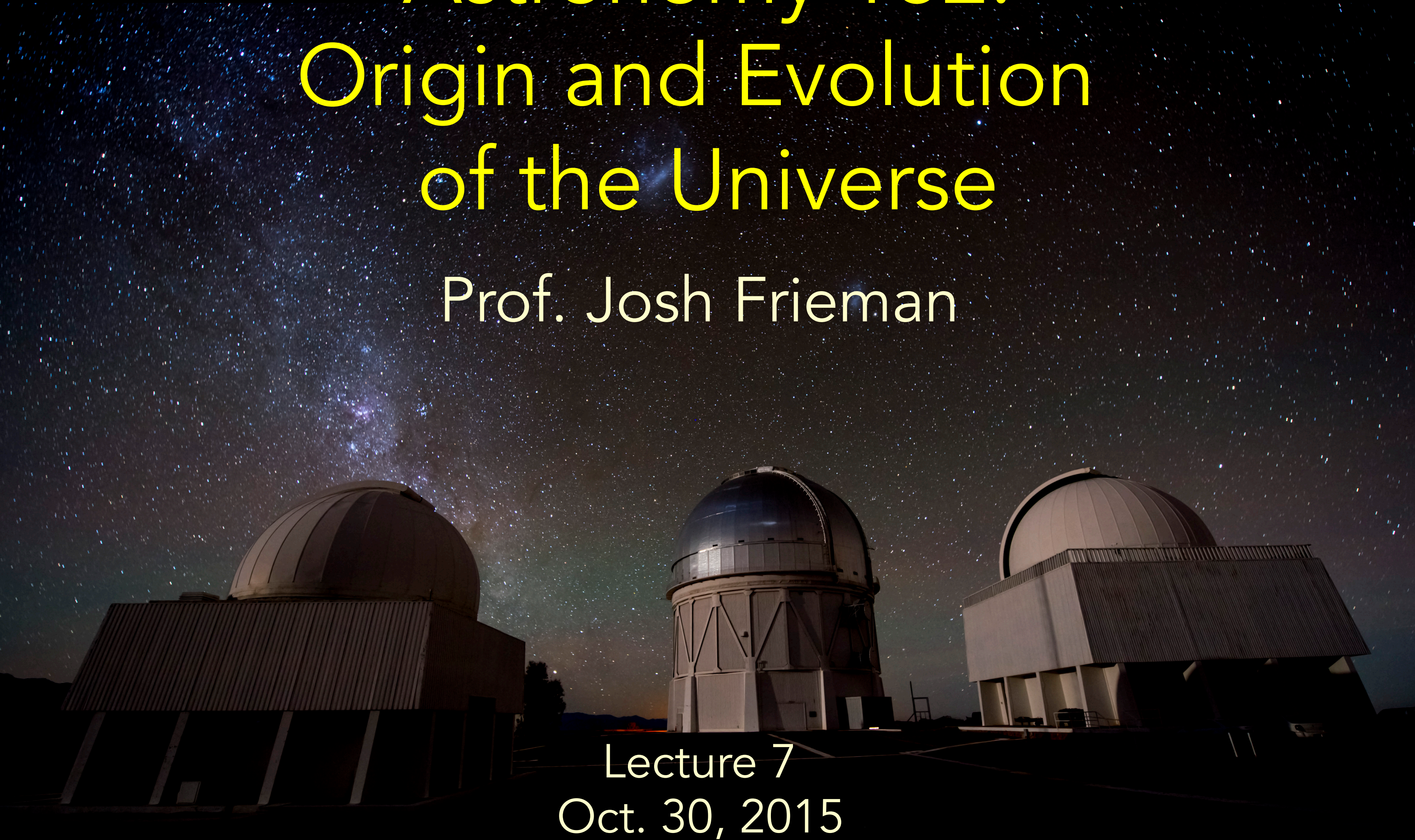
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 7

Oct. 30, 2015

Today

- Relativistic Cosmology
- Dark Side of the Universe I: Dark Matter

Assignments

- This week: read Hawley and Holcomb, Chapters 7-9, 13.
- Today: Lab 2 write-up due in class.
- Next Fri., Nov. 6: Essay due on HH, Chapter 8.

The Expanding Universe

Distance between galaxies given by universal scale factor:

$d(t)=d_0 a(t)$

Dynamics of Cosmic Expansion

- Separation between any pair of galaxies is increasing due to expansion: $d(t)=d_0a(t)$, where $a(t)$ is a universal function. This is consistent with Hubble's law and observed homogeneity and isotropy.

- What determines the time-dependence of the cosmic scale factor $a(t)$?

- On large scales, gravity is the only force that matters. Use General Relativity to determine evolution of $a(t)$.

Friedmann–Lemaitre–Robertson–Walker model

Alexander Friedmann
Russian
1922-24 derivations
(died in 1925)

George Lemaitre
Belgian priest
1927 derivations

Howard Percy Robertson
American
+
Arthur Geoffrey Walker
English

1935 – proof that FLRW expression for spacetime interval is the only one for a universe that is both homogeneous and isotropic

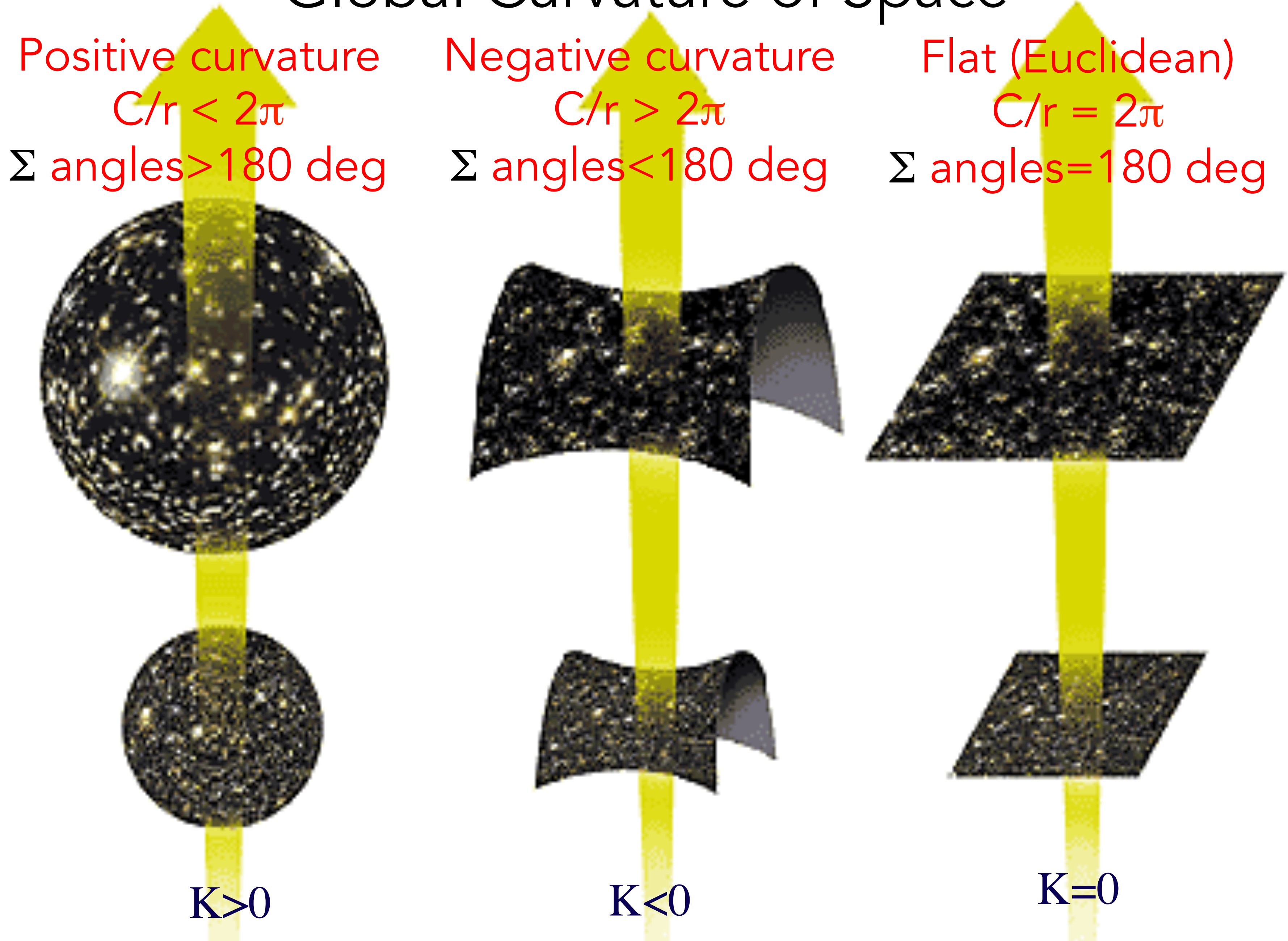
Space vs Spacetime Curvature

Curvature of 3-dimensional Space vs. Curvature of 4-dimensional Spacetime:

General Relativity: implies that Spacetime is generally curved.

Cosmology: mainly concerned with the curvature of 3-dimensional space (K) (i.e., of a `slice' through spacetime at a fixed time) since it is related to the density and fate of the Universe.

