Dark Energy and the Homogeneous Universe

暗能量及宇宙整體之膨脹

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This is a series of 3 talks.

Today: Dark energy and the homogeneous universe

July 11: Dark matter and the large scale structure of the universe

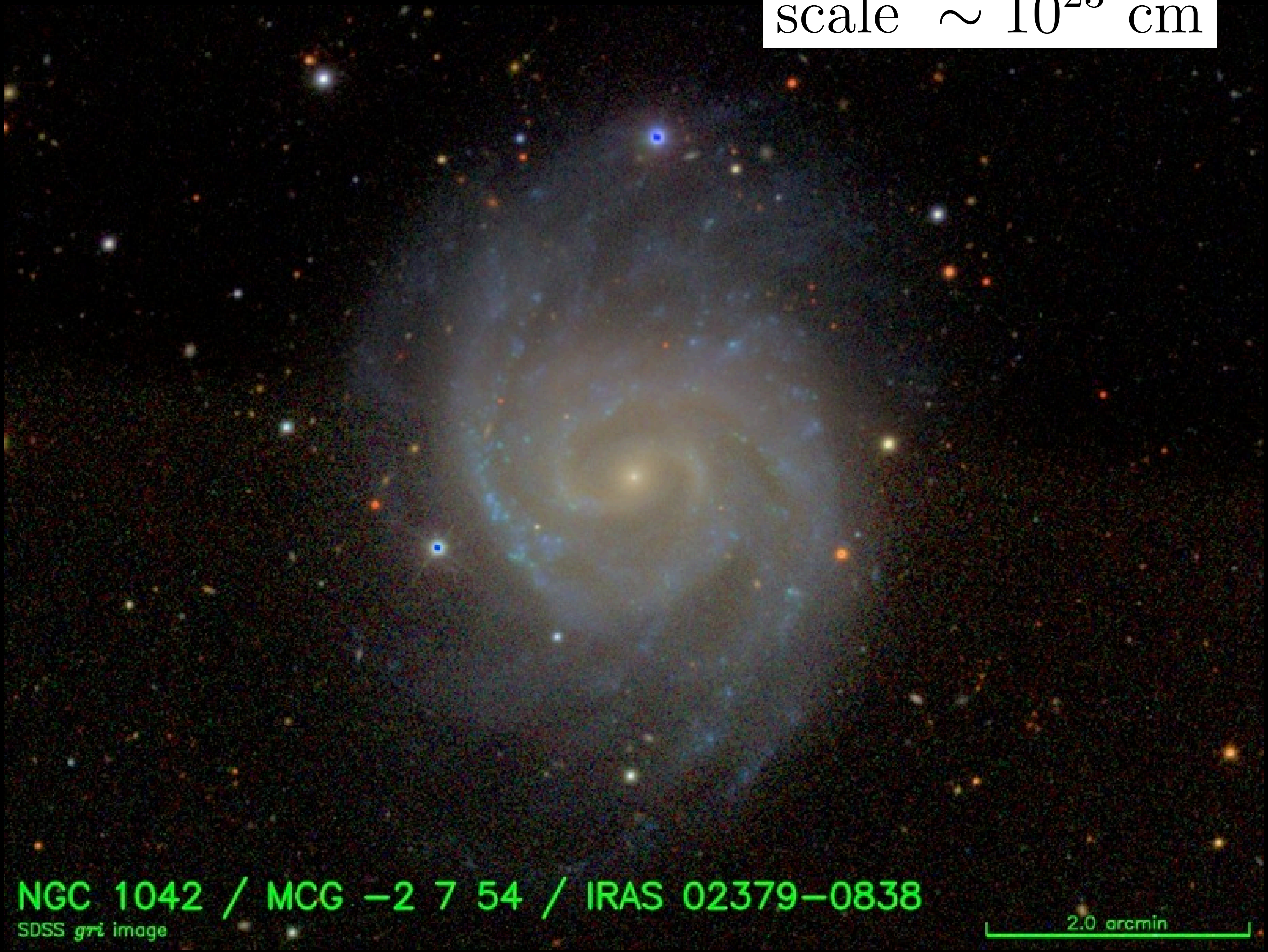
July 18: Inflation and the early universe

Outline

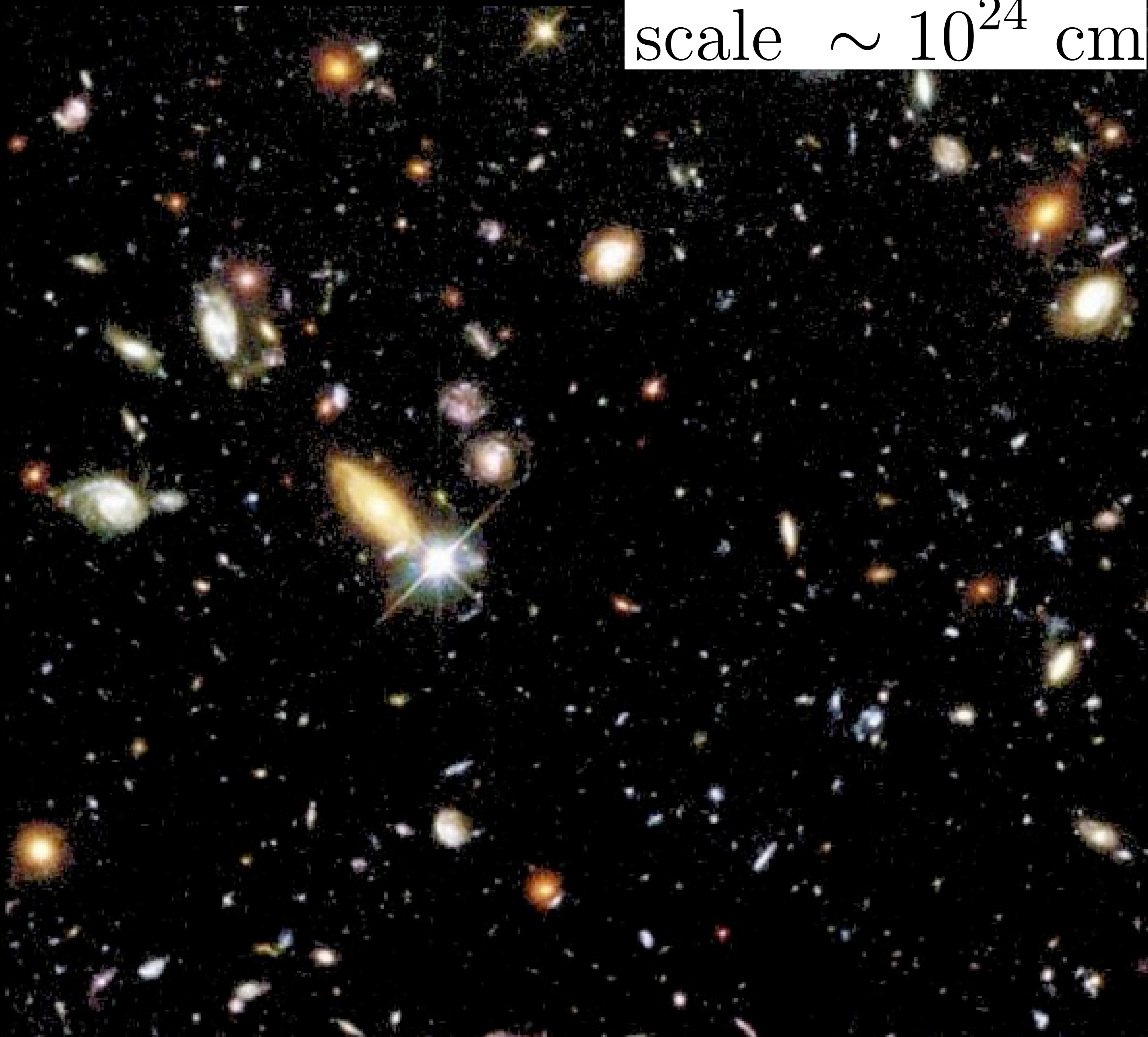
- **Basic concepts:** a homogeneous, isotropic and expanding universe.
- **Measurements:** how do we measure the universe's expansion history?
- **Dynamics:** what determines the expansion rate?
- **Dark energy:** a surprising recent finding.

There is by now much evidence for homogeneity and isotropy.
There is also firm evidence for an expanding universe.

