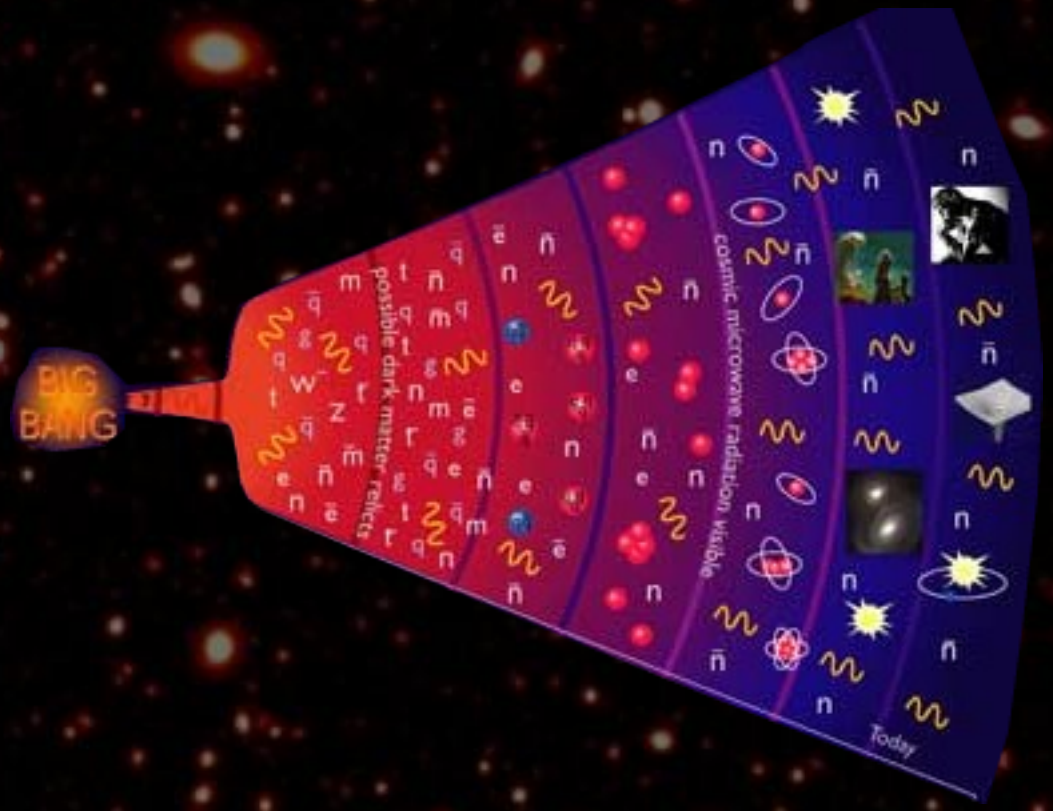
A modern picture of

The Expanding Universe



Robert Knop
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Vanderbilt University

Hypericon II – 2006 June 23

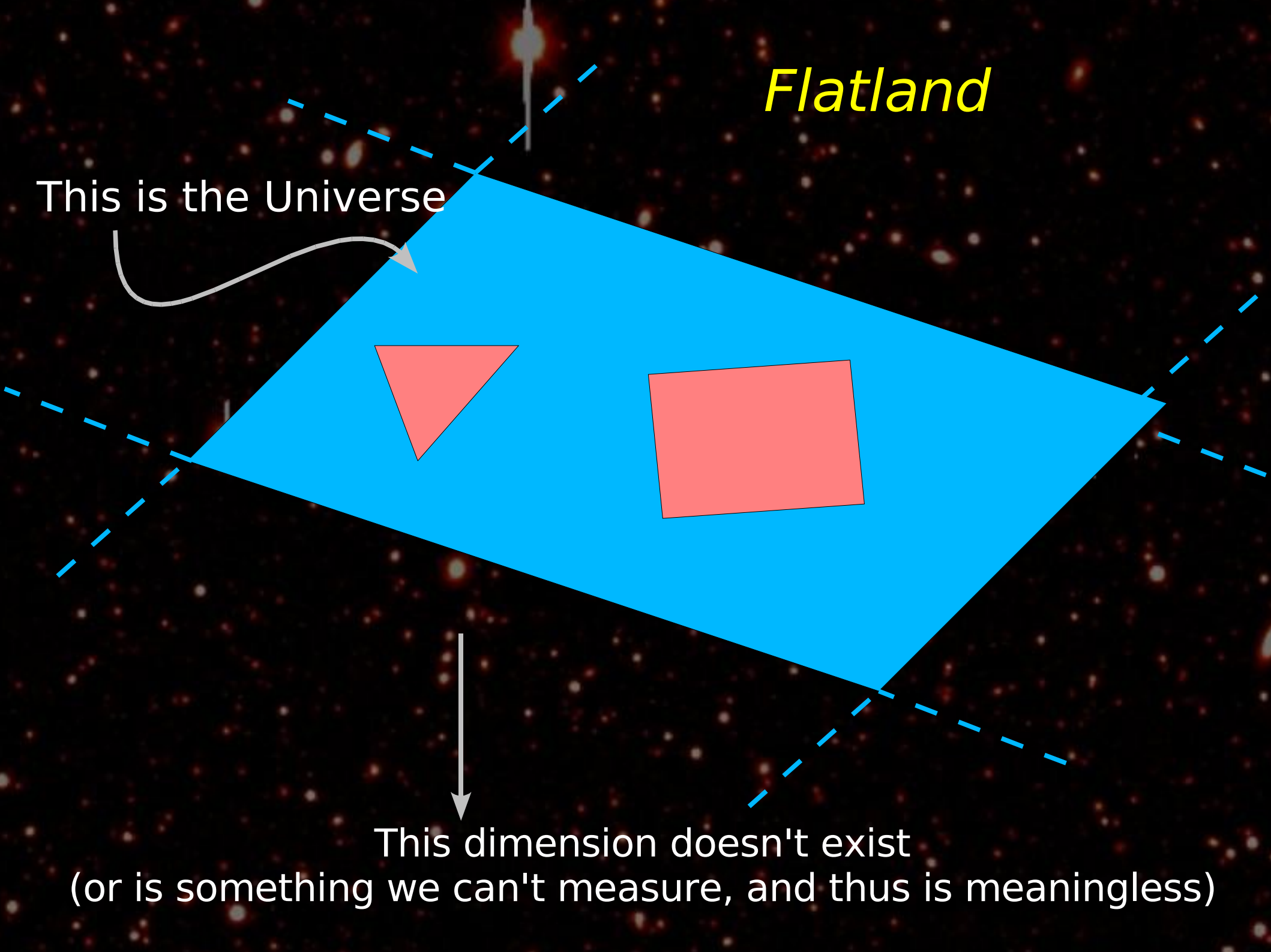
I. The Shape of the Universe.
   - *Flatland* analogy
   - Non-Euclidean Geometry

II. The Expansion of Space
   - Measuring Expansion: Redshift
   - Measuring Expansion Rate

III. A Little Data: how we know
   - A consistent picture of the Whole Universe (!!)

IV. Reality Check: The “old way” of describing the expansion

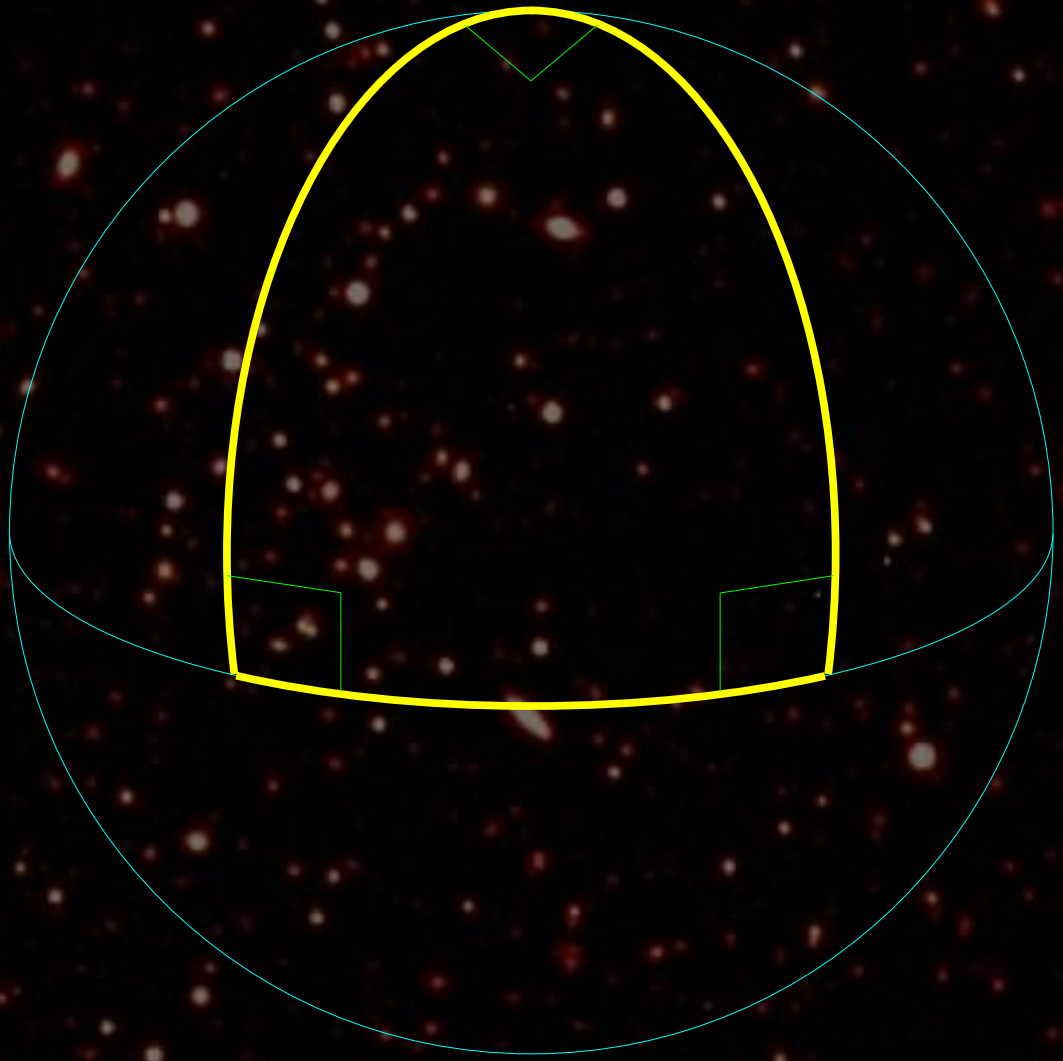
V. How did we get here? The Big Bang....


Flatland
This is the Universe
This dimension doesn't exist
(or is something we can't measure, and thus is meaningless)

Flat (Euclidean) Space:

Any triangle, three interior angles add to 180°

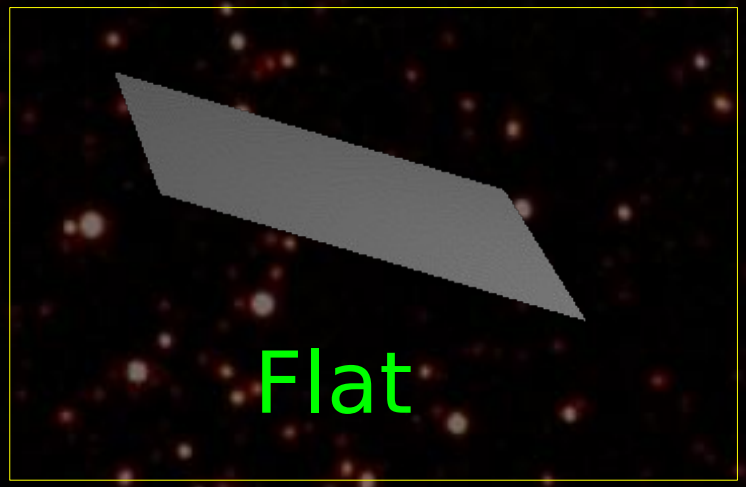
Flatland (2-dimensional) creatures could measure this curvature without reference to the third dimension we use to describe this here!

