ASTRONOMY
STATE OF THE ART

5. Galaxies

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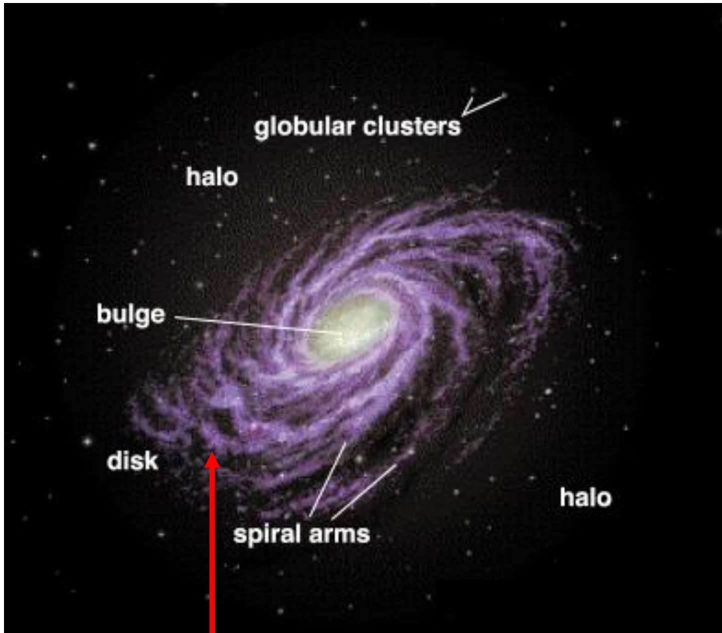
University of Arizona

Milky Way

Regions of the Milky Way



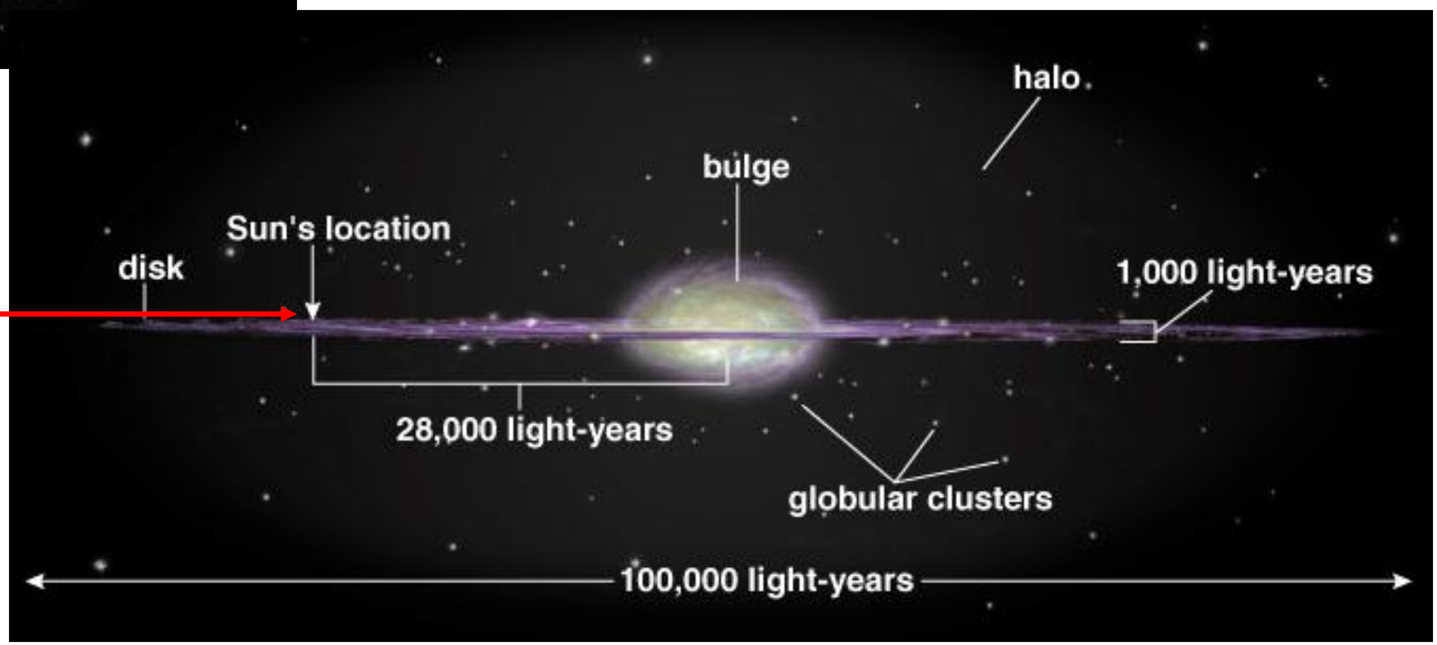
diameter of disk = 100,000 l.y. (30,000 pc)

radius of disk = 50,000 l.y. (15,000 pc)

thickness of disk = 1,000 l.y. (300 pc)

number of stars = 400 billion

Sun is in disk,
28,000 l.y. out
from center



Regions of the Milky Way

- Disk   Population I
  - younger generation of stars
  - contains gas and dust
  - location of the open clusters
- Bulge   Populations I & II
  - mixture of both young and old stars
- Halo   Population II
  - older generation of stars
  - contains no gas or dust
  - location of the globular clusters

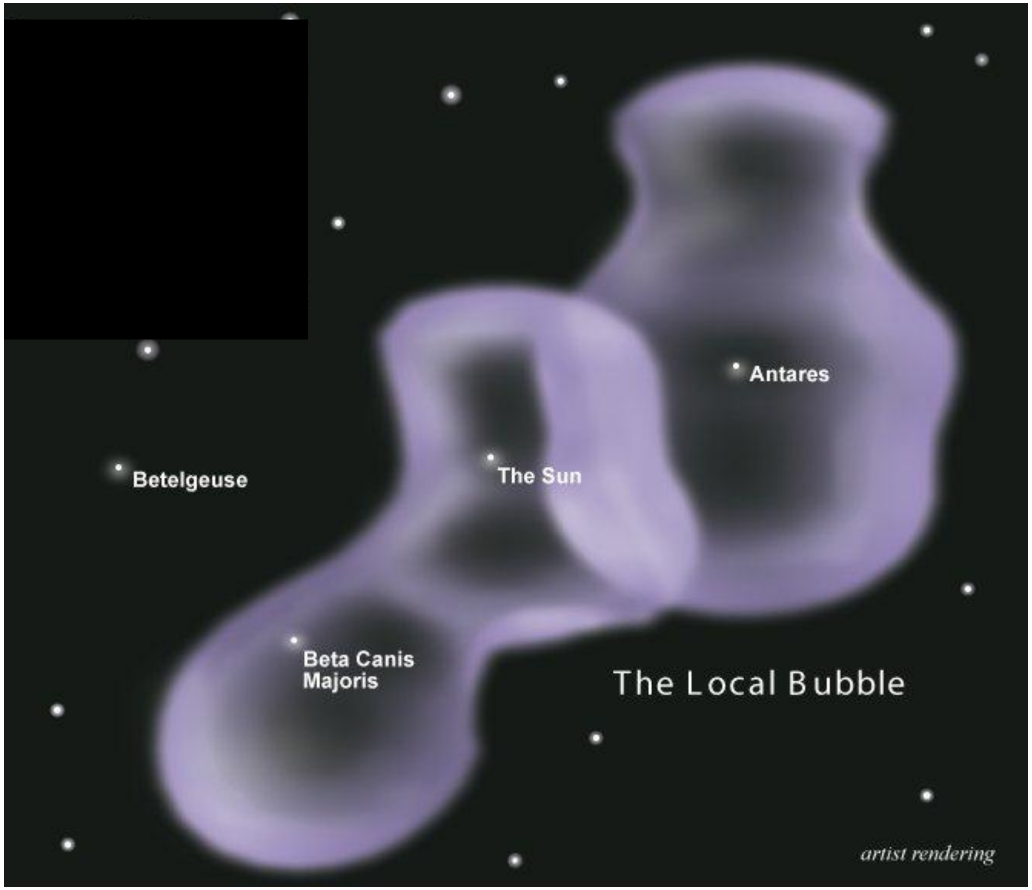
The Interstellar Medium

– The ISM is the "stuff" between all the stars

– It's mostly a vacuum (about 1 atom cm^{-3})

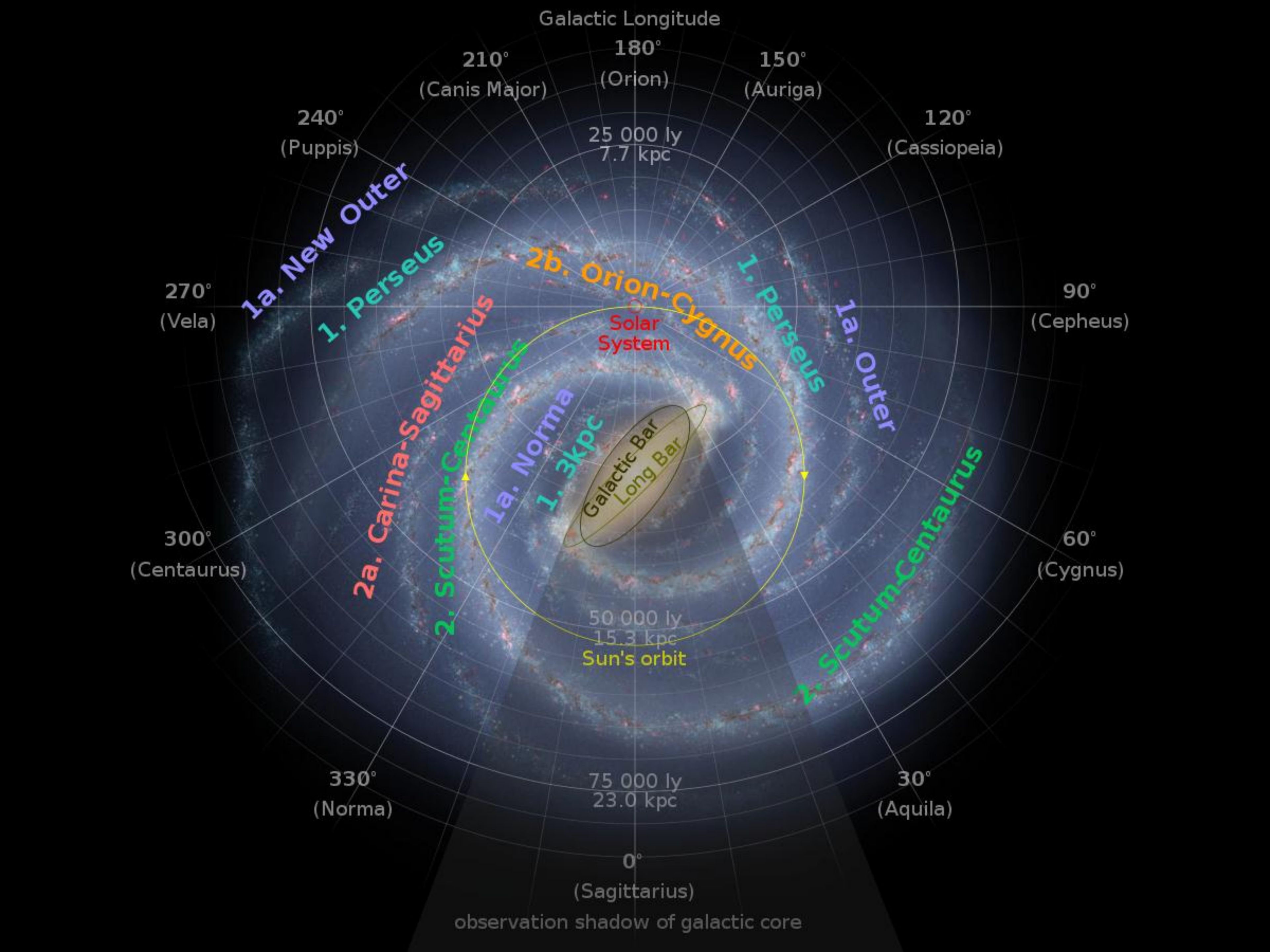
– It's composed of 90% gas and 10% dust

We occupy a local "bubble," where overlapping SN have created a region 1000 x less dense and 100 x hotter than normal material in the ISM



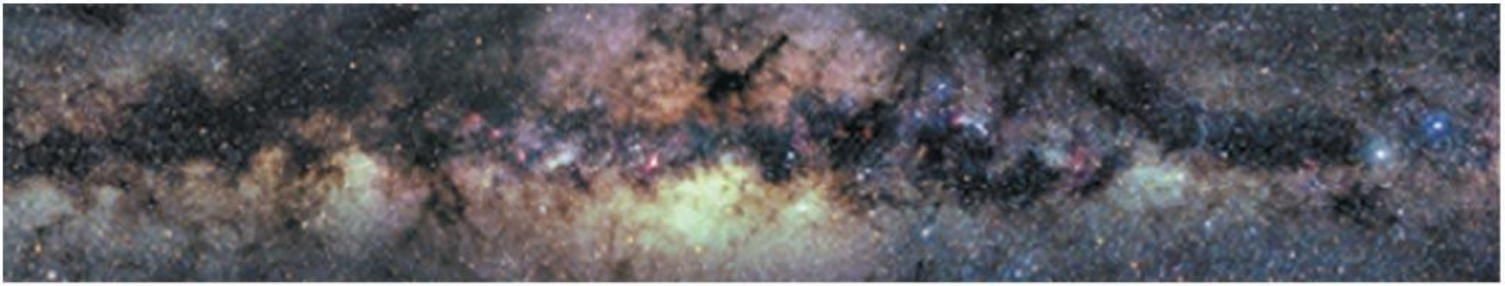
Gas: individual atoms and molecules

Dust: large grains made of heavier elements



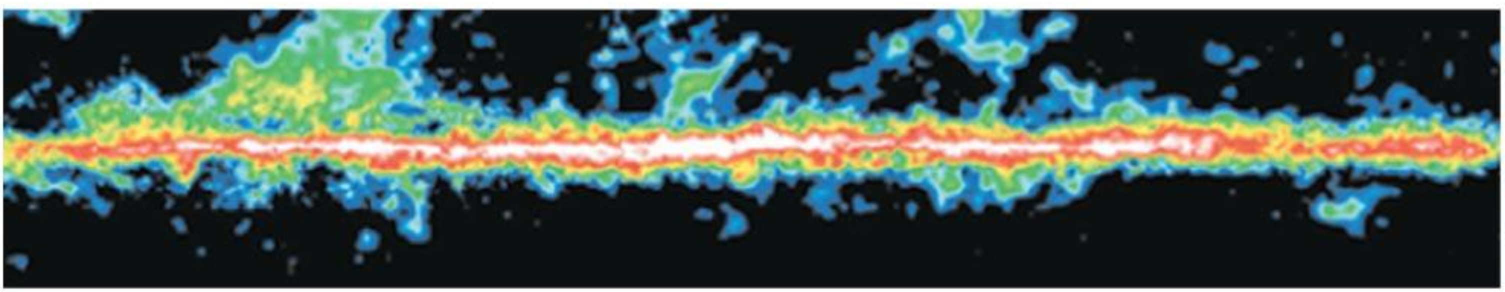
Galactic Longitude
180°
(Orion)
210°
(Canis Major)
150°
(Auriga)
240°
(Puppis)
120°
(Cassiopeia)
25 000 ly
7.7 kpc
270°
(Vela)
90°
(Cepheus)
1a. New Outer
1. Perseus
2b. Orion-Cygnus
1. Perseus
1a. Outer
Solar
System
2a. Carina-Sagittarius
2. Scutum-Centaurus
1a. Norma
1. 3kpc
Galactic Bar
Long Bar
300°
(Centaurus)
60°
(Cygnus)
2. Scutum-Centaurus
50 000 ly
15.3 kpc
Sun's orbit
330°
(Norma)
30°
(Aquila)
75 000 ly
23.0 kpc
0°
(Sagittarius)
observation shadow of galactic core

Multiwavelength



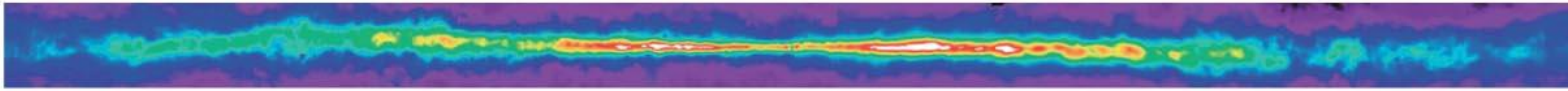
Visible light
from stars

Infrared light
from stars

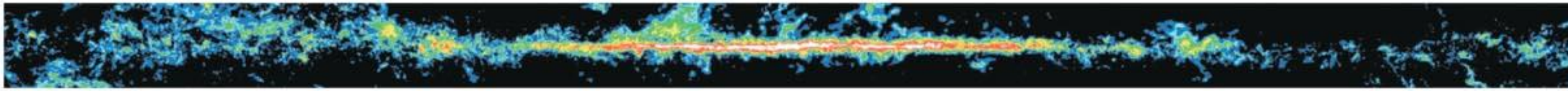


Radio emission
from molecules

X-ray emission
from hot gas



a 21-cm radio emission from atomic hydrogen gas.



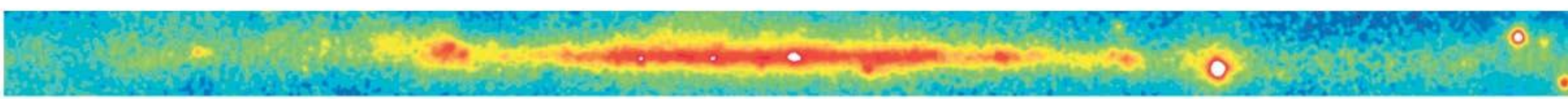
b Radio emission from carbon monoxide reveals molecular clouds.

c Infrared emission from interstellar dust (wavelength 60 to 100 μm).

d Infrared emission from stars that penetrates most interstellar material (wavelength 1 to 4 μm).

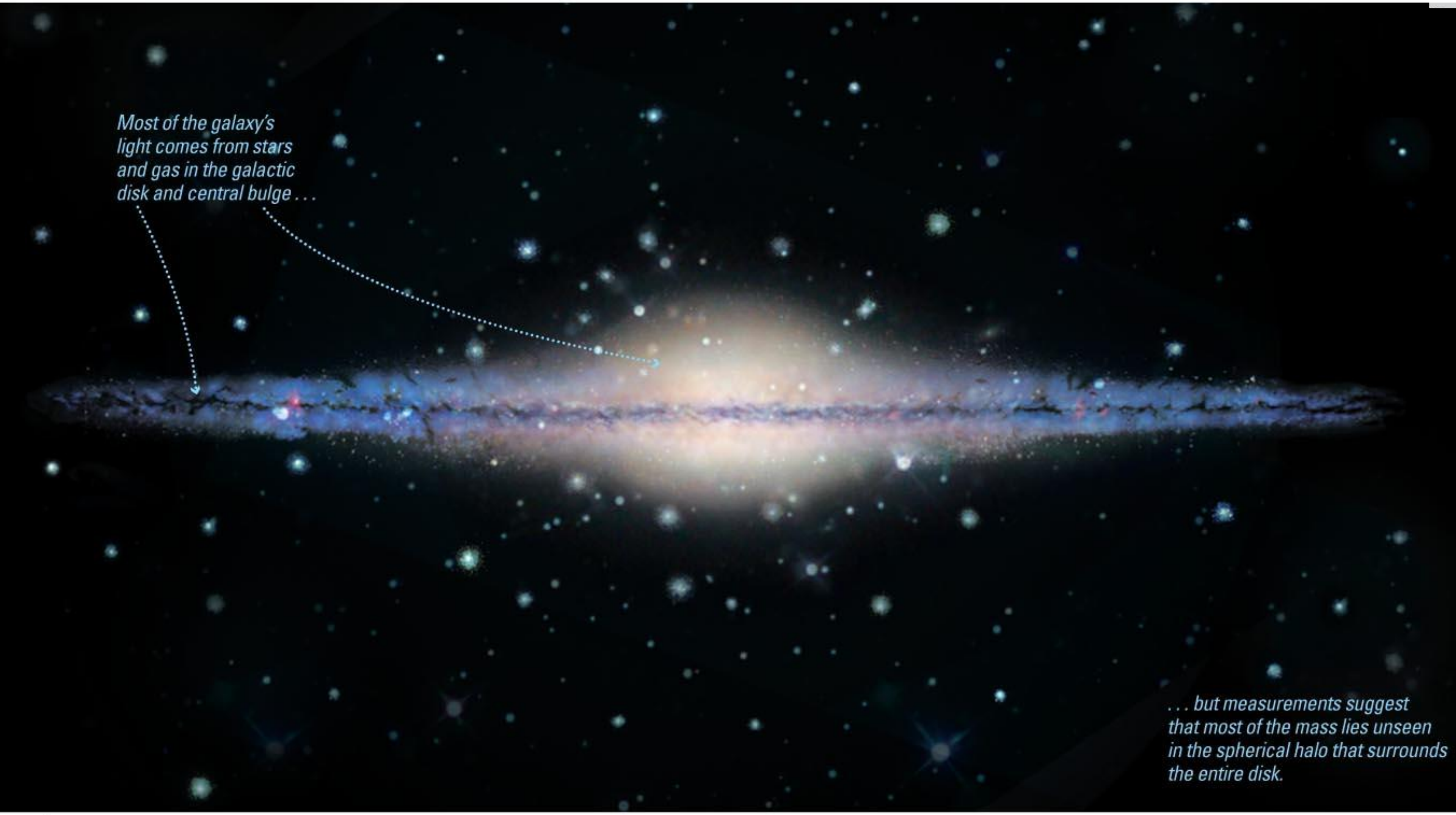
e Visible light emitted by stars is scattered and absorbed by dust.

f X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).

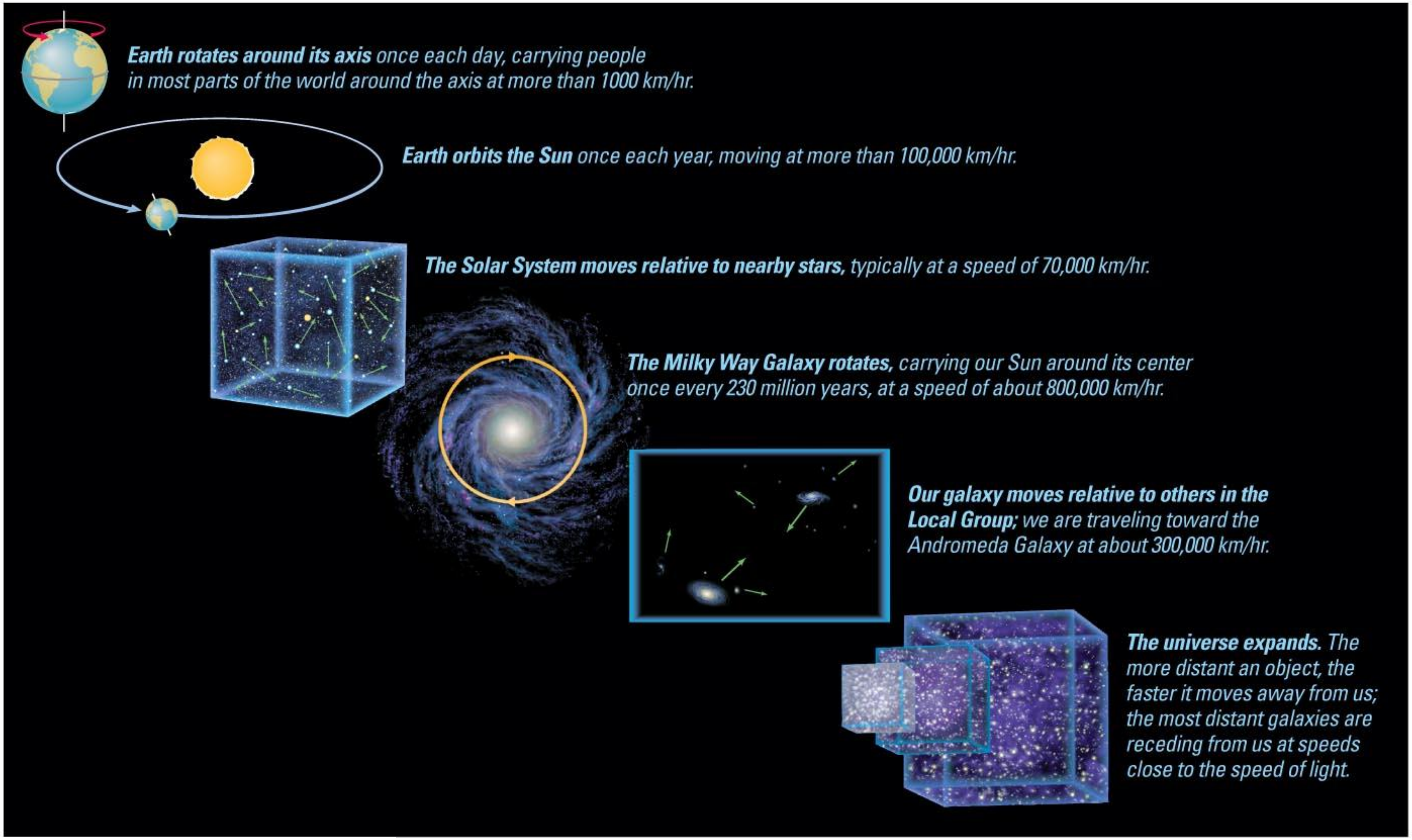


g Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

Mass Motions

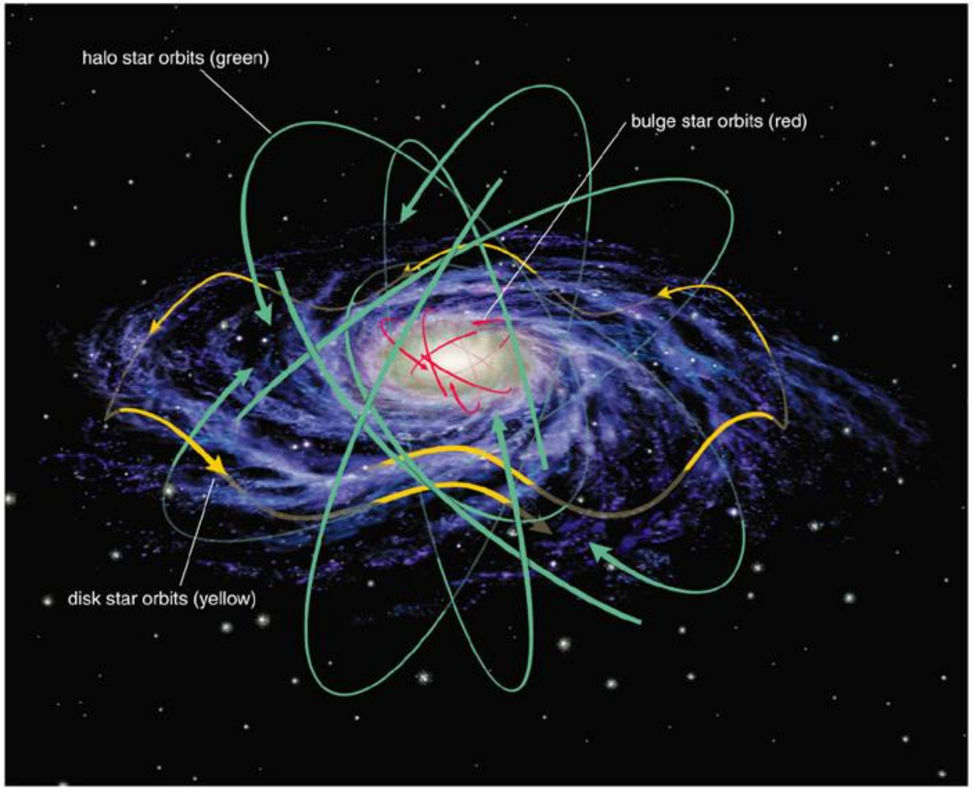


Cosmic Motions

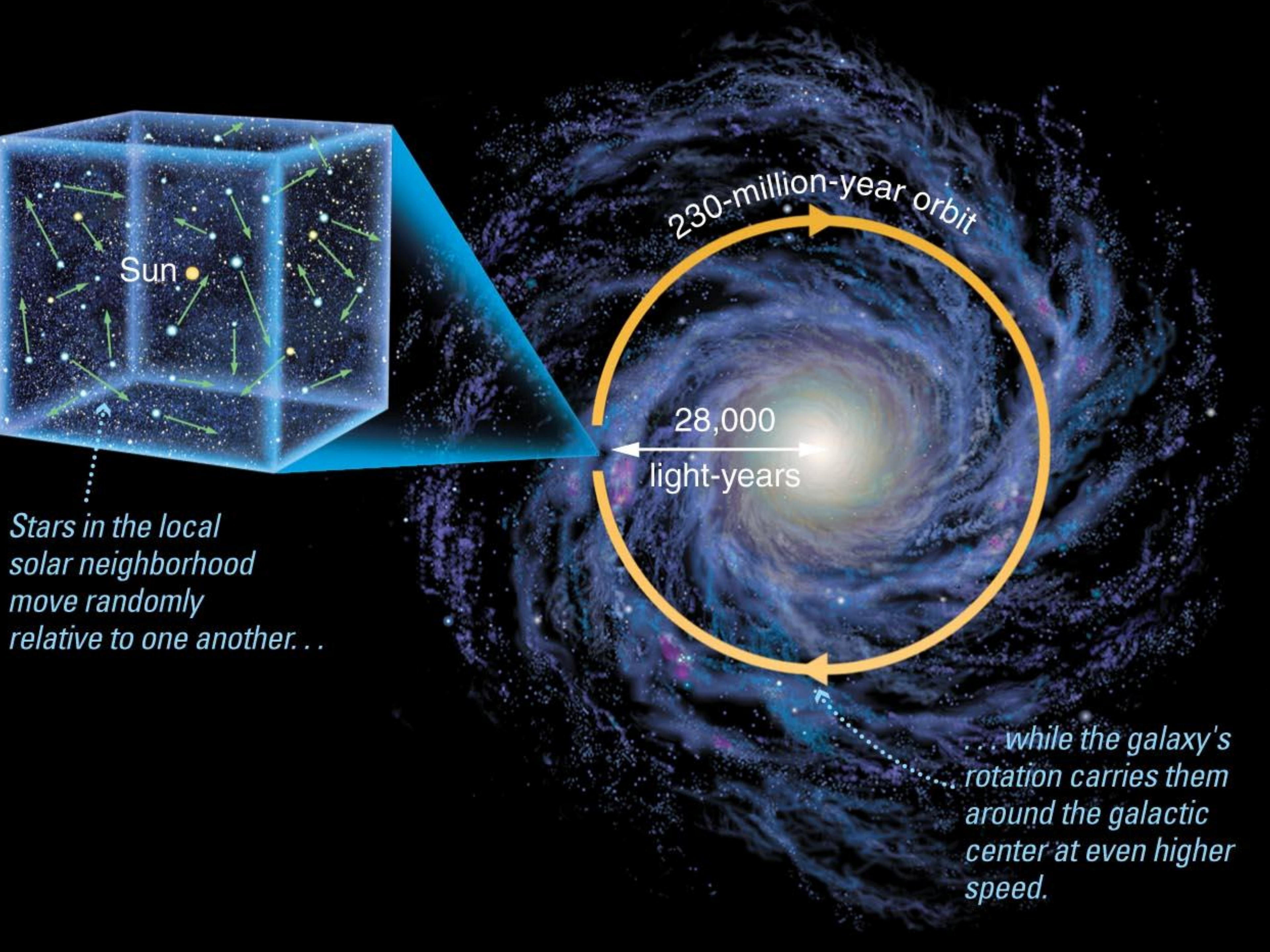


There are a series of motions on successively larger scales, culminating in a cosmic reference frame (defining all space)

Stellar Orbits in the Galaxy



- Stars in the **disk** all orbit the Galactic center:
  - in the same direction
  - in the same plane (like planets do)
  - they "bobble" up and down
    - this is due to gravitational pull from the disk
    - this gives the disk its thickness
- Stars in the **bulge** and **halo** all orbit the Galactic center:
  - in different directions
  - at various inclinations to the disk
  - they have higher velocities
    - they are not slowed by disk as they plunge through it
    - nearby example: *Barnard's Star*


Sun
230-million-year orbit
28,000
light-years
Stars in the local solar neighborhood move randomly relative to one another. . .
. . . while the galaxy's rotation carries them around the galactic center at even higher speed.

STAR WARS INSIDER

PRESENTS

THE GALAXY

This starchart shows all the major regions of the galaxy, the principal trade routes, and important planets. It contains key data for all of the planets from *Star Wars* Galaxies: An Empire Divided, the new massively multiplayer online roleplaying game from LucasArts.

THE GALAXY IS FILLED WITH 400 BILLION STARS, around which circle over a million habitable planets that are home to over 20 million intelligent species. The distance from one side of the galaxy to the other spans approximately 100,000 light years, but a hyperdrive-equipped starship can shrink the whole journey to a matter of a few weeks or months, depending on the class of hyperdrive fitted.

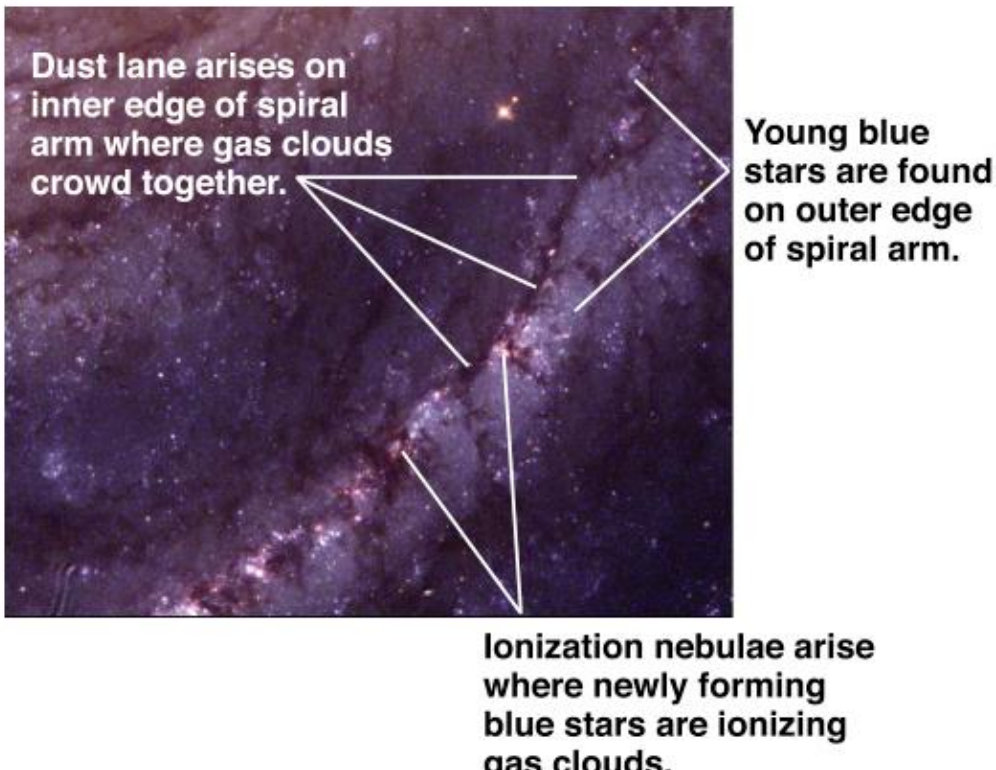
Over many millennia, hyperdrive technology has been the main force drawing the galaxy together. A hyperdrive allows a ship to cross a sector or a region in a few hours or days, and shrinks the journey between one region and another to a matter of days or weeks. Although it is possible to make a hyperspace jump in virtually any direction, most ships tend to travel along established, safe hyperspace routes because of the danger of contact with an uncharted body in hyperspace and the complexity of making new jump calculations.

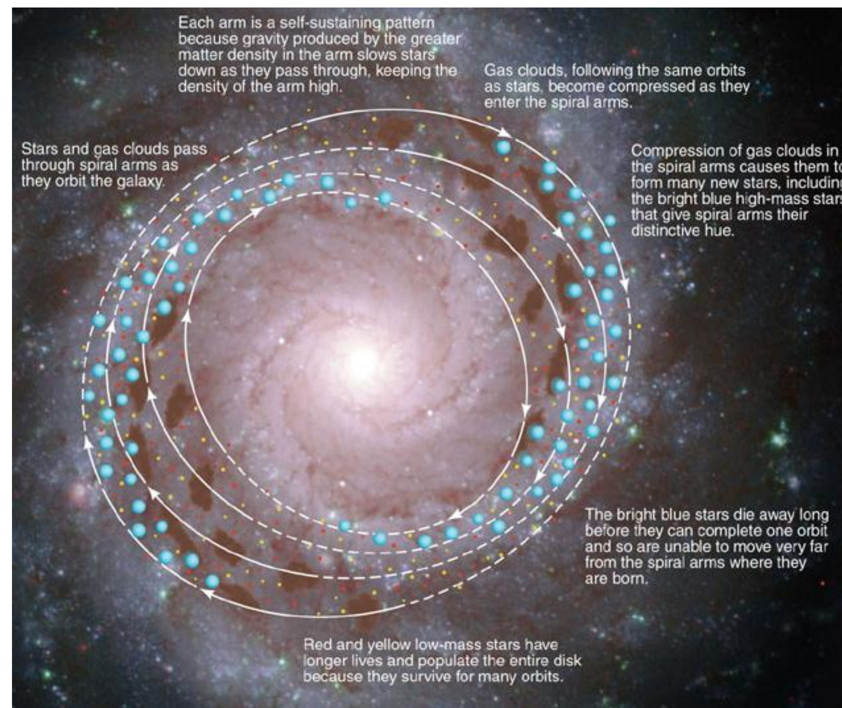
Sublight drives are normally used for local journeys. Starships can move at sublight speeds of several thousand kilometres per second in open space, allowing them to travel from one planet to another in the same star system in a few hours.

