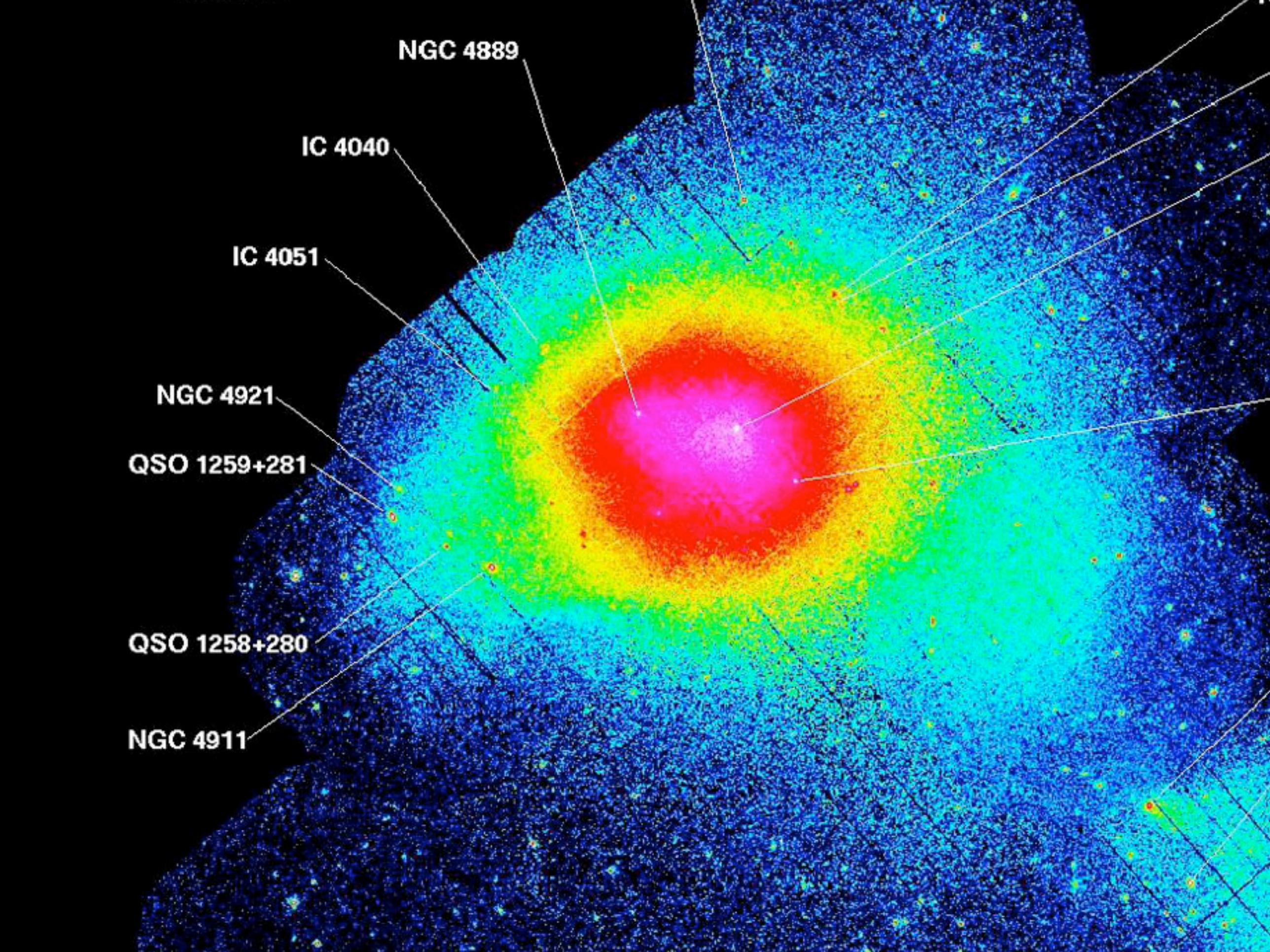

NGC 4889
IC 4040
IC 4051
NGC 4921
QSO 1259+281
QSO 1258+280
NGC 4911

The survey

- 15 responses
- Most learn from the lecture, but a significant minority from the MA homework
- About an equal number dislike MA, LT
  - but some of you like each
- I've been going through slides too fast... this week I've made an effort to go slower
- Most of the class is "pretty reasonable", though the tests are between reasonable and "a bit hard"
- You can still fill it out!

TUTORIAL

- Observable Universe and Expansion
  - The *Observable Universe* is the circle in which light travel time equals the age of the universe

The biggest structures in the universe

Adam Ginsburg & Devin Silvia

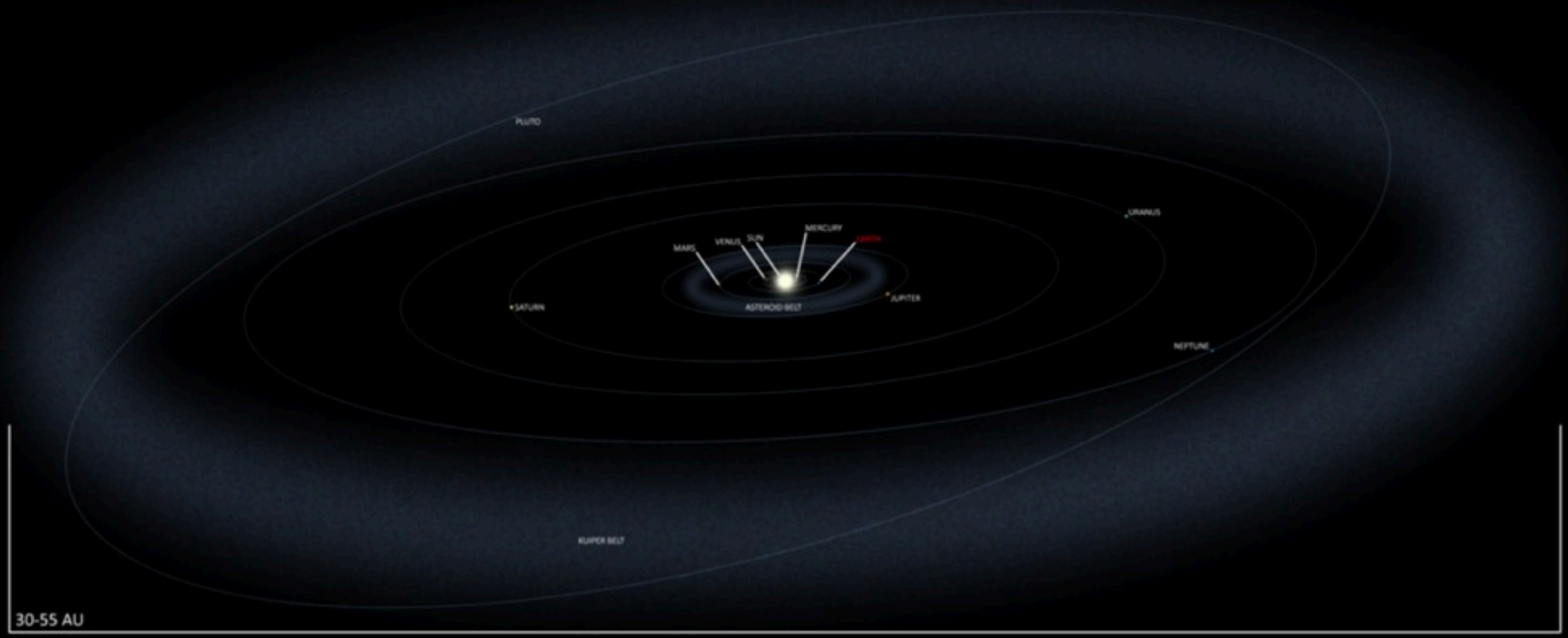
July 29th, 2010

Learning Goals

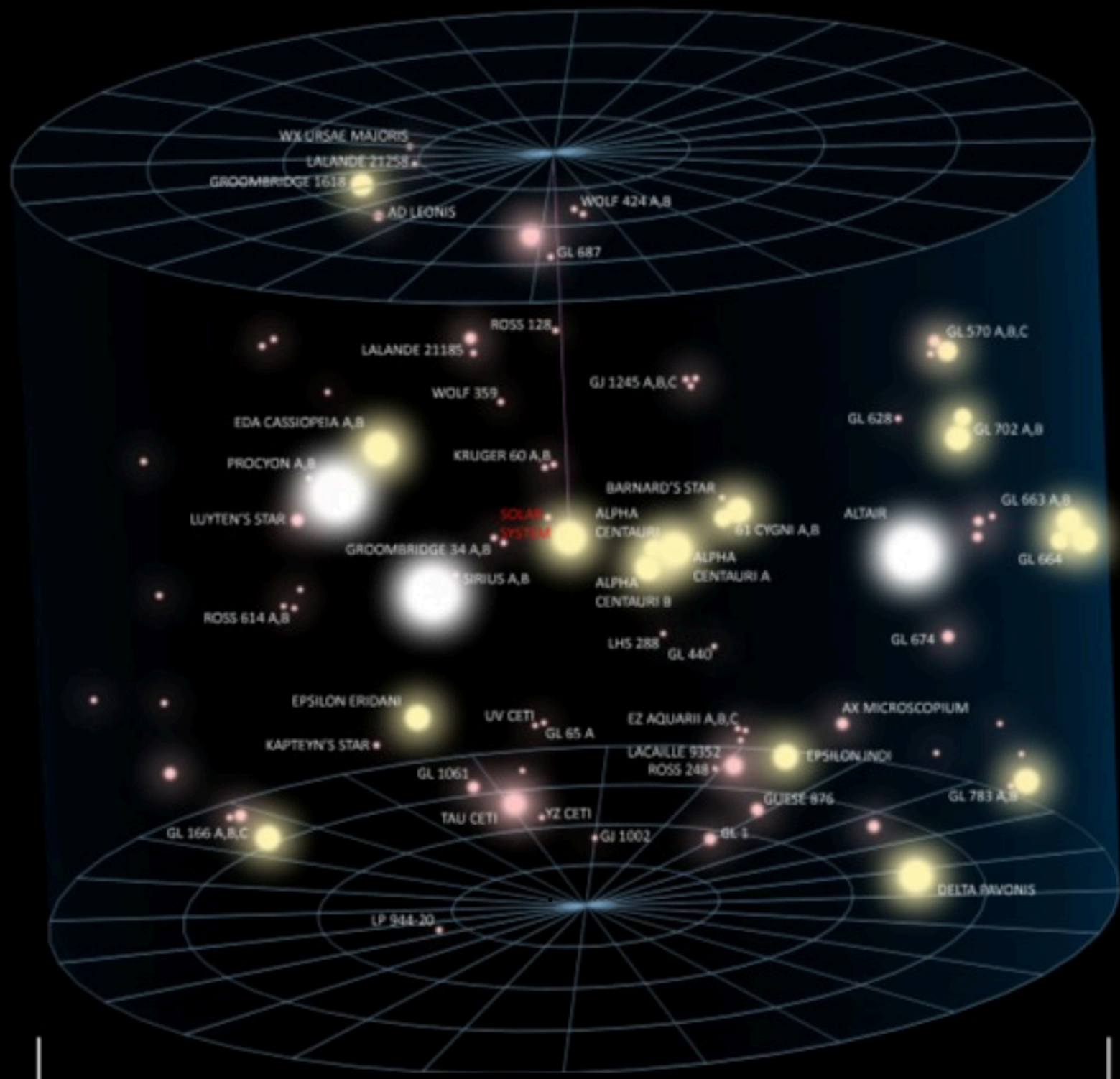
- Revisit scales of the universe
- Is there a Biggest Thing in the universe?
- How do we observe large scale structure? How do we see holes?

