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# Observational Cosmology I

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1. Standard Cosmology: metric, dark energy

-> Taller: Cosmological measures: distance, time, mass

2. LSS: linear theory: Inflation, P(k), CMB
3. LSS: Non-linear theory: Spherical collapse, PS, N-body, Non-gaussianity, CMB

# General Relativity (GR) & Cosmology

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1+kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right]$$

a(t) = scale factor
=1/(1+z)    (a_0 = 1 )

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

Einstein's Field Eq.
R = curvature/metric
T = matter content

Inflation?

# General Relativity (GR) & Cosmology

Hubble Cte (Friedman Eq)
$\rho$ = energy density = $\rho_M + \rho_R$
k = curvature sign
$\Lambda$ = cosmological constant

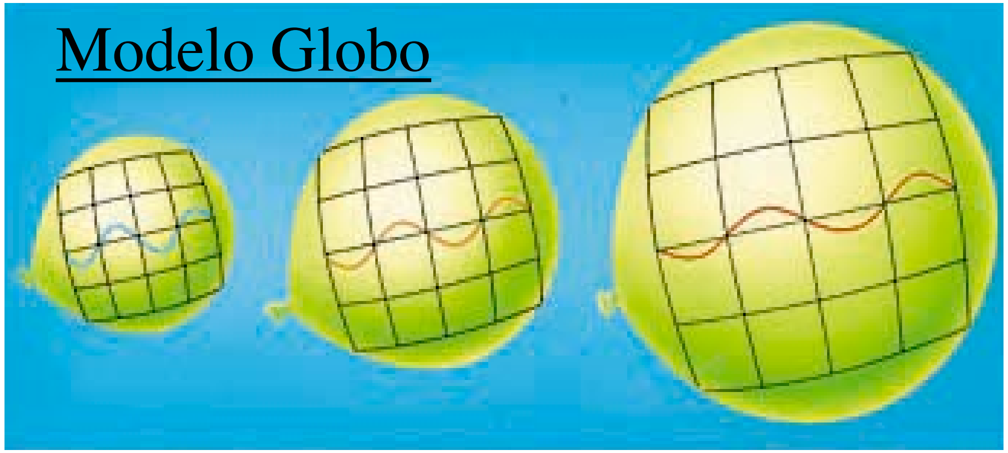
$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G\rho}{3} + \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$H^2 = H_0^2 \left[ \Omega_M \, a^{-3} + \Omega_R \, a^{-4} + \Omega_k \, a^{-2} + \Omega_\Lambda \right]$$

$$D_\theta = \frac{2c}{H_0} \left[ (1+z)^{-1} - (1+z)^{-3/2} \right]$$

$$D_L = = \frac{2c}{H_0} \left[ 1 + z - \sqrt{1+z} \right]$$

# Modelos de Expansión

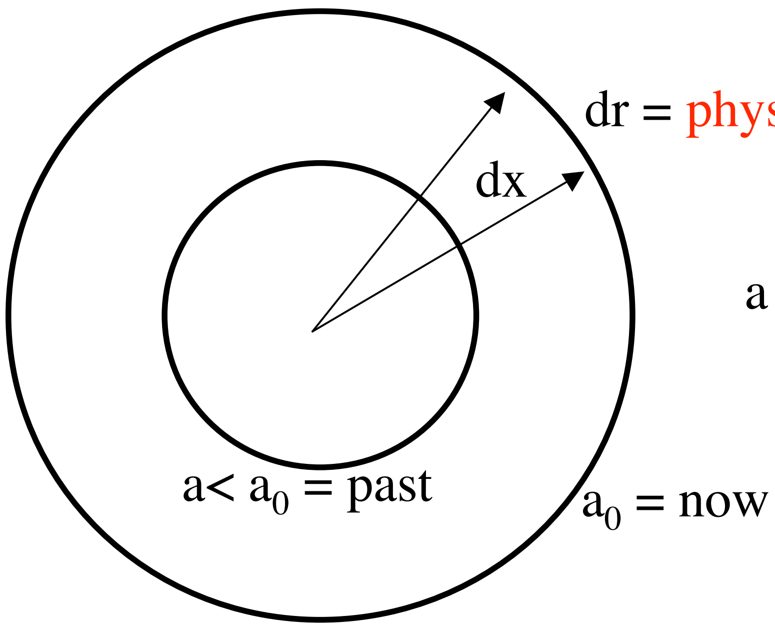




Modelo Bizcocho con pasas

# Scale Factor

2D (1D) illustration

dx = dχ = co-moving coordenate




dr = physical distance = a(t) dx

a = scale factor or radius (4D) = a(t)

$a_0$ = now = 1 => $dr_0$ = dx
(co-moving coordenates = physical coordenates today)

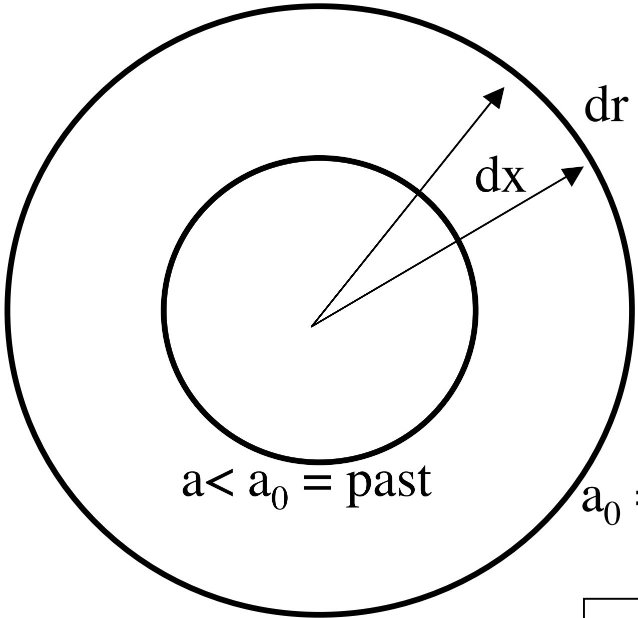
**=> a(t) is observable! => a = dr/$dr_0$ = 1/(1+z)**

$z = (\lambda' - \lambda) / \lambda$

# Metric

2D (1D) illustration

$dx = d\chi$ = co-moving coordenate




$dr$ = physical distance = $a(t)\,dx$

$a_0$ = now

$a$ = scale factor or radius (4D) = $a(t)$

$a_0$ = now = 1 => $dr_0 = dx$
(co-moving coordenates = physical coordenates today)

General Relativy

Proper time: $ds^2 = c^2dt^2 - dr^2 = c^2dt^2 - a^2\,dx^2$

Space-like (simultaneous) events: $dt=0 \rightarrow ds^2 = -\,dr^2 = -\,a^2\,dx^2$

Time-like events: $dx=0 \rightarrow ds^2 = c^2dt^2$

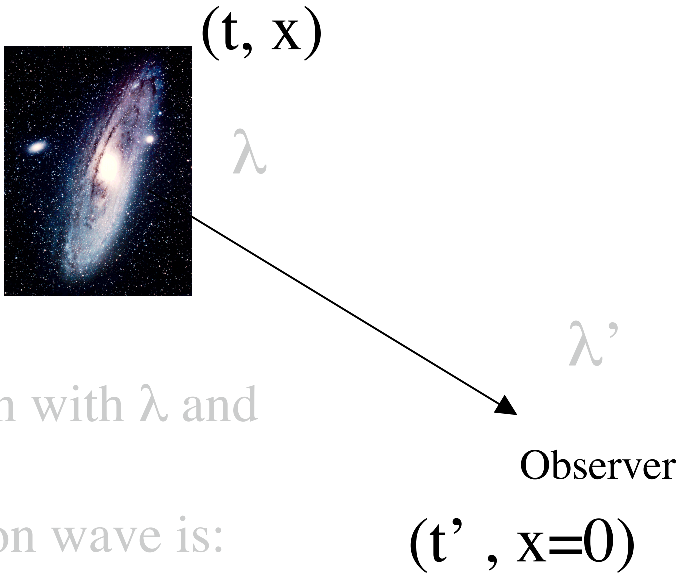
Comovil events: $dx/dt=0$

light-like events: $ds^2=0$

# Redshift

z =redshift coordinate => $1+z = a_0/a = 1/a$

dr = physical distance = a(t) dx




Consider 2 comovil events: emission (t,x) of a photon with λ and its reception (t', x=0).
The time between 2 consecutive maxima in the photon wave is:
dt= c λ at emission and dt'= c λ' at reception.