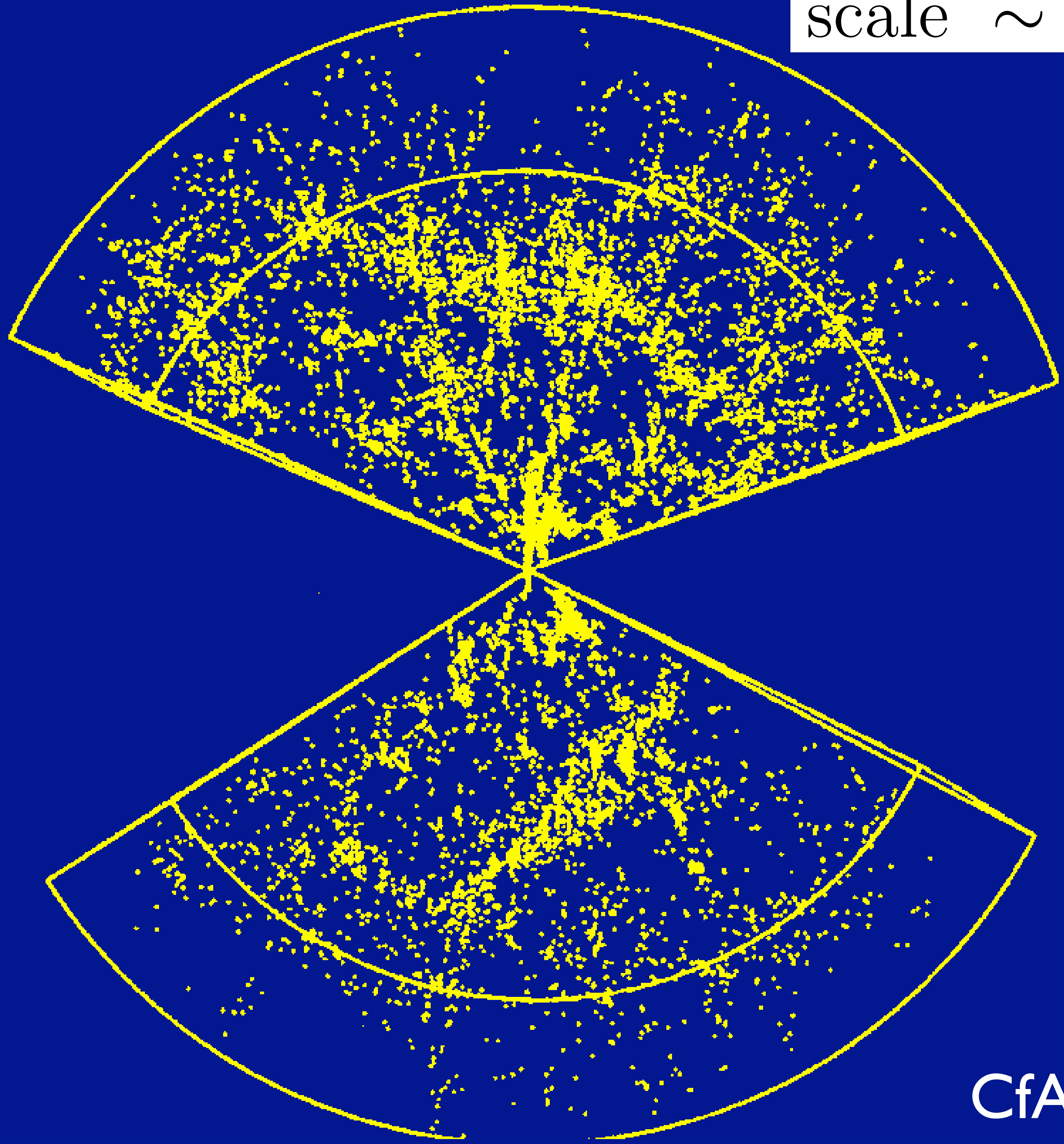
$\text{scale} \sim 10^{23}\ \text{cm}$



Blandton & Hogg



Hubble deep field

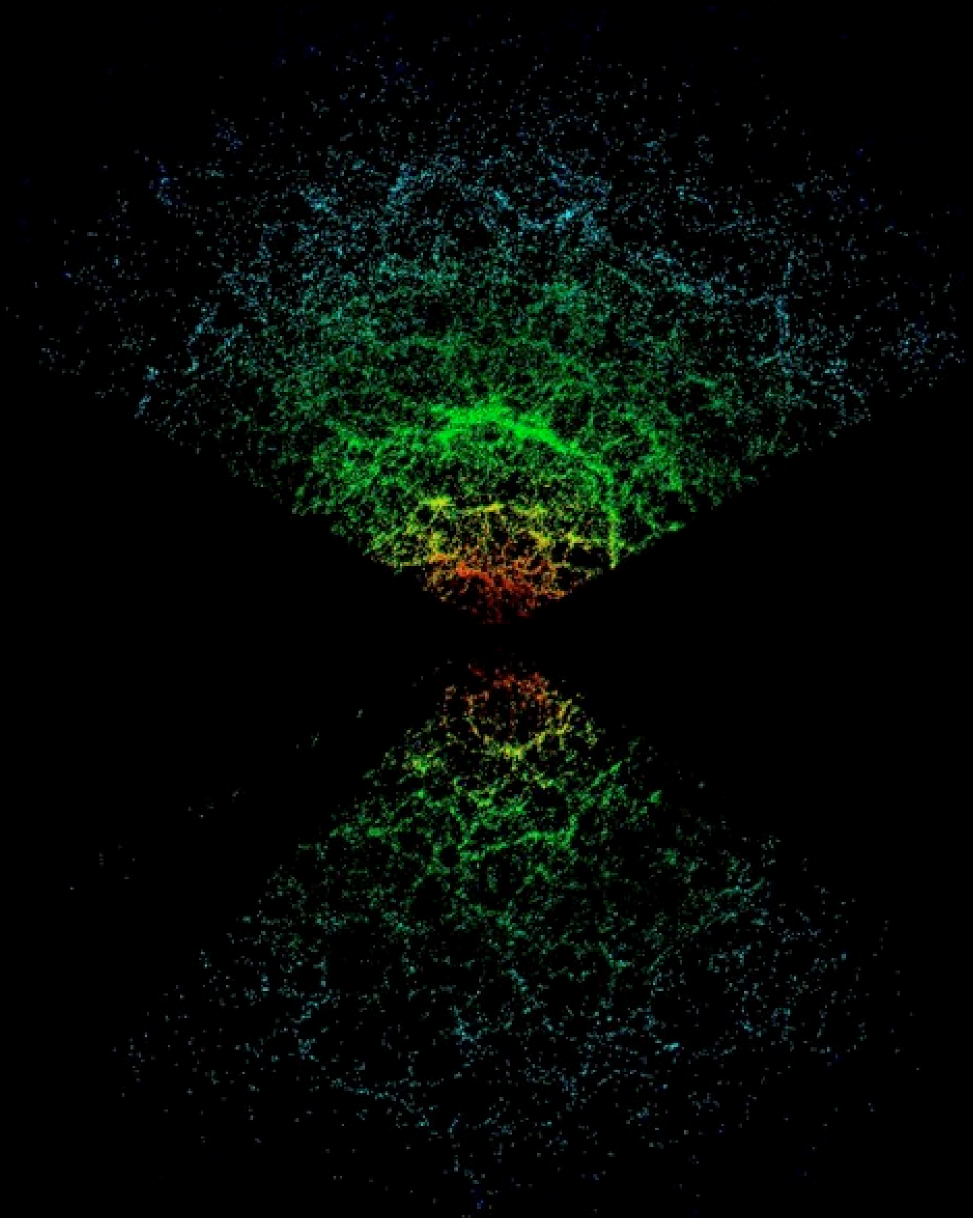


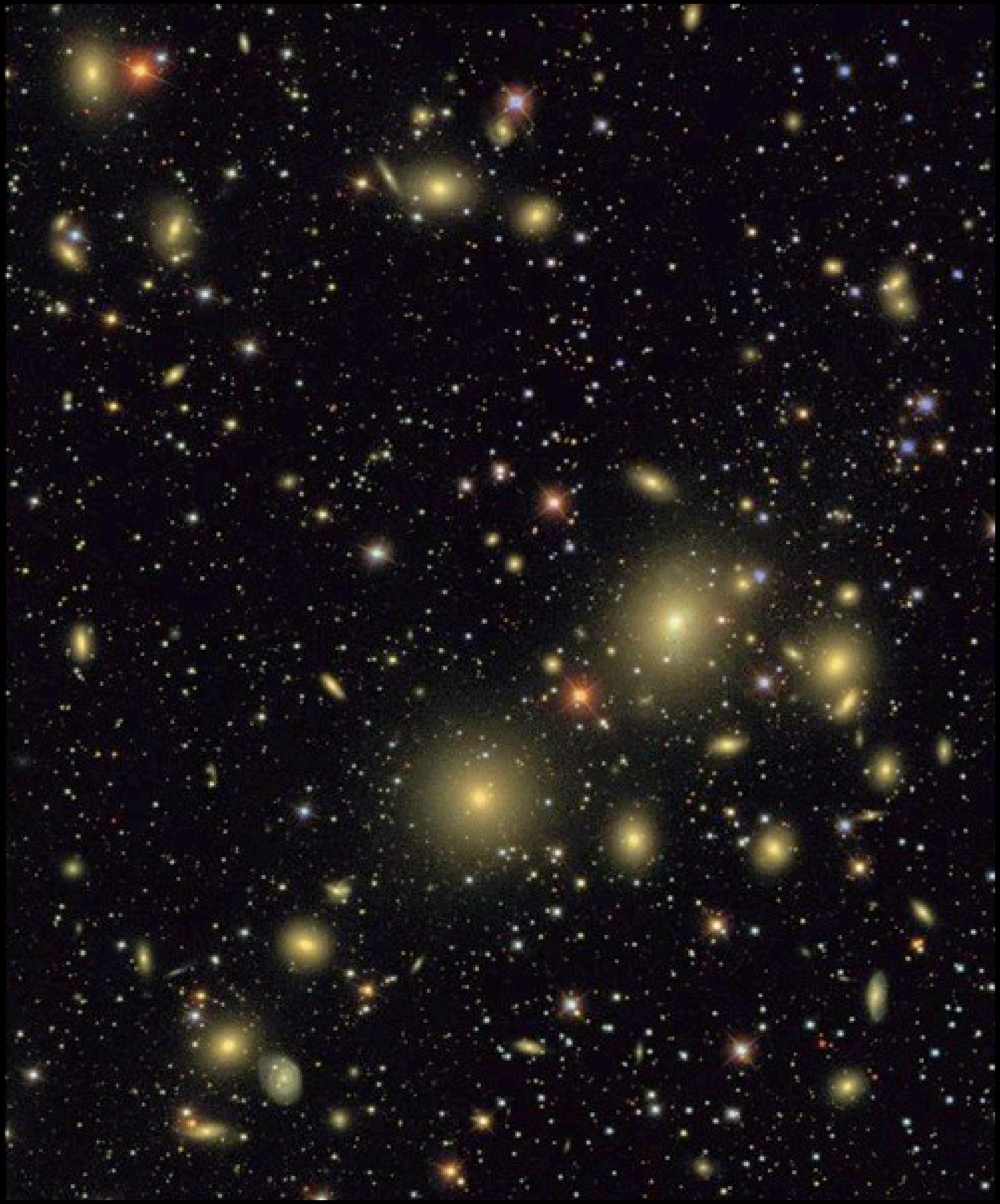
scale $\sim 10^{25}$ cm

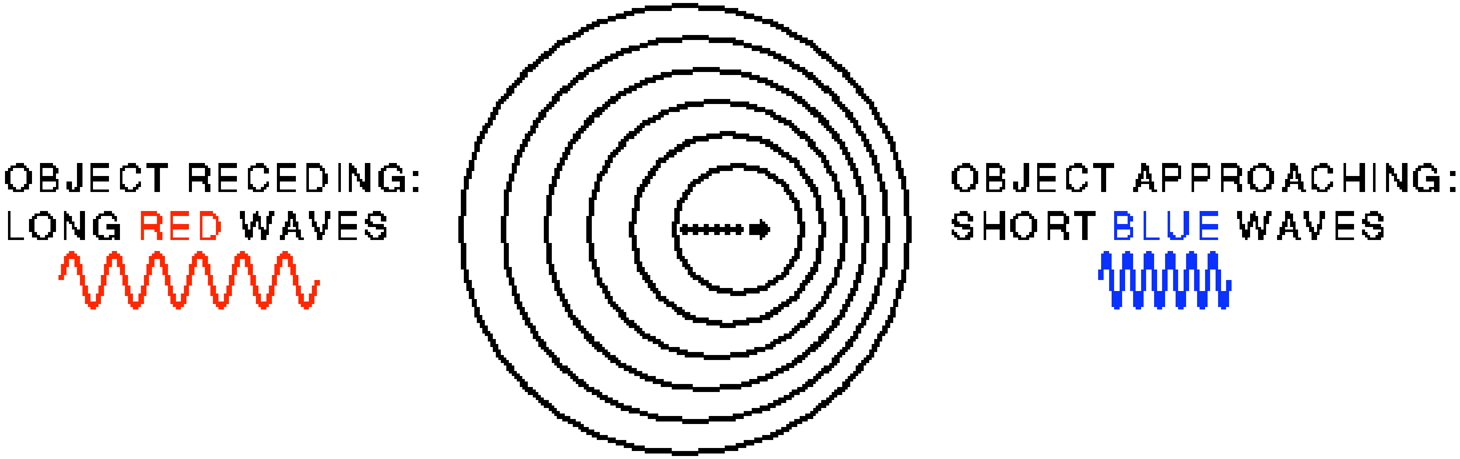
CfA survey

Sloan Digital Sky Survey

scale $\sim 10^{26}$ cm



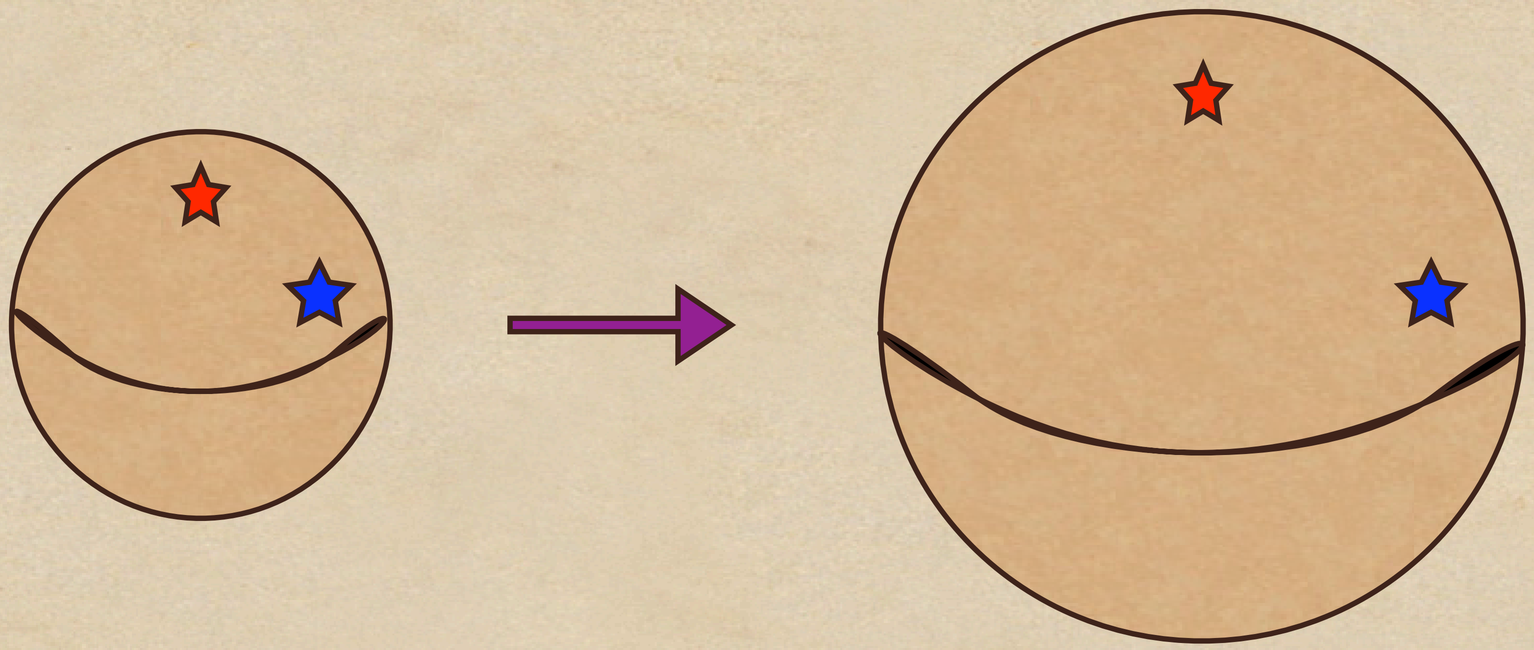



OBJECT RECEDING:
LONG RED WAVES
OBJECT APPROACHING:
SHORT BLUE WAVES

Ned Wright

There is by now much evidence for homogeneity and isotropy.
There is also firm evidence for an expanding universe.

There is by now much evidence for homogeneity and isotropy.
There is also firm evidence for an expanding universe.
But how should we think about it?



