The Large-scale Structure of the Universe

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AST 121 - The Origin and Evolution of the Universe
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How Big is the Observable Universe?

We can think of the observable universe as a sphere with us at the center

t=0 (Big Bang)

t=13.7 Gyr (Present)

t=0 (Big Bang)

The "Horizon"
~40 Glyr = 14 Gpc

t=13.7 Gyr (Present)

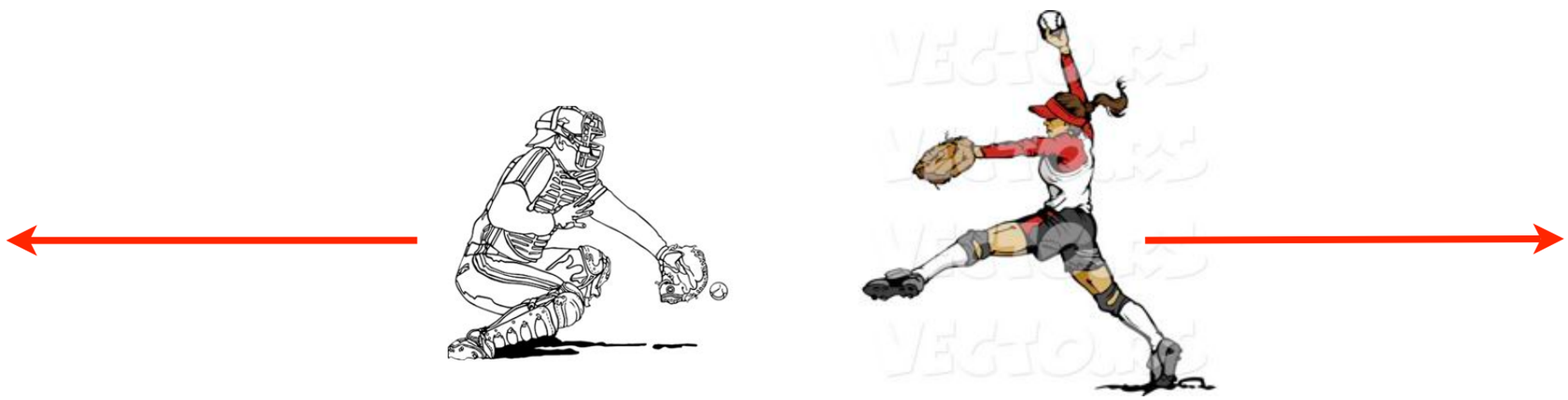
Question:

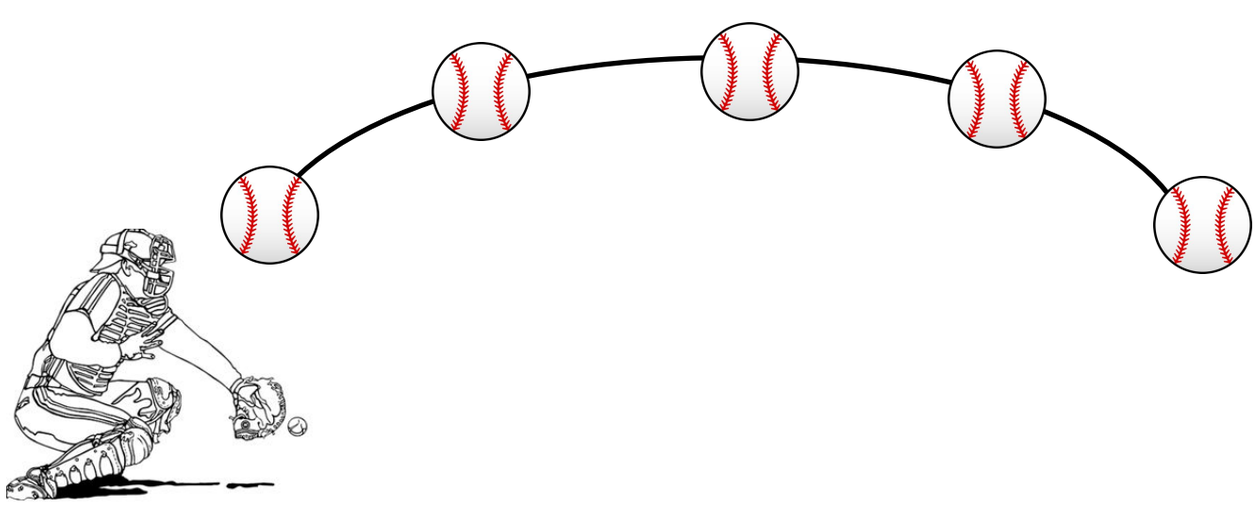
Why do we say the horizon (the surface from which light emitted at the Big Bang is only just now reaching us) is 40 billion light-years away, when the universe is only 13.7 billion years old?

Answer:

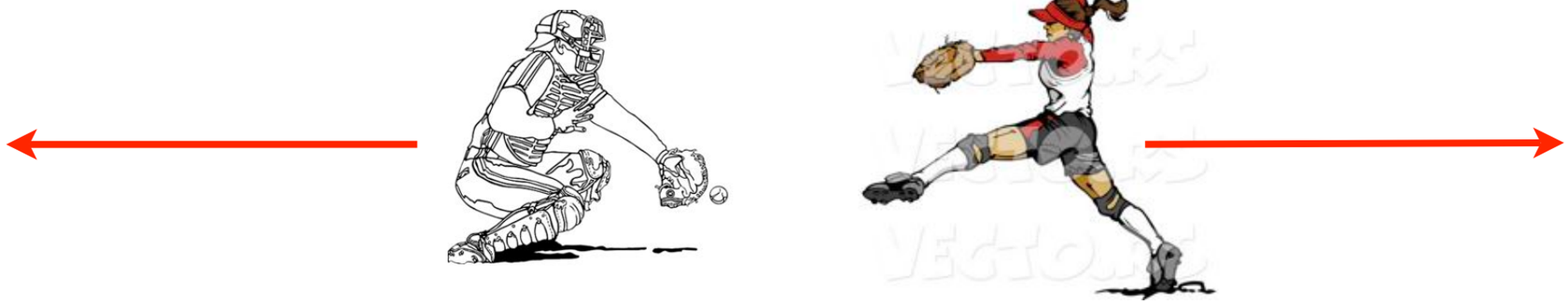
Because of the expansion of the universe...

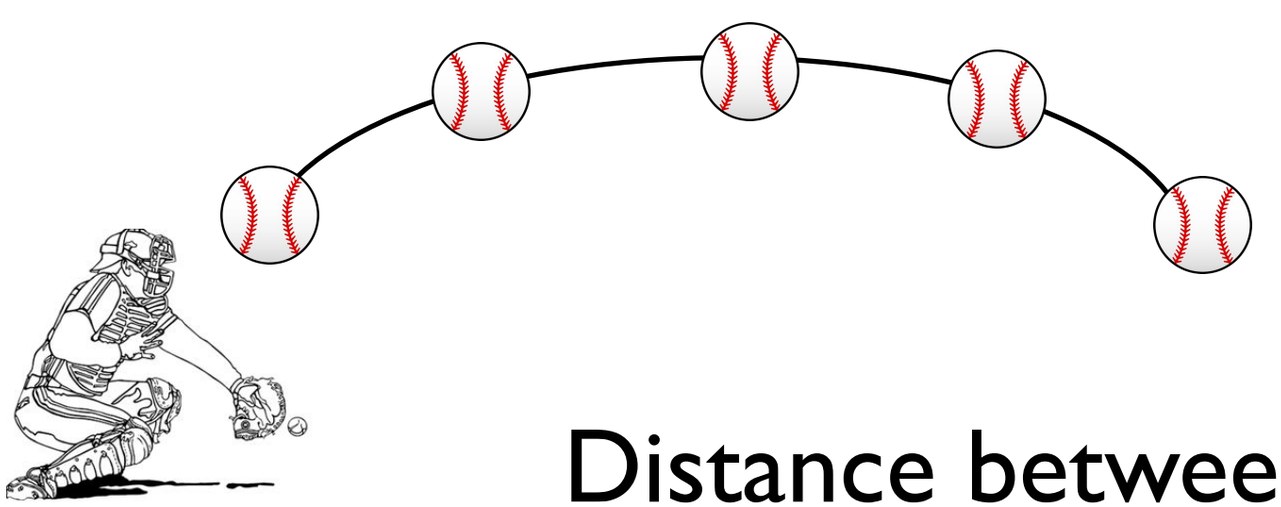
The distance is given in "co-moving" units -- the distance between two objects ***at present***



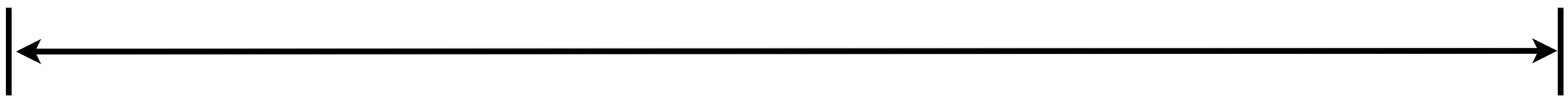


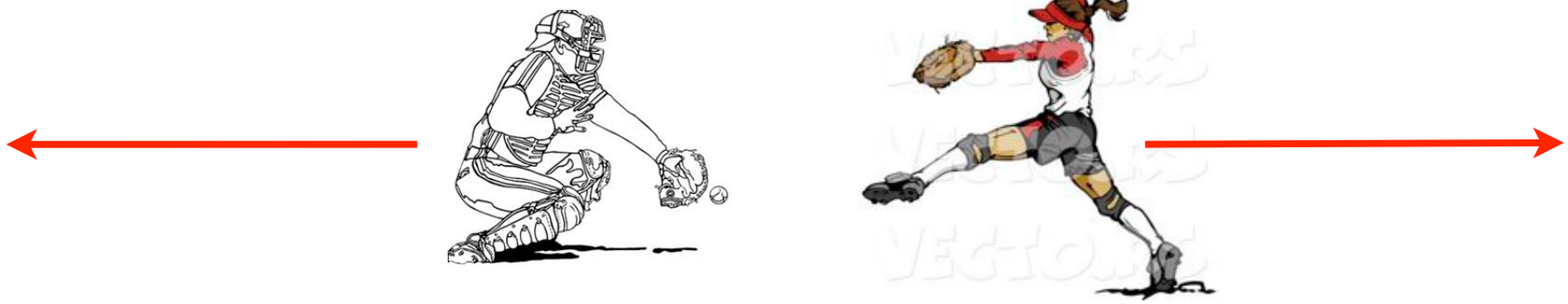
Distance traveled by ball
= velocity x time

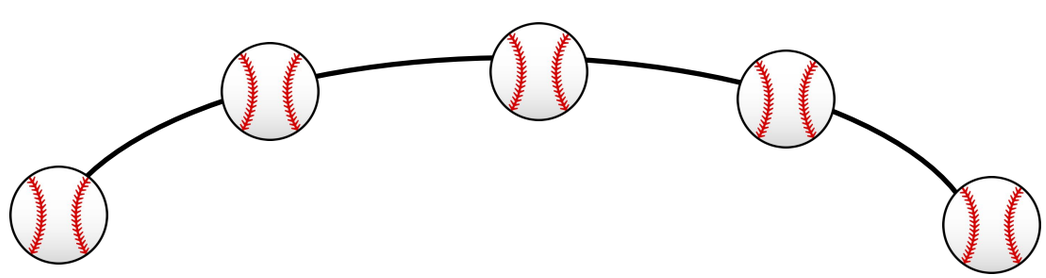




Distance between pitcher and catcher = 2 * velocity * time = ***twice*** distance travelled by ball

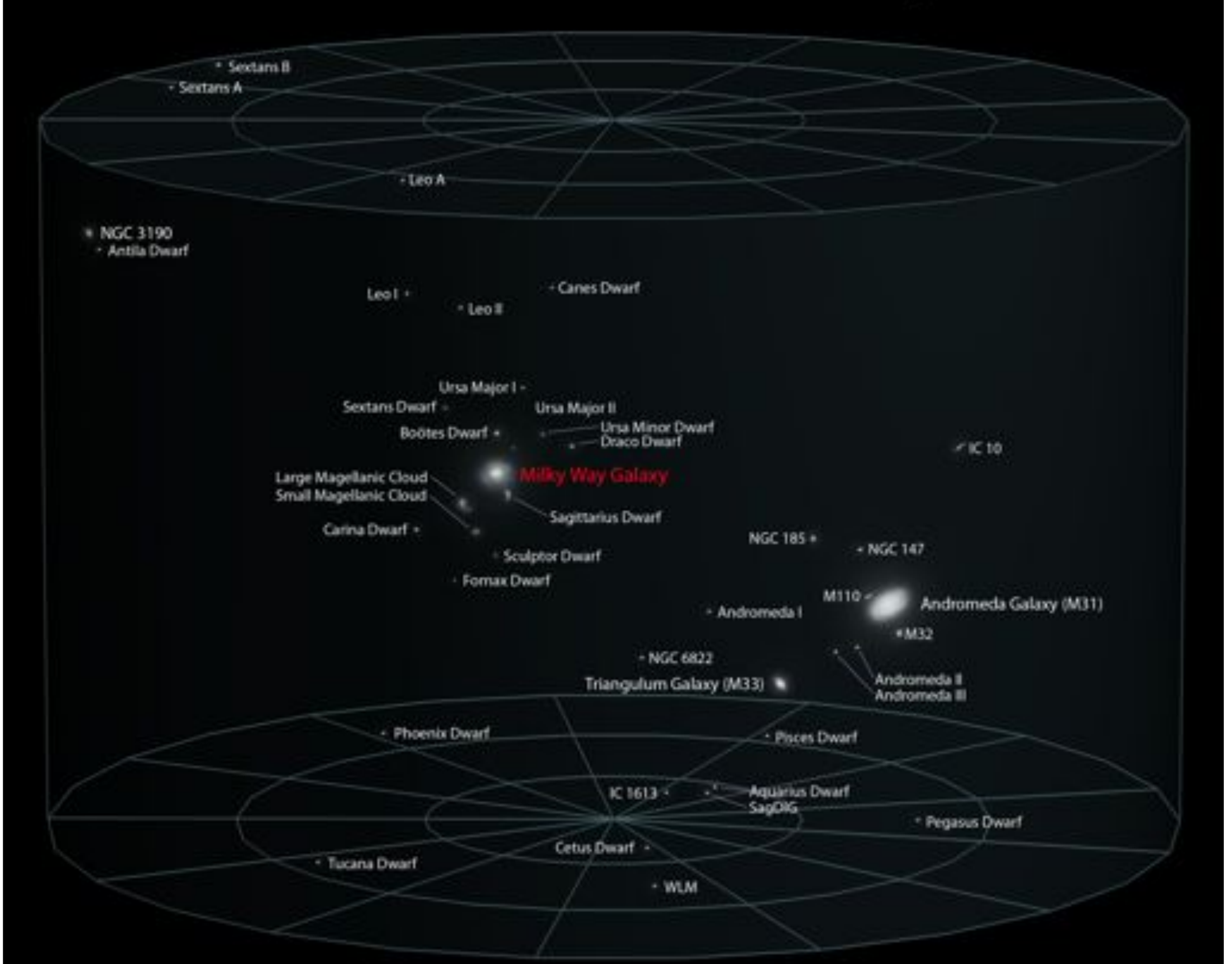






The analogy is not perfect -- unlike a baseball, the speed of a photon does not depend on the observer -- for a universe dominated by matter, relativity tells us it is **three times larger**

The Observed Large-Scale Structure of the Universe


Sextans B
Sextans A
Leo A
NGC 3190
Antlia Dwarf
Leo I
Leo II
Canes Dwarf
Ursa Major I
Sextans Dwarf
Ursa Major II
Boötes Dwarf
Ursa Minor Dwarf
Draco Dwarf
IC 10
Large Magellanic Cloud
Small Magellanic Cloud
Milky Way Galaxy
Sagittarius Dwarf
Carina Dwarf
NGC 185
NGC 147
Sculptor Dwarf
Fornax Dwarf
M110
Andromeda Galaxy (M31)
Andromeda I
M32
NGC 6822
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Andromeda II
Andromeda III
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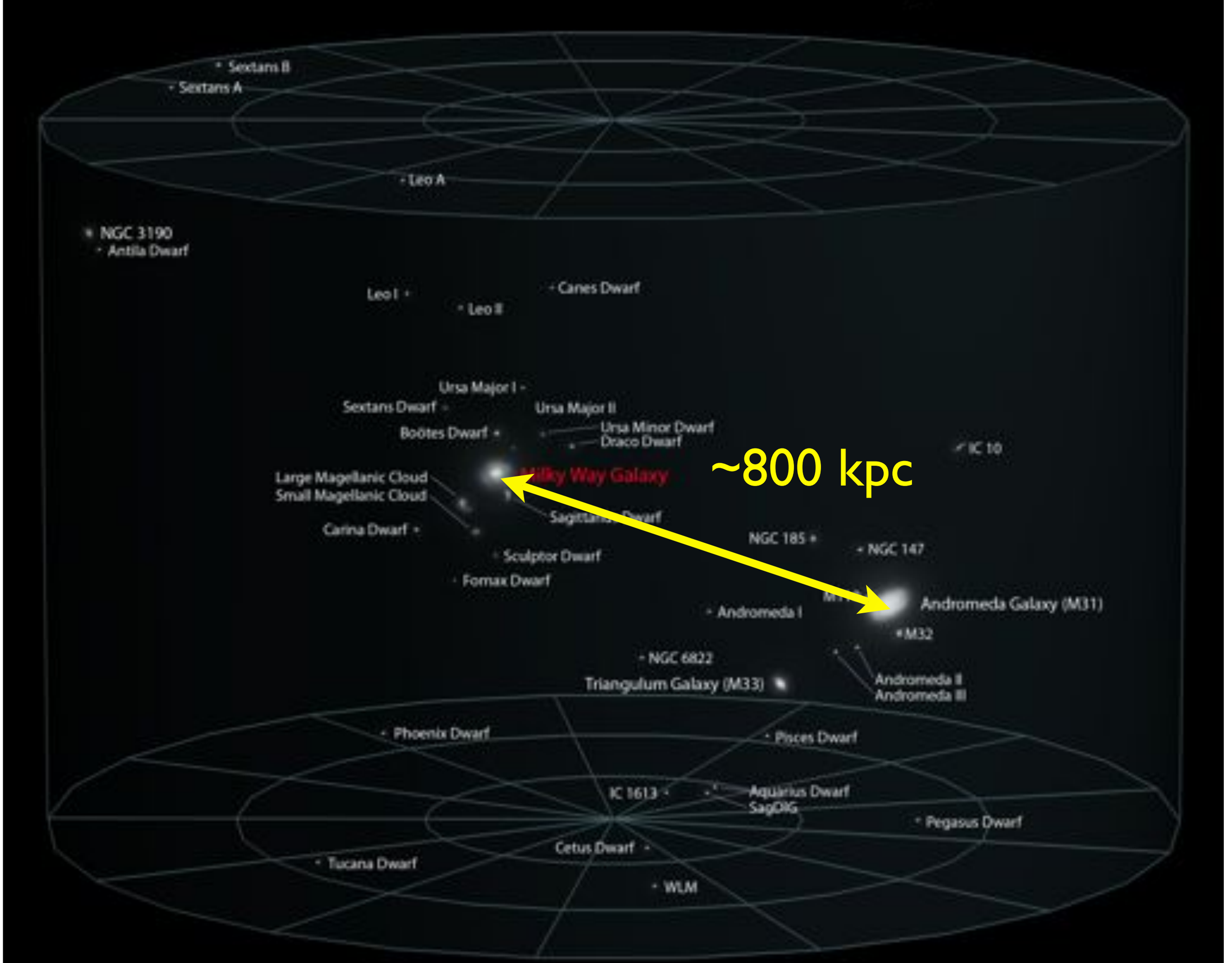
Pisces Dwarf
IC 1613
Aquarius Dwarf
SagDIG
Pegasus Dwarf
Cetus Dwarf
Tucana Dwarf
WLM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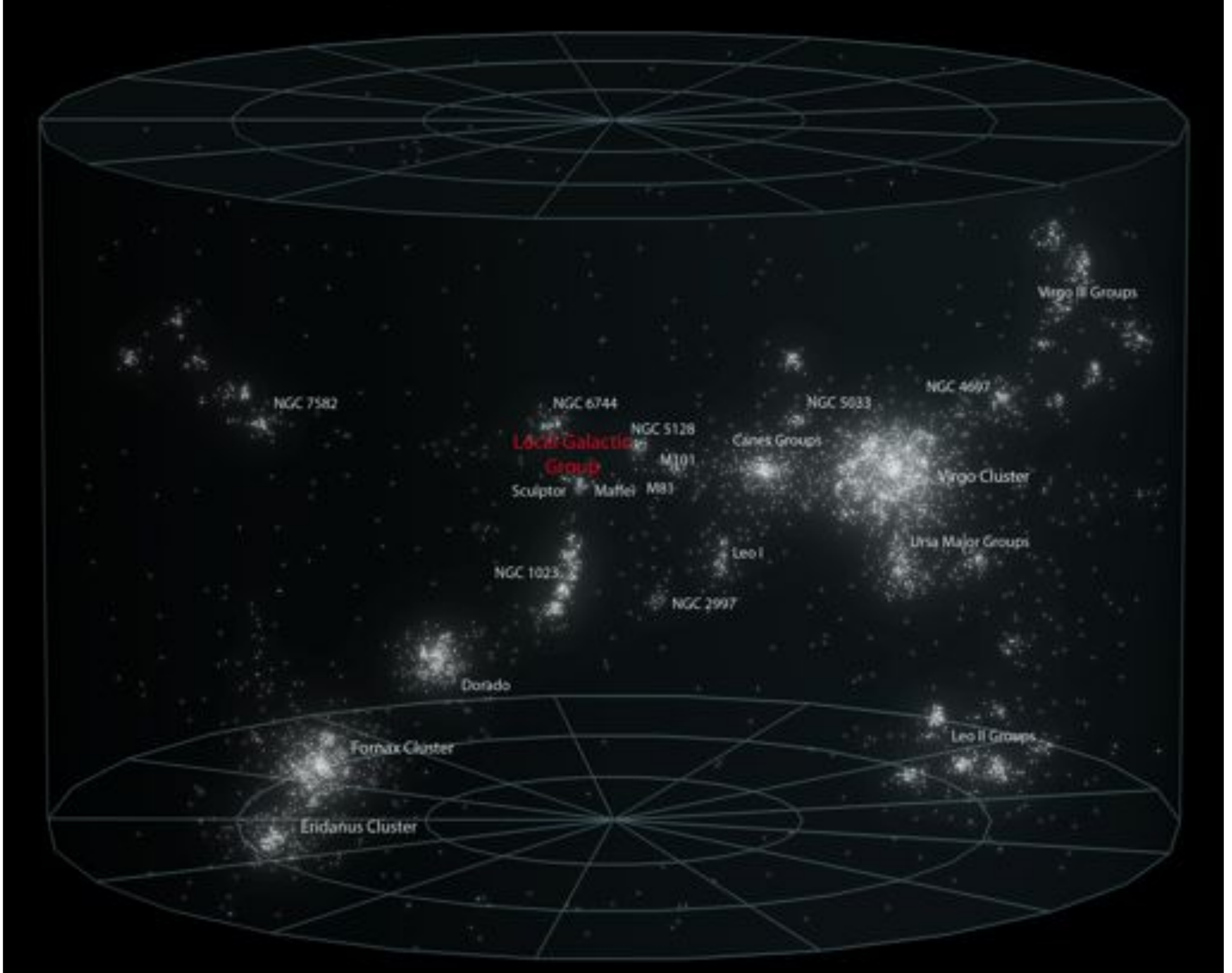
Virgo III Groups
NGC 7582
NGC 6744
NGC 5033
NGC 4697
NGC 5128
Canes Groups
Local Galactic Group
M101
Sculptor
Maffei
M83
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NGC 1023
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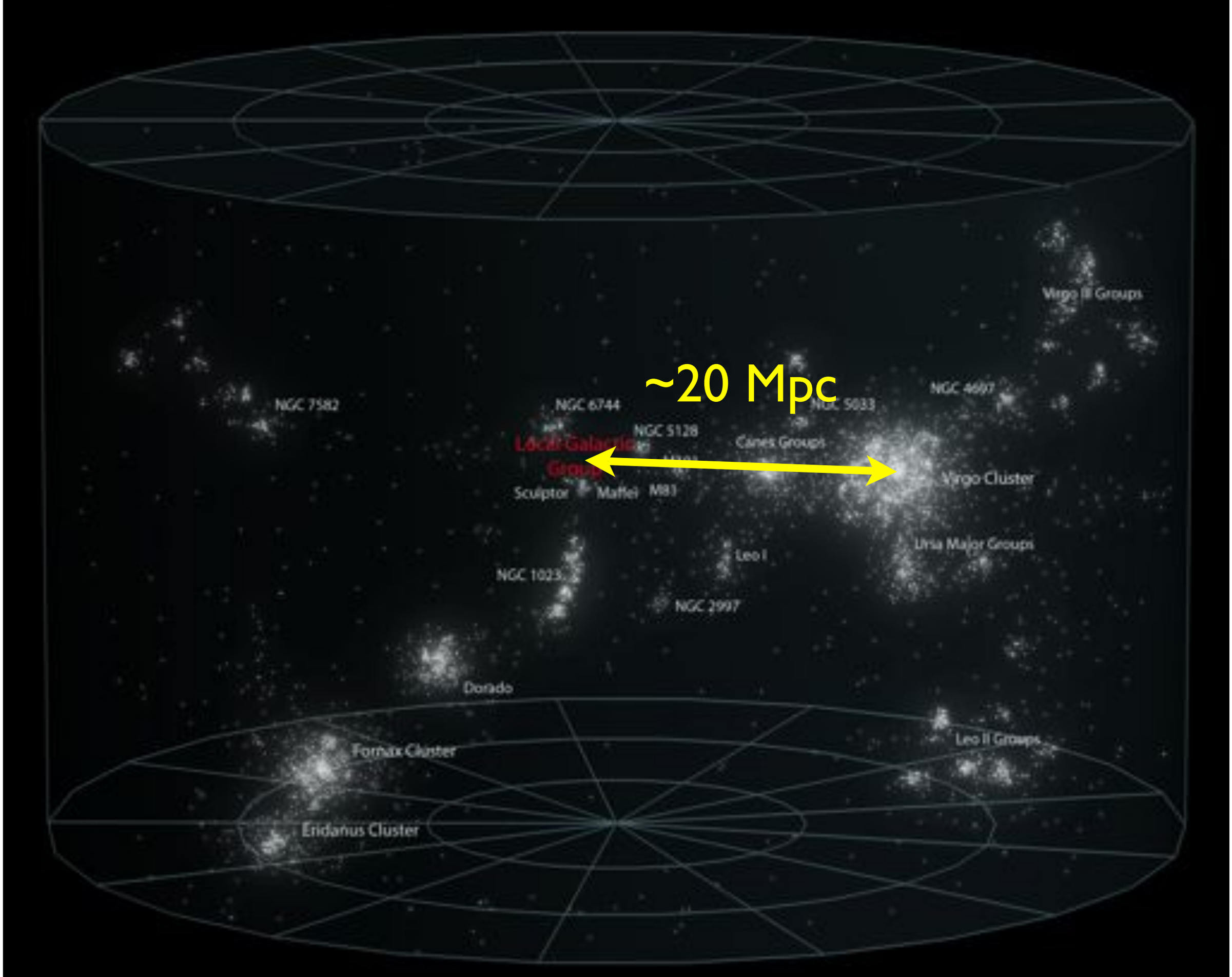
Fornax Cluster
Eridanus Cluster


