ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 21 • From dark matter halos to galaxies to stars

11/16/2021

Homework

- Homework 5 is online, due 12/2 (after Thanksgiving)

Recap

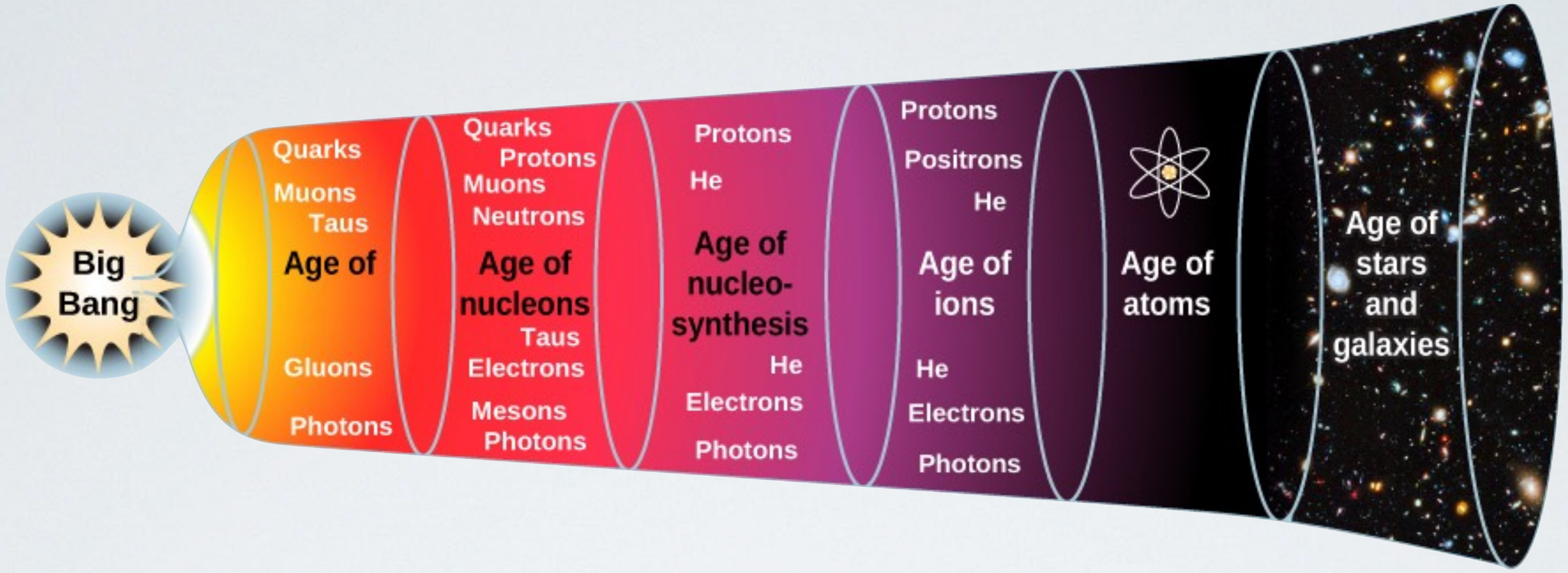
Participation: Recap #1

TurningPoint:
Which force is responsible for their being structure in the Universe?

Session ID: diemer

30 seconds

The big question



How to we go from an almost smooth early Universe to the structure we see today?

Short answer: gravity!

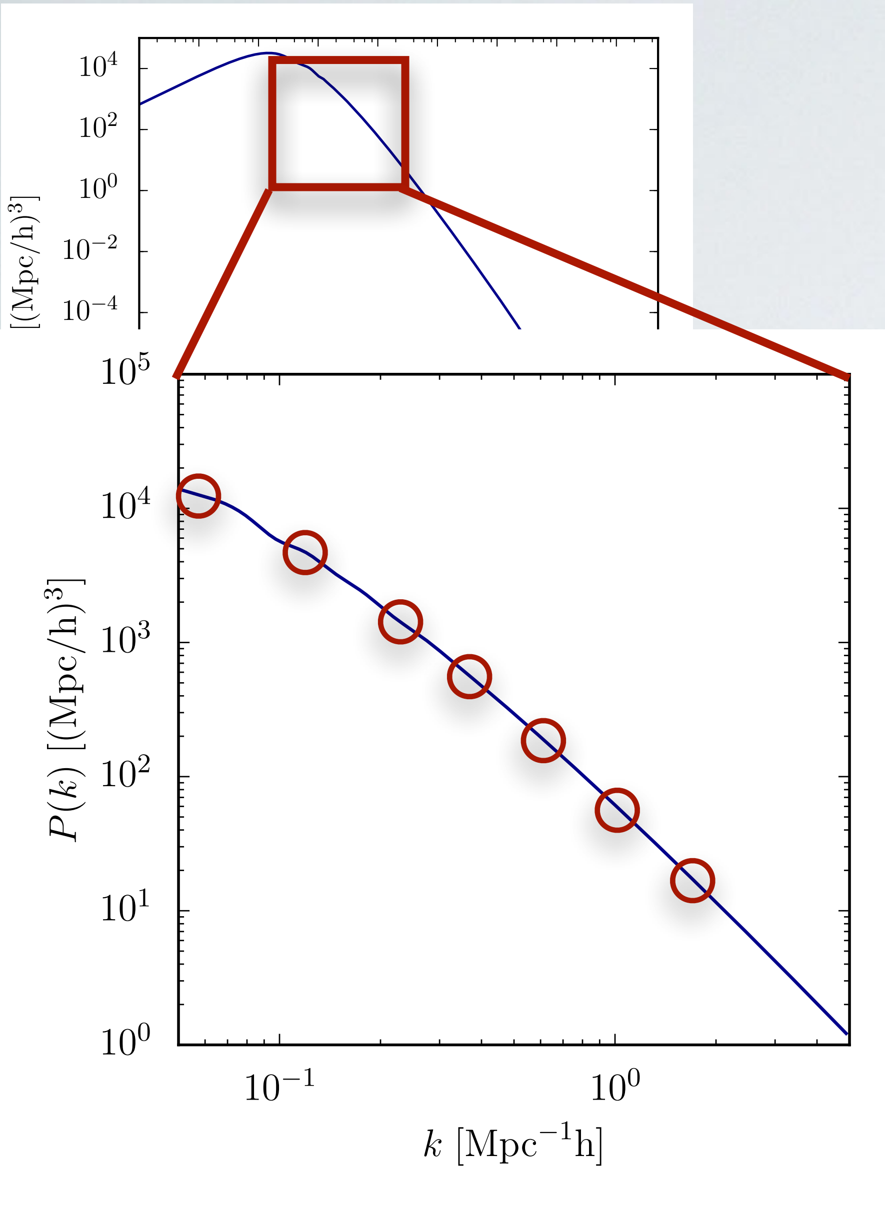
Participation: Recap #2

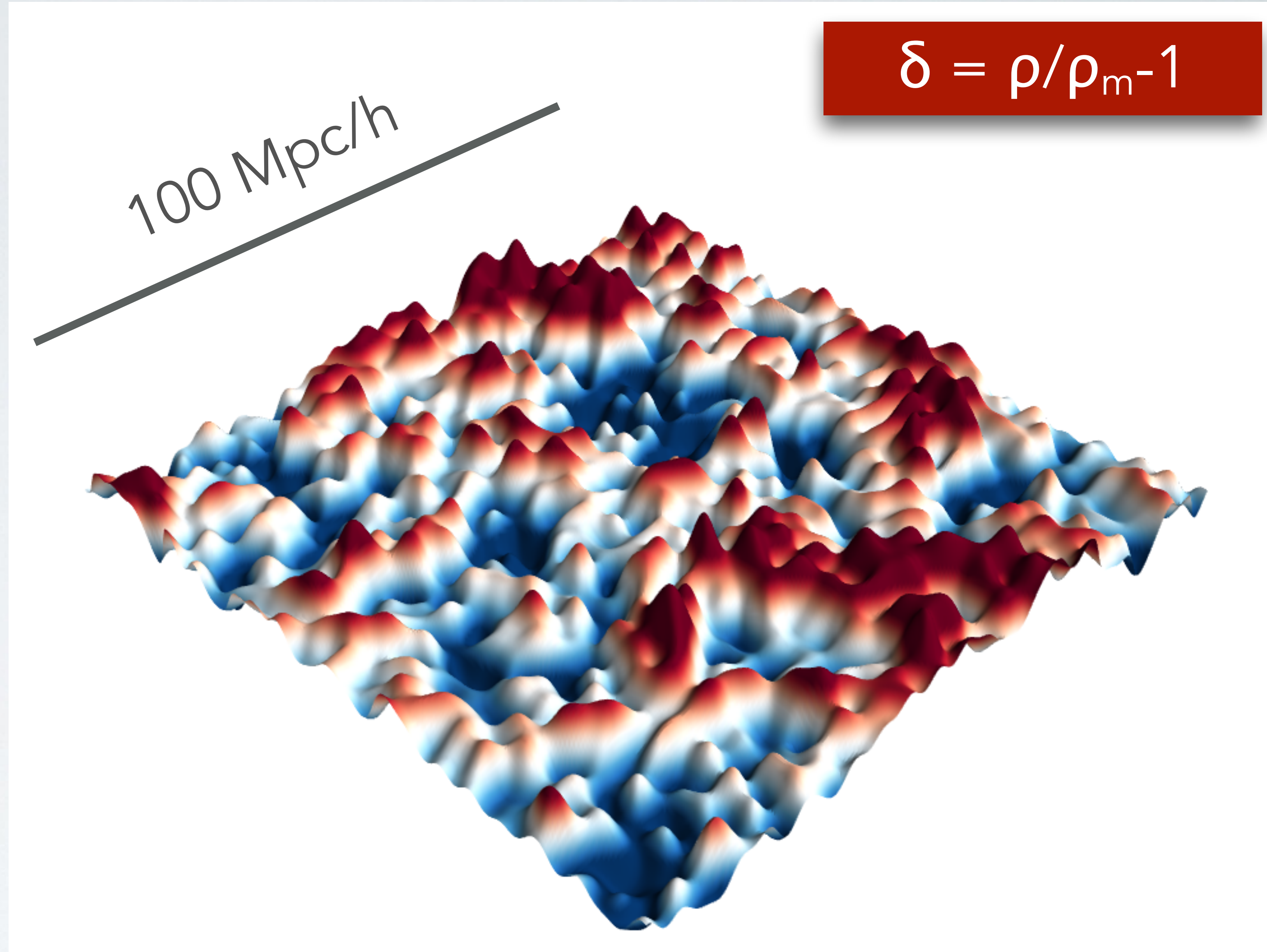
TurningPoint:
What exactly are dark matter simulations simulating?

