National Aeronautics and Space Administration

Cosmology with the low and high redshift Universe

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Program: SURP

Motivation:

The most recent history of the Universe experiences a phase of accelerated expansion (see Fig.1), a completely unexpected behavior indicating new and to date undiscovered physics.

Possible Explanations:
- Vacuum energy density (dark energy, cosmological constant)
- Time-dependent scalar field (time-dependent dark energy)
- Modifications to General Relativity (modified gravity)

Method of exploration:

1. Cosmic acceleration is best measurable at low redshifts using galaxy weak lensing and galaxy clustering.
2. CMB is a high redshift phenomenon and its primary measurements (temperature and polarization) are only marginally sensitive to cosmic acceleration,.
3. However, the CMB is lensed by low redshift structures and this so-called CMB-lensing (Fig. 2) is sensitive to cosmic acceleration.
4. The low redshift Universe also imprint signatures on the CMB, for example through the kinetic Sunyaev-Zeldovich (kSZ) effect.

Idea:

- ➢ Combine high and low redshift probes, i.e. primary CMB, CMB lensing, weak lensing of galaxy shapes, and clustering of galaxy positions, and secondary anisotropies like the kSZ.

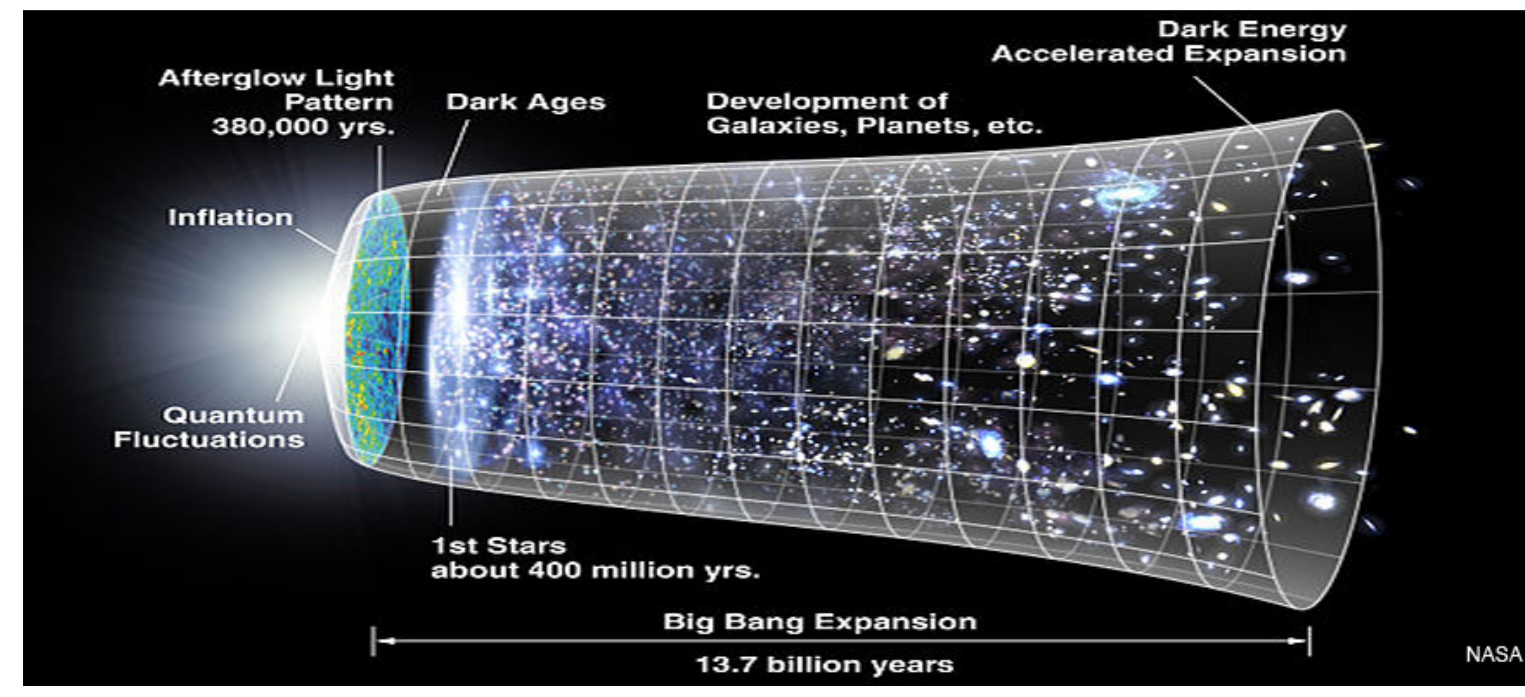

Figure 1: Timeline of the Universe from the early phases of inflation and the Cosmic Microwave Background to today's state of cosmic acceleration.

