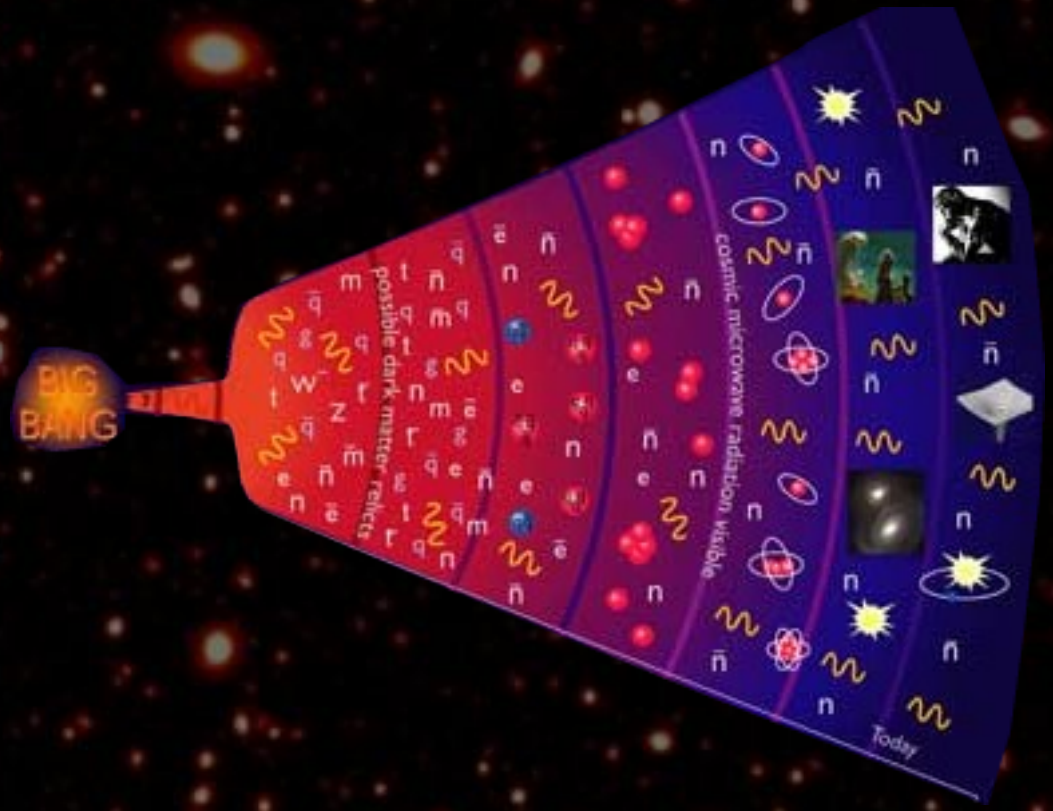
The Three Legs of the Cosmos



Robert Knop
Astronomy 205
Vanderbilt University

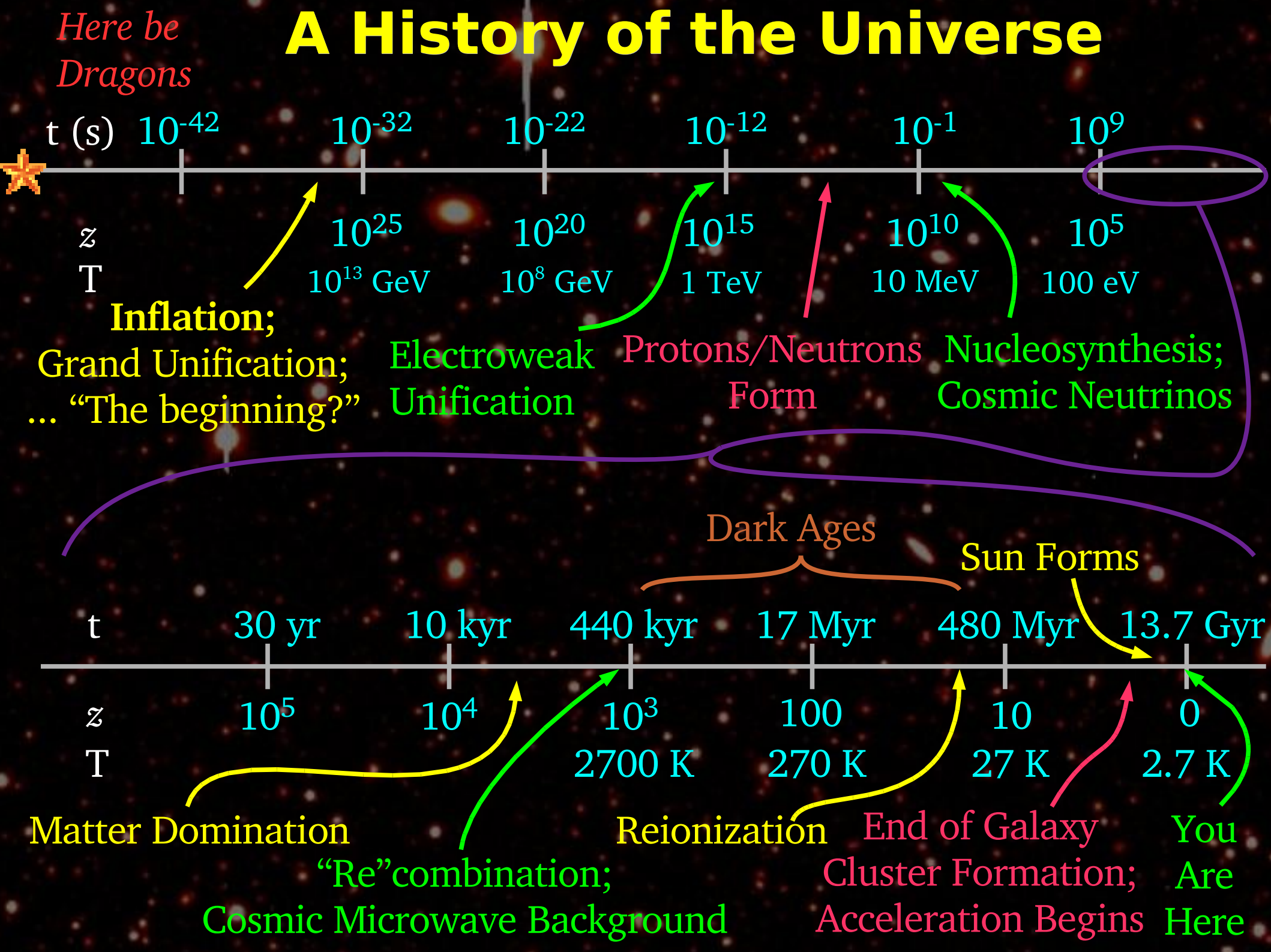
2005-04-25

I. The Expansion of Space
- Flatland Analogy
- Measuring Expansion: Redshift
- Measuring Expansion Rate
- Aside: the “old way” of describing the expansion

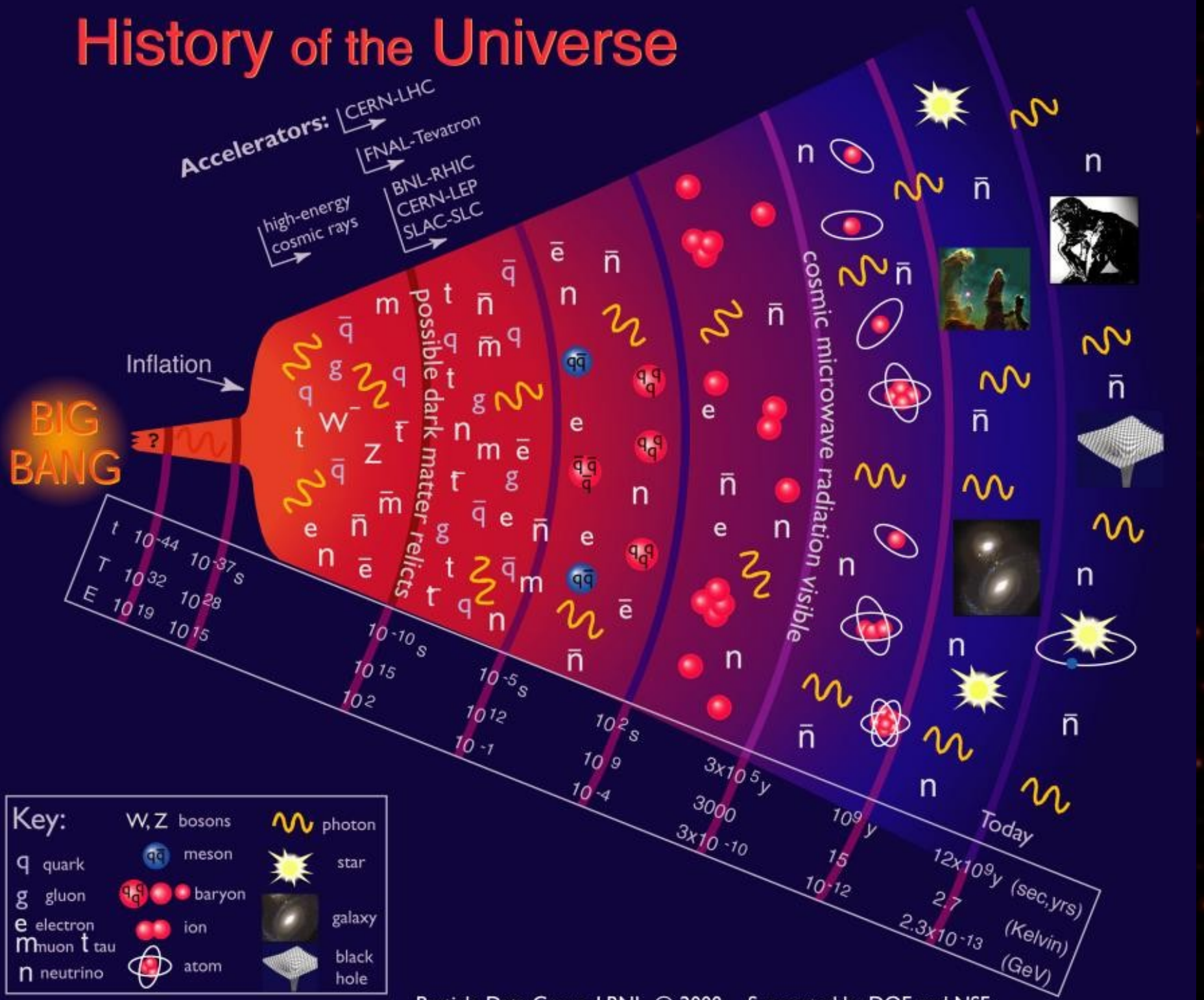
II. The Cosmic Microwave Background
- Distance=Time
- Recombination
- WMAP and other data
- The Shape of the Universe

