Supernovae, Acceleration, and Alternative Gravity

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ADM-50: A Celebration of Current GR Innovation 7/8 Nov 2009
Dick Arnowitt

The Dynamics of General Relativity
REPORT OF THE
DARK ENERGY TASK FORCE

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Robert Cahn, Lawrence Berkeley National Laboratory
Wendy L. Freedman, Carnegie Observatories
Jacqueline Hewitt, Massachusetts Institute of Technology
Wayne Hu, University of Chicago
John Huth, Harvard University
Marc Kamionkowski, California Institute of Technology
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Lloyd Knox, University of California, Davis
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IV. Findings of the Dark-Energy Task Force

1. Four observational techniques dominate the White Papers received by the task force. In alphabetical order:
   a. Baryon Acoustic Oscillations (BAO) are observed in large-scale surveys of the spatial distribution of galaxies. The BAO technique is sensitive to dark energy through its effect on the angular-diameter distance vs. redshift relation and through its effect on the time evolution of the expansion rate.
   b. Galaxy Cluster (CL) surveys measure the spatial density and distribution of galaxy clusters. The CL technique is sensitive to dark energy through its effect on a combination of the angular-diameter distance vs. redshift relation, the time evolution of the expansion rate, and the growth rate of structure.
   c. Supernova (SN) surveys use Type Ia supernovae as standard candles to determine the luminosity distance vs. redshift relation. The SN technique is sensitive to dark energy through its effect on this relation.
   d. Weak Lensing (WL) surveys measure the distortion of background images due to the bending of light as it passes by galaxies or clusters of galaxies. The WL technique is sensitive to dark energy through its effect on the angular-diameter distance vs. redshift relation and the growth rate of structure.
can’t get no respect…

H(z) using almost completely linear physics (unlike SNIa for example which involve highly complex, nonlinear, poorly understood stellar explosions). In addition, they offer the as yet unproven possibility of delivering constraints on growth though the change in the amplitude of the power spectrum. The time-dependence of the matter density perturbations, \( \delta \rho/\rho \) obeys the equation

\[
\frac{\dot{\delta}}{\dot{\bar{\rho}}} = -2 H \frac{\delta}{\bar{\rho}} - \frac{\dot{H}}{H^2} + \frac{\ddot{\bar{\rho}}}{H^2},
\]

**COSMOLOGY**

Dark is the new black

Richard Massey

Rival experimental methods to determine the Universe’s expansion are contending to become the fashionable face of cosmology. Fresh theoretical calculations make one of them the hot tip for next season.

Earth, however, the accelerating expansion of the Universe means that distant supernovae have already receded farther from us and look even fainter. Initial enthusiasm for using supernovae as cosmic distance indicators, and thus as a probe of the Universe’s expansion, garnered vast allocations of time on ground- and space-based telescopes, and triggered the first plans for a dedicated, all-sky successor to the Hubble Space Telescope. Unfortunately, the explosions were later found to depend on the stars’ environment and ingredients, which evolve over cosmic time. Such effects can be parameterized only to a certain precision, and the technique is falling out of fashion.

Distances can also be determined from th-
Supernovae
SN spectra

Type Ia

Core Collapse

Type Ib/c & Type II

(a) SN 1987N (Ia), t ~ 1 week
(b) SN 1987A (II), t ~ 1 week
(c) SN 1987M (Ic), t ~ 1 week
(d) SN 1984L (Ib), t ~ 1 week

Rest Wavelength (Å)

-2.5 log fν + Constant

Sn spectra types:

- Type Ia
- Core Collapse
- Type Ib/c & Type II

Wavelength regions:

- 4000 Å to 10,000 Å

Elements and lines:

- Ca II
- Mg II
- Si II
- Fe II
- S II
- O I
- Si II
- Mg II
- Ca II
- Hα, Hβ, Hγ
- Na I
- Fe II
- He I
- Fe II
- Ca II
Fig. 13.— Combined optical and IR maximum-light spectra of the Type II SN 1999em, the Type Ib/c SN 1999ex, and the Type Ia SN 1999ee.
General light curves

$^{56}\text{Ni} \rightarrow \text{\textit{56Co}} \rightarrow \text{\textit{56Fe}}$
One parameter family

Color

Rate of decline

Peak brightness

Suntzeff (1996)

Phillips (1993)
Absolute magnitudes of Type Ia SNe

\[ M_{\text{max}} = -2.5 \log_{10}(\text{Lum}) + c \]

\( H, K \) probable standard candles

400nm

550nm

750nm

1600nm
Hubble Diagram
effects of correction to $\Delta m_{15}$
Peak effect for L is at about $z \sim 0.8$.

