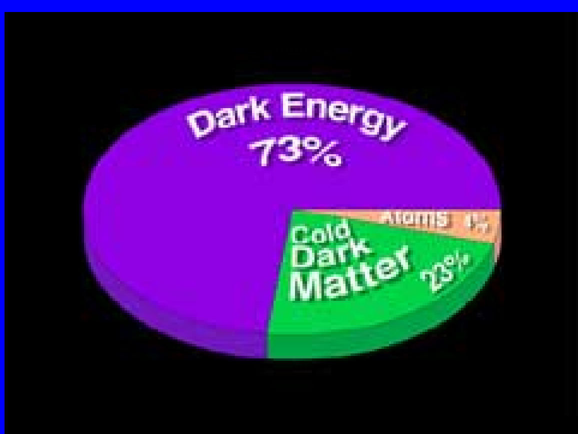
The Accelerating Universe

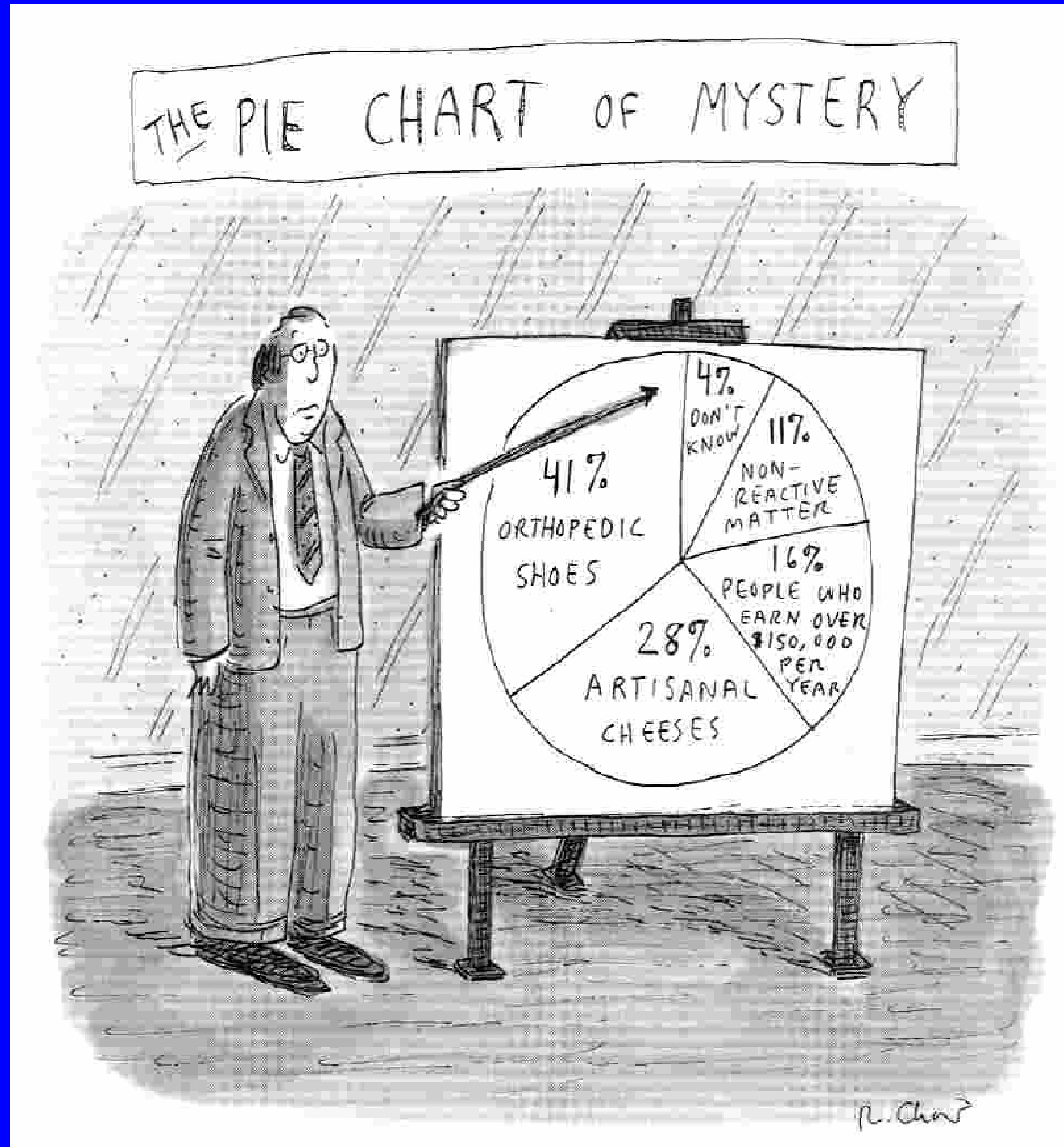
Peter Garnavich

A Universe of the Unknown

Ordinary matter makes up a small fraction of the mass/energy.

Dark matter and dark energy dominate.

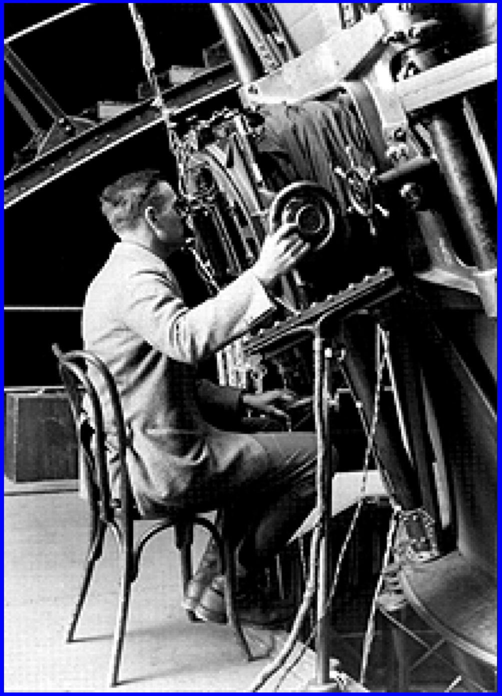


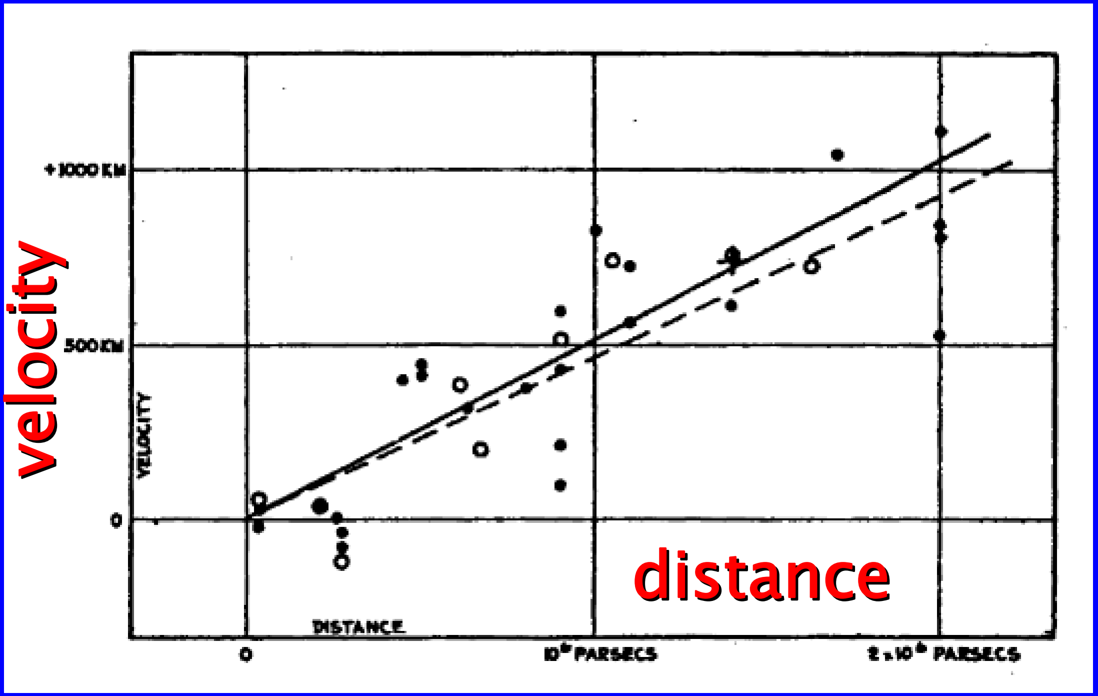


The Universe is Expanding!

1929 Edwin Hubble measured the Doppler shift of nearby galaxies and found a simple relation with their distance –

$$v = H_0 d$$





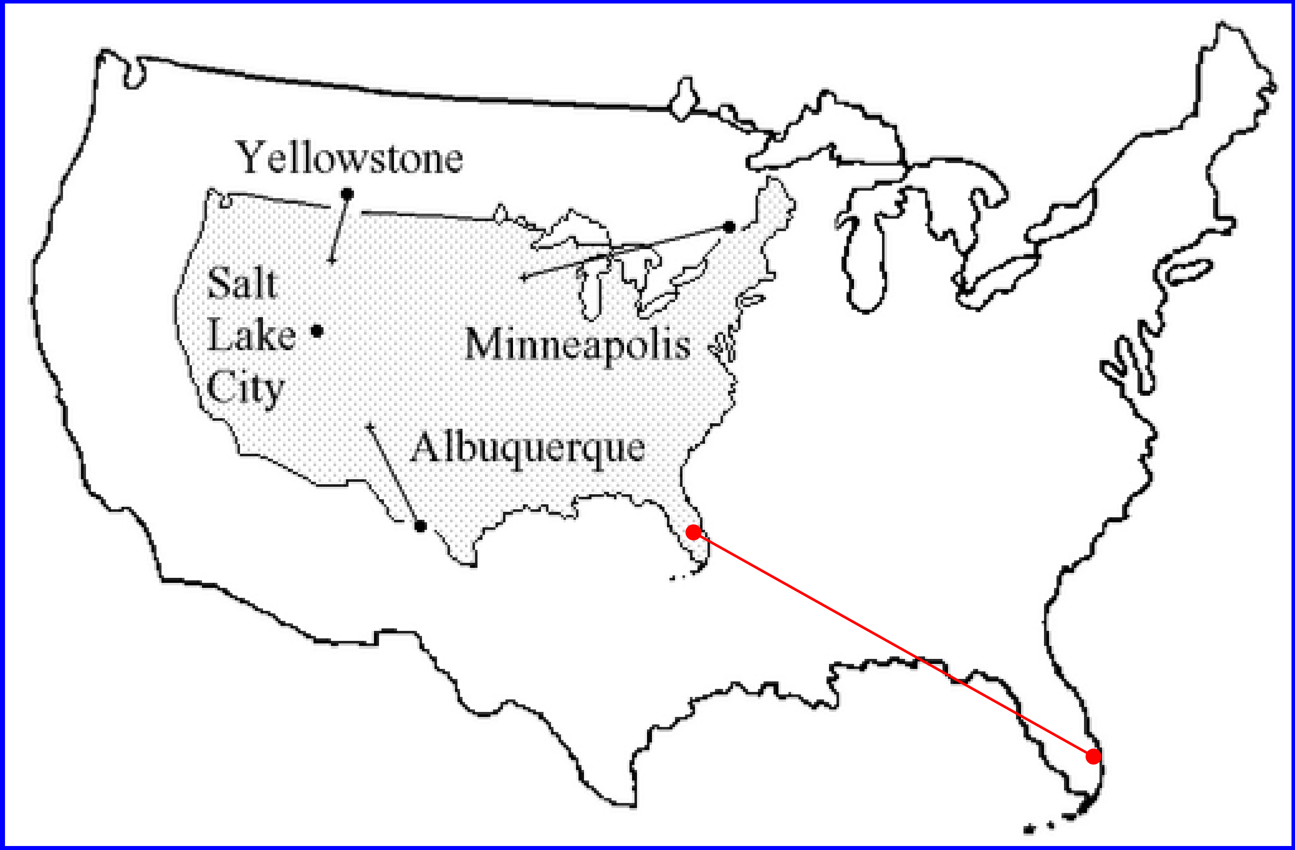
Easy to measure velocity. Hard to measure distance!