Global Curvature of Space



Dynamics of Cosmic Expansion

- GR: curvature of spacetime determined by mass-energy (Einstein equations).
- Apply this to the homogeneous and isotropic Universe: Friedmann equation:

$$\left(\frac{1}{a}\frac{\Delta a}{\Delta t}\right)^2 + \frac{k}{a^2} = \frac{8\pi G\rho}{3}$$

Expansion rate Spatial Curvature Density of Matter

Dynamics of Cosmic Expansion

- Example 1: ρ=0, k=−1: empty, negatively curved universe. In this case, (Δa/Δt)=1, so a(t)~t. Hence, d(t)~t, and galaxies recede at fixed speeds.

$$\left(\frac{1}{a}\frac{\Delta a}{\Delta t}\right)^2 + \frac{k}{a^2} = \frac{8\pi G\rho}{3}$$

Expansion rate Spatial Curvature Density of Matter

Dynamics of Cosmic Expansion

- Example 2: k=0: flat universe. For ordinary (and dark) matter, $\rho \sim 1/a^3$, so $(\Delta a/\Delta t) \sim 1/a^{1/2}$, and $a(t) \sim t^{2/3}$. Hence, $d(t) \sim t^{2/3}$, and galaxies slow down over time due to gravity.

$$\left(\frac{1}{a}\frac{\Delta a}{\Delta t}\right)^2 + \frac{k}{a^2} = \frac{8\pi G\rho}{3}$$

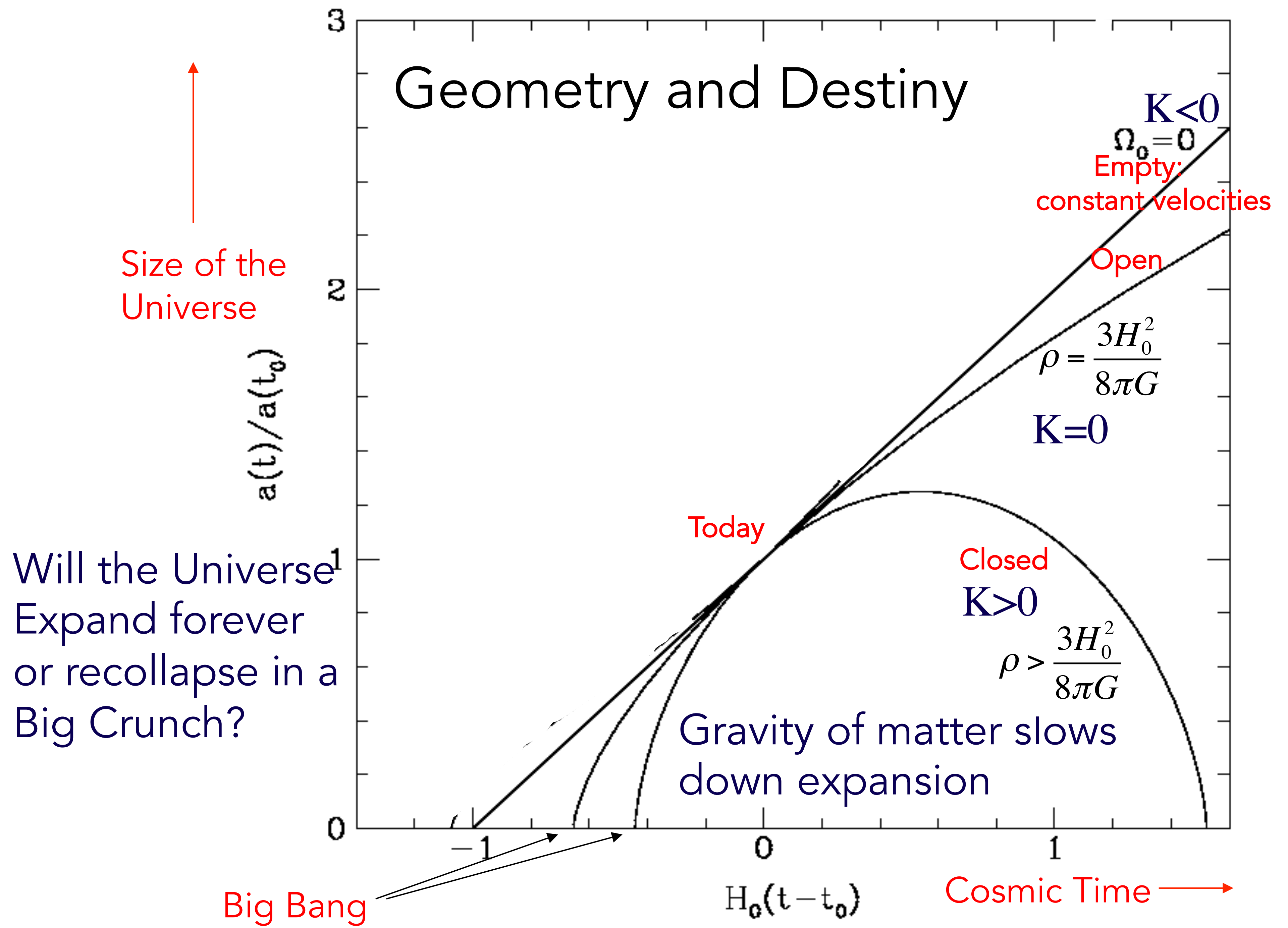
Expansion rate   Spatial Curvature   Density of Matter

Dynamics of Cosmic Expansion

- GR: curvature of spacetime determined by mass-energy (Einstein equations).
- Apply this to the homogeneous and isotropic Universe: Friedmann equation:

$$H^2 = \left(\frac{1}{a}\frac{\Delta a}{\Delta t}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2}$$

Expansion rate   Matter Density   Spatial Curvature



Geometry and Destiny
K<0
$\Omega_0=0$
Empty: constant velocities
Open
$\rho = \frac{3H_0^2}{8\pi G}$
K=0
Today
Closed
K>0
$\rho > \frac{3H_0^2}{8\pi G}$
Gravity of matter slows down expansion
Size of the Universe
a(t)/a(t$_0$)
Will the Universe Expand forever or recollapse in a Big Crunch?
3
2
1
0
−1
0
1
Big Bang
$H_0(t-t_0)$
Cosmic Time

Fate of the Universe

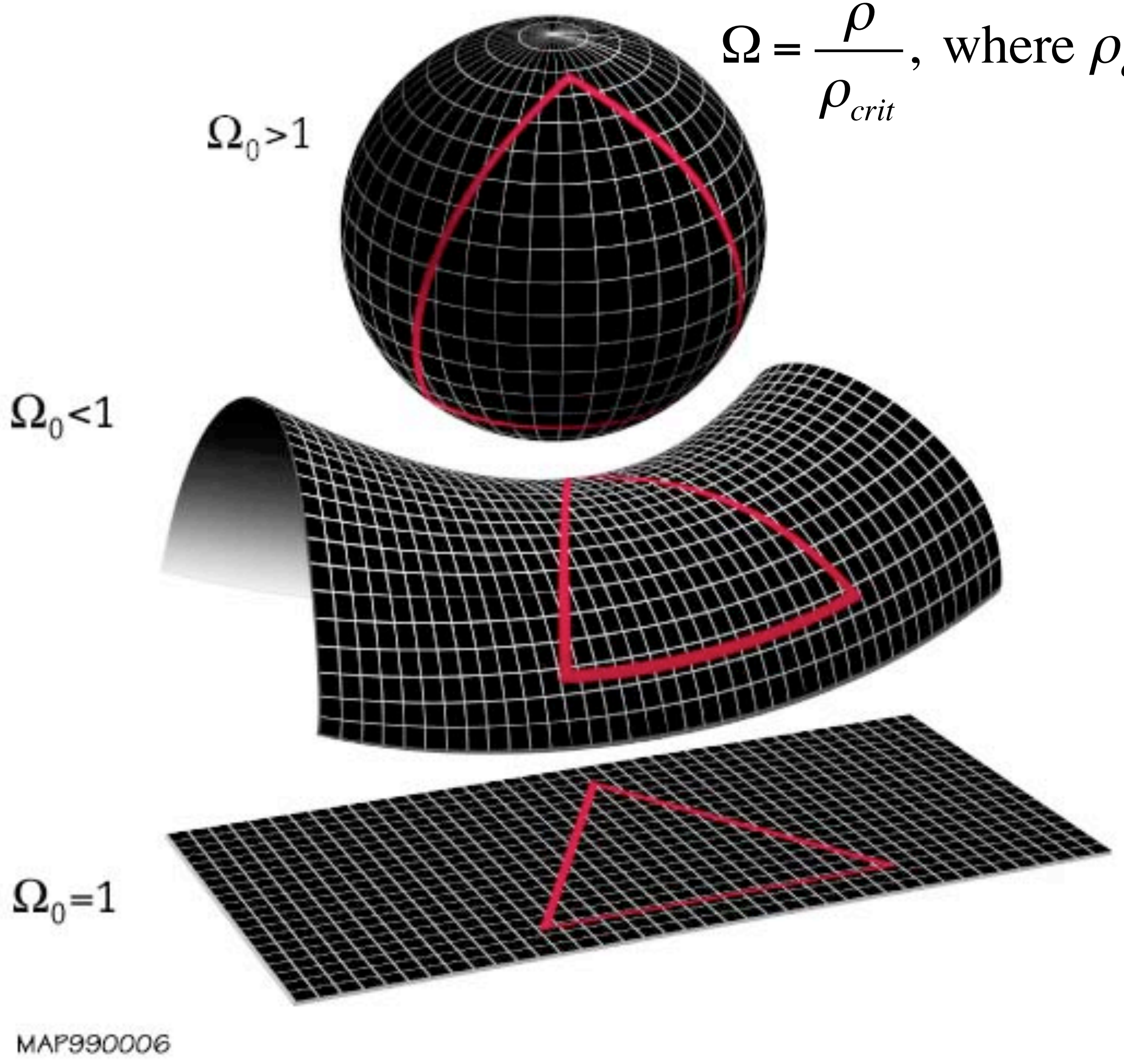
- Will the Universe expand forever or recontract to a Big Crunch?
- Is the mass density of the Universe smaller or larger than the critical value,

$$\rho_{crit} = \frac{3H_0^2}{8\pi G} = 2 \times 10^{-29}\,\mathrm{gm/cm^3}$$

- Density of atoms is well below this. But how much unseen—dark---matter is there? This question dominated discourse through the 1980's.

Geometry and Density

$$\Omega = \frac{\rho}{\rho_{crit}}, \text{ where } \rho_{crit} = \frac{3H_0^2}{8\pi G} = 2 \times 10^{-29}\,\text{gm/cm}^3$$



Fate of the Universe

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$$\rho_{crit} = \frac{3H_0^2}{8\pi G} = 2\times 10^{-29}\,\mathrm{gm/cm^3}$$

- Density of atoms is well below this. But how much unseen—dark---matter is there? This question dominated discourse through the 1980's.
- Discovery of cosmic acceleration in 1998 changed the dynamics from this picture.

