Reading Ahead

- CHAPTER 7 (all)
  - Read the entire chapter with emphasis on pp220-end.
  - ***I will extensively supplement to material in the text.***

- CHAPTER 8 (parts)

  "The Matter and Energy Content of the Universe"

  "In the Beginning"

  "The Supercomputer Approach [to modeling structure]"

Coming up

- Chapter 7 on Dark Energy

Read Now: Coming next

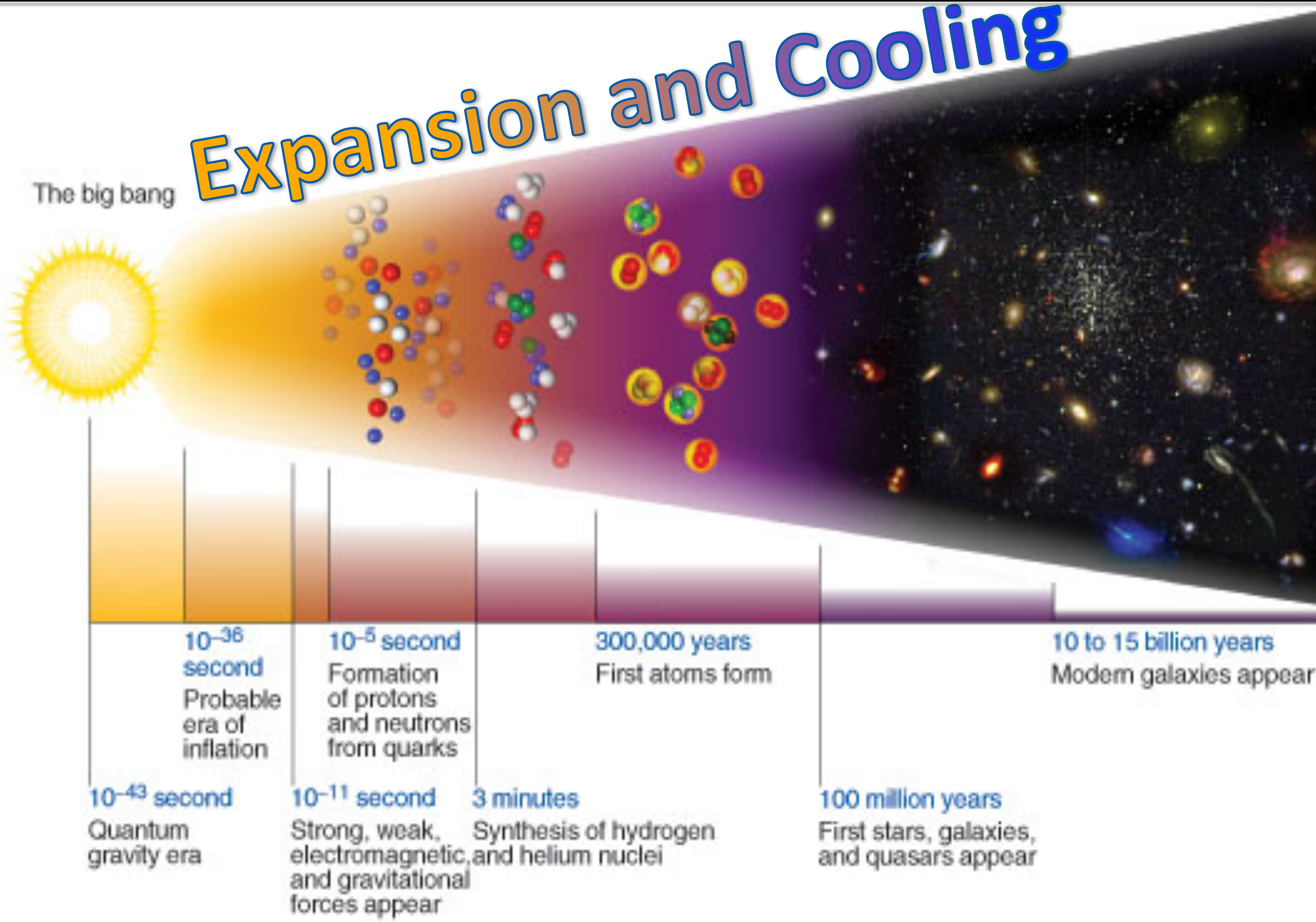
Putting it together

Puzzles and Future Frontiers

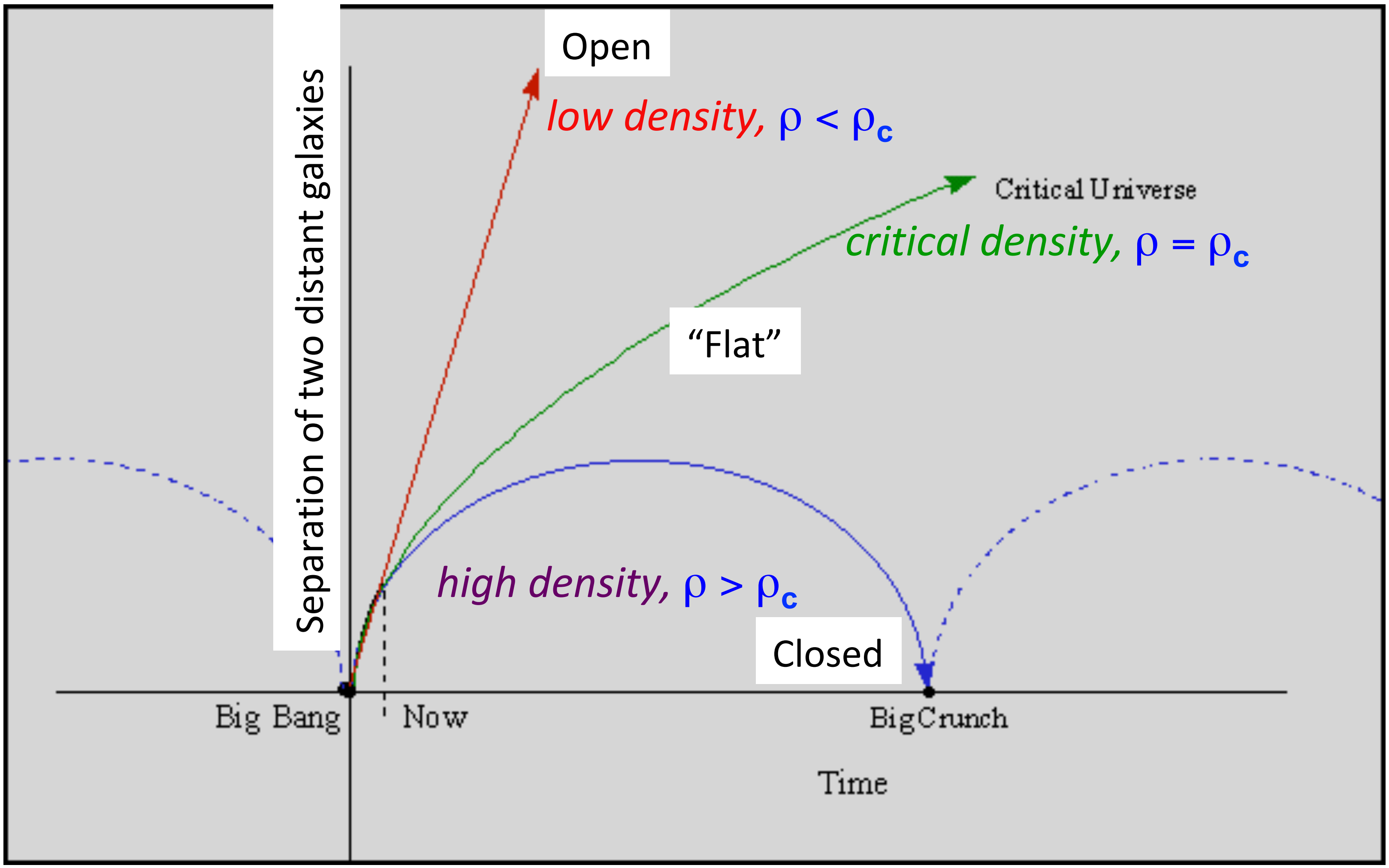
Lecture Content after Ch 7:

From BB to Present
Our Cosmic Future
Anthropic Principle?
Searching for Life

Essences of the BB Model

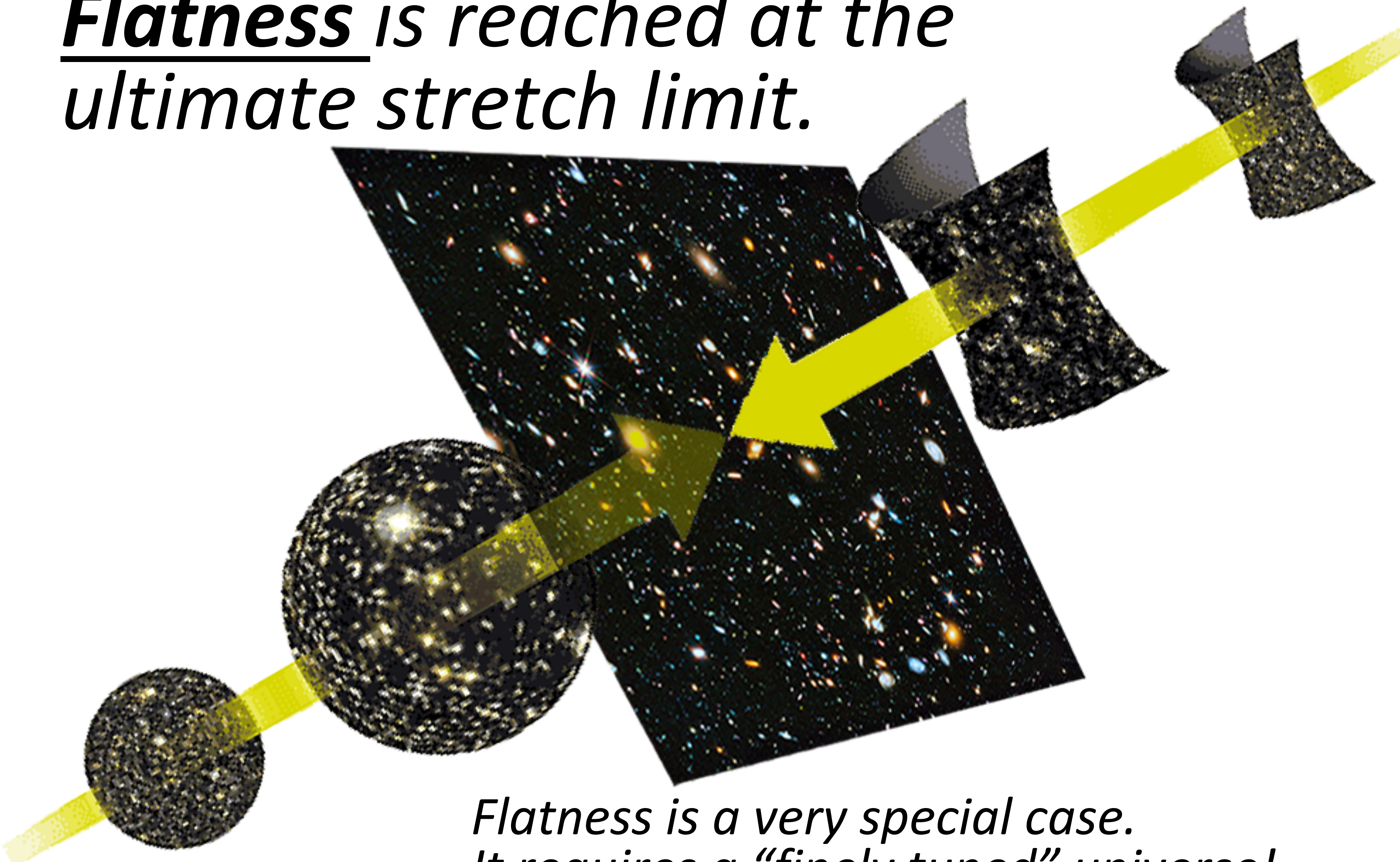


Why Measure the Density?
EINSTEIN: Density is Destiny!



"ρ" = actual cosmic density

Flatness *is reached at the ultimate stretch limit.*



Flatness is a very special case.
It requires a "finely tuned" universe!
So the odds of flatness are slim.

DENSITY IS DESTINY

Mass denstiy = ρ

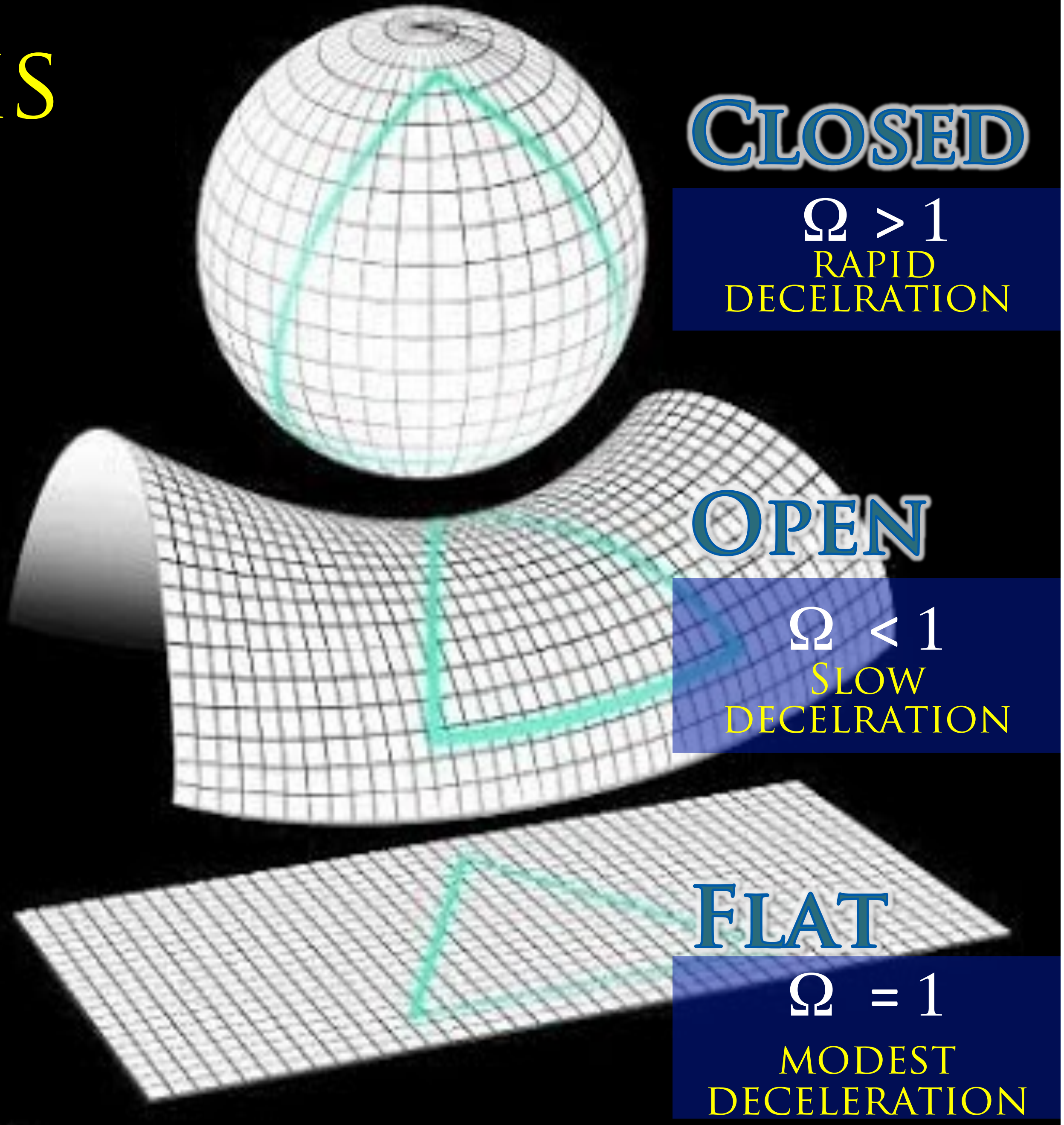
ρ_c = critical density

$\Omega = \rho/\rho_c$

Ω > 1 Universe eventually collapses

Ω < 1 Universe expands while gently slowing down (forever)

Ω = 1 A very special and improbable case



Who Cares about Cosmic Density?

