0. Background on cosmology measurements from supernovae.

1. The science reach of SNAP for dark energy and dark matter.

2. Systematic uncertainties -- and the prerequisites for this science.

3. The complementarity of space based and ground based approaches.

4. SNAP technology readiness and technical status.

5. SNAP cost estimates.

No Big Bang

$\Omega = 3$ Universe

Supernova Cosmology Project
Perlmutter et al. (1998)

SNAP Target Uncertainty

Flattened $\Lambda = 0$ Universe

expands forever

recollapses eventually

mass density

vacuum energy density (cosmological constant)
There are different levels of precision at which one can work:

Past "standard cosmology" has been done with

-50% uncertainties

Recent work is moving towards

-10% uncertainties

Planned CMB satellite work targets

-1% uncertainties

At each of these levels there are appropriately matched levels of systematic uncertainties & simplifying assumptions.

To answer "what we want to know" we must go from 50% through the 10% and on to the 1% level.
### Planned 1-year baseline statistical and systematic uncertainty on...

<table>
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<th>$\Omega_M$</th>
<th>$\Omega_\Lambda$</th>
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Assuming:

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<th>$W'$</th>
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<td>0.05 &lt;0.01</td>
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<td></td>
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<tr>
<td>$\Omega_M, \Omega_k \text{ known}$</td>
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<td></td>
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<tr>
<td>$w = \text{const.}$</td>
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<td>0.02 &lt;0.01</td>
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<td>$w(z) = w + w'z$</td>
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<td>0.12 0.15</td>
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Type Ia Supernovae

Calan/Tololo Supernova Survey

Supernova Cosmology Project

Open
Flat
Closed

MORE REDSHIFT
(More total expansion of universe since light left the Standard Candle)
Accelerating ($\Lambda$)
Open (no $\Lambda$)
Flat (no $\Lambda$)
1998: Acceleration

Graph showing the relationship between redshift and Δmag for different cosmological models: Empty, Accelerating (Λ), Open (no Λ), and Flat (no Λ). The graph illustrates the trend of Δmag becoming fainter with increasing redshift.
Supernovae

Clusters

CMB

No Big Bang

mass density

vacuum energy density

Perlmutter, et al. (1999)
Jaffe et al. (2000)
Bahcall and Fan (1998)

expands forever
recollapses eventually

open
closed
flat
Unknown Component, $\Omega_u$, of Energy Density

Perlmutter et al. (1998)
c.f. Garnavich et al. (1998)

$w = \frac{p_u}{\rho_u}$

$\Omega_M = 1 - \Omega_u$

Flat Universe
Constant $w$

cosmological constant $w = -1$
What do we now want to know?

- **Is our simple cosmological picture on the right track?**
  
  Do we find the same $\Omega_k @ z = 1$ and $z = 1000$?

- **Strength of our conviction that $\Omega_\Lambda > 0$.**
  
  Find a redshift when
  
  $m(z)$ for $\Lambda > 0$ is **not** fainter than $m(z)$ with no $\Lambda$
  
  i.e. the "deceleration era."

  Get tighter constraints on:
  
  -- gray dust & other non-standard dust
  -- any SN Ia evolution
  -- gravitational lensing of SNe.

- **Identity of, and properties of, "Dark Energy" that is apparently accelerating the universe.**
  
  Measure over a range of redshifts to look for varying properties.

**A Basic Measurement:**

The History of the Universe's Expansion
1998: Acceleration

The graph shows the relationship between redshift and Δm, with data points indicating the apparent magnitude fainter compared to a standard candle. Three theoretical scenarios are plotted:

- **Empty** (no Λ)
- **Accelerating** (Λ)
- **Open** (no Λ)

The redshift axis ranges from 0.0 to 2.0, and the Δm axis ranges from -1.0 to 1.0, with markers indicating the observed data points and error bars representing the uncertainty.
New HST data

Supernova Cosmology Project
Preliminary

Δmag vs redshift

Empty
Accelerating (Λ)
Open (no Λ)
Flat (no Λ)
Dust
Empty
Evolving SNe
Accelerating (\(\Lambda\))
Open (no \(\Lambda\))
Flat (no \(\Lambda\))

New HST data

Supernova Cosmology Project
Preliminary

\[ \Delta \text{mag} \]

\[ \text{redshift} \]
Supernovae probing the *deceleration* era in the near-IR
Dust
Empty
Evolving SNe
Accelerating ($\Lambda$)
Open (no $\Lambda$)
Flat (no $\Lambda$)

