Astronomy Update

Recent advances and research priorities

Lectures for the
Lifelong Learning Institute
Fall 2024
Session 4

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Prospectus: Astronomy Update

Introduction: Sources of astronomical news

Part 1. Solar system news

Part 2. Exoplanetary frontiers

Part 3. Mapping galaxies, making galaxies.

Part 4. The universe and the biggest questions

Mapping galaxies –
The cosmic distance ladder:
how far away is this?

$cz \rightarrow d$

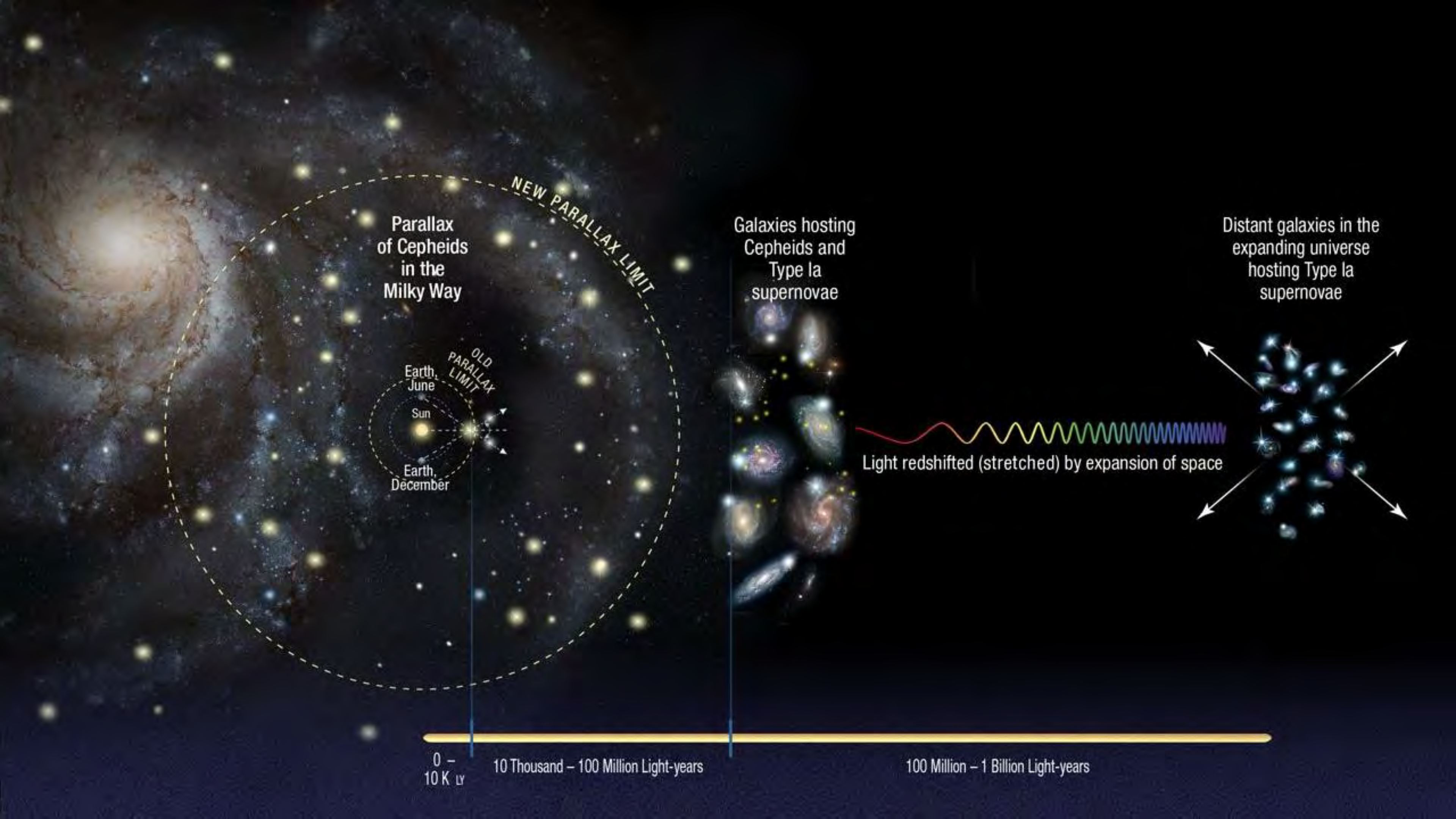
Brightest standards measure the Hubble Flow

SNeIa,

Standard candles give distance to brightest standards

Cepheids, TRGB, etc.

Parallax gives distance to 2nd rung standard candles

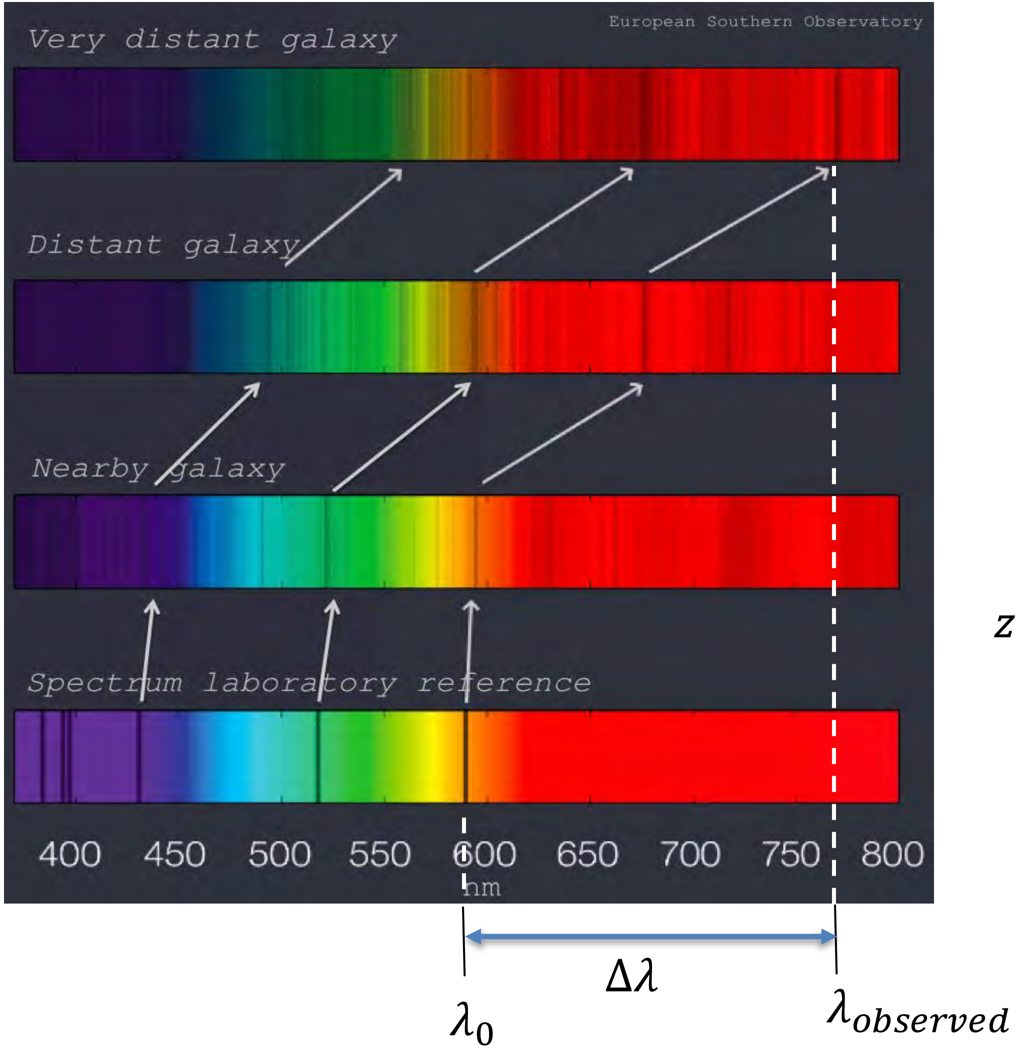


NEW PARALLAX LIMIT
Parallax of Cepheids in the Milky Way
OLD PARALLAX LIMIT
Earth, June
Sun
Earth, December
Galaxies hosting Cepheids and Type Ia supernovae
Light redshifted (stretched) by expansion of space
Distant galaxies in the expanding universe hosting Type Ia supernovae
0 – 10 K LY
10 Thousand – 100 Million Light-years
100 Million – 1 Billion Light-years

NGC 5468 (JWST image) —

At 40 Mpc, the most distant galaxy in which Cepheids and a type Ia SN have both been observed

The Hubble Flow



The redshift parameter

For any nearby object moving with low velocity, the Doppler Effect means:

V_r= Radial velocity

$$z = \frac{\lambda_{observed} - \lambda_0}{\lambda_0} \equiv \frac{\Delta\lambda}{\lambda_0} \cong \frac{V_r}{c} \equiv \beta$$

At large velocities the redshift parameter depends on velocity in a more complex way, so z can be greater than 1

$$z = \frac{\Delta\lambda}{\lambda_0} = \sqrt[2]{\left(\frac{1+\beta}{1-\beta}\right)} - 1$$

The Hubble Law

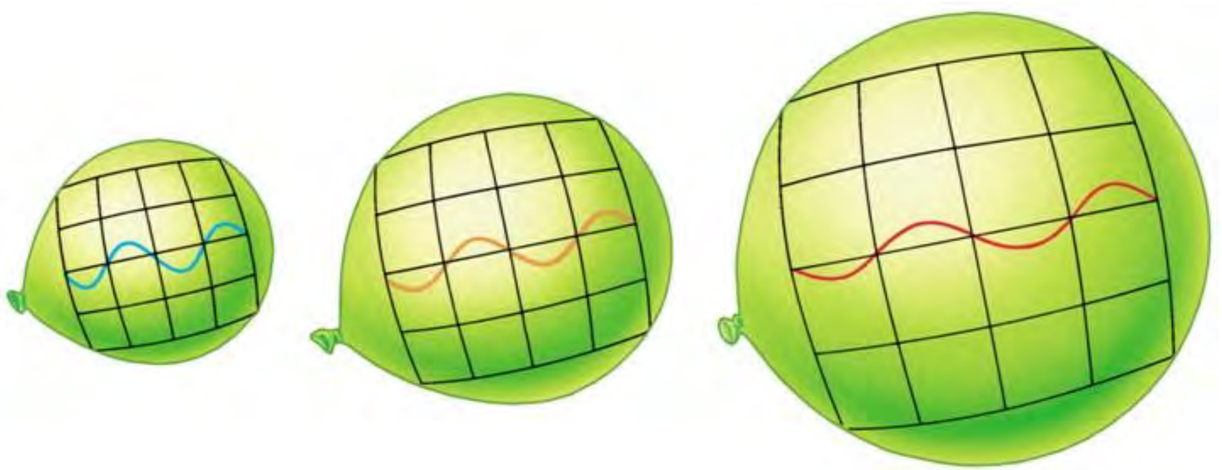
For distant galaxies

The further away an object is, the faster it is moving away from us. (Except for local objects*)

$$V_r = Hd$$

This is interpreted as an expansion of space.

*Strong local interactions can cause objects very near one another (e.g. Andromeda and MWG) to move through this expanding space, but they are still carried along by the expansion.



Hubble Law interpreted as expanding space, causing a cosmological redshift

Wavelength of any wave increases as space expands.

The Hubble Law means that the distance to an object can be determined by measuring its redshift

(provided the value of H is known)

Value of H_o (now, measured in the local universe) is

72.7 ± 1.6 km per sec per Mpc

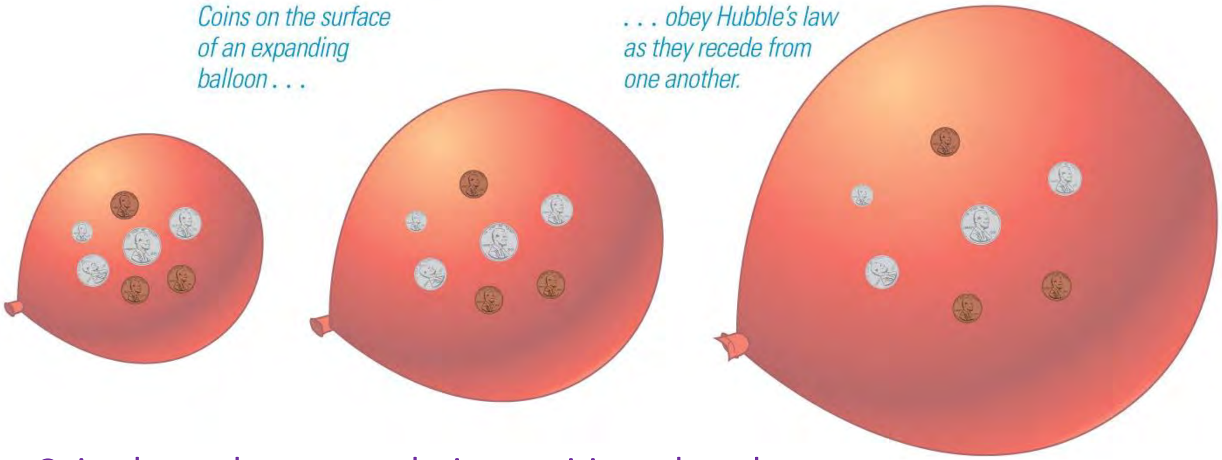
However, measures based on characteristics of the early Universe suggest a value of

67.6 ± 0.6 km per sec per Mpc

This disagreement is the Hubble tension in cosmology

The Expanding Universe

Two dimensional analog: Imagine a balloon with coins stuck to it. If the balloon expands, the coins all move farther and farther apart. There is, on the surface of the balloon, no "center" of expansion.

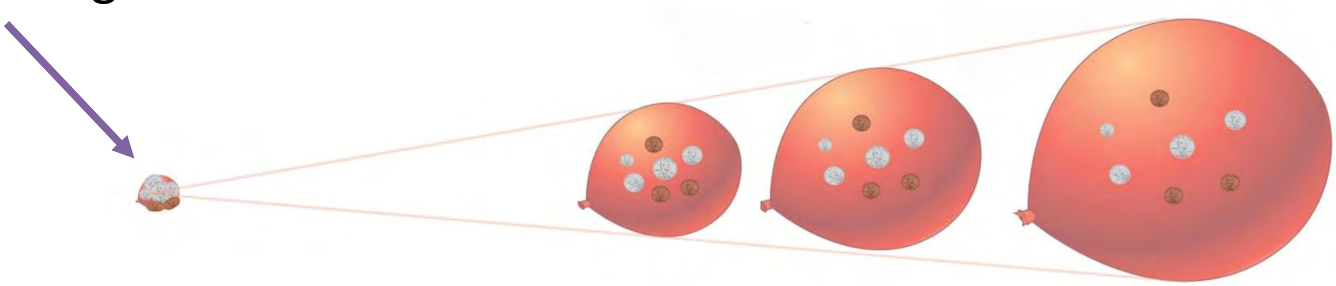


Coins keep the same relative positions, but the SCALE FACTOR of their universe increases with time

If we know the speed of the expansion, we can run it backwards in time until all galaxies were together. So, the expansion started (assuming $H_0 = 68$)

13.787 ± .023 Gyr ago

The Big Bang



What was the Big Bang?

The event 13.8 billion years ago wherein the distance between every two objects in the Universe was zero.

Where was the Big Bang?

Everywhere

Was the expansion uniform after the Big Bang?

Probably not. H, the Hubble "constant," was not the same in the past – it was larger when galaxies were closer together, but other effects in the evolution of the Universe determine H(z)

What was happening at the moment of the Big Bang?

can’t say – math singularities

What was it like just after the Big Bang?

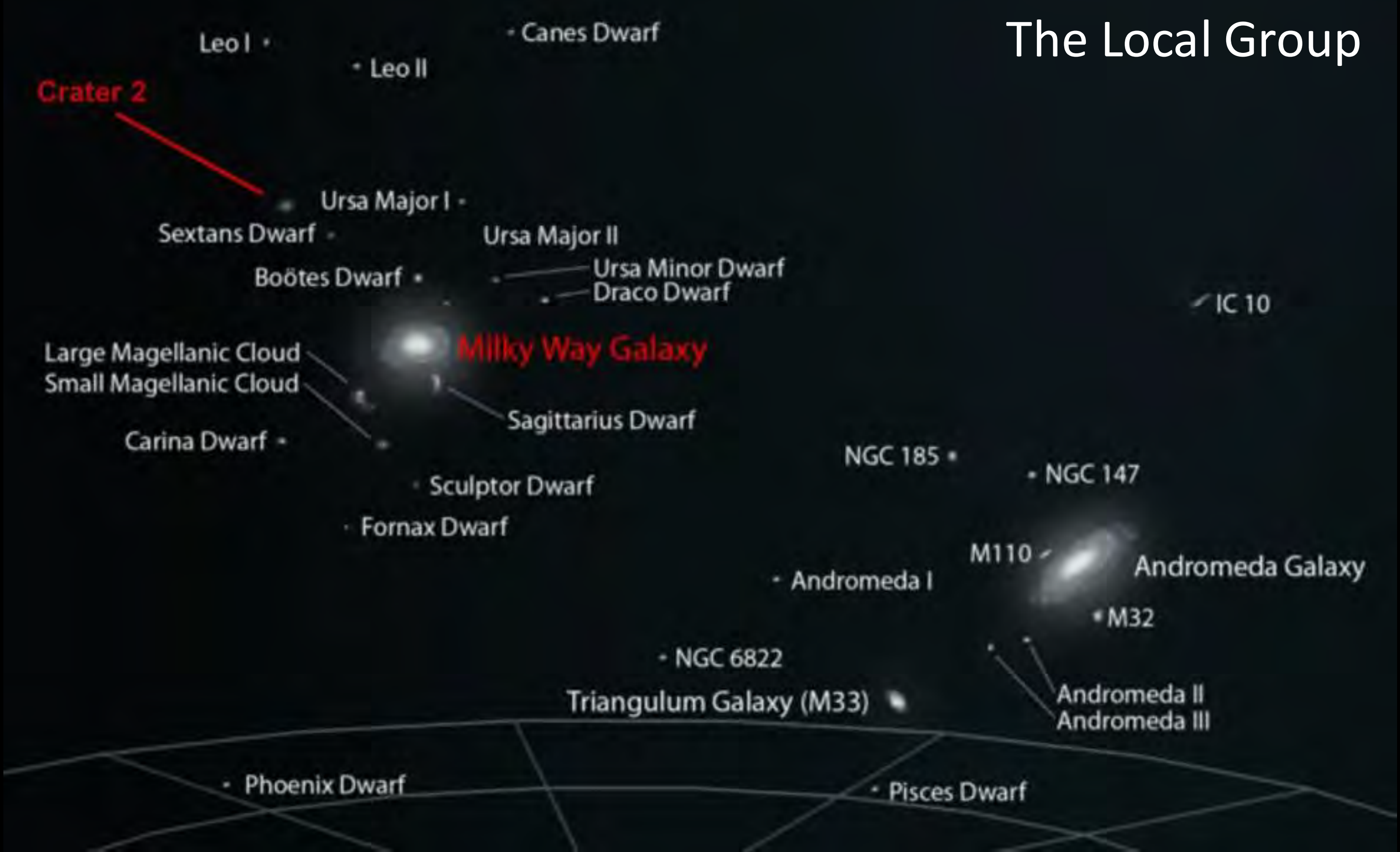
very hot, very dense – too hot for protons, electrons etc.

