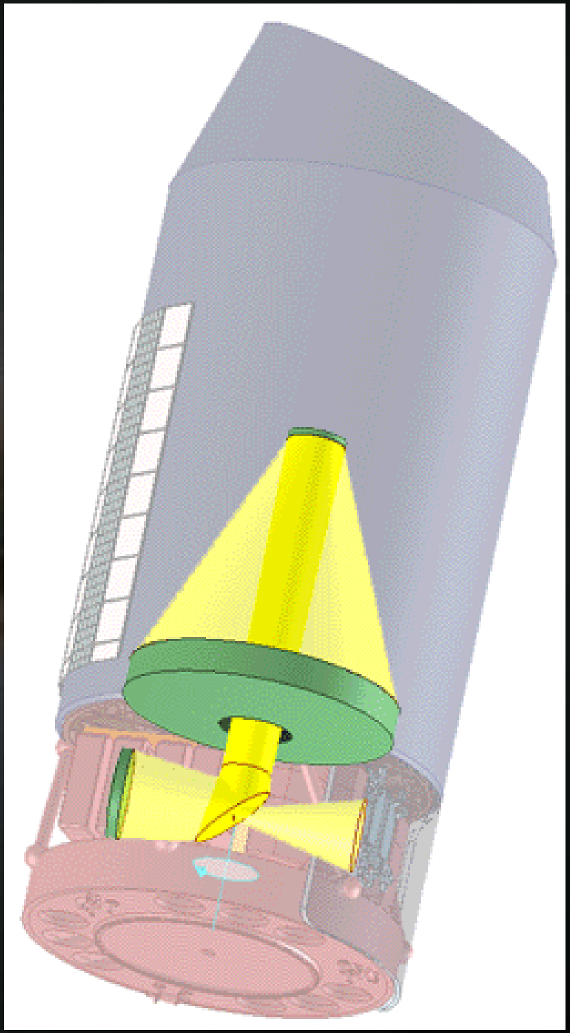
Shedding Light on Dark Energy with the SuperNova/Acceleration Probe (SNAP)

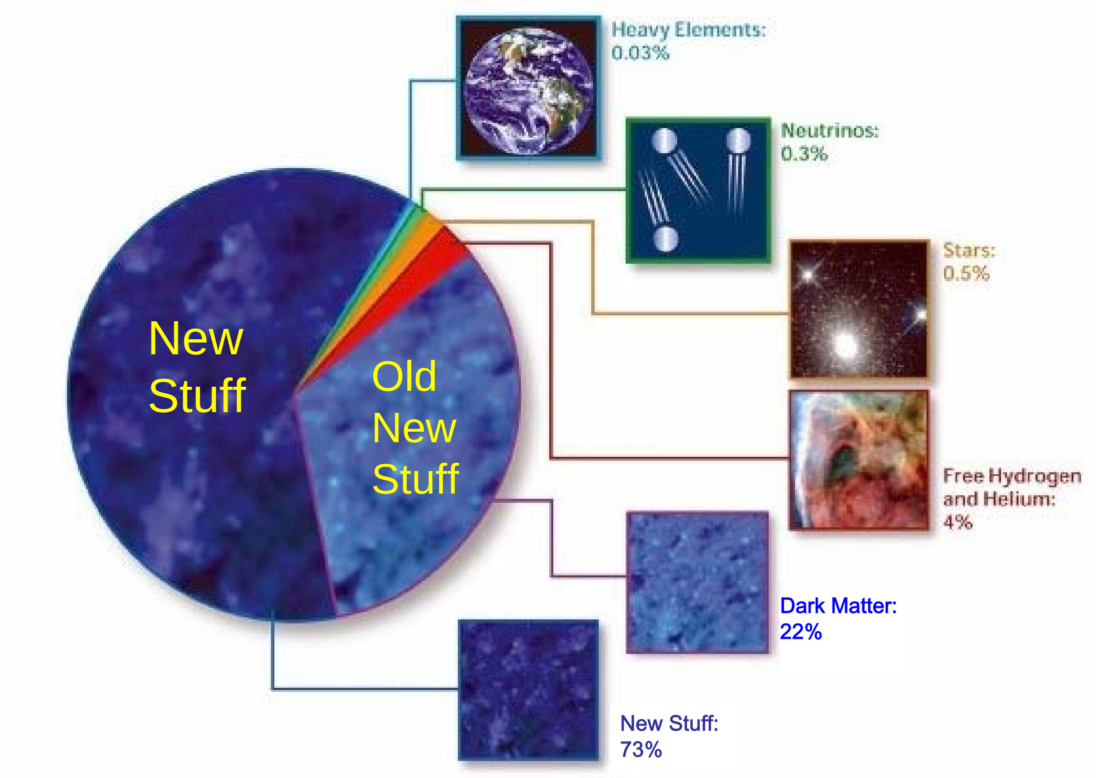


Wolfgang Lorenzon
University of Michigan

Miami 2004

December 17, 2004

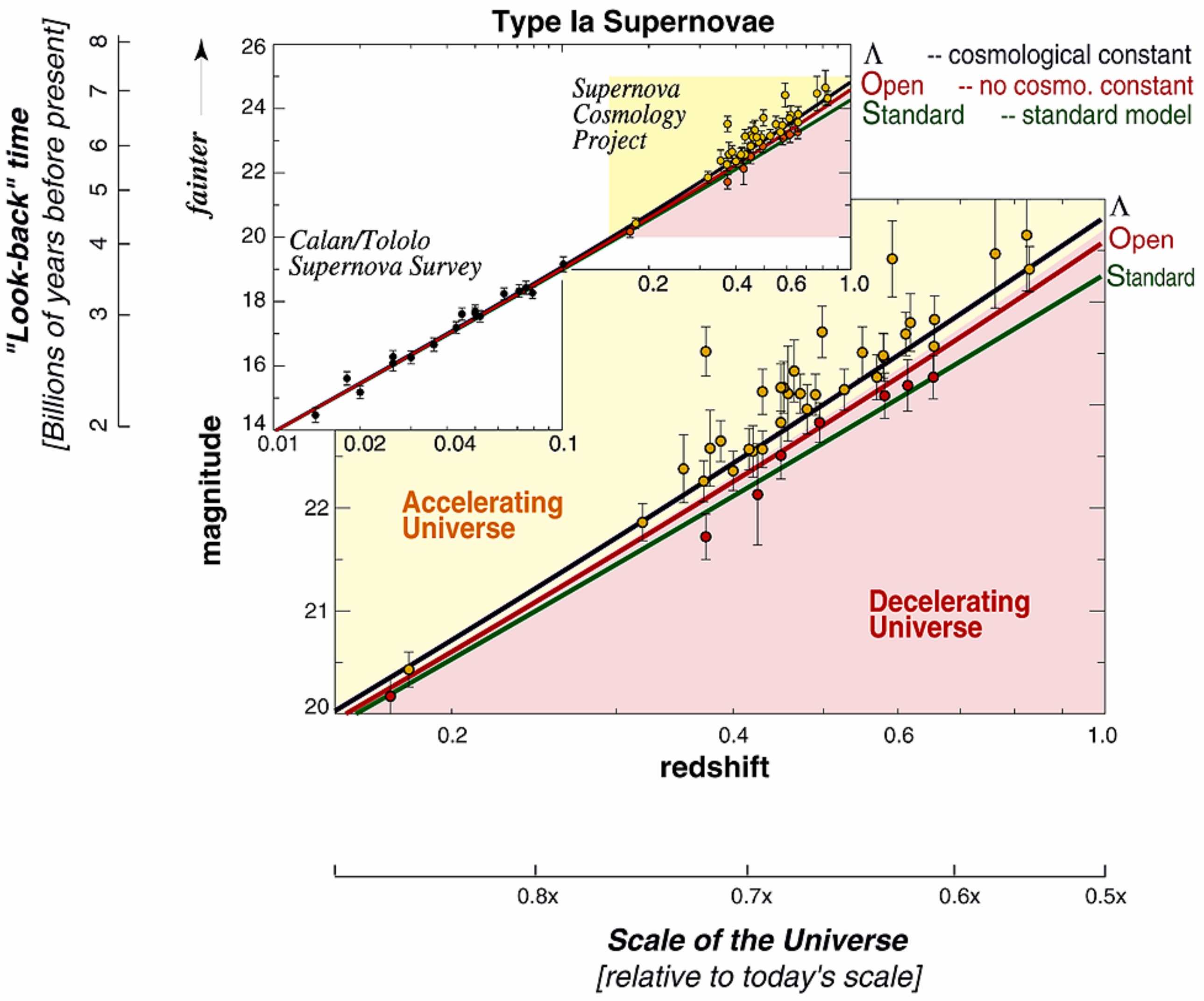
- New “stuff” has been found in the universe



- We don’t know what it is
- It is not made of matter
- 73% of the universe
- It’s growing larger
- It has negative pressure
- It’s accelerating the expansion of the universe
- It’s called Dark Energy

A Startling Discovery

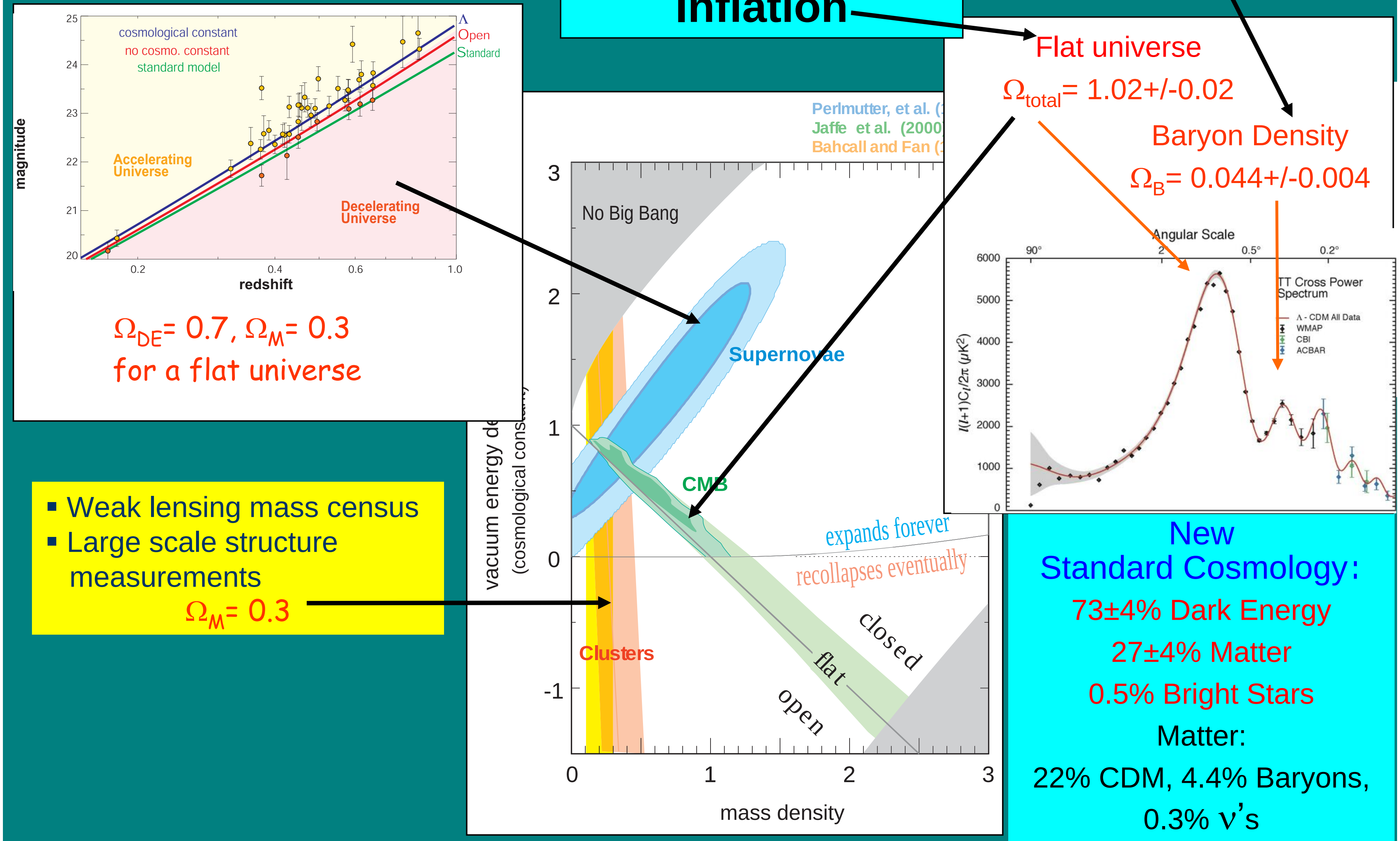
- (1998) Supernova Cosmology Project and High-Z Supernova team construct a Hubble diagram using Type Ia supernovae looking back 7 Byr (1/2 the age of the universe).
- Both found the expansion of the universe is accelerating!



