Cosmic acceleration

1998 - Discovery
2000-2010: confirmation (CMB, LSS, SNe)
  • more precise constraints
  • $w = -1 \pm 0.2$ (with assumptions)

Questions:
  • What is causing cosmic acceleration?
    • Vacuum energy ($\Lambda$) or something else?
    • Dark Energy (DE) or Modification of GR (MG)?

Projects (on-going or under-construction)
  • BOSS, HETDEX, DES, PS-1, SZ surveys: SPT, ACT...

Future: coherent program (ground and space)
  • LSST/PanSTARRS + JDEM
Marginalize over all other parameters find uncertainties in $w_0$ and $w_a$

\[ \rho_{\text{DE}} = \rho_{\text{DE \ (today)}} \exp \left\{ -3 \int [1 + w(a)] \, d \ln a \right\} \]

$\Lambda$CDM: $w(a) = -1$

\[ w(a) = w_0 + w_a(1 - a) \quad w = w_0 \ \text{today} \quad \& \quad w = w_0 + w_a \text{ in the far past} \]

Errors in $w_0$ and $w_a$ are correlated

$\Lambda$CDM value

$\text{DETF FoM} = (\text{area of ellipse})^{-1}$

Errors in $w_0$ and $w_a$ are correlated
Determining the effect of dark energy on the expansion history of the universe by determining $w(a)$

1. Assume growth of structure described by GR
2. Marginalize over all non-$w$ “nuisance” parameters
3. Perform “Principal Component Analysis” of $w(a)$
4. Then assume simple parameterization $w(a) = w_0 + w_a (1 - a)$ and calculate $s(w_p)$, $s(w_a)$, and $z_p$.
• Graph of principal components as function of $z$ informs on redshift sensitivity of technique [analogous to $z_p$] (may want first few PCs)

• Desirable to have reasonable redshift coverage

• Can visualize techniques independently and in combination
Wide field survey facilities

**Ground based:** LSST and PanSTARRS(1,4,16)

**Space:** JDEM and EUCLID

A principal driver of all projects is dark energy.
- BAO
- Weak lensing
- Finding clusters at high z

LSST and PanSTARRS are both imaging only.
PanSTARRS

- **Panoramic Survey Telescope And Rapid Response System**
- A fore-runner to the LSST, funded by AFRL
- A dedicated optical survey instrument, 54 m²deg²
- Collaboration between:
  - IfA
  - MHPCC: Data processing
  - SAIC: Databases
  - MITLL: Detectors
- 1.8m telescope, f/4, 7 deg² FoV, ADC option
- Filters: grizy, SS (V+R)
- In operation now
PanSTARRS-16

**LASST**: Deployment of 3 clones of PanSTARRS-4 at 3 other sites

- 2 in northern/southern hemisphere
- 2 in western/eastern hemisphere

Full sky coverage
Science with Pan-STARRS

- **Moving Object Science**
  - NEO - Near Earth Object threat
  - OSS/MBO - Main Belt and Other Solar System science
  - KBO - Kuiper Belt Objects
  - SOL - Solar Neighborhood (parallaxes and proper motions)

- **Static and Invariable Object Science**
  - WL - Weak Lensing
  - LSS - Large Scale Structure
  - LSB - Low Surface Brightness and dwarf galaxies
  - SPH - Spheroid formation
  - EGGS - Extragalactic and Galactic Stellar science

- **Transient and Variable Object Science**
  - AGN - Active Galactic Nuclei
  - SNE - Supernovae
  - GRB - Gamma Ray Bursts and afterglows
  - EXO - Exoplanets (occulation)
  - YSO - Young Stellar Objects
  - VAR - Variability Science (especially stars)

- **TGBN** (Things that Go Bump in the Night)
SNE Project (Tonry)

- Using Medium-Deep, Ultra-Deep surveys
- Goal is to measure \( w(z) \) to 10% over \( 0 < z < 1 \)
- 5,000 SNe Ia per year, \( 0 < z < 1 \)
  - Most found on the rise
  - 80 per month @ \( I < 22 \) mag
  - 350 per month @ \( 22 \) mag < \( I < 24 \) mag
- Spectrographic follow-up required
  - 365 nights/year on an 8m-class
Pan-STARRS: In General

• Estimate \( \sim 10^4--10^5 \) SNe of all types per year discovered by Pan-STARRS

• In general (i.e., apart from Tonry SN program):
  – Limited colour information (e.g. SS program)
  – Limited temporal information (e.g. 3p survey)

• Need follow-up resources to identify interesting variable sources (SN types, GRB, unknowns)

• SN studies limited by spectroscopic resources
## Survey Modes

- 7 \text{deg}^2, 30 \text{sec} \text{ integrations} \rightarrow 6000 \text{deg}^2/\text{night}, or \text{visible sky thrice per lunation to } R \sim 24 \text{ mag}