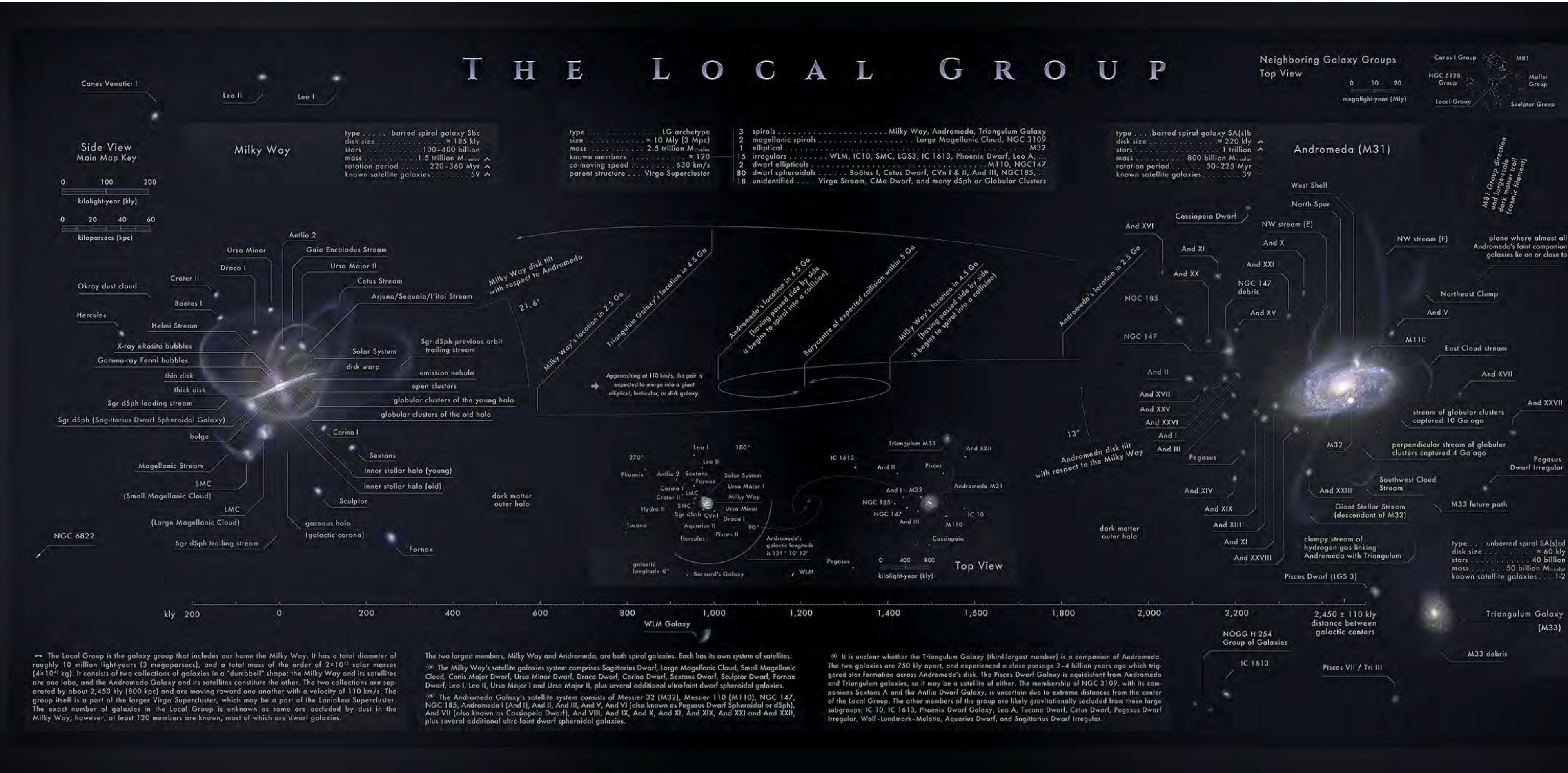
How big was the universe just after the Big Bang?

According to best model, infinite at all times (except at T=0)

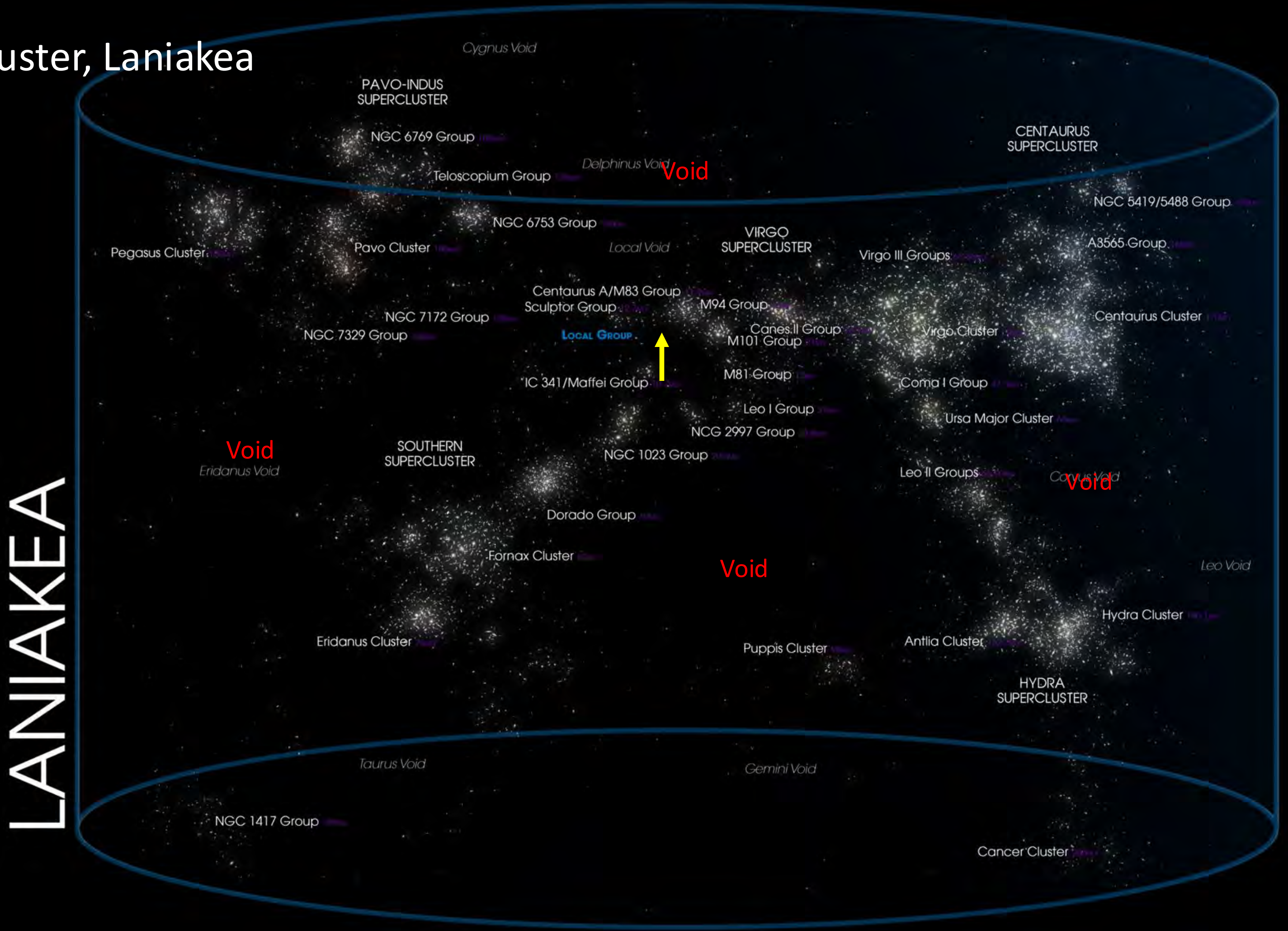
Mapping Galaxies in the Universe

The Local Group

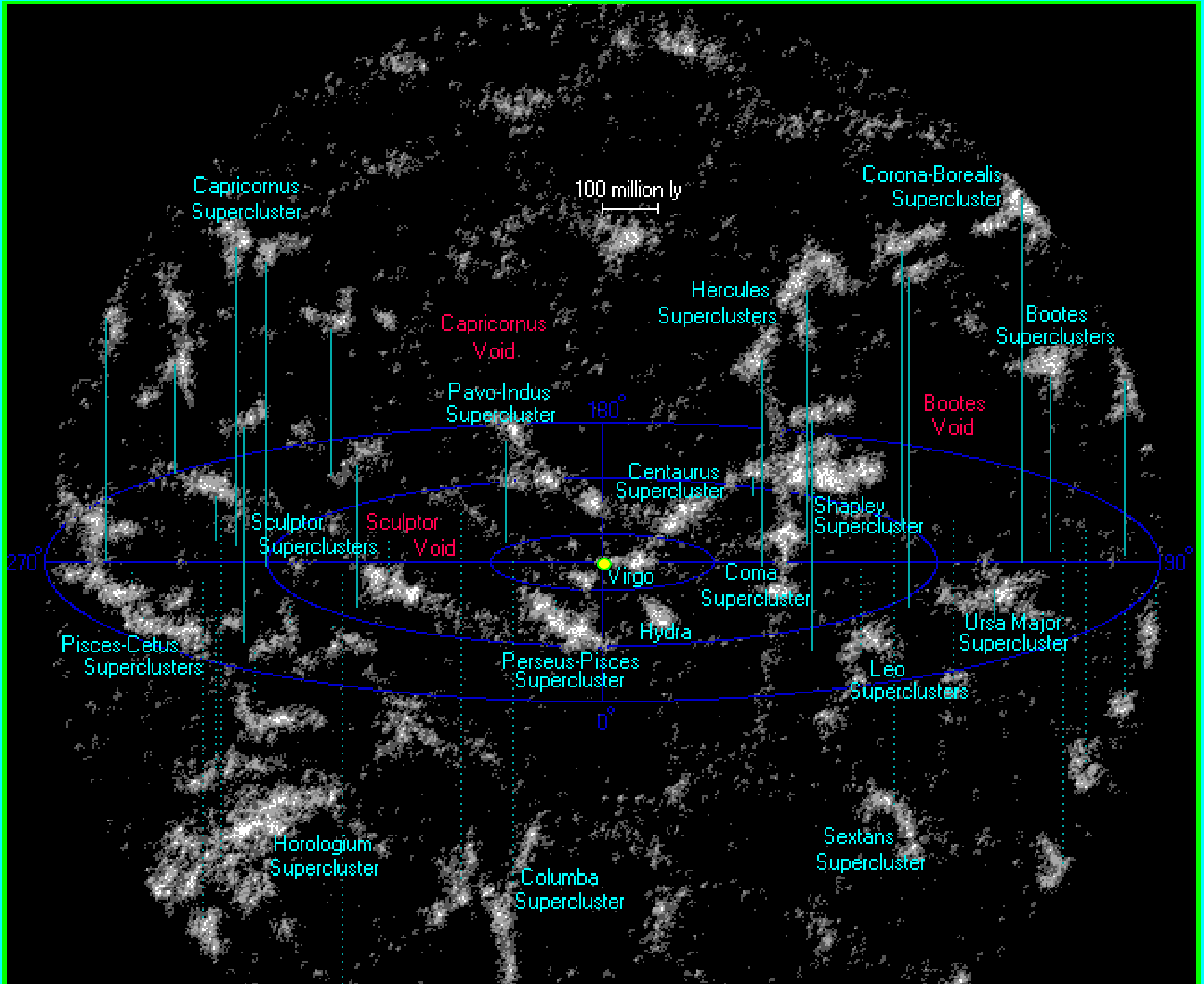



THE LOCAL GROUP
Neighboring Galaxy Groups
Top View
Canes I Group
M81
NGC 5128 Group
Maffei Group
Local Group
Sculptor Group
megalight-year (Mly)
Side View
Main Map Key
kilolight-year (kly)
kiloparsecs (kpc)
Canes Venatici I
Leo II
Leo I
Milky Way
type . . . . . barred spiral galaxy Sbc
disk size . . . . ≈ 185 kly
stars . . . . 100–400 billion
mass . . . . 1.5 trillion M☉
rotation period . . . . . . 220–360 Myr
known satellite galaxies 59
type . . . . LG archetype
size . . . . ≈ 10 Mly (3 Mpc)
mass . . . . 2.5 trillion M☉
known members . . . . ≈ 120
co-moving speed . . . . 630 km/s
parent structure . . . Virgo Supercluster
3 spirals . . . . Milky Way, Andromeda, Triangulum Galaxy
2 magellanic spirals . . . . . . Large Magellanic Cloud, NGC 3109
1 elliptical M32
15 irregulars . . . . . . WLM, IC10, SMC, LGS3, IC 1613, Phoenix Dwarf, Leo A, ...
2 dwarf ellipticals M110, NGC147
80 dwarf spheroidals . . . . . . Boötes I, Cetus Dwarf, CVn I & II, And III, NGC185, ...
18 unidentified . . . . Virgo Stream, CMa Dwarf, and many dSph or Globular Clusters
type . . . barred spiral galaxy SA(s)b
disk size . . . . ≈ 220 kly
stars . . . . 1 trillion
mass . . . . 800 billion M☉
rotation period . . . . . . 50–225 Myr
known satellite galaxies 39
Andromeda (M31)
M81 Group direction and large-scale dark matter trail (cosmic filament)
Antlia 2
Ursa Minor
Gaia Encaladus Stream
Draco I
Ursa Major II
Crater II
Cetus Stream
Okroy dust cloud
Arjuna/Sequoia/I'itoi Stream
Bootes I
Hercules
Helmi Stream
X-ray eRosita bubbles
Gamma-ray Fermi bubbles
Solar System
Sgr dSph previous orbit trailing stream
disk warp
emission nebula
thin disk
open clusters
thick disk
globular clusters of the young halo
Sgr dSph leading stream
globular clusters of the old halo
Sgr dSph (Sagittarius Dwarf Spheroidal Galaxy)
Carina I
bulge
Sextans
Magellanic Stream
inner stellar halo (young)
SMC (Small Magellanic Cloud)
inner stellar halo (old)
Sculptor
LMC (Large Magellanic Cloud)
gaseous halo (galactic corona)
NGC 6822
Sgr dSph trailing stream
Fornax
dark matter outer halo
Milky Way disk tilt with respect to Andromeda
21.6°
Milky Way's location in 2.5 Ga
Triangulum Galaxy's location in 4.5 Ga
Andromeda's location in 4.5 Ga (having passed side by side it begins to spiral into a collision)
Barycentre of expected collision within 5 Ga
Milky Way's location in 4.5 Ga (having passed side by side it begins to spiral into a collision)
Andromeda's location in 2.5 Ga
Approaching at 110 km/s, the pair is expected to merge into a giant elliptical, lenticular, or disk galaxy.
13°
Andromeda disk tilt with respect to the Milky Way
Top View
kilolight-year (kly)
galactic longitude 0°
Barnard's Galaxy
WLM
Pegasus
Andromeda's galactic longitude is 121° 10' 12"
Triangulum M33
And XXII
IC 1613
And II
Pisces
Andromeda M31
And I
M32
NGC 185
NGC 147
IC 10
And III
M110
Cassiopeia
Leo I
Leo II
Phoenix
Antlia 2
Sextans
Fornax
Carina I
LMC
Crater II
Hydra II
SMC
Sgr dSph
CVn I
Tucana
Aquarius II
Hercules
Pisces II
Solar System
Ursa Major I
Milky Way
Ursa Minor
Draco I
West Shelf
North Spur
Cassiopeia Dwarf
NW stream (E)
And XVI
NW stream (F)
plane where almost all Andromeda's faint companion galaxies lie on or close to
And X
And XI
And XXI
And XX
NGC 147 debris
NGC 185
Northeast Clump
And XV
And V
NGC 147
M110
East Cloud stream
And II
And XVII
And XVII
And XXV
And XXVII
And XXVI
stream of globular clusters captured 10 Ga ago
And I
And III
M32
perpendicular stream of globular clusters captured 4 Ga ago
Pegasus
Pegasus Dwarf Irregular
Southwest Cloud Stream
And XIV
And XXIII
M33 future path
Giant Stellar Stream (descendant of M32)
And XIX
And XIII
dark matter outer halo
clumpy stream of hydrogen gas linking Andromeda with Triangulum
And XI
And XXVIII
type . . . unbarred spiral SA(s)cd
disk size . . . . ≈ 60 kly
stars . . . . 40 billion
mass . . . . 50 billion M☉
known satellite galaxies . . . 1-2
Pisces Dwarf (LGS 3)
kly 200 0 200 400 600 800 1,000 1,200 1,400 1,600 1,800 2,000 2,200
2,450 ± 110 kly distance between galactic centers
Triangulum Galaxy (M33)
WLM Galaxy
NOGG H 254 Group of Galaxies
IC 1613
M33 debris
Pisces VII / Tri III
The Local Group is the galaxy group that includes our home the Milky Way. It has a total diameter of roughly 10 million light-years (3 megaparsecs), and a total mass of the order of 2×10¹² solar masses (4×10⁴² kg). It consists of two collections of galaxies in a "dumbbell" shape: the Milky Way and its satellites are one lobe, and the Andromeda Galaxy and its satellites constitute the other. The two collections are separated by about 2,450 kly (800 kpc) and are moving toward one another with a velocity of 110 km/s. The group itself is a part of the larger Virgo Supercluster, which may be a part of the Laniakea Supercluster. The exact number of galaxies in the Local Group is unknown as some are occluded by dust in the Milky Way; however, at least 120 members are known, most of which are dwarf galaxies.
The two largest members, Milky Way and Andromeda, are both spiral galaxies. Each has its own system of satellites:
The Milky Way's satellite galaxies system comprises Sagittarius Dwarf, Large Magellanic Cloud, Small Magellanic Cloud, Canis Major Dwarf, Ursa Minor Dwarf, Draco Dwarf, Carina Dwarf, Sextans Dwarf, Sculptor Dwarf, Fornax Dwarf, Leo I, Leo II, Ursa Major I and Ursa Major II, plus several additional ultra-faint dwarf spheroidal galaxies.
The Andromeda Galaxy's satellite system consists of Messier 32 (M32), Messier 110 (M110), NGC 147, NGC 185, Andromeda I (And I), And II, And III, And V, And VI (also known as Pegasus Dwarf Spheroidal or dSph), And VII (also known as Cassiopeia Dwarf), And VIII, And IX, And X, And XI, And XIX, And XXI and And XXII, plus several additional ultra-faint dwarf spheroidal galaxies.
It is unclear whether the Triangulum Galaxy (third-largest member) is a companion of Andromeda. The two galaxies are 750 kly apart, and experienced a close passage 2–4 billion years ago which triggered star formation across Andromeda's disk. The Pisces Dwarf Galaxy is equidistant from Andromeda and Triangulum galaxies, so it may be a satellite of either. The membership of NGC 3109, with its companions Sextans A and the Antlia Dwarf Galaxy, is uncertain due to extreme distances from the center of the Local Group. The other members of the group are likely gravitationally secluded from these large subgroups: IC 10, IC 1613, Phoenix Dwarf Galaxy, Leo A, Tucana Dwarf, Cetus Dwarf, Pegasus Dwarf Irregular, Wolf–Lundmark–Melotte, Aquarius Dwarf, and Sagittarius Dwarf Irregular.

