Cosmology in 2021: Concordances and Tensions

with the Dark Energy Survey Collaboration

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Pheno '21
Our Simple Universe

On *large scales*, the Universe can be modeled with remarkably few parameters

- age of the Universe
- geometry of space
- density of atoms
- density of matter
- amplitude of fluctuations
- scale dependence of fluctuations

[of course, details are not quite as simple]
Vanilla Cosmology

- Ordinary Matter: 5%
- "Dark Matter": 25%
- "Dark Energy": 70%

"Dark Energy"
- accelerates the expansion
- dominates the total energy density
- acceleration first measured by SN 1998
Vanilla Cosmology

- Dark Energy
  - accelerates the expansion
  - dominates the total energy density
  - acceleration first measured by SN 1998
  - next frontier: understand
    - cosmological constant $\Lambda$: $w = p/\rho = -1$?
      - size of $\Lambda$ difficult to explain
    - dynamic scalar field, $w(a)$?
    - breakdown of GR?

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Vanilla Cosmology

Does the dark energy equation of state change as space expands?

Ordinary Matter

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  - size of $\Lambda$ difficult to explain
- dynamic scalar field, $w(a)$?
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Are data from early Universe and late Universe fit by the same parameters?

Do measurements of expansion history and growth of structure agree?

Does the dark energy equation of state change as space expands?
Measurements of Expansion History

comparison of distance and redshift

**Standard candle:** brightness of source with known luminosity

**Standard ruler:** angle subtended by known scale
Measurements of Expansion History

comparison of distance and redshift

**Standard candle**: brightness of source with known luminosity
- SNe: luminosity can be determined from duration/color

**Standard ruler**: angle subtended by known scale
- CMB: sound horizon in early Universe (380,000 years)
- BAO: same scale, but evolved for billions of years

These measurements are consistent with the CMB in LCDM, tightly constrain flatness, matter density
Early 2000s: Concordance Cosmology

Expansion History Measurements:

- **Cosmic Microwave Background (CMB)** angular scale of sound horizon in the early Universe
- **Baryonic Acoustic Oscillations (BAO)** angular scale of sound horizon imprinted in late-time galaxy distribution
- **Supernovae (SNe)** apparent brightness of exploding white dwarfs with ~known intrinsic luminosity
The Distance Ladder

Three Steps to the Hubble Constant

- Cepheids within the Large Magellanic Cloud
- Galaxies hosting Cepheids and Type Ia supernovas
- Distant galaxies in the expanding universe hosting Type Ia supernovas

Light red-shifted (stretched by expansion of space)

Distance in Light-Years:
- 180,000
- 24-100 million
- 100 million-1 billion
2020s: Concordance Cosmology?

Hubble Parameter - expansion rate

significant tension between early and late Universe physics!
2020s: Concordance Cosmology?

Q: Do all these measurements agree with predictions in the same, fiducial $\Lambda$CDM model?
2020s: Concordance Cosmology?

Hubble Parameter - expansion rate

Significant tension between early and late Universe physics!

S8 - amplitude of structure growth

Hints at possible tension between early and late Universe physics?

→ Let’s shrink these error bars
Photometric LSS Surveys

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<th>Observed galaxy density</th>
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<th>Start Date</th>
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Survey Completion Year
Cosmic Structure Formation

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

Growth of structure constraints complementary to expansion rate.

Linear (large) scales: perturbation theory.

Non-linear evolution: numerical simulations.

- Reliably predict dark matter distribution, for wCDM cosmologies (+ individual MG models).
Cosmic Structure Formation

gravity drives **cosmic structure formation**, dark energy slows it down

growth of structure constraints complementary to expansion rate

~linear (large) scales: perturbation theory

non-linear evolution: numerical simulations

- reliably predict *dark matter distribution*, for wCDM cosmologies (+ individual MG models)

not directly observable

Springel+, 2006
Connecting Theory and Observations

cosmological model + parameters

simulation/perturbation theory

astrophysics (?)

dark matter

galaxies, light

Springel+, 2006

(+ other tracers of structure formation)

