Cosmology with Supernovae

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Outline

Systematics of Type Ia Supernovae

The Hubble diagram of Type Ia Supernovae

From distances to acceleration

The equation of state parameter

The principle

Establish a cosmological distance indicator in the local universe ($z<0.05$)

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evolution (primary and secondary)
interstellar and intergalactic dust
gravitational lensing

Measure objects at cosmological distances

- **establish identity of distance indicator**
- **control measurement errors**

The experiment

Establish a cosmological distance indicator in the local universe (z<0.05)

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evolution → **light curve shapes, colours, spectroscopy**

dust → **colours, spectroscopy**

gravitational lensing → **difficult, need mapping of light beam**

Measure objects at cosmological distances

- **77 distant SNe Ia (0.3<z<1.0) published**

  (Garnavich et al. 1998, Riess et al. 1998, Perlmutter et al. 1997, 1999, Tonry et al. 2003, Suntzeff et al. 2003, Jha et al. 2003, Leibundgut et al. 2003)

Steps in the analysis

Accurate photometry → photometric system

Secure classification → spectroscopy

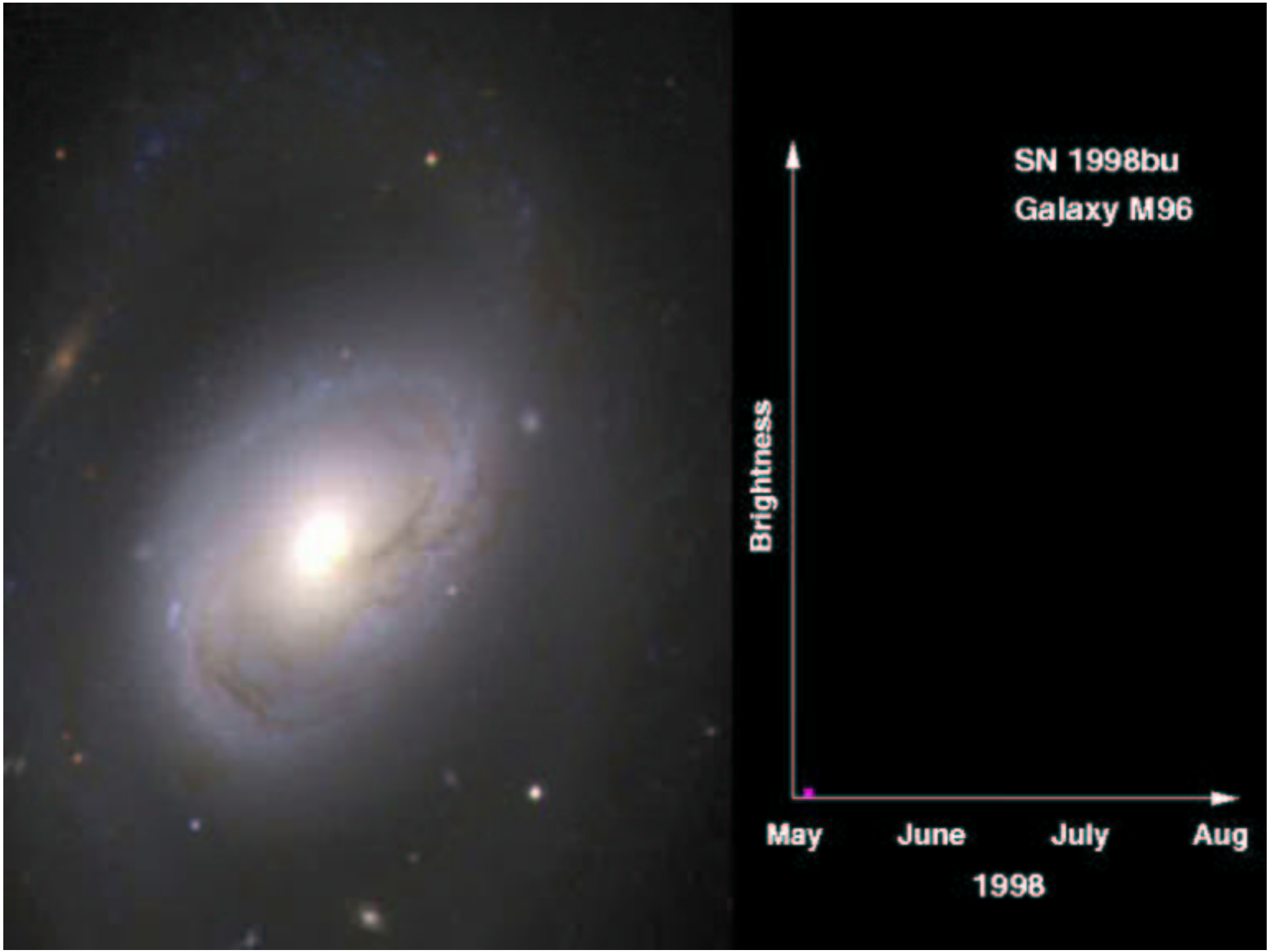
Light curve → photometry, epoch, K-corrections

Normalisation → light curves, colours

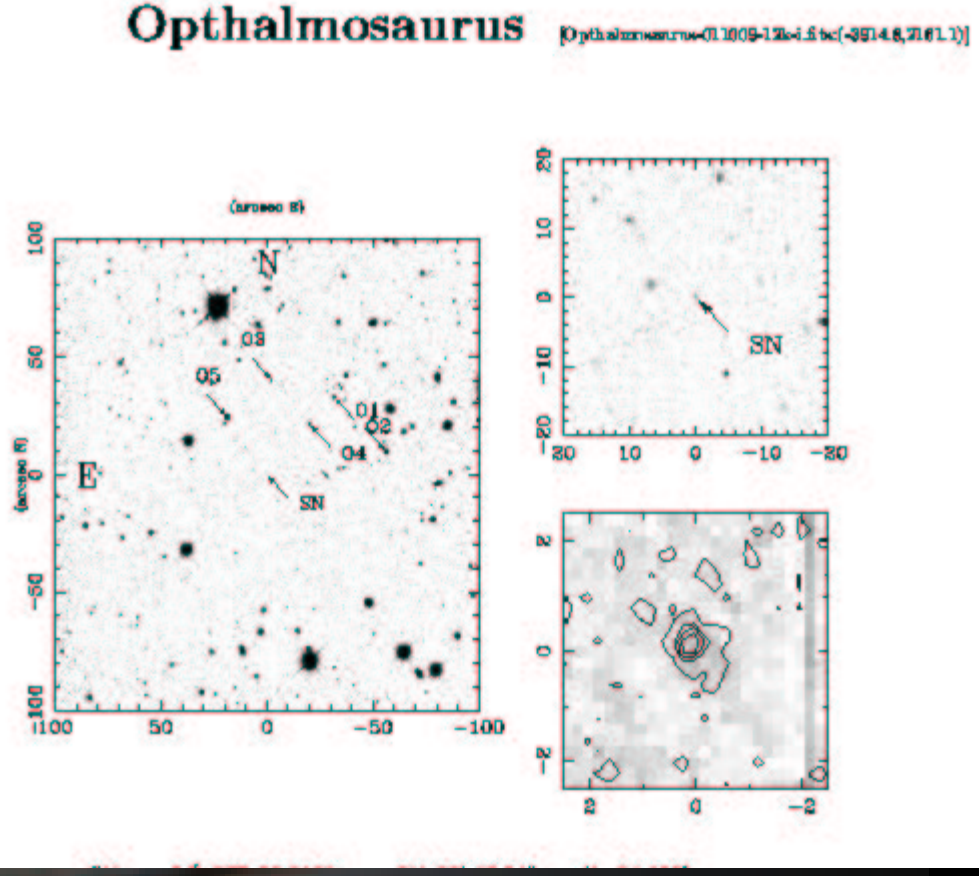
Distances → local calibration

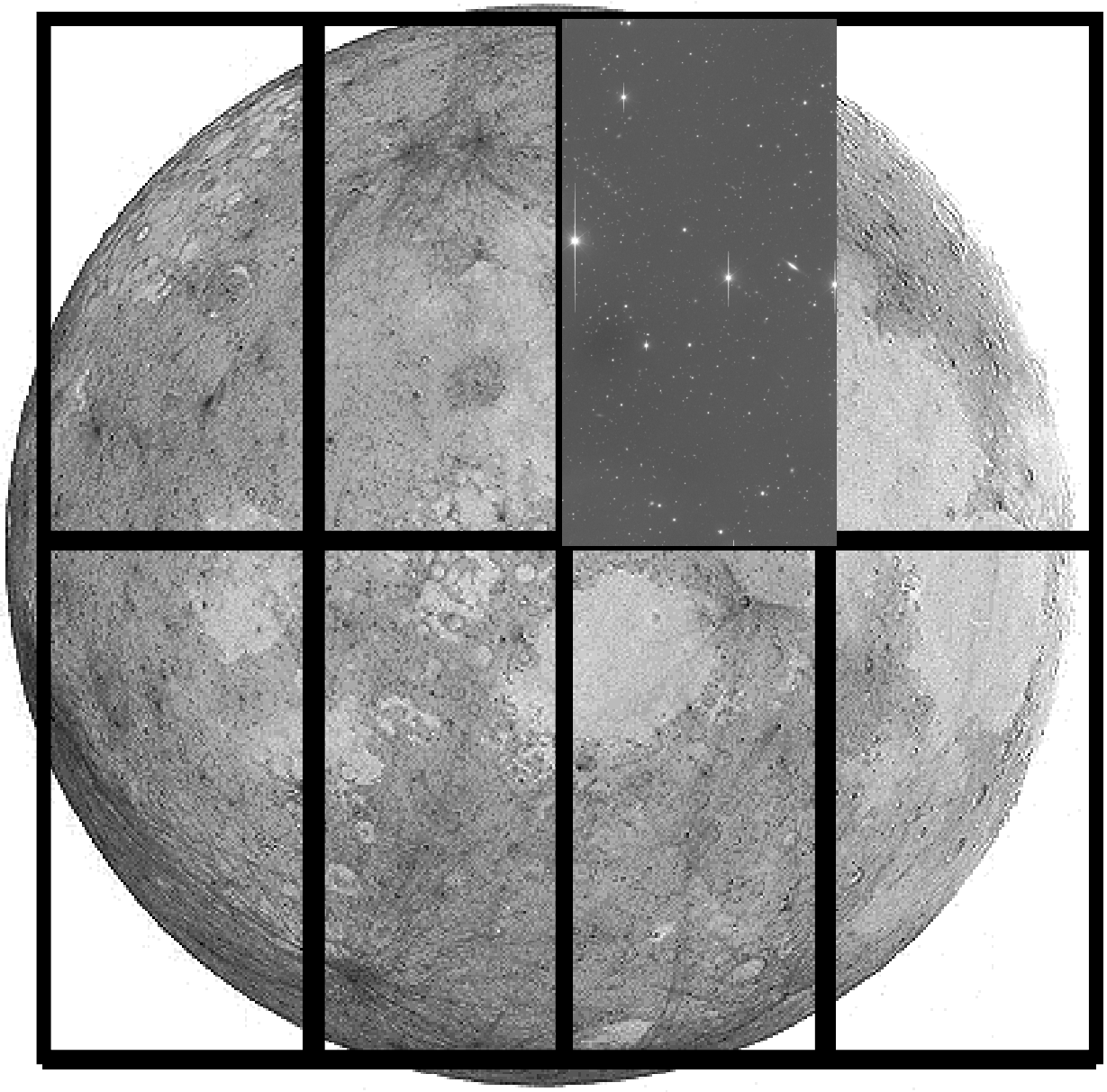
Cosmological parameters → luminosity distances

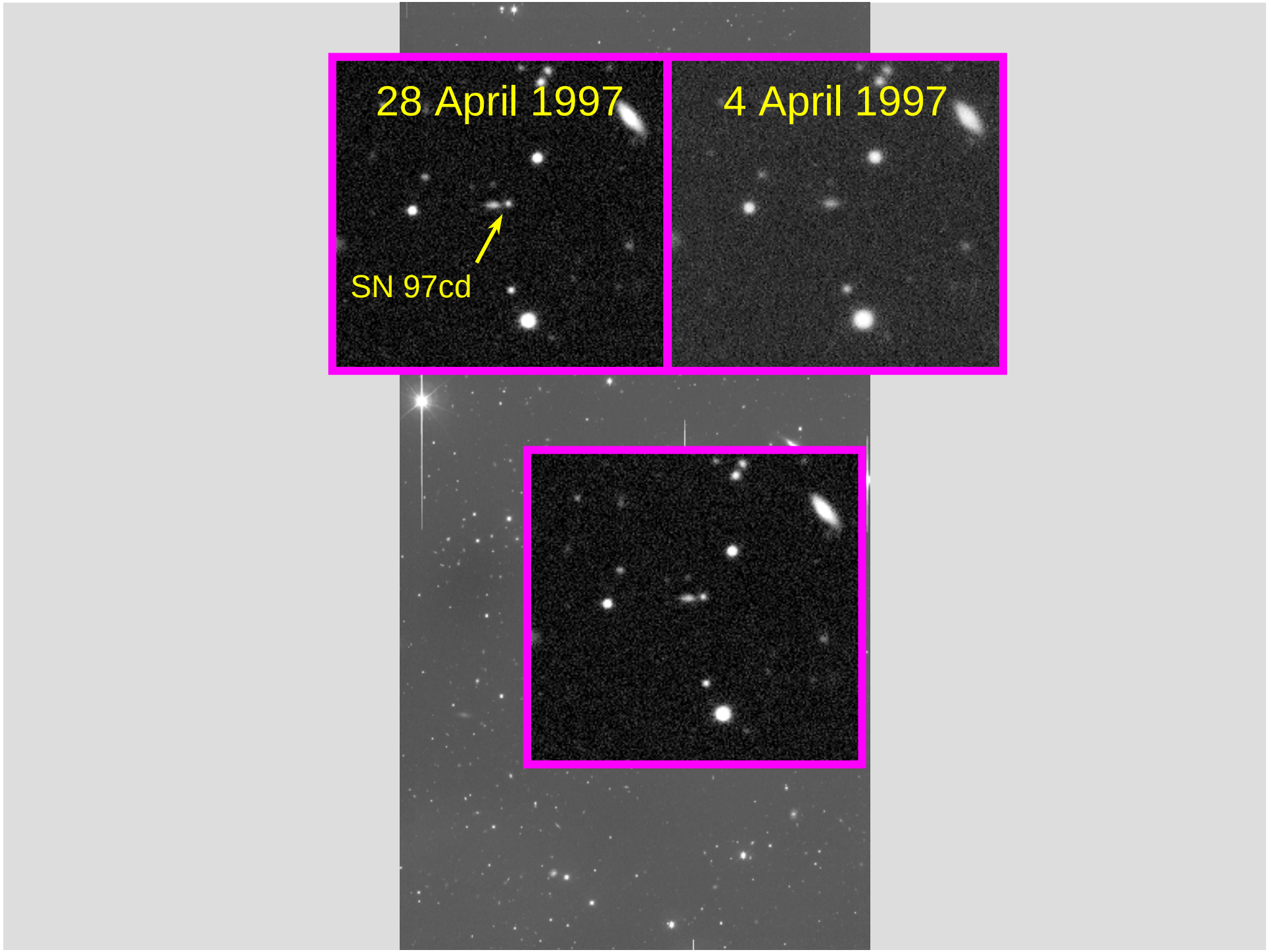
Cosmological implications → cosmological models