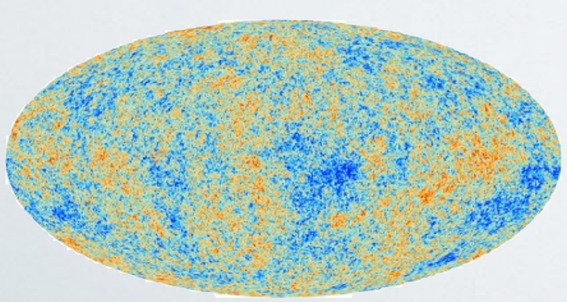
Session ID: diemer

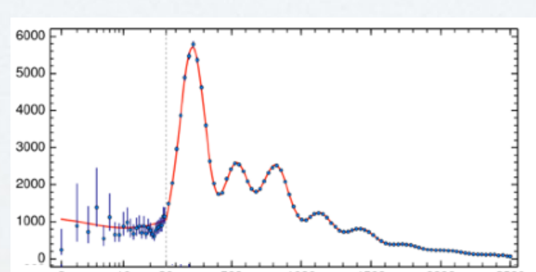
30 seconds

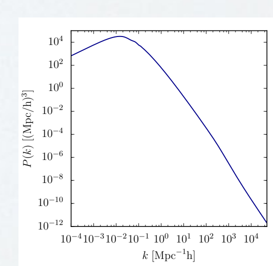
Dark matter power spectrum

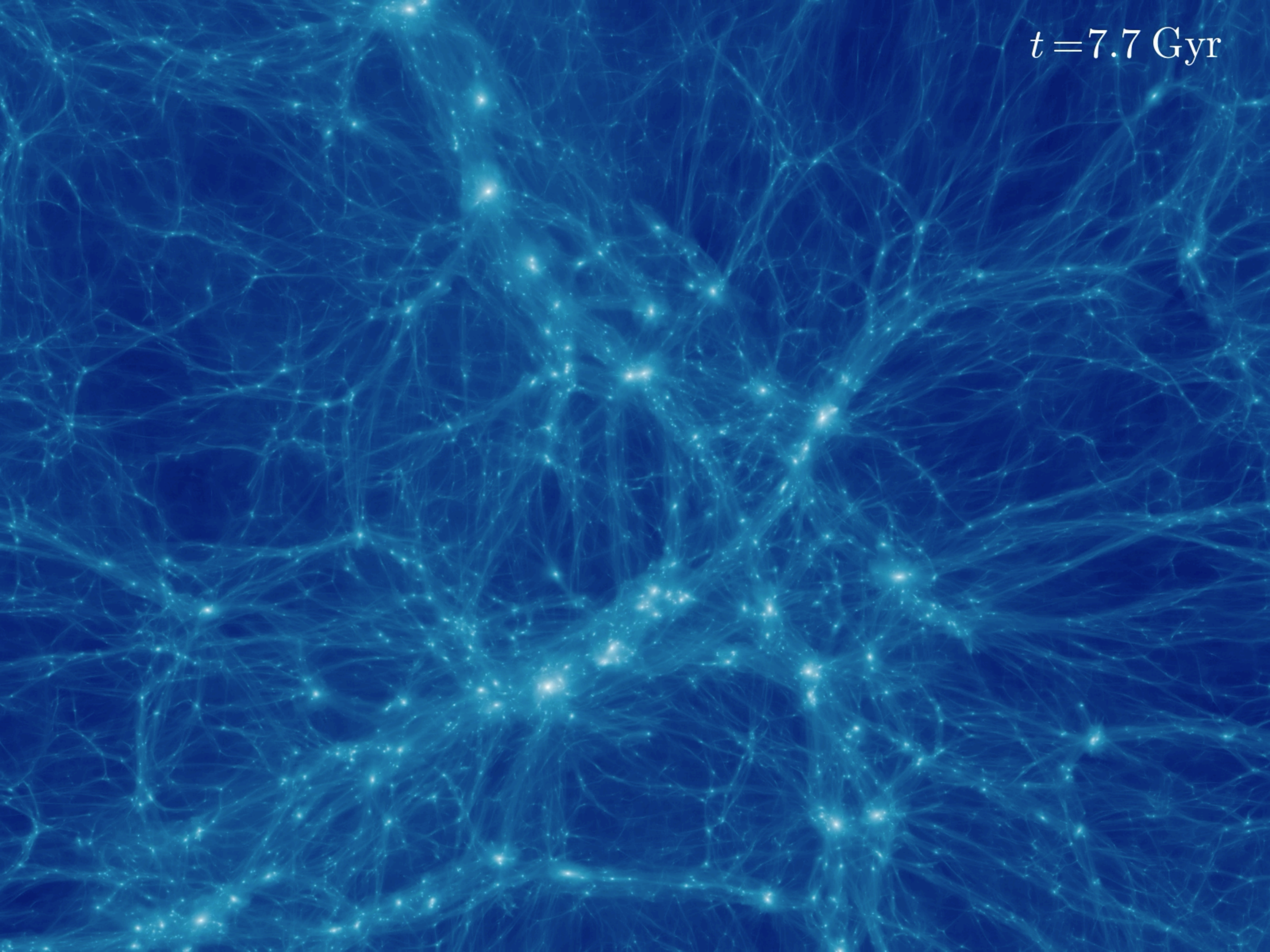











$t = 7.7$ Gyr

Participation: Recap #3

TurningPoint:
How do dark matter halos form?

Session ID: diemer

30 seconds

Formation of halos

Structure forms bottom-up: small structures (halos) form first to make larger structures (halos)

- Halos contain many smaller halos, called “subhalos”
- Merging continues; Milky Way and Andromeda will merge in 5 billion years

Participation: Recap #4

TurningPoint:
What do we know about dark matter?

Session ID: diemer

30 seconds

Dark matter candidates

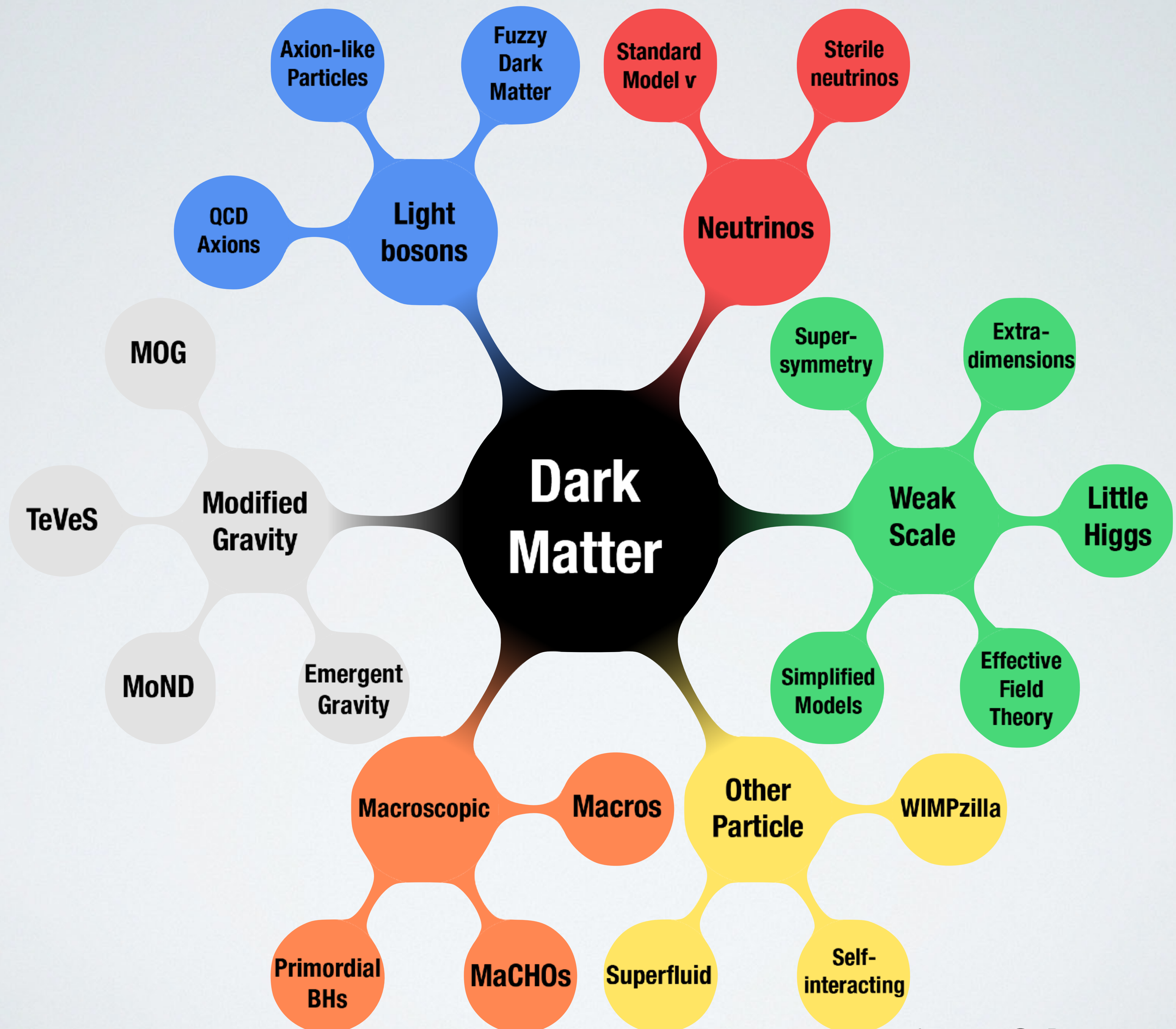
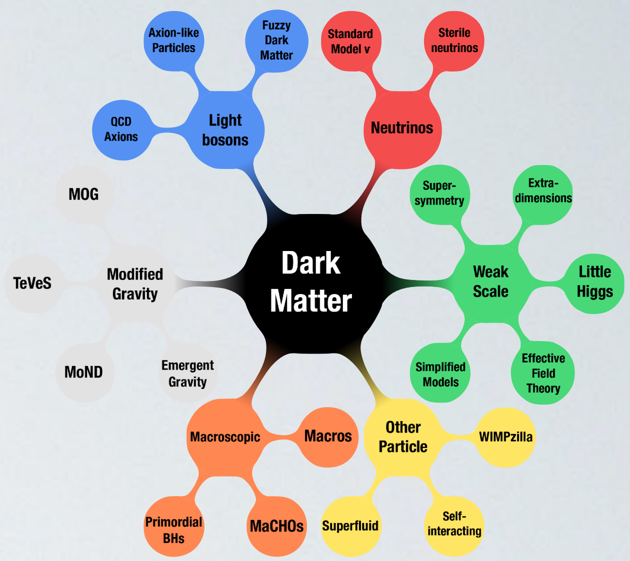


Image: G. Bertone and T. M. P. Tait

Dark matter candidates: Overview

- No detection of any type of dark matter
- **Dark matter must be cold or very slightly warm,** otherwise not enough structure / subhalos



