AS 4022 Cosmology

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Lecture Slides will be on this web page:

http://star-www.st-and.ac.uk/~kdh1/cos/cos.html

Text (intro): Andrew Liddle: Intro to Modern Cosmology

(intermediate): Barbara Ryden: Introduction to Cosmology

Dan Maoz: Astrophysics in a Nutshell

(advanced): John Peacock: Cosmological Physics

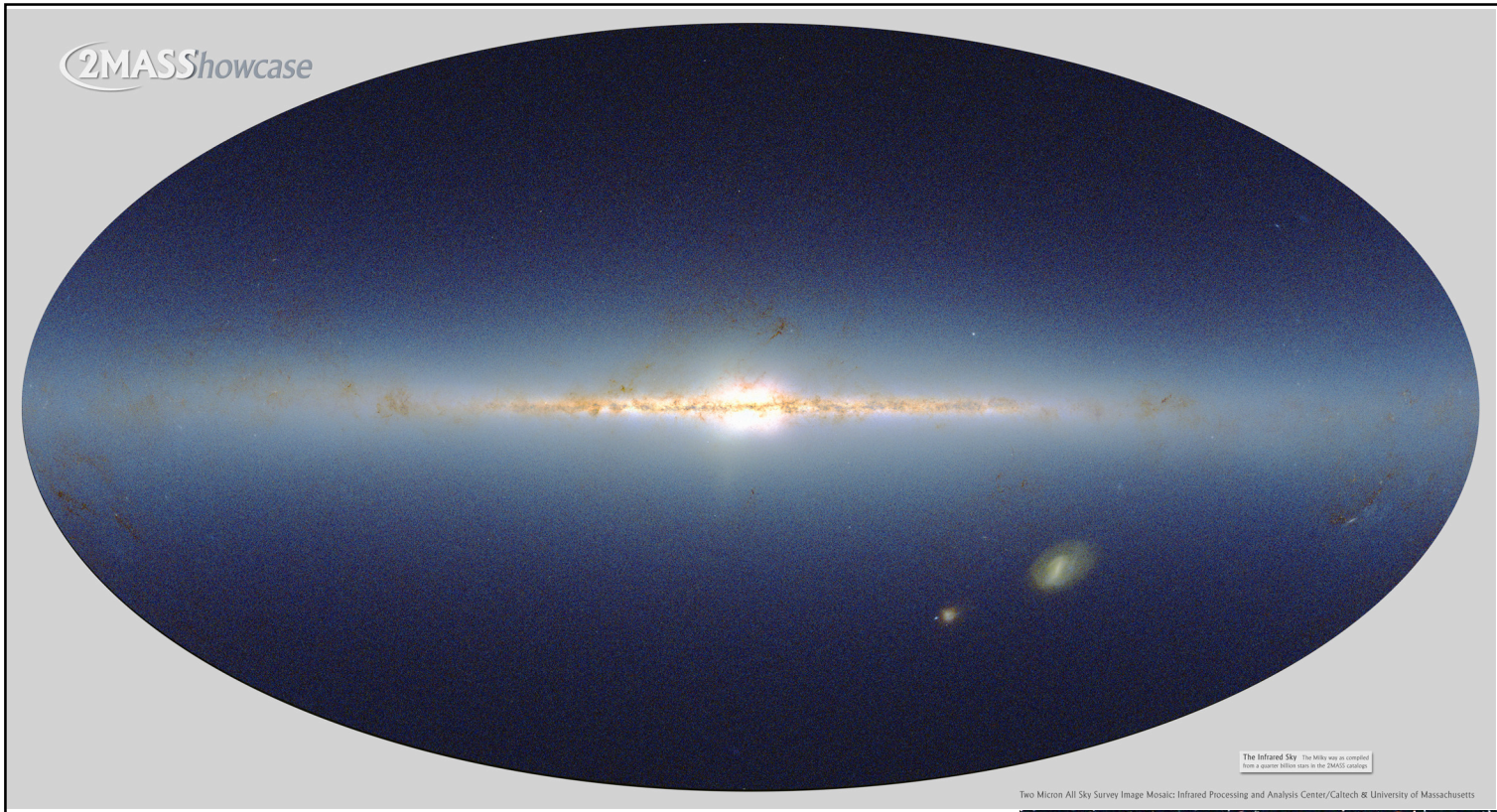
Web Lecture Notes: John Peacock, Ned Wright

Lecture 1

Review / Overview

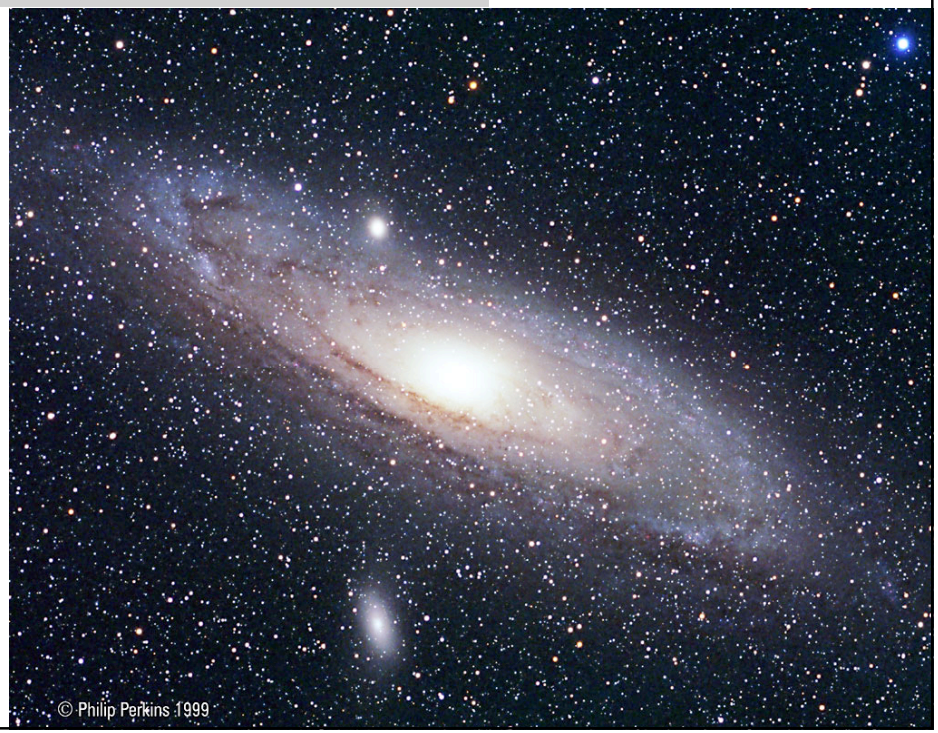
Why Study Cosmology?

- **Fascinating questions:**
  - Birth, life, destiny of our Universe
  - Hot Big Bang --> (75% H, 25% He) observed in stars!
  - Formation of structure (galaxies …)
- **Technology -> much recent progress:**
  - Precision cosmology: uncertainties of 50% --> 2%
- **Deep mysteries remain:**
  - Dark Matter? Dark Energy? General Relativity wrong?
- **Stretches your mind:**
  - Curved expanding spaces, looking back in time, …



Milky Way

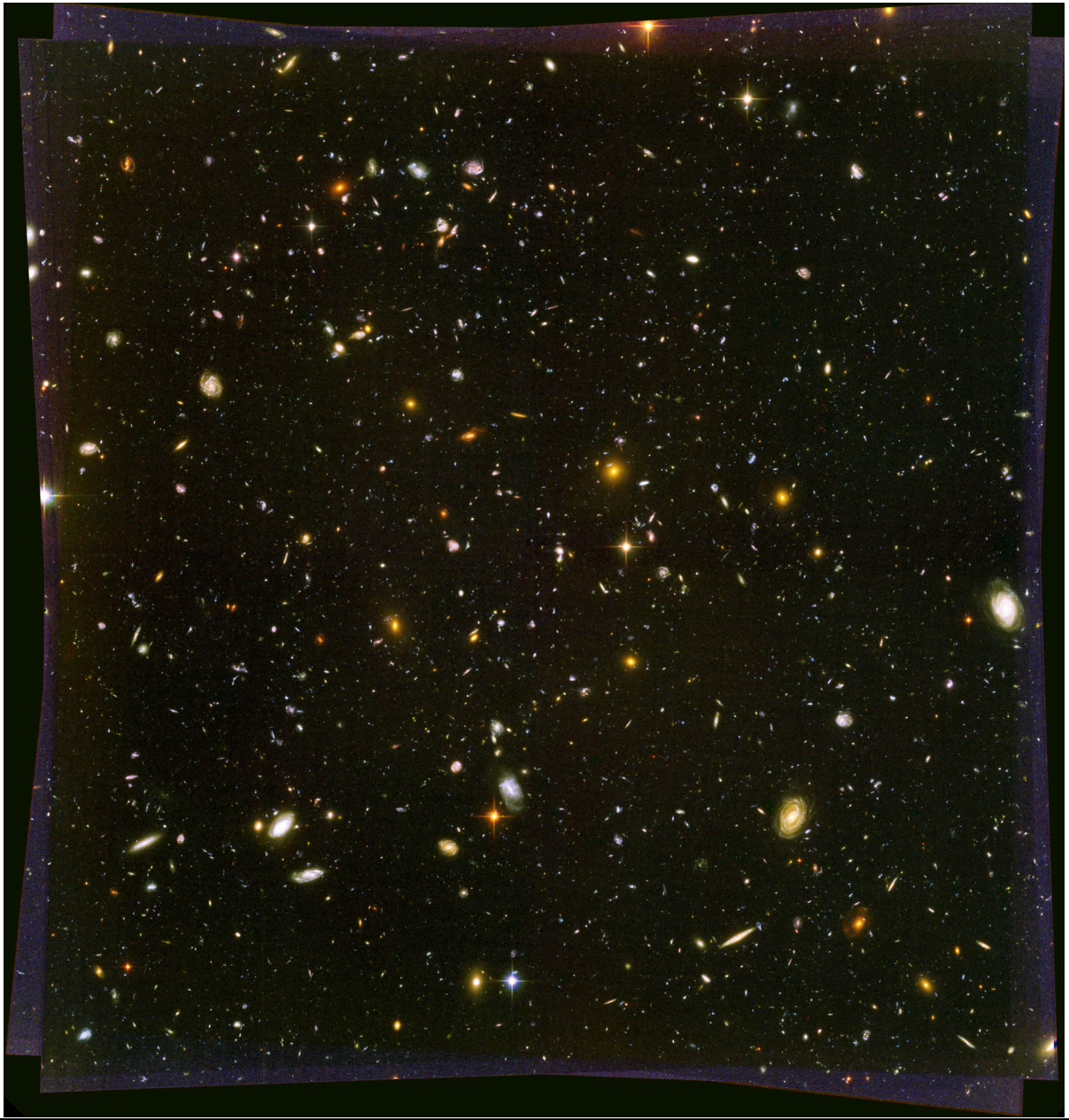
Andromeda



~10^{10} stars per Galaxy:

Hubble Deep Field:

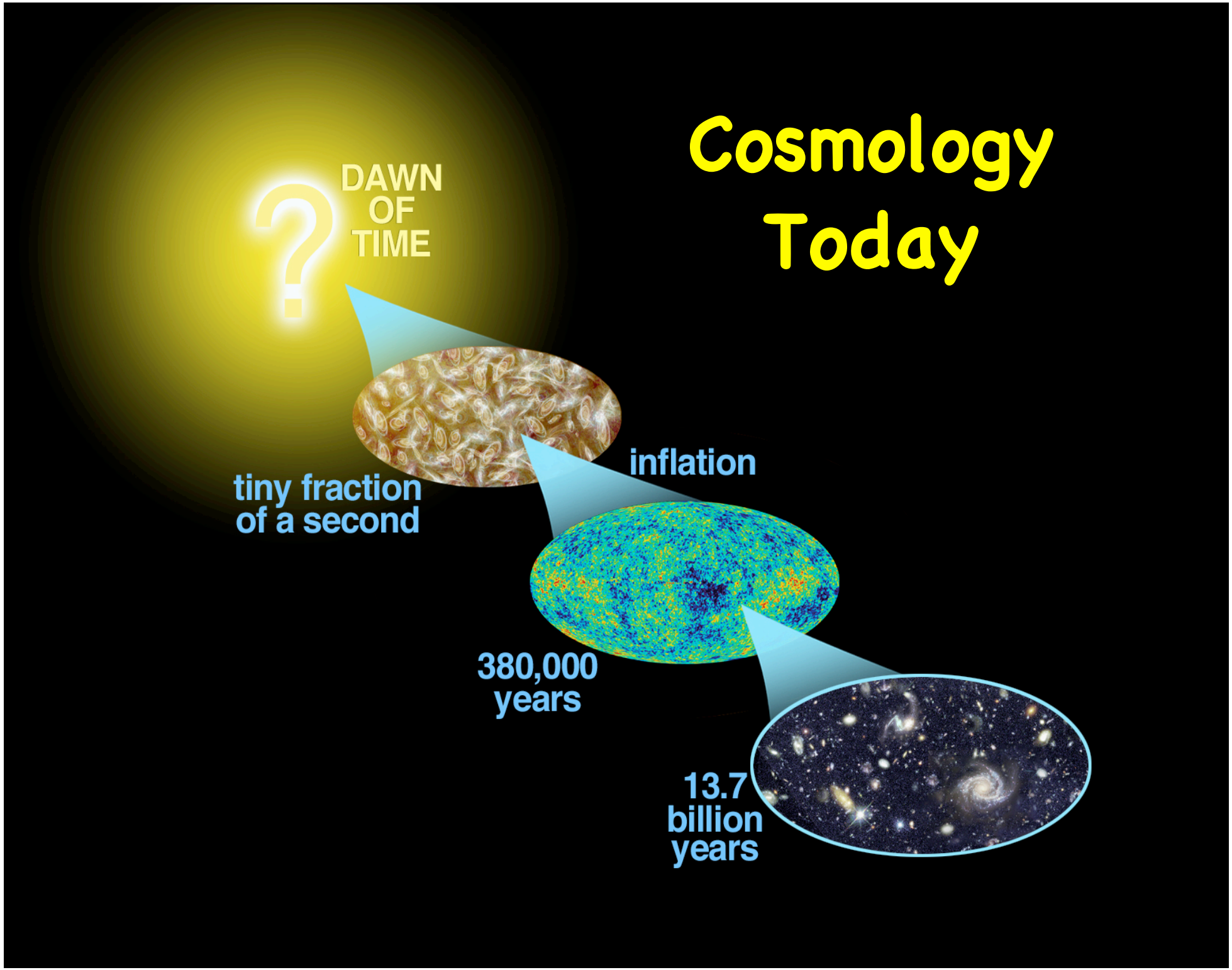
At faint magnitudes, we see **thousands of Galaxies for every star** !



~10^{10} galaxies in the visible Universe

~10^{10} stars per galaxy

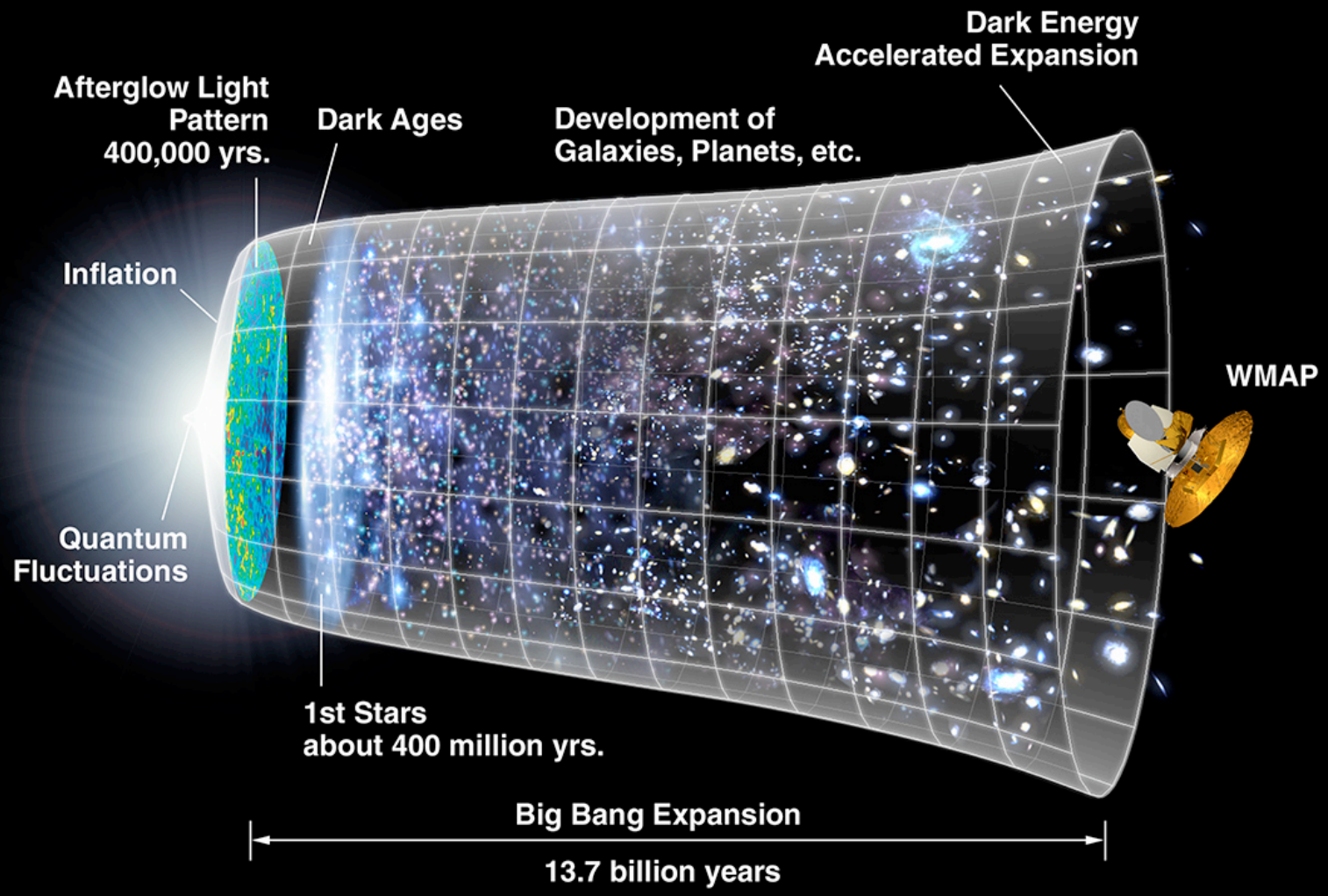
~10^{20} stars in the visible Universe


Cosmology Today
?
DAWN OF TIME
tiny fraction of a second
inflation
380,000 years
13.7 billion years