A Revolution in Cosmology

Big Bang Nucleosynthesis

Inflation



Ω_{DE}= 0.7, Ω_M= 0.3
for a flat universe

Flat universe

Ω_{total}= 1.02+/-0.02

Baryon Density

Ω_B= 0.044+/-0.004

- Weak lensing mass census
- Large scale structure measurements

Ω_M= 0.3

New
Standard Cosmology:

73±4% Dark Energy

27±4% Matter

0.5% Bright Stars

Matter:

22% CDM, 4.4% Baryons,

0.3% ν's

What we don’t know

- Precisely how much mass density (Ω_M) and dark energy density (Ω_{DE}) is there?
- How flat is the universe?
- What is the equation of state ($w = p/\rho$) of the universe and how has it changed in time?

Lots of theories, little data!

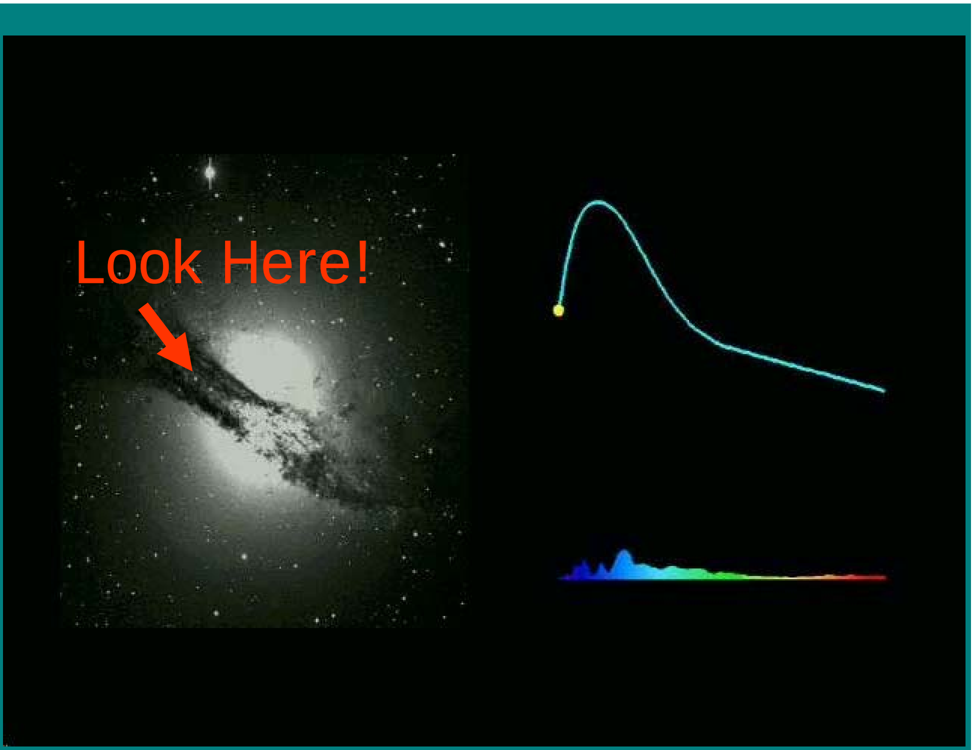
What is the “dark energy?” Theorists have proposed a number of possibilities each with its own unique w(t):

- Cosmological constant with $p = -\rho$ and $w = -1$.
- “Quintessence” models with time varying $-0.4 < w < -0.8$
- Supergravity models
- “Cardassian” expansion
- The “big rip” $w < -1$

…

Type Ia SNe:

- **Type Ia supernovae (SNe Ia) provide a bright "standard candle" that can be used to construct a Hubble diagram looking back over the last 2/3 of the age of the universe.**
- **Accretion sends mass of white dwarf star to Chandrasekhar limit leading to gravitational core collapse and a thermo-nuclear explosion of its outer layers.**
- **Each one is a strikingly similar explosion event with nearly the same peak intensity.**



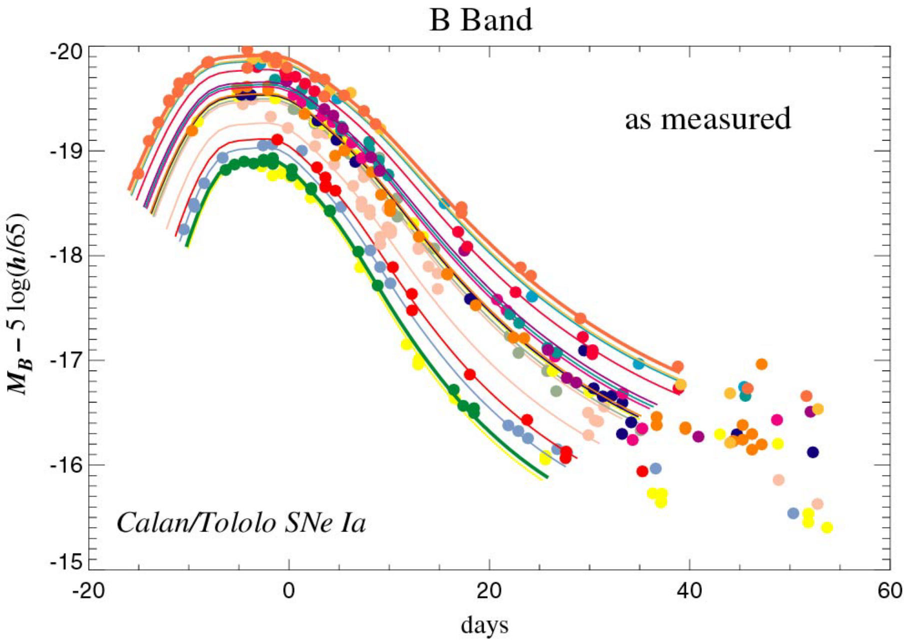
Can measure both intensity and spectra as the supernova brightens and fades over many days.

Comparison of SN Ia redshifts and magnitudes provides straightforward measurement of the changing rate of expansion of the universe:

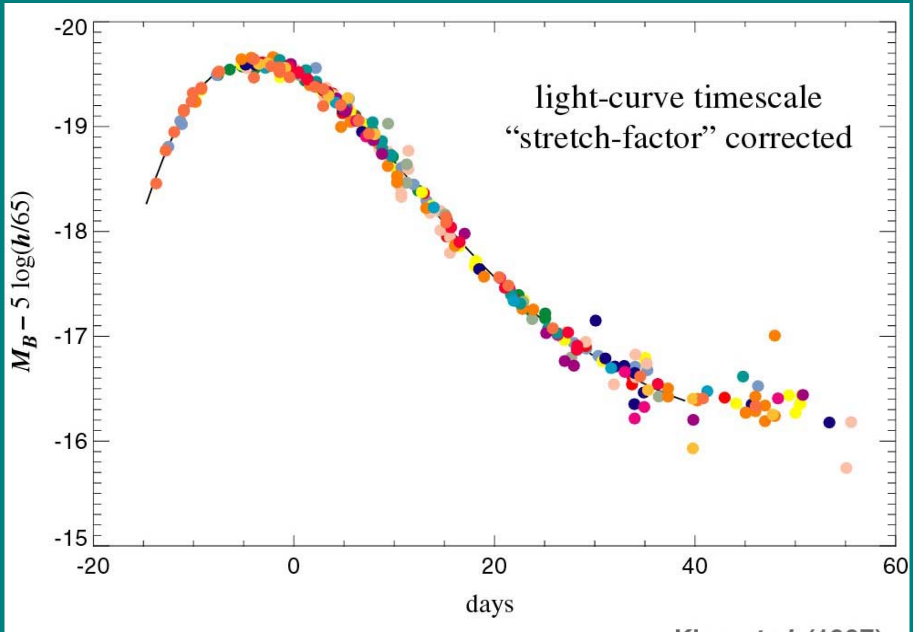
- Apparent magnitude measures distance (time back to explosion)
- Redshift measures the total relative expansion of the universe since that time

☑ Analysis of the spectra characterizes the details of the explosion and helps to control potential systematic errors.

“Standard” Candles

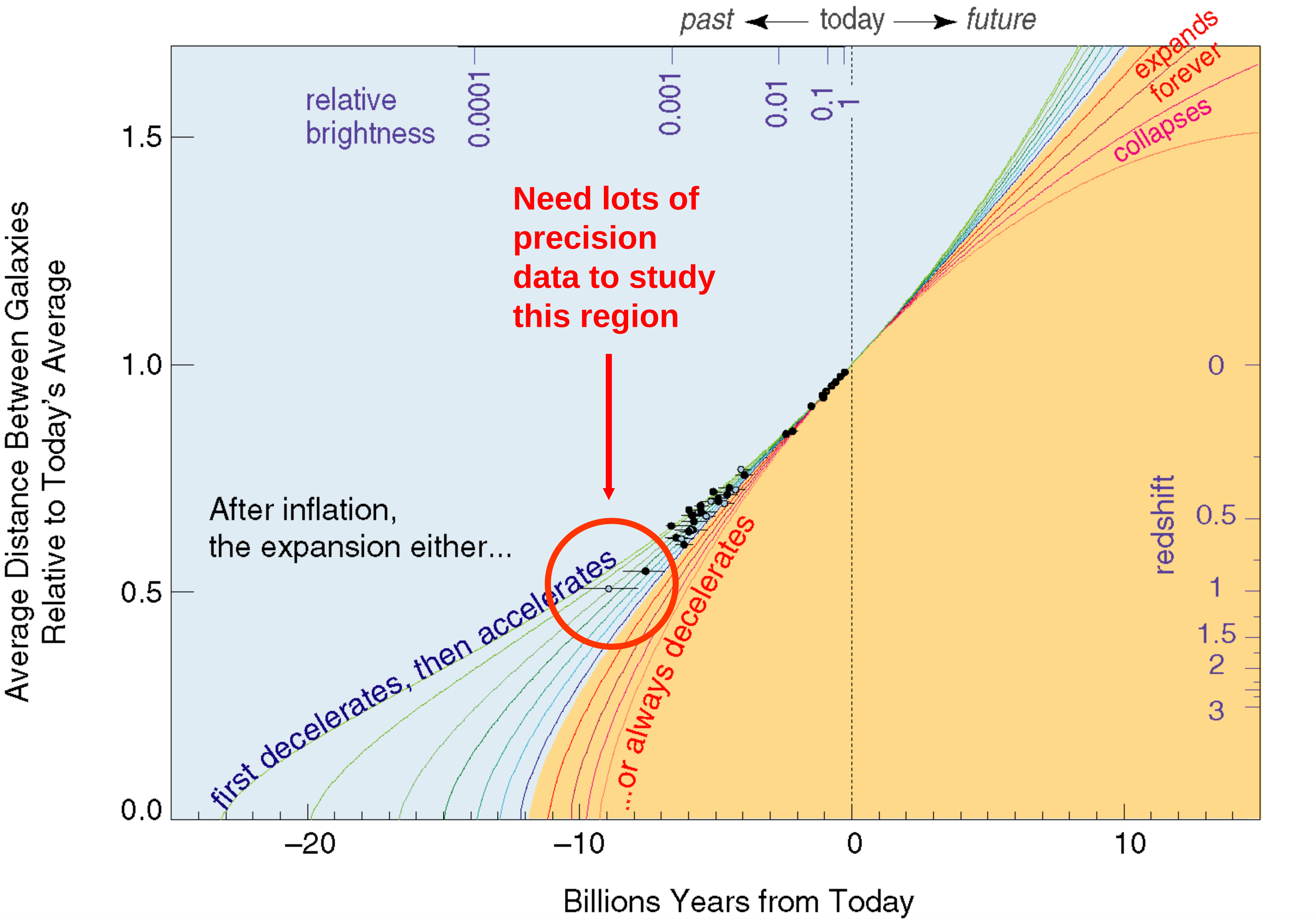


- ➢Nearby supernovae used to study SNe light curve (z<0.1)
- ➢Brightness not quite standard
- ➢Intrinsically brighter SNe last longer
- ➢Correction factor needed