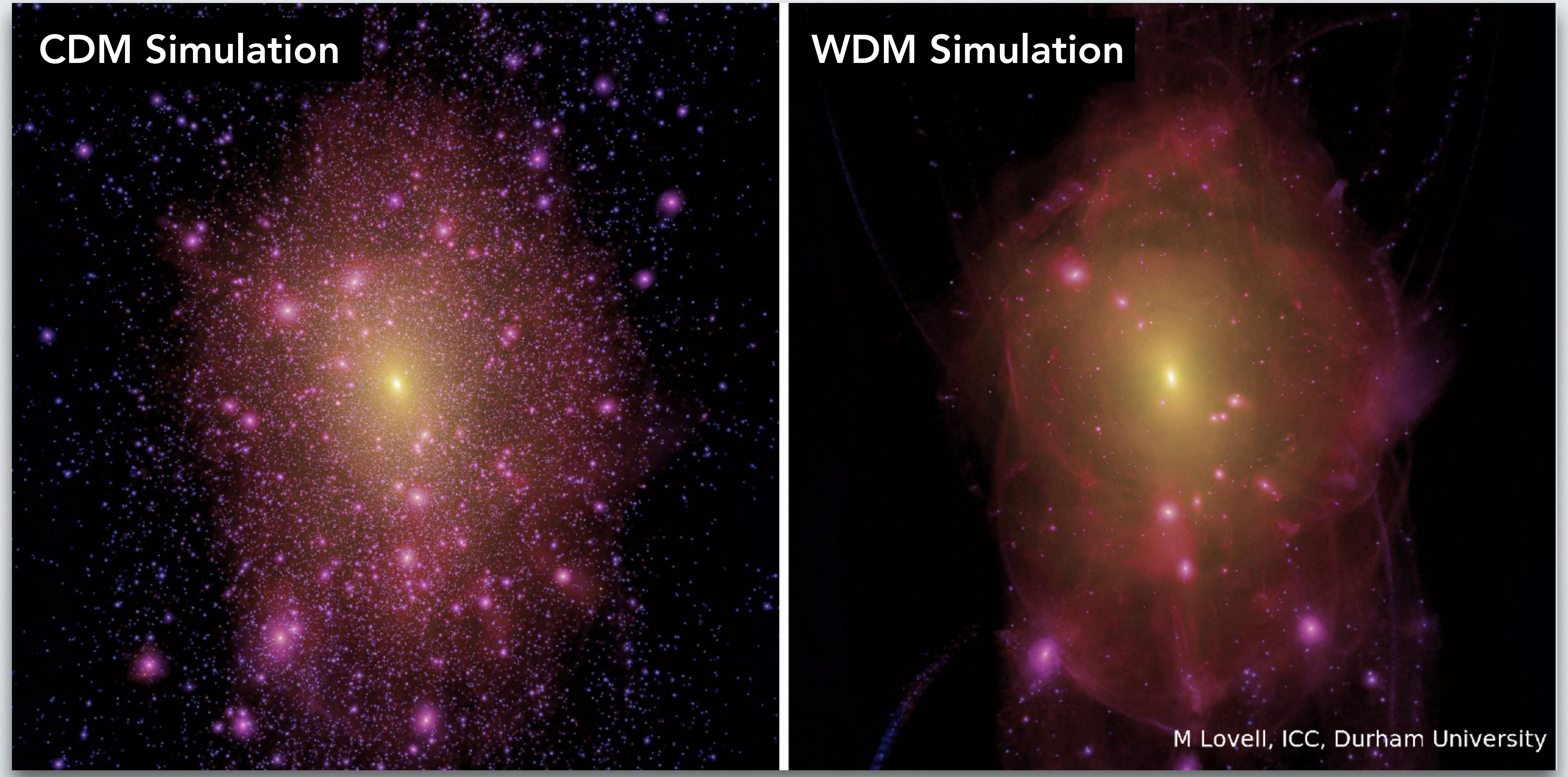


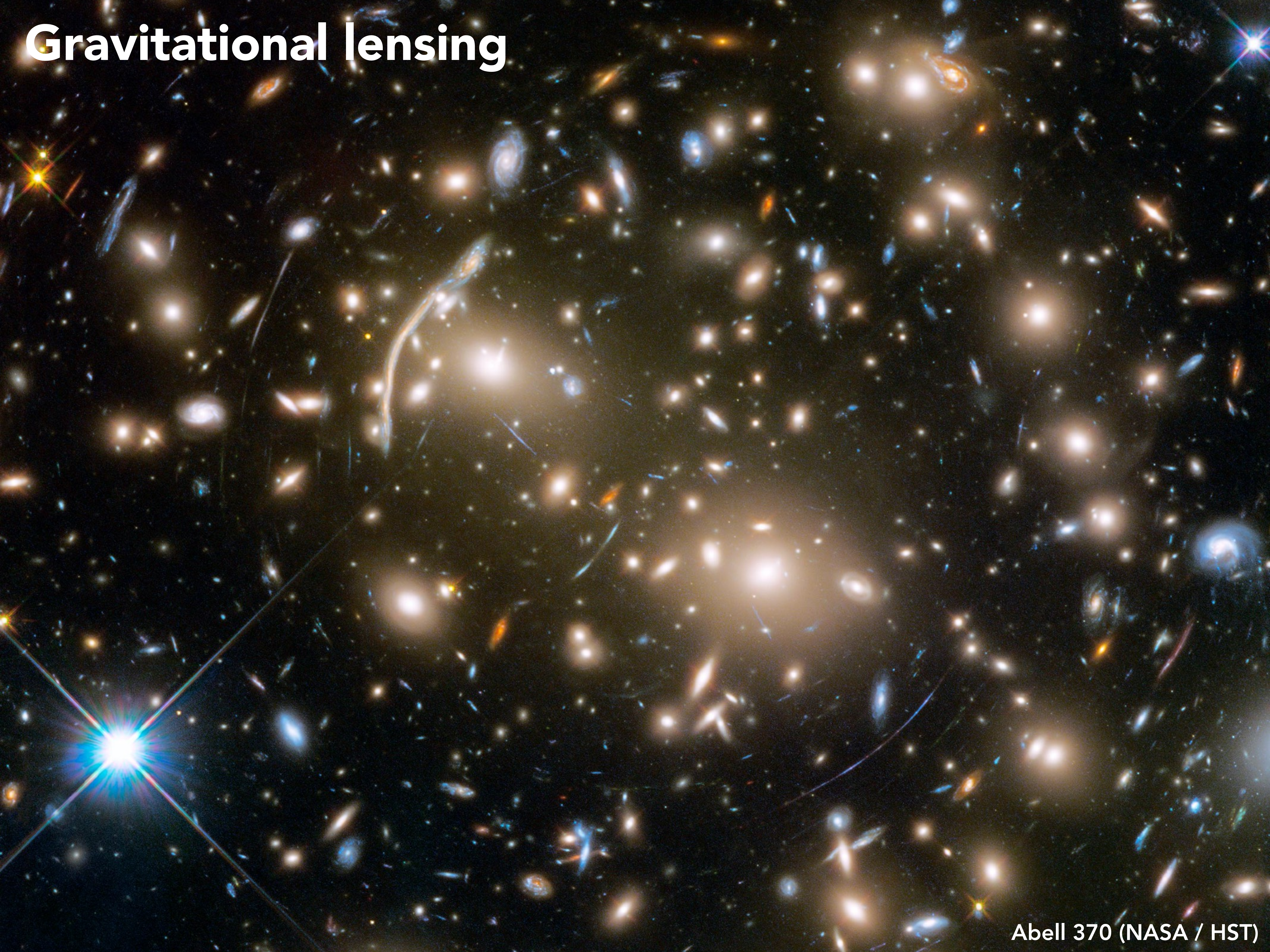
Image: Mark Lovell

Today

- Observing in the dark: weak lensing
- From dark matter to galaxies
- Making stars
- The end of the dark ages

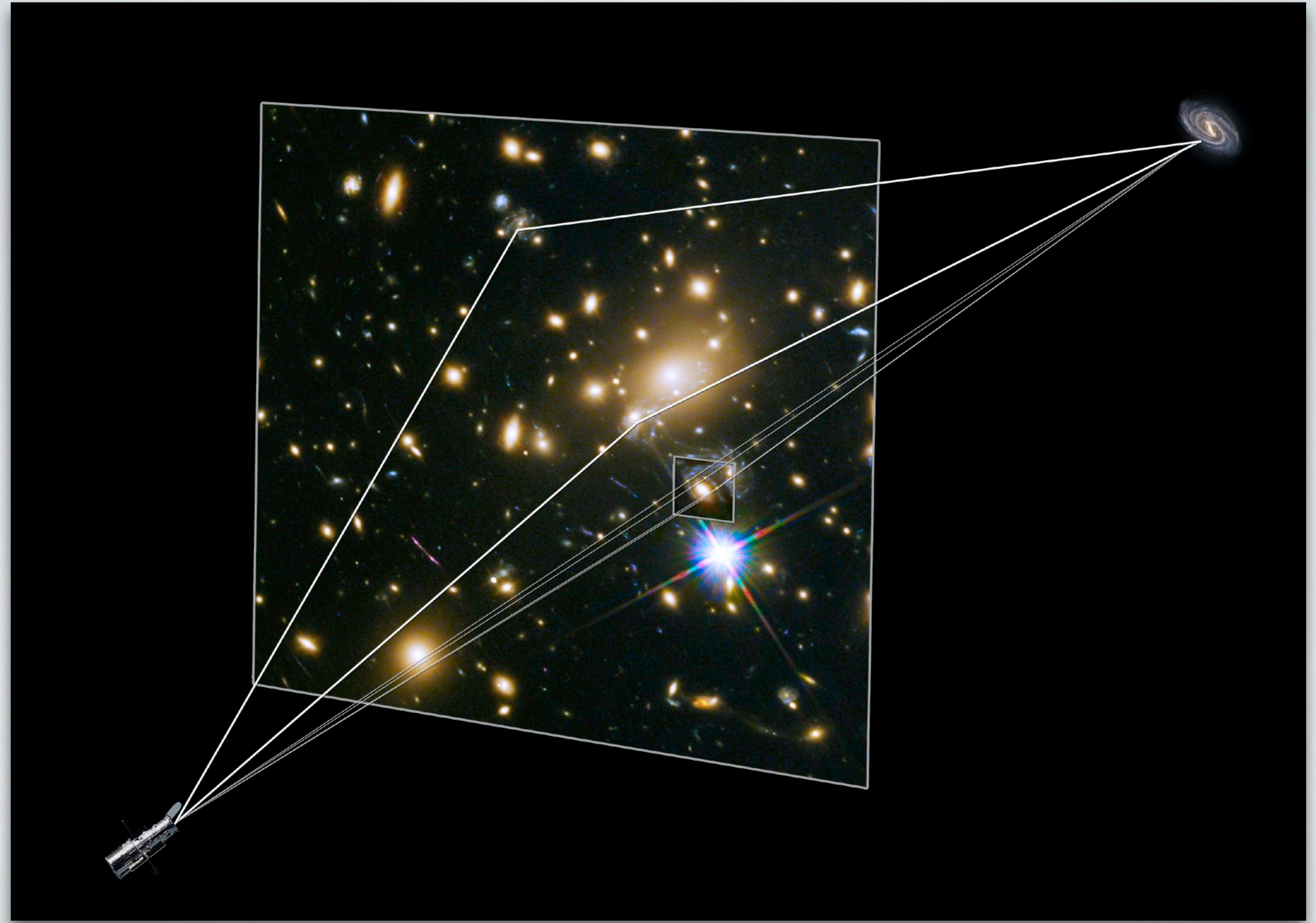
Part 1: Observing in the dark: weak lensing

Gravitational lensing



Abell 370 (NASA / HST)

