CF6 Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities

Conveners:
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CF6: White Papers on Combined Probes, and Summary of New Facilities for Dark Energy (science motivation and description in subgroups)

White papers submitted to CF6 on combined probes:

- ”Opportunities from Cross-survey Analyses of Static Probes”, Eric J. Baxter, Chihway Chang, Andrew Hearin, Jonathan Blazek, Lindsey E. Bleem, et al. arXiv:2203.06795.
- ”Multi-Experiment Probes for Dark Energy – Transients“, Alex G. Kim, Antonella Palmese, Maria E. S. Pereira, Greg Aldering, Felipe Andrade-Oliveira, et al. arXiv:2203.11226.

Many facilities motivated and discussed in CF3,4,5 white papers (https://snowmass21.org/submissions/cf) for example:

- “Observational Facilities to Study Dark Matter” arXiv:2203.06200 (not just DM)
- ”CMB-S4 White Paper” arXiv:2203.08024
- ”Rubin Observatory after LSST”, arXiv:2203.07220
- Optical redshift surveys: DESI-II, FOBOS, MSE, MegaMapper, SpecTel arXiv:1907.11171
- ”21cm Radiation as a Probe of Physics Across Cosmic Ages ”, arXiv:2203.07864
- ”Future Gravitational-Wave Detector Facilities”, arXiv:2203.08228
- “Data Preservation for Cosmology “ arXiv: 2203.08113

Outline of CF6 report

1) Executive summary
2) Introduction
3) Optical Near IR Surveys and Facilities
    a) Rubin - operations will begin soon
    b) DESI - operations in progress - proposal to extend to DESI - II
    c) Future Widefield Multi-object spectroscopy - many options
    d) Complementarity - critical to maximize scientific reach
4) CMB
    a) CMB-S4 (from previous P5, joint NSF-DOE, has DOE CD-0 approval, funding limiting CD-1)
    b) Next generation CMB exp. : e.g. CMB-HD ~ 3x detectors, 6x resolution CMB-S4
5) Opportunities for Cross Survey Analysis - maximize scientific reach
    a) Static Probes
    b) Transient probes
6) Small Projects and Pathfinders: Spectroscopy, LIM, 21-cm
7) Multi-Messenger Probes: GW provide new powerful constraints on cosmology

Status of CF6 report

Writing was open to all CF6 contributors, draft submitted June 28

Google doc collecting comments:
https://docs.google.com/document/d/1f2m7oOfqjL4EgT-eQheGDHtT-H47AMIGX9QxVz6bE9I/edit?usp=sharing

Recommendations: Near-term facilities

- Given the pivotal role of CMB experiments in the landscape of particle physics and cosmology, and their phenomenal successes thus far, **we advocate for continuing the CMB program through strong support of the near-term construction and operation of CMB-S4**, crossing critical, motivated thresholds in the searches for inflationary gravitational waves and new particle species.
- **We advocate for the continued operations of DESI (DESI-II)** as an important part of the spectroscopic roadmap while a Stage V spectroscopic facility is designed and built.
- **We advocate for support of small- and medium-scale projects that enhance the science reach of studies of transients discovered by Rubin LSST and "standard sirens" detected by gravitational wave facilities.** Data from these projects will be combined with infrastructure that enables cross-experiment coordination and data transfer for time-domain astronomical sources and a US-HEP multi-messenger program with dedicated target-of-opportunity allocations on US-HEP and partner facilities.

Recommendations: Longer-term facilities

- Through the Snowmass2021 process, the HEP community has identified the pressing need for next- generation wide-field, massively multiplexed spectroscopic capabilities to complement LSST imaging. **We strongly advocate for the establishment, support and start of construction of a Stage V spectroscopic facility** in the coming decade.
- Recognizing the wealth of fundamental physics that can be probed by a much higher resolution and lower noise wide-area CMB survey, **we strongly advocate for support of design studies of the ~~CMB-HD concept~~** to bring it to technical and construction readiness for the next decade.
  Stage V CMB
- New approaches such as millimeter and 21-cm line-intensity mapping (LIM) hold the promise of exceptional cosmological constraining power. However, the technological readiness of these programs must be further demonstrated before the community is prepared to invest fully in a large-scale project using these technologies. Thus, we **recommend a coordinated program of R&D to advance the technical readiness of these projects**.