Revisiting Scales

SOLAR SYSTEM



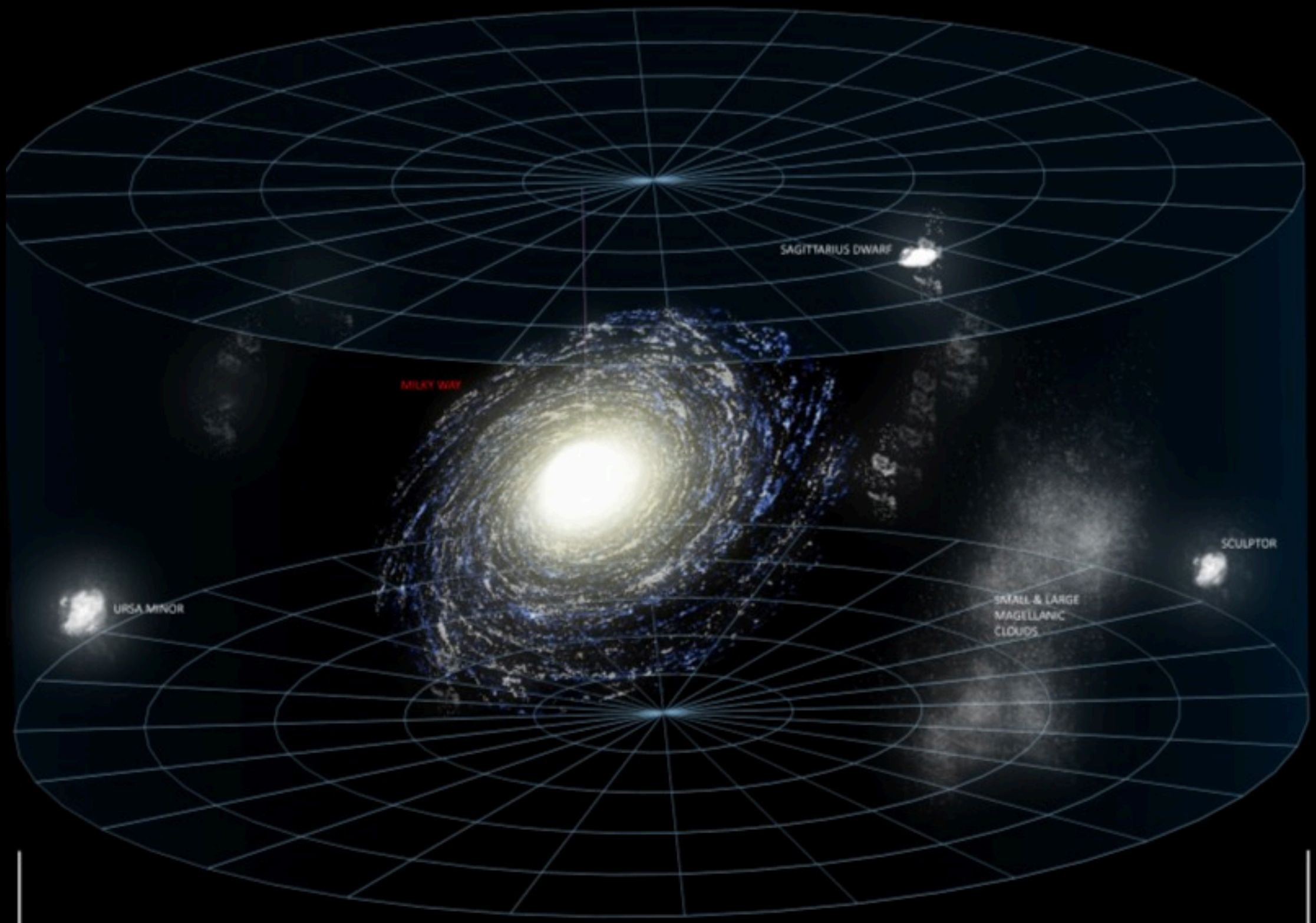
SUN'S NEIGHBORHOOD



x50,000

30°
330°
60°
300°
90°
270°
120°
240°
60,000 ly
45,000 ly
15,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur
x4000

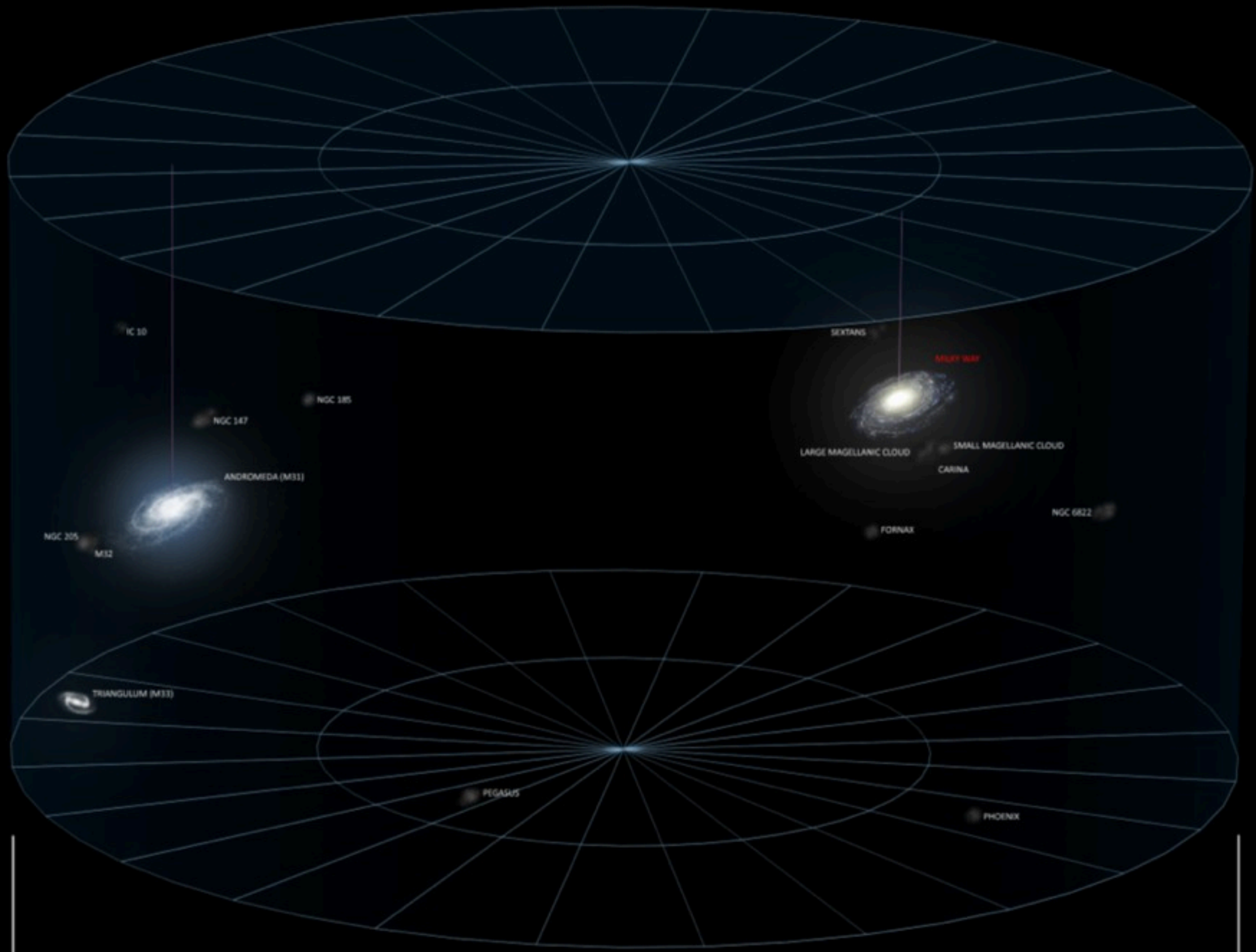
GALACTIC REALM



3x

500,000 LIGHT-YEARS

LOCAL GROUP



8x

4 MILLION LIGHT-YEARS

SUPERCLUSTER

VIRGO

URSA MAJOR

VIRGO W

LOCAL GROUP

FORNAX

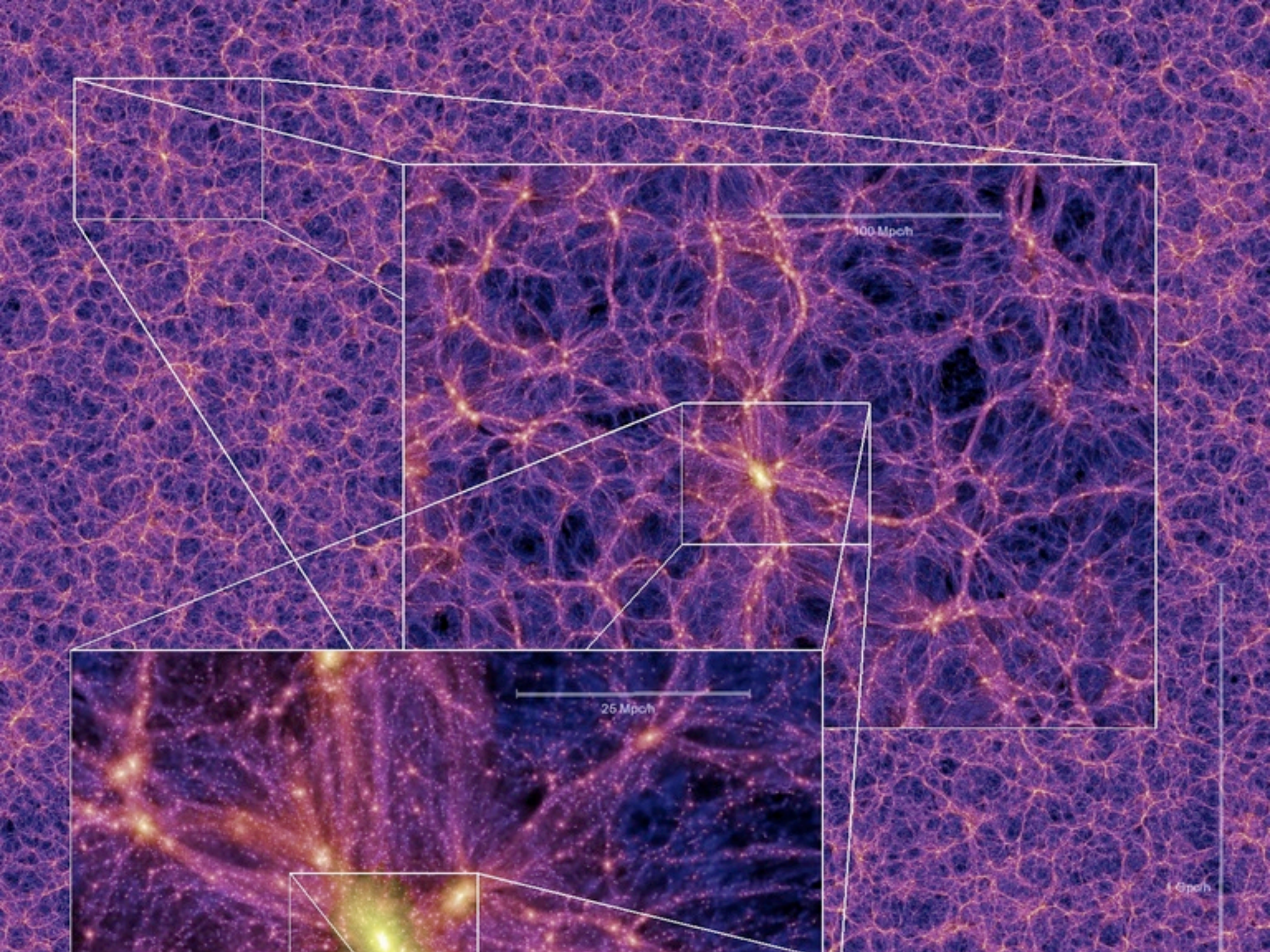
40x

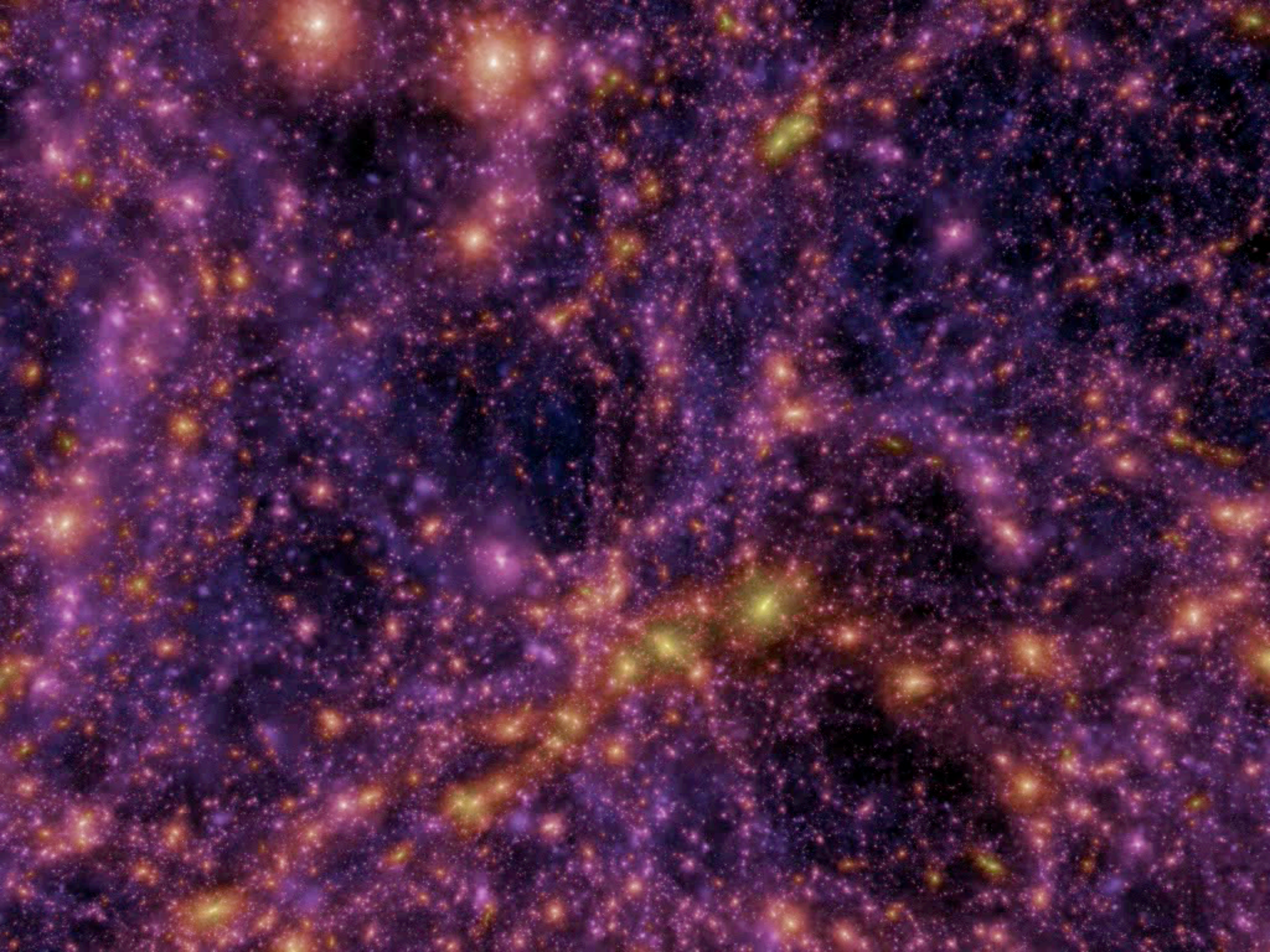
150 MILLION LIGHT-YEARS

Bigger? My, my

- How big are the largest structures?
  - About 300 million light-years across
- What are they?
  - Filaments and Voids
- What happens when you get bigger still?
  - There is no *structure* on scales larger than these. Everything looks approximately the same if you smooth it out.