Kim, *et al.* (1997)

The Expansion History of the Universe

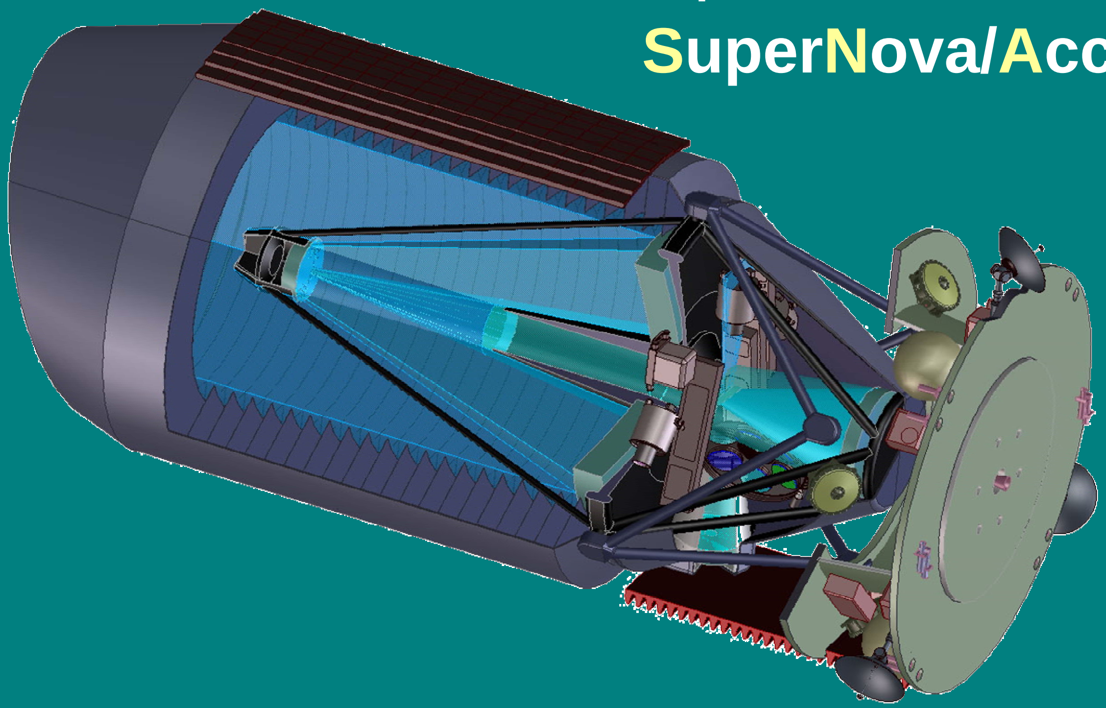


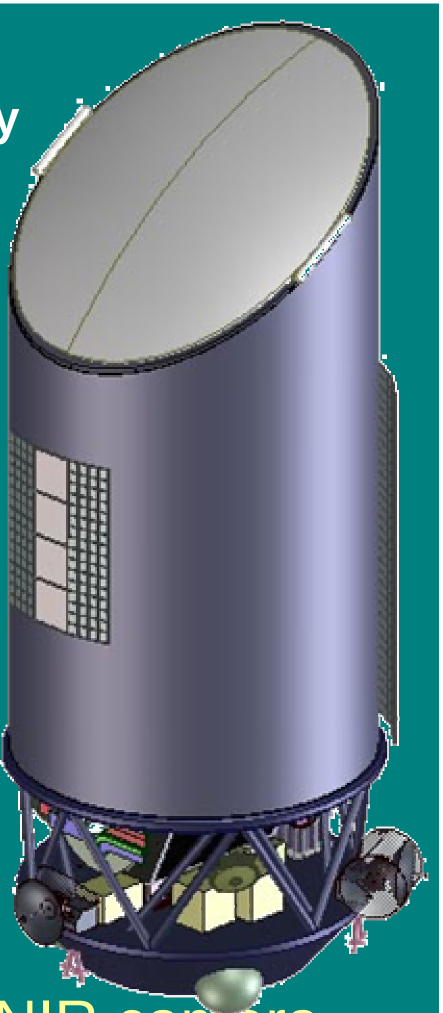
Need lots of precision data to study this region

It’s a SNAP!

To determine what the dark energy is will require a “next generation” experiment, the

SuperNova/Acceleration Probe





A large wide-field telescope with a Giga-pixel visible/NIR camera and a visible/NIR spectrograph will provide:

- a much larger sample of supernovae (thousands).
- much better control of systematic errors (1 – 2%).
- a much larger range of redshifts (out to $z = 1.7$) to see all the way back through the acceleration and deceleration epochs of the universe.

SNAP Collaboration

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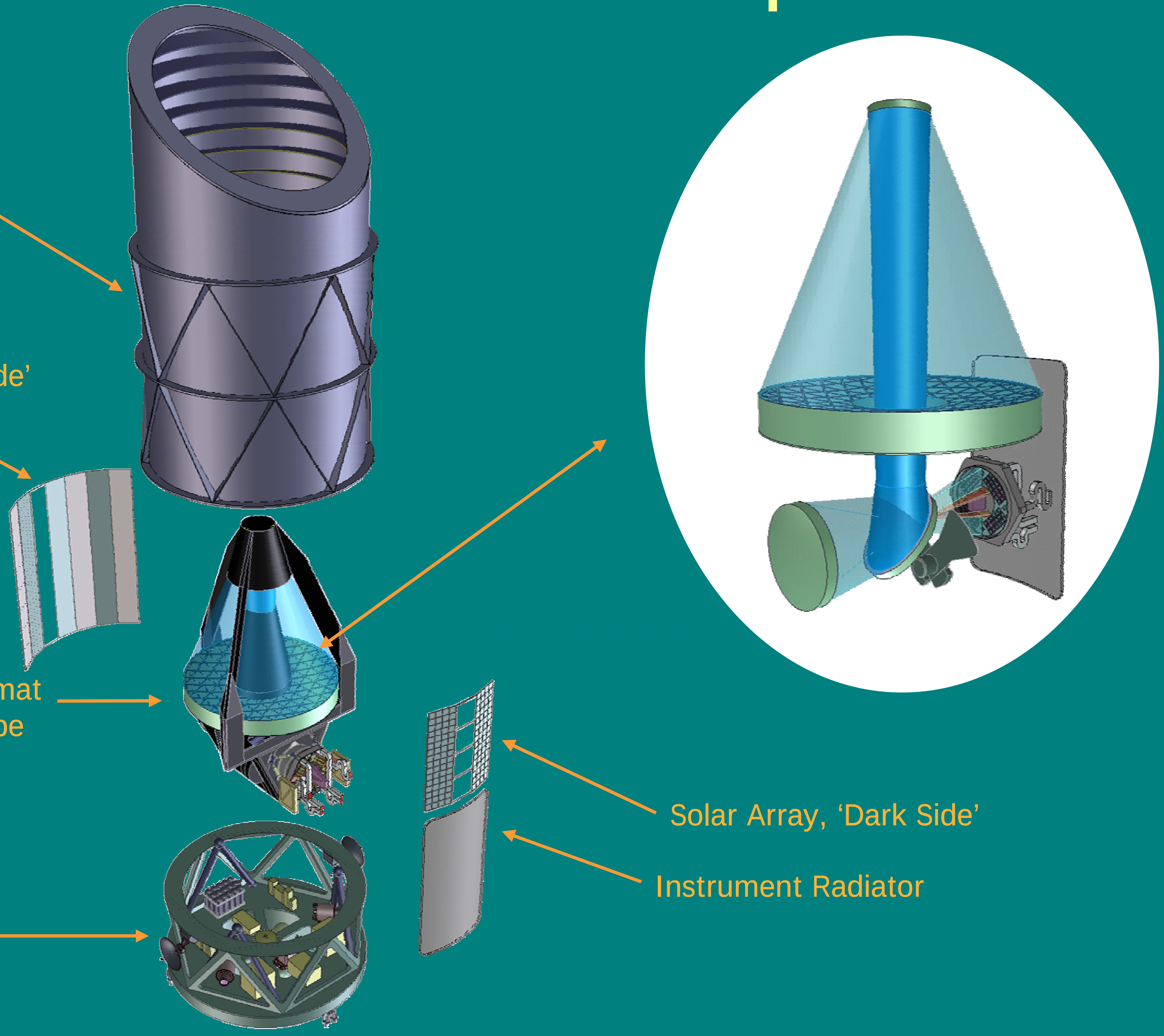
Instrument Concept



Baffled Sun Shade

Solar Array, ‘Sun Side’

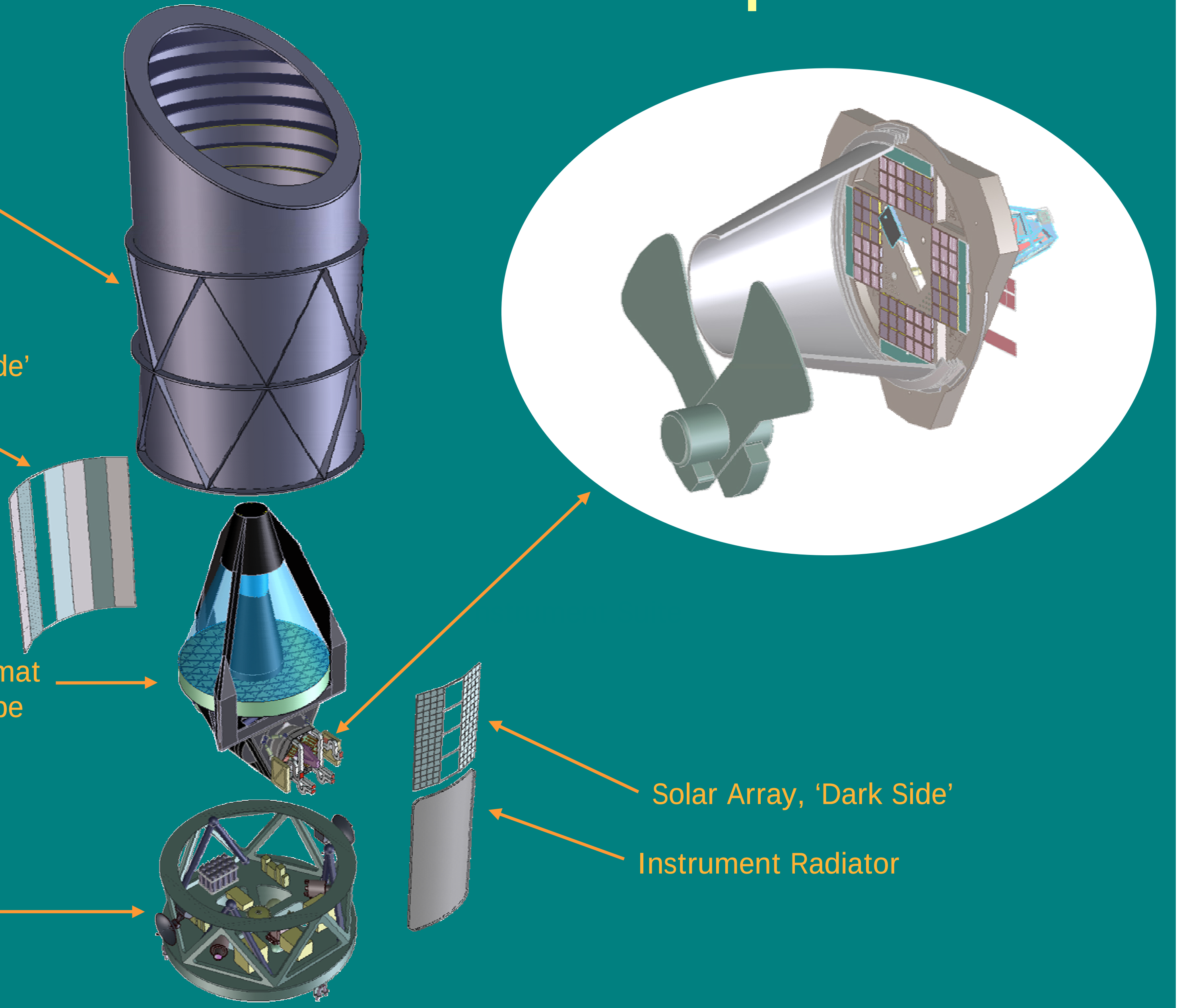
3-mirror anastigmat
2-meter Telescope

Spacecraft Bus

Solar Array, ‘Dark Side’