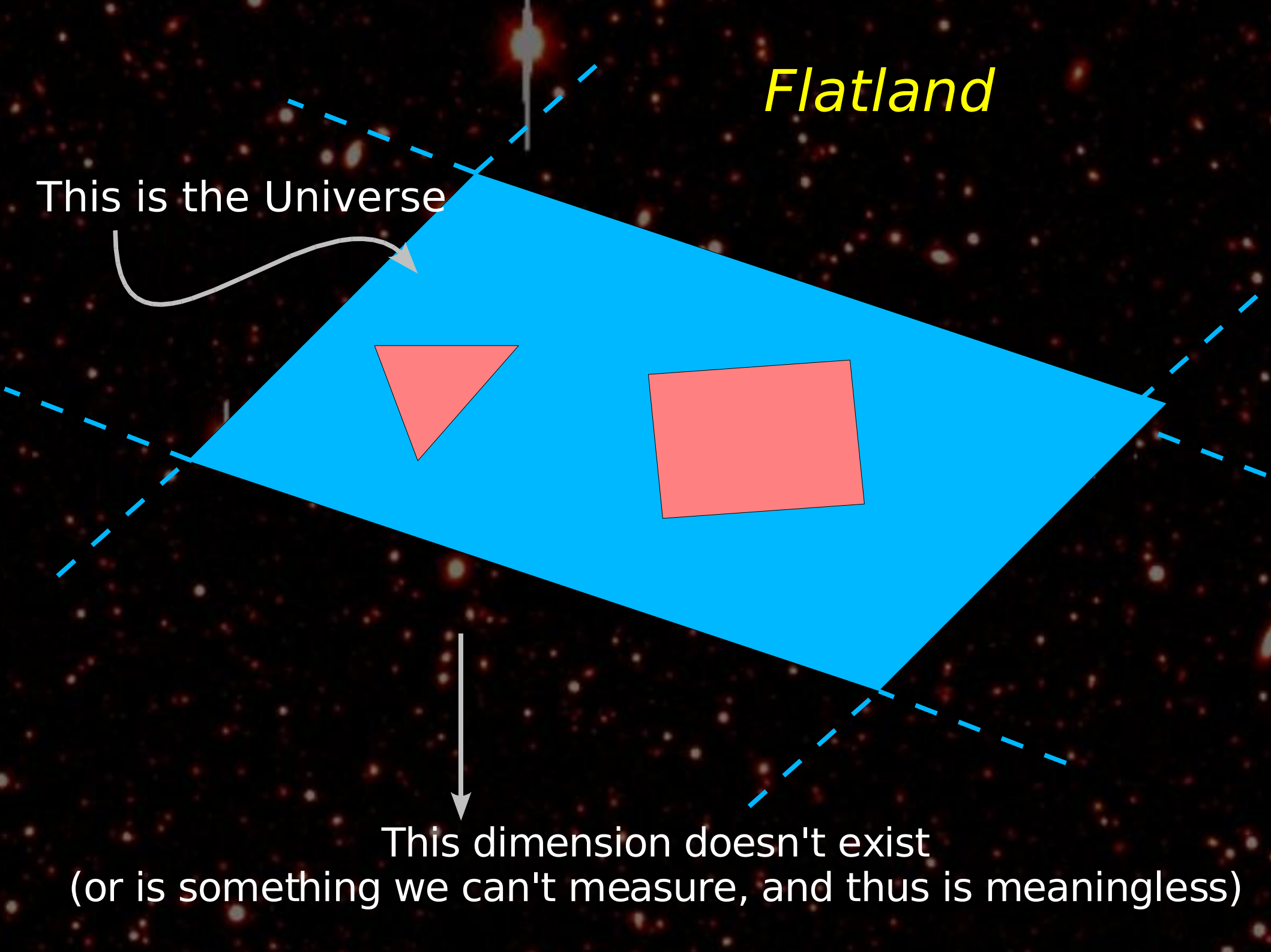
III. Big-Bang Nucleosynthesis

IV. The Big Picture and the Dragons

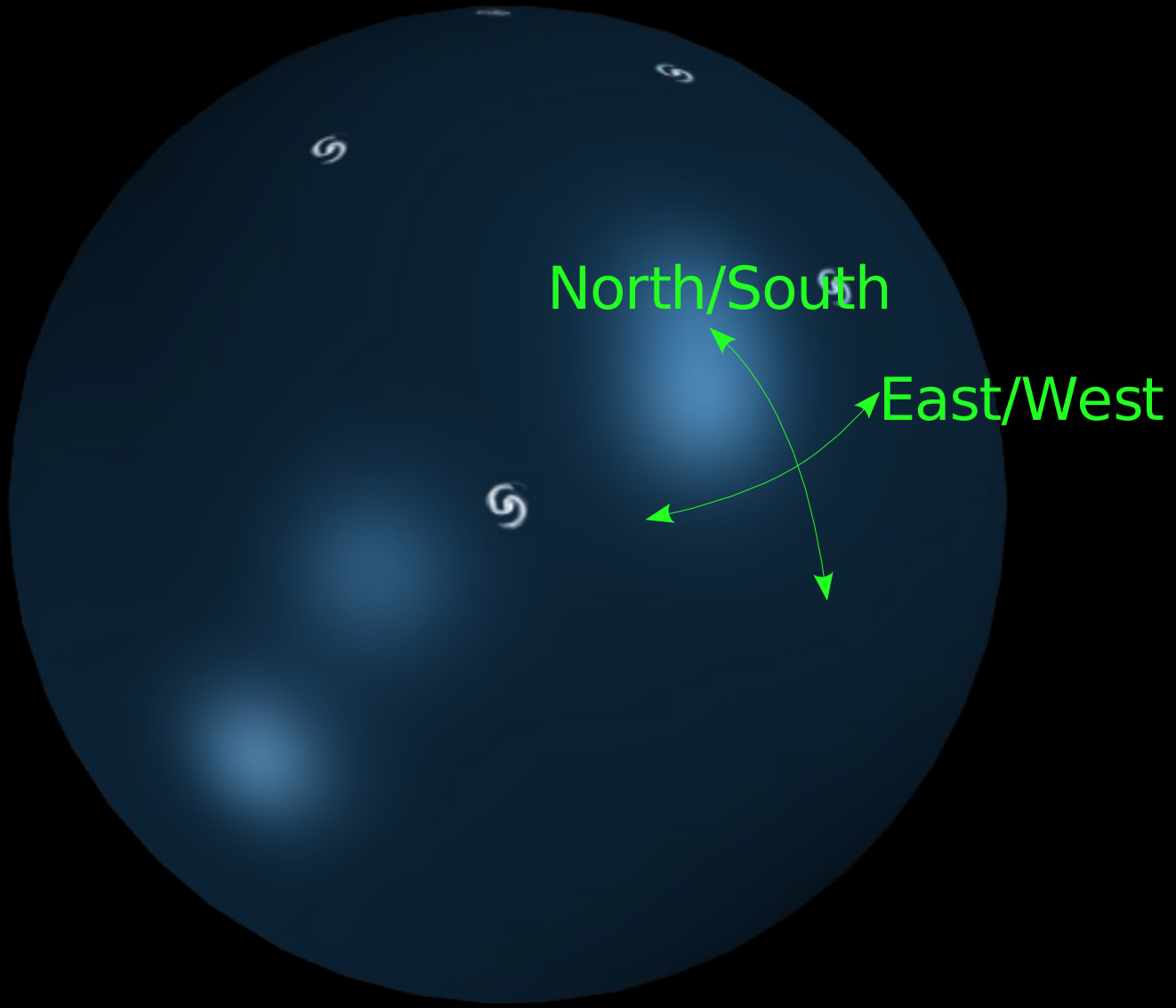

Here be Dragons
A History of the Universe
t (s)
10-42
10-32
10-22
10-12
10-1
109
z
T
1025
1013 GeV
1020
108 GeV
1015
1 TeV
1010
10 MeV
105
100 eV
Inflation;
Grand Unification;
... "The beginning?"
Electroweak Unification
Protons/Neutrons Form
Nucleosynthesis;
Cosmic Neutrinos
Dark Ages
Sun Forms
t
30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

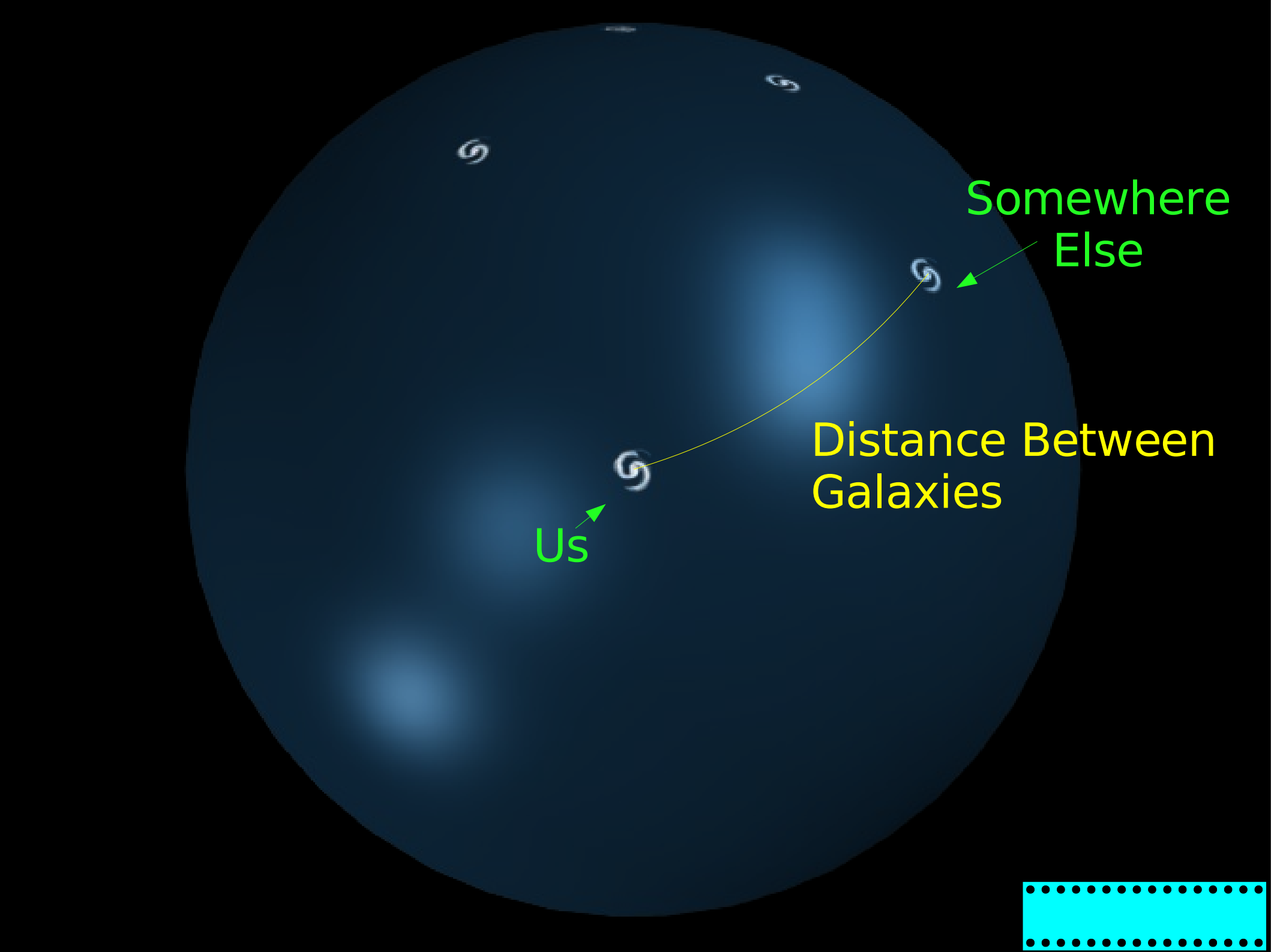
History of the Universe

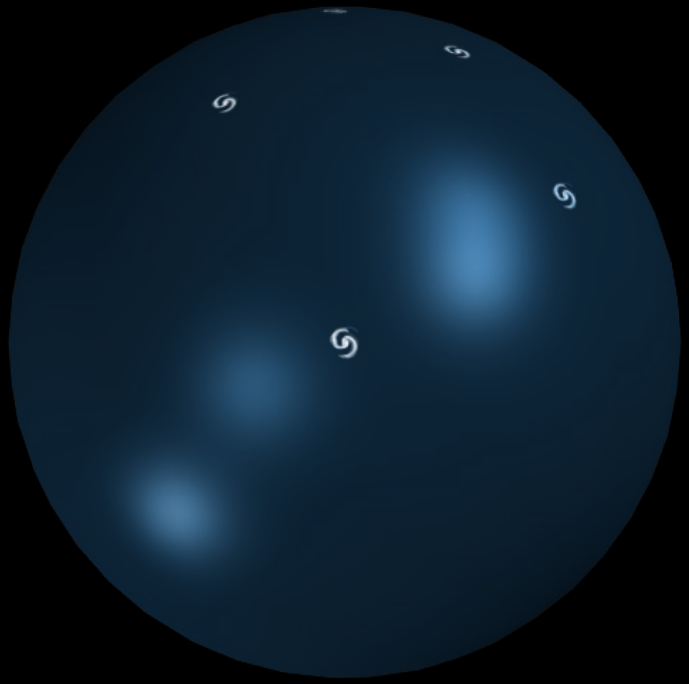



Flatland
This is the Universe
This dimension doesn't exist
(or is something we can't measure, and thus is meaningless)

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




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 Robertson-Walker Metric

$$ds^2 = dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)$$

r, θ, ϕ = "comoving coordinates"

R = scale factor

k = curvature (-1 = open, +1 = closed, 0 = flat)

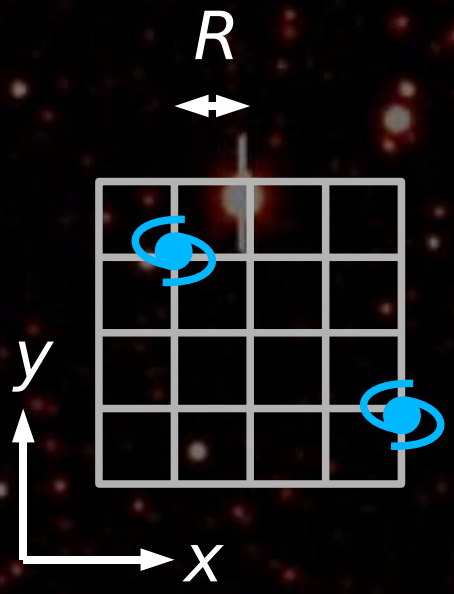
Compare to special relativistic metric:

$$ds^2 = dt^2 - dx^2 - dy^2 - dz^2$$

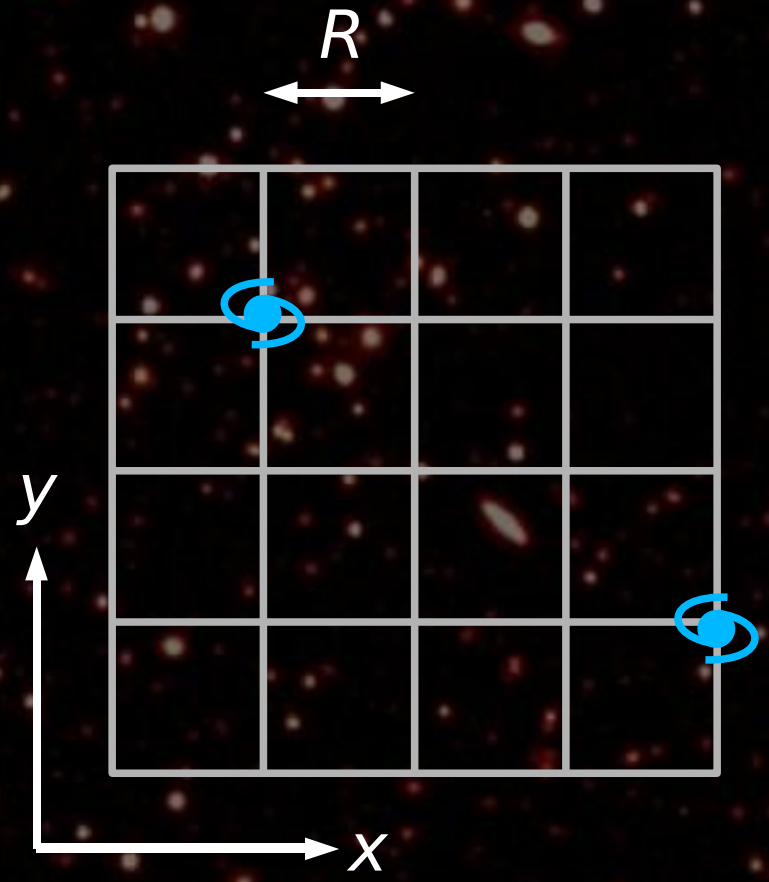
$$ds^2 = dt^2 - \left(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)$$