Mass denstiy = ρ

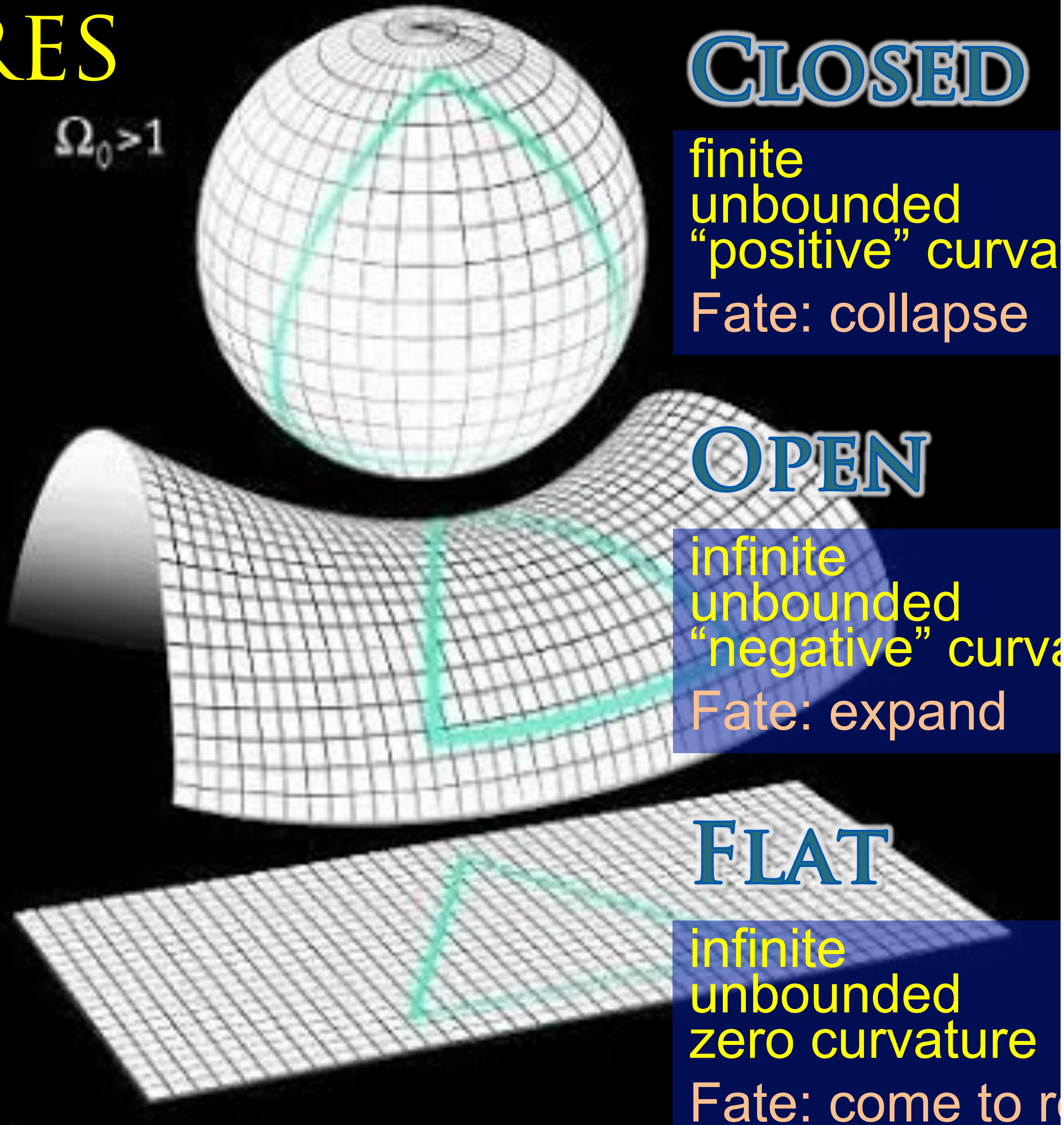
ρ_c = critical density

$\Omega = \rho/\rho_c$

$\Omega > 1$ Universe eventually collapses

$\Omega < 1$ Universe expands while gently slowing down (forever)

$\Omega = 1$ A very special and improbable case



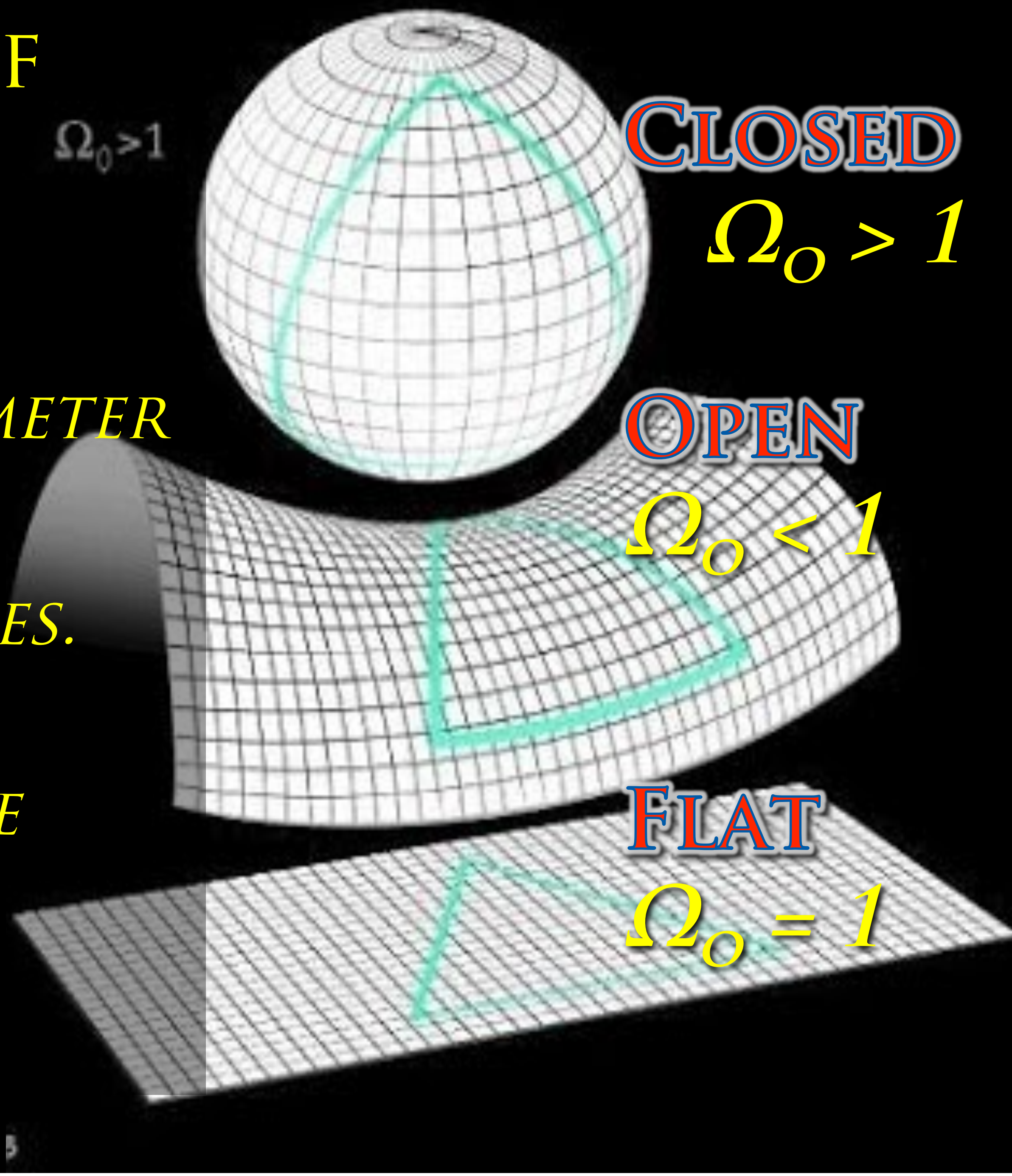
Any (All) of these can Expand,

but the mass density parameter

$$\Omega_o = \rho/\rho_C$$

never changes.

