Cosmology and the origin of structure

Rocky I: Dark Energy

Rocky II: Dark matter and inflation

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viale
dell'Astronomia
via
della Fisica

The universe observed

- **Cosmological parameters:**

$H_0 \rightarrow$ Hubble's constant

$q_0 \rightarrow$ deceleration parameter

$\Omega_i \rightarrow$ the cosmic food chain

$(\Omega_{\text{TOTAL}}, \Omega_M, \Omega_B, \Omega_\Lambda, \Omega_\gamma, \Omega_\nu, ...)$

$t_0 \rightarrow$ age of the universe

$T_0 \rightarrow$ temperature of the universe

- **Power spectra–characterization of perturbations:**

$P(k), \quad C_l$

- **"Standard model": Dark Energy and Dark Matter**

ΛCDM

Big-Bang (theory)

Robertson-Walker metric

$a(t) = \text{cosmic scale factor}$

$k = 0, \pm 1$

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

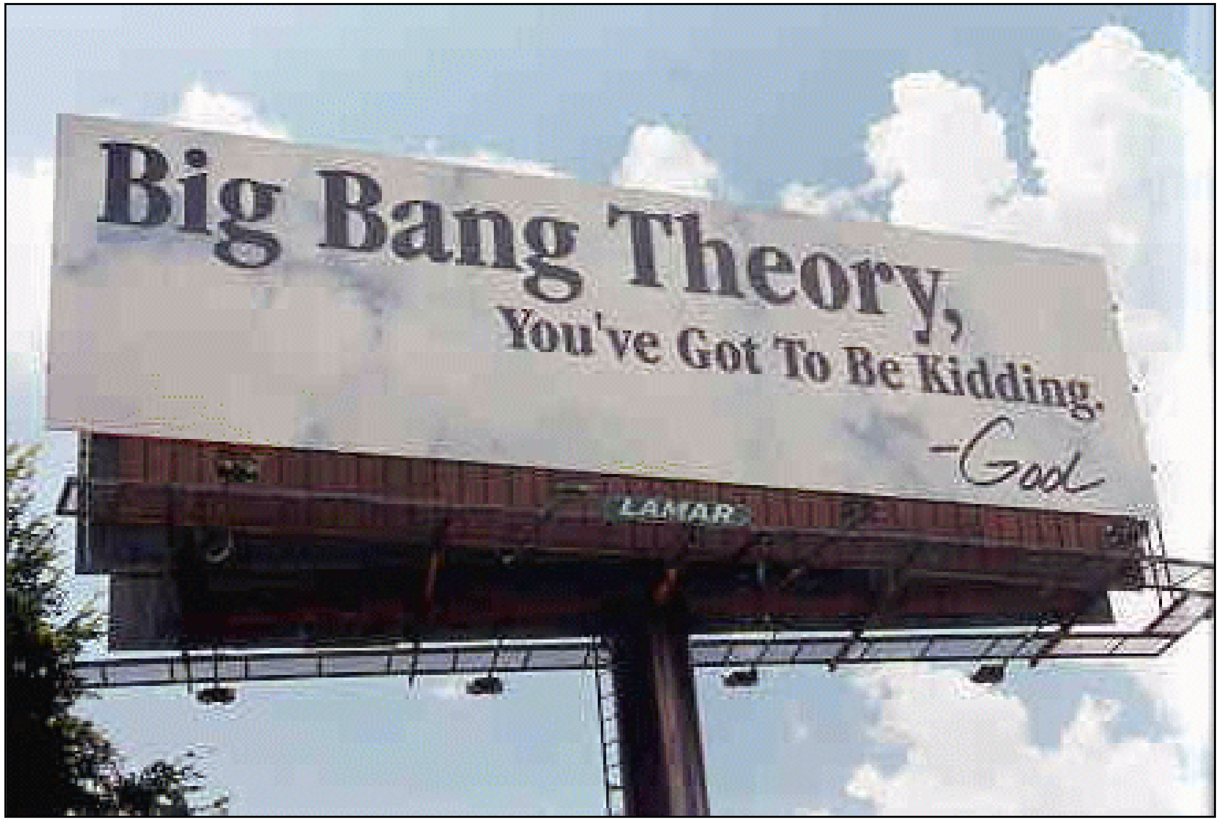
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Perfect-fluid stress tensor

$\rho = \text{ energy density}$

$p = \text{ pressure}$

$T^{\mu}{}_{\nu} = \text{diag}(\rho, p, p, p)$



Field equations

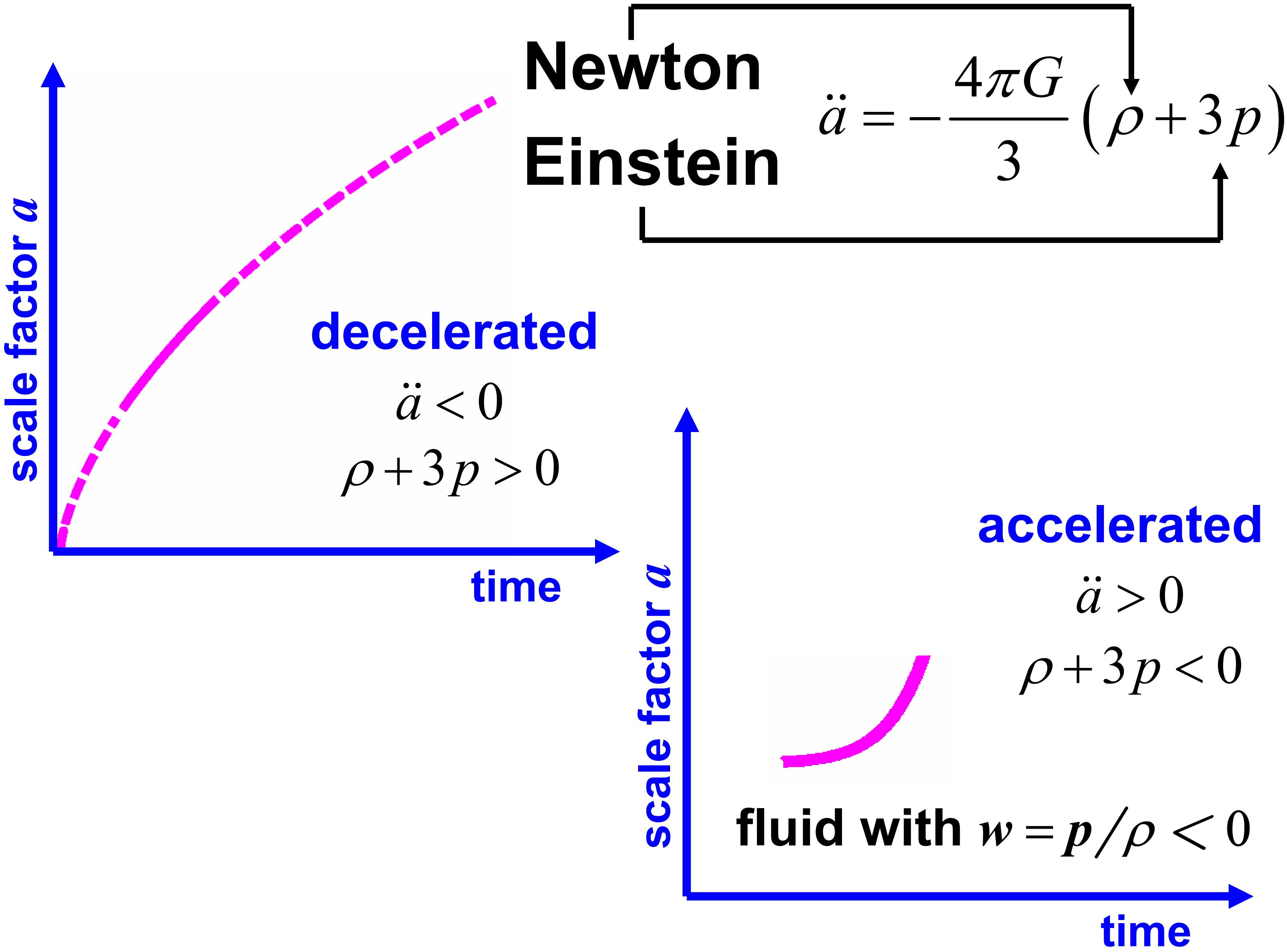
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \qquad H \equiv \frac{\dot{a}}{a} = \text{expansion rate}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \qquad q \equiv -\frac{\ddot{a}}{a}\frac{1}{H^2} = \text{deceleration parameter}$$

$$T^{\mu\nu}{}_{;\nu} = 0 \qquad \rho \propto a^{-3(1+w)} \qquad w = p/\rho$$

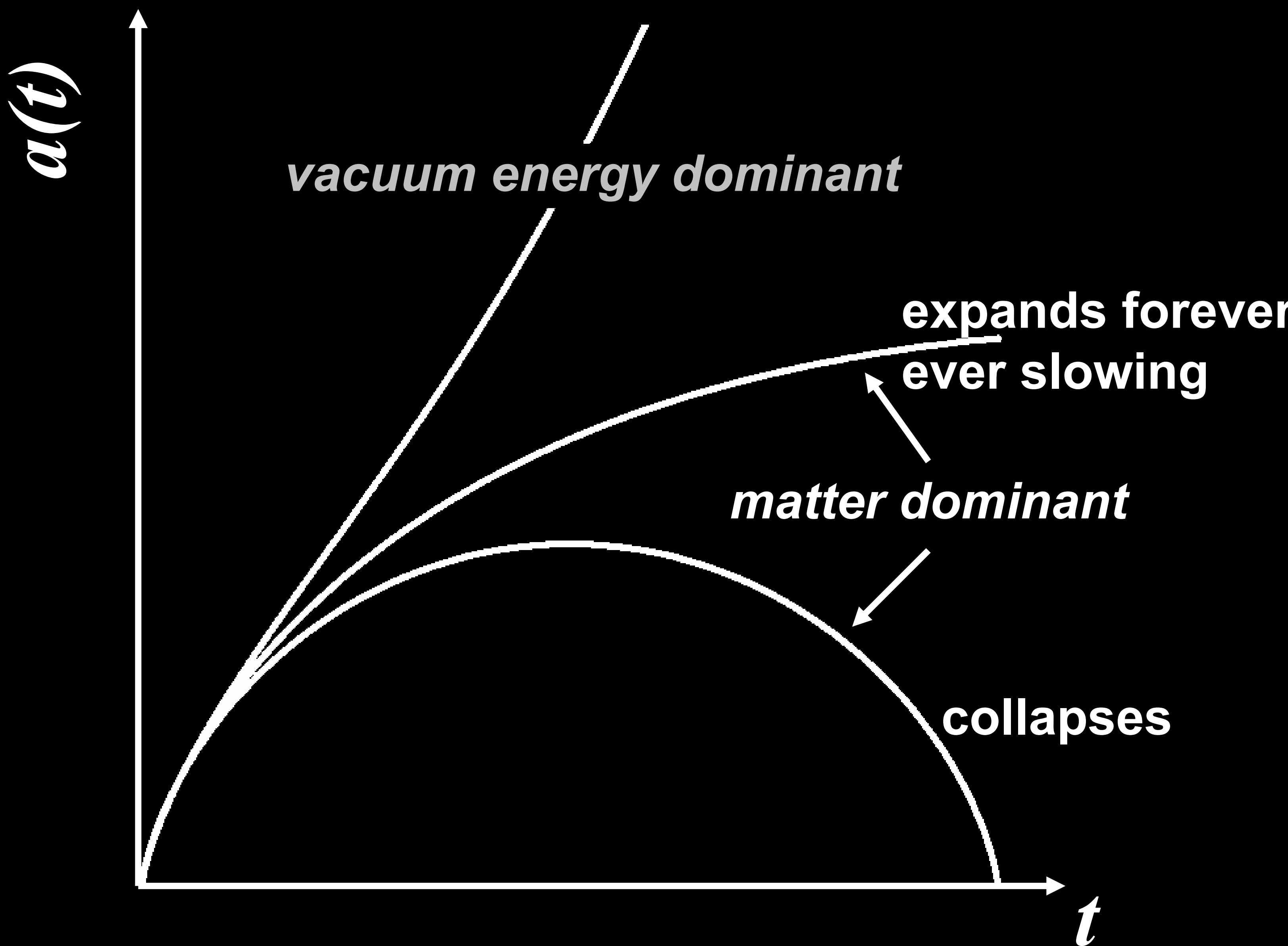
$T^{\mu\nu}$: fluids with different w

matter:	$p_M = 0$	$w = 0$	$\rho_M \propto a^{-3}$
radiation:	$p_R = \rho_R/3$	$w = 1/3$	$\rho_R \propto a^{-4}$
vacuum:	$p_\Lambda = -\rho_\Lambda$	$w = -1$	$\rho_\Lambda \propto a^0$