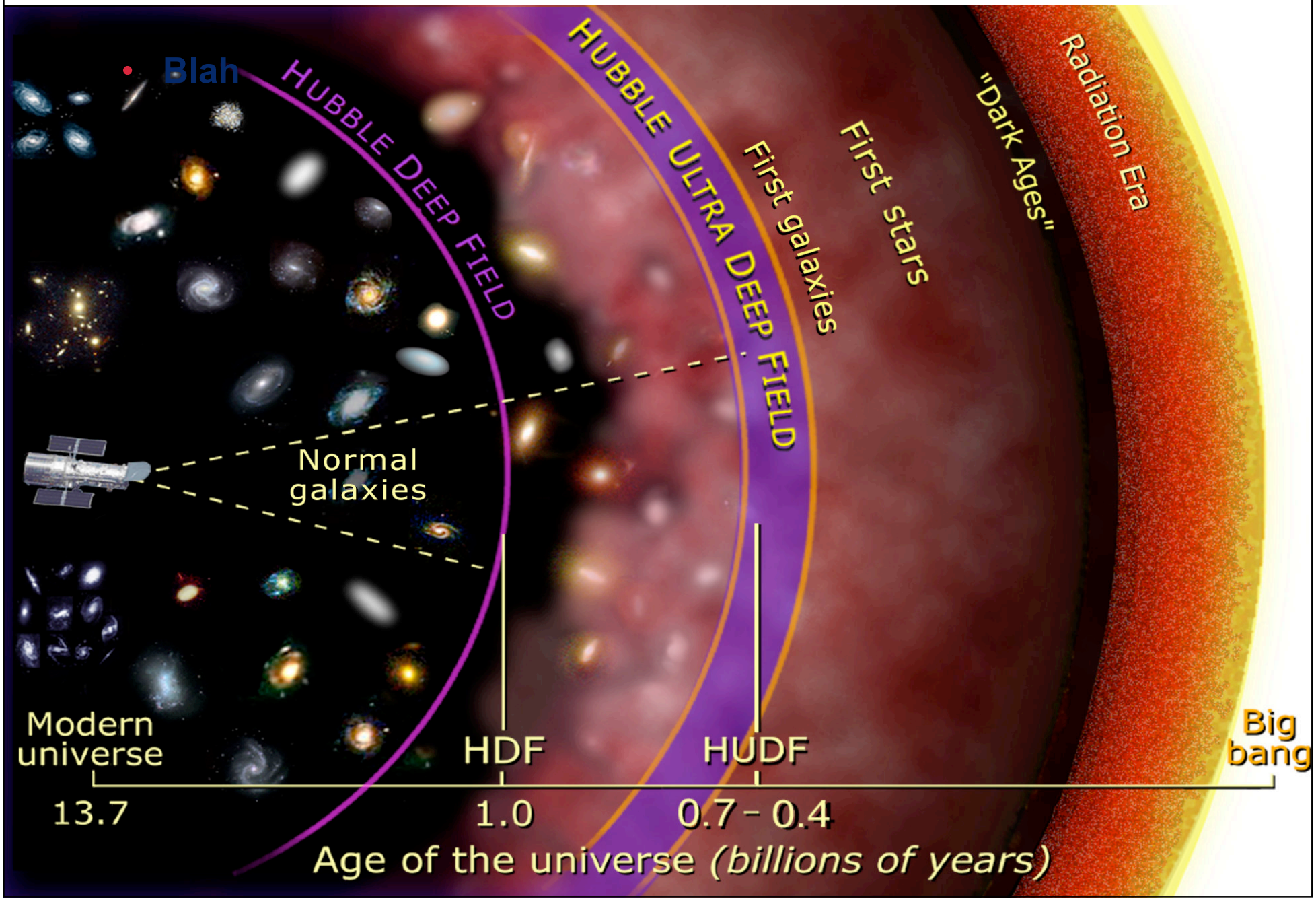
1980: Inflation (Alan Guth)

- Universe born from "**nothing**" ?
- A **quantum fluctuation** produces a tiny bubble of "**False Vacuum**".
- High vacuum energy drives **exponential expansion**, also known as **"inflation."**
- Universe expands by huge factor in tiny fraction of second, as false vacuum returns to true vacuum.
- Expansion so fast that **virtual particle-antiparticle pairs** get separated to become **real particles and anti-particles**.
- Stretches out all structures, giving a **flat geometry** and uniform T and ρ, with **tiny ripples**.
- Inflation launches the **Hot Big Bang**!

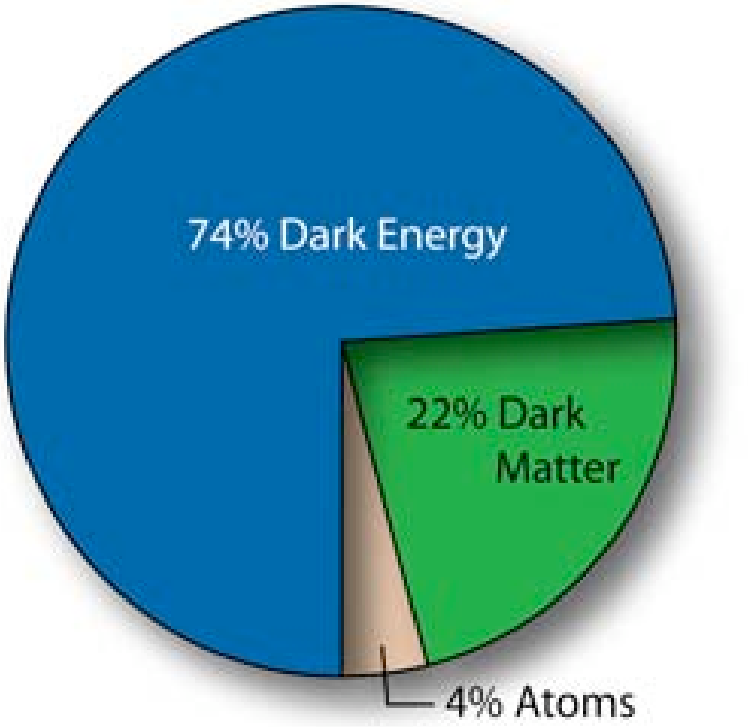
Accelerating/Decelerating Expansion



Looking Back in Time



Current Mysteries



Dark Matter ?

Holds Galaxies together
Triggers Galaxy formation

Dark Energy ?

Drives Cosmic Acceleration.

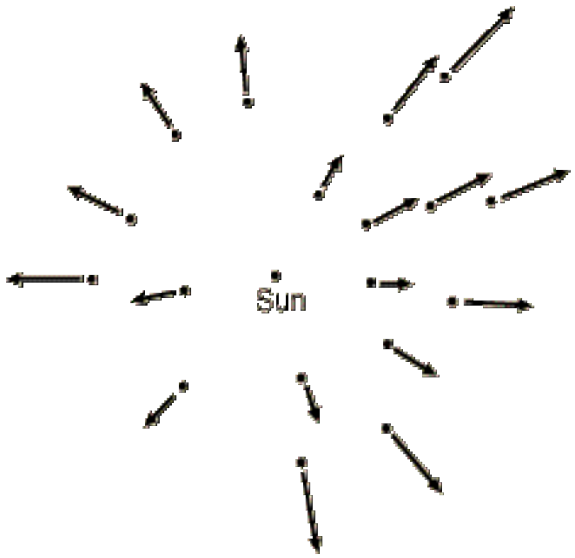
Modified Gravity ?

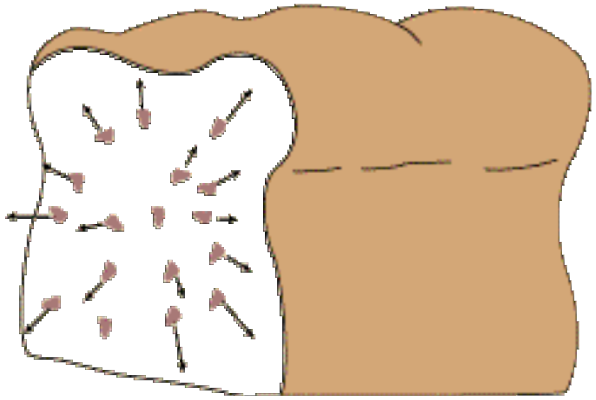
General Relativity wrong ?

Cosmology Milestones

- 1925 Galaxy redshifts $\lambda = \lambda_0 \left(1 + z \right)$ $V = c\, z$
  - Isotropic expansion. (Hubble law $V = H_0 d$)
  - Finite age. ($t_0 = 13 \times 10^9$ yr)
- 1965 Cosmic Microwave Background (CMB)
  - Isotropic blackbody. $T_0 = 2.7$ K
  - Hot Big Bang $T = T_0 (1 + z)$
- 1925 General Relativity Cosmology Models :
  - Radiation era: $R \sim t^{1/2}$ $T \sim t^{-1/2}$
  - Matter era: $R \sim t^{2/3}$ $T \sim t^{-2/3}$
- 1975 Big Bang Nucleosynthesis (BBN)
  - light elements (^{1}H … ^{7}Li) $t \sim 3$ min $T \sim 10^9$ K
  - primordial abundances (75% H, 25% He) as observed!

Isotropic Expansion





Hubble law :

$$V = H_0\, d$$

Hubble "constant":

$H_0 \approx 500$ km s^{-1}Mpc^{-1}

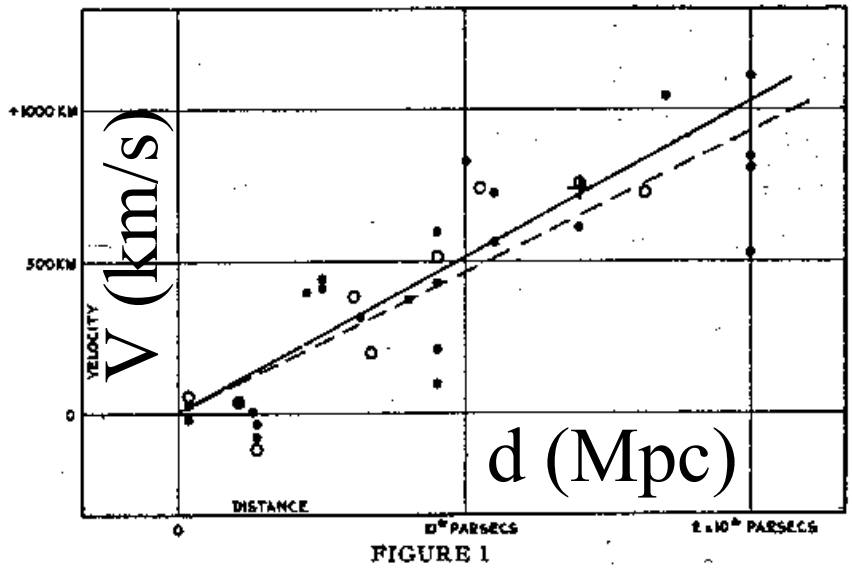


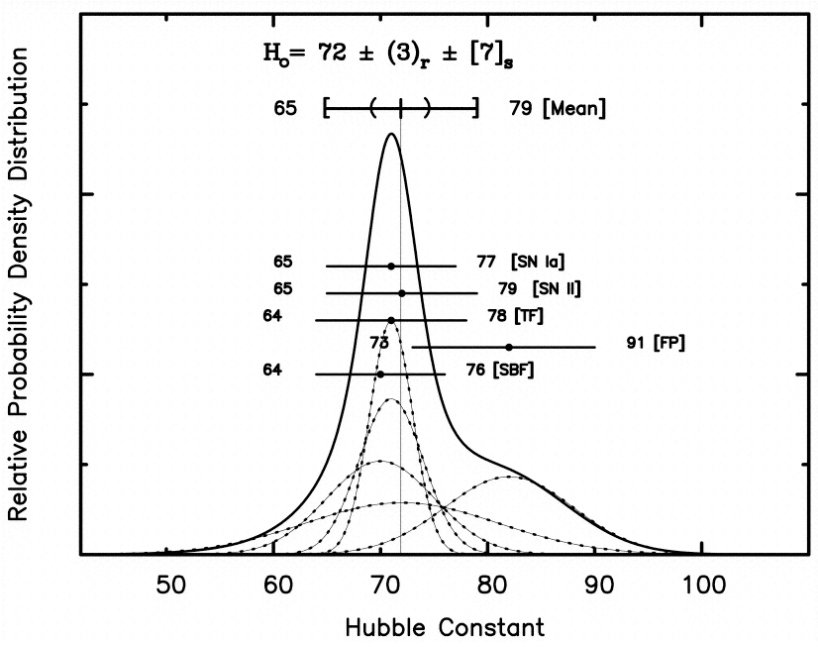
FIGURE 1

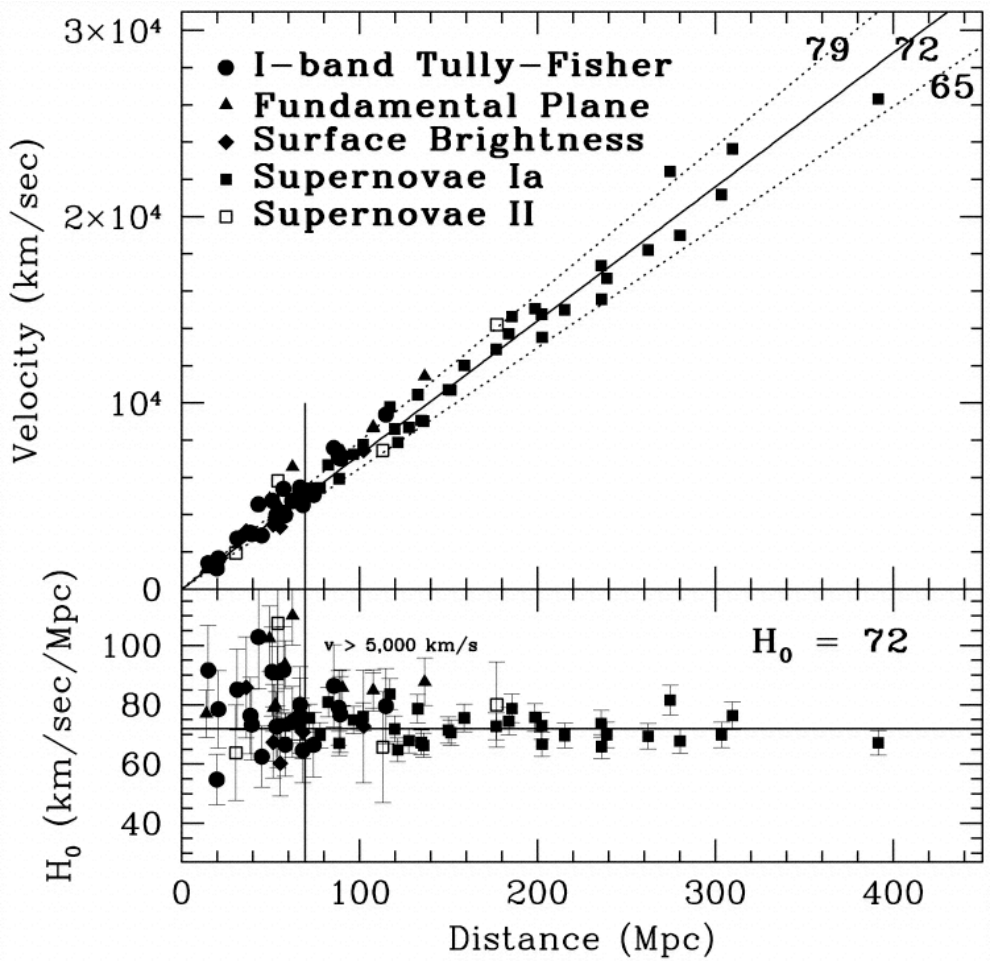
WRONG ! Extinction by interstellar dust was not then known, giving incorrect distances.

H_0 from the HST Key Project

$$H_0 \approx 72 \pm 3 \pm 7 \quad \text{km s}^{-1}\ \text{Mpc}^{-1}$$

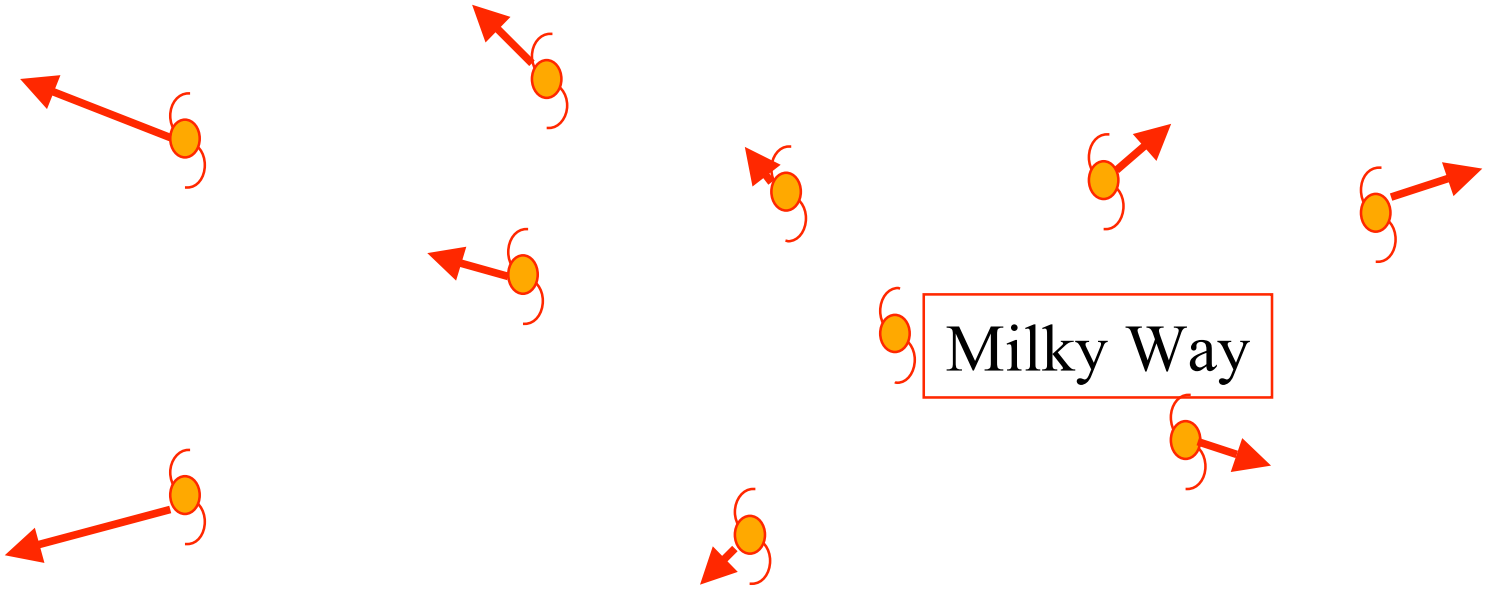
Freedman, et al.
2001 ApJ 553, 47.





