Galaxy Formation

par Avishai Dekel

The Hebrew University of Jerusalem
& Chaire Internationale de Recherche Blaise Pascal, Paris

Une série de cours (en anglais) pour les étudiants en thèse (et M2) et les chercheurs

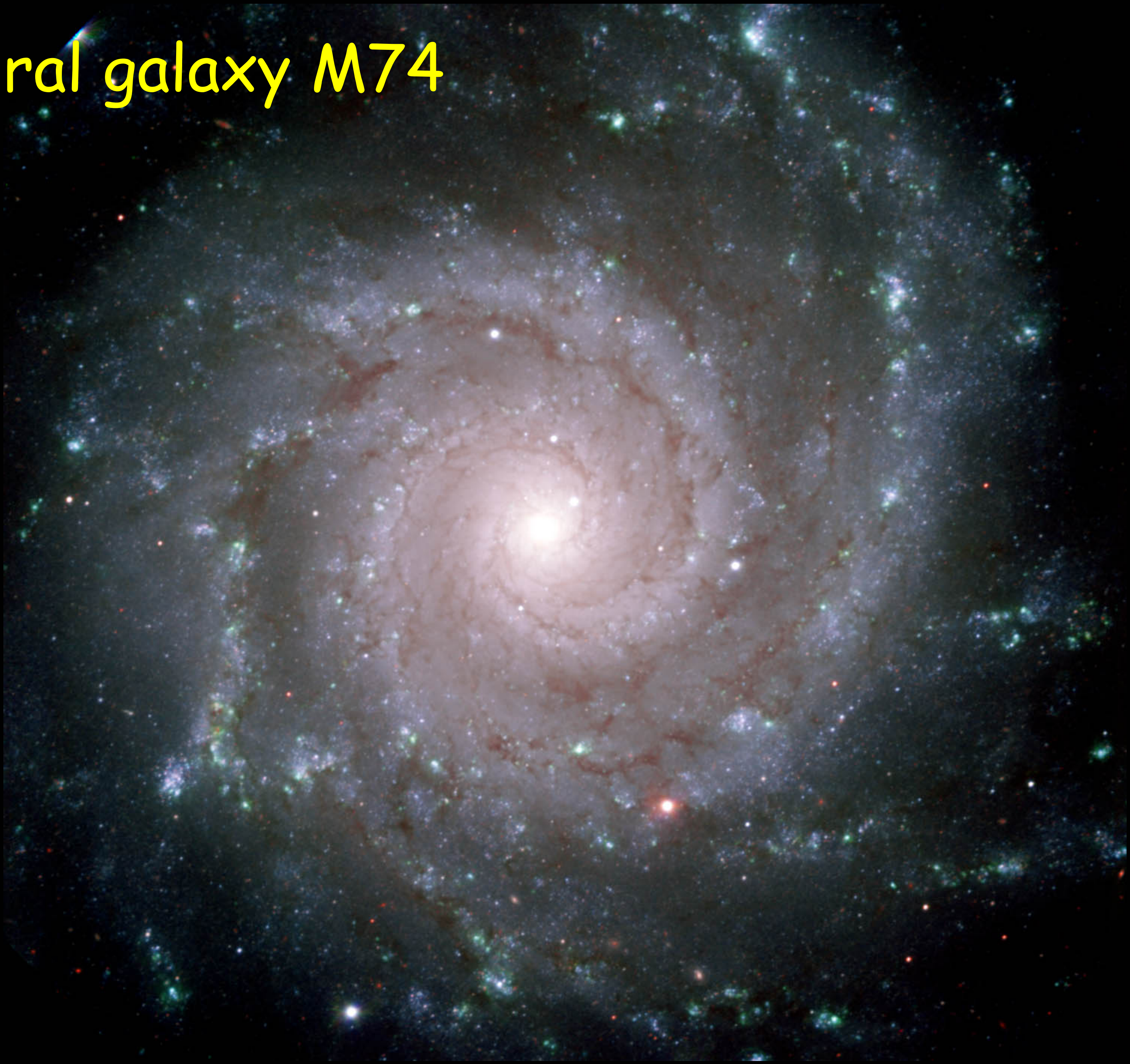
les mercredis, de 17h00 à 19h00 à l'amphithéâtre de l'IAP

98bis Bd Arago - Paris 14ème - M° St Jacques ou Denfert-Rochereau

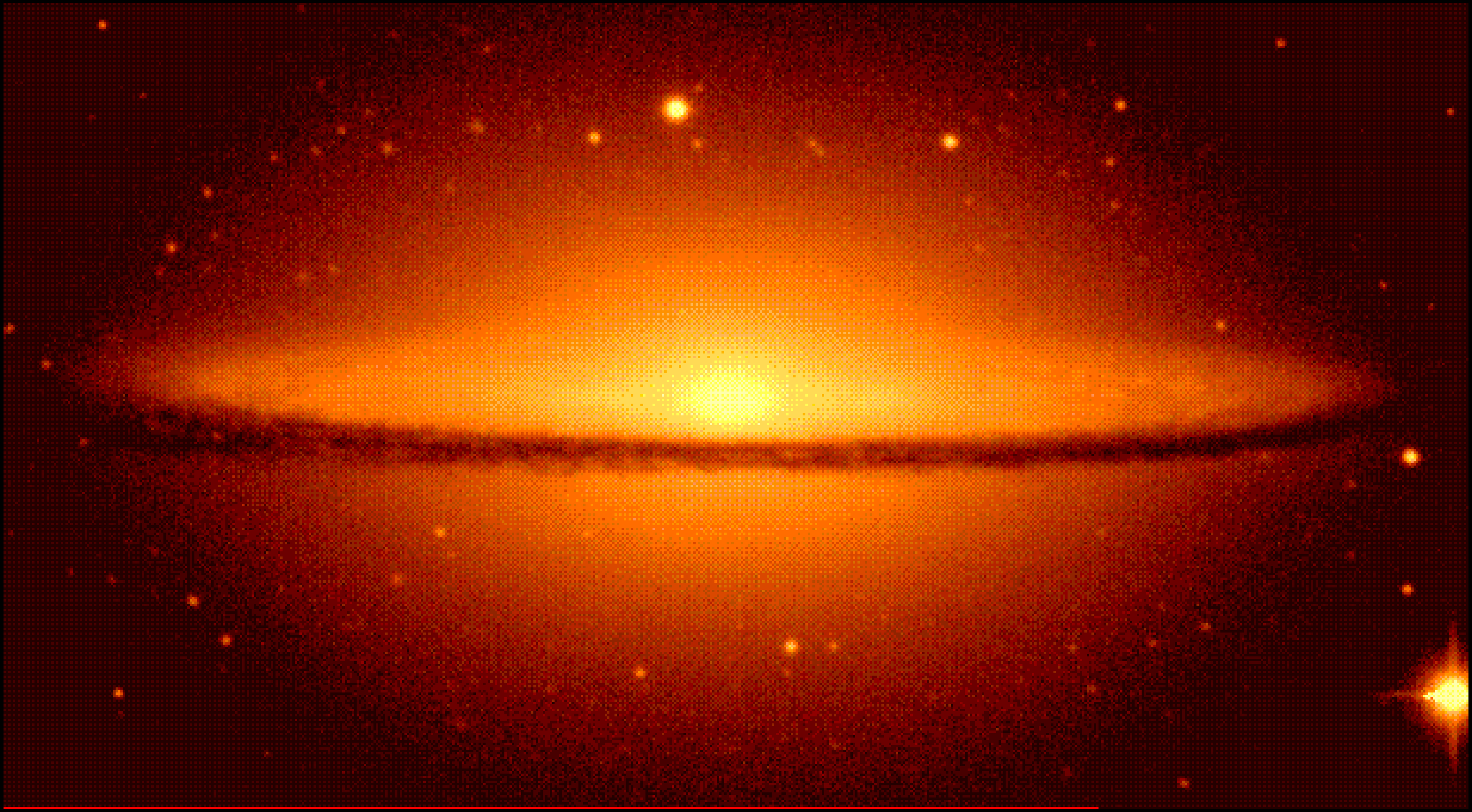
20 octobre

1. The standard cosmology
2. Linear growth of fluctuations by gravitational instability

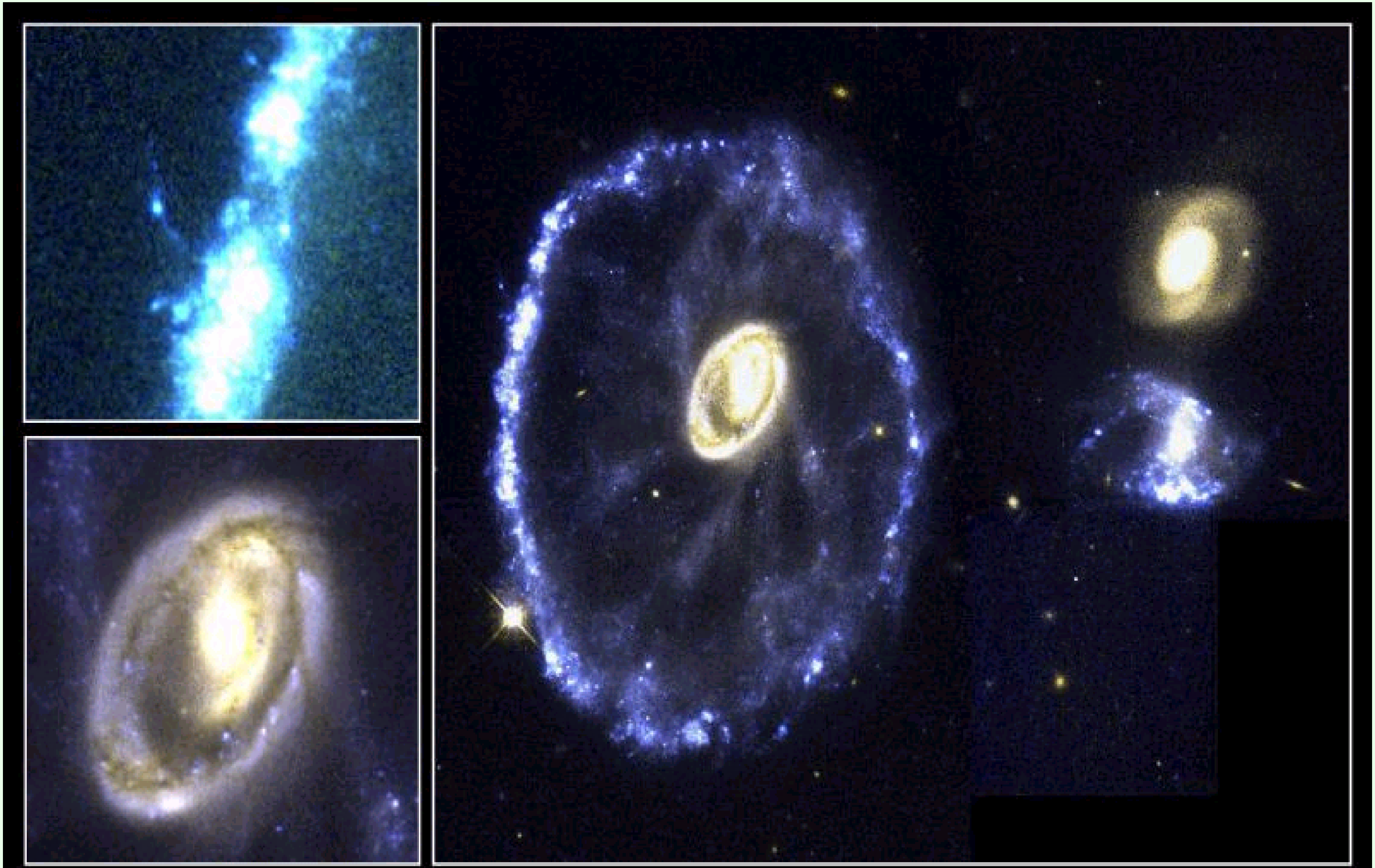
Spiral galaxy M74



The Sombrero M104



Elliptical galaxy M87



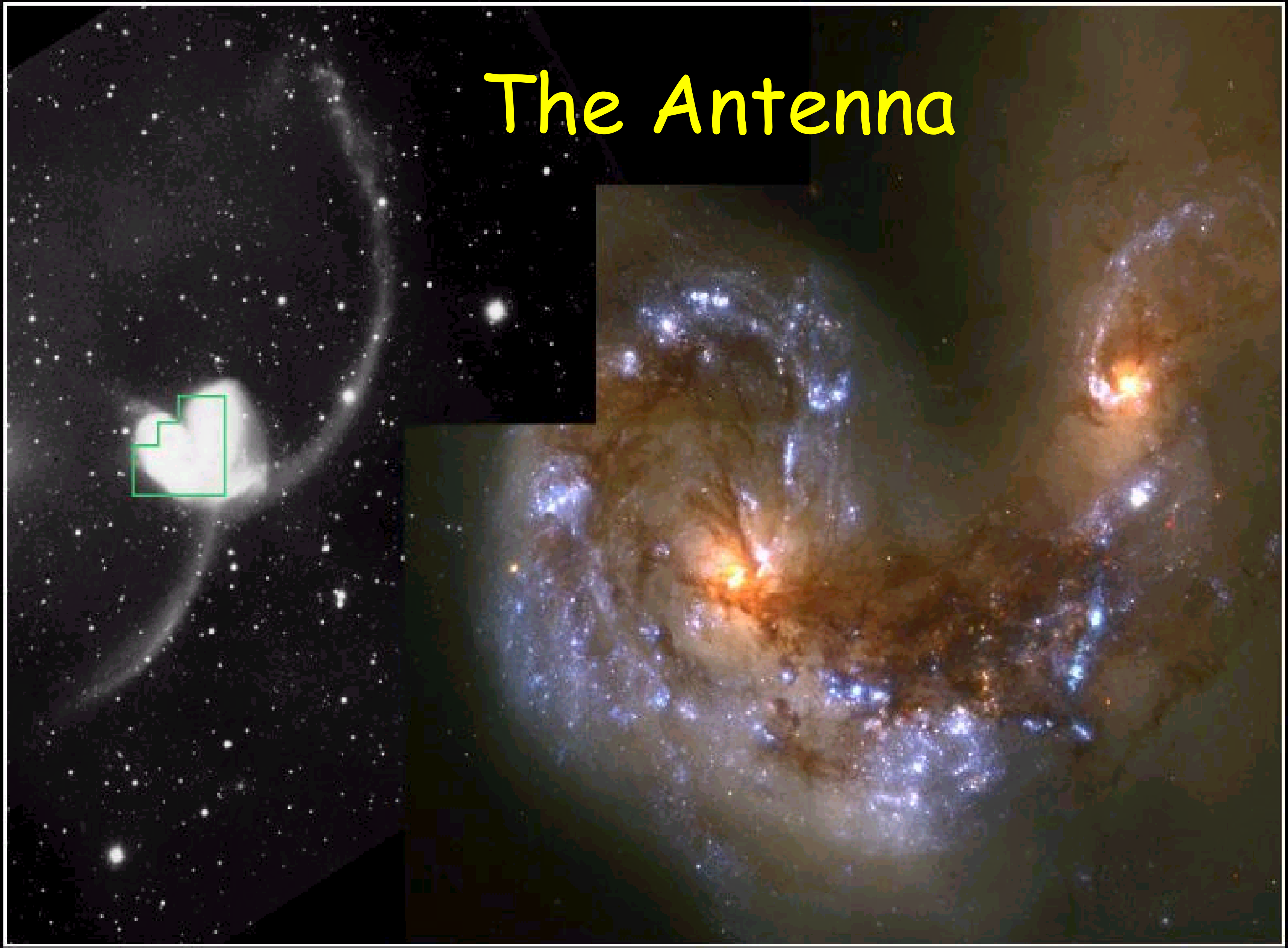
Cartwheel Galaxy

HST • WFPC2

PR95-02 • ST ScI OPO • January 1995 • K. Borne (ST ScI), NASA

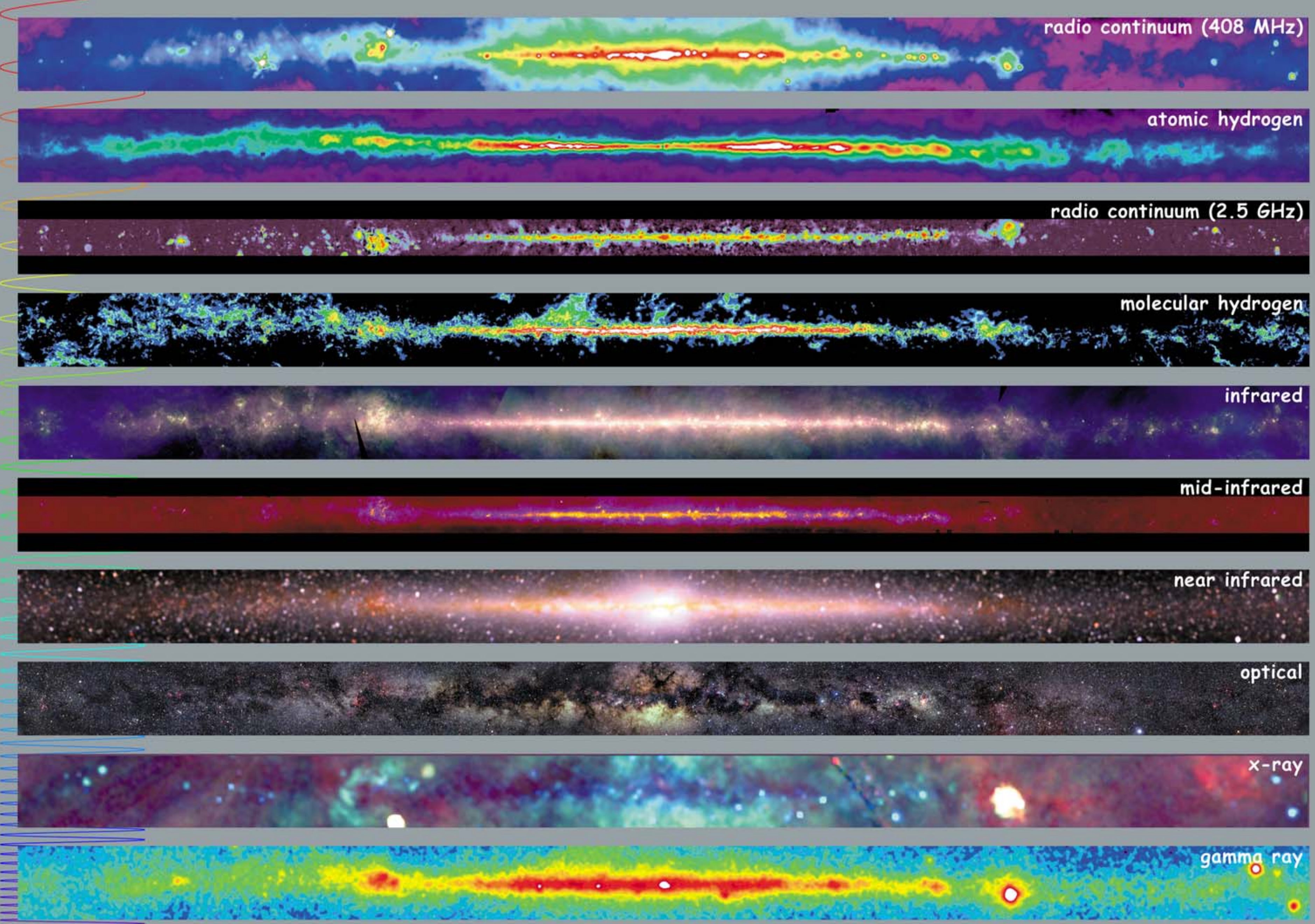
12/23/94 zgl

The Antenna



Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA



http://adc.gsfc.nasa.gov/mw

Multiwavelength Milky Way

A special lecture series on Galaxy Formation

by **Avishai Dekel** (Chaire Internationale Blaise Pascal)

for graduate students and researchers; IAP/OP Wednesdays 17:00-19:00

Octobre 20	1. the standard cosmology
	2. linear growth of fluctuations by gravitational instability
Novembre 17	3. statistics of density fluctuations: the CDM scenario
	4. nonlinear growth: spherical model, filamentary structure
Decembre 8	5. numerical simulations of structure formation
	6. hierarchical clustering: Press-Schechter formalism, biasing
Decembre 15	7. dark-matter halos: density profile, cusp/core problem
	8. halo substructure: dynamical friction, tidal effects, HOD
Janvier 5	9. angular momentum problem: tidal torques, disk formation
	10. the origin of galaxy scaling relations and their scatter
Janvier 12	11. semi-analytic modeling: cooling, star formartion, mergers
	12. feedback processes: supernova, AGN and black holes
Fevrier 9	13. cold flows versus shock heating
	14. origin of bi-modality in galaxies
Fevrier 16	15. dwarf galaxies and the “fundamental line”
	16. dark-dark halos: effect of cosmological photoionization

Lecture 1

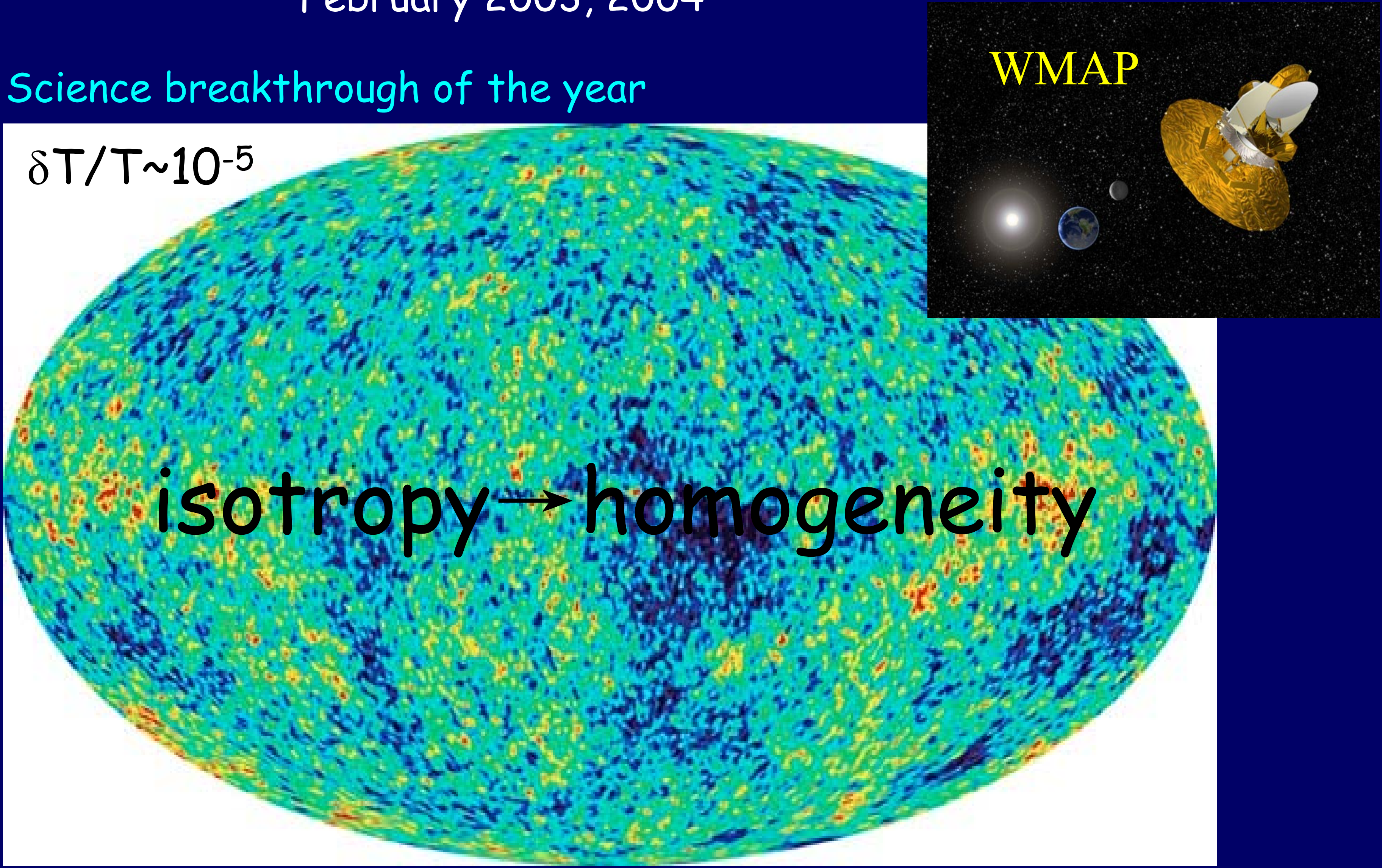
The standard cosmology: LCDM closing in on the cosmological parameters