The Hubble Expansion

Space itself is expanding. Every point in space is getting further from every other point. Everybody sees the same thing!

Imagine the Earth's radius got larger…

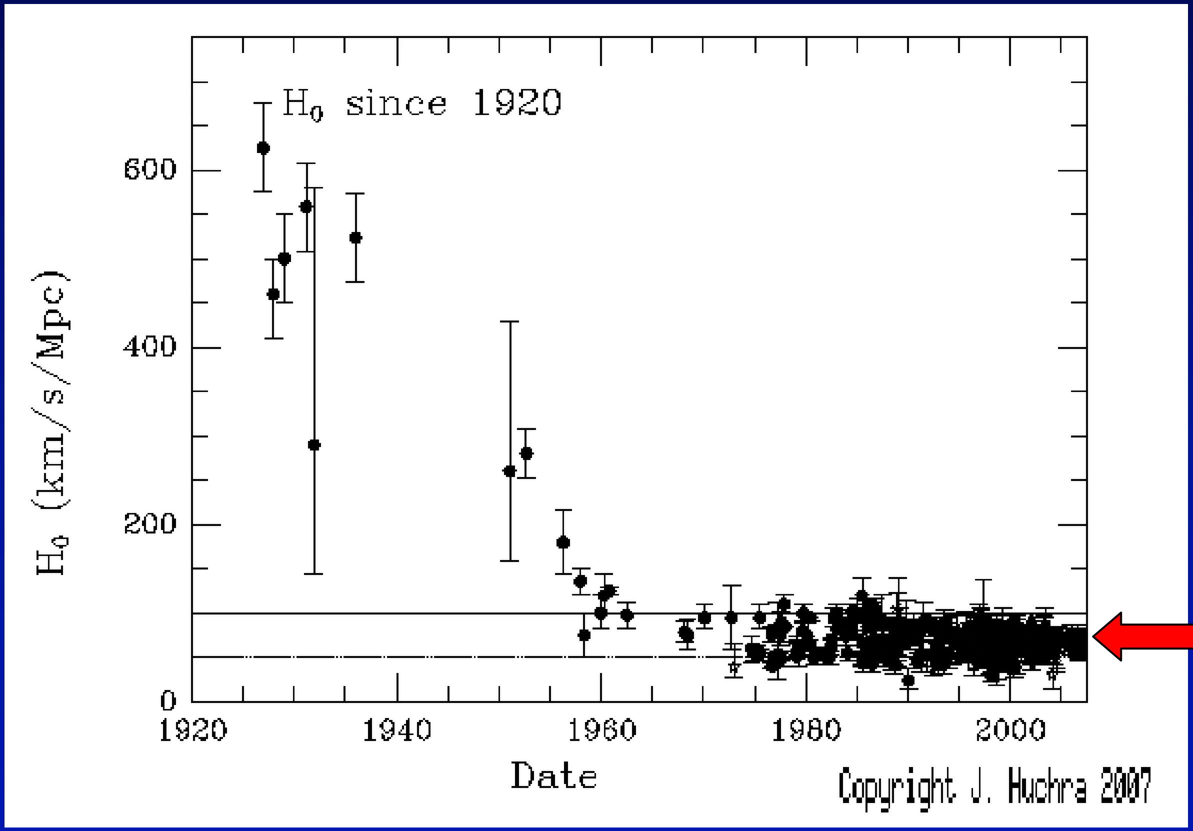
Distance from South Bend to Mishawaka would not change as quickly as the distance between South Bend and New York City.



Hubble was Wrong (sort of)

Hubble's 1929 estimate of the expansion rate was off by a factor nearly 10!

The next 60 years were spent sorting out the distance scale

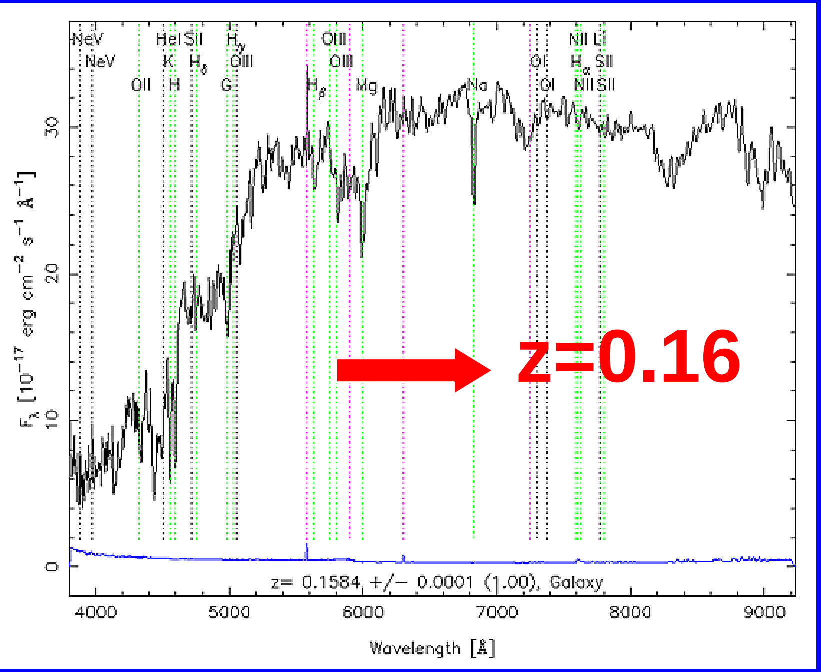


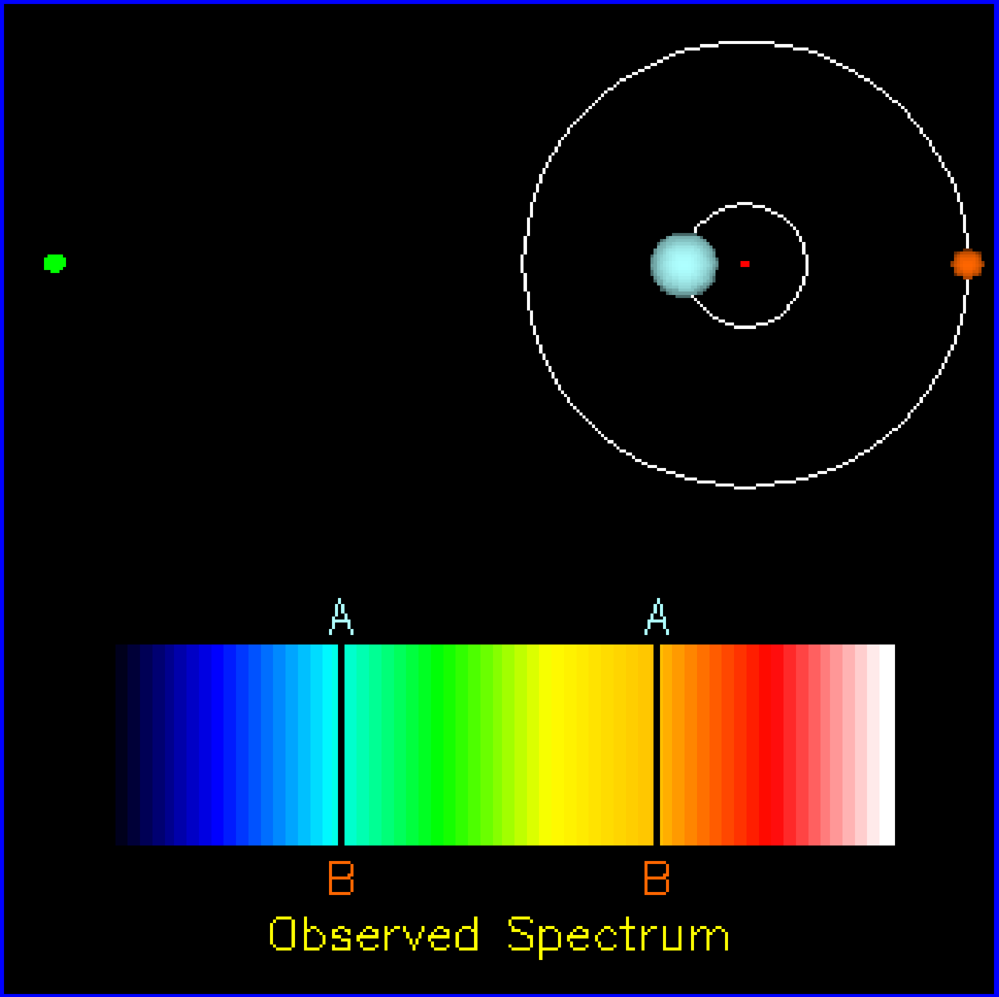
The correct answer is: 70+\- 7

The Doppler Shift – Measure the Velocity

Doppler shift: $$\frac{\Delta\lambda}{\lambda} = \frac{v}{c} = z$$

Orbiting stars will make sinusoidal Doppler shift over an orbit.



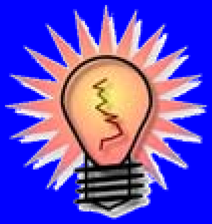


Measuring Distance is Simple but Hard

If street lights have the same wattage, then their relative brightness is a clue to their distance:

The Inverse-Square law

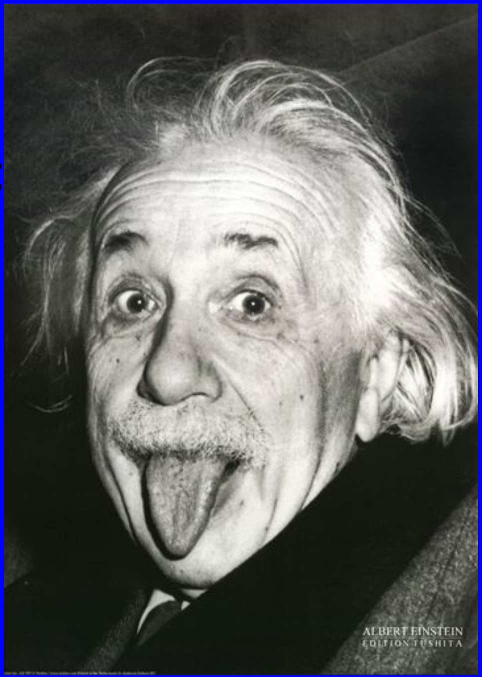
A light bulb twice as far as an <u>identical</u> bulb will appear 4 times fainter



Expansion in Theory

$v = H_0 d$

Hubble law discovered in 1929 could have been predicted by Einstein in 1915 (General Relativity)



Einstein's equations for gravity's effect on space-time showed either an expansion or contraction should occur:

$$H^2 = \frac{8\pi G \rho}{3c^2} + \frac{\Lambda c^2}{3}$$

H is the expansion rate at any time and H_0 is the expansion rate now => the Hubble constant

ρ is the density of matter in the universe=> source of gravity

The equation has two solutions: positive or negative expansion.

Einstein thought the Universe should be static, so he added a term he called the "cosmological constant" that can cancel the matter's gravity => his biggest blunder! (he later said)

Supernovae – Maybe Standard Candles?