100x


100 Mpc/h
25 Mpc/h
1 Gpc/h



Clicker POLL

- In that movie, did things look pretty much the same or very different depending on where you looked?
  (there is no correct answer)

A) the same

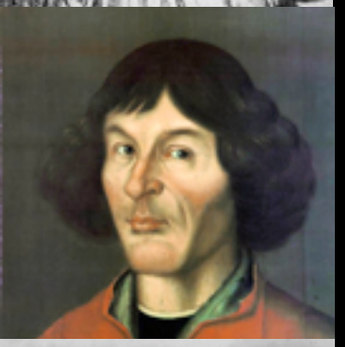
B) different

C) I wasn't really paying attention

D) I'm not sure but I was paying attention, really!

The Cosmological Principle

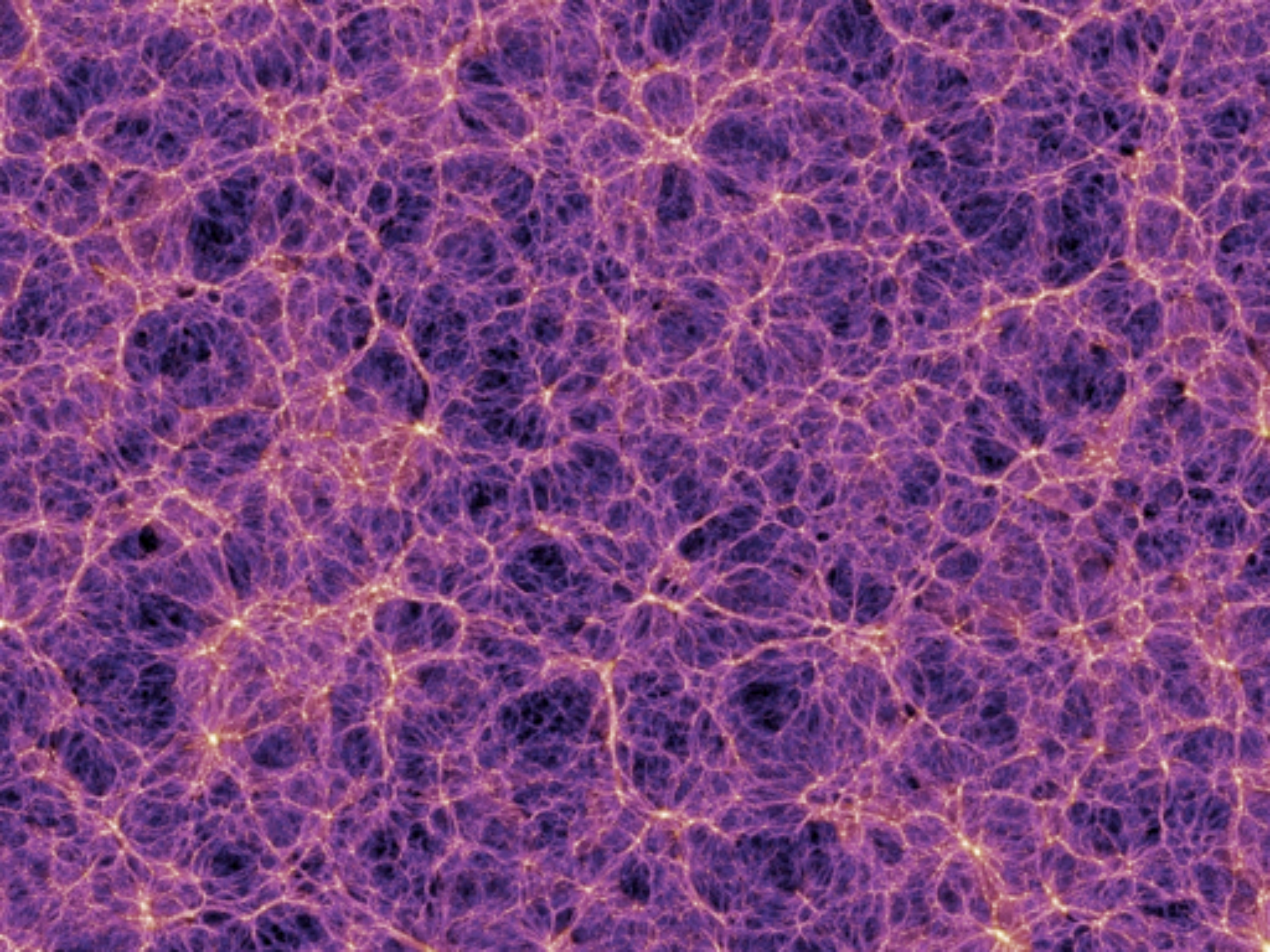
- There is no preferred vantage point anywhere in the universe
  - Not even Matt

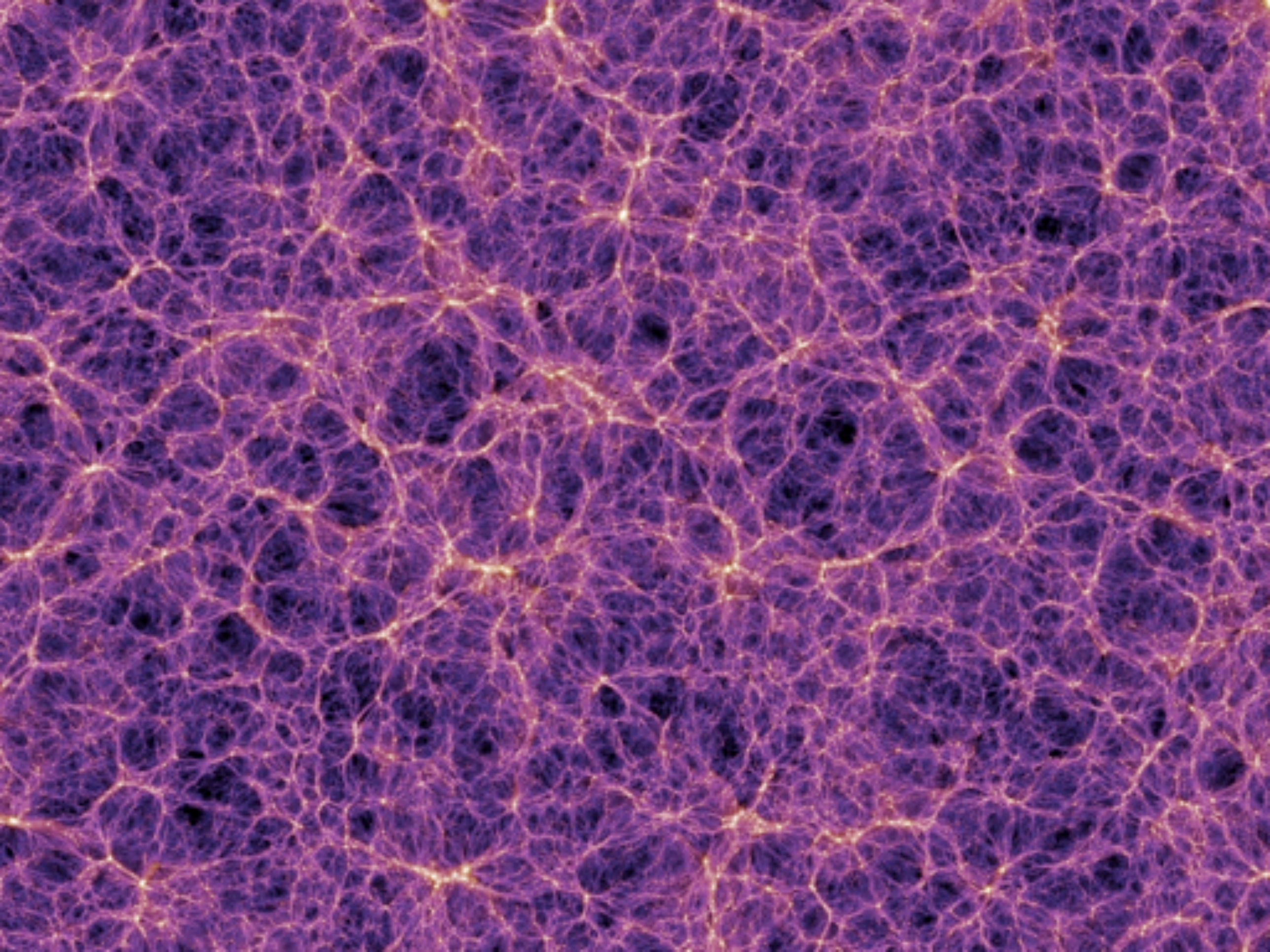


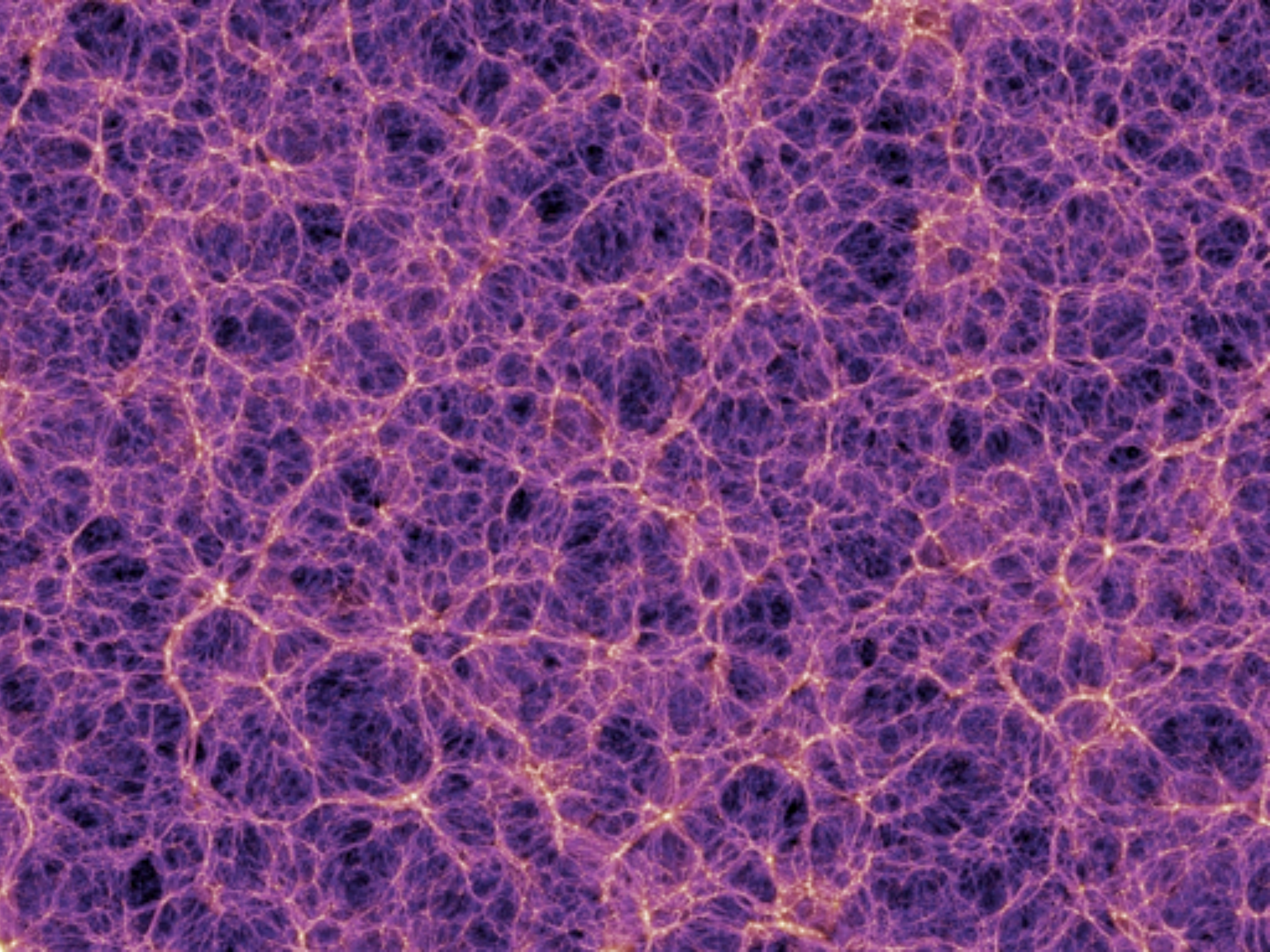
- Historically, a geocentric view prevailed for a long time
  - Copernicus started the shift to a heliocentric view
  - Discoveries by Hubble and others in the 1920's eventually pushed towards an anti-centric view (I made up that word)