$0.0$ $0.5$ $1.0$ $1.5$ $2.0$

-$1.0$ $-0.5$ $0.0$ $0.5$ $1.0$

redshift

$\Delta$ mag
tainter

Simulated
Future HST Data

Evolving SNe
Dust
Empty
Accelerating ($\Lambda$)
Open (no $\Lambda$)
Flat (no $\Lambda$)

SN 1997ff
SN 1998eq
SN 1997ap

Simulated Future HST Data
**Score Card** of Current Uncertainties on $(\Omega_M^{\text{flat}}, \Omega_{\Lambda}^{\text{flat}}) = (0.28, 0.72)$

**Statistical**
- high-redshift SNe: 0.05
- low-redshift SNe: 0.065
  **Total**: 0.085

**Systematic**
- dust that reddens: < 0.03
  \(R_B(z=0.5) < 2 R_B(\text{today})\)
- evolving grey dust
  - clumpy
  - same for each SN
- Malmquist bias difference: < 0.04
- SN Ia evolution
  - shifting distribution of prog mass/metallicity/C-O/..
- K-correction uncertainty: < 0.025
  - including zero-points
  **Total**: 0.05

**Cross-Checks** of sensitivity to
- Width-Luminosity Relation: < 0.03
- Non-SN Ia contamination: < 0.05
- Galactic Extinction Model: < 0.04
- Gravitational Lensing: < 0.06
  - by clumped mass

Perlmutter *et al.* (1998)
astro-ph/9812133
A "Third Generation" Experiment
satellite overview

**Instruments:**

- **~2 m aperture telescope**
  
  *Can reach very distant SNe.*

- **1 square degree mosaic camera, 1 billion pixels**
  
  *Efficiently studies large numbers of SNe.*

- **0.35um -- 1.7um spectrograph**
  
  *Detailed analysis of each SN.*

**Satellite:**

- Dedicated instrument.
- Designed to repeatedly observe an area of sky.
- Essentially no moving parts.

- 4-year construction cycle.
- 3-year operation for experiment
  (lifetime open-ended).
Co-added images: $m_{AB} = 32.0$!
SNAP: observing supernovae with lightcurves & spectra
SNAP SuperNova Acceleration Probe

\[ \approx 2500 \text{ SNe Ia} \]

- Dark Energy Properties
- Dark Matter Properties
- Cosmological Parameters.
Supernova Cosmology Project
Perlmutter et al. (1998)

No Big Bang

Flat $\Lambda = 0$ Universe

42 Supernovae

mass density

vacuum energy density (cosmological constant)

expands forever
recollapses eventually

closed
flat
open
No Big Bang

Flat $\Lambda = 0$ Universe

Supernova Cosmology Project
Perlmutter et al. (1998)

42 Supernovae

Target Uncertainty

Vacuum energy density (cosmological constant)

Mass density

expands forever

collapses eventually

closed

flat

open
No Big Bang

Supernova Cosmology Project
Perlmutter et al. (1998)

It is possible that SNAP will find a result that disproves the flat universe prediction of "Inflation"
Dark Energy

Unknown Component, $\Omega_u$, of Energy Density

Supernova Cosmology Project
Perlmutter et al. (1998)

\[ \Omega_M = 1 - \Omega_u \]
Current ground-based data compared with binned simulated SNAP data and a sample of Dark Energy models.

Each SNAP point represents ~50-supernova bin based on Weller & Albrecht (2001)
Binned simulated SNAP data compared with Dark Energy models currently in the literature.

SNAP
SuperNova
Acceleration
Probe

Based on
Weller & Albrecht (2001)
Binned simulated SNAP data compared with Dark Energy models.

based on
Weller & Albrecht (2000)
SNAP Weak Lensing Science

• Stable instrument and complete knowledge of PSF reduces systematics
• High resolution allows efficient use of faint, high redshift source galaxies
• Near-IR channel allows photo-z to z=3

- High precision measurements of power spectrum and cosmological parameters: $\Omega_m$, $\Omega_\Lambda$, $\sigma_8$, etc… complements SNe and other methods
- Maps of the DM distribution: mass limited cluster catalogs, DM in filaments and voids
- Evolution of large-scale structure: direct tests of gravitational instability via redshift-dependences
- Galaxy-galaxy lensing: galactic mass as function (z,type, environs)
$\Omega \Lambda m \ , \ ,s \ 8$
Primary Cosmology Mission:
Cosmological Parameters, Dark Matter, Dark Energy,...