~20 Mpc
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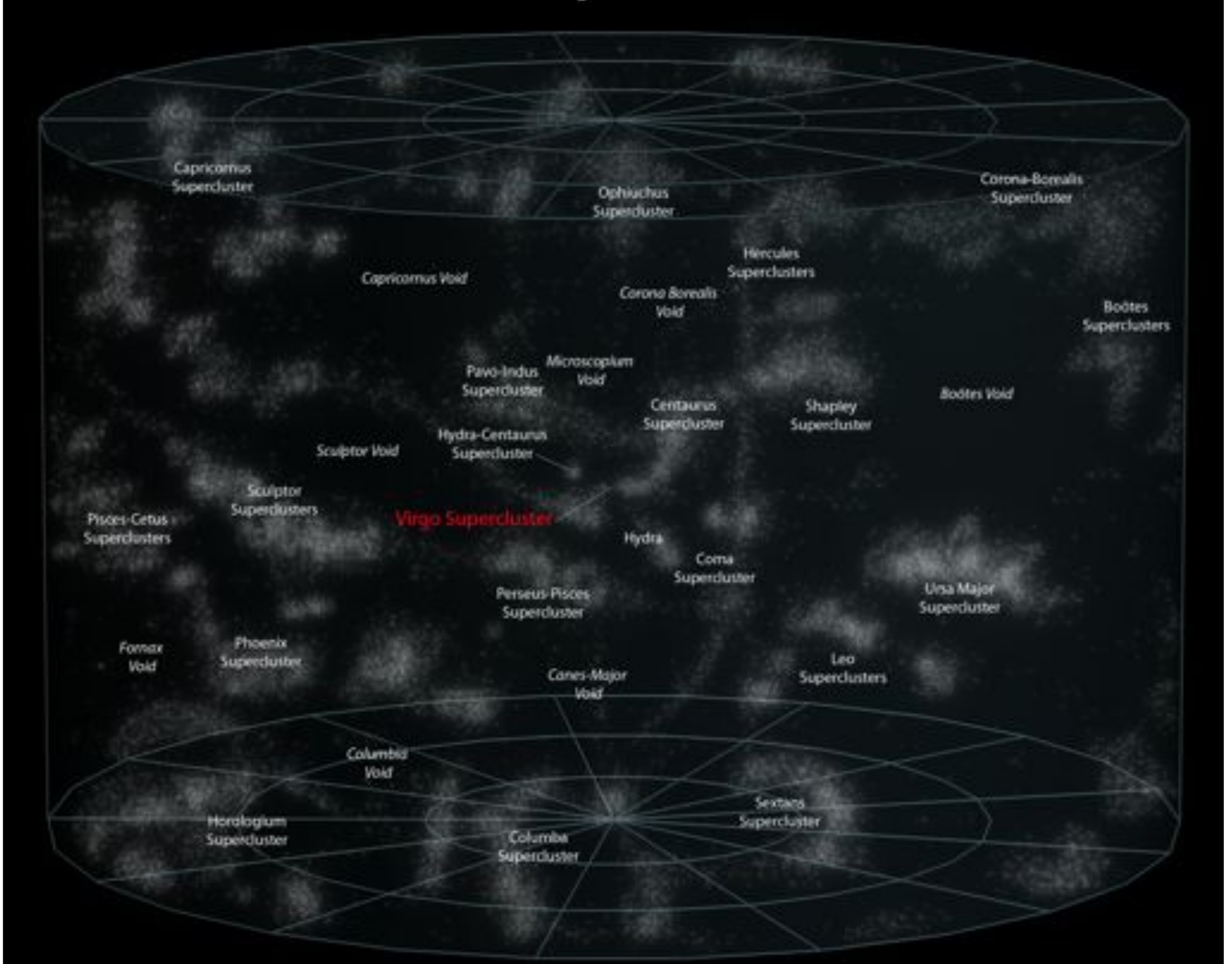
Capricornus Supercluster
Ophiuchus Supercluster
Corona-Borealis Supercluster
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Hercules Superclusters
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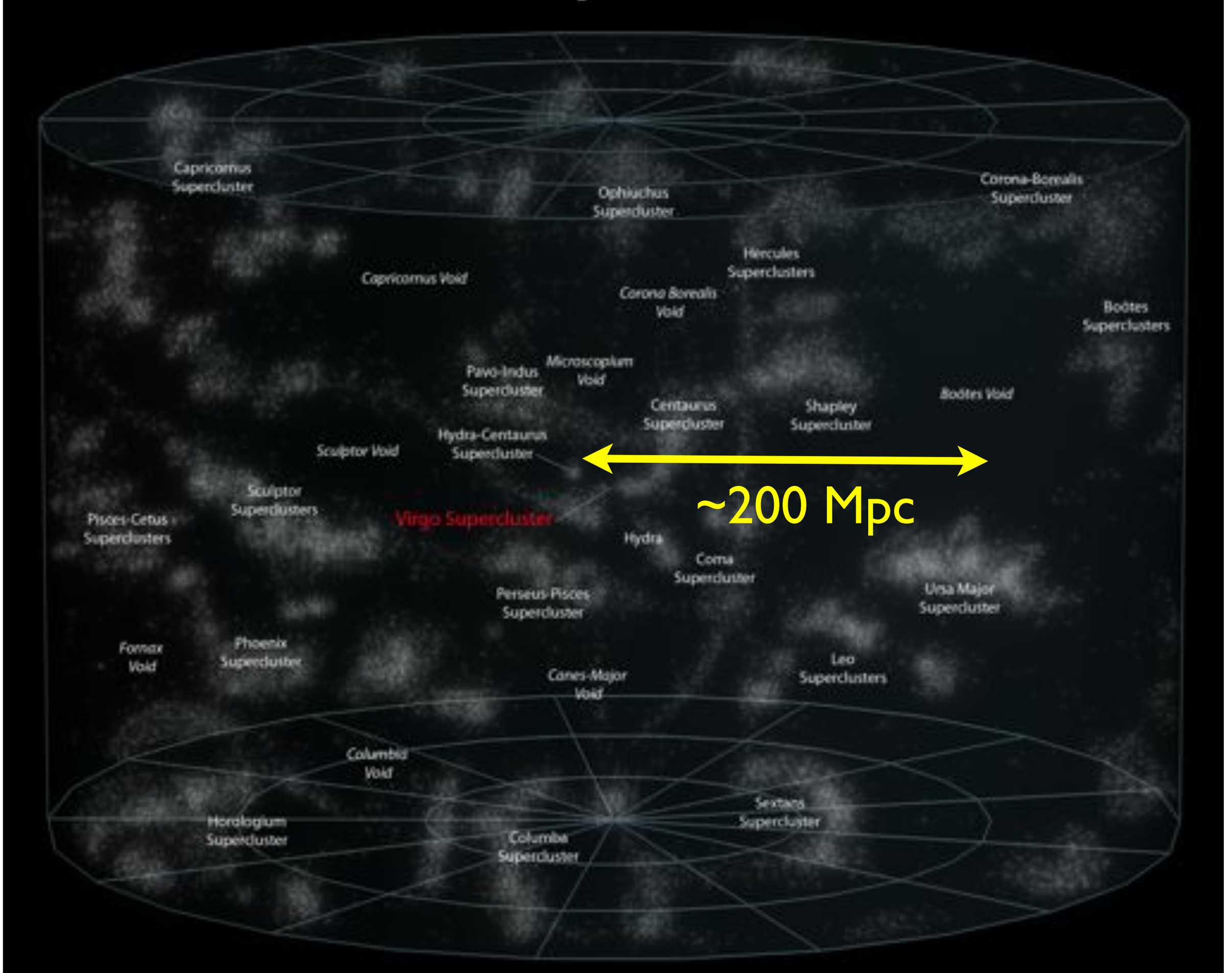
Canes-Major Void
Columbid Void
Sextans Supercluster
Horologium Supercluster
Columba Supercluster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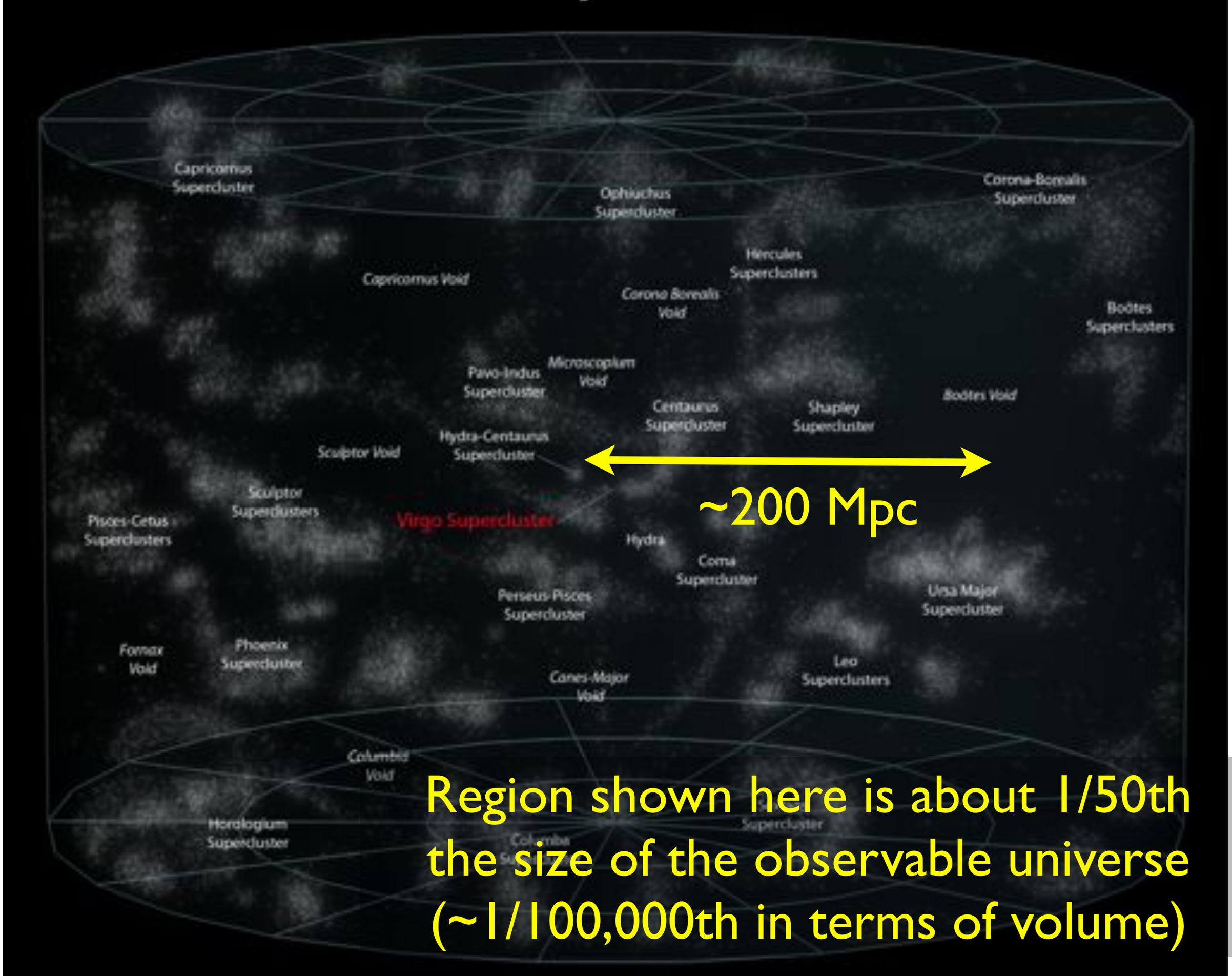
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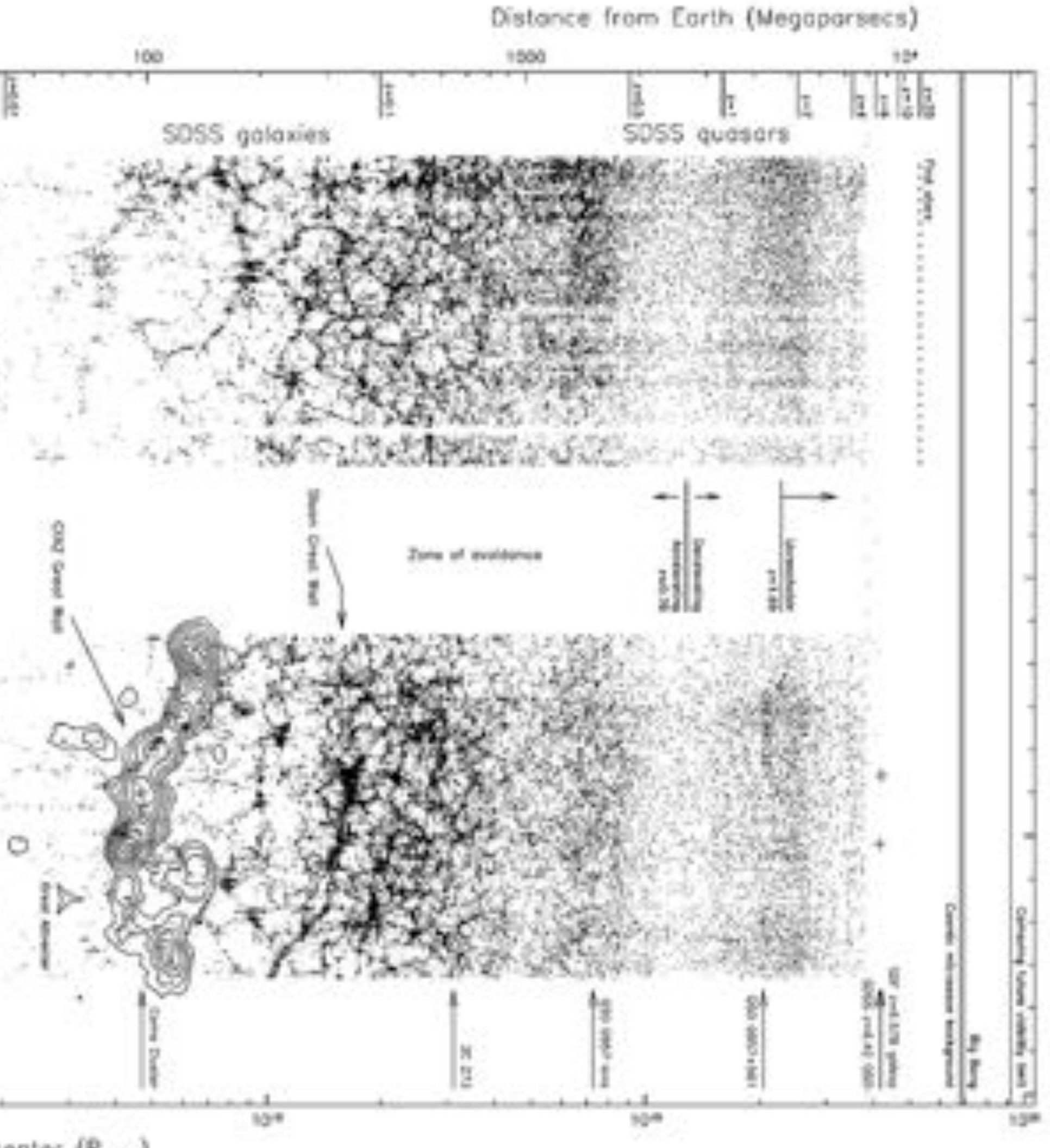
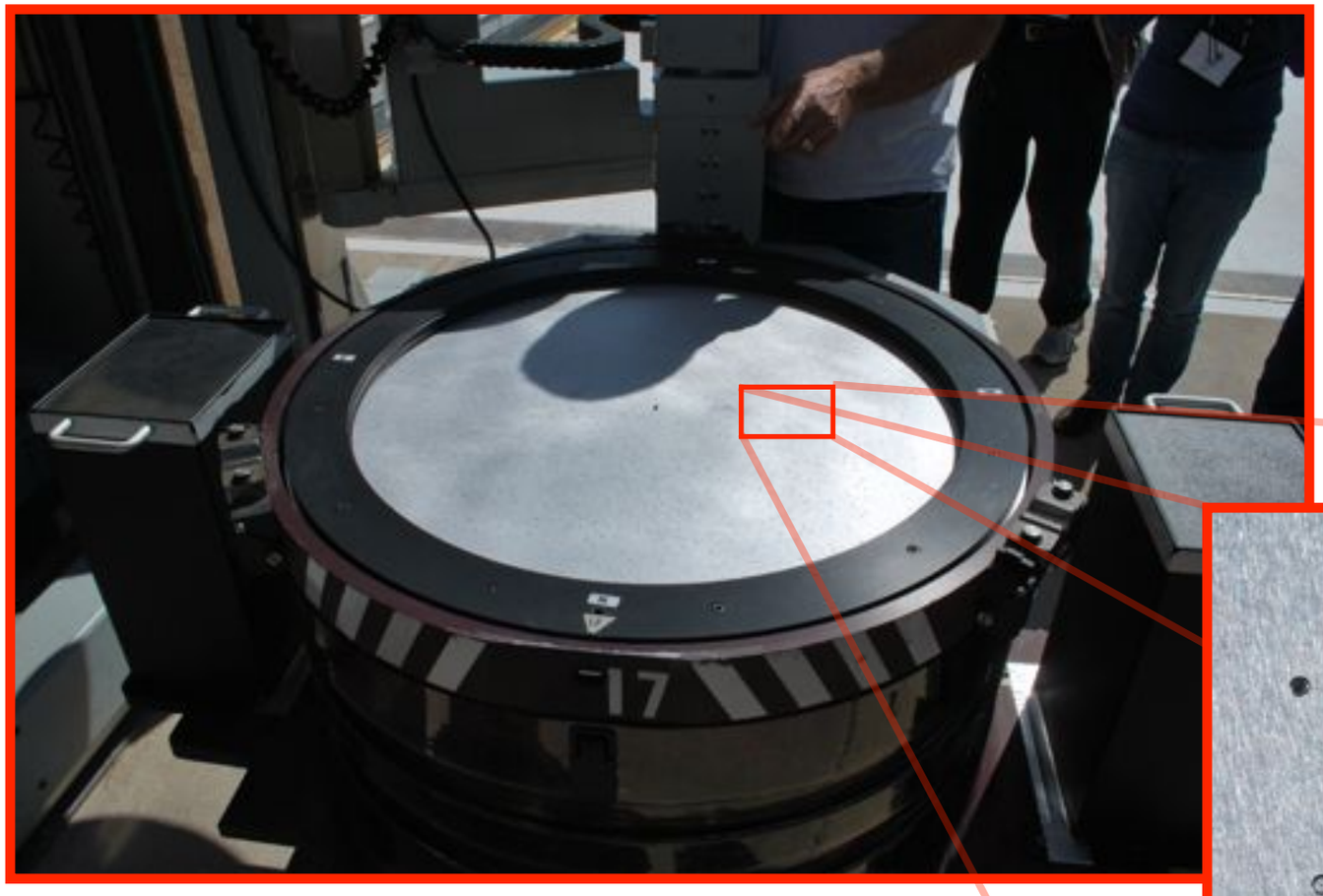
Region shown here is about 1/50th the size of the observable universe (~1/100,000th in terms of volume)