Instrument Radiator

Instrument Concept



Baffled Sun Shade

Solar Array, ‘Sun Side’

3-mirror anastigmat
2-meter Telescope

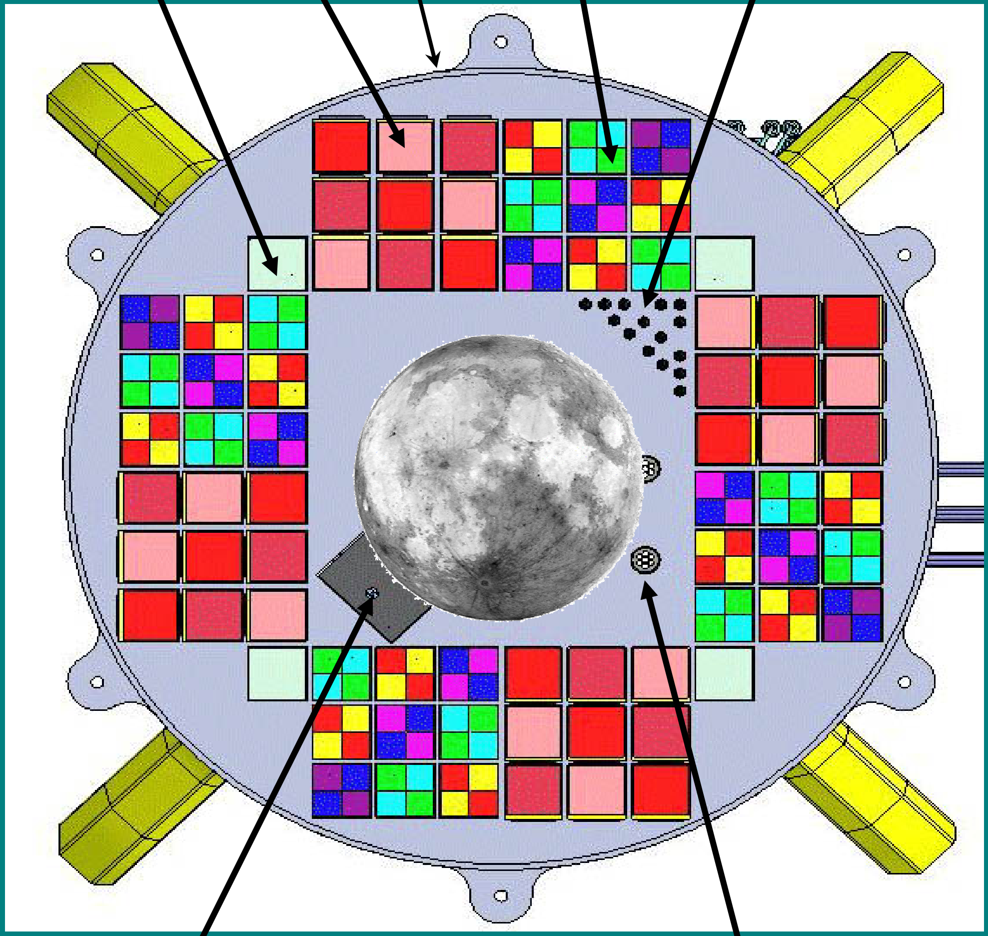
Spacecraft Bus

Solar Array, ‘Dark Side’

Instrument Radiator

Focal plane

D=56.6 cm (13.0 mrad)
0.7 square degrees!



Guider

NIR

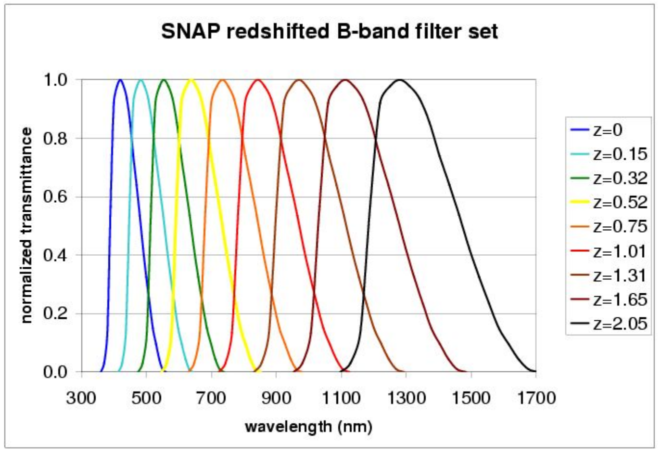
Visible

Focus star projectors

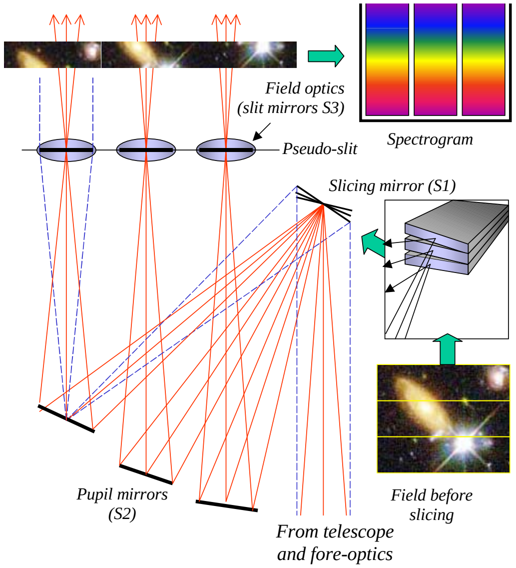
Spectrograph port

Calibration projectors

Fixed filters atop the sensors

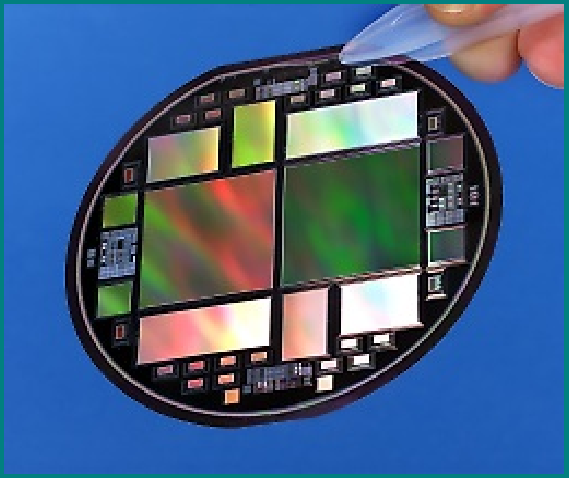


Integral Field Spectrograph



Special “Red-Hot” Visible CCDs for SNAP

- **New kind of Charged Coupled Device (CCD) developed at Lawrence Berkeley National Lab.**
- **Better overall response than more costly “thinned” devices in use.**
- **High-purity “radiation detector” silicon has better radiation tolerance for space applications.**
- **The CCD’s can be abutted on all four sides enabling very large mosaic arrays.**

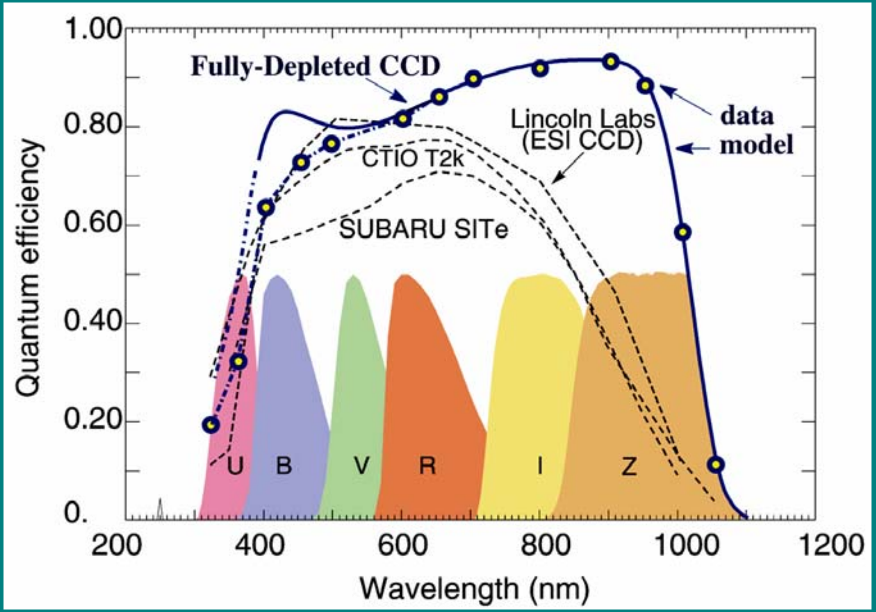


National Optical Astronomy Observatory
Cerro Tololo • Kitt Peak • U.S. Gemini Program

National Solar Observatory
GONG • Kitt Peak • Sacramento Peak

Newsletter 67
September 2001

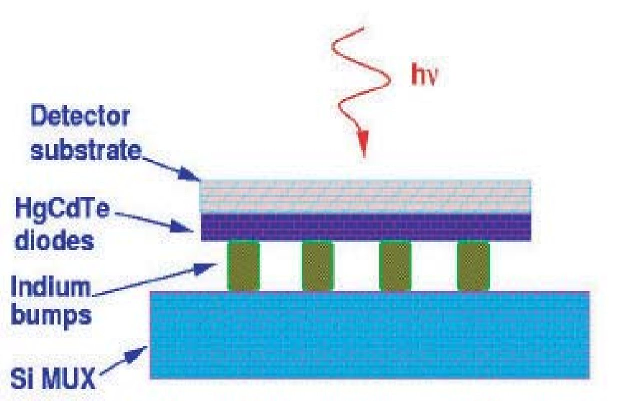
Operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation

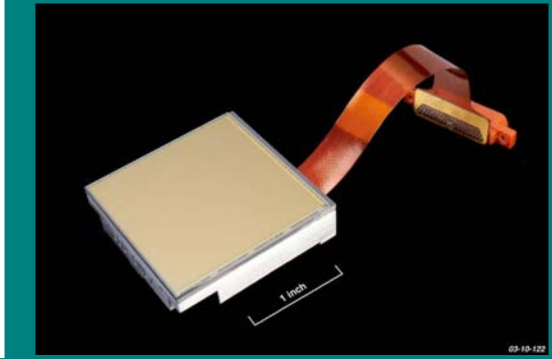


LBNL “Red Hots”: NOAO September 2001 newsletter

Near Infrared (NIR) detectors for SNAP

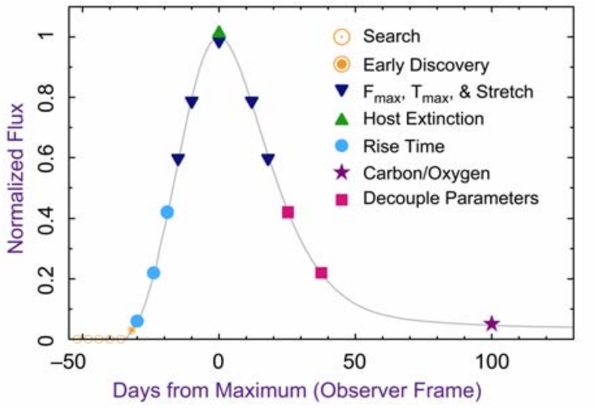
- Large format NIR detectors are a relatively new technology.
- Rockwell Science Center and Raytheon Vision Systems are developing 4 Mpixel (2048 x 2048) NIR focal plane arrays made from HgCdTe (MerCadTel) diodes.
- $Hg_{1-x}Cd_xTe$ composition can be tuned to not “see” long wavelength IR light beyond 1.7 μm, permitting operation at 140K. No active cooling!
- Quantum efficiency, read noise, dark current, uniformity, stability are all being tailored to SNAP requirements.
- Read out by CMOS substrate (> 12 Million transistors) In bump-bonded to HgCdTe diode array (> 4 Million connections).



