AS1001:Extra-Galactic Astronomy

Lecture 10: Quick Review

then

OUR “CRAZY” UNIVERSE

DARK MATTER + DARK ENERGY

AS1001 Exam Format

- Answer one of two questions from each segment of the course.
- Four questions total, each worth 25%.

- **Galaxies & Cosmology**: Exam on Lectures 1 to 9
- Lecture notes etc on the web page (Moodle link)

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

Lecture 1: Distances to Galaxies

How do we measure distances to galaxies?

- **Standard candles**
  - Cepheid Variables

    (don’t memorise P-L relation, but know how to use it.)
- **Distance modulus equation:**
- m – M = 5 log (d / pc) – 5

  = 5 log (d / Mpc) + 25
- M = Absolute magnitude
- m = Apparent magnitude
- (M = m at d = 10 pc)

$$F = \frac{L}{4\pi d^2}$$

$$m_1 - m_2 = -2.5\log_{10}\frac{F_1}{F_2}$$

$$m - M = 5\log_{10}(d/10\,pc)$$

Lecture 2: Galaxy Morphology

- Hubble tuning fork; why NOT evolutionary sequence
- **Galaxy types:** Ellipticals, Spirals, Irregulars
- Main features / components of each type.
- Why are Ellipticals red?
- Understand blackbodies:

  $B_\nu(T)$, $L = 4\,\pi\,R^2\,\sigma\,T^4$, $\lambda_{peak} \sim 1 / T$
- Galaxy Colours

  blue = young hot stars
  red = old cool stars

Lecture 3: Galaxy Fundamentals

- How many stars? $F_{Gal} = n_* F_*$, F_* = "Average star"

  Use:

$$m_{GAL} - m_* = -2.5\log_{10}\frac{F_{GAL}}{F_*}$$

- **Formation scenarios**. Observations for and against.
- **Space density of galaxies:** What *d* and *Volume* do we see down to limiting apparent mag $m = 14$
  for galaxies with absolute mag $M = -20$?
- How far apart are galaxies?

Lecture 3: Galaxy Fundamentals

- **How are galaxies clustered?** Like soap suds, galaxies found on the bubble surfaces: hence voids, walls, filaments, clusters.

- **Mass to Light ratios**:

$$\frac{\mathbf{M}}{L} = X \frac{\mathbf{M}_\otimes}{L_\otimes}$$

  $X = 1$ for Sun; $X \sim 10$ for a galaxy.

  Galaxy M/L ratios indicate Dark Matter

- **Average density of Universe**:

  from galaxy counts and masses.

Lecture 4: Galaxy Spectra

- **Continuum, Absorption lines, Emission lines.**
- **4000A break:** Due to metal absorption lines in stellar atmospheres. Strong in ellipticals, weaker in spirals, absent in irregulars.
- **Absorption lines:** due to metals in stellar atmospheres => old stars. Seen in ellipticals, spiral bulges
- **Emission lines:** HII regions, gas ionized by hot stars => young stars in spiral disks, irregulars
- Radial velocities, redshift:

$$\frac{\mathrm{v}}{c} = \frac{\lambda - \lambda_0}{\lambda_0} = z$$

Lecture 5: Dark Matter

$$M = \frac{v^2 r}{G}$$

- **Virial Equilibrium:** Rotation vs Gravity
  Calculate *M* given v and *r*
- **Rotation curves**: stars trace mass => $v = \sqrt{(G M / r)}$
  Observe: v = constant => Dark Matter
  v = const => $M \sim r$ and $\rho \sim 1 / r^2$ => "dark halo"
- **Dark Matter in galaxy clusters**:
  galaxies move too fast to stay bound
- **Gravitational Lensing:** M given D_L D_S and θ
- **Conclusion**: 90% of the mass is Dark Matter…
  OR gravity theory (General Relativity) needs modified

Lecture 6: Orientation, Black Holes

- **Orientation:**

  Inclination: $\cos i = \dfrac{\text{Observed minor axis}}{\text{Observed major axis}} = \dfrac{b}{a}$

  Line of sight velocity: $v_{obs} = v_{rot} \sin i$

- **Black Holes:** so dense that light cannot escape.

  Be able to derive Schwarzschild radius:
  kinetic energy = gravitational energy $r_S = 2GM/c^2$

- **SMBHs:** observe large speeds at some given distance:
  derive mass:

  $$M = v^2 r / G$$

- Hawking radiation, virtual pairs, BH evaporation
  (no need to memorise formula for T)

Lecture 6: Quasars

- SMBH => Active Galactic Nuclei (AGN) when feeding.
- **Quasars** are bright AGN, star-like but at large redshift

  => Luminosity up to ~10^5 that of normal galaxies.
- **Spectrum:** blackbody emission from accretion disk
  + power law (non-thermal) synchrotron radiation
  (electrons spiraling along **B**-field) from relativistic jets
- Broad emission lines => rapid rotation (v~10^4 km/s)
- **QSO model + unification scheme**
  for Quasars, Blazars, and Radio galaxies
- Many at large redshift (z ~ 2-3) but few nearby

  => common in early Universe, then died out.

Lecture 7: Development of Cosmology

- **Copernican Principle:** nothing special about us
- **Olber's Paradox:** why is sky dark at night? Because the Universe has finite age. Cannot see light from objects beyond ~15 billion light years
- **Modern Cosmology:** Einstein (GR), Hubble (H_0)
- **GR Tests:**
  1. Precession of Mercury's orbit
  2. Gravitational Lensing
  3. Clocks run slow in gravitational field
- **Einstein's blunder:** GR predicts dynamic universe. Einstein added cosmological constant, Λ, to make Universe static. Hubble's observations changed this.

Lecture 8: Universal Expansion

- Hubble discovered expanding Universe
- **Hubble Law:** $V = H_0 \, d$
- Does not violate Copernican Principle:
  all galaxies see other galaxies moving away
- HST Key Project: H_0 = 72 km/s/Mpc
- **Age of Universe:** approx (1 / H_0) = 13 Gyr
- How deceleration/acceleration affects the age.
- Peculiar velocities: $V_{OBS} = H_0 \, d + V_{PEC}$

Lecture 9: Hot Big Bang

- **Cosmological Principle:**

UNIVERSE IS ISOTROPIC AND HOMOGENEOUS

- **Evidence:** Hubble Deep Fields, Large scale surveys, uniformity of Cosmic Microwave Background radiation
- **Fate of Universe:** Re-collapse or eternal expansion: derive **critical density**

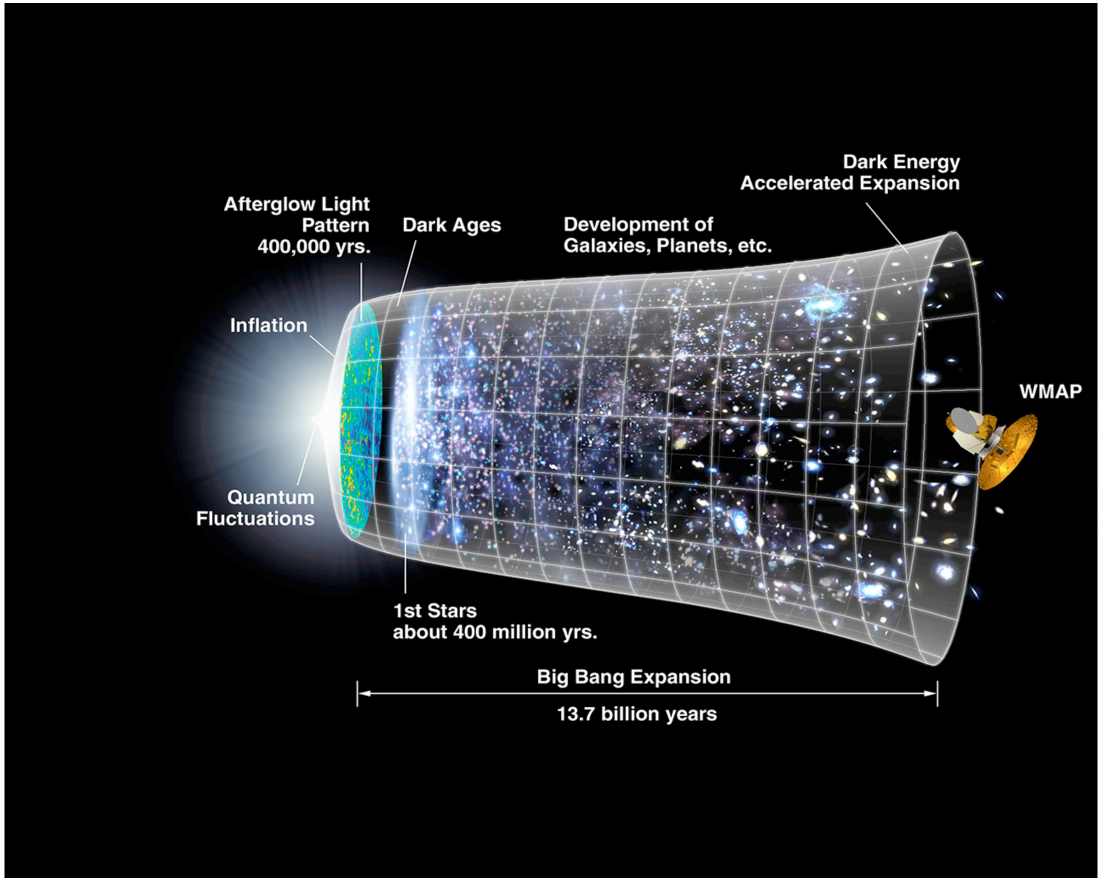
$$\rho_{\mathrm{CRITICAL}} = 3H_o^2 / 8\pi G$$

