SNAP

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Presentation to HEPAP
Washington, DC
Feb 2007

Sign posts for today's presentation

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.

"The science addressed by SNAP in exploring the nature of dark energy is absolutely central." *— HEPAP 20-year Roadmap Facilities Committee*

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*

Department of Energy

"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.

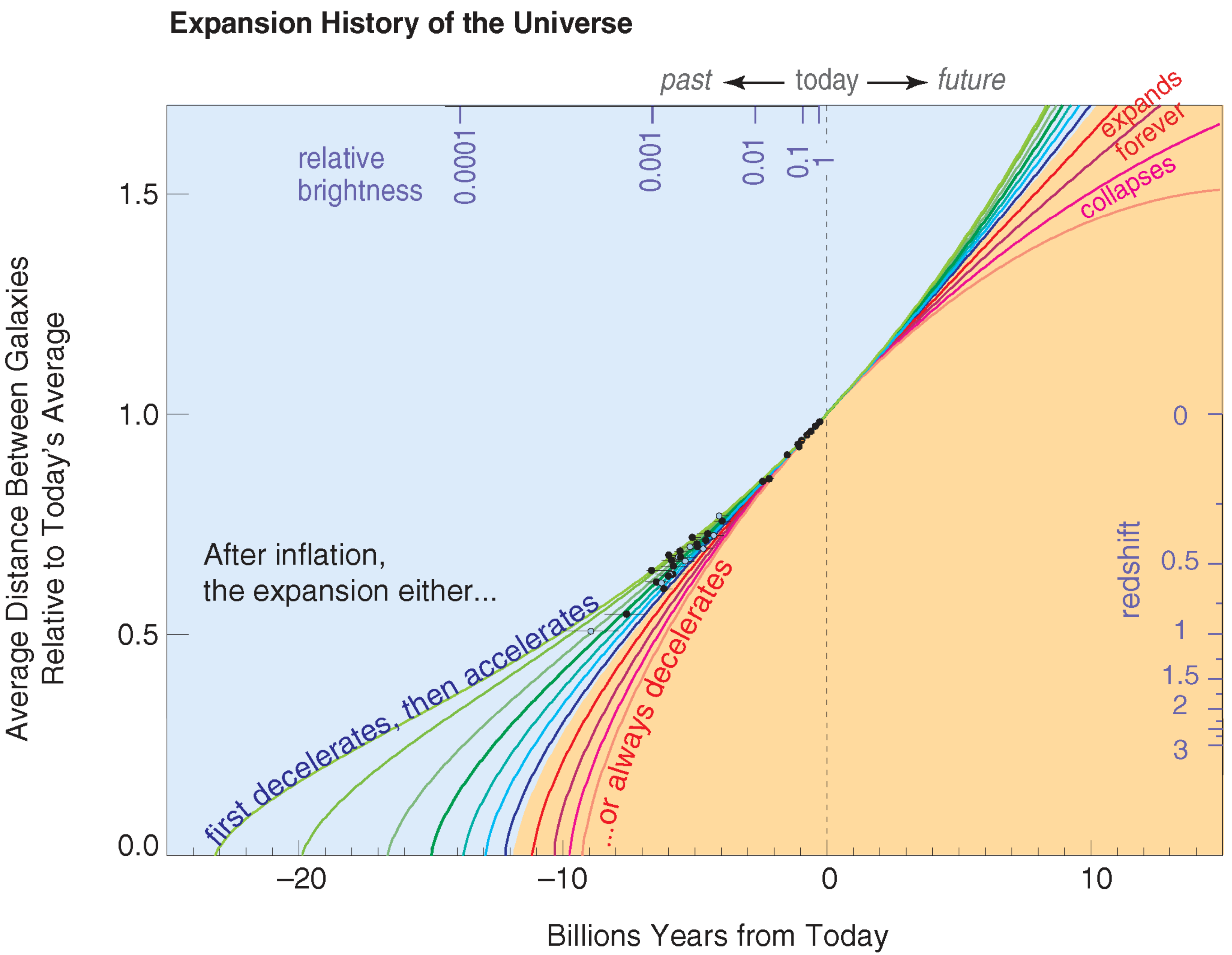
- Using two complementary methods is crucial to separate D.E. from G.R. physics explanations.
- Using two cross-checking methods is rather minimal for a systematics check.

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.

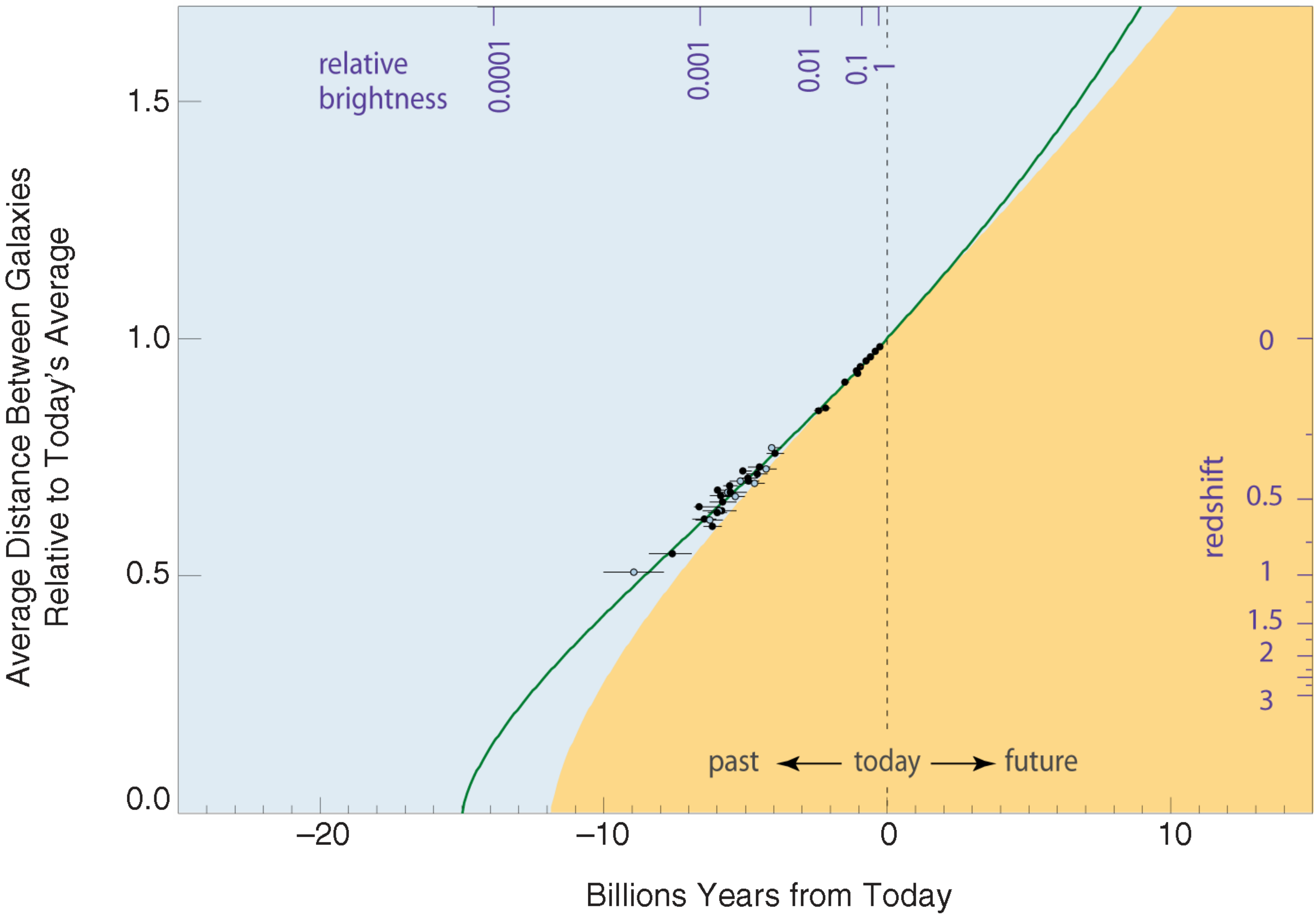
SNAP is designed around this principle for

- the Type Ia Supernova method and
- the Weak Lensing method



Expansion History of the Universe
past
today
future
relative
brightness
0.0001
0.001
0.01
0.1
1
expands
forever
collapses
After inflation,
the expansion either...
first decelerates, then accelerates
...or always decelerates
redshift
0
0.5
1
1.5
2
3
1.5
1.0
0.5
0.0
–20
–10
0
10
Average Distance Between Galaxies
Relative to Today's Average
Billions Years from Today

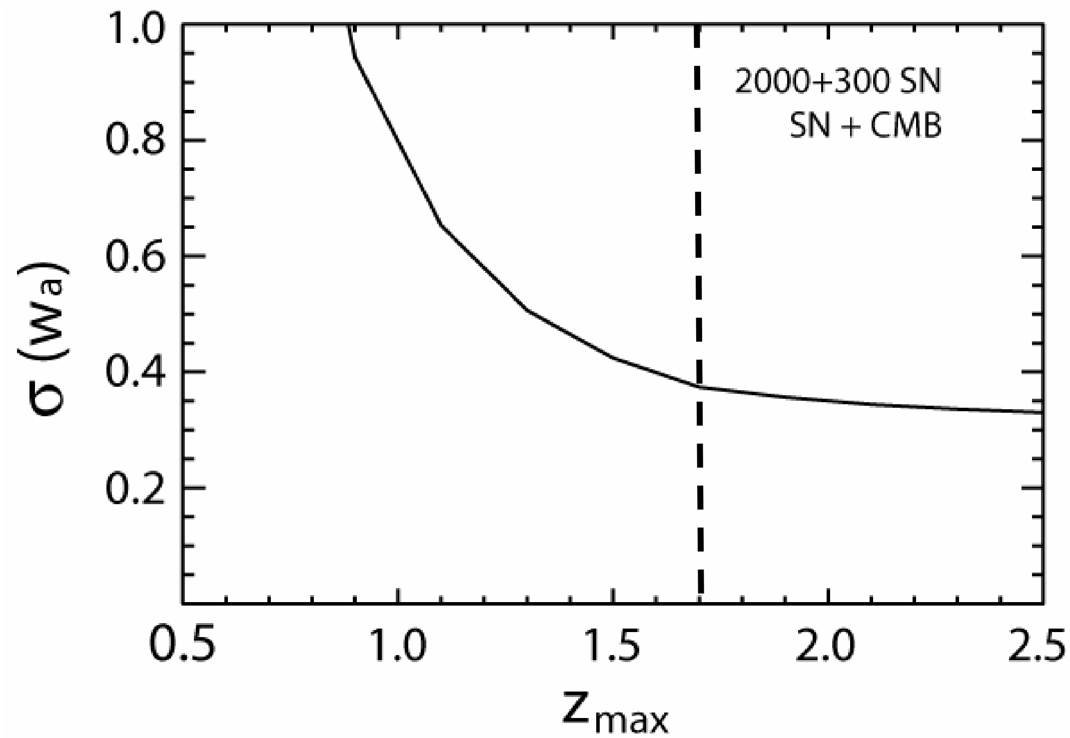
Expansion History of the Universe



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 ~ 1.7



SN Systematics Control

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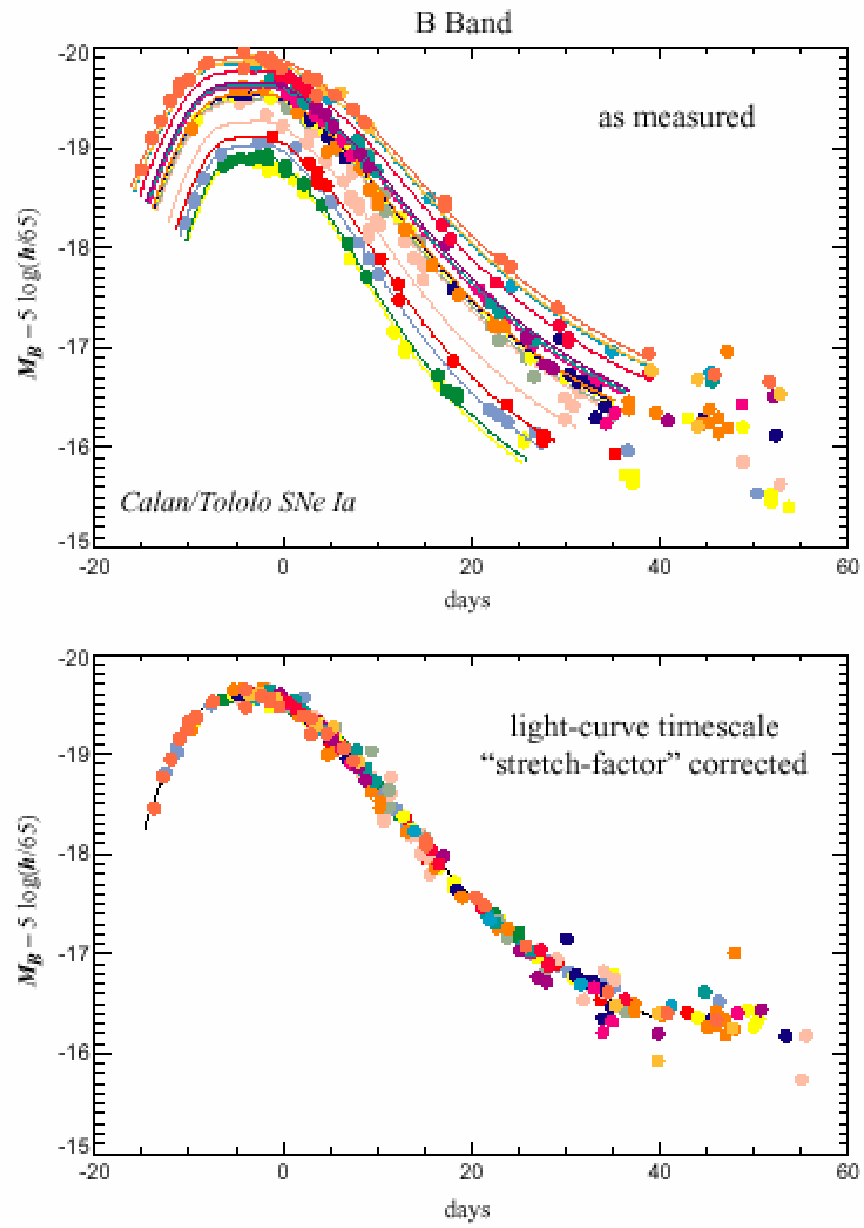
- **SN Lightcurve**
  - — **Recognize differences between SNe**



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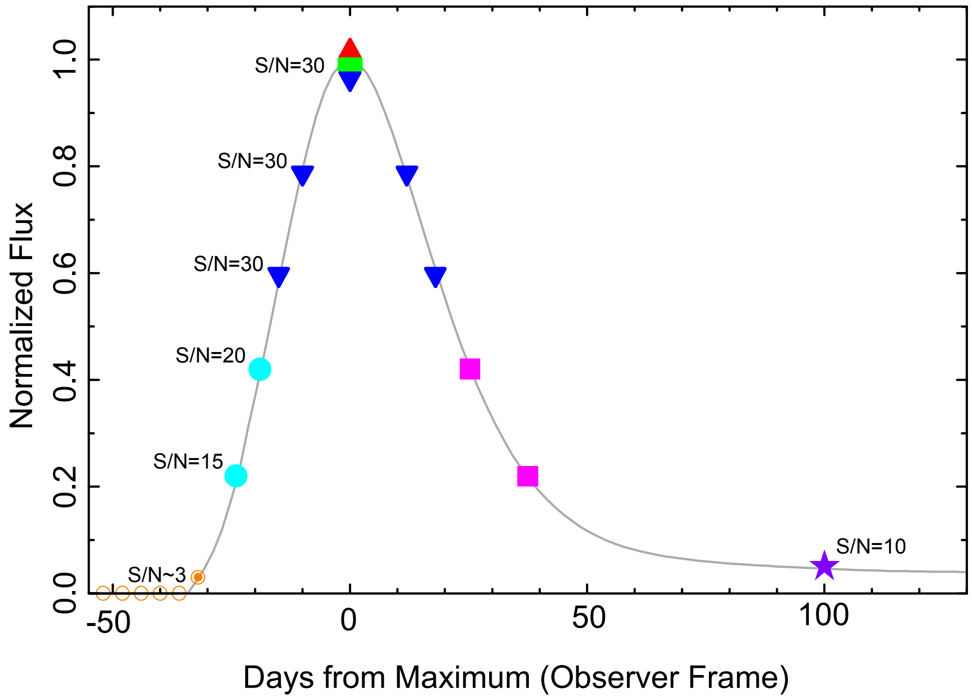

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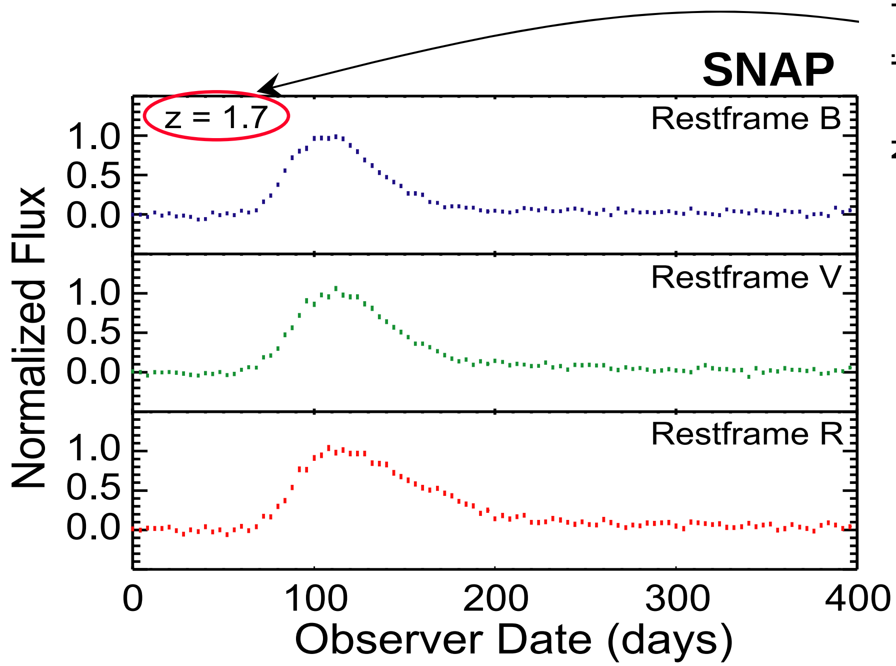