Universal Expansion

Hubble's law appears to violate
The Copernican Principle.
Are we at a special location?

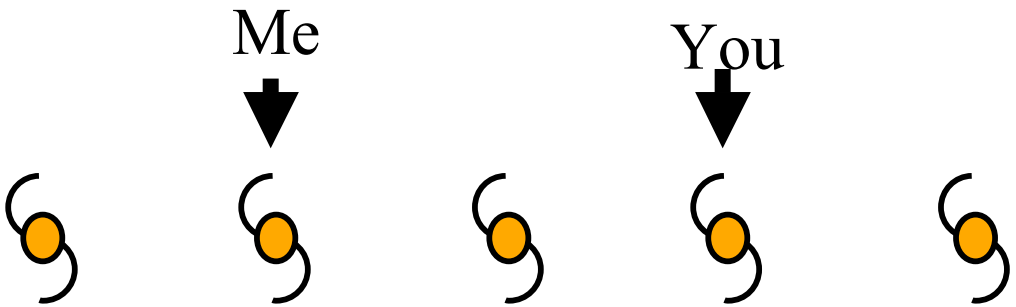


Is everything moving away from us?

Universal Expansion

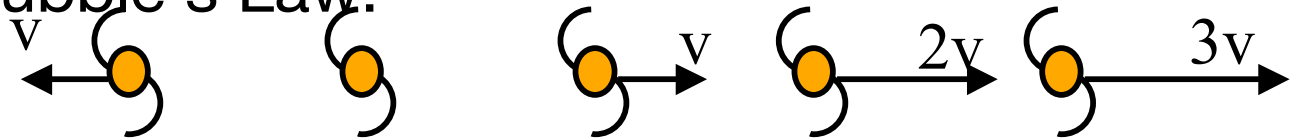
Q : What is so special about our location ?

A : Nothing !

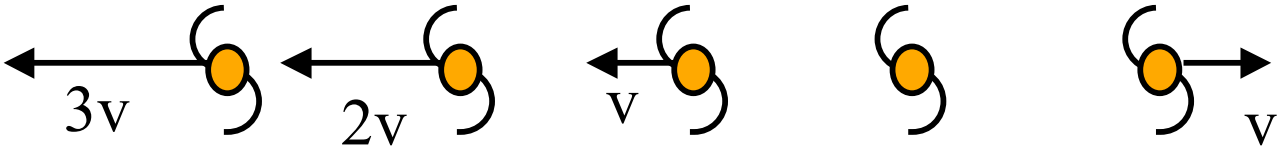


According to Hubble's Law:

I see:



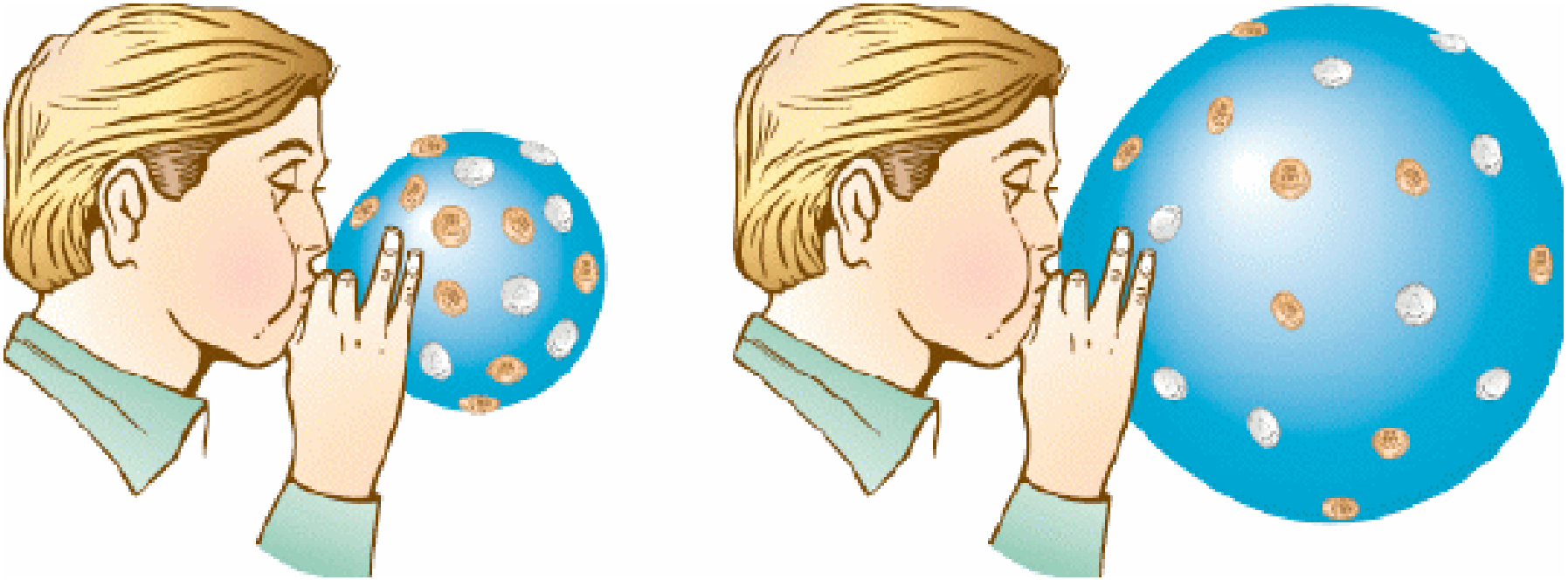
You see:



We all see the same Hubble law expansion.

The Universal Expansion

- **An observer in any galaxy sees all other galaxies moving away, with the same Hubble law.**
- **Expansion (or contraction) produces a centre-less but dynamic Universe.**

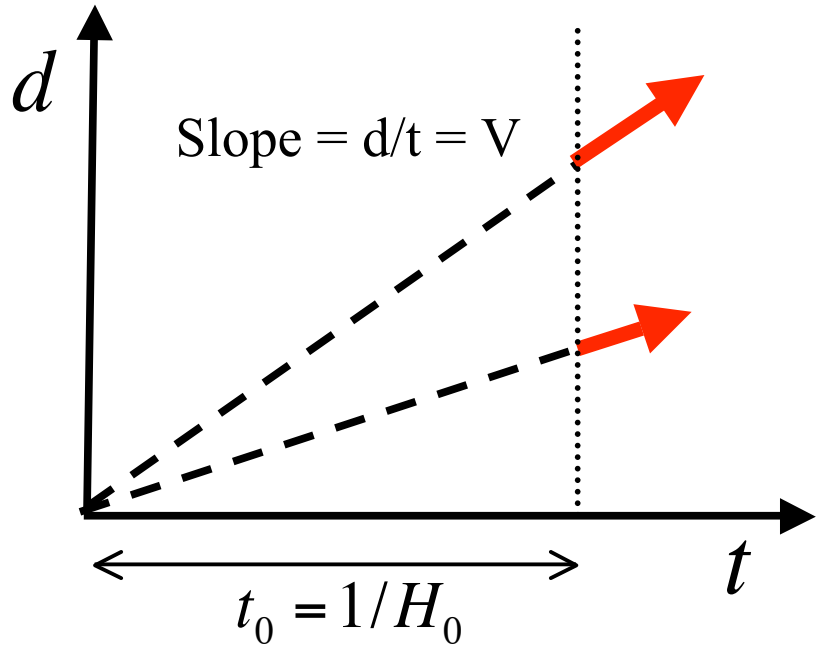


Hubble Law --> Finite age.

$$V = H_0\, d$$

$$t_0 \approx \frac{d}{V} = \frac{1}{H_0} = \left(\frac{1\,\text{Mpc}}{72\,\text{km/s}}\right)\left(\frac{3\times10^{19}\,\text{km}}{\text{Mpc}}\right)\left(\frac{1\,\text{yr}}{3\times10^{7}\,\text{s}}\right)$$

$$\approx 13\times10^{9}\,\text{yr} = 13\ \text{Gyr}.$$



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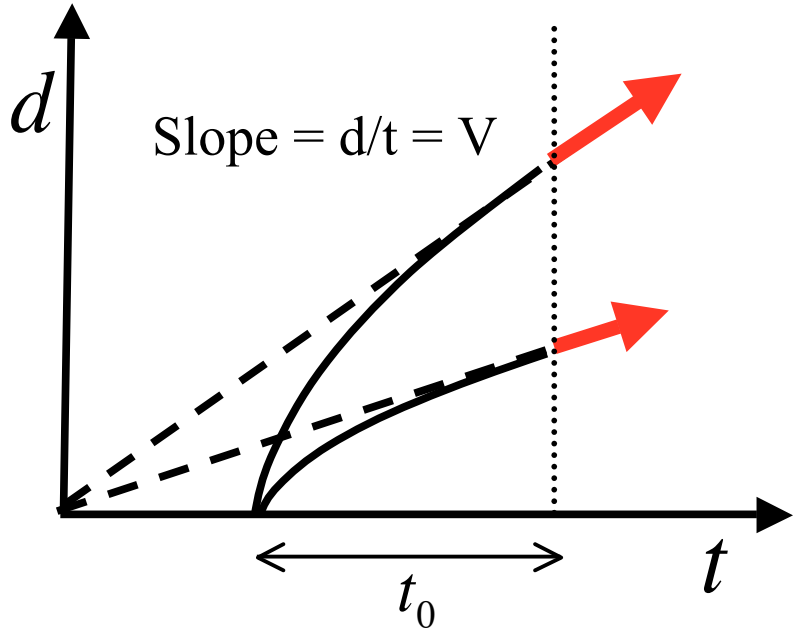
Gravity decelerates:

$$t_0 \approx \frac{2}{3}\frac{1}{H_0}\,.$$



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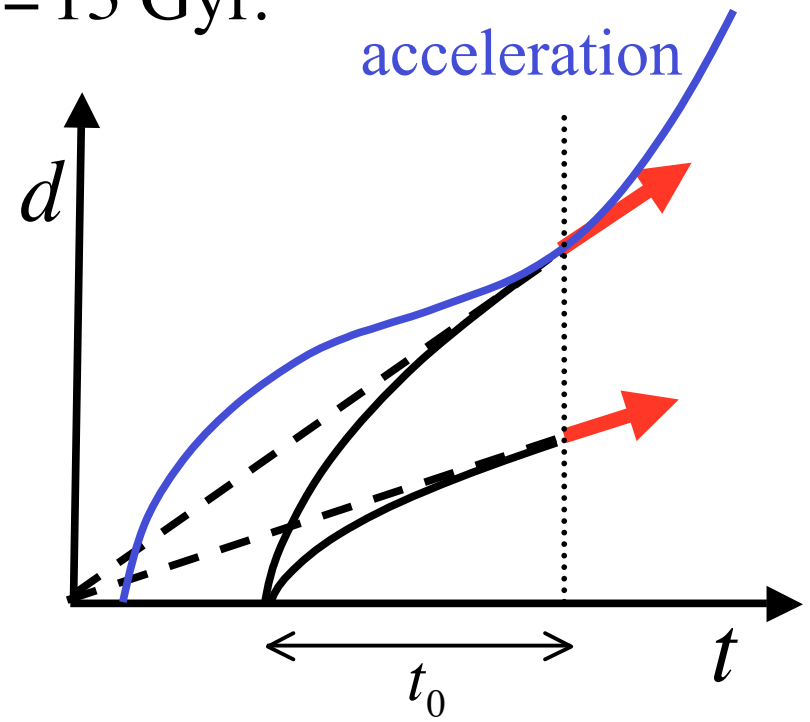
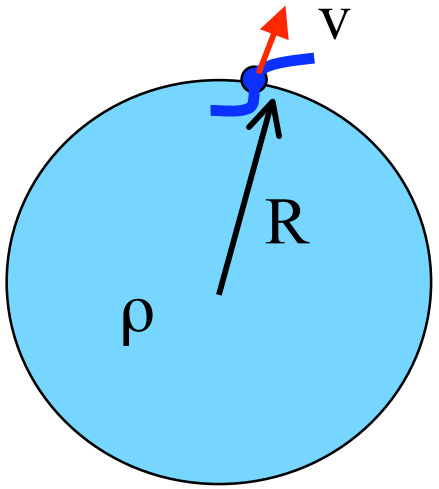
Gravity decelerates:

Dark Energy accelerates

$$t_0 > \frac{2}{3}\frac{1}{H_0}\,.$$



Critical Density



- Newtonian analogy:

escape velocity:

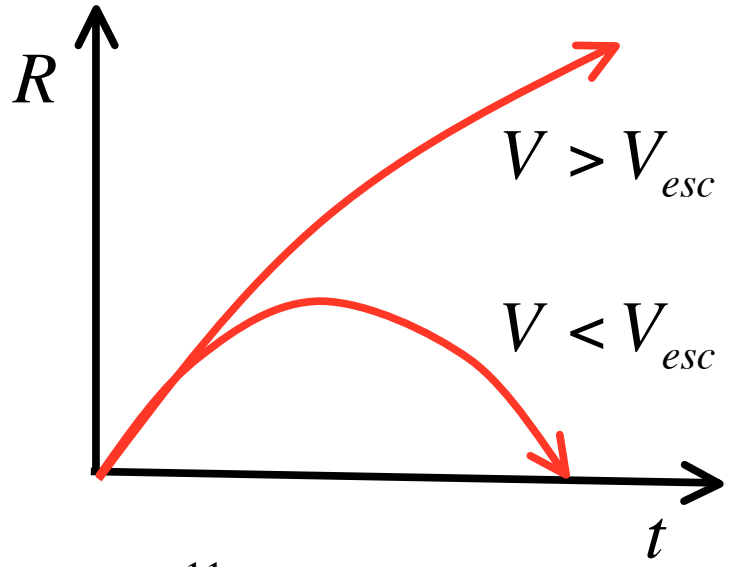
$$V_{esc}^{\ 2} = \frac{2\,G\,M}{R} = \frac{2\,G}{R}\left(\frac{4\pi\,R^3\rho}{3}\right) = \frac{8\pi\,G\,R^2\rho}{3}$$

Hubble expansion:

$$V = H_0\,R$$

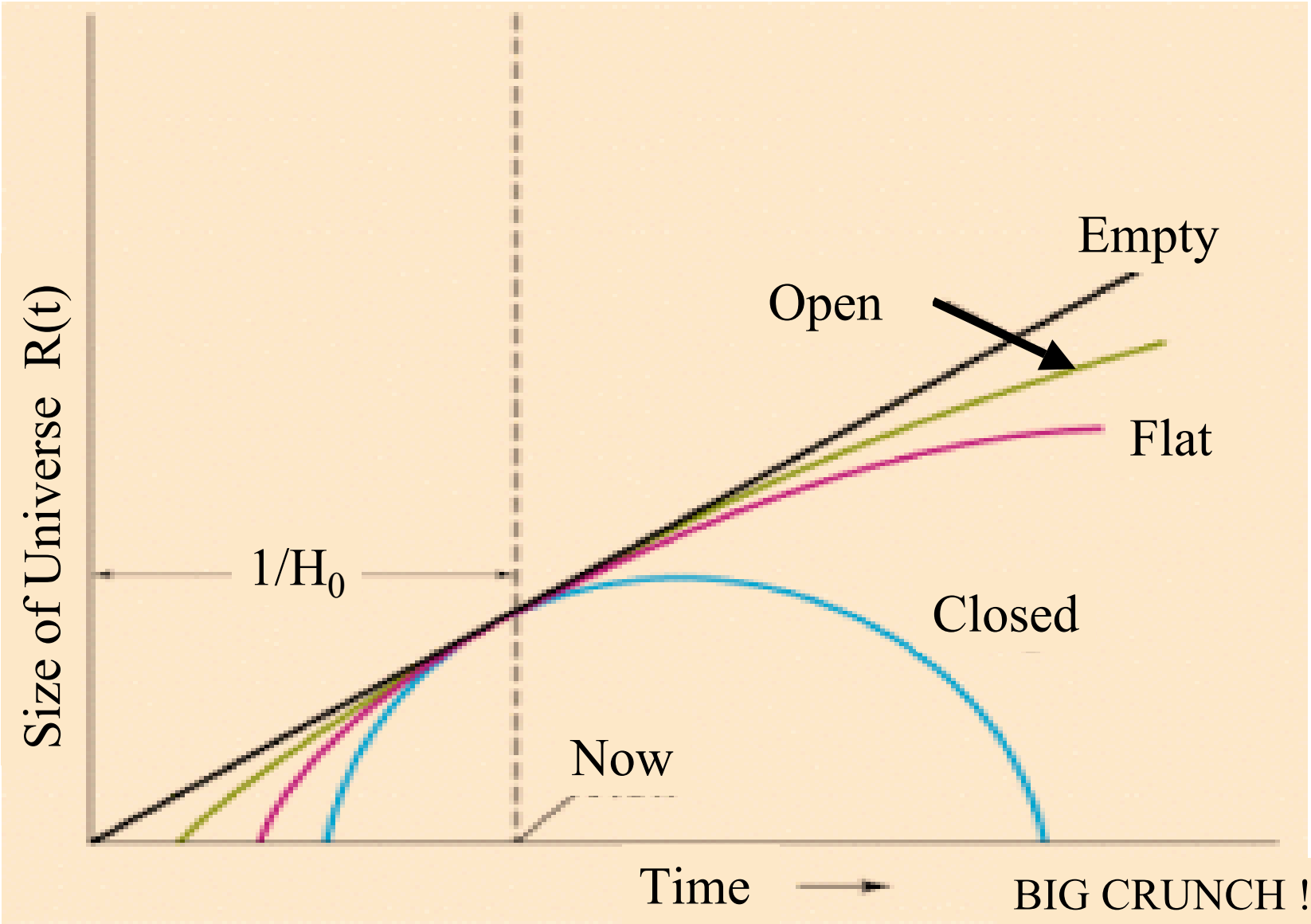
critical density:

$$\left(\frac{V_{esc}}{V}\right)^2 = \frac{8\pi\,G\rho}{3\,H_0^{\ 2}} = \frac{\rho}{\rho_c}$$