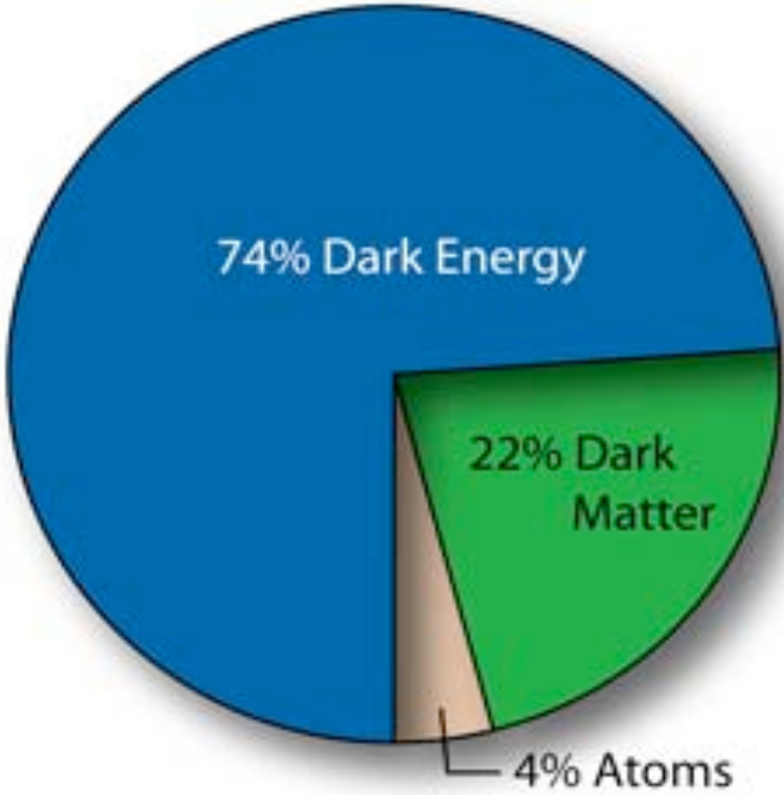
- Density of matter (and radiation) not enough to reach the critical density.
- Lecture 10: Cosmic acceleration
  => DARK ENERGY (or a cosmological constant Λ.

Lecture 10: Our "Crazy" Universe

Dynamical Universe
Size scales as $R(t)$

4% Normal Matter
22% "Dark Matter"
74% "Dark Energy"





Limits of Known Physics: Planck Units

Planck Length: de Broglie wavelength ~ Schwarzschild radius

$$E = M c^2 = \frac{h c}{\lambda} \quad \Rightarrow \quad \lambda = \frac{h}{M c} \qquad\qquad R_S = \frac{2 G M}{c^2}$$

$$\left(\lambda R_S\right)^{1/2} \sim L_P \equiv \left(\frac{\hbar G}{c^3}\right)^{1/2} \sim 10^{-35}\,\mathrm{m}$$

Planck Time $$t_P \equiv \frac{L_P}{c} = \left(\frac{\hbar G}{c^5}\right)^{1/2} \sim 10^{-43}\,\mathrm{s}$$

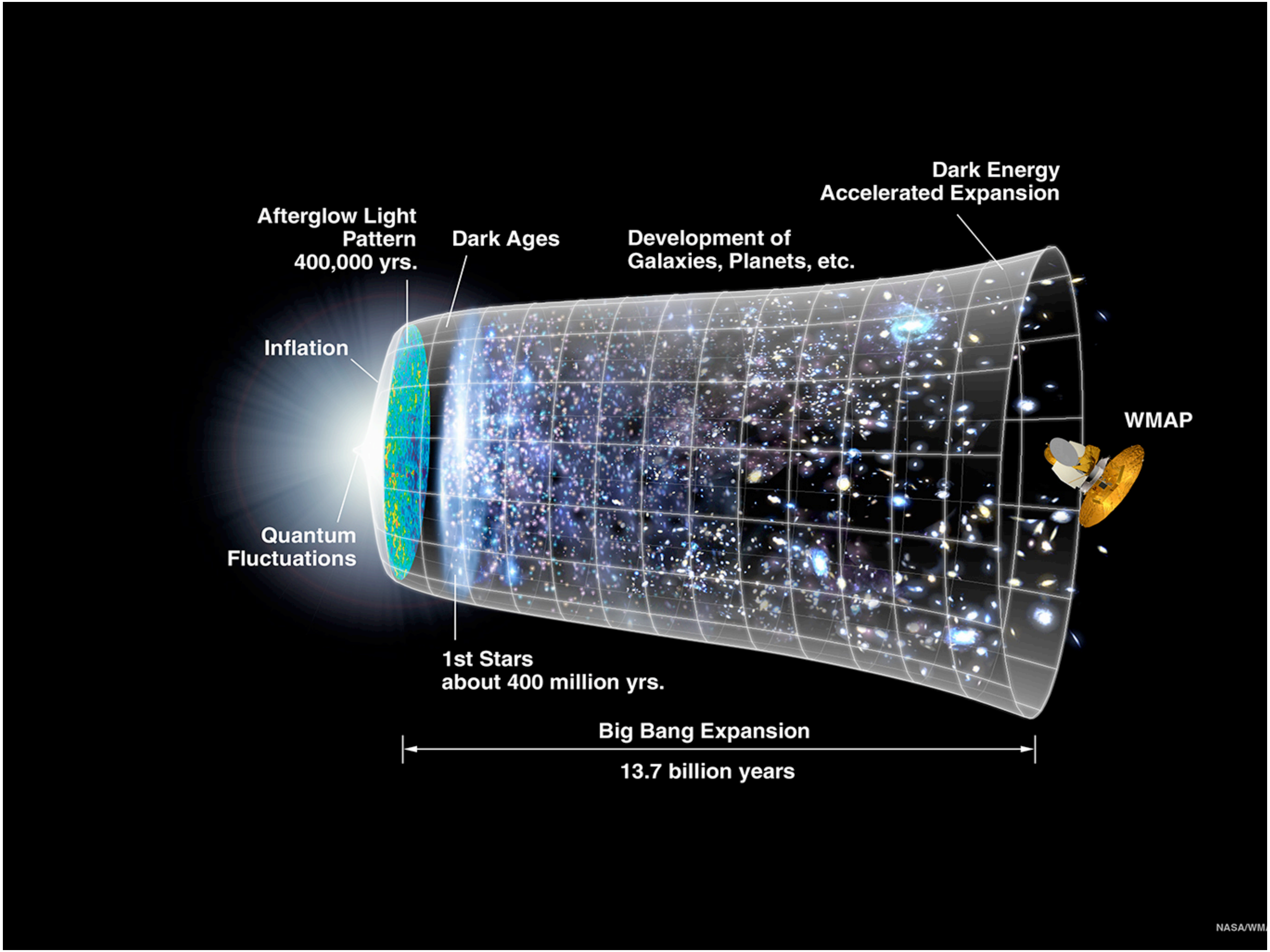
Planck Mass $$M_P = \frac{L_P c^2}{G} = \frac{\hbar}{L_P c} = \left(\frac{\hbar c}{G}\right)^{1/2} \sim 10^{25} m_p \sim 10^{19}\,\mathrm{GeV/c^2}$$

Planck Energy $$E_P \equiv M_P c^2 = \left(\frac{\hbar c^5}{G}\right)^{1/2} \sim 10^{19}\,\mathrm{GeV}$$

Limits of Quantum Mechanics and General Relativity.
Need Quantum Gravity theory (as yet unknown)
to describe physics at these scales.

1980: Inflation (Alan Guth)

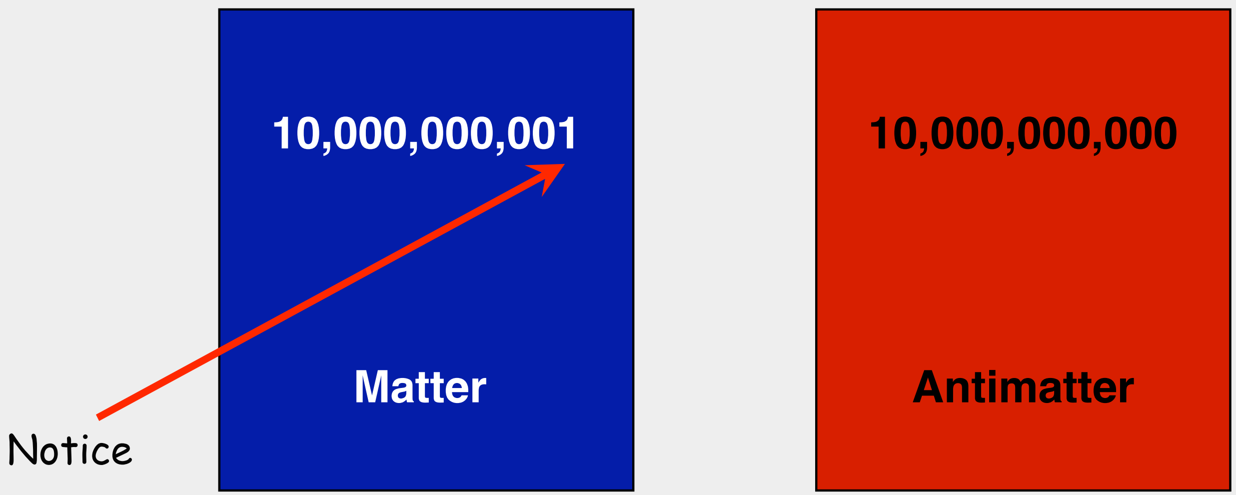
- Universe born from "nothing" ?
- A quantum fluctuation produces
  a tiny bubble of "**False Vacuum**".
- High vacuum energy drives **exponential expansion**.
- Universe expands by huge factor in tiny fraction of second (10^{-33}s), as false vacuum returns back to true vacuum.
- Expansion so fast that **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!**


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

Why is there something, rather than nothing ?