PLANET HIGHLIGHTS

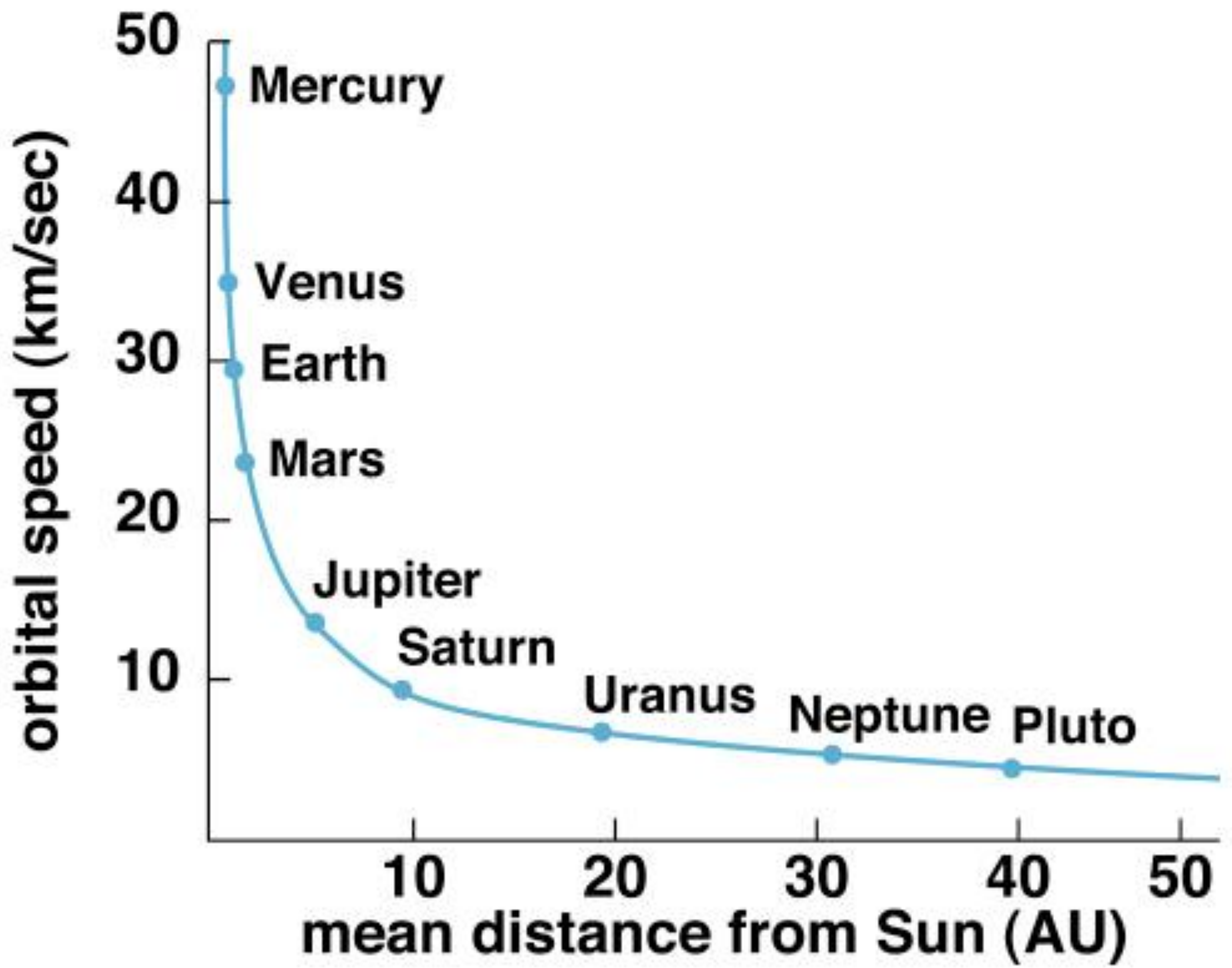
Spiral Arms

- The compression caused by density waves triggers star formation.
  - molecular clouds are concentrated in arms…plenty of source matter for stars
  - short-lived O & B stars delineate the arms and make them blue & bright
  - long-lived low-mass stars pass through several spiral arms in their orbits around the disk

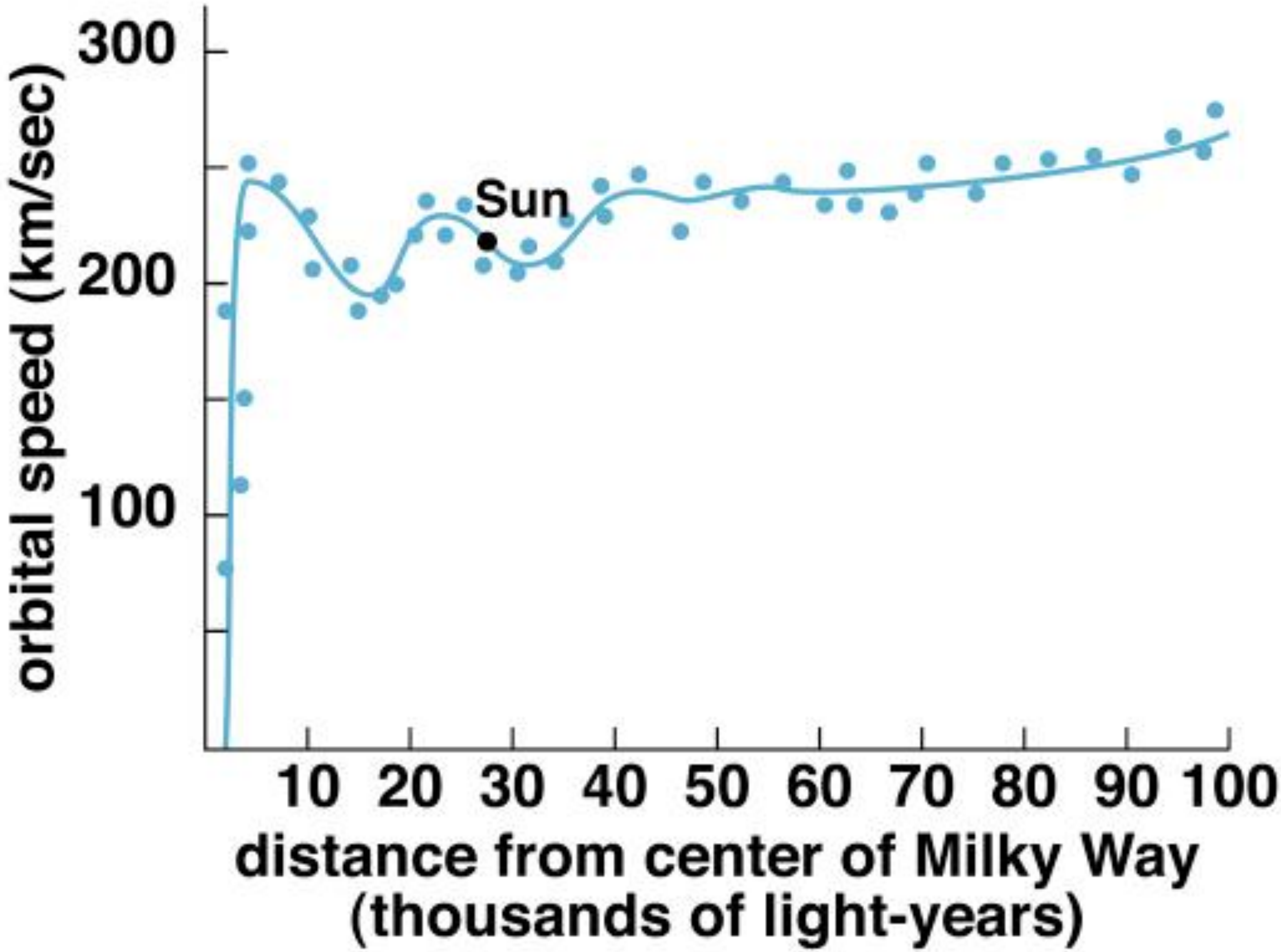




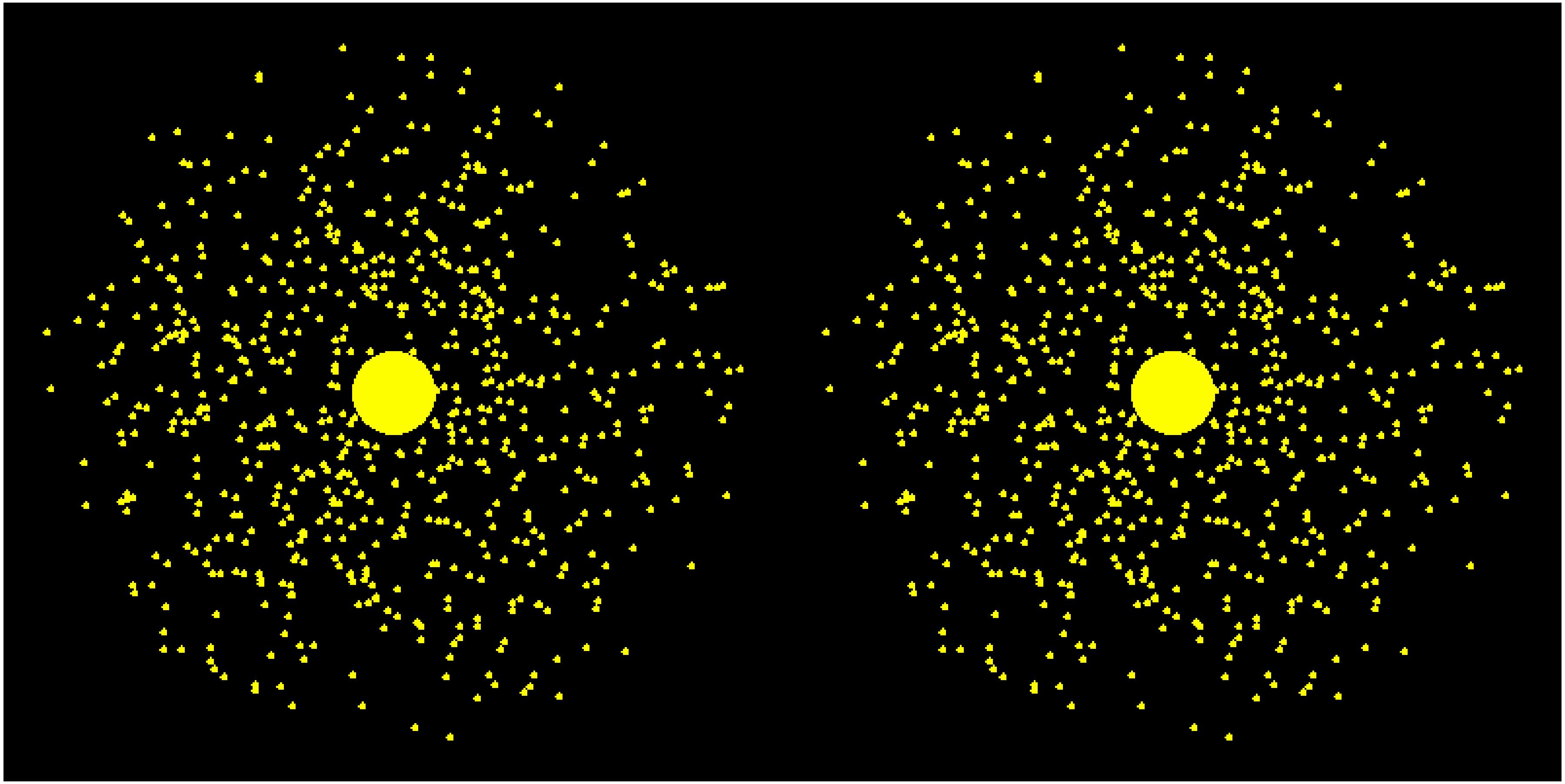
Rotation of Solar System



Rotation of Spiral Galaxy



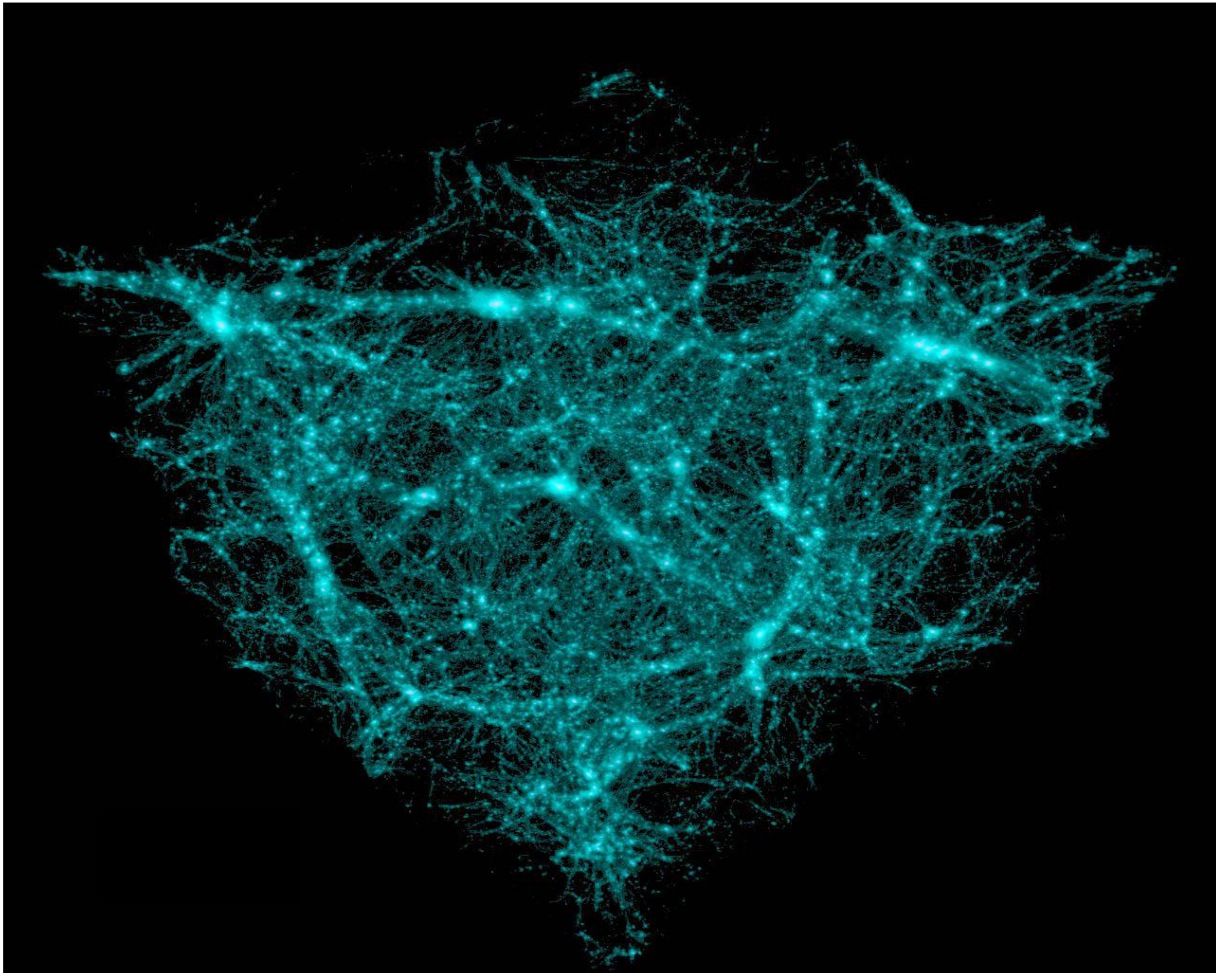
Flat Rotation Curves



If mass was represented by visible stars, the rotation speeds would steadily decline in outer regions.

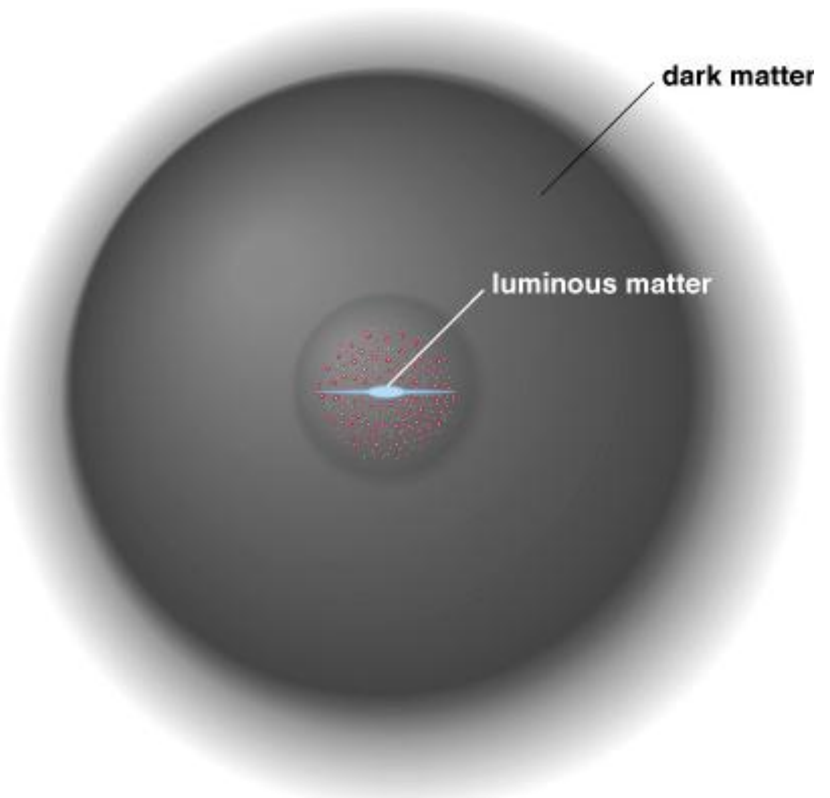
Since rotation speeds stay nearly constant to the galaxy's edge there must be invisible matter all over.

Dark Matter



What is Dark Matter?

- Recall the rotation curve of the Milky Way Galaxy.
  - atomic H clouds beyond our Sun orbit faster than predicted by Kepler's Law
  - most of the Galaxy's light comes from stars closer to the center than the Sun
- There are only two possible explanations for this:
  - We do not understand gravity on the scale of galaxies
  - The H gas velocities are caused by the gravitational attraction of unseen matter…called **dark matter**
- If we trust our theory of gravity...
  - there is 5-6 times more dark matter than luminous matter in our Galaxy
  - luminous matter is confined to the disk
  - dark matter is found in the halo and far beyond the luminous disk



Mass-to-Light Ratio

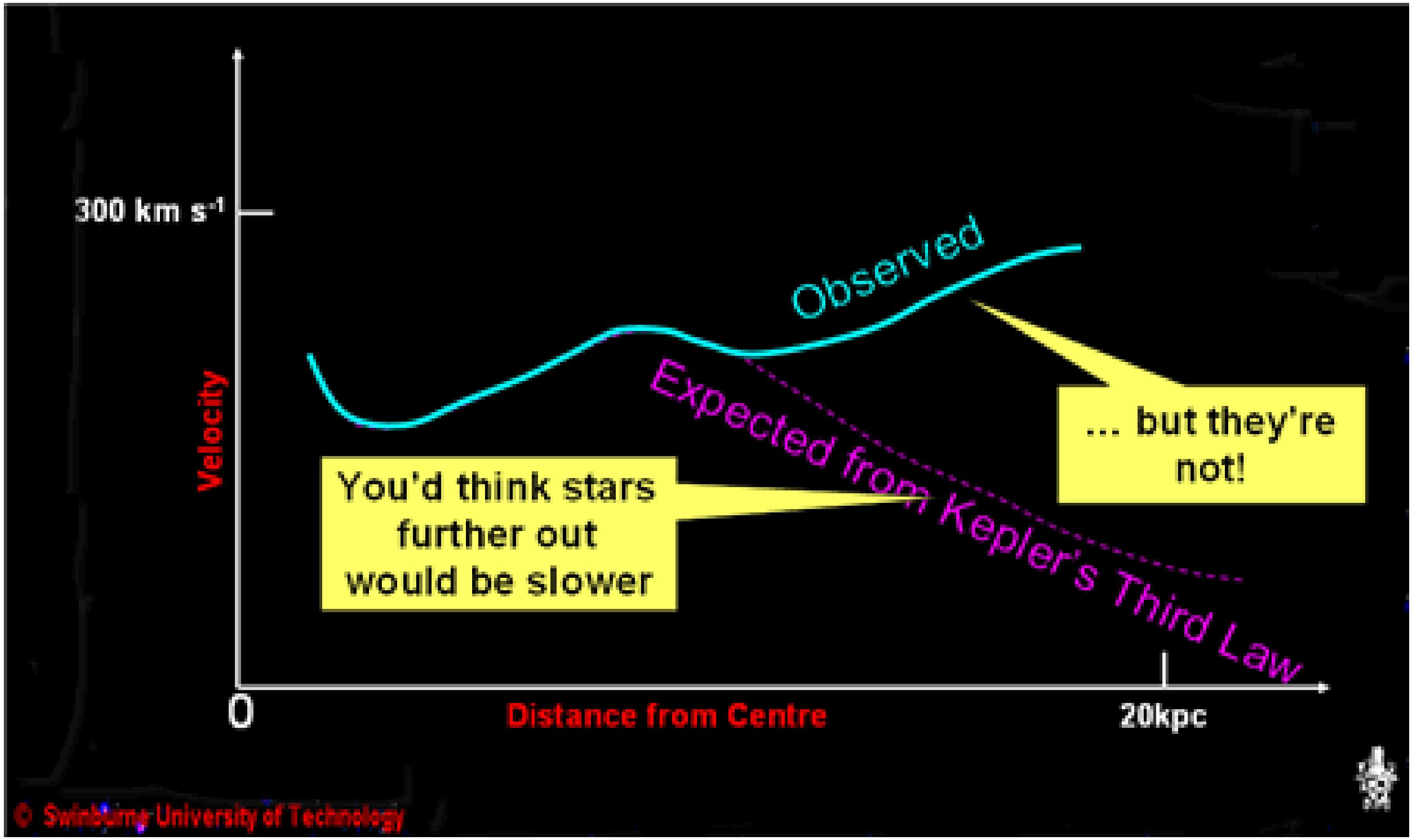
- This is the mass of a galaxy divided by its luminosity.
  - we measure both mass [$M_\odot$] and luminosity [$L_\odot$] in Solar units
- Within the orbit of the Sun, M/L = 6 $M_\odot / L_\odot$ for the Milky Way
  - this is typical for the inner regions of most spiral galaxies
  - for inner regions of elliptical galaxies, M/L = 10 $M_\odot / L_\odot$
    - not surprising since ellipticals contain dimmer stars
- However, when we include the outer regions of galaxies…
  - M/L increases dramatically
  - for entire spirals, M/L can be as high as 50 $M_\odot / L_\odot$
  - dwarf galaxies can have even higher M/L
- Thus we conclude that most matter in galaxies are not stars.
  - the amount of M/L over 6 $M_\odot / L_\odot$ is the amount of dark matter

Mass of the Galaxy

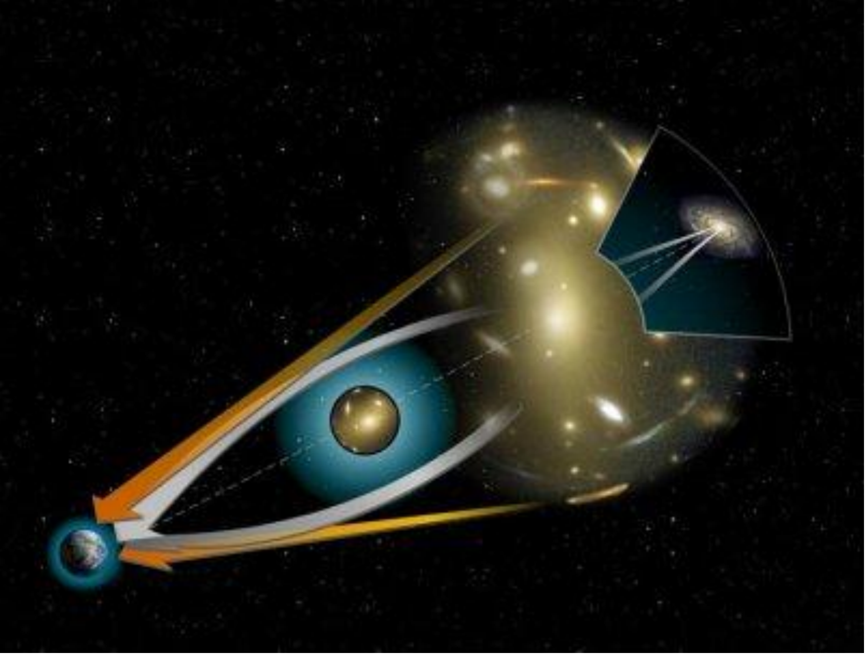
- We can use Kepler's Third Law to estimate the mass
  - Sun's distance from center: 28,000 l.y. = 1.75×10^9 AU
  - Sun's orbital period: 240 million years (2.4×10^8 yr)
  - $P^2 = a^3 \Rightarrow$ mass within Sun's orbit is $10^{11}\ M_\odot$
- Total mass of MW Galaxy : **$2 \times 10^{12}\ M_\odot$**
- Total number of stars in MW Galaxy ≈ **2×10^{11}**

What is Dark Matter?

THE SHORT ANSWER IS: WE DON'T KNOW. BUT SEVERAL LINES OF EVIDENCE INDICATE 6-7X MORE INVISIBLE THAN VISIBLE MATTER

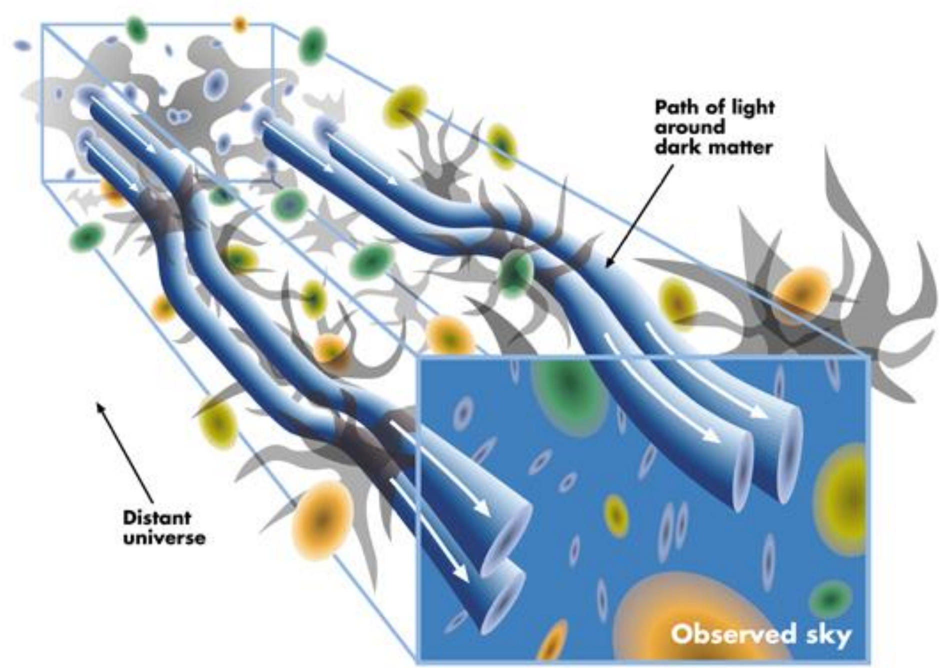


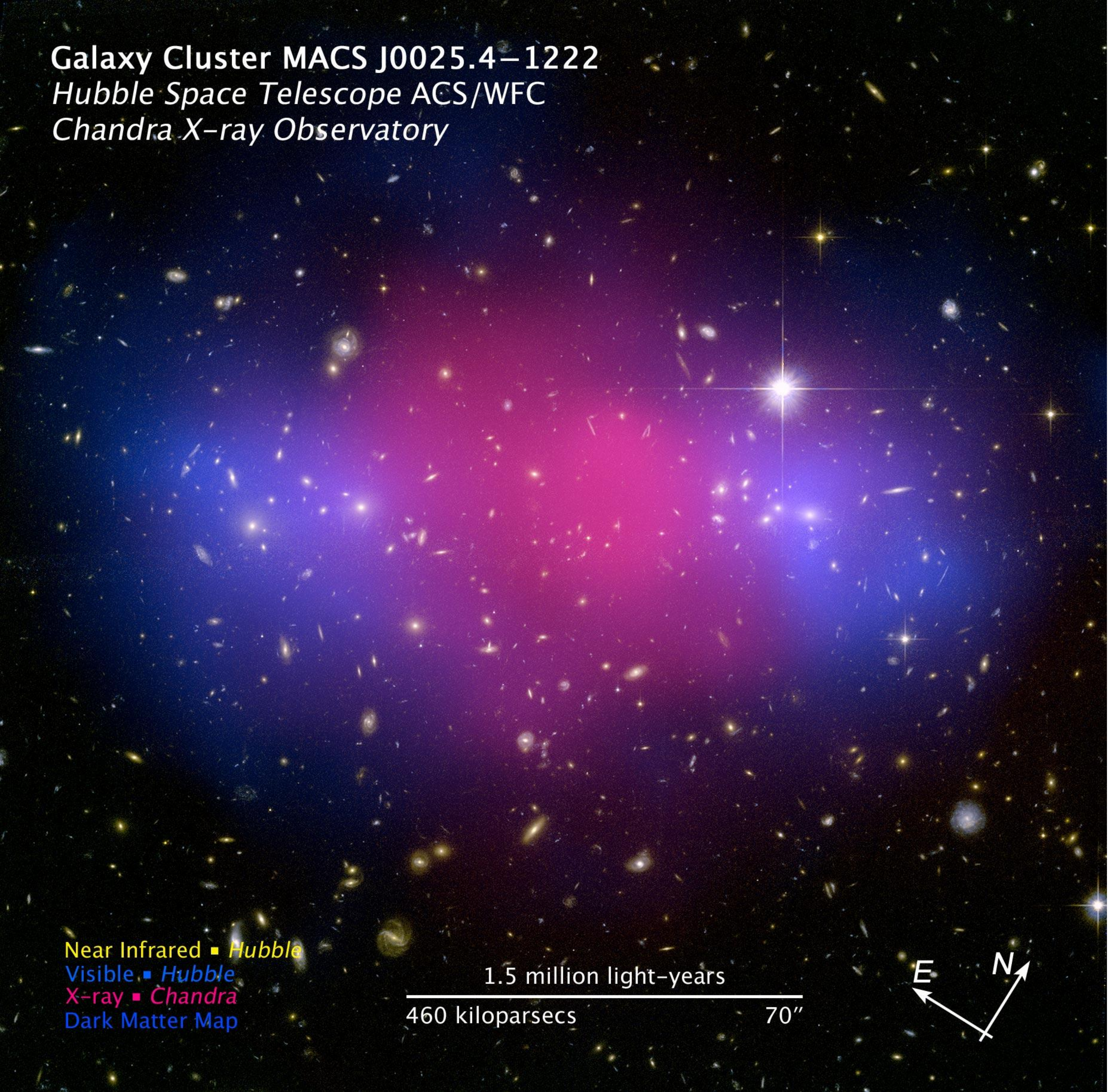
The rotation speed of galaxies does not decline with radius, violating Kepler's law unless without a halo of unseen matter



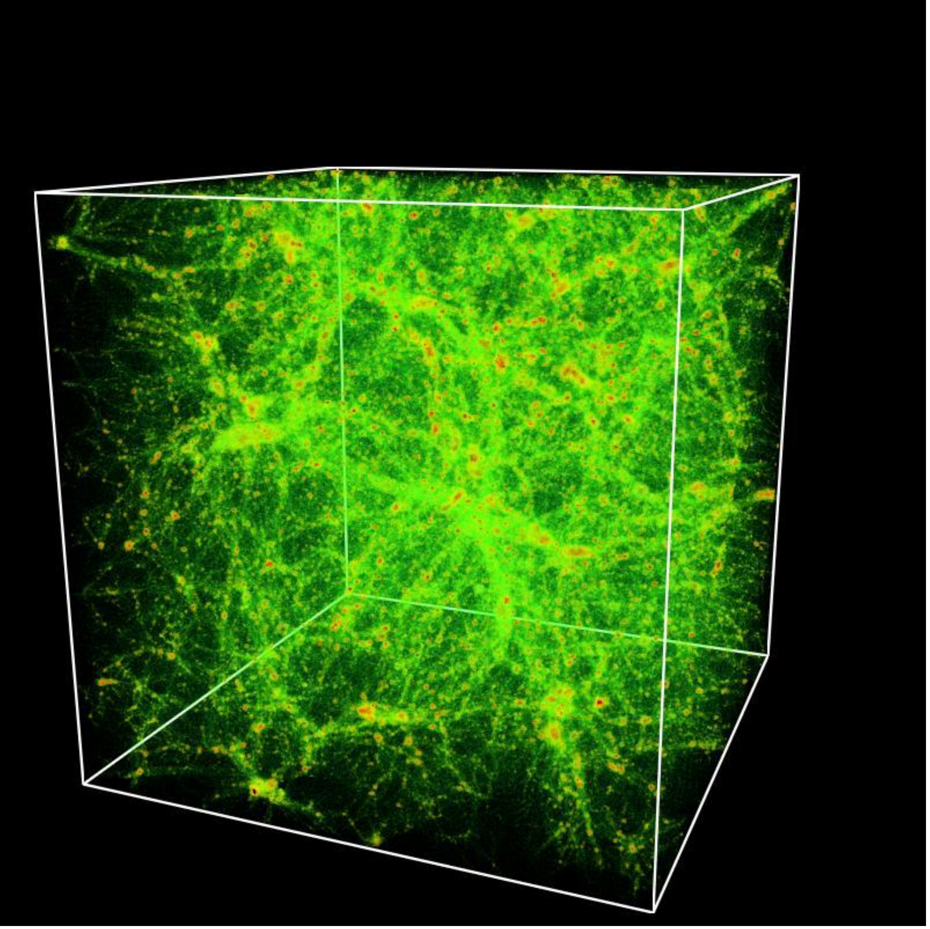
Light from distant galaxies is bent by an intervening cluster to form little arcs. The amount of bending indicates a lot of unseen matter in the cluster.

Light slightly from all distant galaxies is very distorted and bent as it travels through the “sea” of dark matter. With the best images, these distortions of 0.1% in shape can be seen.





In this galaxy cluster, and in another called Bullet Cluster, the gas (red) collided and heated up to emit X-rays, while the dark matter (blue) continued w/o an interaction. So gravity is operating but not any of the EM radiation interactions.



Why are astronomers so confident that dark matter actually exists?

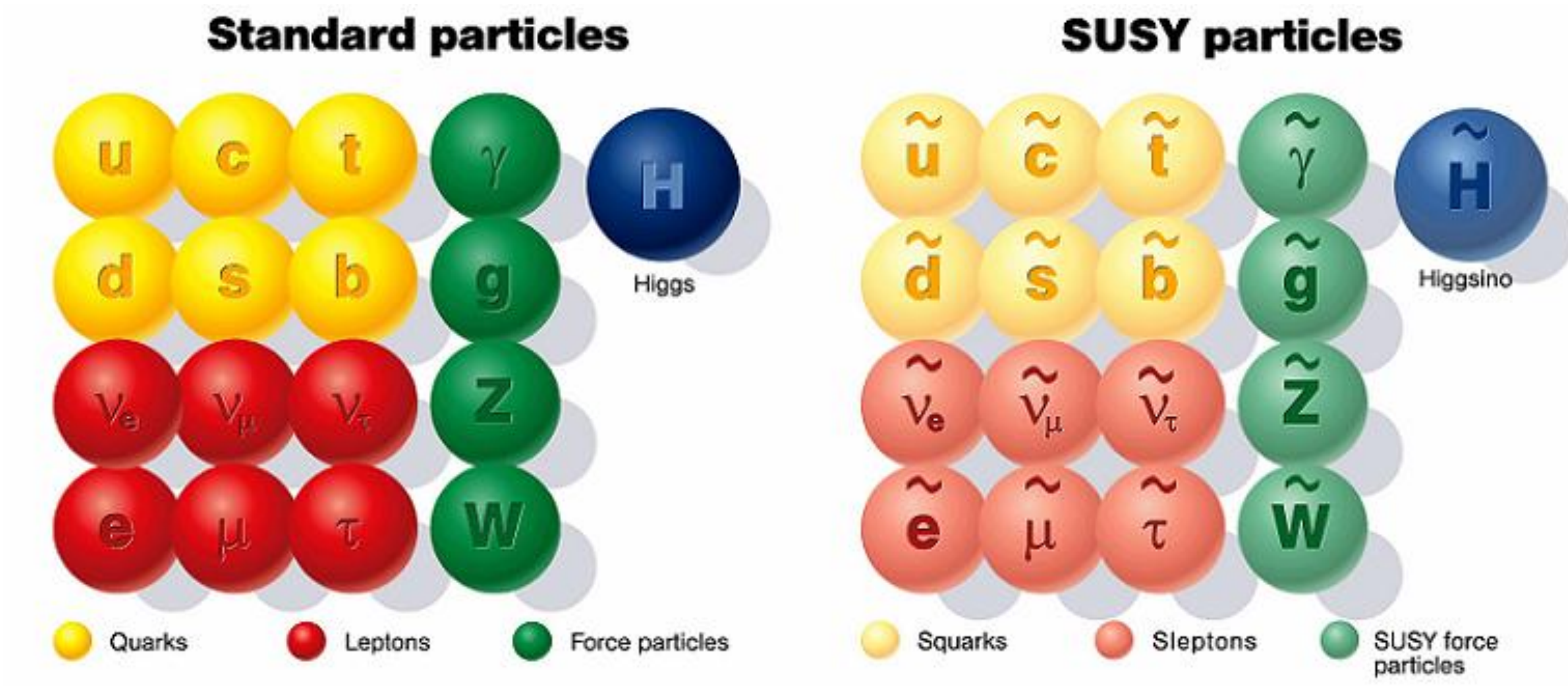
Because the law of gravity has passed so many tests, and if we put dark matter into computer simulations, we evolve structure that looks just like the universe.