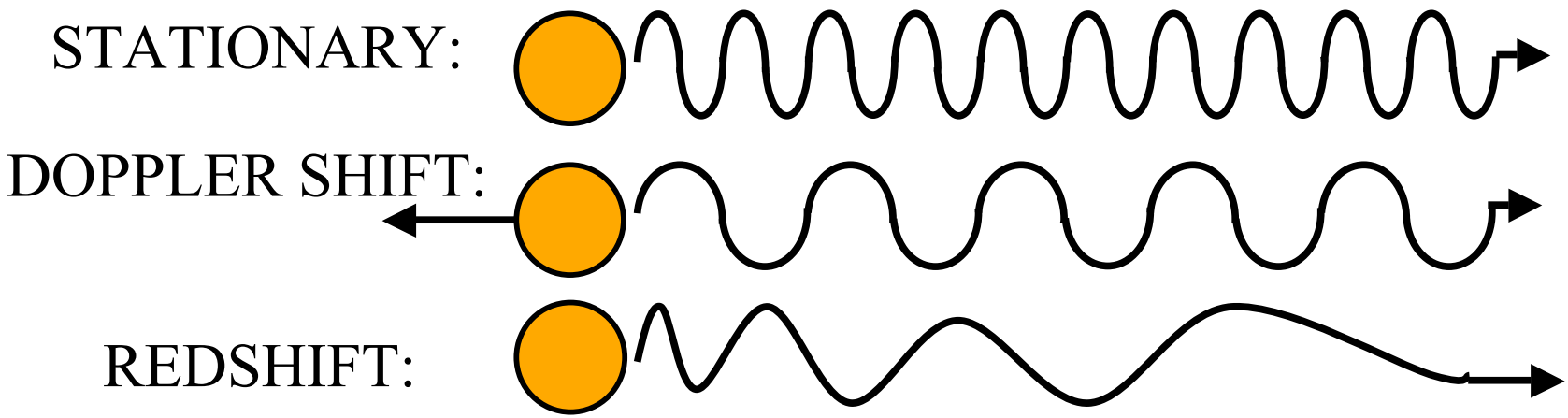
$$\rho_c \equiv \frac{3\,H_0^{\ 2}}{8\pi\,G} \approx 10^{-26}\,\mathrm{kg\ m^{-3}} \approx \frac{1.4\times10^{11}\,\mathrm{Msun}}{(\mathrm{Mpc})^3}$$

Re-collapse or Eternal Expansion ?



Redshift

- Expansion is a stretching of space.
- The more space there is between you and a galaxy, the faster it appears to be moving away.
- Expansion **stretches the wavelength of light**, causing a galaxy's spectrum to be REDSHIFTED:



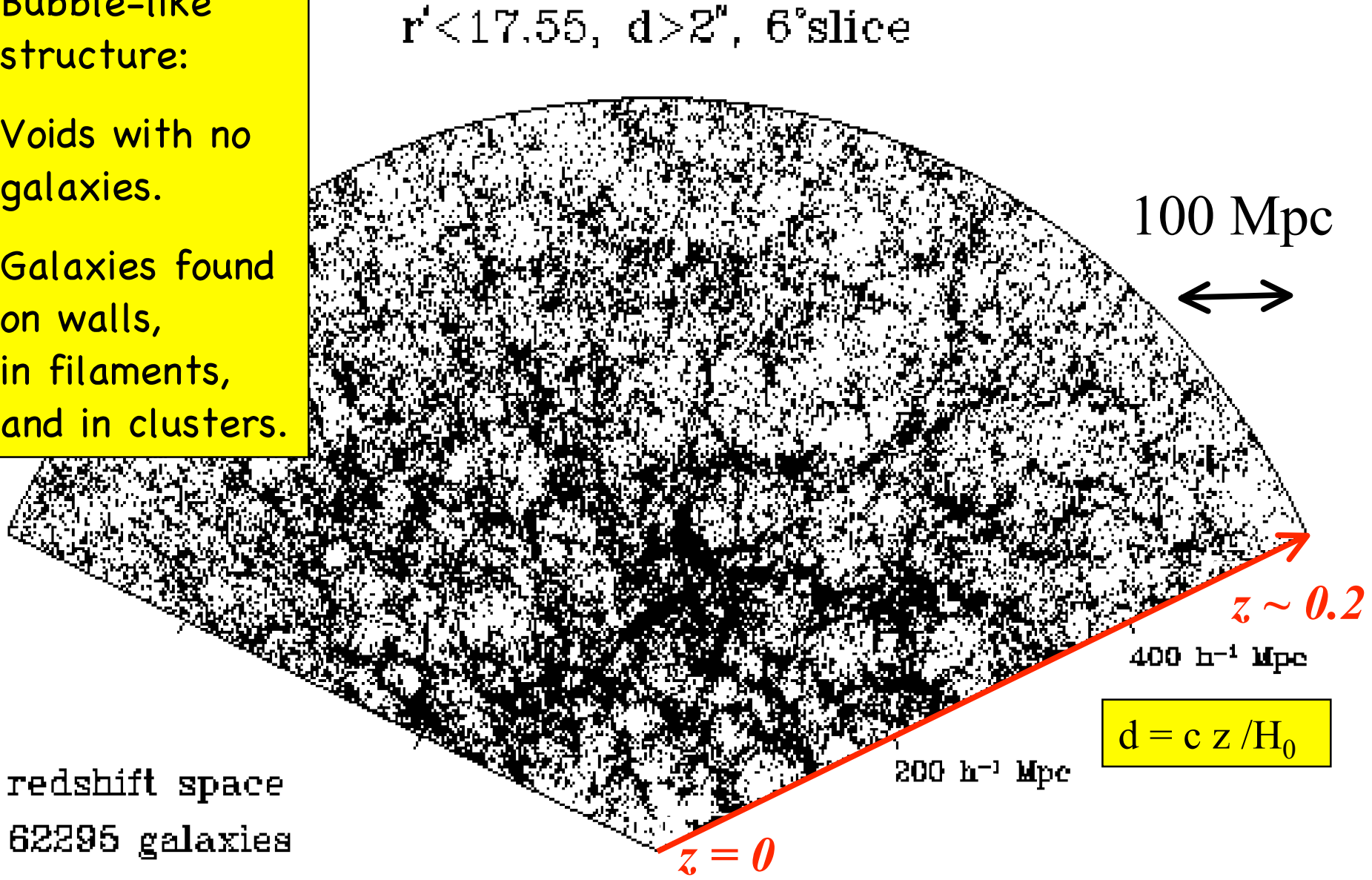
REDSHIFT IS NOT THE SAME AS DOPPLER SHIFT

Galaxy Redshift Surveys

Bubble-like structure:

Voids with no galaxies.

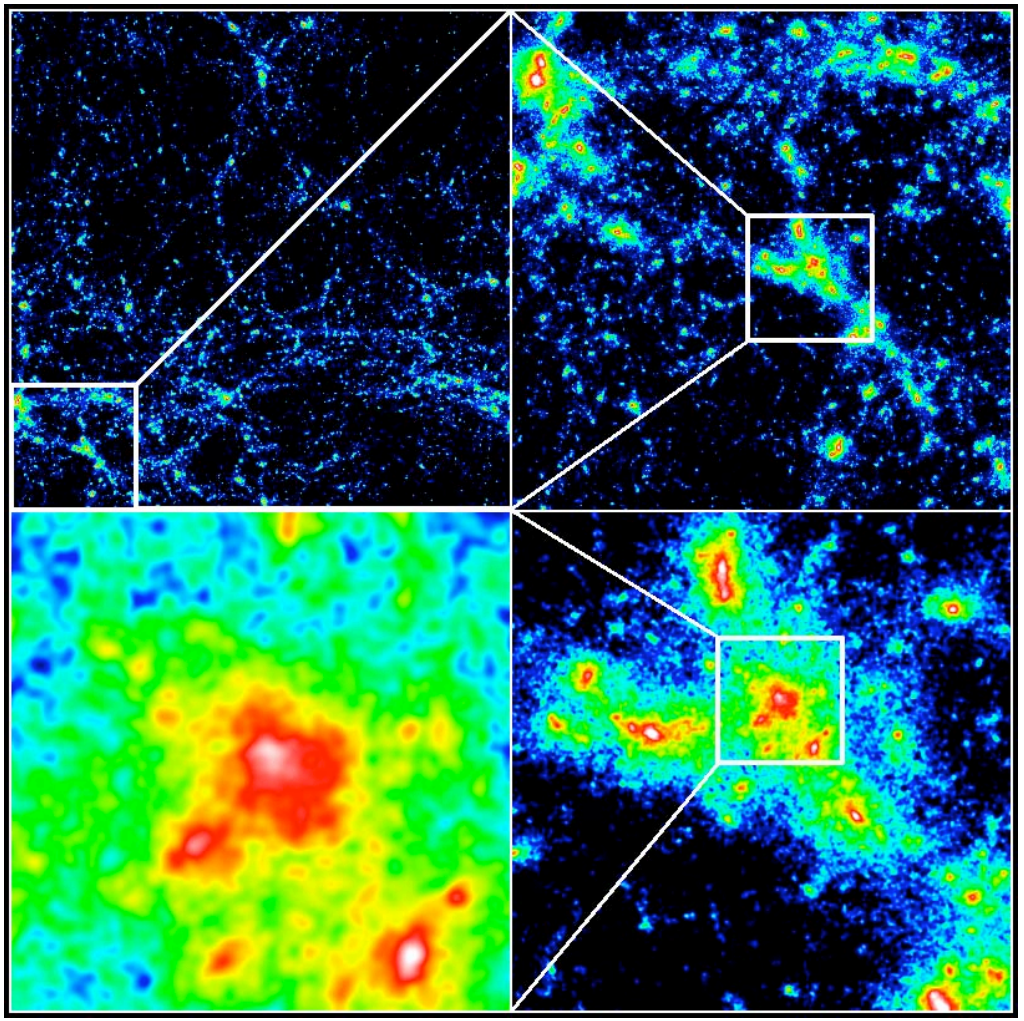
Galaxies found on walls, in filaments, and in clusters.



The Visible Cosmos:

a hierarchy of structure and motion

- Computer simulations of structure formation:



Cosmological Models

Einstein's gravity theory (General Relativity)

Assume Universe filled with uniform density fluid.

[OK on large scales > 100 Mpc]

Density: $\rho = \Omega\, \rho_c$ Energy density: $\varepsilon = \rho\, c^2$

Critical density: $$\rho_c \equiv \frac{3\, H_0^{\,2}}{8\pi\, G} \approx 10^{-26}\,\mathrm{kg\ m^{-3}} \approx \frac{1.4\times 10^{11}\,\mathrm{Msun}}{(\mathrm{Mpc})^3}$$

3 components:

1. ***Radiation*** $\Omega_R \approx 5\times 10^{-5}$

2. ***Matter*** $\Omega_M \sim 0.3$ { "Dark Matter" $\Omega_D \sim 0.26$; baryons $\Omega_B \sim 0.04$

3. "***Dark Energy***" $\Omega_\Lambda \sim 0.7$

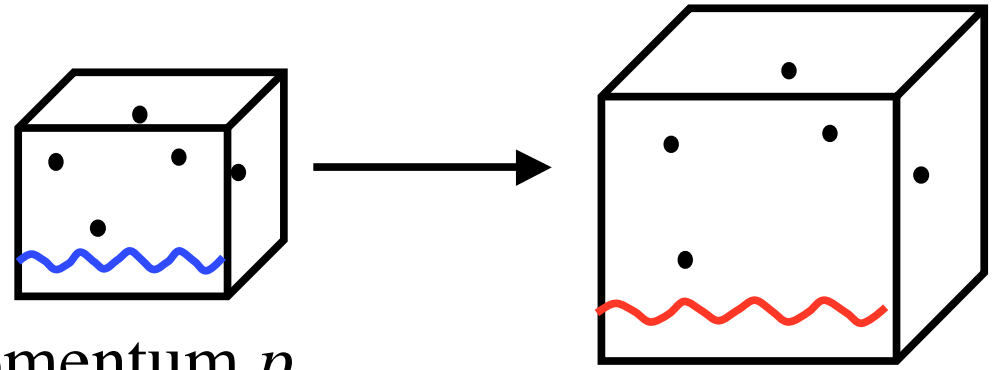
Total $\Omega = \Omega_R + \Omega_M + \Omega_\Lambda = 1$

Only ~4% is matter as we know it!

Energy Density of expanding box

volume R^3

N particles



particle mass m momentum p

energy $E = h\nu = \sqrt{m^2c^4 + p^2c^2} = m\,c^2 + \frac{p^2}{2m} + \ldots$

Cold Matter: ($m > 0,\ p << mc$)

$E \approx m\,c^2 = \text{const}$

$$\varepsilon_M \approx \frac{N\,m\,c^2}{R^3} \propto R^{-3}$$

Radiation: ($m = 0$)

Hot Matter: ($m > 0,\ p >> mc$)

$\lambda \propto R$ (wavelengths stretch):

$$E = h\,\nu = \frac{h\,c}{\lambda} \propto R^{-1}$$

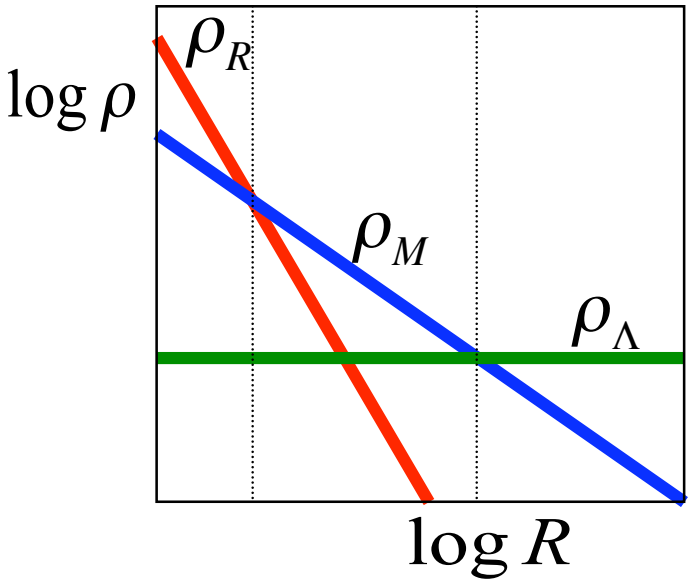
$$\varepsilon_R = \frac{N\,h\,\nu}{R^3} \propto R^{-4}$$

3 Eras: radiation…matter…vacuum

radiation : $\rho_R \propto R^{-4}$

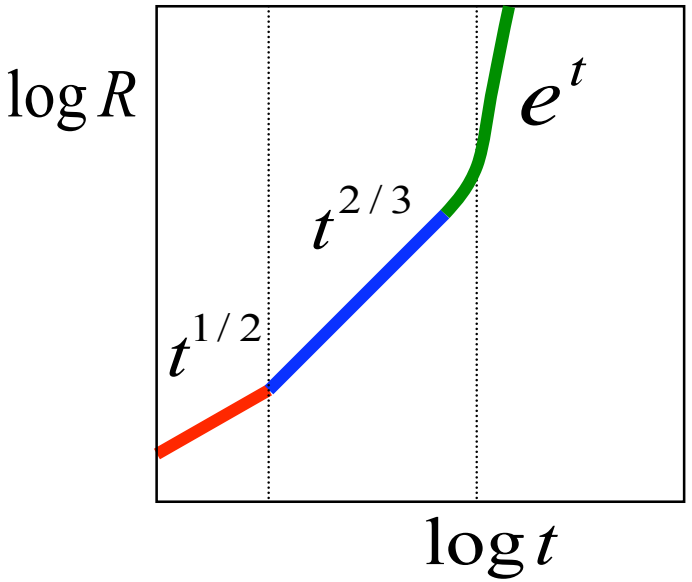
matter : $\rho_M \propto R^{-3}$

vacuum : $\rho_\Lambda = \text{const}$



$$a \equiv \frac{R}{R_0} = \frac{1}{1+z}$$

$$\rho = \frac{\rho_{R,0}}{a^4} + \frac{\rho_{M,0}}{a^3} + \rho_\Lambda$$

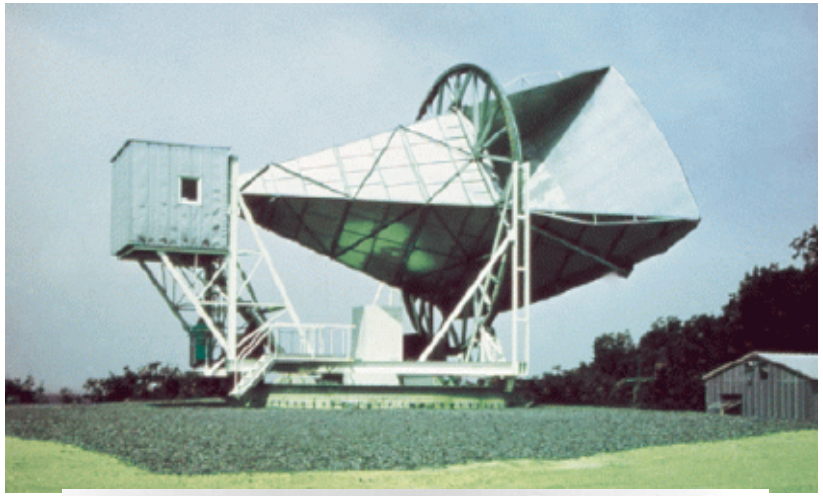


$\rho_R = \rho_M$ at $a \sim 10^{-4}$ $t \sim 10^4$ yr

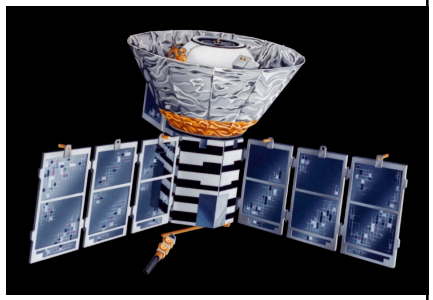
$\rho_M = \rho_\Lambda$ at $a \sim 0.7$ $t \sim 10^{10}$ yr

Cosmic Microwave Background

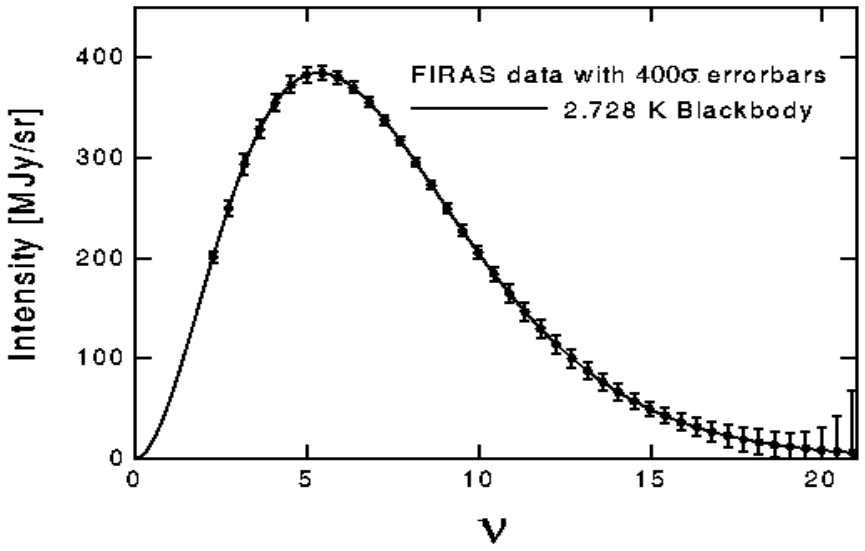
- CMB predicted by Gamov in 1948.
  Discovered by Penzias and Wilson in 1965.



