



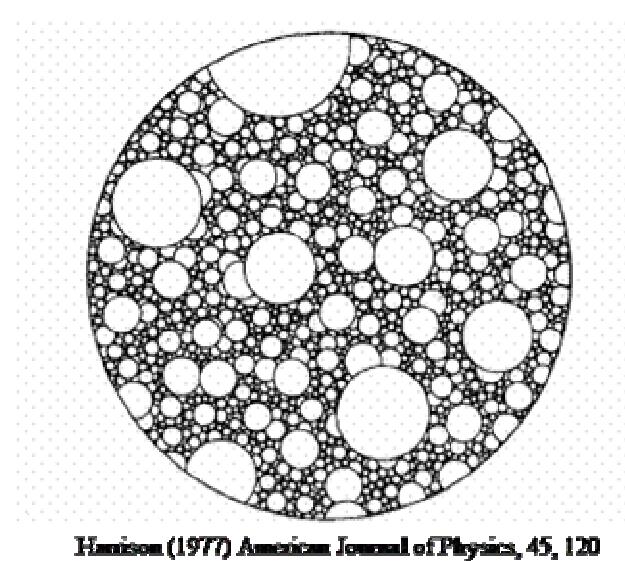
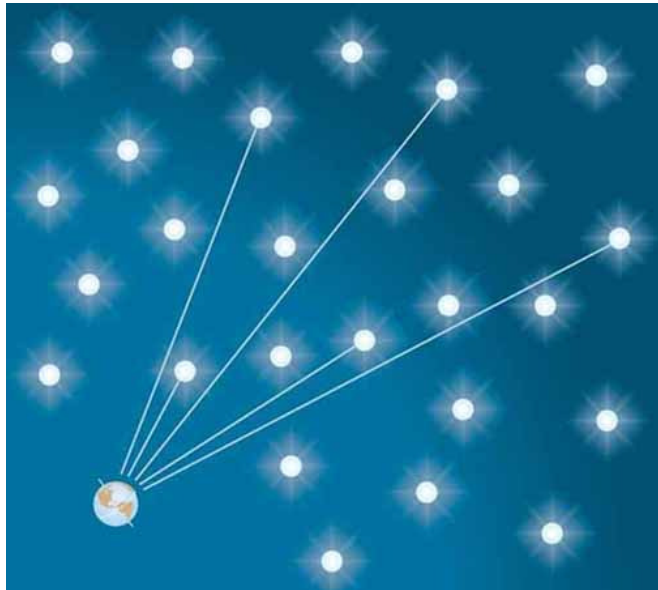
空即是色：現代宇宙觀

辜品高
師大地科系
中研院天文所

evolution (big bang →?)
composition (matter, light, and...)
geometry (flat, open, or closed)

Olbers' Paradox (1826)

- Discussed by Thomas Digges (1576), Johannes Kepler (1610), Edmund Halley (1721)
- If the Universe is infinitely big, is unchanging, and is filled homogenously with stars, then the sky shouldn't be dark at night (as you can see, this is really NOT a “paradox”).





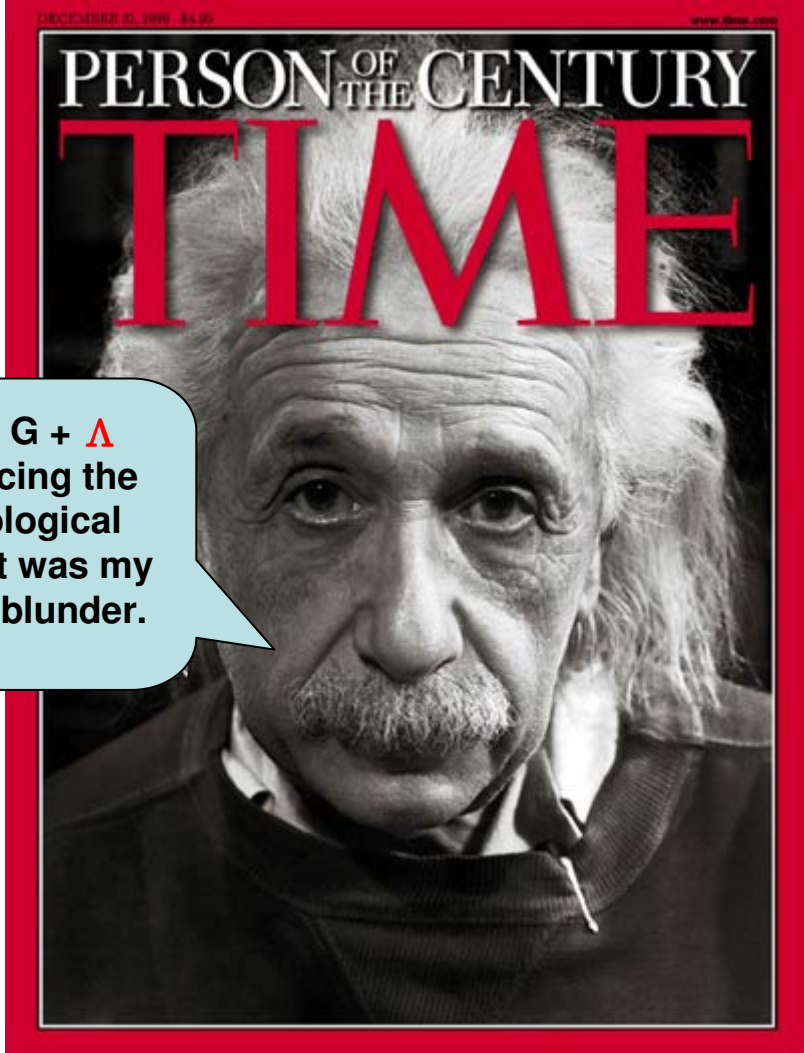
World Year of Physics 2005

- Equivalence of matter and energy
- Gravity : Time is curved & Space is warped
- God plays dice

a few spinoffs....

$E=mc^2$: 10% of our power

Quantum mechanics accounts for 1/3rd of our GDP



$8\pi T = G + \Lambda$
Introducing the cosmological constant was my biggest blunder.

Hubble Flow: expanding Universe

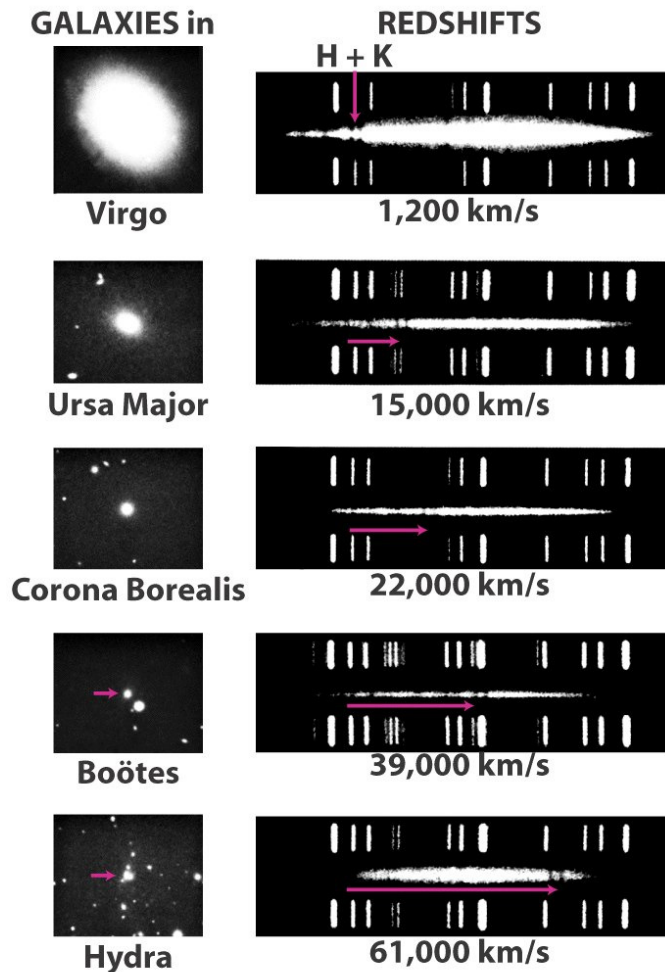
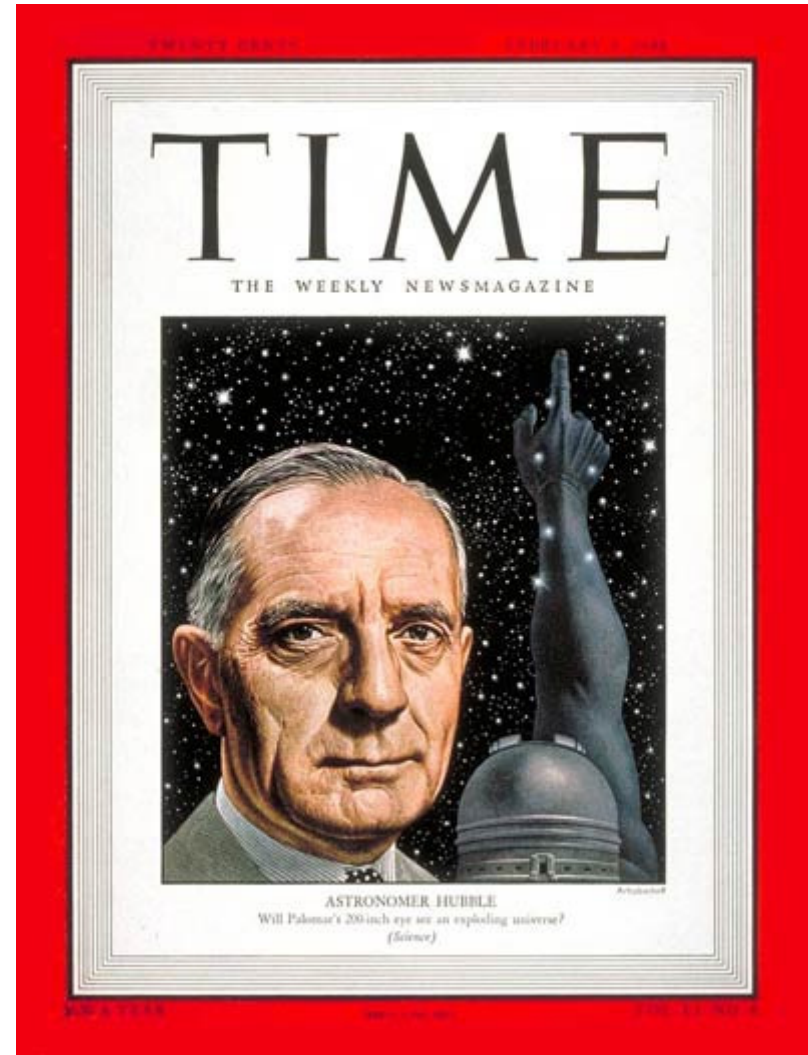


Figure 16-29
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Standard Candles: distance ladder

Luminosity = $f(Q)$, where Q is observable.

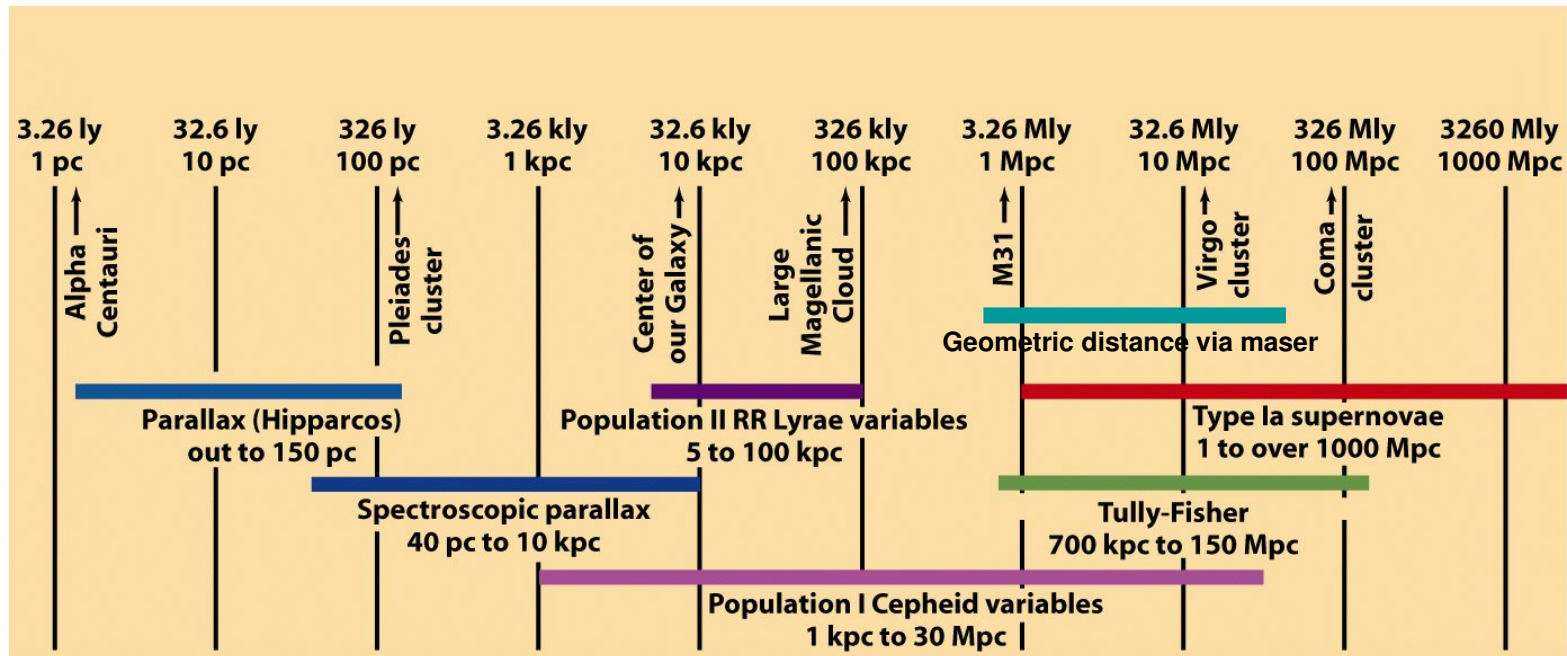


Figure 16-31
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Hubble Constant: $H_0 = v/d$

expansion rate of the Universe

70 years to
rein in the
Hubble
Constant:
550
(conflict to
the age
of globular
clusters)
to 70
km/s/Mpc