Dynamics of Cosmic Expansion

- GR: curvature of spacetime determined by mass-energy (Einstein equations).
- Apply this to the homogeneous and isotropic Universe: Friedmann equation:

$$H^2 = \left(\frac{1}{a}\frac{\Delta a}{\Delta t}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

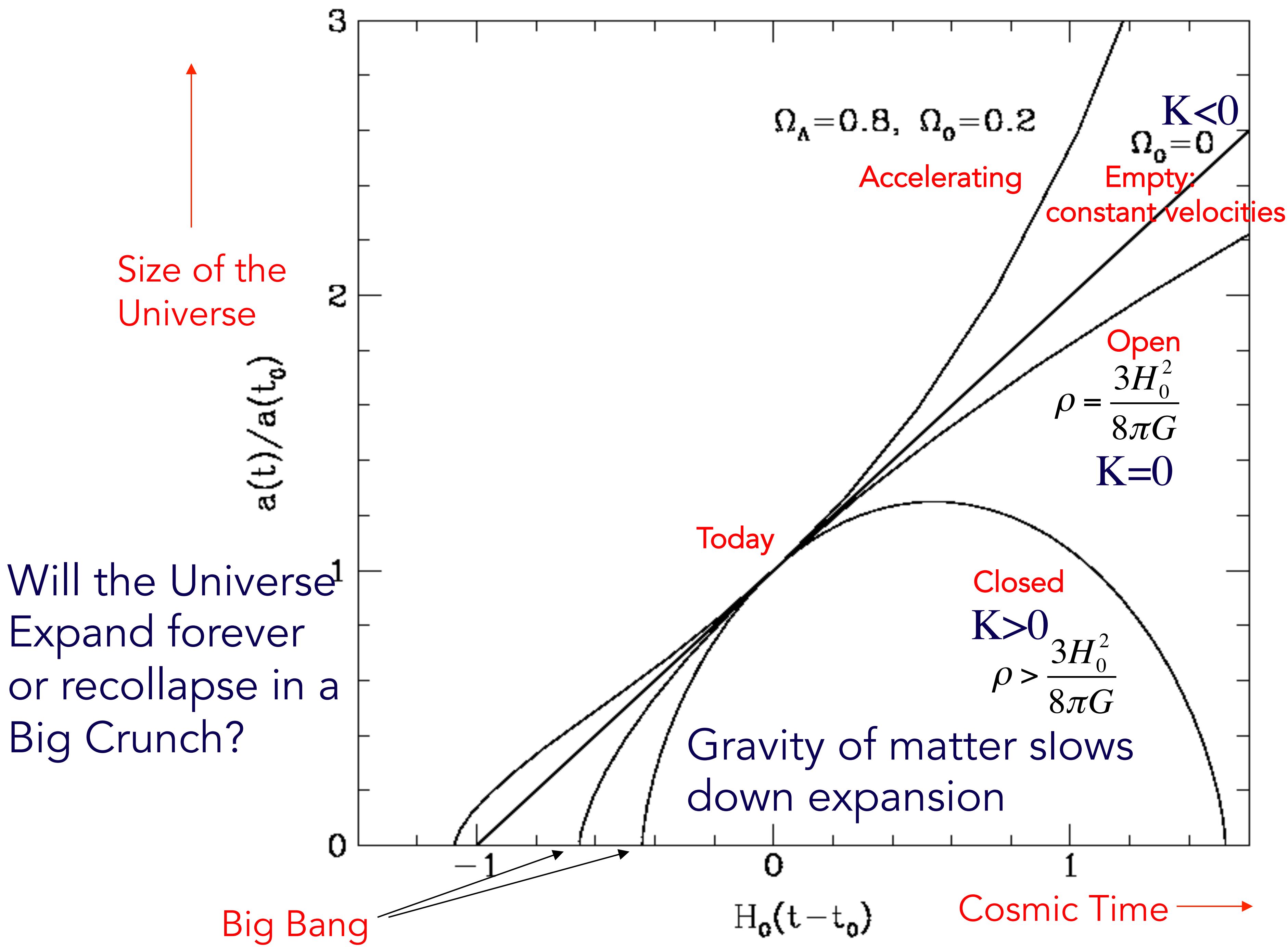
Expansion rate | Matter Density | Spatial Curvature | Cosmological Constant

Dynamics of Cosmic Expansion

- Example 3: $k=\rho=0$: flat, empty universe with cosmological constant. In this case, $a(t) \sim \exp[(\Lambda/3)^{1/2}t]$. Universe grows exponentially: cosmic acceleration. Even for non-zero k and ρ, this is the asymptotic solution in the future.

$$H^2 = \left(\frac{1}{a}\frac{\Delta a}{\Delta t}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

Expansion rate Matter Density Spatial Curvature Cosmological Constant



$\Omega_\Lambda = 0.8, \ \Omega_0 = 0.2$
Accelerating
K<0
$\Omega_0 = 0$
Empty:
constant velocities
Open
$\rho = \frac{3H_0^2}{8\pi G}$
K=0
Today
Closed
K>0
$\rho > \frac{3H_0^2}{8\pi G}$
Gravity of matter slows down expansion
Size of the Universe
$a(t)/a(t_0)$
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2
1
0
−1
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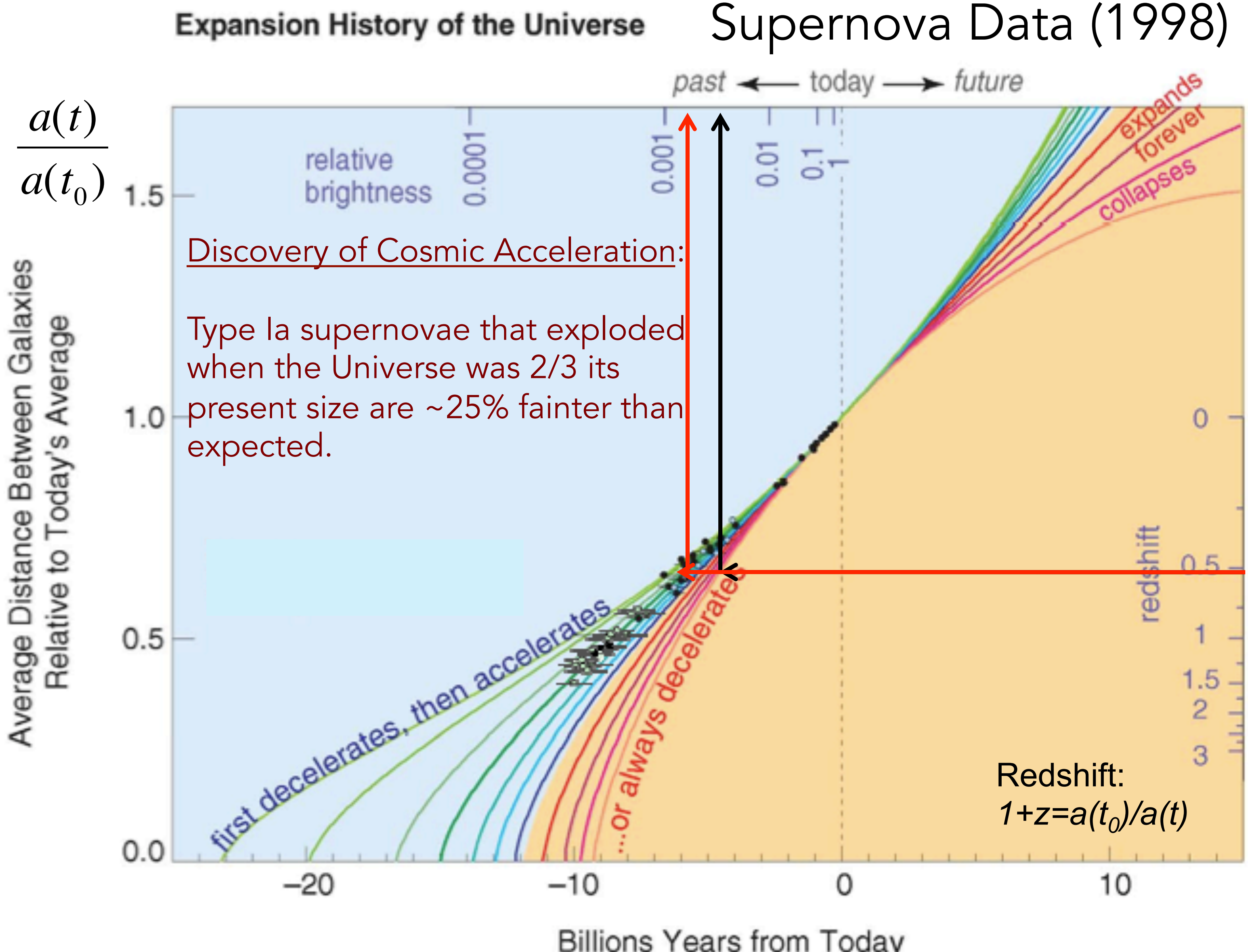
1
$H_0(t-t_0)$
Big Bang
Cosmic Time
Will the Universe Expand forever or recollapse in a Big Crunch?

Supernova Data (1998)



Discovery of Cosmic Acceleration:

Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected.

Redshift:
$1+z=a(t_0)/a(t)$

Cosmic Acceleration

- Throughout the 20th Century, cosmologists attempted to measure the deceleration (slowing) of the expansion due to gravity, but the measurements were inconclusive.
- 1998: Two teams of astronomers, using type Ia supernovae as standard candles, found that instead the expansion is *speeding up* (Nobel Prize 2011).
- To explain this, we either need to modify our understanding of how gravity works on cosmological scales or else invoke a dominant, new component of the Universe---dark energy---that has very different properties from ordinary matter.