Frequently Asked Questions:

1. What is the universe expanding into?

2. Where is the center of expansion?

3. Is our galaxy itself expanding?

Frequently Asked Questions:

1. What is the universe expanding into?

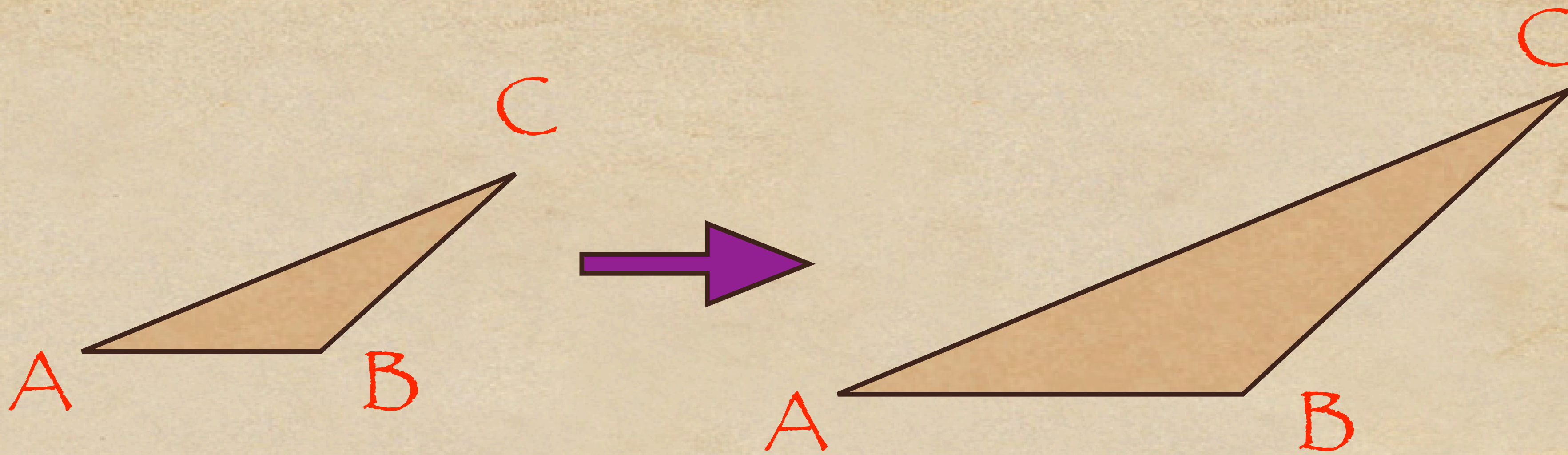
   Nothing.

2. Where is the center of expansion?

   Everywhere and nowhere.

3. Is our galaxy itself expanding?

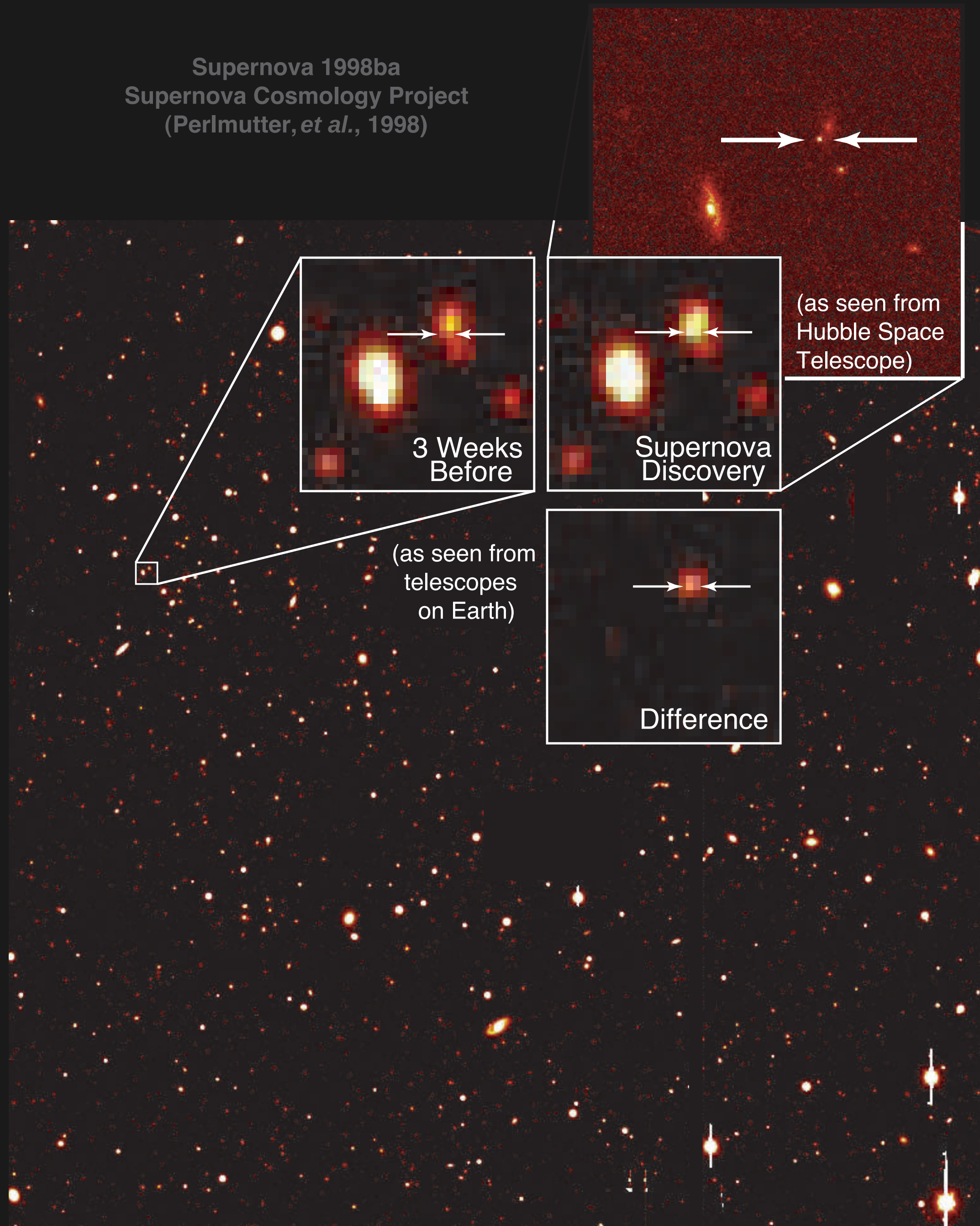
   No.



$$d_{AC} = 2\,d_{AB} \qquad\qquad d_{AC} = 2\,d_{AB}$$

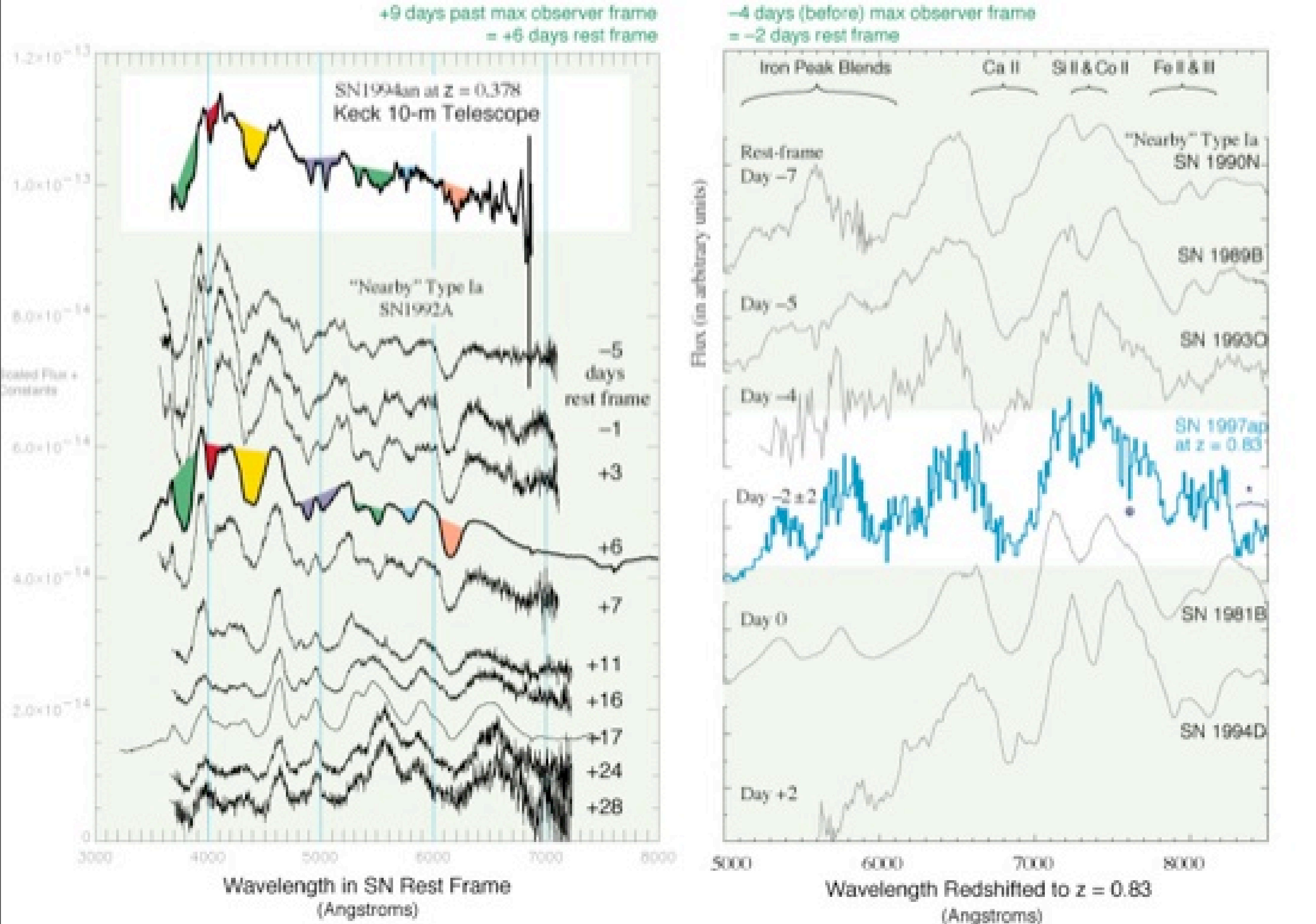
Therefore: $$\frac{\Delta d_{AC}}{\Delta t} = 2\,\frac{\Delta d_{AB}}{\Delta t}$$