Newton
Einstein
$\ddot{a} = -\frac{4\pi G}{3}(\rho + 3p)$
scale factor a
decelerated
$\ddot{a} < 0$
$\rho + 3p > 0$
time
scale factor a
accelerated
$\ddot{a} > 0$
$\rho + 3p < 0$
fluid with $w = p/\rho < 0$
time

Cosmological constant (dark energy)



Evolution of *H(z)* is a key quantity

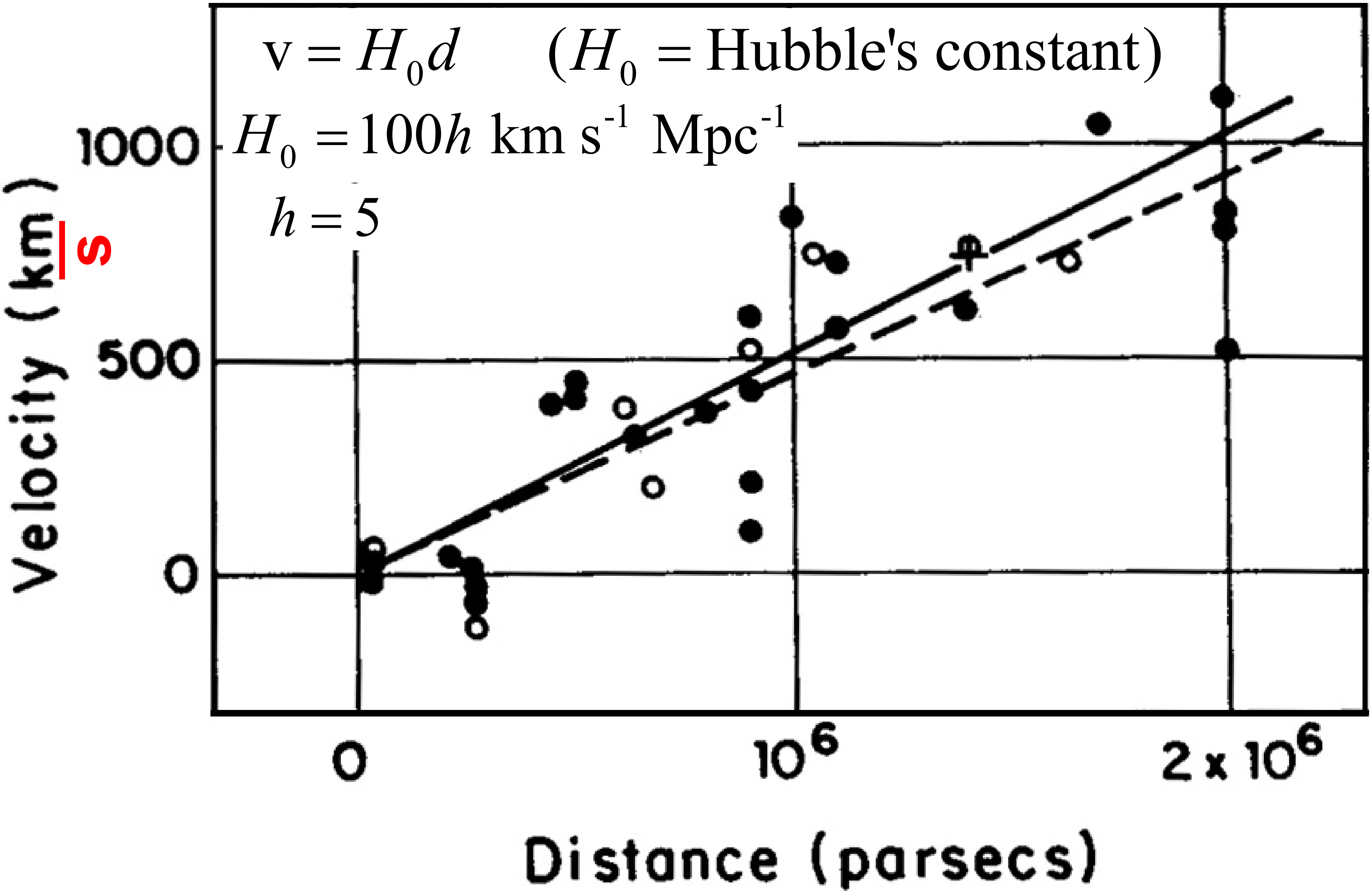
Many observables based on the comoving distance r

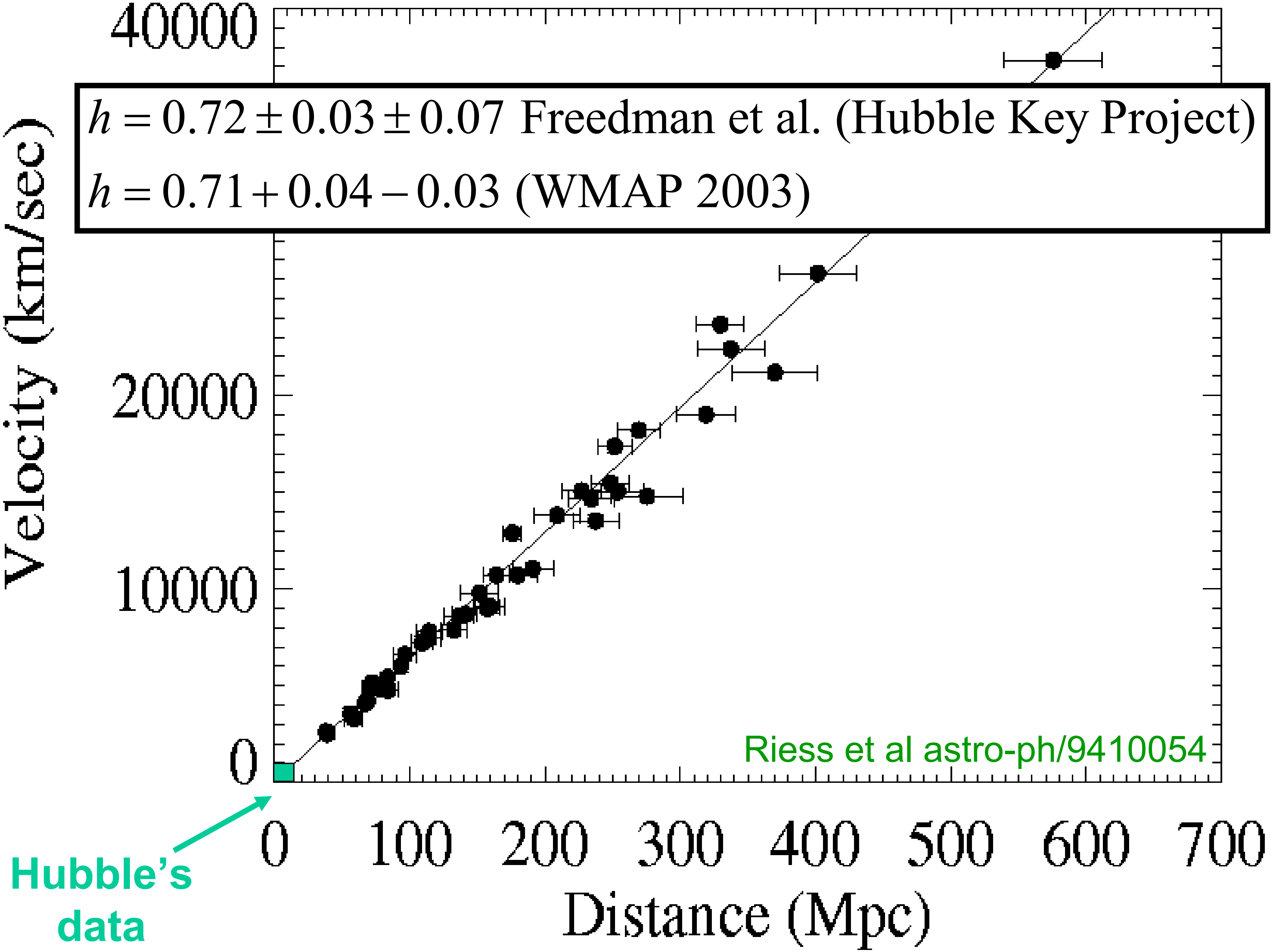
$$r(z) = \int_0^z \frac{dz'}{H(z')}$$

- Luminosity distance $$d_L(z) \propto r(z)(1+z)$$
- Angular diameter distance $$d_A(z) \propto \frac{r(z)}{(1+z)}$$
- Comoving volume element $$\frac{dV(z)}{dz\,d\Omega} \propto \frac{r^2(z)}{H(z)}$$
- Age of the universe $$t(z) \propto \int_0^z dz' \frac{1}{(1+z')H(z')}$$

University of Chicago 1909 National Champions

Hubble's Discovery Paper - 1929





h = 0.72 ± 0.03 ± 0.07 Freedman et al. (Hubble Key Project)
h = 0.71 + 0.04 − 0.03 (WMAP 2003)
Velocity (km/sec)
40000
20000
10000
0
0
100
200
300
400
500
600
700
Distance (Mpc)
Riess et al astro-ph/9410054
Hubble's data

Distance-redshift relation

$F = \dfrac{L}{4\pi d_L^2}$ defines luminosity distance - "know" L, measure F

$4\pi d_L^2 =$ area of ${}^2S$ centered on source at time of detection, t_0

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right) \Rightarrow \text{Area} = 4\pi a^2(t_0)r^2$$

Conservation of energy: flux redshifted: $(1+z)^2 = \left[a(t_0)/a(t_1)\right]^2$

redshift of energy $\times$ redshift of time interval: $(1+z)^2$

$$F = \frac{L}{4\pi a^2(t_0)r^2(1+z)^2} \quad \Rightarrow \quad \boxed{d_L = a(t_0)r(1+z)}$$

light from comoving coordinate r at time t_1 reaches us now redshifted by an amount $(1+z) = a(t_0)/a(t)$

