Dark Matter & Dark Energy

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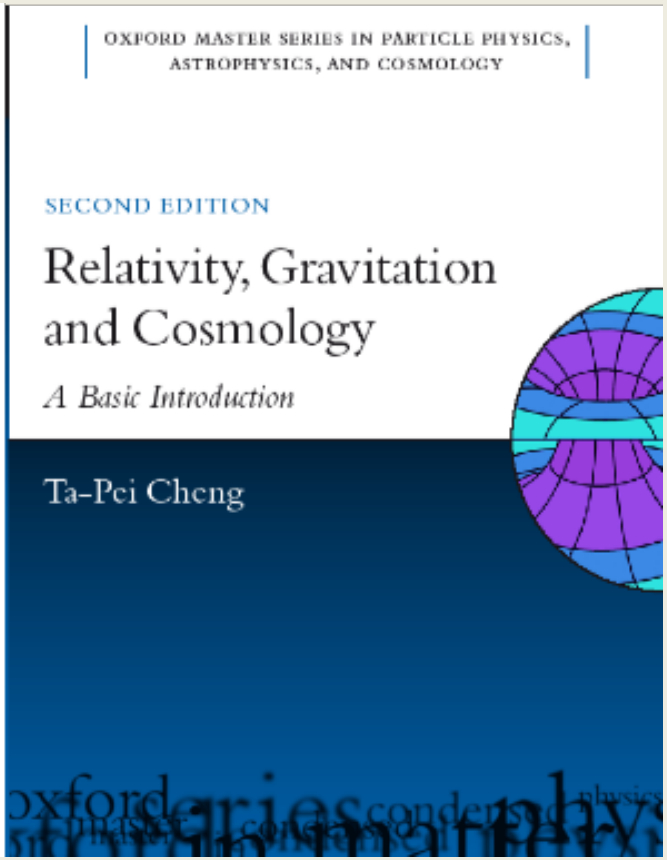
For a more quantitative discussion, see

Relativity, Gravitation & Cosmology:
A Basic Introduction

(Oxford Univ Press) 2nd ed. (2010)



dark matter & dark energy

Astronomical observations suggest that
most of the mass of the universe is in a mysterious form called **dark matter**
most of the energy in the universe is in an even more mysterious form called **dark energy**.

Unlocking the secrets of dark matter and dark energy will illuminate the nature of space and time and connect the quantum with the cosmos

MATTER/ENERGY COMPONENTS OF THE UNIVERSE

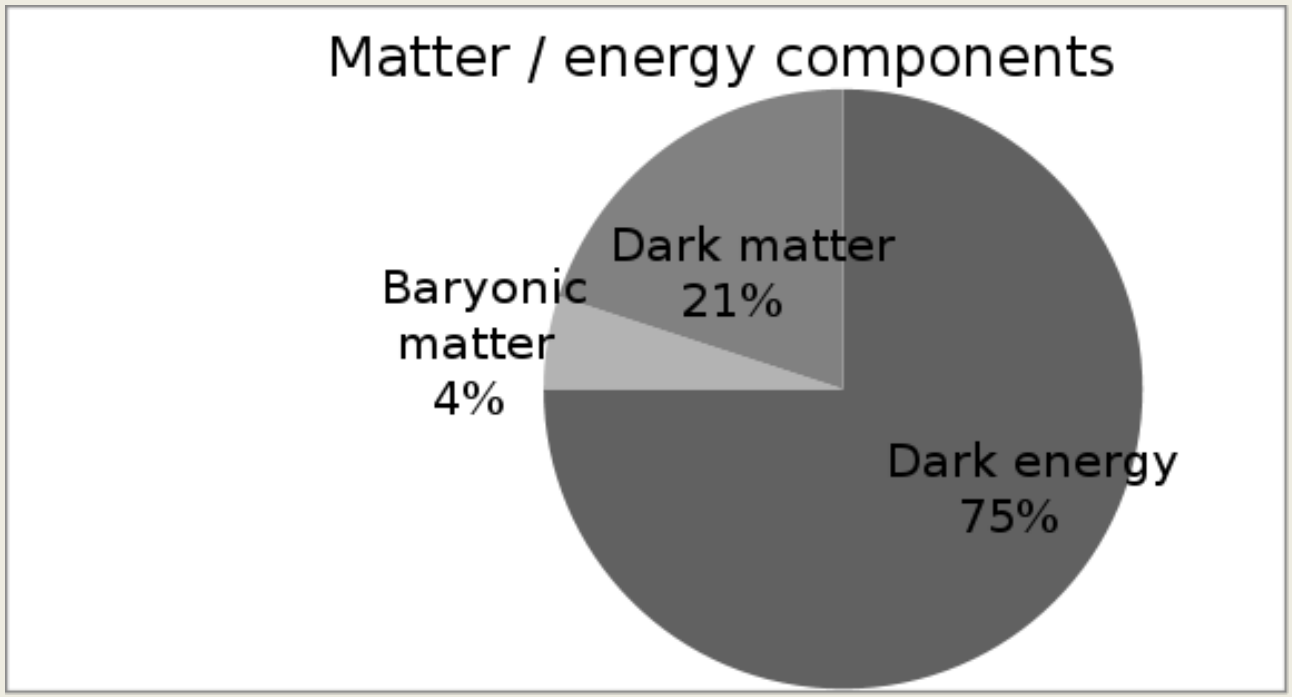
BARYONIC MATTER — **ordinary matter**, can be observed thru their electromagnetic effects

DARK MATTER

DARK ENERGY

→ **no** electromagnetic interaction, detected thru their grav.effects

Radiation energy component is negligible



BARYONIC MATTER

Ordinary matter : Atoms = [(p, n) + e]

Protons, neutrons = “baryons”

Baryonic matter emit and/or absorb light

Luminous (stars) + **non-luminous (gas, plasma,…)**

The dominant component = interstellar gas and plasma.

One way to determine the total content of baryonic matter is through the comparison of observation with calculation of **big bang nucleosynthesis**

Big Bang Nucleosynthesis

Light nuclear elements (H, He, D,...)
created by Big Bang

the universe is expanding, at earlier times
the universe was hotter and denser

Helium were created $2n+2p \rightarrow {}^{4}He^{++}+\gamma$
in the first three minutes after the Big Bang,
along with trace amounts of other light elements
(deuterium, lithium, etc.)