Comoving Coordinates

x, y = comoving coordinates
R = scale factor



t_0



t_1

The Friedmann Equation

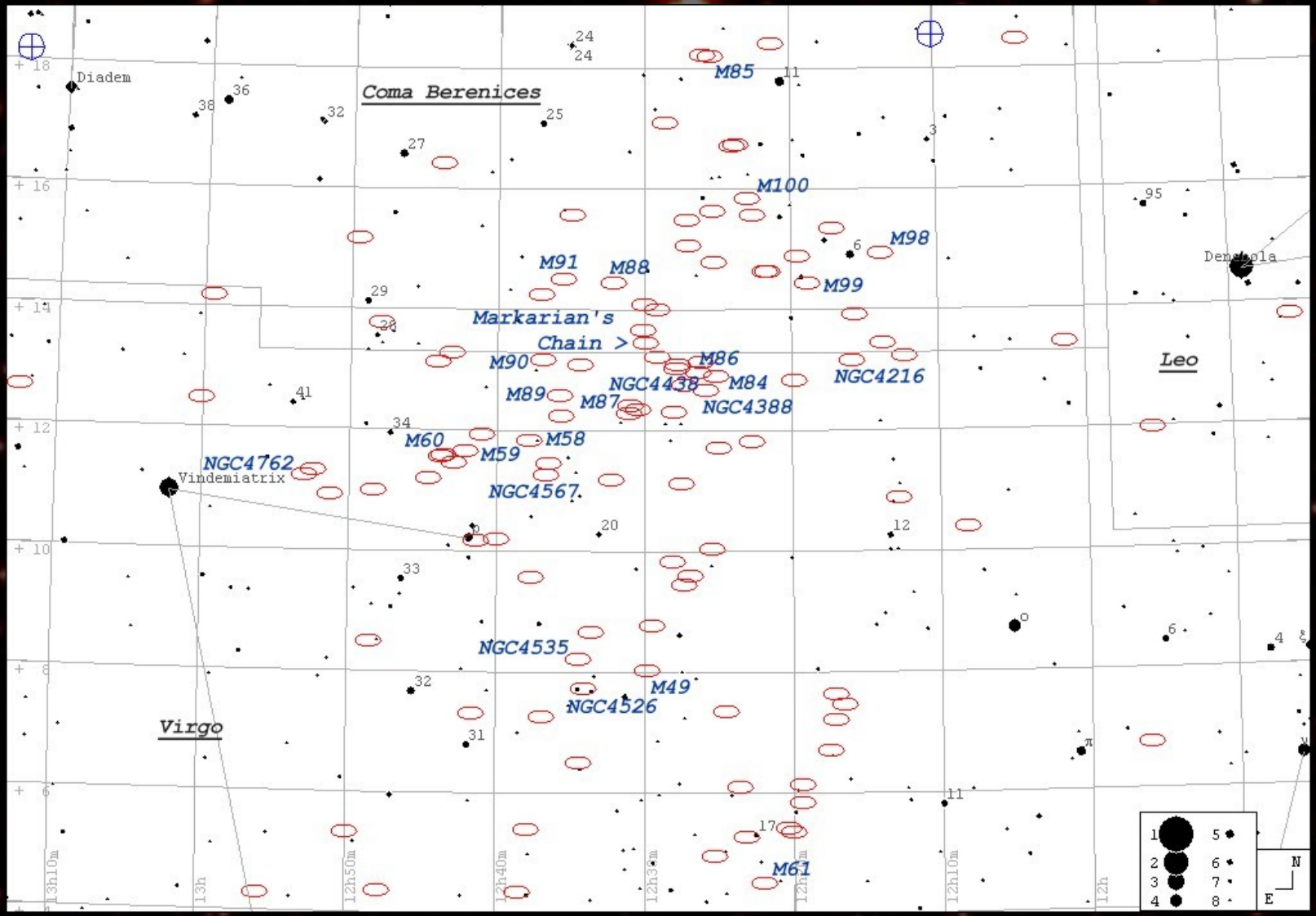
$$\frac{\ddot{R}}{R} = -\frac{4}{3}\pi G(\rho + 3p)$$

or

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8}{3}\pi G\rho + \frac{K}{R^2}$$

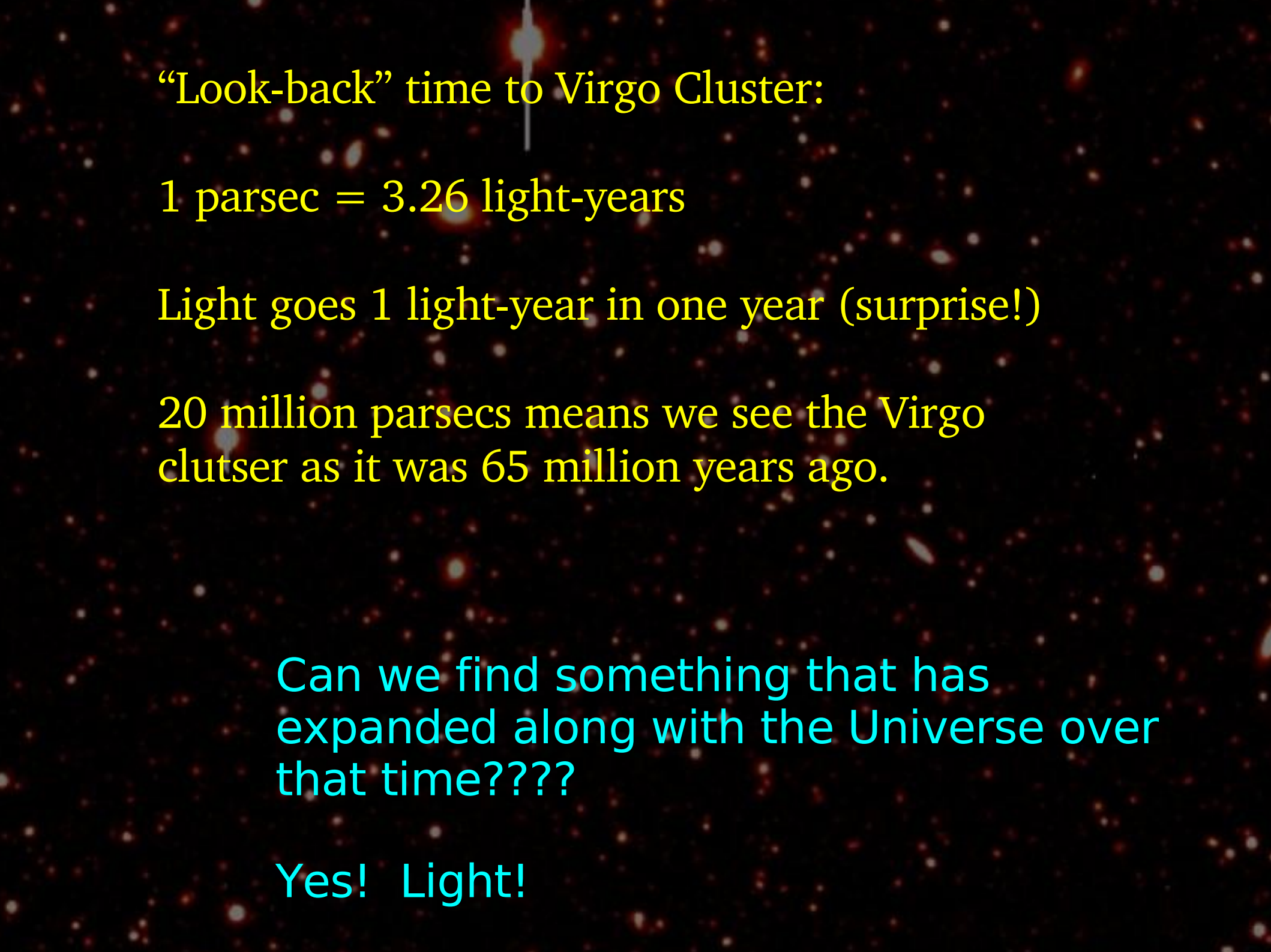
$H_0 = H(t=now)$ = Today's expansion rate

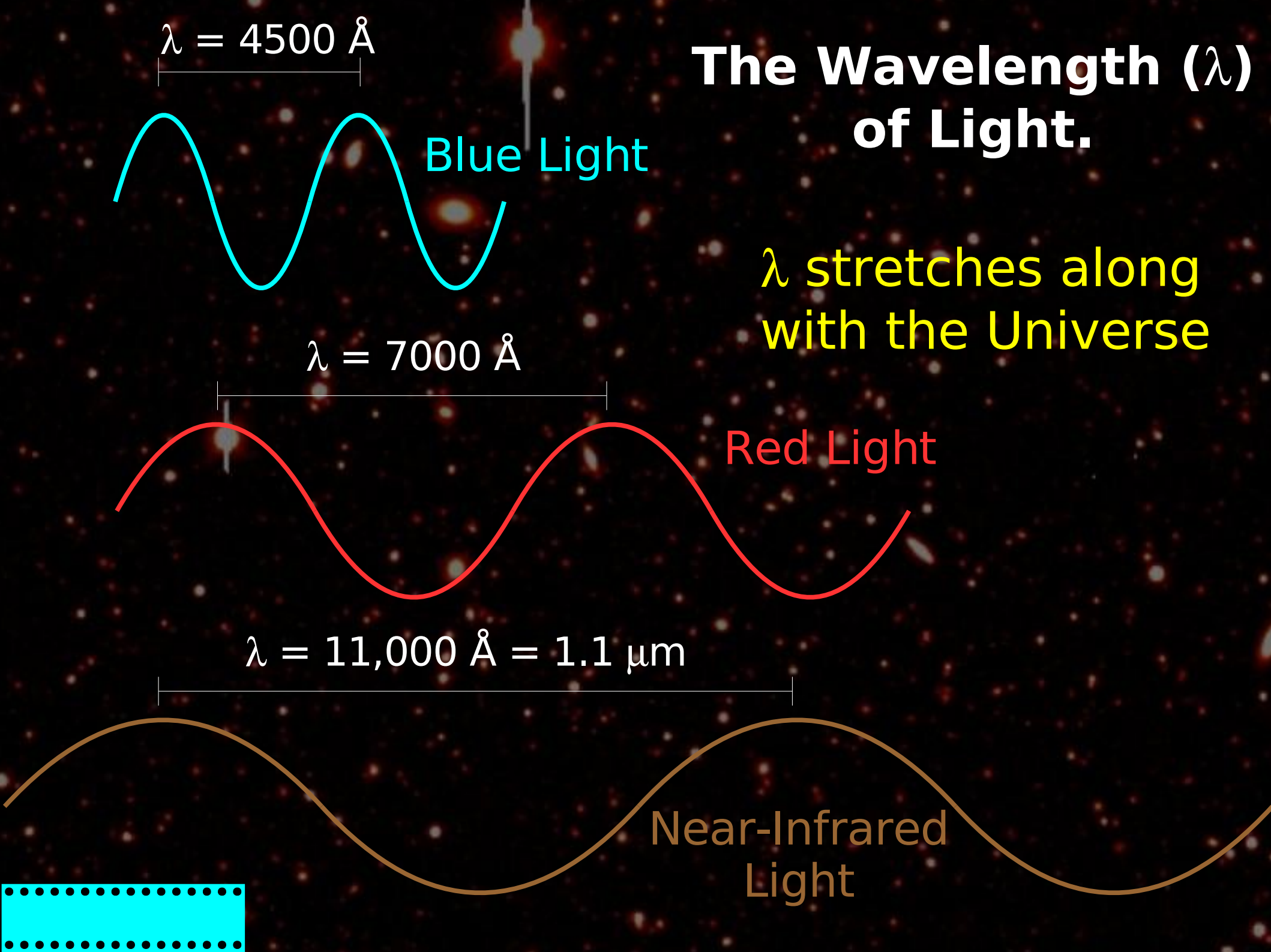
The Virgo Cluster



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)

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

Amount wavelength shifts to the red

Original emitted wavelength

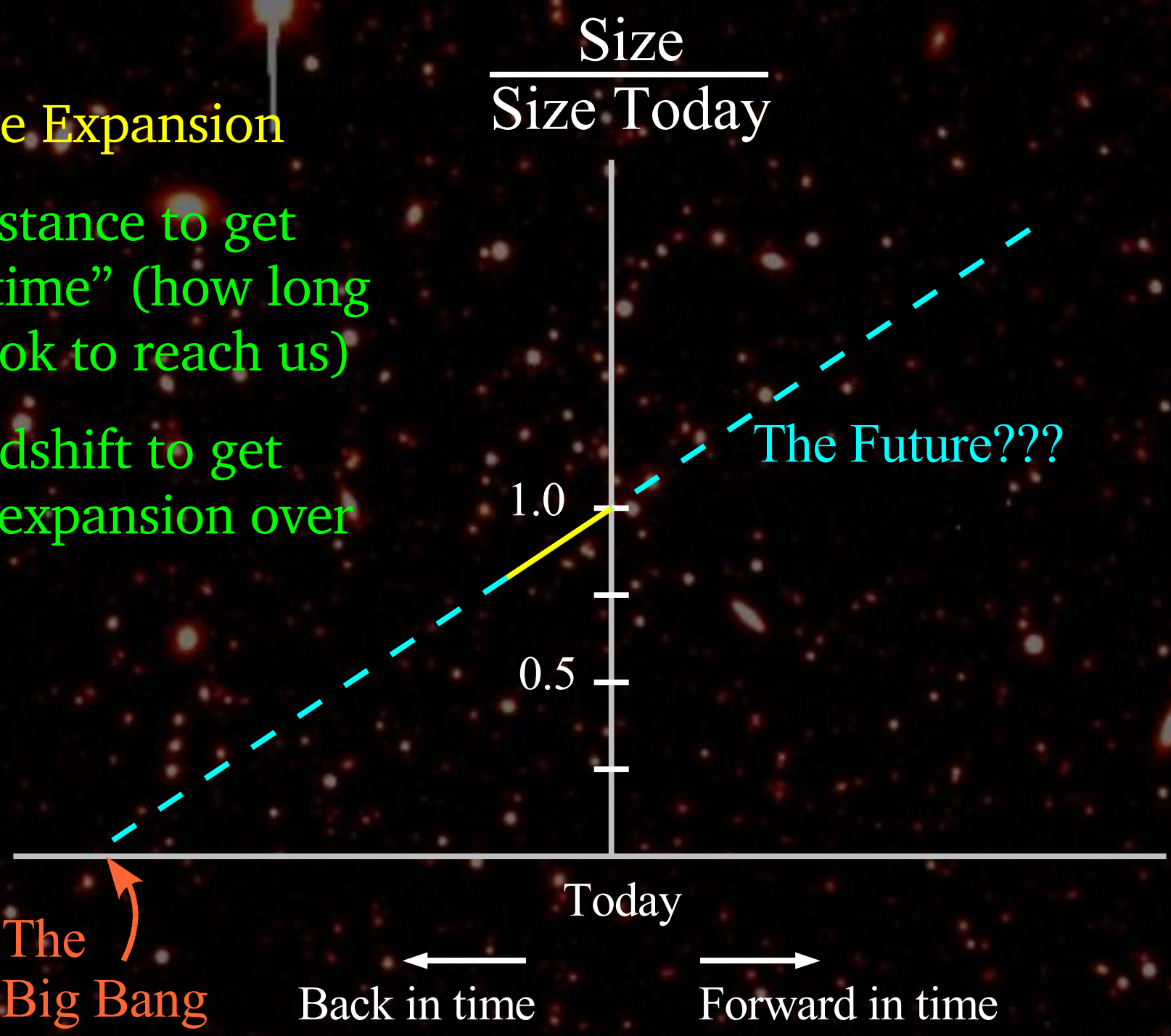
$$1 + z = \frac{\lambda + \Delta\lambda}{\lambda} = \frac{\lambda_{observed}}{\lambda_{original}}$$