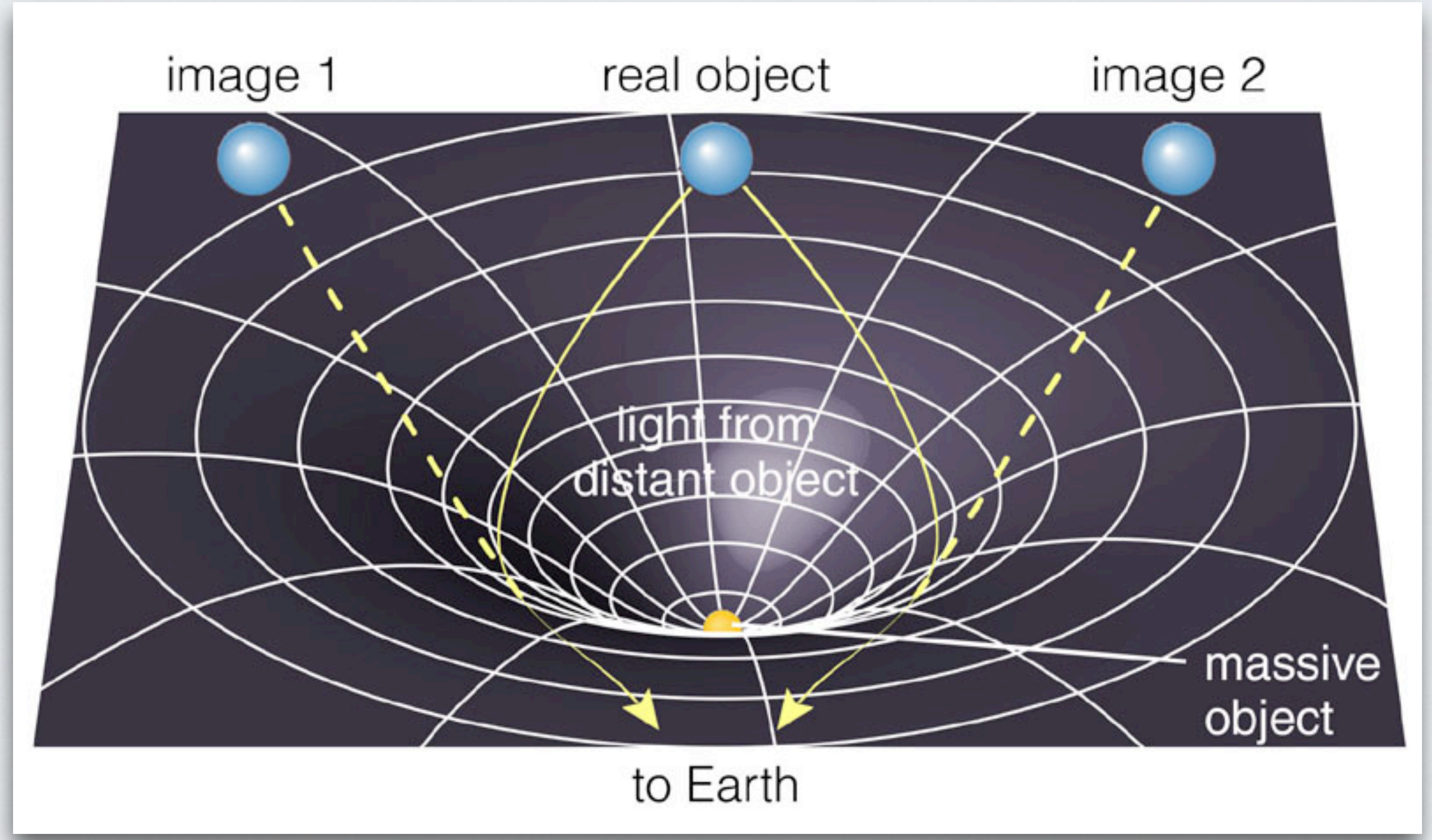
Strong lensing from galaxy clusters



Images: NASA

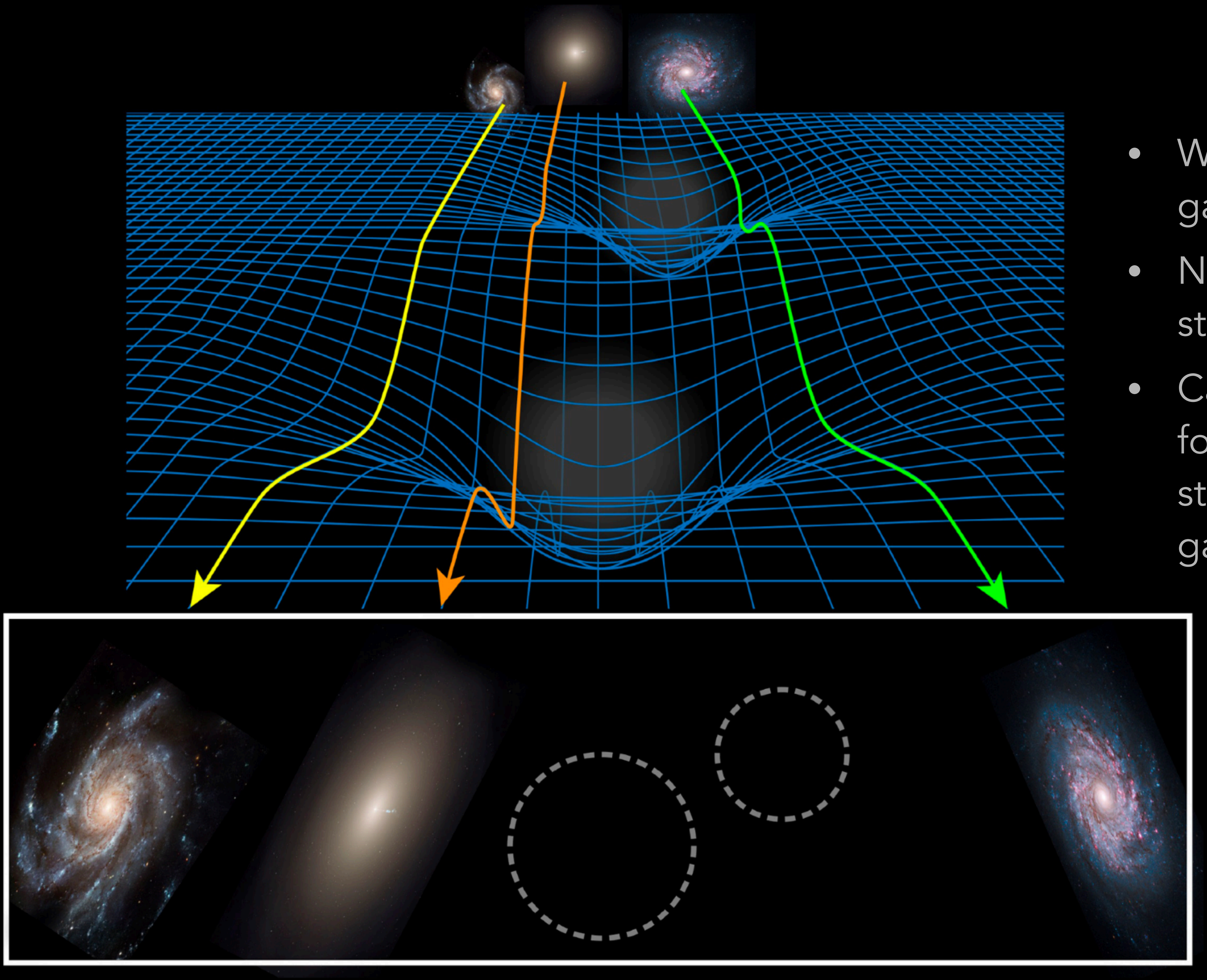
Lensing from galaxy clusters

- Light rays from distant quasar or galaxy provide **background source**
- Massive galaxy or cluster is **foreground lens**
- Two or more **images** can appear



Images: NASA / University of Georgia

Weak lensing



- Weak lensing: background galaxies are **distorted**
- No multiple images as in strong lensing
- Cannot detect the effect for a single galaxy, but statistically for many galaxies

APS / Alan Stonebraker / STScI/AURA, NASA, ESA, and the Hubble Heritage Team

Weak lensing

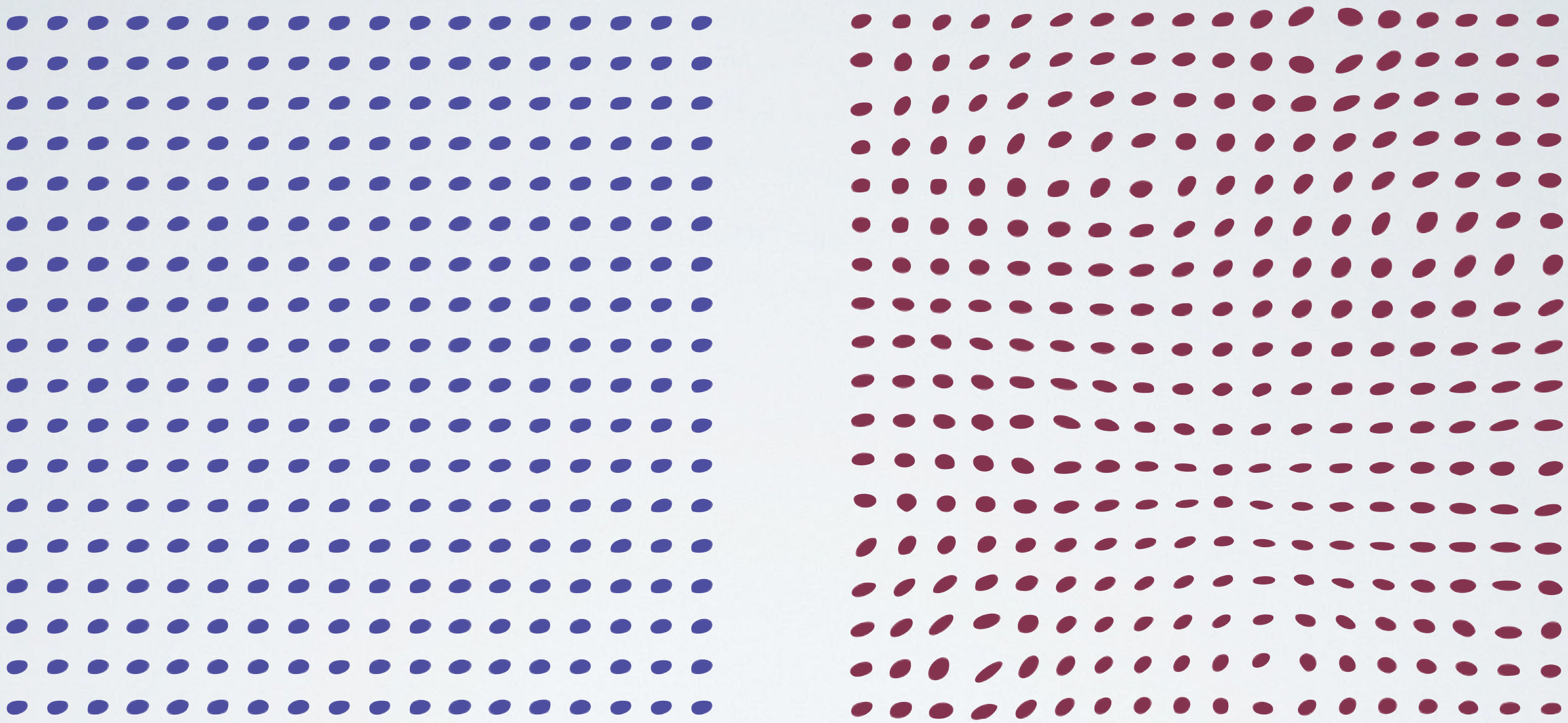
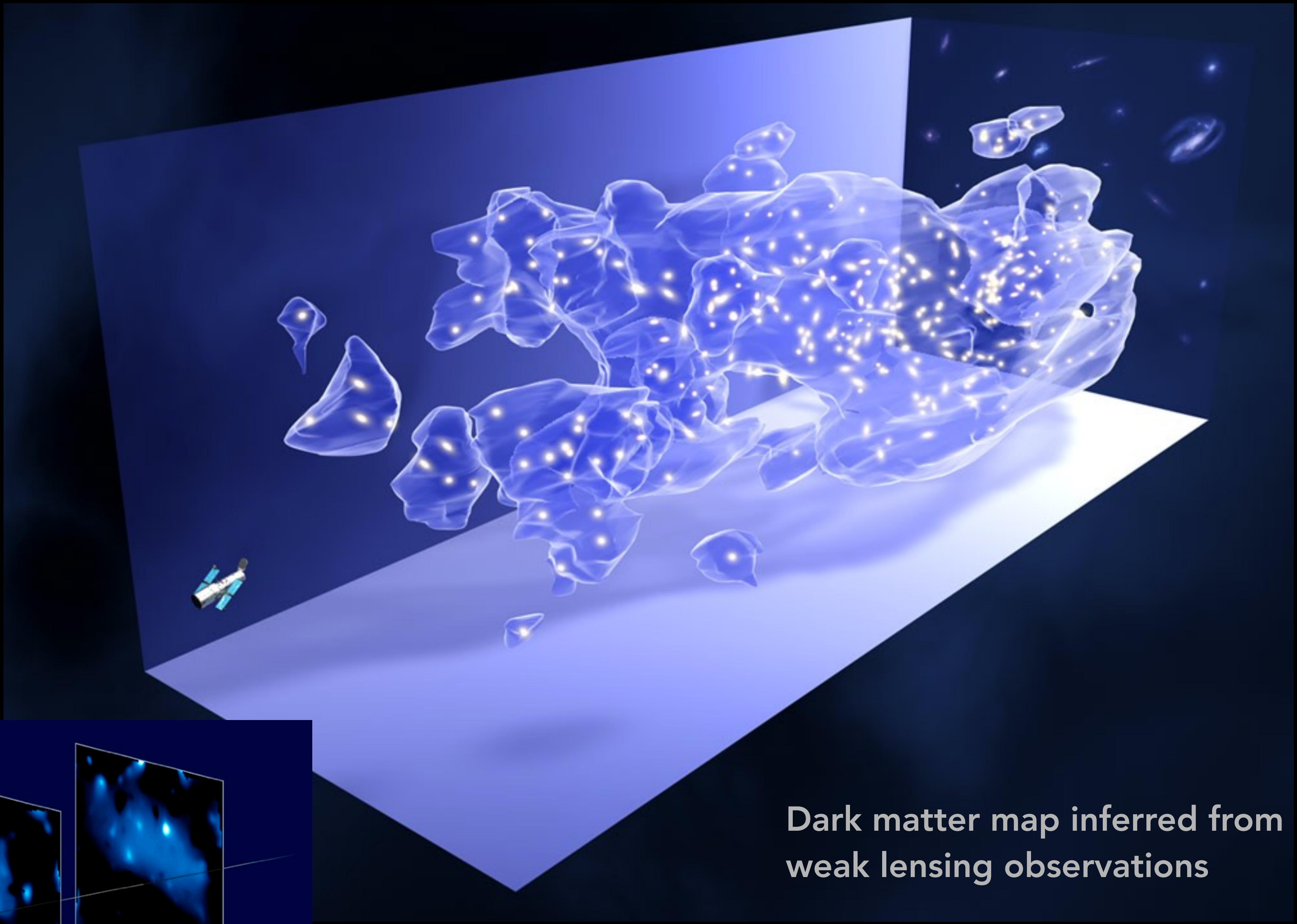
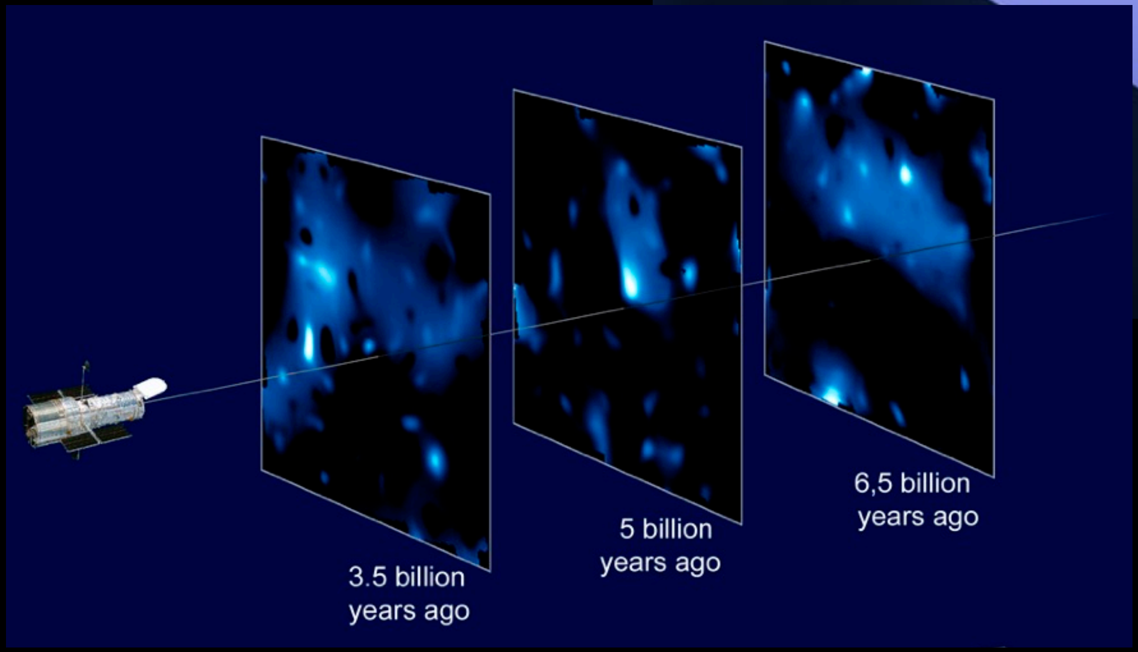


