Astro2020 Science White Paper

Science from an Ultra-Deep, High-Resolution Millimeter-Wave Survey

Thematic Areas:
Primary Area: Cosmology and Fundamental Physics
Secondary Area: Galaxy Evolution

Principal Author:
Name: Neelima Sehgal
Institution: Stony Brook University & Flatiron Institute
Email: neelima.sehgal@stonybrook.edu
Phone: 631-632-8229

Co-authors: Hô Nam Nguyểń1, Joel Meyers2, Moritz Munchmeyer1, Tony Mroczkowski3, Luca Di Mascolo4, Eric Baxter5, Francis-Yan Cyr-Racine6,7, Mathew Madhavacheril8, Benjamin Beringue9, Gil Holder10, Daisuke Nagai11, Simon Dicker5, Cora Dvorkin6, Simone Ferraro12, George M. Fuller13, Vera Gluscevic14, Dongwon Han15, Bhuvnesh Jain6, Bradley Johnson16, Pamela Klaassen17, Daan Meerbtt9, Pavel Motloch18, David N. Spergel19,8, Alexander van Engelen18

Endorsers: Peter Adshead10, Robert Armstrong20, Carlo Baccigalupii21, Darcy Barron7, Kaustuv Basu22, Bradford Benson23,24, Florian Beutler25, J. Richard Bond18, Julian Borrill12, Erminia Calabrese26, Omar Darwish9, S. Lucas Denny27, Kelly A. Douglass28, Tom Essinger-Hileman29, Simon Foreman18, David Frayer30, Martina Gerbino31, Satya Gontcho A Gontcho32, Evan B. Grohs33, Nikhel Gupta34, J. Colin Hill35,19, Christopher M. Hirata36, Selim Hotinli37, Matthew C. Johnson38,1, Marc Kamionkowski39, Ely D. Kovetz40, Erwin T. Lau41, Michele Liguori42, Toshiya Nomikawa9, Laura Newburgh11, Bruce Partridge42, Francesco Piacentini43, Benjamin Rose44, Graziano Rossii45, Benjamin Saliwanchikii11, Emmanuel Schaaf12,33, Huanyuan Shan47, Sara Simon48, Anže Slosar49, Eric R. Switzer50, Hy Trac51, Weishuang Xu6, Matias Zaldarriaga35, Michael Zemcov52

Abstract: Opening up a new window of millimeter-wave observations that span frequency bands in the range of 30 to 500 GHz, survey half the sky, and are both an order of magnitude deeper (about 0.5 µK-arcmin) and of higher-resolution (about 10 arcseconds) than currently funded surveys would yield an enormous gain in understanding of both fundamental physics and astrophysics. In particular, such a survey would allow for major advances in measuring the distribution of dark matter and gas on small-scales, and yield needed insight on 1.) dark matter particle properties, 2.) the evolution of gas and galaxies, 3.) new light particle species, 4.) the epoch of inflation, and 5.) the census of bodies orbiting in the outer Solar System.
1 Introduction

Opening up a new window of millimeter-wave survey observations that are both deeper and of higher-resolution than previous surveys would yield an enormous gain in understanding of both fundamental physics and astrophysics. The major advances enabled by a deep (about 0.5 µK-arcmin), high-resolution (about 10 arcsecond), millimeter-wave survey are: i) the use of gravitational lensing of the primordial microwave background to map out the distribution of matter on small scales ($k \sim 10 h\text{Mpc}^{-1}$), and ii) the measurement of the thermal and kinetic Sunyaev-Zel’dovich effects (tSZ and kSZ) on small scales to map the gas density and gas pressure profiles of galaxy clusters and groups. In addition, such a survey, covering half the sky, would allow us to cross critical thresholds in fundamental physics: i) ruling out or detecting any new, light, thermal particles, which could potentially be the dark matter, and ii) testing a wide class of multi-field models that could explain an epoch of inflation in the early Universe. Lastly, such a survey enables the detection of an Earth-size planet thousands of AU from the Sun, and more broadly provides a census of asteroids and planetary bodies in the outer Solar System. This survey would also enable the detection of exo-Oort clouds around other solar systems, shedding light on planet formation.

2 Dark Matter Distribution and Properties

What is the distribution of matter on small scales?

What are the particle properties of dark matter?

There is compelling evidence for non-baryonic dark matter [1–7], however, its nature remains elusive. Direct and indirect dark-mater searches may set tight limits in the next decade, but still turn up empty-handed in terms of detecting a new particle. One may then ask what is the next best avenue to probe dark-matter properties. The only place we have directly detected the impact of dark matter is through its gravitational interactions. Thus it makes sense to explore this direction for further insight into dark-matter particle properties. In particular, well-motivated models of dark matter that differ from the standard cold, collisionless model (CDM), predict different distributions of matter on small scales [8–41]. However, observations of the small-scale matter distribution to date are challenging because they often infer the matter distribution through baryonic tracers of the matter [42–58], which may not trace the dark matter reliably [59–61]. While very promising, alternative techniques using strong gravitational lensing to find low-mass dark-matter halos [62–71] face the challenge of disentangling the complex structure of the background source from the substructure signal; using strong lensing to measure the matter power spectrum faces a similar challenge [72–79]. In contrast, measuring the small-scale matter power spectrum from weak gravitational lensing using the cosmic microwave background (CMB) as a backlight suffers from no such degeneracies, since we have detailed knowledge of the intrinsic properties of the source [80]. This may provide a powerful complementary probe of dark-matter physics [80].

As shown in Figure 1, by measuring the small-scale matter power spectrum, one can distinguish between CDM and a dark matter model that alters the matter distribution in a way that differs from the CDM prediction [80]. Such a measurement has the potential to determine both dark-matter particle properties and the effect of baryons on the small-scale matter distribution; both of which can affect the shape of the small-scale matter power spectrum, albeit in potentially different ways [80–85]. Recently, it has been shown, by comparing the output of multiple hydrodynamic
simulations with different baryonic prescriptions, that there may be a finite set of ways that baryons can alter the matter power spectrum; moreover, these changes to the matter power spectrum may depend on just a few free parameters\cite{85} that can potentially be distinguished from dark matter model parameters. We note that such a measurement of the small-scale matter power spectrum, in any case, will constrain both models of dark matter and baryonic physics.

