
The discovery of
The Accelerating Universe
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High Point University
2007-10-22

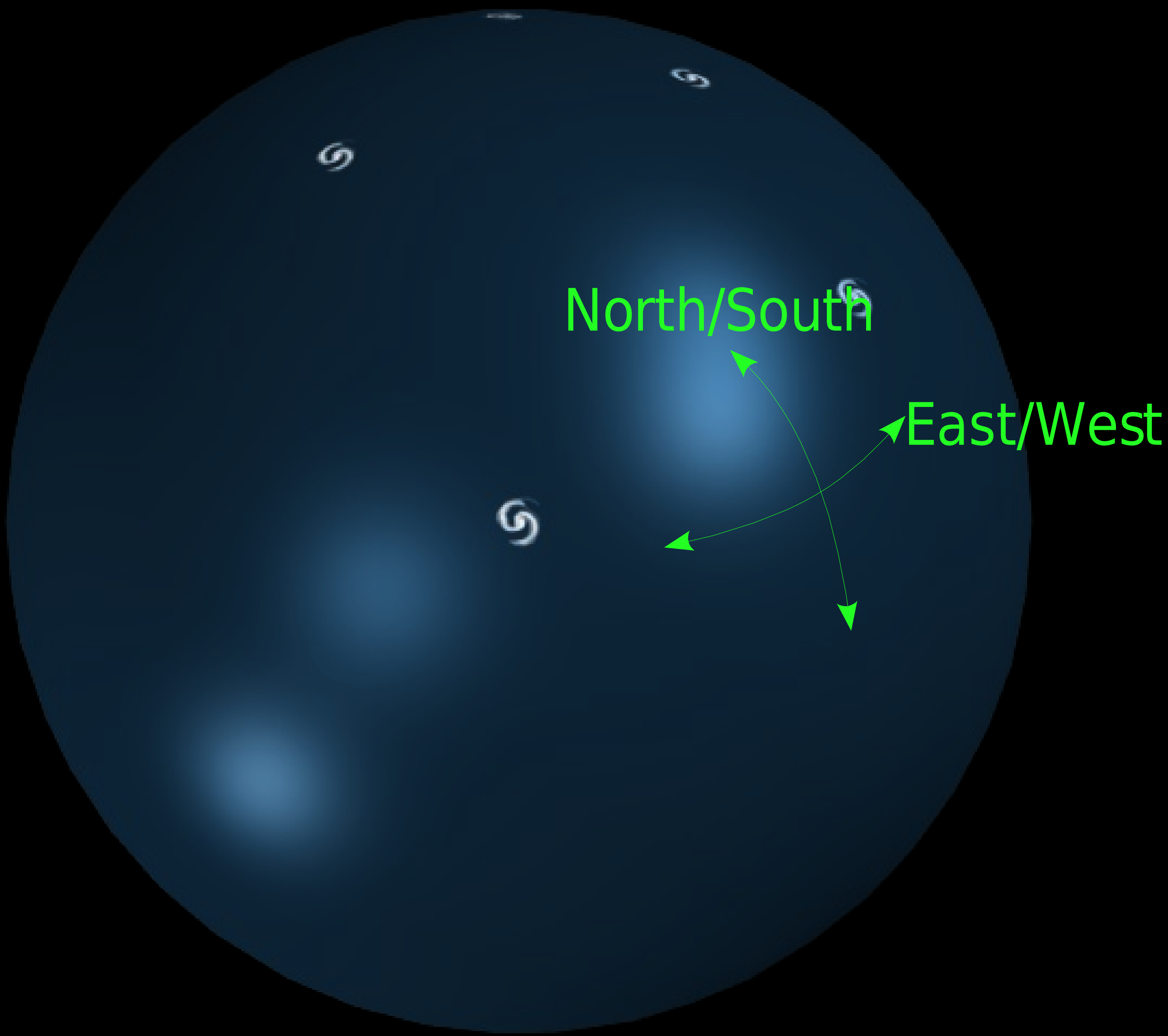
I. Describing the Whole Universe
- A “modern way” to talk about the expansion
- Just 3 numbers

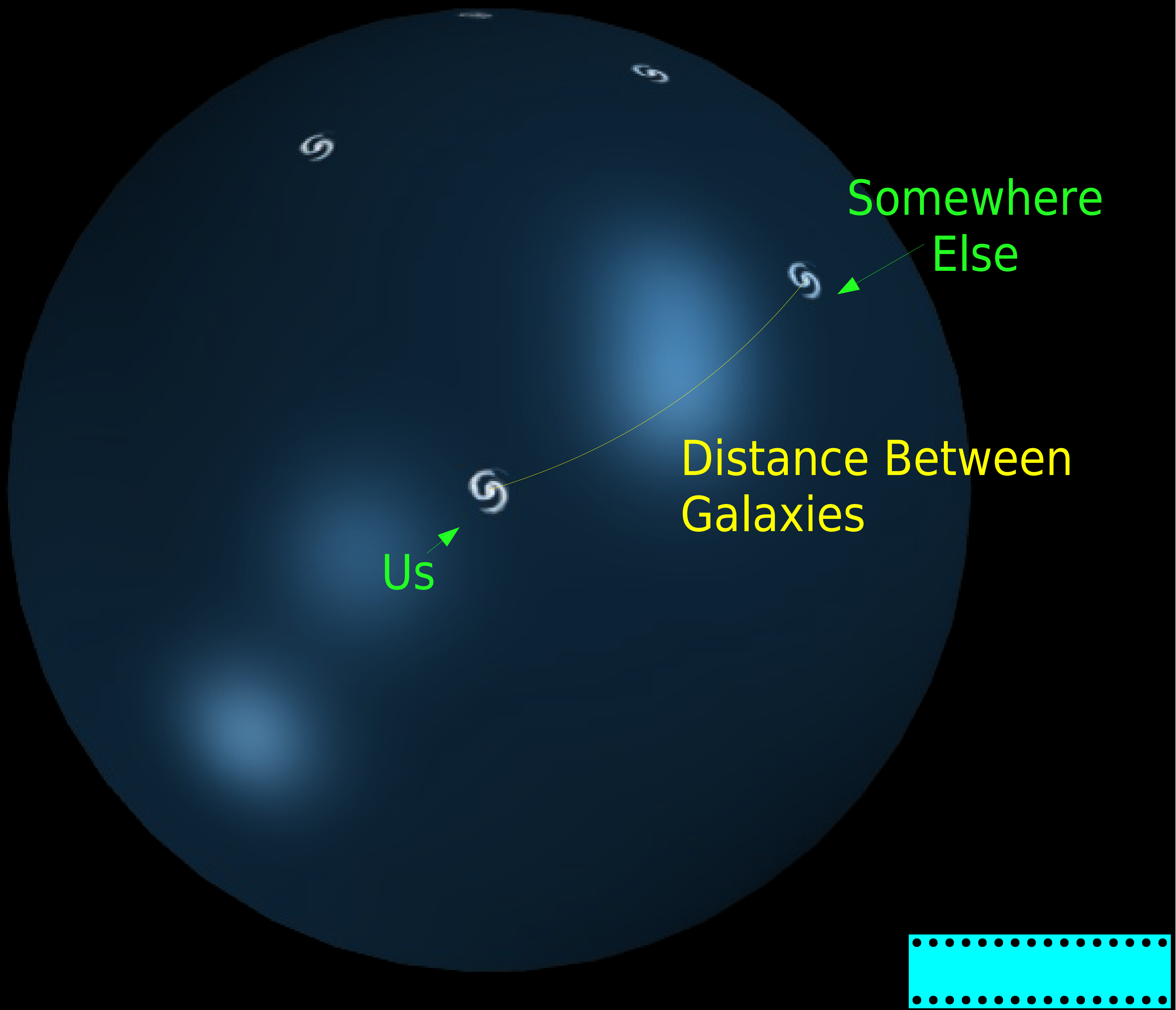
II. Measuring The Expansion of Space
- Lookback Time
- Measuring Expansion: Redshift
- Measuring Expansion Rate

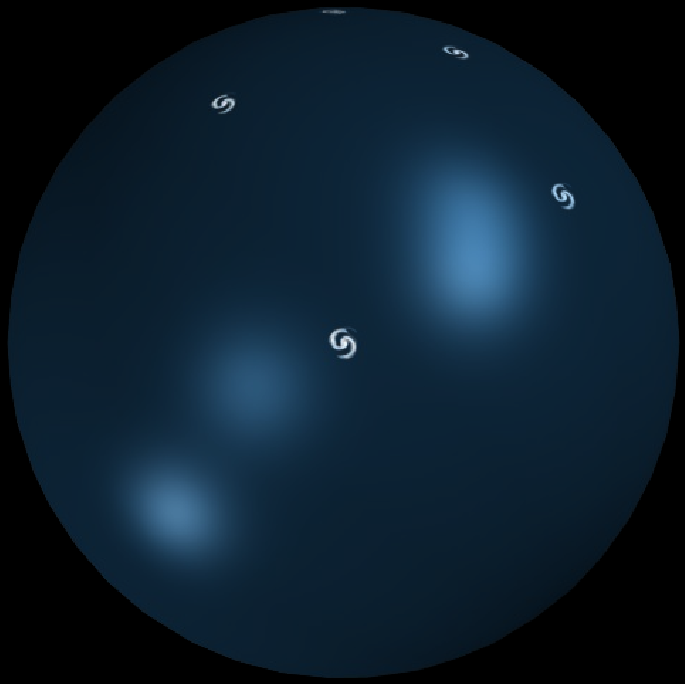
III. Discovery of the Acceleration
- Our Standard Candle: Type Ia Supernovae
- The Evidence for Acceleration
- What Does it all Mean?
- A Consistent Picture of the Universe

IV. How did we get here? The Big Bang….

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



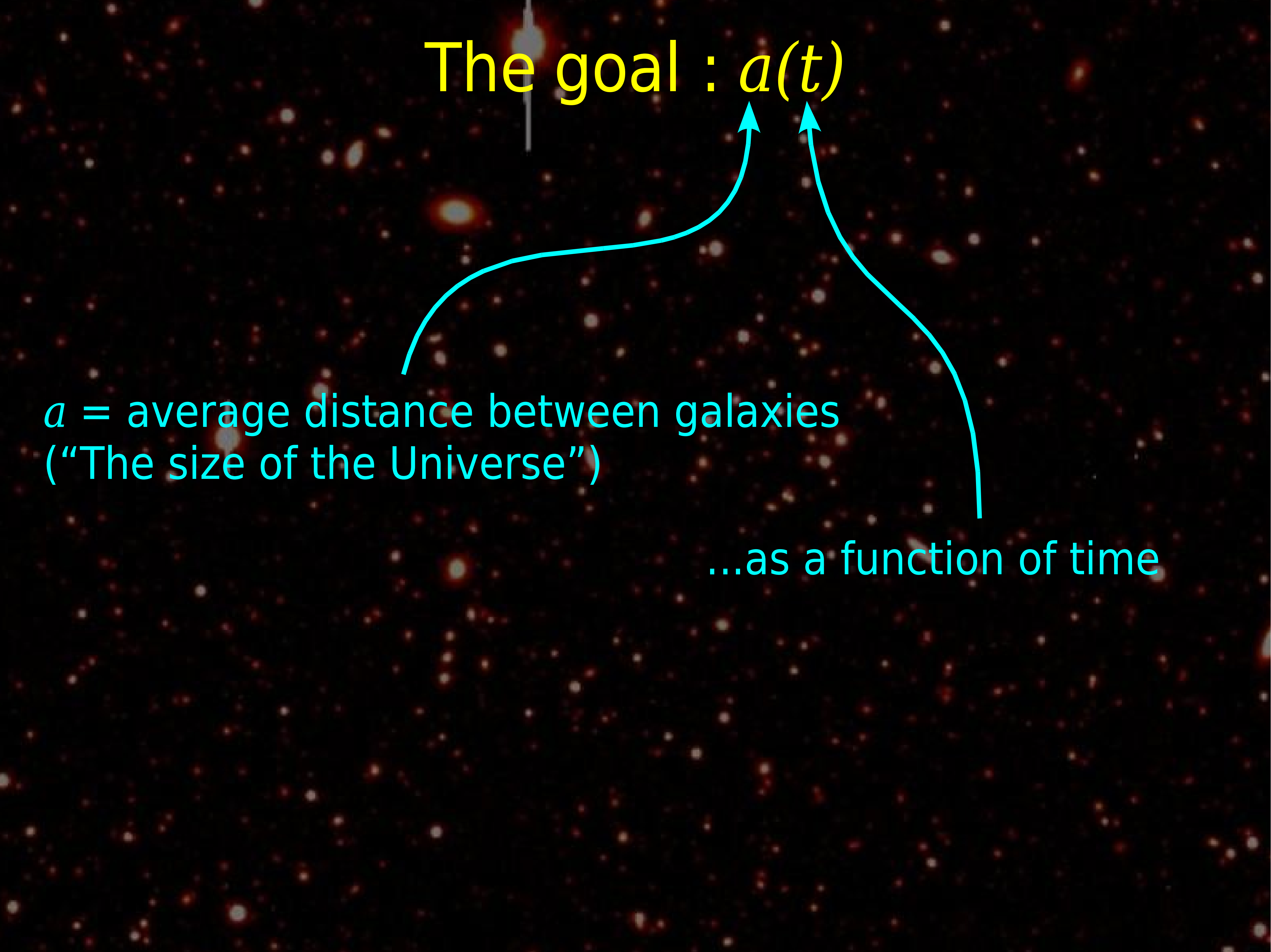

Somewhere
Else
Distance Between
Galaxies
Us



Points to notice

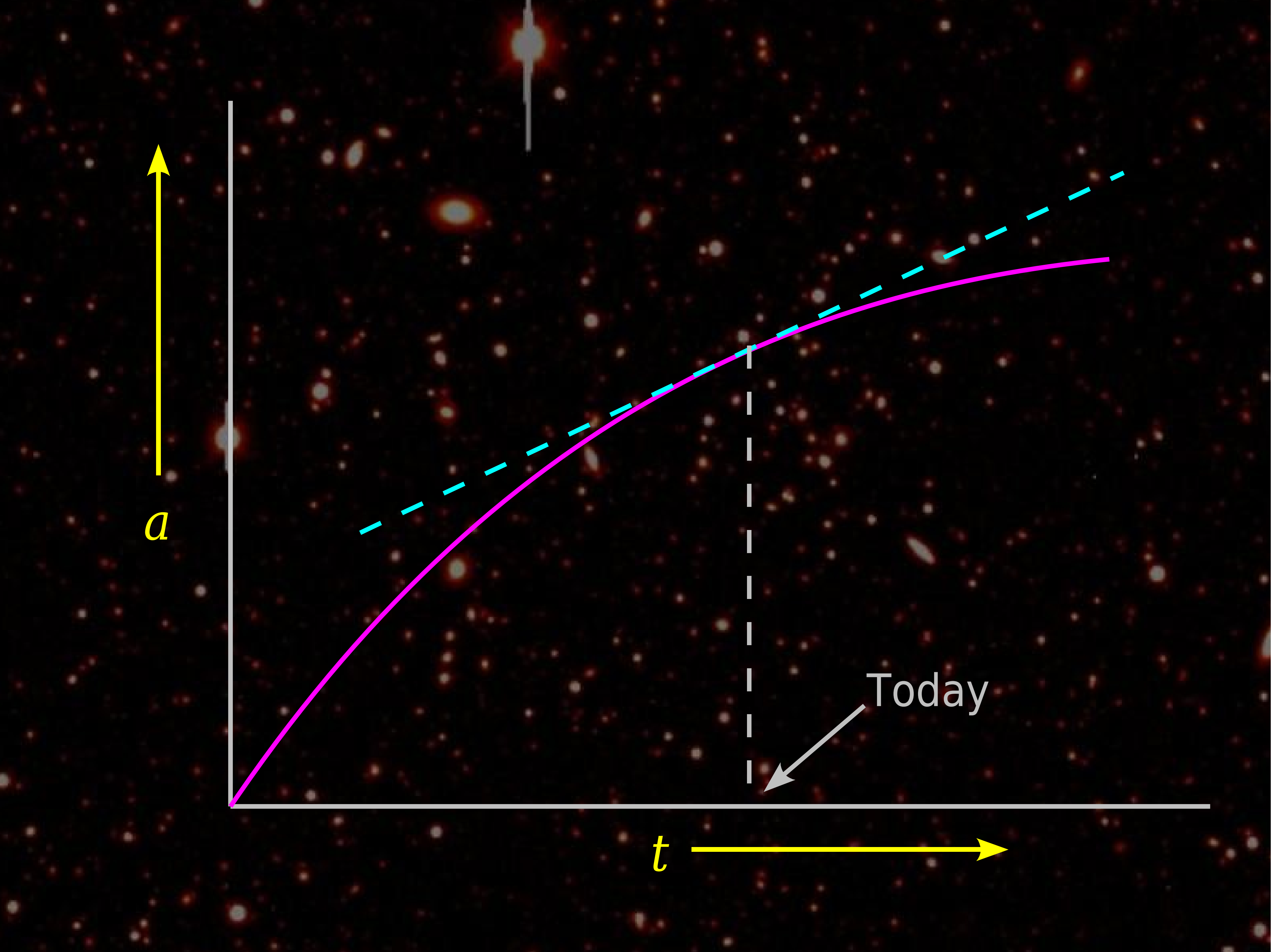
- As the Universe expands, galaxies get farther apart, but...
- ...galaxies are *not* moving *through space* **
- Galaxies *don't* expand themselves
- This is probably not the explanation you've heard (i.e. galaxies flying apart with greater speeds at greater differences), but better expresses the modern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

The goal : $a(t)$



a = average distance between galaxies
("The size of the Universe")

...as a function of time


a
t
Today

Einstein's General Relativity + the Freedman-Robertson-Walker metric tell us that only three numbers control the expansion history of the Universe:

$$a(t) = a(t\ ; H_{0,} \Omega_M , \Omega_\Lambda)$$

H_0 The “Hubble Constant”, the current expansion rate

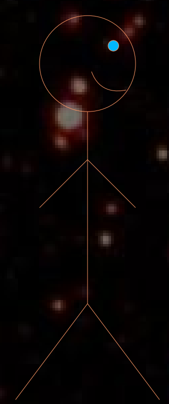
Ω_M The density of matter (normal matter plus dark matter)

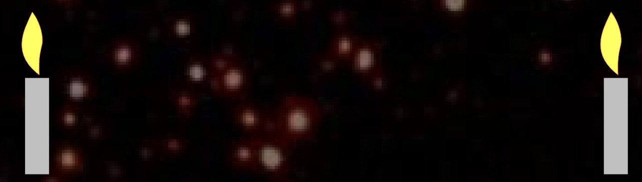
Ω_Λ The cosmological constant (or Vacuum Energy density or Dark energy density)

(Things under the rug include at least Ω_R, $w(t)$)

Looking Back in Time

The brightness of a "standard candle" measures "Lookback Time"





The candle which is farther will appear dimmer.