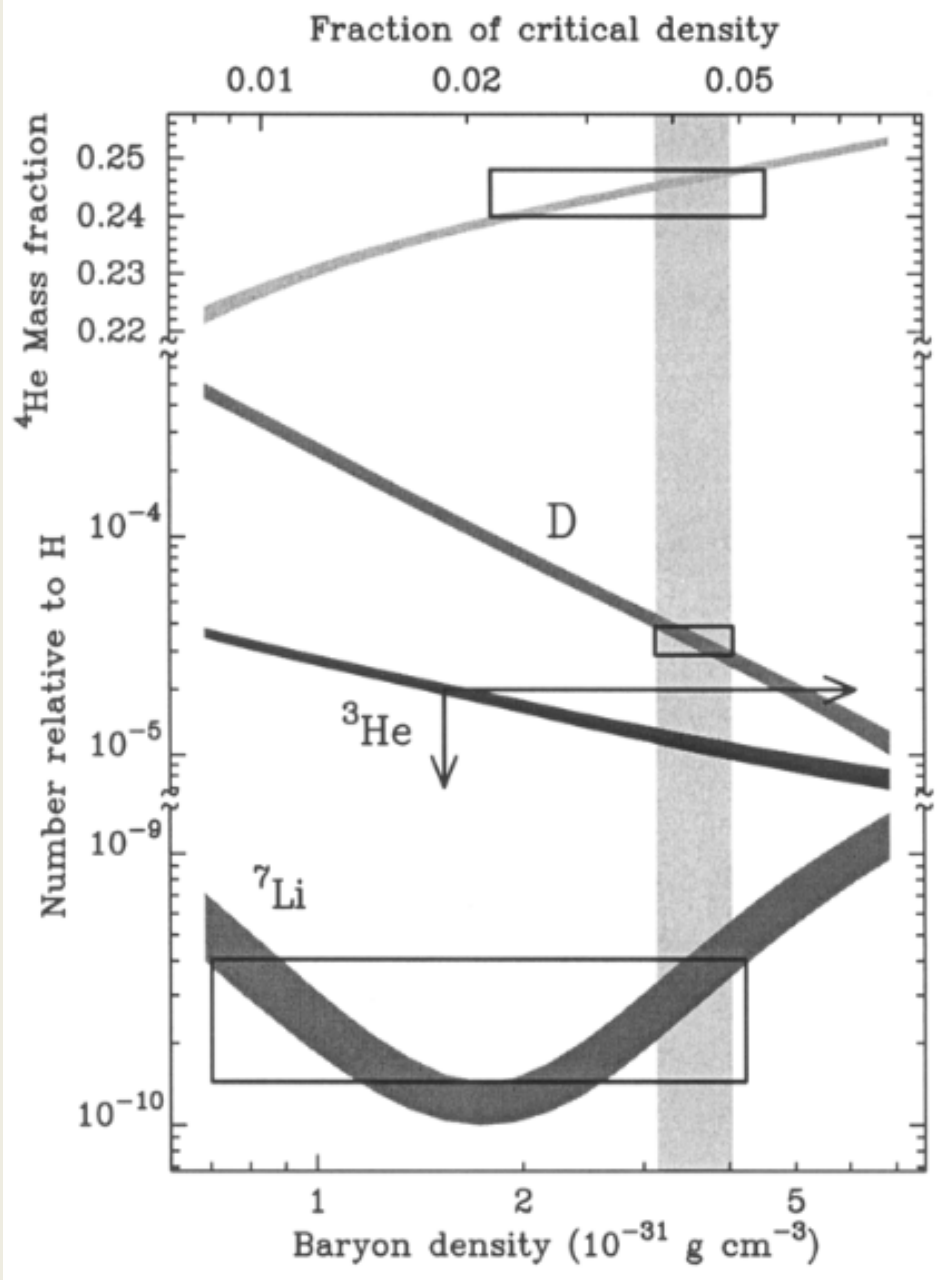
the correct relative amounts (e.g., 23% helium, as in the Sun)
are obtained **only if the density of baryonic matter is about 4.0% of the total mass/energy density of the universe**

Big Bang Nucleosynthesis

The expected abundance of light nuclear elements are calculated as a function of baryon density

Compared to observed abundance

% of baryon density ≈ 0.043



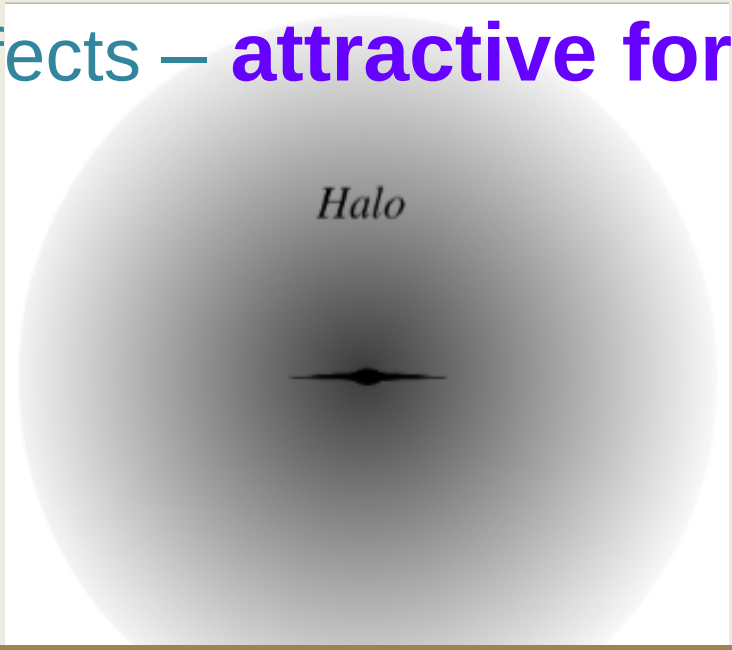
DARK MATTER

Matter, observed thru their grav effects – **attractive force**

1930's Zwicky:
Coma cluster of galaxies
1970's Rubin & Ford:
galactic rotation curves