In Table 1, we show forecasts of how well one can potentially distinguish between fuzzy or warm dark matter models (FDM or WDM) and CDM, in the absence of baryonic effects. We show this with differing levels of residual kSZ, which is a frequency-independent foreground that arises when CMB photons are Doppler boosted after scattering off ionized gas with a bulk motion. This kSZ signal arises from scattering off the ionized gas bound in dark-matter halos (late-time kSZ), and the ionized gas present during the epoch of reionization when the first stars were forming (reionization kSZ). From Table 1, we see that the reionization kSZ has a modest impact on the signal-to-noise ratio, while we potentially can remove much of the late-time kSZ with techniques facilitated by an overlapping galaxy survey \cite{86, 87}. Frequency-dependent foregrounds can likely be removed with a combination of multi-frequency channels and high-resolution observations, the latter of which allow extragalactic foregrounds to be resolved and subtracted from survey maps.

| Sky fraction ($f_{\text{sky}}$) | Noise at 150 GHz ($\mu$K-arcmin) | Dark matter signal-to-noise ratio | | | |
|----------------|-----------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.5            | 0.5             | 11                              | 9               | 5               | 24              | 19              | 7               | 4               | 5               | 2               | 3               |
| 0.5            | 0.25            | 8                               | 7               | 4               | 17              | 13              | 5               | 5               | 2               | 3               | 3               |
| 0.25           | 0.5             | 5                               | 4               | 2               | 11              | 9               | 3               | 3               | 2               | 3               | 3               |
| 0.25           | 0.25            | 8                               | 7               | 4               | 17              | 13              | 5               | 5               | 2               | 3               | 3               |
| 0.1            | 0.5             | 5                               | 4               | 2               | 11              | 9               | 3               | 3               | 2               | 3               | 3               |
| 0.1            | 0.25            | 8                               | 7               | 4               | 17              | 13              | 5               | 5               | 2               | 3               | 3               |

Table 1: Significance with which an $m \sim 10^{-22}$ eV FDM (or 1 keV WDM) model can be distinguished from a CDM model, based on observations of CMB lensing. Here we assume 10” resolution and vary observed sky fraction, noise levels in temperature, and residual kSZ.
Figure 2: The SZ effects of a merging galaxy cluster extracted from the Omega500 cosmological hydrodynamical simulation [88], with some X-ray quantities for comparison. Shown quantities are the tSZ signal (top-left), kSZ signal (top-middle), projected mass-weighted temperature (top-right), X-ray surface brightness (bottom-left), electron opacity (bottom-middle), and projected X-ray temperature (bottom-right). Combining low-noise, high-resolution tSZ and kSZ measurements allows one to separate the pressure, density, velocity, and temperature of the gas [89–91].

3 Baryonic Physics and Galaxy Evolution

What is the evolution of gas in and around dark matter halos?

A high-resolution, low-noise millimeter-wave survey would open a new window on tSZ and kSZ measurements [92, for a recent review]. tSZ measurements probe the thermal pressure of ionized gas in and around galaxy clusters and groups [93]. kSZ measurements probe the gas momentum density [94]. The combination of kSZ and tSZ measurements at three or more frequencies, with low-noise and high-resolution, would allow one to measure the gas density, bulk velocity, and temperature separately [89–91]. The advantage of SZ over X-ray measurements is that the SZ signal is proportional to the gas density (not density squared) and the flux of the signal is redshift independent; thus SZ measurements are a powerful probe of the gas in galaxy cluster outskirts, in low-mass halos, and in high-redshift halos.

Over the past decade, the tSZ effect has also been used to find hundreds of previously-unknown clusters of galaxies out to $z \sim 2$ [95–97]. Higher resolution and better sensitivity will push this to lower-mass and higher-redshift systems, allowing direct imaging of many systems where X-ray observations would require exceptionally long integration times. Stacking the tSZ detections will allow one to probe the gas physics in and around halos out to $z \sim 2$ and with masses below $10^{12} \, M_{\odot}$. The gas in halos reflects the impact of feedback and merging processes and serves as a reservoir of star formation. For example, as shown in Figure 2, tSZ and kSZ measurements probe gas accretion, non-thermal and non-equilibrium processes, AGN feedback, and splashback and shock radii [98–101]. Therefore, the science gain of such measurements is a deeper understanding of galaxy cluster astrophysics, the physics of the intergalactic and circumgalactic medium, and galaxy evolution.
Sky fraction ($f_{\text{sky}}$) & Noise at 150 GHz ($\mu$K-arcmin) & Constraint on new particle species ($\sigma(N_{\text{eff}})$) with kSZ foregrounds & no foregrounds \\
0.5 & 0.5 & 0.019 & 0.014 \\
0.5 & 0.25 & 0.018 & 0.013 \\
0.25 & 0.5 & 0.027 & 0.019 \\
0.25 & 0.25 & 0.025 & 0.018 \\

Table 2: Constraint on the density of light relics, $N_{\text{eff}}$. We assume 10” resolution and vary the noise and sky area. We show constraints with and without including the kSZ foregrounds for temperature maps. *Planck* and expected Simons Observatory data are included. **Note that the critical threshold of $\sigma(N_{\text{eff}}) = 0.027$ is the minimum change to $N_{\text{eff}}$ created by any new light particle species in thermal equilibrium with standard model particles in the early Universe** [102].

4 Thermal History of The Early Universe

Do new light particle species exist that were in thermal equilibrium with standard model particles during the early Universe?

Any light particles that were relativistic when the CMB formed (i.e., masses less than about 0.1 eV) and that were in thermal equilibrium with standard model particles at any time in the early Universe leave an imprint on the CMB power spectrum at small angular scales. The critical threshold for the density of light relics, $N_{\text{eff}}$, is $\sigma(N_{\text{eff}}) = 0.027$, which represents the minimum change to $N_{\text{eff}}$ created by any new light species in thermal equilibrium with standard model particles in the early Universe (assuming no significant dilution by new states beyond the standard model particle content) [102]. This includes light species that were in thermal equilibrium with the standard model right after the Big Bang, probing back to about $10^{-30}$ seconds after the creation of the Universe. These particles may well be too weakly interacting to be seen with significance in Earth-based experiments; thus probing them with cosmology may be the only avenue. Many dark matter models, including many axion models, predict new light thermal relics [103, 104]. Thus ruling out, or detecting, the existence of such a particle would yield insight on dark matter particle properties.

