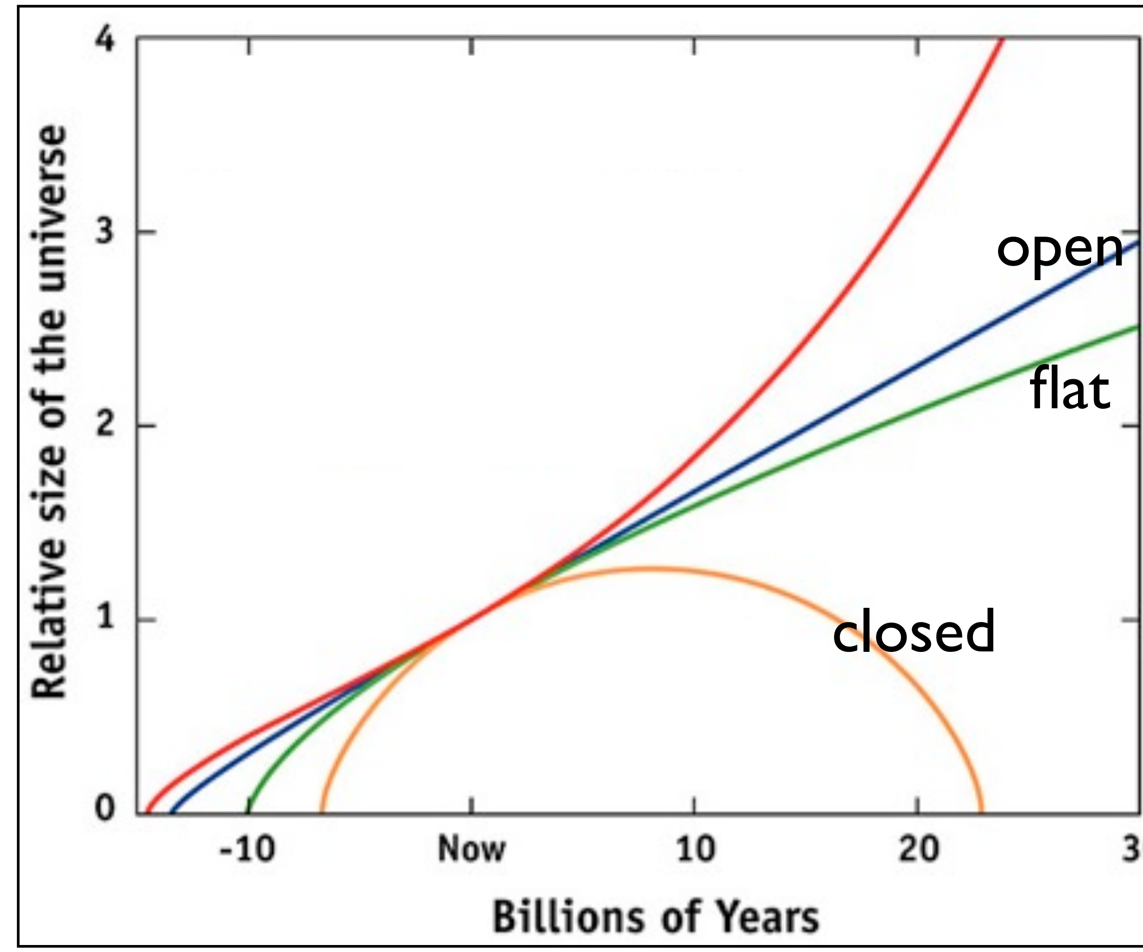
Friedmann's equation for matter-dominated universe

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

$E = 1/2\ m\ v^2 - GMm/r$



$E = 0$, flat, $k = 0$
$E > 0$, open, $k = -1$
$E<0$, closed, $k = +1$

- Expansion of the universe analogous to the motion of a rocket shot upward.
- H_0 fixes the current expansion rate. But need to know matter density to tell the future/past.
- In all cases, cosmic expansion slowed down with time as expected --- like the rocket.

Friedmann's equation for **flat** universe

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} \to 0$$

E = 1/2 m v^2 - GMm/r = 0

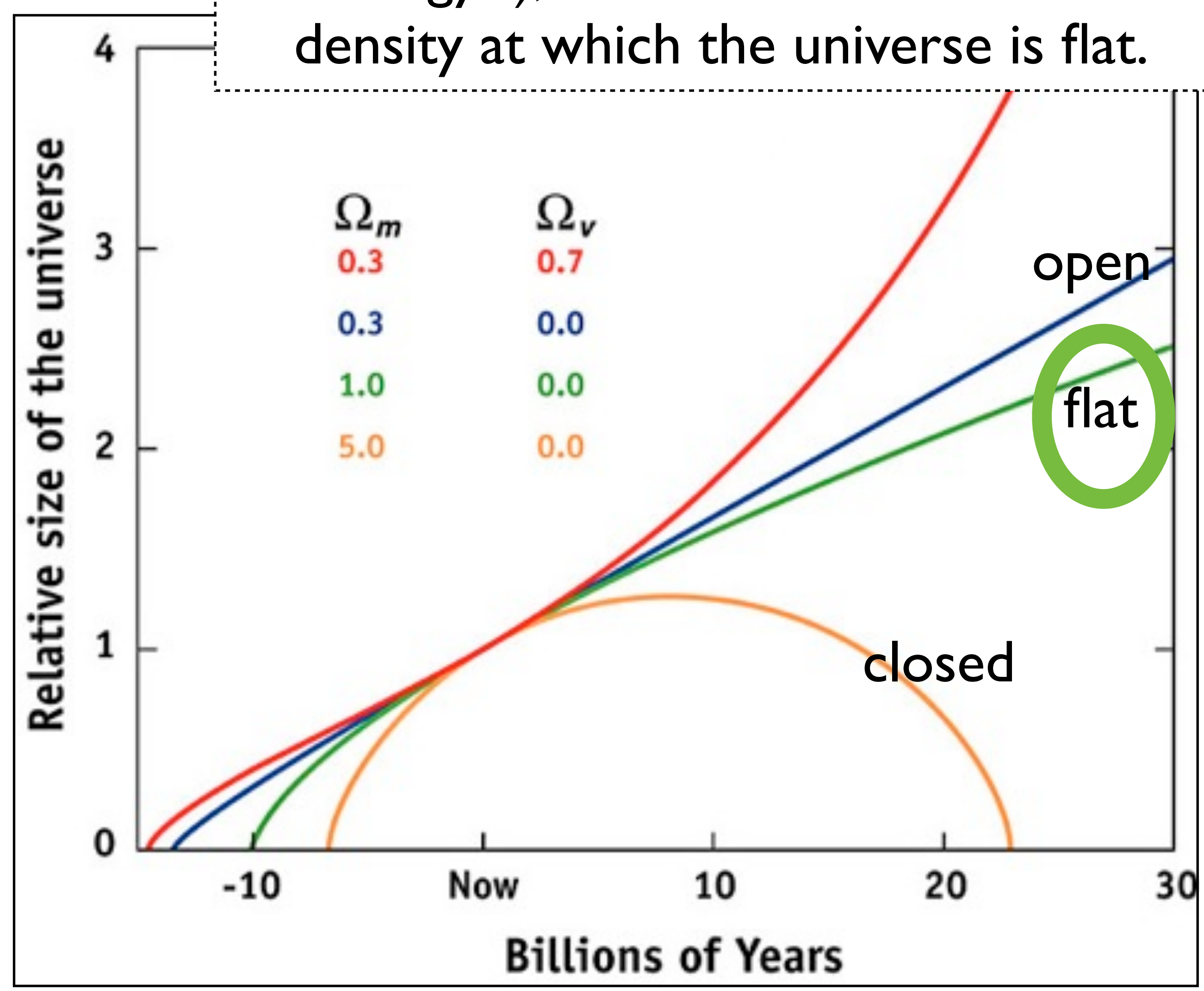
we define $\rho_{\rm crit} \equiv \frac{3H^2}{8\pi G}$

as universe ages, expansion just so that

ρ = $\rho_{\rm crit} \equiv \frac{3H^2}{8\pi G}$

at all times

Critical Density -- in a universe dominated by matter (no radiation, dark energy...), there exists a threshold density at which the universe is flat.



