Dark Matter and Dark Energy

Rocky I: Evidence for dark matter and dark energy

Rocky II: Dark matter candidates

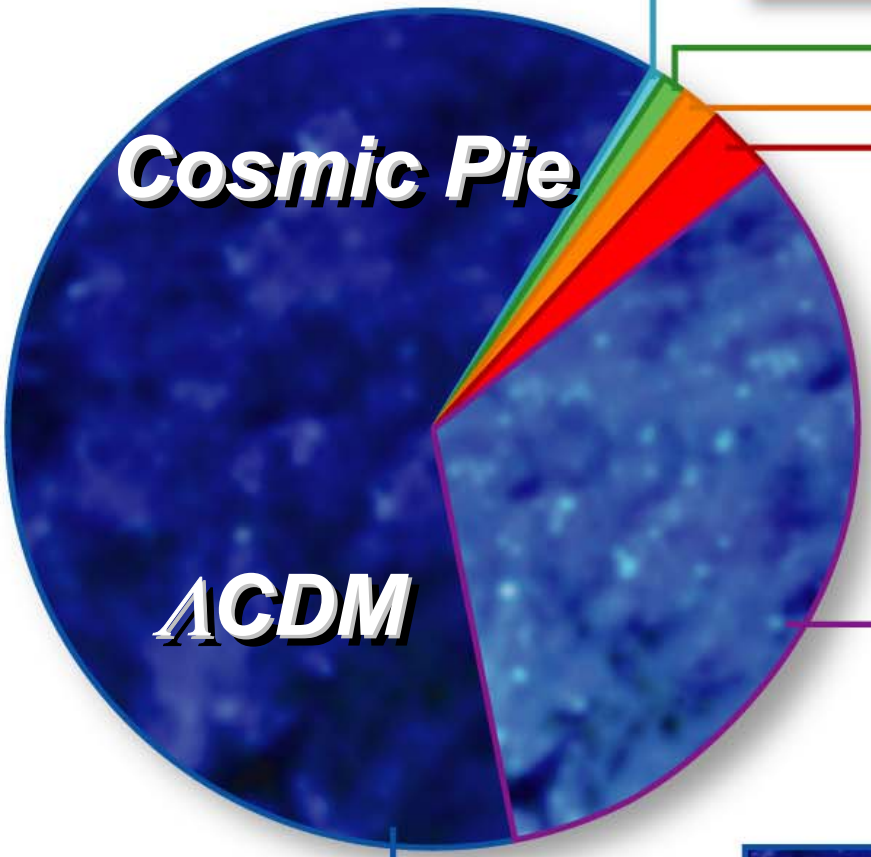
Rocky III: Dark energy reloaded

SLAC Summer Institute, August 2003

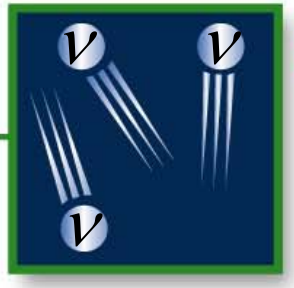
Rocky Kolb, Fermilab & The University of Chicago

$$\Omega_i \equiv \rho_i / \rho_{\text{CRITICAL}}$$

$$\Omega_{\text{TOTAL}} = 1$$

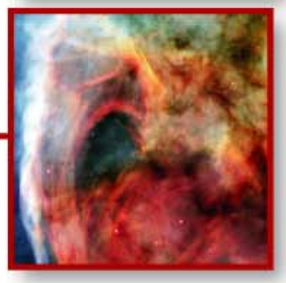


Heavy Elements:
Ω=0.0003

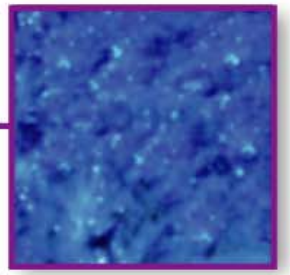


Neutrinos (ν):
Ω=0.0047

Stars:
Ω=0.005



Free H & He:
Ω=0.04



Cold Dark Matter:
Ω=0.25

Dark Energy (Λ):
Ω=0.70

What We "Know" *

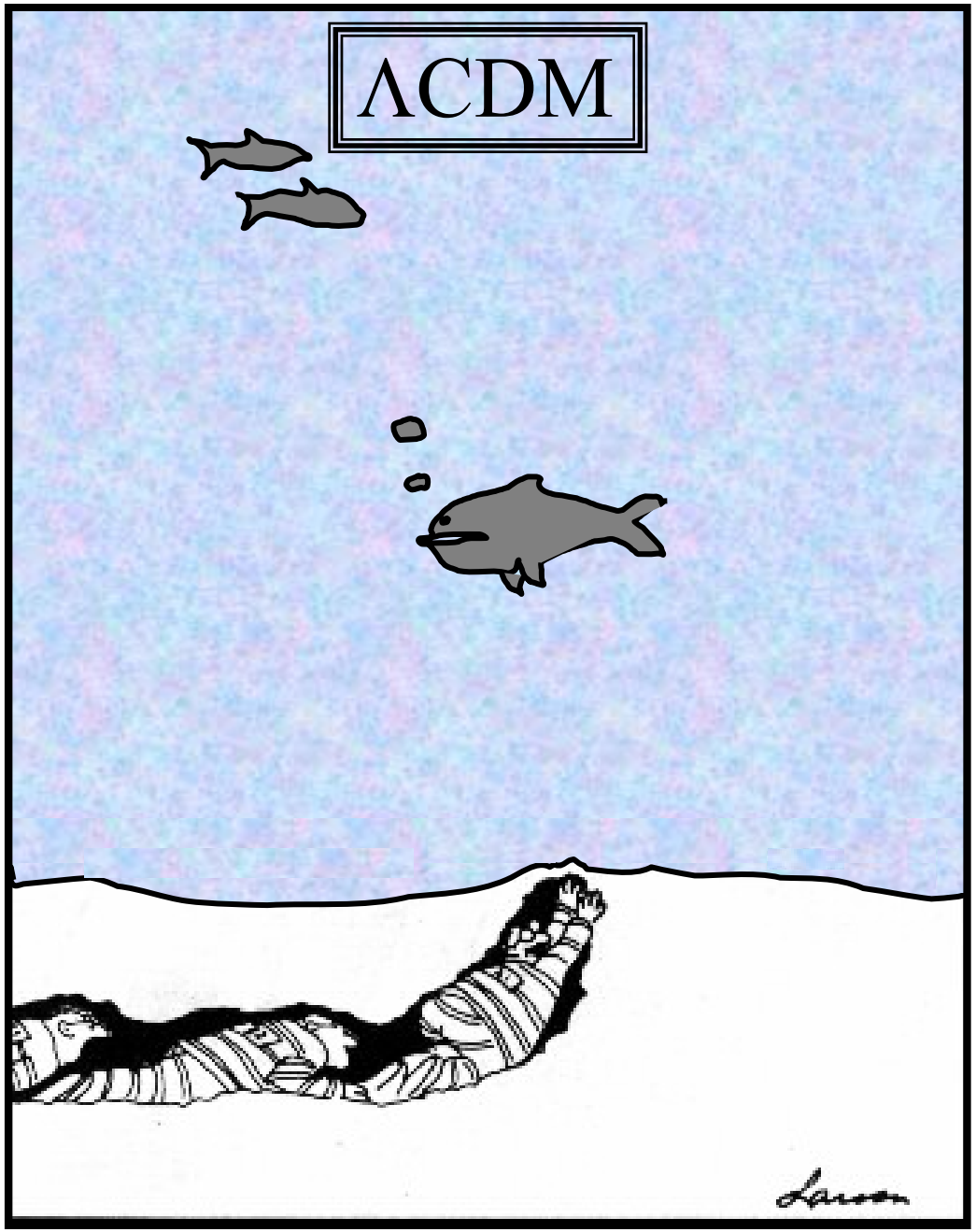
The matter density is dominated by cold dark matter,
which we know nothing about!

The baryon asymmetry arises in the GUT or EWK era through B, CP, and equilibrium violation (Sakharov's ingredients),
EWK doesn't seem to work….GUT scenarios are not simple!

The perturbations arise from inflationary dynamics, which depends on particle physics at high energies,
which we know nothing about!

The universe is dominated by a cosmological term (dark energy, funny energy, quintessence, polenta, cosmological constant, cosmo-illogical constant, ….),
which we know less than nothing about!

*** It ain't what you don't know, it's what you know that ain't so!**



We’re almost free, I just felt the first drops of rain

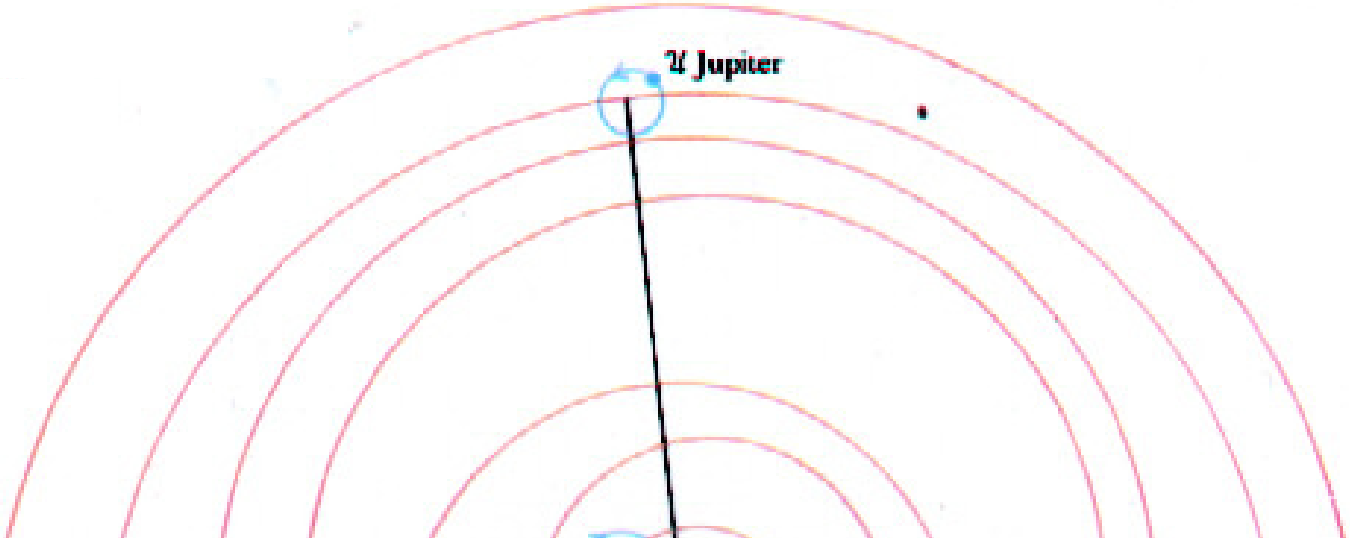
Do we have concordance- a standard cosmological model?*

- Radiation
- Neutrinos
- Dark matter
- Dark baryons
- Dark energy
- Inflation
- Baryo/leptogenesis

- Hypotheses?
- Saving the appearances?
- Epicycles?

** Do we want one? The goal is not concordance, but correctness!*

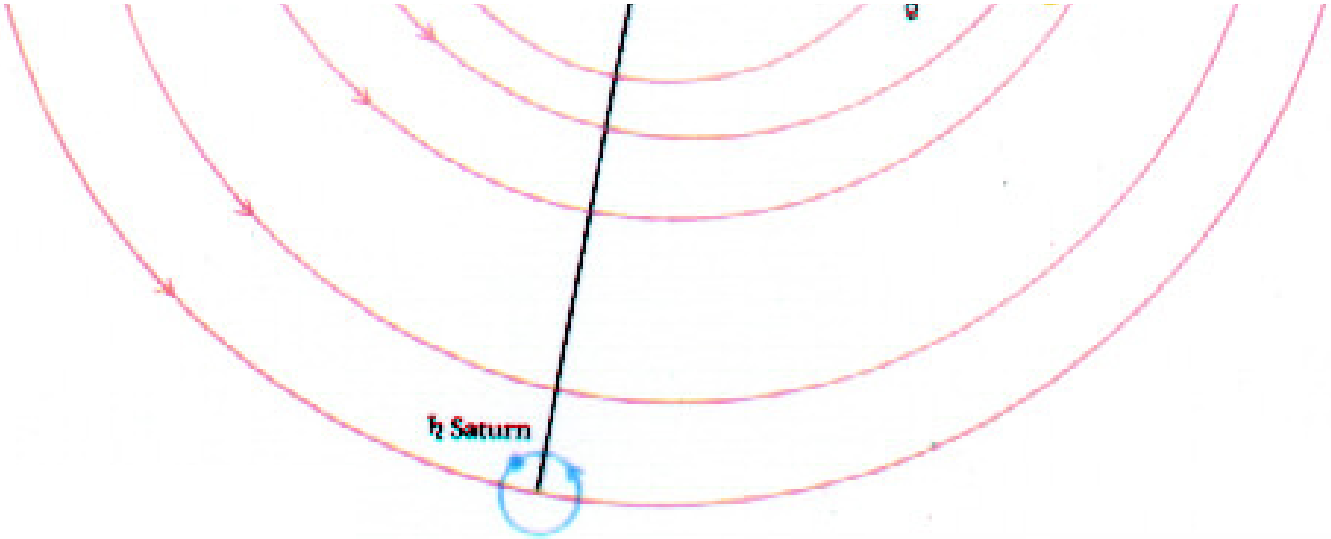
System



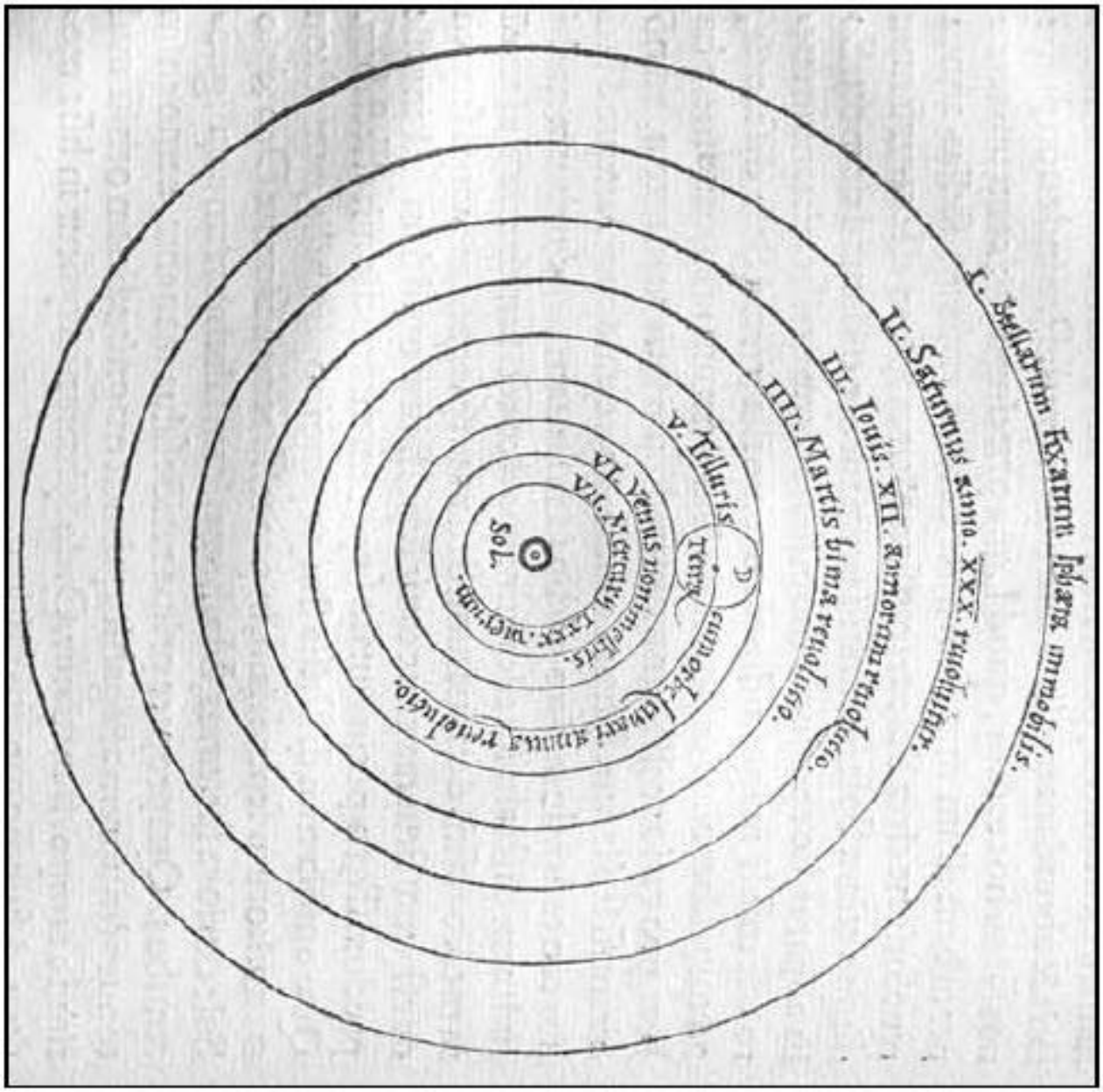
If I had been present at creation, I would have suggested a simpler scheme.