With an ultra-deep, high-resolution millimeter-wave survey, one could cross the critical threshold of $\sigma(N_{\text{eff}}) = 0.027$. The ability to cross this threshold comes from i) surveying a wide sky area, ii) having low noise, and iii) probing small angular scales ($\ell_{\text{max}} \gtrsim 5000$). In Table 2, we show the constraints on $N_{\text{eff}}$ for different noise levels and sky areas, for a $\Lambda$CDM + $N_{\text{eff}} + \sum m_\nu$ model and assuming BBN consistency. We also show constraints with and without including the kSZ foregrounds in temperature maps; this foreground can potentially be reduced with an overlapping galaxy survey. We assume 10 arcsecond resolution and use lensed CMB spectra. We note that delensing the CMB spectra can modestly improve the $N_{\text{eff}}$ constraints [105, 106], and including the effect of Rayleigh scattering can potentially have a significant impact depending on the noise levels of the higher-frequency channels (e.g. 15-30% improvement with 5/10 $\mu$K-arcmin noise at 400/500 GHz) [107, 108]. From Table 2, in a scenario where foregrounds are effectively removed (via multi-frequency cleaning, resolving and subtracting extragalactic sources, and removing kSZ from the maps), such a survey can potentially rule out or find evidence for new light thermal particles with 95% confidence level.
| Sky fraction \((f_{sky})\) | Noise \((\mu\text{K-arcmin})\) | Resid. lensing B-mode \((A_{lens})\) | Non-Gaussianity \((\sigma(f_{NL}))\) |
|---|---|---|---|
| 0.5 | 0.5 | 0.1 | 0.26 |
| 0.5 | 0.25 | 0.05 | 0.26 |
| 0.25 | 0.5 | 0.1 | 0.40 |
| 0.25 | 0.25 | 0.05 | 0.40 |

Table 3: Third column: Expected residual lensing B-mode power after delensing \((A_{lens})\). Removing the lensing B-mode signal is critical to detecting primordial gravitational waves from inflation; for example, \(A_{lens} \leq 0.1\) is necessary to achieve \(\sigma(r) = 5 \times 10^{-4}\). Note we adopt a conservative \(l_{min} = 1000\) cut for B-modes; \(l_{min} = 100\) for B-modes decreases \(A_{lens}\) by 30%. Fourth column: Constraints on primordial non-Gaussianity from a kSZ survey overlapping with LSST [110]. These constraints are galaxy-shot-noise limited, yielding minimal gain from lowering the noise below \(0.5\mu\text{K-arcmin}\). Achieving \(\sigma(f_{NL}) < 1\) can distinguish between single and multi-field inflation models. We assume 10” resolution.

5 Signatures from the Newborn Universe

Do primordial gravitational waves from an epoch of inflation exist?

If inflation happened, did it arise from multiple or a single new field?

In order to detect primordial gravitational waves from inflation via their B-mode fluctuations, using a ground-based experiment, it is necessary to subtract the B-mode fluctuations due to gravitational lensing of E-modes. To reach a target for the tensor-to-scalar ratio, \(r\), of \(\sigma(r) < 5 \times 10^{-4}\), requires removal of at least 90\% of the lensing B-mode power, i.e. \(A_{lens} \leq 0.1\) [102]. This \(\sigma(r)\) target, in the absence of a detection, would rule out or disfavor all inflation models that naturally explain the observed value of the scalar spectral index, and which have a characteristic scale in field space larger than the Planck scale [102]. The third column of Table 3 shows that such an \(A_{lens}\) target is well within reach. In addition, as shown in the fourth column, maps of the kSZ signal cross correlated with an overlapping galaxy survey such as LSST, can constrain primordial non-Gaussianity, crossing the critical threshold of \(\sigma(f_{NL}) < 1\) that would rule out a wide class of multi-field inflation models [87, 109–111].

6 Planetary and Exo-Solar System Studies

What is the census of bodies in the outer Solar System, and around other stars?

Millimeter-wave surveys can open a new discovery space of bodies in the outer Solar System, and planetary systems around other stars. High-resolution, low-noise millimeter-wave surveys could detect undiscovered Solar System planets via their thermal flux and parallactic motion [112]. In the outer Solar System, the main source of heating for planets is internal. Optical observations, in contrast, are sensitive to the bodies’ reflected light from the Sun. Since the flux from reflected light falls faster with distance than directly sourced emission, millimeter-wave surveys have an advantage over optical surveys in finding objects in the far Solar System [113]. A deep, high-resolution millimeter-wave survey could detect, for example, Earth-sized planets at thousands of AU from the Sun. Such a survey, combined with optical measurements, would allow large population studies of the sizes and albedos of these objects [114]. Deep millimeter-wave surveys can also enable the detection of exo-Oort clouds around other stars [115], opening a new window into the study of planetary systems.
Affiliations

1 Perimeter Institute
2 Southern Methodist University
3 European Southern Observatory
4 Max Planck Institute for Astrophysics
5 University of Pennsylvania
6 Harvard University
7 University of New Mexico
8 Princeton University
9 University of Cambridge
10 University of Illinois at Urbana-Champaign
11 Yale University
12 Lawrence Berkeley National Laboratory
13 University of California, San Diego
14 University of Florida
15 Stony Brook University
16 Columbia University
17 UK Astronomy Technology Centre
18 CITA, University of Toronto
19 Flatiron Institute
20 Lawrence Livermore National Laboratory
21 SISSA, Trieste
22 University of Bonn
23 Fermi National Accelerator Laboratory
24 Kavli Institute for Cosmological Physics
25 University of Portsmouth
26 Cardiff University
27 Florida State University
28 University of Rochester
29 Goddard Space Flight Center
30 Green Bank Observatory
31 Argonne National Laboratory
32 University of Rochester
33 University of California, Berkeley
34 The University of Melbourne
35 Institute for Advanced Study
36 The Ohio State University
37 Imperial College, London
38 York University
39 Johns Hopkins University
40 Ben-Gurion University
41 University of Miami
42 Haverford College
43 Sapienza University of Rome
44 Space Telescope Science Institute
45 Sejong University
46 University of Padova
47 Shanghai Astronomical Observatory
48 University of Michigan
49 Brookhaven National Laboratory
50 Goddard Space Flight Center
51 Carnegie Mellon University
52 Rochester Institute of Technology
References

[1] F. Zwicky. On the Masses of Nebulae and of Clusters of Nebulae. ApJ, 86:217, October 1937. doi:10.1086/143864.

[2] V. C. Rubin and W. K. Ford, Jr. Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions. ApJ, 159:379, February 1970. doi:10.1086/150317.

[3] J. P. Ostriker, P. J. E. Peebles, and A. Yahil. The size and mass of galaxies, and the mass of the universe. ApJL, 193:L1–L4, October 1974. doi:10.1086/181617.

[4] D. Fabricant, M. Lecar, and P. Gorenstein. X-ray measurements of the mass of M87. ApJ, 241:552–560, October 1980. doi:10.1086/158369.

