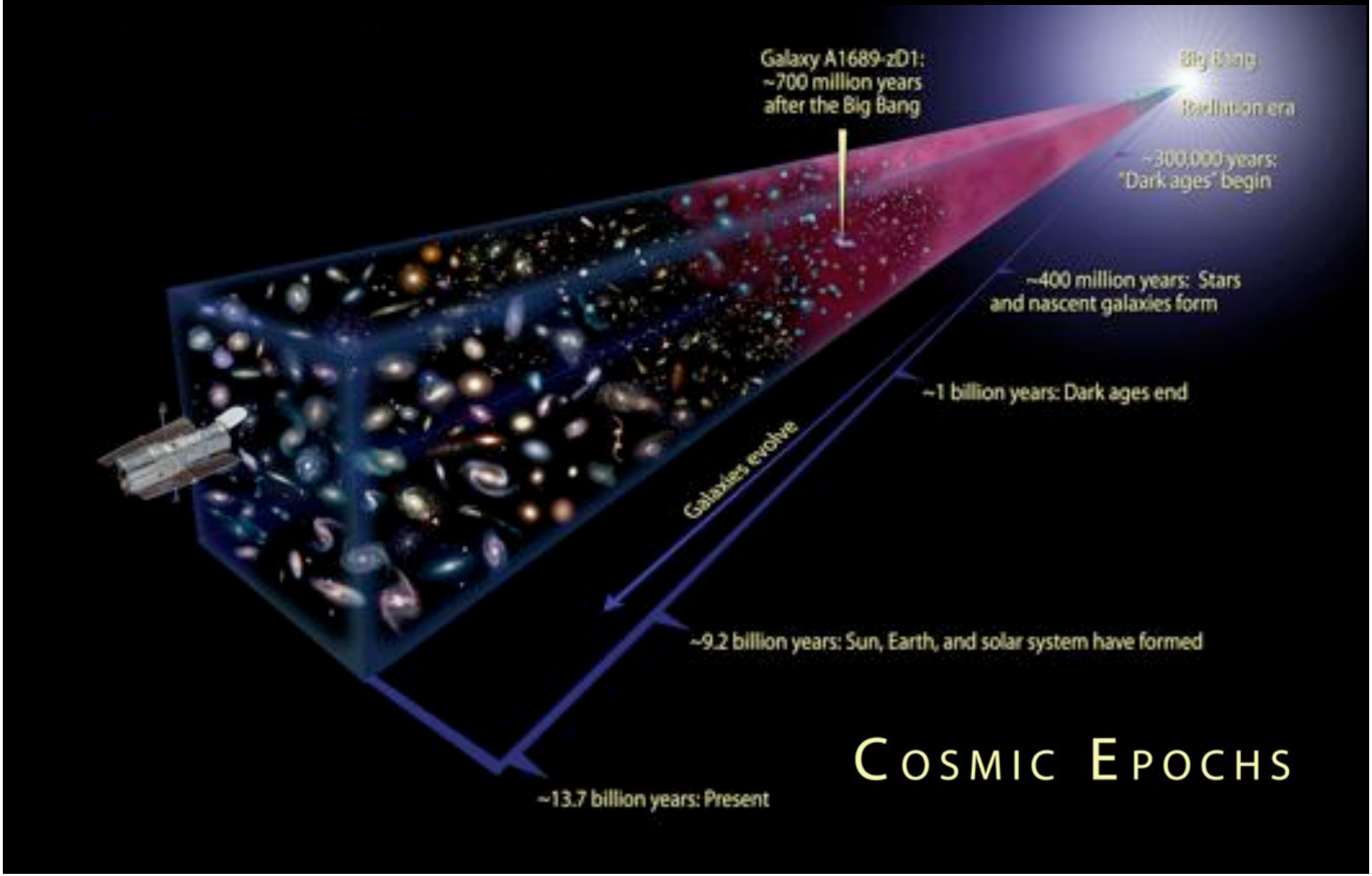
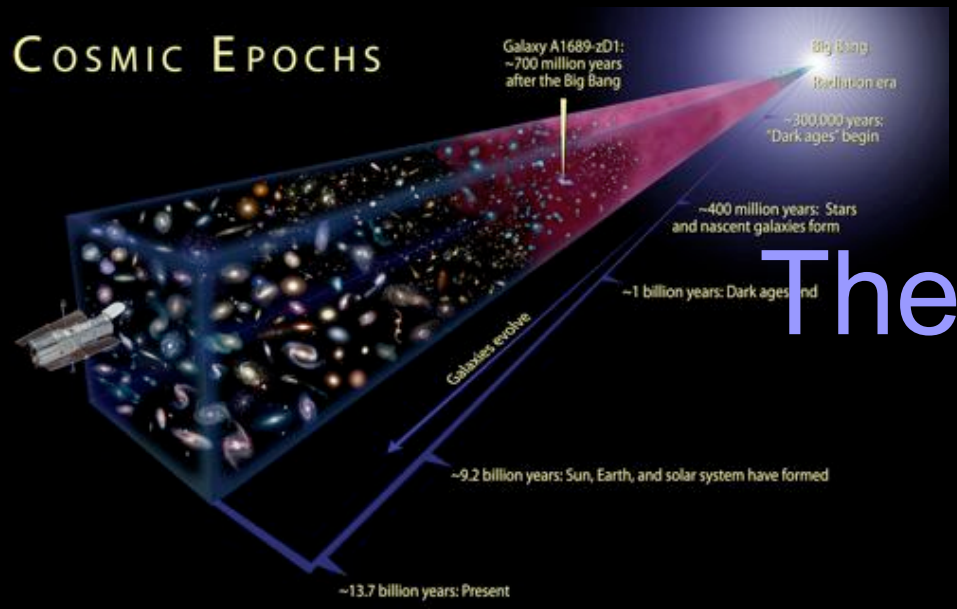
Cosmology – After the Big Bang

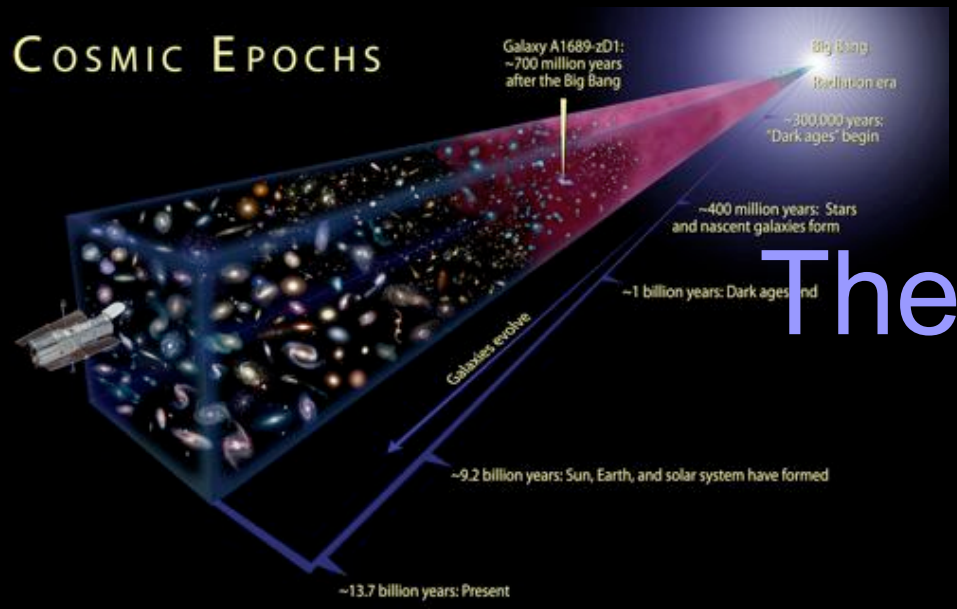




The Cosmological Principle

Provided you average over very large scales [say > billion light years]:

- ***The Universe is "homogeneous"***
  - Appears same everywhere
- ***The Universe is "isotropic"***
  - Appears same in all directions

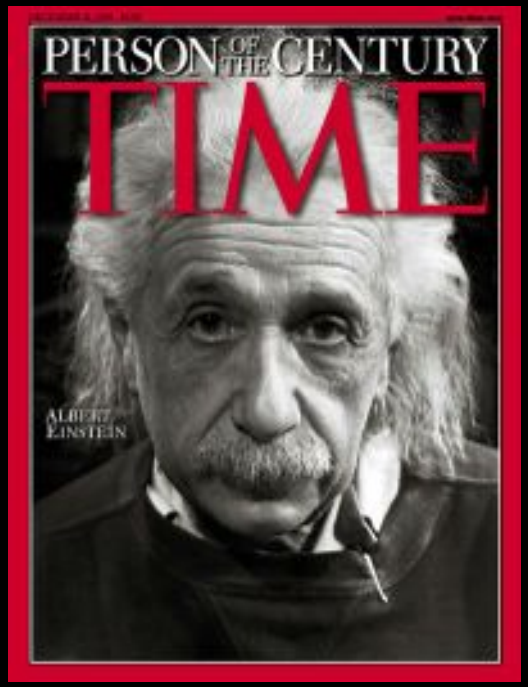


The Cosmological Principle

- ***Q: Does this also mean that the Universe is "static"?***

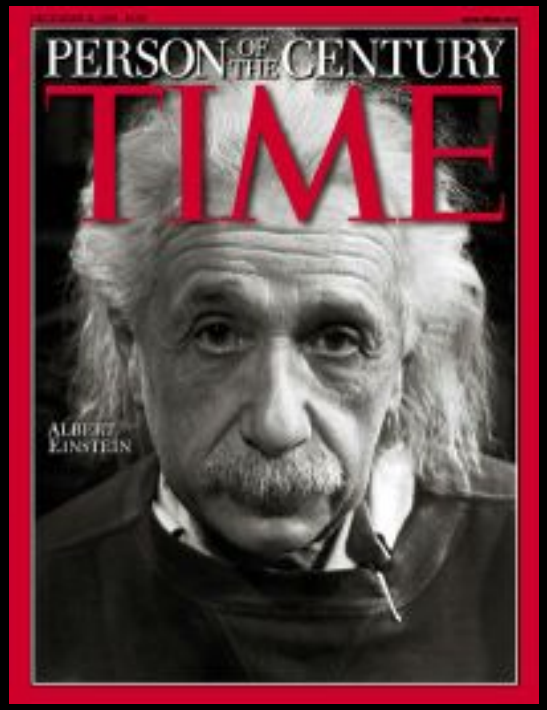
Einstein, General Relativity, and the Expanding Universe

1915: Source of Gravity = Curvature of space



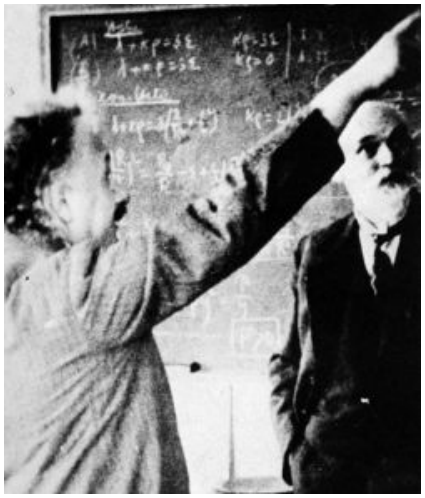
- 1917 – General Relativity allows no stable solution for the Universe.
- Therefore, the Universe must be either expanding or contracting.

Einstein, General Relativity, and the Expanding Universe



Source of Gravity = Curvature of space + Λ

large-scale repulsive force
"cosmological constant"
"vacuum energy"



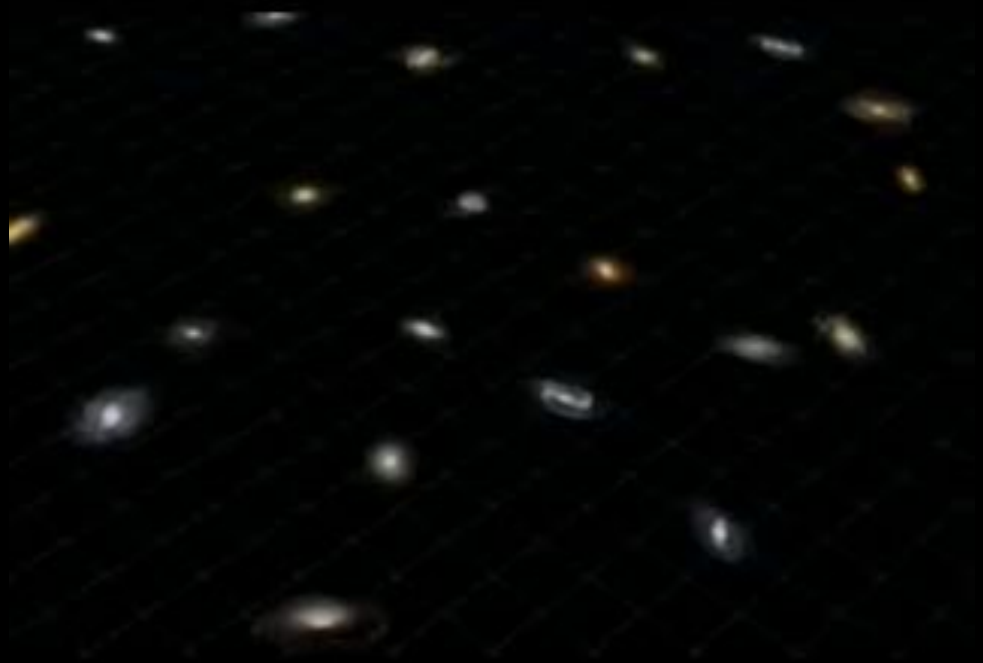
Einstein's Legacy

- DeSitter (1917) - expanding "empty" Universe models with cosmological constant

- Friedman 1923, Lemaitre 1927 - equations for evolution of Universe with matter and cosmological constant