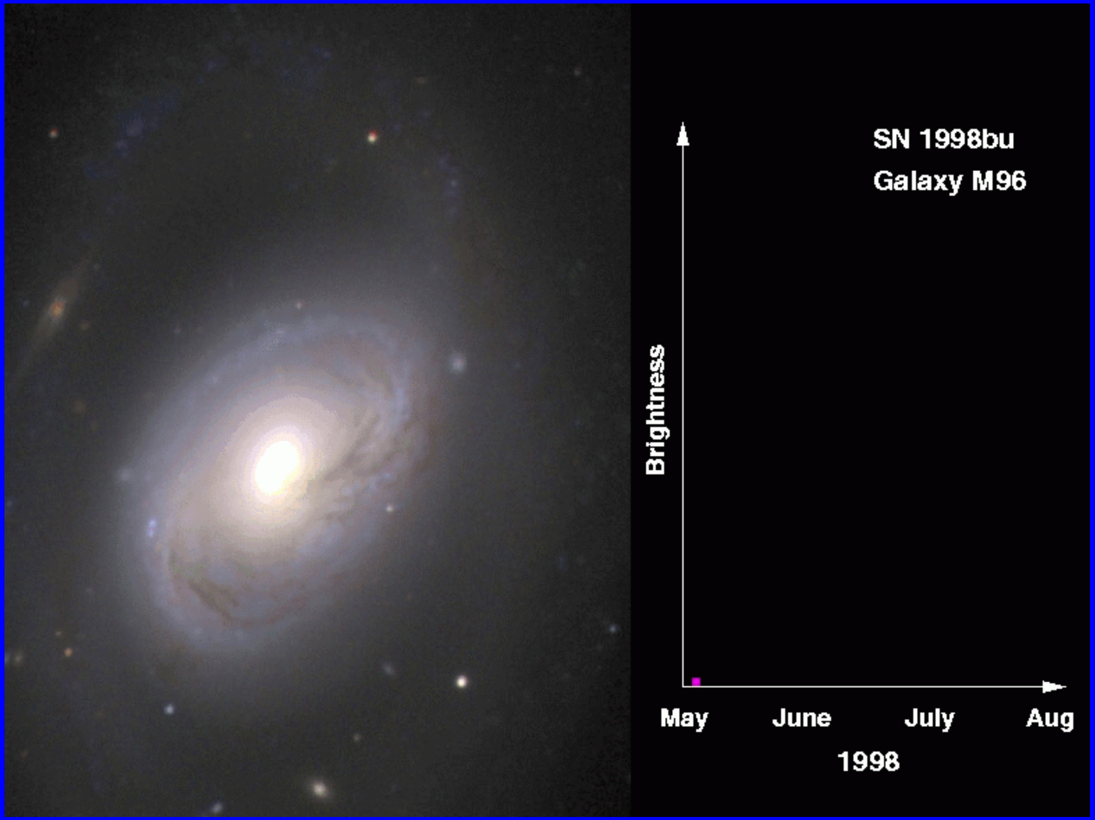
Can outshine all the other 100 billion stars in their host galaxy. Make most of the elements heavier than H,He

Zwicky –1930 suggested they are the collapse of a massive star when it runs out of fuel.

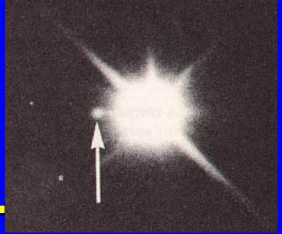
Really two completely different types:

Massive stars–core collapse

"White Dwarf" – detonation



Detonation of a Small Star – Type Ia

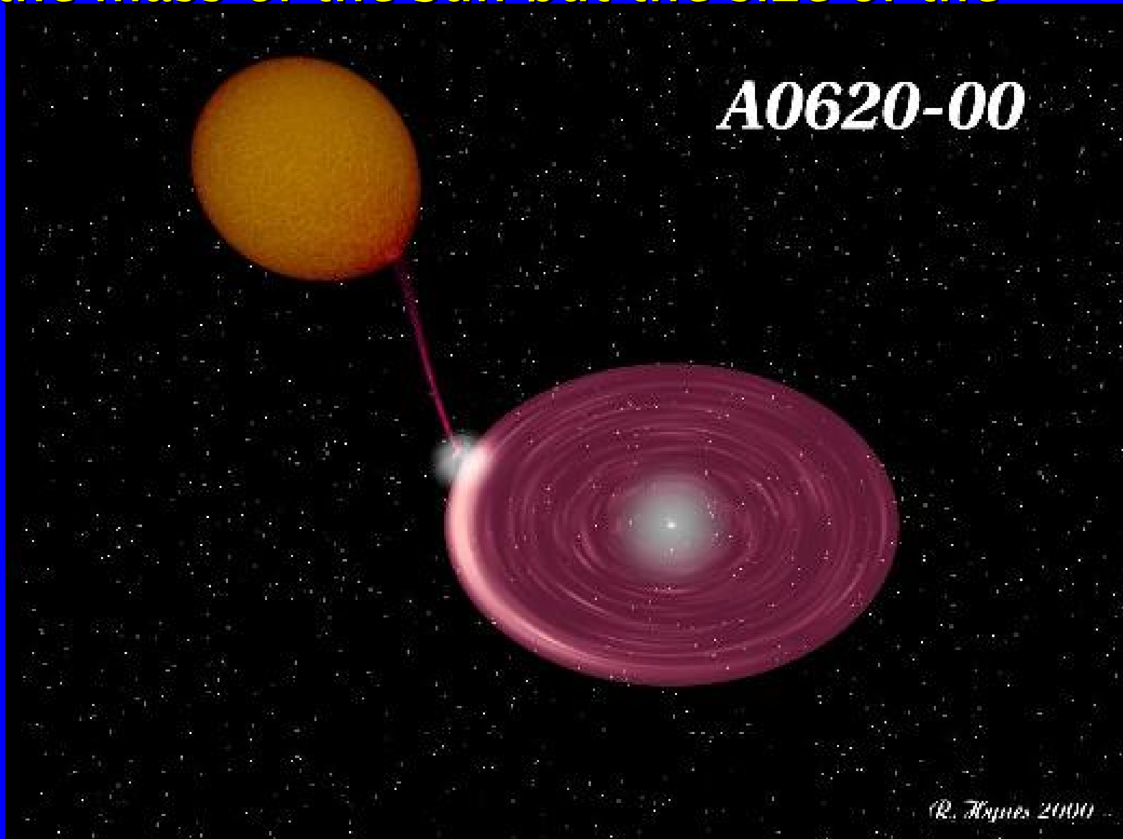


Normal stars like the Sun fuse H => He => C in their cores.
When their fuel is exhausted gravity takes over and compresses the star until the matter becomes "degenerate": quantum mechanics prevents
electrons from getting any closer => White Dwarf

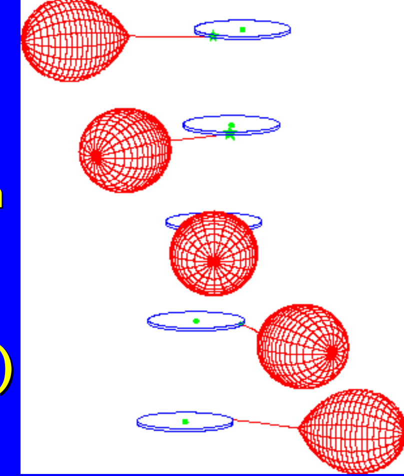
White Dwarf stars are about the mass of the Sun but the size of the Earth

Electron degeneracy can only support a WD for masses <1.4 Msun (the Chandrasekar Limit)

If a companion star donates mass to the white dwarf, it can reach the Chandra limit and compress=> igniting the Carbon in the center... BOOM



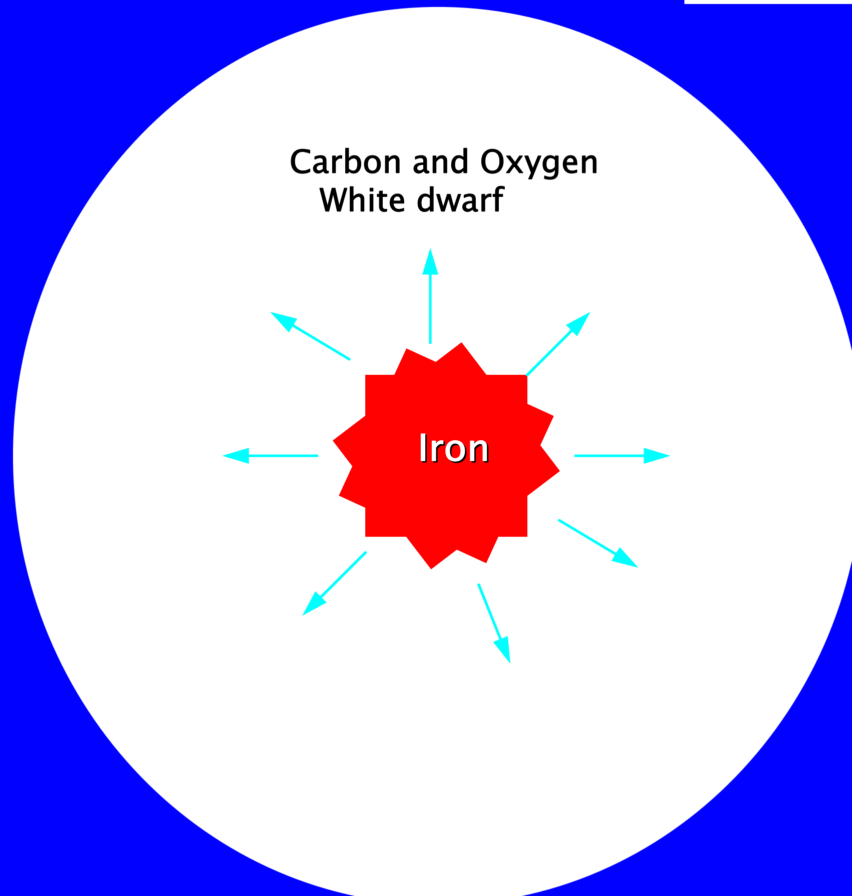
"Explosion" of a Star – Type Ia



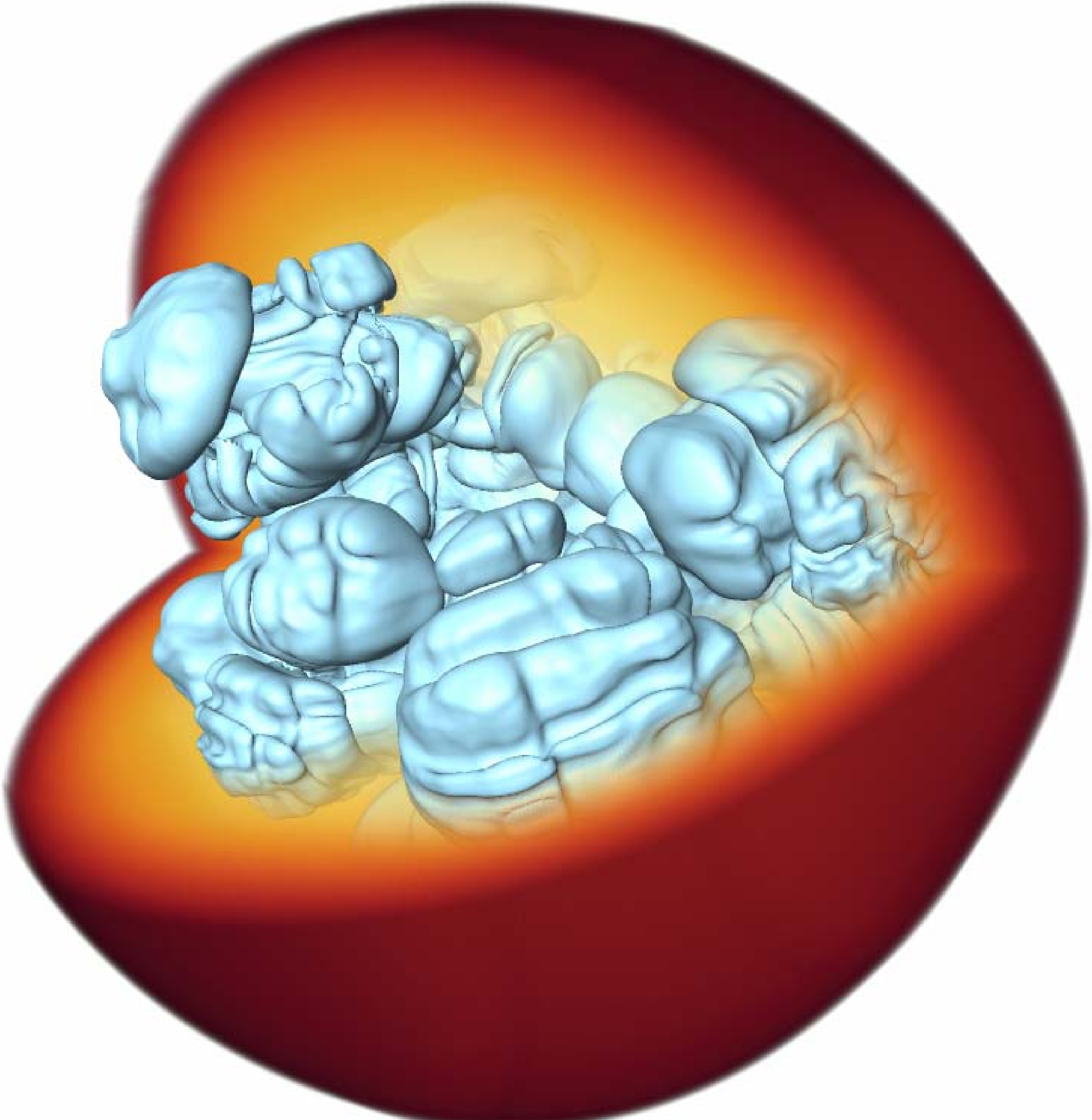
Companion donates mass to white dwarf until ~1.4 M_{sun}
Once fusion of C+O starts in the core =>
the burning front moves out through the star leaving
0.5 M_{sun} Nickel which decays to Cobalt (half-life 7 days)
and then decays to Iron
(half-life of 2 months)