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

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

Measuring the Expansion

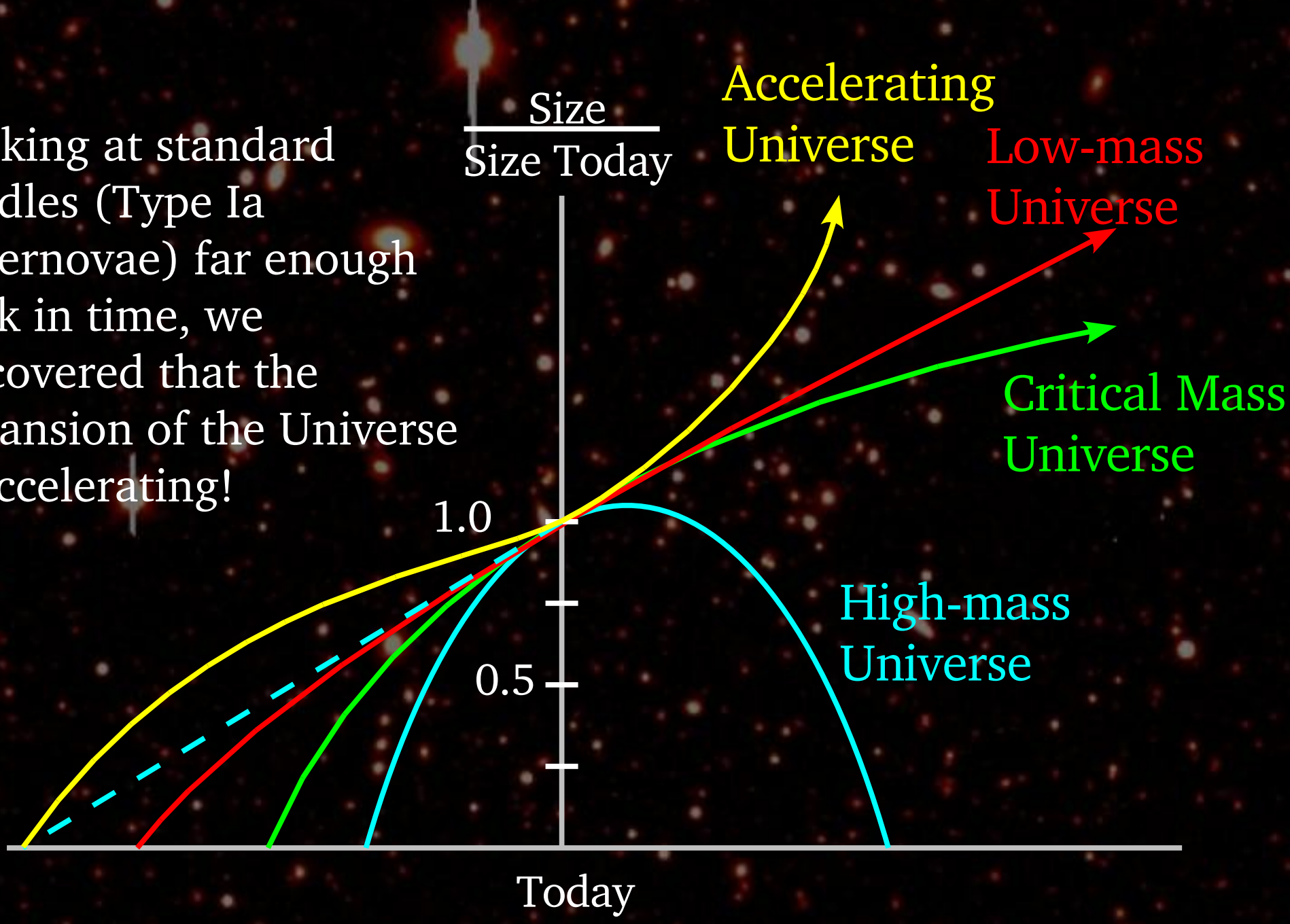
- Measure distance to get "lookback time" (how long the light took to reach us)
- Measure redshift to get amount of expansion over that time.

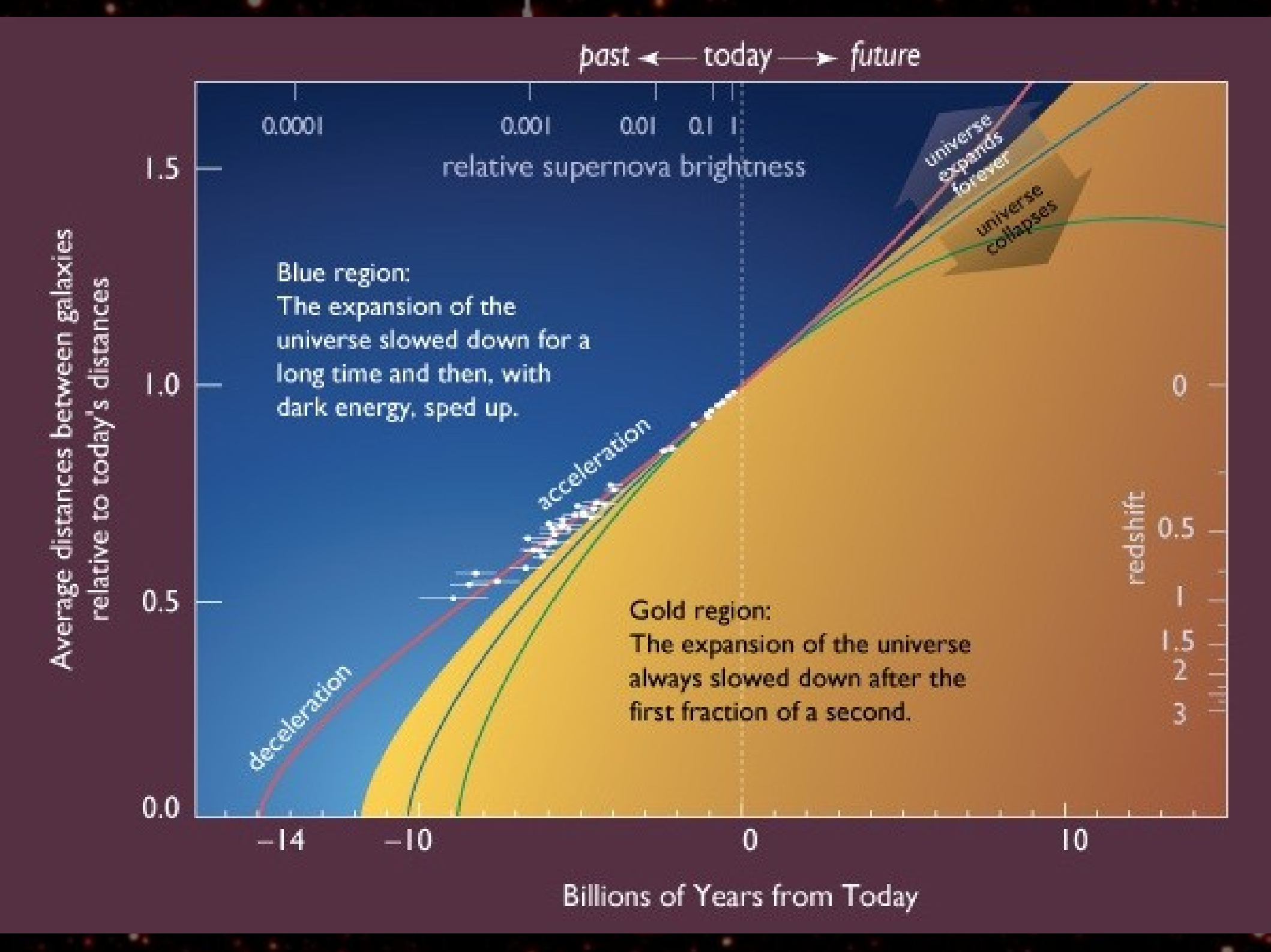


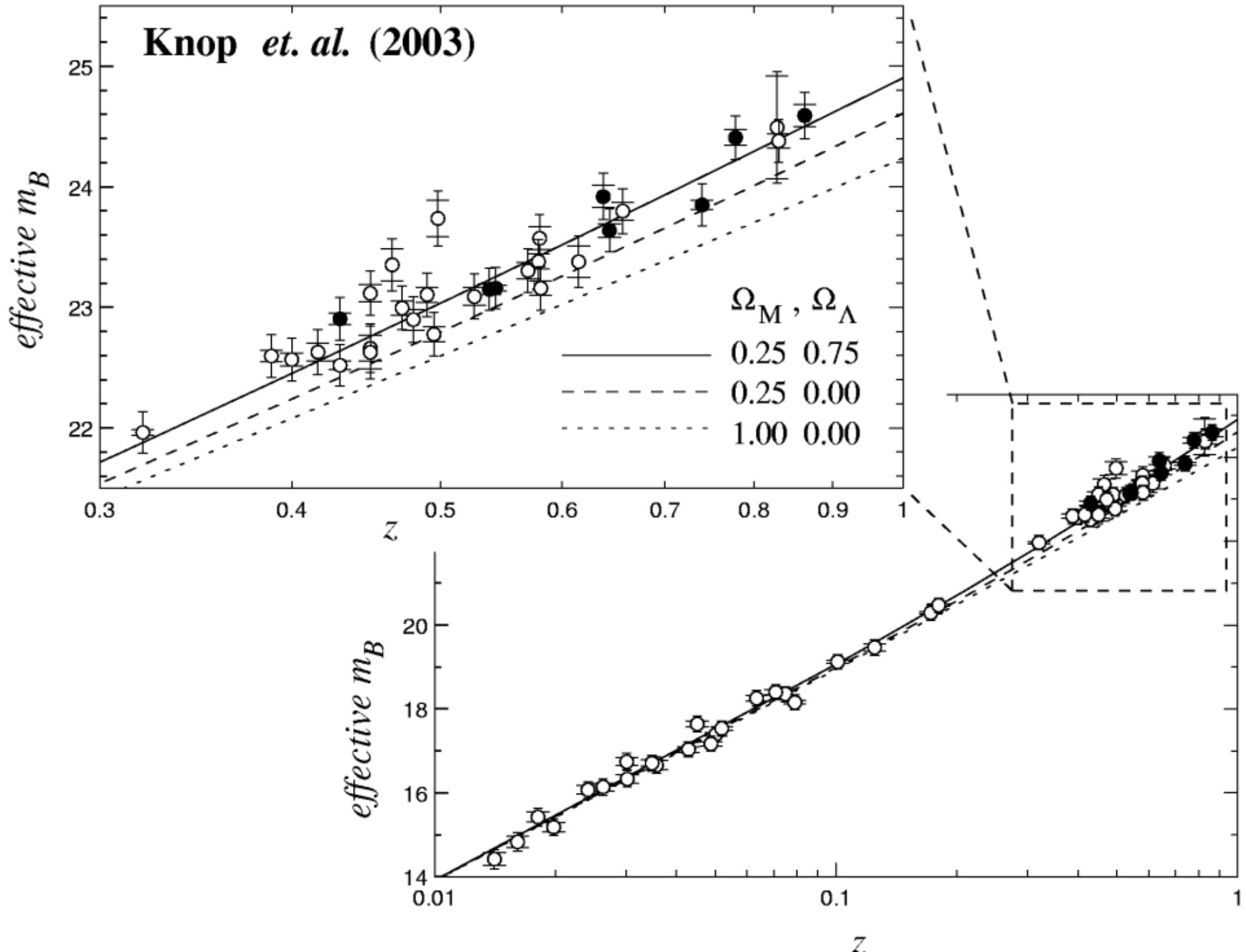
Lookback Times

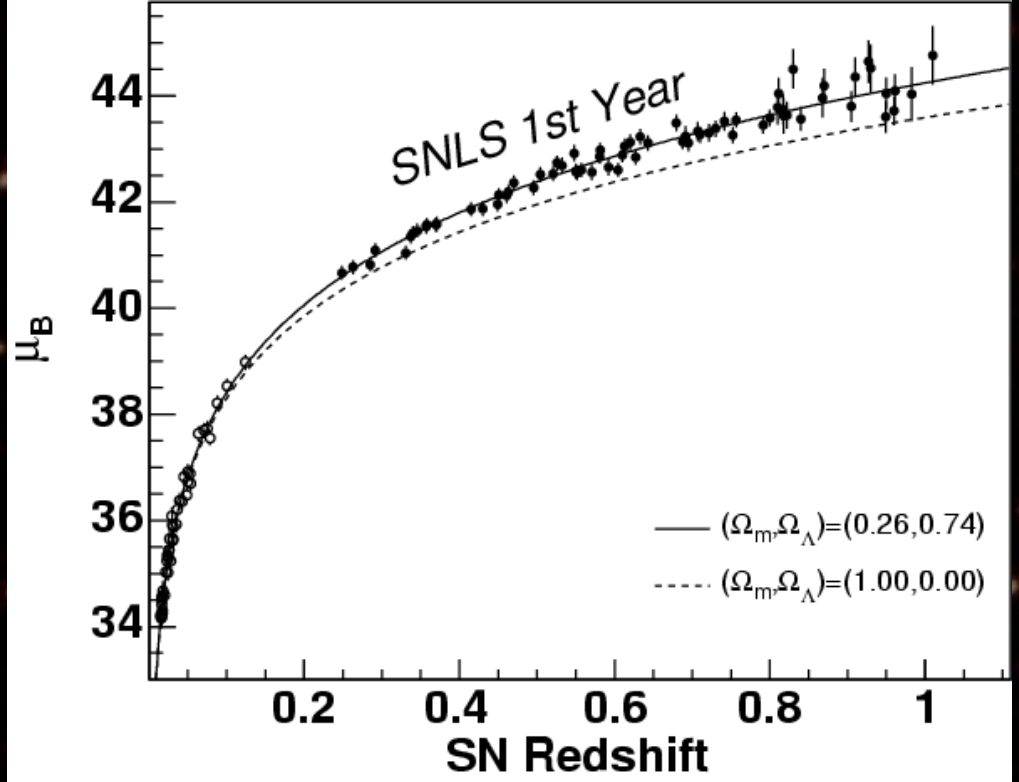
Object	Lookback Time
Sun	8 minutes
Alpha Centauri	4 years
Andromeda Galaxy	2 million years
Seyfert Galaxy NGC1068	16 million years
Quasar 3C273 at z=0.158	2 billion years
Galaxy at z=1	7 billion years
Age of Universe	13.7 billion years

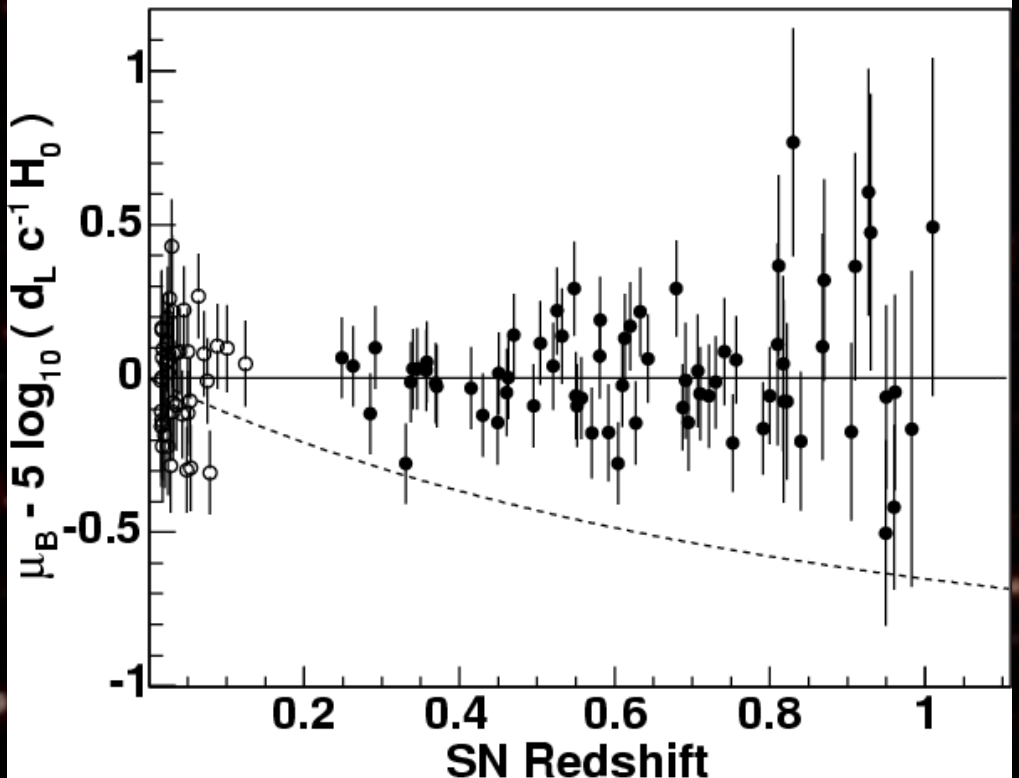
Looking at standard candles (Type Ia supernovae) far enough back in time, we discovered that the expansion of the Universe is accelerating!



