Physics 390
Winter 2006

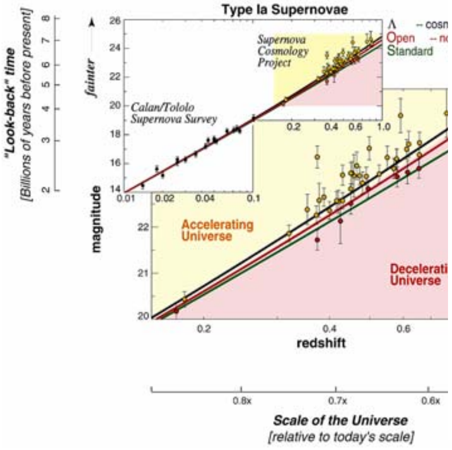
Introduction to Cosmology II

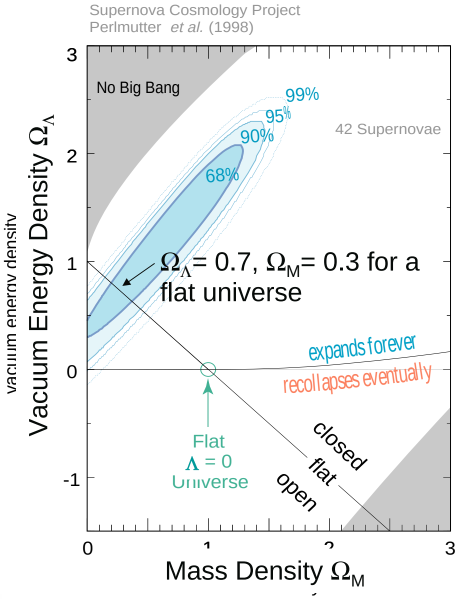
Recap from last lecture

- The universe is expanding since its launch 13.7 By ago (the Big Bang)?
- Three pillars of Big Bang cosmology
  - The Hubble expansion
  - The 3K Cosmic Microwave Background Radiation
  - Big Bang Nucleosynthesis $\Omega_B = 0.045$
- Problems (solved by inflation with $\Omega_{Tot} = 1$)
  - Horizon problem
  - Flatness problem
- Dark matter present on all scales but only $\Omega_M = 0.3$, not enough to flatten the universe!

A Startling Discovery

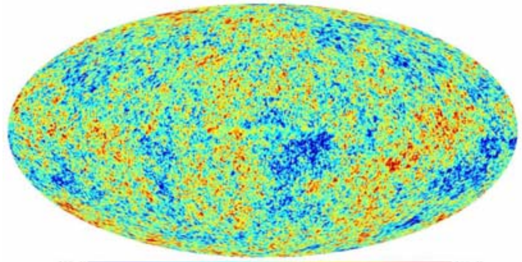
In 1998 the Supernova Cosmo
Supernova team used Type Ia
candles" to construct a Hubble
found that the expansion of the