Recommendations: Complementarity

- No single experiment can reveal the nature of dark energy. Such a breakthrough will require data from a network of experiments, small and large, working in tandem to probe the early- and late-time Universe. At present, cross-survey analyses are challenging to initiate, organize, and fund. **We advocate for the creation of clear pathways to support cross-survey analyses as part of the core mission of the HEP Cosmic Frontier.**

  … including joint analysis tools and shared simulations

- Multi-messenger measurements of gravitational wave events are an emerging complementary technique for probing cosmology through standard sirens. **Support for coordination with future large facilities (such as the European Einstein telescope) will enable maturation of this novel technique for measuring dark energy.**

CF6 Figure 1 - Facilities

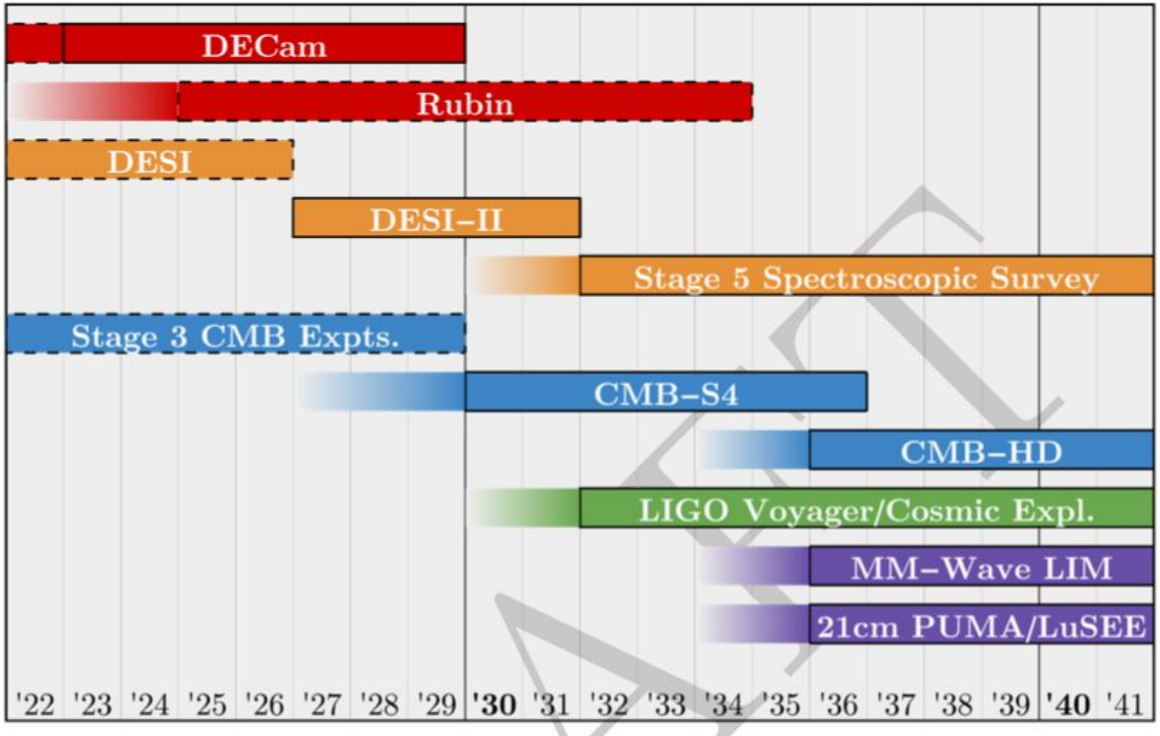


Figure 6-1. *Current and potential future facilities probing cosmic acceleration that are or may be supported by the HEP Cosmic Frontier. Dashed boxes indicate fully-funded facilities. Facilities in red are optical imaging, in orange are optical spectroscopy, in blue are CMB, in green are gravitational waves, and in purple are radio/mm spectroscopy. The fade-in regions indicate commissioning periods, while the solid boxes indicate full survey observations.*