We are lucky because…

Immediately after the Big Bang,
the matter and antimatter… were NOT exactly equal

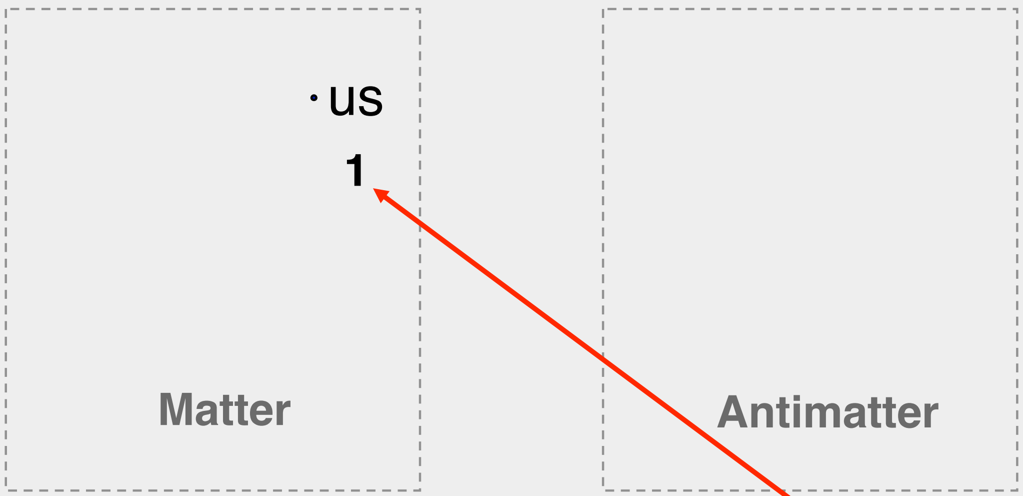


The Great Annihilation followed !!!

Why is there something, rather than nothing ?

Slight (10^{-9}) asymmetry between matter and anti-matter.

After the Great Annihilation…



All the antimatter, and all but a tiny part of the matter were gone … and that tiny part is us

1975: Big Bang Nuclear Fusion

Big Bang + 3 minutes

T ~ 10^9 K

First atomic nuclei forged.

Calculations predict:

75% H and 25% He

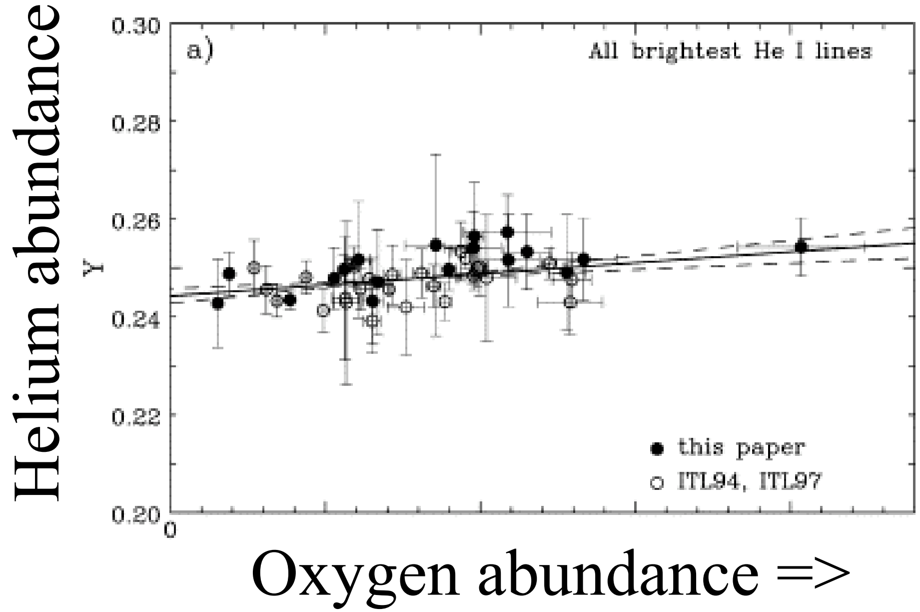
AS OBSERVED !

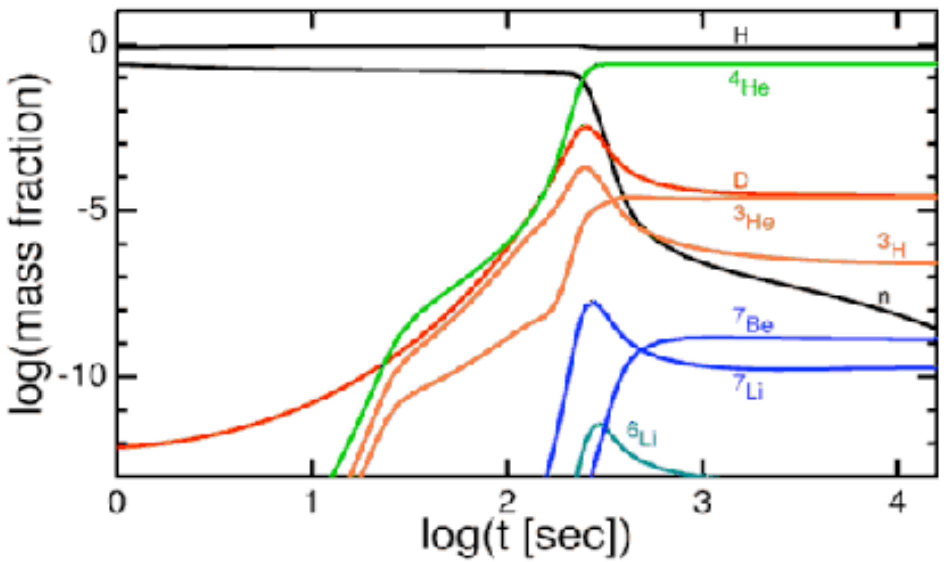
+ traces of light elements

D, ^{3}H, ^{3}He, ^{7}Be, ^{7}Li

=> **normal matter only**

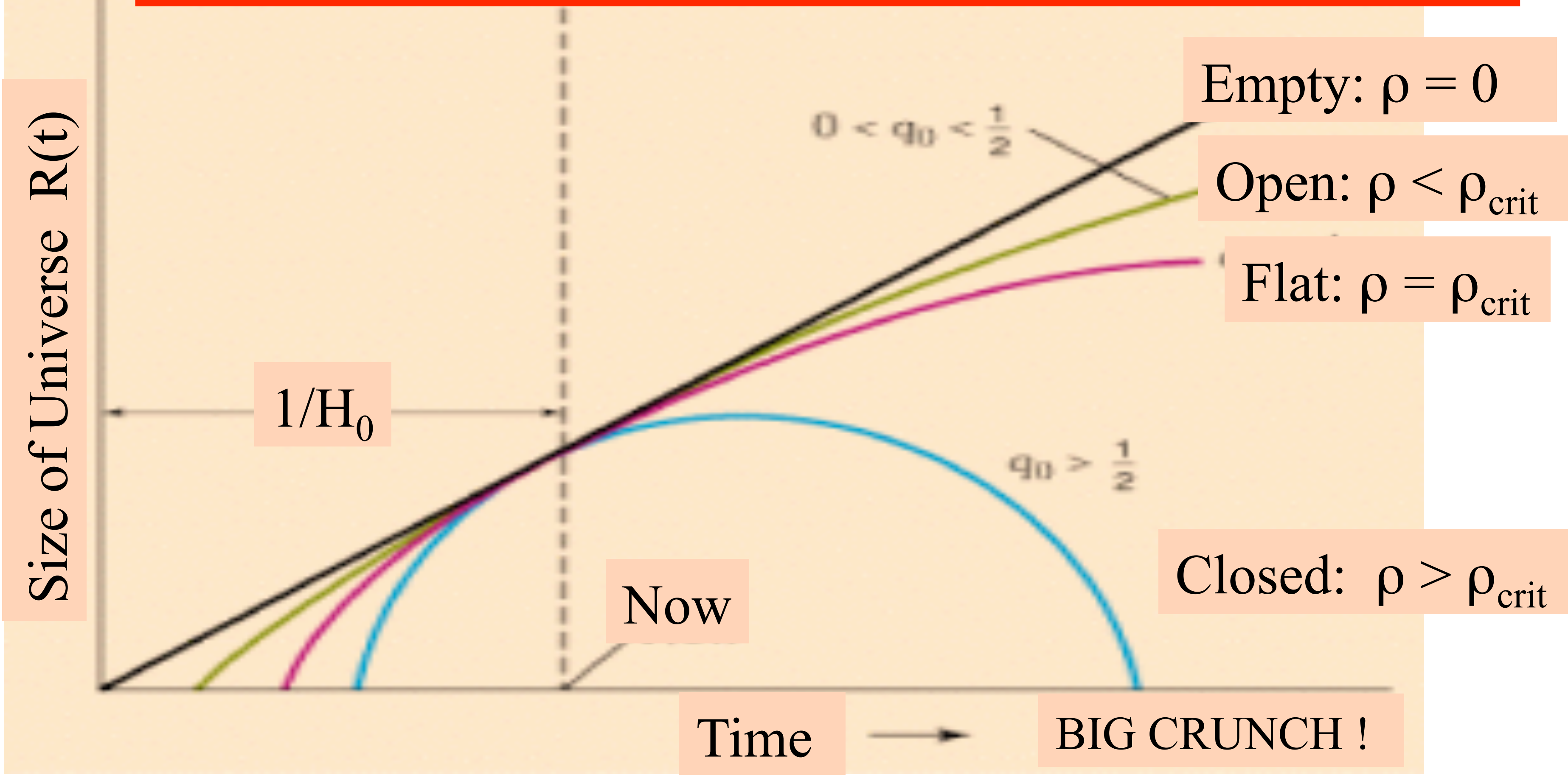
4% of critical density.





