1. Dark Energy is at the heart of our HEP science: scientifically this is an extremely important measurement.

2. The definitive exploration of Dark Energy requires a space-based project.

3. A major accomplishment: a successful 4-year R&D program, funded by DOE, removed remaining technical risks, so that SNAP is now ready to build.

4. Two routes to a launch.

All of the above is well-reviewed and validated by national panels.
Scientifically, this is an extremely important measurement.

“Right now, not only for cosmology but for elementary particle theory, this is the bone in our throat.” — Steven Weinberg

“Maybe the most fundamentally mysterious thing in basic science.” — Frank Wilczek

“Would be Number 1 on my list of things to figure out.” — Edward Witten

“The science addressed by SNAP in exploring the nature of dark energy is absolutely central.” — HEPAP 20-year Roadmap Facilities Committee
“Come hell or high water, DOE will fund JDEM.”

-- Dr. Raymond Orbach, Director, Office of Science, May 2004
Scientifically, this is an extremely demanding measurement.
Scientifically, this is an extremely demanding measurement because we are looking for the signature of a revolutionary change in our picture of physics:

- a previously unknown component that makes up most of the universe, or
- GR is wrong, or
- evidence of more than 4 dimensions, or
- a clue to combining gravity/GR with the other forces/QCD or…
Whatever these projects find, many people will say:

“That’s just an artifact of this or that systematic effect.”

So the question at the heart of these Dark Energy projects is:

If you see a surprising result, would you or anybody else trust it?
How do we design based on this scientific challenge of unusually good control of systematics?

Complementary and cross-checking methodologies.

All projects use at least two of the three or four known approaches.

- Using two complementary methods is crucial to separate D.E. from G.R. physics explanations.
- Using two cross-checking methods is rather minimal for a systematics check.
How do we design based on this scientific challenge of unusually good control of systematics?

With so few methods available, each one has to “stand on its own feet” as robustly as possible.

SNAP is designed around this principle for
- the Type Ia Supernova method and
- the Weak Lensing method
Expansion History of the Universe

After inflation, the expansion either... first decelerates, then accelerates... or always decelerates. Depending on the expansion rate, the universe either expands forever or collapses.
Expansion History of the Universe

Average Distance Between Galaxies Relative to Today's Average

Billions Years from Today

relative brightness

past ← today → future

redshift

0

0.5

1

1.5

2

3

0.0

0.5

1.0

1.5
SN Systematics Control

- Supernova measurement sample
  - Requires ~2000 well measured SNe
  - Study cosmologically significant redshift range up to 1.7

The measurement uncertainty on the variation of the dark energy equation-of-state improves significantly out to redshift $z \sim 1.7$
SN Systematics Control

- Supernova measurement sample
  - Requires ~2000 well measured SNe
  - Study cosmologically significant redshift range up to 1.7

- SN Lightcurve
  - Recognize differences between SNe
SN Systematics Control

- Supernova measurement sample
  - Requires ~2000 well measured SNe
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- SN Lightcurve
  - Recognize differences between SNe
SN Systematics Control

- **Supernova measurement sample**
  - Requires ~2000 well measured SNe
  - Study cosmologically significant redshift range up to 1.7

- **SN Lightcurve**
  - Recognize differences between SNe
  - Recognize and correct for evolving dust extinction: requires 3 colors
SN Systematics Control

• Supernova measurement sample
  — Requires ~2000 well measured SNe
  — Study cosmologically significant redshift range up to 1.7

• SN Lightcurve
  — Recognize differences between SNe
  — Recognize and correct for evolving dust extinction: requires 3 colors

• Spectrum
  — Identify SN type
  — Subclassification
  — Low resolution, R~70 spectrum into NIR

• Going to space makes these measurements possible over the full redshift range.
“To fully characterize the expansion history and probe the dark energy will require a wide-field telescope in space (such as the Supernova/Acceleration Probe).”
Gravitational Weak Lensing

Observed galaxy shapes are distorted (smeared tangentially) by the gravitational field of mass concentrations along the line-of-sight between the galaxy and our telescopes.