If the fusion front moves at greater than the sound speed => detonation
Too much ^{56}Ni

If the fusion front is subsonic => deflagration
Too little ^{56}Ni



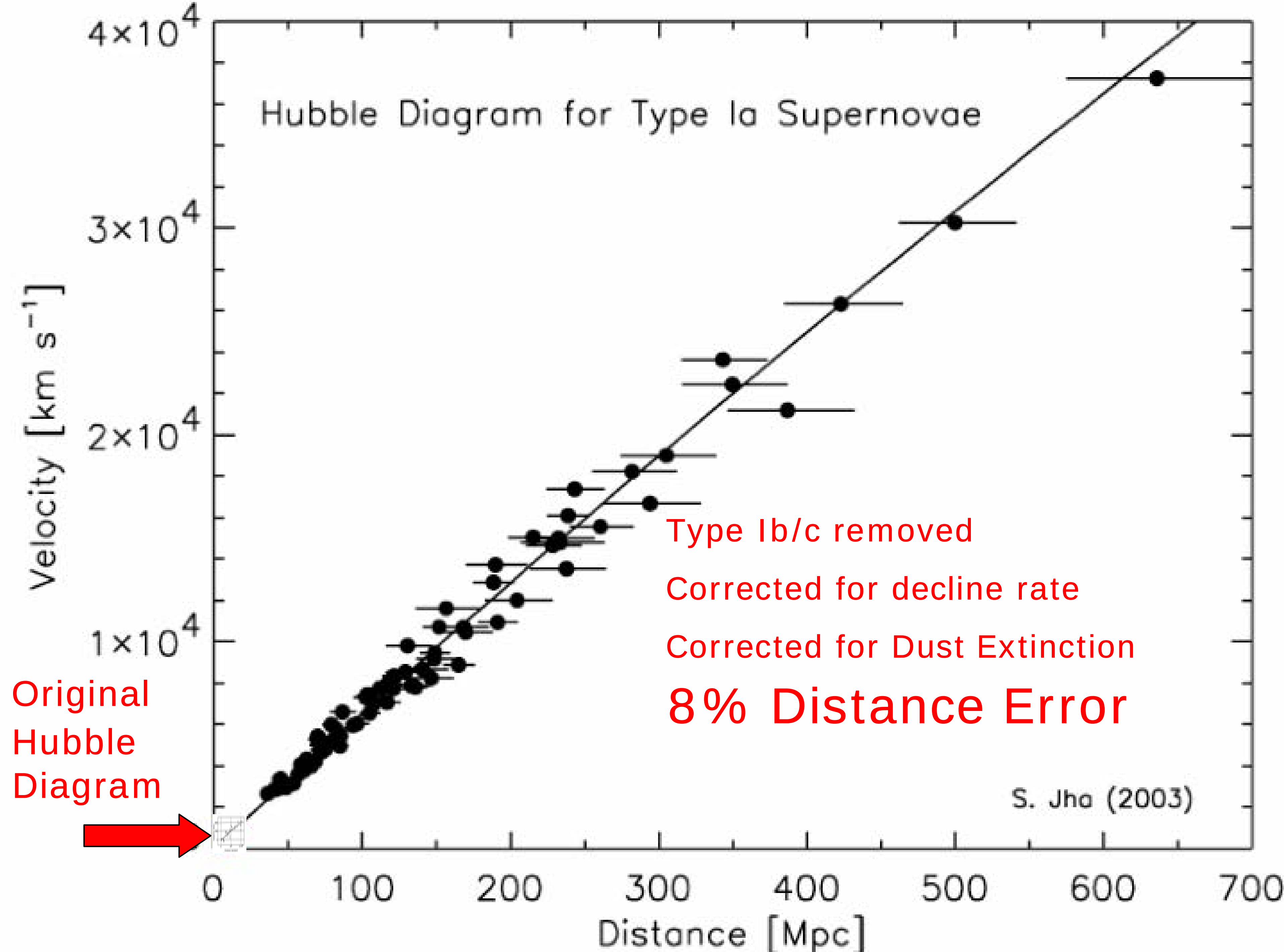
Range of peak brightness probably due to ^{56}Ni spread



Type Ia SN: exploding white dwarfs

Computer Model:From crinkled flames grow lumpy supernovae

Things more complicated than simple spherical model


Hubble Diagram for Type Ia Supernovae
Velocity [km s^{-1}]
4×10^4
3×10^4
2×10^4
1×10^4
0
100
200
300
400
500
600
700
Distance [Mpc]
Type Ib/c removed
Corrected for decline rate
Corrected for Dust Extinction
8% Distance Error
S. Jha (2003)
Original
Hubble
Diagram

How Much Matter?

Matter density determines the gravitational pull that slows the expansion

Deceleration rate measures the density of matter created in the Big Bang.

Density only about: 10^{-29} gram/cm^3

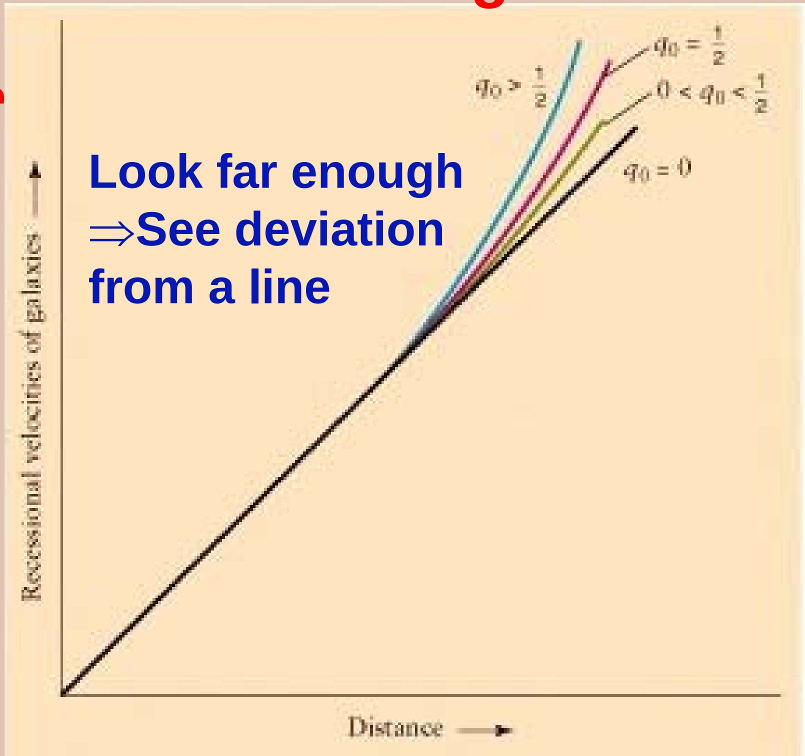
Extending the Hubble Diagram

The linear Hubble Law is only an approximation. The rate of expansion in the past depends on the matter/energy density of the universe.