Speed of Light = 300,000 km/s

= 1 light-year / year

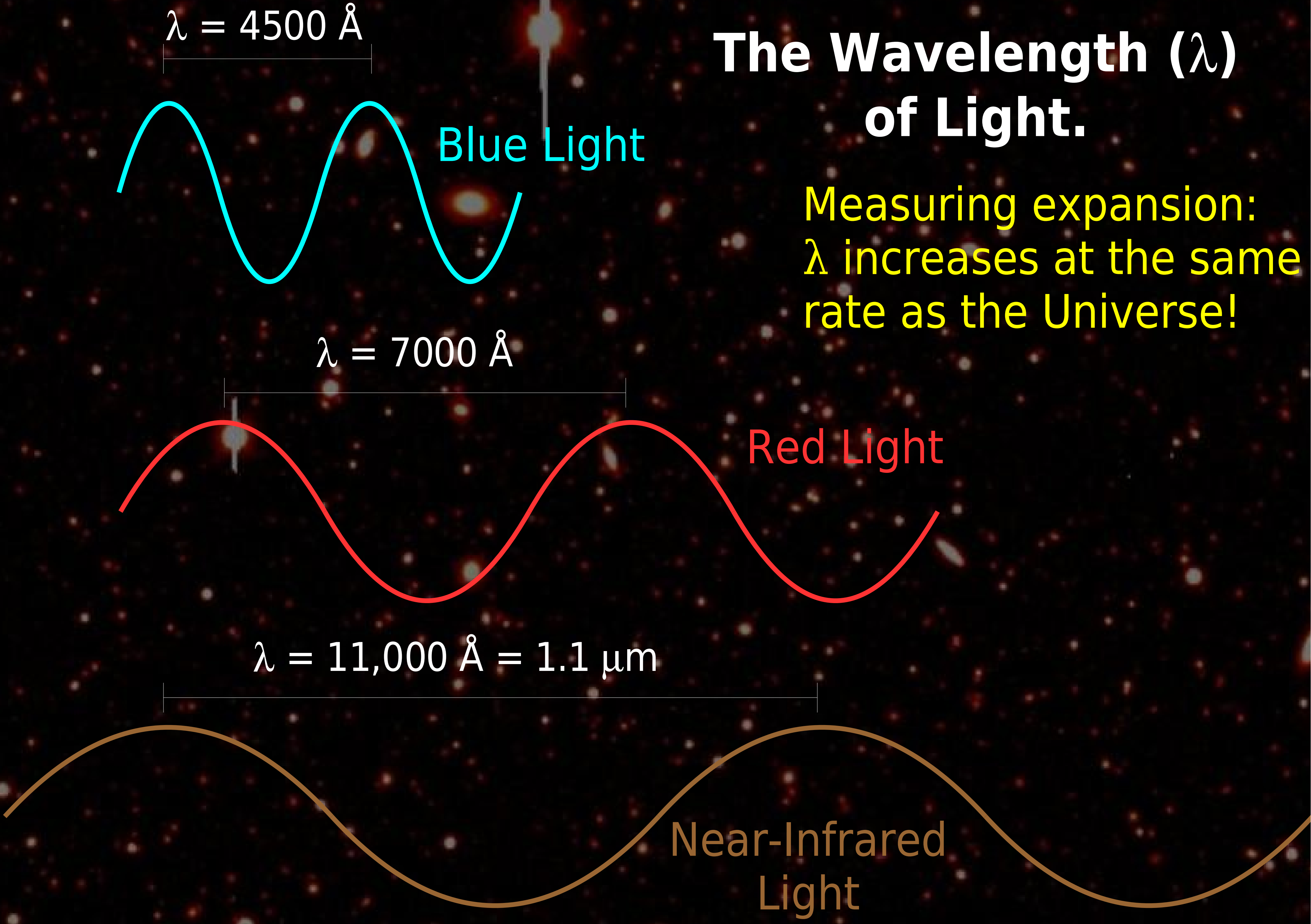
Dimmer = Farther Away = *Further Back in Time!*

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

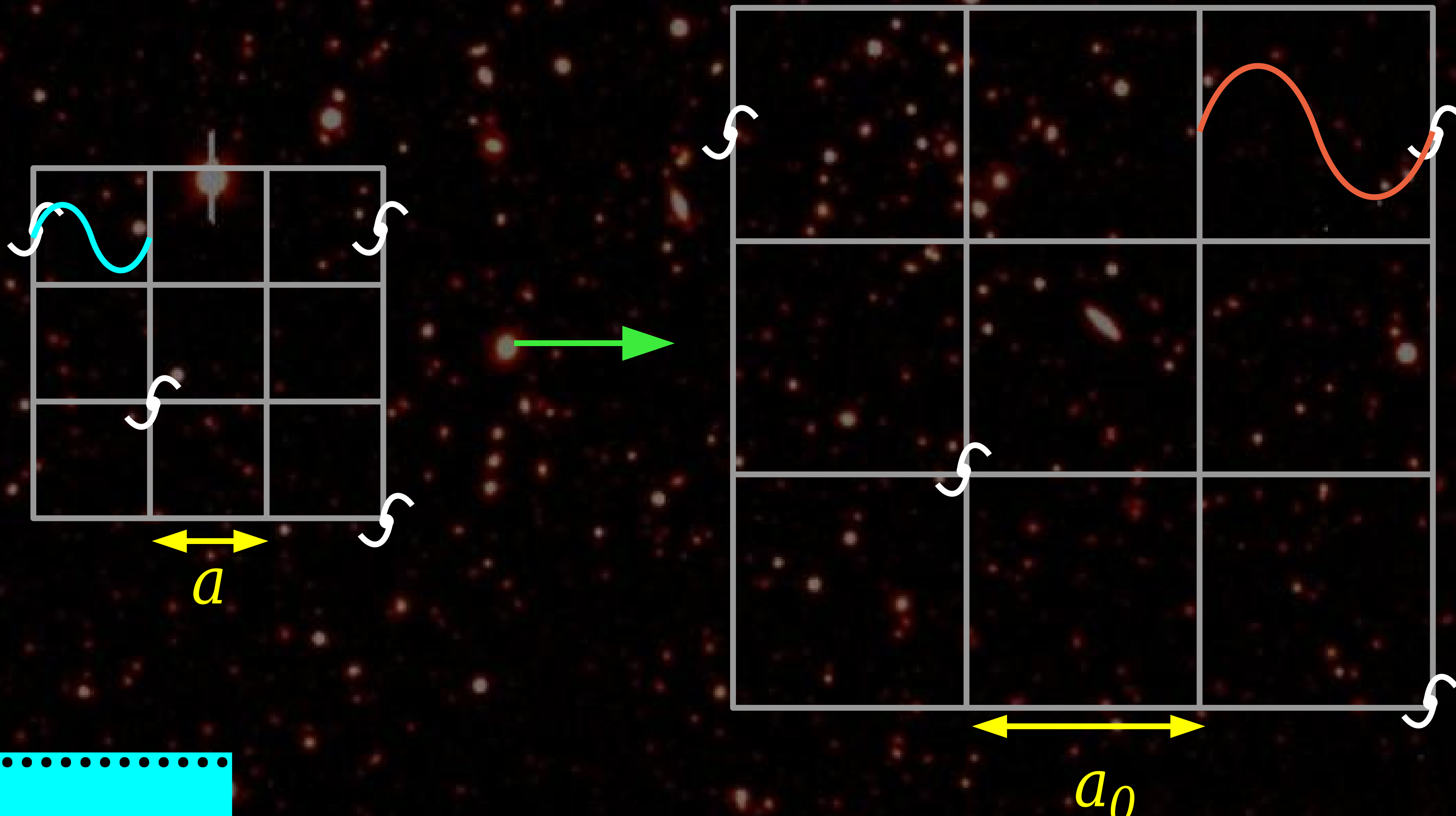
The Wavelength (λ) of Light.

Measuring expansion:
λ increases at the same rate as the Universe!



Cosmological Redshift z:
How much has the Universe expanded?

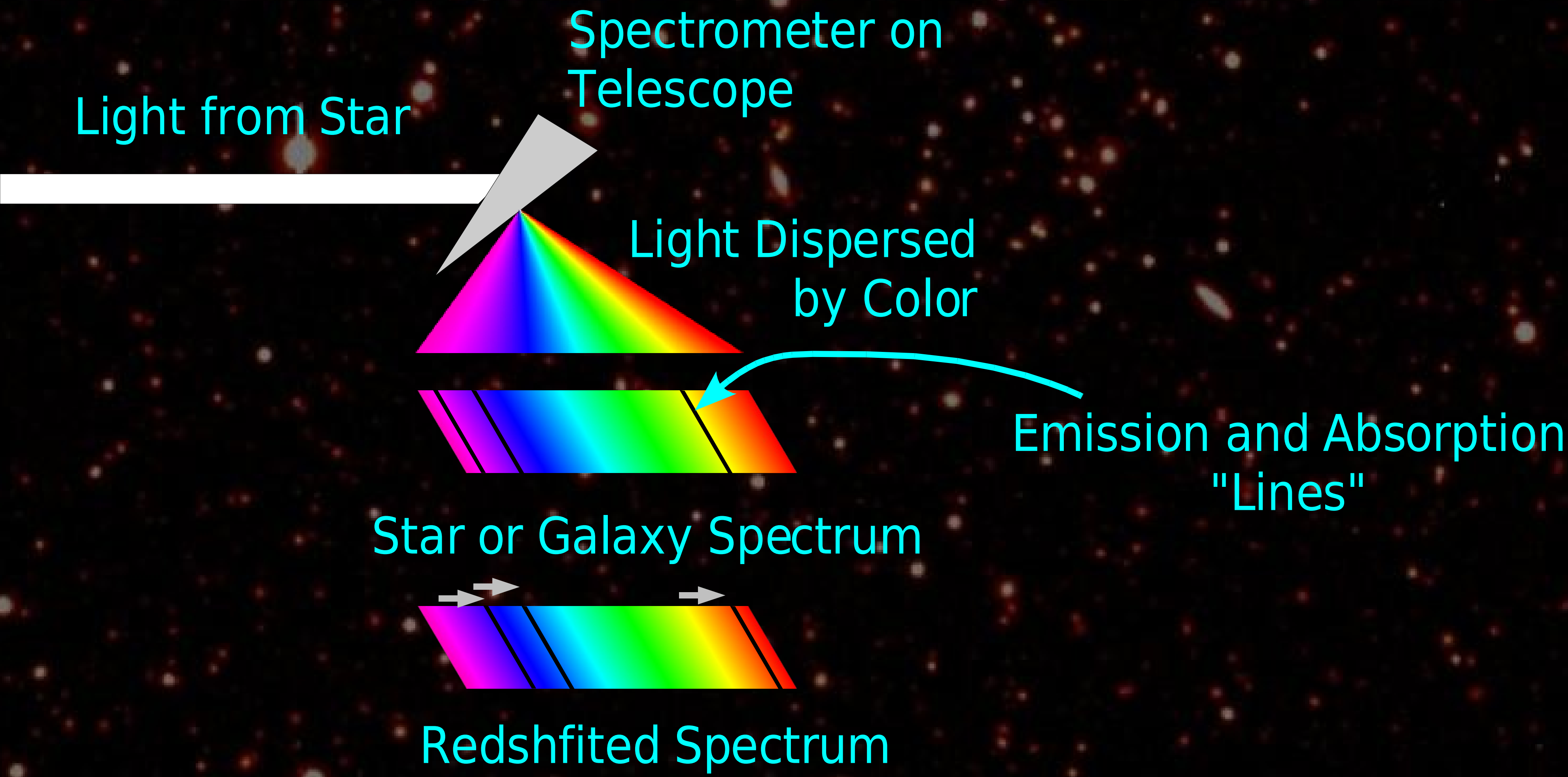
$$1 + z = \frac{a_0}{a} = \frac{\text{Size at Detection}}{\text{Size at Emission}}$$

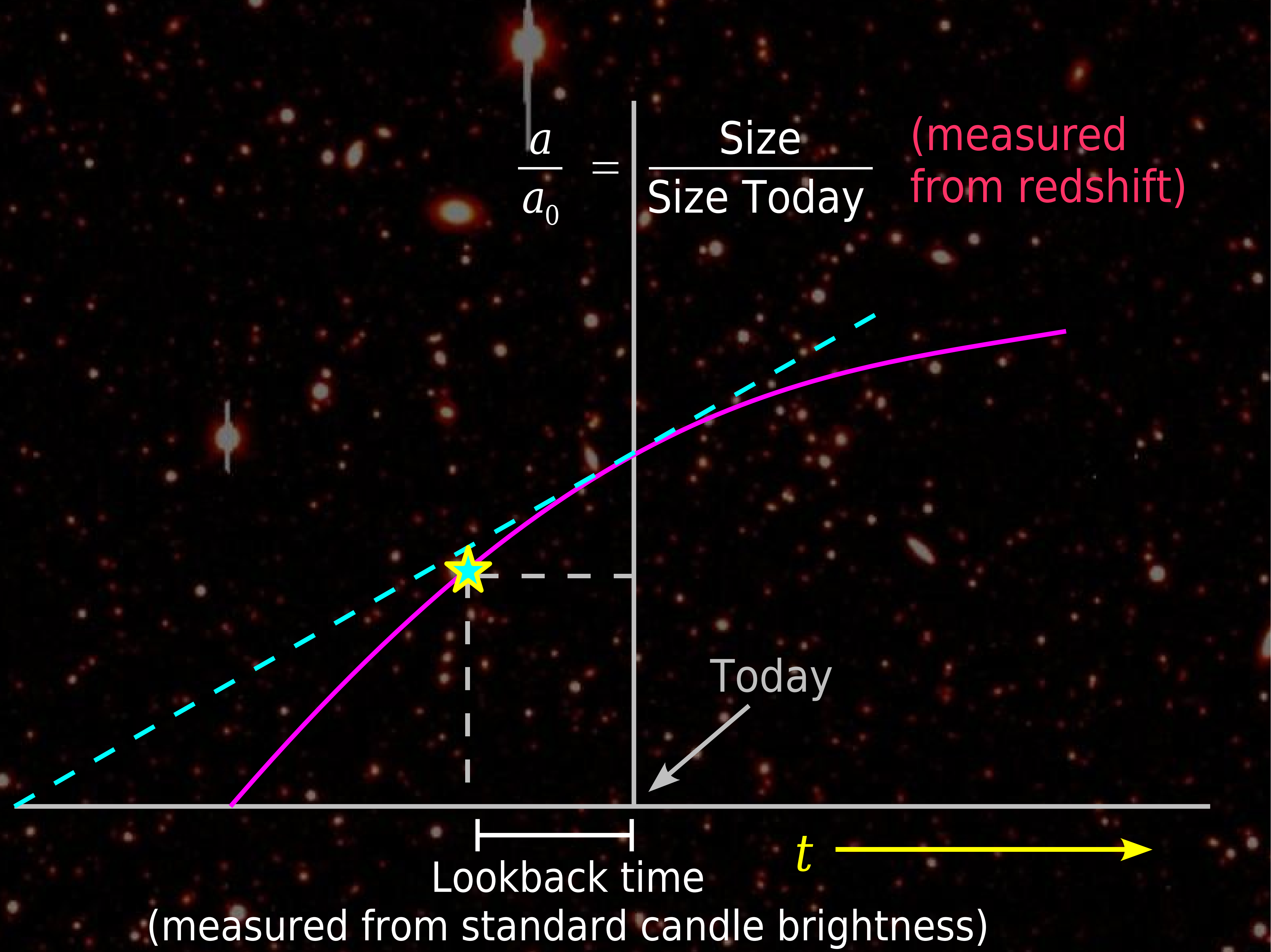


Spectroscopy:

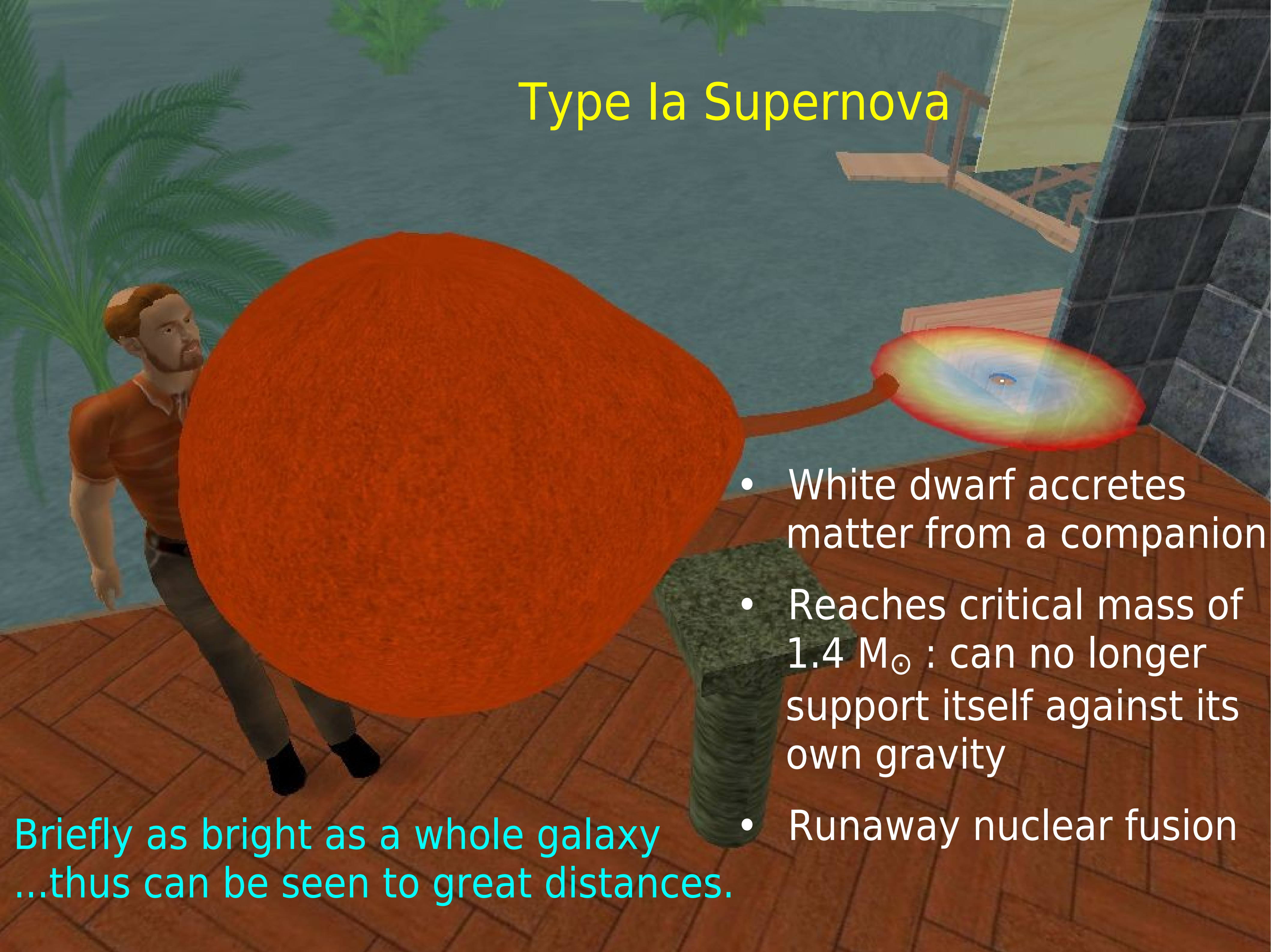
Measuring Redshifts

$$z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$$





$\frac{a}{a_0} = \frac{\text{Size}}{\text{Size Today}}$
(measured from redshift)
Today
Lookback time
(measured from standard candle brightness)
t