The Local Supercluster, Laniakea



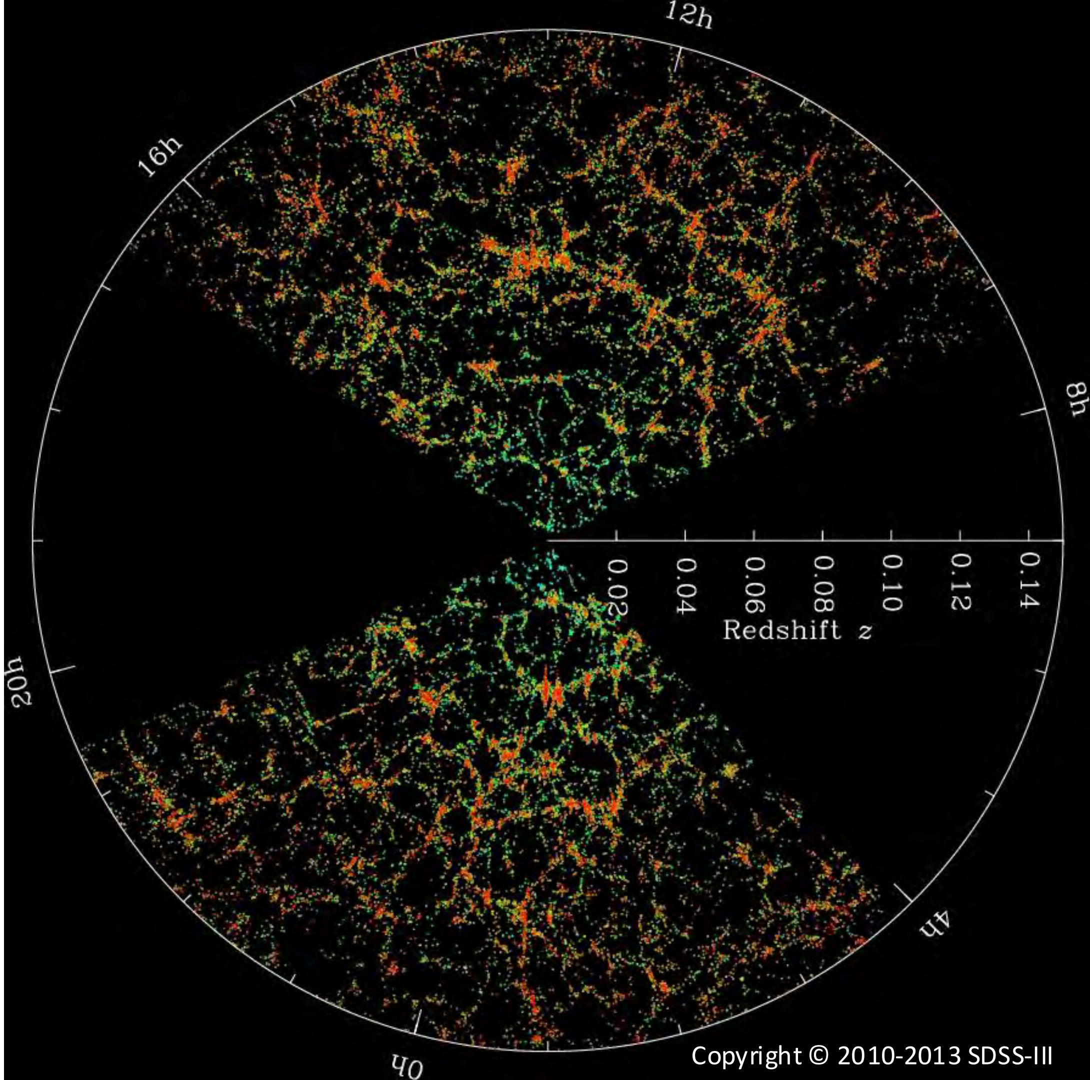
Nearby superclusters and voids, out to 300Mpc or Z = 0.06



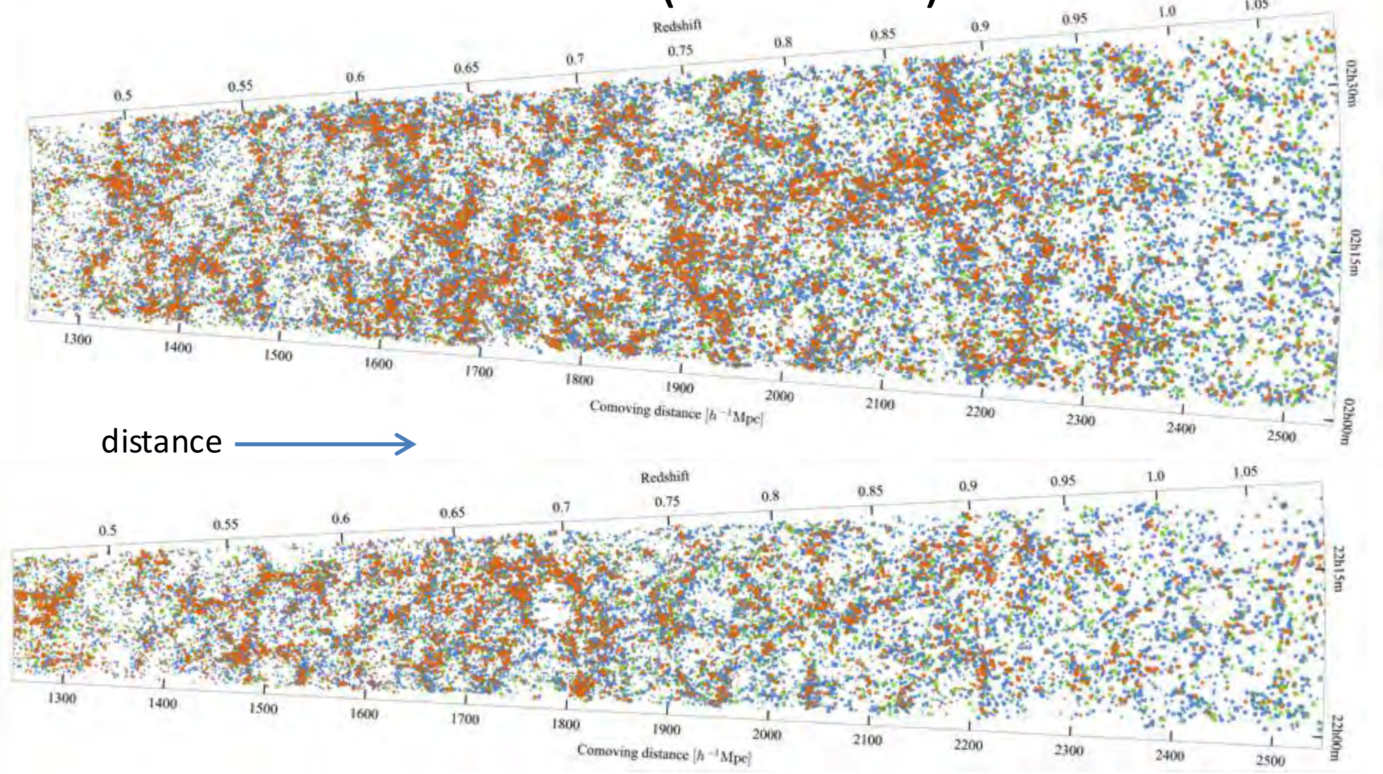
SDSS – Survey of nearby Galaxies

Each dot is a galaxy, and its distance is determined spectroscopically from its redshift.

Galaxies are colored according to the ages of their stars, with the redder, more strongly clustered points showing galaxies that are made of older stars.

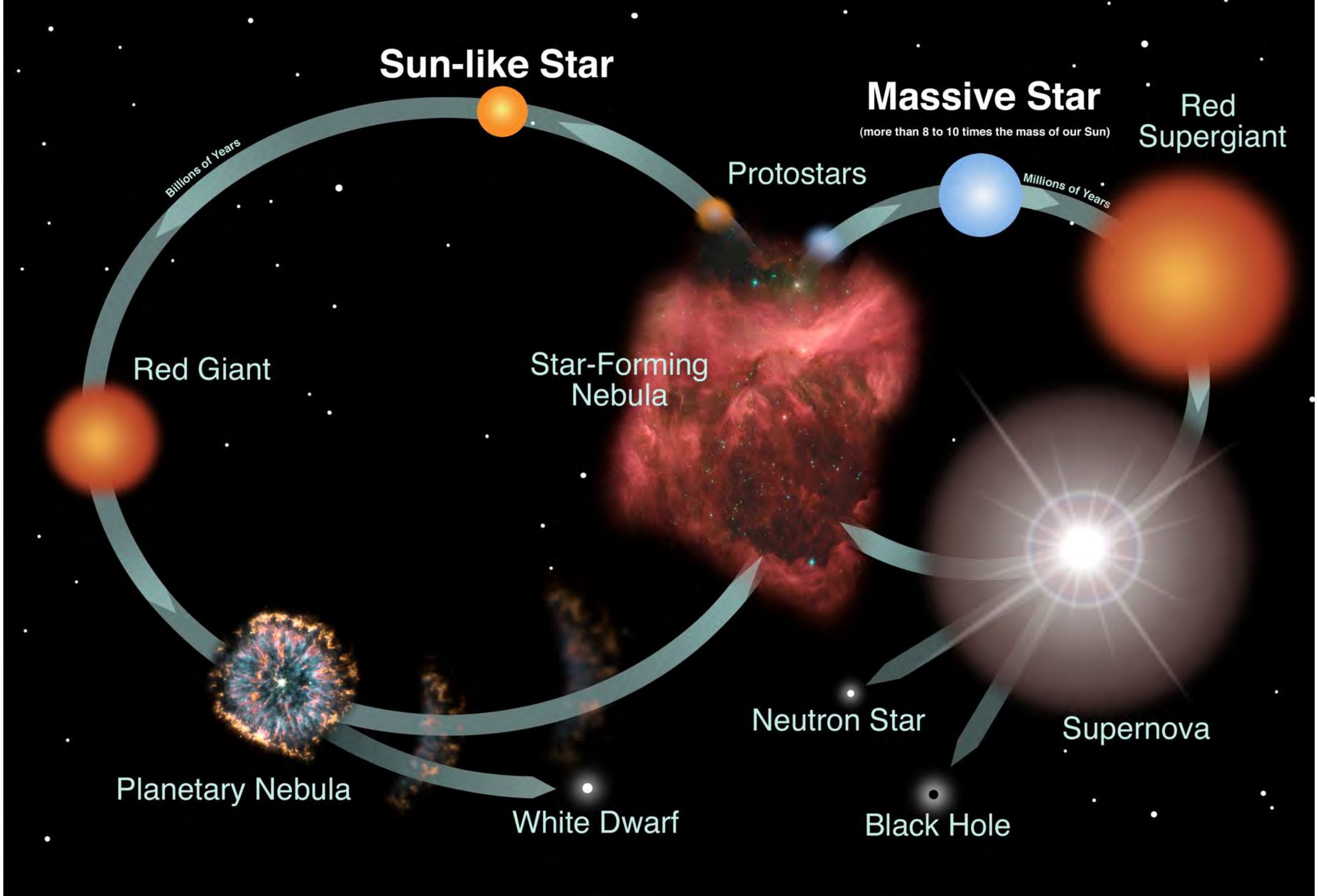


VIPERS (Nov 2016)



Map of 90,00 more distant galaxies

Making Galaxies Over Time



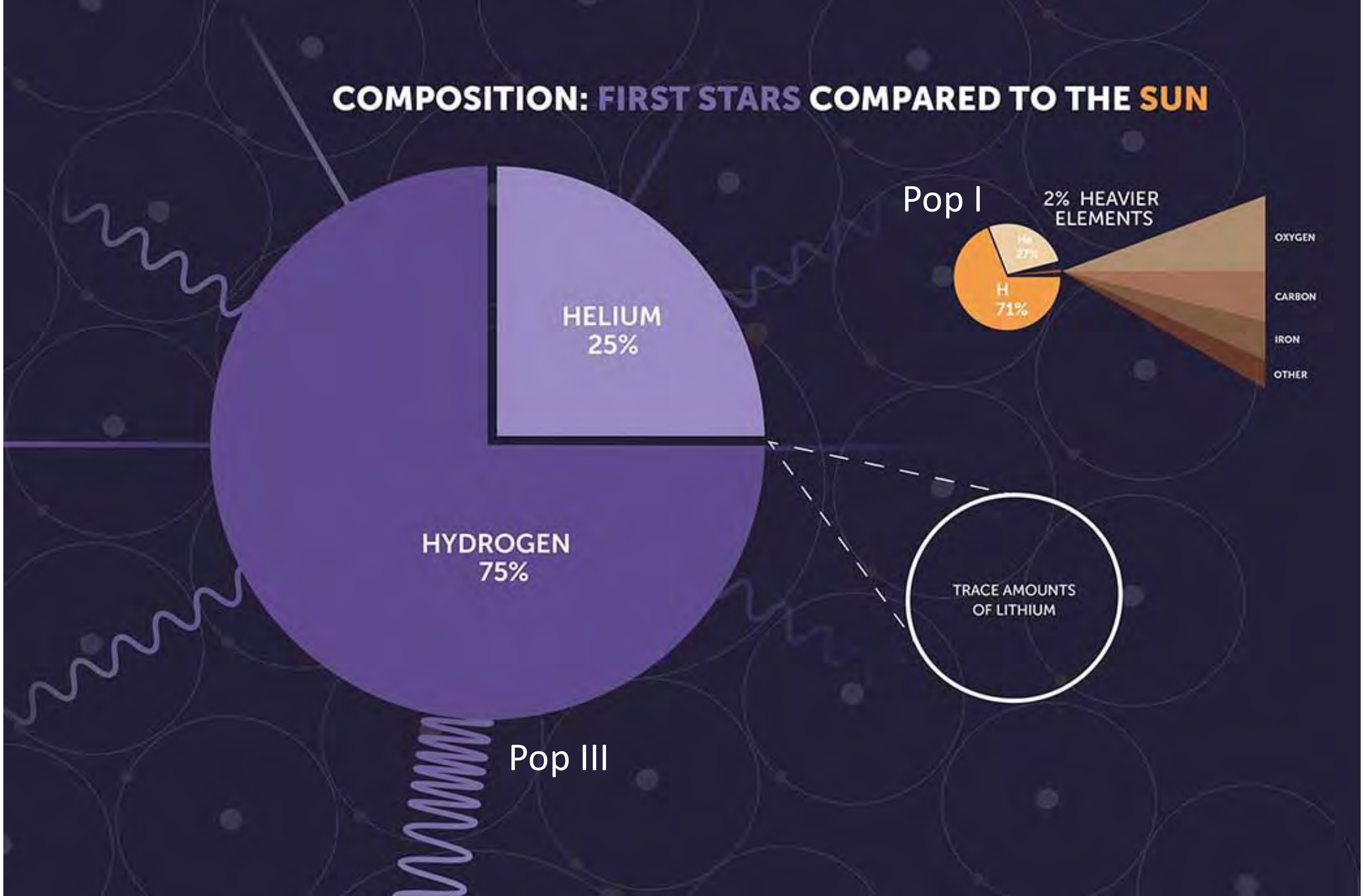
Sun-like Star
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Billions of Years
Millions of Years
Protostars
Red Giant
Star-Forming Nebula
Neutron Star
Supernova
Planetary Nebula
White Dwarf
Black Hole

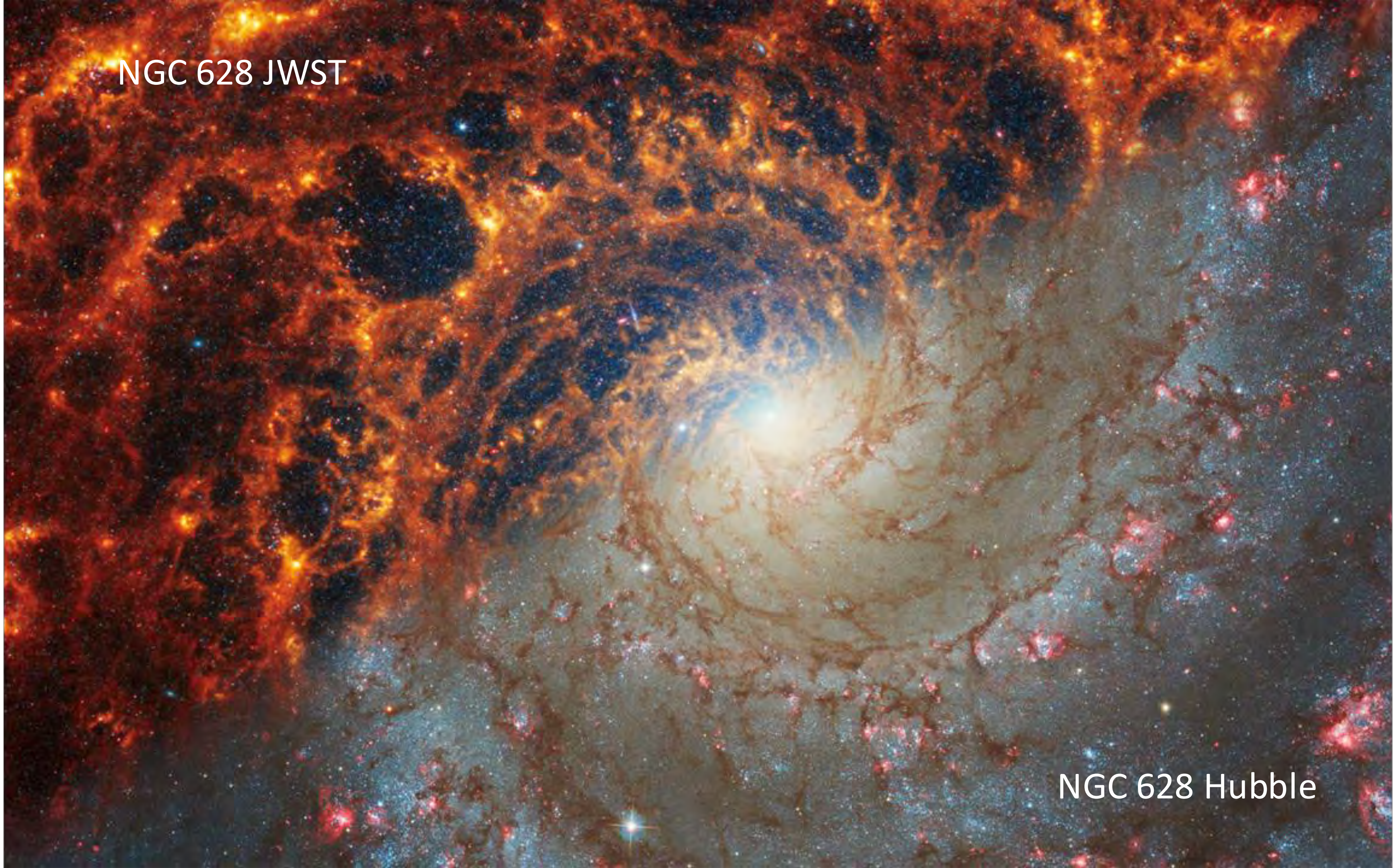
Stellar Populations –

Pop I – stars like the sun – younger, formed from metal-rich gas, astrophysicaly determined ages < 9 Gyrs