Gravitational masses of galaxies are generally **five times as large** as the masses in their stars and gases (baryonic matter)
i.e., 80% of matter is dark

The vast majority of the matter in the universe is some unknown and invisible *collisionless* material

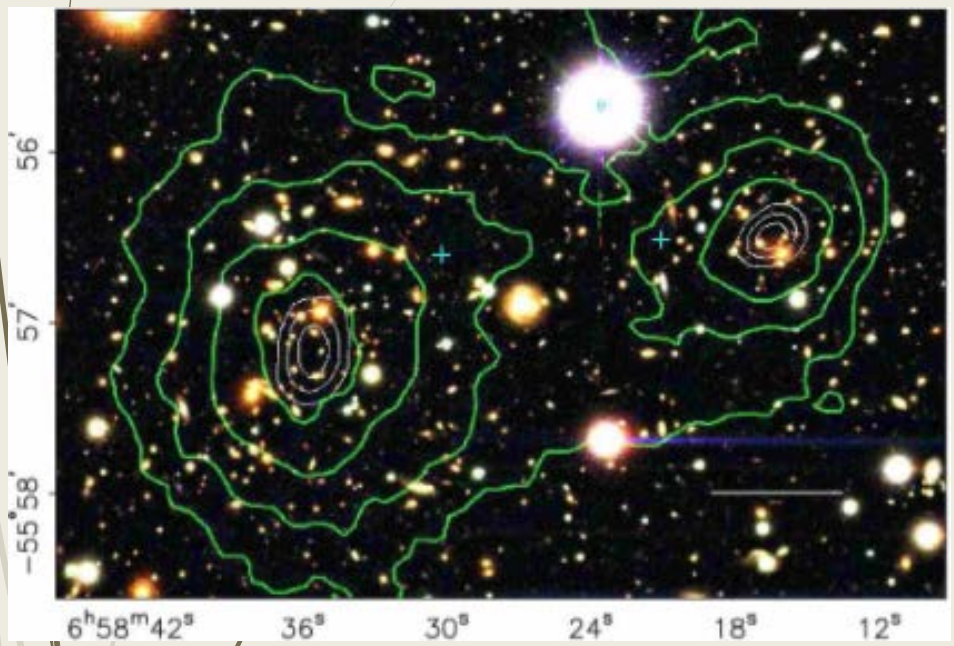


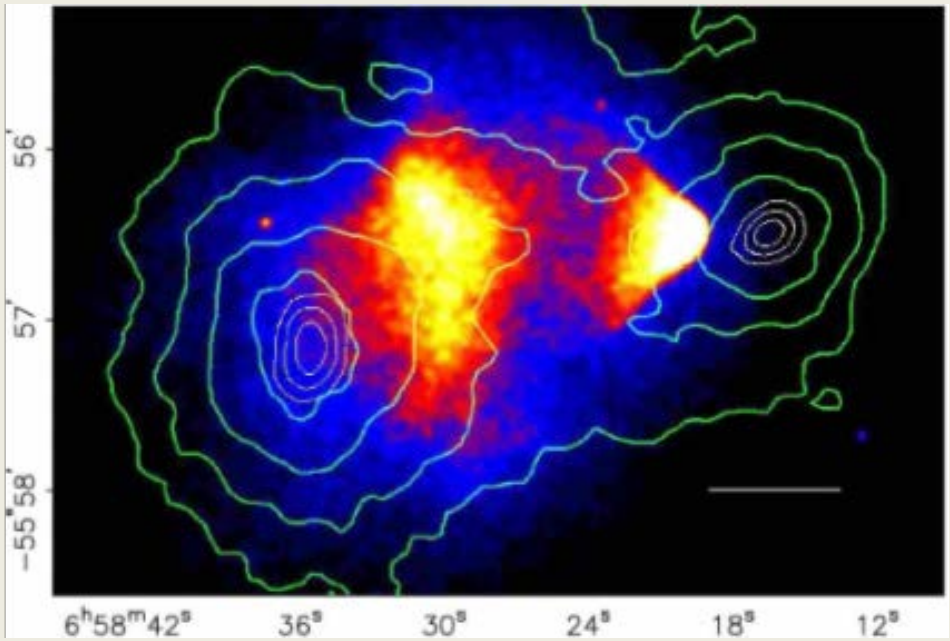
Cosmic structure formation →
~~Hot~~ DM *vs* Cold DM

Dark matter inevitable?
May be Law of gravity needs to be changed for distant cosmos?
May be the 2 comp matter (BM+DM) assumption is incorrect?

Bullet Cluster resulting from **two merging clusters**

As direct proof of two matter components, one being collisionless, ie, DM effects not due to altered gravity





Gravitational lensing result (contours) showing dominant mass distribution

HST picture showing galaxies (BM) mostly follow gravitational potential Wells (due to DM)

Chandra X-ray picture showing that the dominant baryonic component (plasma) separated from the main mass distribution

The physical origin of DARK MATTER?

exotic form of matter never found on Earth, in the stars, etc.
DM = some unknown elementary particle that was produced in huge amounts in the Big Bang

Favorite candidate: weakly interacting massive particles

CDM = WIMP predicted by some yet-to-be-proven particle physics theories
neutralinos of **supersymmetry** ?….

***active programs** searching for CMD particles*:

- high energy accelerators (LHC, …)
- gamma ray satellite telescopes (GLAST,…)
- in deep-underground labs.

Today's main topic

DARK ENERGY

Observed thru its gravitational effect:
repulsive force

Definition, observational evidence, phys origin

General Relativity
Einstein's
theory of gravity

General relativity

SR: *Physics arena = 4D spacetime*
GR: *gravity = structure of spacetime*

GR = classical field theory of gravity

source → ***field*** → ***test body***

field eqn eqn of motion

GR: gravity *field = curved spacetime*

- Spacetime tells matter how to move
- Matter tells spacetime how to curve

GR eqn of motion = *geodesic eqn*
GR field eqn = *Einstein eqn*

GR: *gravity = structure of spacetime*

mass/energy bring about curvature of ST

GR field eqn = *Einstein equation*

$$G_{\mu\nu} = g_N T_{\mu\nu}$$

geometry *mass/energy*

It reduces to Newton's eqn, in NR weak field limit

$G_{\mu\nu}$ = curvature tensor
2nd derivatives of the metric $g_{\mu\nu}$

$T_{\mu\nu}$ = energy momentum tensor

GR = framework of cosmology

dynamic spacetime => *e.g.* expanding univ

grav attraction => decelerating universe ?