- Alfonse the Wise

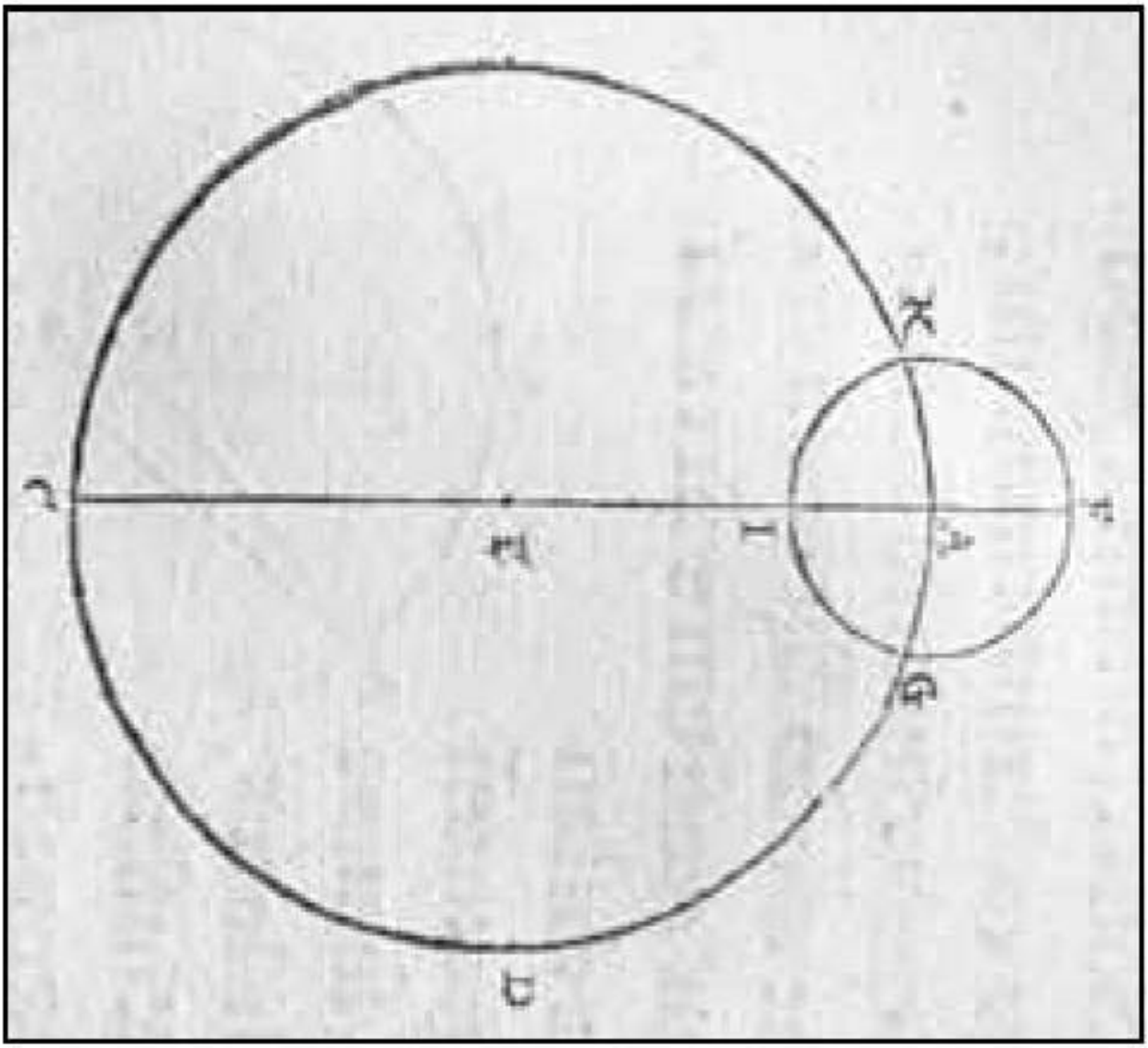
The Ptol



From Book I of De Revolutionibus



From Book III of De Revolutionibus



Epicycle I – Inflation

Inflation, as a whole, can be divided into three parts

1. Beginning

   eternal inflation, wave function of the universe, did the universe have a beginning ????

2. Middle

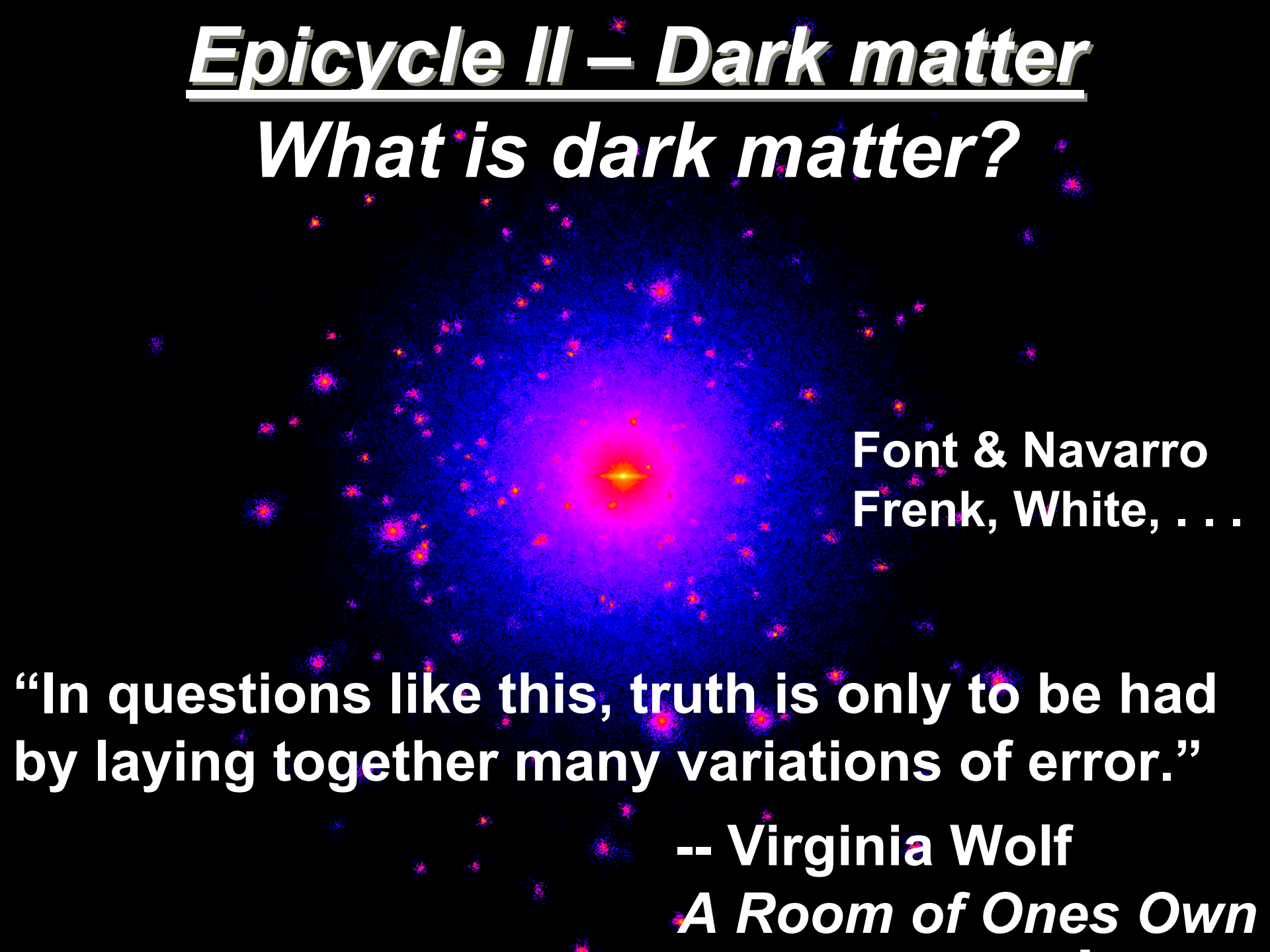
   density perturbations, gravitational waves, (particle production in the expanding universe)

3. End

   defrosting, heating, preheating, reheating, baryogenesis, phase transitions, dark matter, (particle production in the expanding universe)

Epicycle II – Dark matter

What is dark matter?



Font & Navarro
Frenk, White, . . .

"In questions like this, truth is only to be had by laying together many variations of error."

-- Virginia Wolf
A Room of Ones Own

Epicycle III – Dark Energy

What is the nature of dark energy

"In questions like this, truth is only to be had by laying together many variations of error."

-- Virginia Wolf

A Room of Ones Own

The universe observed

- **Cosmological parameters:**

$H_0 \rightarrow$ Hubble's constant

$q_0 \rightarrow$ deceleration parameter

$\Omega_i \rightarrow$ the cosmic food chain

$$\left(\Omega_{\mathrm{TOTAL}}\ ,\ \Omega_M\ ,\ \Omega_B\ ,\ \Omega_\Lambda,\ \Omega_\gamma\ ,\ \Omega_\nu\ ,\ \ldots\ldots\right)$$

$t_0 \rightarrow$ age of the universe

$T_0 \rightarrow$ temperature of the universe

- **Power spectra:**

$P(k), \quad C_l$

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

ΛCDM

Big-Bang Theory

Robertson-Walker metric

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

$k = 0, \pm 1$

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

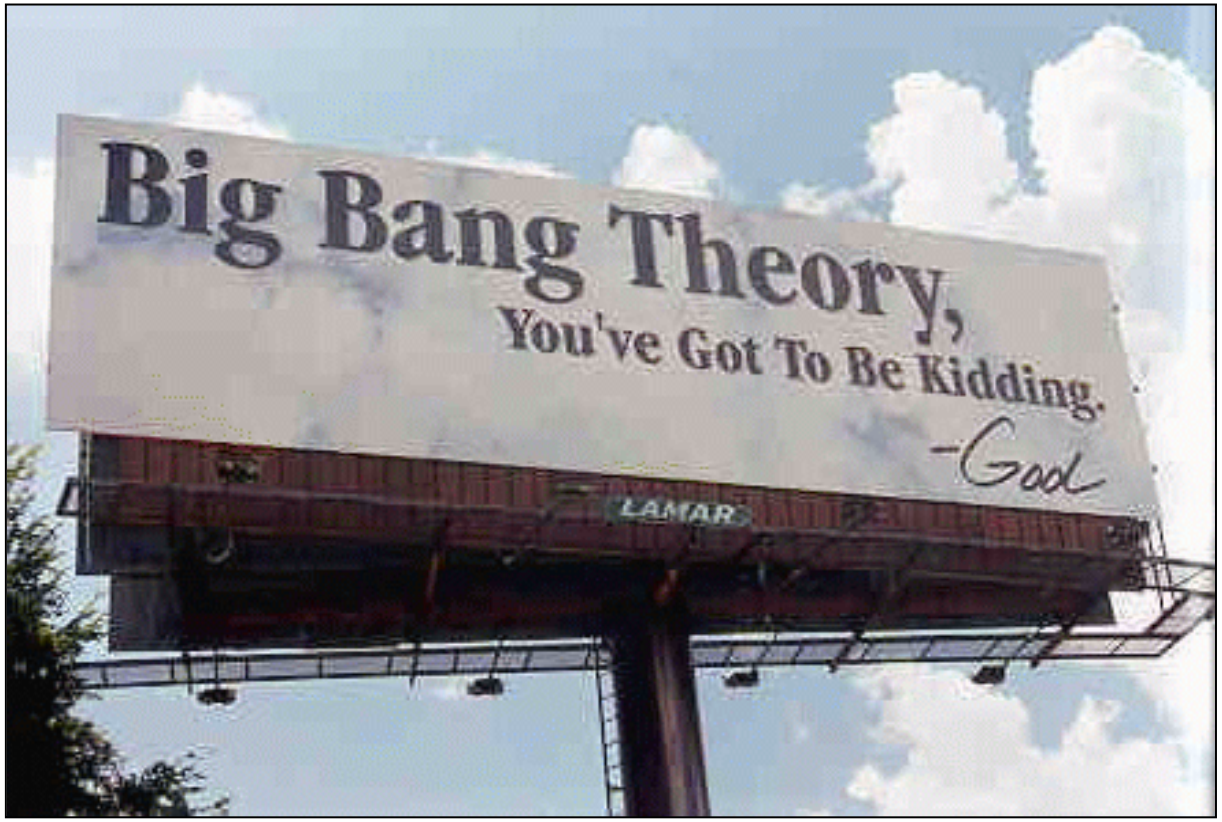
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Perfect-fluid stress tensor

$\rho =$ energy density

$p =$ pressure

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



Field equations

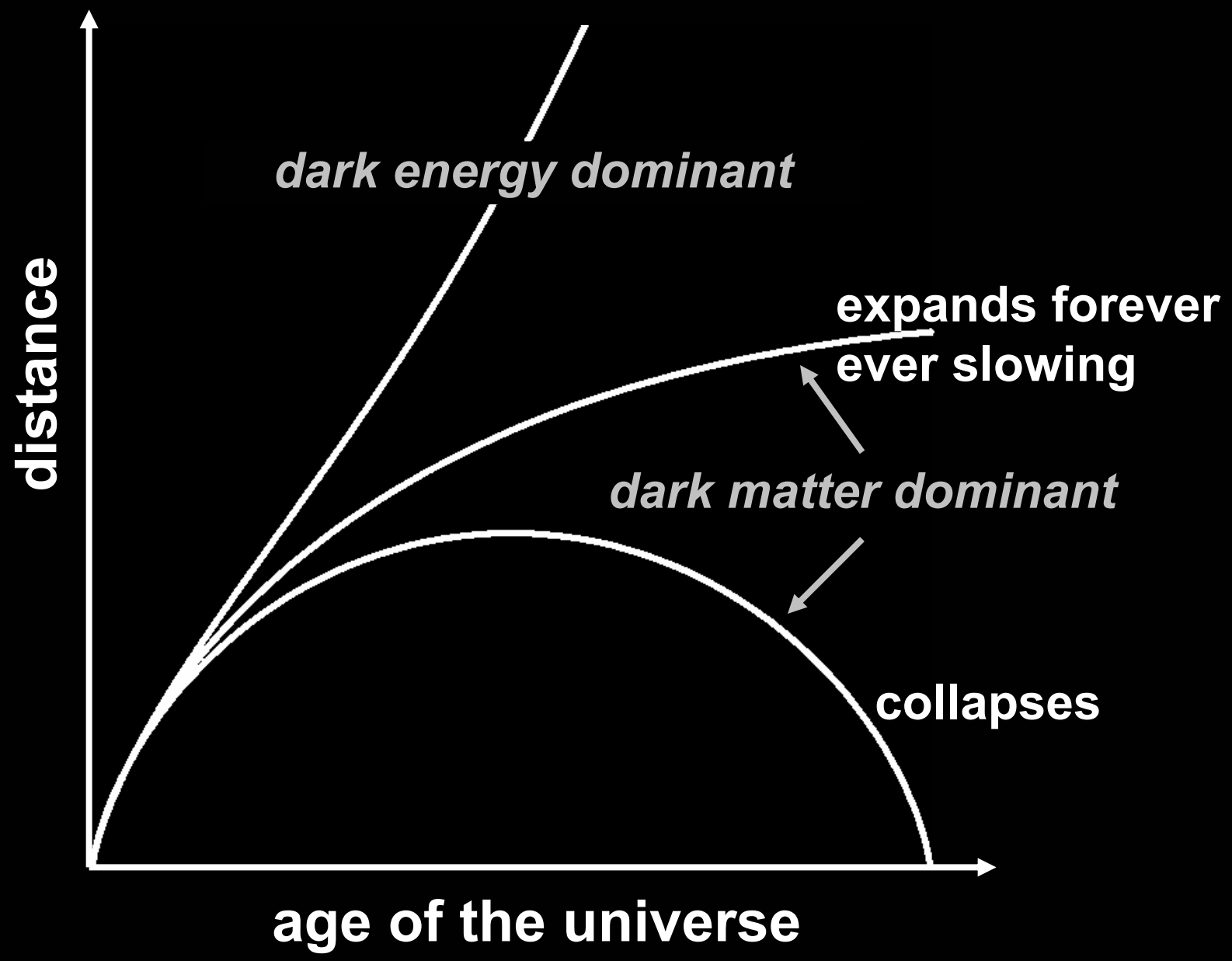
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \qquad H \equiv \frac{\dot{a}}{a} = \text{expansion rate}$$

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

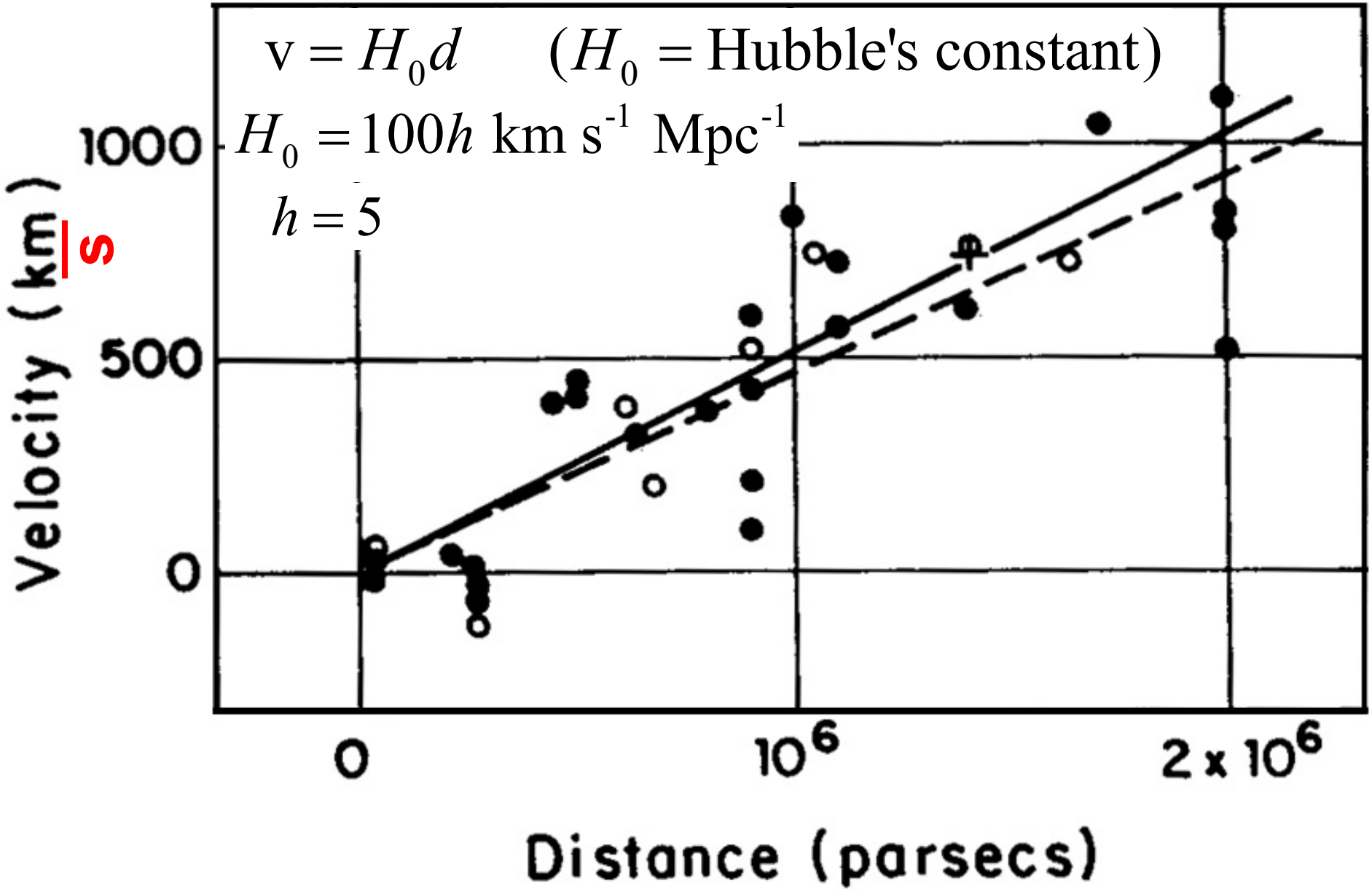
$$\rho = \rho_M + \rho_R + \rho_\Lambda + \text{whatever}$$

whatever:	$p_w = w\rho_w$	$w = p/\rho$	$\rho_w \propto a^{-3(1+w)}$
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:	$p_\Lambda = -\rho_\Lambda$	$w = -1$	$\rho_\Lambda \propto a^{0}$