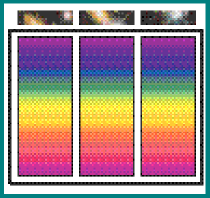


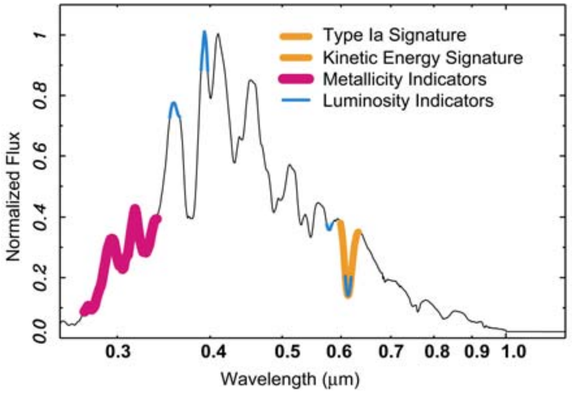
Photometry and Spectroscopy Illustration

Lightcurve & Peak Brightness



Redshift & SN Properties



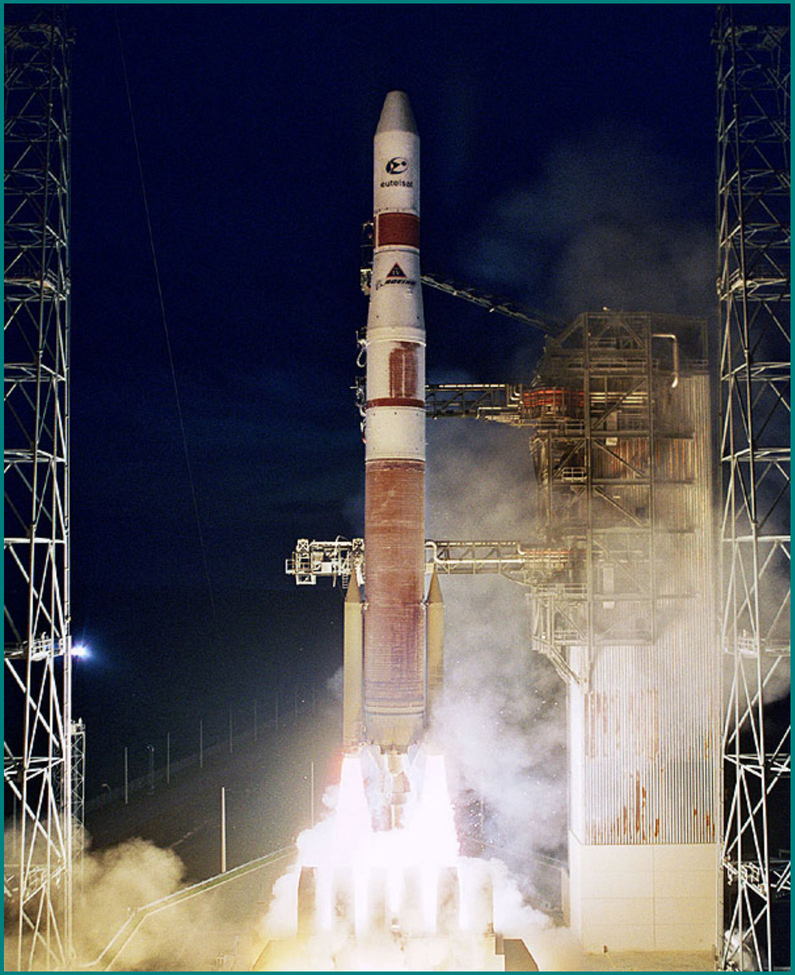


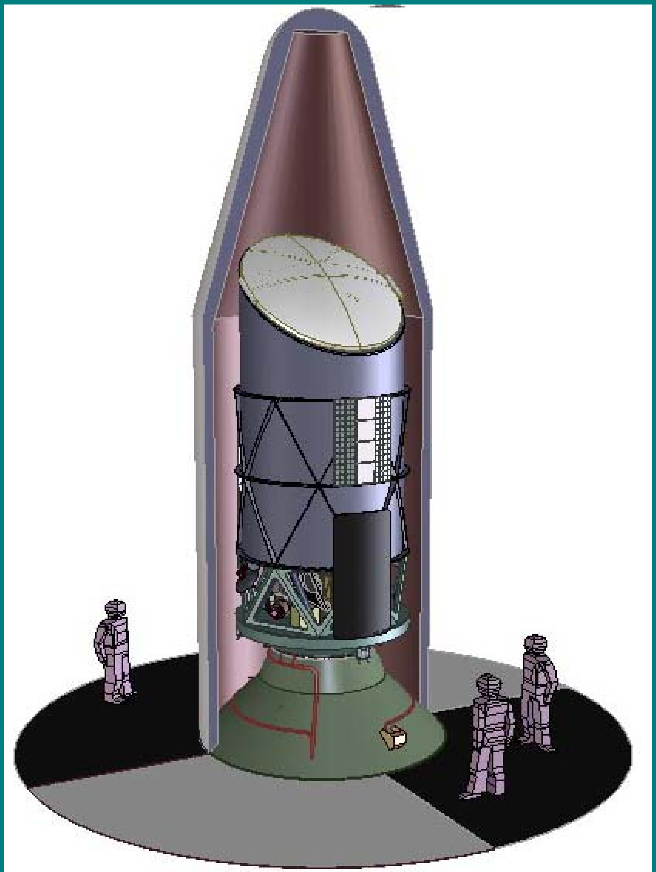
Ω_M and Ω_Λ
Dark Energy
Properties

Data → Analysis → Physics

Launch early in the next decade

1600 kg satellite can be lifted by a Delta IV [recent first flight] to our orbit with margin. Can use equivalent Delta IV, Atlas, or Sea Launch.





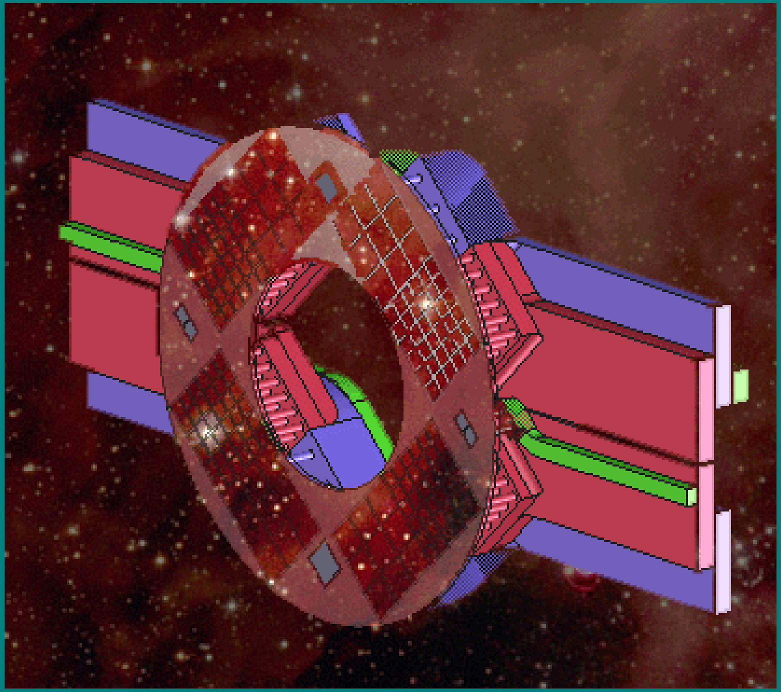
Launch early in the next decade

1600 kg satellite can be lifted by a Delta IV [recent first flight] to our orbit with margin. Can use equivalent Delta IV, Atlas, or Sea Launch.

Observing

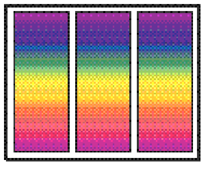
Step ‘n Stare – All Supernovae in all colors

- ➢ Repetitive imaging program (SN discovery and light curve measurement)
    - Observe 15 square degrees every three days in all filters “mowing the sky”.
- ➢ ~50% of time devoted to spectroscopy of individual SNe near maximum light.

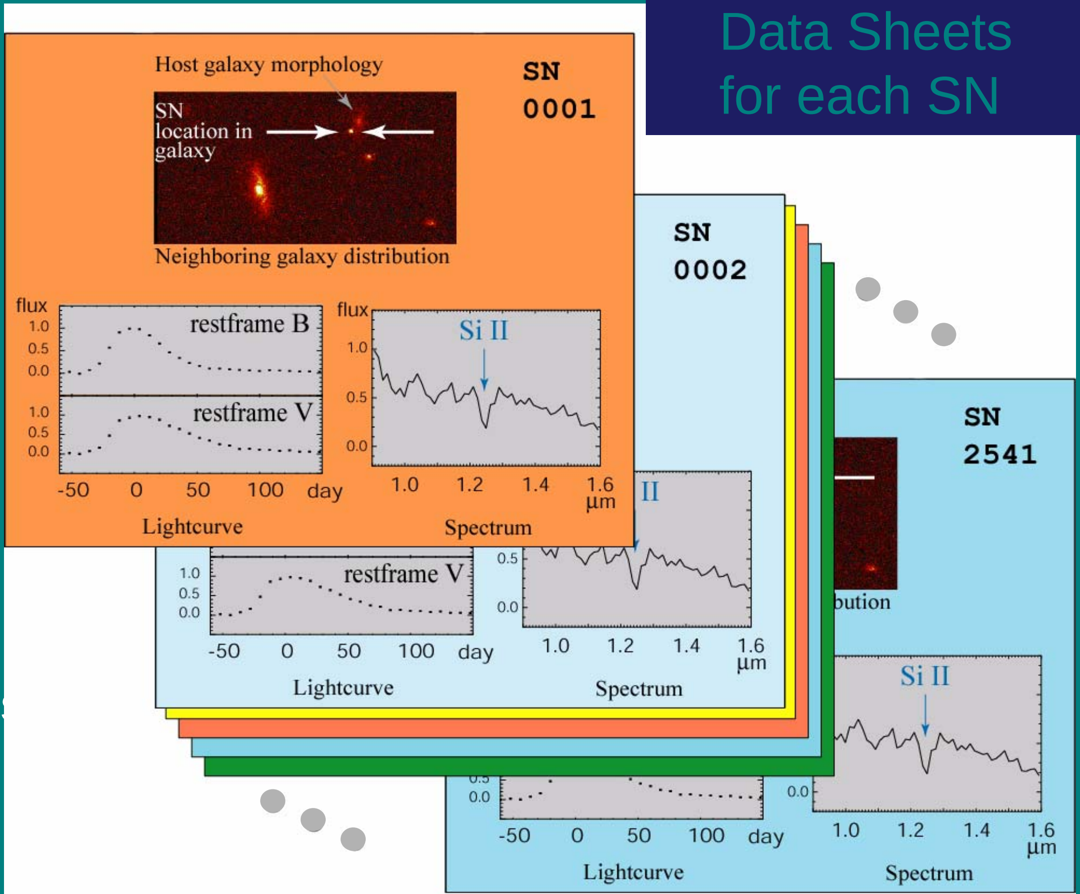


Data Sheets to Cosmological Parameters

Lightcurve &
Peak Brightness



Redshift &
SN Propertie

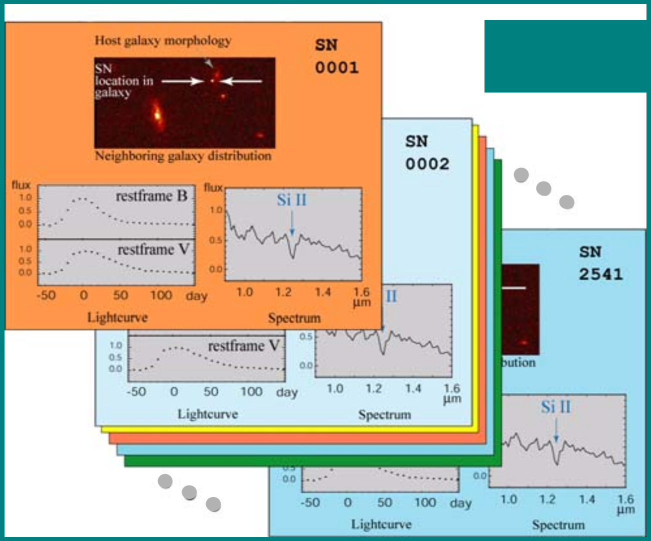


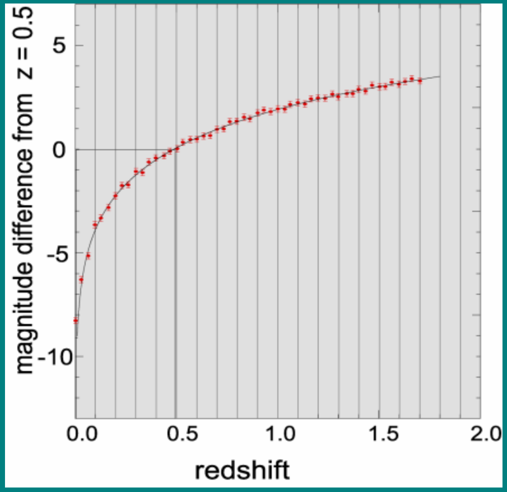
Data Sheets
for each SN

Instrument → Observed Data

Mission Plan

Data Sheets to Cosmological Parameters

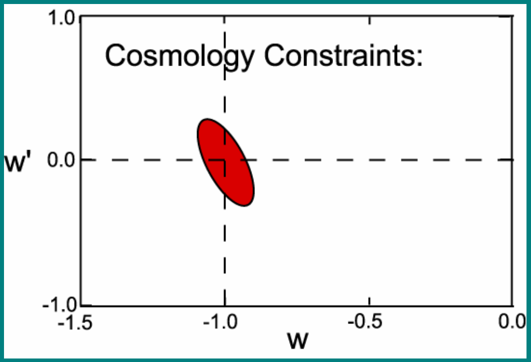




Ω_M and Ω_Λ

Dark Energy Properties

(w_0 and w')