1. Friedman-Robertson-Walker Model

Microwave Anisotropy Probe

February 2003, 2004

Science breakthrough of the year



$\delta T/T \sim 10^{-5}$

isotropy → homogeneity

Homogeneity and Isotropy → Robertson-Walker Metric

$$ds^2 = dt^2 - a^2(t)[du^2 + S_k(u)\,d\gamma^2]$$

expansion factor

comoving radius

$r = a(t)u$

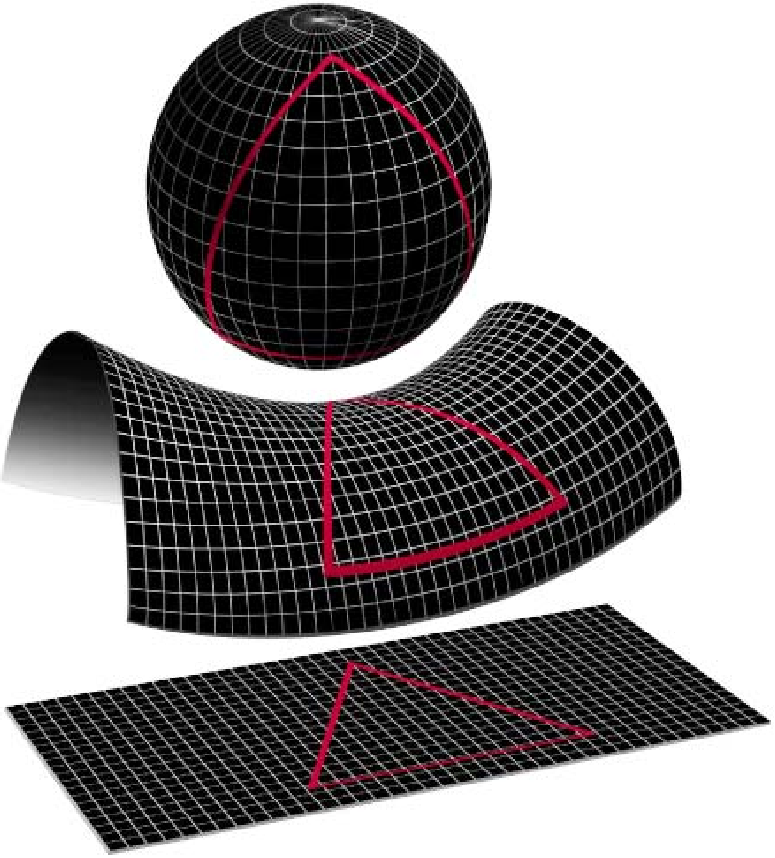
angular area

$d\gamma^2 \equiv d\theta^2 + \sin^2\theta\, d\varphi^2$

$S_k(u) = \sin u \qquad k = +1$

$= \sinh u \qquad k = -1$

$= u \qquad k = 0$

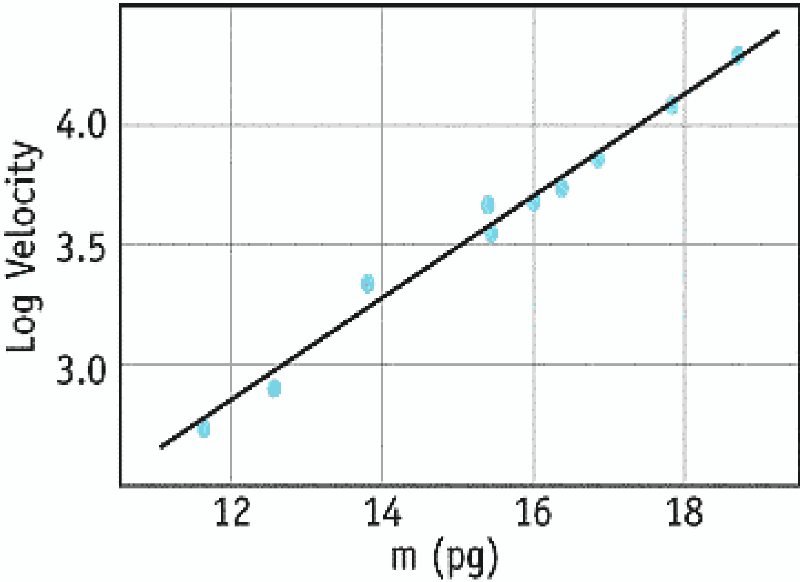


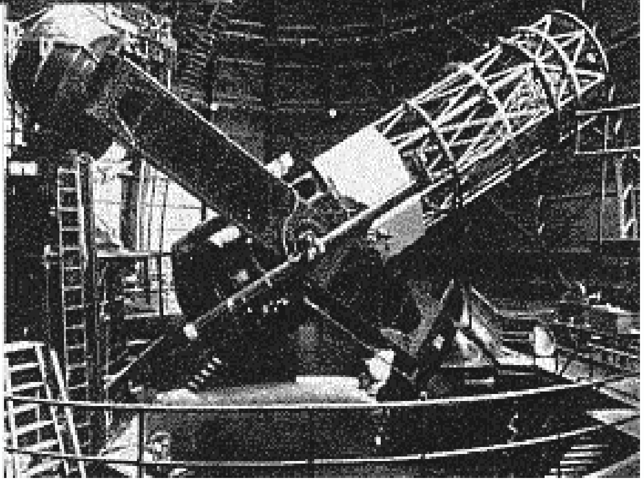
the universe is expanding

היקום מתפשט

DISCOVERY OF EXPANDING UNIVERSE 1929

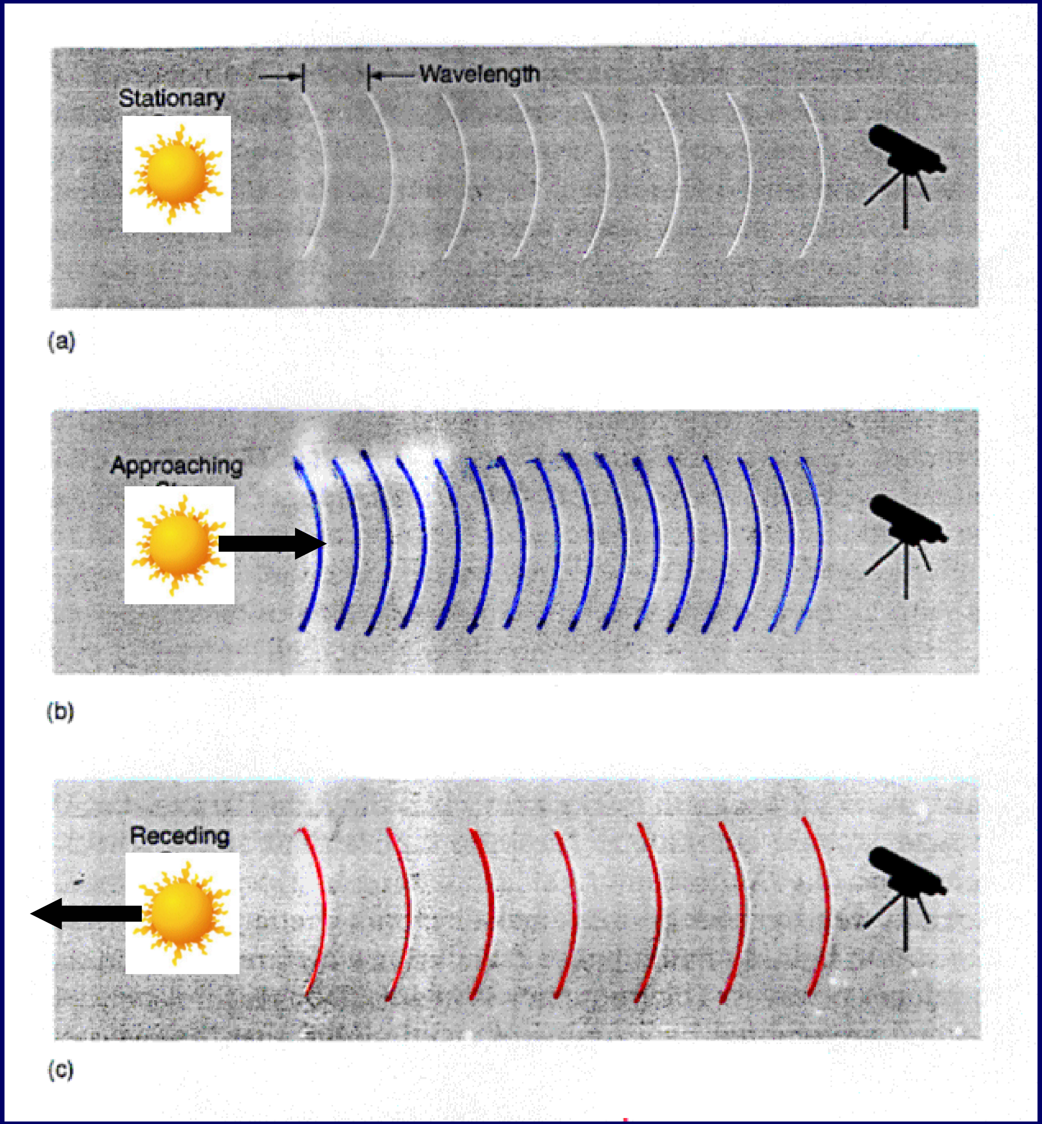
Edwin Hubble





Mt. Wilson
100 Inch
Telescope

Doppler Shift

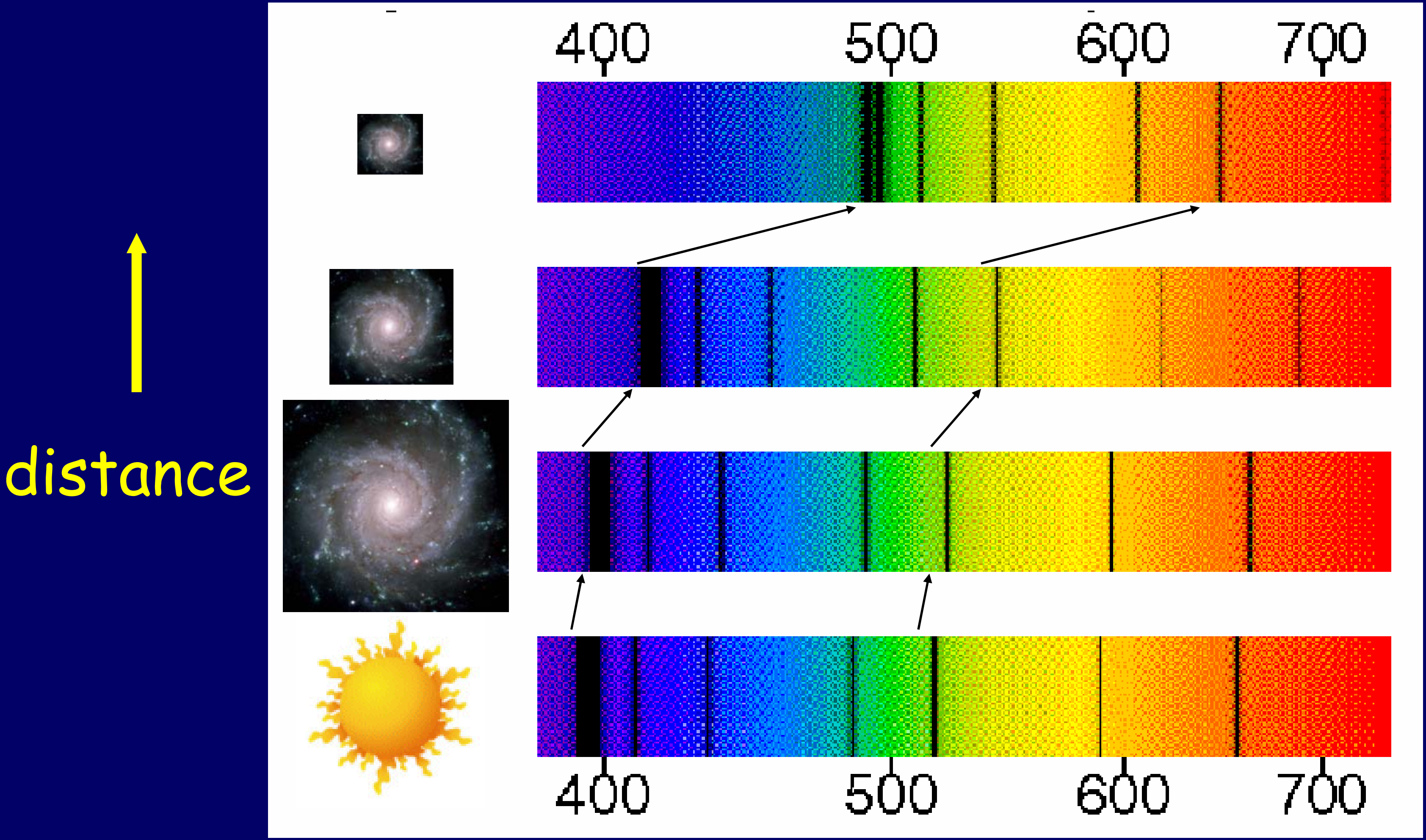


sorce
at rest

approaching

recedning

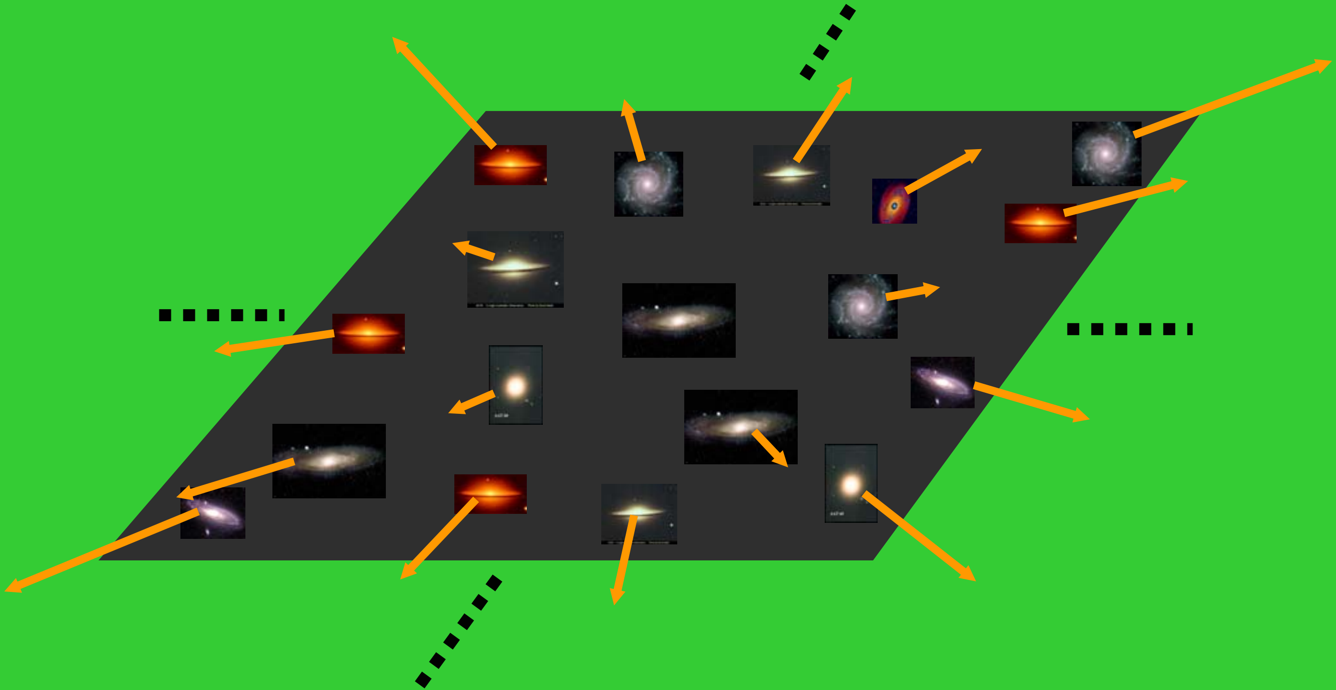
Red-shift



distance

wave length

Hubble Expansion

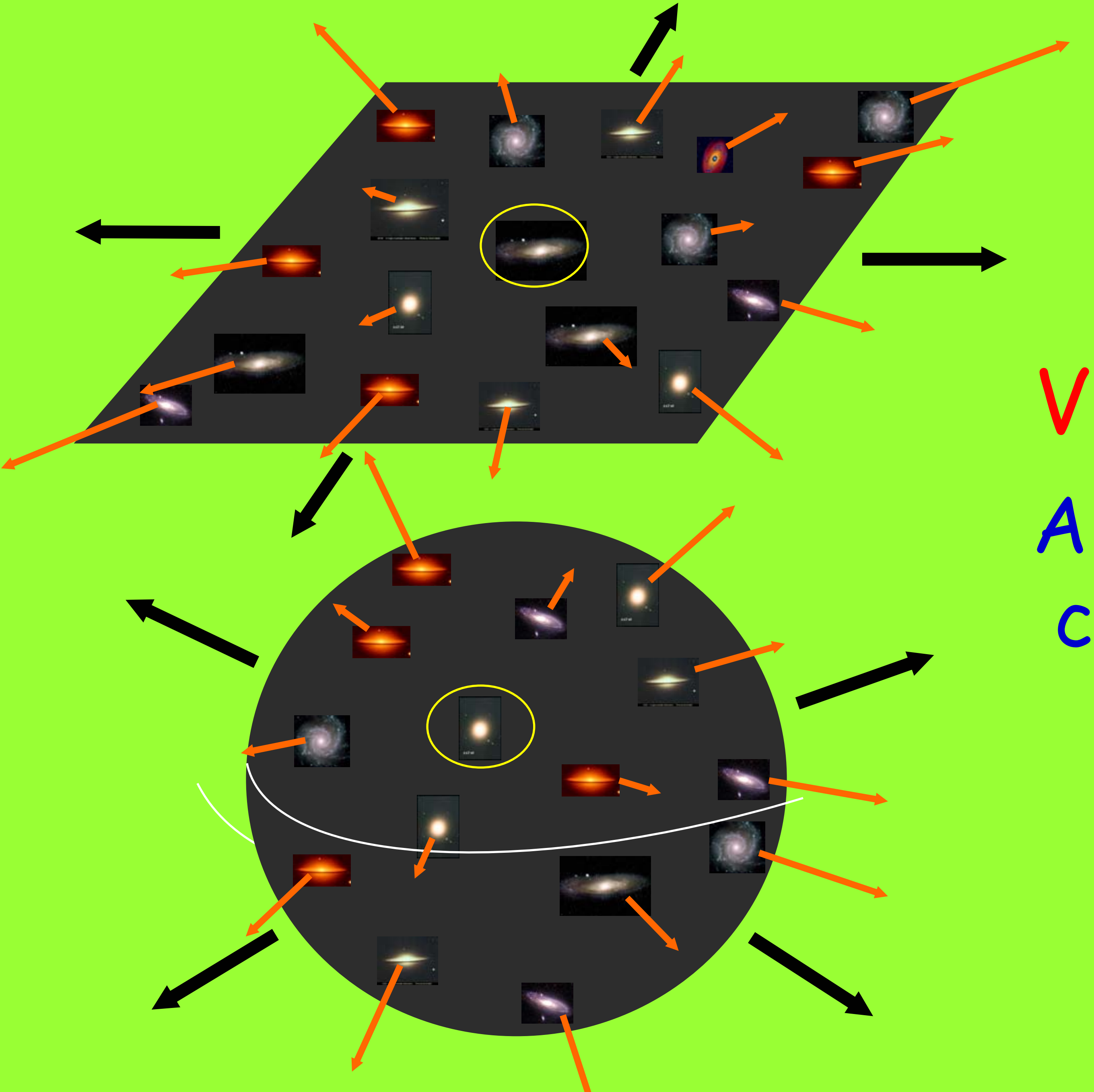


velocity

distance

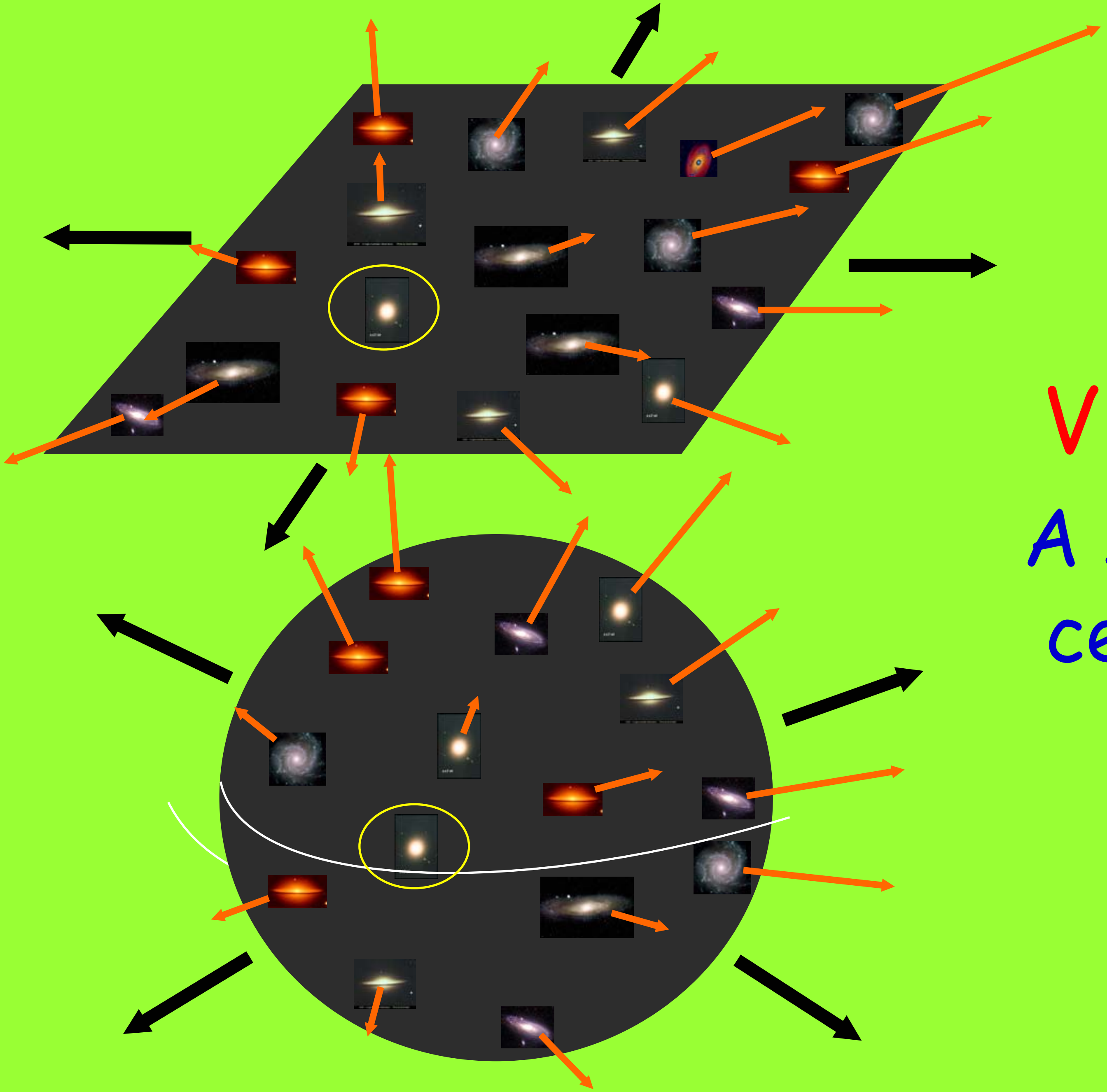
$$V = HR$$

Hubble constant



$V = H R$

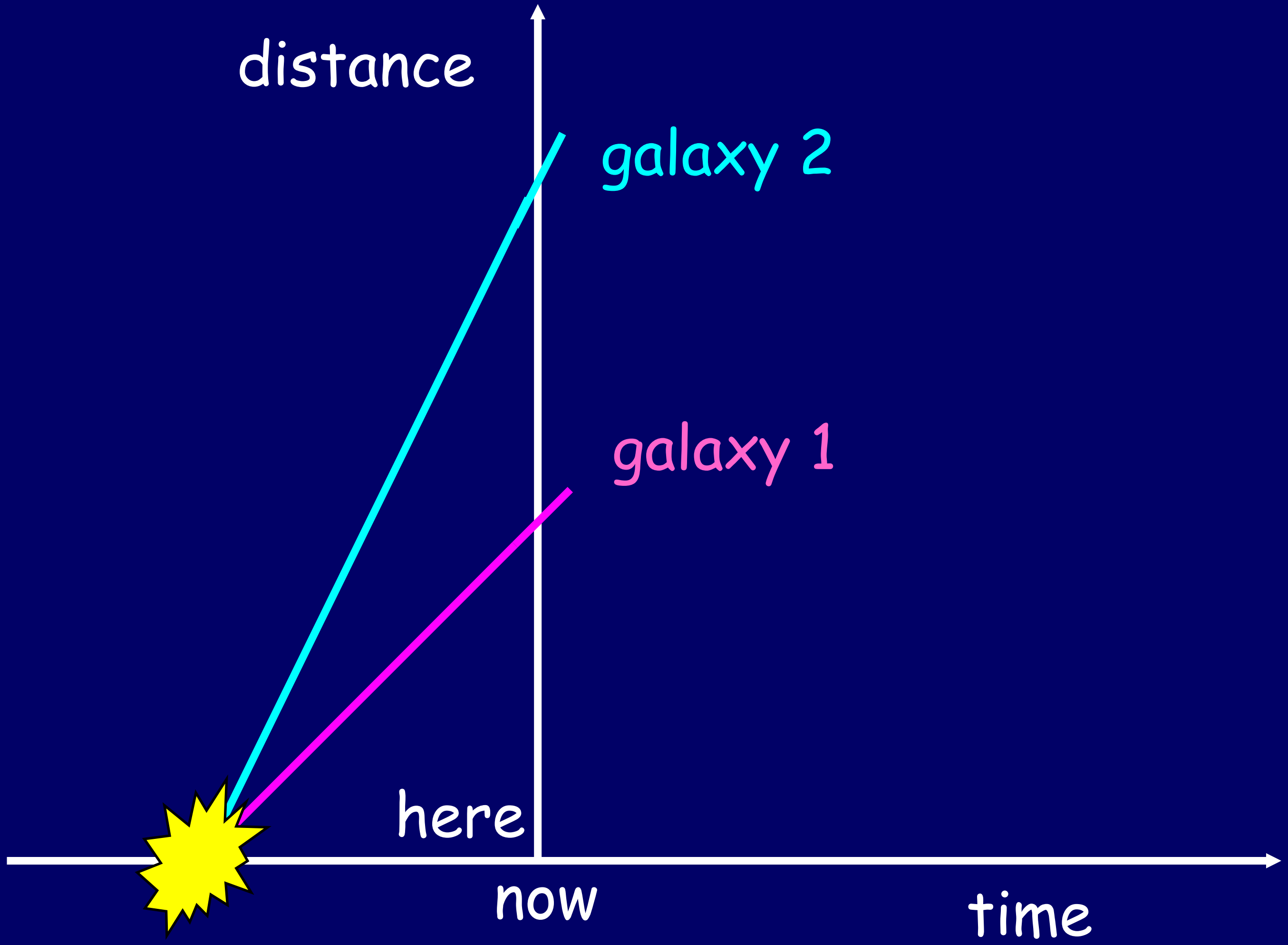
A special center?



