Fundamental Physics from Galaxy Surveys

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Cosmology – a Beyond Standard Model Experiment

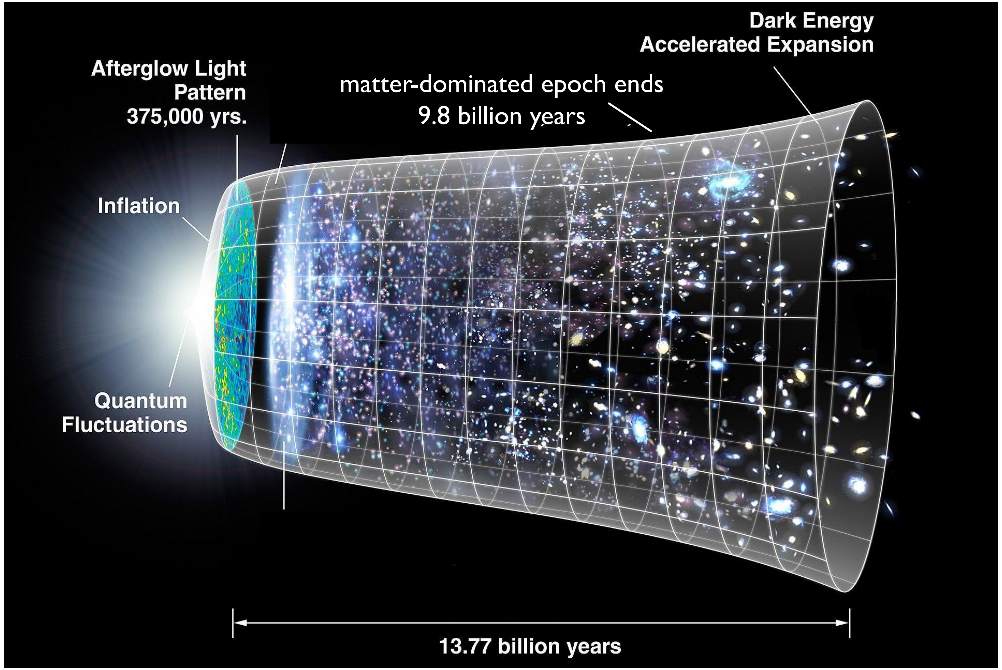
The ΛCDM model accurately describes a broad range of cosmological observations at the 10% level and in many cases at the 1% level or better.

It requires

- initial conditions created by **inflation,**
- **dark matter, dark energy** to describe expansion history and growth of structure,

which all are beyond standard model physics.

adapted from NASA/WMAP



Cosmology – a Beyond Standard Model Experiment

The standard cosmological model in simplest form assumes:

- GR is the correct theory of gravity on cosmic scales
- Dark matter is weakly interacting and cold
- Dark energy is constant in space and time
- Primordial fluctuations come from single-field, slow-roll inflation with a simple potential
- The only "light" degrees of freedom are 3 neutrino species.

Clear departures from any of these assumptions would be a major breakthrough in fundamental physics and cosmology.
Departures can be sought by sharpening the precision of observations, extending to new ranges of redshift and scale, or measuring new phenomena.

Galaxy Survey Landscape

Photometric surveys

image the sky → angular coordinates

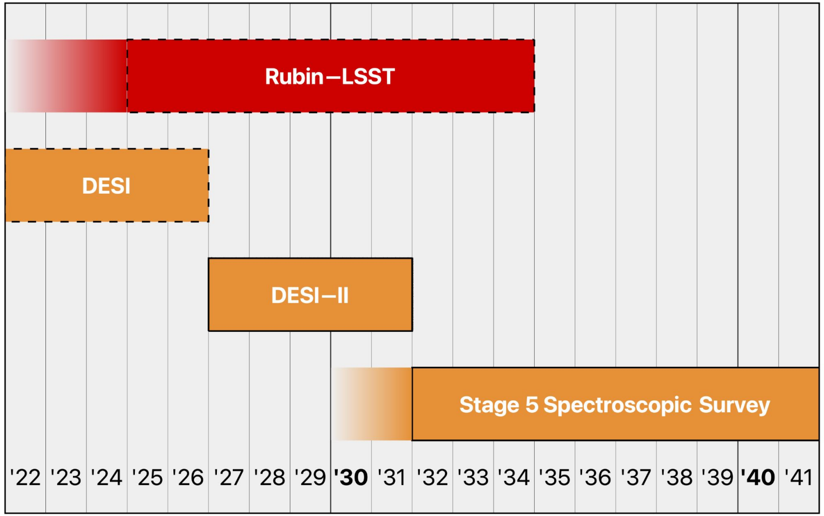
multiple filters → galaxy colors, estimates of redshift/radial coordinates

Spectroscopic surveys

spectra for target galaxy samples → redshifts

This session: ground-based, US-led projects.

Current surveys (Rubin-LSST/DESI) complemented by near-term space missions (ESA's Euclid, NASA's Roman & SPHEREx) and international ground-based projects (ESO's 4MOST, Japan's PFS surveys).



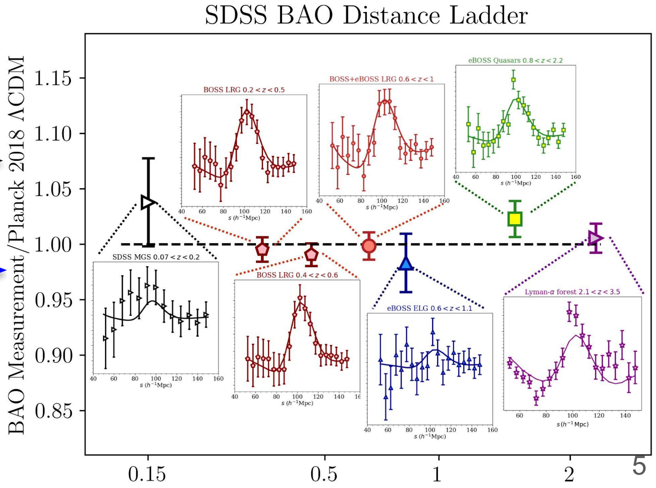
Current and potential future optical surveys probing cosmic acceleration that are or may be supported by DOE and/or NSF. Dashed boxes indicate fully-funded experiments.