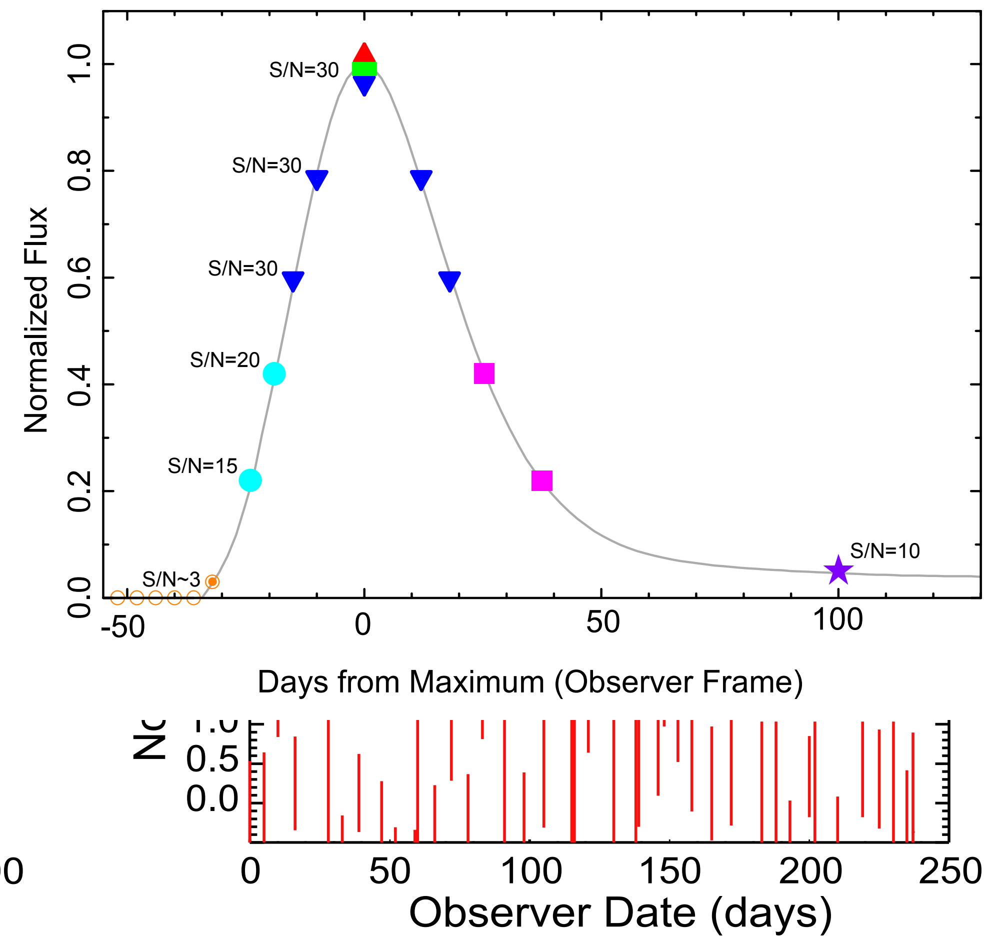

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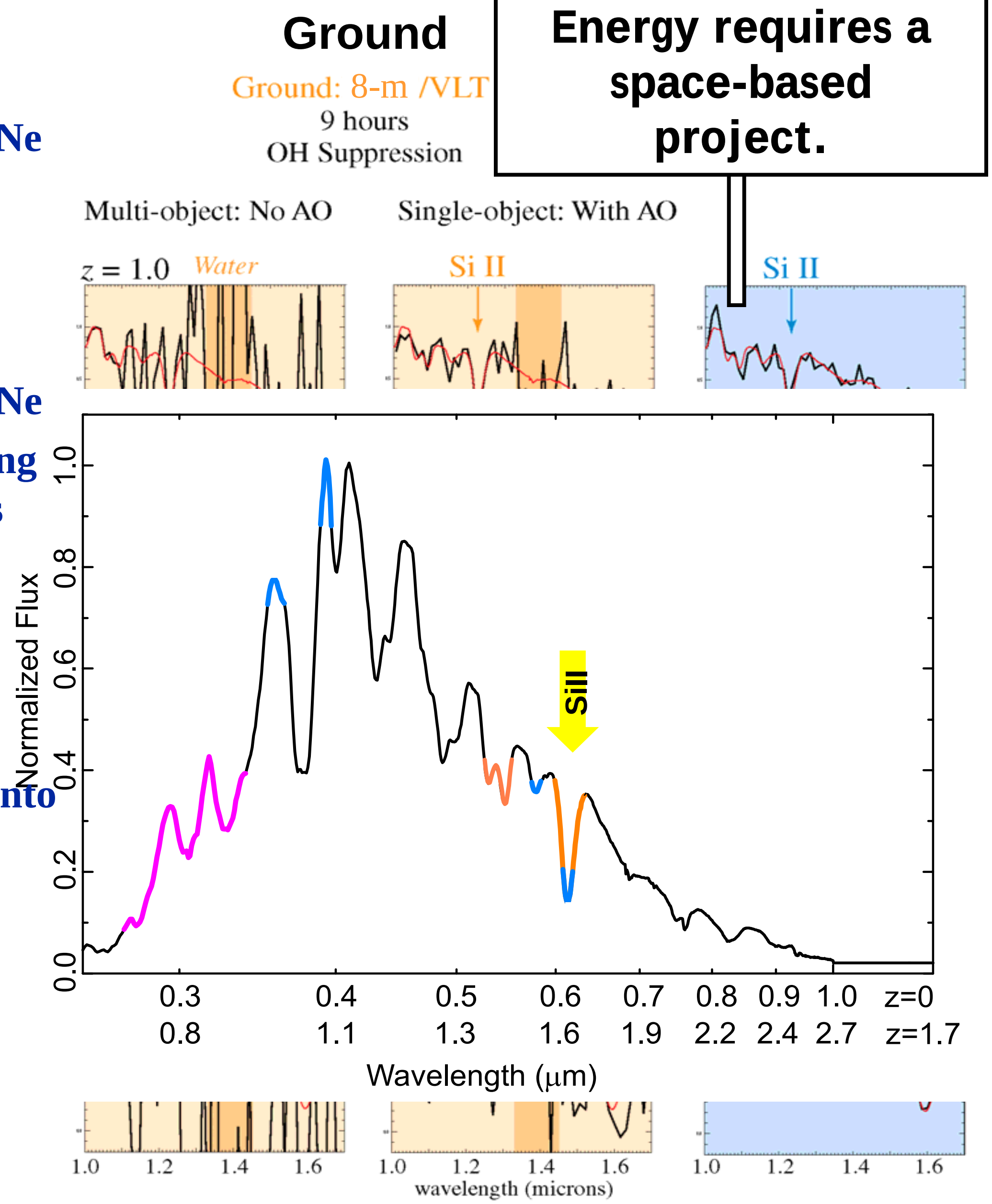
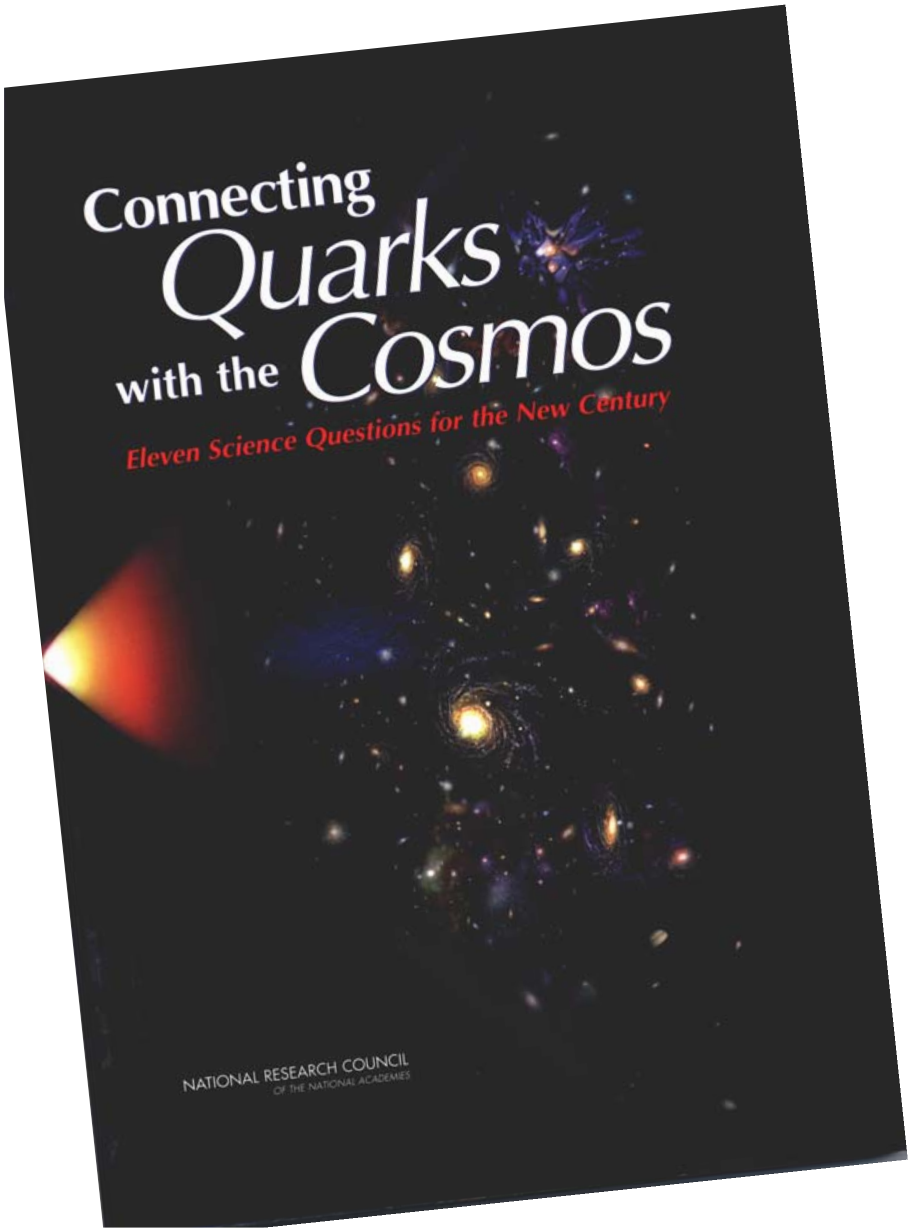
  - — **Recognize and correct for evolving dust extinction: requires 3 colors**
- **Spectrum**
  - — **Identify SN type**
  - — **Subclassification**
  - — **Low resolution, R~70 spectrum into NIR**
- **Going to space makes these measurements possible over the full redshift range.**

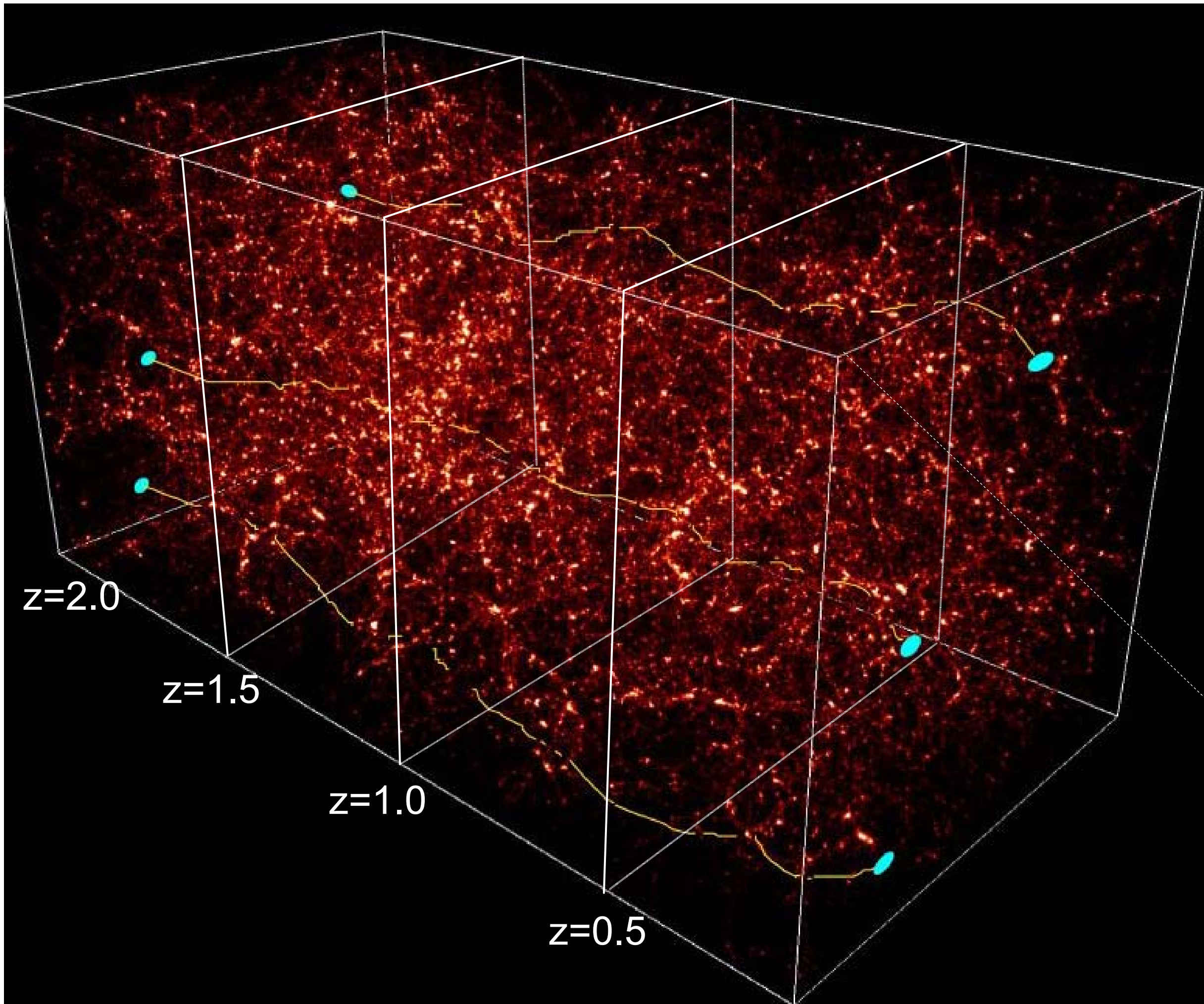
The definitive exploration of Dark Energy requires a space-based project.

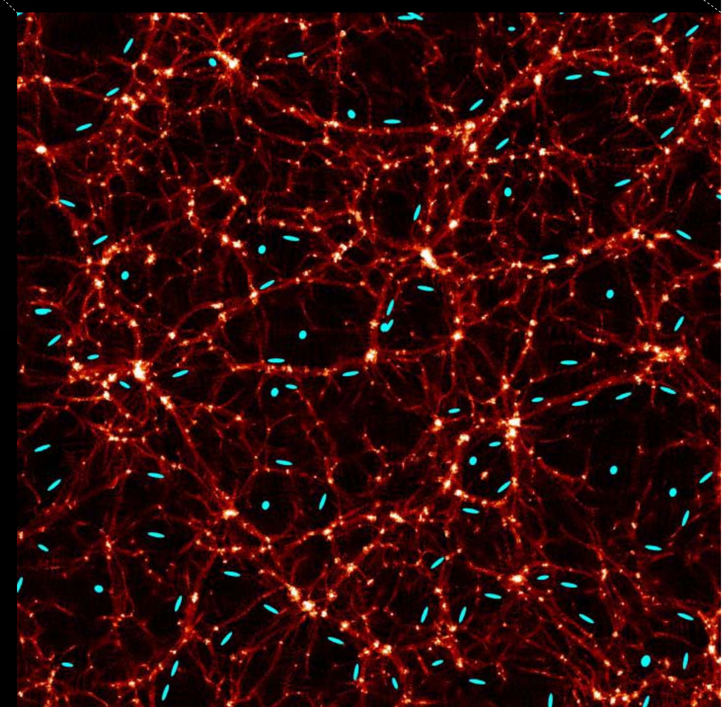


Report from the National Academy of Sciences Committee on the Physics of the Universe



- "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)."