Expansion of the Universe

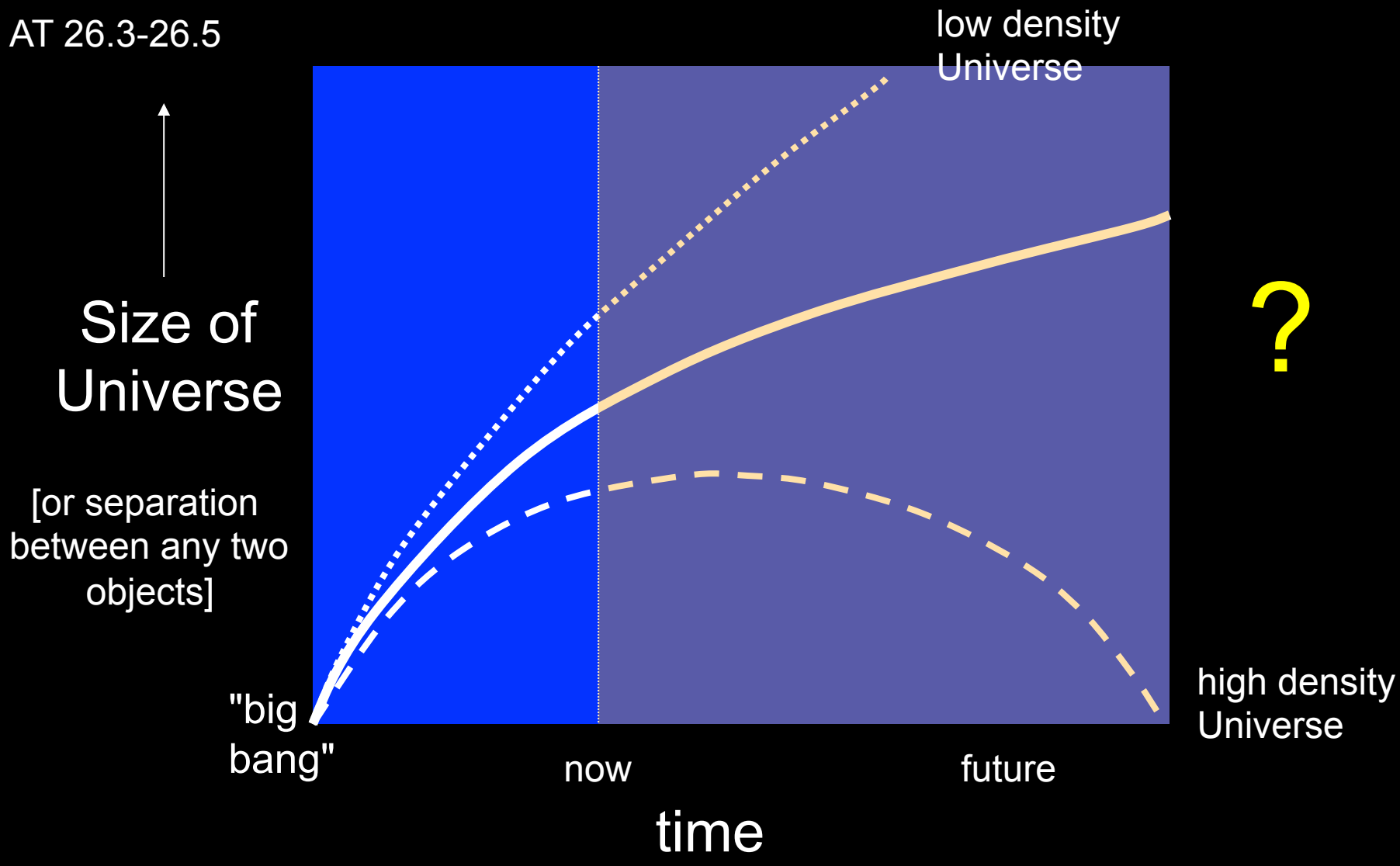
Hubble 1929



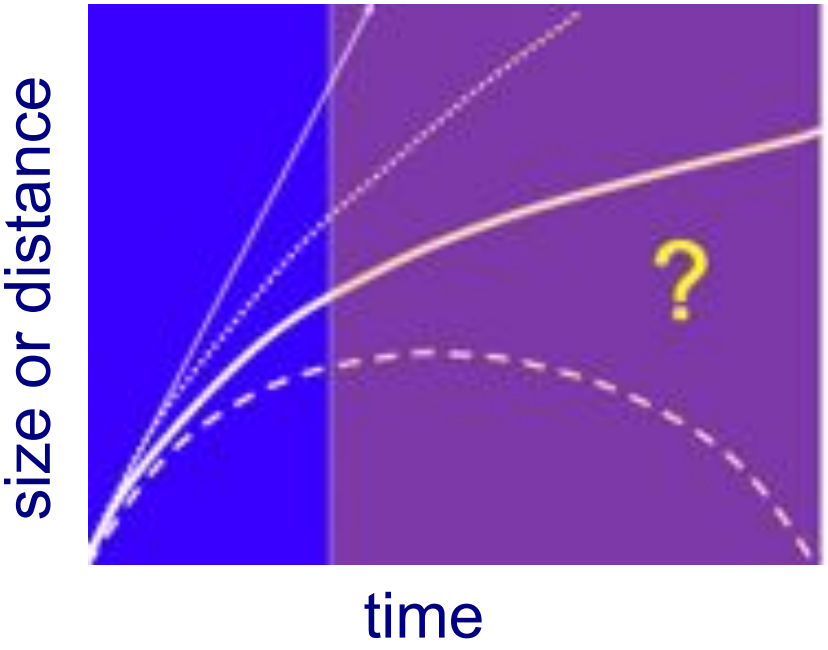
cosmological constant Λ discarded

"Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder of his life." – G. Gamow, "My World Line" (1970)

Fate of the Universe [matter only]



Fate of the Universe



Universe should slow down its expansion because of gravity.

How much? Depends on Ω.

- Density parameter:

$$\Omega = \frac{\text{density}}{\text{critical density}}$$

$\Omega > 1$: high density

$\Omega = 1$: critical density

$\Omega < 1$: low density

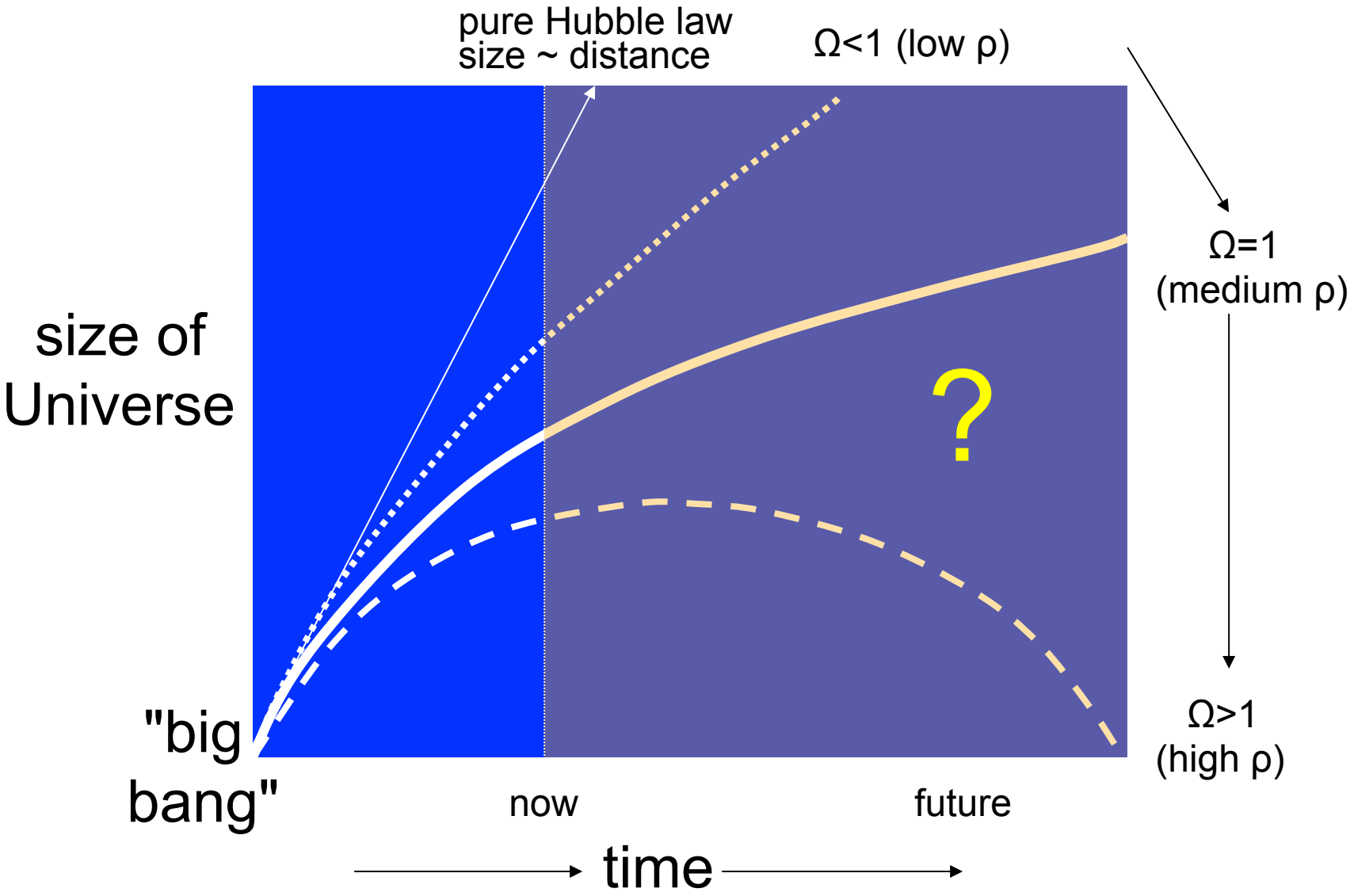
Fate of the Cosmos (AT26.3)

- Critical density (Ω=1) is the boundary between eventual collapse and expansion forever.
  - At this density the universe still expands forever, but the expansion speed goes to zero as time goes on.
- Critical density is approximately

$$9 \times 10^{-27}\ \text{kg/m}^3$$ (Depends on H_o)

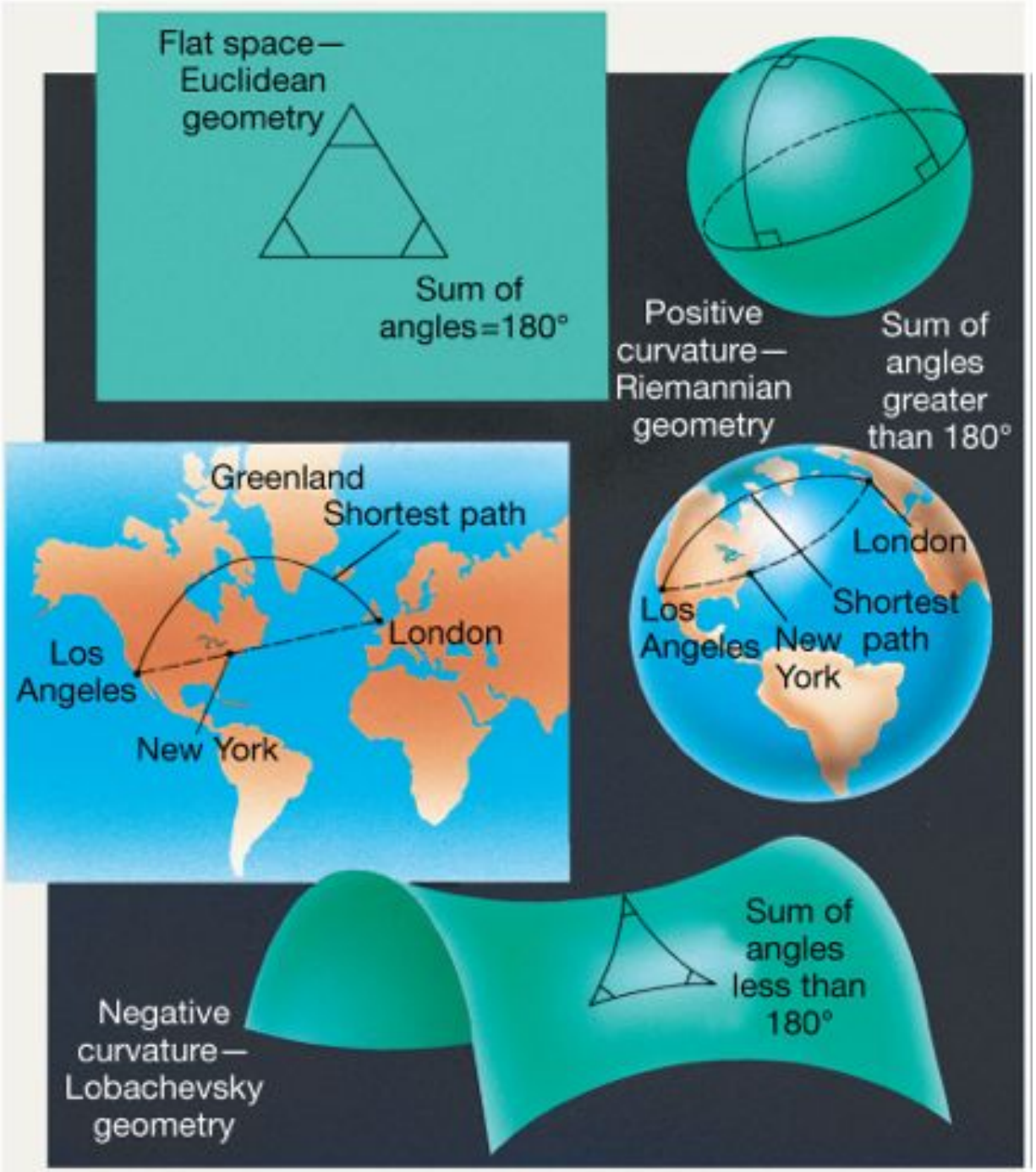
  - This is about five hydrogen atoms per cubic meter.

Fate of the Universe



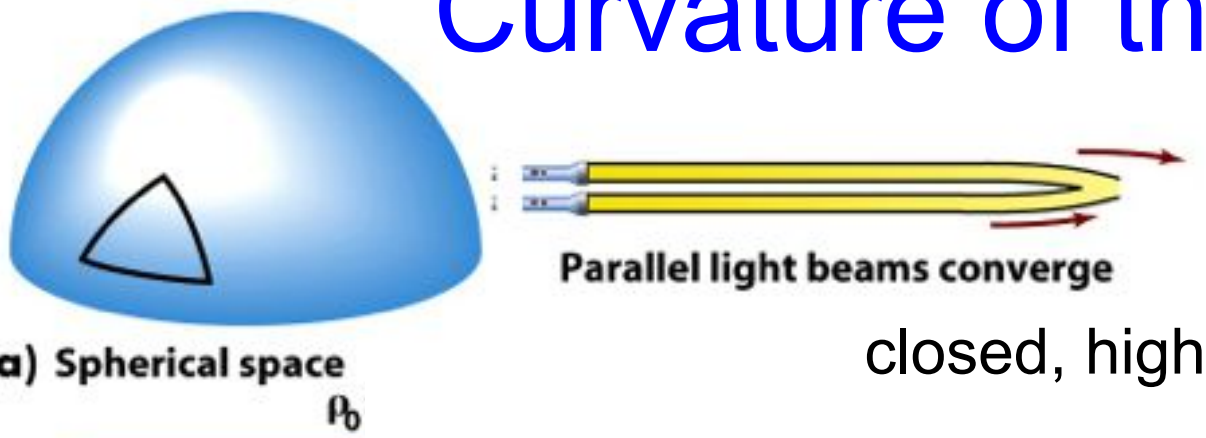
Curved Space

- closed geometry is like the surface of a sphere
- the flat one is flat
- the open geometry is like a saddle.