Distance from Earth (Megaparsecs)
100
1000
SDSS galaxies
SDSS quasars
Zone of avoidance
Center (R_{Earth})

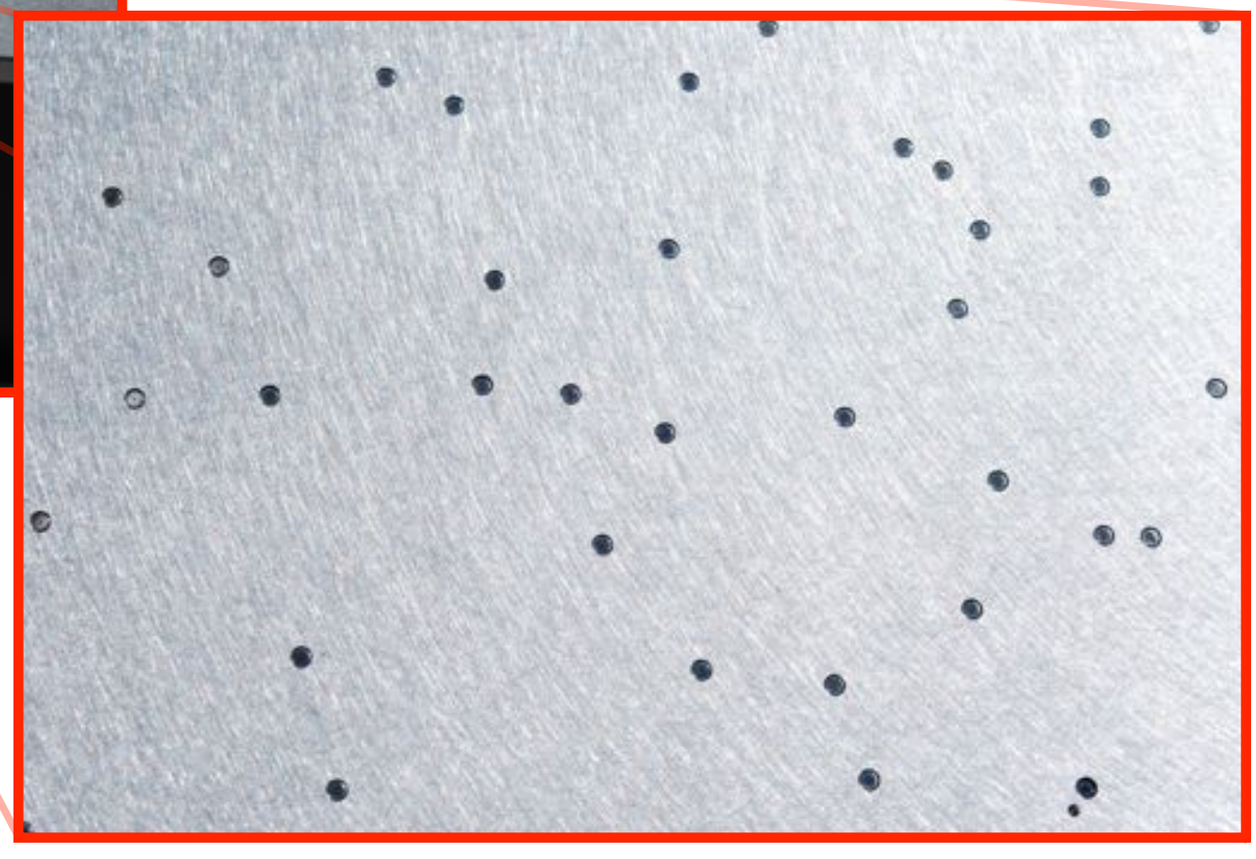
The Sloan Digital Sky Survey (SDSS)

- Largest galaxy survey to date
- Uses 2.5-meter telescope in New Mexico
- Has found ~ 1 million galaxies to date(!!)
- Galaxies out to z=0.7, and Quasars to z=7
- Uses holes drilled into an aluminum plate to obtain galaxy spectrum -- one hole for each galaxy

The Sloan Digital Sky Survey (SDSS)



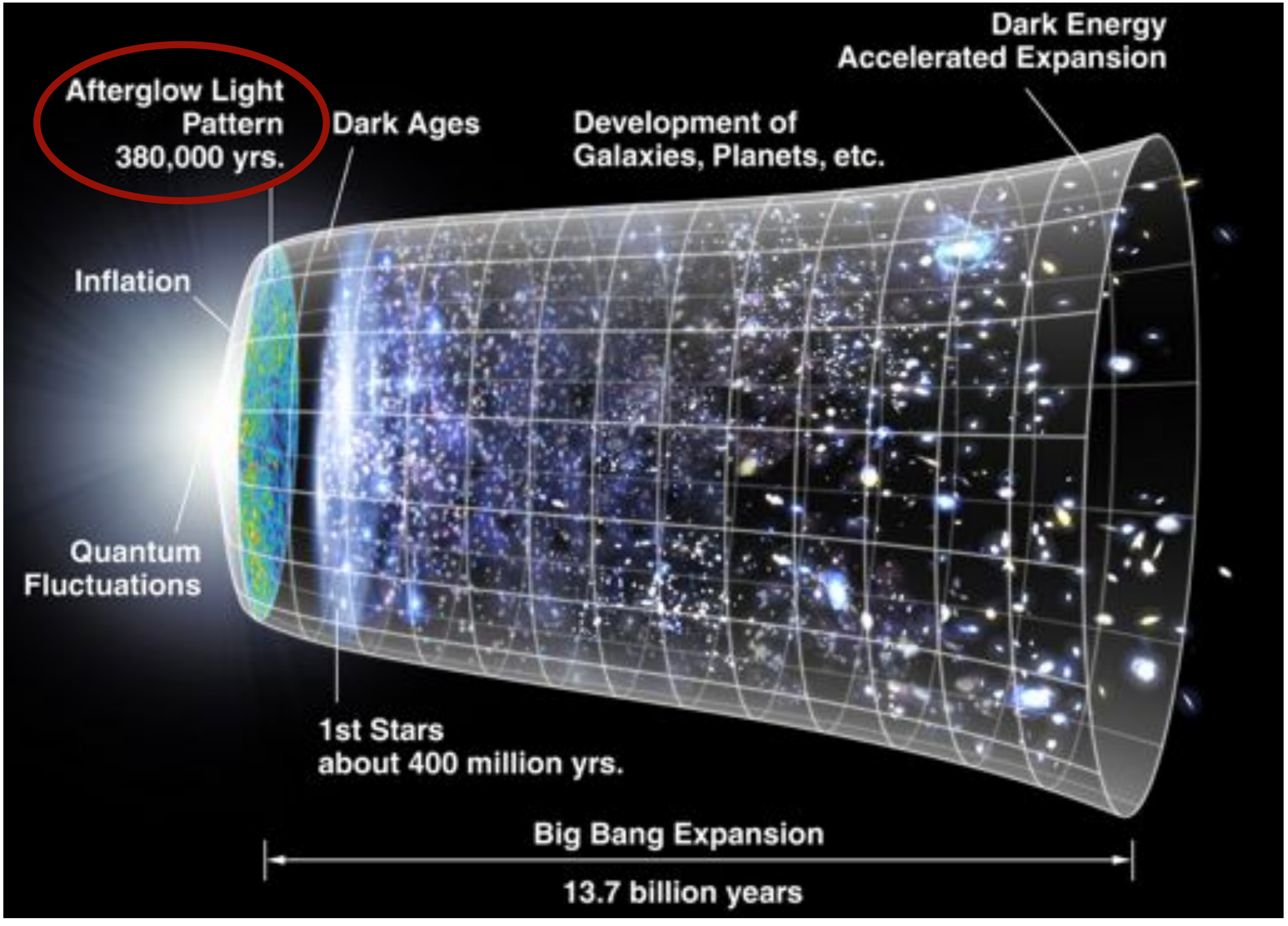
Optical fibers run from each hole to a spectrograph, which can then be used to determine galaxy redshift



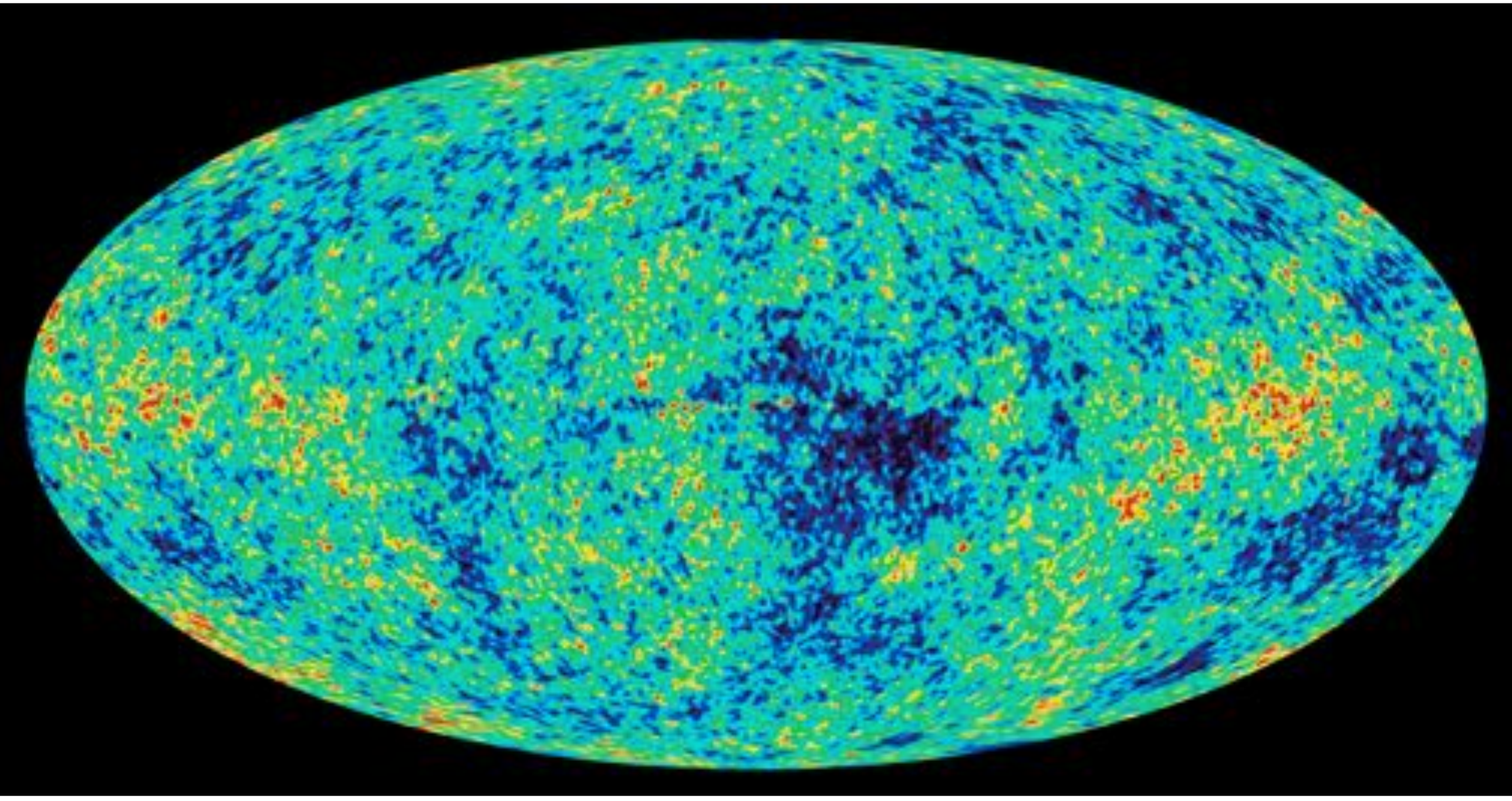
The redshift gives information about how far away the galaxy is, not just its position on the sky. This allows a 3D map of the galaxies to be made

The Theory of Cosmic Structure Formation

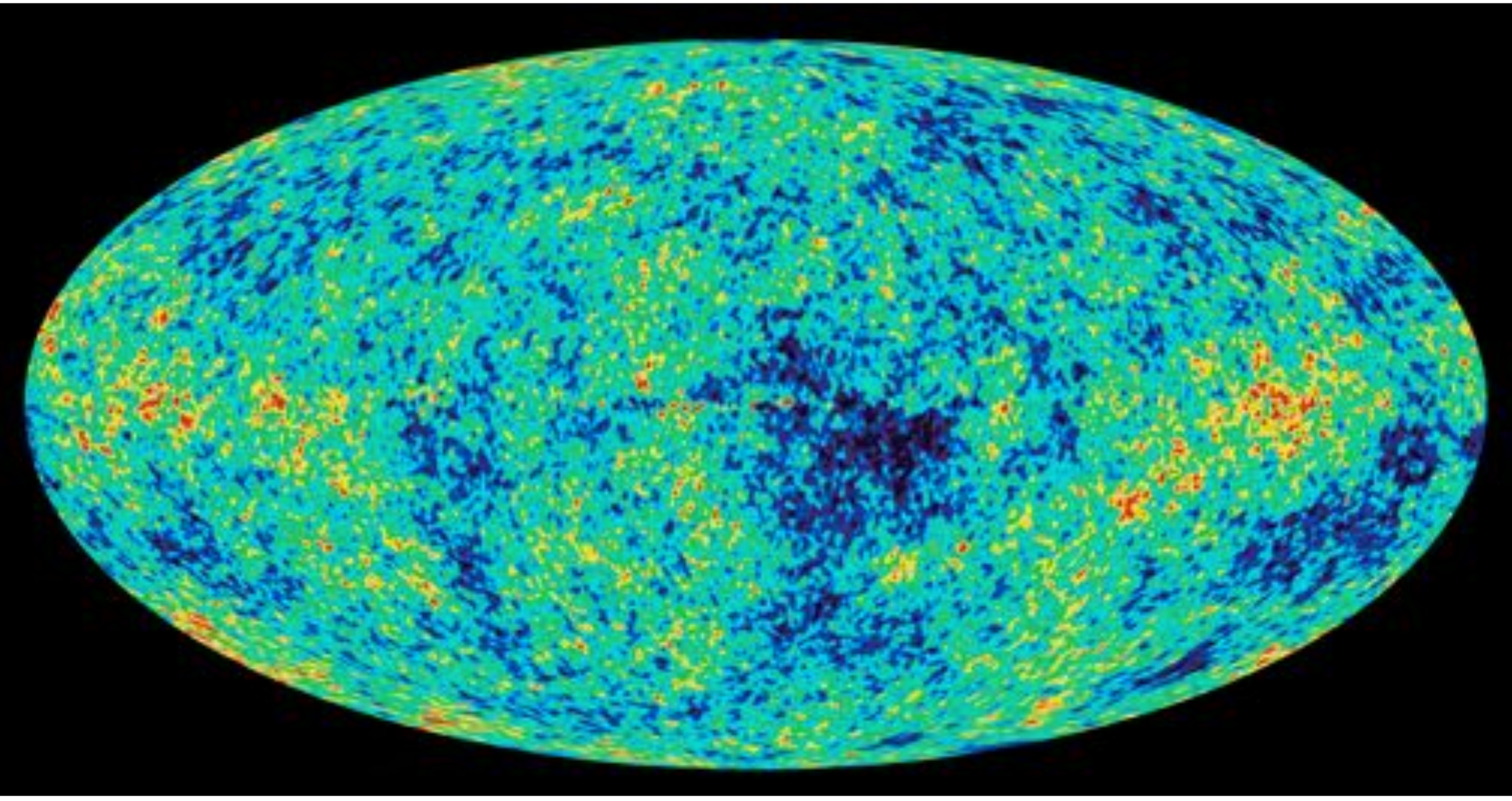
The Story Begins at t~380,000 Years



The Cosmic Microwave Background (CMB) is “Baby Picture” of Universe at 380,000 years

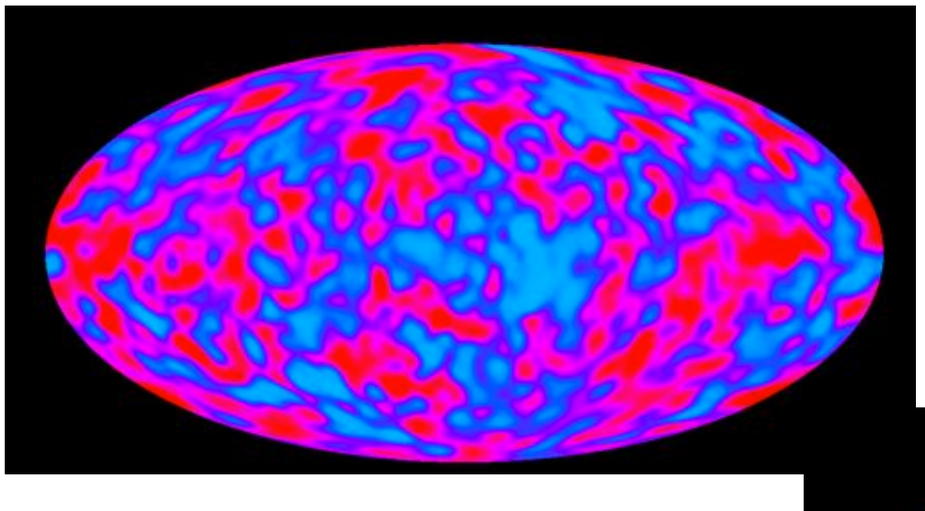


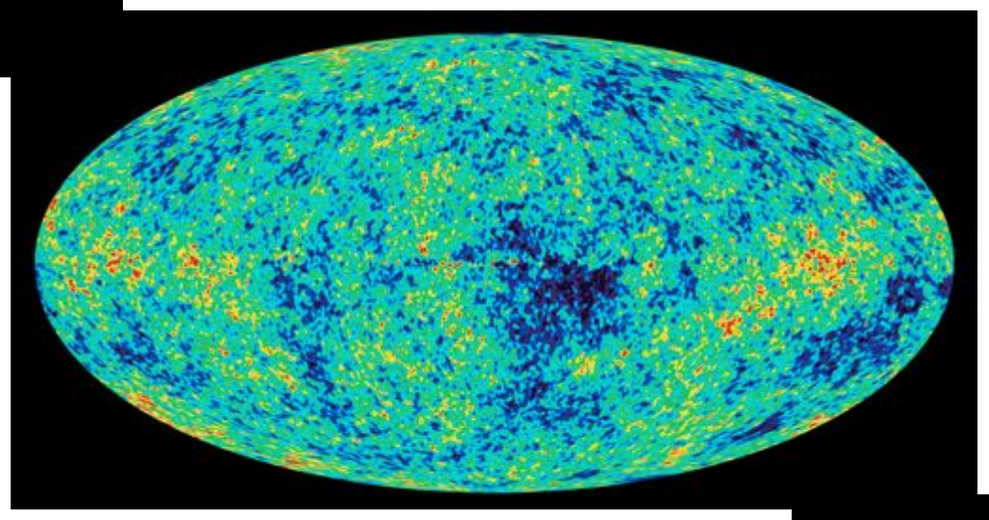
Density Fluctuations Were Tiny at this Time:
About 0.001% or 1 part in 100,000

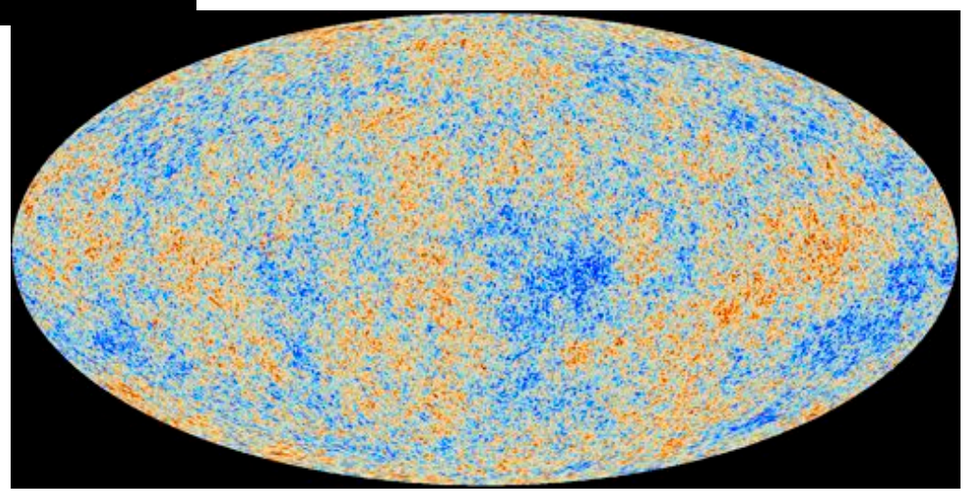


Centimeter-tall Ripples on the Surface of a Kilometer-deep Lake.

