnachie (NRC Herzberg). Although there were always suspicions that we had not found all the dwarf galaxies that actually existed around the Milky Way, I think the sheer number of faint satellites that have been found since 2005 is quite startling. The faintness of some of these systems is ridiculous — 'galaxies' with literally the equivalent of only a few hundred or thousands of stars. These systems promise a way to probe not only dark matter haloes but also the entire galaxy formation process, down to incredibly low mass limits. Their incredibly low stellar mass also makes them observationally extremely challenging to pin down. That combination of challenge and importance is leading to a very exciting time in this research field.

Josh Simon (Carnegie). In the past two decades, the biggest discovery was the detection of the first ultra-faint dwarf galaxies in 2005, by Beth Willman, Dan Zucker and their collaborators. These unbelievably dim galaxies have opened up new windows on topics ranging from the nature of dark matter to the synthesis of the heaviest elements.

Eline Tolstoy (University of Groningen). In my opinion, there are many important and interesting discoveries in the field of dwarf galaxies over the past 20 years. My personal favourite is the discovery of complex chemical abundance patterns in the individual stars of dwarf spheroidals (starting with ref. [18]) — and especially the interesting differences between dwarf spheroidals and ultra-faint dwarfs (for example, the case of Ret II (ref. [19])). Another topic is the chemical differences between dwarf galaxies and the Milky Way, which is becoming especially apparent as samples became larger and larger (for example, ref. [20]). I tend to prefer studies made with high spectral resolution — even though this means the samples are smaller — because this is the only way to get reliable measurements. This has been beautifully displayed in the papers by Nissen and Schuster (starting in 2010[21]), who detected very small differences in abundance patterns in samples of Galactic halo stars through highly accurate abundance analysis, later confirmed by much larger samples with Gaia — and now hinting to be a dwarf galaxy dominating the (local) halo stellar samples.

What is the biggest question/controversy in observations/simulations?

Dave Sand (University of Arizona). For me, the most exciting thing is to push to the edge — I would like to know the ultra-faint dwarf galaxy content at the edge of the Local Group, and what their star formation histories might be. I am also curious to find true ultra-faint dwarf galaxies beyond our Local Group — and by this I mean systems with $M_V \approx -4$ or -5, very faint systems. Do they exist around hosts as small as NGC 3109 ($D \approx 1.3$ Mpc)? Can we identify them around some of our nearest neighbours (or in the field) with Subaru + HSC or Roman? Understanding how such small dark matter haloes light up is what excited me about the field in the years to come.

Rodrigo Ibata (Strasbourg Observatory). My feeling is that the most pressing issue on dwarf galaxies is the old dark matter problem, which has overshadowed the field since the 1980s. Are dwarf galaxies really embedded in vastly massive dark matter haloes that outweigh the stars and gas by factors of a hundred or more? Do these galaxies have a cuspy profile in their centres as would be expected for dark matter-dominated structures or is the paltry fraction of baryons in some systems sufficient to make the haloes have a cored profile? Establishing the true distribution of dark matter in dwarf galaxies would undoubtedly provide major insights into the nature of the dark matter itself. For this reason, I am looking forward to seeing whether the stellar radial velocities of large panoramic samples of stars in dwarf galaxies (from the WEAVE and 4MOST experiments) will show any interesting signs of binary-induced motion. A related question is whether these systems are even in equilibrium!

Ting Li (University of Toronto). I think the biggest question I have (and would like to explore in the next decade) is what is the fundamental difference between ultra-faint dwarf galaxies and the outer halo star cluster and how we can tell them apart? In the traditional sense, dwarf galaxies are dark matter dominated and large in size (half-light radii around 100–1,000 pc); star clusters, or at least globular clusters, on the other hand, are dark matter free and very compact (half-light radii <10 pc). With the advent of the modern sky surveys, more and more stellar systems are found in our Milky Way's halo (at a heliocentric distance of say 30–100 kpc), with very low luminosity ($M_v > -4$) and half-light radii around 5–50 pc. What are these systems? Are they star clusters or galaxies? Did they come to the Milky Way from accretion? Were they accreted alone or together with their parent galaxy? Do they reside in a dark matter halo? Is there a way we could answer these questions from observations or simulations?