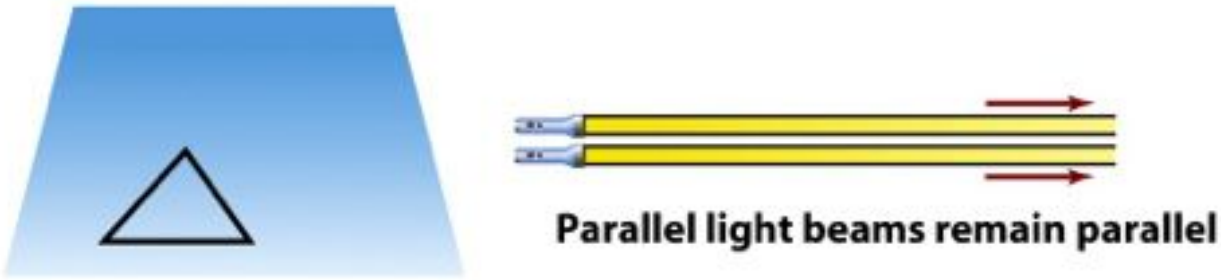


AT 26.4

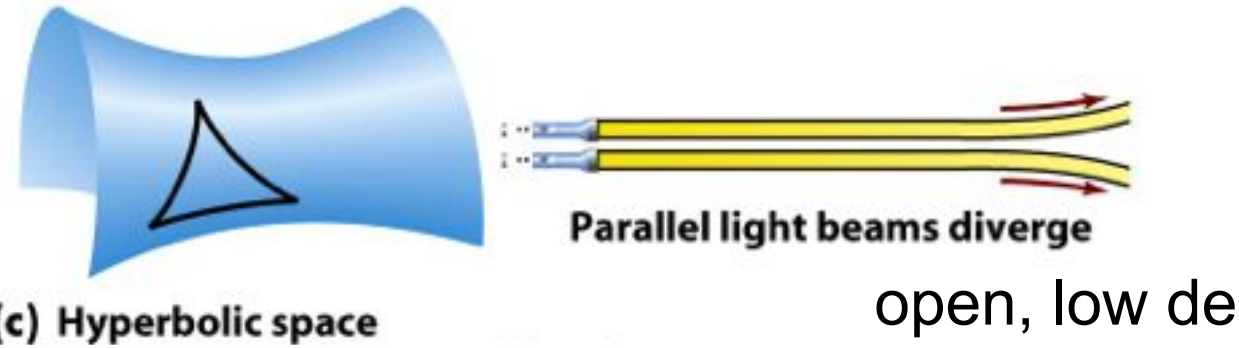
Curvature of the Universe



closed, high density, Ω > 1

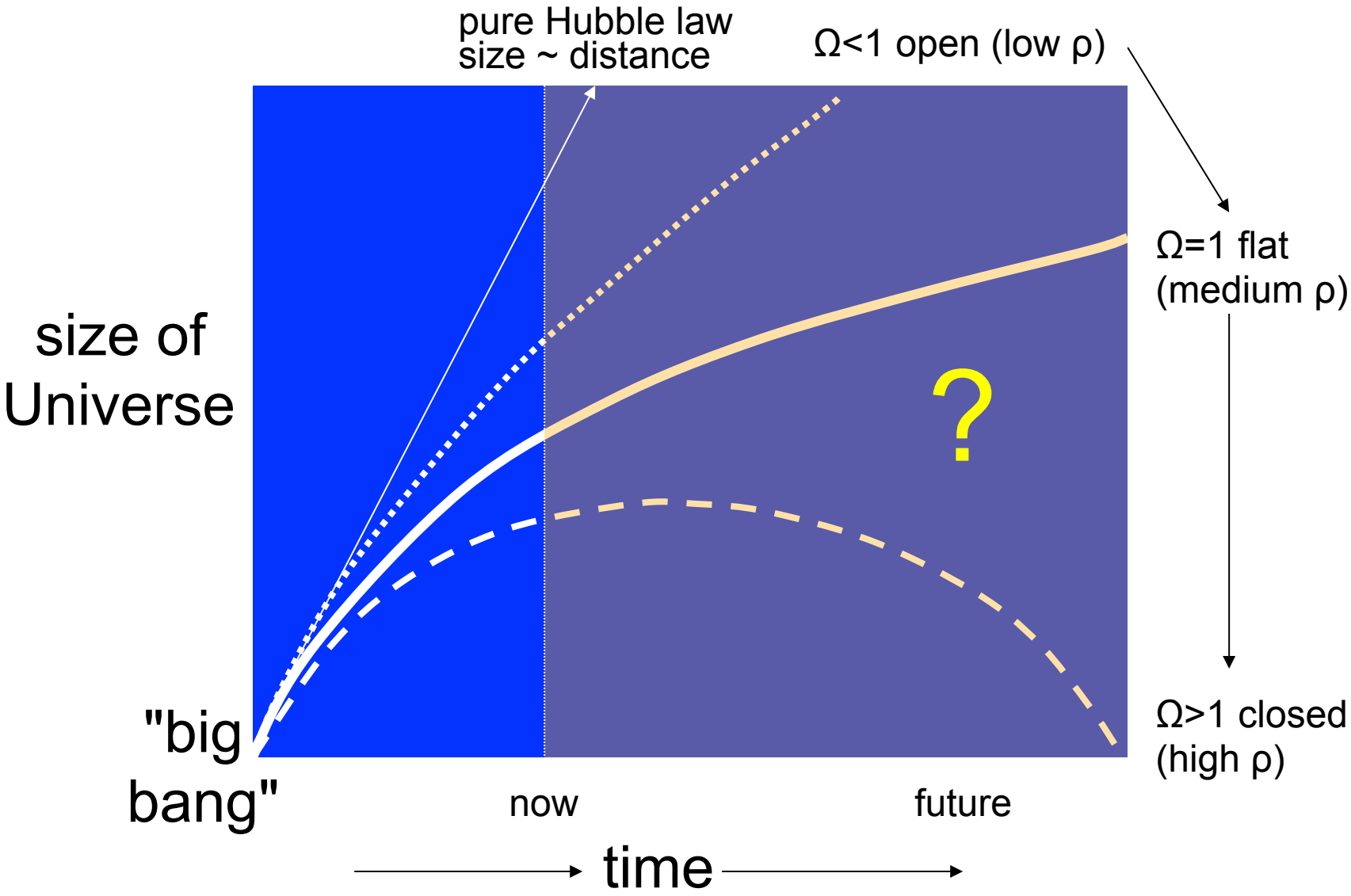


flat, intermediate density, Ω = 1



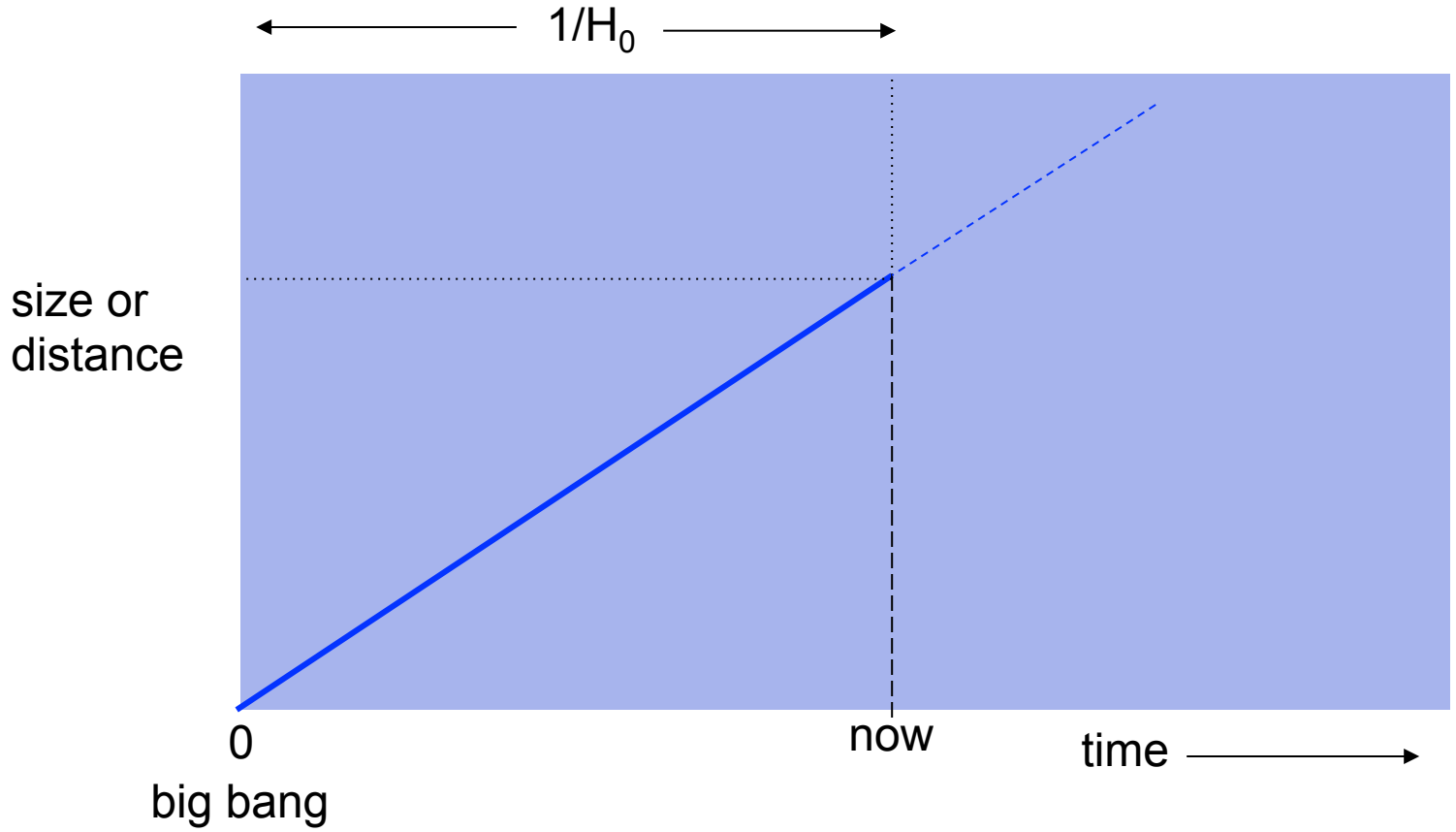
open, low density, Ω < 1

Fate of the Universe



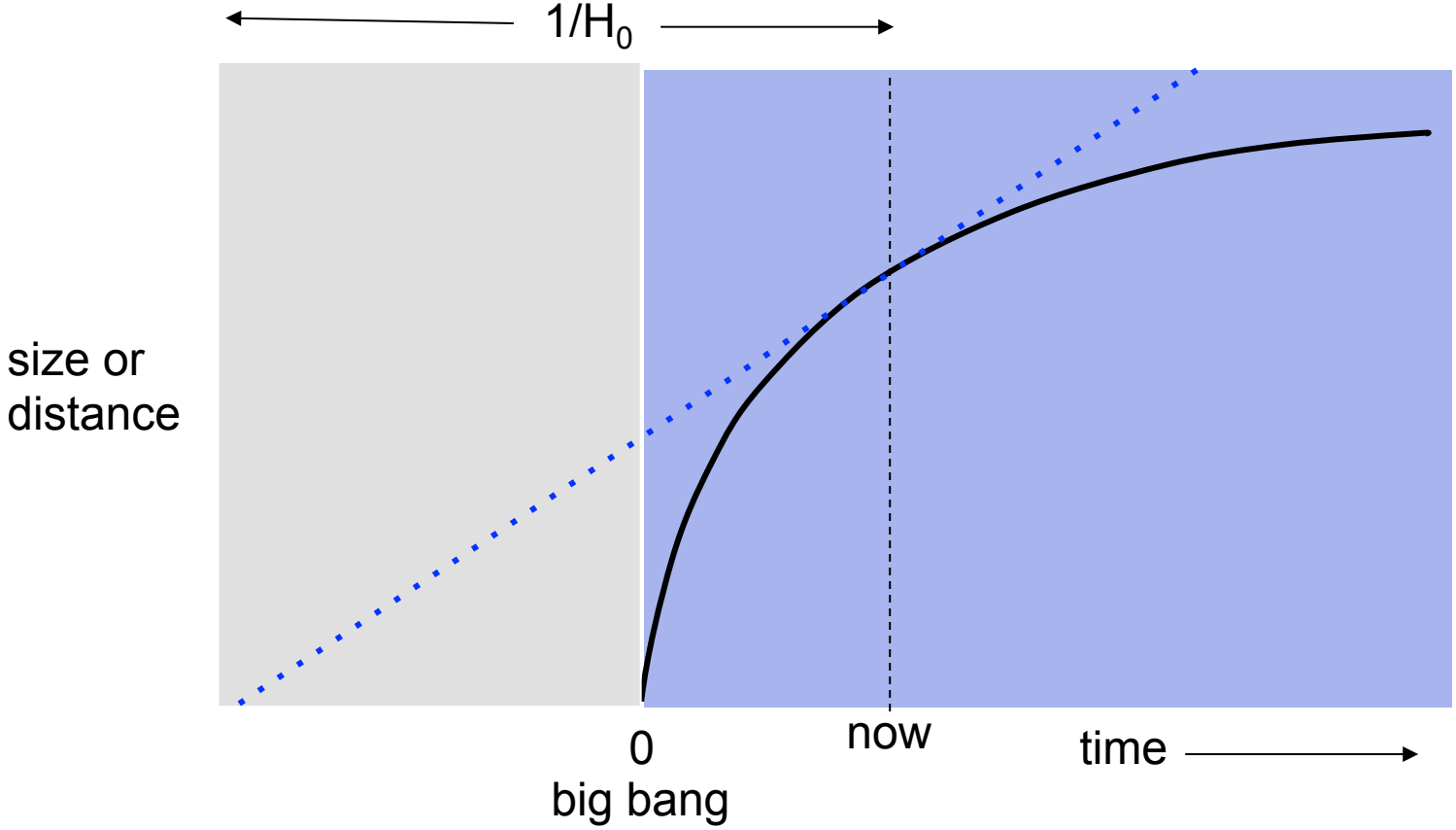
Age of Universe

- Uniform expansion: $t=1/H_o$



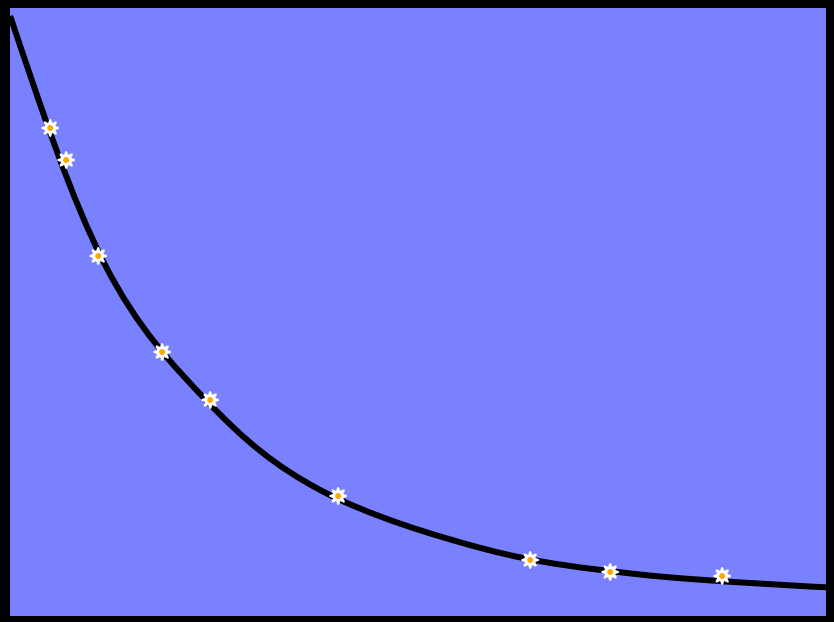
Age of Universe $< 1/H_0$!

- In a universe *with matter* and gravity (but nothing else), the Hubble expansion age $1/H_0$ is an <u>over-estimate</u>!

