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

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University of Michigan

Physics Seminar
TUNL

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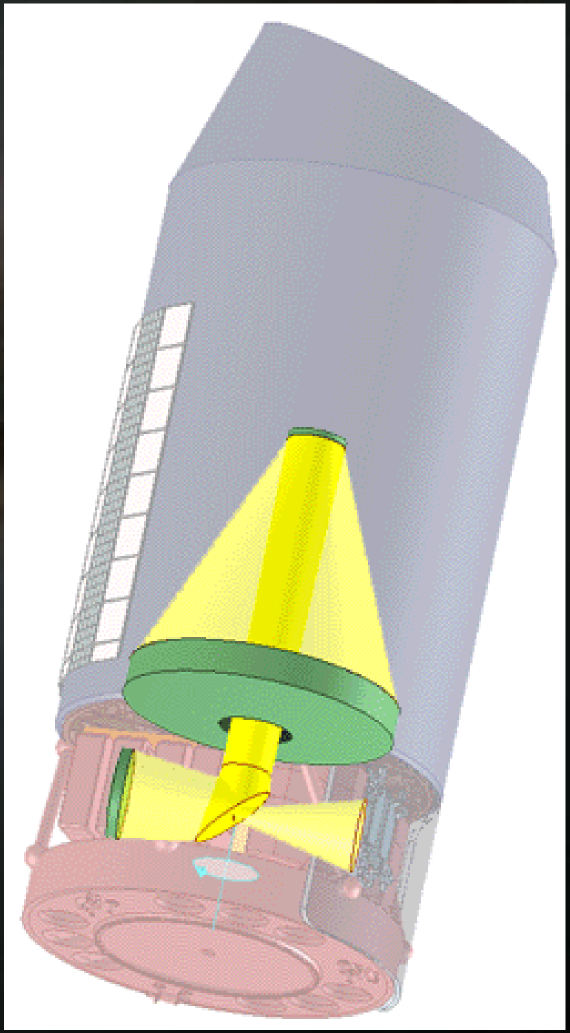
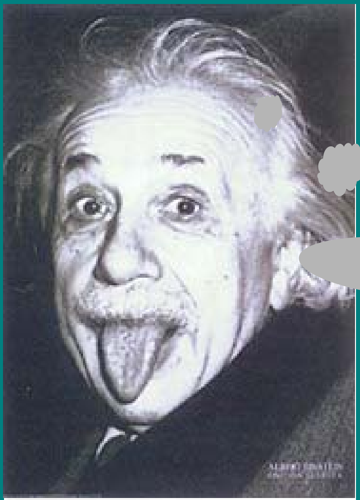


The Cosmological Constant

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R \qquad = -8\pi G T_{\mu\nu}$$

- 1917 Albert Einstein develops General Relativity.
- In GR the source for gravity in $T_{\mu\nu}$ is $\rho_{tot} + 3p$, matter and energy density (and pressure!).
- The content of the universe affects its evolution and its destiny.
- Problem! GR predicts that any universe containing only matter will collapse on itself.

The Cosmological Constant



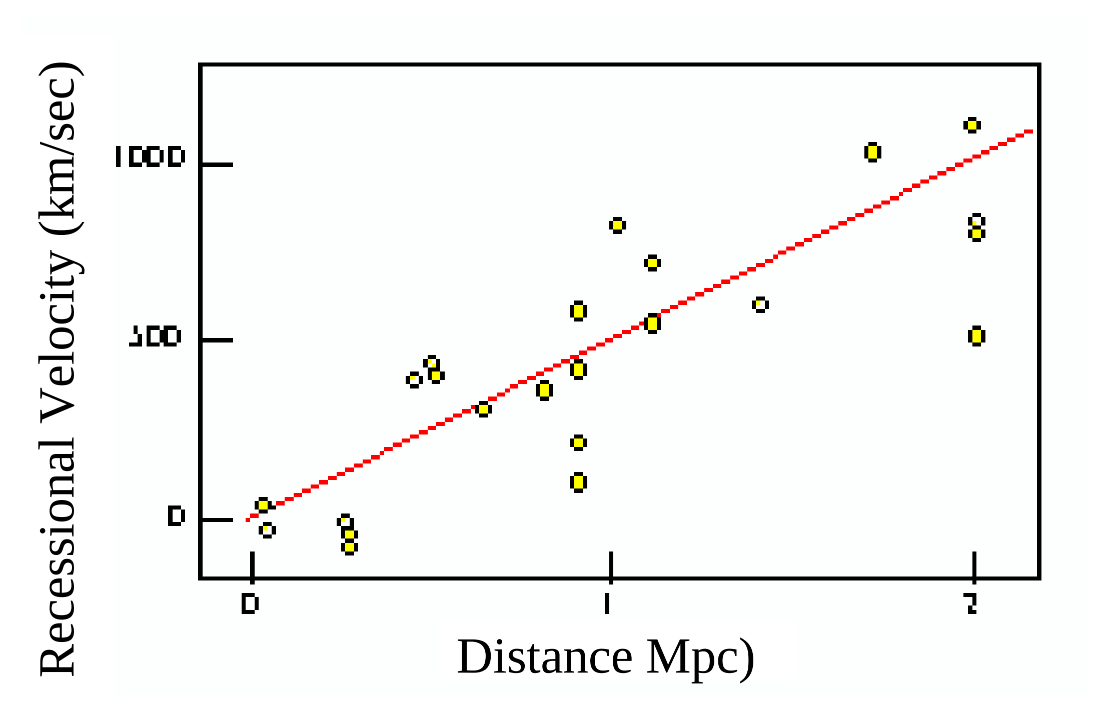
$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R - \boxed{\Lambda} g_{\mu\nu} = -8\pi G T_{\mu\nu}$$

- Einstein put a cosmological constant Λ (vacuum energy) into his equations of GR to allow for a static universe.
  - Equivalent to a negative pressure ($p < 0$).
  - The equation of state for a pure cosmological constant is $w = p/\rho = -1$.
- By tuning Λ, attractive gravity due to matter density and vacuum energy density (ρ_{tot}) and the "repulsive" effect of the negative pressure (3p) can be made to just balance.
- Danger! Runaway solution if Λ is large and positive!

Negative Pressure!

- Vacuum energy has negative pressure!
- With an ordinary gas of particles, as you increase the volume of the box, the particles dilute.
- Because the **positive** pressure does work **on** the box, the internal energy of the gas decreases.
- For a box filled with vacuum energy the energy content increases with increasing volume.
- The pressure of this vacuum energy must be **negative** so that positive work is done **by** the box.

Hubble's Great Discovery - The Universe is Expanding!



$$\text{velocity} \propto \text{distance}$$

$$v = H_o r$$

- In 1929 Hubble measured the redshift (velocity) of nearby galaxies and found that nearly all were moving away from us.
- He used Cepheid variables as "standard candles" to measure distances.
- **Result: The faster they are moving, the farther away they are.**
- **The Universe is expanding! Einstein declares Λ his "Biggest Blunder."**

“Brooklyn is not expanding!”

- The expansion of the universe is an expansion of space itself. It is **not** an explosion with pieces flying out from a common center through space.
- The universe is not expanding into anything. It is creating new space between the galaxies as it grows.
- Except for motion due to local gravity through space, each galaxy is at rest with the Hubble flow and “sees” the other galaxies moving away with an apparent speed that increases with distance according to the Hubble law $v = H_0 r$.
- As gravitationally bound structures form, they leave the Hubble flow. Local gravity takes over and drives the continued growth of structure over “billions of years.”

Geometry versus Destiny

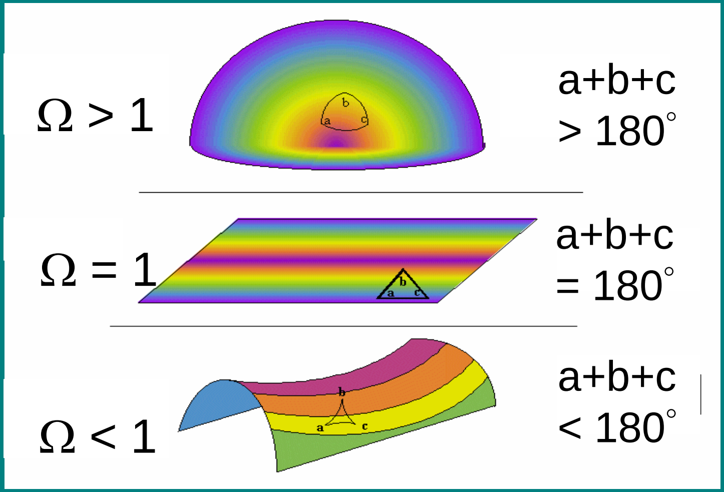
- General Relativity: Geometry ⇒ Destiny
- For a universe made entirely of matter (with $\rho \geq 0$, $p = 0$) the geometry is determined by “Omega” $\Omega = \rho_{TOT}/\rho_{crit}$, the ratio between total density of matter and the critical density.

$\rho_{crit} = 3H_0^2/8\pi G = 10^{-29}$ g/cm³ for $H_0 = 71$ km/s/Mpc (7 H atoms/m³)

$\Omega > 1$ Positive curvature, closed universe ⇒ eventual collapse.

$\Omega = 1$ Flat space, open infinite universe ⇒ decelerates to rest.

$\Omega < 1$ Negative curvature, open infinite universe, expands forever.



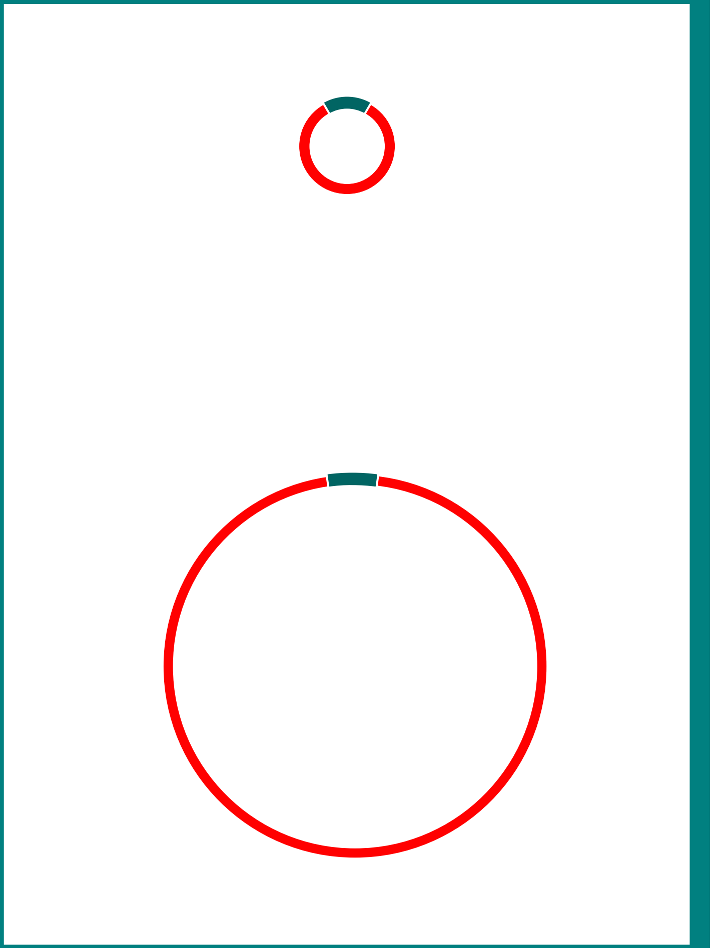
- Vacuum energy (with $\rho \geq 0$, $p < 0$), such as a cosmological constant, increases in total energy as the universe expands. This will accelerate the expansion of the universe.

Problems with the Big Bang

- The Horizon Problem
  - CMBR measurements show that the temperature is the same in all directions.
  - If we follow the Hubble expansion back in time, regions of the sky separated by more than a few degrees could have never been in contact with each other and could not have come into thermal equilibrium.
- The Flatness Problem
  - If $\Omega \neq 1$, it rapidly evolves away from $\Omega = 1$ as the universe expands.
  - If Ω is close to unity now, it had to be within 10^{-28} of unity (0.999999999999999999999999999) near the beginning of time.
  - Only if Ω is precisely = 1 would it remain = 1.
  - What mechanism could fine-tune the universe to this degree?