[5] Neta A. Bahcall, Lori M. Lubin, and Victoria Dorman. Where is the Dark Matter? ApJ, 447:L81, Jul 1995. arXiv:astro-ph/9506041, doi:10.1086/309577.

[6] Douglas Clowe, Maruša Bradač, Anthony H. Gonzalez, Maxim Markevitch, Scott W. Randall, Christine Jones, et al. A Direct Empirical Proof of the Existence of Dark Matter. ApJ, 648:L109–L113, September 2006. arXiv:astro-ph/0608407, doi:10.1086/508162.

[7] Planck Collaboration, N. Aghanim, Y. Akrami, M. Ashdown, J. Aumont, C. Baccigalupi, et al. Planck 2018 results. VI. Cosmological parameters. arXiv e-prints, page arXiv:1807.06209, July 2018. arXiv:1807.06209.

[8] Pedro Colin, Vladimir Avila-Reese, and Octavio Valenzuela. Substructure and Halo Density Profiles in a Warm Dark Matter Cosmology. ApJ, 542:622–630, October 2000. arXiv:astro-ph/0004115, doi:10.1086/317057.

[9] Paul Bode, Jeremiah P. Ostriker, and Neil Turok. Halo Formation in Warm Dark Matter Models. ApJ, 556:93–107, July 2001. arXiv:astro-ph/0010389, doi:10.1086/321541.

[10] Celine Boehm, Alain Riazuelo, Steen H. Hansen, and Richard Schaeffer. Interacting dark matter disguised as warm dark matter. Phys. Rev. D, 66:083505, 2002. arXiv:astro-ph/0112522, doi:10.1103/PhysRevD.66.083505.

[11] Celine Boehm and Richard Schaeffer. Constraints on dark matter interactions from structure formation: Damping lengths. Astron. Astrophys., 438:419–442, 2005. arXiv:astro-ph/0410591, doi:10.1051/0004-6361:20042238.

[12] Matteo Viel, Julien Lesgourgues, Martin G. Haehnelt, Sabino Matarrese, and Antonio Riotto. Constraining warm dark matter candidates including sterile neutrinos and light gravitinos with WMAP and the Lyman-α forest. Phys/ Rev. D, 71:063534, March 2005. arXiv:astro-ph/0501562, doi:10.1103/PhysRevD.71.063534.

[13] Michael S. Turner. Coherent scalar-field oscillations in an expanding universe. Phys. Rev. D, 28:1243–1247, Sep 1983. URL: https://link.aps.org/doi/10.1103/PhysRevD.28.1243, doi:10.1103/PhysRevD.28.1243.

[14] William H. Press, Barbara S. Ryden, and David N. Spergel. Single mechanism for generating large-scale structure and providing dark missing matter. Phys. Rev. Lett., 64:1084–1087, Mar 1990. URL: https://link.aps.org/doi/10.1103/PhysRevLett.64.1084, doi:10.1103/PhysRevLett.64.1084.

[15] Sang-Jin Sin. Late-time phase transition and the galactic halo as a bose liquid. Phys. Rev. D, 50:3650–3654, Sep 1994. URL:
[16] Wayne Hu, Rennan Barkana, and Andrei Gruzinov. Fuzzy cold dark matter: The wave properties of ultralight particles. *Phys. Rev. Lett.*, 85:1158–1161, Aug 2000. URL: https://link.aps.org/doi/10.1103/PhysRevLett.85.1158, doi:10.1103/PhysRevLett.85.1158.

[17] J. Goodman. Repulsive dark matter. *New A.*, 5:103–107, April 2000. arXiv:astro-ph/0003018, doi:10.1016/S1384-1076(00)00015-4.

[18] P. J. E. Peebles. Fluid dark matter. *The Astrophysical Journal*, 534(2):L127–L129, may 2000. URL: https://doi.org/10.1086%2F312677, doi:10.1086/312677.

[19] Luca Amendola and Riccardo Barbieri. Dark matter from an ultra-light pseudo-Goldsone-boson. *Physics Letters B*, 642:192–196, November 2006. arXiv:hep-ph/0509257, doi:10.1016/j.physletb.2006.08.069.

[20] Hsi-Yu Schive, Tzihong Chiueh, and Tom Broadhurst. Cosmic structure as the quantum interference of a coherent dark wave. *Nature Physics*, 10:496–499, July 2014. arXiv:1406.6586, doi:10.1038/nphys2996.

[21] David J. E. Marsh. Axion cosmology. *Phys. Rep.*, 643:1–79, July 2016. arXiv:1510.07633, doi:10.1016/j.physrep.2016.06.005.

[22] E. D. Carlson, M. E. Machacek, and L. J. Hall. Self-interacting dark matter. *ApJ*, 398:43–52, October 1992. doi:10.1086/171833.

[23] David N. Spergel and Paul J. Steinhardt. Observational evidence for self-interacting cold dark matter. *Phys. Rev. Lett.*, 84:3760–3763, Apr 2000. URL: https://link.aps.org/doi/10.1103/PhysRevLett.84.3760, doi:10.1103/PhysRevLett.84.3760.

[24] Mark Vogelsberger, Jesus Zavala, and Abraham Loeb. Subhaloes in self-interacting galactic dark matter haloes. *MNRAS*, 423:3740–3752, July 2012. arXiv:1201.5892, doi:10.1111/j.1365-2966.2012.21182.x.

[25] Cora Dvorkin, Kfir Blum, and Marc Kamionkowski. Constraining Dark Matter-Baryon Scattering with Linear Cosmology. *Phys. Rev.*, D89(2):023519, 2014. arXiv:1311.2937, doi:10.1103/PhysRevD.89.023519.

[26] A. Bastidas Fry, F. Governato, A. Pontzen, T. Quinn, M. Tremmel, L. Anderson, et al. All about baryons: revisiting SIDM predictions at small halo masses. *MNRAS*, 452:1468–1479, September 2015. arXiv:1501.00497, doi:10.1093/mnras/stv1330.

[27] Oliver D. Elbert, James S. Bullock, Shea Garrison-Kimmel, Miguel Rocha, Jose Oñorbe, and Annika H. G. Peter. Core formation in dwarf haloes with self-interacting dark matter: no fine-tuning necessary. *MNRAS*, 453:29–37, October 2015. arXiv:1412.1477, doi:10.1093/mnras/stv1470.

[28] Manoj Kaplinghat, Sean Tulin, and Hai-Bo Yu. Dark matter halos as particle colliders: Unified solution to small-scale structure puzzles from dwarfs to clusters. *Phys. Rev. Lett.*, 116:041302, Jan 2016. URL: https://link.aps.org/doi/10.1103/PhysRevLett.116.041302, doi:10.1103/PhysRevLett.116.041302.