Image: Chieh-an Lin

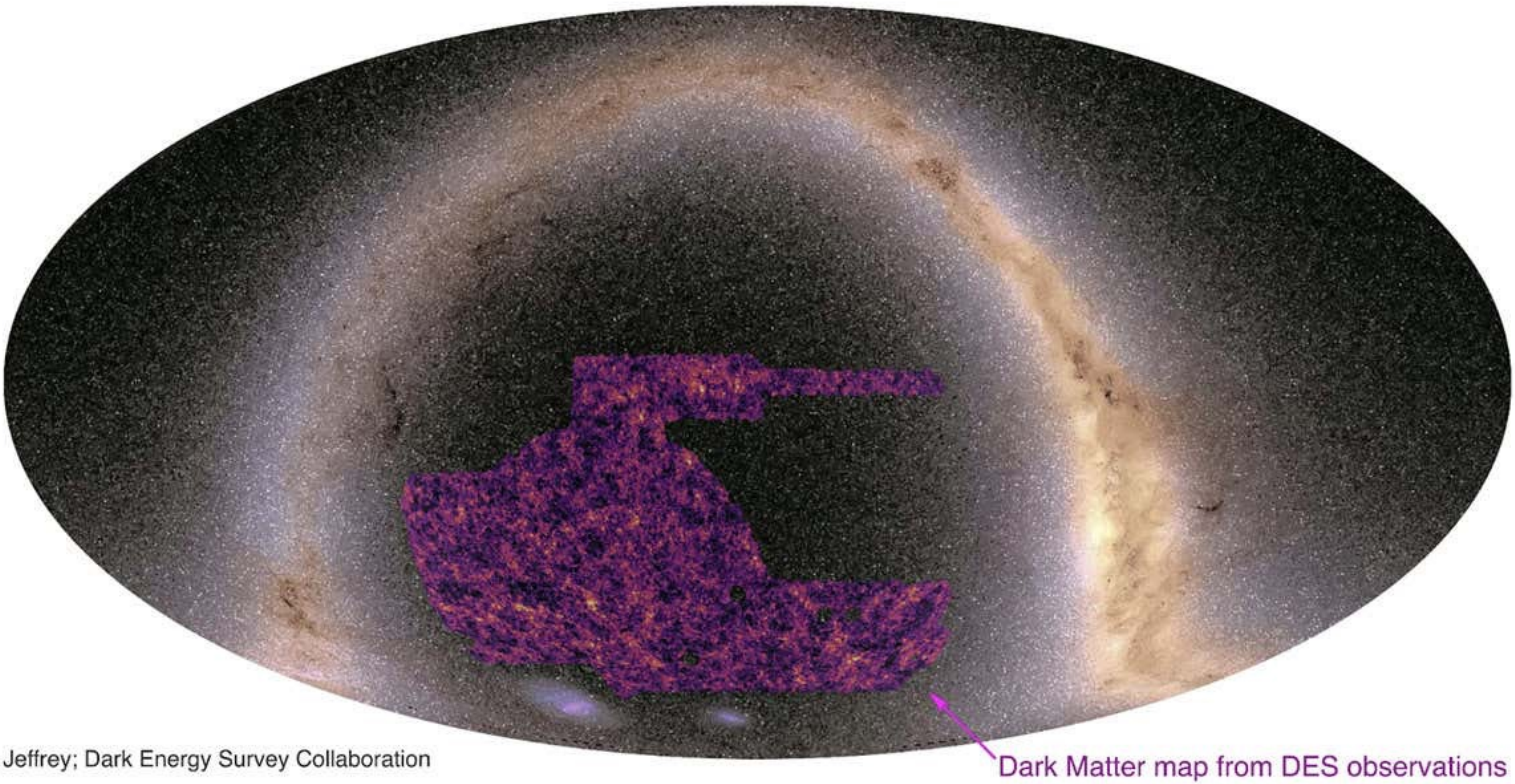
Weak lensing map of dark matter





NASA / ESA / R. Massey

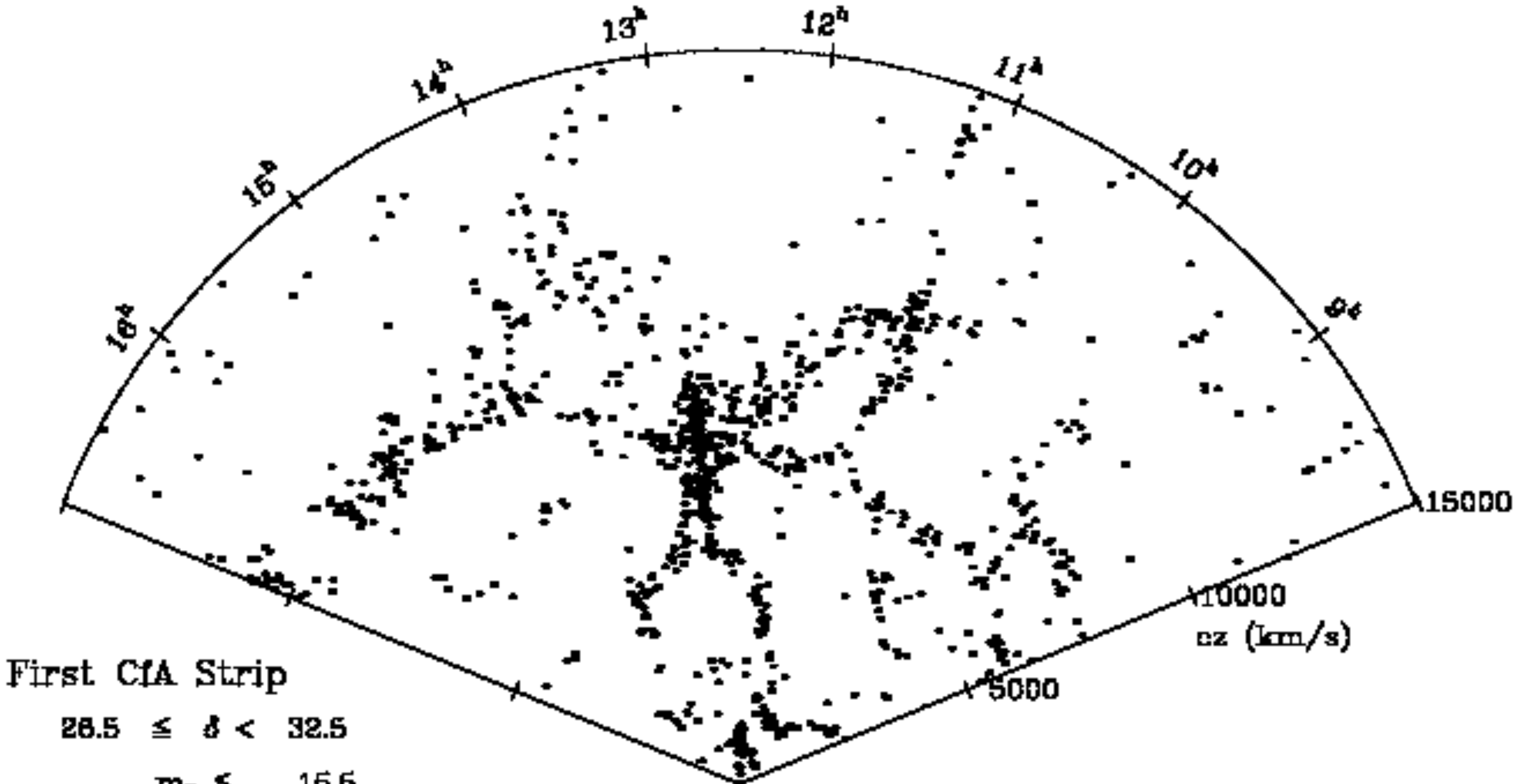
Weak lensing map of dark matter



N. Jeffrey; Dark Energy Survey Collaboration

Part 2: From dark matter to galaxies

Observational map of galaxies



CfA Redshift Survey • Huchra & Geller 1998

Participation: Galaxies

TurningPoint:
How many galaxies have we observed by now?

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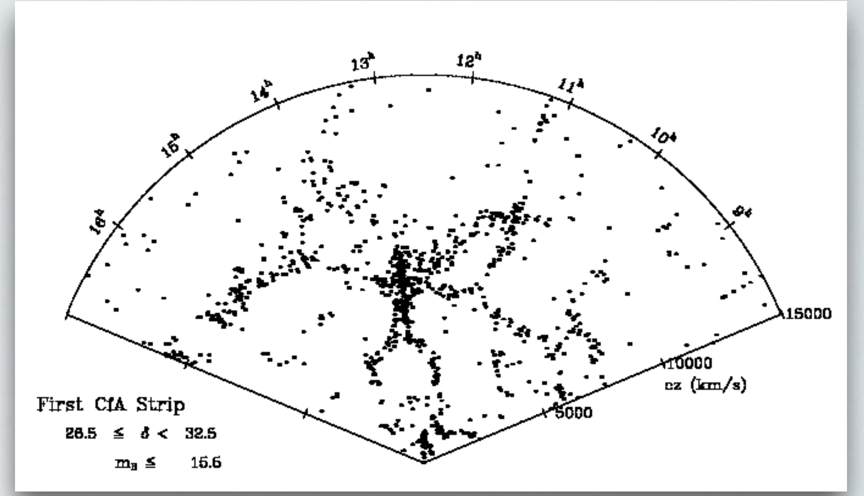
30 seconds

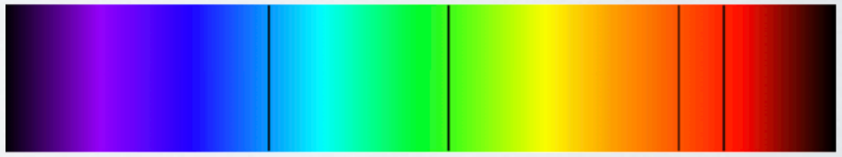
Observing galaxy structure: Sky surveys

- Photograph as much of the sky as possible
- Identify galaxies (rather than stars and other objects)
- This gives us two dimensions (polar coordinates); but how do we know how far away a galaxy is?
- Use redshift and use Hubble's law / a distance-redshift relation from cosmology
- Need to take a spectrum
- Random velocity adds or subtracts from motion due to cosmic expansion; true distance will differ somewhat



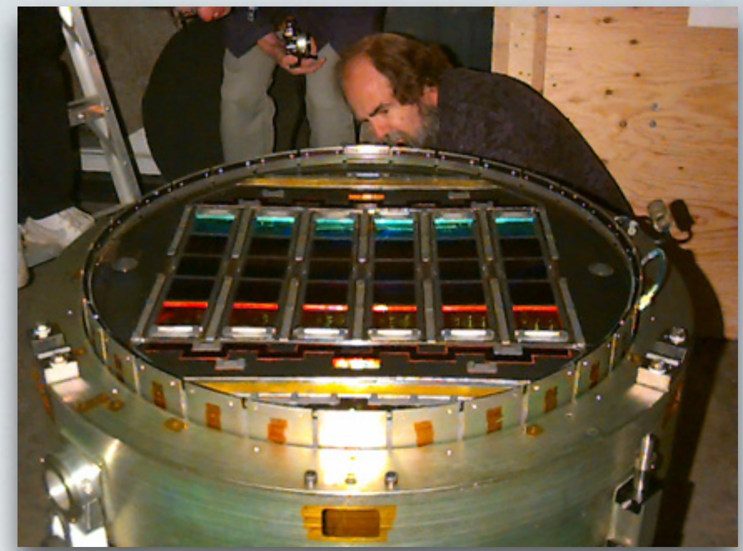
Spectrum observed in laboratory:

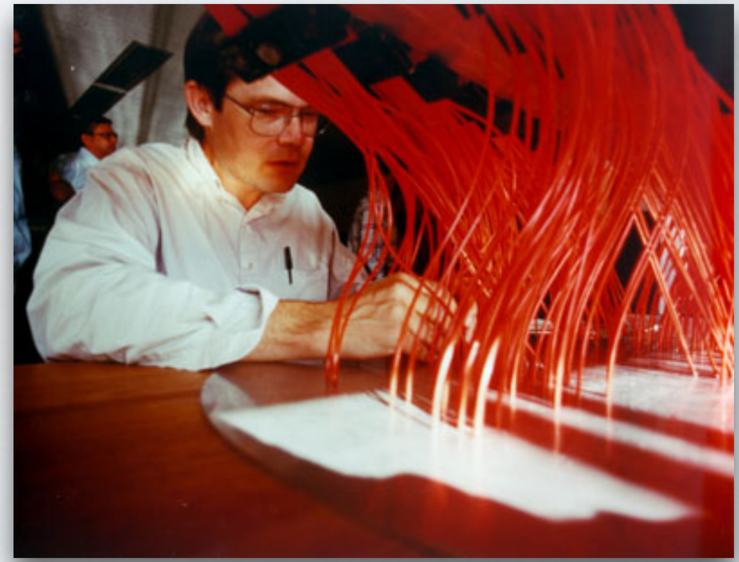
Galaxy spectrum (redshifted):



Sloan Digital Sky Survey (SDSS)