So far, we can only rule items out:

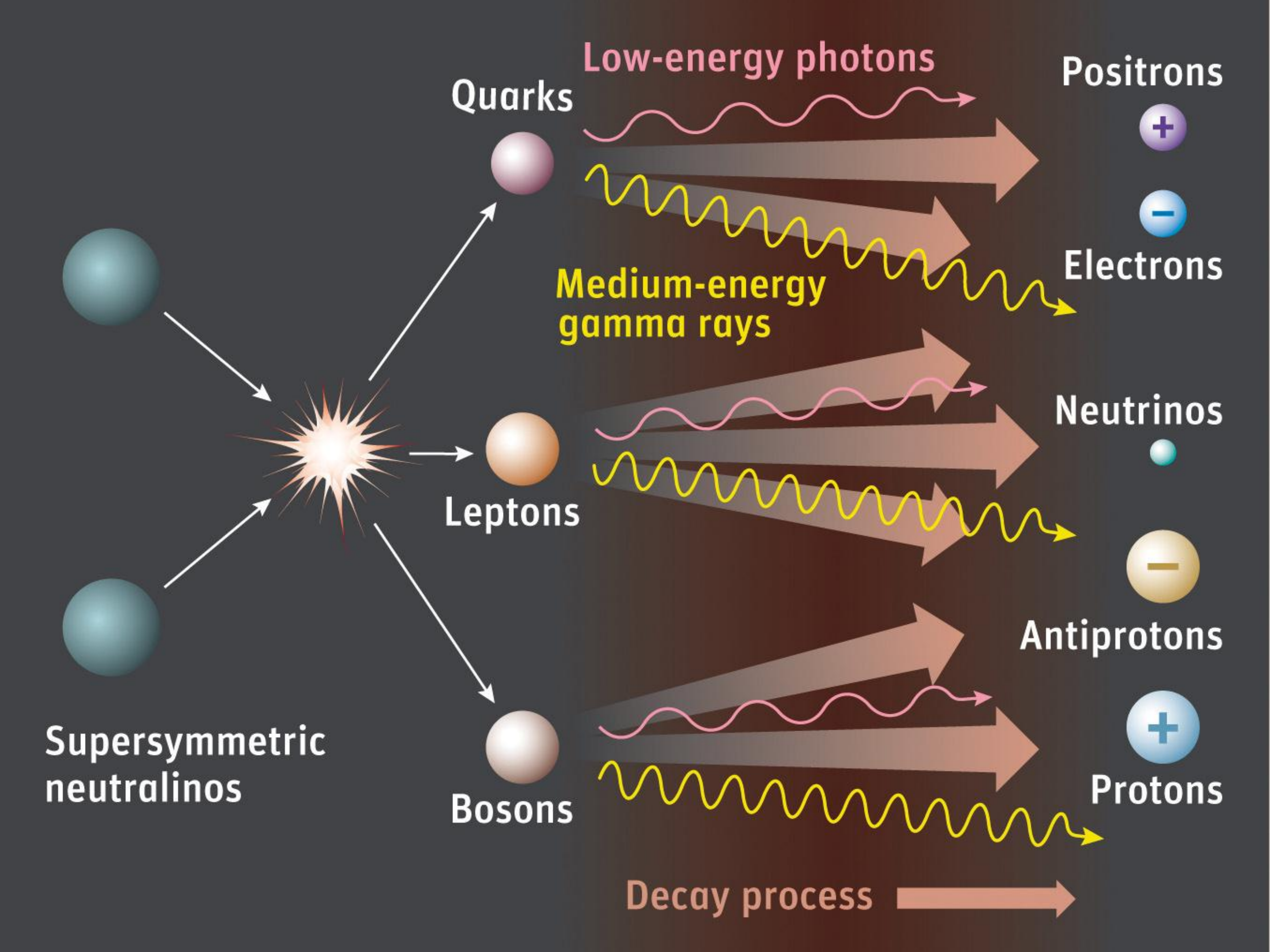
Stars:	**(normal matter)**	**census of stars does not allow it**
MACHOs:	**(sub-stars & planets)**	**gravitational lensing rules it out**
Black holes:	**(dark, collapsed stars)**	**no sign of preceding supernovae**
Dust:	**(dust up to rocks)**	**re-radiation in infrared not seen**

Which leaves: weakly interacting particles, supersymmetric extension to standard model

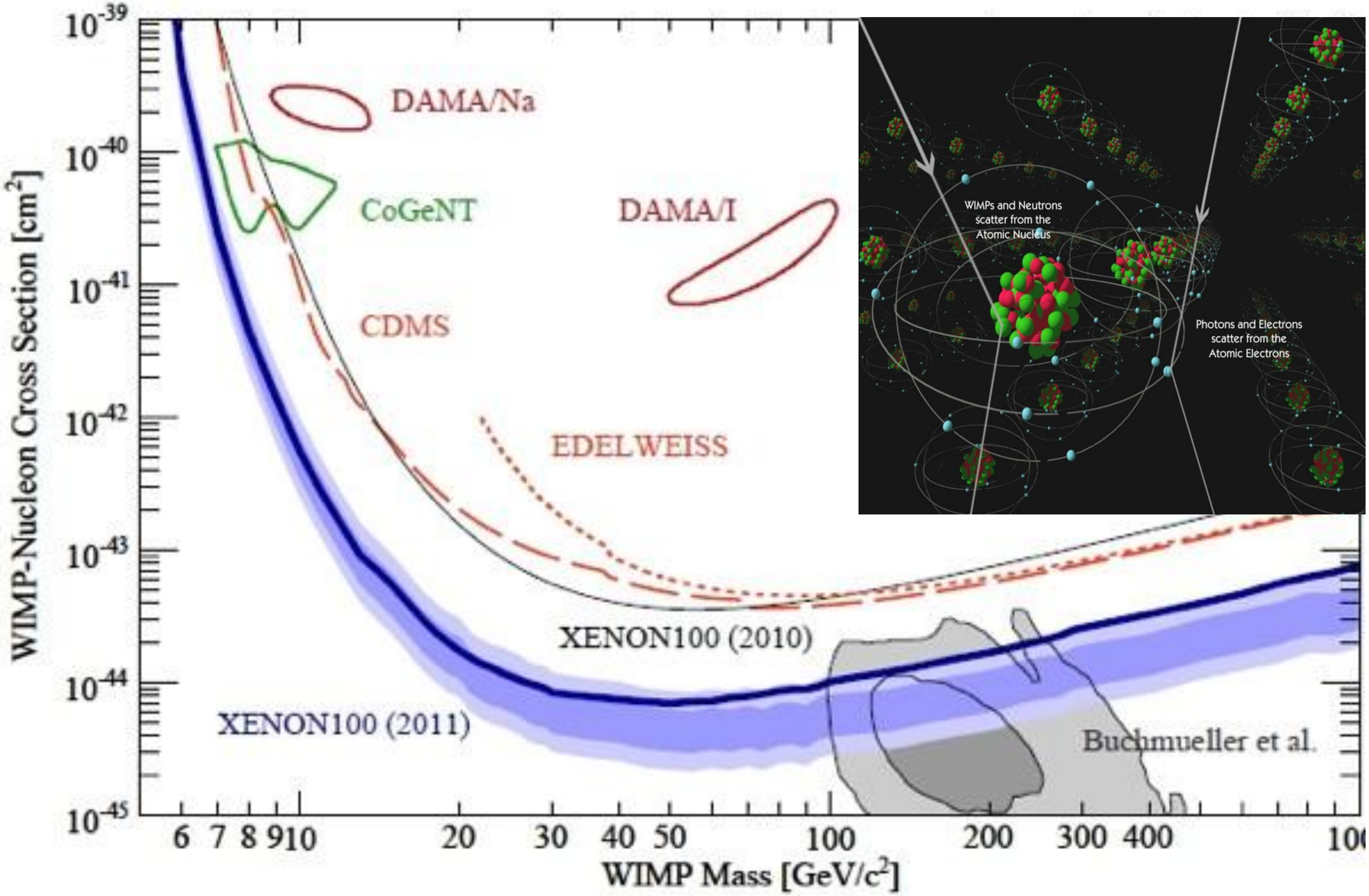
Supersymmetry



Supersymmetry is an extension to the "standard model" of particle physics that unifies fermions and bosons through a set of "shadow" particles of higher mass. The theory has been around for 30 years, but experiments at the LHC haven't found supersymmetric particles.

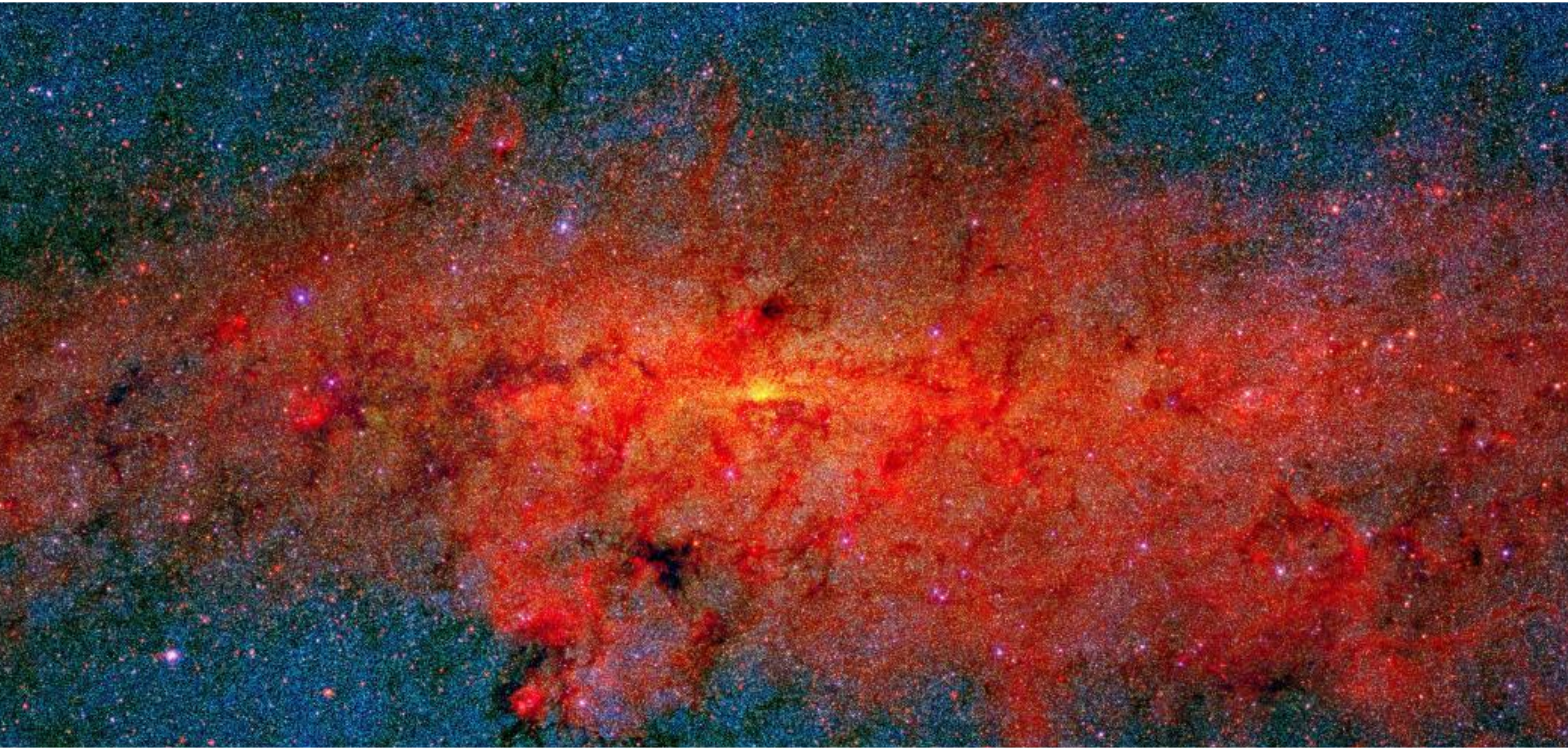

Low-energy photons
Quarks
Positrons
+
−
Electrons
Medium-energy gamma rays
Neutrinos
Leptons
−
Antiprotons
+
Supersymmetric neutralinos
Bosons
Protons
Decay process

Dark Matter Direct Detection



Deep in mines, to shield from cosmic ray contaminating signals, solid state detectors looks for the rare recoil of DM particles with heavy atomic nuclei.

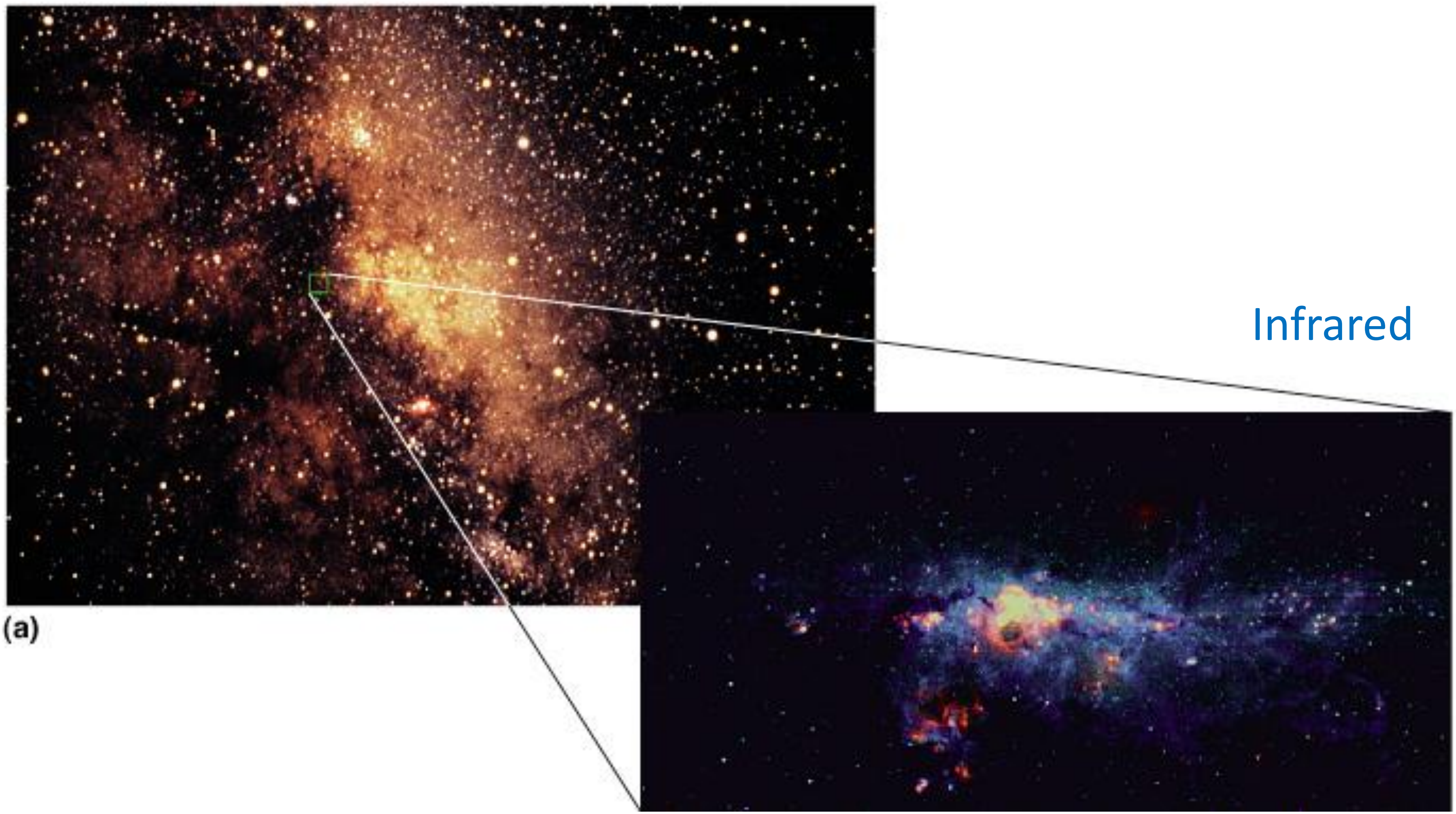
Galactic Center



Center of the Galaxy

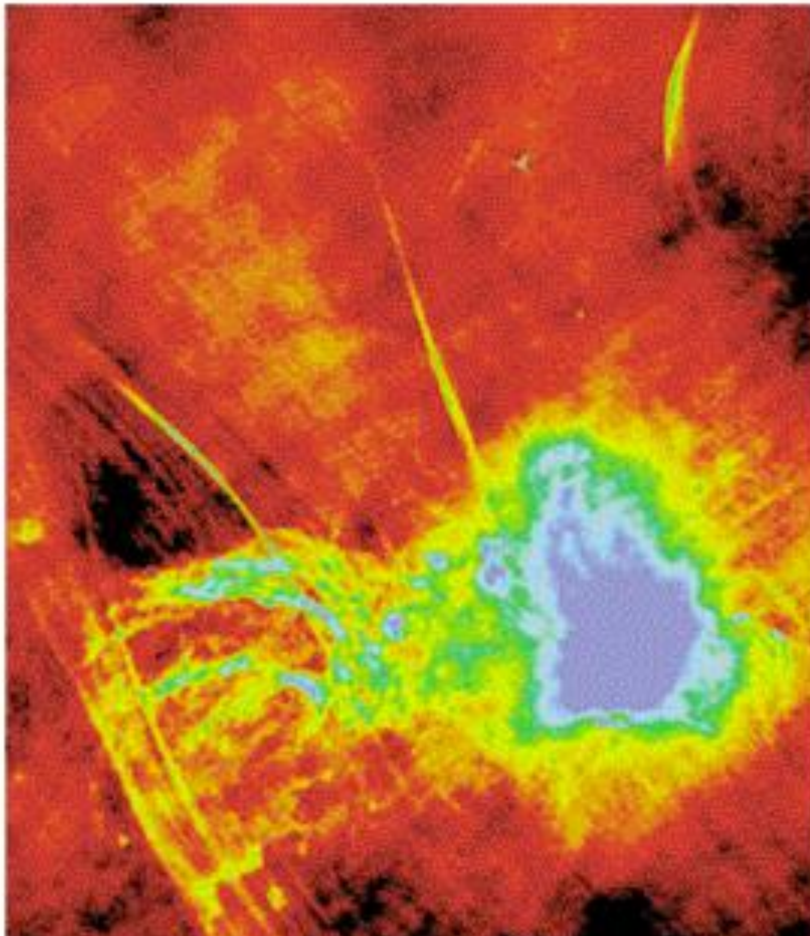
Visual

Infrared



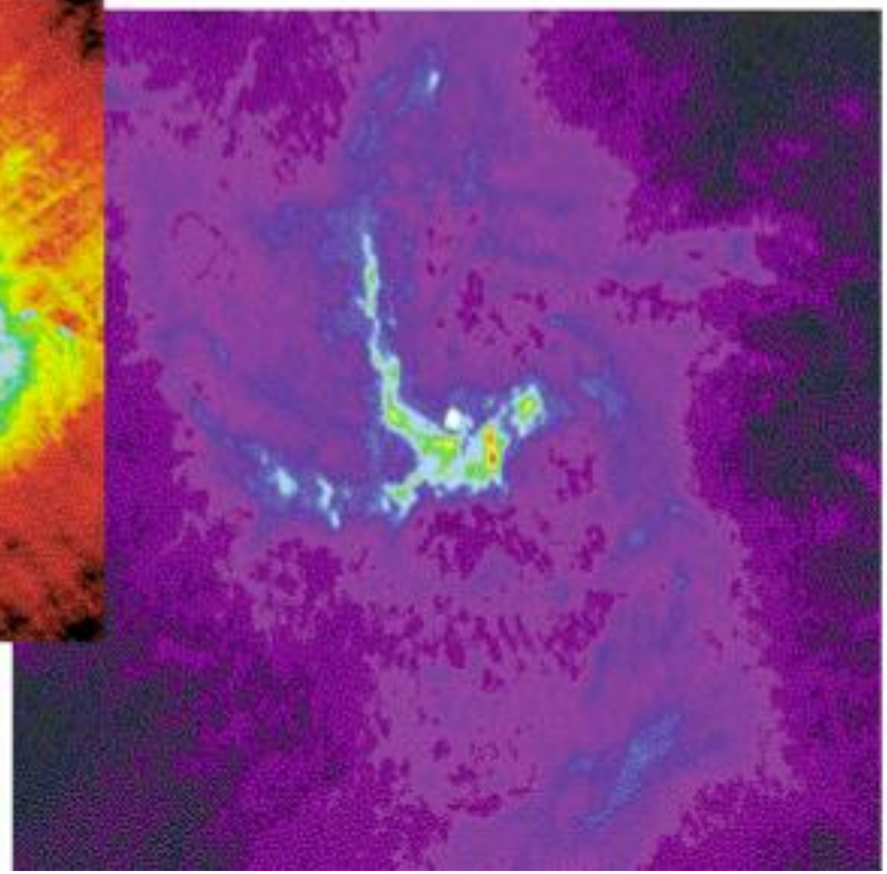
(a)

Center of the Galaxy

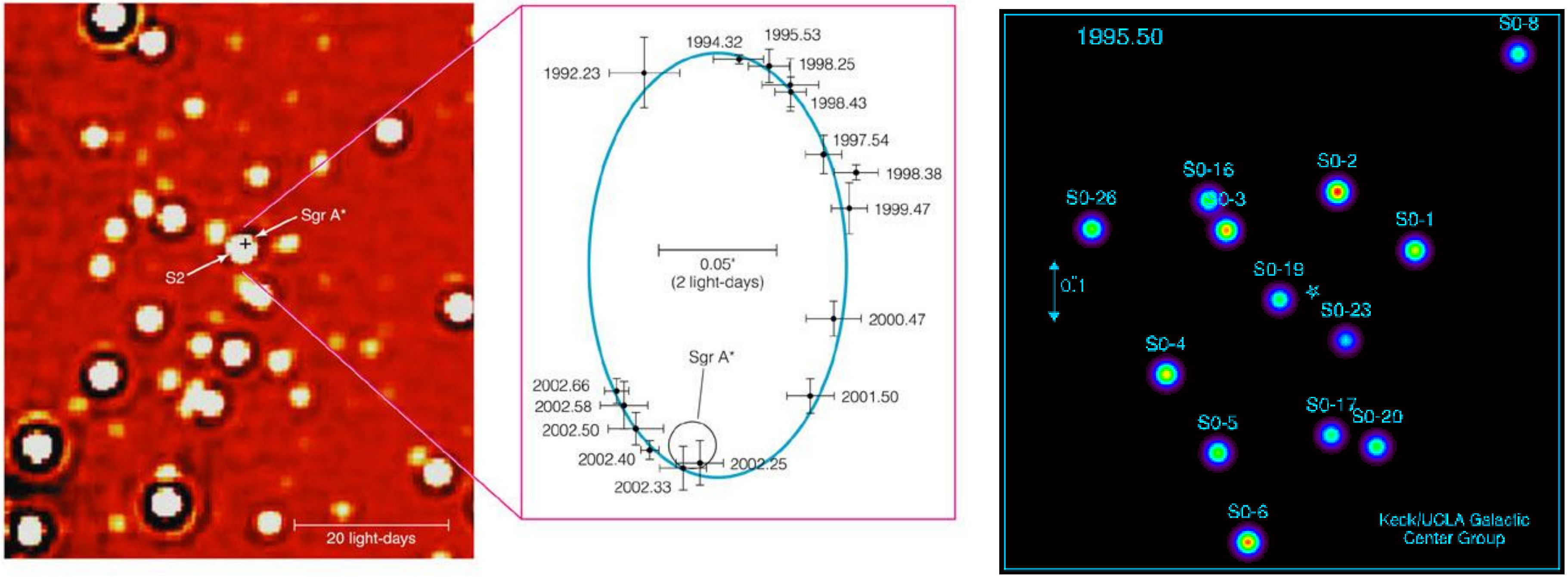


(c)

Radio



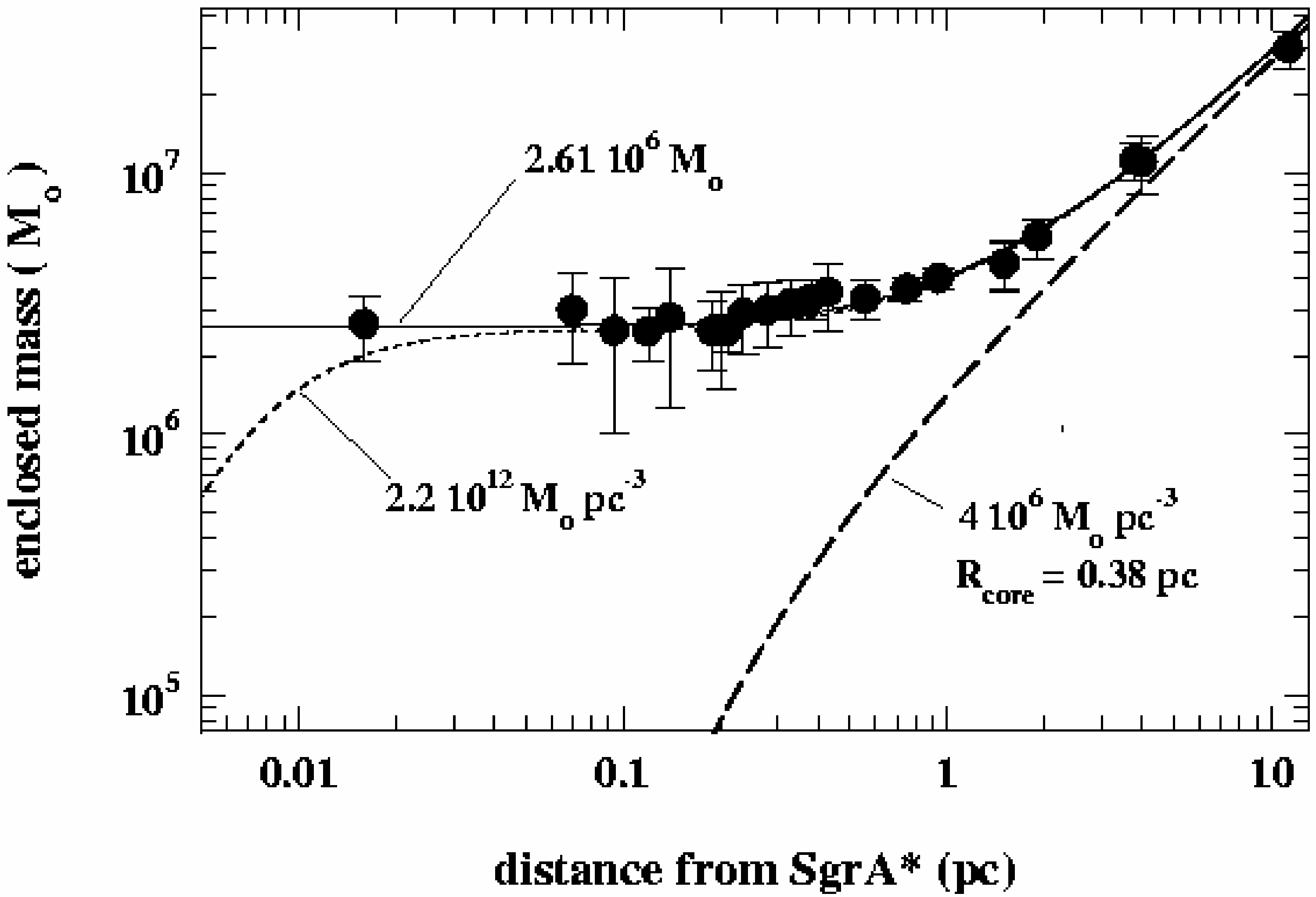
Center of the Galaxy



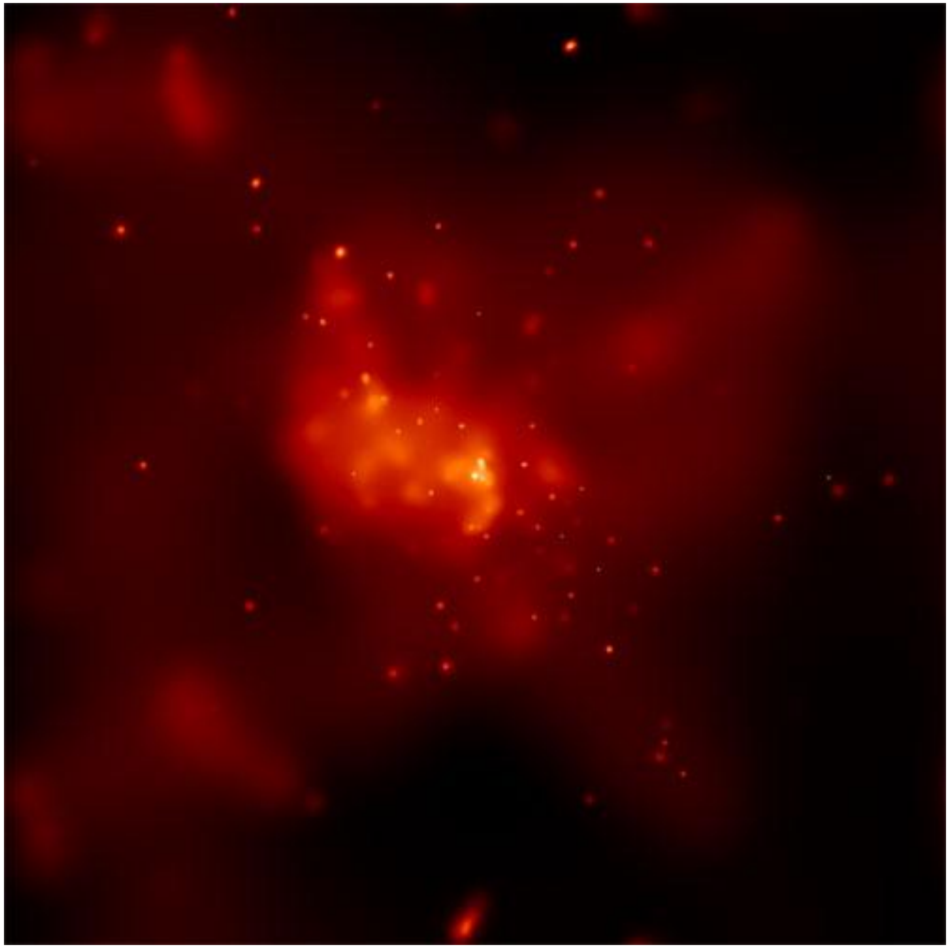
- We measure the orbits of individual fast-moving stars near the Galactic center, within light days to light weeks.
    - these measurements must be made in the infrared
    - in particular, this star passed within 1 light-day of Sgr A*
    - using Kepler's Law, we infer a mass of 4 million $M_\odot$ for Sgr A*
- What can be so small, yet be so massive?

Center of the Galaxy

Modeling Keplerian velocities leads to enclosed mass, which far exceeds the mass from a star cluster in the central parsec.



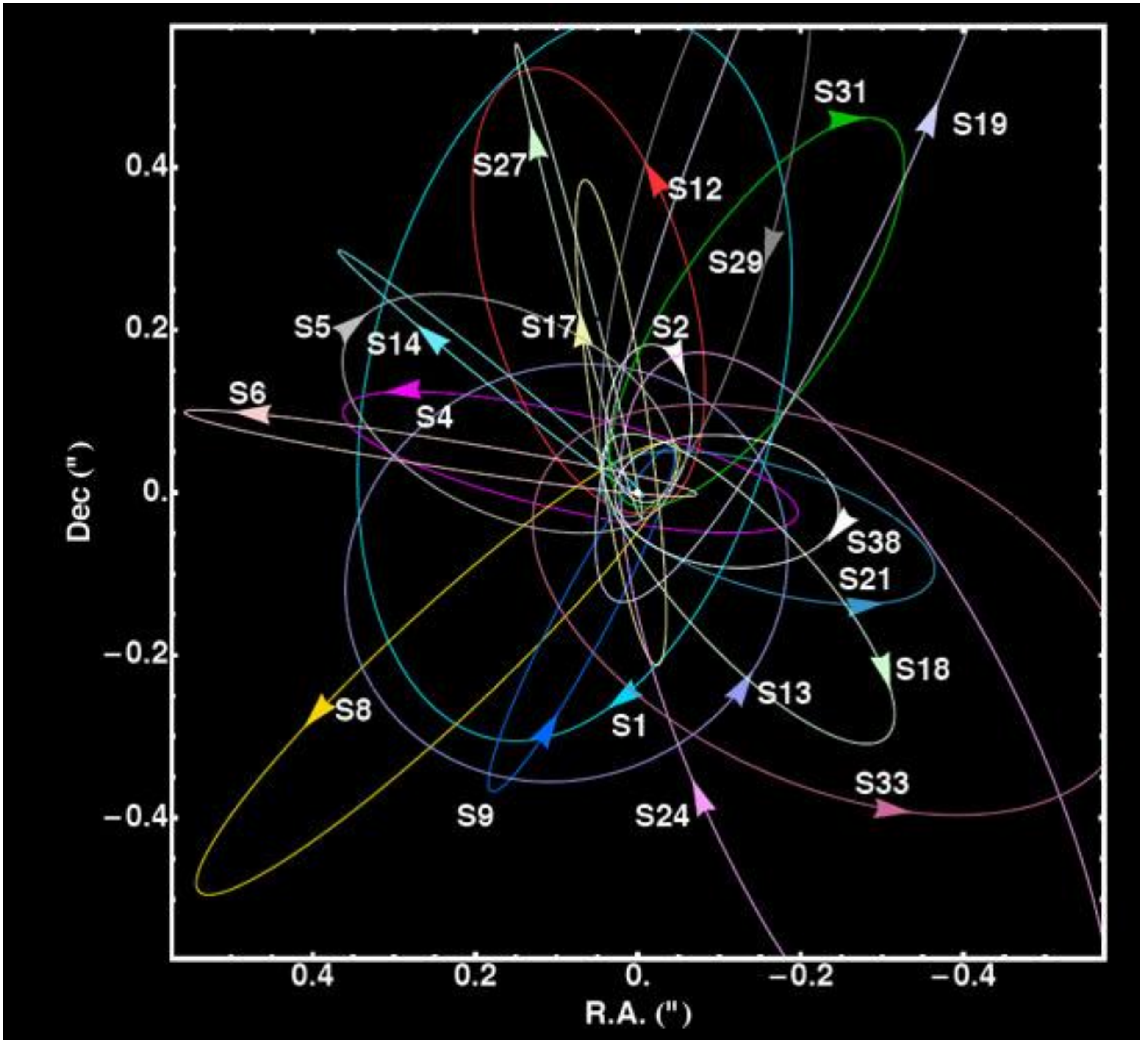
X-ray Flare from Sgr A*



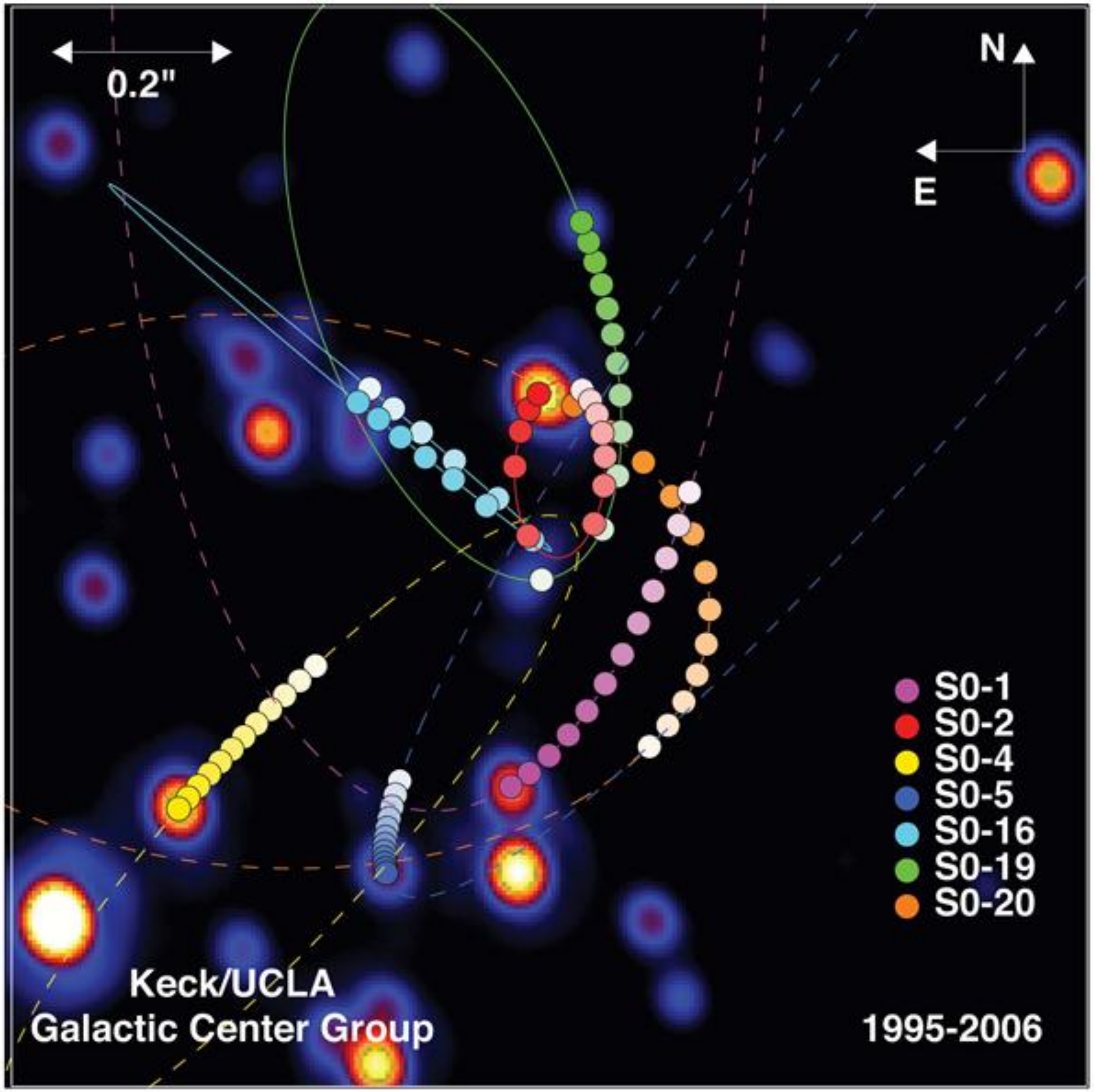
*Chandra image of Sgr A**

- The rapid flare rise/drop time (< 10 min) implied that the emission region is only 20 times the size of the event horizon of the 4 million $M_\odot$ black hole at Sgr A*.
- Observations are consistent with the existence of a supermassive black hole at the center of our Galaxy.
- Energy from flare probably came from a comet-sized lump of matter…torn apart before falling beneath the event horizon!