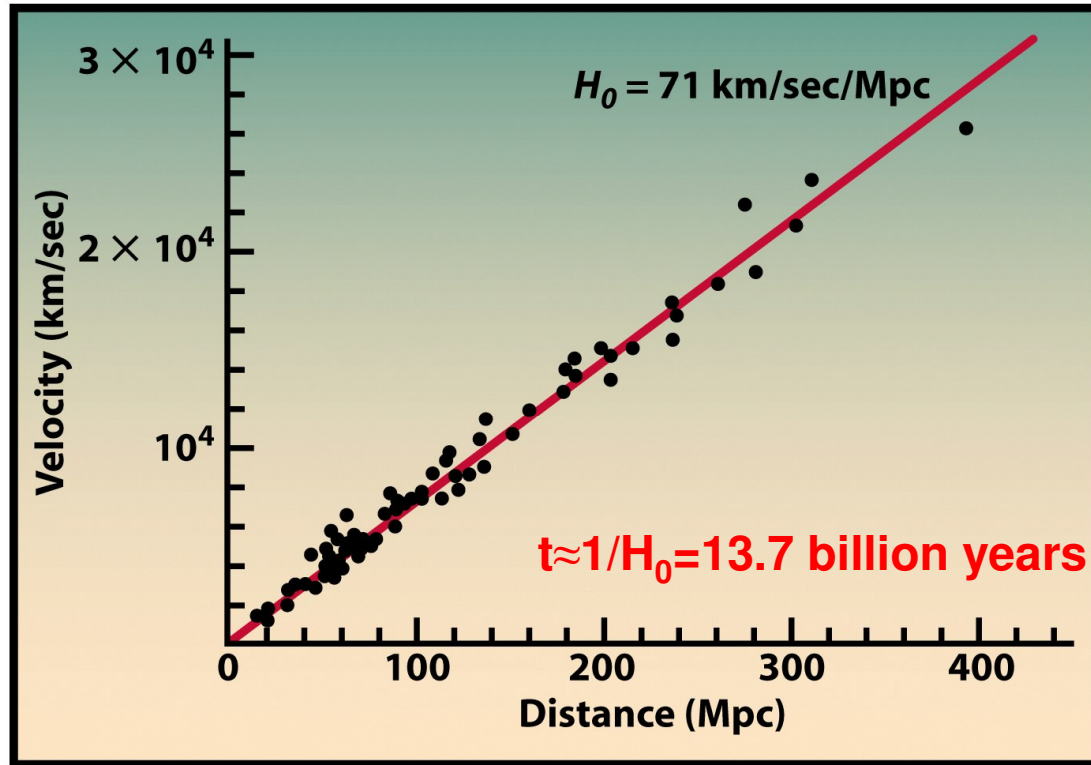
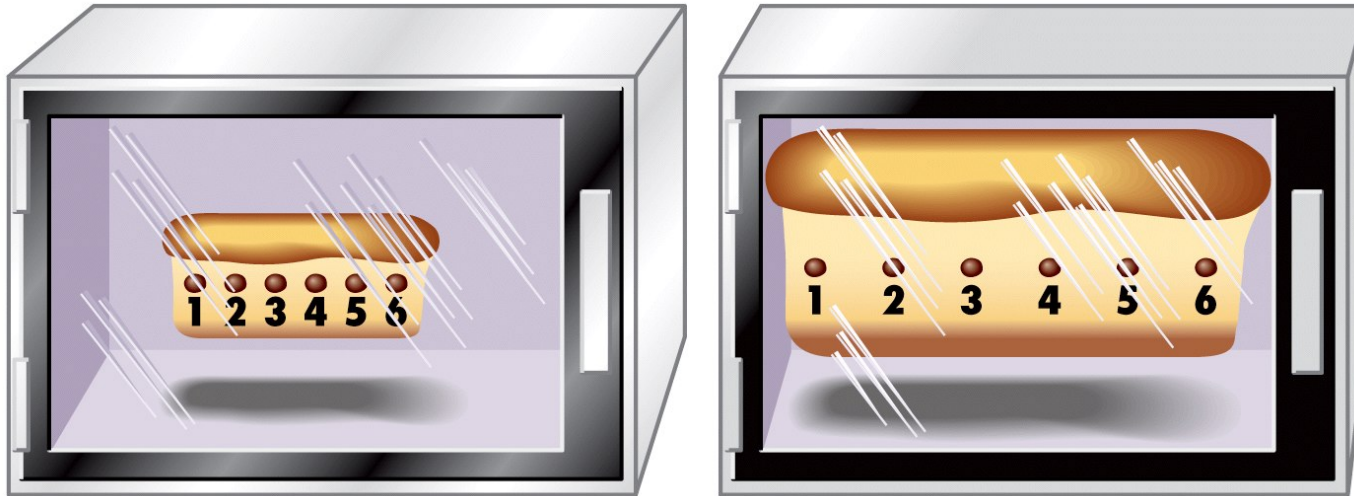


Figure 16-30
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距離每增加一百萬光年，宇宙膨脹的速度每秒增加22.1公里

The Universe is expanding like a cake

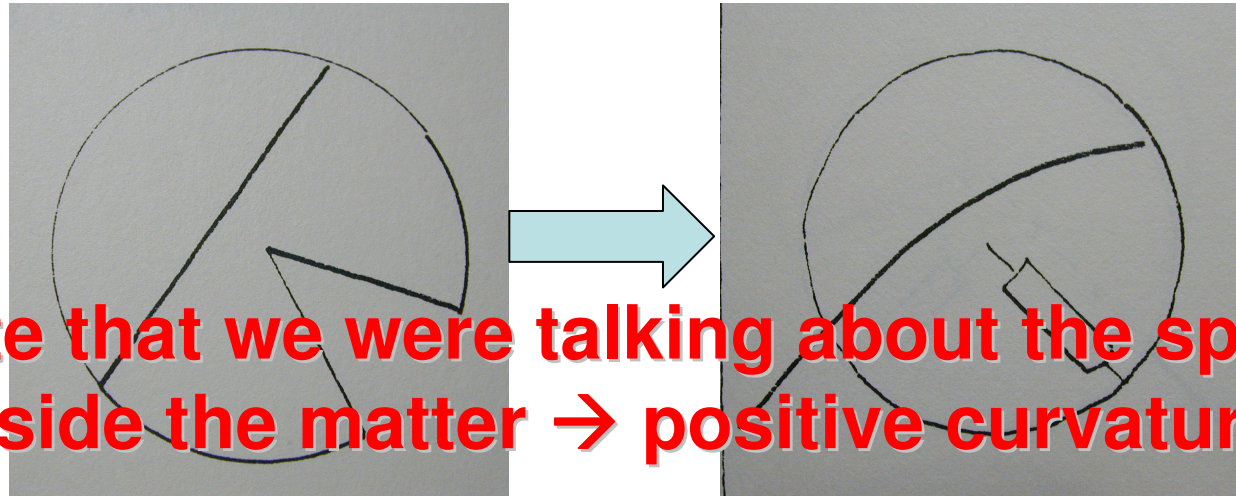


Unnumbered figure pg 464
Discovering the Universe, Seventh Edition
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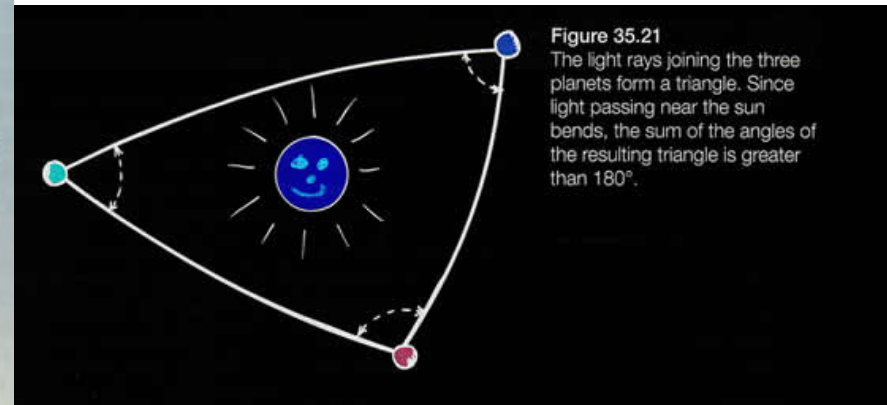
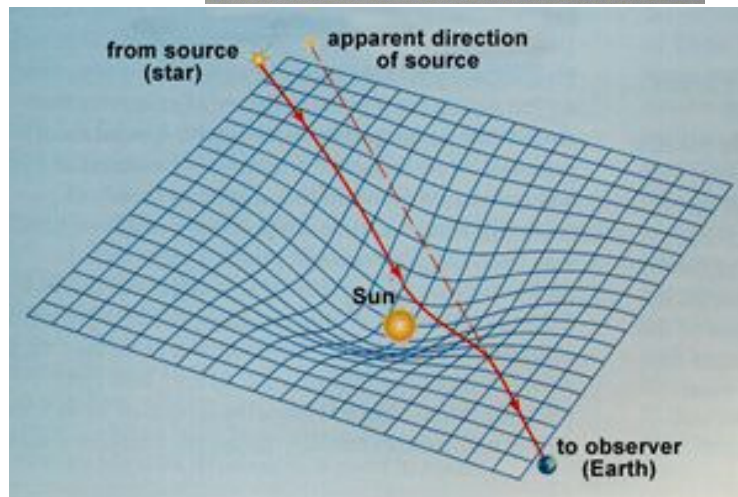
**But, please don't let this analogy mislead you...
the Universe has no center and edge!**

General Relativity (mass \rightarrow space warps)

Geodesic: shortest path on a flat/curved space



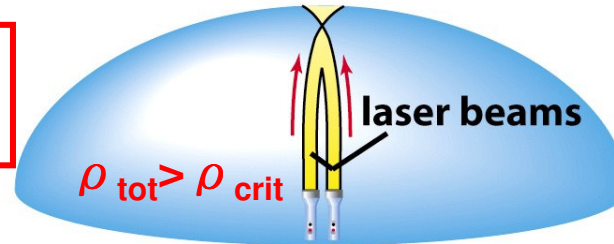
Note that we were talking about the space outside the matter \rightarrow positive curvature



General Relativity (mass/energy → space warps)

Critical Density

$$\rho_{\text{crit}} = 9 \times 10^{-30} \text{ g/cm}^3$$



spherical space:
positive curvature,
closed & finite universe

a Parallel light beams converge

Be careful of language:

The Universe

1: no edge & center

2: does not need

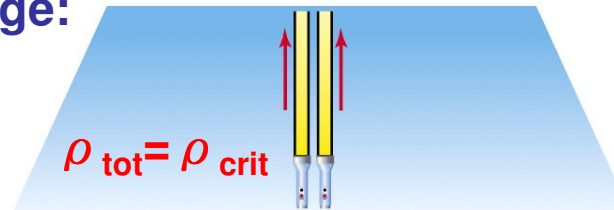
additional room to

expand → increase

in volume is due to

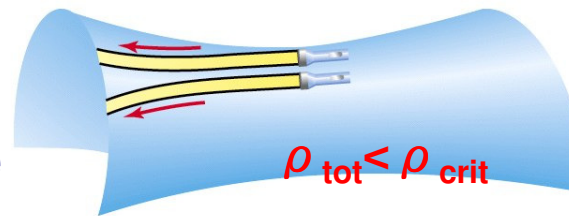
the change in the

nature of space-time



flat space:
zero curvature,
flat & infinite universe

b Parallel light beams remain parallel

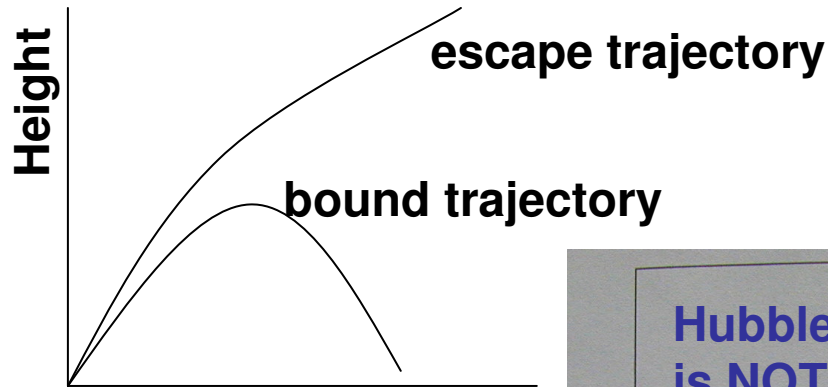


hyperbolic space:
negative curvature,
open & infinite universe

c Parallel light beams diverge

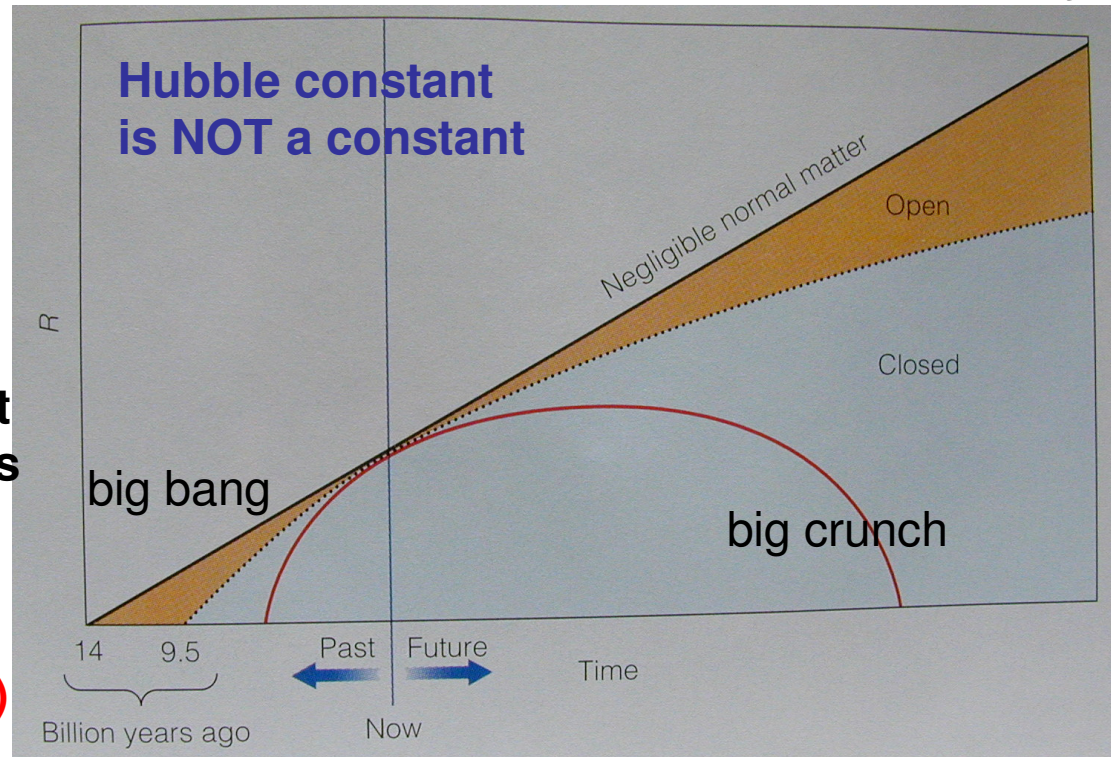
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Age & Fate of the Universe



