Dark Energy and Dark Matter: Cosmology with Large Redshift Surveys

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1. Dark energy is measured using the expansion of the universe and the growth of structure. Large-scale structure also provides evidence for dark matter.

2. **All current evidence** for dark energy & dark matter comes from astrophysical datasets.

3. These measurements are sensitive to the microphysics of elementary particles.
Cosmology: the Current Picture

Inflation smooths out the primordial plasma.

Microscopic density fluctuations grow via gravitational attraction. (The rich get richer.)

Photons decouple from baryons and free stream as the cosmic-microwave background.

Large scale structure evolves via gravitational collapse; affected by dark energy.
On cosmic scales, the universe is a **homogeneous fluid in expanding space**, governed by GR. “Equation of motion”:

\[
\left(\frac{\dot{a}}{a}\right)^2 = \Omega_m a^{-3} + \Omega_{\Lambda} a^{-3(1+w)} + \Omega_r a^{-4} + \Omega_\kappa a^{-2}
\]

- **\(\Omega_m\)**: mean matter density \(\Omega_c + \Omega_b\)
- **\(\Omega_{\Lambda}\)**: dark energy E.O.S. \(w=-1\)

**Additional parameters (some fixed, some calculated):**

- \(\sigma_8\): amplitude of density fluctuations in matter power spectrum.
- \(\Sigma m_v\): sum of neutrino masses.
- \(N_{\text{eff}}\): number of neutrino (\& other light relic) species.
- \(n_s\): spectral index of primordial density fluctuations.
- \(H_0\): expansion rate of the universe today.
ΛCDM + Data: Matter Power Spectrum

Q: What is the dark matter? What is the dark energy? ΛCDM doesn’t answer that.

Q: Will ΛCDM continue to be the best model we have?

Credit: Planck 2018 results: I. Overview
Testing $\Lambda$CDM: The Next 5 Years

Credit: D. Kirkby
Measuring Dark Energy

Focus on Redshift Surveys and the
Dark Energy Spectroscopic Instrument (DESI)
**Probing Dark Energy**

- Redshift space distortions
- Local peculiar velocity fields
- Cosmic shear (weak lensing)
- Galaxy cluster abundances
- CMB
- BAO
- Standard candles & sirens

**Important:**
many observational probes with different (and often complementary) systematic uncertainties.
Dark Energy Program (US-Centric)

Dark Energy Experiments: 2013 - 2031

Credit: Dodelson+ 2013 (Snowmass) arXiv:1309.5386

BOSS

Dark Energy Survey (DES)

HETDEX

HSC imaging

PFS spectroscopy

Extended BOSS (eBOSS)

Dark Energy Spec. Instrument (DESI)

Euclid

Large Synoptic Survey Telescope (LSST)

WFIRST-AFTA

DETF: mid-scale projects

Stage III

Stage IV

DETF: large-scale projects
• **Photometry**: record intensity of light passed through colored filters

• **Advantages:**
  - Identify spatial features.
  - Object discovery – e.g., dwarf galaxies around the Milky Way.
  - High cadence & throughput.

• **Spectroscopy**: record intensity of light passed through dispersive grating.

• **Advantages:**
  - Narrow absorption & emission features.
  - High-res measurements of redshift.
  - *Gold standard for object classification!*
Redshift Surveys: 1980s to Today

- 1980s: $\mathcal{O}(10^{3})$ redshifts; e.g., CfA.
- 1990s: $\mathcal{O}(10^{4})$ redshifts; e.g., LCRS.
- 2000s: $\mathcal{O}(10^{5})$ redshifts; e.g., SDSS.
- 2010s: $\mathcal{O}(10^{6})$ redshifts; e.g., BOSS.
- Coming decade: >$10^{7}$ galaxy redshifts!