$$H^2(a) = H_0^2 \, [\, \Omega_m a^{-3} + (1 - \Omega_m)\, a^{-2} \,]$$

Hubble Diagram

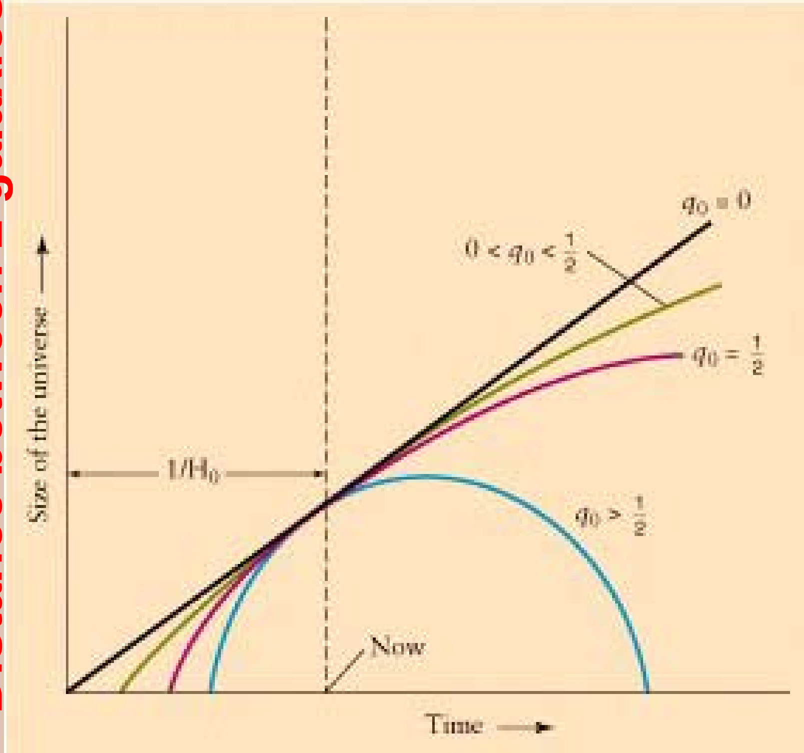
Redshift = velocity



Distance from Us

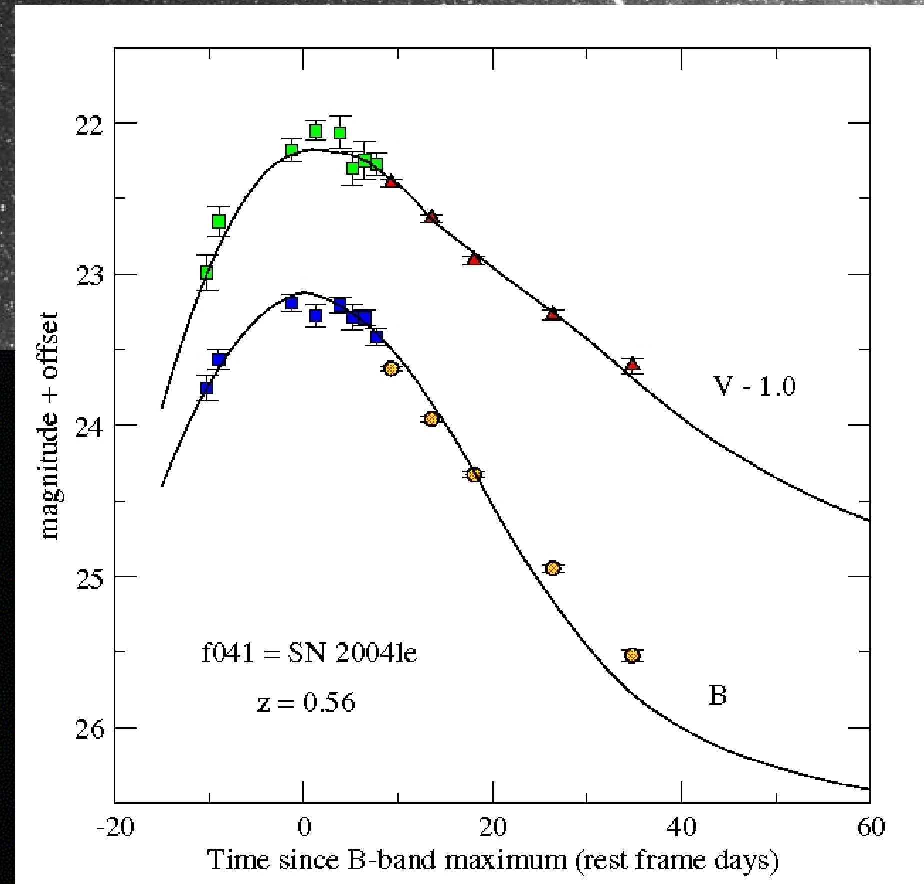
God's Eye View

Distance between 2 galaxies

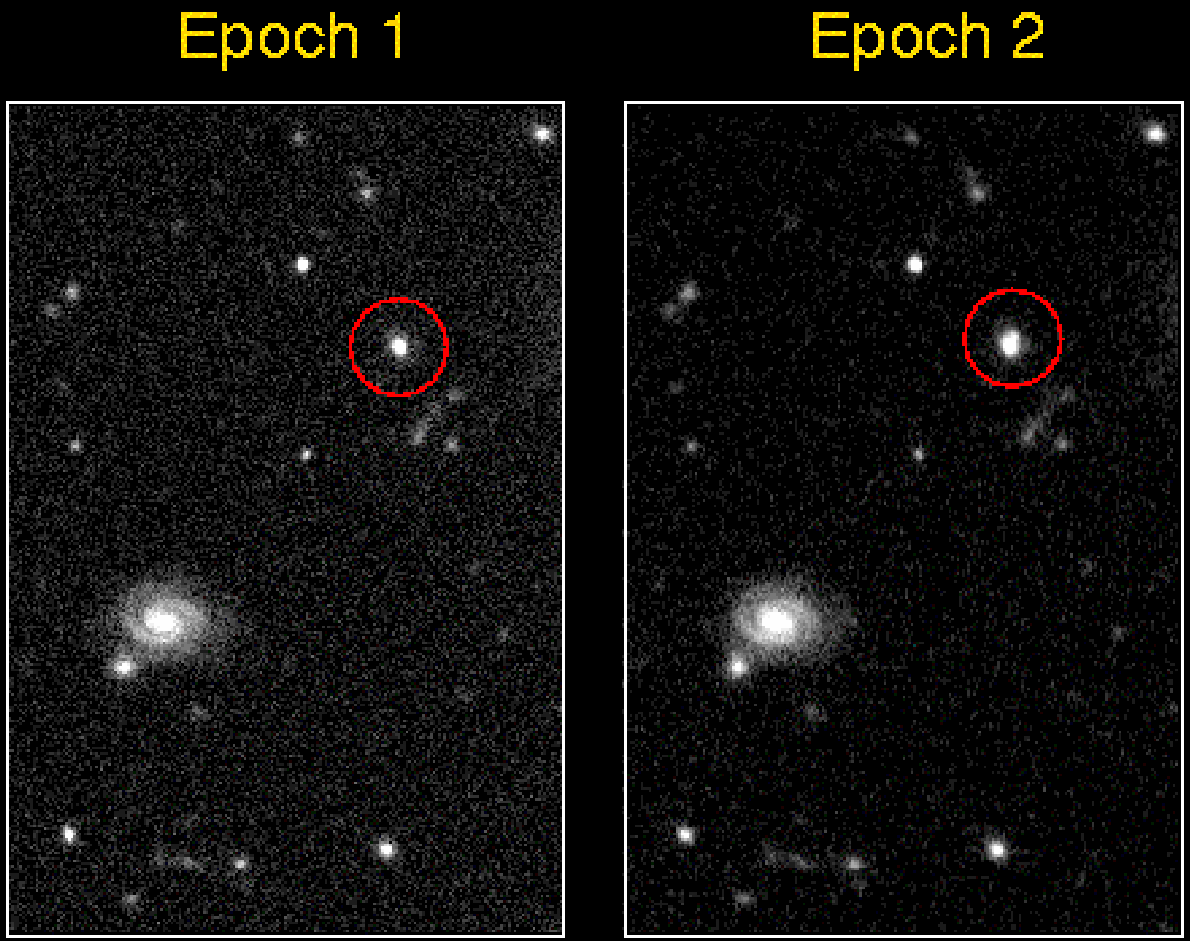


Time

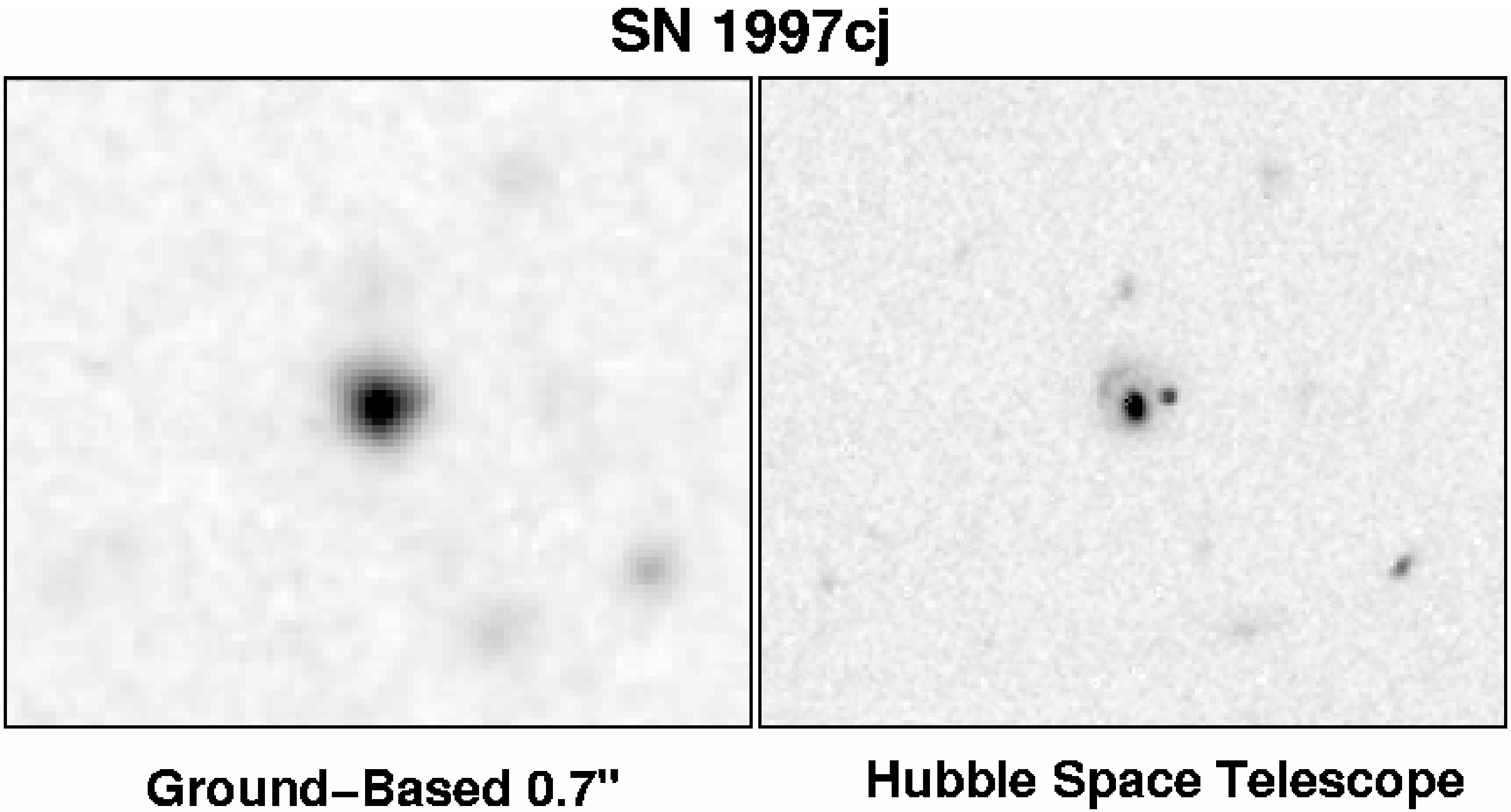
Searching for Distant Supernovae



Searching for Supernovae



Advantage Space



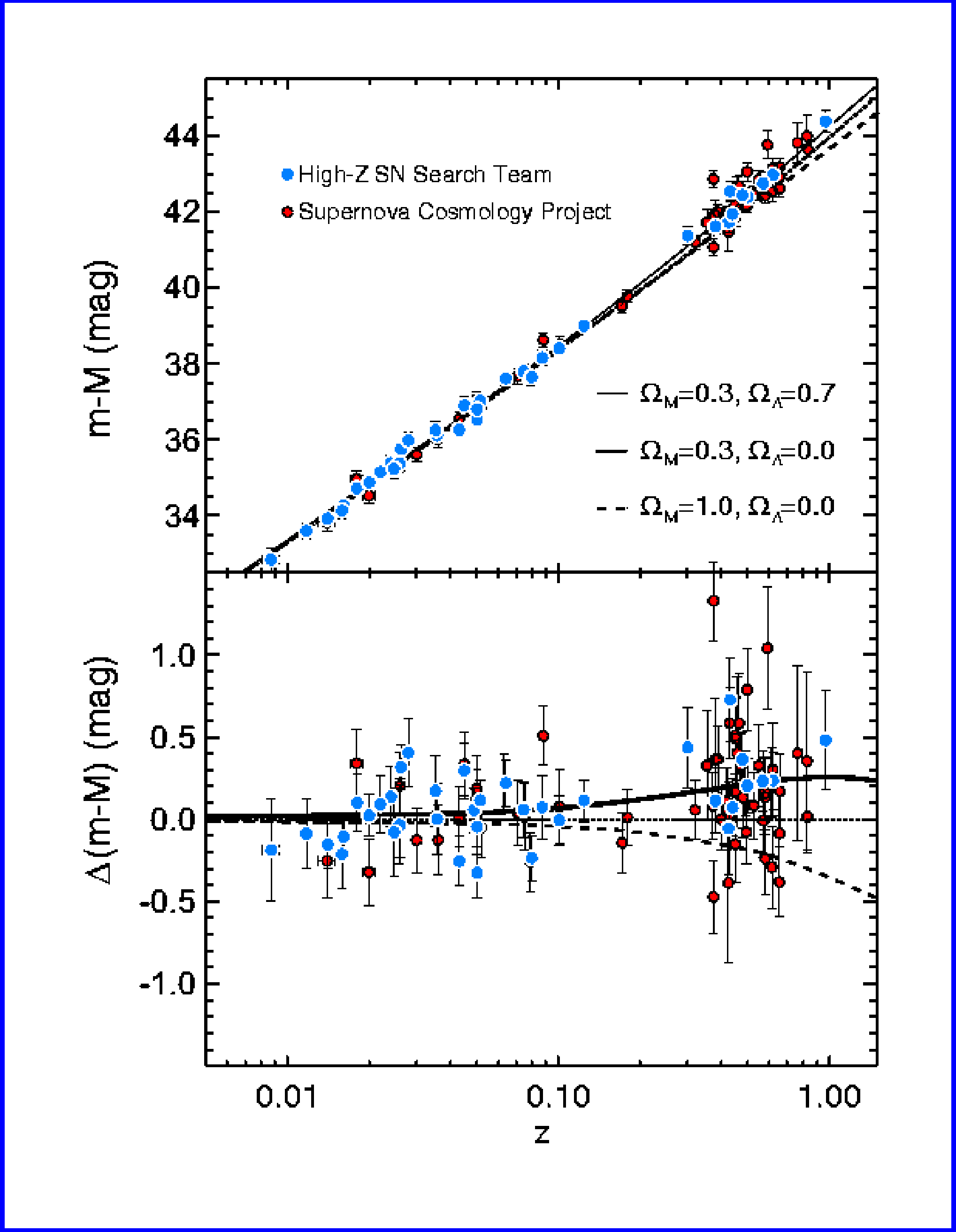
Our atmosphere blurs stars: even a small telescope has a big advantage in space.