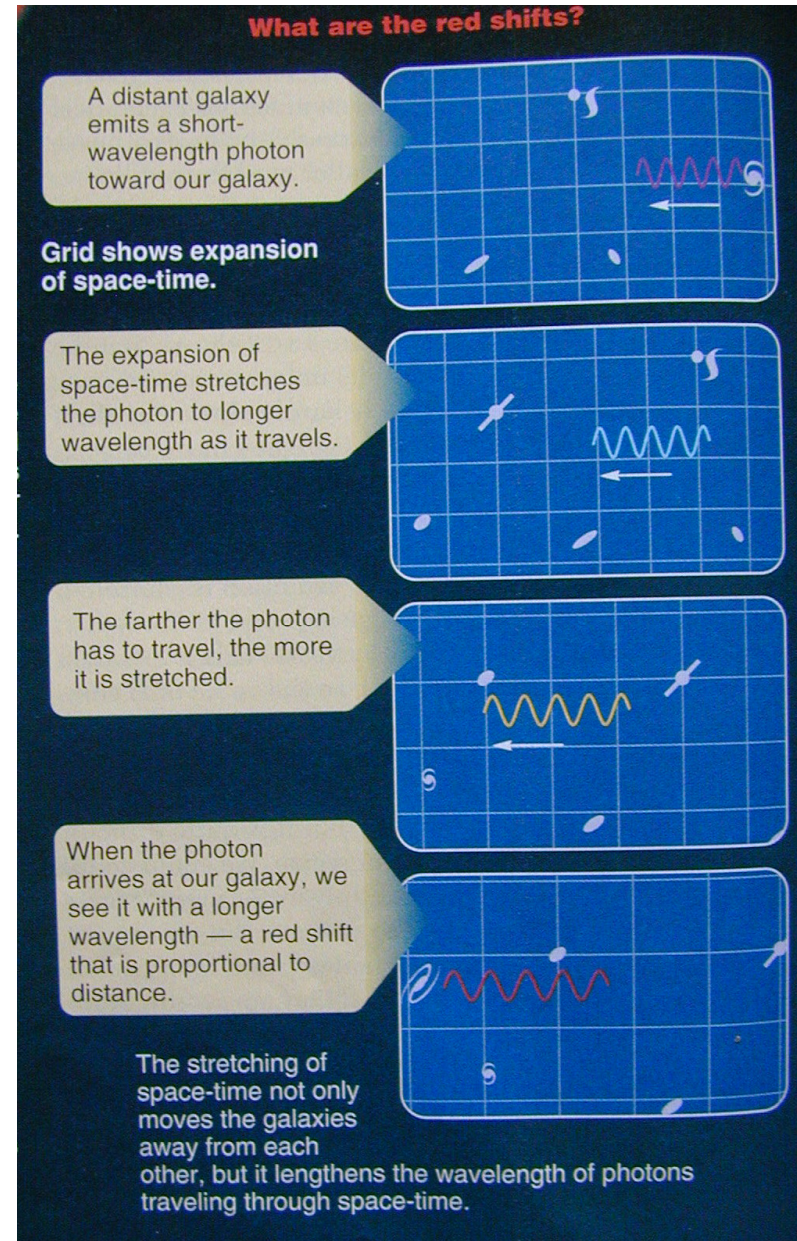
Michael Seeds: Astronomy

flat universe +
current Hubble constant
→ Age \approx 9.5 billion years
(younger than globular
clusters!!!)
solution: **dark energy**
(**cosmological constant**)



Redshift due to space stretching (i.e. consider General Relativity) is ***different*** from the usual redshift due to the relative velocity (i.e. the Doppler effect)

Michael Seeds:
Astronomy



Be careful of words (道可道，非常道)

- The Universe has no edge and center. → The big bang did not happen at the “center” of the Universe, but occurred everywhere in the Universe.
- The Universe does not need additional room to expand; increase in volume is due to the change in the nature of space-time
- Our bodies, the Solar System, the Milky Way, and gravitationally bound galaxies in a cluster do not expand with the space.

Difference between the big bang & a black hole

- **The big bang and a black hole seem to share a common feature: a single point with infinite density (singularity). Are they the same? Ans: No!**
- **A black hole is connected to the external Universe, and presents a static gravity field. On the other hand, there is no external Universe for the big bang to connect to, and it is not static but expanding.**
- **A black hole singularity is time-like, but the big bang singularity is space-like. A black hole has an event horizon, but the big bang does not.**

The Big Bang Model

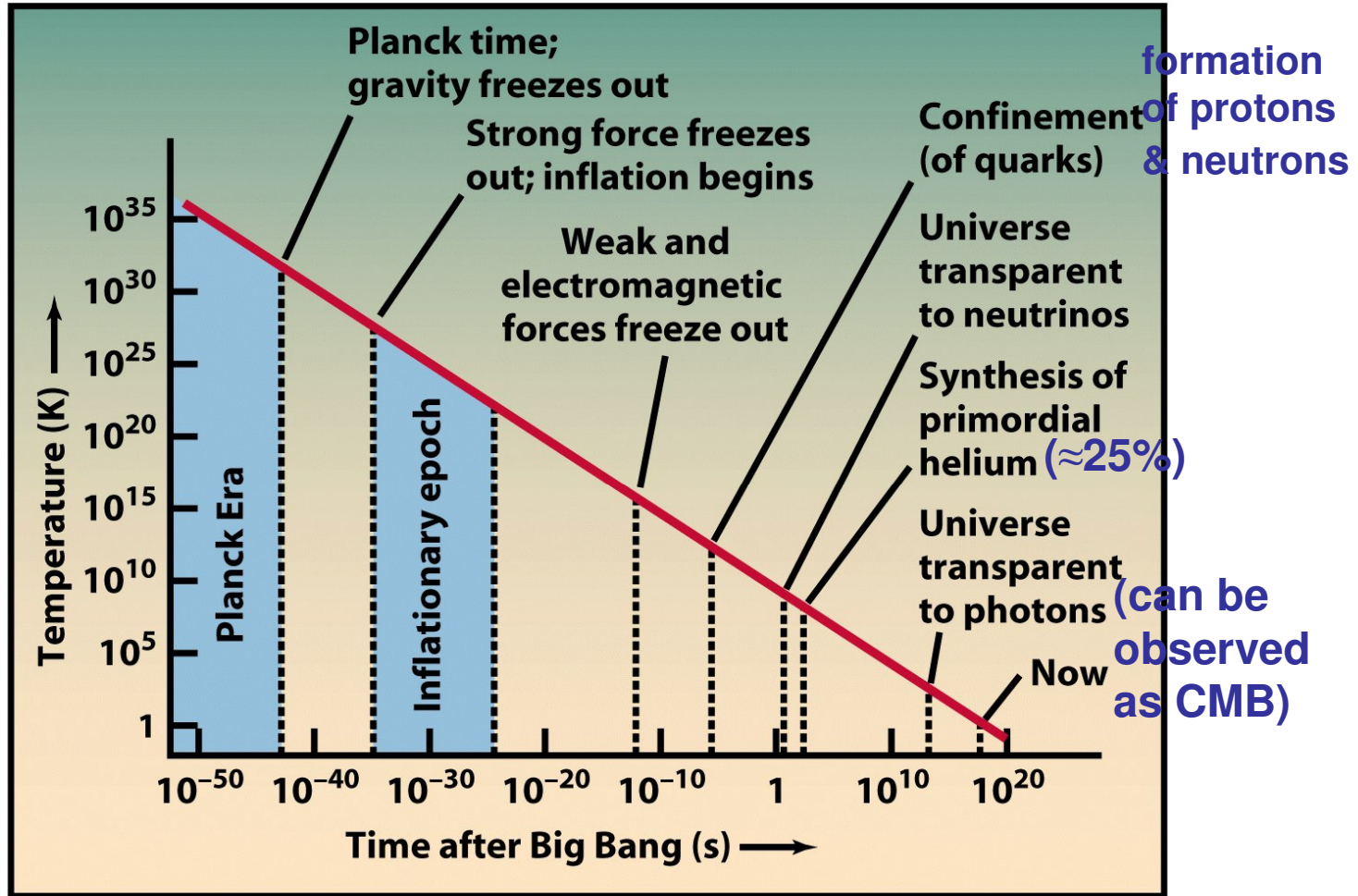


Figure 18-8
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The Inflation Epoch (Alan Guth, Andrei Linde 1981)



- Isotropy/horizon Problem in a scale larger than superclusters (CMB isotropy)
- Flatness Problem (zero curvature)
- Seeds for the formation of the large-scale structure: quantum fluctuations → density fluctuations (CMB anisotropy) → gravitational collapse

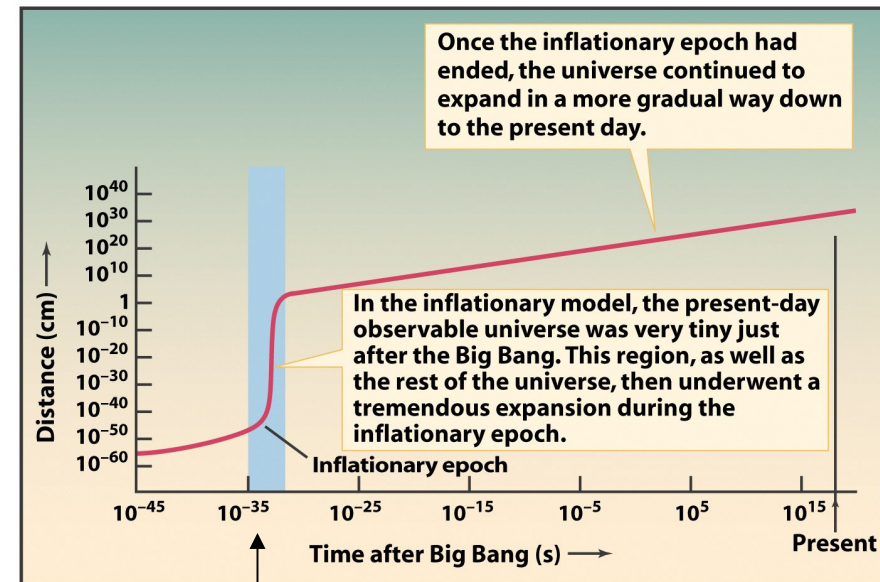
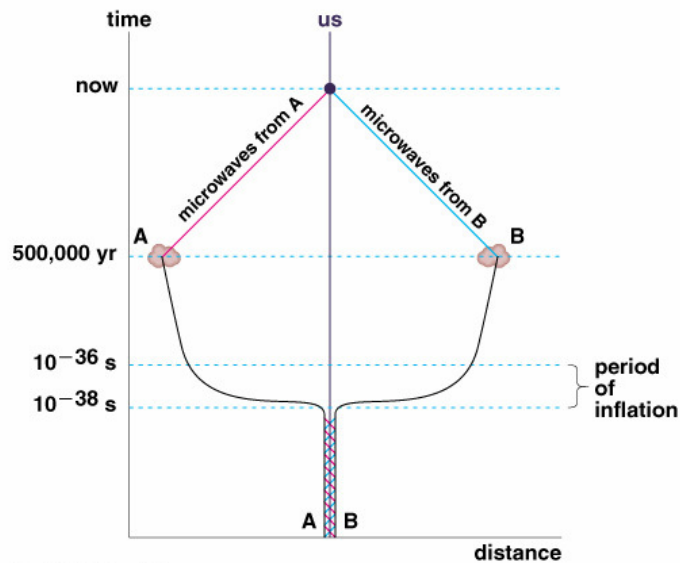
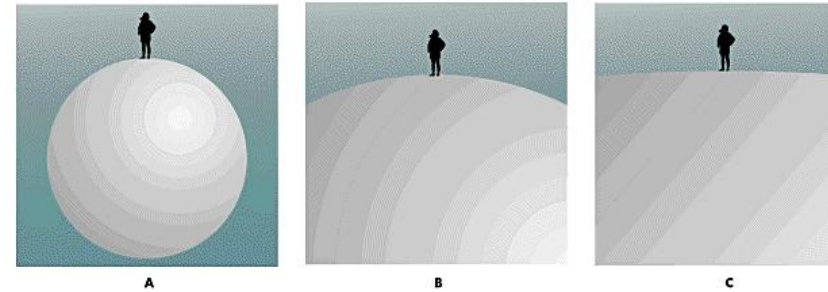
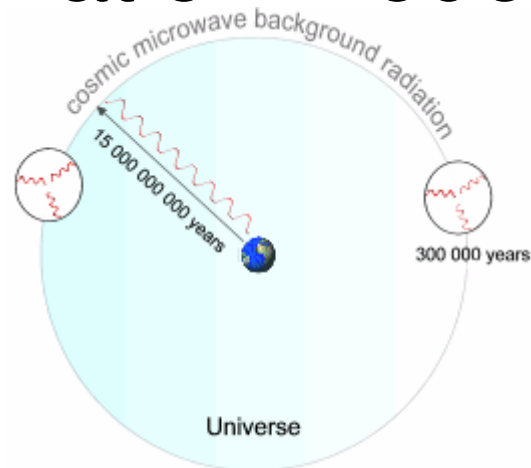