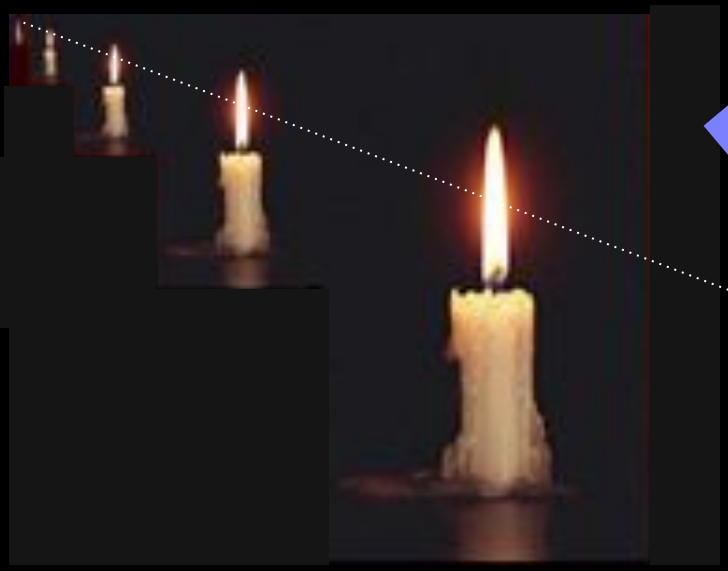


Standard Candles

apparent
brightness

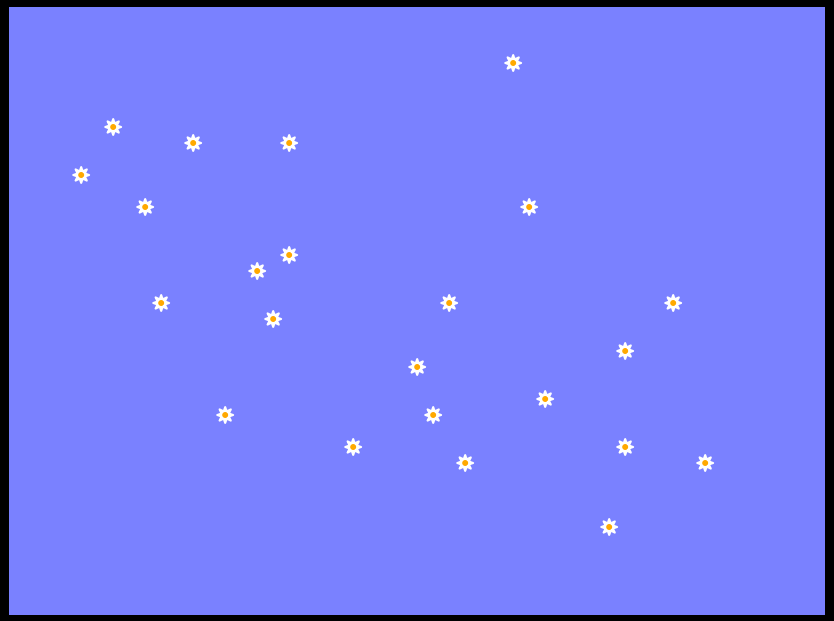


distance

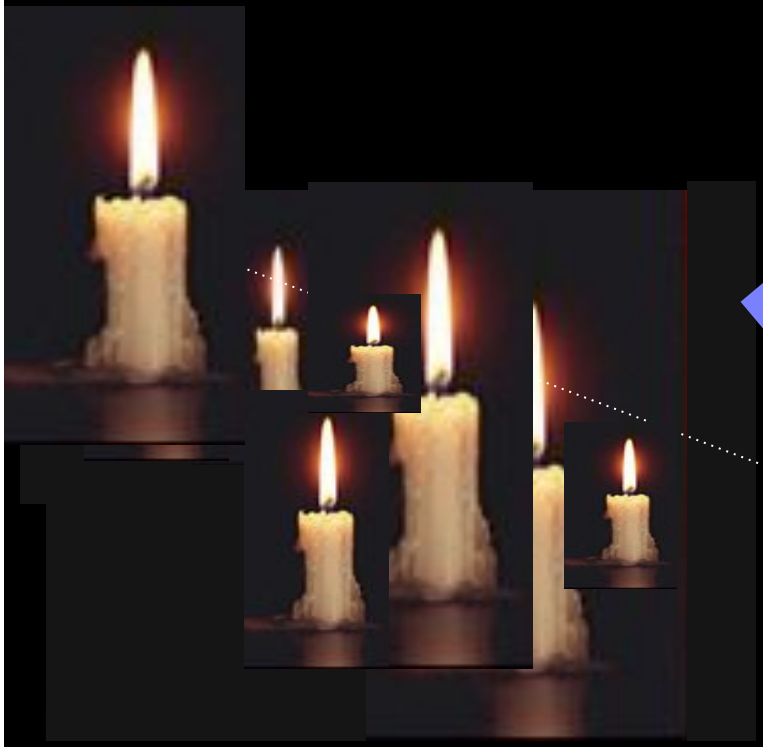


Non-Standard Candles

apparent
brightness



distance



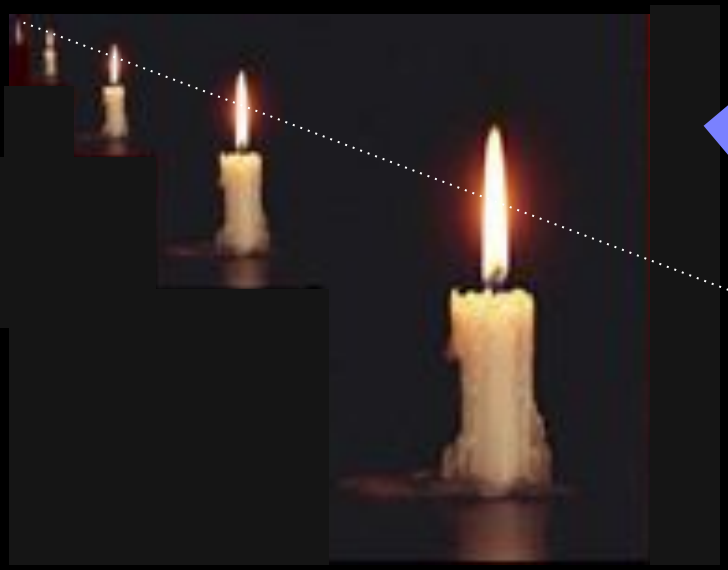
Standard Candles

faint

apparent magnitude

bright

log (distance or velocity)



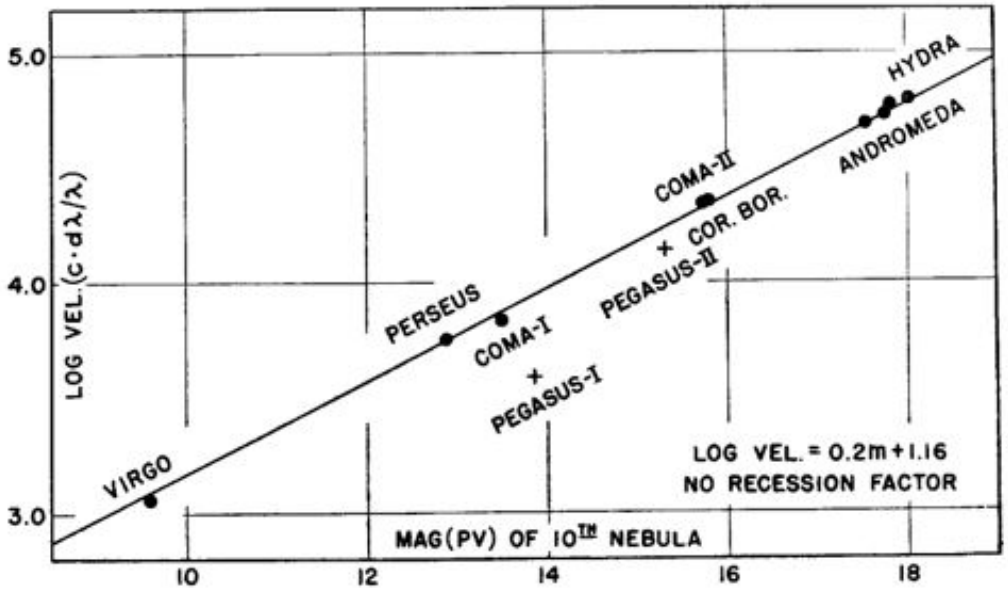
Only for standard candle

The “Hubble Diagram”

Magnitude – Redshift Relation

- another way Hubble demonstrated expansion of Universe

Hubble við sjónaukann sem byggður var á Palomar-fjalli

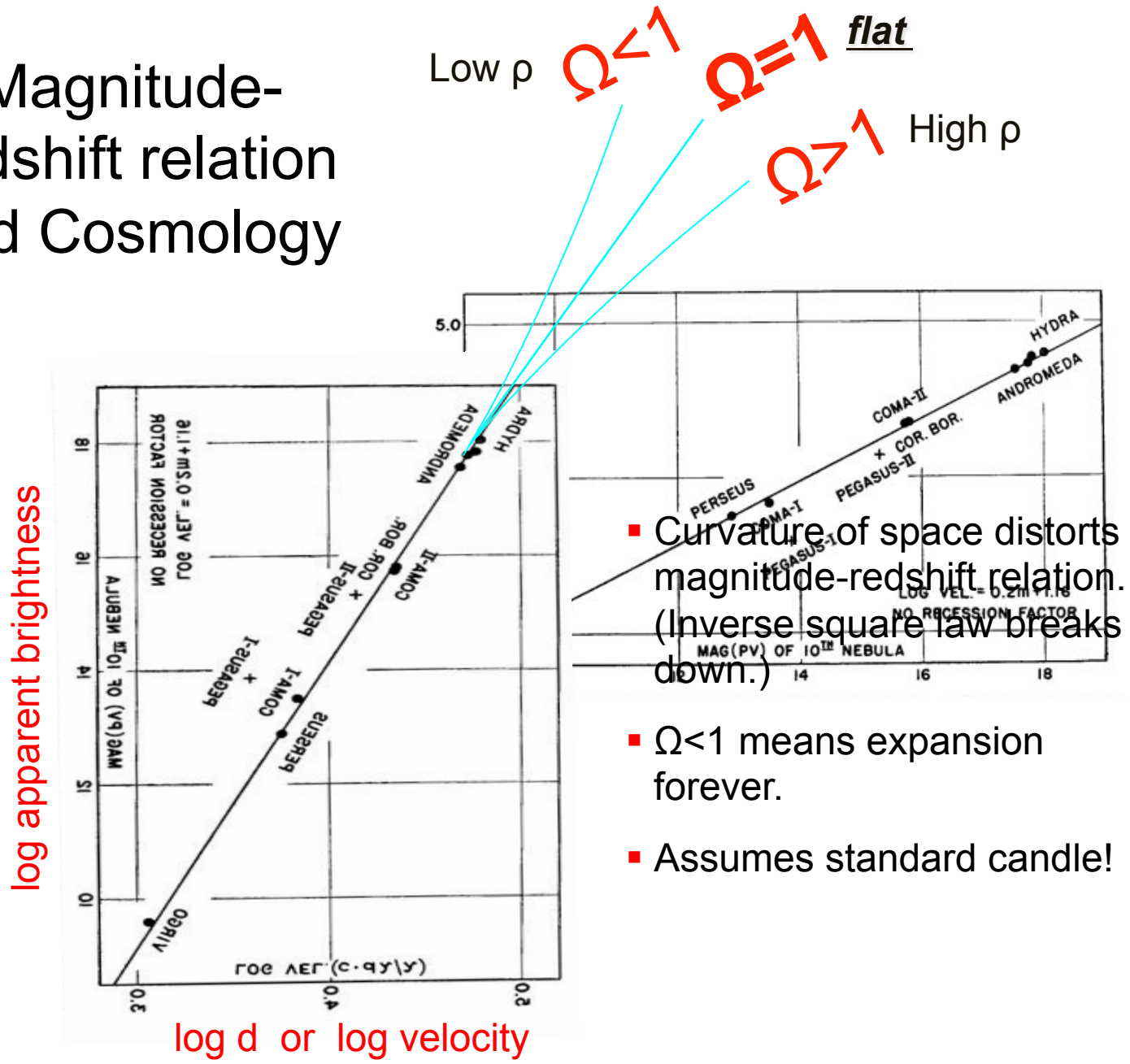


George Darwin Lecture, delivered by Dr Edwin Hubble on* 1953 *May* 8

Standard candle used here is “the brightest galaxies in clusters of galaxies”.

Assumptions: Inverse square law, Euclidean space; **Standard candle**

Magnitude-redshift relation and Cosmology



- Curvature of space distorts magnitude-redshift relation. (Inverse square law breaks down.)
- Ω<1 means expansion forever.
- Assumes standard candle!

Cosmology – A Search for 2 Numbers?

H_o– rate of expansion ($v=H_o d$)

Ω – matter density

THE ASTROPHYSICAL JOURNAL

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VOLUME 133 MARCH 1961 NUMBER 2

THE ABILITY OF THE 200-INCH TELESCOPE TO DISCRIMINATE BETWEEN SELECTED WORLD MODELS

ALLAN SANDAGE

Mount Wilson and Palomar Observatories

Carnegie Institution of Washington, California Institute of Technology

Received October 24, 1960; revised November 5, 1960

ABSTRACT

The present paper reviews several tests which can be performed to decide between world models. Each test is discussed in terms of the capabilities of the 200-inch Hale telescope. The tests include (1) the deviation from linearity of the red-shift–magnitude relation, (2) the galaxy-count–magnitude relation, (3) the angular-diameter–red-shift relation treated for both metric and isophotal diameters, and (4) the time scale. Selected expanding models of the Friedmann type and the steady-state model are considered. The object of the tests is to determine observationally the deceleration parameter q_0. Once q_0 is known, the world model follows from equations given in Section I.

mid 1970's

Gunn and Oke 1975

"… although the heterogeneity of the sample makes conclusions about cosmology slightly suspect."

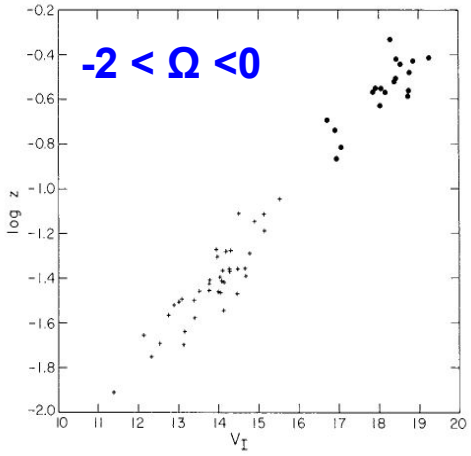


FIG. 2.—The Hubble diagram for the data used in the paper. *Solid dots*, scanner data; *crosses*, broad-band photometric data.

>400 nights of Palomar 200" time!

evolution (mass and age)

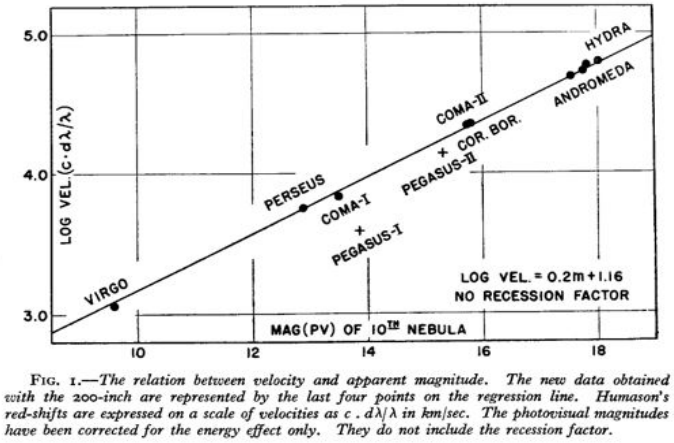
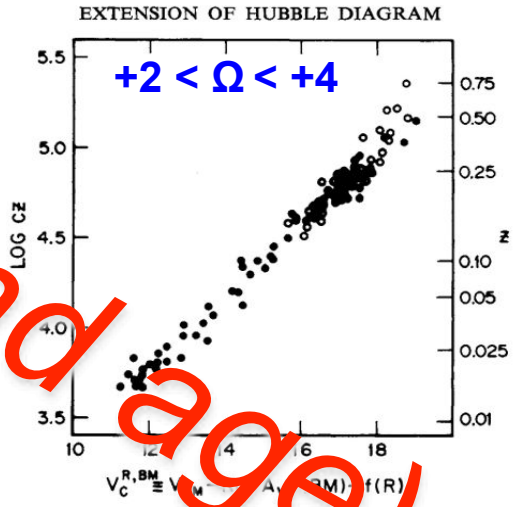


FIG. 1.—*The relation between velocity and apparent magnitude. The new data obtained with the 200-inch are represented by the last four points on the regression line. Humason's red-shifts are expressed on a scale of velocities as c . dλ/λ in km/sec. The photovisual magnitudes have been corrected for the energy effect only. They do not include the recession factor.*



Kristian, Sandage an
Westphal 1978

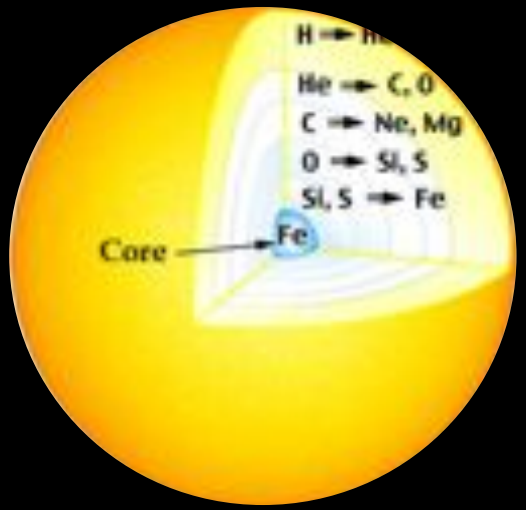
problems with the standard candle

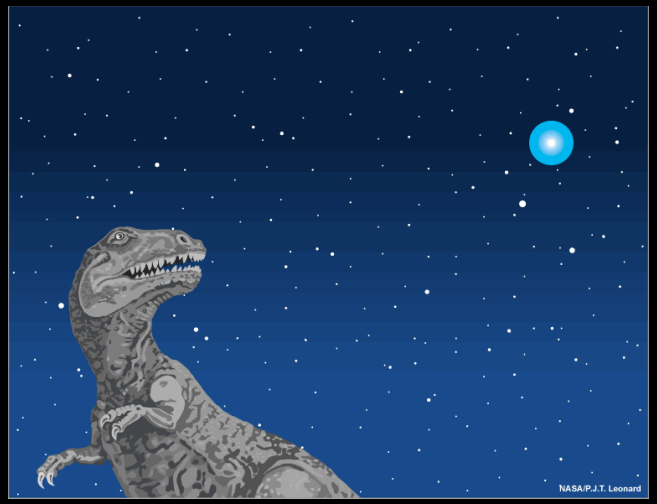
And, that's where things rested for more than 20 years …

In the late 1990's:

- H_o uncertain
- density parameter Ω uncertain
- fate of Universe's expansion unknown

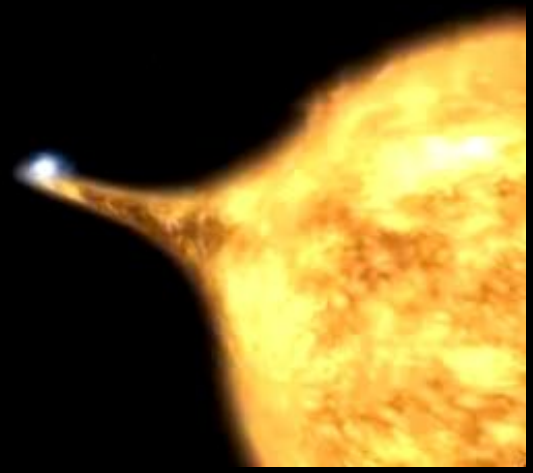
Why are Supernovae Interesting?