Model Orbits

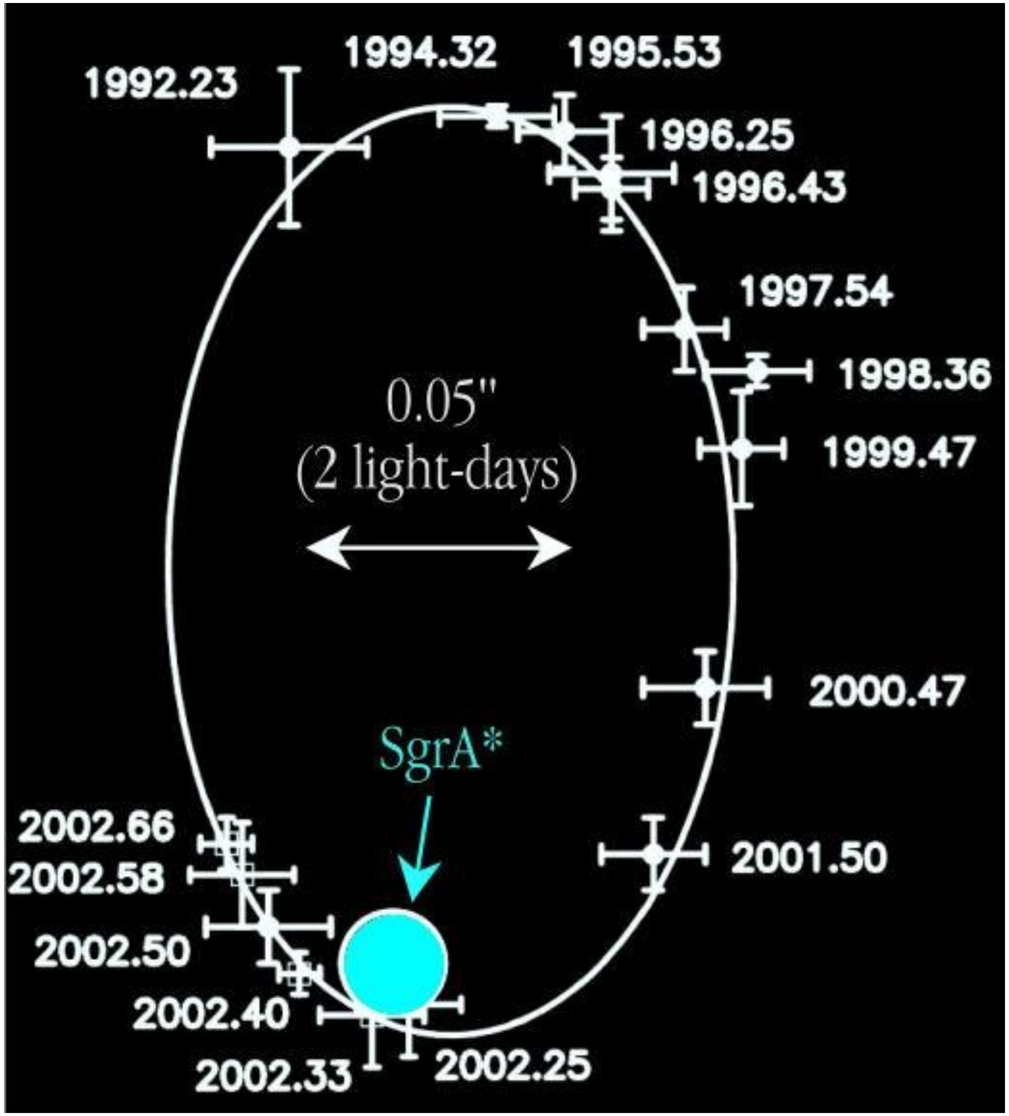


Orbital Data

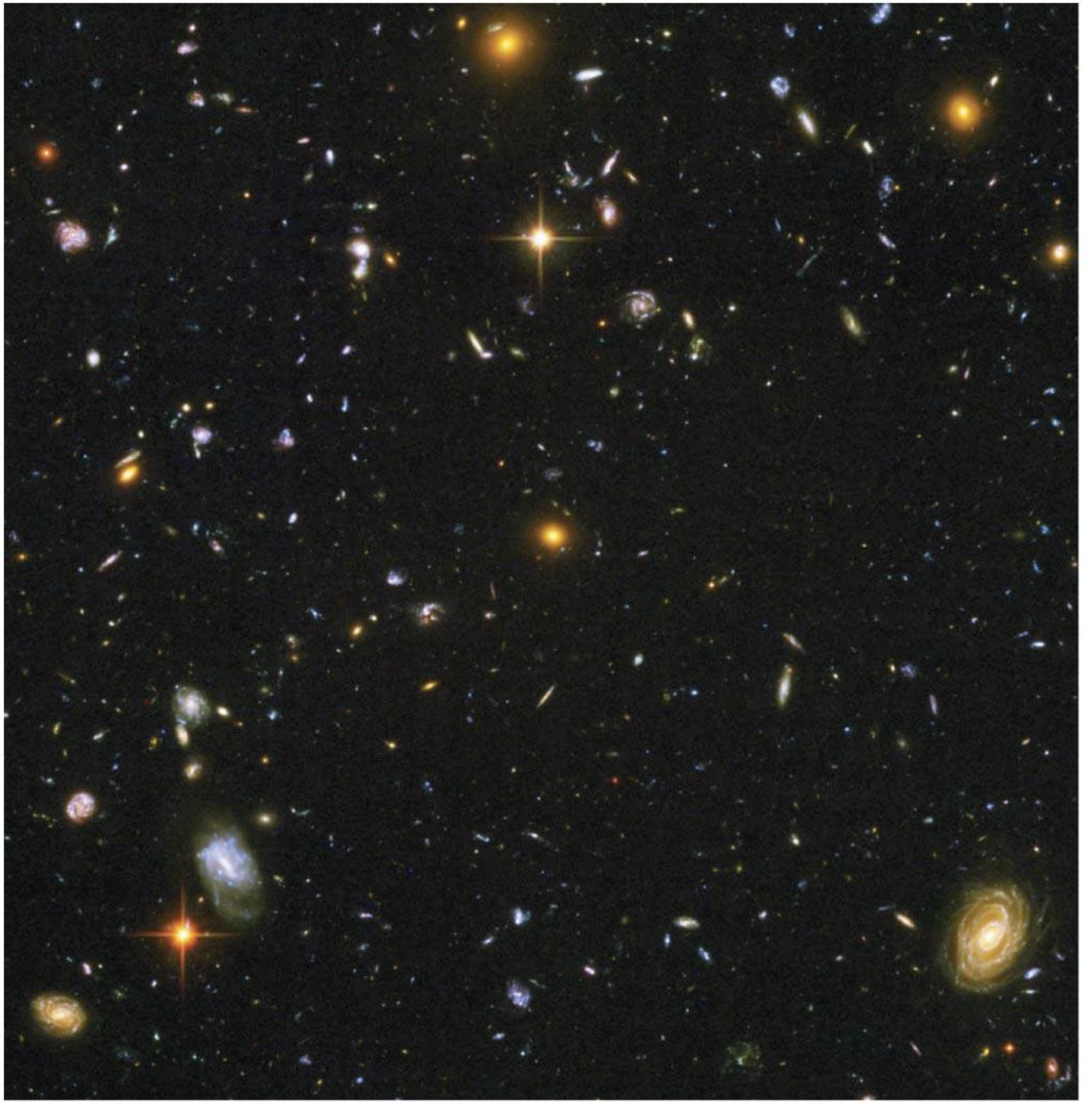


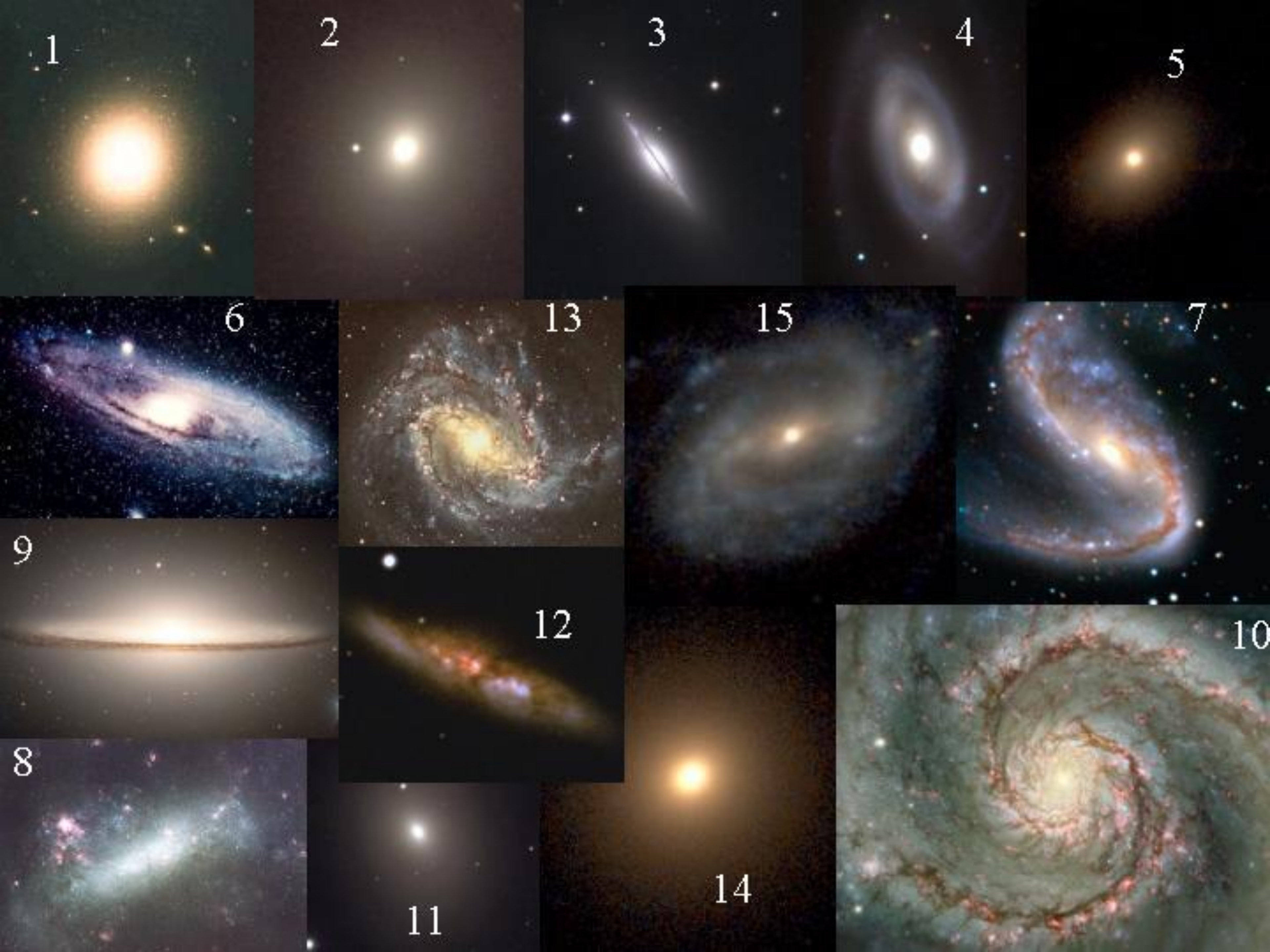
Edge of the Horizon

The hope is, with deep enough data to have a lot more probes of the gravitational potential, to find a star that goes behind (shadowed by) the event horizon, and allows a test of general relativity in new ways.



Galaxies




1
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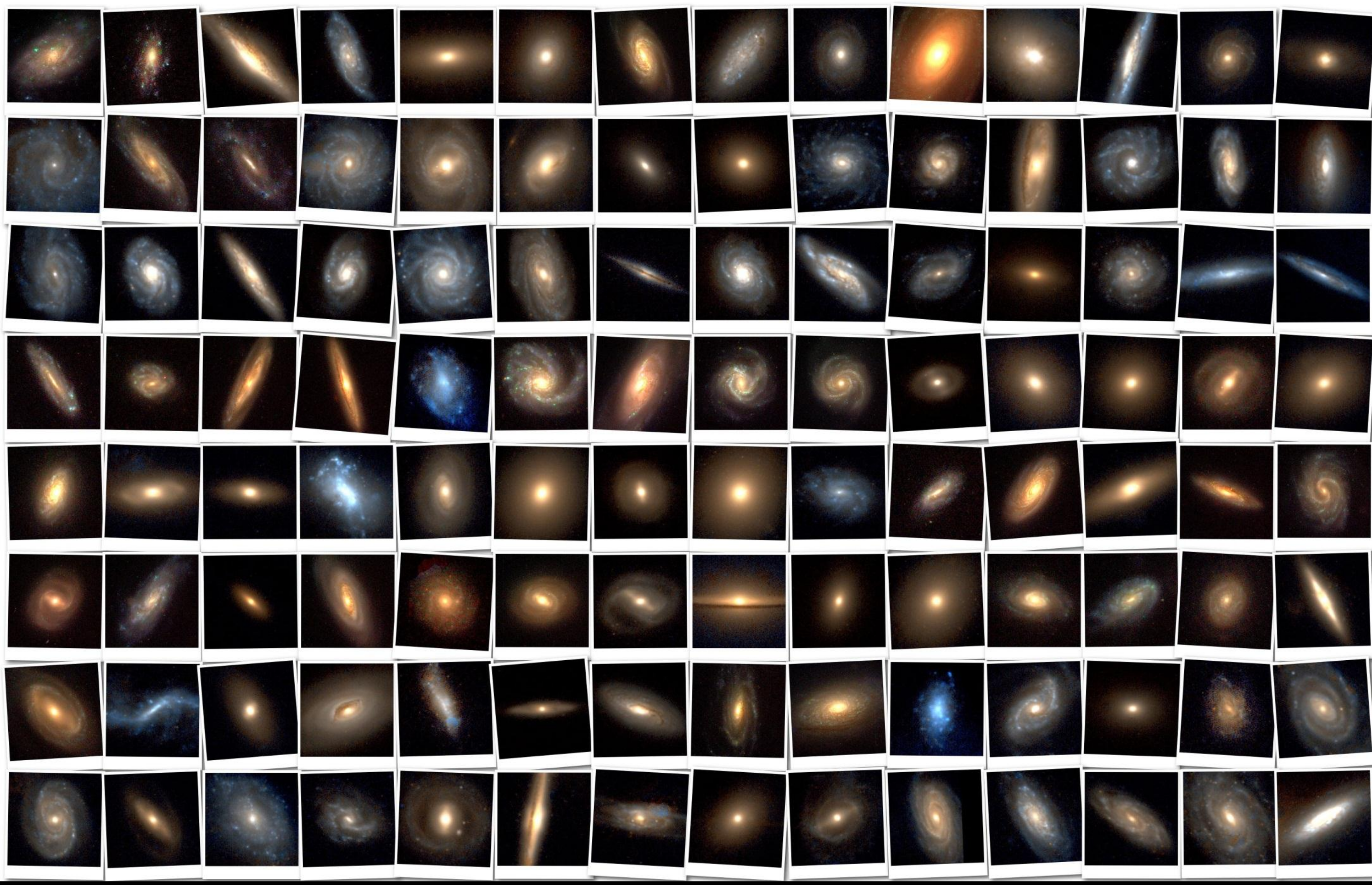
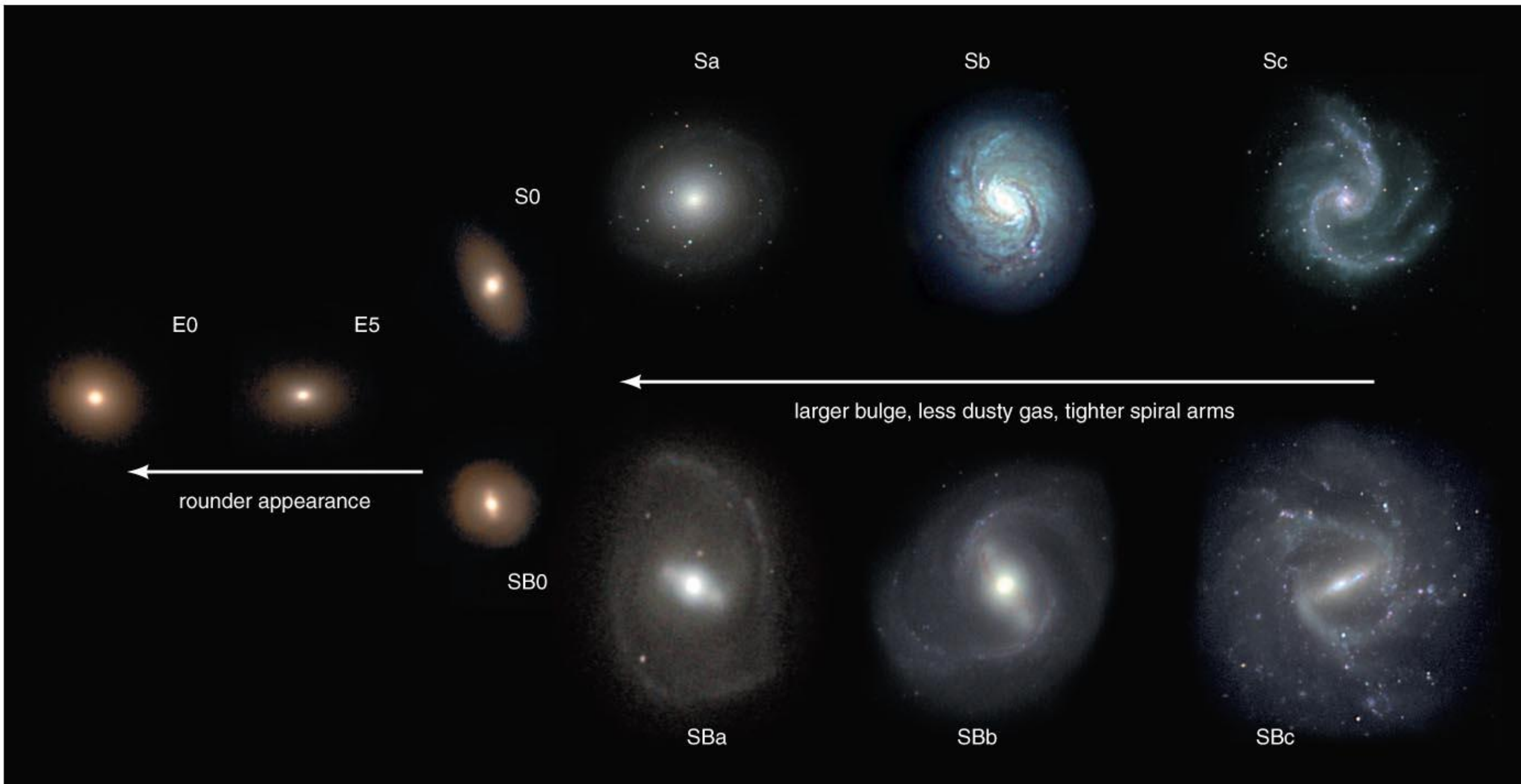
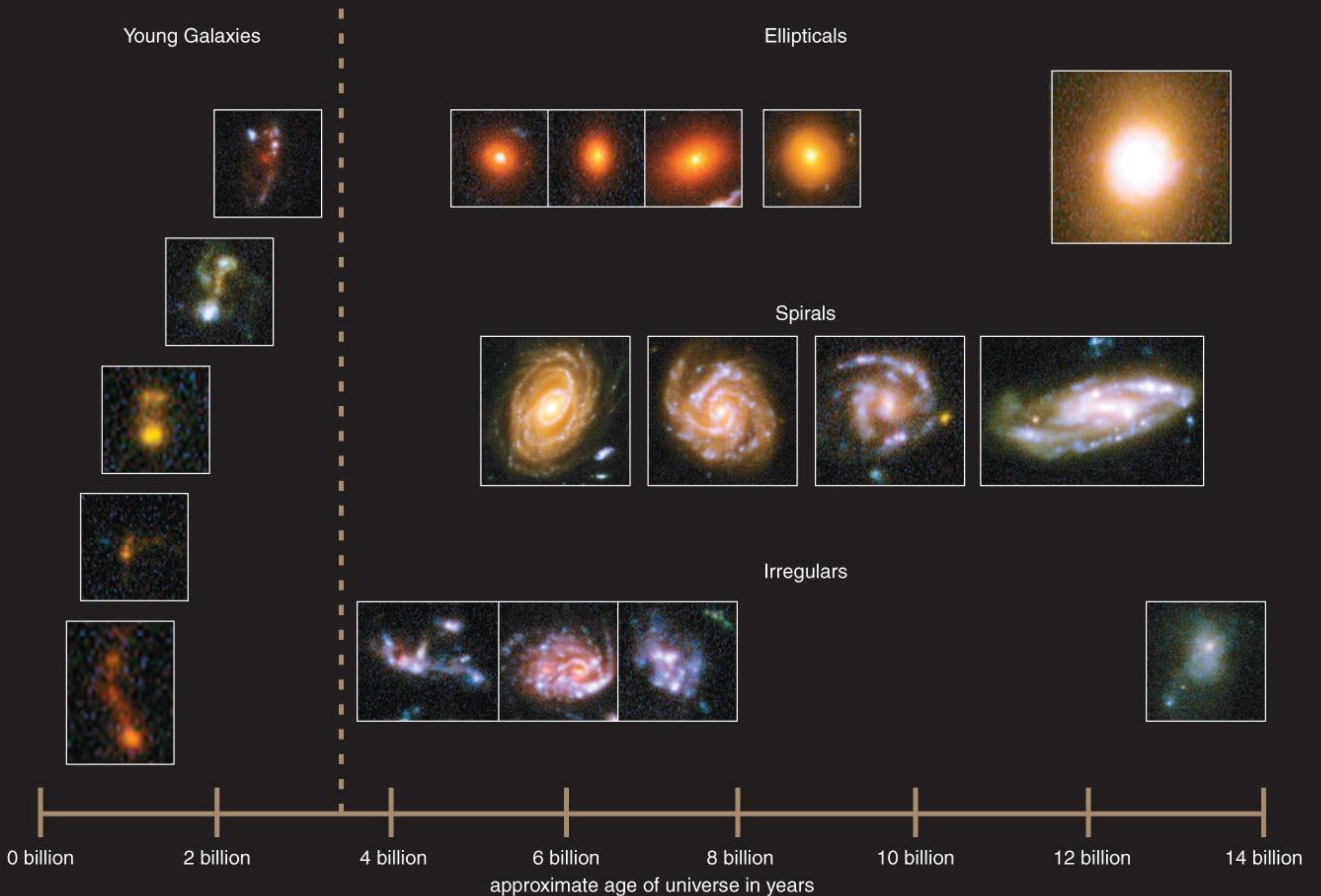
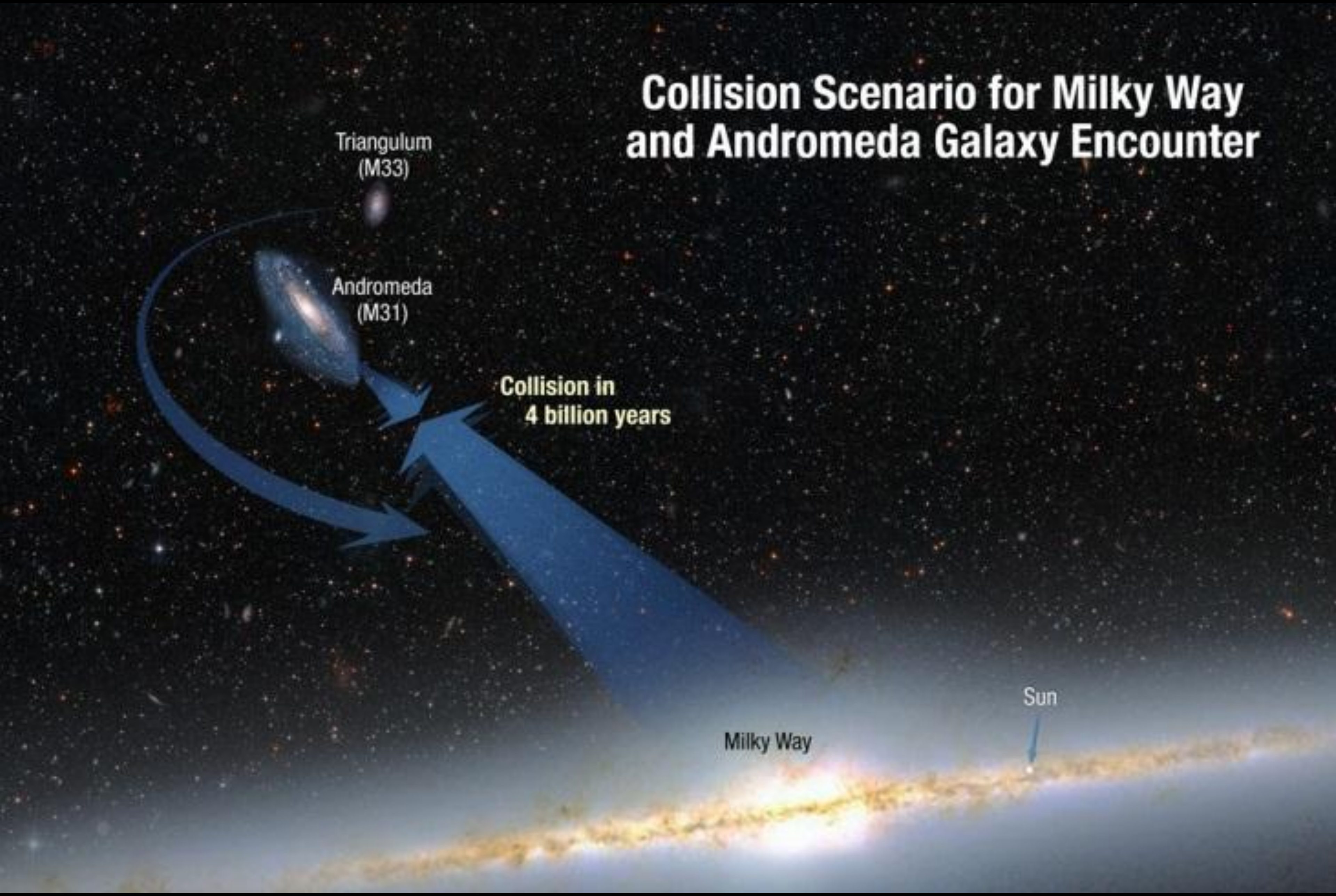
11
14



The Hubble “sequence” was originally thought to be an evolutionary sequence. Galaxies cannot interconvert, but they can grow or change by merging over time.




Young Galaxies
Ellipticals
Spirals
Irregulars
0 billion
2 billion
4 billion
6 billion
8 billion
10 billion
12 billion
14 billion
approximate age of universe in years


Collision Scenario for Milky Way and Andromeda Galaxy Encounter
Triangulum (M33)
Andromeda (M31)
Collision in 4 billion years
Sun
Milky Way

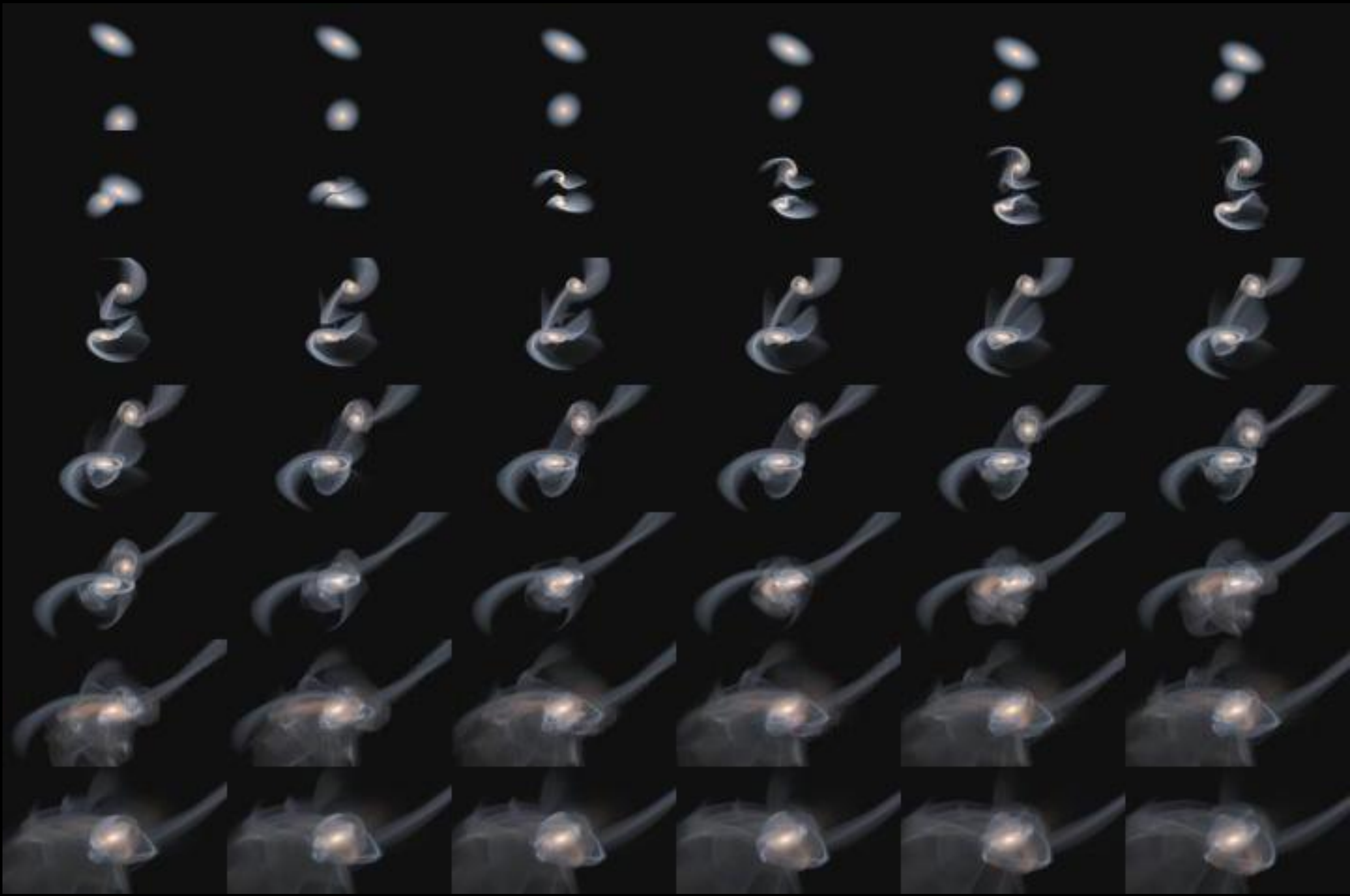
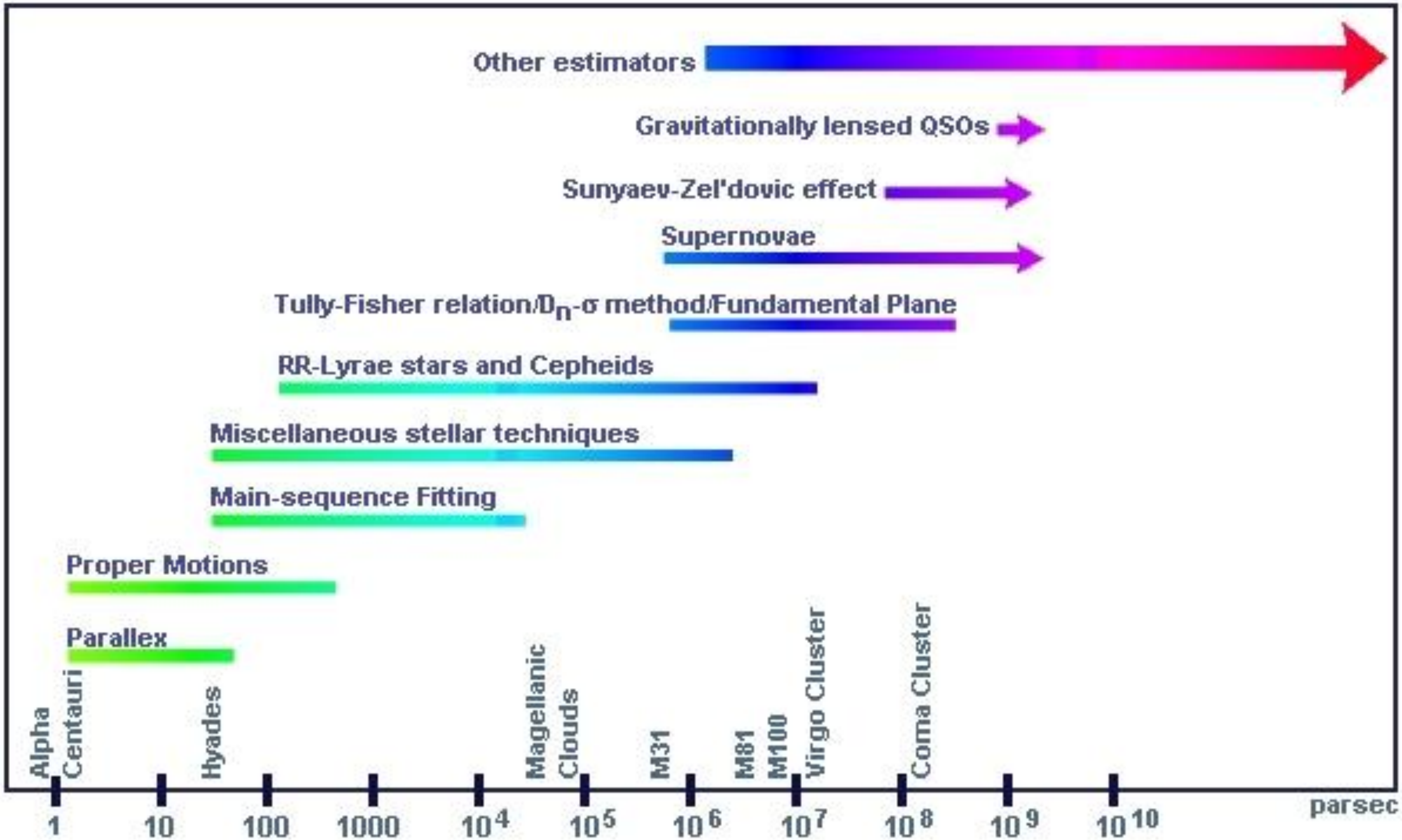


Illustration Sequence of the Milky Way
and Andromeda Galaxy Colliding

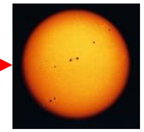
Distances



Other estimators
Gravitationally lensed QSOs
Sunyaev-Zel'dovic effect
Supernovae
Tully-Fisher relation/D_n-σ method/Fundamental Plane
RR-Lyrae stars and Cepheids
Miscellaneous stellar techniques
Main-sequence Fitting
Proper Motions
Parallex
Alpha Centauri
Hyades
Magellanic Clouds
M31
M81
M100
Virgo Cluster
Coma Cluster
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
parsec

Distance Units

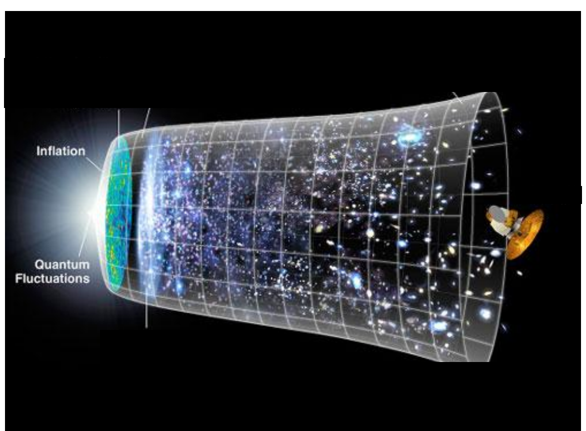
1 pc



Typical distance between stars is 1 pc = 3.36 light years = 6 trillion km, or 6,000,000,000,000 km.

1 Mpc

Typical distance between galaxies is 1 Mpc = 10^6 pc or 3 million light years. It's an incredible 10^{19} km.

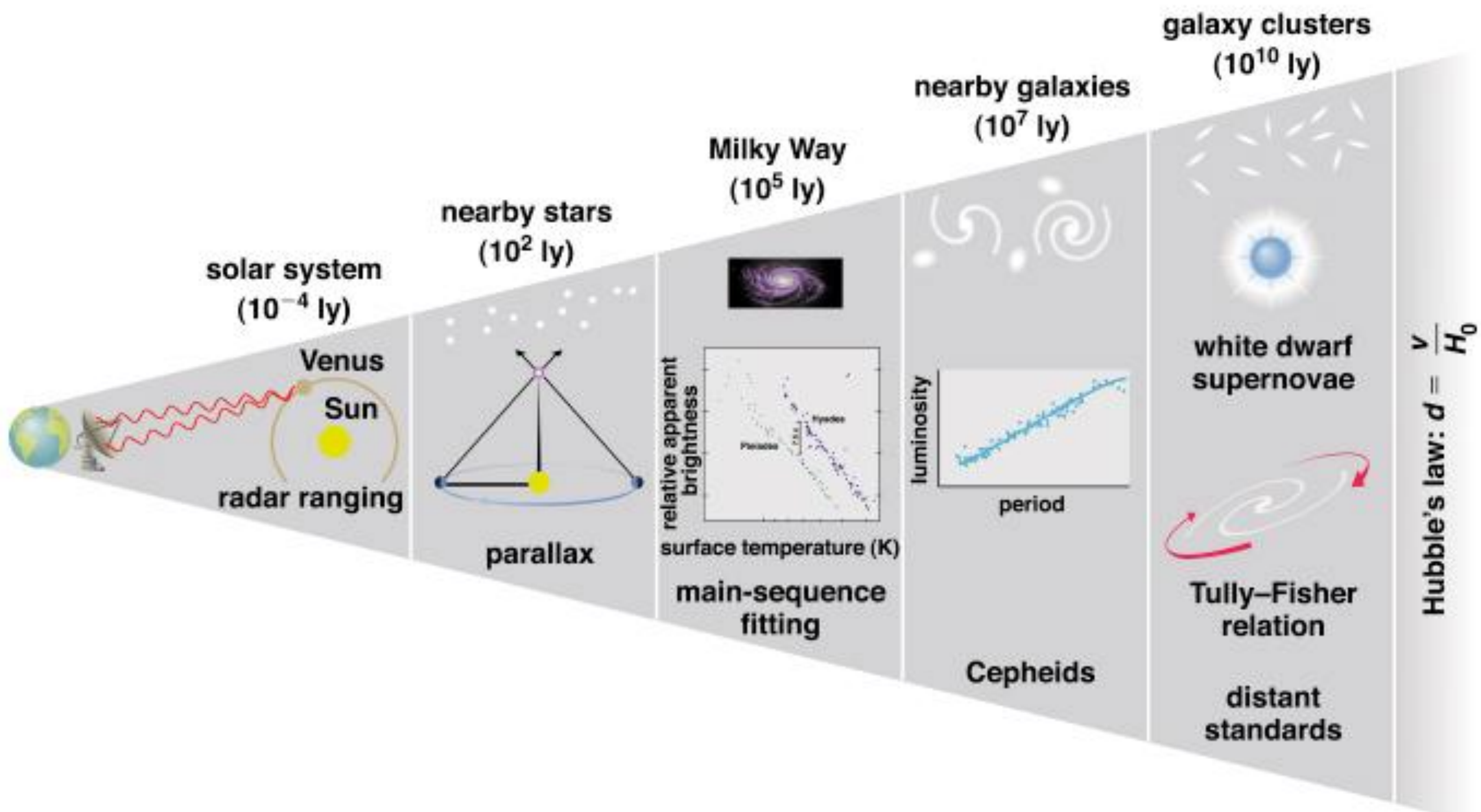


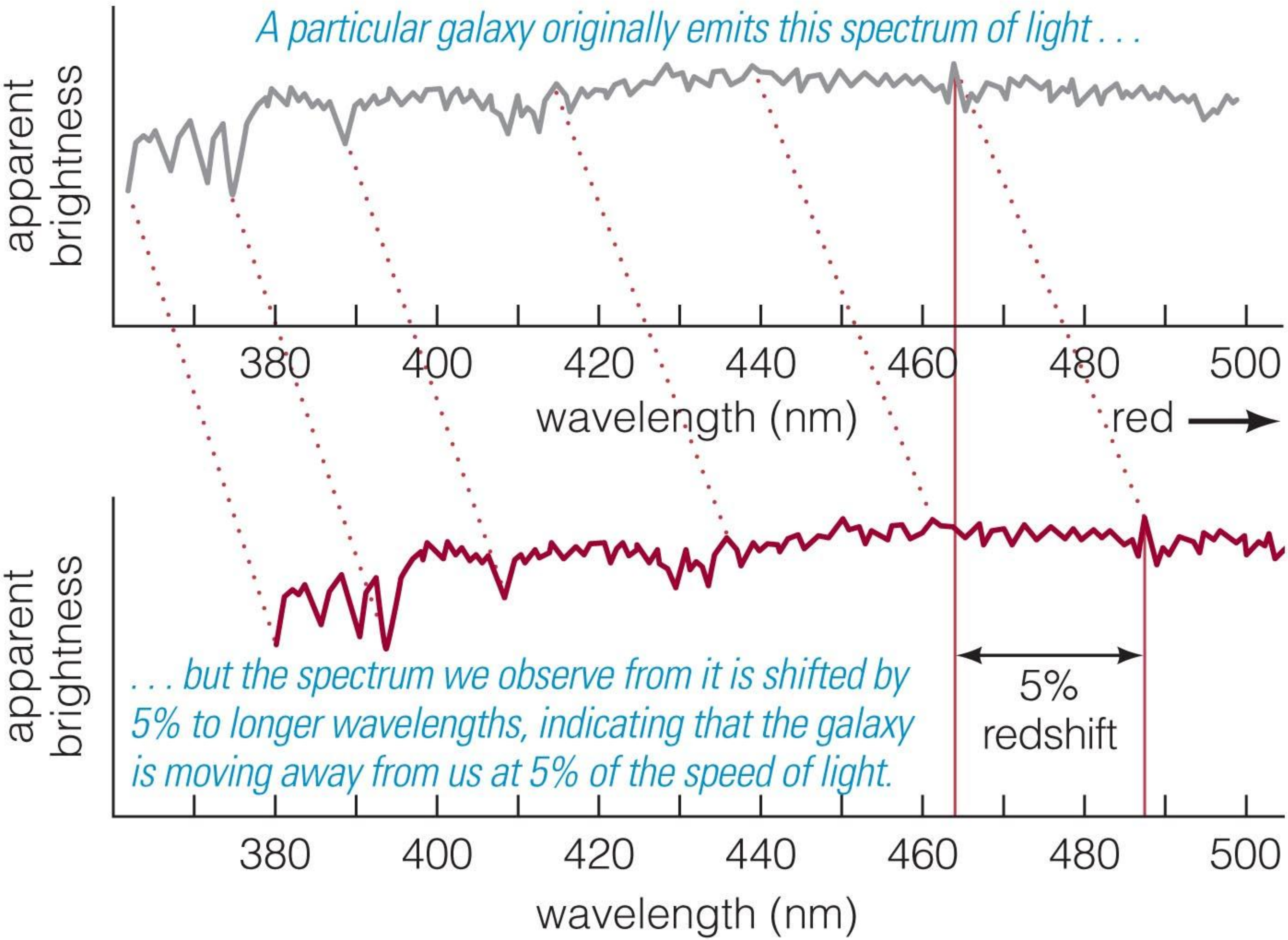
10 Gpc

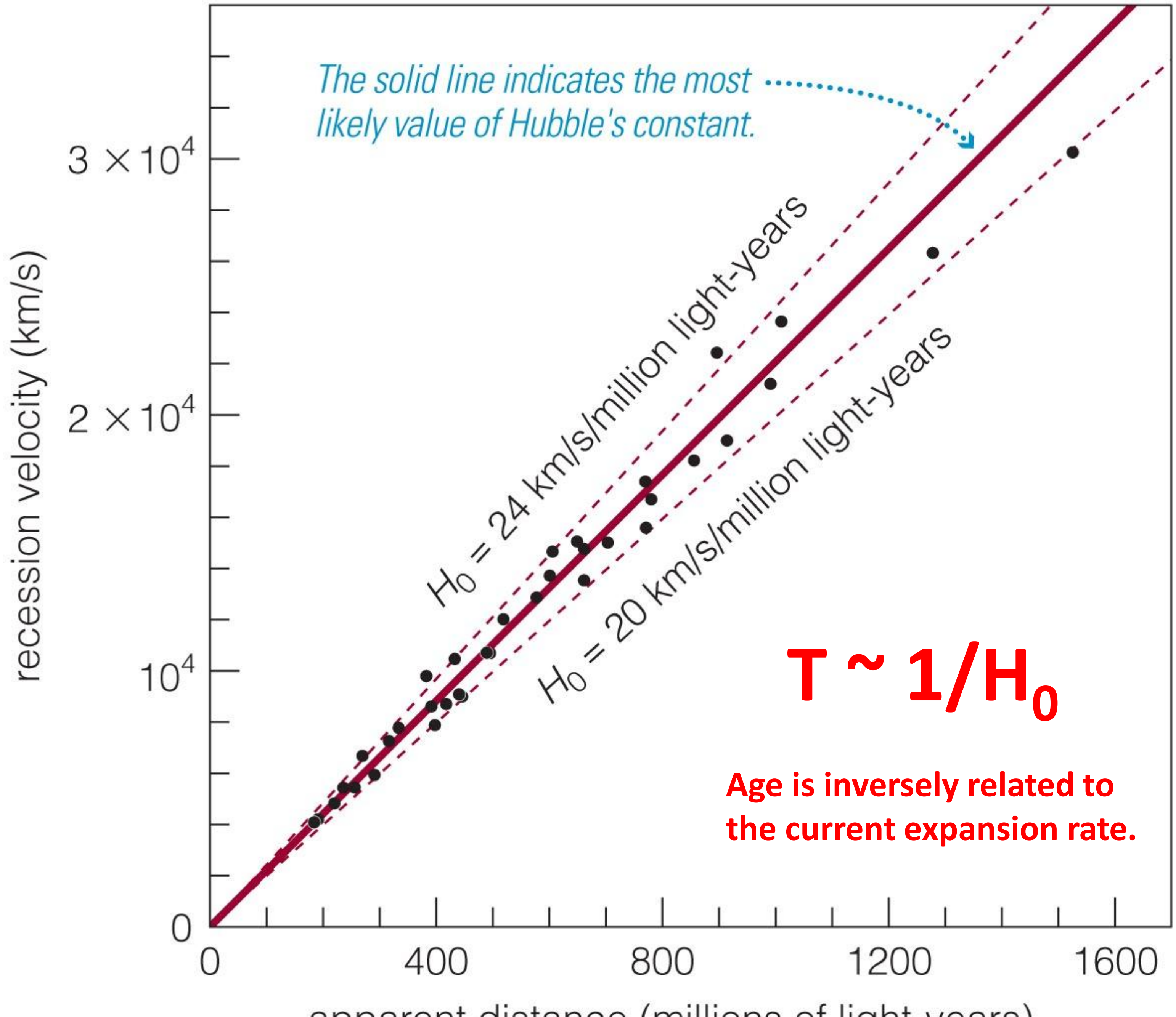
The size of the observable universe is about 10 Gpc = 10^{10} pc, or 30 billion light years. That distance is an unimaginable 10^{23} km.