Re-collapse or Eternal Expansion ?

Inflation => expect FLAT GEOMETRY
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?

- Type Ia Supernovae used as "standard candles":
  (same luminosity *L* at peak brightness)
- 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 ($M > 8\ M_\odot$) explode at end of life, when $M_{core} = 1.4\ M_\odot$

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

Good “standard bombs”.

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

Finding faint Supernovae

Observe 10^6 galaxies.

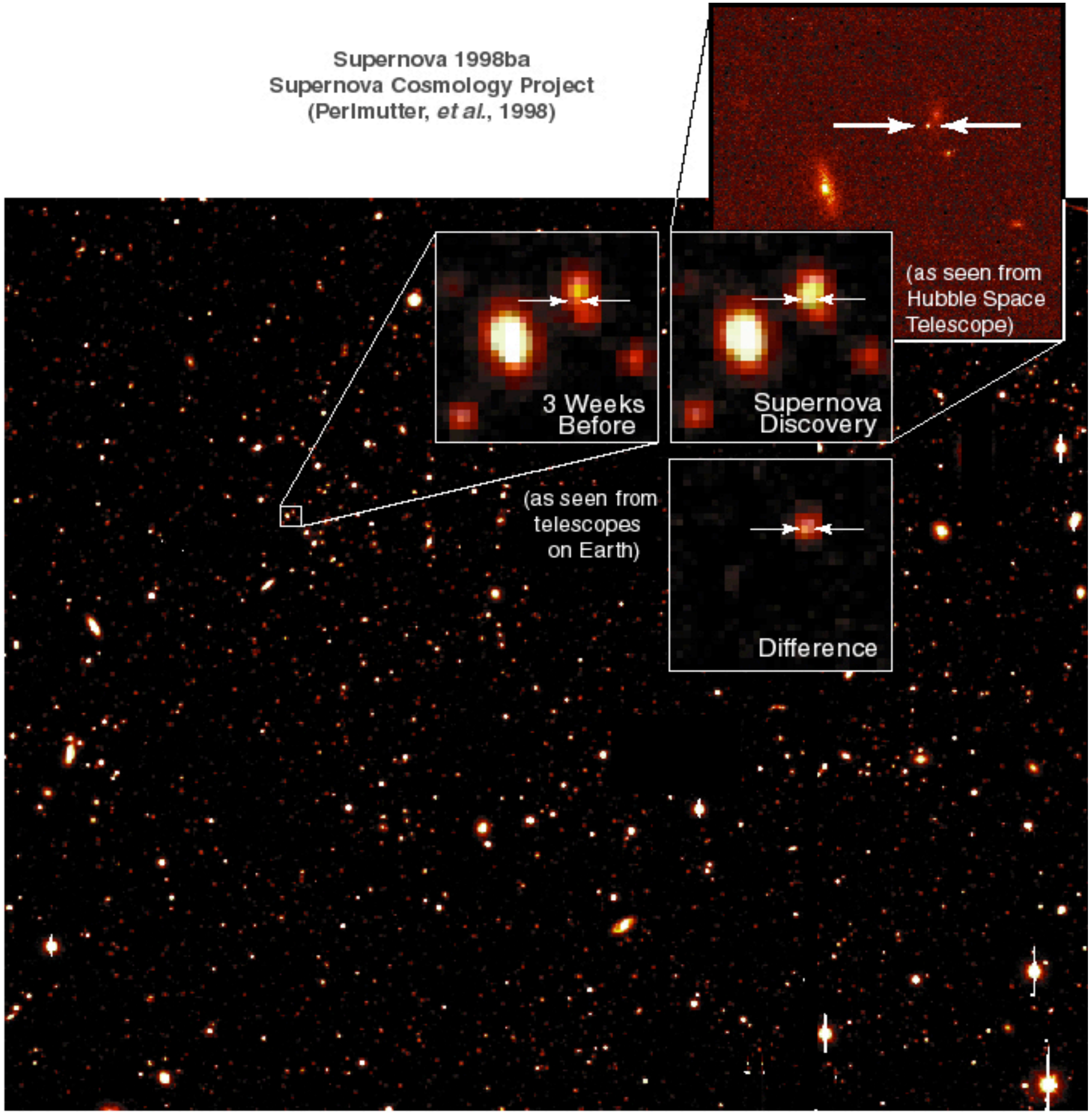
Again, 3 weeks later.

Find “new stars”.

Measure lightcurves.

Take spectra.

(Only rare Type Ia Supernovae work).



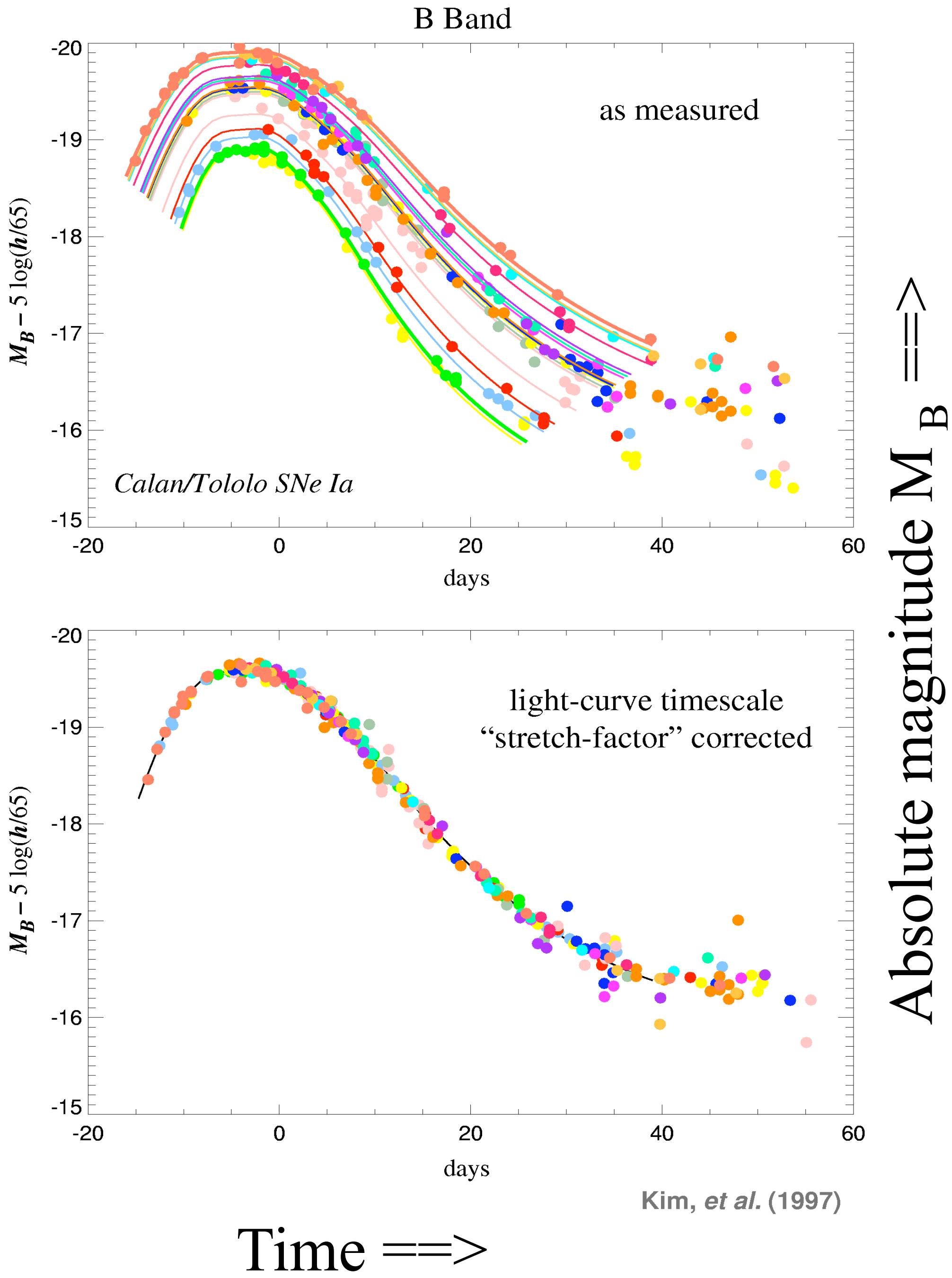
Calibrating "Standard Bombs"