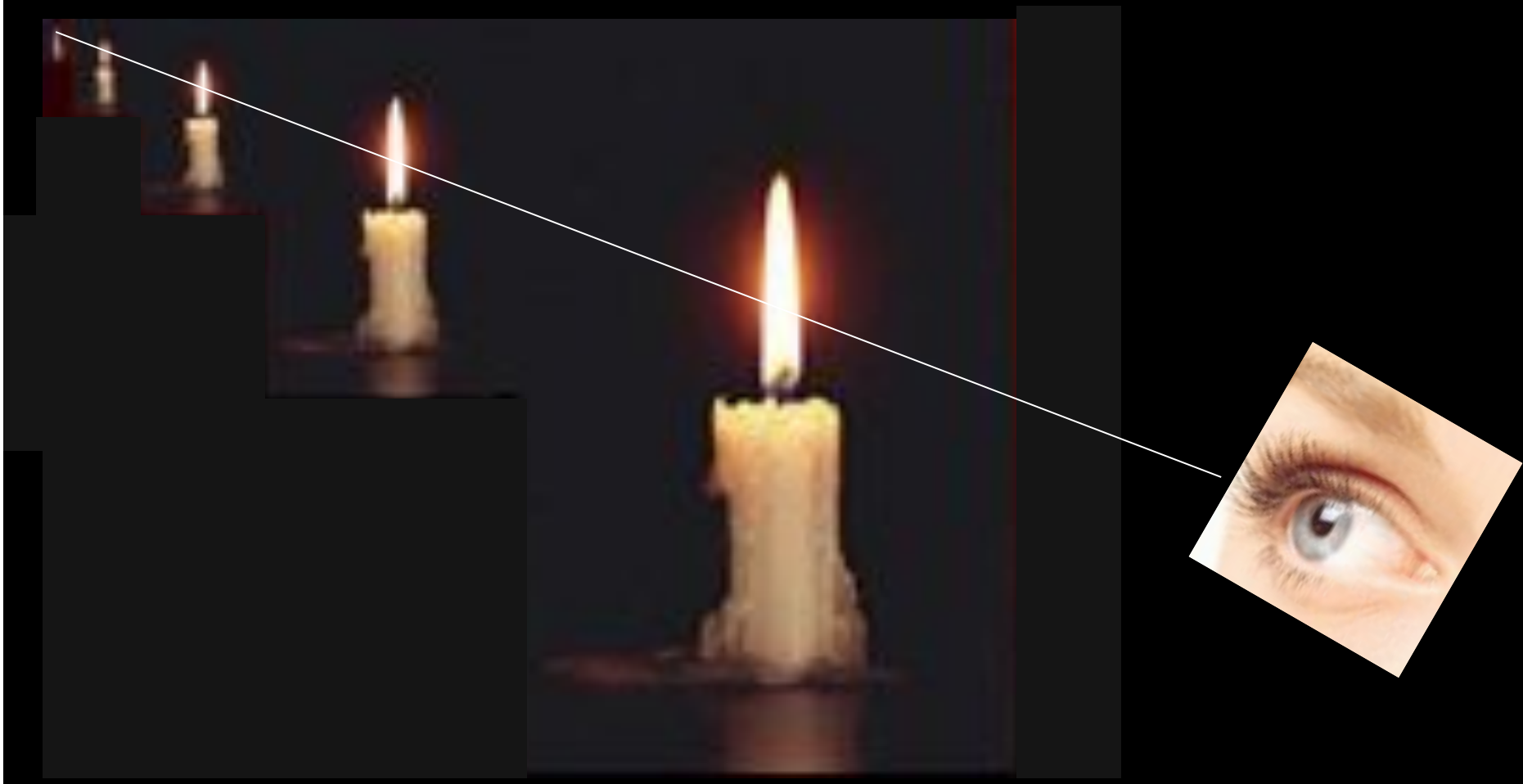


What are Type Ia Supernovae?

exploding white dwarfs

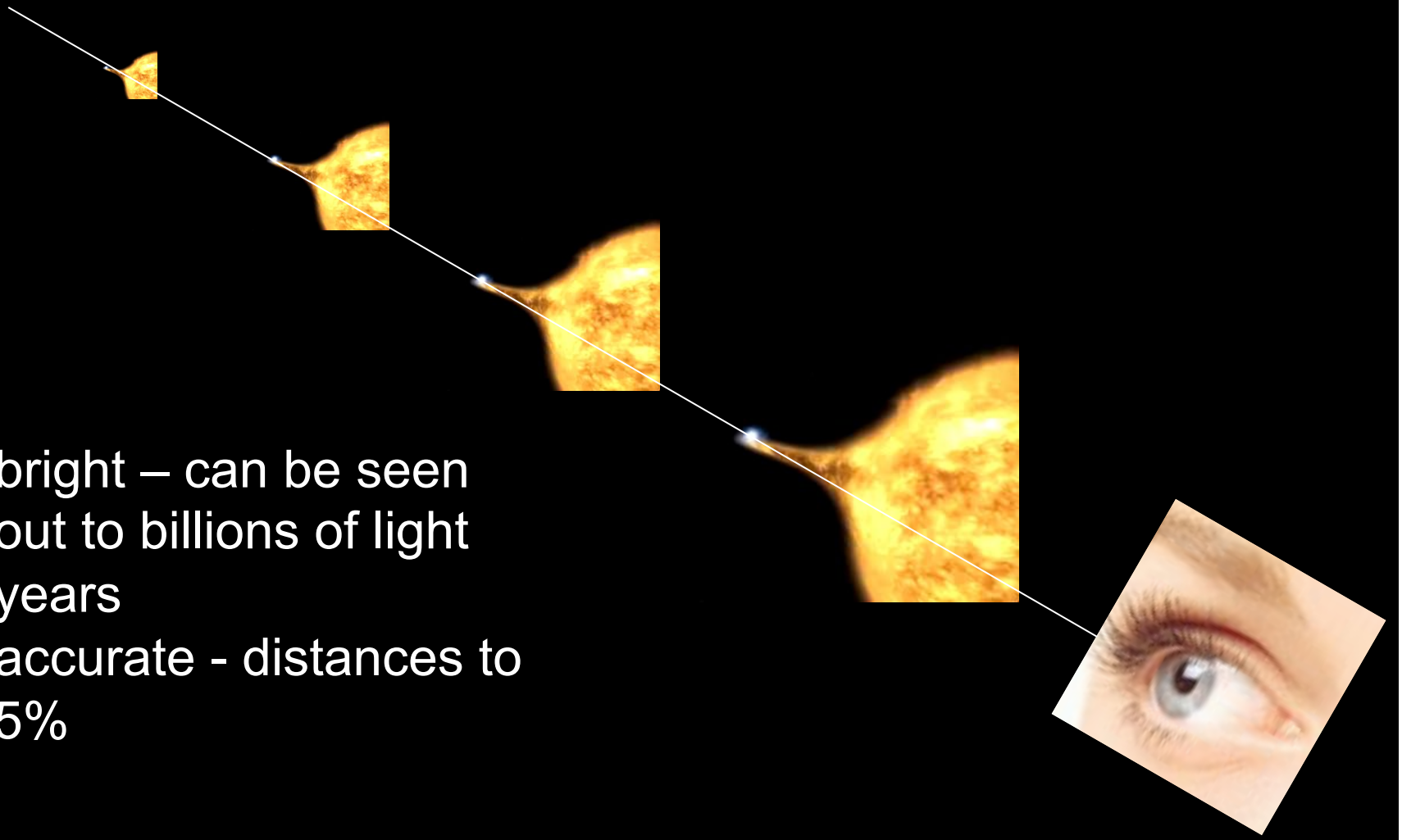


Standard Candles



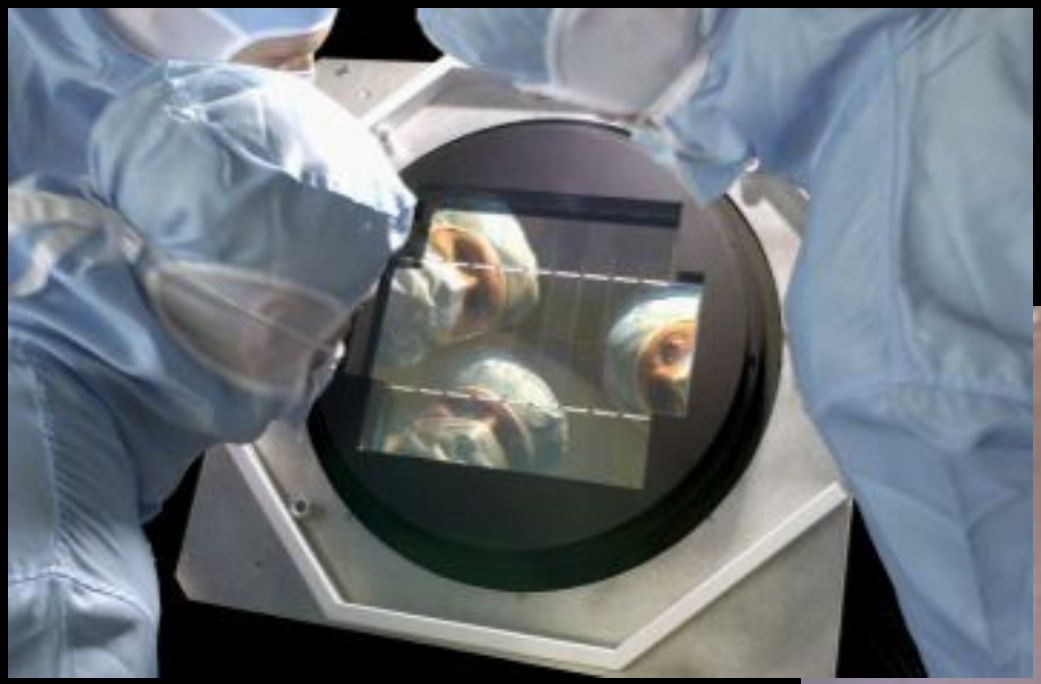
AT 26.5-26.6

Type Ia Supernovae are Standard Candles!



- bright – can be seen out to billions of light years
- accurate - distances to 5%

MegaCam at CFHT



Supernova Legacy Survey

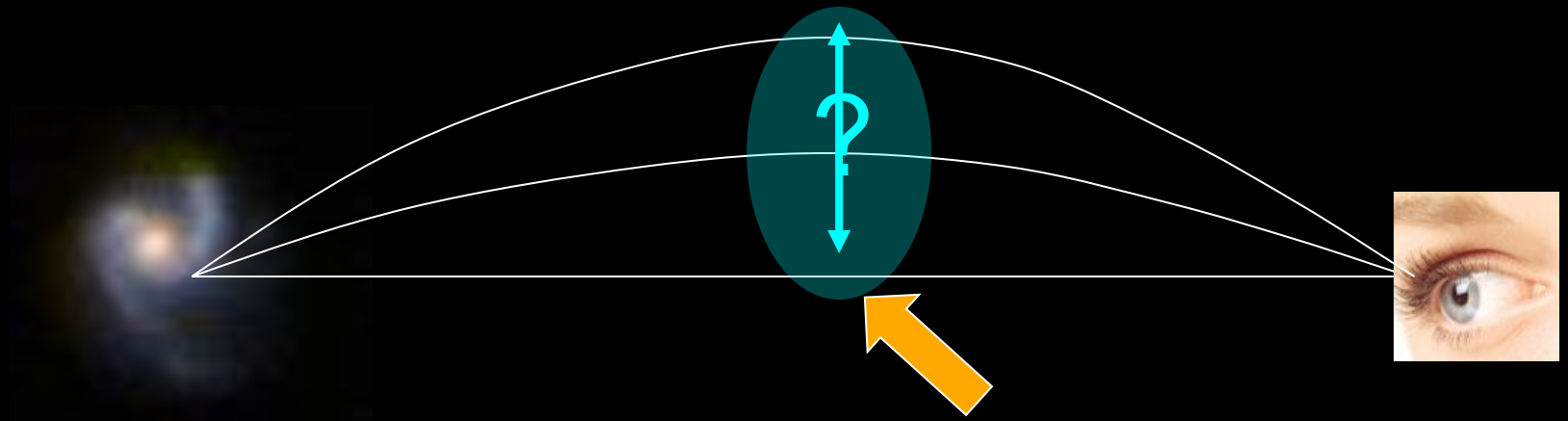
Zoom

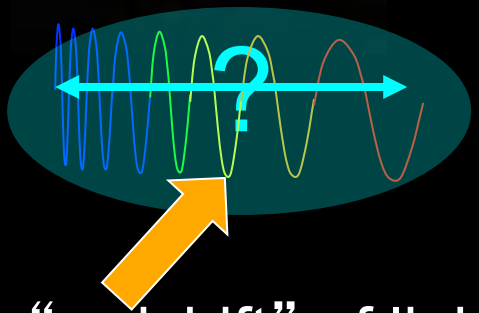
June 2003 *(c030622-07)*

z=0.25

Brightness and "redshift"

billions of light years!