Hubble law: Velocity $\propto$ Distance



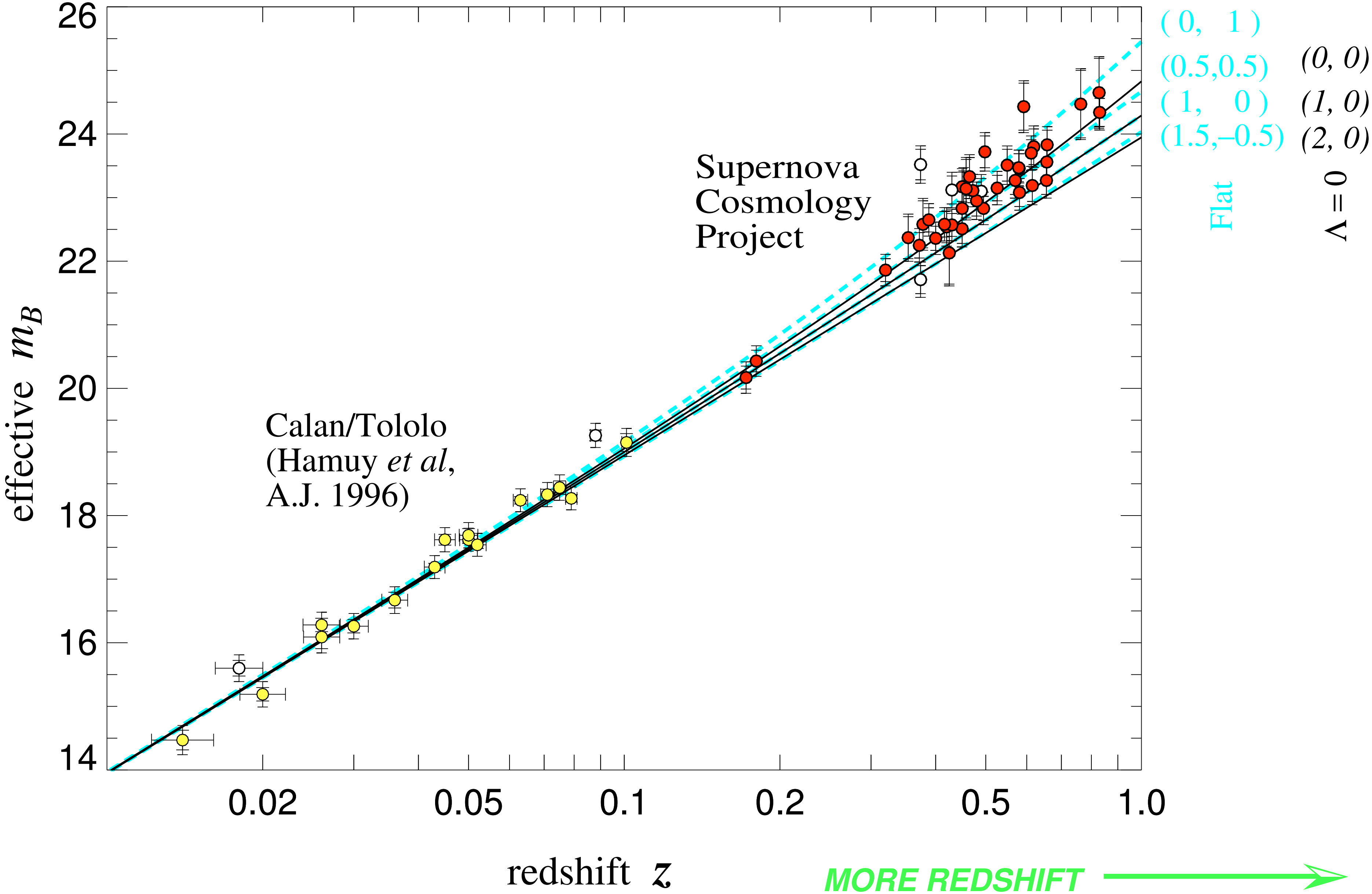
Supernova 超新星 as standard candle

at z = 0.38 . . .   . . . at z = 0.83



Perlmutter, et al., Nature (1998)

Perlmutter, *et al.* (1998)



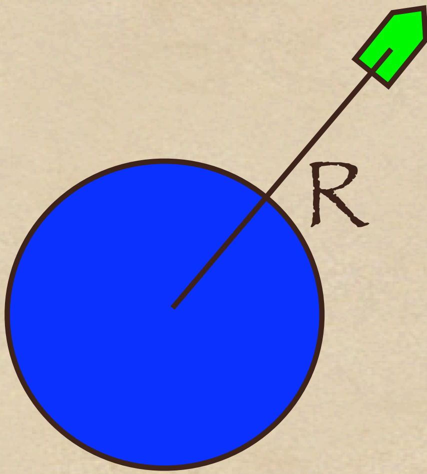
MORE REDSHIFT →
(More total expansion of universe since the supernova explosion)

See also Riess et al. 98

Age of Universe

Slope ≈ Distance/Velocity ≈ 10 billion years

Dynamics: what determines the expansion rate and how it changes with time?

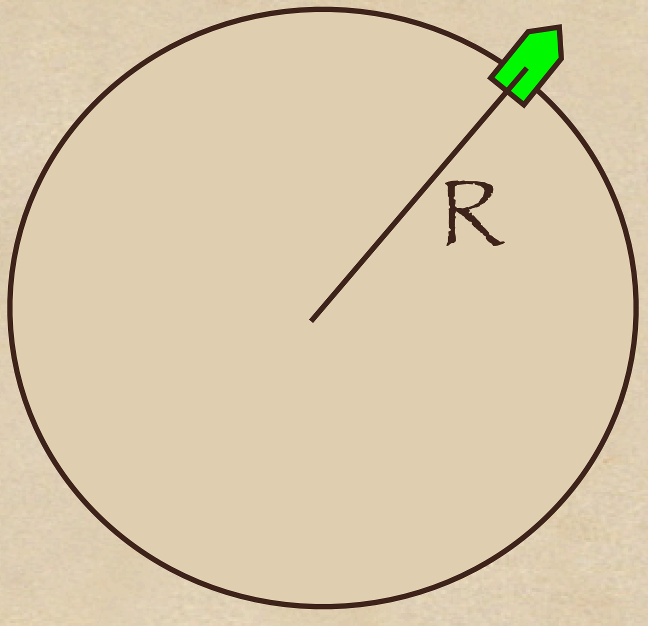


Secondary school physics:

$$\frac{1}{2}mv^2 - \frac{GMm}{R} = E$$

$$\text{For simplicity set } E = 0 : \frac{1}{2}v^2 = \frac{GM}{R}$$

Apply to the expanding universe:



$$\frac{1}{2}v^2 = \frac{GM}{R}, \quad \text{but remember}: M = \frac{4\pi}{3}R^3\rho$$

Important equation: $\frac{1}{2}v^2 = \frac{GM}{R}$ where $M = \frac{4\pi}{3}R^3\rho$