Our Knowledge of CMB Anisotropies has come a Long Way in the Last Twenty Five Years

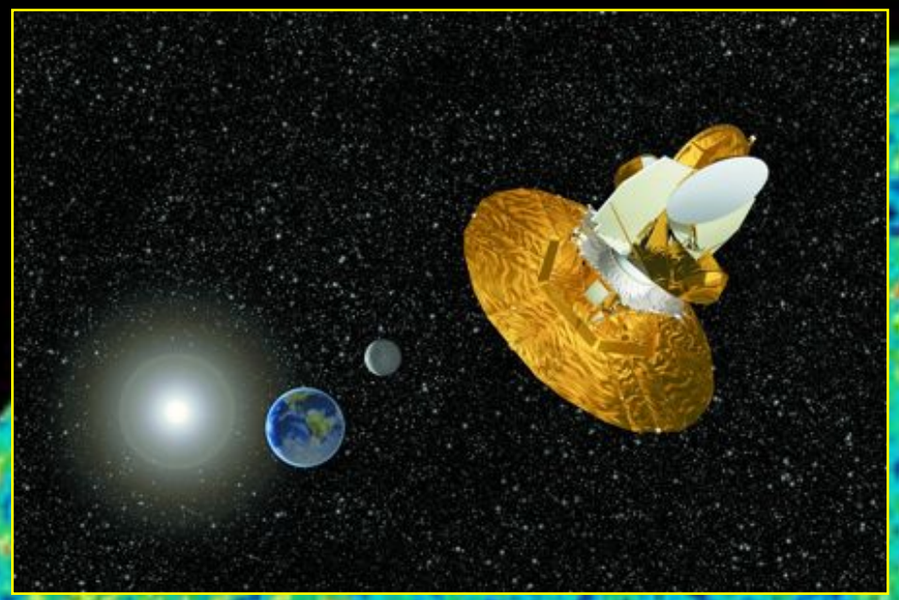




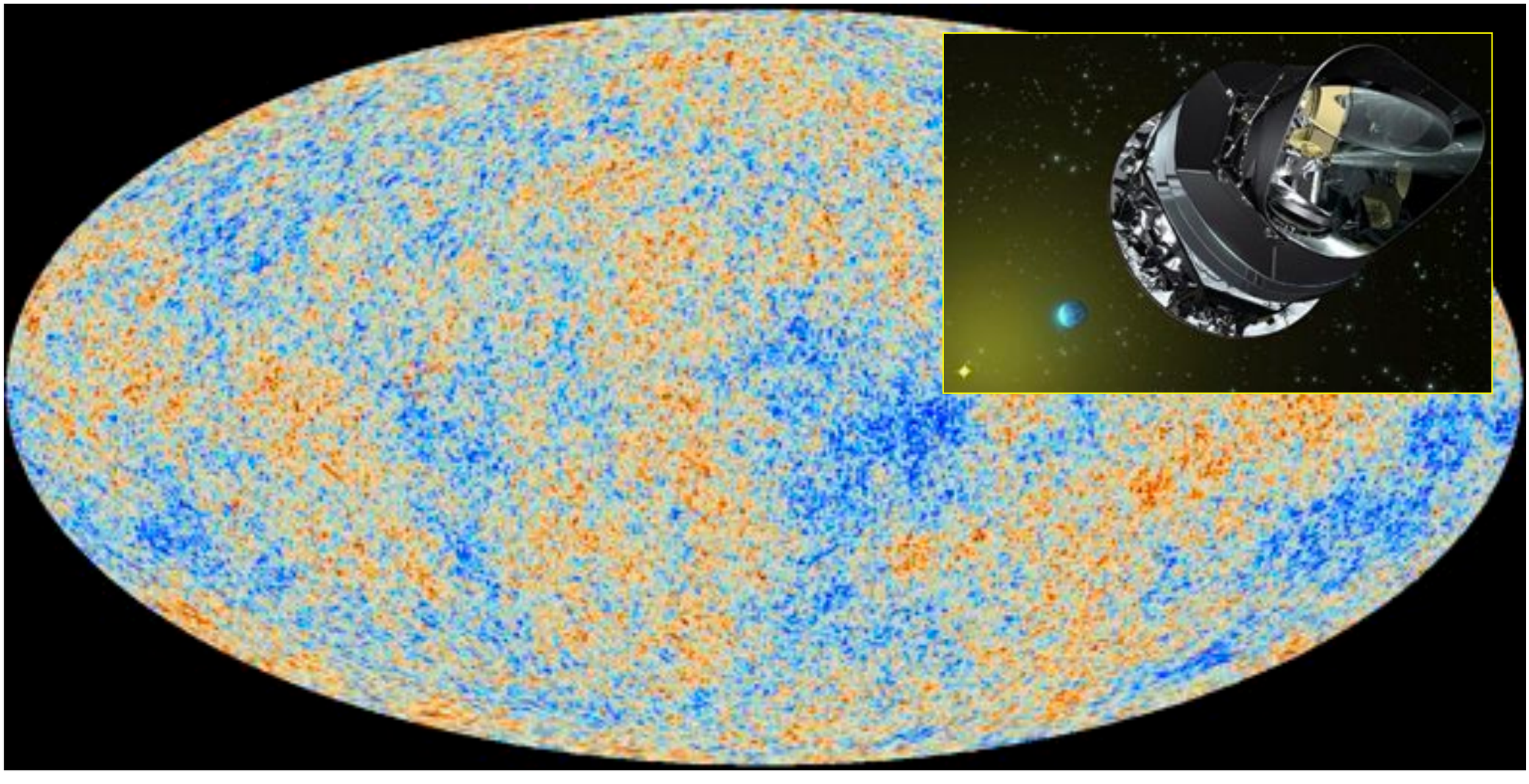


Cosmic Background Explorer (COBE - Launched 1989)

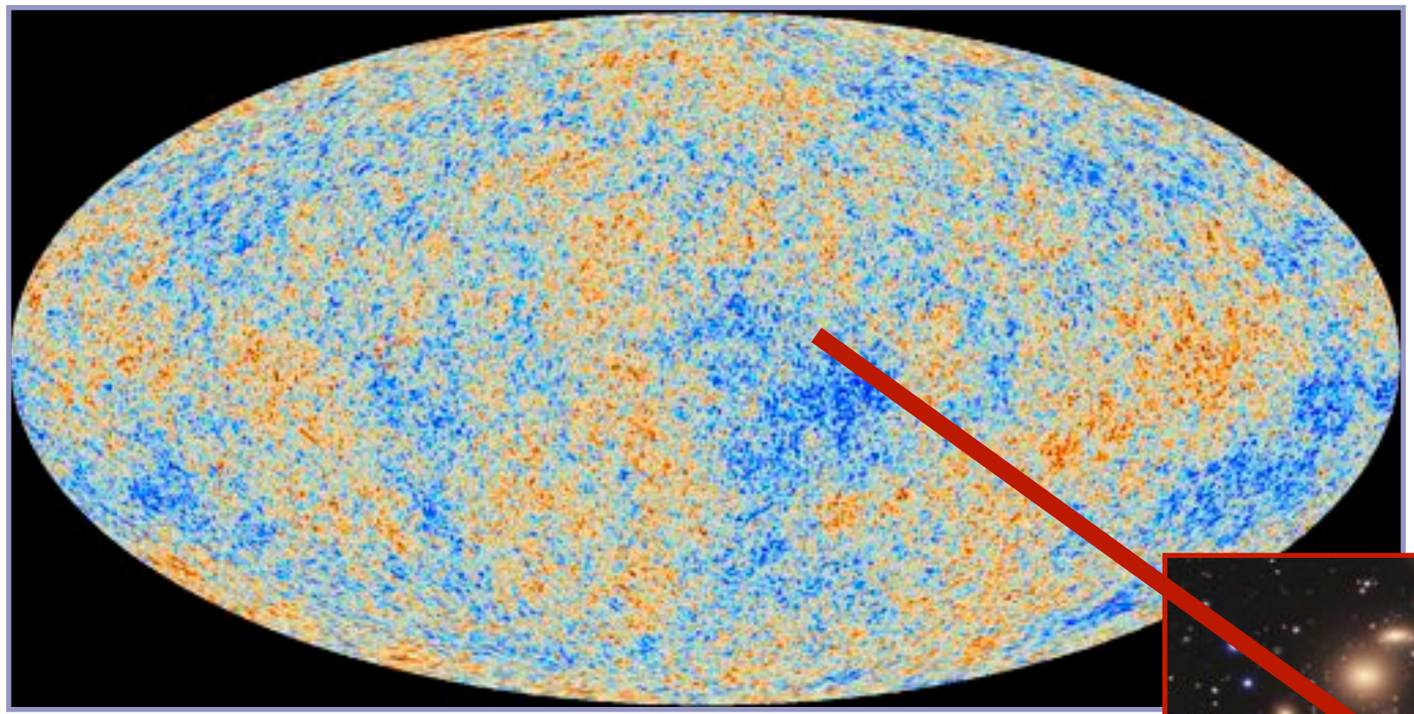
Wilkinson Microwave Anisotropy Probe (WMAP - Launched 2001)



Latest Baby Picture of the Universe Released Yesterday (Planck - Launched 2009)



Back to the Ripples: How did these *Linear Perturbations* Grow Into Planets, Galaxies, Superclusters, etc.?



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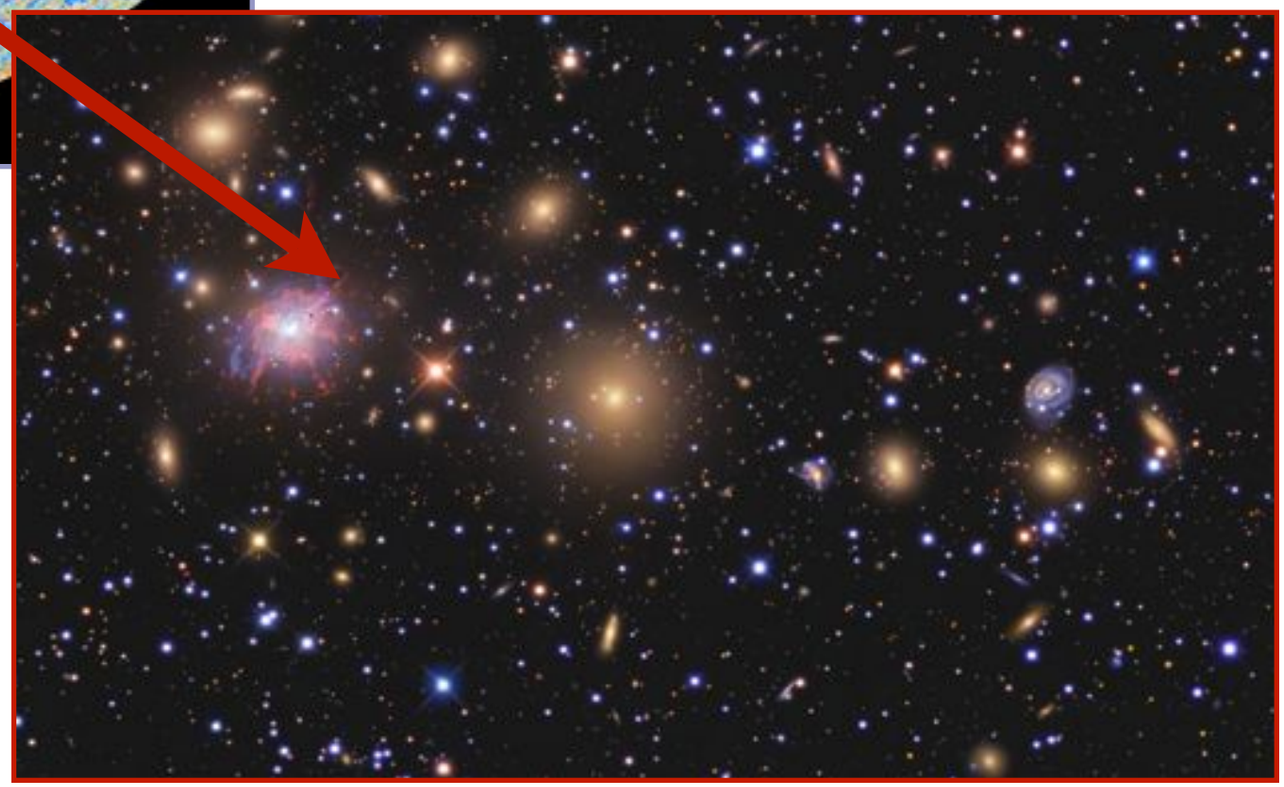

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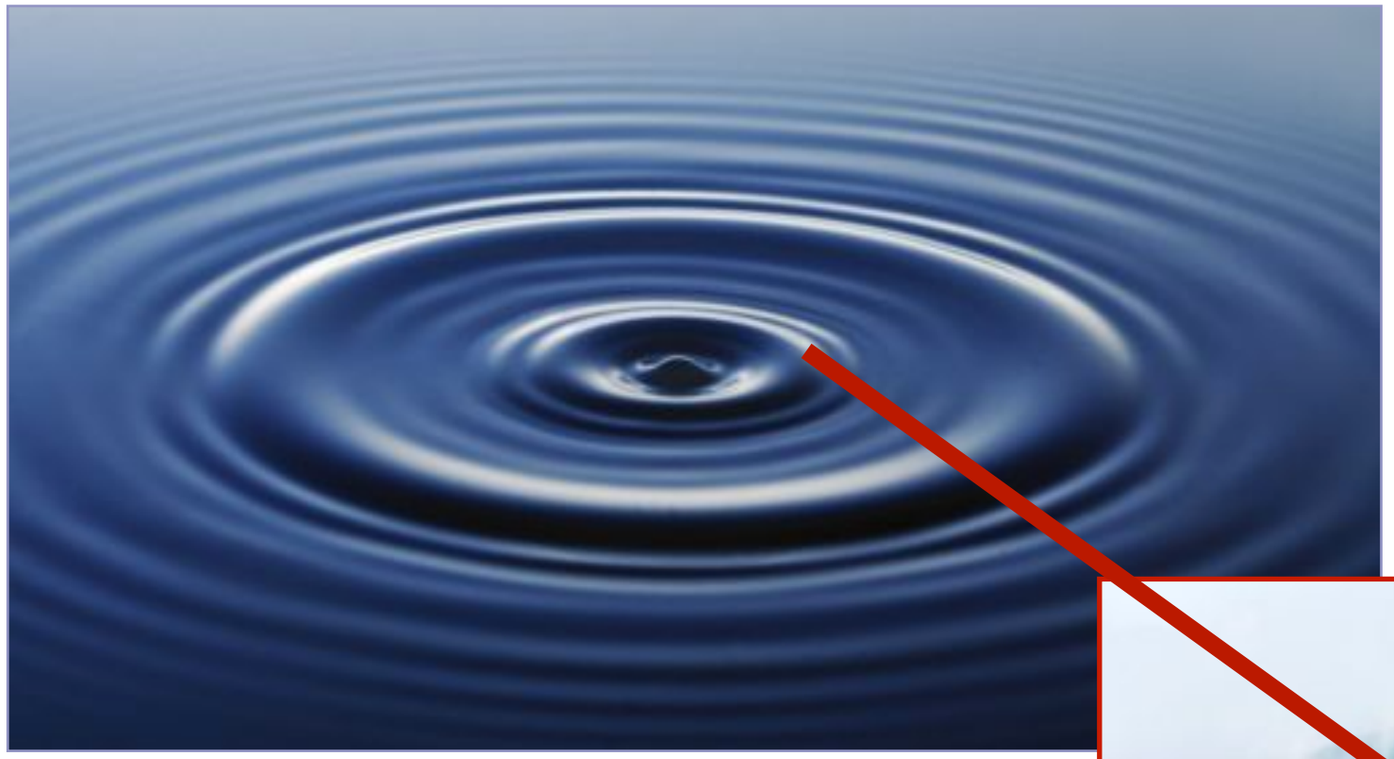

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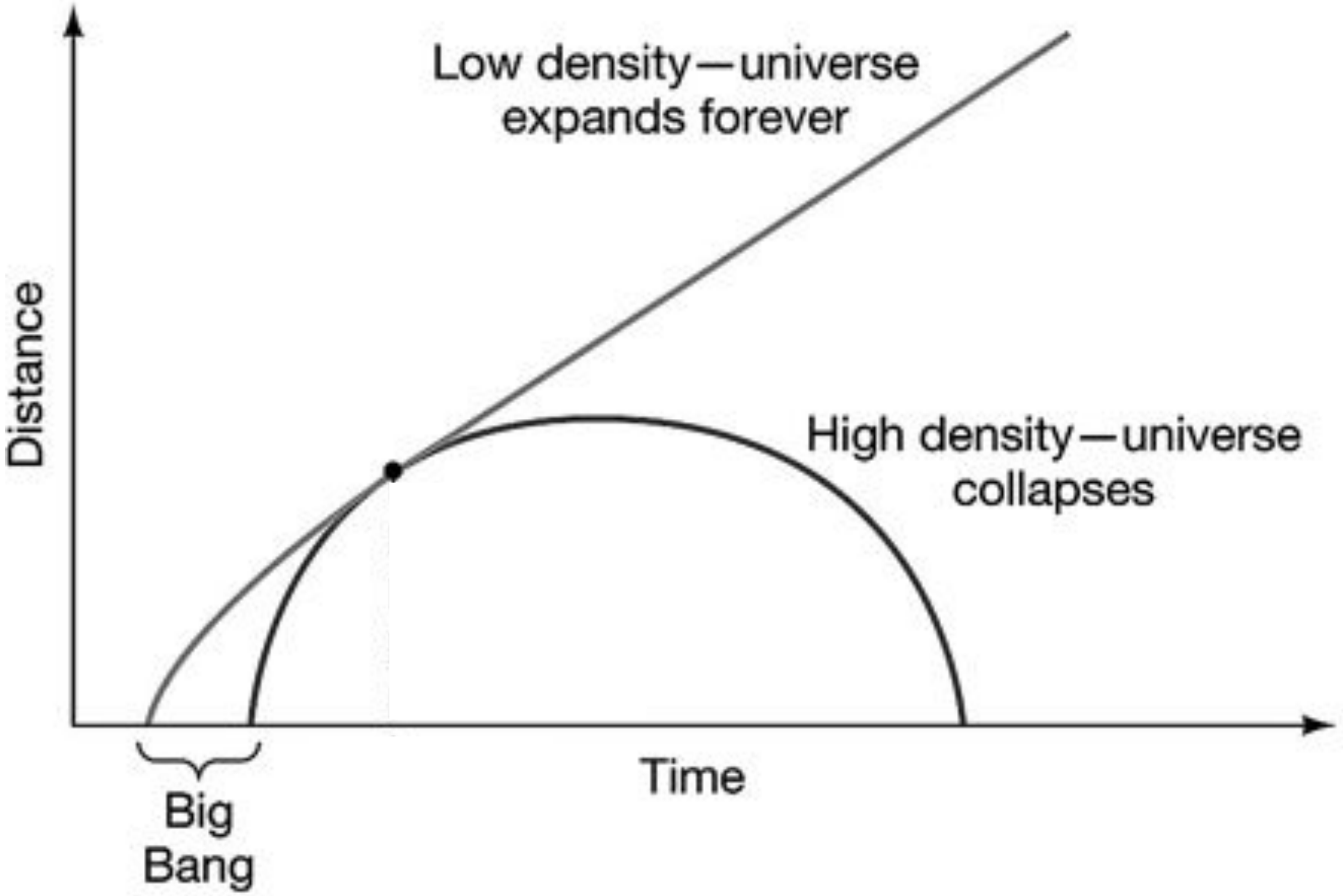
Answer: *Gravitational Instability*