That is, the shape of space is fixed when the universe was born.

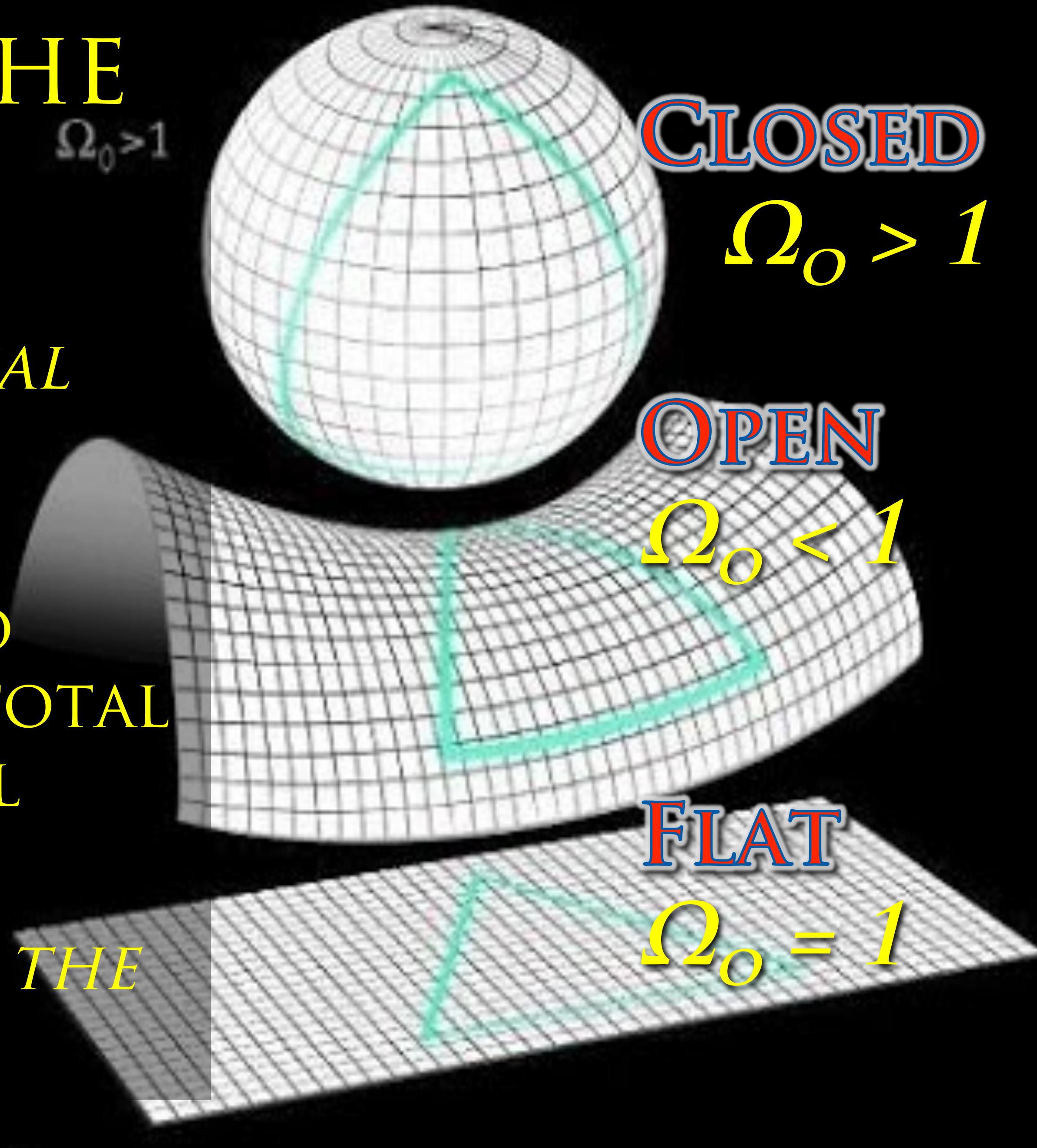


What's the Answer?

No theoretical prediction!

Design an experiment to measure the total gravitational mass ρ.

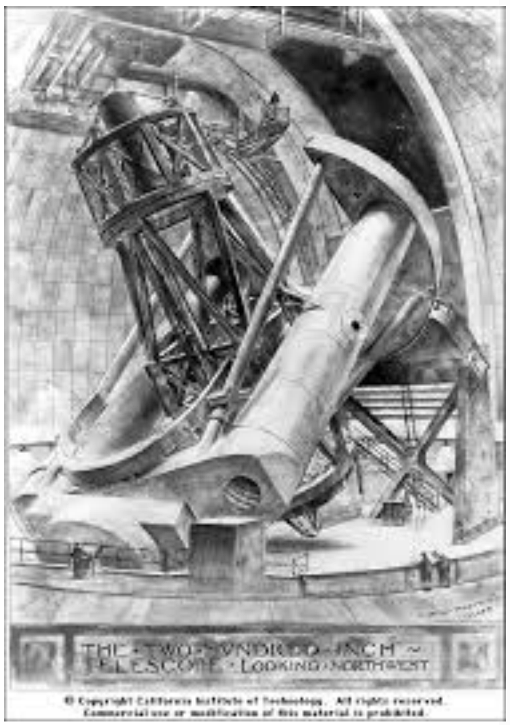
Curvature in the Hubble line!



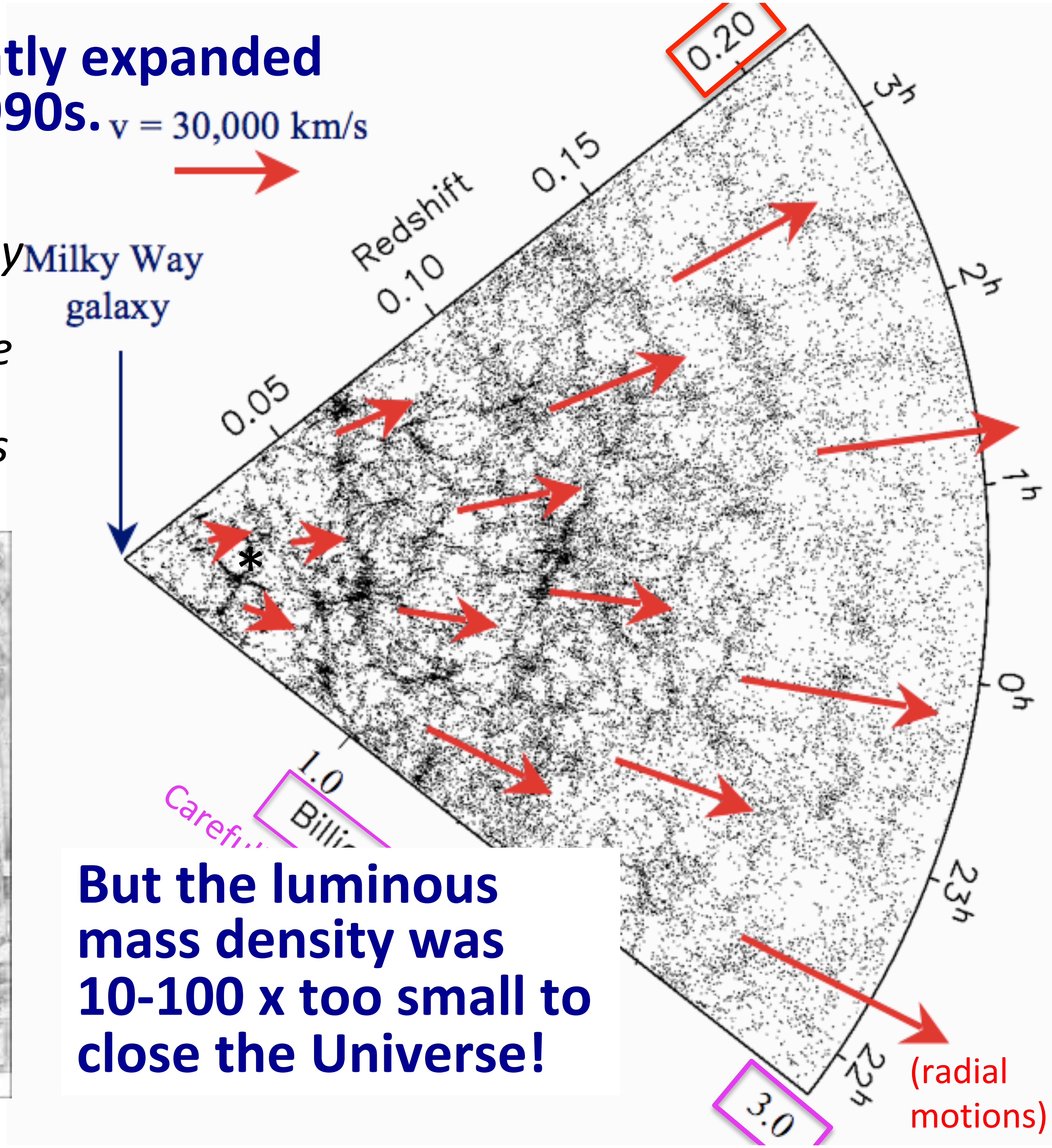
The effort greatly expanded through the 1990s.