The Distance Scale

- The most accurate methods for measuring distance
  - have the shortest range of applicability, so they're used…
  - to calibrate the next-most accurate method, and so on until…
  - a chain of methods can be used to measure the size of the universe!



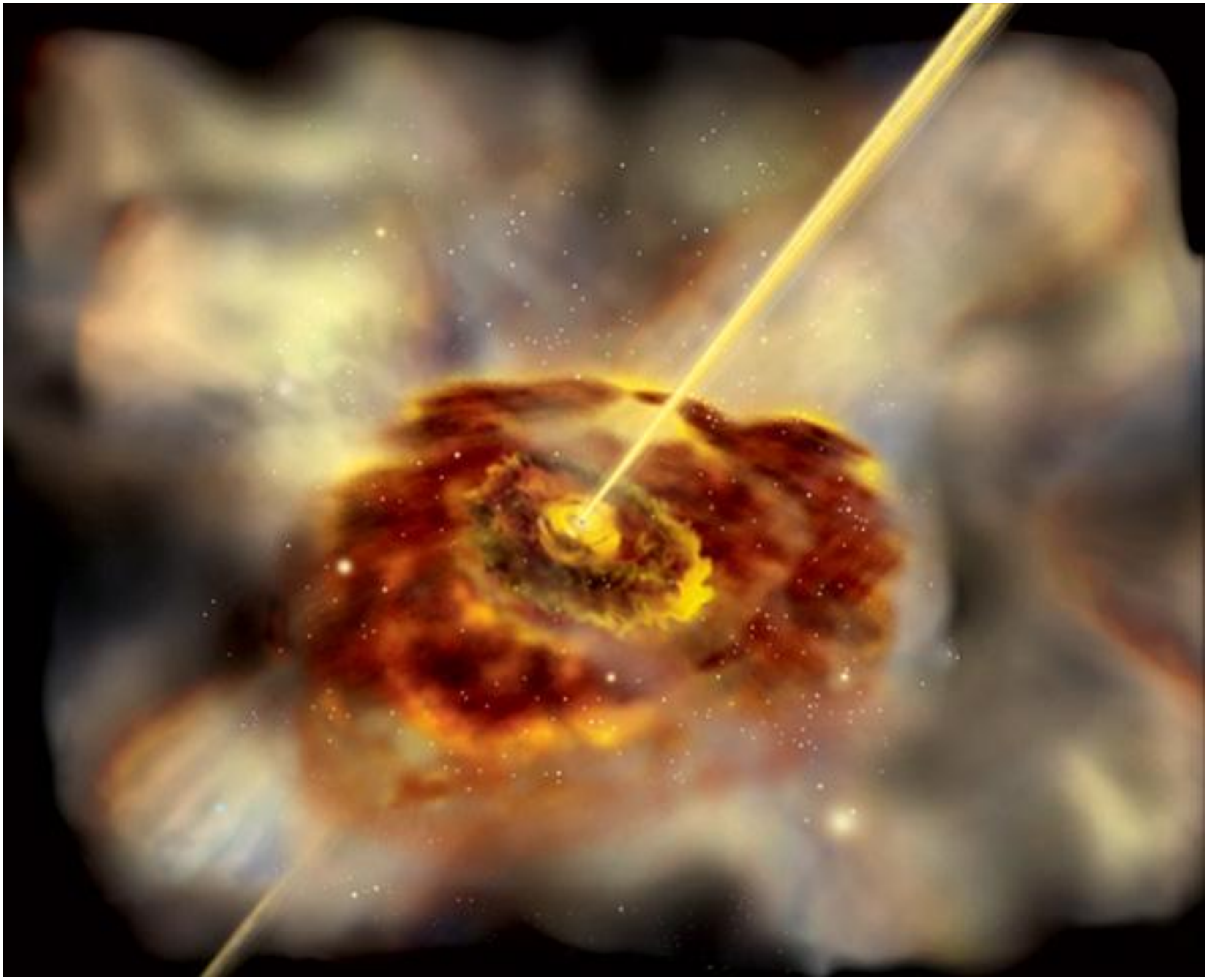

A particular galaxy originally emits this spectrum of light . . .
apparent brightness
380
400
420
440
460
480
500
wavelength (nm)
red
apparent brightness
. . . but the spectrum we observe from it is shifted by 5% to longer wavelengths, indicating that the galaxy is moving away from us at 5% of the speed of light.
5% redshift
380
400
420
440
460
480
500
wavelength (nm)



$T \sim 1/H_0$

Age is inversely related to the current expansion rate.

Active Galaxies



Active Galaxies

Seyfert Galaxies

- spiral galaxies with an incredibly bright, star-like center (nucleus)
- they are very bright in the infrared
- their spectra show strong **emission** lines

NGC 1566

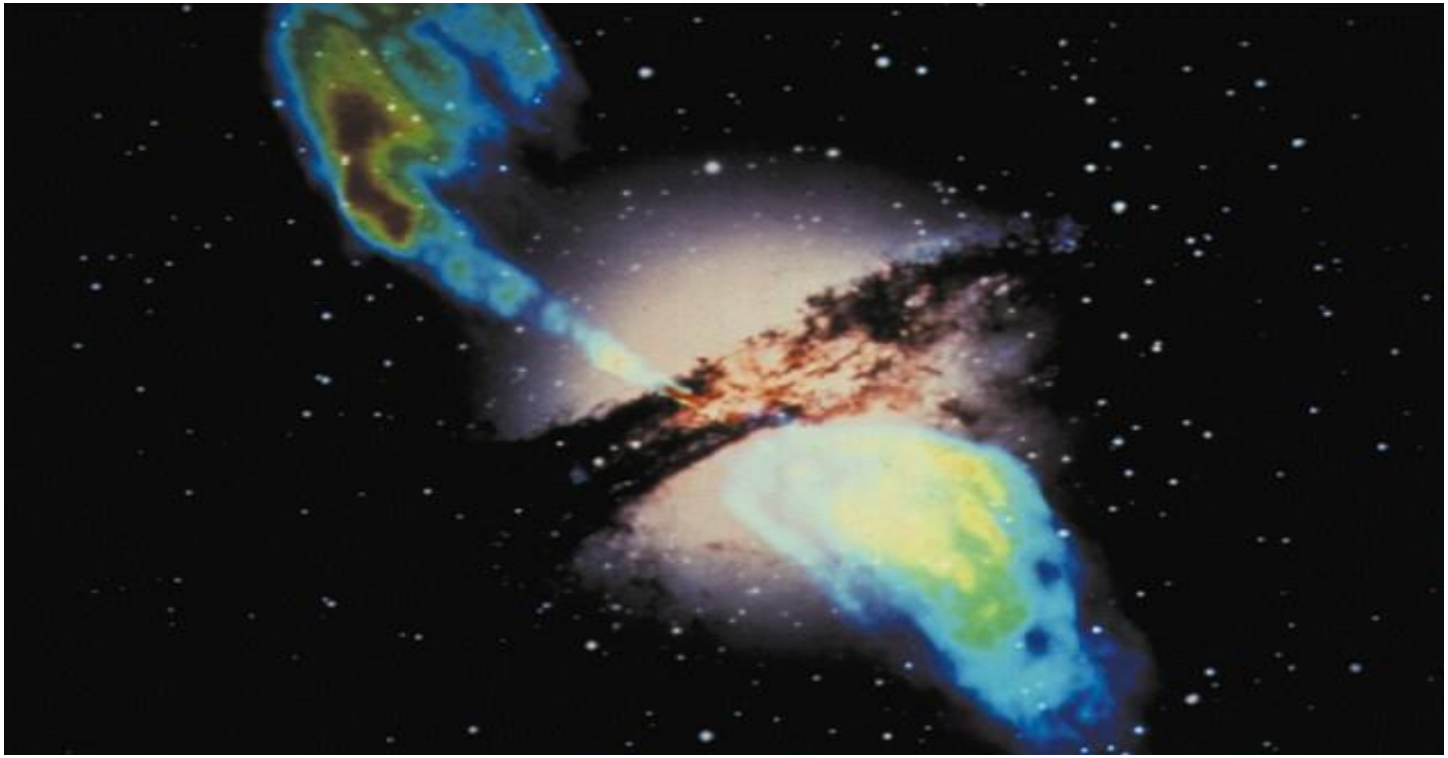
The luminosity can vary by as much as the entire brightness of the Milky Way Galaxy!

Active Galaxies

Radio Galaxies

- galaxies which emit large amounts of radio waves
- the radio emission come from *lobes* on either side of the galaxy; **not** the galaxy itself

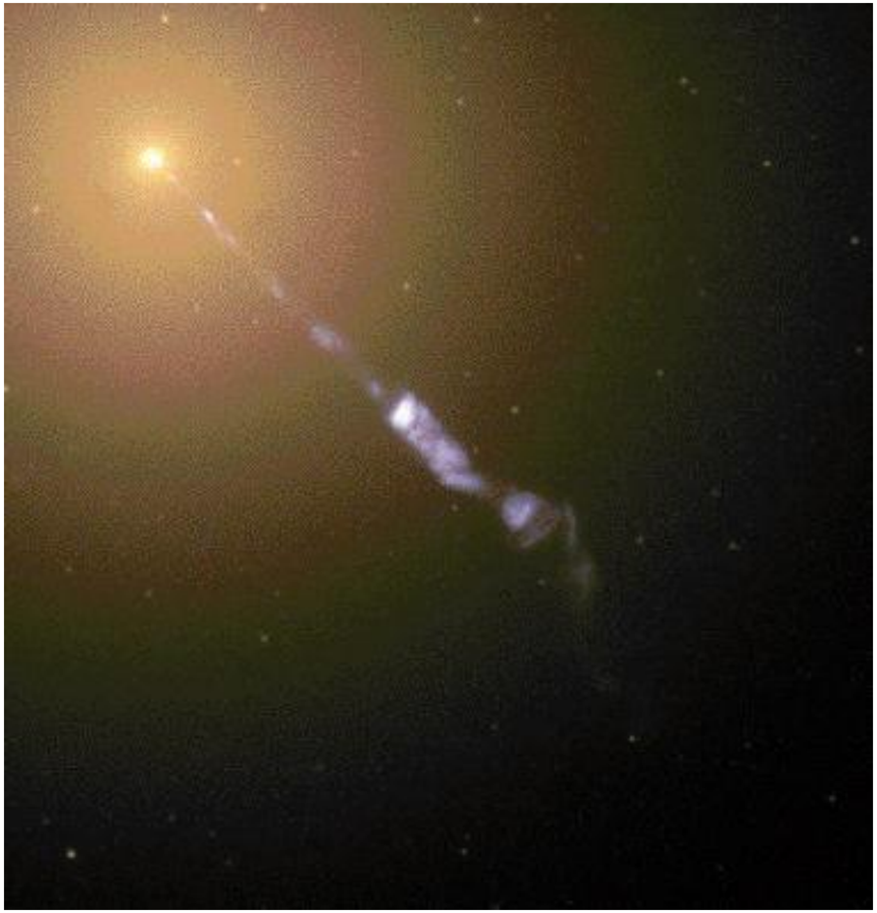
Centaurus A



Active Galactic Nuclei

Jets of matter are shooting out from these galaxies and emitting radio waves, but the matter is **not** cold.

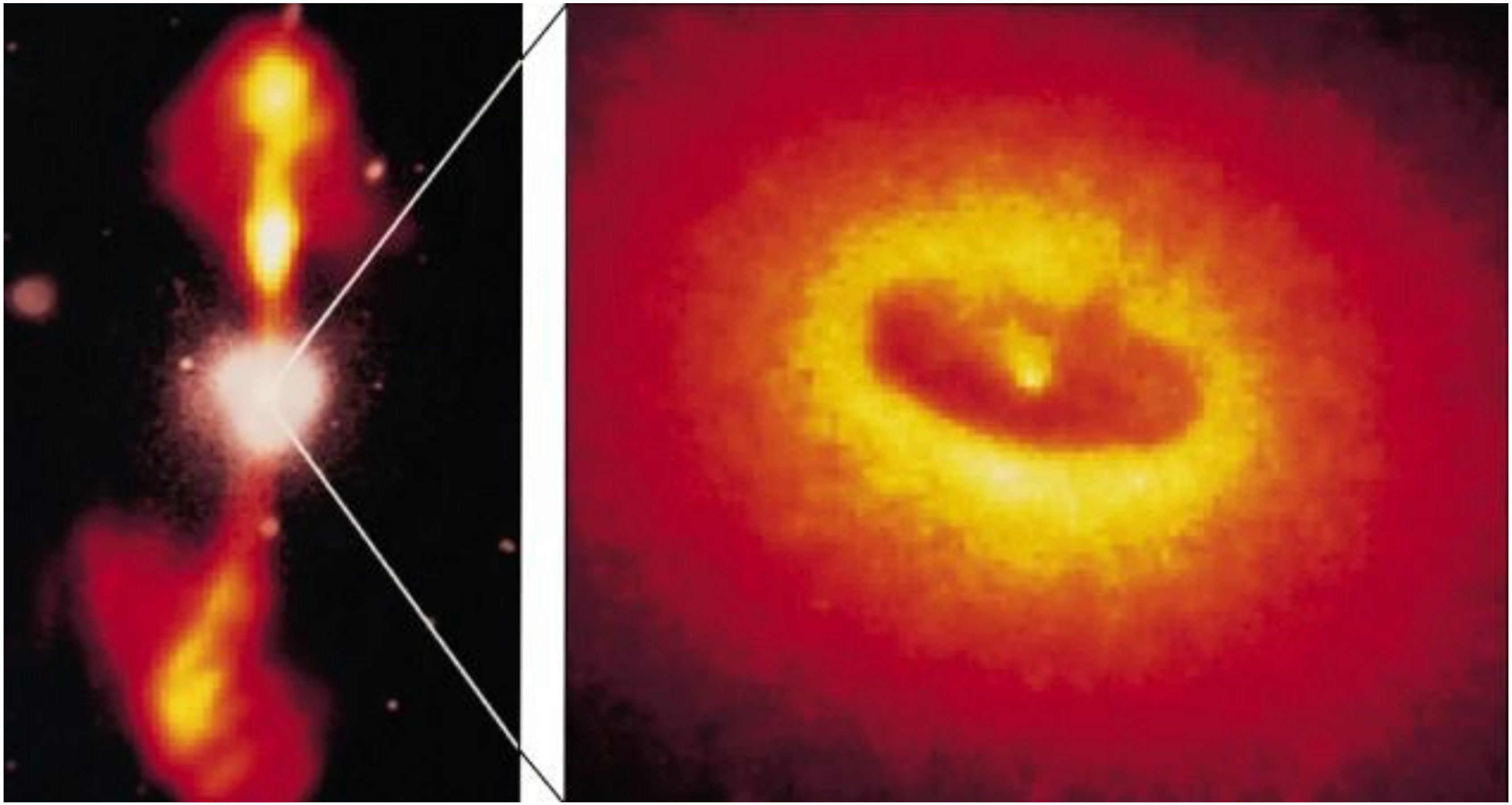
Synchrotron emission: a non-thermal process where light is emitted by charged particles moving close to the speed of light around magnetic fields. Energies far exceed those of the world's best accelerators.



M 87

What powers these Active Galaxies?

Hubble Space Telescope gave us a clue

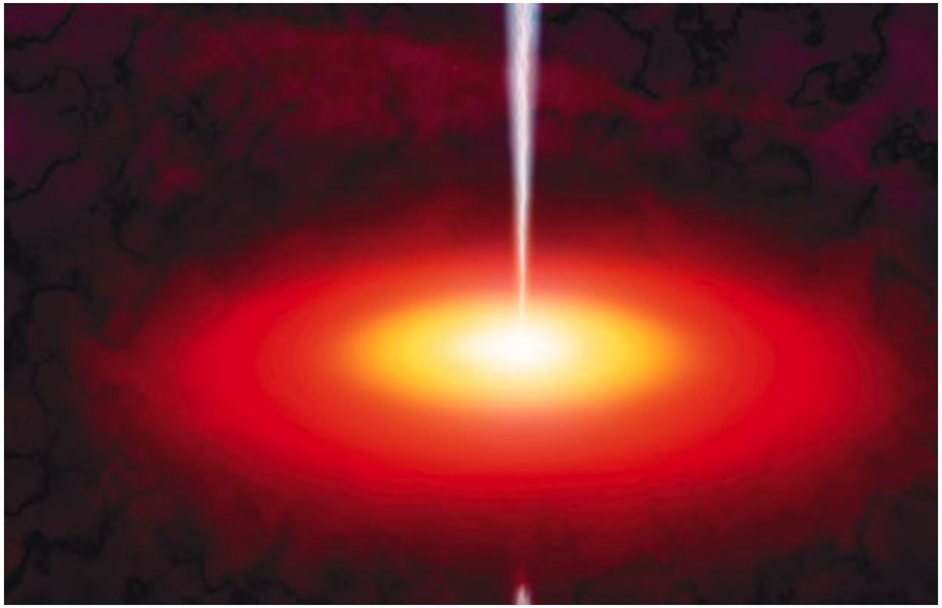


NGC 4261

Active Galactic Nuclei (AGN)

- The energy is generated by a gravity "engine," from matter falling onto a vast **supermassive black hole**.
  - $1 \times 10^9\ M_\odot$ for NGC 4261
  - $3 \times 10^9\ M_\odot$ for M87

It sits precisely at the center (nucleus) of the galaxy.

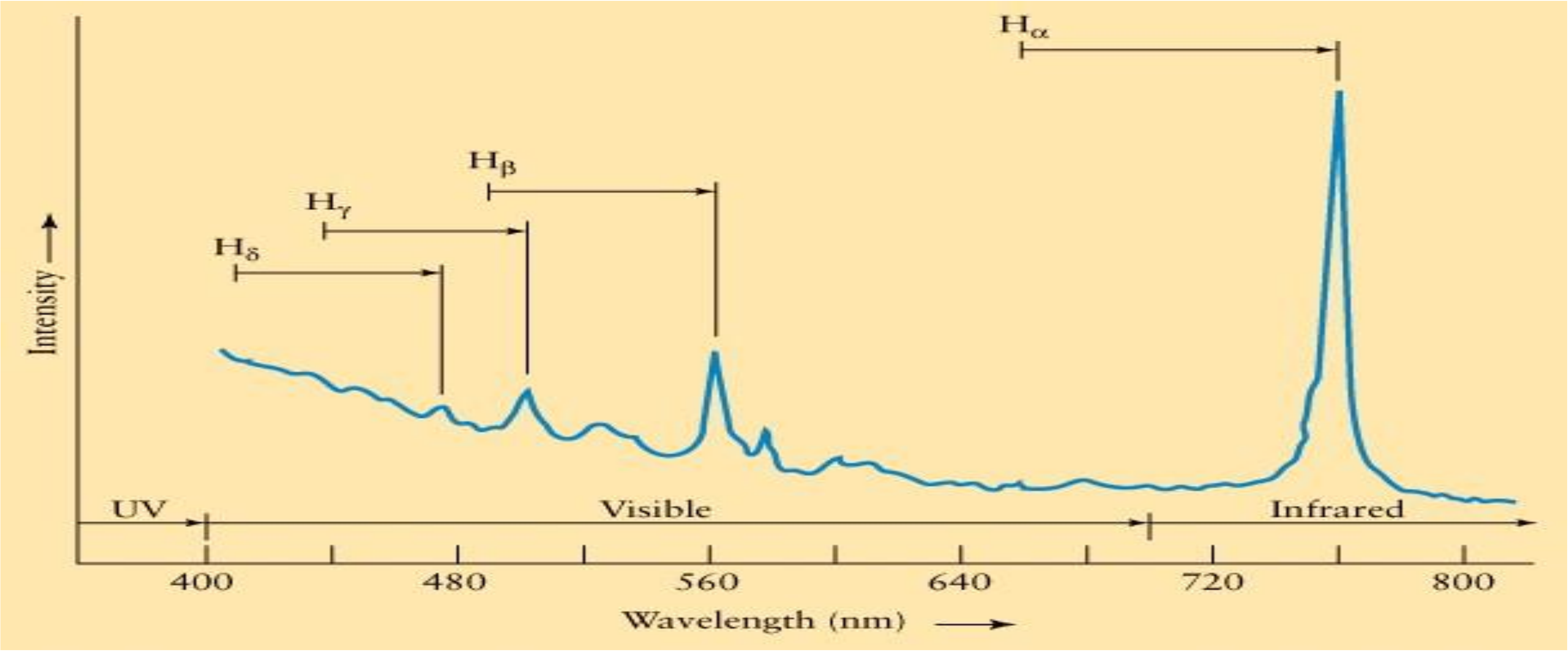


- Matter swirls through an accretion disk before crossing over the event horizon.
- Gravitational pot. energy lost
  - $= mc^2$ the mass energy
  - 10 – 40% of this is radiated away
- Process is very efficient for generating energy.

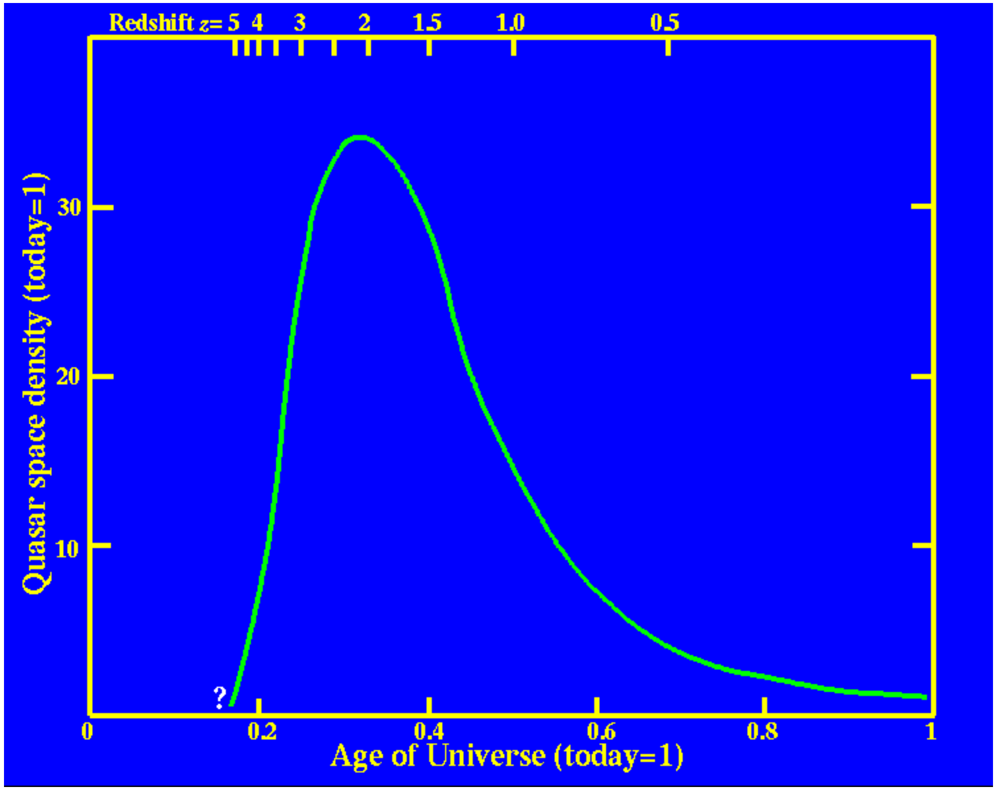
Quasars

Star-like objects which:

- can be strong radio sources
- have spectra which look nothing like a star
- show UV emission from an accretion disk



Quasars



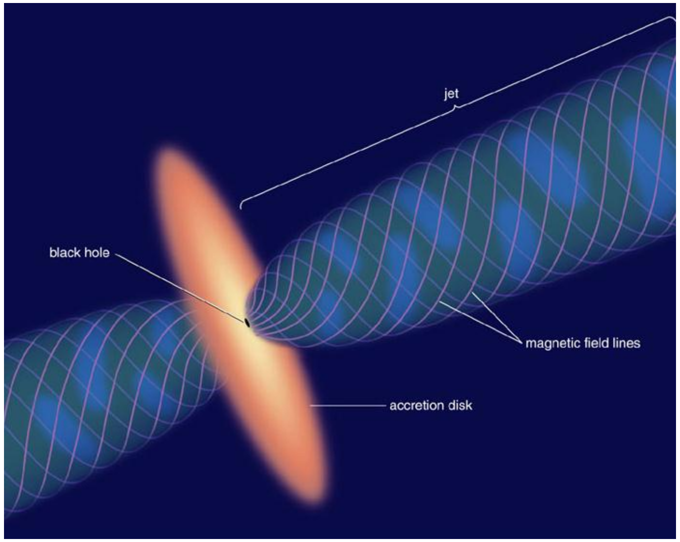
Maarten Schmidt discovered that the broad emission lines belonged to normal elements, but they're highly redshifted (to up to 50% of light speed).

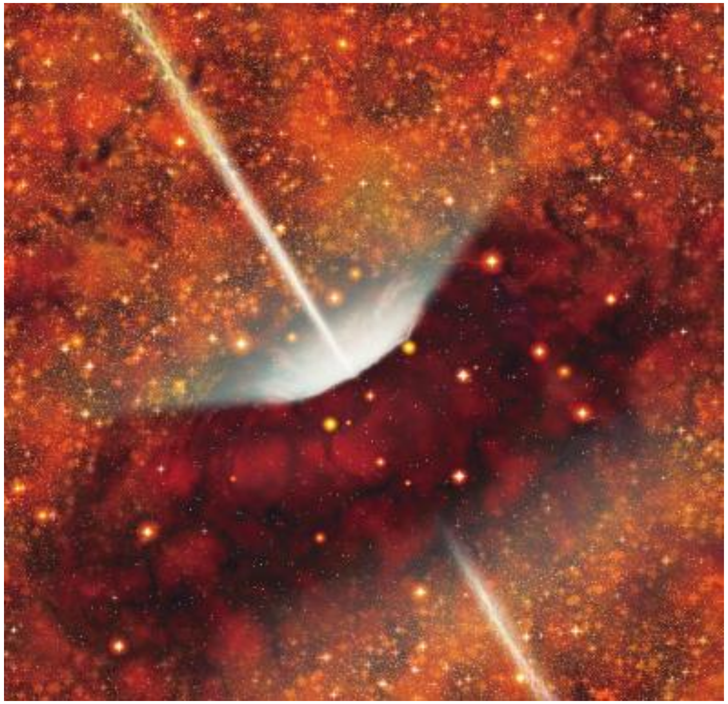
The quasars are all very (> 10^{10} light years) remote. The farther away we look out in distance, the farther back we also look in cosmic *time*!

Quasars peaked in number and brightness about 8 billion years and have faded or died since then.

Formation of Jets

- twisted magnetic fields in accretion disks
- they pull charged particles out of the disk and accelerate them like a slingshot
- particles are bound to a magnetic field; then focused in a beam

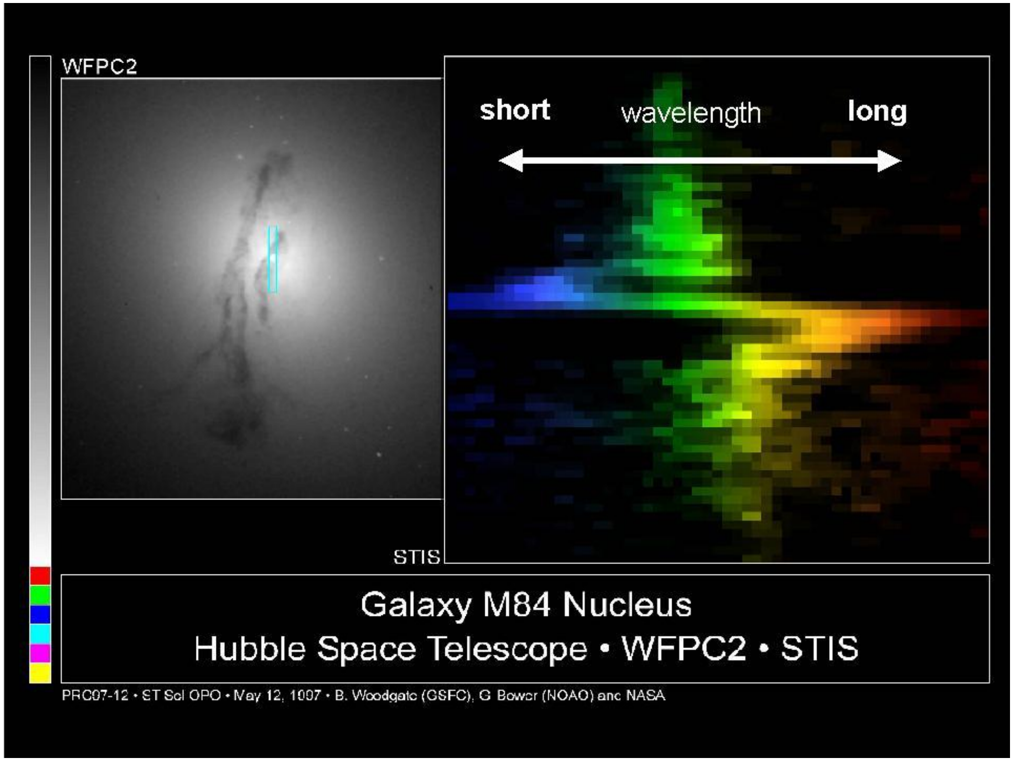




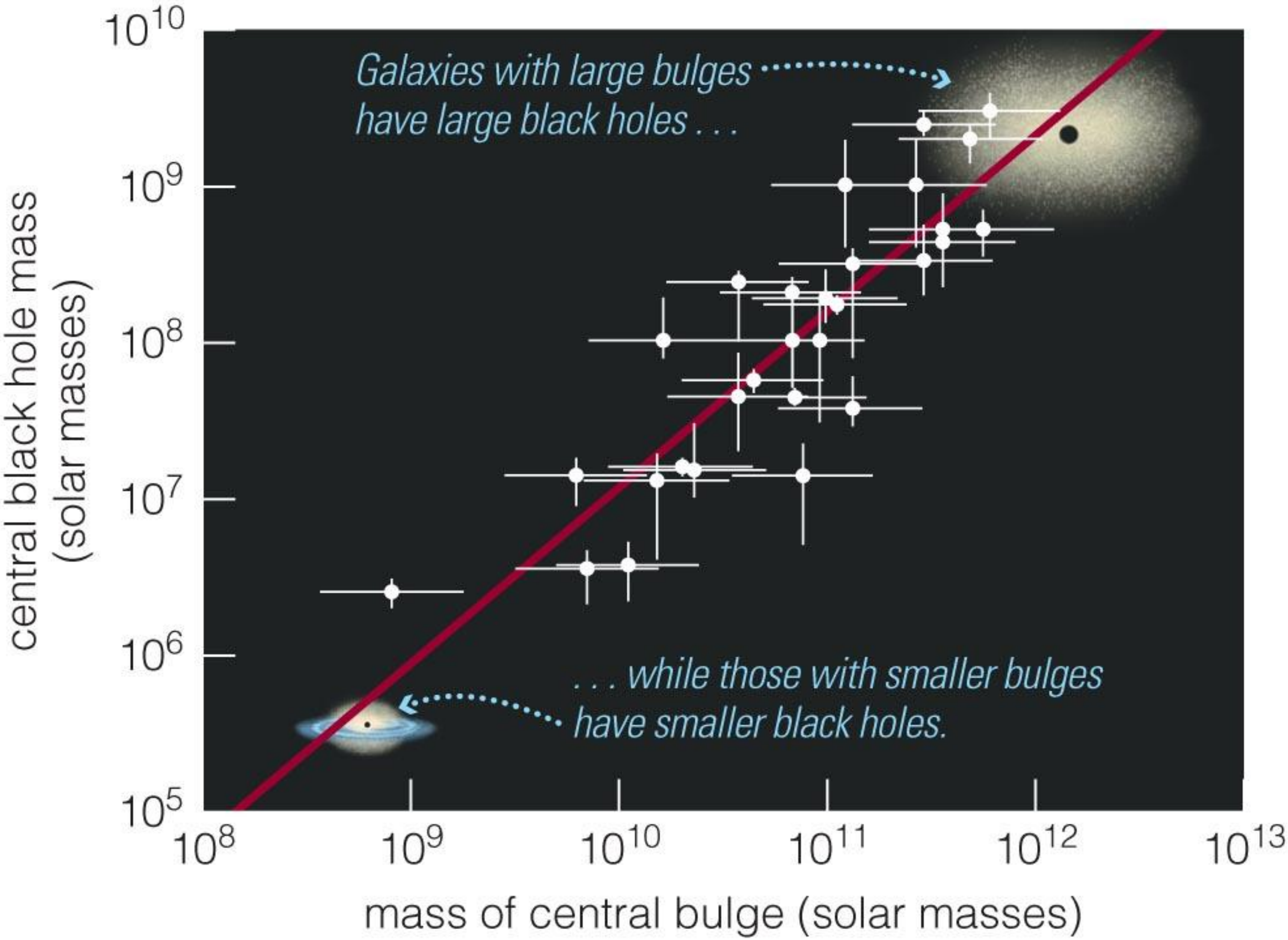
- The orientation of the beam determines what we see:
  - if beams points at us, we see a **quasar**
  - if not, the molecular clouds/dust of the galaxy block our view of the nucleus
  - so we see a **radio galaxy**
  - lobes are where jets impact intergalactic medium, heating the diffuse gas

Black Holes in Galaxies

- Many nearby galaxies—perhaps all of them—have supermassive black holes at their centers. The Milky Way is a good example.
- These black holes seem to be dormant active galactic nuclei.
- All galaxies may have passed through a quasar-like stage earlier in time. The BH is revealed by high gas velocities near the center.