Fig credit: Neelima Seghal

CF6 Figure 2 - Complementarity

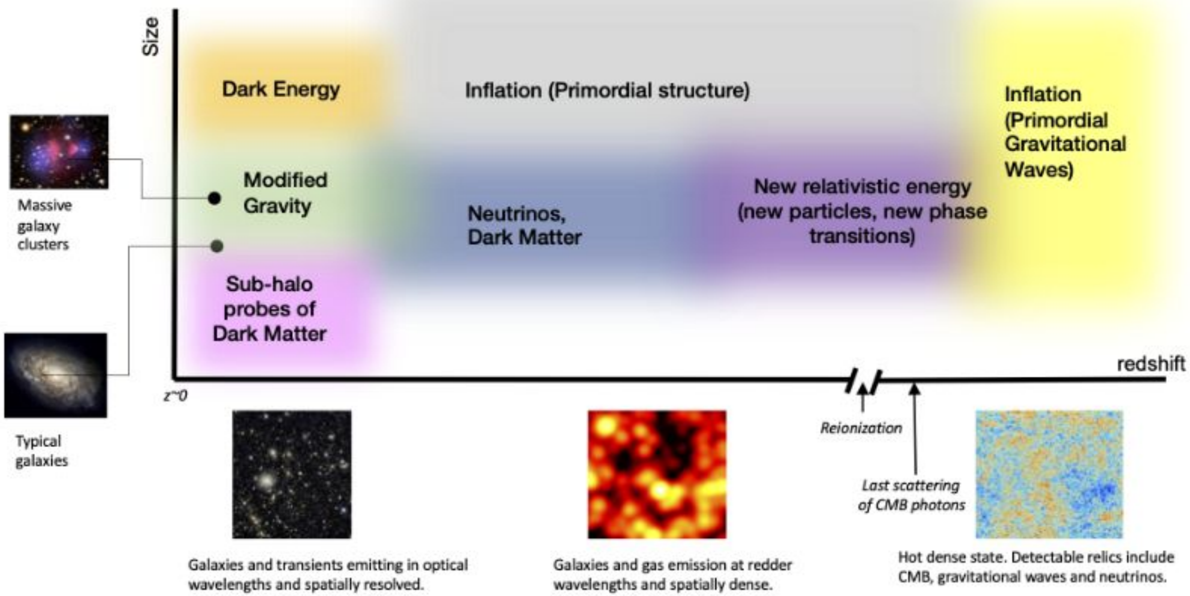


Figure 6-2. *Key scientific opportunities in HEP targeted by cosmic survey facilities. The colored areas illustrate regions in spatial scale and redshift favored for various scientific targets. Dark Energy and modified gravity favor measurements at lower redshift at large-to-moderate spatial scales. Inflationary signals are best explored at the largest spatial scales. Small-scale, low-redshift surveys explore dark matter in the sub-halo regime, and precision measurements of the matter power spectrum at moderate-to-small scales out to high redshift are sensitive to neutrinos, dark matter, and new relativistic energy in the early Universe. Each independent technique explores and constrains a broad set of physics, while the full suite has multiple complementary measurements providing robust results.*