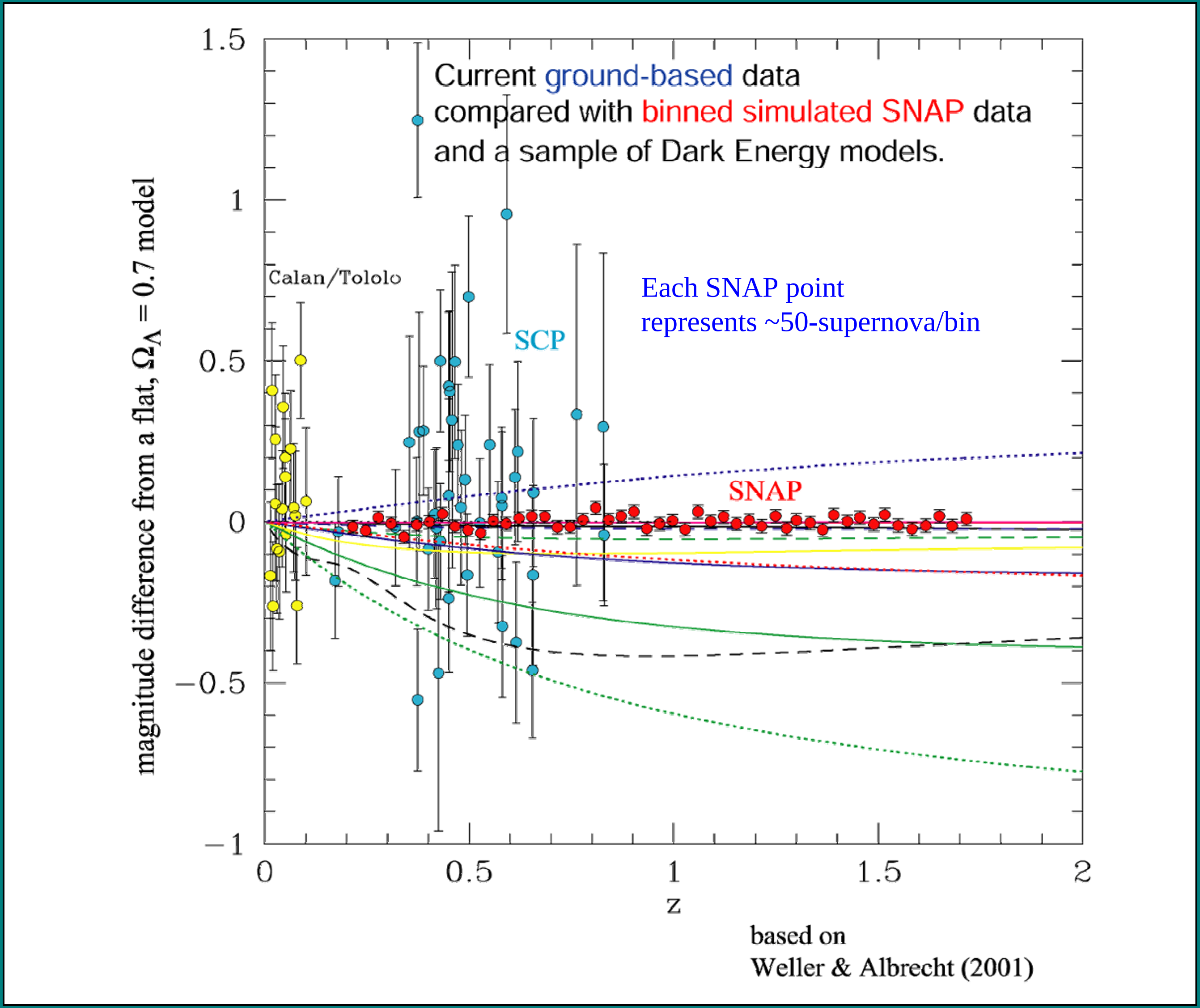


Data ⟶ Analysis ⟶ Physics

Calibration, External SN Obs.

Priors, External Cosmology

Simulated SNAP Data

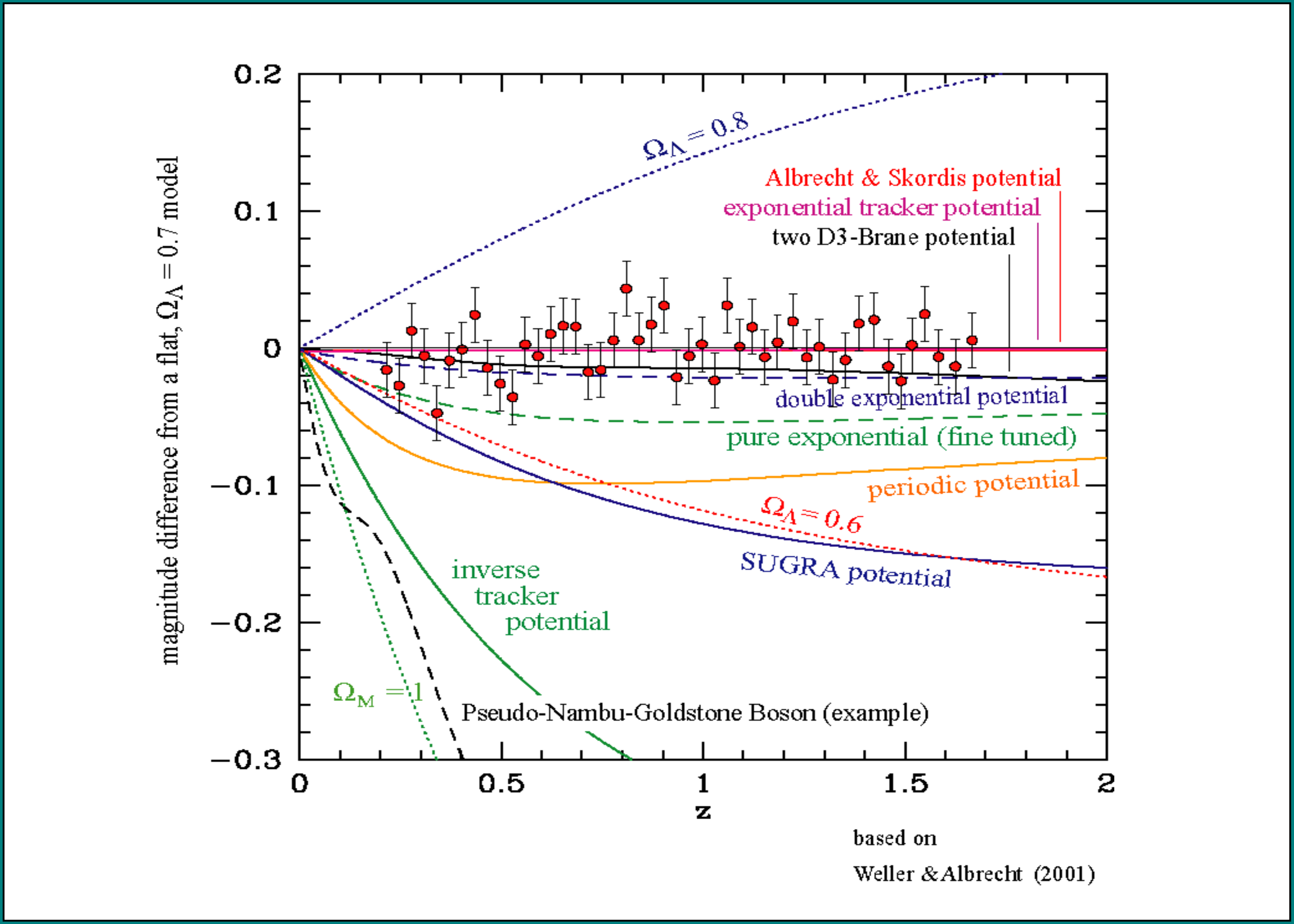


Current ground-based data compared with binned simulated SNAP data and a sample of Dark Energy models.

Each SNAP point represents ~50-supernova/bin

based on Weller & Albrecht (2001)

Understanding Dark Energy



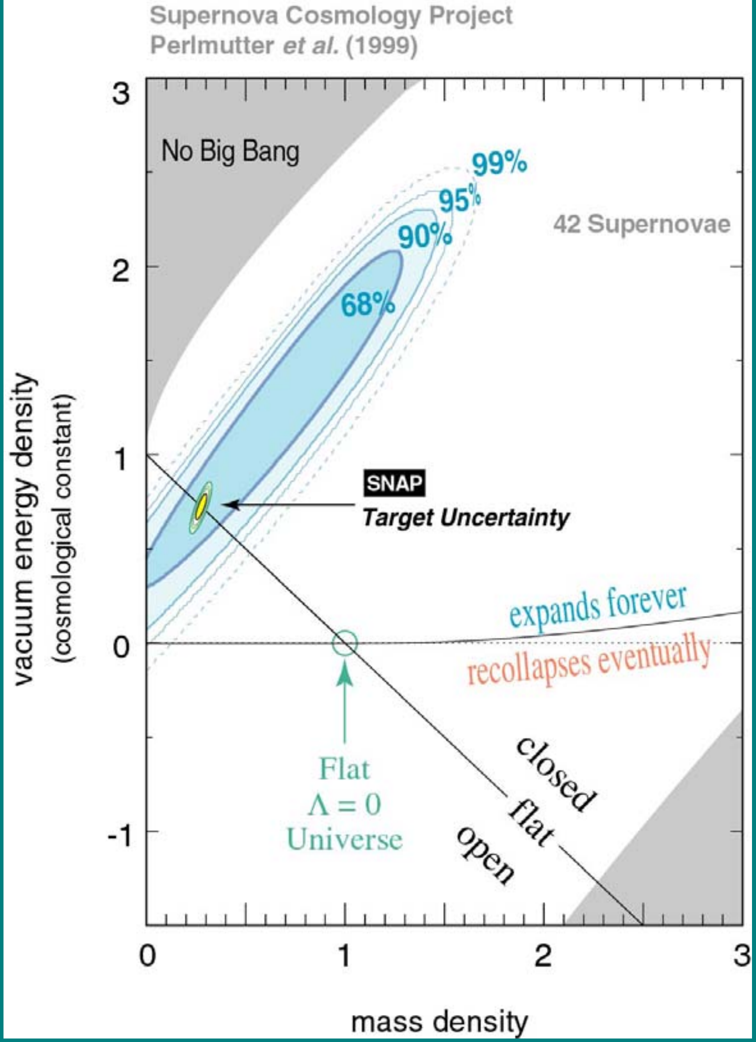
based on

Weller & Albrecht (2001)

Determination of CosmologicalParameters

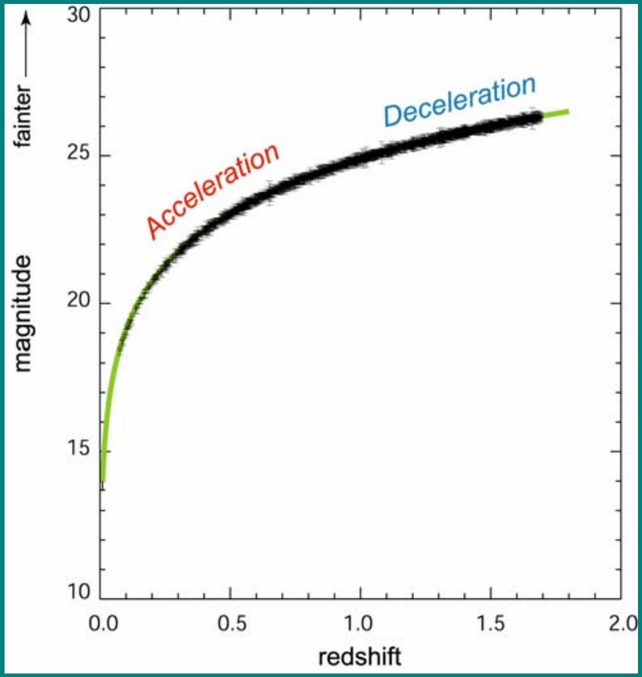
SNAP will measure
(if w= -1)
Ω_Λ to ± 0.02 and
Ω_M to ± 0.03.