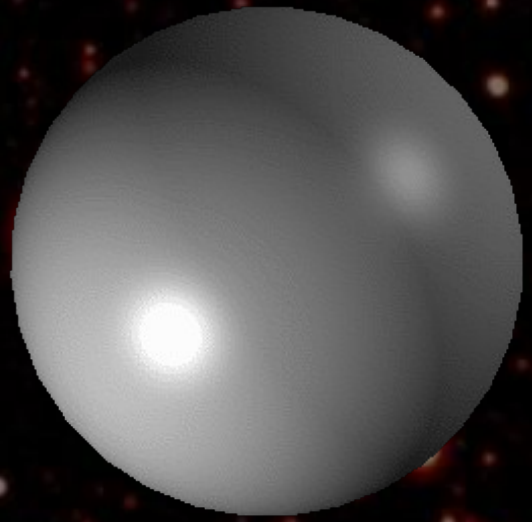


Curved Space: *This* triangle, three interior angles add to 270°

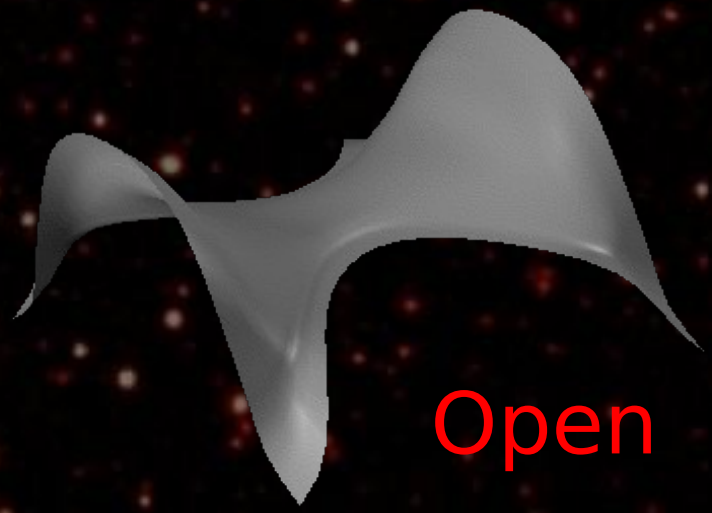
(In general: >180° : positive curvature
<180° : negative curvature)

Possible Shapes of the Universe



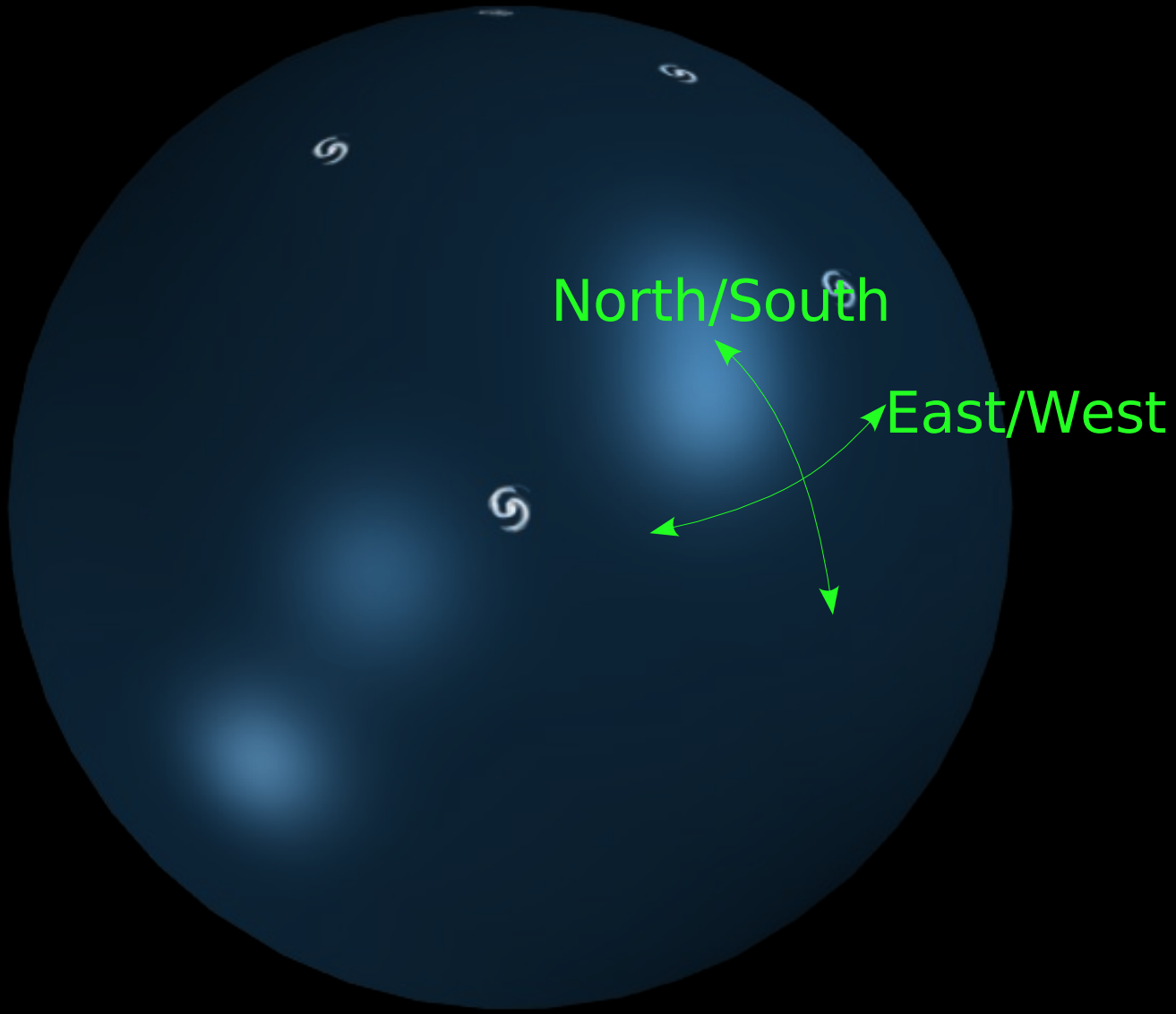


Closed

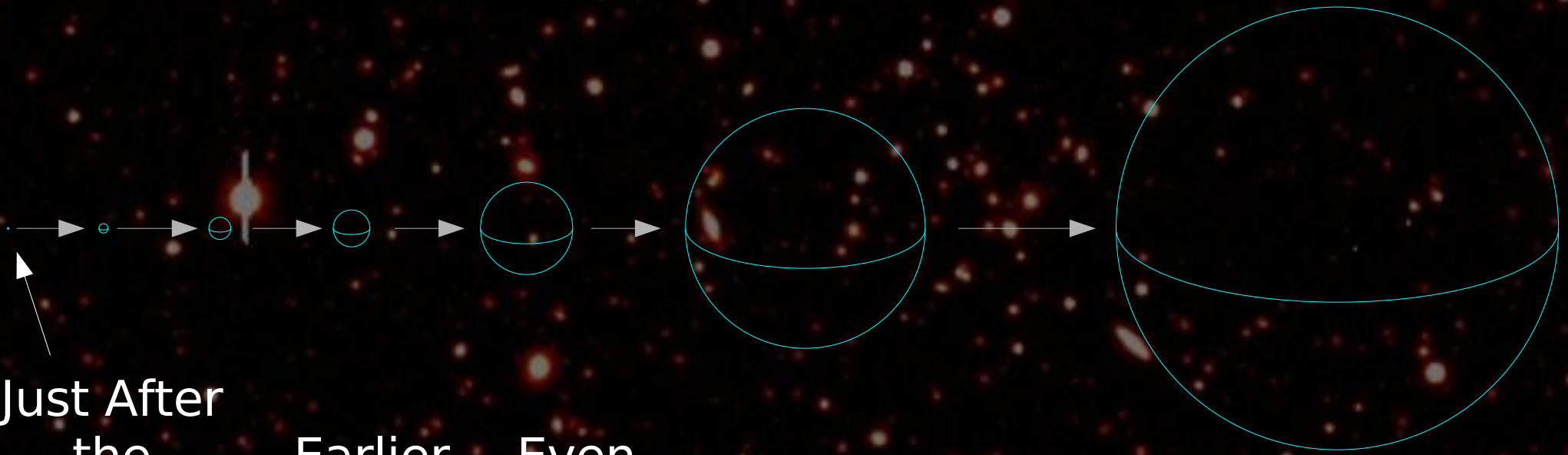


Open

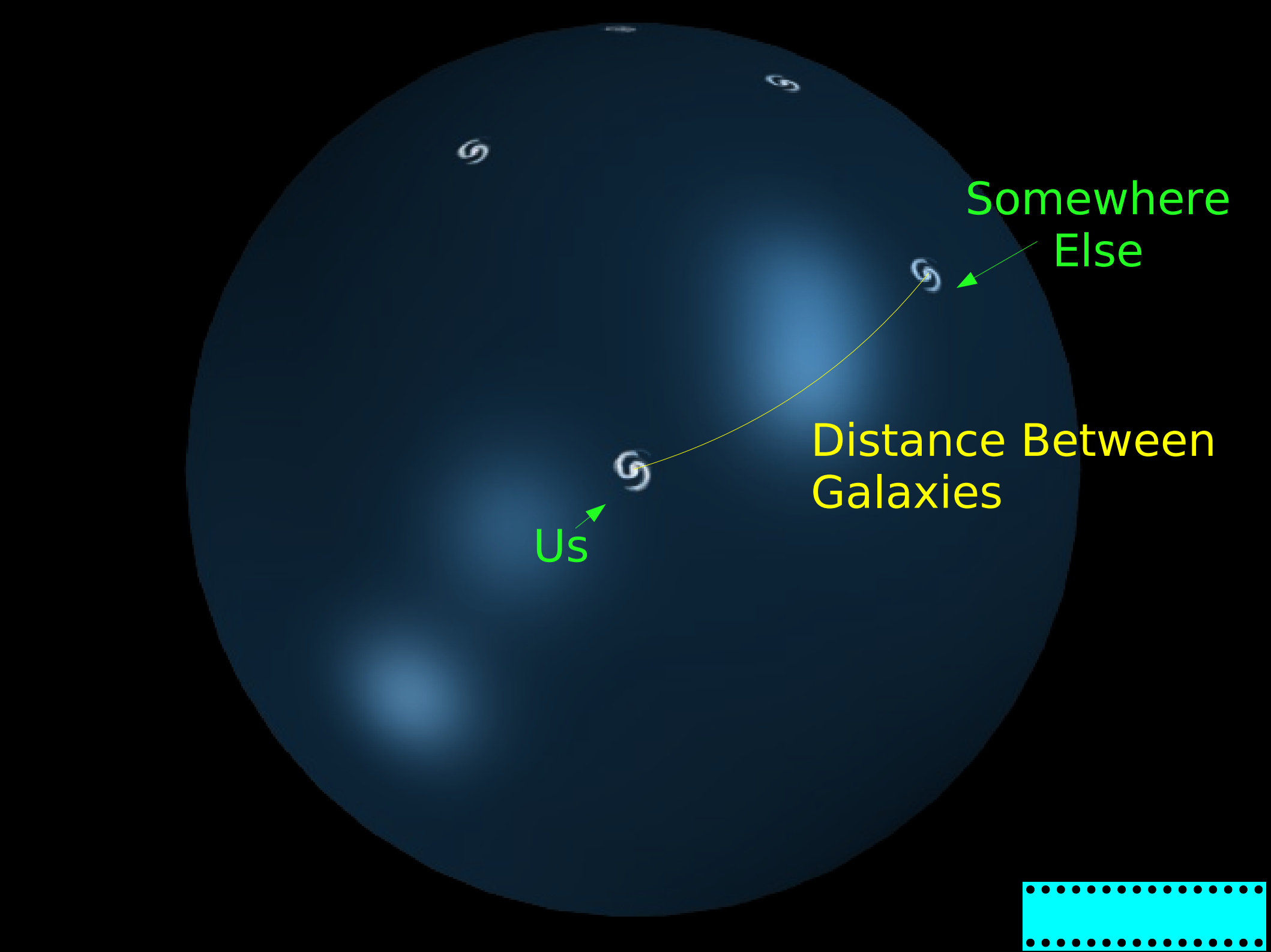
A model 2-d closed Universe: the ***surface*** of a sphere

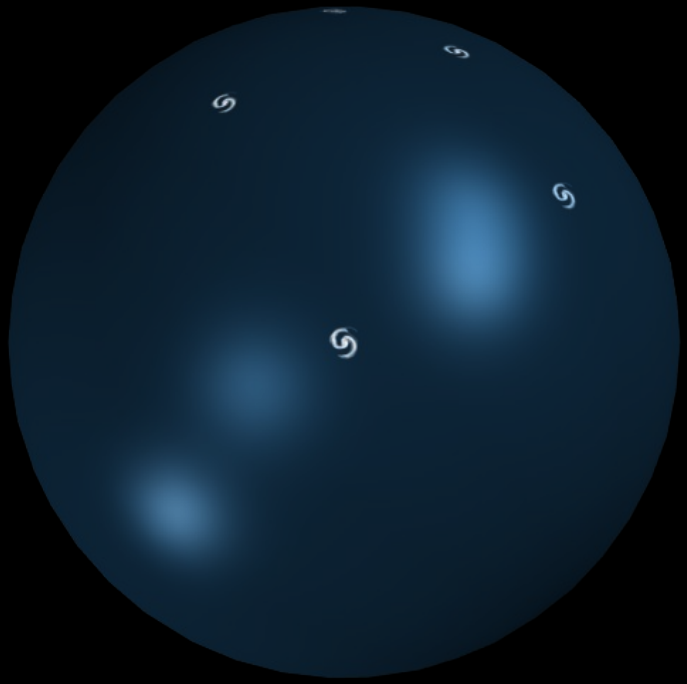


Taking the expansion back in time towards the beginning....