Defining Ω_m: gravity against expansion

Friedmann's equation $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$

turns into

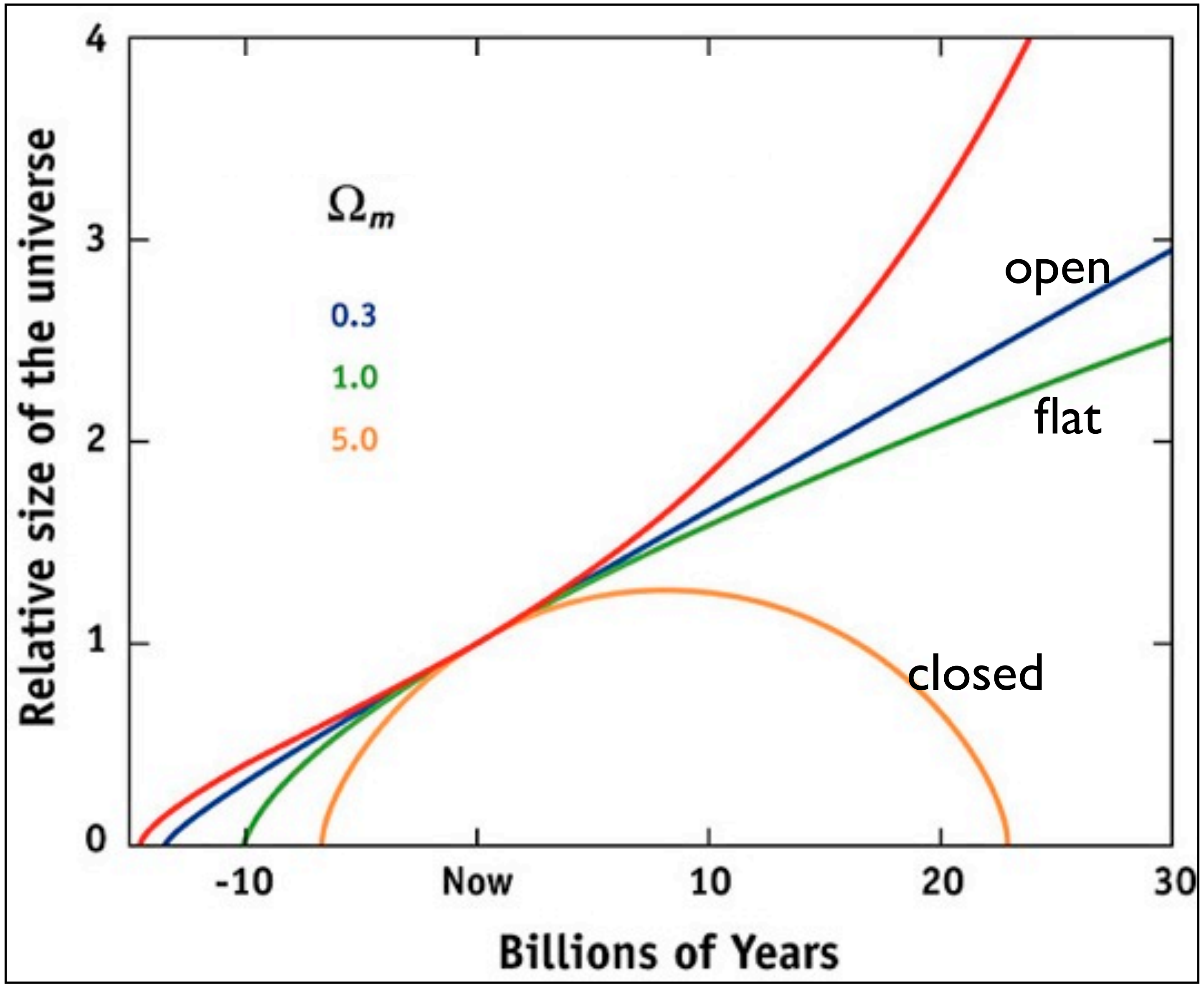
$$\boxed{\Omega_m \equiv \frac{\rho}{\rho_{\rm crit}}} = 1 + \frac{kc^2}{a^2 H^2}$$

$\Omega_m < 1$ gravity loses, open
"big freeze"

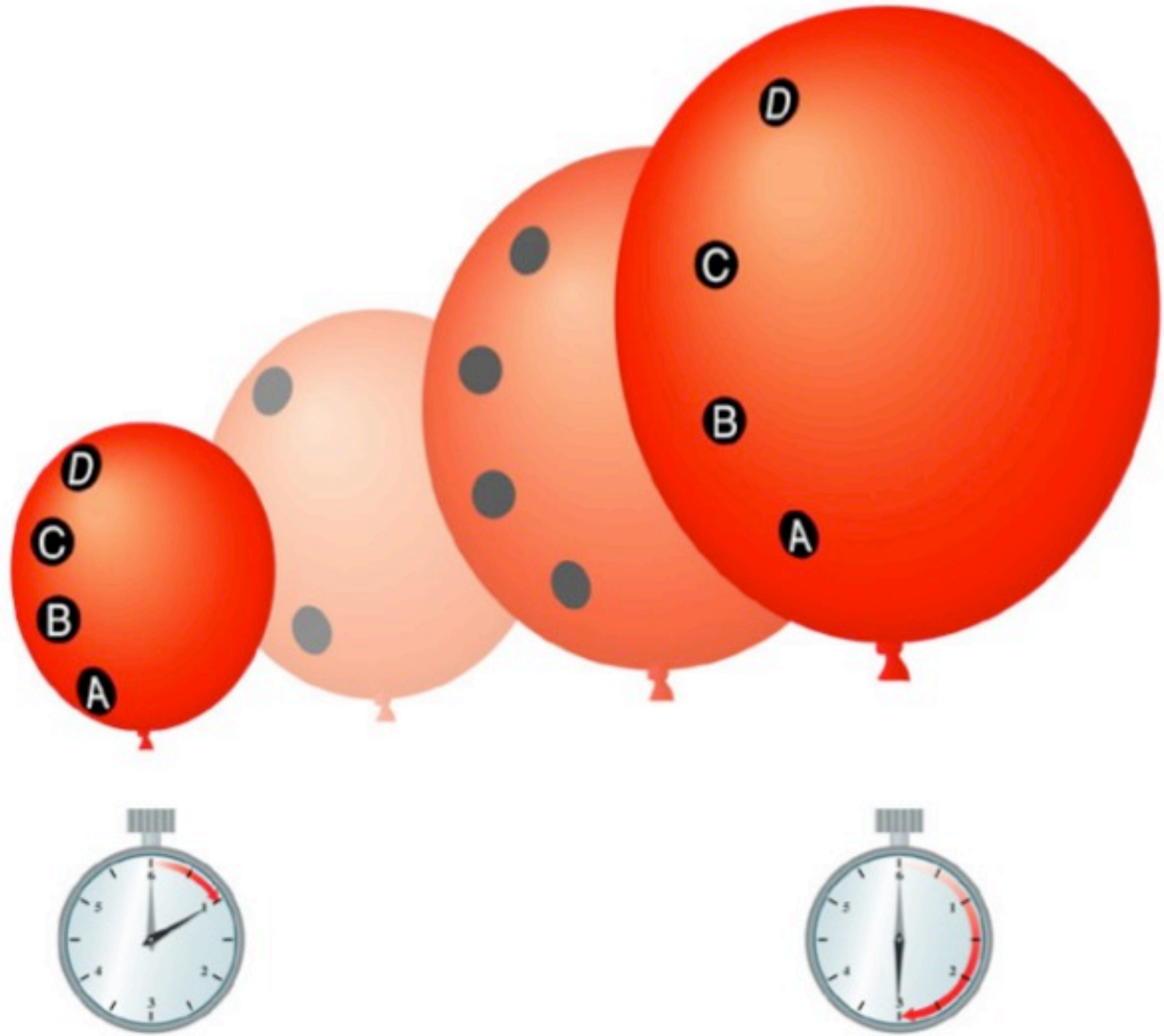
$\Omega_m = 1$ flat

$\Omega_m > 1$ gravity wins, closed
"big crunch"

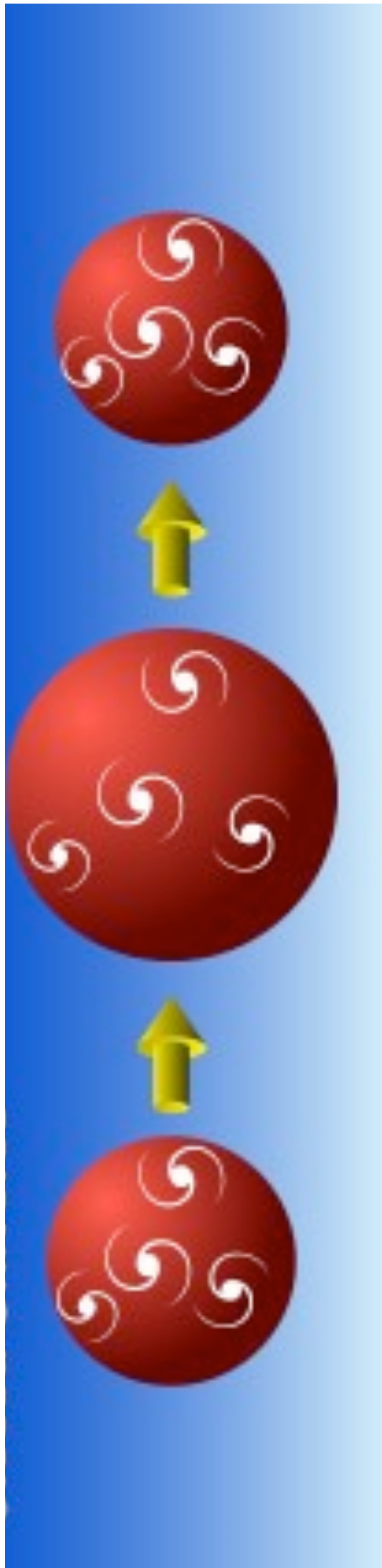
(ignoring dark energy for the moment)