- Go to one of the darkest places in the US (in New Mexico)
- Photograph sky (with a powerful camera), identify galaxies
- Create metal plates with holes in the position where the galaxies are
- Place a spectrograph on each galaxy (with fibers)
- Measure spectrum for each galaxy
- Convert to redshift



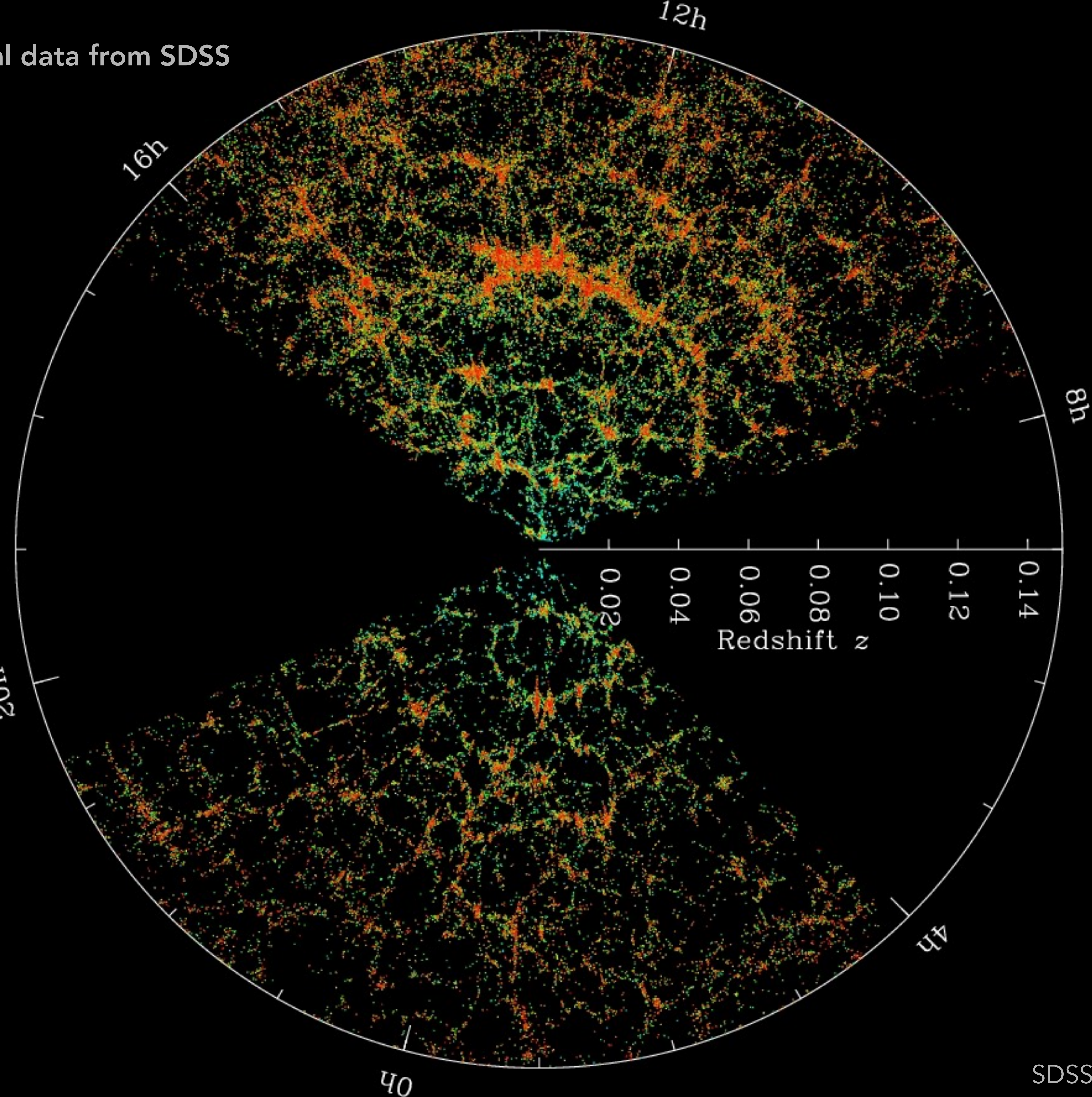


Images: SDSS Collaboration

SDSS Telescope Operations

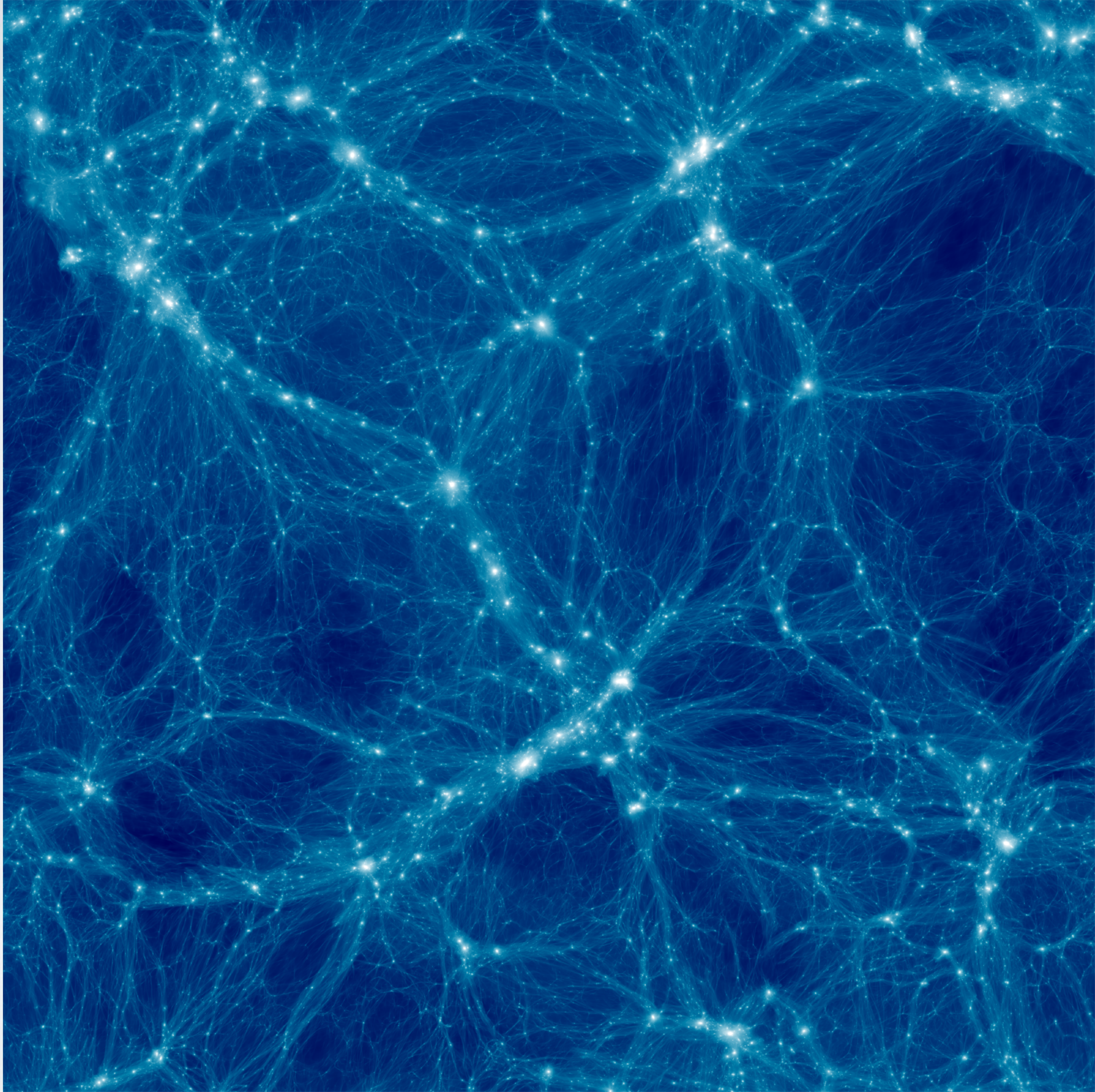
SDSS Collaboration