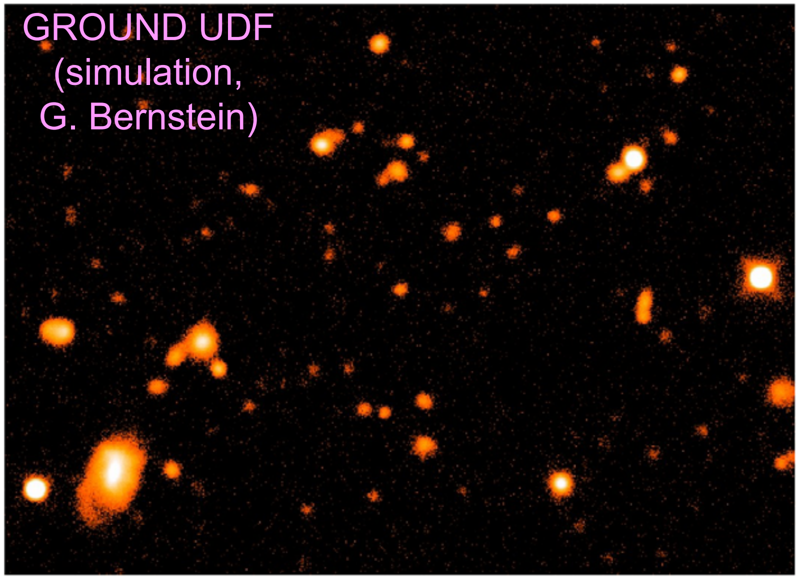
Gravitational Weak Lensing

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.

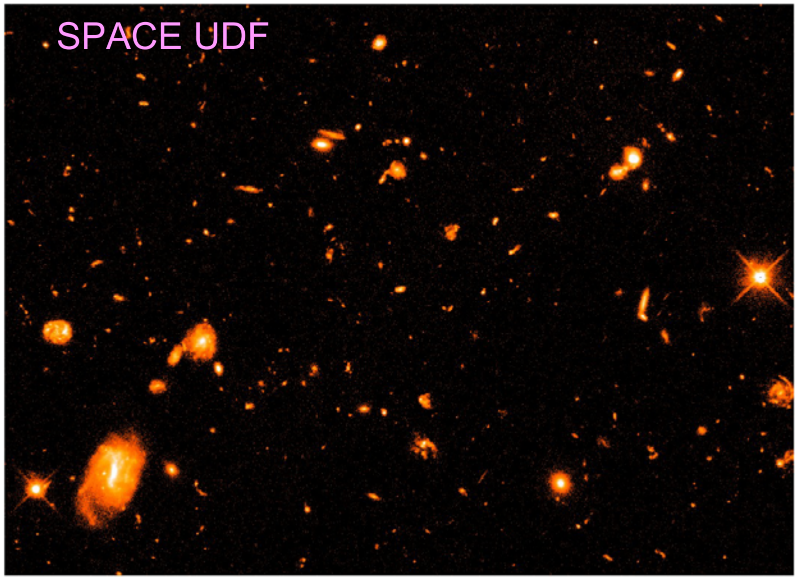
This effect can be very small and yet detectable statistically after averaging over the measured ellipticity of many galaxies.

WL Systematics Control

- **Large number of resolution elements on the sky**
  - **—To get sufficient quantity of <u>resolved</u> galaxies**



<u>Hubble Space Telescope Ultra Deep Field</u> shows many more small specks of light – these are the resolved galaxies that can be seen from space but not from the ground



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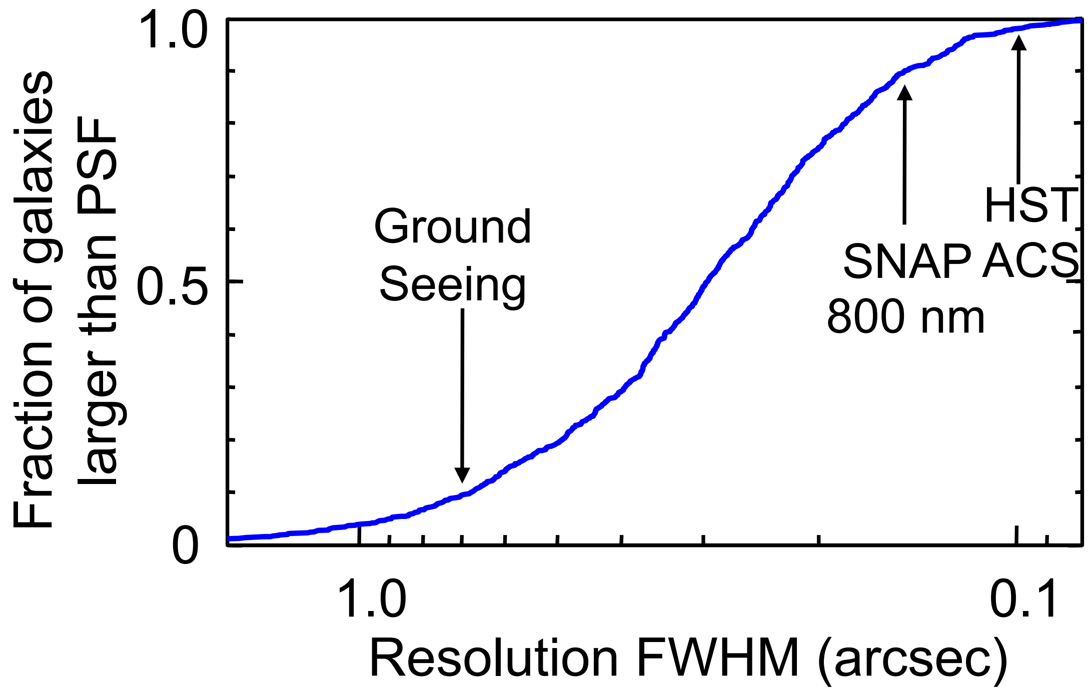


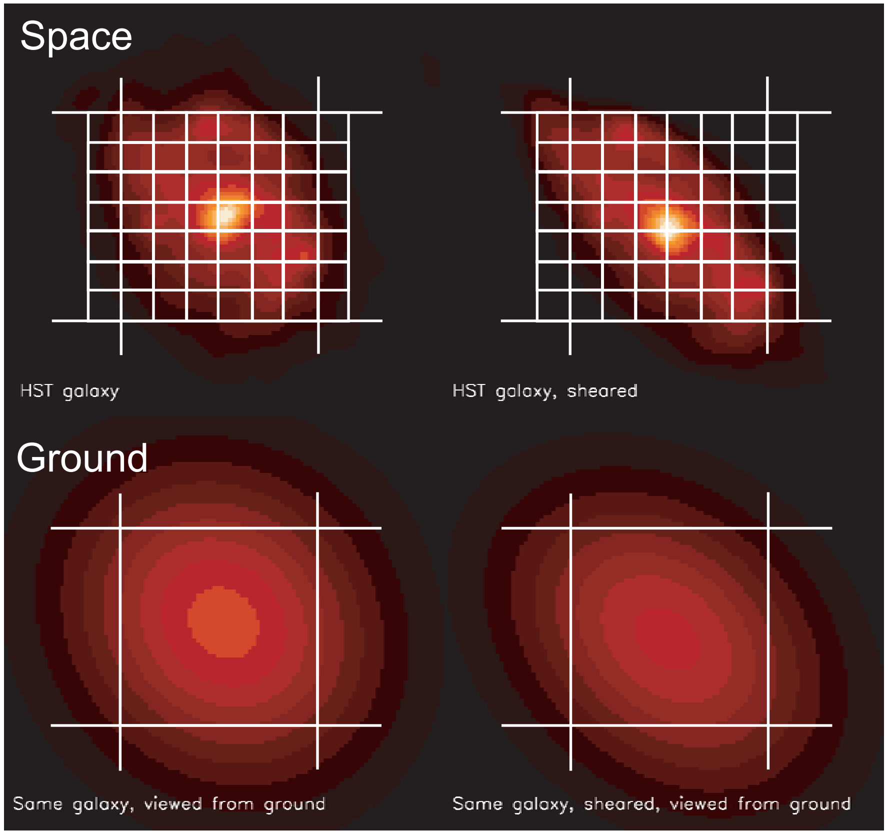
Fraction of galaxies that can be studied from space with SNAP is close to one.

WL Systematics Control

- **Large number of resolution elements on the sky**
  - — **To get sufficient quantity of resolved galaxies**
- **Measurement of the galaxy ellipticities (shear)**
  - — **<u>Requires "space" resolution</u>**
  - — Demands stable optics

Shear accuracy ~ $(r_{psf} / r_{galaxy})^2$

Weak lensing galaxy shear observed from space
versus
Weak lensing galaxy shear observed from the ground.



(Bacon, Ellis, Refregier, Nov. 2000)

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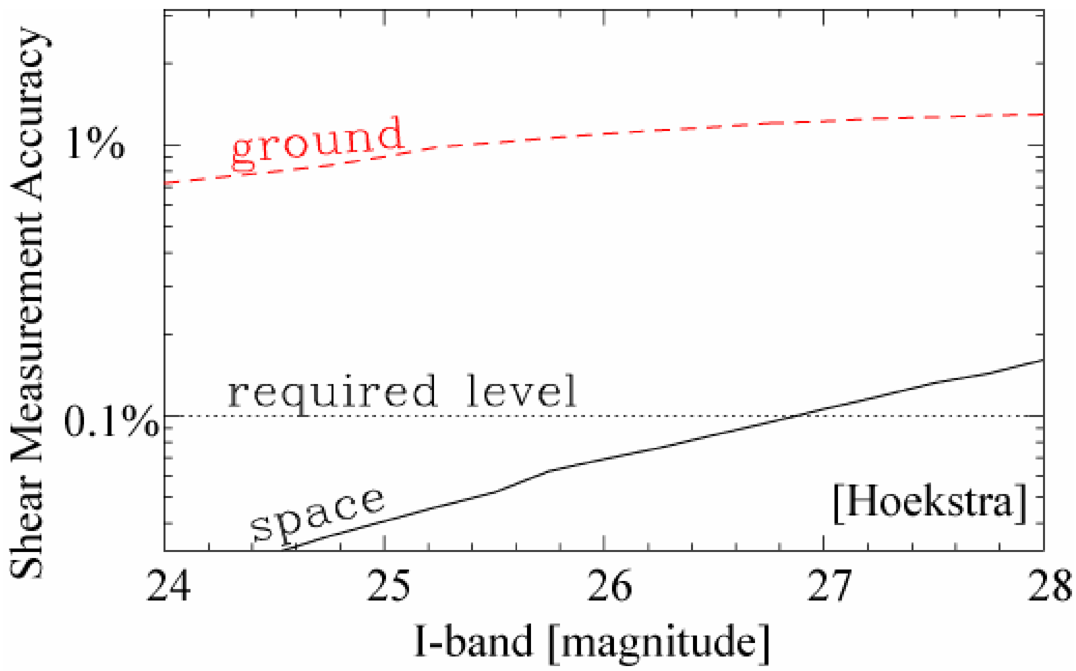
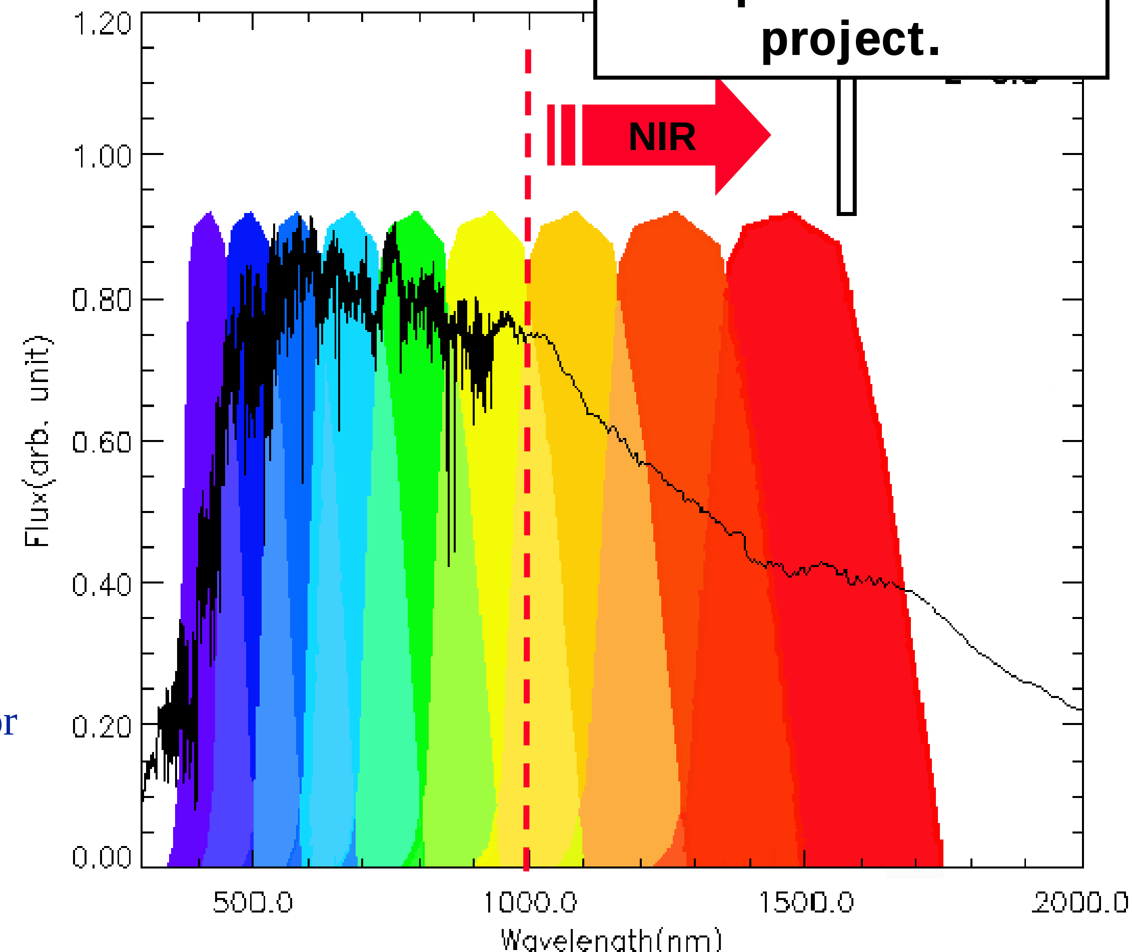


WL Systematics Control

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

- **Large number of resolution elements on the sky**
  - — **To get sufficient quantity of resolved galaxies**
- **Measurement of the galaxy ellipticities (shear)**
  - — **<u>Requires “space” resolution</u>**
  - — Demands stable optics
- **Measurement of galaxy redshift**
  - — Needs excellent photometry, for photometric redshift
  - — **<u>Requires NIR</u>**
- **Going to space ameliorates all these problems, controls systematics**--and why the DETF considers this to be <u>the option that guarantees results</u>



We can and must thus
push the envelope
in control of systematics.

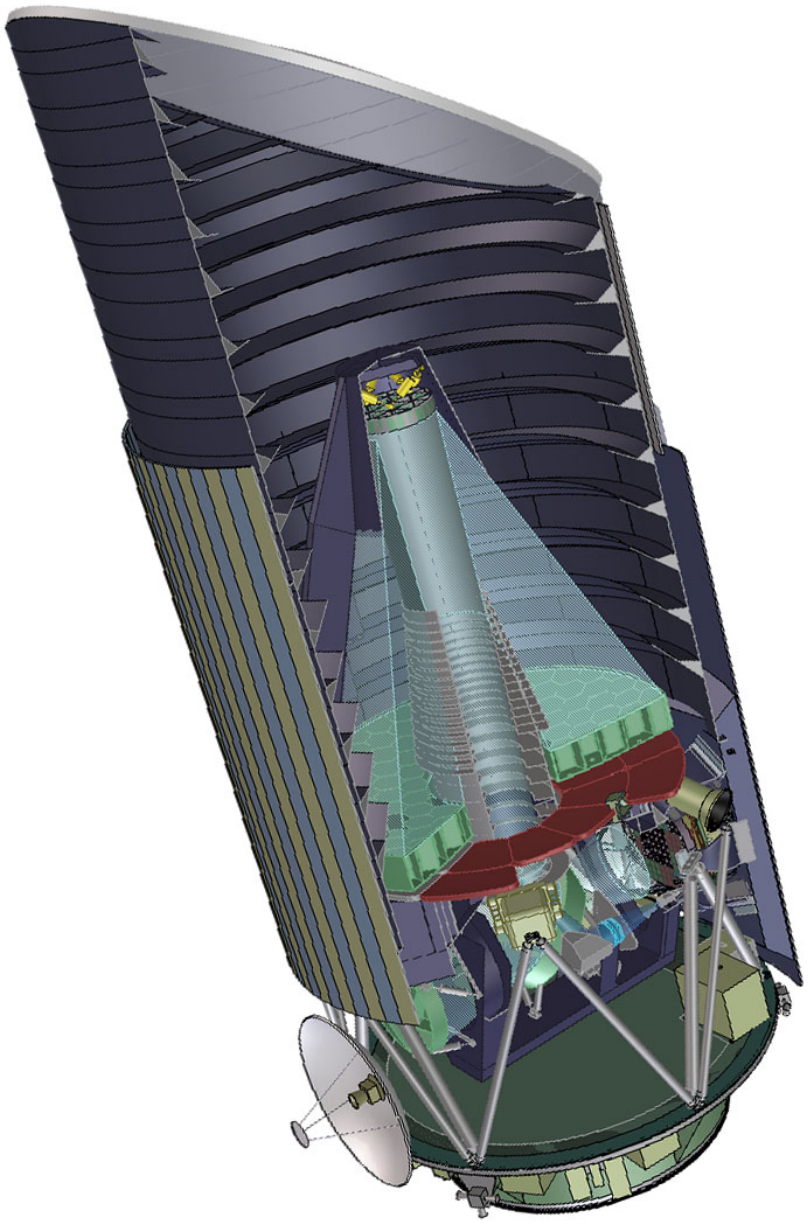
We do not need or want to
push the envelope
in technical innovation.