We are looking for about a 0.25m effect.
Equation-of-State Signal

Assume

\[ P = w \rho c^2 \]

Difference in apparent SN brightness vs. \( z \)

\[ \Omega_\Lambda = 0.70, \text{ flat cosmology} \]
My history in SNe or
I am not part of the Harvard Group - they are
a part of my group.

- 1986G & 1989B with Mark Phillips
- 1989 - Sandage challenge to measure $H_0$ and $q_0$ with Ia’s
- 1990-4 - Calan/Tololo Survey to calibrate Ia: Hamuy, Maza, Phillips, & Suntzeff
- 1994 - Schmidt & Suntzeff start High-Z SN Search Team
- 1998 - Riess et al. & Perlmutter et al. announce $q_0 < 0$
- 2002 - ESSENCE founded
- 2005 - Carnegie Supernova Project founded
The ESSENCE Survey

- Determine \( w \) to 10% or \( w! = -1 \)
- 6-year project on CTIO/NOAO 4m telescope in Chile; 12 sq. deg.
- Wide-field images in 2 bands
- Same-night detection of SNe
- Spectroscopy
  - Keck, VLT, Gemini, Magellan
- Goal is 200 SNeIa, \( 0.2 < z < 0.8 \)
- Data and SNeIa public real-time
ESSENCE Status
Summary

- 200 SNeIa from 2002-2007
- 60 good light curves (Wood-Vasey, et al 2007)
- Data from Keck, Gemini, VLT, CTIO, HST
- 6.2 Ia per sq-deg per month
Gold→Union→Constitution→?? set

SDSS SN plot
Lesson in plotting

Being from Texas, I suggest the Confederate Set is next
Carnegie Supernova Project

- Phillips, Freedman, Hamuy, Madore, Burns, Follatelli, Cadenas, Suntzeff
High-z project

I-band measurements
Cosmology fits
Carnegie Low-z Sample

- 5-year project, 270n per year on 1m Swope + nights on Magellan, du Pont, VLT
- Ending 2009 (around now)
- $ugriBVYJHK_s$. $K_s$ with WIRC on duPont
- Spectra where we can [more hot spectrographs on 2m telescopes are needed]
- Follow all types with $z \leq 0.08$ (if caught early)
- 200 Sne with 100 Type Ia
What we are trying to do

- So many data samples with so many methods of analysis have confused us

- We want to “rewrite” history, that is, start with a clean data set and redo our analyses to find the weaknesses of our techniques.

- Purely phenomenological guided by simple physics

- Basic parameter - $\Delta m_{15}$, *measured from the light curves, NOT from a black box program*

- Measure photometry in the natural system with measured precise transmission functions

- Ultimately the goal is an accuracy of <1% in distance for cosmology with no systematics.
Flat, isotropic, constant-$w$

$w = -1.05 \pm 0.11 \pm 0.13$

(Wood-Vasey et al., submitted to ApJ)
Flat, isotropic, constant-$w$

\[ w = -1.07 \pm 0.09 \pm 0.13 \]

(Wood-Vasey et al., submitted to ApJ)
Summary of Sample

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
The secondary maximum is not tightly correlated with the peak luminosity.

Bolometric light curves
Hubble Diagram

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

$\delta m = 0.12$

$\delta z = 0.001$
Potential sources of systematic error

- Flux calibrations
- Bias in distance determination codes
- Extinction
  - Host galaxy
  - Our Galaxy
  - Atmosphere
- Extinction law
- Passband errors
  - K corrections
  - Photometry normalization
- Nonlinearity in flux measurements
More Potential Systematics

- “Hubble bubble” trouble
- Gravitational lensing
- Evolutionary effects in SNe
- Biases in low redshift sample
- Search efficiency/selection
Table 5. Potential Sources of Systematic Error on the Measurement of $w$