Distance-redshift relation

$$d_L = a(t_0)\, r\,(1+z)$$

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

light travels on geodesics

$$ds^2 = 0$$

$$\int \frac{dr}{\sqrt{1-kr^2}} = \int \frac{dt}{a(t)} = \int \frac{da}{H(a)a^2}$$

$$H^2 = H_0^2\left[(1-\Omega_{\mathrm{TOTAL}})(1+z)^2 + \Omega_M(1+z)^3 + \ldots\right]$$

$$\Omega_i = \rho_i \Big/ \left(3H_0^2/8\pi G\right)$$

$$\Omega_{\mathrm{TOTAL}} = \Omega_M + \Omega_\Lambda + \Omega_R + \Omega_w + \ldots \qquad (1-\Omega_{\mathrm{TOTAL}}) \propto k$$

$$\int_0^r \frac{dr'}{\sqrt{1-kr'^2}} = \int_0^z \frac{a^{-1}(t_0)H_0^{-1} \quad dz'}{\sqrt{(1-\Omega_0)(1+z')^2 + \Omega_M(1+z')^3 + \Omega_w(1+z')^{3(1+w)} + \ldots}}$$

Distance-redshift relation

$$d_L = a(t_0)\, r\, (1+z)$$

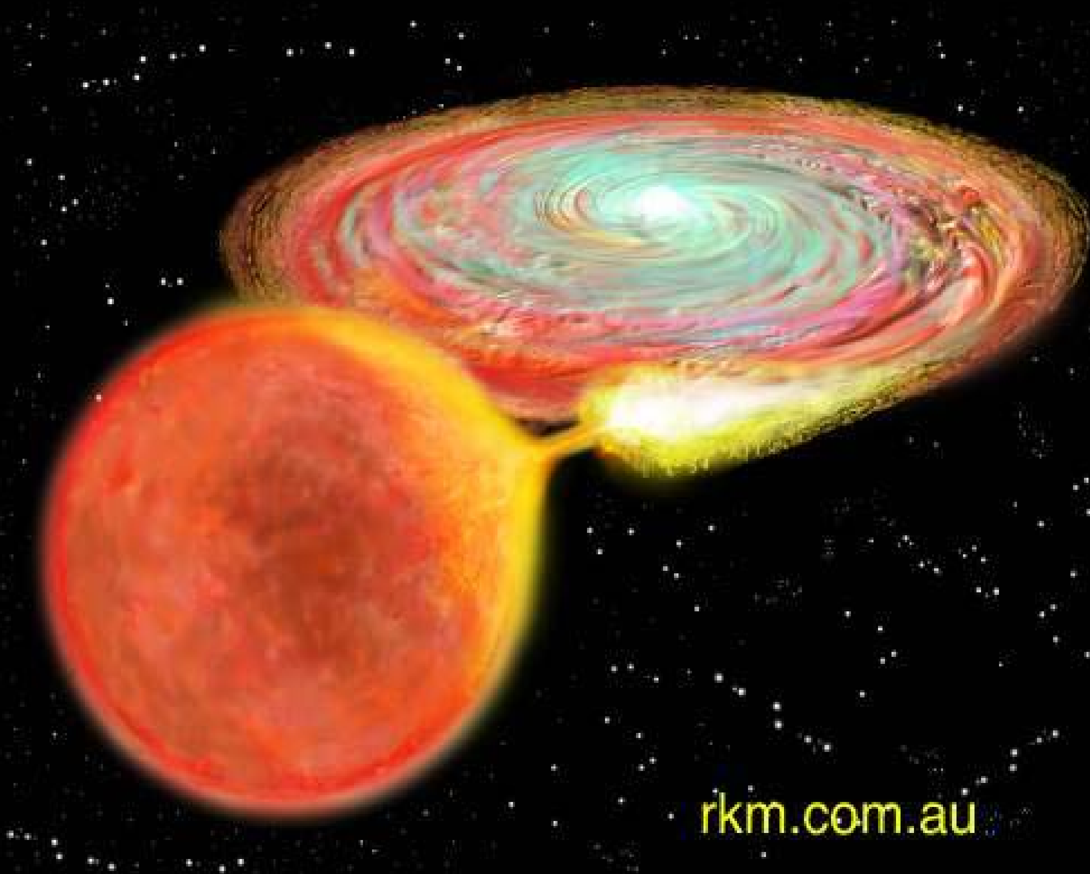
$$a(t_0)r \text{ from } \int_0^r \frac{dr'}{\sqrt{1-kr'^2}} = \int_0^z \frac{a^{-1}(t_0)H_0^{-1} \qquad dz'}{\sqrt{(1-\Omega_{\mathrm{TOTAL}})(1+z')^2 + \Omega_M (1+z')^3 + \dots}}$$

Program:

- **measure** d_L **(via** $d_L{}^2 = L/4\pi F$ **) and** z
- **input** Ω_i **(a model cosmology) and calculate** $a(t_0)\, r$
- **compare to data** $F = L \big/ 4\pi d_L^2$
- **need bright "standard candle"**

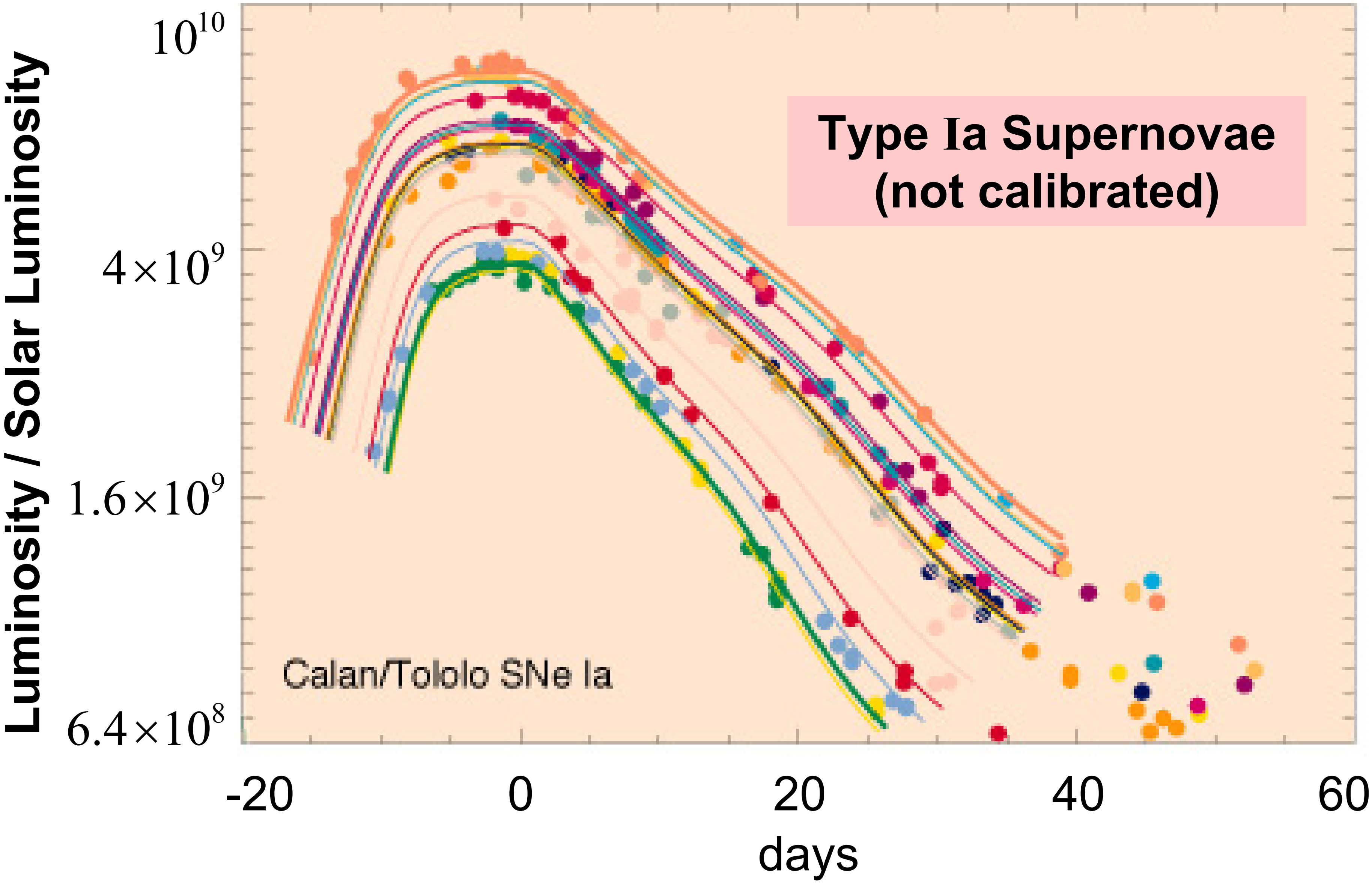
Monastic Chronicles re: Supernova 1006:

Type Ia supernova

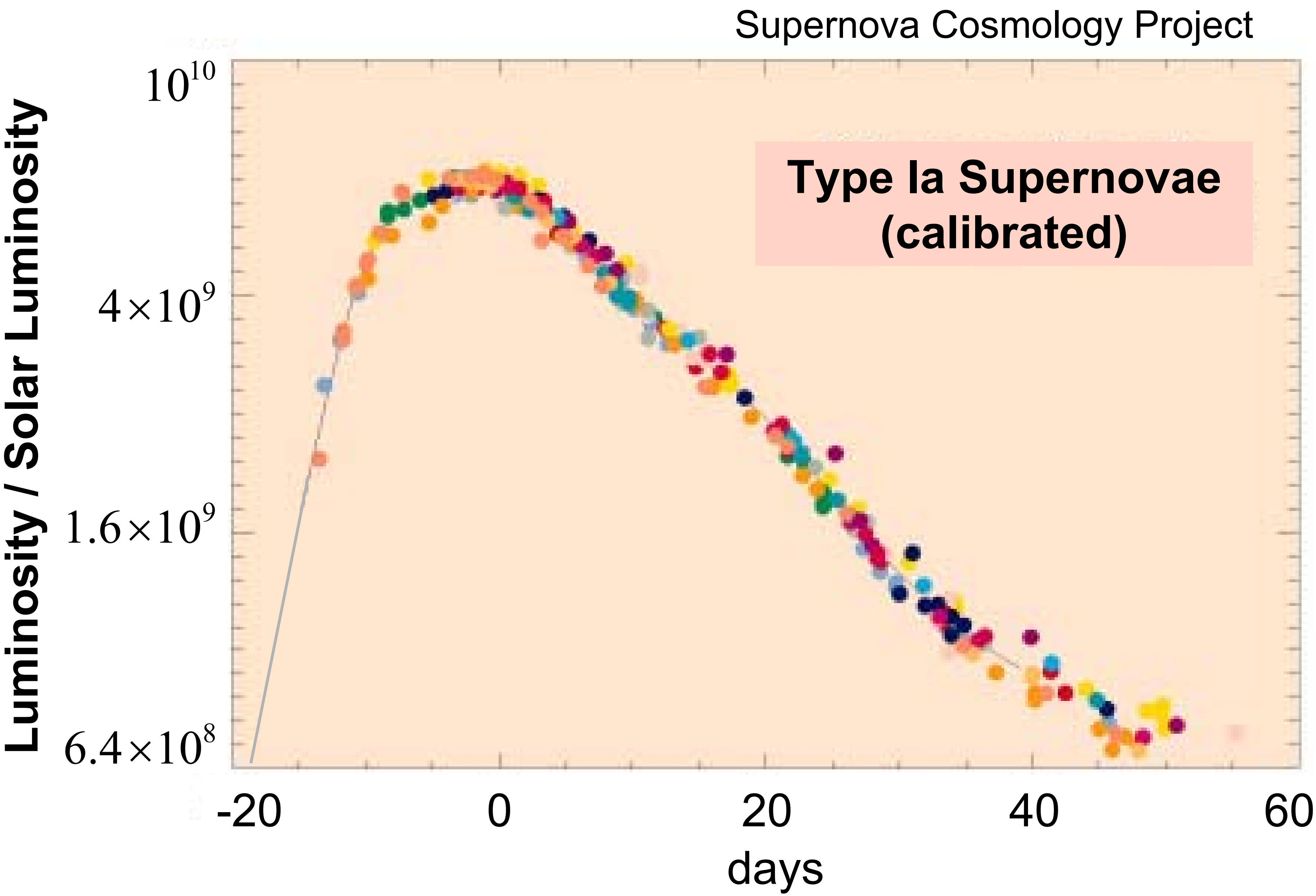


Type Ia supernova

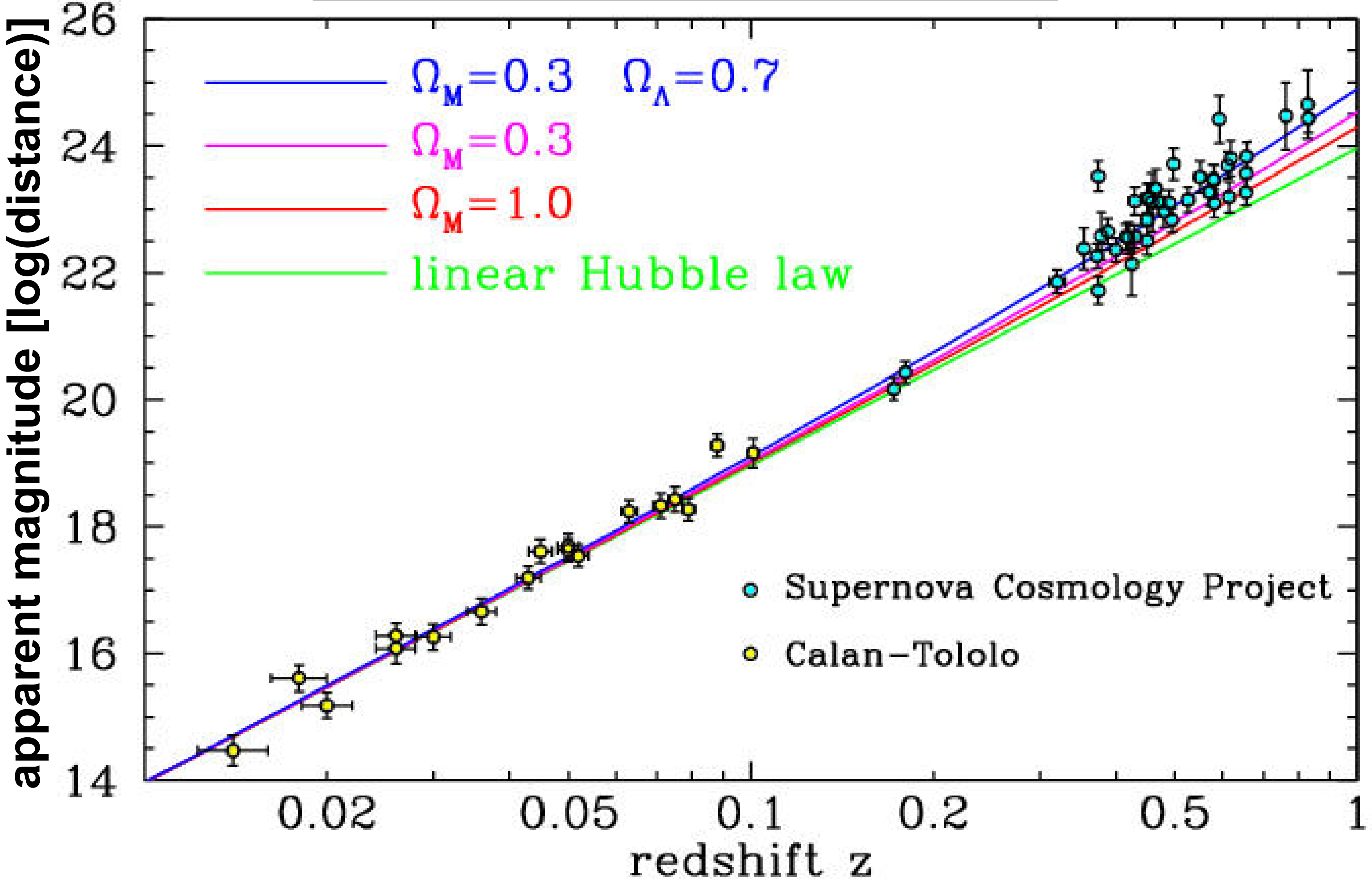
Supernova Cosmology Project



Type Ia supernova



Type Ia supernova



The mysterious language of astronomy

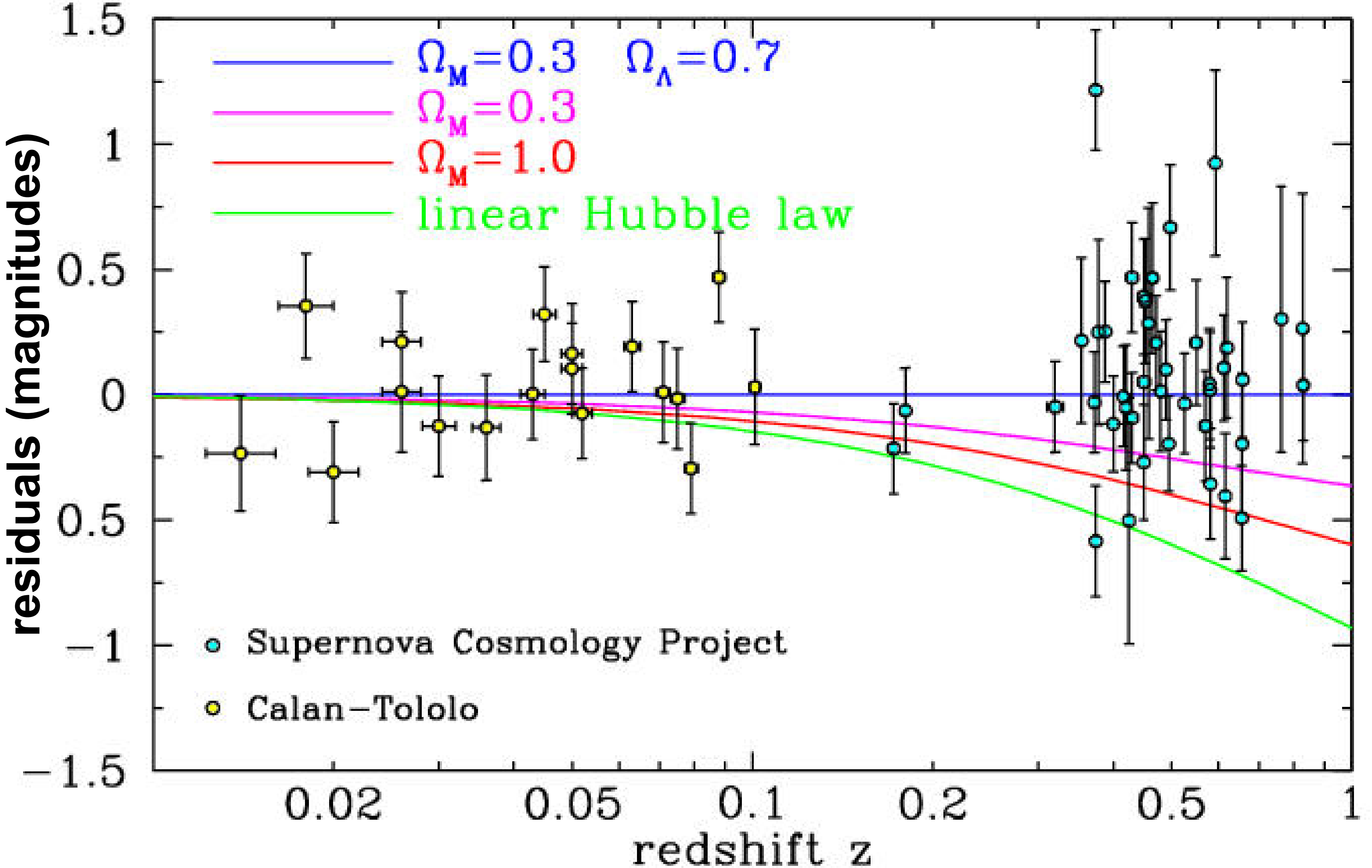
$$m_1 - m_2 = -2.5 \log \frac{I_1}{I_2}$$ apparent magnitude

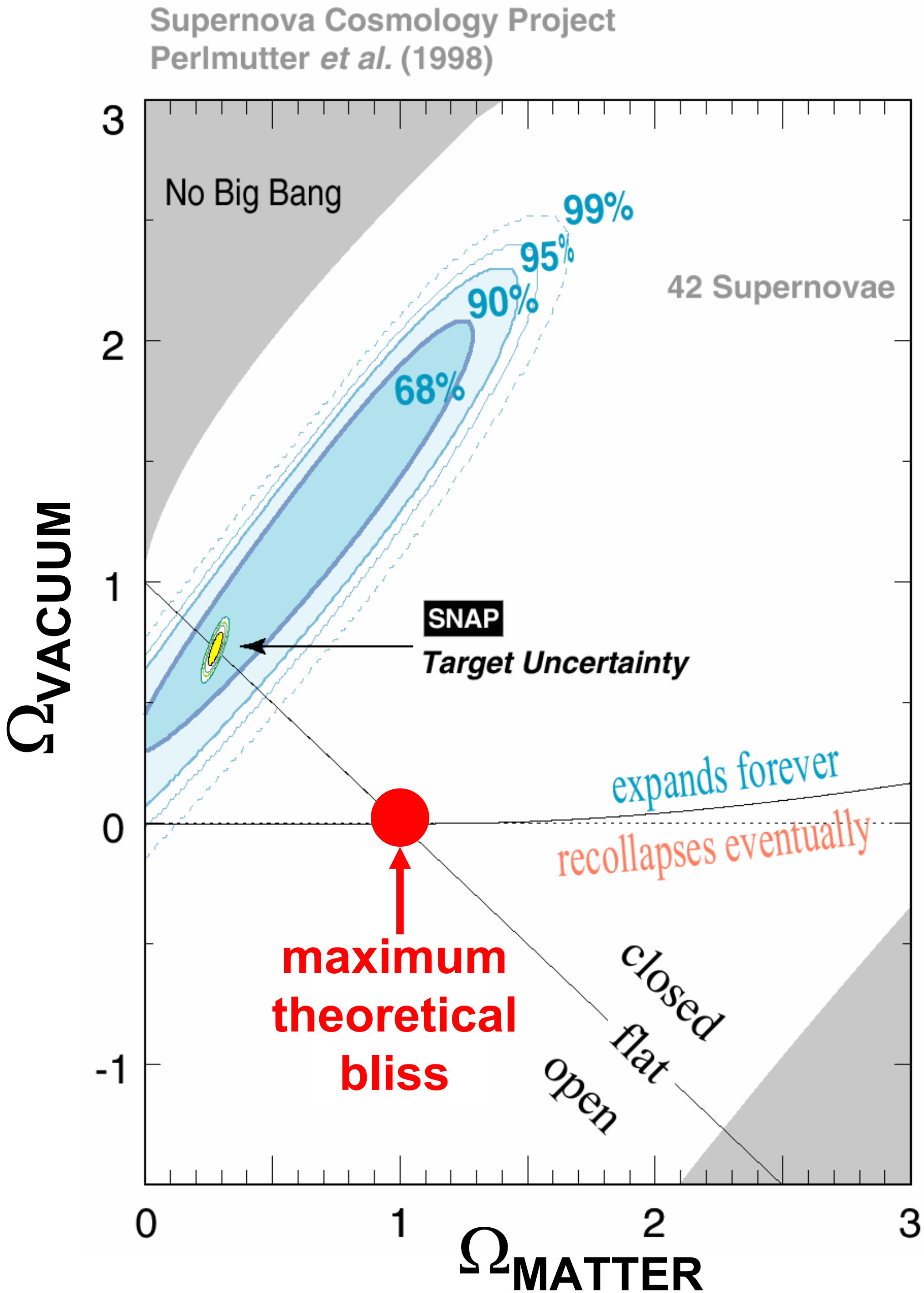
$$M_1 - M_2 = -2.5 \log \frac{L_1}{L_2}$$ absolute magnitude