Figure 18-10
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**expands faster than
the speed of light!**

Inflation model solves the Problems

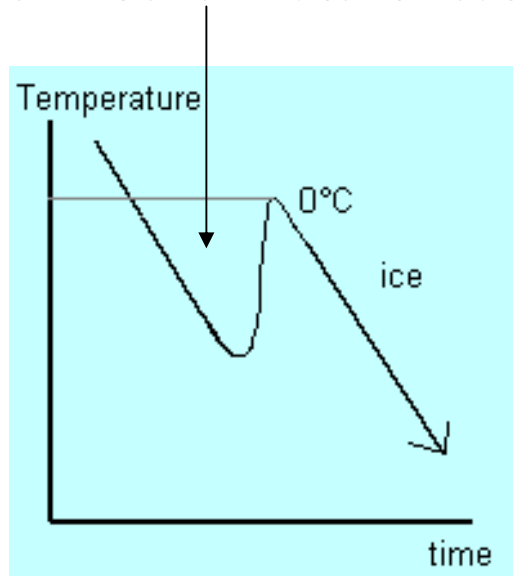


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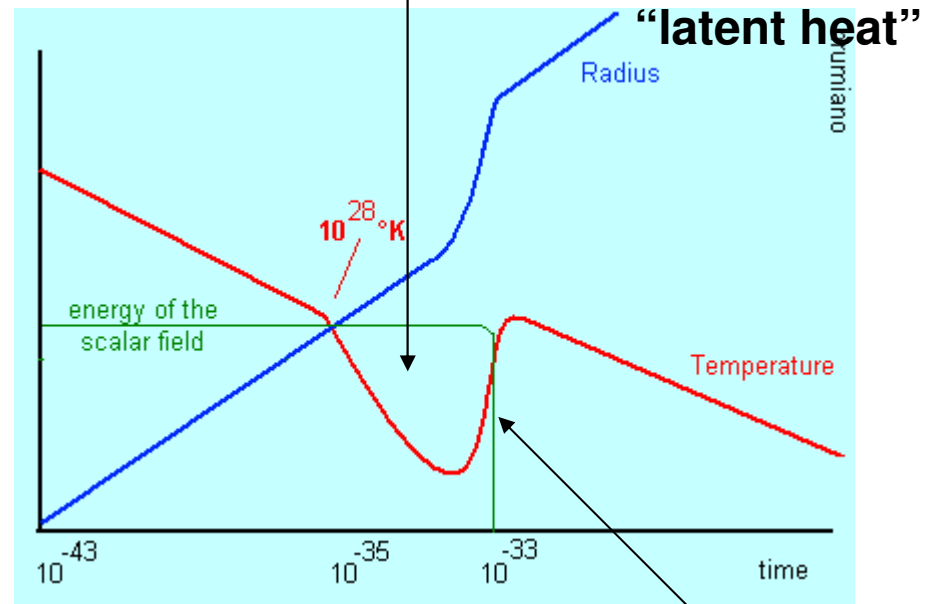
Phase Transition

http://nrumiano.free.fr/Ecosmo/cg_inflation.html

symmetry breaking:
liquid → solid + latent heat



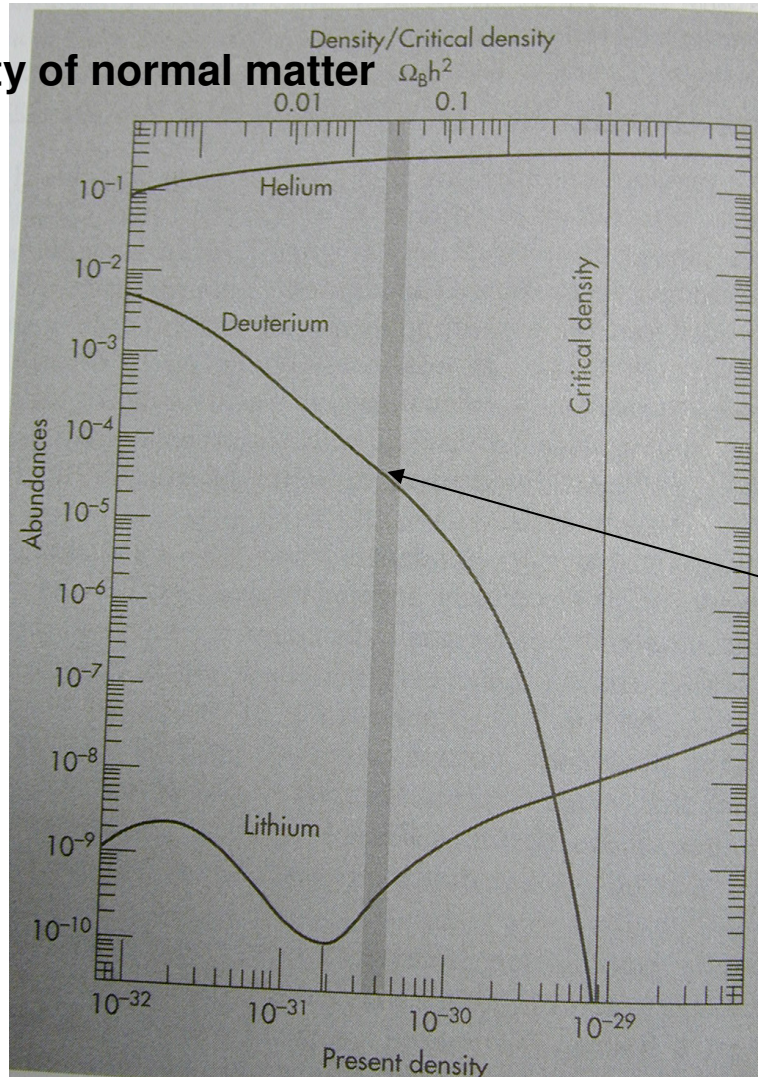
symmetry breaking:
strong force separates → inflation +



“latent heat” of vacuum → matter & radiation that re-heats the universe
Recall: Hawking Radiation

Big Bang Nucleosynthesis

density of normal matter $\Omega_B h^2$

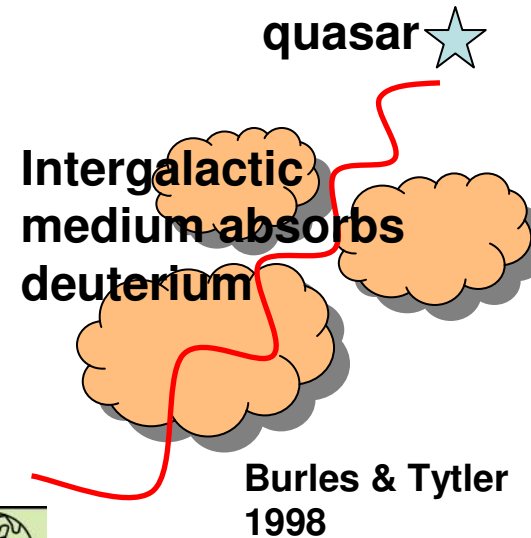


Schramm & Turner

1) H:He \approx 3:1

2) After He was made, density & temperature of the expanding universe is too low for further nuclear fusing to heavier elements

3) deuterium (重氫) \rightarrow abundance of normal matter (ie made of protons and neutrons)



Catch the Ancient Light!

Cosmic Microwave Background (CMB)

Isotropic temperature: 2.726 K
The Inflation era explains the isotropy.



Robert Dicke

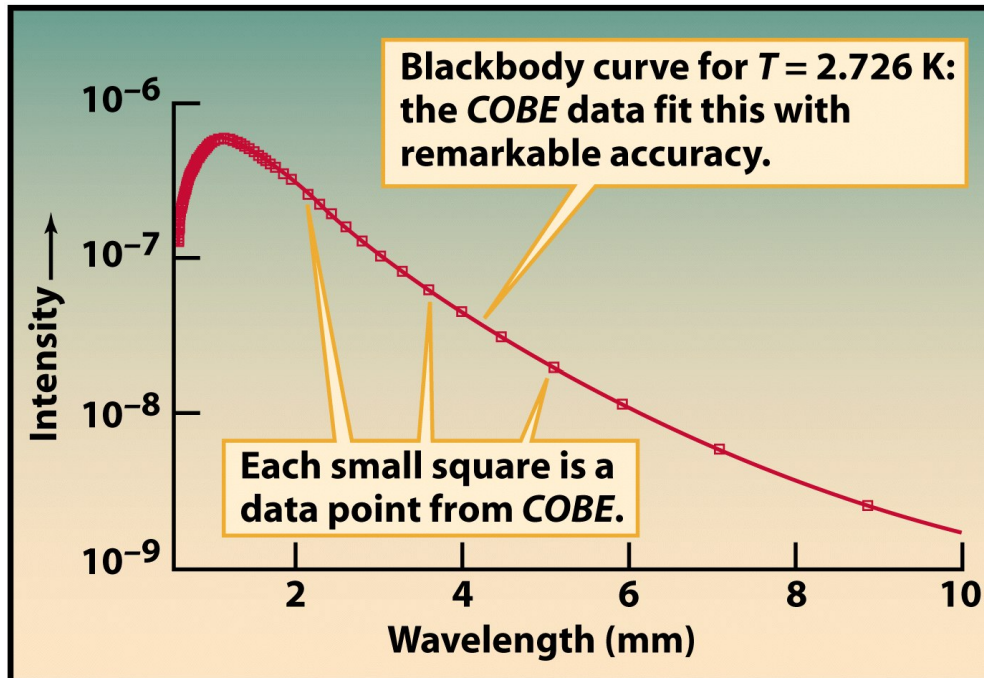


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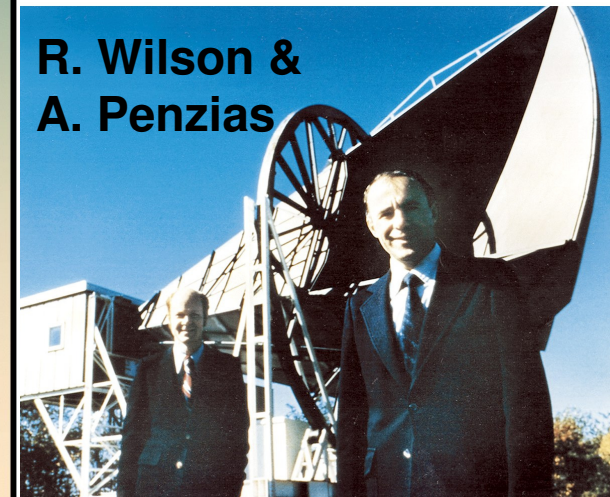
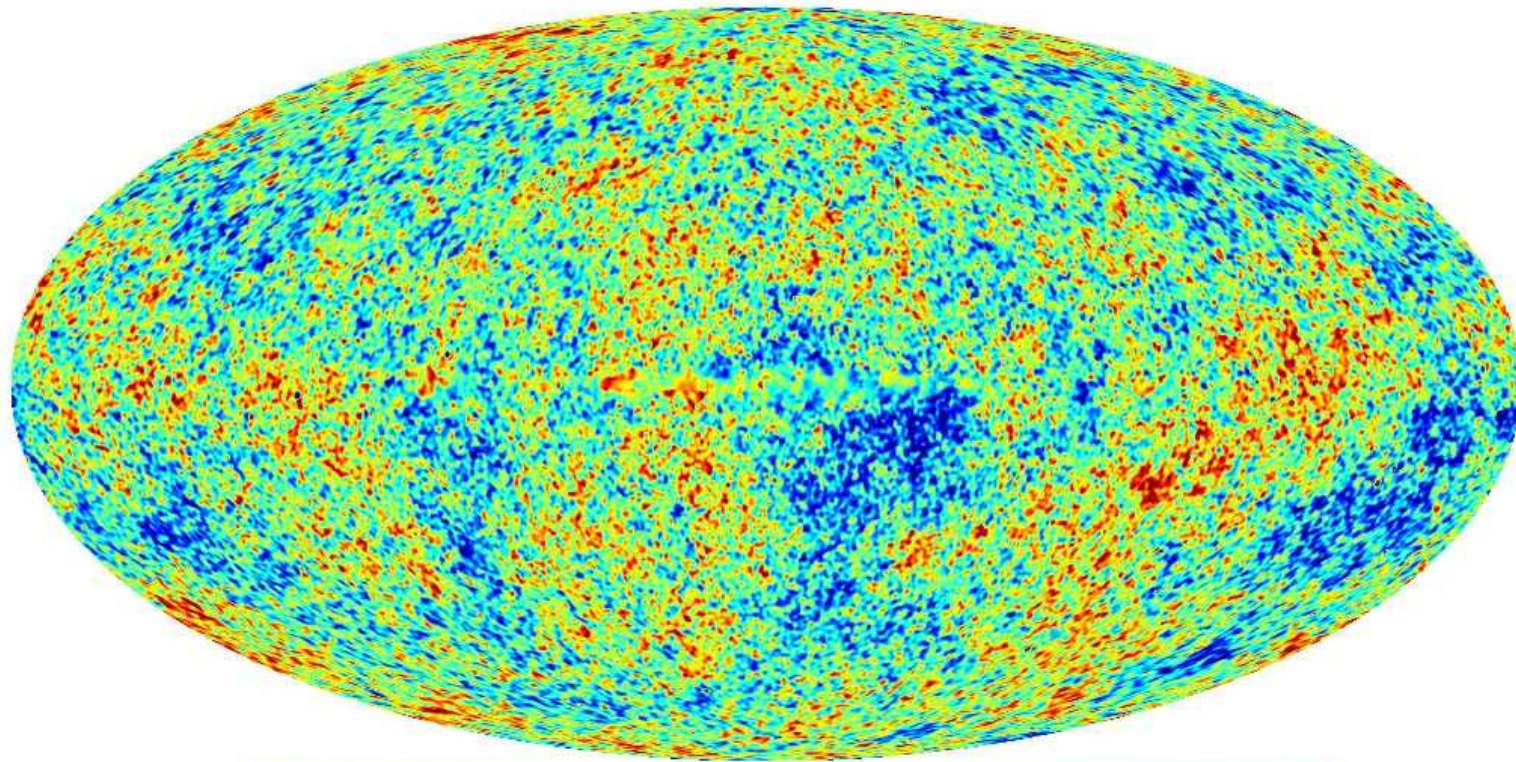