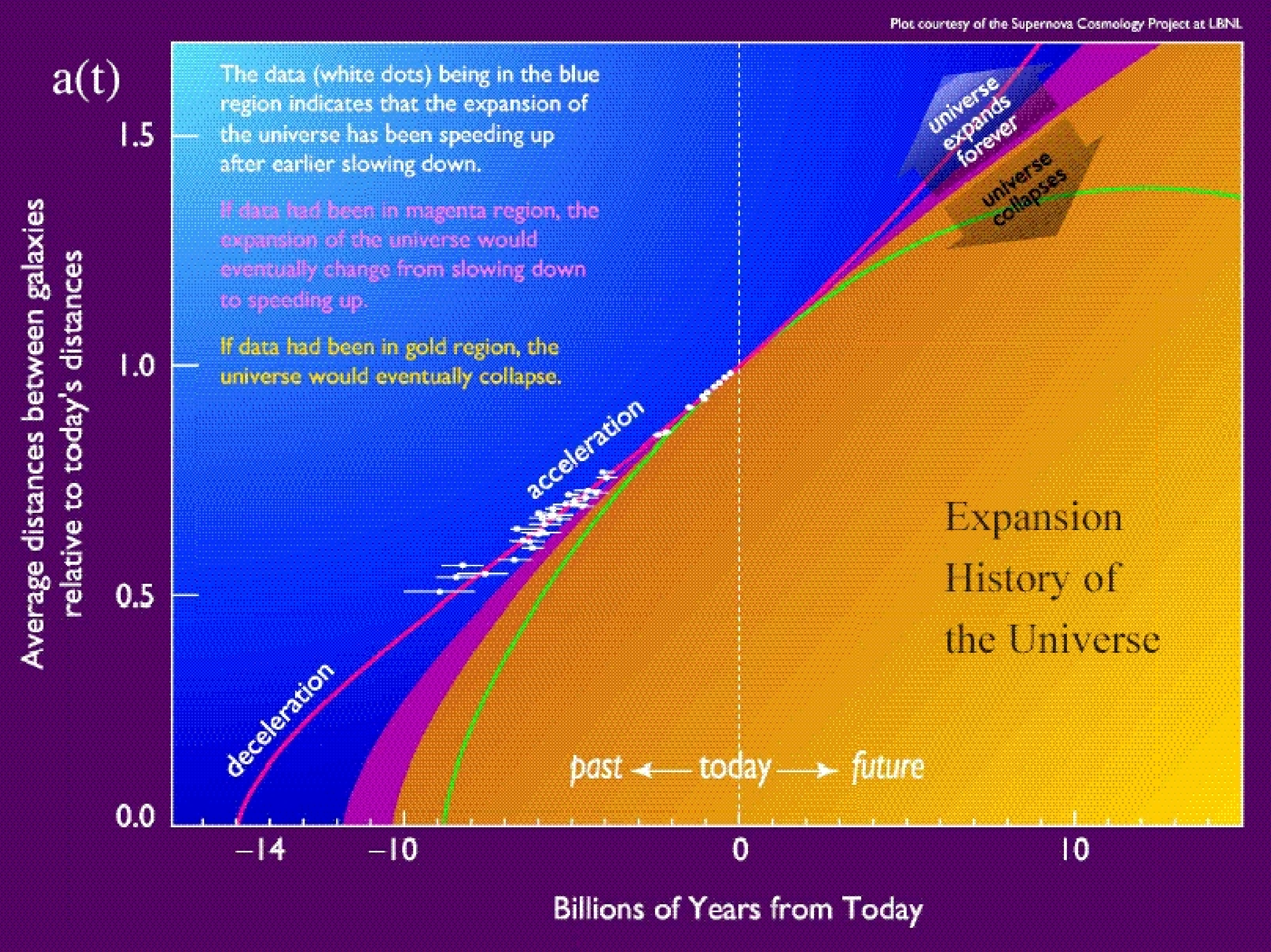
Distant Hubble Diagram

Both groups found that the type Ia supernovae were fainter than they expected for a matter domintated universe

In fact, the universe was not decelerating, but was accelerating =>

Requires another kind of "energy". A vacuum energy or "cosmological constant"





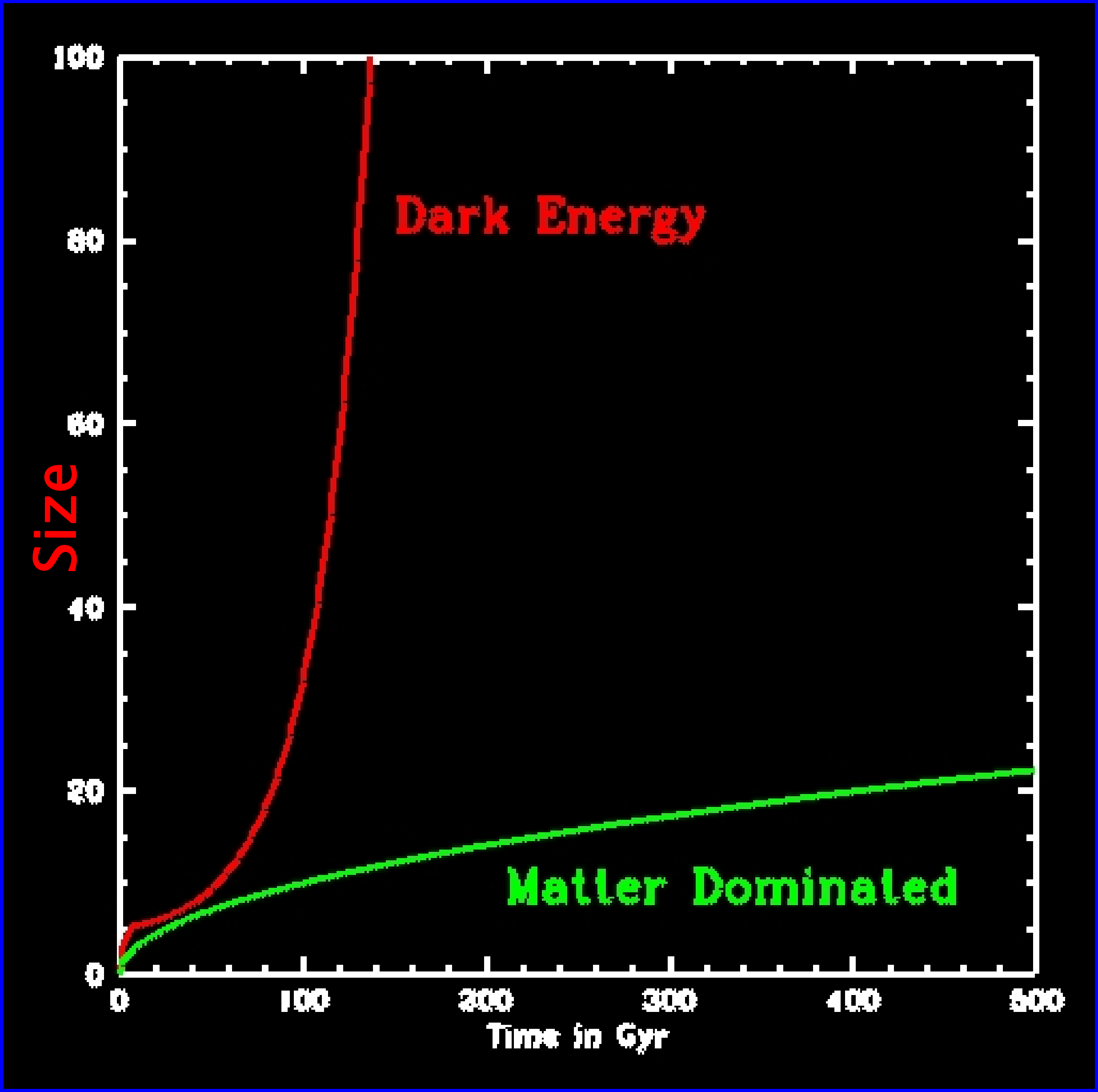
Plot courtesy of the Supernova Cosmology Project at LBNL
a(t)
The data (white dots) being in the blue region indicates that the expansion of the universe has been speeding up after earlier slowing down.
If data had been in magenta region, the expansion of the universe would eventually change from slowing down to speeding up.
If data had been in gold region, the universe would eventually collapse.
universe expands forever
universe collapses
acceleration
deceleration
Expansion History of the Universe
past ← today → future
Average distances between galaxies relative to today's distances
1.5
1.0
0.5
0.0
−14
−10
0
10
Billions of Years from Today

Acceleration

Universe will look very different in future
if there is a Vacuum energy

Space will be stretch out very quickly due to the acceleration

Galaxies will disappear…



The Big Rip

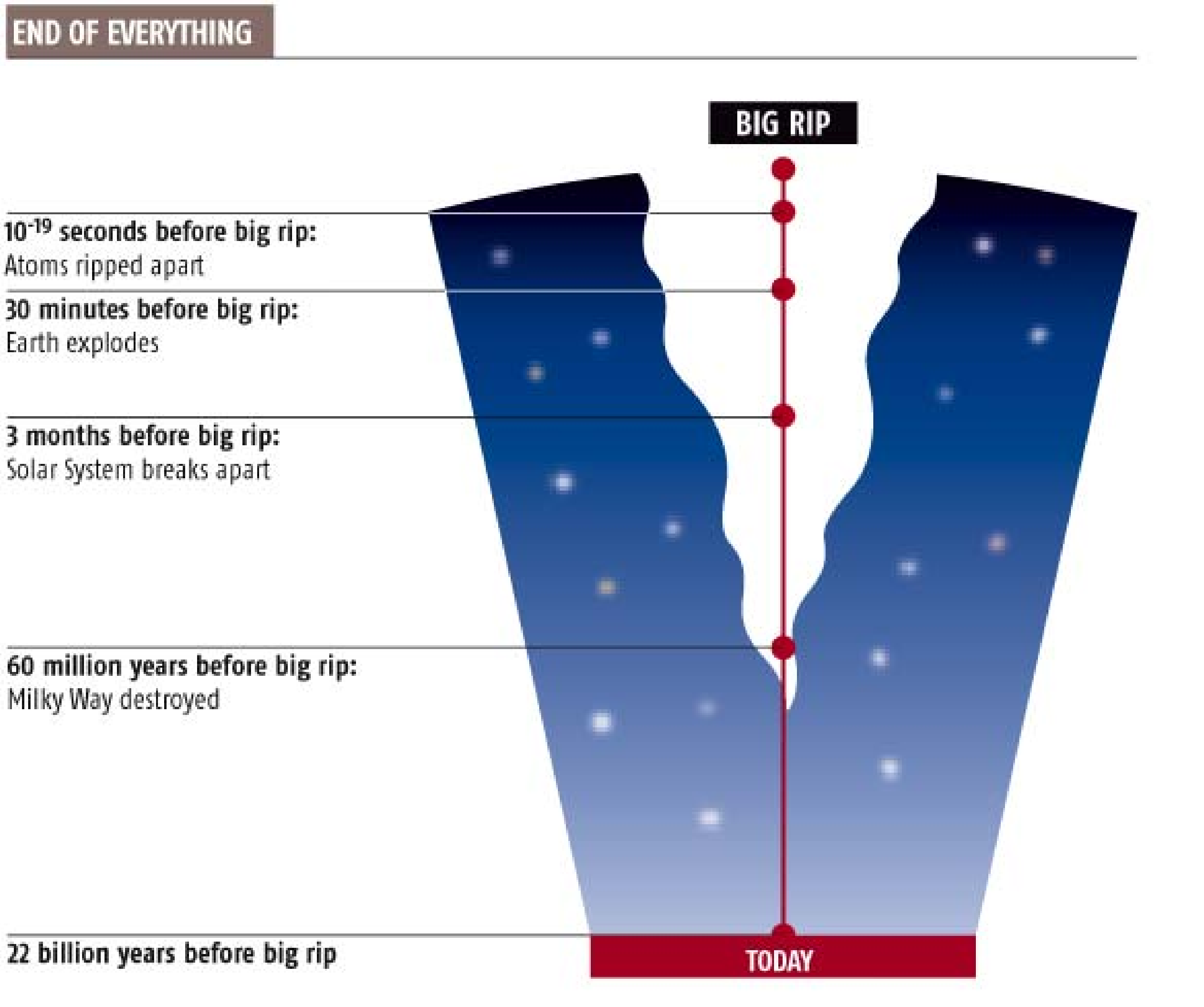
Vacuum energy does not accelerate the expansion fast enough to tear apart galaxies.