Example 1 - ordinary matter

$$\rho \propto \frac{3}{4\pi R^3} \quad (M = \text{constant}) \quad \Longrightarrow v^2 \propto \frac{1}{R}$$

$$\text{Therefore} : v \downarrow \Longleftrightarrow R \uparrow$$

Example 2 - cosmological constant

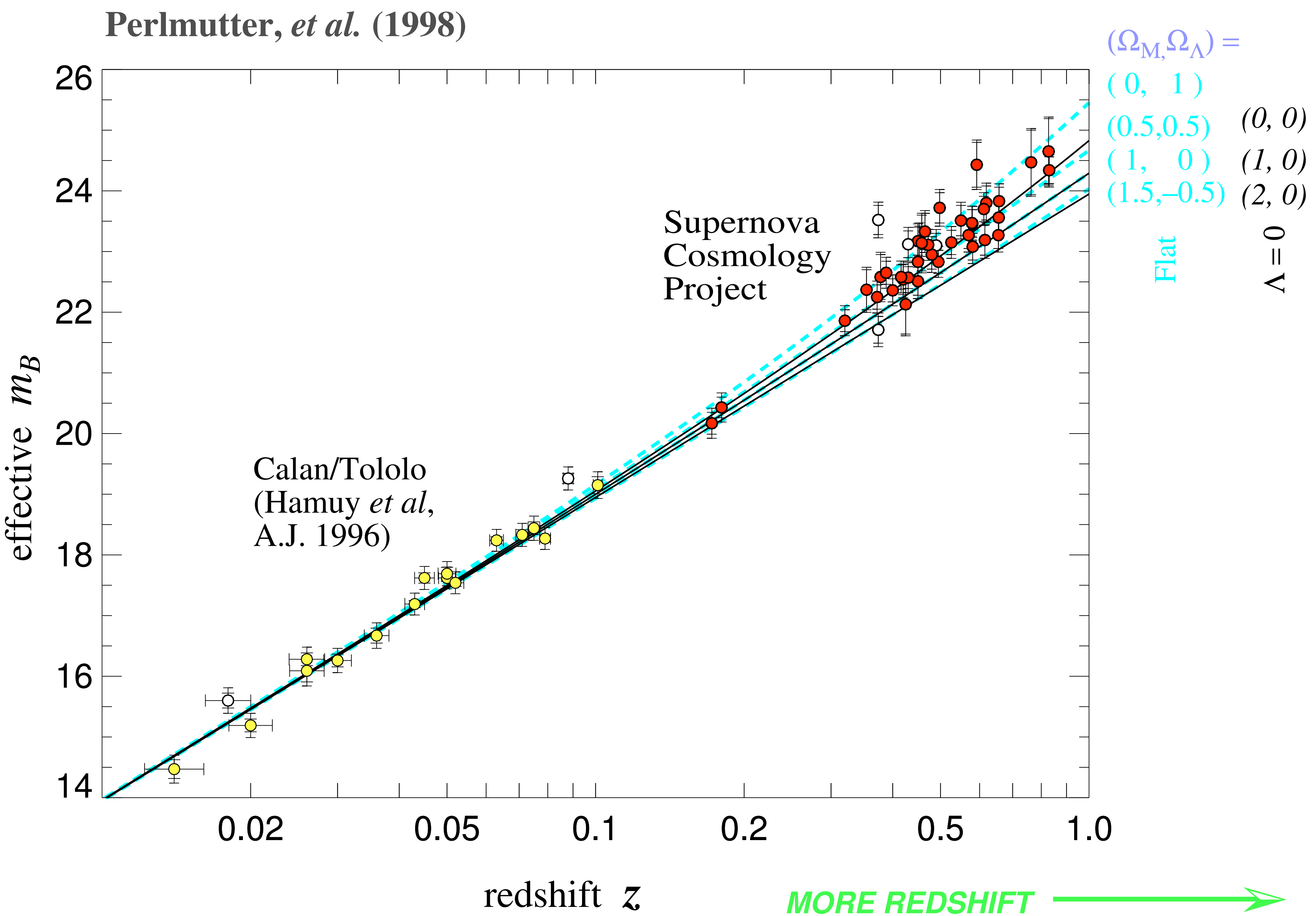
$$\rho = \text{constant} \Longrightarrow v^2 \propto R^2$$

$$\text{Therefore} : v \uparrow \Longleftrightarrow R \uparrow$$

Acceleration!

Dark Energy: ρ drops slower than $\frac{1}{R^2}$

i.e. $\rho \propto R^{-3(1+w)}$ with $w < -1/3$



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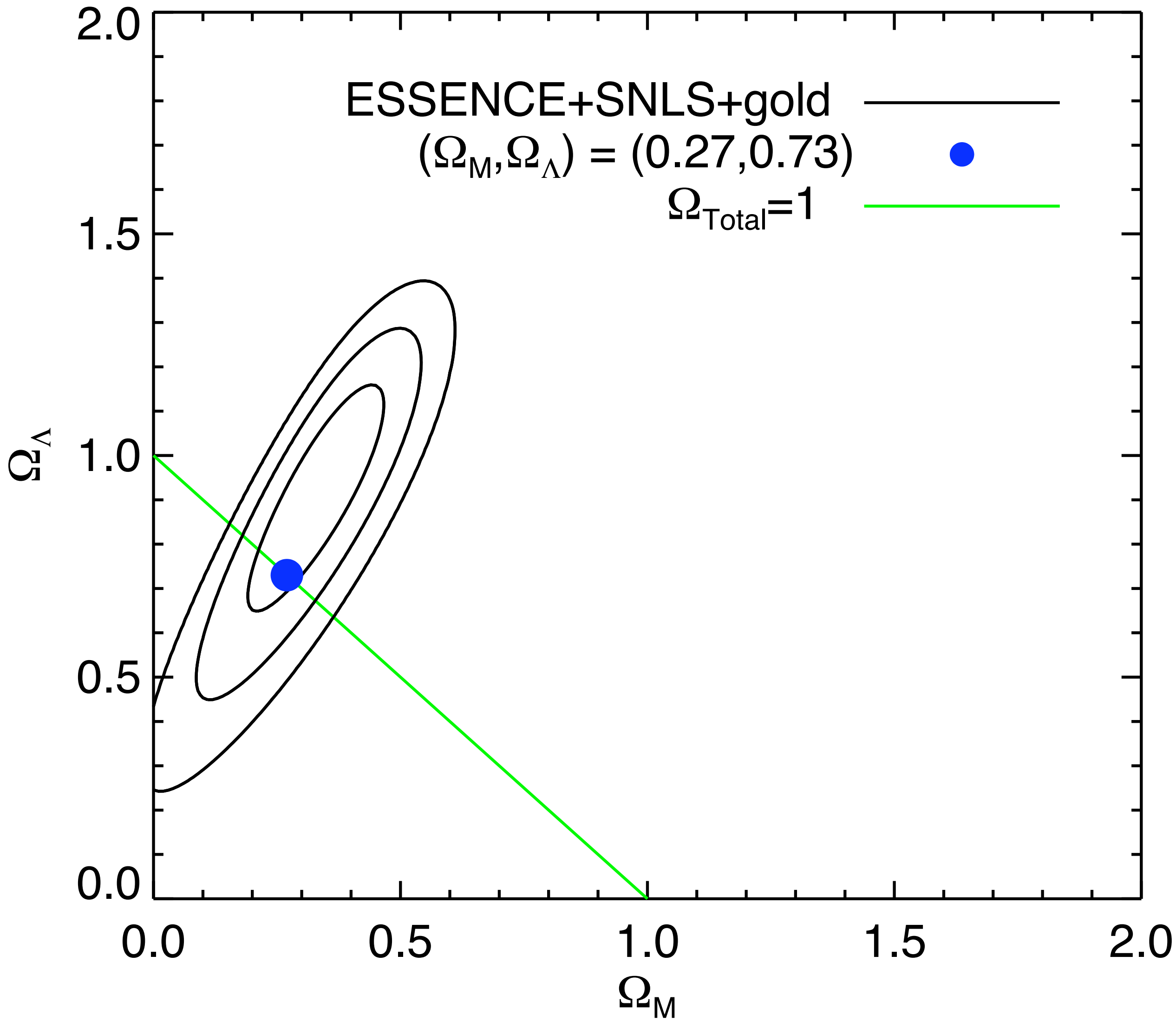
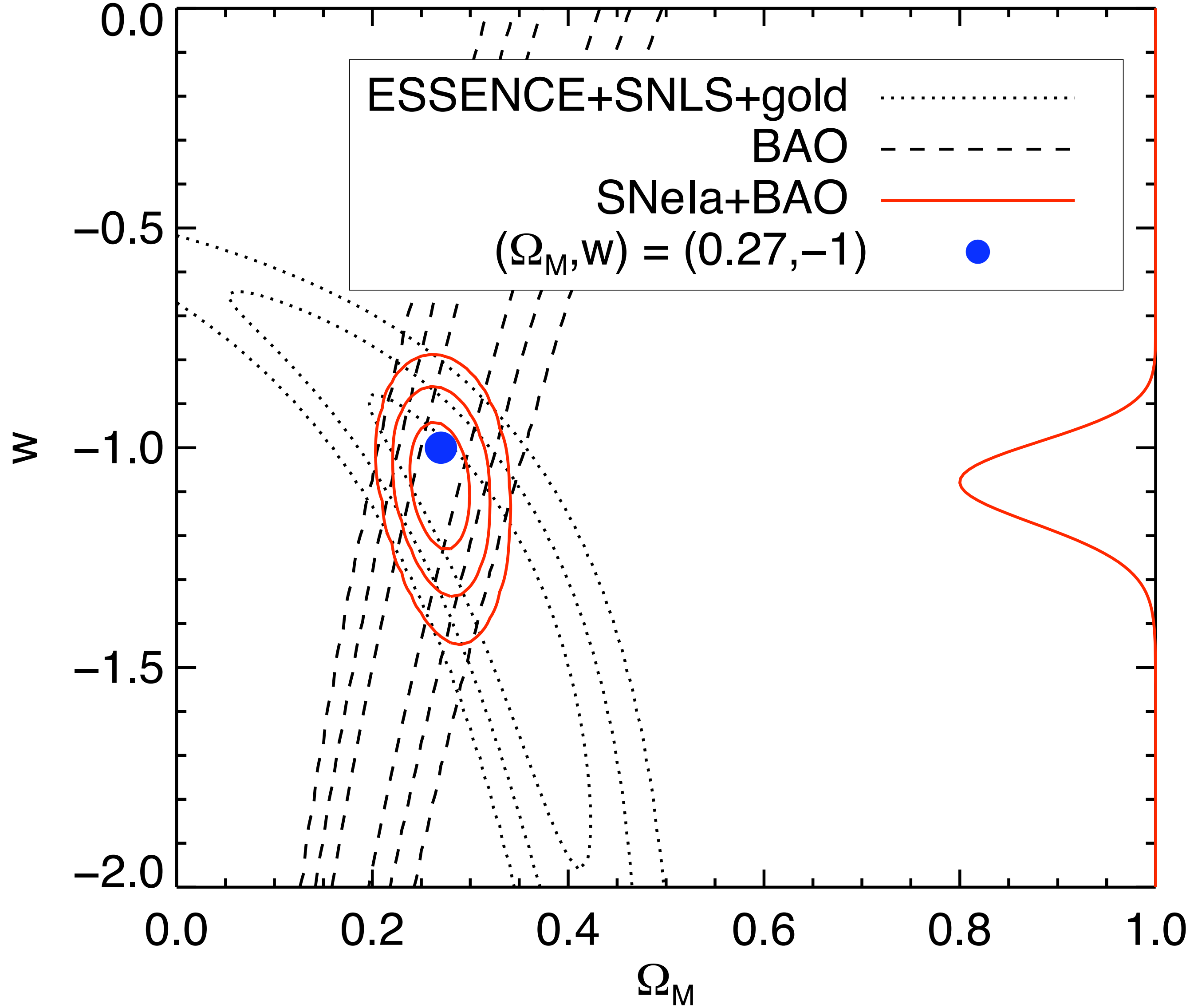
Wood-Vasey et al. 07