This effect can be very small and yet detectable statistically after averaging over the measured ellipticity of many galaxies.
WL Systematics Control

• Large number of resolution elements on the sky
  — To get sufficient quantity of resolved galaxies

Hubble Space Telescope Ultra Deep Field shows many more small specks of light – these are the resolved galaxies that can be seen from space but not from the ground.
WL Systematics Control

- Large number of resolution elements on the sky
  —To get sufficient quantity of resolved galaxies

Fraction of galaxies that can be studied from space with SNAP is close to one.
WL Systematics Control

- Large number of resolution elements on the sky
  - To get sufficient quantity of resolved galaxies

- Measurement of the galaxy ellipticities (shear)
  - Requires “space” resolution
  - Demands stable optics

Shear accuracy $\sim \left(\frac{r_{psf}}{r_{galaxy}}\right)^2$
WL Systematics Control

- Large number of resolution elements on the sky
  - To get sufficient quantity of resolved galaxies

- Measurement of the galaxy ellipticities (shear)
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Shear accuracy $\sim (r_{\text{psf}} / r_{\text{galaxy}})^2$
WL Systematics Control

- Large number of resolution elements on the sky
  - To get sufficient quantity of resolved galaxies

- Measurement of the galaxy ellipticities (shear)
  - Requires “space” resolution
  - Demands stable optics

- Measurement of galaxy redshift
  - Needs excellent photometry, for photometric redshift
  - Requires NIR

- Going to space ameliorates all these problems, controls systematics—and why the DETF considers this to be the option that guarantees results

The definitive exploration of Dark Energy requires a space-based project.
We can and must thus push the envelope in control of systematics.
We do not need or want to push the envelope in technical innovation.
The science is hard, the implementation is mostly more pedestrian:

Location, location, location
Stability, stability, stability
Smallest launch vehicle in its class
Standard bus and known ACS capabilities
Traditional telescope
One instrument bay, one focal plane
Very few moving parts, with redundancy
An extremely stable environment: L2

L2 Orbit, puts most “work” in the Launch Vehicle, small fuel for injection, station keeping, angular momentum.
SNAP concept eliminates complexity:

- Innovative telescope design does IR imaging with room temperature optics

---

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Aperture</td>
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<tr>
<td>Field of View</td>
<td>1.37 square deg</td>
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<tr>
<td>Resolution</td>
<td>&lt; 0.06 arcsec FWHM blur</td>
</tr>
<tr>
<td>Bandpass</td>
<td>0.35-1.7 µm</td>
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</table>
SNAP concept eliminates complexity:

- The fixed solar panels, passive cooling, fixed, antenna eliminates major mission risks.

...With very few moving parts.
A single focal plane

All instruments/detectors on single focal plane.
- Passively cooled to 140K
- 0.7 square degrees instrumented FOV
- 9 fixed filters from 350nm to 1700nm
Science Operations

- Commissioning 2 Months
- Supernova Survey 22 Months
- Weak Lensing Survey 12 Months
- Extended WL Survey 36 Months

All modes use Step ’n’ Stare concept:
- Drag star through multiple fixed length
- 300 second exposures
- Four exposures in 2X2 dither pattern
- Move telescope by one filter for next set of four exposures

Daily operations concept:
- 21 Hours data collection
- 2 Hours downlink
- 1 Hour maneuvers and calibration

Focal Plane is rotationally symmetric, we rotate the satellite every 3 months.
Synergy of Supernovae + Weak Lensing

- Comprehensive: no external priors required!
- Independent test of flatness to 1-2%
- Complementary (SNe + WL only):
  conservative:
  \( w_0 \) to ±0.05, variation \( w' \) to ±0.12 \((\text{with systematics})\) Λ model
  \( w_0 \) to ±0.03 variation \( w' \) to ±0.06 \((\text{with systematics})\) SUGRA model