<table>
<thead>
<tr>
<th>Source</th>
<th>$dw/dx$</th>
<th>$\Delta x$</th>
<th>$\Delta w$</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>Phot. errors from astrometric uncertainties of faint objects</td>
<td>1/mag</td>
<td>0.005 mag</td>
<td>0.005</td>
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<tr>
<td>Bias in diff im photometry</td>
<td>0.5 / mag</td>
<td>0.002 mag</td>
<td>0.001</td>
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<tr>
<td>CCD linearity</td>
<td>1 / mag</td>
<td>0.005 mag</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Photometric zeropoint diff in $R,I$</td>
<td>2 / mag</td>
<td>0.02 mag</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Zpt. offset between low and high $z$</td>
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<td>0.02 mag</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>K-corrections</td>
<td>0.5 / mag</td>
<td>0.01 mag</td>
<td>0.005</td>
<td></td>
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<tr>
<td>Filter passband structure</td>
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<td>0.001 mag</td>
<td>0</td>
<td></td>
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<tr>
<td>Galactic extinction</td>
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<td>0.01</td>
<td></td>
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<tr>
<td>Host galaxy $R_V$</td>
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<td>0.5</td>
<td>0.01</td>
<td>“glosz”</td>
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<td>Host galaxy extinction treatment</td>
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<td>prior choice</td>
<td>0.08</td>
<td>different priors</td>
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<td>Intrinsic color of SNe Ia</td>
<td>3 / mag</td>
<td>0.02 mag</td>
<td>0.06</td>
<td>interacts strongly with prior</td>
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<tr>
<td>Malmquist bias/selection effects</td>
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<td>0.03 mag</td>
<td>0.02</td>
<td>“glosz”</td>
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<tr>
<td>SN Ia evolution</td>
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<td>0.02 mag</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Hubble bubble</td>
<td>$3/\delta H_{effective}$</td>
<td>0.02</td>
<td>0.06</td>
<td></td>
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<tr>
<td>Gravitational lensing</td>
<td>$1/\sqrt{N}$ / mag</td>
<td>0.01 mag</td>
<td>$&lt; 0.001$</td>
<td>Holz &amp; Linder (2005)</td>
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<tr>
<td>Grey dust</td>
<td>1 / mag</td>
<td>0.01 mag</td>
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<tr>
<td>Subtotal w/o extinction+color</td>
<td>⋯</td>
<td>⋯</td>
<td>0.082</td>
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<tr>
<td>Total</td>
<td>⋯</td>
<td>⋯</td>
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<td>⋯</td>
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<tr>
<td>Joint ESSENCE + SNLS Total</td>
<td>⋯</td>
<td>⋯</td>
<td>0.13</td>
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</table>
Fig. 2.— Binned supernova data vs. redshift compared to a flat $\Lambda$CDM model with $\Omega_M = 0.369$. The filled circles are binned points from the full dataset, while the open circles have omitted the “Silver” subset.
Figure 3. Evolution of $w_{de}$, the dark energy's ratio of pressure to energy density, as determined from the supernova data. Negative pressure tends to accelerate the cosmic expansion. If the dark energy is the vacuum energy of Einstein’s cosmological constant, $w_{de}$ is $-1$ forever (dotted line). Competing quintessence models let $w_{de}$ change over time. The Higher-Z team concludes, with 98% confidence, that $w_{de}$ was already negative from redshift 1.8 to 1.0, that is, from 10 to 6 billion years ago. (Adapted from ref. 3.)

Figure 4. Ancient and recent spectra of type 1a supernovae show no evolutionary change over 10 billion years. The green band is a composite spectrum of the Higher-Z team’s 13 best-measured supernovae with redshifts $z$ above 1, transformed into each exploding star’s rest frame. The black curve with gray error bars is a template used to verify the type 1a designation for supernovae with redshifts less than 0.1, which would have exploded within the past billion years or so. (Adapted from ref. 3.)
Summary

- The accelerating Universe poses a significant challenge to theory, experiment and observation.
- Current goal: $w$ to 10%
- The SNIa data are consistent with a flat Universe with a cosmological constant.
Time Dilation in the Universe

Fig. 10.— Upper panel: comparison of supernova rest-frame ages (in days from maximum light) obtained from cross-correlation with spectral templates ($t_{90\%}$) and from fits to the light curve ($t_{90\%}$). 145 age measurements for the subsample of 22 low-redshift SNe Ia are shown in gray. The dashed line represents the one-to-one correspondence between $t_{90\%}$ and $t_{90\%}$. Middle panel: Age residuals, $\Delta t = t_{90\%} - t_{90\%}$. We also indicate the standard deviation ($\sigma$) and mean residual ($\mu$). Lower panel: Same as above, where each point has been corrected for the mean offset between $t_{90\%}$ and $t_{90\%}$ for a given supernova.