Observational data from SDSS



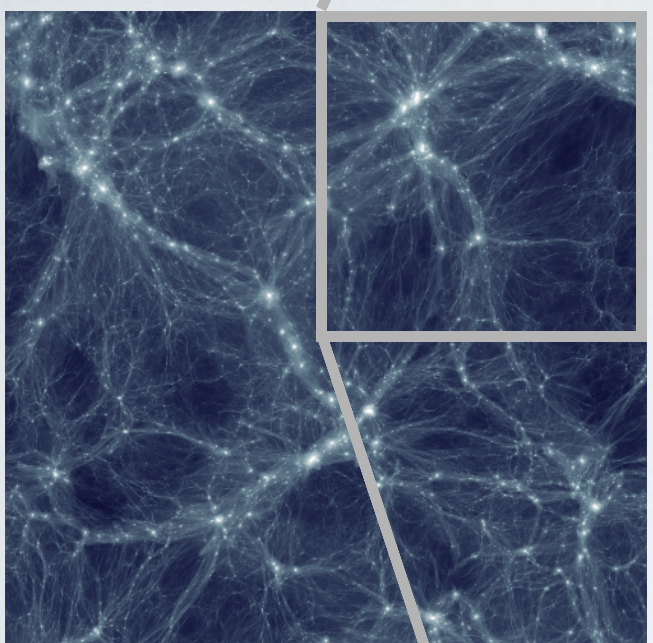
SDSS Collaboration

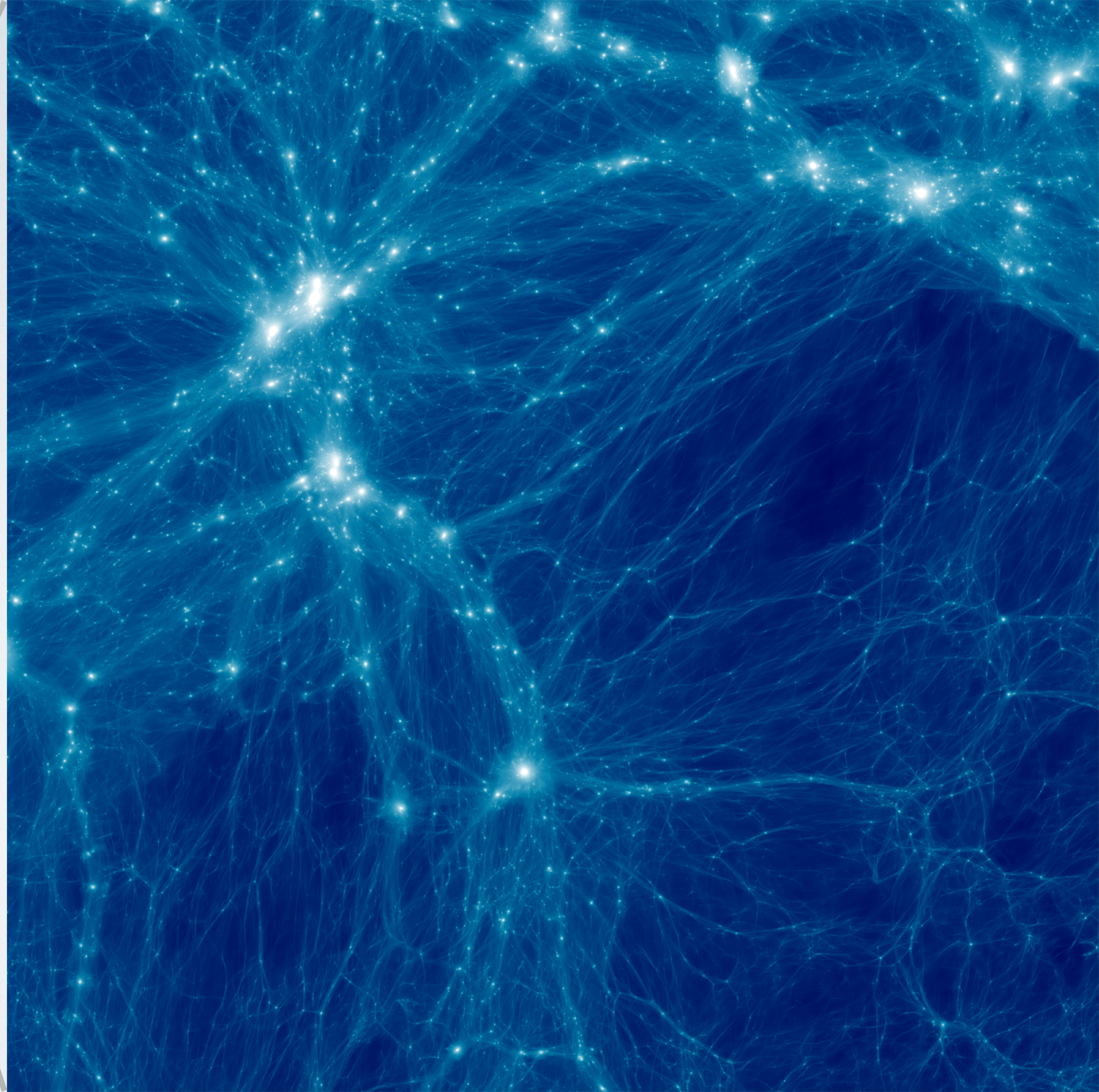
Dark matter simulation



Visualization code:
Phil Mansfield

Dark matter simulation





Visualization code:
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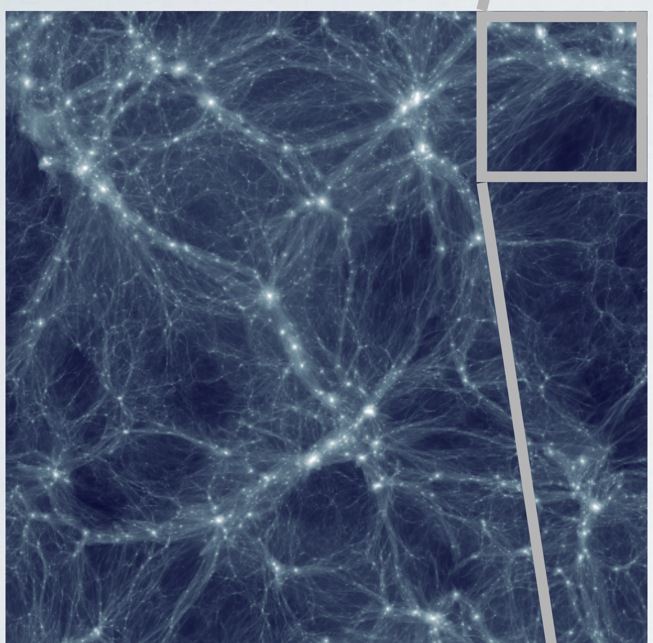
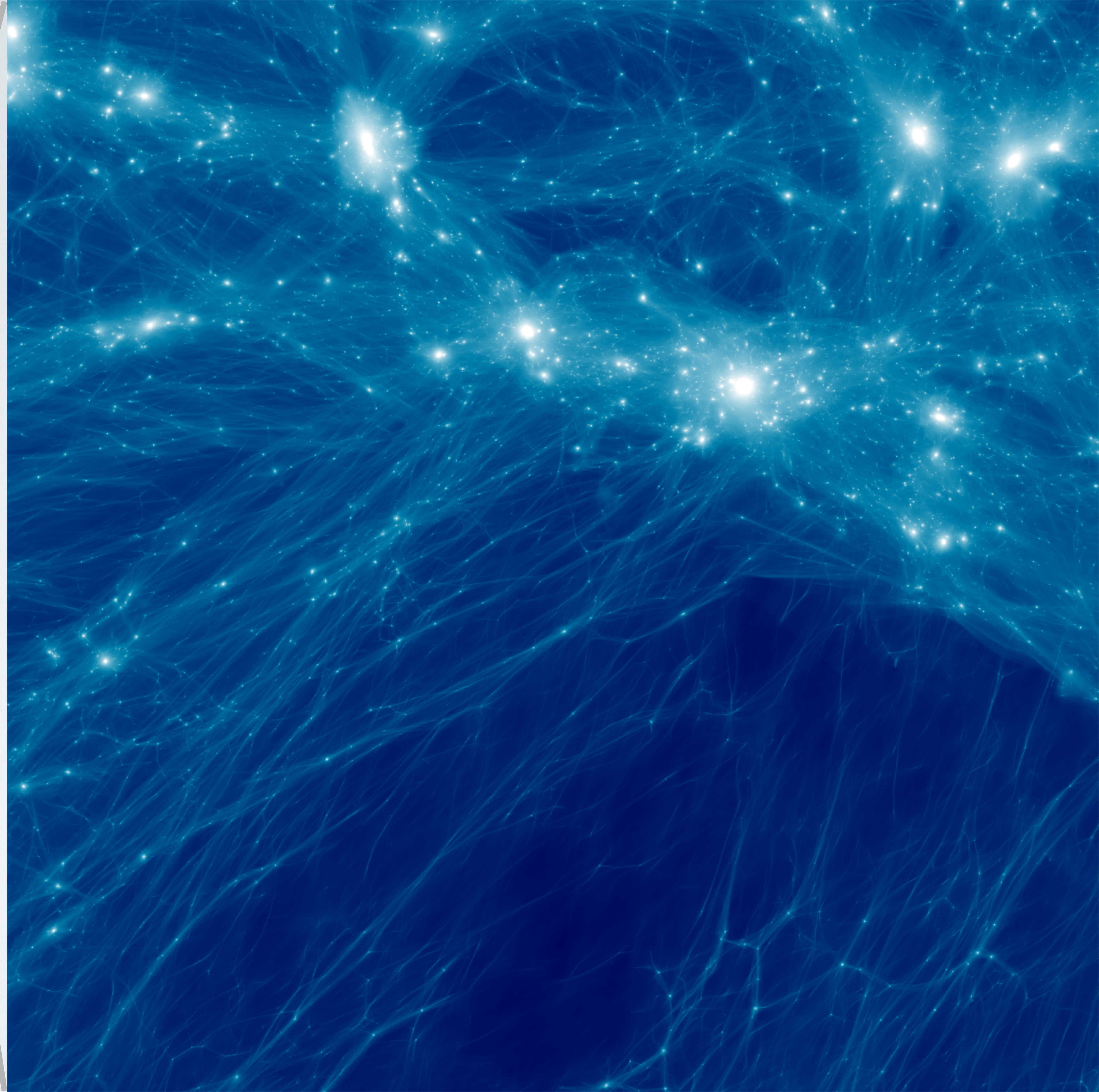
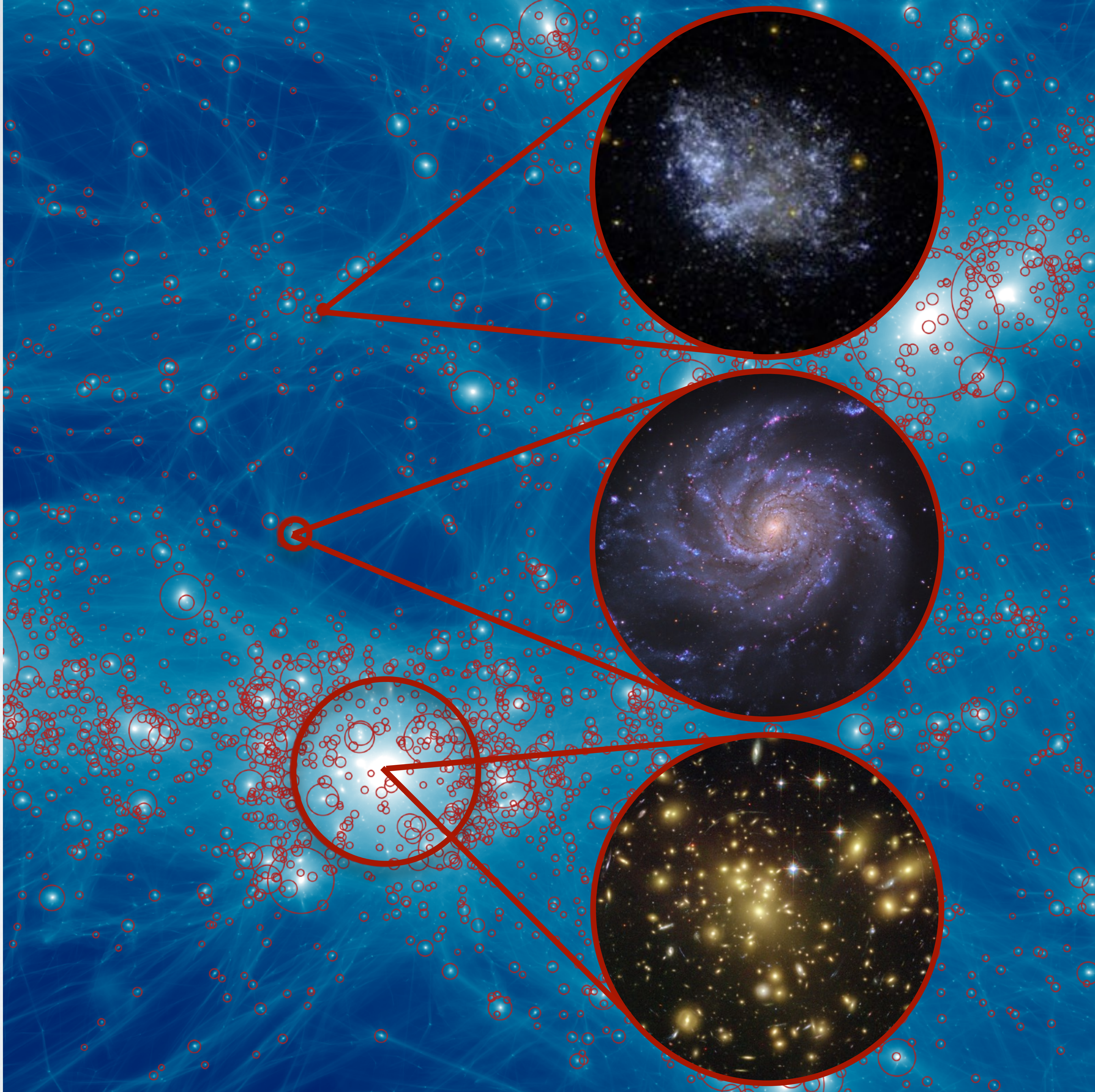
Dark matter simulation





