Dark Matter, Dark Energy and Distant Galaxies

Prof. Eric Gawiser

Hubble Space Telescope Image (UVUDF)
Pop Quiz!

2/3 of the universe's energy is...  dark energy

4/5 of the universe's matter is...  dark matter

3/4 of the baryonic matter is...  hydrogen
A Standard Model of Cosmology: \( \Lambda \text{CDM} \) (after Planck)

Age of universe: 13.8 Gyr
Average curvature: flat (\( \Omega_{\text{total}} = 1.00 \))
Dark Energy: 68\% (\( \Omega_{\text{DE}} = 0.68 \))
Dark Matter: 27\% (\( \Omega_{\text{DM}} = 0.27 \))
Baryons: 5\% (\( \Omega_{\text{B}} = 0.05 \))
Primordial power spectrum: \( n = 0.96 \) (consistent with inflation)
What the Universe is currently made of:

- Dark Energy: 70%
- Dark Matter: 25%
- Free Hydrogen & Helium: 4%
- Stars: 0.5%
- Neutrinos: 0.3%
- Heavy Elements: 0.03%
Let There Be Light!

- Afterglow Light Pattern 400,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.
- Big Bang Expansion
- 13.7 billion years
Motivation

"A revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration."

(Dark Energy Task Force, Albrecht et al. 2006)
What is Dark Energy?

\[ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3} \]

We observe \( \ddot{a} > 0 \) which can happen in 3 ways:

- Non-zero cosmological constant: \( \Lambda > 0 \)
- Universe is dominated by some particle or field with: \( \rho + 3P < 0 \)
  \[ w = \frac{P}{\rho} < -1/3 \]
- The equation is not a proper model:
  - GR is incorrect or incomplete.

slide from Saurabh Jha
Cosmic Microwave Background anisotropy, Large-scale structure both show Baryon Acoustic Oscillations (BAO)

Percival et al. 2007

SDSS
Baryon Acoustic Oscillations

Baryon Acoustic Oscillation signal on 150 Mpc comoving
= 1-2 degree angular scales

sdss3.org
The Hobby Eberly Telescope Dark Energy Experiment (HETDEX):

→ Spectroscopic survey on upgraded 9-meter Hobby-Eberly Telescope
→ 400 square degrees
→ 700,000 redshifts of distant galaxies from Lyman Alpha emission
→ Reveal dark energy properties via clustering of those galaxies
→ Discriminate between dark energy and modifications to General Relativity as cause of cosmic acceleration

TIMELINE: 2018-2024
PRICETAG: $40M
Project Scientist: Karl Gebhardt (UT Austin, Rutgers Ph.D. 1994)
HET is the world’s fourth largest telescope. It is being upgraded with a powerful new instrument consisting of 150 units, VIRUS (Visible Integral-field Replicable Unit Spectrograph).
The active galaxy NGC1068, imaged using an Integral Field Unit
Image: Stephen Todd, ROE and Douglas Pierce-Price, JAC.
Several HETDEX Emission Lines
Vera C. Rubin Observatory’s Legacy Survey of Space and Time (LSST)

**TIMELINE:** 2022-2032

**Director:** Steve Kahn

**PRICETAG:** $600M (NSF+DOE+donors)
LSST: A Dedicated Survey

$r<24.5 \, (<27.5@10\text{yr}) \quad 18000+ \, \text{deg}^2 \quad 10\text{mas astrom.} \quad 0.5-1\% \, \text{photometry (sys)}$

Imaging the visible sky, once every 3 days, for 10 years (825 revisits)

"LSST" is the database. The Google Index of the Optical Sky
slide from Mario Juric
LSST: Data Volume

- 15 TB of raw scientific image data (=3,000 DVDs) per night
- 60 PB of raw data (=12 million DVDs) over 10-year survey
- Catalog of 40 billion objects (25B galaxies, 15B stars)
- Catalog of 30 trillion photometric measurements
- 2 million "events" per night, for 10 years
- Will transmit alerts to the world within 60 seconds
LSST will study Dark Energy with 1 billion distant galaxies

Survey covers 20,000 square degrees (half the sky)