SN 1998bu
Galaxy M96
Brightness
May
June
July
Aug
1998

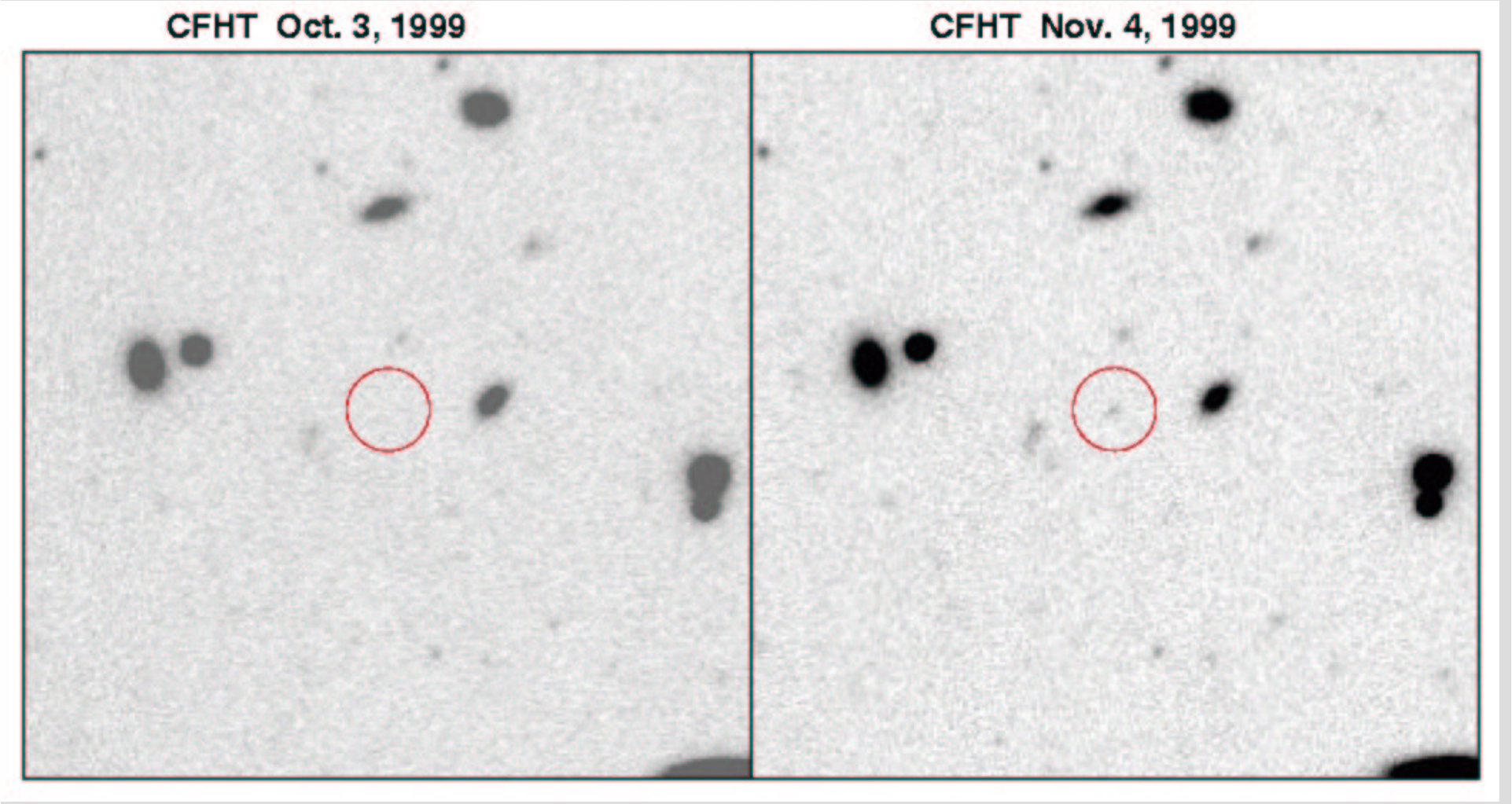
SN 1994D



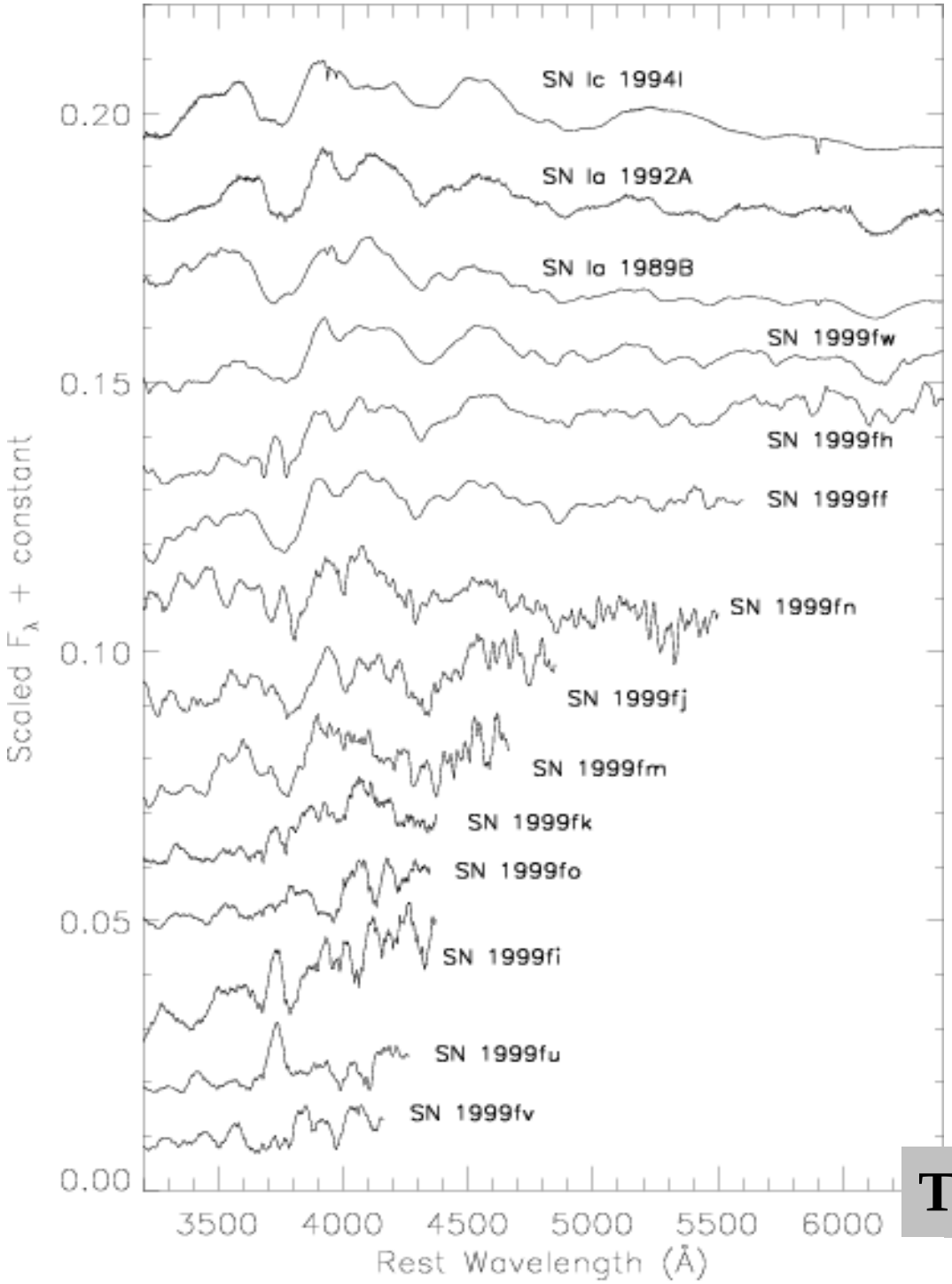



28 April 1997
4 April 1997
SN 97cd

Tonry et al. 2003



Dudley Do-Right

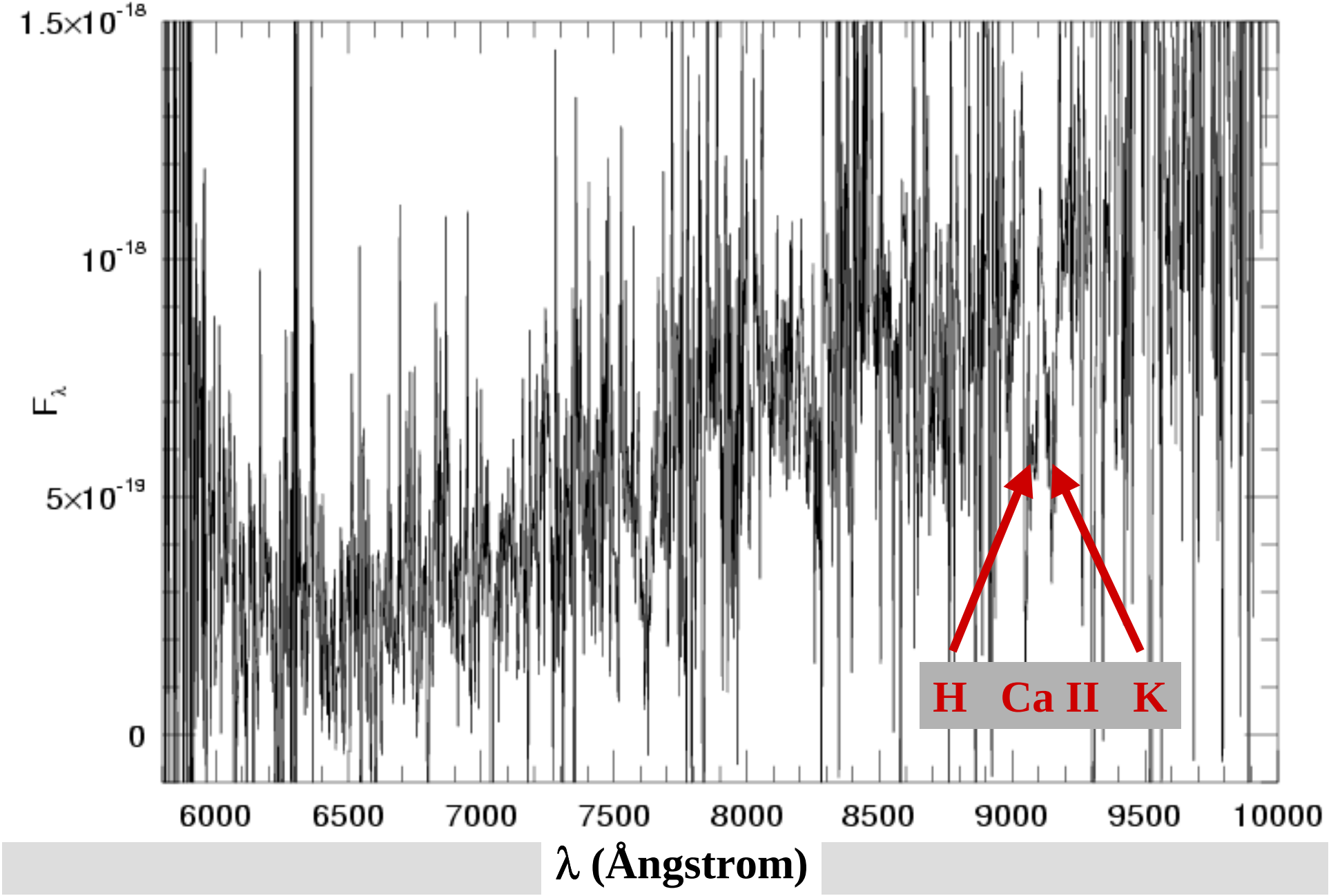


Classification

ype Ia Supernova

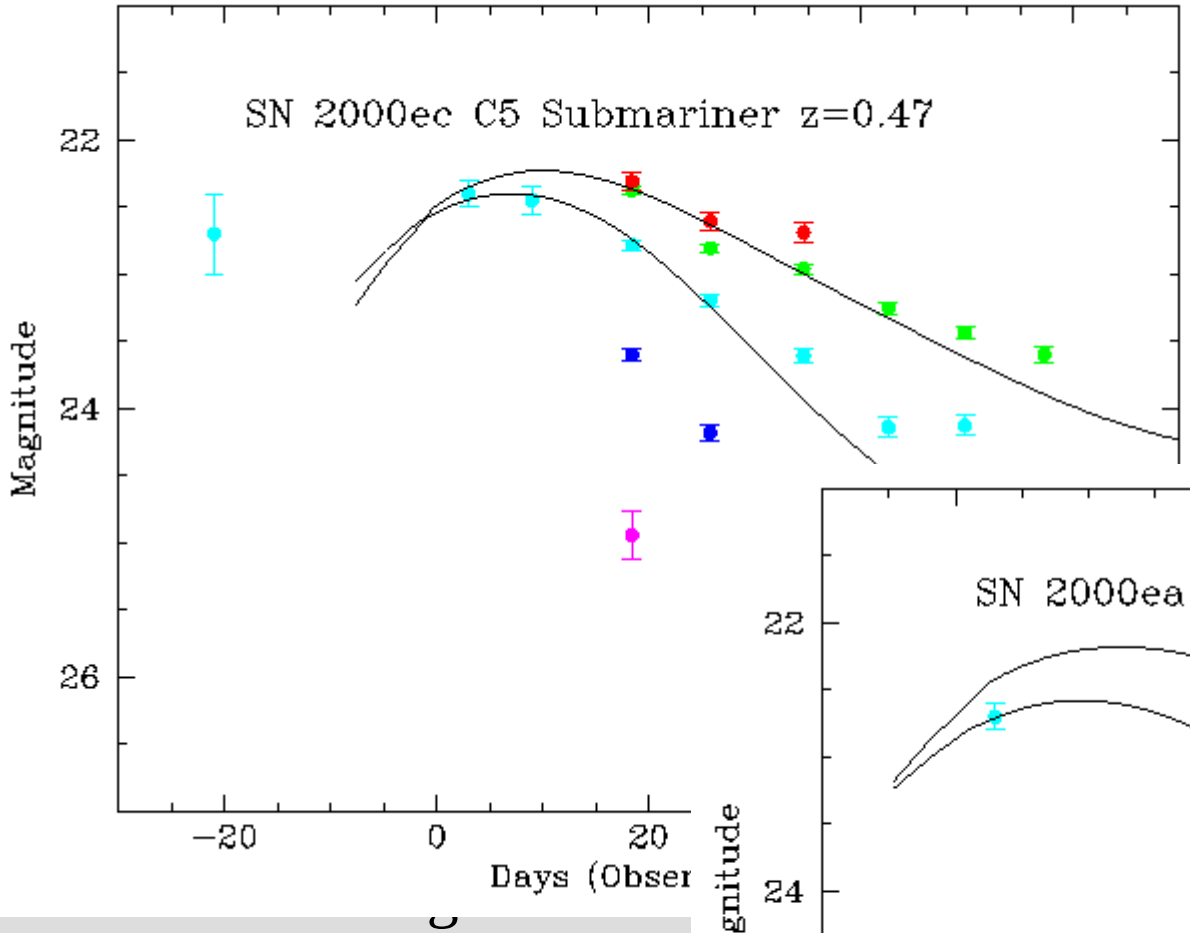
ernovae

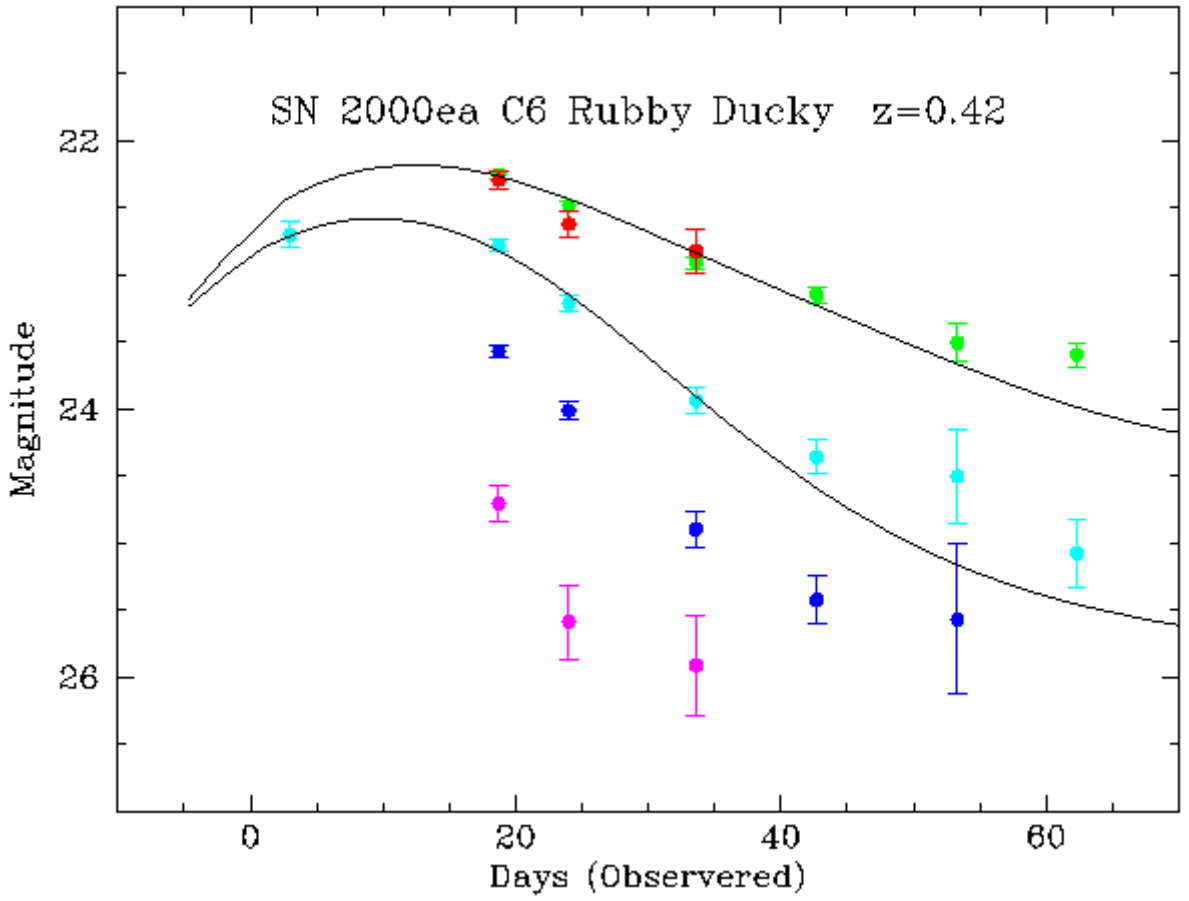
Tonry et al. 2003


1.5×10-18
10-18
5×10-19
0
Fλ
6000
6500
7000
7500
8000
8500
9000
9500
10000
λ (Ångstrom)
H
Ca II
K

ght Curves

the distance





Light Curves

Determine the maximum for the distance determination

- **K-corrections**
  - based on spectral series from nearby supernovae
- **light curve fitting**
  - light curve shape – luminosity correlation

