Lecture 9

Observational Cosmology

Discovery of “Dark Energy”

Age Crisis (~1995)

$$H_0\ t_0 = \int_1^\infty \frac{dx}{x\sqrt{\Omega_M\ x^3 + \Omega_\Lambda + (1-\Omega_0)\ x^2}}$$

observations :

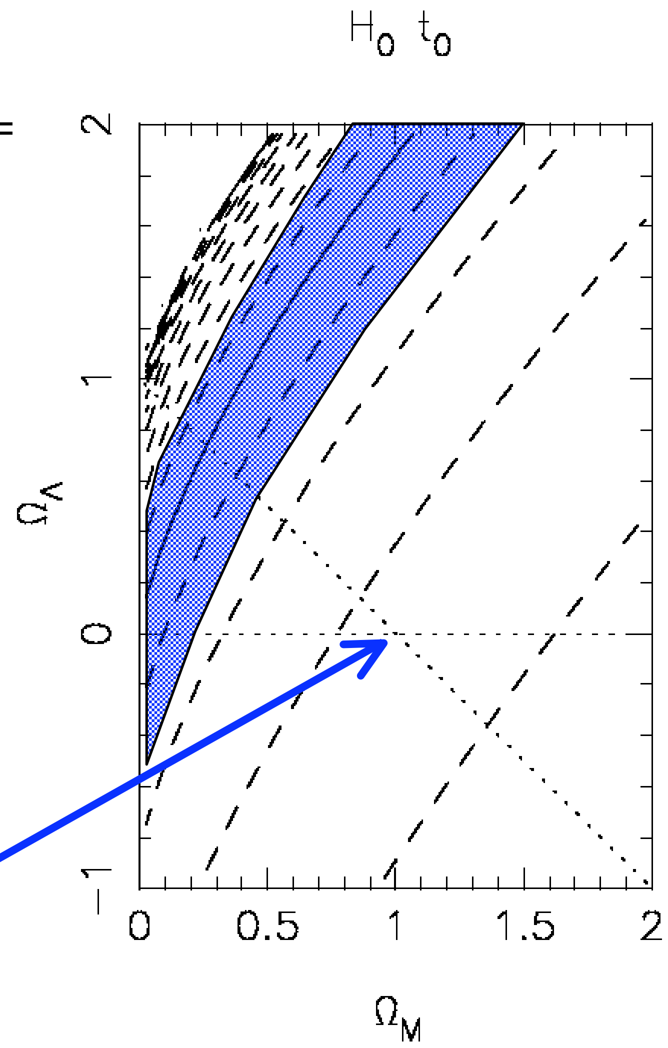
$$H_0 = 72 \pm 8\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

$$t_0 \geq 14 \pm 2\ \mathrm{Gyr}\ \ \text{old globular clusters}$$

$$H_0\ t_0 \geq 1.0 \pm 0.15$$

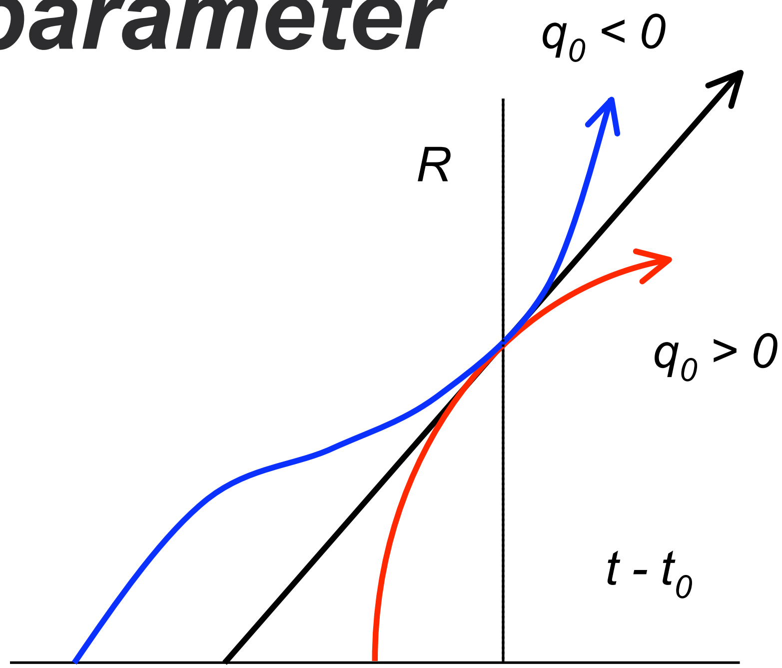
Globular clusters older than the Universe ?
Inconsistent with critical-density matter-only model :

$$H_0\ t_0 = \frac{2}{3} \quad \text{for } \left(\Omega_M, \Omega_\Lambda\right) = (1,0)$$



Strong theoretical prejudice for inflation. $\left(\Omega_0 = 1\right)$
Doubts about stellar evolution therory (e.g. convection).

Deceleration parameter



Dimensionless measure of the *deceleration* of the Universe

$$q \equiv -\frac{\ddot{R}\,R}{\dot{R}^2} = -\frac{\ddot{R}}{R\,H^2}$$

$$q_0 \equiv -\left(\frac{\ddot{R}\,R}{\dot{R}^2}\right)_0 = -\left(\frac{\ddot{R}}{R\,H^2}\right)_0$$

$$a(t) \equiv \frac{R(t)}{R_0} = 1 + H_0\,(t - t_0) - \frac{q_0}{2}\,H_0^{\,2}\,(t - t_0)^2 + \ldots$$

$$\dot{a} = H\,a \qquad \ddot{a} = -q\,H^2 a$$

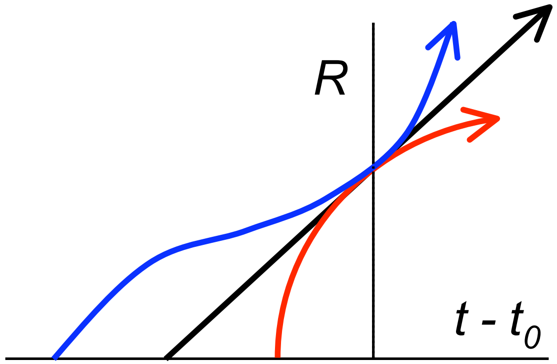
$q_0 > 0$ => **deceleration**

$q_0 = 0$ => *coasting at constant velocity*

$q_0 < 0$ => **acceleration**

Deceleration parameter

$$q \equiv -\frac{\ddot{R}\,R}{\dot{R}^2} = -\frac{\ddot{R}}{R\,H^2} \qquad q_0 \equiv -\left(\frac{\ddot{R}\,R}{\dot{R}^2}\right)_0 = -\left(\frac{\ddot{R}}{R\,H^2}\right)_0$$



Friedmann momentum equation:

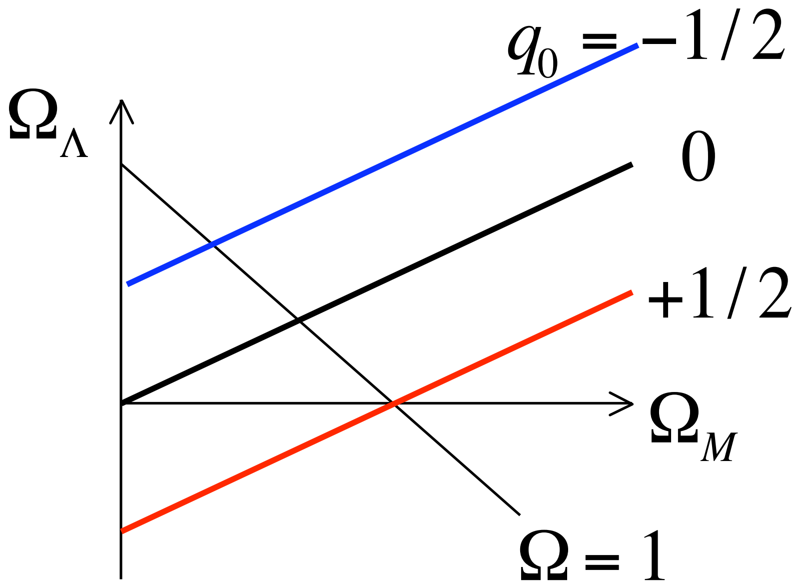
$$\ddot{R} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)R + \frac{\Lambda}{3}R$$

$$\frac{\ddot{R}}{H_0{}^2 R} = -\frac{4\pi G}{3H_0{}^2}\rho\left(1+3w\right) + \frac{\Lambda}{3H_0{}^2}$$

$\rho,\, p > 0$ decelerate, $\Lambda > 0$ accelerates

Equation of state: $p = \sum_i w_i\, \rho_i\, c^2$

$$w_R = \frac{1}{3} \quad w_M = 0 \quad w_\Lambda = -1$$



$$q_0 = -\left(\frac{\ddot{R}}{R\,H^2}\right)_0 = \sum_i\left(\frac{1+3\,w_i}{2}\right)\Omega_i = \Omega_R + \frac{\Omega_M}{2} - \Omega_\Lambda$$

Deceleration Parameter

$$q_0 \equiv -\left(\frac{\ddot{R}\,R}{\dot{R}^2}\right)_0 = \frac{\Omega_M}{2} - \Omega_\Lambda$$

Matter decelerates

Vacuum (Dark) Energy accelerates

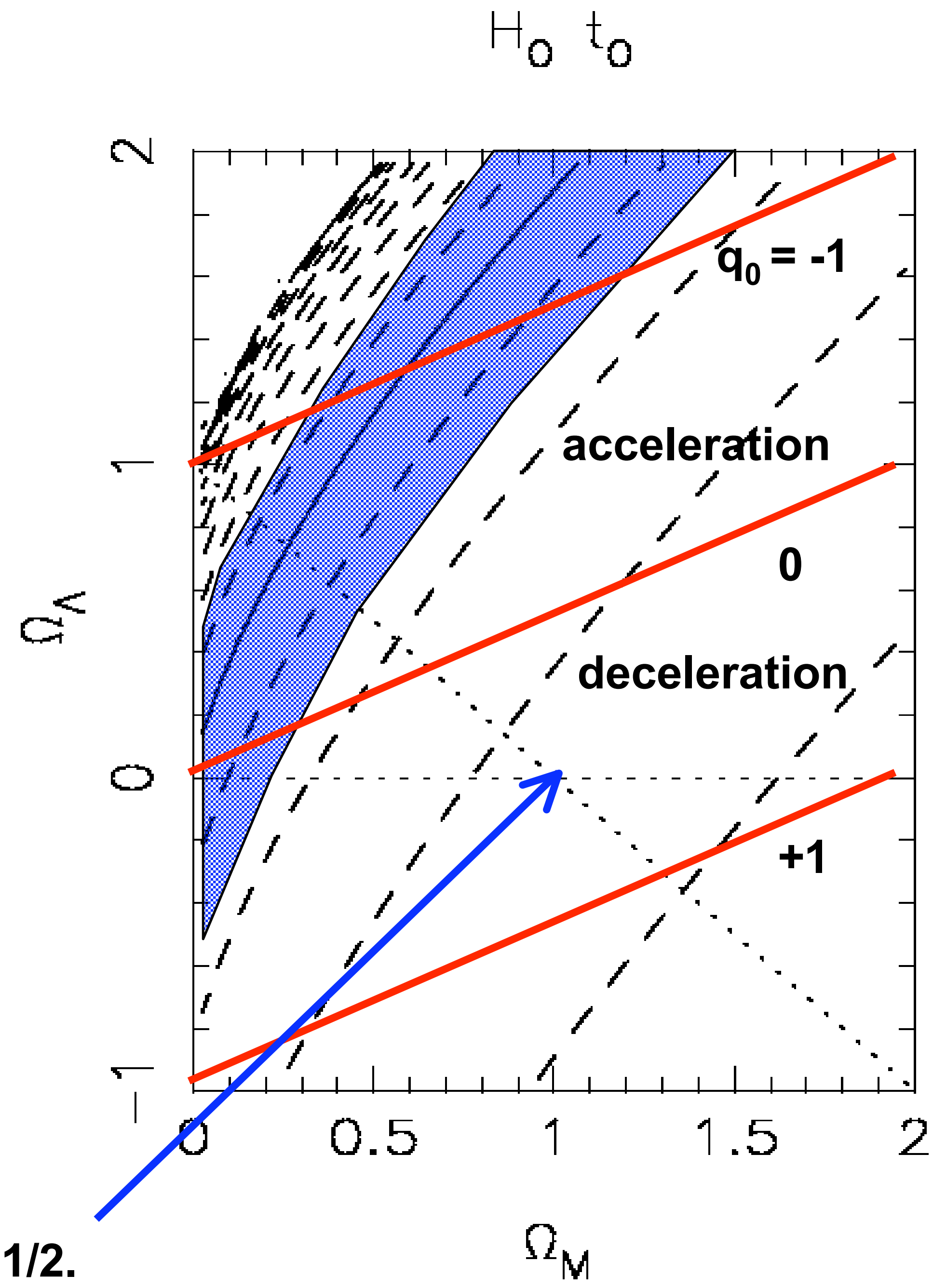
Measure q_0 via :

1 . $D_A(z)$

(e.g. radio jet lengths)

2. $D_L(z)$

(curvature of Hubble Diagram)



Critical density matter-only --> q_0=1/2.

Observable Distances

angular diameter distance :

$$\theta = \frac{l}{D_A} \qquad D_A = \frac{r_0}{(1+z)} = \frac{c\,z}{H_0}\left(1 - \frac{q_0+3}{2}\,z + \ldots\right)$$

luminosity distance :

$$F = \frac{L}{4\pi\, D_L^{\,2}} \qquad D_L = r_0\,(1+z) = \frac{c\,z}{H_0}\left(1 + \frac{1-q_0}{2}\,z + \ldots\right)$$

deceleration parameter :