Fig credit: Clarence Chang

CF6 Figure 3 - Complementarity

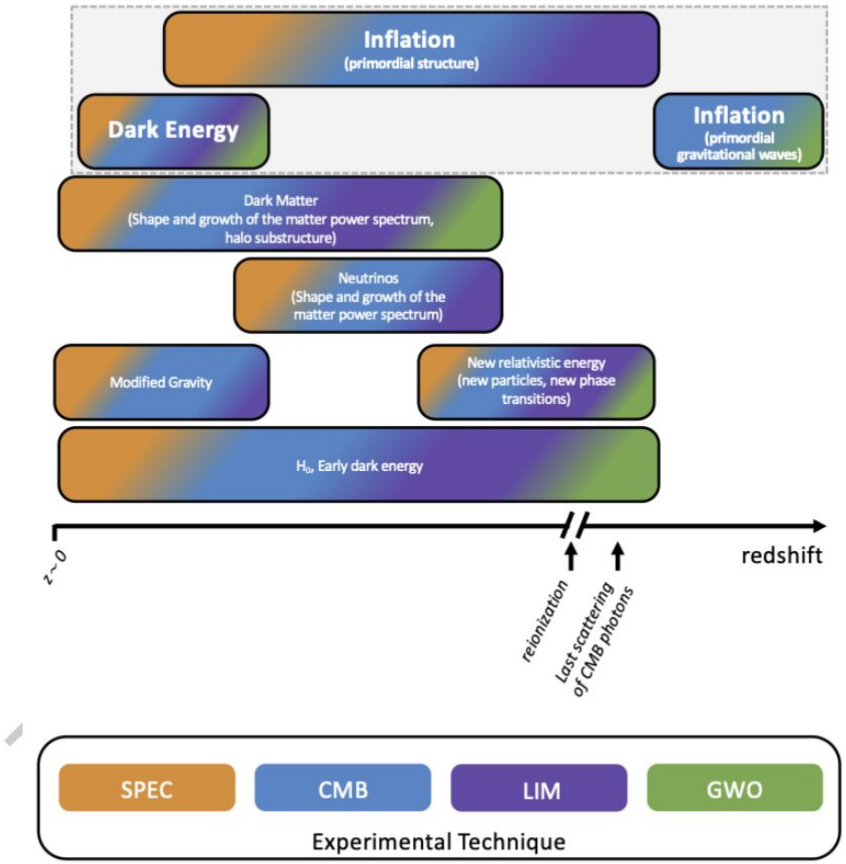


Figure 6-3. *A simplified summary of the key scientific opportunities. The horizontal extent of each box corresponds to the redshift of the tracer, while the coloring indicates the experimental technique used to*

Fig credit: Amy Bender

CF6 Figure 4 - Optical/IR survey facilities

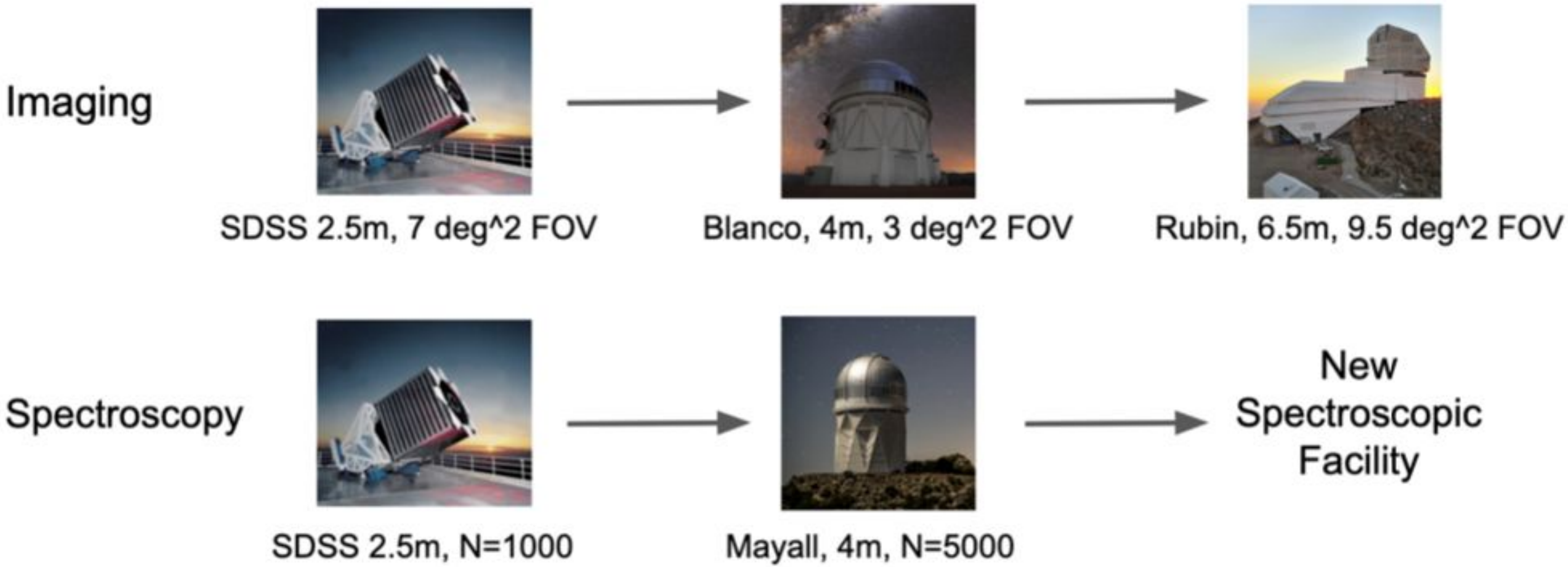
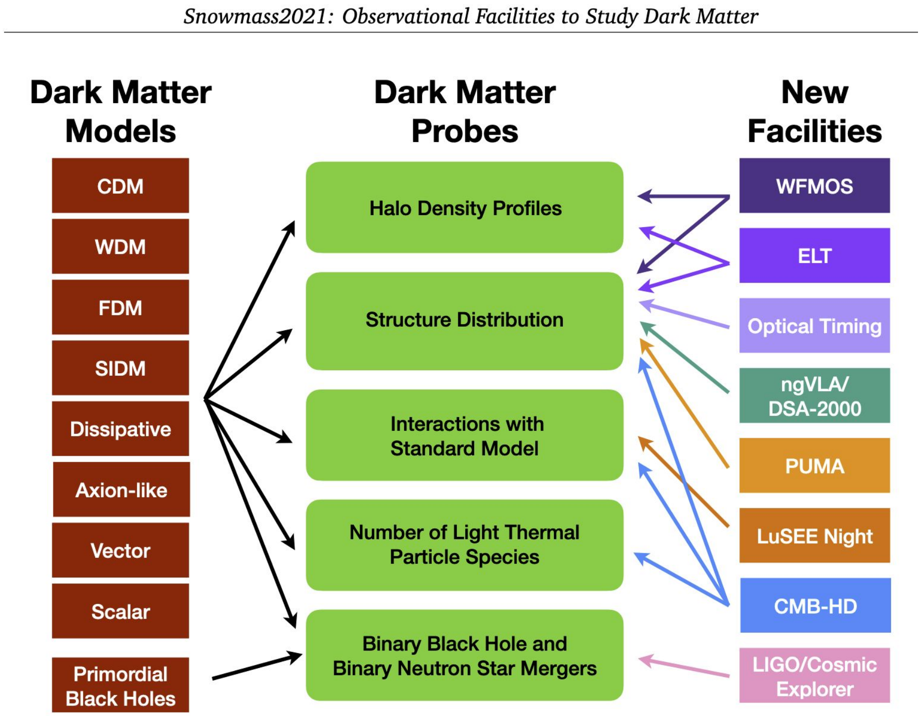