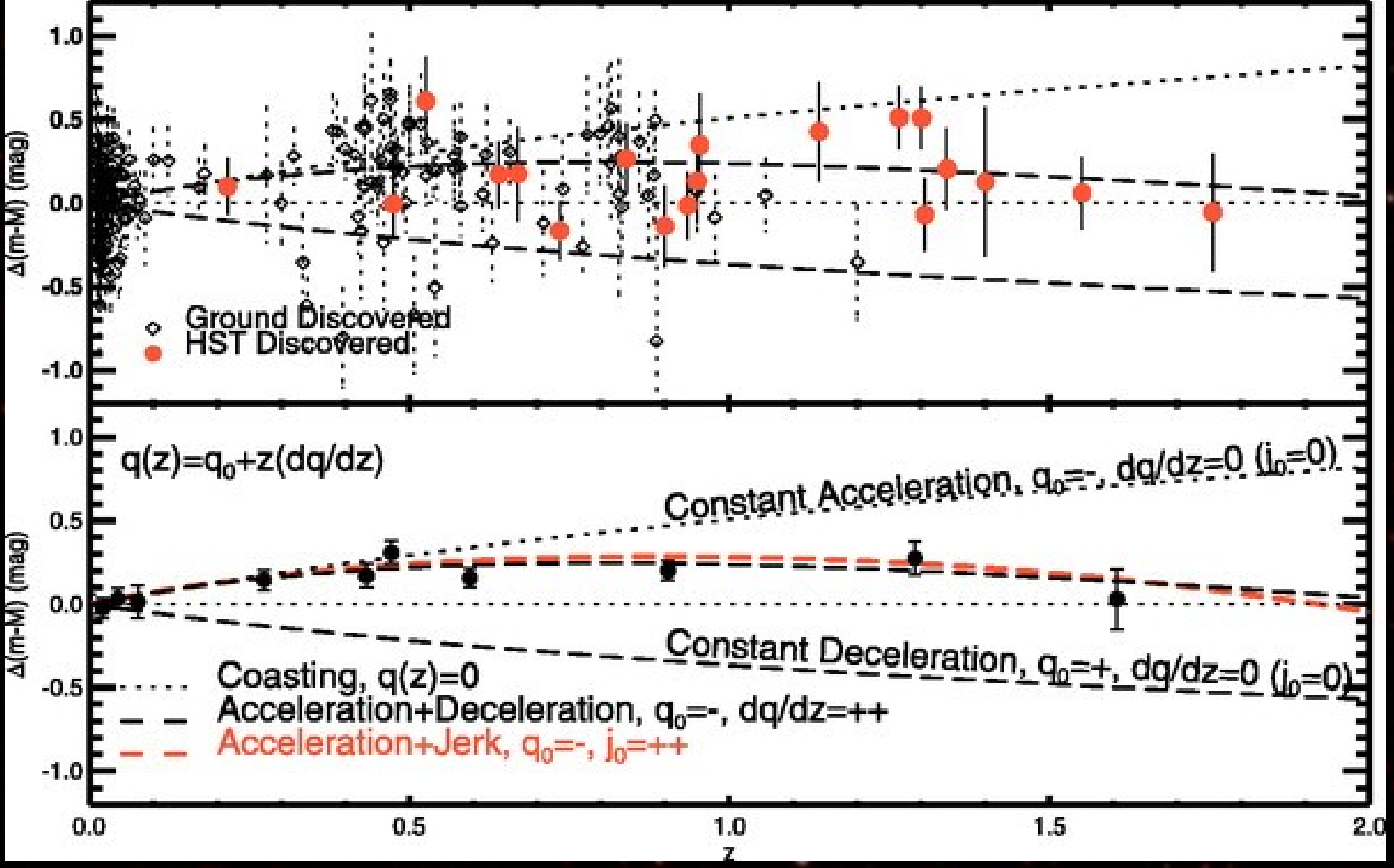

past
today
future
0.0001
0.001
0.01
0.1
1
relative supernova brightness
universe expands forever
universe collapses
Blue region:
The expansion of the universe slowed down for a long time and then, with dark energy, sped up.
acceleration
deceleration
Gold region:
The expansion of the universe always slowed 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



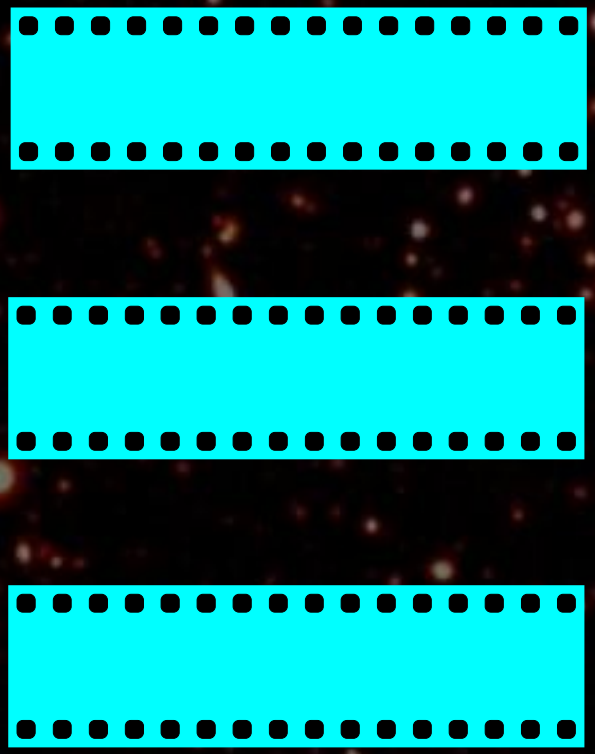


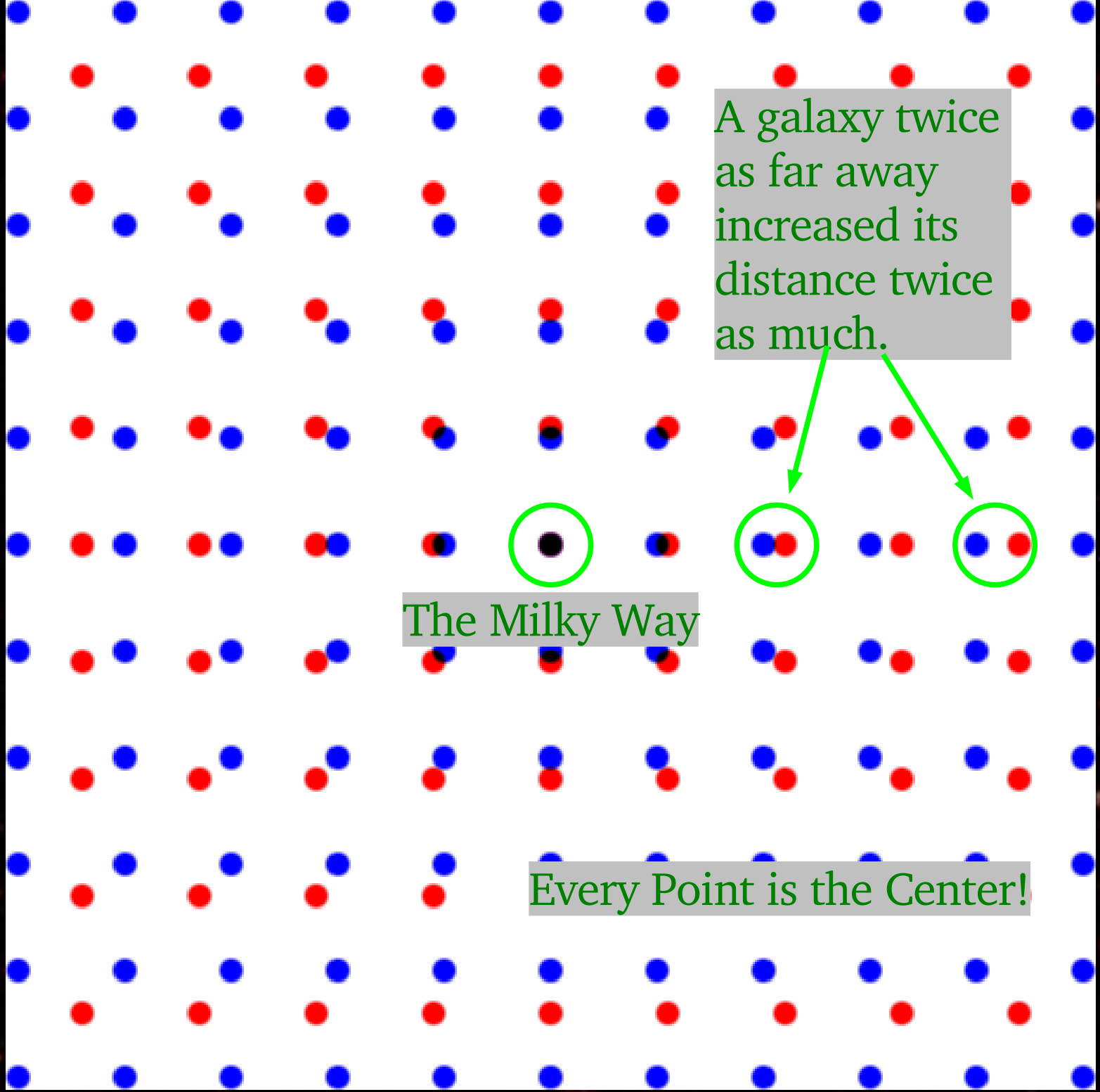
Astier et al., 2006, A&A, 447, 31

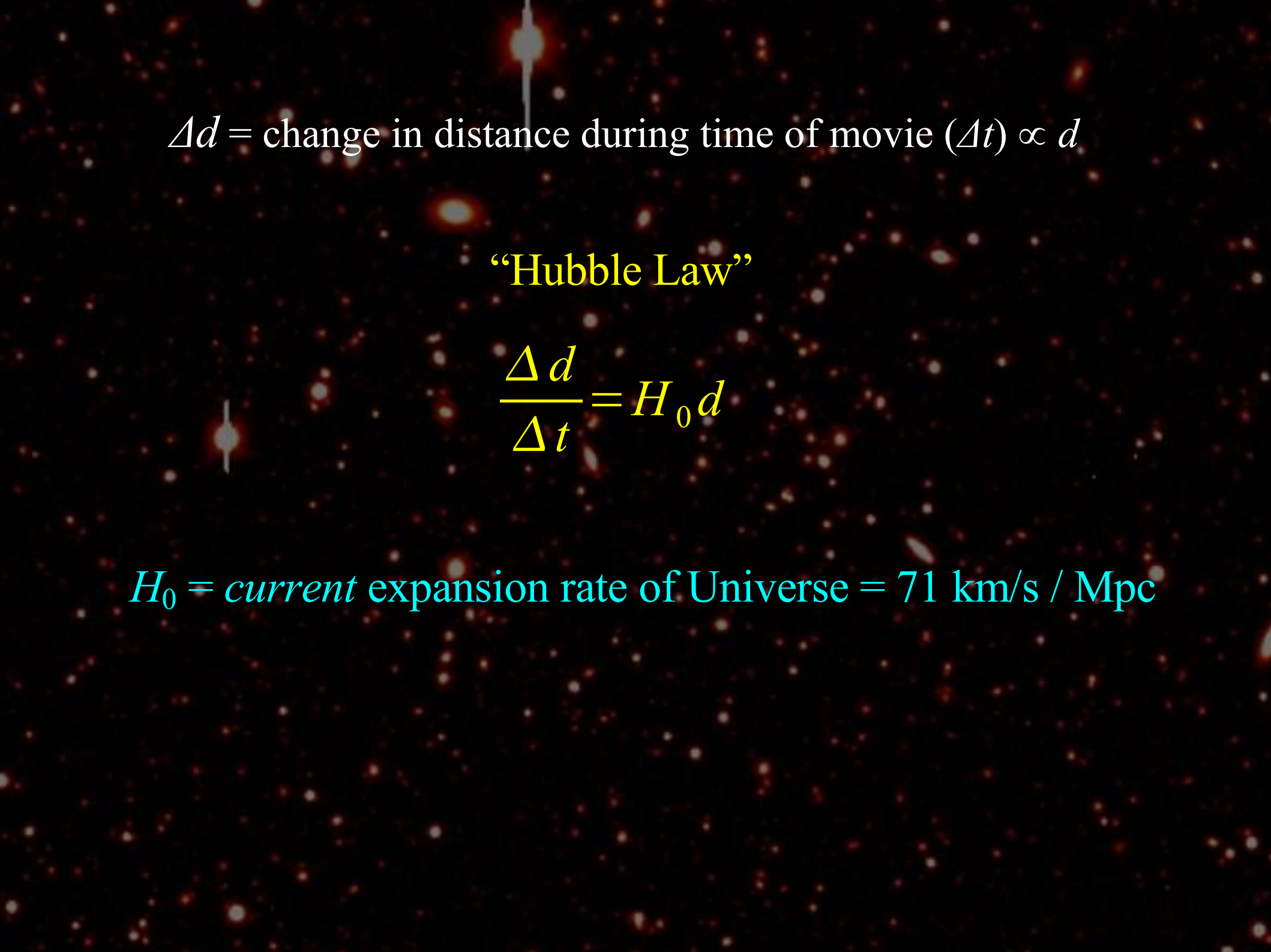


Riess et al., 2004, ApJ, 607, 665

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.

Distance = Time

Standard candle magnitude=
"luminosity distance" = lookback time

Age of Universe = size of horizon
(how far a photon can have gone)

(Please do not look under the rug.)

The Cosmic Microwave Background

Photons emitted from the “surface of last scattering” at recombination when the universe became transparent.