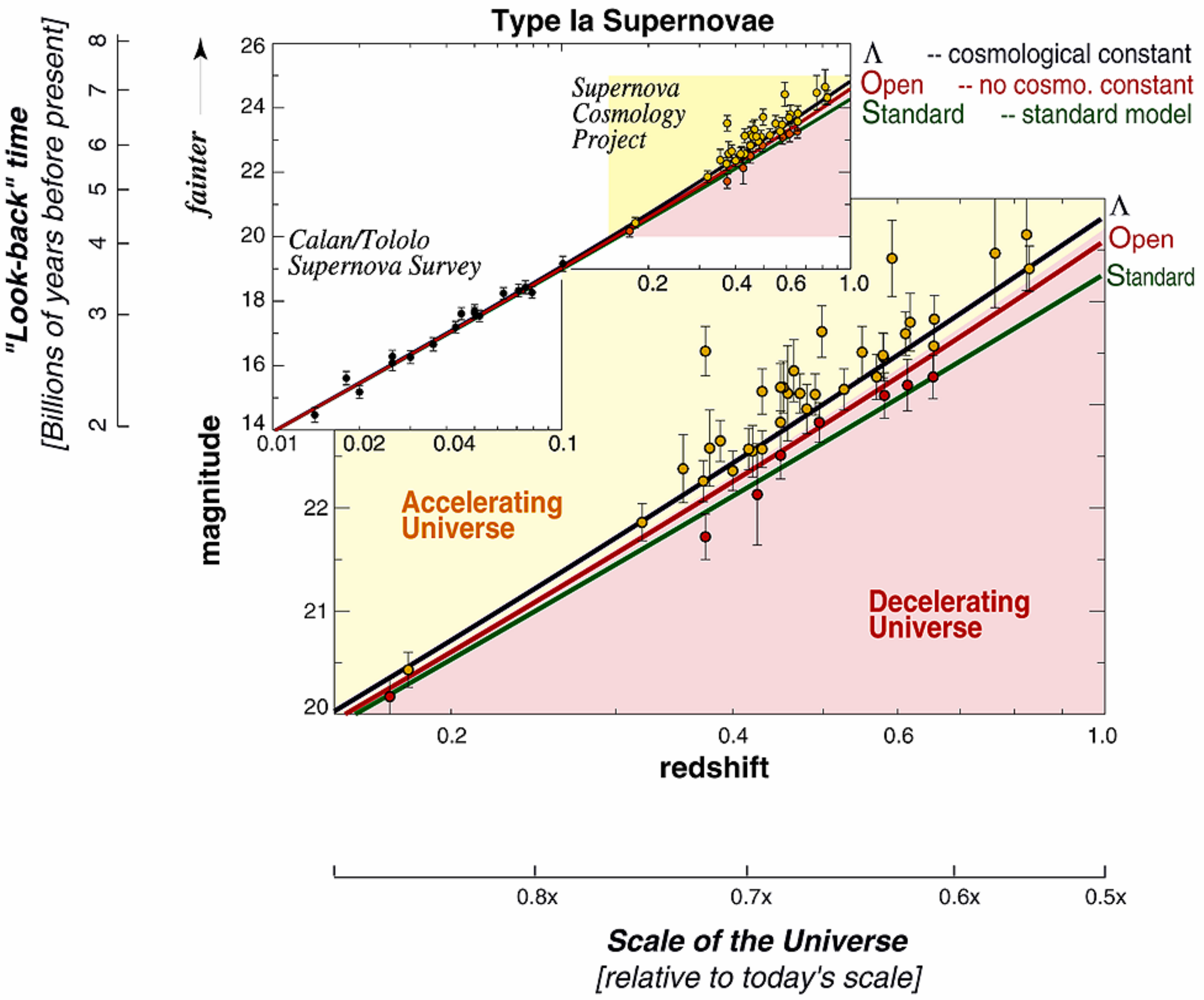
Inflation

- In 1979 Alan Guth proposed an inflationary universe to solve the “horizon problem” and to explain the apparent “flatness” of the universe.
- From ~10^{-35} - 10^{-33} s, the inflationary universe doubled in size every 10^{-35} s, expanding by a factor of 10^{28} and setting $\Omega = 1$.
- Quantum fluctuations in the early universe were expanded into the “seeds” that nucleated the large-scale structures in the universe today.
- Inflation was powered by a time-dependent vacuum energy ($p < 0$) that transformed itself into all the matter and energy in the universe today.

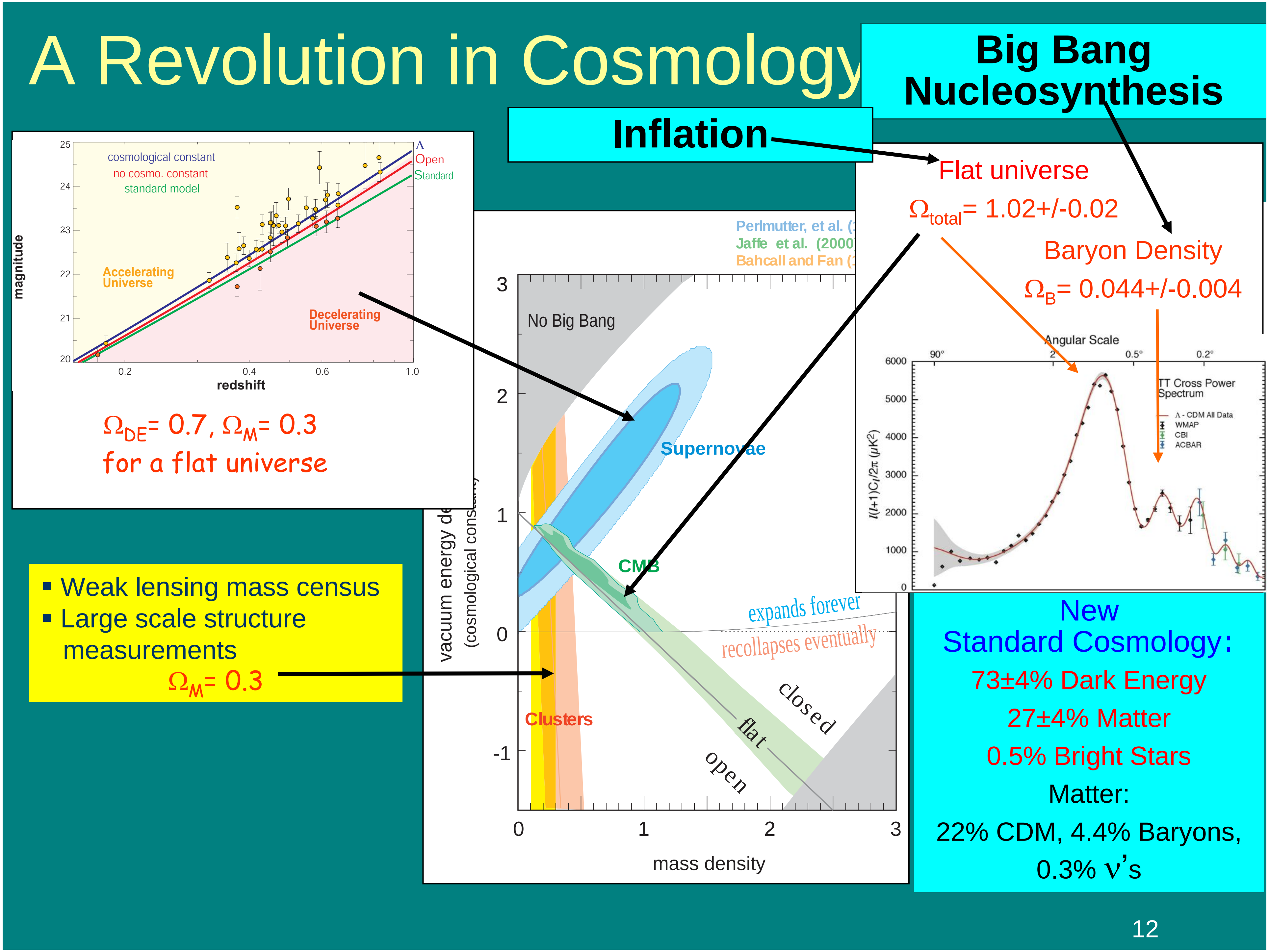


A Startling Discovery

- (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

Flat universe

Ω_{total}= 1.02+/-0.02

Baryon Density

Ω_B= 0.044+/-0.004

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

- 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

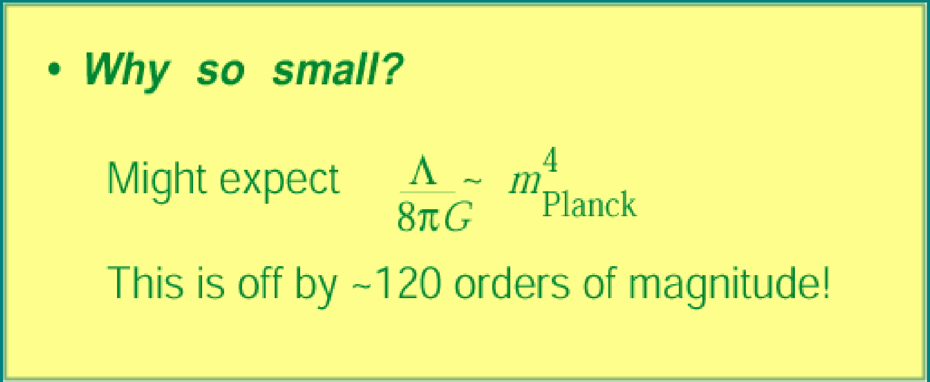
Matter:

22% CDM, 4.4% Baryons,

0.3% ν's

Who Ordered That?!

What’s wrong with a Vacuum Energy/Cosmological constant?



- ***Why so small?***

Might expect $\frac{\Lambda}{8\pi G} \sim m^4_{\text{Planck}}$

This is off by ~120 orders of magnitude!

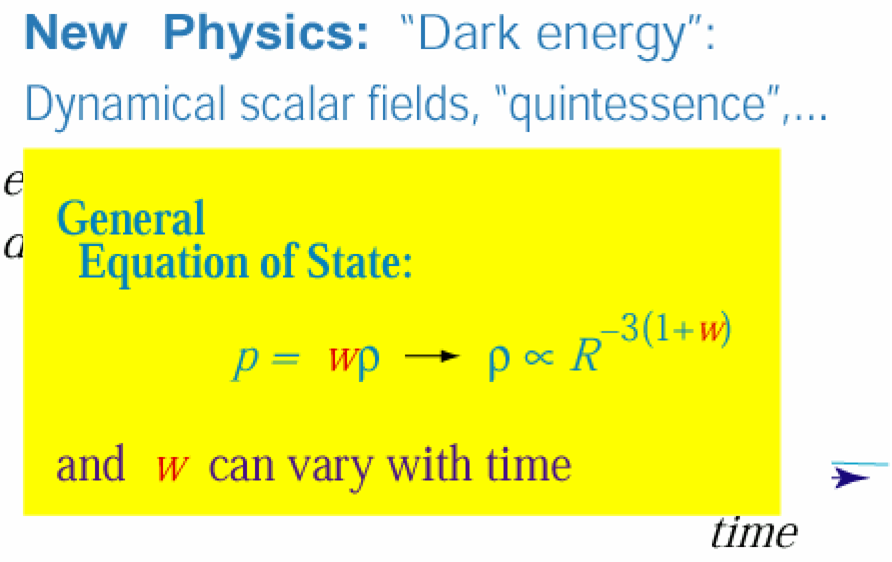
Some remarkable unknown symmetry of nature must have cancelled this vacuum energy to allow our universe to spring into existence. But how could it do so and leave a part in 10^{-120} remaining?

- ***Why now? Why, why, why?***

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3p)$$

Matter: $p = 0 \rightarrow \rho \propto R^{-3}$

Vacuum Energy: $p = -\rho \rightarrow \rho \propto \textit{constant}$



New Physics: “Dark energy”:

Dynamical scalar fields, “quintessence”,...

General
Equation of State:

$$p = w\rho \longrightarrow \rho \propto R^{-3(1+w)}$$

and w can vary with time

Implications of Cosmic Acceleration

There is a previously unseen “dark energy” pervading all of space that is now accelerating the expansion of the universe.

Whatever its origin (Cosmological Constant, Vacuum Energy…) the dark energy has a negative pressure ($p < 0$).

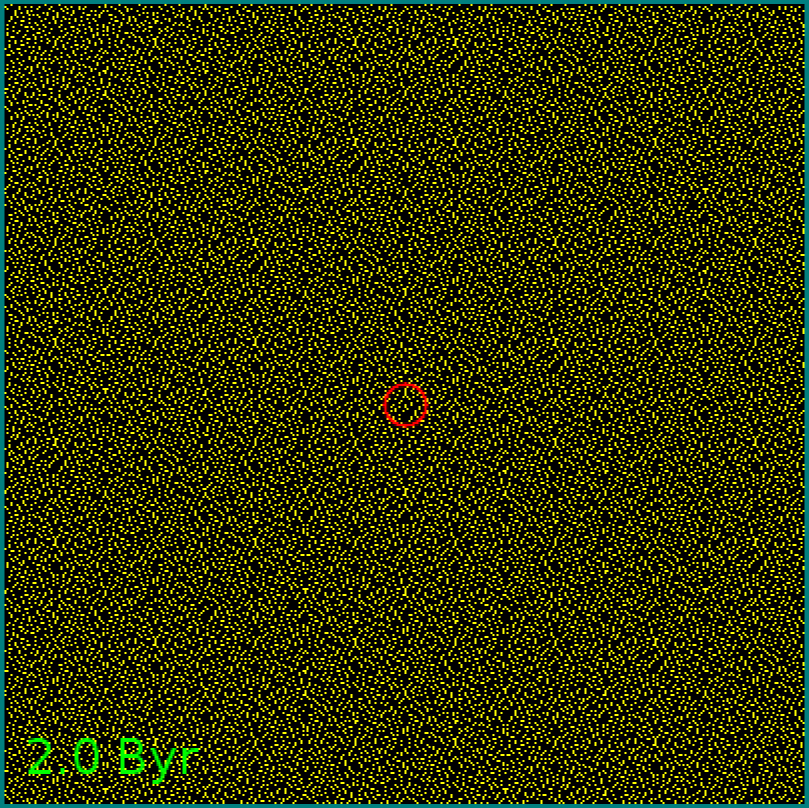
This dark energy is the major constituent of the universe today (~2/3) and will continue to increase its share as the universe expands.

The expansion is NOT slowing to a halt and then collapsing (i.e., the universe is not “coming to an end”). In the simplest models, it will expand forever.

In the not so distant past (> 5 Byr ago) the universe was dominated by matter and was decelerating. Larger and larger structures formed as each new scale entered the horizon.

The formation of structure ended when dark energy prevailed over matter.

The largest structures in the universes are now being accelerated beyond our horizon - e.g. Virgo Cluster will be leave our horizon in 118 billion years.


2.0 Byr

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!