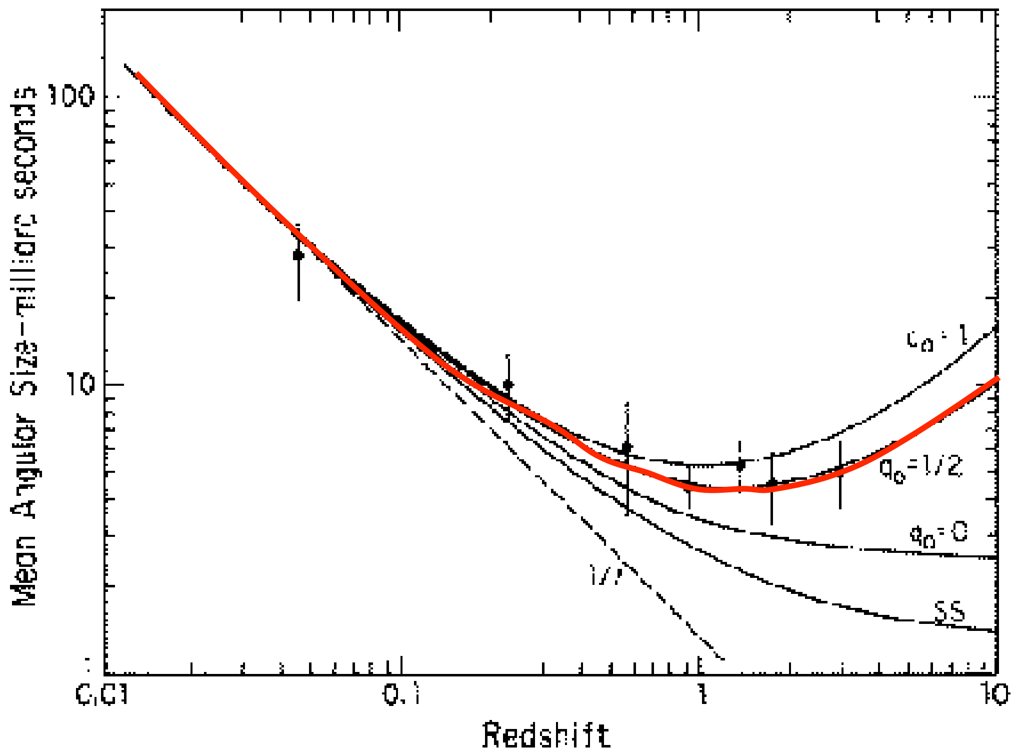
$$q_0 = \frac{\Omega_M}{2} - \Omega_\Lambda$$

Verify these low-z expansions.

1993 - Angular Size of Radio Jets

$$\theta = \frac{l}{D_A(z)}$$

Kellerman 1993 for $\Omega_\Lambda = 0$



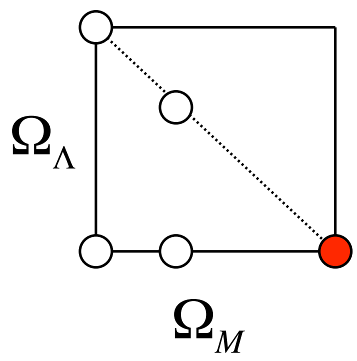
Deceleration

$$q_0 \sim +0.5$$

as expected for

$$(\Omega_M, \Omega_\Lambda) = (1,0)$$

But, are radio jets standard rods ?



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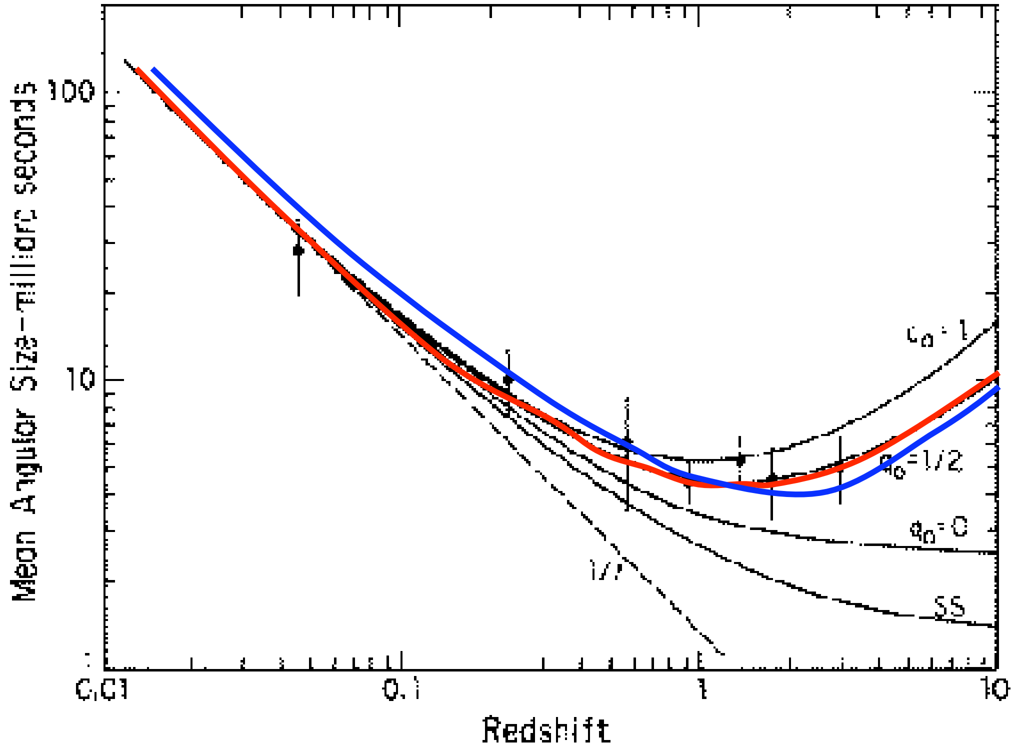
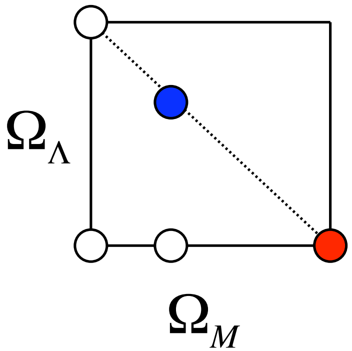