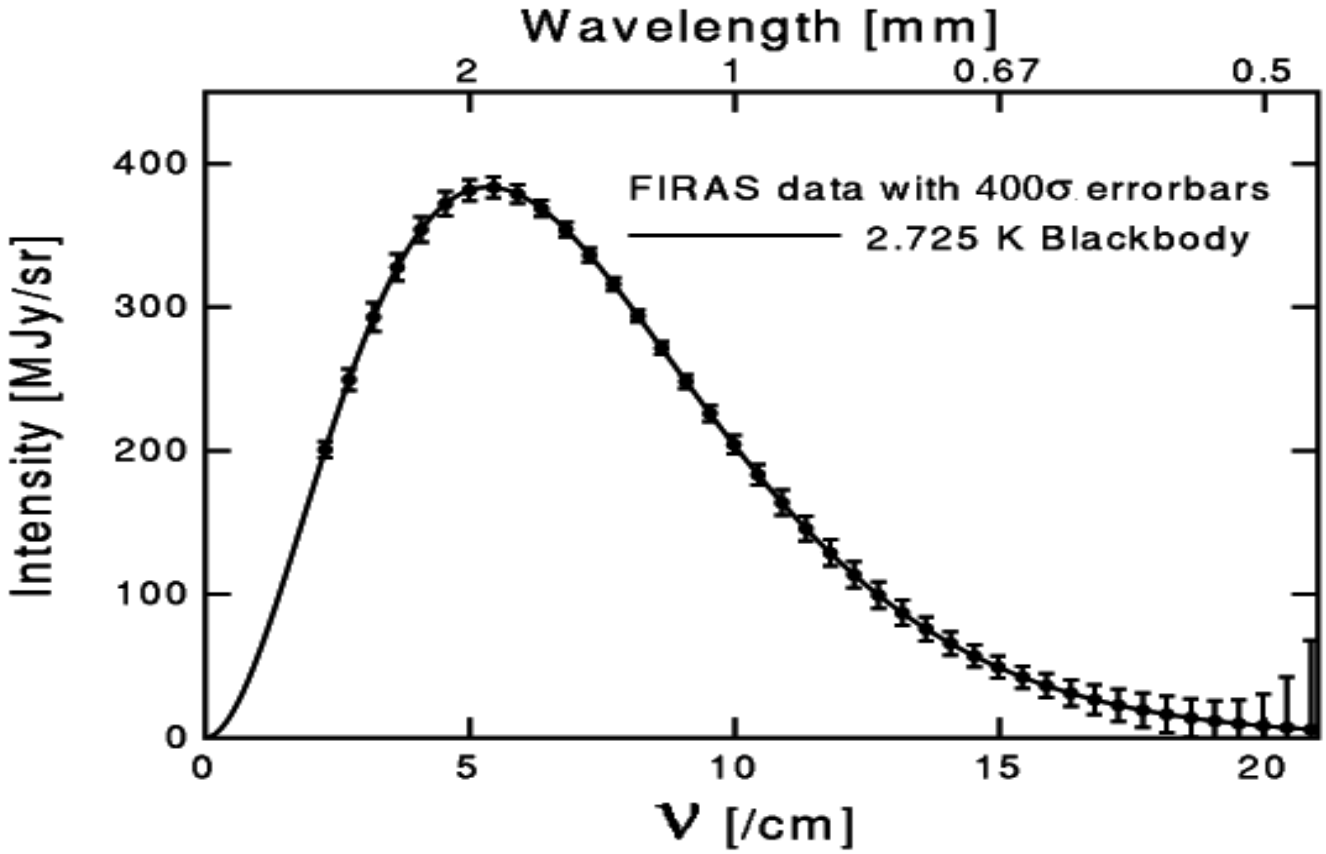
1992 NASA -
COBE
COsmic Background Explorer



A perfect Blackbody!



COBE spectrum of CMB

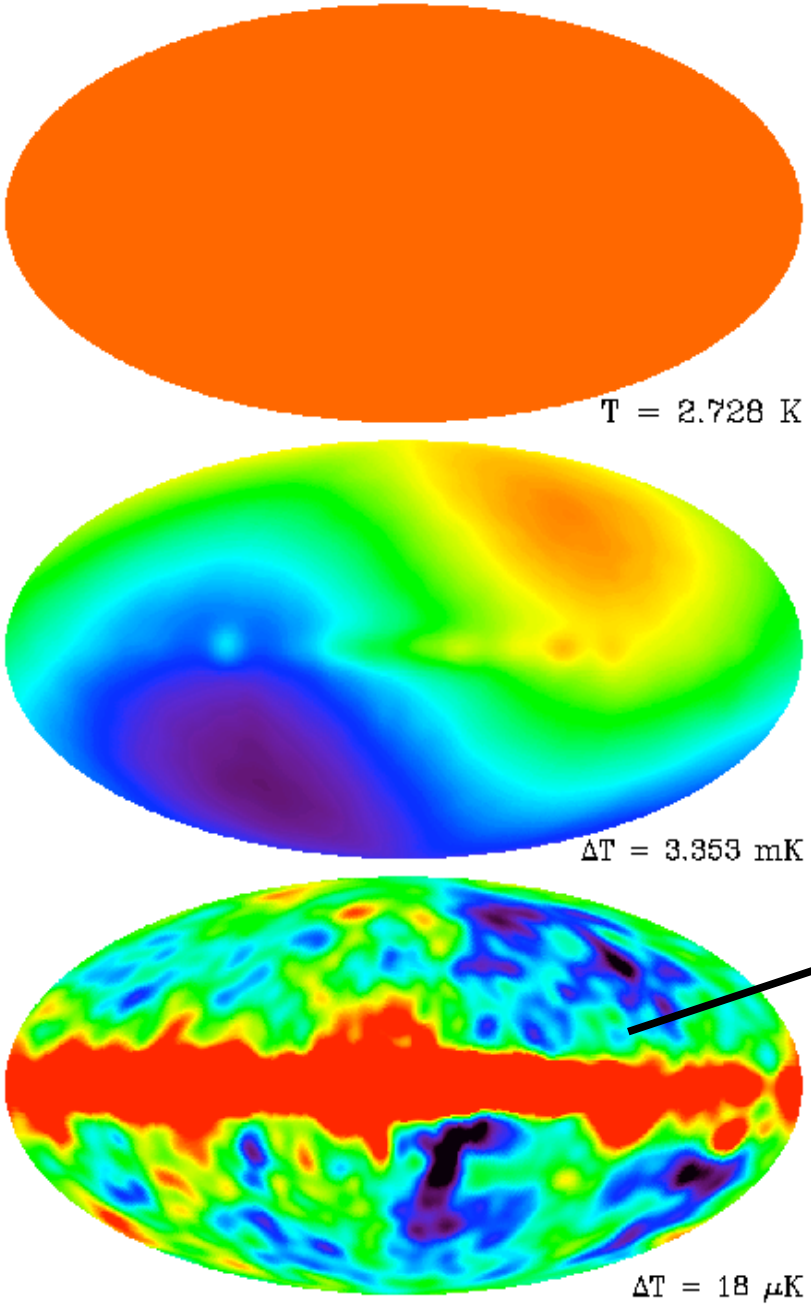


A perfect Blackbody !

No spectral lines -- strong test of Big Bang.
Expansion preserves the blackbody spectrum.

$$T(z) = T_0 (1+z) \qquad T_0 \sim 3000\ K \quad z \sim 1100$$

Cosmic Microwave Background



Almost isotropic

$T = 2.728$ K

Dipole anisotropy

$$\frac{V}{c} = \frac{\Delta\lambda}{\lambda} = \frac{\Delta T}{T} \approx 10^{-3}$$

Our velocity:

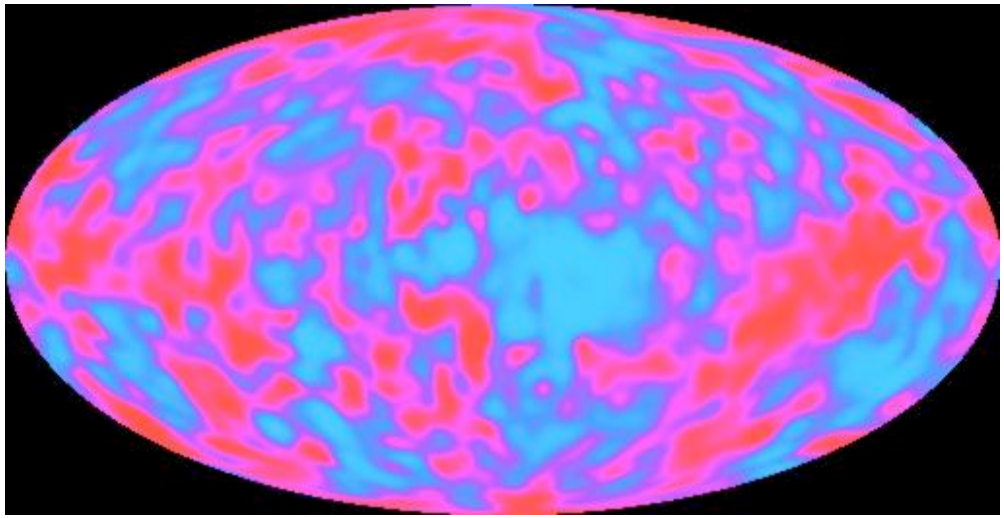
$V \approx 600$ km/s

Milky Way sources

+ anisotropies $\frac{\Delta T}{T} \sim 10^{-5}$

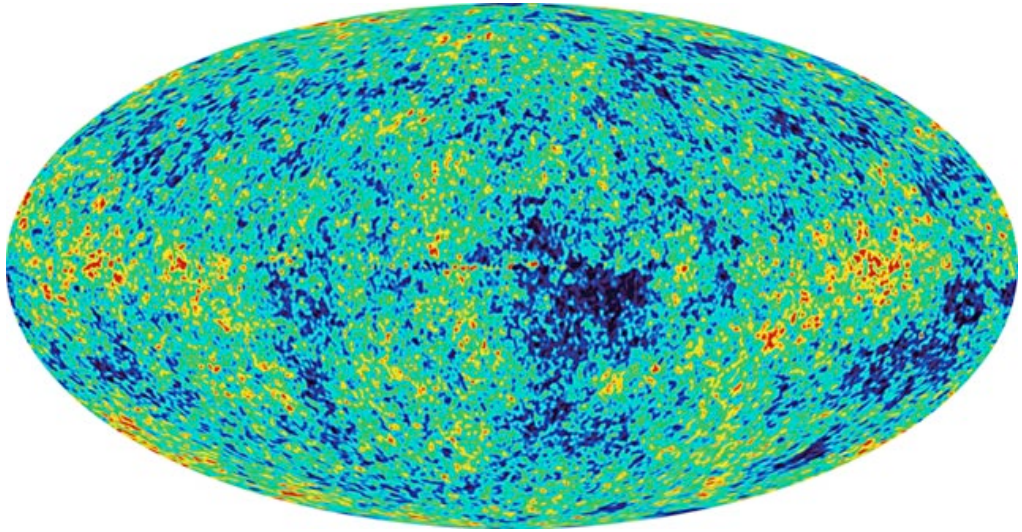
CMB Anisotropies

COBE
1994



$$\frac{\Delta T}{T} \sim 10^{-5}$$

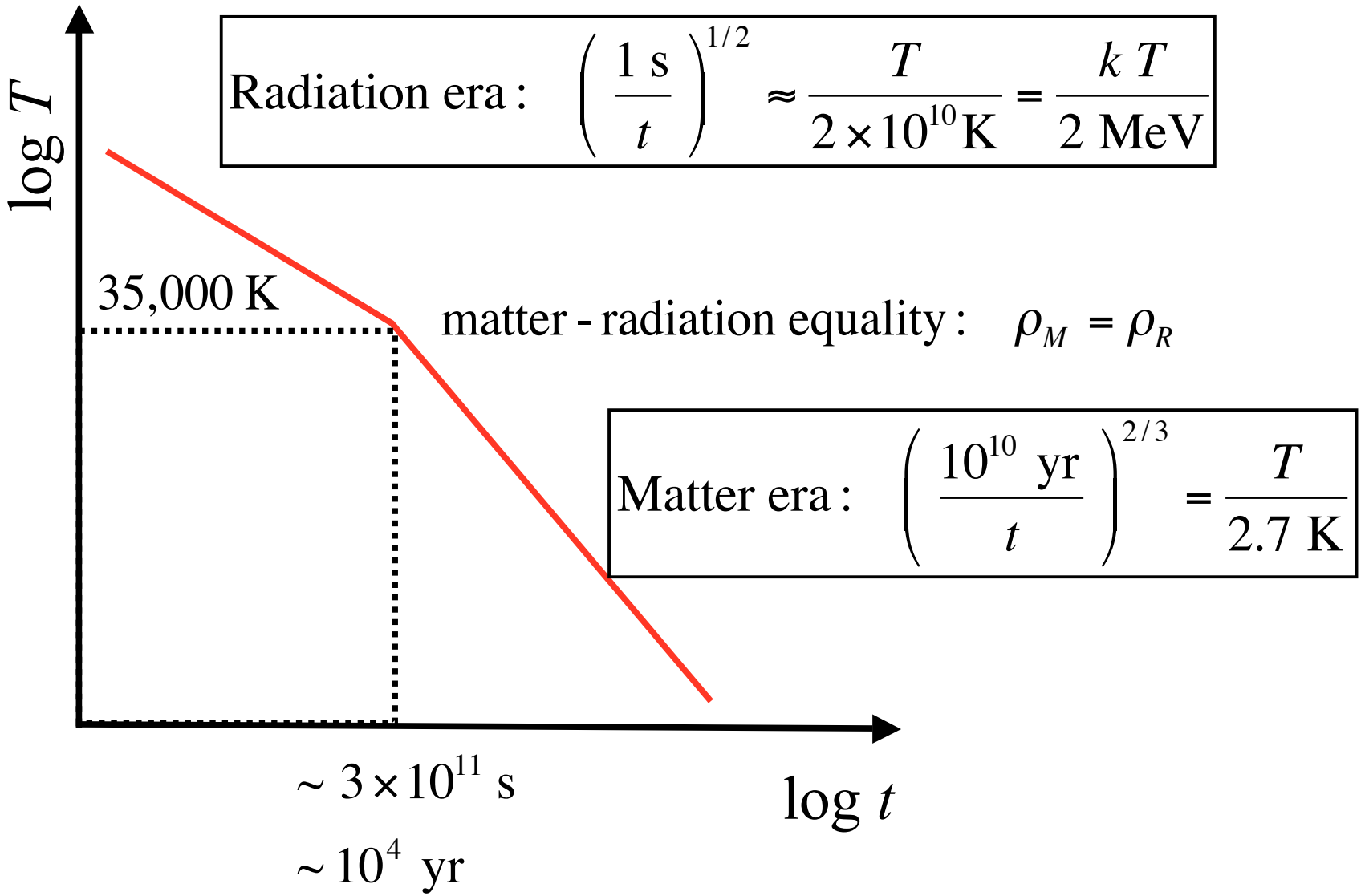
WMAP
2004



$$\Delta\theta \sim 1^{\circ}$$

Snapshot of Universe at z = 1100
Seeds that later form galaxies.

Cooling History: T(t)



Radiation era : $\left(\frac{1\ \mathrm{s}}{t}\right)^{1/2} \approx \frac{T}{2\times10^{10}\ \mathrm{K}} = \frac{kT}{2\ \mathrm{MeV}}$

matter - radiation equality : $\rho_M = \rho_R$

Matter era : $\left(\frac{10^{10}\ \mathrm{yr}}{t}\right)^{2/3} = \frac{T}{2.7\ \mathrm{K}}$

1975: Big Bang Nuclear Fusion

Big Bang + 3 minutes

T ~ 10^9 K

First atomic nuclei forged.