Phantom Energy: a form of Quintessence that has an equation of state $w<-1$ so that it increases in density as the universe expands.

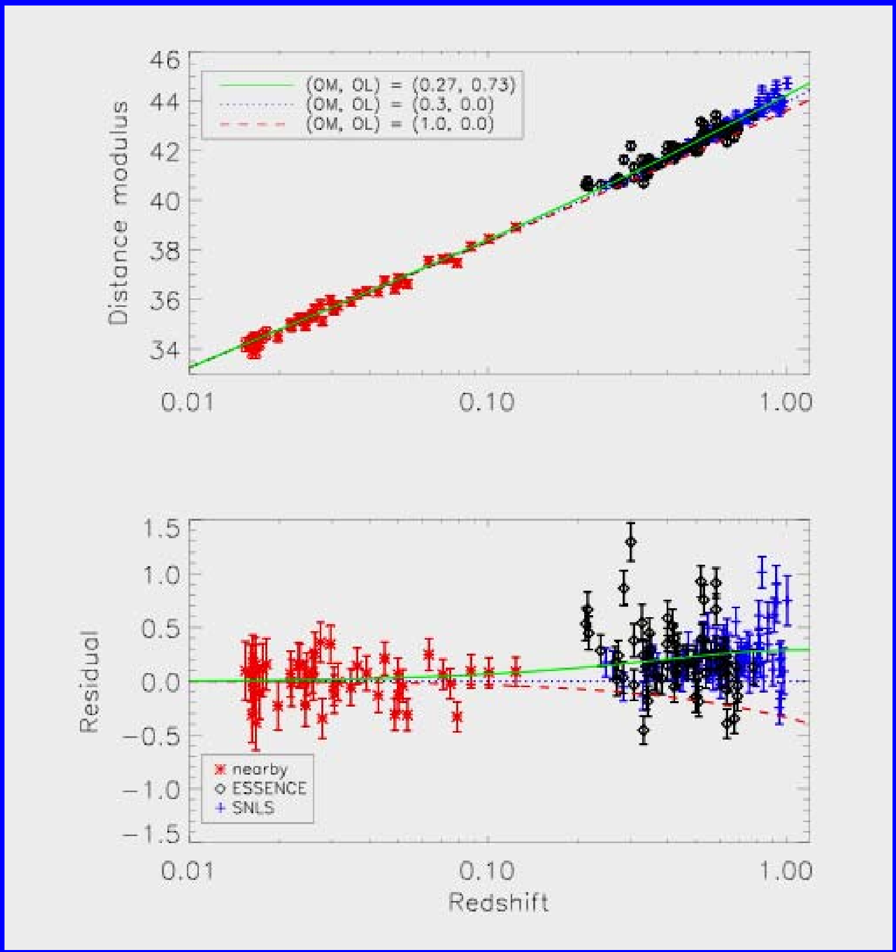
Plus it drives the expansion!

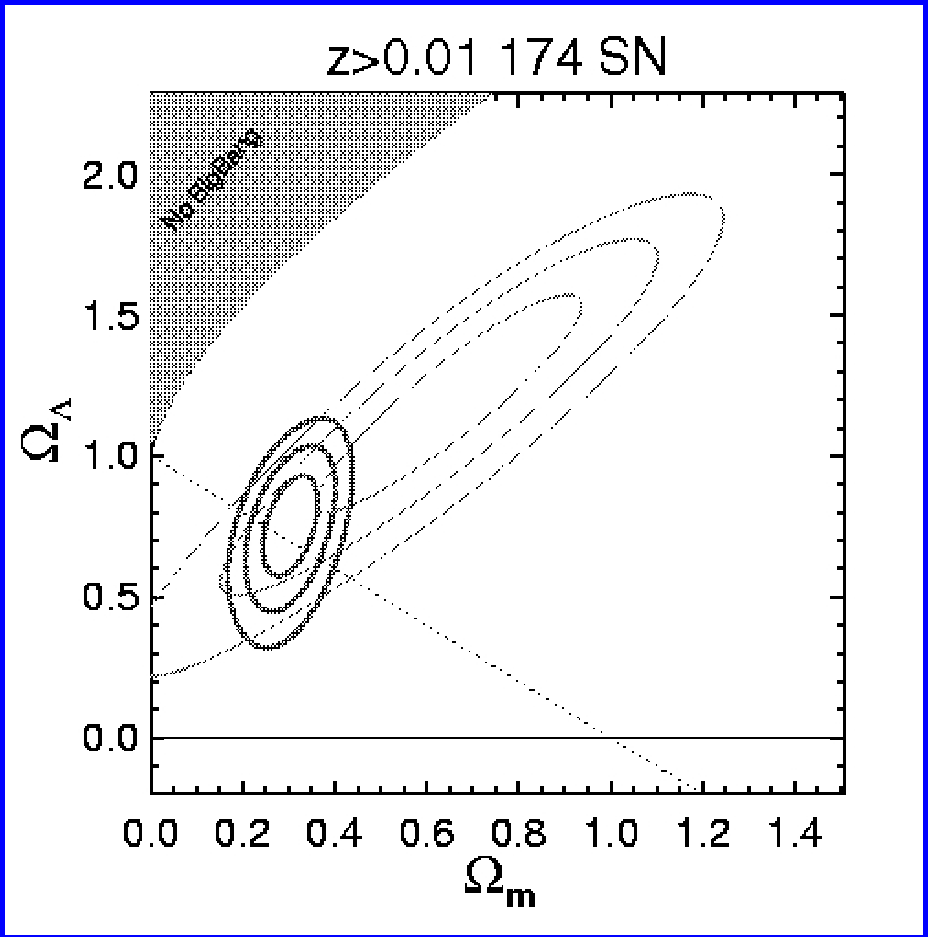
The "Big Rip" results from the super-accelerated expansion.

Good news: probably not the right answer



What is the dark energy?





Things Dark Energy Might Be:

1) Einstein's Cosmological Constant

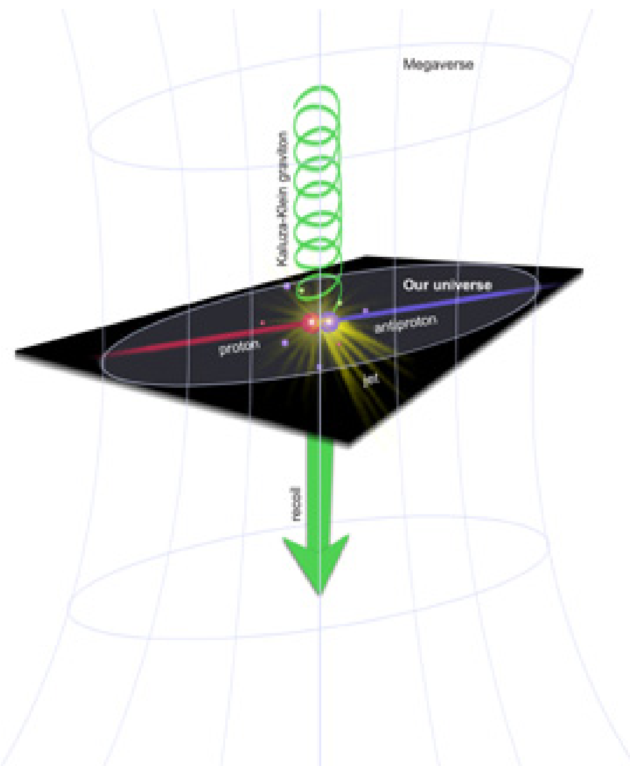
2) The "vacuum" has a non-zero energy

3) A new particle with very low mass

4) Gravity leaking from large extra dimensions

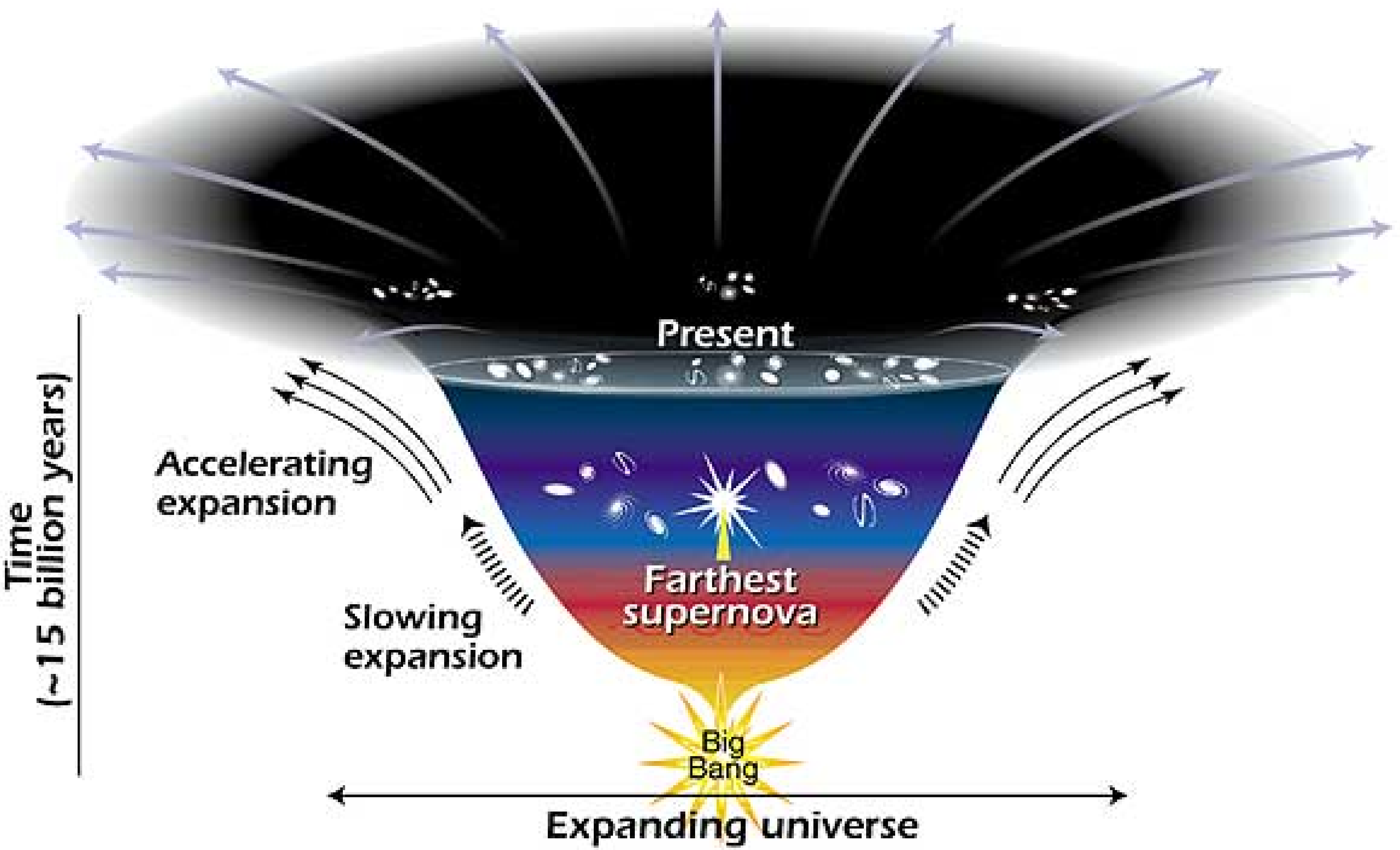
5) General Relativity is wrong on large scales

