The Next 20 Years of Cosmic Observations

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Snowmass at Seattle
Stage-IV and Beyond

- Well-defined measurement goals
  - Dark Energy
  - Inflation
  - New physics from early Universe messengers

- Optical/IR spectroscopy, imaging, and Cosmic Microwave Background
  - Baryonic matter, dark matter, gravitational waves
  - Galaxy cluster to horizon scales
  - Current epoch to inflationary epoch

- Discovery potential
  - New techniques in development
  - High precision measurements across multiple probes
  - Consistency and tests for new physics
Galaxies emitting in optical wavelengths and spatially resolved.

Galaxies and gas emission at redder wavelengths and spatially dense.

Inflation (Primordial structure) Early Dark Energy

Modified Gravity

Neutrinos, hot dark matter, rate of structure growth

New relativistic energy (new particles, new phase transitions)

Astro. probes of Dark Matter

BAO scale and larger

Size of a galaxy cluster

Size (Mpc)

DESI/LSST

Acoustic Peak, Hubble constant

Inflation (Primordial Gravitational Waves)

Cosmic Discovery Space

CMB-S4

z^~0

z^~6

z^~1100

Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

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Cosmic Discovery Space: Stage-IV

Z~1100

Z~6

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Dark Energy

- Figure of Merit for Stage-IV dark energy surveys: From discovery to precision
  - Expansion history
  - Growth of structure

- vacuum energy
- new field
- beyond General Relativity
New Physics

- Early Universe versus late Universe: over-constrain direct $H_0$ measures to the percent level

[Diagram]

neutrino couplings
new particle or field
alternate model for dark energy

Credit: Henze/NASA
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Cosmic Discovery Space: CMB-S4

BAO scale and larger

Size of a galaxy cluster

Size (Mpc)

$10^3$

$10^2$

$10^1$

$z = 0$

$z = 6$

$z = 1100$

DES/LSST

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CMB-S4

Neutrinos, hot dark matter, rate of structure growth

Rate of structure growth

Cosmic Discovery Space: CMB-S4

BAO scale and larger

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Inflation

- Determine tensor-to-scalar ratio at threshold $r=0.001$: the energy scale of inflation

$r>0.003$: Super-Planckian field excursion, shift symmetry in quantum gravity

$r>0.001$: simplest models of inflation with characteristic scale $> M_{\text{Planck}}$.

$r<0.001$: Small field inflation with spontaneous symmetry breaking
Inflation

- Direct detection of gravitational waves: Synergy with gravitational wave observatories

- inflaton coupling to a gauge field
- new pre-radiation dominated epoch
- alternatives to inflation
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Cosmic Discovery Space: Stage-V

OIR spectroscopic survey

BAO scale and larger

Size of a galaxy cluster

DESI/LSST

Acoustic Peak, Hubble constant

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Size (Mpc)

10^3

10^2

10^1

10^0

redshift

z^-0

z^-6

z^-1100

DESI/LSST

CMB-S4
Stage-V Spectroscopic Survey

- Massively multiplexed spectrograph on large aperture telescope
  - 10X++ improvement in survey speed over current facilities
  - 10X++ increase in z>2 sample size
  - Samples at z<1.5 near sample-variance limit to single halo scales

- DESI → Stage-V roadmap
  - Establish and characterize z>2 samples
  - High precision BAO and RSD at z>2
  - Development of structure growth measurements in limit of high density clustering at z<1

- Imaging and CMB
  - Weak lensing, galaxy-galaxy lensing, target selection, galaxy clusters from Rubin
  - Lensing, Sunyaev-Zel’dovich, amplitude of clustering, optical depth from CMB
  - Full constraints only possible with full suite of measurements
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Cosmic Discovery Space: non-Gaussianity

DESI/LSST z~1100 z~6 z~0

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Inflation

- Measure fNL local to 0.2 precision: dynamics of inflation

Local: single or multi-field inflation
Orthogonal: excited states
Equilateral: inflaton/particle interactions

Dalal et al., 2008
Dark Energy

- Baryon acoustic oscillations and the redshift/distance relation at $z>2$

- Early dark energy
- Non-zero global curvature
- Tension in concordance model
Dark Energy

- Decadal Survey: Measure $\sigma_8$ (growth of structure) to 0.2% precision

- New properties of dark matter
- New fields or interactions
- Modifications to General Relativity

Amon and Efstathiou, 2022
Inflation and New Physics

- High precision power spectrum measurements: 1-2 order of magnitude improvement in search for departures from scale invariance in the inflationary field

10^{-22} \text{ eV axion-like particles}

early universe particle production

periodic corrections to potential
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z~0

z~6

z~1100

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New Physics

- Snowmass 2013: Measure sum of neutrino masses to 15 meV precision

![Graph showing absolute neutrino mass, inverted or normal hierarchy, and new massive particles or dark sector interactions]

Snowmass neutrino white paper, 2022
New Physics

- Early radiation content to precision $\sigma(\text{Neff})=0.027 \rightarrow$ tests beyond standard model

- Particle contents since inflation
- Axion and axion-like particles
- Thermalized dark sector with more than 5 degree of freedom
Cosmological Observations: the next 20 years

- Vast discovery space available
  - Dark Energy across cosmic time
  - Multi-dimensional tests of inflation
  - Neutrino masses, new particles, and new interactions

CF4 - CF7 roadmap to these discoveries