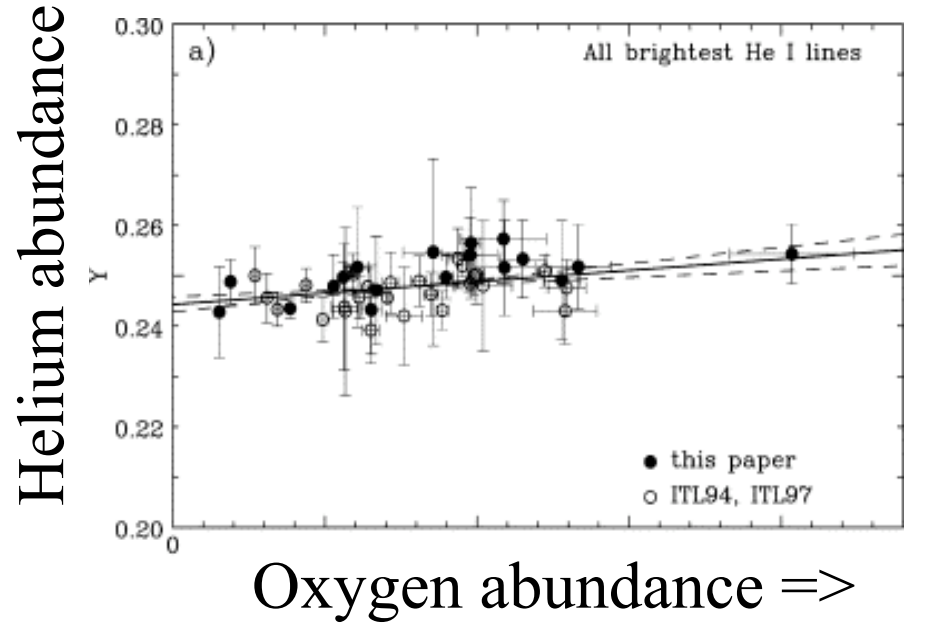
Calculations predict:

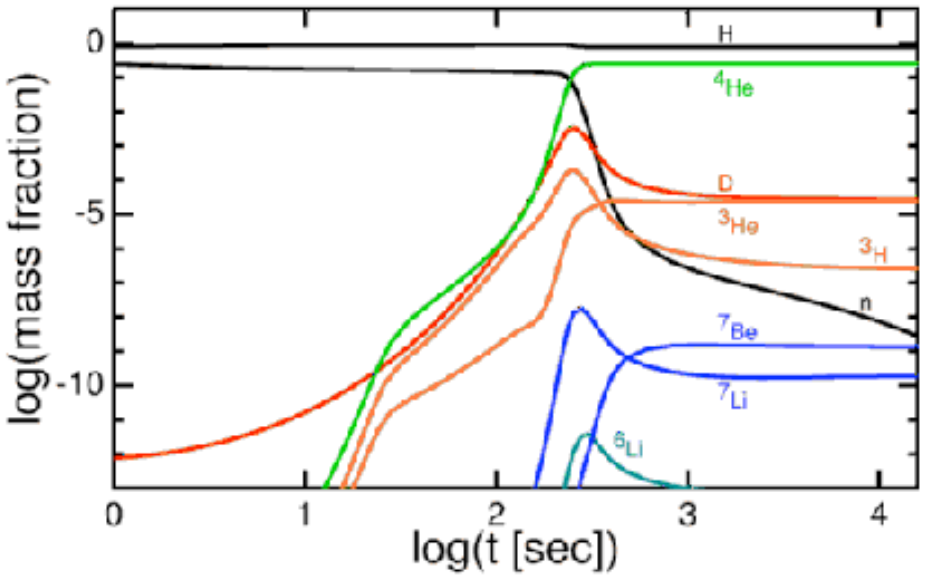
75% H and 25% He

AS OBSERVED !

+ traces of light elements
D, ^{3}H, ^{3}He, ^{7}Be, ^{7}Li

=> normal matter only 4% of critical density.





1998: Supernova Cosmology

- Do galaxies at VERY large distances have the same distance/velocity relationship as the Hubble Law?
- Has the rate of expansion changed?

- SN Ia as “standard candles”: same maximum *L*
- Search lots of galaxies for SN Ia: very bright

SN Type Ia in Virgo Galaxy NGC 4526

Supernova outshines the entire galaxy, but only for a month or so.

Type II -- massive stars ($M > 8\ M_{SUN}$) explode at end of life.

Type Ia -- white dwarf in a binary system accretes mass, collapses when $M_{WD} = 1.4\ M_{SUN}$.

Good “standard bombs”.

Calibrate SN distances using HST to see Cepheids in Virgo galaxies.

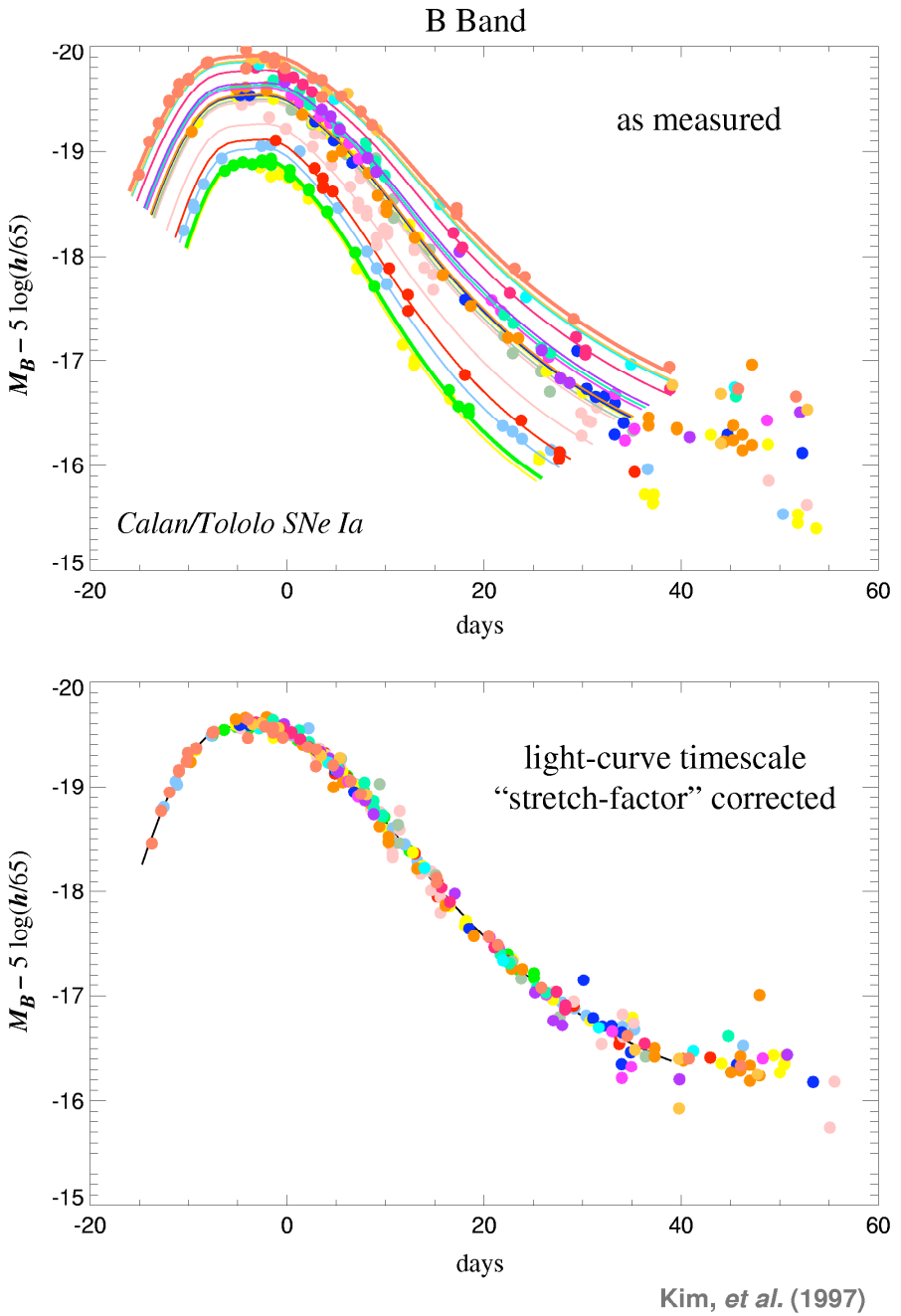
Calibrating "Standard Bombs"

1. Brighter ones decline more slowly.

2. Time runs slower by factor (1+z).

AFTER correcting:
Constant peak brightness
M_B = -19.7

Observed peak magnitude:
m = M + 5 log (d/Mpc) + 25
gives the distance!

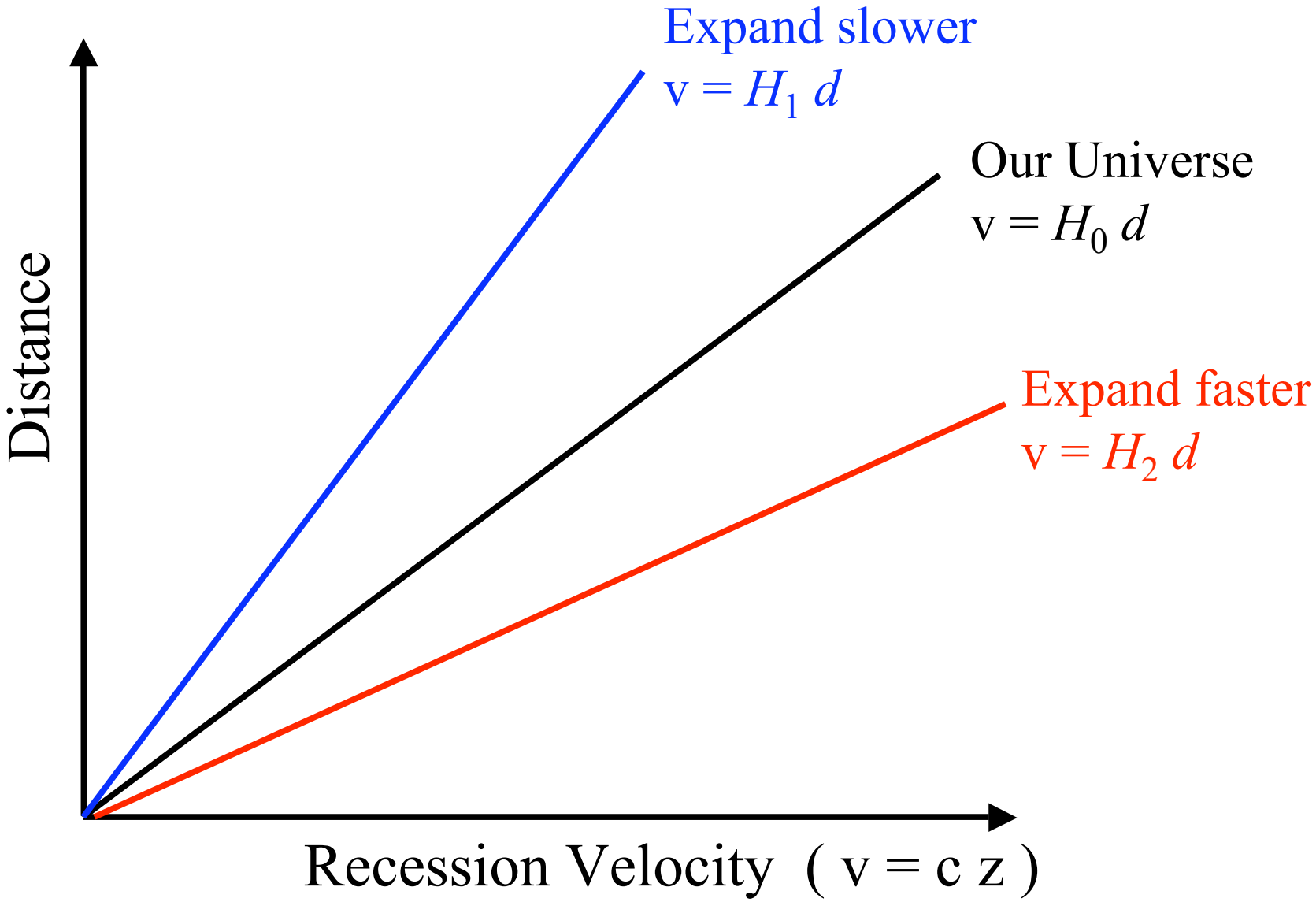


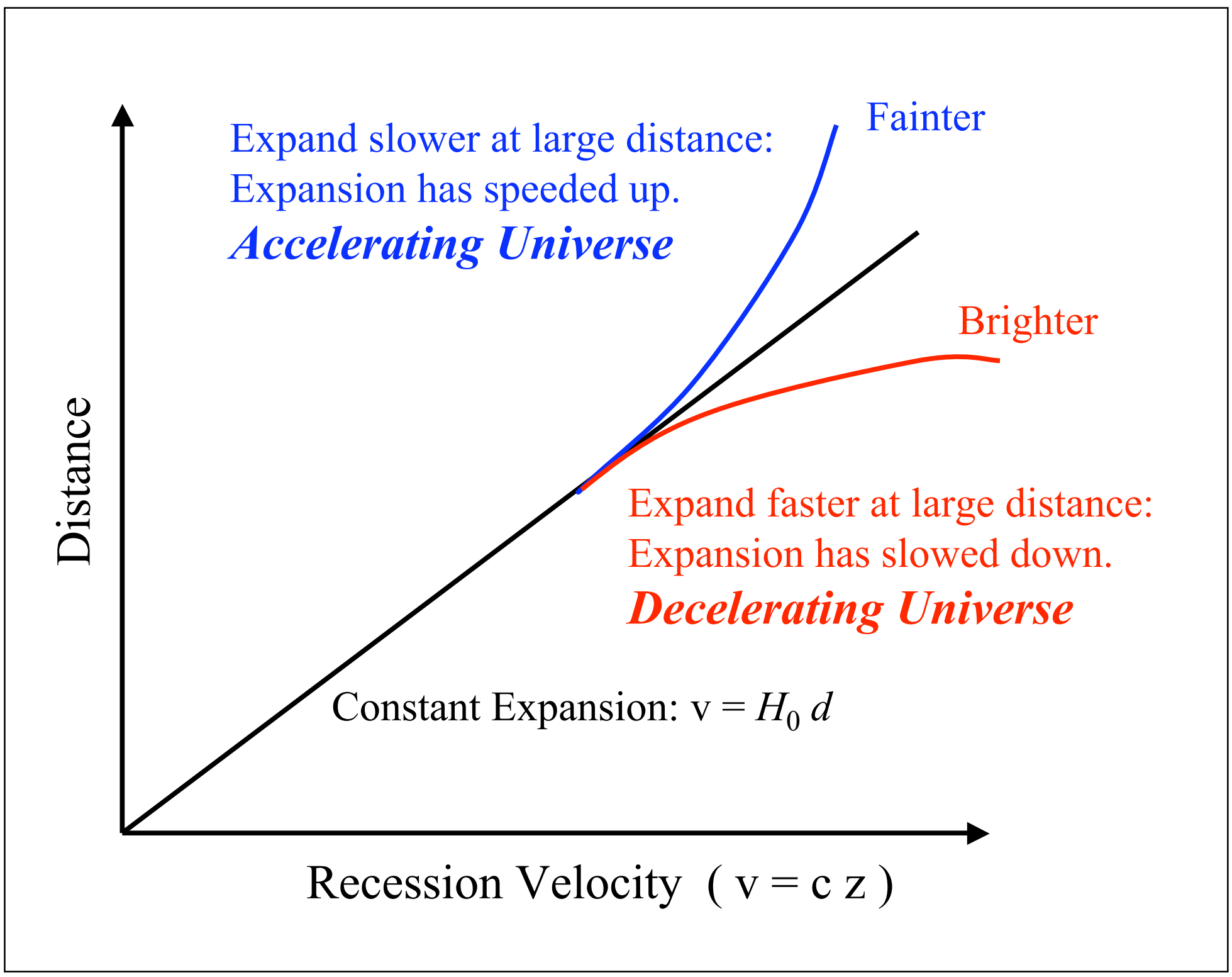
Absolute magnitude M_B ==>

Time ==>

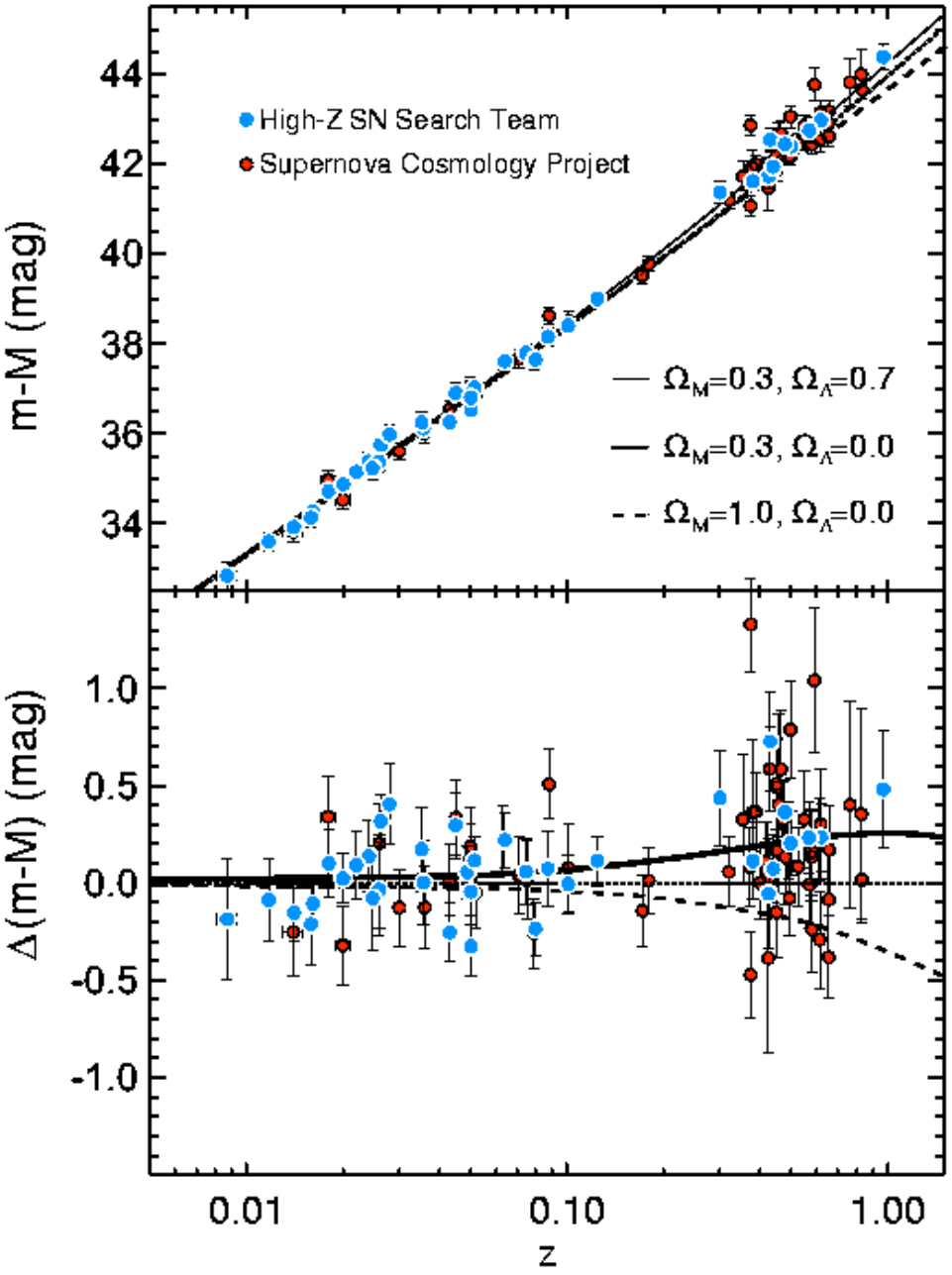
Kim, *et al.* (1997)

Varying Hubble Laws




Fainter
Expand slower at large distance:
Expansion has speeded up.
Accelerating Universe
Brighter
Expand faster at large distance:
Expansion has slowed down.
Decelerating Universe
Constant Expansion: v = H_0 d
Distance
Recession Velocity (v = c z)

1998: Accelerating Universe !?