Figure 6-4. *Summary of imaging and spectroscopic surveys and facilities, ongoing and planned, that are supported by DOE/NSF partnerships. The international ground and space-based landscape of optical wide-field surveys, ongoing and planned, is very rich but for clarity is not represented here. SDSS had both imaging and spectroscopic capabilities, the Blanco telescope was used to carry out the DES, and the Mayall is currently used for DESI. In the near future, the Rubin Observatory will begin LSST. A new spectroscopic facility would open up new scientific opportunities.*

Observational Facilities for Dark Energy and Cosmic Acceleration Overlap with Dark Matter Facilities (2203.06200)

- Emphasis on complementarity with dark energy, neutrino physics and inflation science
- Many of the facilities for Dark Energy and Inflation would also be capable dark matter probes



Observational Facilities to Study Dark Energy & Inflation

Upgrading/repurposing facilities

- Dark Energy Camera
- Rubin (arXiv:2203.07220)
- DESI
- CMB-S4

Future facilities – most of these would be dual-purpose

- Dark energy & inflation, ***and***
- Cosmic probes of dark matter

arXiv:2203.06200

Snowmass2021: Observational Facilities to Study Dark Matter

Facility	Type	Reference	Section
Cosmic Microwave Background-High Definition (CMB-HD)	CMB (mm)	[15]	§ V B
next-generation Very Large Array (ngVLA)	radio (mm-cm)	[16]	§ VI B
Deep Synoptic Array-2000 (DSA-2000)	radio (cm)	[17]	§ VI B
Lunar Surface Electromagnetics Experiment (LuSEE) Night	21 cm (m)	[18]	§ VII B
Packed Ultrawideband Mapping Array (PUMA)	21 cm (cm)	[19]	§ VII C
Thirty Meter Telescope (TMT)	optical/near-IR	[20]	§ VIII B
Giant Magellan Telescope (GMT)	optical/near-IR	[21]	§ VIII B
Dark Energy Spectroscopic Instrument II (DESI-II)	optical	[22]	§ VIII C 1
MegaMapper	optical	[23]	§ VIII C 2
Maunakea Spectroscopic Explorer (MSE)	optical/near-IR	[24]	§ VIII C 3
SpecTel	optical/near-IR	[25]	§ VIII C 4
Cosmic Explorer	gravitational wave	[26]	§ IX B
LIGO Voyager	gravitational wave	[27]	§ IX C

TABLE I. Future astrophysical facilities for dark matter science.