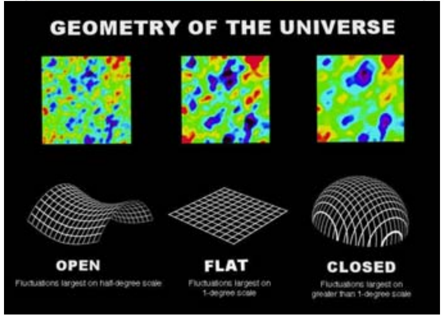




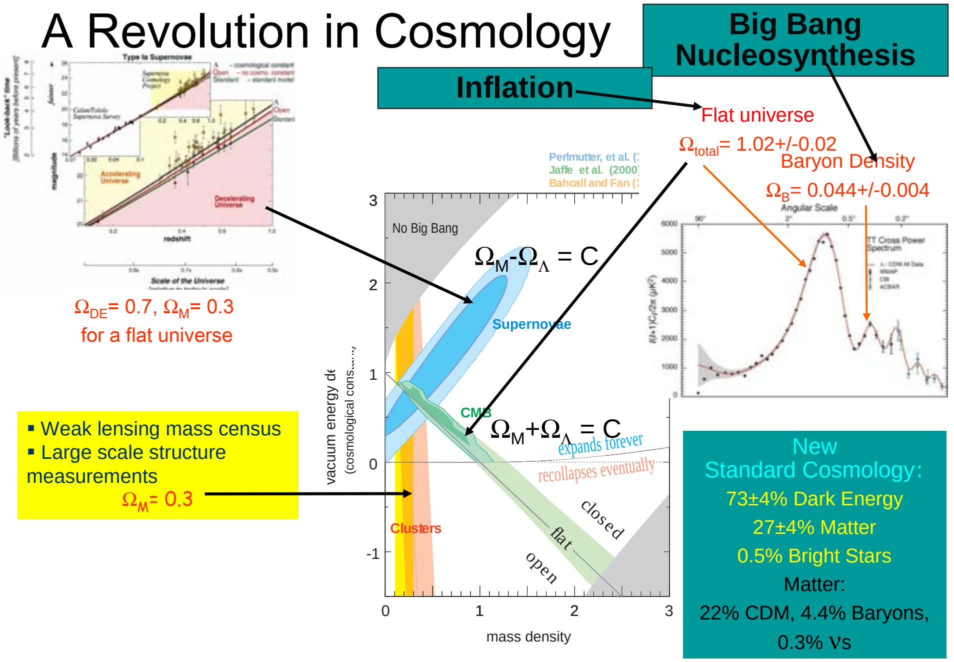
Fluctuations in the CMBR

- Within the last 1.5 years the Wilkinson Microwave Anisotropy Probe (WMAP) has measured fluctuations in the CMBR on angular scales as fine as 0.1°.
- The hot and cold spots correspond to regions of high and low density at the time of recombination.
- The dominant angular scale is sensitive to the geometry of the universe.
- They conclude that the universe is flat.
  Ω_{total}= 1.02+/-0.02





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

Ω_M-Ω_Λ = C

Ω_M+Ω_Λ = C

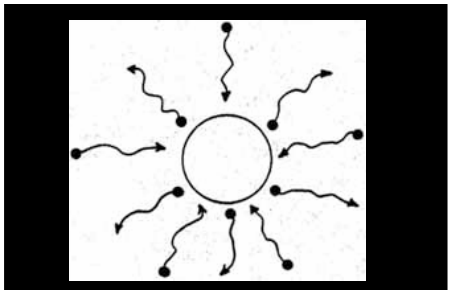
- Weak lensing mass census
- Large scale structure measurements

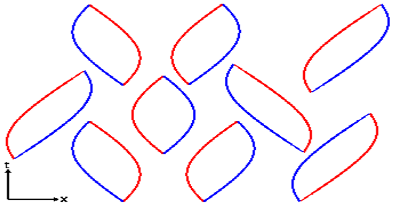
Ω_M= 0.3

New
Standard Cosmology:
73±4% Dark Energy
27±4% Matter
0.5% Bright Stars
Matter:
22% CDM, 4.4% Baryons,
0.3% νs

Vacuum Energy

- Virtual particles are a basic part of Quantum Field Theory.
- Virtual particles can be created out of nothing as long as Heisenberg's Uncertainty Principle ΔEΔt > ħ is not violated.
- You can create particle-antiparticle pairs $\Delta E = 2mc^2$ from nothing as long as the energy is paid back in a time Δt which is short enough: $\Delta t < \hbar /(2mc^2)$
- Elementary particles "polarize" the vacuum around them and are thus surrounded by a "cloud" of virtual particles that affect the properties (mass, charge…) that we measure.





Vacuum Energy

Implications:

- The vacuum is not empty! It is teaming with virtual particle pairs.
- In principle, empty space can have an energy density associated with it.
- Reality check: We have no idea how to calculate this vacuum energy.

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 and the energy content 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.