Light curve shape – luminosity

Δm_{15} relation

Phillips (1993), Hamuy et al. (1996), Phillips et al. (1999)

MLCS

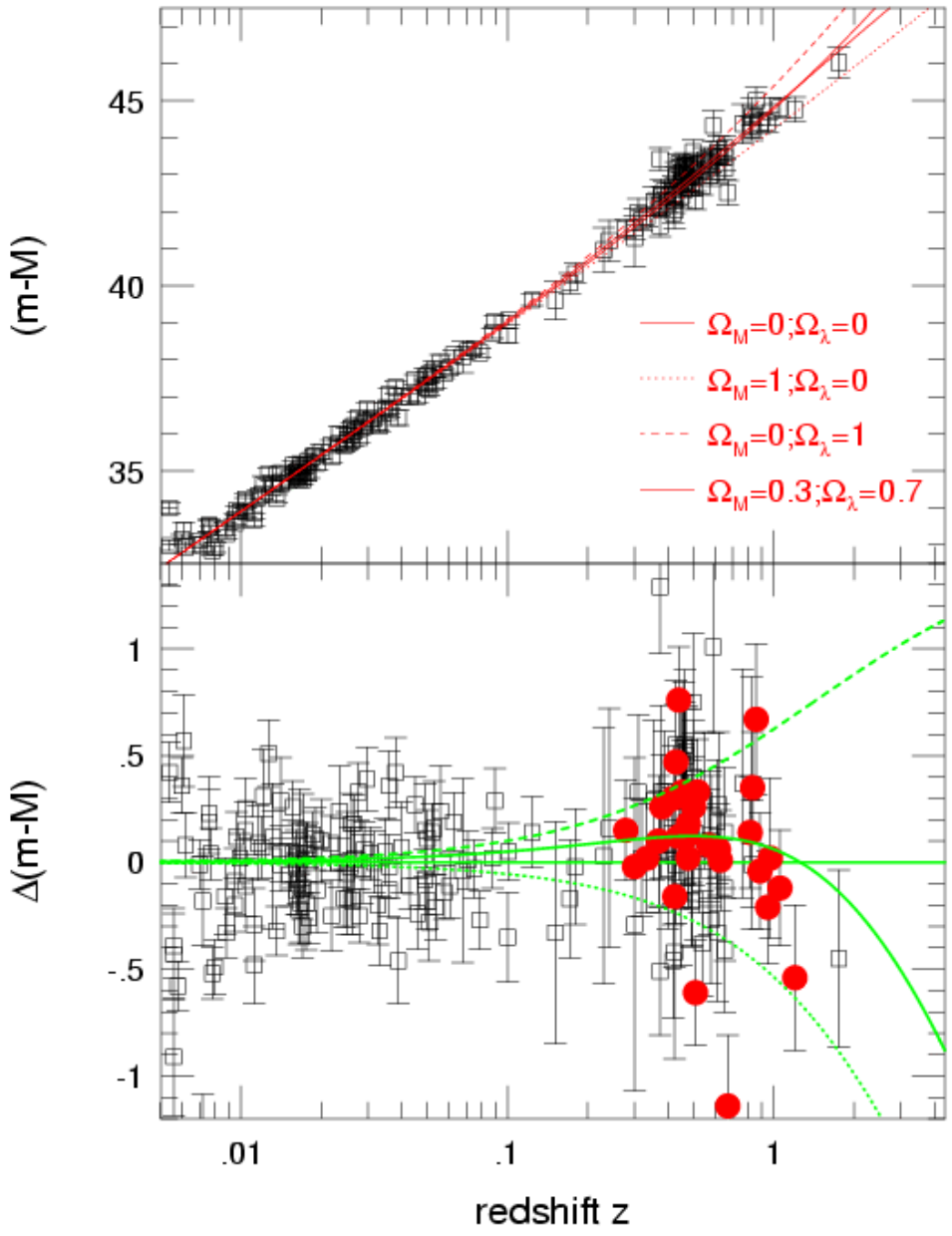
Riess et al. (1996, 1998), Jha et al. (2003)

stretch

Perlmutter et al. (1997, 1999), Goldhaber et al. (2001)

MAGIC

Wang et al. (2003)



Supernova cosmology

Tonry et al. 2003

Starting from Einstein's Field equation

Friedmann cosmology

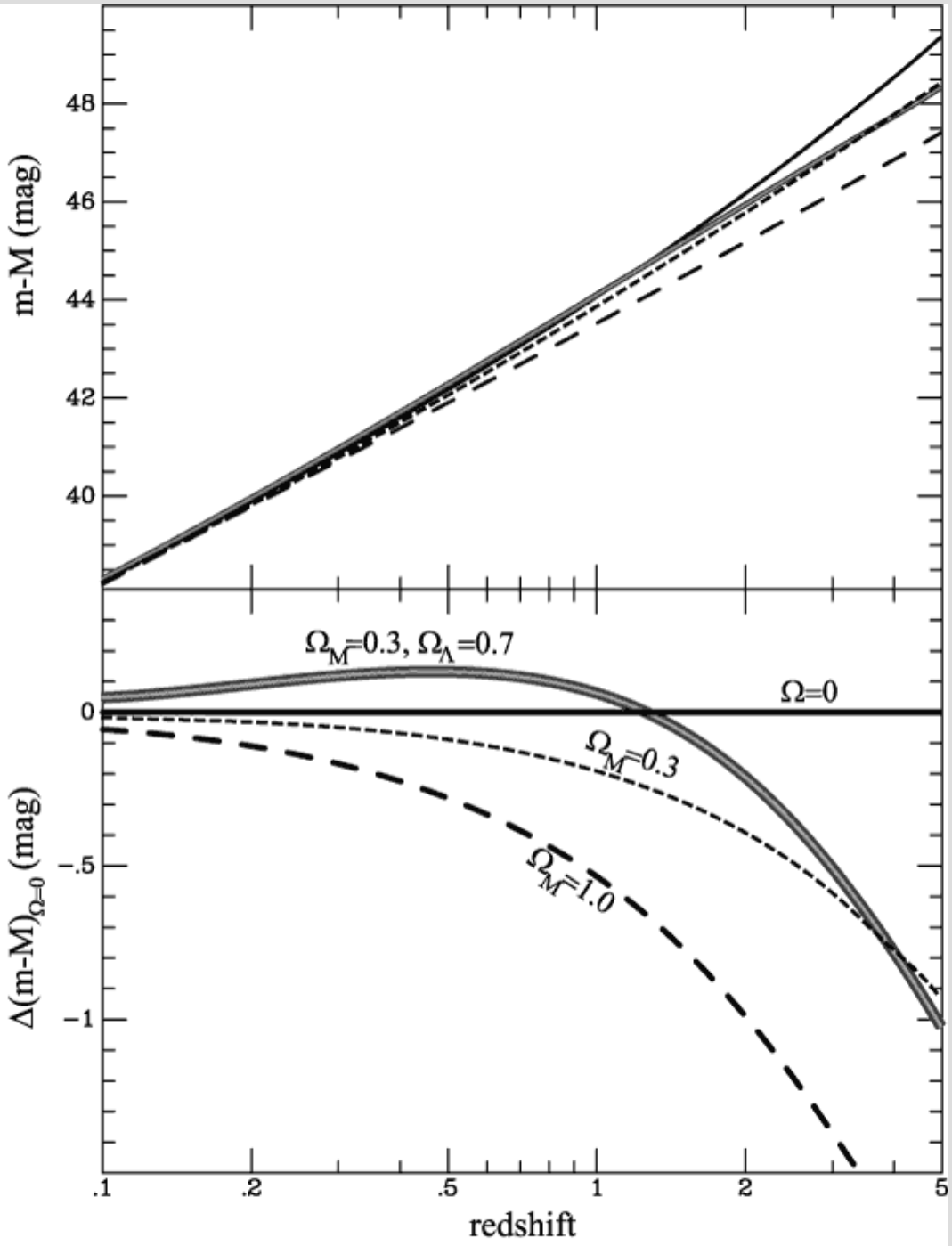
Assumption:
homogeneous and isotropic universe

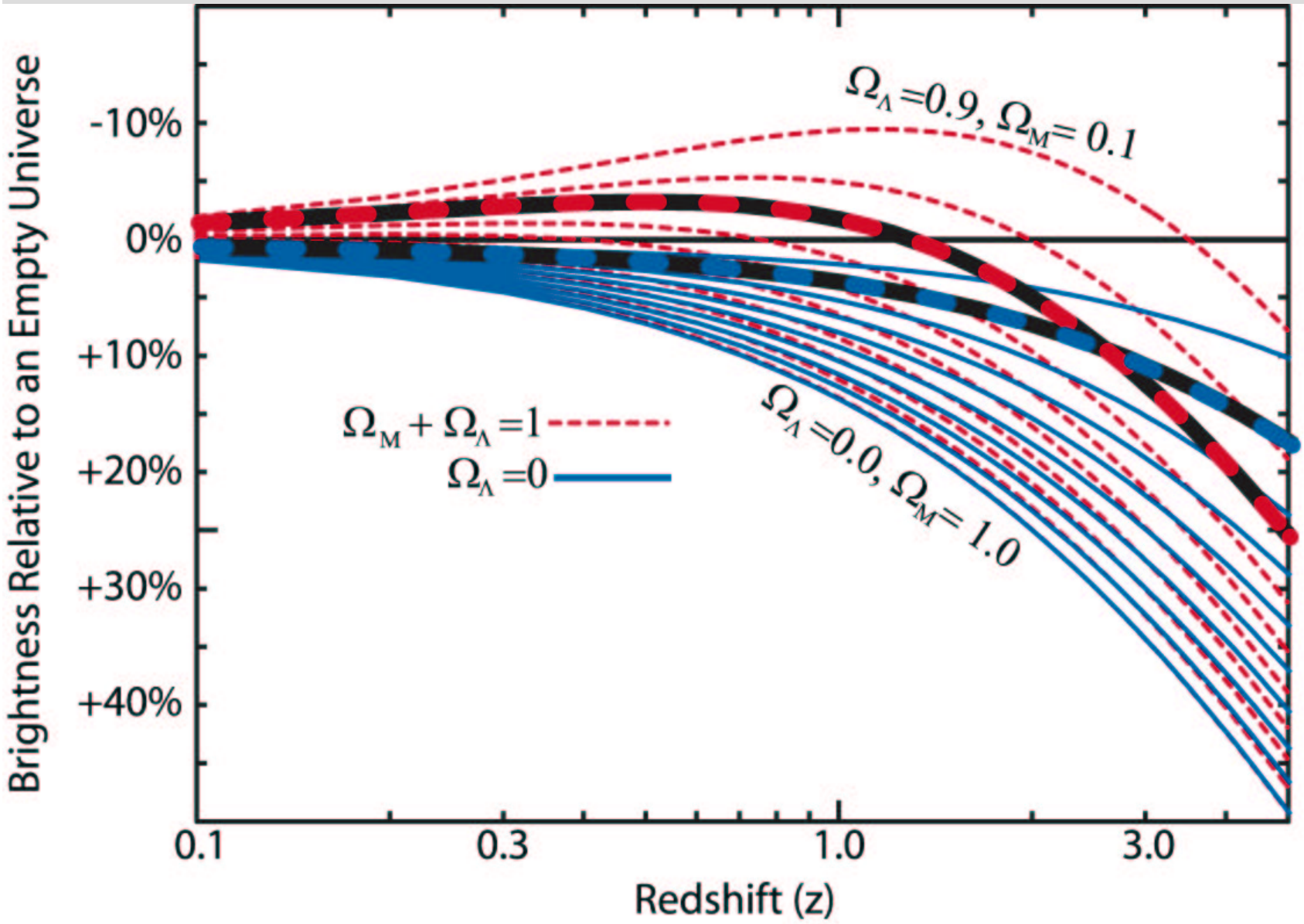
Null geodesic in a Friedmann-Robertson-Walker metric:

$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}}\, S\left\{\sqrt{|\Omega_\kappa|}\int_0^z \left[\Omega_\kappa (1+z')^2 + \Omega_M (1+z')^3 + \Omega_\Lambda\right]^{-1/2} dz'\right\}$$