1. Brighter ones decline more slowly.

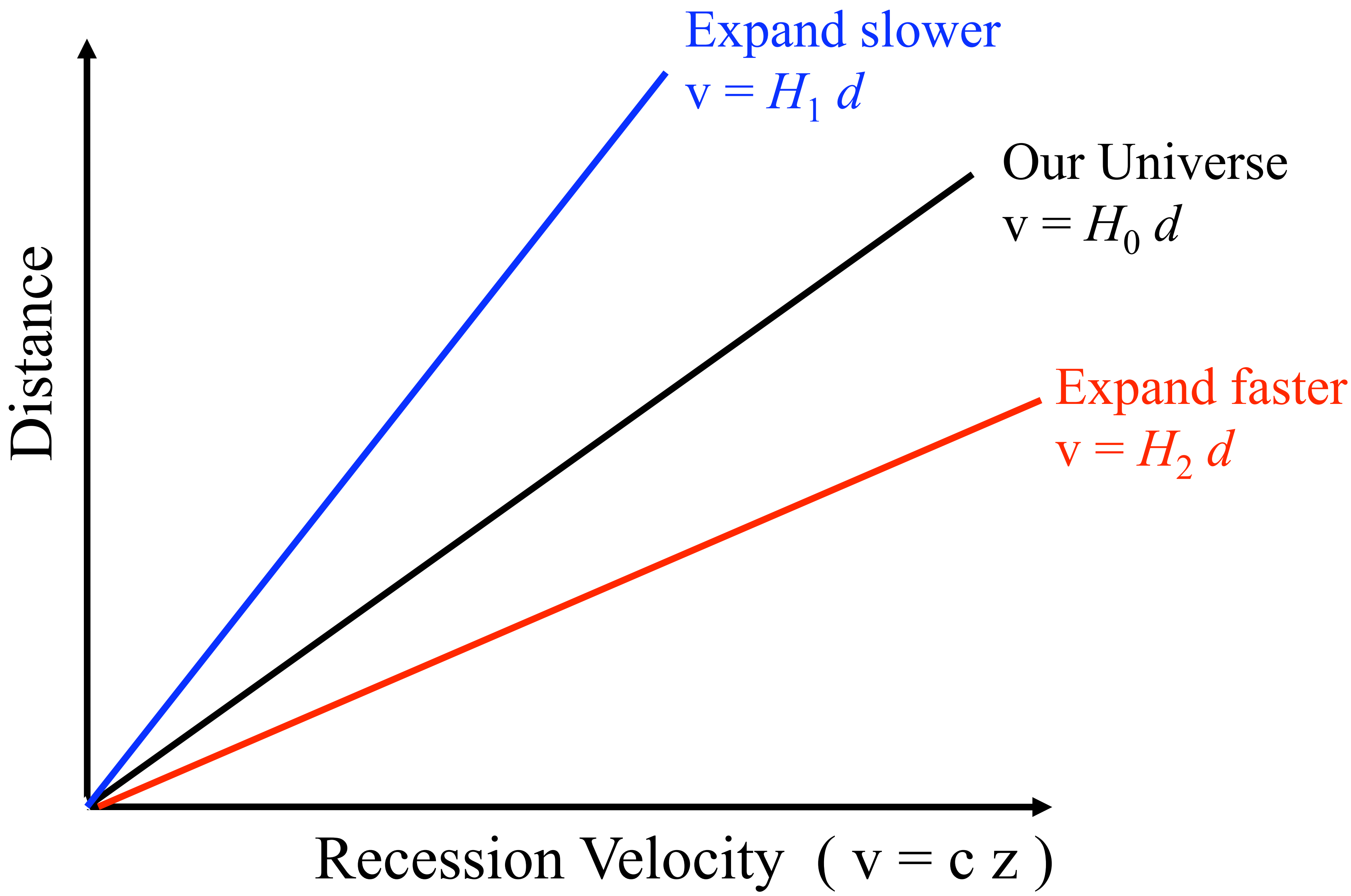
2. Time runs slower by factor (1+z).

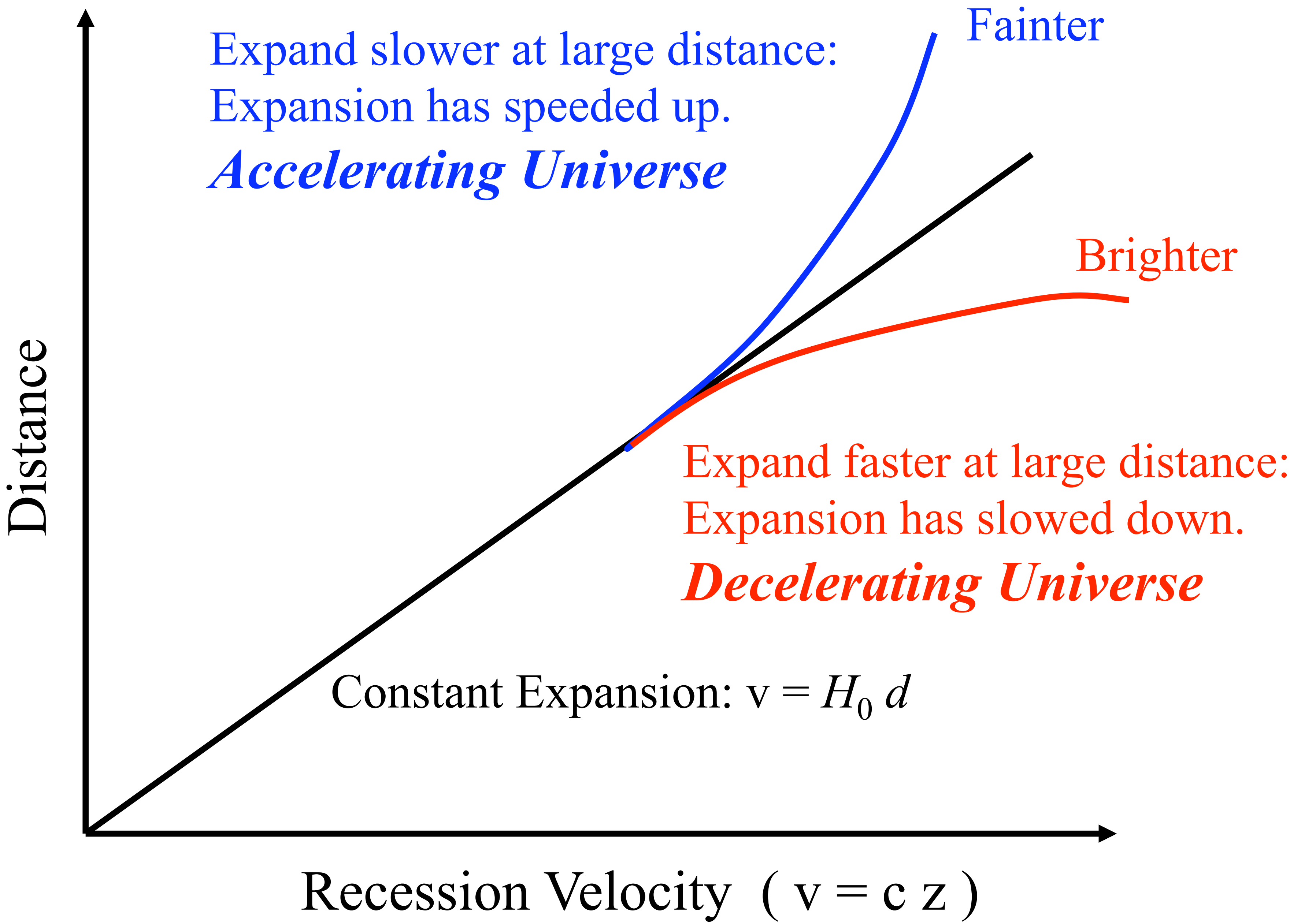
AFTER correcting:
Constant peak brightness
M_B = -19.7