$V = H R$

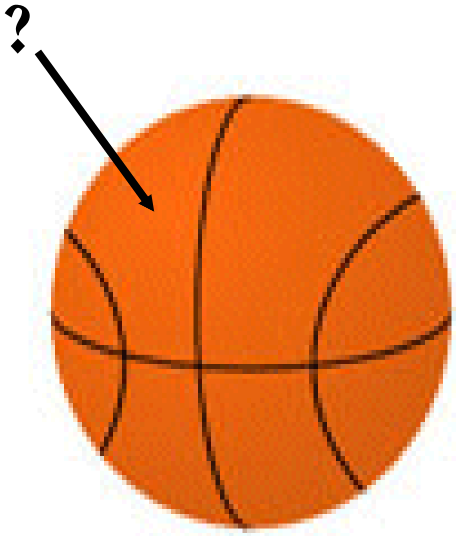
A special center?

התפשטות סביב
נקודה אחרת



The Big Bang $t_0 \approx 13.7$ Gyr

Where was the Big Bang?
At one point? At many points?



Friedman Equation

Homogeneity + Gravity $(G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}) \rightarrow$

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G\rho}{3} - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

kinetic potential curvature vacuum

$$\rho = \rho_m + \rho_r$$

$$\rho_m = \rho_{m0} a^{-3} \quad \rho_r = \rho_{r0} a^{-4}$$

$$1 = \Omega_m + \Omega_k + \Omega_\Lambda$$

$$\Omega_m \equiv \frac{\rho_m}{\boxed{3H^2/8\pi G}} \quad \Omega_k \equiv -\frac{kc^2}{a^2H^2} \quad \Omega_\Lambda \equiv \frac{\Lambda c^2}{3H^2}$$

two free parameters

$$\rho_{crit} \sim 10^{-29}\,\mathrm{g\,cm^{-3}}$$

$$\Omega_{tot} \equiv \Omega_m + \Omega_\Lambda = 1 - \Omega_k$$

closed/open

$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}\Omega_m - \Omega_\Lambda$$

decelerate/accelerate

Solutions of Friedman eq.

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G\rho_{m0}}{3a^3} - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$1 = \Omega_m + \Omega_k + \Omega_\Lambda$$

matter era, Λ=0

$$\dot{a}^2 - \frac{2a^*}{a} = -k$$

$$a^* \equiv \frac{4\pi G\rho_{m0}}{3} = const.$$

$k = 0: \quad a \propto t^{2/3}$

a small: $\quad a \propto t^{2/3} \quad$ any k

a large, $k = -1: \quad a \propto t$ $\quad \Omega_m << 1$

$k = +1$ $\quad d\eta \equiv dt/a(t)$

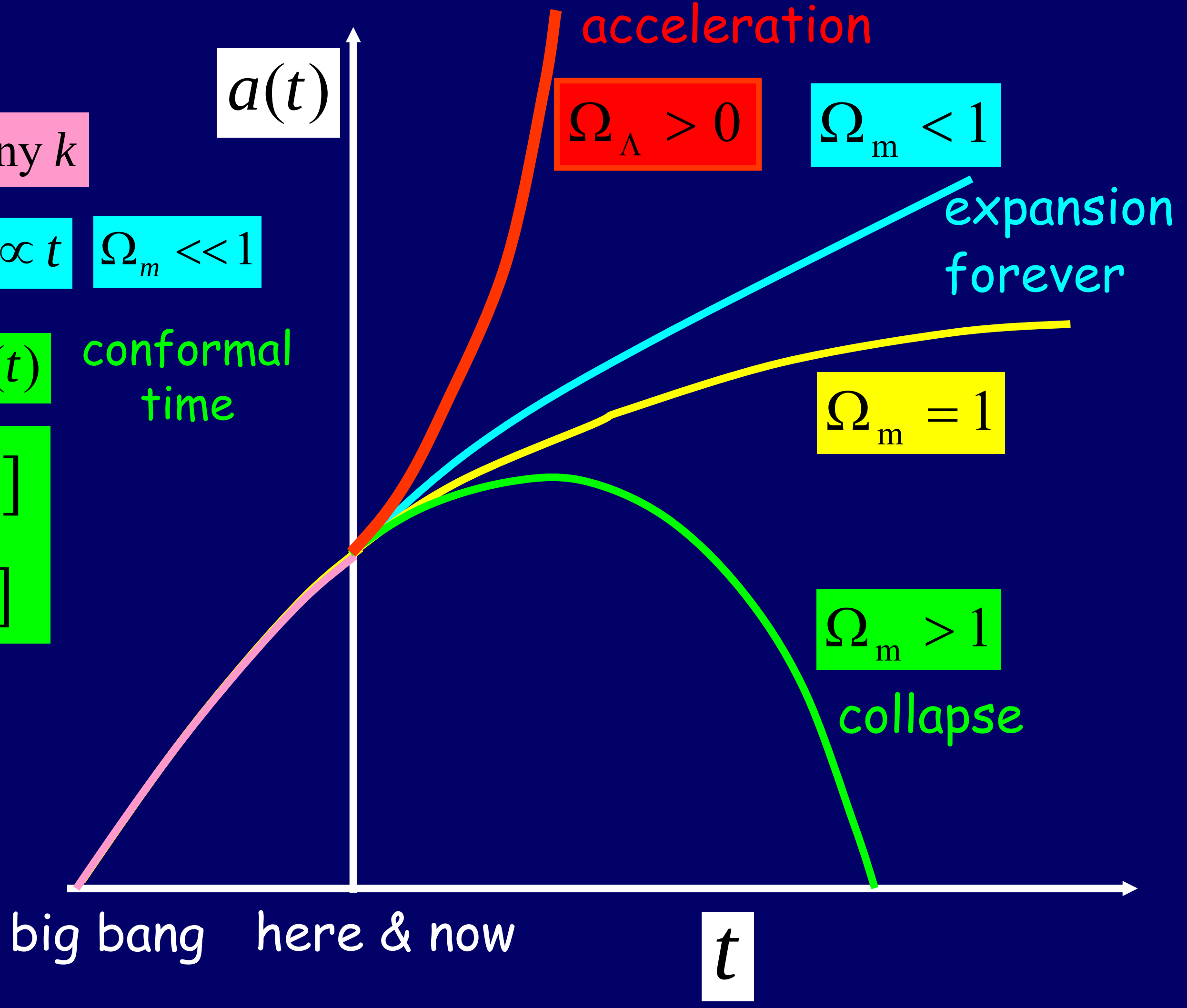
conformal time

$$a = a^*[1 - \cos(\eta)]$$

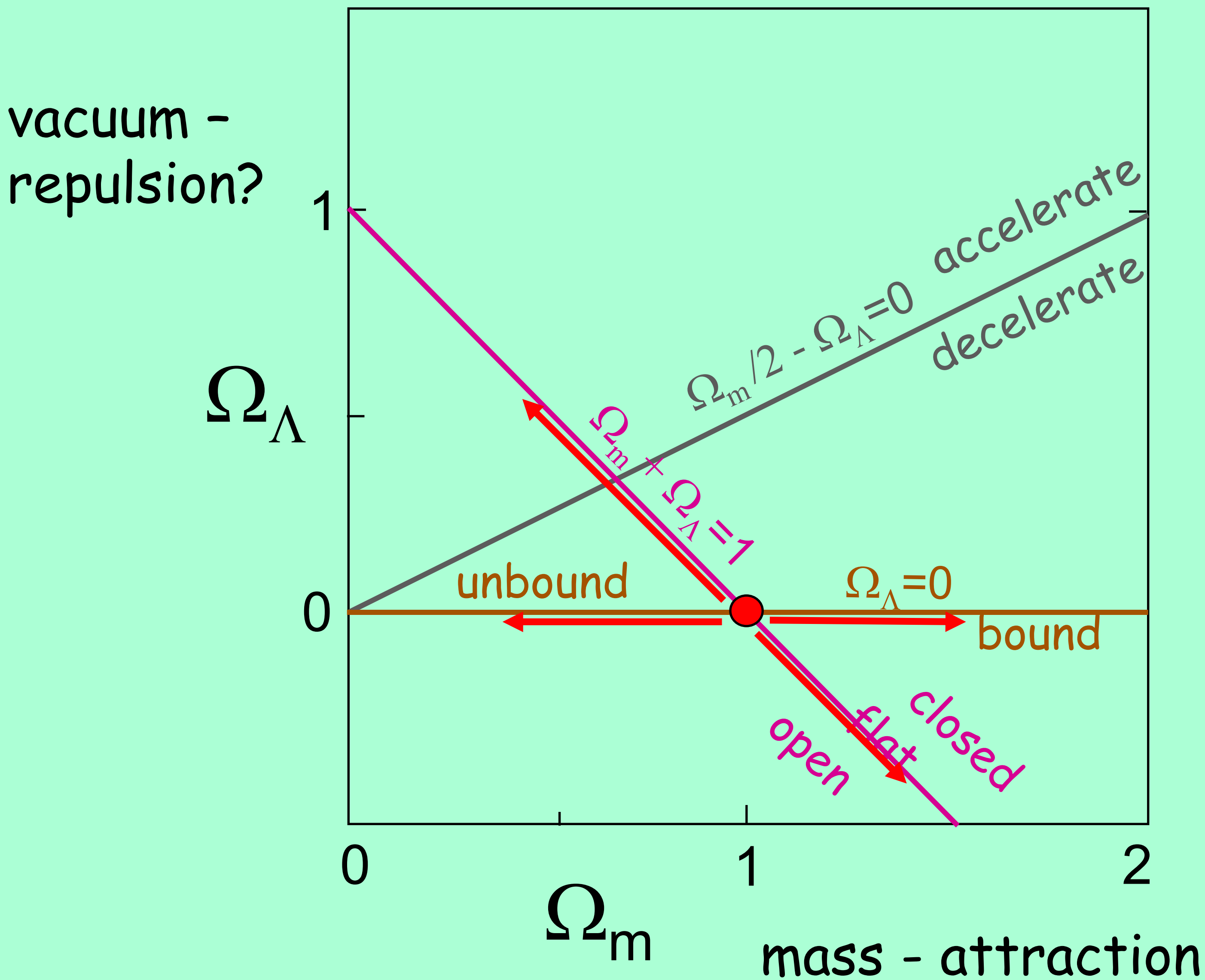
$$t = a^*[\eta - \sin(\eta)]$$

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{\Lambda c^2}{3}$$

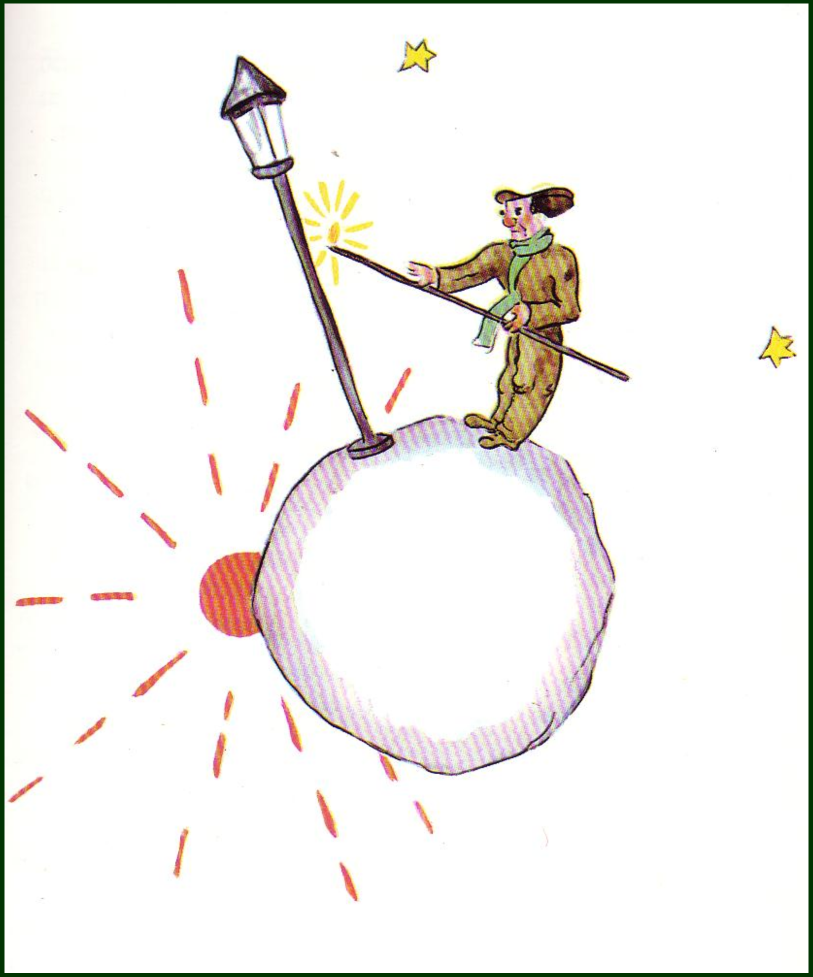
$$\rightarrow a \propto e^{Ht}$$



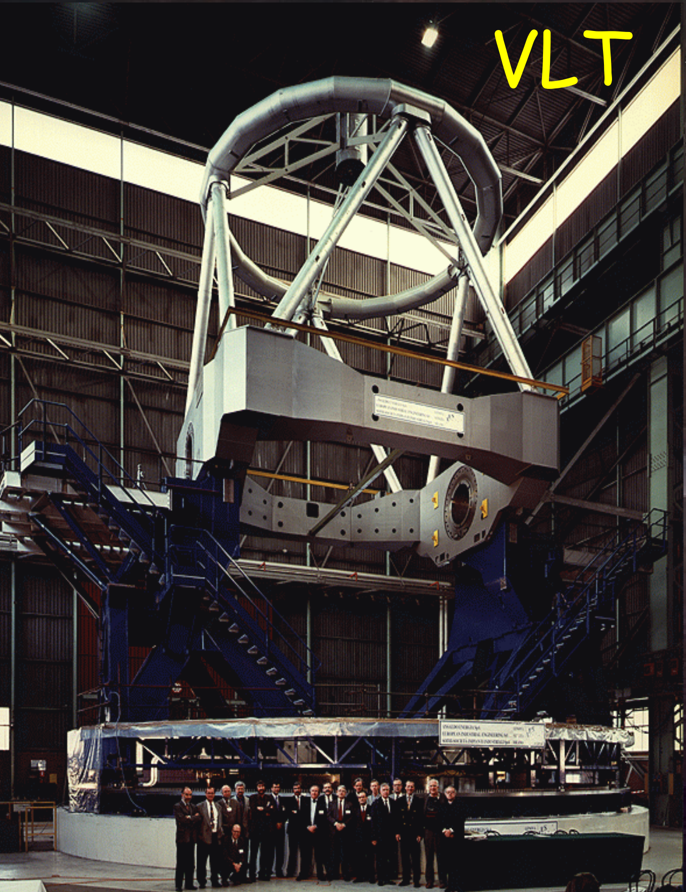
Dark Matter and Dark Energy



2. Luminous Matter



Keck Telescope
10 meter



Hubble Space Telescope

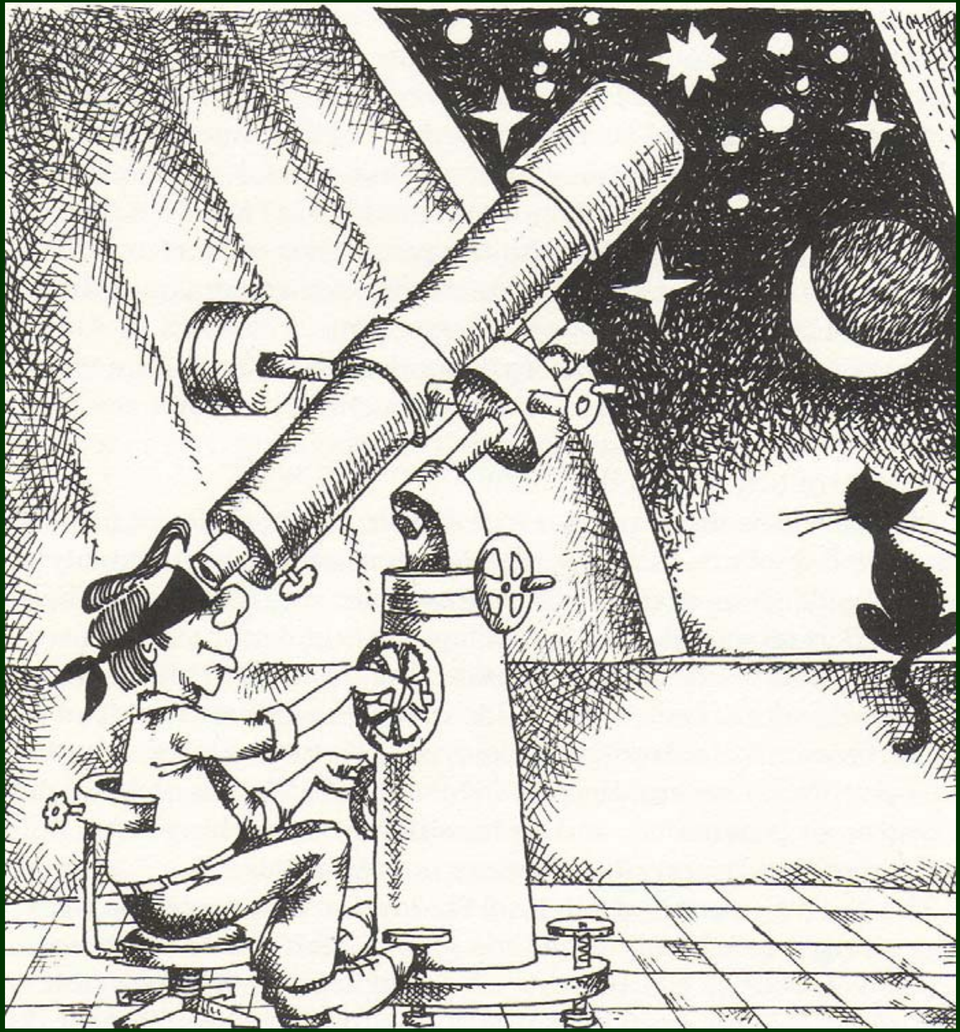
Luminous mass

all sources, all wavelengths

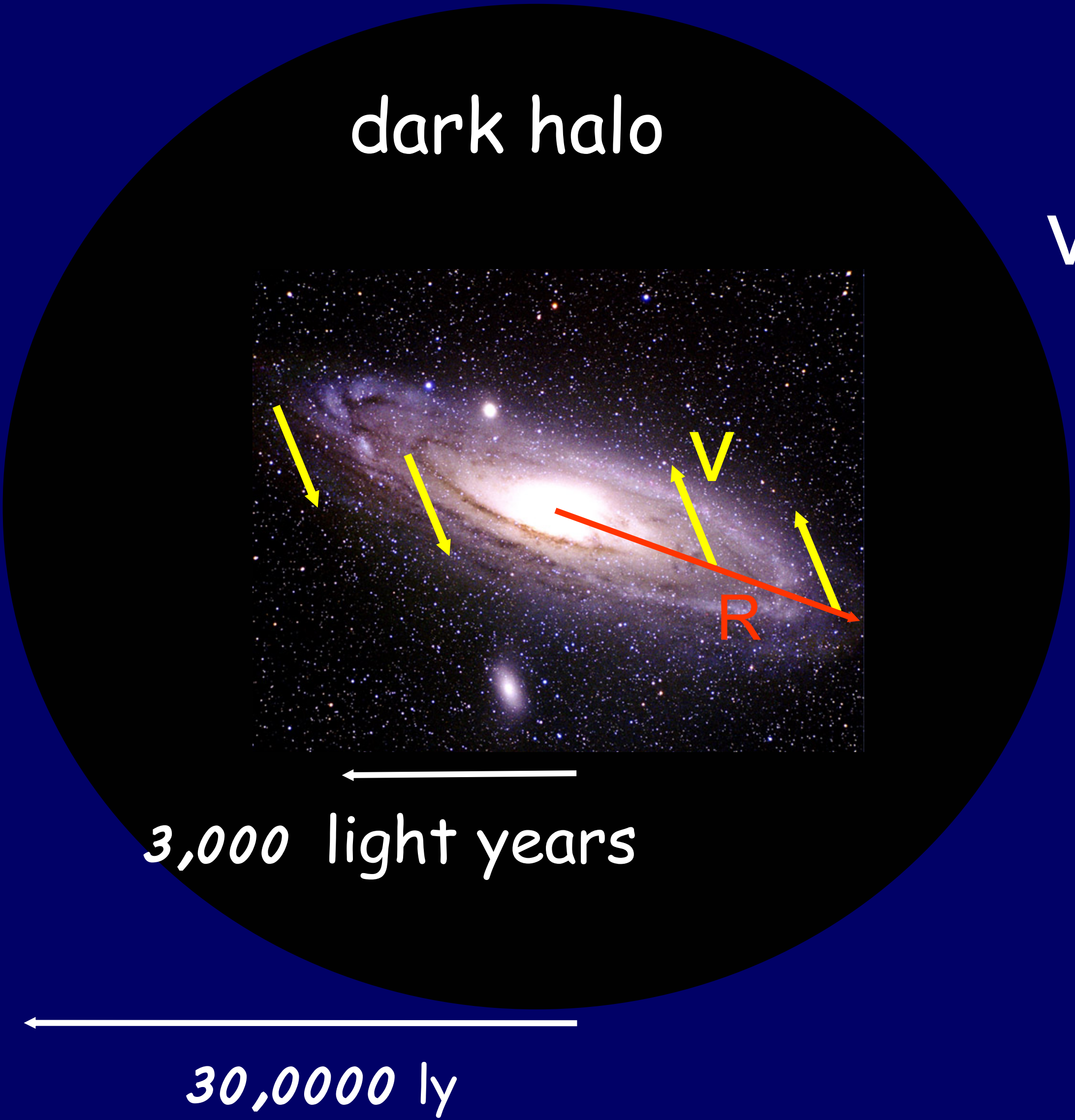
$$\boxed{\Omega_{\text{luminous}} \approx 0.01}$$

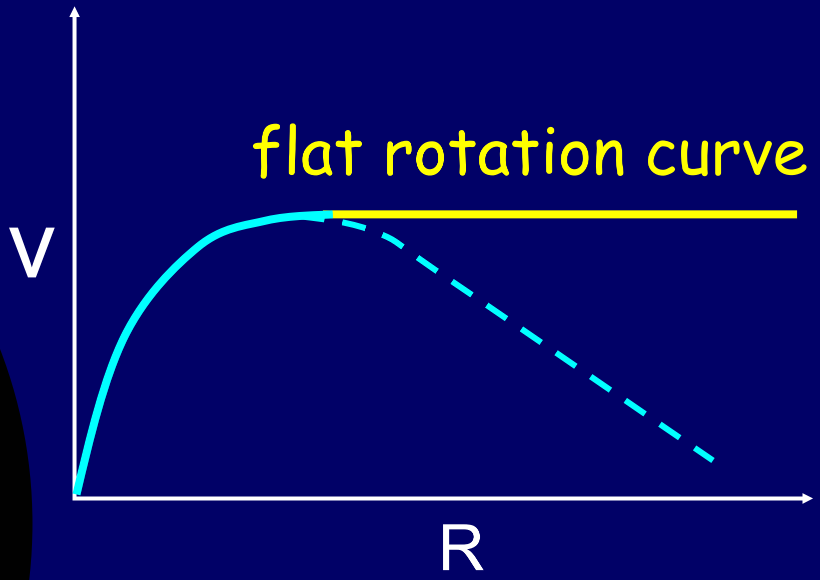
With $\Lambda=0$,
Universe unbound and infinite?