The Fluid Equation

- Conservation of energy in a comoving volume
- Time derivative

$$\dot{E} + P\dot{V} = 0$$

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi (ra)^3$$

$$\dot{V} = \frac{4\pi}{3} r^3 (3a^2\dot{a}) = V\left(3\frac{\dot{a}}{a}\right)$$

$$E = V\varepsilon$$

$$\dot{E} = V\dot{\varepsilon} + \dot{V}\varepsilon = V\left(\dot{\varepsilon} + 3\frac{\dot{a}}{a}\varepsilon\right)$$

- Subst. E-Cons. Eq.

$$V\left(\dot{\varepsilon} + 3\frac{\dot{a}}{a}\varepsilon + 3\frac{\dot{a}}{a}P\right) = 0$$

- The Fluid Eq.

$$\dot{\varepsilon} + 3\frac{\dot{a}}{a}(\varepsilon + P) = 0$$

Acceleration Equation

- a^2 (Friedmann Eq.)

$$\dot{a}^2 = \frac{8\pi G}{3c^2}\varepsilon a^2 - \frac{\kappa c^2}{R_0^2}$$

- Time derivative

$$2\dot{a}\ddot{a} = \frac{8\pi G}{3c^2}\left(\dot{\varepsilon}a^2 + 2\varepsilon a\dot{a}\right)$$

- Divide by $2a\dot{a}$

$$\frac{\ddot{a}}{a} = \frac{4\pi G}{3c^2}\left(\dot{\varepsilon}\frac{a}{\dot{a}} + 2\varepsilon\right)$$

- Subst. Fluid Eq.

$$\dot{\varepsilon}\frac{a}{\dot{a}} = -3\left(\varepsilon + P\right)$$

- Acceleration Equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}\left(\varepsilon + 3P\right)$$

Evolution of energy density

- Conservation of energy in a co-moving volume

$$d\left(\varepsilon R^3\right) = -p\,d\left(R^3\right)$$

- Equation of state *w*

$$w \equiv \frac{p}{\varepsilon}$$

$$d\ln\left(\varepsilon\right) = -3(1+w)\,d\ln R$$

$$\varepsilon \propto \exp\left[-3\int (1+w)\,d\ln R\right]$$

- If *w* is indep. of *t* $\quad \varepsilon \propto R^{-3(1+w)}$
- Radiation $\quad p = \frac{\varepsilon}{3}, w = \frac{1}{3}, \quad \varepsilon \propto R^{-4}$
- Matter $\quad p = 0, w = 0, \quad \varepsilon \propto R^{-3}$
- Vacuum energy $\quad p = -\varepsilon, w = -1, \quad \varepsilon \propto const$

Who Ordered That?!

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

- ***Why so small?***

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

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 me, why now? Why, why, why" Nancy Kerrigan (1994)***

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

MATTER: $\quad p = 0 \longrightarrow \rho \propto R^{-3}$

VACUUM ENERGY: $\quad p = -\rho \longrightarrow \rho \propto constant$

New Physics: "Dark energy":

Dynamical scalar fields, "quintessence",...

General Equation of State:

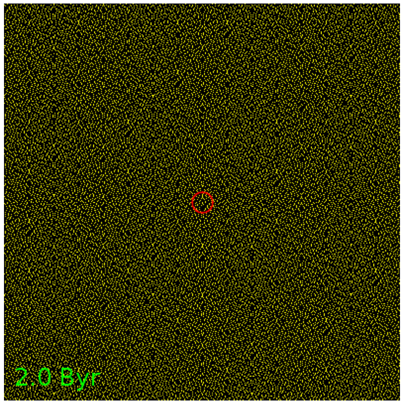
$$p = w\rho \longrightarrow \rho \propto R^{-3(1+w)}$$

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.

Acceleration and Deceleration Epochs



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!

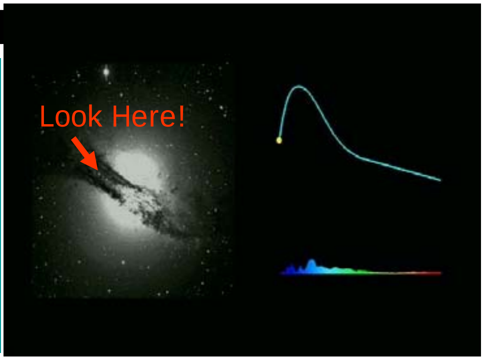
What is the “dark energy?” Theorists have proposed a number of possibilities each with its own unique w(t):

- 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: T

- 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.