[29] Ayuki Kamada, Manoj Kaplinghat, Andrew B. Pace, and Hai-Bo Yu. Self-Interacting Dark Matter
Can Explain Diverse Galactic Rotation Curves. Phys/ Rev. Letters, 119:111102, September 2017. arXiv:1611.02716, doi:10.1103/PhysRevLett.119.111102.

[30] Vera Gluscevic and Kimberly K. Boddy. Constraints on Scattering of keV–TeV Dark Matter with Protons in the Early Universe. Phys. Rev. Lett., 121(8):081301, 2018. arXiv:1712.07133, doi:10.1103/PhysRevLett.121.081301.

[31] Kimberly K. Boddy and Vera Gluscevic. First Cosmological Constraint on the Effective Theory of Dark Matter-Proton Interactions. Phys. Rev., D98(8):083510, 2018. arXiv:1801.08609, doi:10.1103/PhysRevD.98.083510.

[32] Zack Li, Vera Gluscevic, Kimberly K. Boddy, and Mathew S. Madhavacheril. Disentangling dark physics with cosmic microwave background experiments. Phys/ Rev. D, 98:123524, Dec 2018. arXiv:1806.10165, doi:10.1103/PhysRevD.98.123524.

[33] Kimberly K. Boddy, Vera Gluscevic, Vivian Poulin, Ely D. Kovetz, Marc Kamionkowski, and Rennan Barkana. A Critical Assessment of CMB Limits on Dark Matter-Baryon Scattering: New Treatment of the Relative Bulk Velocity. 2018. arXiv:1808.0001.

[34] Sean Tulin and Hai-Bo Yu. Dark matter self-interactions and small scale structure. Phys. Rep., 730:1–57, February 2018. arXiv:1705.02358, doi:10.1016/j.physrep.2017.11.004.

[35] Justin Khoury. Dark Matter Superfluidity. arXiv e-prints, page arXiv:1605.08443, May 2016. arXiv:1605.08443.

[36] M. Vogelsberger, J. Zavala, F.-Y. Cyr-Racine, C. Pfrommer, T. Bringmann, and K. Sigurdson. ETHOS - an effective theory of structure formation: dark matter physics as a possible explanation of the small-scale CDM problems. MNRAS, 460:1399–1416, August 2016. arXiv:1512.05349, doi:10.1093/mnras/stw1076.

[37] Francis-Yan Cyr-Racine and Kris Sigurdson. The cosmology of atomic dark matter. Phys. Rev. D, 87:103515, 2013. URL: http://arxiv.org/abs/1209.5752, arXiv:1209.5752.

[38] F.-Y. Cyr-Racine, K. Sigurdson, J. Zavala, T. Bringmann, M. Vogelsberger, and C. Pfrommer. ETHOS – an effective theory of structure formation: From dark particle physics to the matter distribution of the Universe. Phys/ Rev. D, 93(12):123527, June 2016. arXiv:1512.05344, doi:10.1103/PhysRevD.93.123527.

[39] J. A. Schewtschenko, R. J. Wilkinson, C. M. Baugh, C. Boehm, and S. Pascoli. Dark matter-radiation interactions: the impact on dark matter haloes. MNRAS, 449(4):3587–3596, 2015. arXiv:1412.4905, doi:10.1093/mnras/stv431.

[40] Rebecca Krall, Francis-Yan Cyr-Racine, and Cora Dvorkin. Wandering in the Lyman-alpha Forest: A Study of Dark Matter-Dark Radiation Interactions. JCAP, 1709(09):003, 2017. arXiv:1705.08894, doi:10.1088/1475-7516/2017/09/003.

[41] Weishuang Linda Xu, Cora Dvorkin, and Andrew Chael. Probing sub-GeV Dark Matter-Baryon Scattering with Cosmological Observables. Phys. Rev., D97(10):103530, 2018. arXiv:1802.06788, doi:10.1103/PhysRevD.97.103530.

[42] Sergey E. Koposov, Andrew R. Casey, Vasily Belokurov, James R. Lewis, Gerard Gilmore, Clare Worley, et al. Kinematics and Chemistry of Recently Discovered Reticulum 2 and Horologium 1 Dwarf Galaxies. ApJ, 811:62, September 2015. arXiv:1504.07916, doi:10.1088/0004-637X/811/1/62.
[43] A. Drlica-Wagner, K. Bechtol, E. S. Rykoff, E. Luque, A. Queiroz, Y. Y. Mao, et al. Eight Ultra-faint Galaxy Candidates Discovered in Year Two of the Dark Energy Survey. ApJ, 813:109, November 2015. arXiv:1508.03622, doi:10.1088/0004-637X/813/2/109.

[44] N. Menci, A. Merle, M. Totzauer, A. Schneider, A. Grazian, M. Castellano, et al. Fundamental Physics with the Hubble Frontier Fields: Constraining Dark Matter Models with the Abundance of Extremely Faint and Distant Galaxies. ApJ, 836:61, February 2017. arXiv:1701.01339, doi:10.3847/1538-4357/836/1/61.

[45] Andrei Mesinger, Rosalba Perna, and Zoltán Haiman. Constraints on the Small-Scale Power Spectrum of Density Fluctuations from High-Redshift Gamma-Ray Bursts. ApJ, 623:1–10, April 2005. arXiv:astro-ph/0501233, doi:10.1086/428770.

[46] R. S. de Souza, A. Mesinger, A. Ferrara, Z. Haiman, R. Perna, and N. Yoshida. Constraints on warm dark matter models from high-redshift long gamma-ray bursts. MNRAS, 432:3218–3227, July 2013. arXiv:1303.5060, doi:10.1093/mnras/stt674.

[47] Ben Moore, Sebastiano Ghigna, Fabio Governato, George Lake, Thomas Quinn, Joachim Stadel, et al. Dark Matter Substructure within Galactic Halos. ApJ, 524:L19–L22, October 1999. arXiv:astro-ph/9907411, doi:10.1086/312287.

[48] Kathryn V. Johnston and Raymond G. Carlberg. Tidal Debris as a Dark Matter Probe. In Heidi Jo Newberg and Jeffrey L. Carlin, editors, Tidal Streams in the Local Group and Beyond, volume 420 of Astrophysics and Space Science Library, page 169, January 2016. arXiv:1603.06602, doi:10.1007/978-3-319-19336-6_7.

[49] R. G. Carlberg. Star Stream Folding by Dark Galactic Subhalos. ApJ, 705:L223–L226, November 2009. arXiv:0908.4345, doi:10.1088/0004-637X/705/2/L223.