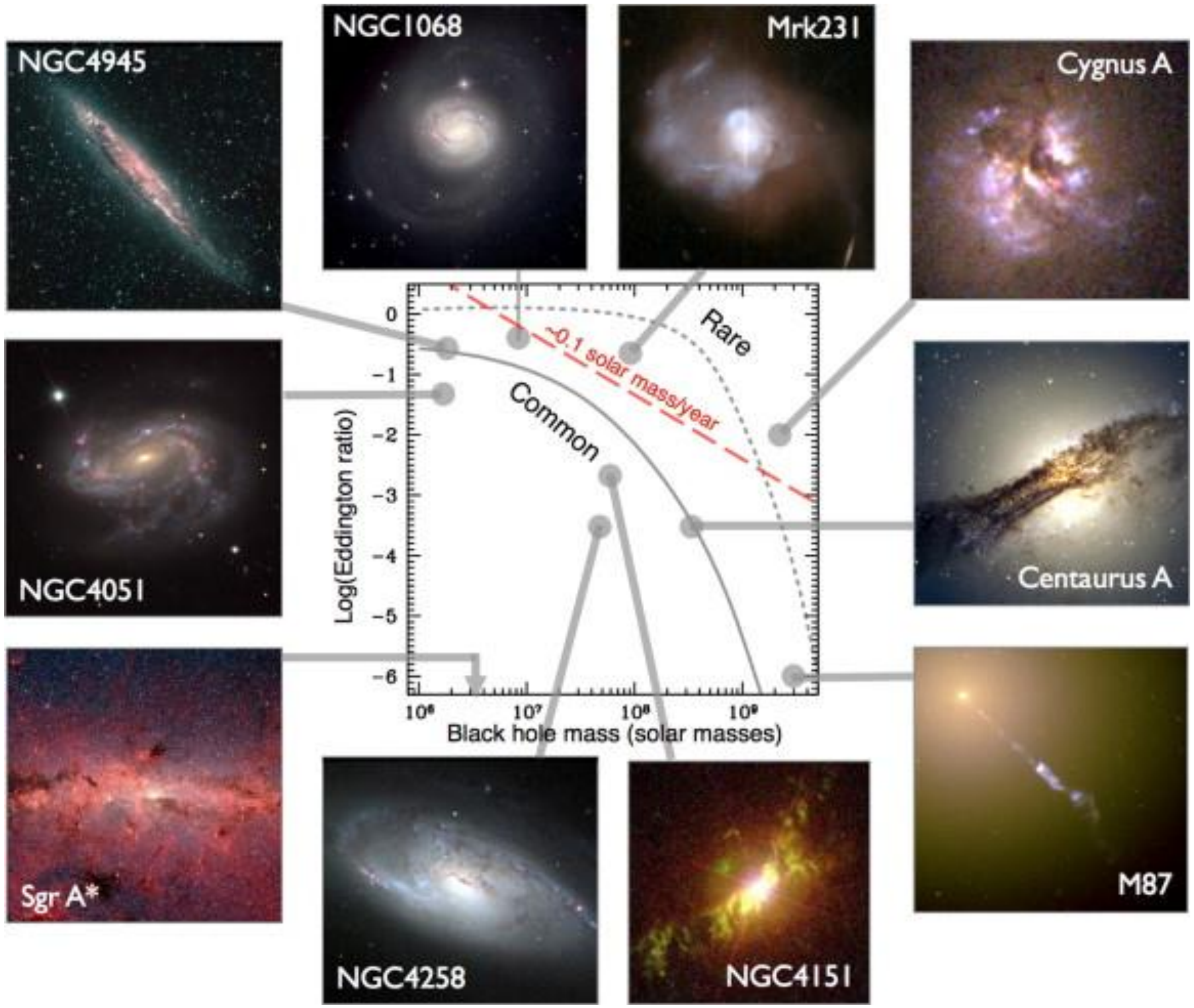


Galaxies and Black Holes



AGN Fueling

Rapid Fueling

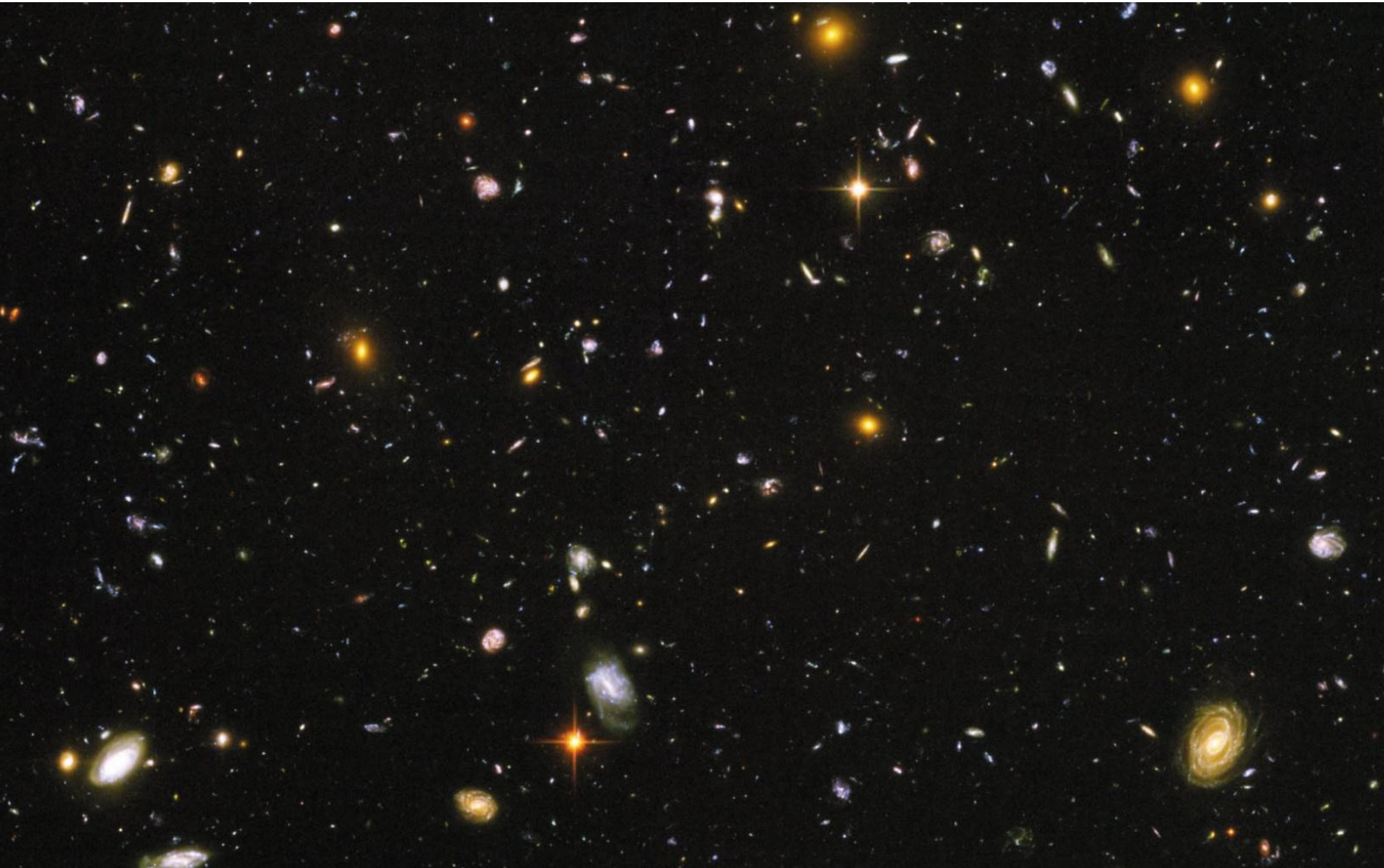


Slow Fueling

Low Mass

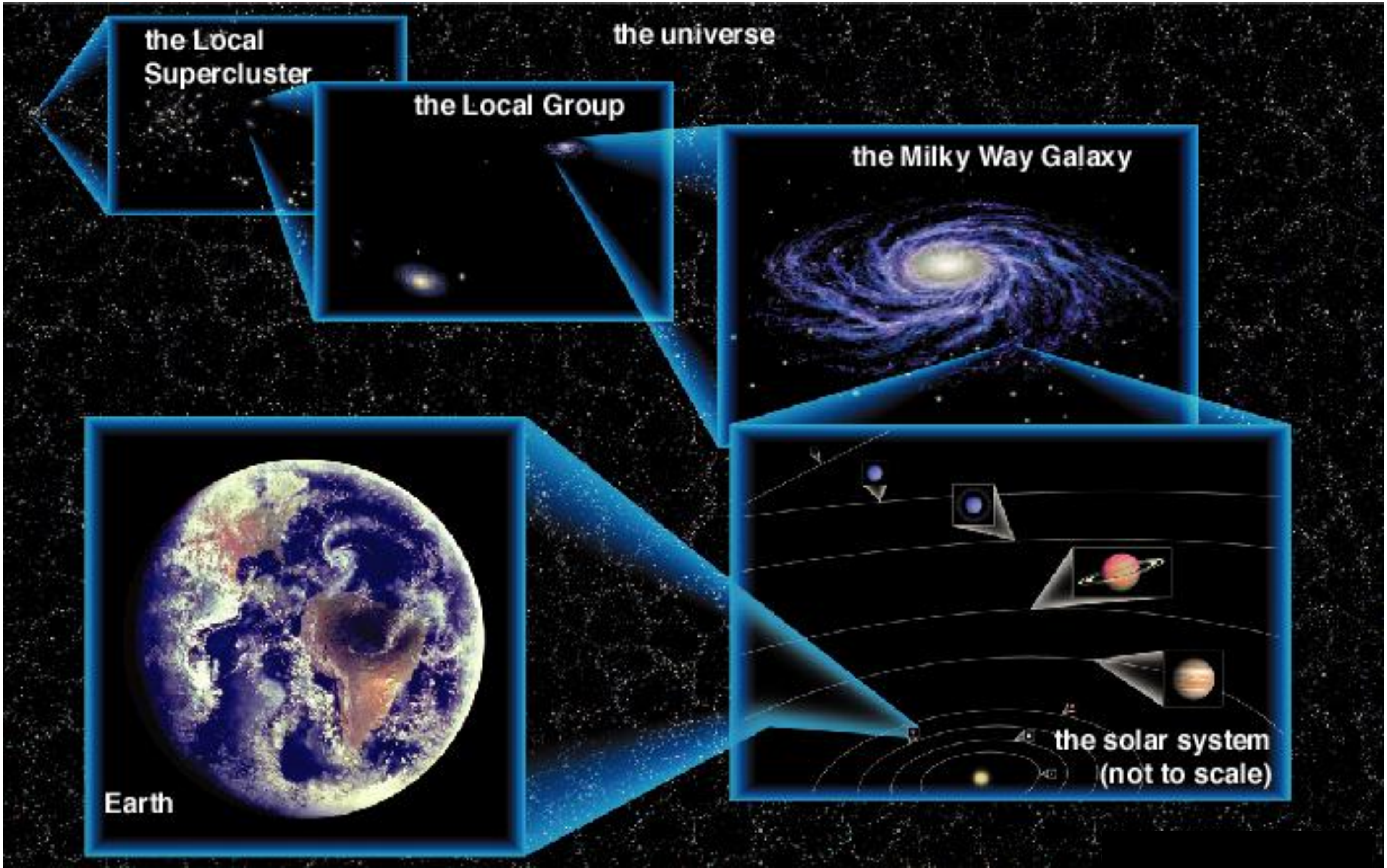
High Mass

Large Scale Structure

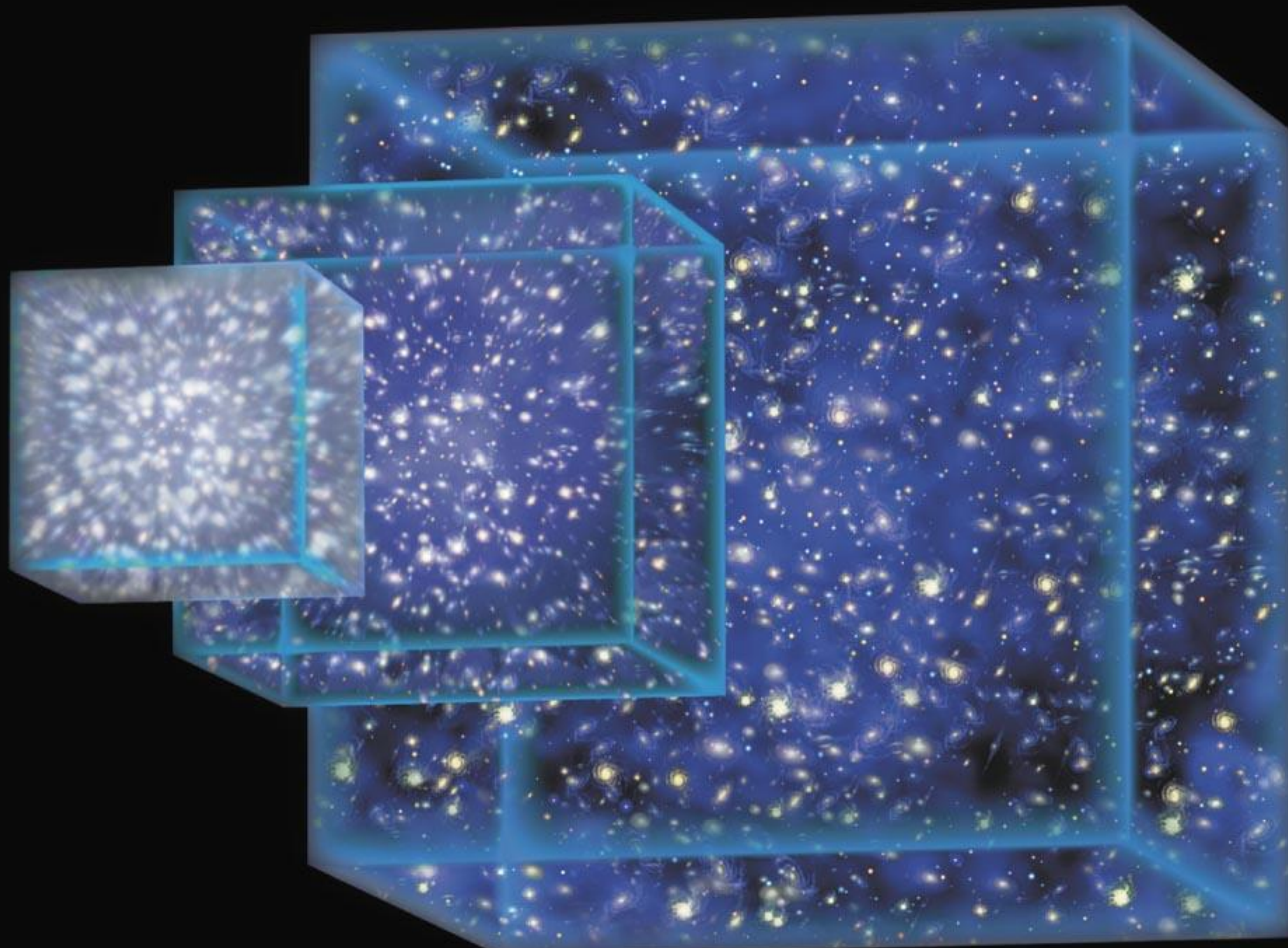


What is our place in the universe?

- Our “Cosmic Address” on a vast hierarchy of different scales.

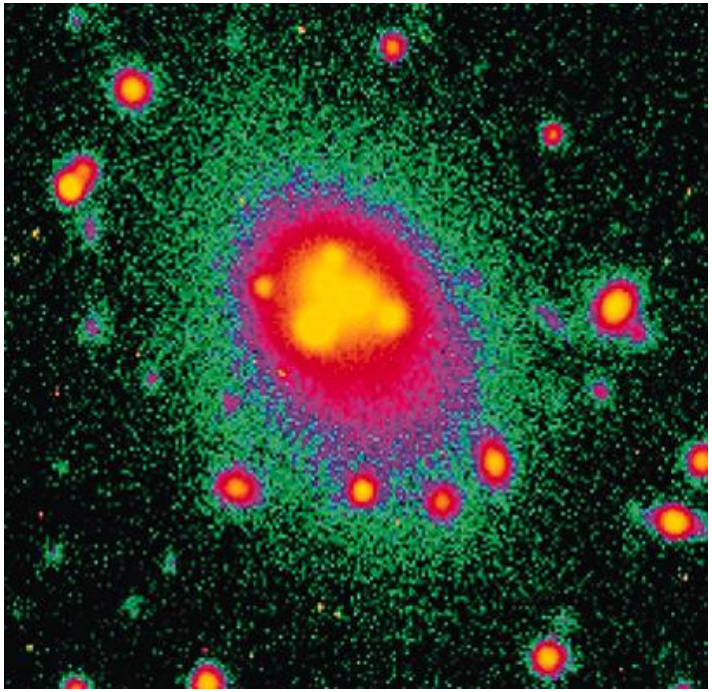


1 **Birth of the Universe:** The expansion of the universe began with the hot and dense Big Bang. The cubes show how one region of the universe has expanded with time. The universe continues to expand, but on smaller scales gravity has pulled matter together to make galaxies.



Galaxy Clusters

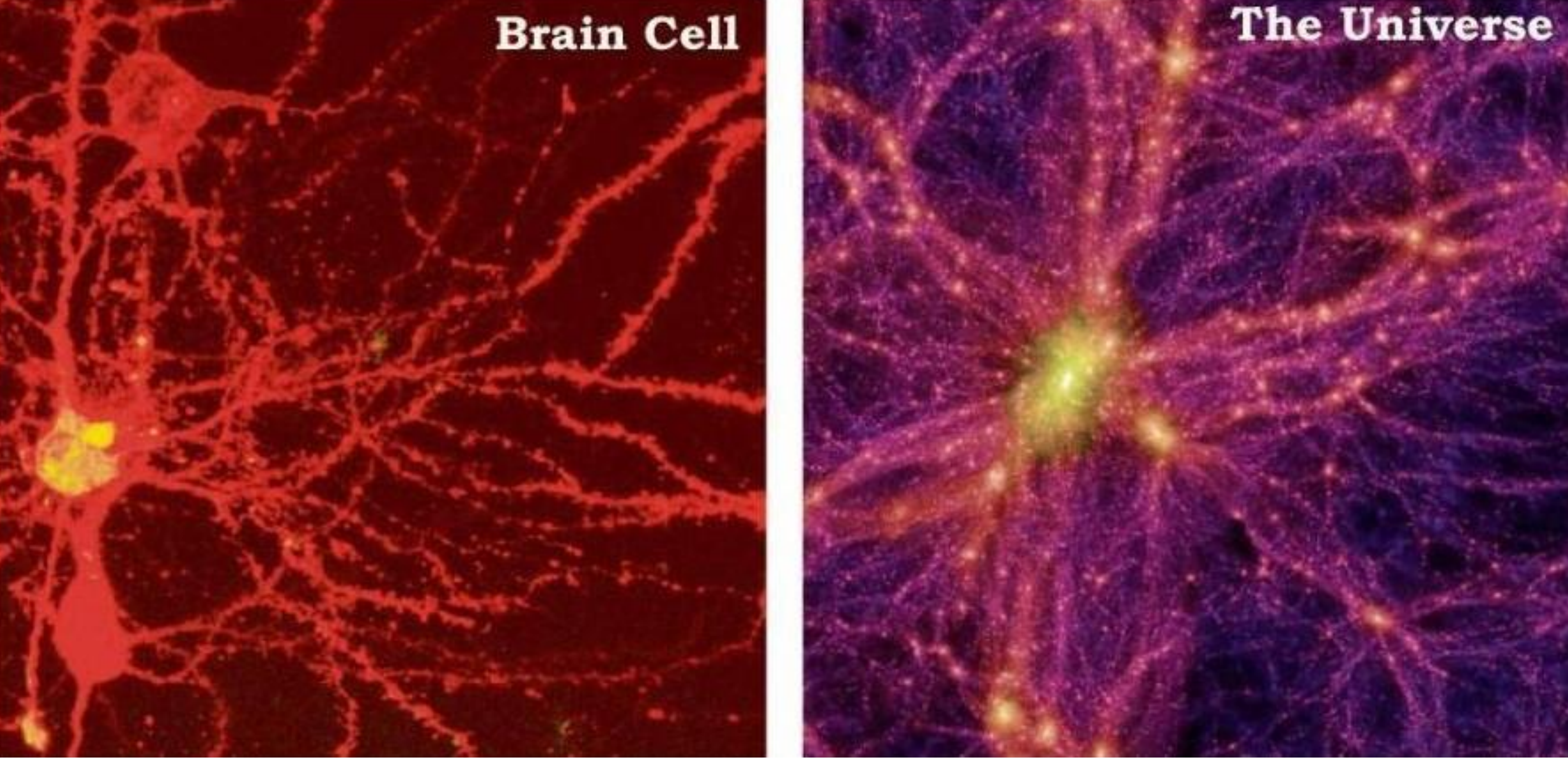
- Galaxy clusters provide evidence that some galaxies are shaped by interactions:
  - elliptical galaxies are more common in cluster centers
  - collisions will occur more often in crowded cluster centers
  - **central dominant (CD) galaxies** are gigantic ellipticals in cluster centers
  - they grow large by consuming other galaxies



- These giant galaxies often contain tightly bound clumps of stars.
- They are probably the leftover cores of galaxies which were *cannibalized* by the CD.
- Some are more than 10 times as massive as the Milky Way.

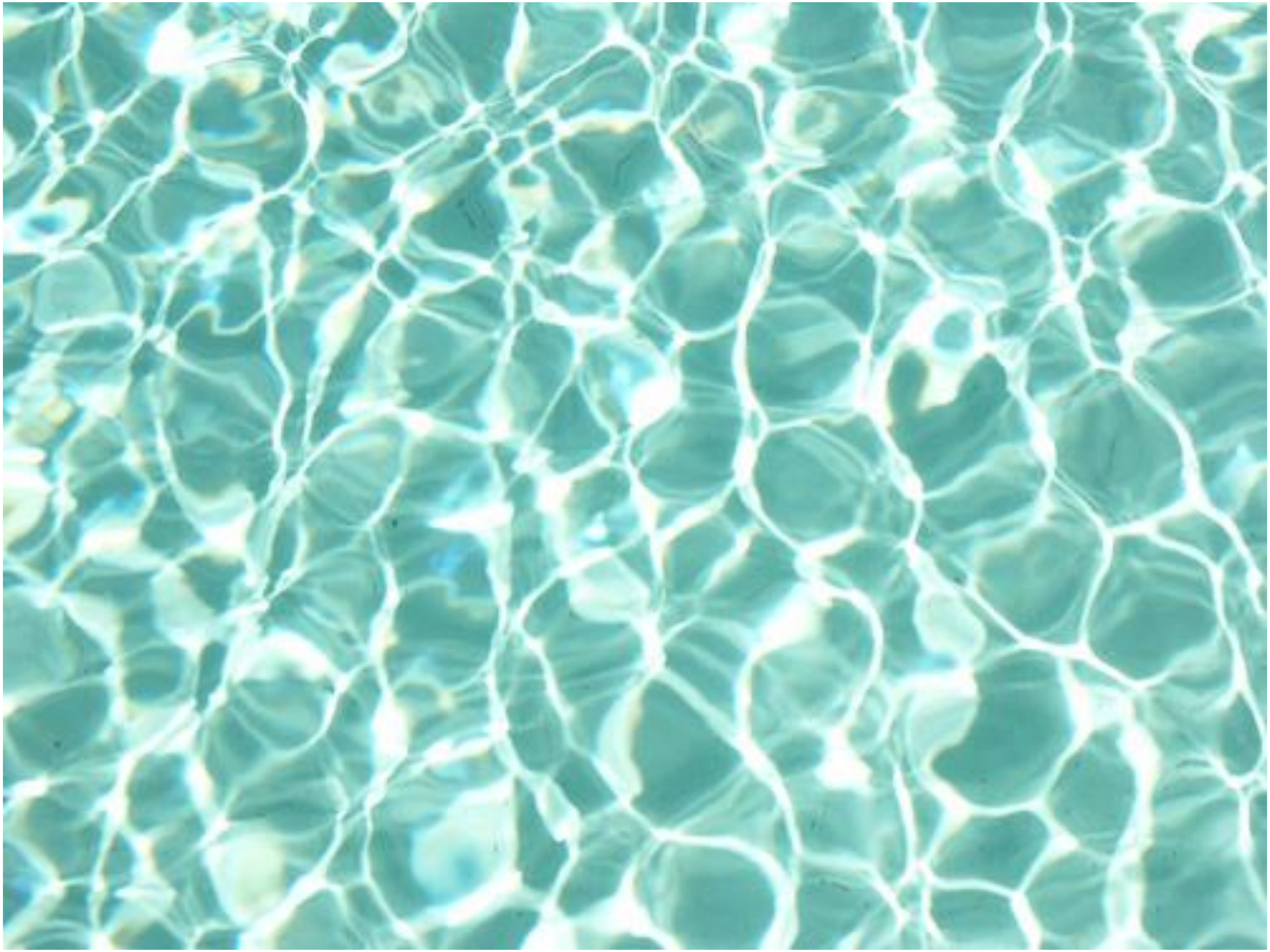
Mass of a Cluster

- There are three independent ways to measure galaxy cluster mass:
  1. measure the **speeds and positions of the galaxies** within the cluster
  2. measure the **temperature and distribution of the hot gas** between the galaxies
  3. observe how **clusters bend light** as gravitational lenses
- They all agree within a factor of two or so and indicate that 80-90% of a cluster is dark matter.

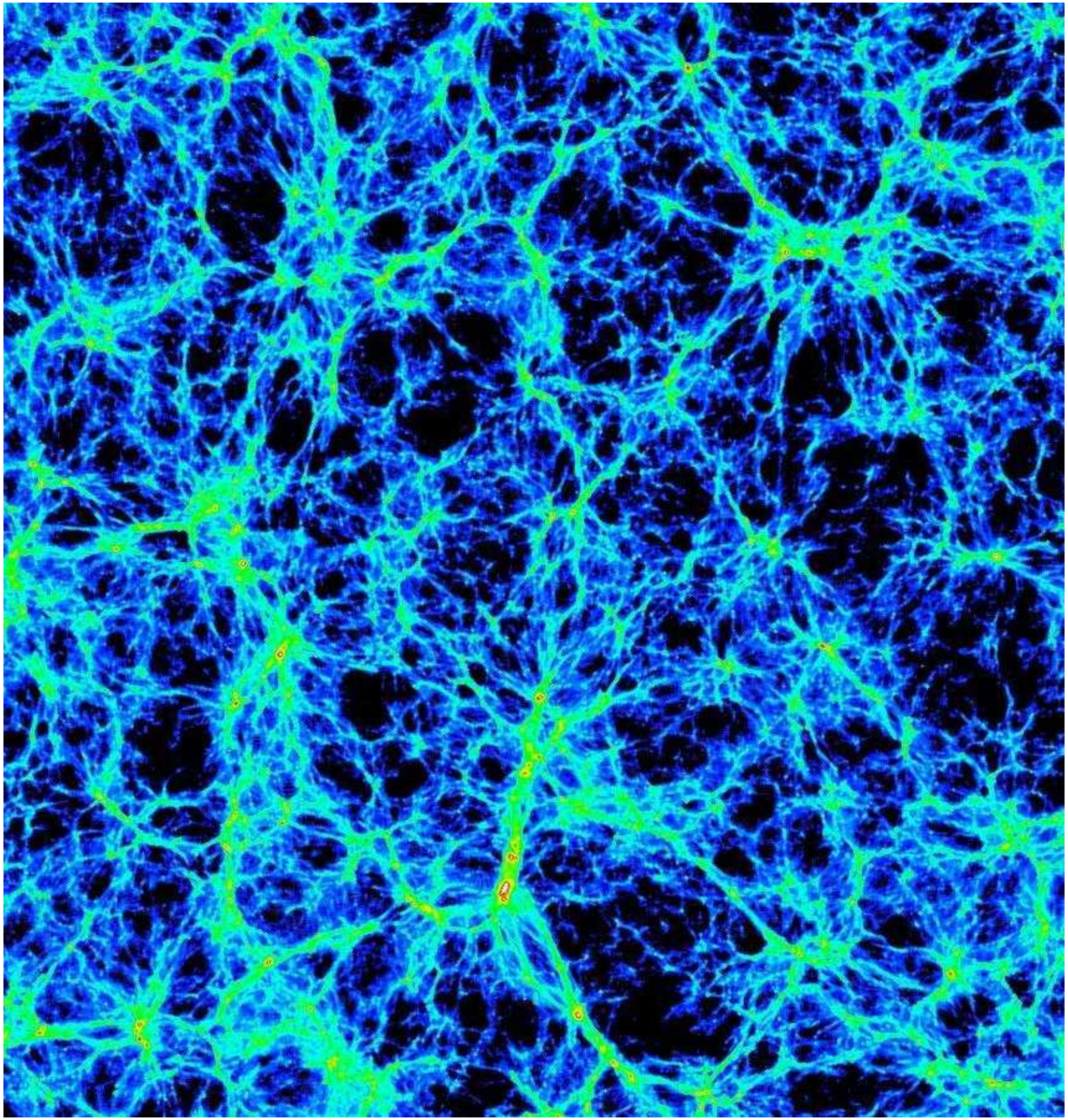


Sometimes the structures in physics and biology are strikingly similar, and can be described by similar mathematical forms, in this case a multi-scale fractal pattern.

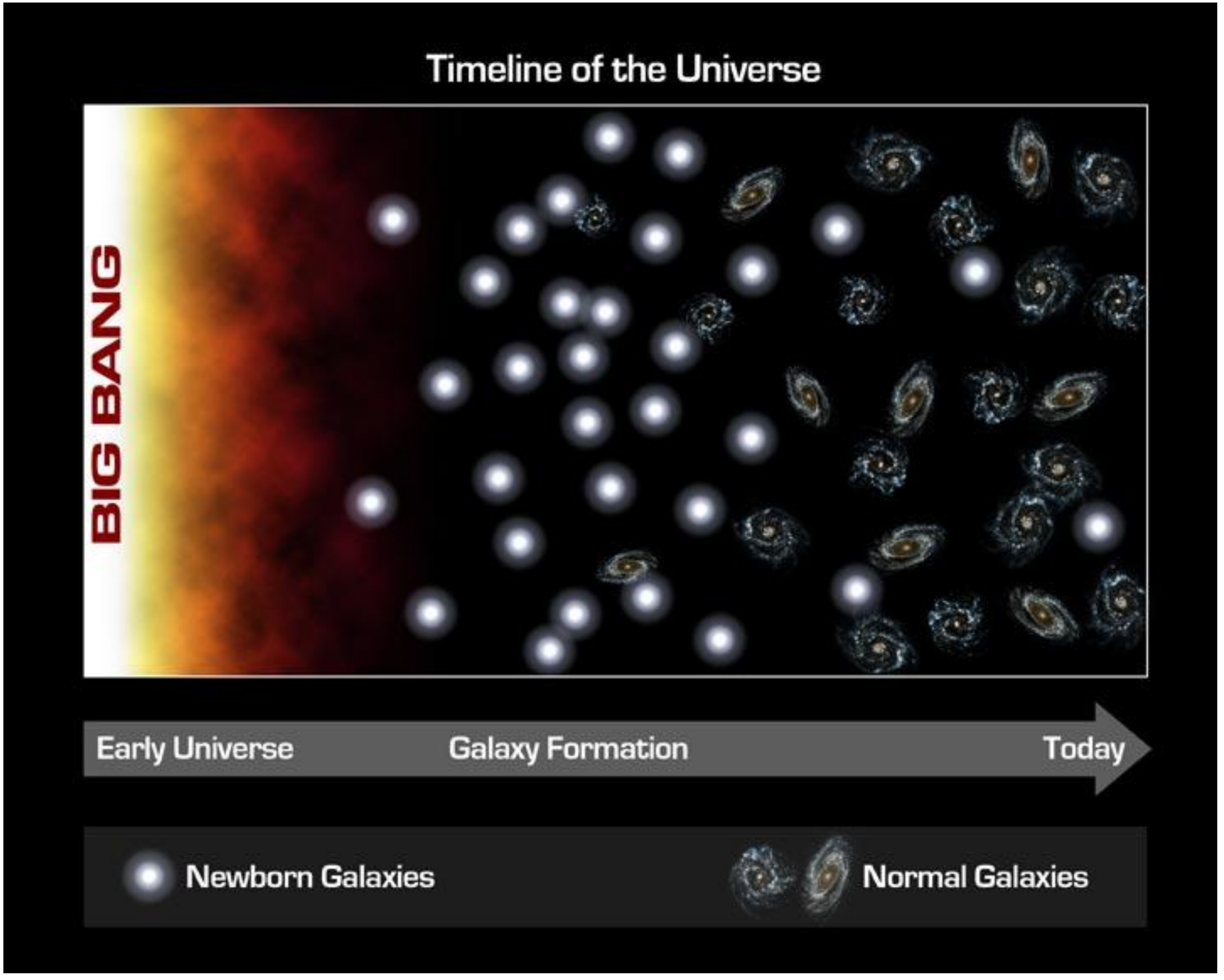
STRUCTURE AND COMPLEXITY: LIGHT IN A POOL



AND STRUCTURE IN THE UNIVERSE

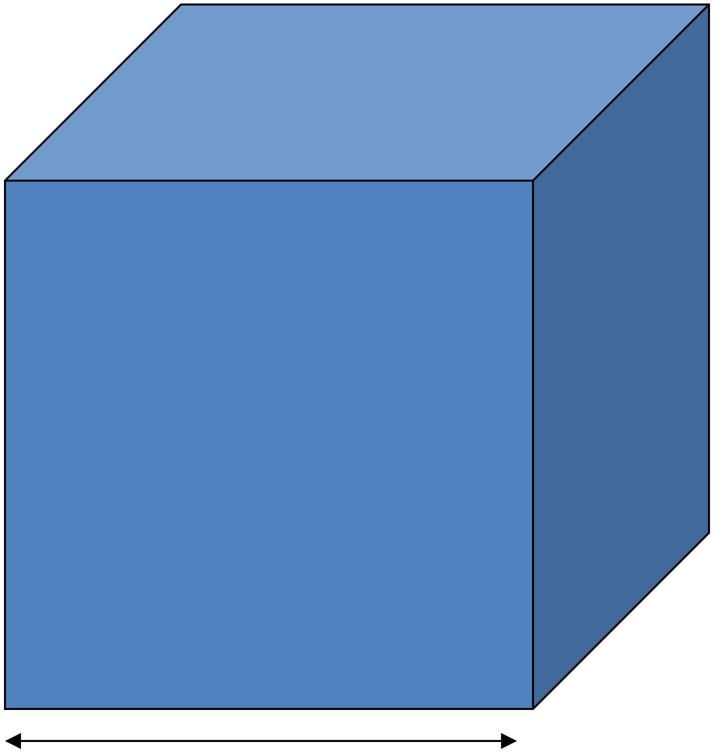


Structure Formation



Simulations

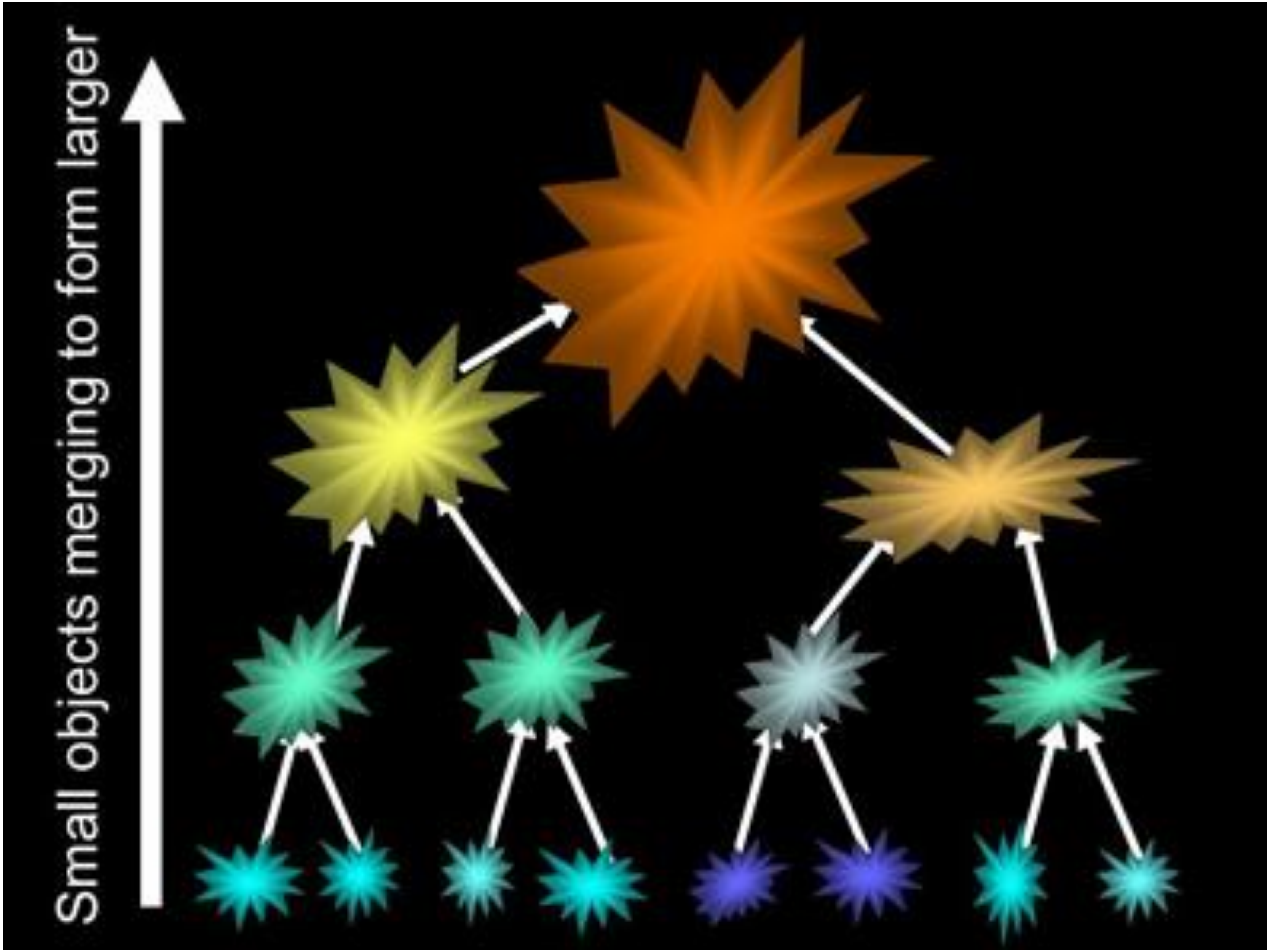
UNIVERSE IN A COMPUTER

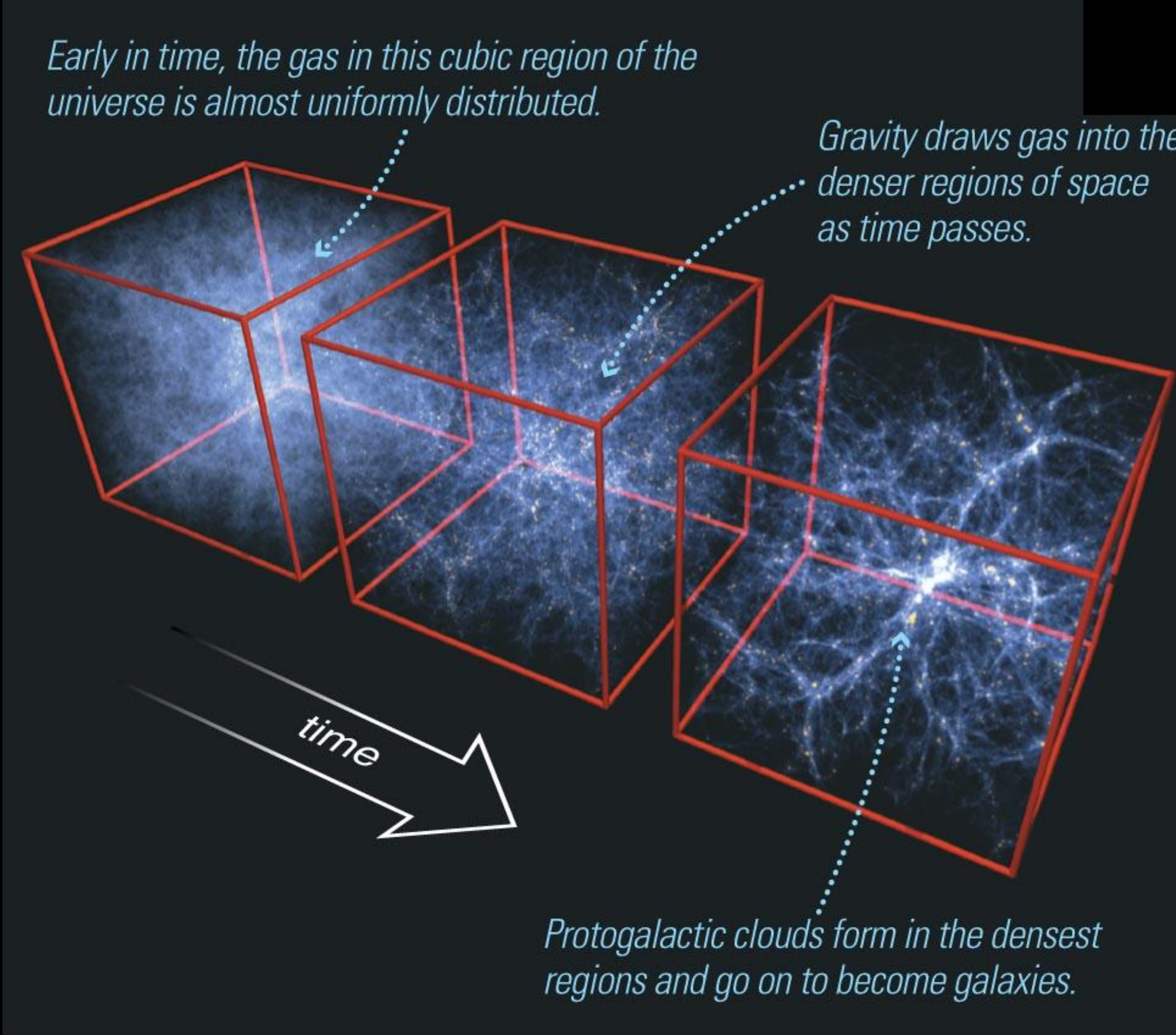


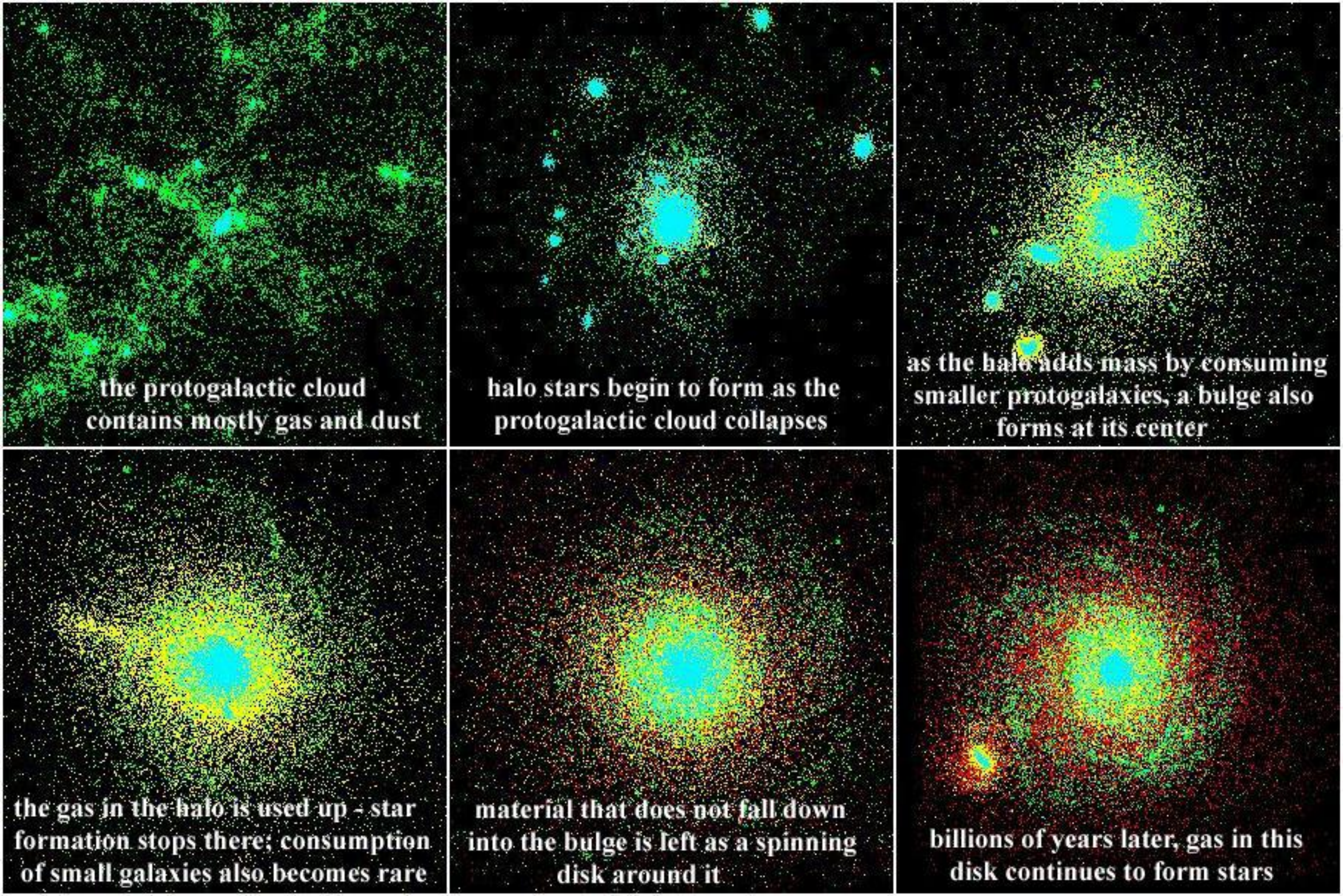
Astronomers can set up a "virtual space" with a computer program and program its evolution.