The science is hard, the implementation is mostly more pedestrian:

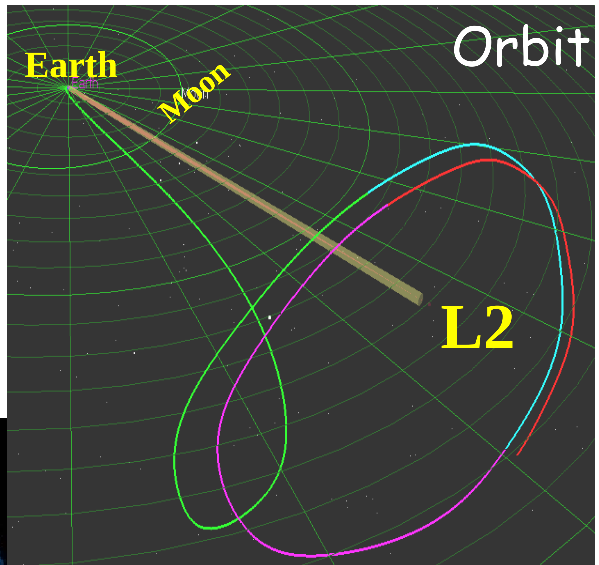
Location, location, location
Stability, stability, stability

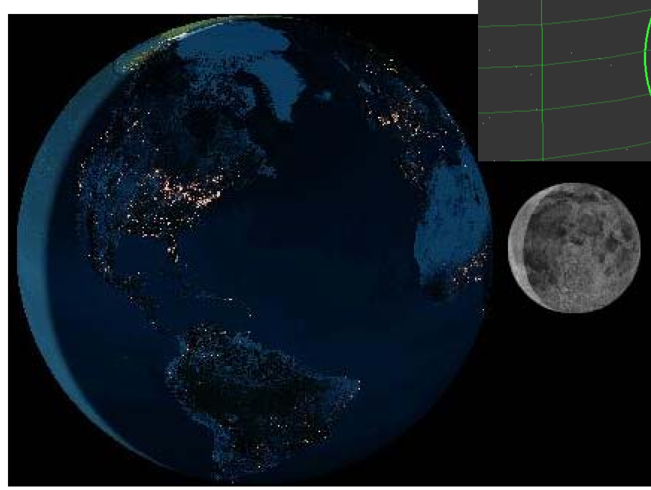
Smallest launch vehicle in its class
Standard bus and known ACS capabilities
Traditional telescope
One instrument bay, one focal plane
Very few moving parts, with redundancy

An extremely stable environment: L2



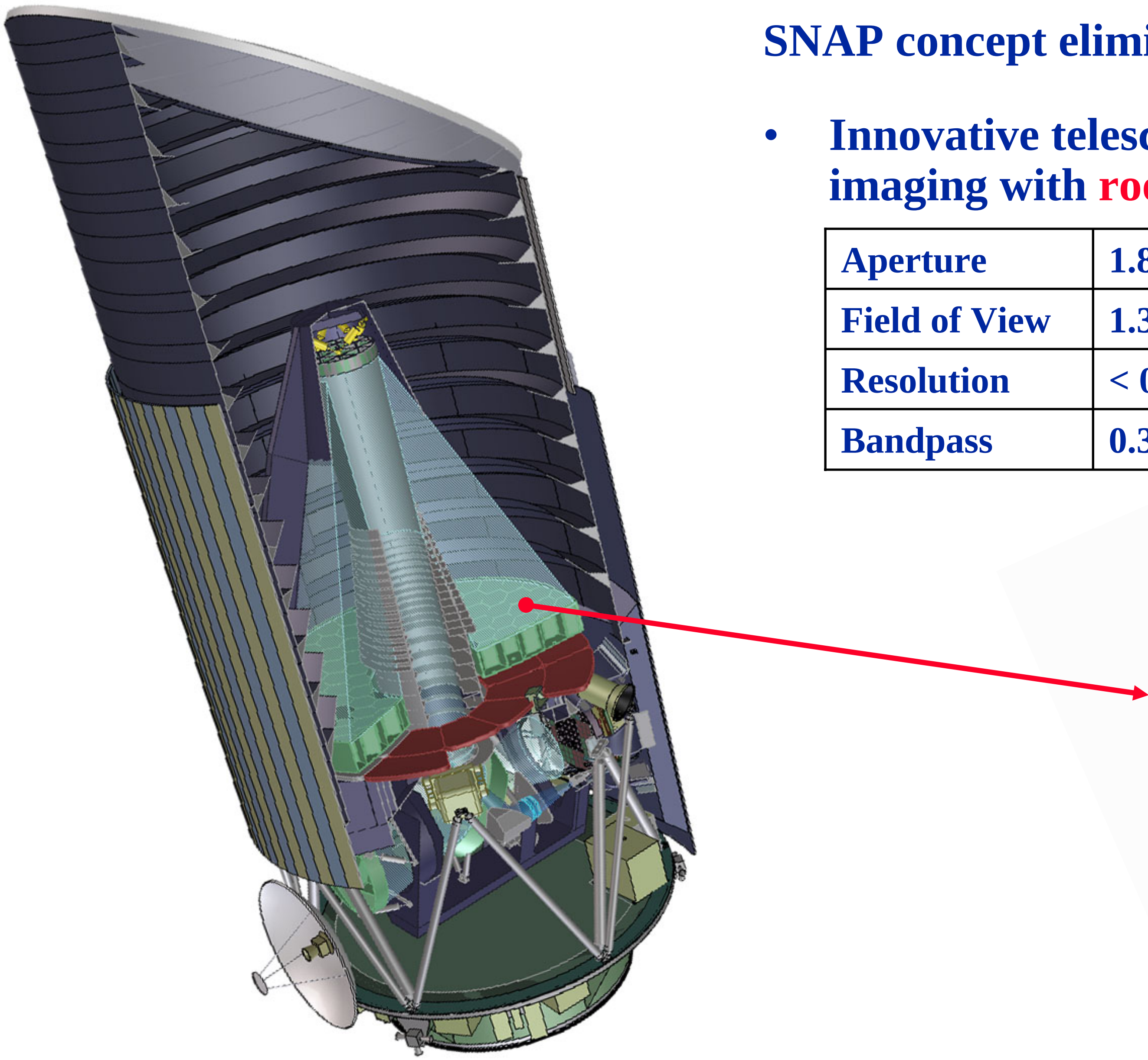
L2 Orbit, **puts most "work" in the Launch Vehicle, small fuel for injection, station keeping, angular momentum.**





Earth and Moon Illumination

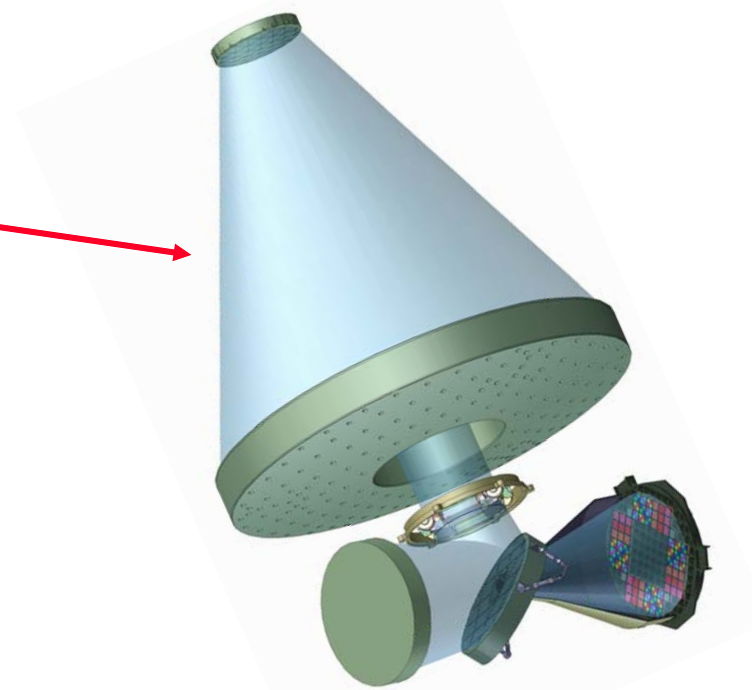
A simple design



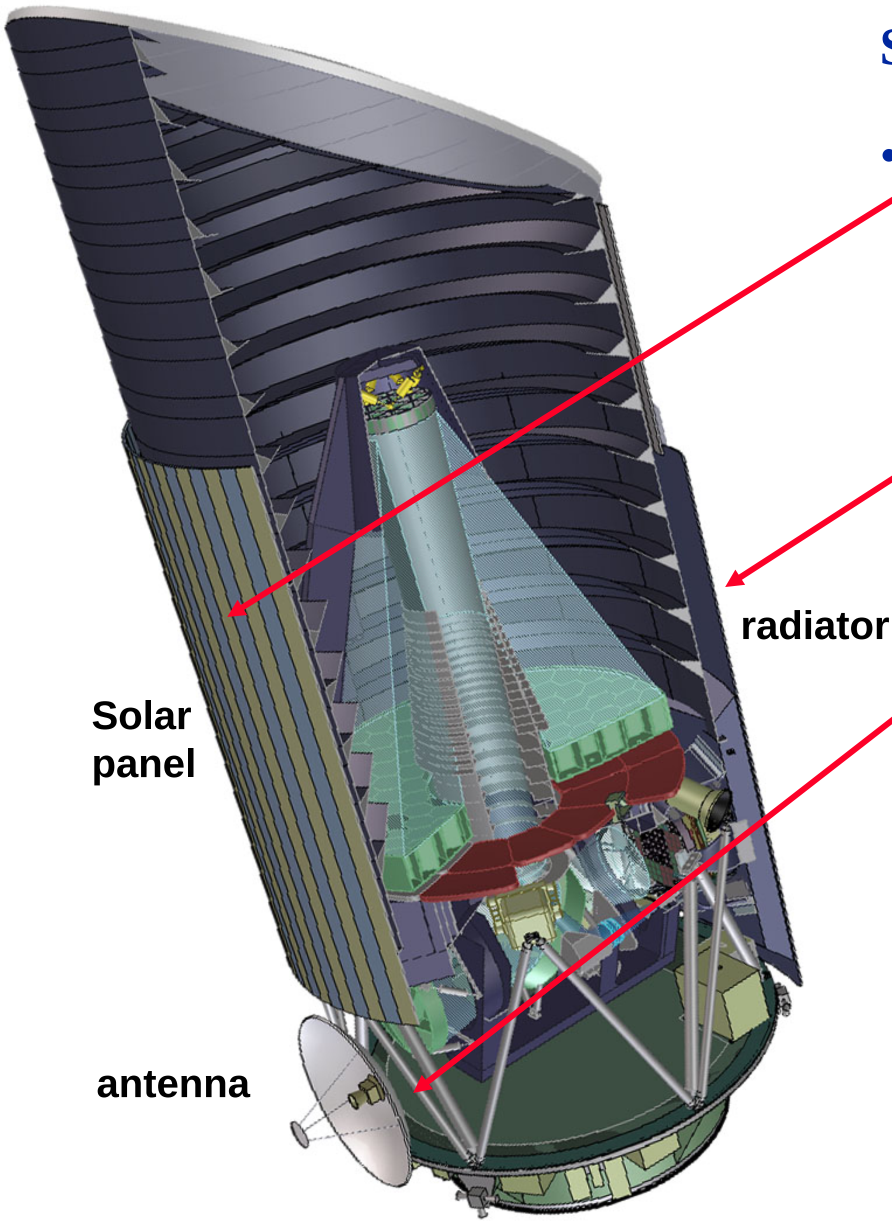
SNAP concept eliminates complexity:

- **Innovative telescope design does IR imaging with room temperature optics**

Aperture	**1.8 meter**
Field of View	**1.37 square deg**
Resolution	**< 0.06 arcsec FWHM blur**
Bandpass	**0.35-1.7 μm**



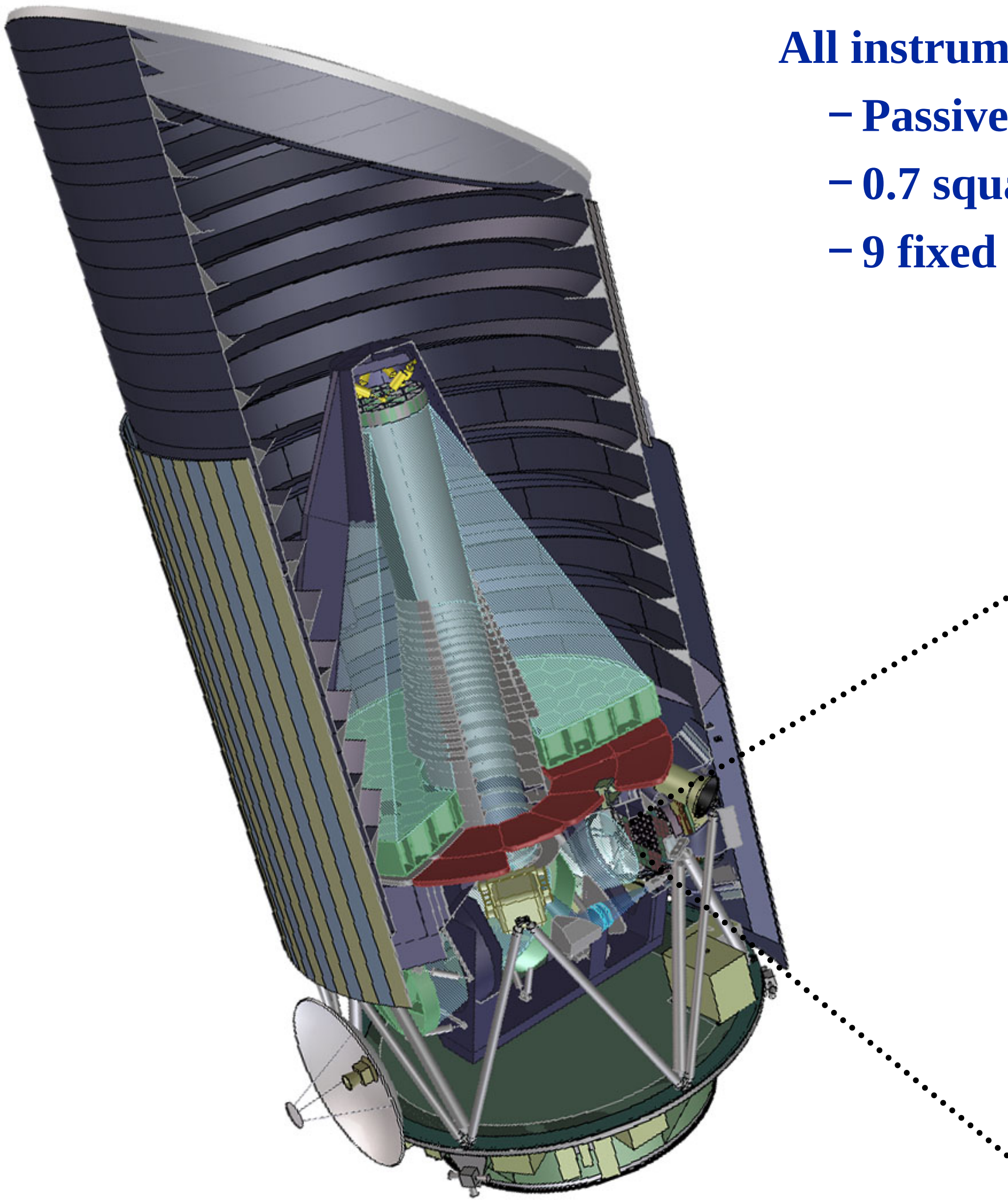
…With very few moving parts.



