# Roman CCS White Paper

**Title:** Improving cosmological constraints from the Roman High Latitude Wide Area Survey by choosing its survey footprint to maximally overlap with the deep SPT-3G Survey

**Roman Core Community Survey**: *High Latitude Wide Area Survey*

**Scientific Categories**: *Large scale structure of the universe; galaxies; the intergalactic medium and the circumgalactic medium*

**Additional scientific keywords**: *Gravitational lensing; galaxy clusters; cosmological parameters*

## List of lead authors:

- Prof. Bradford Benson, University of Chicago USA, email: bbenson@astro.uchicago.edu
- Dr. Lindsey Bleem, Argonne National Laboratory USA, email: lbleem@anl.gov
- Dr. Sebastian Grandis, University of Innsbruck, Austria, email: sebastian.grandis@uibk.ac.at
- Dr. Laila Linke, University of Innsbruck, Austria, email: laila.linke@uibk.ac.at
- Prof. Tim Schrabback, University of Innsbruck, Austria, email: tim.schrabback@uibk.ac.at

## List of contributing and endorsing authors:

- Dr. Sebastian Bocquet, LMU Munich, Germany, sebastian.bocquet@physik.lmu.de
- Prof. Michael McDonald, MIT Kavli Institute for Astrophysics and Space Research, USA, email: mcdonald@space.mit.edu
- Prof. Anja von der Linden, Stony Brook University, USA, email: anja.vonderlinden@stonybrook.edu

**Executive summary:** With its *High Latitude Wide Area Survey* (HLWAS) Roman will provide the deepest wide-area weak lensing (WL) survey of the decade, delivering an unprecedented map of the total large-scale mass distribution over $\sim 1,700$ deg$^2$ of the sky. This total mass distribution is dominated by invisible dark matter ($\sim 80\%$), for which accurate statistical predictions can be derived from N-body simulations. However, predictions for the distribution of ordinary matter are much more uncertain given our poor understanding of relevant gas astrophysics. Together with the non-negligible mass fraction of ordinary matter ($\sim 20\%$), this leads to a serious systematic uncertainty in the interpretation of the WL measurements. This problem can be solved if we additionally obtain a very deep map of the dominant component of ordinary matter, which is hot intergalactic plasma. X-ray surveys are subject to cosmic dimming, which is why their measurements primarily probe nearby structures, not matching the outstanding depth of Roman. The only way out is given by very deep Sunyaev-Zel'dovich (SZ) measurements, which probe hot plasma unaffected by cosmic dimming. The only current SZ survey that provides sufficient SZ depth over an area comparable to the planned Roman HLWAS is the deep component of the third generation South Pole Telescope Survey (SPT-3G, which is also expected to remain the only comparable survey until at least $\sim$ 2030). Therefore, we propose to place the HLWAS such that it maximally overlaps with the deep SPT-3G Survey footprint. As second key science motivation, the proposed common footprint of the two surveys will provide the most powerful data set to constrain cosmology via the mass function of distant galaxy clusters, improving

parameter constraints by a factor $\sim$ 5–10 compared to current published results. Furthermore, the data combination will facilitate a wide range of astrophysical investigations, not only probing the interplay of all dominant forms of matter (dark matter, hot gas, and stars) in thousands of galaxy clusters, but also providing a high-resolution view of the first generation of cluster galaxies.

**Baryon feedback: A major astrophysical contaminant to cosmological weak lensing surveys:** WL surveys probe the total mass distribution in the Universe. On large scales, this distribution closely mirrors the distribution of dark matter, for whose statistics we have reliable models as a function of cosmological parameters (e.g. Smith et al. 2003; Takahashi et al. 2012; Mead et al. 2021; Euclid Collaboration: Knabenhans et al. 2019). However, on smaller scales, the situation becomes more complex due to astrophysical processes such as feedback from active galactic nuclei (AGN) and supernova (SN) explosions, collectively known as "baryon feedback". These processes cause a reshuffling of the baryonic matter, which exists primarily in the form of hot plasma (e.g. van Daalen et al. 2011; Semboloni et al. 2011; Chisari et al. 2018).