3. Dark Matter



Dark Halos





$$V^2 = \frac{GM(R)}{R}$$

$$\rightarrow M(R) \propto R$$


Brian McLeod, Center for Astrophysics,
Cambridge MA & Univ of Arizona (Castle)

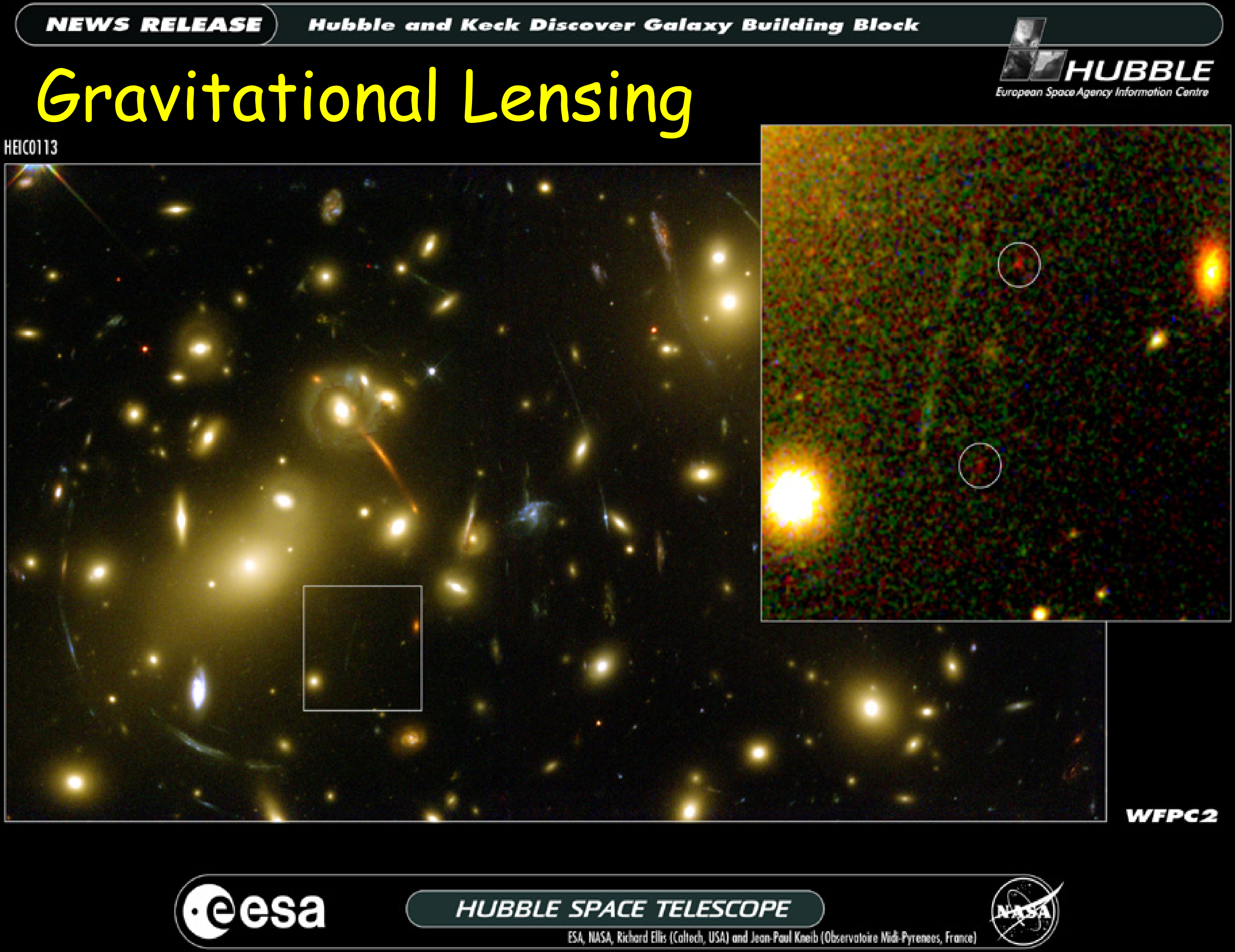
Gravitational Lens
Galaxy Cluster 0024+1654

HST • WFPC2

PRC96-10 • ST ScI OPO • April 24, 1996

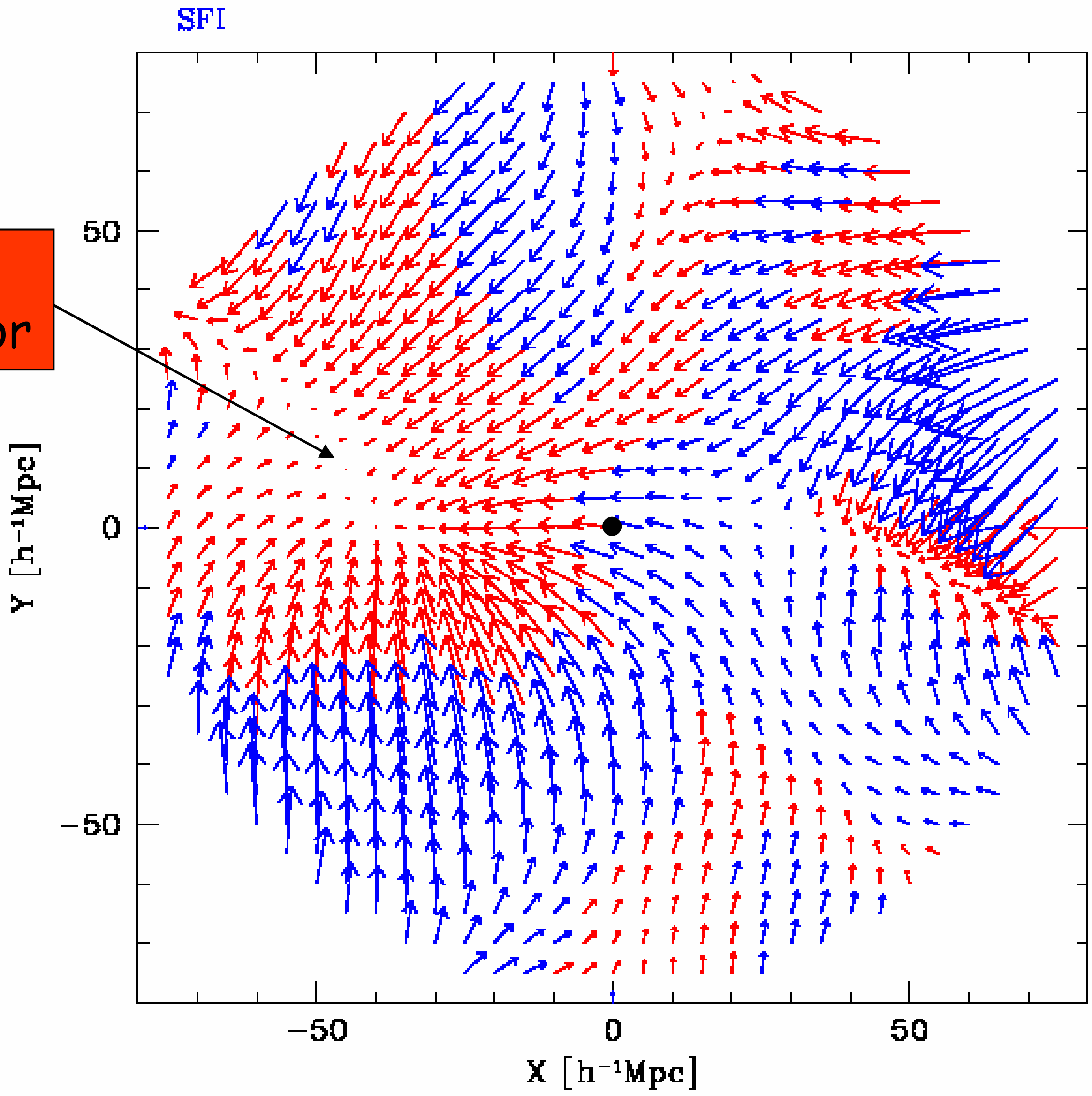
W.N. Colley (Princeton University), E. Turner (Princeton University), J.A. Tyson (AT&T Bell Labs) and NASA

Gravitational Lensing

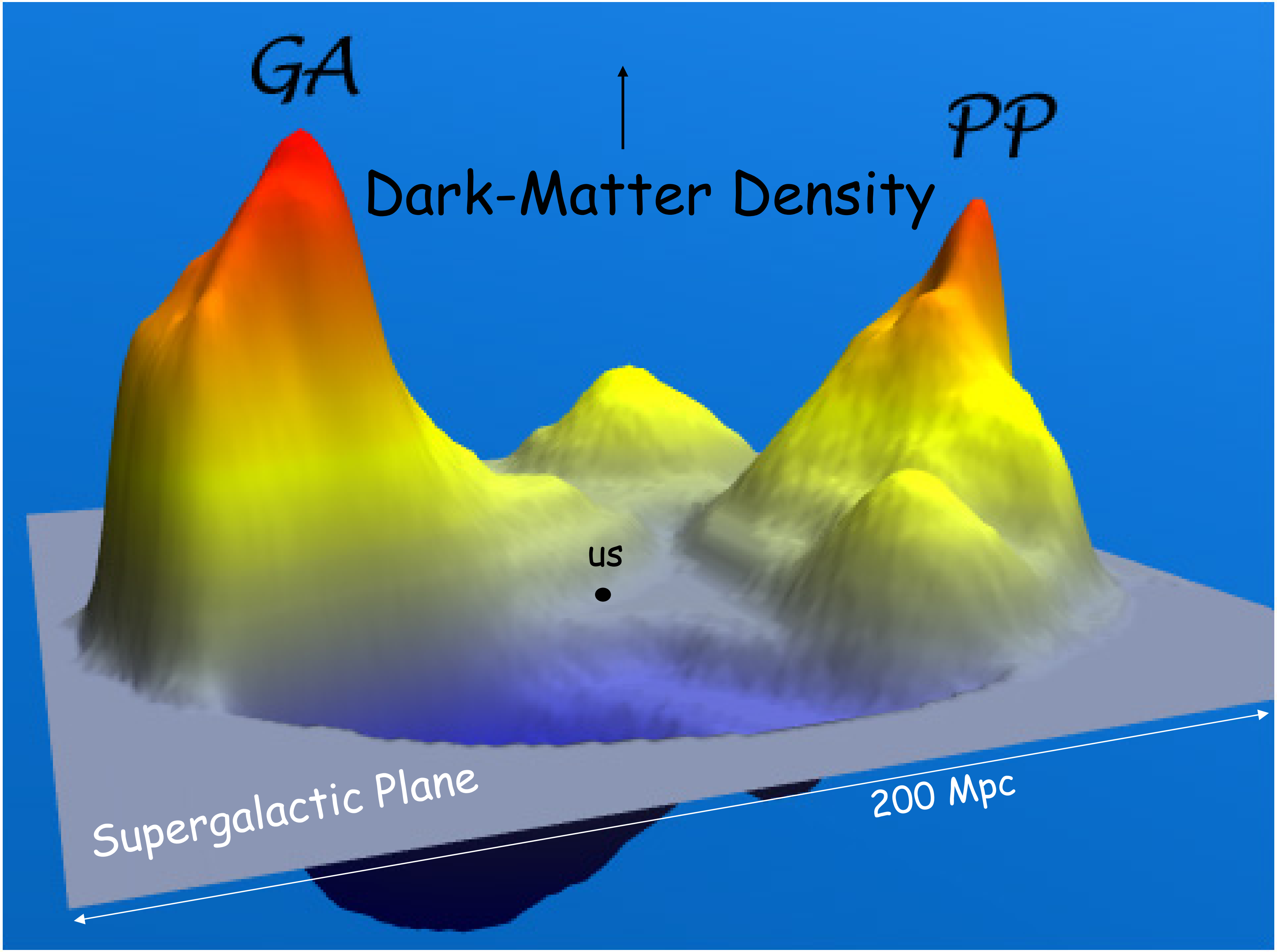


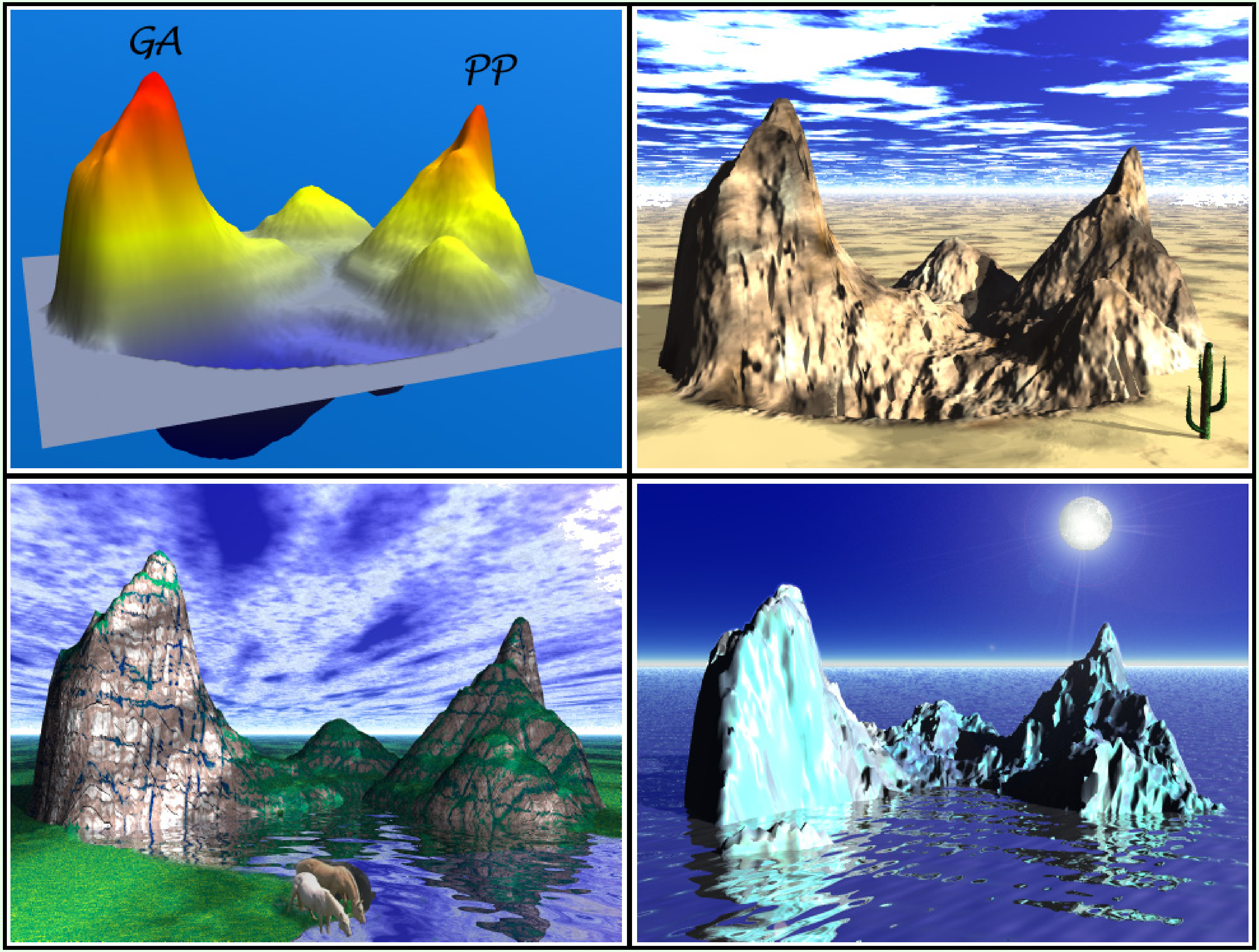
ESA, NASA, Richard Ellis (Caltech, USA) and Jean-Paul Kneib (Observatoire Midi-Pyrenees, France)

Cosmic Flows - POTENT



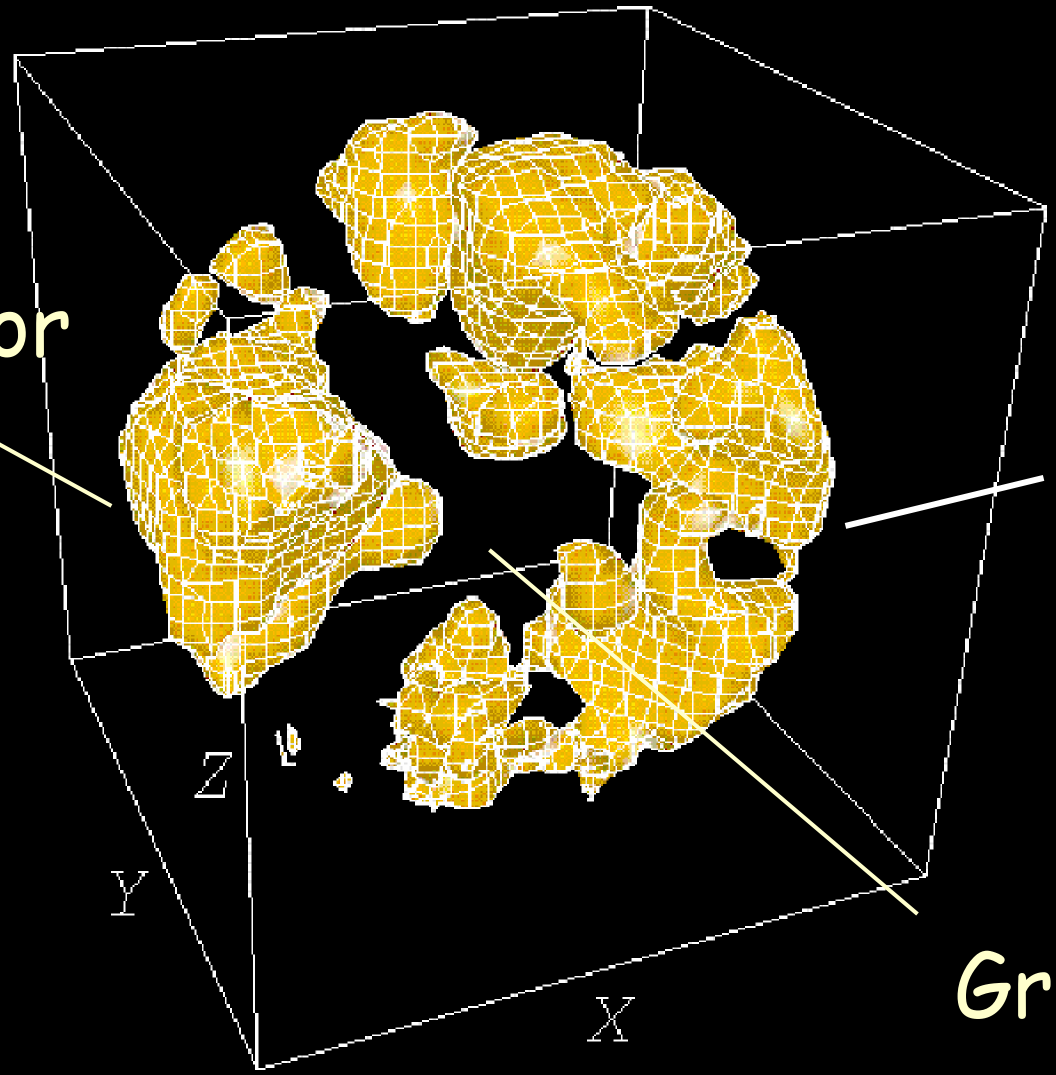
Great Attractor


GA
Dark-Matter Density
PP
us
Supergalactic Plane
200 Mpc



Artist conception

Mass Density in 3D



Great Attractor

Perseus Pisces

Great Void

Most of the mass is dark!

(exerting attraction)

$$\Omega_{\mathrm{m}} = 0.3 \pm 0.05$$

With $\Lambda=0$, Universe unbound and infinite?

What is the dark matter made of?