$z \approx 1100$

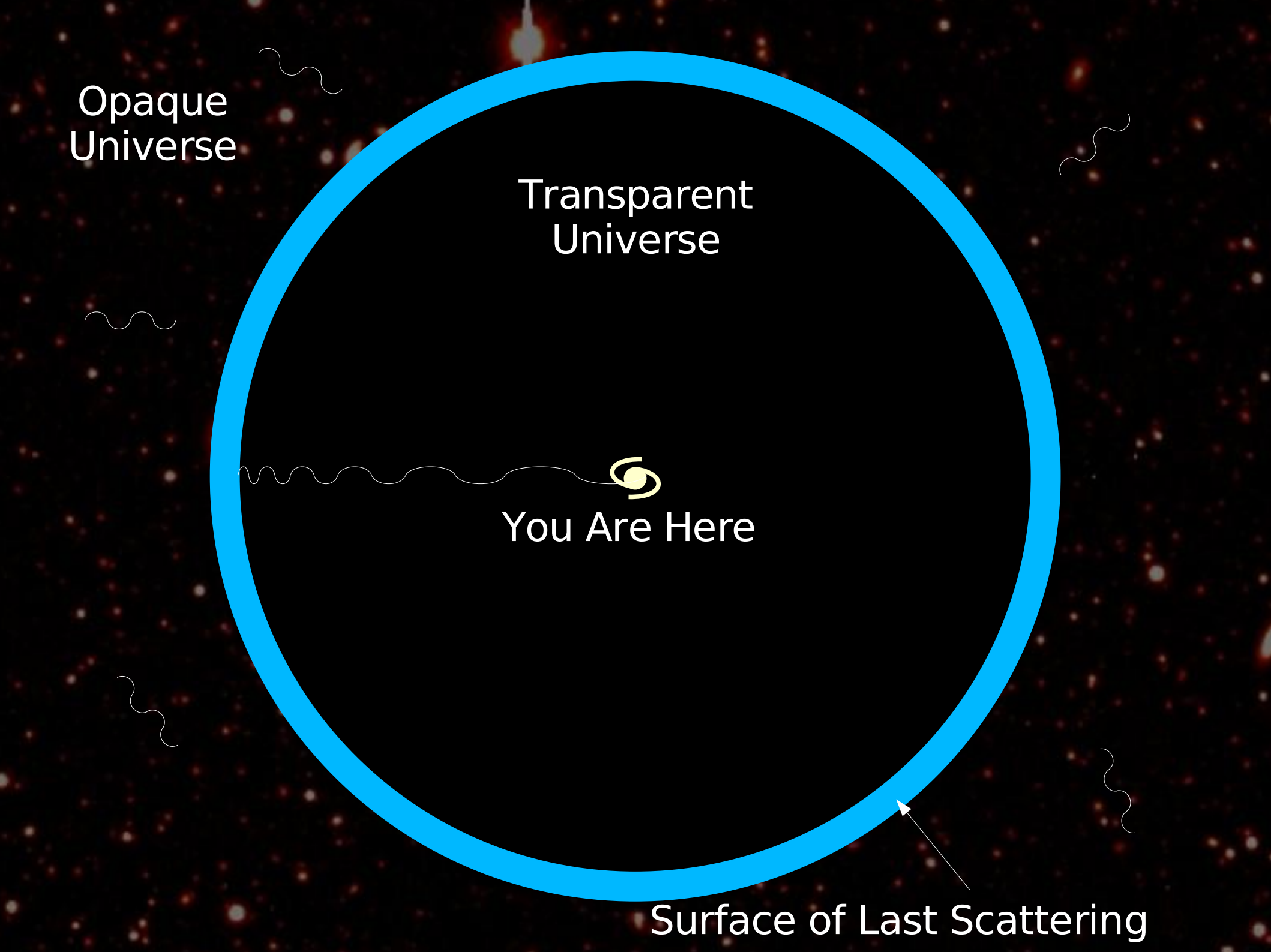
Size of universe = 10^{-3} today's size

Spectrum = Blackbody

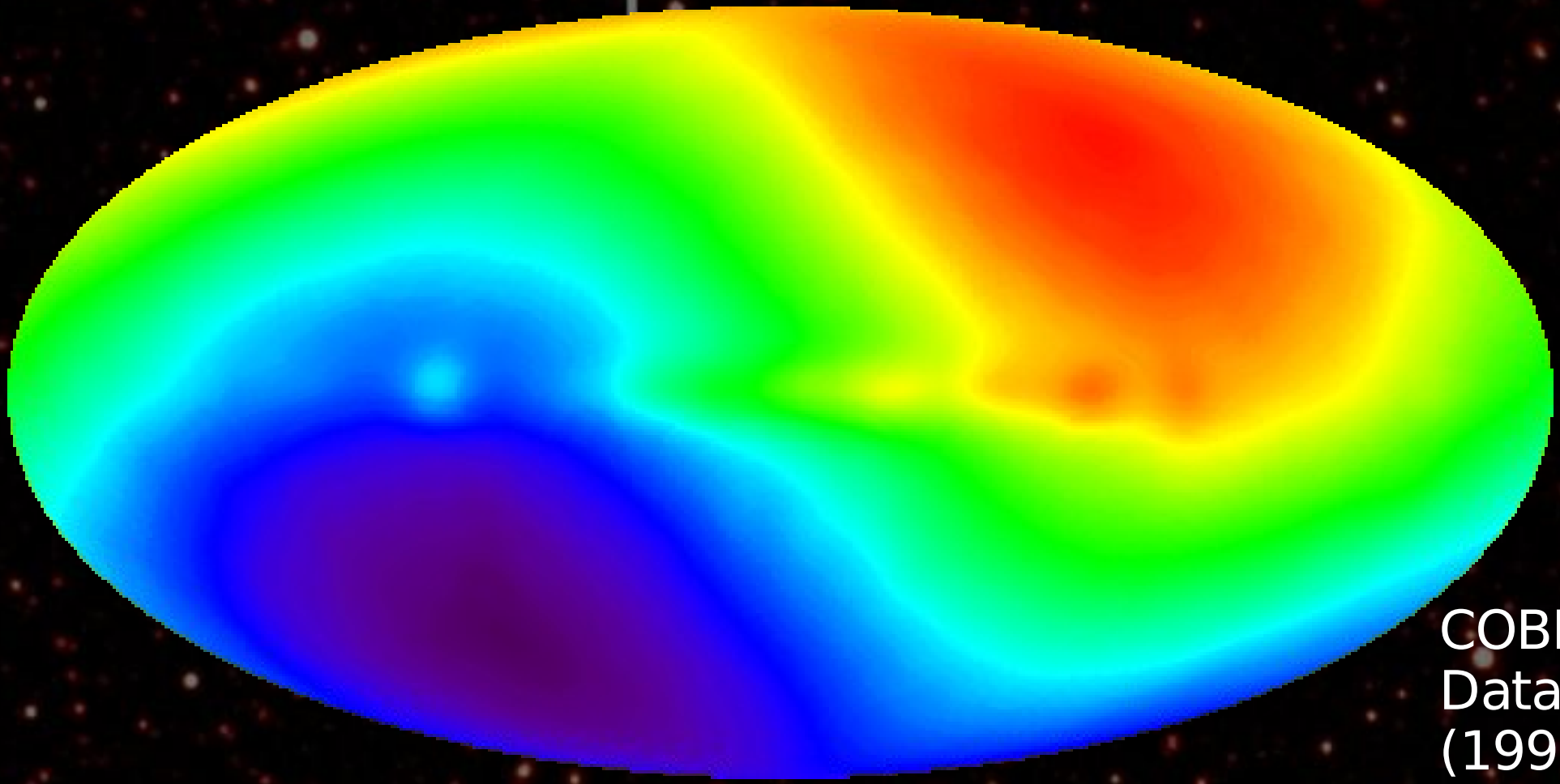
Temperature today: 2.7 K

Temperature at emission: 3000 K

Spatially very smooth (isotropic)


Opaque
Universe
Transparent
Universe
You Are Here
Surface of Last Scattering

CMB Anisotropy 1 : Dipole

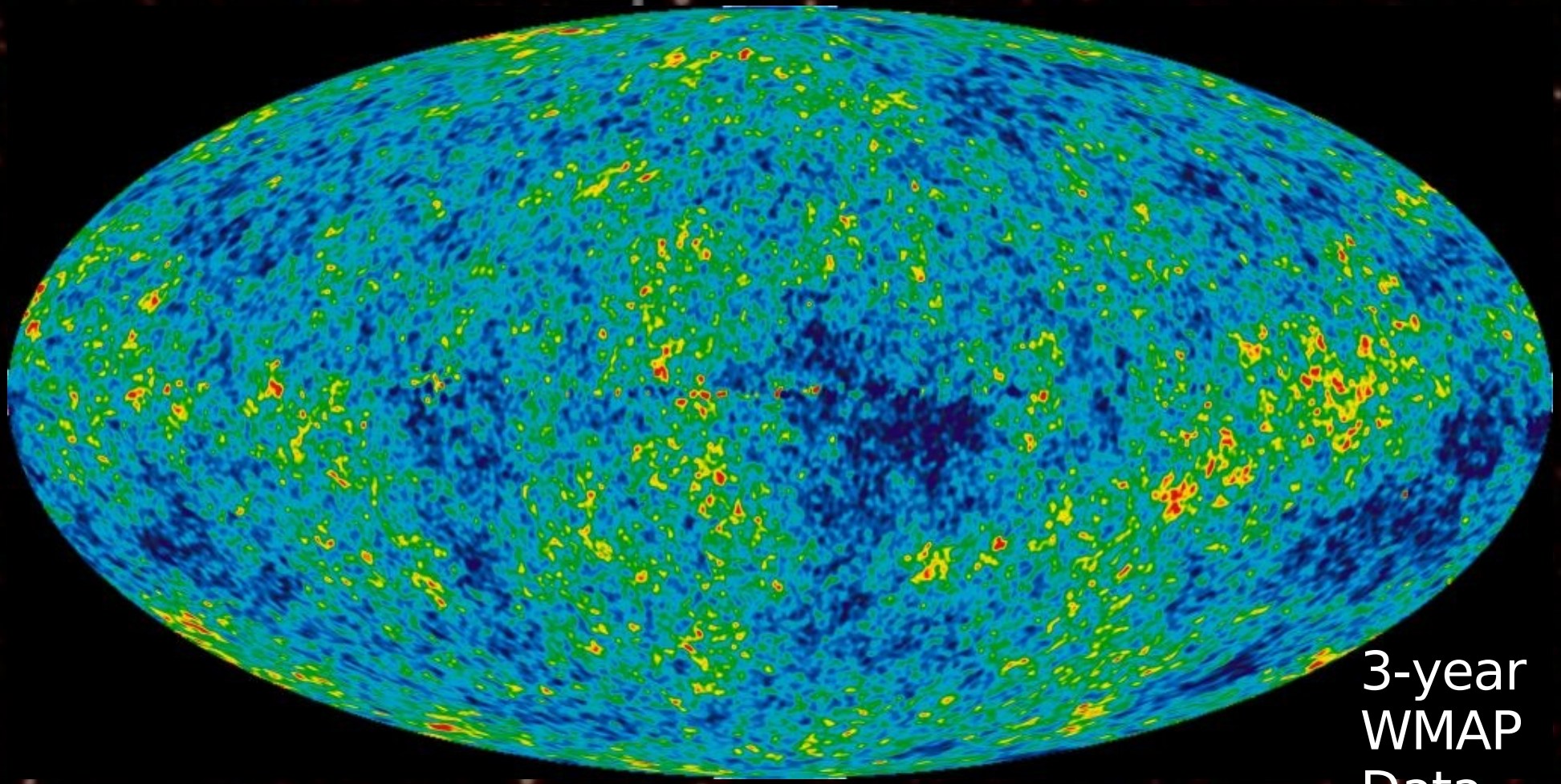


COBE
Data
(1992)

Motion of Sun (Galaxy, Local Group) Relative to CMB

3.346 ± 0.017 mK towards (l,b) = (263.85°, 48.25°)