Pop II – formed from metal poor gas, ages > 8-10 Gyrs – oldest stars observed < 13.8 ± .8 Gyrs

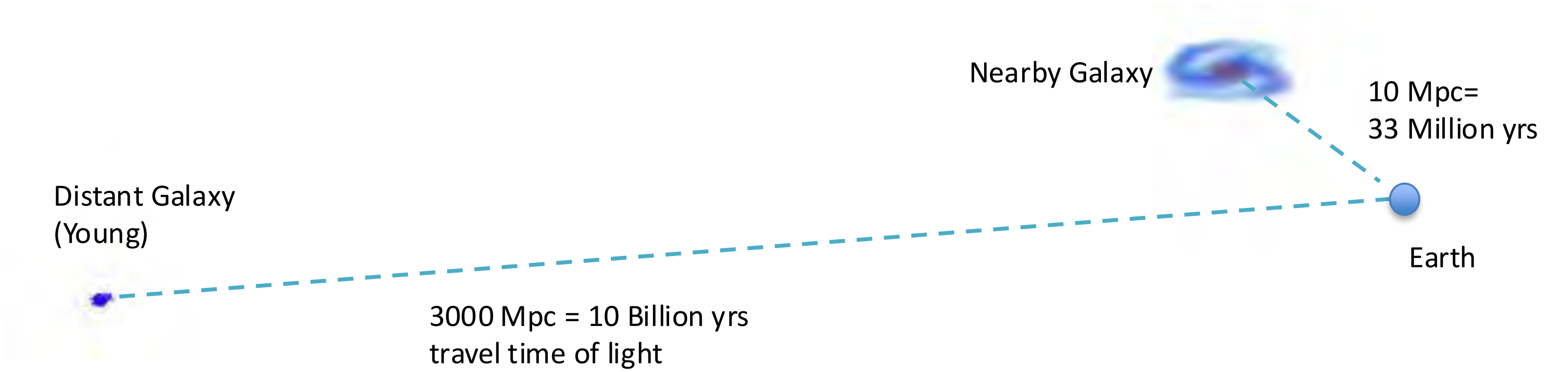
Pop III - first generation of stars formed from primordial H and He, no metals. Form at end of dark ages of the universe. Should be 13.5 Gyrs old. None observed so far?


COMPOSITION: FIRST STARS COMPARED TO THE SUN
Pop I
2% HEAVIER ELEMENTS
He 27%
H 71%
OXYGEN
CARBON
IRON
OTHER
HELIUM 25%
HYDROGEN 75%
TRACE AMOUNTS OF LITHIUM
Pop III


NGC 628 JWST
NGC 628 Hubble

Lookback Time

We see distant objects as they were
when they emitted the light we receive.



Lookback time for distant galaxies:

$z \rightarrow apply$ Hubble law $\rightarrow$ Distance $\rightarrow$ Lookback time

$$\text{Lookback time} = \frac{d}{c} = \frac{V_r/H_0}{c} = \frac{cz}{cH_0} = \frac{z}{H_0}$$

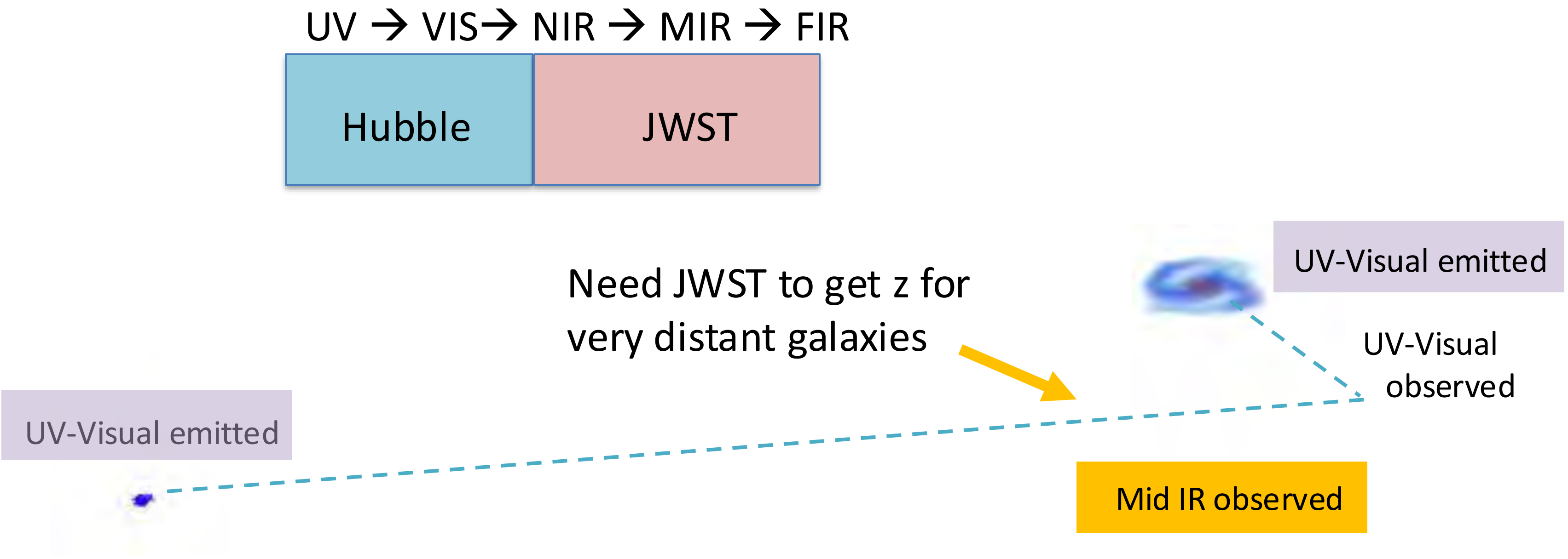
Only for nearby objects

Cosmological model dependent, and usually compute

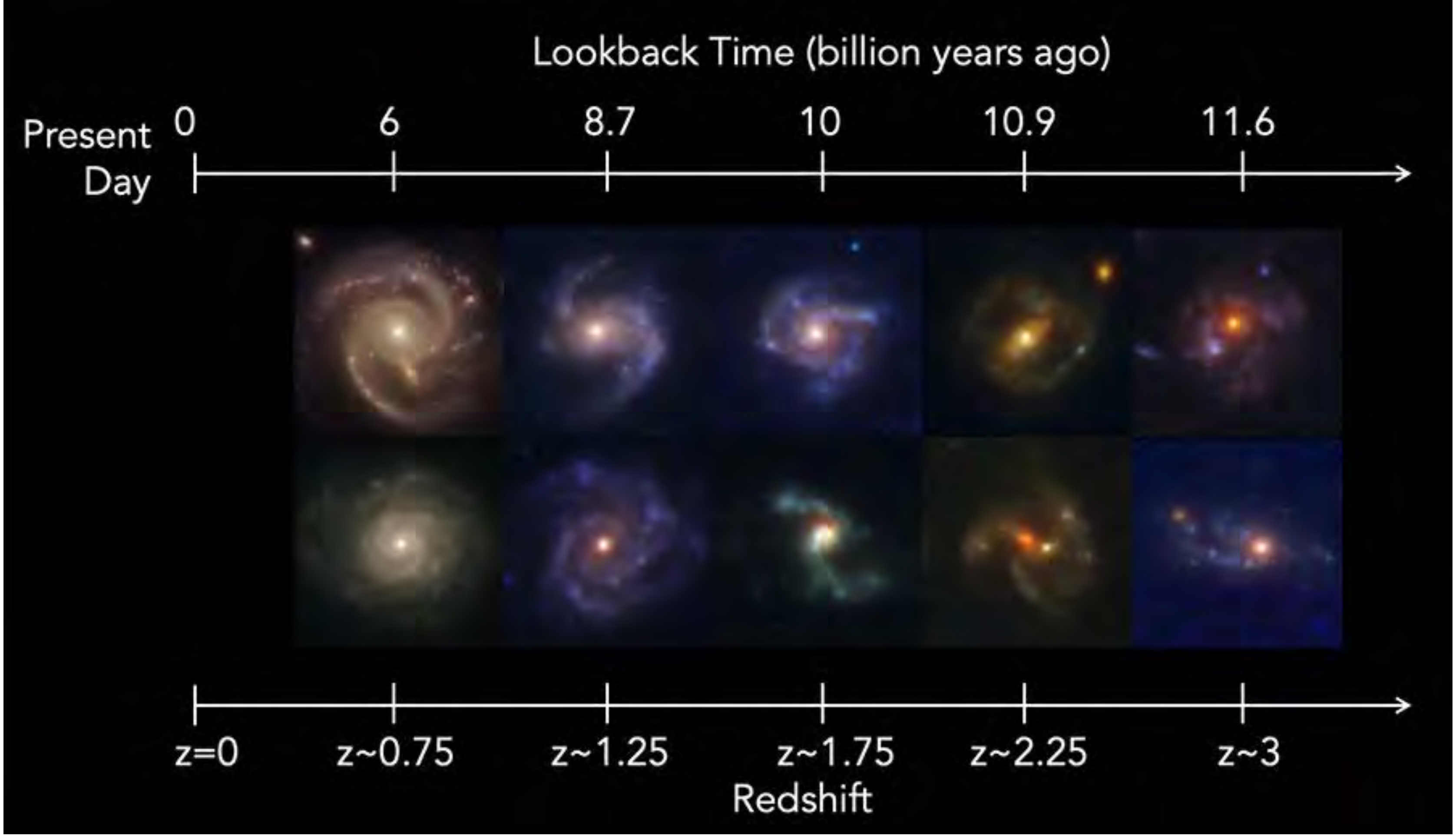
T = time after Big Bang that light was emitted

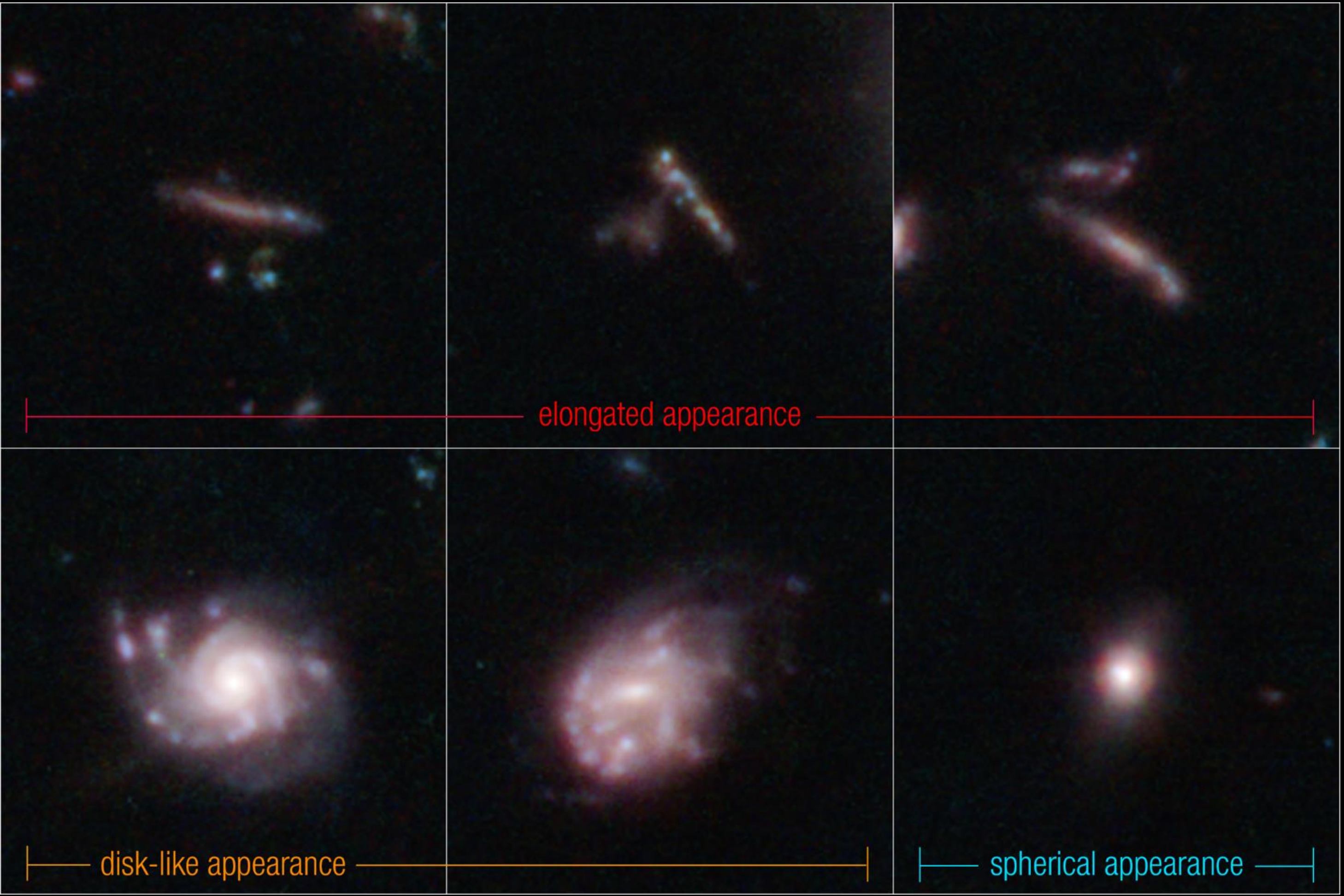
Look at galaxies at increasing T(z) → See galaxy evolution

Light from distant galaxies is shifted to longer wavelengths → look in IR



	z	Time since Big Bang
	0.0	13.79 Gyr
	0.05	13.04
	0.25	10.7
	0.50	8.6
	1.0	5.9
Ground	2.0	3.3
	3.0	2.20
Hubble DF	6.0	0.94
Hubble UDF	10.0	0.48
	14.0	0.30 = 300 Million yrs
JWST	20.0	0.18 = 180 Million yrs
CMB	1100.0	0.00038 = 380,000 yrs

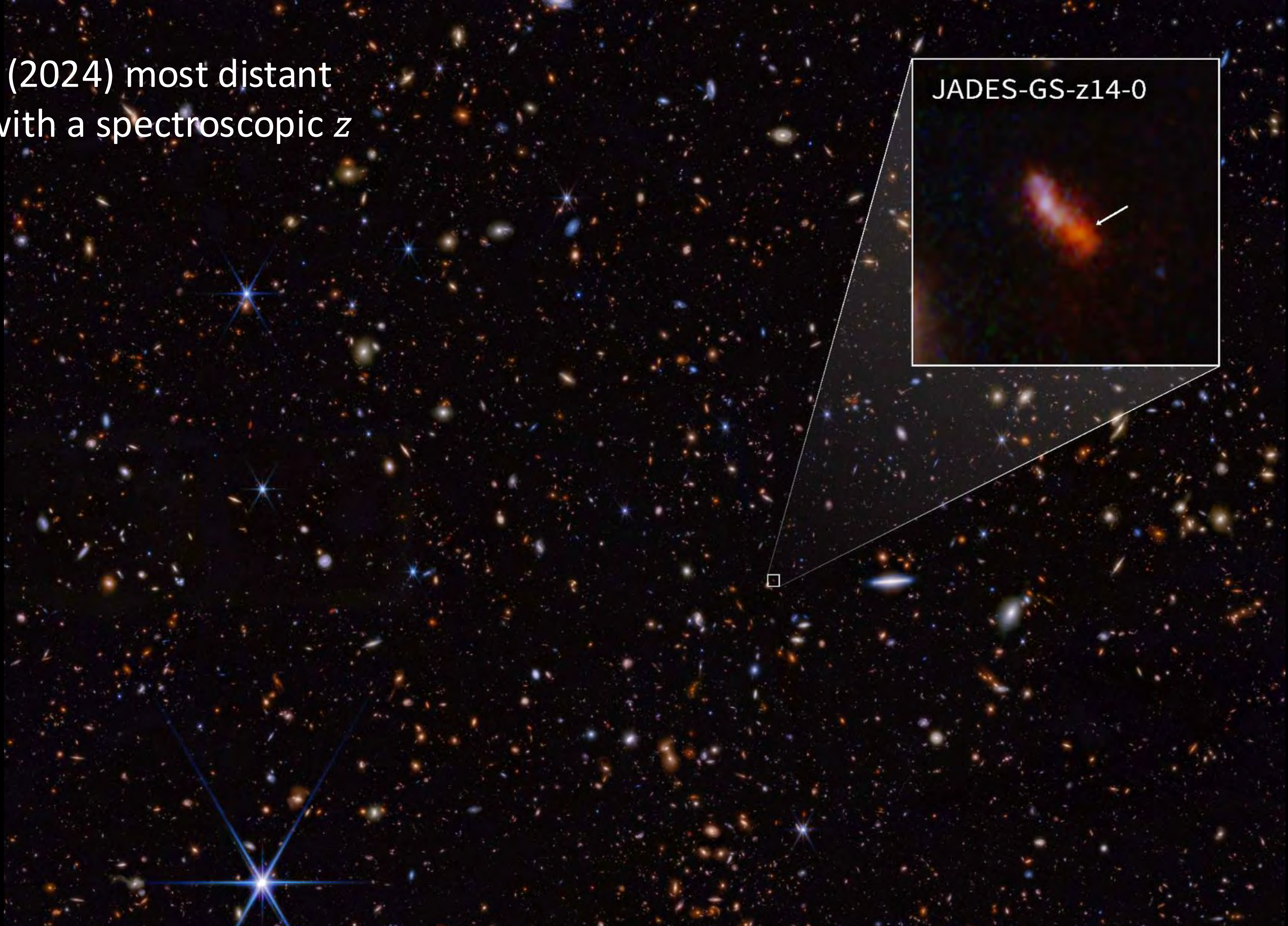

Lookback Time (billion years ago)
Present Day
0
6
8.7
10
10.9
11.6
z=0
z~0.75
z~1.25
z~1.75
z~2.25
z~3
Redshift