These events are light-like: $ds^2 = 0 = c^2dt^2 - a^2 dx^2$

Both maxima travel the same comovil distance x

$$x = \int dx = \int_t^{t'} c\, dt/a = \int_{t+dt}^{t'+dt'} c\, dt/a \quad \Rightarrow$$

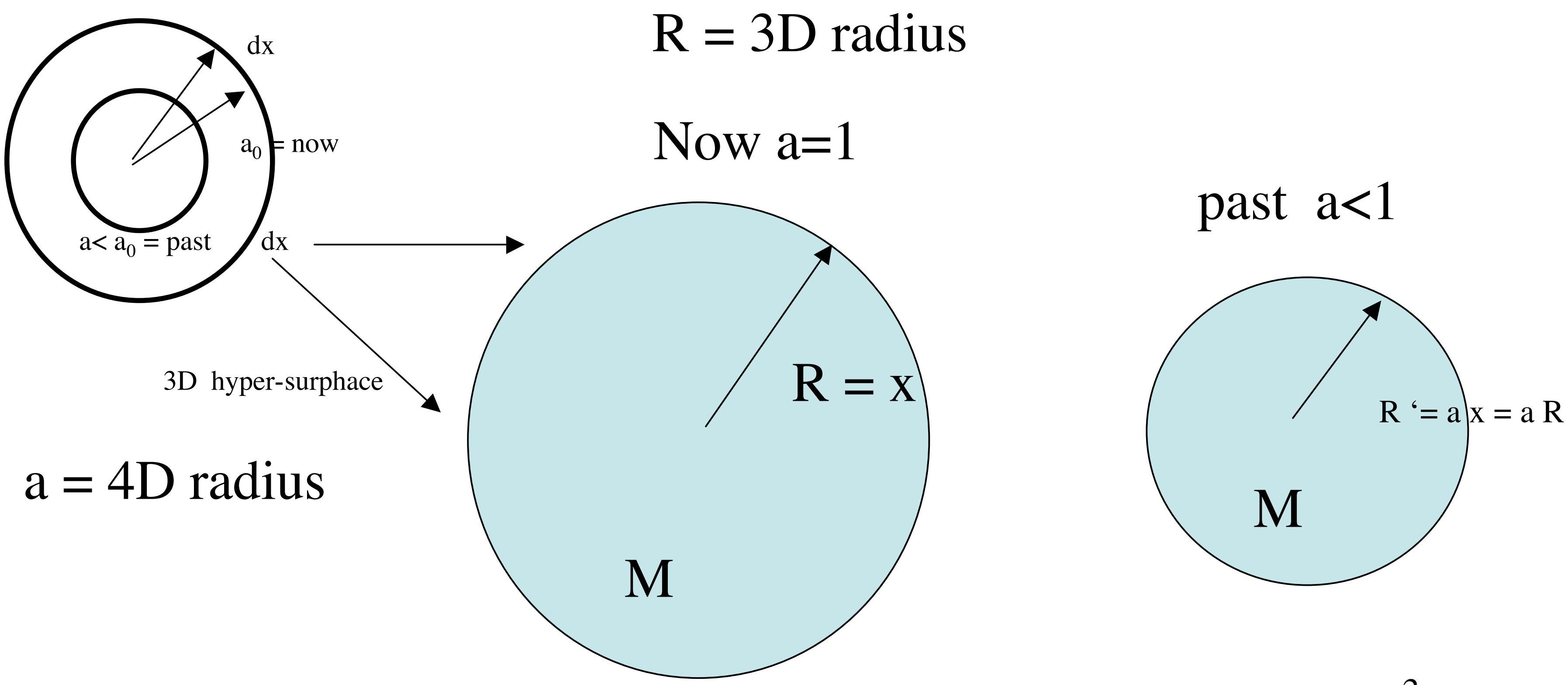
$\Rightarrow dt/dt' = a/a' = \lambda/\lambda' \Rightarrow$ $1+z \equiv \lambda'/\lambda = a'/a = 1/a$

⇒ the change in frequency only depends on the ratio of scale factor "a" at emission and reception.

# Energy & density

2D (1D) illustration

Matter contend: radiation dominates in the past (a -> 0)