A 2D metaphor for the 3D expansion



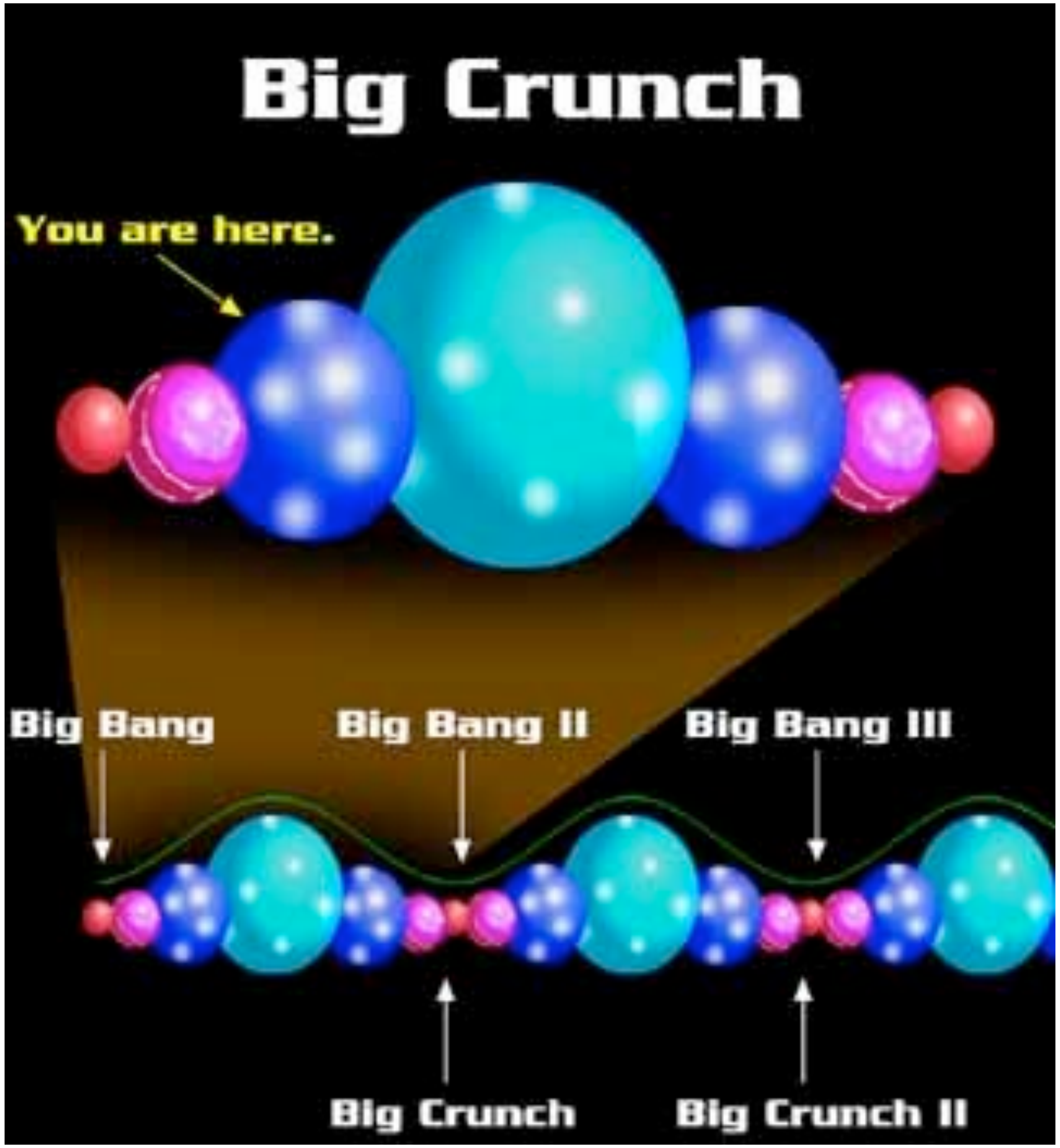
How does it feel to be living in a ... closed universe ($\Omega_m > 1$)



to visualize, we imagine the universe sits on a 2-D balloon

- space and number of galaxies finite
- but no edge. nor centre.
- at some point, your horizon encompasses the whole universe
- light travels along geodesics (great circles), you can see your rear, given enough time.
- but universe will contract, H < 0, big crunch into a single blackhole.

Life after death? Big Bounce?



some suggest that a big crunch may be the seed for the next big bang, so on, and so on.... cyclical universe

How does it feel to be living in an ... open universe

(Ω_m< or = 1)

- space and number of galaxies infinite.
- no edge. nor centre.
- light never returns to same point
- enlargement of your horizon < expansion of space. finally, only one mega-galaxy left visible.
- with time, the universe cools, all stars run out of nuclear fuel and become dark objects (neutron stars, white dwarfs and blackholes), no more light/heat, cold death ("big freeze")

Universe in the far future (Krauss & Scherrer, Sci. American, 2008)

COSMIC MILESTONES

10^{-30} second
Cosmic inflation occurs

100 seconds
Deuterium and helium are created

400,000 years
Microwave background is released

8 billion years
Expansion begins to accelerate

13.7 billion years
Today

20 billion years
Milky Way and Andromeda collide

100 billion years
All other galaxies are invisible

1 trillion years
Primordial isotopes are lost or diluted

100 trillion years
Last star burns out

- future civilization won't discover expansion of the universe
- other galaxies are beyond or approaching horizon, with enormous redshifts
- cosmic microwave background too cold to be observed
- light element ratios lost finger print of big bang
- we live truly in an island universe where all vestiges of the big bang is erased... may come to the wrong idea about the origin of the universe

Show us the number.

Adding up the mass...

$\Omega_m \sim 0.3$, gravity loses, open

Fukugita & Peebles, Astrophysical Journal, 2004

Parameter		Components[a]	Totals[a]
Dark sector:			0.954 ± 0.003
Dark energy		0.72 ± 0.03	
Dark matter		$\boxed{0.23 \pm 0.03}$	
Primeval gravitational waves		$\lesssim 10^{-10}$	
Primeval thermal remnants:			0.0010 ± 0.0005
Electromagnetic radiation		$10^{-4.3 \pm 0.0}$	
Neutrinos		$10^{-2.9 \pm 0.1}$	
Prestellar nuclear binding energy		$-10^{-4.1 \pm 0.0}$	
Baryon rest mass:			$\boxed{0.045 \pm 0.003}$
Warm intergalactic plasma		0.040 ± 0.003	
Virialized regions of galaxies	0.024 ± 0.005		
Intergalactic	0.016 ± 0.005		
Intracluster plasma		0.0018 ± 0.0007	
Main-sequence stars: spheroids and bulges		0.0015 ± 0.0004	
Main-sequence stars: disks and irregulars		0.00055 ± 0.00014	
White dwarfs		0.00036 ± 0.00008	
Neutron stars		0.00005 ± 0.00002	
Black holes		0.00007 ± 0.00002	
Substellar objects		0.00014 ± 0.00007	
H I + He I		0.00062 ± 0.00010	
Molecular gas		0.00016 ± 0.00006	
Planets		10^{-6}	
Condensed matter		$10^{-5.6 \pm 0.3}$	
Sequestered in massive black holes		$10^{-5.4}(1 + \epsilon_n)$	

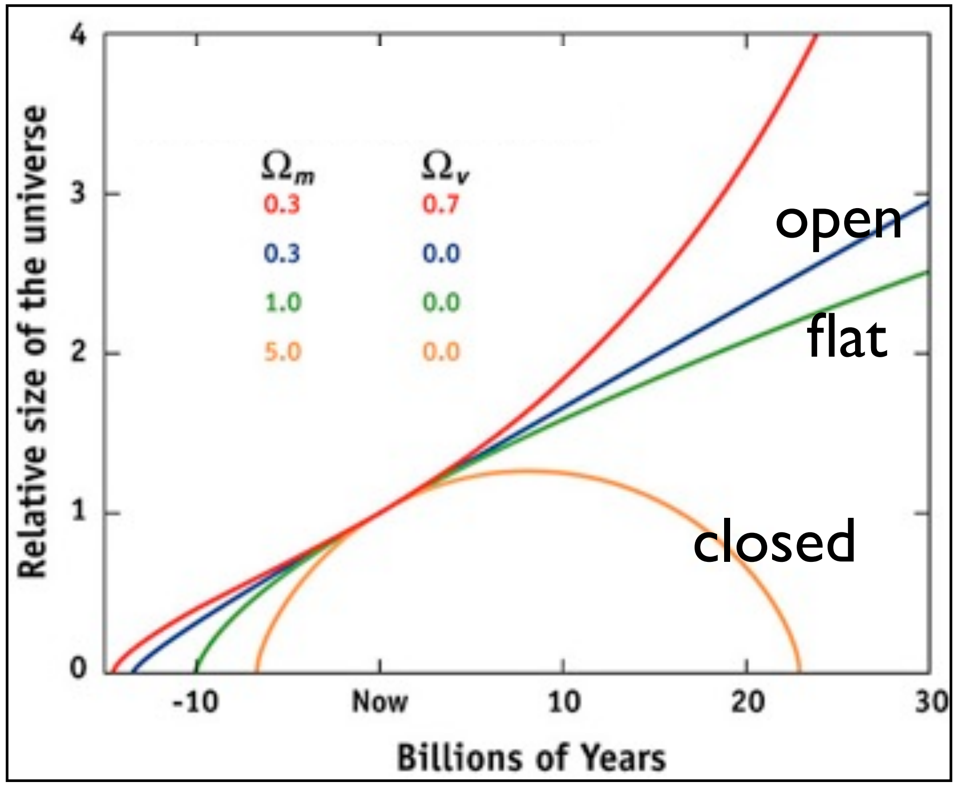
The real density doesn't have to be close to Critical Density