CMB Anisotropy 2 : Fluctuations

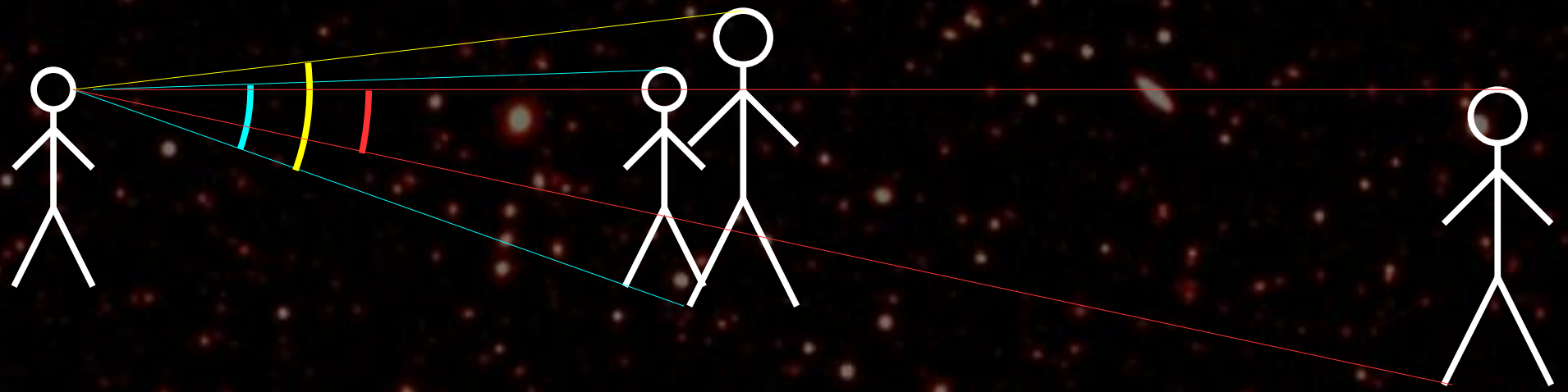


3-year
WMAP
Data

Maximum fluctuation amplitude : 75 μK

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

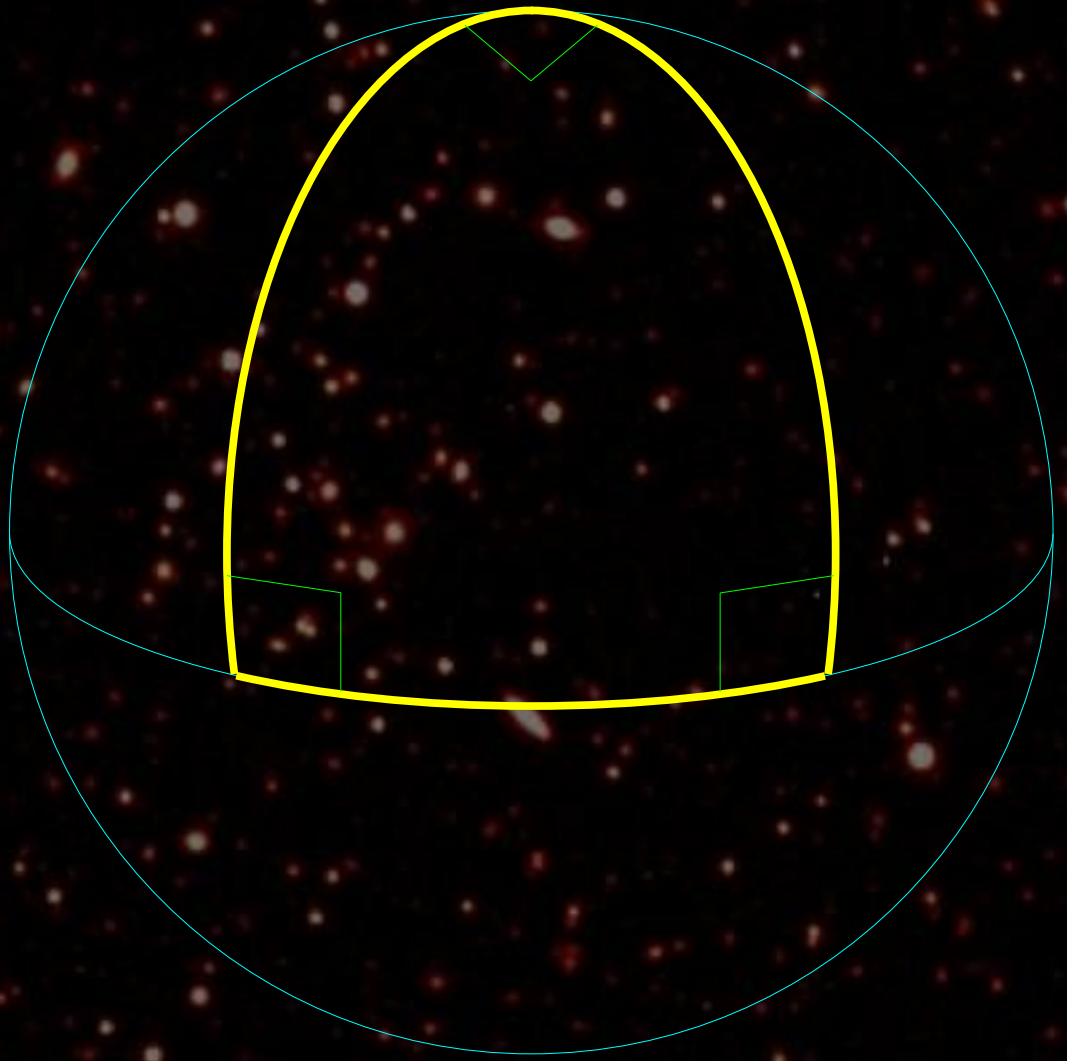
The angle that it *subtends*.



Flat (Euclidean) Space:

Any triangle, three interior angles add to 180°

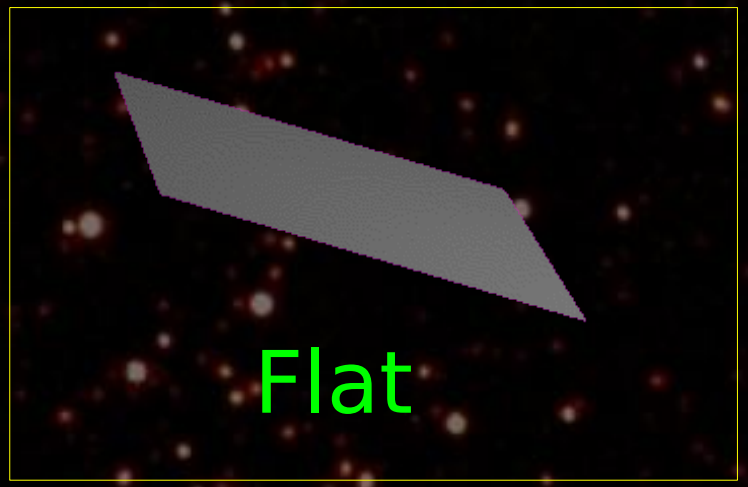
Flatland (2-dimensional) creatures could measure this curvature without reference to the third dimension we use to describe this here!

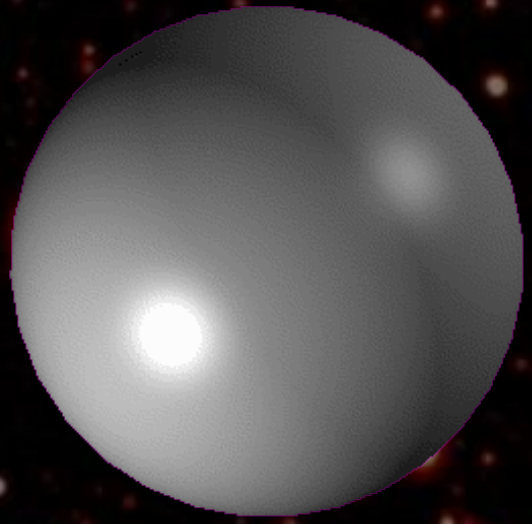


Curved Space: *This* triangle, three interior angles add to 270°

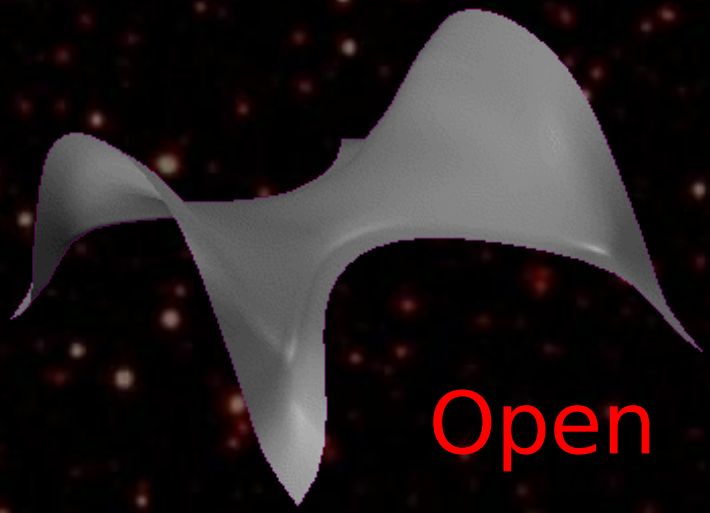
(In general: >180° : positive curvature
<180° : negative curvature)