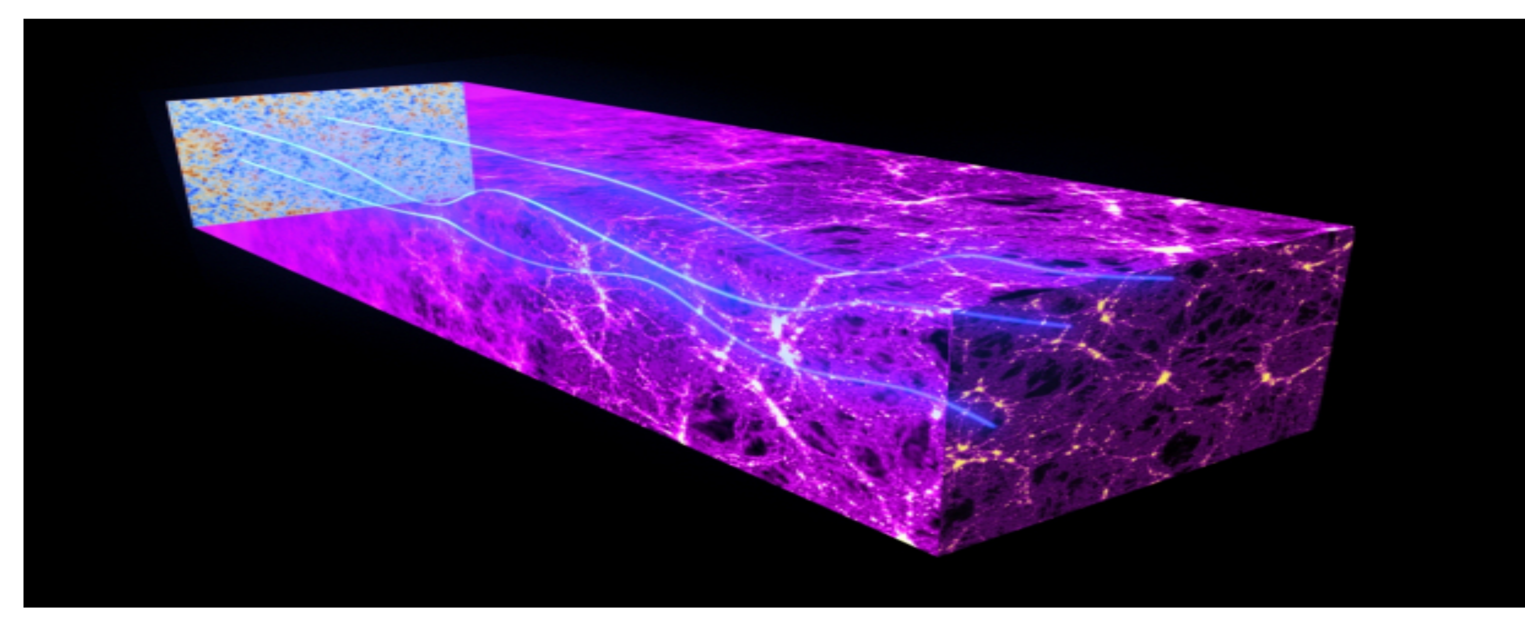

Figure 2: CMB photons (indicated through blue rays above) are lensed by the structure of the Universe as they travel through the tidal field of the Universe's (dark and luminous) matter. CMB lensing is sensitive to cosmic acceleration physics.

Results:

1. In the past years, we have developed an analysis framework for a joint analysis of high and low redshift observables.
2. We have the unique ability to account properly for all correlations across the different cosmological probes.
3. We simulate a likelihood analysis for Dark Energy Survey (DES) Year 1 data and early CMB data from the South Pole Telescope (SPT) (Fig. 3 left)
4. Capabilities 1-3 were employed in an early version of a joint high and low redshift analysis (DES collaboration 2018) which will substantially improve over the coming years.
5. We decided this year to extend to 21 cm, CO, or [CII] intensity mapping survey such as HIRAX, CHIME, TIME, and COMAP which are a good match in redshift to CMB lensing. We are currently adapting the methodology of Sugiyama et al. 2017 to these observables to devise new cosmological probes at high redshift.