Adapted from CF6 report.

Observational Cosmology: Expansion History

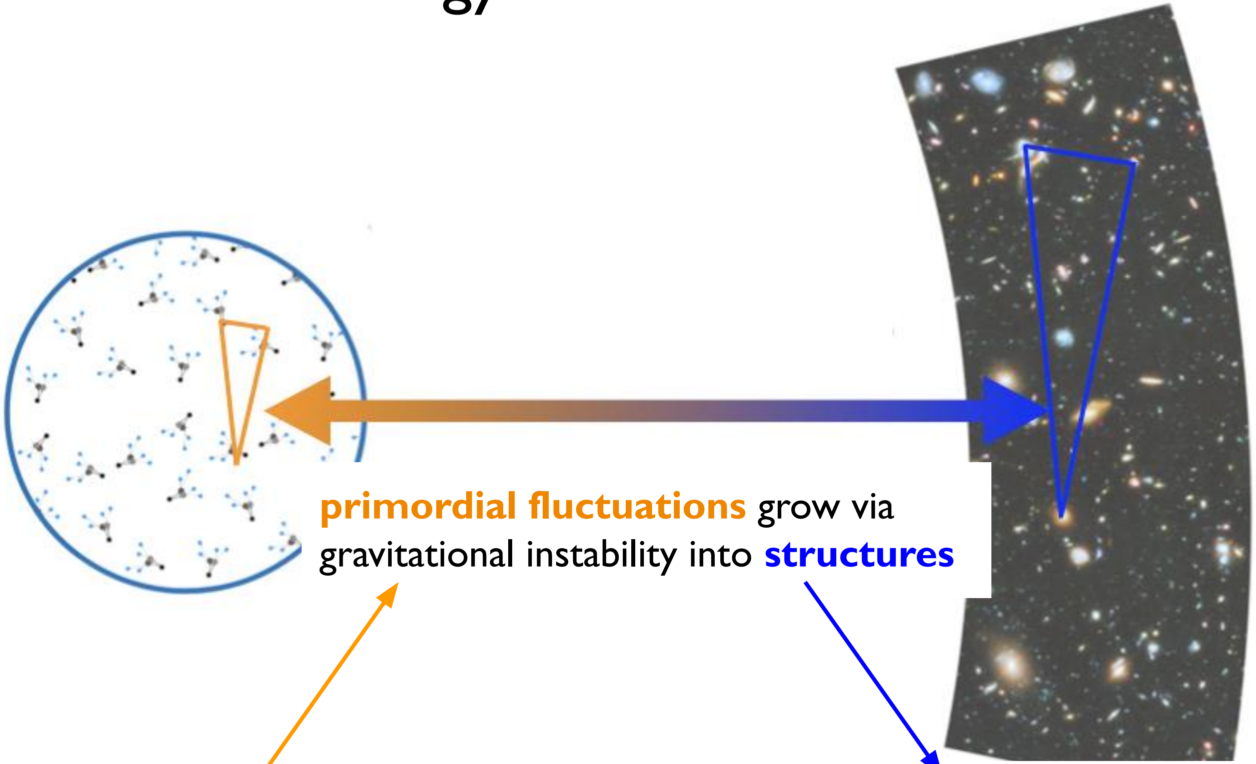
Measure distance-redshift relation:

- **Standard candle:** brightness of source with known luminosity.
    - Type Ia supernovae: apparent brightness of exploding white dwarfs with ~known intrinsic luminosity.
- **Standard ruler:** angle subtended by known scale.
    - Cosmic Microwave Background (CMB): angular scale of sound horizon in the early Universe.
    - Baryonic Acoustic Oscillations (BAO): angular scale of sound horizon imprinted in the late-time galaxy distribution.



Credit: Ashley J. Ross and SDSS

Observational Cosmology: Growth of Structure



primordial fluctuations grow via gravitational instability into **structures**

configuration of **quantum fluctuations** during **inflation**

distribution of **galaxies** in the **late Universe**

Observational Cosmology: Growth of Structure

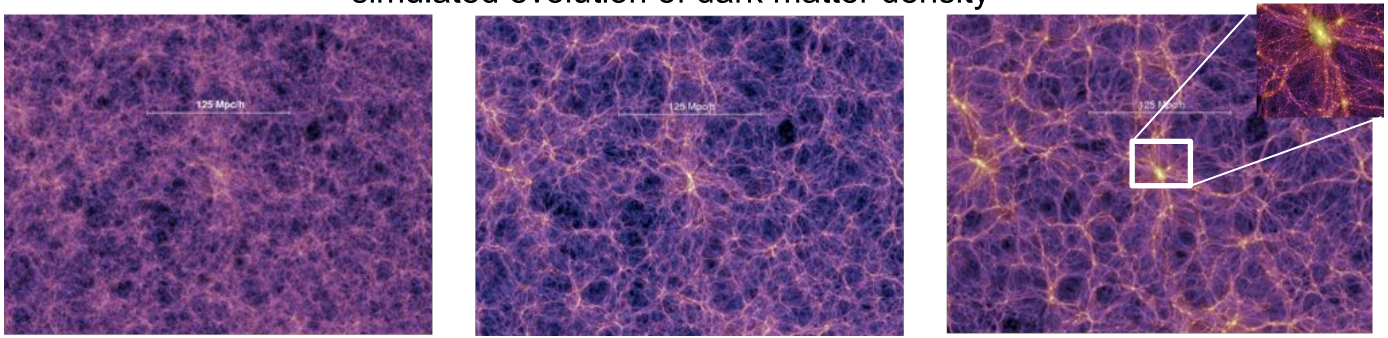
Gravity drives cosmic structure formation, dark energy slows it down.

- Massive neutrinos, inflation impart characteristic scale dependences.

Relative fluctuations ~ 10^{-5} at time of CMB, highest perturbations collapse into gravitationally bound halos at late times.