Type Ia supernova calibrated candle:
Hubble diagram to $z = 1.7$

Type II supernova expanding photosphere:
Hubble diagram to $z = 1$ and beyond.

Weak lensing:
Direct measurements of $P(k)$ vs $z$
Mass selected cluster survey vs $z$

Strong lensing statistics: $\Omega_\Lambda$
10x gains over ground based optical resolution, IR channels + depth.

Galaxy clustering:
$W(\Theta)$ angular correlation vs redshift from 0.5 to 3.0
Expected cosmological measurements at time of SNAP results

Other cosmological measurement approaches

Weak Lensing*

Number Counts, \( N(z) \)
- clusters*
- galaxies
  -- selected by rotation velocity

S-Z angular size

\( w = p_u / \rho_u \)

\( \Omega_M \)

\( (P) = \text{using CMB polarization} \)

*SNAP measurements using this approach
Are there science prerequisites?

No: Supernova studies are now so developed that we can design an experiment constraining systematic uncertainties.

Ongoing supernova studies (near and far) will improve this further, and make the experiment even more efficient.
## Score Card of Current Uncertainties on \((\Omega_M^{\text{flat}}, \Omega_{\Lambda}^{\text{flat}}) = (0.28, 0.72)\)

### Statistical
- High-redshift SNe: 0.05
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- Evolving grey dust: ???
- Clumpy: ???
- Same for each SN: ???
- Malmquist bias difference: < 0.04
- SN Ia evolution: ???
  - Shifting distribution of prog mass/metallicity/C-O/..
- K-correction uncertainty: < 0.025
  - Including zero-points
- Total: 0.05
  - Identified entities/processes

### Cross-Checks of sensitivity to
- Width-Luminosity Relation: < 0.03
- Non-SN Ia contamination: < 0.05
- Galactic Extinction Model: < 0.04
- Gravitational Lensing: < 0.06
  - By clumped mass

---

Perlmutter et al. (1998)
astro-ph/9812133
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- Total: 0.05

SNAP Requirement to satisfy \(\delta M(\text{peak}) < 0.02\)

Discover and follow 2000+ SN Ia per year

Optical & NIR calibrated spectra to observe wavelength dependent absorption

Detection of every SN 2.5 mag below peak for \(z = 0\) to 1.7

Spectral features and lightcurve features. Go to high redshift.

Restframe B matched filters, spectral time series, cross wavelength relative flux calibration,

Cross-Checks of sensitivity to
- Width-Luminosity Relation: < 0.03
- Non-SN Ia contamination: < 0.05
- Galactic Extinction Model: < 0.04
- Gravitational Lensing: < 0.06

Restframe Sill.

SDSS+SIRTF & SNAP WD spectra

~75 SN per redshift bin. SNAP microlensing experiments
What makes the supernova measurement special?
Control of systematic uncertainties.

At every moment in the explosion event, each individual supernova is “sending” us a rich stream of information about its internal physical state.
B Band

as measured

Calan/Tololo SNe Ia

$M_B - 5 \log(h/65)$

light-curve timescale
“stretch-factor” corrected

$M_B - 5 \log(h/65)$

days

Kim, et al. (1997)
The time series of spectra is a “CAT Scan” of the Supernova

-14 days

maximum

+10 days

+20 days
Control of Evolution Systematics: Matching Supernovae

Supernova Host Galaxy's Star Formation History

SN Progenitor Stars:
- progenitor mass
- heavy element abundance
- binary star system parameters
- white dwarf's carbon/oxygen ratio

SN Physical Properties:
- Amount of Nickel fused in explosion
- Distribution of Nickel
- Opacity of atmosphere's inner layers
- Kinetic energy of the explosion
- Metallicity

SN Observables
- Spectral feature widths & minima
- Spectral feature ratios
- Lightcurve rise time
- Lightcurve stretch
- Lightcurve plateau level

Galaxy Observables
- Color vs. luminosity
- Absorption/emission lines
- 4000 A break
- Galaxy morphology
- SN location in host galaxy
B-band Lightcurve Photometry for $z = 0.8$ Type Ia
Type Ia Spectral Features