$\Omega_m = \rho/\rho_{crit}$

$\Omega_m << 1$ expansion too fast, prevent galaxies & stars to form

$\Omega_m \sim 1$, permitted range for life

$\Omega_m >> 1$ universe re-collapse too fast before life develops

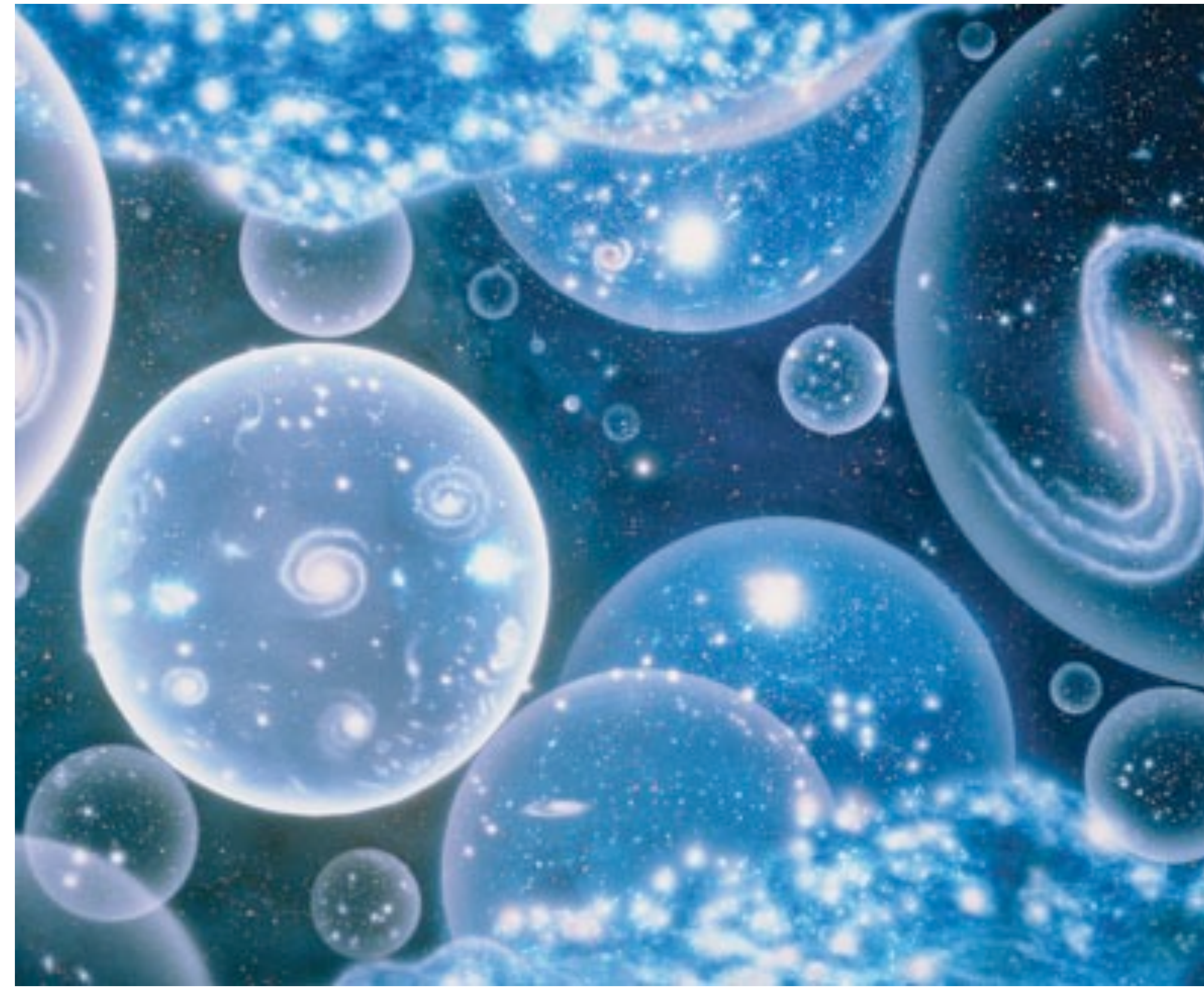


To have Ω_m ~ 0.3 today, Ω_m will have to be within $1/10^{15}$ of unity at one second after big-bang

(Rees 'Just six numbers')

Some other ideas...

Multiverse: our universe is but one of many universes that occur simultaneously, some matter, some anti... they may collide



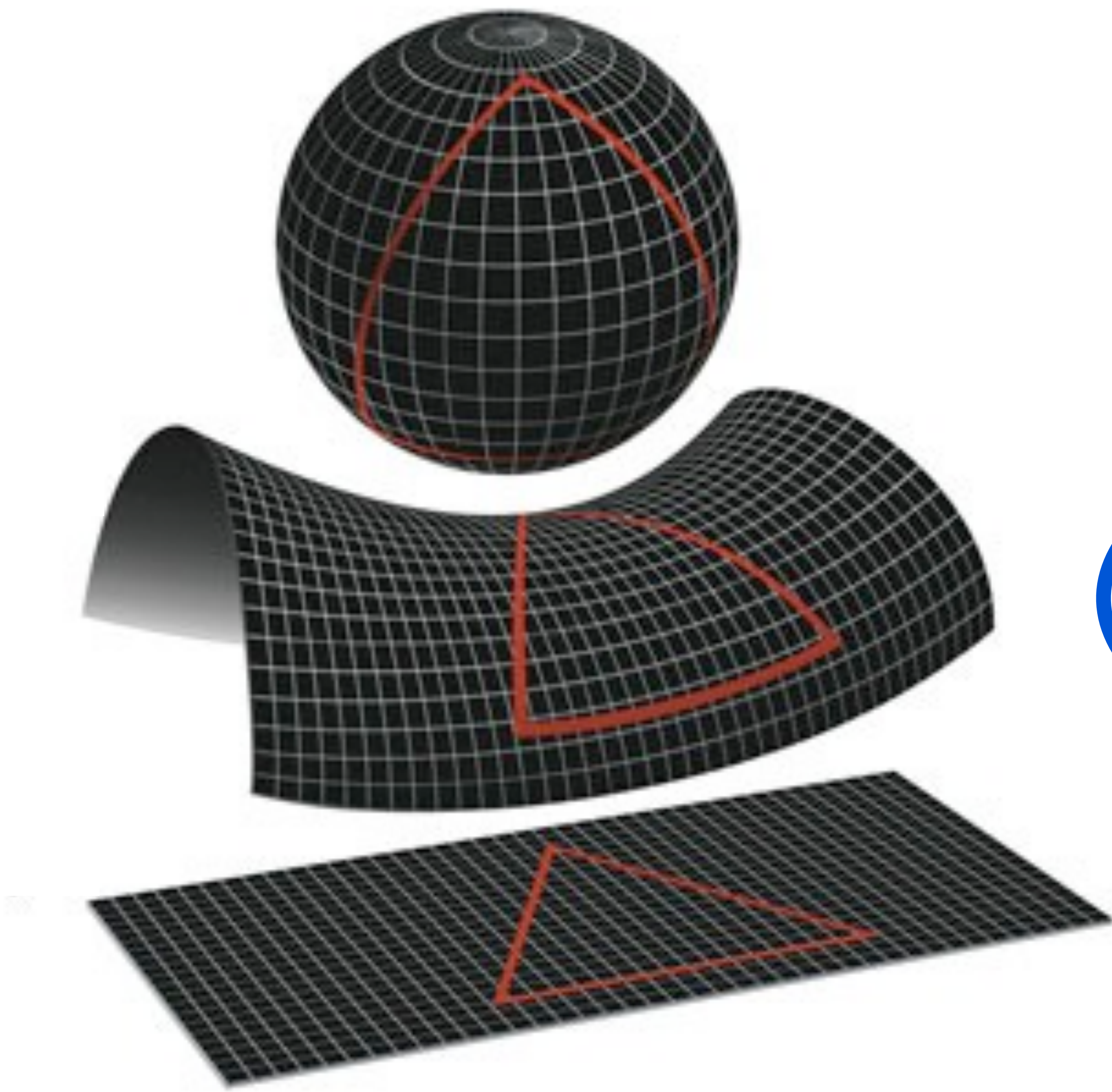
favored by some inflation theorists

fundamental constants in our universe conducive to intelligence, other universes?

density also determines Shape of the universe

$$\Omega_m \equiv \frac{\rho}{\rho_{\mathrm{crit}}} = 1 + \frac{kc^2}{a^2 H^2}$$

$\Omega_m = \rho/\rho_{crit}$



$\Omega_m > 1$, matter curves space closed (positive curvature)

$\Omega_m < 1$, expansion shapes the universe open (negative curvature)

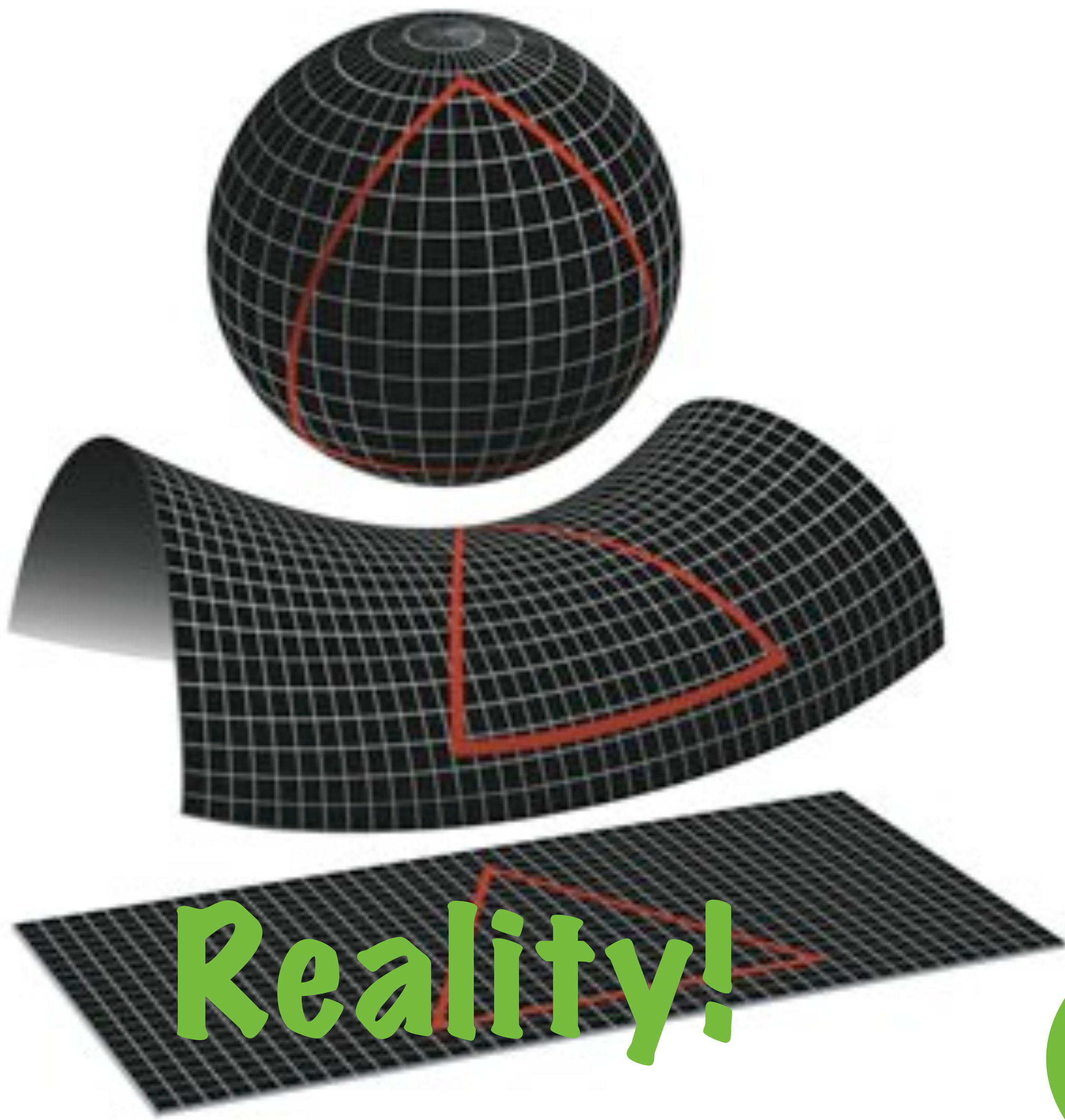
$\Omega_m = 1$, just the right amount of matter, flat geometry (zero curvature)