- Non-linear structure: powerful test of dark energy/nature of gravity, simulations including new physics + astrophysics essential for interpretation.

simulated evolution of dark matter density



t = 1.0 Gyr   t = 4.7 Gyr   t = 13.6 Gyr

Springel et al. 2006

Observational Cosmology: Growth of Structure

Measure observable tracers of structure formation over time:

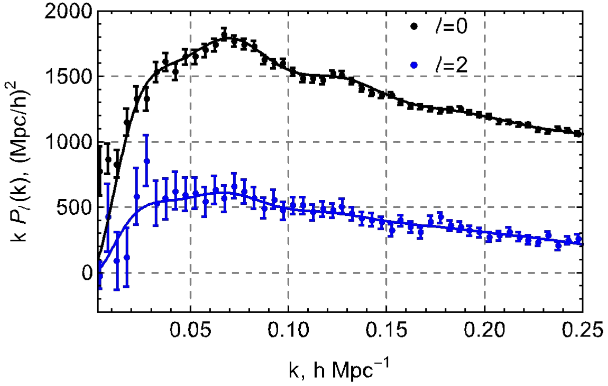
Galaxy clustering: summary statistics of galaxy distribution, e.g., 2-point correlation function/power spectrum.

- Anisotropy due to peculiar velocities induced by gravitational collapse, i.e., redshift space distortions, (RSD).

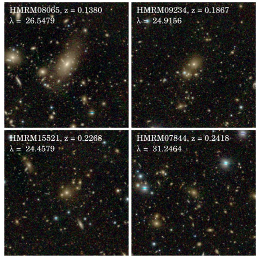
Clusters of galaxies: abundance of largest bound structures as a function of mass.

- Major challenge is to determine masses of clusters once we find them.

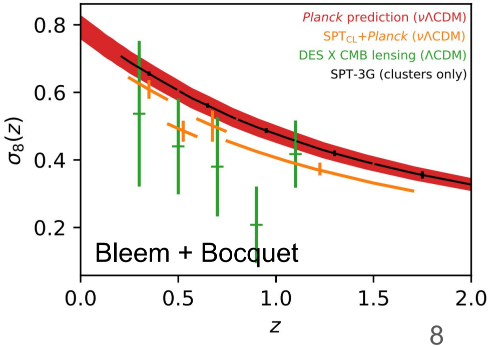
BOSS DR12, Ivanov et al. 2019



wavenumber



Sohn et al. 2018



redshift

Observational Cosmology: Growth of Structure

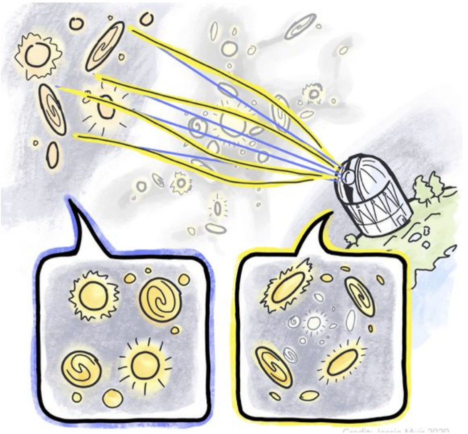
Measure observable tracers of structure formation over time:

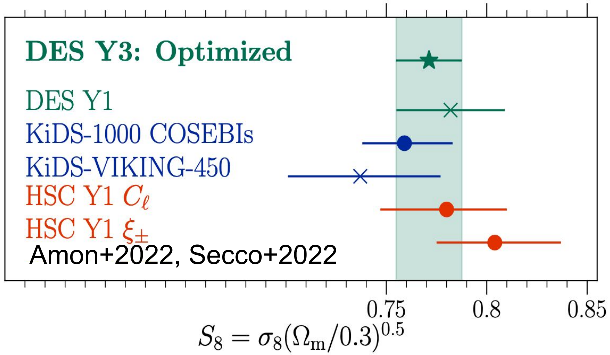
Weak Lensing: deflection of photons by large-scale tidal field → coherent distortion ("shear") of background galaxies' shapes probes foreground (dark+luminous) matter distribution.

- Per galaxy S/N << 1 → average over very large numbers of galaxies.
- Requires multi-band imaging to estimate redshifts from photometric colors ("photo-zs").

Current weak lensing surveys (DES, HSC, KiDS) measure amplitude of cosmic structure fluctuations, S_8, to 5%, will reach 0.5% precision with Rubin.