JWST galaxies in the early Universe

Excess of bright galaxies
14 > z > 7

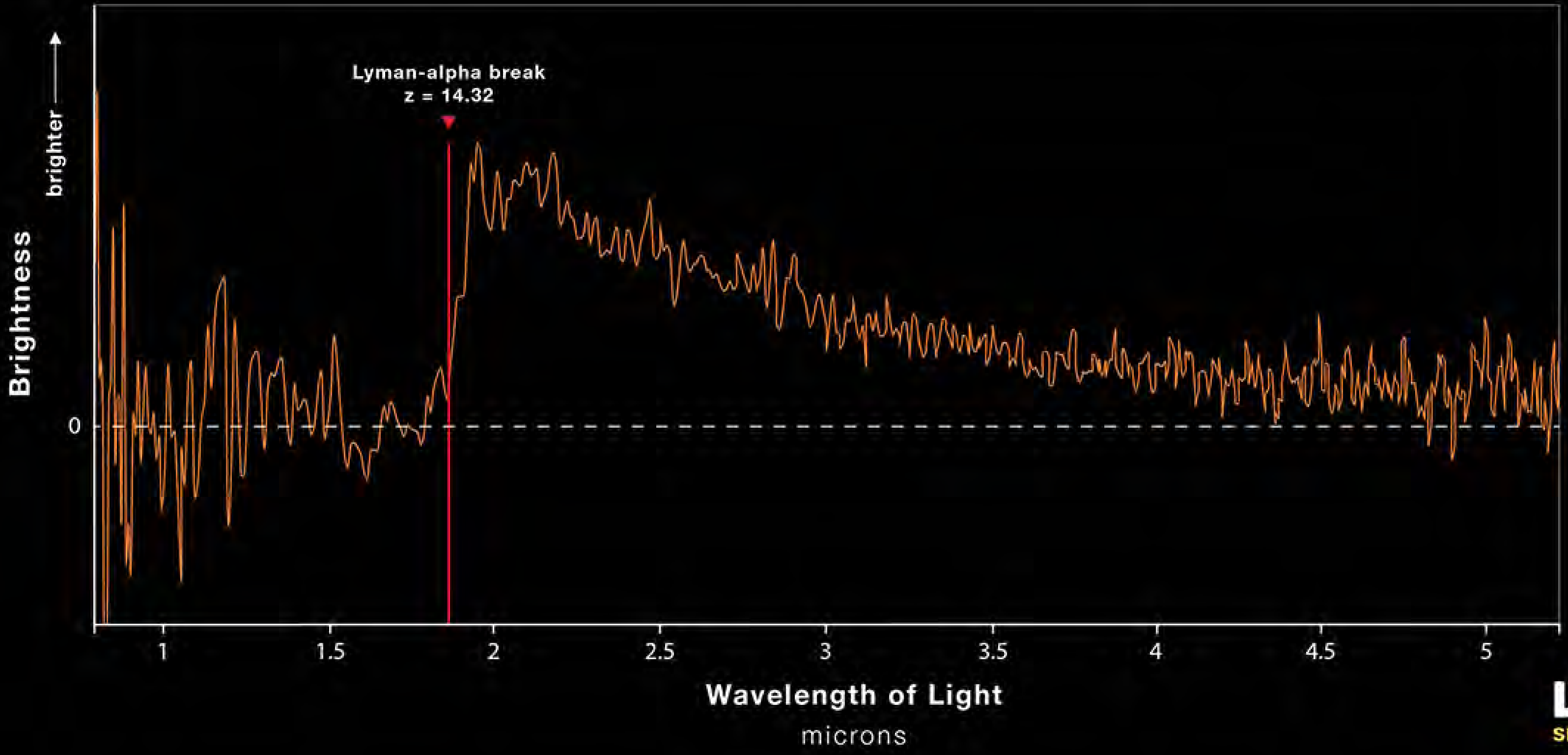
Current (2024) most distant galaxy with a spectroscopic z



GALAXY JADES-GS-Z14-0

GALAXY EXISTED 300 MILLION YEARS AFTER BIG BANG

NIRSpec Microshutter Array Spectroscopy



WEBB
SPACE TELESCOPE

Can we see further back than z=14?

Maybe: Pop III stars should form at around z = 25. The search is on.

No stars expected earlier than z=30

However

The Cosmic Microwave Background

Discovered fortuitously in 1964, as Penzias and Wilson tried to get rid of the last bit of “noise” in their radio antenna.

Instead, they found that the “noise” came uniformly from all directions and times. They realized they were detecting photons left over from the Big Bang.

Emitted at T = 380,000 years (z = 1100)

Awarded the 1978 Nobel Prize in Physics .

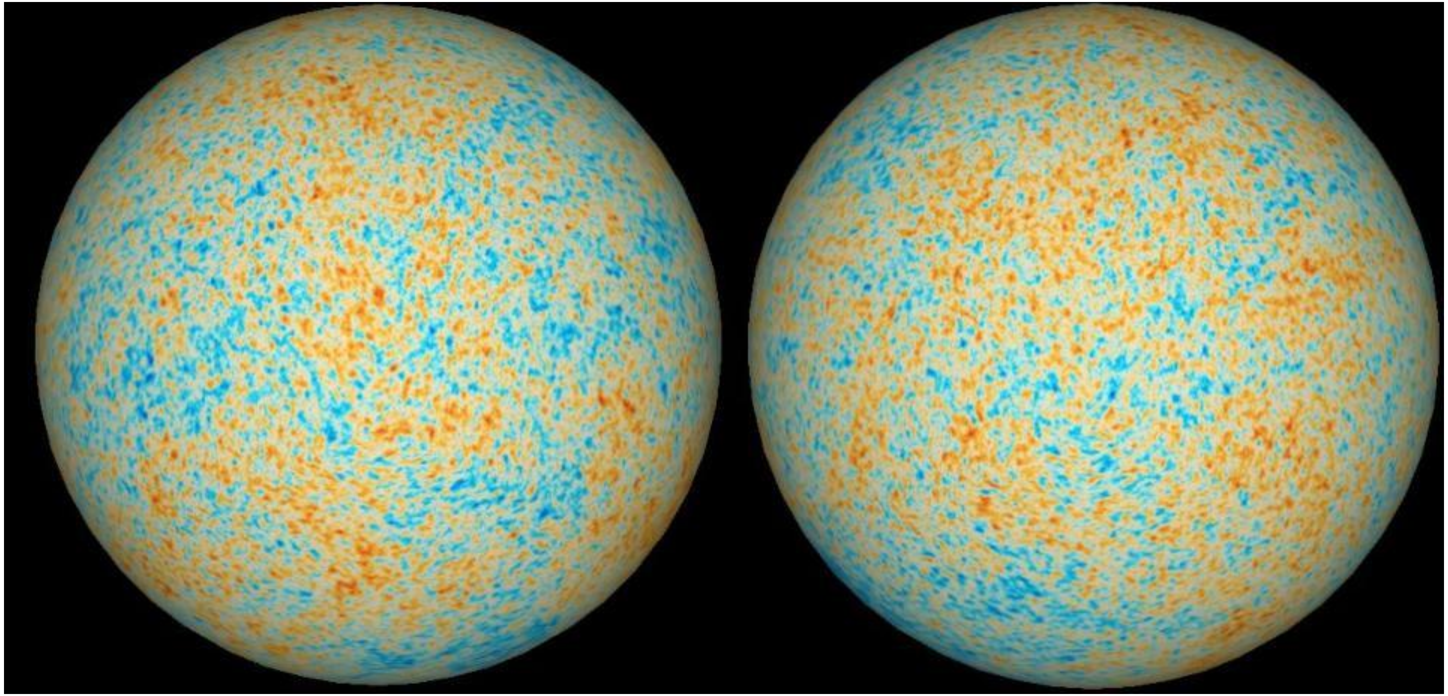
Map of the CMB

This is what the universe looked like when it was 380,000 years old

Temperature now 2.725 K, redshift z=1100, Temperature emitted =3000 K

Any details?
CMB –Remove motion towards Virgo

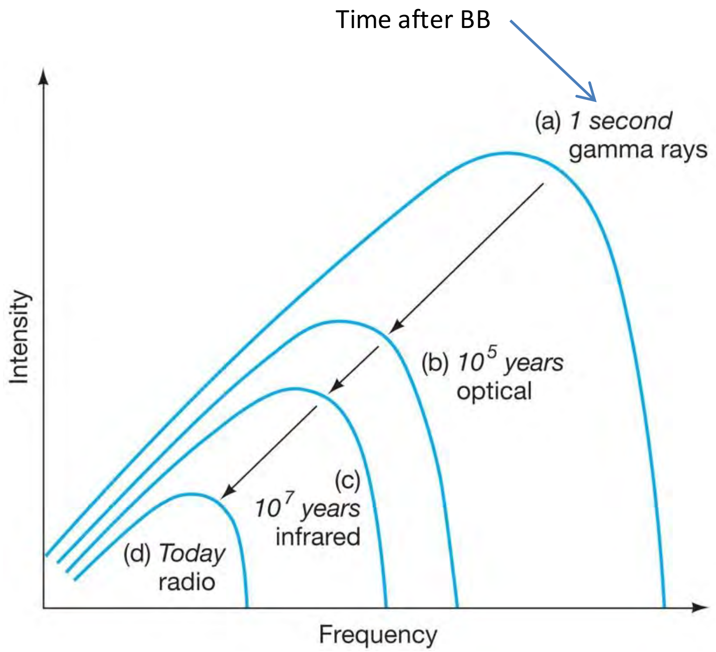
Fluctuations 1:100,000



Cosmic Microwave Background

When these photons were created, it was only 380,000 years after the Big Bang, and they were very highly energetic.

The expansion of the universe has redshifted (z = 1100) their wavelengths so that now they are in the radio-microwave spectrum, with a blackbody curve corresponding to 2.73 K.



BIG QUESTIONS

Explain the universe: account for all observations (Hubble flow, evolution, CMB, etc.) with one theory.

LCDM

(Lambda-Cold Dark Matter)

The Standard Model

Best account for all observations.
Many proposed alternatives, none successful

ΛCDM in three steps:

First step:

The universe is the entirety of space-time and all it contains.

(“Other universes” may exist, but they are not now, and may never be, subject to cosmological investigation)

Second step: Make some very informed assumptions

The most important dynamical effect in the universe is gravity

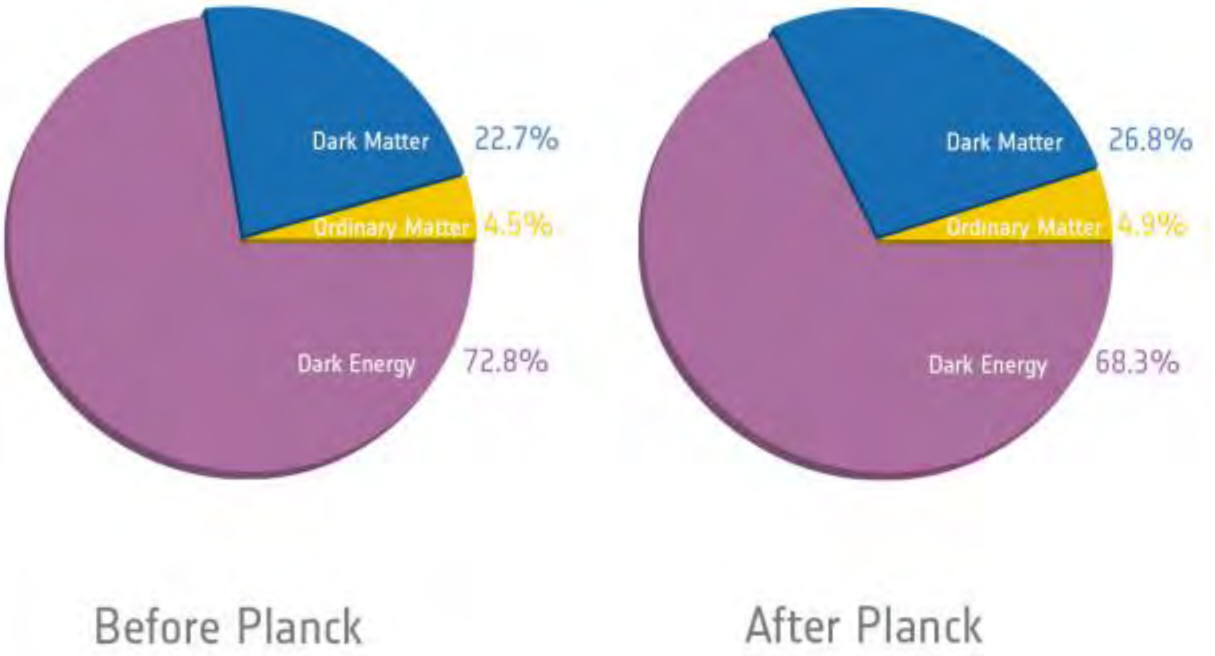
The best description of gravity is General Relativity

Hubble's Law describes an expansion of space

The universe on large scales is both homogeneous and isotropic:

- No special place (no boundaries), no variation in contents
- No special direction

Third step: Contents of the Universe

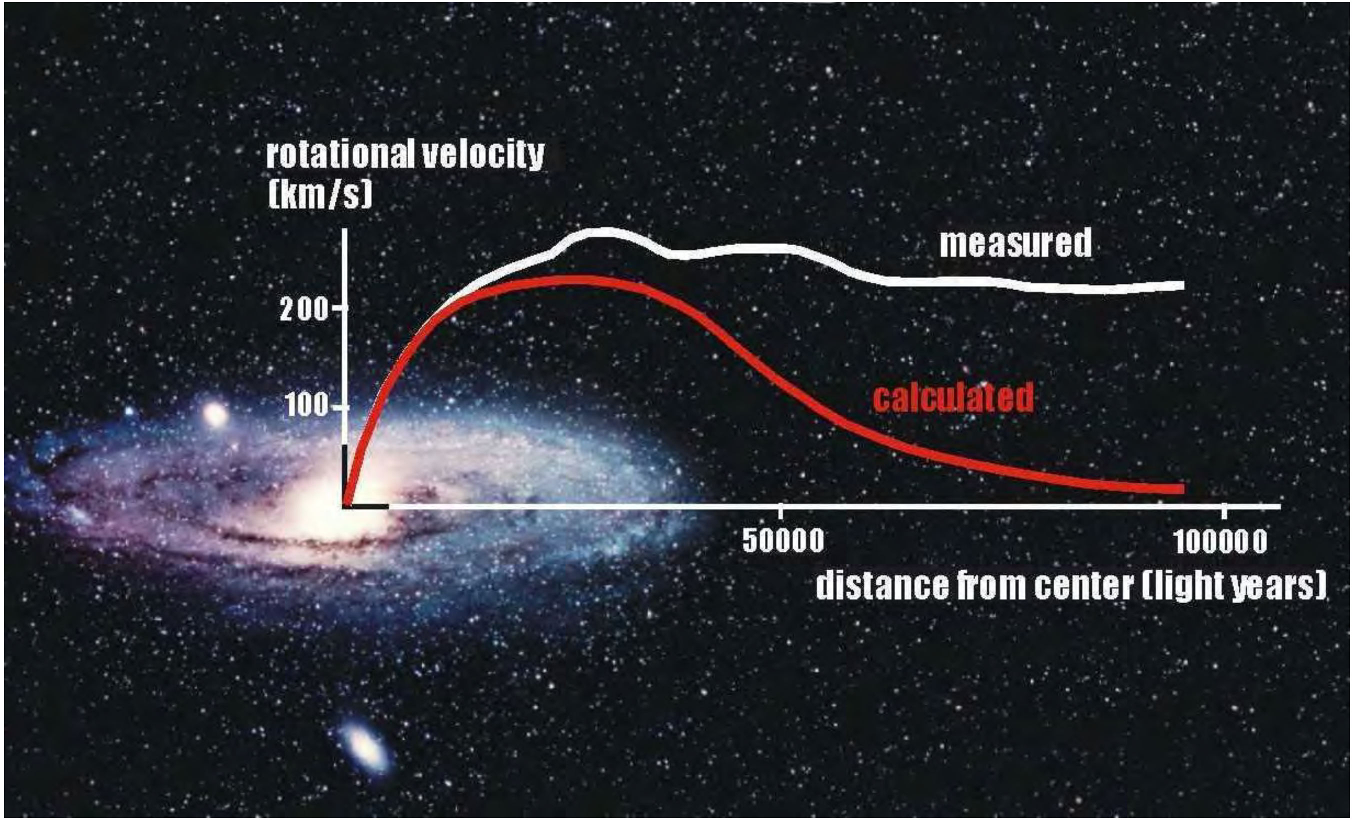


DARK MATTER:

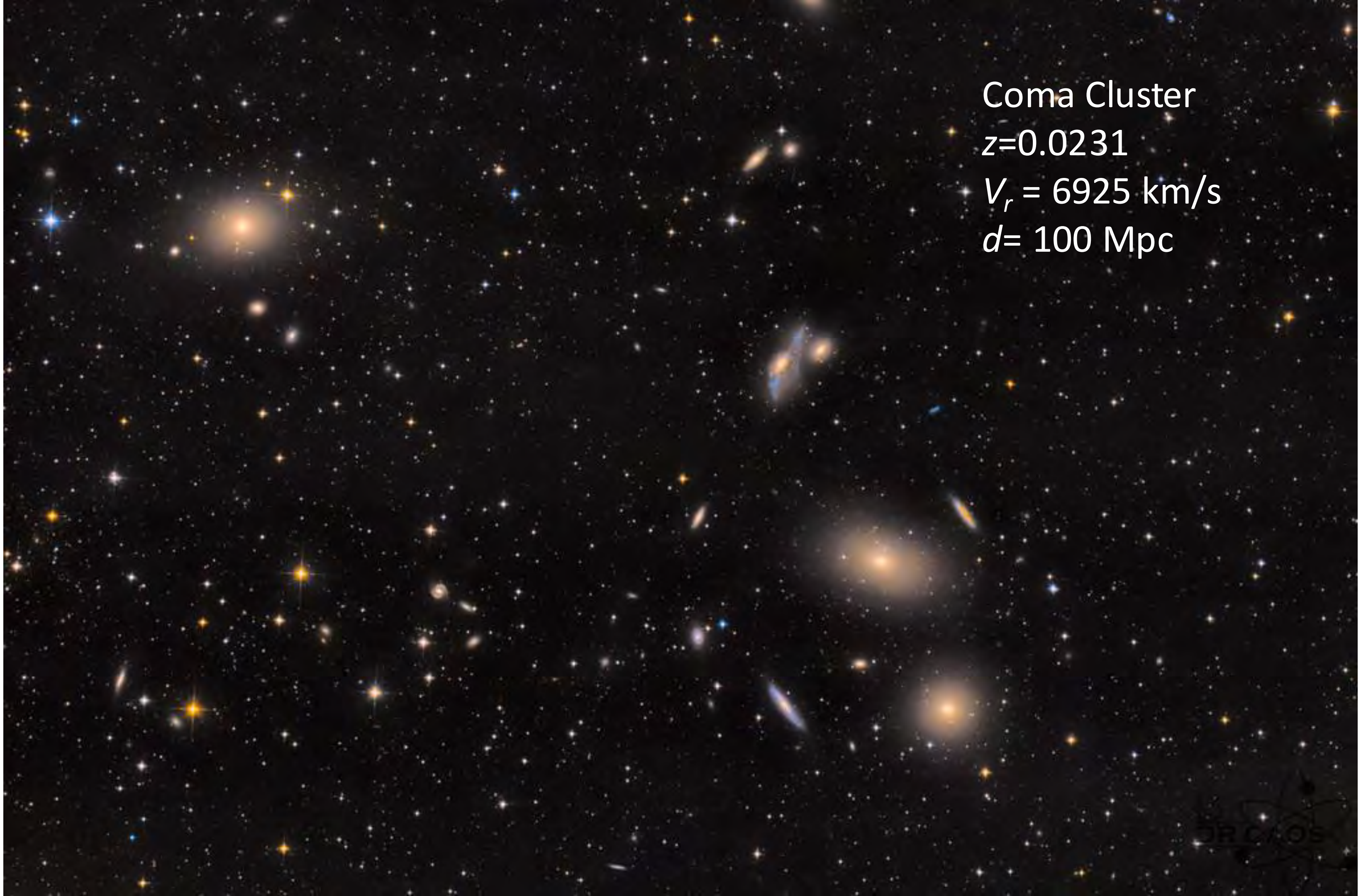
- NO electromagnetic interactions: DM neither absorbs nor emits light, radio waves, x-rays, etc.