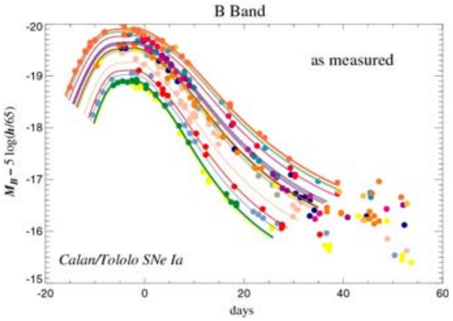
Comparison of SN Ia redshifts and magnitudes provides straightforward measurement of the changing rate of expansion of the universe:

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

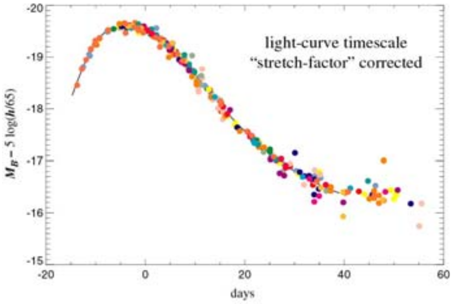
☑ Analysis of the spectra characterizes the details of the explosion and helps to control potential systematic errors.

Observation of a Supernova

“Standard” Candles

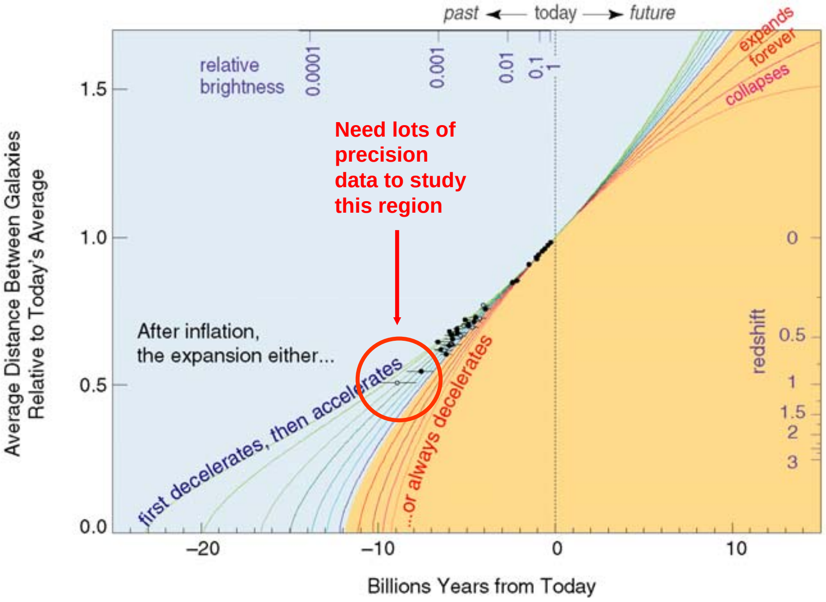


- ➢Nearby supernovae used to study SNe light curve (z<0.1)
- ➢Brightness not quite standard
- ➢Intrinsically brighter SNe last longer
- ➢Correction factor needed



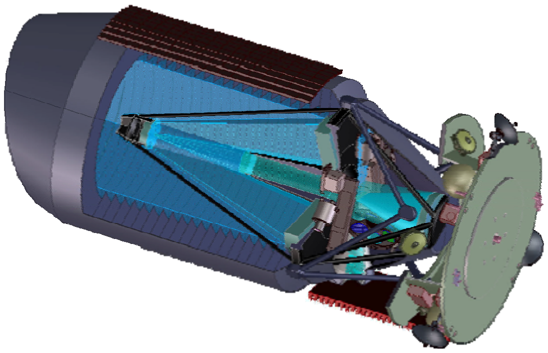
Kim, *et al.* (1997)

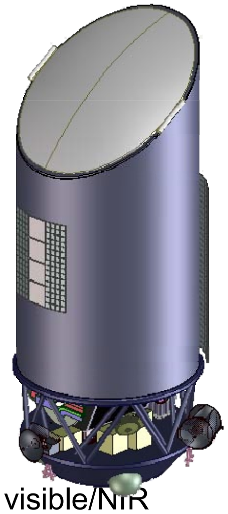
The Expansion History of the Universe



Need lots of precision data to study this region

It’s a SNAP!