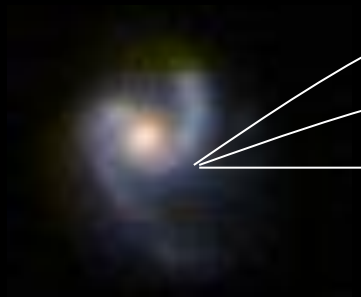


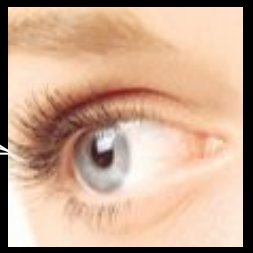


apparent brightness tells you the path length and hence light travel time across the Universe

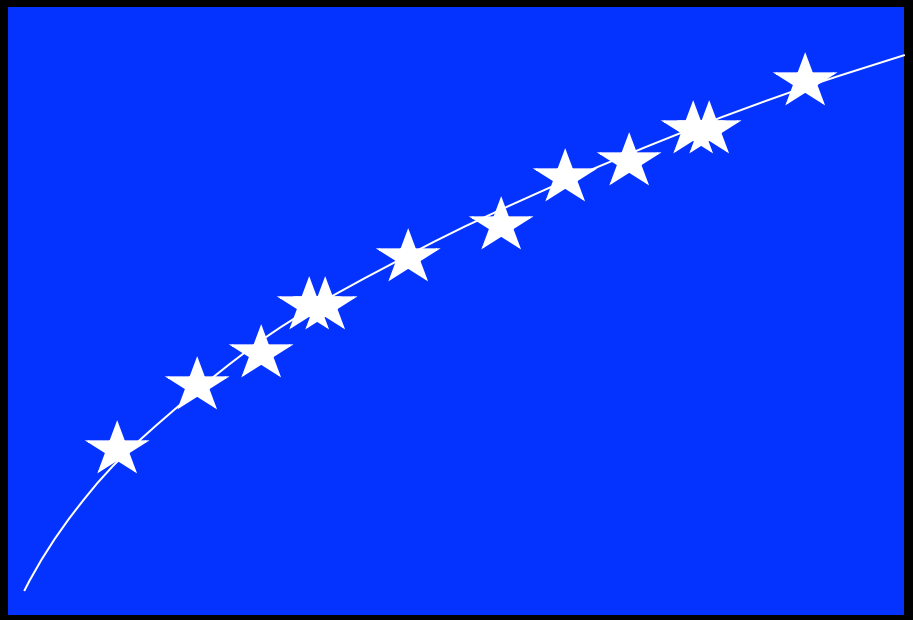
“redshift” of light tells you exactly how much the Universe has expanded, independently of cosmological model

billions of light years!





size of Universe



0

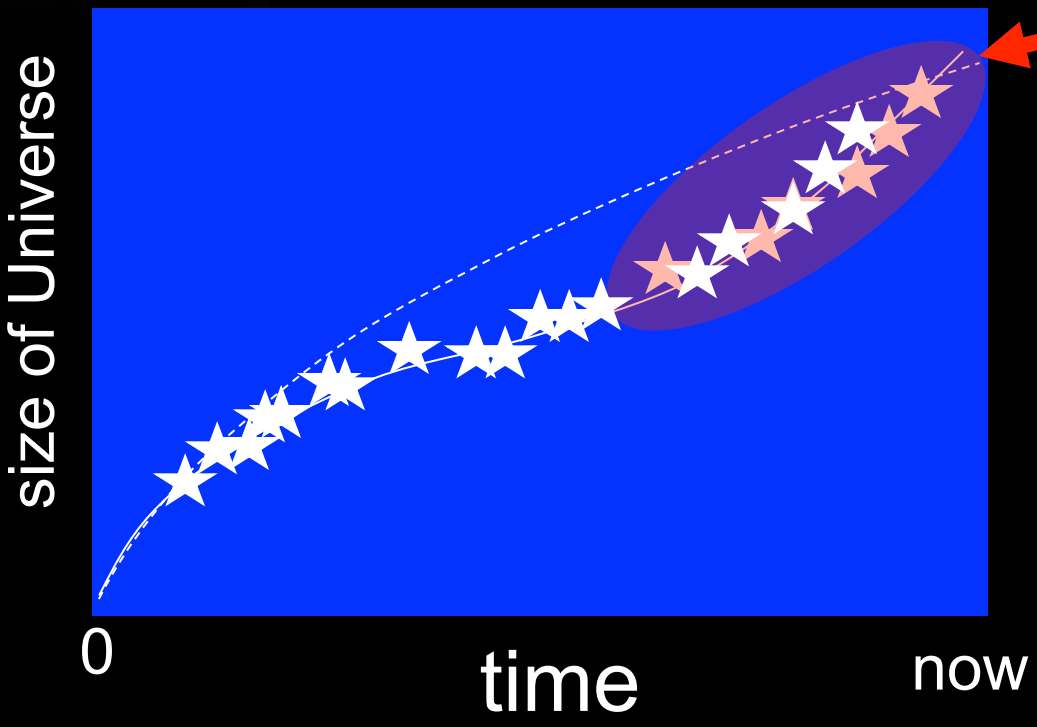
time

now

We expected the Universe to be slowing down, from gravity

Riess et al. 1998; Perlmutter et al. 1999

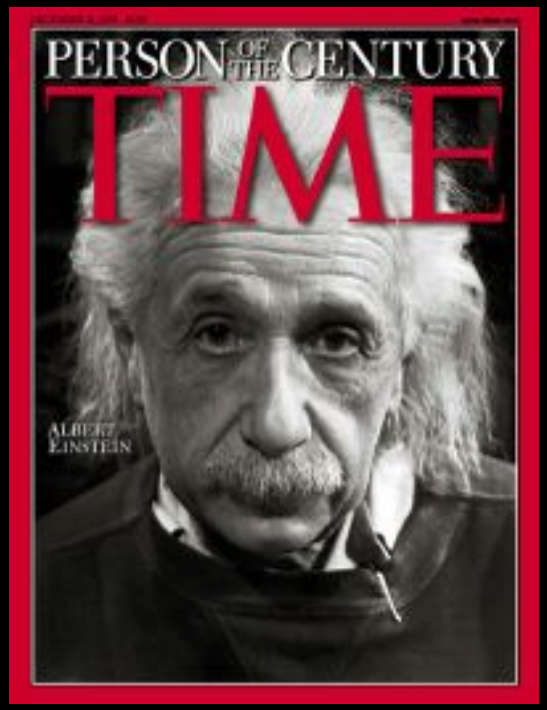
CFHT Supernova Legacy Survey (2008)



- Universe is accelerating!
- Dark Energy – also known as the cosmological constant!

Einstein was right!

Einstein, General Relativity, and the Expanding Universe



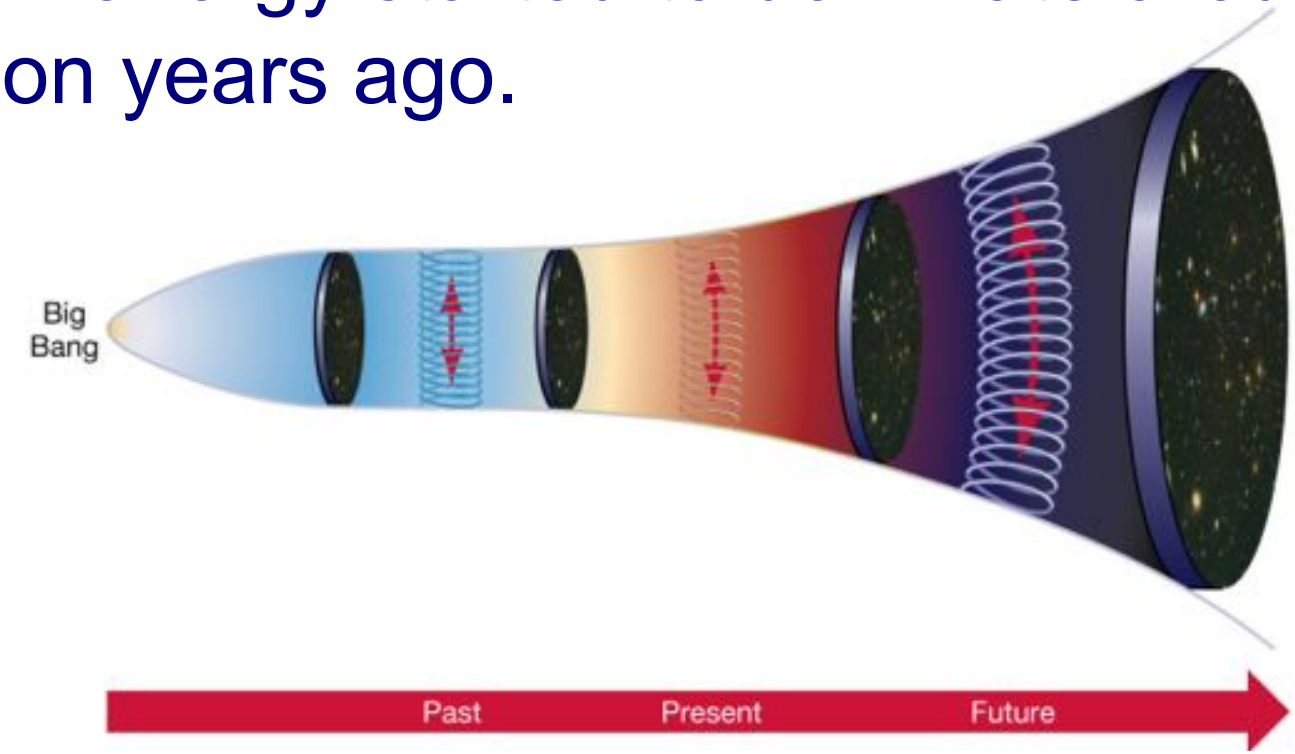
Source of Gravity = Curvature of space + Λ

large-scale repulsive force
"cosmological constant"
"vacuum energy" or "dark energy"

Will the Universe Expand Forever?

Yes. The repulsive effect of the dark energy increases as the Universe expands.

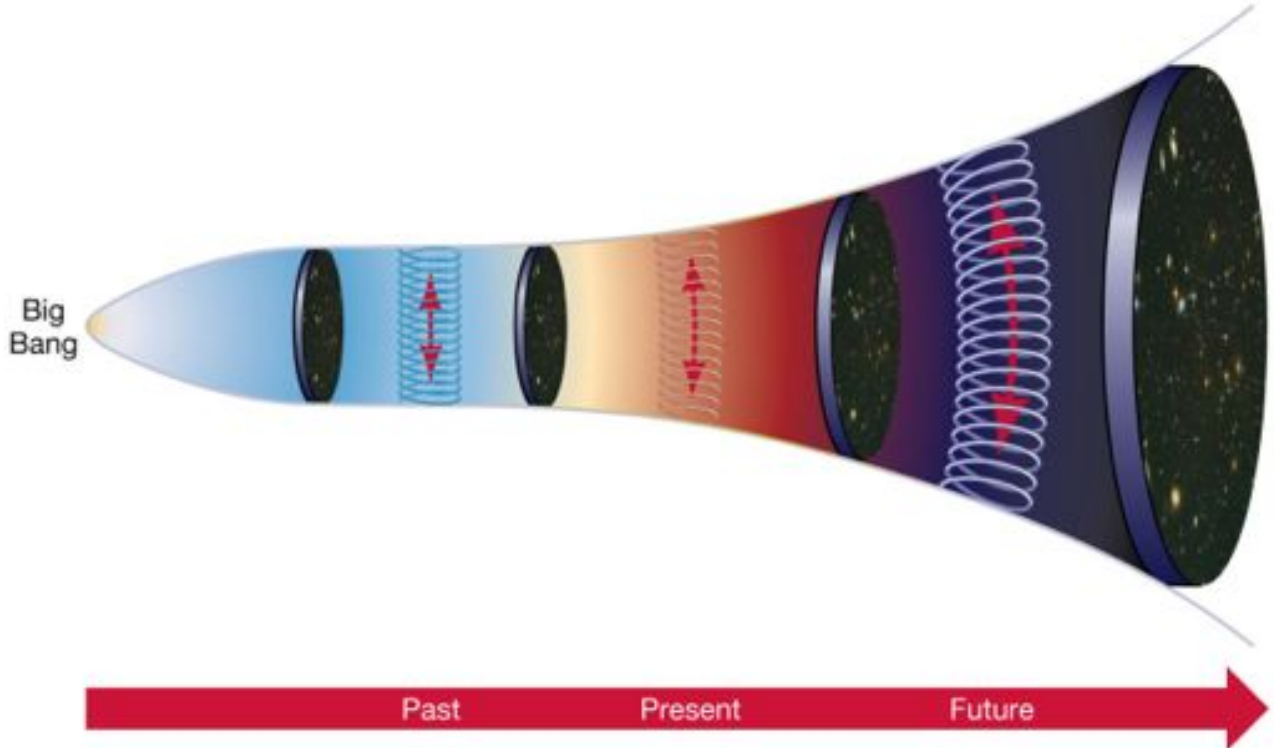
Dark energy started to dominate around 5 billion years ago.



Ch 26.5

Dark Energy content of Universe

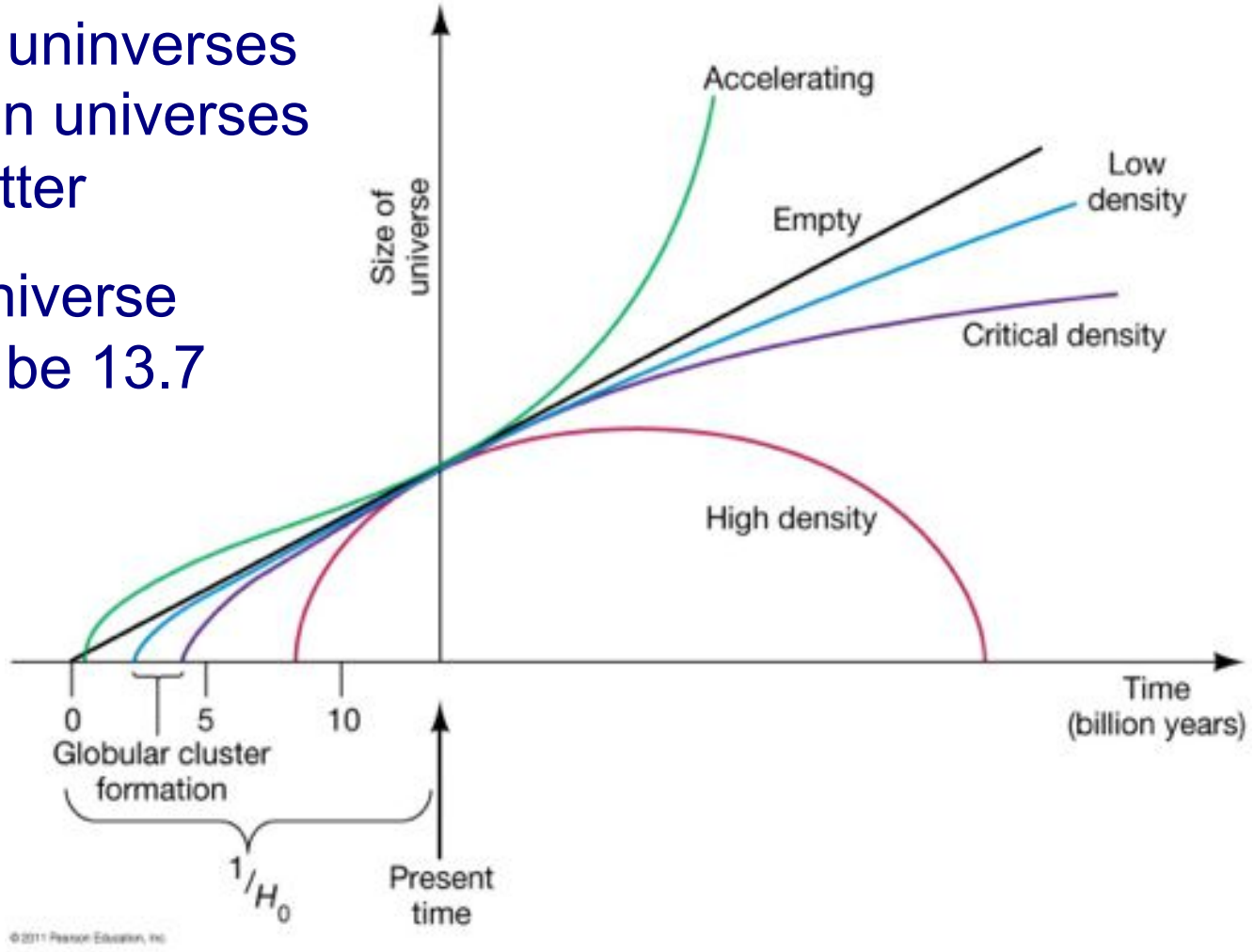
Darl Energy content of universe is growing with time. Where does it come from??



Ch 26.5

Dark Energy and Cosmology (26.6)

- accelerating uninverses are older than universes with only matter
- age of the universe works out to be 13.7 billion years.