Where, on the surface of this sphere, is the center?

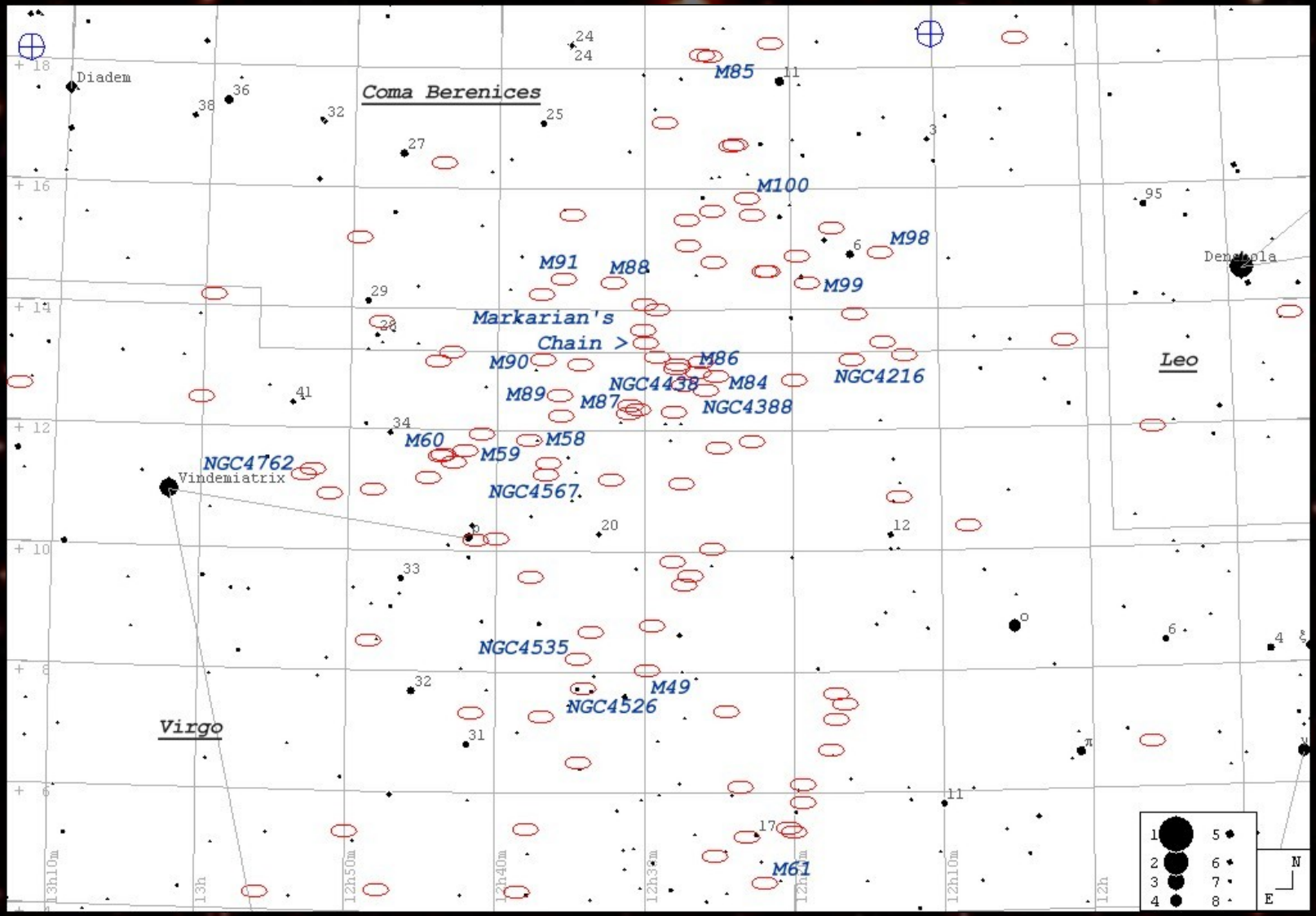

Somewhere
Else
Distance Between
Galaxies
Us



Points to notice

- As the Universe expands, galaxies get farther apart, but...
- ...galaxies are *not* moving *through space* **
- Galaxies *don't* expand themselves
- This is probably not the explanation you've heard (i.e. galaxies flying apart with greater speeds at greater differences), but better expresses the modern view of how the Universe works.

The Virgo Cluster



Map by
Jan Wisniewski

Distance today: 20 Mpc (million parsecs)

Distance in 100 years: 20 Mpc + 1×10^{-9} Mpc. (Oh well)

“Look-back” time to Virgo Cluster:

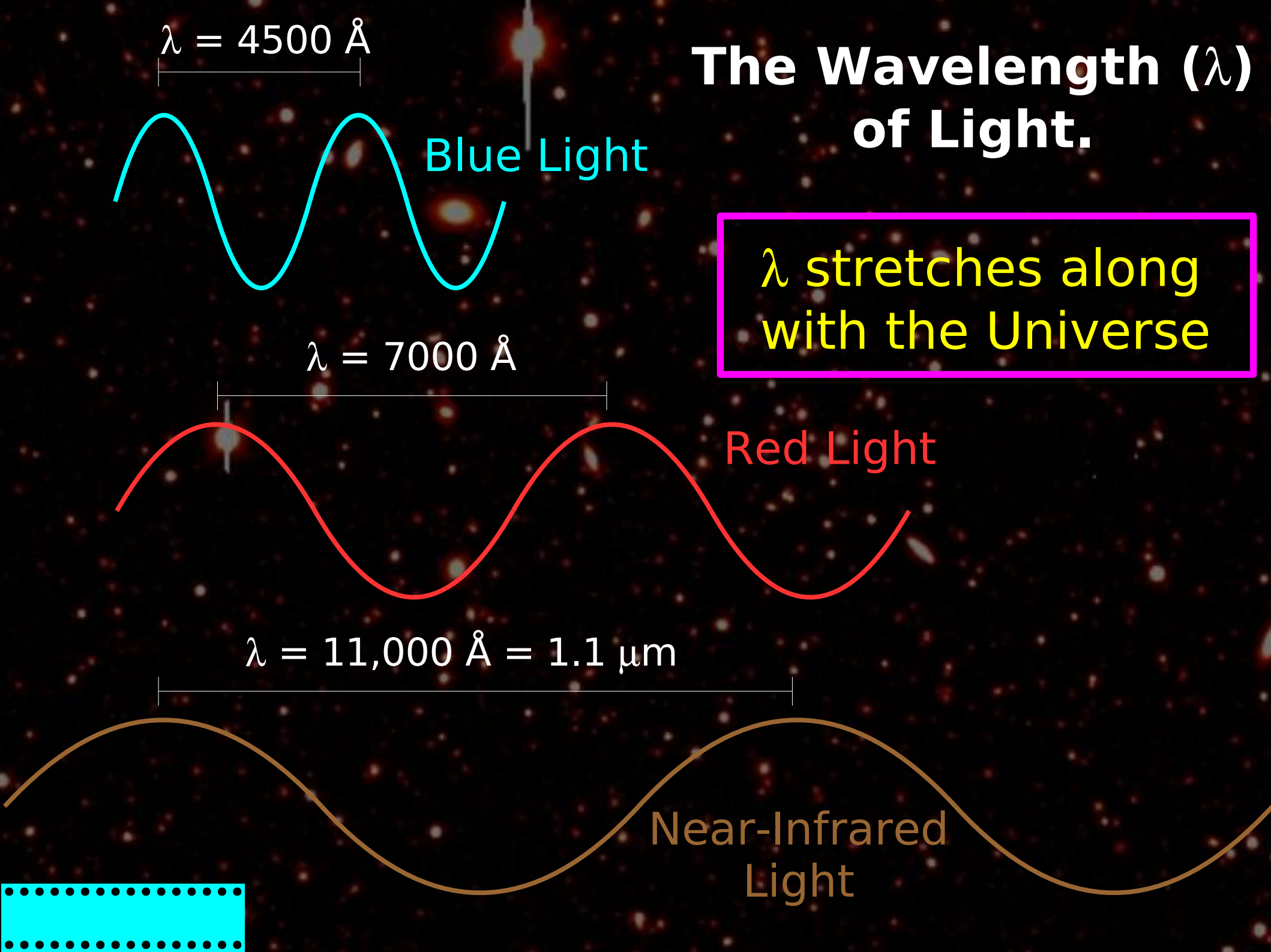
1 parsec = 3.26 light-years

Light goes 1 light-year in one year (surprise!)

20 million parsecs means we see the Virgo clutser as it was 65 million years ago.

Can we find something that has expanded along with the Universe over that time????

Yes! Light!



The Wavelength (λ) of Light.

λ stretches along with the Universe

Cosmological Redshift (z)