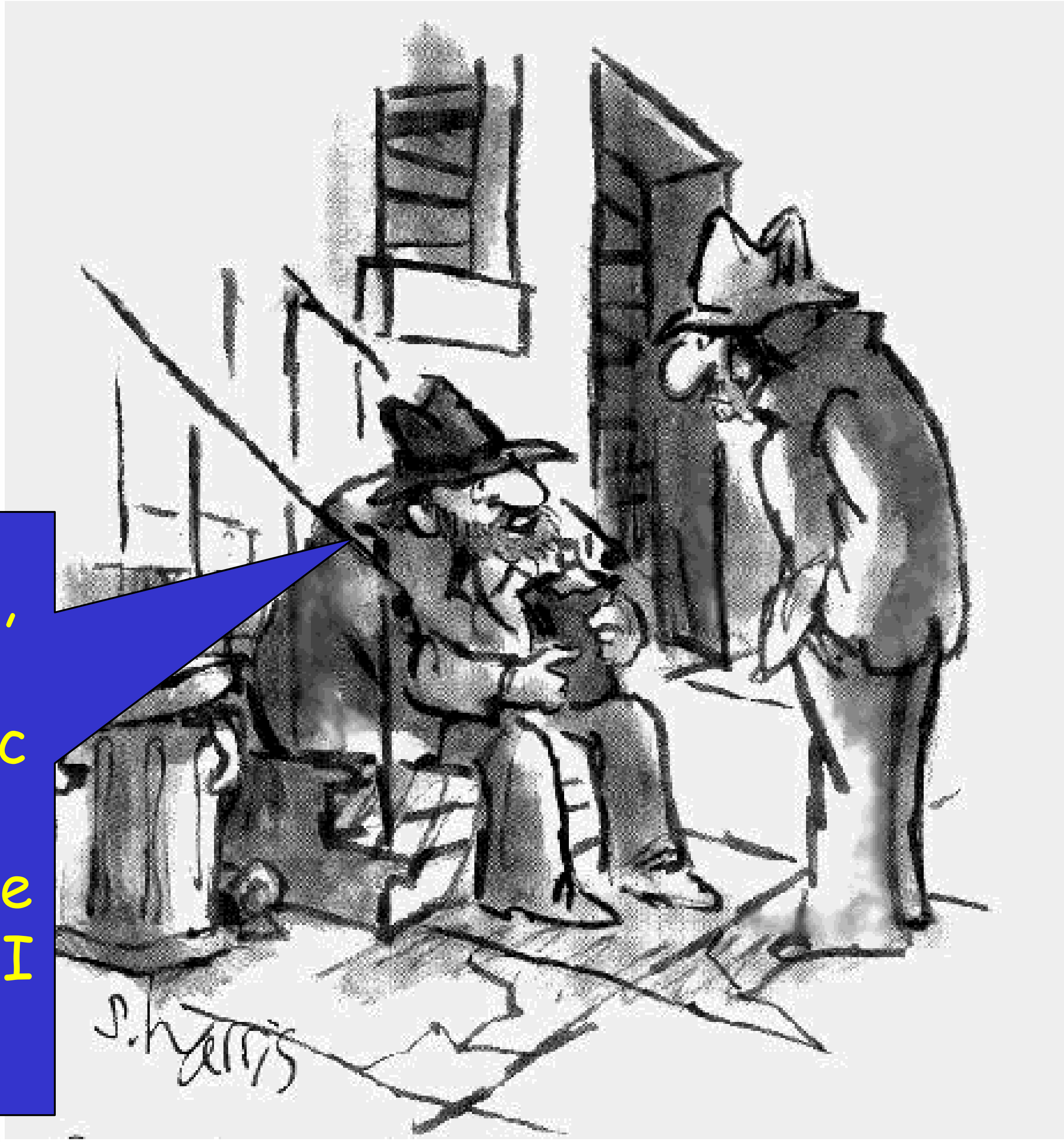
$$\Omega_{\mathrm{baryons}} = 0.044 \pm 0.004$$

Baryonic dark matter: planets, black holes

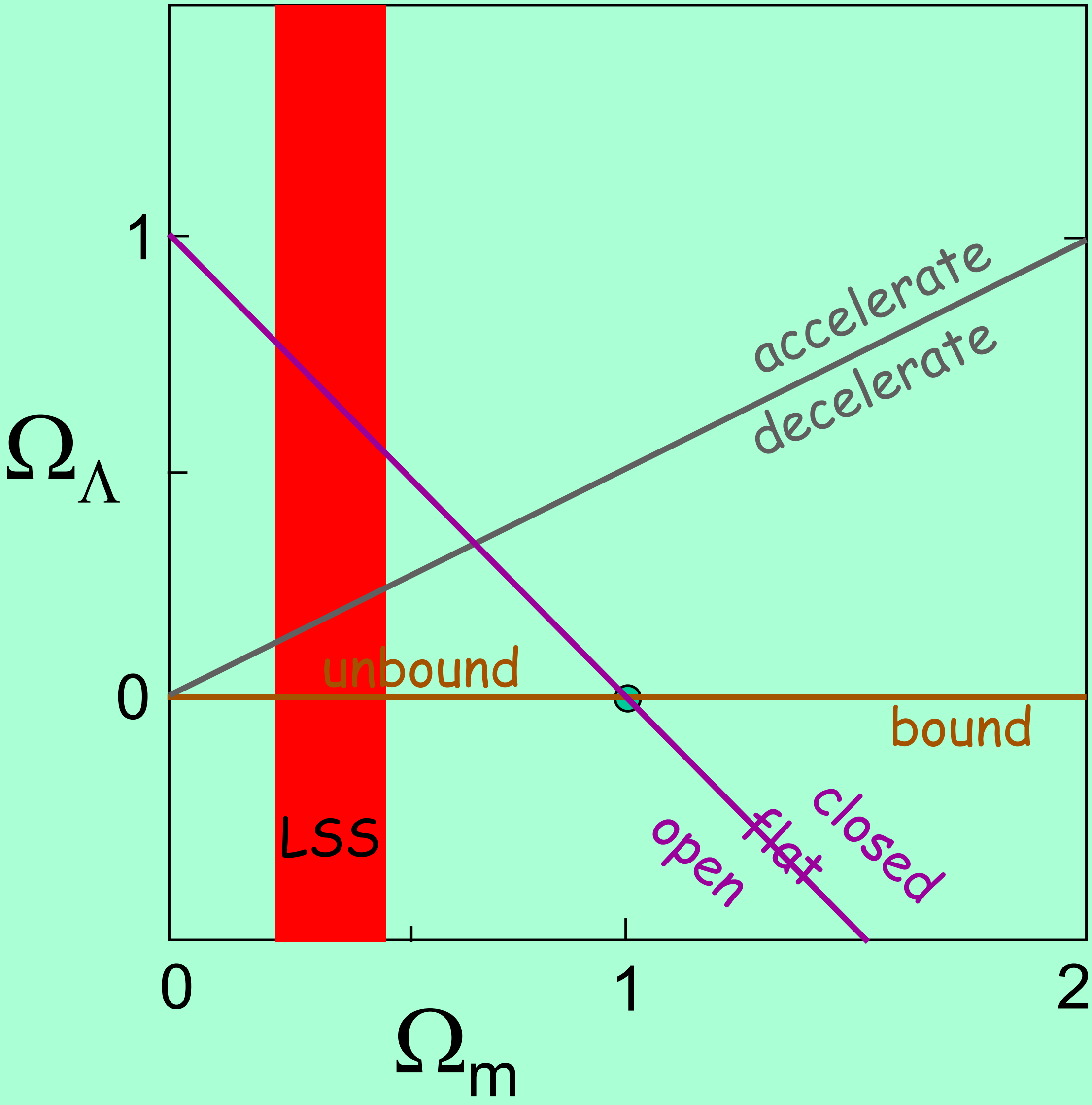
$$\Omega_{\text{baryons}} = 0.044 \pm 0.004$$

non-baryonic dark matter particles

Neutralinos, photinos, axions, ... all those damn super-symmetric particles you can't see... that's what drove me to drink... but **now** I **can** see them!



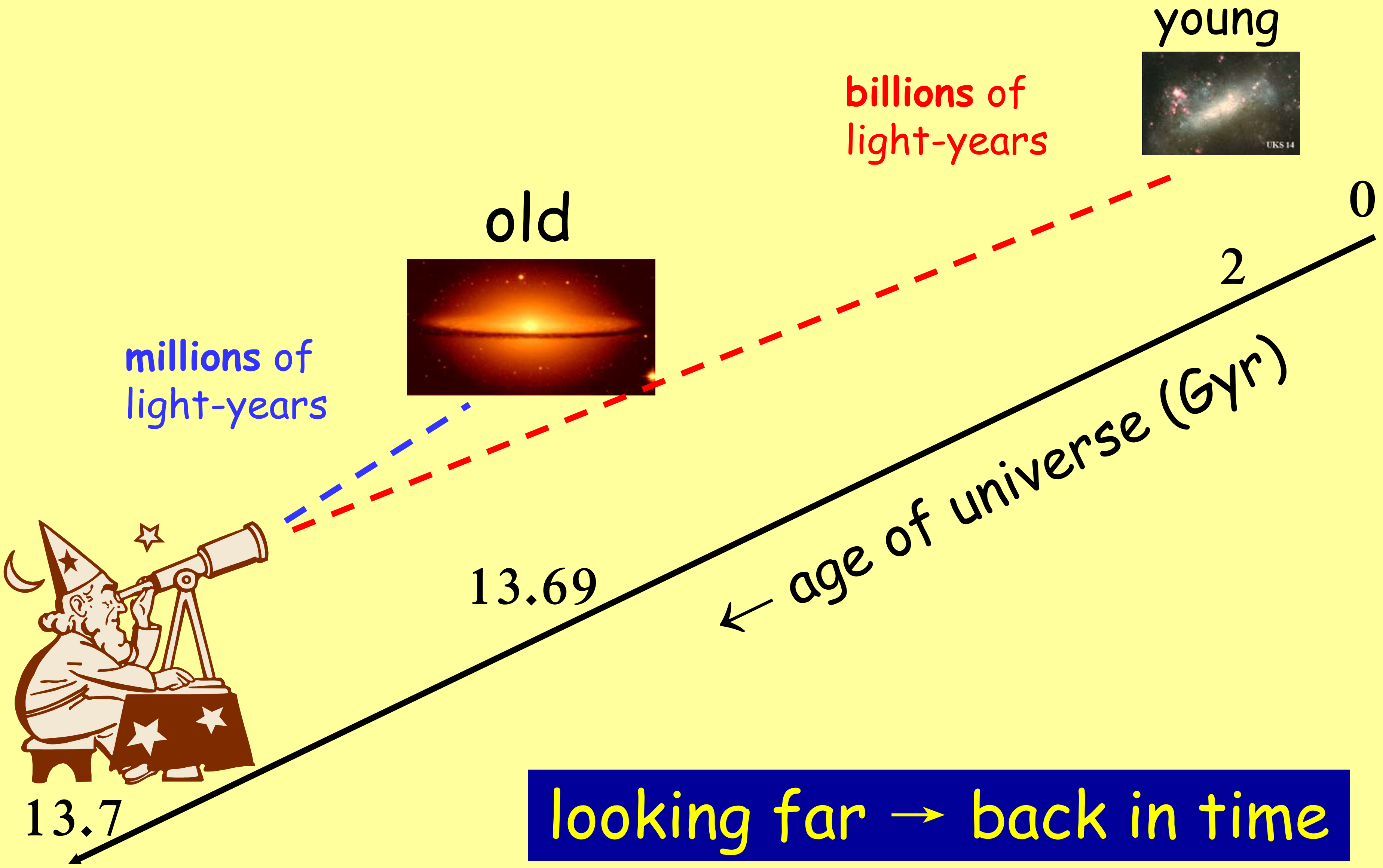
Cosmological Parameters



4. Dark Energy

measure the expected deceleration under gravitational attraction

The Telescope as a Time Machine



young

billions of
light-years

0

2

old

millions of
light-years

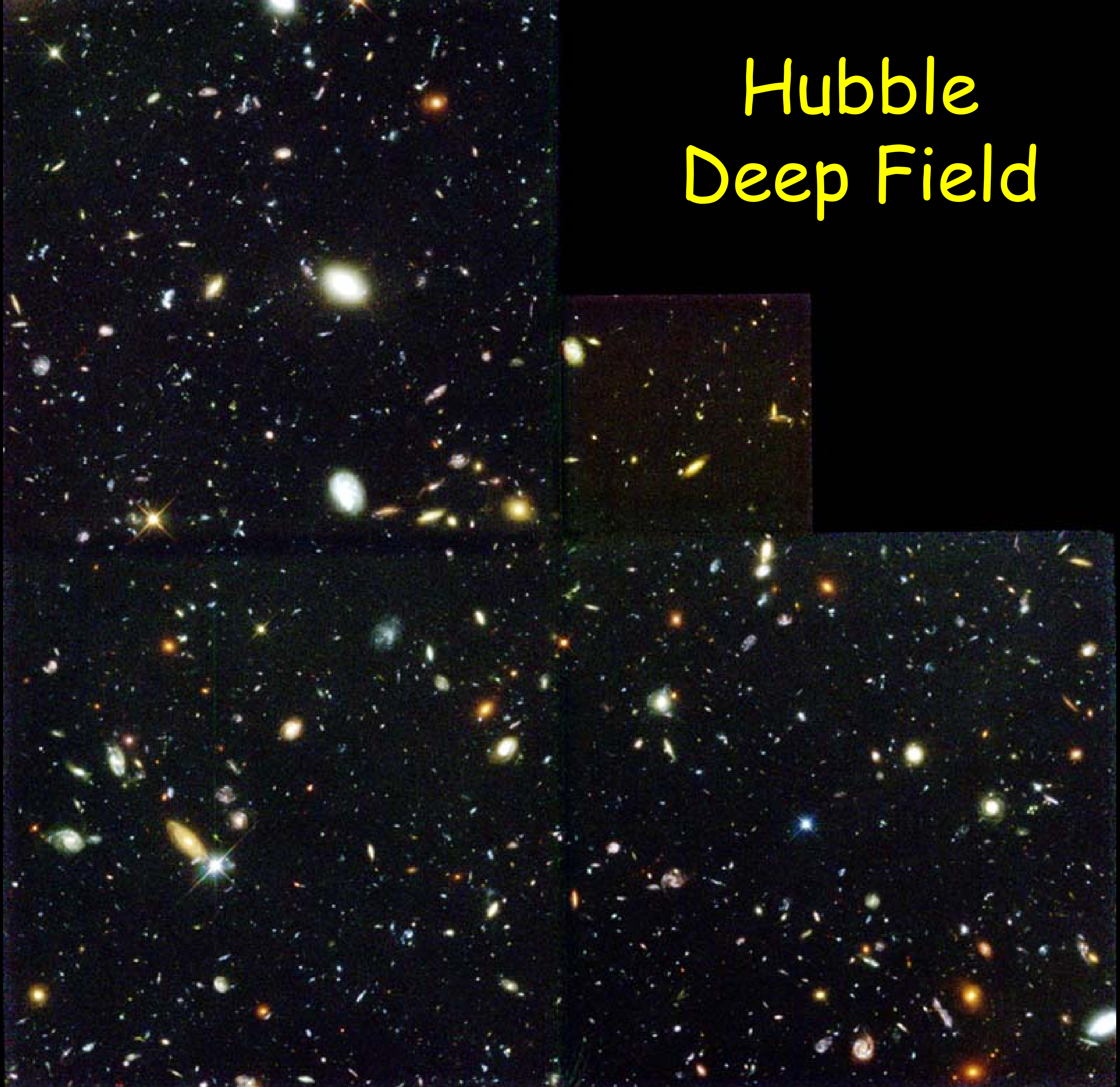
13.69

← age of universe (Gyr)