- **Type Ia Signature**
- **Kinetic Energy Signature**
- **Metallicity Indicators**
- **Luminosity Indicators**

Normalized Flux

Wavelength (μm)
In summary, constrain with:

- **High Redshift**
- **Near IR**
- **Spectrophotometry to 1.7 um**

![Graph showing redshift vs. magnitude with markers for different types of SNe and lines for different cosmological models.]
Comparison of ground and space based optical surveys

We have completed detailed comparisons of ground based and space based optical surveys from first principles

Gary Bernstein, 2001, submitted to PASP

- Calculations for PSF photometry
- Includes undersampled and dithered images
- Includes cosmic ray rates
- Includes intra-pixel sensitivity variations (10% gutters)
- Calculated for point source and galaxy photometry
- Determines astrometric errors
- Determines galaxy shape errors

Allows us to answer some commonly arising questions about imaging strategies:
- What amount of dithering is ideal?
- What pixel size optimizes the productivity of a camera?
- Which is more efficient; space-based or ground-based observing?
Supernova survey efficiency for SNAP and LSST

Solid lines are LSST 0.5" seeing; dashed line is 0.7".
Supernova survey efficiency for SNAP and LSST

Bernstein (2001)

Brightness and restframe B band wavelength of SNe Ia at peak

[Graph showing supernova survey efficiency with different bands (U, B, V, R, I, Z, J, H') and markers for z=1.0 and z=1.5.]
Supernova survey efficiency for SNAP and LSST

Bernstein (2001)

- Brightness and V band wavelength of SNe Ia at peak
- Discovery brightness to prevent Malmquist bias
Simulated LSST and SNAP Lightcurves for restframe V-band.

*LSST with a NIR camera and 9 hours per filter.*

\[ z = 0.8 \quad \text{SNAP} \quad z = 1.2 \]

**LSST/Paranal weather & 0.5 arcsec seeing**

**LSST/Paranal seeing & weather**

**LSST/Mauna Kea seeing & weather**
Weak Lensing Survey Speed: including effects of galaxy size

Galaxies must be resolved for use in weak lensing analyses. HDF studies (Gardner & Satyapal, 2000) show that galaxies become much smaller at faint magnitudes.

Bernstein (2001)

Approximately 85% of galaxies with $r<30$ are between $r=27$ and 30.
Baseline One-Year Sample

~2500 SNe Ia

Diagram showing the relationship between magnitude and redshift, with annotations for Dark Energy Properties, Dark Matter Properties, and Cosmological Parameters.
Add ground based discovery at $z < 0.6$ with SNAP follow-up sample.

Add NGST spectroscopy for SNAP SNe at $z > 1.7$.
Technical Readiness
### Science
- Measure $\Omega_M$ and $\Lambda$
- Measure $w$ and $w(z)$

### Statistical Requirements
- Sufficient (~2000) numbers of SNe Ia
- ...distributed in redshift
- ...out to $z < 1.7$

### Systematics Requirements
- Identified & proposed systematics:
  - Measurements to eliminate / bound each one to +/-0.02mag

### Data Set Requirements
- Discoveries 3.8 mag before max.
- Spectroscopy with S/N=15 at 30 Å bins.
- Near-IR spectroscopy to 1.7 µm.

### Satellite / Instrumentation Requirements
- ~2-meter mirror
- 1-square degree imager
- Low-resolution spectrograph (0.35 µm to 1.7 µm)
- Derived requirements:
  - High Earth orbit
  - ~50 Mb/sec bandwidth
Observatory

Simple Observatory consists of:

1) 3 mirror telescope w/ separable kinematic mount
2) Optics Bench w/ instrument bay
3) Baffled Sun Shade w/ body mounted solar panel and instrument radiator on opposing side
4) Spacecraft bus supporting telemetry (multiple antennae), propulsion, instrument electronics, etc

No moving parts (ex. filter wheels, shutters), rigid simple structure.
Instrumentation

GigaCam Imager
1 square degree field of view with CCD's + HgCdTe Devices

Spectrograph
low resolution, R~75
high throughput
350 nm -- 1700 nm
**GigaCAM, a one billion pixel array**

- Depending on pixel scale approximately 1 billion pixels
- 132 Large format CCD detectors and 25 HgCdTe devices
- Looks like the SLD vertex detector in Si area (0.1 - 0.2 m²)
- Larger than SDSS camera, smaller than BaBar Vertex Detector (1 m²)

The Moon (for scale)

3 IR filters on HgCdTe
8 visible filters on CCD
LBNL CCD Technology

High quantum efficiency from near UV to near IR
No thinning, no fringing.
High yield.
Radiation hard.