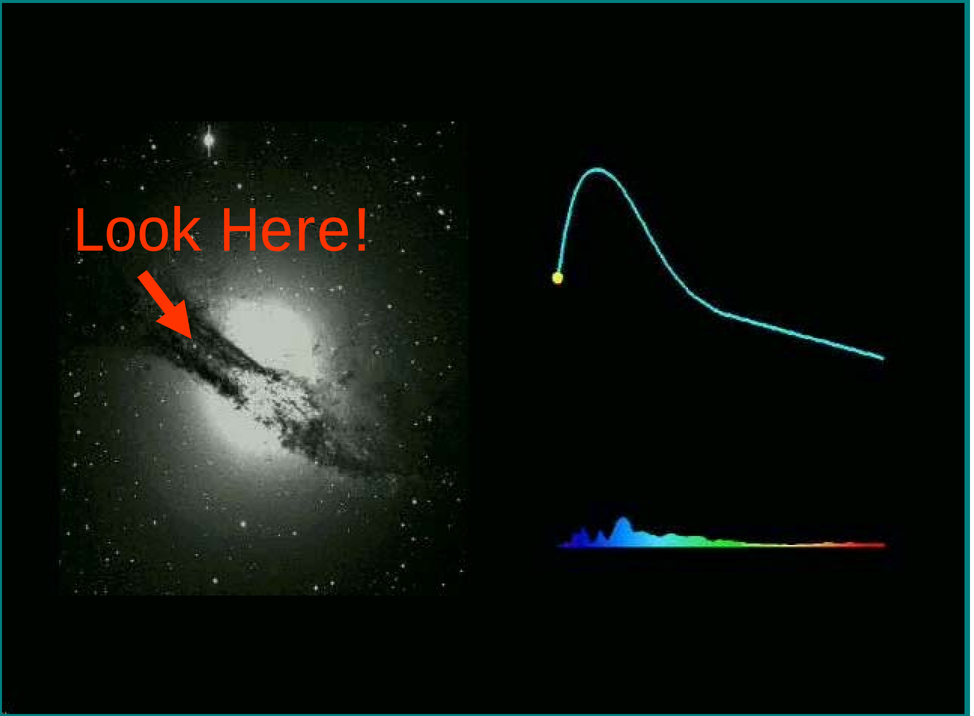
What is the “dark energy?” Theorists have proposed a number of possibilities each with its own unique w(t):

- 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.**



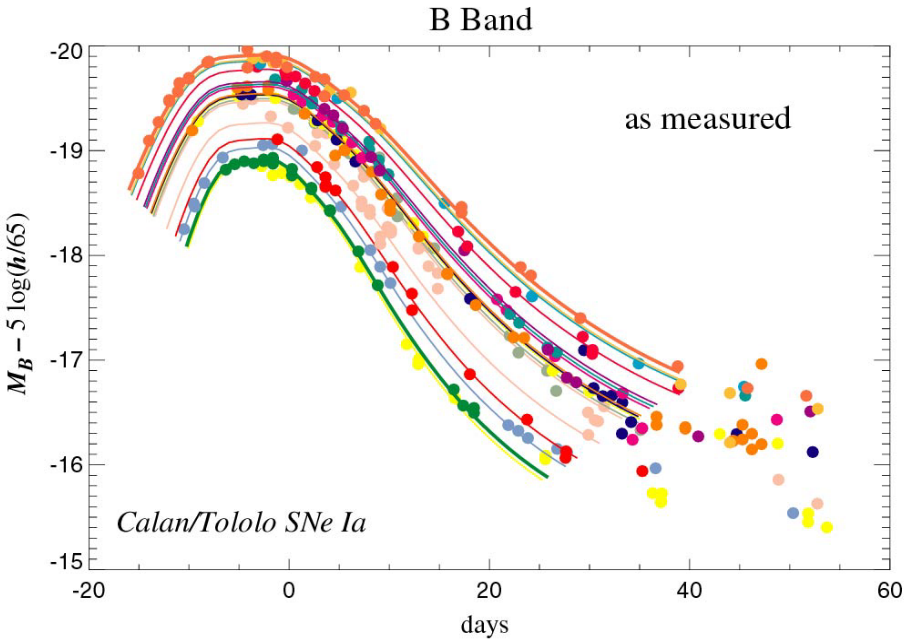
Can measure both intensity and spectra as the supernova brightens and fades over many days.

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

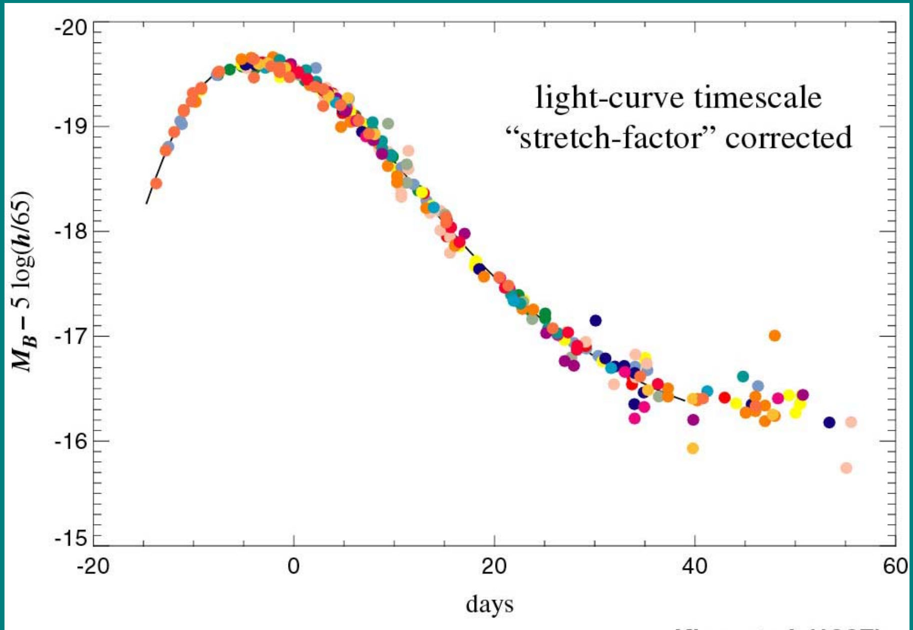
- Apparent magnitude measures distance (time back to explosion)
- Redshift measures the total relative expansion of the universe since that time

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

“Standard” Candles

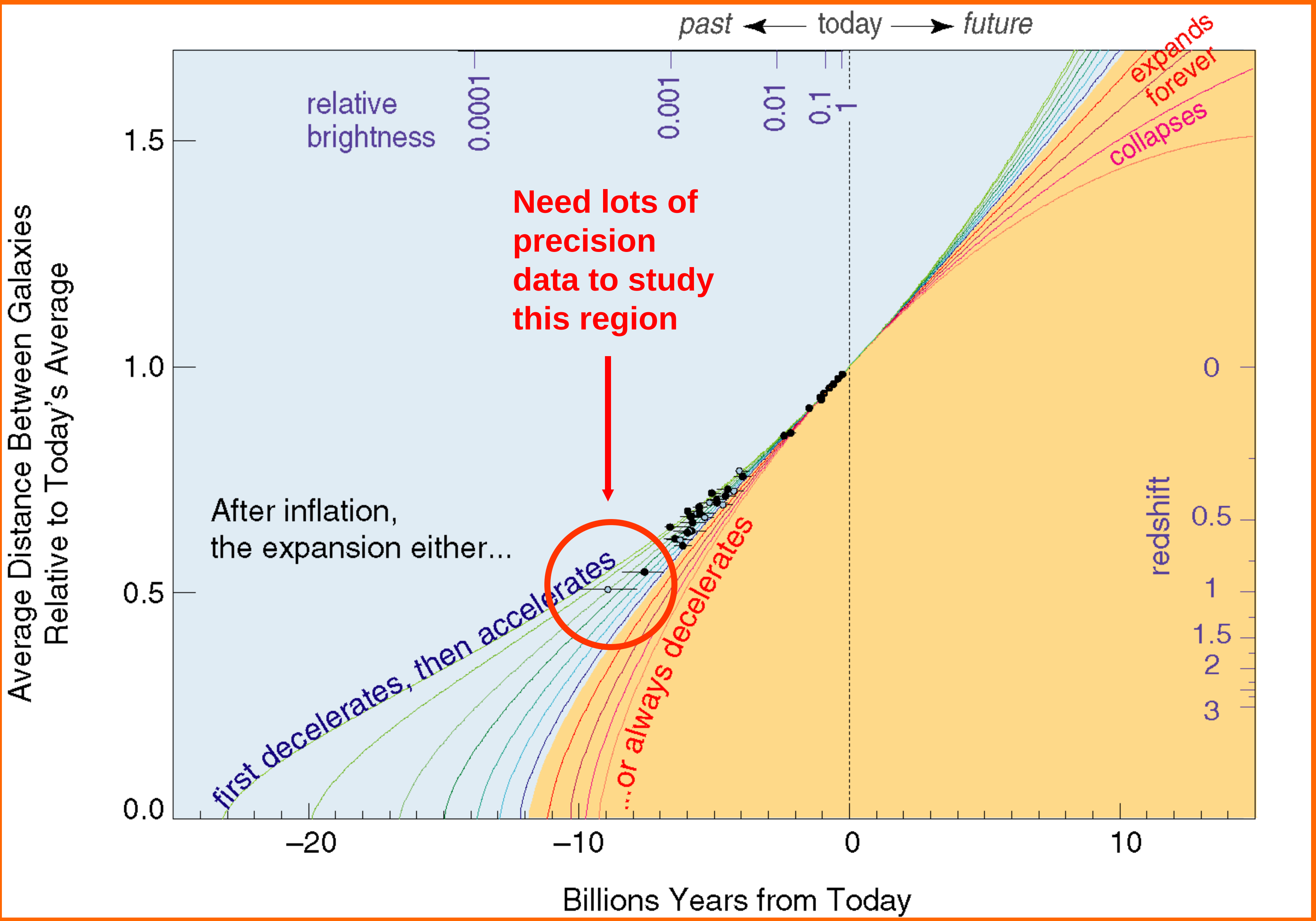


- Nearby supernovae used to study SNe light curve (z<0.1)
- Brightness not quite standard
- Intrinsically brighter SNe last longer
- Correction factor needed



Kim, *et al.* (1997)

The Expansion History of the Universe

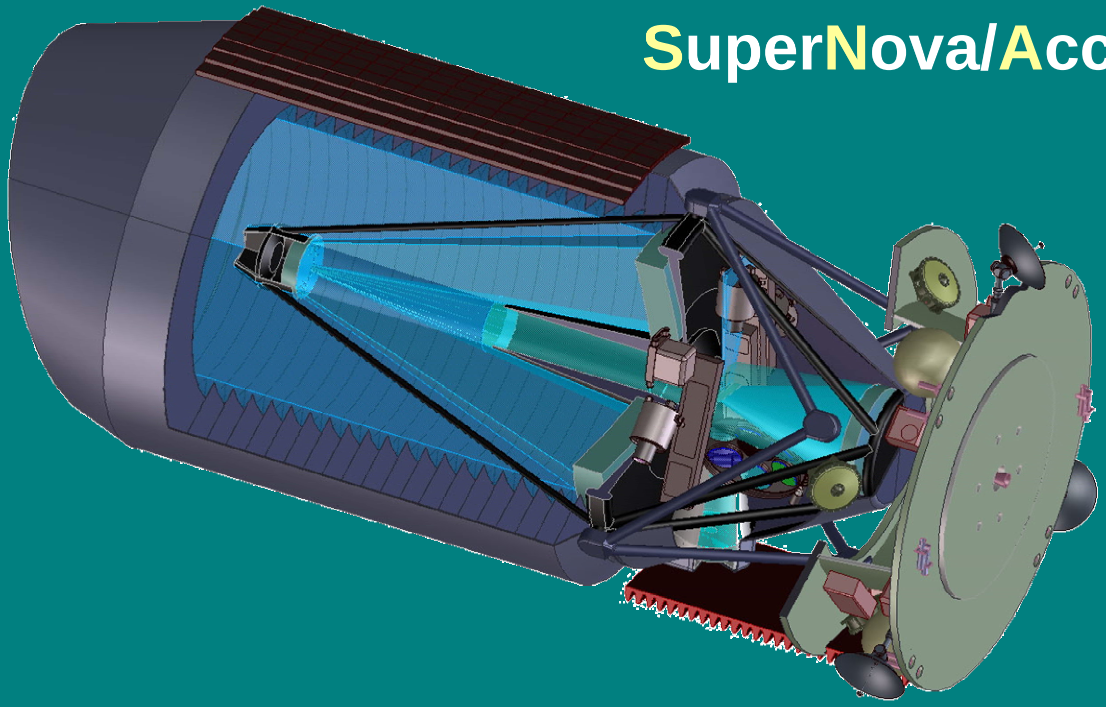


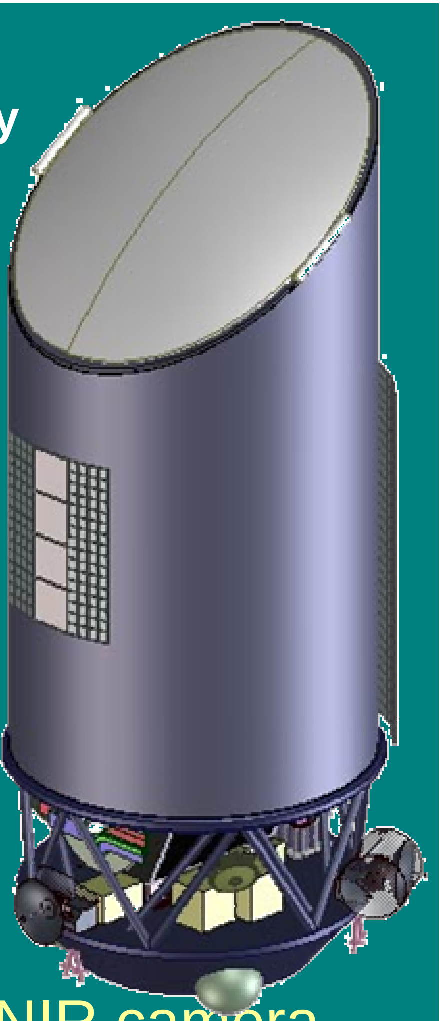
Need lots of precision data to study this region