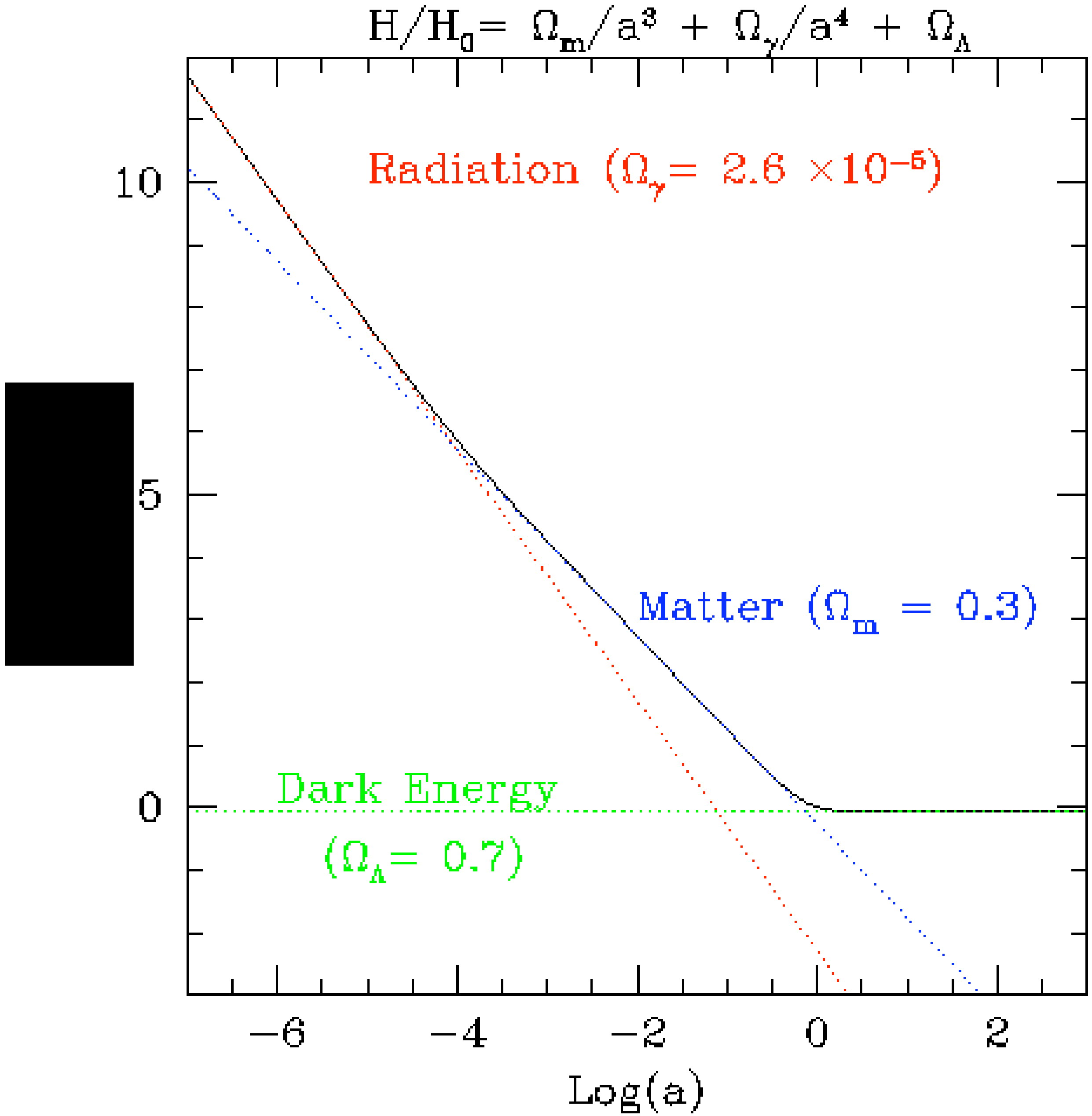

$\rho_0 = M/\ (4/3\ \pi\ R^3)$

$\rho = \rho_0\ a^{-3}$

radiation is also redshifted **=>** $\mathbf{E(t) = E_0\ a^{-4}}$

**(Universe was hotter and denser)**

$$\rho_{\mathbf{m}}\, a^{-3} + \rho_{\mathbf{R}}\, a^{-4} + \rho_{\mathbf{k}}$$

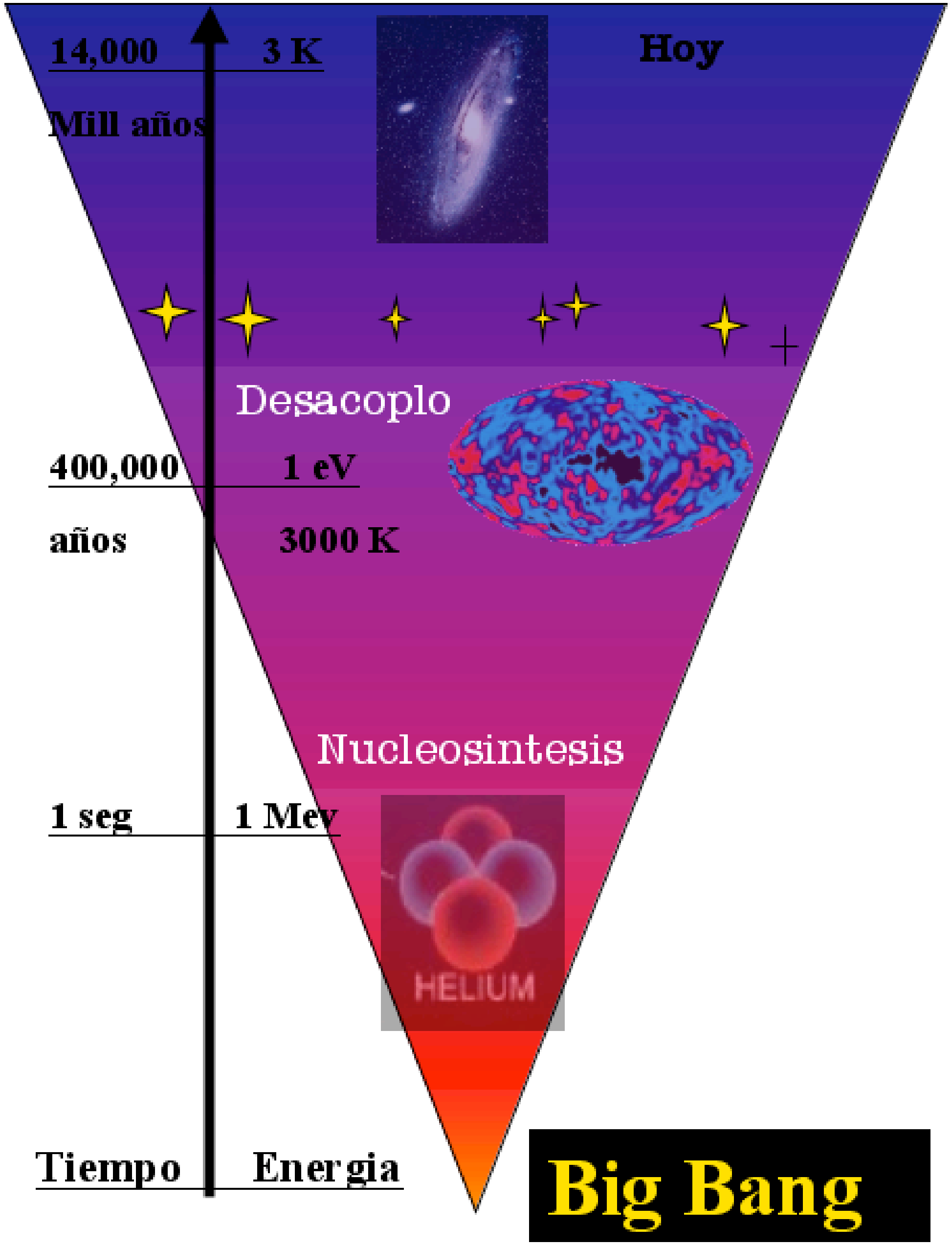


Predicciones del modelo

*Big Bang:*

# ÁTOMOS

El universo está lleno de una radiación de fondo cuya temperatura es unos grados encima del cero absoluto. Cuando se formaron los átomos neutros (aproximadamente 400,000 anyos después del Big Bang), la radiación electromagnética esencialmente paró su interacción con la materia. La expansión de espacio enfrió la radiación de su valor inicial de aproximadamente 3000 K a su presente bajo valor de 3K



# Hubble law

x = co-moving coordenate    r = physical distance = a(t) x

a = scale factor or radius (4D) = a(t)

$r = a(t)\ x \quad \Rightarrow \quad v = dr/dt = r' = \quad a'\ x \quad + \quad a\ x'$

total v = (expansion v.) x da/dt + (proper v.) a dx/dt

Observer

I

if there is no proper motion (comovil events) dx/dt=0 or <dx/dt>=0 :

$$v = a'\ x = (a'/a)\ r$$

**v = H(t) r ( Hubble law)**

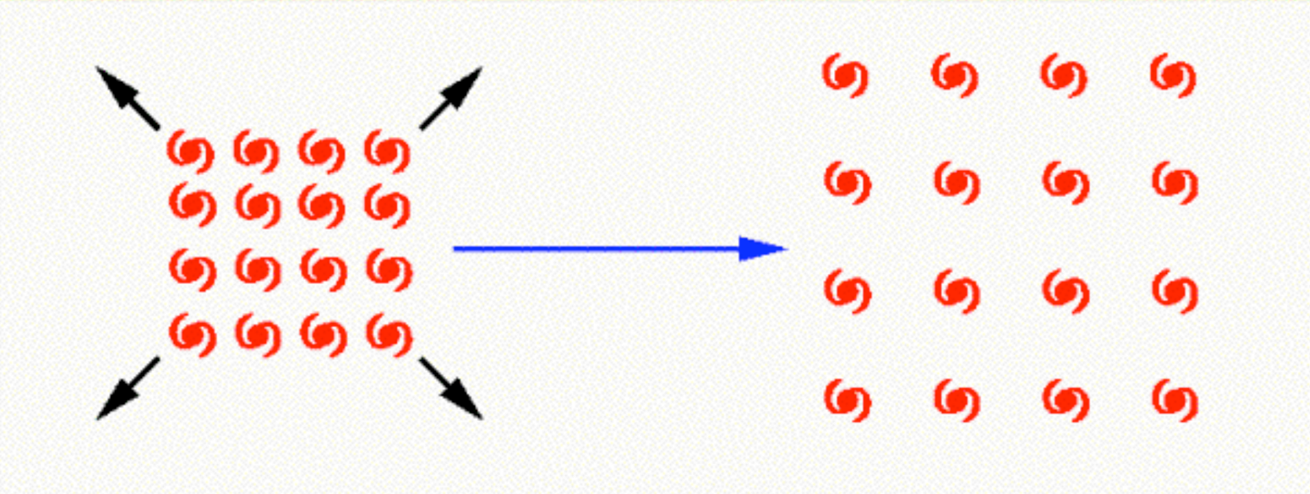
Hubble "constant": $H \equiv a'/a = (da/dt)/a$

Expansion

# Hubble's Law

$$V = cz = Hd \quad (H = 70\ \mathrm{km\ s^{-1}\ Mpc^{-1}} \pm 10\%)$$

Recession velocity proportional to distance



- Get Hubble's law if the galaxy distribution expands uniformly
- No outside to the expansion

# Measure Hubble constant

**$v = H(t)\ r$ ( Hubble law)**

Hubble "constant": $H \equiv a'/a = (da/dt)/a$

How to masure it?

$z = (\lambda' - \lambda)/\lambda = \Delta\lambda/\lambda = \Delta a/a = H\ \delta t = H\ (r/c)$