with ~ 0.3, the universe should be open and negative curvature

density also determines Shape of the universe

$$\Omega_m \equiv \frac{\rho}{\rho_{\rm crit}} = 1 + \frac{kc^2}{a^2 H^2}$$

$\Omega_m = \rho/\rho_{crit}$



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with ~ 0.3, the universe should be open and negative curvature

density + H_0: also determine age of the universe

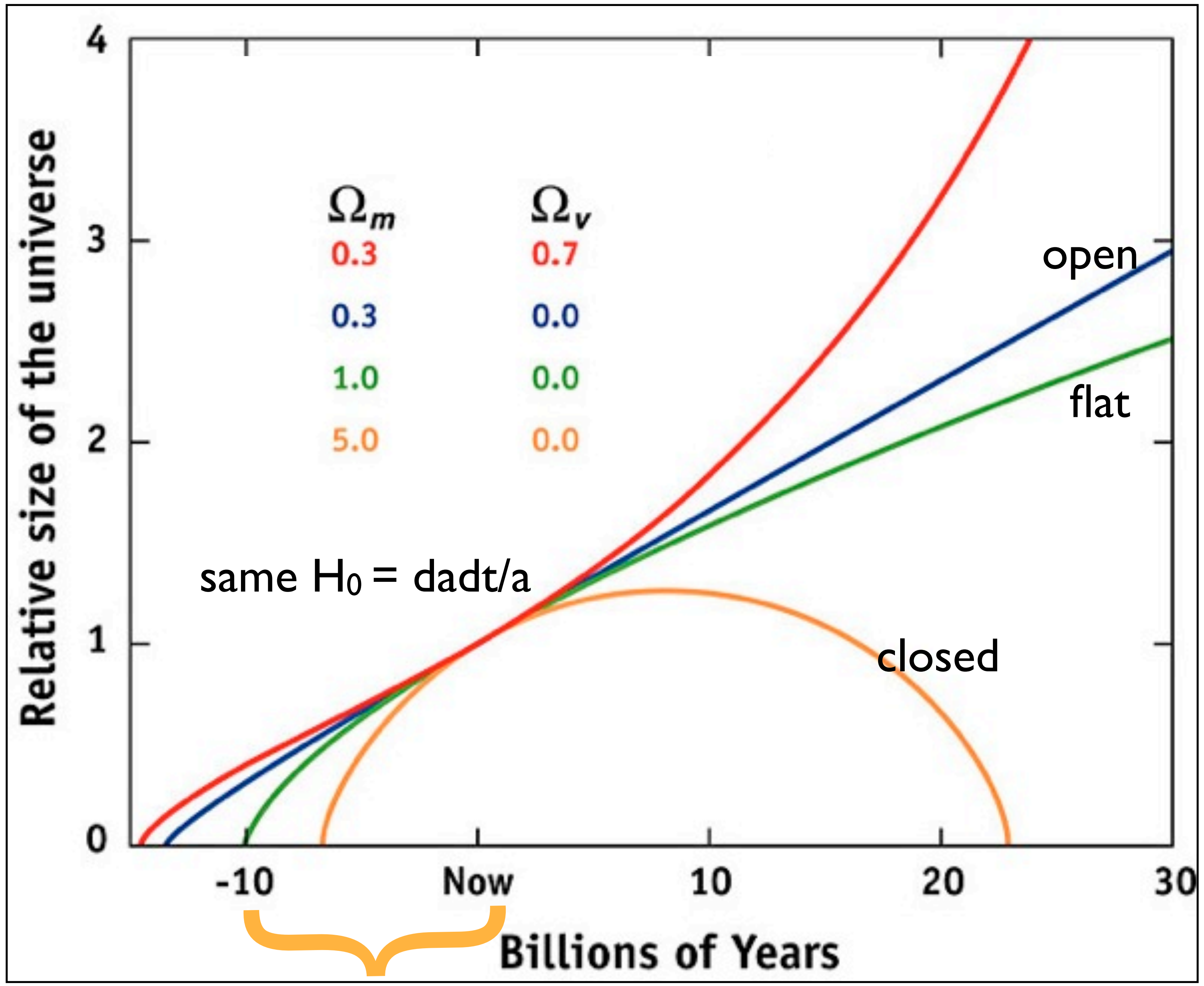
Let $t_{Hubble} = H_0^{-1} \sim 13.7$ Gyrs

- $\Omega_m > 1$, $0 <$ age $< 2/3 t_{Hubble}$
- $\Omega_m = 1$, age $= 2/3 t_{Hubble} = 9.1$ Gyrs
- $\Omega_m < 1$, $2/3 t_{Hubble} <$ age $< t_{Hubble}$

a denser universe is younger

- $\Omega_m = 0.30$: age = 11.2 Gyrs

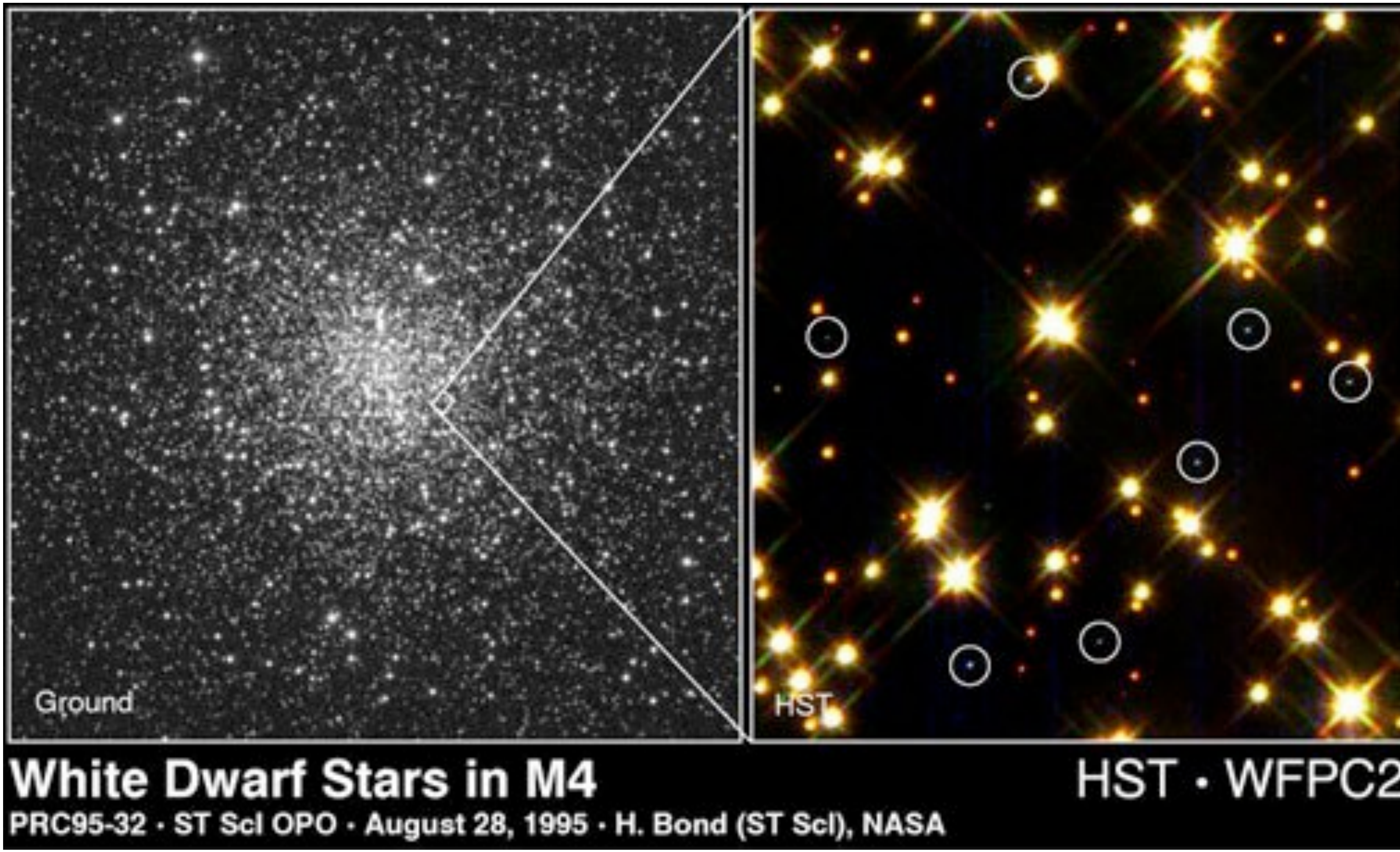
(1 Gyrs = 10^9 yrs)



this age, however, conflicts with the measured age of the universe

observations:

Globular star cluster M4:
age = 12.7 +/- 0.7 Gyrs



The state of our knowledge: 1998

Observations measure: $\Omega_m = \varrho/\varrho_{crit} \sim 0.3$

Theory (using Friedmann eq.) then predicts

1) space is open
2) universe is 11.7 Gys old

Both predictions **conflict** with further observations:

1) space is flat
2) universe is at least 12.7 Gyrs old.

lots of finger pointing
and incriminations....