Basic working hypothesis: Cosmological Principle

Homogeneous & isotropic space filled with a *cosmic fluid*

$T_{\mu\nu}$ in terms of mass density and pressure (ρ, p)

Gen Relativity: geometry ⟺ avg mass content

"Critical density" $\rho_{crit}c^2 \approx (2.5\times10^{-3}\text{eV})^4/(\hbar c)^3$ as *the standard*:

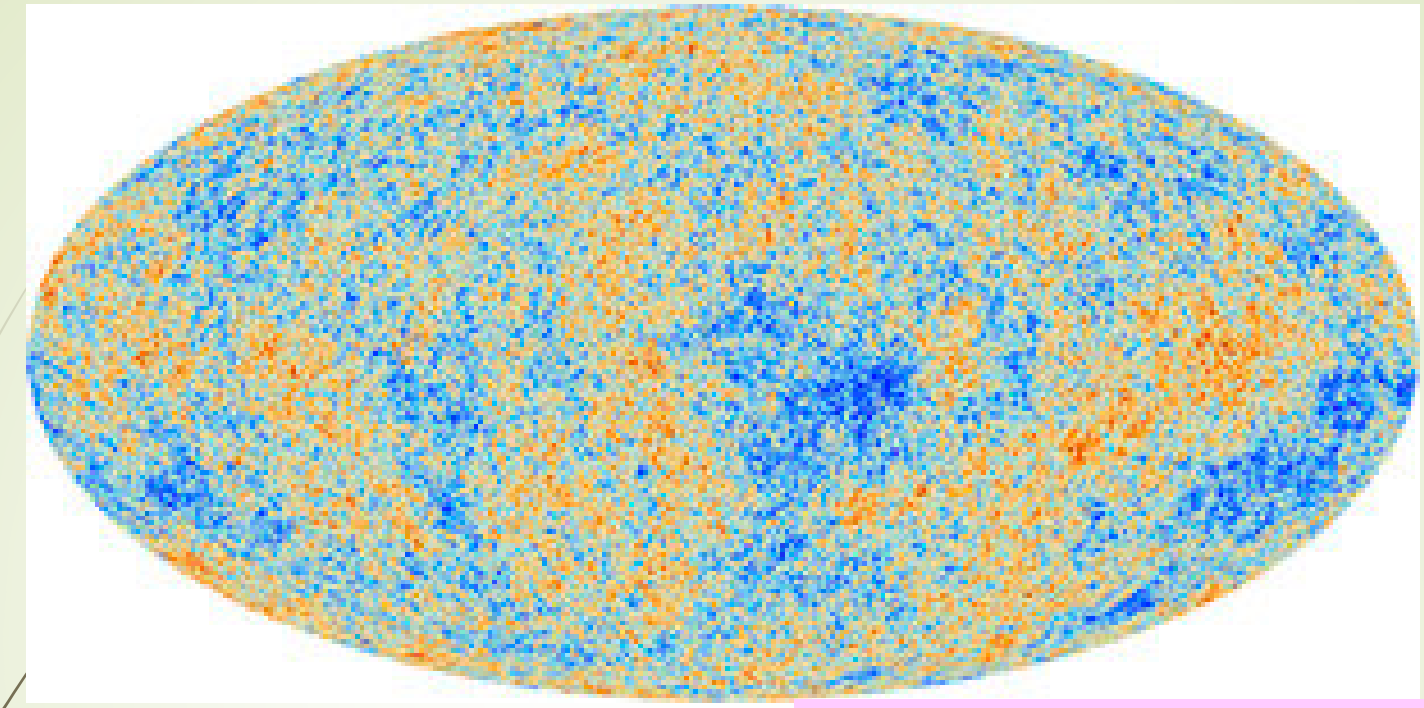
$\Omega = (\rho/\rho_{crit})$, $\quad \Omega_{BM} = (\rho_{BM}/\rho_{crit}) \approx 0.04$

$\Omega > 1$ $\rho > \rho_{crit}$	$\Omega = 1$ $\rho = \rho_{crit}$	$\Omega < 1$ $\rho < \rho_{crit}$
• Closed Univ • pos. curv.	• Flat Univ • zero curv.	• Open Univ • neg. curv.

($\Omega_{BM} < 1$) negatively curved universe?