Baryon Acoustic Oscillations via angular clustering will determine distances to 1%, which measures dark energy equation-of-state to 5% ($\delta w = 0.05$)
Blake & Bridle 2005, Seo & Eisenstein 2003

Compare with other techniques (weak lensing, Type Ia supernovae from LSST) to see evolution in $w$ (a.k.a. $w_a$)
LSST will study Dark Energy with 1 billion distant galaxies

Forecasted 68% credible regions on \((w_0, w_a)\) for individual probes and their combination after all LSST data is analyzed.

\[
P = w \rho
\]

\[
w = w_0 + w_a(1-a)
\]

LSST-DESC Science Requirements Document v1, arXiv:1809.01669
The Cosmological Principle

On large scales, the Universe looks statistically the same at all locations (homogeneity) and in all directions (isotropy).

Testing the Cosmological Principle:

Check for inhomogeneities in behavior of dark energy/modified gravity by comparing expansion rate and structure growth along multiple lines of sight

(See LSST Science Book Fig.15.12)
Non-trivial survey design task to cover 18,000 square degrees divided into 2000 pointings, each observed ~150 times in each of 6 filters. Feasibility shown via Operations Simulator (OpSim)
Simulation enigma_1189: night25

Aitoff plot showing HA/Dec of simulated survey pointings

- 20 deg elevation limit
- Galactic plane
- Moon (Dark=Full) (Light=New)
- Zenith
- Ecliptic plane

Year 0 Day 25.3690

https://www.youtube.com/watch?v=GW---5VehuE

Slide from Lynne Jones (UW)
LSST Image Simulations

Photon Simulator (PhoSim) used by LSST Dark Energy Science Collaboration for Data Challenges

100 Million CPU hours at National Energy Research Scientific Computing Center (NERSC) used to simulate 1% of survey area
Breaking News: First LSST Camera Images

A next-generation Cosmic Microwave Background telescope array

We are building a series of telescopes to collect photons from the Cosmic Microwave Background (CMB), the most ancient light in the universe. The CMB is the relic radiation that began propagating freely shortly after the big bang, nearly 14 billion years ago. These primordial photons can answer questions in subjects ranging from cosmology and fundamental physics to the astrophysics of distant objects.

The properties of the CMB tell us about the condition of the universe at the time that this light was first emitted. By looking at the CMB today, we learn about the distant, ancient universe; this is the beauty of CMB cosmology.
Rutgers Astrophysics Faculty

Andrew Baker – submillimeter observations of distant galaxies
Alyson Brooks – computer simulations of nearby galaxies
Matt Buckley – dark matter & astroparticle physics
Blakesley Burkhart – turbulence & star formation
Eric Gawiser – observational cosmology & galaxy formation
Jack Hughes – X-ray observations of clusters, supernova remnants, Atacama Cosmology Telescope
Saurabh Jha – Type Ia Supernovae, dark energy
Chuck Keeton – gravitational lensing
Kristy McQuinn – star formation in nearby galaxies
South African Large Telescope (10m)
Rutgers owns 10%
For spectroscopic redshifts
Some Considerations About Astrophysics

- easy to do small project to “get your feet wet” or test your interest
- opportunities to travel for observing and conferences
- close connection between data and interpretation
- sometimes conclusions are approximate/speculative
- Two Ph.D. students working with me graduated recently, so let me know if you’re looking for a research project in this area!
Conclusions

• Dark Energy is a mystery driving major new collaborations
• Rutgers is active in several of these, including
  – HETDEX (Gawiser)
  – LSST (Jha, Keeton, Hughes, Gawiser)
  – Simons Observatory (Hughes, Gawiser)
• HETDEX will use 700,000 Lyman Alpha Emitting galaxies to measure the curvature of the universe and the dark energy equation-of-state and to test for modifications to General Relativity
• "Big Data" from LSST will
  – Identify Earth-killer asteroids
  – Find more Plutos
  – Map the structure of the Milky Way's 100 billion stars
  – Measure the sum of neutrino masses to 0.02 eV precision
  – Test the cosmological principle
  – Determine the cause of cosmic acceleration