- Acts gravitationally like a mass: causes space to contract, attracts ordinary matter. Know it exists because stuff (stars, galaxies) moves in response to it

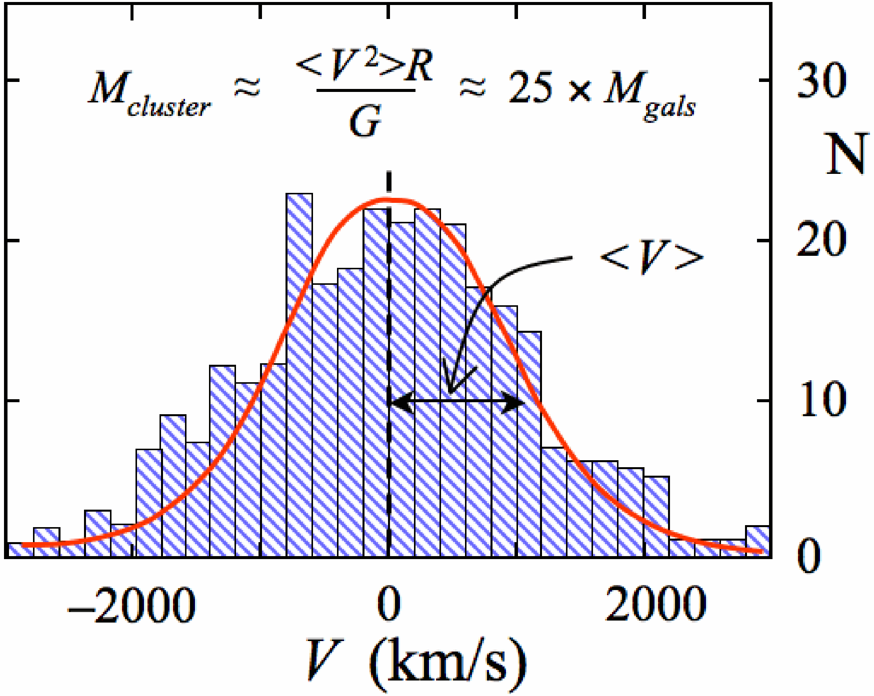
- Possible other very weak interactions with ordinary matter, but none detected.



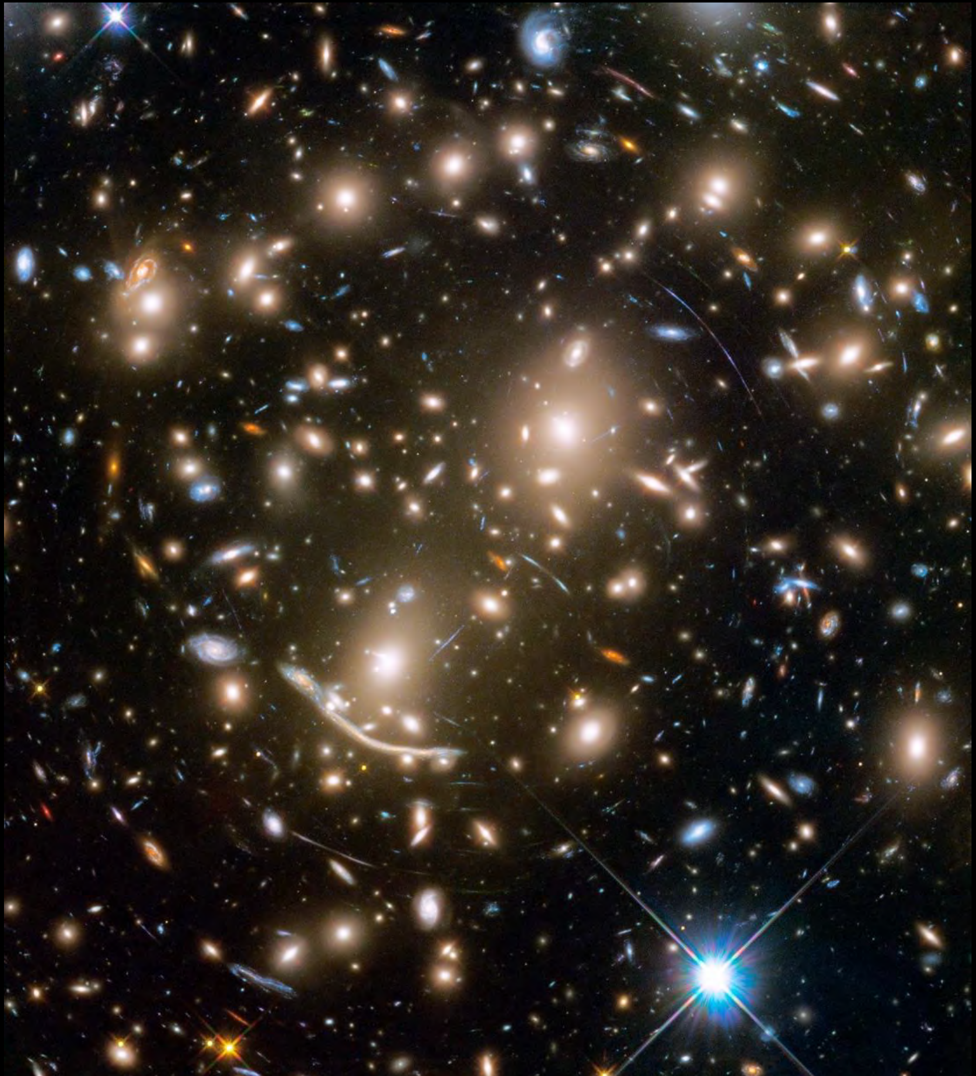
Dark matter revealed in the 1970’s by observing motion of stars and gas in spiral galaxies
(Vera Rubin, Vassar ‘48)


Coma Cluster
z=0.0231
V_r = 6925 km/s
d= 100 Mpc

Coma cluster (central part)



Dark matter also revealed by motions of galaxies in clusters
DM is 25 x visible stars, 9 x (stars + gas)



Supercluster of
galaxies
Abel 370.

Gravitational lens by dark matter reveals its presence – visible galaxies insuficient to cause lensing

DARK ENERGY:

- No known interaction with ordinary matter

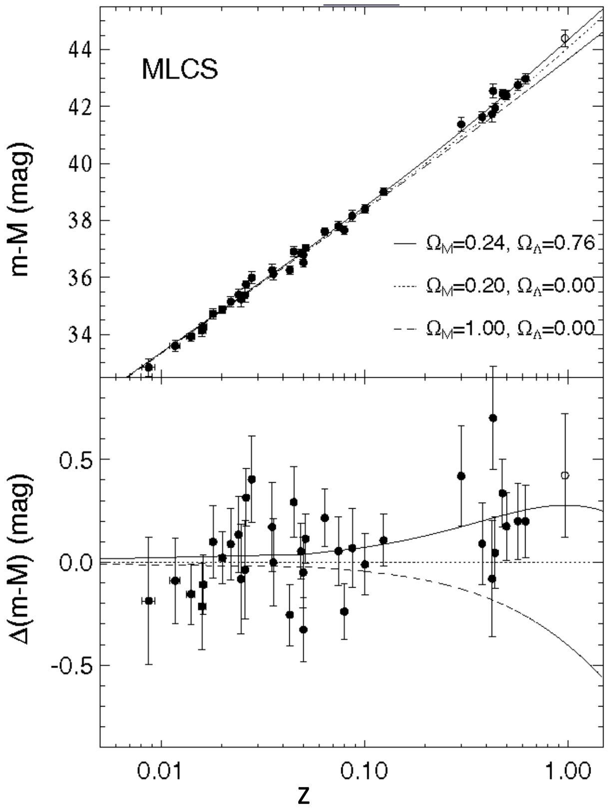
- Acts like a “negative pressure”

  Matter (energy, momentum, pressure) causes space to contract

  Negative pressure causes space to expand

- Consistent with a non-zero cosmological constant (a property of space, if space expands, dark energy increases)

Accelerating Expansion Rate



The supernova Ia distance modulus from multicolor light curve shapes

vs

redshift (velocity)

plot implies an accelerating expansion rate, galaxies at a given distance are moving too slowly

Or, SNe are too bright (too nearby) for a given redshift

Gravity in General Relativity – Einstein's Field Equations (16 Equations, usually reduces to 6)

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

Curvature of space-time

Stress-Energy content of space

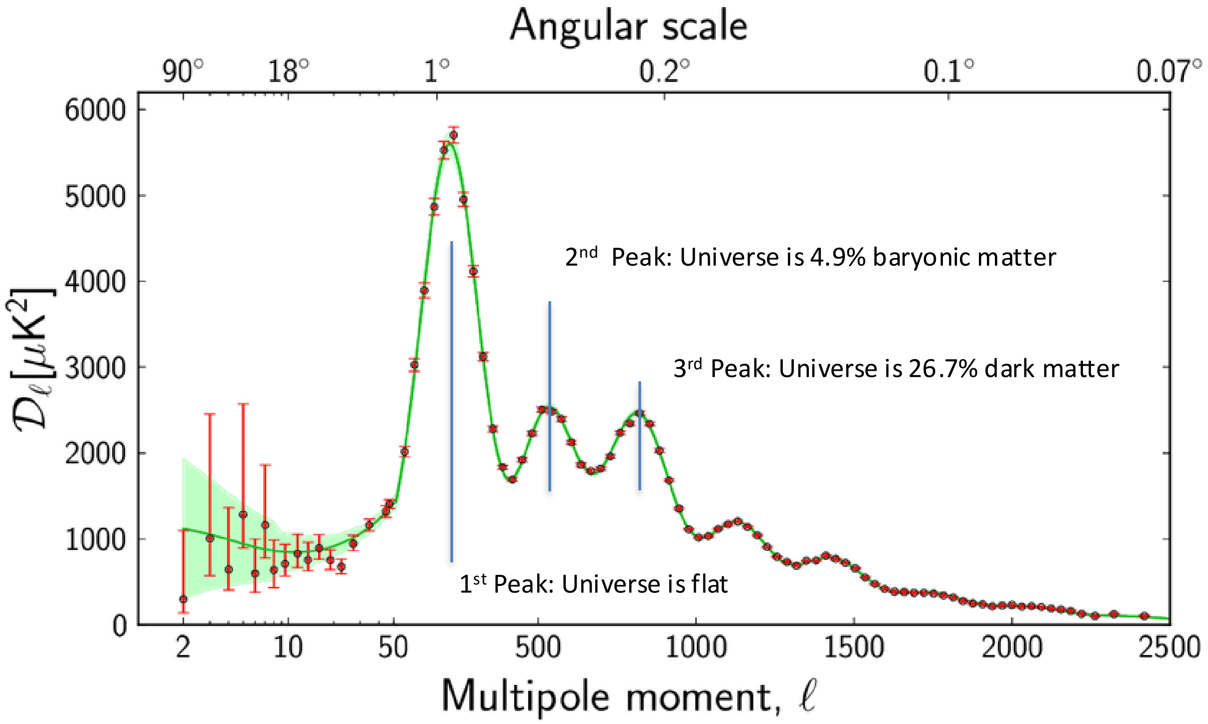
Cosmological Constant

This could be dark energy

Specifies the how material moves through space-time

This describes the contents of space (mass, pressure, energy and dark energy)

Angular scale of fluctuations in CMB confirms evidence for amounts of ordinary and dark matter, as well as enough dark energy to make the geometry of the universe flat



A rough history of the Universe

Beginning and End of the Universe

One can compute Universe's characteristics forward or backward

Newton (1642-1727)

In the absence of any other proof, the thumb alone would convince me of God's existence.

Laplace (1749-1827)

Je n'avais pas besoin de cette hypothèse-là.

Laplace says:

Give me:

Laws of Physics

+

Present conditions

I can give you:

Past and future of the big things in the Universe

Laplacian determinism: Given

- Initial conditions (H_0, Positions and motions of galaxies, etc.)
- Laws of physics (GR, QM, Astrophysics)

Can compute entire future history

Gravity + Dark Energy main determinants

(Quantum Mechanical uncertainty not an issue for late-time cosmology)

Limits:

Never know conditions perfectly

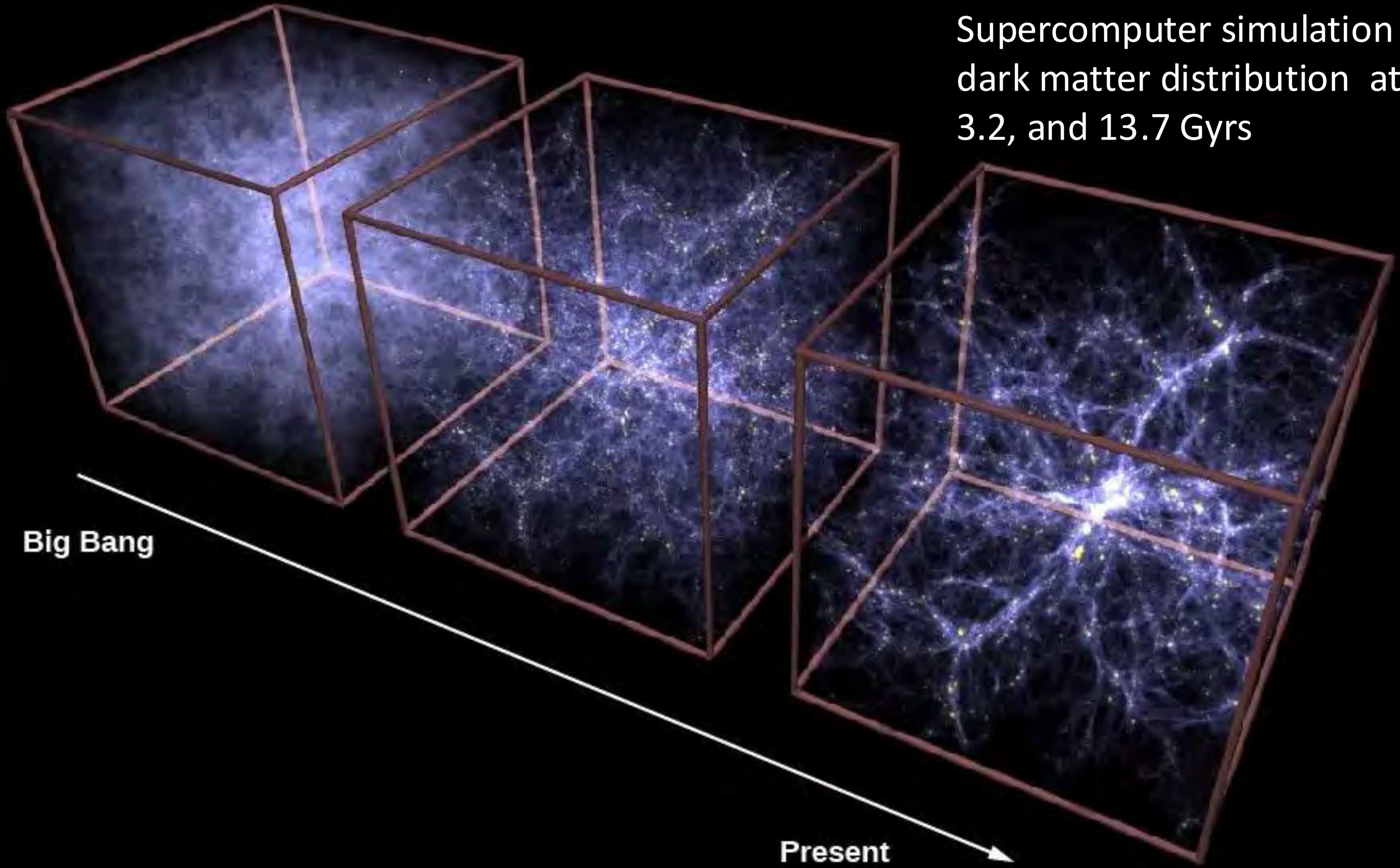
May not know applicable laws perfectly

What are the laws for dark energy? (Is it L ?)