CMB temperature+polarization (Planck)

galaxy positions+shapes+colors (DES)
Summary Statistics from the Galaxy Distribution

- two-point correlations
- clusters (over densities)
- voids (under densities)
- three-point correlations,...
Tracer: Galaxy Clustering

two-point correlations
excess probability of galaxy pairs
(over random distr.)
as function of separation
Tracer: Galaxy Clustering

requires ~3D distances (redshift), relation between galaxy density and dark matter density (galaxy bias)

Two-point correlations
excess probability of galaxy pairs (over random distr.)
as function of separation

matter power spectrum

linear growth

non-lin. structure

BAOs

$k [h/\text{Mpc}]$
Tracer: Gravitational Lensing

galaxy

galaxy cluster

lensed galaxy images

distorted light-rays

Earth

credit: ESA
Tracer: Gravitational Lensing
Tracer: Weak Gravitational Lensing of Galaxies

- light deflected by tidal field of large-scale structure
  - coherent distortion of galaxy shapes - "shear"
  - shear related to (projected) matter distribution

Key uncertainties
- shape measurements
- average over many galaxies assuming random intrinsic orientation
Weak Gravitational Lensing: typical DES galaxies
Real World Example: DES-Y1

Survey Completion Year
‘09 ‘09 ‘12 ‘19 ‘19 ‘20
End Date

Observed galaxy density
CFHTLS 11
COSMOS 65
DLS 17

Survey Area [sqr deg]
CFHTLS 154
COSMOS 2
DLS 20

KiDS 11
Kilo Degree Survey

DES 10
Dark Energy Survey

HSC 26
Hyper Suprime Cam

Nancy G. Roman Space Telescope
Euclid 30
Vera Rubin Observatory 50

Dark Energy Survey
Hyper Suprime Cam

KiDS 1200
Kilo Degree Survey

COSMOS 20

DES Y1 26M galaxies

Billions of galaxies

~ Start Date
’23 ’25 ’23

End Date
’09 ‘09 ‘12 ‘19 ‘19 ‘20
DES-Y1 WL x LSS Analysis

660K redMaGiC galaxies split in 5 redshift bins

26M source galaxies split in 4 redshift bins

galaxies x galaxies: angular clustering

galaxies x lensing: galaxy-galaxy lensing

lensing x lensing: cosmic shear
baseline systematics marginalization (20 parameters)

- linear bias of lens galaxies, per lens z-bin
- lens galaxy photo-zs, per lens z-bin
- source galaxy photo-zs, per source z-bin
- multiplicative shear calibration, per source z-bin
- intrinsic alignments, power-law/free amplitude per per source z-bin

-> this list is known to be incomplete

how much will known, unaccounted-for systematics bias \( Y_1 \)?

-> remove contaminated data points (i.e., throw out large fraction of S/N)

-> choice of parameterizations \( \neq \) universal truth

are these parameterizations sufficiently flexible for \( Y_1 \)?
DES Y1 Results:
LCDM Multi-Probe Constraints

- marginalized 4 cosmology parameters, 10 clustering nuisance parameters, and 10 lensing nuisance parameters
- consistent cosmology constraints from weak lensing and clustering in configuration space

(Matter Density vs. Amplitude of Structure Growth)
(DES Collaboration 18)
DES Y1 ↔ Early Universe (Planck)

- DES-Y1 and Planck (TT+lowP, without CMB lensing) constrain $S_8$ and $\Omega_m$ with comparable strength
- Central values differ by $>1\sigma$, in the same direction as other lensing analyses (CFHTLS, KiDS, HSC)
- Future: observe more galaxies, combine more probes, and achieve better systematics control!
Beyond DES-Y1 3x2pt: Cluster Counts x 2PCFs

To, EK+ 2021a,b: cluster cosmology constraints from abundances and large-scale two-point statistics

- **3x2pt:**
  - **Method:** Krause&Eifler et al. (2017)
  - **Simulation:** MacCrann&DeRose et al. (2018)
  - **Results:** DES Collaboration (2018)

- **4x2pt+N:**
  - **Method:** To&Krause et al. (2020a)
  - **Simulation:** To&Krause et al. (2020a)
  - **Results:** This work