checking geometry…

Cosmic Background Radiation = “after-glow” of big bang



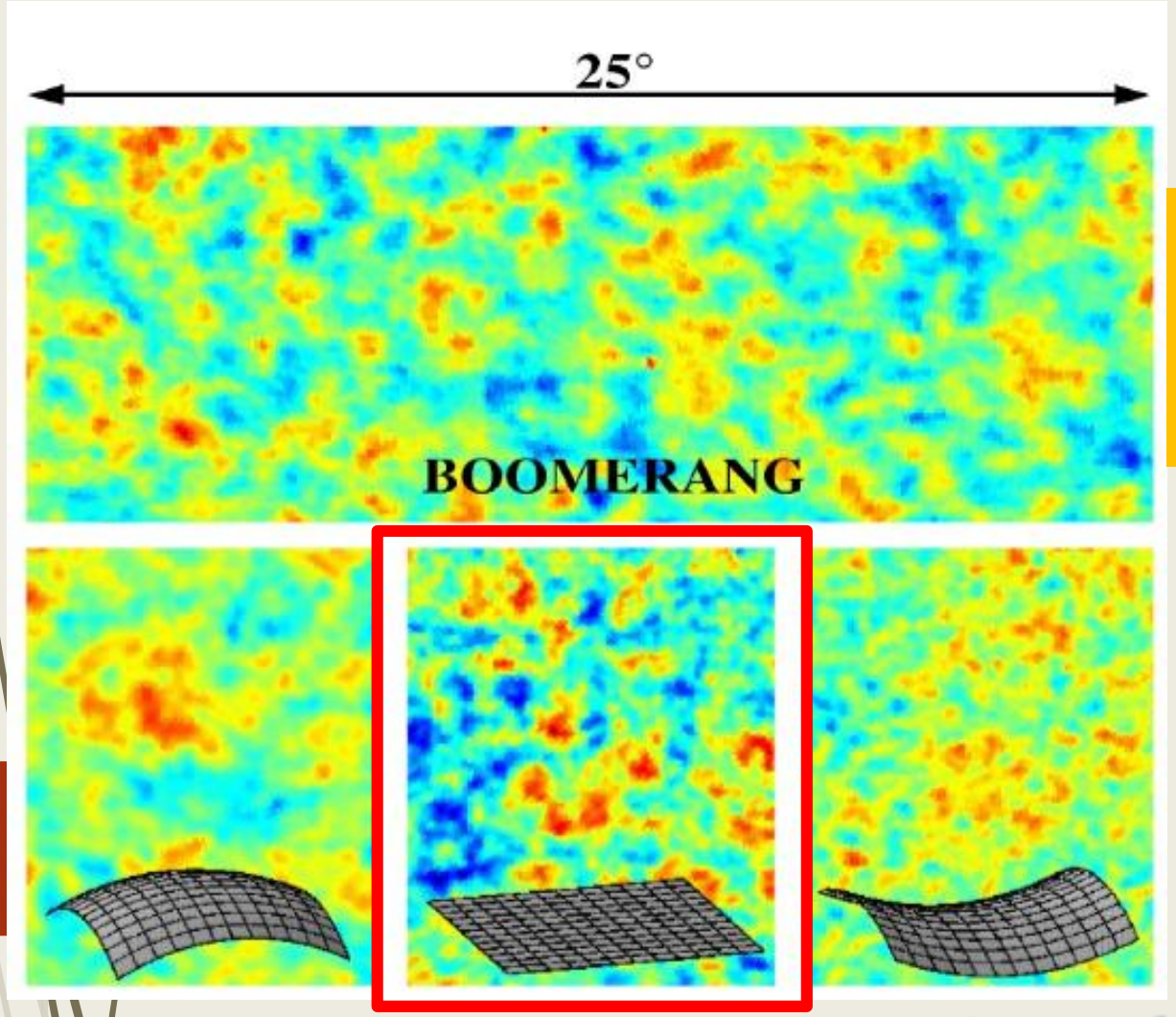
CBR = Photons from “the last scattering”-- as all charged particles were bound into neutral atoms & U became transparent to photons

The irregularity reflects matter density fluctuation (primordial quantum effect?) = seeds of structure formation in later stages of cosmic evolution

Extraordinarily small 10^{-5} temperature irregularity confirming *“cosmological principle”*

Cosmic Background Radiation

anisotropy, 1st observed in 1990's



Anisotropy of CBR =
baby picture of the universe
(If the universe were 100 yr-old, this is its 1-day-old picture)

The geometry of the U can be deduced from the observed pattern of anisotropy as it had traveled thru almost the entire age of the U

Observation: geometry of the universe is flat

CMB anisotropy measurement showing a **flat** spatial geometry

GR: *a **flat** universe must have density* $\rho = \rho_{crit}$

namely, $(\Omega = 1) >> (\Omega_{BM} = 0.04)$

a "missing energy problem"

Exotic matter/energy to make up $\Omega = 1$?

Even with dark matter, $\Omega_{BM} + \Omega_{DM} = \Omega_M = 0.25$ (< 1)

Cosmological difficulties in mid 1990's

Missing energy problem $\Omega = \Omega_M = 0.25\ (< 1)$

and

Cosmic age problem $\Omega = \Omega_M$ *age of flat U too short*

generally accepted solution at present time:

We live in a ***Dark Energy*** **(Λ) dominated universe**

DE is the missing energy $\Omega = \Omega_M + \Omega_\Lambda = 1$?

DE leads to an *accelerating universe*

slower expansion in the past $\rightarrow$ a longer age for the universe

DARK ENERGY = a uniform background that is accelerating the expansion of the universe

The name "dark energy" is neither descriptive nor accurate !

For example, *black holes, neutrinos*,… are all "dark" and carry energy, but they are NOT counted as "dark energy" because they do not give rise to repulsion

Proper definition:

"Equation of state": $p = w\rho c^2$, examples: $w_M=0$, $w_R=1/3$

Dark Energy = system having negative pressure $w < -1/3$

leading to gravitational repulsion

The simplest form of dark energy…."the cosmological constant"

Einstein:

GR naturally has such a feature

The Cosmological Constant

= the simplest form of "dark energy"

$p = -\rho c^2$ namely, $w = -1$

Einstein's original motivation: to obtain a "static universe" solution by a modification of his GR equation
(repulsion to counteract the familiar attraction)

Introducing the cosmological constant

Einstein's eqn $G_{\mu\nu} = g_N T_{\mu\nu}$ *math property*

geometry *matter/energy*

NR weak field limit, it reduces to Newton's equation

Einstein: *a new term in geometry side* $G_{\mu\nu} - \Lambda g_{\mu\nu} = g_N T_{\mu\nu}$

in order **not** to contradict the Newton's law,
the new term Λ must be extremely small at normal distances
but, ***important on the cosmic scale***

Hence the name: "the cosmological constant"

For easier physical interpretation of Λ

Move it, from the geometry side, to the energy side

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = g_N T_{\mu\nu}$$

$$G_{\mu\nu} = g_N(T_{\mu\nu} + g_N^{-1}\Lambda\, g_{\mu\nu}) = g_N(T_{\mu\nu} + T^{\Lambda}_{\mu\nu})$$

$T^{\Lambda}_{\mu\nu}$ = "the energy-momentum tensor of the vacuum"