Amount wavelength shifts to the red

$$z = \frac{\Delta\lambda}{\lambda}$$

Original emitted wavelength

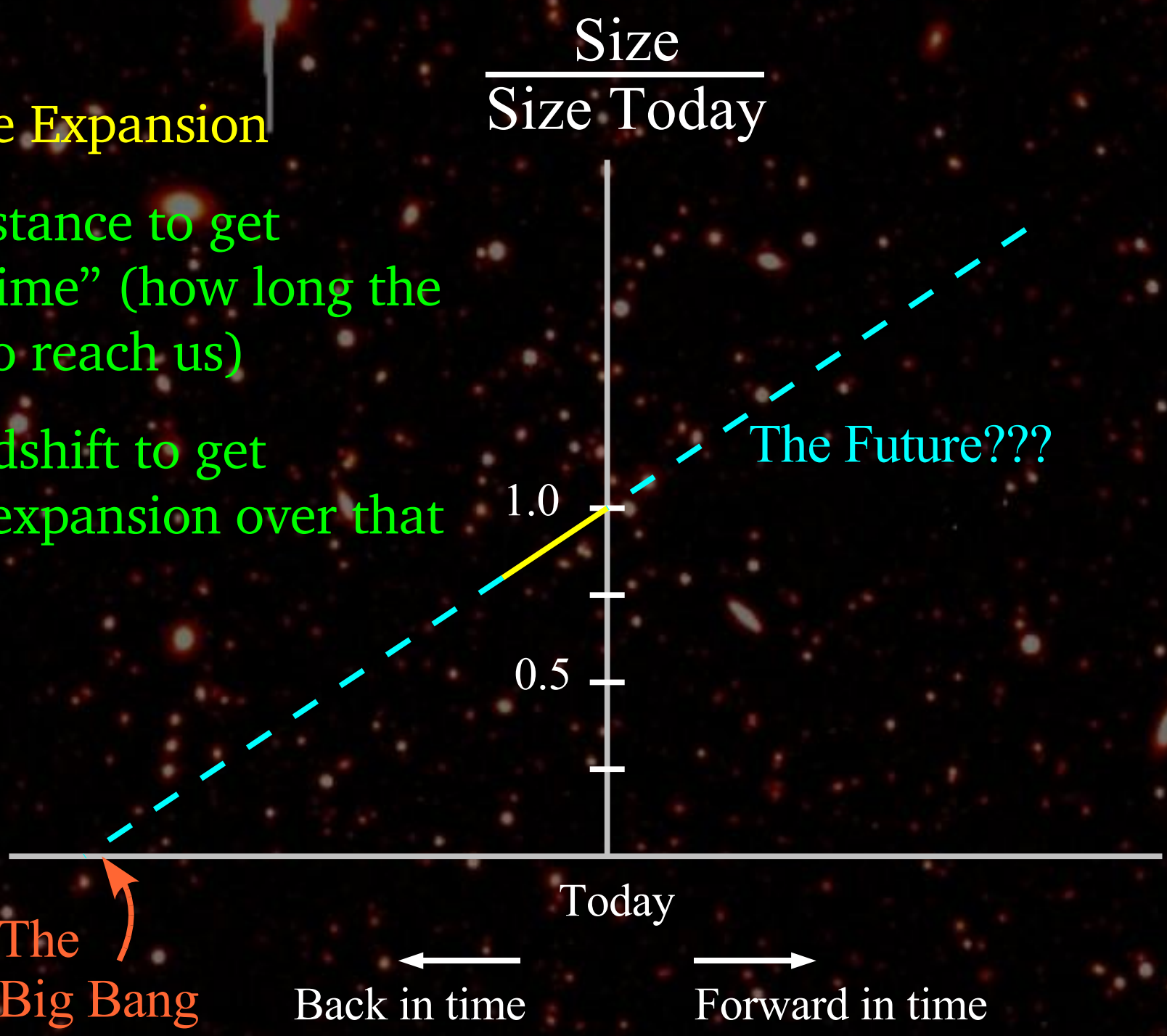
$$1 + z = \frac{\lambda + \Delta\lambda}{\lambda} = \frac{\lambda_{observed}}{\lambda_{original}}$$

$$= \frac{\text{Size of Universe at Detection}}{\text{Size of Universe at Emission}} = \frac{\text{Size Now}}{\text{Size Then}}$$

Redshift tells us directly how much the Universe has expanded while the light was traveling to us.

Measuring the Expansion

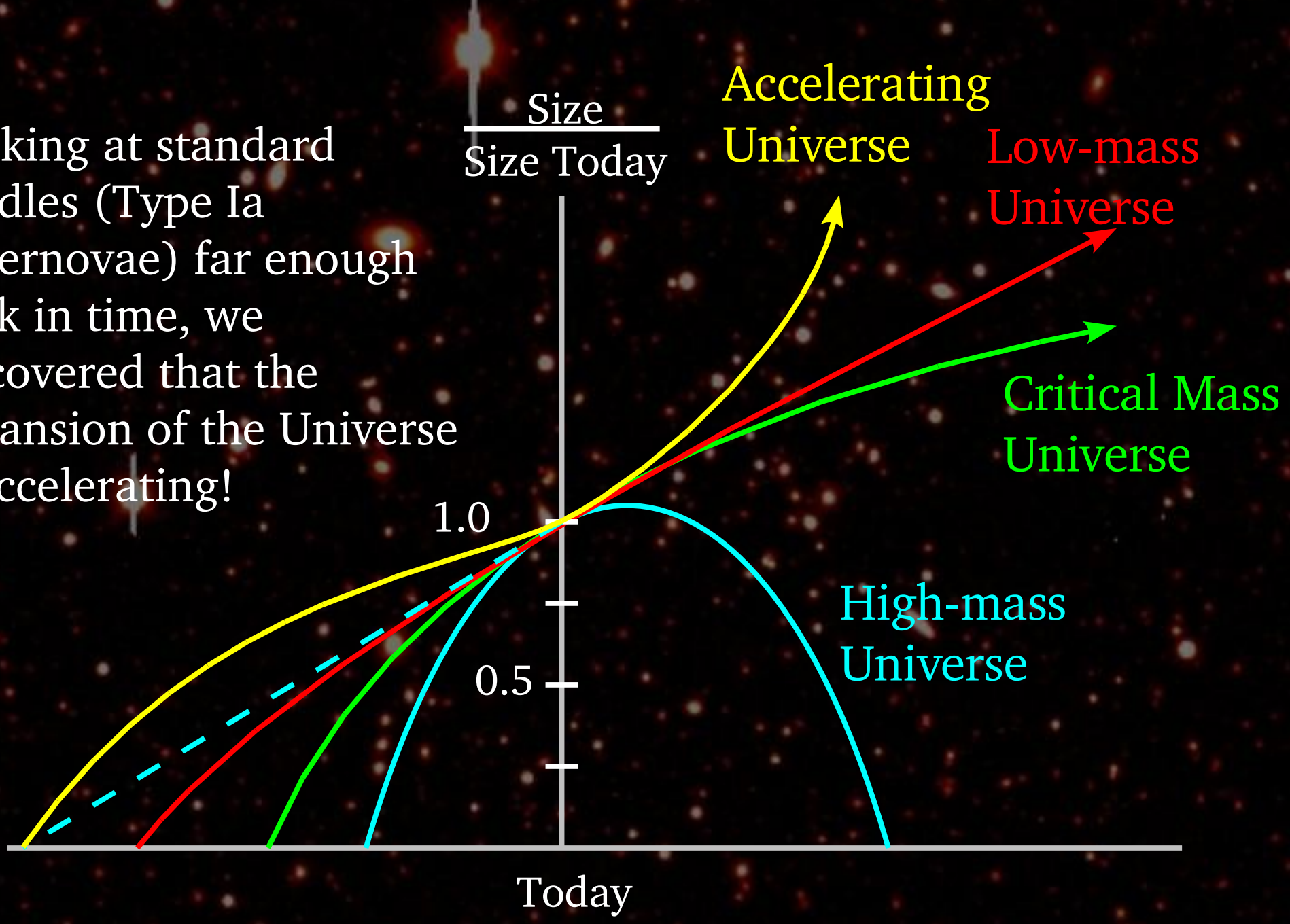
- Measure distance to get "lookback time" (how long the light took to reach us)
- Measure redshift to get amount of expansion over that time.



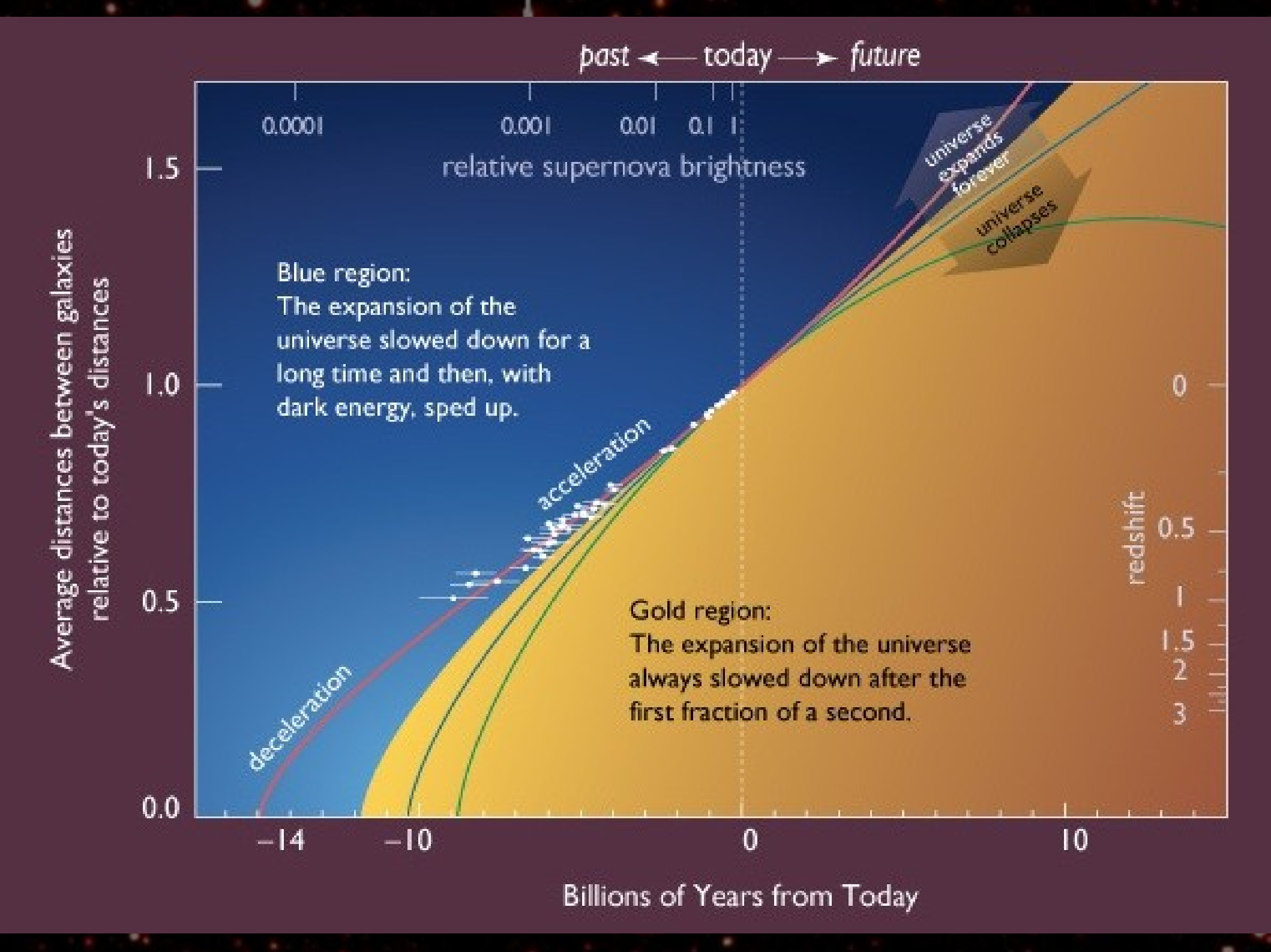
Lookback Times

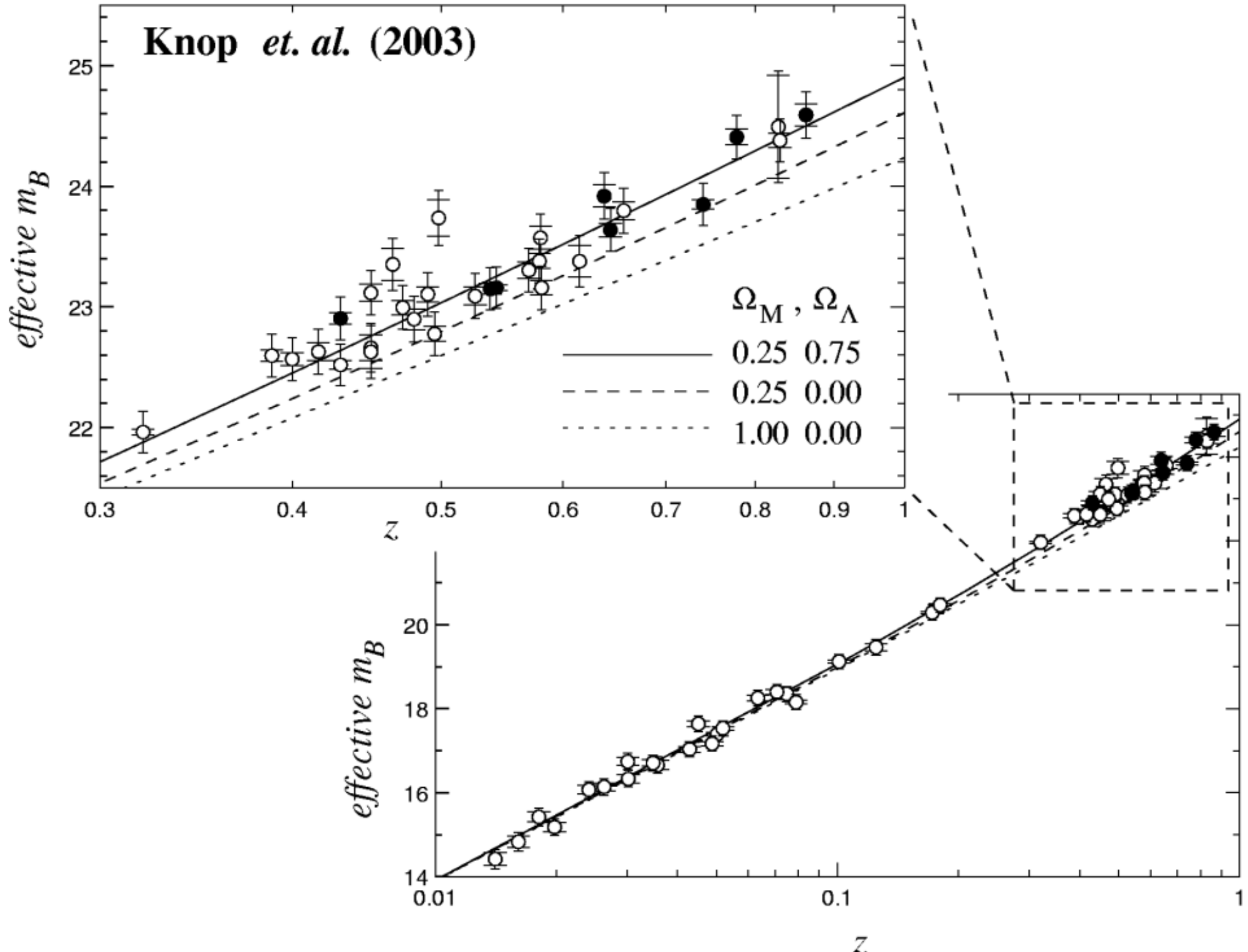
Object	Lookback Time
Sun	8 minutes
Alpha Centauri	4 years
Andromeda Galaxy	2 million years
Seyfert Galaxy NGC1068	16 million years
Quasar 3C273 at z=0.158	2 billion years
Galaxy at z=1	7 billion years
Age of Universe	13 billion years