Adding extended survey and better systematics:
  \( w_0 \) to ±0.03, variation \( w' \) to ±0.06 \((\text{with systematics})\) Λ model
  \( w_0 \) to ±0.015 variation \( w' \) to ±0.03 \((\text{with systematics})\) SUGRA model

### SNAP Surveys

<table>
<thead>
<tr>
<th>Survey</th>
<th>Area (sq.deg)</th>
<th>Depth (AB mag)</th>
<th>Size x HST (HDF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep/SNe</td>
<td>8 (repeated)</td>
<td>30</td>
<td>6,000</td>
</tr>
<tr>
<td>Wide</td>
<td>1000</td>
<td>28</td>
<td>800,000</td>
</tr>
<tr>
<td>Extended</td>
<td>4000</td>
<td>28</td>
<td>2,000,000</td>
</tr>
</tbody>
</table>

* and SNAP is 9 colors!
The biggest jobs are

Procuring sufficiently good sensors
Assembling a mosaic camera for space

but we will not be way out in front, blazing a trail on either of these, and this is where we now have years of successful R&D supported by DOE.
History: DOE support for SNAP R&D

1999: SNAP 260-page proposal submitted to DOE

2000: Reviewed by SAGENAP; recommended R&D

2001: HEPAP endorsed recommendation for R&D

2002: Beginning of R&D program for SNAP funded by DOE

2002: Agency-led technical review of planned program
...Resulting in an international effort:
SNAP Collaboration

LBNL
Berkeley
Caltech
Fermi National Laboratory
GSFC
Indiana U.
IN2P3-Paris-Marseille
JPL
LAM (France)
RIT
Sonoma State
Univ. of BC/Victoria
Univ. of Michigan
Univ. of Pennsylvania
Univ. of Stockholm
SLAC
STScI
Yale U.

In discussion:
Univ. of Maryland
Kurchatov Institute of Atomic Energy
DoE R&D focused on detectors and electronics

All instruments/detectors on single focal plane.
- Passively cooled to 140K
- 0.7 square degrees instrumented FOV
- 9 fixed filters from 350nm to 1700nm
New CCD technology tolerates radiation in space

- Traditional n-channel CCDs are sensitive to radiation damage due to loss of Charge Transfer Efficiency (CTE)
- LBNL p-channel CCDs are 10-50x more radiation tolerant
NIR sensors now exceed original SNAP goal

- NIR QE was low when R&D began.
- Noise reduced factor 4 to 100.
- Largest detector was 1kx1k, now 2kx2k.
- Previously, only a single manufacturer.
NIR Sensors: Dark Current

Where we started

Rockwell 103
Raytheon 09A

NIR Sensors: Dark Current

Where we started

Rockwell 103
Raytheon 09A
Matching ASIC electronics developed

- Converts analog detector signals to digital values
- Based on ASIC’s
- Operate at 140 K
- Irradiated, cryogenic test
Spectrograph developed in France with NASA/Goddard

- Our Marseille SNAP group, with Goddard, is developing our spectrograph. The French effort is currently being funded by the French Space Agency and IN2P3.

- Spectrograph
  - Compact
  - Visible and NIR, $R = 70 - 100$
  - Image slicer: 3 arcsec of imaging & spectra
# Focal Plane Effort