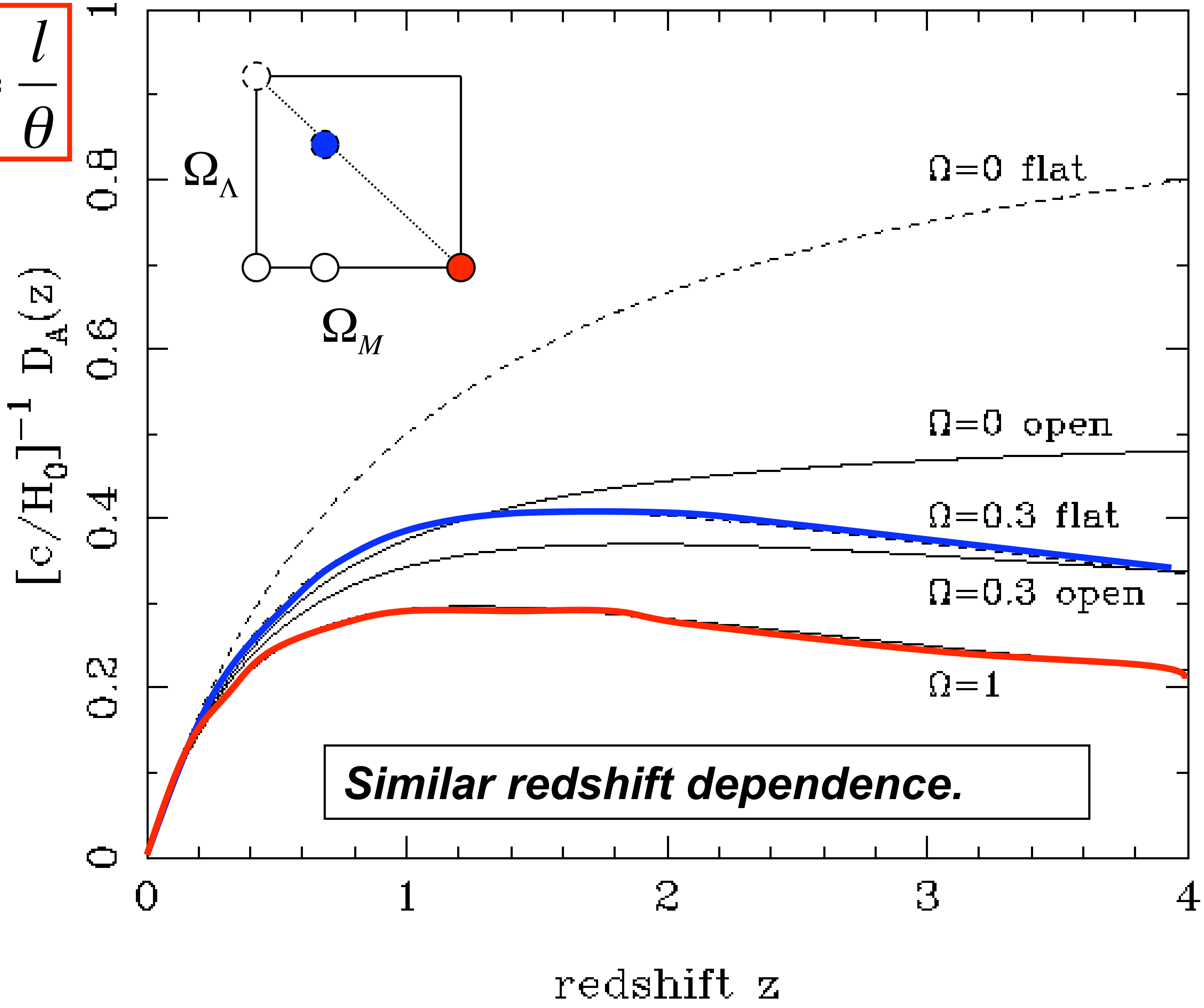


Also compatible with Concordance Model.

$$(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$$

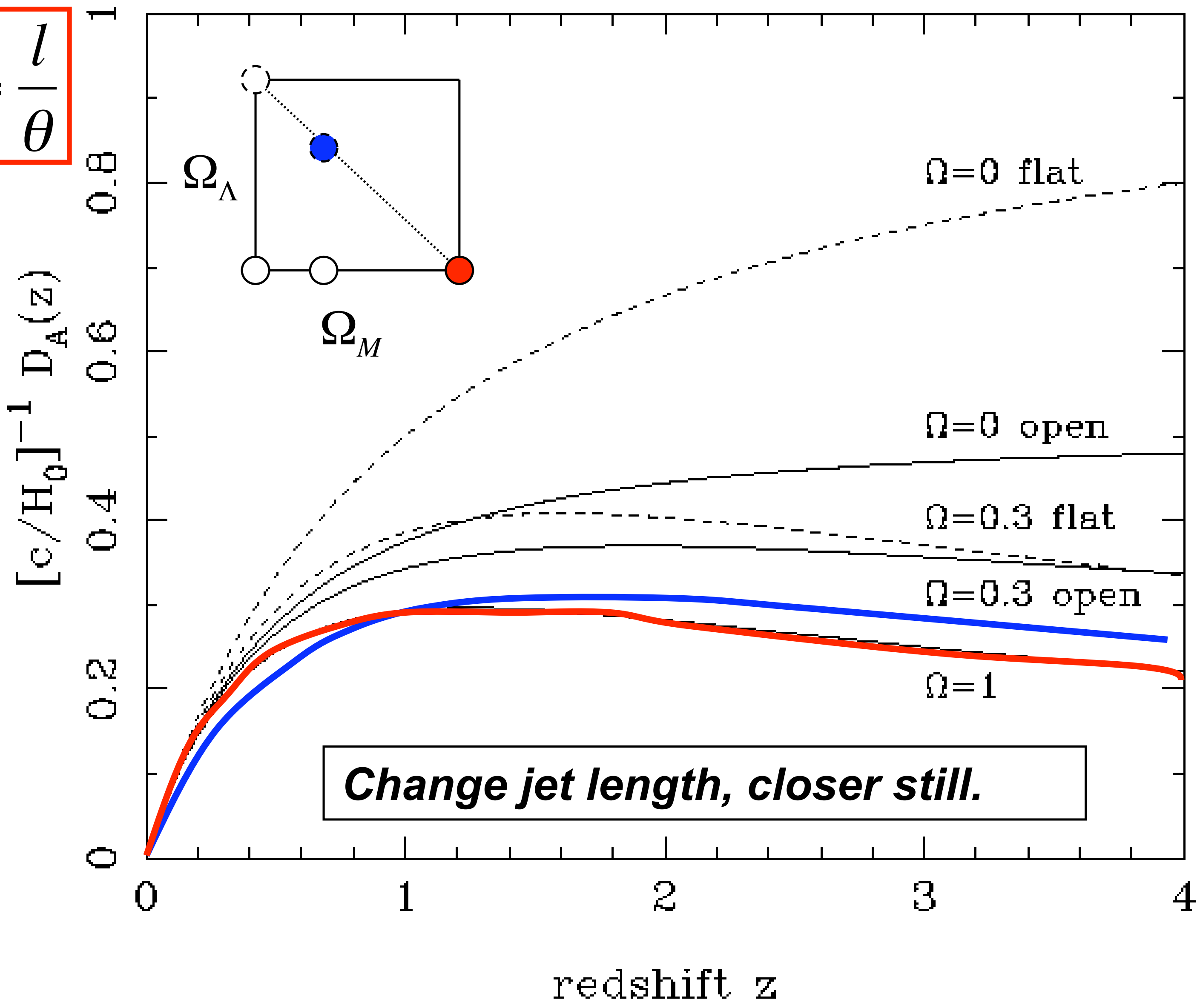
Angular Diameter Distance

$$D_A(z) = \frac{l}{\theta}$$



Angular Diameter Distance

$$D_A(z) = \frac{l}{\theta}$$



Hubble Diagram

$$m = M + 5\log\left(\frac{D_L(z)}{\text{Mpc}}\right) + 25$$

$$+ A + K(z)$$

m = apparent mag

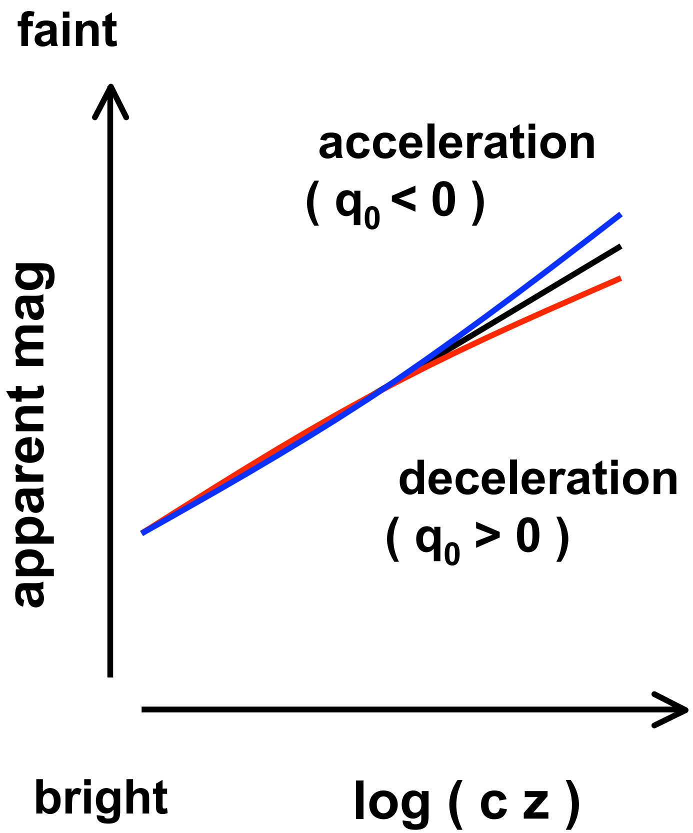
M = absolute mag

A = extinction (dust in galaxies)

$K(z)$ = K correction

(accounts for redshift of spectra relative to observed bandpass)

$$D_L(z) = \frac{c\,z}{H_0}\left(1 + \frac{1 - q_0}{2} z + \ldots\right)$$



slope = +5

vertical shift --> H_0

curvature --> q_0

Finding faint Supernovae

Observe 10^6 galaxies.