Looking at standard candles (Type Ia supernovae) far enough back in time, we discovered that the expansion of the Universe is accelerating!



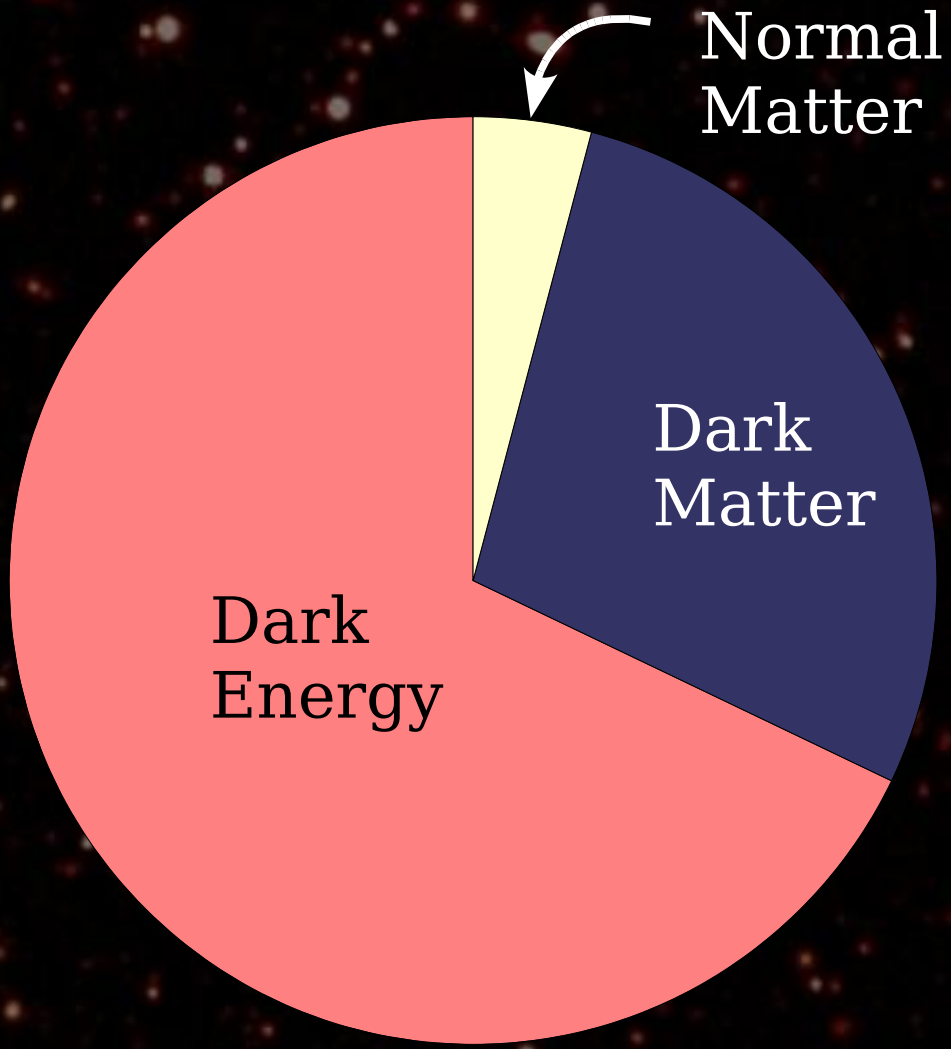

A little data...

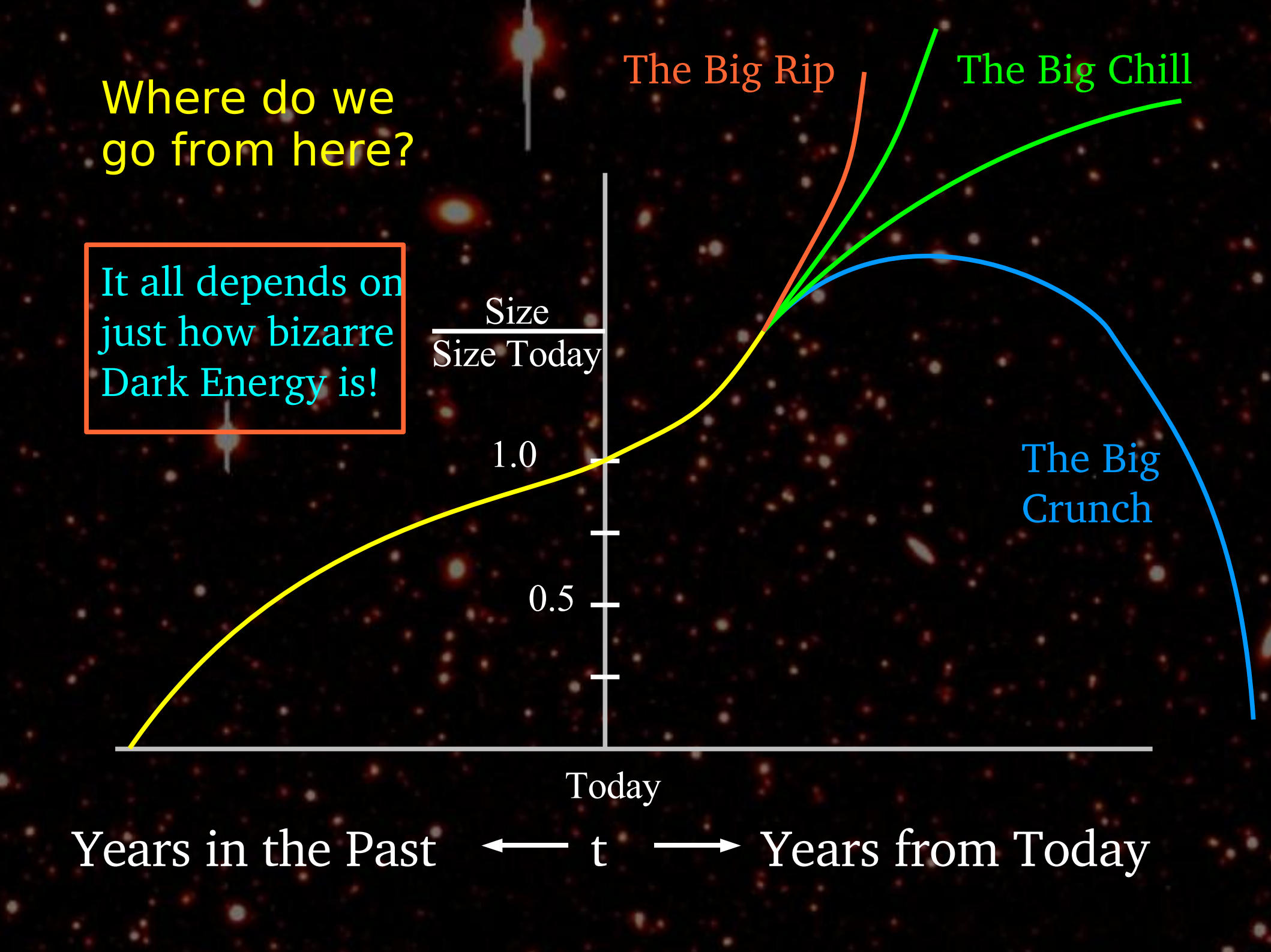

past
today
future
0.0001
0.001
0.01
0.1
1
relative supernova brightness
universe expands forever
universe collapses
Blue region:
The expansion of the universe slowed down for a long time and then, with dark energy, sped up.
acceleration
deceleration
Gold region:
The expansion of the universe always slowed down after the first fraction of a second.
redshift
0
0.5
1
1.5
2
3
Average distances between galaxies relative to today's distances
0.0
0.5
1.0
1.5
−14
−10
0
10
Billions of Years from Today


Knop et. al. (2003)
effective m_B
z
Ω_M , Ω_Λ
0.25 0.75
0.25 0.00
1.00 0.00
25
24
23
22
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
20
18
16
14
0.01
0.1
1