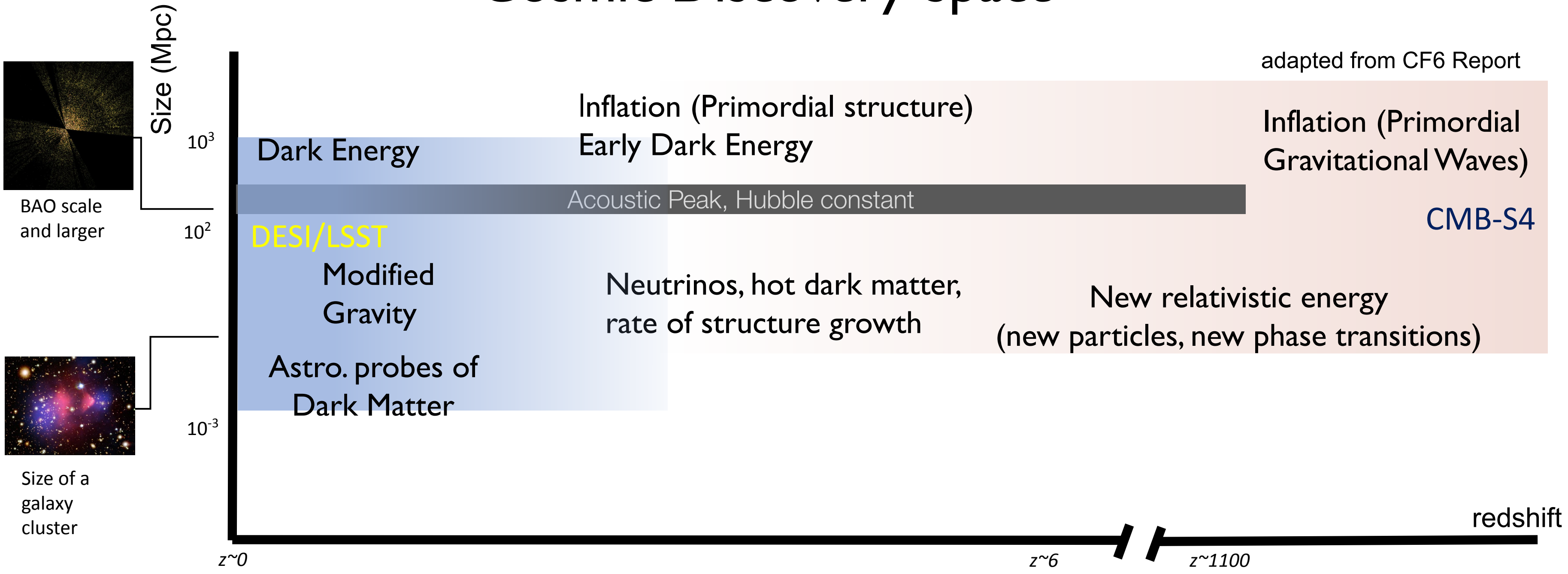
Jessie Muir/DArchive

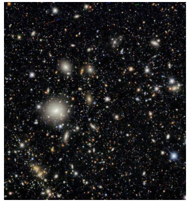




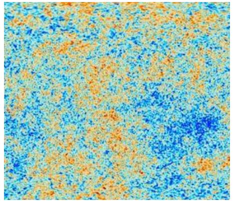
amplitude of structure fluctuations

Cosmic Discovery Space



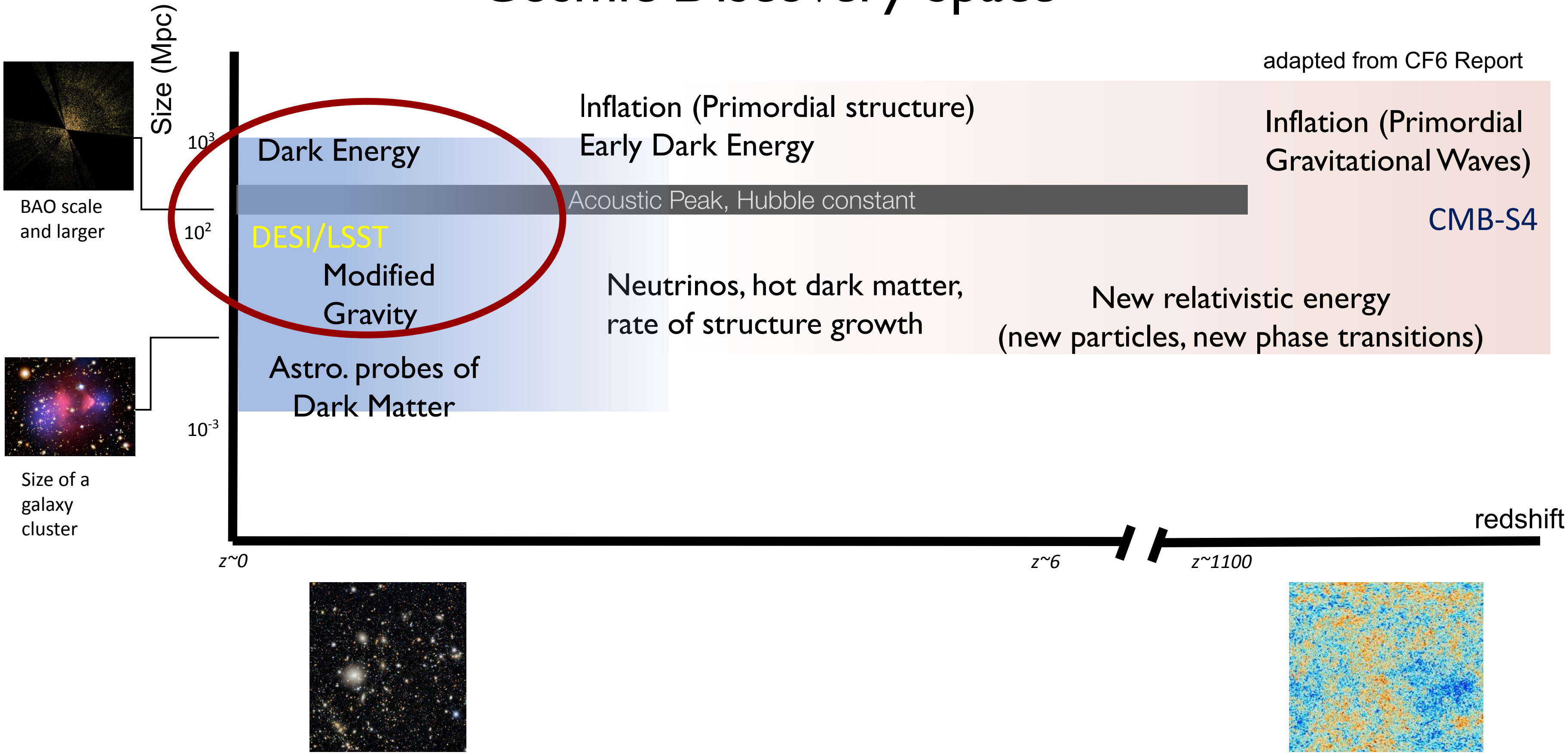


Galaxies emitting in optical wavelengths and spatially resolved.



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

Cosmic Discovery Space



Galaxies emitting in optical wavelengths and spatially resolved.