- **6x2pt+N:**
  - **Results:** This work

- joint likelihood analysis validated on DES-like mock catalogs (Buzzard, DeRose+2020)
- MOR calibrated from large-scale clustering, account for selection bias
- ✓ cosmology constraints consistent with other DES probes
Beyond DES-Y1 3x2pt: Cluster Counts x 2PCFs

this analysis unlocks constraining power from number counts
substantial gain, iff accurate MOR calibration

Rubin/LSST joint probes forecast EK & Eifler '17
DES-Y1 Systematics Mitigation

Opportunity Space...

Galaxy lensing + galaxy counts also depends on galaxy bias parameters. Marginally consistent/small tension with Planck. Some others more significant, but all require complex modeling. For example, DES-Y1 independent 3x2pt analysis by A. Lewis. Modeling these scales requires new systematics parameterizations. Potential gain if current systematics model constrained from external data.

-independent 3x2pt analysis by A. Lewis
Systematics Opportunities and Challenges: Baryonic Effects in WL Analyses

Illustration from OWLS collaboration
DESY1 WL Correlation functions

DESY-Y1 baseline: small scale correlation function measurements excluded because of baryonic effects

Huang+2020: reanalyze DESY1 including all WL measurements down to 2.5′
Baryonic Effects in WL Analyses
Baryonic Effects in WL Analyses

Cosmology Constraints

- DES-Y1 including all scales, baryons not included in the modeling (don’t do that!)
- DES-Y1 baseline (conservative scale cuts)
- DES-Y1 including all scales, baryonic effects modeled using PCA with non-informative prior

Huang+ 2020
Baryonic Effects in WL Analyses
Cosmology Constraints

- DES-Y1 baseline (conservative scale cuts)
- DES-Y1 including all scales, baryonic effects modeled using PCA with non-informative prior
- DES-Y1 including all scales, baryonic effects modeled using PCA with informative prior

Huang+ 2020
This Thursday: DES-Y3 Cosmology

Analysis of DES Year-3 3x2pt: webinar on 5/27, 11:30 am Eastern

- full area (~5000 sqdeg) + increased depth
- algorithmic + modeling improvements in all analysis stages

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Diagram:

- Point Spread Function Modelling
  - Jarvis +
  - Gatti, Sheldon +

- Redshift calibration
  - Myles, Alarcon +
  - Everett +
  - Gatti, Giannini +
  - Sanchez, Prat +
  - Cordero, Harrison +

- Image Simulations
  - MacCrann +

- Shear measurement & null tests
  - Sevilla, Bechtol +

- Redshift samples

- Wide Field Images
  - Hartley, Choi, Amon +

- Deep Field Photometry

- Validated shape catalogue

- 2-point function measurements

- Lens clustering sample

- Galaxy clustering & galaxy-galaxy lensing

- Cosmic shear cosmology
  - Amon +
  - Secco, Samuroff +

- Mock analysis
  - de Rose +

- Mitigate experimenter bias
  - Muir +

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- Jarvis +
  - Hartley, Choi, Amon +
  - MacCrann +
  - de Rose +
  - Secco, Samuroff +
  - Muir +
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  - de Rose +
  - Secco, Samuroff +
  - Muir +

- \( \sigma_8 \)
- \( \Omega_m \)

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\[ \text{Coordinated by Michael Troxel, Elisabeth Krause, Scott Dodelson} \]
Conclusions

The simple, 6-parameter LCDM model has been remarkably successful

› describes wide range of cosmological epochs and observables
› intriguing tension (H0) and fluctuation (S8) are emerging
› (most) cosmological constraints will be systematics limited
  › require astrophysics, accurate systematics parameterizations+priors
› DES-Y3 results coming this week: webinar 5/27, 11:30 am Eastern
  › https://fnal.zoom.us/j/94822142182?pwd=UnlPSzg0NXdNdIFzK3R2VWV6aEk1dz09
› Precision cosmology requires collaboration across surveys + wavelengths, planning for analysis frameworks to combine data from all surveys!