$$I = \frac{L}{4\pi d_L^2}$$ definition of luminosty distance

$$m \propto 5 \log d_L$$

Type Ia supernova





High-z SNeIa are fainter than expected in an Einstein-deSitter model

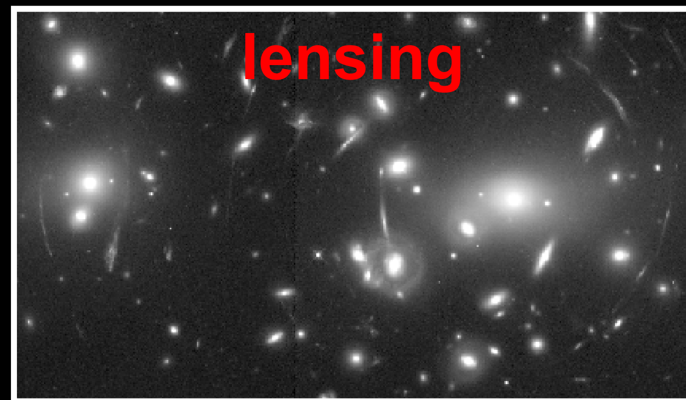
cosmological constant, or
…some changing non-zero vacuum energy, or
… or some unknown systematic effect(s)

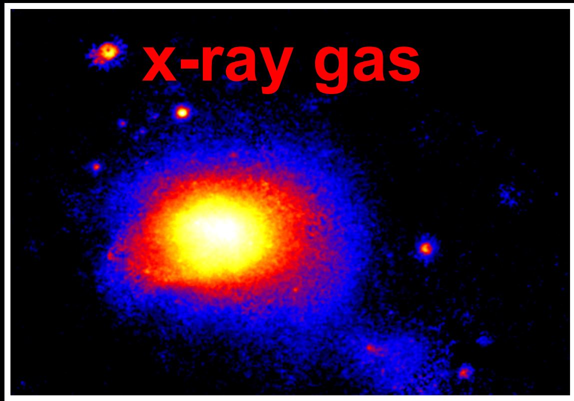
<u>The case for Λ:</u>

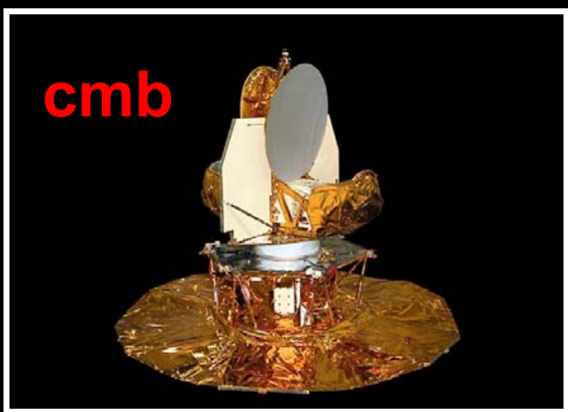
1) Hubble diagram

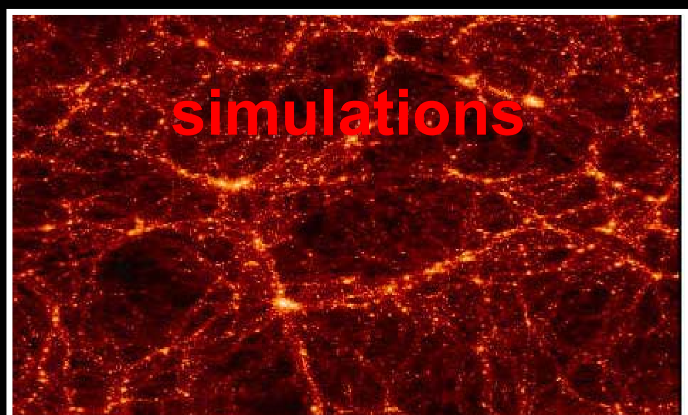
2) subtraction

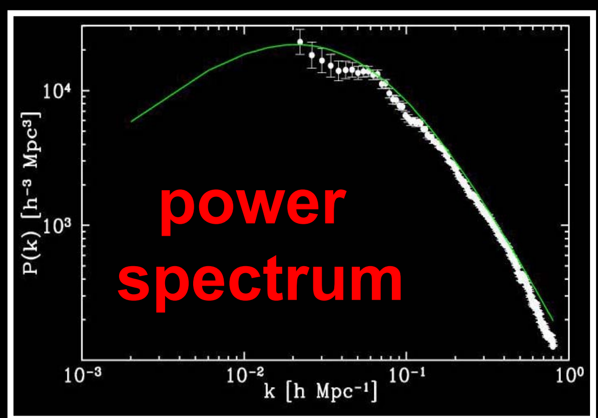
Matter $\Omega_M \sim 0.3$









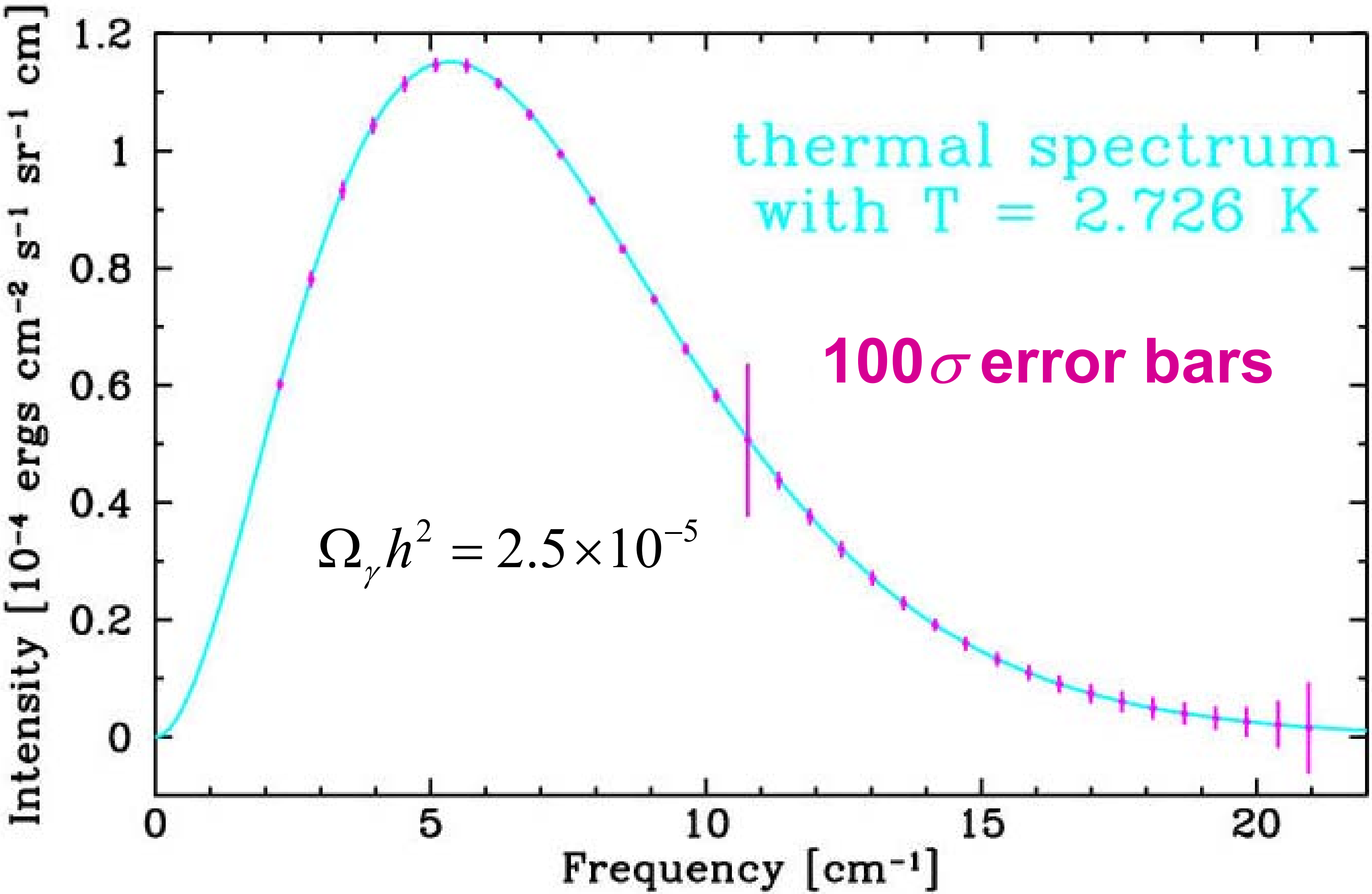


$\Omega_{\mathrm{TOTAL}} = 1, \ \Omega_M = 0.3$ $\quad 1 - 0.3 = 0.7$

Theorist's view of the universe

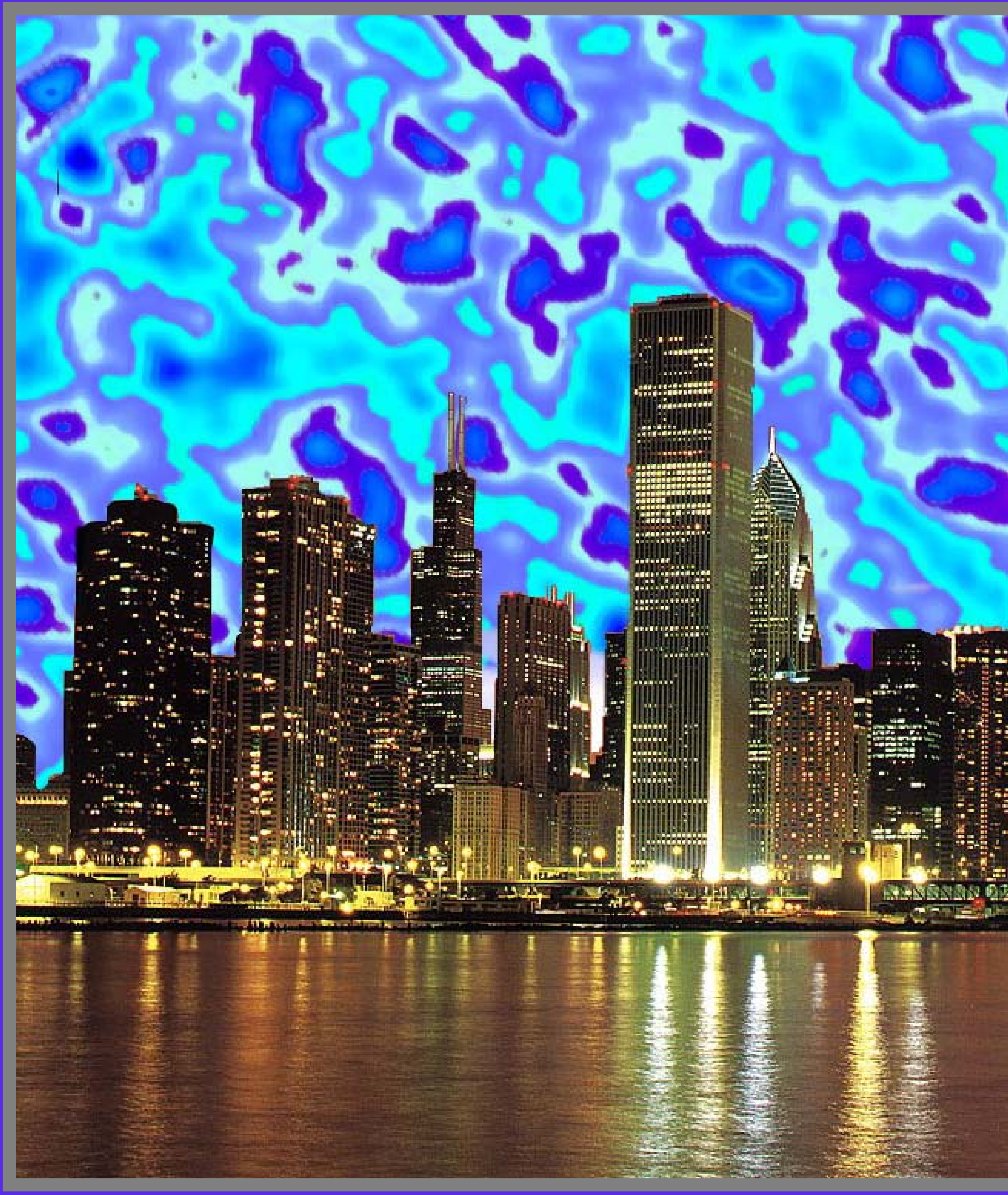
(isotropic)