Possible Shapes of the Universe

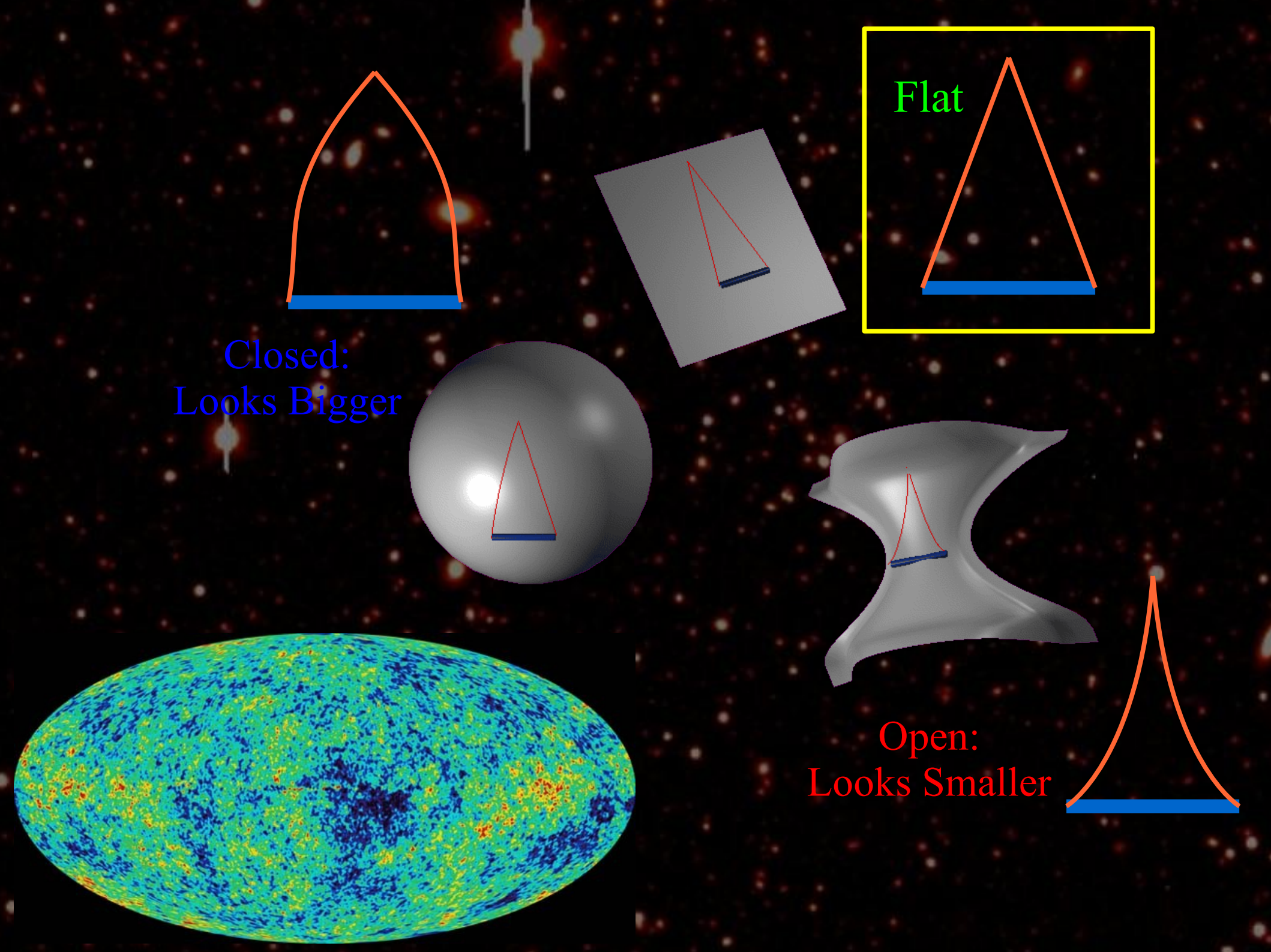




Closed

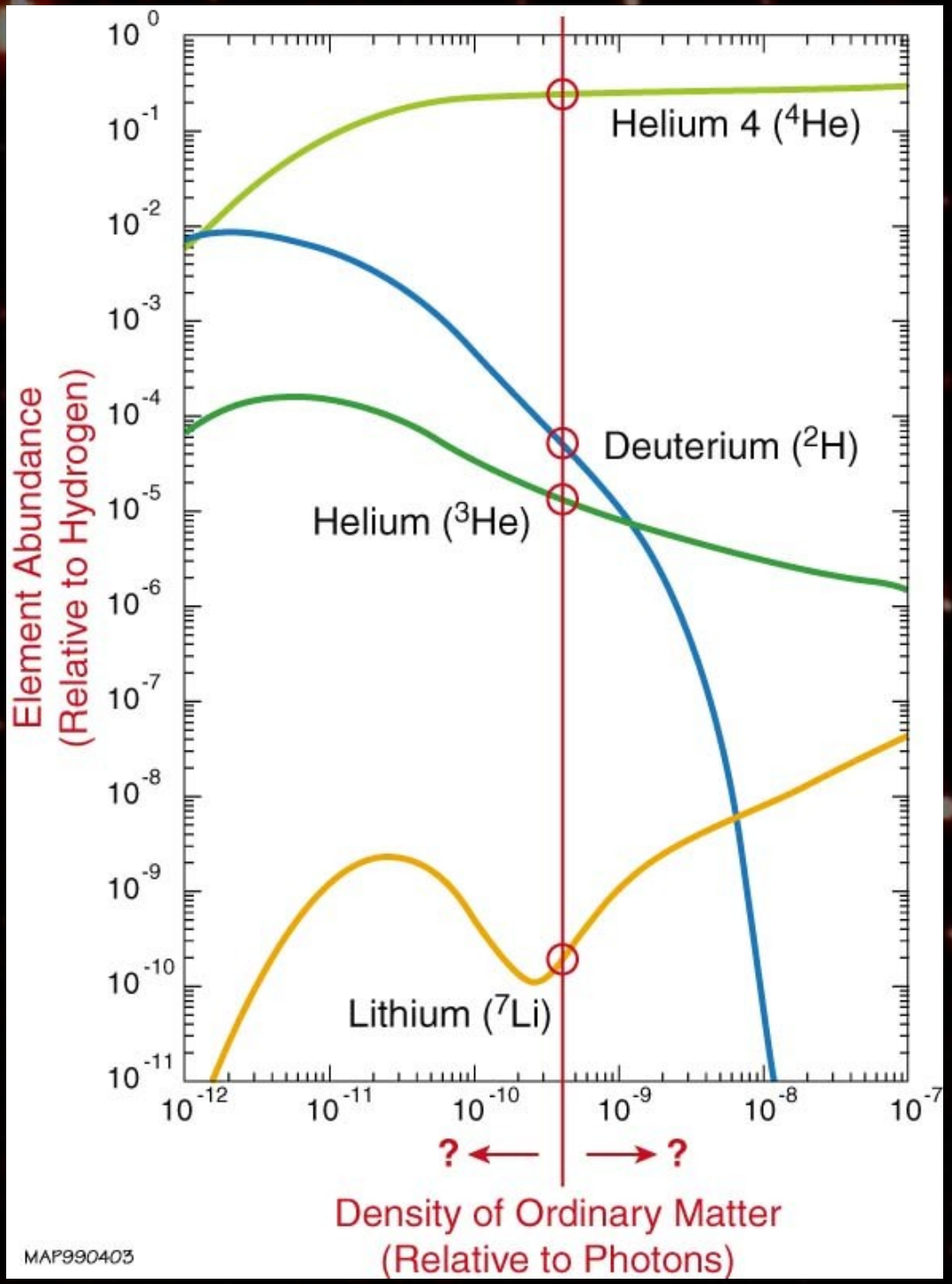


Open


Flat
Closed:
Looks Bigger
Open:
Looks Smaller

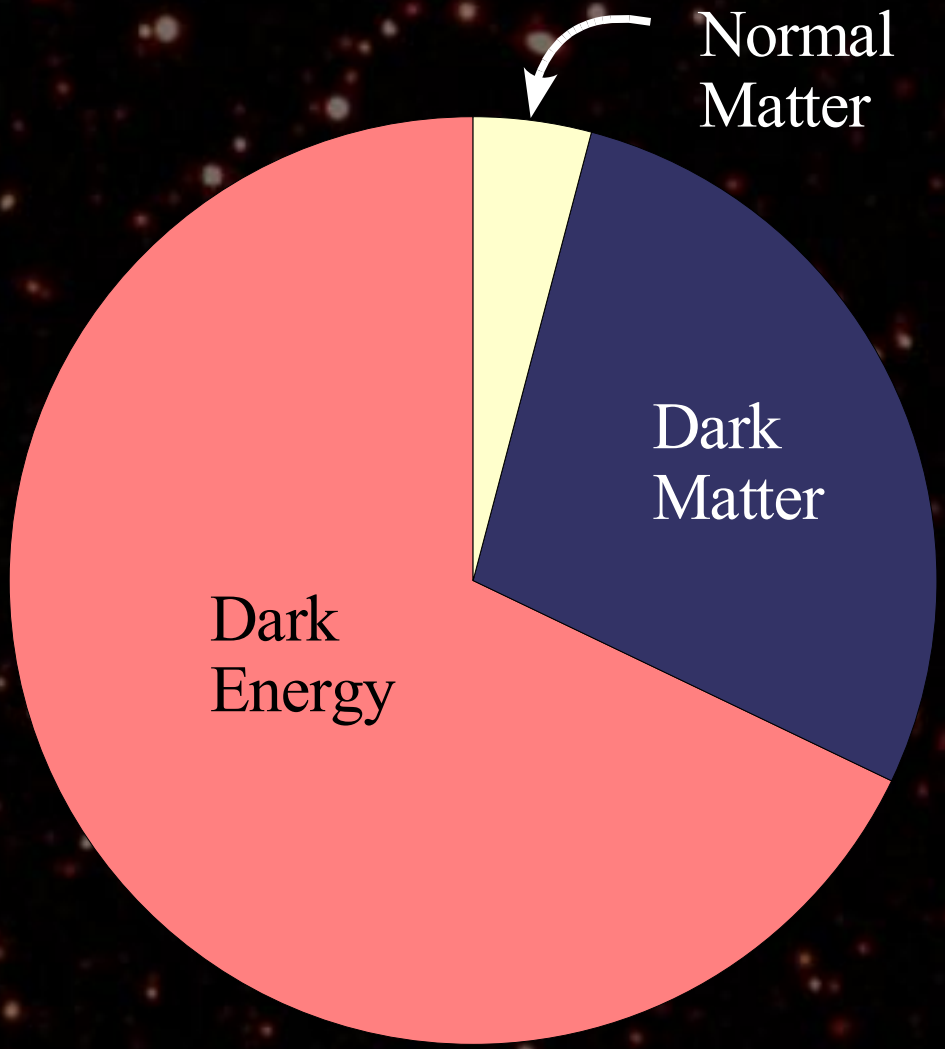
Nuclear Alchemy

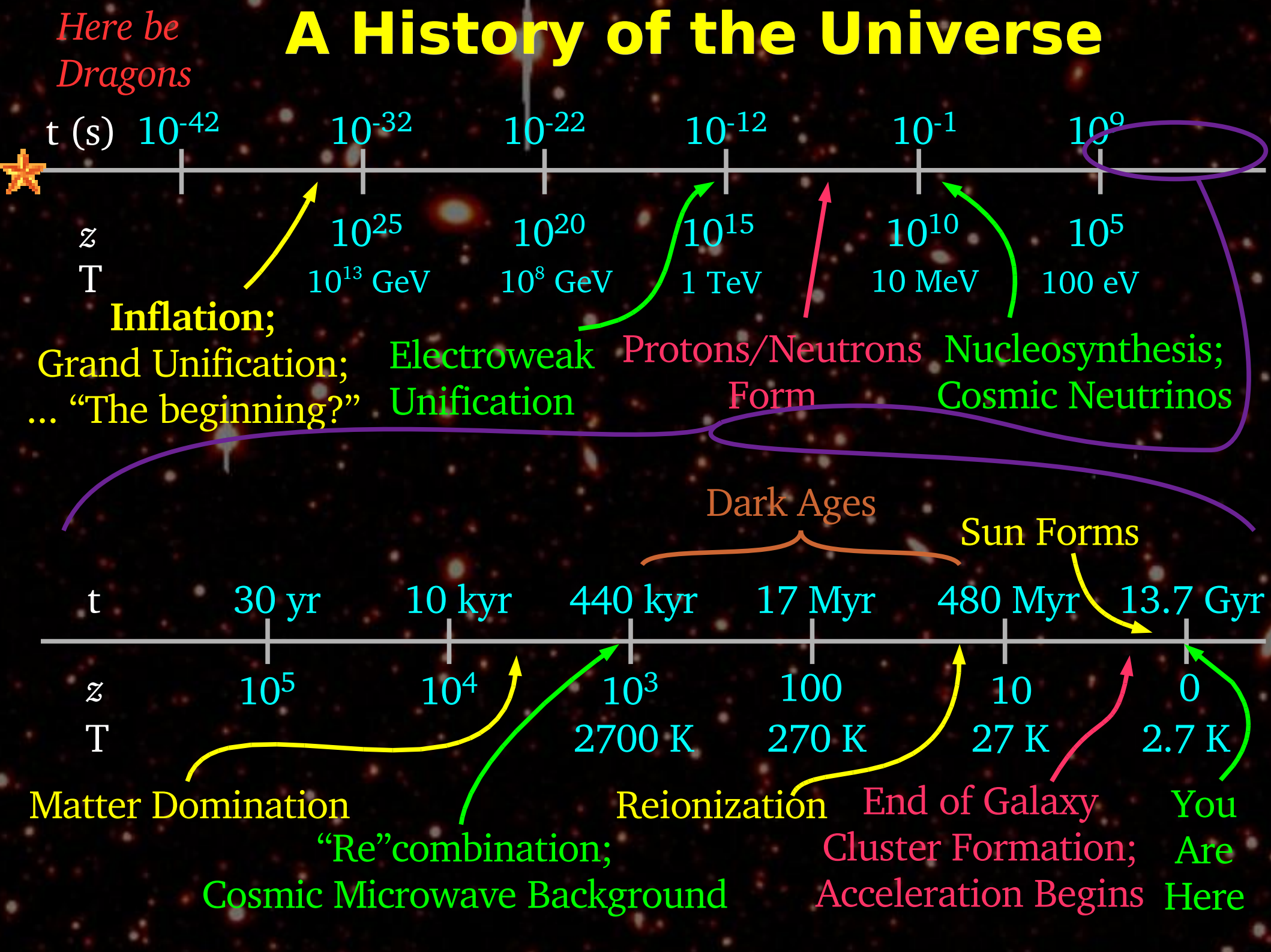
Big Bang theory properly predicts the relative primordial densities of elements in the Universe.



A Consistent Picture of the Universe

- 13.7 Billion Years Old
- Flat Geometry
- Crititcal Mass+Energy Density
- Expansion Accelerating




Here be Dragons
A History of the Universe
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1 TeV
1010
10 MeV
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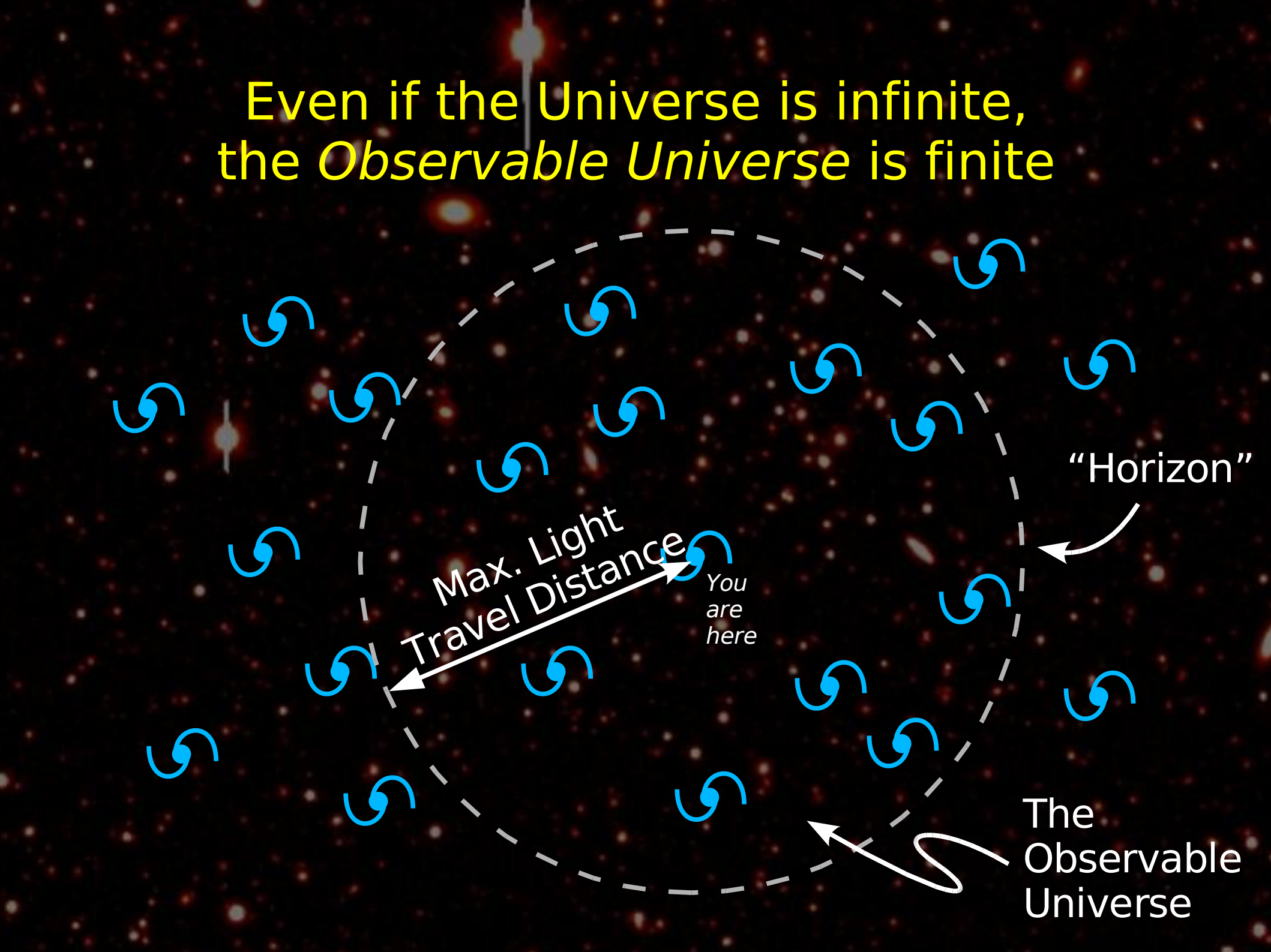
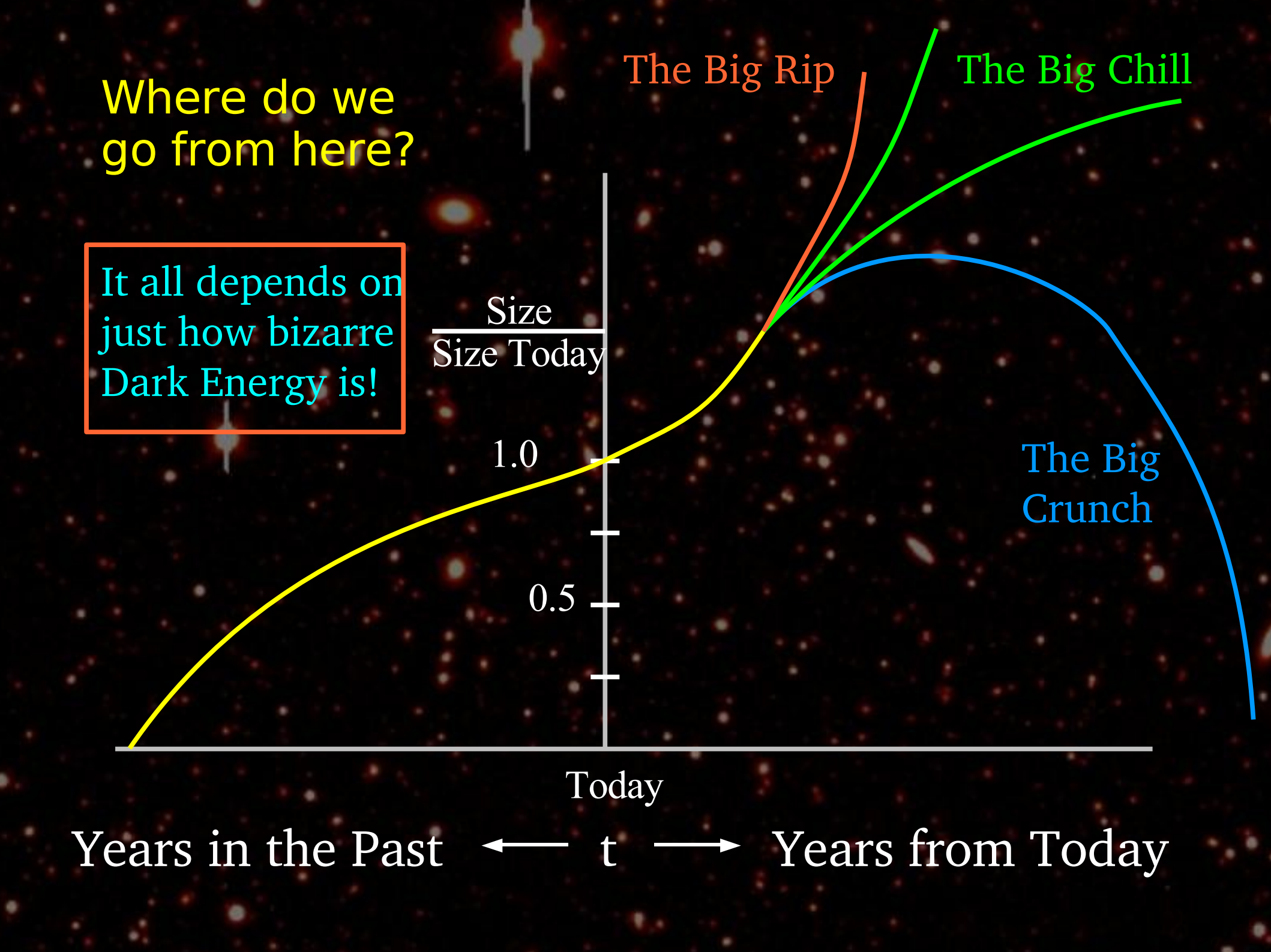
100 eV
Inflation;
Grand Unification;
... "The beginning?"
Electroweak Unification
Protons/Neutrons Form
Nucleosynthesis;
Cosmic Neutrinos
Dark Ages
Sun Forms
t
30 yr
10 kyr
440 kyr
17 Myr
480 Myr
13.7 Gyr
z
105
104
103
100
10
0
T
2700 K
270 K
27 K
2.7 K
Matter Domination
"Re"combination;
Cosmic Microwave Background
Reionization
End of Galaxy Cluster Formation;
Acceleration Begins
You Are Here

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

(Actual Size)


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


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