Historical Note: Einstein Static Universe

- Friedmann equations:

$$H^2 = \left(\frac{1}{a}\frac{\Delta a}{\Delta t}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

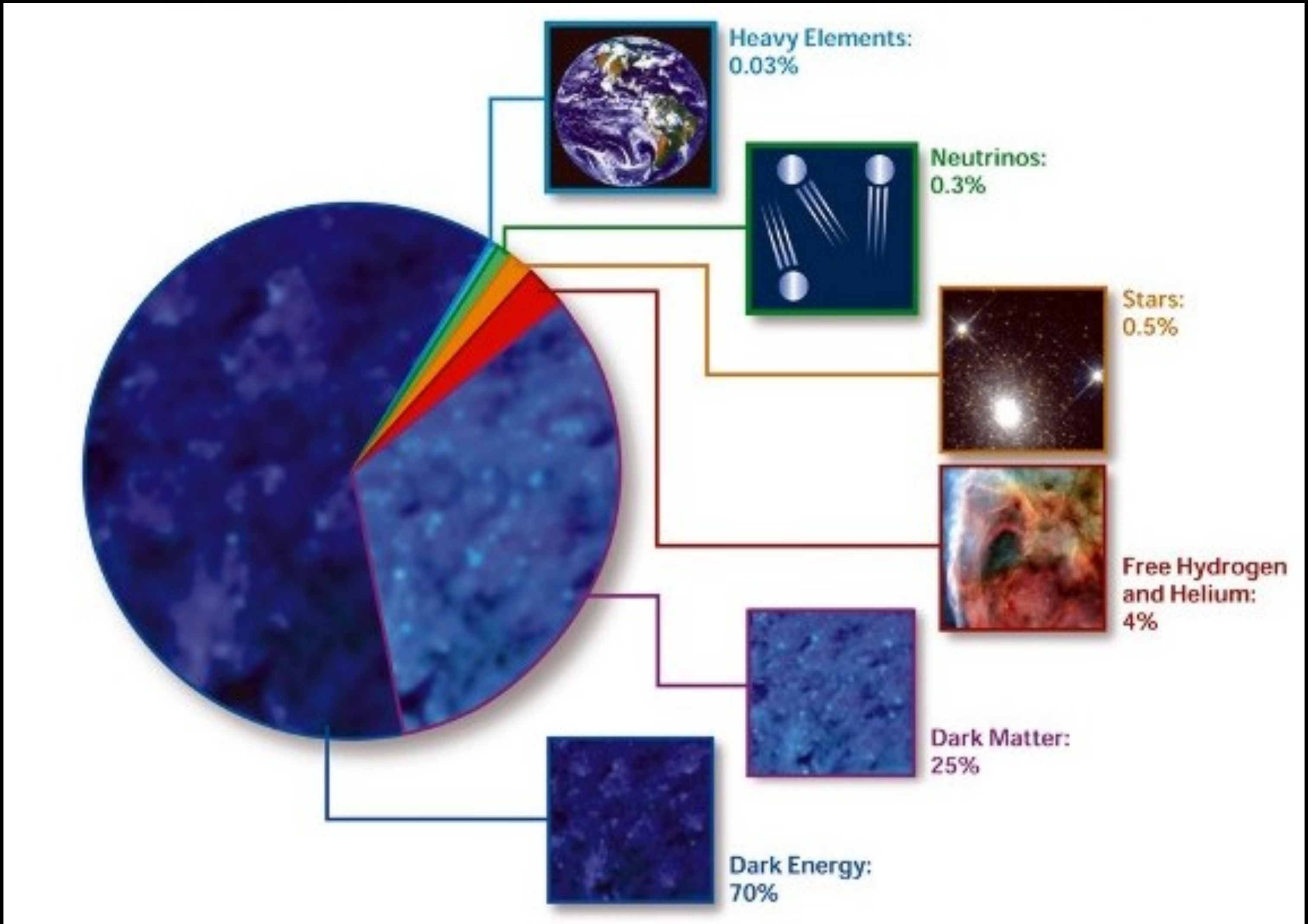
$$\frac{1}{a}\frac{\Delta}{\Delta t}\left(\frac{\Delta a}{\Delta t}\right) = -\frac{4\pi G}{3}\rho + \frac{\Lambda}{3}$$

- For static solution: $\rho=\Lambda/4\pi G=1/4\pi G a_0^2$=constant
- Problem: this solution is unstable and will eventually expand or contract.

Contents of the Universe

- To determine the evolution of the Universe, we need to know what forms of matter and energy there are and how much there is of each:
    - Ordinary matter (stars, gas, planets,…, made of atoms)
    - Neutrinos
    - Electromagnetic Radiation (Cosmic Microwave Background)
    - Dark Matter
    - Dark Energy
    - …

Contents of the Universe



Non-relativistic Matter

- Includes ordinary matter (stars, gas, planets,…, anything made of atoms), dark matter, massive neutrinos: anything that moves slowly compared to the speed of light c
- Recall Einstein's famous equation:

$$E=mc^2=m_0c^2/(1-v^2/c^2)^{1/2}$$

where m_0 is the 'rest mass'
- For a slowly moving particle, $v<<c$, and $E\approx m_0c^2$.
- In this case, the energy per unit volume is

$$\rho=nE=nm_0c^2$$

where n is the number of particles per unit volume

Non-relativistic Matter

- Now assume that particles are not created or destroyed. Then the total number of particles in a volume V is fixed:

$$N = nV = \text{constant}$$

- Thus the number density of particles obeys

$$n \sim 1/V$$

- In the expanding Universe, the volume $V \sim a^3$ so that

$$n \sim 1/a^3$$

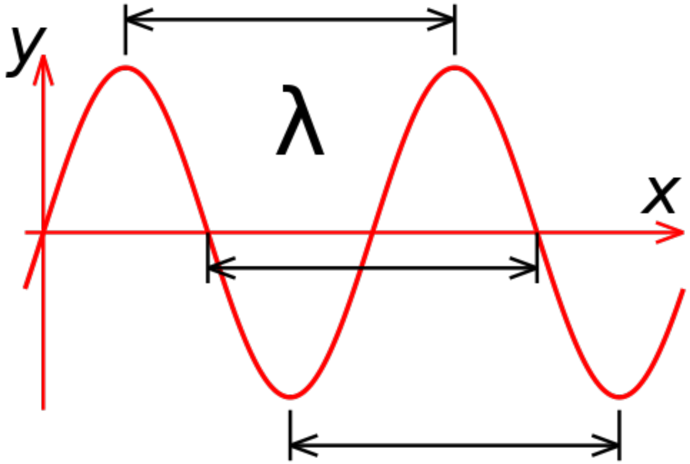
and therefore for non-relativistic matter:

$$\rho = n m_0 c^2 \sim 1/a^3$$

Radiation (Relativistic Particles)

- Includes electromagnetic radiation (light) and any other stuff that moves at or very near the speed of light (e.g., gravity waves or extremely light particles).

Light is an Electromagnetic Wave



λ – wavelength –
distance between wavecrests

$\lambda\nu = c$
(speed of light)

ν – frequency
$\nu = 1/\Delta t =$
1/period (time between wavecrests)
Unit: Hz = 1/second

Energy per photon:
$E_\gamma = h\nu = hc/\lambda$ (quantum)
Since expansion stretches wavelength, $\lambda \sim a(t)$ (redshift), it follows that $E_\gamma \sim 1/a(t)$

Wikipedia - waves

Radiation

- Now assume that radiation (e.g., photons) is not created or destroyed. Then the total number of particles in a volume V is fixed:

$$N = nV = \text{constant}$$

- Thus the number density of particles obeys

$$n \sim 1/V$$

- In the expanding Universe, the volume $V \sim a^3$ so that

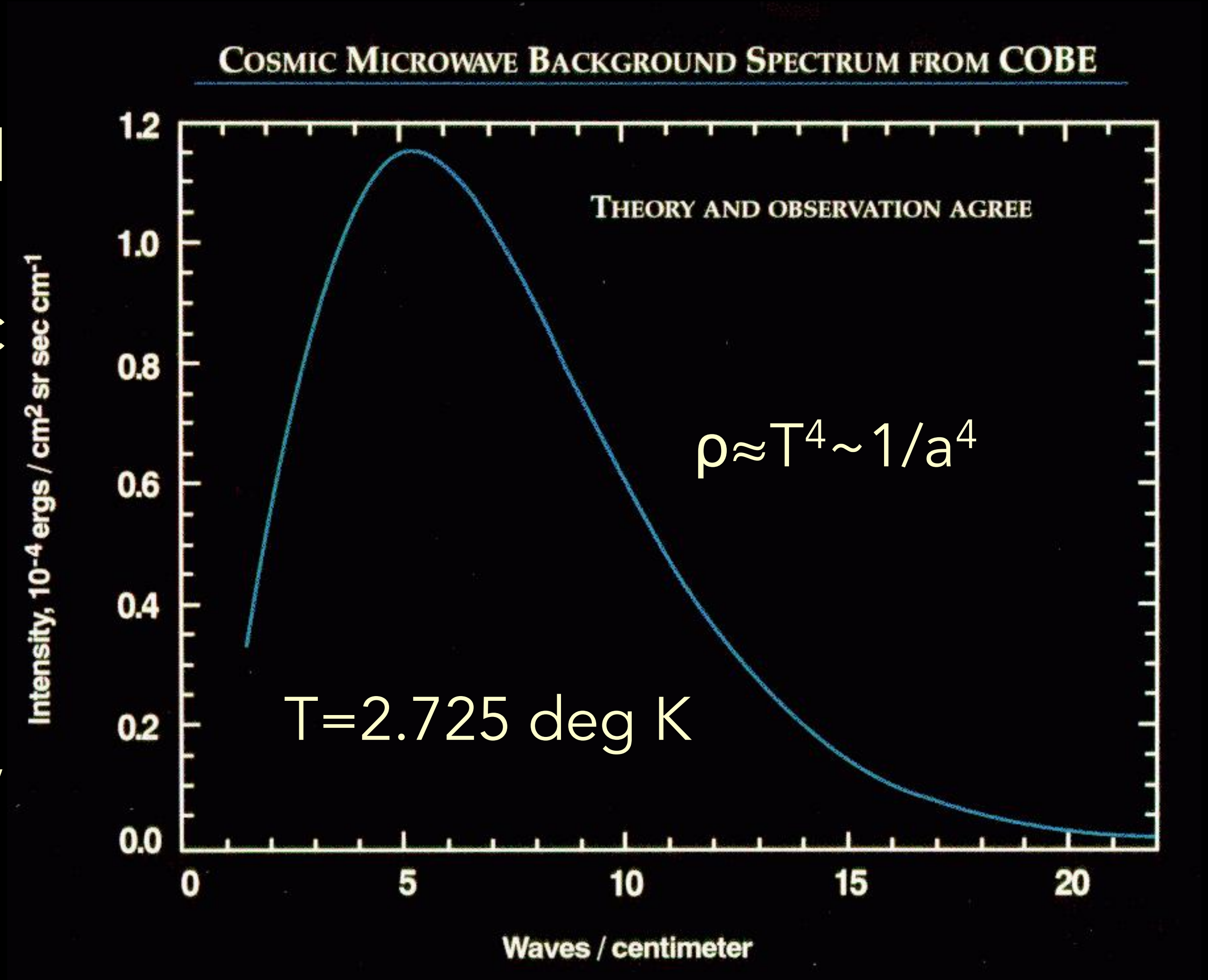
$$n \sim 1/a^3$$

and therefore for radiation:

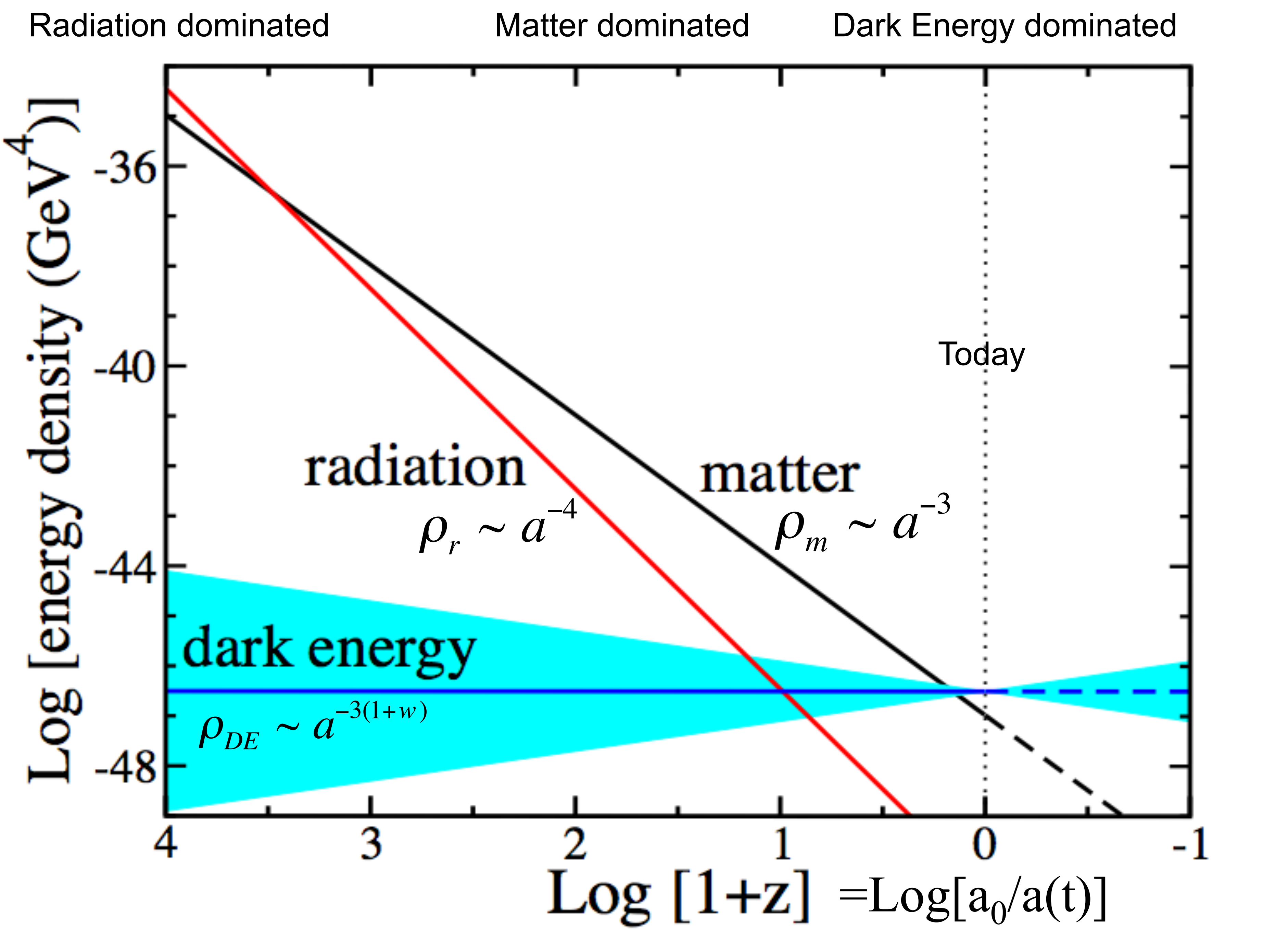
$$\rho = nE_\gamma \sim (1/a^3)(1/a) \sim 1/a^4$$

Cosmic Microwave Background

- Universe is filled with thermal electromagnetic radiation: the Cosmic Microwave Background (CMB) radiation, remnant from the hot early Universe.

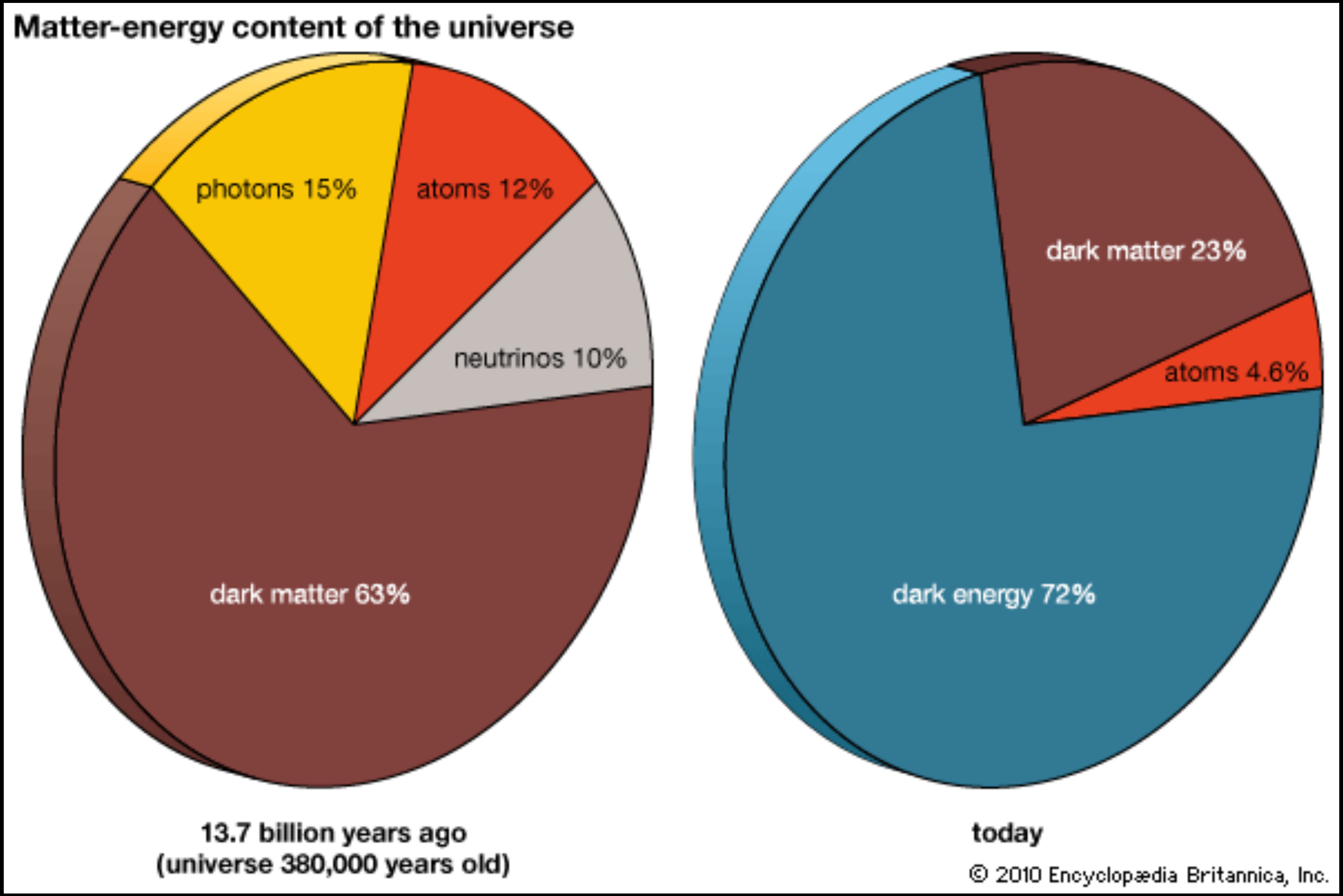


ν – frequency



Radiation dominated
Matter dominated
Dark Energy dominated
Log [energy density (GeV^4)]
-36
-40
-44
-48
Today
radiation
$\rho_r \sim a^{-4}$
matter
$\rho_m \sim a^{-3}$
dark energy
$\rho_{DE} \sim a^{-3(1+w)}$
4
3
2
1
0
-1
Log [1+z] =Log[a_0/a(t)]