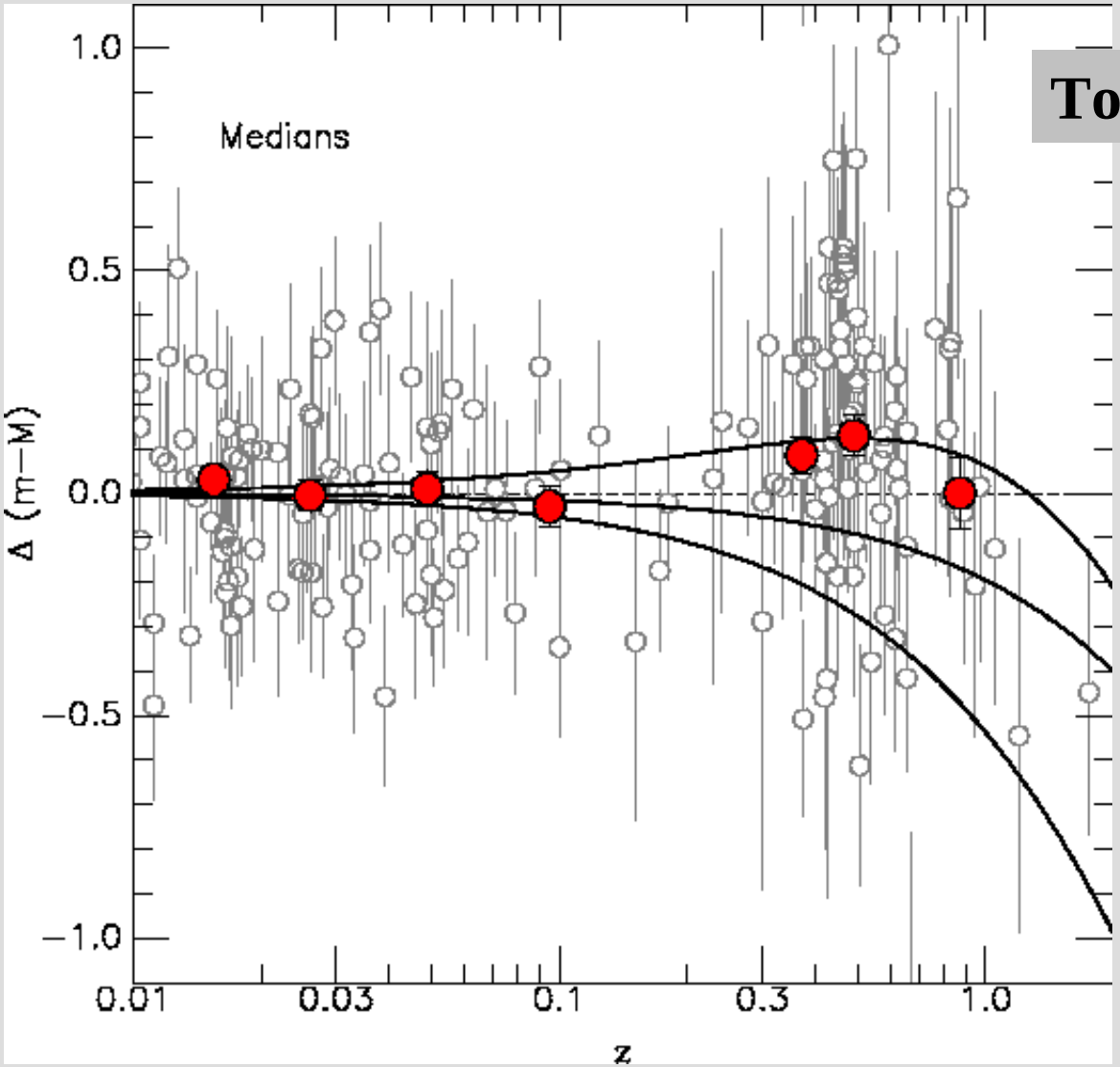
$$\Omega_M = \frac{8\pi G}{3H_0^2}\rho_M \qquad \Omega_k = -\frac{kc^2}{R^2 H_0^2} \qquad \Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$$

Cosmology in the Hubble diagram




Brightness Relative to an Empty Universe
-10%
0%
+10%
+20%
+30%
+40%
0.1
0.3
1.0
3.0
Redshift (z)
$\Omega_\Lambda = 0.9, \Omega_M = 0.1$
$\Omega_M + \Omega_\Lambda = 1$
$\Omega_\Lambda = 0$
$\Omega_\Lambda = 0.0, \Omega_M = 1.0$

209 SN Ia and medians



Tonry et al. 2003

Distant SNe Ia

Distant objects appear fainter than their nearby counterparts

This is a 2.5σ result (High-z SN Team and Supernova Cosmology Project)

- **evolution**
- **dust**
- **cosmology**

Checks:

Dust

- **observations over many filters**

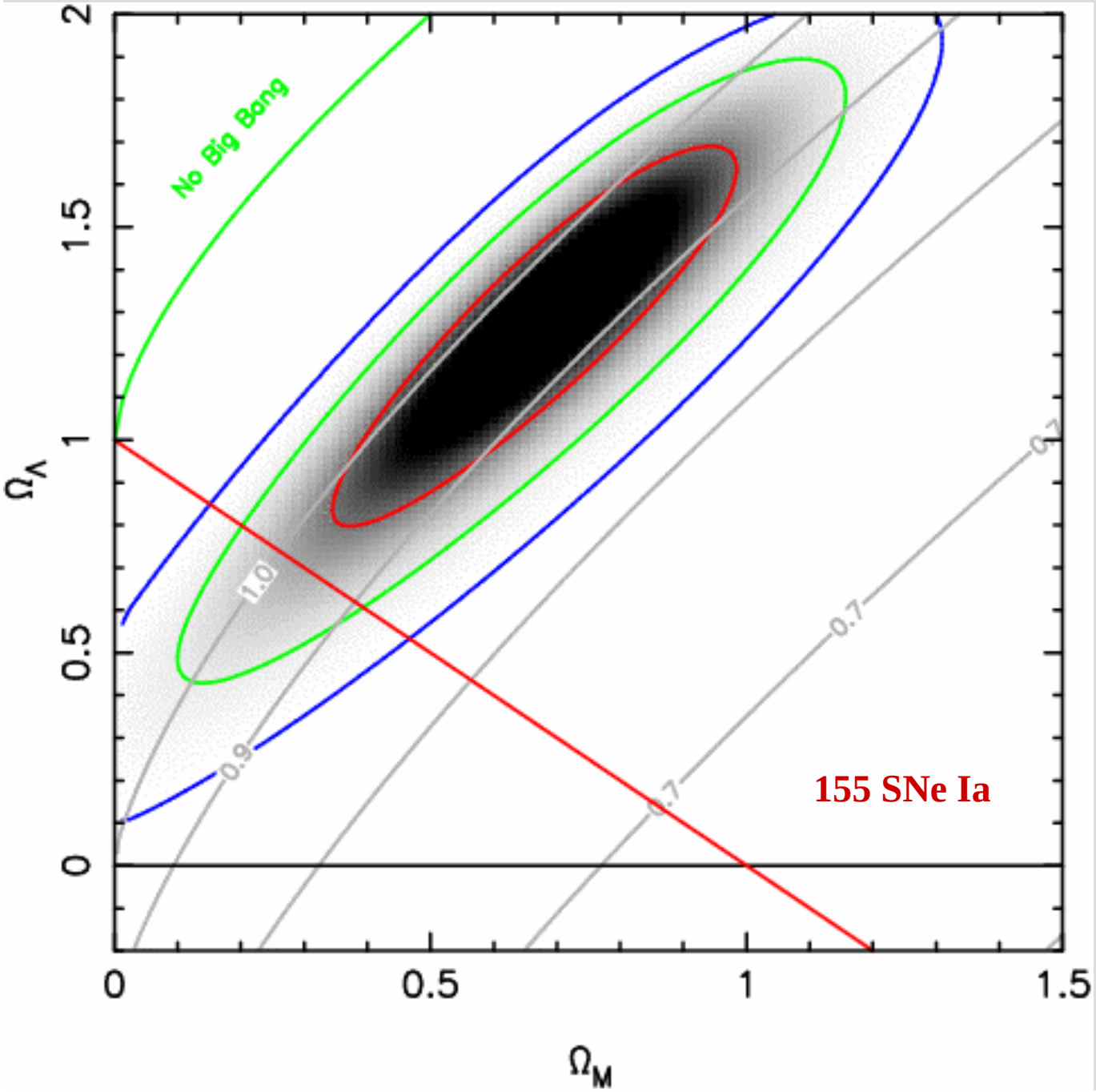
Evolution

- **spectroscopy**

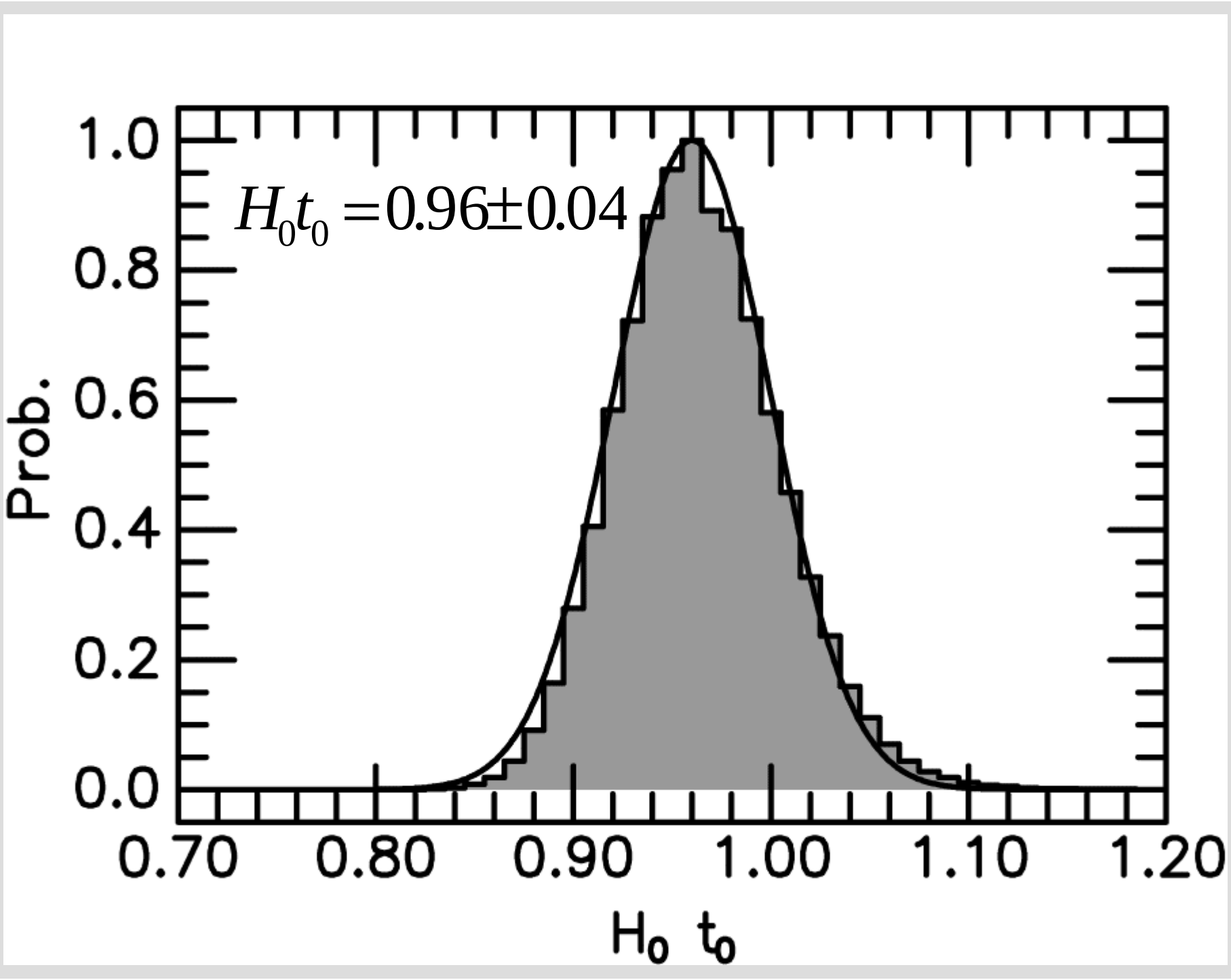
Cosmology

- **more distant SNe Ia**

Cosmology



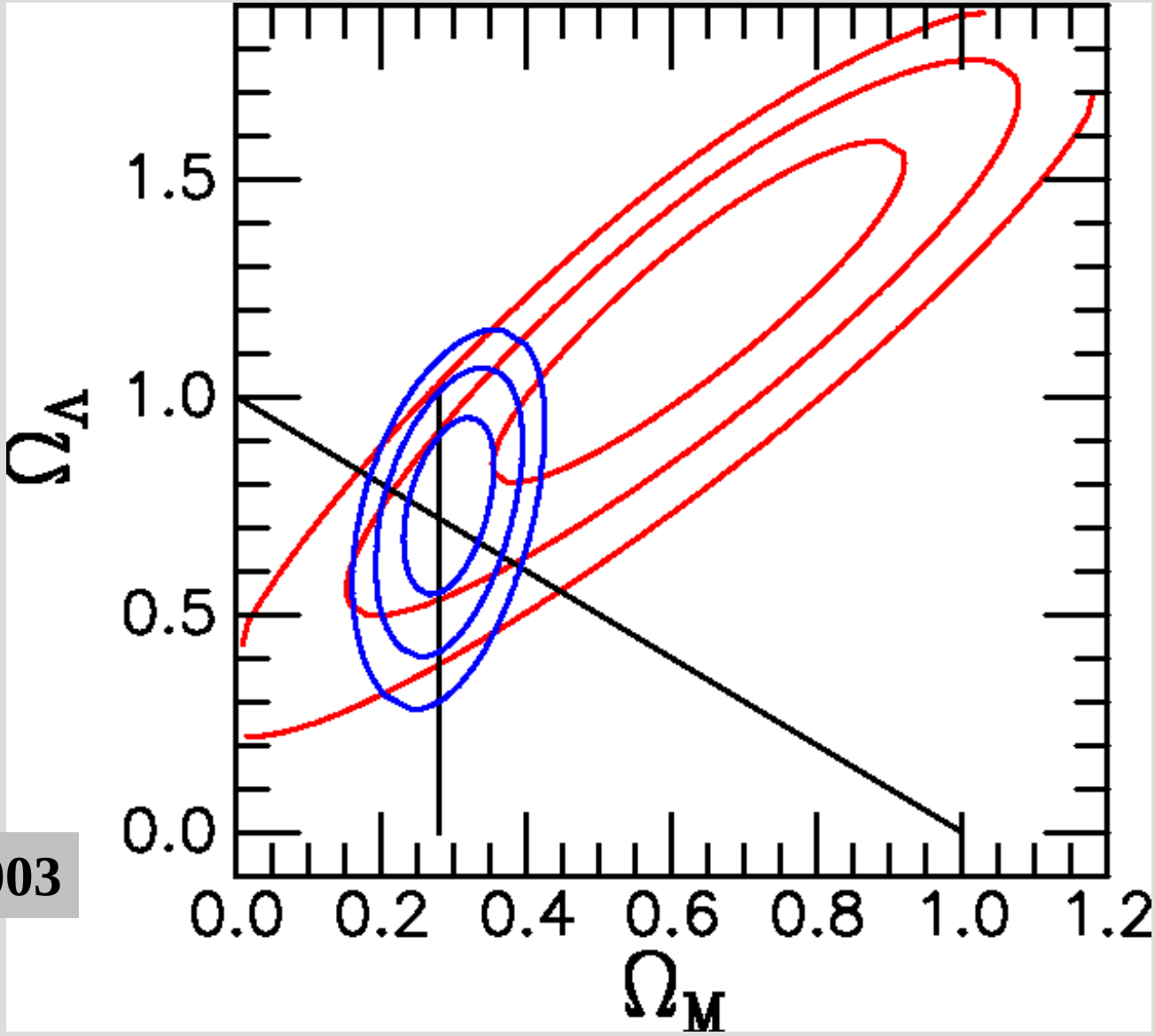
Tonry et al. 2003


$H_0 t_0 = 0.96 \pm 0.04$
Prob.
1.0
0.8
0.6
0.4
0.2
0.0
0.70
0.80
0.90
1.00
1.10
1.20
$H_0\ t_0$