<table>
<thead>
<tr>
<th>Mode</th>
<th>PSY</th>
<th>Area</th>
<th>Cad.</th>
<th>SS</th>
<th>B/g</th>
<th>r</th>
<th>i</th>
<th>z</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS NEO</td>
<td>1.1d 0.2b</td>
<td>7000</td>
<td>h/d/m</td>
<td>27.5</td>
<td>300</td>
<td>28.8</td>
<td>28.7</td>
<td>25.1</td>
<td></td>
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<tr>
<td>SS KBO</td>
<td>1.0d 0.2b</td>
<td>3π</td>
<td>hdmy</td>
<td>26.5</td>
<td>60</td>
<td>28.8</td>
<td>28.7</td>
<td>25.1</td>
<td></td>
</tr>
<tr>
<td>Var.</td>
<td>0.8d 0.8b</td>
<td>133</td>
<td>4 min</td>
<td>29.4</td>
<td>22000</td>
<td>28.8</td>
<td>28.7</td>
<td>25.1</td>
<td>4400</td>
</tr>
<tr>
<td>3π</td>
<td>1.3d 2.5b</td>
<td>3π</td>
<td>14d</td>
<td>26.1</td>
<td>30</td>
<td>25.8</td>
<td>25.6</td>
<td>24.1</td>
<td>22.5</td>
</tr>
<tr>
<td>Med. Deep</td>
<td>0.6d 0.9b</td>
<td>1200</td>
<td>4d</td>
<td>27.3</td>
<td>271</td>
<td>27.2</td>
<td>27.5</td>
<td>25.2</td>
<td>24.2</td>
</tr>
<tr>
<td>Ultra Deep</td>
<td>0.5d 0.7b</td>
<td>28</td>
<td>4d</td>
<td>29.3</td>
<td>10000</td>
<td>29.2</td>
<td>28.2</td>
<td>27.2</td>
<td>26.2</td>
</tr>
</tbody>
</table>

**5-σ limit (AB)**

**Total int. (min)**

Survey Modes

- 7 \text{deg}^2, 30 \text{sec} \text{ integrations} \rightarrow 6000 \text{deg}^2/\text{night}, or \text{visible sky thrice per lunation to } R \sim 24 \text{ mag}
Data Products

- Subtracted images
- List of transients identified in subtracted images
  - Depending upon cadence, may be uncertainty in proper motion for up to several days
- Static sky images
- Source catalogues
- Client Science Programs will plug in to have access to the streams (e.g. planet occultations)
- Other access via Virtual Observatory
Final Data Products

- **Sky, the wallpaper:**
  - 10 Tpix x 6 colors x N versions

- **Sky, the movie:**
  - 10 Tpix x 6 colors x 50 epochs

- **Sky, the database:**
  - $2 \times 10^{10}$ objects (x 6 colors x 20-60 epochs)
  - $10^9$ proper motions (complete over 3)
  - $10^8$ variable stars and AGN
  - $10^7$ asteroids ($10^4$ NEO/PHA)
  - $10^7$ transients (SN, GRB, etc.)
  - $3 \times 10^5$ stars within 100 pc (with good parallax)
LSST Technical Concept

- 8.4 Meter Primary Aperture
  - 3.4 M Secondary
  - 5.0 M Tertiary
- 3.5 degree Field Of View
- 3 Gigapixel Camera
  - 4k x 4k CCD Baseline
  - 65 cm Diameter
- 30 Second Cadence
  - Highly Dynamic Structure
  - Two 15 second Exposures
- Data Storage and Pipelines Included in Project
LSST: overview

• Unique time domain opportunities
• Large area, 3.5 deg FOV
• 6 filters: u,g,i,r,z,y
• 30,000 sq deg coverage to r=24.5 in single visit
• Rapid response, 1 min alert
• 90%: uniform, deep, wide, fast survey
  • 1000 revisits over 20,000 sq deg
  • co-added map w/ point source limit @ 27.5mag
• 10%: very deep and fast time domain

• 8.4m outer, 5m inner => effective aperture of 6.7m
• Etendue = 319 m

Important point: all measurements made with same basic set of observations, using facility designed for this purpose.
Why is the LSST unique?

- **Primary mirror diameter**: 10 m
- **Field of view**: 3.5 degrees (full moon is 0.5 degrees)
Relative Survey Power

![Relative Figure of Merit for LSST, Pan-STARRs, DEC, Subaru, CFHT, SDSS, and MMT, with time, stellar, and galactic power phases.]
Principle LSST Science “Missions”

- **Dark Energy / Matter**
  - Weak lensing - PSF Shape / Depth / Area
  - Super Novae + Photo z - Filters /
- **Map of Solar System Bodies**
  - NEA - Cadence
  - KBO - faint multicolor survey w/ frequent time sampling & relative photometric accuracy of 0.005 mag => light curves => rotation periods, shape, spin
- **Optical Transients and Time Domain**
  - GRB Afterglows - Image Differencing
  - Unknown transients -
- **Assembly of the Galaxy and Solar Neighborhood**
  - $10^9$ stars: light curves, geometric parallax, proper motions
    - Similar accuracy to Hipparcos but 10 mags fainter!
  - Galactic Halo Structure and Streams from proper motions
  - Parallax to 200pc below H-burning limit
LSST and Dark Energy

• **LSST will measure 250,000 resolved high-redshift galaxies per square degree!**
  The full survey will cover 18,000 square degrees.