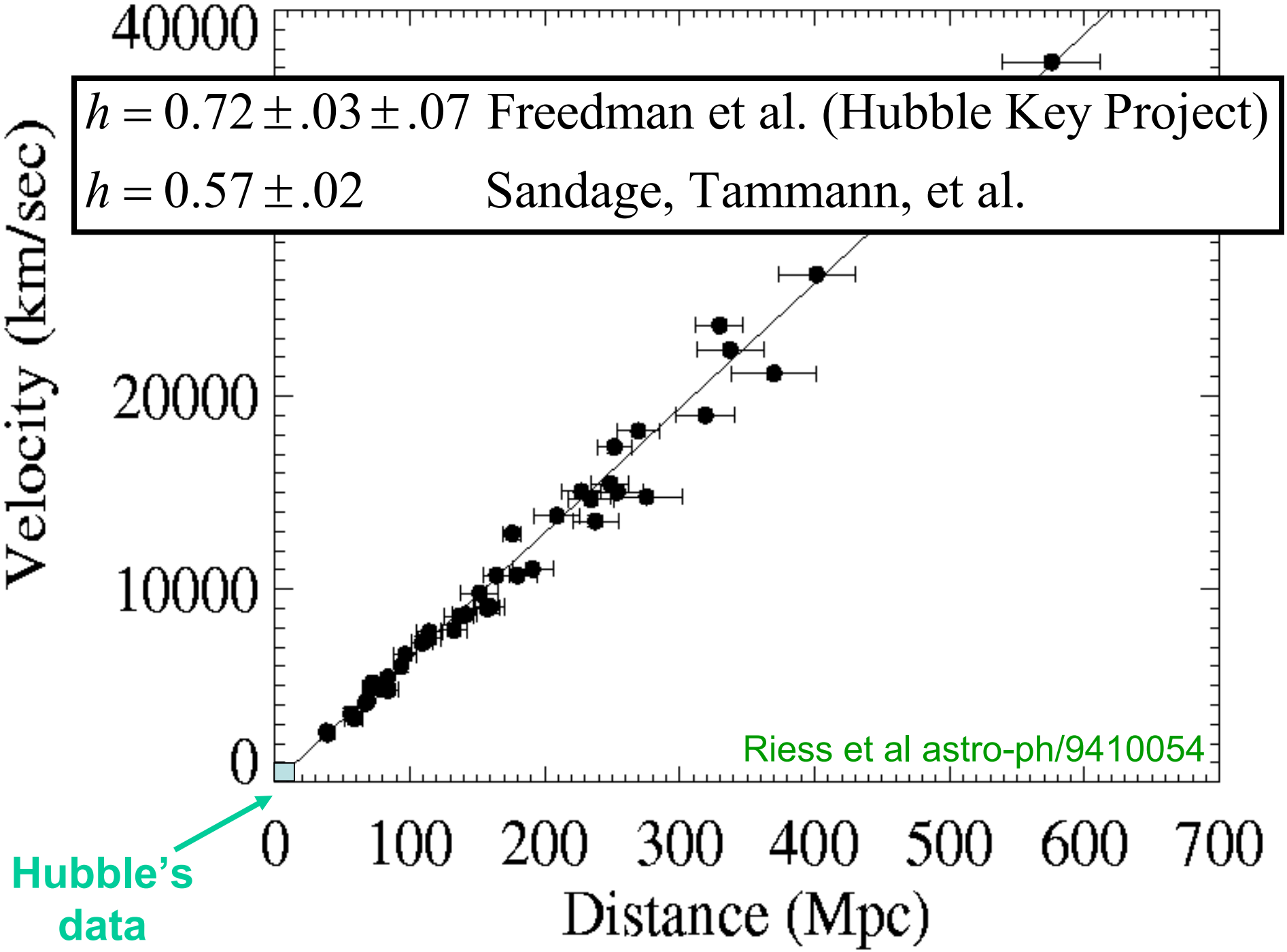
Cosmological constant (dark energy)



Hubble's Discovery Paper - 1929



University of Chicago 1909 National Champions


$h = 0.72 \pm .03 \pm .07$ Freedman et al. (Hubble Key Project)
$h = 0.57 \pm .02$ Sandage, Tammann, et al.
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

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

Λ

Field equation: $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$

Perfect fluid stress tensor: $T^{\mu}{}_{\nu} = \mathrm{diag}\left(\rho, -p, -p, -p\right)$

"I found it very ugly indeed that the field law of gravitation should be composed of two logically independent terms connected by addition. About the justification of such feelings concerning logical simplicity it is difficult to argue. I cannot help to feel it strongly and I am unable to believe that such an ugly thing should be realized in nature."

Einstein in a letter to Lemaitre, Sept. 26, 1947

Modern view: "It belongs on the right-hand side, and has many contributions."

$$\tilde{T}^{\mu}{}_{\nu} = \mathrm{diag}\left(\rho_\Lambda, \rho_\Lambda, \rho_\Lambda, \rho_\Lambda\right) \qquad \rho_\Lambda = \Lambda / 8\pi G$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(T_{\mu\nu} + \tilde{T}_{\mu\nu}\right)$$

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

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

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

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

Program:

- **measure** d_L **(via** $d_L^2 = L/4\pi F$**) and** z
- **input** Ω_i **and calculate** $a(t_0)r$

$$\boxed{\begin{array}{c} H_0 d_L = z + O(z^2) \\ \Omega_i \hookleftarrow \end{array}}$$