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

LBNL	G. Aldering, C. Bebek, W. Carithers, C. Day, R. DiGennaro, S. Deustua[†], D. Groom, M. Hoff, S. Holland, D. Huterer[†], A. Karcher, A. Kim, W. Kolbe, W. Kramer, B. Krieger, G. Kushner, N. Kuznetsova, R. Lafever, J. Lamoureux, M. Levi, E. Linder, S. Loken, R. Miquel, P. Nugent, H. Oluseyi[†], N. Palaio, S. Perlmutter, N. Roe, A. Spadafora, H. Von Der Lippe, J-P. Walder, G. Wang
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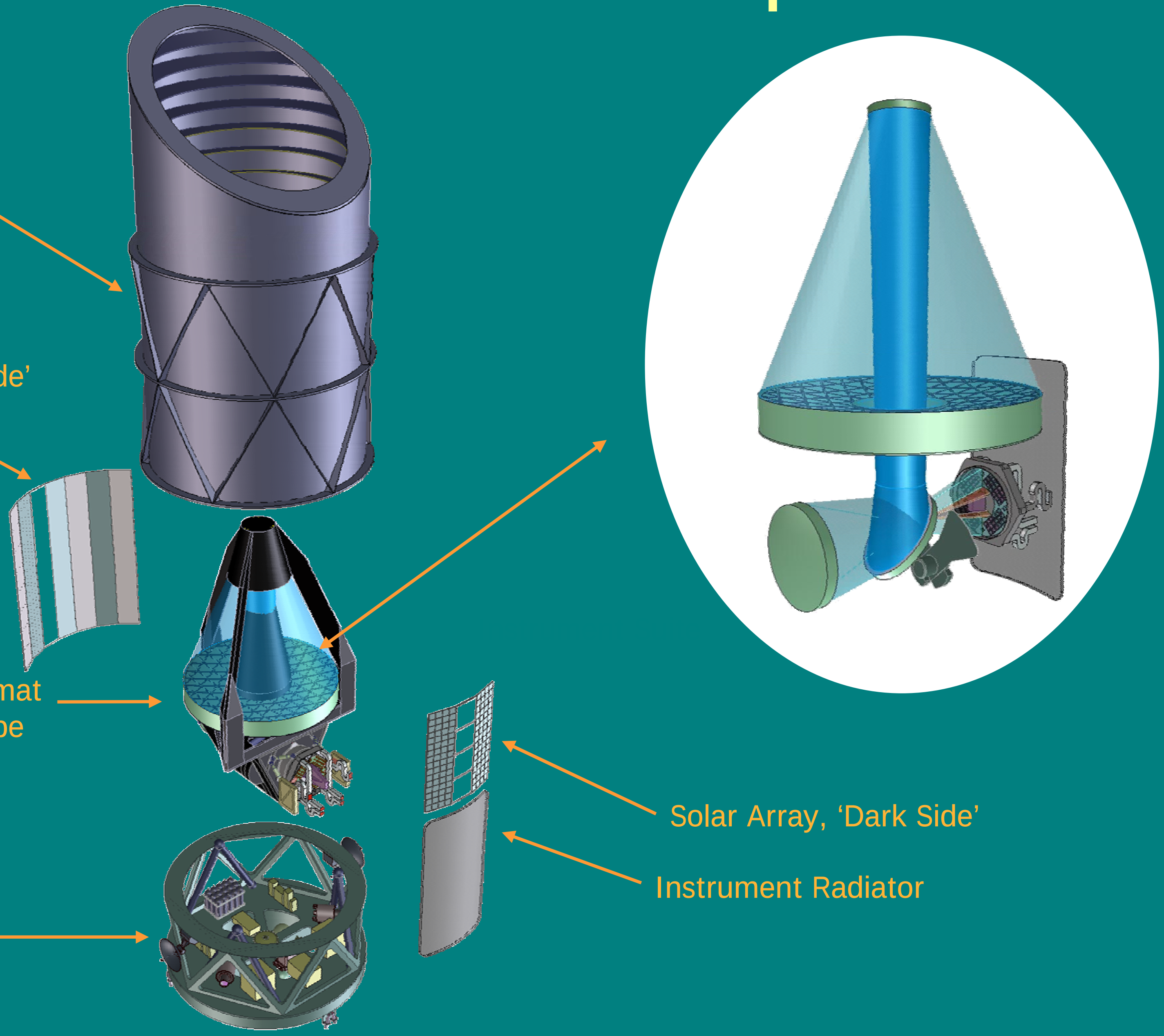
Instrument Concept



Baffled Sun Shade

Solar Array, ‘Sun Side’

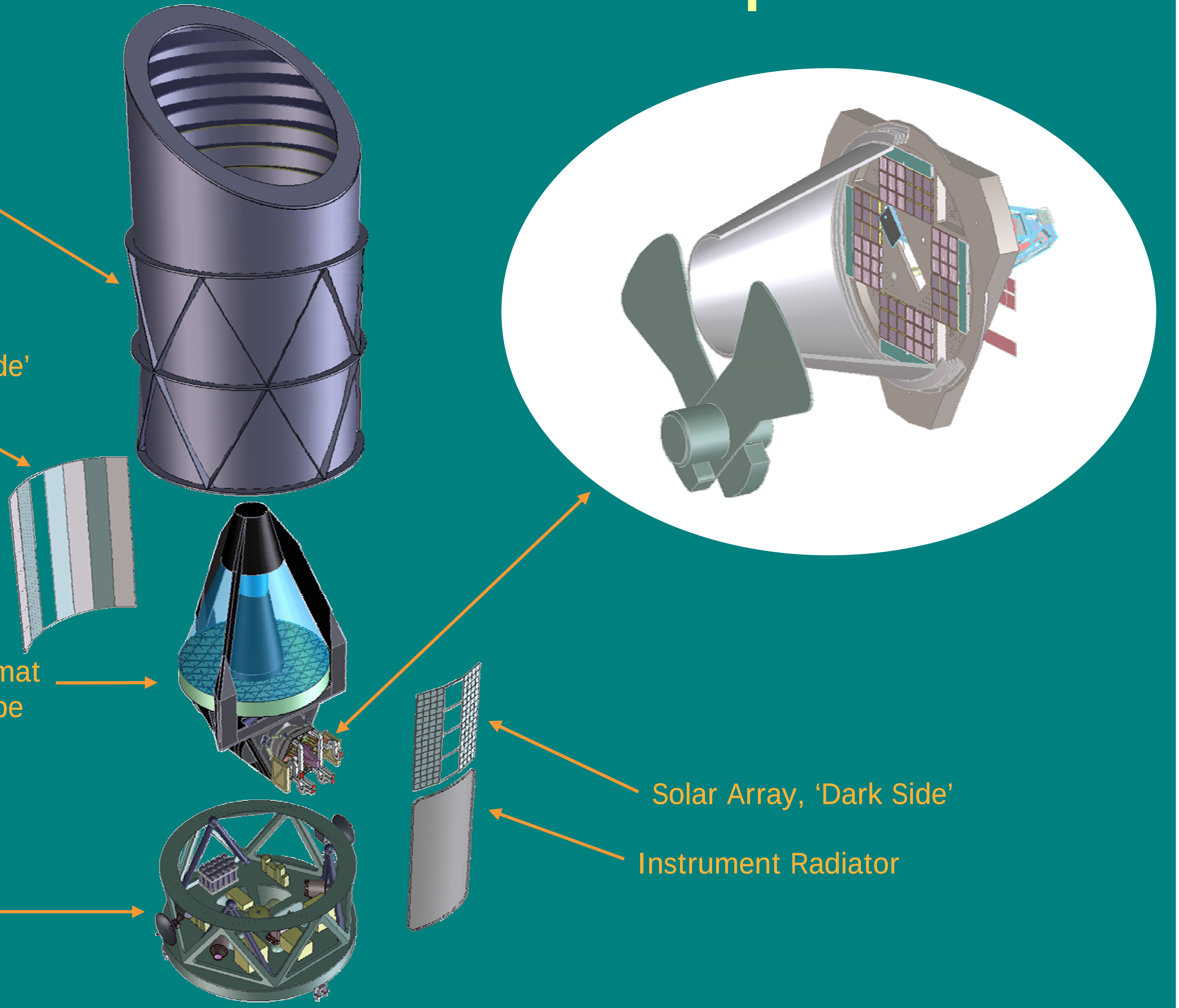
3-mirror anastigmat
2-meter Telescope

Solar Array, ‘Dark Side’

Instrument Radiator

Spacecraft Bus

Instrument Concept



Baffled Sun Shade

Solar Array, ‘Sun Side’

3-mirror anastigmat
2-meter Telescope

Spacecraft Bus

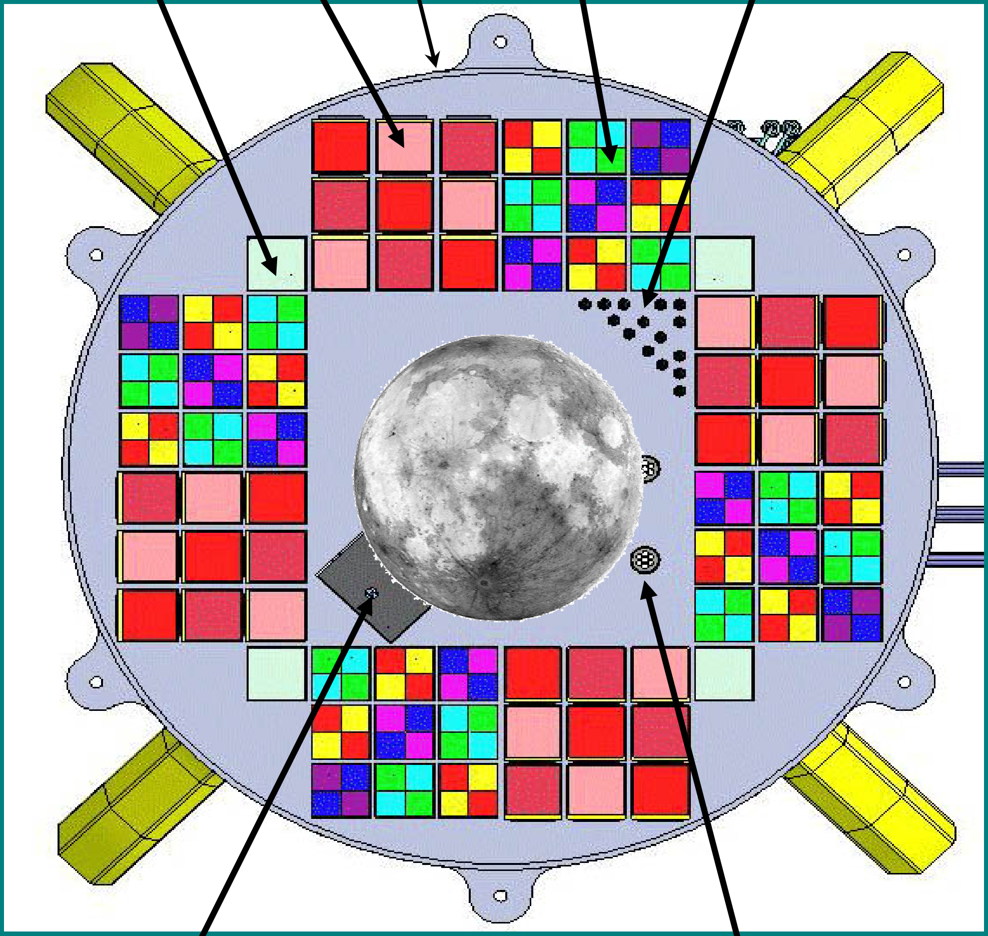
Solar Array, ‘Dark Side’

Instrument Radiator

Focal plane

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

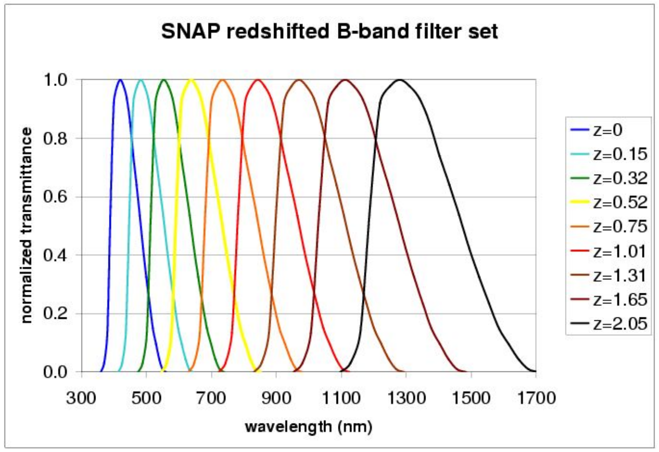
Guider
NIR
Visible
Focus star projectors