- Newton's law of gravitation
- Up to 100 billion "particles"
- Initially smooth distribution
- "Turn on" gravity; calculate how all the particles move
- Trillions of calculations but computers are powerful
- "Speed up" time so billions of years takes a few weeks
- Gradually structures form by the action of gravity
- Majority of the mass is in dark matter not normal atoms

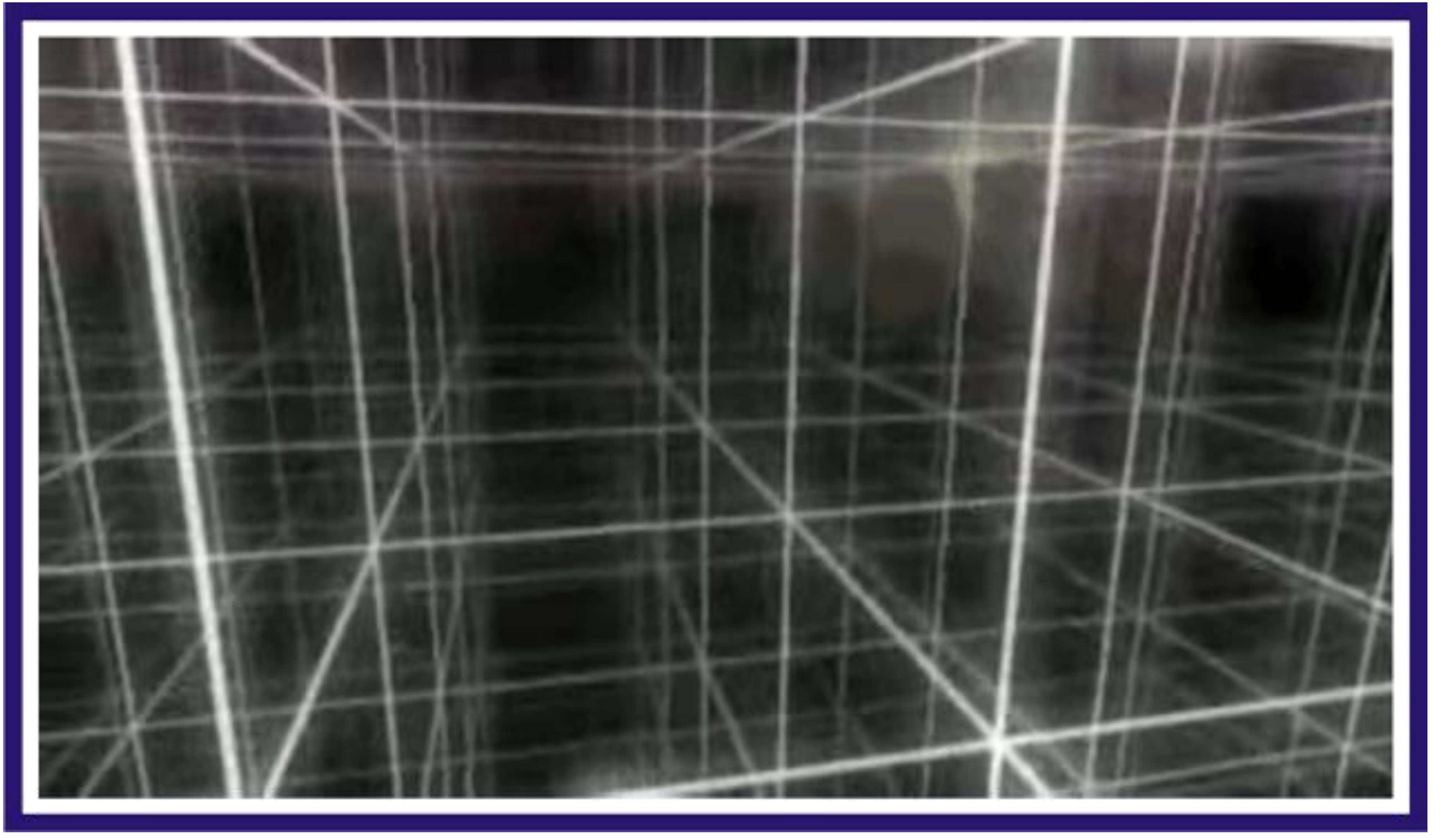
Heirarchical Structure




Early in time, the gas in this cubic region of the universe is almost uniformly distributed.
Gravity draws gas into the denser regions of space as time passes.
time
Protogalactic clouds form in the densest regions and go on to become galaxies.

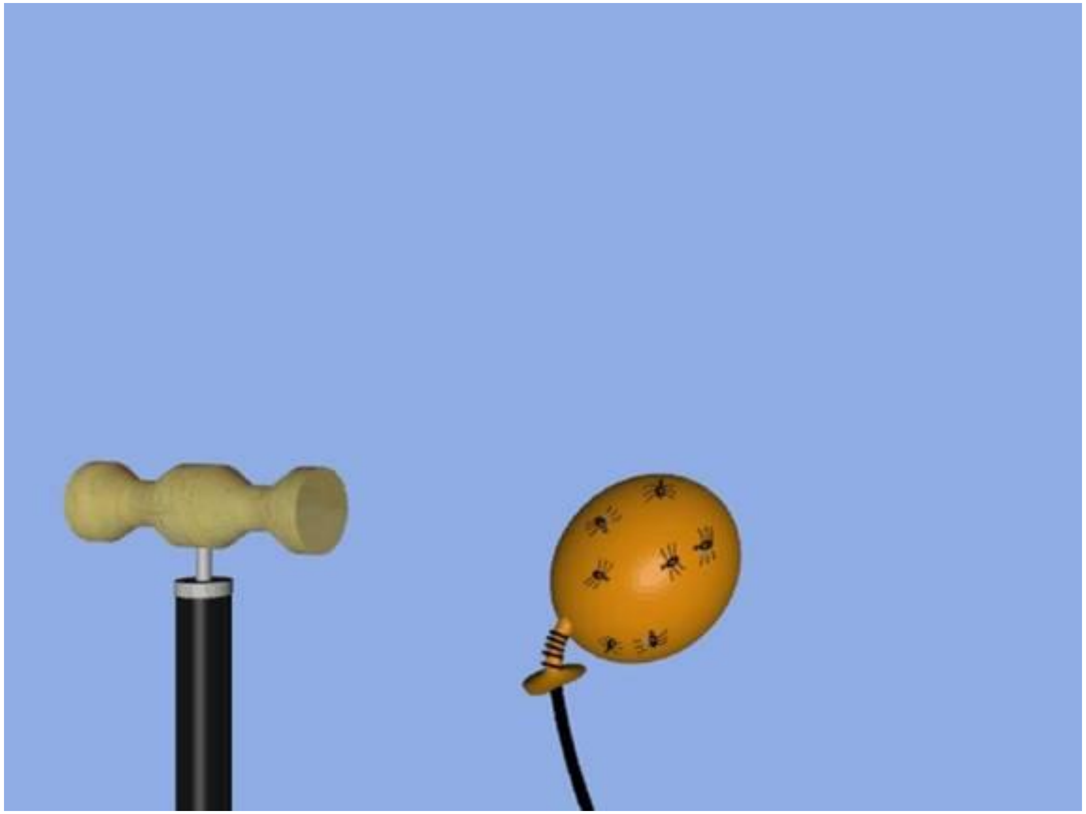

the protogalactic cloud
contains mostly gas and dust
halo stars begin to form as the
protogalactic cloud collapses
as the halo adds mass by consuming
smaller protogalaxies, a bulge also
forms at its center
the gas in the halo is used up - star
formation stops there; consumption
of small galaxies also becomes rare
material that does not fall down
into the bulge is left as a spinning
disk around it
billions of years later, gas in this
disk continues to form stars

Expansion

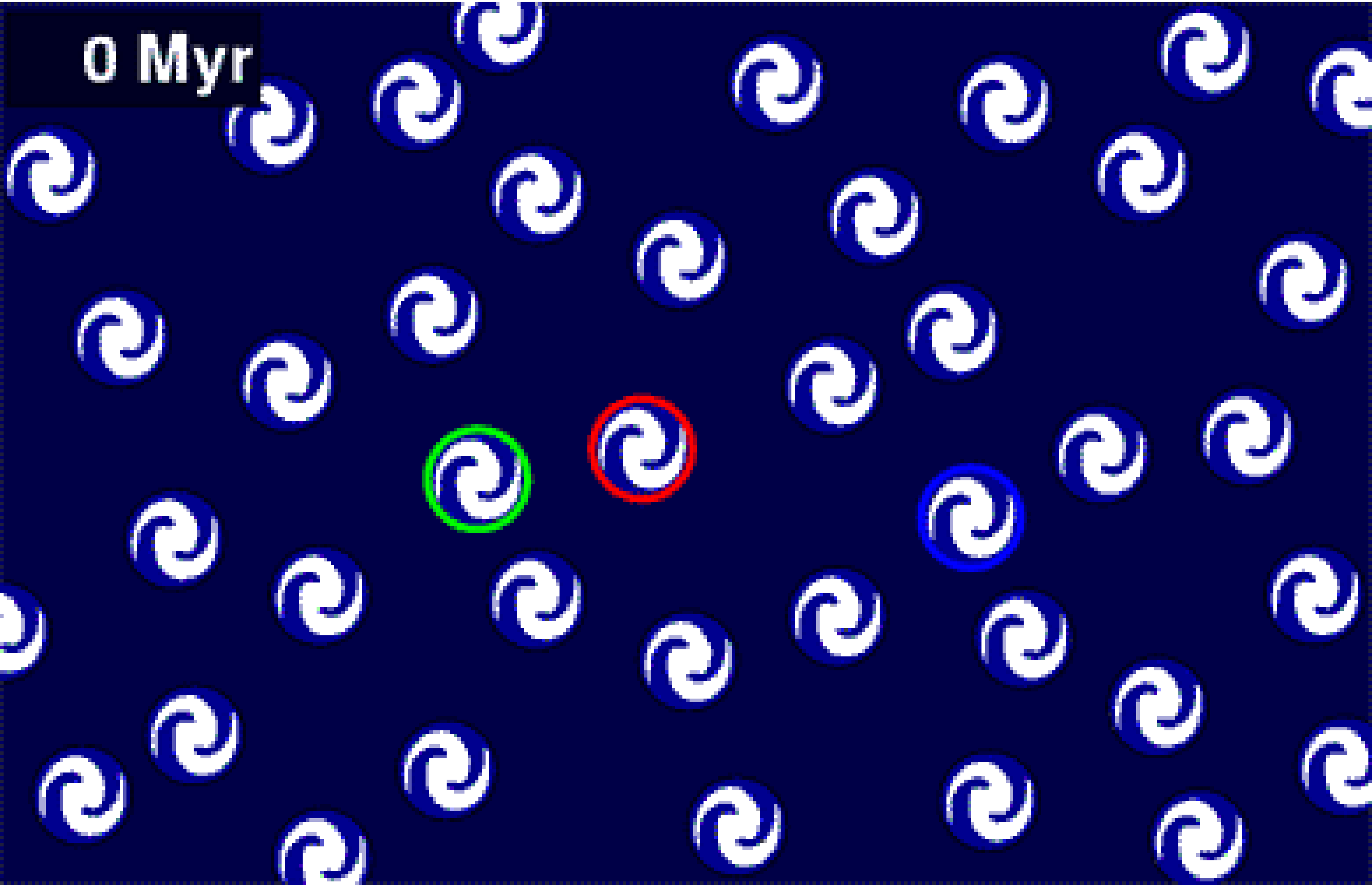


Hubble Law

- Hubble's Law ($v = H_o d$) implies:
  - The universe is expanding.
  - The **slope** of the line in Hubble's Diagram (H_o) gives us the **rate** of this expansion.

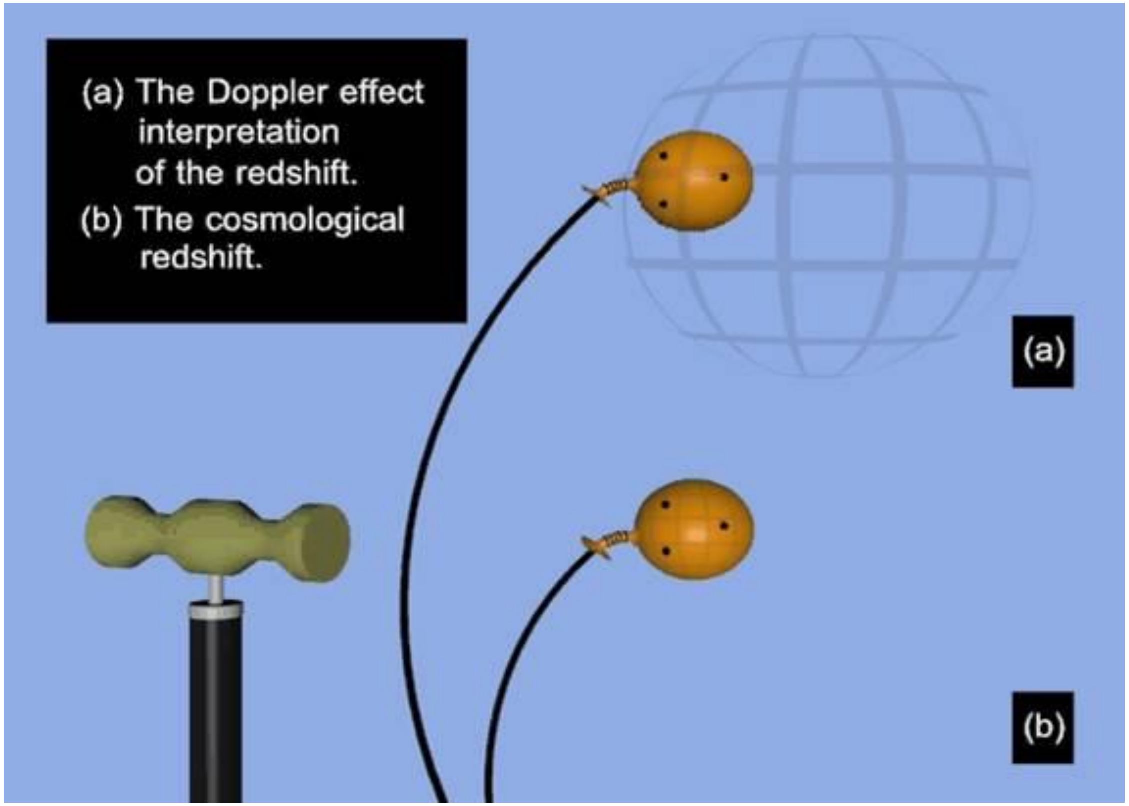


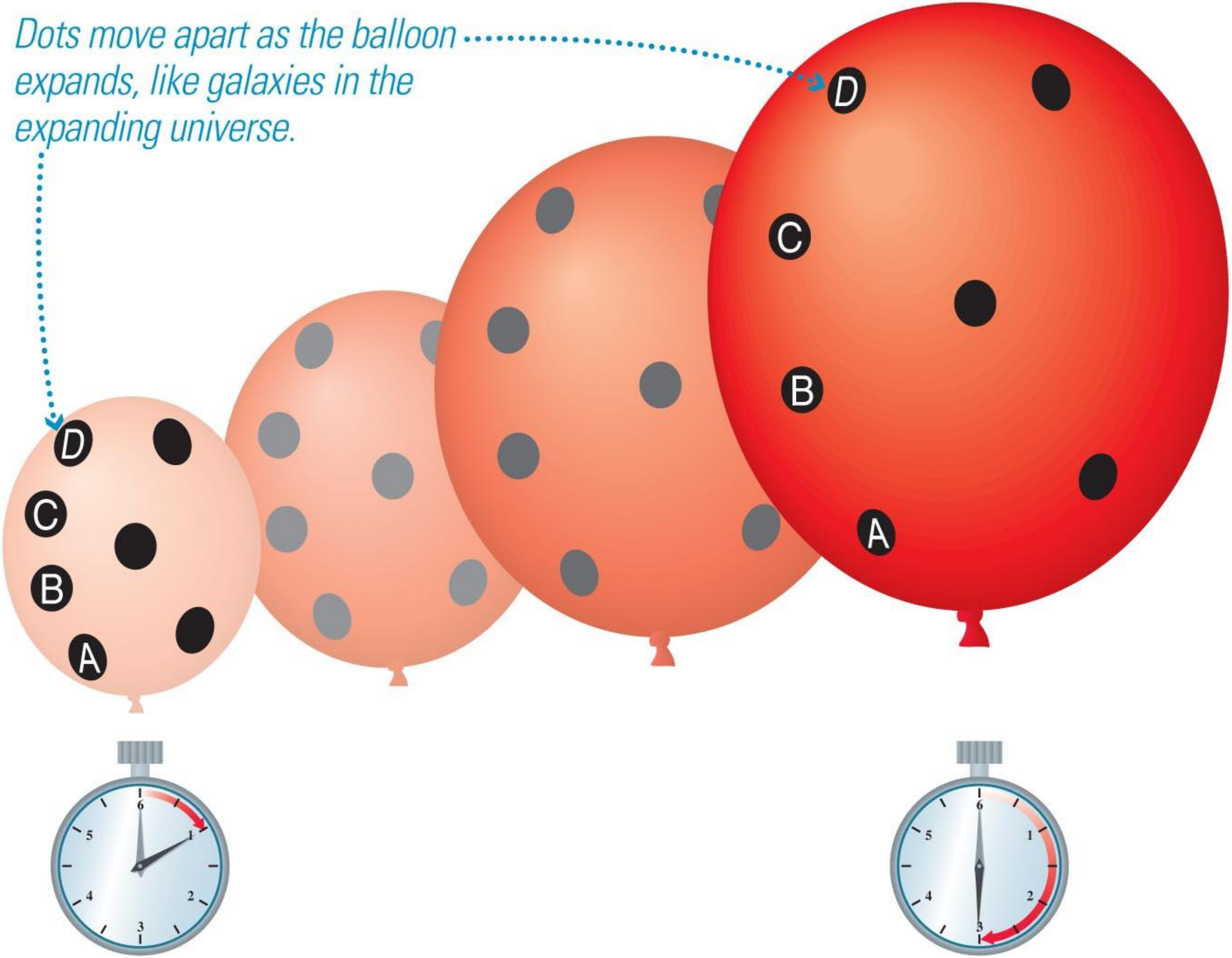
Linear Expansion

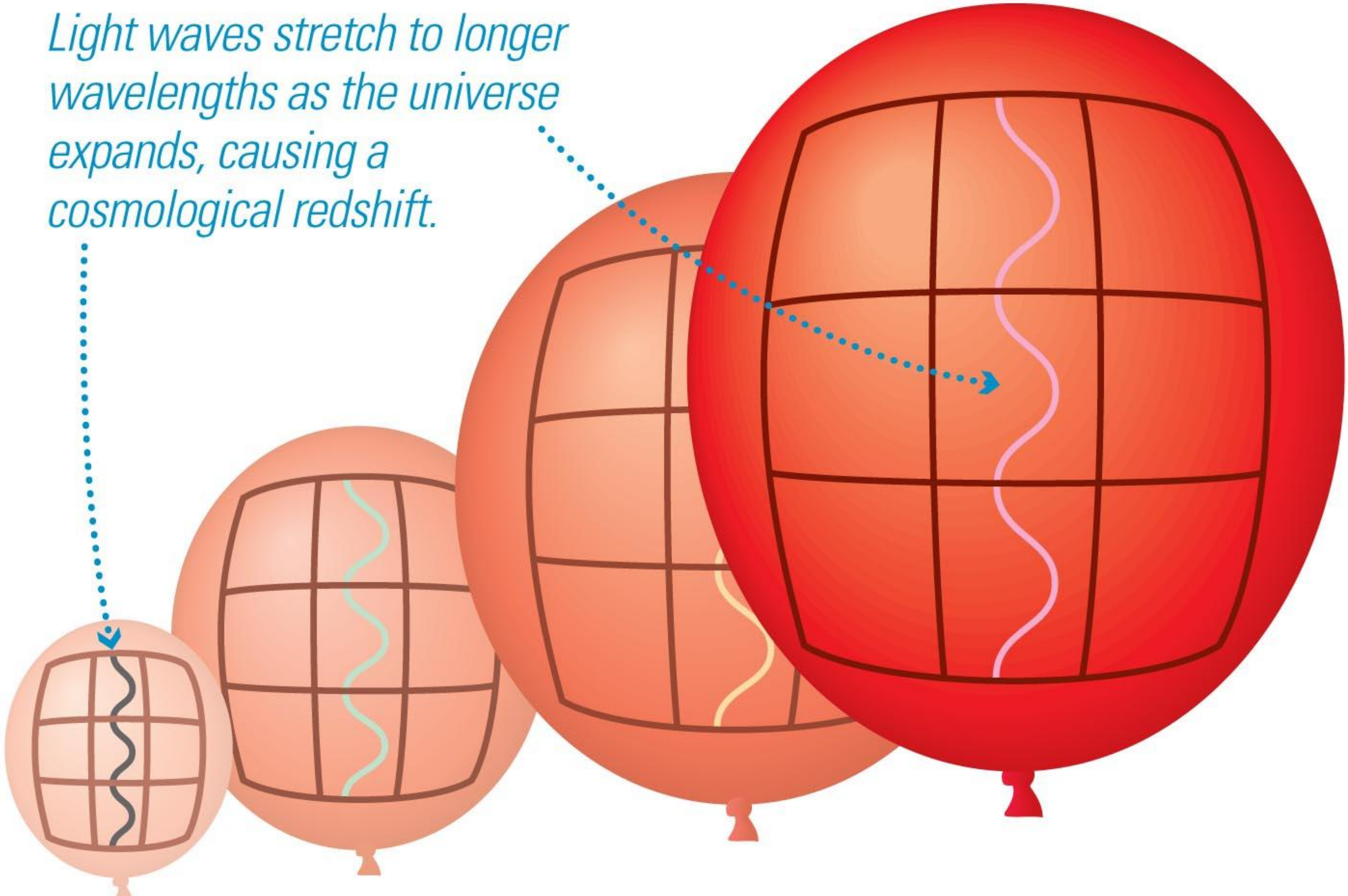


Expanding Space

- The redshift seen in galaxy spectra:
  - is *not* caused by the Doppler shift!
  - is caused by the fact that space itself is expanding
- We call this the **cosmological redshift**.



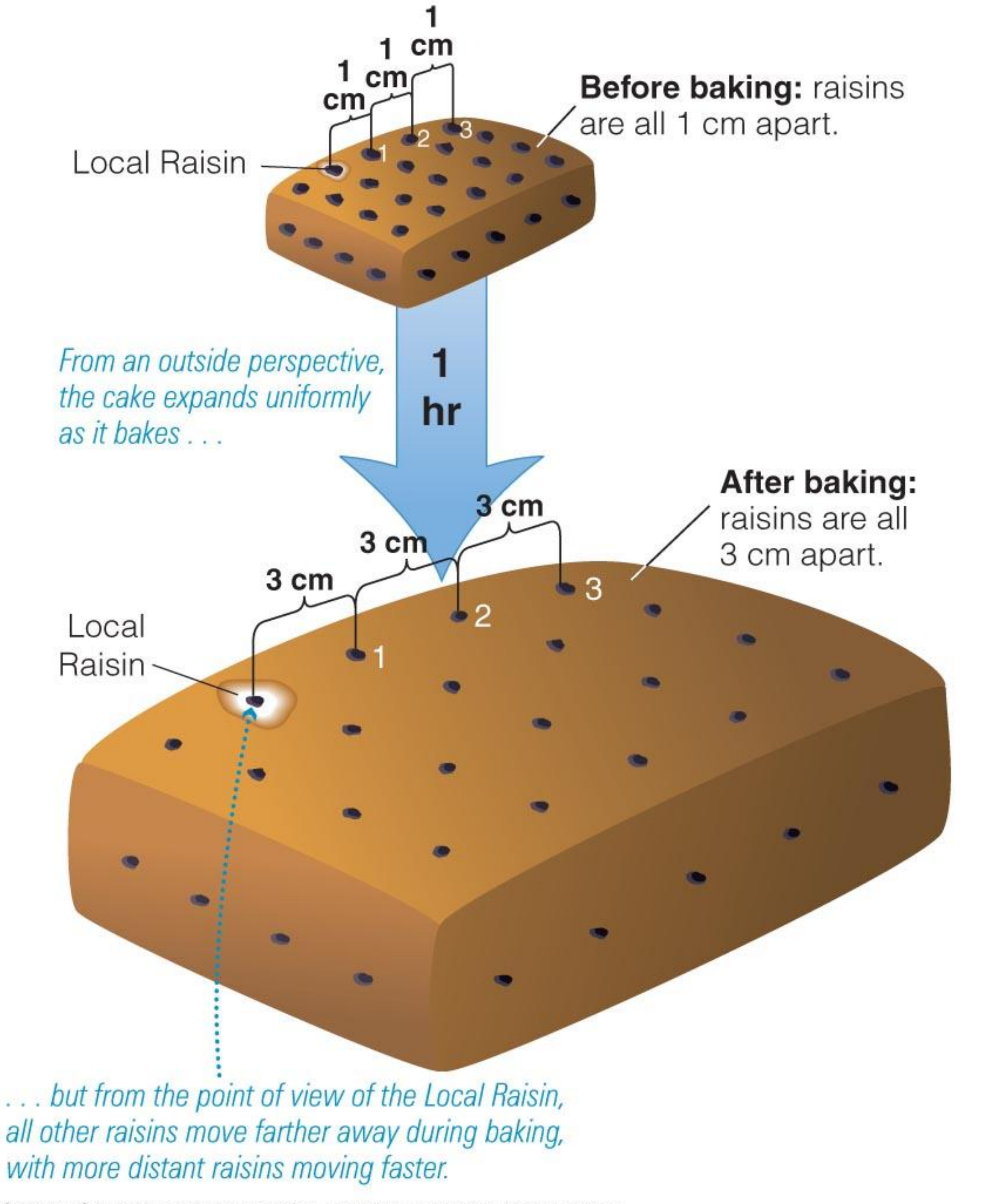

Dots move apart as the balloon expands, like galaxies in the expanding universe.
D
C
B
A
D
C
B
A
6
1
2
3
4
5
6
1
2
3
4
5


Light waves stretch to longer wavelengths as the universe expands, causing a cosmological redshift.

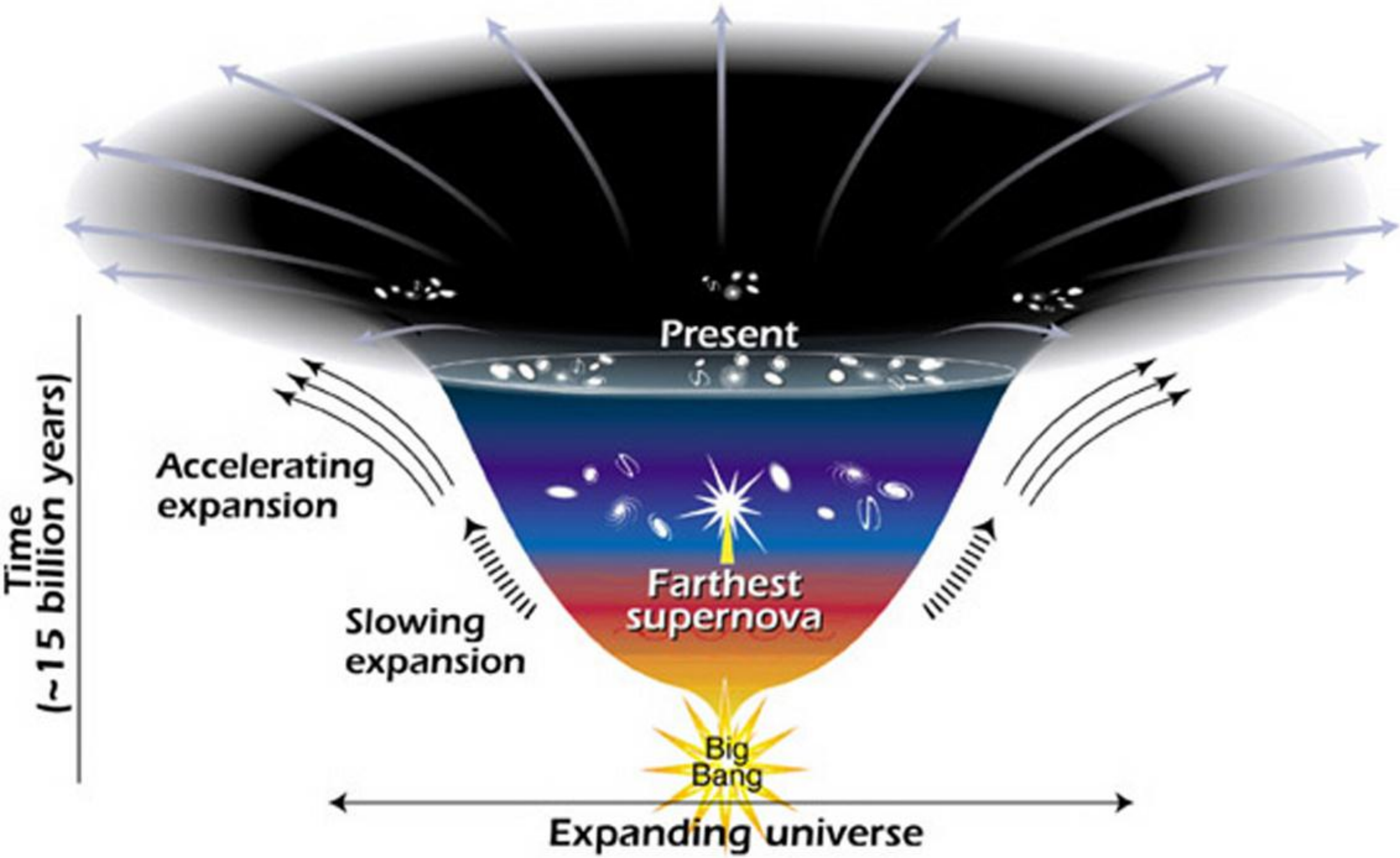
- Galaxies are all moving away from each other, so every galaxy sees the same Hubble expansion, i.e there is no center.

- The cosmic expansion is the unfolding of all space since the big bang epoch, i.e. there is no edge.

- We are limited in our view by the time it takes distant light to reach us, i.e. the universe has an edge in time not space.



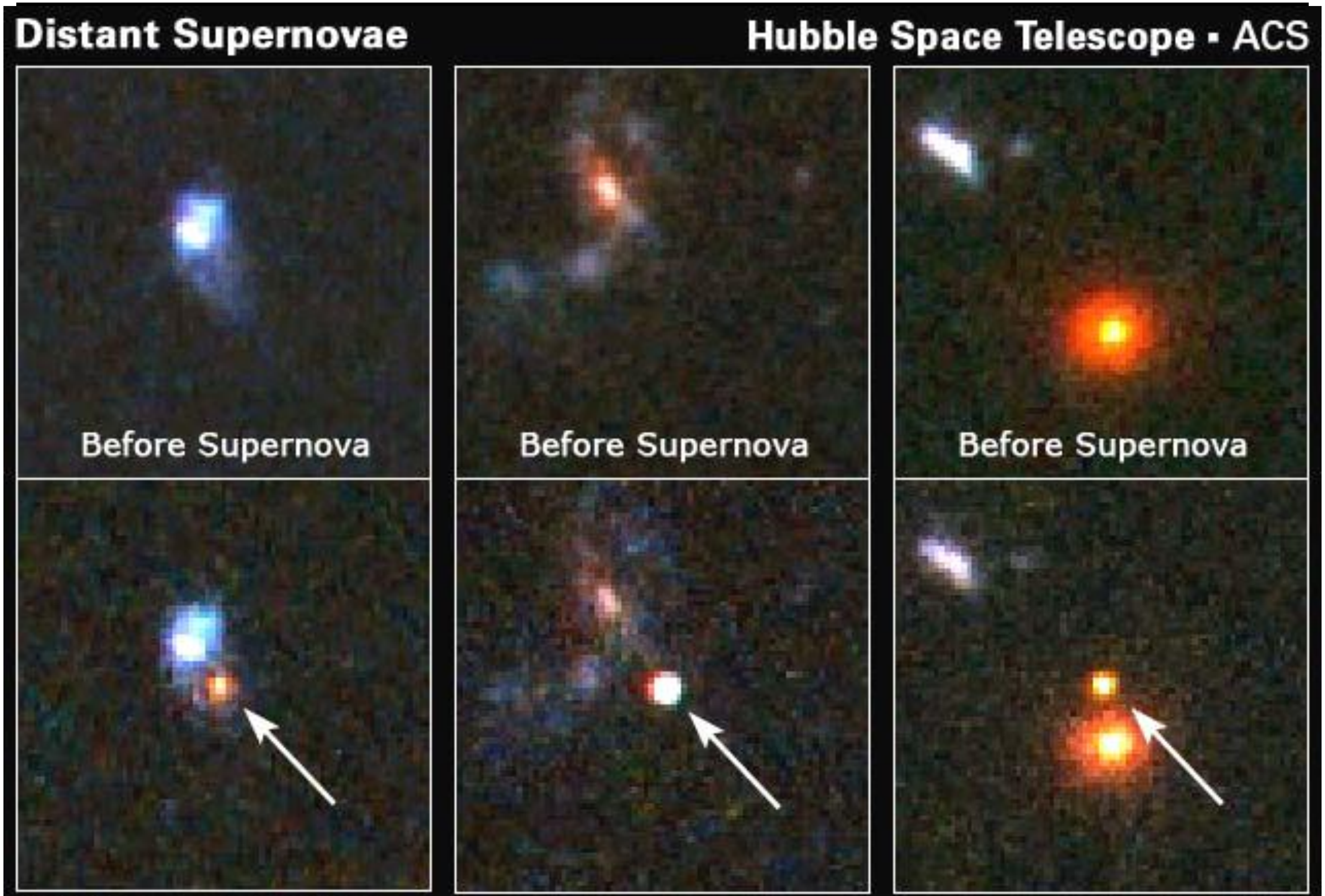
Dark Energy



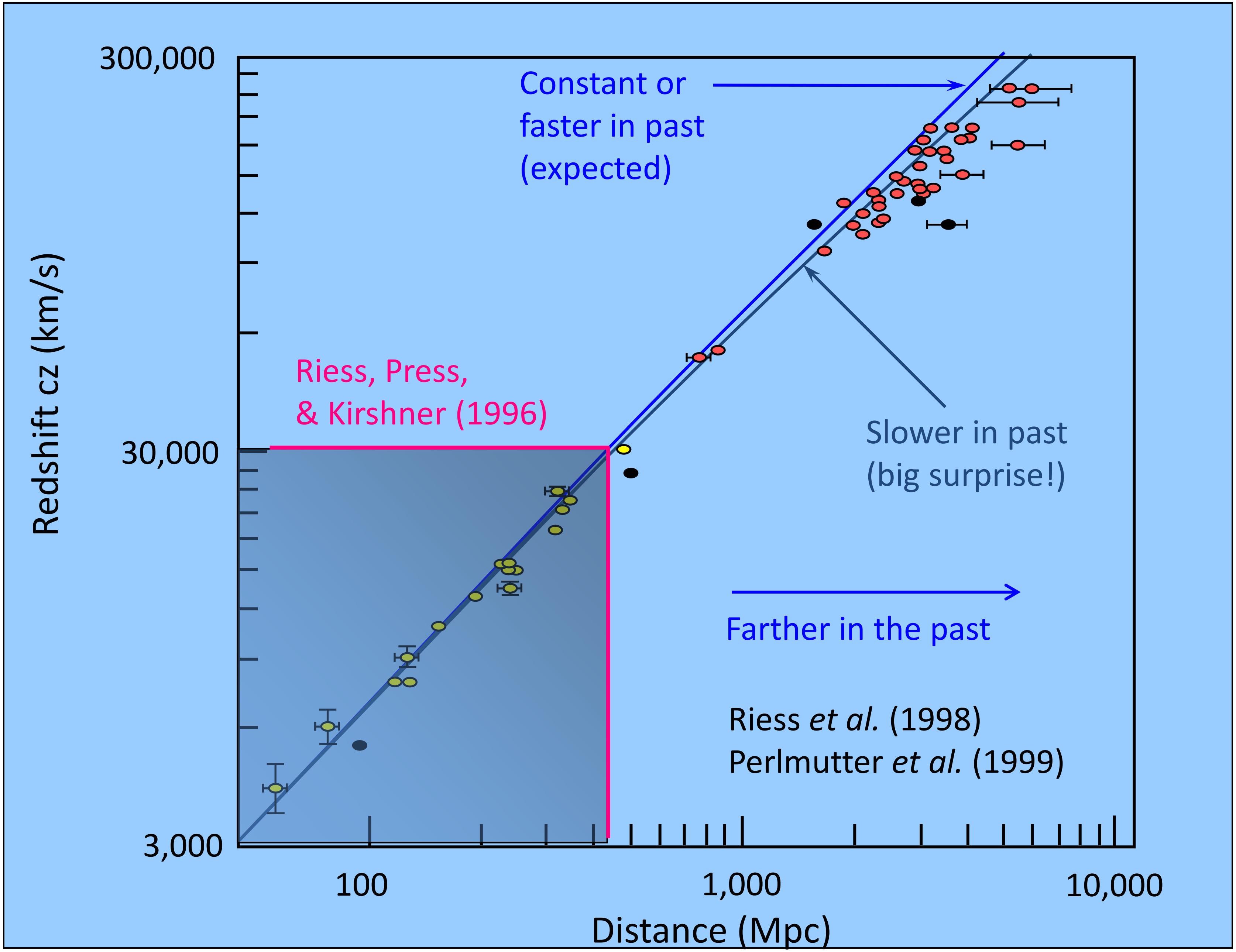
Time
(~15 billion years)
Present
Accelerating
expansion
Farthest
supernova
Slowing
expansion
Big
Bang
Expanding universe

What is Dark Energy?