1950s to 1980s

Sandage and many others use the 200-inch telescope to estimate the density of galaxies



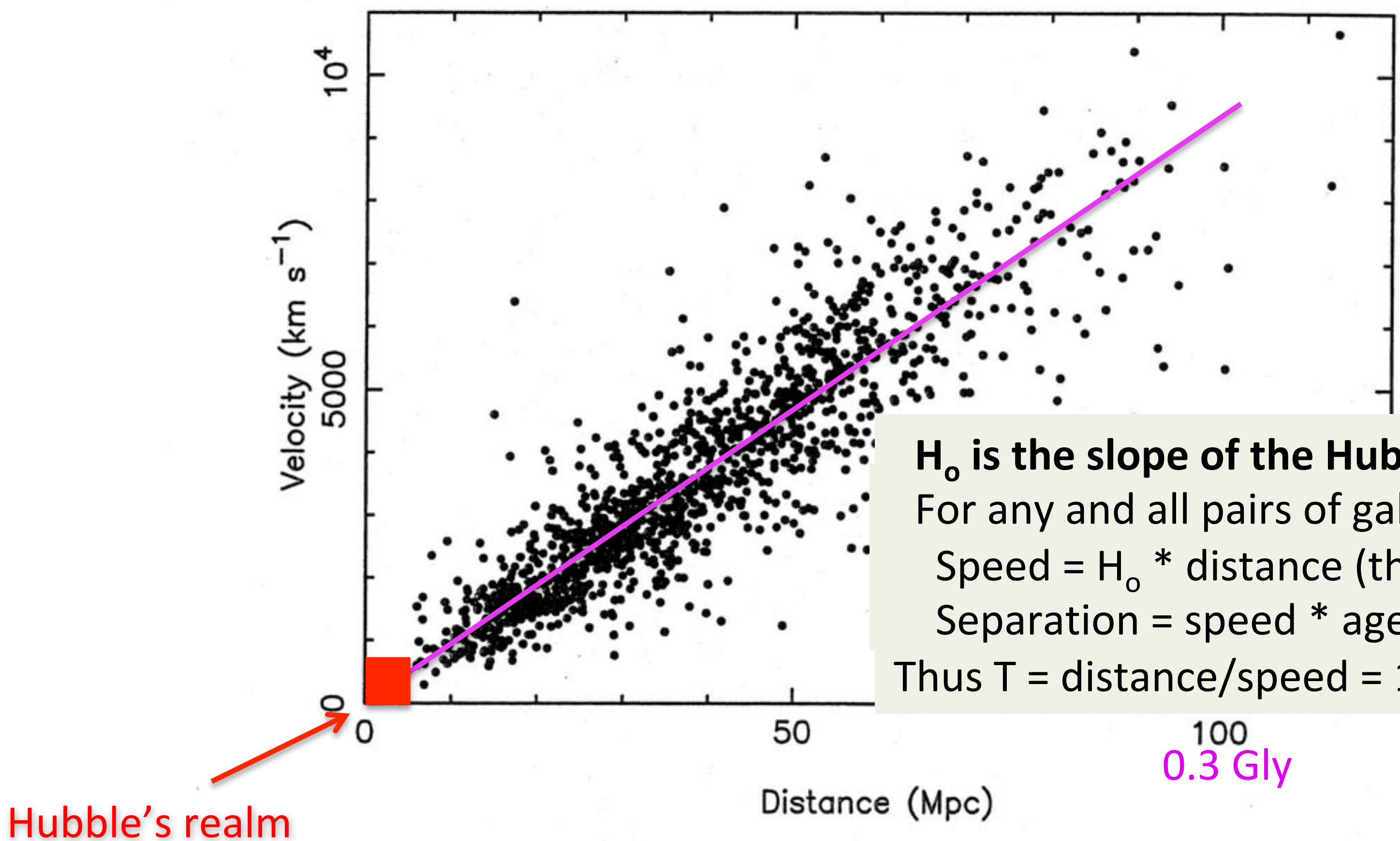
Palomar 200-inch Telescope



But the luminous mass density was 10-100 x too small to close the Universe!

Cosmic Deceleration Measures Gravitational Mass

(**all mass** whether visible or not)



H_o is the slope of the Hubble Law

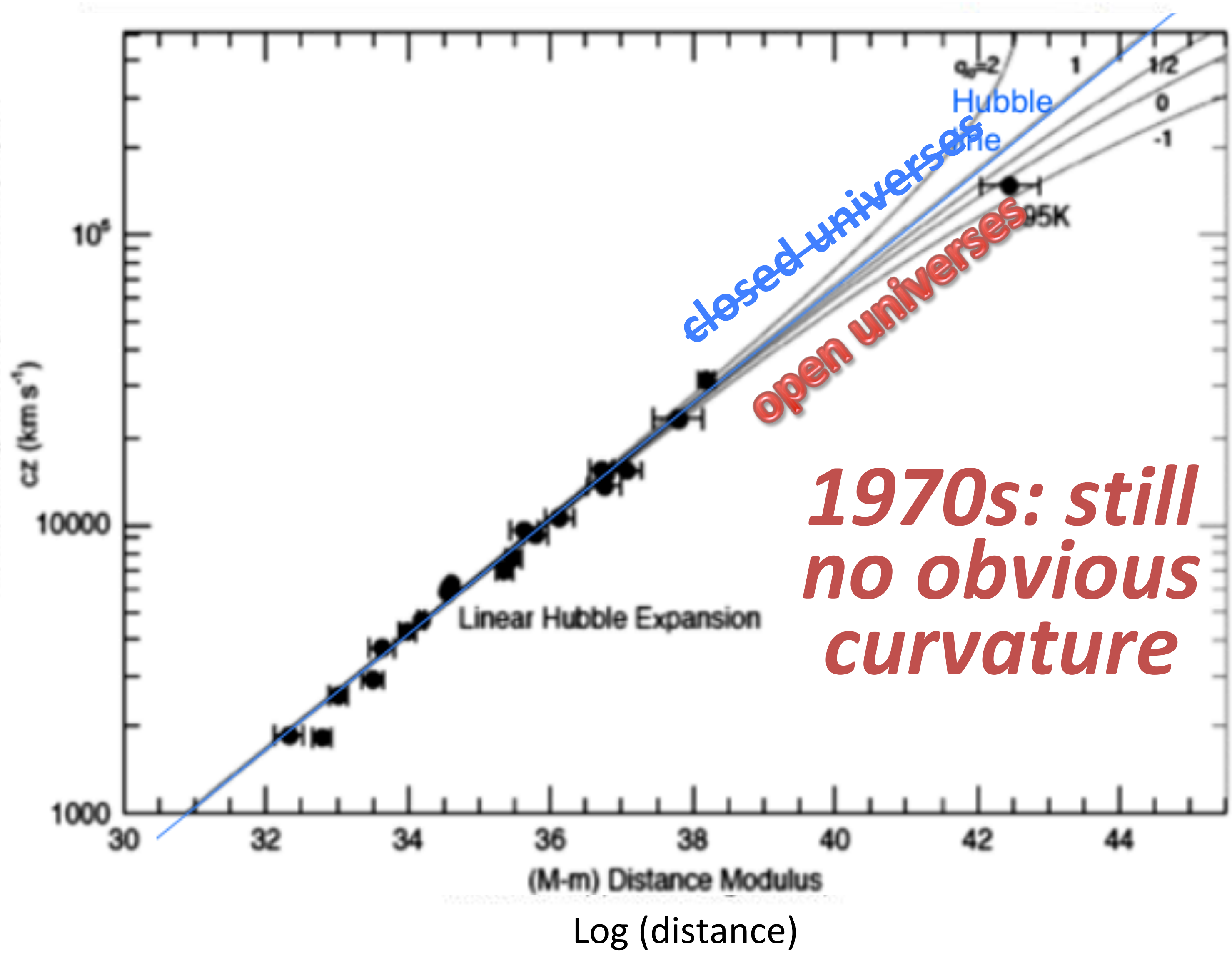
For any and all pairs of galaxies:

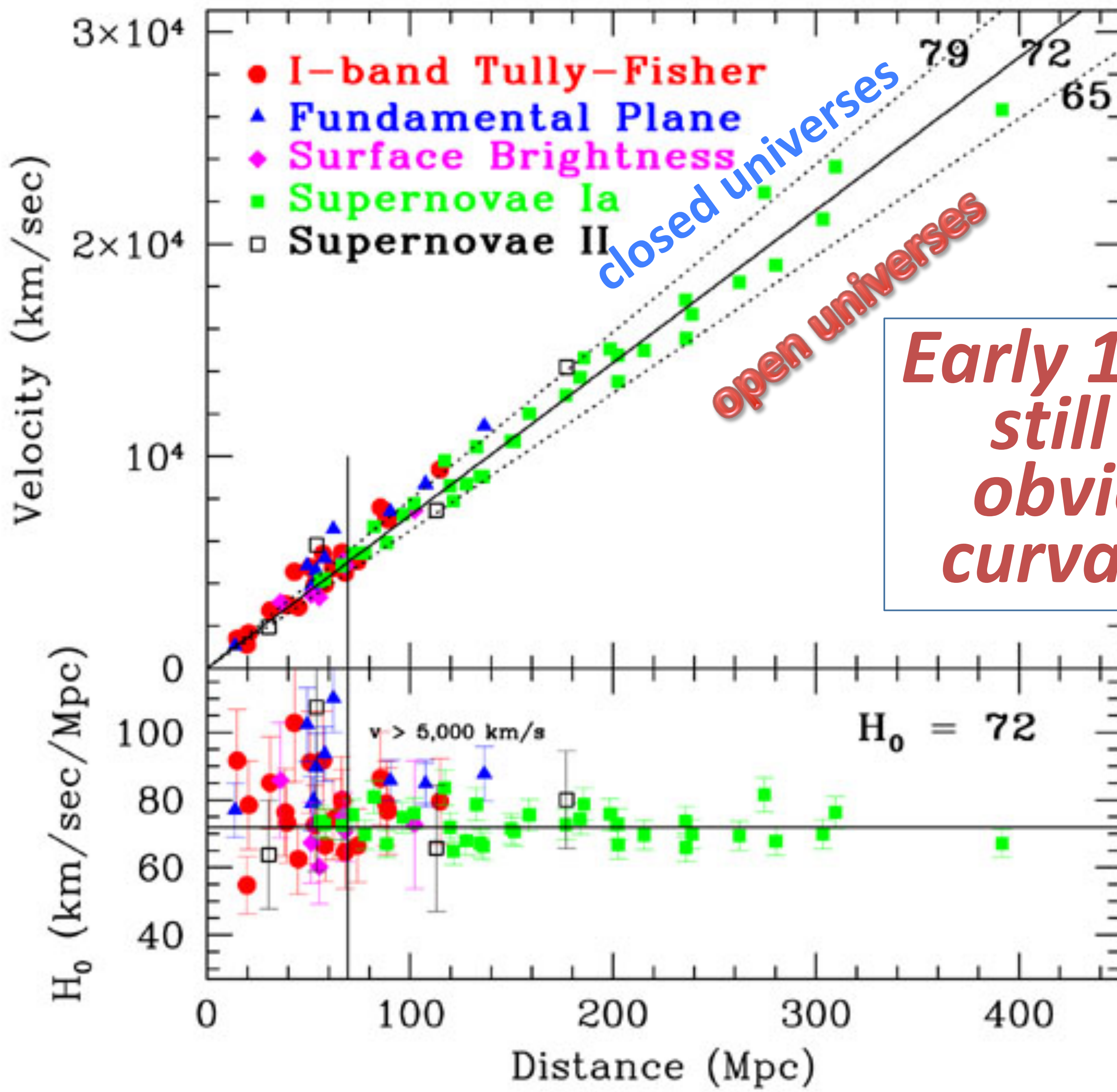
Speed = H_o * distance (this graph)

Separation = speed * age of Universe T

Thus T = distance/speed = 1 / H_o

Figure 2.5 A plot of velocity versus estimated distance for a set of 1355 galaxies. A straight-line relation implies Hubble's law. The considerable scatter is due to observational uncertainties and random galaxy motions, but the best-fit line accurately gives Hubble's law. [The x-axis scale assumes a particular value of H_0.]


closed universes
Hubble line
open universes
1970s: still no obvious curvature
Linear Hubble Expansion
95K
1
1/2
0
-1
cz (km s⁻¹)
10000
1000
30
32
34
36
38
40
42
44
(M-m) Distance Modulus
Log (distance)



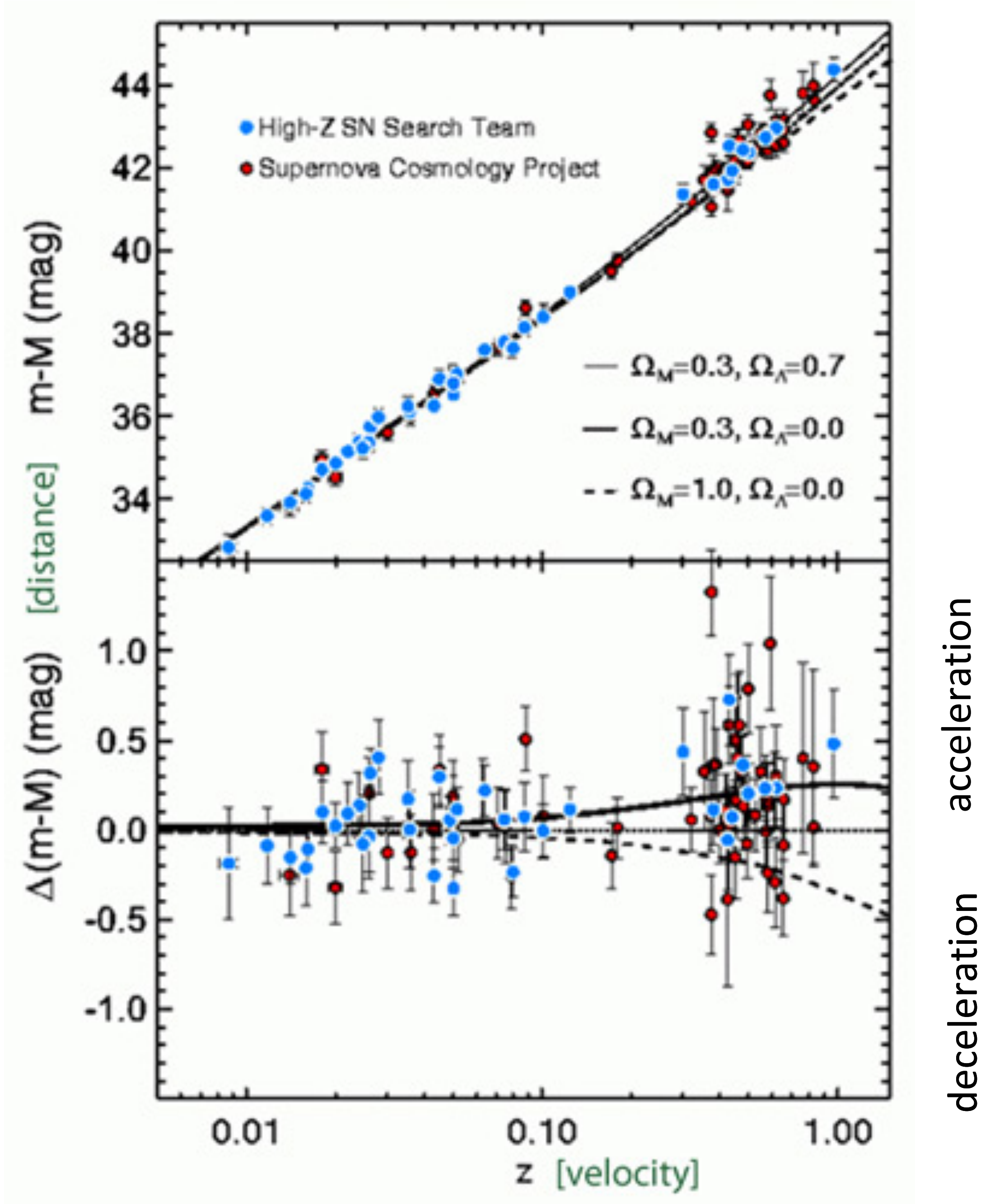
Early 1990s: still no obvious curvature

Curvature! At long last!