Components Then and Now



Dark Matter

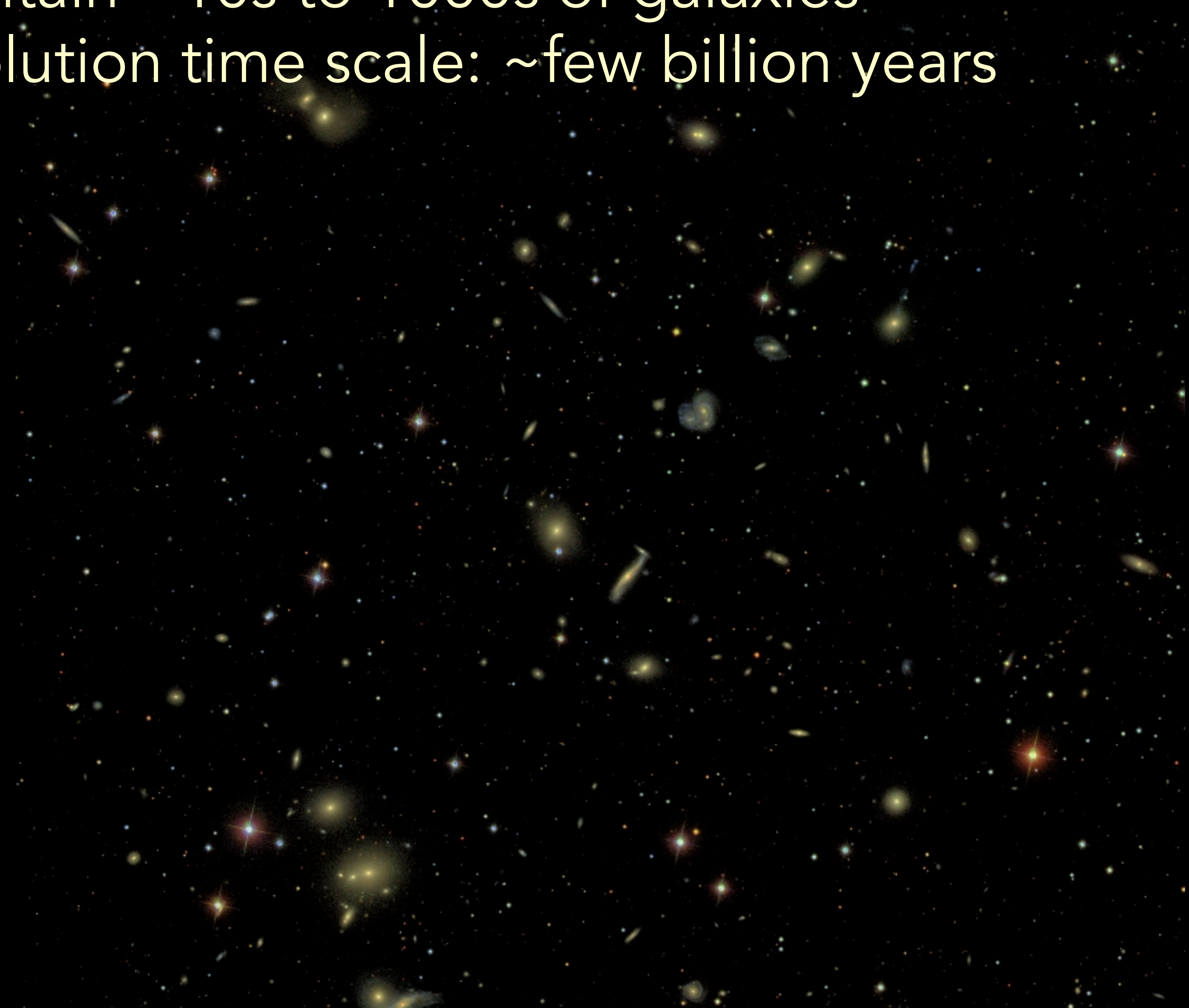
- A component that does not interact with (emit or absorb) light but whose presence is inferred from its gravitational effect on luminous matter or light.
- 1930's: initial evidence for dark matter (clusters)
- 1970's-80's: mounting evidence for dark matter (spiral galaxy rotation curves)
- 1990's-2000's: confirmation via gravitational lensing and cosmological measurements

Clusters of Galaxies: Size ~ few Million light years

Mass ~ 1 quadrillion (1000 x 1 trillion) M_{sun}

Contain ~10s to 1000s of galaxies

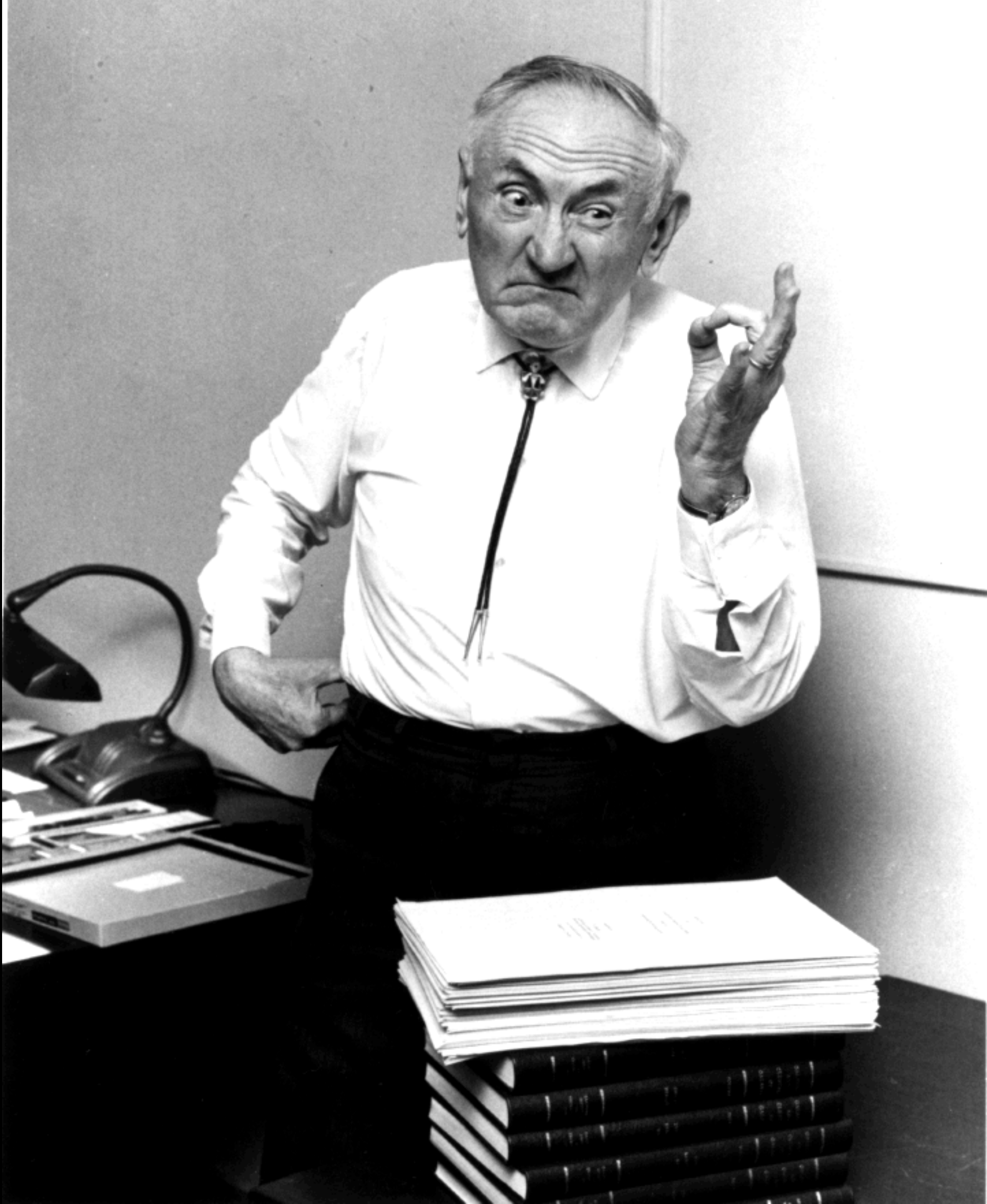
Evolution time scale: ~few billion years



Coma Cluster of Galaxies

Fritz Zwicky
(1898-1974)

1930's: studied the motions of galaxies within the Coma cluster, found they are moving too fast, ~1000 km/sec, to remain confined by Coma's gravitational field. Why is Coma still there?



Dark Matter (F. Zwicky)

- The galaxies in Coma cluster are moving around faster than we can explain.
- The gravity of something *that we can't see* must be keeping the galaxies from flying off into space: Dark Matter
- Clusters are mostly made of dark matter: galaxies are like sprinkles on dark matter ice cream.
- We know dark matter is there because it exerts gravitational pull on the galaxies we can see in clusters.

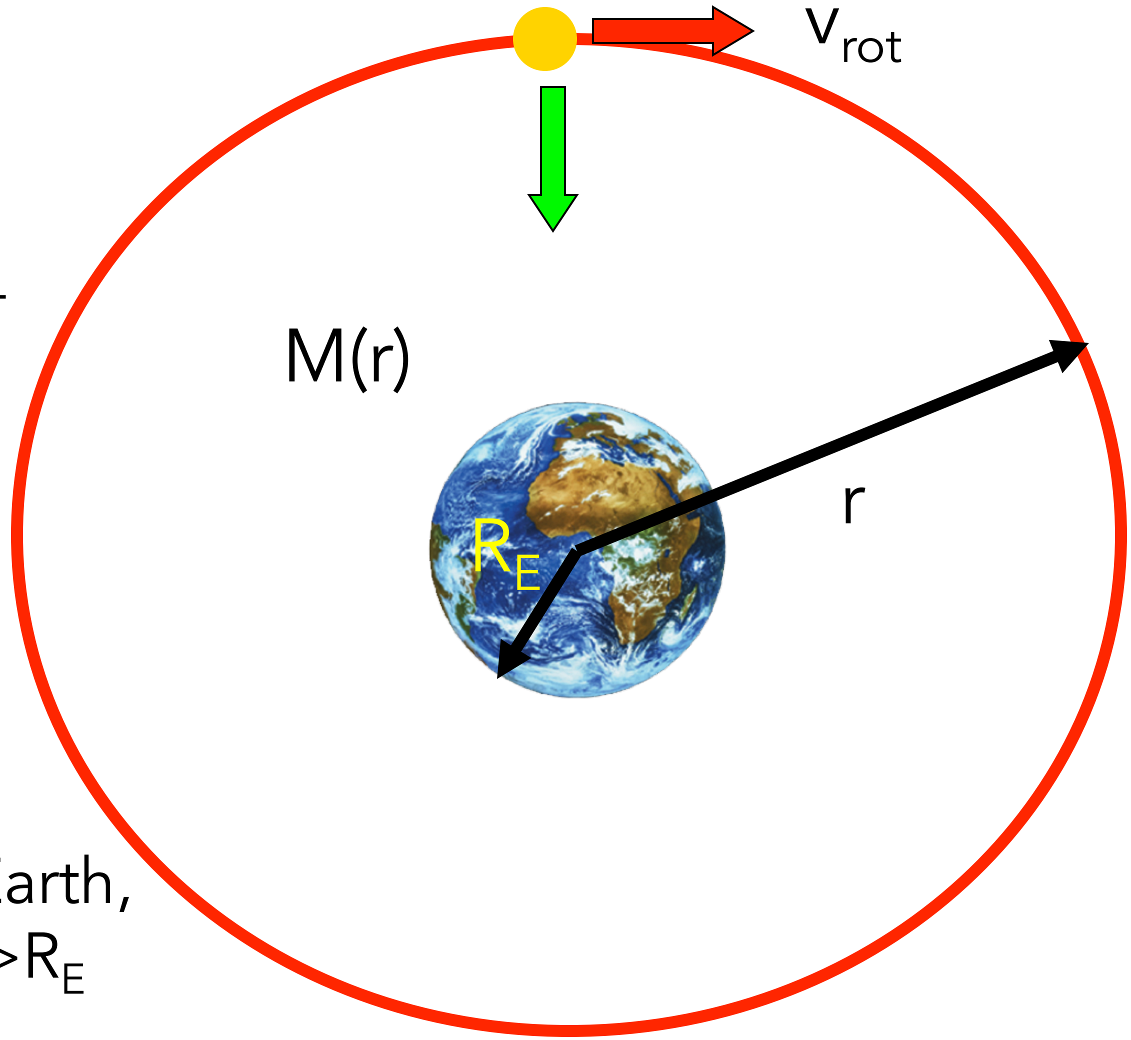
How do we determine Masses of Astrophysical Objects?