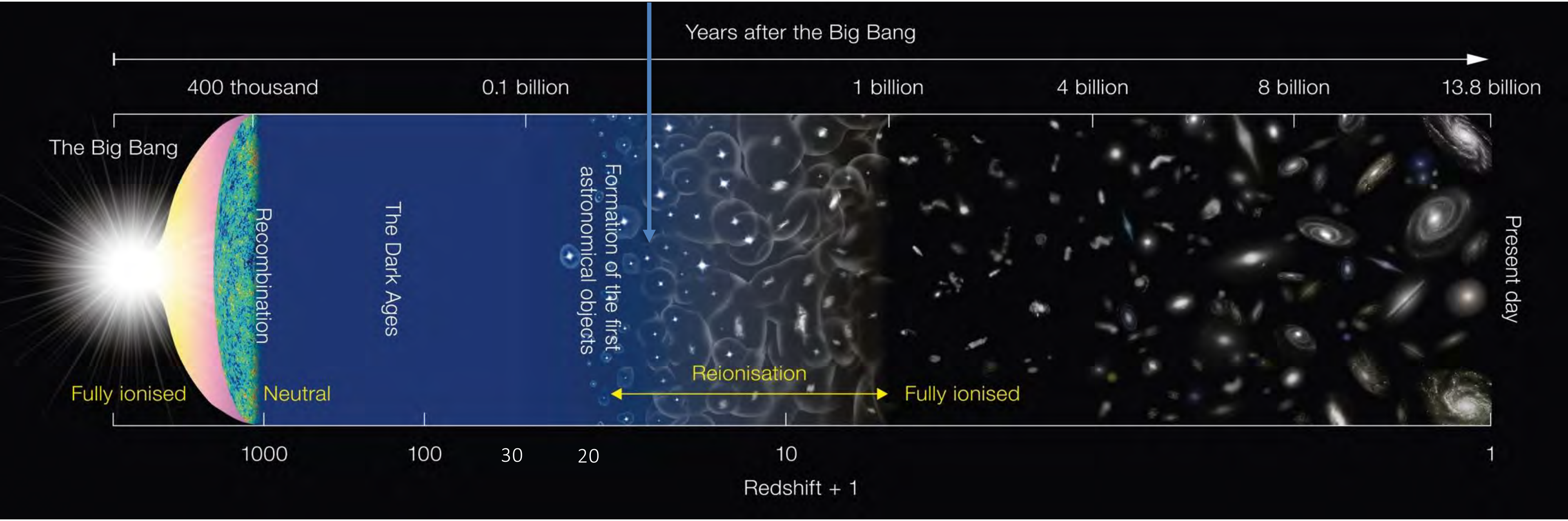
What are the laws of particle physics beyond the standard model?

How to reconcile GR and Quantum Mechanics?

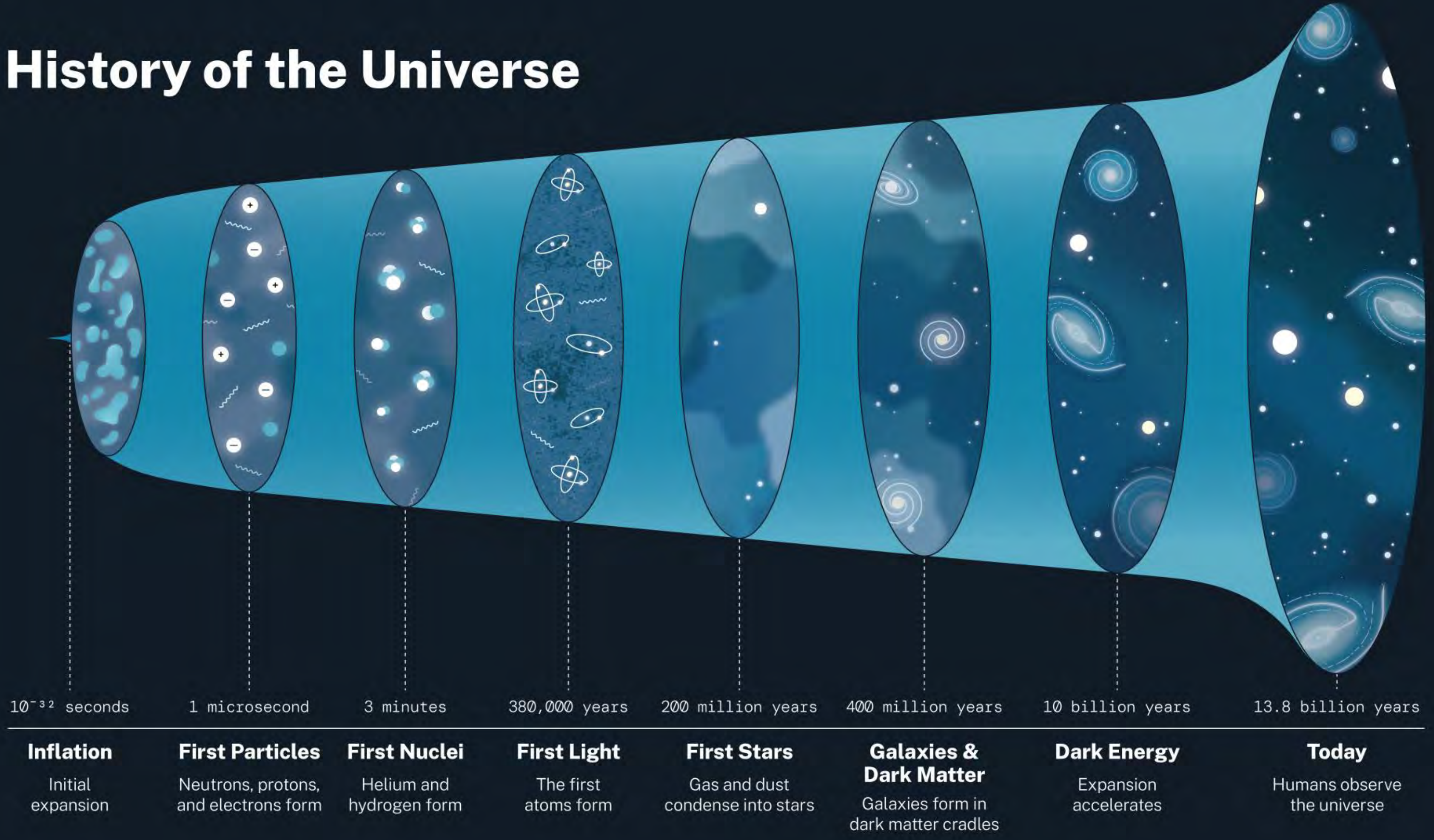
Supercomputer simulation of dark matter distribution at 0.9, 3.2, and 13.7 Gyrs

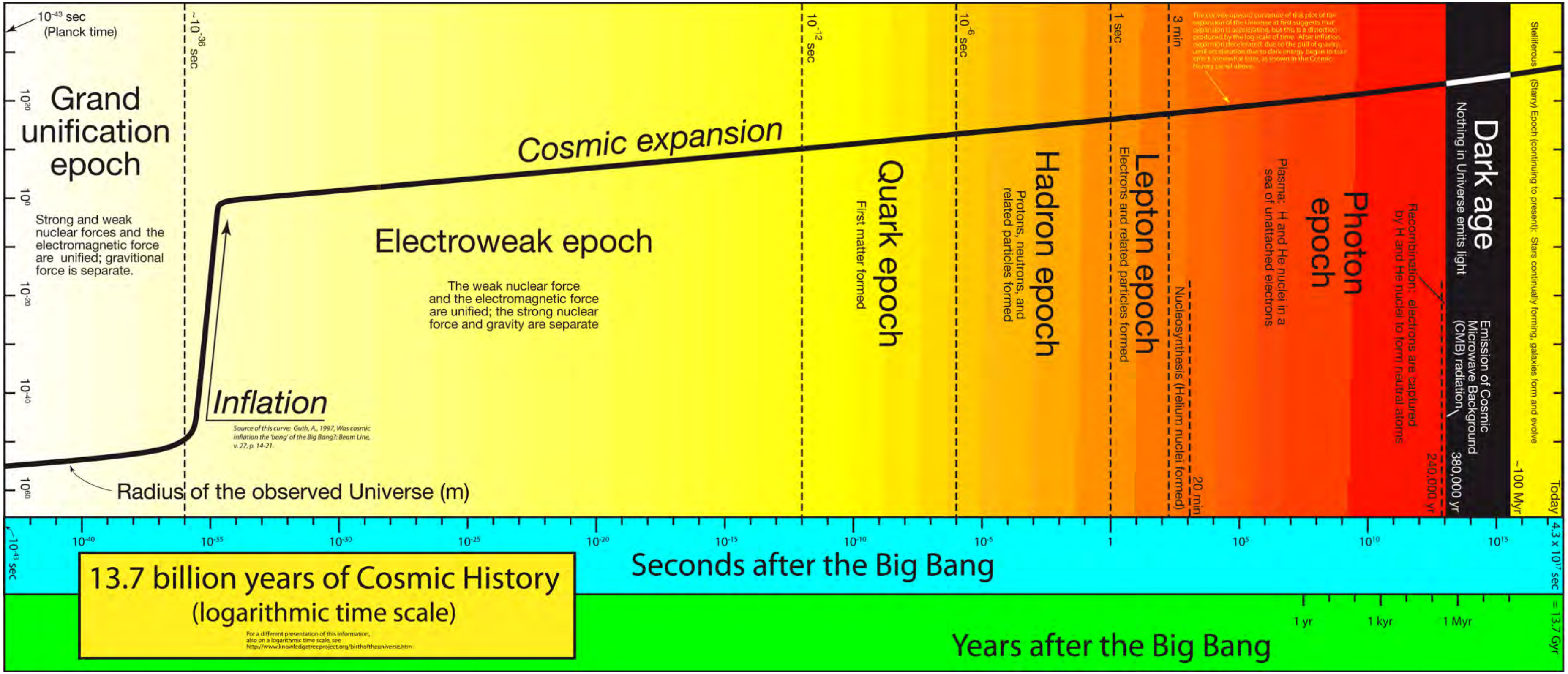


Jades-GS-z14-0



History of the Universe




13.7 billion years of Cosmic History
(logarithmic time scale)
For a different presentation of this information, also on a logarithmic time scale, see http://www.knowledgetreeproject.org/birthoftheuniverse.htm
10^{-43} sec (Planck time)
~10^{-36} sec
10^{-12} sec
10^{-6} sec
1 sec
3 min
20 min
240,000 yr
380,000 yr
~100 Myr
Today
Grand unification epoch
Strong and weak nuclear forces and the electromagnetic force are unified; gravitional force is separate.
Inflation
Source of this curve: Guth, A., 1997, Was cosmic inflation the 'bang' of the Big Bang?: Beam Line, v. 27, p. 14-21.
Electroweak epoch
The weak nuclear force and the electromagnetic force are unified; the strong nuclear force and gravity are separate
Cosmic expansion
Radius of the observed Universe (m)
10^{20}
10^{0}
10^{-20}
10^{-40}
10^{-60}
Quark epoch
First matter formed
Hadron epoch
Protons, neutrons, and related particles formed
Lepton epoch
Electrons and related particles formed
Nucleosynthesis (Helium nuclei formed)
Photon epoch
Plasma: H and He nuclei in a sea of unattached electrons
Recombination: electrons are captured by H and He nuclei to form neutral atoms
The convex-upward curvature of this plot of the expansion of the Universe at first suggests that expansion is accelerating, but this is a distortion produced by the log scale of time. After inflation, expansion decelerated, due to the pull of gravity, until acceleration due to dark energy began to take effect somewhat later, as shown in the Cosmic history panel above.
Dark age
Nothing in Universe emits light
Emission of Cosmic Microwave Background (CMB) radiation
Stelliferous (Starry) Epoch (continuing to present); Stars continually forming, galaxies form and evolve
10^{-43} sec
10^{-40}
10^{-35}
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
10^{5}
10^{10}
10^{15}
4.3×10^{17} sec
Seconds after the Big Bang
1 yr
1 kyr
1 Myr
= 13.7 Gyr
Years after the Big Bang

A rough history of the Universe:

NOW: 13.8 Gyr after BB

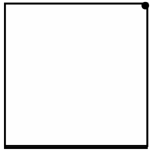
0.2 Hydrogen atoms, 0.02 He atom .003 “metal” atoms (mostly O, C, N) per cubic meter. Traces of ^{2}H, ^{3}He, ^{7}Li.

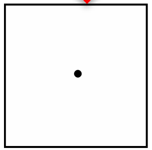
T = -270° C

9 Gyr after BB:

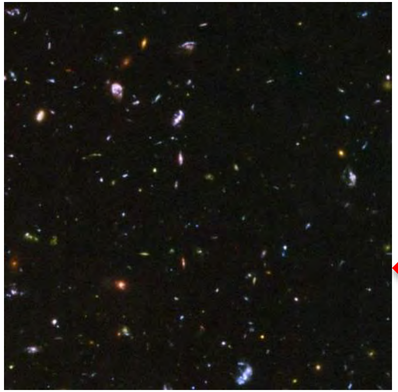
Solar system gone. Stars are younger, more gas clouds, galaxies closer. 1 H atom /cubic m, fewer metal atoms.

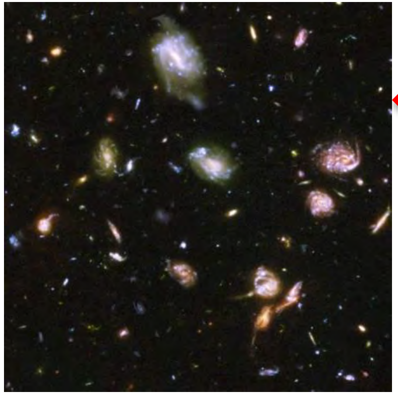
T = -269.4° C





Density of particles





Visual image of sky

A rough history of the Universe:

1.0 Gyr = 1,000,000,000 yr after BB

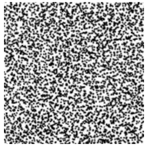
First galaxies and stars forming, 500 atoms/m^3,

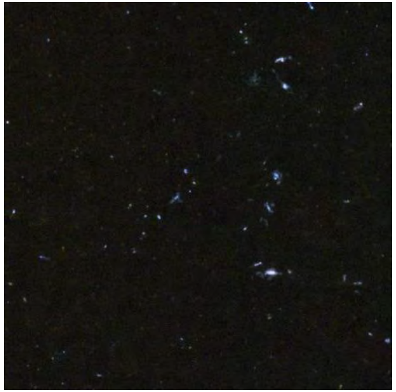
71 He atoms

No metals. Traces of He^3, Li, Be.

Gravity stronger

T = -263 C



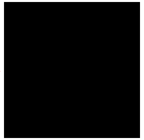


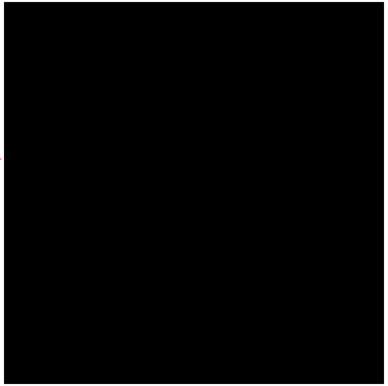
10 Myr after BB:

The dark ages: No stars.

2 million atoms / m^3

T = -170 C

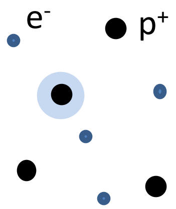




A rough history of the Universe:

400,000 yr after BB:
Atoms have lost all electrons,
Universe is opaque.
CMB photons will be released over the next several thousand years

T = 2700 C



A rough history of the Universe:

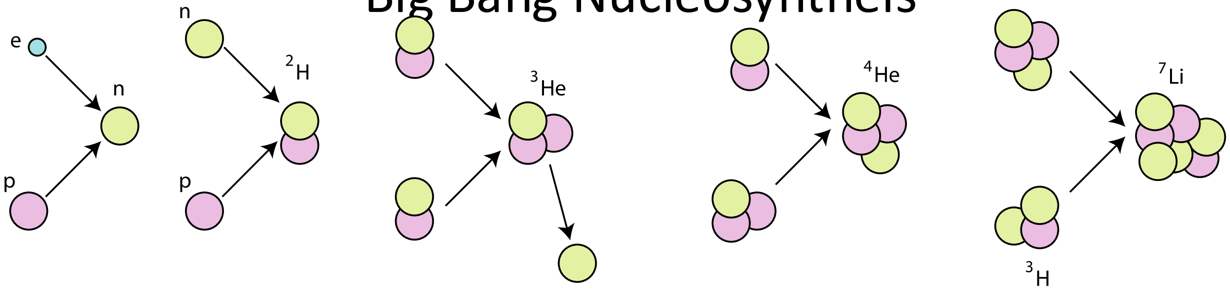
1 Minute after BB:

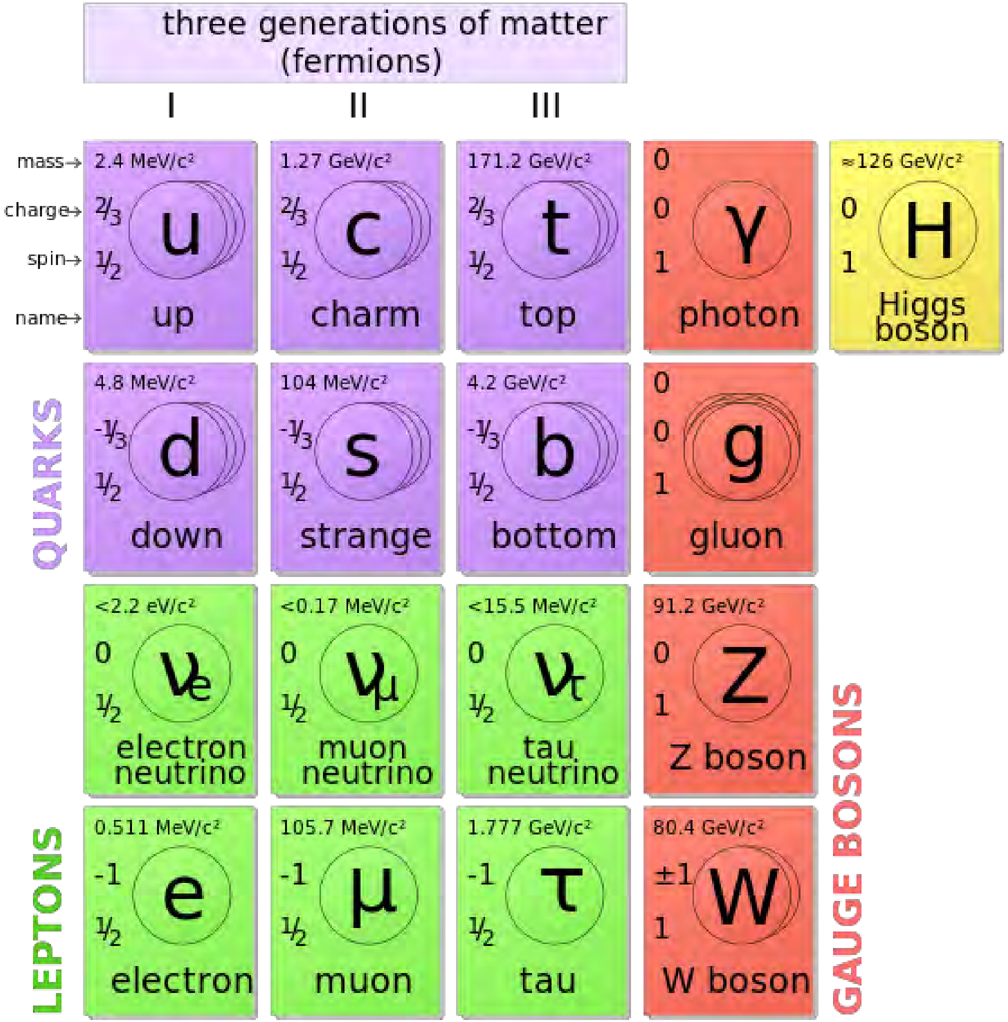
Going backwards in time–enough heat and density that atoms are smashed. All atomic material reduced to protons, neutrons, and electrons. T= 10^{10} K

T = 10,000,000,000 K, density like interior of Earth

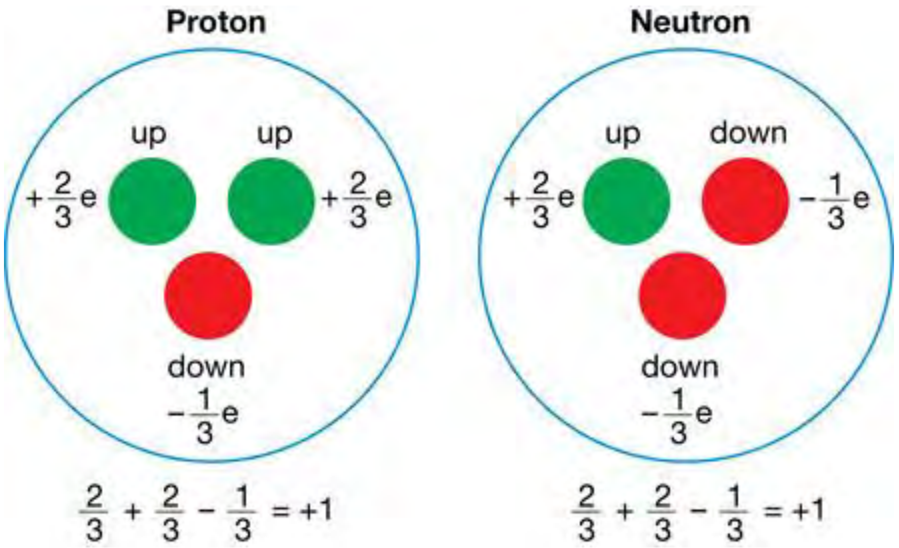
Going forwards in time at 1 minute: creation of Deuterium, ^{3}He, ^{4}He, ^{7}Li.