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

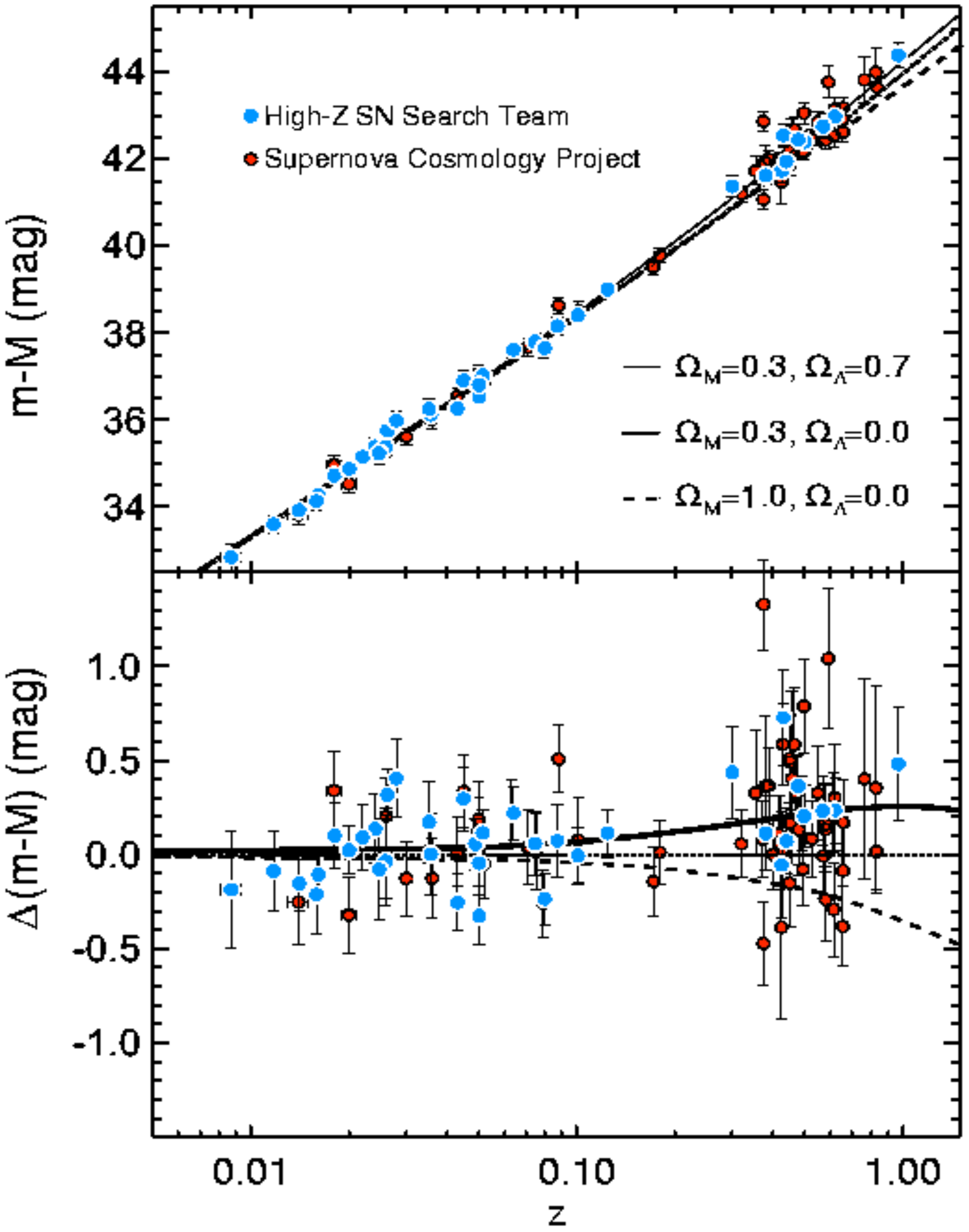


Varying Hubble Laws




Expand slower at large distance:
Expansion has speeded up.
Accelerating Universe
Fainter
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!**

Resurrection of the cosmological constant Λ, interpreted as DARK ENERGY.

Proposed space missions:
e.g. ***SNAP***
S*uper****N****ova* ***A****cceleration* ***P****robe*
to find even more distant SNe …

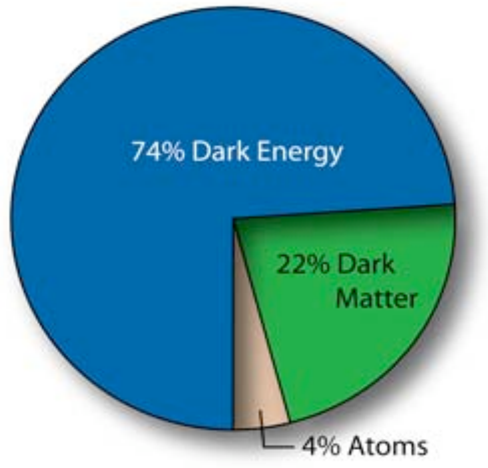
Acceleration by DARK ENERGY

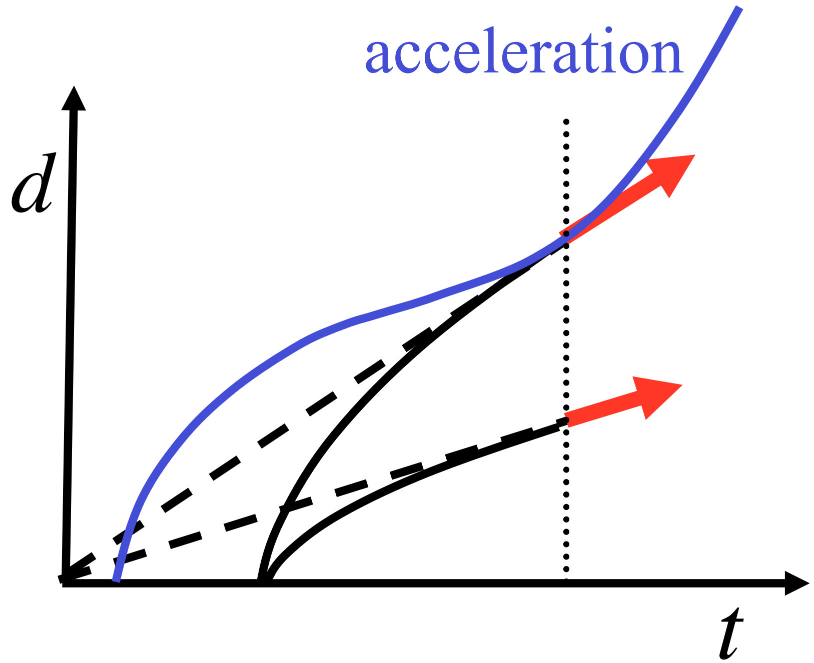
First, gravity from high matter density decelerates the expansion.

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

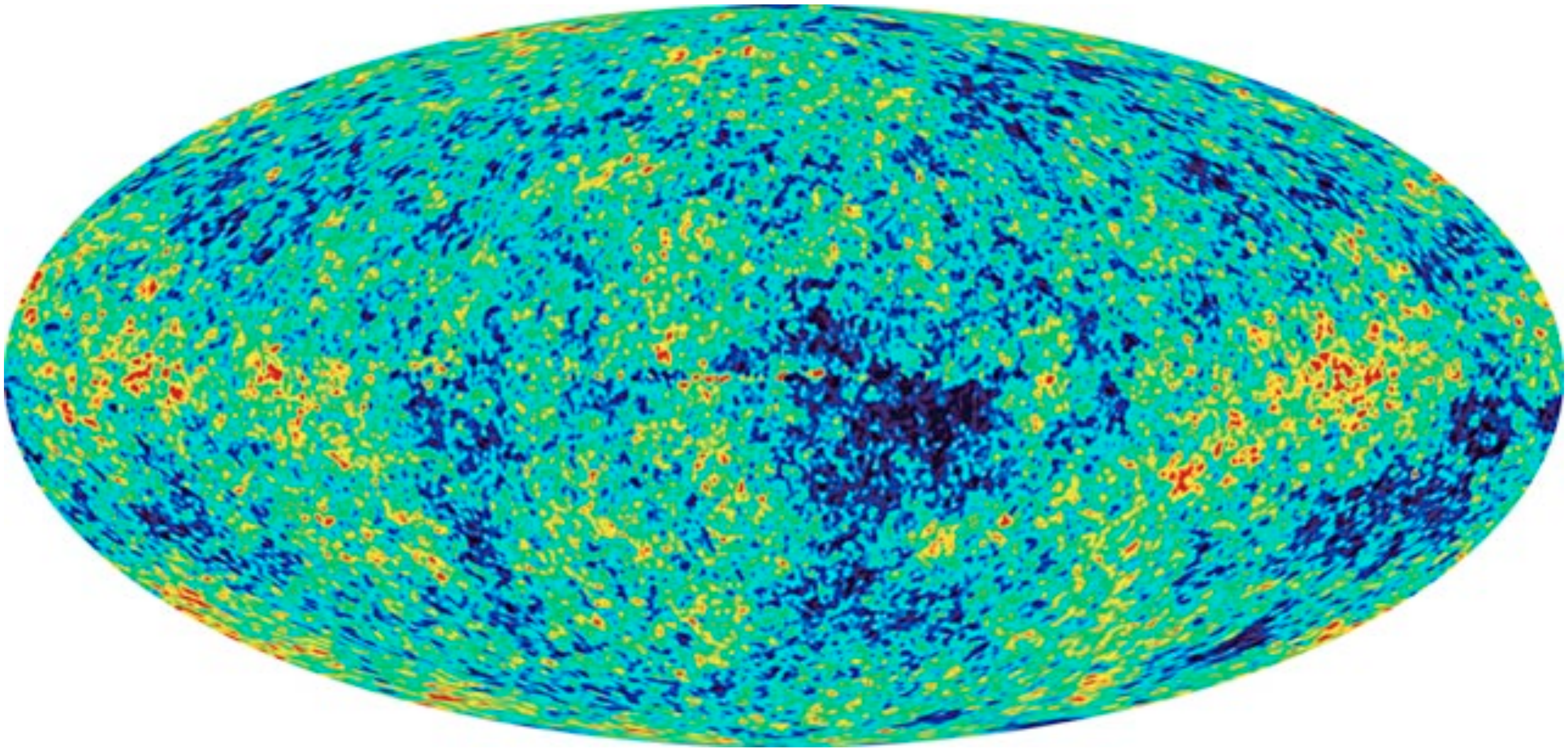




2004: WMAP all-sky CMB temperature map.