70% dark energy, 30% matter

Wood-Vasey et al. 07



Dark energy $\rho \propto R^{-0.6}$ to $R^{1.2}$

What is dark energy?

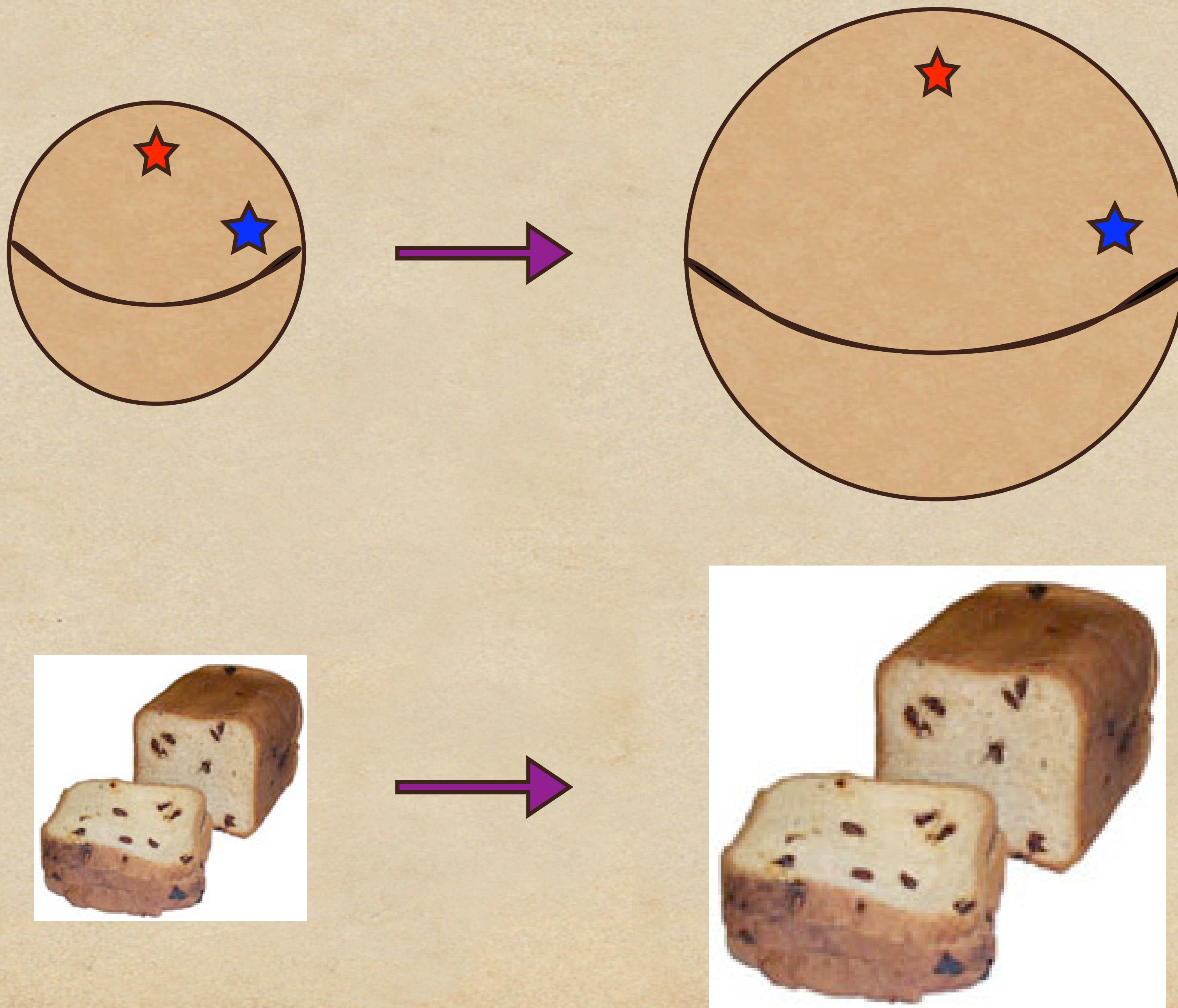
1. Vacuum energy
(Einstein's cosmological constant)