Given $g_{\mu\nu}$ can interpret $T^{\Lambda}_{\mu\nu}$ in terms of ρ_Λ, p_Λ

Energy density $\rho_\Lambda c^2 = \Lambda / g_N$ = *constant*

Pressure $p_\Lambda = -\rho_\Lambda c^2$ = *negative* ***(w = -1)***

GR: not only mass, but also pressure = source of gravity

source $\rho \rightarrow \quad \Delta\phi = g_N \rho \quad \rightarrow \quad -1/r^2$ *force*

$\rho + p \rightarrow \quad \Delta\phi = g_N (\rho + 3p/c^2)$

Negative pressure => gravitational repulsion

$(\rho + 3p/c^2) < 0$ (namely, $w<-1/3$) => repulsion

For a Λ–dominated system

$F_\Lambda = +\Lambda\, r$ **instead of the familiar** $-1/r^2$ **force**

a repulsive force that increases with distance

…can be relevant on the cosmic scale

To recapitulate :

Dark energy = energy that brings about gravitational repulsion

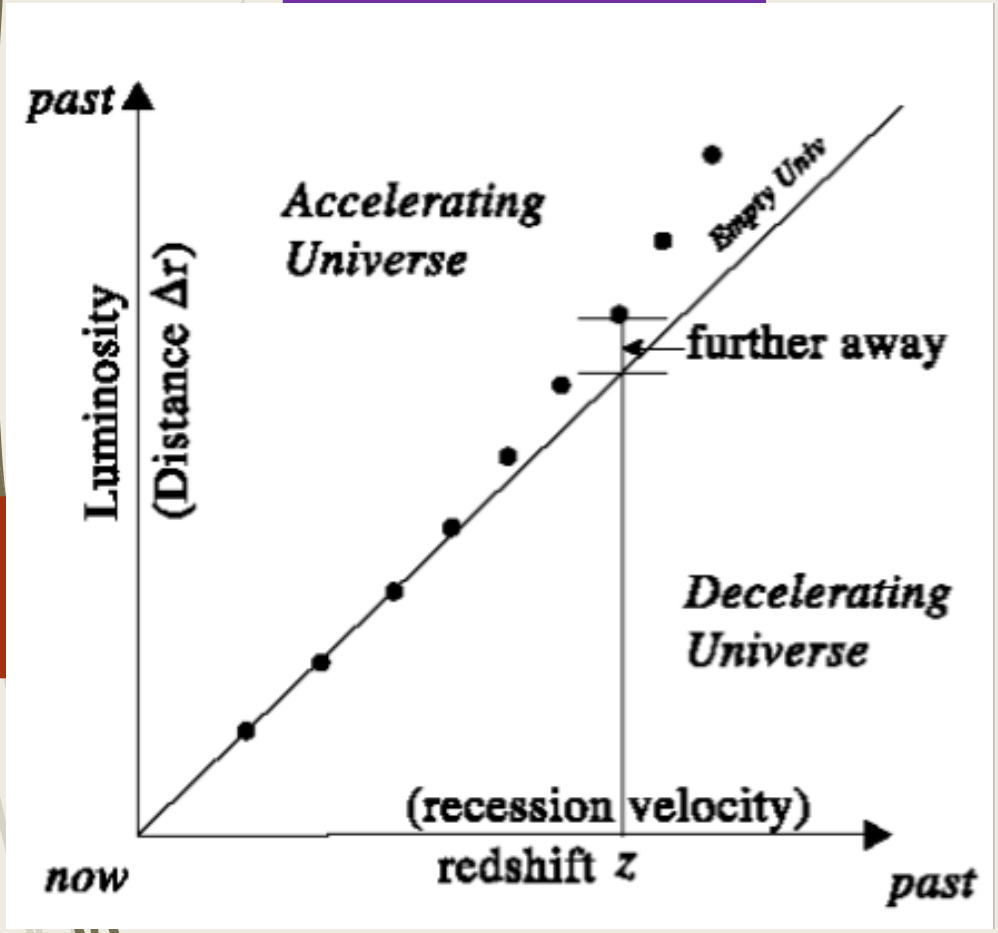
The simplest DE = cosmological constant
Their presence can counteract the usual gravitational attraction

Instead of a decelerating universe
a dark-energy-dominated universe
has an accelerated expansion
An accelerating universe

Evidence for an accelerated expansion?

Examine **the expansion history** over cosmic time scale

Hubble diagram



For an **accelerating universe**, expansion was slower in the past (smaller velocity for a given R). The Hubble curve **bends upwards**. A light source at given redshift on the ***Hubble curve***, would be further out in distance (curve up, i.e. *dimmer*) than anticipated.

To see the bending of the *Hubble curve*, *need to measure objects across enormous distances.* Just such 'standard candles' have been found:***Type-1a Supernovae***

Surprising discovery

two teams announced in 1998:

►Supernova Cosmological Project
(LBL: S.Permutter et al.)