SN Ia and 2dF constraints

2dF:
Ω_M=0.2±0.03

KP:
h = 0.72 ± 0.08



Tonry et al. 2003

2dF:
Ω_M=0.2±0.03

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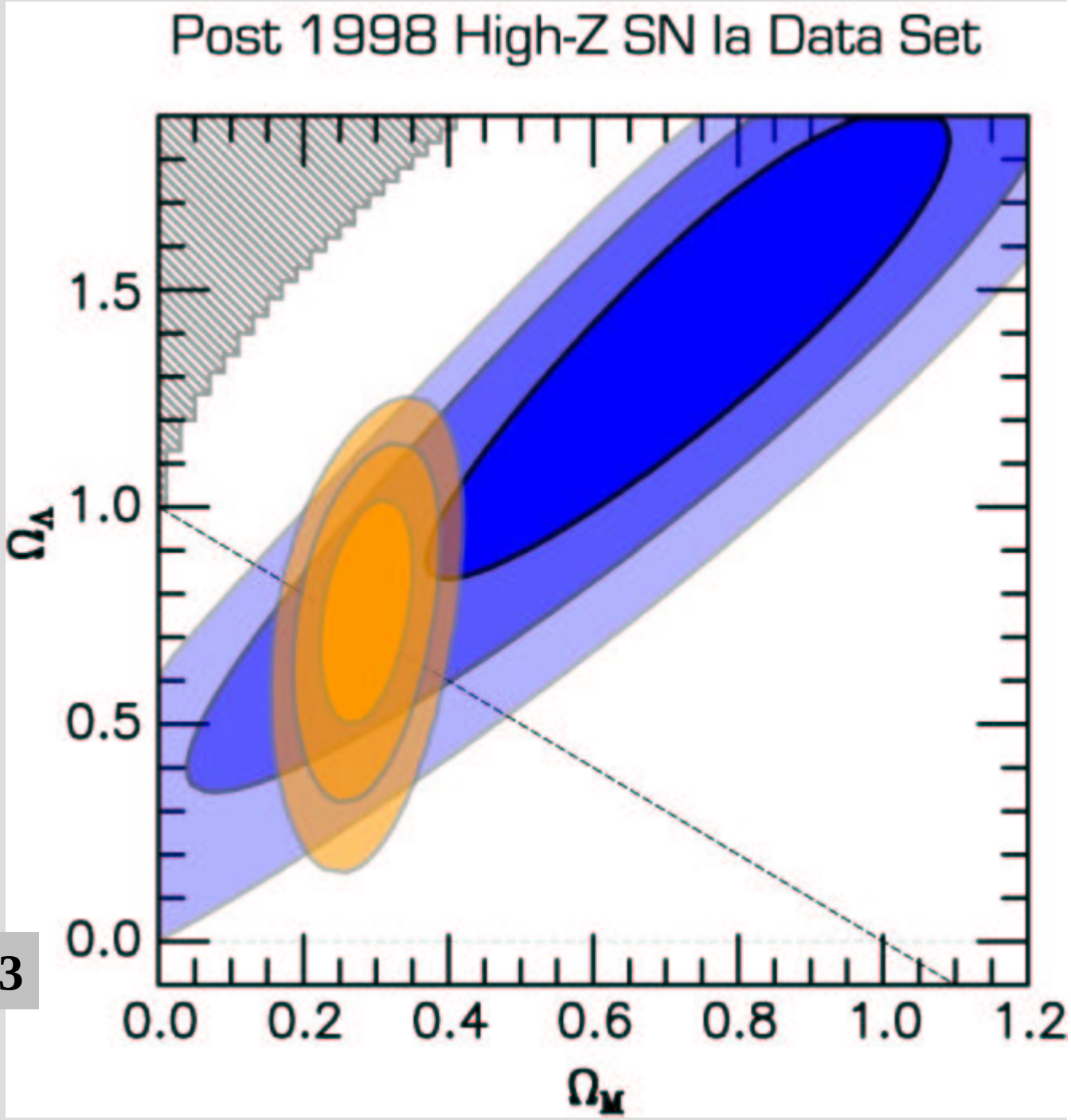


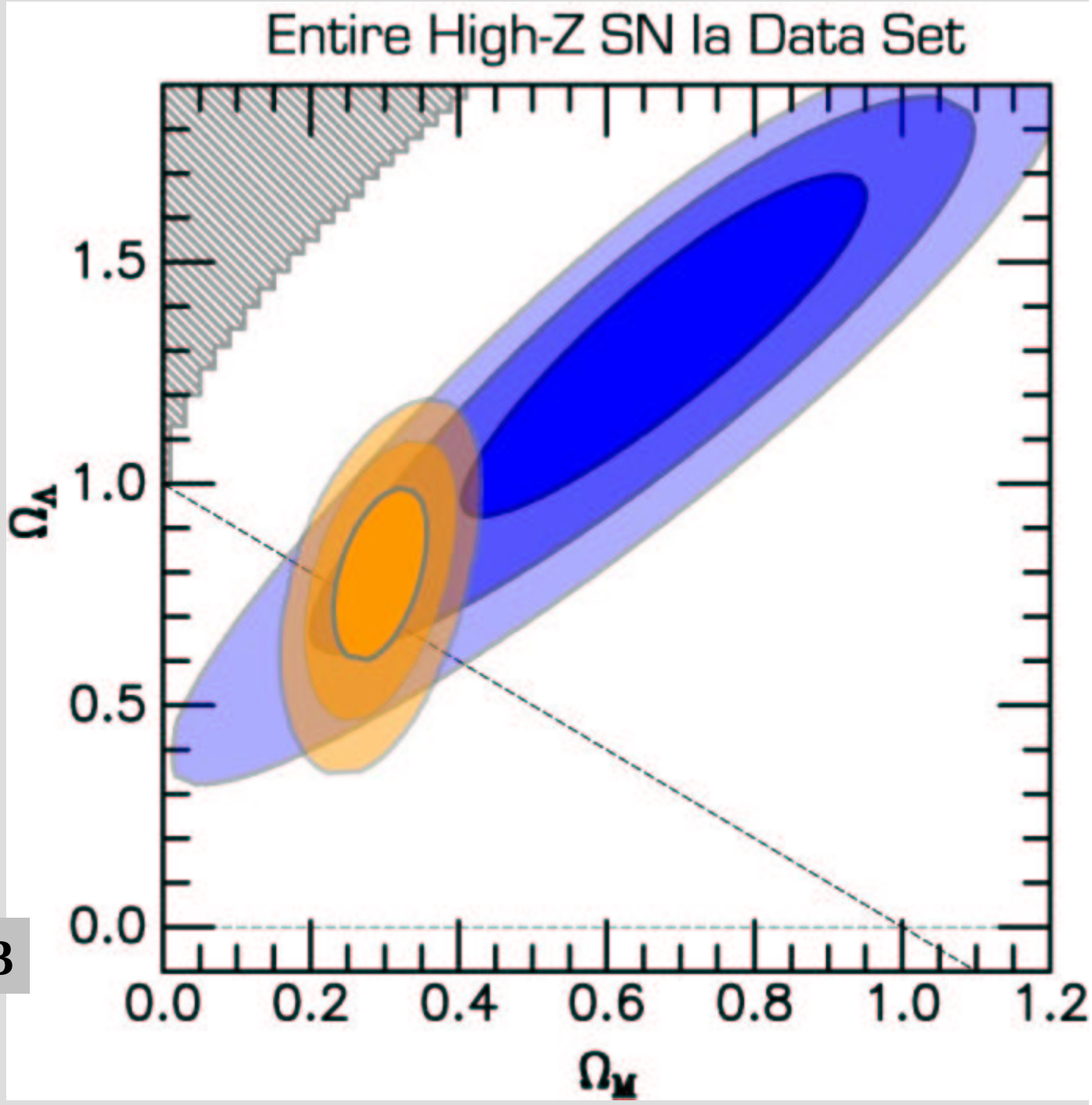
Tonry et al. 2003

2dF:

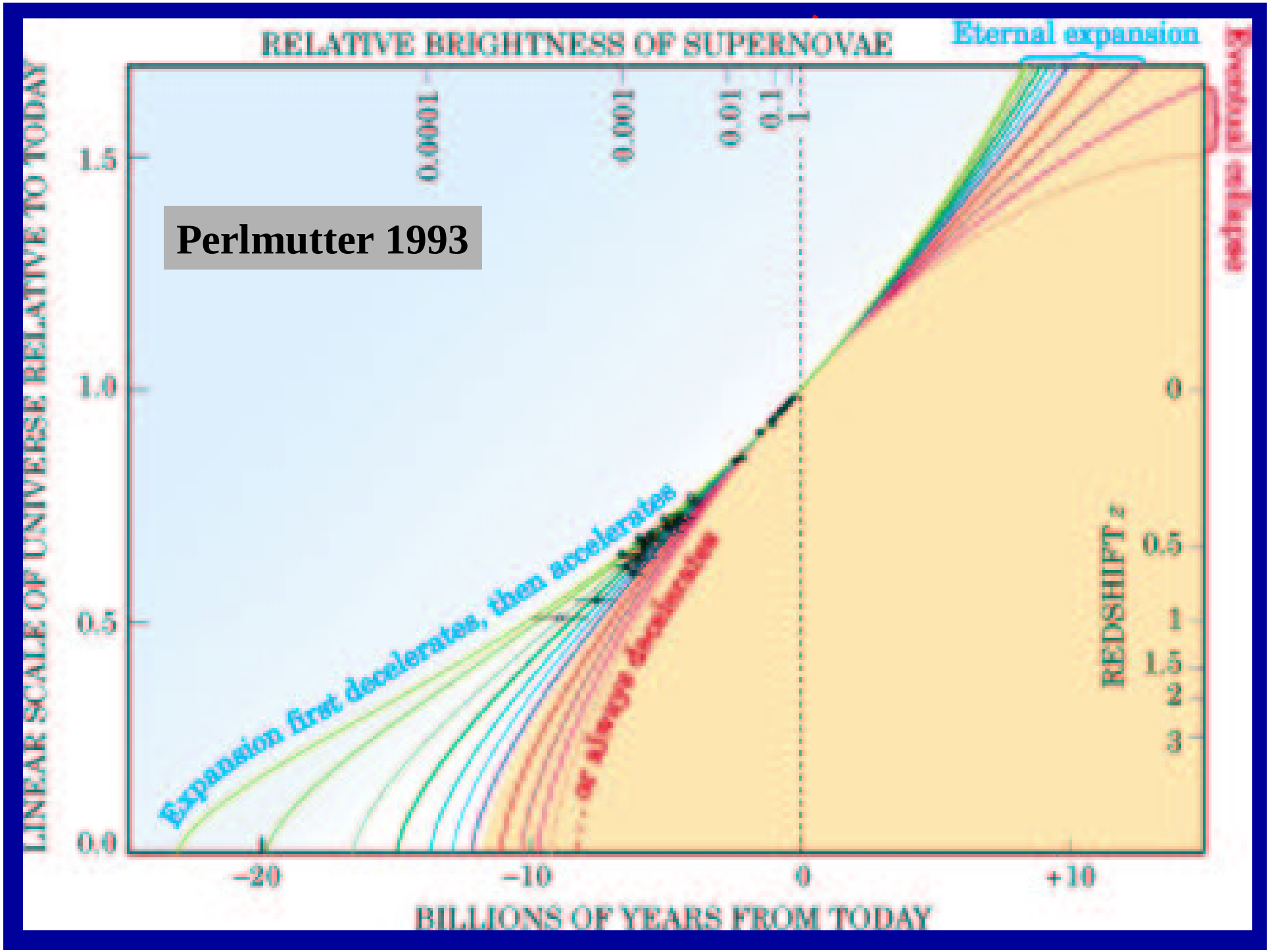
Ω_M*=0.2±0.03*

KP:

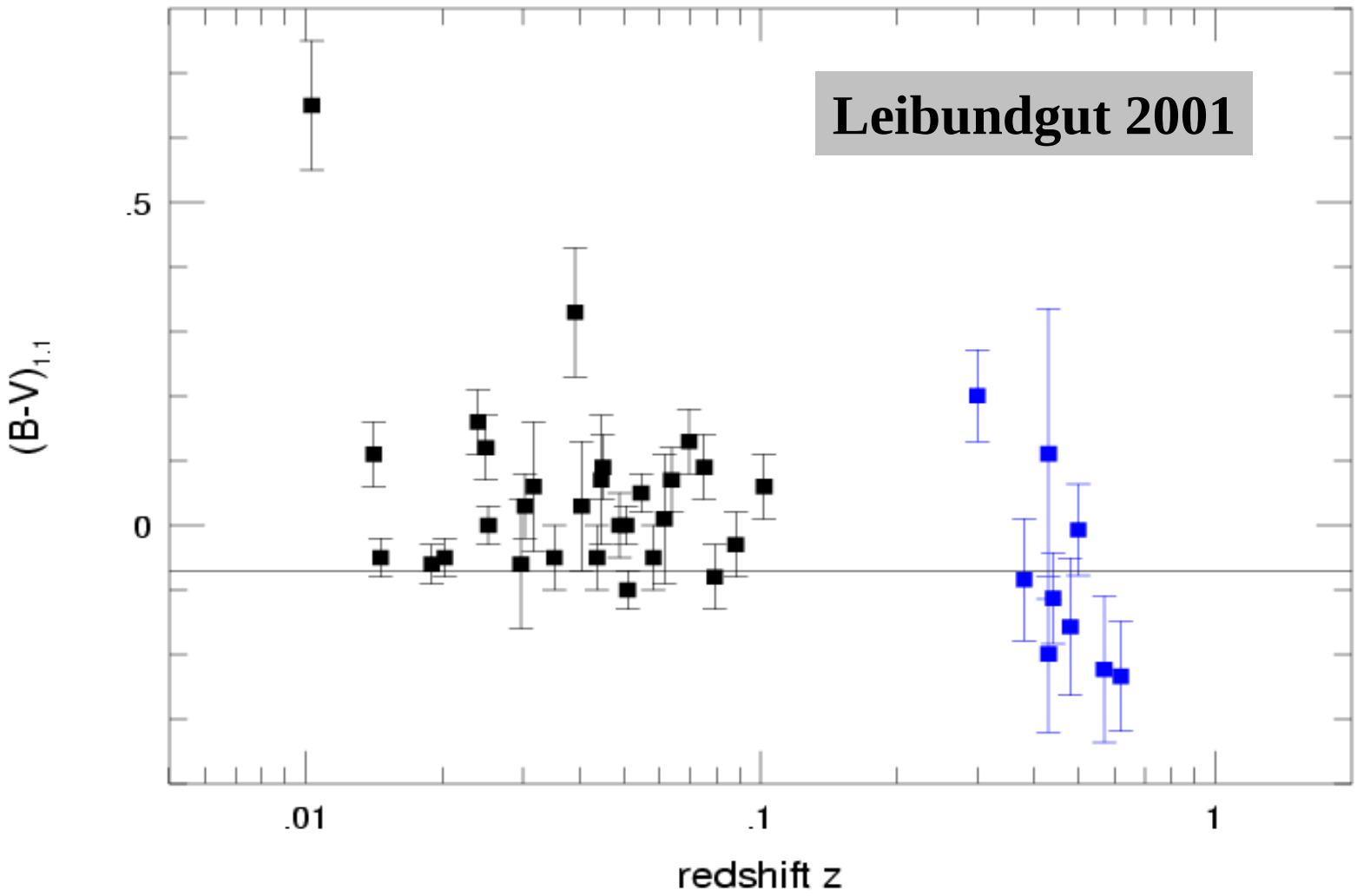
h = 0.72 ± 0.08



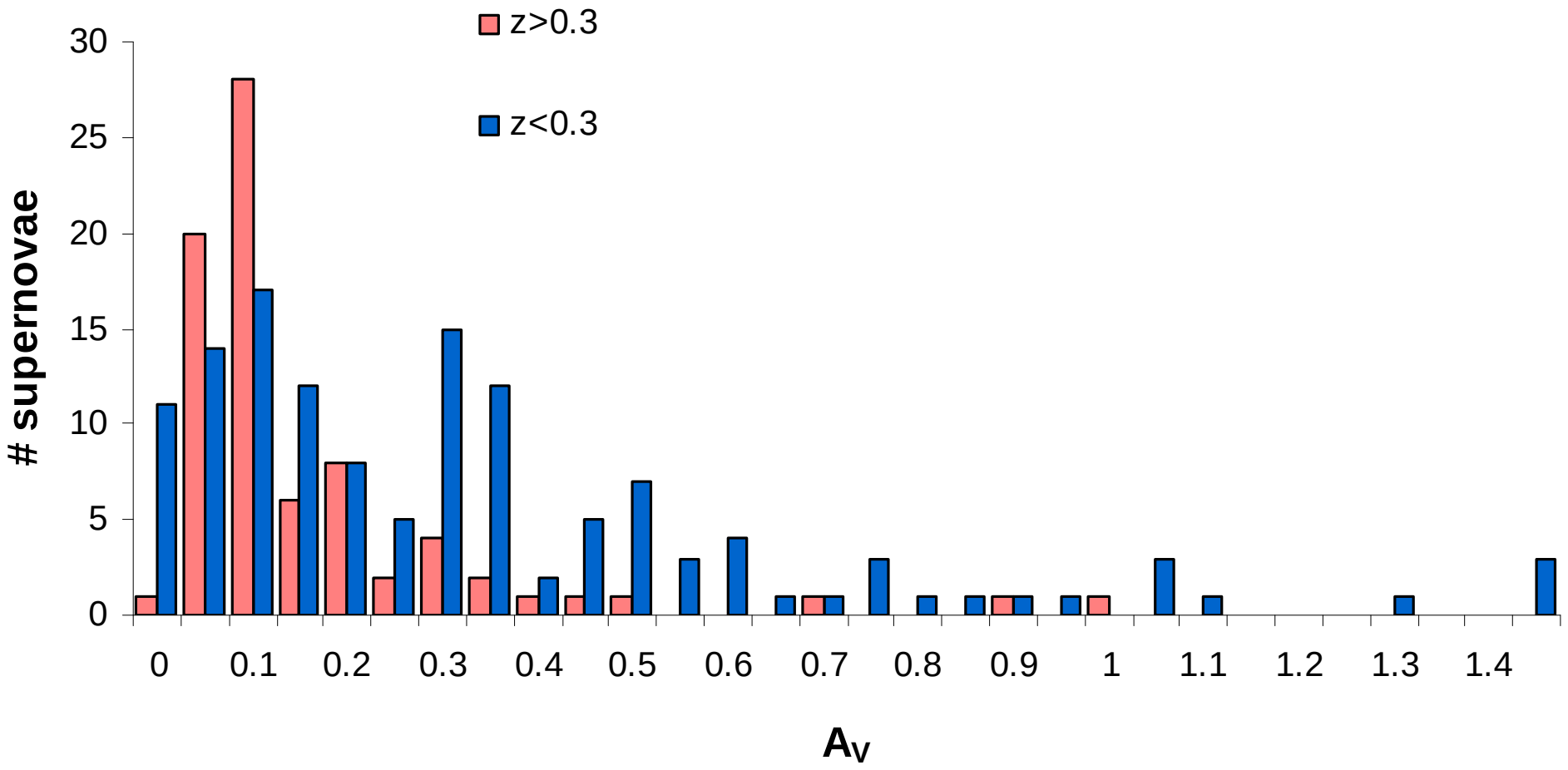
Tonry et al. 2003


RELATIVE BRIGHTNESS OF SUPERNOVAE
Eternal expansion
0.0001
0.001
0.01
0.1
1
LINEAR SCALE OF UNIVERSE RELATIVE TO TODAY
1.5
1.0
0.5
0.0
Perlmutter 1993
Expansion first decelerates, then accelerates
REDSHIFT z
0
0.5
1
1.5
2
3
−20
−10
0
+10
BILLIONS OF YEARS FROM TODAY

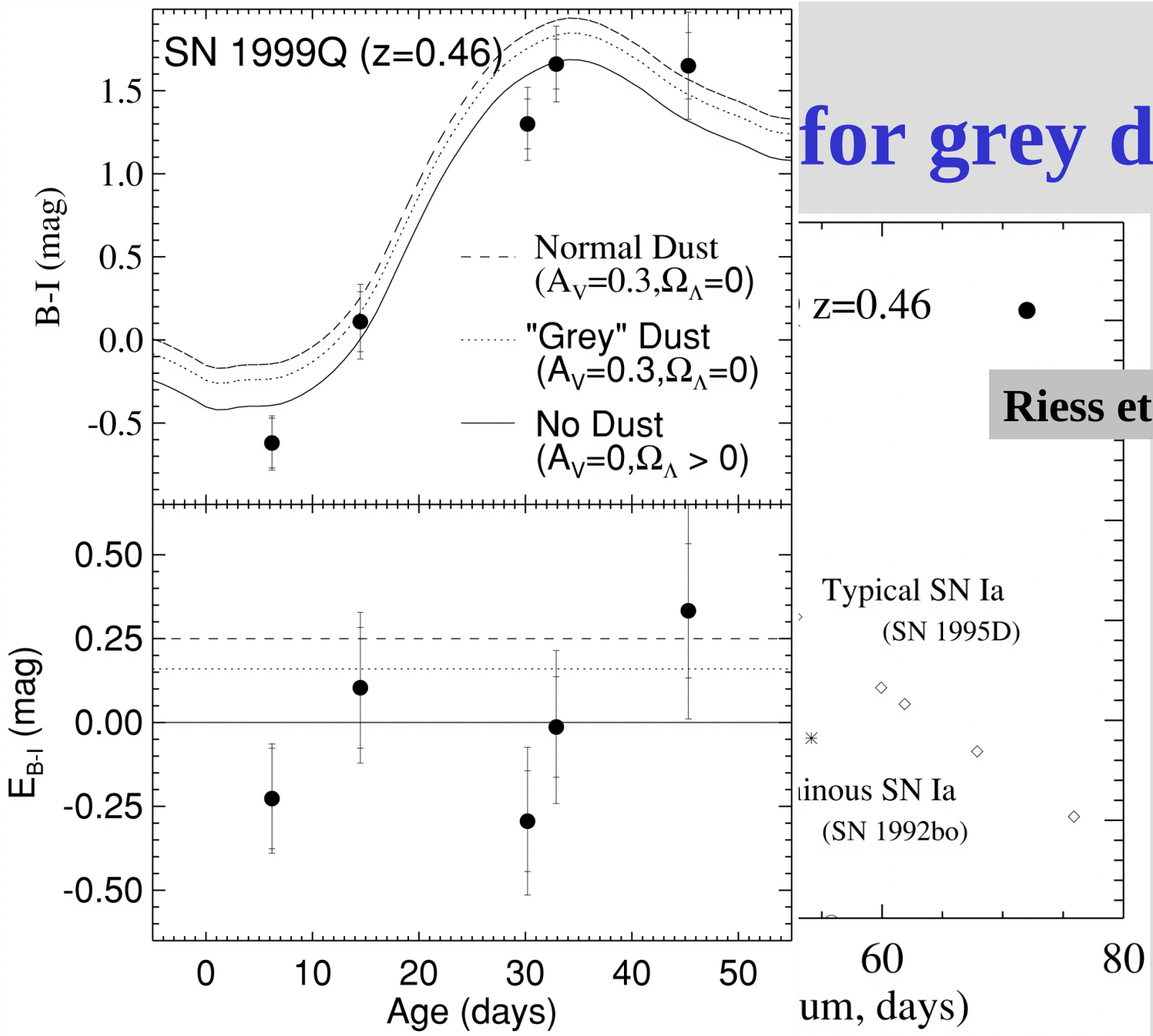
Is evolution a problem?