2. Scalar field (Bose Einstein condensate)

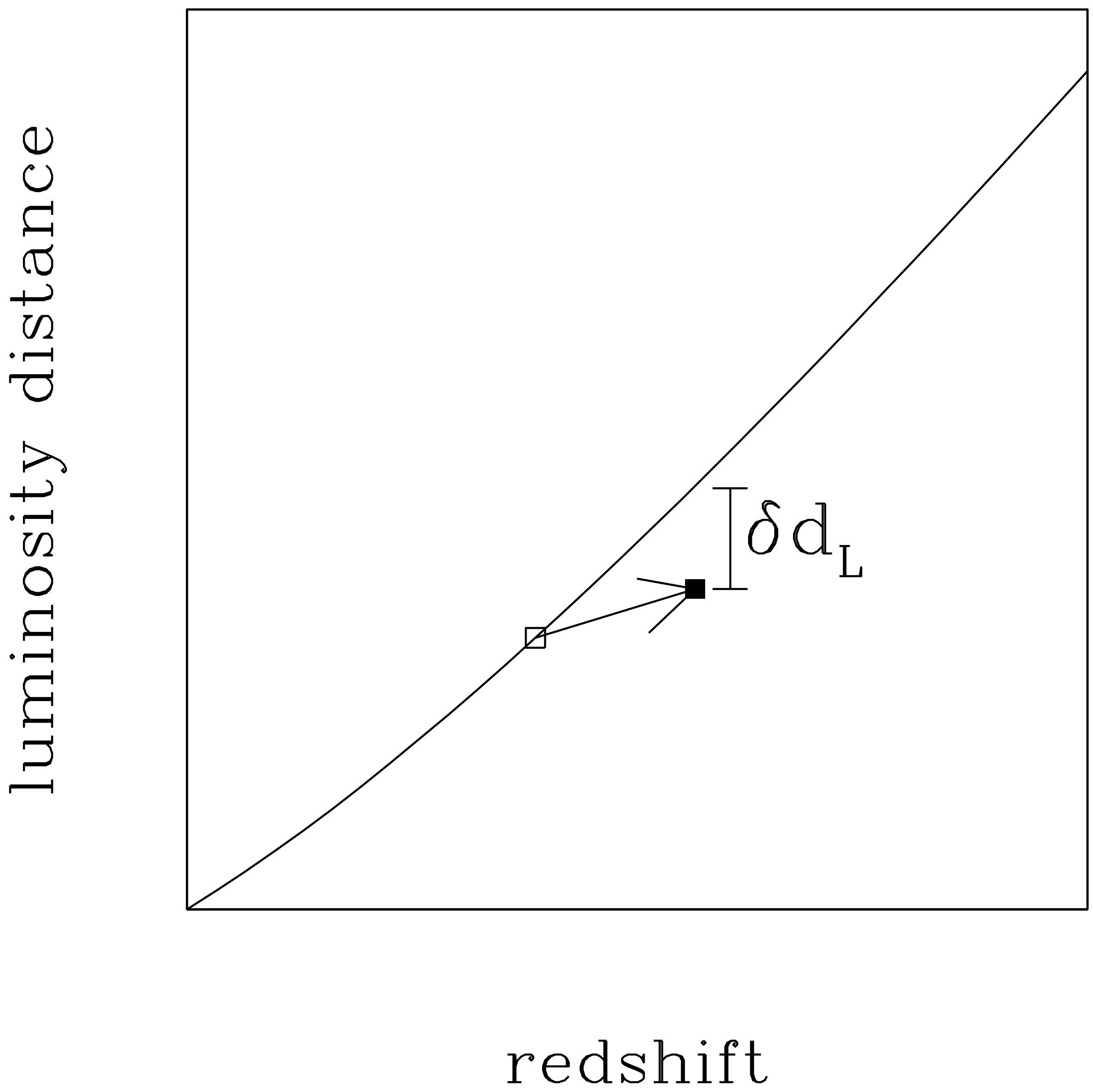
3. Modified gravity (Einstein was wrong!)

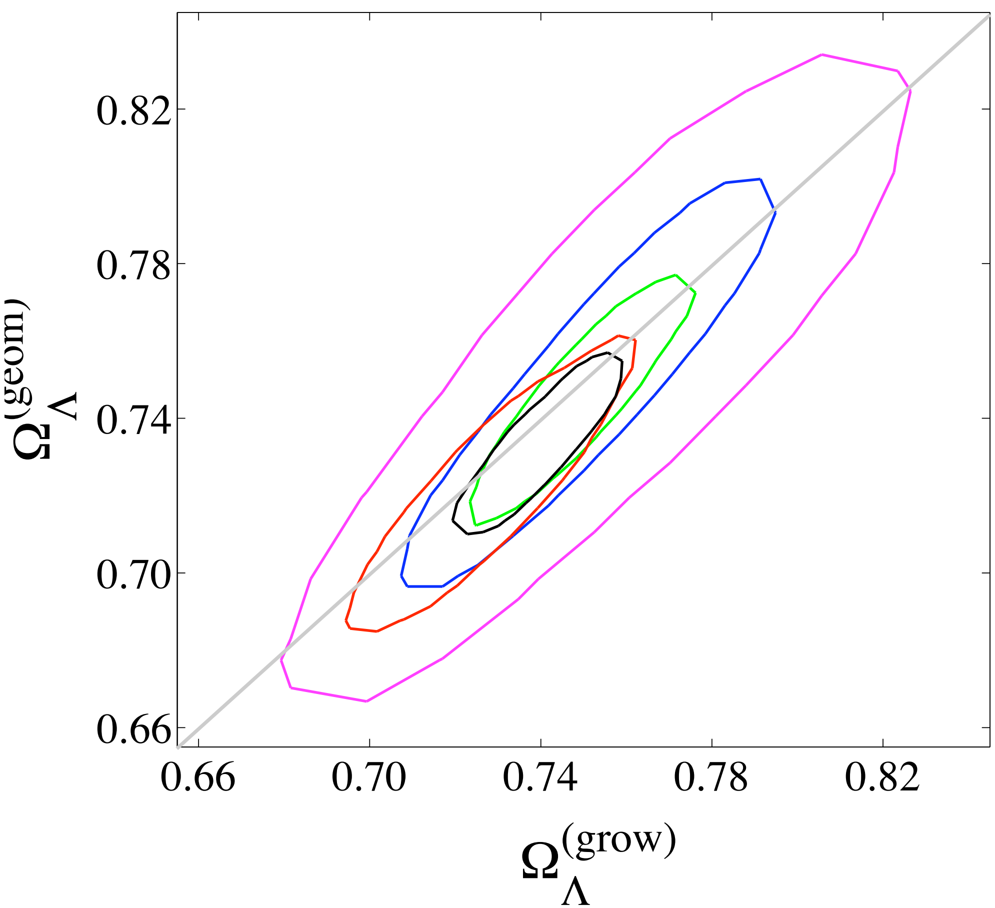
What is dark energy?

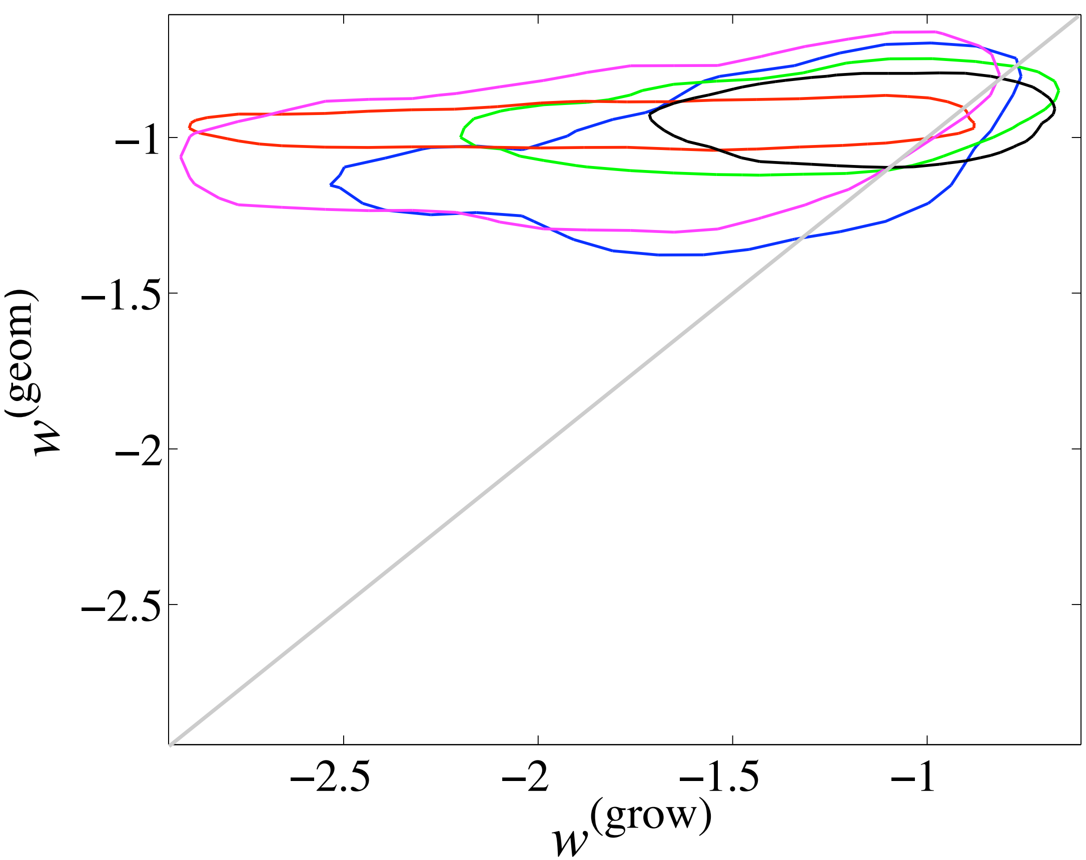
1. Vacuum energy (Einstein's cosmological constant)
   Observed value too small.
2. Scalar field (Bose Einstein condensate)
   Required mass too small.
3. Modified gravity (Einstein was wrong!)
   No compelling theory.



LH & Greene 06







Wang, LH, May & Haiman 07

See also Li & Chu, Li, Chan & Chu 06

Summary

- Basic concepts of a homogeneous, isotropic and expanding universe.
- Surprisingly, our current expansion appears to be accelerating. Explaining it, and measuring it precisely, is a major goal of cosmology today.

Let there be light.

Genesis 1:3