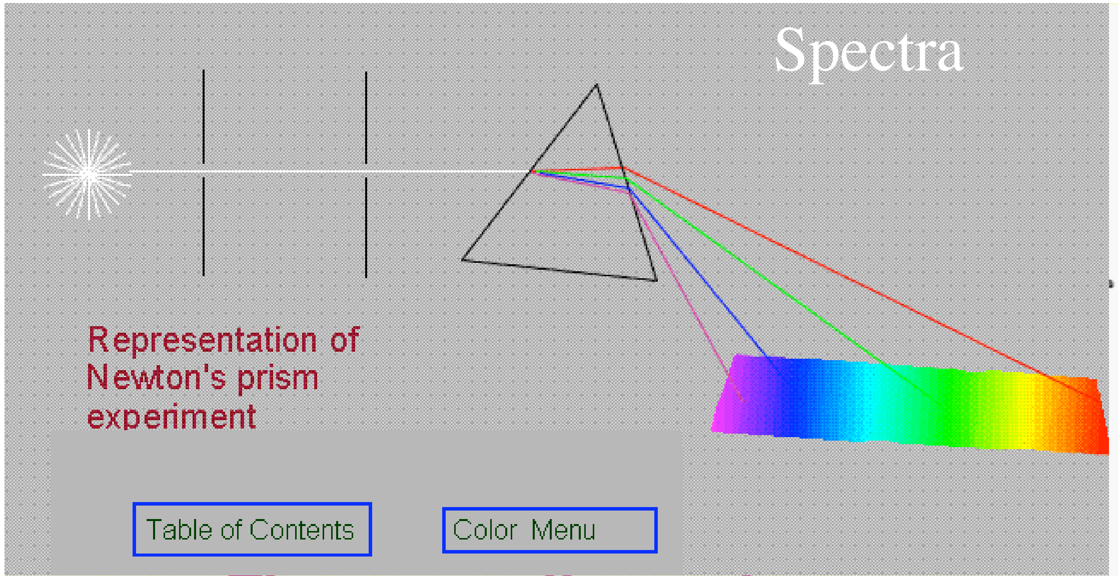
$c = r/\delta t$

Observer

–> $H = z\,c/r = v/r$

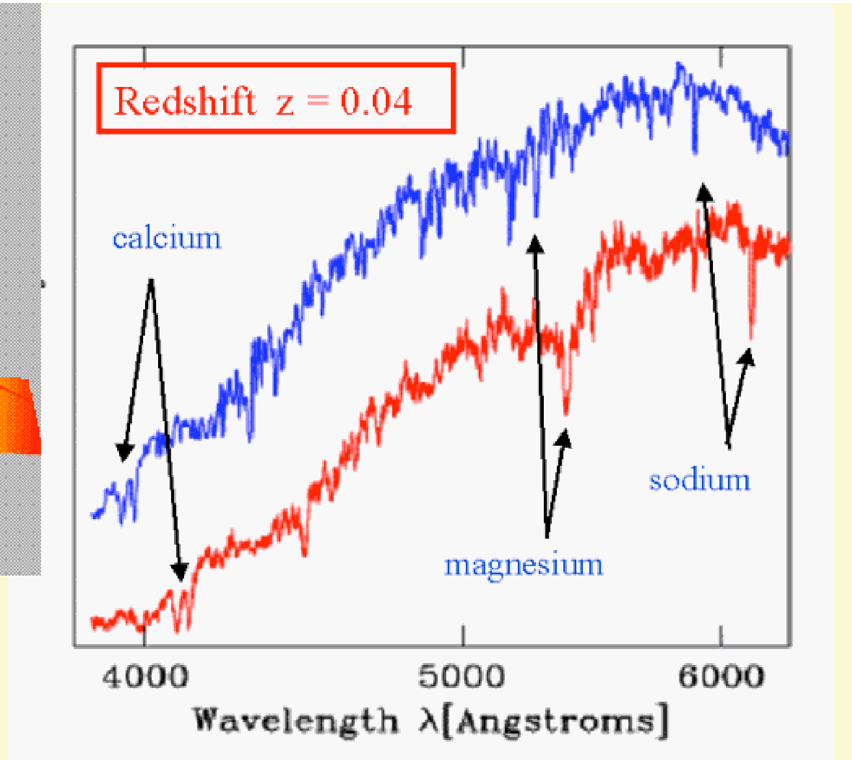
**=> $a = 1/(1+z)$ is observable! + (a') $H(t)$ is observable = r/zc**

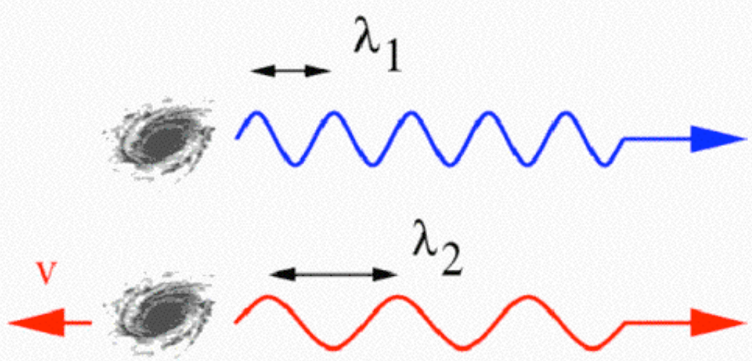
$H_0$ = value today = 70 Km/s/Mpc => Age $t = r/v = 1/H$ = 14 Gyr




# The expanding universe

1912 - 1920s: Slipher finds most galaxies are redshifted



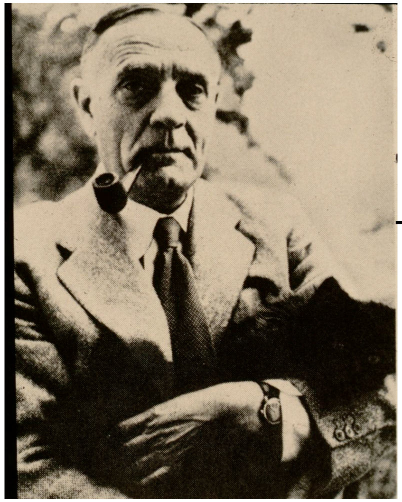




Vesto Slipher (1875 - 1969)

$$1 + z = \frac{\lambda_2}{\lambda_1} \simeq 1 + \frac{v}{c}$$

The Doppler (red)shift

# Problems to measure $H_0$



Hubble's law: (1929)

$v = cz \approx H\, d$

- initial value $H_0$= 500 Km/h/Mpc
- $H_0$ = 50 (Sandage/Tammann) ?
- $H_0$ = 100 (deVaucoulers)?

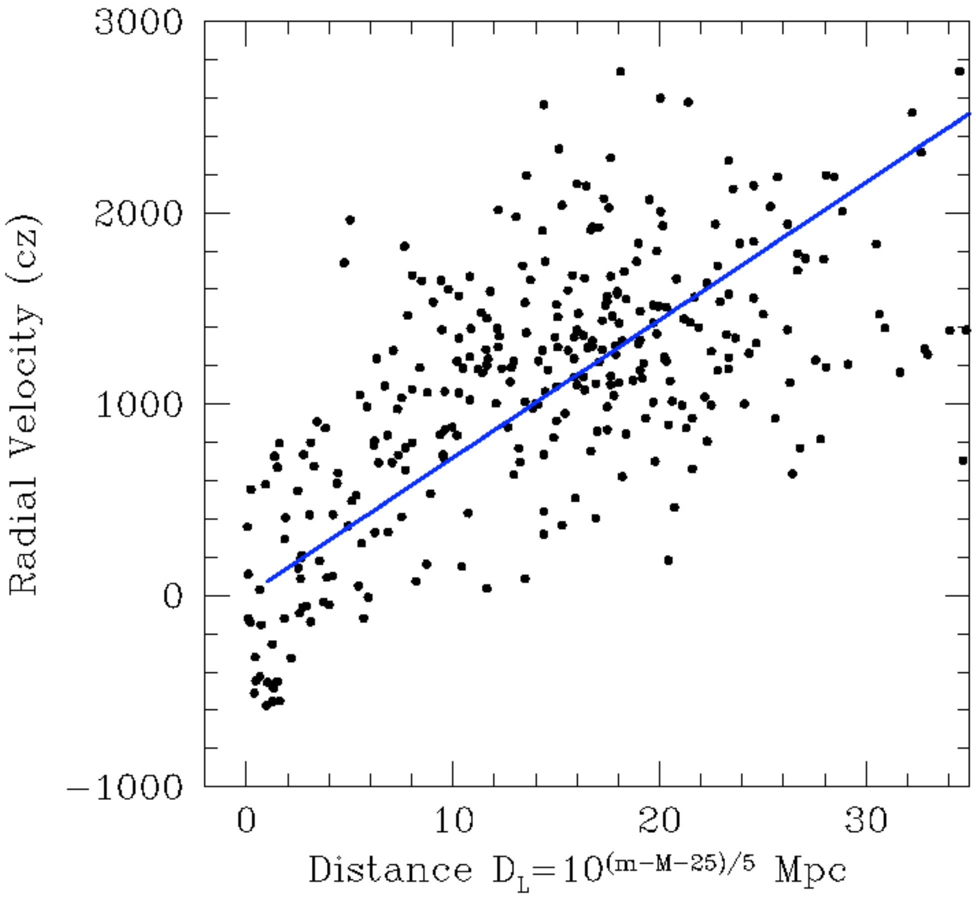
-$H_0$ = 72 ± 8 km/s/Mpc (HST)

--> h=0.72 ± 0.08 -> t0 ~ 1 /$H_0$ ~14 Gyr!

$$\rho_c \equiv \frac{3\,H_0^2}{8\pi G} \simeq 1.88 \times 10^{-29}\ h^2\ gr/cm^3$$