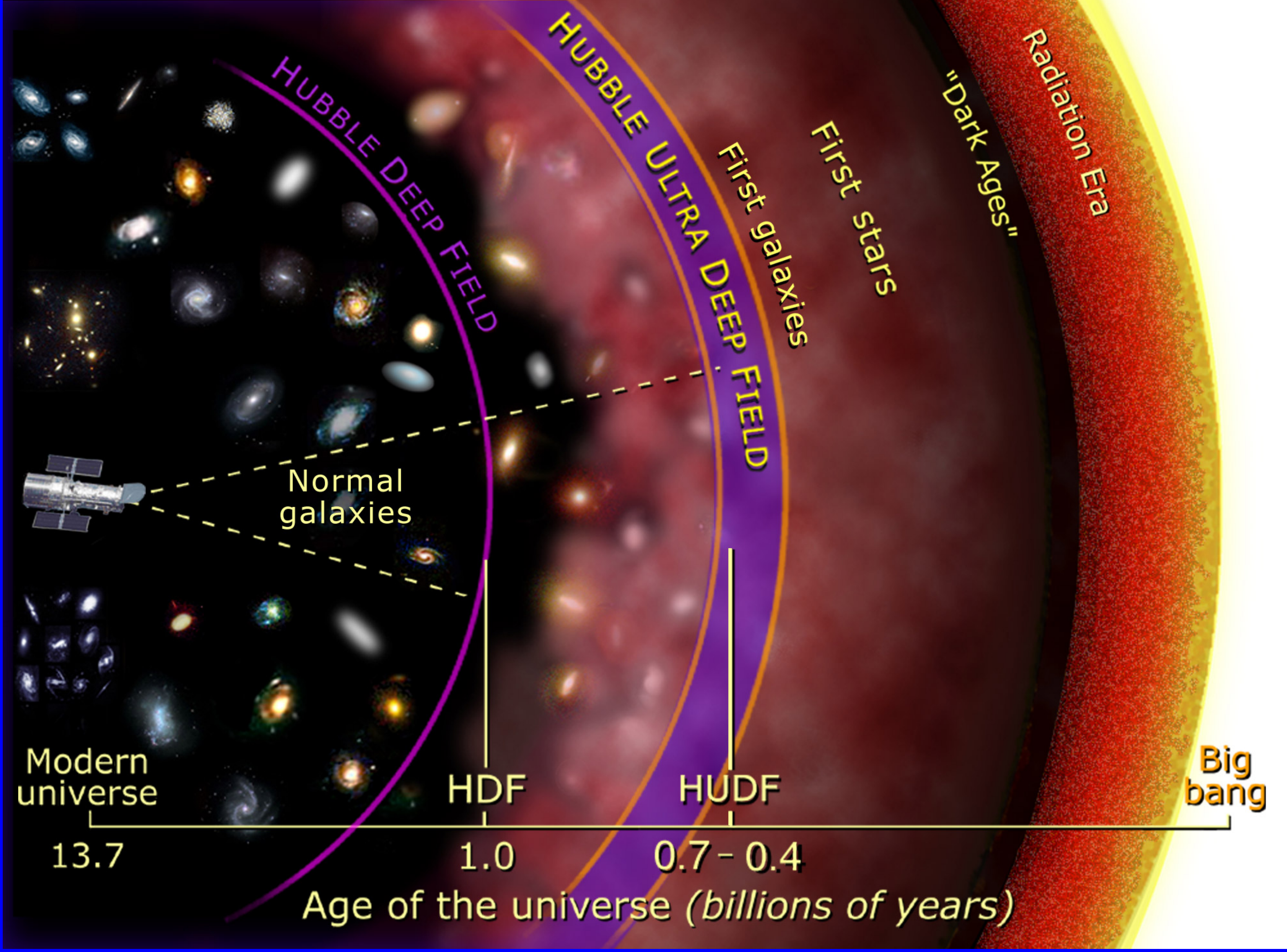
0) Something we have not thought of



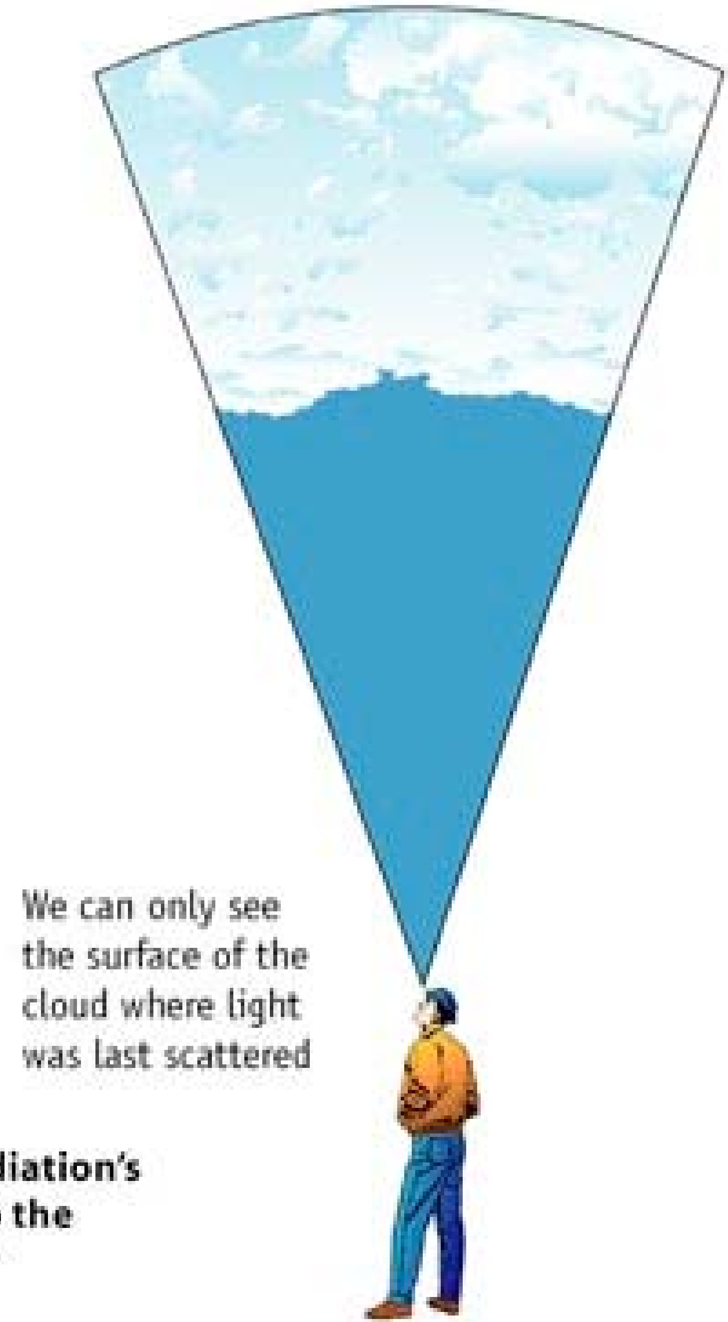
A Dark, Accelerating Universe

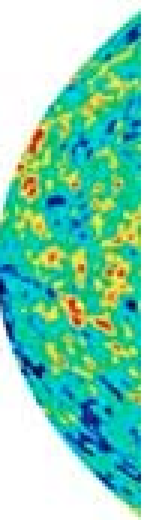
0.1% visible matter, 25% dark matter, 75% dark energy

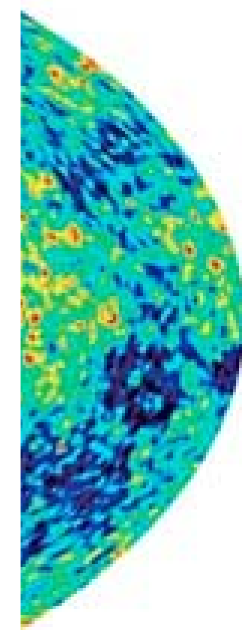




HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

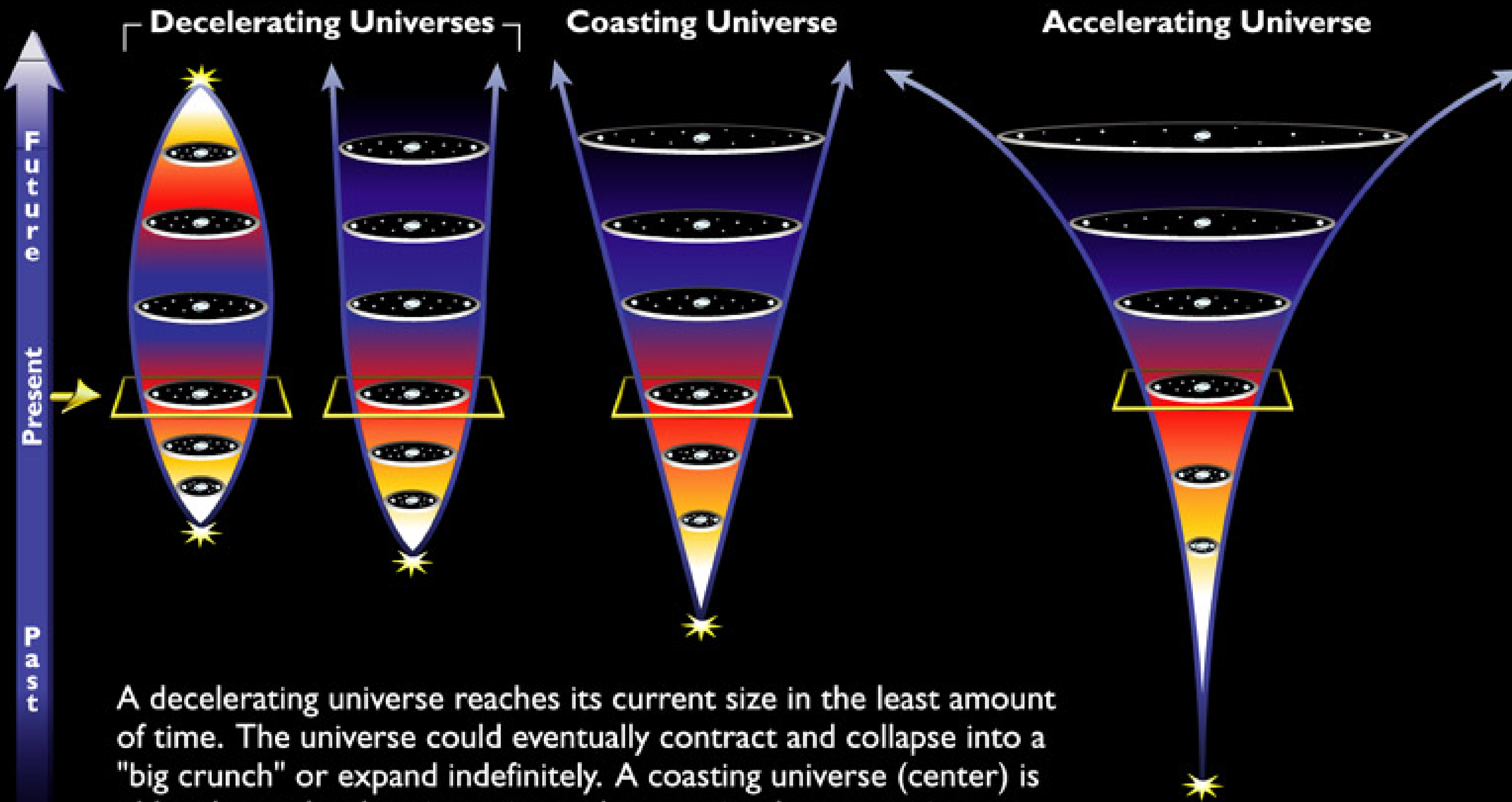






The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

Possible Models of the Expanding Universe



A decelerating universe reaches its current size in the least amount of time. The universe could eventually contract and collapse into a "big crunch" or expand indefinitely. A coasting universe (center) is older than a decelerating universe because it takes more time to reach its present size, and expands forever. An accelerating universe (right) is older still. The rate of expansion actually increases because of a repulsive force that pushes galaxies apart.

Inflation

Expanded a small piece of the Universe: implies there is much of the Universe outside our horizon. Which may have very different constants and properties.