Opportunities using Static Probes: **2203.06795**

Combining probes provides powerful cosmological constraints

- Future large data sets present opportunities and challenges
- Coordinate overlap of survey footprints, i.e. extending LSST footprint to overlap existing and future redshift surveys
- Need to move from independent isolated surveys that only combine at the end (cosmological parameters) to coordinated analysis
- Joint Modeling and analysis: coordination of survey strategies, choices in modeling systematics, agreements for data sharing
- Joint Simulations: data sets need to be very large. Should serve multiple probes
- Archival storage of large unique data sets for future analysis
- Compute resources and access to supercomputers
- New initiatives (funding) needed to encourage cooperation between collaborations on combined probes: Cosmic Analysis Centers

CF6 Figure 6

Snowmass2021: Opportunities from Cross-survey Analyses of Static Probes

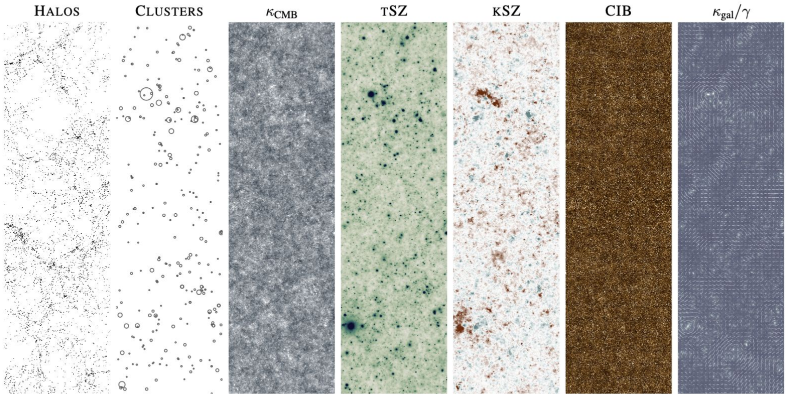


FIG. 1. Simulated maps of the same patch of the Universe, as measured with several different cosmological probes (from left to right): dark matter halos (detectable via the galaxies they host), galaxy clusters (with the size of the circles indicating the cluster mass), gravitational lensing of the CMB ($\kappa_{\rm CMB}$), the thermal Sunyaev Zel'dovich effect (tSZ), the kinematic Sunyaev Zel'dovich effect (kSZ), the cosmic infrared background (CIB), and gravitational lensing of galaxy shapes (shading indicates the convergence, $\kappa_{\rm gal}$, while white lines indicate the shear, γ). Although each probe is very different, they are all sourced by the same underlying large scale structure, and are therefore correlated. Joint analyses of these different probes can yield access to new cosmological information about the underlying structure. Simulated data from Omori (in prep.).

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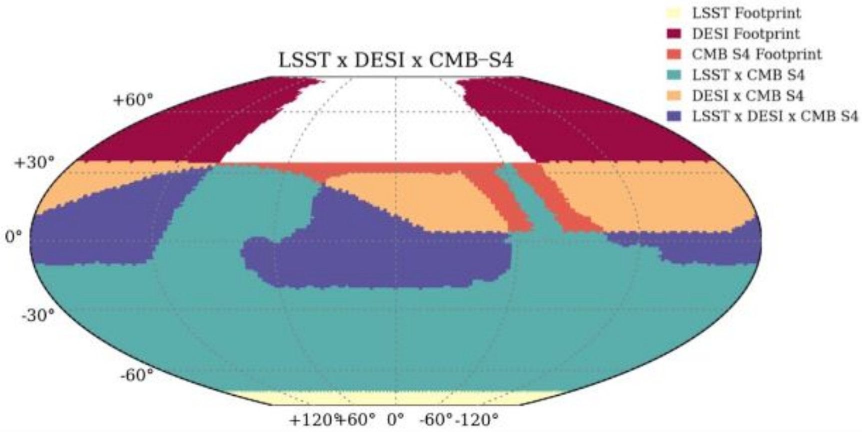

Transient constraints on Dark Energy: Multi-messenger, Multi-Experiment (2203.11226)

- Examples: new constraints on Hubble constant from detection of optical counterparts to GW detections and to strongly-lensed supernovae; follow-up Rubin SN detections; follow-up IceCube Neutrino Events
- Advocate for development of a US-HEP multi-messenger program:
  - Infrastructure to coordinate multiple facilities and data transfer
  - Repurposing (and support) of smaller (3-4m) telescopes for high-efficiency follow-up, search and discovery of GW and other transients
  - Theory and modeling to improve cosmological constraints
  - Develop agreements for dedicated target of opportunity observing across multiple facilities, negotiate schedules, develop decision process for target follow-up
  - Computing resources, access to High Performance Computing