Figure 18-2
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Ancient Light is not 100% isotropic! CMB anisotropy



-200 μ K

200 μ K

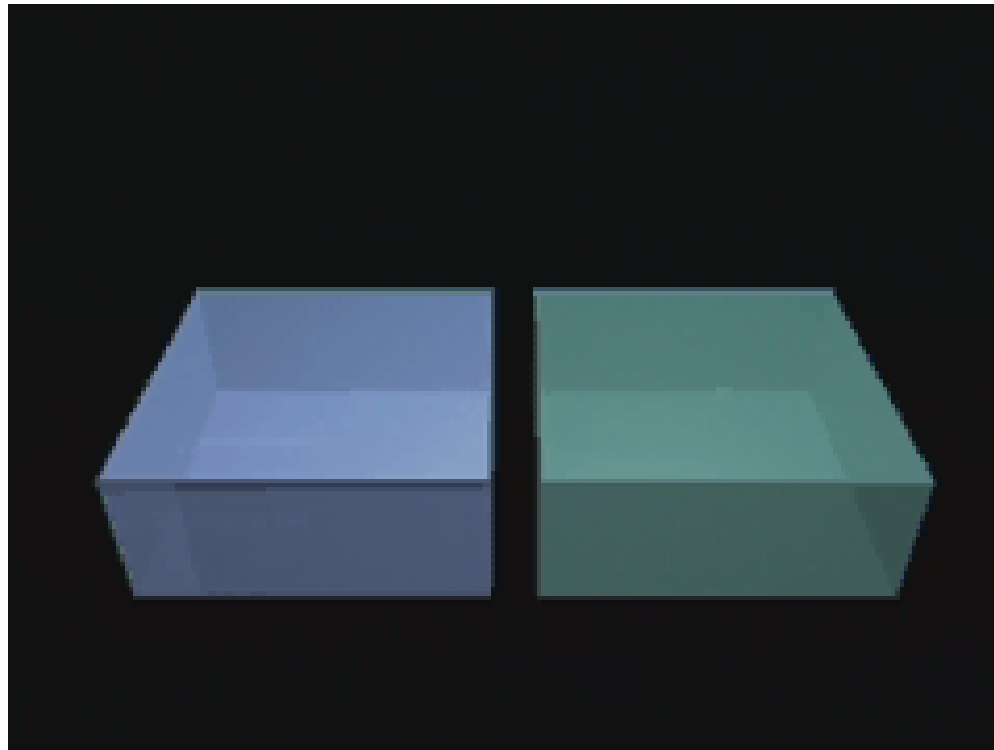
WMAP (Wilkinson Microwave Anisotropy Probe)

CMB anisotropy

quantum fluctuations → density fluctuations

normal matter (hot gas) and radiation (light) **fall into** the dark matter's gravitational field and then rebound due to intense radiation pressure → sound-like oscillation

→ **temperature variation**



http://map.gsfc.nasa.gov/m_or/mr_media2.html

Our Universe is “flat”

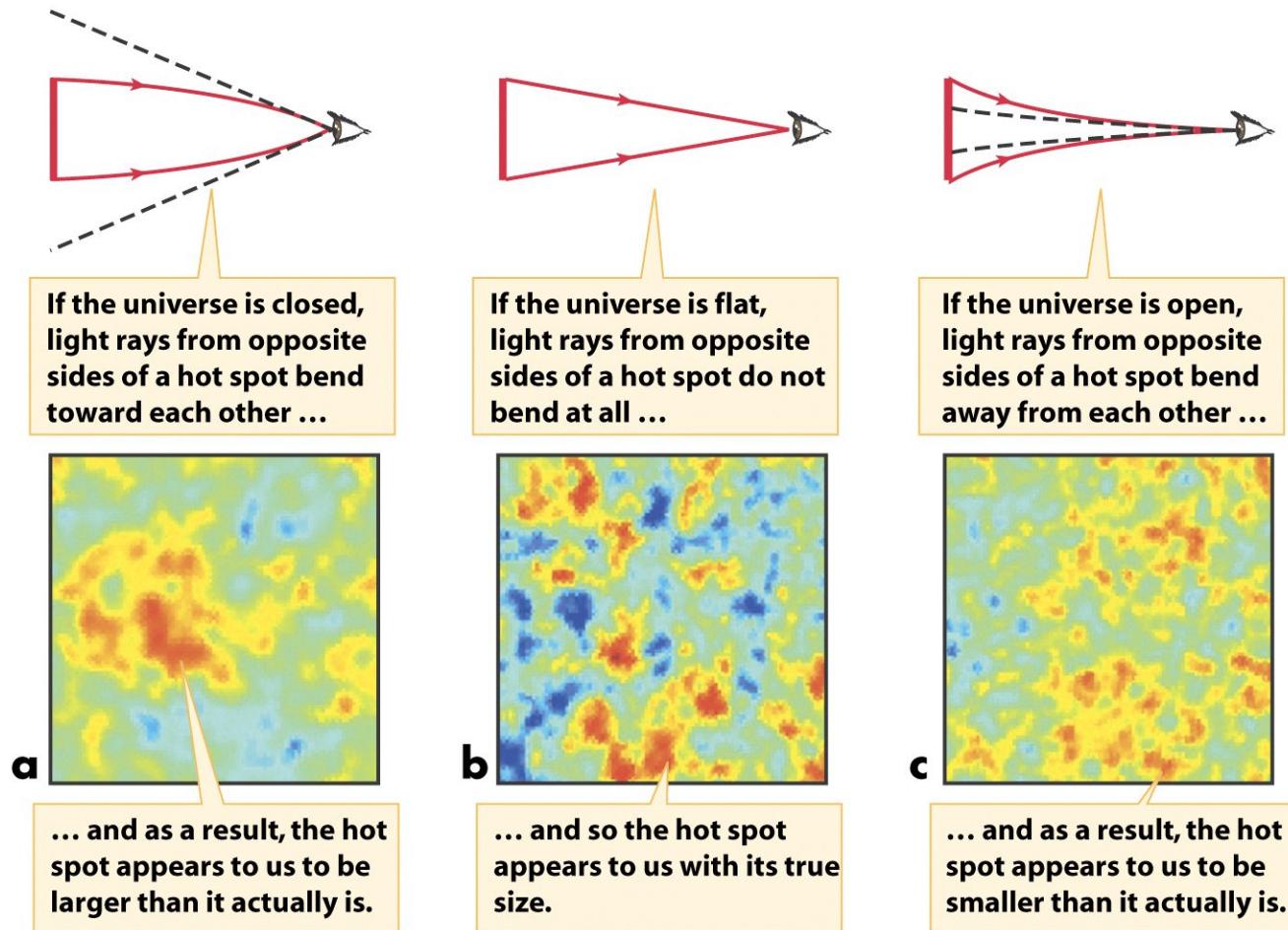


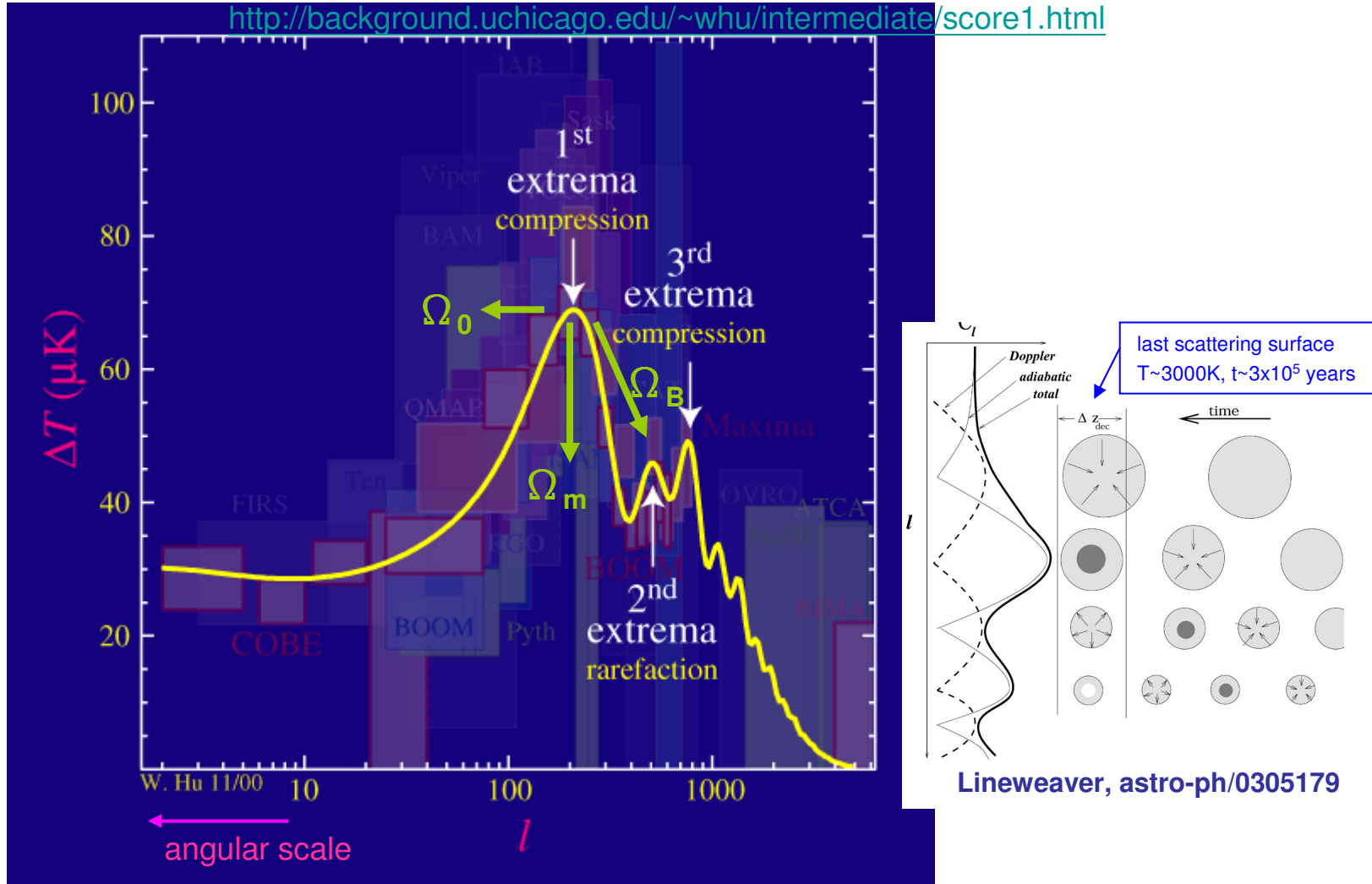
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The inflation era can explain this.