Hydrodynamical simulations predict that these effects will lead to a smoothing of the matter distribution on small scales, resulting in a reduction of the expected WL signal (see the left panel of Fig. 1). However, the underlying astrophysical processes are still not fully understood, leading to significant variations between different simulations in terms of the amplitude and physical scale of the suppression. As a consequence, there are substantial systematic uncertainties in the predicted small-scale WL signal, potentially introducing biases in the inferred cosmological parameters (see the right panel of Fig. 1).

The currently most robust way to mitigate these uncertainties is to limit WL analyses to large scales, which significantly reduces their cosmological constraining power (e.g. Amon et al. 2022; Troxel et al. 2018; Heymans et al. 2013). Alternatively, some analyses assume a functional form for the suppression, characterized by specific parameters that are simultaneously fitted with the cosmological parameters (e.g. Li et al. 2023; Dalal et al. 2023; Asgari et al. 2021; Joudaki et al. 2017). However, this approach also reduces the sensitivity to cosmological parameters and carries the risk of biased results if an inappropriate functional form is chosen initially.

The optimal solution lies in conducting complementary measurements that directly constrain the matter redistribution caused by baryon feedback. Such measurements would enable accurate corrections to the WL model predictions. In the case of Roman's HLWAS, the most effective approach would be a combination with SPT-3G, as we elaborate in the subsequent paragraphs.

**How can the addition of a deep Sunyaev-Zel'dovich (SZ) survey solve the problem?** The main physical reasons for the modification of the matter distribution by baryon feedback are the condensation of a fraction of the baryonic material into central halo galaxies and the redistribution of the hot gas component due to AGN feedback. These effects can be effectively modelled by introducing free parameters in the halo model that alter the halo matter profiles to account for their deviation from gravity-only expectations (Schneider & Teyssier 2015; Debackere et al. 2020; Aricò et al. 2021). Determining the total matter, as well as the hot gas and stellar matter profiles of halos is thus the prime avenue to empirically constrain baryon feedback processes.

It is in this context that we see a very strong synergy between the planned Roman HLWAS and the third generation South Pole Telescope Survey (SPT-3G). Employing the Sunyaev-Zel'dovich (SZ) effect, which describes inverse Compton scattering of CMB photons off the hot intra-cluster plasma, SPT-3G will provide a clean halo catalog, selection galaxy clusters and massive galaxy groups, down to masses $M_{500\mathrm{c}} \sim 10^{14}\ \mathrm{M_{sun}}$ and out to the highest redshifts where they exist (Benson et al. 2014). This is possible since the SZ effect is not an emissive process like X-ray emission, but rather a spectral distortion of primary CMB photons. HLWAS will enable to us to measure the total matter profiles of these groups and clusters via weak gravitational lensing. This measurement can be complemented with constraints on their hot gas component from SPT-3G itself, as well as on the stellar mass distribution from HLWAS. These ingredients directly predict the suppression of the gravity-only matter fluctuations by baryonic feedback processes. They will serve as indispensable observation priors to unlock the cosmological potential of small-scale cosmological weak lensing.

Besides direct constraints on the impact of baryonic feedback on halo matter profiles, cross correlations between the thermal SZ maps, the kinetic SZ maps, and the CMB gravitational lensing derived from the SPT-3G data with the cosmic shear and galaxy distribution maps from HLWAS will provide independent constraints of the large-scale baryonic feedback processes (for a review, see Baxter et al. 2022). In addition to constraining baryon feedback effects, these cross-correlation studies also provide independent cosmological constraints (Omori et al. 2019; Tröster et al. 2022; Chang et al. 2023; Sánchez et al. 2023).