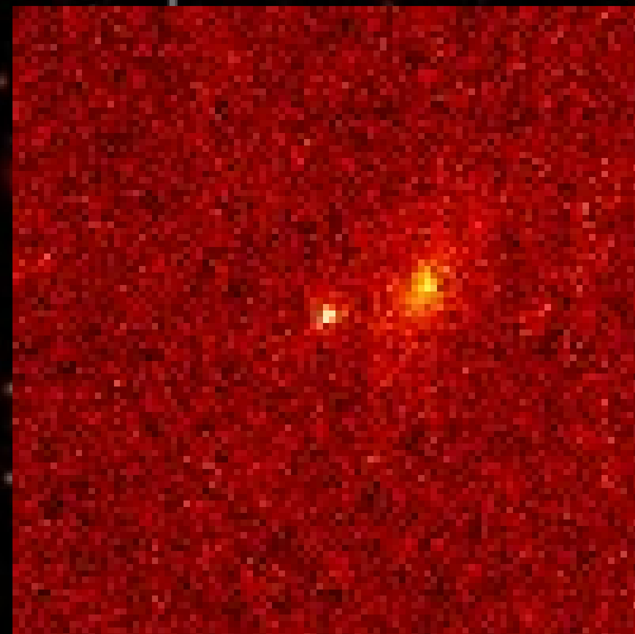
Type Ia Supernova

- White dwarf accretes matter from a companion
- Reaches critical mass of 1.4 $M_{\odot}$: can no longer support itself against its own gravity
- Runaway nuclear fusion

Briefly as bright as a whole galaxy
...thus can be seen to great distances.

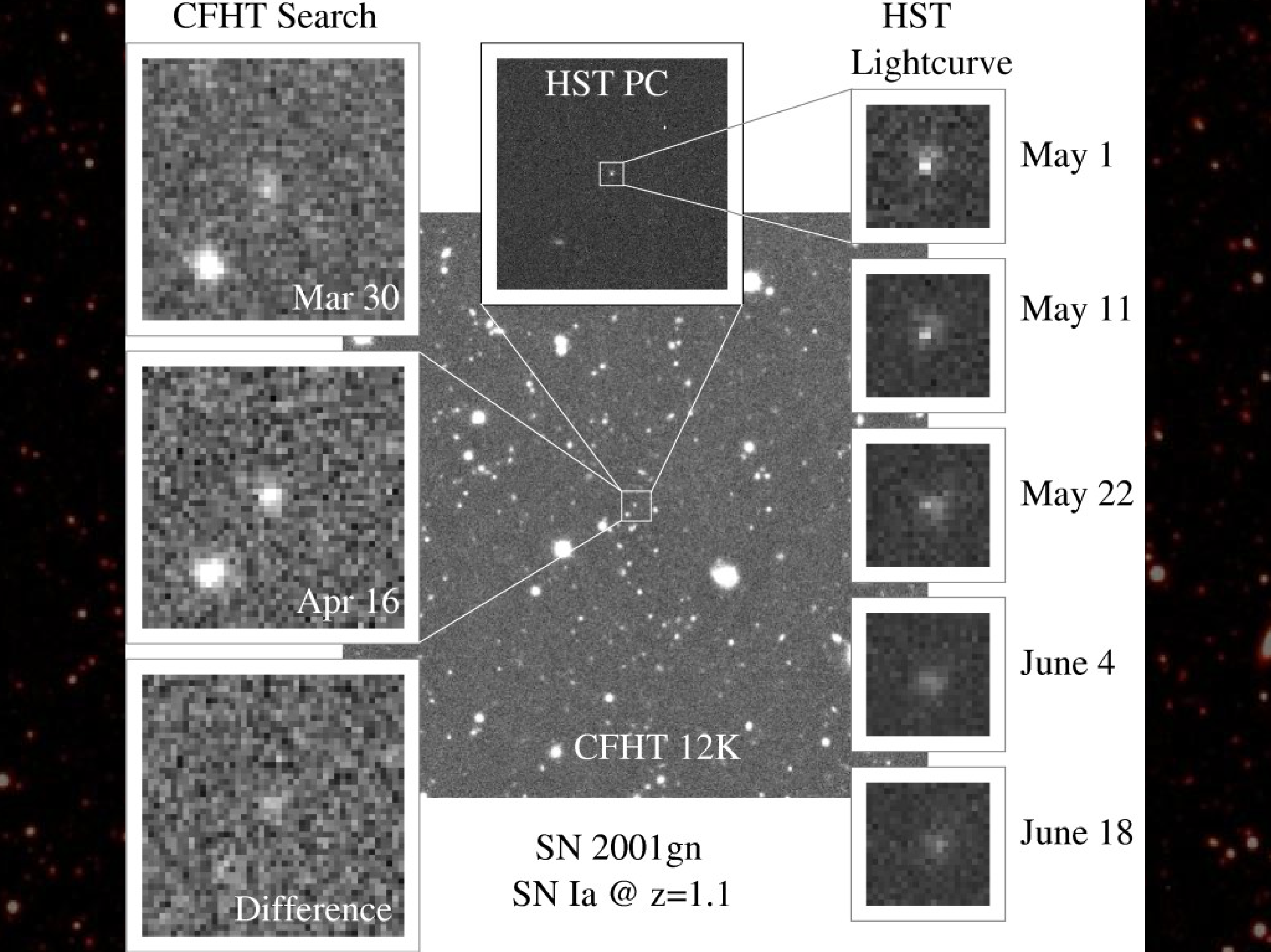
Nearby supernova 1994D

Supernova 1997ek (z=0.86)

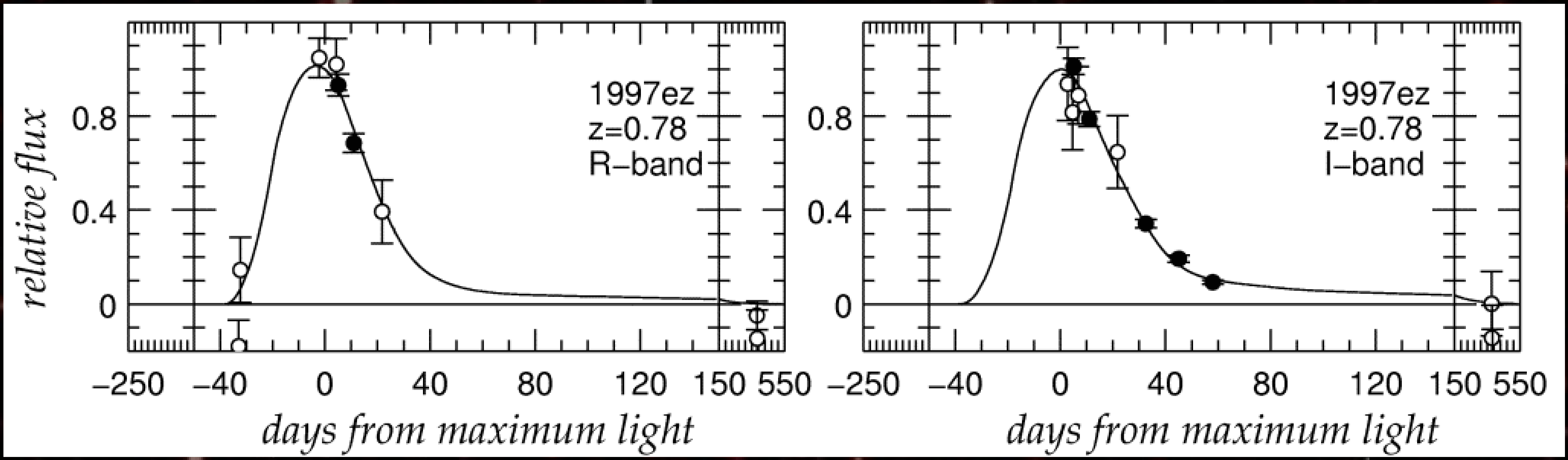


It exploded 7 billion years ago, when the Universe was 54% its present size....

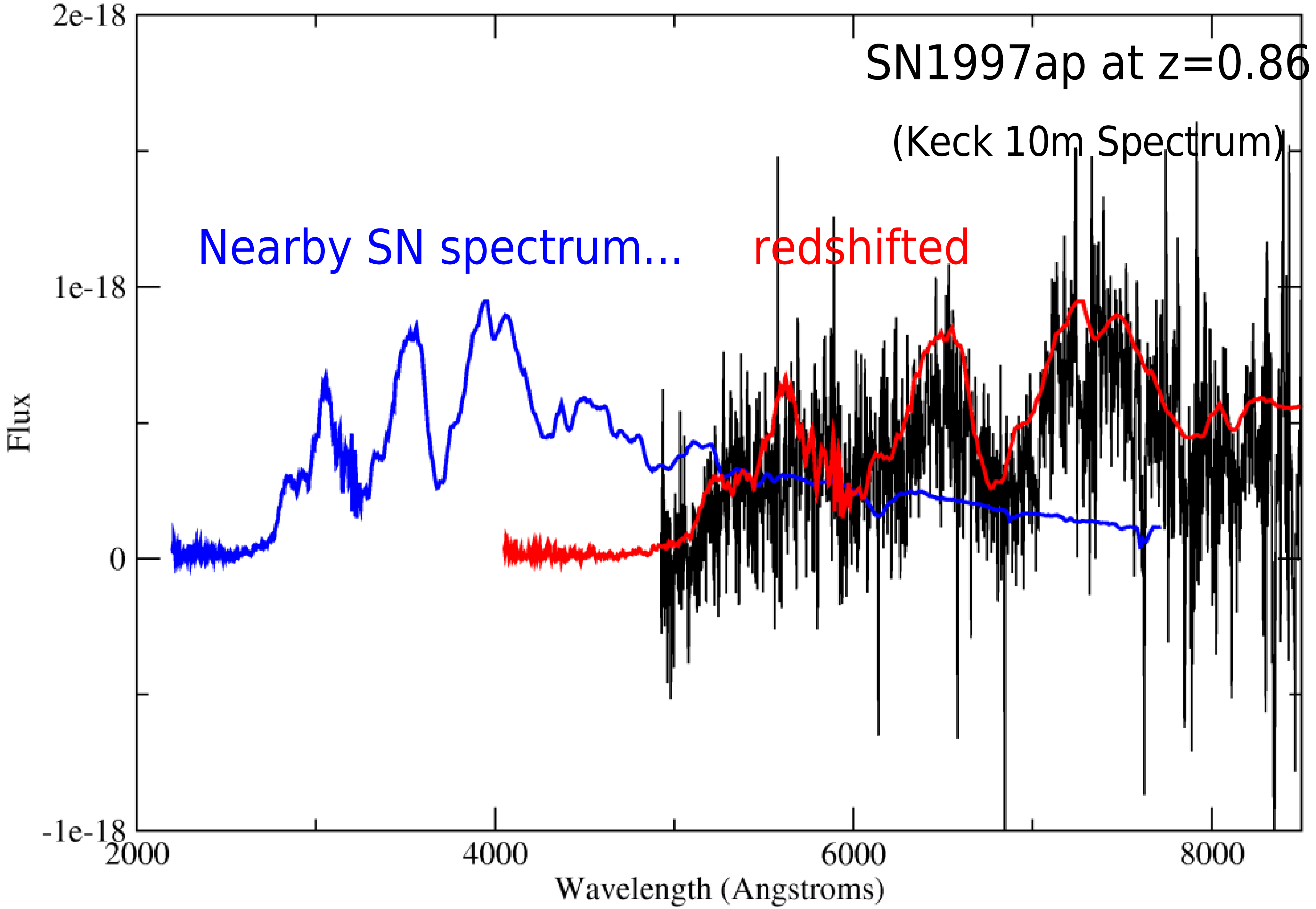
...we saw it in December 1997.


CFHT Search
Mar 30
Apr 16
Difference
HST PC
CFHT 12K
HST
Lightcurve
May 1
May 11
May 22
June 4
June 18
SN 2001gn
SN Ia @ z=1.1

Type Ia Supernova 1997ez



- Discovered at the CTIO 4m in December 1997
- Type and redshfit measured at Keck 10m
- Followed by CTIO 4m, INT 2.5m, WIYN 3.5m, HST
- Exploded 6.7 billion years ago, when the Universe was 56% its present size.