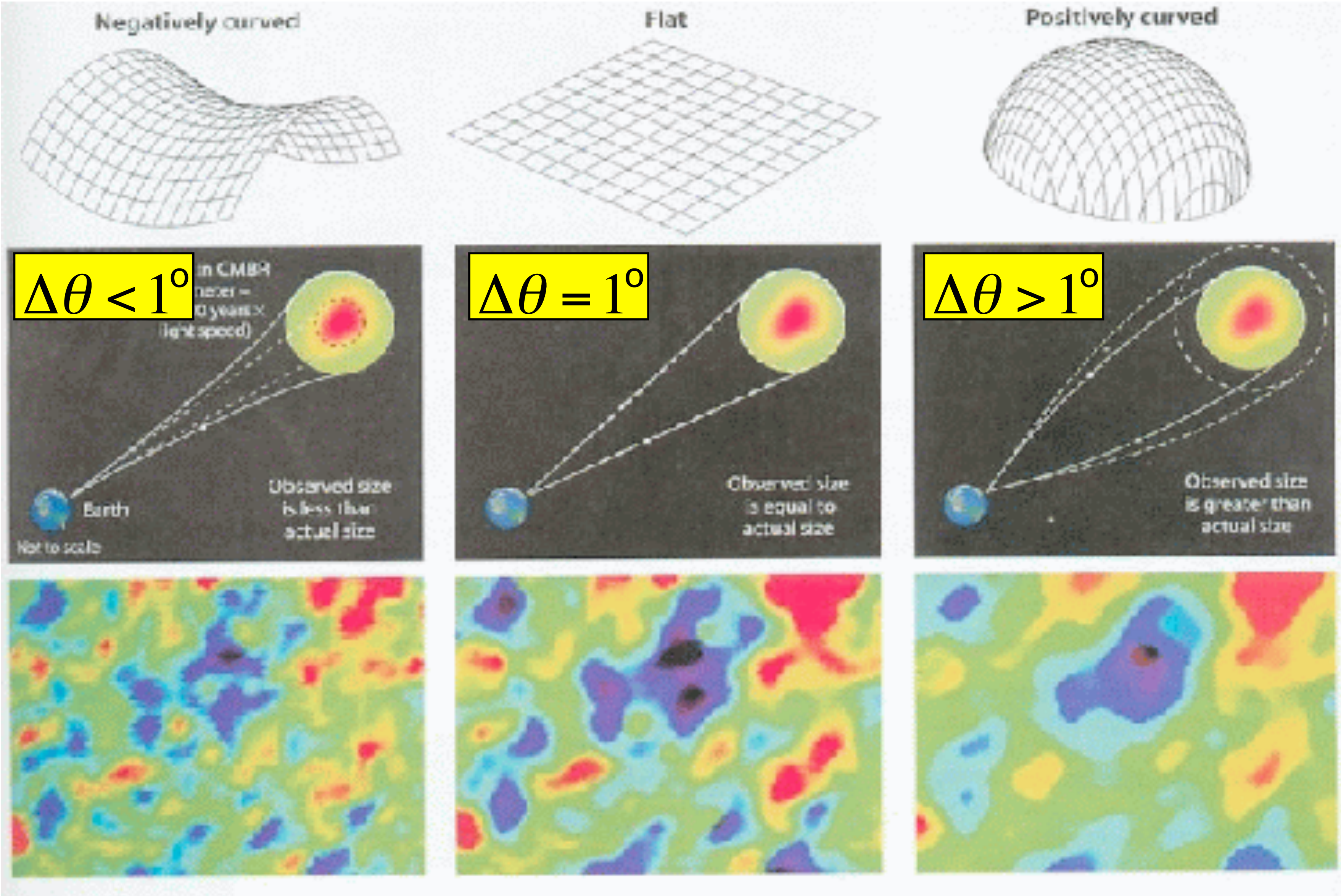
Tiny ripples (at z=1100, T=3000K, t=3x10^5 yr)
are the seeds of galaxy formation!