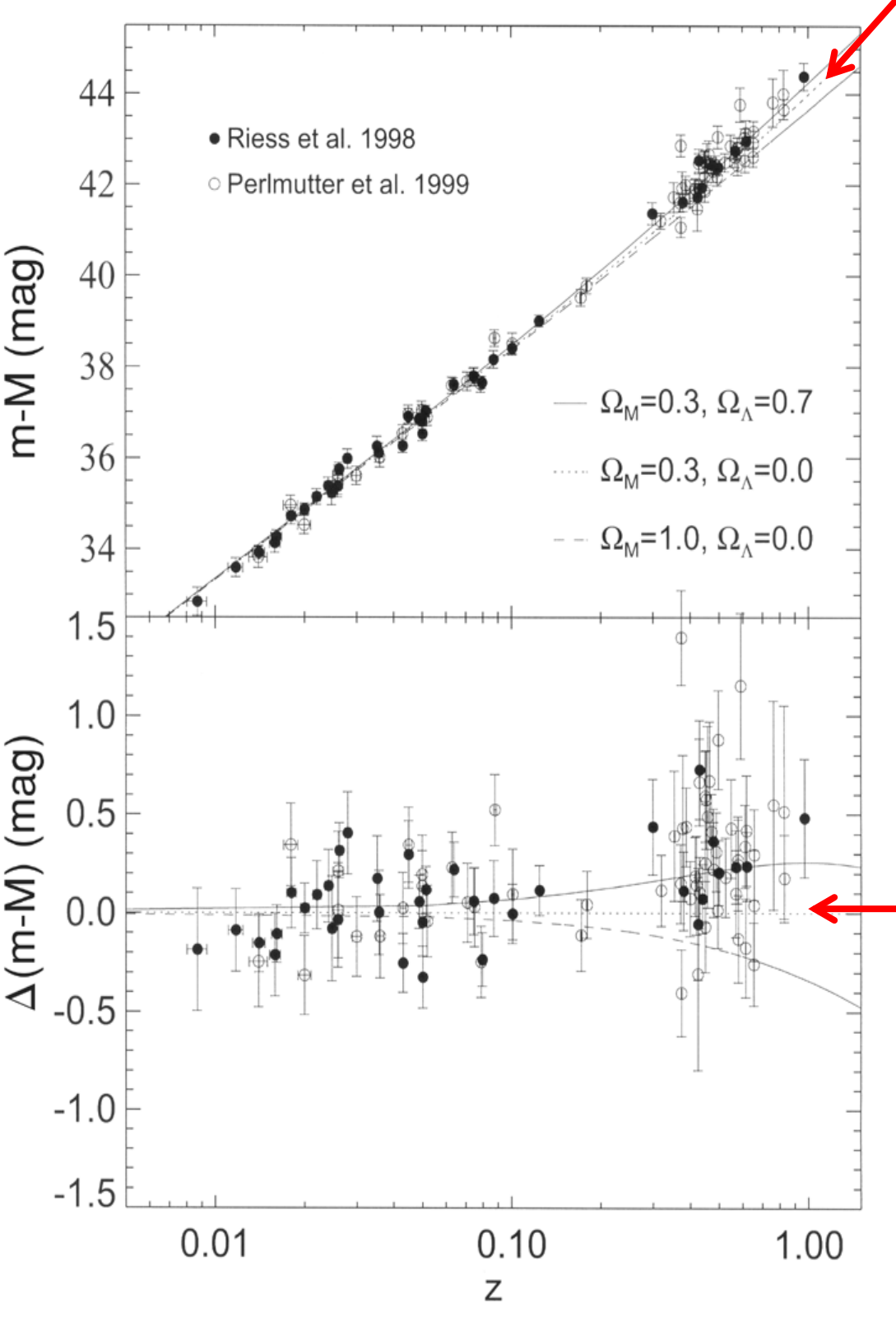
►High-z Supernovae Search Team
(Australian/American: A. Reiss et al.)

Distant SNe ≈25% less luminous than expected

Remarkable achievement

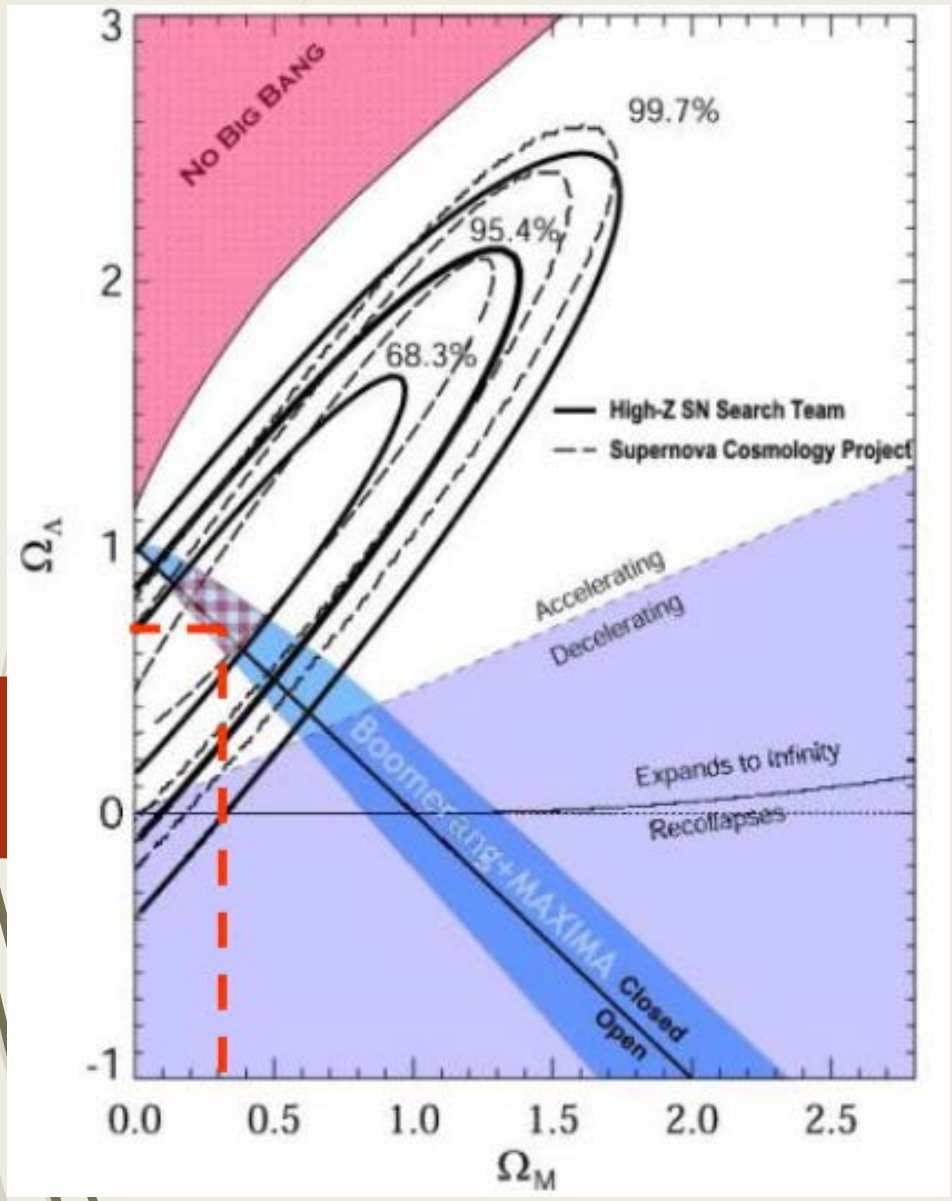
Involves catching the light of exploding stars **emitted billions of years ago**