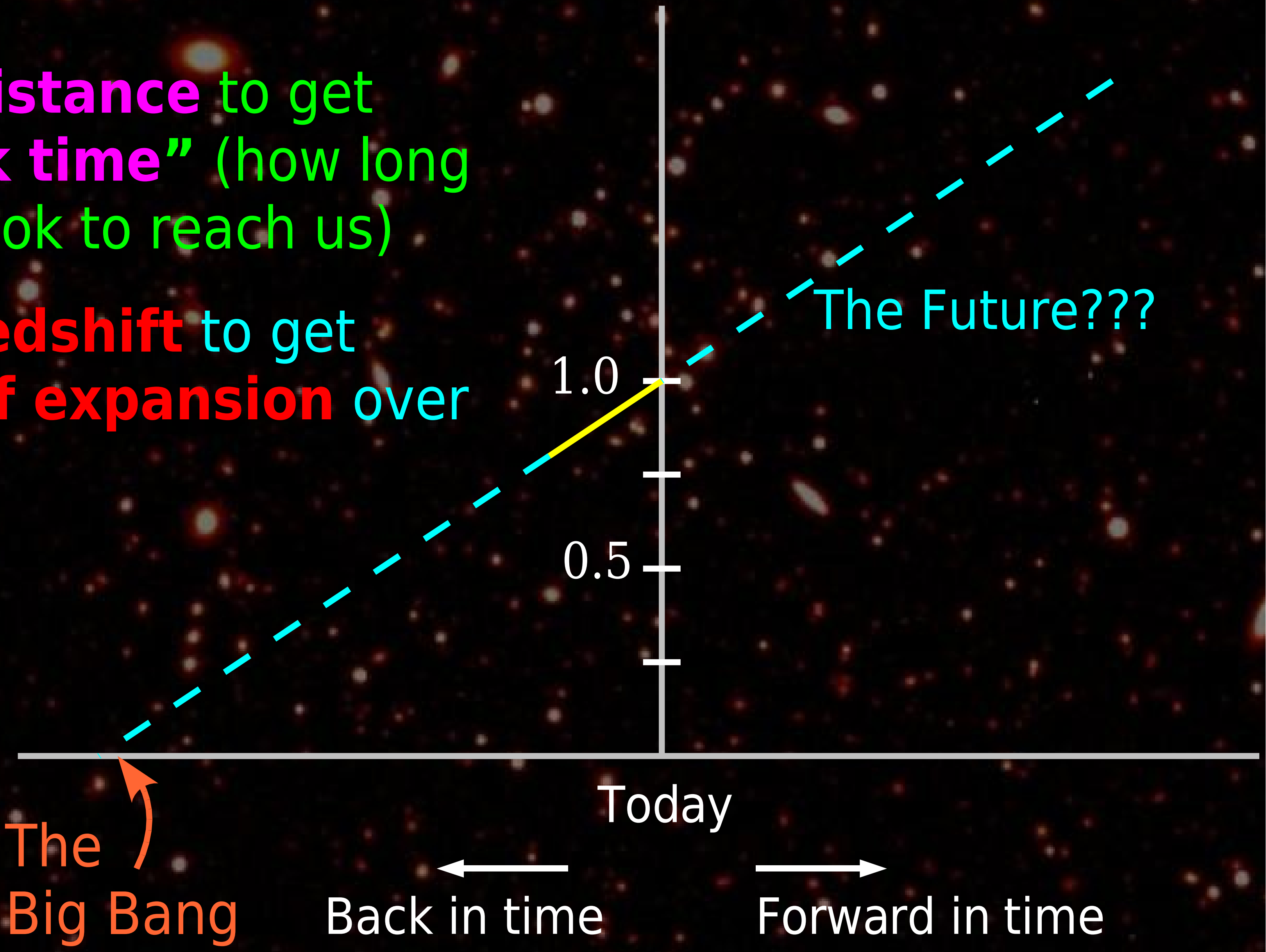


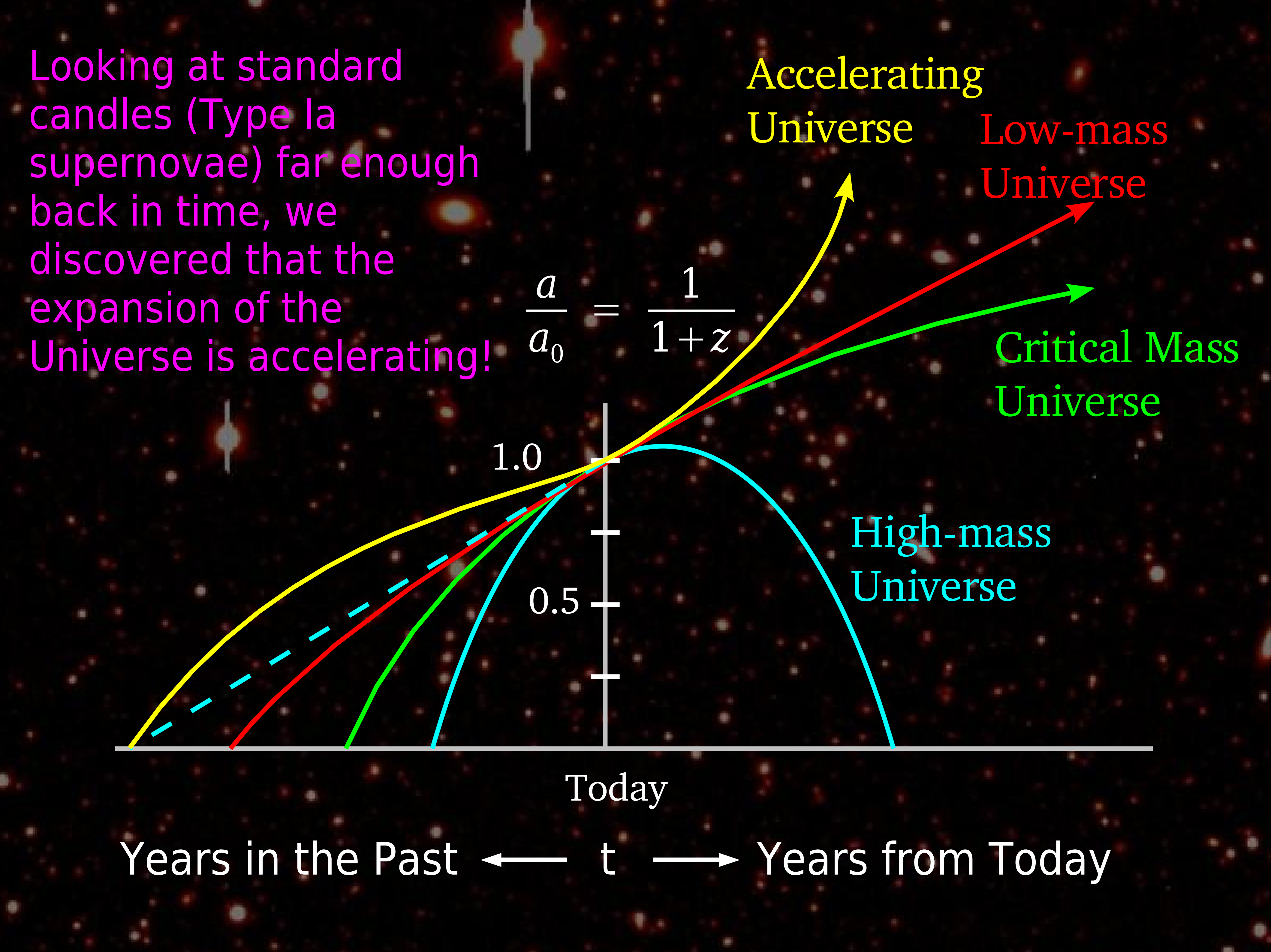
SN1997ap at z=0.86
(Keck 10m Spectrum)
Nearby SN spectrum...
redshifted
2e-18
1e-18
0
-1e-18
Flux
2000
4000
6000
8000
Wavelength (Angstroms)

Measuring the Expansion

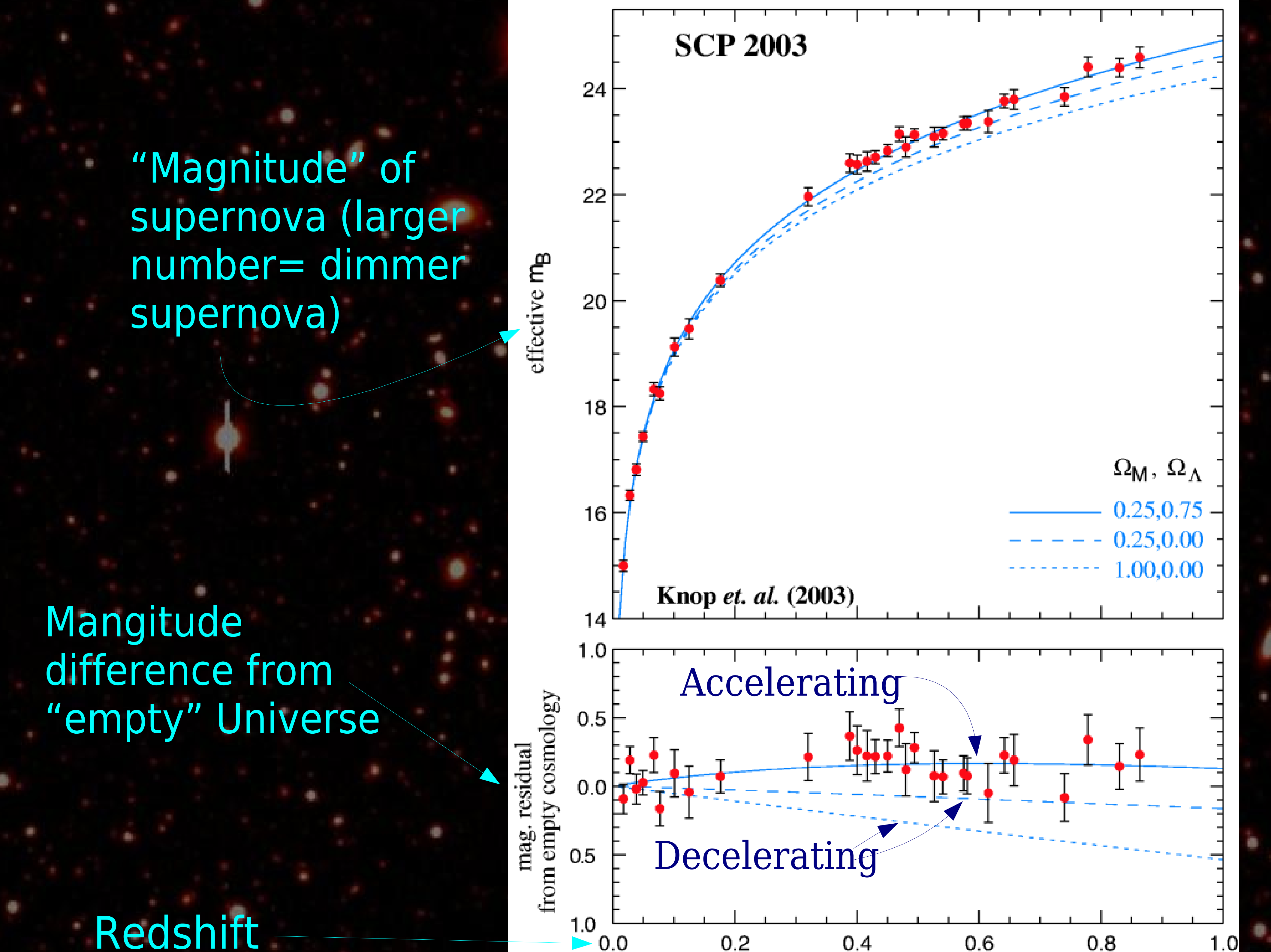
$$\frac{a}{a_0} = \frac{\text{Size}}{\text{Size Today}} = \frac{1}{1+z}$$

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

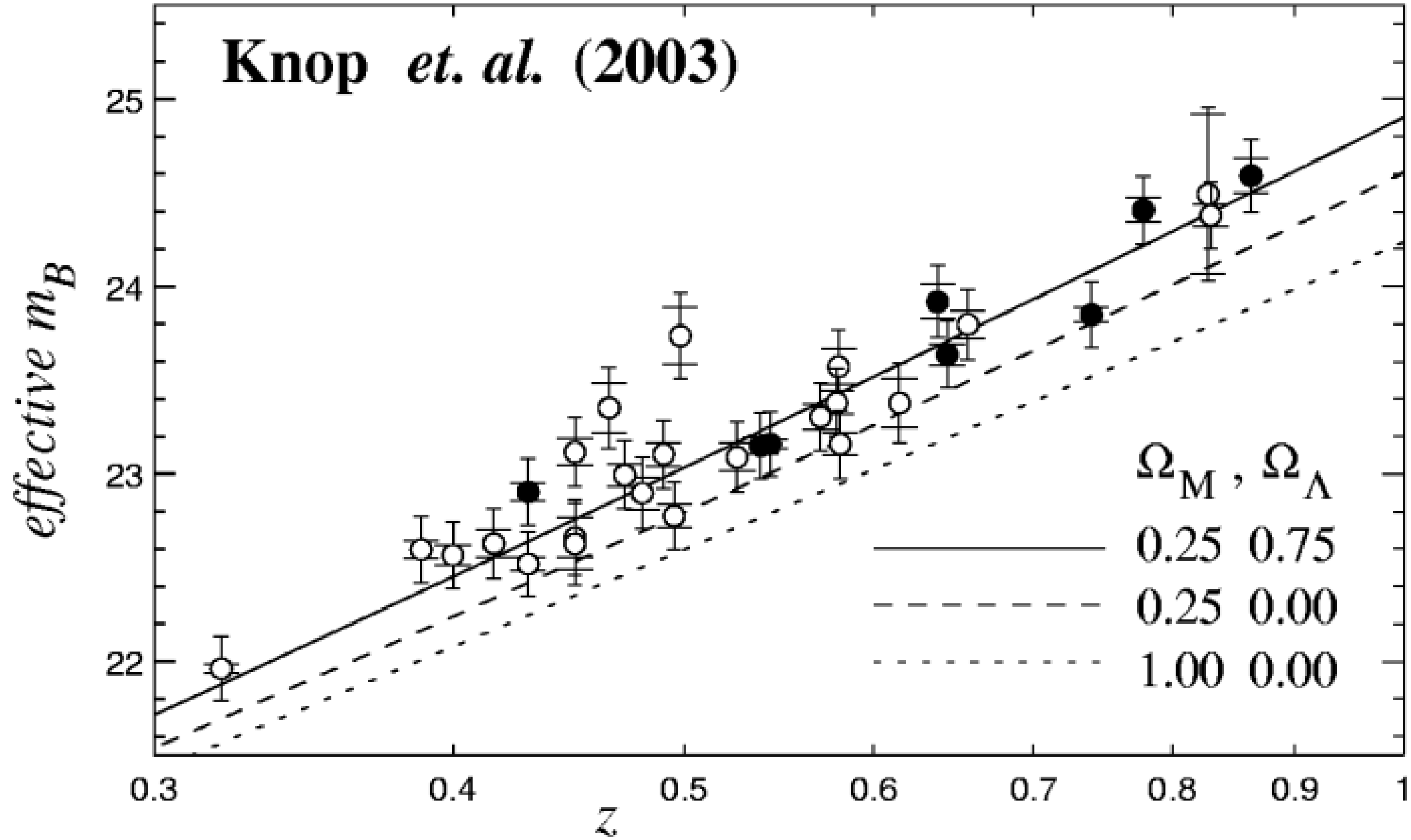


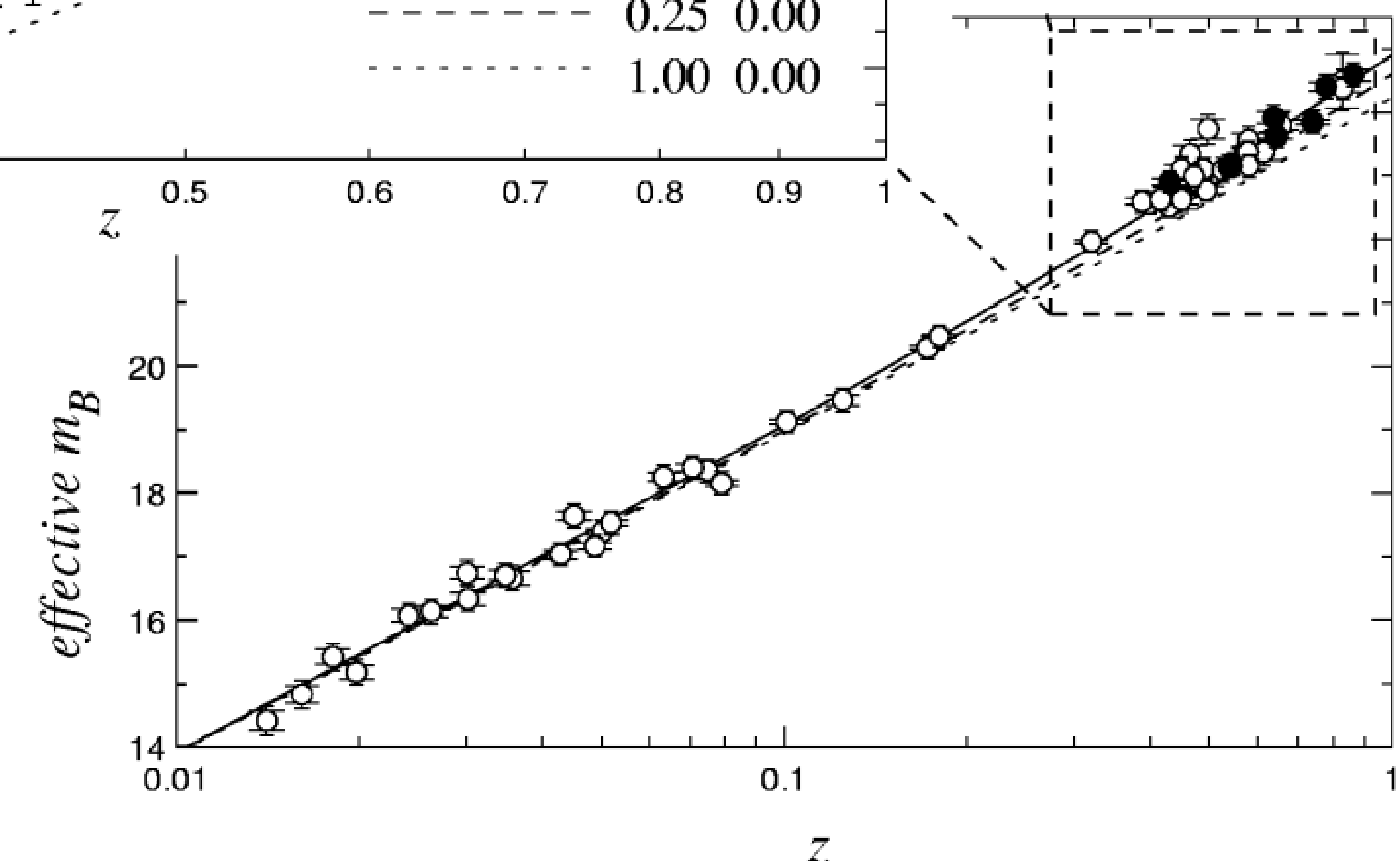


Looking at standard candles (Type Ia supernovae) far enough back in time, we discovered that the expansion of the Universe is accelerating!
$\frac{a}{a_0} = \frac{1}{1+z}$
Accelerating Universe
Low-mass Universe
Critical Mass Universe
High-mass Universe
1.0
0.5
Today
Years in the Past ⟵ t ⟶ Years from Today



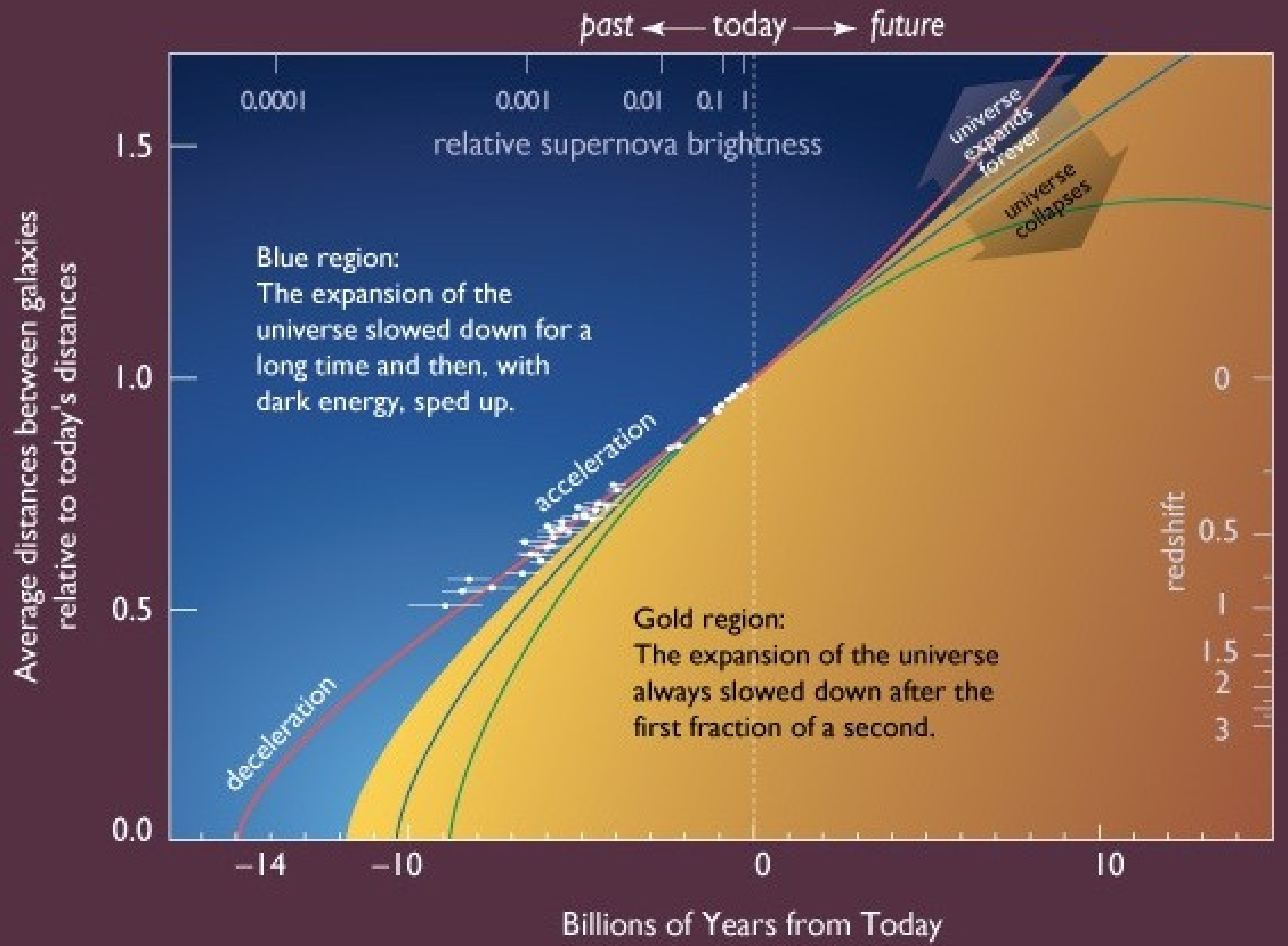
“Magnitude” of supernova (larger number= dimmer supernova)
Mangitude difference from “empty” Universe
Redshift
SCP 2003
Knop et. al. (2003)
effective m_B
Ω_M, Ω_Λ
0.25,0.75
0.25,0.00
1.00,0.00
mag. residual from empty cosmology
Accelerating
Decelerating
14
16
18
20
22
24
1.0
0.5
0.0
0.5
1.0
0.0
0.2
0.4
0.6
0.8
1.0