No “tired light” - whoopee
**Fig. 1.** Evidence for dark matter or for deviations from GR tend to appear in systems in which the acceleration scale is weak (below the solid horizontal line) at about $10^{-8}$ cm s$^{-2}$. There is strong evidence for either of the above in dwarf galaxies, spiral galaxies, clusters of galaxies, the large-scale structure of the universe, and in the expansion of the universe itself. [Source: X-ray: NASA/CXC/CfA/M. Markevitch et al.; Optical: NASA/STScI; Magellan/U. Arizona/D. Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U. Arizona/D. Clowe et al.]
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
## Dwarf Spheroidals in MOND

<table>
<thead>
<tr>
<th>Name</th>
<th>$R_{MW}$ (kpc)</th>
<th>$c$</th>
<th>$R_t$ (pc)</th>
<th>$M_V$</th>
<th>$L_V$ ($10^5 L_\odot$)</th>
<th>$V_T$ (km s$^{-1}$)</th>
<th>$r_\alpha$ (pc)</th>
<th>$\alpha_0$</th>
<th>$r_\beta$ (pc)</th>
<th>$\beta_0$</th>
<th>$M/L_V$ (pc)</th>
<th>$M/L_N$</th>
<th>$\chi^2_{red}$</th>
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<tr>
<td>Cartina</td>
<td>101 ± 5</td>
<td>0.51±0.08</td>
<td>581 ± 86</td>
<td>-9.3±0.2</td>
<td>4.4±1.1</td>
<td>8</td>
<td>2000</td>
<td>24</td>
<td>-294</td>
<td>76±7</td>
<td>150±110</td>
<td>120±85</td>
<td>0.6</td>
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<tr>
<td>Draco</td>
<td>93 ± 6</td>
<td>0.72±0.05</td>
<td>1225 ± 80</td>
<td>-9.0±0.3</td>
<td>3.3±1.1</td>
<td>-294</td>
<td>1500</td>
<td>14</td>
<td>75</td>
<td>76±7</td>
<td>450±150</td>
<td>120±85</td>
<td>0.93</td>
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<tr>
<td>Leo I</td>
<td>257 ± 3</td>
<td>0.39±0.07</td>
<td>1002 ± 50</td>
<td>-12.4±0.2</td>
<td>76±7</td>
<td>178</td>
<td>3700</td>
<td>22</td>
<td>178</td>
<td>400</td>
<td>400±600</td>
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<td>Sextans</td>
<td>93.5 ± 3</td>
<td>0.98±0.14</td>
<td>3445 ± 1141</td>
<td>-9.7±0.2</td>
<td>6.5±1.4</td>
<td>75</td>
<td>1200</td>
<td>6</td>
<td>75</td>
<td>76±7</td>
<td>1250±600</td>
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<tr>
<td>Fornax</td>
<td>138 ± 8</td>
<td>0.72±0.05</td>
<td>2078 ± 177</td>
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<td>158±16</td>
<td>-36</td>
<td>3200</td>
<td>14</td>
<td>-36</td>
<td>28±4</td>
<td>770±1500</td>
<td>770±1500</td>
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<td>Sculptor</td>
<td>87 ± 4</td>
<td>1.12±0.12</td>
<td>1329 ± 107</td>
<td>-11.1±0.2</td>
<td>28±4</td>
<td>95</td>
<td>1200</td>
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<td>95</td>
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<td>Leo II</td>
<td>233 ± 15</td>
<td>0.48±0.1</td>
<td>554 ± 68</td>
<td>-9.9±0.3</td>
<td>7.6±3</td>
<td>22</td>
<td>2500</td>
<td>30</td>
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<td>280±255</td>
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<tr>
<td>UMi</td>
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<td>1977 ± 104</td>
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<td>11.0±4.8</td>
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<td>6000</td>
<td>25</td>
<td>-87</td>
<td>-87</td>
<td>5000±4750</td>
<td>5000±4750</td>
<td>0.73</td>
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QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
Palomar 14

\[ \sigma = 0.38 \text{ km/s} \]