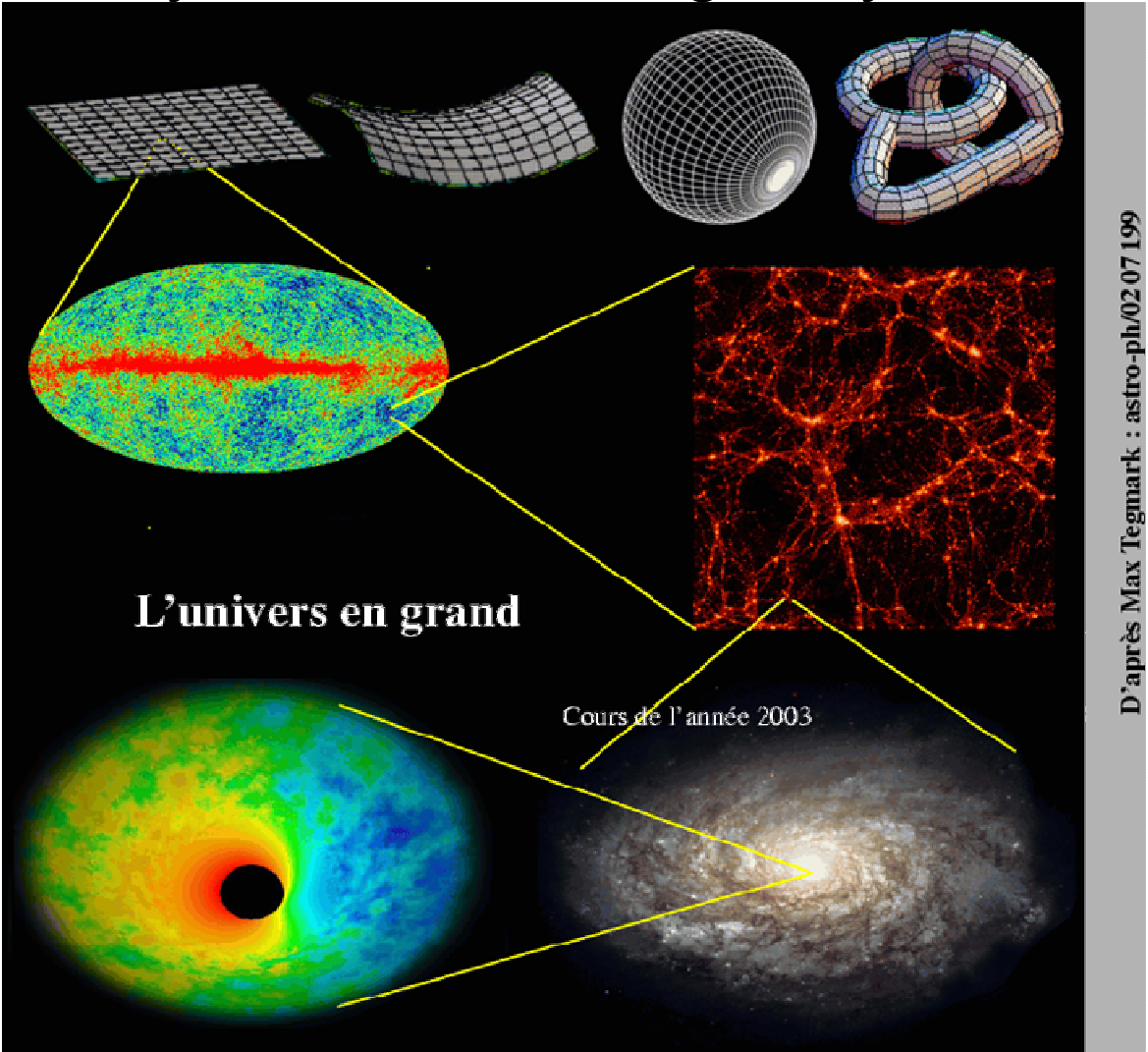
What is the Universe made of?

anisotropy of cosmic microwave background

<http://background.uchicago.edu/~whu/intermediate/score1.html>



density fluctuations & galaxy formation



Crisis in Cosmology before 1998

- CMB \rightarrow flat universe (can be explained by the inflation model which also explains the horizon problem)
- Matter density is lower than the critical density \rightarrow open universe (but inconsistent with CMB results), need something more to become a flat universe
- Globular clusters are older than a flat Universe

need “something else” to make the Universe flat and older

Accelerating Universe

Perlmutter: Cosmology Supernova Project Riess: high-z supernova search

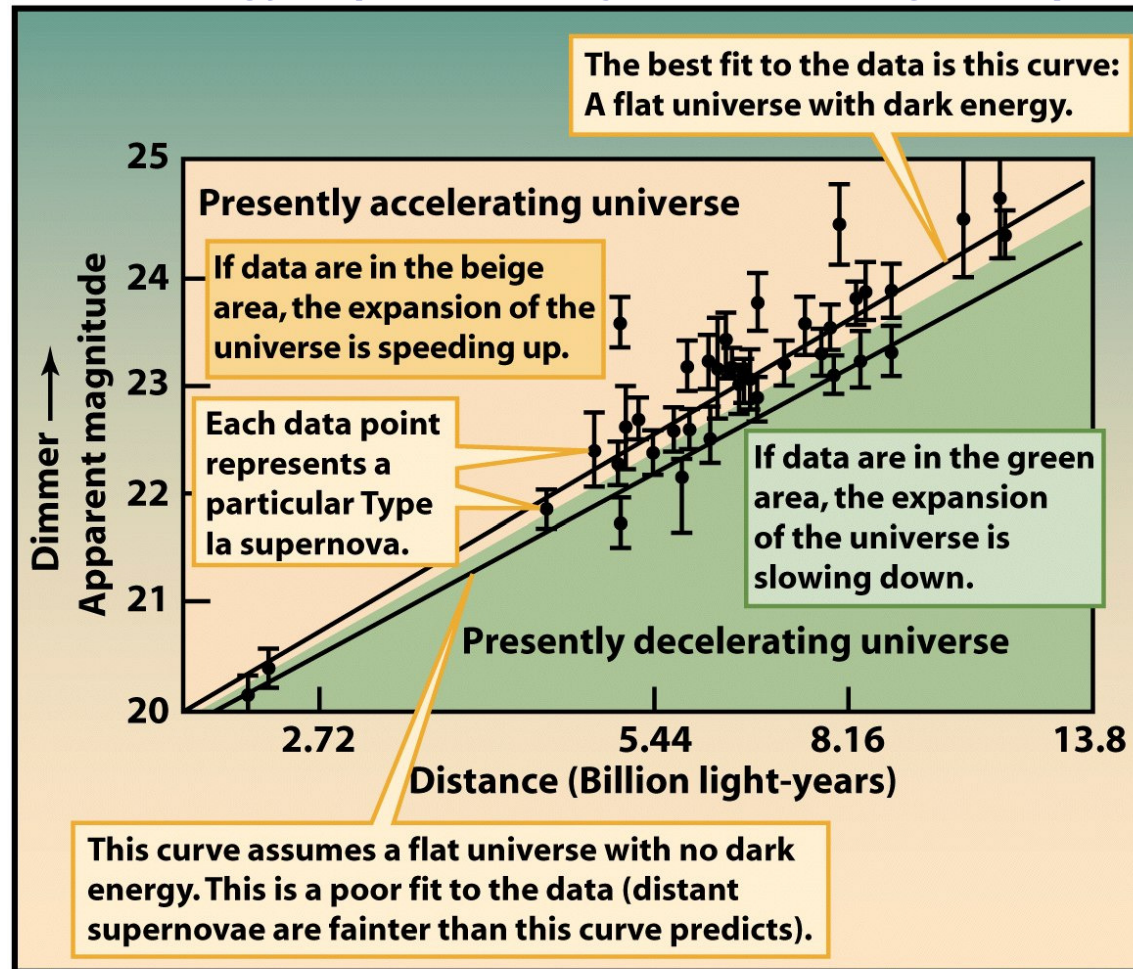


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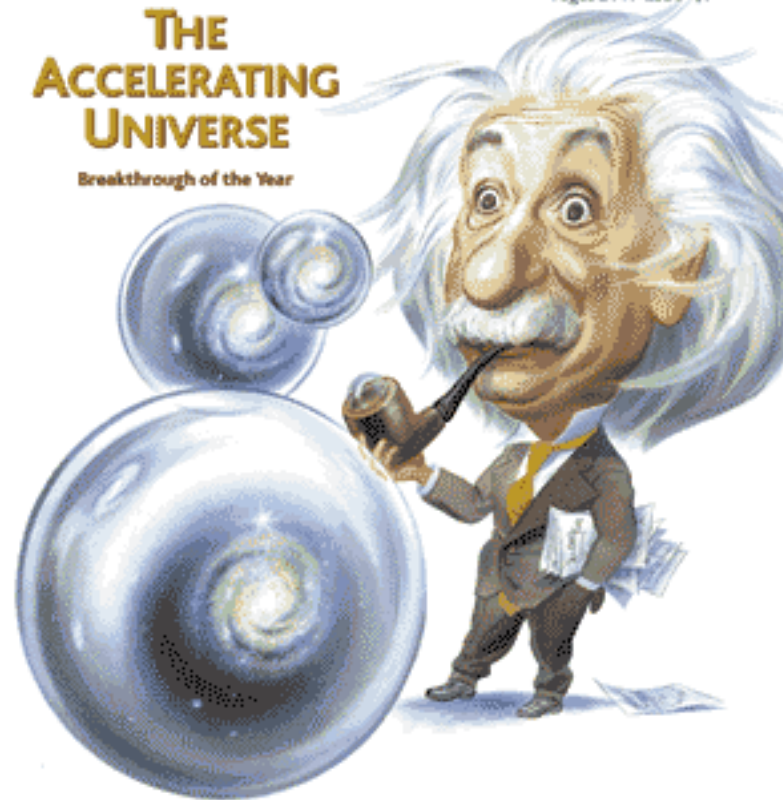
Science

18 December 1998

Vol. 282 No. 5397
Pages 2141-2336 \$7

THE ACCELERATING UNIVERSE

Breakthrough of the Year



 AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

Nothing is Something: Vacuum Energy

Newton's Gravity : composition does not matter! $F = \frac{GMm}{r^2}$

General Relativity : composition affects gravity!

$$P = -\rho \quad (\text{nothing})$$

$$\rho + 3p = -2p \quad (\text{"nothing" is very repulsive})$$

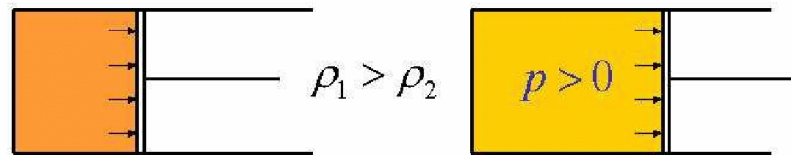
空即是色

Garcia-Bellido

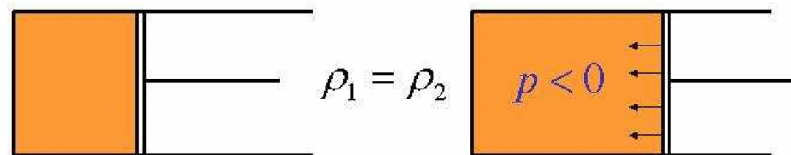
NORMAL MATTER

1: before expansion

2: after expansion



$$d(\rho V) + pdV = TdS$$

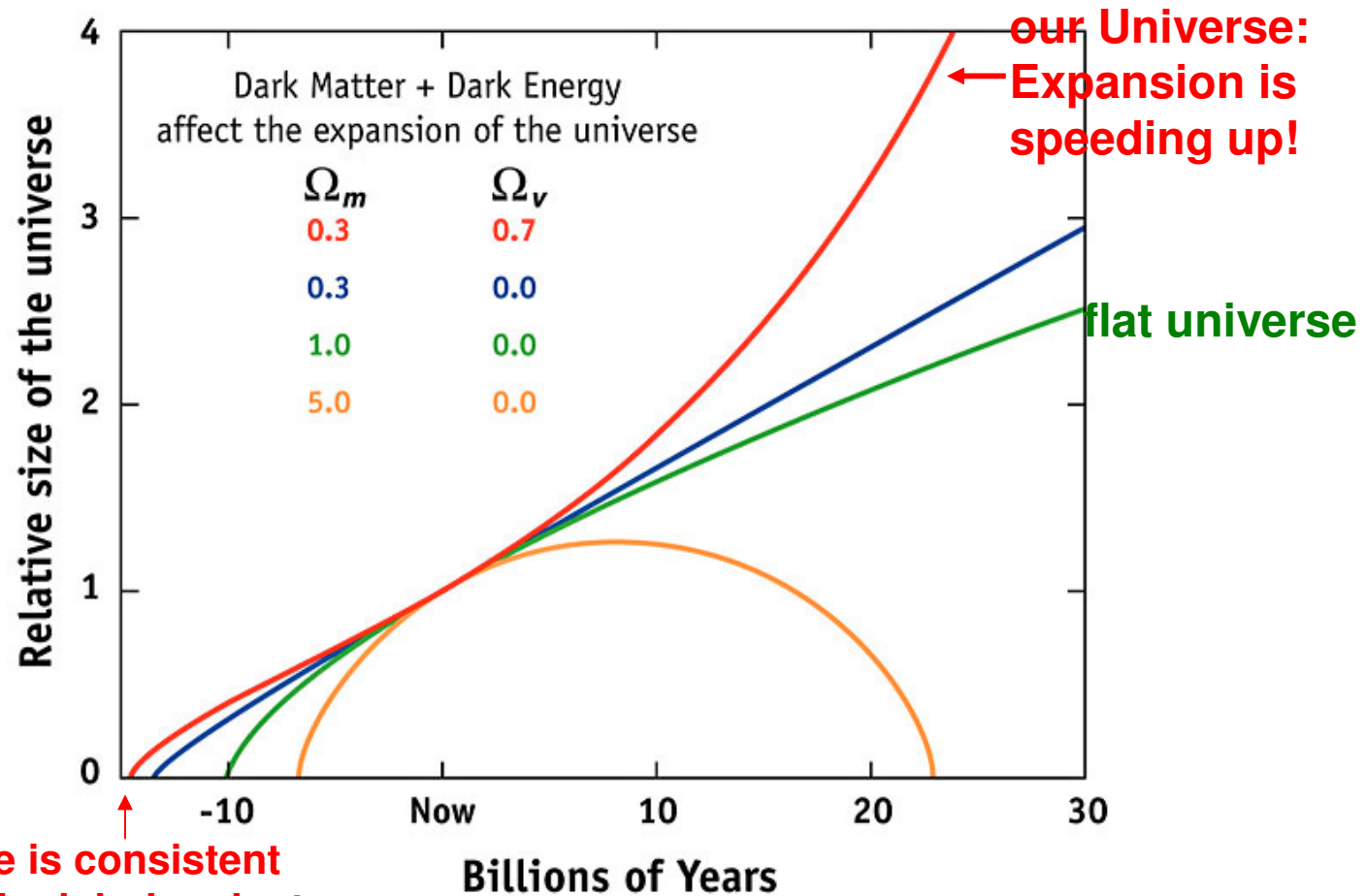


VACUUM ENERGY (dark energy)

Age & fate of the Universe (including dark energy)

http://map.gsfc.nasa.gov/m_uni/101bb2_1.html

EXPANSION OF THE UNIVERSE



Age is consistent
with globular clusters

Can we believe SN Ia results?

- Is SN Ia a really good standard candle?
- Could cosmic dusts dim the distant supernovae?