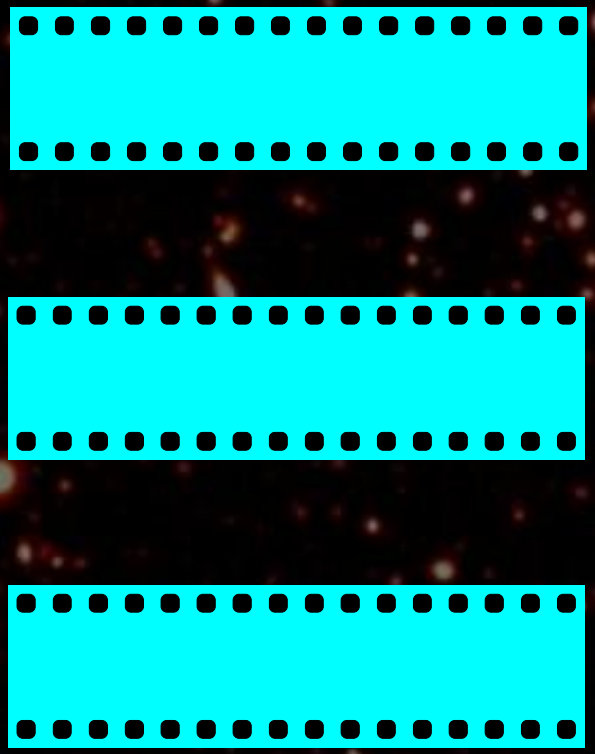
A Consistent Picture of the Universe

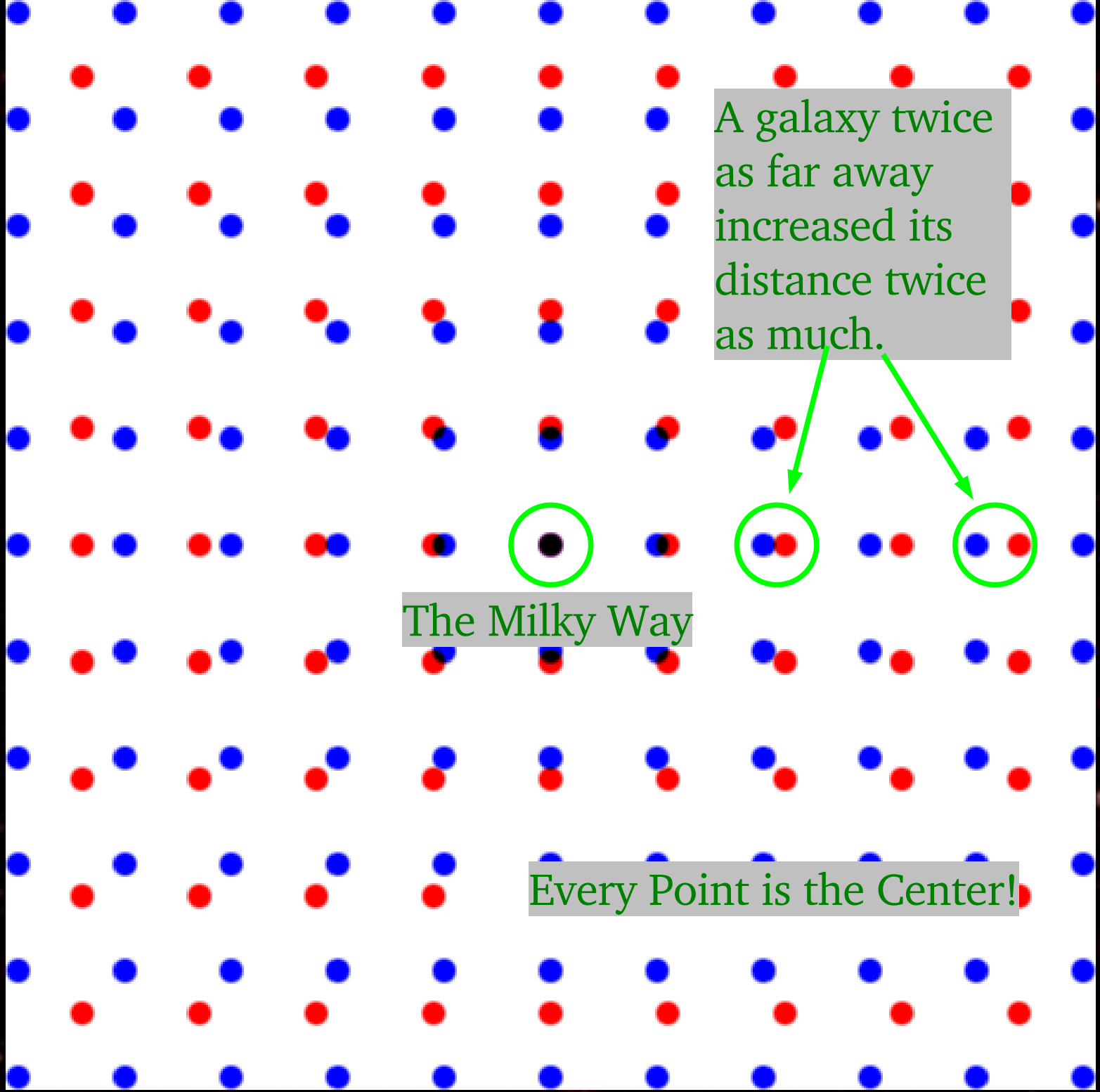
- 13.7 Billion Years Old
- Flat (Euclidean) Spatial Geometry
- Critical Mass+Energy Density
- Expansion Accelerating




Where do we go from here?
It all depends on just how bizarre Dark Energy is!
The Big Rip
The Big Chill
The Big Crunch
Size
Size Today
1.0
0.5
Today
Years in the Past
t
Years from Today

OK, Rob, what about that whole business of farther galaxies moving at higher speeds that we always hear about?




A galaxy twice as far away increased its distance twice as much.
The Milky Way
Every Point is the Center!

Δd = change in distance during time of movie (Δt) $\propto d$

"Hubble Law"

$$\frac{\Delta d}{\Delta t} = H_0 d$$

H_0 = *current* expansion rate of Universe = 71 km/s / Mpc

Doppler Shift (z)

Amount wavelength shifts to the red

$$z = \frac{\Delta \lambda}{\lambda}$$

Original emitted wavelength

$$z \approx \frac{v}{c} \quad (\text{For } v \ll c)$$

Compare to Cosmological redshift:

$$1+z = \frac{\text{Size Now}}{\text{Size Then}} = \frac{d+\Delta d}{d} = \frac{d+vt}{d} = 1+\frac{vt}{d} = 1+\frac{v}{d/t} = 1+\frac{v}{c}$$

For nearby galaxies (out to a few hundred million light-years), the cosmologic redshift looks just like a doppler shift. The “galaxies flying apart” description is a local Universe approximation.

Summary

- The expansion of the Universe is an expansion of *space itself*. Galaxies get farther apart, much as do raisins in rising bread, pennies pasted on the surface of an expanding balloon, or paper clips on a stretching elastic band.

- As the Universe expands, the wavelengths of light expand at the same rate.

- The three dimensional space of the Universe can be *intrinsically curved*, but large-scale geometry is flat (Euclidean). (Whew!)

- The expansion of the Universe is accelerating, and indicates that the Universe is filled with *Dark Energy*.

Coda: The Big Bang

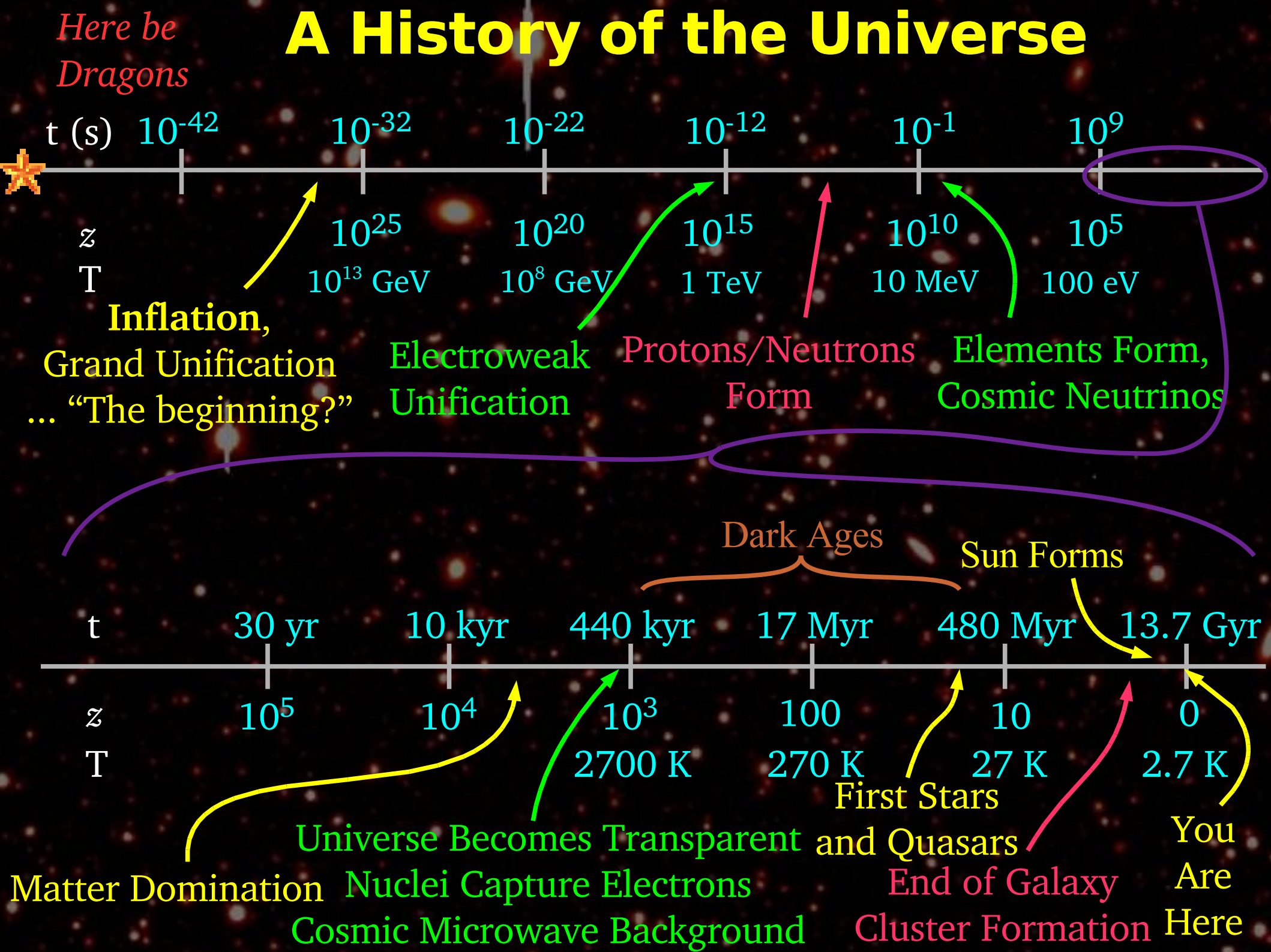
If the Universe is expanding, then in the past it was smaller... far enough back, *much* smaller.

The Big Bang Theory tells us that the Universe has evolved to its present state from a very condensed and hot state over the course of about 14 billion years.

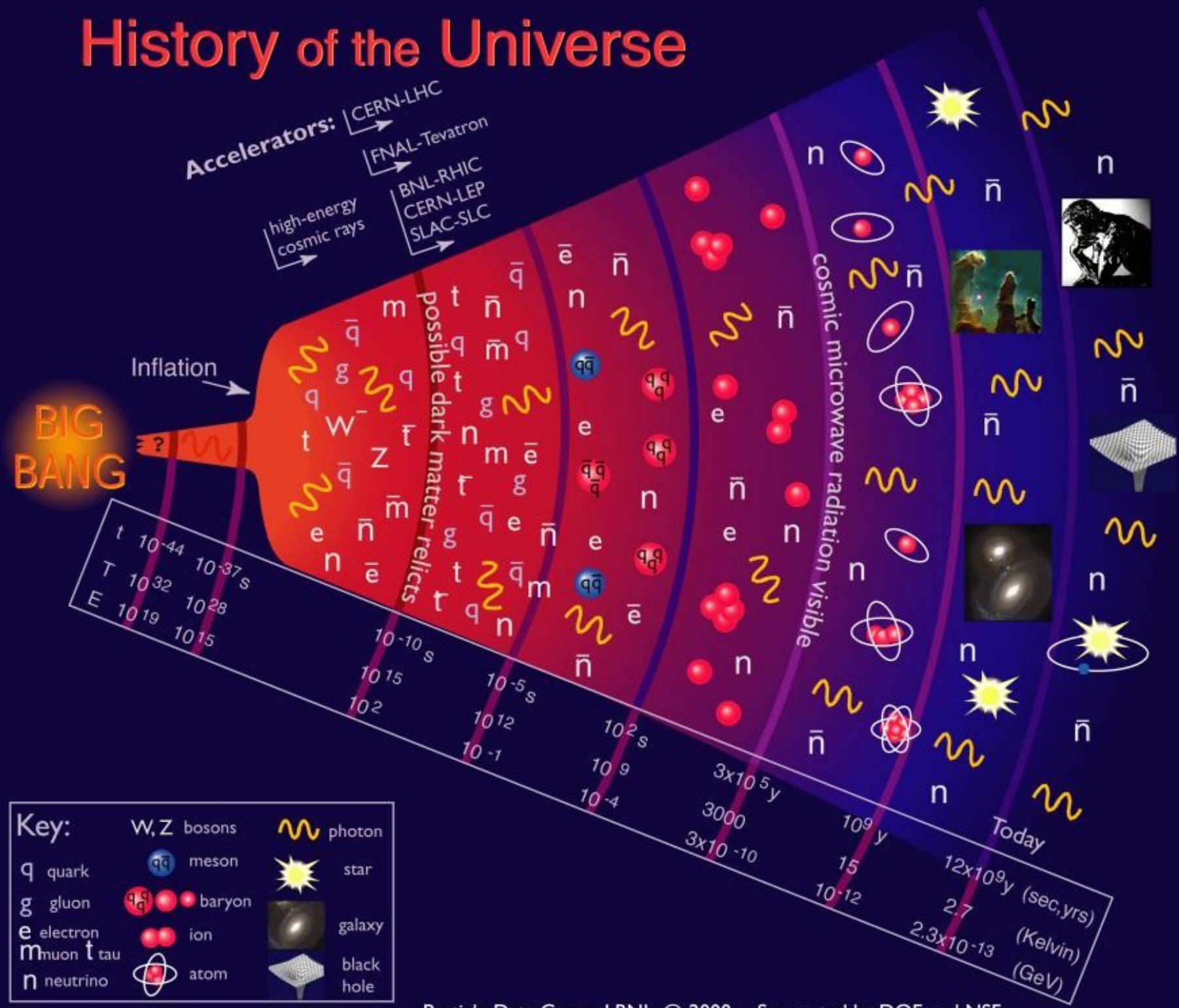
It does not currently tell us about the *actual moment of creation*, or what happened *before* that 14 billion years... there is a point before which our Physics breaks down! (String Theory??)