Fig. 10. — Theoretically predicted velocity dispersion as a function of mass. The two black curves are the predictions in MONDian dynamics (open circles) and in classical Newtonian dynamics (open squares). The observed velocity dispersions (and the errors) are drawn as the two horizontal lines, the light gray without Star 15, dark gray with Star 15. The vertical lines mark the observed lower mass limit and the two extrapolated lower mass limits.
Alternative Gravities

**TABLE 1**

<table>
<thead>
<tr>
<th>Model</th>
<th>Abbrev. a</th>
<th>Parameters b</th>
<th>Section</th>
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<tr>
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<td>$\Lambda$</td>
<td>$\Omega_m, \Omega_\Lambda$</td>
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<td>Fw</td>
<td>$\Omega_m, w$</td>
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<tr>
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<td>DGP</td>
<td>$\Omega_k, \Omega_{rc}$</td>
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<td>Ca</td>
<td>$\Omega_m, q, n$</td>
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<td>FGCh</td>
<td>$A, \alpha$</td>
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<tr>
<td>Gen. Chaplygin</td>
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<td>Ch</td>
<td>$\Omega_k, A$</td>
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</table>

a The abbreviations used in Figure 7. b The free parameters in each model. Note that when fitting the SN Ia data we also fit an additional parameter, $M$, for the normalization of SN magnitudes. We include this in the number of degrees of freedom and in $k$, but have not listed it here as a parameter in each model.

**TABLE 2**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2$/dof</th>
<th>GoF (%)</th>
<th>$\Delta$AIC</th>
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</tbody>
</table>

NOTE. — The flat cosmological constant (flat $\Lambda$) model is preferred by both the AIC and the BIC. The $\Delta$AIC and $\Delta$BIC values for all other models in the table are then measured with respect to these lowest values. The goodness of fit (GoF) approximates the probability of finding a worse fit to the data. The models are given in order of increasing $\Delta$AIC.

Here we choose several of the most popular models discussed in the literature and examine whether they are consistent with the data currently available to us:

1. Standard dark energy models, including varying $w$.
2. Dvali-Gabadadze-Porrati (DGP) brane world model.
3. Cardassian expansion.

Davis et al (2007)
Using Bayesian and Akaike Information Criteria
The Nature of Gravity

The growth of mass density perturbations depends on the expansion \textit{and} the theory of gravity.

The tension between cosmic distance measurements and large scale structure mass growth measurements reveals deviations from GR.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Diagram showing the relationship between $W_a$ and $W_0$.}
\end{figure}

$\Delta \gamma$ gives deviations in growth from GR

Huterer & Linder 2006
Closing thoughts

- The scale of dark matter
- DETF and future measures of dark energy
- The Hubble constant
- Gamma-ray bursts (a type of supernova)
The Bullet Cluster

Direct evidence for dark matter?
DETF - minority (me) report

- Era of \((N)^{-1/2}\) statistics - beware!
- Sne, BAO, Clusters, WL - we need to do more than 1
- SNe, BAO, Clusters, WL. Can’t we do better?
- Is \(w'\) even likely? That is, for \(w=\pm \varepsilon\) as \(\varepsilon \to 0\), does \(P(w' \neq -1) \to 0\) ? See Caldwell & Linder (2005) for restricting the search for \(w'\) given errors on \(w\) - thawing/freezing.
- Help observers find *easier* observations to do. Don’t forget Spergel’s law!
Nature is more creative than we are
Entire “thawing” region looks like $<w> = -1 \pm 0.05$. Need $w'$ experiments with $\sigma (w') \approx 2(1+w)$. 

Distinct, narrow regions of $w-w'$

Steepness of potential vs. Hubble drag

Caldwell & Linder 2005  
PRL 95, 141301; astro-ph/0505494
Dark Energy and Gravity

Is cosmic acceleration revealing a new ingredient (dark energy) or new laws of gravity?

Track record for gravity puzzles:

- Inner solar system motions $\rightarrow$ General Relativity
- Outer solar system motions $\rightarrow$ Neptune
- Galaxy rotation curves $\rightarrow$ Dark Matter

“Dark energy” could be new gravity.

Joint Dark Energy Mission (JDEM) is a gravity experiment.