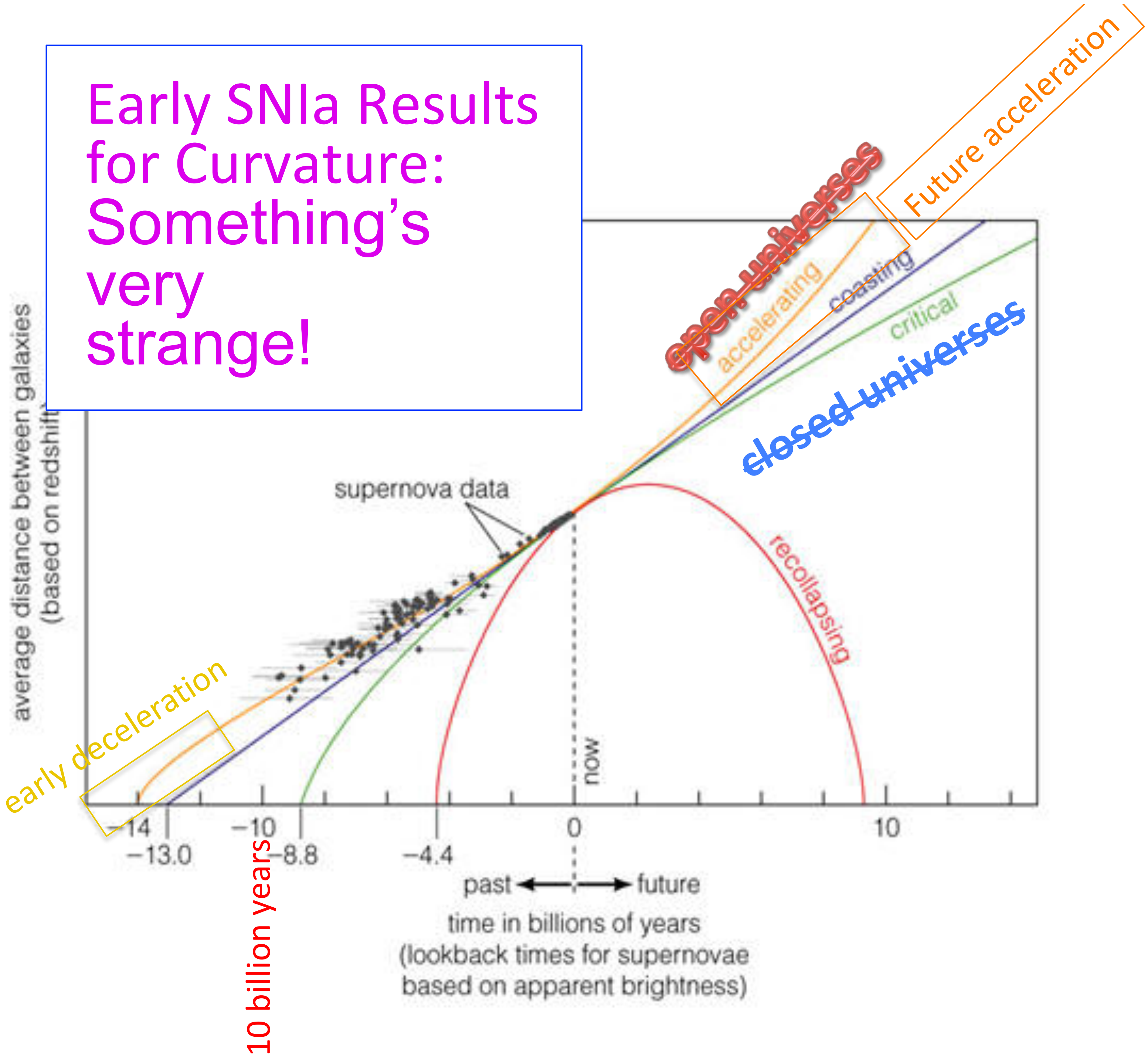
But. . .

The curvature went the wrong way!!

The data refused to fit any classical model of deceleration.

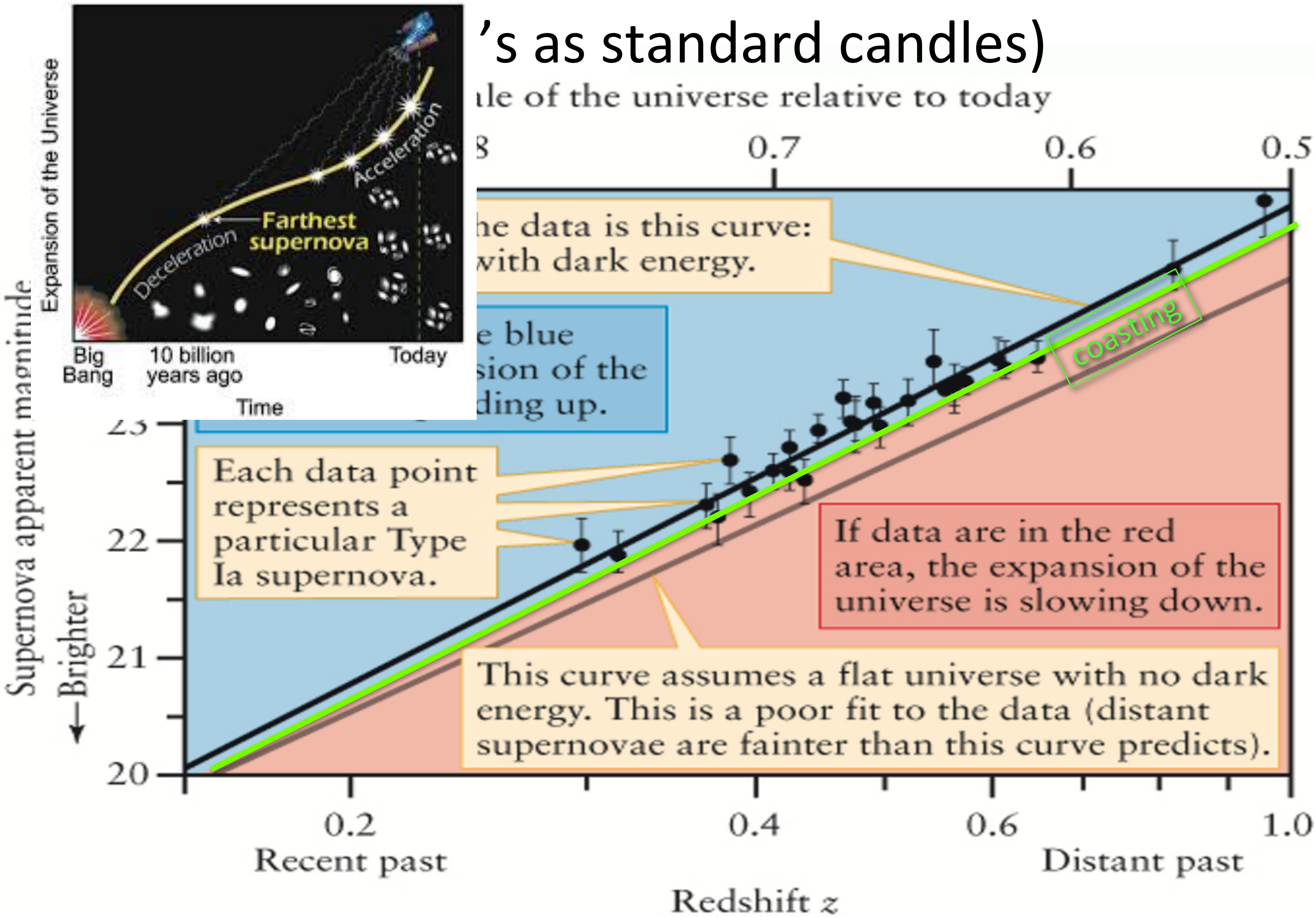


Early SNIa Results for Curvature: Something's very strange!