Distant SNe ($z \sim 0.8$) are **25% fainter** than the Hubble Law.
=> **ACCELERATING!**

Need cosmological constant Λ or DARK ENERGY.

Proposed satellite: ***SNAP*** ***SuperNova Acceleration Probe*** to find even more distant SNe …

Acceleration by DARK ENERGY

First, gravity from high matter density decelerates the expansion.

Expansion reduces matter density, deceleration slows.

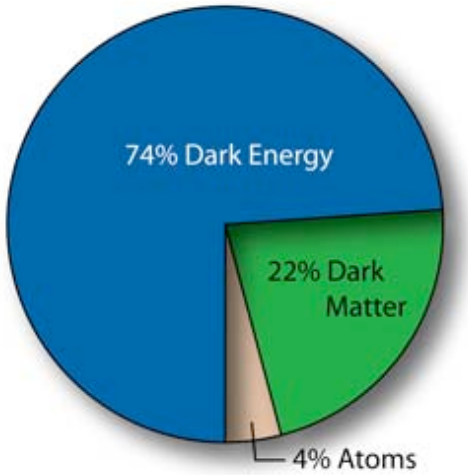
Then, **DARK ENERGY** accelerates.

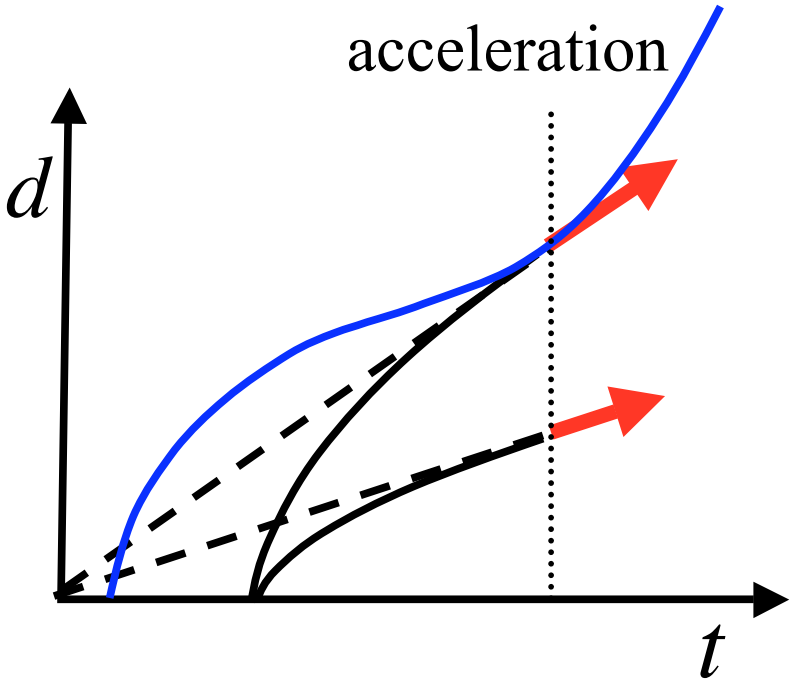
Slight Problem:
Quantum vacuum predicts Dark Energy density

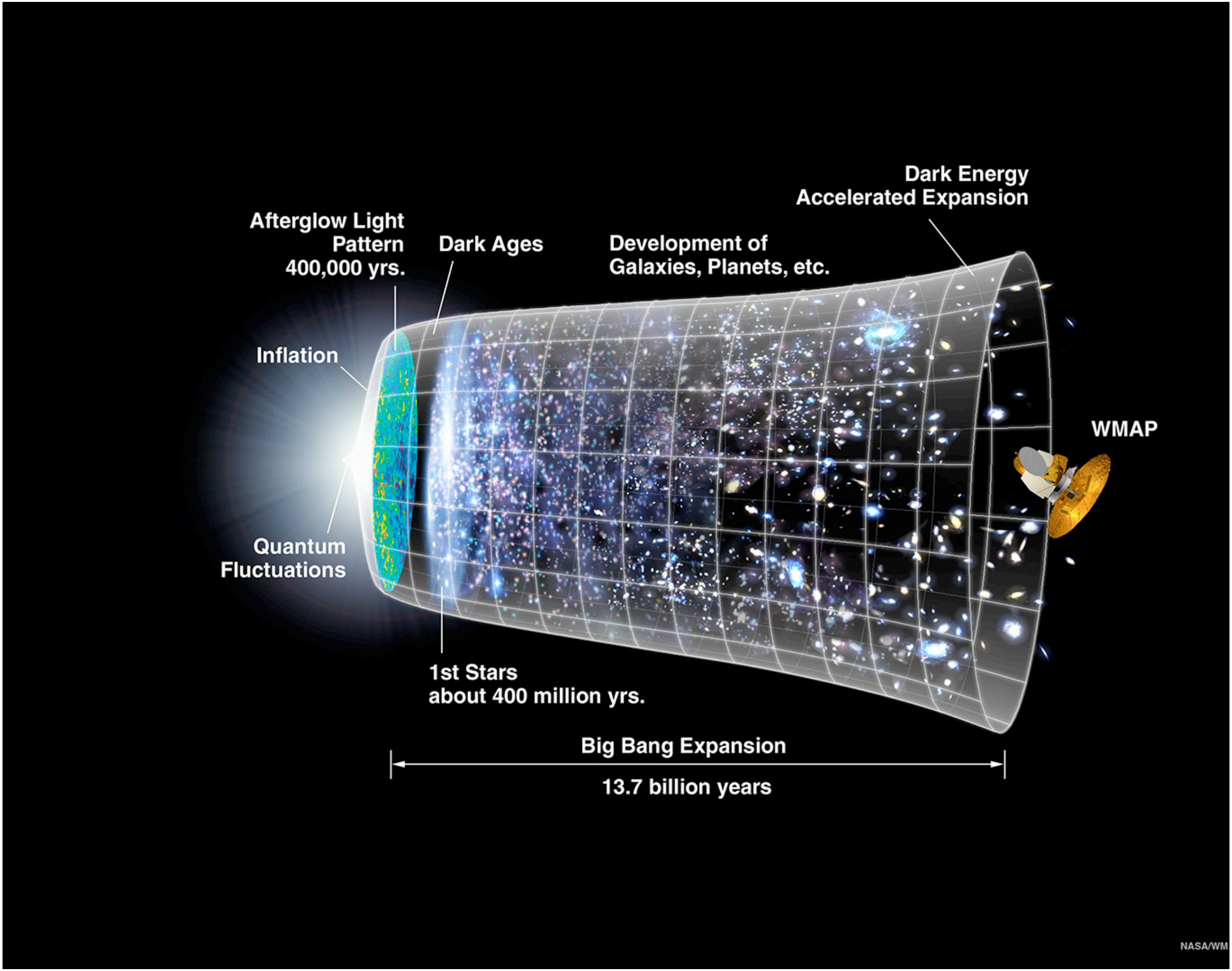
$$\rho_\Lambda = 10^{120}\ \rho_{CRIT}$$

Observed:

$$\rho_\Lambda = 0.7\ \rho_{CRIT}$$

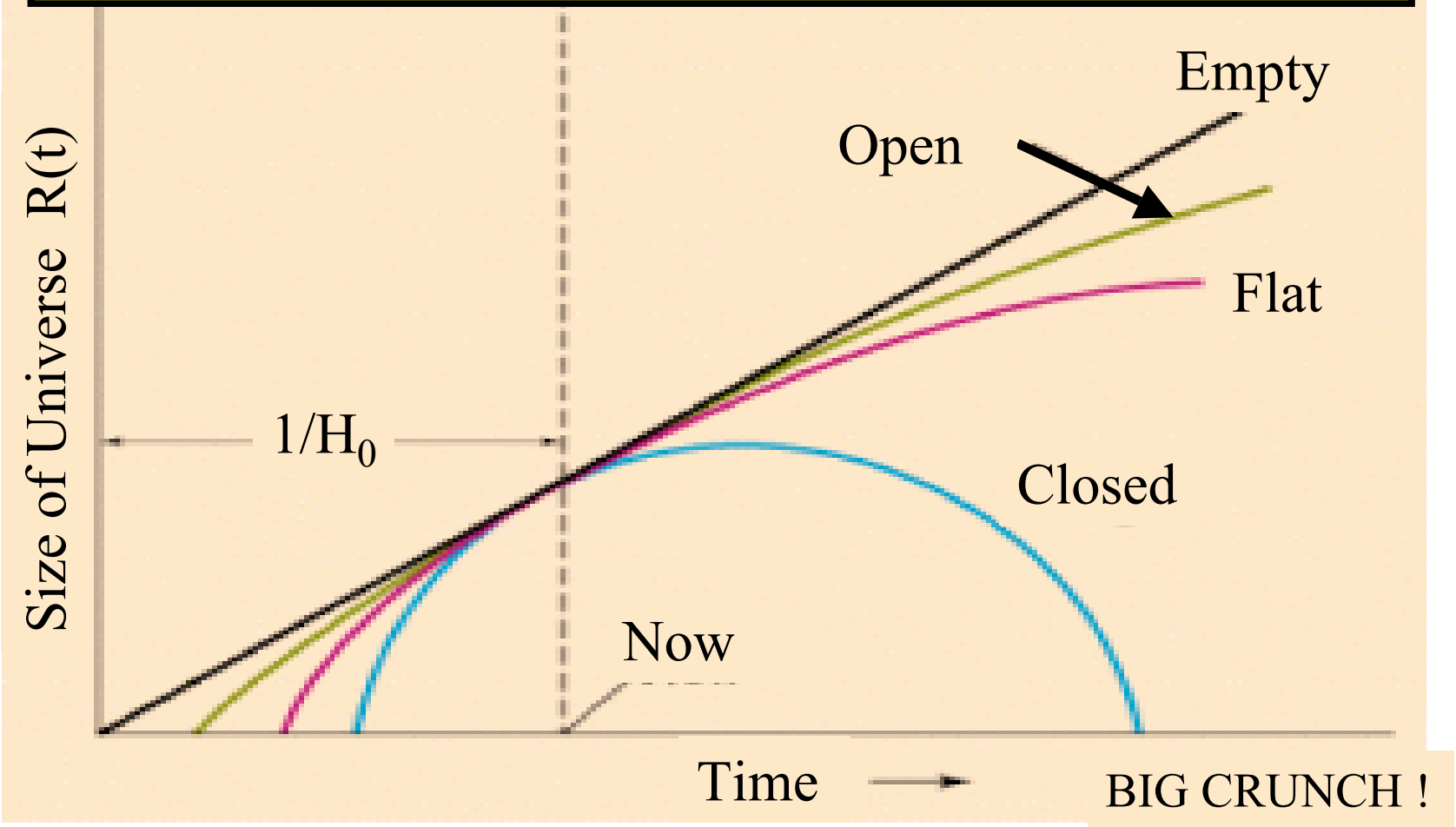





Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WM

Re-collapse or Eternal Expansion ?

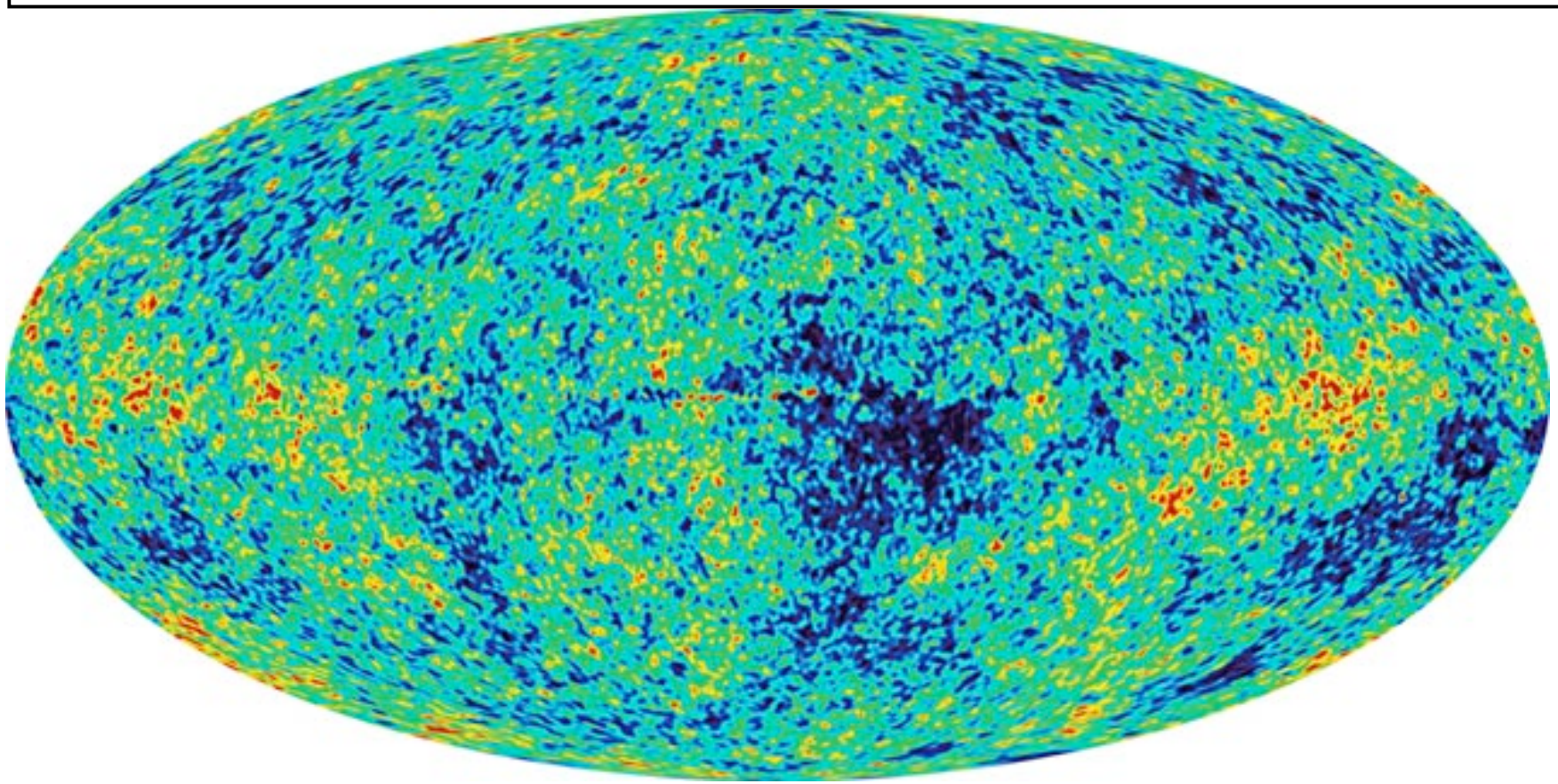
Inflation => expect FLAT GEOMETRY
CRITICAL DENSITY



2004: WMAP all-sky CMB temperature map.