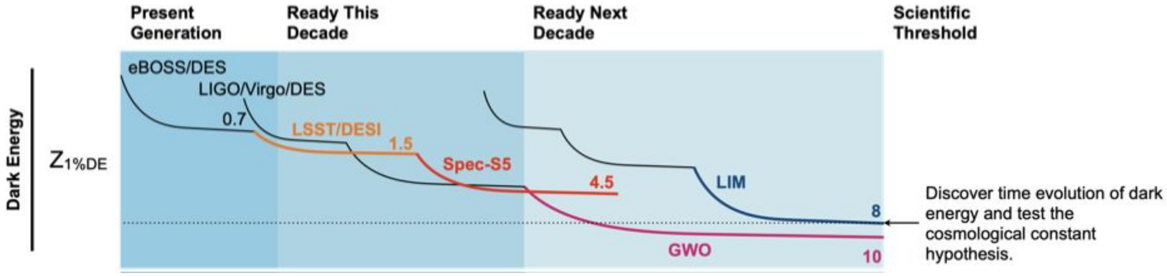
Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

Dark Energy

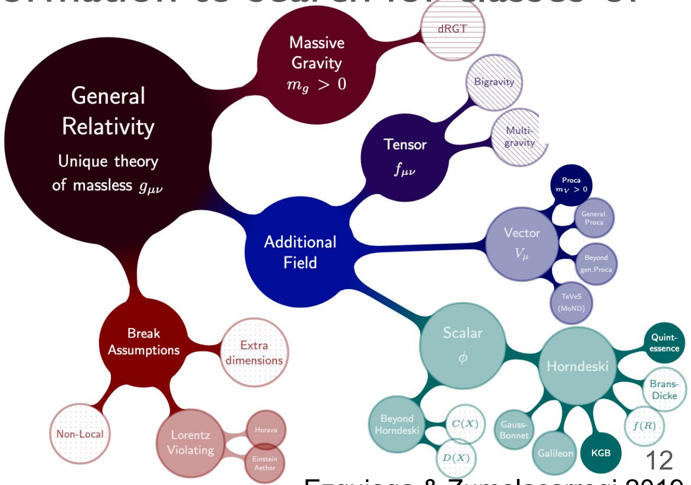
Measurement target: Measure redshift dependence of dark energy equation of state w = P/ϱ to 1% into matter-dominated epoch.

Physical implications: stringent test of vacuum dark energy paradigm (w=-1), put tight constraints on additional scalar fields (e.g., Early Dark Energy).

Discovery space: Precision measurements of structure formation to search for classes of modifications to GR.

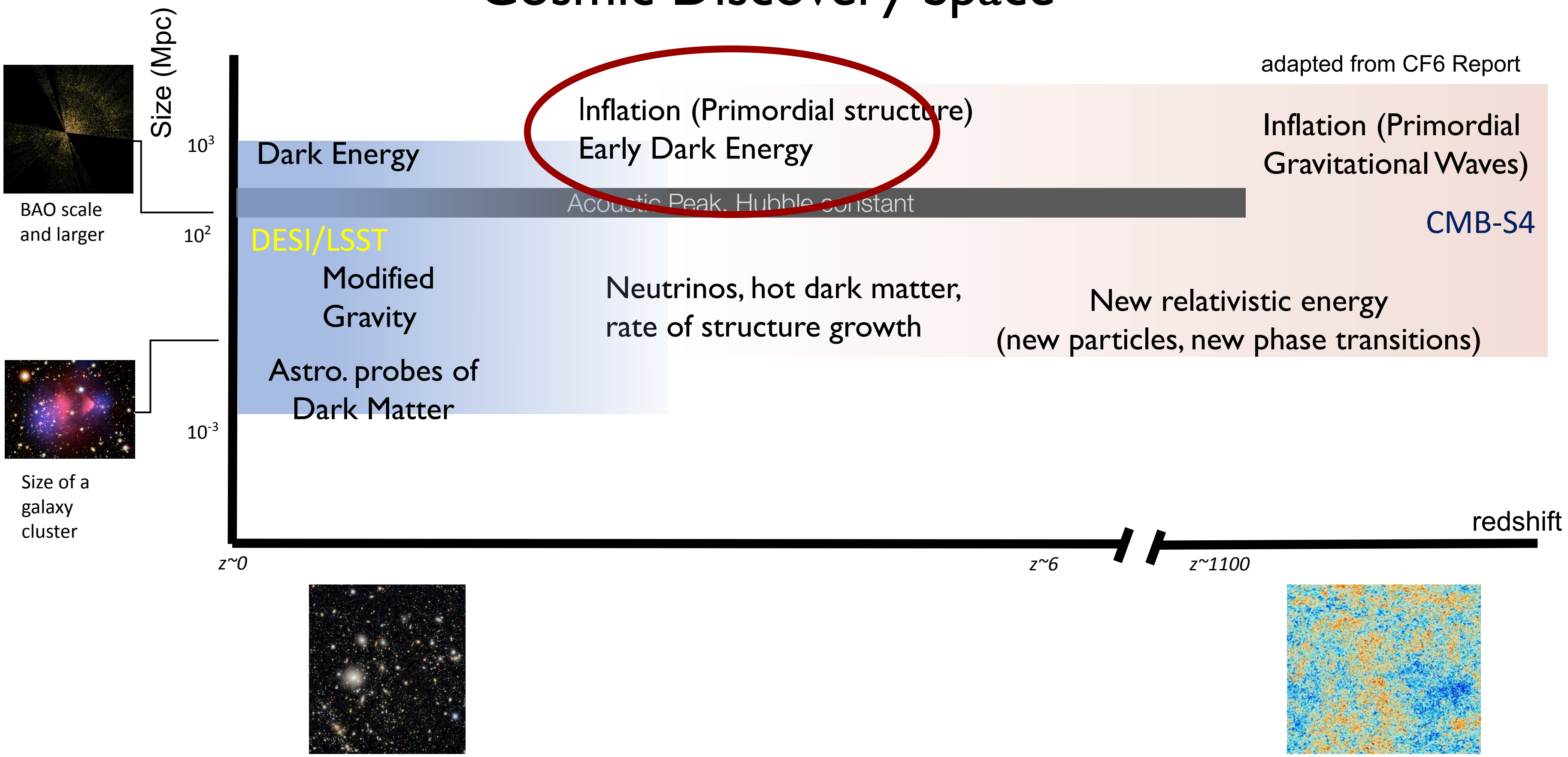


Adapted from CF5 report



Ezquiaga & Zumalacarregi 2019

Cosmic Discovery Space



Galaxies emitting in optical wavelengths and spatially resolved.