Temperature of the universe

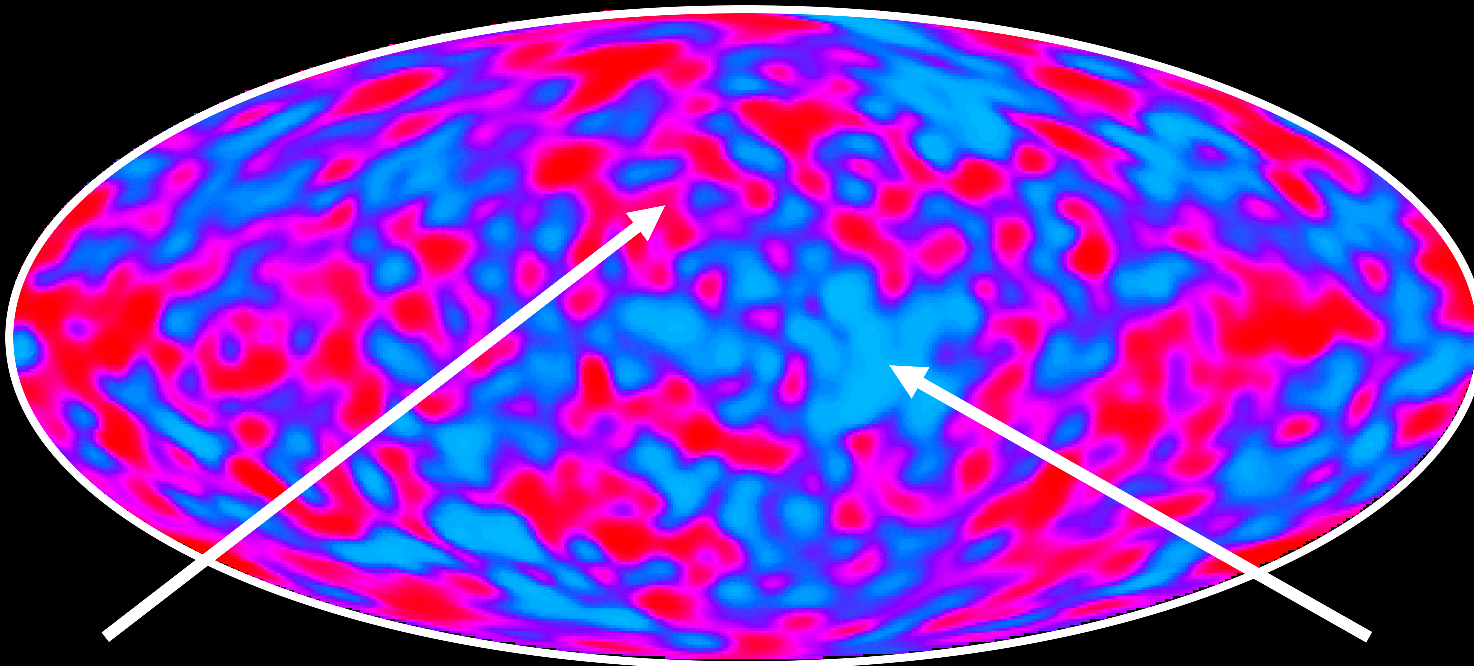


Observer's view of the universe

(fluctuations)



Angular power spectrum



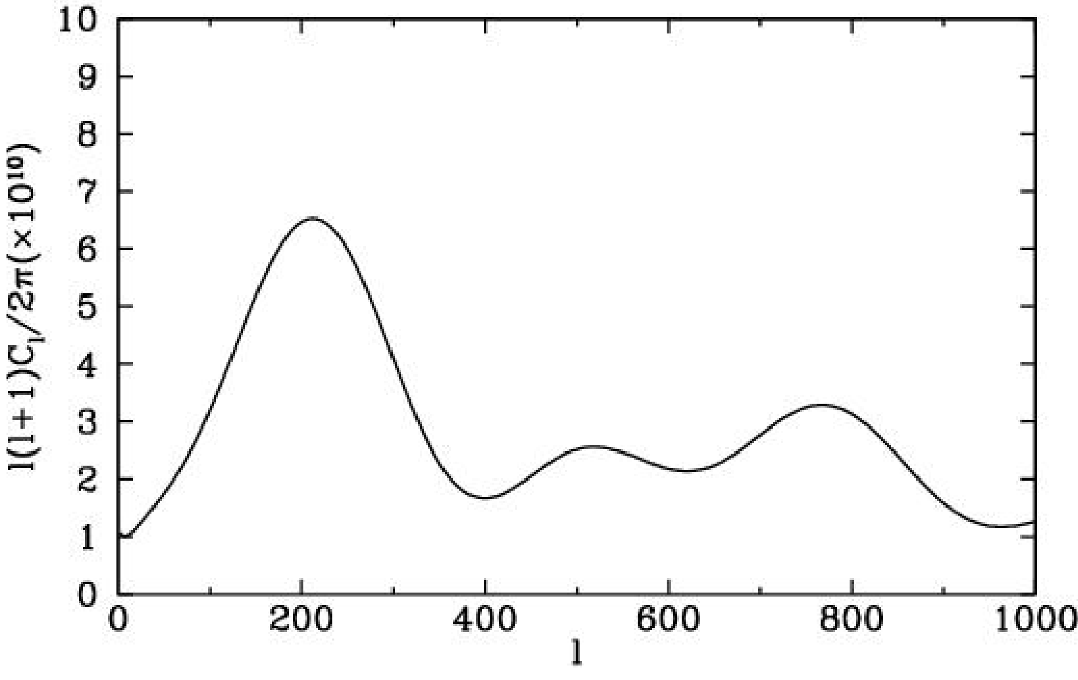
$\delta T(\theta_1, \phi_1)$ $\delta T(\theta_2, \phi_2)$

$$\delta T(\theta,\phi) = \sum a_{lm} Y_{lm}(\theta,\phi)$$

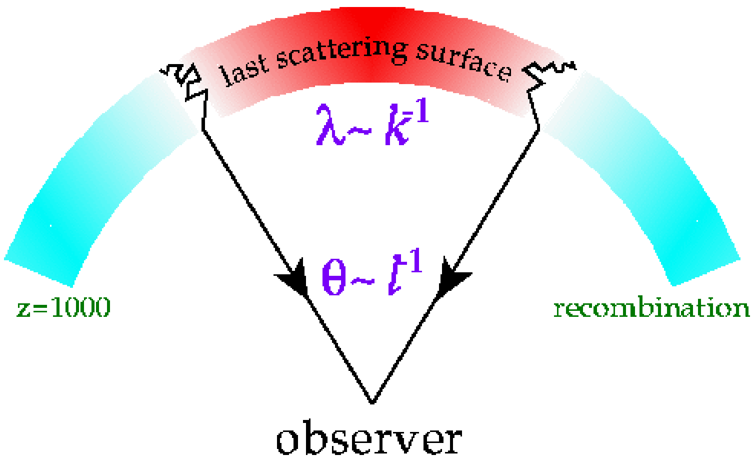
$$C_l \equiv \left\langle \left| a_{lm} \right|^2 \right\rangle$$

Acoustic peaks

- At recombination, baryon–photon fluid undergoes "acoustic oscillations" $A\cos kt + B\sin kt$
- Compressions and rarefactions change T_γ
- Peaks in ΔT_γ correspond to extrema of compressions and rarefactions
- Multipole number corresponds to a physical length scale