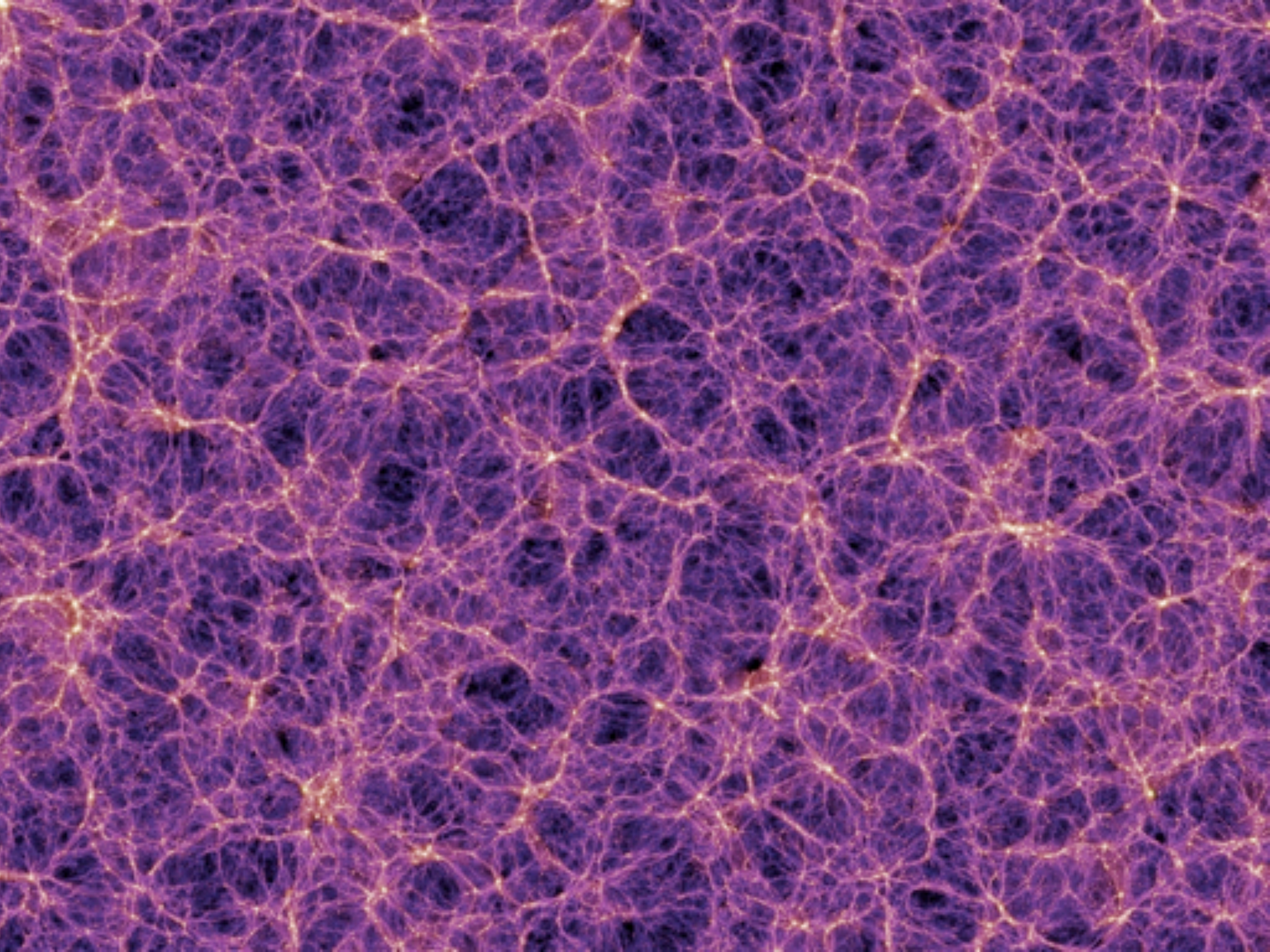
Cosmological Principle

- Consequences:
  - Homogeneity:
    - On large scales, everything acts and looks the same
    - But people, planets, stars, galaxies, and clusters can look very different because they are dominated by gravity and other forces
  - Isotropy:
    - There is no preferred *direction* either - any way you look, you'll see the same thing









Homogeneity & Isotropy

The universe is homogeneous and isotropic. Say we talk to an alien in another galaxy that is moving away from us at 500 km/s. What would they see the Milky Way doing?

A) Coming towards them at 500 km/s

B) Moving away at 500 km/s

C) Sitting still at the center of the universe

D) Orbiting the center of the universe

Maps

Say you were lost in the universe, but you had a map with a resolution of 300 million light-years. Could you find your way home?

A) No, everything looks exactly the same

B) No, there are paths leading every which way but the galaxy is just too small

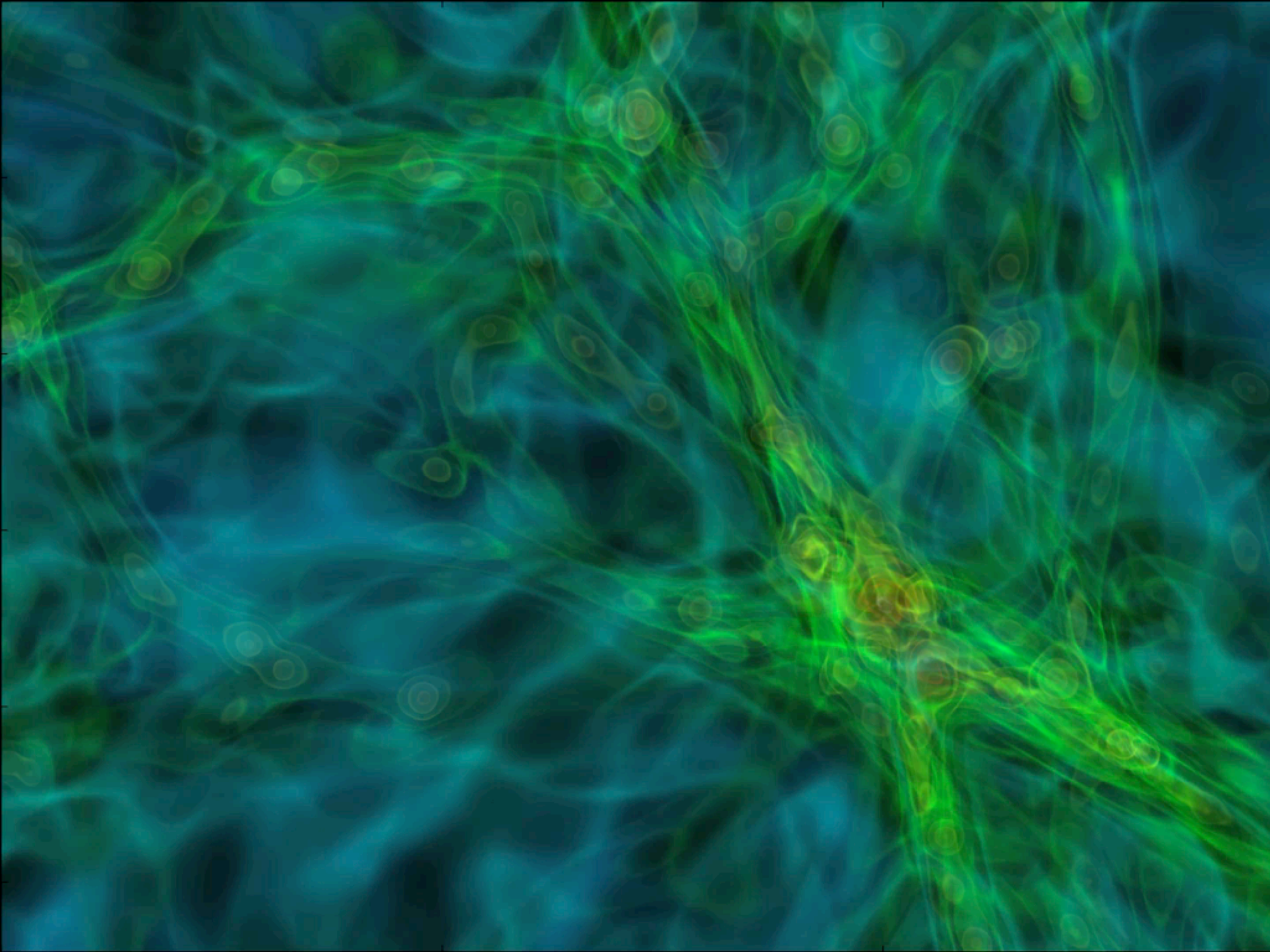
C) Yes, the Milky Way should be right at the center of the universe

D) Yes, just look for the Local Supercluster, and the Milky Way should be somewhere near there

E) If I was lost in a supermarket and you gave me a map and a GPS I'd still be lost and starving inside an hour

Simulations

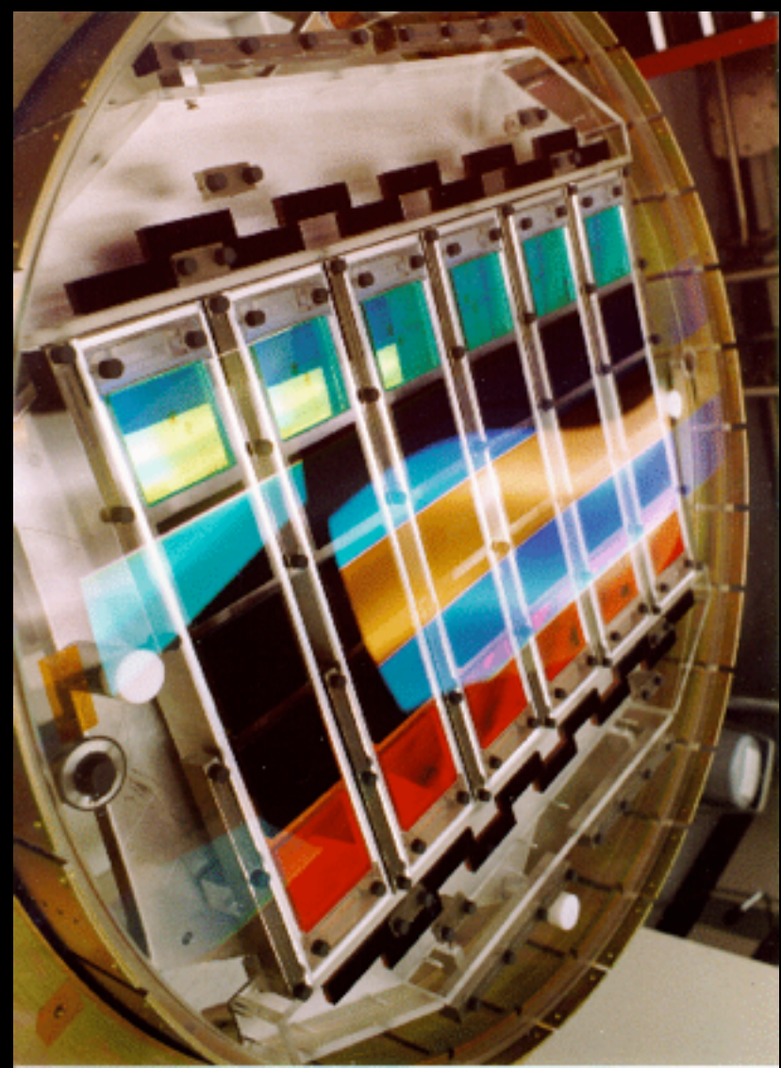
- "Cosmological Simulations" start from the initial conditions of the universe, which we think we know well (next week)
- They take millions or billions of dark matter particles and let them move around under the influence of gravity
- Gravity naturally forms sheets and filaments



How do we know?