Where is the mistake?

Enters the Supernova...

Cepheids are not bright enough for galaxies outside ~100 million light years. For those, we use Supernova Type Ia as standard candle.

some stars go supernova at the end of life

sudden brightening (~ the entire galaxy); can be seen to the edge of the visible universe

gradual fading over tens of days; an intrinsically brighter supernova fades slower

a great tool for determining distances!

supernova are rare (~ 1/a few centuries/per galaxy)
one of the most recent ones in our galaxy: AD1054

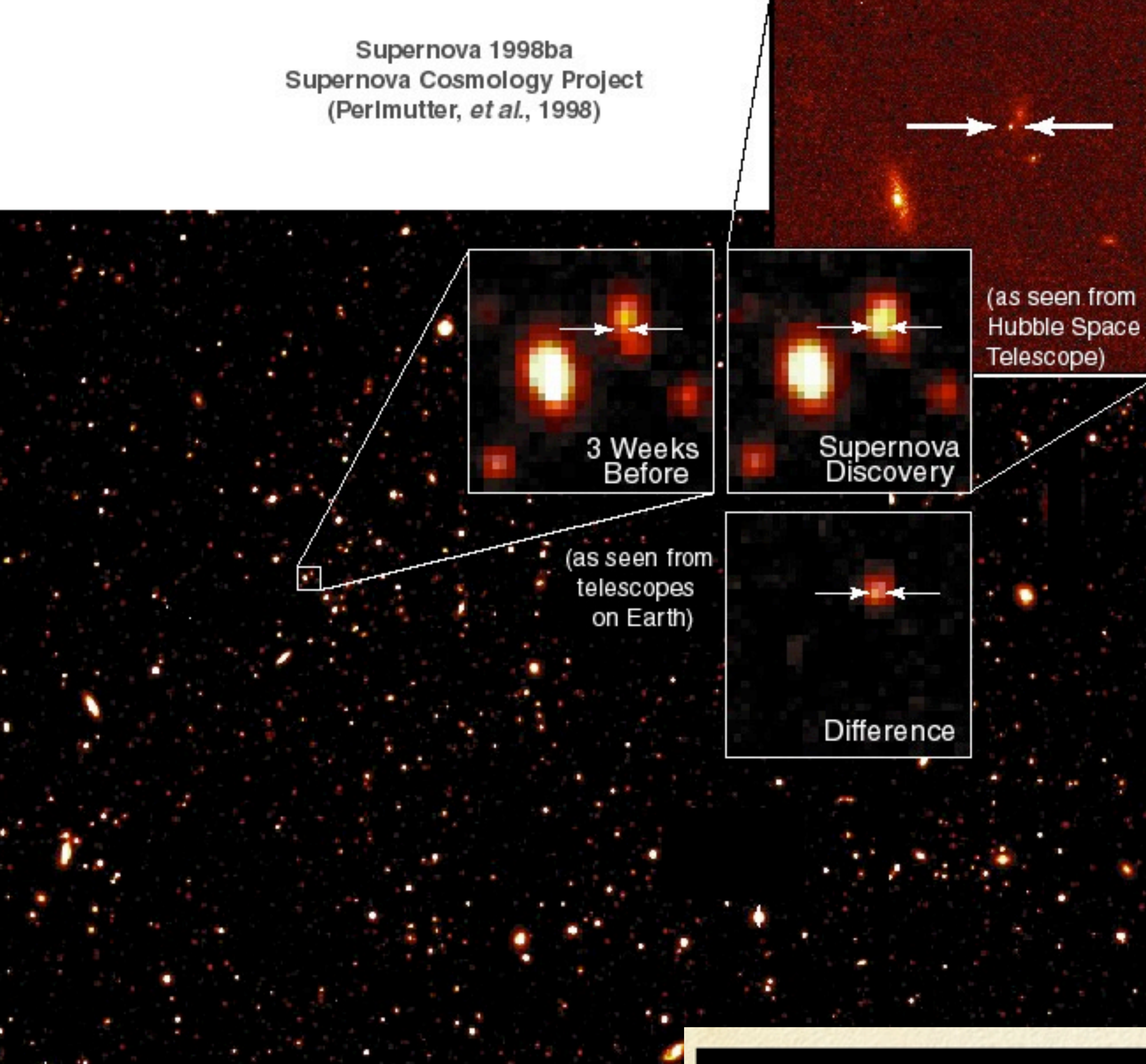
Anasazi petrograph of SN1054?

凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅大星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

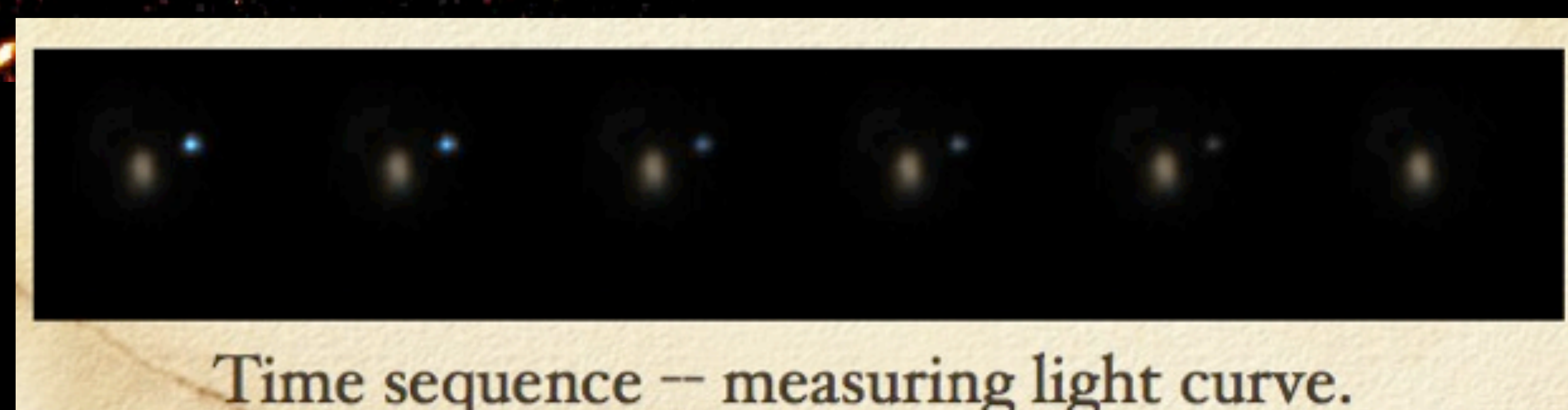
‘Guest star’ supernova 1054

".. In the 1st year of the period Chih-ho, the 5th moon, the day chi-ch'ou, a guest star appeared approximately several inches south-east of Tien-Kuan [Zeta Tauri]. After more than a year, it gradually became invisible .."   It was visible for a month during daylight.

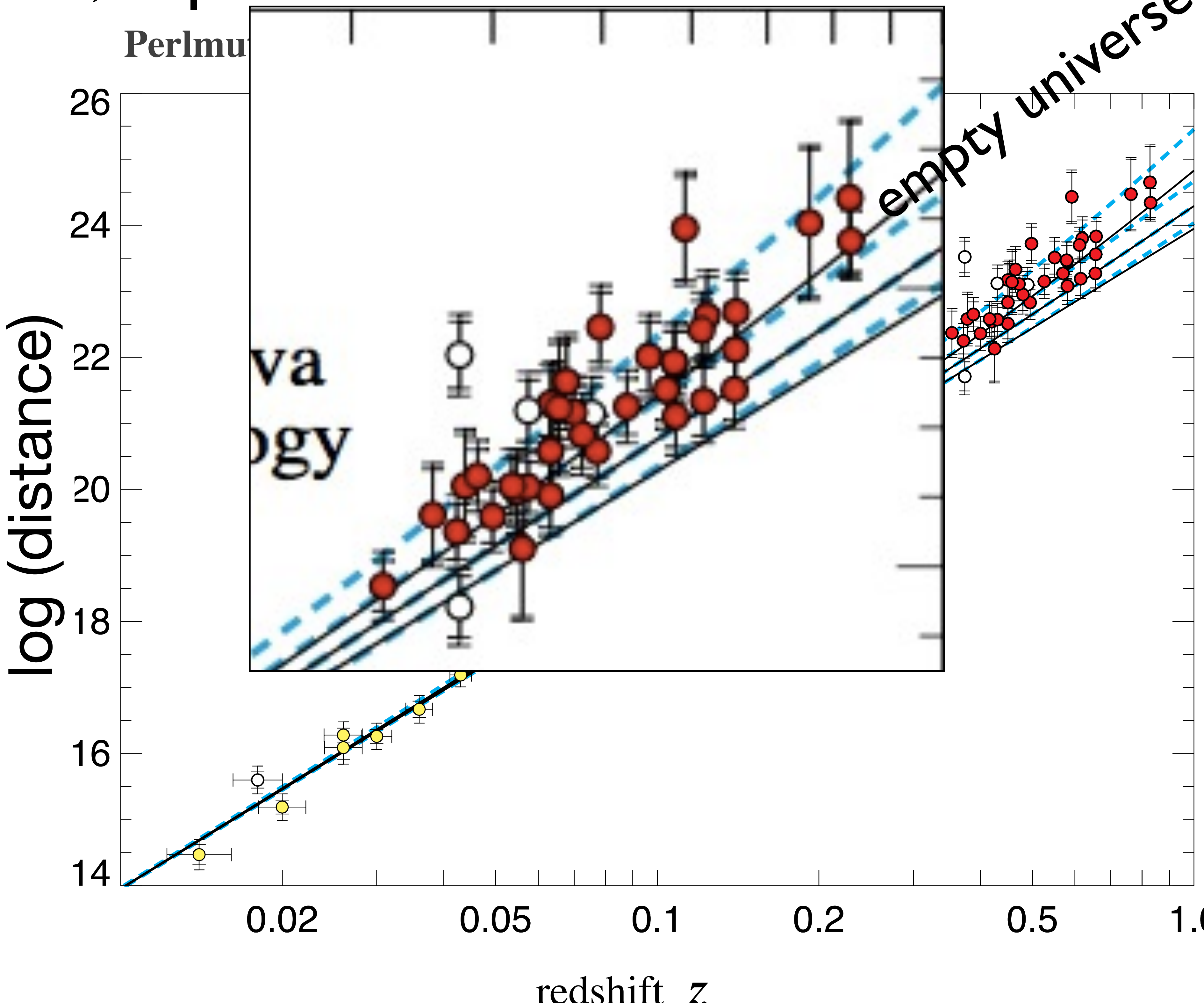


z=0.43

from nearby supernova, we know that longer lasting SN are intrinsically brighter; so by measuring their time sequence....