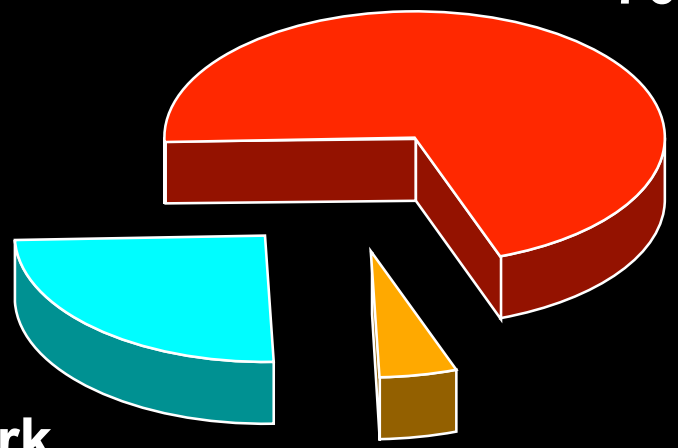
Nobel Prize 2011

- Saul Perlmutter, Adam Riess, Brian Schmidt

Matter and Energy in the Universe – a

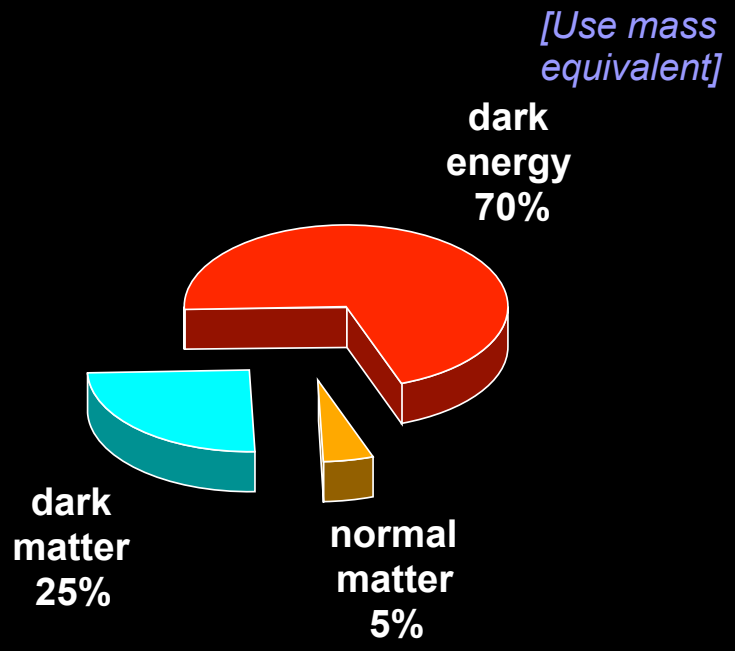
StrangeBrew

[Use mass equivalent]



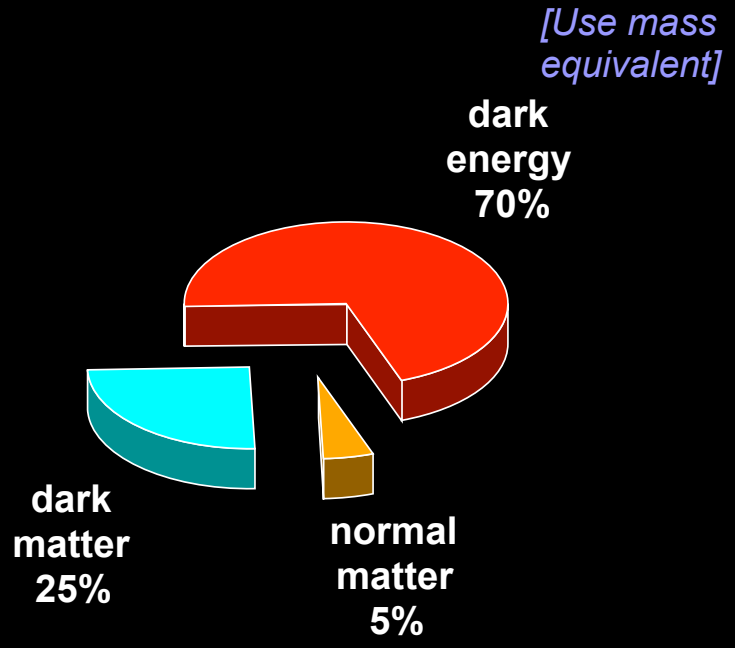
Matter and Energy in the Universe – a StrangeBrew

- Space is almost FLAT!
  - Sum of these 3 components adds up to critical density!
- Note: Dark energy and dark matter are totally unrelated.
- What about other components?



Matter and Energy in the Universe – a Strange Brew

- Even stranger: dark energy content of the Universe is growing rapidly with time!



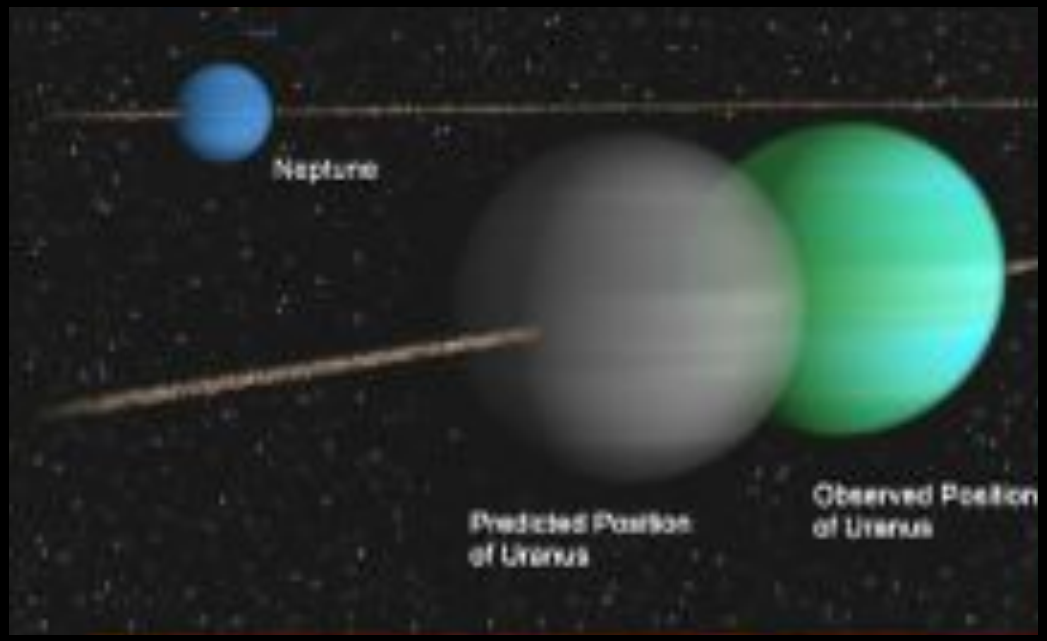
What is the Dark Energy ?

Rather than dealing directly with the cosmological constant a number of alternative routes have been proposed which skirt around this thorny issue [4, 5, 6, 7, 8]. They come in a a number of flavors. An incomplete list includes: Quintessence models [9, 10] (see also Refs. [11, 12]) which invoke an evolving canonical scalar field with a potential (effectively providing an inflaton for today) and makes use of the scaling properties [13, 14] and tracker nature [15, 16] of such scalar fields evolving in the presence of other background matter fields; scalar field models where the small mass of the quintessence field is protected by an approximate global symmetry by making the field a pseudo-Nambu-Goldstone boson [17]; Chameleon fields in which the scalar field couples to the baryon energy density and is homogeneous being allowed to vary across space from solar system to cosmological scales [18, 19]; a scalar field with a non-canonical kinetic term, known as K-essence [20, 21, 22] based on earlier work of K-inflation [23]; modified gravity arising out of both string motivated [24] or more generally General Relativity modified [25, 26, 27] actions which both have the effect of introducing large length scale corrections and modifying the late time evolution of the Universe; the feedback of non-linearities into the evolution equations which can significantly change the background evolution and lead to acceleration at late times without introducing any new matter [28]; Chaplygin gases which attempt to unify dark energy and dark matter under one umbrella by allowing for a fluid with an equation of state which evolves between the two [29, 30, 31]; tachyons [32, 33] arising in string theory [34]; the same scalar field responsible for both inflation in the early Universe and again today, known as Quintessential inflation [35]; the possibility of a network of frustrated topological defects forcing the universe into a period of accelerated expansion today [36]; Phantom Dark Energy [37] and Ghost Condensates [38, 39]; de-Sitter vacua with the flux compactifications in string theory [40]; the String Landscape arising from the multiple numbers of vacua that exist when the string moduli are made stable as non-abelian fluxes are turned on [41]; the Cyclic Universe [42]; causal sets in the context of Quantum Gravity [43]; direct anthropic arguments [44, 45, 46, 47]; all of these are more or less exotic solutions to the dark energy question.

Discovery of Uranus 1781

Discovery of Neptune 1846

- New physical component?
- New physical law?



LeVerrier

Perihelion advance of Mercury

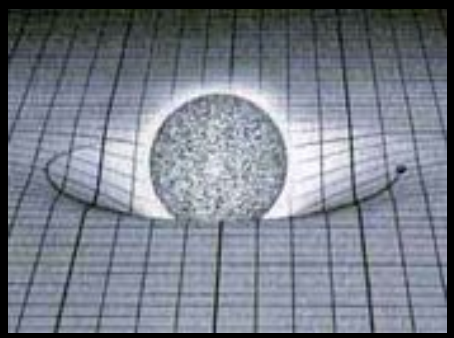
5600 arcsec/century, of which 43 arcsec/century is unexplained

Perihelion advance of Mercury

1859

5600 arcsec/century, of which 43 arcsec/century is unexplained

- New physical component?
  - Vulcan? (LeVerrier!)
  - Solar oblateness (Dicke)
- New physical law?

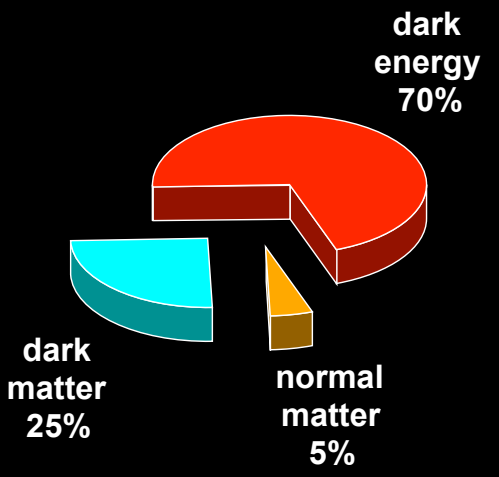


Motions in Clusters of Galaxies

"It is not certain how these startling results must ultimately be interpreted." – Zwicky 1933

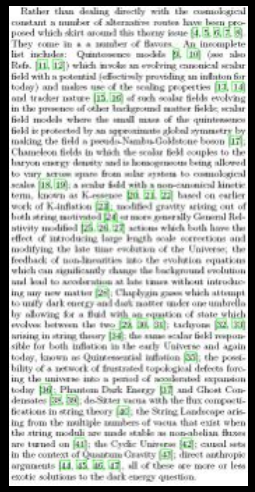
- New physical component?
- New physical law?

What is the DE?



New physical component?

- Cosmological Constant (pure vacuum energy)
- scalar field models, quintessence …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New physical law?

- e.g. modifications to General Relativity?

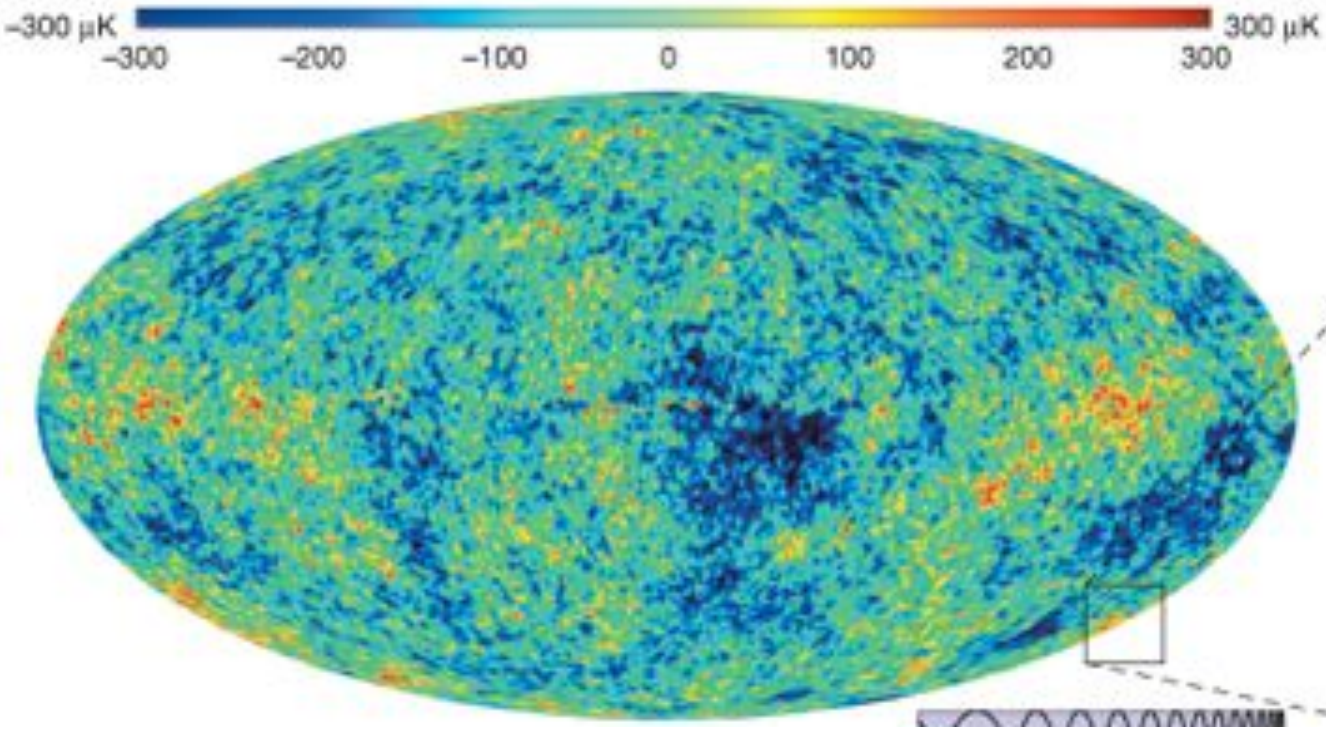
Rocky Horror Show

"On a good day I can think of 3 or 4 plausible candidates for dark matter. The same cannot be said for dark energy."

Rocky Kolb

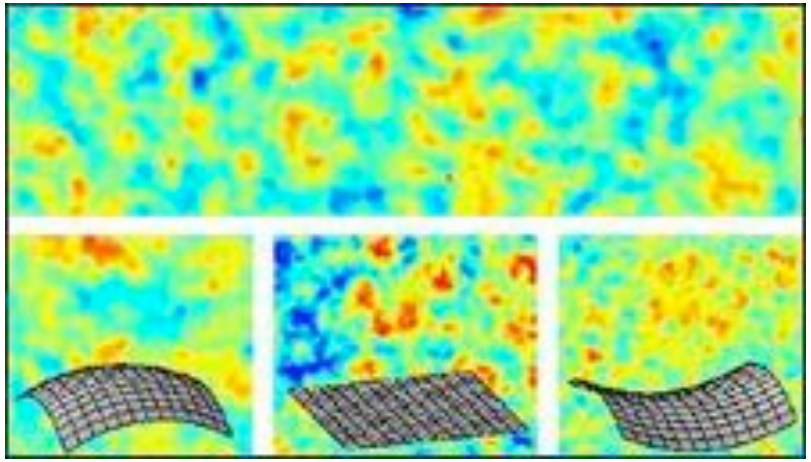
Is there Independent Evidence for Dark Energy?

- Yes. Cosmic Microwave Background Radiation



WMAP satellite - Observations of entire sky after removing smooth components. The fluctuations are about 10^{-5} of the total signal.