With prior Ω_M measured by other techniques (e.g. CMB) to ± 0.03,
SNAP will measure
Ω_M to ± 0.01 and
w to ± 0.05.



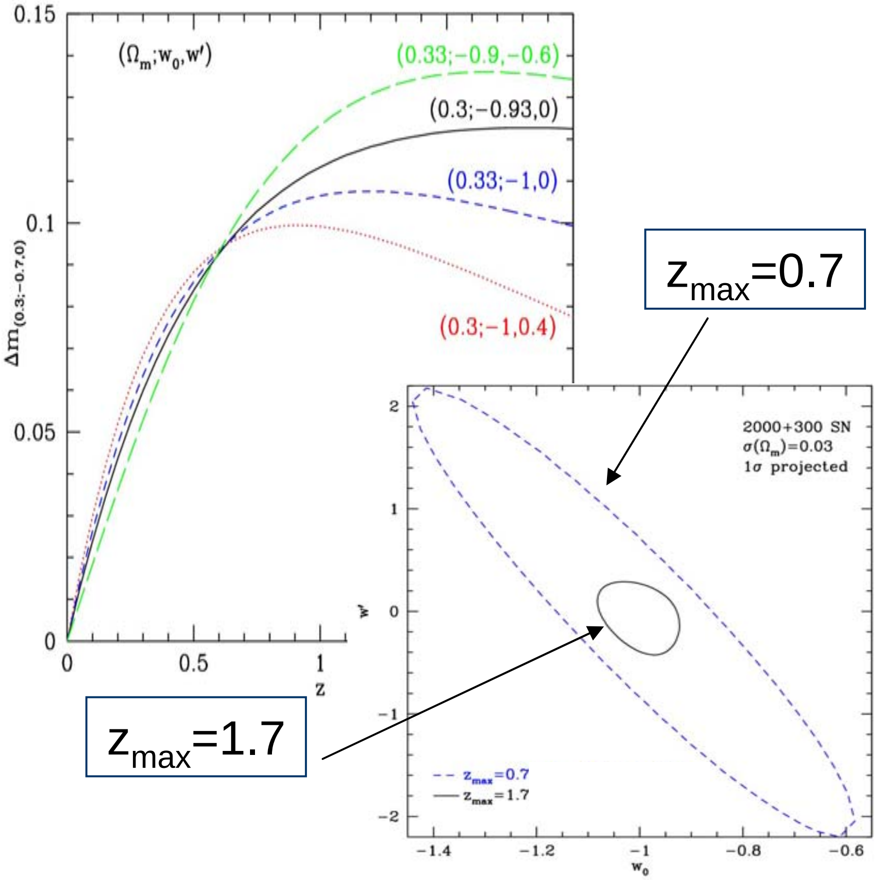
Why go to high redshifts?

- **Dark energy can be detected at low redshift (SCP, High-z). To determine what it is and not just that it is, requires measurements over both the acceleration and deceleration epochs.**
- **This long reach breaks essential degeneracies which low redshift data alone cannot.**



SNAP will

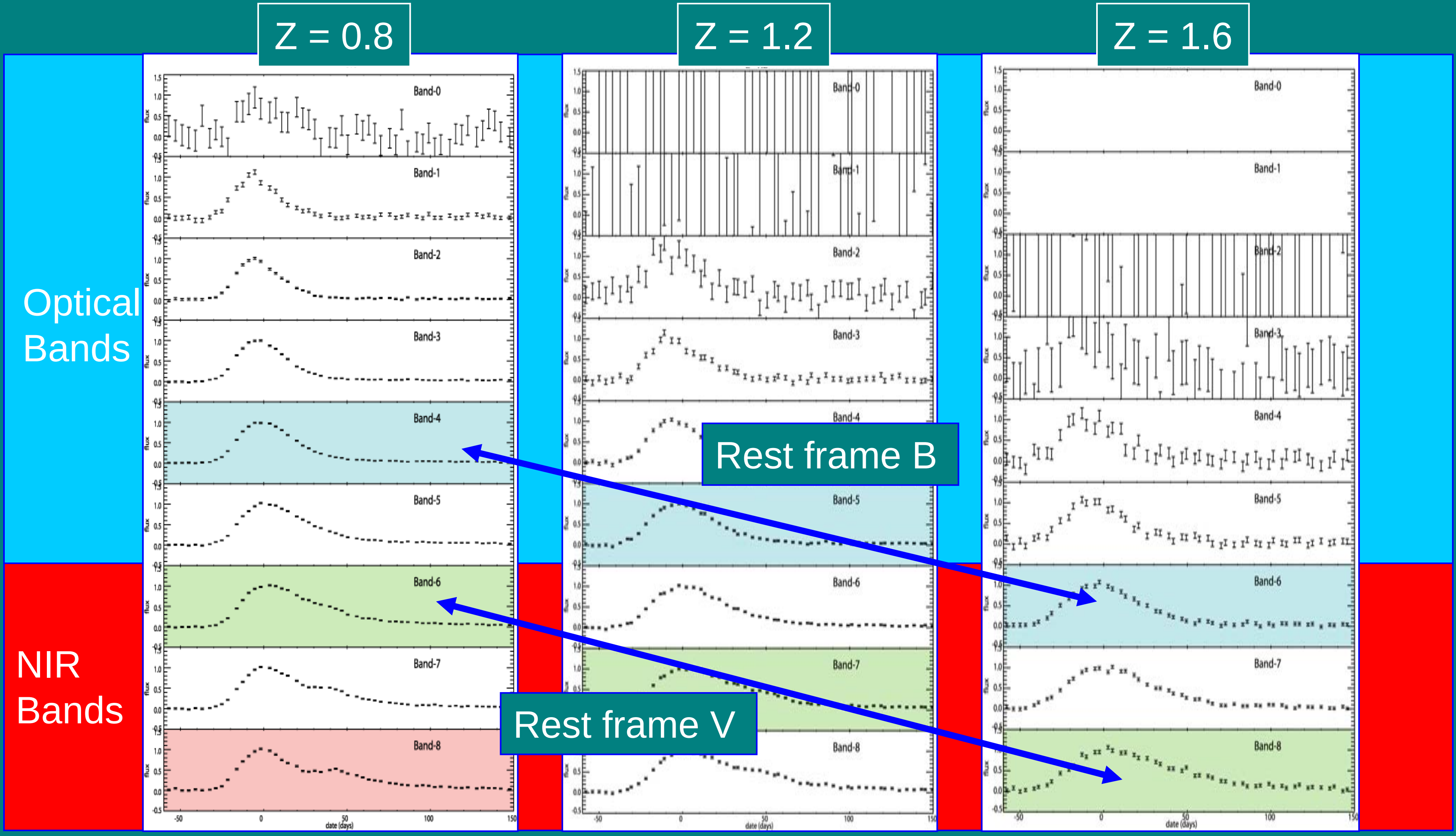
- ✓ probe the variability of w, providing an essential clue to the nature of DE.
- ✓ measure w_0 precisely to determine whether it is a cosmological constant.



z_{max}=0.7

z_{max}=1.7

Rest frame B and V shift to NIR



Z = 0.8

Z = 1.2

Z = 1.6

Optical Bands

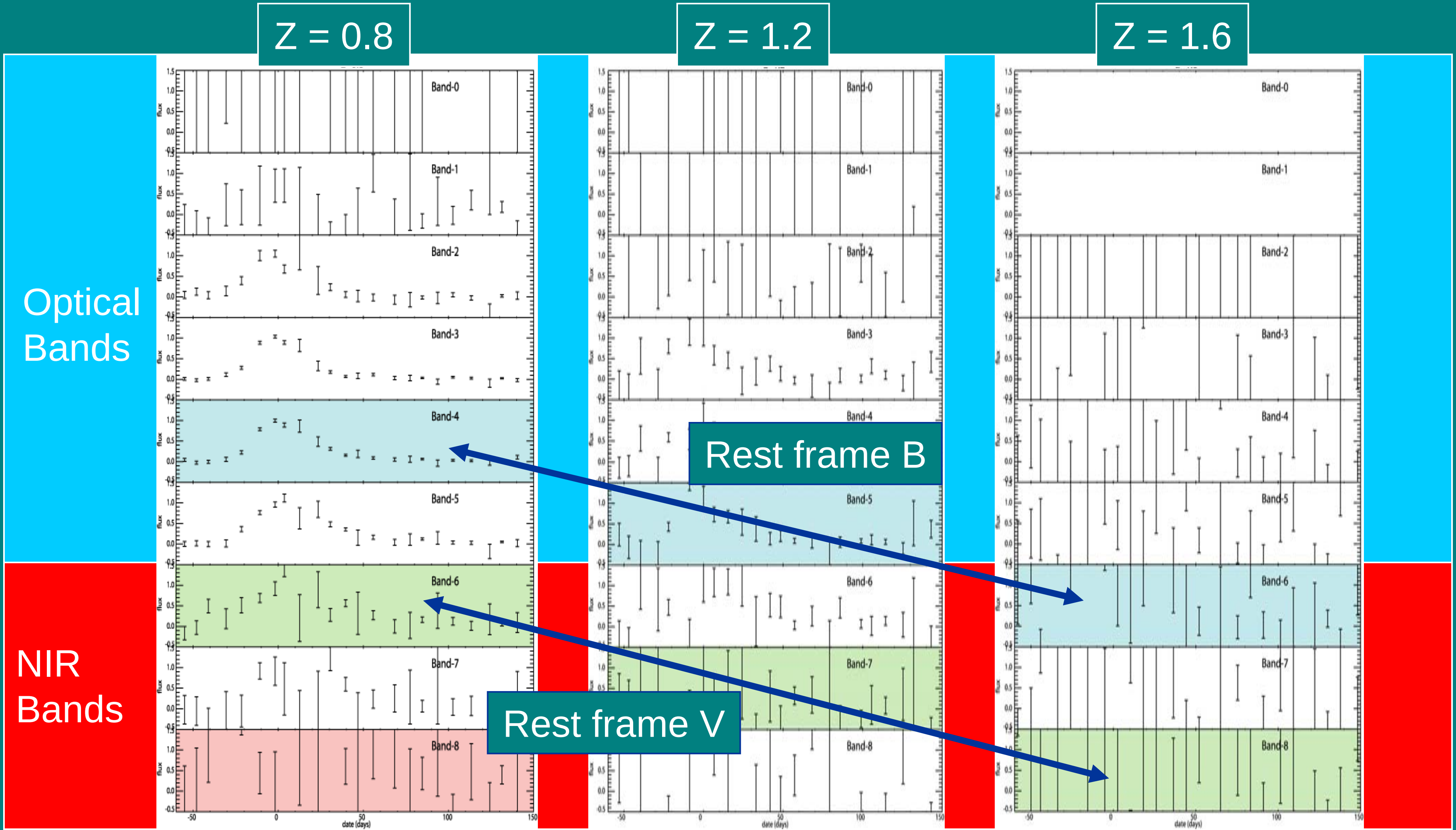
NIR Bands

Rest frame B

Rest frame V

Simulated SNAP observations of high redshift SNe

This can’t be done on the ground!