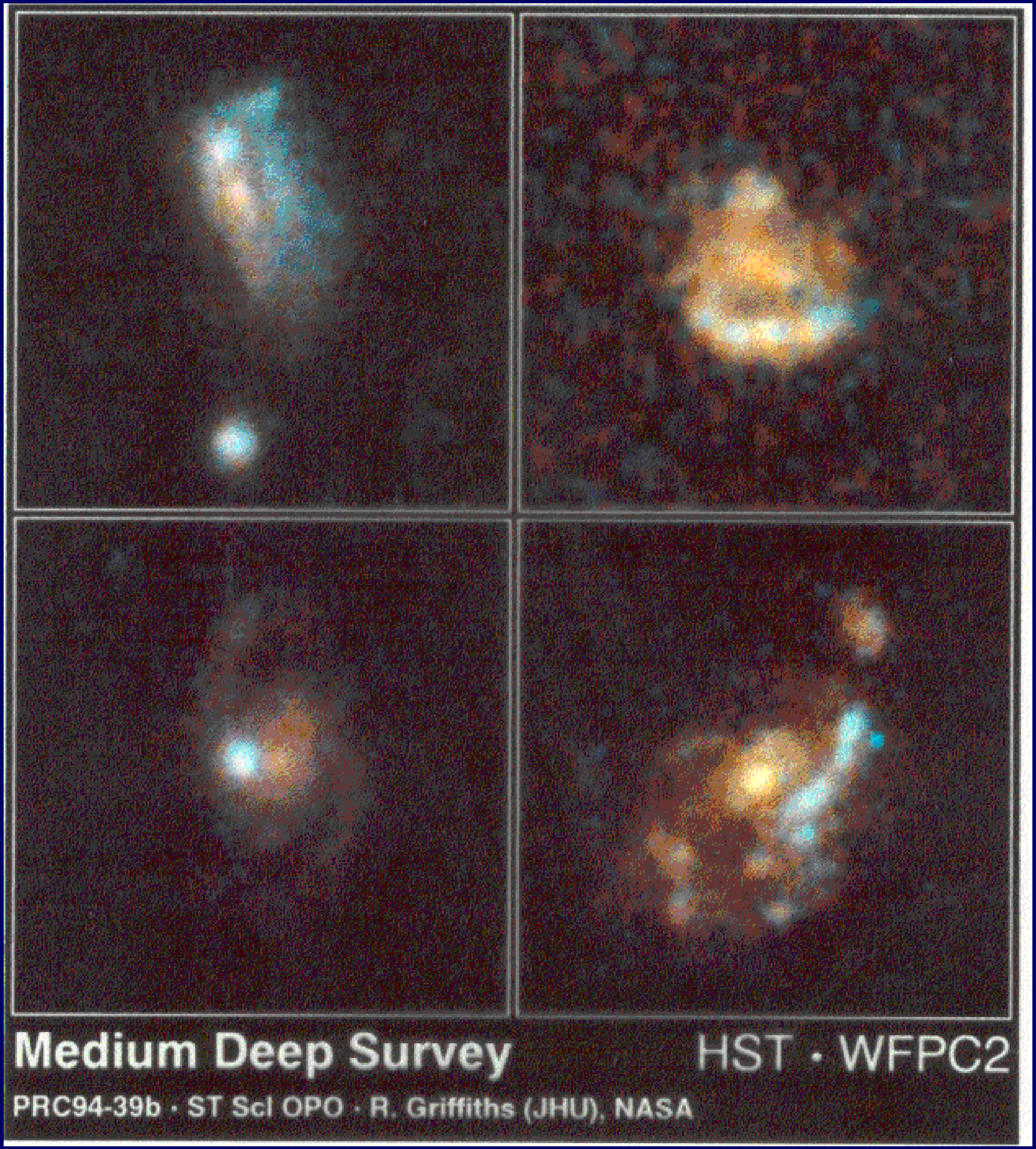
13.7

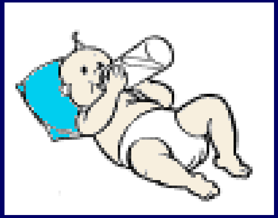
looking far → back in time

Hubble Deep Field

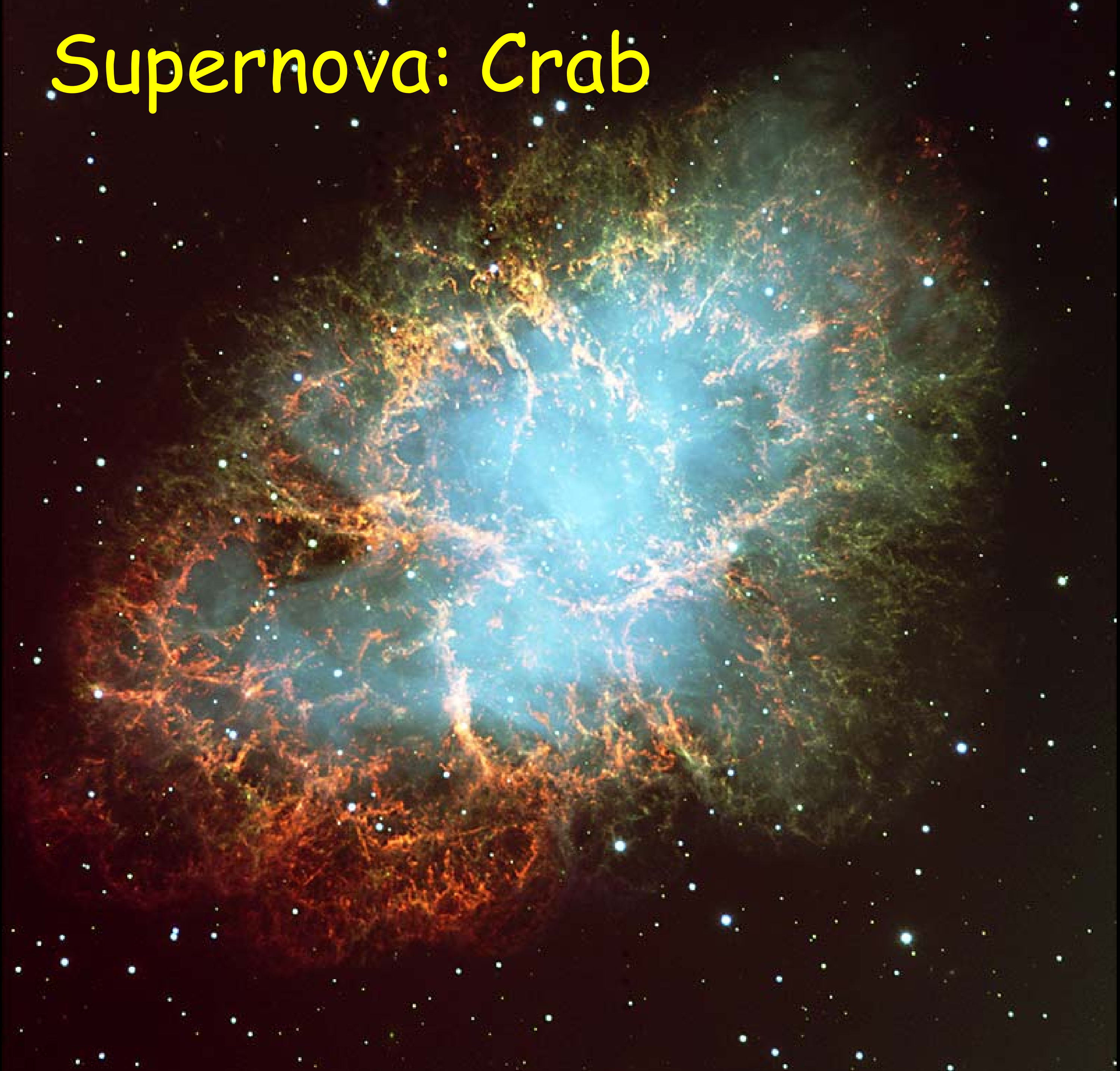


Baby galaxies in early universe

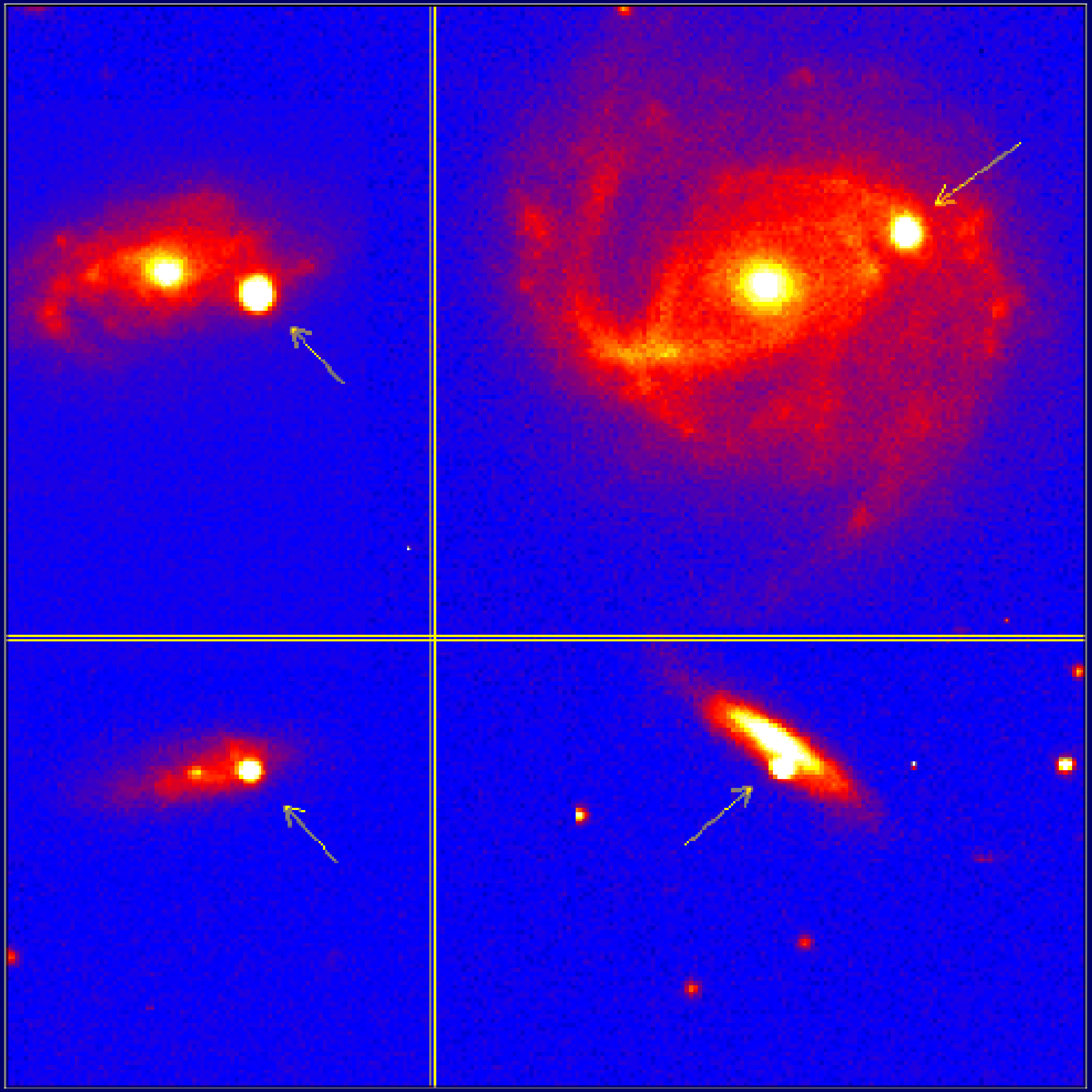




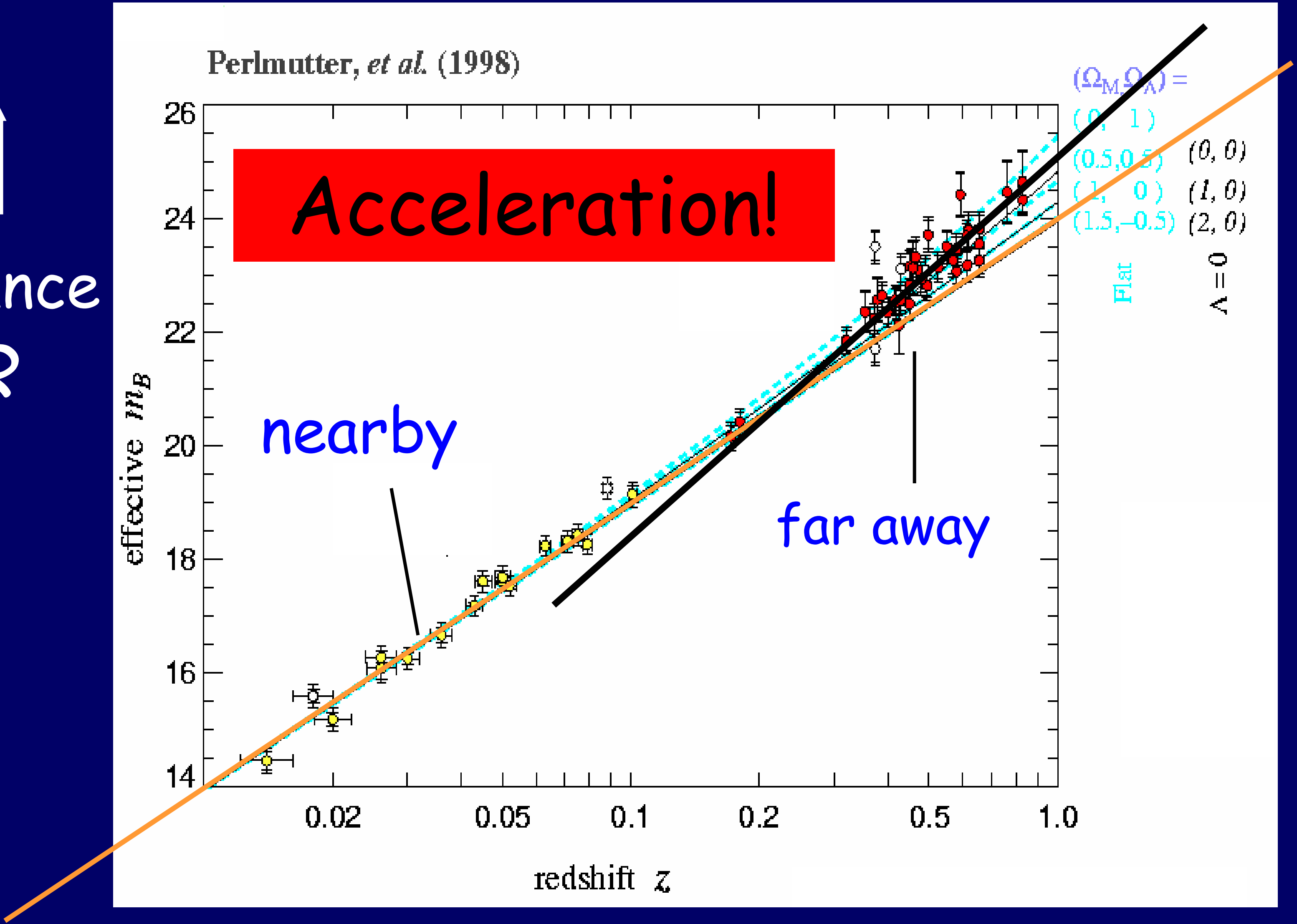
Supernova: Crab



Distant supernovae: standard candles



Past expansion rate V=H(t) R



distance

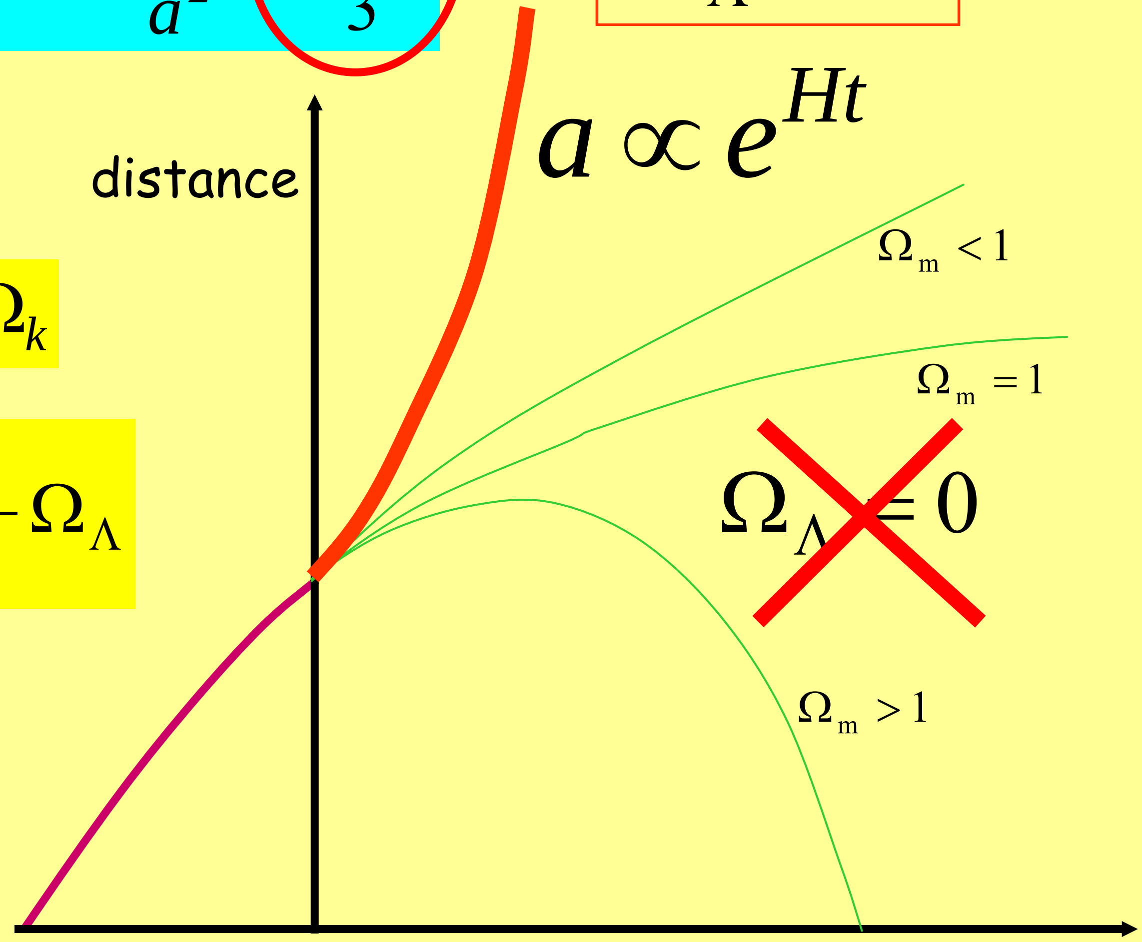
R

velocity V

Acceleration by a cosmological constant:

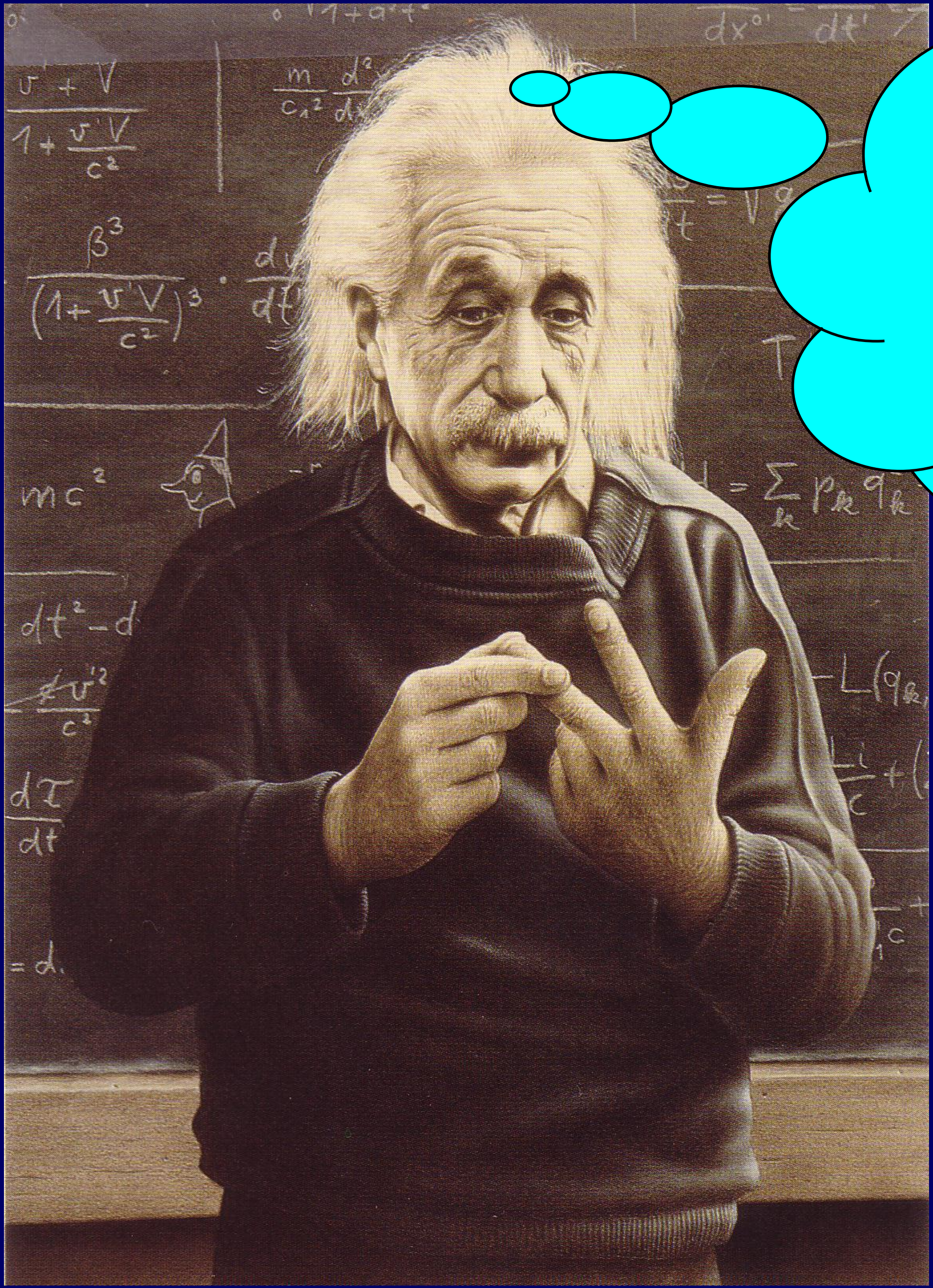
$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G\rho_{m0}}{3a^3} - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$\boxed{\Omega_\Lambda > 0}$$



$$\Omega_m + \Omega_\Lambda = 1 - \Omega_k$$

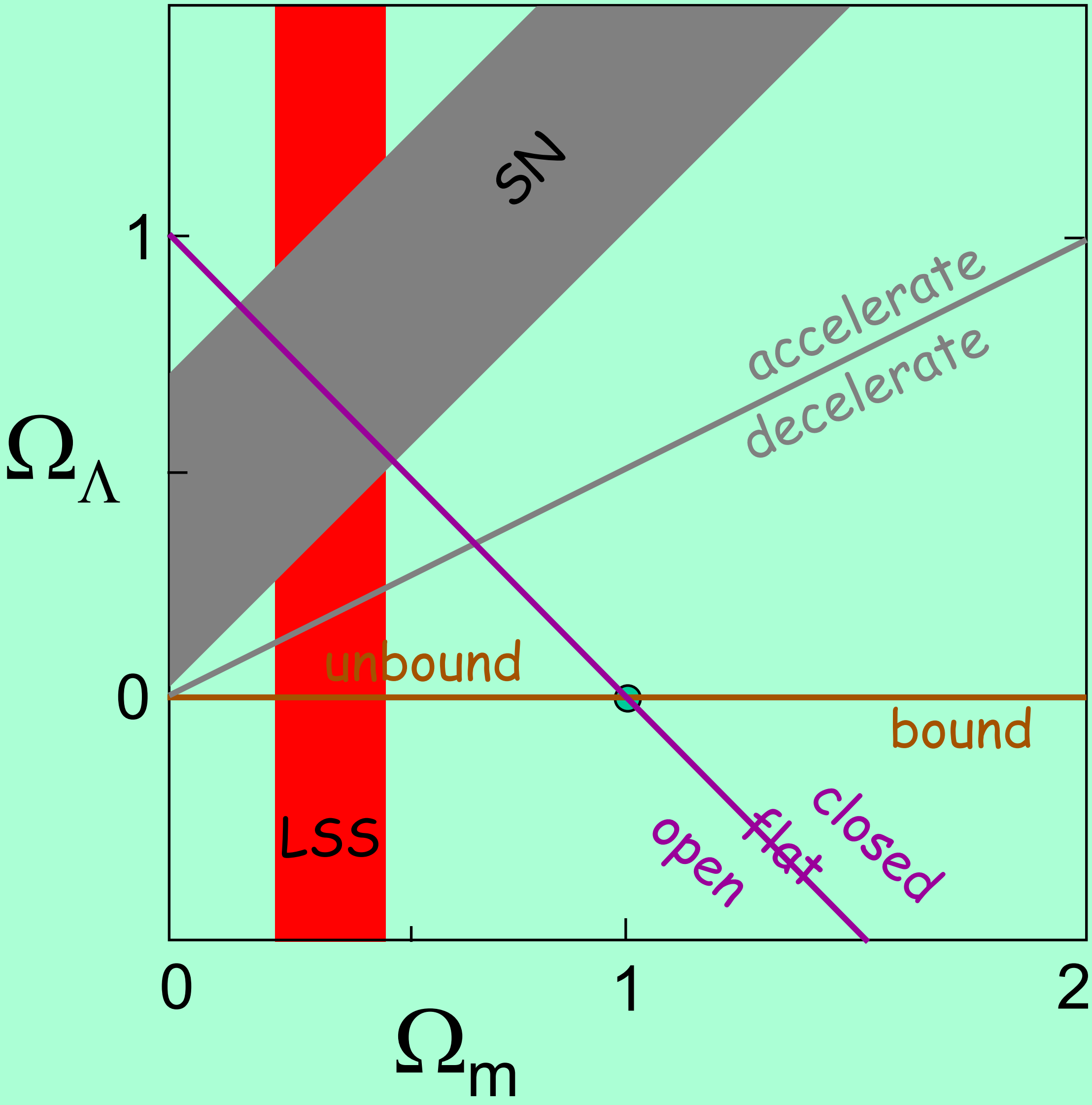
$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}\Omega_m - \Omega_\Lambda$$



Cosmological constant?... No cosmological constant?...

The static universe of Einstein: the vacuum repulsion balances the gravitational attraction.

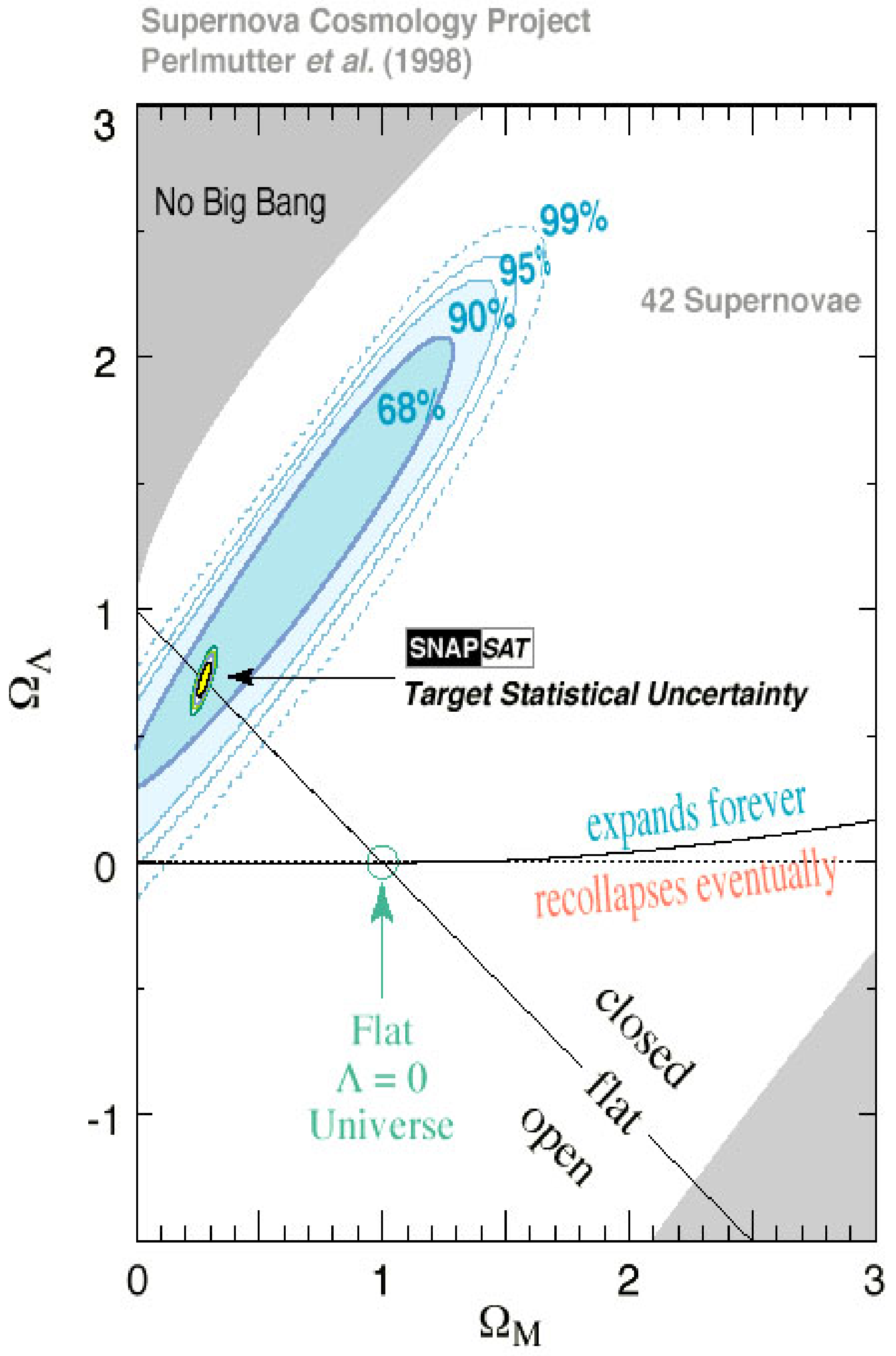
Cosmological Parameters



Vacuum Energy

$$\Omega_\Lambda = 0.7 \pm 0.05 \geq \Omega_m$$

repulsion → acceleration



Future SN Cosmology Project

Generalized Dark Energy

Energy conservation during expansion:

$$d(\rho_{tot} c^2 a^3) = -p\, d(a^3)$$

Cosmological constant:

$$\rho_{tot} = \rho_\Lambda = const.$$

Equation of state:

$$\rightarrow p = -\rho c^2$$

negative pressure

General eq. of state:

$$p \equiv w \rho c^2$$

e.g. Quintessence

$$w(x,t)\,?$$

$$\Lambda \quad \leftrightarrow \quad w = -1$$

$$\ddot{a} > 0 \quad \leftrightarrow \quad w < -1/3$$

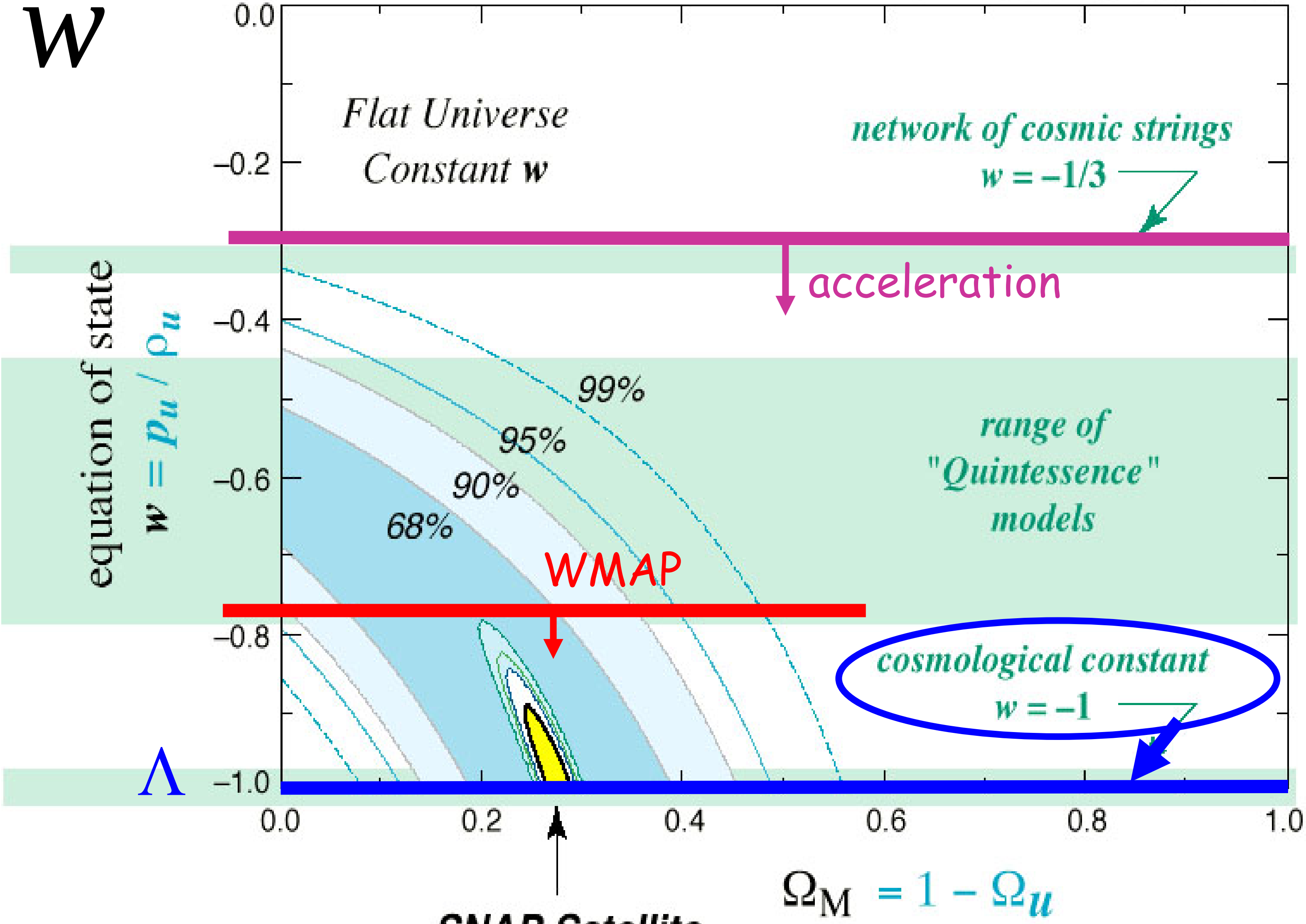
$$\text{FRW } (k=0) \qquad \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho_{tot}$$

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

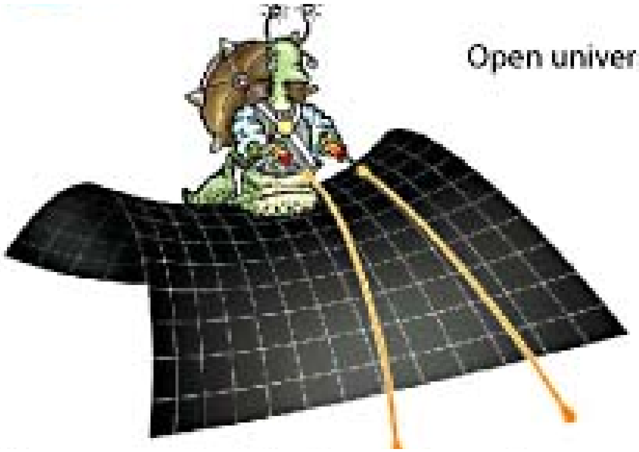
Dark Energy

w

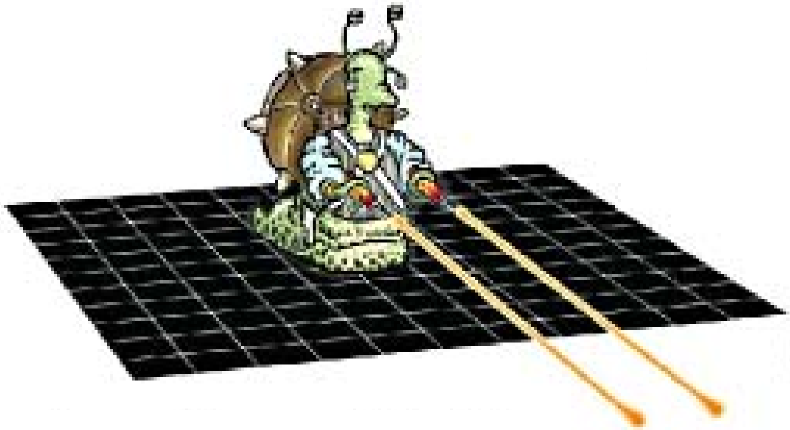
Supernova Cosmology Project
Perlmutter *et al.* (1998)