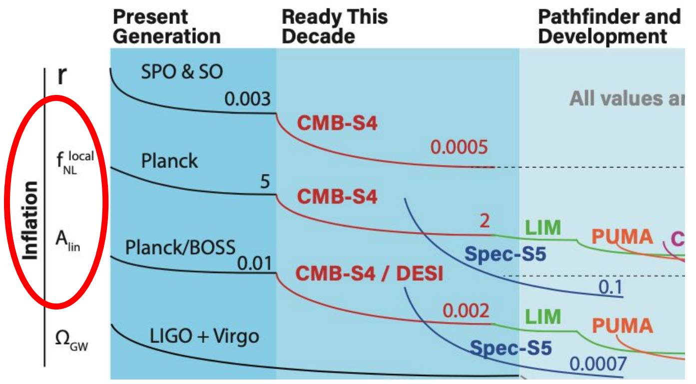
Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

Inflation Constraints from Galaxy Surveys

Simplest inflationary model predicts nearly Gaussian primordial fluctuations. Physics beyond single-field, slow roll inflation produces unique signatures:

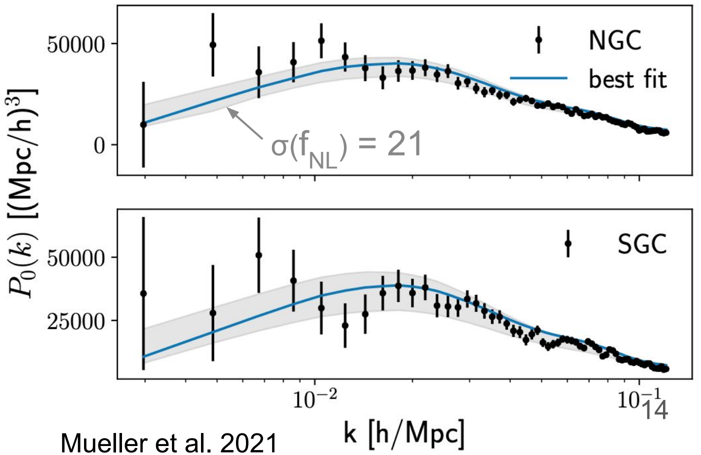
- Additional light field: primordial Non-Gaussianity (PNG) with local shape
- Inflaton self-interactions: equilateral/orthogonal PNG
- Departure from scale invariance: power spectrum features

CF5 report



Measurement target: f_{NL} local from galaxy clustering to $\sigma(f_{NL})$ = 0.2, discriminate between single/multi-field.

Discovery space: Improve over current constraints on the amplitude of power spectrum features, A_{lin}, by two orders of magnitude.



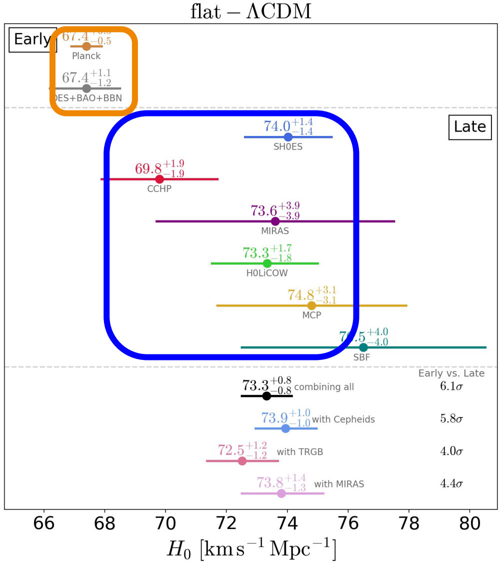
Mueller et al. 2021

Tension(s) within ΛCDM

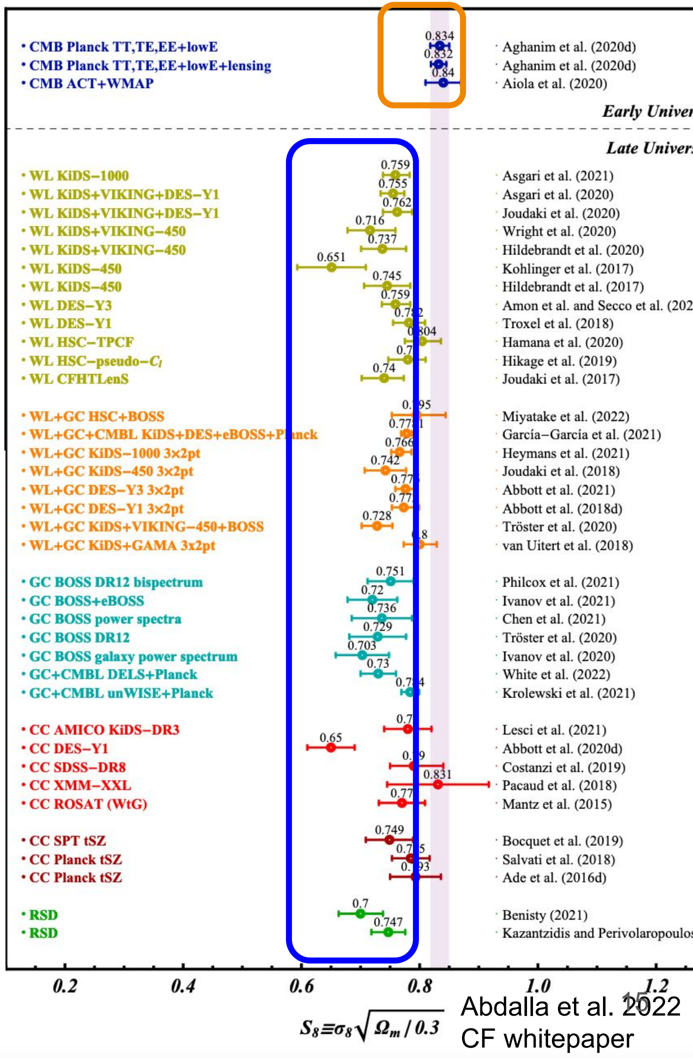
Hubble rate/drag scale H_0: > 5σ tension between **early Universe/late Universe**

Amplitude of structure growth S_8: late Universe measurements skew low w.r.t. **early Universe**

- Cosmological origin would require explanation outside ΛCDM!
- Triggered many new theoretical ideas which will soon be tested.
- *Next-stage data and extensive systematics studies required.*



Verde et al. 2019



Abdalla et al. 2022
CF whitepaper

Three Observational Opportunities for Discovery

Simplified proxy for measurement S/N: $\sqrt{N_{modes}}$, number of Fourier modes measured

- in 3D, N_{modes} ~ (largest scale/smallest scale)^3

limited by survey volume (largest scale)

limited by modeling (non-linear/systematics) (smallest scale)

To increase discovery potential/constraining power:

1. Enhance science return from existing facilities with **innovative analyses** (CF4).
2. Improve conversion of S/N to physics constraints with **cross-correlations of different surveys** (CF6).
3. Increase survey volume, number of linear modes with **new facilities** (CF4-7).