Evolution of H(z) is a key quantity

In a flat universe, many measures based on the comoving distance

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

- Luminosity distance

$$d_L(z) = r(z)(1+z)$$

- Angular diameter distance

$$d_A(z) = \frac{r(z)}{(1+z)}$$

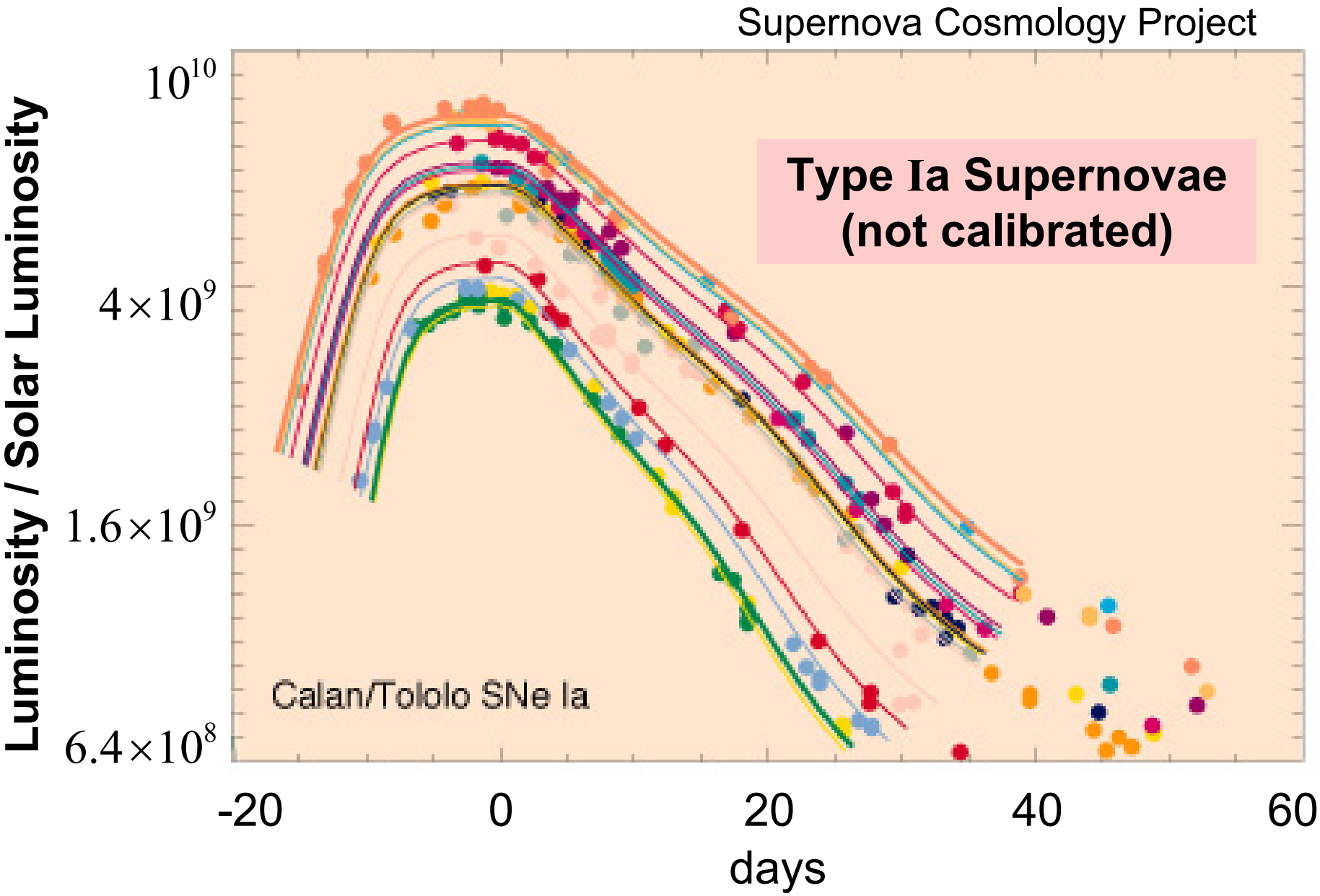
- Comoving volume element

$$\frac{dV(z)}{dz\,d\Omega(z)} = \frac{r^2(z)}{H(z)}$$

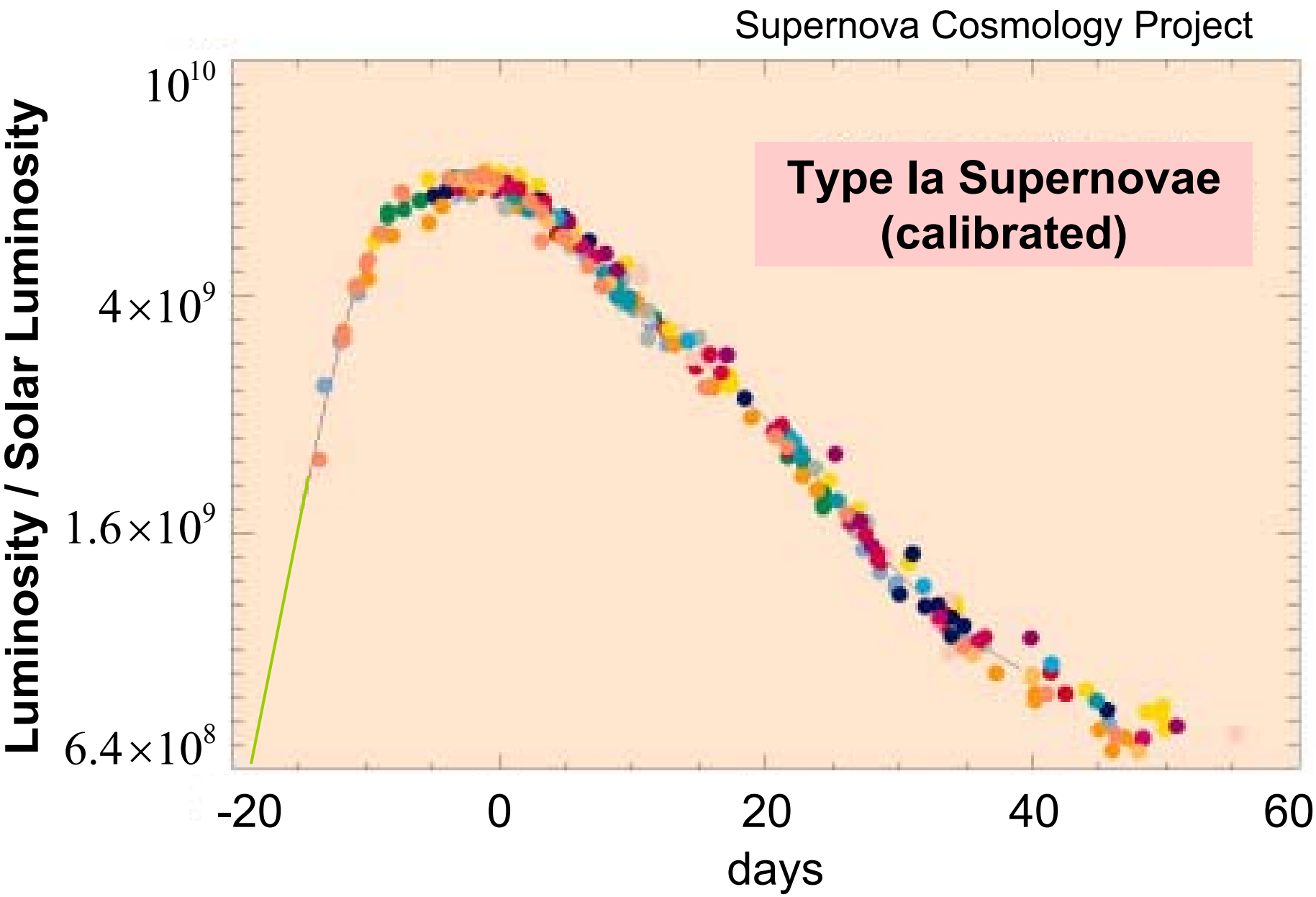
- Age of the universe

$$t(z) = \int_0^z dz \frac{1}{(1+z)H(z)}$$

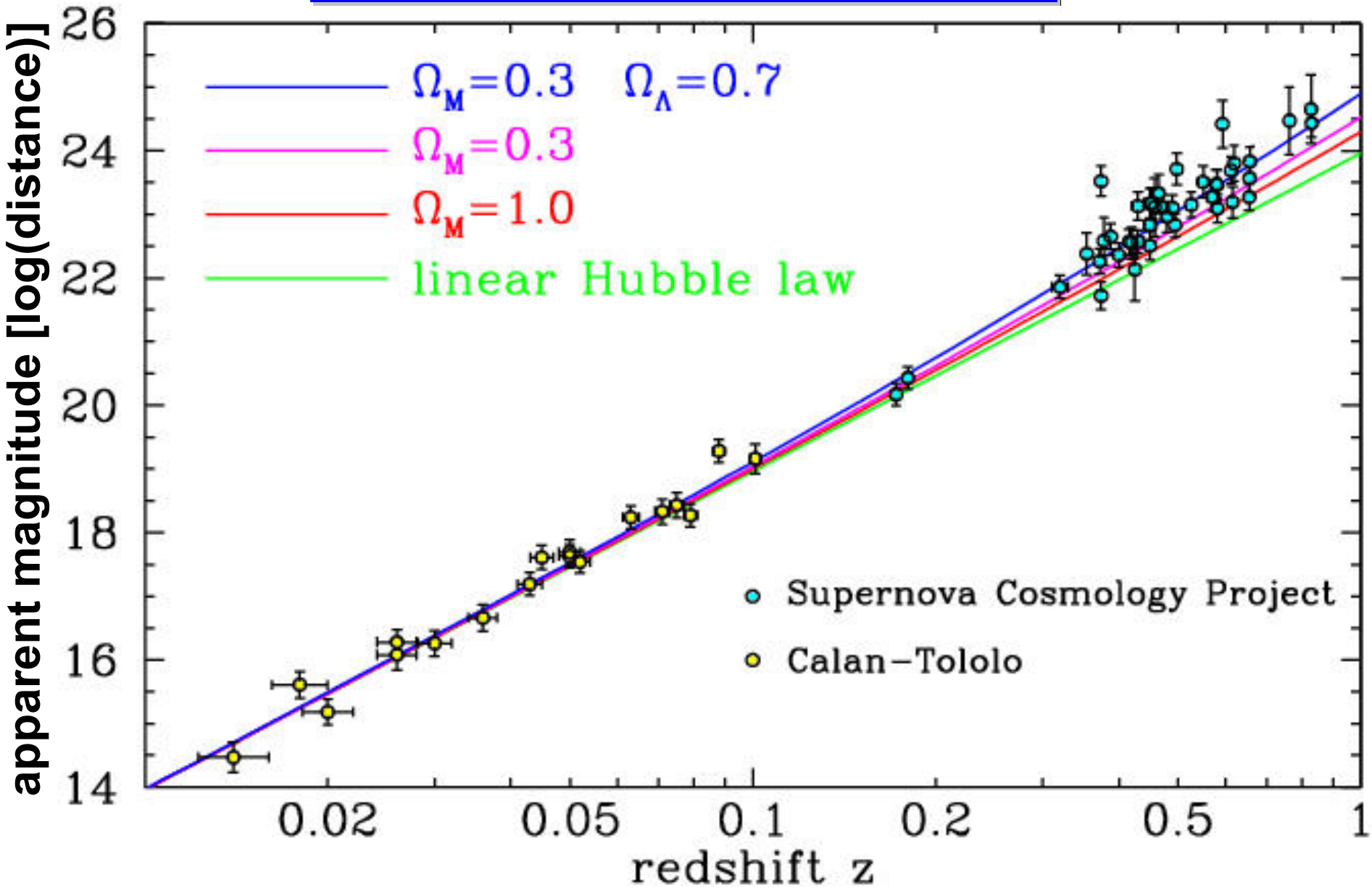
Type Ia supernova



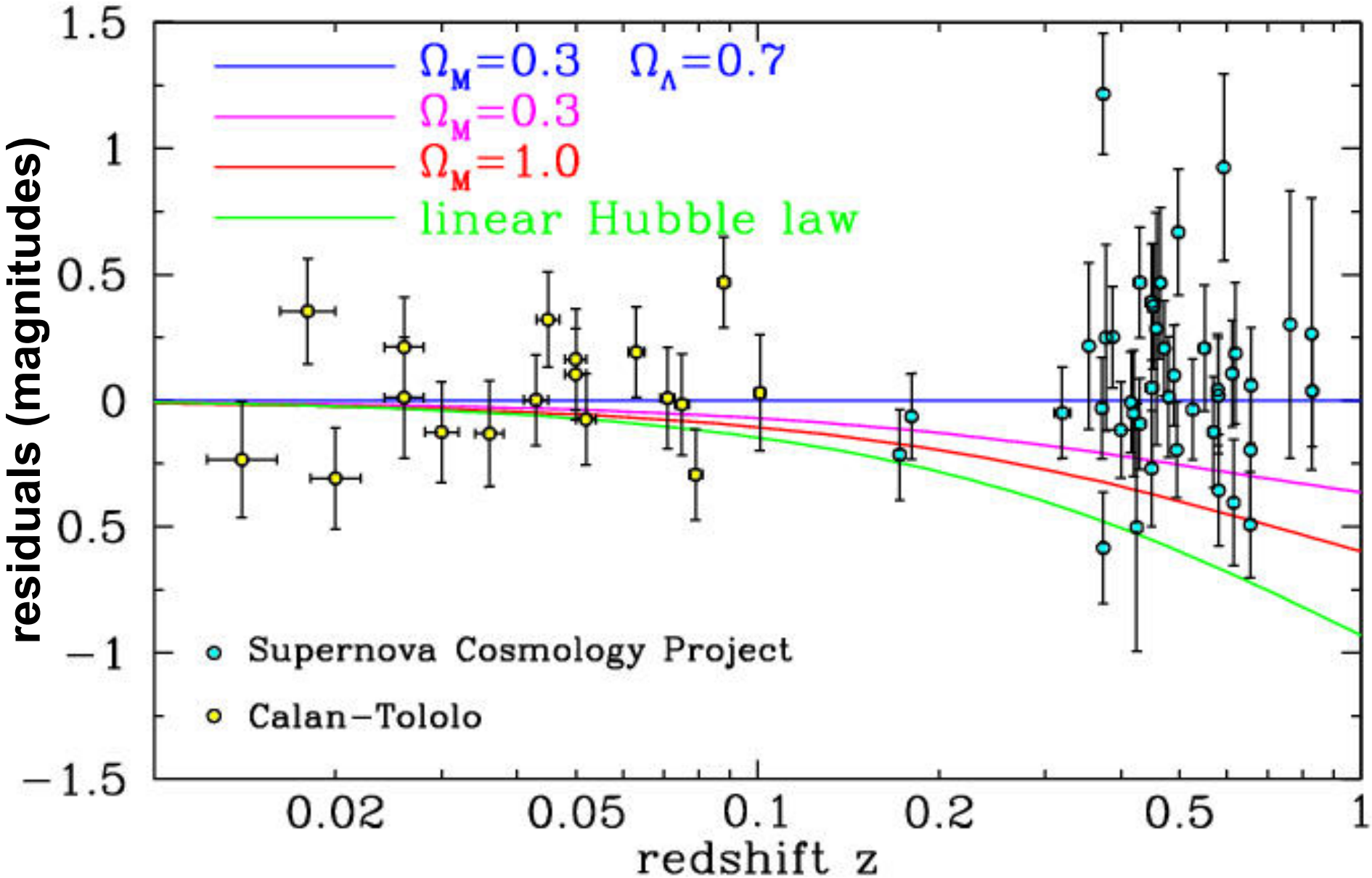
Type Ia supernova

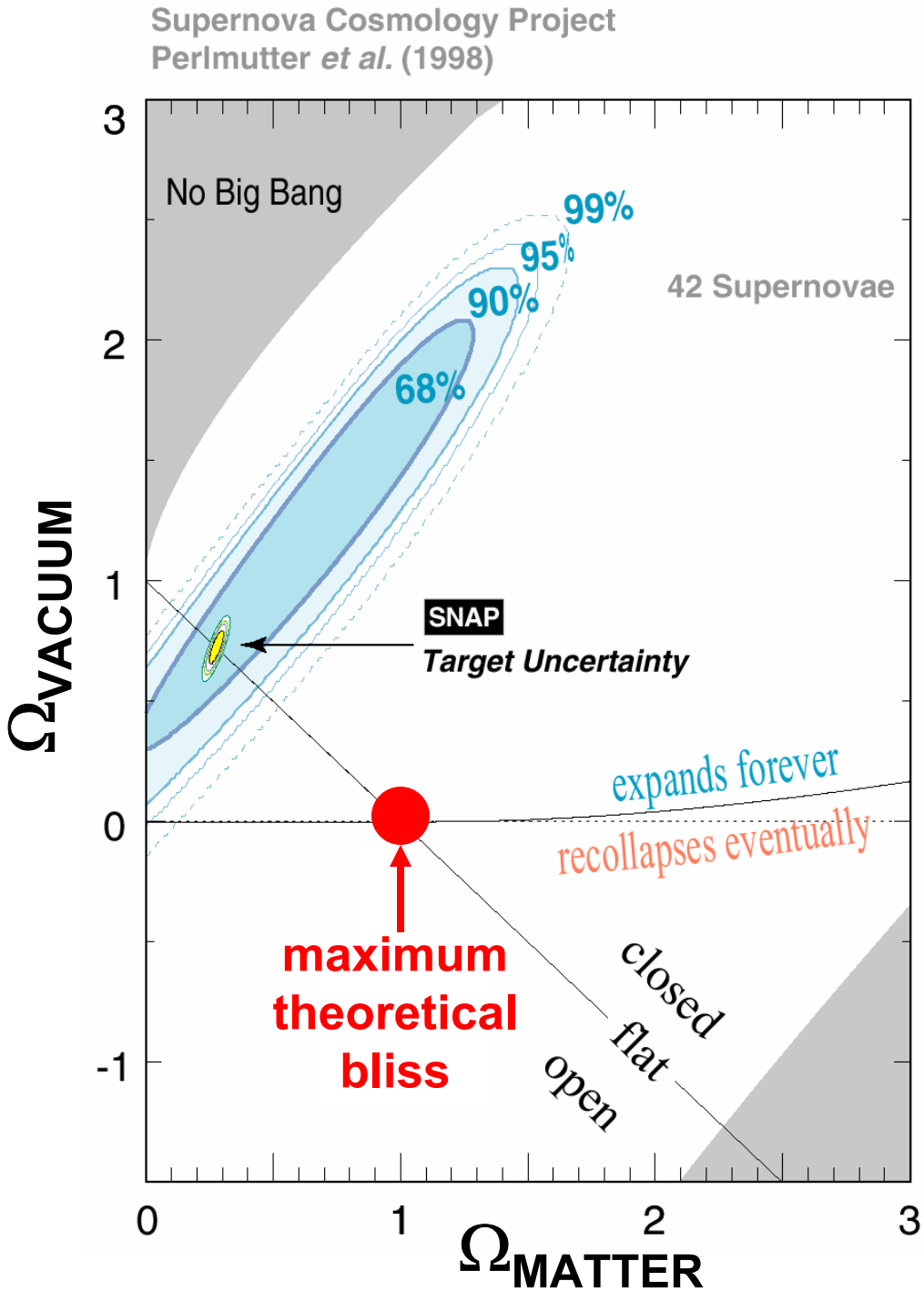


Type Ia supernova



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

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

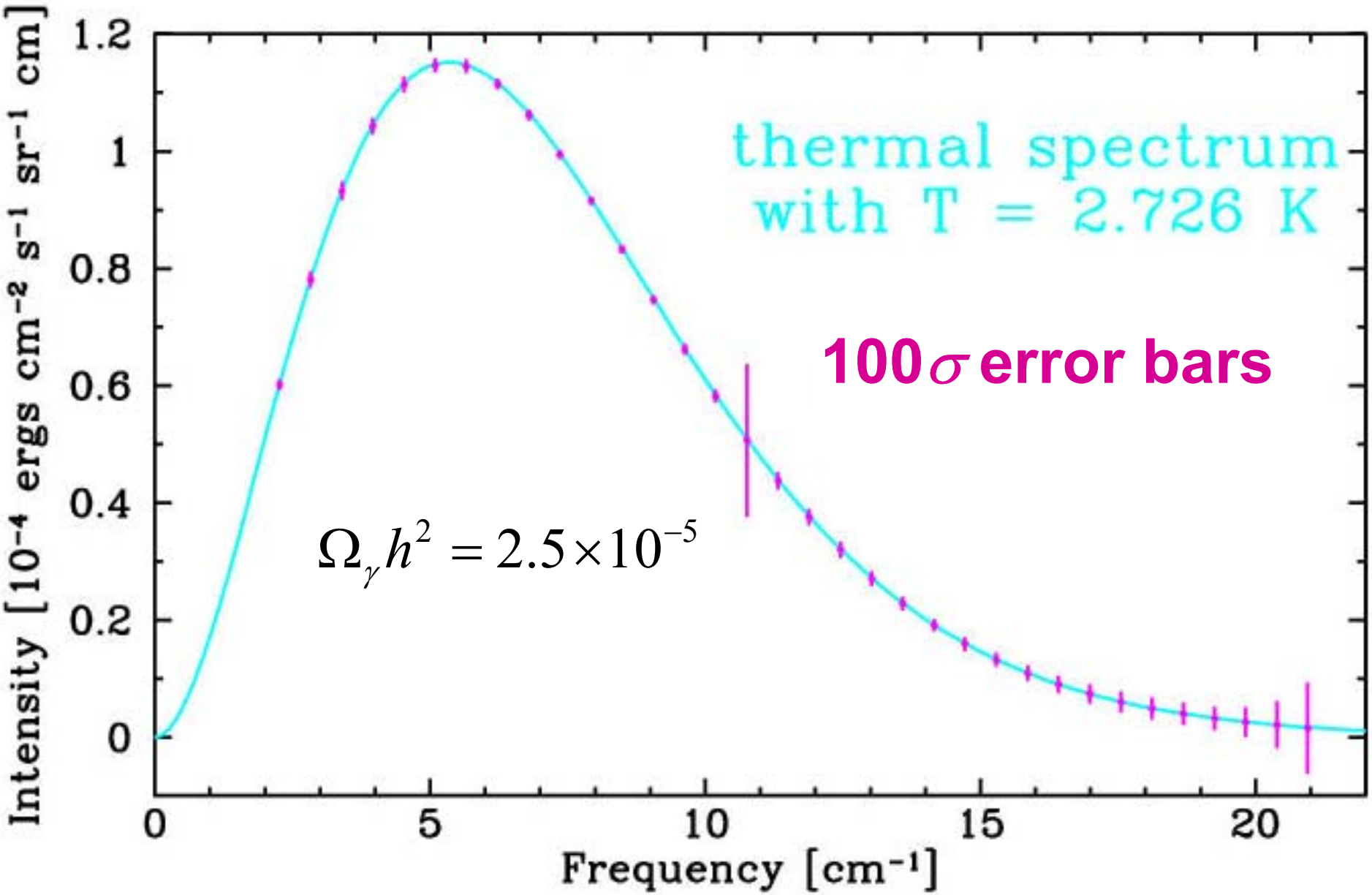
3) age of the universe

4) structure formation

Theorist's view of the universe

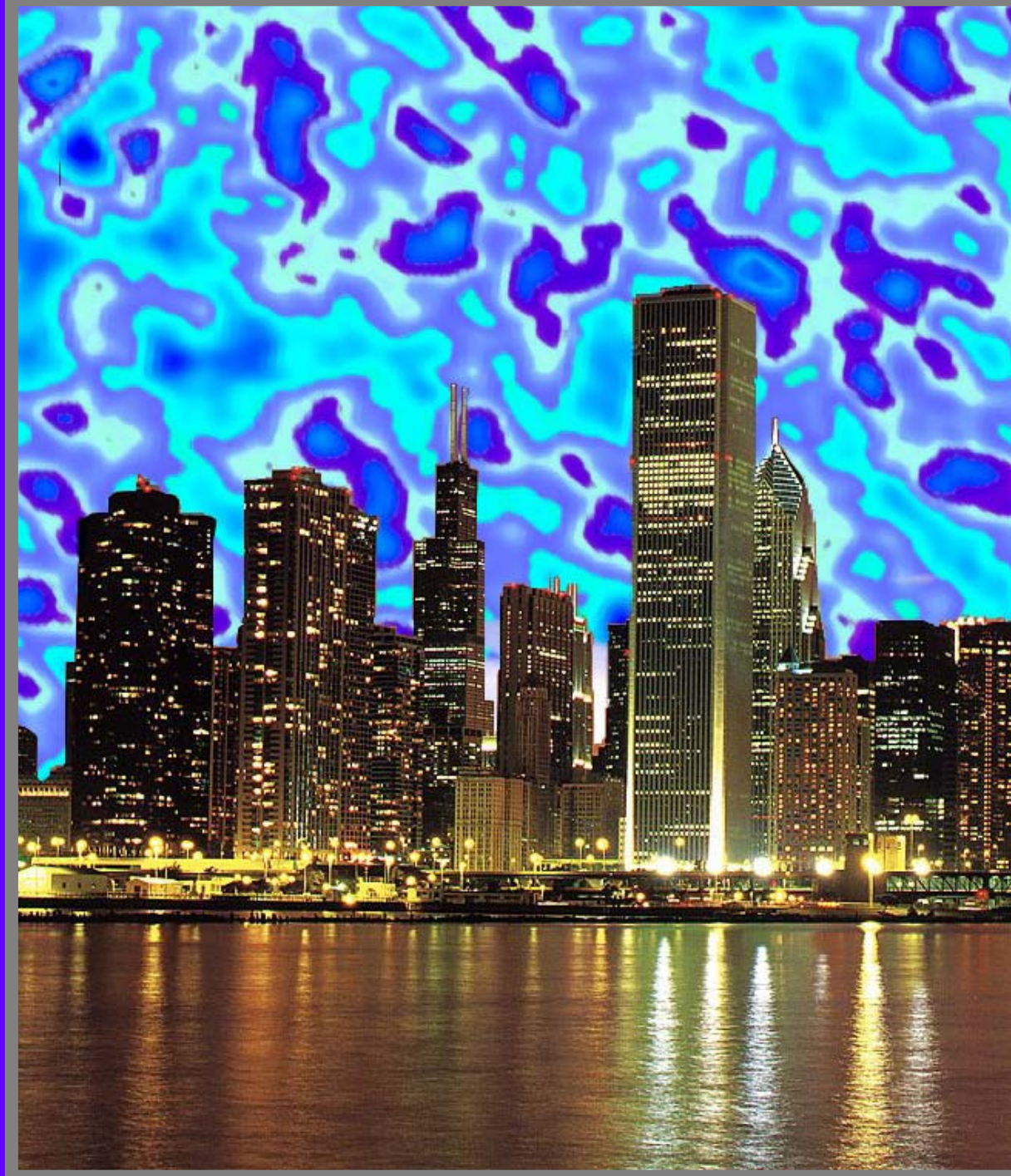
(isotropic)