… and their intrinsic luminosity understood



Ω_M ***decelerated*** *expansion, bends Hubble curve* ***down***

Ω_Λ ***accelerated*** *expansion, bends Hubble curve* ***up***



Just the missing ingredient for a concordant cosmology

Solving the missing energy problem

$$\Omega_M + \Omega_\Lambda \approx 0.25 + 0.75 = 1.0$$

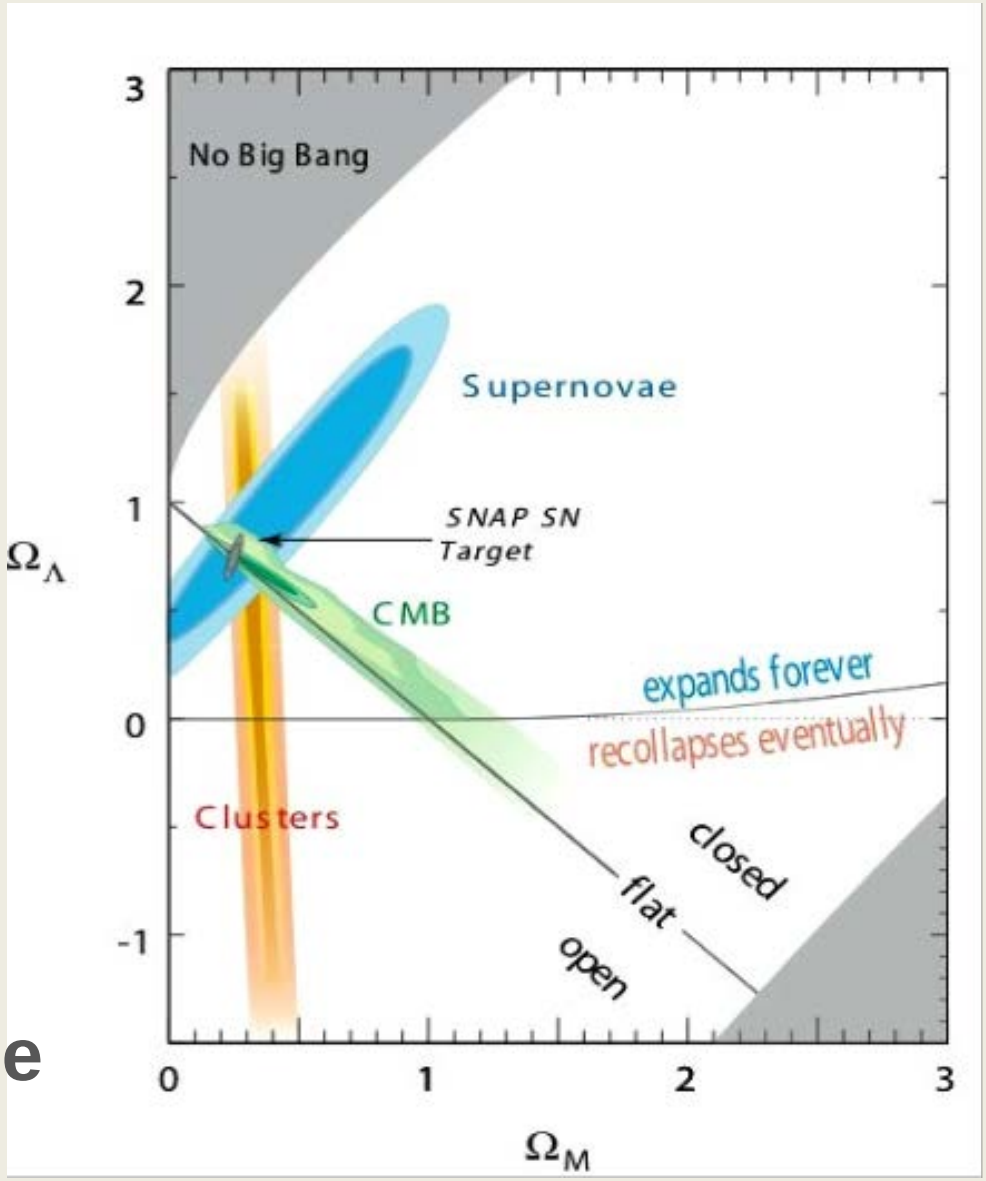
Solving the cosmic age problem

► $t_0 \approx 14$ Gyr

Matter/energy content and geometry of the universe have been measured in several ways:

- **Supernovae Hubble relation** between recession velocity and brightness of Sne
- **CMB** anisotropy = small irregularities in the background radiation left over from the Big Bang
- **Clusters** = large-scale distribution of galaxies

3 types of estimates all agree



Ordinary **BARYONIC MATTER** $\Omega_{BM} = 0.04$

Exotic **DARK MATTER** $\Omega_{DM} = 0.21$

Mysterious **DARK ENERGY** $\Omega_{\Lambda} = 0.75$

$\Omega_{BM} + \Omega_{DM} + \Omega_{\Lambda} = 1$ compatible w/ a flat universe

A model of the universe with these properties does a remarkably good job of **fitting all the observational data**

Hence, the generally accepted view:

ΛCDM = Standard Model of Cosmology

Dark Matter / Dark Energy

Although we may know their properties,
but **don't know their physical origin**

What is Dark Matter?

We have some plausible ideas
e.g. supersymmetric *neutralinos*, etc.

What is Dark Energy?

….. is truly mysterious!

The physical origin of **DARK ENERGY**?

The natural candidate is found in QFT:

quantum vacuum energy $\neq 0$ quantum-fluctuation

Has just the correct physical property of

constant energy density and negative pressure….

However, the estimated size is *completely off*

Too large by 120 orders of magnitude !!

"Cosmological constant problem"

If the currently accepted interpretation of observational data as showing a DARK ENERGY dominated universe **is correct….**

….. to understand Dark Energy is one of the central problems for 21st century physics

Recall the claim: unlocking such secret will illuminate the nature of space and time and connect the quantum with the cosmos