THE FUTURE OF OBSERVATIONAL COSMOLOGY

Prospects for understanding Dark Energy

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Joint ECFA-EPS session
UNDERSTANDING DARK ENERGY

- Dark Energy against Gravity
- How to probe Dark Energy
- Current constraints on DE Equation of State
- Ongoing and future (large) DE projects
HOW DID THE INITIAL FLUCTUATIONS EVOLVE IN THE STRUCTURES WE SEE TODAY?
THREE EPOCHS, EACH DOMINATED BY DIFFERENT PHYSICS

- $t \approx 10^{-35}$ sec: Early acceleration, *Inflation*
- $300,000$ years < $t < 8$ B- yrs: Growth of Structure, fueled by *Dark Matter*
- $t > 8$ B- yrs: Late Acceleration, associated with *Dark Energy*

Described by GR:

$$ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} $$

Observed late-time acceleration points to *Dark Energy* that remains roughly constant

Equation of State of Dark Energy: $w = p/\rho \approx \text{constant}$
Cosmological Constant/Vacuum Energy

Constant Energy Density associated with empty space

\[ T_{\mu\nu} = g_{\mu\nu} \frac{\Lambda}{8\pi G} \]

and \( w = p/\rho = -1 \)

Could it be quantum fluctuations? which are expected to contribute to the vacuum energy

But expected amplitude is (much) too large (by 120 orders of magnitude..)
Require roughly constant energy density

Potential energy larger than kinetic energy

Mass must be very small: $m<10^{-33} \text{ eV}$ (Hubble rate today) or else field oscillates

Slowly rolling field has equation of state $w$ different from -1

$$\ddot{\varphi} + 3H \dot{\varphi} + m^2 \varphi = 0$$
General Relativity has to be modified …

and the acceleration equation generalizes to:

\[
\frac{\ddot{a}}{a} = - \frac{4 \pi G}{3} \left( \rho + 3P \right) + \left[ \frac{\partial f}{\partial R} H^2 - \frac{f}{6} - \frac{\partial f / \partial R}{2} \right]
\]

Get acceleration if these terms are positive
WILL WE BE ABLE TO TELL? : DARK ENERGY PROBES

- Supernova Brightness
- Baryon Acoustic Oscillations
- Gravitational Lensing
- Galaxy Cluster Abundance

Cosmic Microwave Background precise cosmology (Planck 2015)

\[ w(z) = w_0 + w_a \frac{z}{1+z} \]

Constraints on the DE EoS : \( w_0, w_a \)

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WHERE DO WE STAND TODAY?

The most precise constraints on DE today come from measurements of the expansion history from Supernovae and Baryon Acoustic Oscillations

• BAO from The Sloan Digital Sky Survey (SDSS)

• SN from SDSS and The SuperNova Legacy Survey (SNLS)
SDSS : THE SLOAN DIGITAL SKY SURVEY

Imaging and spectroscopic survey

Dedicated 2.5 m telescope
(Apache Point, New Mexico)

Reached 8000 deg$^2$
~700,000 galaxy spectra
+ quasars, stars, ....

Since 2000 in 4 phases producing
Images, spectra & catalogs
~ once a year
Drift scanning (56 s/band)
~ 225 deg² per night

- Fiber-fed spectrograph : 7 deg² field-of-view.
  ~ 600 objects per pointing
- Fibers (manually) plugged in precision-drilled plates
SDSS : CORRELATION FUNCTION OF LRGs

55000 Luminous Red Galaxies
Over 4000 deg$^2$ up to z~0.48
$\langle z \rangle = 0.35$

Eisenstein et al [SDSS Collab.] 2005
2 million targets over 10,000 square degrees
2.1% distance measurement to $z=0.32$ (1% to $z=0.57$)

$z=0.57$

$z=0.32$
BAO detection in the Intergalactic Medium

- Use Lyman $\alpha$ Forest from 160000 quasars to produce a map of intergalactic neutral hydrogen
- BAO detection at $5\,\sigma$: a 3% measurement of H at $z=2.4$

Delubac et al. (2014)
THE HUBBLE DIAGRAM OF TYPE Ia SUPERNOVAE

Latest High-z Supernova compilation (JLA : 2014)

4m telescope with ~deg2 camera for imaging

8m telescopes for SN id and z
CURRENT CONSTRAINTS IN A FLAT $\text{wCDM}$ MODEL

Planck + BA0
$w = -1.01 \pm 0.08$

Planck + SNe
$w = -1.018 \pm 0.057$

Betoule et al, 2014
We now start to put (week) constraints on $w(z)$
A WORLD WIDE EFFORT TO UNDERSTAND DARK ENERGY : ONGOING AND PLANNED SURVEYS


+ Radio (21 cm) surveys such as the planned Square Km Array (SKA)
4 Examples: DES, DESI, LSST, Euclid, ...