After D. Schlegel+ 2019 (arXiv:1907.11171)
Stage IV Redshift Survey: Dark Energy Spectroscopic Instrument

COMMISSIONING: October 2019
SURVEY VALIDATION: January 2020
SURVEY START: June 2020

Mayall 4-m (KPNO)

Atmospheric Dispersion Corrector
Focal Plane 5000 fibers
Fiber Bundles
Primary Mirror 3.2° FOV
Spectrographs (10x) $\lambda/\Delta\lambda \sim 3000 - 5000$, b,r,z cameras
DESI Survey: 35M redshifts in 5 years

- 0.7M Ly-α QSOs
- 1.7M QSOs: $0.5 < z < 3.5$
- 4M luminous red galaxies: $0.4 < z < 1.0$
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18M emission line galaxies: $0.6 < z < 1.6$

10M bright galaxies ($r < 19.5$): $z < 0.4$

Milky Way Survey: $\sim 10M$ stars

8/5/19
Dark Energy Part I: The Hubble Expansion

Baryon Acoustic Oscillations: a Standard Ruler
Measuring the Hubble Expansion

Distance vs. Redshift

\[ \frac{c}{H(z)} \approx \frac{c}{H_0} \left( \frac{1}{\sqrt{\Omega_m (1 + z)^3 + \Omega_\Lambda}} \right) \]

\[ D_C(z) = \int_0^z \frac{c}{H(z')} dz' \]

Credit: D. Kirkby
Measuring the Hubble Expansion

Standard Candle

\[
\text{flux} = \frac{L}{4\pi[(1+z)D_c(z)]^2}
\]

Credit: D. Kirkby
Measuring the Hubble Expansion

Standard Siren

\[
\text{strain} = \frac{L_{GW}}{4\pi [(1 + z)D_C(z)]^2}
\]

Credit: D. Kirkby
Standard Ruler

\[ \delta \theta = \frac{d}{(1 + z)^{-1} D_c(z)} \]

Measuring the Hubble Expansion

Credit: D. Kirkby
Baryon Acoustic Oscillations

• “Bubbles” embedded in large scale structure after baryon-photon decoupling. Structure today is traced by galaxies.

\[ s^* = 110 \text{ Mpc}/h: \]

\[ r_s \approx 150 \text{ Mpc} \text{ (sound horizon)} \]

\[ \delta \theta \approx 1.6^\circ \text{ @ } z = 2 \]

Tracer galaxy “test particles”
Measuring BAO
SDSS-III DR8 Northern Galactic Cap

Credit: SDSS III Collaboration, Aihara+ 2011
BAO: 2-pt Correlation (angle-averaged)

\[ \xi(s) = \frac{DD(s) - 2DR(s) + RR(s)}{RR(s)} \]

Excess galaxy pair counts in data w.r.t. random background pair counts in survey volume.

Graph showing the BAO standard ruler with comoving galaxy-galaxy separation on the x-axis and \( s^2 \) x correlation function \( \xi(s) \) on the y-axis.
Systematics: Redshift Space Distortions

- Tracer galaxies are gravitationally attracted to clusters (peculiar motion).
- In redshift space, clusters appear squashed and voids appear stretched along the line of sight.
- Redshift space distortions (RSDs) create artificial anisotropy in the BAO.
“Reconstruction” of Displacement Field

Literature on “reconstruction” and its robustness:
- Eisenstein+ 2007
- Padmanabhan+ 2009
- Noh+ 2009
- Seo+ 2010
- Mehta+ 2011
- Padmanabhan+ 2012

Applicability at large size scales (“linear theory”):
- Kaiser 1987
- Hamilton 1998
- Scoccimaro 2004
BAO after Reconstruction (BOSS DR11)
Dark Energy Part II: The Growth of Structure
• RSD must be removed to study the BAO standard ruler, but they are extremely useful in their own right!

• The anisotropy produced by RSD constrains $f\sigma_8$, where $f$ is the growth rate of structure and $\sigma_8$ is the normalized amplitude of mass fluctuations.
Growth Index: Testing General Relativity

• Q: can we add modifications to gravity (GR) that explain cosmological data without invoking a new form of energy?