Temperature of the universe

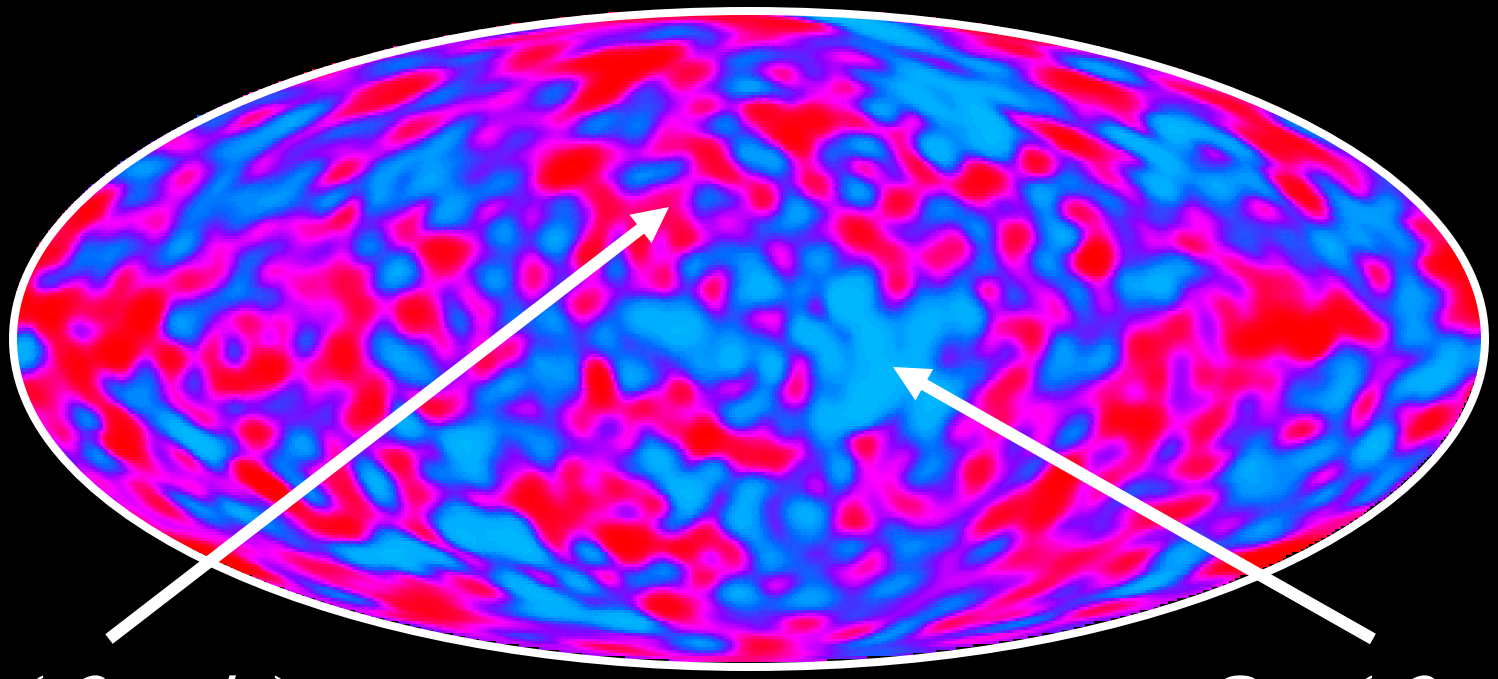


Observer's view of the universe

(fluctuations)



Angular power spectrum



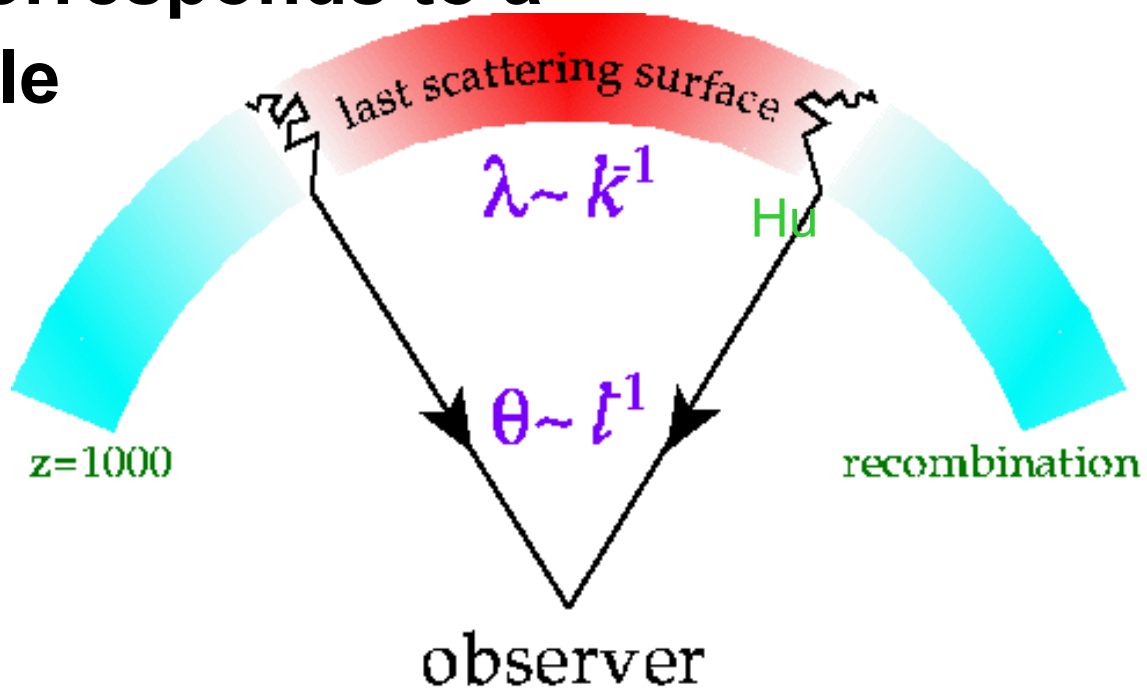
$\delta T(\theta_1, \phi_1)$ $\delta T(\theta_2, \phi_2)$

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

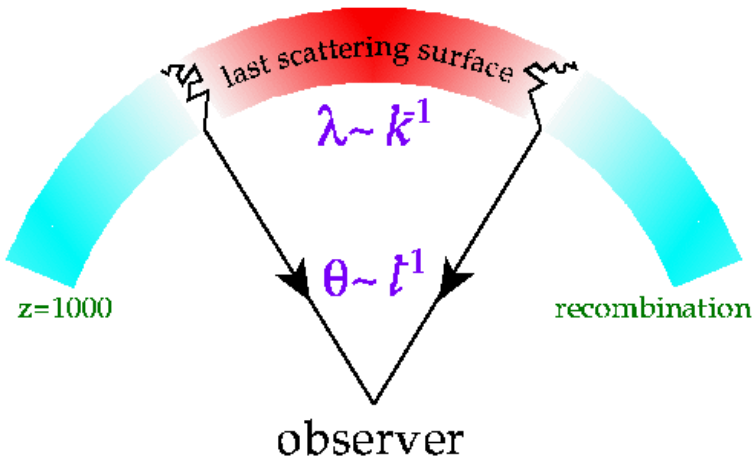
$$C_l \equiv \left\langle \left| a_{lm} \right|^2 \right\rangle$$

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

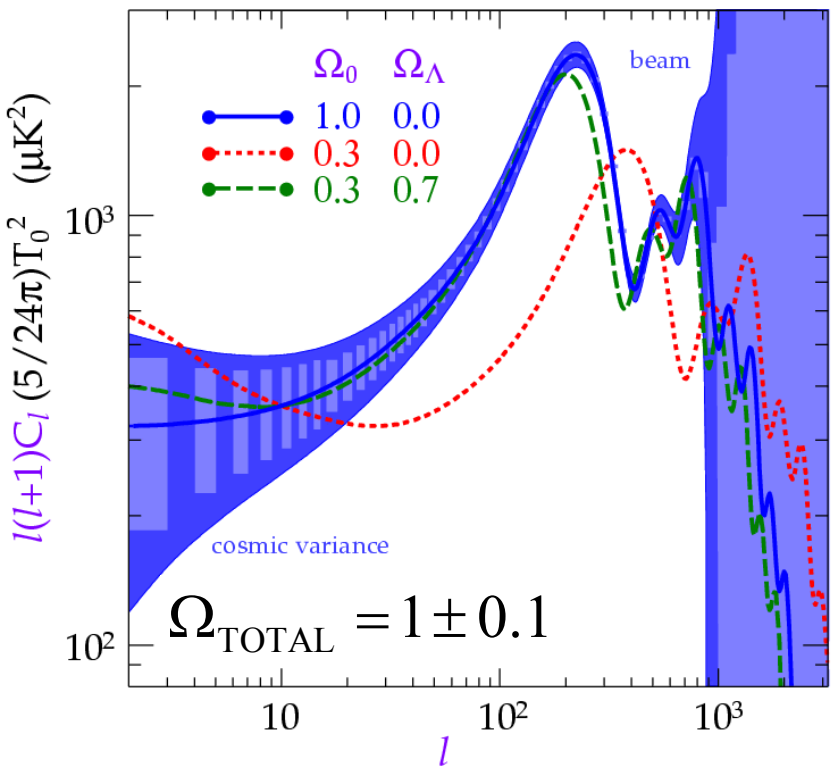


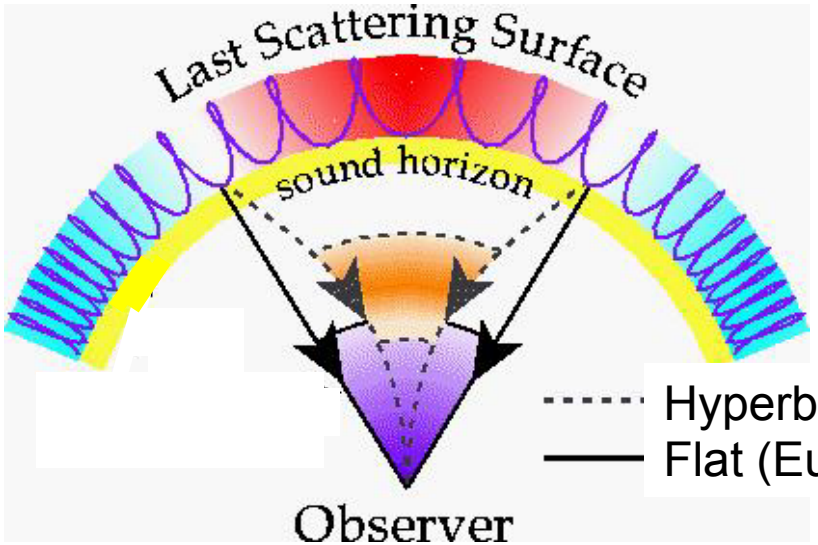
Acoustic peaks



Sound travel distance known

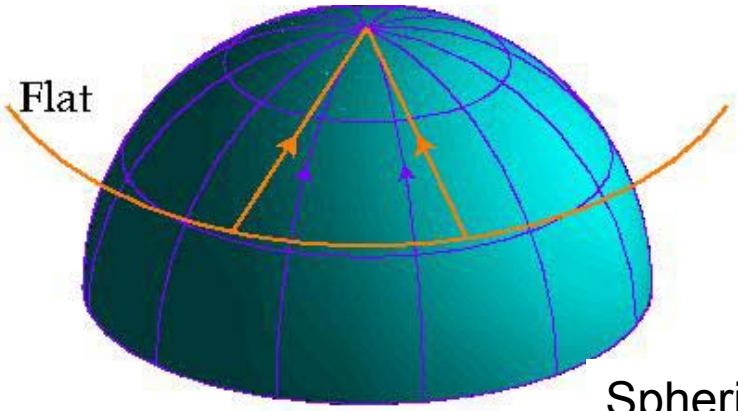
Observed l_{peak} ~ geometry





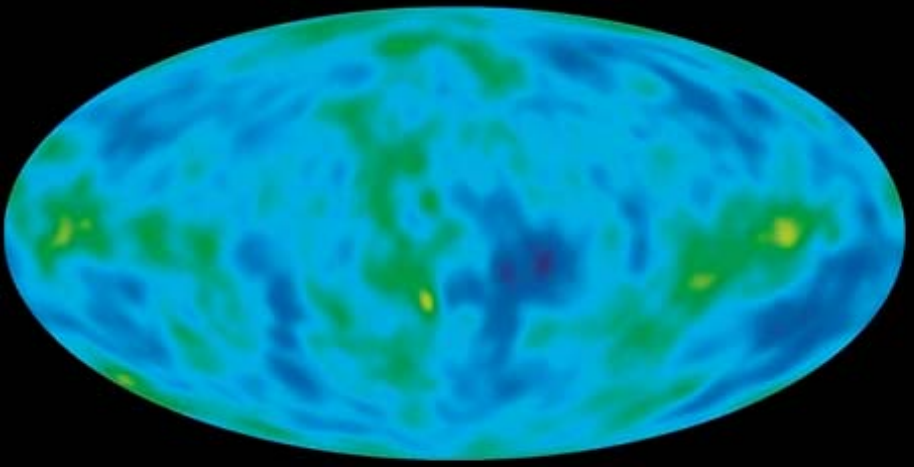
Hyperbolic (open)

Flat (Euclidean)

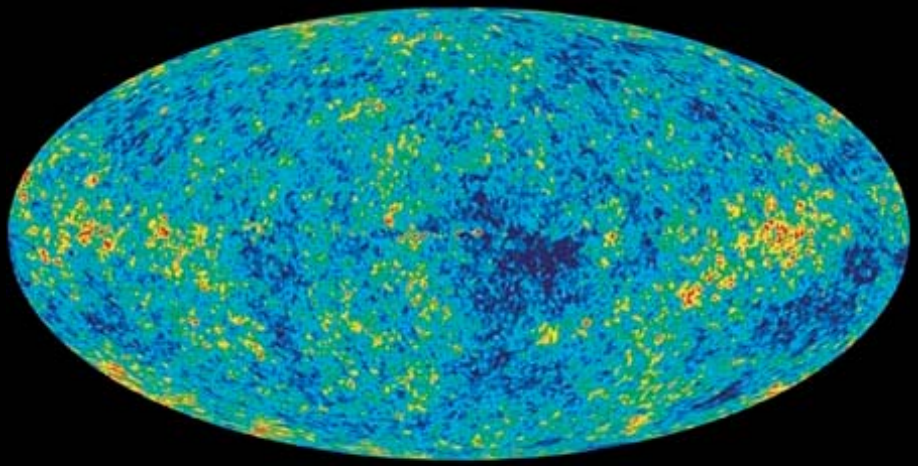


Spherical (closed)

