Report from the Early and Late Universe:

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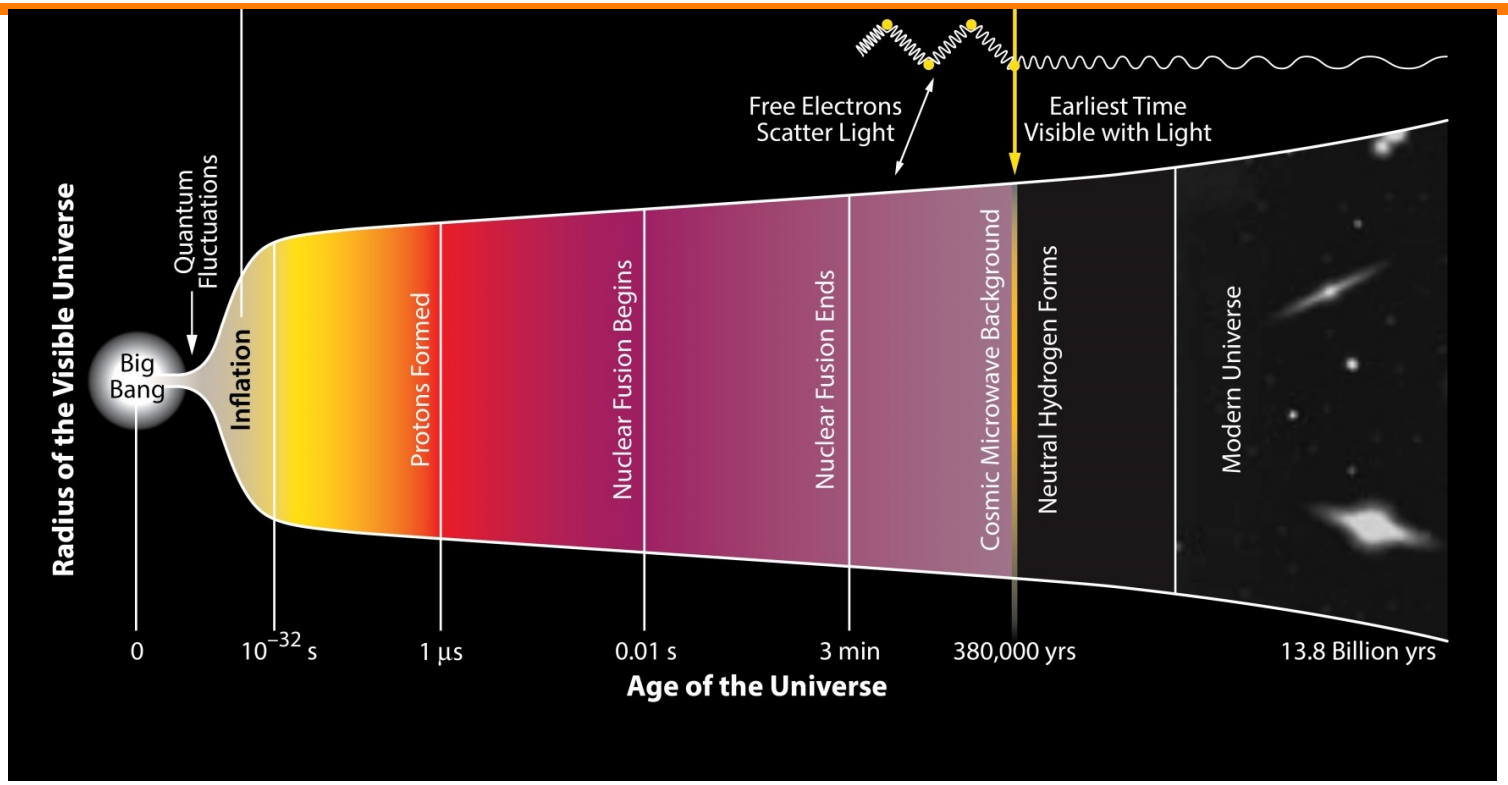
B. Benson, M. Niemack

Brief Introduction



- **Early Universe** (< 400,000 years)
  - Inflation (r to ~ 0.001)
  - Relativistic energy density (N_{eff} to ~ 1%)
- **Late Universe** (> 400,000 years)
  - Dark Energy
  - Neutrino Mass sum (to ~ 10 meV)