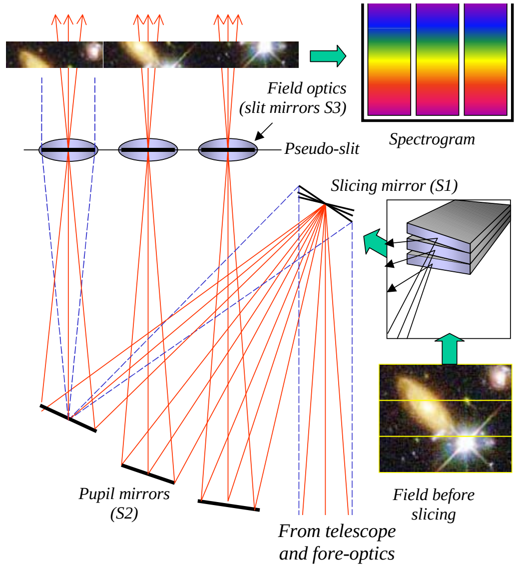
Spectrograph port

Calibration projectors

Fixed filters atop the sensors

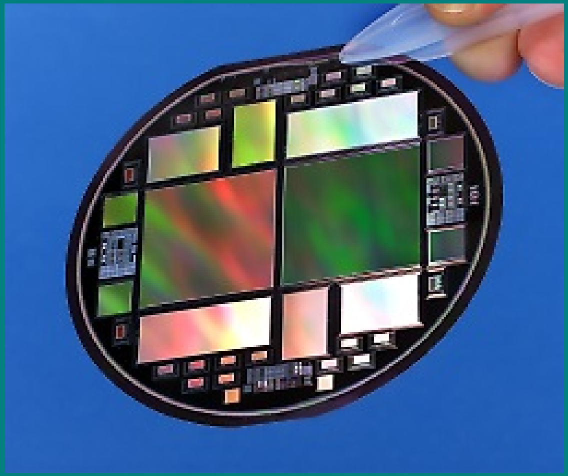


Integral Field Spectrograph



Special "Red-Hot" Visible CCDs for SNAP

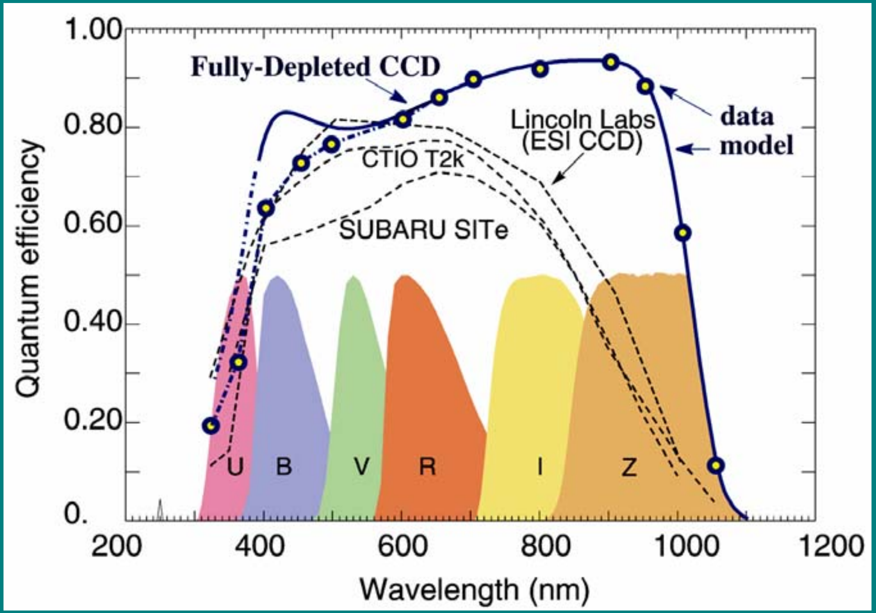
- **New kind of Charged Coupled Device (CCD) developed at Lawrence Berkeley National Lab.**
- **Better overall response than more costly "thinned" devices in use.**
- **High-purity "radiation detector" silicon has better radiation tolerance for space applications.**
- **The CCD's can be abutted on all 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

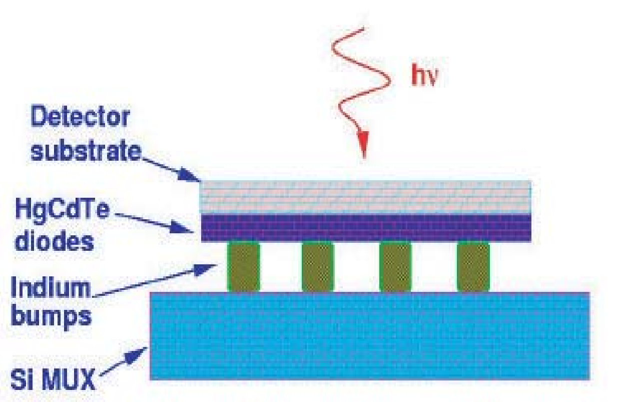
Newsletter 67
September 2001

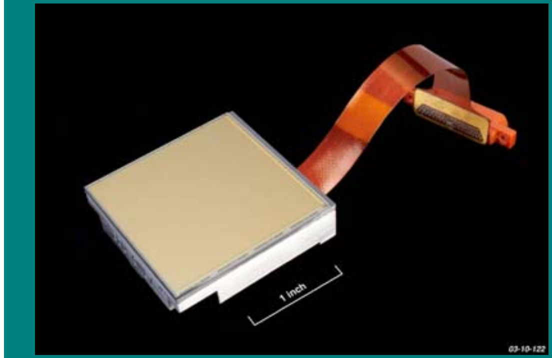


LBNL "Red Hots": NOAO September 2001 newsletter

Near Infrared (NIR) detectors for SNAP

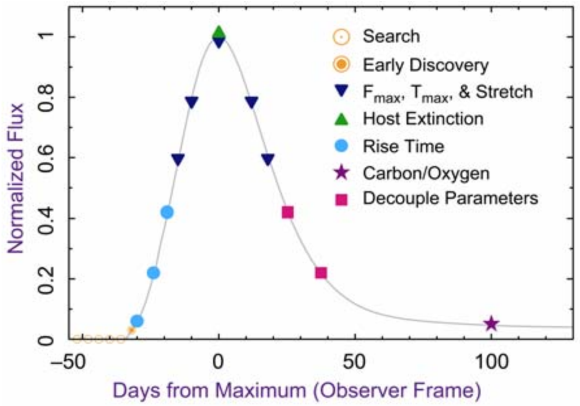
- Large format NIR detectors are a relatively new technology.
- Rockwell Science Center and Raytheon Vision Systems are developing 4 Mpixel (2048 x 2048) NIR focal plane arrays made from HgCdTe (MerCadTel) diodes.
- $Hg_{1-x}Cd_xTe$ composition can be tuned to not “see” long wavelength IR light beyond 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).



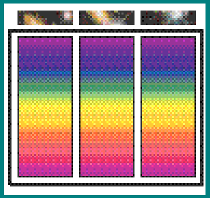


Photometry and Spectroscopy Illustration

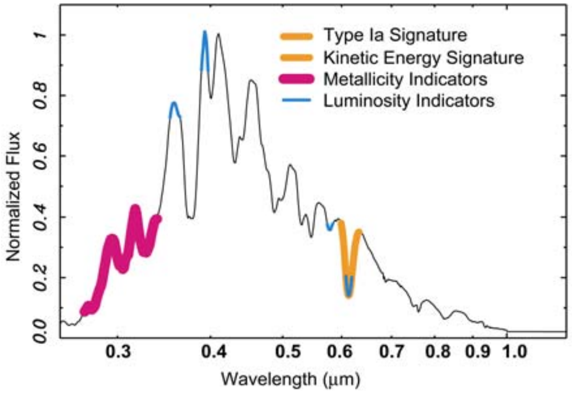
Lightcurve & Peak Brightness



Ω_M and Ω_Λ
Dark Energy
Properties



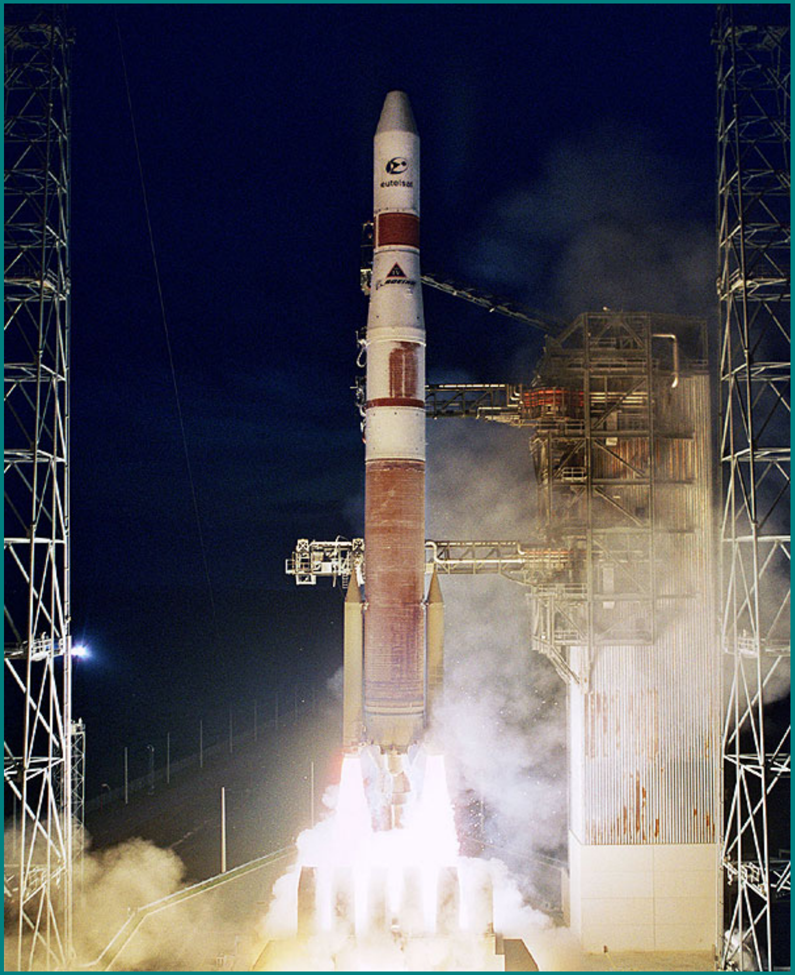
Redshift & SN Properties

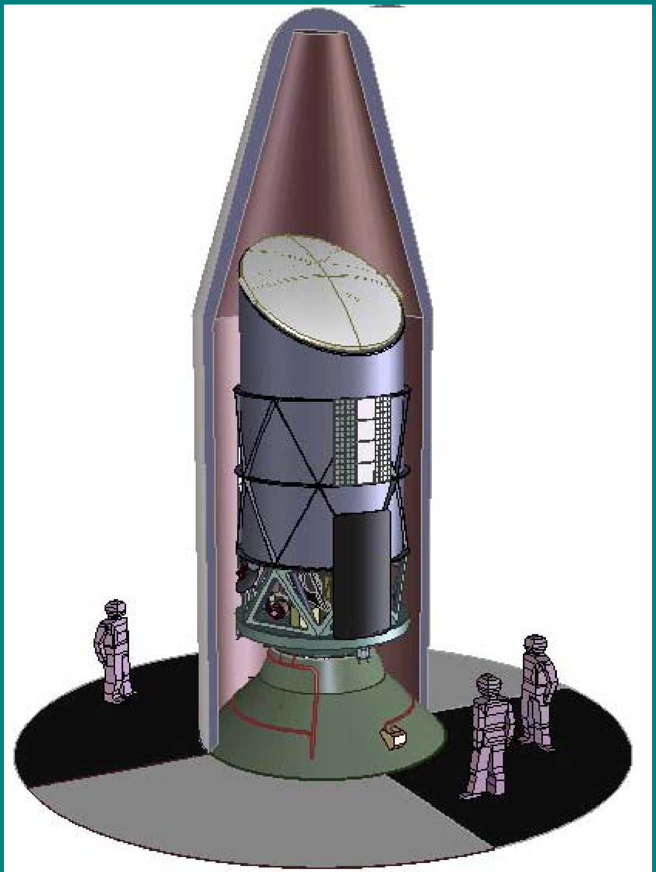


Data → Analysis → Physics

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.





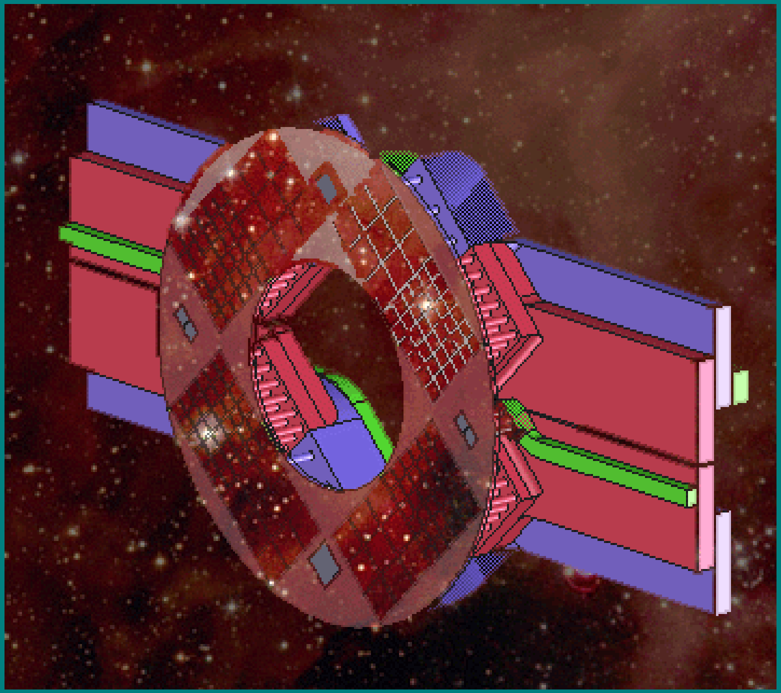
Launch early in the next decade

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 – <u>All</u> Supernovae in <u>all</u> colors

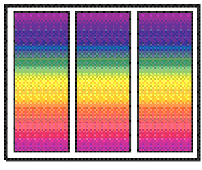
- ➢ Repetitive imaging program (SN discovery and light curve measurement)
  - Observe 15 square degrees every three days in all filters “mowing the sky”.
- ➢ ~50% of time devoted to spectroscopy of individual SNe near maximum light.