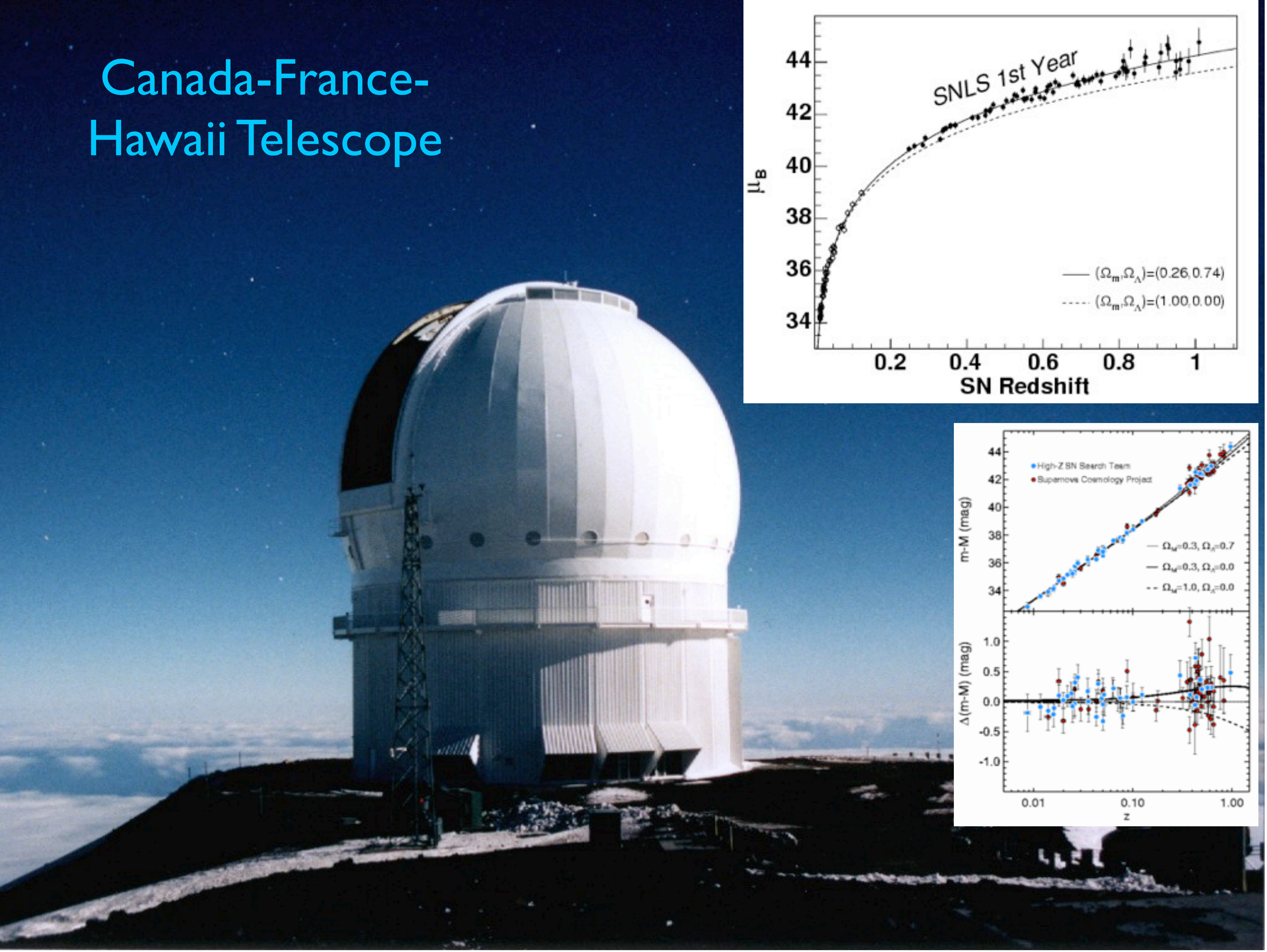


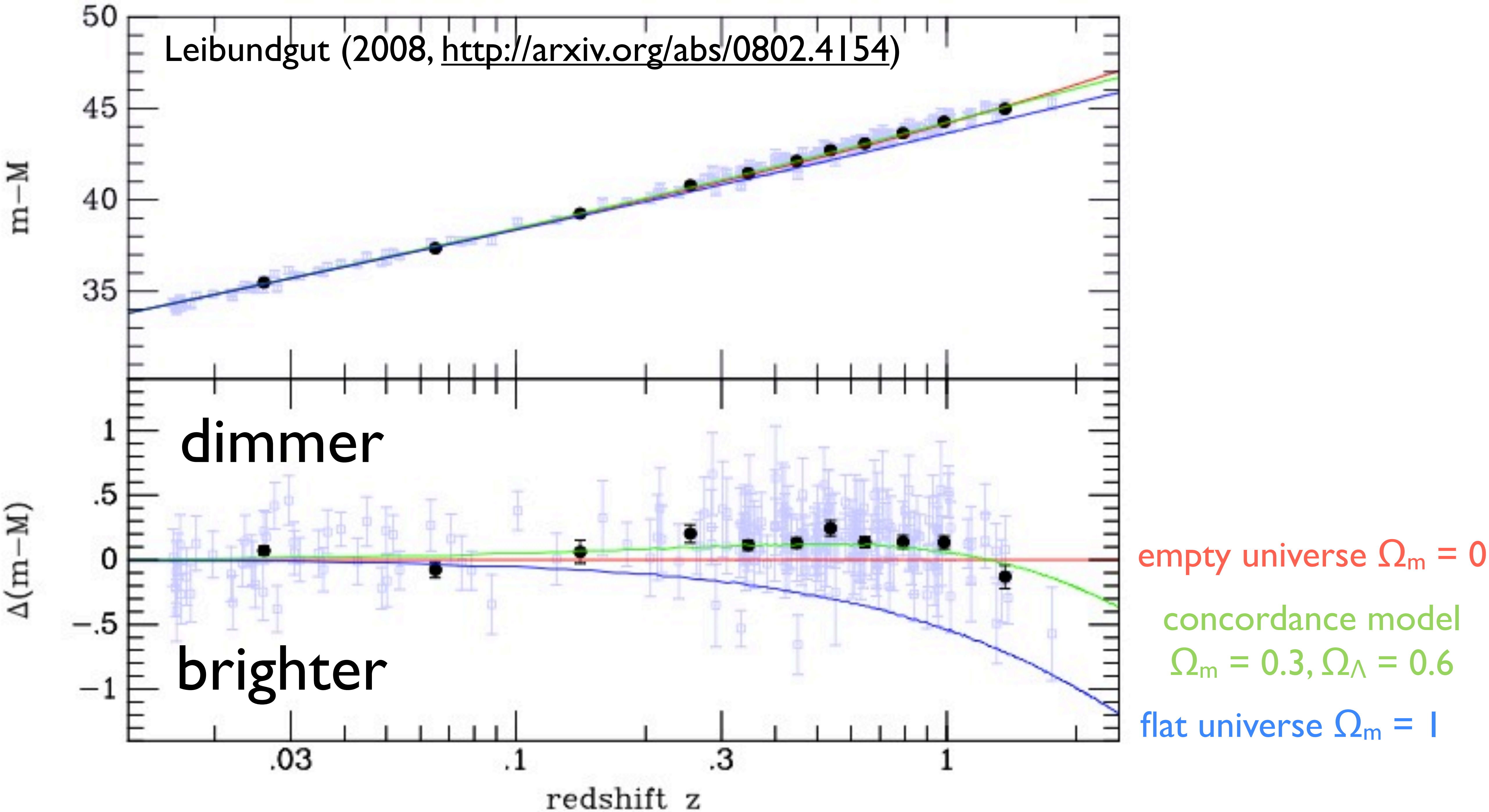
Like Cepheid Stars, Supernova are ‘**standard Candles**’



empty universe ($\Omega_m = 0$): has stretched the most; supernova at a given z should look the dimmest. But real supernova appear even dimmer (1998) --> The universe has stretched even more.