• Parameterize the redshift evolution of the growth rate as

\[ f(z) \approx \Omega_m(z)^\gamma \]

• GR predicts \( \gamma \approx 0.55 \). Significant deviations from this value would motivate alternatives to GR on cosmic scales.
Growth Index: Testing General Relativity

- Current constraints on $\gamma$ are consistent with GR.
- 2-3x improvement in constraints with DESI LRG + peculiar velocity surveys at low-$z$. **Model discrimination at 3$\sigma$ level.**

Credit: eBOSS Collaboration, Zhou+ 2018

Projected DESI sensitivity (DESI FDR 2016, Kim+ 2019)
Does Dark Energy Evolve: $w = w(a)$?

Credit: DESI Science FDR 2016; see also Linder 2005, Linder+Cahn 2007
Particle Microphysics & Large Scale Structure

Cosmic Neutrinos (and other Light Relics)
Information in the Power Spectrum

Credit: K. Bechtol/LSST-DESC

Size scale: Cosmic

Clusters

Galactic

Primordial Fluctuations

Total Matter Density

Baryon Acoustic Oscillations

Dark Matter Microphysics

$k (\text{Mpc}^{-1})$

$P(k) (\text{Mpc}^3)$
Information from the Power Spectrum: Neutrino Mass

Size scale: Cosmic  Clusters  Galactic

Massive neutrinos suppress formation of structure at small size scales.

Neutrinos escape from small grav. potential wells ("free streaming").

If $\Omega_\nu$ is a bigger component of $\Omega_m$ then small-scale structure is suppressed.

Credit: K. Bechtol/LSST-DESC; see also Abazajian+ 2013.
Limits on $\Sigma m_\nu$: Projected Sensitivity

- Oscillations require $\Sigma m_\nu > 59$ meV (normal hierarchy) and $> 98$ meV (inverted).
- Next-gen CMB+LSS: expect $\sigma_{\Sigma m} \approx 17$ meV.
- Small $\Sigma m_\nu$ can rule out inverted hierarchy at $3.5\sigma$ (best-case).
- Note: NH with $\Sigma m_\nu$ well above the minimum allowed would not be distinguishable from IH.
Additional Information: $N_{\text{eff}}$

- CMB + LSS are sensitive to light relic particles.

- Very obvious candidate population: the cosmic neutrino background ($C\nu B$).

- Energy $\sim 1$ $\mu$eV; direct detection not likely...
$N_{\text{eff}} > 3.046$: “Dark Radiation”

- We’ve assumed no massless or light relic particles beyond photons and known active neutrinos.
- Expect $N_{\text{eff}} = 3.046$ from cosmological limits: gradual neutrino decoupling at $T \sim 2$ MeV + flavor oscillations (de Salas + Pastor 2016).
- Larger $N_{\text{eff}} \rightarrow$ dark radiation. E.g., a sterile neutrino or other light relic.

\[ \Delta N_{\text{eff}} = N_{\text{eff}} - 3.046 \]

Credit: Lesgourges + Verde 2018
Present Limits on $N_{\text{eff}}$

- Planck 2D constraints on $N_{\text{eff}}$ and $H_0$; both allowed to vary.

- $N_{\text{eff}} > 3$ favors larger $H_0$, but also higher $\sigma_8$.

- Planck+BAO favor $\Lambda$CDM values.

- Data don’t seem to justify $\Delta N_{\text{eff}} > 0$ at present.
Systematic Errors, or New Physics?

A brief update on the $H_0$ “crisis”
History lesson: measuring distance is hard!
Measurement Status of $H_0$: August 2019

- $H_0$ from the tip of the Red Giant Branch (TGRB): Freedman+ 2019.

- Discrepancy between $H_0$ measured by CMB and local distance ladder is inspiring many new techniques with independent systematics.
H_0 from Standard Siren GW170817

Credit: Abbott+ 2017 (LIGO, Virgo, 1M2H, DES, et al.)

Credit: HST/NASA
Also: $H_0$ from **Dark Sirens**

- $H_0$ from a GW with no optical counterpart ("dark siren").
- Marginalize over all hosts in localized volume around GW event.
- **Try to win with statistics**: 10x more BBH events than kilonovae!

Credit: Soares-Santos+ 2019 (DES, LIGO-Virgo)
Conclusion
Key Points

1. Dark energy is measured using the expansion of the universe and the growth of structure. Large-scale structure also provides evidence for dark matter.