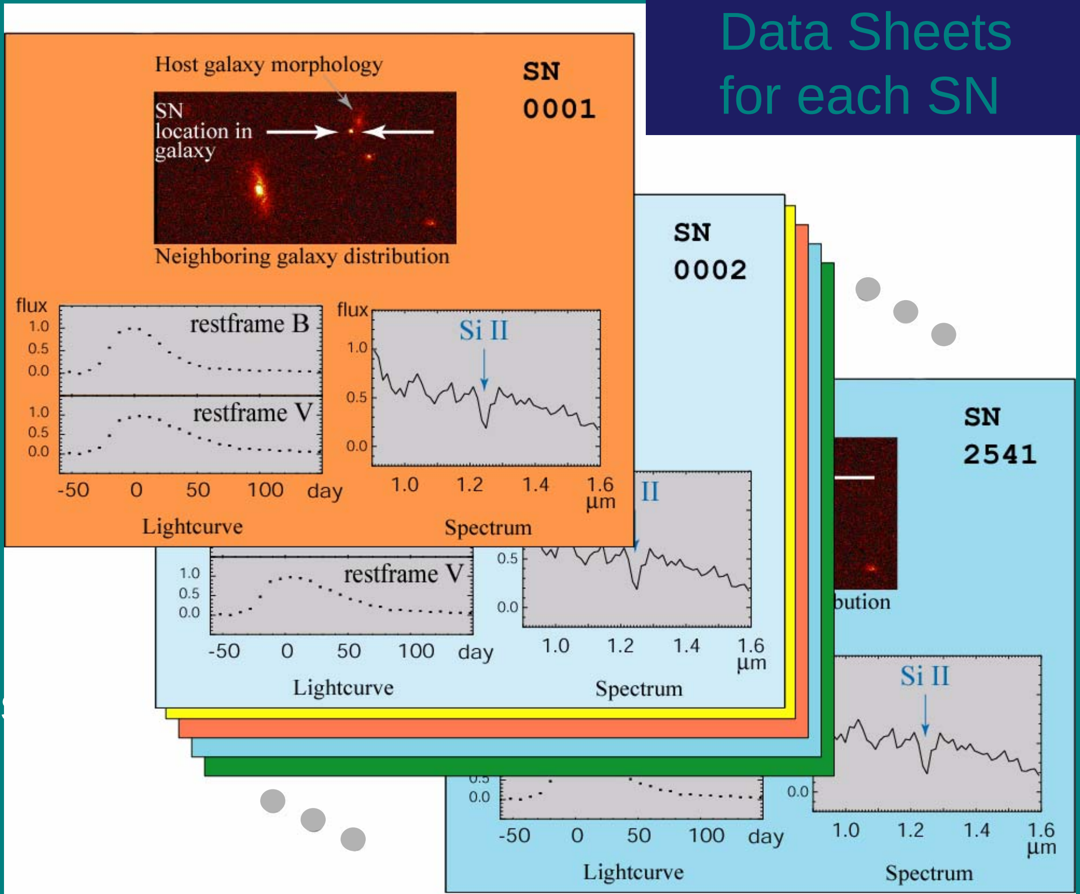
Data Sheets to Cosmological Parameters

Lightcurve &
Peak Brightness

Redshift &
SN Propertie



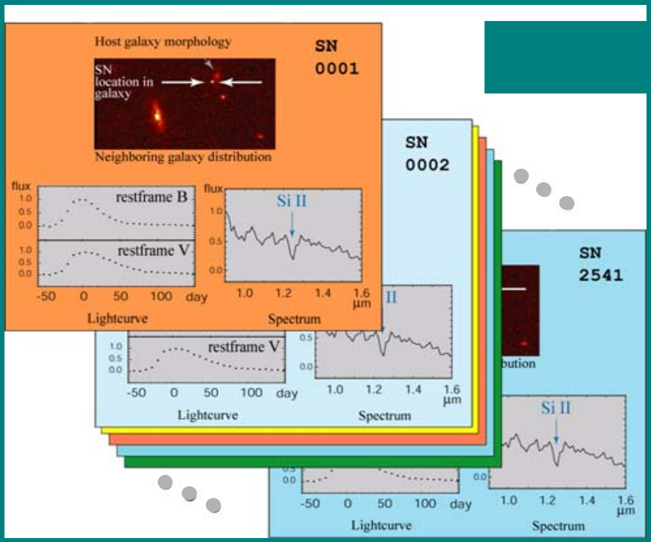
Data Sheets
for each SN

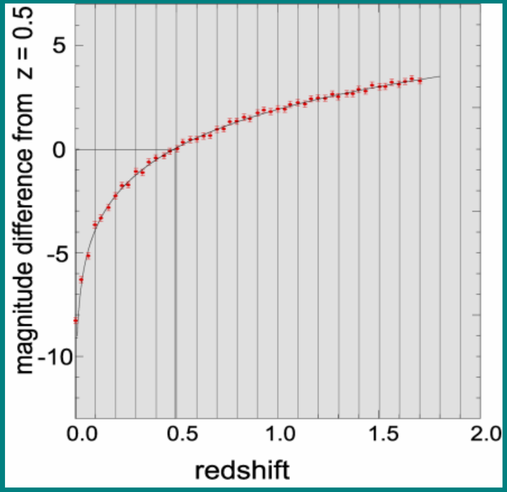


Instrument ⟶ Observed Data

Mission Plan

Data Sheets to Cosmological Parameters

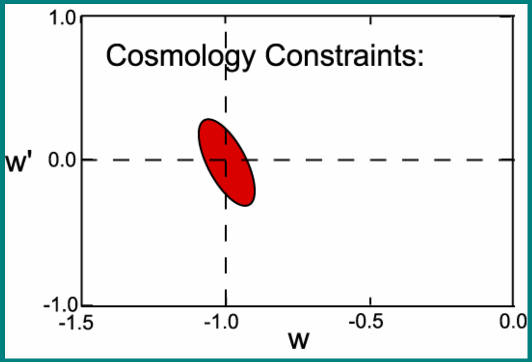




Ω_M and Ω_Λ

Dark Energy Properties

(w_0 and w’)

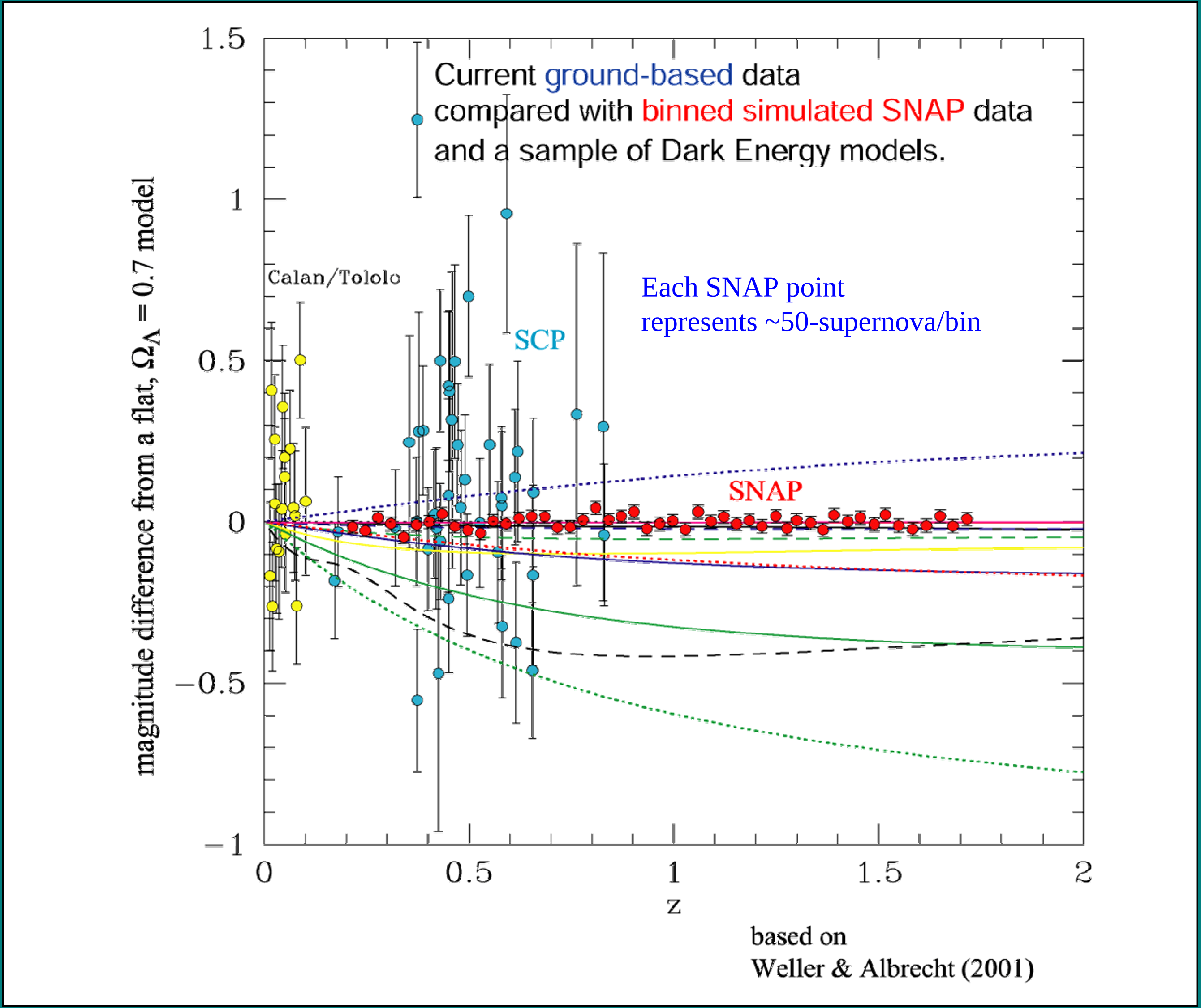


Data → Analysis → Physics

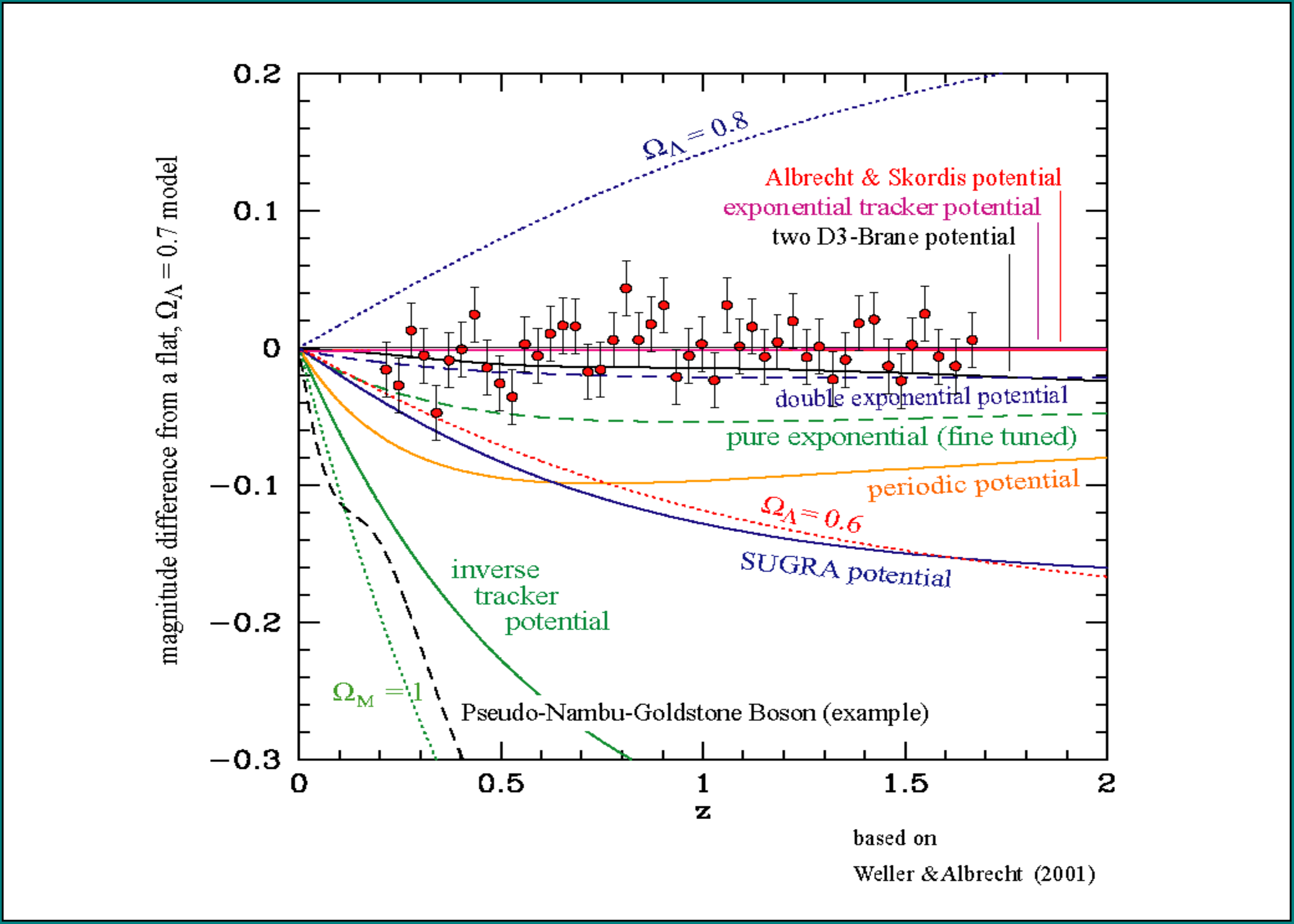
Calibration, External SN Obs.

Priors, External Cosmology

Simulated SNAP Data



Understanding Dark Energy



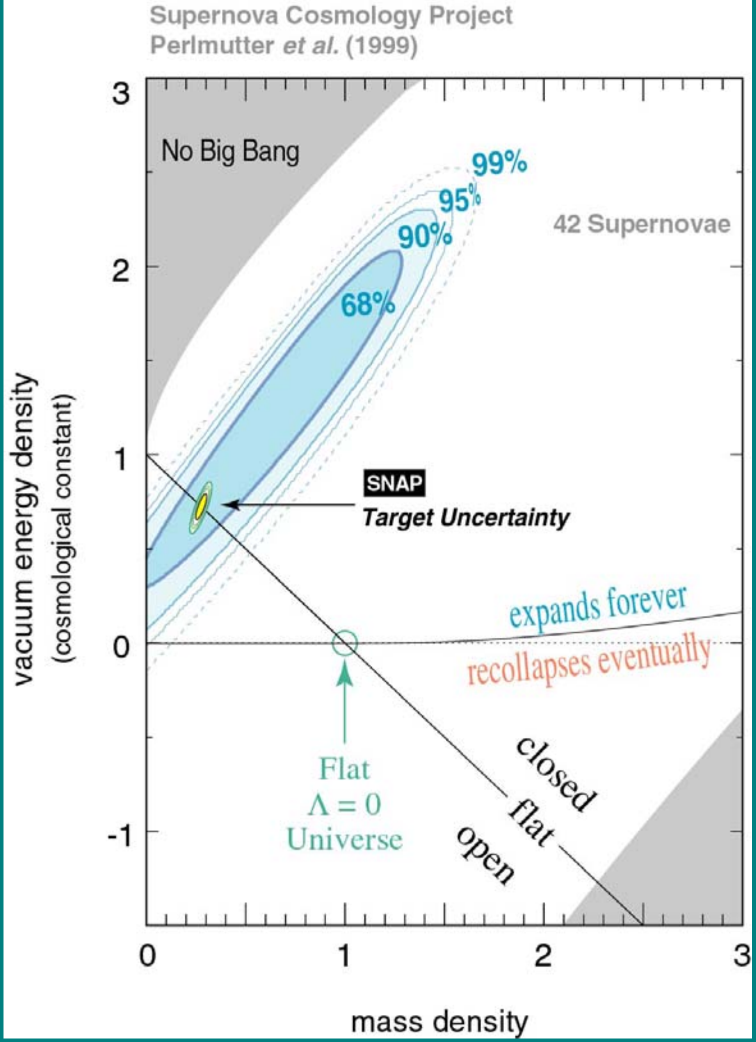
based on

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.