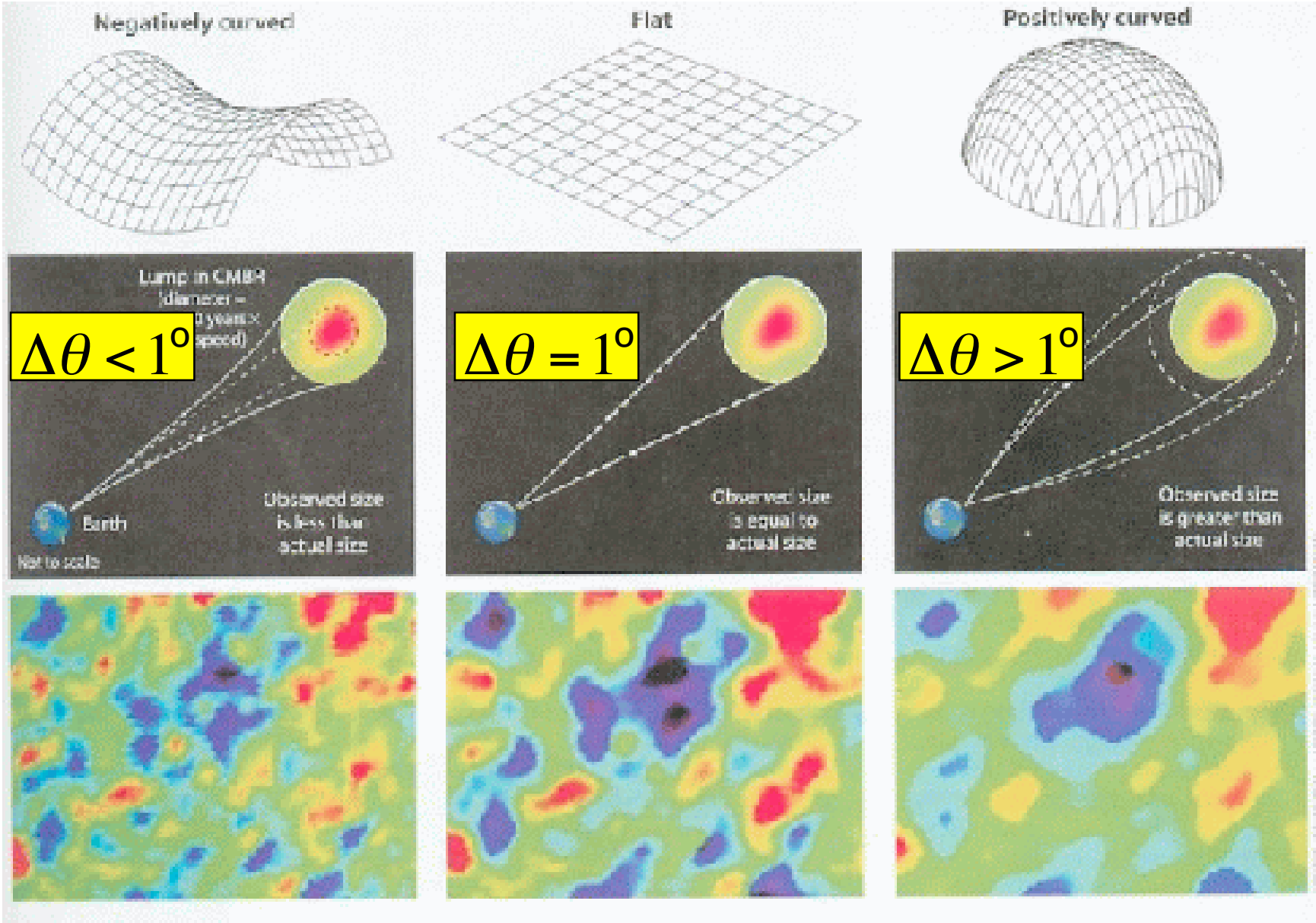
Tiny ripples (at z=1100, T=3000K, t=3×10^5 yr)
are the seeds of galaxy formation!

Angular size $\Delta\theta = 1^o$ => FLAT GEOMETRY

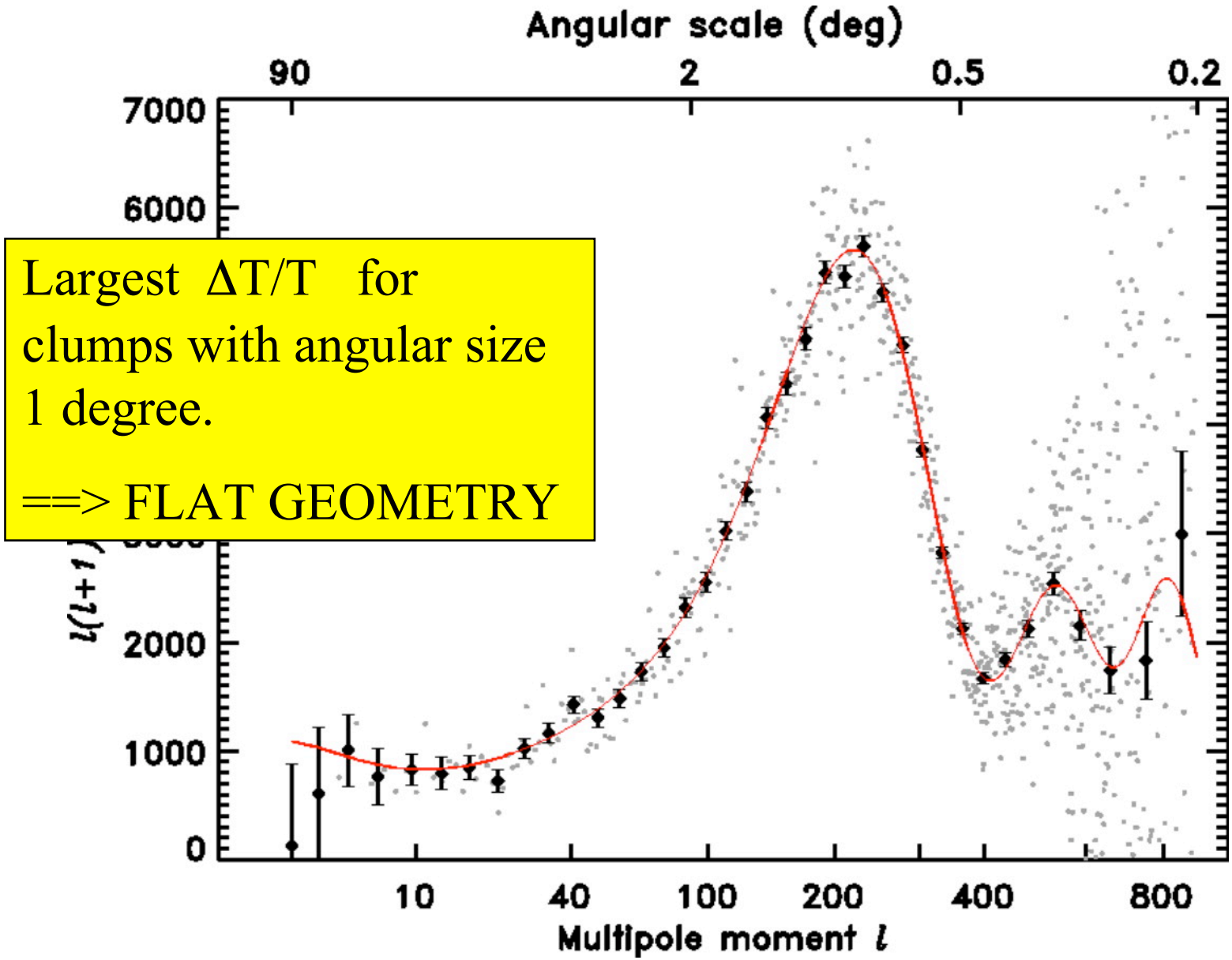


Curvature of the Universe

Negative FLAT Positive



2004: WMAP - Power Spectrum



Largest ΔT/T for clumps with angular size 1 degree.

==> FLAT GEOMETRY

Possible Universes

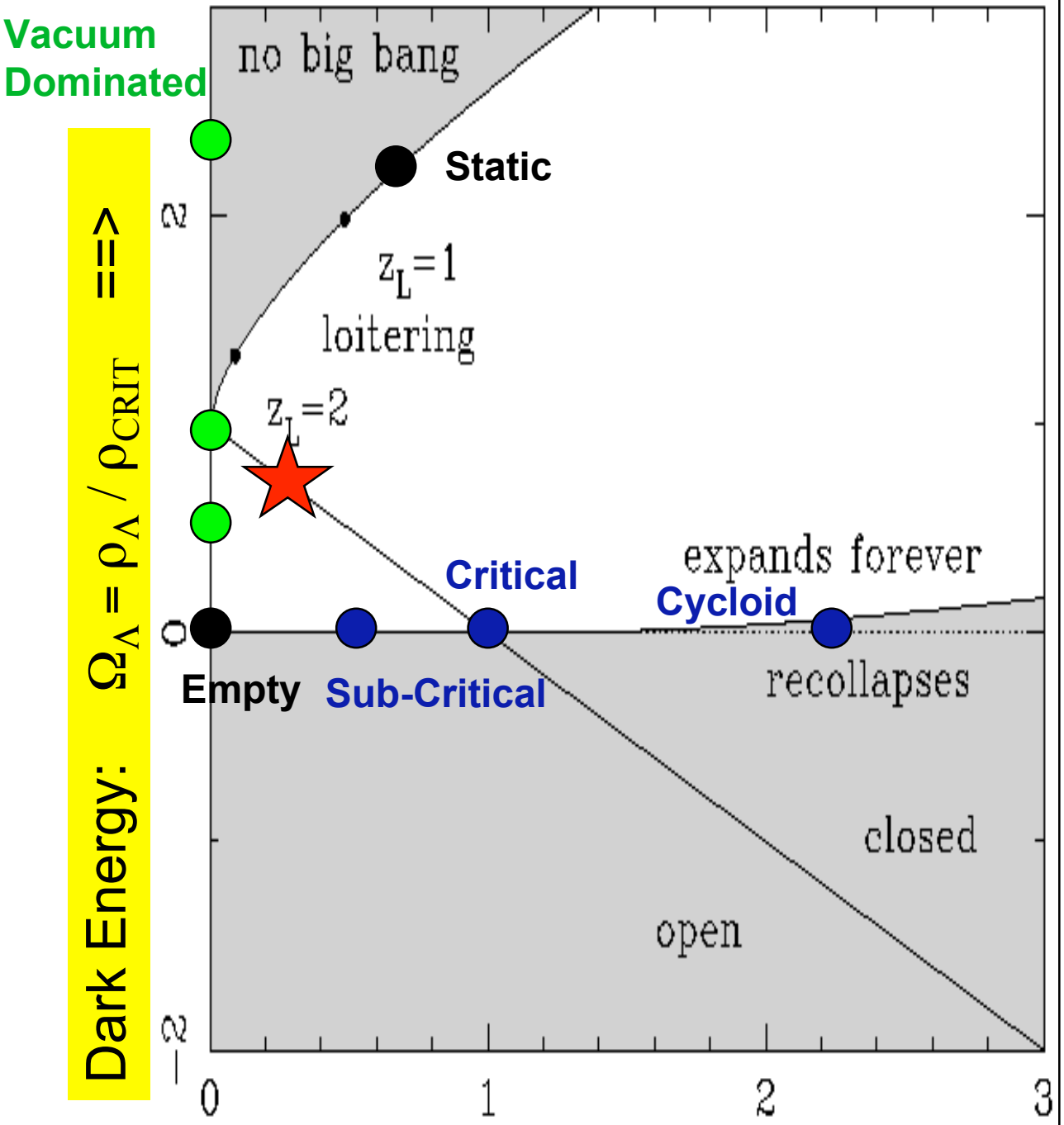
$$H_0 \approx 72 \frac{\text{km/s}}{\text{Mpc}}$$

$$\Omega_M \sim 0.3$$

$$\Omega_\Lambda \sim 0.7$$

$$\Omega_R \sim 8 \times 10^{-5}$$

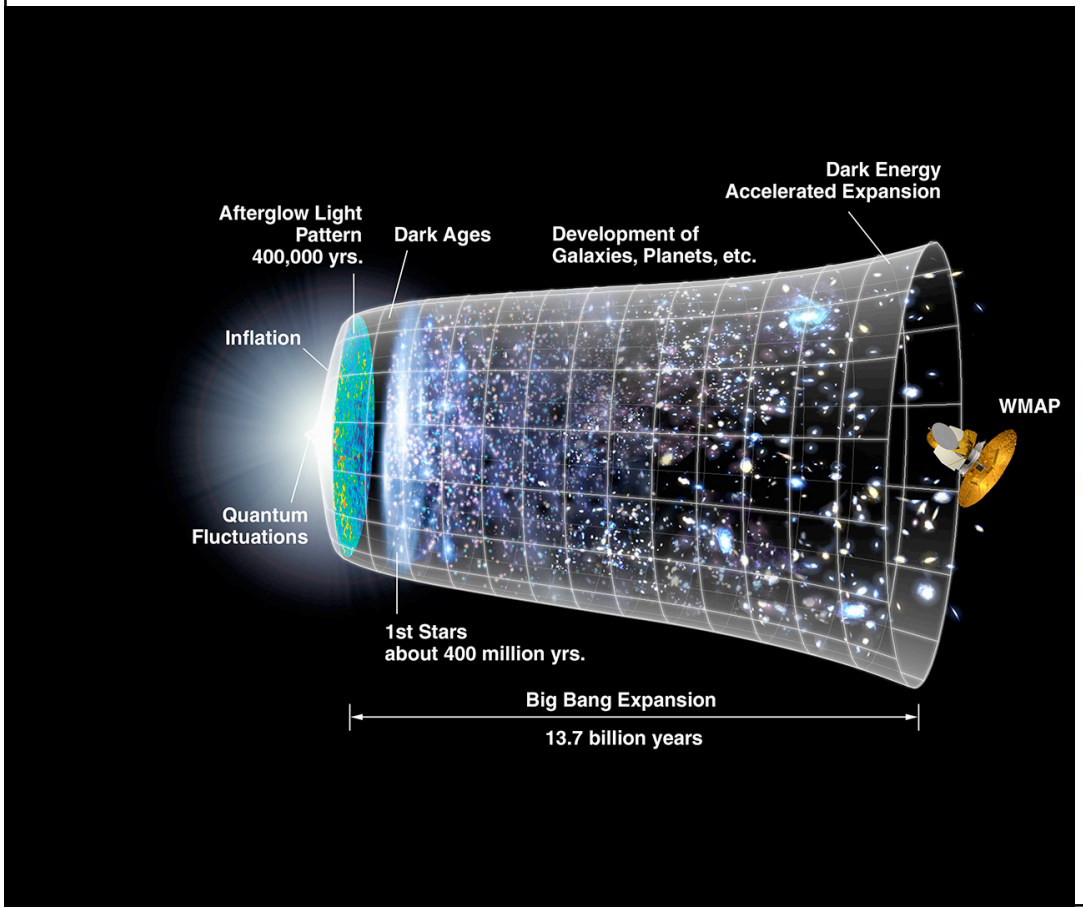
$$\Omega = 1.0$$

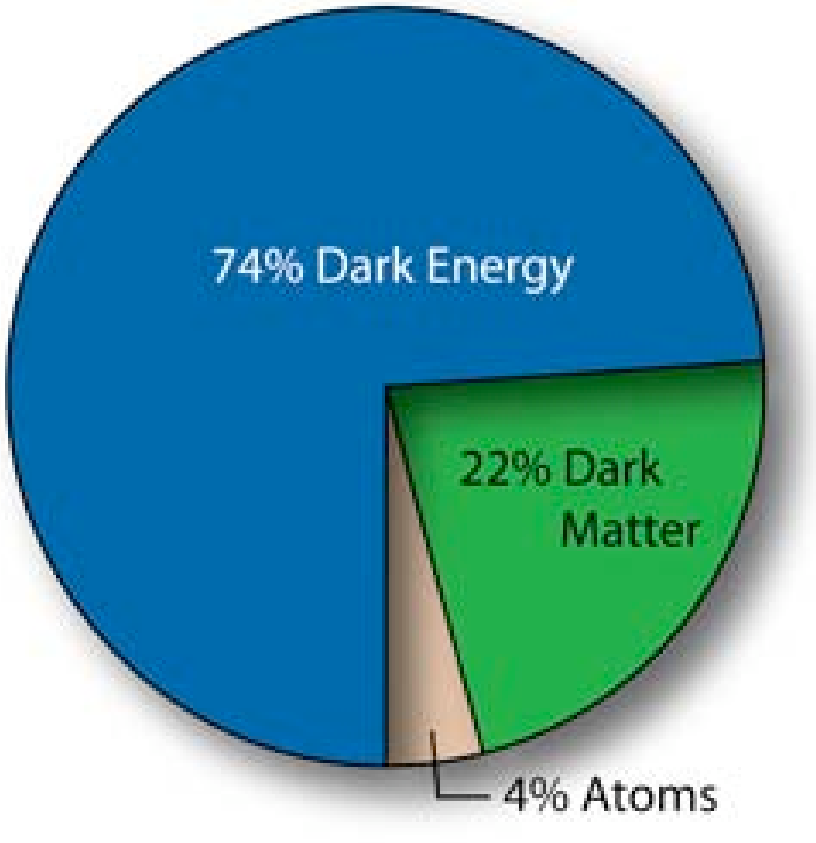


Matter: $\Omega_M = \rho_M / \rho_{CRIT}$ --

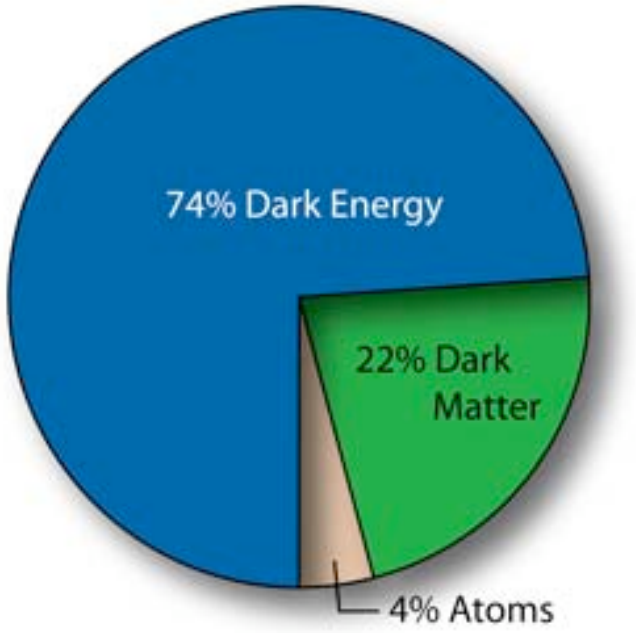
Our “Crazy” Universe

~4% Normal Matter
~22% “Dark Matter”
~74% “Dark Energy”





Or …. Has General Relativity Failed ?



Can an *Alternative Gravity* Model fit all the data without Dark Matter and Dark Energy ?

No luck yet, but people are trying.