A large wide-field space telescope with a 0.6 Gpixel visible/NIR imager and a visible/NIR spectrograph will provide:

- a much larger statistical sample of supernovae (~2000 SNe with ~50 SNe/0.03 z).
- much better controlled systematic errors (1 – 2%).
- a much larger range of redshifts (out to z = 1.7) that cannot be obtained with any existing or planned facilities.

The SNAP Collaboration

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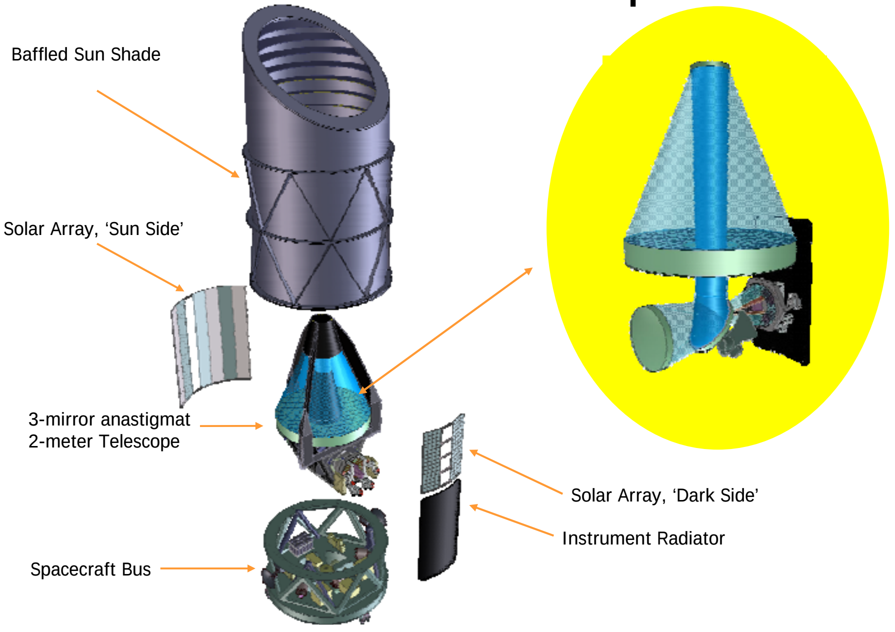
Instrument Concept



Baffled Sun Shade

Solar Array, 'Sun Side'