Dark Matter (observations)

- First evidence by Zwicky in 1933
- Rotational curves of spiral galaxies
- Dispersion velocities in elliptical galaxies
- Dispersion velocities in clusters of galaxies
- X-ray emitted from clusters of galaxies
- Gravitational lensing by clusters of galaxies
- CMB anisotropy

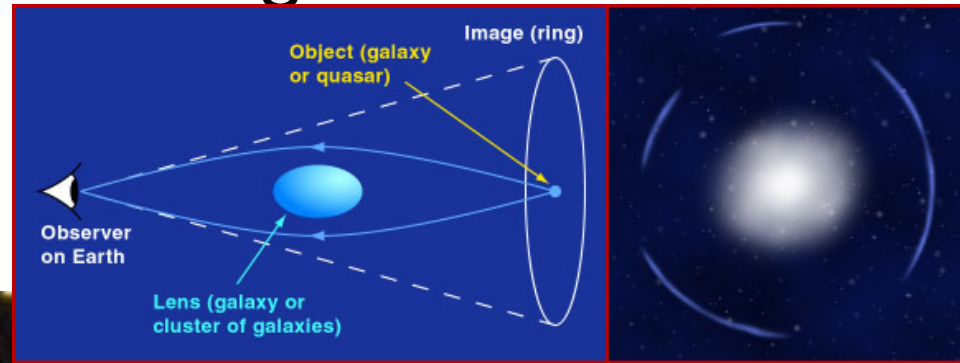
More fraction of matter is “dark” in a larger scale!

Method	M/L (M_{\odot}/L_{\odot})	Ω_0
Solar neighborhood	3	$0.002h^{-1}$
Elliptical galaxy cores	$12h$	0.007
Local escape speed	30	$0.018h^{-1}$
Satellite galaxies	30	$0.018h^{-1}$
Magellanic Stream	> 80	$> 0.05h^{-1}$
X-ray halo of M87	> 750	$> 0.46h^{-1}$
Local Group timing	100	$0.06h^{-1}$
Groups of galaxies	$260h$	0.16
Clusters of galaxies	$400h$	0.25
Virgo-centric flow	—	0.25
Gravitational lenses	—	0.1 – 0.3
Big Bang nucleosynthesis	—	0.065 ± 0.045
Preliminary large-scale studies	—	> 0.3
Inflation model	—	1.0

Carroll & Ostlie: an introduction to modern astrophysics

Gravitational Lensing → mass

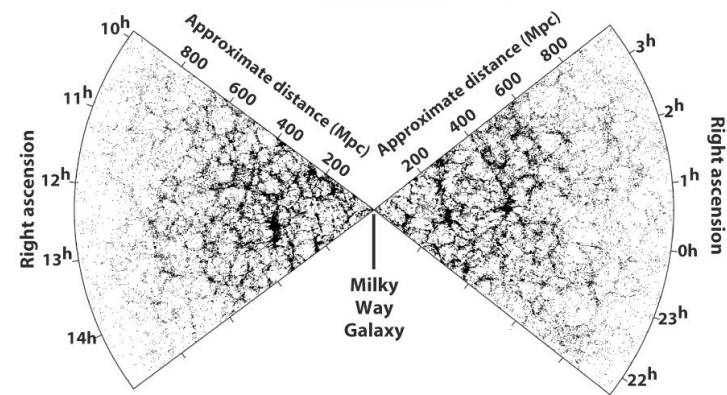
Abell 2218: a galaxy cluster lens



<http://hubblesite.org/newscenter/newdesk/archive/releases/2000/07/>

What is the dark matter?

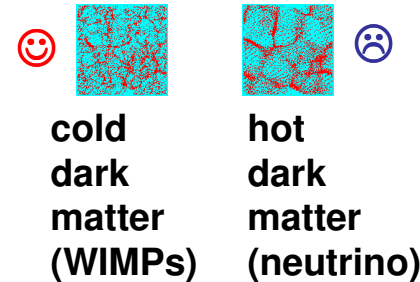
- normal matter? low mass stars/brown dwarfs (not favored by microlensing); big bang nucleosynthesis can't generate so much normal matter
- neutrino? Computer simulations show they can not generate the observed large-scale structure.
- black holes? The nearby star forming regions do not show a huge population of very massive stars.
- Strange particles (weak interacting massive particles)?



The 2dF galaxy survey

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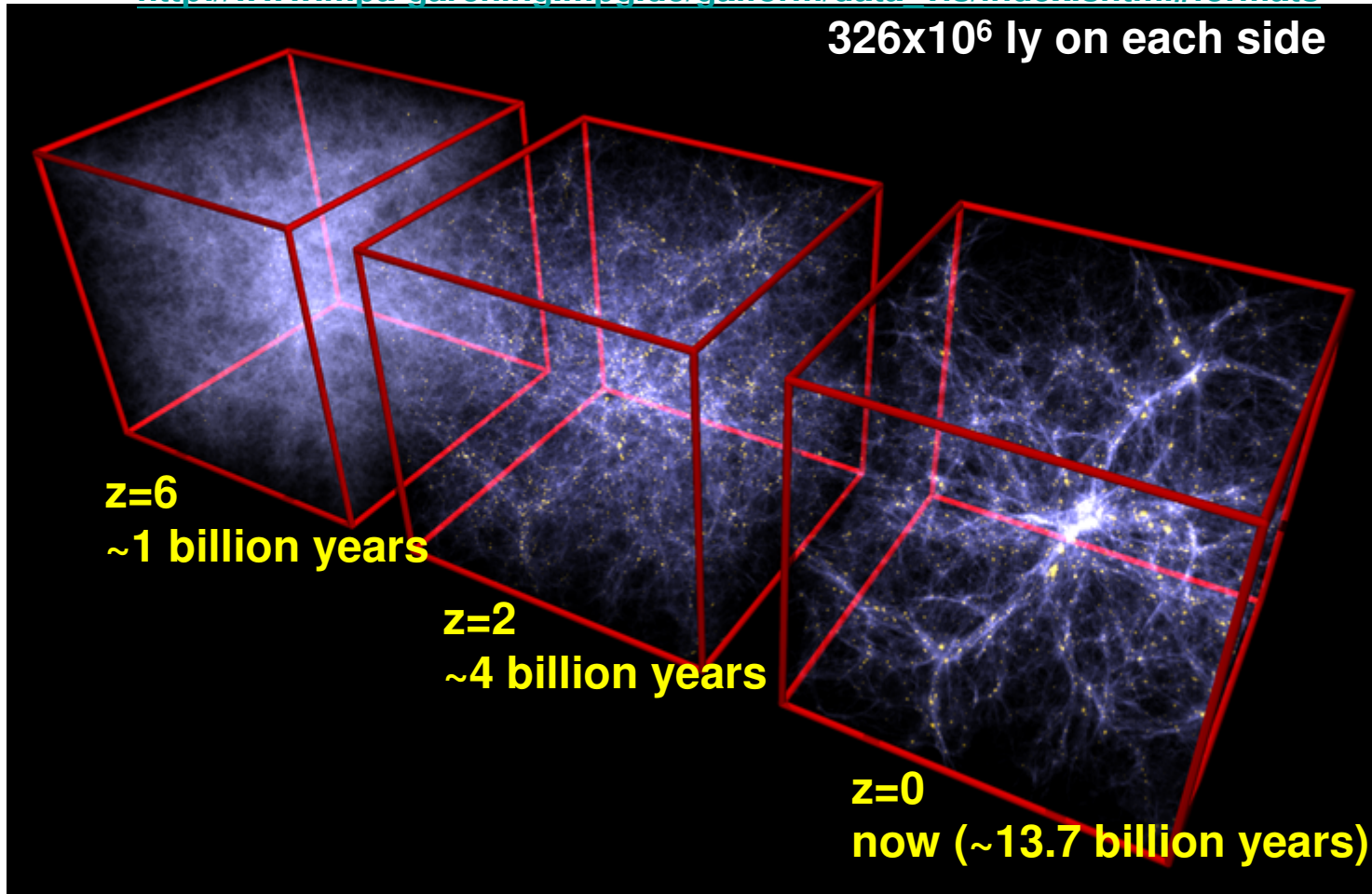
compare



<http://cfa-www.harvard.edu/~mwhite/modelcmp.html>

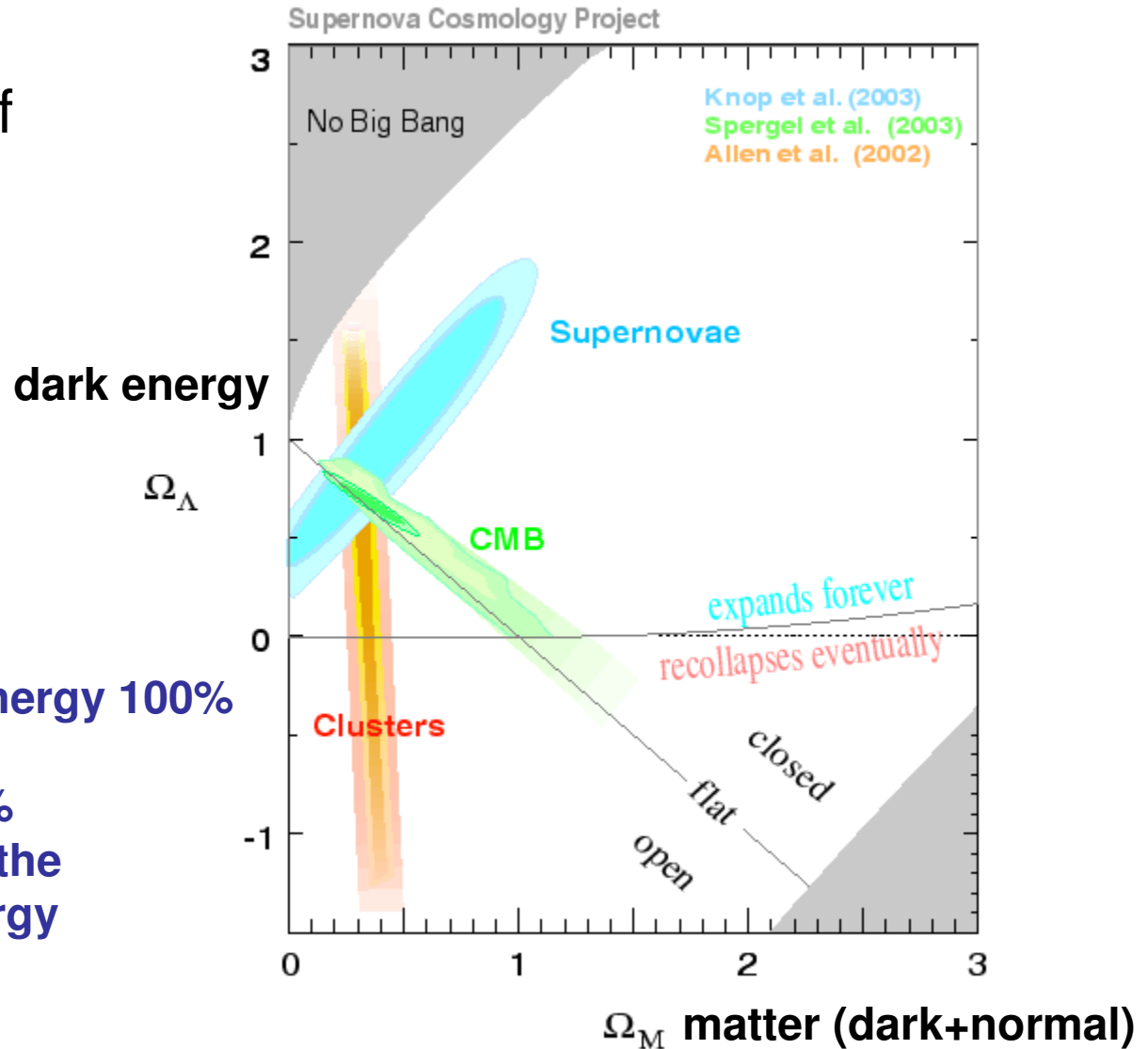
Structure Formation

http://www.mpa-garching.mpg.de/galform/data_vis/index.shtml#formats



Current understanding of the cosmic compositions

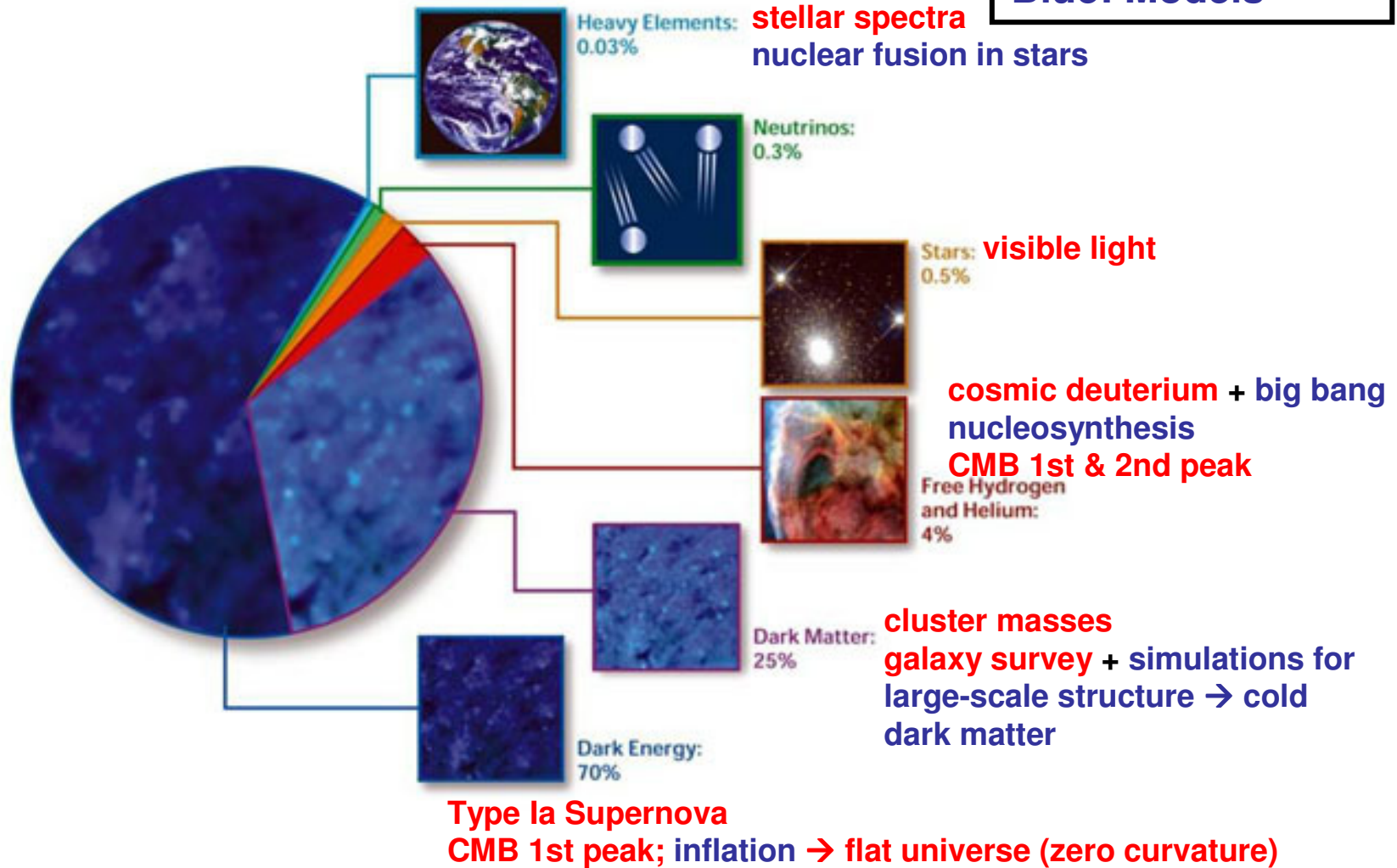
CMB: matter + dark energy 100%
Cluster: matter 27%
i.e. dark energy is 73%
Supernova: confirms the existence of dark energy