Z = 0.8

Z = 1.2

Z = 1.6

Optical Bands

NIR Bands

Rest frame B

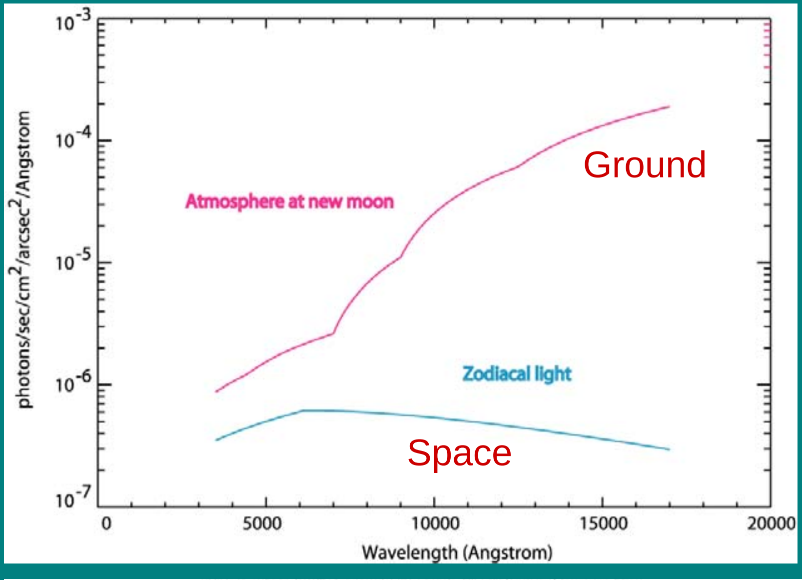
Rest frame V

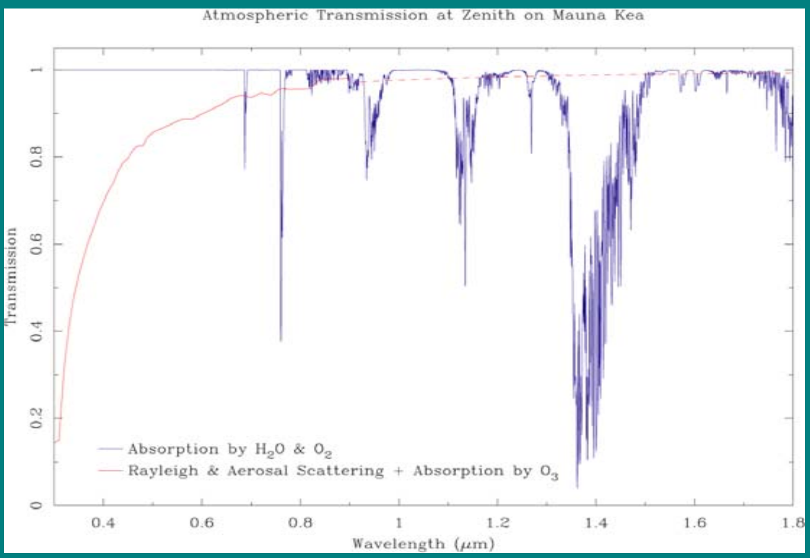
Simulated 8m telescope ground based observations of high redshift SNe

NIR available only in space

Crucial near-infrared observations are impossible from the ground

- ➢ Sky is very bright in NIR, about 500x brighter at 1.5µm, like observing the sky in Manhattan
- ➢ Sky is not transparent in NIR, absorption due to H_2O molecular absorption bands is very strong and extremely variable





Confronting Systematic Errors

Spectroscopy fixes these

- on
  evolution
  - Shifting distribution of progenitor mass/metallicity/C-O
  - Shifting distribution of SN physics parameterss:
    - Amount of Nickel fused in explosion
    - Distribution of Nickel
    - Kinetic energy of explosion
    - Opacity of atmosphere's inner layers
    - Metallicity
- Gravitational Lensing (de)amplification

NIR fixes these

- Dust/Extinction
  - Dust that reddens
  - Evolving gray dust
    - Clumpy
    - Homogeneous
  - Galactic extinction model
- Observational biases
  - Malmquist bias differences
  - non-SN Ia contamination
  - K-correction uncertainty
  - Color zero-point calibration

Beyond Dark Energy

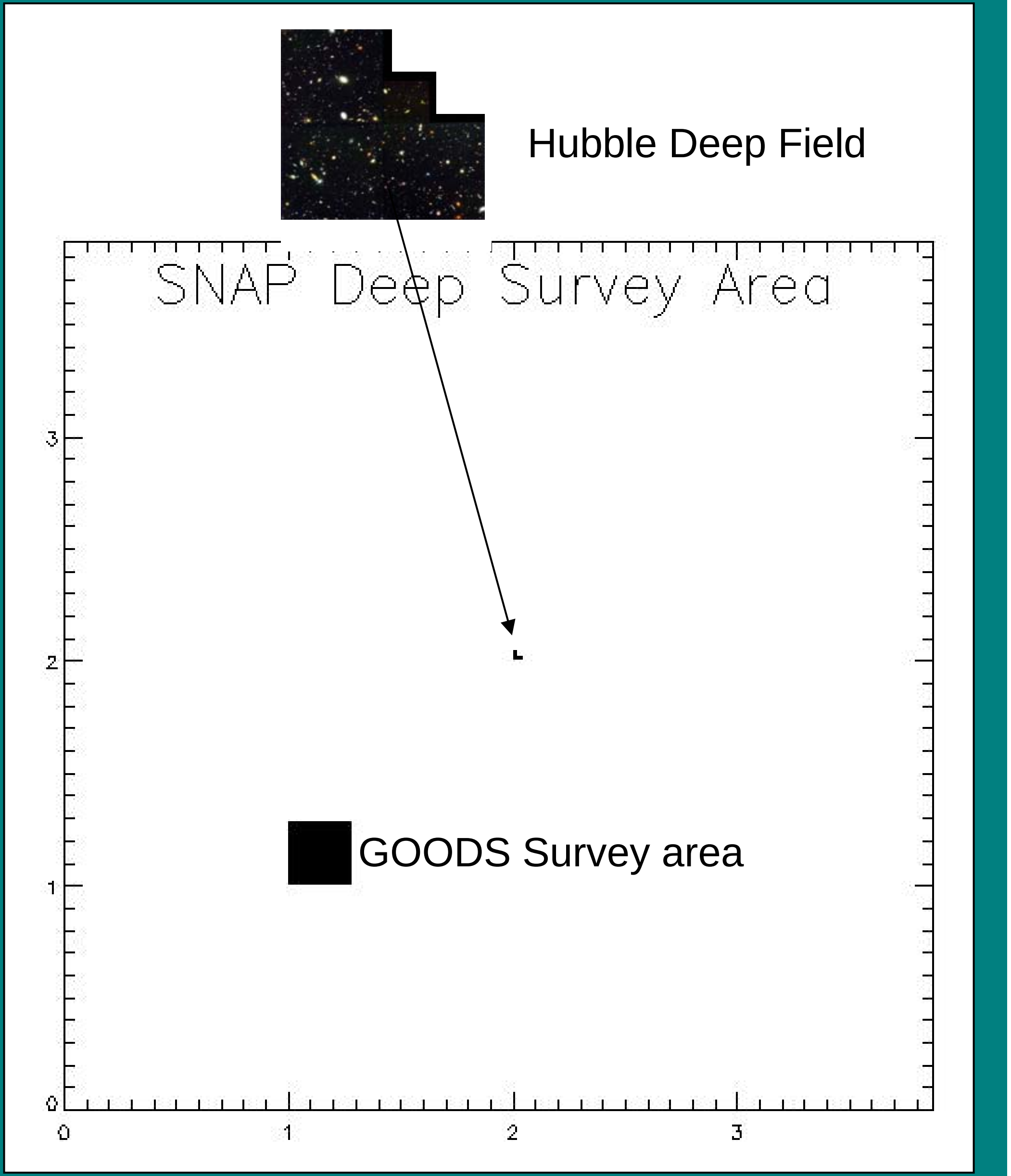
1. Galaxy studies: evolution and clustering.
2. Galaxy clusters: identification of high redshift galaxy clusters, faint and small constituents
3. High-z quasar studies: mapping quasars to z = 10, probing the re-ionization of the universe.
4. Transients; Gamma Ray Bursts, Quasars/Active Galactic Nuclei, outer solar system objects
5. Cool stars in the Milky Way
6. Lensing: evolution of the galaxy/dark matter correlation, determination of galaxy cluster masses, etc.
7. Targets: Identification of targets for the James Webb Space Telescope (JWST), California Extremely Large Telescope (CELT), etc…

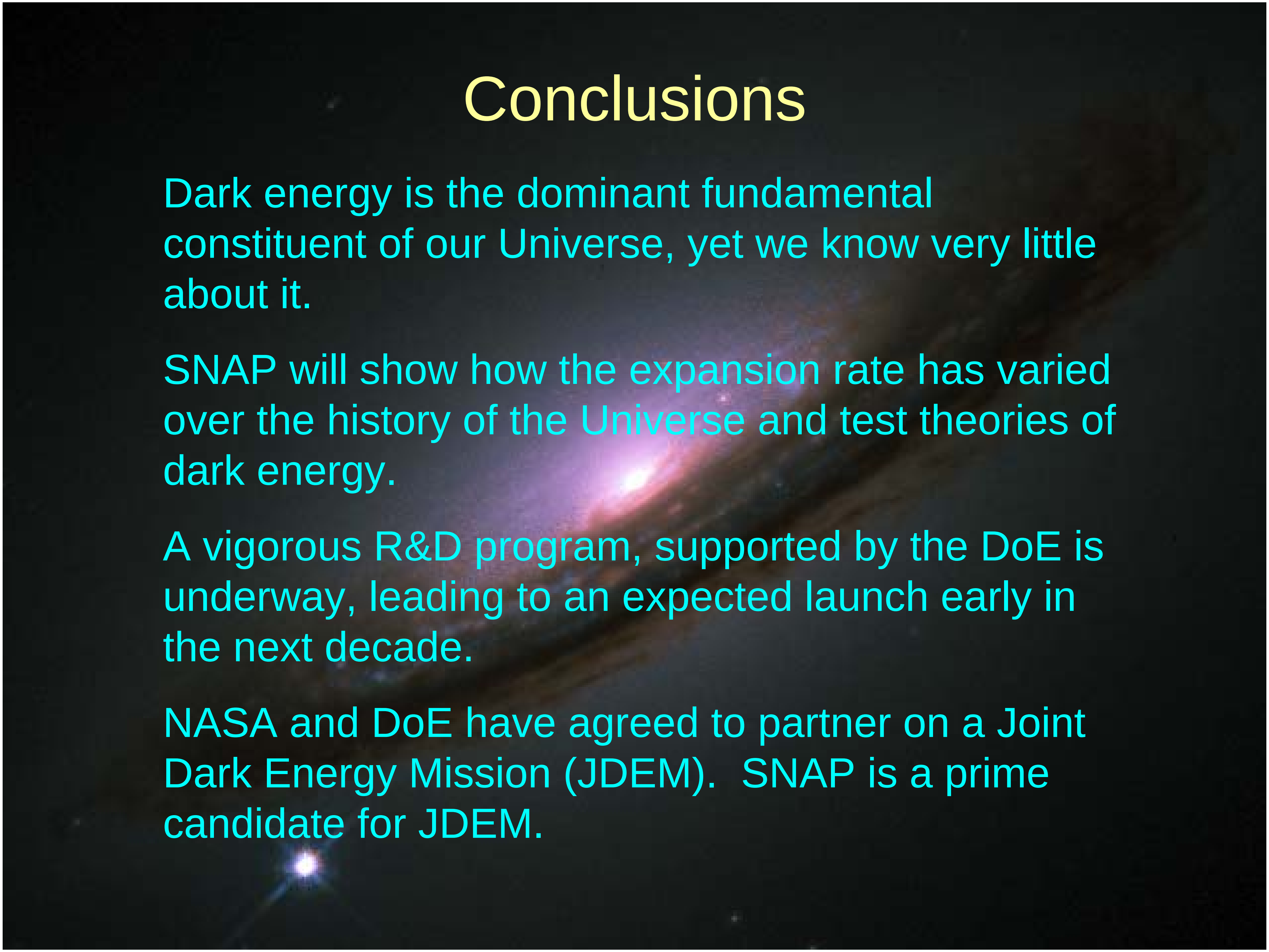
SNAP Observation Program

Base SNAP survey:

15 square degrees near ecliptic poles

- **~9,000 × as large as Hubble Deep Field, same resolution but 1.5 mag deeper (in nine optical and IR bands)**





Conclusions

Dark energy is the dominant fundamental constituent of our Universe, yet we know very little about it.

SNAP will show how the expansion rate has varied over the history of the Universe and test theories of dark energy.

A vigorous R&D program, supported by the DoE is underway, leading to an expected launch early in the next decade.

NASA and DoE have agreed to partner on a Joint Dark Energy Mission (JDEM). SNAP is a prime candidate for JDEM.

THE END