- DES: The Dark Energy Survey
- DESI: The Dark Energy Spectroscopic Instrument
- LSST: The Large Synoptic Survey Telescope
- The Euclid space project

An important goal of these surveys is to see whether the cosmological constant ($w_0=-1; w_a=0$) drives acceleration.

Use Figure of Merit $=1/(\text{area of } w_0-w_a \text{ ellipse})$ ~20 today]
THE DARK ENERGY SURVEY

Build a new 3 deg$^2$, 570 Mpix camera (DECam) and Data Management system, and carry out two multi-band optical surveys (~500 nights):

- 5000 deg$^2$ to 24$^{\text{th}}$ magnitude in grizY bands
- 30 deg$^2$ repeat scan SN survey (~10% of observing time)

Four complementary approaches to DE science:

- Galaxy cluster counts
- Weak gravitational lensing and cosmic shear
- Large scale structure / baryon acoustic oscillations
- Type Ia supernova

Factor of 10 more cosmic volume than SDSS, and over 1 PB of public image and catalog data
Each DES field contains approximately:

- 200,000 galaxies
- 100 galaxy clusters

6 yr data taking: 2013-2018

← simulated image
Dark Energy Survey will measure fluxes in 5 bands to map the Universe out to $\sim 10^7$ Light-yr away ($z=1$) in 2.5 dimensions (photometric)

Will map 5000 square degrees with more than $10^8$ galaxies

Clusters, SN, WL, 2.5D BAO

Increase Figure of Merit by $\sim 5$
DESI: Dark Energy Spectroscopic Instrument

- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view
- 10 spectrographs

- will be installed on the Mayall 4m Telescope at Kitt Peak, Tucson, AZ

- Expect data taking: 2018-2022

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(Expected) DESI BAO Hubble Diagram

Expansion Rate

Redshift

$w_0/w_a$ FoM: $\sim 300-600$
LSST: WIDE DEEP AND FAST

Field of view:
3.5 deg (9.6 deg²)
Focal plane diameter: 64 cm

- ~200 4kx4k CCDs
- 3024 Channels
- >3 × 10⁹ pixels
- Readout: 2s

Camera
SLAC led construction

M1M3 primary (8.4m) &
Tertiary mirrors

Moving Structure 350 tons
60 tons optical systems

10 μm pixels CCDs
UV to NIR sensitive

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A SINGLE OBSERVATION PLAN & MANY SCIENCE TOPICS

- 6-band Survey: ugrizy 320–1080 nm
- Sky area covered: > 20,000 deg2, 0.2 arcsec / pixel
- Each 9.6 sq.deg FOV revisited ~ 1000 times during 10-Year Duration:
- Photometric precision: 0.01 absolute; 0.0005 mag repeatability

> $5 \times 10^6$ exposure:
15 s pose + 2 s read + 15 s pose =>
Points to new positions every 37 seconds
15 TB and 10 M transients per night => 0.5 Exabyte images total

Survey start date: **2022**
EXPECTED PRECISION ON DE FROM THE LSST

Will map 20000 square degrees with 4 Billion galaxies

All 4 probes + more

Figure of Merit by 2030 will be close to ~1000
The large SN Ia statistic will allow to build SN Ia Hubble diagram for different directions in the sky. Will provide time-dependent imaging of an unprecedented sample of rare strong gravitational lensing events. => sensitive to H(z) at the lens location

LSST: DE Science with High Statistics SN Ia

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THE EUCLID SPACE MISSION

• A ESA space mission with visible and Infrared observations of all sky, both in photometry and spectroscopy

• a wide survey of 15000 deg$^2$ and a deep survey of 40 deg$^2$

• Will measure the expansion history $H(z)$ to unprecedented accuracy, with good control of systematic effects:
  – Using Weak Gravitational Lensing from high-resolution imaging survey
  – Using Baryonic Acoustic Oscillations from a large spectroscopic survey

• Expected launch date : ~2020
• FoM after 6 years ~1000

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SUMMARY

• Understanding Dark Energy is a key question - New physics may be at reach

• Several approaches are followed, based on astronomical observations, and implemented in several (large) world wide efforts

• Using Multiple and Combined probes is key to reduce uncertainties (incl. systematics) and allows testing of GR

• An ambitious program : building instruments, software, simulation, analyses, … is now being put together

• Lots of data to come –
UNDERSTANDING THE MECHANISM DRIVING ACCELERATION

Extracted from the US P5 planning exercise
Trends in Optical Astronomy Survey Data

- CCD pixels total
- CCD survey galaxies / year
- Glass area, sq.cm
- Transistors / CPU