<table>
<thead>
<tr>
<th>NIR</th>
<th>Visible</th>
<th>Filters</th>
<th>Spectrograph</th>
<th>Electronics</th>
<th>Mech/Therm</th>
<th>Calibration</th>
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<td>Michigan HgCdTe</td>
<td>LBNL CCD devel. and testing</td>
<td>Indiana Stability/aging</td>
<td>LAM Optics and mechanics</td>
<td>SLAC/SSL Architecture CCD FE</td>
<td>LBNL/SSL Focal plane concept</td>
<td>LBNL/SSL Optics and mechanics</td>
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<tr>
<td>Cal Tech HgCdTe</td>
<td>Yale CCD testing and packaging</td>
<td>Michigan Discrete filter mounts</td>
<td>Paris/Lyons Detectors</td>
<td>SLAC Instr. control</td>
<td>LBNL/SSL Therm./Mech.</td>
<td>Indiana Lamps</td>
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<td>JPL InGaAs</td>
<td>STScI Si PIN hybrid testing</td>
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<tr>
<td>Indiana Abs. QE</td>
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<td></td>
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<tr>
<td></td>
<td>Star Guider</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>SLAC Fine star guider</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Risks retired:

✓ Optical sensors: Radiation
✓ IR sensors: Noise, QE
✓ Sensor Electronics: cryogenic
✓ Lightweight optics: mass
✓ ACS: pointing stability
✓ Telemetry: Ka-Band
✓ Stray-light: Short baffle
✓ Telescope: Warm, yet NIR
Completed Engineering Studies:

- Spacecraft (IMDC at Goddard, Team-X at JPL, Lockheed)
- SNAP Orbital Properties (SSL & LBNL)
- Launch Vehicle Study (Boeing)
- Telemetry (SSL)
- Focal Plane Guider (SSL, SLAC)
- Attitude Control System (Ball Aerospace, Lockheed, LBNL, SSL)
- Telescope Optics (SSL)
- Telescope Design, Fabrication, and Testing (BATC, ITT [formerly Kodak])
- Mirror Blank (Corning, ITT, Ball Aerospace)
- Telescope Stray Light (Goddard, SSL & LBNL)
- Focal Plane Layout (U.Mich., LBNL, SSL)
- Thermal Study (SSL)
- Calibration (IU, STScI, SSL, AAS)
- Computing (STScI, LBNL)

Plus scientific simulation effort by the collaboration…
SNAP Instrumentation Papers
2001 to present... page 1

IR:

Spectrograph:

Electronics:

Calibration:
1. HST Stellar Standards with 1% Accuracy, R. Bohlin, ASP Conference Series V.999 (2007).

Telescope:
SNAP Instrumentation Papers
2001 to present... page 2

Focal Plane:

CCD:


7. Models for Type Ia Supernovae and Cosmology, E.Linder, P. H¨oflich, C. Gerardy, and H. Marion, in Lecture Notes in Physics,


17. Wide-Field surveys from the SNAP Mission, A. Kim et al., SPIE 4836.


17. Weak Lensing from Space III: Cosmological Parameters, Refregier et al.
29. Cosmological parameters from lensing power spectrum and bispectrum tomography, Takada & Jain, submitted to MNRAS.
35. Physics of SNeIa and Cosmology, Hoeflich, Gerardy, Linder, & Marion, in Stellar Candles, Lecture Notes in Physics.
47. Constraining the mass distribution of galaxies using galaxy-galaxy lensing in clusters and in the field, Limousin, Kneib, Natarajan, MNRAS 356, 309 (2005)
51. Seeing the Nature of the Accelerating Physics: it’s a SNAP, SNAP collaboration, DETF white paper, astro-ph/0507458
52. Supernova/Acceleration Probe: studying dark energy with Type Ia supernovae, SNAP collaboration, DETF white paper, astro-ph/0507459
55. Ideal Bandpasses for Type Ia Supernova Cosmology, Davis, Schmidt, Kim, PASP 118, 205 (2006)
57. Spectral Diversity of Type Ia Supernovae, James, Davis, Schmidt, Kim, MNRAS 370, 933 (2006)
64. Going Nonlinear with Dark Energy Cosmologies, Linder & White, Phys Rev D 72, 061304(R) (2005)
69. Snapping Supernovae at z>1.7, Aldering et al., Astropart Phys accepted, astro-ph/0607030
70. Separating Dark Physics from Physical Darkness: minimalist modified gravity vs. dark energy, Huterer & Linder, Phys Rev D accepted, astro-ph/0608681
71. Importance of Supernovae at z<0.1 for Probing Dark Energy, Linder, Phys Rev D accepted, astro-ph/0609507
73. HST Stellar Standards with 1% Accuracy in Absolute Flux, Bohlin, in Future Photometric, Spectrophotometric, and Polarimetric Standardization, ed. C. Sterken, astro-ph/0608715
Successful 4-year R&D program means that SNAP is now ready to build.