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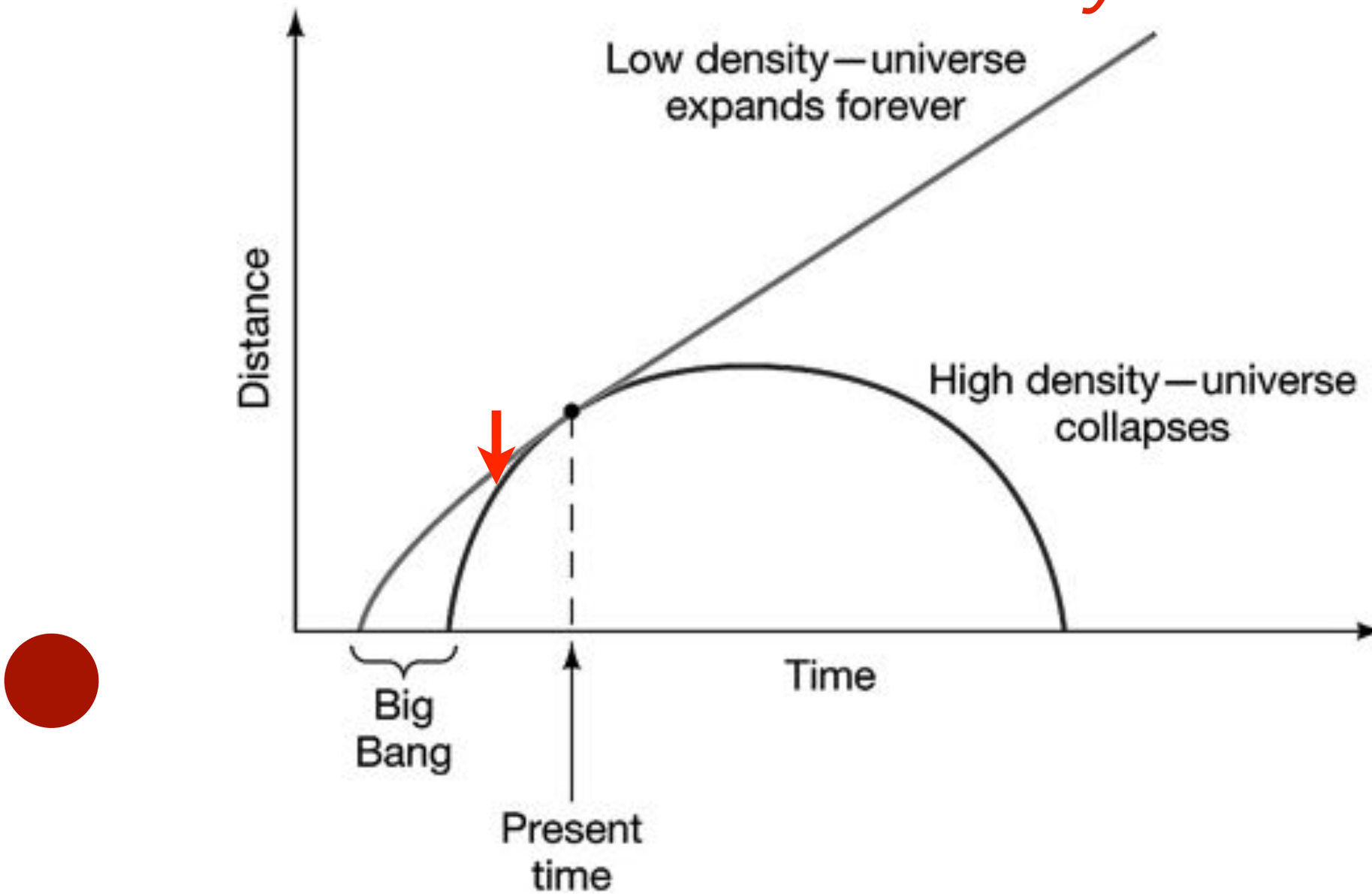

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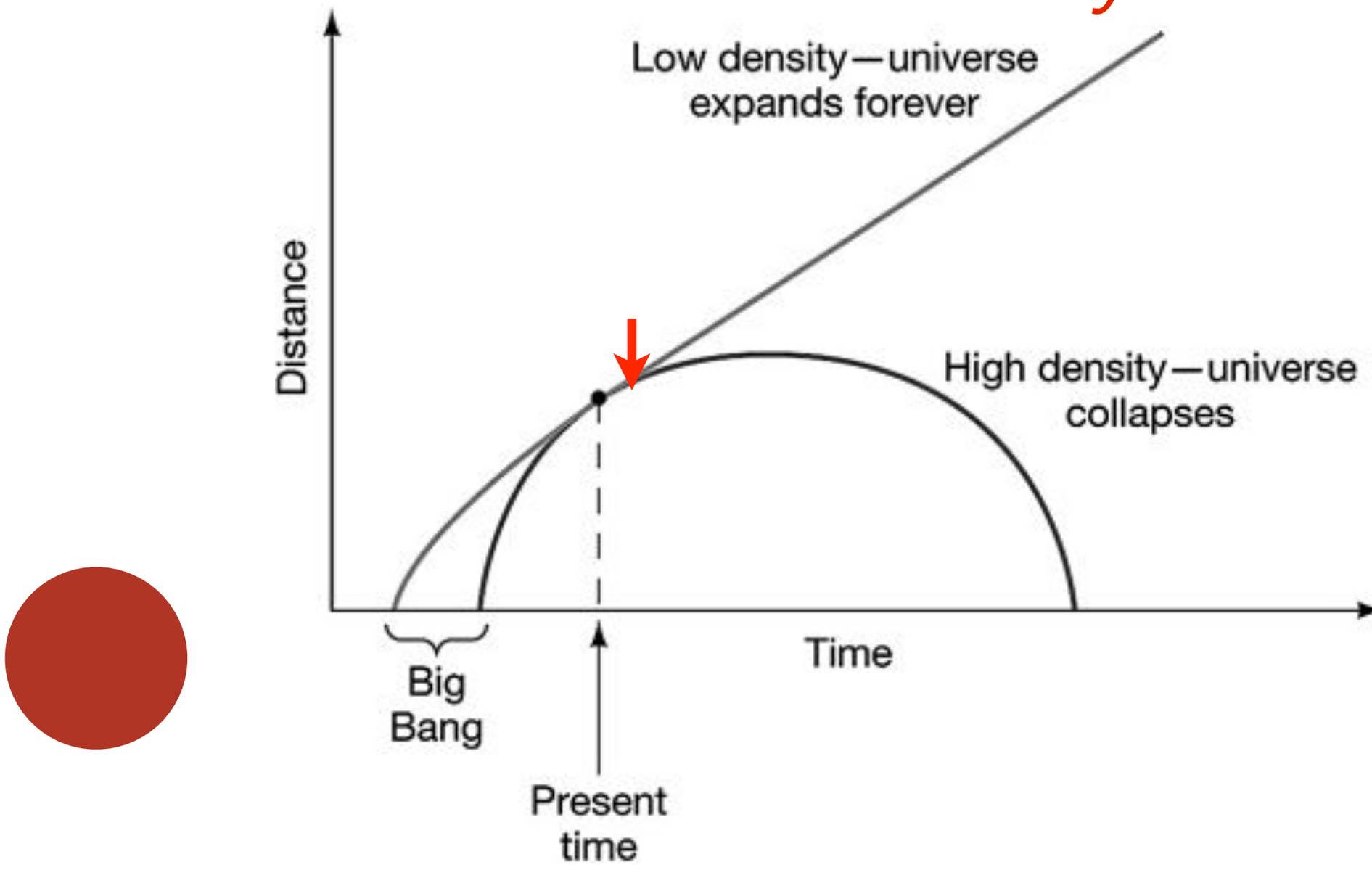

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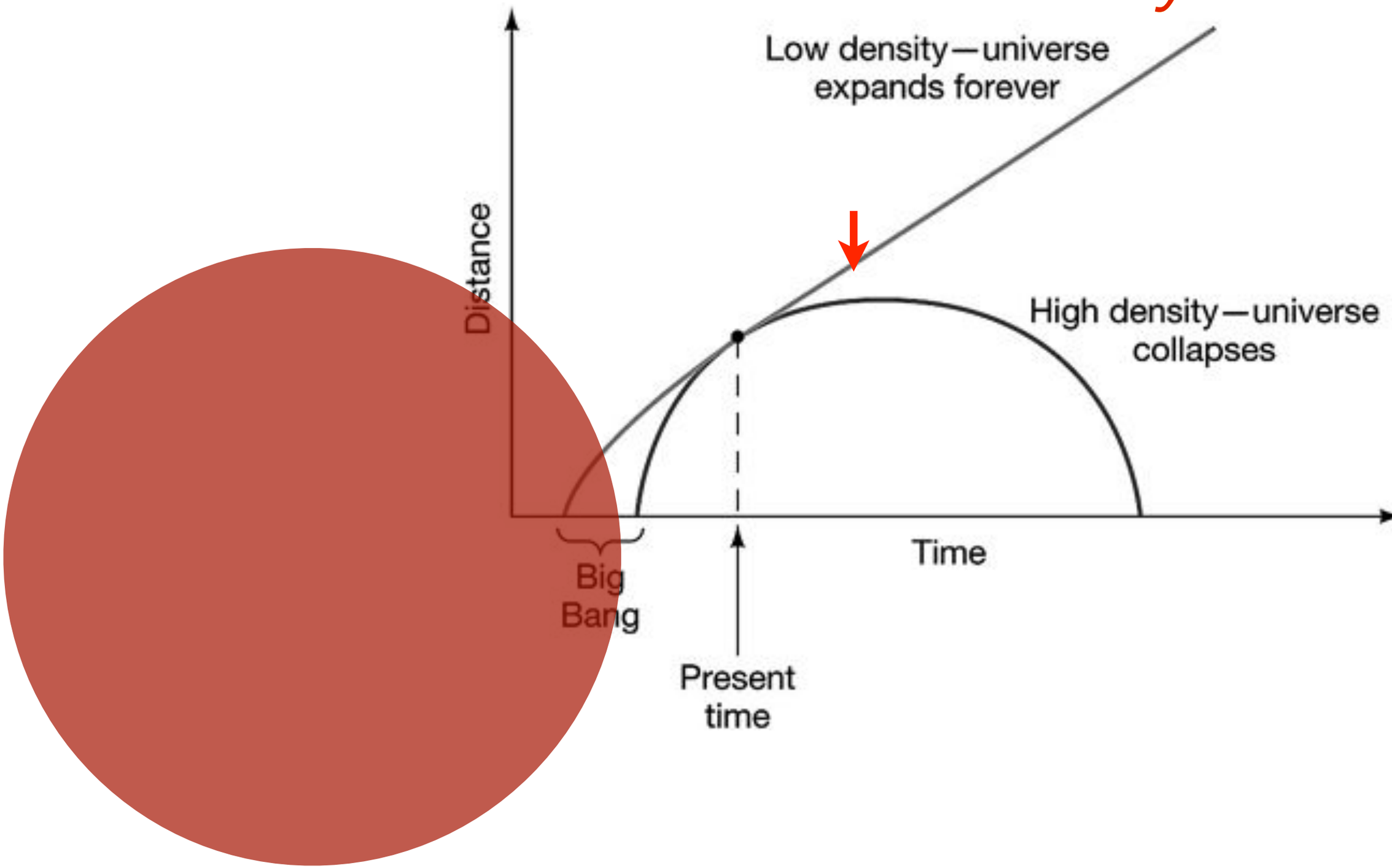

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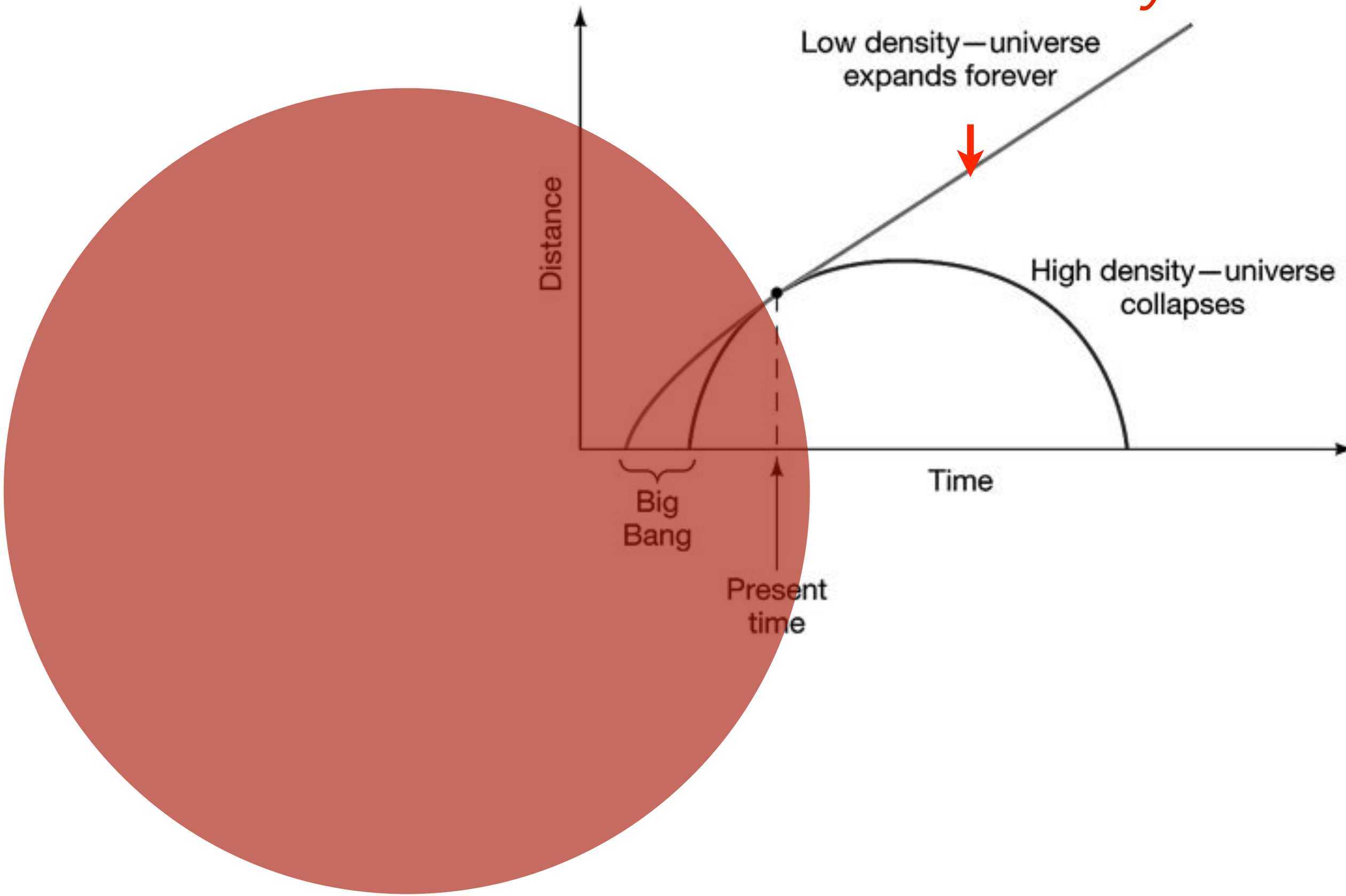

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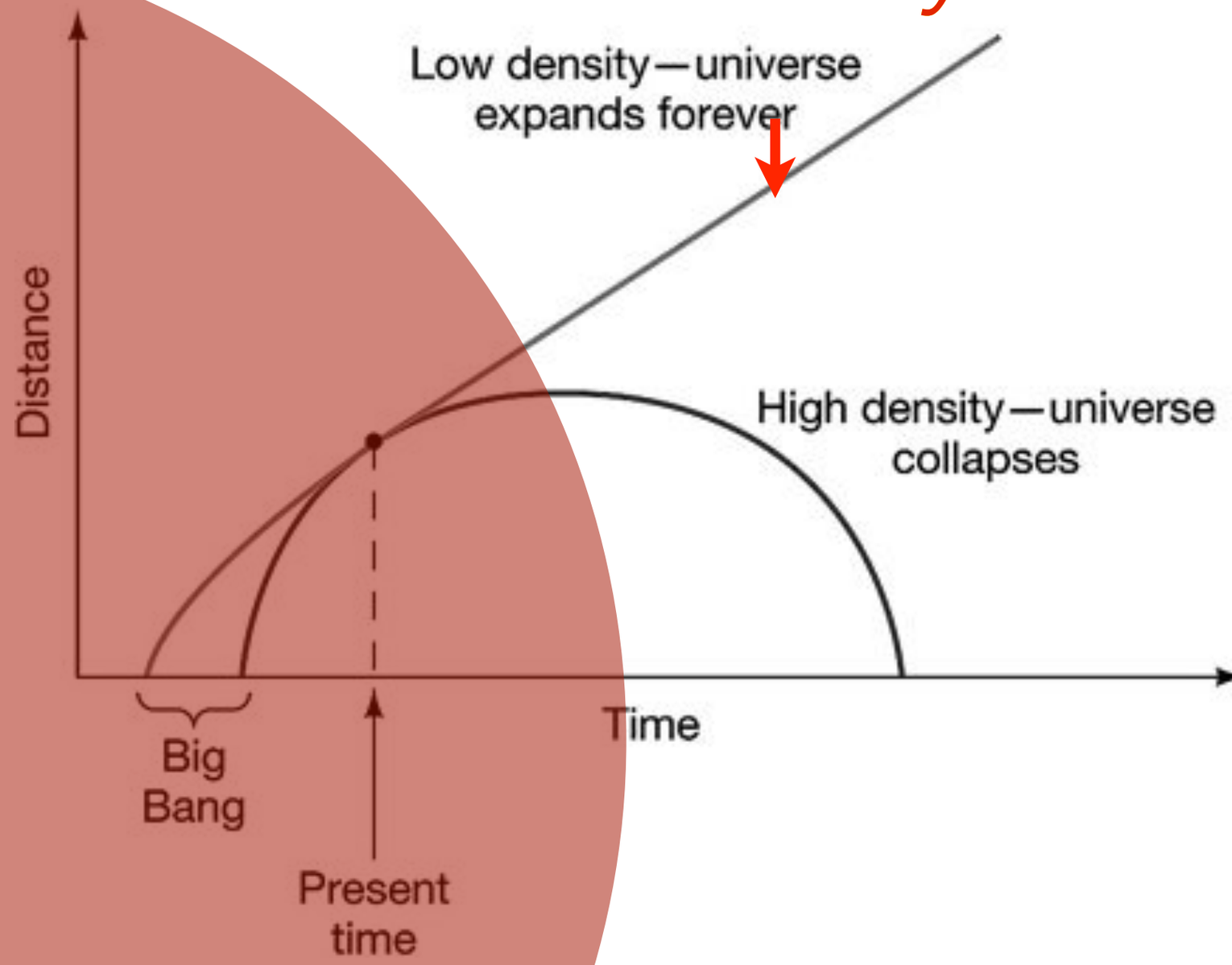

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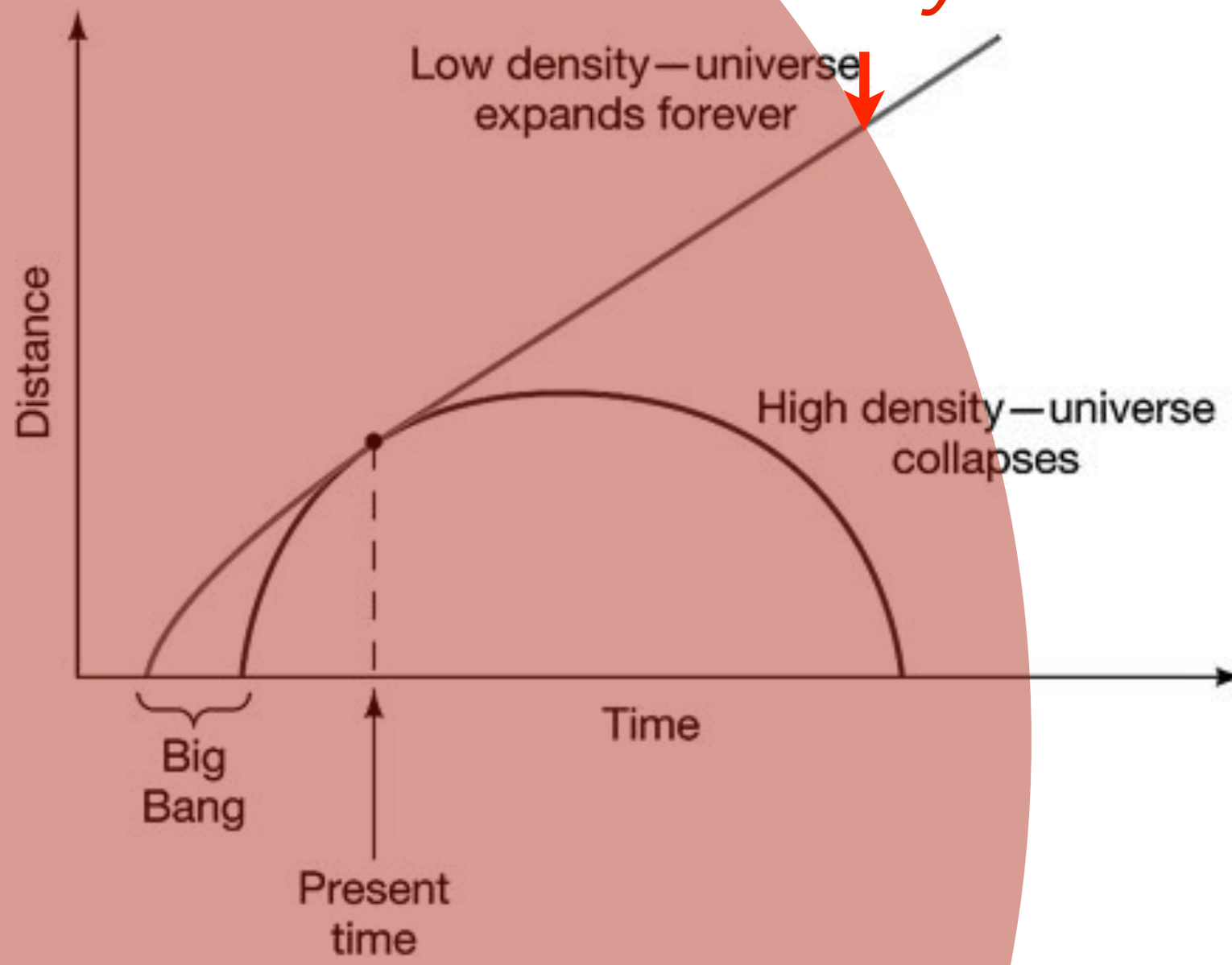