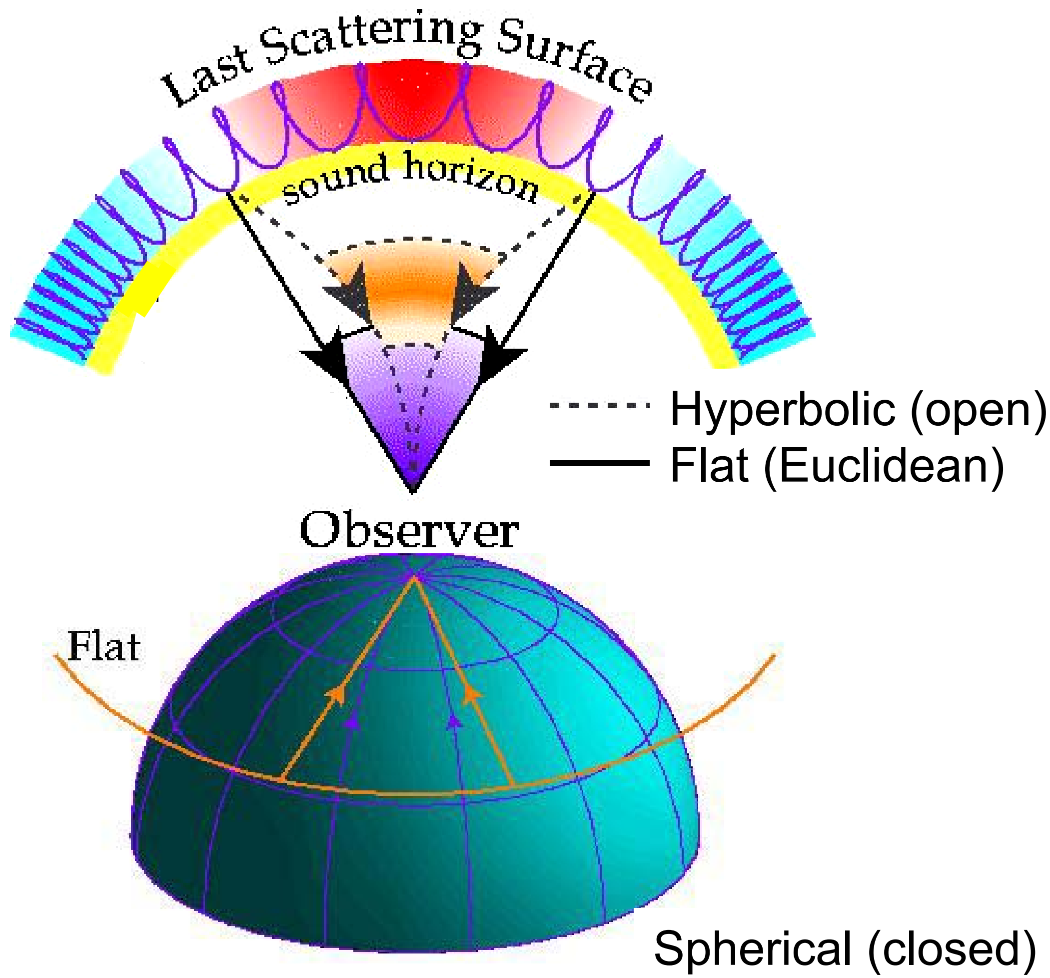


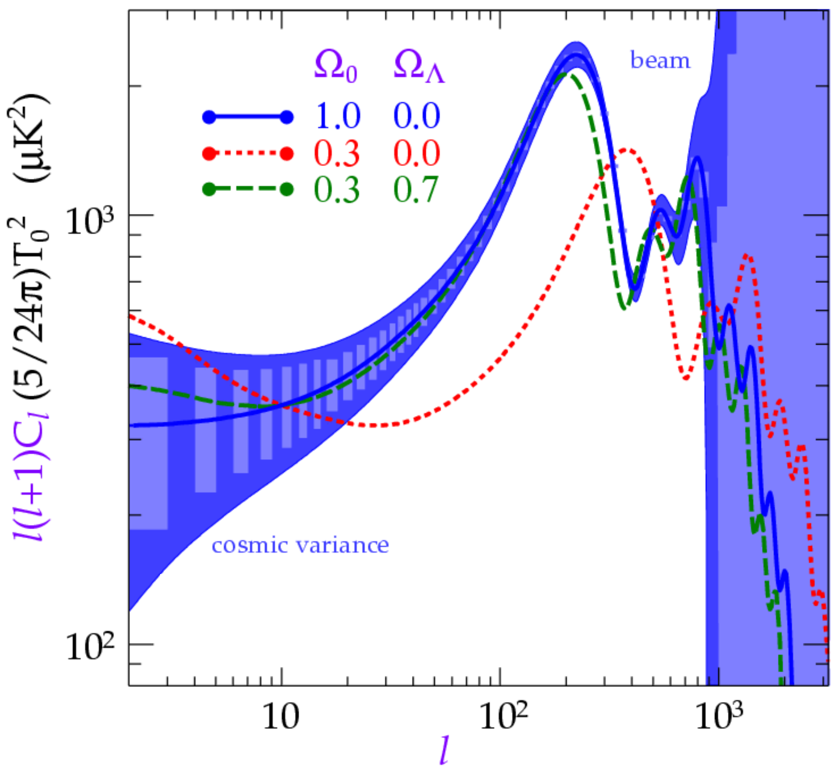
Acoustic peaks



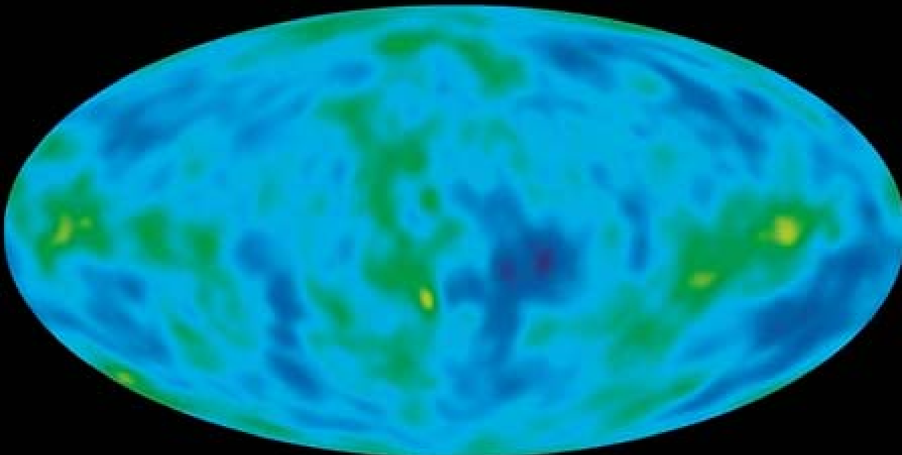
Sound travel distance known

Observed l_{peak} ~ geometry

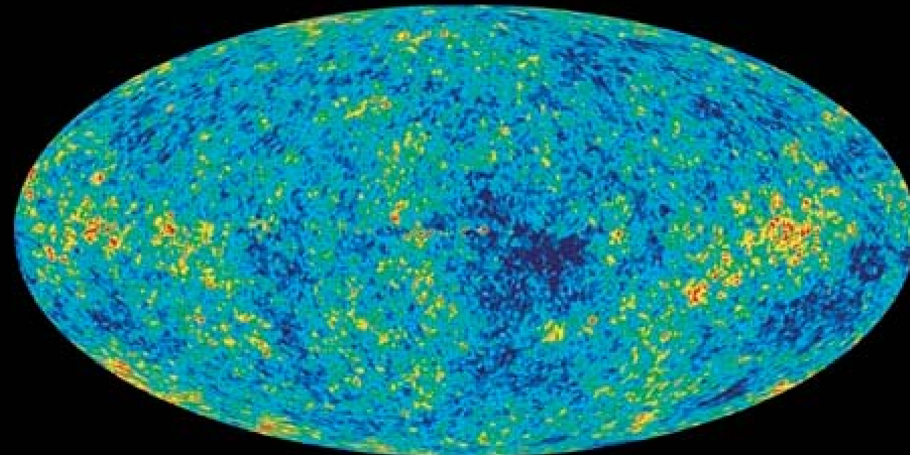




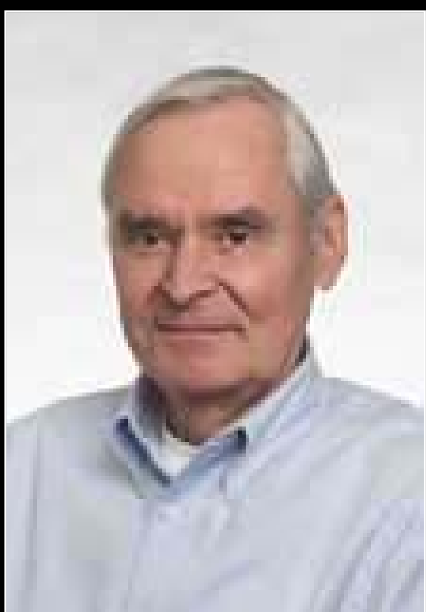
WMAP



COBE



WMAP



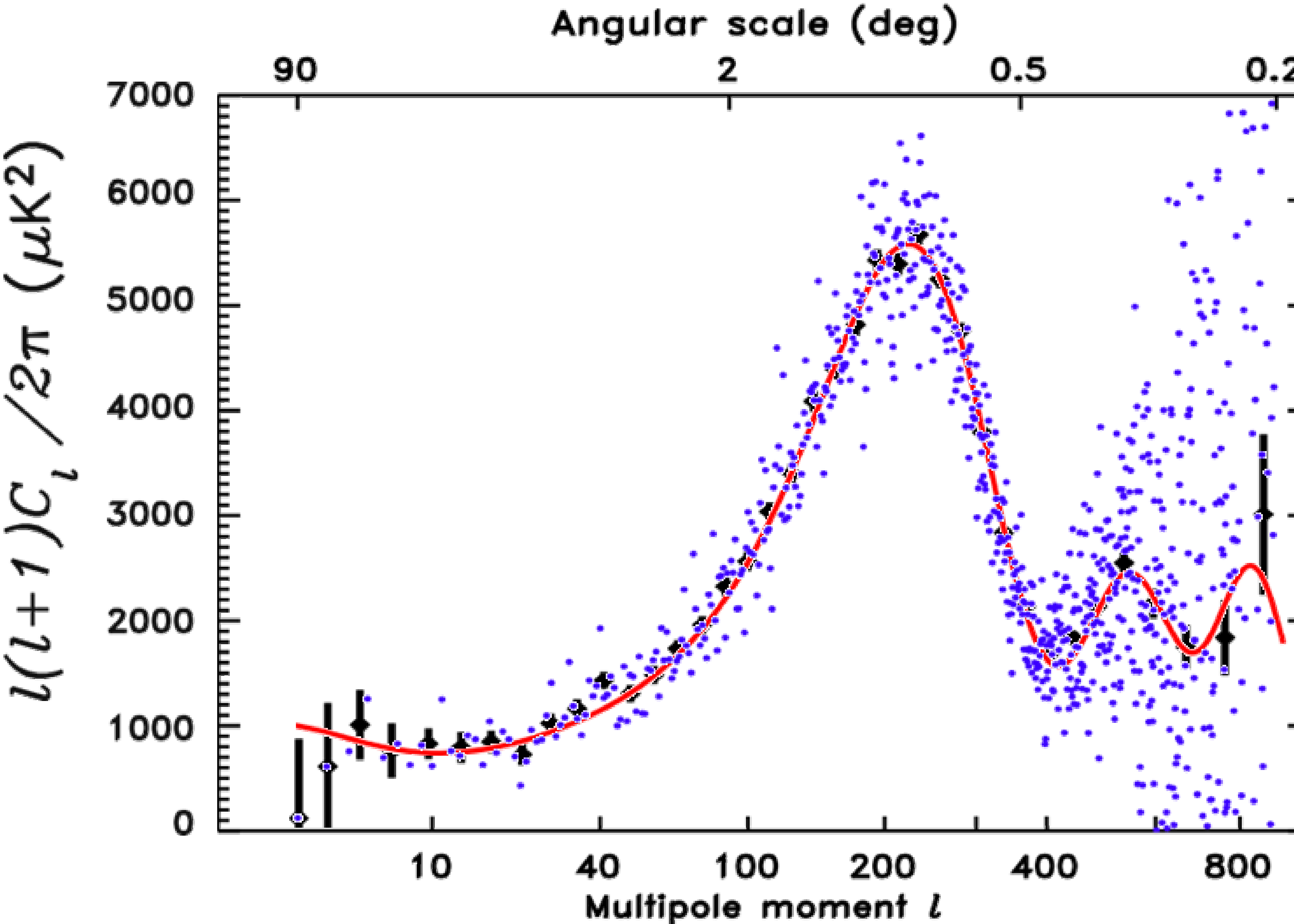
David T. Wilkinson
1935-2002

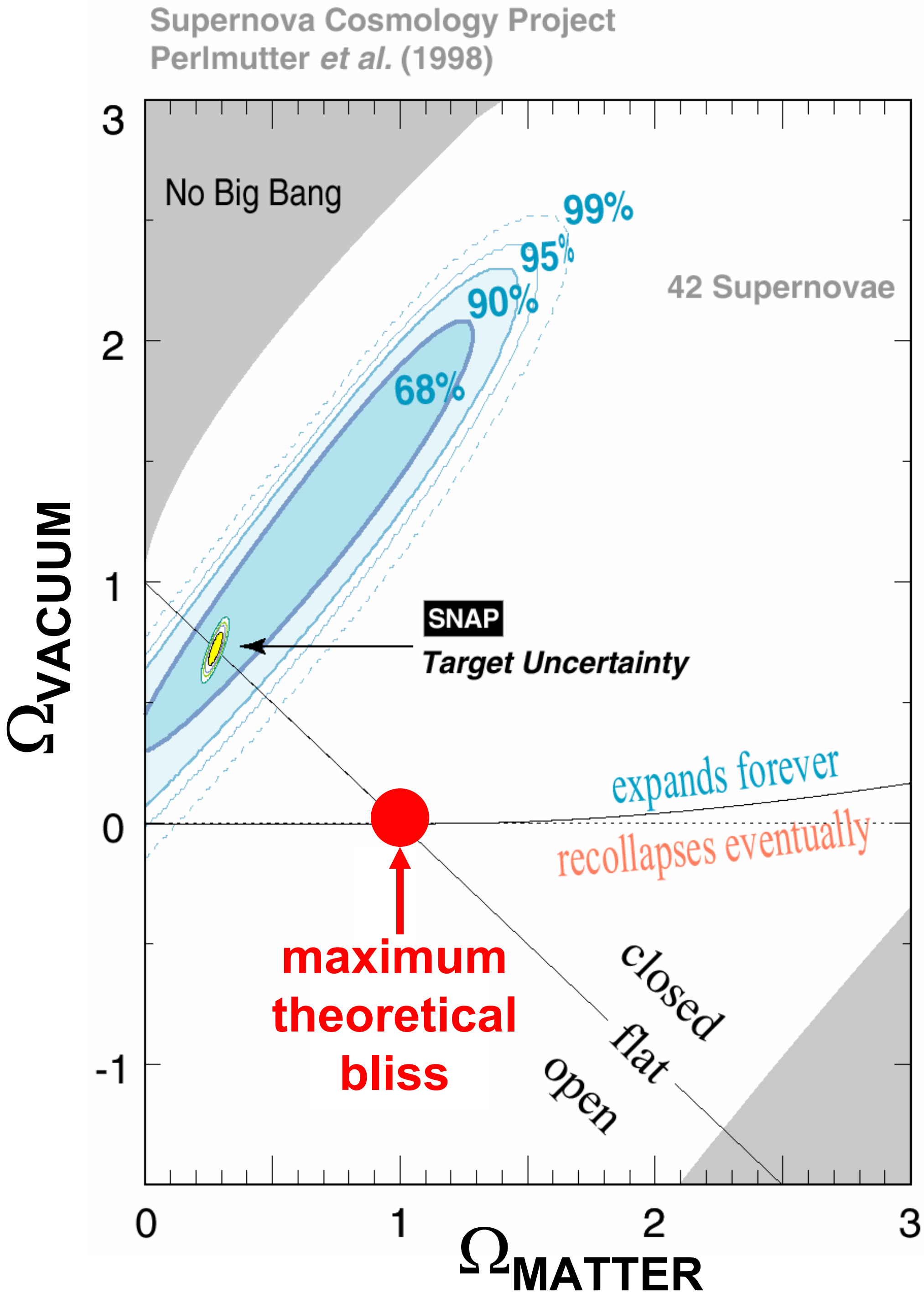
WMAP model

WMAP science team

WMAP Angular Power Spectrum

$$\Omega_{\mathrm{TOTAL}} = 1.02 \pm 0.02$$





High-z SNeIa are fainter than expected in an Einstein-deSitter model

cosmological constant, or
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The case for Λ:

1) Hubble diagram

2) subtraction

$\Omega_{TOTAL} = 1$
$\Omega_M = 0.3$
$1 - 0.3 = 0.7$

3) age of the universe

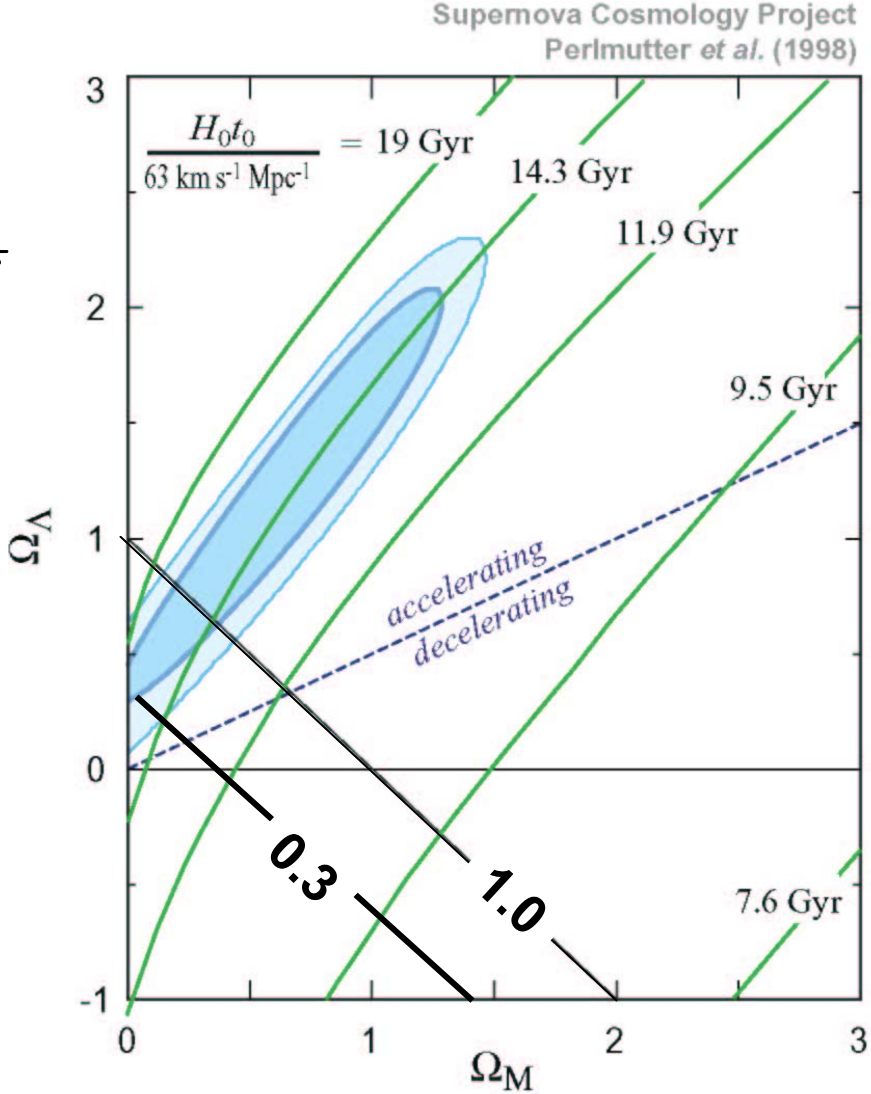
t_0 : age of the universe

Example: matter + lambda ⟶ $\Omega_{\mathrm{TOTAL}} = \Omega_M + \Omega_\Lambda$

Integrate Friedmann equation:

$$H_0 t = \int_0^1 \frac{dx}{\sqrt{1 - \Omega_{\mathrm{TOTAL}} + \sum_w \Omega_w x^{-1+3w}}}$$

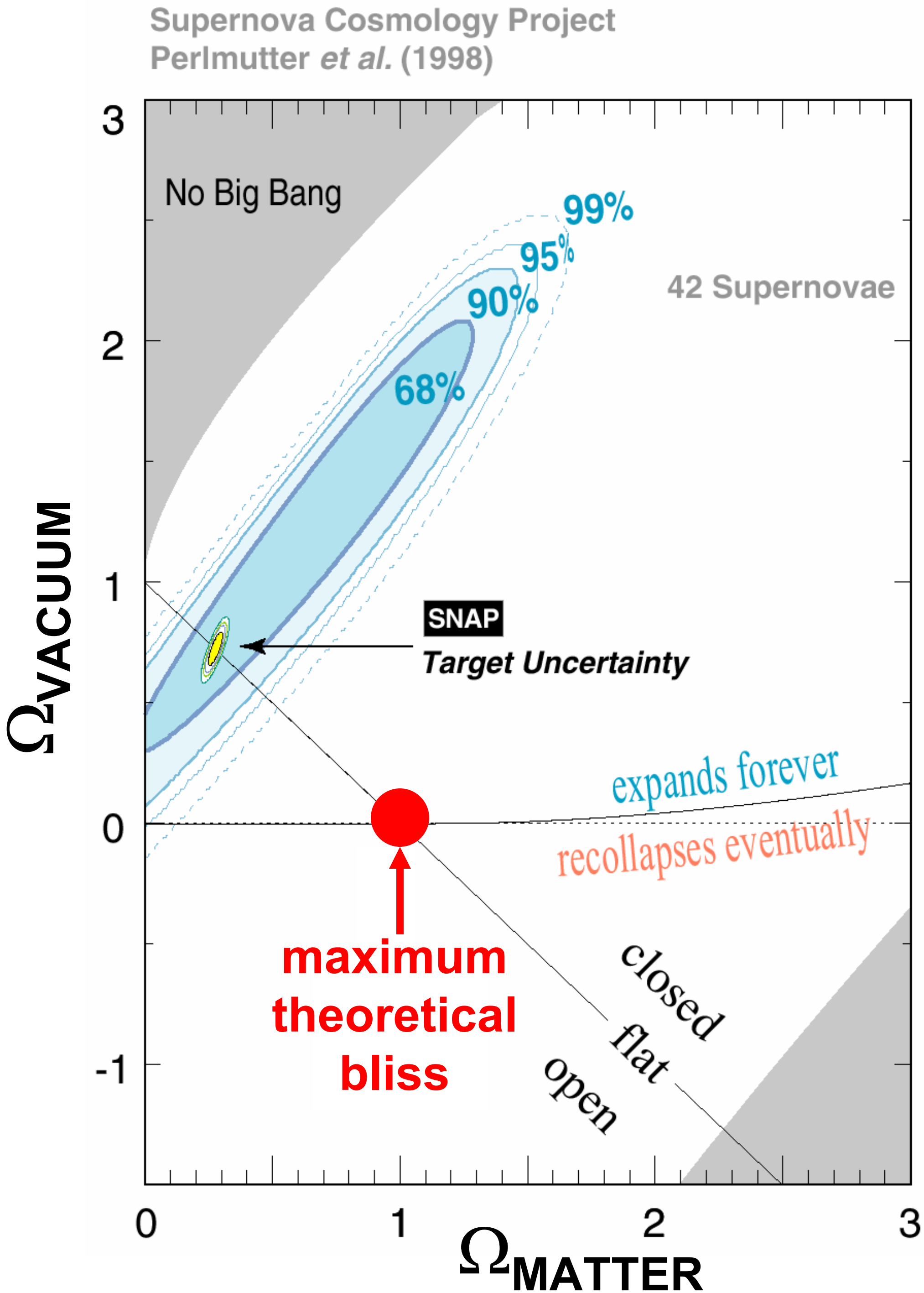
$$\Omega_{\mathrm{TOTAL}} = \Omega_M + \Omega_\Lambda$$



t_0 : age of the universe

- **white dwarf cooling** 11 ± 2 Gyr
- **nucleocosmochronology** 12.6 ± 3 Gyr
- **globular cluster evolution** 13.5 ± 2 Gyr

$H_0 = 70$	Ω_M	Ω_Λ	t_0 (Gyr)
Flat	1.0	0	9.3
Open	0.3	0	12
Open	0.2	0	14
Flat	0.3	0.7	13.5
Flat	0.2	0.8	15



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The case for Λ:

1) **Hubble diagram**
2) **subtraction**

$\Omega_{TOTAL} = 1$

$\Omega_M = 0.3$

$1 - 0.3 = 0.7$

3) **age of the universe**
4) **structure formation**

Cosmology and the origin of structure

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Einstein's Biggest Blunder?

1917 Einstein proposes cosmological constant

1929 Hubble discovers Expansion of the universe

1934 Einstein calls it "my biggest blunder"

1998 Astronomers find evidence for it