Annika Peter (Ohio State University). On the observational side, the rate-limiting factor to new physics is that we do not have really complete samples of dwarf galaxies across a range of environments. Much of our intuition about the galaxy–halo connection and dwarf baryonic physics is based on the Milky Way's satellite system and (to a lesser extent) on Andromeda's. To really understand the life and times of dwarf galaxies, we need to get out of the Local Group and explore many environments, and that means very deep surveys with excellent surface brightness sensitivity. This is important not only for studying environmental quenching mechanisms but also for understanding, for example, how patchy reionization is, and how the patchiness affects the earliest stages of galaxy evolution. On the theory side, the major question is whether baryons can explain all of the 'odd' features of galaxy populations, or if novel dark matter physics are required. One challenge is resolution — it is very costly to simulate dwarf galaxies in even moderately dense environments, especially when the physics of star formation and feedback still need to be tested on the small scales on which stars actually form. Another issue is taste in problems — the largest set of high-resolution simulations focus on the Milky Way. Again, if we want to understand dwarf galaxies, we need to simulate them in a range of environments, and with a range of plausible baryonic and dark matter models. That is costly, and so exploring ways to better connect simulations with semi-analytic and semi-empirical models is also extremely important. Another challenge is connecting the two sides. This is where semi-analytic and semi-empirical models can be helpful, but we also need to be thinking about likelihood functions, and we can learn from dark energy cosmologists on this front.

Dan Weizs (University of California, Berkeley). We have a very limited understanding of dwarf galaxies that form and evolve in isolation. Because they are so far away, only a handful of isolated systems have been characterized at even a modest level of detail. Even more fundamentally, basic demographics (locations, distances, luminosities, mass functions and so on) of dwarf galaxies in low-density regions (for example, voids and filaments) are largely unknown. It is unclear whether truly isolated dwarf galaxies have similar formation histories to their satellite counterparts and whether challenges to the current cosmological paradigm motivated by Milky Way satellites (for example, the missing-satellite, core–cusp and too-big-to-fail problems) also exist in the field dwarf galaxy population.

What will be the biggest discovery or theoretical advancement in the coming decade?

Alyson Brooks (Rutgers). The thing that I am most excited about in the next decade is the discovery of (probably) hundreds of ultra-faint dwarfs by the Vera Rubin Observatory's Legacy Survey of Space and Time (LSST). It is possible that the LSST will discover hundreds of dwarfs as faint as roughly 1,000 L_{Sun}, out to about 1 Mpc. This will be an absolute game changer. The number of dwarfs discovered is a key test of our CDM cosmology, because these smallest scales can vary in currently allowed dark matter models. We will learn whether dwarf galaxies are uniformly distributed around our Galaxy, or have a special preference in their spatial distribution. We will also be able to study these tiny galaxies far away from the influence of our own Galaxy, and discover whether star formation has proceeded differently in them. This will allow fundamental tests of our current models for star formation, and how the energetic feedback from stars and supernovae has influenced these shallowest of gravitational potential wells.

Shany Danieli (Princeton University). Current and upcoming astronomical instruments and surveys will revolutionize our understanding of the interplay between dark matter and baryons on the smallest galactic scales. Uncovering the role of baryons in shaping the substructure of the smallest dark matter haloes will allow us to differentiate between various theorized models of dark matter. We will be able to fully test the observational signatures such models predict while resolving the physical processes that were responsible for the formation of the smallest galaxies in the early Universe.

Anna Frebel (MIT). I expect that within the next decade, theoretical simulations will have advanced enough to tell us in detail how small the smallest surviving galactic structures can principally be, and to what extent any of the observed dwarfs around the Milky Way relate to or formed from the first galaxies that came about soon after the Big Bang. Simulations should also be able to reveal how metals are produced, injected and mixed within dwarf galaxies. I see dwarf galaxies as valuable tools for understanding the chemical evolution and associated dynamics of larger galaxies, and these breakthroughs are only a matter of time before they happen.

Carme Gallart (Instituto Astrofisica Canarias). Future deep sky surveys such as the Vera Rubin LSST will discover a large number of faint isolated dwarf galaxies, among which ultra-faint dwarfs with an extended star formation history (like Leo T) may (or may not) be found. This will settle the question of whether reionization is indeed responsible for the early quenching of these dwarfs. Finding more 'Leo Ts' in isolated environments would point to local drivers of early dwarf galaxy evolution, with implications on classic questions regarding the origin of the dwarf galaxy types (see ref. [22]) and the physics of galaxy evolution.

Evan Kirby (University of Notre Dame). The biggest astronomical discovery of the 2020s will be the definitive identification — at last — of the nature of thermonuclear (type Ia) supernovae, which will be made possible by using galactic archaeology in dwarf galaxies. These explosions were the centrepiece of the discovery of cosmic acceleration, which won the 2011 Nobel Prize in Physics. Despite their importance, we still do not know what they are. We are fairly sure that they are the explosions of white dwarfs, supported by quantum mechanical degeneracy pressure, but we do not know for sure why they explode. It was thought for a while that they exploded because they reached a fundamental limit, the Chandrasekhar mass, but evidence over the past decade suggests that the Chandrasekhar mass has nothing to do with many of these explosions. New hydrodynamical simulations and new observations of current and historic thermonuclear supernovae in dwarf galaxies will finally answer this question in the next ten years.