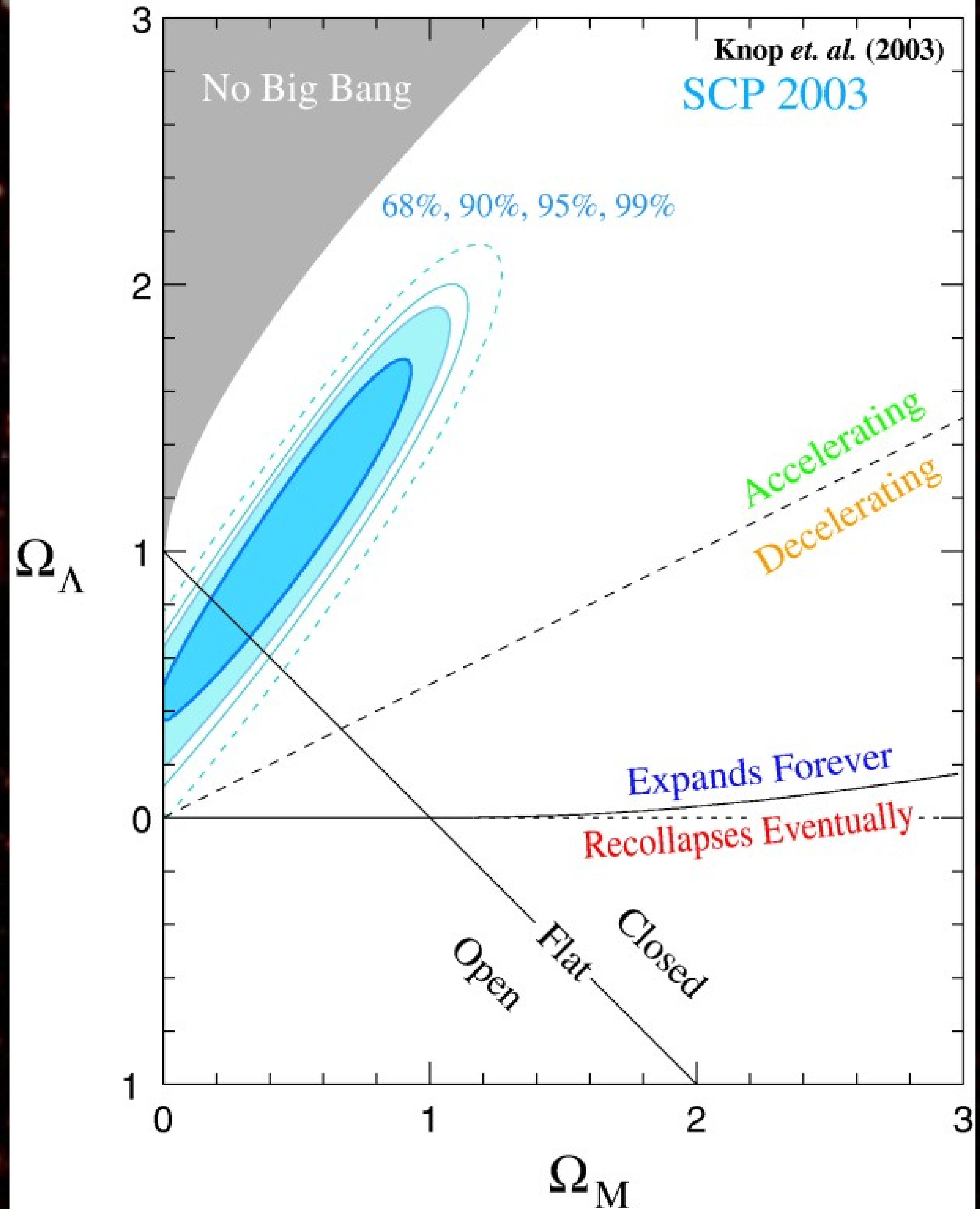


Ω_M = Matter Density

Ω_Λ = Dark Energy Density

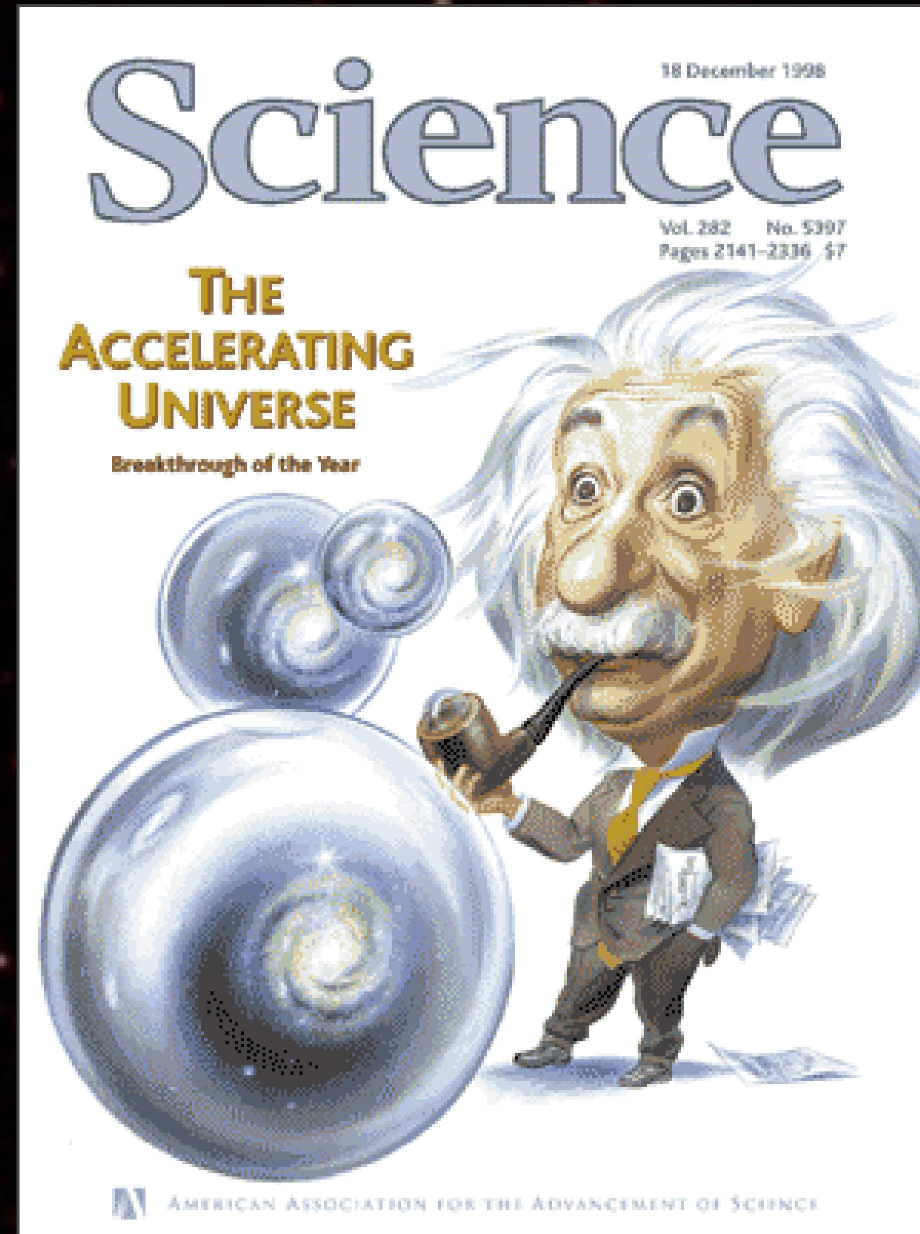


past ← today → future
0.0001
0.001
0.01
0.1
1
relative supernova brightness
universe expands forever
universe collapses
1.5
1.0
0.5
0.0
Average distances between galaxies relative to today's distances
Blue region:
The expansion of the universe slowed down for a long time and then, with dark energy, sped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



Knop et. al. (2003)
SCP 2003
No Big Bang
68%, 90%, 95%, 99%
Accelerating
Decelerating
Expands Forever
Recollapses Eventually
Open
Flat
Closed
Ω_Λ
Ω_M
3
2
1
0
1
0
1
2
3

Science Magazine
“Breakthrough of the Year”
in 1998

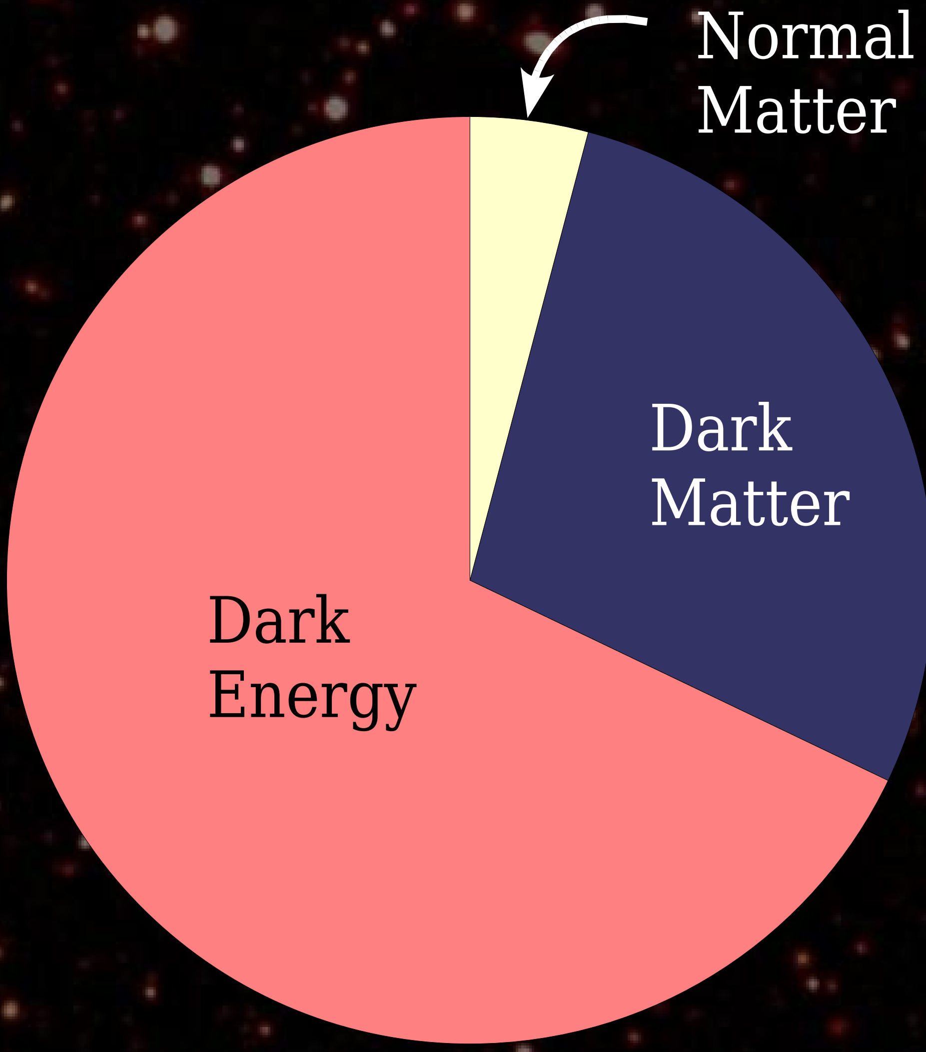


2007 Gruber Prize in Cosmology

- Brian Schmidt
- Saul Perlmutter
- Brian's Team
- Saul's Team

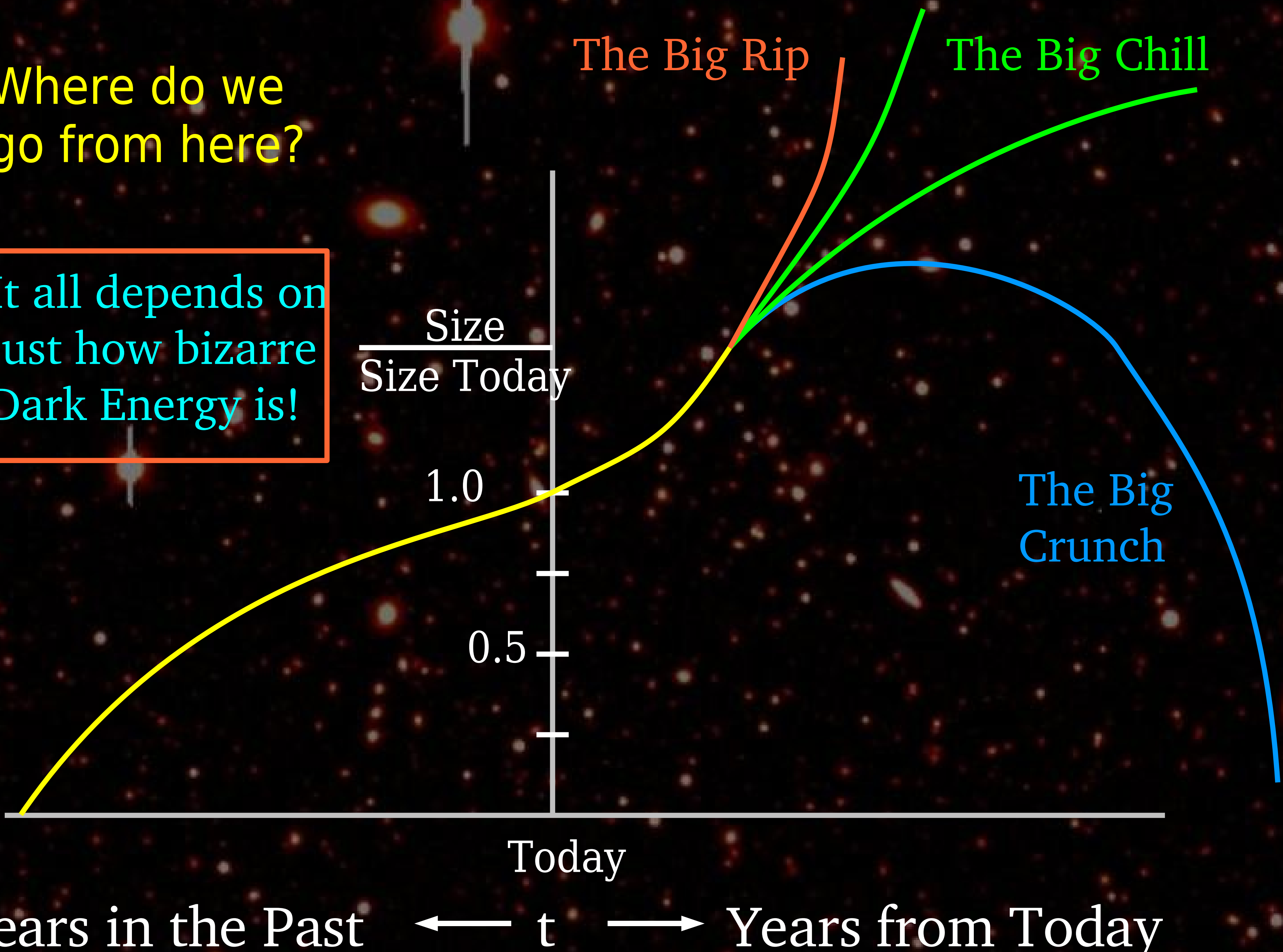
A Consistent Picture of the Universe

- 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!



Coda: The Big Bang

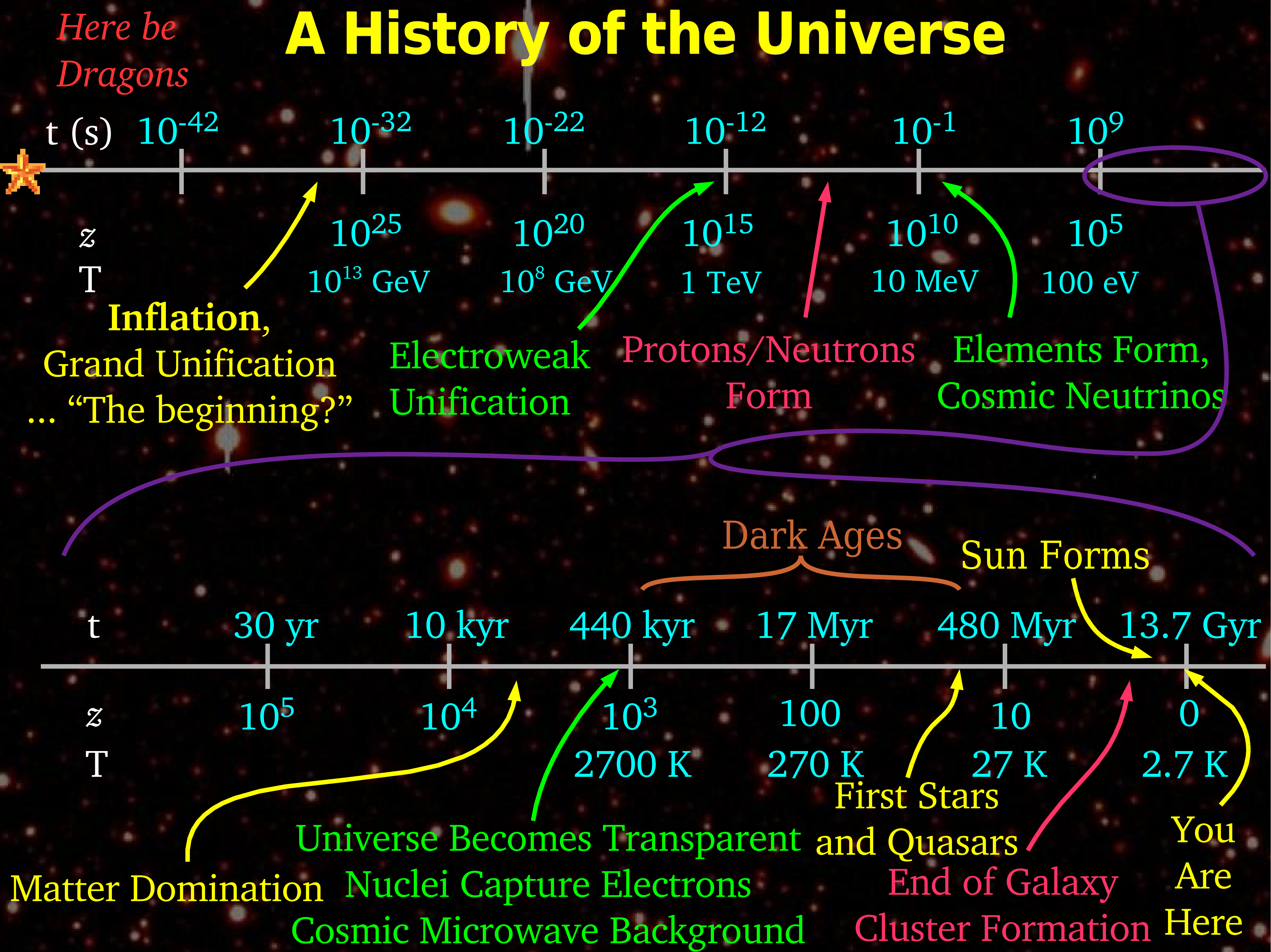
If the Universe is expanding, then in the past it was smaller... far enough back, *much* smaller.