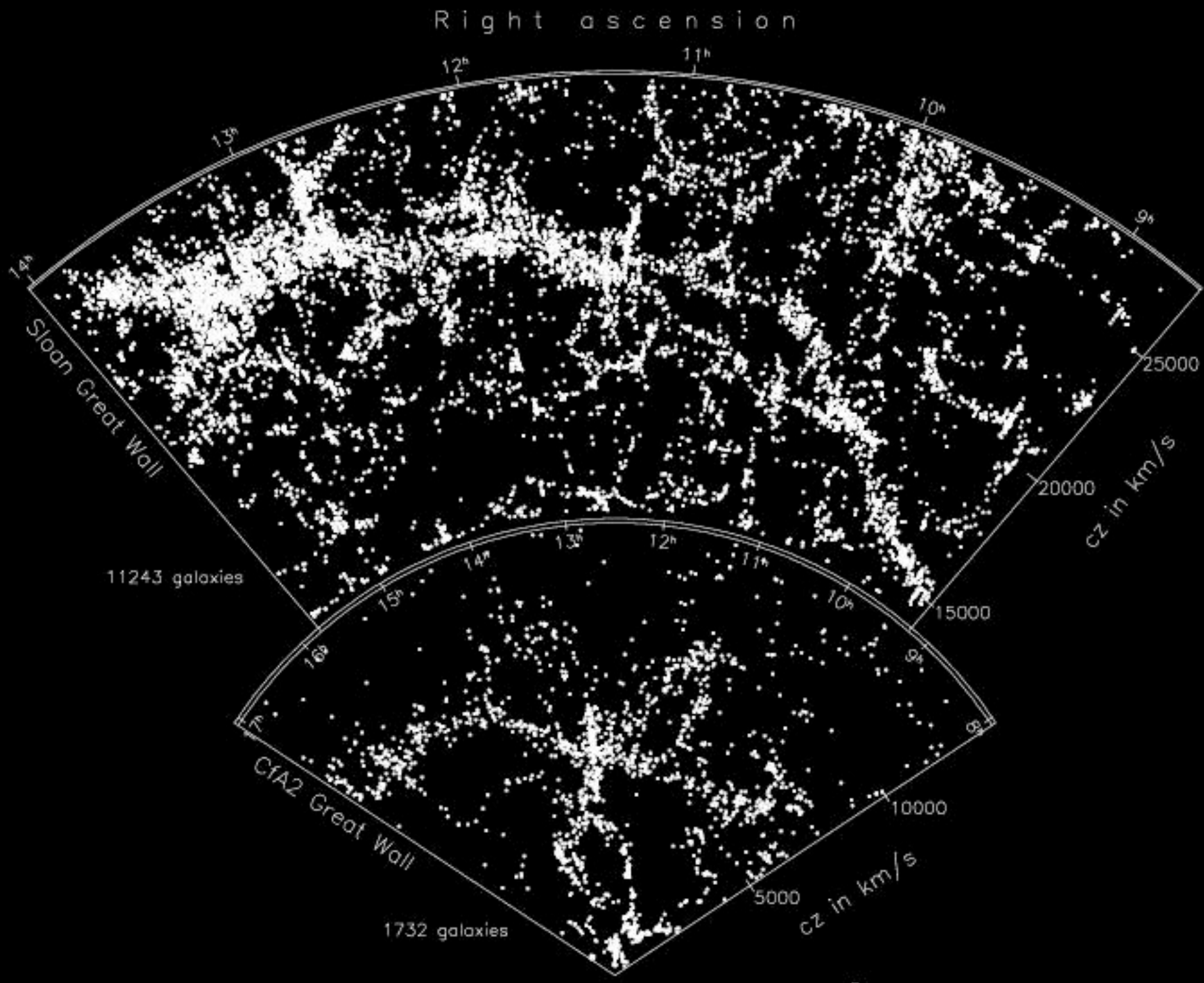
- Gigantic sky surveys have measured redshifts of thousands of galaxies
- The best to date is the Sloan Digital Sky Survey

A dedicated 2.5m telescope at the Apache Point Observatory was the first to use digital detectors (instead of film) for large-scale surveys (~1 million galaxy spectra)



SDSS went deeper than previous surveys

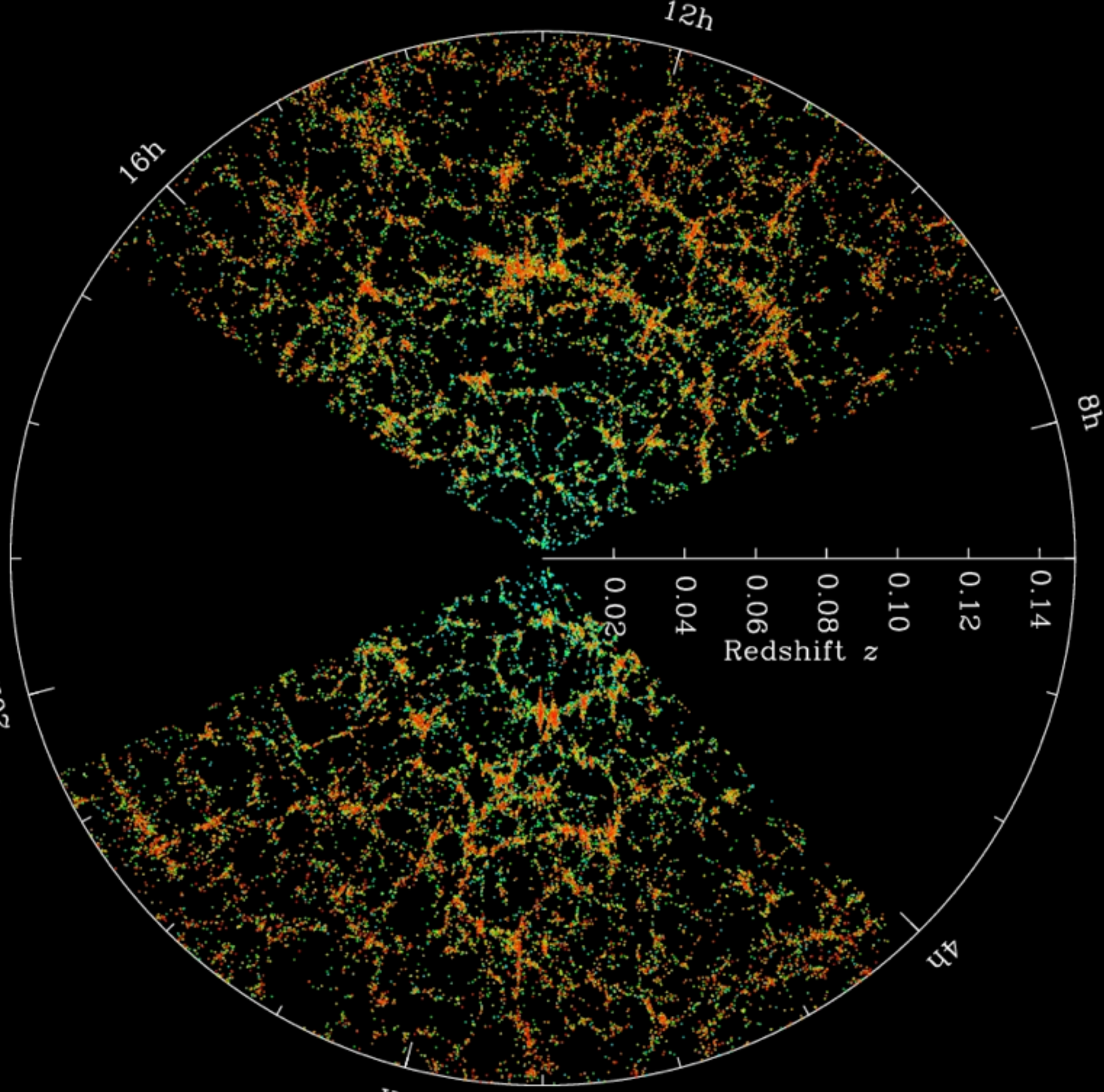
Deeper means we see fainter objects that are further away



“Fingers of God”

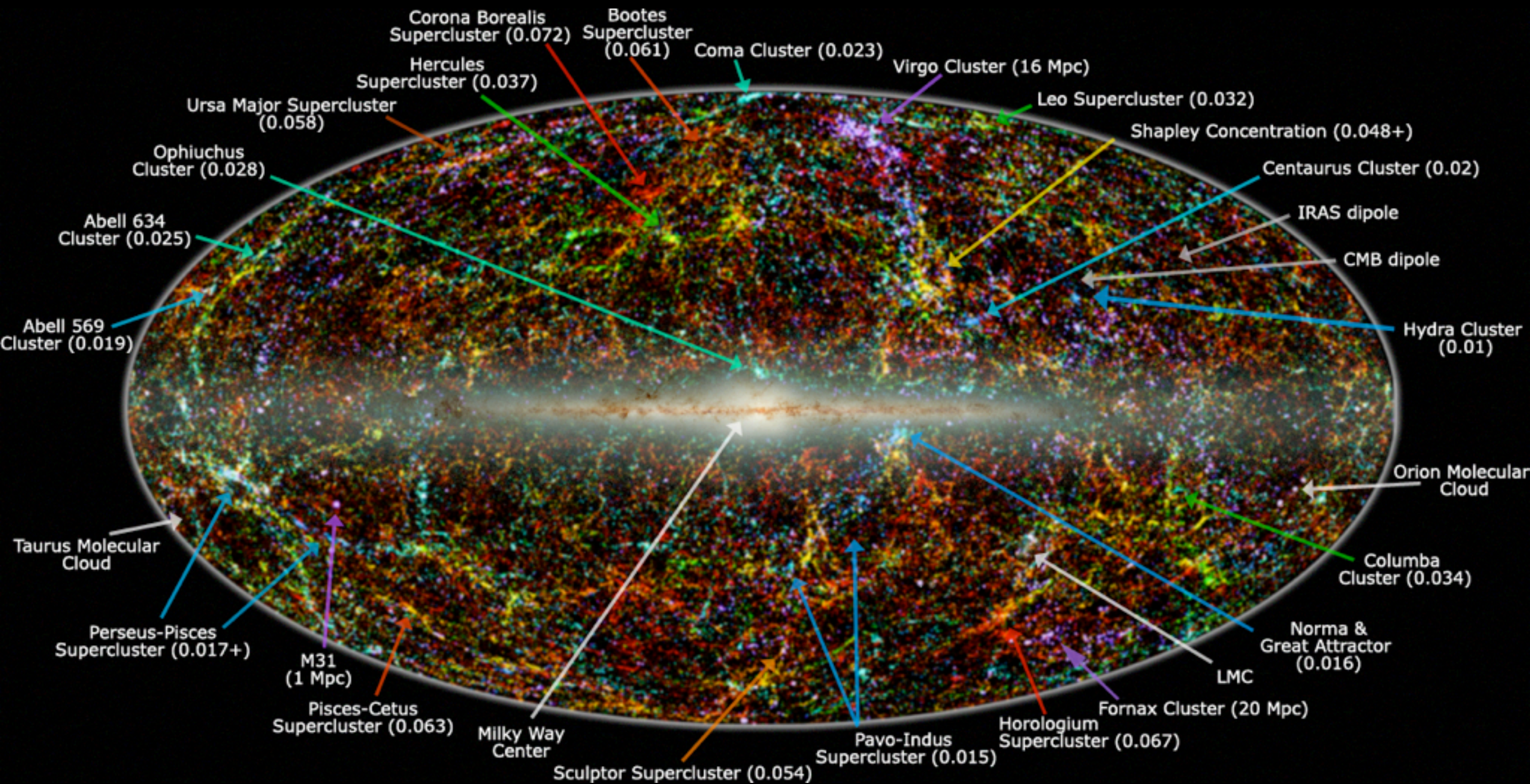
Lines of galaxies popped up in redshift surveys... looks like they’re pointing at us!

What’s really going on?

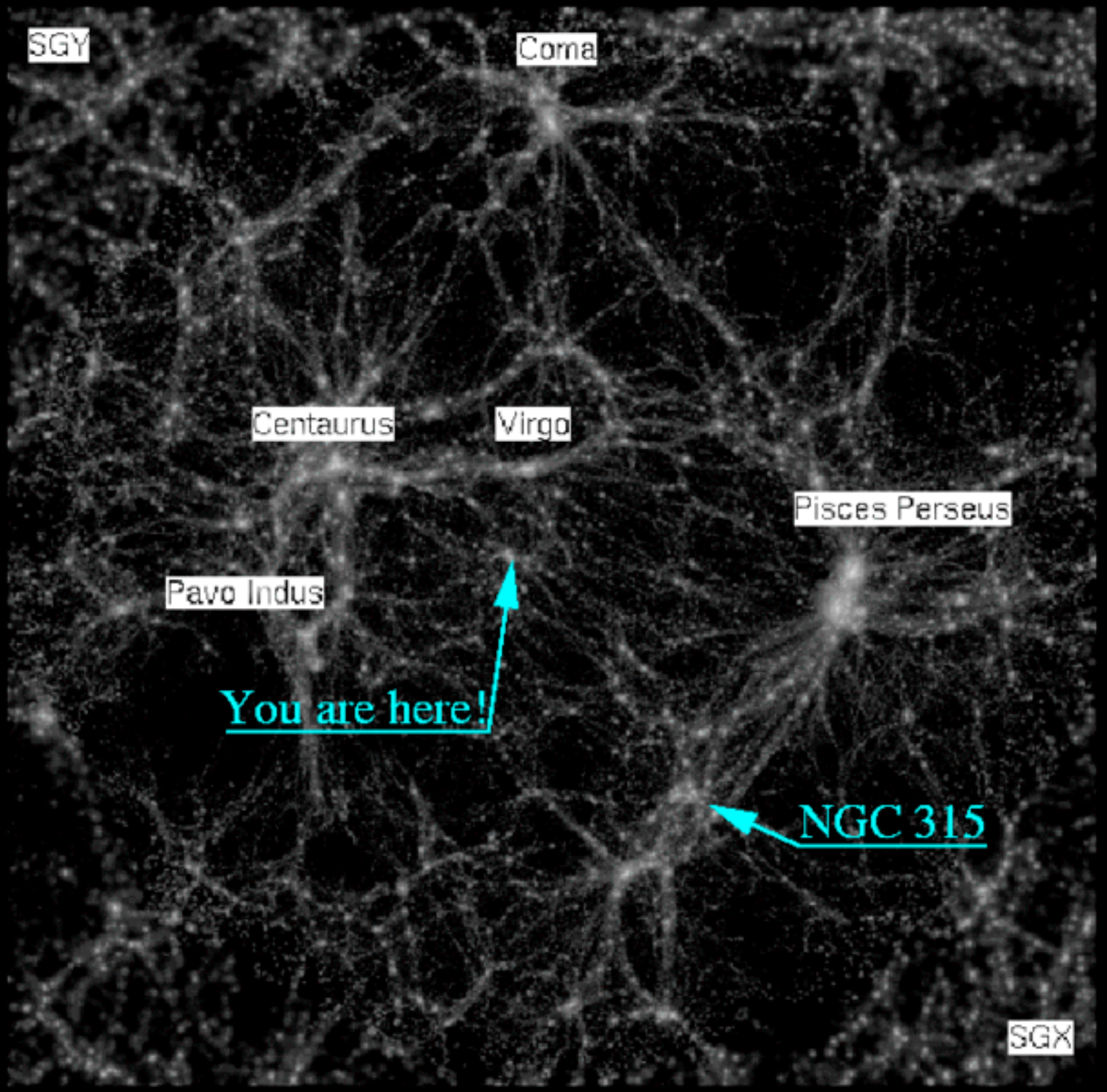


Galaxies all around - 2MASS saw the whole sky

We may be gravitationally bound to the “Shapley Concentration” or the “Great Attractor”