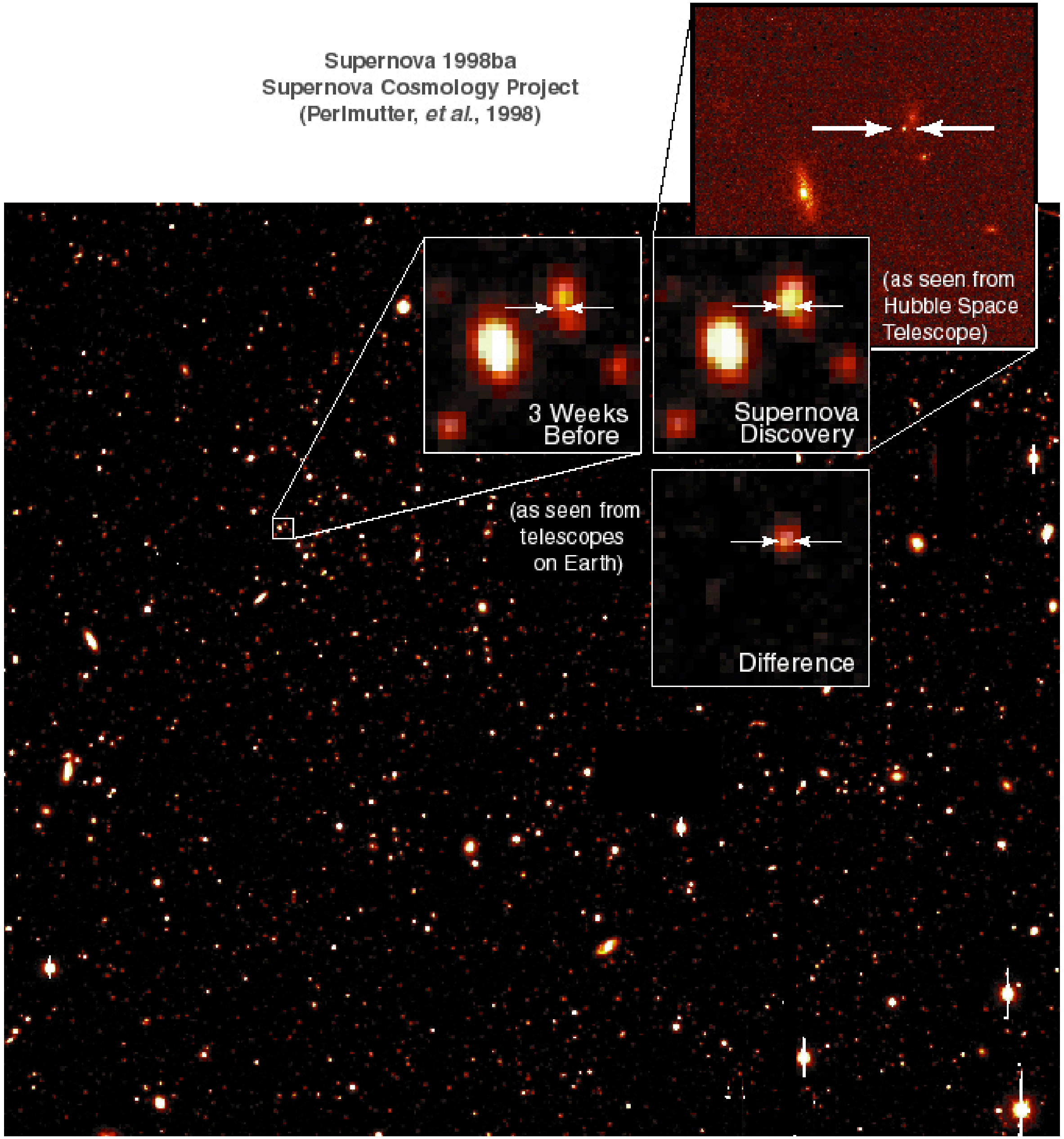
Again, 3 weeks later.

Find "new stars".

Measure lightcurves.

Take spectra.

(Only rare Type Ia Supernovae work).



Hi-Z Supernova Spectra

SN II --- hydrogen lines

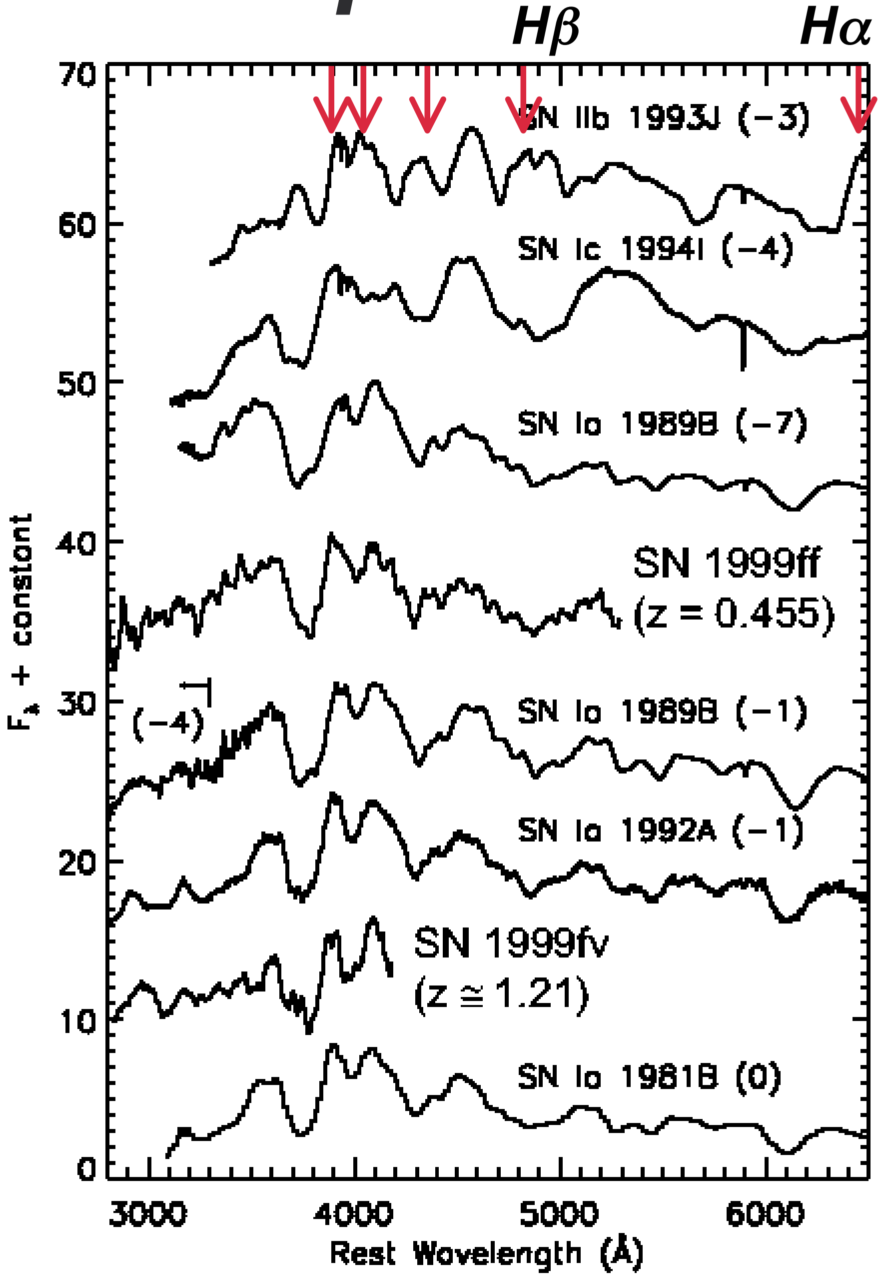
(collapse and rebound of the core of a massive star)

SN I --- no hydrogen lines

(no H-rich envelope surrounding the core)

SN Ia --- best known standard candles

(implosion of 1.4 Msun white dwarf, probably due to accretion in a mass-transfer binary system).