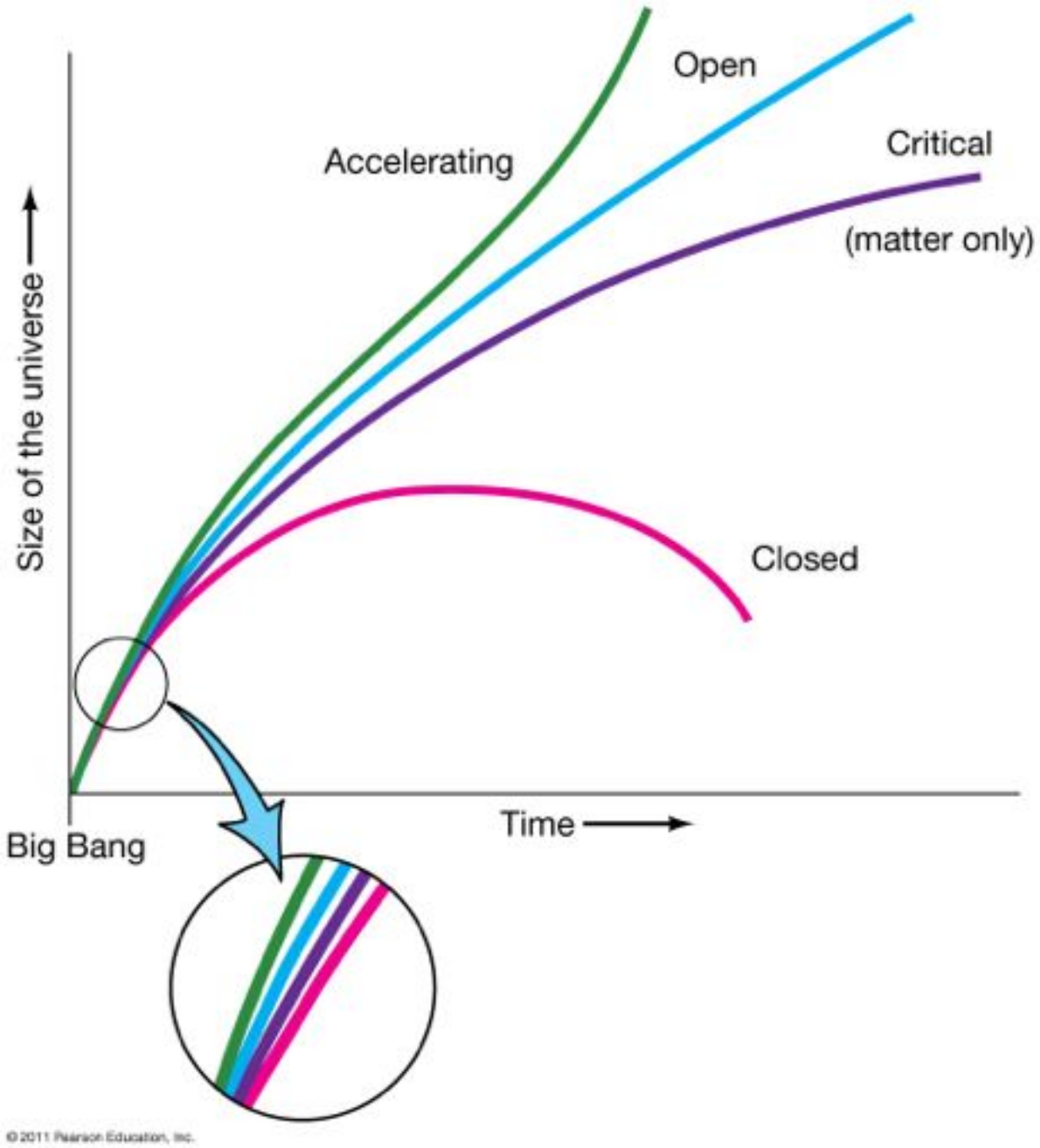
Independent Evidence for Dark Energy – WMAP satellite



Exact appearance of sky in CMB depends on cosmological parameters.

- **Space is flat.**
- 73% dark energy, 23% dark matter, 4% ordinary matter
  - similar to supernova results!

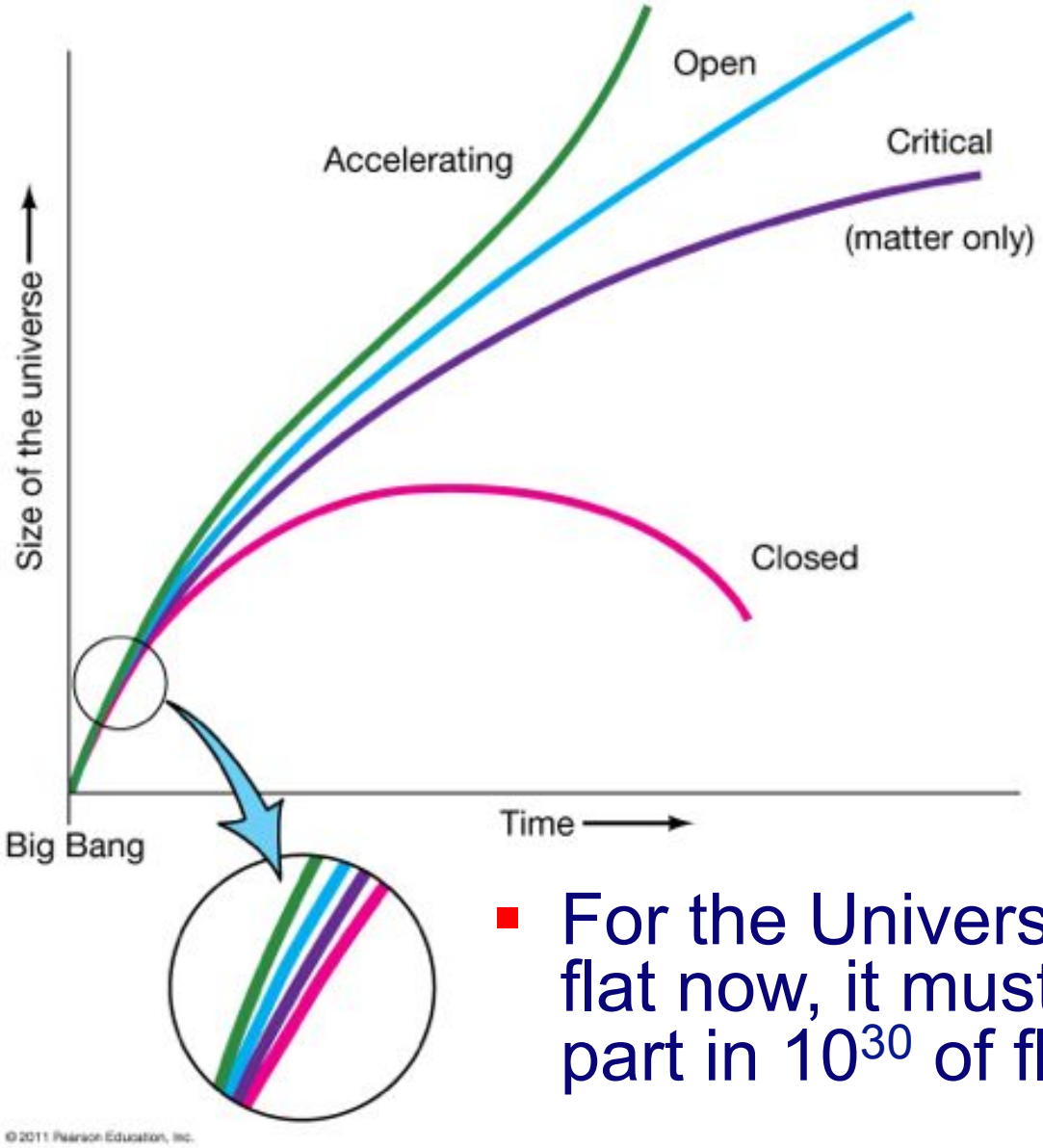
AT 27.4



Flatness Problem

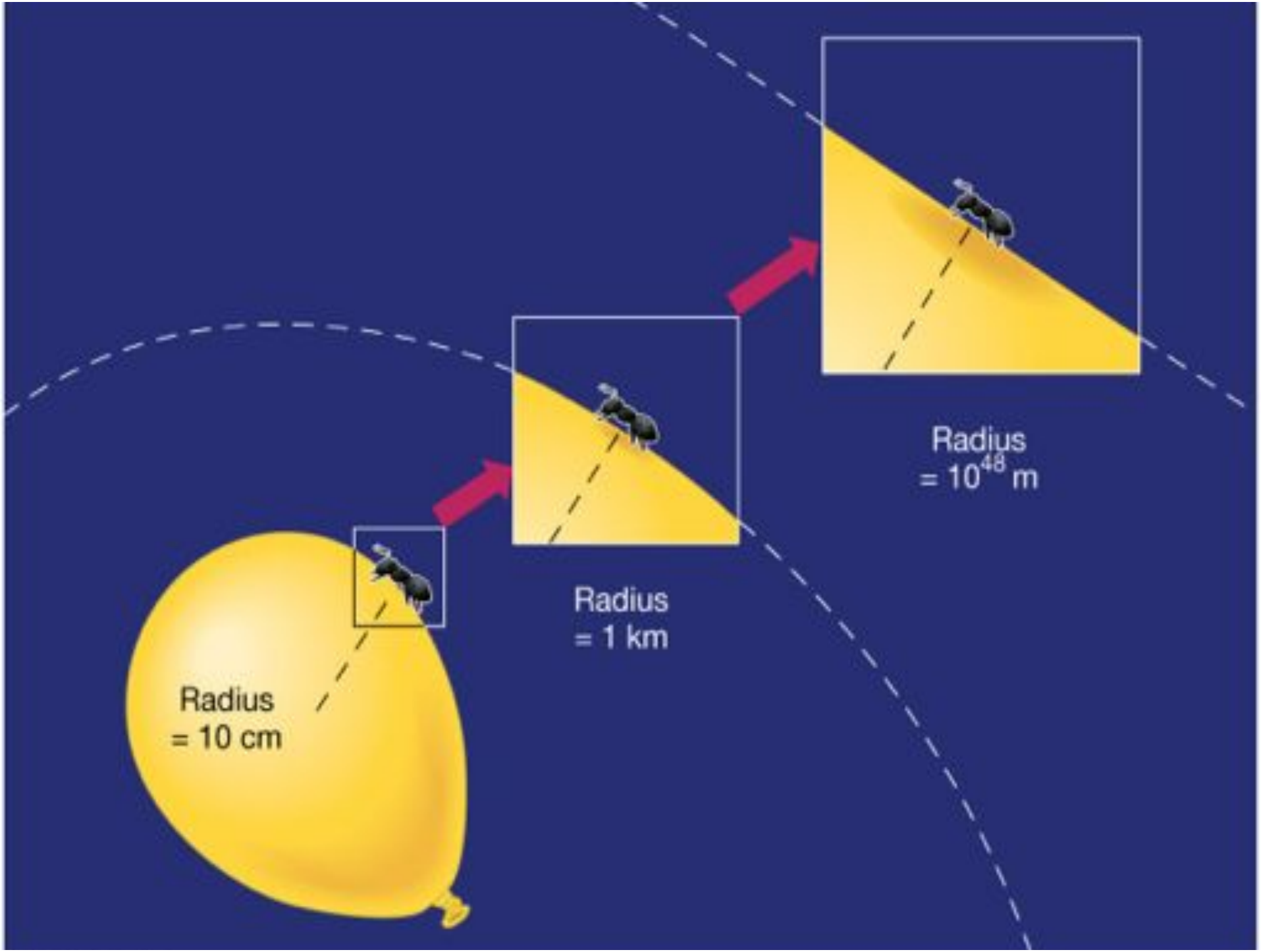
Flatness Problem

AT 27.4

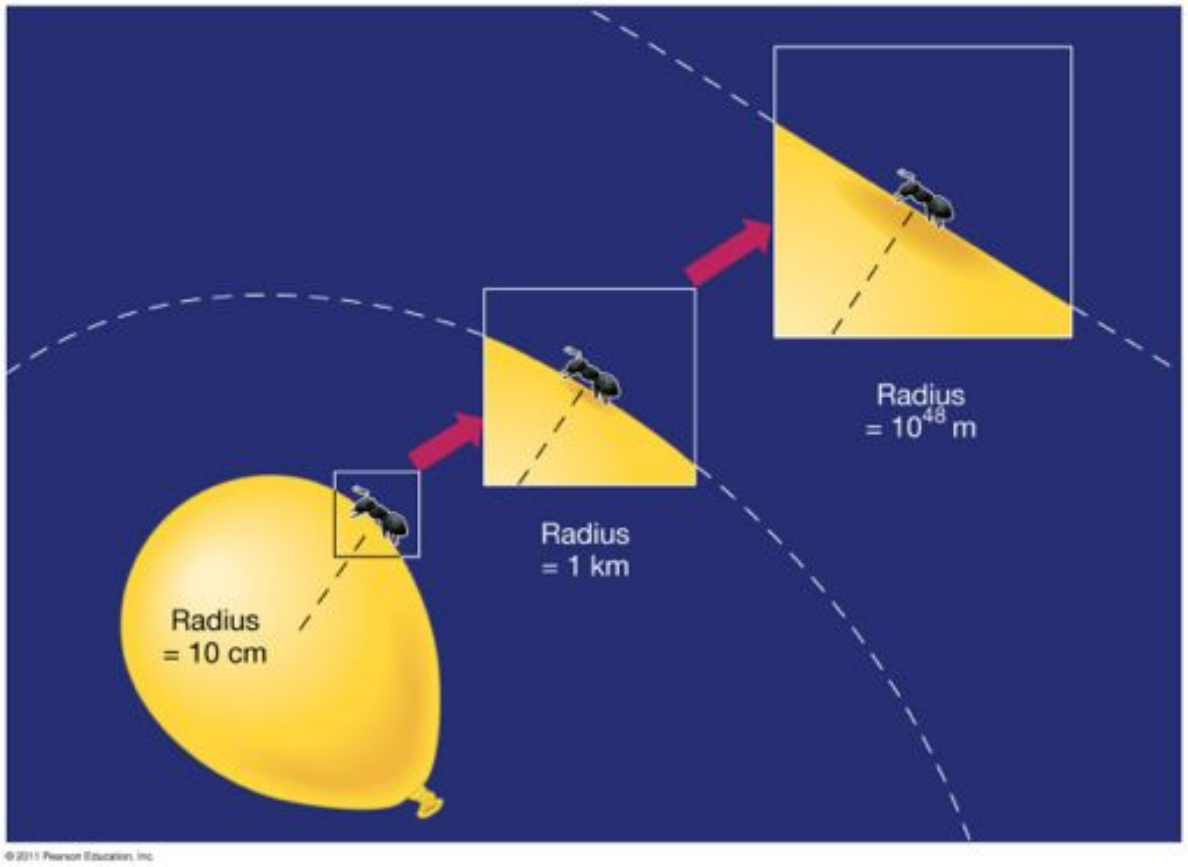


- If the Universe deviates even slightly from flat = critical density at early times, that deviation grows rapidly with time.

- For the Universe to be within 1% of flat now, it must have been within 1 part in 10^{30} of flat at early times. Why?


Radius
= 10 cm
Radius
= 1 km
Radius
= 10^{48} m

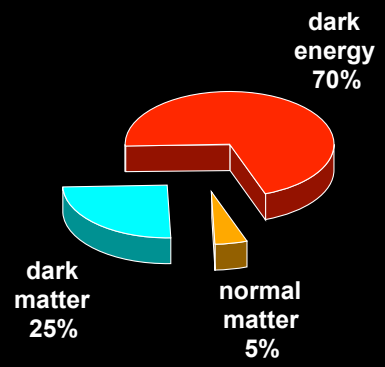
Flatness Problem Solved



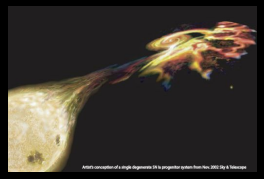
Inflation solves the problem. Take a curved surface and expand it enormously in size. To an ant on the surface the balloon looks virtually flat when the expansion is complete.

A fourth of piece of evidence for the hot dense big bang!

Conclusions



- The Universe is expanding.
- The expansion of the Universe is speeding up, not slowing down.
- The Universe is filled with a mysterious substance which we call "dark energy" that causes this acceleration in the expansion.
- Space is flat.
- Dark energy is one of the greatest mysteries in Physics and Astronomy in the past century.
- Stay tuned!



The reason that space in the Universe is almost flat is because:

A. Olbers' paradox says so
B. Hubble's law requires it
C. The density of matter requires it
D. Inflation "blew up" any residual curvature the Universe had
E. The Universe is colliding with another Universe