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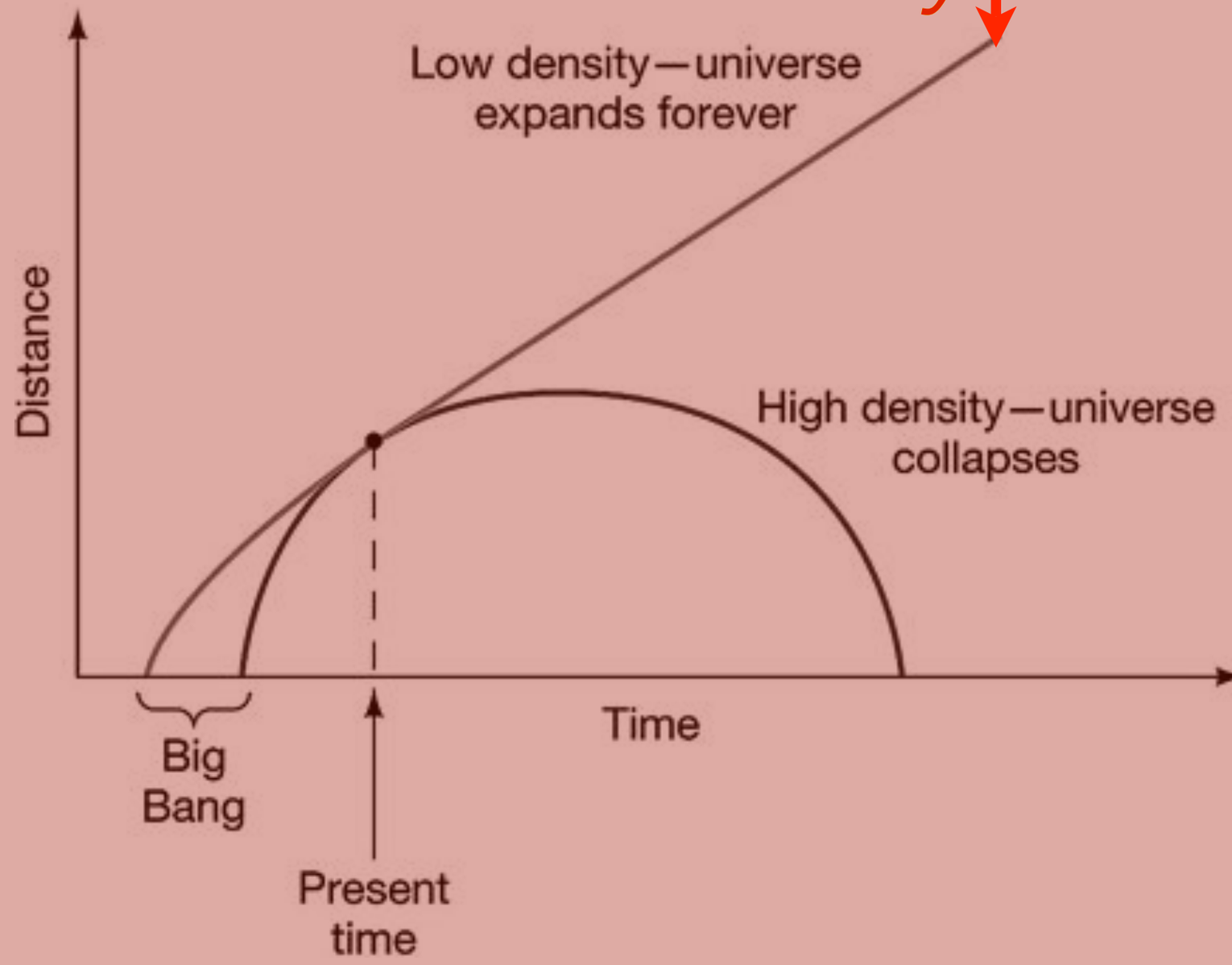

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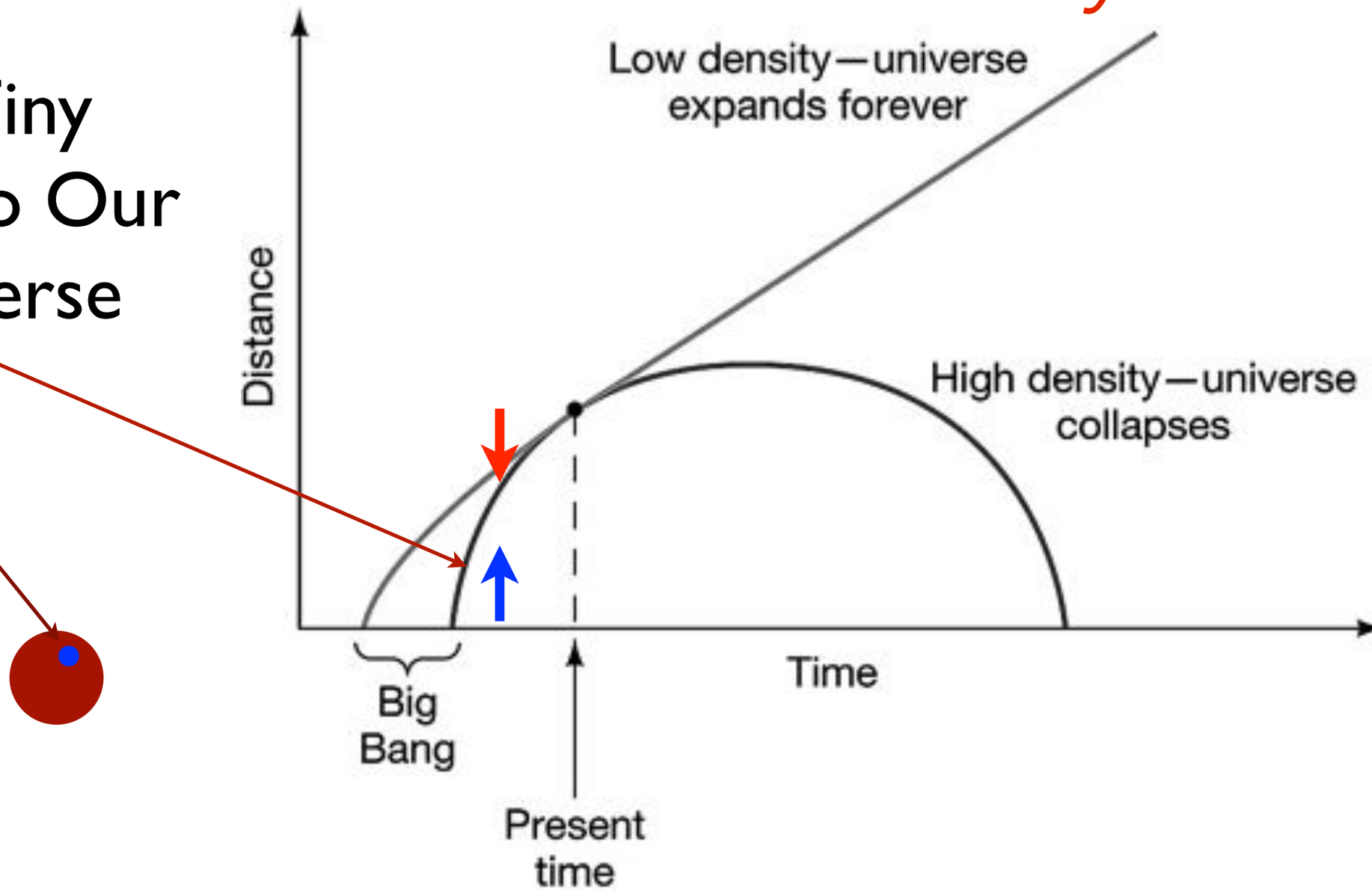
Now Put a Tiny *Perturbation* into Our Smooth Universe



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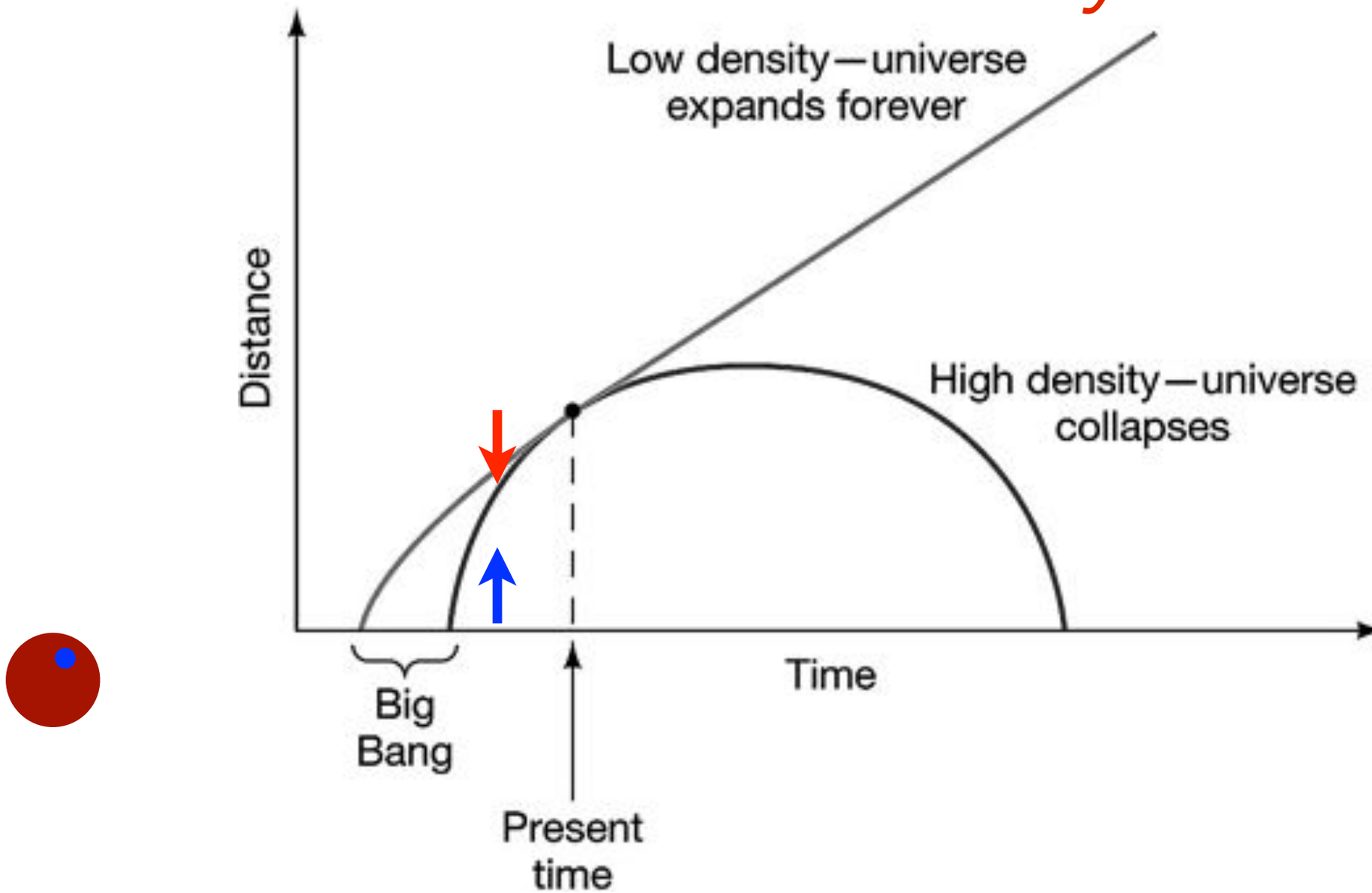

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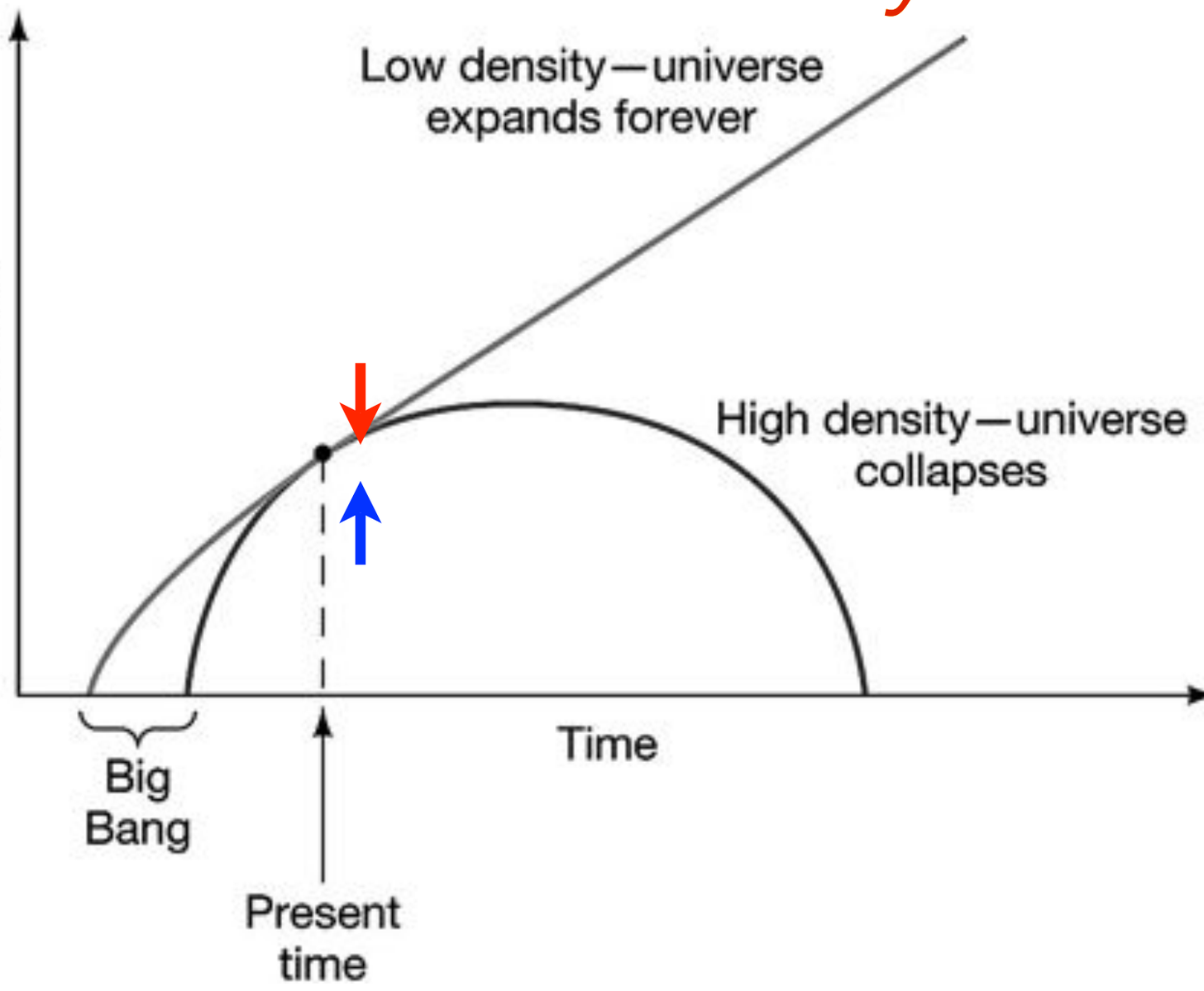

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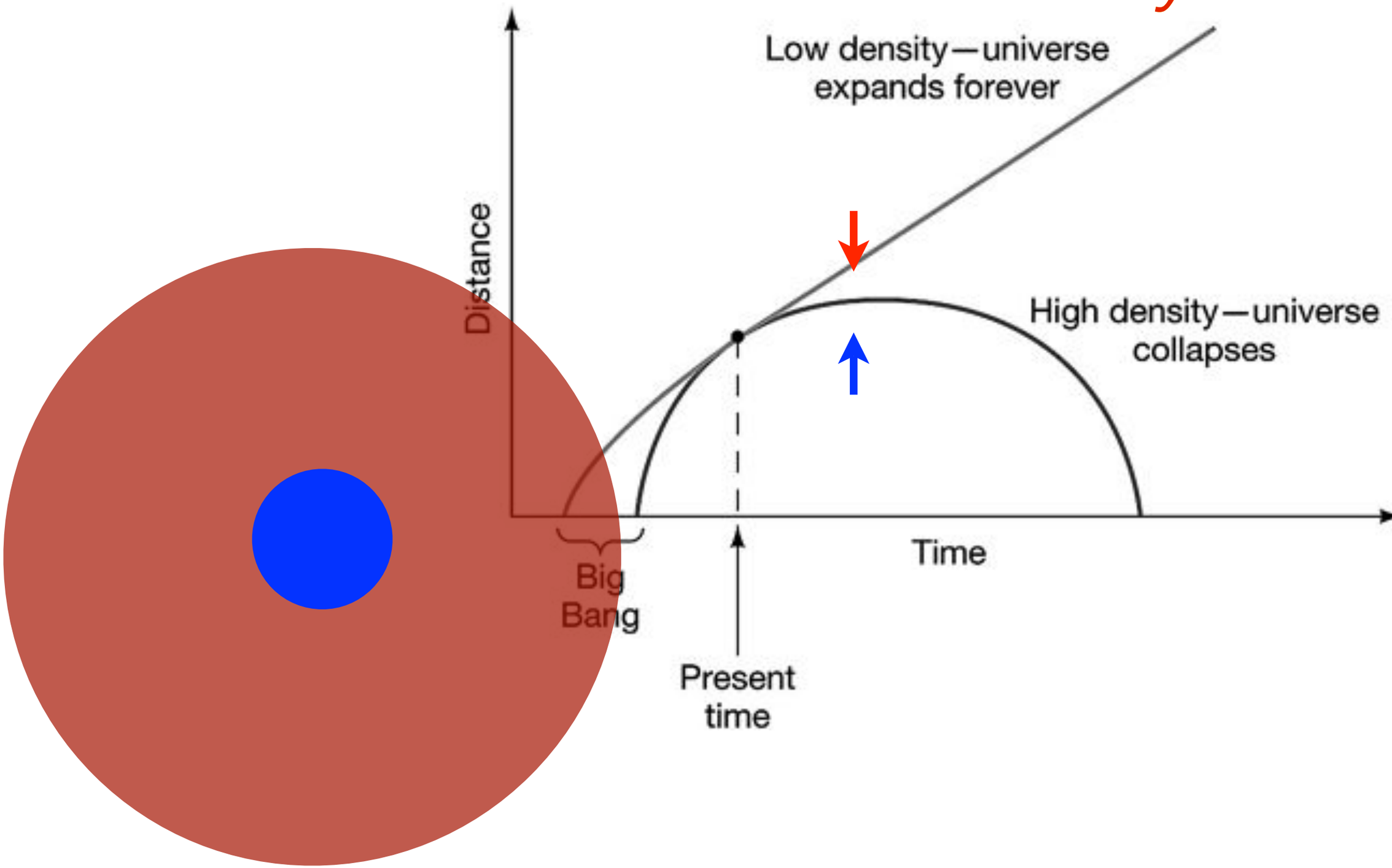