[50] D. Erkal and V. Belokurov. Properties of dark subhaloes from gaps in tidal streams. MNRAS, 454:3542–3558, December 2015. arXiv:1507.05625, doi:10.1093/mnras/stv2122.

[51] Jo Bovy. Dynamical Modeling of Tidal Streams. ApJ, 795:95, November 2014. arXiv:1401.2985, doi:10.1088/0004-637X/795/1/95.

[52] Renyue Cen, Jordi Miralda-Escudé, Jeremiah P. Ostriker, and Michael Rauch. Gravitational Collapse of Small-Scale Structure as the Origin of the Lyman-Alpha Forest. ApJ, 437:L9, December 1994. arXiv:astro-ph/9409017, doi:10.1086/187670.

[53] L. Hernquist, N. Katz, D. H. Weinberg, and J. Miralda-Escudé. The Lyman-Alpha Forest in the Cold Dark Matter Model. ApJL, 457:L51, February 1996. arXiv:astro-ph/9509105, doi:10.1086/309899.

[54] Rupert A. C. Croft, David H. Weinberg, Max Pettini, Lars Hernquist, and Neal Katz. The Power Spectrum of Mass Fluctuations Measured from the Lyα Forest at Redshift z = 2.5. ApJ, 520:1–23, July 1999. arXiv:astro-ph/9809401, doi:10.1086/307438.

[55] Lam Hui. Recovery of the Shape of the Mass Power Spectrum from the Lyα Forest. ApJ, 516:519–526, May 1999. arXiv:astro-ph/9807068, doi:10.1086/307134.

[56] Matteo Viel, George D. Becker, James S. Bolton, and Martin G. Haehnelt. Warm dark matter as a solution to the small scale crisis: New constraints from high redshift Lyman-α forest data. Phys/ Rev. D, 88:043502, August 2013. arXiv:1306.2314, doi:10.1103/PhysRevD.88.043502.

[57] Julien Baur, Nathalie Palanque-Delabrouille, Christophe Yèche, Christophe Magneville, and Matteo Viel. Lyman-alpha forests cool warm dark matter. Journal of Cosmology and Astro-Particle Phys/
[58] Vid Iršič, Matteo Viel, Martin G. Haehnelt, James S. Bolton, Stefano Cristiani, George D. Becker, et al. New constraints on the free-streaming of warm dark matter from intermediate and small scale Lyman-α forest data. Phys/ Rev. D, 96:023522, July 2017. arXiv:1702.01764, doi:10.1103/PhysRevD.96.023522.

[59] Till Sawala, Carlos S. Frenk, Azadeh Fattahi, Julio F. Navarro, Tom Theuns, Richard G. Bower, et al. The chosen few: the low-mass haloes that host faint galaxies. MNRAS, 456:85–97, February 2016. arXiv:1406.6362, doi:10.1093/mnras/stv2597.

[60] K. A. Oman, J. F. Navarro, A. Fattahi, C. S. Frenk, T. Sawala, S. D. M. White, et al. The unexpected diversity of dwarf galaxy rotation curves. MNRAS, 452:3650–3665, October 2015. arXiv:1504.01437, doi:10.1093/mnras/stv1504.

[61] Lam Hui, Jeremiah P. Ostriker, Scott Tremaine, and Edward Witten. Ultralight scalars as cosmological dark matter. Phys/ Rev. D, 95:043541, February 2017. arXiv:1610.08297, doi:10.1103/PhysRevD.95.043541.

[62] N. Dalal and C. S. Kochanek. Direct Detection of Cold Dark Matter Substructure. ApJ, 572:25–33, June 2002. arXiv:astro-ph/0111456, doi:10.1086/340303.

[63] L. V. E. Koopmans. Gravitational-mass imaging of CDM substructure. Mon. Not. Roy. Astron. Soc., 363:1136, 2005. arXiv:astro-ph/0501324, doi:10.1111/j.1365-2966.2005.09523.x.

[64] S. Vegetti and L. V. E. Koopmans. Statistics of mass substructure from strong gravitational lensing: quantifying the mass fraction and mass function. MNRAS, 400:1583–1592, December 2009. arXiv:0903.4752, doi:10.1111/j.1365-2966.2009.15559.x.

[65] S. Vegetti, O. Czoske, and L. V. E. Koopmans. Quantifying dwarf satellites through gravitational imaging: the case of SDSSJ120602.09+514229.5. MNRAS, 407:225–231, September 2010. arXiv:1002.4708, doi:10.1111/j.1365-2966.2010.16952.x.

[66] S. Vegetti, L. V. E. Koopmans, A. Bolton, T. Treu, and R. Gavazzi. Detection of a dark substructure through gravitational imaging. MNRAS, 408:1969–1981, November 2010. arXiv:0910.0760, doi:10.1111/j.1365-2966.2010.16865.x.

[67] S. Vegetti, D. J. Lagattuta, J. P. McKean, M. W. Auger, C. D. Fassnacht, and L. V. E. Koopmans. Gravitational detection of a low-mass dark satellite galaxy at cosmological distance. Nature, 481:341–343, January 2012. arXiv:1201.3643, doi:10.1038/nature10669.

[68] Yashar Hezaveh, Neal Dalal, Gilbert Holder, Michael Kuhlen, Daniel Marrone, et al. Dark Matter Substructure Detection Using Spatially Resolved Spectroscopy of Lensed Dusty Galaxies. Astrophys. J., 767:9, 2013. arXiv:1210.4562, doi:10.1088/0004-637X/767/1/9.

[69] S. Vegetti, L. V. E. Koopmans, M. W. Auger, T. Treu, and A. S. Bolton. Inference of the cold dark matter substructure mass function at z = 0.2 using strong gravitational lenses. MNRAS, 442:2017–2035, August 2014. arXiv:1405.3666, doi:10.1093/mnras/stu943.

[70] Yashar D. Hezaveh, Neal Dalal, Daniel P. Marrone, Yao-Yuan Mao, Warren Morningstar, Di Wen, et al. Detection of Lensing Substructure Using ALMA Observations of the Dusty Galaxy SDP.81. ApJ, 823:37, May 2016. arXiv:1601.01388, doi:10.3847/0004-637X/823/1/37.

[71] E. Ritondale, S. Vegetti, G. Despali, M. W. Auger, L. V. E. Koopmans, and J. P. McKean. Low-mass
halo perturbations in strong gravitational lenses at redshift \( z \sim 0.5 \) are consistent with CDM. 2018. arXiv:1811.03627.