Kristen McQuinn (Rutgers). New observing facilities, capable of imaging large areas of the sky with greater sensitivity, will enable the detection of extremely low-surface-brightness and extremely low-mass galaxies out to larger distances and, importantly, in isolated environments (that is, where the evolution of the galaxies has not been dominated by the influence of a massive host). The identification and characterization of such galaxies will yield present-day measurements of the galaxy mass function independent of environmental effects, empirically constraining the limit of galaxy formation and informing on the nature of dark matter, the baryon physics in galaxies, and the impact reionization may play in halting the growth of low-mass structures in the early Universe.

Ferah Munshi (University of Oklahoma). In the next decade, we will see a wealth of new results from surveys ranging from DES, Vera Rubin's LSST, and the James Webb and Nancy Roman space telescopes. Of particular importance will be the need in the dwarf galaxy community to absorb and interpret these results in terms of both galaxy evolution and the astrophysical constraints on dark matter. On the dark matter front, the challenge for the next decade hinges on the development of theory, simulation and analysis tools to reliably identify beyond CDM signals across physical scales and throughout cosmic history. The convergence of scales and methods provided by the observatories described above, from direct, detailed observations and number counts to lensing measurements of smaller and smaller halo masses, has the potential to disentangle the signature of a particular dark matter model from the physics of what we can see. This is the era that will provide the most stringent astrophysical and statistical dark matter constraints so far, and has the potential to eliminate many beyond-CDM models. ❐

Denija Crnojević [1] ✉ and
Burçin Mutlu-Pakdil [2,3] ✉
[1]University of Tampa, Tampa, FL, USA.
[2]Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL, USA.
[3]Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL, USA.
✉e-mail: dcrnojevic@ut.edu; burcinmp@uchicago.edu

Published online: 13 December 2021
https://doi.org/10.1038/s41550-021-01563-1

References

1. Bullock, J. S. & Boylan-Kolchin, M. *Annu. Rev. Astron. Astrophys.* **55**, 343–387 (2017).
2. Willman, B. et al. *Astron. J.* **129**, 2692–2700 (2005).
3. Bechtol, K. et al. *Astrophys. J.* **807**, 50 (2015).
4. Drlica-Wagner, A. et al. *Astrophys. J.* **813**, 109 (2015).
5. Martin, N. F. et al. *Astrophys. J.* **804**, L5 (2015).
6. Torrealba, G. et al. *Mon. Not. R. Astron. Soc.* **475**, 5085–5097 (2018).
7. Cerny, W. et al. *Astrophys. J. Lett.* **920**, L44 (2021).
8. Laevens, B. P. M. et al. *Astrophys. J.* **813**, 44 (2015).
9. Torrealba, G. et al. *Mon. Not. R. Astron. Soc.* **463**, 712–722 (2016).
10. Torrealba, G. et al. *Mon. Not. R. Astron. Soc.* **488**, 2743–2766 (2019).
11. Martin, N. F. et al. *Astrophys. J.* **705**, 758–765 (2009).
12. Pawlowski, M. S. et al. *Mon. Not. R. Astron. Soc.* **442**, 2362–2380 (2014).
13. Mutlu-Pakdil, B. et al. *Astrophys. J.* **918**, 88 (2021).
14. Crnojević, D. et al. *Astrophys. J.* **823**, 19 (2016).
15. Bennet, P. et al. *Astrophys. J.* **850**, 109 (2017).
16. Mao, Y.-Y. et al. *Astrophys. J.* **907**, 85 (2020).
17. Tanoglidis, D. et al. *Astrophys. J. Suppl. Ser.* **252**, 18 (2021).
18. Shetrone, M. D., Côté, P. & Sargent, W. L. W. *Astrophys. J.* **548**, 592–608 (2001).
19. Ji, A. P., Frebel, A., Simon, J. D. & Chiti, A. *Astrophys. J.* **830**, 93 (2016).
20. Hill, V. et al. *Astron. Astrophys.* **626**, 15 (2019).
21. Nissen, P. E. & Schuster, W. J. *Astron. Astrophys.* **511**, 10 (2010).
22. Gallart, C. et al. *Astrophys. J. Lett.* **811**, 18 (2015).
23. Massey, P. et al. *Astron. J.* **133**, 2393–2417 (2007).

Acknowledgements

Research by D.C. is supported by NSF grant AST-1814208. B.M.-P. is supported by an NSF Astronomy and Astrophysics Postdoctoral Fellowship under award AST-2001663. We thank all the contributing experts for their time and insights. We have strived to strike a geographical and gender balance in the experts we reached out to. Not all contacted experts were available for comment.

Competing interests

The authors declare no competing interests.