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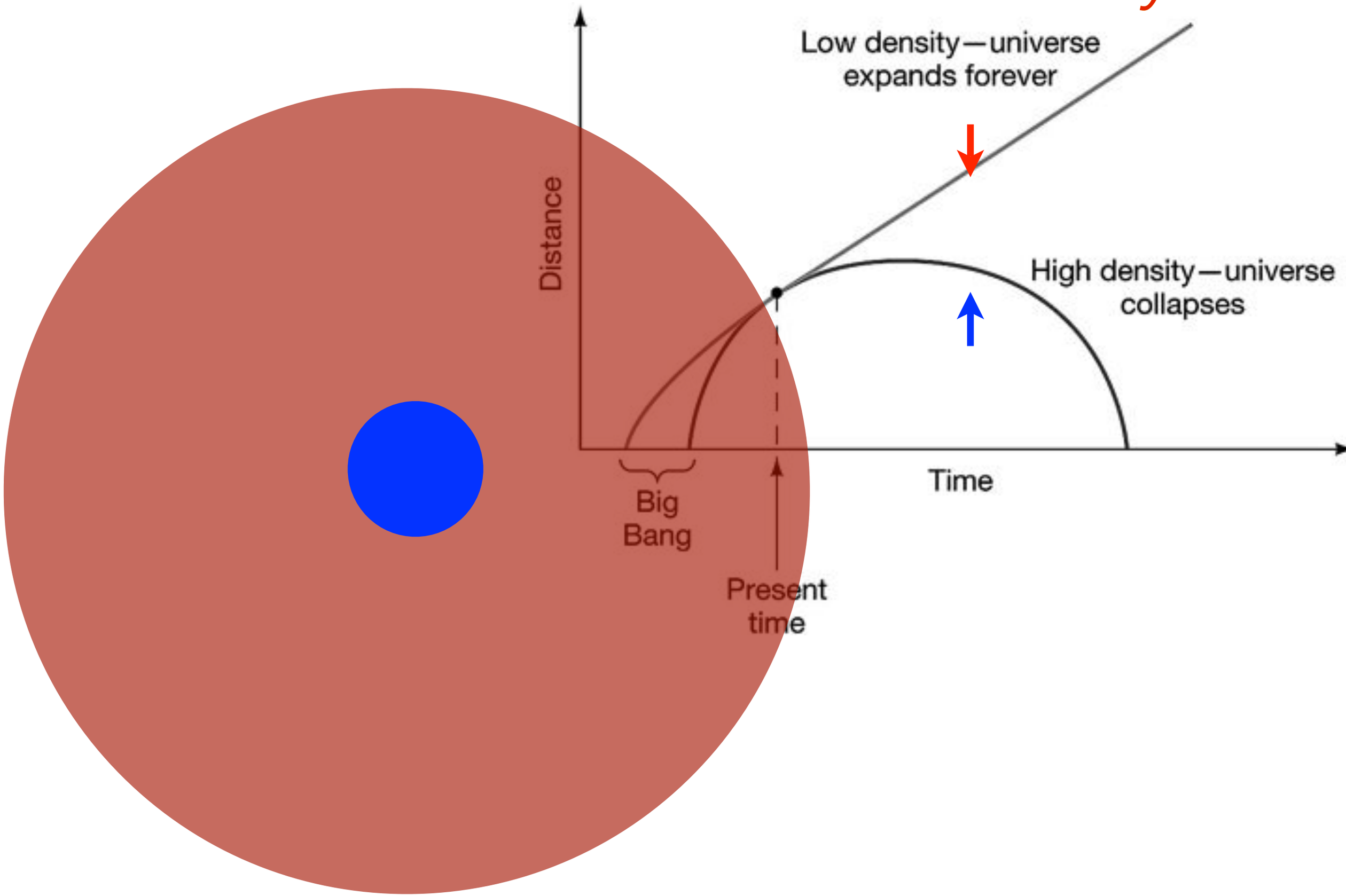

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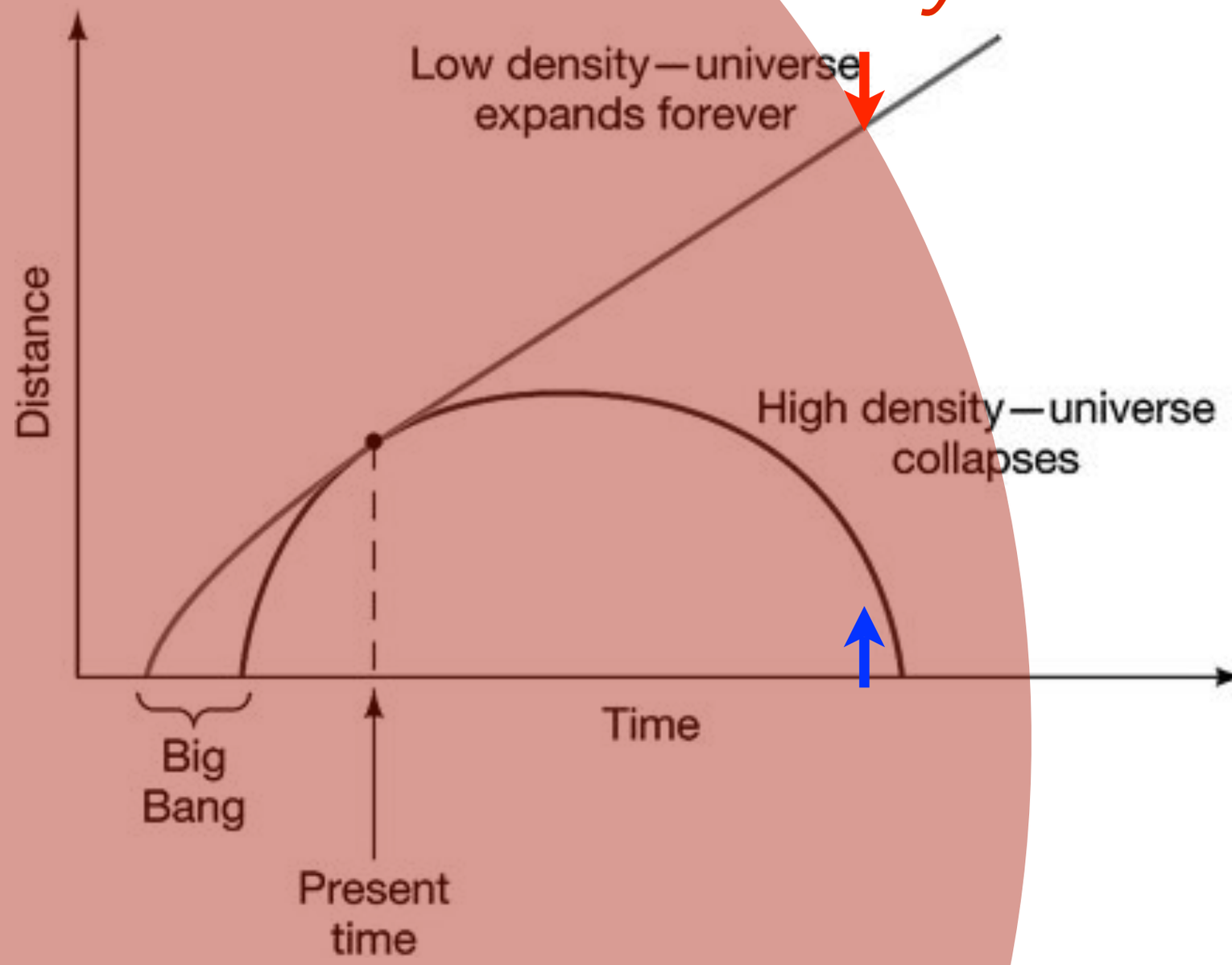

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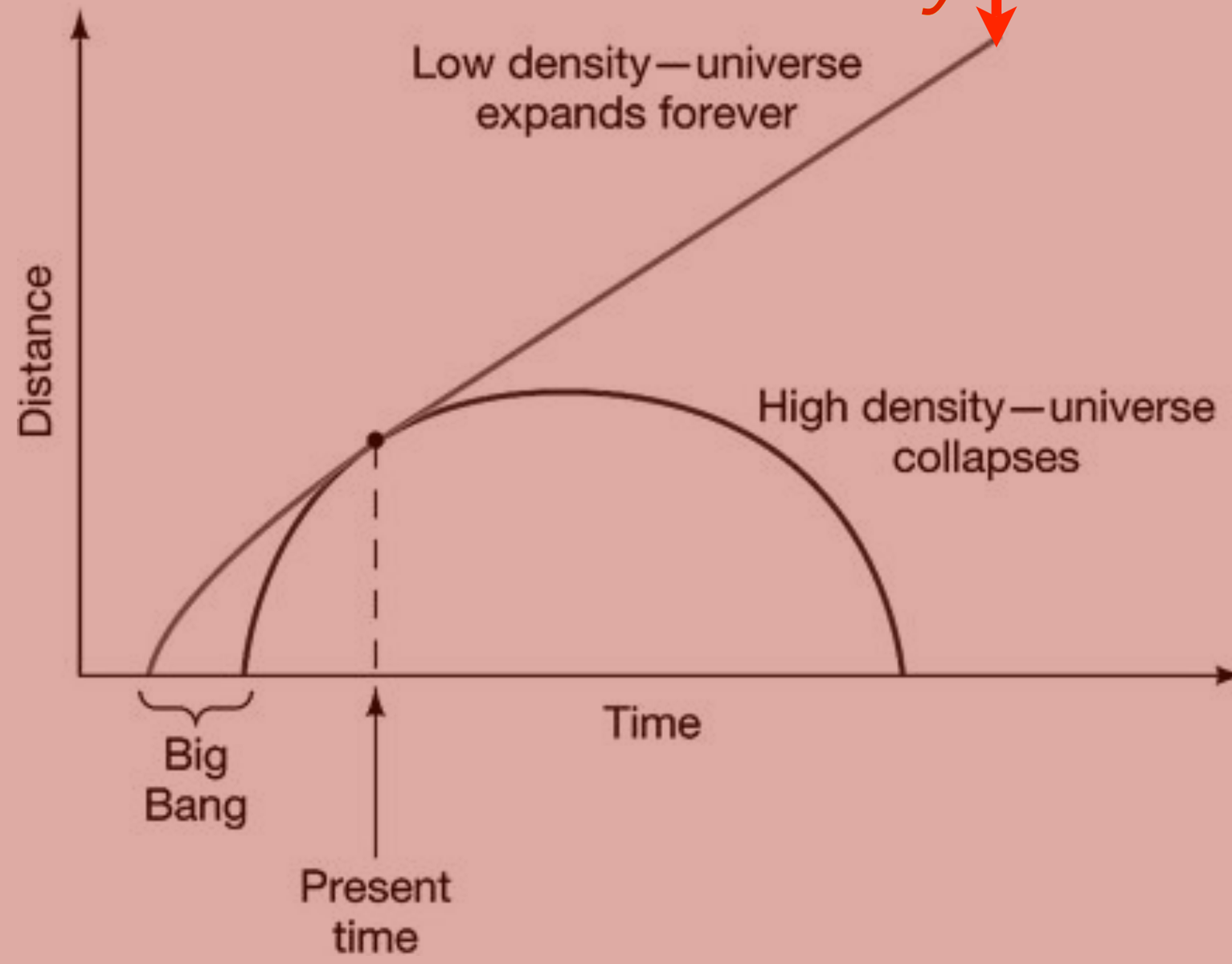
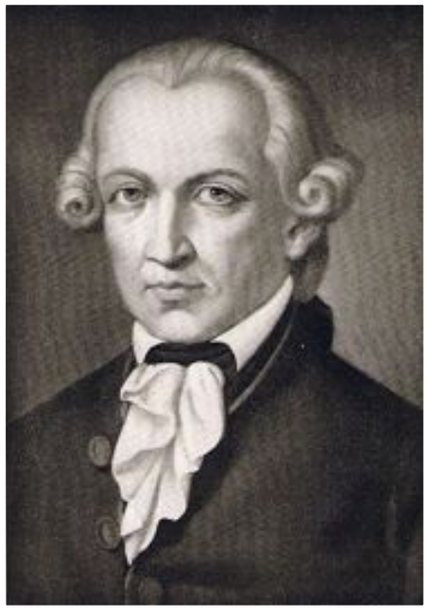


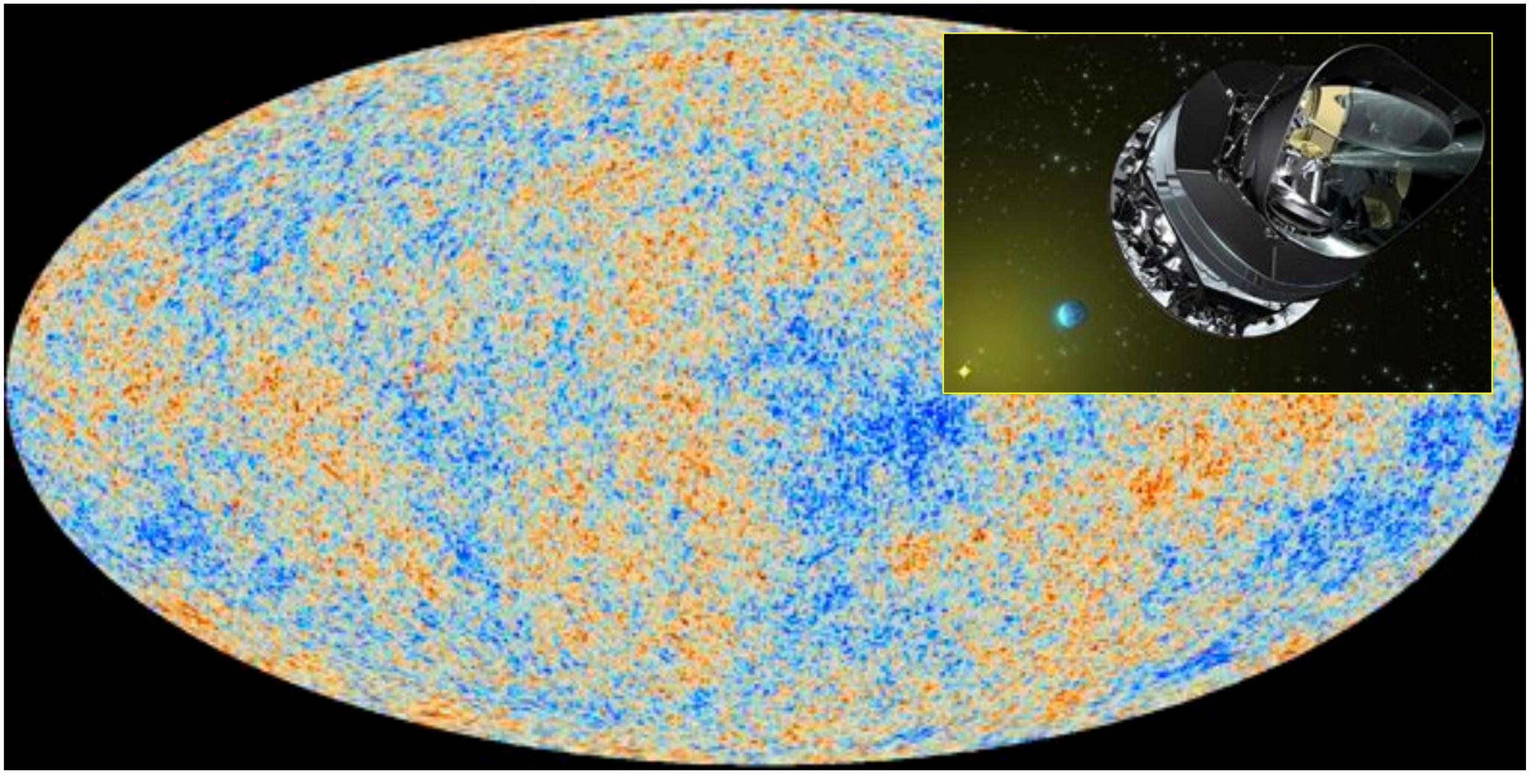
“It is far more natural and conceivable to regard [the elliptical nebulae] as being not such enormous single stars but systems of many ... all this is in perfect harmony with the view that these elliptical figures are just universes and, so to speak, Milky Ways ...”

- Immanuel Kant, 1768



Dark Matter and the Nature of Structure Formation

Latest Results from Planck are yet Another Success for the so-called Lambda-CDM model



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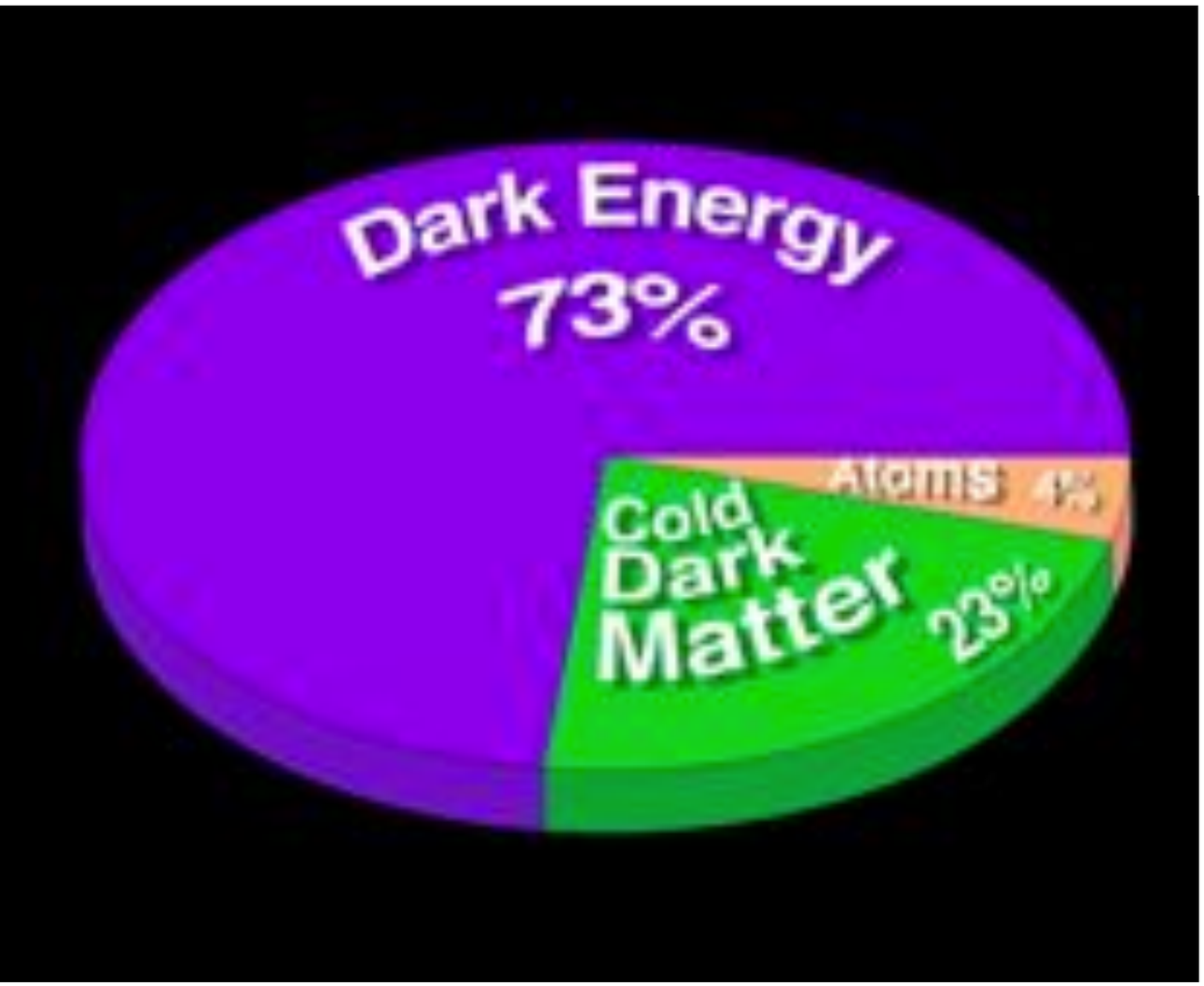

Astronomy & Astrophysics manuscript no. draft˙p1011
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Planck 2013 results. XVI. Cosmological parameters

Planck Collaboration: P. A. R. Ade[93], N. Aghanim[63], C. Armitage-Caplan[96], M. Arnaud[77], M. Ashdown[74,6], F. Atrio-Barandela[19], J. Aumont[63], C. Baccigalupi[89], A. J. Banday[99,10], R. B. Barreiro[70], J. G. Bartlett[1,72], E. Battaner[102], K. Benabed[64,98], A. Benoît[61], A. Benoit-Lévy[26,64,98], J.-P. Bernard[10], M. Bersanelli[37,53], P. Bielewicz[99,10,89], J. Bobin[77], J. J. Bock[72,11], A. Bonaldi[73], J. R. Bond[9], J. Borrill[14,93], F. R. Bouchet[64,98],

Parameter	*Planck* Best fit	*Planck* 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072
Ω_Λ	0.6825	0.686 ± 0.020
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σ_8	0.8344	0.834 ± 0.027

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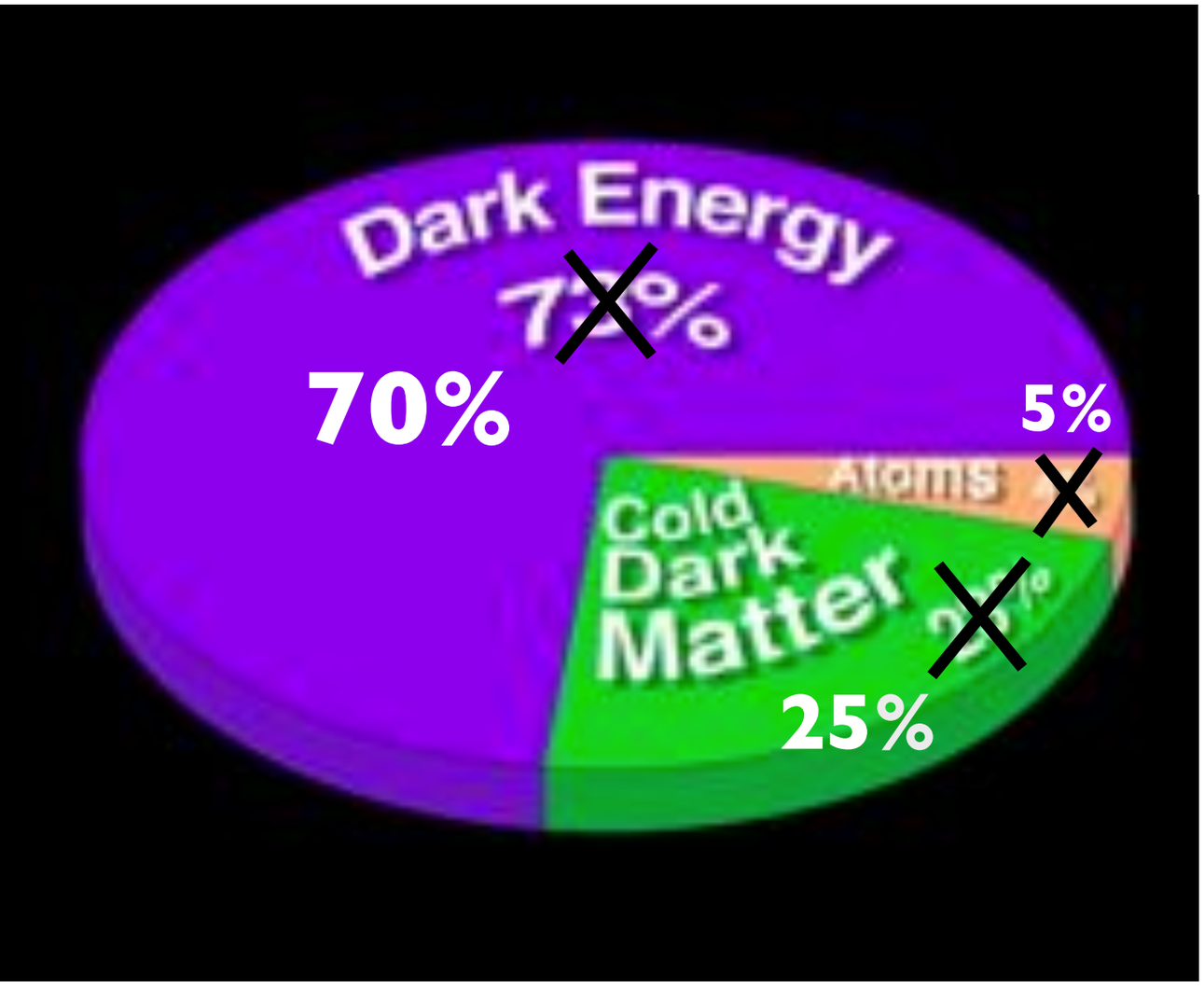