Big Bang Nucleosyntheis





three generations of matter (fermions)
I
II
III
mass→
charge→
spin→
name→
2.4 MeV/c²
2/3
1/2
u
up
1.27 GeV/c²
2/3
1/2
c
charm
171.2 GeV/c²
2/3
1/2
t
top
0
0
1
γ
photon
≈126 GeV/c²
0
1
H
Higgs boson
4.8 MeV/c²
-1/3
1/2
d
down
104 MeV/c²
-1/3
1/2
s
strange
4.2 GeV/c²
-1/3
1/2
b
bottom
0
0
1
g
gluon
QUARKS
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
91.2 GeV/c²
0
1
Z
Z boson
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
80.4 GeV/c²
±1
1
W
W boson
LEPTONS
GAUGE BOSONS


Proton
up
up
$+\frac{2}{3}e$
$+\frac{2}{3}e$
down
$-\frac{1}{3}e$
$\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$
Neutron
up
down
$+\frac{2}{3}e$
$-\frac{1}{3}e$
down
$-\frac{1}{3}e$
$\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$

Scientific American, May 2015, Pgs. 46-47.

Illustration by Moonrunner Design

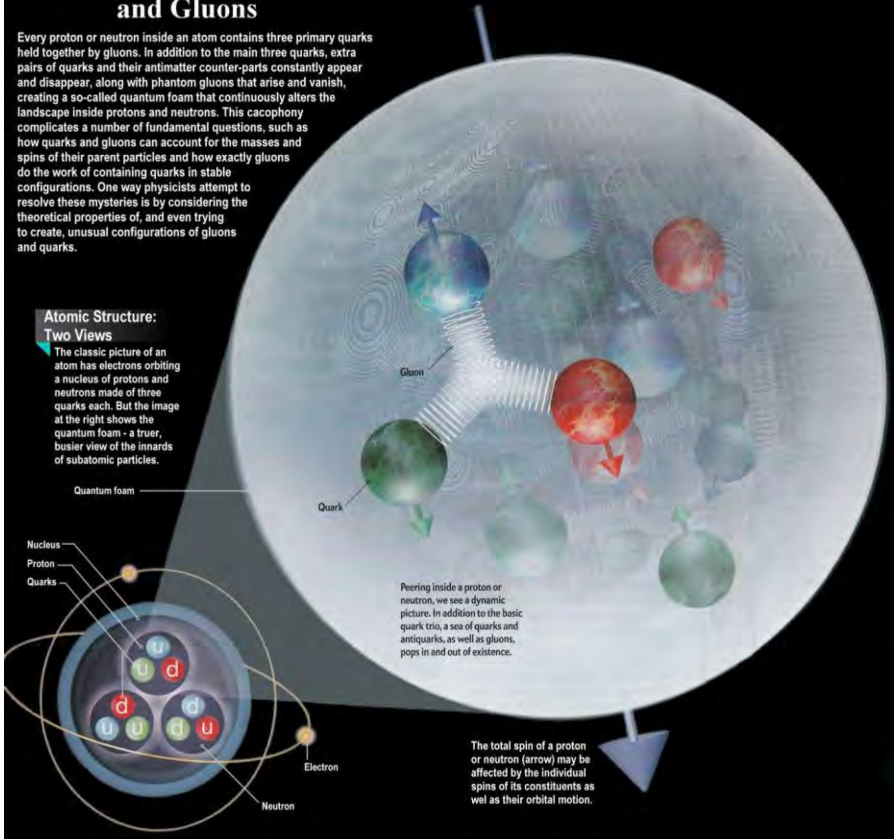
NUCLEAR PHYSICS

The Quandaries of Quarks and Gluons

Every proton or neutron inside an atom contains three primary quarks held together by gluons. In addition to the main three quarks, extra pairs of quarks and their antimatter counter-parts constantly appear and disappear, along with phantom gluons that arise and vanish, creating a so-called quantum foam that continuously alters the landscape inside protons and neutrons. This cacophony complicates a number of fundamental questions, such as how quarks and gluons can account for the masses and spins of their parent particles and how exactly gluons do the work of containing quarks in stable configurations. One way physicists attempt to resolve these mysteries is by considering the theoretical properties of, and even trying to create, unusual configurations of gluons and quarks.

Atomic Structure: Two Views

The classic picture of an atom has electrons orbiting a nucleus of protons and neutrons made of three quarks each. But the image at the right shows the quantum foam - a truer, busier view of the innards of subatomic particles.



Peering inside a proton or neutron, we see a dynamic picture. In addition to the basic quark trio, a sea of quarks and antiquarks, as well as gluons, pops in and out of existence.

The total spin of a proton or neutron (arrow) may be affected by the individual spins of its constituents as wel as their orbital motion.

Exotic States of Matter

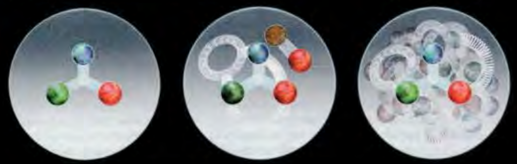
Physicists have theorised and, in a few cases, created unusual combinations of quarks and gluons beyond the familiar protons and neutrons. These exotic states offer new possibilities for studying the interactions that can occur between quarks and gluons – potentially helping to resolve some basic mysteries of matter.

Glueballs and Their Kin

Theoretical simulations suggest that quarks and gluons can combine to create other particles beyond protons and neutrons. For example, "glueball" particles (*a*) made exclusively of gluons may exist, as well as "hybrid" particles made of quark-antiquark-gluon bound states (*b*), or "tetra quark" states where two antiquarks are bound to two quarks (*c*). There is now increasing evidence that tetra quarks have been found, although glueballs and hybrids remain to be discovered.

Saturated State

When protons and neutrons are accelerated to extreme speeds, the gluons inside them multiply. At high speeds the proton's energy increases and gluons split into daughter pairs, each with slightly less energy than the original. The new gluons, in turn, create more daughter gluons with even less energy. Eventually the proton reaches a "maximum occupancy" limit where no more gluons can fit inside—a theorized state called a color glass condensate. Strong hints of such a state have appeared in particle accelerators, but no firm proof exists so far.



Mimic of the Infant Universe

When the cosmos was young, it was too hot for atoms or even stable protons and neutrons to form. Quarks and gluons buzzed around freely in a roiling swarm. Accelerators on Earth recently succeeded in replicating this state, called a quark-gluon plasma (*artist's conception, below left*), by smashing atomic nuclei together at near light speed. By studying the plasma as it cools, physicists can learn not just about the behavior of quarks and gluons but also about the early evolution of our universe.

A rough history of the Universe:

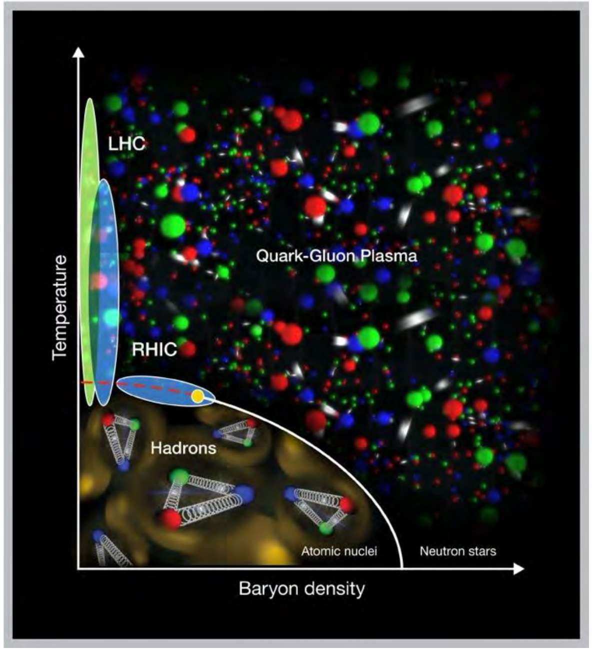
10^{-6} -10^{-11} Seconds after BB:

Expect quarks and gluons can no longer be confined to nucleons.

T = 10^{13}-10^{16} K, density greater than nucleon density

Quark-Gluon Plasma:

Only quarks, gluons, leptons (electrons) and Higgs bosons.



A rough history of the Universe:

10^{-12} -10^{-33} Seconds after BB:

Expect electromagnetic and weak nuclear forces are undifferentiated (gravitational and strong nuclear forces still separate) LHC observable.

Fermions are massless.

Electro-weak Era

$T = 10^{16}$-10^{26} K

>10^{-33} Seconds after BB:

Strong and electro-weak forces become undifferentiated. A (not yet developed) Grand Unification Theory (GUT), describes interactions. Gravity still separate. The

GUT Era

The phase transition between GUT and electro-weak may trigger cosmic

INFLATION

A rough history of the Universe:

10^{-33}-10^{-36} Seconds after BB:

INFLATION

Universe expands exponentially by a factor of at least 10^{26}
In 10^{-33} seconds. Different locations in the universe must separate very much faster than the speed of light.

(Not a violation of special relativity, since no object is moving *through* space with $v > c$.
Space is permitted to expand at whatever rate postulated)

Why inflation?

1. Inflation explains why the universe is flat (any curvature due to gravity has been diluted)

2. Inflation explains why the universe is homogeneous.

3. Inflation consistent with structure in the CMB

A rough history of the Universe:

10^{-43} Seconds after BB:

Planck Era

Quantum Theory of Gravity would be needed to understand the physics here. Don't have this theory.

Even given such a theory, expectation is that quantum uncertainty makes measurement of times shorter than 10^{-43} sec impossible.

Cannot go earlier than this. Probably very hot $T>10^{32}$ and dense, although those notions may be meaningless at this scale (eg. Temperature measures motion (distance/time) of particles or energy of waves, but if time has no meaningful measure, temperature has no meaning)

A rough history of the Universe: Before the Big Bang

Does the BB need a cause?

If so, what caused the Big Bang (Created the Universe)?
Or, why is ther something, rather than nothing? (Many have asked this question)

If there was a cause, what came before the Big Bang?

Our best physics (Special Relativity) describes how space and time must be treated as a single entity. Cosmology is the study of space-time and all it contains. If we think of the Universe as existing only after the Big Bang, is it even possible, then, to think of a time before space-time was created?

Any measurement of time in our Universe involves things that move through space (light waves emitted by atoms, an electric current, a vibrating crystal, a swinging pendulum) . Can we speak about a time before time can be measured?

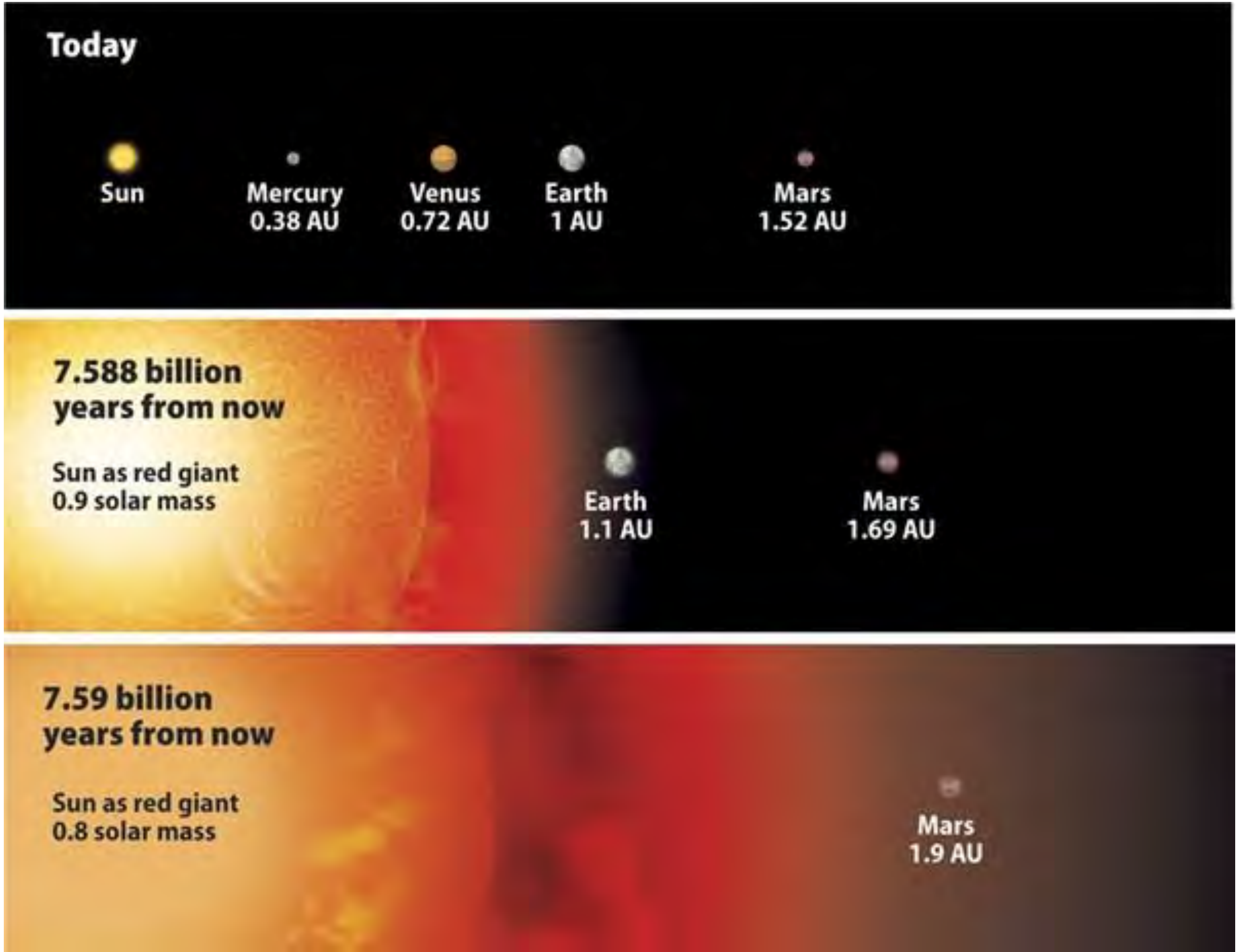
Computing the Future

4-8 Gyrs from present

2 events for us:

1. Sun becomes a red giant: swallows Mercury and Venus,
   scorches Earth. Sun then becomes a white dwarf.

2. Andromeda and Milky Way Collide (4-5 Gyr from present
   Instigate a “starburst” in both galaxies
   Tidal disruption may fling sun out of Galaxy
   Disrupted gas feeds into central black holes – temporary AGN
   Eventual merger to one galaxy. “Milkomeda”?
   “Andromilky Way” ?


Today
Sun
Mercury
0.38 AU
Venus
0.72 AU
Earth
1 AU
Mars
1.52 AU
7.588 billion
years from now
Sun as red giant
0.9 solar mass
Earth
1.1 AU
Mars
1.69 AU
7.59 billion
years from now
Sun as red giant
0.8 solar mass
Mars
1.9 AU

First pass of Andromeda

Collision causes star loss
and star formation bursts
NGC 4038 + 4039
The Antenae

100 Gyr (10^{11} yrs) from present

Most bright stars have become white dwarves or black dwarves

Our Galaxy becomes featureless, only low temperature stars

Dark energy has moved all galaxies except the local group
beyond 10^{11} light years - no longer have visual access.

10^{12} yrs from present

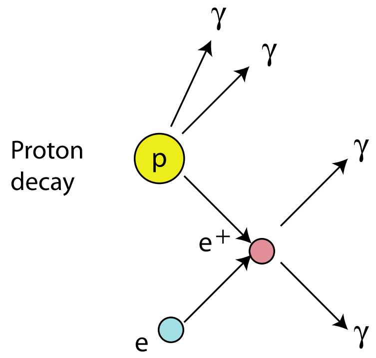
Only red dwarf stars survive

Life of any sort requires energy: Life is huddled around the remaining red dwarf stars.

10^{14} yrs no stars at all. Dark Universe. Only black dwarf stars, Black holes.

10^{32} yrs from present

Possible **proton decay**? No more matter!



The Universe contains only photons and black holes.
If protons do not decay, Universe also contains very cold star husks, which fall, eventually, into black holes.

10^{100} yrs from present (or thereabouts)

Last black holes “evaporate” via Hawking radiation

Universe contains only photons at homogeneous
and ever decreasing temperature. No useful energy.

Heat Death of the Universe