Absorption distributions

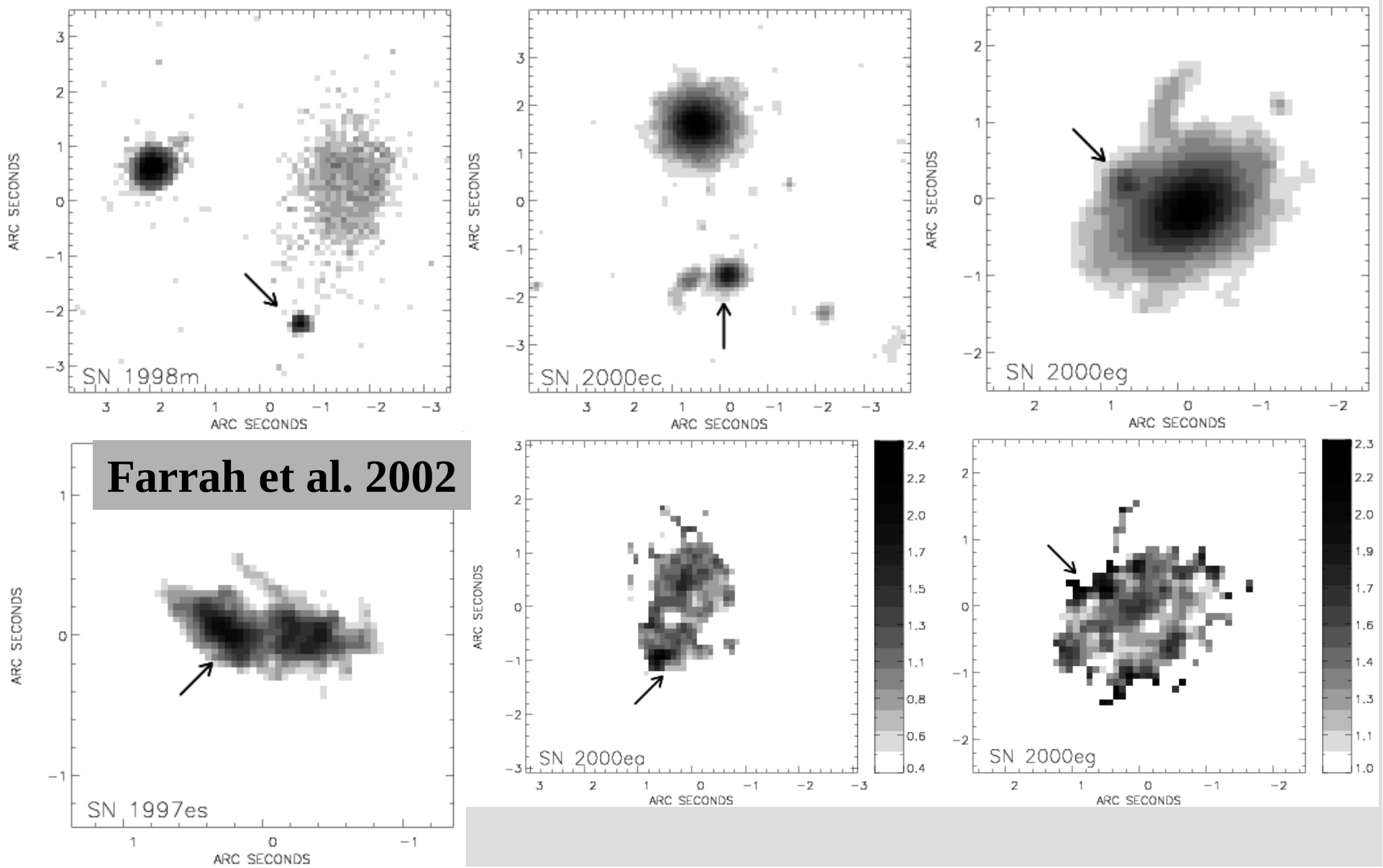


for grey dust



Riess et al. 2000

Host galaxies of distant SNe Ia

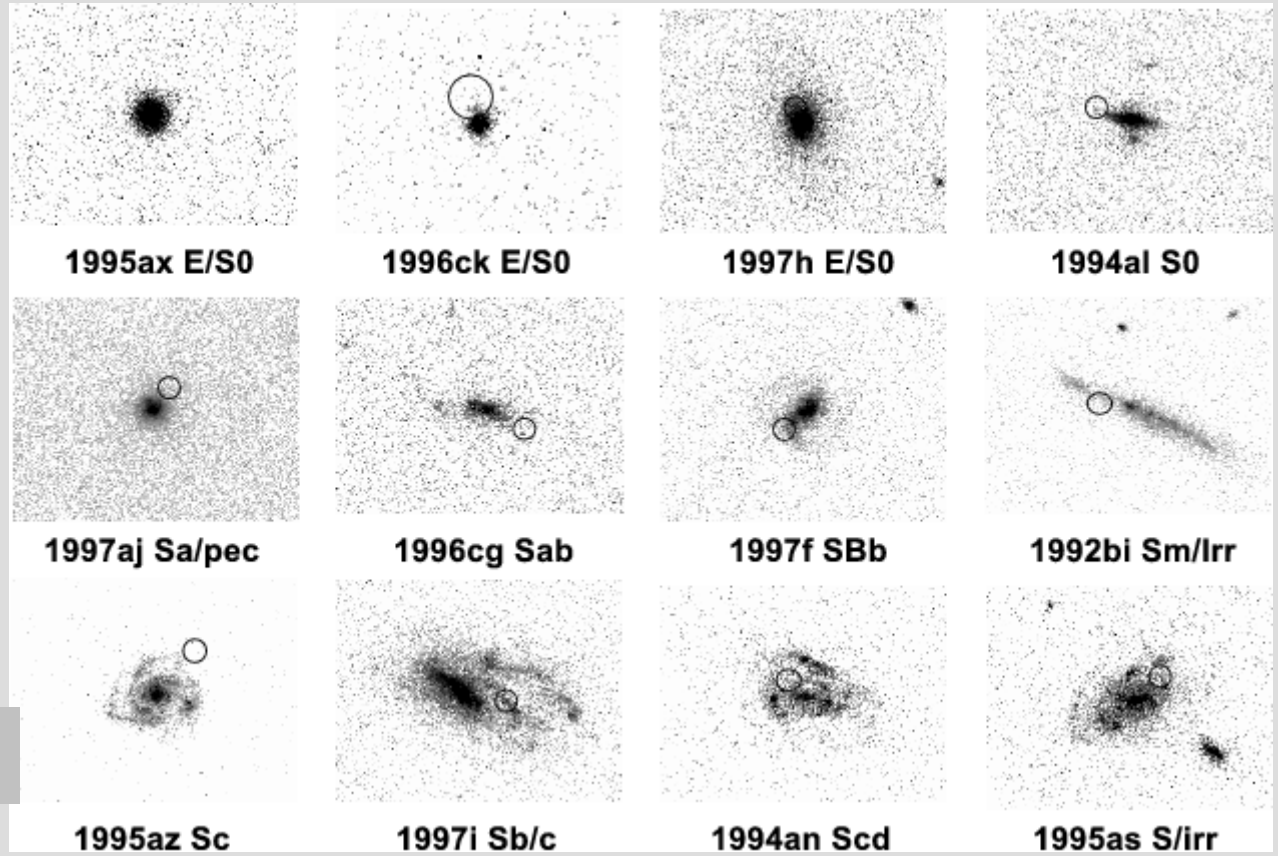


Farrah et al. 2002

SNe Ia in elliptical galaxies

Determination of host galaxy morphologies

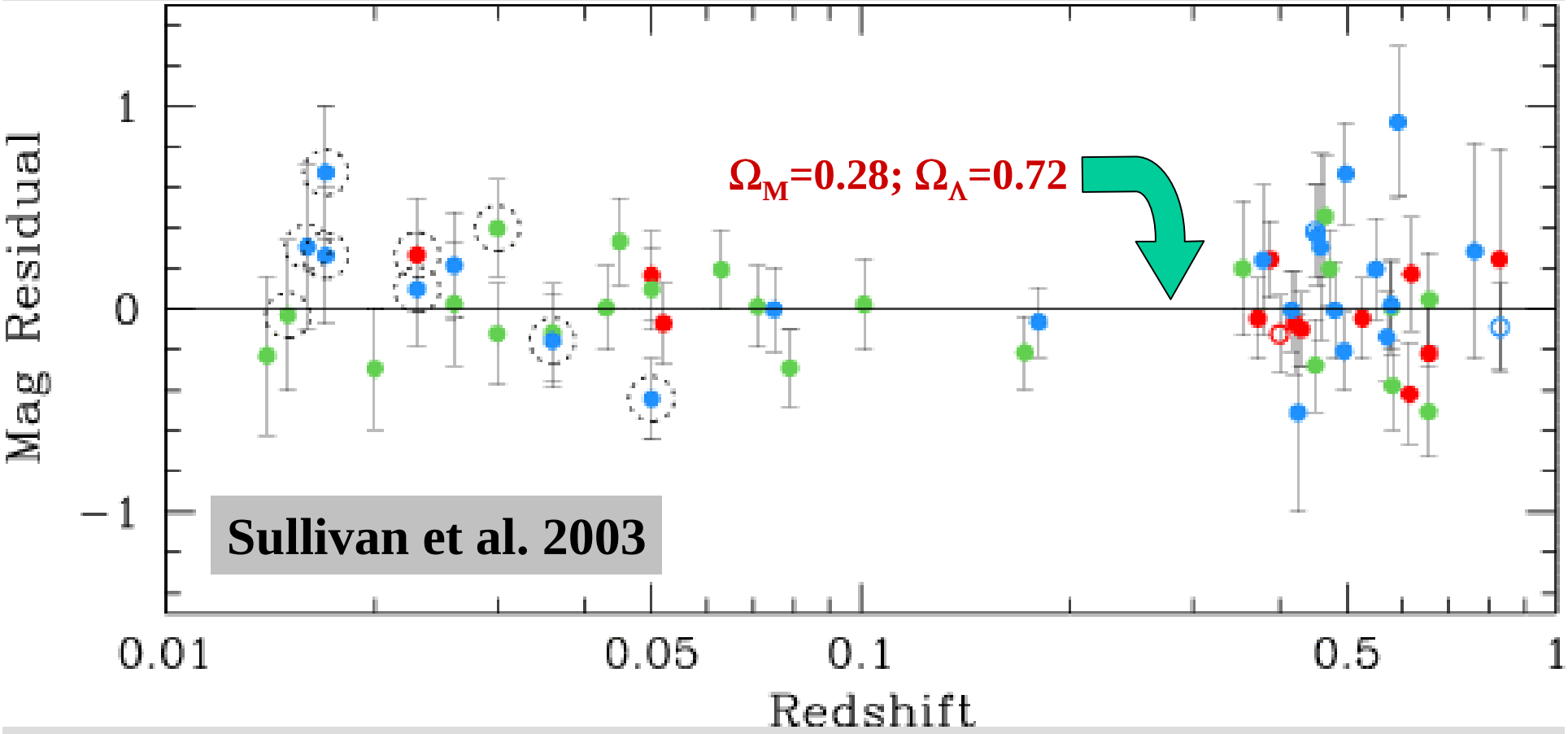
- **38 SNe Ia from the SCP sample**



Sullivan et al. 2003

Modified Hubble diagram

Supernova Cosmology Project Sample



SN Ia Systematics?

Explosions not fully understood

- **many possible models**
  - – Chandrasekhar-mass models
  - – deflagrations vs. detonations

Progenitor systems not known

- **white dwarfs yes, but …**
  - – double degenerate vs. single degenerate binaries

➔ Evolution very difficult to control

Is Λ real?

YES

- ✓ (age of the universe)
- ✓ (CMB and cluster masses)
- ✓ (inflation)

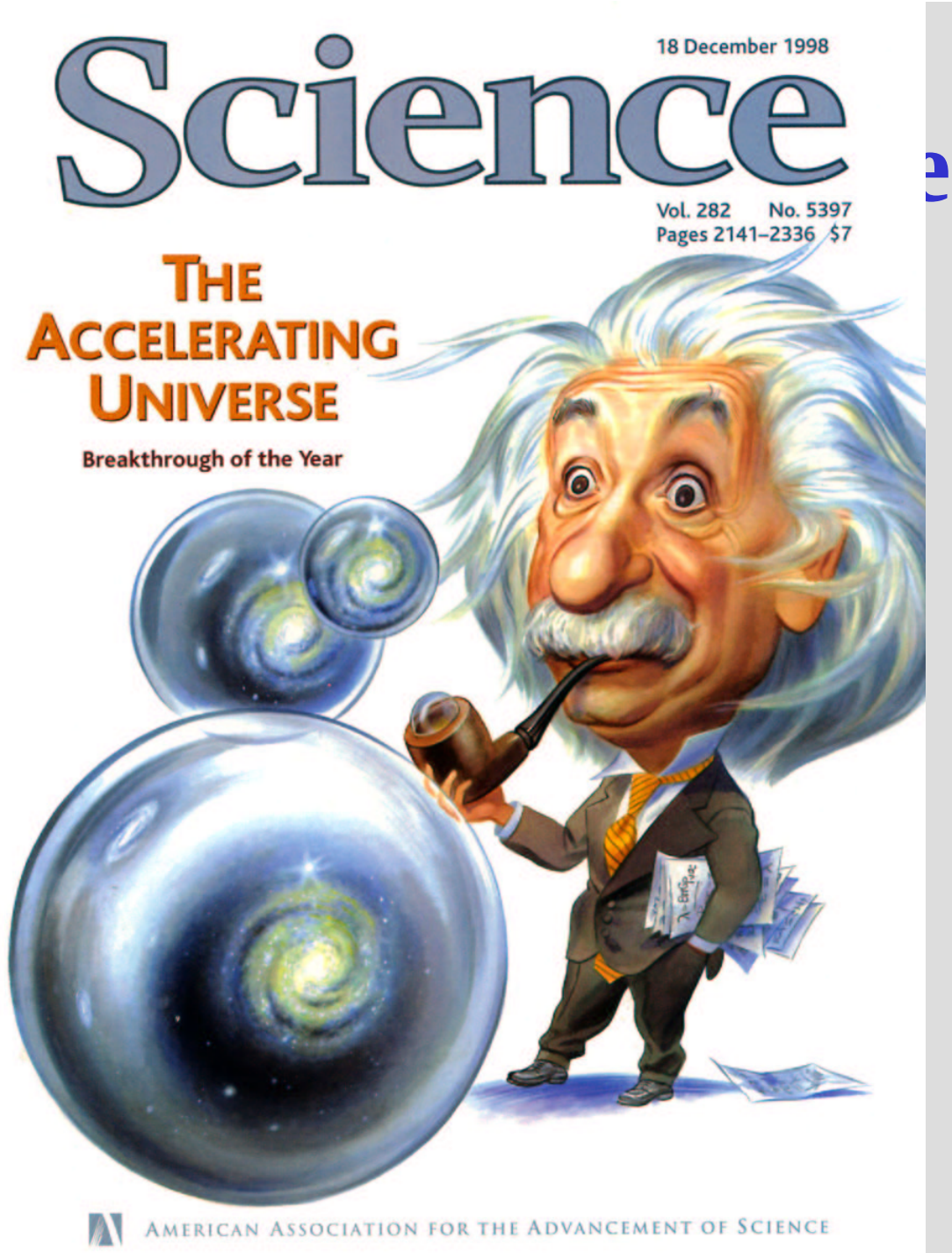
NO

- ☹ evolution
- ☹ dust
- ☹ gravitational lensing
- ☹ selection biases
- ☹ inhomogoneities
- ☹ changing constants (G, α, c)
- ☹ particle physics

N ergy?

Curren

- **cos**



Nature of the Dark Energy?

Currently four proposals:

- **cosmological constant**
- **quintessence**
  - decaying particle field
  - signature:
    - equation of state parameter $\omega \neq -1$ with $\omega = \frac{p}{\rho c^2}$
- **leaking of gravity into a higher dimension**
- **phantom energy → leads to the Big Rip**

On to new physics?

All proposed solutions would require additions beyond the current standard model of physics.

Type Ia Supernovae can distinguish between those possibilities

- **required is a large *homogeneous* set (about 200) of distant ($0.2 < z < 0.8$) supernovae**

The equation of state parameter ω

General luminosity distance

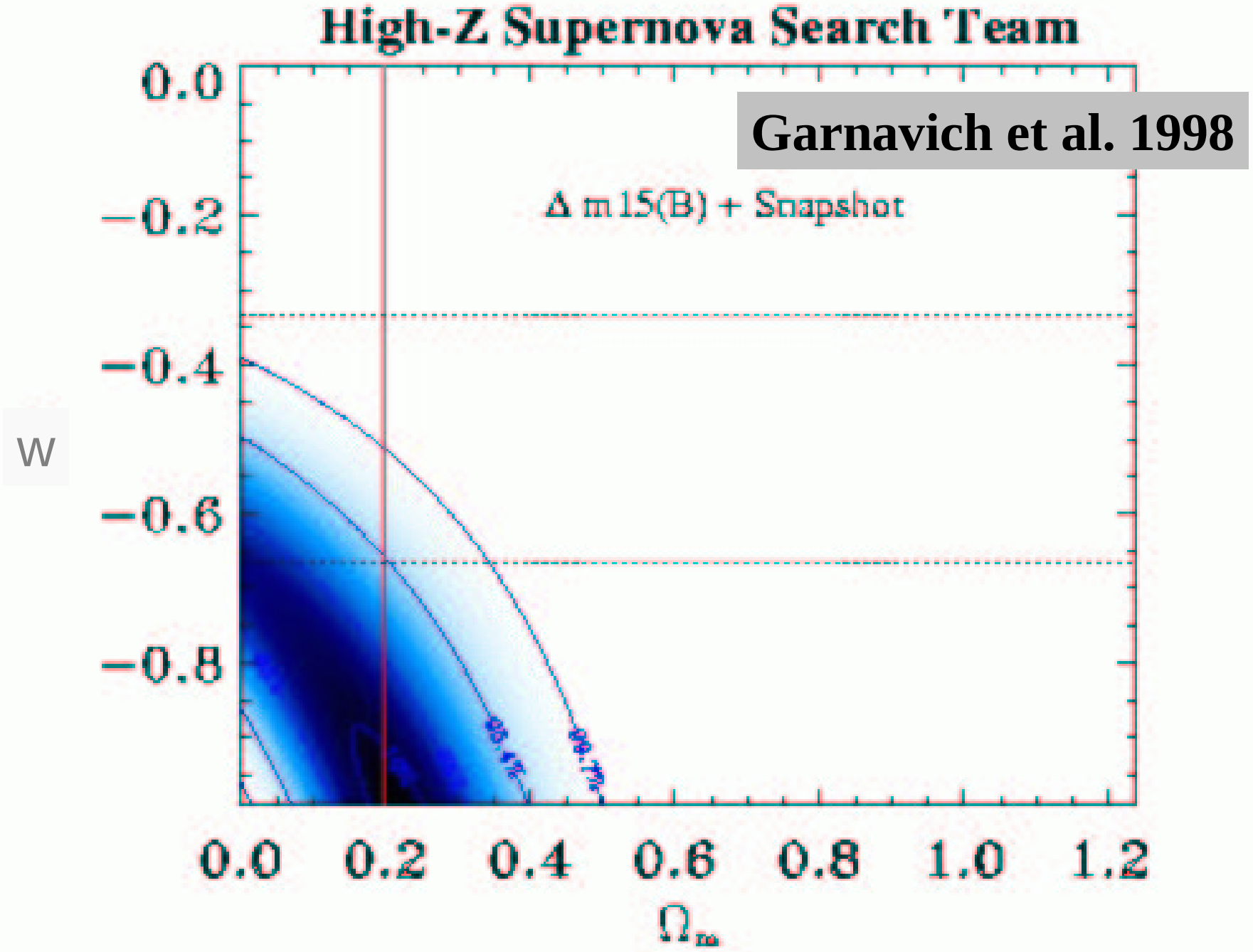
$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}}\, S\left\{\sqrt{|\Omega_\kappa|}\int_0^z \left[\Omega_\kappa(1+z')^2 + \sum_i \Omega_i (1+z')^{3(1+\omega_i)}\right]^{-1/2} dz'\right\}$$

- **with** $\kappa = 1 - \sum_i \Omega_i$ **and** $\omega_i = \frac{p_i}{\rho_i c^2}$

$\omega_M = 0$ (matter)

$\omega_R = ⅓$ (radiation)

$\omega_\Lambda = -1$ (cosmological constant)


High-Z Supernova Search Team
Garnavich et al. 1998
Δ m15(B) + Snapshot
w
0.0
−0.2
−0.4
−0.6
−0.8
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ωm