SUMMARY

COMPOSITION OF THE COSMOS

Red: Observations
Blue: Models



Evolution of Density

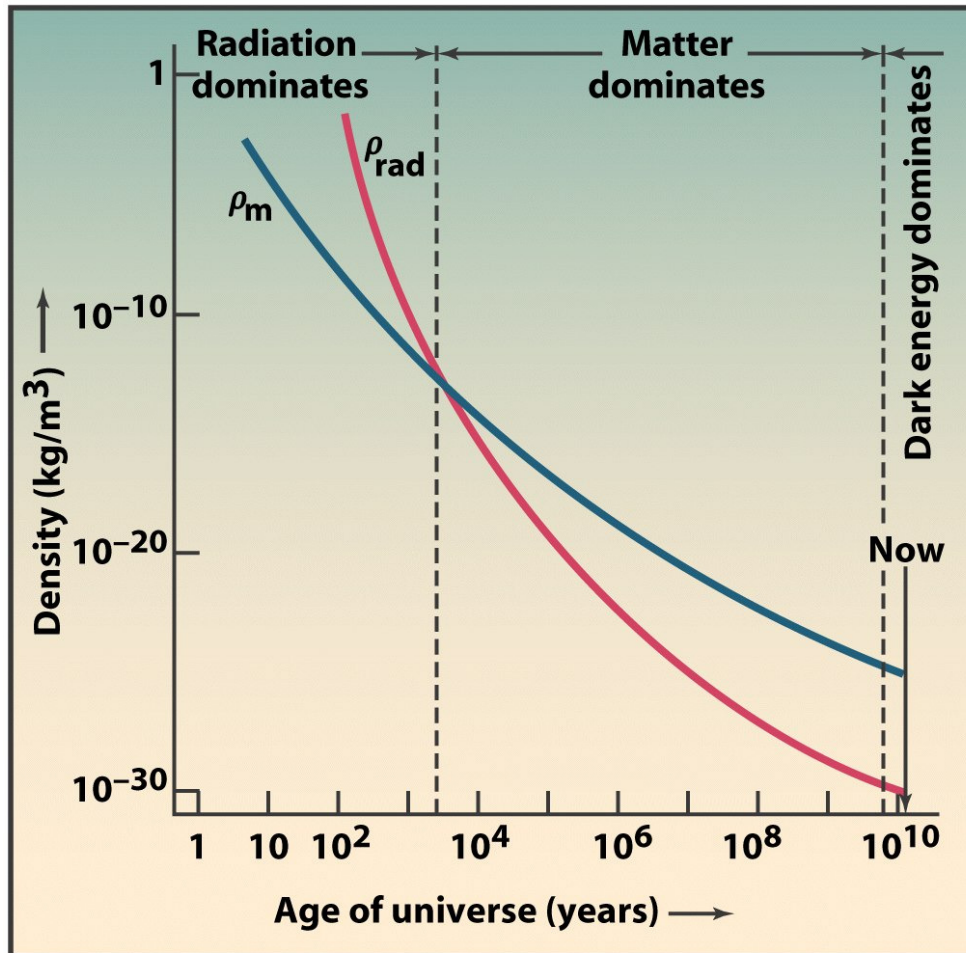


Figure 18-12
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Will the Universe speed up its expansion forever?

We don't have an answer because We don't know the nature of the dark energy (please refer to

<http://www.arxiv.org/abs/astro-ph/0301087>).

Cosmic Timeline

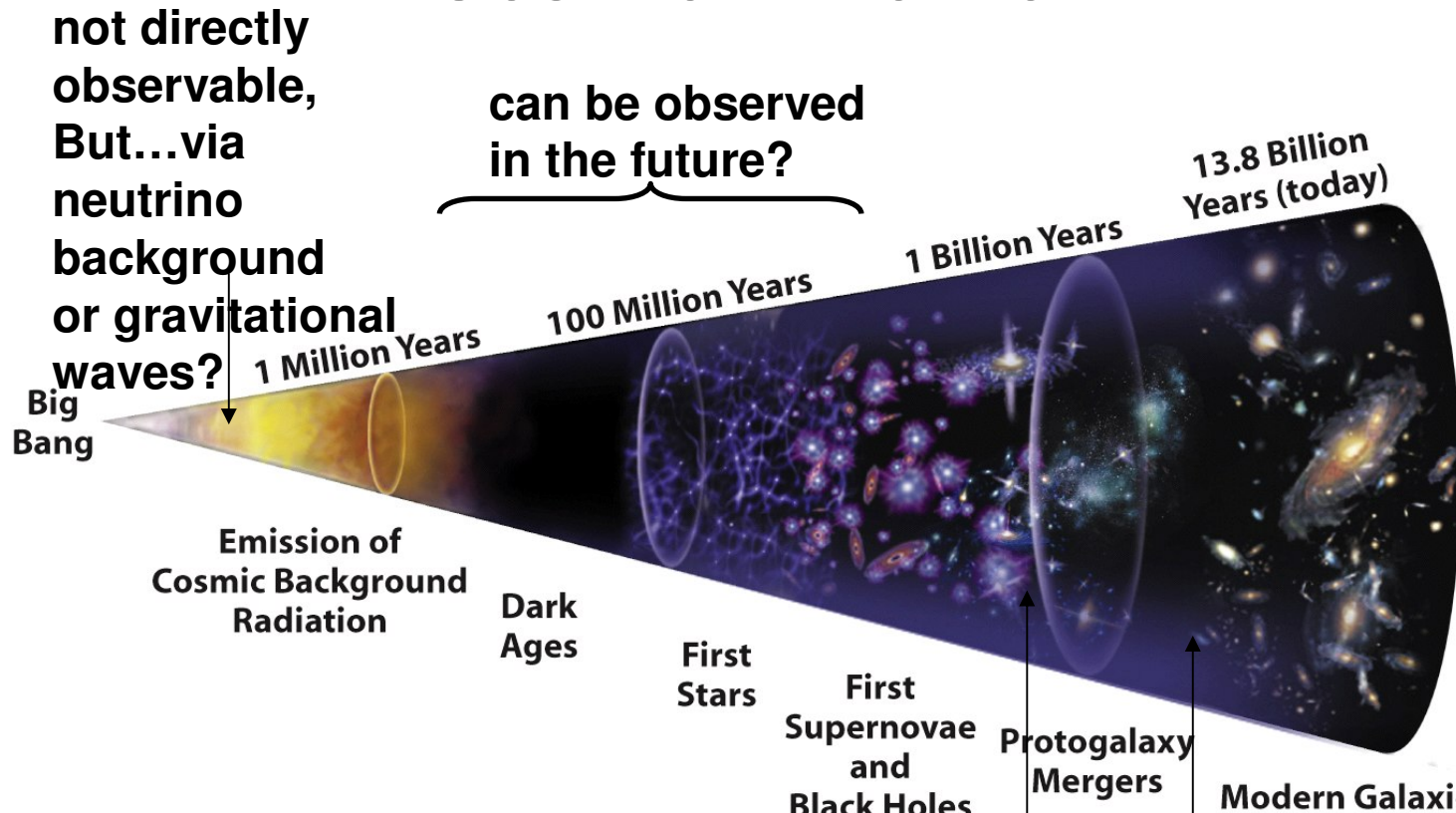


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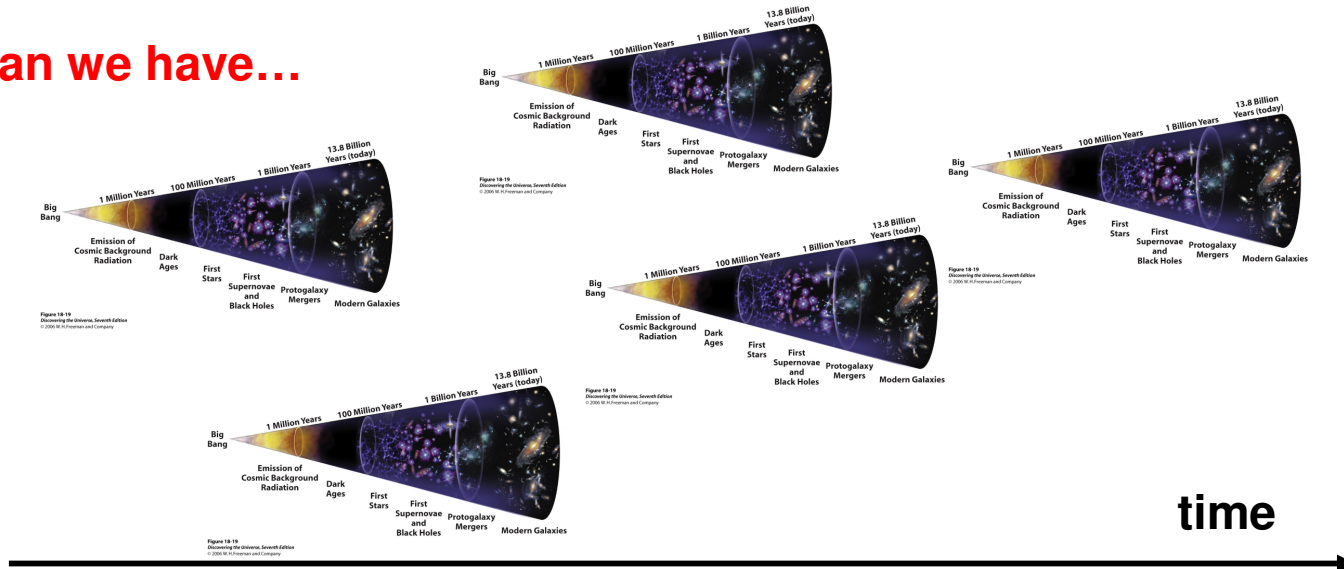
Can we better understand the formation of the large-scale structure and the supermassive black holes?

Can we better understand the nature of the dark energy?

Universe or Multiverse?

Einstein's big bang: creation of space, time, matter, and energy.
However, what happened before the big bang?

Can we have...



The Anthropic Principle

- Existence of us → how “our” universe should evolve
- Could the universe start with different initial conditions (or say different fundamental constants such as the speed of light, the mass of electron...) allow our existence? (in other words, fundamental constants are not “fundamental”!)
- For instance, in 1973 C. Collins & S. Hawking used this idea to discuss the flatness problem.
- Can we test this idea?

Summary

- ◆ 解決 Olbers' Paradox (夜如晝)：可觀測的宇宙有限；宇宙非靜態(大霹靂)
- ◆ 哈伯發現遙遠(不可用附近的)星系的光譜呈現紅移(非單純都卜勒效應)，於是測量宇宙膨脹的速率(哈伯常數)：大霹靂說(爆炸的時空)。但這不意味著宇宙有中心和邊緣，也不意味著我們身體跟著膨脹！
- ◆ 宇宙的空間受所包含的物質和能量所扭曲(試想二度曲面上的螞蟻)：封閉(>臨界密度)、平坦(=臨界密度)、開放(<臨界密度)。
- ◆ 宇宙早期高溫高密度(但不同於黑洞)，隨膨脹而逐漸降溫，製造出氫與氦(3:1)。隨後因繼續膨脹，密度過低而無法製造出更重的元素(我們是星塵)。
- ◆ 宇宙背景輻射是當宇宙早期變透明時(氫原子在形成)所留下來的光，以後隨宇宙膨脹而能量下降至現在的2.7K。
- ◆ 宇宙背景輻射在小區域的微小變化，是日後造成星系團和星系團間空隙的形成(網狀結構)，並且告訴我們，宇宙的空間是平坦的(=臨界密度)。
- ◆ 遙遠超新星比預期的暗淡，或許暗示著宇宙在後期時正加速膨脹。造成的原因未知，懷疑真空能給予所謂的黑暗能量，使宇宙加速膨脹(空即是色)。
- ◆ 目前宇宙大約有70%黑暗能量，25%黑暗物質，以及5%正常物質。
- ◆ 根據以上的組成，宇宙年齡大約137億年。這與用目前的哈伯常數來簡單估計的宇宙年齡意外相同。這也不與球狀星團(現知最老的天體)的年齡相抵觸。
- ◆ 宇宙的命運未知(膨脹或塌縮?)，因為我們目前不清楚黑暗能量的本質。
- ◆ 人擇原理(Anthropic Principle)：我們的存在 → 宇宙如何演化