CF*N* = Report of Cosmic Frontier Topical Group *N*

Opportunities for Discovery: 1. Innovative Analyses

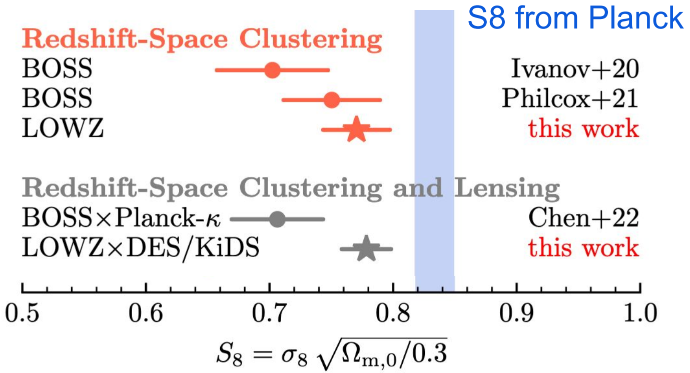
Snowmass Report: "Precision cosmology with existing telescopes: […] **For these surveys to reach their full potential, funding for innovative science analyses – including simulations and cross-survey measurements – will be needed"**. (CF overview, 5.2.3) "Operations funding for these experiments will ensure that the necessary data are obtained and disseminated, but does not cover the necessary cosmological analyses. *Sufficient support to carry out the rich science enabled by these datasets will therefore be of utmost importance to the progress of our understanding of cosmic acceleration over the next decade*". (CF4, 4.4.1)

- DESI and LSST-DESC are vibrant collaborations, with more than 1000 creative scientists excited for the tasks ahead, and need to be supported sufficiently
- In addition, many innovative analyses will be enabled by theory & computing advances, that require explicit support for cross-frontier research

Opportunities for Discovery: 1. Innovative Analyses

Unlocking information from non-linear scales enabled by theory & computing advances. AI and EFT approaches may open up information beyond power spectrum (field level inference, higher-order statistics).

Lange et al. 2023: simulation-based inference from BOSS clustering, factor ~3 gain in constraining power!



Enhancing the science reach of large facilities with additional data (CF4,6): modest follow-up programs for Rubin with outsized impact, e.g.,

- supernovae and strong lensing cosmology,
- multi-messenger science,
- new cosmological probes (e.g., low-z peculiar velocities of supernovae),
- enhanced calibration of photometric redshifts with targeted programs.

Opportunities for Discovery: 2. Multi-Survey Synergies

The need for multiple probes & surveys

DESI, Rubin and CMB-S4 are highly complementary in measurements, astrophysics, scales/redshifts coveraged.

→ test consistency of independent measurements
  → demonstrate robustness of results to measurement techniques & astrophysics
    ○ e.g., galaxy lensing and CMB lensing
  → or identify previously unknown systematics

→ joint multi-survey analyses incl. cross-correlations
  → break parameter degeneracies & self-calibrate systematics to maximize constraining power
  → constrain parameters inaccessible for individual analyses

CF Overview report (p.18): **Taking advantage of complementary experiments**: The experiments in our program will probe dark energy physics in a variety of different ways, enabling cross-checks for and control of systematic uncertainties to obtain robust and rigorous results. For example, […] will be subject to very different systematics from observables such as […]. Furthermore, different experiments provide complementary information about the universe that yields more powerful constraints on cosmology when analyzed in combination.

Opportunities for Discovery: 2. Multi-Survey Synergies

Snowmass Report: "**Taking advantage of complementary experiments**: [...] However, such combined analyses present more challenges (particularly organizationally) than those which only involve one science collaboration. *Key needs to ensure the success of multi-experiment analyses are to:*

- **Create funding streams and support for cross-survey analyses.**
- **Develop and support coordination between large facilities** for optimized design, timely execution, and joint analyses.
- **Create and support development of a diverse set of simulated data** sets that could be used in joint analyses. [...]" (CF Overview report, p.18)

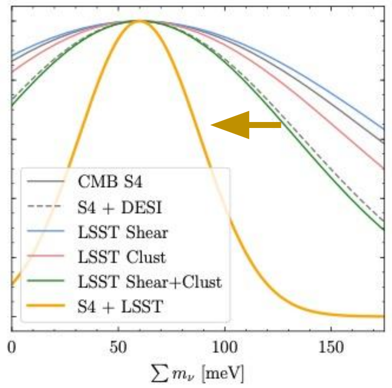
Note: Cross-survey analyses may involve surveys and facilities from different agencies!

Opportunities for Discovery: 2. Multi-Survey Synergies

Improved constraining power with cross-correlations

parameter degeneracy breaking transformative for constraining power, e.g., neutrino mass with galaxy clustering x CMB-S4 lensing.