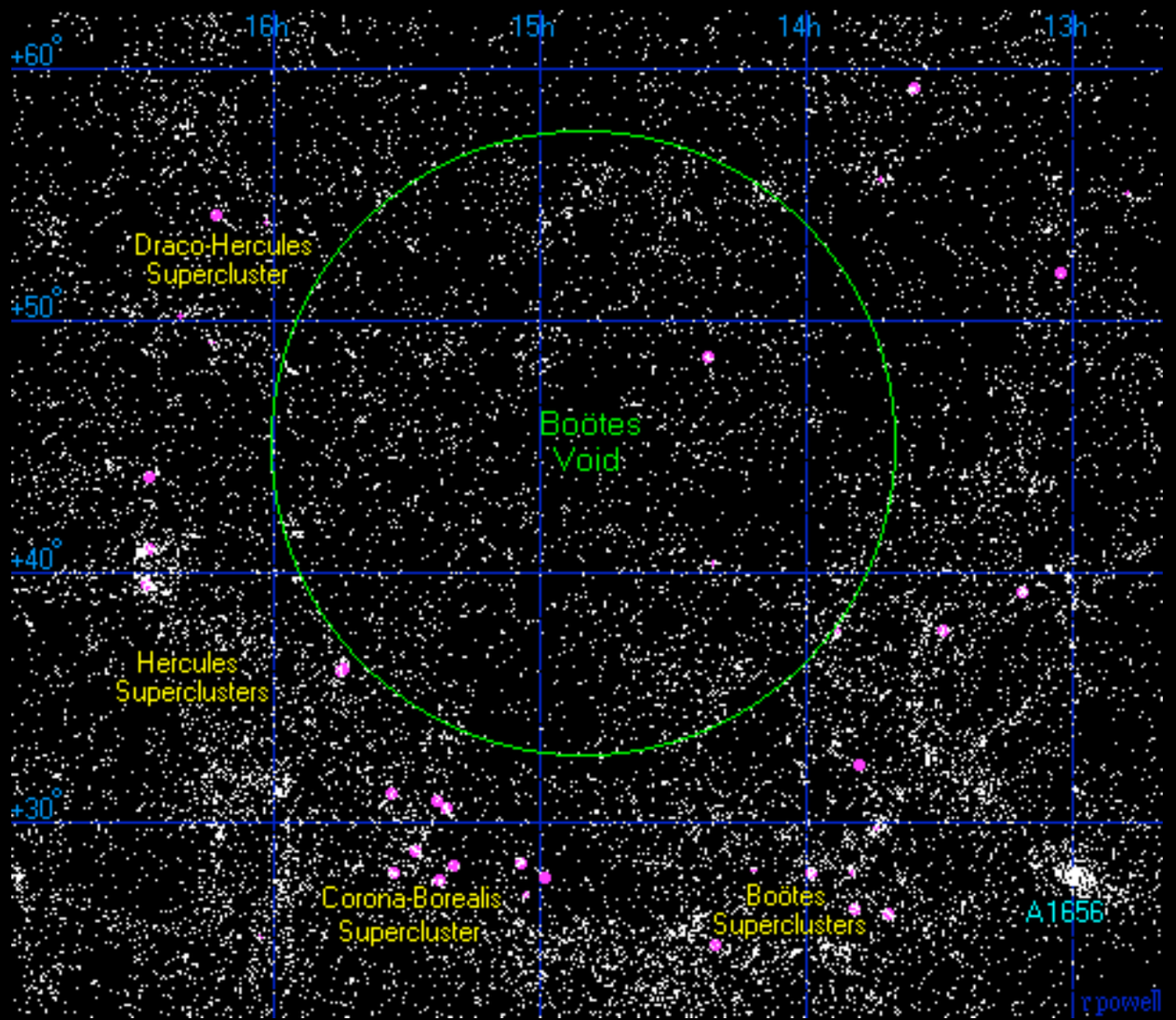


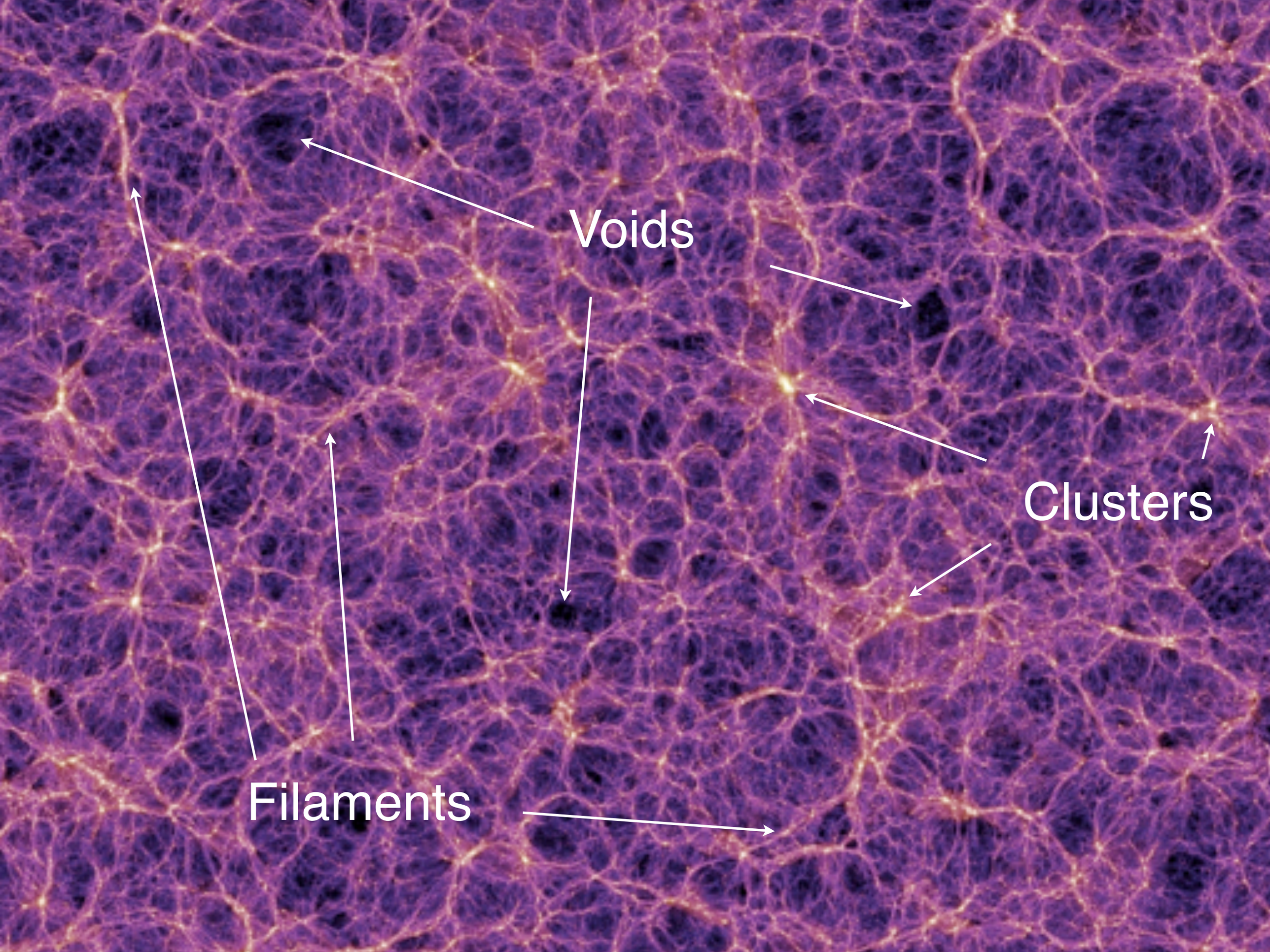
Combine data with simulations - maybe we're in a small filament?



Voids

- Voids are empty spots, the absence of structures
- They’re about the same size as filaments (~300 Mly across) but more spherical and very empty




Voids
Clusters
Filaments

Voids…

- Is there any way to see voids?
  - Not really: we can only observe their absence
  - Galaxies will appear to be moving away from voids because the force of gravity is always pointing away from them

Voids and Vacuum

- How empty are voids?
  - The atmosphere has $6x10^{20}$ particles per cubic centimeter
    - that's what you breathe
  - A really good vacuum still has ~10^{6} particles per cubic centimeter
  - Outer Space (around Earth) has ~1 particle per cubic centimeter
  - The Intracluster Medium (the hot X-ray gas in clusters) has 0.001 particles per cc on average, or one particle per 2-3 inch cube
  - Voids are super-empty: 10^{-8} per cc, or 1 particle in a cubic meter
    - That means each particle might only meet up with any other a few times during the whole lifetime of the universe

Filaments

- Filaments are a different story
  - They contain galaxies and galaxy clusters
  - They also contain the Intergalactic Medium: there's gas out there that hasn't formed or joined galaxies
- We can see these! They are clouds of cool gas. If we find quasars in the background, what kind of spectrum can we observe?

Gas absorption in
Intergalactic Medium (IGM)

Oxygen

Hydrogen

Quasar PKS 0405-123

Brightness

IGM Filament 1

IGM Filament 2

1190

1200

1210

1220

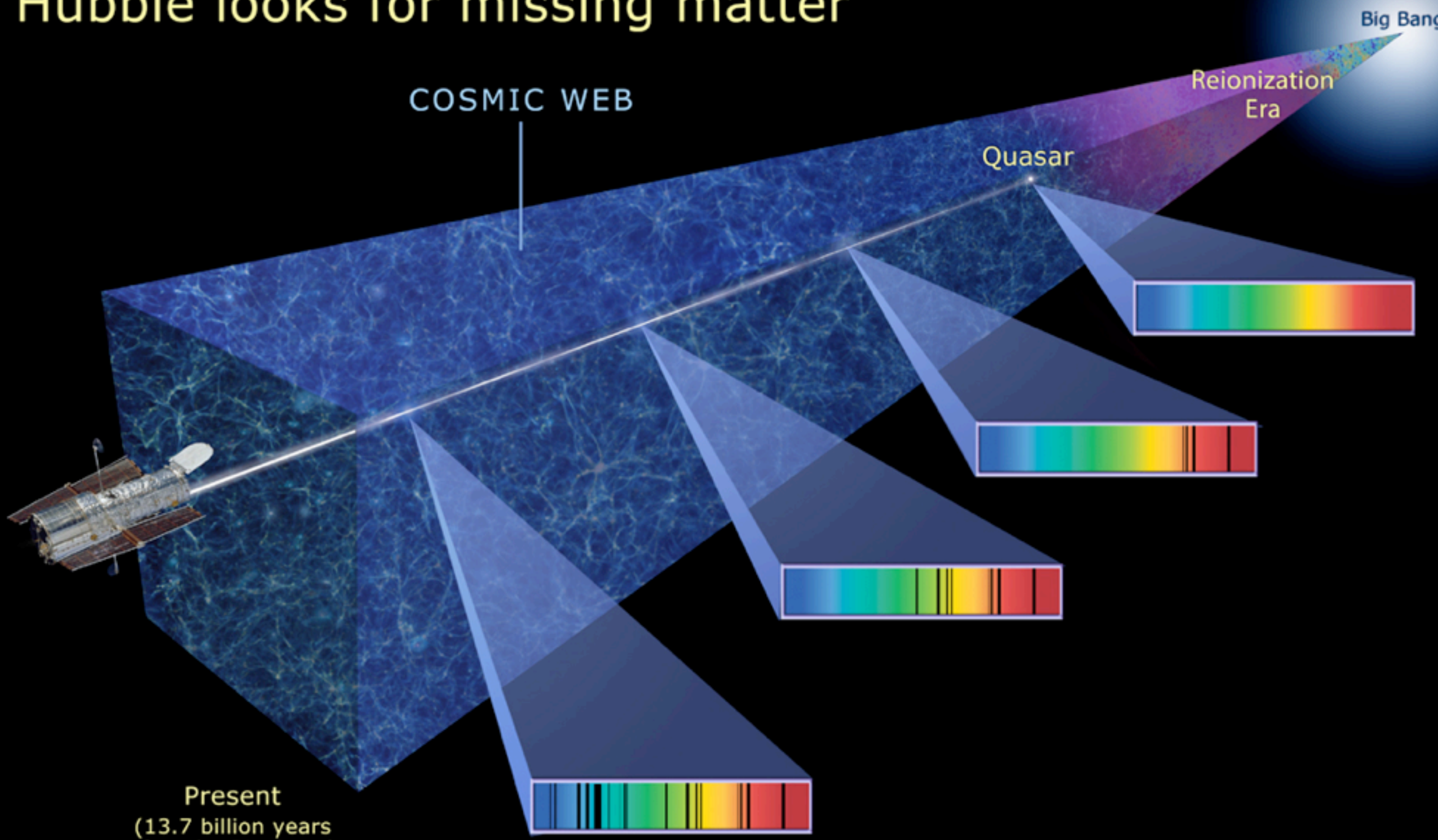
1230

Wavelength (Ångstroms)