Canada-France-Hawaii Telescope





Compared to matter-only model (ρ/ρ_{crit}=0.3)

observed supernova looks dimmer at high redshift

--> further away

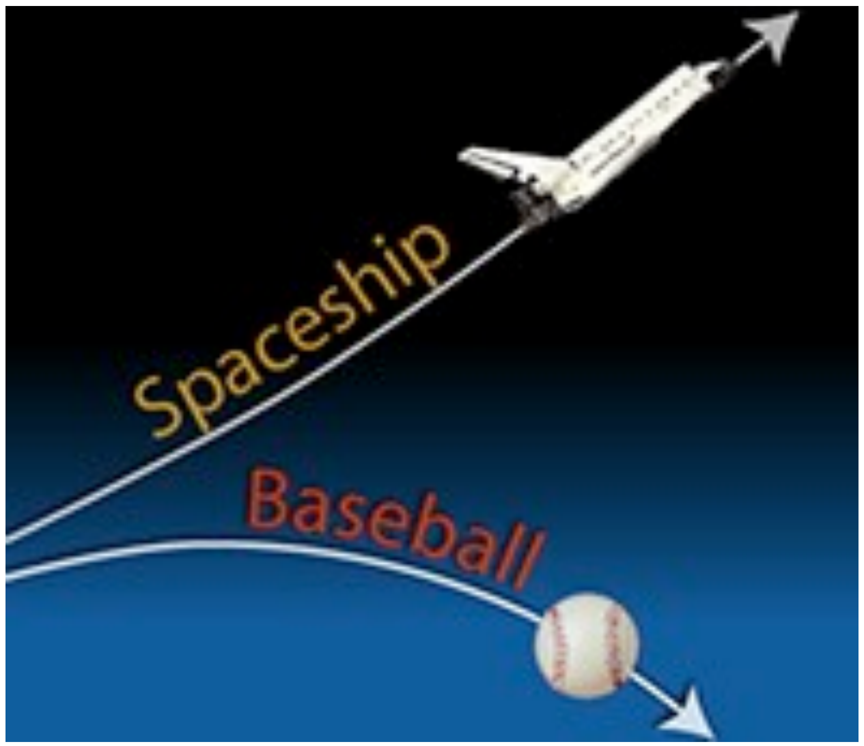
--> H = c*z/r smaller in the past, $\boxed{H^2 = \left(\frac{\dot{a}}{a}\right)^2}$

--> expansion of the universe is now **accelerating**!

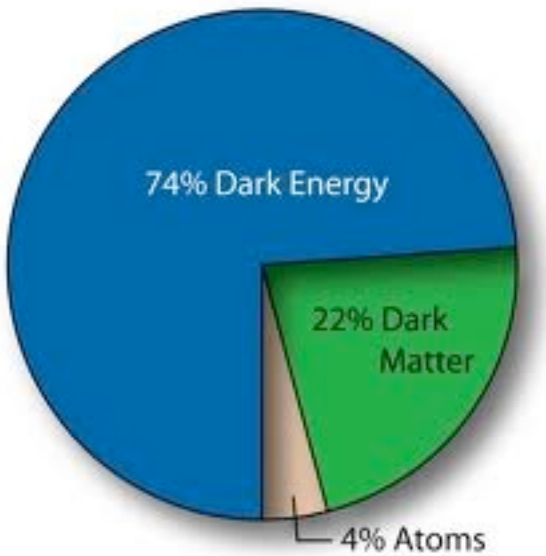
How can the universe expand faster than an empty one?

Distance bigger than even in the empty model.

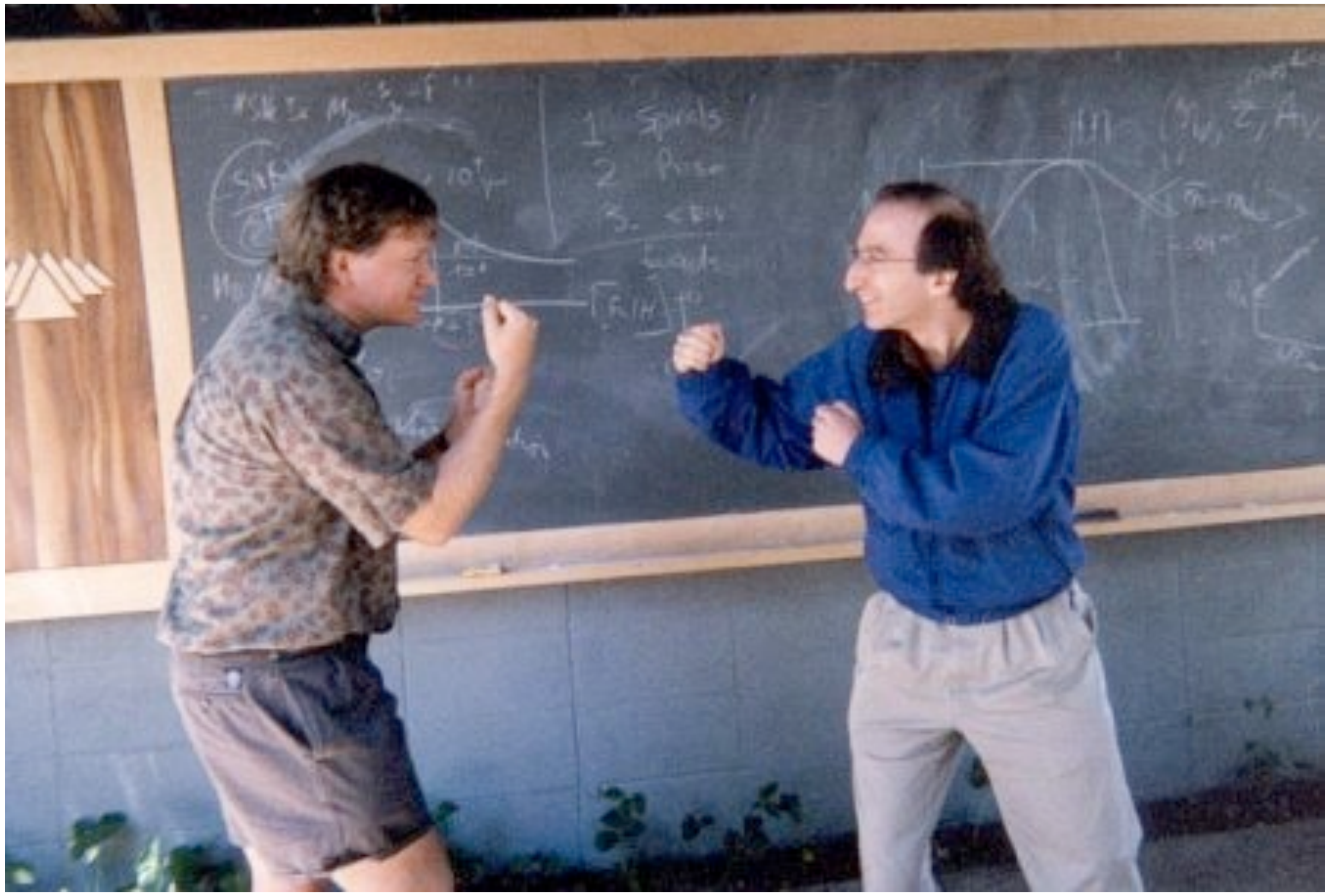
the expansion is picking up (accelerating)



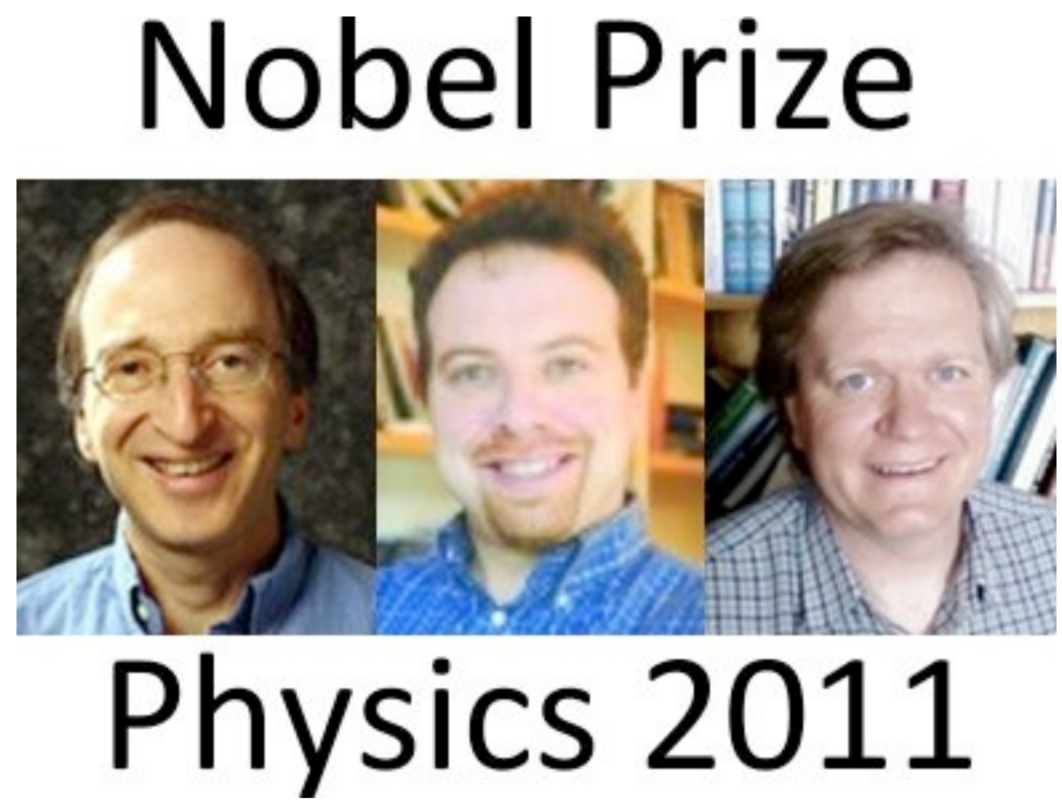
while a ball thrown upward can only decelerate with time, expansion of the universe actually accelerates with time!



So enters the stage: **DARK ENERGY**



first announcements (1998) came from two independent groups led by B. Schmidt & S. Perlmutter, respectively...



However, supernova data can mean a number of things...

The Exciting: the Universe is accelerating.

The Heretical: General Relativity is as sacred as anything in Physics, but it may be wrong.

The Mundane: We are simply wrong, perhaps high redshift supernova are intrinsically dimmer. They are not standard candles. Perhaps there is cosmic ‘fog’ making them look dimmer.

Mistake here!
Dark energy solved
these two conflicts

Observations measure:

$\Omega_m = \varrho/\varrho_{crit} \sim 0.3$

Theory (using Friedmann eq.) then predicts

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