“The committee felt that there were no technical issues that would preclude readiness of the mission.”

“The overall design concept of SNAP as presented is technically sound and well developed ... The team should be commended for an excellent system approach and associated point-design for the space hardware elements.”

--External Technical Review

“SNAP remains an extremely well-motivated experiment for determining the nature of the dark energy that is causing the accelerated expansion of the universe. We endorse the team's approach of understanding and minimizing systematic errors.”

--SAGENAP
Two routes to a launch.
SNAP Reviews/Studies/Milestones

1998 Discovery of the acceleration of the universe and dark energy using supernovae.

Mar 2000 DOE/NSF SAGENAP committee recommends SNAP R&D
Sep 2000 NASA Structure and Evolution of the Universe (SEU)
Dec 2000 National Academy of Sciences Committee on Astro. & Astrophysics

Jan 2001 DOE-HEP Review R&D (SNAP is uniquely able)
Mar 2001 DOE High Energy Physics Advisory Panel (HEPAP)
Jun 2001 NASA Integrated Mission Design Center (determines feasibility)
July 2001 National Academy of Sciences, Committee on Physics of the Universe
Dec 2001 NASA/SEU Strategic Planning Panel
Dec 2001 NASA Instrument Synthesis & Analysis Lab
Mar 2002 DOE/NSF SAGENAP committee update
Apr 2002 National Academy of Sciences: Physics of the Universe report
July 2002 DOE Office of Science R&D Review (Lehman)
Dec 2002 JPL Team-X Study (studies potential NASA cost)
Jan 2003 NASA releases SEU roadmap: Beyond Einstein
Feb 2003 DOE High Energy Physics Facilities Prioritization Panel
Feb 2003 SNAP R&D in the DOE budget
Jun 2003 SNAP Awarded NASA 3 Mission Concept Studies
Nov 2003 JDEM Announcement from DOE & NASA
Nov 2003 Secretary of Energy’s 20-year Facilities Plan
Nov 2003 Technical Review of SNAP (could be launched ~2011)
May 2004 OSTP Strategic Plan (JDEM top recommendation)
Aug 2006 NASA selects advanced mission concept studies (ROSES).
Assess the five proposed Beyond Einstein missions (Con-X, LISA, JDEM, Inflation Probe, and Black Hole finder) and recommend which of these five should be developed and launched first, using a funding wedge that is expected to begin in FY2009.
<table>
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<tr>
<th>Project/Mission</th>
<th>FY07</th>
<th>FY08</th>
<th>FY09</th>
<th>FY10</th>
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<td>69.4</td>
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</table>
• France is already involved with the development of our spectrograph, one of the two instruments on SNAP. This effort is currently being funded by the French Space Agency.

This past November, CNES (French Space Agency) initiated a study of SNAP and French participation in SNAP.
International Context (-)

• A French National mission, DUNE, a Weak Lensing space mission was under formulation, though now seeking broader support through ESA.

• ESA has developed a program line called Cosmic Visions, that could include a Dark Energy Mission for launch 2015 (or later). ESA is expected to issue a call later this year to start the process.
International Context (+)

Delta IV

Soyuz-ST/Fregat (2-1B)
1. Dark Energy is at the heart of our HEP science: scientifically this is an extremely important measurement.

2. The definitive exploration of Dark Energy requires a space-based project.

3. A major accomplishment: a successful 4-year R&D program, funded by DOE, means that SNAP is now ready to build.

4. Two routes to a launch.

All of the above is well-reviewed and validated by national panels.