**SPT-3G: The best possible existing SZ complement to the Roman HLWAS:** The SPT-3G camera on the South Pole Telescope (SPT) is the most powerful cosmic microwave background (CMB) camera in operation. In 2023, SPT-3G began the fifth year of an eight year survey (see Fig. 2), which in total comprises over 10,000 deg$^2$ mapped to lower noise levels than any existing high-resolution CMB survey. This area includes the ultra-deep 1500 deg$^2$ Main Survey, already measured to a depth that is expected to be unmatched by any high-resolution CMB survey until CMB-S4 in $\sim$ 2030 (CMB-S4 Collaboration et al. 2019), which also plans to observe the SPT-3G Main survey field to a factor of several greater depth. In total, the SPT-3G surveys are expected to contain more clusters than even the under-construction Simons Observatory (SO) (Simons Observatory Collaboration et al. 2019) baseline survey (see Fig. 2, right). Additionally, the varied depth of the SPT-3G surveys will sample a wide range of cluster masses at all redshifts, providing access to both the most massive systems, and clusters in more typical environments. Perhaps most uniquely, the high-angular resolution and unprecedented depth of the SPT-3G data will open a new window on cluster formation by discovering systems at the highest redshifts accessible.

**Cluster cosmology constraints enabled by a joint survey footprint of Roman HLWAS and SPT-3G:** Massive clusters trace the densest regions in the cosmic large-scale structure. Their growth is completely dominated by gravity (e.g., Bocquet et al. 2016), which is why robust constraints on their number density as a function of mass and redshift offer a powerful approach to probe the cosmological model using well-understood physics (e.g. Mantz et al. 2015; Bocquet et al. 2019; Zubeldia & Challinor 2019; Chiu et al. 2023). For such analyses two key ingredients are required: Large galaxy cluster samples with a well-modeled selection function, plus accurate calibrations of cluster mass proxies using WL. Also here SPT-3G and Roman/HLWAS complement each other optimally: With its deep SZ survey and well-matched angular resolution, SPT-3G provides the deepest wide-area SZ cluster sample, finding essentially all clusters in the survey footprint with a mass $M_{\mathrm{500c}} \gtrsim 10^{14}$ M$_{\mathrm{sun}}$ (Benson et al. 2014). In contrast to optical samples, which are severely limited by projection effects (e.g. Costanzi et al. 2021), SPT-3G benefits from the well-modeled selection function of high-resolution SZ surveys (Bleem et al. 2015, 2020). As an optimal complement, Roman/HLWAS will provide the deepest wide-area WL survey, ideally capable to sensitively calibrate the masses of the SPT-3G clusters out to redshifts $z \sim 1.5$. At even higher redshifts the sensitivity of galaxy weak lensing drops rapidly even for the very deep Roman data, but also here some (weaker) cluster mass constraints can still be derived for the joint data set from SPT-3G CMB lensing measurements (Raghunathan et al. 2019).

Previous work in the field employed clusters from the precursor SPT-SZ survey (see Fig. 3), combined with deep WL measurements for 13 high-redshift clusters from the *Hubble* Space Telescope (Schrabback et al. 2018a) plus 19 lower-redshift clusters from Magellan (Dietrich et al. 2019), already providing some of the most competitive cluster cosmology constraints on parameters such as the matter density $\Omega_{\mathrm{m}}$, the normalization of the matter power-spectrum $\sigma_8$, the species-summed neutrino mass $\sum m_\nu$, and the dark energy equation of state parameter $w$ to date (Bocquet et al. 2019, see also Fig. 3). If Roman/HLWAS and SPT-3G share the same footprint, their combination will enable similar measurements, but using $\sim 5,000$ clusters instead of 32, leading to an expected improvement in cosmological constraints by factors $\sim$ 5–10! Note that it will not be possible to achieve the same constraining power when combining SPT-3G with Rubin/LSST or *Euclid*. Given their poorer resolution or depth, these surveys cannot provide a comparable WL source density as Roman, thereby generally leading to less sensitive WL constraints. They especially lack measurements for a significant number density of distant ($z \gtrsim 1.5$) background galaxies, which is why they are not able to extend cluster mass constraints significantly beyond cluster redshifts $z \sim 1$. As a result, the combination of Roman/HLWAS and SPT-3G will be unique for studying cosmology with distant ($1 \lesssim z \lesssim 1.5$) clusters, which are especially powerful for testing cosmological scenarios beyond the standard ΛCDM model, such as non-Gaussian initial density fluctuations (Verde 2010) or early dark energy (Klypin et al. 2021), which has been proposed as a solution to resolve the Hubble tension (Poulin et al. 2019).