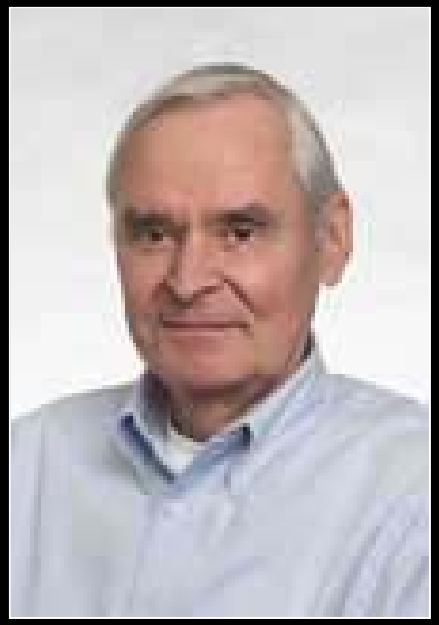
WMAP



COBE



WMAP



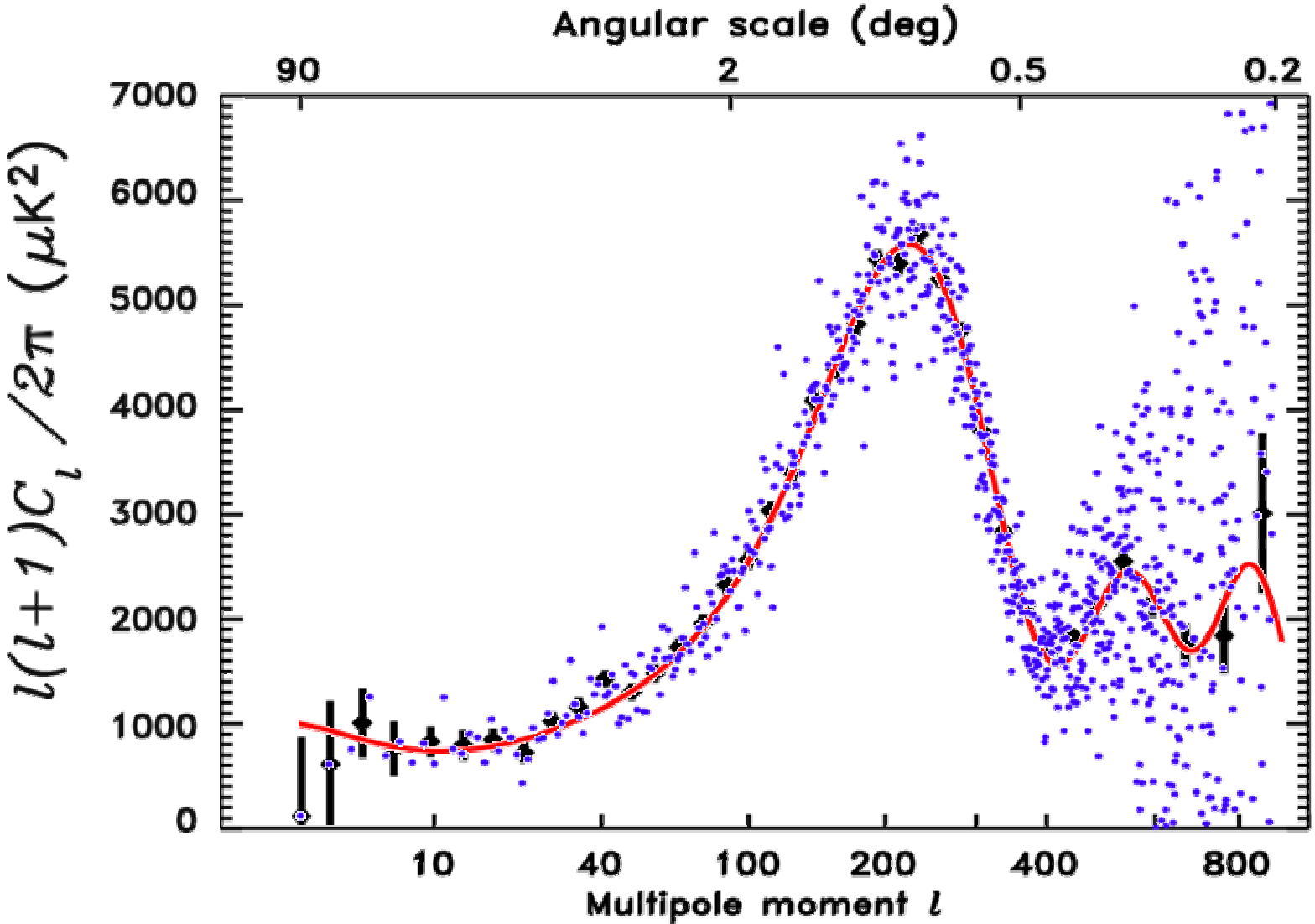
David T. Wilkinson
1935-2002

WMAP model

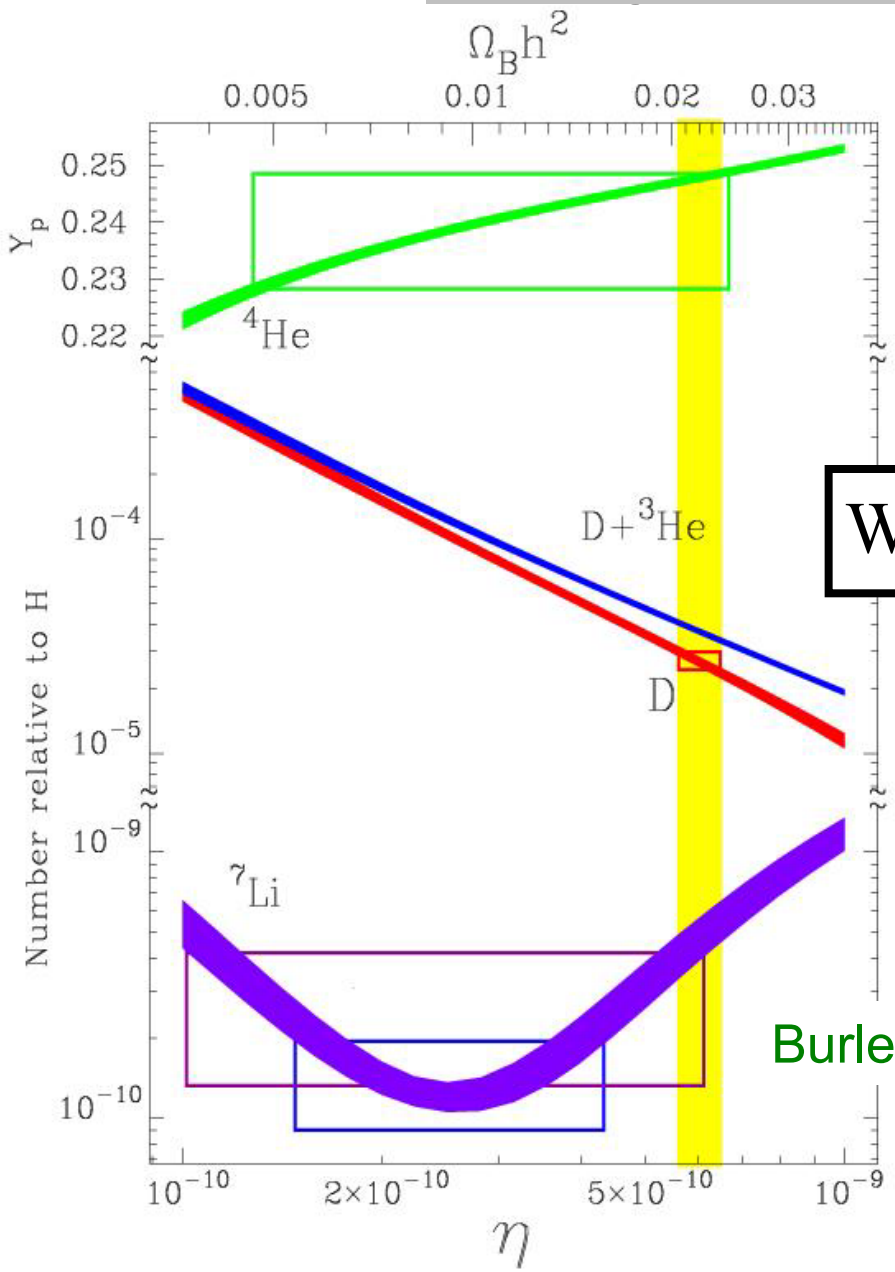
WMAP science team

WMAP Angular Power Spectrum

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



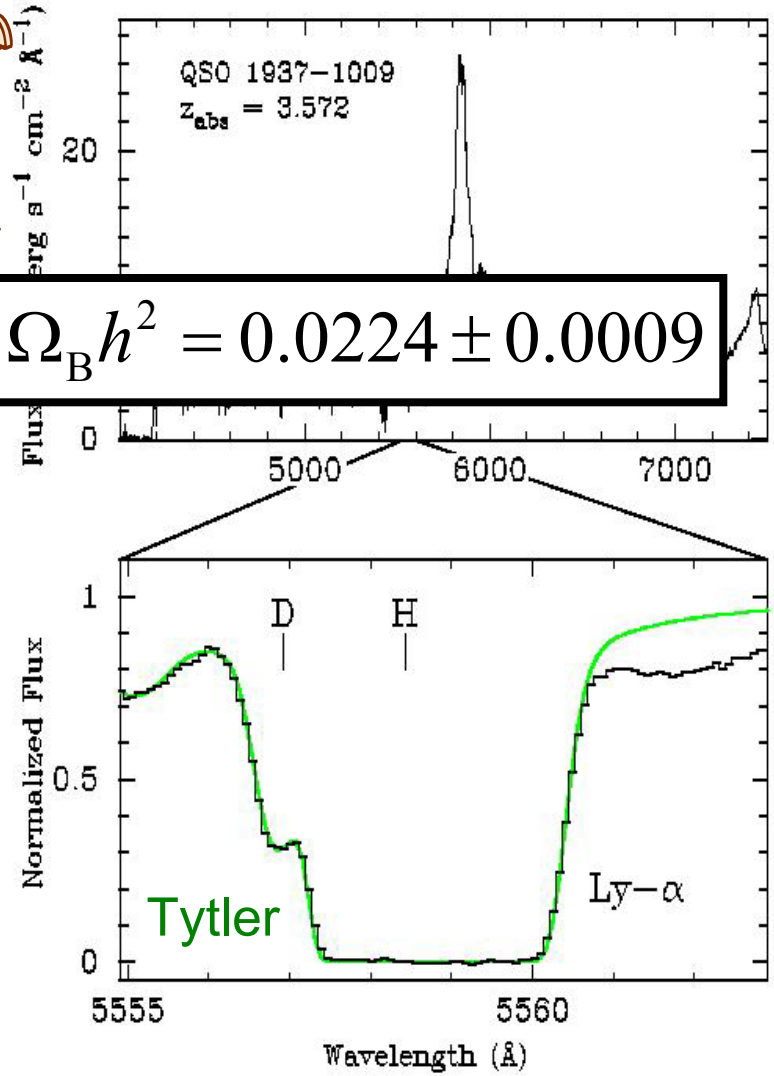
Baryons $\Omega_B h^2 \sim 0.02$



Burles et al.

Ly−α

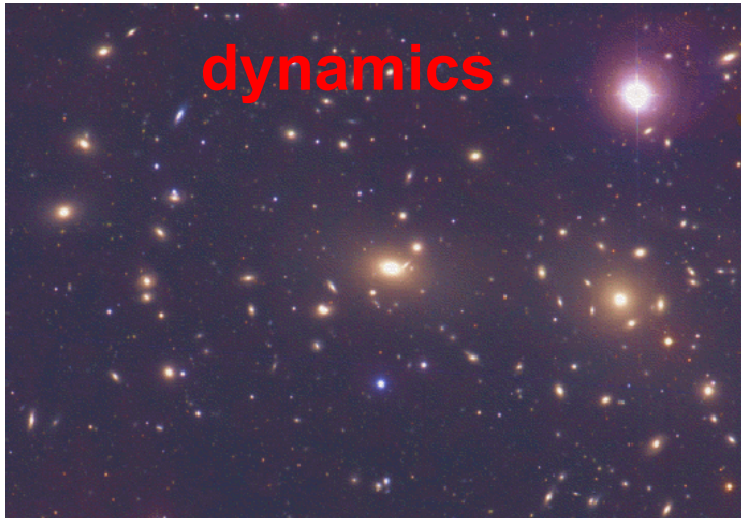
QSO 1937-1009

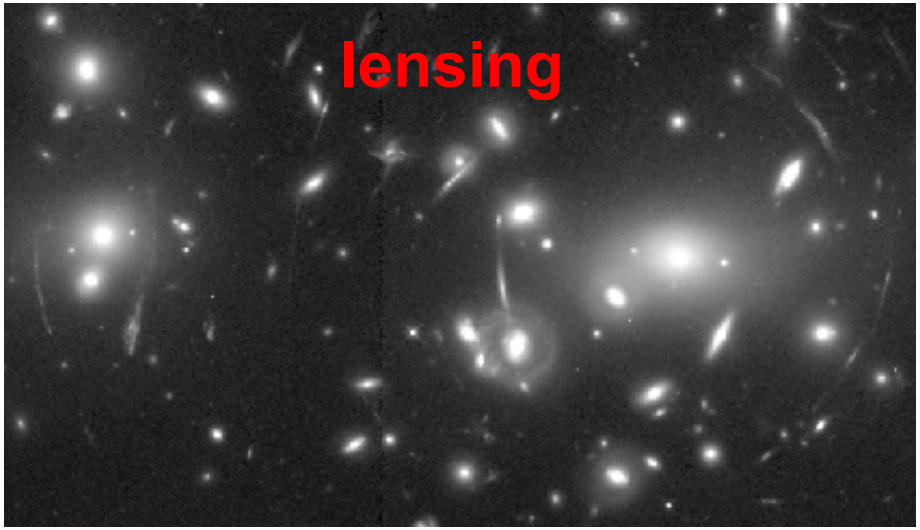


Tytler

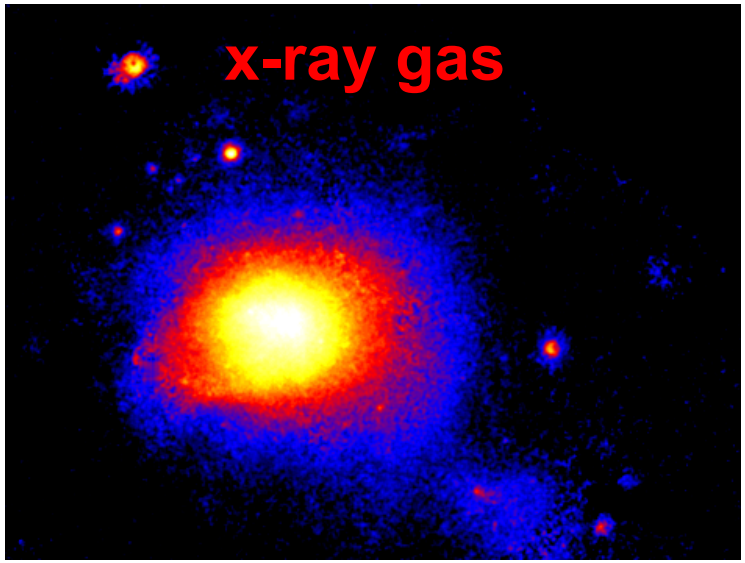
$$\text{WMAP: } \Omega_B h^2 = 0.0224 \pm 0.0009$$

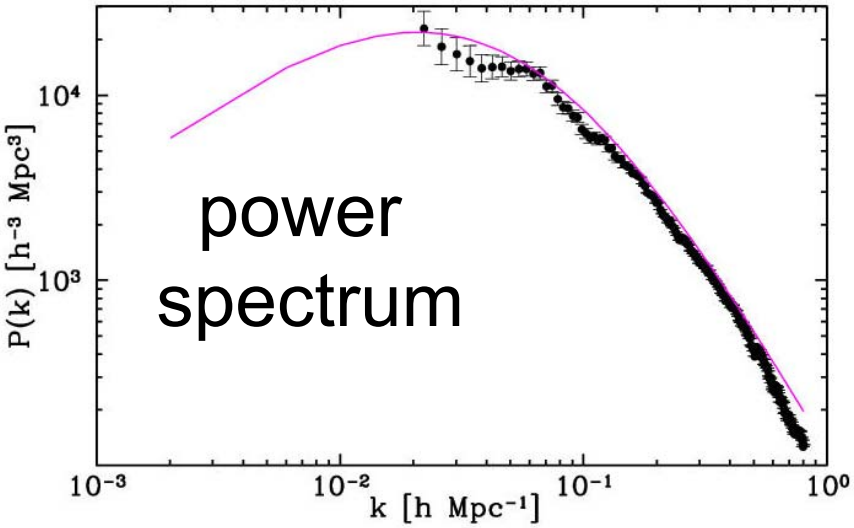
Matter $\Omega_M \sim 0.3$

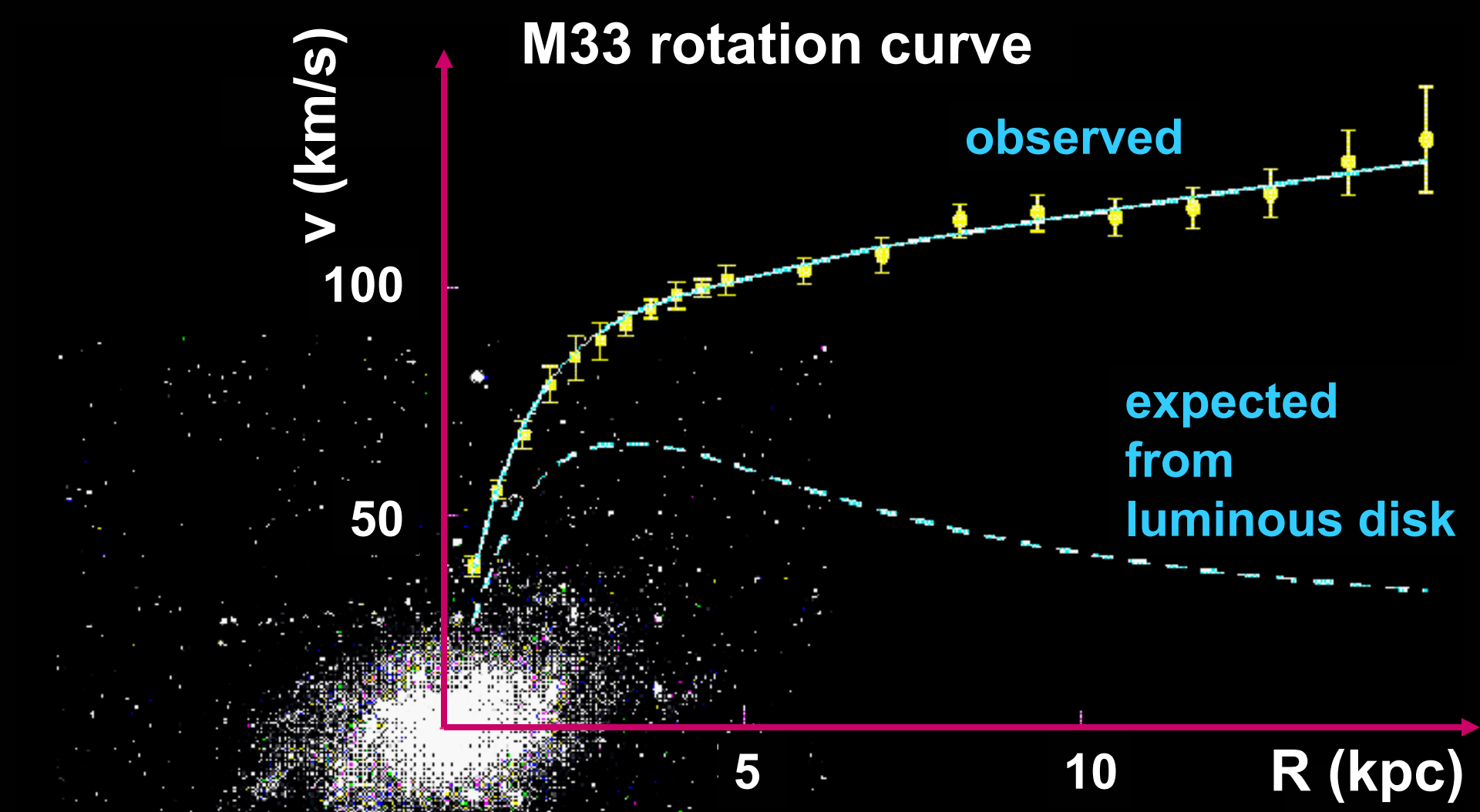




$\Omega_{\text{TOTAL}} = 1, \ \Omega_M = 0.3$ $\qquad$ $1 - 0.3 = 0.7$



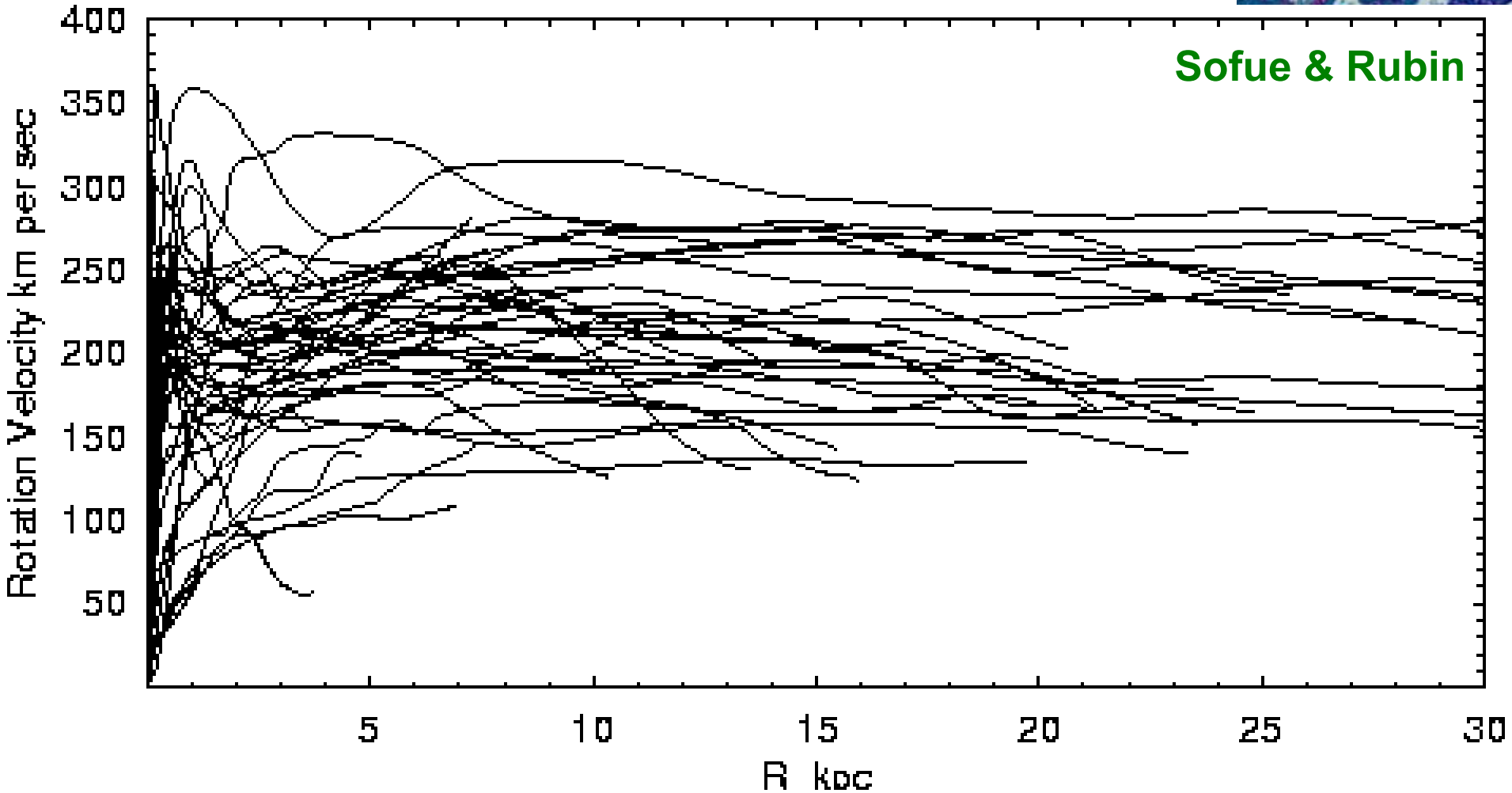




- galaxy & cluster dynamics
- gravitational lensing
- structure formation
- CMB observations