SNAP concept eliminates complexity:

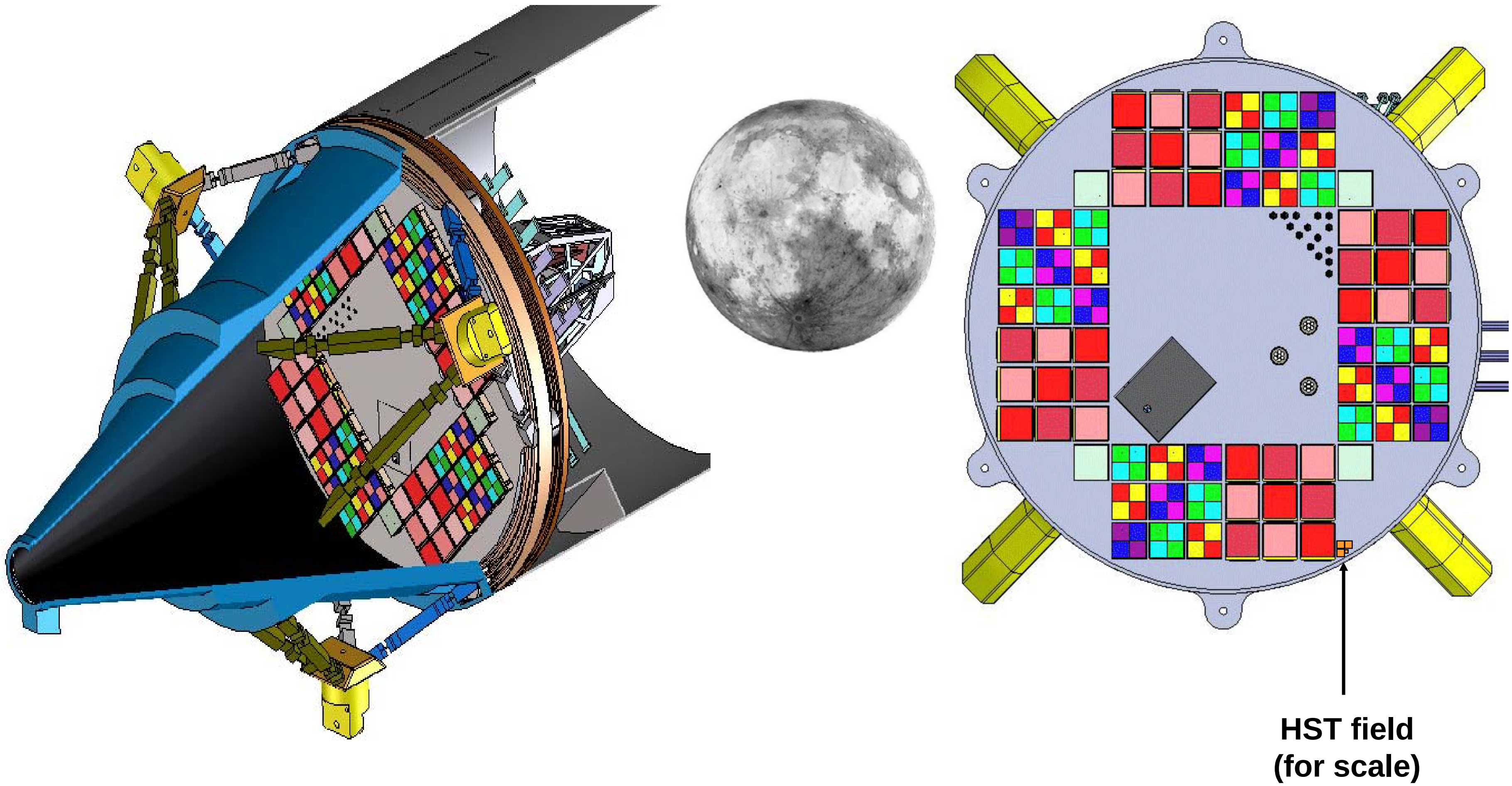
- **The fixed solar panels, passive cooling, fixed, antenna eliminates major mission risks.**

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**


HST field
(for scale)

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**

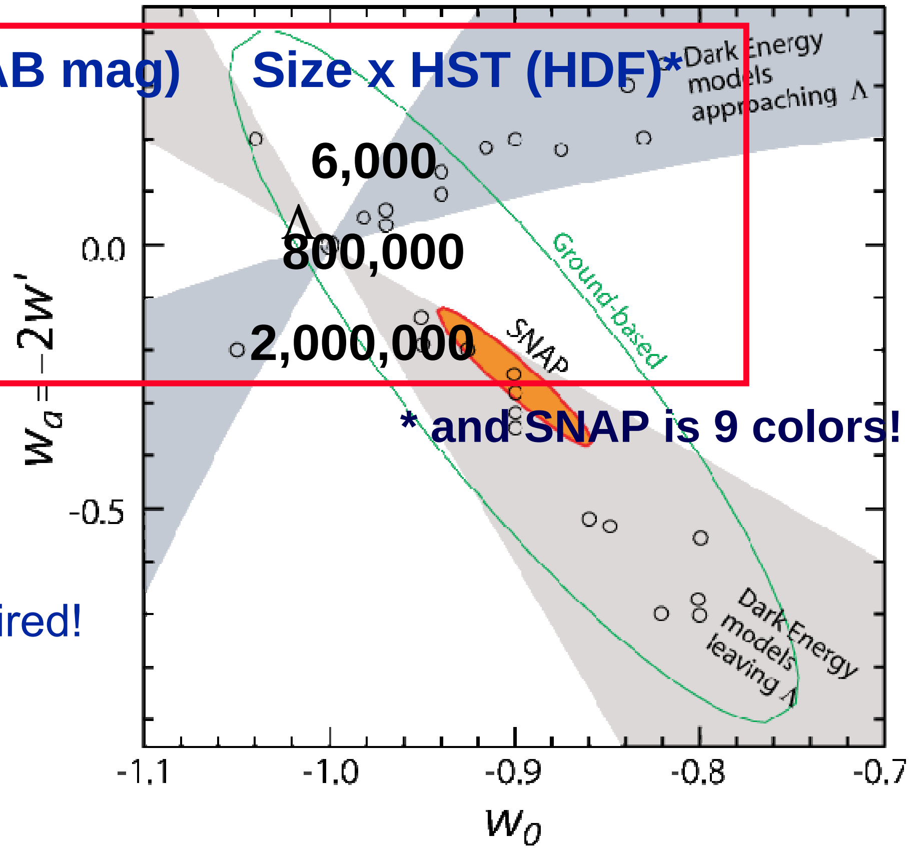
Daily operations concept:

— **21 Hours data collection**
— **2 Hours downlink**
— **1 Hour maneuvers and calibration**

Focal Plane is rotationally symmetric, we rotate the satellite every 3 months.

SNAP Surveys

Survey	Area(sq.deg)	Depth(AB mag)	Size x HST (HDF)*
Deep/SNe	8 (repeated)	30	6,000
Wide	1000	28	800,000
Extended	4000	28	2,000,000



* and SNAP is 9 colors!

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 (*with systematics*) Λ model
    - w_0 to ±0.03 variation w' to ±0.06 (*with systematics*) SUGRA model
  - Adding extended survey and better systematics:
    - w_0 to ±0.03, variation w' to ±0.06 (*with systematics*) Λ model
    - w_0 to ±0.015 variation w' to ±0.03 (*with systematics*) SUGRA model

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

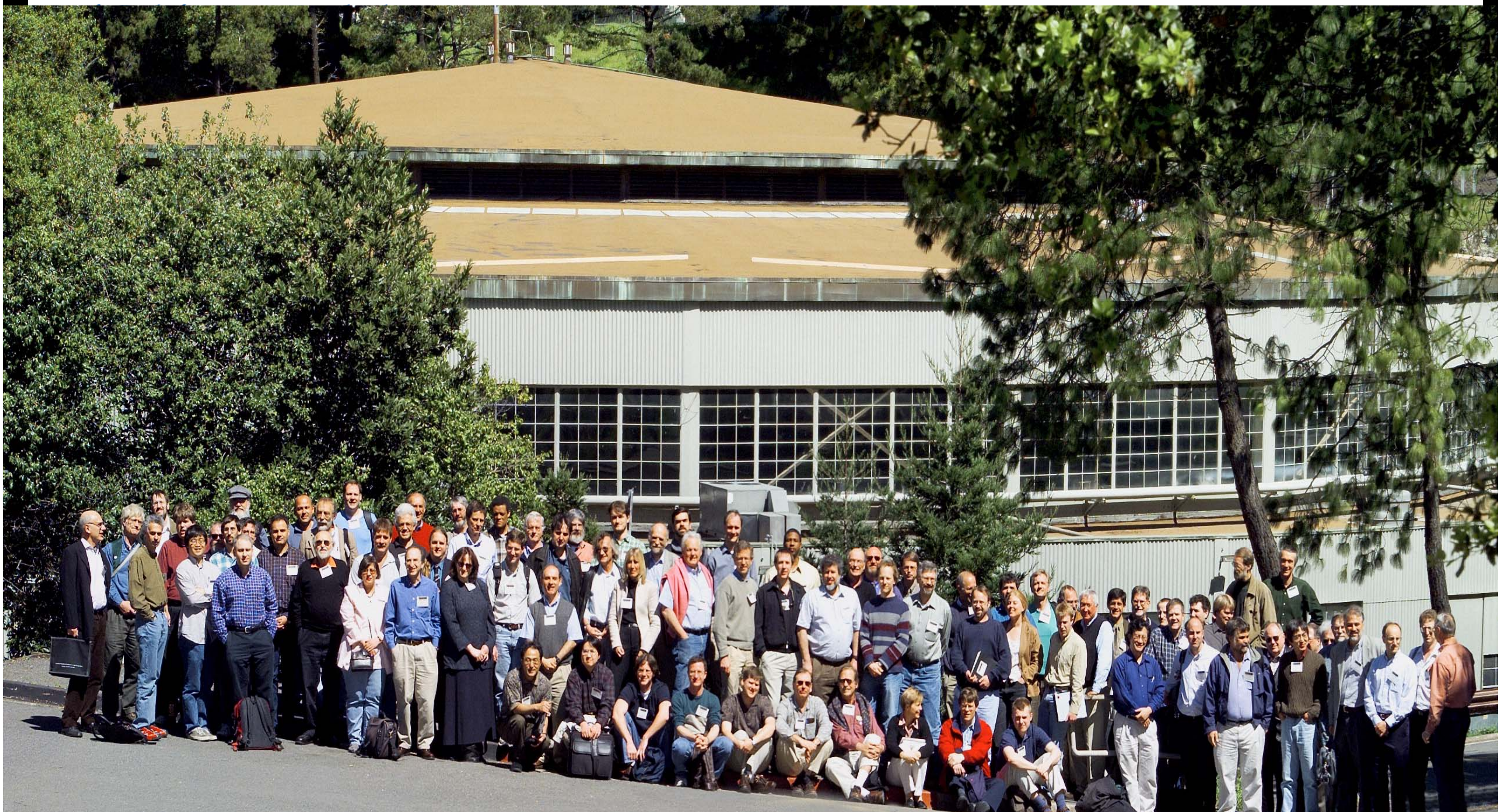
2000: Reviewed by SAGENAP; recommended R&D

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.

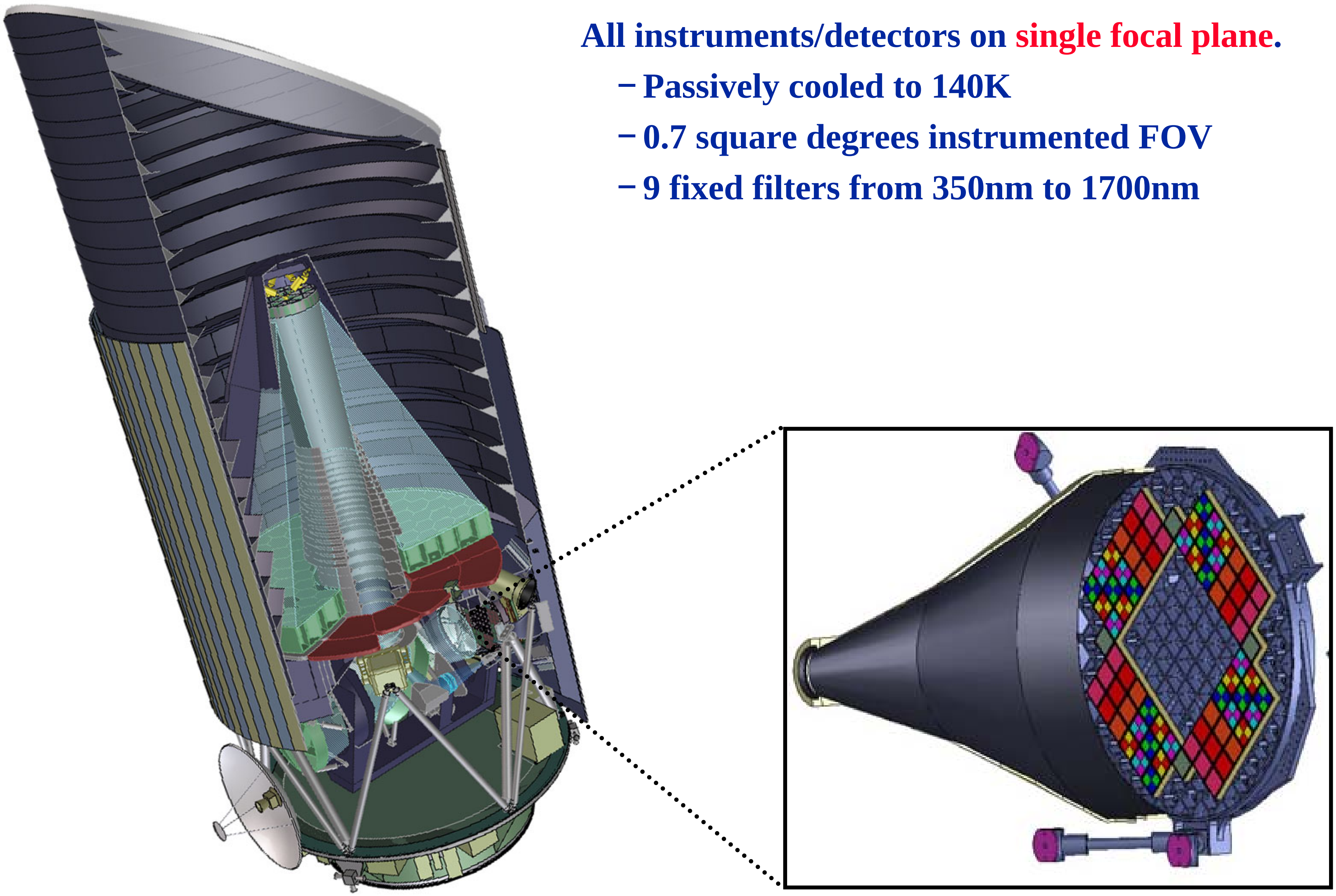
In discussion:

Univ. of Maryland

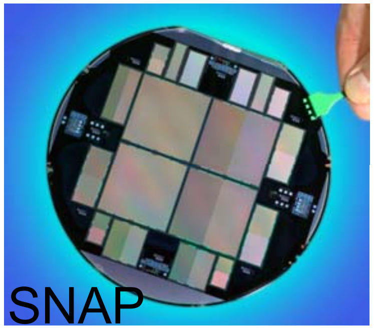
Kurchatov Institute of Atomic Energy

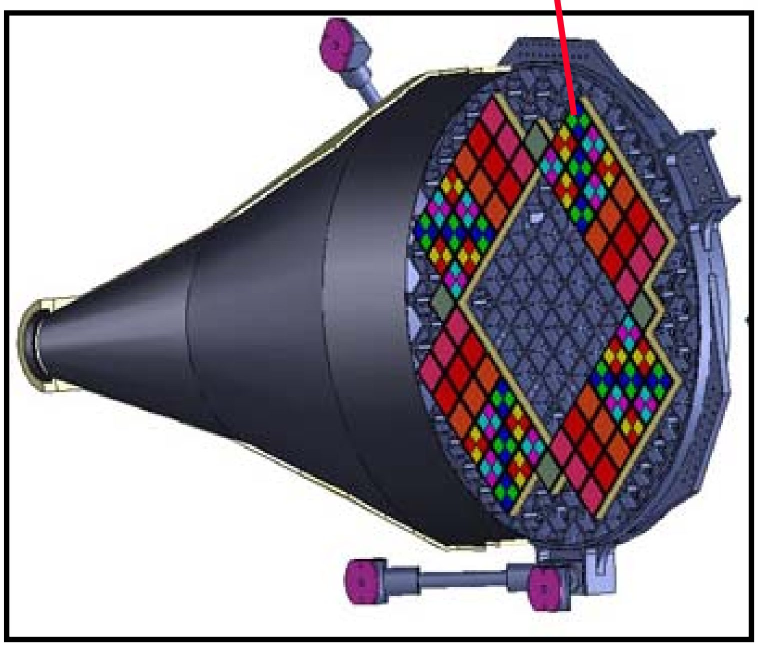
DoE R&D focused on detectors and electronics

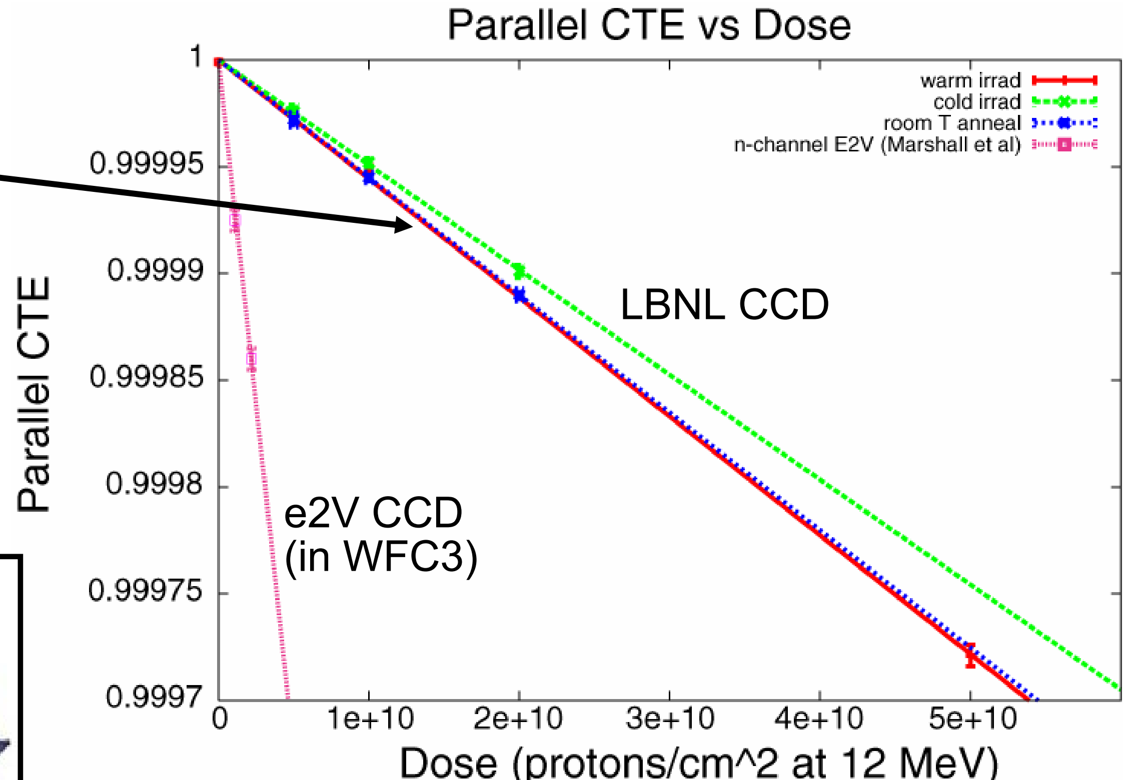
All instruments/detectors on single focal plane.
- **Passively cooled to 140K**
- **0.7 square degrees instrumented FOV**
- **9 fixed filters from 350nm to 1700nm**