SNAP Satellite
Target Statistical Uncertainty

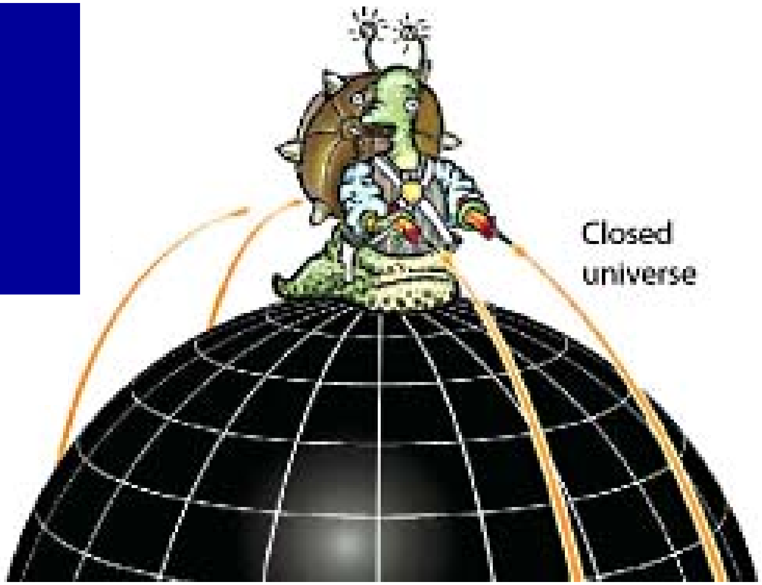


Open universe



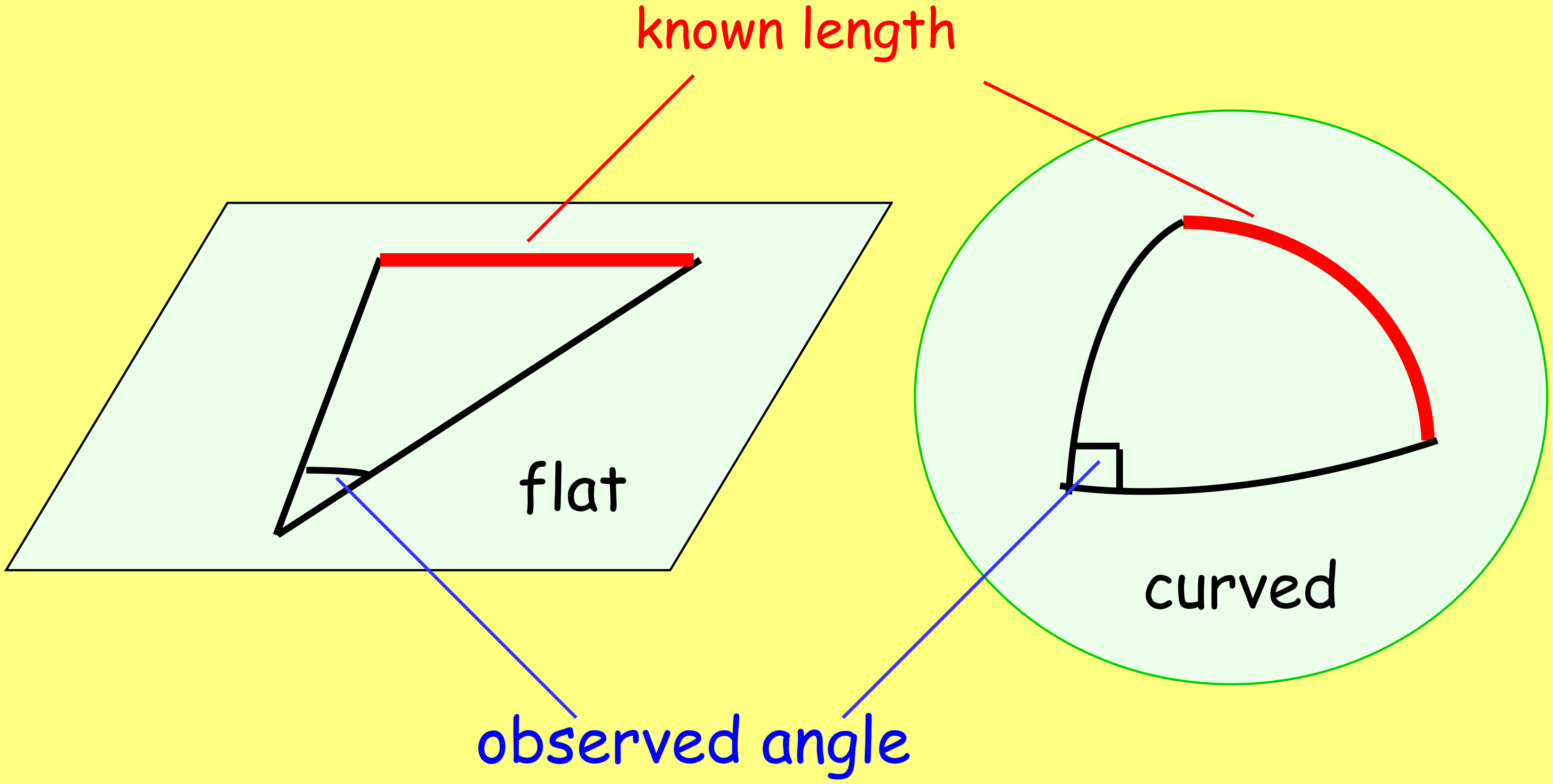
Flat universe

5. Curvature

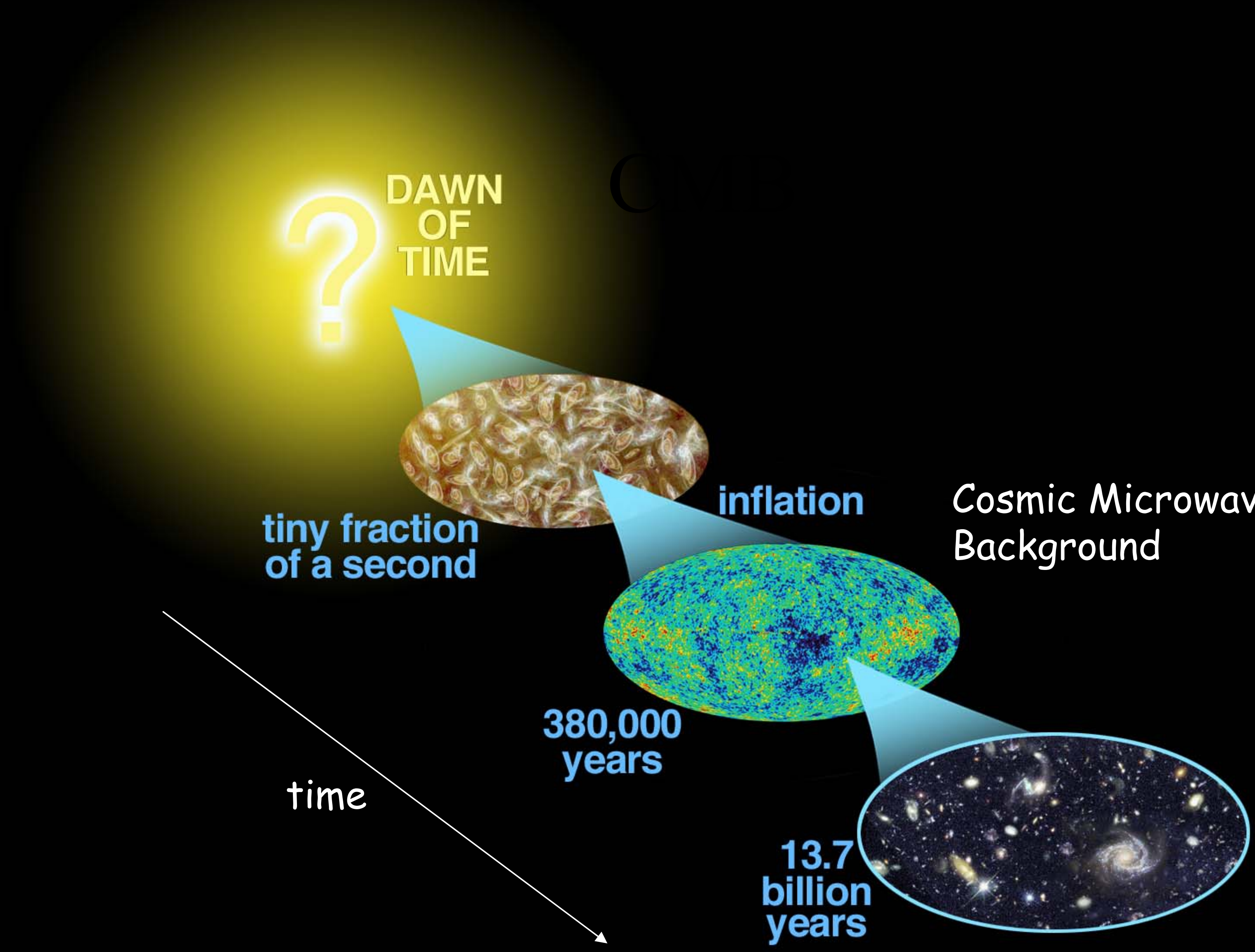


Closed universe

Measuring Curvature



CMB

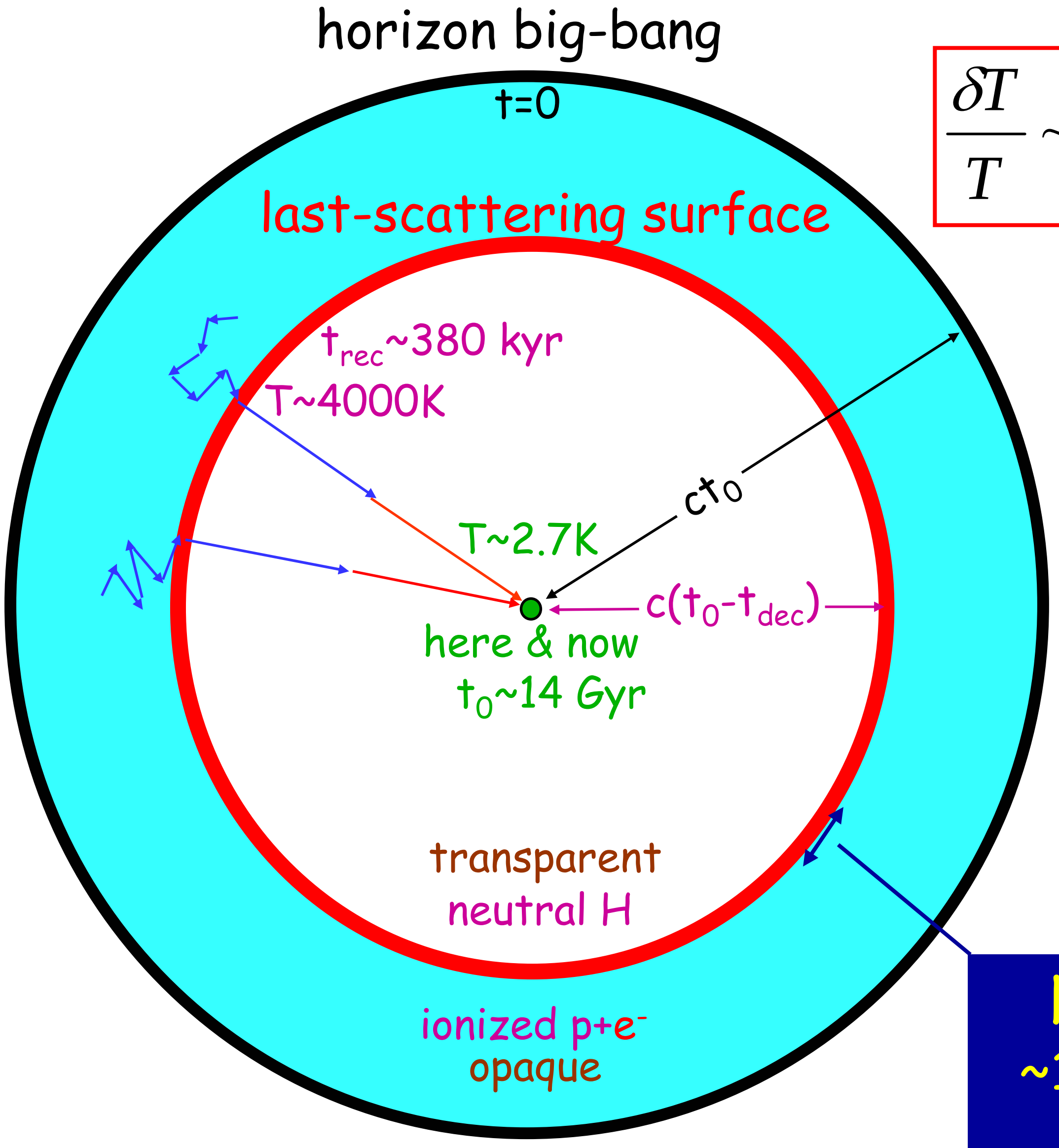


Cosmic Microwave Background

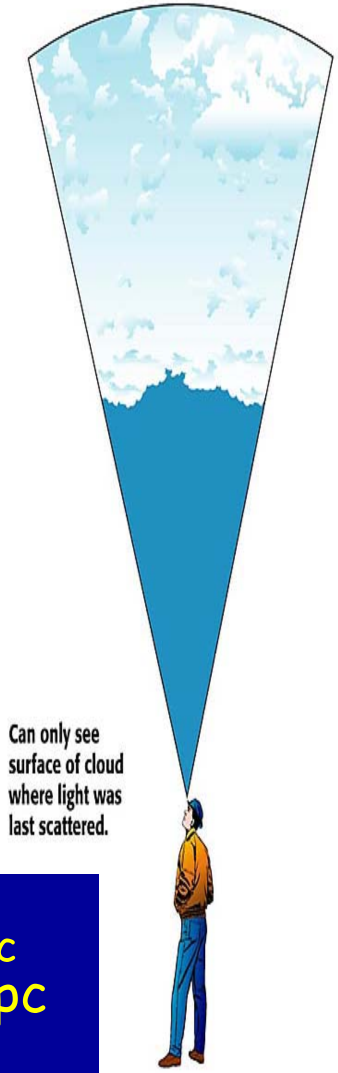
time

Origin of Cosmic Microwave Background

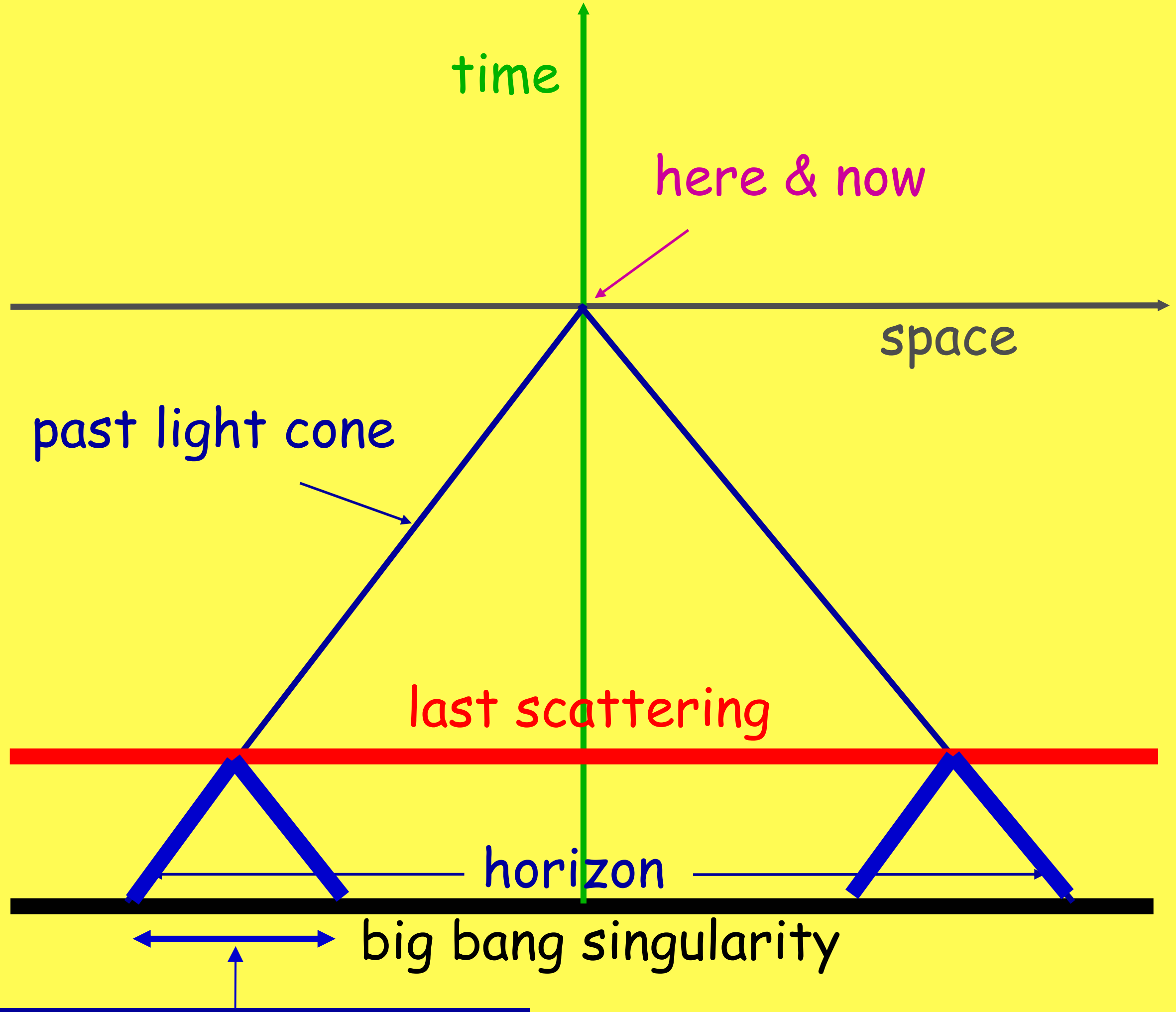
$$\frac{\delta T}{T} \sim \frac{1}{10}\frac{\delta\rho}{\rho} \sim 10^{-5}$$