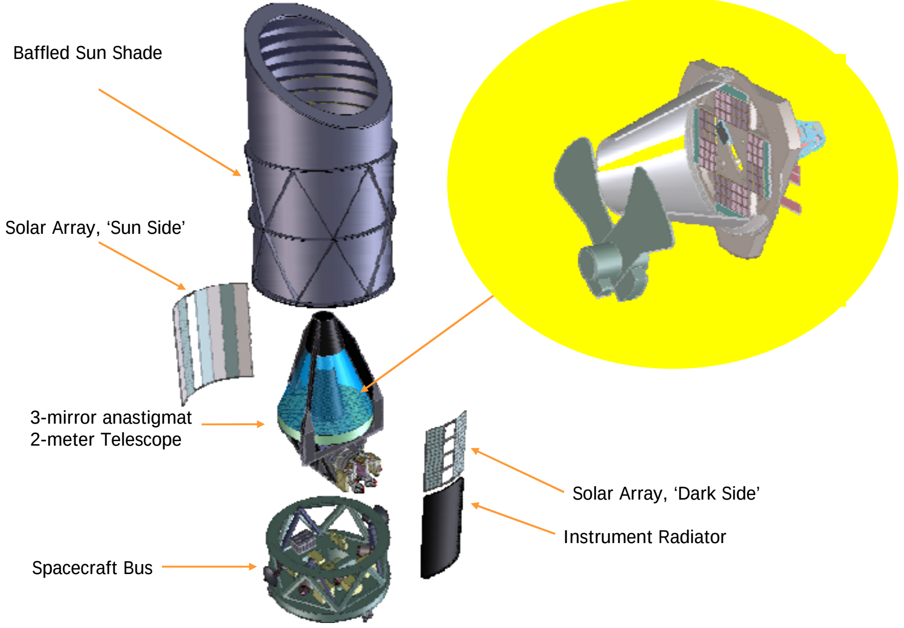
3-mirror anastigmat
2-meter Telescope

Solar Array, 'Dark Side'

Instrument Radiator

Spacecraft Bus

Instrument Concept



Baffled Sun Shade

Solar Array, 'Sun Side'

3-mirror anastigmat
2-meter Telescope

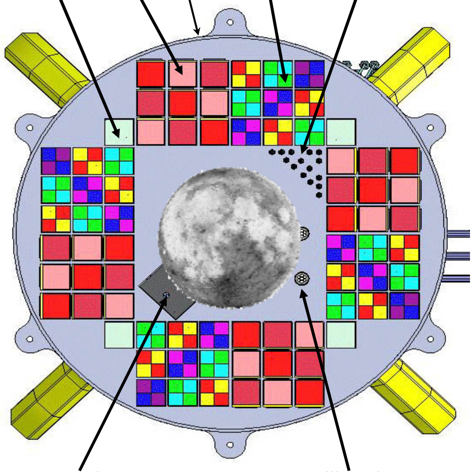
Solar Array, 'Dark Side'