New CCD technology tolerates radiation in space

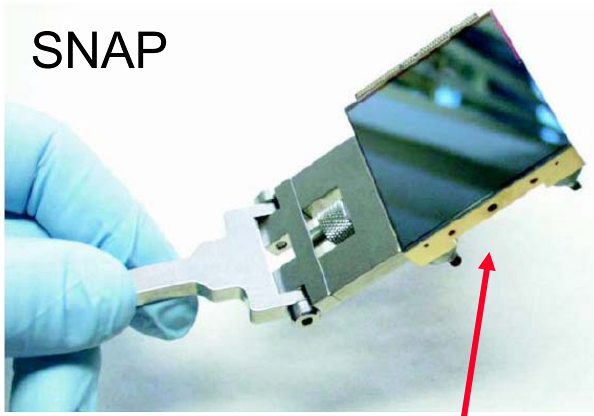


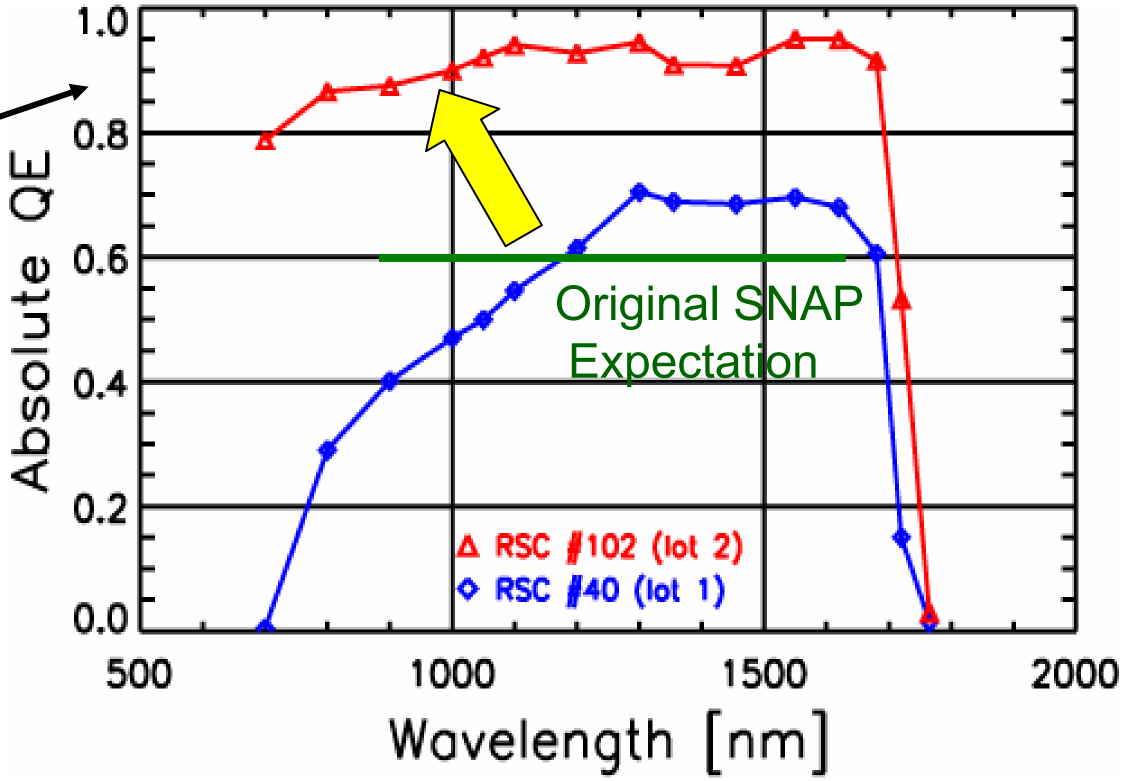


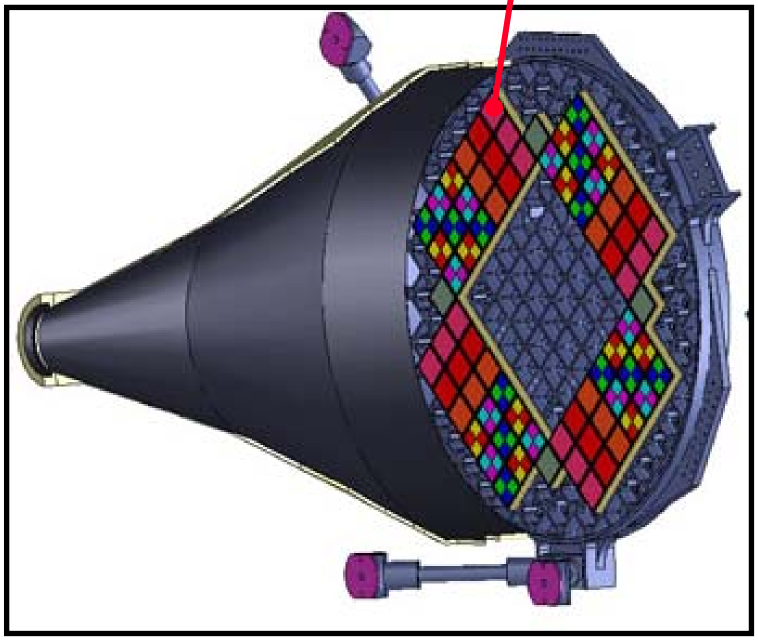


- Traditional n-channel CCDs are sensitive to radiation damage due to loss of Charge Transfer Efficiency (CTE)
- LBNL p-channel CCDs are 10-50x more radiation tolerant

NIR sensors now exceed original SNAP goal

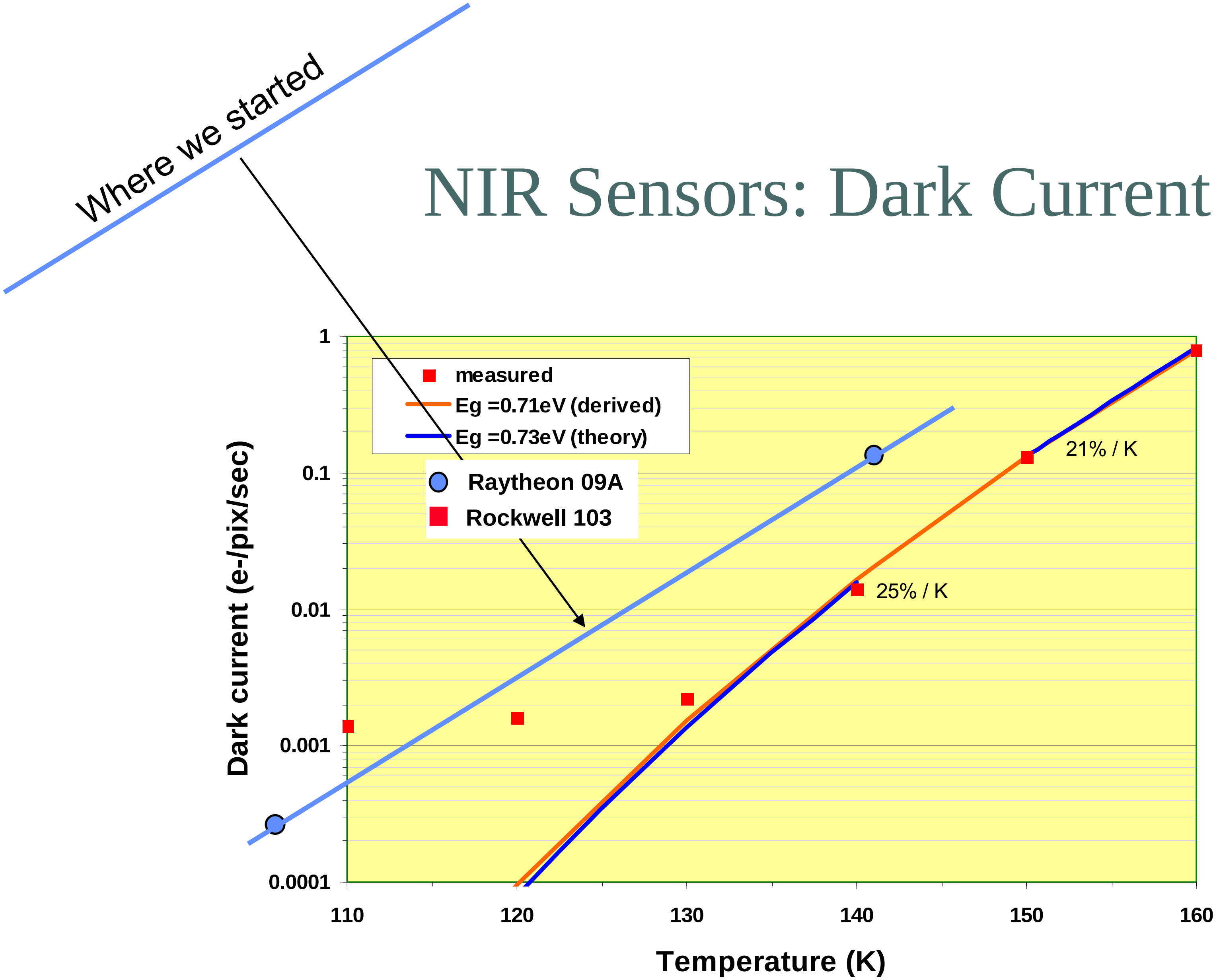






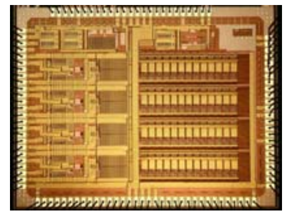
- NIR QE was low when R&D began.
- Noise reduced factor 4 to 100 .
- Largest detector was 1kx1k, now 2kx2k.
- Previously, only a single manufacturer.

NIR Sensors: Dark Current

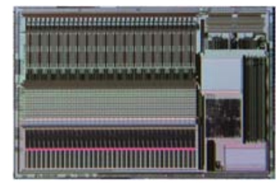


Matching ASIC electronics developed

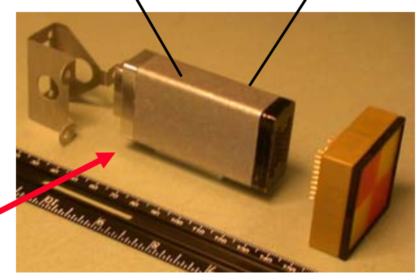
CCD CDS-ADC

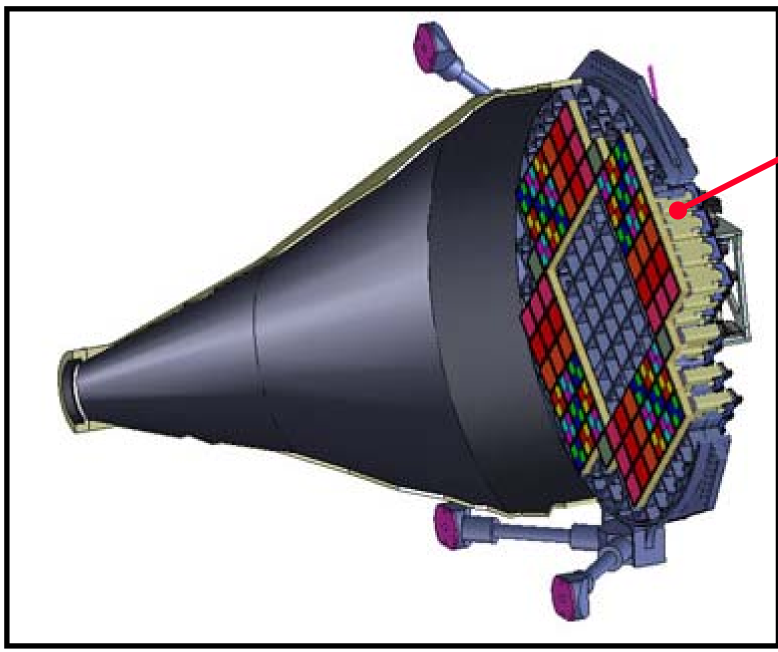


Rockwell SIDECAR



Electronics Module

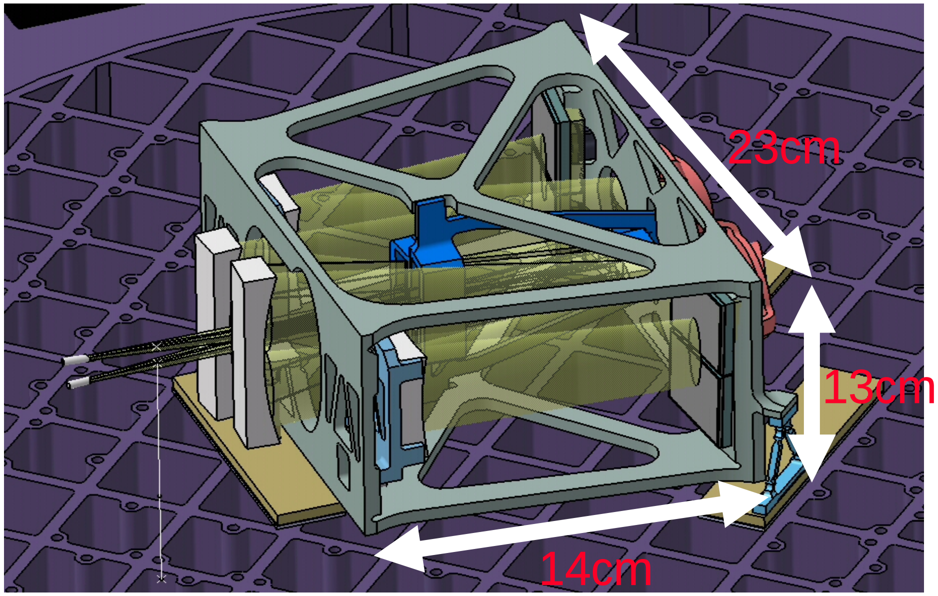


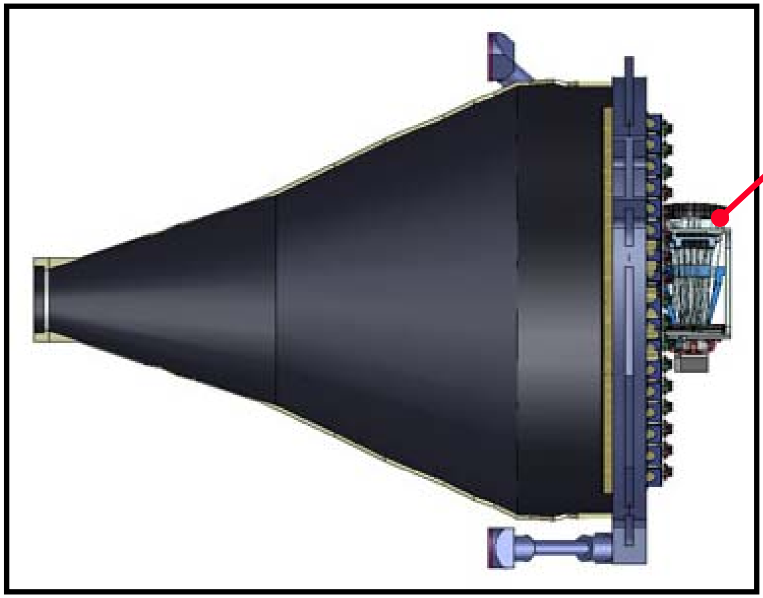


- Converts analog detector signals to digital values
- Based on ASIC’s
- Operate at 140 K
- Irradiated, cyrogenic test

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.