horizon at t_{rec}
~100 comoving Mpc
~1°

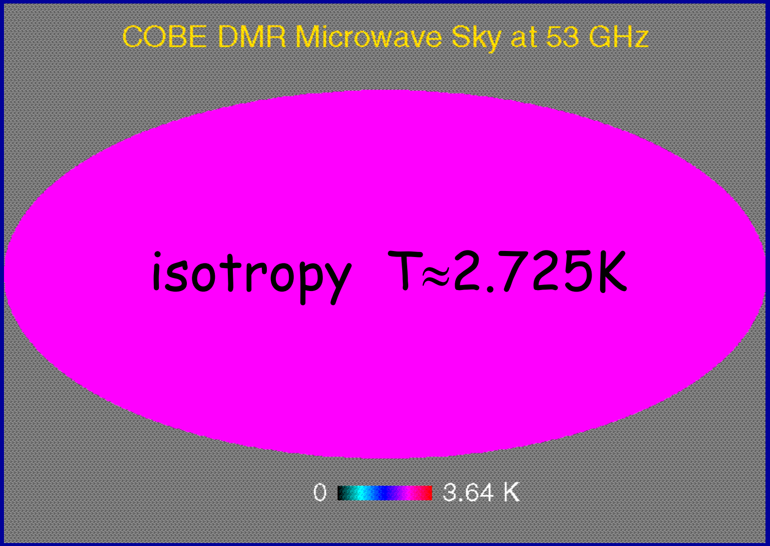


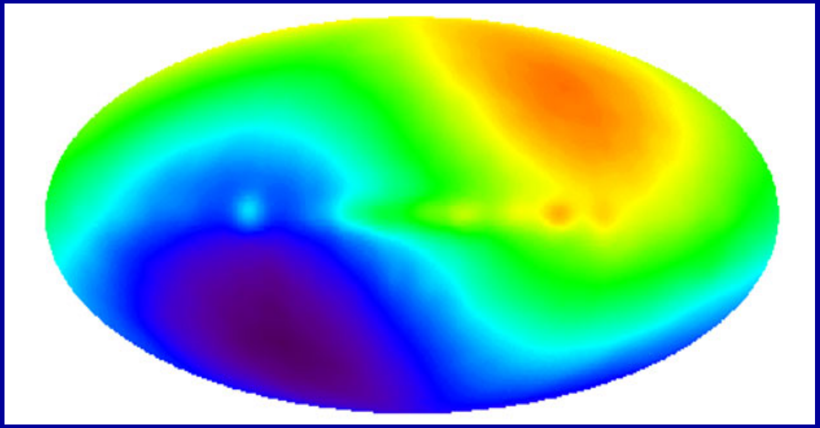
Characteristic Scale



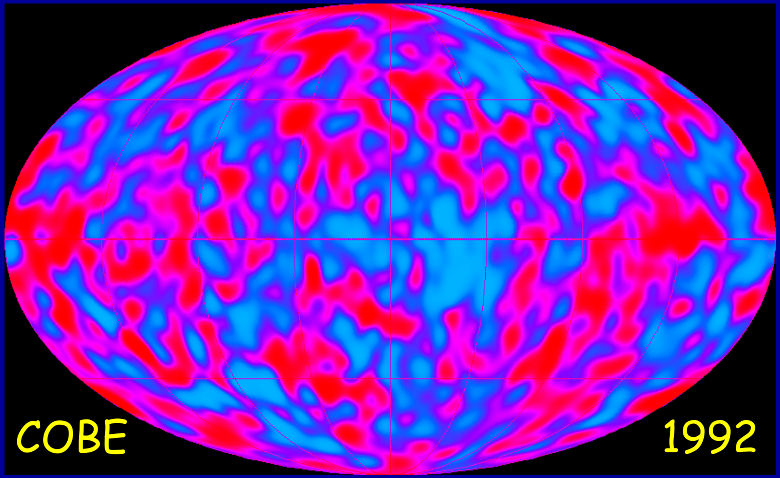
horizon at last scattering

CMB Temperature Maps

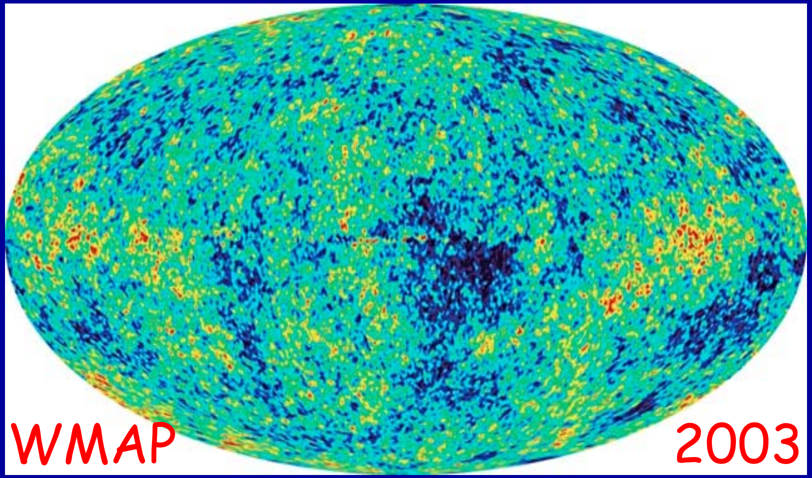




$\delta T/T \sim 10^{-3}$ dipole



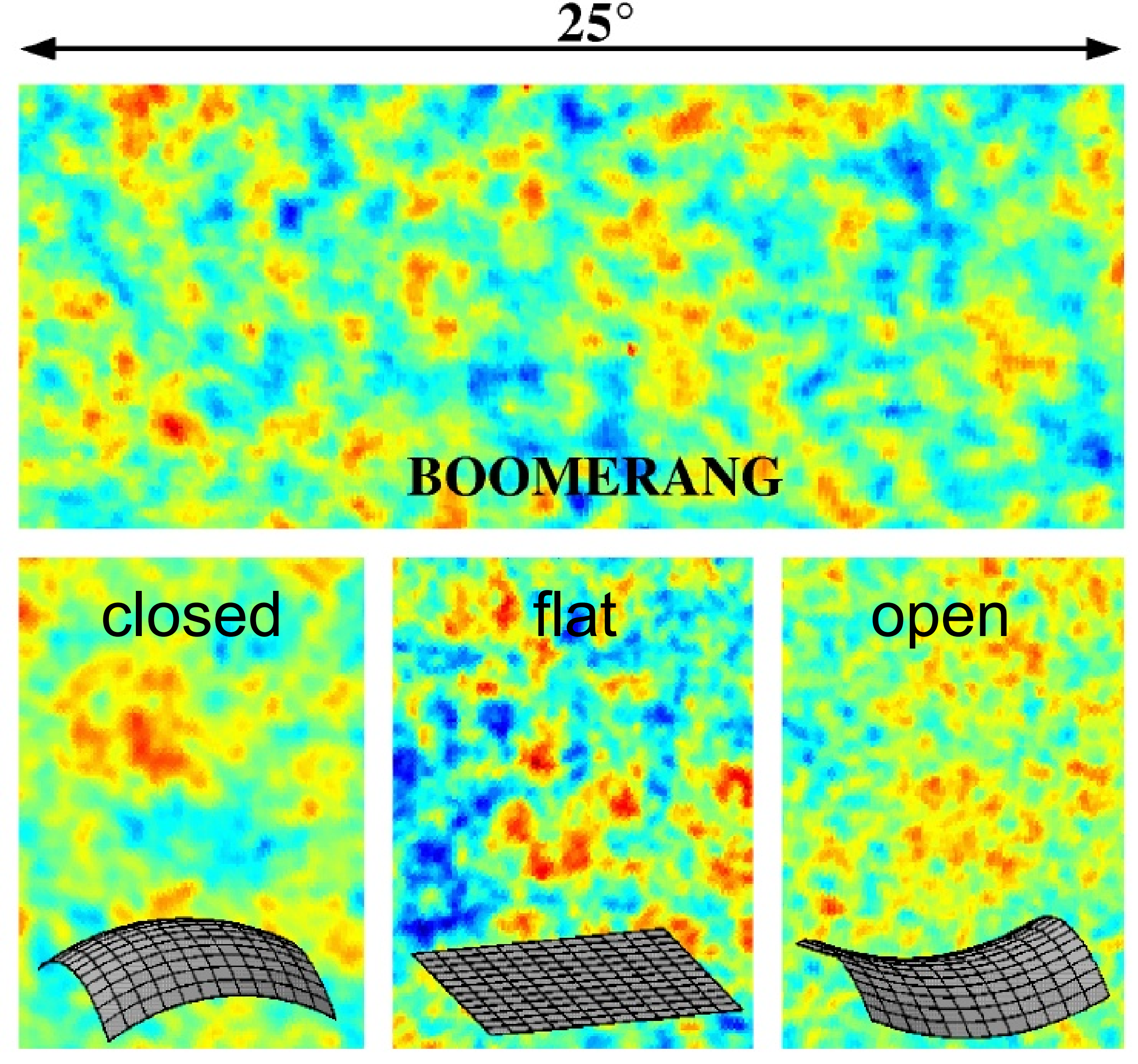
resolution ~10°



$\delta T/T \sim 10^{-5}$

resolution ~ 10′

Curvature

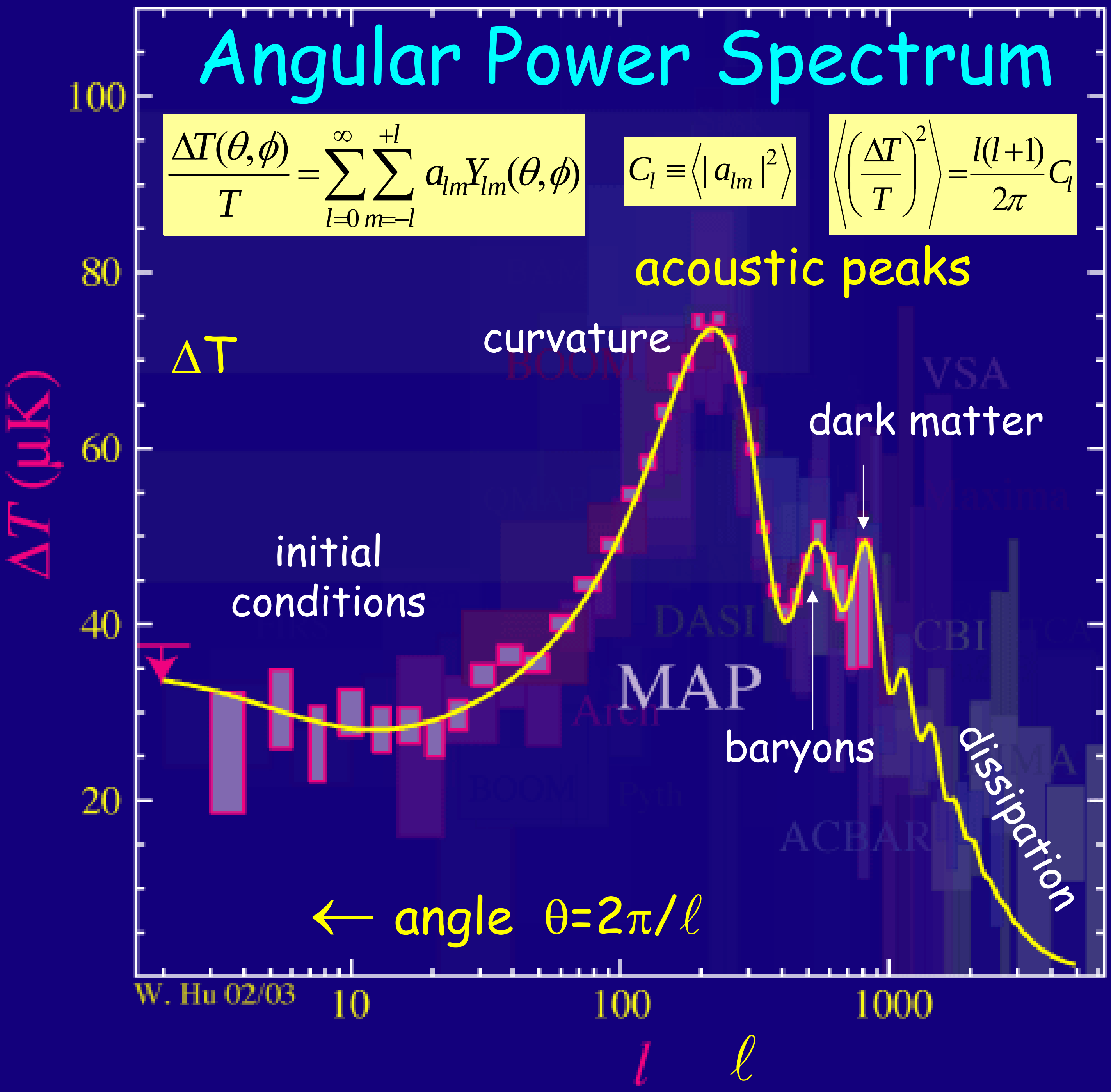


Angular Power Spectrum

$$\frac{\Delta T(\theta,\phi)}{T} = \sum_{l=0}^{\infty}\sum_{m=-l}^{+l} a_{lm}Y_{lm}(\theta,\phi)$$

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

$$\left\langle \left(\frac{\Delta T}{T}\right)^2 \right\rangle = \frac{l(l+1)}{2\pi} C_l$$



acoustic peaks

curvature

ΔT

dark matter

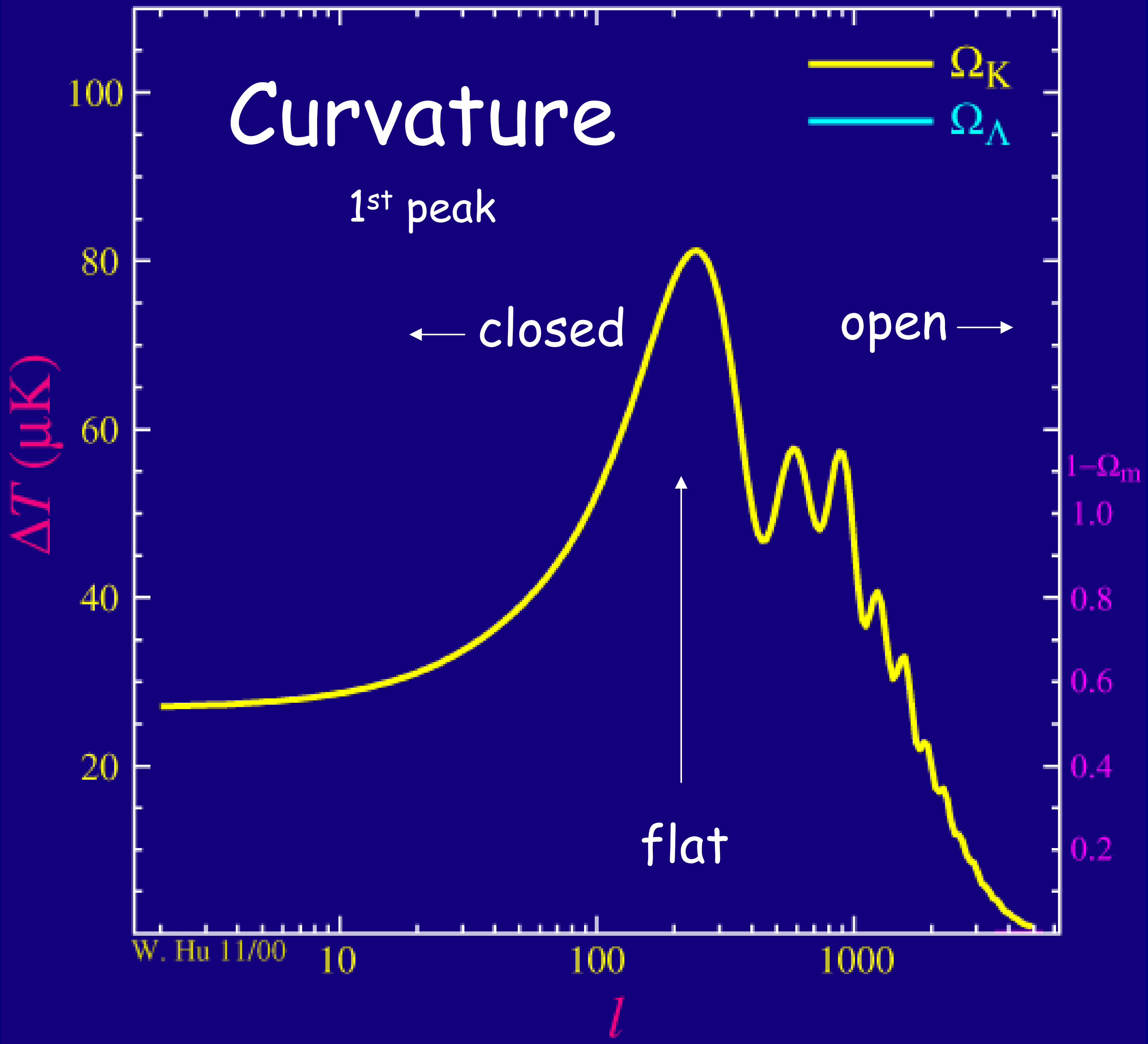
initial conditions

baryons

dissipation

← angle θ=2π/ℓ

Curvature


1st peak
closed
open
flat
Ω_K
Ω_Λ
100
80
60
40
20
ΔT (μK)
$1-\Omega_m$
1.0
0.8
0.6
0.4
0.2
W. Hu 11/00
10
100
1000
l

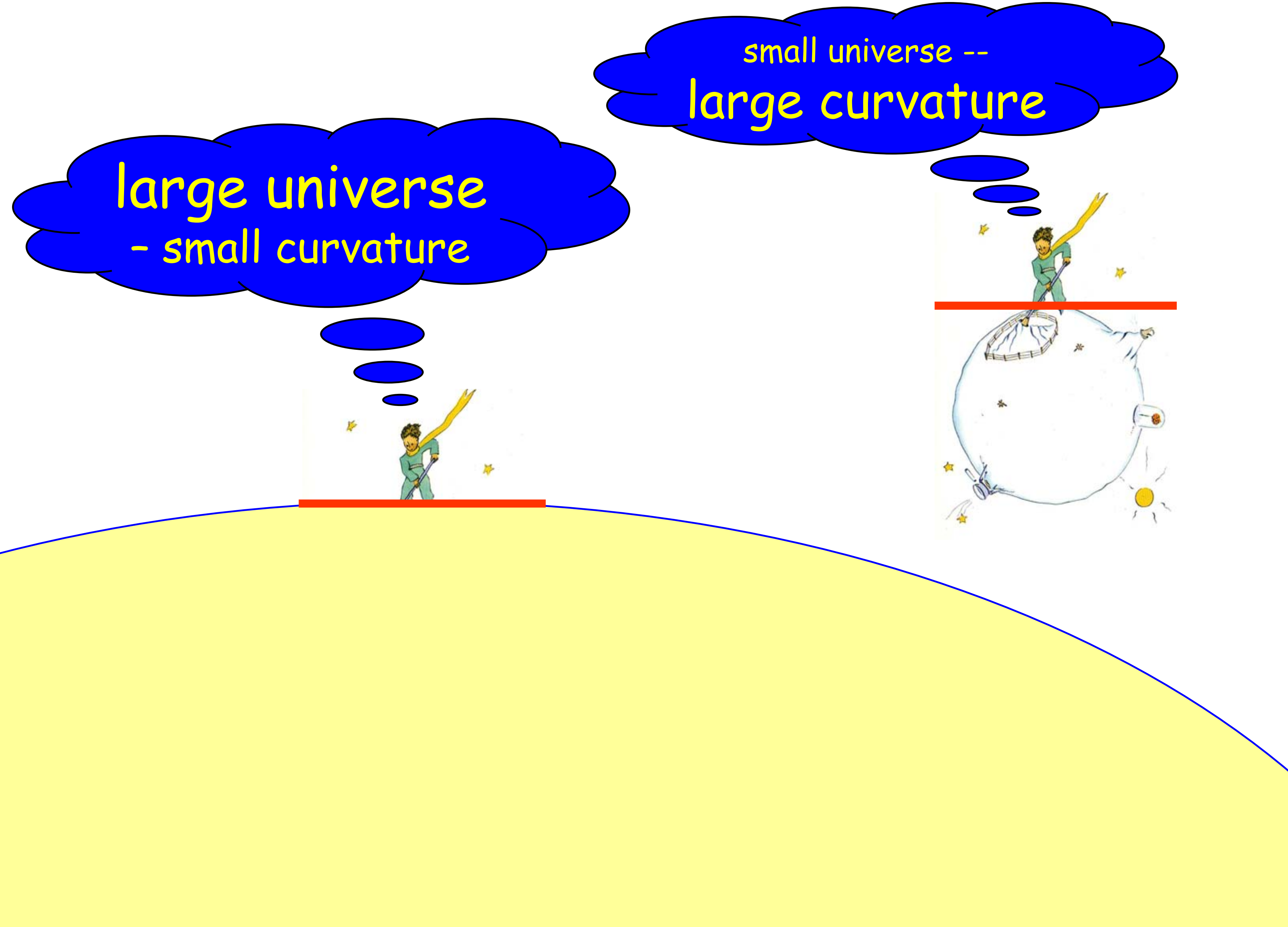
Curvature

The Universe is nearly flat:

$$\boxed{1-\Omega_k=\Omega_{\mathrm{m}}+\Omega_\Lambda=1.02\pm0.02}$$

Open? Closed?

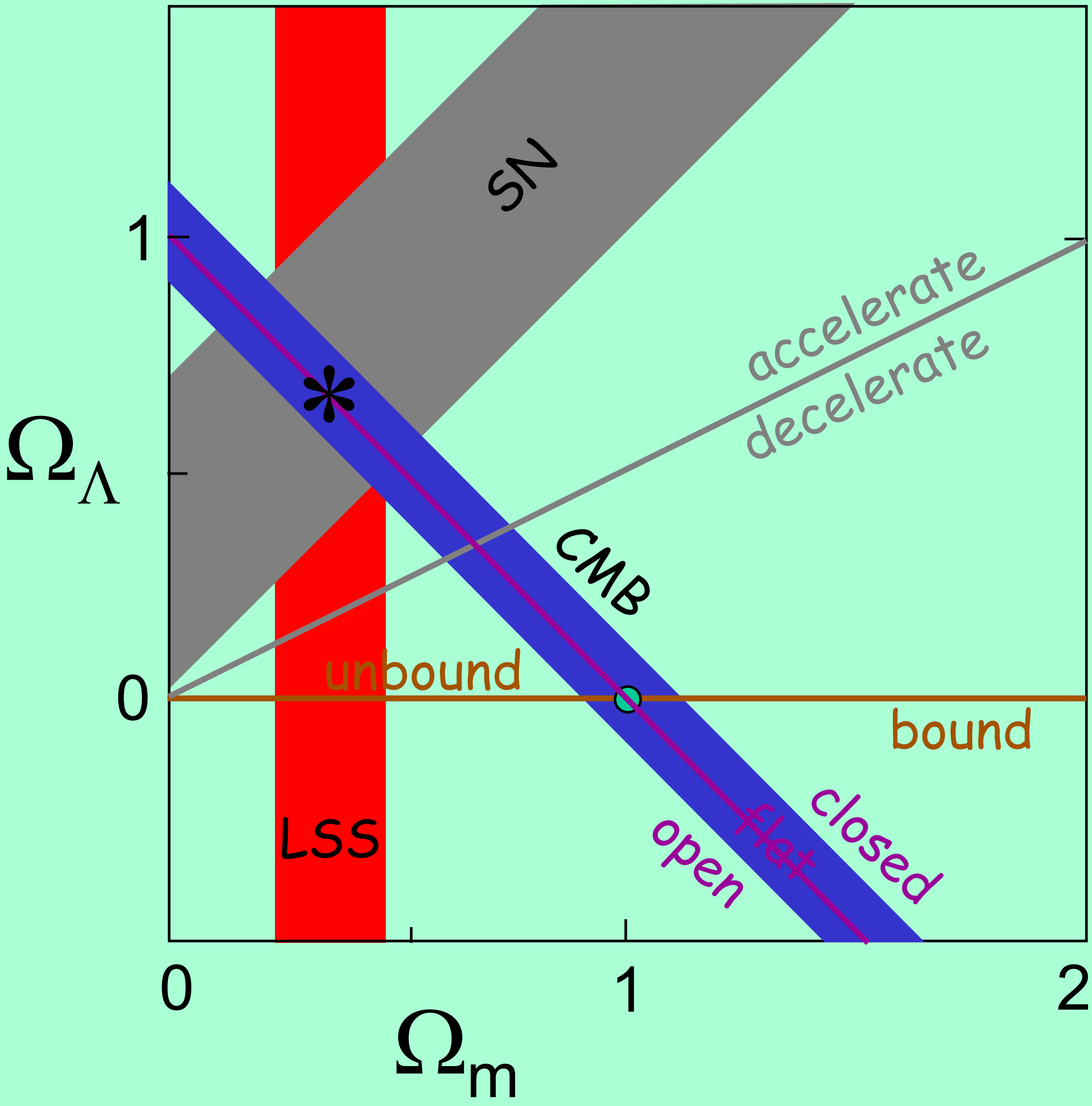
Surely much larger than our horizon!



large universe
- small curvature

small universe --
large curvature

Cosmological Parameters



Our Universe

Nearly flat: $\Omega_{\mathrm{tot}} = 1.02 \pm 0.02$

but a bizzare mixture:

$$\Omega_{\mathrm{luminous}} \approx 0.01$$

$$\Omega_{\mathrm{baryons}} = 0.044 \pm 0.004$$

$$\Omega_{\mathrm{mass}} = 0.30 \pm 0.05$$

$$\Omega_{\Lambda} = 0.70 \pm 0.05$$

5% baryons, 25% dark matter, 70% dark energy

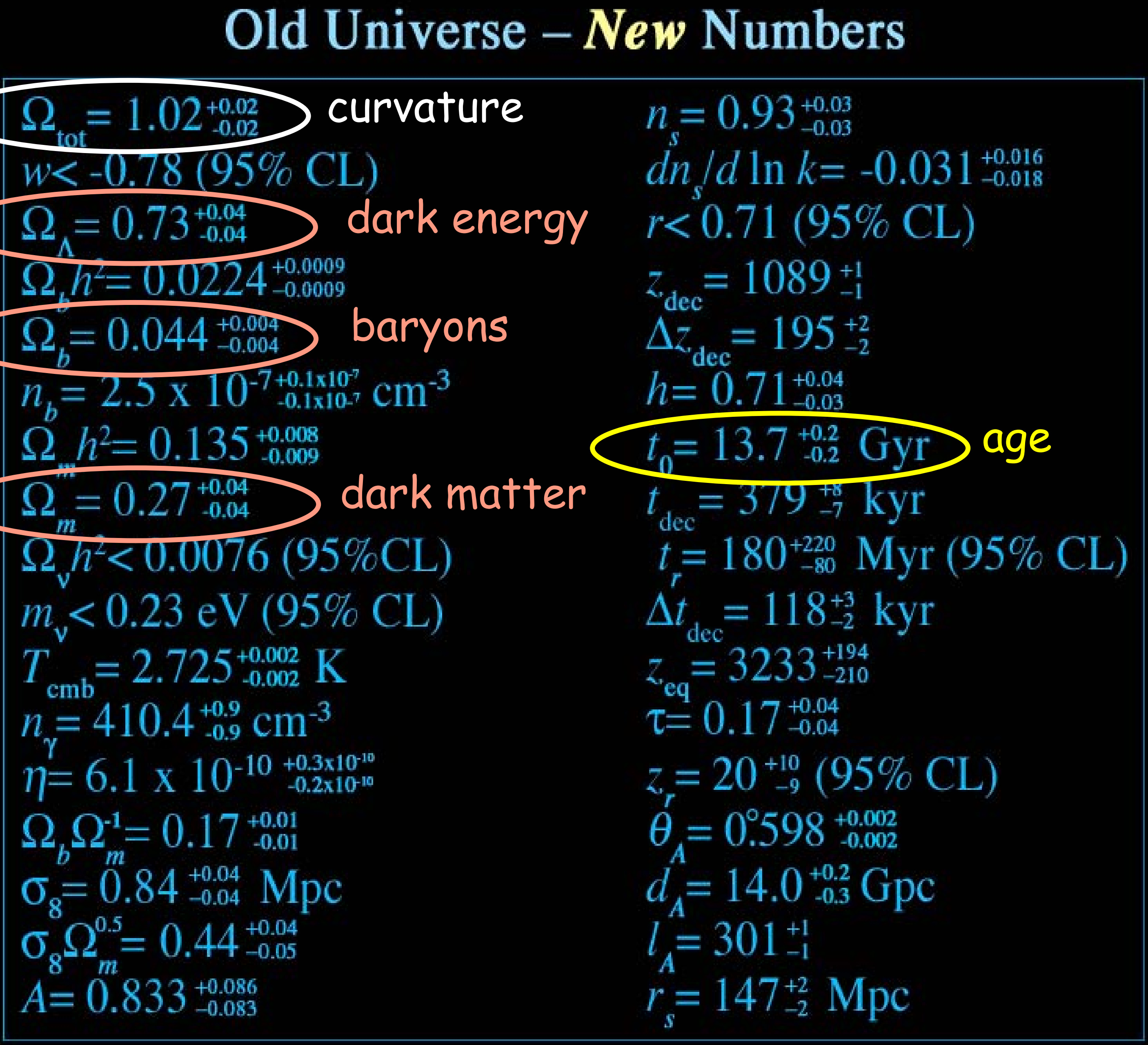
Our Universe

Luminous matter	1%	attractive
Dark baryonic matter	4%	
Dark matter – exotic particles	25%	
Dark energy	70%	repulsive

Expansion forever!
accelerated by the repulsion of the vacuum

From measurements of anisotropy in the Cosmic Microwave Background:
Eulidean geometry in the observable volume – the universe is open or closed but very BIG!

Cosmological Parameters by WMAP



Old Universe – *New* Numbers

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$ curvature

$w < -0.78$ (95% CL)

$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$ dark energy

$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$

$\Omega_b = 0.044^{+0.004}_{-0.004}$ baryons

$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}

$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$

$\Omega_m = 0.27^{+0.04}_{-0.04}$ dark matter

$\Omega_\nu h^2 < 0.0076$ (95%CL)

$m_\nu < 0.23$ eV (95% CL)

$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K

$n_\gamma = 410.4^{+0.9}_{-0.9}$ cm^{-3}

$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$

$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$

$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc

$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$

$A = 0.833^{+0.086}_{-0.083}$

$n_s = 0.93^{+0.03}_{-0.03}$

$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$

$r < 0.71$ (95% CL)

$z_{dec} = 1089^{+1}_{-1}$

$\Delta z_{dec} = 195^{+2}_{-2}$

$h = 0.71^{+0.04}_{-0.03}$

$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr age

$t_{dec} = 379^{+8}_{-7}$ kyr

$t_r = 180^{+220}_{-80}$ Myr (95% CL)

$\Delta t_{dec} = 118^{+3}_{-2}$ kyr

$z_{eq} = 3233^{+194}_{-210}$

$\tau = 0.17^{+0.04}_{-0.04}$

$z_r = 20^{+10}_{-9}$ (95% CL)

$\theta_A = 0.^\circ598^{+0.002}_{-0.002}$

$d_A = 14.0^{+0.2}_{-0.3}$ Gpc

$l_A = 301^{+1}_{-1}$

$r_s = 147^{+2}_{-2}$ Mpc