$$\simeq 1.06 \times 10^{4}\ h^2\ eV/cm^3$$

$$\simeq 2.78 \times 10^{11}\ h^2\ M_\odot/Mpc^3$$



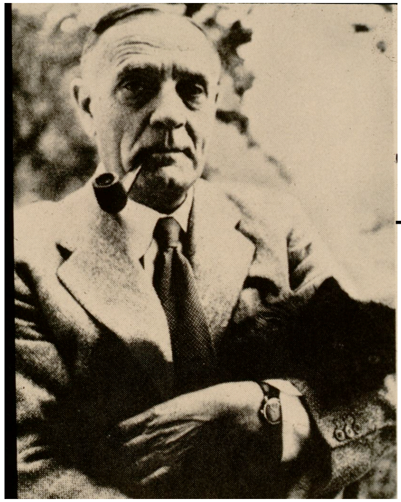

-Absolute distance callibrations are very difficult

-Scatter in distance indicators

-Peculiar velocities

-Malmquist bias

# Problems to measure $H_0$



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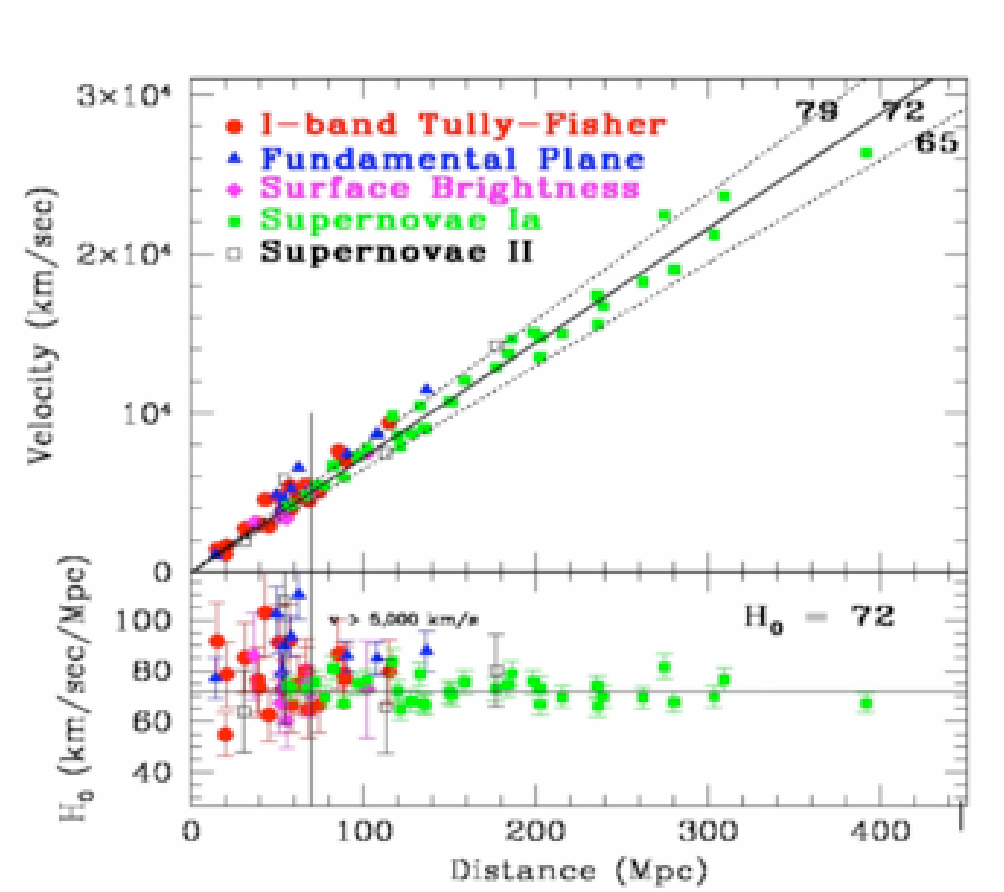


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Absolute distance callibrations are very difficult

Scatter in distance indicators and in peculiar velocities

Malmquist bias

**Coincidence #1**

# The Energy of the Universe

$$\rho = 3\, H^2 / 8\, \pi\, G$$

Measurements: energy density vs expansion rate

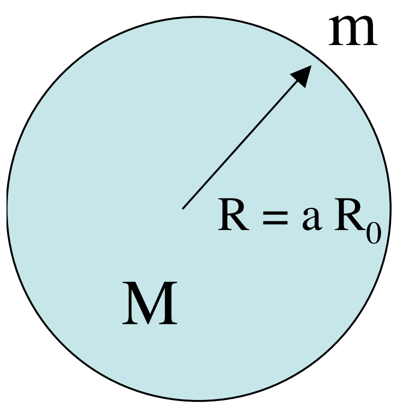
or

age vs expantion rate

# Cosmic Energy

Newtonian cosmology

$E = K + \phi = 1/2\ m\ v^2 - G\ M\ m/R = \text{constant!}$




$E = 1/2\ m\ H^2\ R^2 - 4/3\ \pi\ G\ m\ R^2\ \rho$

$M = 4/3\ \pi\ R^3\ \rho$

$\rho = \rho_0\ a^{-3}$

Einstein-deSitter (EdS) Universe: E=0

$\rho = 3\ H^2 / 8\ \pi\ G$ critical density $\rho_c \equiv \rho(E=0)$

$\Omega \equiv \rho_0 / \rho_c$ In the general case $(t=t_0)$

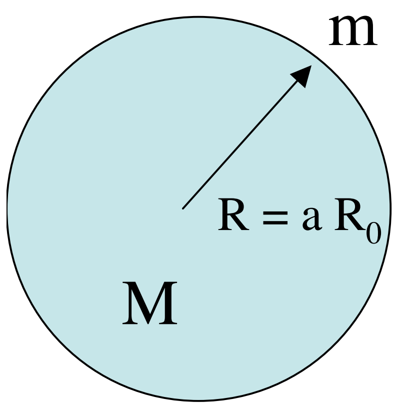
In turns out that **$\Omega_m$ =0.2-0.3**, so we do not seem to be in a EdS.
But note how closely related are $H^2$ and $\rho$. Can not be a coincidence!

# Friedmann Equation

Newtonian cosmology

$$E = 1/2\, m\, H^2 R^2 - 4/3\, \pi\, G\, m\, R^2\, \rho \equiv 1/2\, m\, \mathbf{k}\, R_0^2$$

IC constant = curvature




$$H^2 = 8/3\, \pi\, G\, \rho_0\, a^{-3} + k\, a^{-2}$$

$$H^2 = H_0^2\, (\, \Omega_m\, a^{-3} + \Omega_k\, a^{-2}\, )$$

$$M = 4/3\, \pi\, R^3\, \rho$$

$$\rho = \rho_0\, a^{-3}$$

$$\Omega = \rho_0 / \rho_c$$

$$\rho_c = 3\, H_0^2 / 8\, \pi\, G$$

$$\Omega_m + \Omega_k = 1$$

$$\Omega_T = 1 - \Omega_k$$

EdS $\Omega_k = 0 \;\; \Rightarrow \;\; \Omega_T = 1$

**Measure** $\Omega_m$ & $\Omega_k \Rightarrow H(t) \Rightarrow a(t)$

# Friedmann Equation

$\rho_c = 3 H_0^2 / 8 \pi G$

$\Omega = \rho_0 / \rho_c$

$H^2 = H_0^2 ( \Omega_m a^{-3} + \Omega_R a^{-4} + \Omega_k a^{-2} )$

$\Omega_m + \Omega_k + \Omega_R = 1$ $(\Omega_R = 0)$

$\Omega_T = 1 - \Omega_k$ (EdS $\Omega_k = 0$ => $\Omega_T = 1$)

**Measure** $\Omega_m$ & $\Omega_k$ <=> H(t) => a(t)

Some solutions:

MD: $\Omega_R = 0$ & $\Omega_k = 0$ => $a'/a = H_0 \; a^{-3/2}$ => $a \sim t^{2/3}$

RD: $\Omega_m = 0$ & $\Omega_k = 0$ => $a'/a = H_0 \; a^{-2}$ => $a \sim t^{1/2}$

# Cosmic Aceleration

Newtonian cosmology

$$(a'/a)^2 = H_0^2 \,(\,\Omega_m\, a^{-3} + \Omega_k\, a^{-2}\,)$$

$\Omega_m + \Omega_k = 1$

$\Omega_T = 1 - \Omega_k$

EdS $\Omega_k = 0 \Rightarrow \Omega_T = 1$

$$a'' = - H_0^2 \,(\Omega_m/2)\, a^{2} < 0 \Rightarrow \text{(independent of } \Omega_k\text{ !)}$$