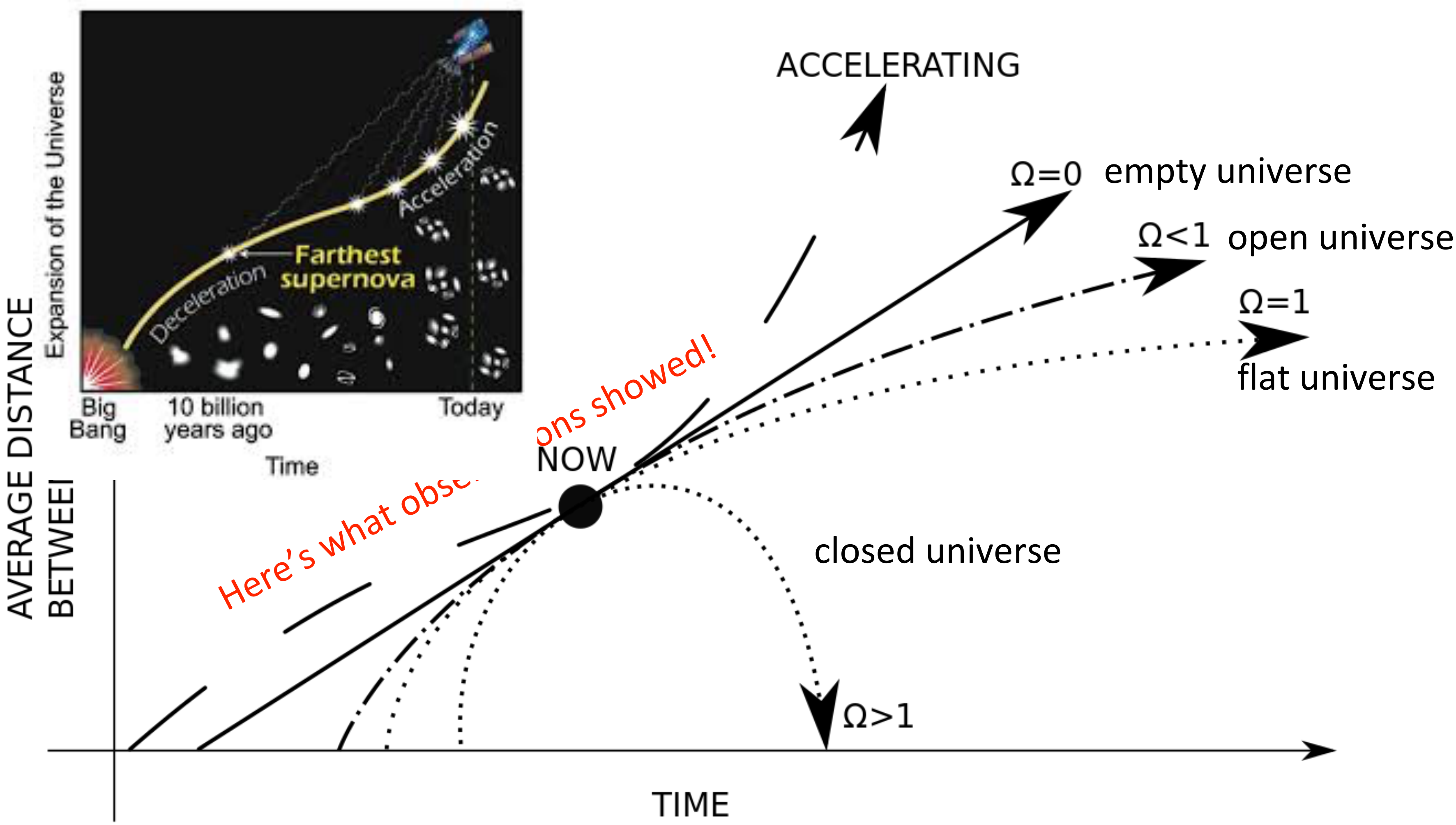


First detection of Dark Energy (1998)

’s as standard candles)

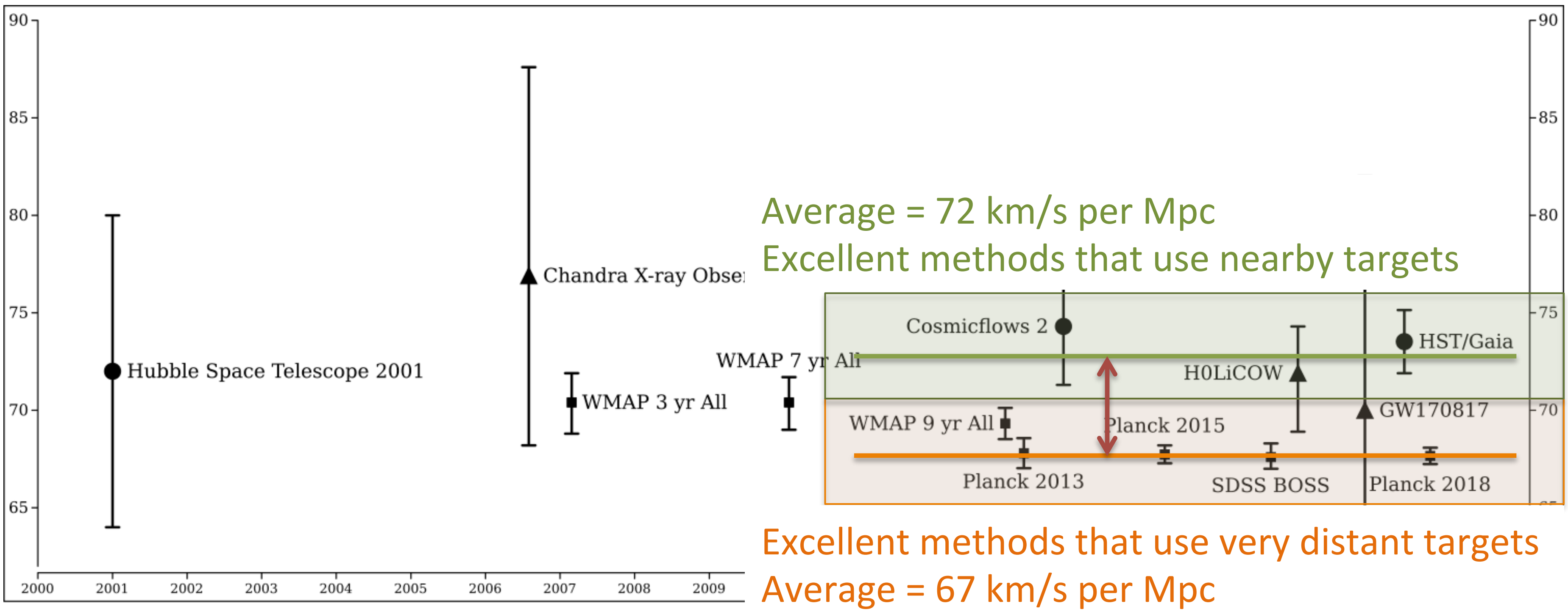


Surprise!
Dark Energy Changes the Game



The expansion of the Universe started increasing 5 billion years ago!

Also strange:
2018 Results for the slope H_o



Is the difference real or unrecognized systematic error?

Taken at face value, the rate of cosmic expansion is ≈10% faster now than when the CMB radiation was emitted!