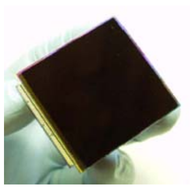




- **Spectrograph**
  - **Compact**
  - **Visible and NIR, R = 70 - 100**
  - **Image slicer: 3 arcsec of imaging & spectra**

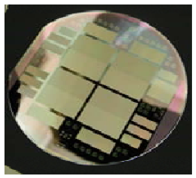
Focal Plane Effort

NIR



- Michigan — HgCdTe
- Cal Tech — HgCdTe
- JPL — InGaAs
- Indiana — Abs. QE
- STScI — HgCdTe
- GSFC — HgCdTe

Visible

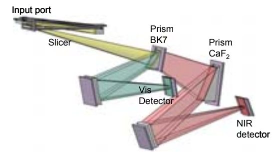


- LBNL — CCD devel. and testing
- Yale — CCD testing and packaging
- STScI — Si PIN hybrid testing

Filters

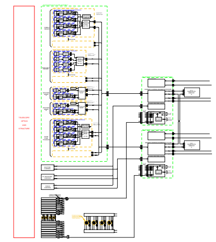
- Indiana — Stability/aging
- Michigan — Discrete filter mounts

Spectrograph



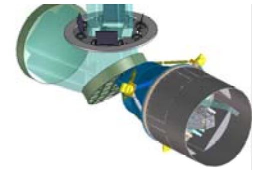
- LAM — Optics and mechanics
- Paris/Lyons — Detectors
- GSFC — Detectors

Electronics



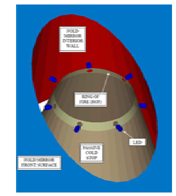
- SLAC/SSL — Architecture CCD FE
- SLAC — Instr. control
- FNAL — Data flow/ Compression

Mech/Therm



- LBNL/SSL — Focal plane concept
- LBNL/SSL — Therm./Mech.
- FNAL — Shielding

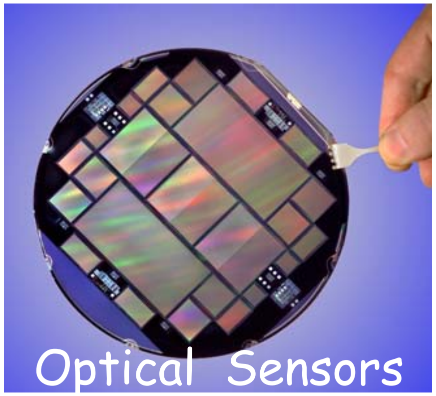
Calibration

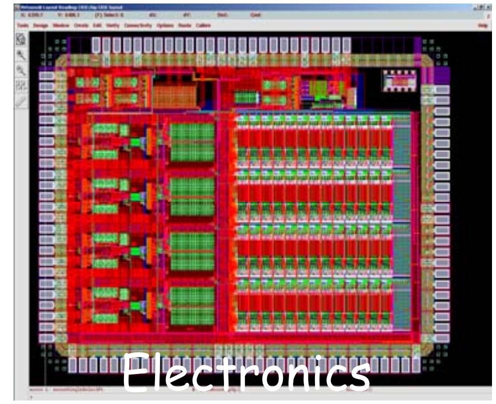


- LBNL/SSL — Optics and mechanics
- Indiana — Lamps

Star Guider

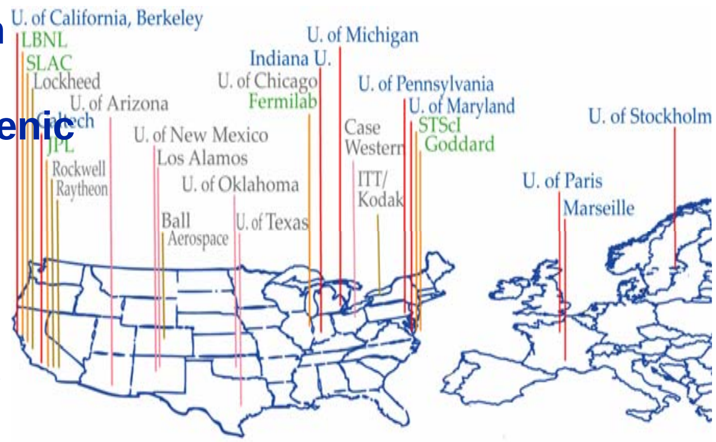
- SLAC — Fine star guider

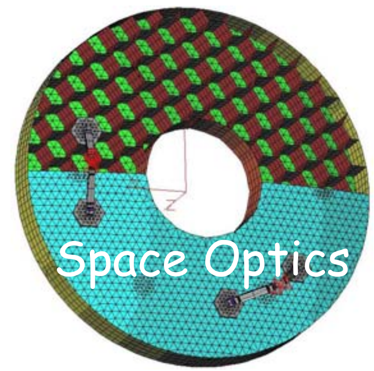


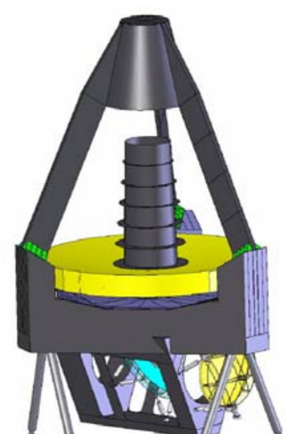


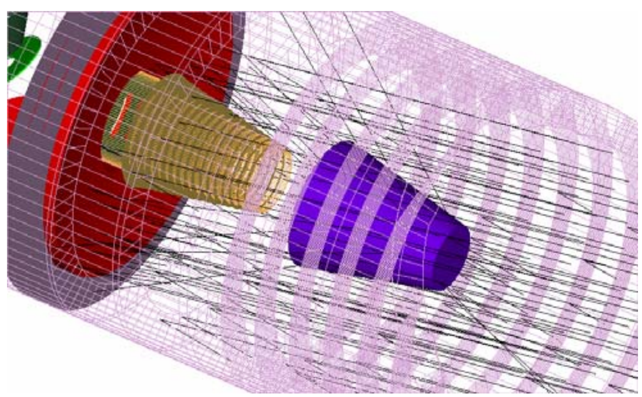
Risks retired:

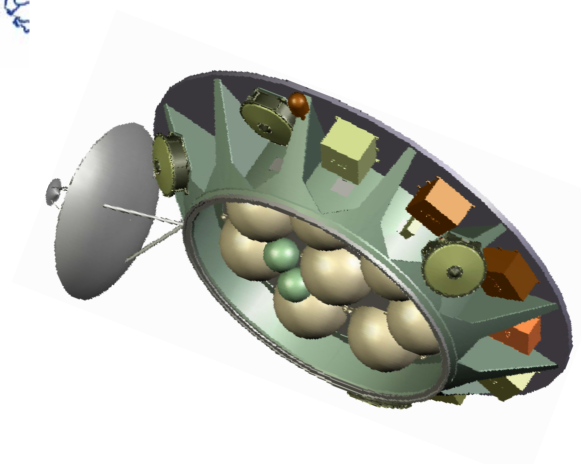
- ✓ Optical sensors: Radiation
- ✓ IR sensors: Noise, QE
- ✓ Sensor Electronics: cryogenic
- ✓ Lightweight optics: mass
- ✓ ACS: pointing stability
- ✓ Telemetry: Ka-Band
- ✓ Stray-light: Short baffle
- ✓ Telescope: Warm, yet NIR











Result of Work, Studies Undertaken

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:

1. **VIRGO-2K 2.25-μm HgCdTe dark current, R. Smith et al, Proc. SPIE 5499 (2004).**
2. **SNAP Near Infrared Detectors, G. Tarle et al, Proc. SPIE 4850 (2003).**
3. **Development of NIR detectors and science-driven requirements for SNAP, M G Brown et al, Proc. SPIE 6265 (2006).**
4. **Characterization of NIR InGaAs imager arrays for the JDEM SNAP mission concept, S Seshadri et al, Proc. SPIE 6276 (2006).**
5. **Noise and zero point drift in 1.7 mu m cutoff detectors for SNAP, Roger Smith et al, Proc. SPIE 6276 (2006).**
6. **Near infrared detectors for SNAP, M Schubnell et al, Proc. SPIE 6276 (2006).**

Spectrograph:

1. **An integral field spectrograph for SNAP, A. Ealet et al, Proc. SPIE 5487 (2004).**
2. **An integral field spectrograph for SNAP supernova studies, A. Ealet et al, Proc. SPIE 4850 (2003).**

Electronics:

1. **Integrating Signal Processing and A/D Conversion in One Focal-Plane Mounted ASIC, Turning photons into bits in the cold, A. Karcher et al, Scientific Detectors for Astronomy 2005, J. E. Beletic, J. W. Beletic, P. Amico editors, Springer (2006).**
2. **Proton irradiation effects on 2Gb flash memory, W. Wester et al, Radiation Effects Data Workshop, 2004 IEEE (2004).**
3. **A low power, wide dynamic range multigain signal processor for the SNAP CCD, J-P. Walder et al, Nuclear Science Symposium Conference Record, 2003 IEEE (2003).**

Calibration:

1. **HST Stellar Standards with 1% Accuracy, R. Bohlin, ASP Conference Series V.999 (2007).**
2. **Calibrating SNAP, S. Deustua et al, Proc. SPIE 5164 (2003).**

Telescope:

1. **Point-spread function stability of the SNAP telescope, M. J. Shol et al, Proc. SPIE 5899 (2005).**
2. **SNAP Telescope, M. Sholl et al, Proc. SPIE 5487 (2004).**
3. **SNAP Telescope: an update, M. Lampton et al, Proc. SPIE 5166 (2004).**
4. **SNAP Telescope: M. Lampton et al, Proc. SPIE 4849 (2003).**

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Focal Plane:

1. SNAP Focal Plane, C. Bebek et al, Proc. SPIE 4854 (2004).
2. SNAP Satellite Focal Plane Development, C. Bebek et al, Proc. SPIE 5164 (2003).

CCD:

1. High-voltage-compatable, fully depleted CCDs, S E Holland et al, Proc. SPIE 6276 (2006).
2. Quantum efficiency characterization of back-illuminated CCDs: Part II. Reflectivity measurements, Maximilian H Fabricius et al, Proc. SPIE 6068 (2006).
3. Quantum efficiency characterization of LBNL CCD's: Part I. The quantum efficiency machine, Donald E Groom et al, Proc. SPIE 6068 (2006).
4. Improved Charge Diffusion in Thick, Fully-Depleted CCDs with Enhanced Red Sensitivity, Jessamyn A. Fairfield et al, IEEE Trans Nucl. Sci, accepted for publication, (2006).
5. Point-spread function stability of the SNAP telescope, M J Sholl et al, Proc. SPIE 5899 (2005).
6. Characterization and deployment of large-format fully depleted back-illuminated p-channel CCDs for precision astronomy, Hakeem M Oluseyi et al, Proc. SPIE 5570 (2004).
7. Development of fully depleted back-illuminated charge-coupled devices, Christopher J Bebek et al, Proc. SPIE 5499 (2004).
8. LBNL four-side buttable CCD package development, Hakeem M Oluseyi et al, Proc. SPIE 5301 (2004).
9. Fully depleted back-illuminated p-channel CCD development, Christopher J Bebek et al, Proc. SPIE 5167 (2004).
10. CCD Development Progress at Lawrence Berkeley National Laboratory, W. F. Kolbe et al, Scientific Detectors for Astronomy 2005, J. E. Beletic, J. W. Beletic, P. Amico editors, Springer (2006).Development of Fully Depleted, Back-Illuminated Charge Coupled Devices, C.J. Bebek et al, SPIE 5499 (2004).
11. Measurement of Lateral Charge Diffusion in Thick, Fully Depleted, Back-illuminated CCDs, A. Karcher et al, IEEE Trans. Nucl. Sci. 51 (2004).
12. Fully Depleted, Back-Illuminated Charge-Coupled Devices Fabricated on High-Resistivity Silicon, S. Holland et al, IEEE Trans. Electron Dev. 50 (2003).
13. Fully depleted back-illuminated p-channel CCD development, C. Bebek et al, Proc. SPIE 5167 (2003).
14. Proton radiation damage in high-resistivity n-type silicon CCDs, C. Bebek et al, Proc. SPIE 4669 (2003).
15. Proton Radiation Damage in P-Channel CCDs Fabricated on High-Resistivity Silicon, C. Bebek et al, IEEE Trans Nucl. Sci. 49 (2002).
16. An overview of CCD development at Lawrence Berkeley National Laboratory, Steve Holland, Proceedings of the Scientific Detectors Workshop (Waimea, HI, 2002).
17. Point-spread function in depleted and partially depleted CCDs, D. E. Groom, et al, Proc. 4th ESO Workshop on Optical Detectors for Astronomy, Garching, Germany (Kluwer, 2000).

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2001 to present… page 1

1. **Supernova / Acceleration Probe: A Satellite Experiment to Study the Nature of the Dark Energy, submitted to PASP (astro-ph/0405232).**
2. **Probing Dark Energy with Supernovae: Exploiting Complementarity with the Cosmic Microwave Background, E. Linder, J. Frieman, D. Huterer, M. Turner, Phys. Rev. D 67, 083505 (2003).**
3. **Exploring the Expansion History of the Universe, E. Linder, Phys. Rev. Lett. 90, 091301 (2003).**
4. **Dark Energy and Dark Matter with SNAP, E. Linder et al, Nucl. Ph. B 124, 76 (2003).**
5. **Probing Dark Energy with SNAP, in Identification of Dark Matter, ed. N.J.C. Spooner and V. Kudryavtsev (World Scientific, 2003); astro-ph/0210217.**
6. **Cosmic Shear from Next Generation Galaxy Surveys as a Cosmological Probe, Phys. Rev. D 68, 083503 (2003).**
7. **Models for Type Ia Supernovae and Cosmology, E.Linder, P. H¨oflich, C. Gerardy, and H. Marion, in Lecture Notes in Physics,**
8. **Stellar Candles, eds. Gieren et al.; astro-ph/0301334.**
9. **Light Thoughts on Dark Energy, E. Linder, New Astronomy Reviews 49 (2005).**
10. **Observing Dark Energy with SNAP, E. Liner, in Observing Dark Energy, ASP Conference proceedings, ed. S. Wolff; astro-ph/0406186.**
11. **Reconstructing and Deconstructing Dark Energy, Phys. Rev. D 70, 061302 (2004),**
12. **Is Dark Energy Dynamical? Prospects for an Answer, E. linder and R. Miquel, Phys. Rev. D 70, 123516 (2004).**
13. **Dark Entropy: Holographic Cosmic Acceleration, E. Linder, submitted to Phys. Rev. D; hep-th/0410017.**
14. **Dealing with Dark Energy, E. Linder, to appear in DARK2004, 5th International Heidelberg Conference (Springer Verlag)**
15. **Safety in Numbers: Gravitational Lensing Degradation of the Distance-Redshift Relation, E. Linder and D. Holz, submitted to ApJ; astro-ph/0412173.**
16. **Overview of the SuperNova/Acceleration Probe (SNAP) G. Aldering et al., SPIE 4835.**
17. **Wide-Field surveys from the SNAP Mission, A. Kim et al., SPIE 4836.**
18. **Importance of SNe at z>1.5, E. Linder, D. Huterer, Phys.Rev. D67 (2003).**
19. **Frieman, Huterer, Linder, & Turner: Probing Dark Energy with Supernovae: Exploiting Complementarity with the CMB Phys. Rev. D 67, 083505 (2003).**
20. **Weak Lensing from Space I: Prospects for The Supernova/Acceleration Probe, Rhodes et al. Astro. Phys. 20, 377 (2004). Weak Lensing from Space II: Dark Matter Mapping, Massey et al.**

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17. Weak Lensing from Space III: Cosmological Parameters, Refregier et al.
18. Effects of Systematic Uncertainties on the Supernova Determination of Cosmological Parameters, A. Kim, et al., MNRAS 347 (2004).
19. Dark Energy Constraints from Weak Lensing Cross-Correlation Cosmography, Bernstein & Jain, ApJ 600, 17 (2004).
20. Cross-correlation Tomography: Measuring Dark Energy Evolution with Weak Lensing, Jain & Taylor, PRL 91, 2003.
21. Baryon Oscillations as a Cosmological Probe, Linder, PRD 68, 083504 (2003).
22. Dark Energy, Expansion History of the Universe, and SNAP, Linder, AIP Conf.Proc. 655, 193 (2003).
23. Gravitational Lensing by Cosmic Strings in the Era of Wide-Field Surveys, Huterer & Vachaspati, PRD 68, 041301 (2003).
28. Joint Galaxy-Lensing Observables and the Dark Energy, Hu & Jain, submitted to PRD.
29. Cosmological parameters from lensing power spectrum and bispectrum tomography, Takada & Jain, submitted to MNRAS.
30. Strong Gravitational Lensing and Dark Energy Complementarity, Linder, Phys. Rev. D 70 (2004).
31. Testing the Cosmological Constant as a Candidate for Dark Energy, Kratochvil, Linde, Linder, & Shmakova, JCAP 407 (2004).
32. Mapping the Dark Energy Equation of State, Linder, in Maps of the Cosmos, IAU 216.
33. Observational Bounds on Cosmic Doomsday, Kallosh, Kratochvil, Linde, Linder, & Shmakova, JCAP 310, 15 (2003).
34. Cosmic Structure Growth and Dark Energy, Linder & Jenkins, MNRAS 346, 573 (2003).
35. Physics of SNeIa and Cosmology, Hoeflich, Gerardy, Linder, & Marion, in Stellar Candles, Lecture Notes in Physics.
36. Redshift Accuracy Requirements for Future Supernova and Number Count Surveys, Huterer, Kim, Krauss, Broderick (2004) ApJ, 615:595.
37. Effects of systematic uncertainties on the supernova determination of cosmological parameters, Kim, Linder, Miquel, Mostek (2004), MNRAS, 347, 909.
38. Probing Dark Matter and Dark Energy with Space-based Weak Lensing, Massey, Refregier, Rhodes, in "Gravitational Lensing: unique tool for cosmology" astro-ph/0403229
39. Probing Dark Energy with Supernovae: bias from the time evolution of the equation of state, Virey et al., Phys Rev D 70, 043514 (2004)
40. Absolute Flux Distribution of the SDSS Standard BD +17º4708, Bohlin & Gilliland, AJ 128, 3053 (2004)
41. Constraining the mass distribution of galaxies using galaxy-galaxy lensing in clusters and in the field, Limousin, Kneib, Natarajan, MNRAS 356, 309 (2005)