Rotation curves

CO – central regions
Optical – disks
HI – outer disk & halo

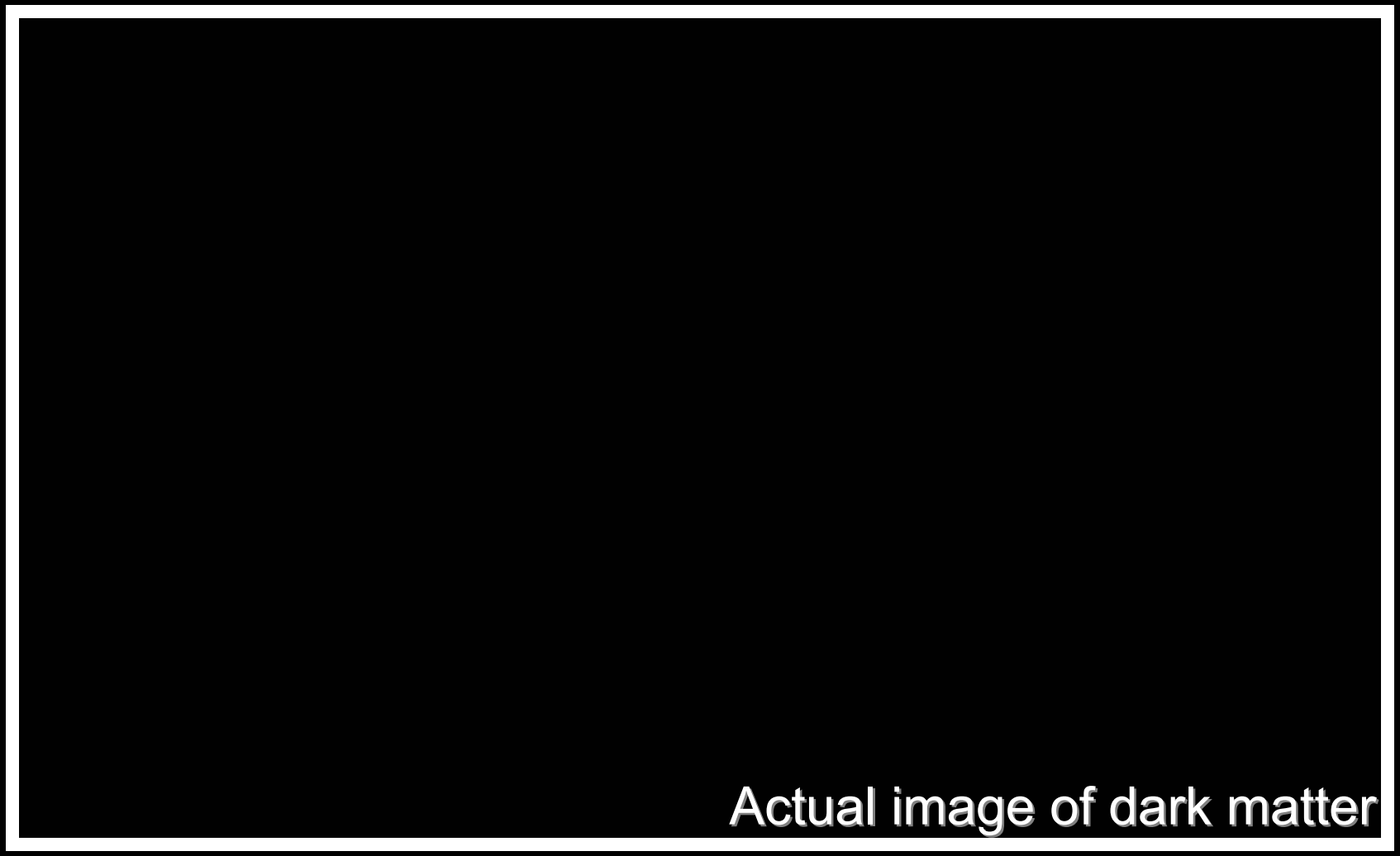


Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope • WFPC2

Observer's view of the universe

lumpy (inhomogeneous and anisotropic)
full of stars, galaxies, clusters, ….

Theorist's view of the universe



smooth (homogeneous and isotropic)
full of dark matter (and dark energy)

Power spectrum

- Assume there is an average density $\bar{\rho}$

- Expand density contrast $\delta(\vec{x})$ in Fourier modes

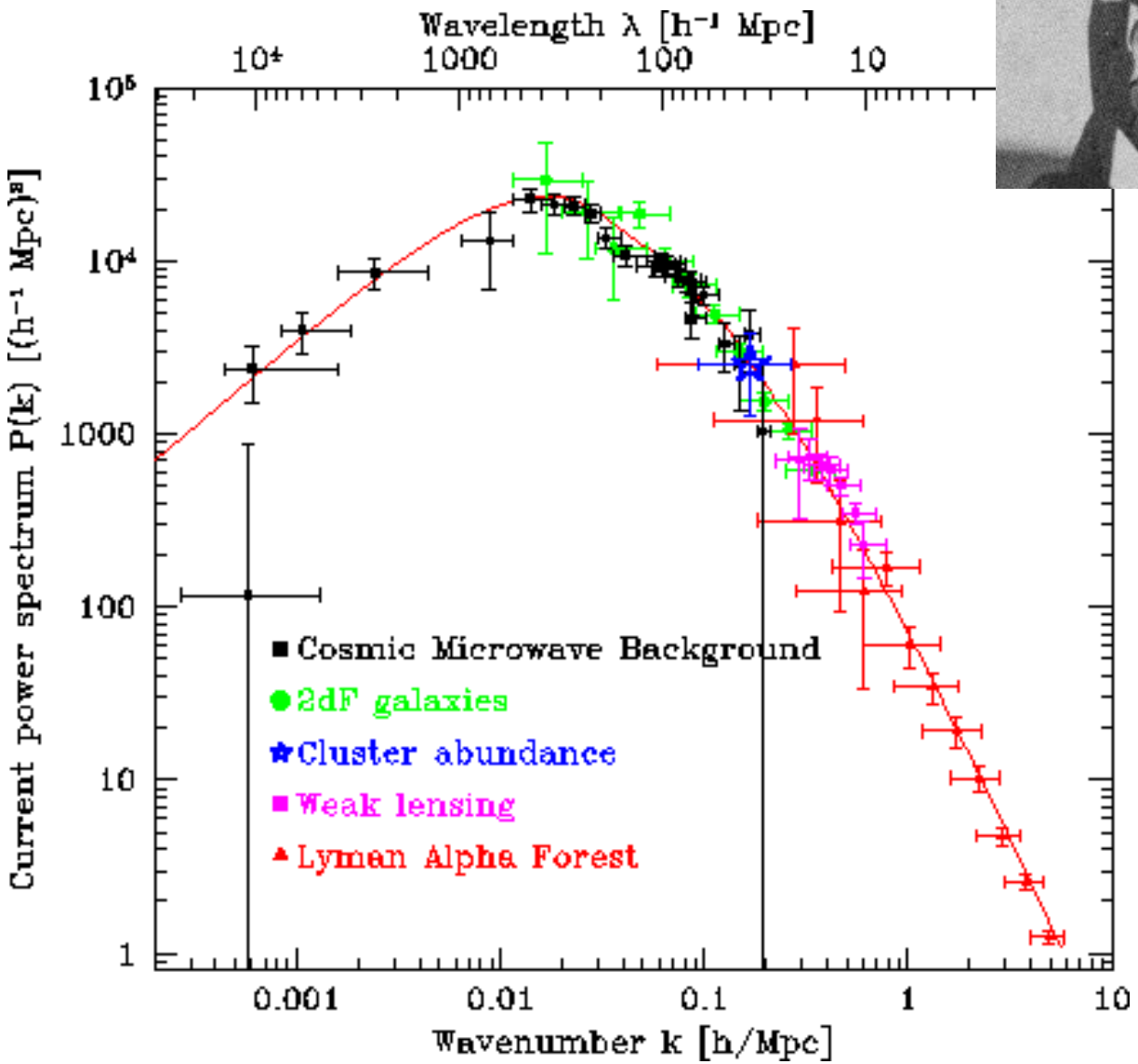
$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}} = \int \delta_{\vec{k}} \exp\left(-i\vec{k}\cdot\vec{x}\right) d^3k$$

- Autocorrelation function defines power spectrum

$$\left\langle \frac{\delta\rho(\vec{x})}{\bar{\rho}} \right\rangle^2 = \left\langle \delta(\vec{x})\delta(\vec{x}) \right\rangle = \int_0^\infty \frac{dk}{k} \frac{k^3 \left|\delta_{\vec{k}}^2\right|}{2\pi^2}$$

$$\Delta^2(k) \equiv \frac{k^3 \left|\delta_{\vec{k}}^2\right|}{2\pi^2} \qquad P(k) \equiv \left|\delta_{\vec{k}}^2\right|$$

Harrison-Zel'dovich Spectrum

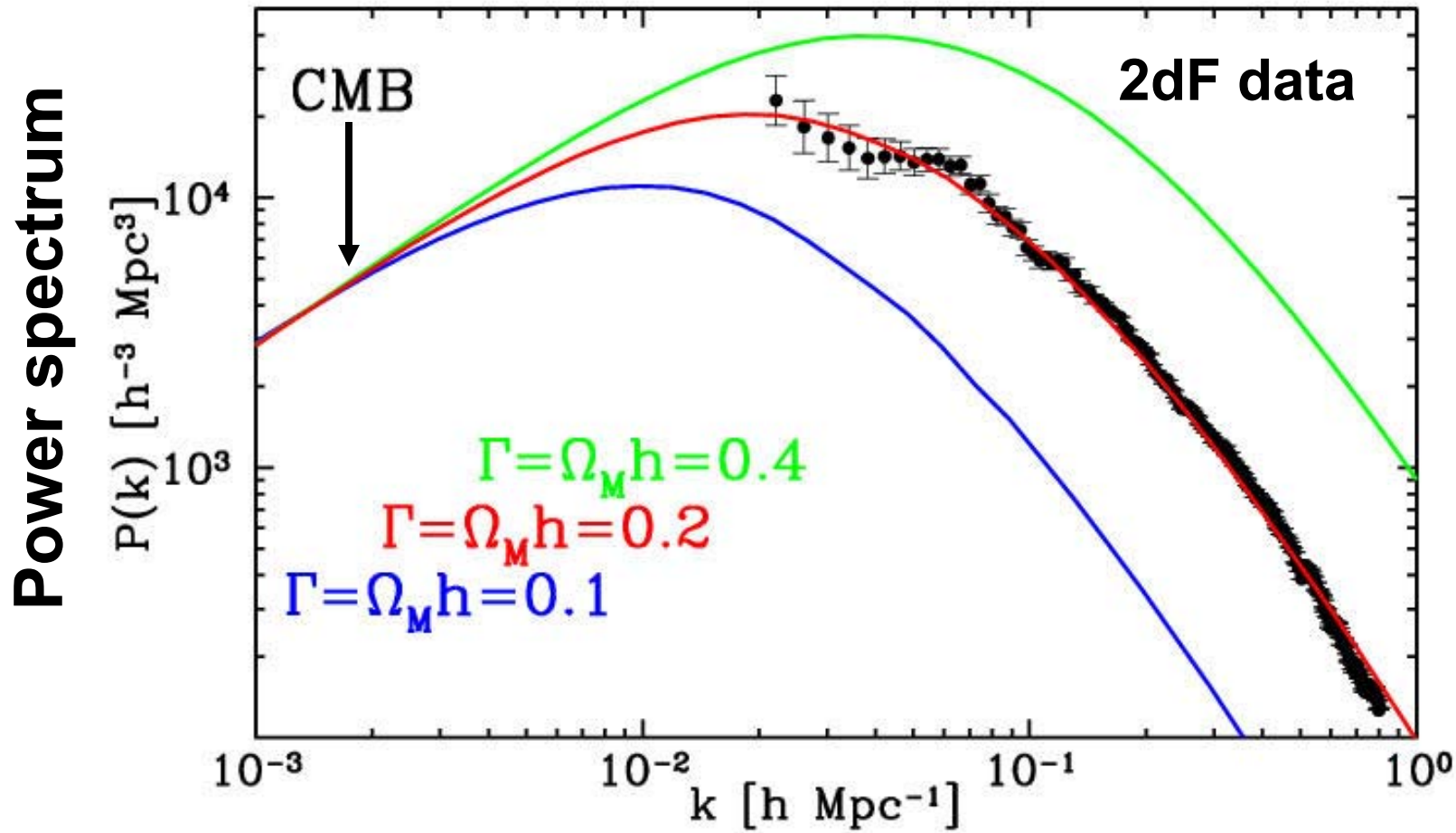


Tegmark

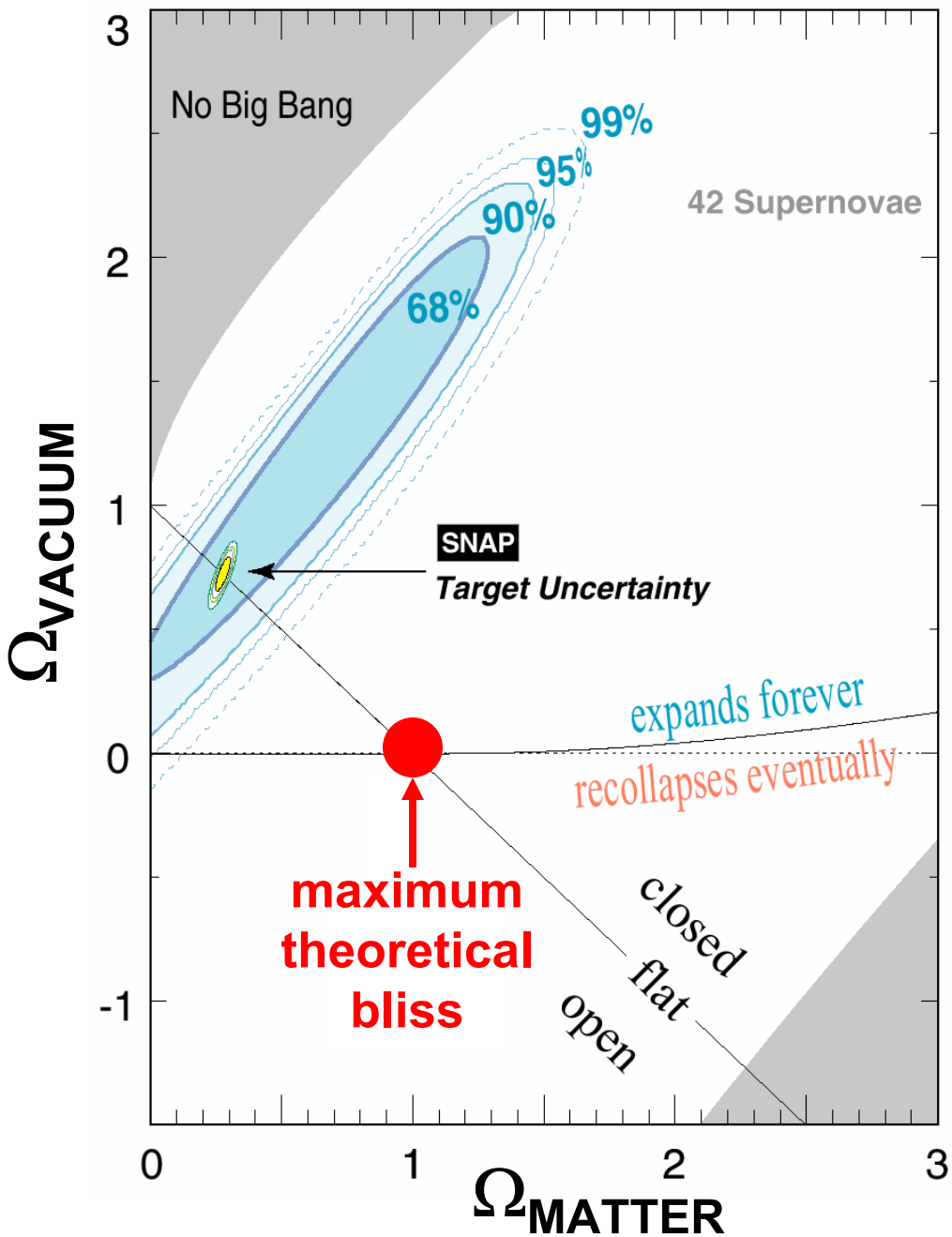
Shape factor

$$\Gamma \sim \Omega_M h \sim 0.25 \pm 0.05$$

$\Omega_M h$	Ω_M	h
0.25	1	0.25
0.25	0.35	0.70



Supernova Cosmology Project
Perlmutter *et al.* (1998)