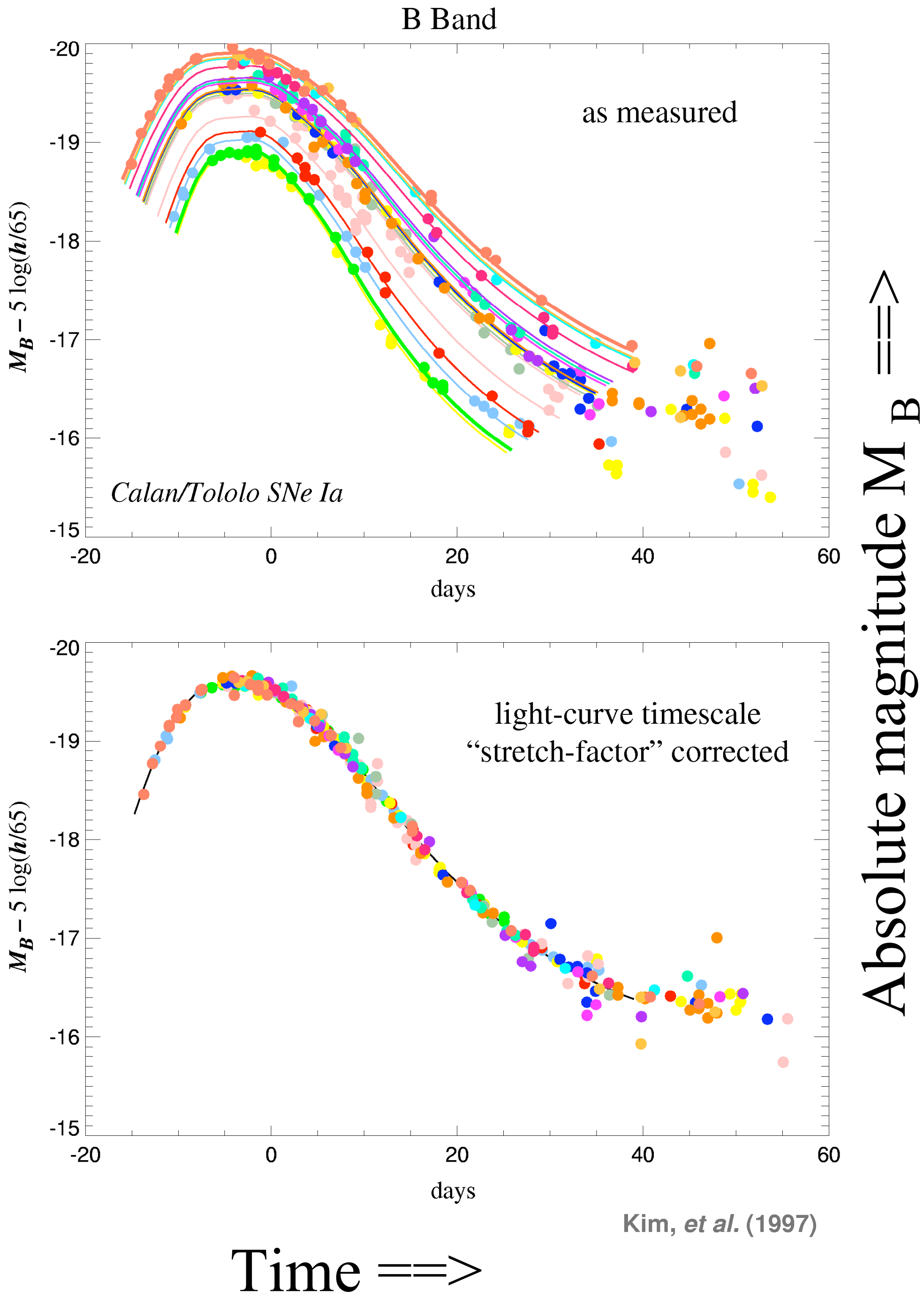
Calibrating "Standard Bombs"

1. Brighter ones decline more slowly.

2. Time runs slower by factor (1+z).

AFTER correcting:
Constant peak brightness
$M_B = -19.7$

Observed peak magnitude:
$m = M + 5 \log (d/\text{Mpc}) + 25$
gives the distance!



SN Ia at z ~ 0.8 are ~25% fainter than expected

Acceleration (! ?)