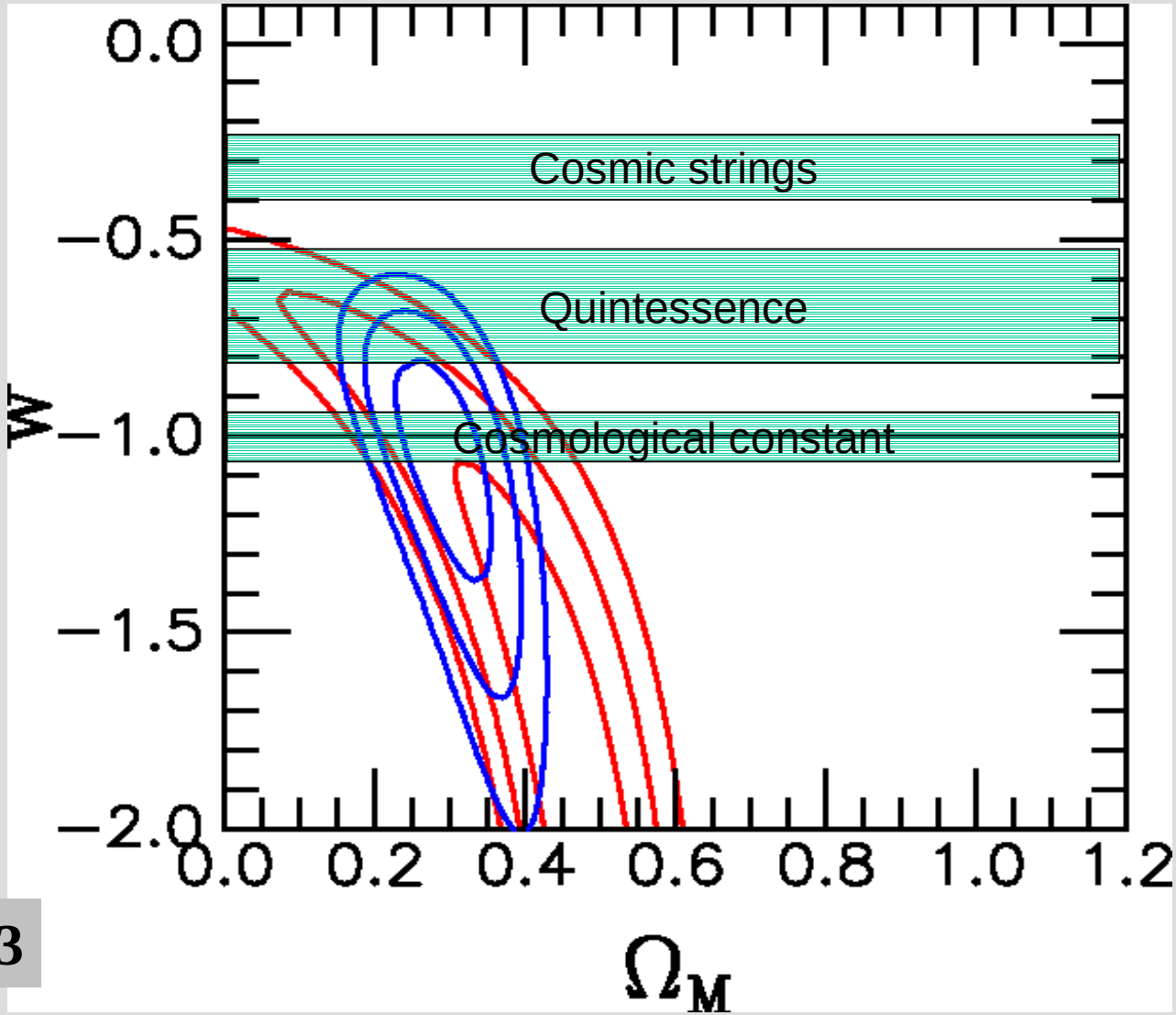
SN Ia and 2dF constraints

2dF:

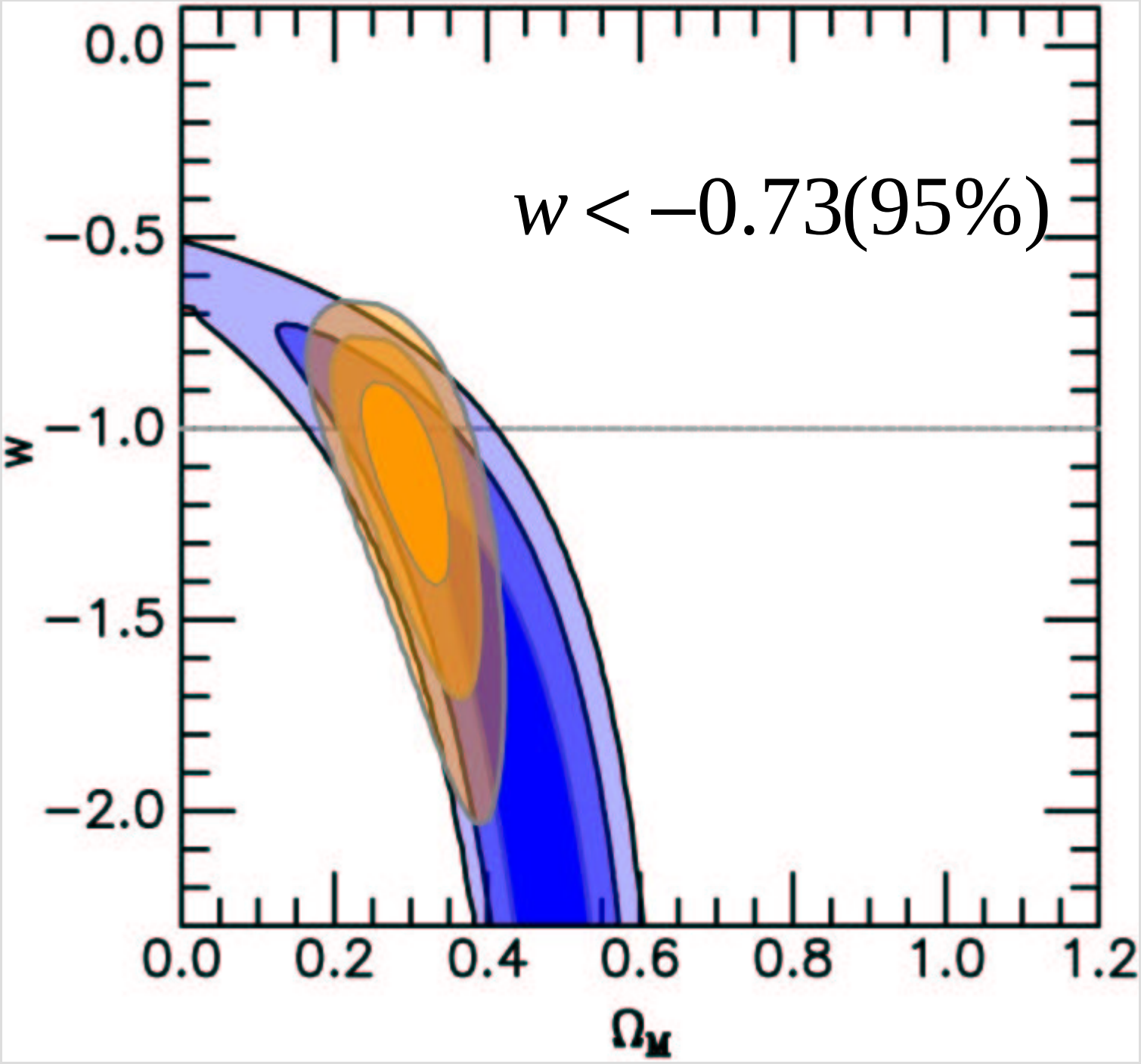
$\Omega_M h = 0.2 \pm 0.03$

KP:

$h = 0.72 \pm 0.08$

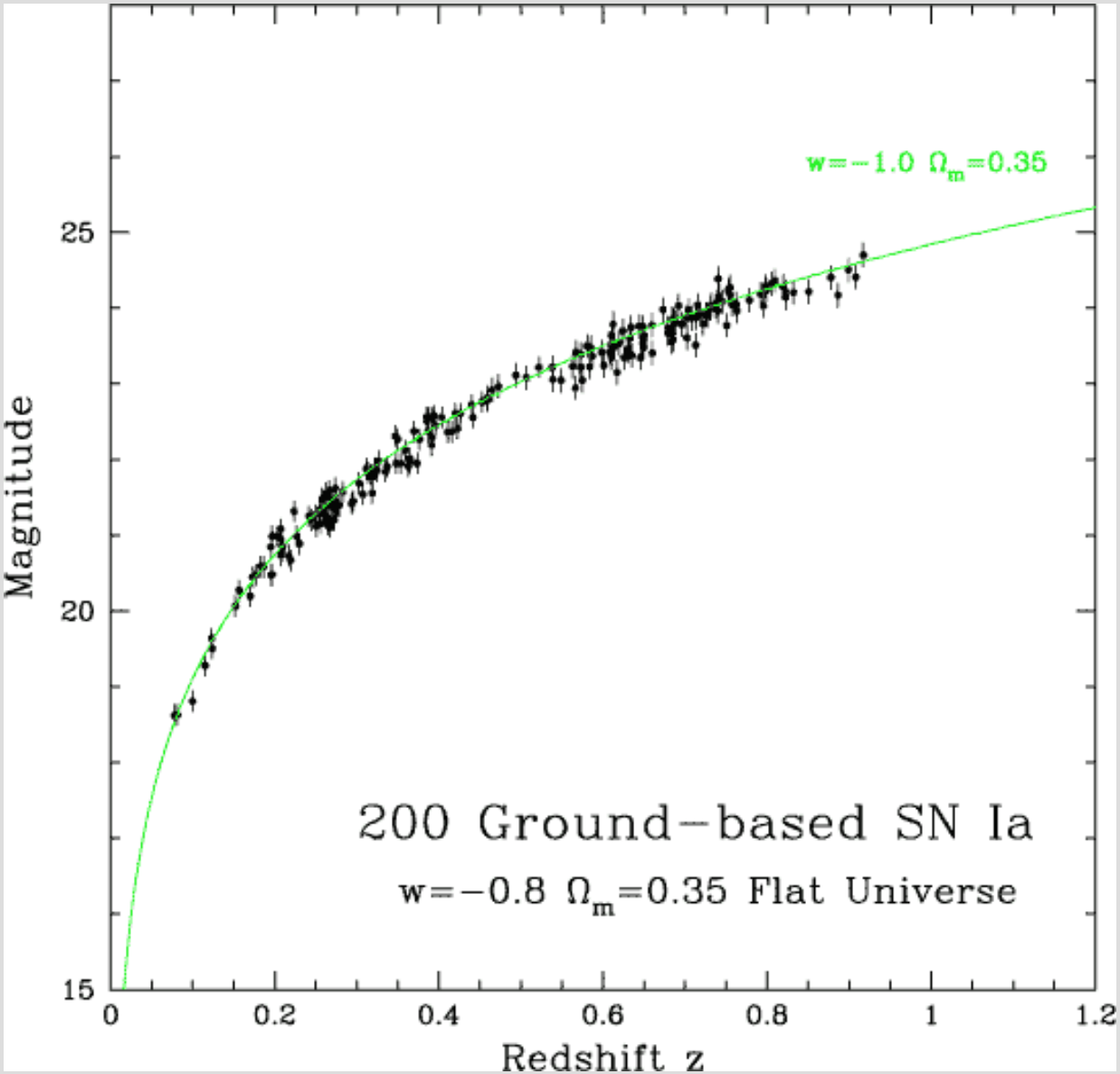


Tonry et al. 2003


$w < -0.73(95\%)$
0.0
−0.5
−1.0
−1.5
−2.0
w
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ω_M

Essence

The High-Z SN Search



Summary

Supernovae measure distances over a large cosmological range

They are complementary to the CMB measurements in that they can measure the dynamics of the cosmic expansion

➔ map the cosmological expansion

- **SNe Ia indicate accelerated expansion for the last 6 Gyr**
- **There are indications that the accelerations turns into a deceleration at z>1 (>8 Gyr)**
- **dynamic age of the universe $H_0 t_0 = 0.95 \pm 0.04$**
  (13 Gyr for H_0=72 km $s^{-1}Mpc^{-1}$; 15 Gyr for H_0=64 km $s^{-1}Mpc^{-1}$)

Summary (Problems)

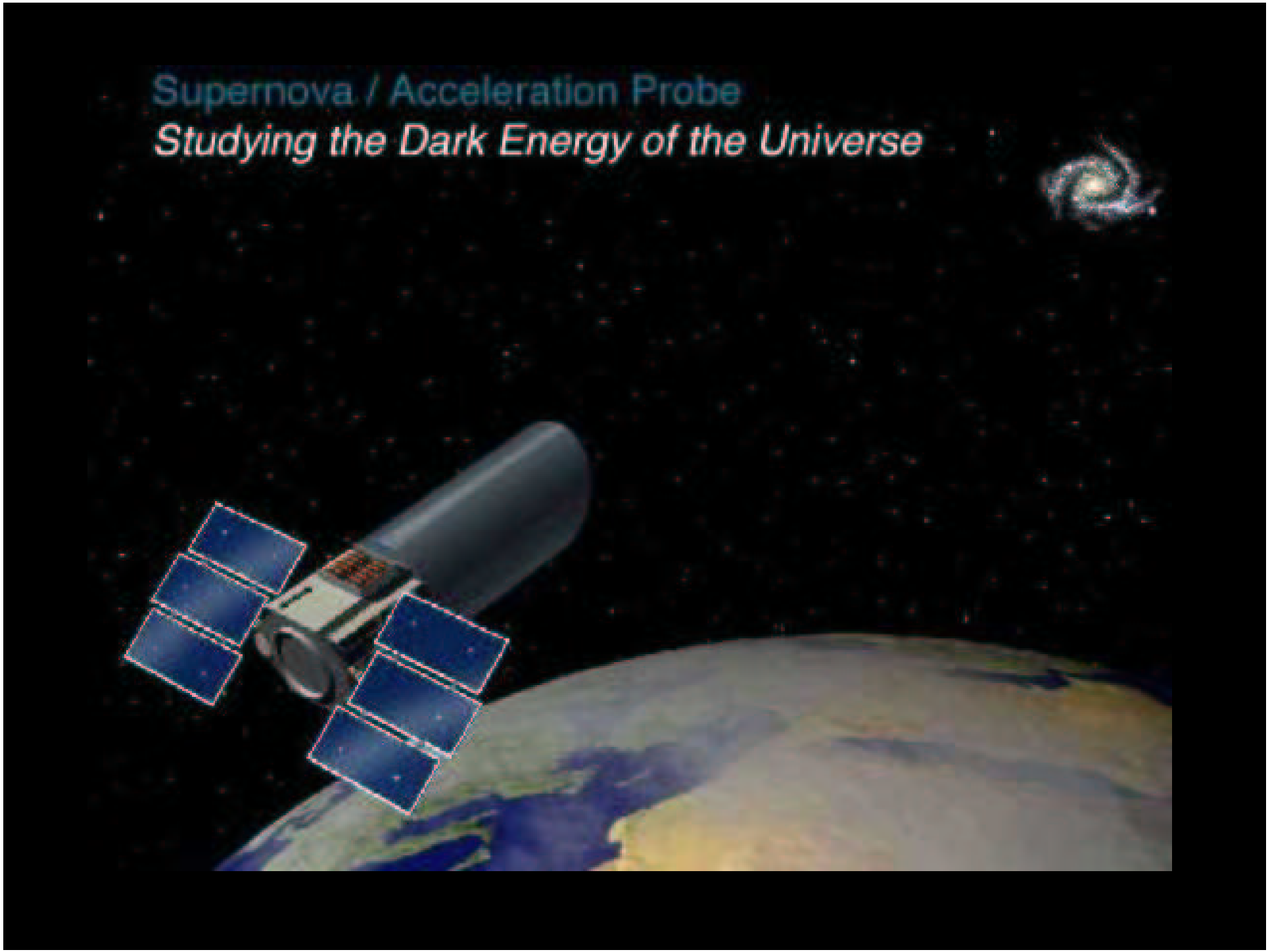
Supernova systematics

- **unknown explosion mechanism**
- **unknown progenitor systems**
- **light curve shape correction methods for the luminosity normalisation (SCP vs. HZT)**
- **signatures of evolution in the colours?**
- **spectroscopy?**

The Future

Future experiments will distinguish between a cosmological constant or quintessence

- **ESSENCE, CFHT Legacy Survey, VST, VISTA, NGST, LSST, SNAP**


Supernova / Acceleration Probe
Studying the Dark Energy of the Universe

The Future

Future experiments will distinguish between a cosmological constant or quintessence

- **ESSENCE, CFHT Legacy Survey, VST, VISTA, NGST, LSST, SNAP**

Systematic uncertainties depend on our understanding of the supernovae

- **nearby samples, explosion models, radiation hydrodynamics**