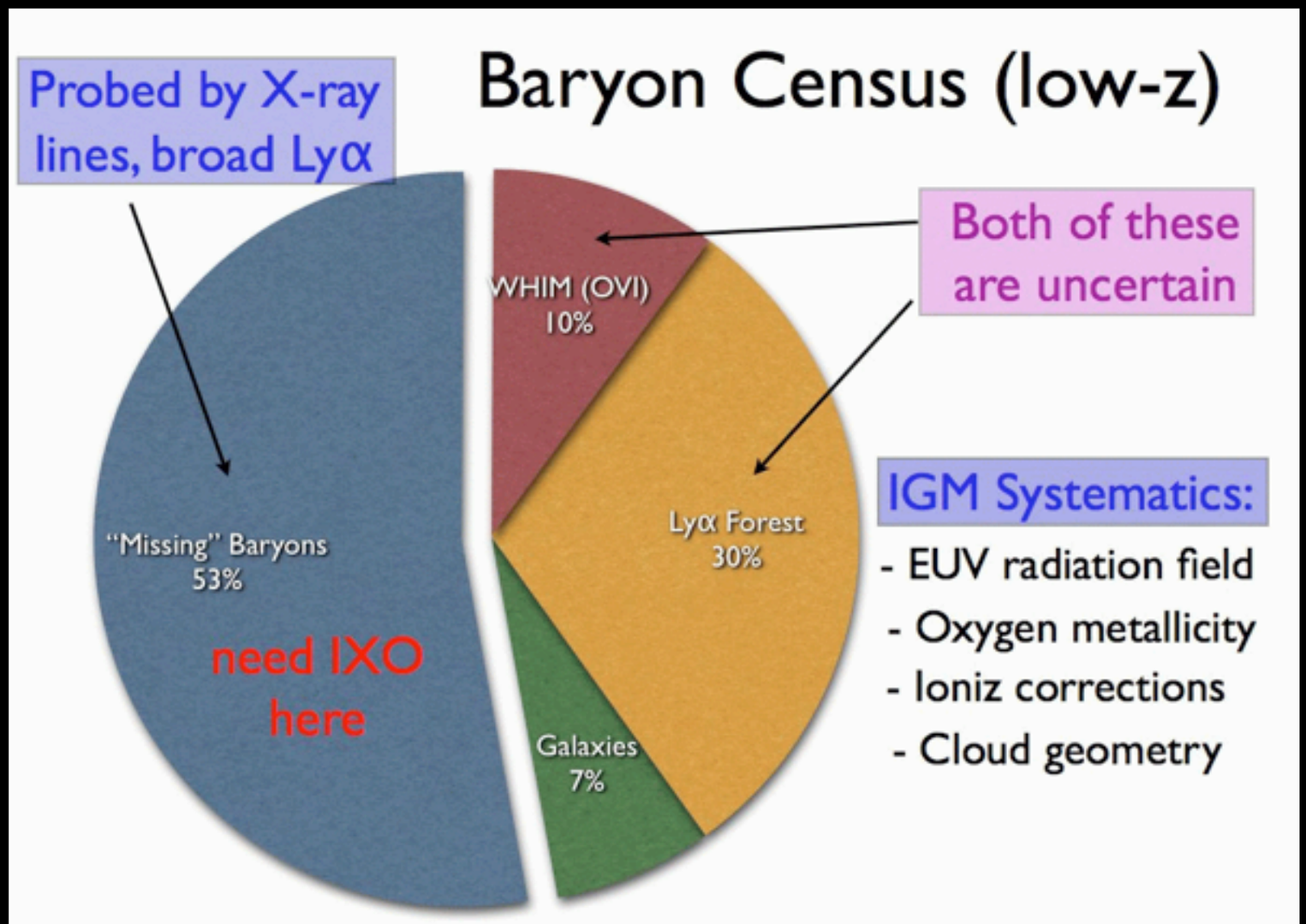
Hubble Space Telescope • COS

NASA, ESA, the Hubble SM4 ERO Team, and DSS
STScI-PRC09-25g

Hubble looks for missing matter

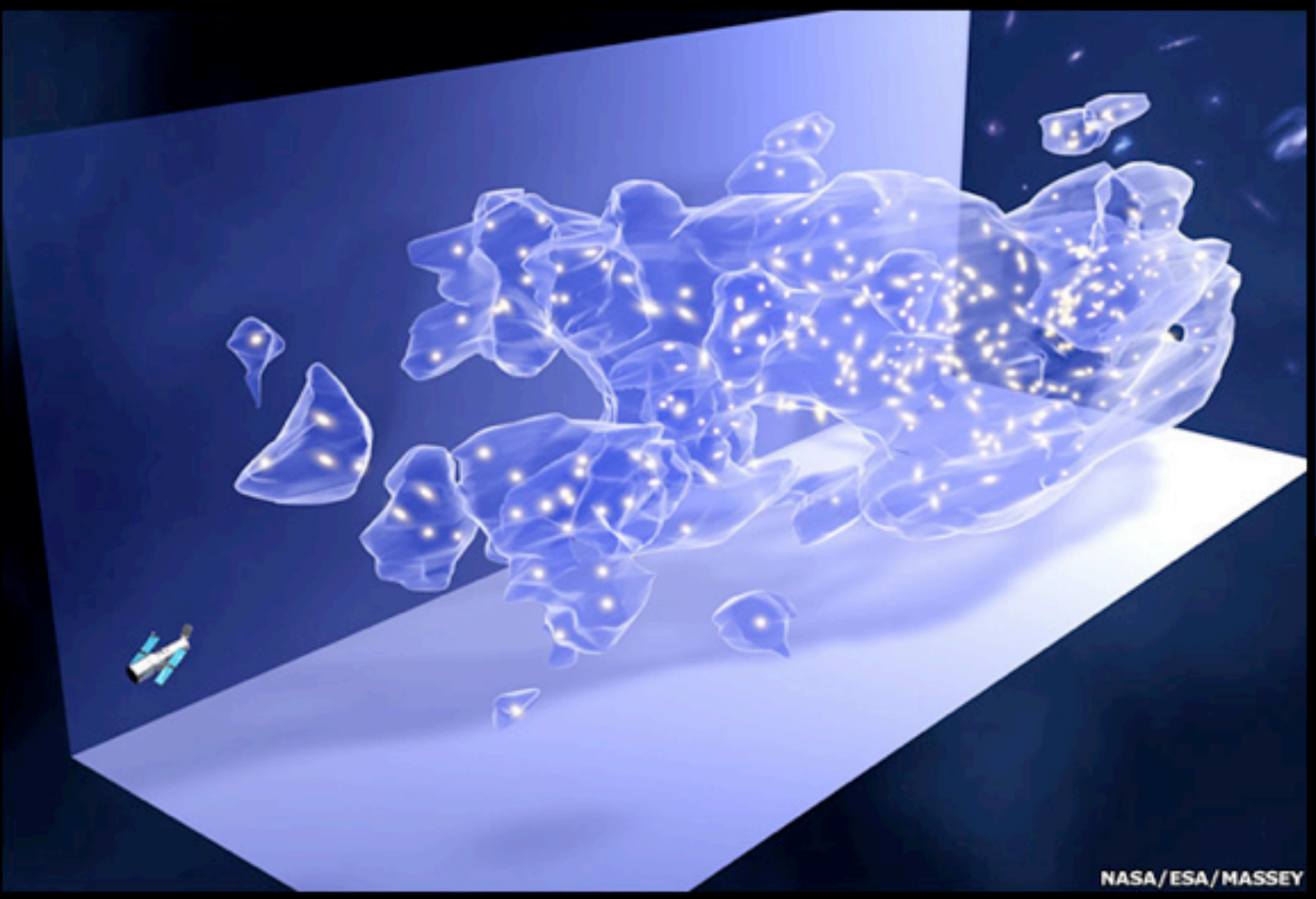


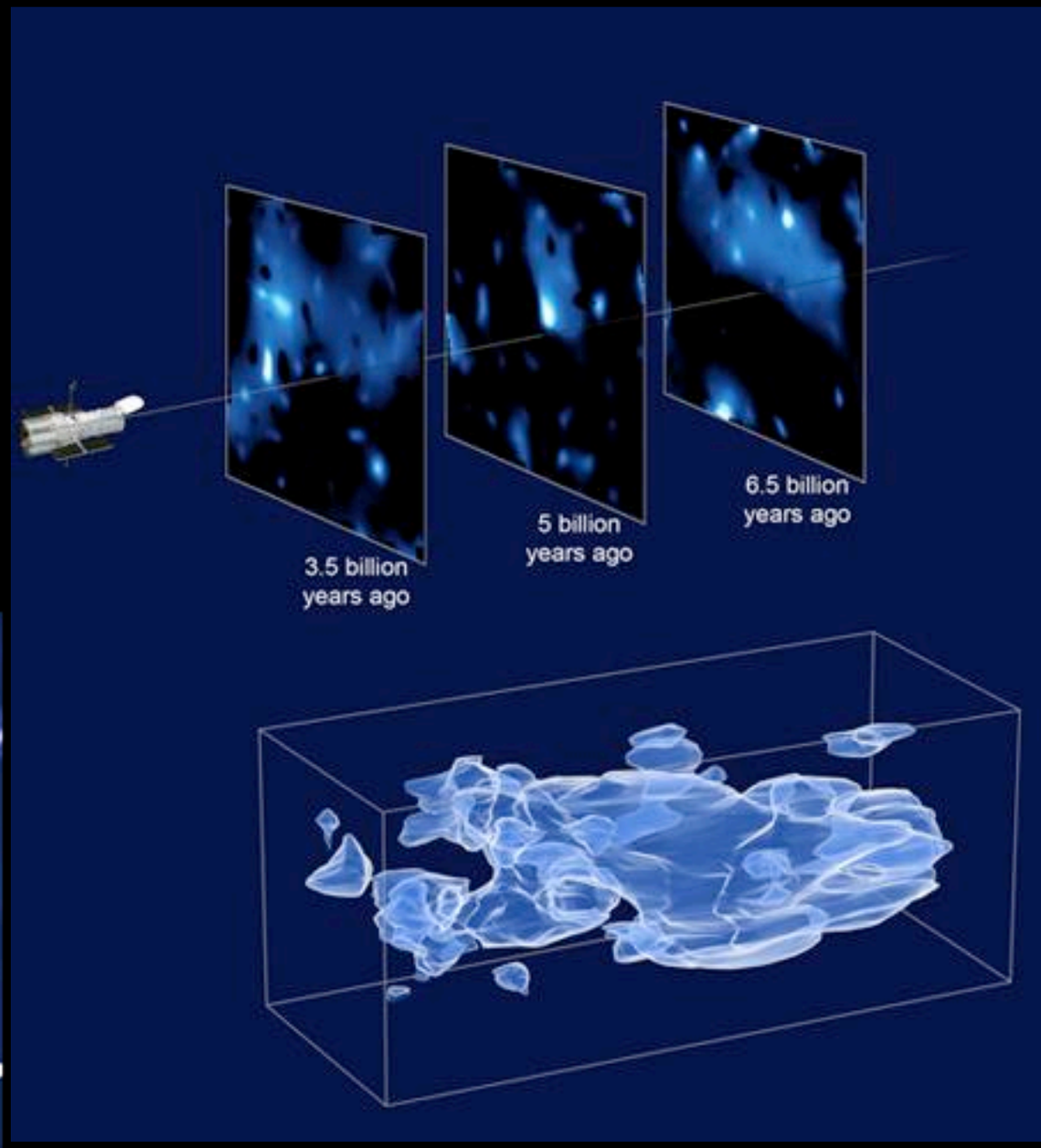
Even though dark matter is >> normal matter, there is a lot of unaccounted-for normal matter hiding in the IGM



Some of our neighbors upstairs work on this

Gravitational lensing can also be used to extract the 3D distribution of dark matter in filaments





z=20.0

TUTORIAL

- Expansion, Lookback Time, and Distance
- What happens to light under special relativity?
  - Even though galaxies are moving away from each other, in special relativity light travels at the same speed no matter where you're observing it
    - (as long as you're not accelerating)

Sidestep… little galaxies

- We can see lots of smaller galaxies falling into the center of cluster potentials in these simulations
- These guys are “Dwarf Galaxies” - the little guys that didn’t make it
- They still have dark matter, which distinguishes them from globular clusters that can reach nearly the same size