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.

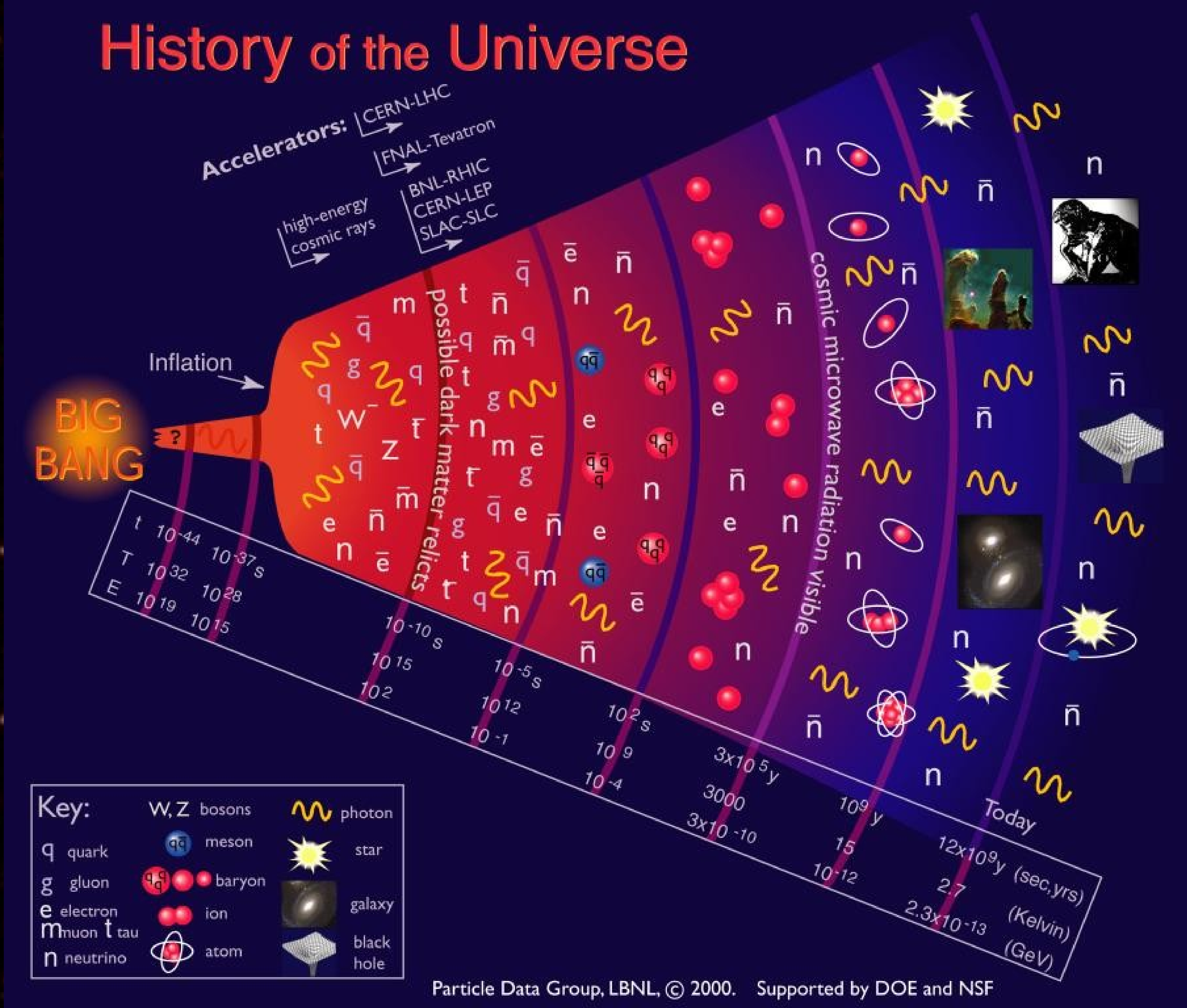
It does not currently tell us about the *actual moment of creation*, or what happened *before* that 14 billion years... there is a point before which our Physics breaks down! (String Theory??)

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
10^9
z
T
10^25
10^13 GeV
10^20
10^8 GeV
10^15
1 TeV
10^10
10 MeV
10^5
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
10^5
10^4
10^3
2700 K
100
270 K
10
27 K
0
2.7 K
First Stars and Quasars
Matter Domination
Universe Becomes Transparent
Nuclei Capture Electrons
Cosmic Microwave Background
End of Galaxy Cluster Formation
You Are Here

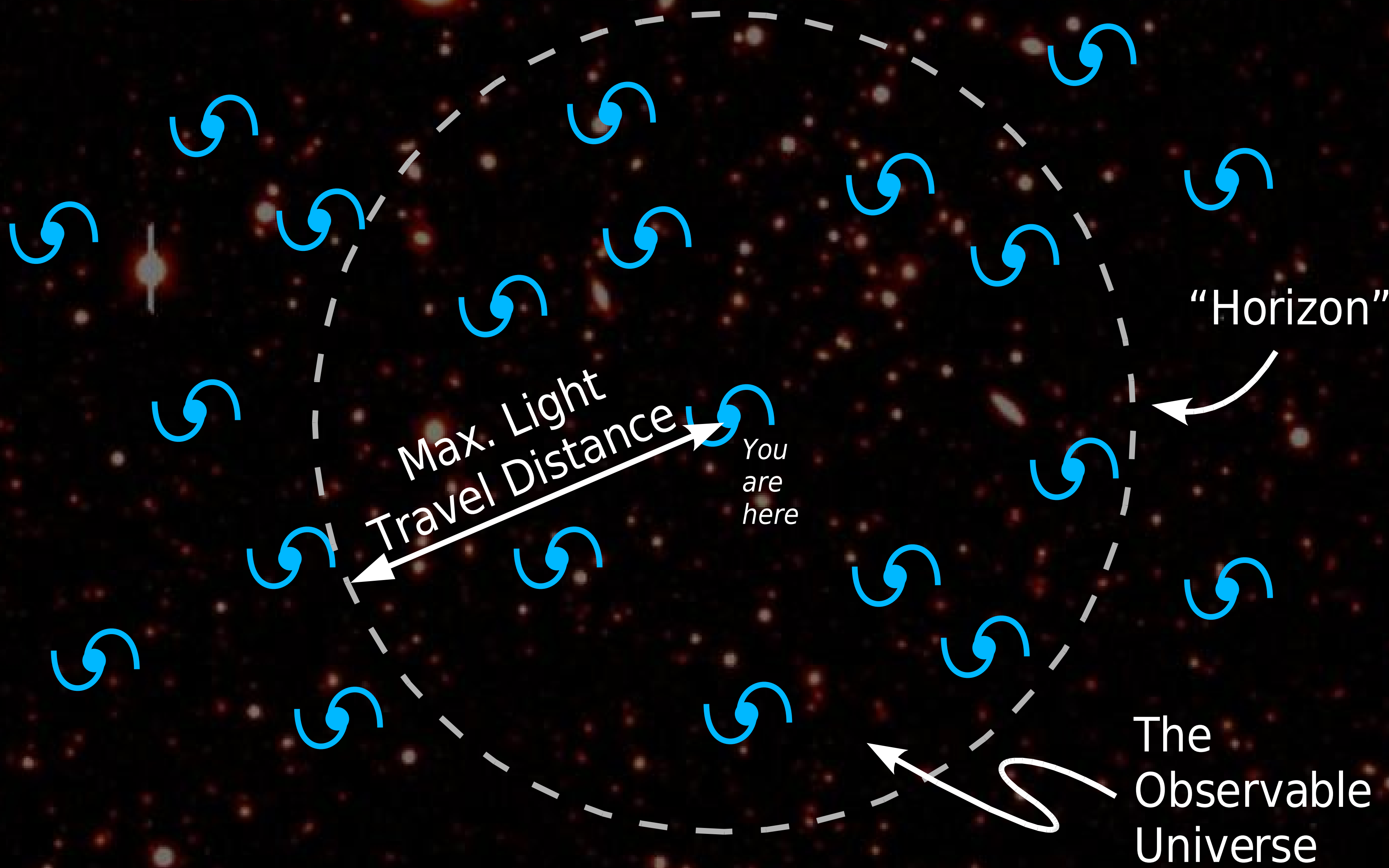

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t
T
E
10^-44
10^32
10^19
10^-37 s
10^28
10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

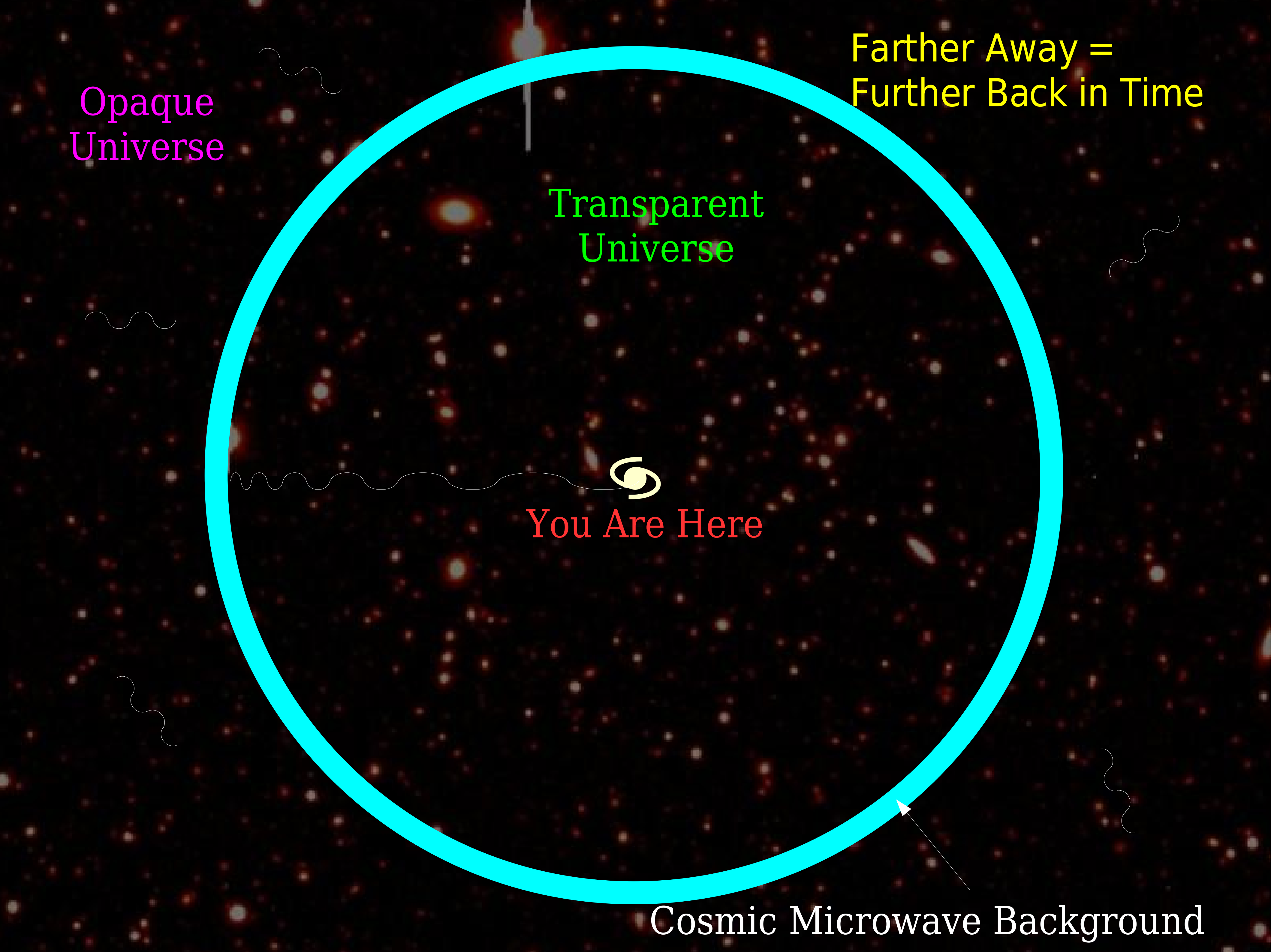

Extra Slides...

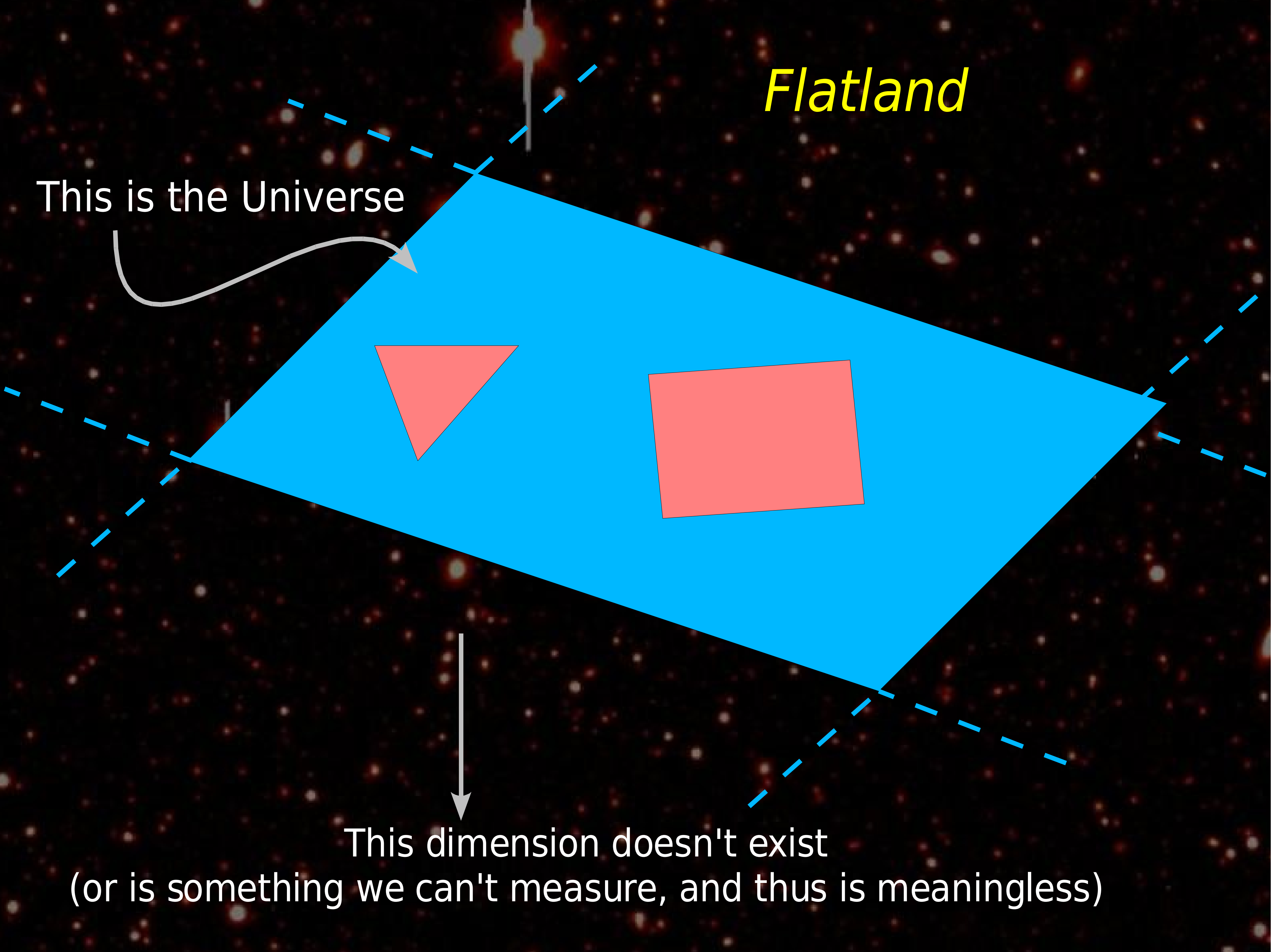
The *observable* Universe, 10^{-43} seconds after the Big Bang:

(Actual Size)

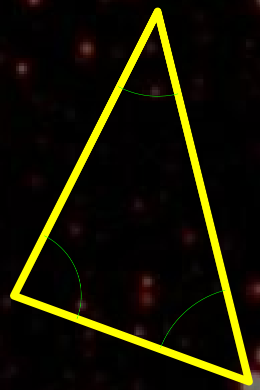
Even if the Universe is infinite, the *Observable Universe* is finite