Mishra-Sharma et al. 2018



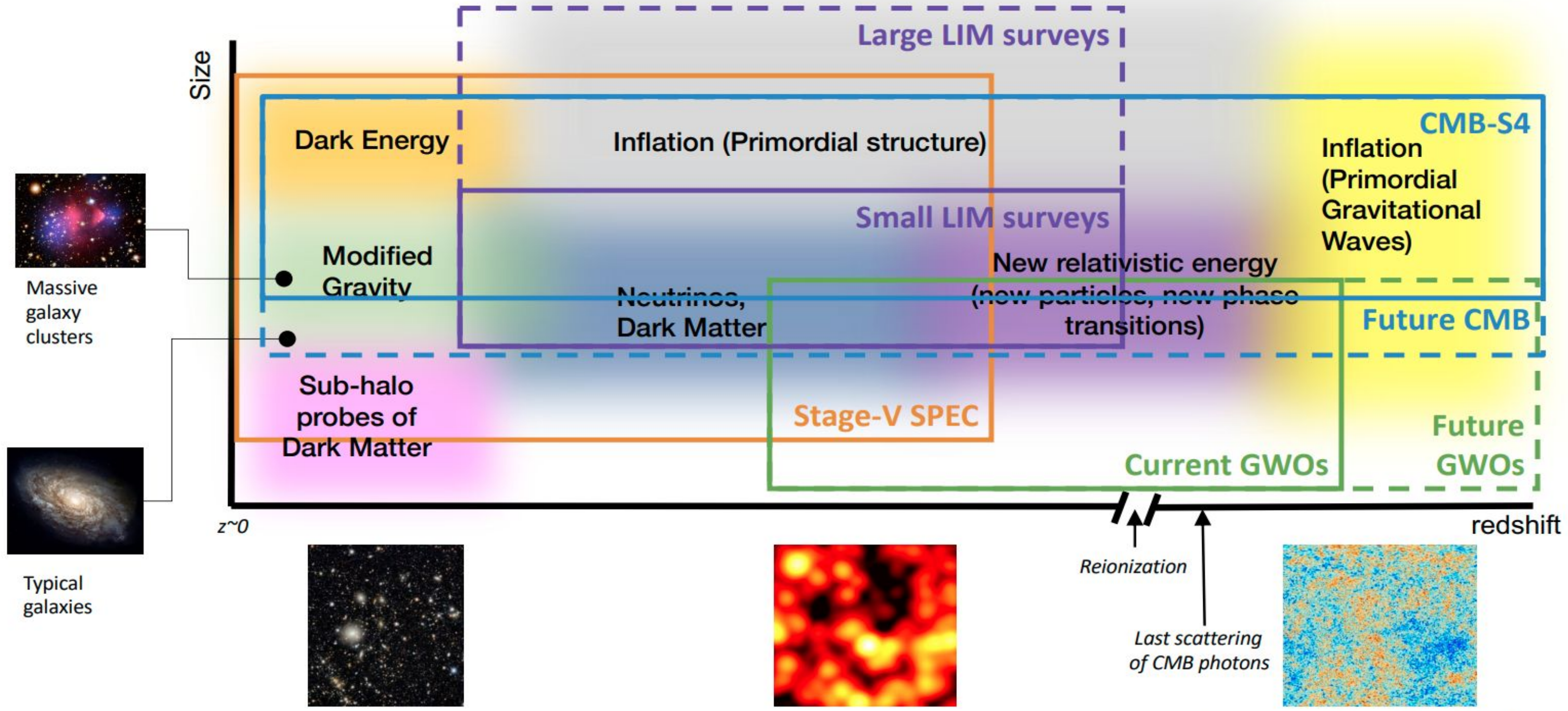
Tests of new physics enabled by cross-correlations

Tests of Gravity: Cross-correlation of spectroscopic clustering (RSD, G_{matter}) and weak lensing (G_{light}, Rubin/S4) enable new theory-agnostic tests of cosmic acceleration; tests of GR using stacked phase space around clusters tests in the weakly non-linear regime.

Anisotropic Primordial non-Gaussianity:
Intrinsic galaxy shapes as a detector for tensor perturbations, enables measurements of PNG amplitudes beyond the monopole, predicted by some models of inflation (e.g., light higher-spin fields).

Opportunities for Discovery: 3. New Facilities

CF6 Report



Galaxies and transients emitting in optical wavelengths and spatially resolved.

Galaxies and gas emission at redder wavelengths and spatially dense.

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

CF6 Report

Summary

Next 20 years of galaxy surveys offer a vast discovery space for fundamental physics

- Dark Energy across cosmic time
- Multi-dimensional tests of inflation
- Dark matter properties, neutrino masses, new particles, and new interactions

Opportunities for discovery will be maximized through

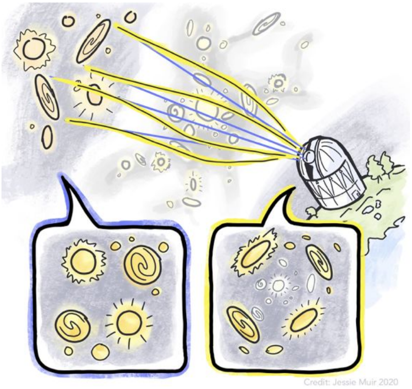
- Sufficient research support for **innovative analyses**.
- Creation of funding streams and facilities for **cross-survey analyses**.
- A portfolio of complementary and synergistic **new facilities**, enabled by a robust **instrumentation R&D program**.

Three Opportunities for Discovery: Multi-Survey Synergies

Robustness of measurements:
Galaxy lensing (shape distortions) and CMB lensing (remapping of CMB primary anisotropies) probe the same physics with completely different measurement techniques.

Predict CMB lensing statistics based on fit to galaxy lensing measurements.

- Agreement: two independent measurements confirm cosmological interpretation!
- Disagreement: use CMB lensing x galaxy lensing to calibrate measurement systematics (e.g., forecasts by Valinotto et al. 2012, Schaan et al. 2017).



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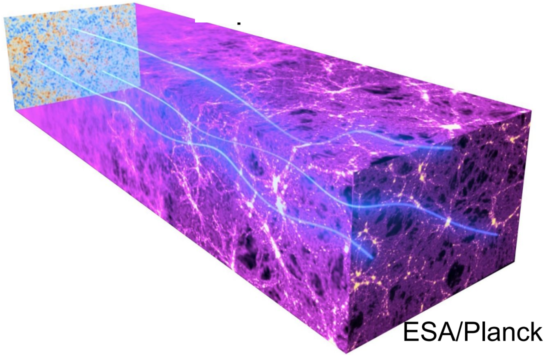
ESA/Planck