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

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

3) age of the universe

4) structure formation

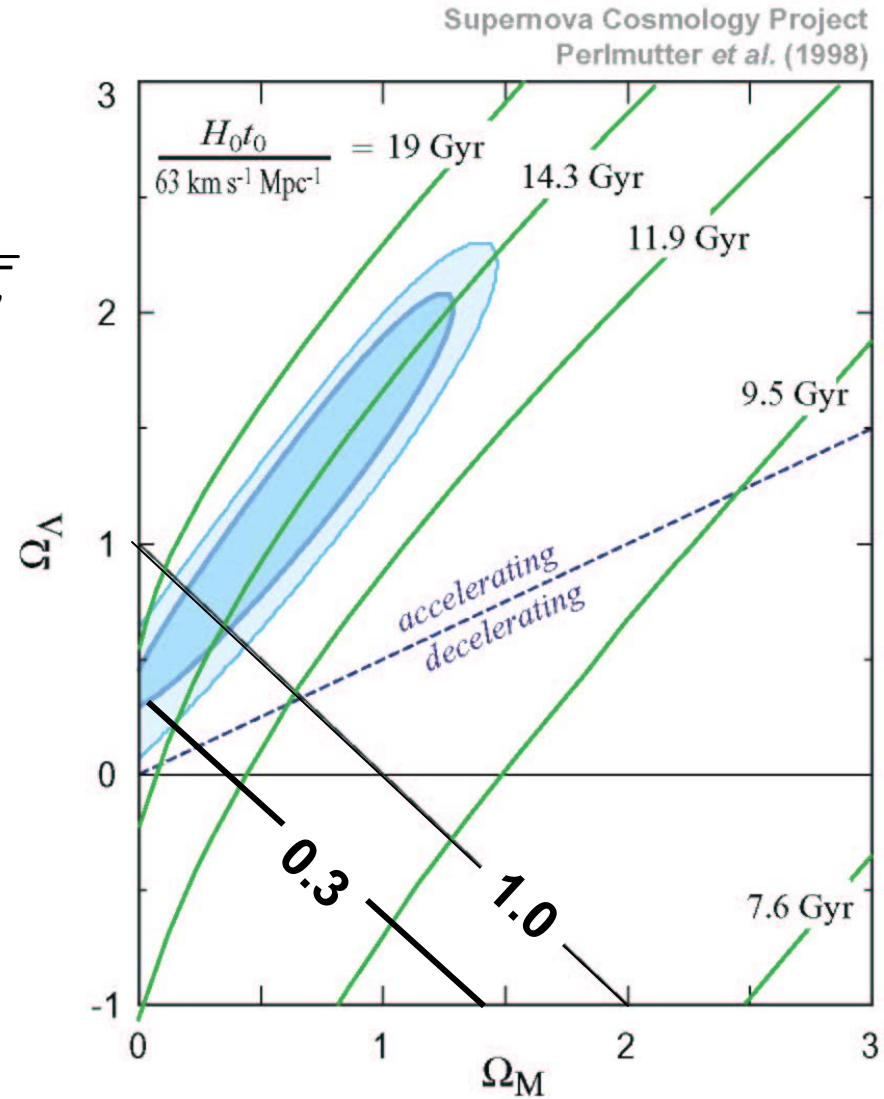
t_0 : age of the universe

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

Integrate Friedmann equation:

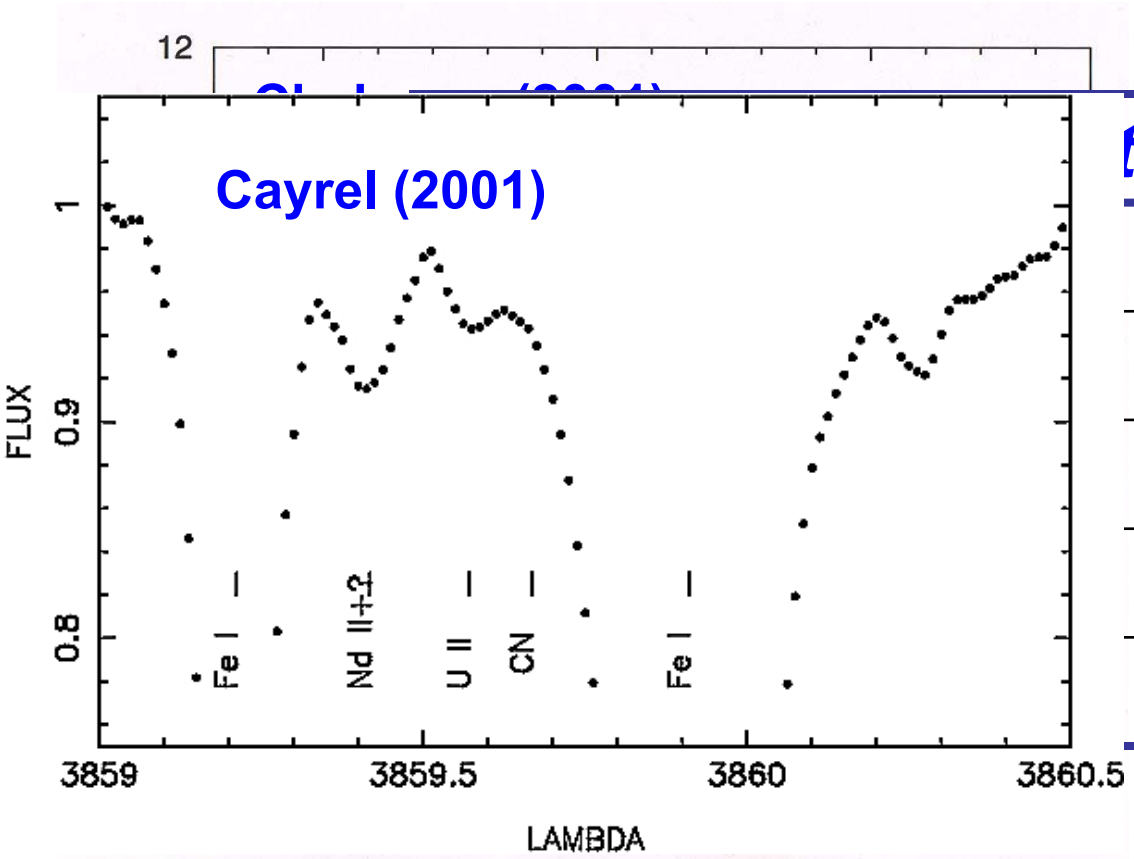
$$H_0 t = \int_0^1 \frac{dx}{\sqrt{1 - \Omega_{\mathrm{TOTAL}} + \sum_w \Omega_w x^{-1+3w}}}$$

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



t_0 : age of the universe

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



t_0 (Gyr)
9.3
12
14
13.5
15

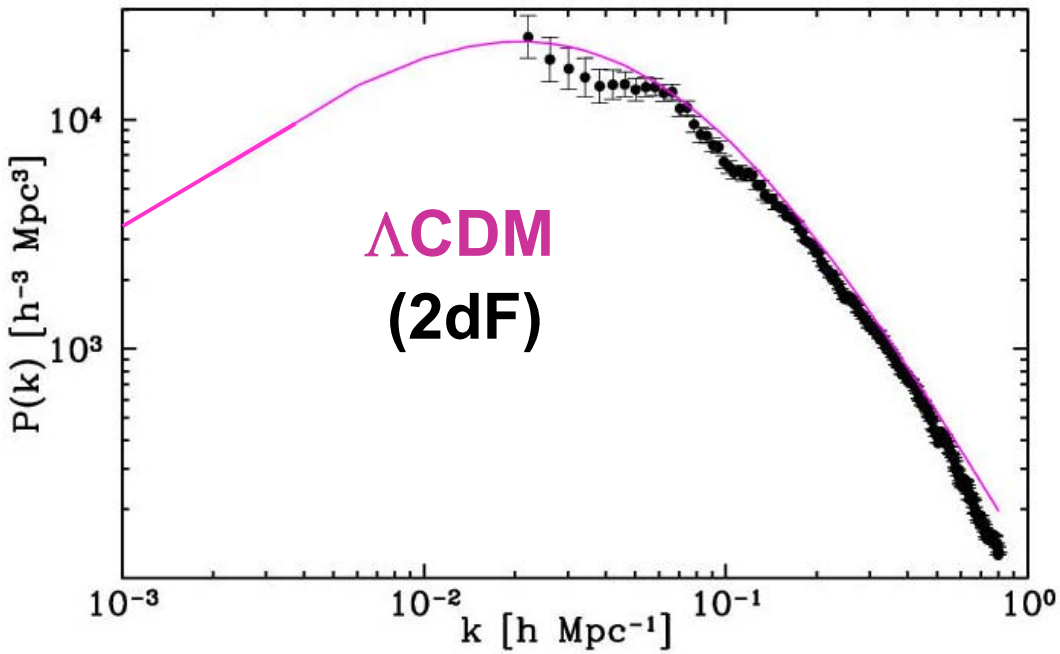
First measurement of stellar uranium

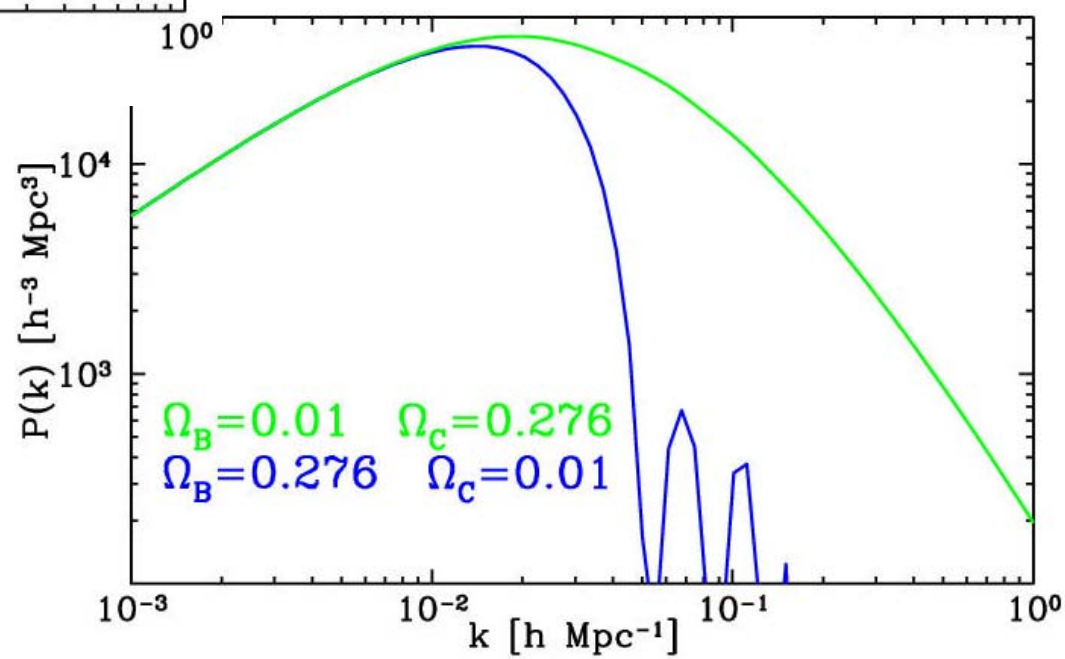
Everything in the universe:

Clusters
Galaxies
Stars
Planets
Poodles
Pigeons
Pond Scum
Donald Rumsfeld
.
.

From inflationary perturbations

Silk damping of baryon pert'ns





Cosmo-illogical constant

Mass density of space:

$$\rho \simeq 10^{-30}\,\mathrm{g\ cm^{-3}}$$

$$\simeq (10^{-13}\ \mathrm{GeV})^4$$

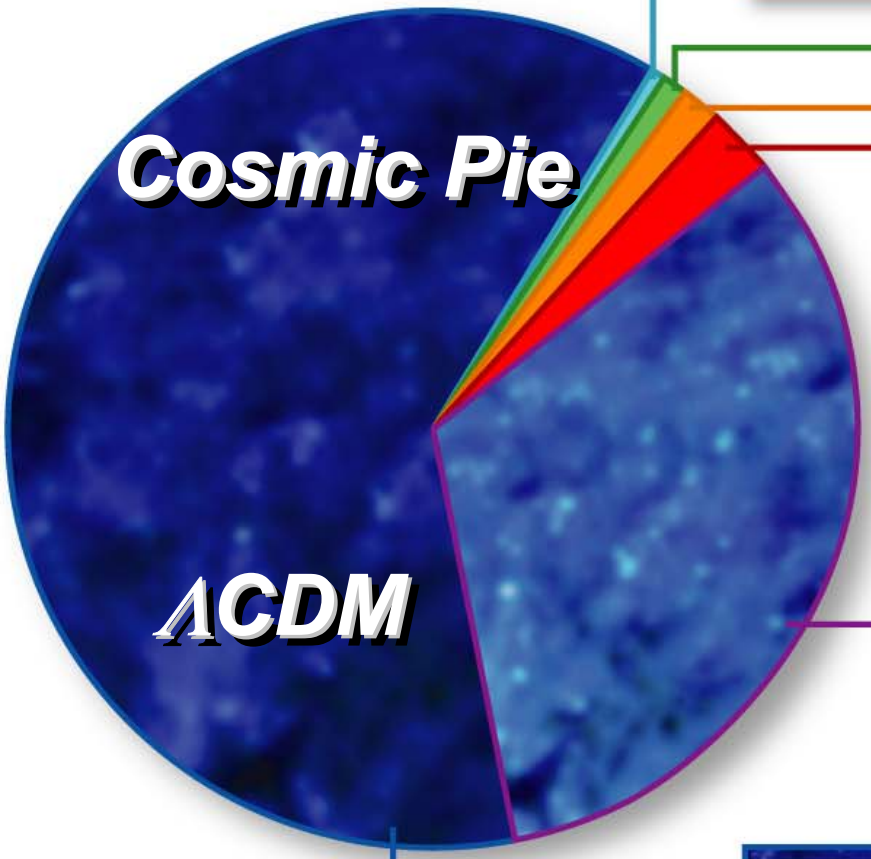
$$\simeq (10^{-4}\ \mathrm{eV})^4$$

$$\simeq (10^{-4}\ \mathrm{cm})^{-4}$$

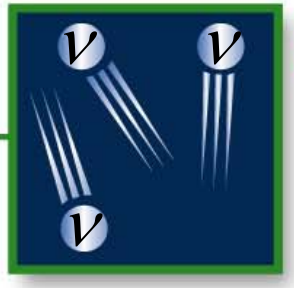
Who ordered that?

$$\Omega_i \equiv \rho_i / \rho_{\text{CRITICAL}}$$

$$\Omega_{\text{TOTAL}} = 1$$

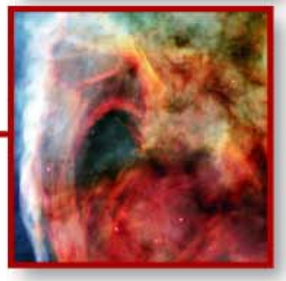


Heavy Elements:
Ω=0.0003

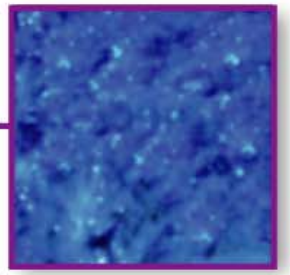


Neutrinos (ν):
Ω=0.0047

Stars:
Ω=0.005



Free H & He:
Ω=0.04



Cold Dark Matter:
Ω=0.25

Dark Energy (Λ):
Ω=0.70

The cosmic food chain (Ω_i)

Massless neutrinos (2) :	0.002%
Photons:	0.005%
Metals:	0.023%
Massive Neutrino (1) $m = 0.2$ eV:	0.47 %
Stars:	0.50 %
Dark neutrons & protons:	4. %
Dark matter:	25. %
Dark energy:	70. %

Cosmological standard model

ΛCDM

Cosmological parameters

$$h \simeq 0.7 \simeq 1/\sqrt{2}$$

$$\Omega_{\mathrm{TOTAL}} = 1$$

- $\Omega_{\Lambda} \simeq 2/3$
- $\Omega_{\mathrm{CDM}} \simeq 1/3$
- $\Omega_{\mathrm{B}} \simeq 0.04$
- $\Omega_{\nu} \simeq 0.005$
- $\Omega_{\gamma} \simeq 0.00005$

Initial perturbations

Harrison-Zel'dovich (adiabatic curvature perturbations with an initial n=1 spectrum)

Dark Matter and Dark Energy

Rocky I: Evidence for dark matter and dark energy

Rocky II: Dark matter candidates

Rocky III: Dark energy reloaded

SLAC Summer Institute, August 2003

Rocky Kolb, Fermilab & The University of Chicago