Evidence for the Big Bang:

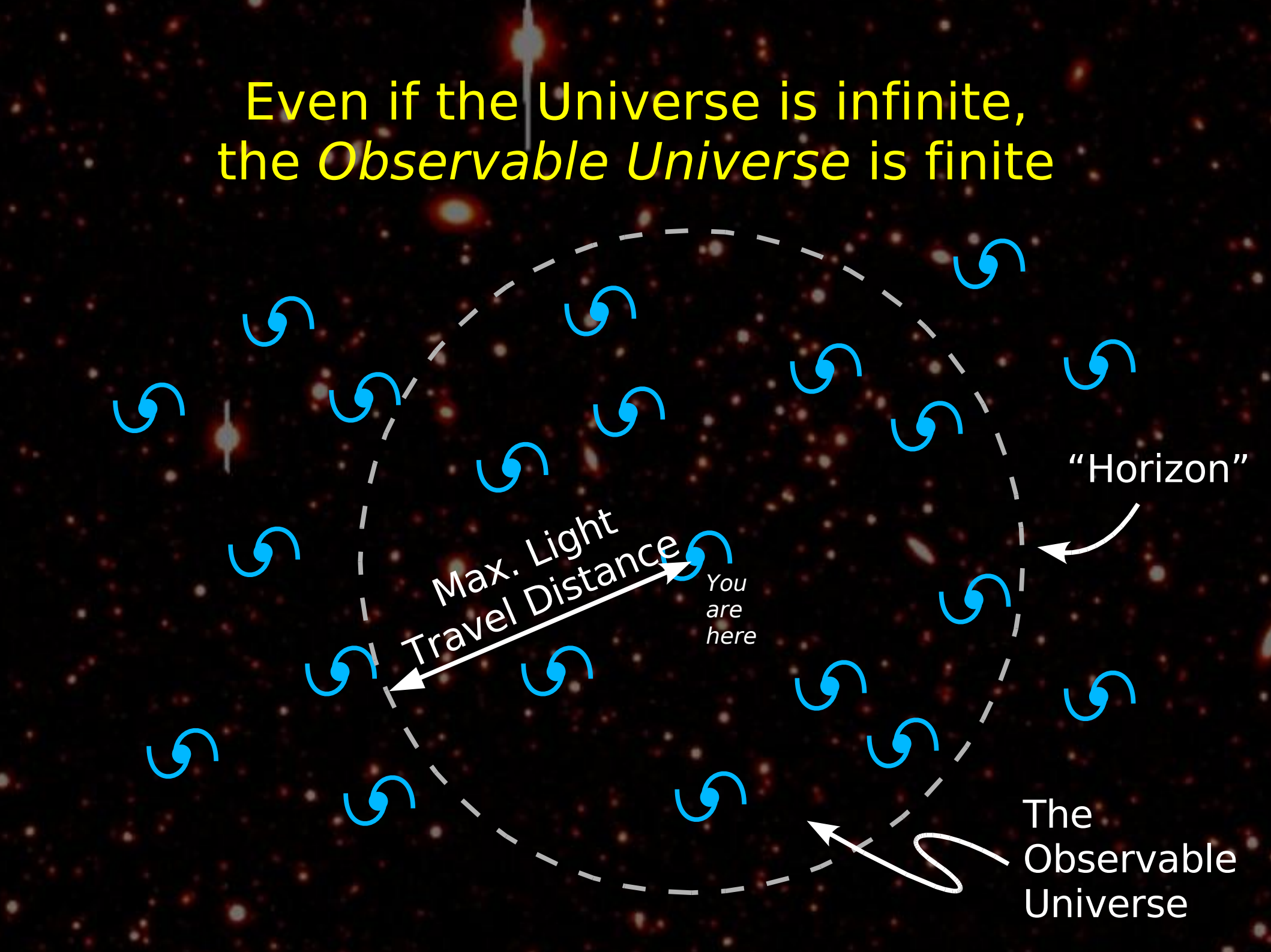
- Expanding Universe
- Cosmic Microwave Background
- Fraction of Deuterium and Helium


Here be Dragons
A History of the Universe
t (s)
10-42
10-32
10-22
10-12
10-1
109
z
T
1025
1013 GeV
1020
108 GeV
1015
1 TeV
1010
10 MeV
105
100 eV
Inflation, Grand Unification ... "The beginning?"
Electroweak Unification
Protons/Neutrons Form
Elements Form, Cosmic Neutrinos
Dark Ages
Sun Forms
t
30 yr
10 kyr
440 kyr
17 Myr
480 Myr
13.7 Gyr
z
T
105
104
103
2700 K
100
270 K
10
27 K
0
2.7 K
Matter Domination
Universe Becomes Transparent
Nuclei Capture Electrons
Cosmic Microwave Background
First Stars and Quasars
End of Galaxy Cluster Formation
You Are Here

History of the Universe

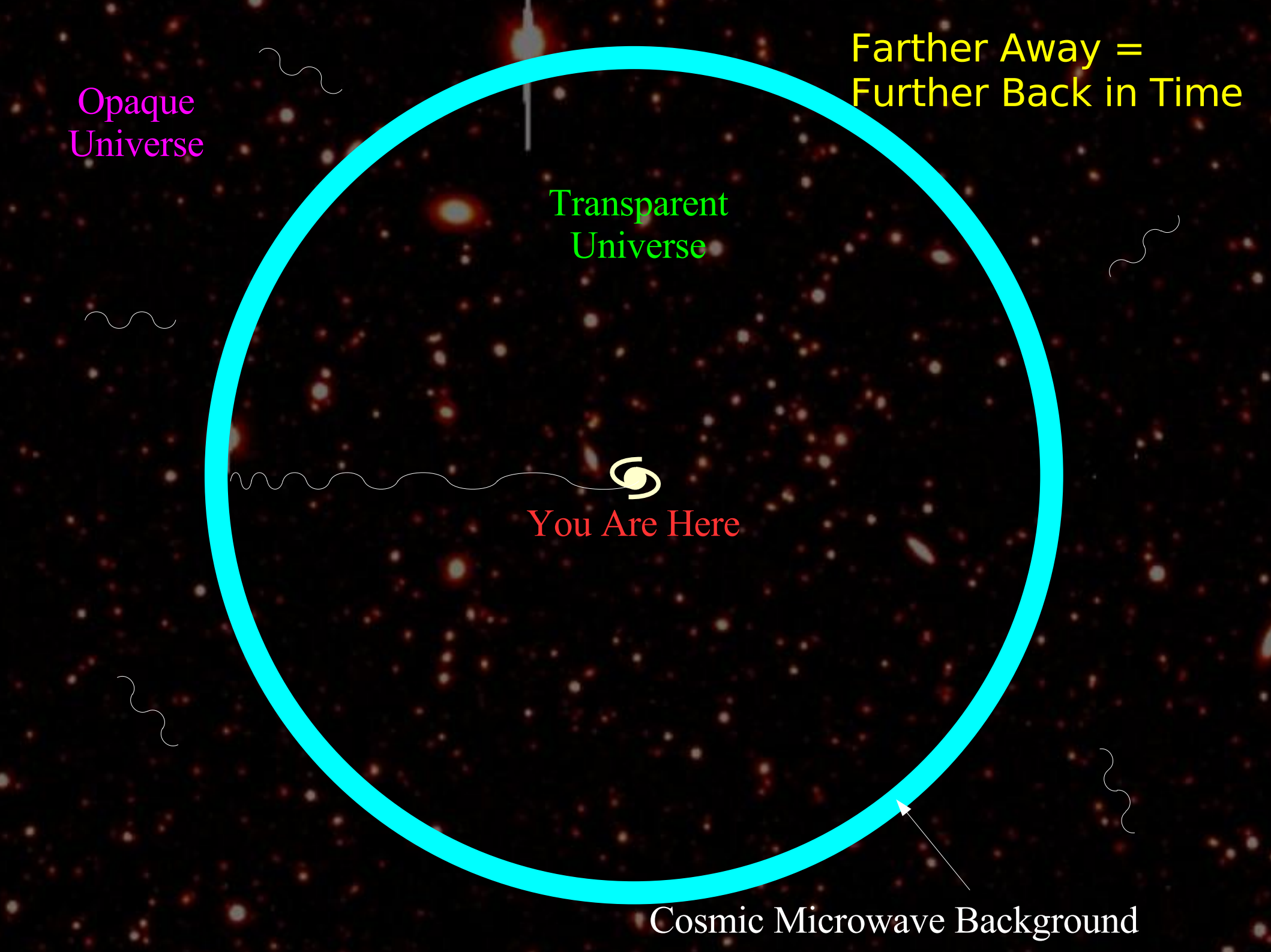


Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

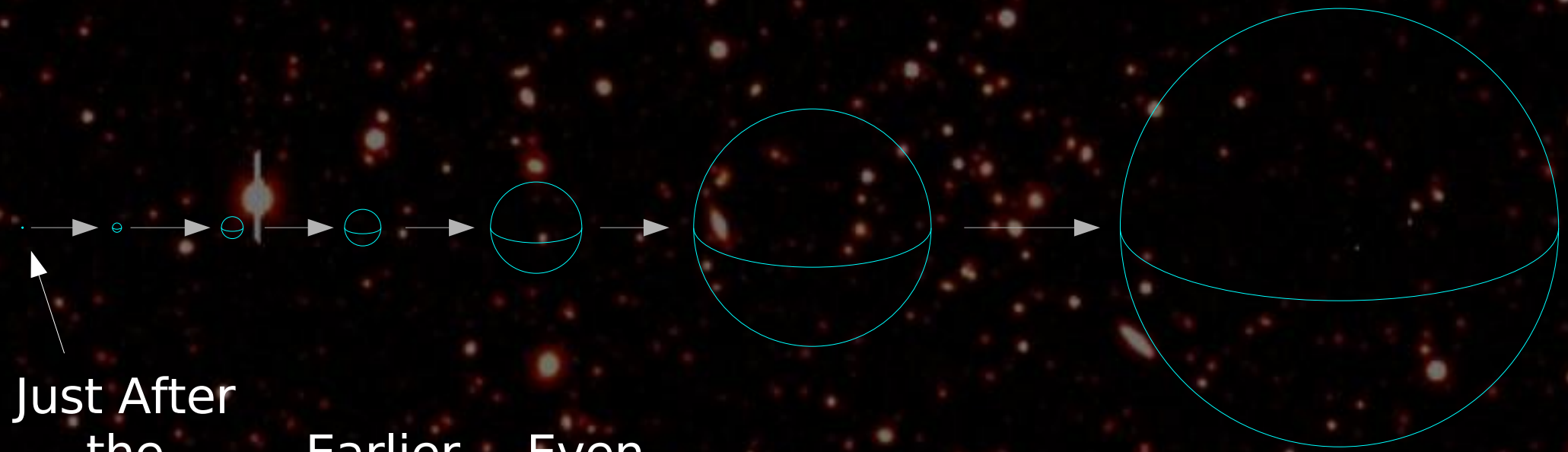

Even if the Universe is infinite,
the *Observable Universe* is finite
Max. Light
Travel Distance
You
are
here
“Horizon”
The
Observable
Universe

The *observable* Universe, 10^{-43} seconds after the Big Bang:

(Actual Size)


Farther Away =
Further Back in Time
Opaque
Universe
Transparent
Universe
You Are Here
Cosmic Microwave Background

Taking this expansion back in time towards the beginning....