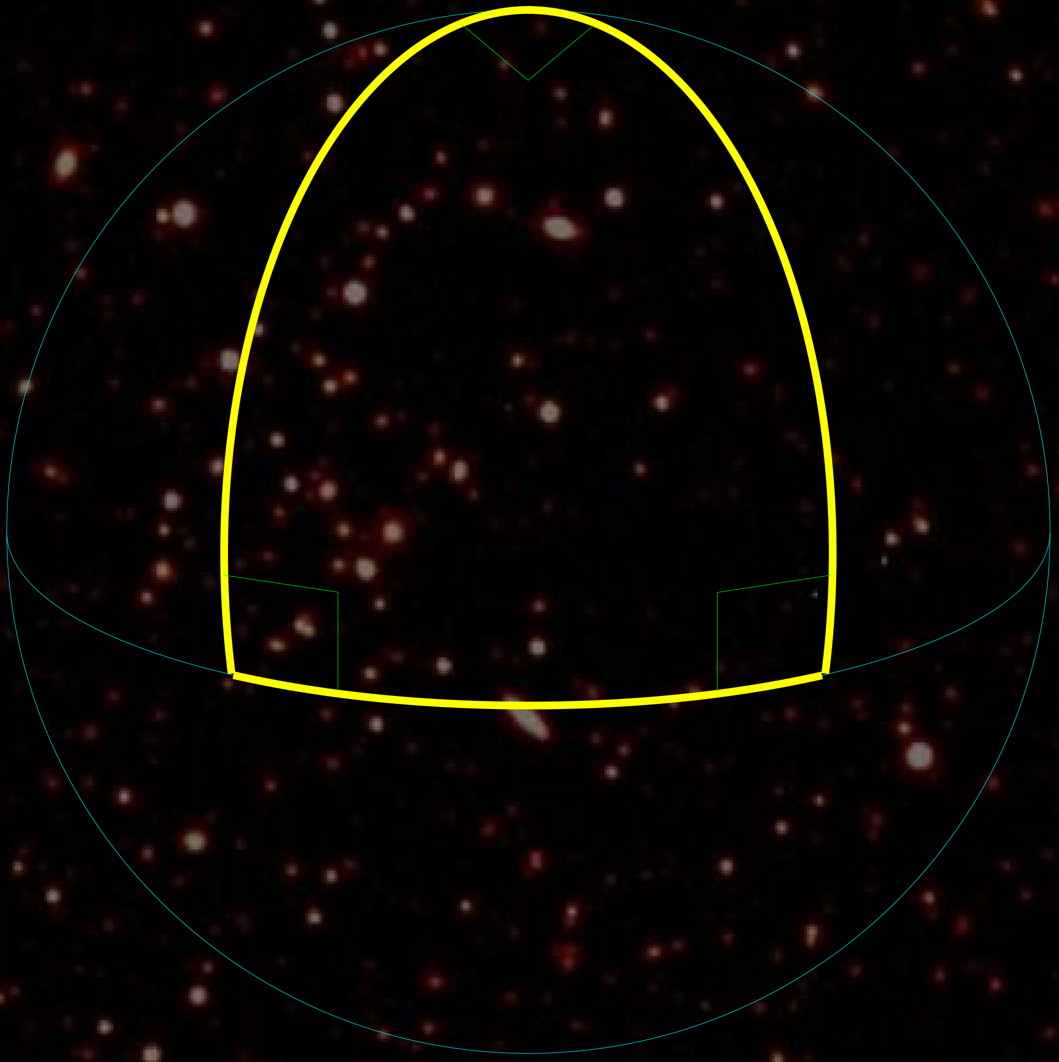

Farther Away =
Further Back in Time
Opaque
Universe
Transparent
Universe
You Are Here
Cosmic Microwave Background


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°



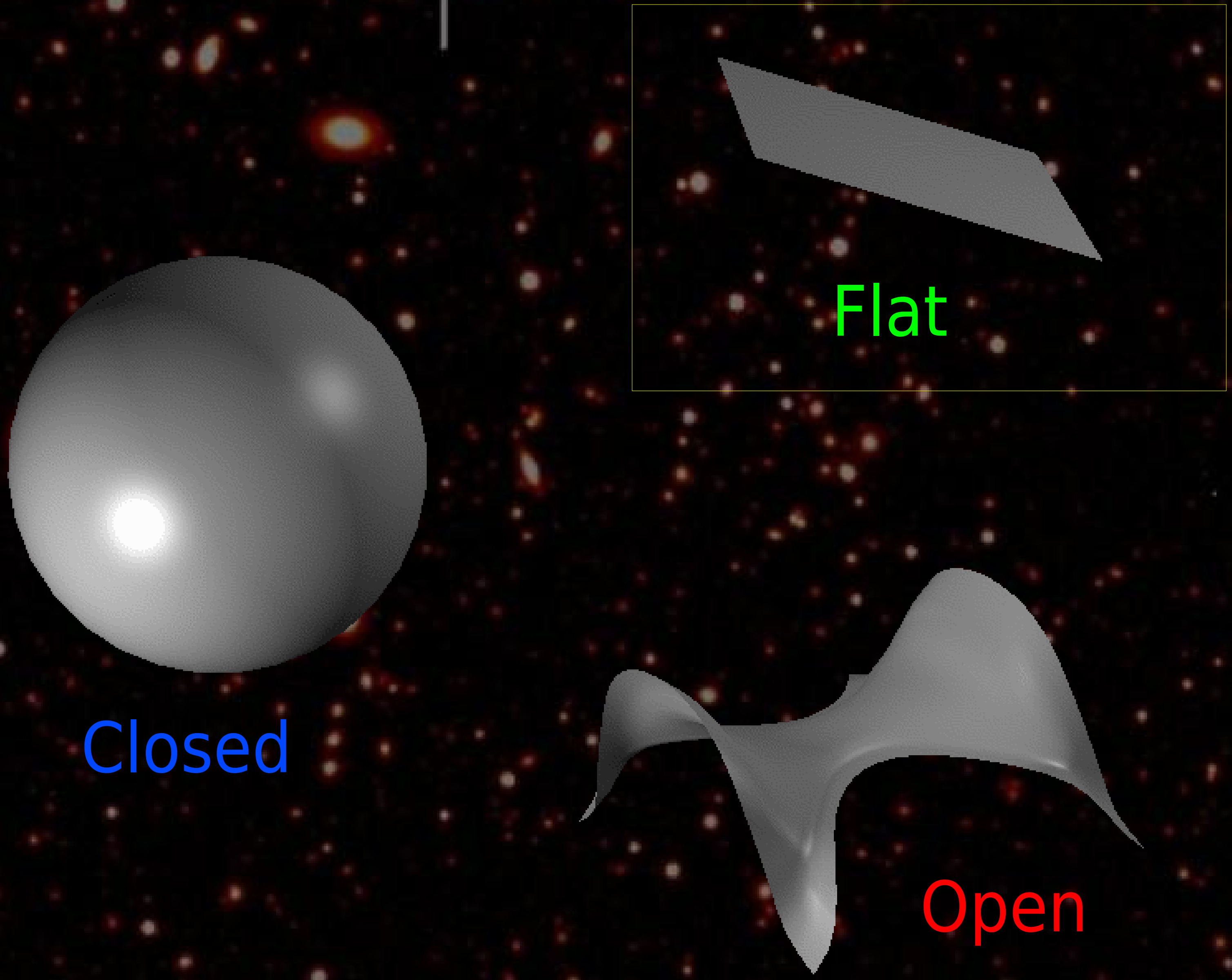
Flatland (2-dimensional) creatures could measure this curvature without reference to the third dimension we use to describe this here!



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

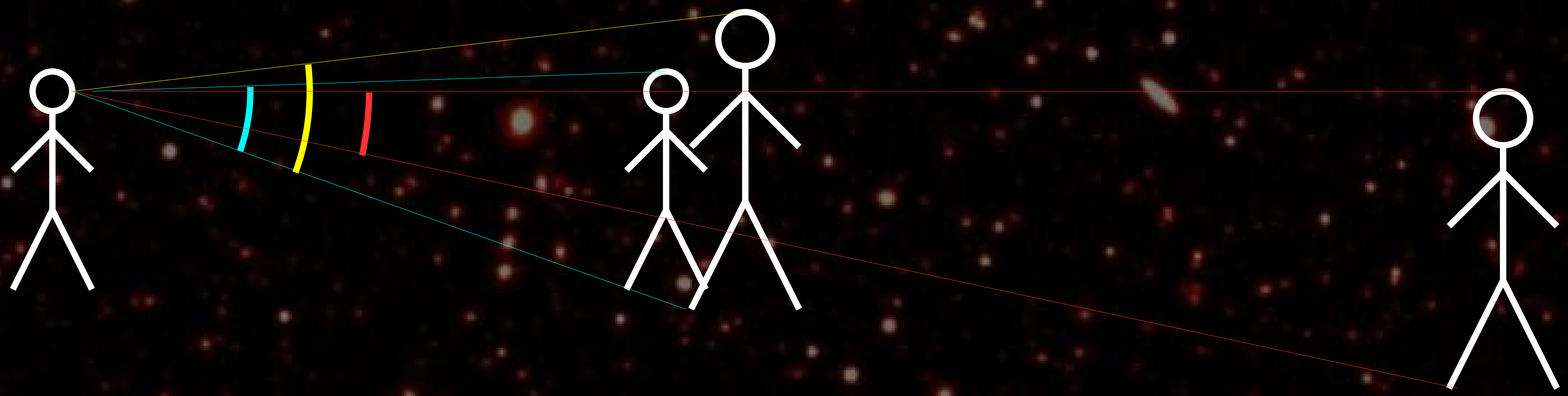
(In general: >180° : positive curvature
<180° : negative curvature)

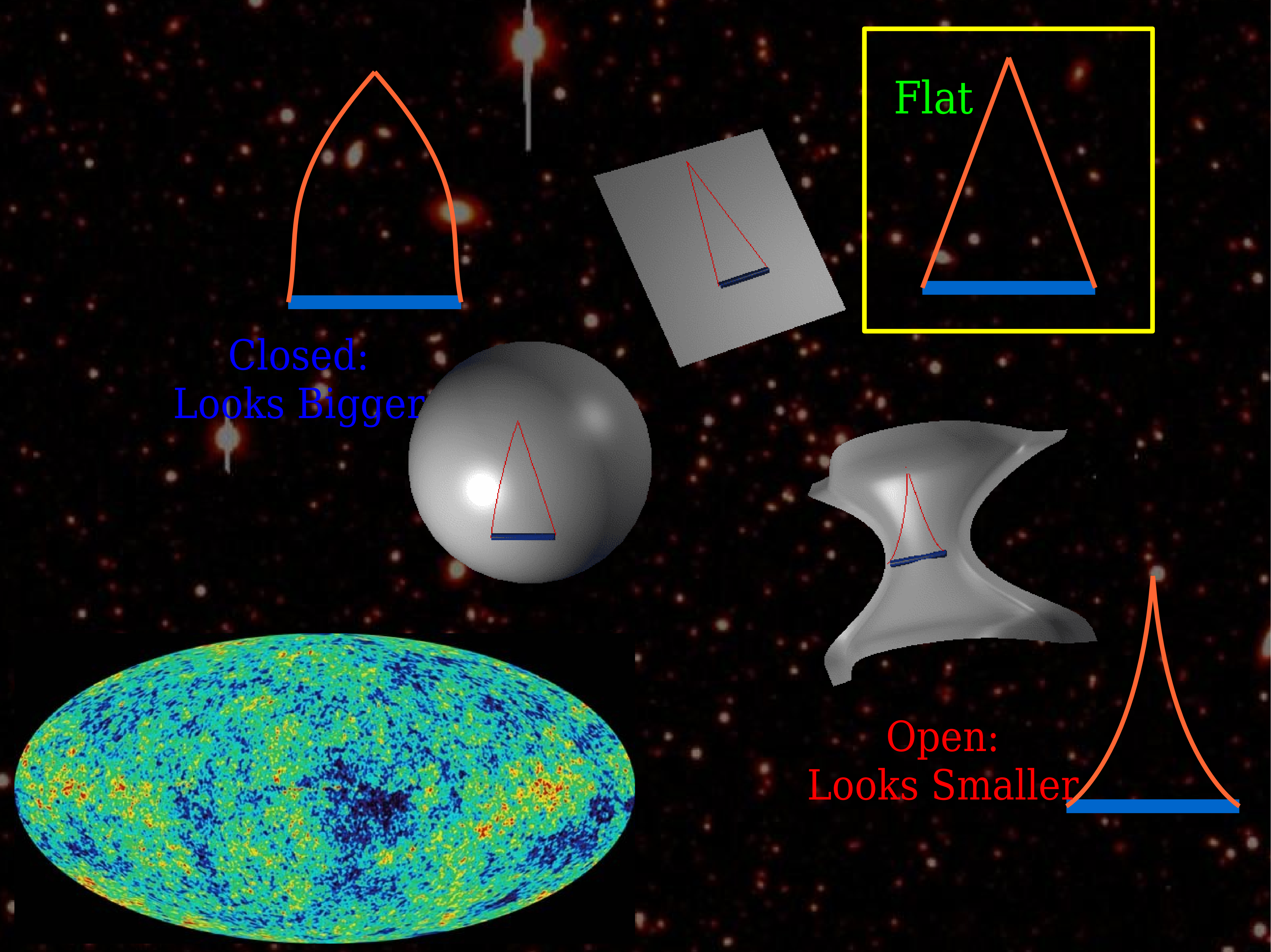
Possible Shapes of the Universe



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

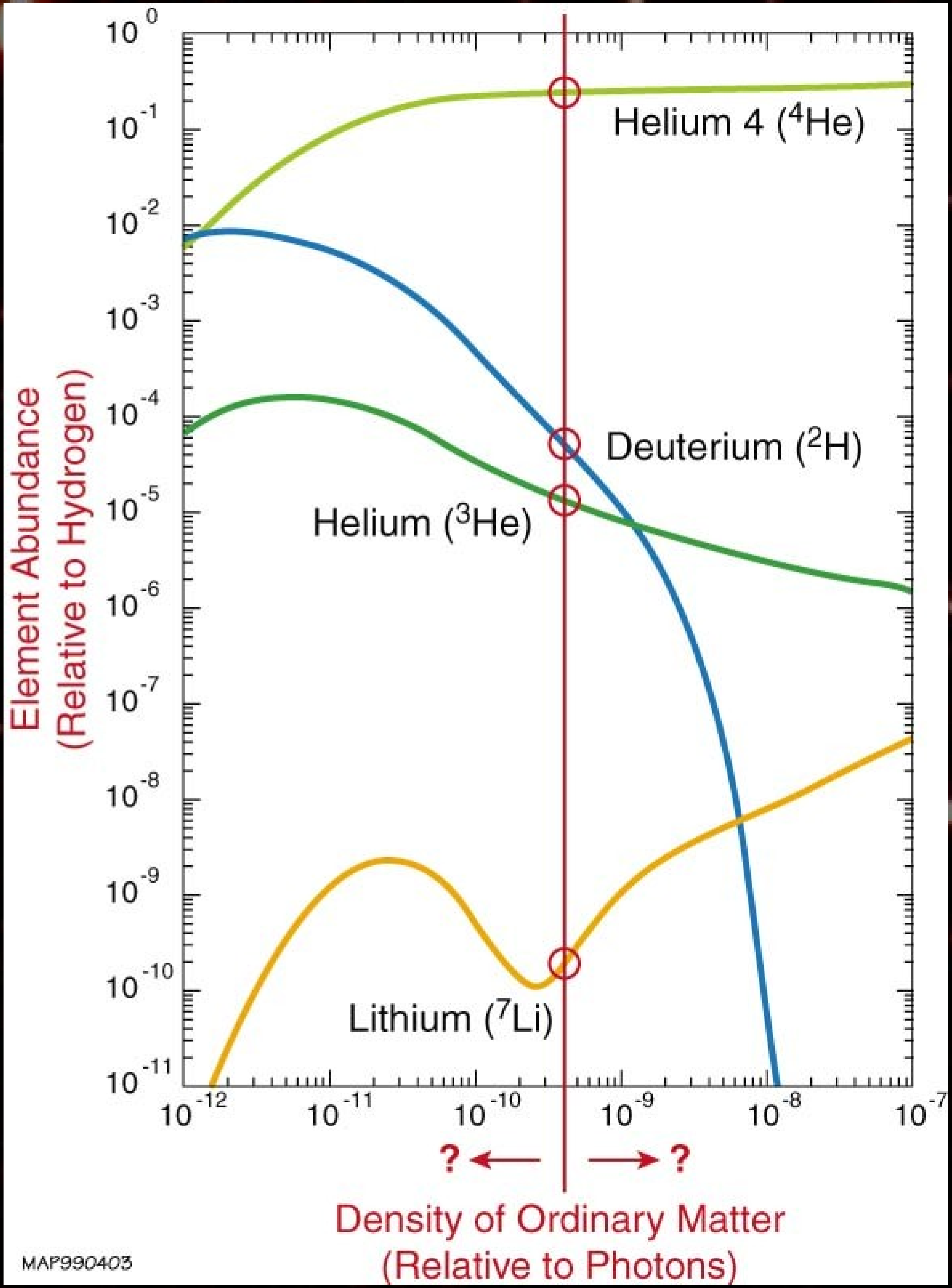
The angle that it *subtends*.