**Cluster astrophysics:** The combination of Roman/HLWAS and SPT-3G will probe the astrophysics of galaxy clusters via multiple routes. First, the measurements of mass, gas, and stellar profiles constrain baryon feedback models as described above. The underlying astrophysics models can additionally be tested by constraining cluster mass-observable scaling relations and comparing results to predictions from hydrodynamical simulations (Le Brun et al. 2014). The combination of Roman/HLWAS and SPT-3G data cannot only measure profiles and global properties, but will additionally provide maps of the 2D distribution of dark matter, stellar mass, and hot gas in massive clusters, enabling investigations of their dynamical state and the identification of special configurations, such as mergers or relaxed systems. Finally, the data combination will be unique in order to study the era of cluster formation (at $2 \lesssim z \lesssim 3$, see Fig. 2): Here SPT-3G will discover the first massive matter halos hosting a hot intra-cluster medium, for which Roman/HLWAS provides high-resolution imaging to study the first generation of cluster galaxies.

**Further comments on the HLWAS survey design:** The proposed science requires a deep HLWAS weak lensing survey covering all or most of the footprint of the SPT-3G Main Survey (see Fig. 2). Importantly, sufficient depth is required for sensitive WL shape measurements of faint high-$z$ sources (equivalent to at least single-orbit depth with *Hubble* in a broad-band filter). In order to select high-redshift WL source galaxies, NIR imaging is essential. A particularly efficient approach was demonstrated by Schrabback et al. (2018b), who combine high-resolution $K_\mathrm{s}$-band imaging (which also provides the WL shapes) with very deep $g + z$-band photometry for a galaxy selection in $g - z$ versus $z - K_\mathrm{s}$ color-color space. An equivalent strategy could be provided by a deep Roman $K$-band survey (or $H$-band if $K$-band is not available), complemented with deep Rubin optical photometry. Alternatively, measurements in multiple Roman filters could be combined. Note that high-redshift WL studies using NIR-selected source samples also benefit from lower WL shape noise and a more accurate calibration of the source redshift distribution compared to analyses using optically selected samples (Schrabback et al. 2018b).