Cosmic Acceleration Projects in P5

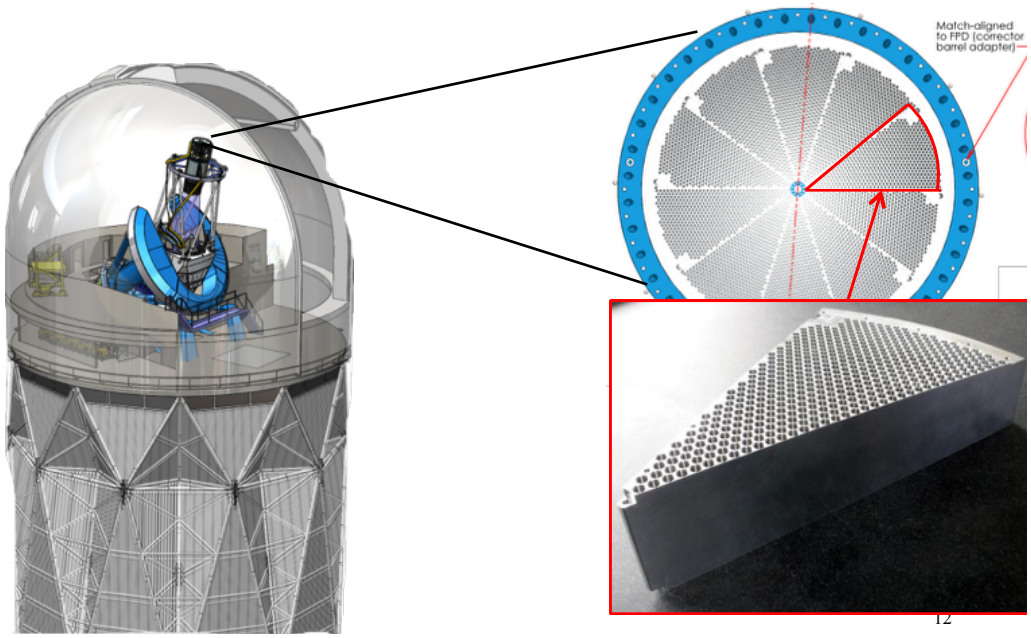
- **LSST**
  - optical photometric survey to probe late-time acceleration at CD3
- **DESI**
  - optical spectroscopic survey to probe late-time acceleration at CD2
- **CMB-S4**
  - Optimized to probe early acceleration (i.e., inflation) and neutrino density (i.e., number of neutrinos)
  - working towards CD0

- All projects measure late-time Universe, with sensitivity to neutrino mass and dark energy using different probes

LSST and DESI

- Technologies are already well-developed for each; projects at CD-3 and CD-2, respectively.

DESI Technologies



CMB-S4

- Primary technical challenge is scaling up of detector arrays
  - Need to scale up detector fabrication ~100x more than current Stage-3 experiments
- Detector readout needs to scale up commensurately, likely will require ~GHz bias frequencies
  - Readout development has strong synergies with TES and MKID detectors across multiple wavebands (mm-wave, optical, X-ray)
- Fabrication and readout have broad applications across fields: astronomy, cosmology, advanced light source, security applications, etc.
- R&D required to couple to detectors
  - Camera technologies: anti-reflection coatings, modulators, camera optics designs
  - High-throughput telescope designs

A Stage-5 Cosmology Experiment

- A Stage-5 cosmology experiment will have potential for significant scientific discovery
  - The universe has > 5 billion spatial modes, only ~100 million of which will be measured by LSST
- "Cosmic Visions" panel convened by DOE to help develop potential science case and possible techniques
  - Constraints on inflation from non-Gaussianity and flatness
  - Constraints on dark energy and gravity beyond Stage IV

Identification of Risks and Opportunities

- Measuring early cosmic acceleration is unique to CMB, U.S. is a world leader
- Synergy between cosmic projects: cross correlations between P5 experimental probes will be a powerful new test of physics
- Significant discovery potential: fundamental questions in the physics of dark energy, dark matter, inflation
  - Cosmological neutrino constraints have strong complementarity with terrestrial HEP experiments

Recommendations

- Prioritize development of technologies for CMB-S4 in collaboration with CMB university groups
- Develop fabrication facilities for superconducting detector arrays that could be used for a range of activities (CMB-S4, photon science, a Stage V cosmology project, dark matter, neutrino research, and others)
- Develop technologies for microwave readout of superconducting detectors (TES and KIDs) that can be applied to a similar range of science topics
- Explore techniques for next generation spectrometers for a Stage V cosmology survey
  - Integral field spectrometer with spectral resolution $R > 10^3$

Possible Grand Challenge Ideas

- **Leave no mode left behind*:*** Measure all modes in universe to understand both early and late acceleration
  - Define Stage V cosmology case spanning electromagnetic spectrum
- **Extract entire primordial information content of the CMB**