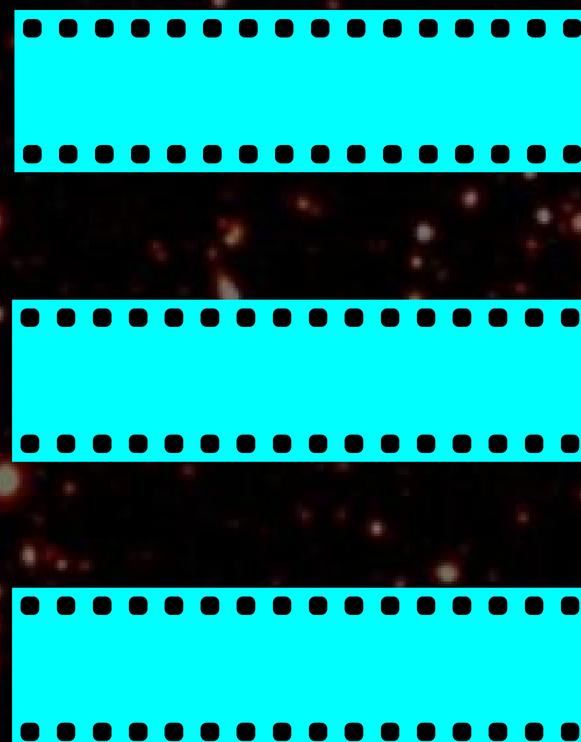

Flat
Closed:
Looks Bigger
Open:
Looks Smaller

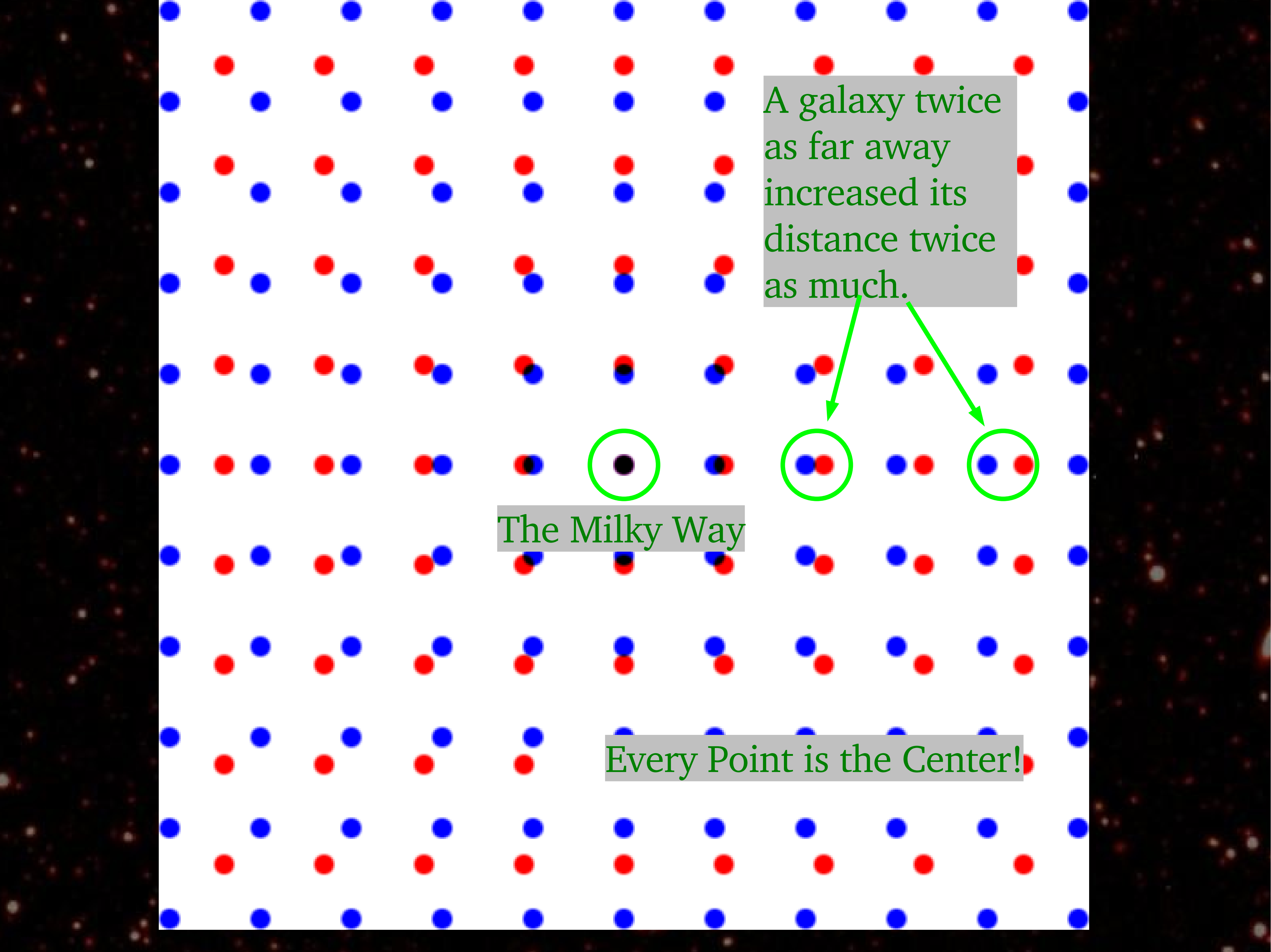
Nuclear Alchemy

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

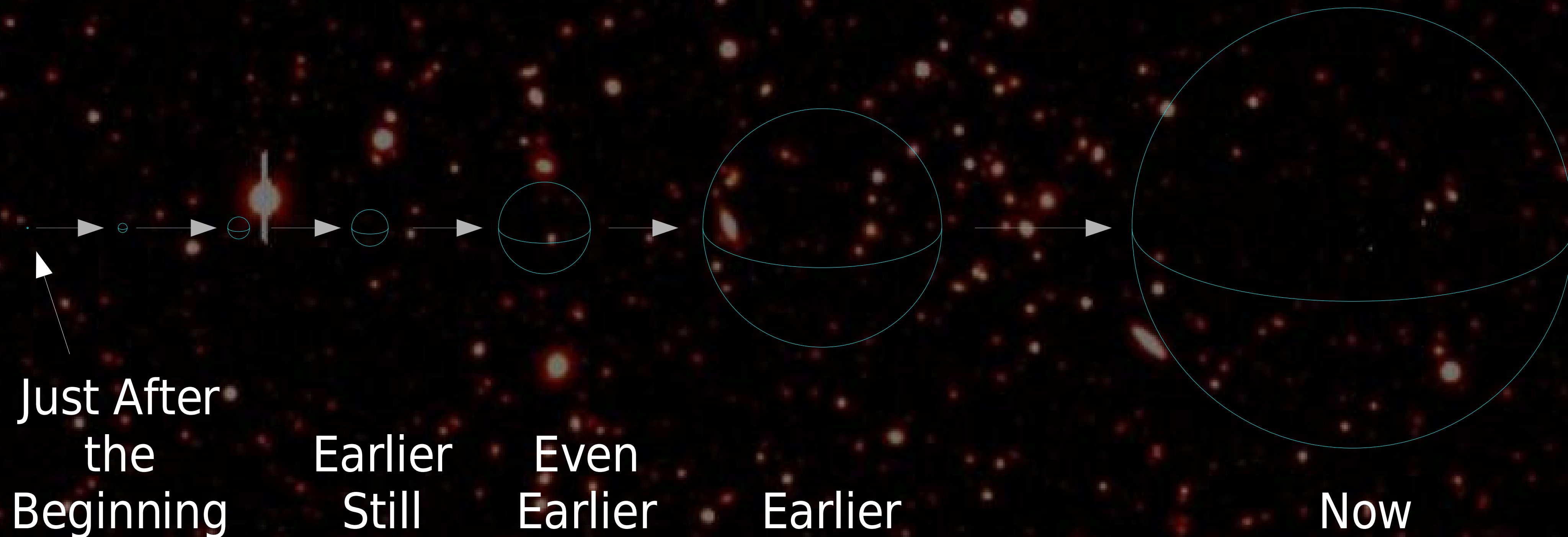


OK, Rob, what about that whole business of farther galaxies moving at higher speeds that we always hear about?

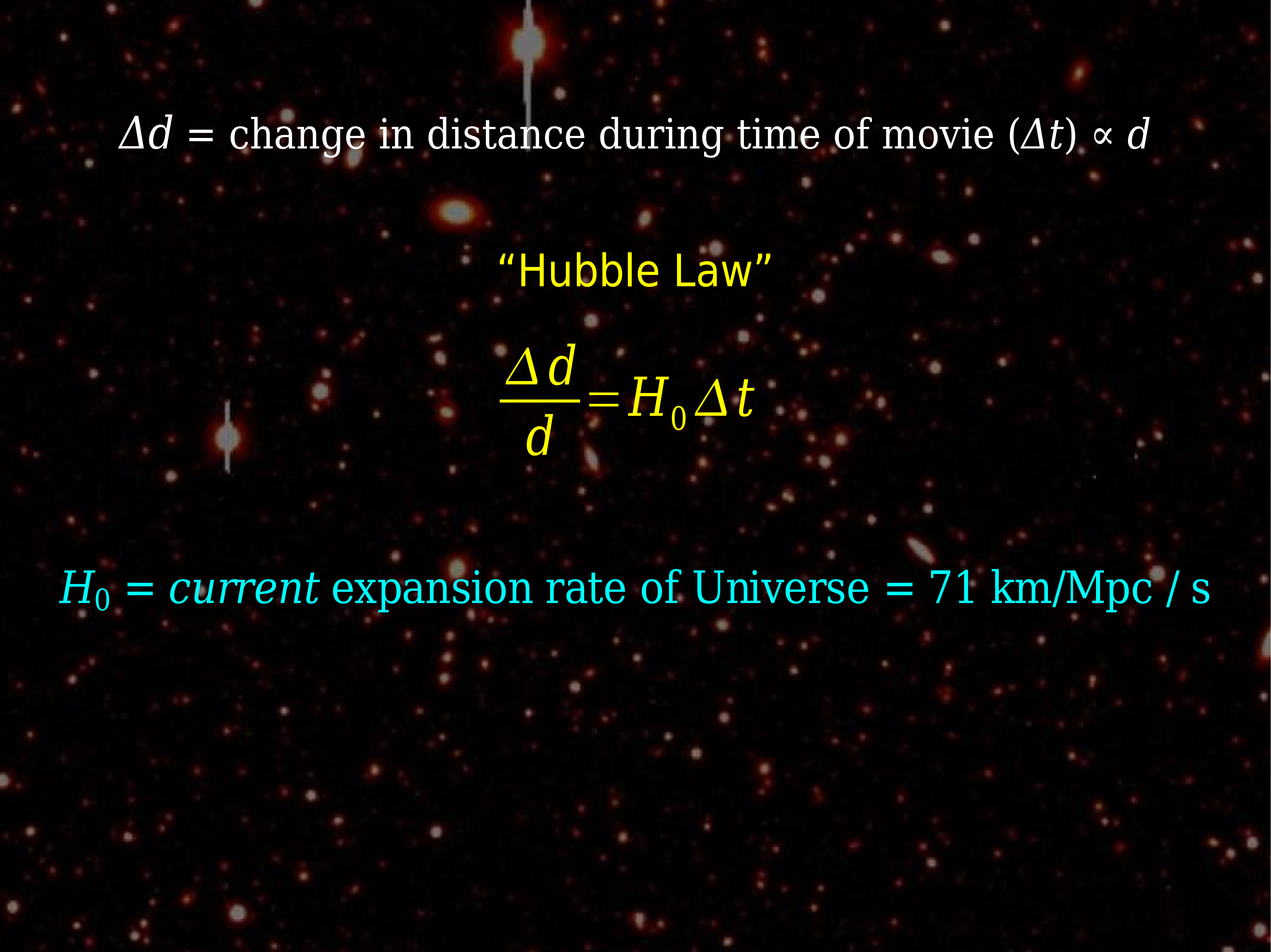



A galaxy twice as far away increased its distance twice as much.
The Milky Way
Every Point is the Center!

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



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



Δd = change in distance during time of movie (Δt) ∝ d

"Hubble Law"

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

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

Doppler Shift (z)

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

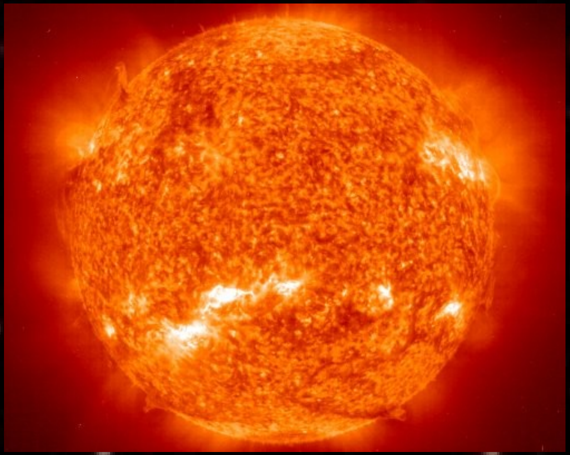
- $\Delta\lambda$: Amount wavelength shifts to the red
- λ: Original emitted wavelength

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

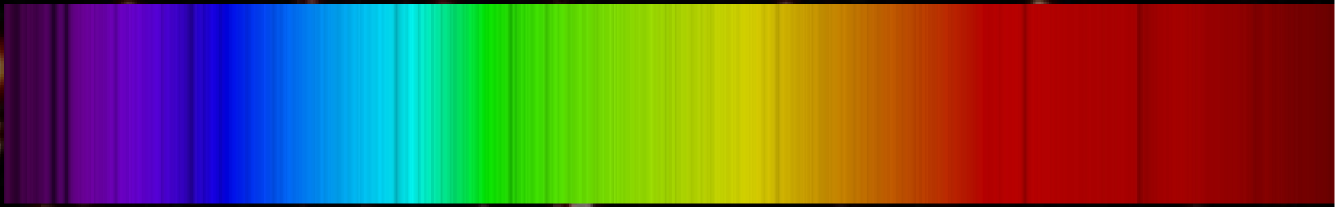
Compare to Cosmological redshift:

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

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*.



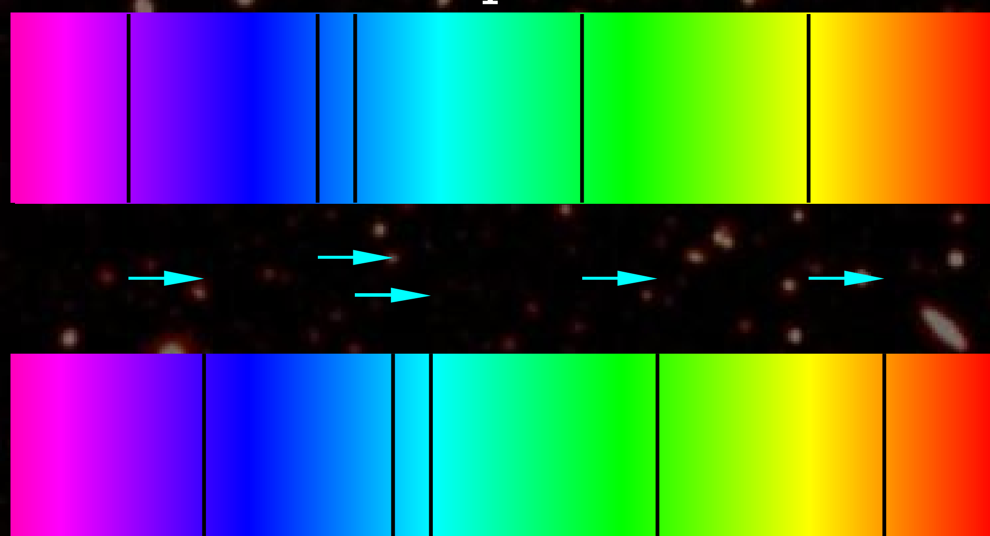
Stars: Absorption Lines



Nebulae: Emission lines

Redshift

Lines in a spectrum



Redshfited Lines

The "Metric" of Special Relativity

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

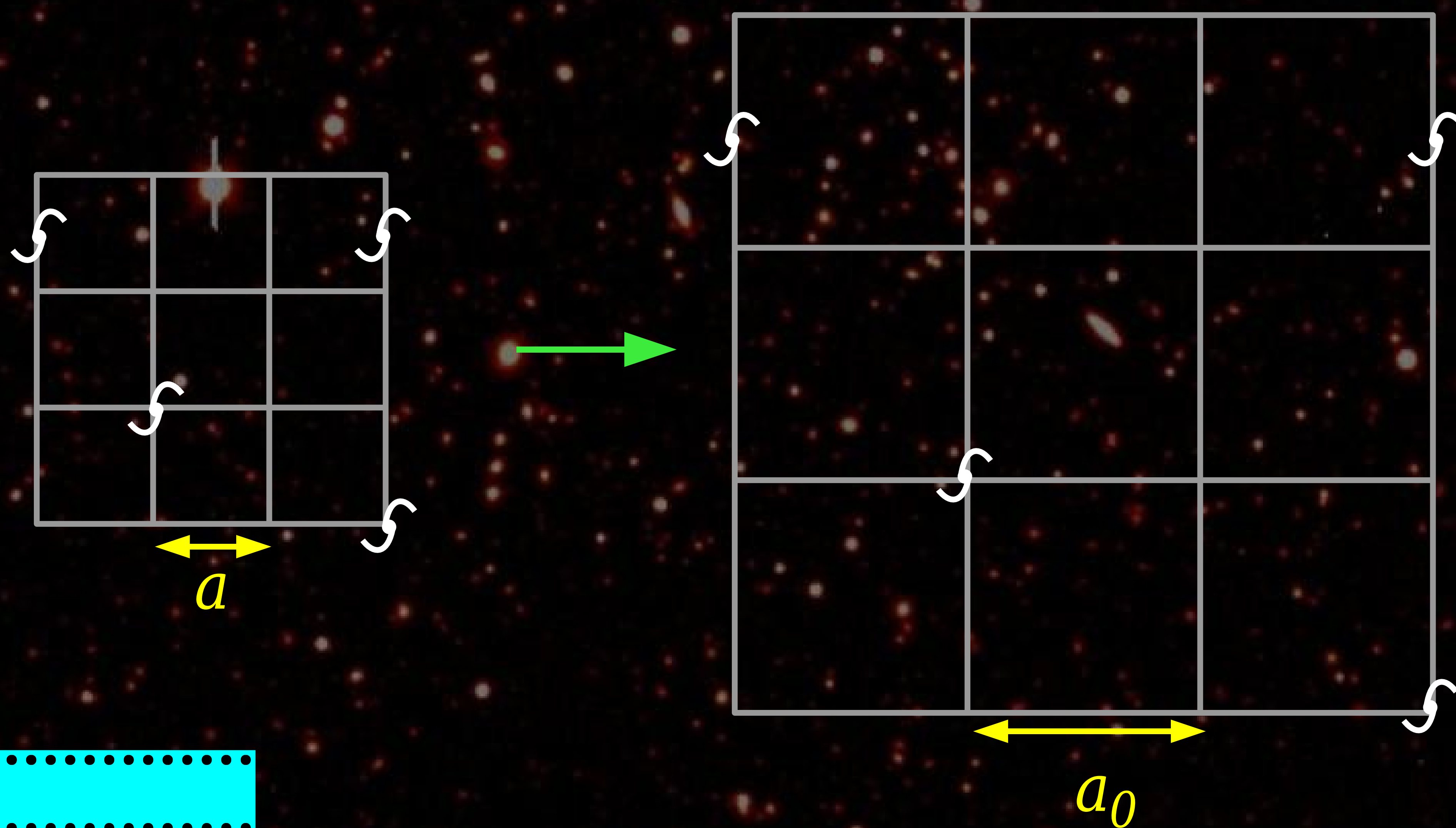
The Friedmann-Robertson-Walker Metric

$$ds^2 = -c^2 dt^2 + a(t)^2 (dx^2 + dy^2 + dz^2)$$

x,y,z are "comoving coordinates"

a(t) **is the "scale factor"... this function of time describes the expansion history of the Universe!!!**

Comoving Coordinates



The Friedmann Equation:

$$\left(\frac{1}{a}\right)\left(\frac{d^2 a}{dt^2}\right) = -4\pi G\,(\rho + 3\mathrm{p})$$

a the scale factor

G gravitational constant

ρ energy density

p pressure

If $\mathrm{p} < \rho/3$, $d^2a/dt^2 > 0$

Dark Energy : something with *negative* pressure $\mathrm{p} < \rho/3$

The Gruber Prize is "only" a $500,000 prize, but it attracted a metion in *Nature* why?

Last week, the day after astrophysicist Robert Knop decided to quit academia, he and 52 other scientists won the 2007 Gruber Cosmology Prize for discovering that the Universe's expansion is accelerating. "It gave me pause, but not much," says Knop. He is moving on to write code for Second Life, the alternative-reality computer program (right) run by the Linden Lab in San Francisco, California.....

(From "News in Brief", 2007 July 26)