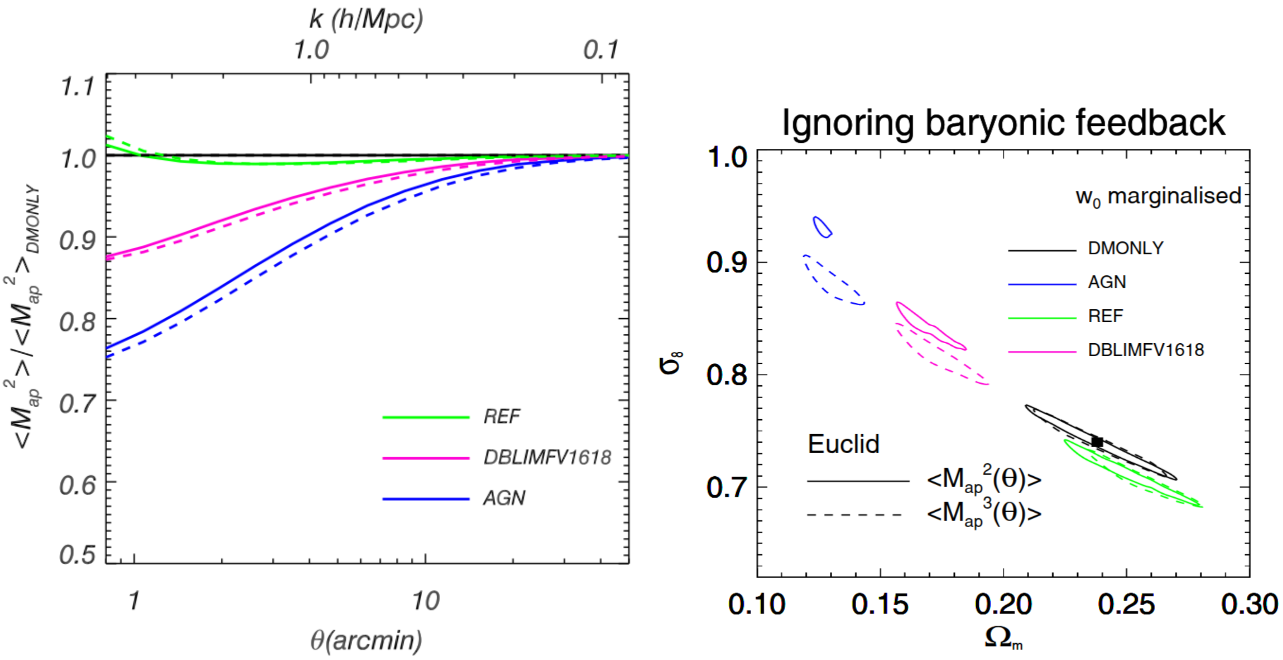

Figure 1: **Left:** Ratio of the signal for one weak lensing statistic (dispersion $\langle M_{\rm ap}^2\rangle$ of the aperture mass) measured in three different hydro-dynamical simulations with differing baryon feedback prescriptions to a reference dark matter-only simulation. At small scales (1 arcmin) a $\sim 20\%$ suppression occurs in a hydro-dynamical simulation with AGN feedback ("AGN"), while only a minor effect is seen for the "REF" simulation without AGN feedback (from Semboloni et al. 2013). **Right:** The solid contours show $1\sigma$ constraints that would be inferred from a next-generation weak lensing survey (here Euclid, similar for Roman HLWAS). The black square marks the input cosmology, which would be correctly recovered in the case of no baryon feedback (black contour). The colored contours show how the inferred cosmological parameters shift when the WL signal measured from the different hydro-dynamical simulations is modeled using standard predictions without baryon feedback. Accordingly, the shift compared to the black contours indicates the bias in cosmological parameters that would be caused if the impact of baryon feedback was ignored (from Semboloni et al. 2013).

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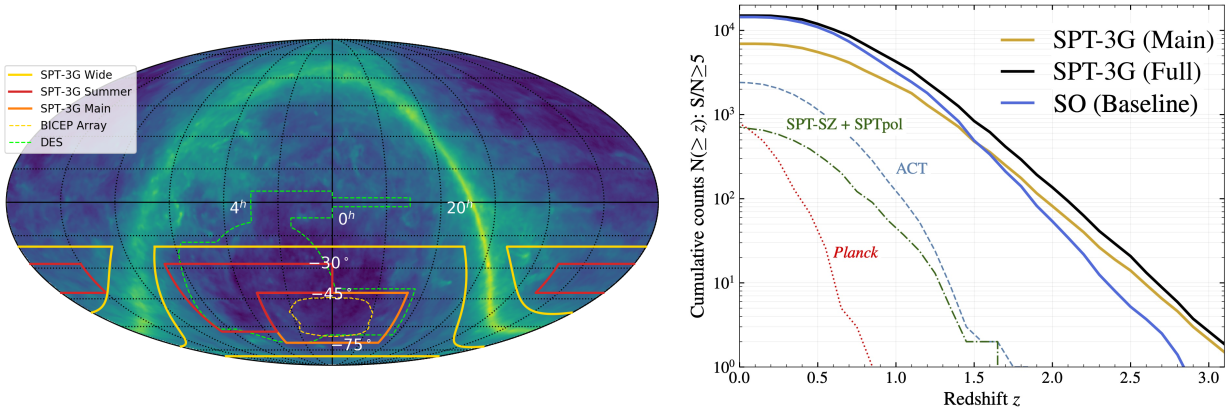