1. Bad Observations?

-- 2 independent teams agree

1. Dust ?

-- corrected using reddening

2. Stellar populations ?

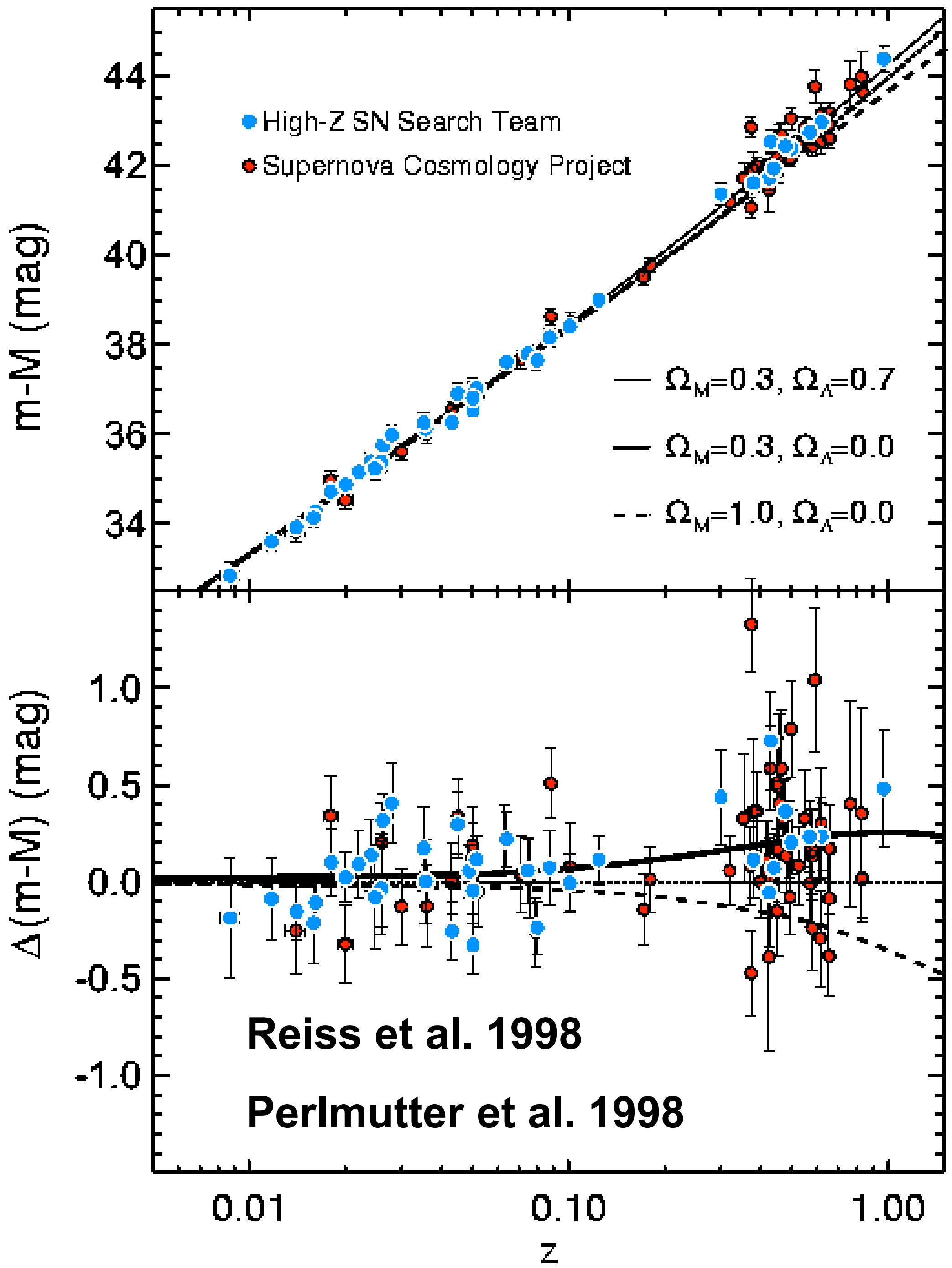
-- earlier generation of stars

-- lower metalicity

3. Lensing?

-- some brighter, some fainter

-- effect small at z ~ 0.8



1998 cosmology revolution

Acceleration (! ?)

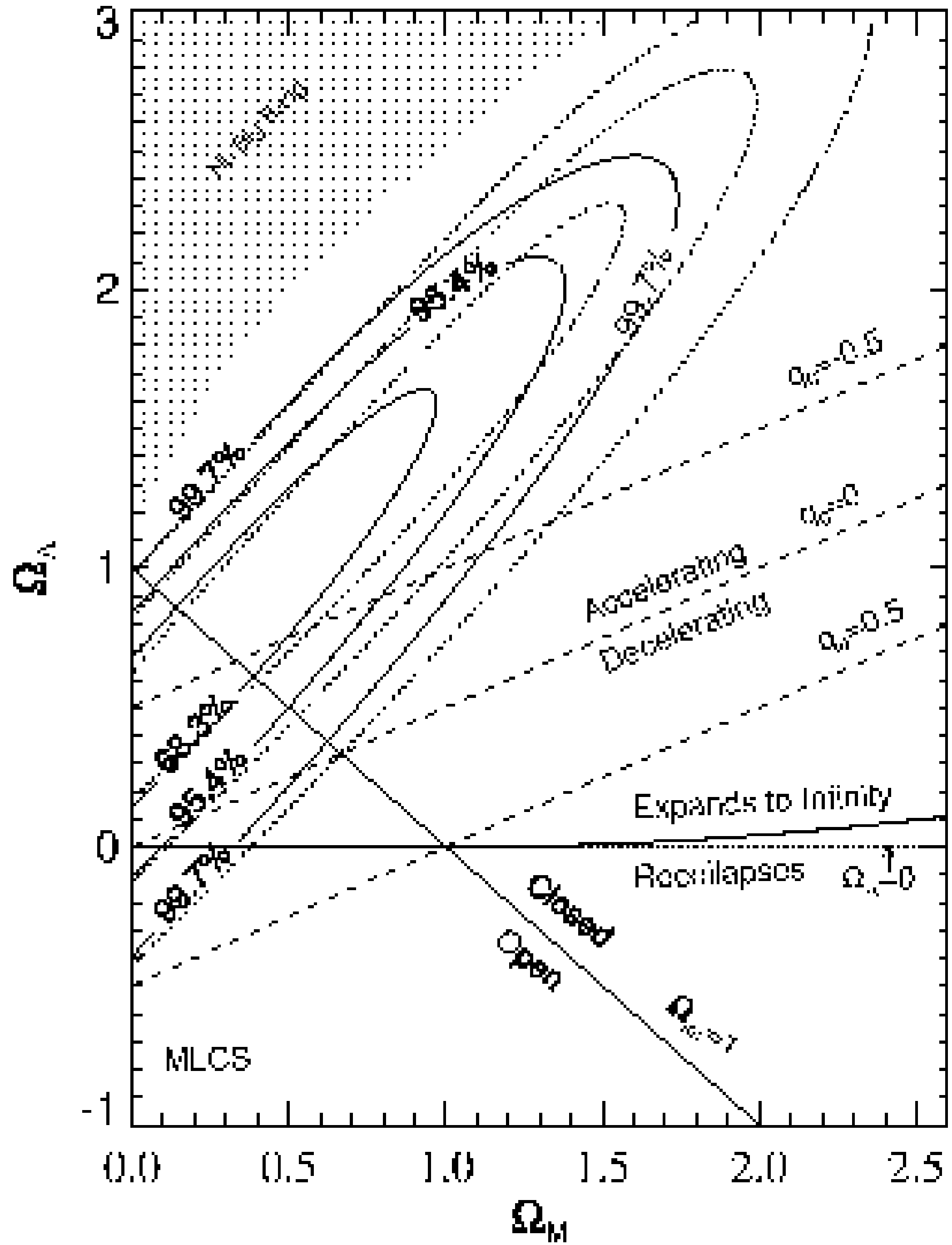
matter-only models ruled out

cosmological constant $\Lambda > 0$

“Dark Energy”

$$\text{if} \quad \Omega_0 = \Omega_M + \Omega_\Lambda = 1$$

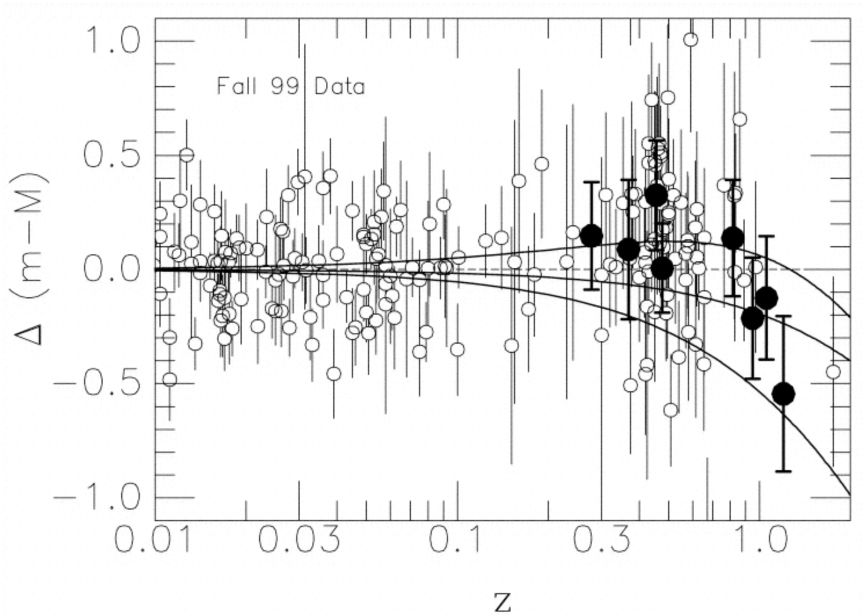
$$\text{then } \Omega_M \sim 0.3 \quad \Omega_\Lambda \sim 0.7$$