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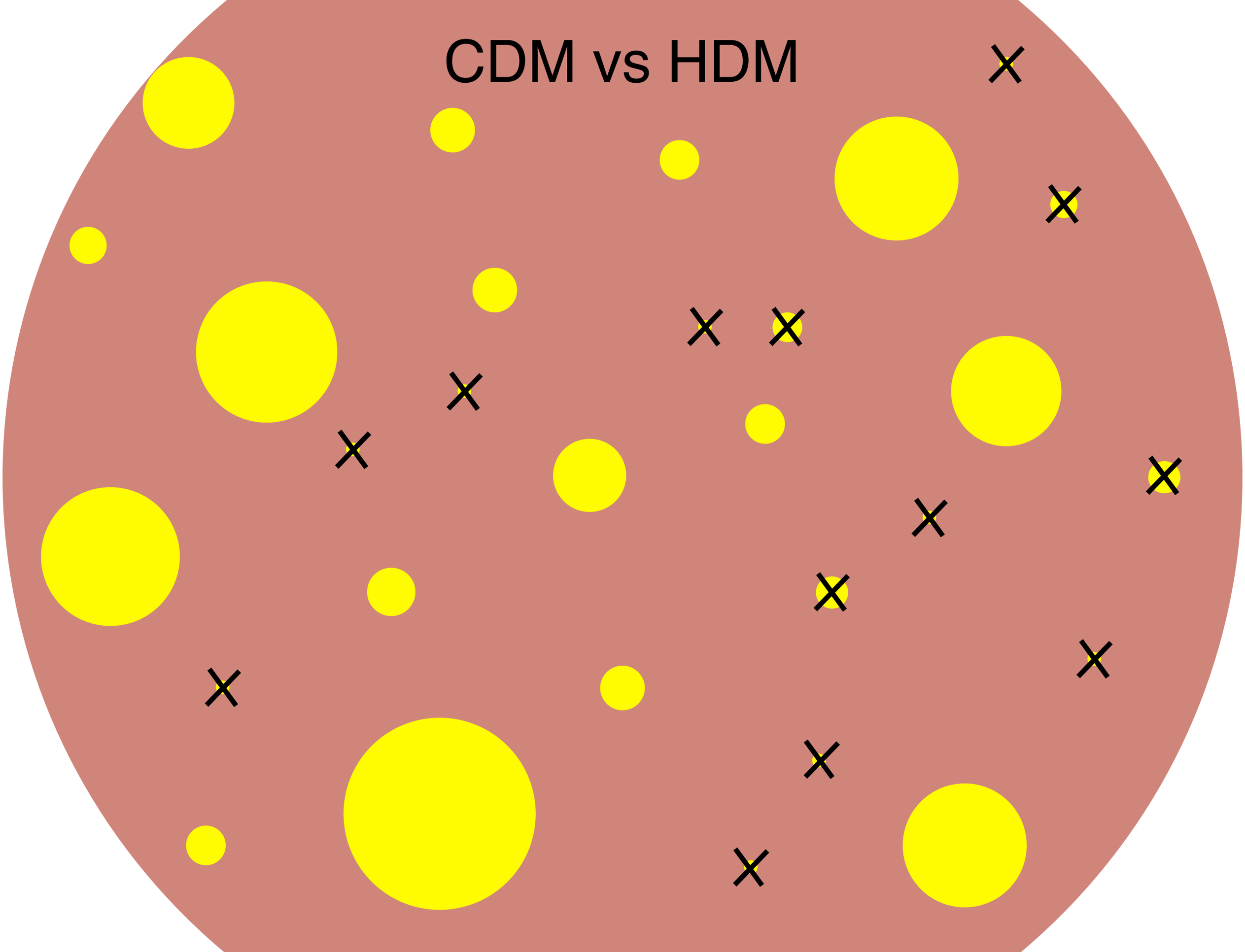
Cold Dark Matter (CDM)
vs
Hot Dark Matter (HDM)

CDM vs HDM

- Cold dark matter particles are moving slowly, so CDM can form structure can form at all scales
- Hot dark matter particles, on the other hand, are moving close to the speed of light at early times.
- HDM suffers from "free-streaming" effects, whereby fluctuations on small scales are erased: particles escape the fluctuations before they can grow and collapse. Large-scale fluctuations still collapse.
- Structure formation with HDM is "Top-down", while in CDM it is "Bottom-up" or "Hierarchical"

CDM vs HDM



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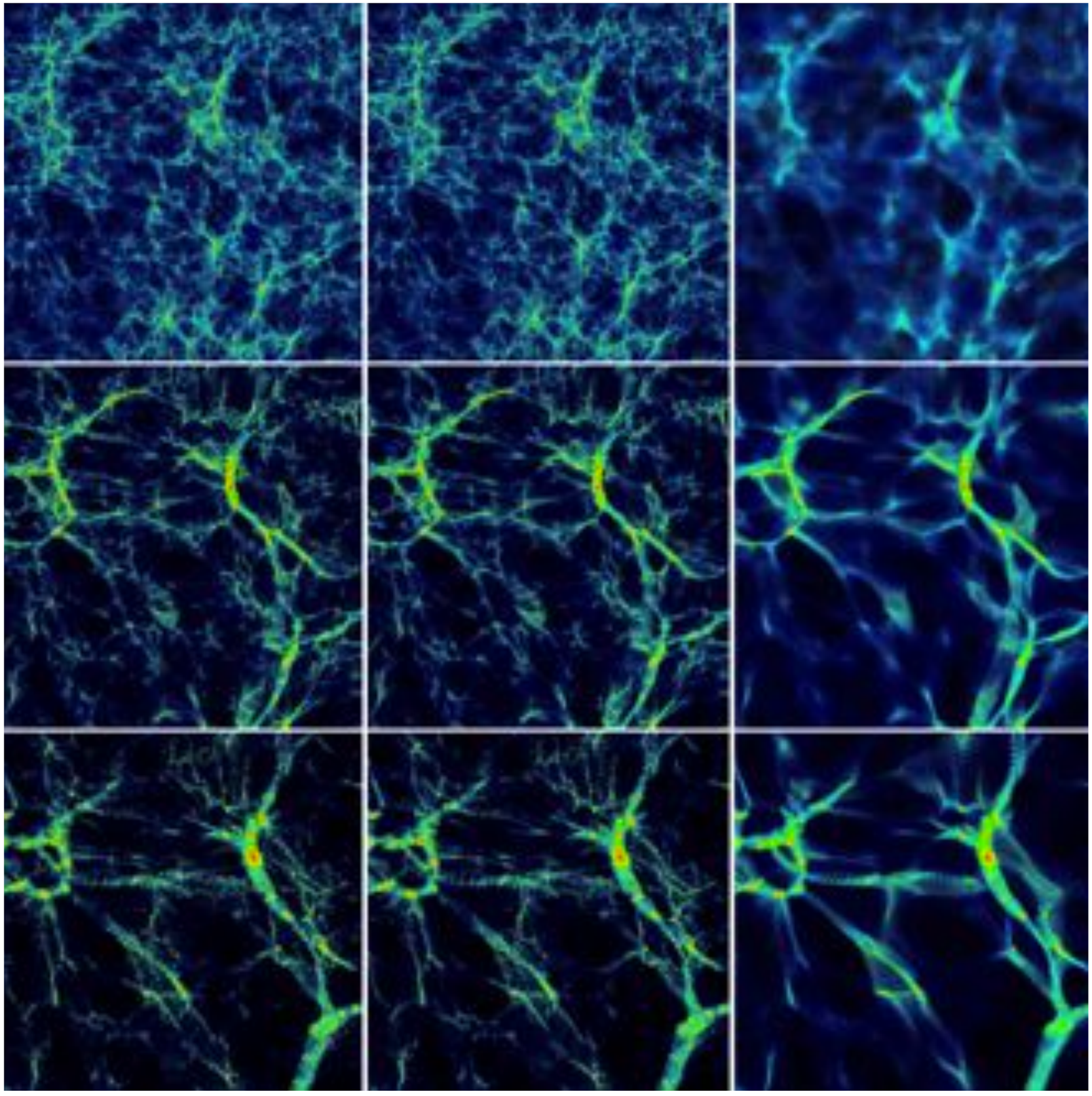
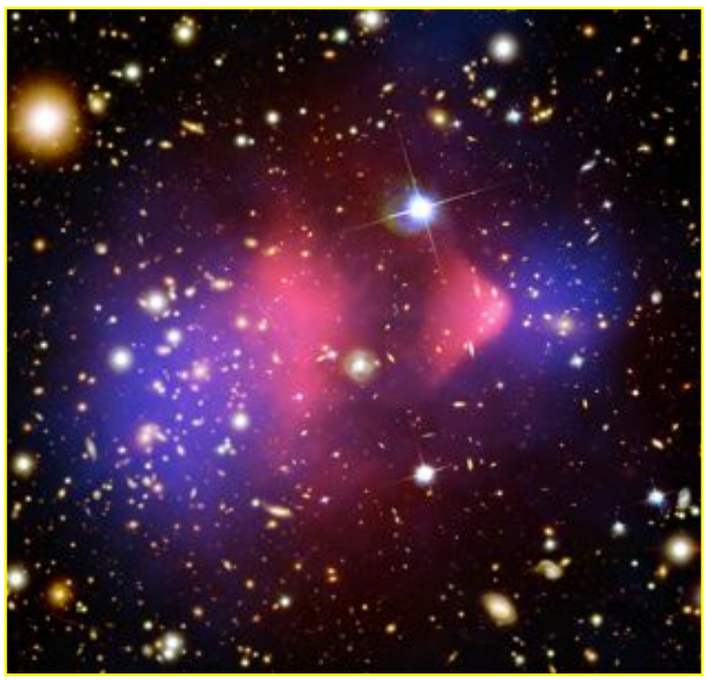
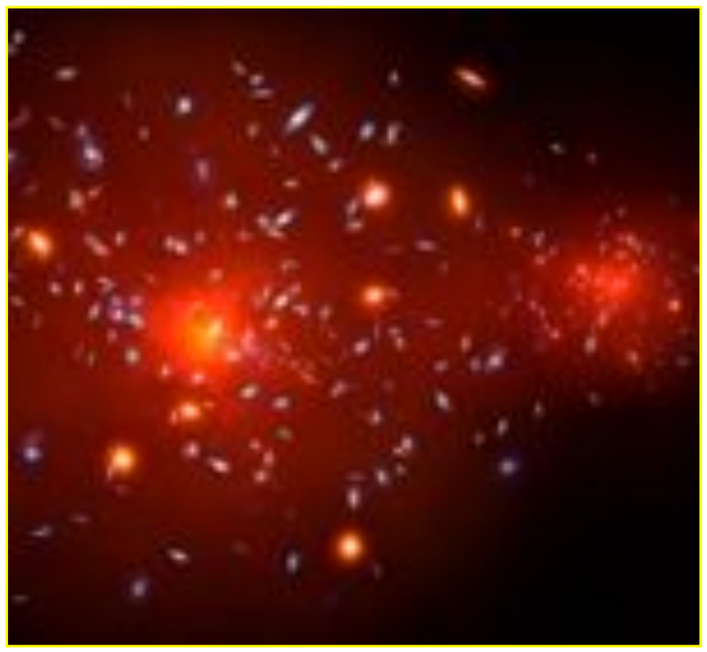


Hierarchical Clustering in CDM

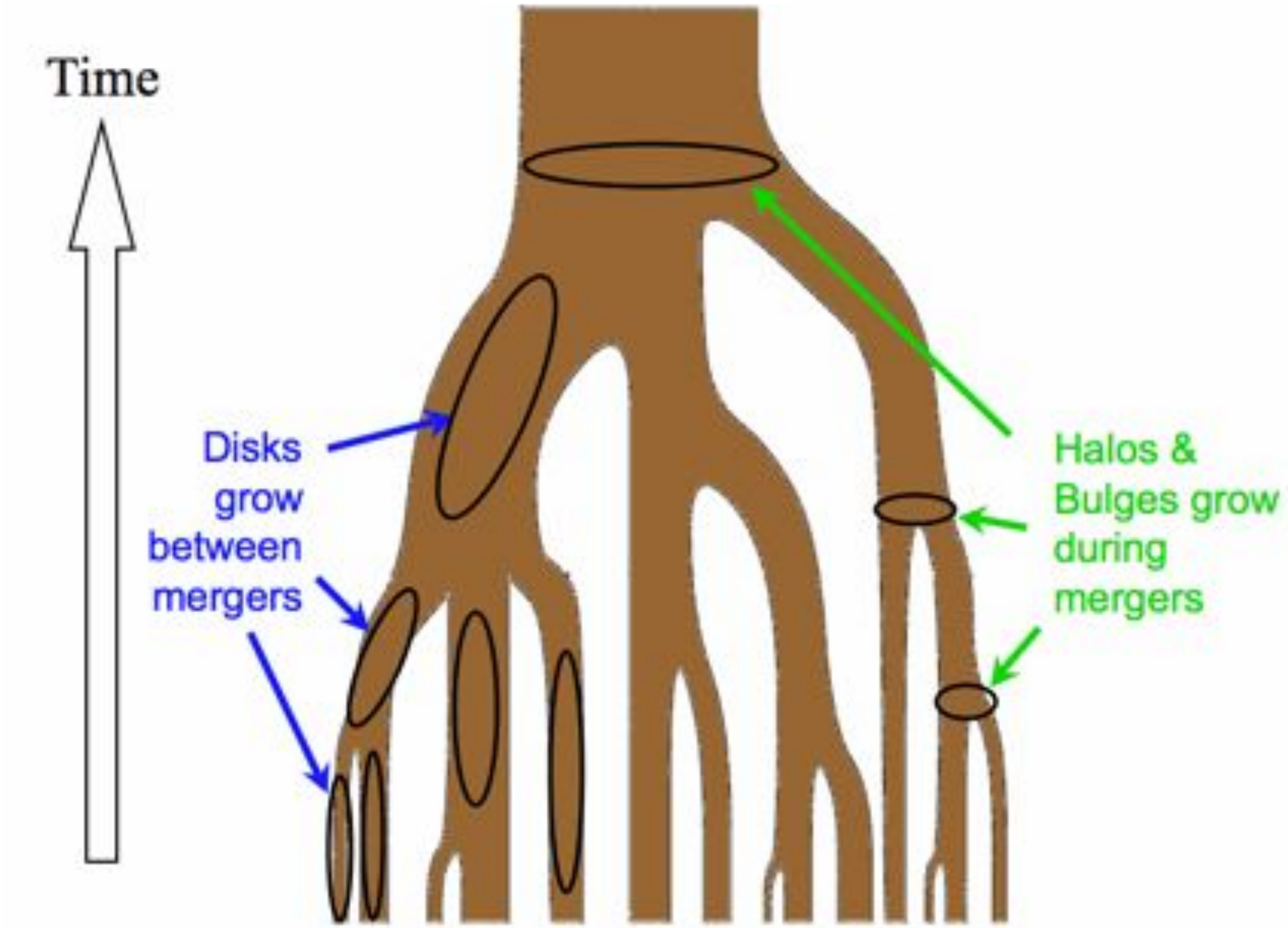
- Cold dark matter particles are moving slowly, so CDM can form structure can form at all scales
- Structure Formation in CDM is "Bottom-up" or "Hierarchical"
- Small dark matter halos form first, and merge to form larger and larger halos - this process is known as hierarchical merging.
- The history of a given halo can be traced backwards in time with its merger tree. Galaxy mergers are an example of hierarchical merging in action.

Hierarchical Clustering in CDM





Dark Matter Halo Merger Tree



Cosmological Simulations of Structure Formation

- Structure formation is highly-complex and non-linear phenomenon. To make accurate predictions, supercomputers must be used.

- Dark Matter is dominant component of matter, so it is the most important ingredient in simulations of structure formation.

- CDM is represented by N particles, and evolved with an N-body code that solves for the mutual gravitational forces between all particles.

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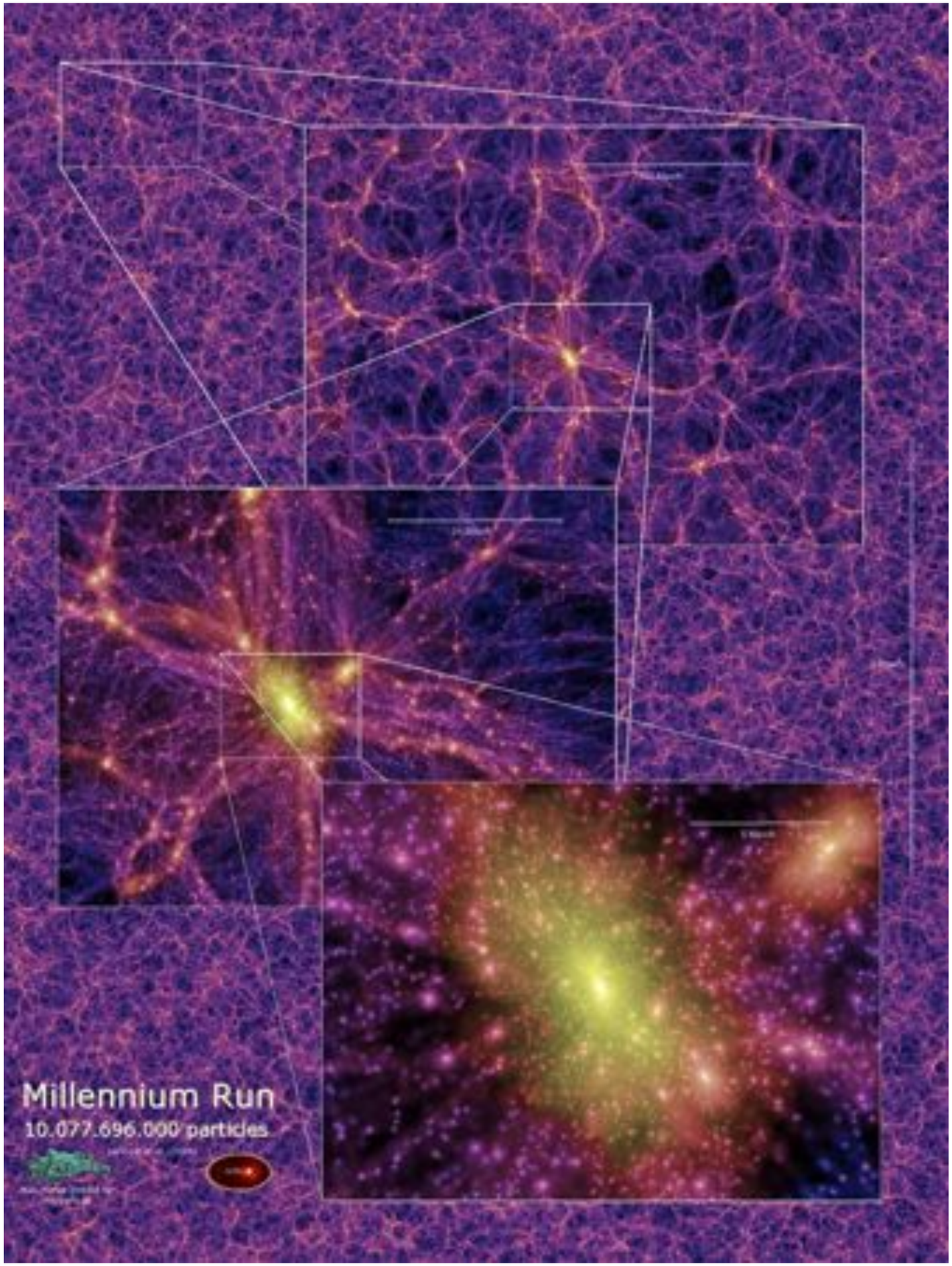

Summary

- The Observable Universe is like a sphere with us at center. The radius is larger (~14 Gpc) than 13.8 billion light-years (~3.5 Gpc) because of cosmic expansion.
- Galaxies are arranged in a cosmic web of sheets, filaments, halos, and voids. The largest identifiable structures are superclusters.
- Gas density fluctuations at CMB 400,000 years after Big Bang were tiny - one part in 100,000.
- These tiny fluctuations grew because of gravitational instability - regions denser than the average behave like individual closed universes.
- The current heavily favored cosmological model is Lambda-CDM. Lambda for dark energy (~68%) and CDM for Cold Dark Matter (~27%).
- In CDM small dark matter halos form first, and merge to form larger and larger halos - hierarchical merging.
- Calculations of structure formation almost always start with dark matter as the main ingredient. Problem is so complex, N-body simulations running on supercomputers are required to obtain accurate predictions from theory.