Figure 2: **Left:** Mollweide view of the three SPT-3G surveys, totalling 10,000 deg$^2$, including the ultra-deep 1500 deg$^2$ Main field, which is already measured to a noise level unprecedented for a wide-area, high-resolution CMB survey and nearly 20 times lower than the *Planck* satellite. **Right:** Expected number of clusters detected above a given redshift for the Main and Full SPT-3G surveys (for more details on method, see Raghunathan 2022). The SPT-3G catalog contains more clusters at high redshift than any currently forecasted pre-CMB-S4 experiment, including the baseline forecast for the under-construction Simons Observatory (SO).

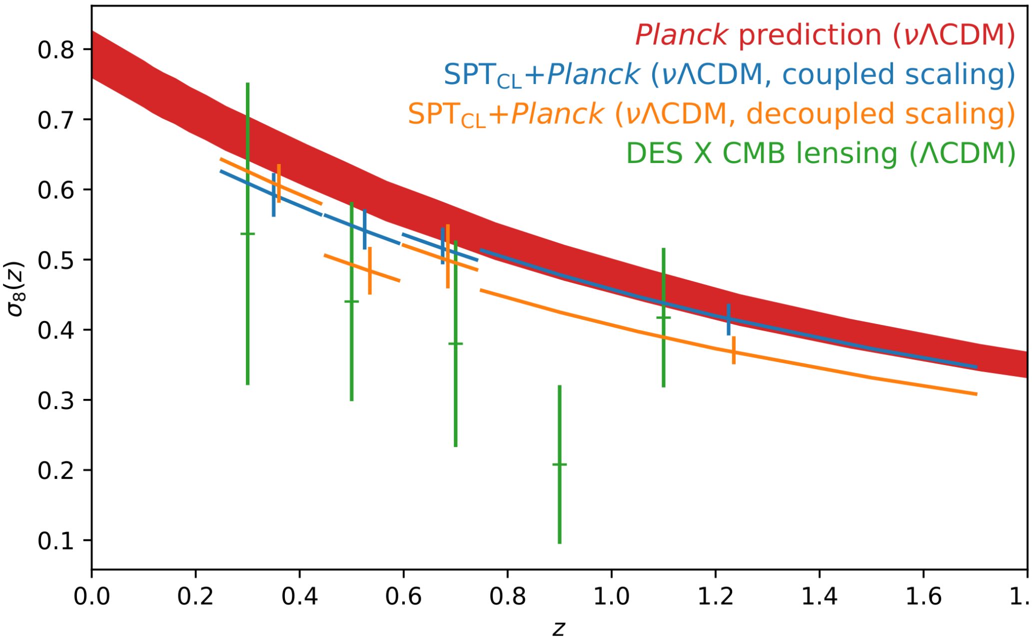

Figure 3: *Planck* $\Lambda$CDM estimate (red) of the redshift-dependent normalization $\sigma_8(z)$ of the matter fluctuation power spectrum compared to constraints from SPT-SZ cluster number counts and WL measurements from 32 clusters (Schrabback et al. 2018a; Dietrich et al. 2019), split into redshift bins (orange, *Planck* data inform the expansion history but not $\sigma_8(z)$). This provides a non-parametric test for redshift-dependent deviations of the growth of structure from $\Lambda$CDM predictions (figure from Bocquet et al. 2019). The combination of Roman/HLWAS and SPT-3G data is expected to tighten constraints on $\sigma_8(z)$ to the $\sim$ 1–2%-level out to redshift $z \sim 1.5$.

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