**deceleration parameter : $q \equiv - a'' / H^2 / a^2$**

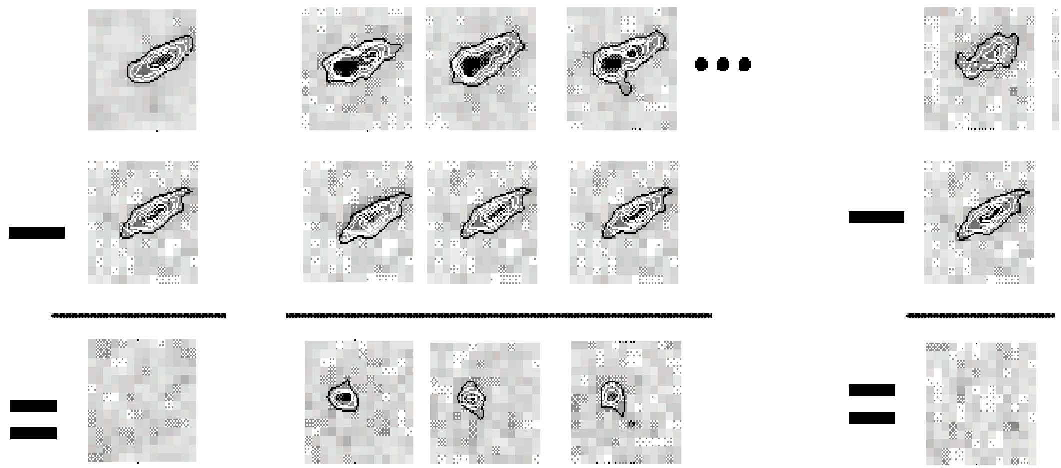
$$q_0 = \Omega_m/2 \approx 0.15$$

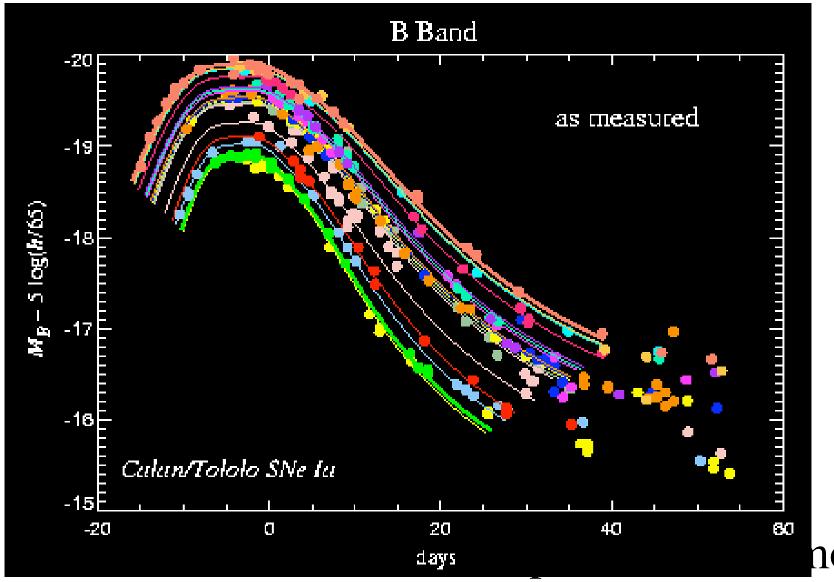
But SNIa results find $q_0 \approx -0.5$ ! =>

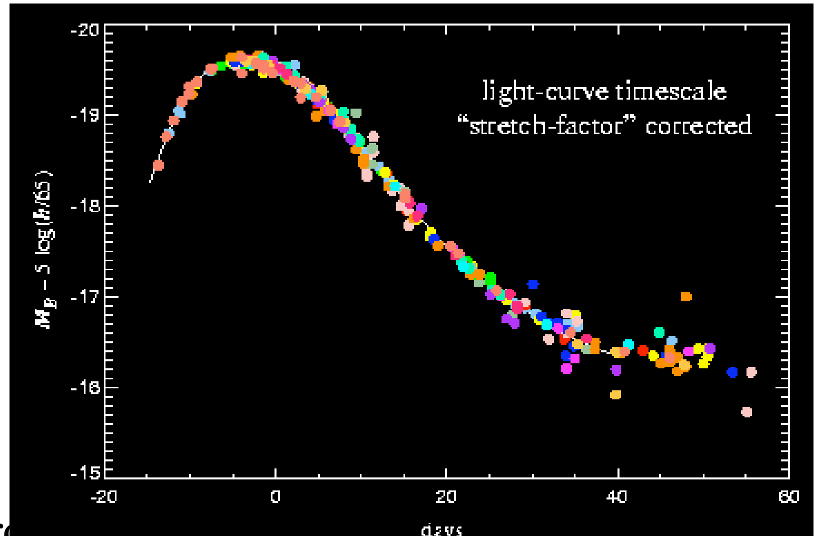
# Type Ia Supernovae

- Bright as a galaxy
- 2 / galaxy / 1000 yr
- Rise time ~ 20 days
- standard candles?
- M = -2.5 log (L/L0)

- M = m + 2.5 log(D/10pc)





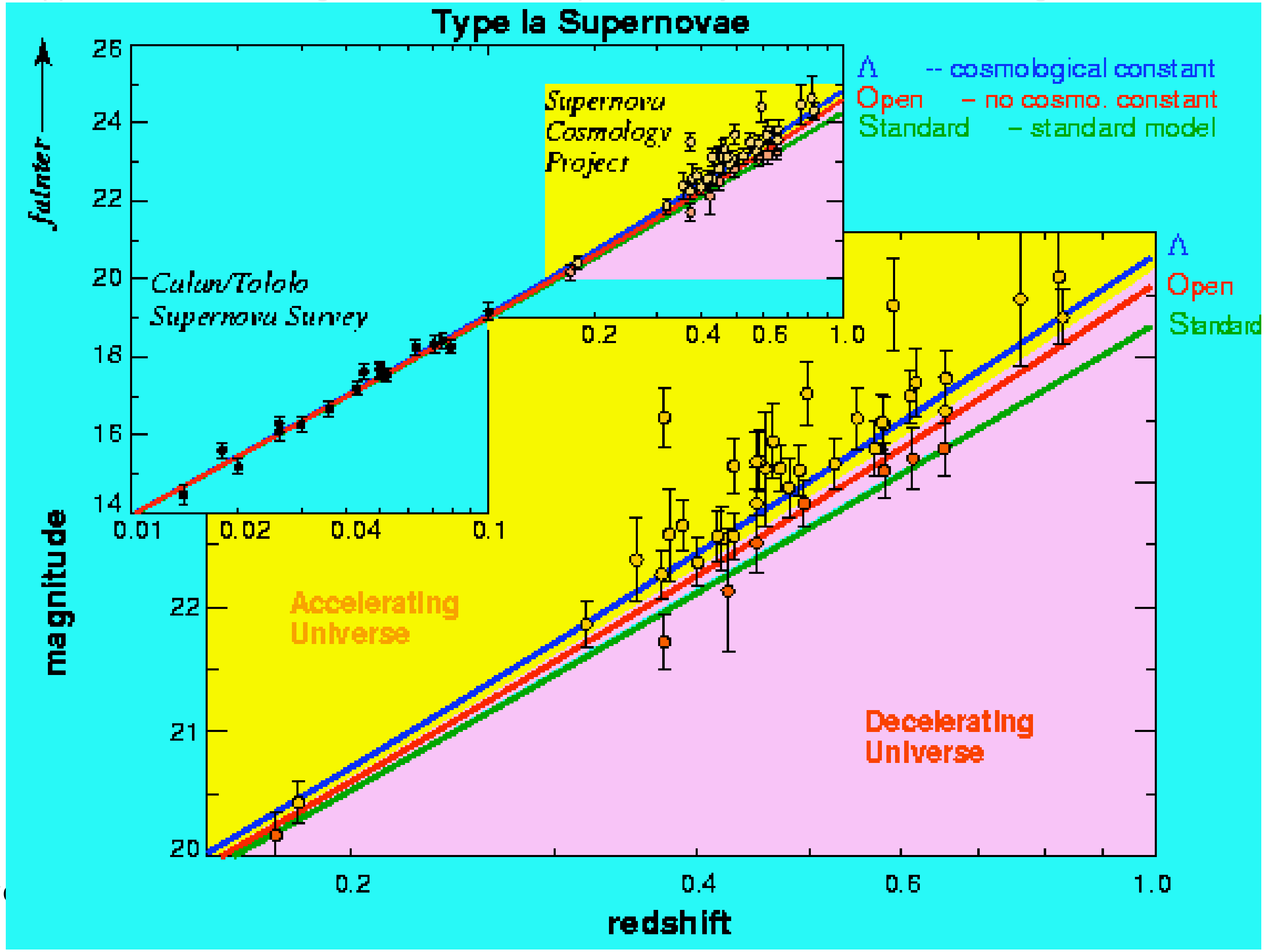




nology Project) .see http://snfactory.lbl.gov

# Type Ia Supernovae

$$q = \frac{1}{2}\,\Omega_T - \Omega_\Lambda = -\,a''/a^2/H^2$$

Using 42 high redshift Type Ia SNe and 18 low redshift SNe, both the Supernova Cosmology Project (Pelmuter et al 1999) and the High-z Supernova Search Team (Ries etal 1998) found that the peak luminosities of distant supernovae appear to be $0.2$ magnitude fainter than predicted by a standard decelerating universe :