[72] Y. Hezaveh, N. Dalal, G. Holder, T. Kisner, M. Kuhlen, and L. Perreault Levasseur. Measuring the power spectrum of dark matter substructure using strong gravitational lensing. JCAP, 11:048, November 2016. arXiv:1403.2720, doi:10.1088/1475-7516/2016/11/048.

[73] Tansu Daylan, Francis-Yan Cyr-Racine, Ana Diaz Rivero, Cora Dvorkin, and Douglas P. Finkbeiner. Probing the small-scale structure in strongly lensed systems via transdimensional inference. Astrophys. J., 854(2):141, 2018. arXiv:1706.06111, doi:10.3847/1538-4357/aaaa1e.

[74] D. Bayer, S. Chatterjee, L. V. E. Koopmans, S. Vegetti, J. P. McKean, T. Treu, et al. Observational constraints on the sub-galactic matter-power spectrum from galaxy-galaxy strong gravitational lensing. 2018. arXiv:1803.05952.

[75] Ana Diaz Rivero, Francis-Yan Cyr-Racine, and Cora Dvorkin. Power spectrum of dark matter substructure in strong gravitational lenses. Phys/ Rev. D, 97:023001, January 2018. arXiv:1707.04590, doi:10.1103/PhysRevD.97.023001.

[76] S. Chatterjee and L. V. E. Koopmans. The inner mass power spectrum of galaxies using strong gravitational lensing: beyond linear approximation. MNRAS, 474:1762–1772, February 2018. arXiv:1710.03075, doi:10.1093/mnras/stx2674.

[77] Francis-Yan Cyr-Racine, Charles R. Keeton, and Leonidas A. Moustakas. Beyond subhalos: Probing the collective effect of the Universe’s small-scale structure with gravitational lensing. 2018. arXiv:1806.07897.

[78] Sean Brennan, Andrew J. Benson, Francis-Yan Cyr-Racine, Charles R. Keeton, Leonidas A. Moustakas, and Anthony R. Pullen. Quantifying the power spectrum of small-scale structure in semi-analytic galaxies. arXiv e-prints, page arXiv:1808.03501, August 2018. arXiv:1808.03501.

[79] Ana Díaz Rivero, Cora Dvorkin, Frances-Yan Cyr-Racine, Jesús Zavala, and Mark Vogelsberger. Gravitational Lensing and the Power Spectrum of Dark Matter Substructure: Insights from the ETHOS N-body Simulations. Phys. Rev., D98(10):103517, 2018. arXiv:1809.00004, doi:10.1103/PhysRevD.98.103517.

[80] H. N. Nguyễn, N. Sehgal, and M. S. Madhavacheril. Measuring the small-scale matter power spectrum with high-resolution CMB lensing. Phys/ Rev. D, 99(2):023502, January 2019. arXiv:1710.03747, doi:10.1103/PhysRevD.99.023502.

[81] M. P. van Daalen, J. Schaye, C. M. Booth, and C. Dalla Vecchia. The effects of galaxy formation on the matter power spectrum: a challenge for precision cosmology. MNRAS, 415:3649–3665, August 2011. arXiv:1104.1174, doi:10.1111/j.1365-2966.2011.18981.x.

[82] Alyson M. Brooks, Michael Kuhlen, Adi Zolotov, and Dan Hooper. A Baryonic Solution to the Missing Satellites Problem. ApJ, 765:22, March 2013. arXiv:1209.5394, doi:10.1088/0004-637X/765/1/22.

[83] A. Brooks. Re-examining astrophysical constraints on the dark matter model. Annalen der Physik, 526:294–308, August 2014. arXiv:1407.7544, doi:10.1002/andp.201400068.

[84] Aravind Natarajan, Andrew R. Zentner, Nicholas Battaglia, and Hy Trac. Systematic errors in the measurement of neutrino masses due to baryonic feedback processes: Prospects for stage IV lensing
[85] Aurel Schneider, Romain Teyssier, Joachim Stadel, Nora Elisa Chisari, Amandine M. C. Le Brun, Adam Amara, et al. Quantifying baryon effects on the matter power spectrum and the weak lensing shear correlation. arXiv e-prints, page arXiv:1810.08629, October 2018. arXiv:1810.08629.

[86] Emmanuel Schaan, Simone Ferraro, Mariana Vargas-Magaña, Kendrick M. Smith, Shirley Ho, Simone Aiola, et al. Evidence for the kinematic Sunyaev-Zel’dovich effect with the Atacama Cosmology Telescope and velocity reconstruction from the Baryon Oscillation Spectroscopic Survey. Phys/ Rev. D, 93:082002, April 2016. arXiv:1510.06442, doi:10.1103/PhysRevD.93.082002.

[87] Kendrick M. Smith, Mathew S. Madhavacheril, Moritz Münchmeyer, Simone Ferraro, Utkarsh Giri, and Matthew C. Johnson. KSZ tomography and the bispectrum. arXiv e-prints, page arXiv:1810.13423, October 2018. arXiv:1810.13423.

[88] K. Nelson, E. T. Lau, D. Nagai, D. H. Rudd, and L. Yu. Weighing Galaxy Clusters with Gas. II. On the Origin of Hydrostatic Mass Bias in ΛCDM Galaxy Clusters. ApJ, 782:107, February 2014. arXiv:1308.6589, doi:10.1088/0004-637X/782/2/107.

[89] L. Knox, G. P. Holder, and S. E. Church. Effects of Submillimeter and Radio Point Sources on the Recovery of Sunyaev-Zel’dovich Galaxy Cluster Parameters. ApJ, 612:96–107, September 2004. arXiv:astro-ph/0309643, doi:10.1086/422447.

[90] N. Sehgal, A. Kosowsky, and G. Holder. Constrained Cluster Parameters from Sunyaev-Zel’dovich Observations. ApJ, 635:22–34, December 2005. arXiv:astro-ph/0504274, doi:10.1086/497258.

[91] Nicholas Battaglia, Simone Ferraro, Emmanuel Schaan, and David N. Spergel. Future constraints on halo thermodynamics from combined Sunyaev-Zel’dovich measurements. Journal of Cosmology and Astro-Particle Physics, 2017:040, November 2017. arXiv:1705.05881, doi:10.1088/1475-7516/2017/11/040.

[92] T. Mroczkowski, D. Nagai, K. Basu, J. Chluba, J. Sayers, R. Adam, et al. Astrophysics with the Spatially and Spectrally Resolved Sunyaev-Zeldovich Effects. A Millimetre/Submillimetre Probe of the Warm and Hot Universe. Space Sci. Rev., 215:17, February 2019. arXiv:1811.02310, doi:10.1007/s11214-019-0581-2.