• Each galaxy will be moved on the sky and slightly distorted due to lensing by intervening dark matter. Using photometric redshifts, we can determine the shear as a function of $z$.

• **Measurements of weak lensing shear over a sufficient volume can determine DE parameters through constraints on the expansion history of the universe and the growth of structure with cosmic time.**
Cosmological Constraints from Weak Lensing Shear

Underlying physics is extremely simple General Relativity: FRW Universe plus the deflection formula. Any uncertainty in predictions arises from (in)ability to predict the mass distribution of the Universe.

Method 1: Operate on large scales in (nearly) linear regime. Predictions are as good as for CMB. Only "messy astrophysics" is to know redshift distribution of sources, which is measurable using photo-z's.

Method 2: Operate in non-linear, non-Gaussian regime. Applies to shear correlations at small angle. Predictions require N-body calculations, but to ~1% level are dark-matter dominated and hence purely gravitational and calculable with foreseeable resources.

Hybrids: Combine CMB and weak lens shear vs redshift data. Cross correlations on all scales.
Measurement of the Cosmic Shear Power Spectrum

• A key probe of DE comes from the correlation in the shear in various redshift bins over wide angles.

• Using photo-z’s to characterize the lensing signal improves the results dramatically over 2D projected power spectra (Hu and Keeton 2002).

• A large collecting area and a survey over a very large region of sky is required to reach the necessary statistical precision.

• Independent constraints come from measuring higher moment correlations, like the 3-point functions.

• LSST has the appropriate etendue for such a survey.

From Takada et al. (2005)
Constraints on DE Parameters

From Takada et al. (2005)
LSST Optical Design

M2 3.4m f/0.92
M3 5.0m f/0.84
M1 8.4m f/1.14

Flat 3.5 deg. FOV
0.64m dia. @ f/1.2

L3 0.73m
Filter 0.74m
L2 1.13m
L3 1.54m

1.75 deg
1.0 deg
0 deg

0.6”
Focal plane array

201 CCDs total

Raft = 9 CCDs
+ 1cm x 1cm reserved for wavefront sensors

3.5° FOV → 64 cm

Strawman CCD layout
4K x 4K, 10 µm pixels
32 output ports
LSST Data Management Infrastructure

15 Tb/night!

Archive Computing Center
- 1 PB disk
- 25 TFLOP
- 10^3 to 4 km
- .35 GB/s

Base Camp Center
- 150 TB disk
- 10 TFLOP
- 10^1 to 2 km
- 1.2 GB/s

Telescope Site
- 15 TB disk, 5 TFLOP
- 10^-1 km
- .6 GB/s

Mirror Sites
- 10^3 to 4 km
- .4 GB/s

Portal
- Portal User
- GRID, Internet 2

Notes: B = bytes, b = bits
LSST Project Organization

- Three main sub-project teams:
  
**Telescope/Site (NSF):**

*NOAO, U. of Arizona, LLNL*

**Camera (DOE):**

*SLAC, BNL, LLNL, Harvard, UIUC, UCSC, OSU, U. of Penn, ...*

**Data Management (Both):**

*NCSA, LSSTC, LLNL, SLAC, U. of Arizona, U. of Washington, Princeton, Harvard, ...*
On December 1, 2009 the Chilean Regional Authority of the Environmental Protection Agency (COREMA) unanimously approved the LSST environmental impact statement, thereby granting the permits for LSST construction and operation on Cerro Pachón.

Craig Foltz talk to AAAC
Joint Dark Energy Mission (JDEM)

NASA and DOE program for space-based dark energy mission
  • Mission design/spec still evolving JDEM, JDEM-Omega
    but something like:
      • 1.5m aperture
      • 200 Megapixel NIR imager (0.8 – 2 microns)
      • 3? Filters
      • 0.2 arcsec filters
      • Grism spectroscopy (redshifts)
Dark energy probes

• BAO: distances; low systematics
  • Ground: $z < 1.5$; space: $z > 1.5$, NIR
• SNe: distances; mature method
  • Ground: $z < 0.8$ optical; space: $z < 0.8$ (NIR) and/or $z > 1$ optical
• WL: distances+growth of structure; high statistical power
  • Ground vs space: NIR helps photo-z’s, stable platform above atmosphere for shapes
• CL: distances+growth; optical+SZ+Xray+lensing;
  • Piggyback on WL surveys

• Need both distances and growth to distinguish DE from MG
• Multiple probes also provide systematics cross-checks and combined for more powerful constraints on $w$ and its evolution
• Disagreement about which probes are best (or must be) done from space vs. ground; uncertainties in systematics levels.
• Must push to much greater sensitivity than current.
LSST + JDEM Program

Dark energy plus other science (value added)
LSST: wide, fast, deep surveying; opens up time domain
JDEM*: wide, deep, high resolution NIR surveys

Need combined program

- LSST optical + JDEM NIR photometry for WL photo-z's + shapes
- JDEM NIR SNe followup requires large optical SN survey from ground
- Large ground-based BAO redshift survey to z~1 (BigBOSS)
- Ground-based spectroscopy for SNe survey followup