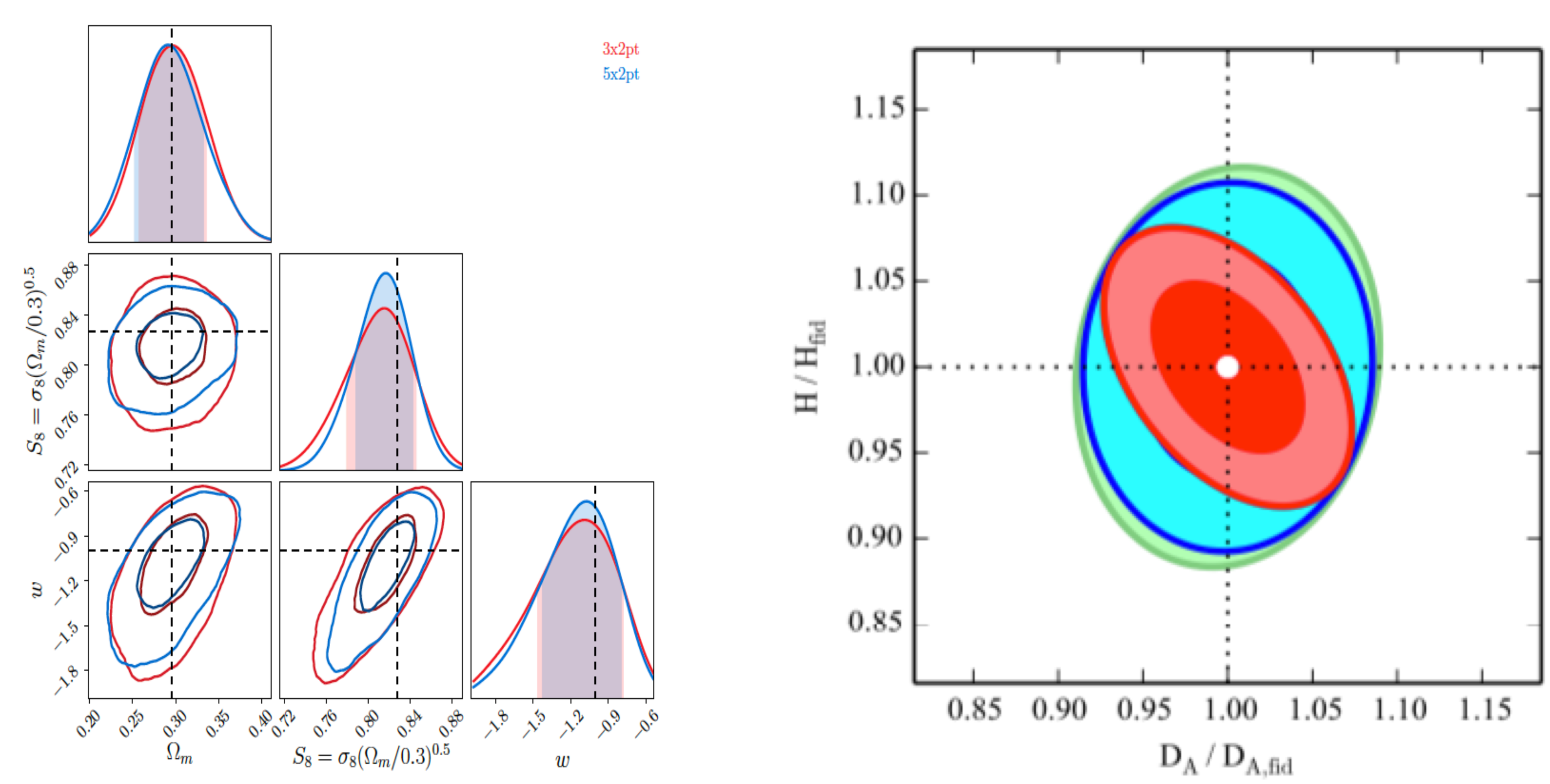

Figure 3: *Left:* Forecasted constraining power for a DES Y1+SPT(early data) analysis (blue contours) compared to the DES Y1 only analysis (red). *Right*: Confidence contours (1- and 2-σ colored ellipses) placed on all pairs of parameters derived from Fisher matrix analysis from the galaxy+kSZ (red regions) and galaxy-only (green regions) information are shown. The galaxy+kSZ information improves the galaxy-only constraints for the growth rate f(z), the expansion rate H(z), and the effective optical depth τT. (from Sugiyama et al. 2017)

Benefits to NASA and JPL:

- Developed capability to run joint analyses of CMB primary, CMB lensing, weak lensing, kSZ, and galaxy clustering surveys in the context of cosmic acceleration and cosmology.
- Important to forecast and optimize the science return of future NASA missions and concept studies, such as Euclid, WFIRST, LSST in combination with the CMB-Stage 4 experiment or a possible NASA. CMB polarization mission such as the PICO probe concept under study.
- Near term application to existing data from DES, SPT, Atacama Cosmology Telescope (ACT), TIME, COMAP, and CCAT.

Publications:

- Elisabeth Krause, Tim Eifler et al 2017: "Dark Energy Survey Year 1 Results: Multi-Probe Methodology and Simulated Likelihood Analyses." arXiv:1706.09359
- Abbott et al. 2018 (incl. Eifler) "Dark Energy Survey Year 1 Results: Joint Analysis of Galaxy Clustering, Galaxy Lensing, and CMB Lensing Two-point Functions" arXiv:1810.02322
- Sugiyama et al., "Will kinematic Sunyaev-Zel'dovich measurements enhance the science return from galaxy redshift surveys?", Journal of Cosmology and Astroparticle Physics, Issue 01, article id. 057 (2017)

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