Instrument Radiator

Spacecraft Bus

Focal plane

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



Guider

NIR

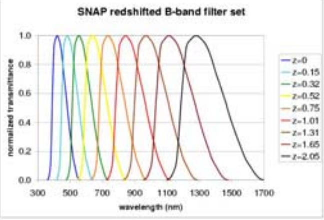
Visible

Focus star projectors

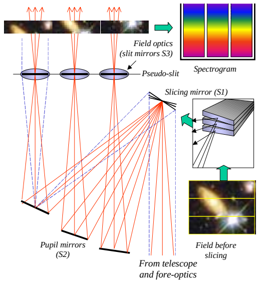
Spectrograph port

Calibration projectors

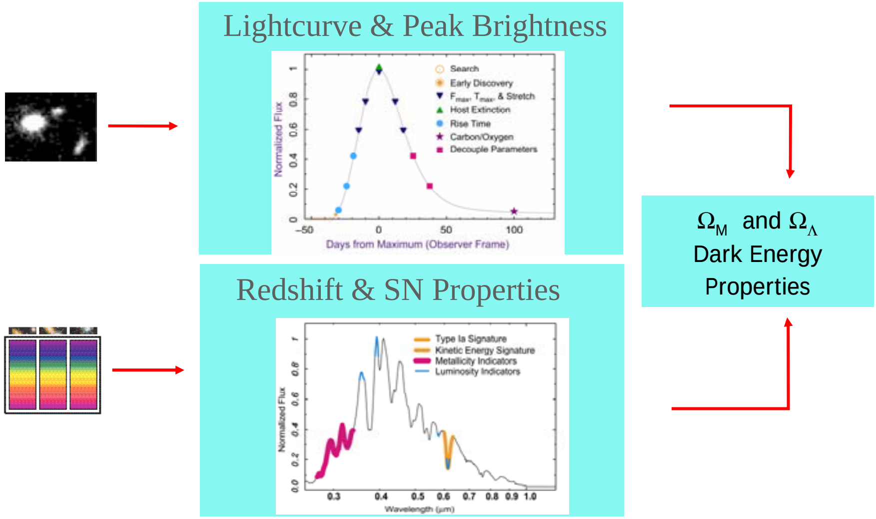
Fixed filters atop the sensors



Integral Field Spectrograph



Photometry and Spectroscopy Illustration



Lightcurve & Peak Brightness

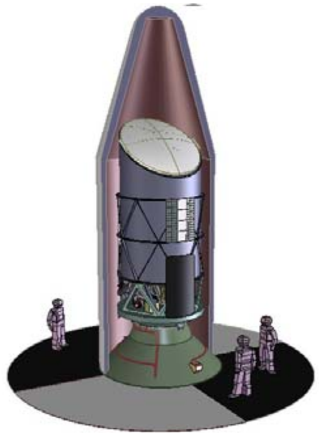
Redshift & SN Properties

Ω_M and Ω_Λ
Dark Energy
Properties

Data → Analysis → Physics

Launch early in the next decade

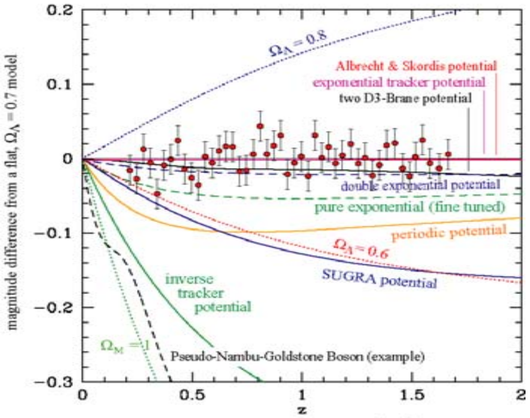
1600 kg satellite can be lifted by a Delta IV [recent first flight] to our orbit with margin. Can use equivalent Delta IV, Atlas, or Sea Launch.



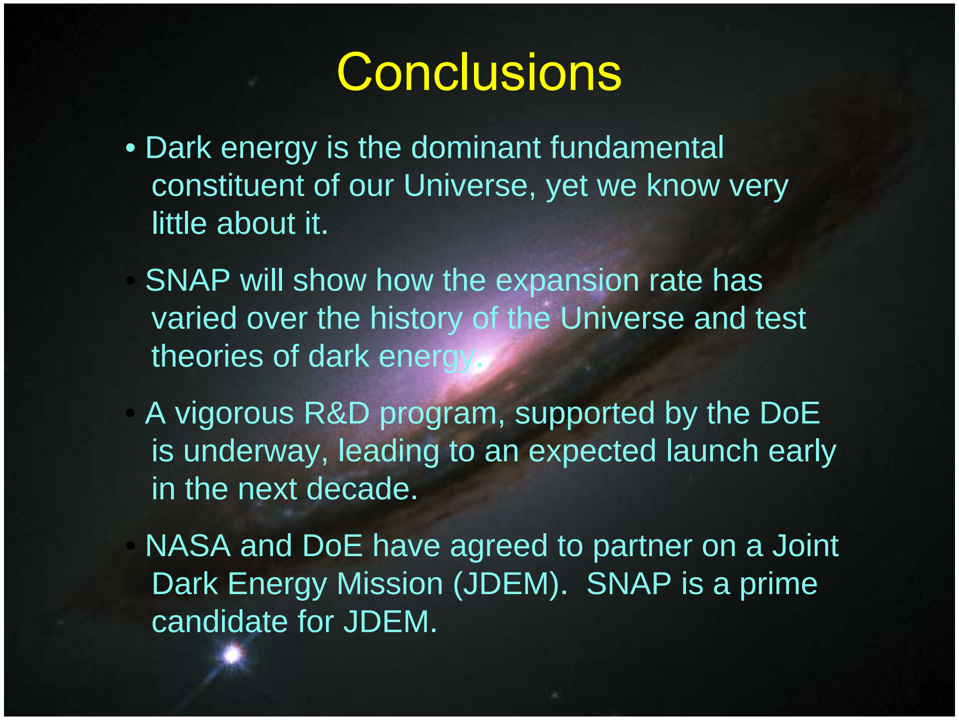
Launch early in the next decade

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.

Understanding Dark Energy



based on
Weller & Albrecht (2001)



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