Dark Energy Equation of State

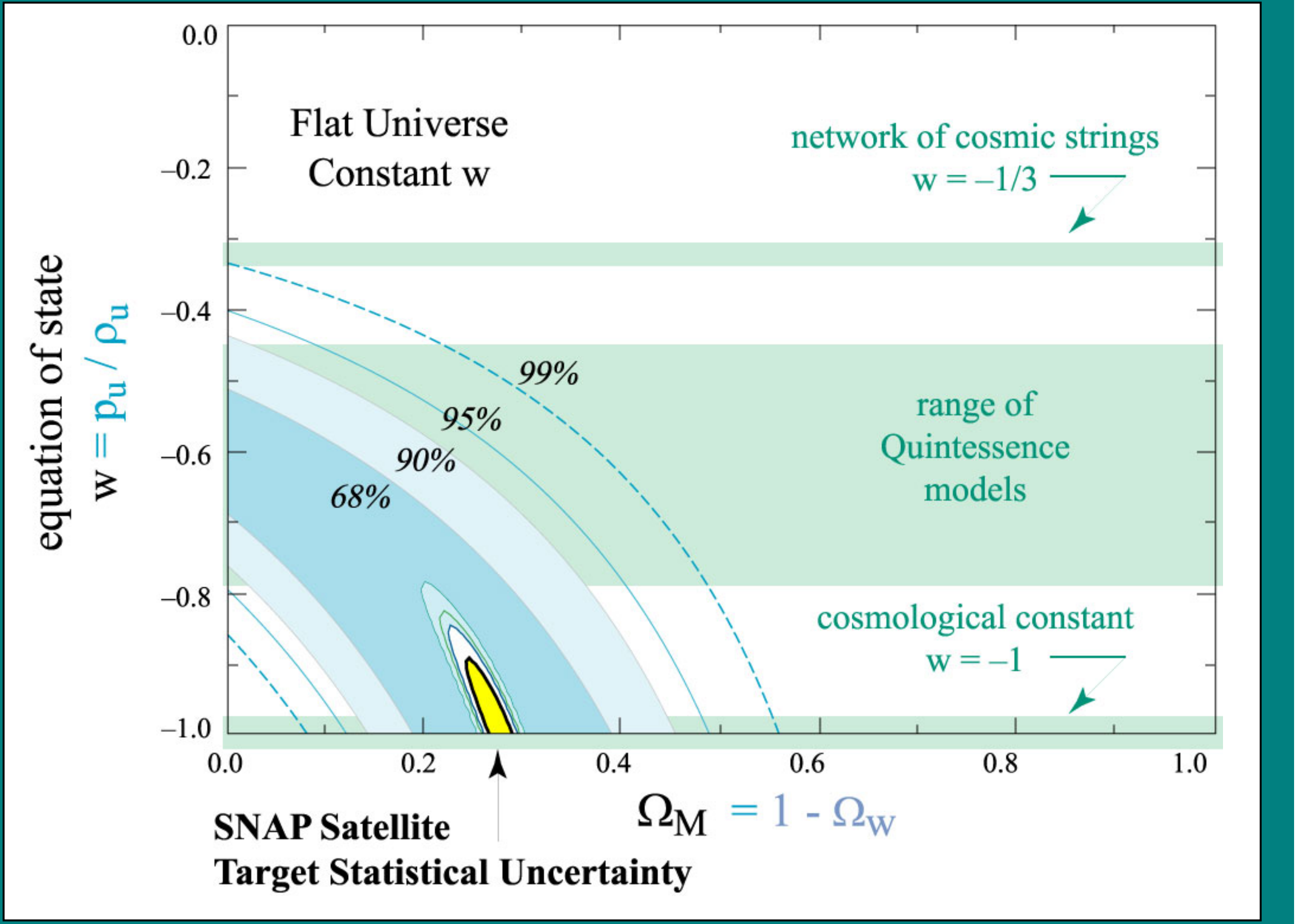
Is w = -1? By measuring the evolution of $w = p/\rho$ to high precision

SNAP will determine the nature of the Dark Energy.

For a flat universe with prior Ω_M measured to ± 0.03, SNAP will measure

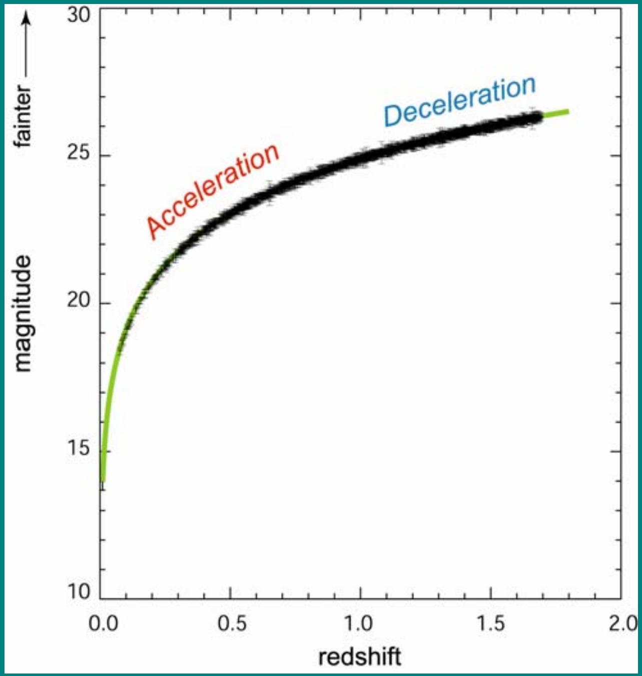
w_0 to ± 0.05 and

w' to ± 0.27.



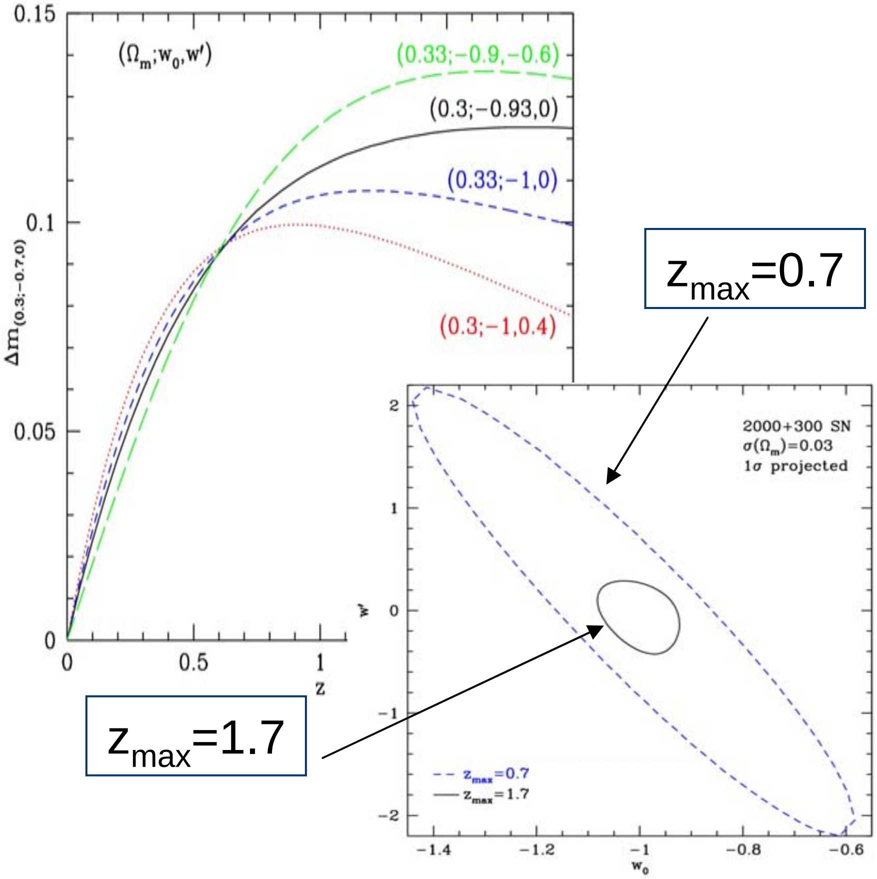
Why go to high redshifts?

- **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

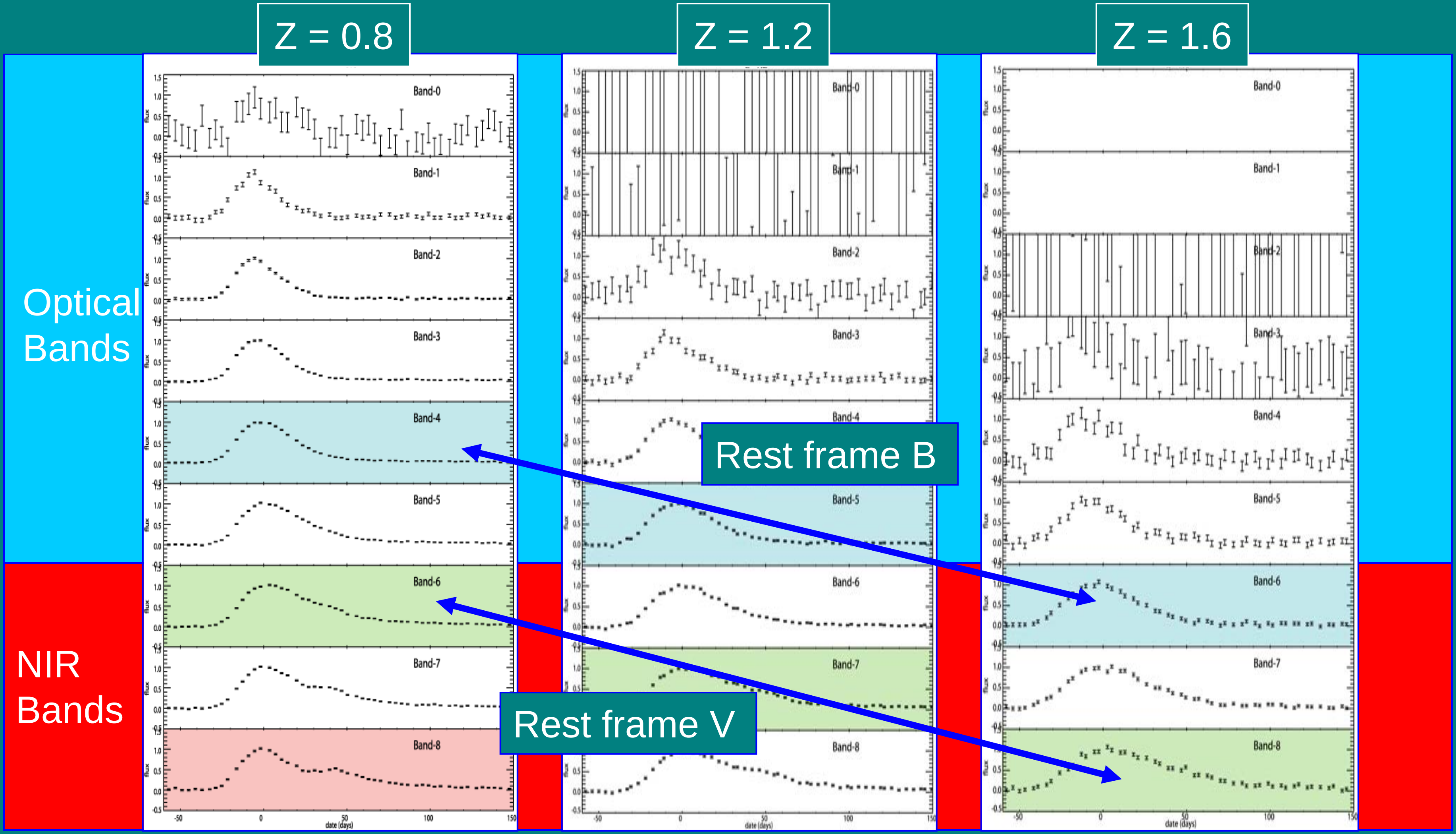
- ✓ probe the variability of w, providing an essential clue to the nature of DE.
- ✓ measure w_0 precisely to determine whether it is a cosmological constant.