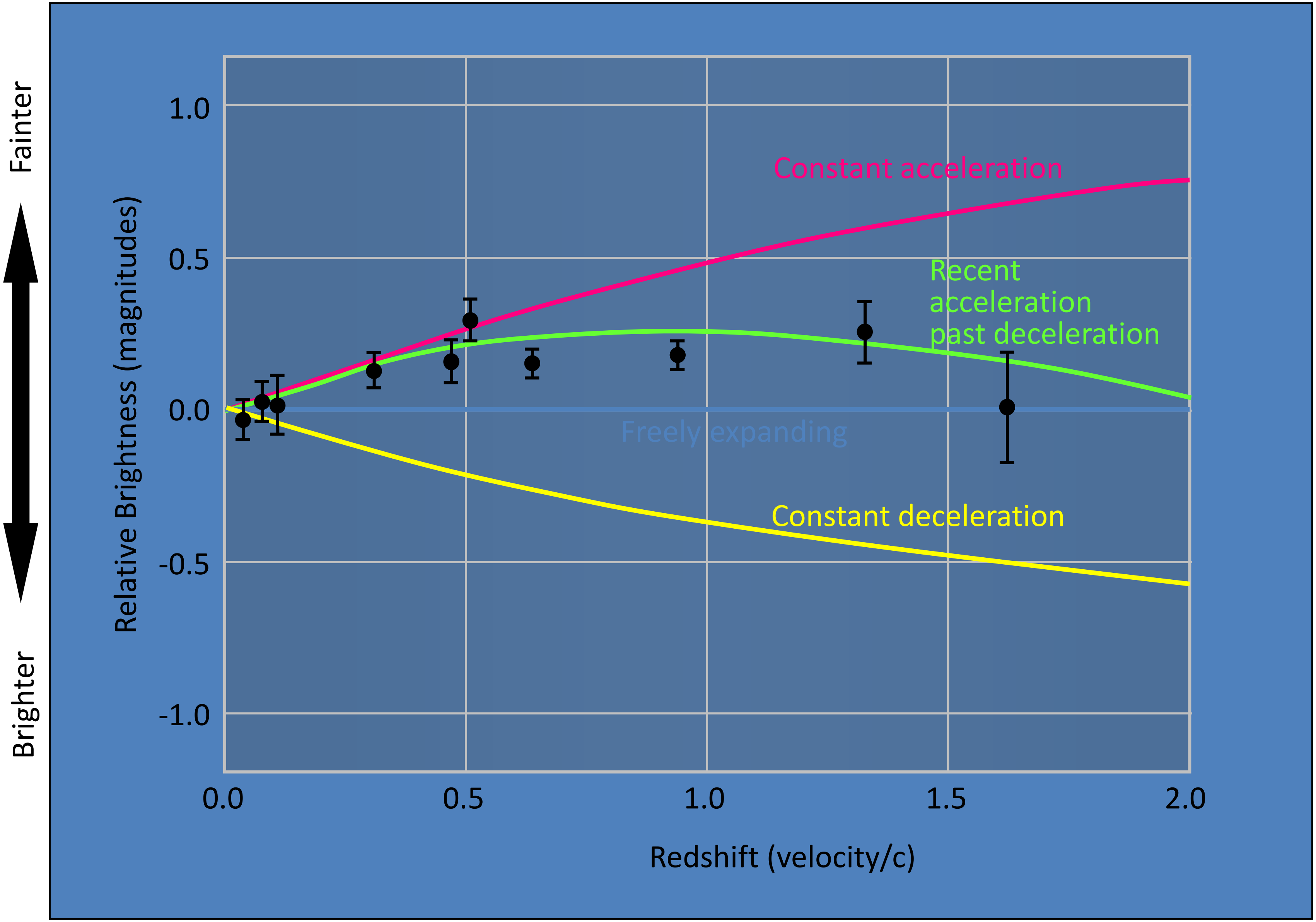
THE SHORT ANSWER IS: WE DON'T KNOW. BUT THE OBSERVATION OF DISTANT SUPERNOVAE POINTED TO A COSMIC ACCELERATION



Expansion History of the Universe

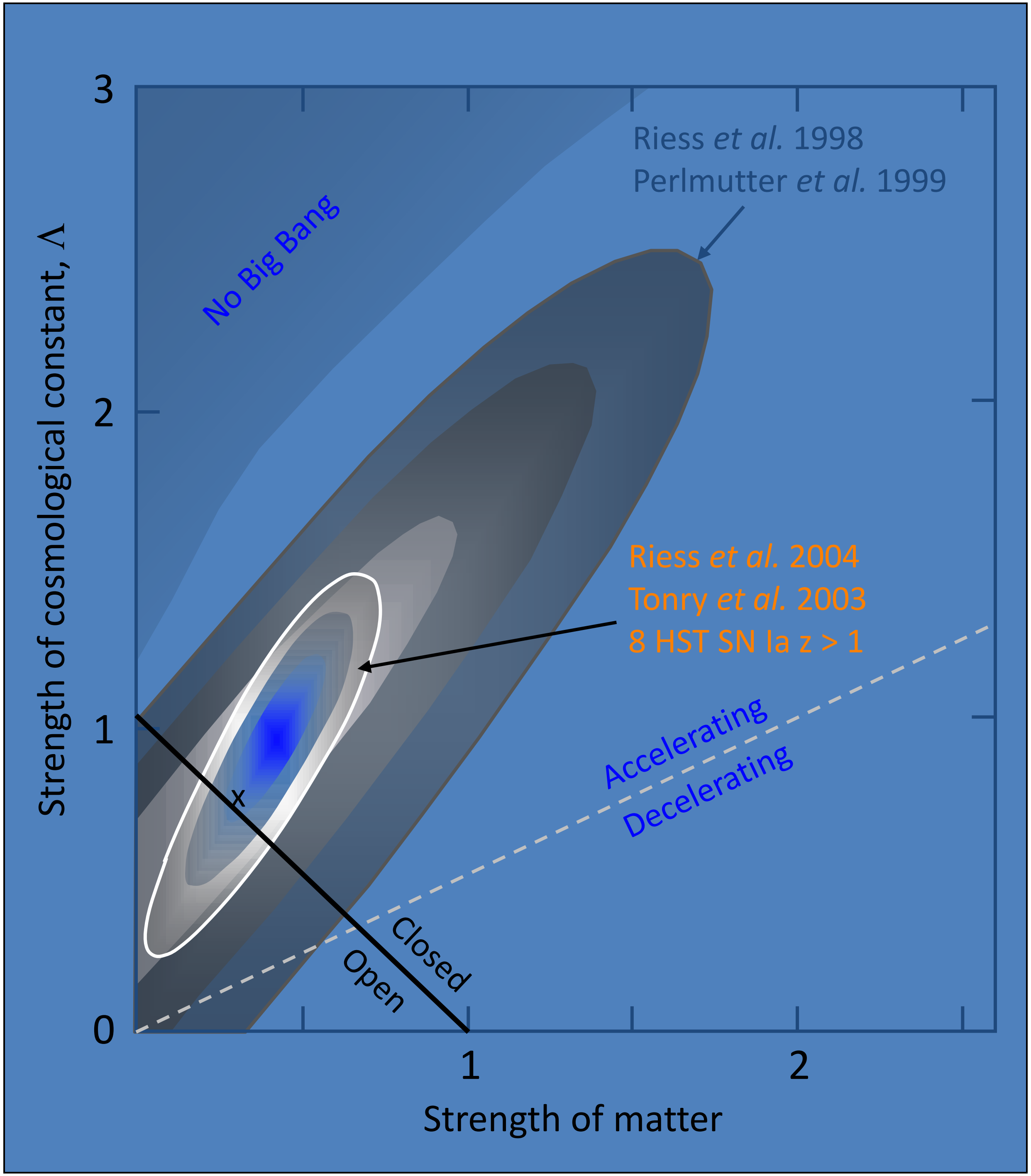


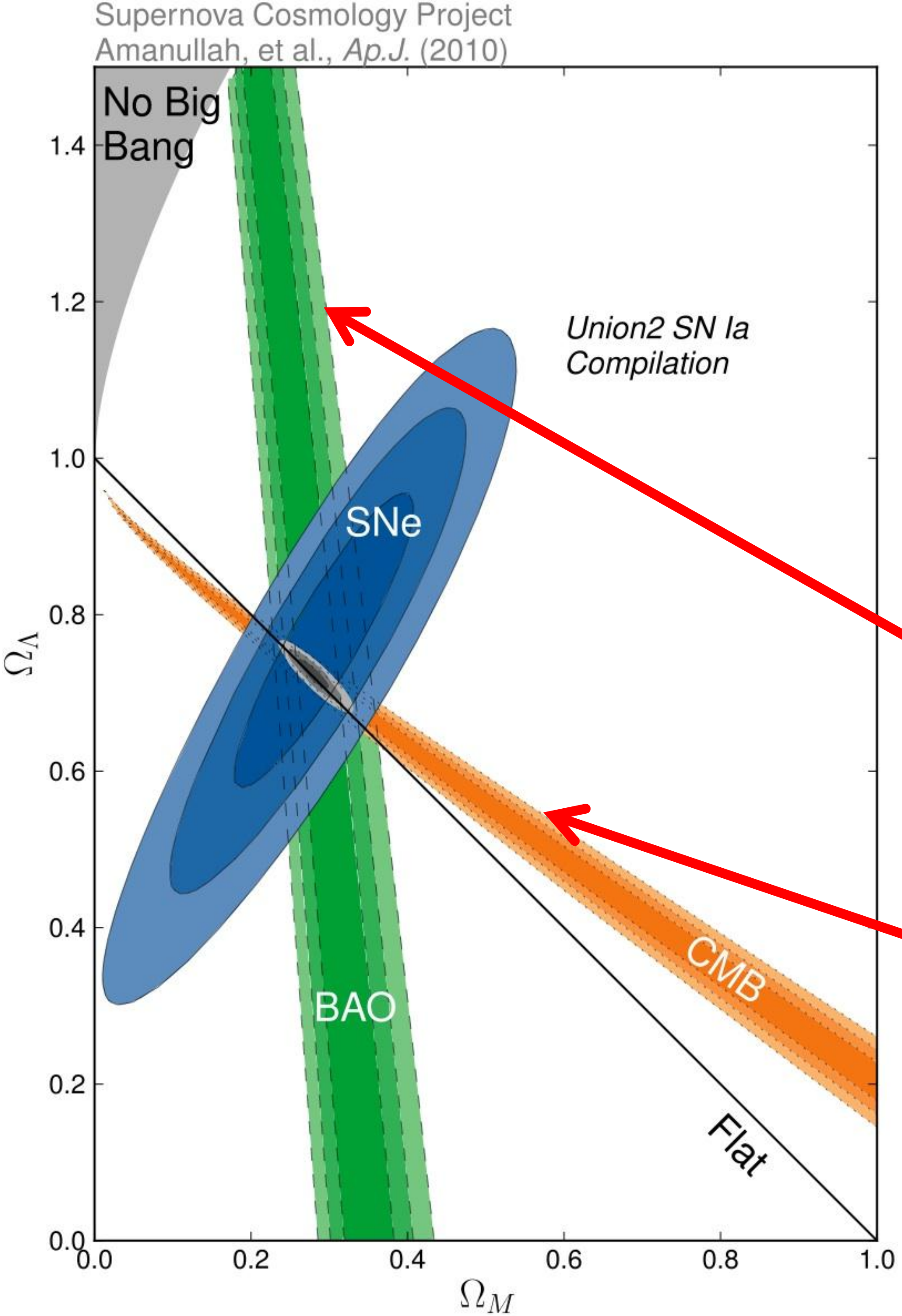
Deceleration Changed to Acceleration



Dark Energy and Dark Matter Drive the Universe

Current acceleration is driven by the dark energy, which is now strong than the dark matter by a factor of 3. The dark matter in turn exceeds normal matter by a factor of 5-7 all places we look.





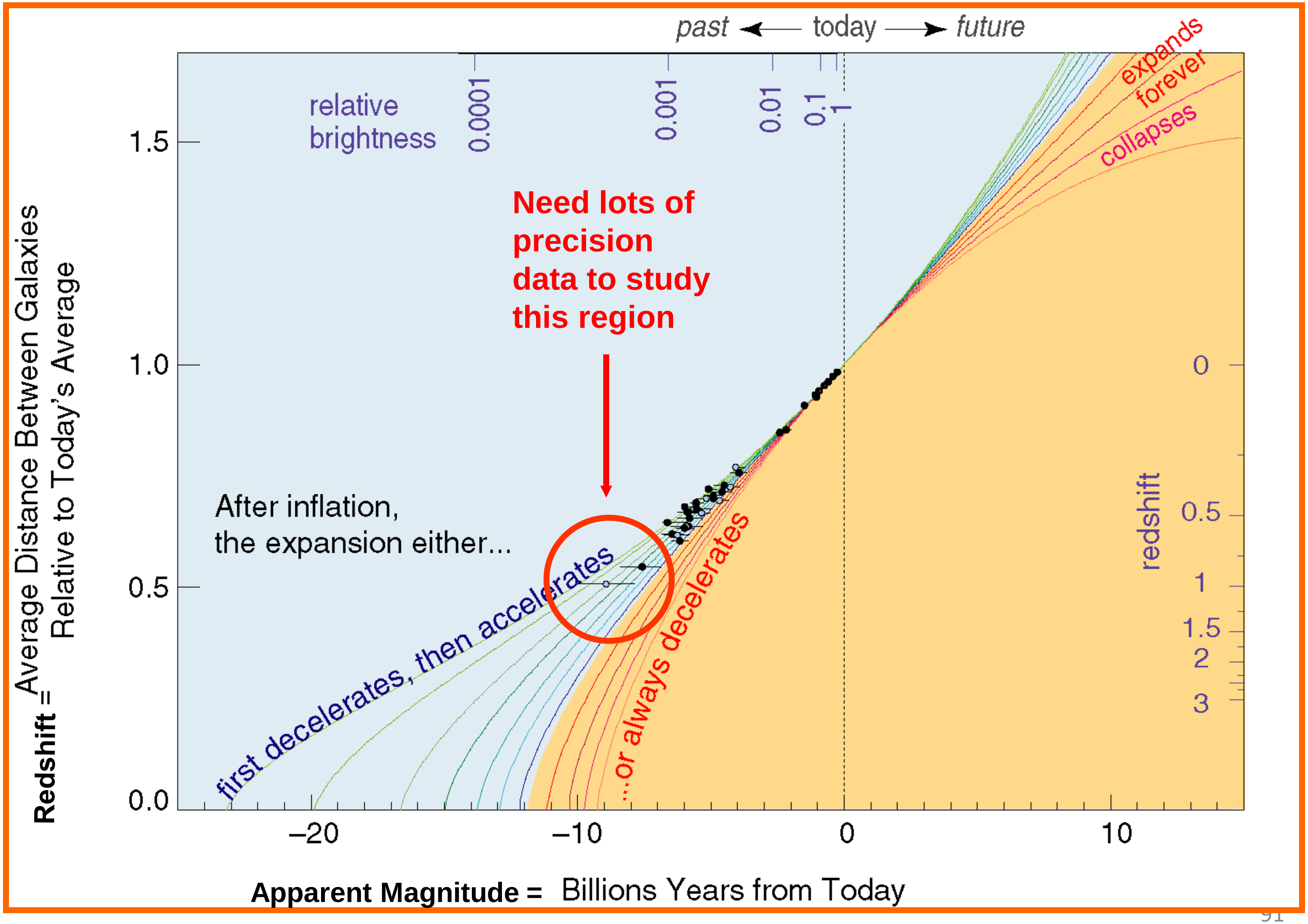
Concordance

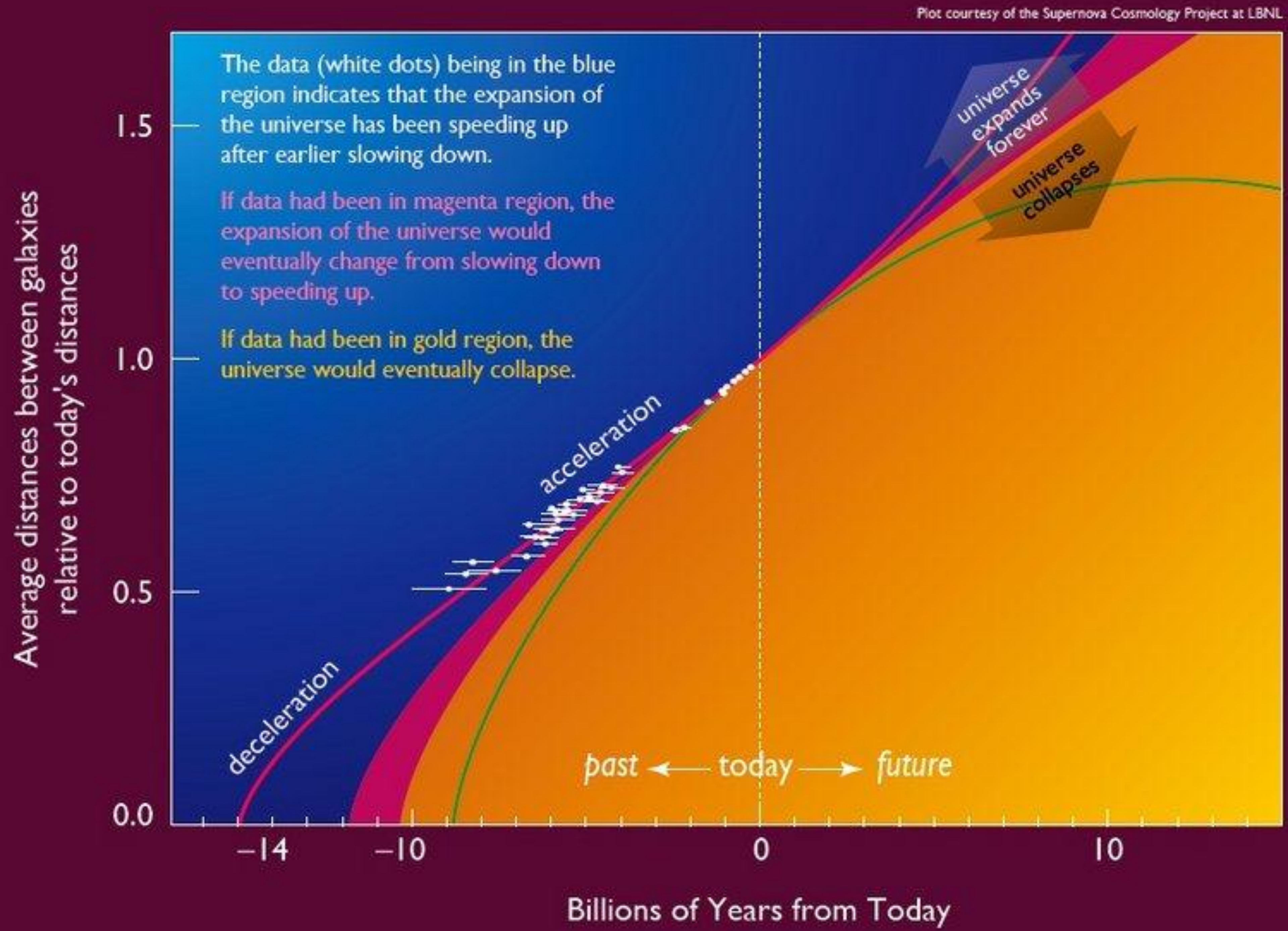
Although the only ***direct*** evidence for dark energy is acceleration traced by supernovae, presence of dark energy is supported by additional evidence:

Large scale structure with a characteristic scale of 120 Mpc (400 million l.y.)

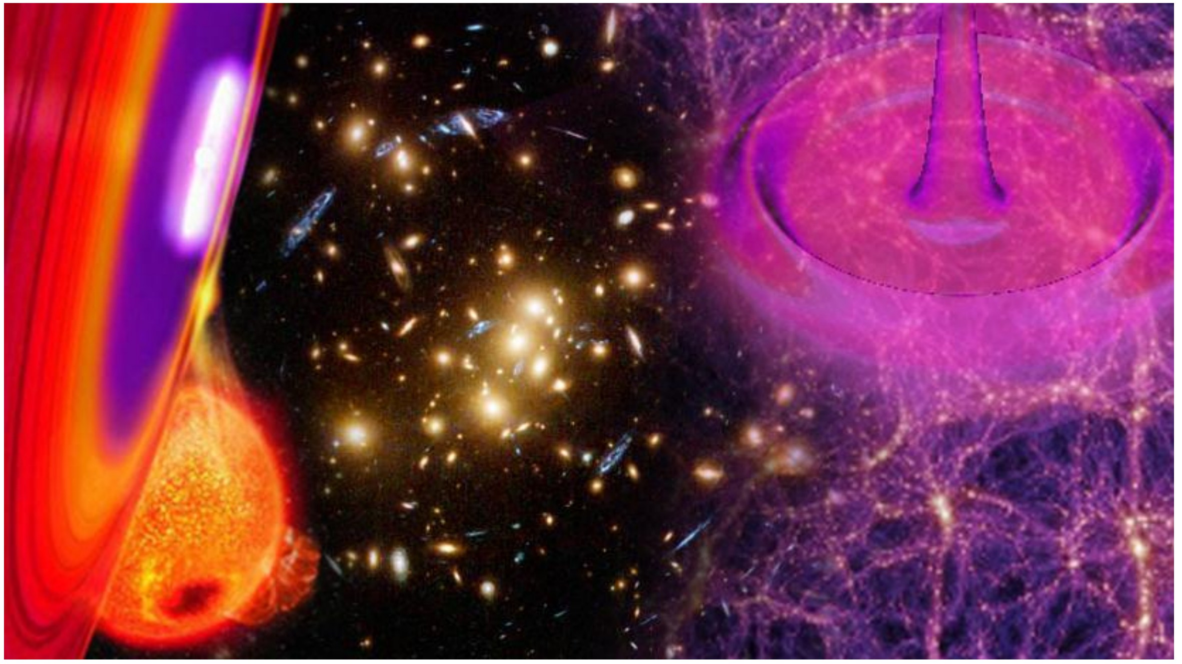
Microwave background data indicating space is geometrically nearly flat.

The Expansion History of the Universe

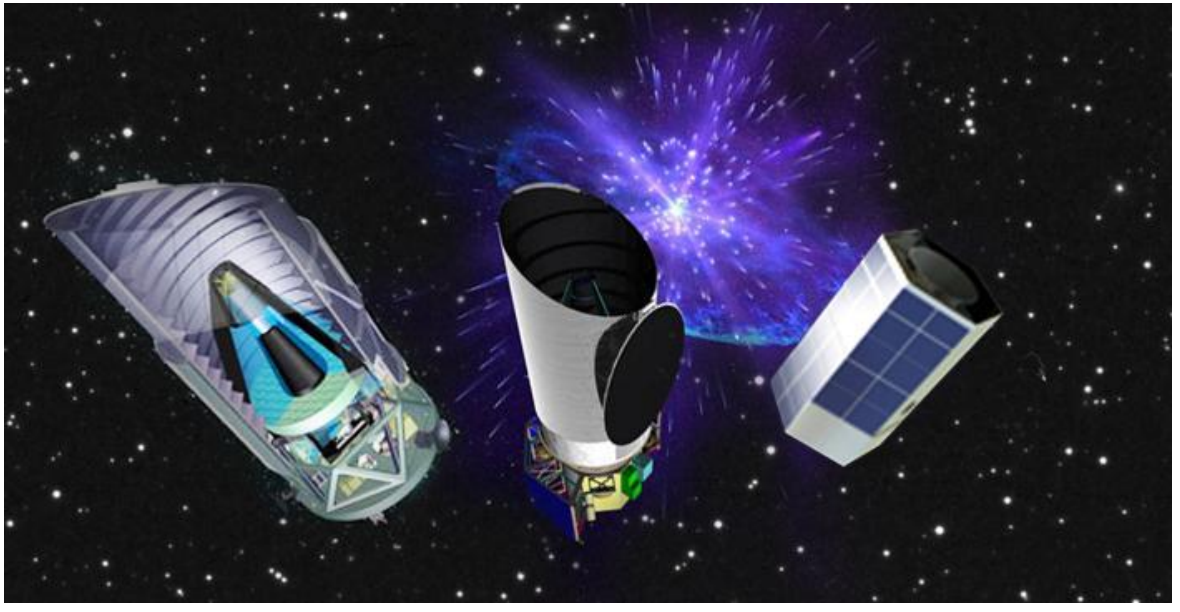



Plot courtesy of the Supernova Cosmology Project at LBNL
The data (white dots) being in the blue region indicates that the expansion of the universe has been speeding up after earlier slowing down.
If data had been in magenta region, the expansion of the universe would eventually change from slowing down to speeding up.
If data had been in gold region, the universe would eventually collapse.
universe expands forever
universe collapses
acceleration
deceleration
past ← today → future
1.5
1.0
0.5
0.0
−14
−10
0
10
Average distances between galaxies relative to today's distances
Billions of Years from Today

How To Learn More About Dark Energy



Measure its properties using three different methods: supernova brightness, the lensing of faint galaxies, and the imprint of acoustic oscillations on large scale galaxy structure.



Combine concepts into the Joint Dark Energy Mission, to improve DE constraints by a factor of 10, and new mission is highly ranked, with a potential launch: 2016.

Who Ordered That?!

What's wrong with a Vacuum Energy/Cosmological constant?

- ***Why so small?***

Might expect $\frac{\Lambda}{8\pi G} \sim m^4_{\text{Planck}}$

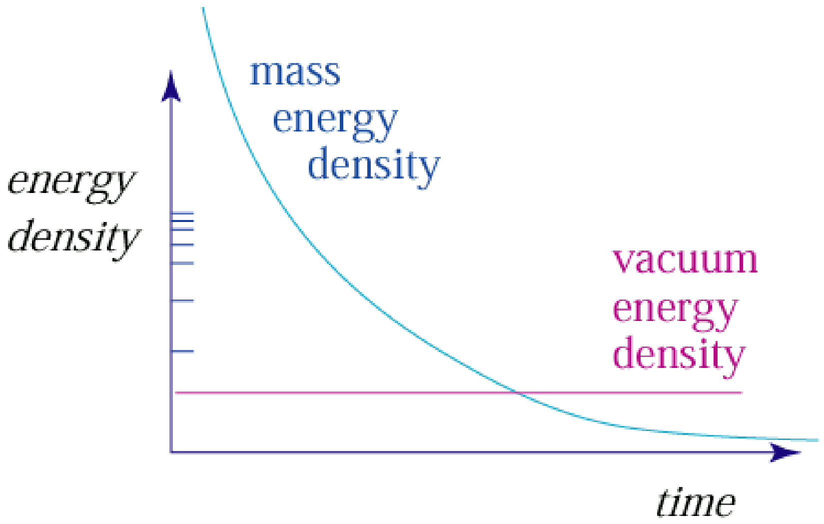
This is off by ~120 orders of magnitude!

Some remarkable and unknown symmetry of nature must have cancelled this vacuum energy to allow our universe to spring into existence. But how could it do so and somehow leave just one part in 10^{-120} remaining???

- ***Why now?***

Matter: $\rho \propto R^{-3}$

Vacuum Energy: $\rho \propto$ ***constant***

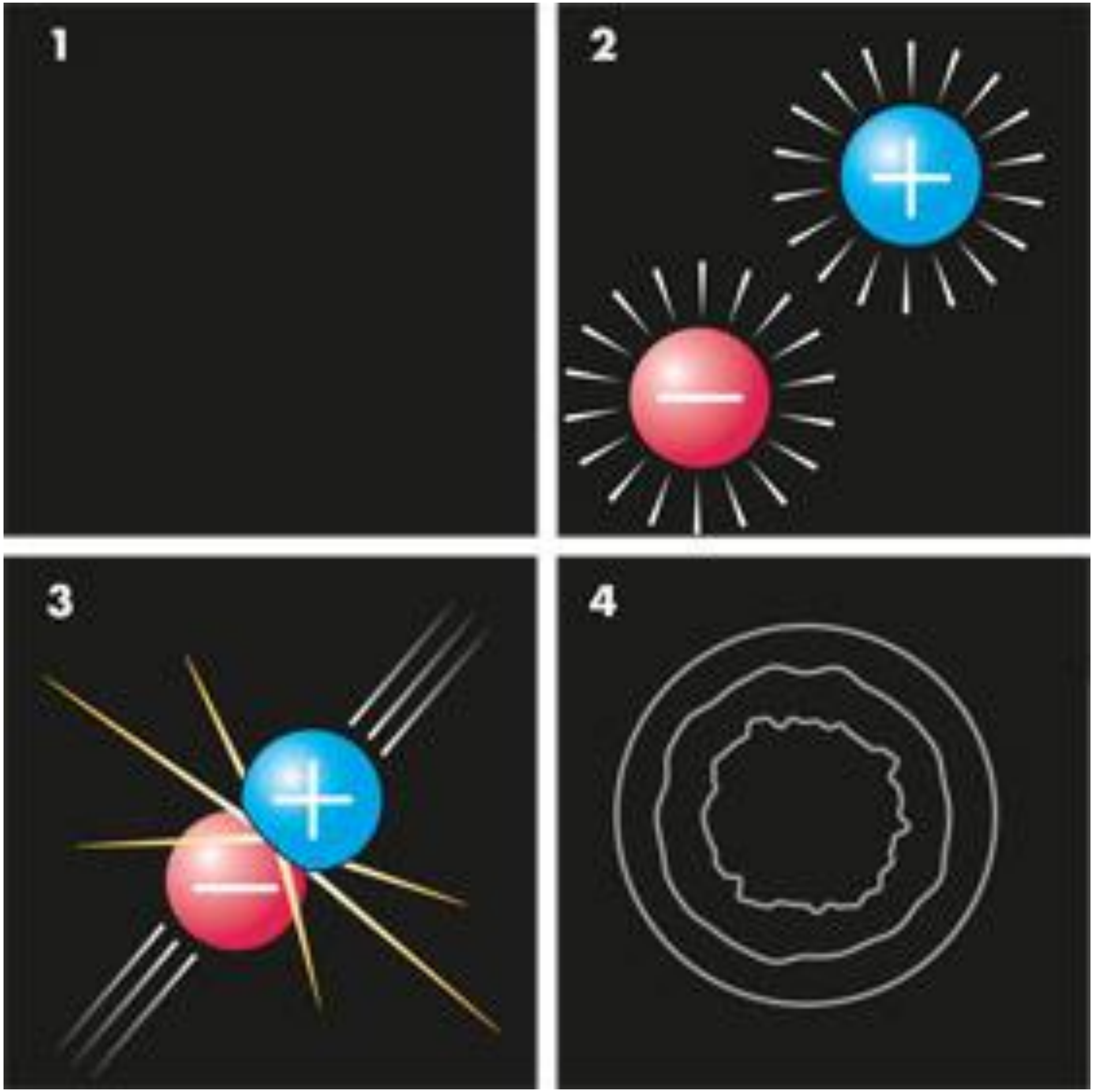


What We Don't Know

- Precisely how much mass density (Ω_M) and dark energy density (Ω_{DE}) is there?
- How flat is the universe?
- What is the "equation of state" of the dark energy, the ratio of pressure to density $w = p/\rho$?
- Has w changed in time or is w' = 0?

What is the "dark energy?" Theorists have proposed a number of possibilities each with its own unique w(t):

- Cosmological constant with $p = -\rho$ and $w = -1$.
- "Quintessence" models with time varying $-0.4 < w < -0.8$
- Supergravity models
- The "big rip" $w < -1$
- Hundreds of papers per year.



A pure vacuum of space (1) can create particle & and anti-particle pairs (2) briefly, and then they annihilate (3) to create gamma rays. But there may be enough disruption to the fabric of space-time (4) to cause local expansion.

The "Vacuum"

Every possible boson

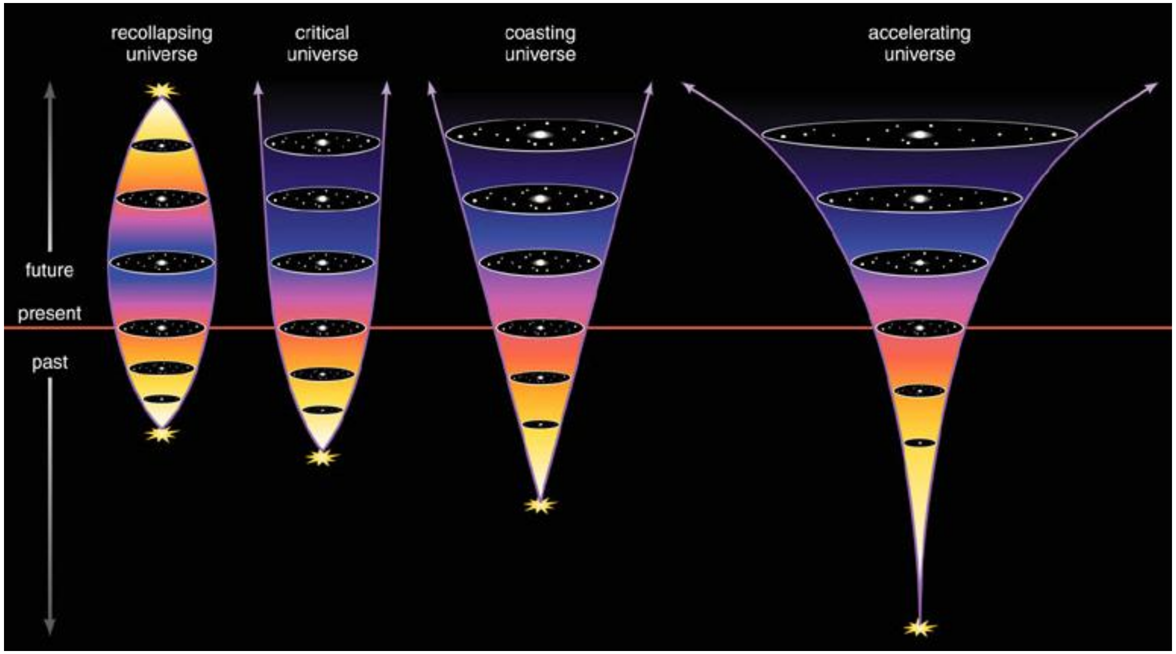
Every possible particle-antiparticle pair!

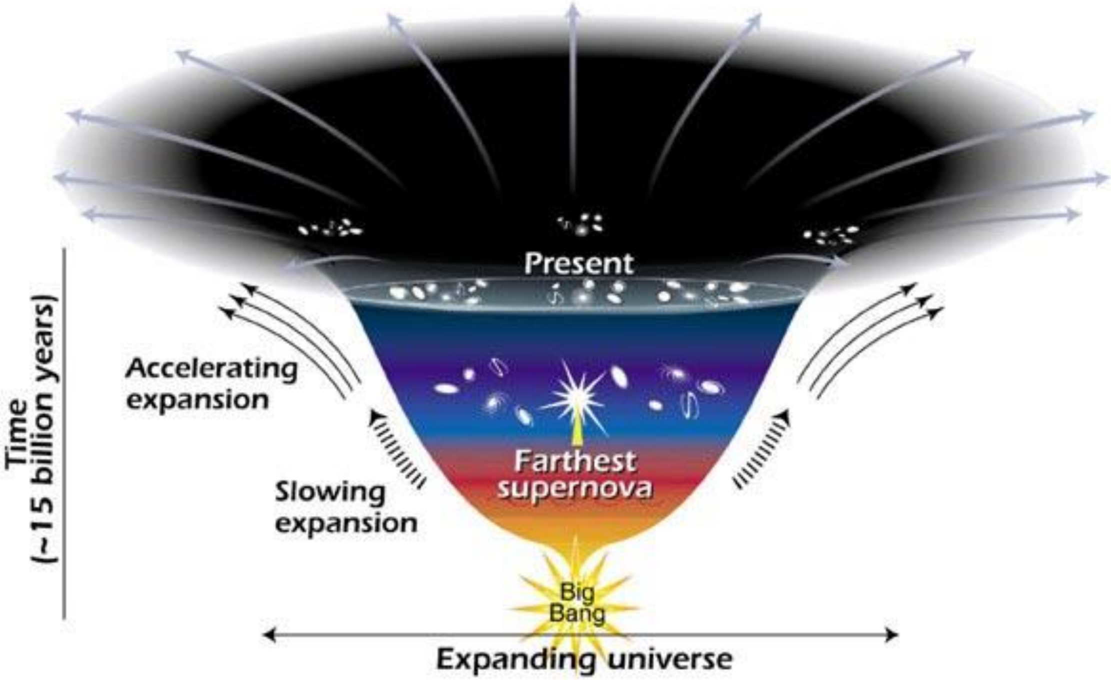
and this is just the lowest-order term...

Future of the Universe

1. Recollapsing Universe: the expansion will someday halt and reverse into a "big crunch" [closed]
2. Critical Universe: will not collapse, but will expand more slowly with time, asymptotic [flat]
3. Coasting Universe: will expand forever with little slowdown and ever-decreasing density [open]
4. Accelerating Universe*: expansion will accelerate with time

*currently favored





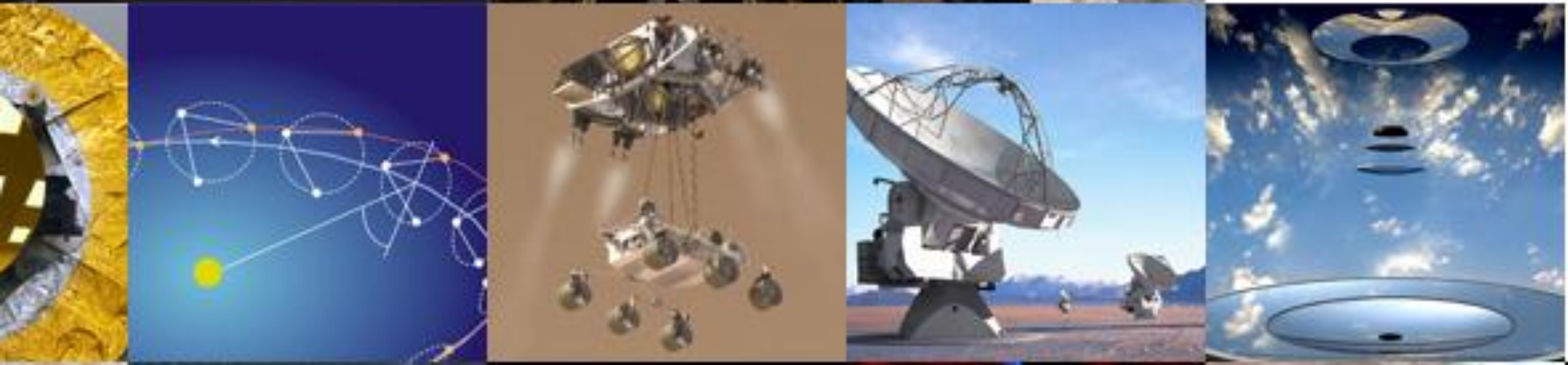
Dark energy is much more mysterious than even dark matter. It's existence rests on the unexpectedly faint distant supernovae, and a few less direct arguments. The direct detection of dark energy is ***very*** challenging

Dark energy is a repulsive force that counter gravity. It does not change its strength with time (Einstein's gravitational constant "blunder")

Physics provides no assistance. The vacuum of space could have energy in quantum theory, but it would be 10^{120} times larger than is observed!

The density of dark energy and dark matter are roughly equal, this is the only time in the history of the universe that is true: is this a coincidence?

Astronomy
State of the Art



With Chris Impey of the University of Arizona