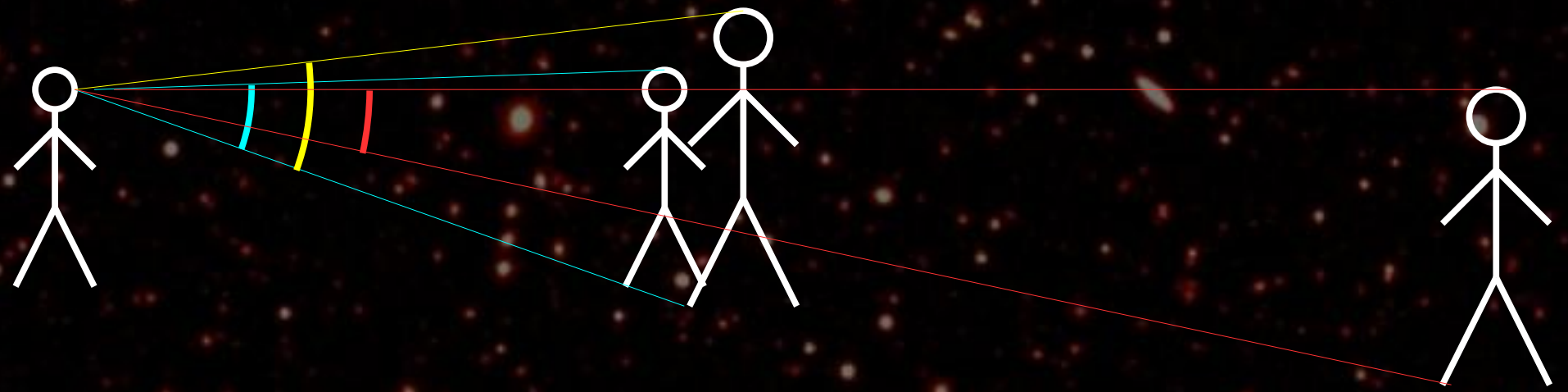


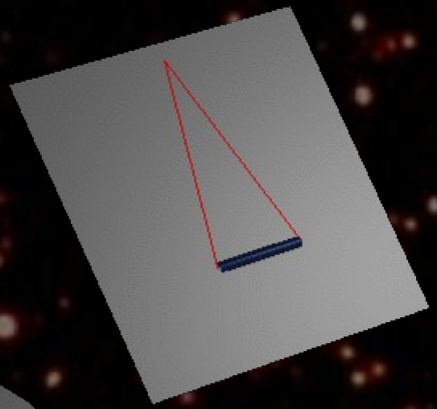
Where, on the surface of this sphere, is the center?


Extra Slides...

What do we mean when we say how big something looks?

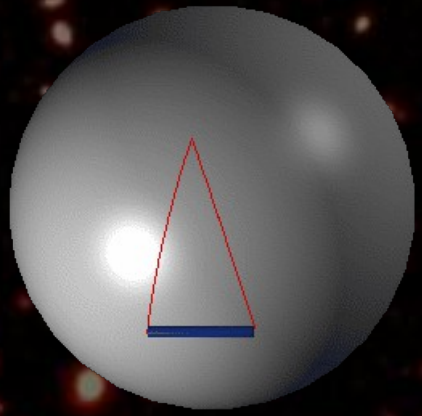
The angle that it *subtends*.

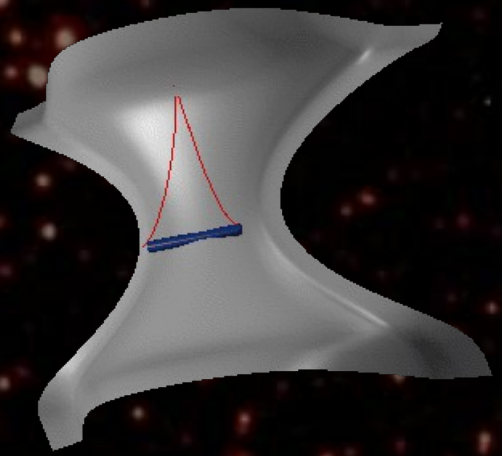


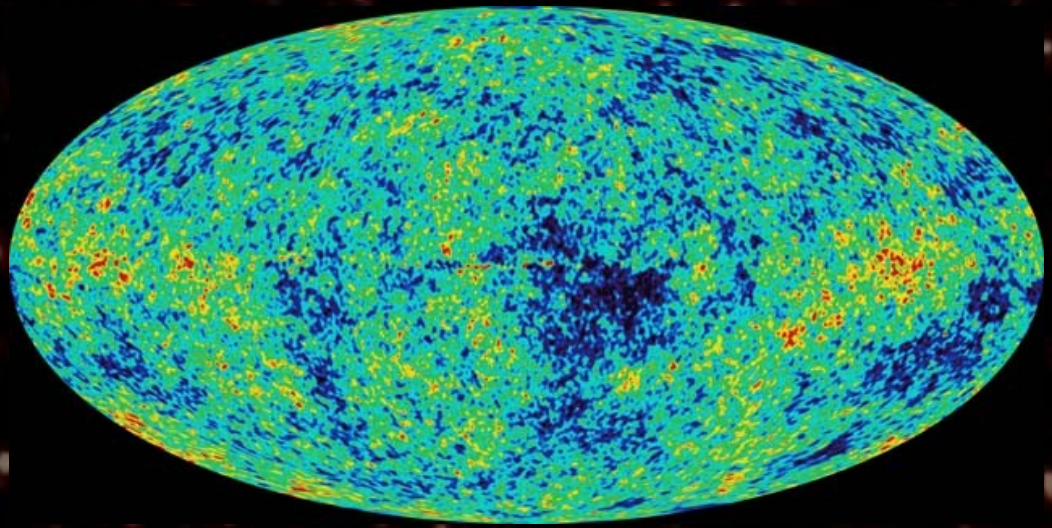


Flat

Closed:
Looks Bigger



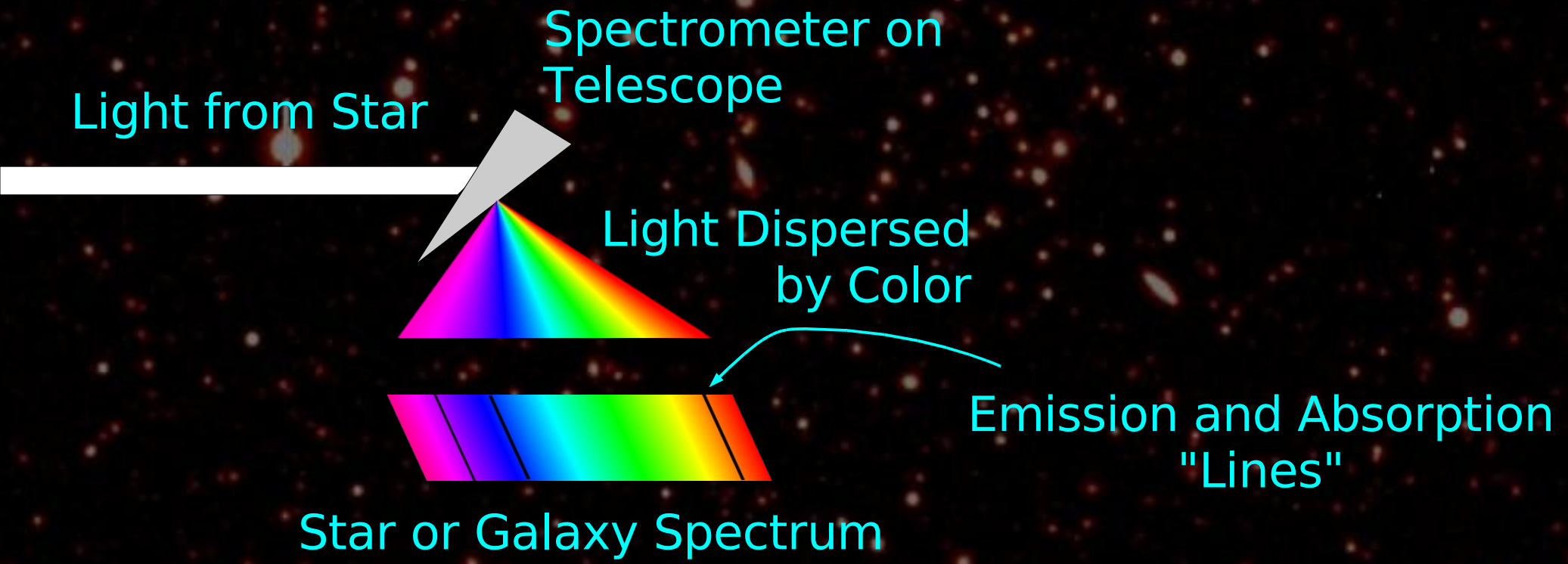




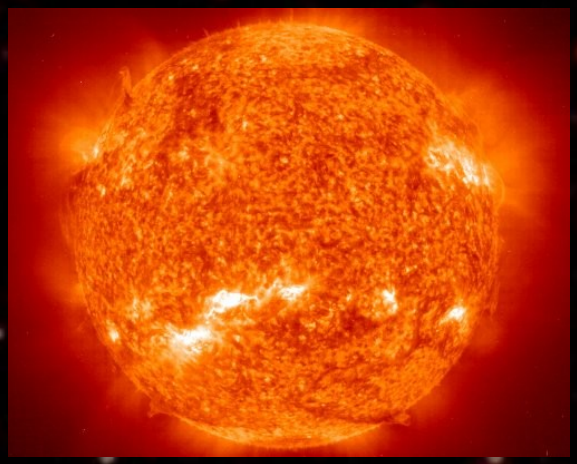
Open:
Looks Smaller

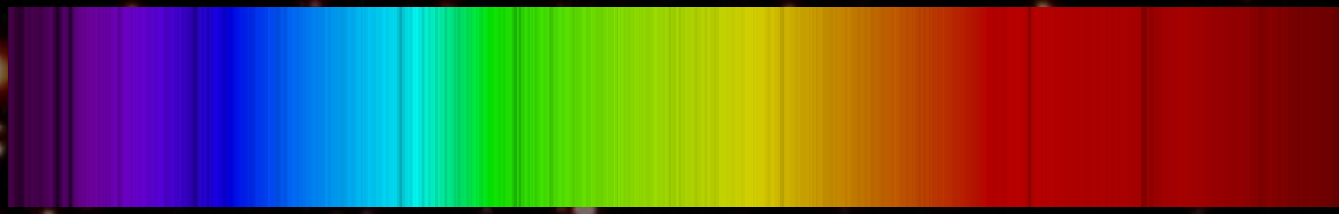
Spectroscopy

"Fingerprinting" Stars and Galaxies



Stars: Absorption Lines

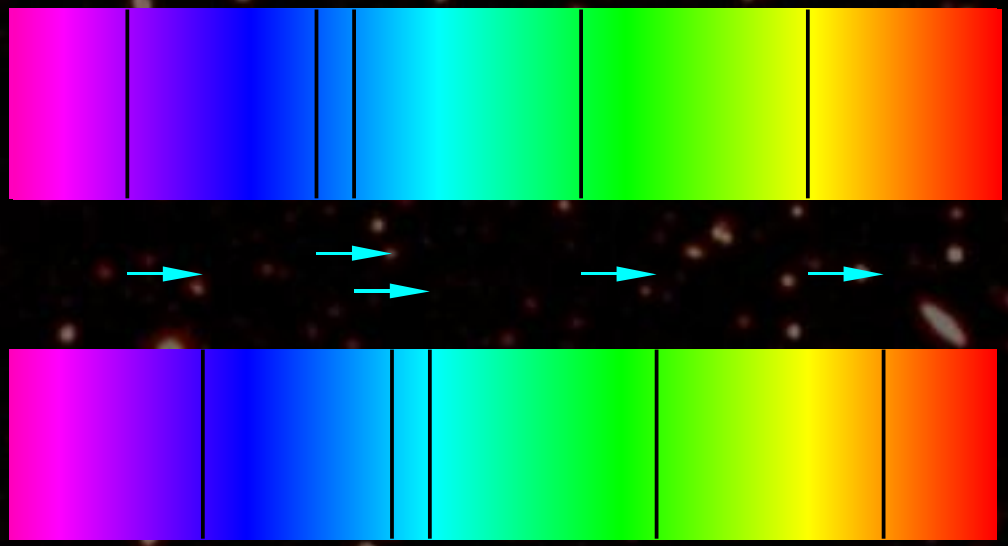




Nebulae: Emission lines

Redshift

Lines in a spectrum



Redshfited Lines