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42. The SNAP Strong Lens Survey, Marshall, Blandford, Sako, New Ast Rev 49, 387 (2005)
43. Systematic Errors in Future Weak Lensing Surveys: requirements and prospects for self-calibration, Huterer, Takada, Bernstein, Jain, MNRAS 366, 101 (2006)
44. Probing Dark Matter and Dark Energy with Space-based Weak Lensing, Massey, Refregier, Rhodes, in "Gravitational Lensing: unique tool for cosmology" astro-ph/0403229
45. Probing Dark Energy with Supernovae: bias from the time evolution of the equation of state, Virey et al., Phys Rev D 70, 043514 (2004)
46. Absolute Flux Distribution of the SDSS Standard BD $+17^{o}4708$, Bohlin & Gilliland, AJ 128, 3053 (2004)
47. Constraining the mass distribution of galaxies using galaxy-galaxy lensing in clusters and in the field, Limousin, Kneib, Natarajan, MNRAS 356, 309 (2005)
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49. Systematic Errors in Future Weak Lensing Surveys: requirements and prospects for self-calibration, Huterer, Takada, Bernstein, Jain, MNRAS 366, 101 (2006)
50. Exploring Dark Energy with SNAP, Aldering, New Ast Rev 49, 346 (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
53. Probing Dark Energy via Weak Gravitational Lensing with the Supernova/Acceleration Probe, SNAP collaboration, DETF white paper, astro-ph/0507460
54. Optimal Extraction of Cosmological Information from Supernova Data in the Presence of Calibration Uncertainties, Kim & Miquel, Astropart Phys 24, 451 (2006)
55. Ideal Bandpasses for Type Ia Supernova Cosmology, Davis, Schmidt, Kim, PASP 118, 205 (2006)
56. Type Ia Supernova Spectral Line Ratios as Luminosity Indicators, Bongard et al., ApJ submitted, astro-ph/0512229
57. Spectral Diversity of Type Ia Supernovae, James, Davis, Schmidt, Kim, MNRAS 370, 933 (2006)
58. Supernovae, Lensed CMB, and Dark Energy, Hu, Huterer, Smith, ApJ Letter submitted, astro-ph/0607316
59. Dynamical behavior of generic quintessence potentials: constraints on key dark energy observables, Huterer & Peiris, Phys Rev D submitted, astro-ph/0610427

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60. How Many Dark Energy Parameters? Linder & Huterer, Phys Rev D 72, 043509 (2005)
61. Limits of Quintessence, Caldwell & Linder, Phys Rev Lett 95, 141301 (2005)
62. Cosmic Growth History and Expansion History, Linder, Phys Rev D 72, 043529 (2005)
63. Curved Space or Curved Vacuum? Linder, Astropart Phys 24, 391 (2005)
64. Going Nonlinear with Dark Energy Cosmologies, Linder & White, Phys Rev D 72, 061304(R) (2005)
65. On Oscillating Dark Energy, Linder, Astropart Phys 25, 167 (2006)
66. Paths of Quintessence, Linder, Phys Rev D 73, 063010 (2006)
67. Dark Energy in the Dark Ages, Linder, Astropart Phys 26, 16 (2006)
68. Biased Cosmology: pivots, parameters, and figures of merit, Linder, Astropart Phys 26, 102 (2006)
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
72. Theory Challenges of the Accelerating Universe, Linder, J Phys A accepted, astro-ph/0610173
73. HST Stellar Standards with 1% Accuracy in Absolute Flux, Bohlin, in Future Photometric, Spectrophotometric, and Polarimateric 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

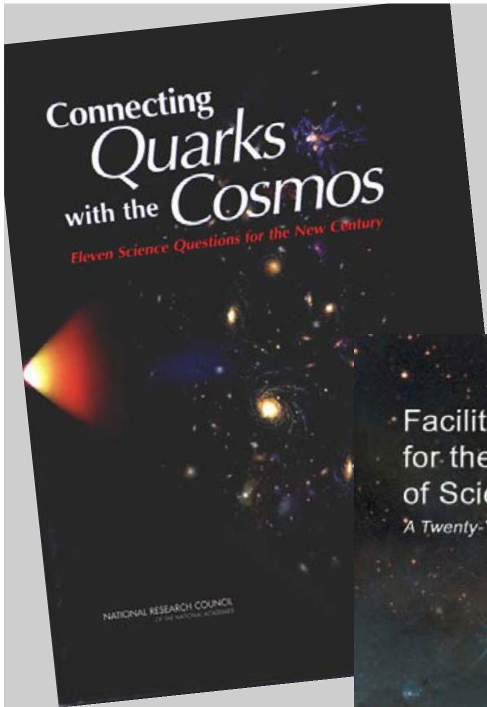
1998 Discovery of the acceleration of the universe and dark energy using supernovae.

2000 Confirmation of dark energy using cosmic microwave background measured from balloons.

2003 Confirmation of dark energy using cosmic microwave background measured from space (WMAP).

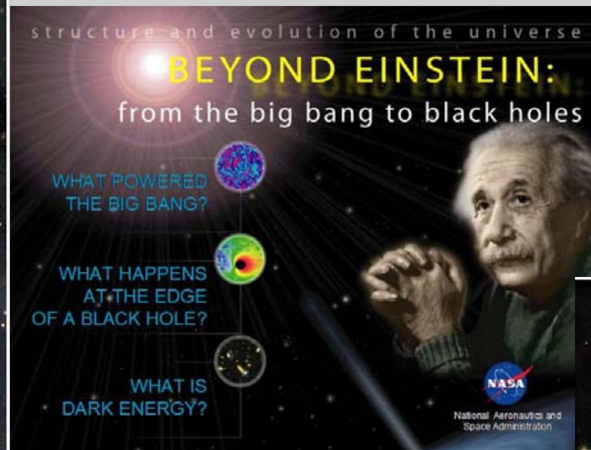
Nov 1999 Original SNAP proposal submitted to DOE
Mar 2000 DOE/NSF SAGENAP committee recommends SNAP R&D
Sep 2000 NASA Structure and Evolution of the Universe (SEU)
Dec 2000 National Academy of Sciences Committee on Astro. & Astrophysics
Jan 2001 DOE-HEP Review R&D (SNAP is uniquely able)
Mar 2001 DOE 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
Jan 2002 DOE subpanel report: High Energy Physics Long Range Planning
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)
Feb 2005 Nat'l Academy Sciences: Cmt. on Astro.&Astrophys. reaffirms priorities.
Aug 2006 NASA selects advanced mission concept studies (ROSES).

National Academy of Sciences

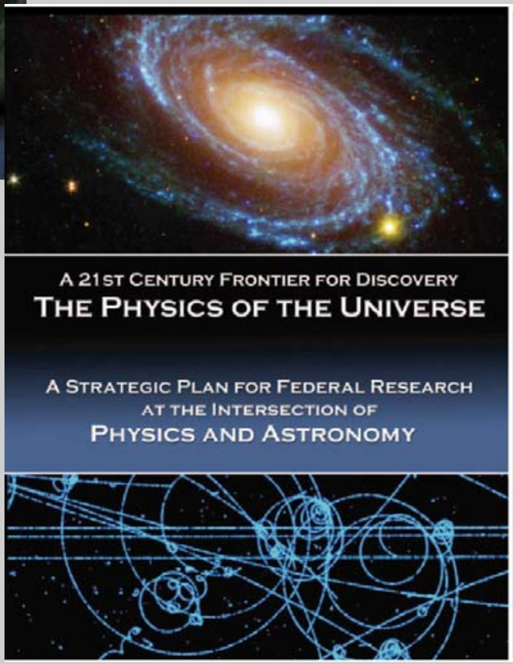


Department of Energy

NASA



OSTP



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.

January 18, 2007

NASA's Beyond Einstein Program: An Architecture for Implementation

In response to a request from the National Aeronautics and Space Administration and the Department of Energy, the Space Studies Board and the Board on Physics and Astronomy have organized an assessment of the NASA Beyond Einstein Program. The assessment will be carried out by an NRC committee whose charge and membership are outlined below. The committee will conduct a series of meetings at which it will hear briefings on the relevant science and the projects. Most of the meetings will be open to the public. In addition, the committee will organize a series of regional town hall meetings to provide an opportunity for committee members to brief the community on the progress of the study and to receive the community's views on the issues before the committee. These meetings and their agendas will be listed below as they are scheduled.

The committee will be charged to address the following tasks:

1. Assess the five proposed Beyond Einstein missions (Constellation-X, Laser Interferometer Space Antenna, Joint Dark Energy Mission, Inflation Probe, and Black Hole Finder probe) and recommend which of these five should be developed and launched first, using a funding wedge that is expected to begin in FY 2009. The criteria for these assessments include:
a. Potential scientific impact within the context of other existing and planned space-based and ground-based missions; and
b. Realism of preliminary technology and management plans, and cost estimates.

2. Assess the Beyond Einstein missions sufficiently so that they can act as input for any future decisions by NASA or the next Astronomy and Astrophysics Decadal Survey on the ordering of the remaining missions. This second task element will assist NASA in its investment strategy for future technology development within the Beyond Einstein Program prior to the results of the Decadal Survey.

View committee roster here.

Astrophysics: Content of FY08 Budget

	FY07	FY08	FY09	FY10	FY11	FY12
FY 08 President's Budget	1,563.0	1,565.8	1,304.2	1,268.9	1,266.2	1,393.8
Navigator	124.7	57.1	58.4	59.5	61.0	62.5
SIM	94.2	20.2	20.7	22.0	22.3	22.6
Keck Interferometer / Single Aperture / Ops	10.0	13.0	11.8	10.5	10.3	10.7
TPF	0.0	6.1	6.2	6.3	6.4	6.5
Other Navigator	12.4	13.6	15.4	16.4	17.7	18.3
Institutional	8.0	4.3	4.3	4.3	4.3	4.5
JWST	468.5	545.4	452.1	376.9	321.1	285.9
Direct	391.0	447.5	372.0	311.1	265.1	236.2
Institutional	77.5	98.0	80.1	65.7	55.9	49.7
Hubble Space Telescope	343.0	277.7	165.2	152.8	151.4	151.3
Development	188.9	136.6	45.8	37.6	35.9	35.0
Operations and Data Analysis	95.6	90.0	89.5	88.1	88.9	89.8
Institutional	58.5	51.1	29.9	27.1	26.7	26.5
SOFIA	0.0	77.3	89.1	88.6	89.9	92.1
Direct	0.0	63.1	72.9	72.9	74.1	75.9
Institutional	0.0	14.2	16.1	15.7	15.8	16.2
GLAST	90.7	42.2	28.3	28.3	29.3	30.2
Direct	75.2	34.4	23.2	23.3	24.1	24.9
Institutional	15.5	7.8	5.1	5.0	5.2	5.3
Discovery	105.0	93.0	25.7	16.3	16.2	17.6
Kepler	89.2	79.5	21.4	13.4	13.3	14.5
Institutional	15.7	13.5	4.4	2.9	2.9	3.1
*Astrophysics Explorer	69.4	99.1	88.8	28.2	11.7	5.7
WISE	52.7	72.7	65.2	13.0	5.2	1.6
Swift, Suzaku	9.1	13.1	11.4	11.7	5.1	3.2
Institutional	7.6	13.2	12.2	3.5	1.4	0.8
Astrophysics Research	319.8	315.2	306.1	331.9	378.5	491.4
Research and Analysis	50.0	47.5	48.9	46.2	48.1	49.8
Chandra	61.1	62.9	65.0	67.8	68.5	70.2
Spitzer	76.3	75.4	71.7	48.9	44.3	43.2
Astrophysics Future Missions			0.2	42.7	78.1	164.6
Other Operating Missions / D A / Archives	67.8	60.0	50.9	50.7	55.5	58.6
Balloons	19.8	22.0	24.1	23.9	23.8	25.1
Institutional	44.8	47.4	45.3	51.8	60.1	79.7
ISSC	19.8	26.5	39.1	38.7	36.5	35.2
Herschel & Planck	18.5	24.8	36.6	36.3	34.2	33.0
Institutional	1.3	1.7	2.5	2.4	2.3	2.2
Beyond Einstein	22.1	32.3	51.5	147.6	170.6	222.1
Direct	18.3	26.5	42.3	121.5	140.7	183.2
Institutional	3.8	5.8	9.2	26.1	29.9	38.8
*Future Explorer (non-add; in Heliophysics)	9.1	11.6	47.8	110.4	154.3	172.5

International Context (+)

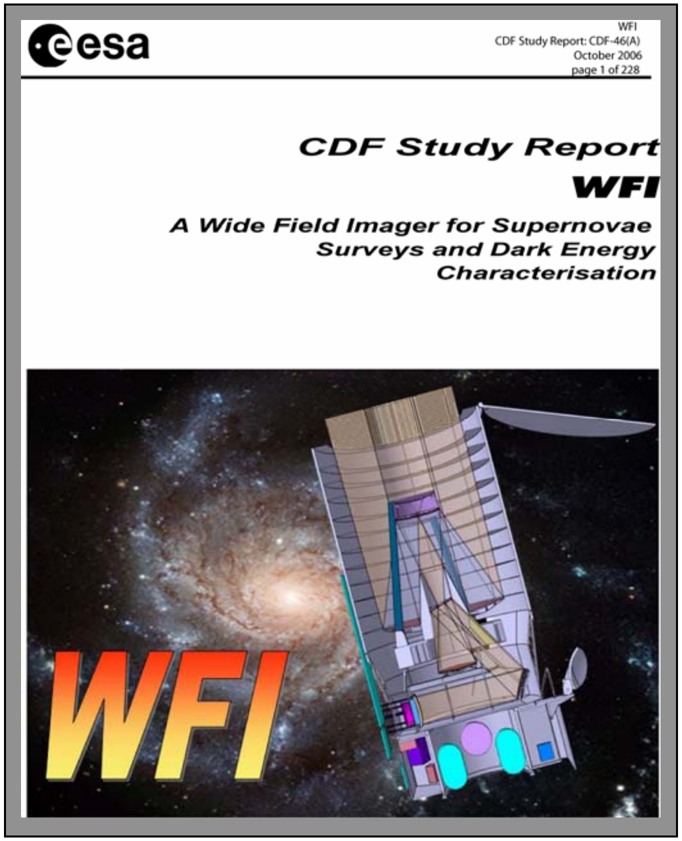
- France is already involved with the development of our spectrograph, one of the two instruments on SNAP. This effort is currently being funded by the French Space Agency.

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 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.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CDF Study Report

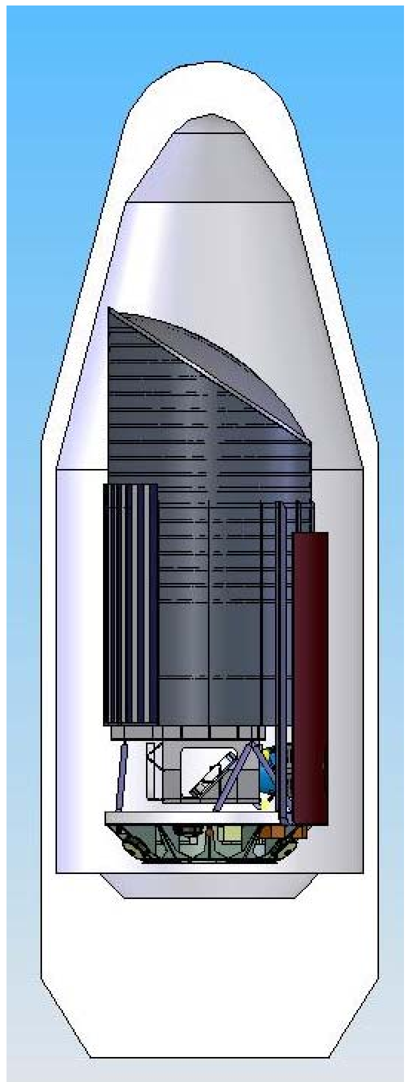
WFI

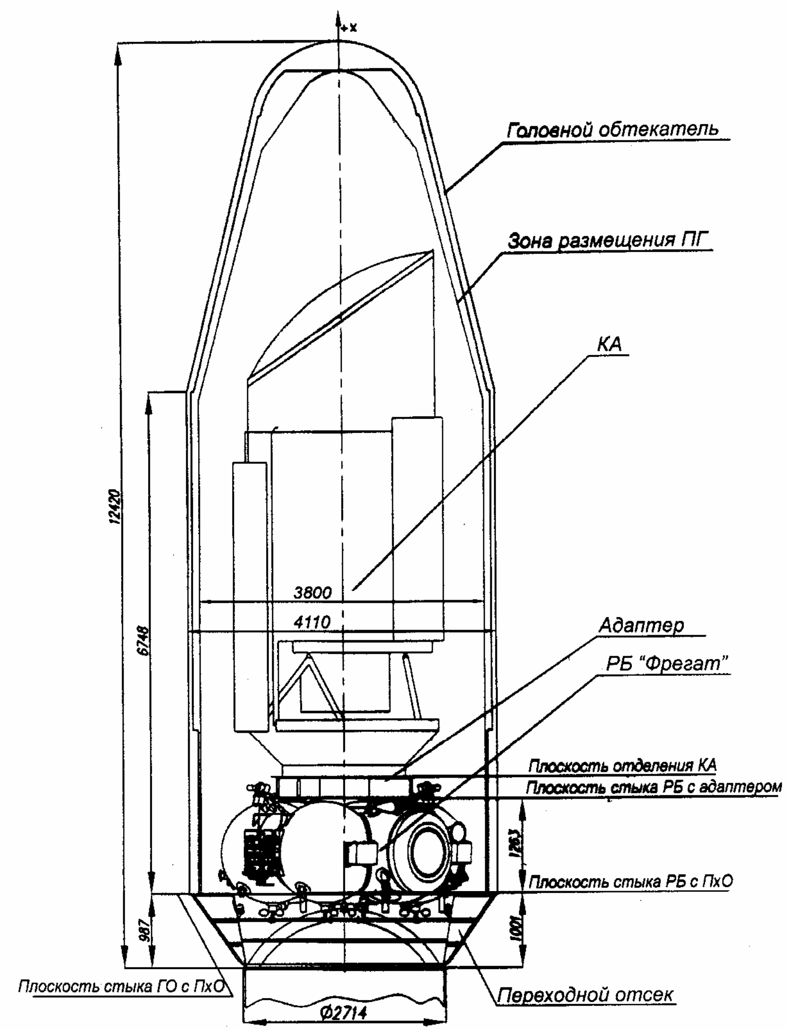
A Wide Field Imager for Supernovae Surveys and Dark Energy Characterisation

International Context (+)

Delta IV

Soyuz-ST/Fregat (2-1B)





Sign posts for today's presentation

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.