4 side abuttable.
**IFU Spectrometer Concept**

[Diagram of IFU Spectrometer Concept]

- Slicer mirror array
- Feed
- Synthetic slit
- Relay 1:3
- Pupil mirror array
- Detector
- Collimator mirror
- Silica prism
- Camera mirror
SNAP: observing supernovae with lightcurves & spectra

$z = 0.8$

$z = 1.0$

$z = 1.2$

$z = 1.4$

$z = 1.6$
**Advantages of particular high earth orbit:**

— Minimum Thermal Change on Telescope (annual eclipse) – very stable PSF
— Excellent Telemetry, reduces risk on satellite
— Outside Radiation Belts
— Passive Cooling of Detectors
— Minimizes Earth Albedo
— MAP currently proving orbit concept
Technology readiness and remaining hurdles

NIR sensors
- HgCdTe stripped devices are being developed for NGST and are ideal in our spectrograph.
- "Conventional" devices with appropriate wavelength cutoff are being developed for WFC3 and ESO.

CCDs
- We have demonstrated radiation hardiness that is sufficient for the SNAP mission.
- Extrapolation of earlier measurements of diffusion's effect on PSF indicates we can get to the sub 4 micron level. Needs demonstration.
- Industrialization of CCD fabrication has produced useful devices. More wafers have just arrived.
- Detectors & electronics are the largest cost uncertainty.
- ASIC development is required.

Filters
- We are investigating three strategies for fixed filters.
  - Suspending filters above sensors
  - Gluing filters to sensors
  - Direct deposition of filters onto sensors.

Shutter
- Goddard has proposed a scale-up of a heritage shutter.

On-board data handling
- We have opted to send all data to ground to simplify the flight hardware and to minimize the development of flight-worthy software.
- 50 Mbs telemetry, and continuous ground contact are required. Goddard has validated this approach.
Calibration
• There is an active group investigating all aspects of calibration.

Pointing
• The new generation HgCdTe multiplexor and readout IC support high rate readout of regions of interest for generating star guider information.
• Next generation attitude control systems may have sufficient pointing accuracy so that nothing special needs be done with the sensors.

Telescope
• Ground-based end to end testing
**Science**
- Measure $\Omega_M$ and $\Lambda$
- Measure $w$ and $w(z)$

**Statistical Requirements**
- Sufficient (~2000) numbers of SNe Ia
- ...distributed in redshift
- ...out to $z < 1.7$

**Systematics Requirements**
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- Spectroscopy with S/N=15 at 30 Å bins.
- Near-IR spectroscopy to 1.7 µm.
- ...

**Satellite / Instrumentation Requirements**
- ~2-meter mirror
- 1-square degree imager
- low-resolution spectrograph (0.35 µm to 1.7 µm)

Derived requirements:
- High Earth orbit
- ~50 Mb/sec bandwidth
NASA Goddard Integrated Mission Design Center

SNAP intensive design study
Current membership:

31 physicists,  
18 astronomers,  
and 8 senior engineers.

Current institutions:

Lawrence Berkeley National Laboratory,  
University of California Berkeley,  
CNRS/IN2P3/CEA/CNES --France  
University Paris VI & VII,  
University of Michigan,  
University of Maryland,  
California Institute of Technology,  
Space Telescope Sciences Institute,  
University of Stockholm, University of Edinburgh,  
European Southern Observatory,  
and Instituto Superior Tecnico.

We expect further institutions and personnel to participate including: NASA Goddard, U.S. Universities (Indiana, Ohio State, Purdue, ...), and additional faculty at the above listed institutions
Project Chronology

First public presentation of idea at Fermilab "Inner Space/Outer Space" symposium. end of May 1999

Letter of Intent (pre-proposal) to DOE & NSF-Physics Nov 1999

Review panel for Letter of Intent Dec 1999

Science proposal for study phase to DOE & NSF-Physics Feb 2000

SAGENAP review for DOE & NSF-Physics end of March 2000

SAGENAP peer review panel report July 2000

Study proposal to NSF-Physics Review in process. end of Sept 2000

Presentation to the NASA SEU subcommittee Nov 2000

Dedicated session on SNAP at the 2001 AAS meeting Jan 2001

Study review for DOE Jan 2001
How does a project get proposed and prioritized by peer-review in this multi-disciplinary, multi-agency "Connections" environment?
A Resource for the Science Community: 
The only wide-field deep survey in space -- with HST resolution.