Milky Way

Dwarfs

Tidal Debris

Leading tidal debris

Sun

Milky Way disk

Direction of motion

Trailing tidal debris

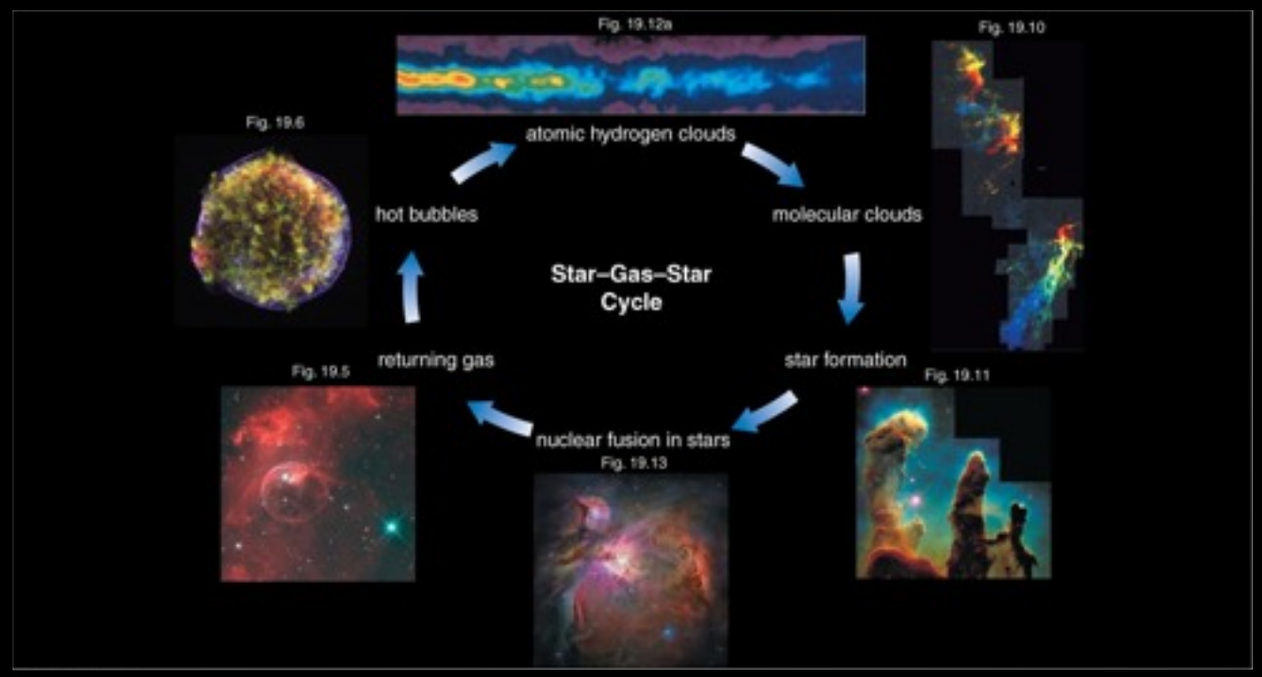
Sgr. core

Feeding

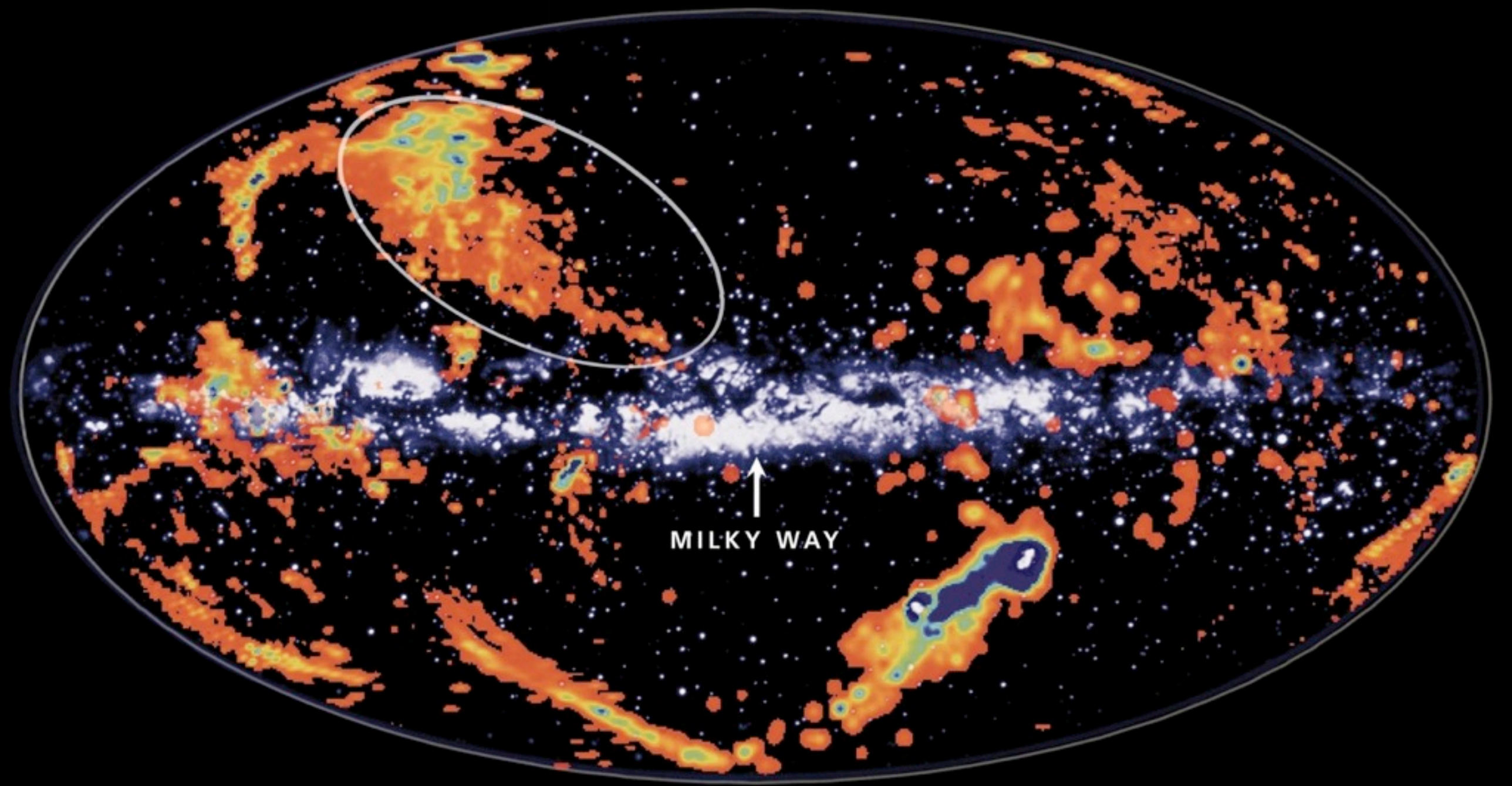
- Some galaxies have already stopped forming stars (ellipticals), while some haven’t
- Maybe the galaxies still forming stars are doing so because they paced themselves and ate slowly

How do galaxies run out?

- The star-gas-star cycle is not 100% efficient: some gas gets trapped in stars
- Other gas gets blown out into the Intergalactic Medium



Besides dwarf galaxies, big star-forming galaxies may also feed on infalling clouds of gas that never formed stars

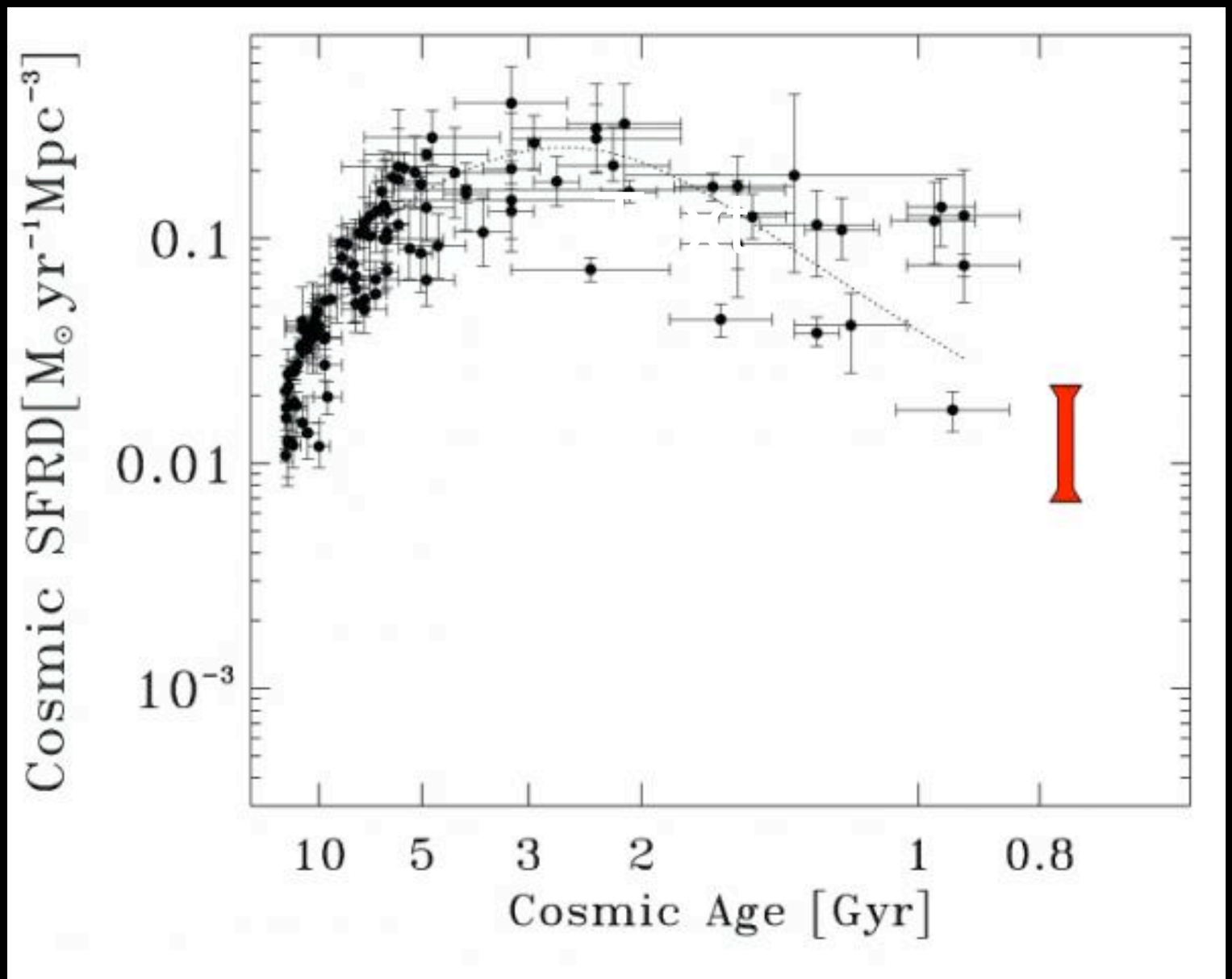


Star Formation History

- One of the "hot topics" in astronomical research right now
- Galaxy Evolution (Monday) is all about how stars and black holes formed in galaxies
- Your homework discusses Star Formation Rate Density as a function of Cosmic Age
  - The star formation rate goes up as gas collapses into structures
  - Eventually it slows down as gas collapse is slowed by expansion of the universe and galaxies run out of food

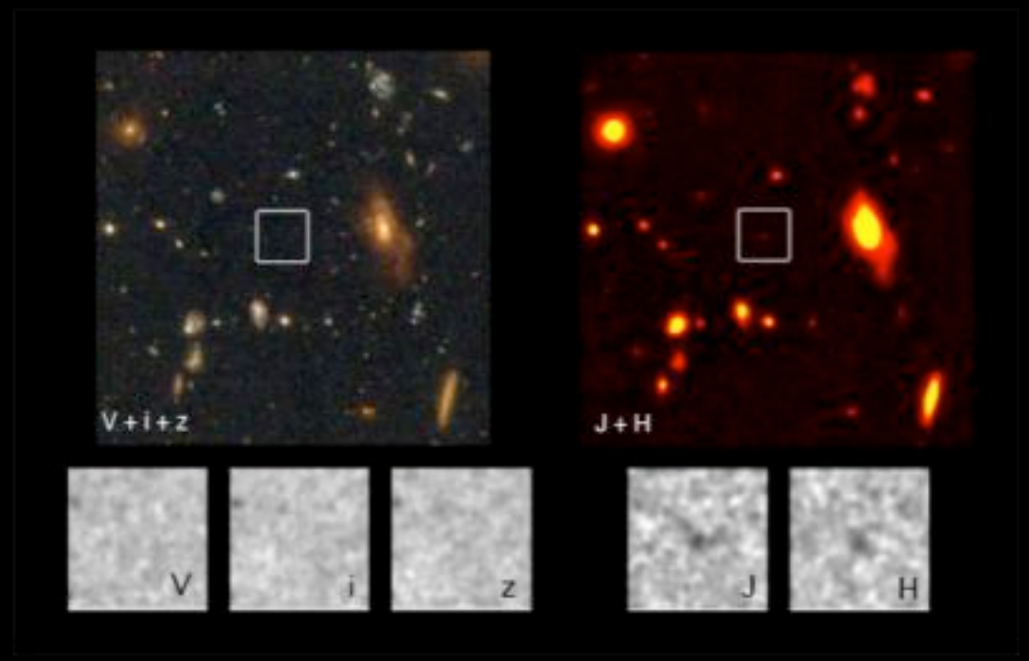
A plot similar to the homework

Which way does redshift go?



How do we explore SFRD?

- High-redshift galaxies are very far away
- Their luminosities are dominated by massive stars, which tell exactly how fast stars are forming because they live short lifetimes
- Can also look for dust in the infrared - starburst galaxies often hide their light behind dust and can only be seen in IR



Learning Goals

- Revisit scales of the universe
  - Yeah, it's big
- Is there a Biggest Thing in the universe?
  - There are largest scales: nothing bigger than filaments
- How do we observe large scale structure? How do we see holes?
  - Absorption line studies
  - Absence of material