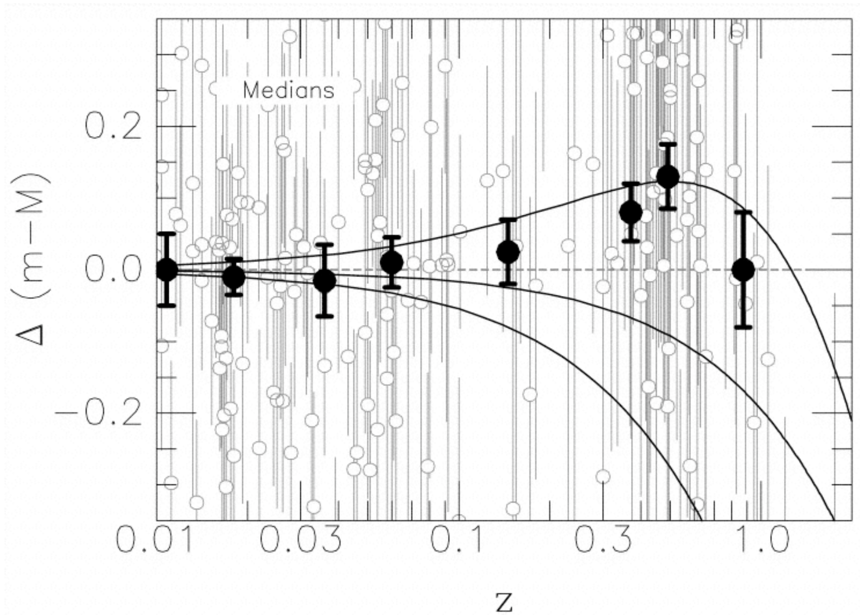


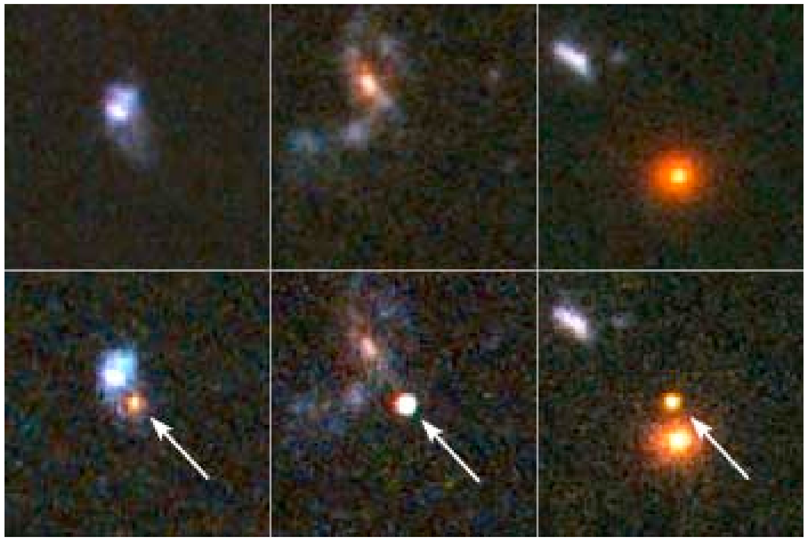
HST Supernova Surveys

Tonry et al. 2004.

HST surveys to find SN Ia beyond z = 1

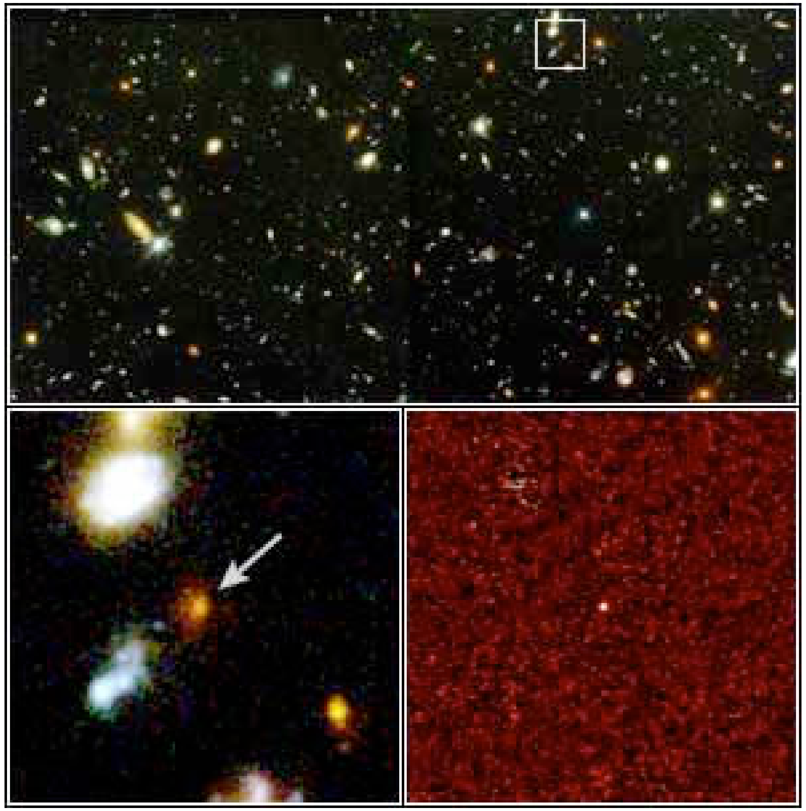




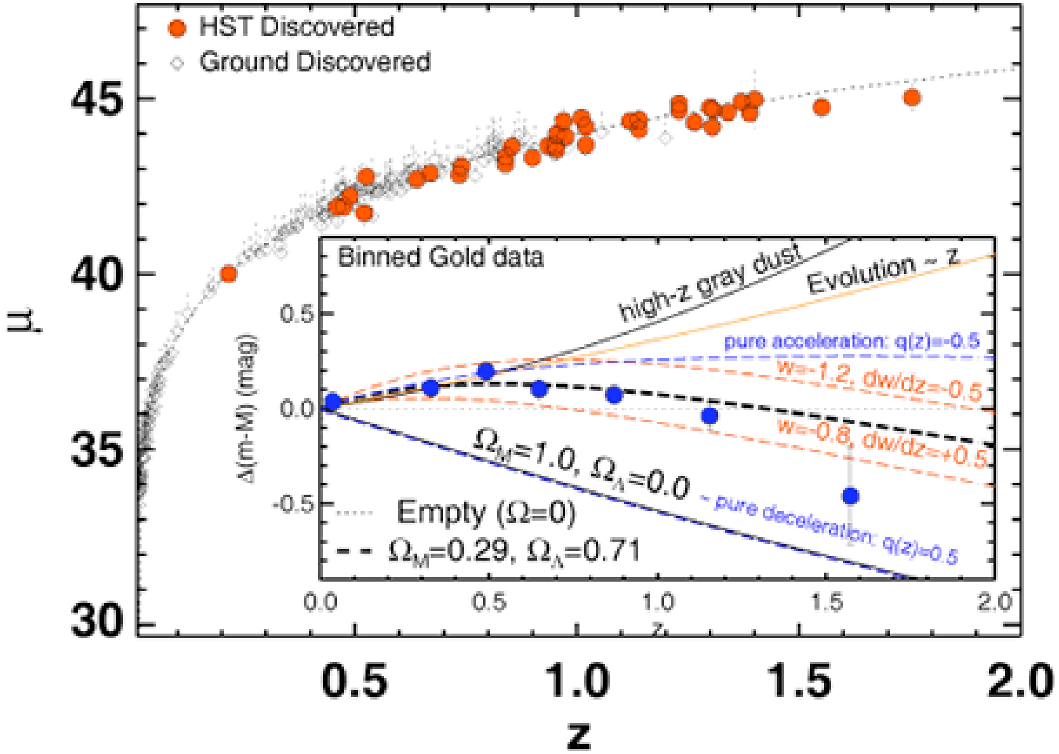


25 HST SN 1a beyond z = 1

Most distant Supernova
SN 2007ff z =1.75



Reiss et al. 2007.



SNAP = SuperNova Acceleration Probe

1.5m wide-angle multi-colour space telescope --- 1000 SN 1a

(Not Yet Funded)