[93] R. A. Sunyaev and Y. B. Zeldovich. The Spectrum of Primordial Radiation, its Distortions and their Significance. Comments on Astrophysics and Space Physics, 2:66, March 1970.

[94] R. A. Sunyaev and Y. B. Zeldovich. The Observations of Relic Radiation as a Test of the Nature of X-Ray Radiation from the Clusters of Galaxies. Comments on Astrophysics and Space Physics, 4:173, November 1972.

[95] T. A. Marriage, V. Acquaviva, P. A. R. Ade, P. Aguirre, M. Amiri, J. W. Appel, et al. The Atacama Cosmology Telescope: Sunyaev-Zel’dovich-Selected Galaxy Clusters at 148 GHz in the 2008 Survey. ApJ, 737:61, August 2011. arXiv:1010.1065, doi:10.1088/0004-637X/737/2/61.

[96] K. Vanderlinde, T. M. Crawford, T. de Haan, J. P. Dudley, L. Shaw, P. A. R. Ade, et al. Galaxy Clusters Selected with the Sunyaev-Zel’dovich Effect from 2008 South Pole Telescope Observations. ApJ, 722:1180–1196, October 2010. arXiv:1003.0003, doi:10.1088/0004-637X/722/2/1180.
[97] Planck Collaboration, P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, et al. Planck 2013 results. XXIX. The Planck catalogue of Sunyaev-Zeldovich sources. A&A, 571:A29, November 2014. arXiv:1303.5089, doi:10.1051/0004-6361/201321523.

[98] D. Nagai and E. T. Lau. Gas Clumping in the Outskirts of ΛCDM Clusters. ApJL, 731:L10, April 2011. arXiv:1103.0280, doi:10.1088/2041-8205/731/1/L10.

[99] K. Nelson, E. T. Lau, and D. Nagai. Hydrodynamic Simulation of Non-thermal Pressure Profiles of Galaxy Clusters. ApJ, 792:25, September 2014. arXiv:1404.4636, doi:10.1088/0004-637X/792/1/25.

[100] E. T. Lau, D. Nagai, C. Avestruz, K. Nelson, and A. Vikhlinin. Mass Accretion and its Effects on the Self-similarity of Gas Profiles in the Outskirts of Galaxy Clusters. ApJ, 806:68, June 2015. arXiv:1411.5361, doi:10.1088/0004-637X/806/1/68.

[101] C. Avestruz, D. Nagai, E. T. Lau, and K. Nelson. Non-equilibrium Electrons in the Outskirts of Galaxy Clusters. ApJ, 808:176, August 2015. arXiv:1410.8142, doi:10.1088/0004-637X/808/2/176.

[102] Kevork N. Abazajian, Peter Adshead, Zeeshan Ahmed, Steven W. Allen, David Alonso, Kam S. Arnold, et al. CMB-S4 Science Book, First Edition. arXiv e-prints, page arXiv:1610.02743, October 2016. arXiv:1610.02743.

[103] Daniel Baumann, Daniel Green, and Benjamin Wallisch. New Target for Cosmic Axion Searches. Phys. Rev. Lett., 117(17):171301, 2016. arXiv:1604.08614, doi:10.1103/PhysRevLett.117.171301.

[104] Daniel Green and Surjeet Rajendran. The Cosmology of Sub-MeV Dark Matter. JHEP, 10:013, 2017. arXiv:1701.08750, doi:10.1007/JHEP10(2017)013.

[105] Daniel Baumann, Daniel Green, Joel Meyers, and Benjamin Wallisch. Phases of New Physics in the CMB. JCAP, 1601:007, 2016. arXiv:1508.06342, doi:10.1088/1475-7516/2016/01/007.

[106] Daniel Green, Joel Meyers, and Alexander van Engelen. CMB Delensing Beyond the B Modes. JCAP, 1712(12):005, 2017. arXiv:1609.08143, doi:10.1088/1475-7516/2017/12/005.

[107] Antony Lewis. Rayleigh scattering: blue sky thinking for future CMB observations. Journal of Cosmology and Astro-Particle Physics, 2013:053, Aug 2013. arXiv:1307.8148, doi:10.1088/1475-7516/2013/08/053.

[108] Elham Alipour, Kris Sigurdson, and Christopher M. Hirata. Effects of Rayleigh scattering on the CMB and cosmic structure. Phys. Rev., D91(8):083520, 2015. arXiv:1410.6484, doi:10.1103/PhysRevD.91.083520.

[109] Marcelo Alvarez et al. Testing Inflation with Large Scale Structure: Connecting Hopes with Reality. 2014. arXiv:1412.4671.

[110] M. Münchmeyer, M. S. Madhavacheril, S. Ferraro, M. C. Johnson, and K. M. Smith. Constraining local non-Gaussianities with KSZ tomography. arXiv e-prints, page arXiv:1610.02743, October 2018. arXiv:1810.13424.

[111] Anne-Sylvie Deutsch, Emanuela Dimastrogiovanni, Matthew C. Johnson, Moritz Münchmeyer, and Alexandra Terrana. Reconstruction of the remote dipole and quadrupole fields from the kinetic Sunyaev Zel’dovich and polarized Sunyaev Zel’dovich effects. Phys/ Rev. D, 98:123501, December 2018. arXiv:1707.08129, doi:10.1103/PhysRevD.98.123501.
[112] Nicolas B. Cowan, Gil Holder, and Nathan A. Kaib. Cosmologists in Search of Planet Nine: The Case for CMB Experiments. ApJ, 822:L2, May 2016. arXiv:1602.05963, doi:10.3847/2041-8205/822/1/L2.

[113] Eric J. Baxter, Bhuvnesh Jain, Cullen Blake, Gary Bernstein, Mark Devlin, and Gil Holder. Planet X in CMB and Optical Galaxy Surveys. arXiv e-prints, page arXiv:1812.08701, December 2018. arXiv:1812.08701.

[114] D. W. Gerdes, M. Sako, S. Hamilton, K. Zhang, T. Khain, J. C. Becker, et al. Discovery and Physical Characterization of a Large Scattered Disk Object at 92 au. ApJ, 839:L15, April 2017. arXiv:1702.00731, doi:10.3847/2041-8213/aa64d8.

[115] Eric J. Baxter, Cullen H. Blake, and Bhuvnesh Jain. Probing Oort Clouds around Milky Way Stars with CMB Surveys. Astron. J., 156:243, November 2018. arXiv:1808.00415, doi:10.3847/1538-3881/aae64e.