The biggest HST deep survey will be the ACS survey:
   6300x smaller than SNAP main survey
   and almost as deep
Discovery potential ~6000x greater than ACS deep

Complementary to NGST: target selection for rare objects
   1950s+1960s: Palomar 48” feeds 200”
   2000: SDSS feeds 8 and 10 meter telescopes
   2010: SNAP feeds NGST

→ Archive data distributed

→ Guest Survey Program

Whole sky can be observed every few months
### Example One-Year Survey Sensitivities

Magnitudes given are for S/N>=5 detections for 95% of point sources. 2x2 interlacing has been enforced under the assumption that this is a survey mode, so we will want to have minimal aliasing. All magnitudes are AB system.

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<tr>
<td>B</td>
<td>27.65</td>
<td>29.3</td>
<td>30.65</td>
</tr>
<tr>
<td>U</td>
<td>26.6</td>
<td>28.5</td>
<td>29.9</td>
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</tbody>
</table>
Science Goals for
The First Wide-field Survey in Space

Ultra-deep 11 band imaging survey

Galaxy populations and morphology to co-added $m = 32$
Low surface brightness galaxies in $H'$ band
Quasars to redshift 10 (when is this, how old is universe)
Epoch of reionization through Gunn-Peterson effect
Galaxy evolution studies, merger rate
Evolution of stellar populations
Ultraluminous infrared galaxies
Globular clusters around galaxies
Extragalactic stars (in clusters or otherwise)
Intracluster objects (globulars, dwarf galaxies, etc.)
Lensing projects:
  Mass selected cluster catalogs
  Evolution of galaxy-mass correlation function
    and its scaling relations
  Maps of mass in filaments
Science Goals for
The First Wide-field Survey in Space

Time-Domain Survey

GRB optical counterparts: rates, lightcurves, and spectra
  => GRB afterglows with or without GR satellite
  => unknown fast transients

Kuiper belt objects

Supernova rates of all types vs. galaxy type
Supernova phenomenology studies for all types

Proper motions for halo objects
  L and T dwarfs
  Cool white dwarfs and other rare halo objects

Faint comets
No Big Bang

Supernova Cosmology Project
Perlmutter et al. (1998)

Supernovae

Target Uncertainty

Flat Universe

(expands forever)

recollapses eventually

mass density

vacuum energy density

(cosmological constant)

SNAP

42 Supernovae

(open)

(target)

(99%)

(95%)

(90%)

(68%)

(100%)

(50%)

90%
CMB data before BOOMARANG and MAXIMA

\[ \Delta T \, (\mu K) \]

\[ l \]

BOOMARANG

MAXIMA
Supernovae probing the *deceleration* era with NICMOS
Binned simulated SNAP data compared with Dark Energy models currently in the literature.

Based on
Weller & Albrecht (2001)

**Figure Description:**
- The graph plots the magnitude difference from a flat model, $\Omega_\Lambda = 0.7$, against redshift $z$.
- Various dark energy models are compared, including:
  - $\Omega_\Lambda = 0.6$ potential
  - Exponential tracker potential
  - SUGRA potential
  - Albrecht & Skordis potential
  - Double exponential potential
  - Pure exponential (fine tuned)
  - Periodic potential
  - Inverse tracker potential
  - Pseudo-Nambu-Goldstone Boson (example)
- The data points represent simulated SNAP data, which are compared with the theoretical models.
Expansion History of the Universe

- **Scale of Universe**
  - Past
  - Future

- **Time** [Gyr (65/h₀)]
  - Today

- **Scale of Universe**
  - Open: Λ = 0
  - Critical: Λ = 0
  - Closed: Λ = 0

- **Ω_M = 0.3**
- **Ω_Λ = 0.7**

- **a(t)/a(0)**
- **redshift**
- **decel.**
- **accel.**

- **Time, measured from present** [Gyr (65/h₀)]
Conclusions:

1. The mystery of Dark Energy presents us with an extraordinary science opportunity.

2. Supernovae provide the most mature technique.

3. SNAP is the best tool to address this science.