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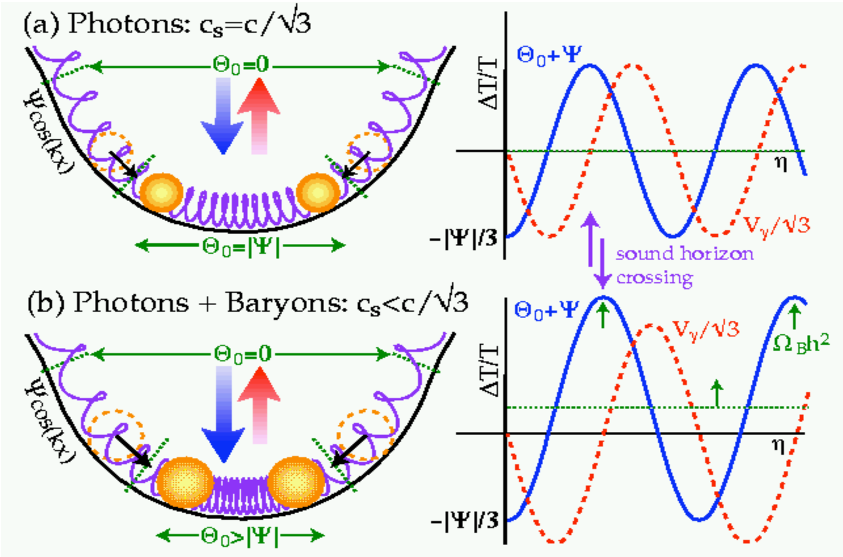
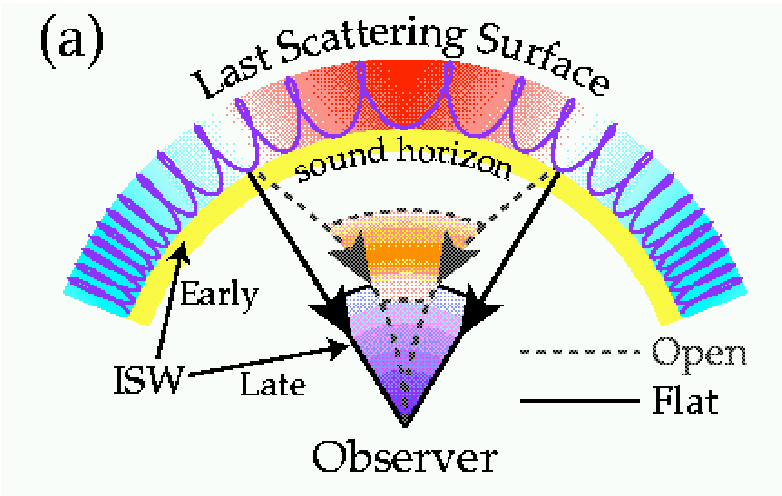
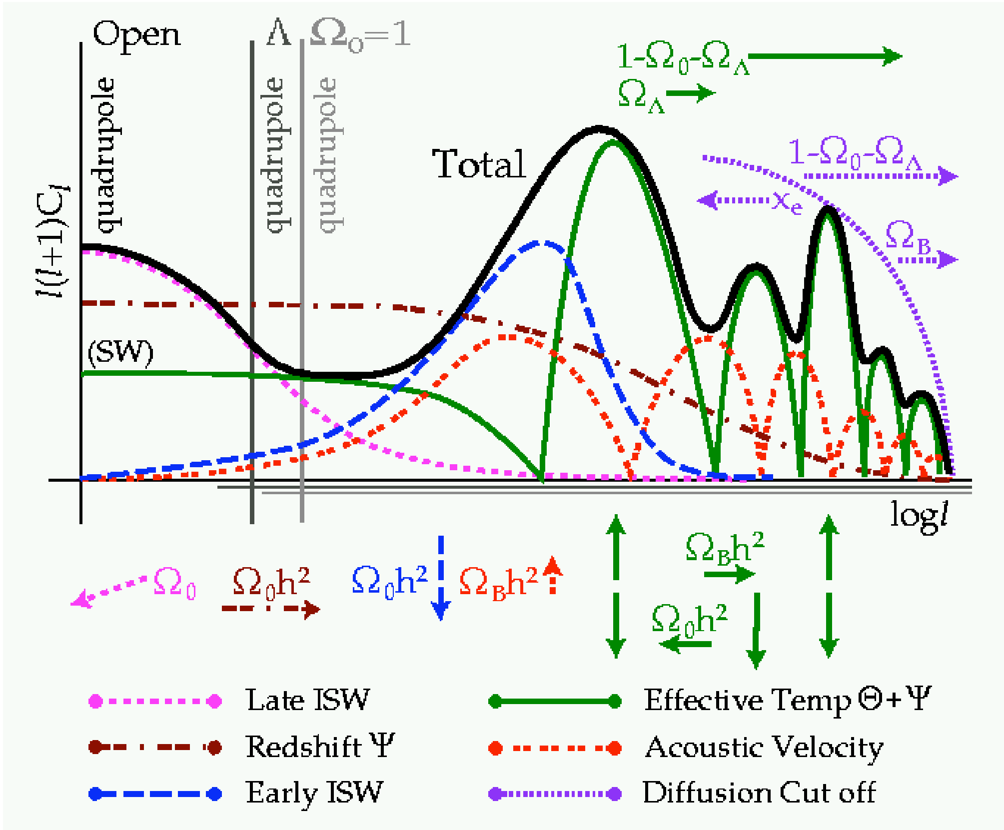
# The Physics of CMB

Hu, Sugiyama, Silk (Nature, 1995)



# Cosmic Aceleration

Newtonian cosmology

$(a'/a)^2 = H_0^2\,(\,\Omega_m\, a^{-3} + \Omega_k\, a^{-2}\,)$

$\Omega_m + \Omega_k = 1$

$\Omega_T = 1 - \Omega_k$

EdS $\Omega_k = 0 \Rightarrow \Omega_T = 1$

$a'' = -\,H_0^2\,(\Omega_m/2)\,a^{2} < 0 \Rightarrow$ (independent of $\Omega_k$ !)

deceleration parameter : $q \equiv -\,a''/\,H^2/\,a^2$

$$q_0 = \Omega_m/2 \approx 0.15$$

But SNIa results find $q_0 \approx -0.5$ !

Fist Acoustic peak => $\Omega_k = 0 \Rightarrow \Omega_m \approx 1 \Rightarrow q_0 \approx +0.5$ !

# Dark Energy

Newtonian cosmology

$H^2 = (a'/a)^2 = H_0^2 \, ( \Omega_m a^{-3} + \Omega_k a^{-2} )$

$\Omega_m + \Omega_k = 1$

$\Omega_T = 1 - \Omega_k$

EdS $\Omega_k = 0 \Rightarrow \Omega_T = 1$

$H^2 = 8/3 \, \pi G \rho + k a^{-2}$

Let's assume: $\rho = \rho_0 a^{-3} + \rho_\Lambda$ where $\rho_\Lambda$ is a constant

$H^2 = (a'/a)^2 = H_0^2 \, ( \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda )$

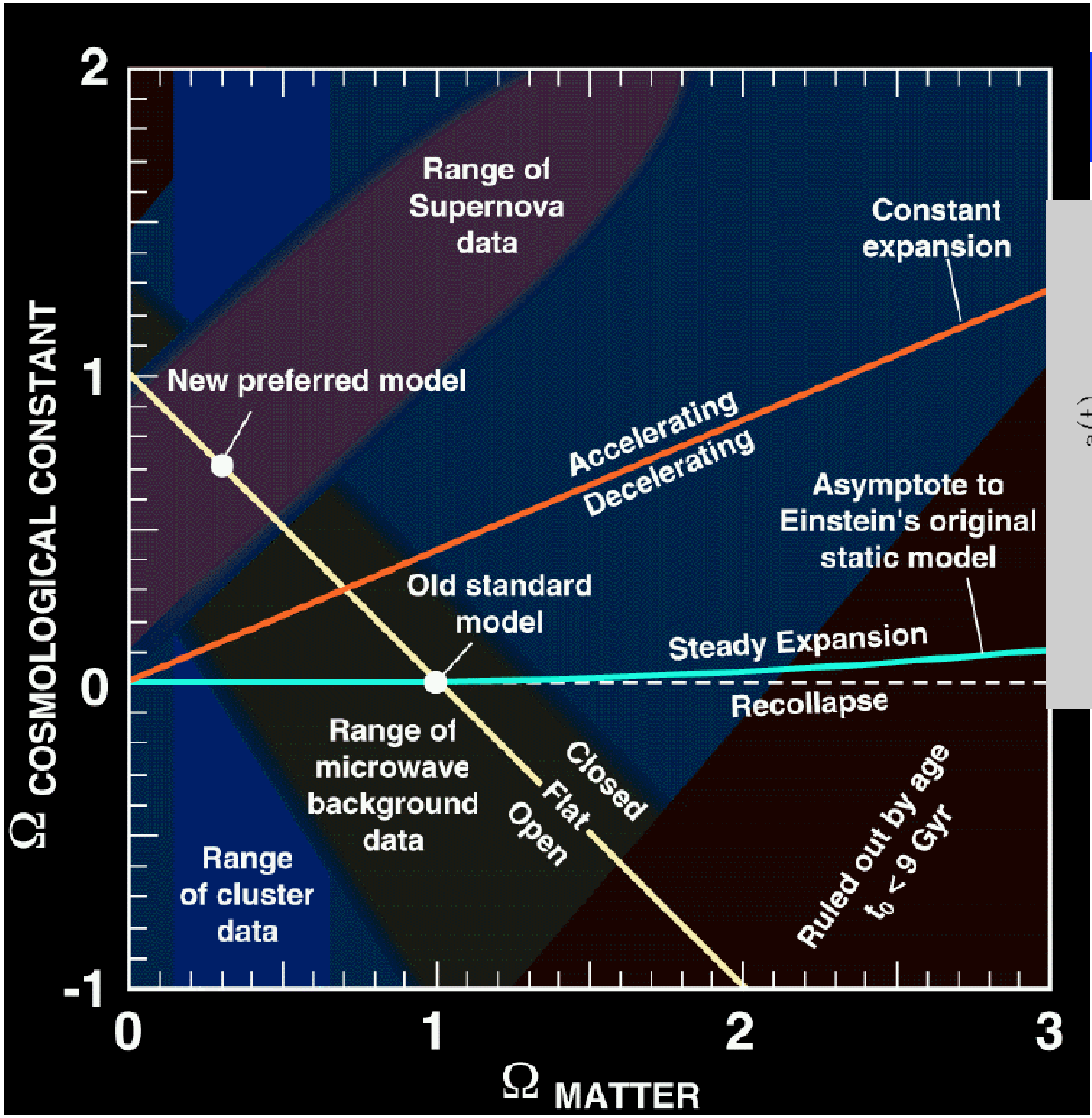
$1 = \Omega_m + \Omega_k + \Omega_\Lambda$