2. All current evidence for dark energy & dark matter comes from astrophysical datasets.

3. These measurements are sensitive to the properties of elementary particles and other fundamental physics. For dark matter, there is a huge parameter space at small scales that we haven’t yet explored.

4. Present data are in broad agreement with $\Lambda$CDM. Expect 5x to 10x improved precision by 2025.
Robotic Multiplexed Spectrographs

**BOSS optical fiber plug plate.**

- 640 fibers (1999-2009)
- 1000 fibers (2009-2018)

Credit: SDSS + Apache Point Observatory

**DESI petal with fiber positioners.**

- 500 fibers × 10 petals, 600,000 components

Credit: DESI/LBL
DESI Petal Installation: July 2019

Focal plane, July 22/23. Credit: R. Besuner (LBL)

Backlit fibers, July 25/26. Credit: P. Fagrelius (LBL)

Positions in Fiber View Camera, July 25/26. Credit: P. Fagrelius (LBL)
DESI Luminous Red Galaxies (LRGs)

300/sq. degree
0.4 < z < 1.0
4.2 M
>95% completeness

Expansion Rate

H(z)/(1+z) (km/s/Mpc)

Relative Flux

Wavelength (nm)

4000 Å Break

DESI predictions
DESI Emission Line Galaxies (ELGs)

1280/sq. degree
0.6 < z < 1.6
17.9 M
>90% completeness

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redshift accuracy of $\Delta z < 0.0005(1+z) \text{ rms}$
resolution of OII feature drives L3 spectral resolution requirement at red end.
DESI Quasars (QSOs)

120/sq. degree
0.9 < z < 2.1
1.7 M
>90% completeness

DESI predictions
DESI Lyman-α Forest Quasars

50/sq. degree
z > 2.1
0.7 M
72% completeness

DESII predictions
Systematics: Peculiar Velocities (PV)

Peculiar Motion: tracers falling into gravitational wells

Hubble Flow
(smooth expansion)

Credit: Woods Hole Oceanographic Institute
Neutrino Mass Limits: CMB + Ly-\(\alpha\) Forest

- Push to \(k = 0.07\ \text{s km}^{-1}\) using BOSS + VLT/XSHOOTER Ly-\(\alpha\) spectra + Planck cosmological parameters.
- Ly-\(\alpha\) constrains \(\Omega_m\) and \(\sigma_8\) independent of \(\Sigma m_\nu\); compare to correlations seen in CMB constraints from Planck.

Credit: Yeche+ 2017
Constraints on $H_0$ with eBOSS

- Constraints based on redshift slices from eBOSS.
- Each slice probes a slightly different part of the $\Omega_m - H_0$ parameter space.
Sensitivity Forecast for DESI

- Expect much tighter contours in the $\Omega_m - H_0$ plane with DESI due to 10x higher statistics.
Constraints on Primordial Density Fluctuations

- Constrain primordial density perturbations using multiwavelength data.

- E.g., non-observation of evaporating primordial black holes constrains density perturbations to nearly point-like spatial scales.
Baryon-Photon Acoustic Oscillations

The Slow Mo Guys, © 2013
Performance of ΛCDM

• Current measures of the growth of structure \( f\sigma_8 \) are also still consistent with ΛCDM.

• But measurements of \( H_0 \), the expansion rate today, disagreed at >3σ in 2018; the difference today is 4.4σ (Riess+ 2019).
Projected Sensitivity to $N_{\text{eff}}$

Credit: Abazajian+ 2013 (Snowmass Dark Energy + CMB WG)
$H_0$ from Gravitational Wave Events: Help from Spectroscopic Surveys

- Measure $H_0$ with sirens at $z < 0.1$: here the Hubble Law is independent of cosmology ($cz = H_0d$).
- At low $z$ the error $\delta z/z$ due to peculiar velocities is significant.
- **DESI**: map local peculiar velocity field with 10M bright galaxies!

Credit: after Mortlock+ 2018, Palmese + Graur 2019