Recall Newtonian acceleration:

$$a = \frac{F}{m} = \frac{GMm}{r^2 m} = \frac{GM}{r^2}$$

For body in circular motion, $a = v_{rot}^2/r$, so

$v_{rot}^2 = GM(r)/r$



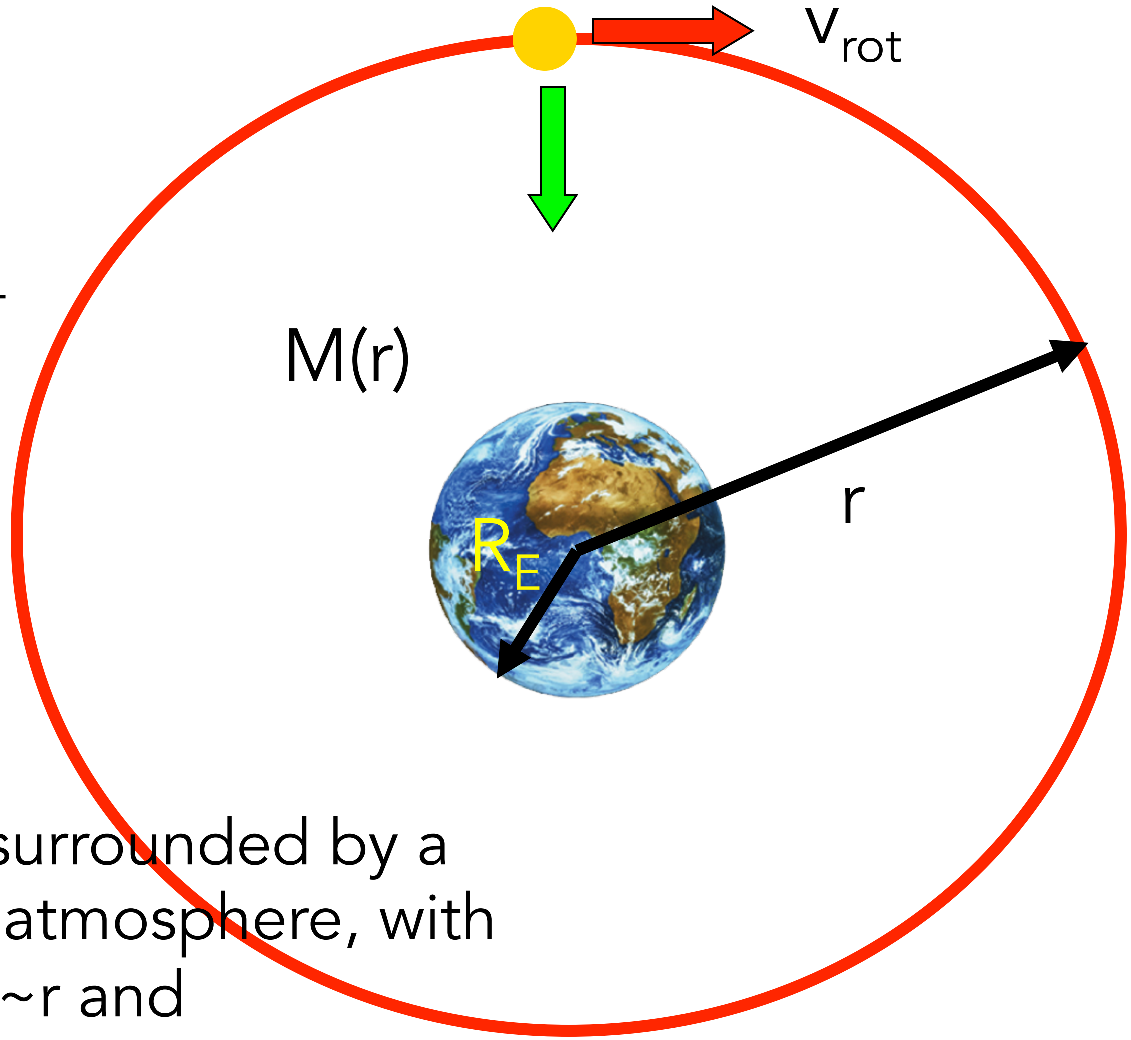
For satellite around Earth,
$M(r>R_E)$= const. for $r>R_E$
$v_{rot}(r>R_E) \propto r^{-1/2}$

How do we determine Masses of Astrophysical Objects?

Recall Newtonian acceleration:

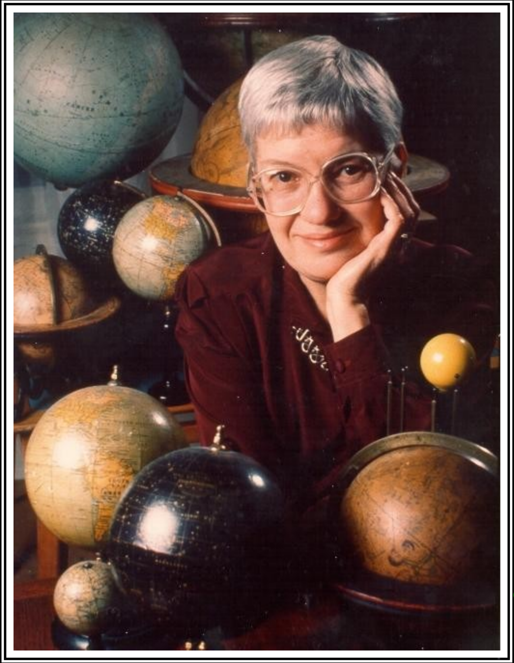
$$a = \frac{F}{m} = \frac{GMm}{r^2 m} = \frac{GM}{r^2}$$

For body in circular motion, $a = v_{rot}^2/r$, so $v_{rot}^2 = GM(r)/r$

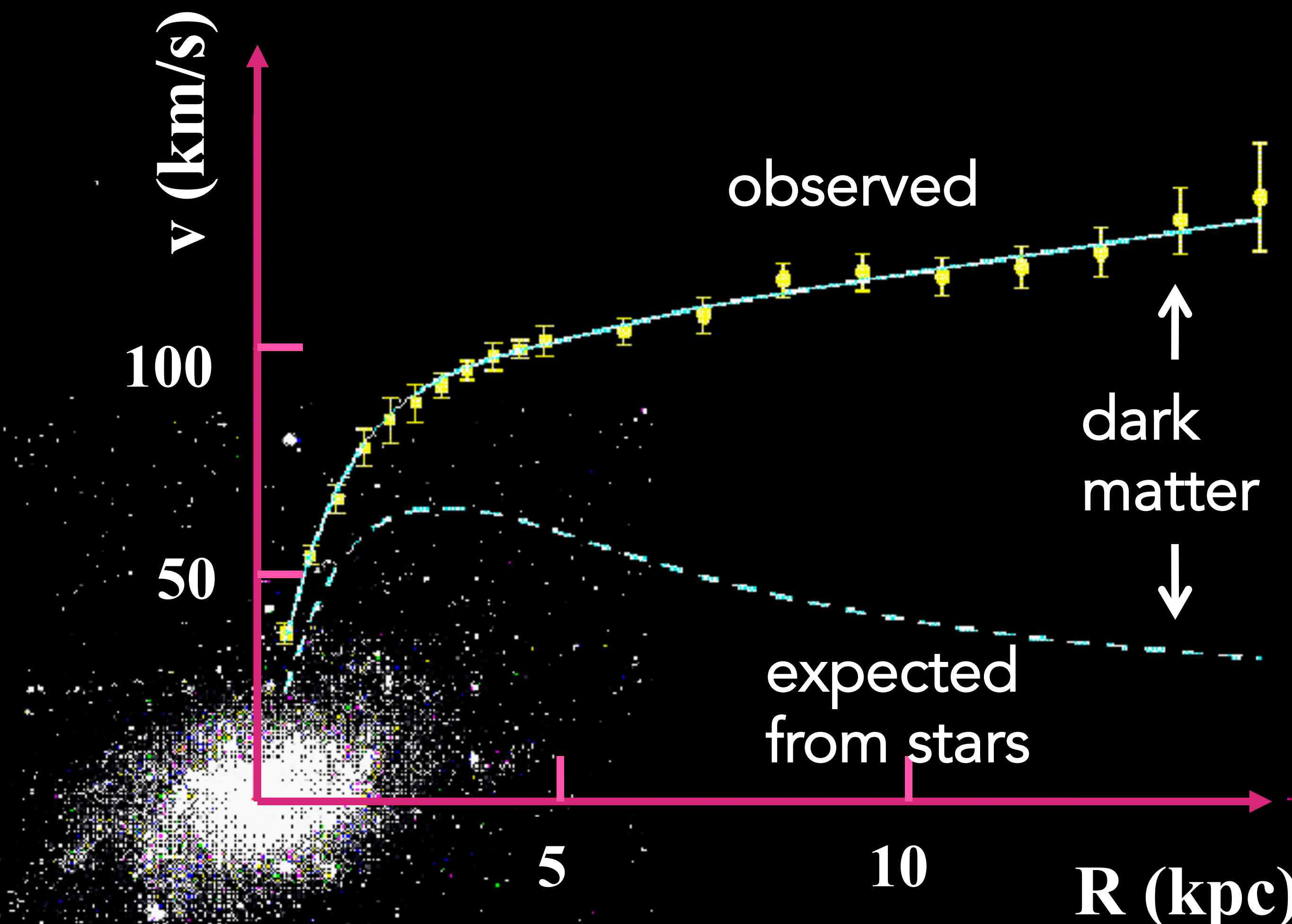


Suppose earth were surrounded by a much thicker, denser atmosphere, with $\rho \sim 1/r^2$. Then $M(r>R_E) \sim r$ and $v_{rot}(r>R_E) \propto$ constant