Deceleration $q_0 \equiv - \mathbf{a}_0'' / H_0^2 = \Omega_m /2 - \Omega_\Lambda < 0$ ?

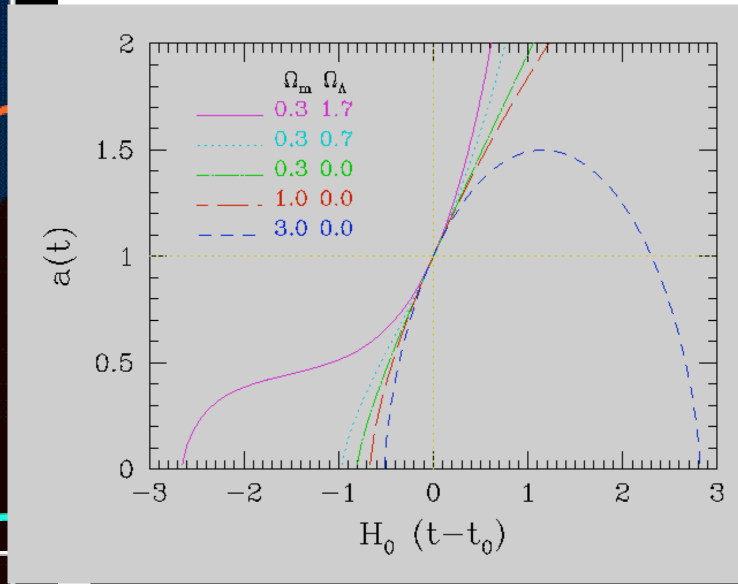
First Acoustic peak $\Rightarrow \Omega_k = 0 \Rightarrow \Omega_\Lambda \approx 1 - \Omega_m \approx$ **0.7-0.8** $\Rightarrow$
$q_0 \approx - 0.5$ ! In agreement with SNIa results find $q_0 \approx -0.5$ !

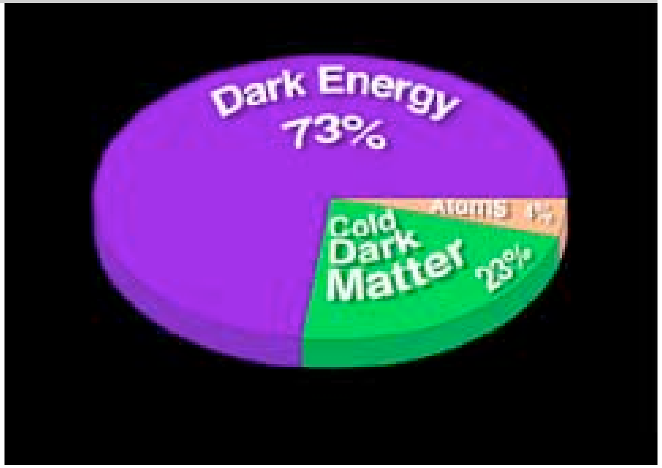
# Cosmological parameters

$$H^2 = H_0^2 \left[ \Omega_M \, a^{-3} + \Omega_R \, a^{-4} + \Omega_k \, a^{-2} + \Omega_\Lambda \right]$$




$$q = \frac{1}{2}\,\Omega_T - \Omega_\Lambda$$



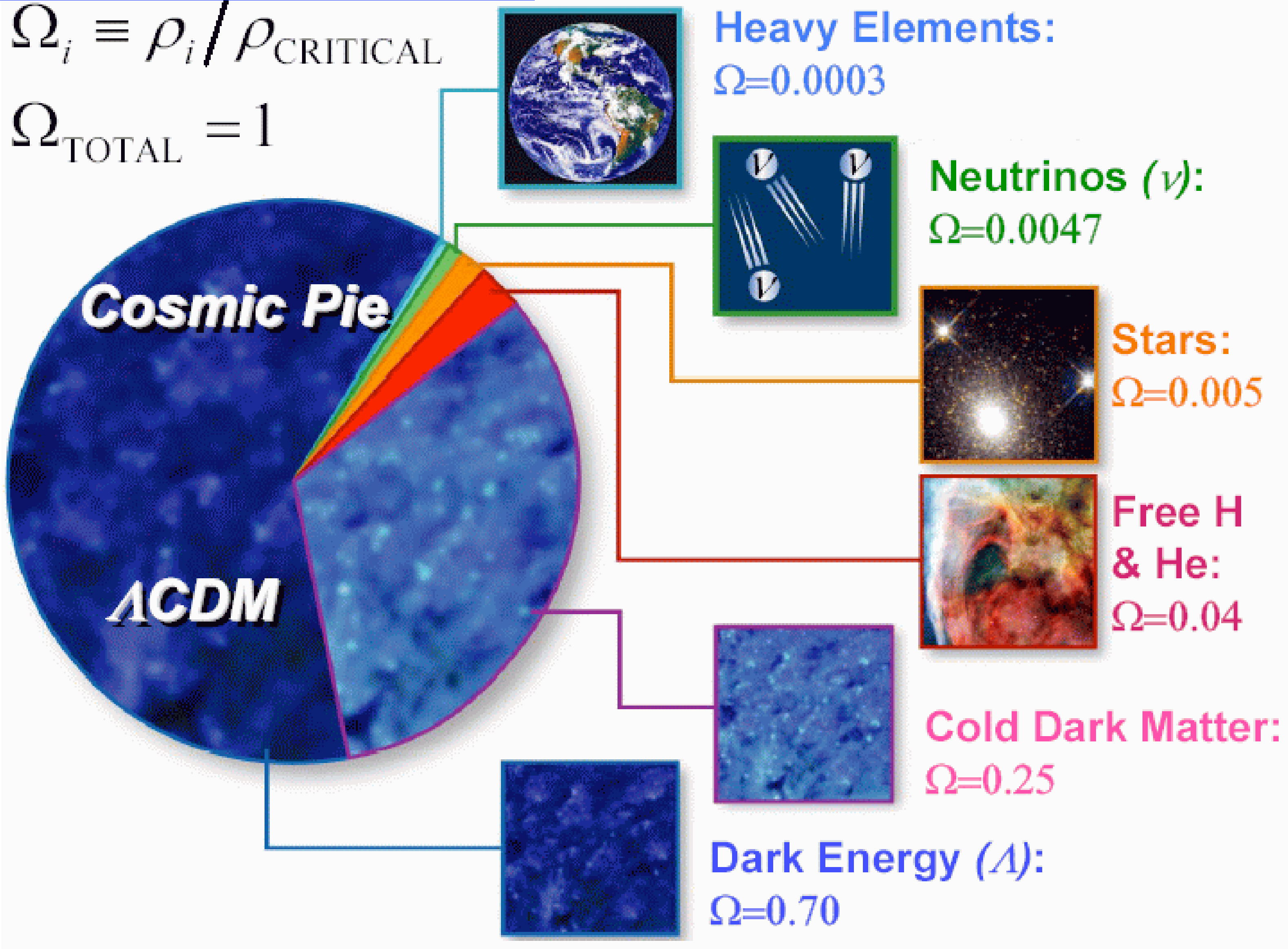
# FAILURE?

Background: Evolution of scale factor a(t).

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

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

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



# Problemas

- Que edad tiene el universo cuando T=1 Mev?
Pista: $T_0$=3K ahora y T=3000K recombinación

- Con qué ángulo observamos el horizonte causal en recombinación?

- Cuál es la diferencia en magnitud aparente (o flujo) entre una SNIa en z=0 y en z=2?