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

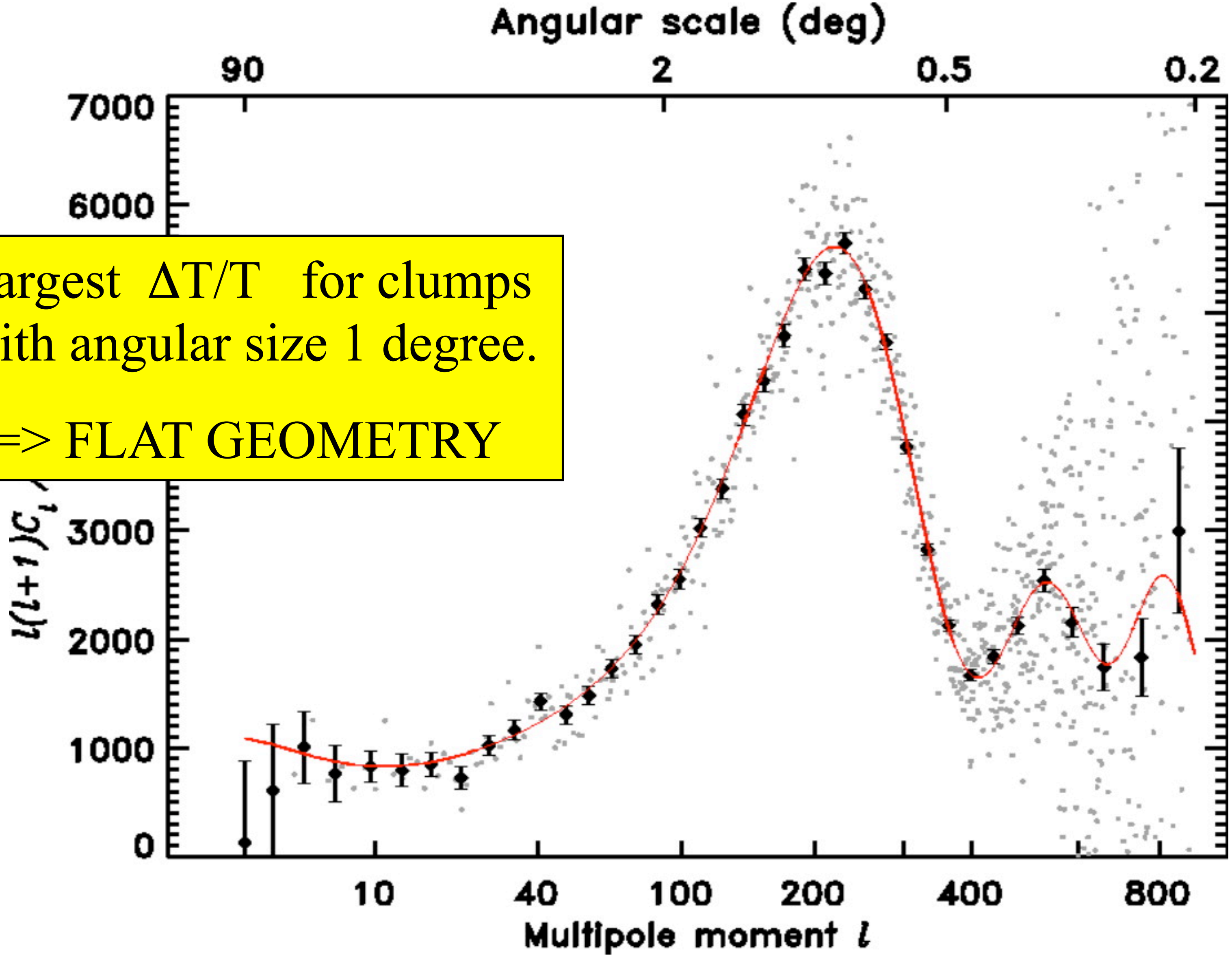


Geometry of Universe

Negative *FLAT* *Positive*



2004: WMAP - Power Spectrum



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

==> FLAT GEOMETRY

Possible Universes

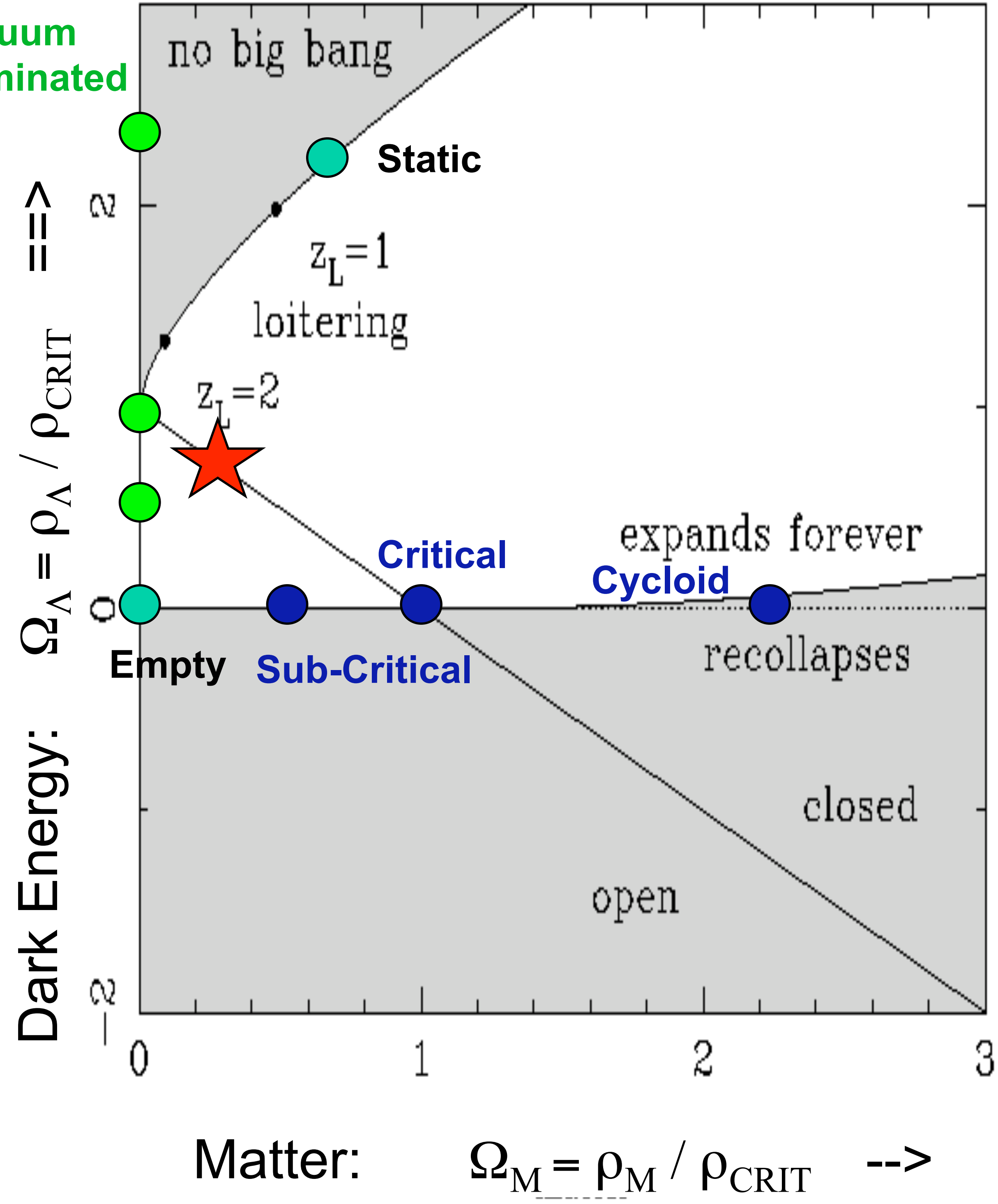
$$H_0 \approx 72 \frac{\text{km/s}}{\text{Mpc}}$$

$$\Omega_M \sim 0.3$$

$$\Omega_\Lambda \sim 0.7$$

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

$$\Omega = 1.0$$



Our "Crazy" Universe

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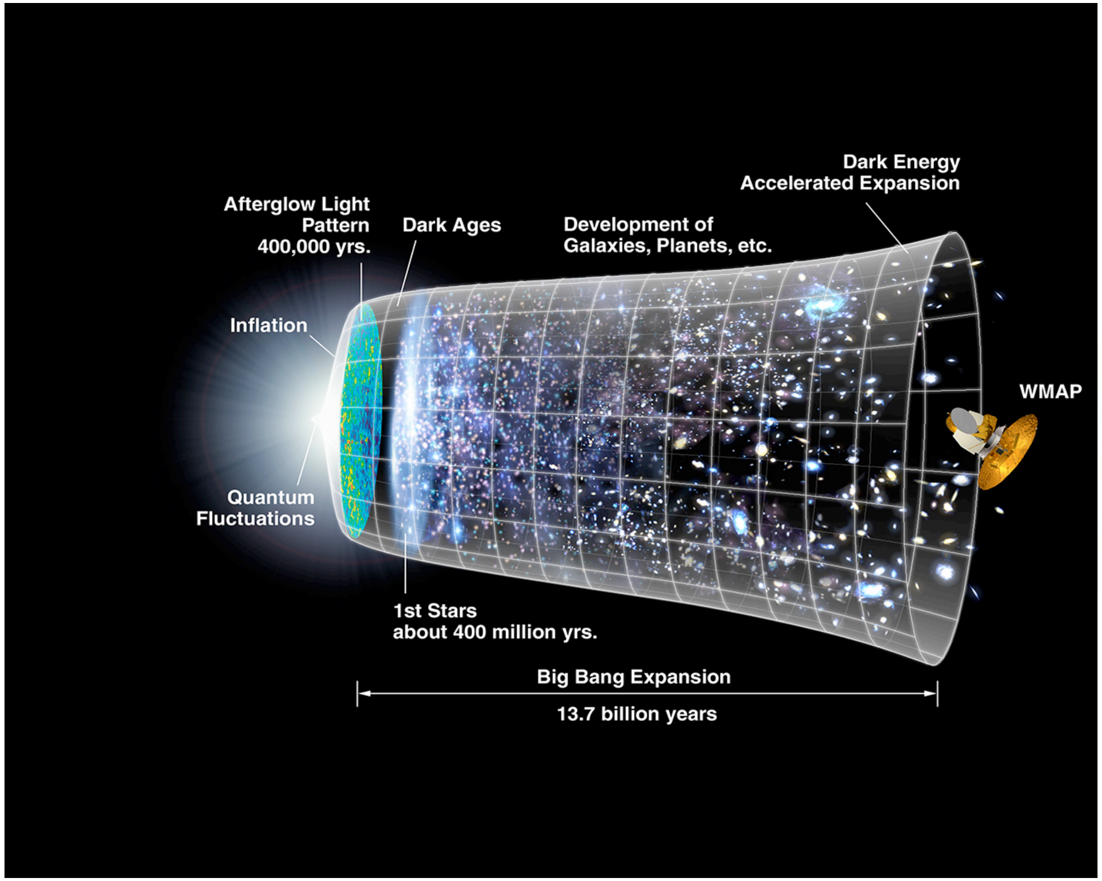
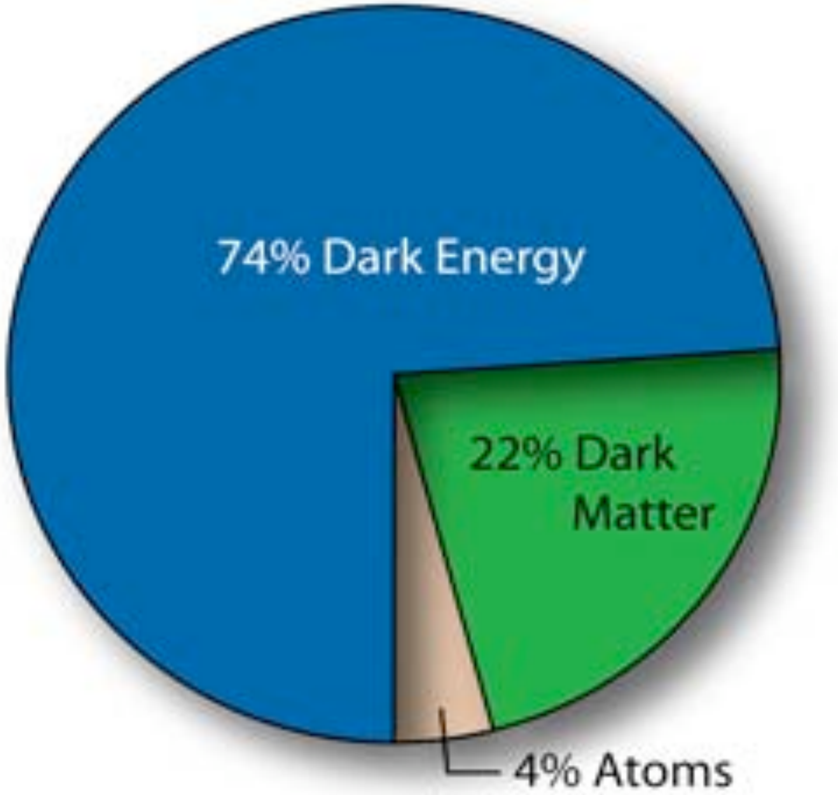
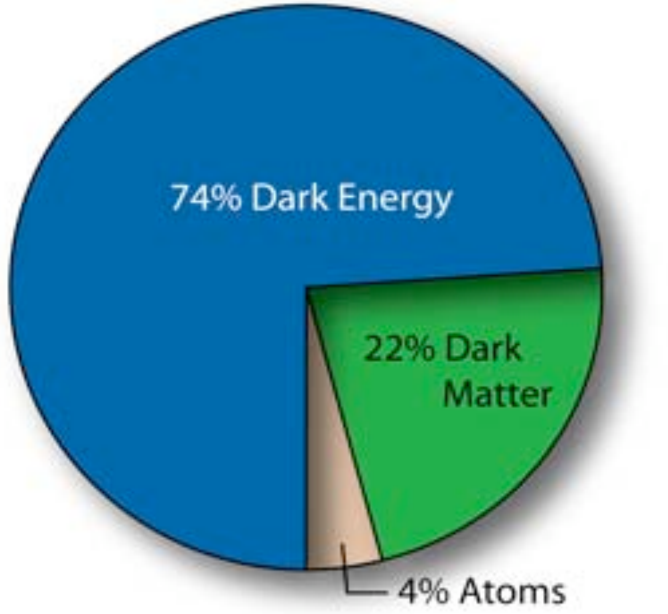




Or .... Has General Relativity Failed ?



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

No luck yet, but people are trying.

Thanks for Listening!

For more details:
AS2001
AS4022