Rotation of Stars around Galaxies

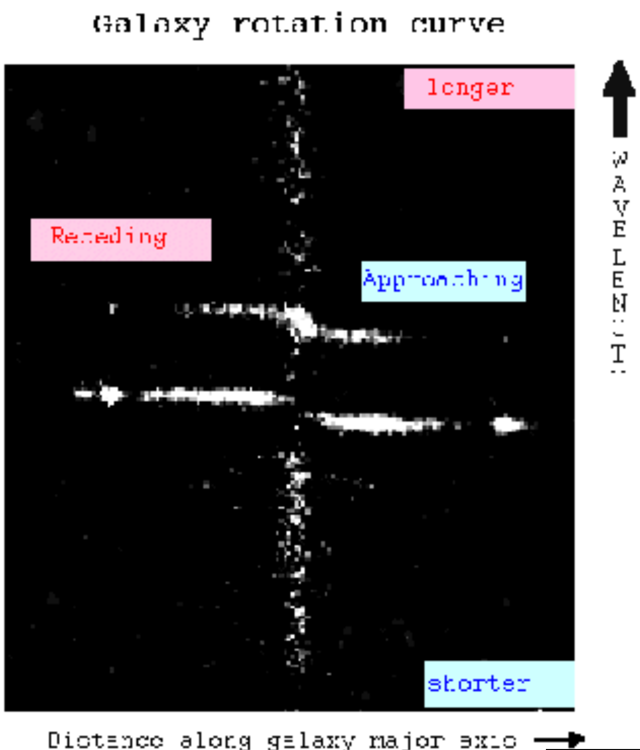


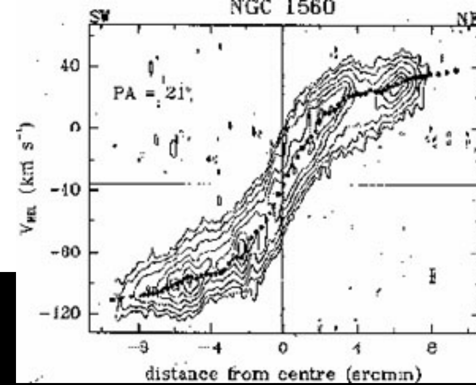
Vera Rubin
(1970's)

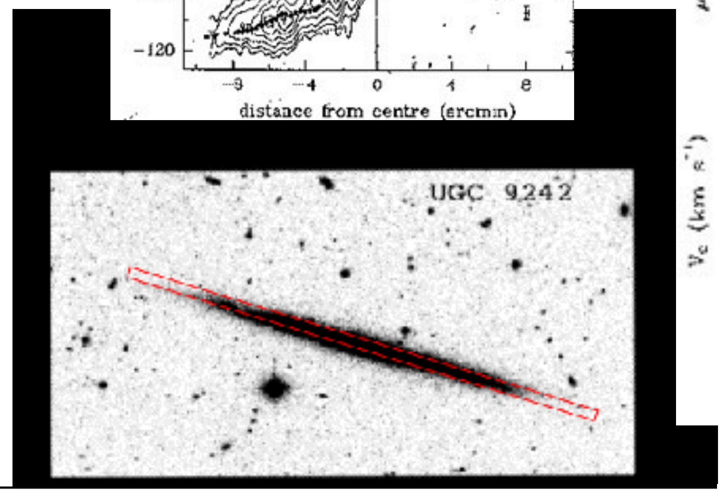


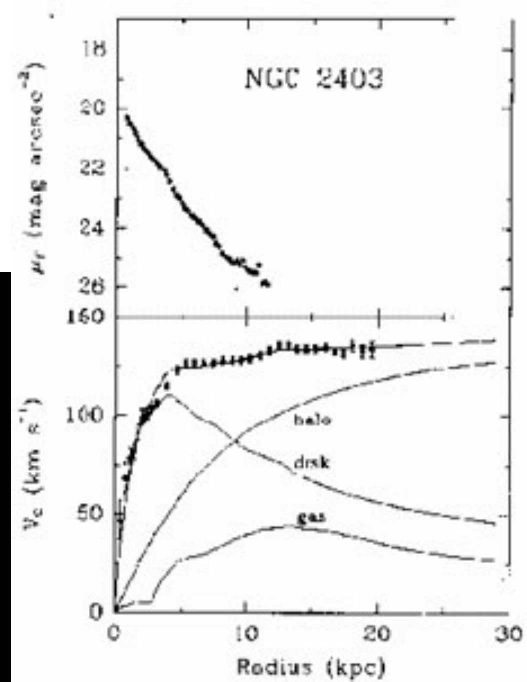
Galaxies surrounded by halos of dark matter

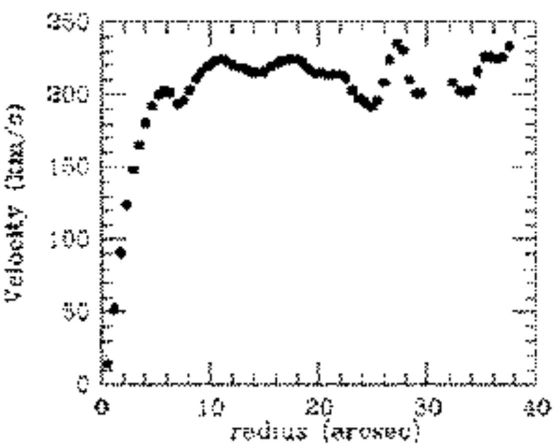
M33 rotation curve
(contrast Solar System)

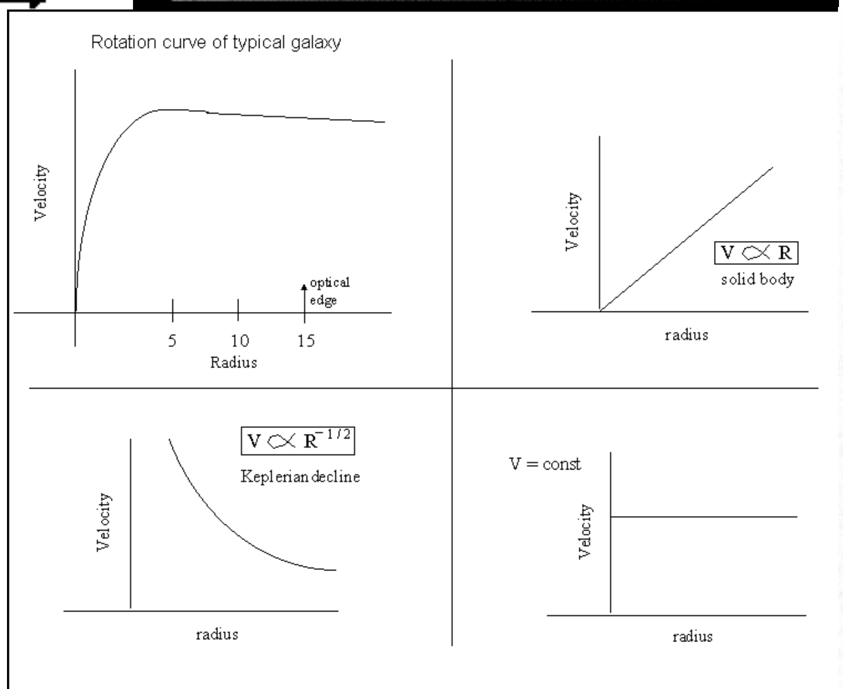

Galaxy rotation curve
longer
Receding
Approaching
shorter
WAVELENGTH
Distance along galaxy major axis

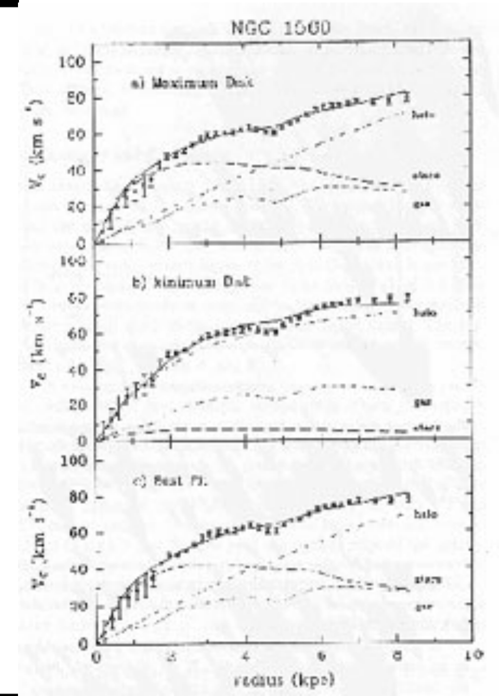

NGC 1560
SW
NE
PA = 21°
distance from centre (arcmin)


UGC 9242


NGC 2403
halo
disk
gas
Radius (kpc)


Velocity (km/s)
radius (arcsec)


Rotation curve of typical galaxy
Velocity
optical edge
Radius
V ∝ R
solid body
radius
V ∝ R^-1/2
Keplerian decline
V = const


NGC 1560
a) Maximum Disk
b) Minimum Disk
c) Best Fit
halo
stars
gas
radius (kpc)

Dark Matter (V. Rubin)

- The stars in a galaxy are moving around faster than we can explain.
- The gravity of something *that we can't see* must be keeping the stars from flying off into space: Dark Matter
- <u>Galaxies are mostly made of dark matter</u>: stars are like sprinkles on dark matter ice cream.
- We know dark matter is there because it exerts gravitational pull on the stars we can see in galaxies.