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

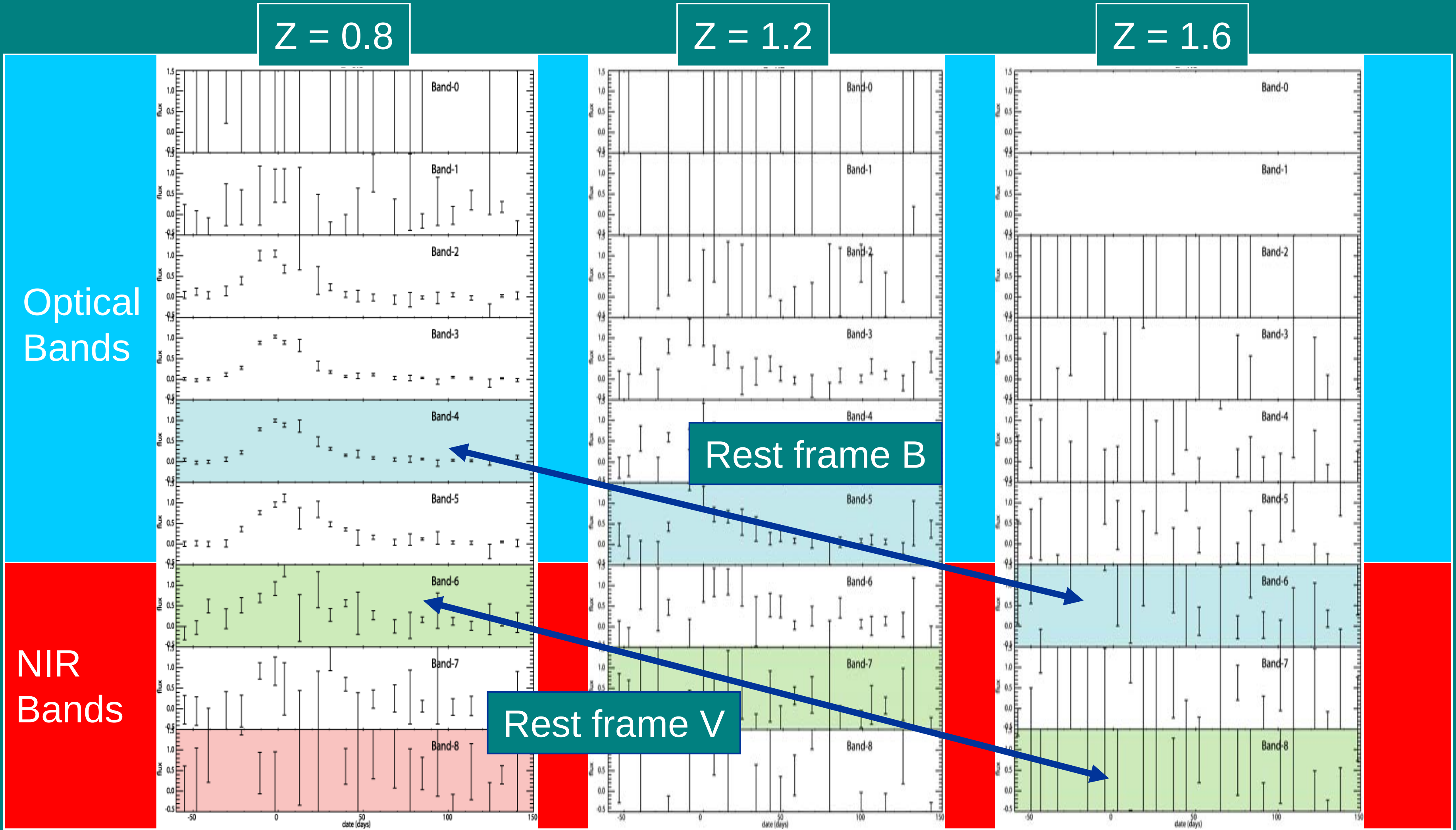
NIR Bands

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

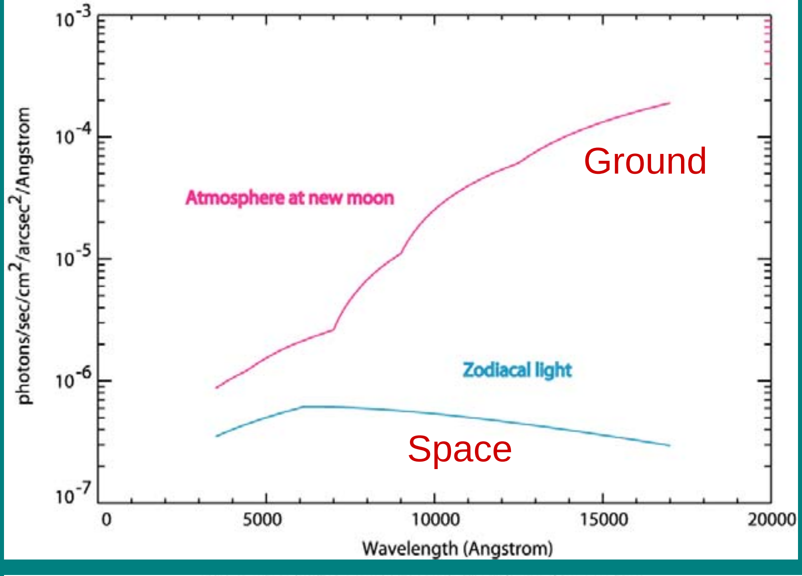
Rest frame V

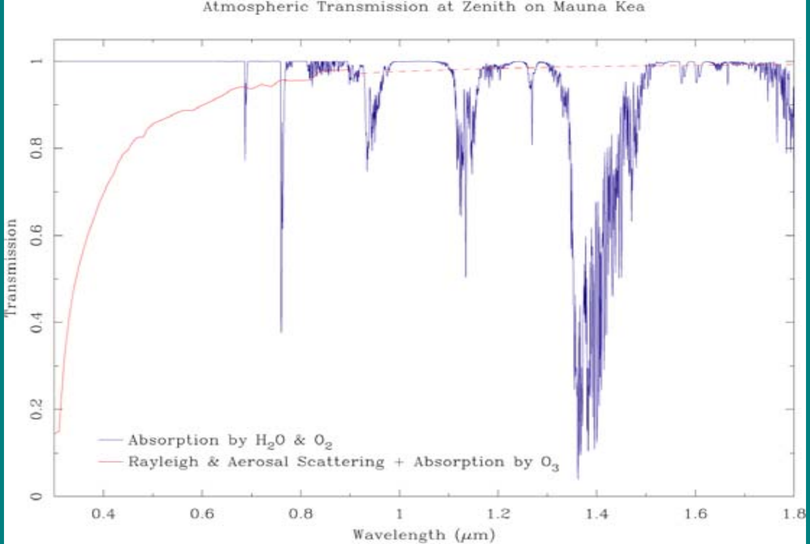
Simulated 8m telescope ground based observations of high redshift SNe

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
- 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

NIR fixes these

Beyond Dark Energy

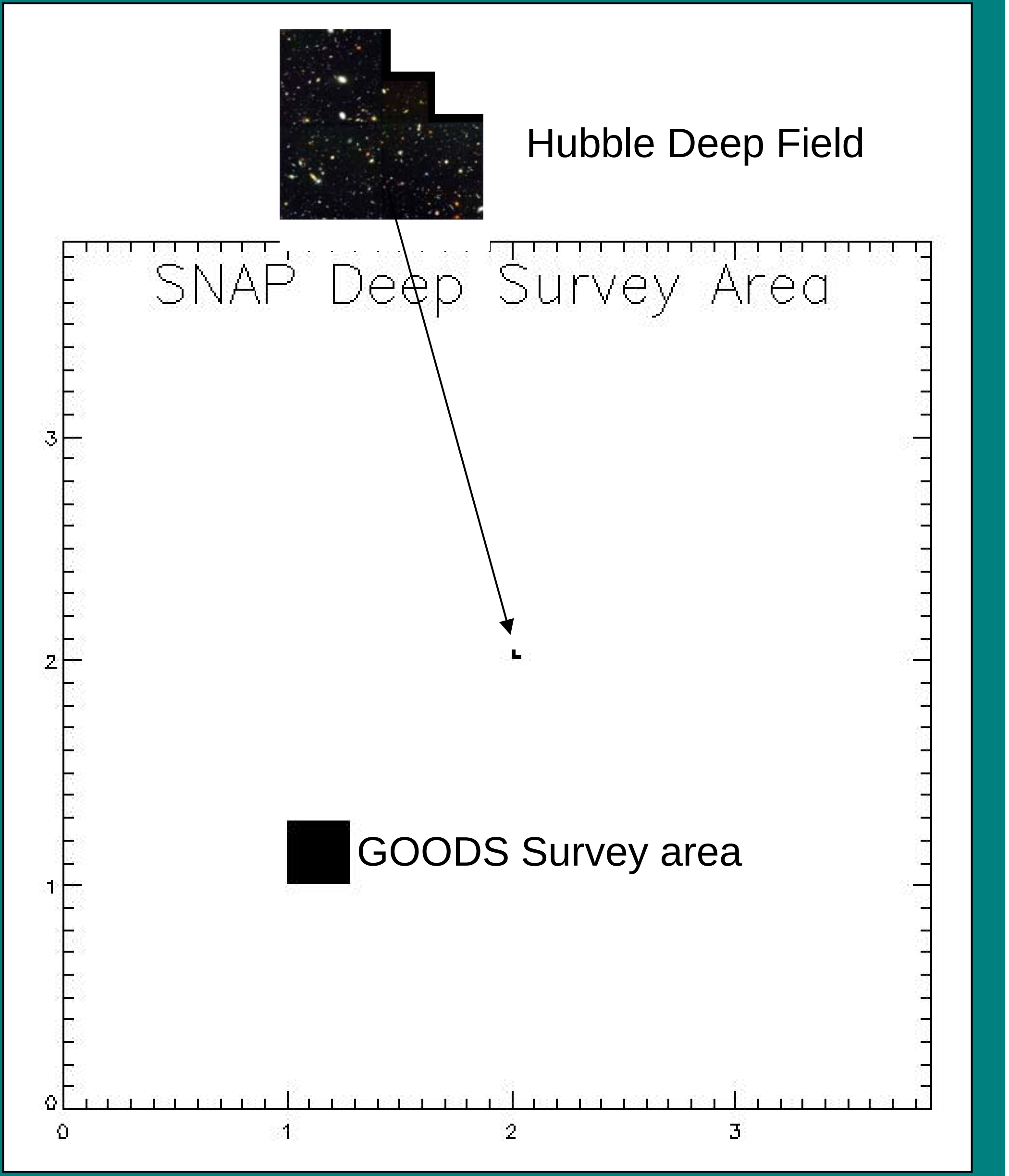
1. Galaxy studies: evolution and clustering.
2. Galaxy clusters: identification of high redshift galaxy clusters, faint and small constituents
3. High-z quasar studies: mapping quasars to z = 10, probing the re-ionization of the universe.
4. Transients; Gamma Ray Bursts, Quasars/Active Galactic Nuclei, 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…

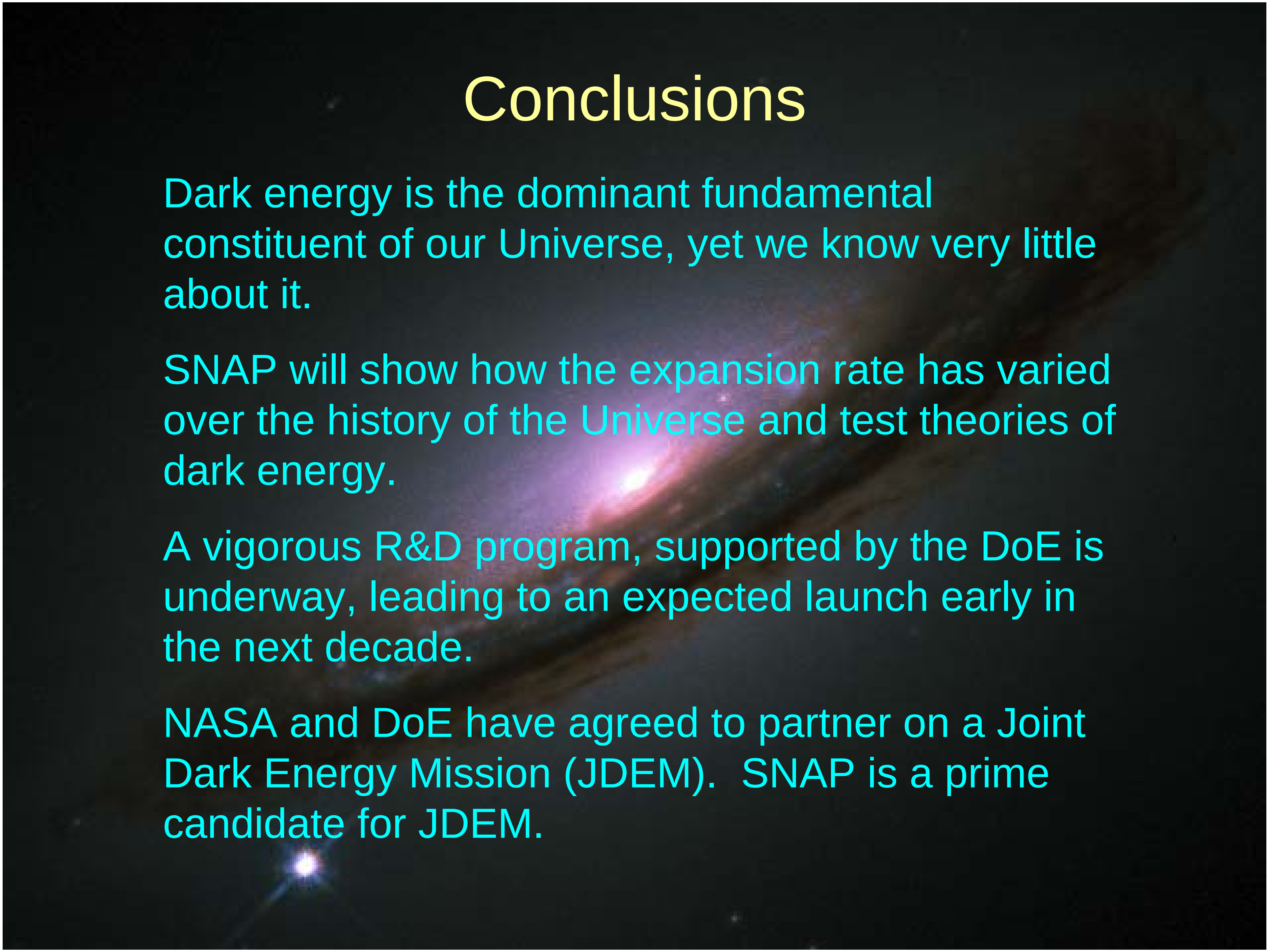
SNAP Observation Program

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