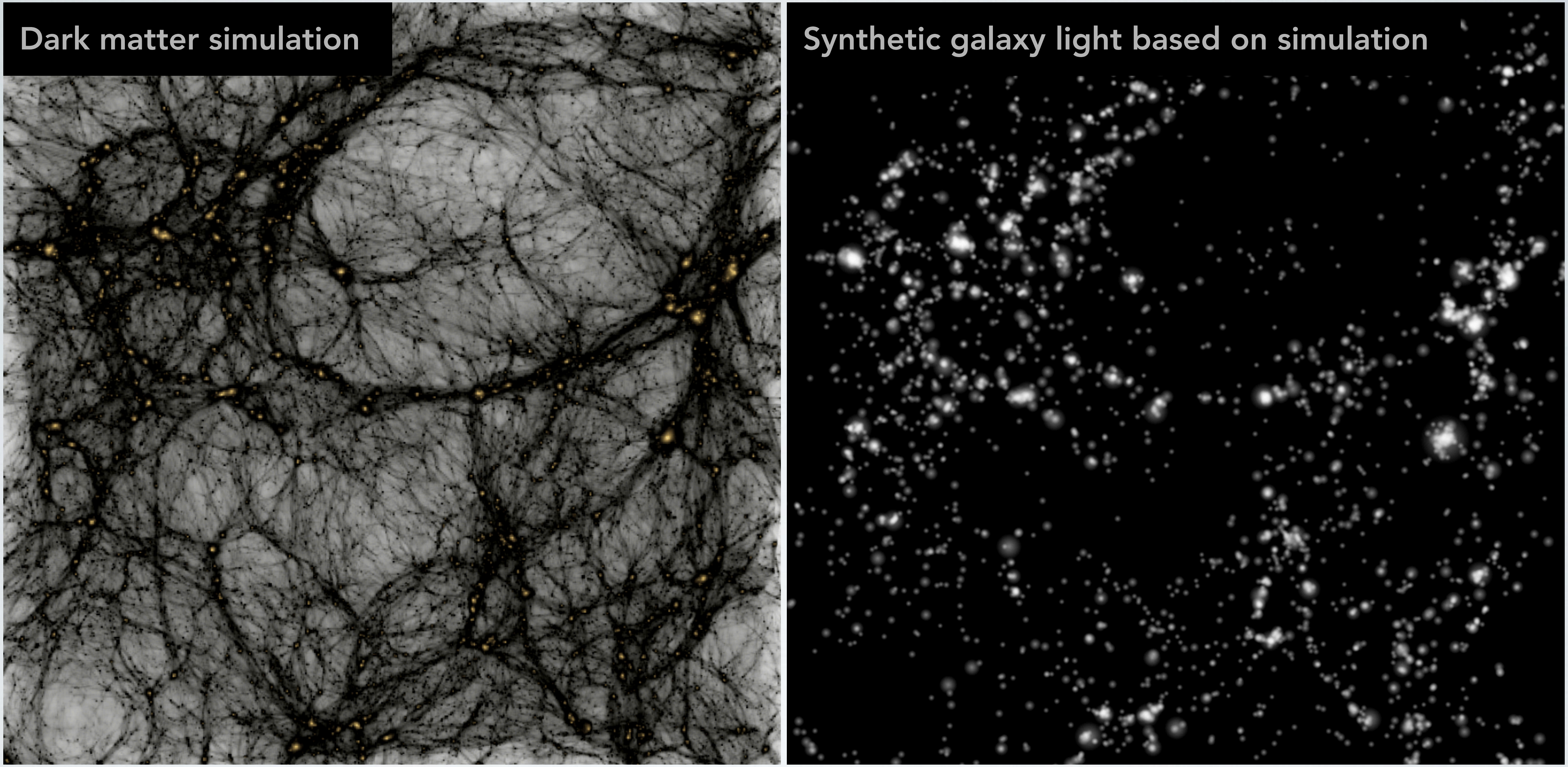
Visualization code:
Phil Mansfield

Dark matter simulation



Visualization code:
Phil Mansfield

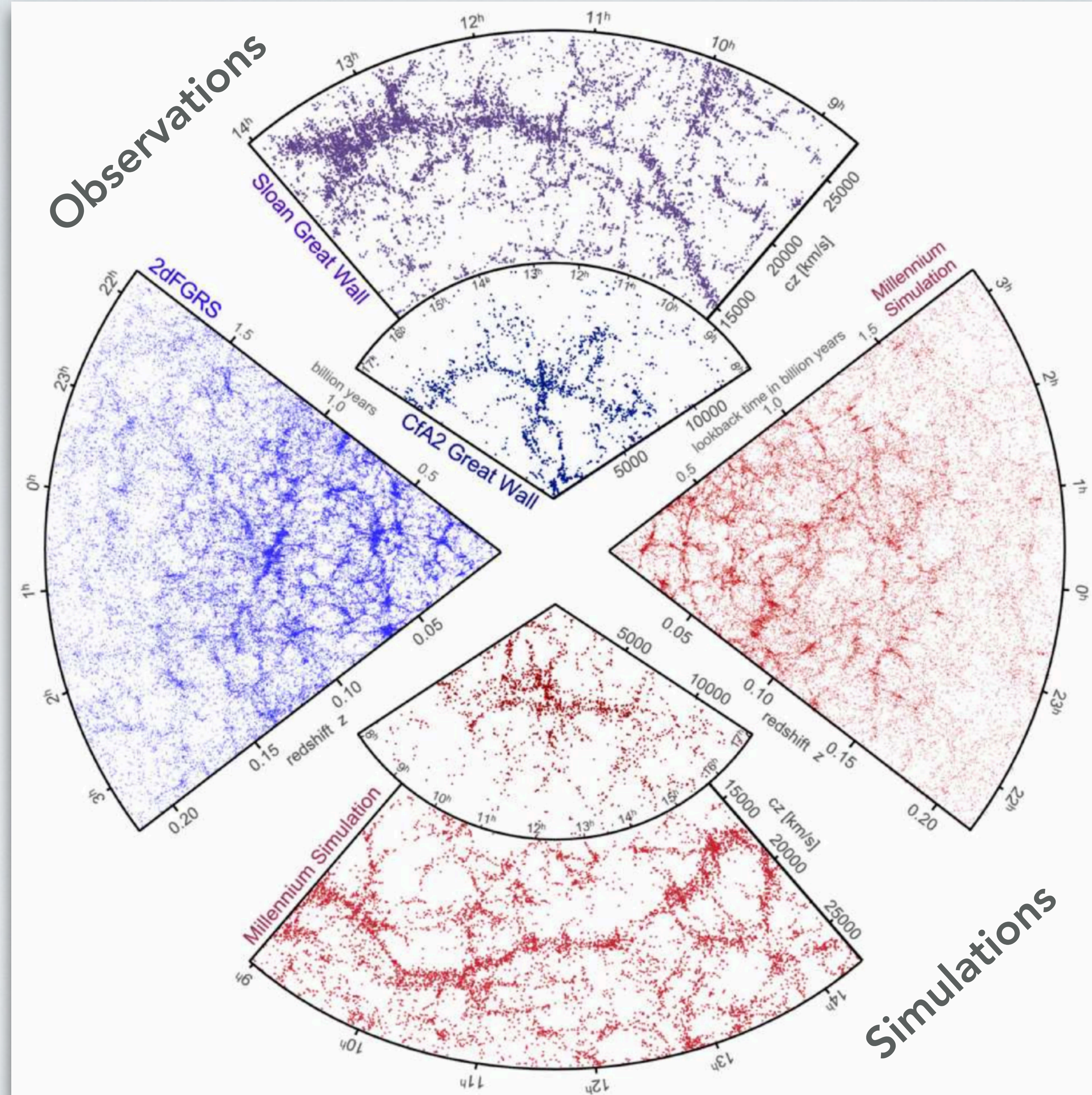
Galaxy-halo connection



- Simple recipe: **measure galaxy luminosities**, count how many galaxies are how luminous
- **Find halos** in simulation of cosmic web
- Assign **largest luminosity to biggest halo**, second-largest luminosity to second-biggest and so on
- Very simplistic! There are more complicated methods as well

Wechsler & Tinker 2018

Observations vs. simulations



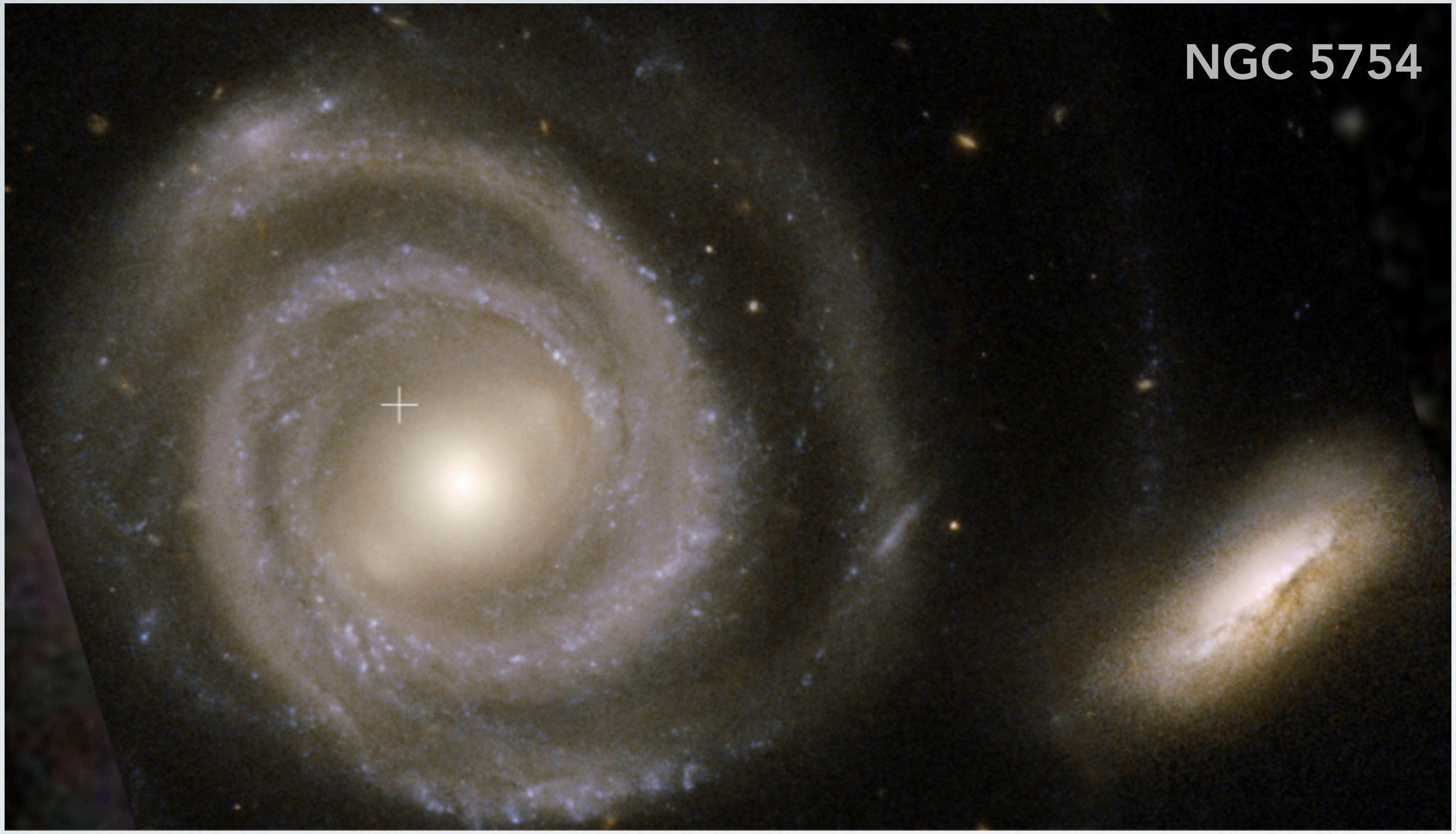
Springel et al. 2006

From dark matter to galaxies

- Simulations of dark matter + simple assumption of how galaxies populate halos
- Get prediction of statistics of galaxy structure
- Matches observations very well
- Means that the basic idea works:

Each galaxy lives at the center of a dark matter halo

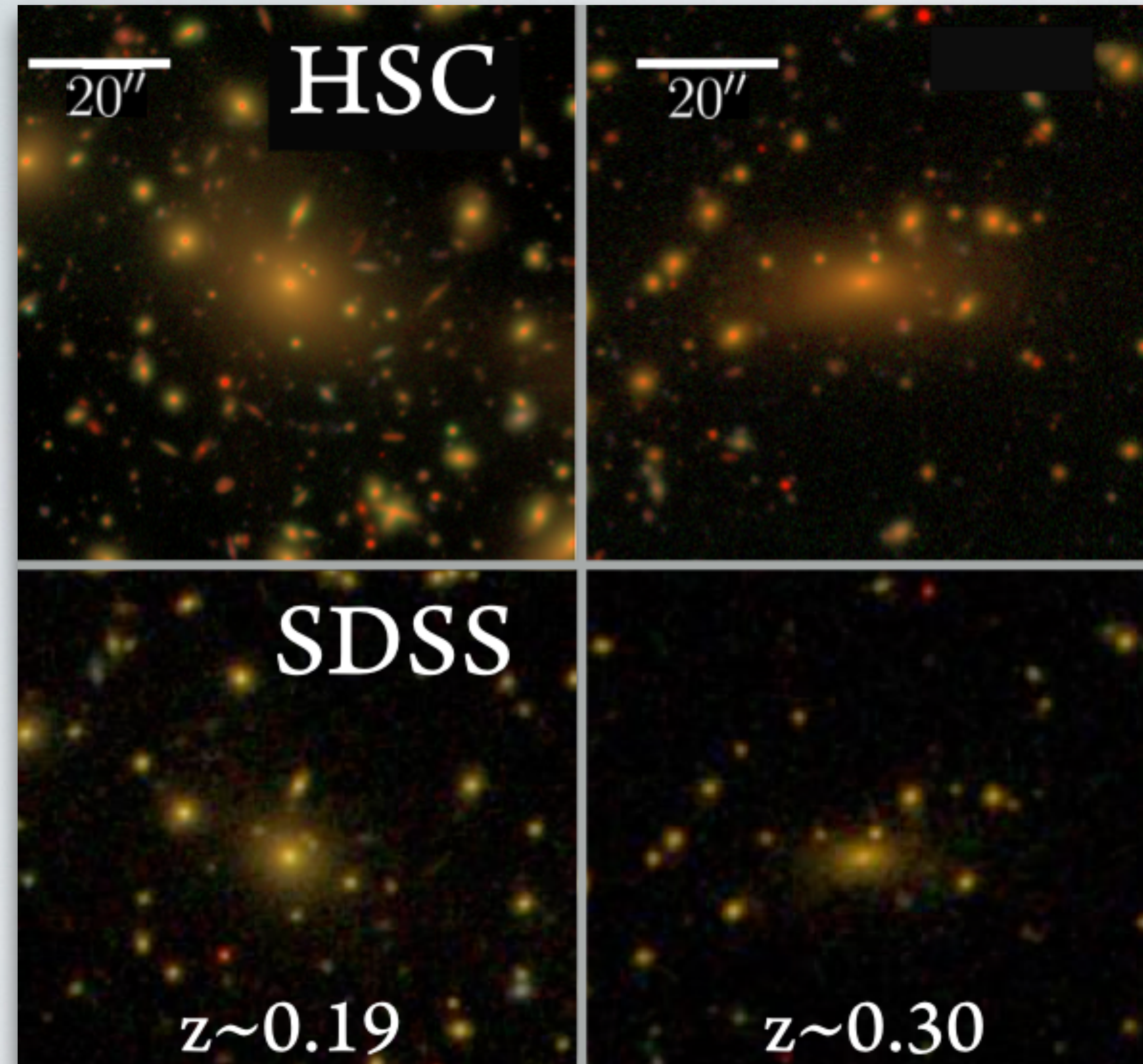
Demo: World Wide Telescope



Hubble Space Telescope

SDSS Survey

Newer surveys compared to SDSS



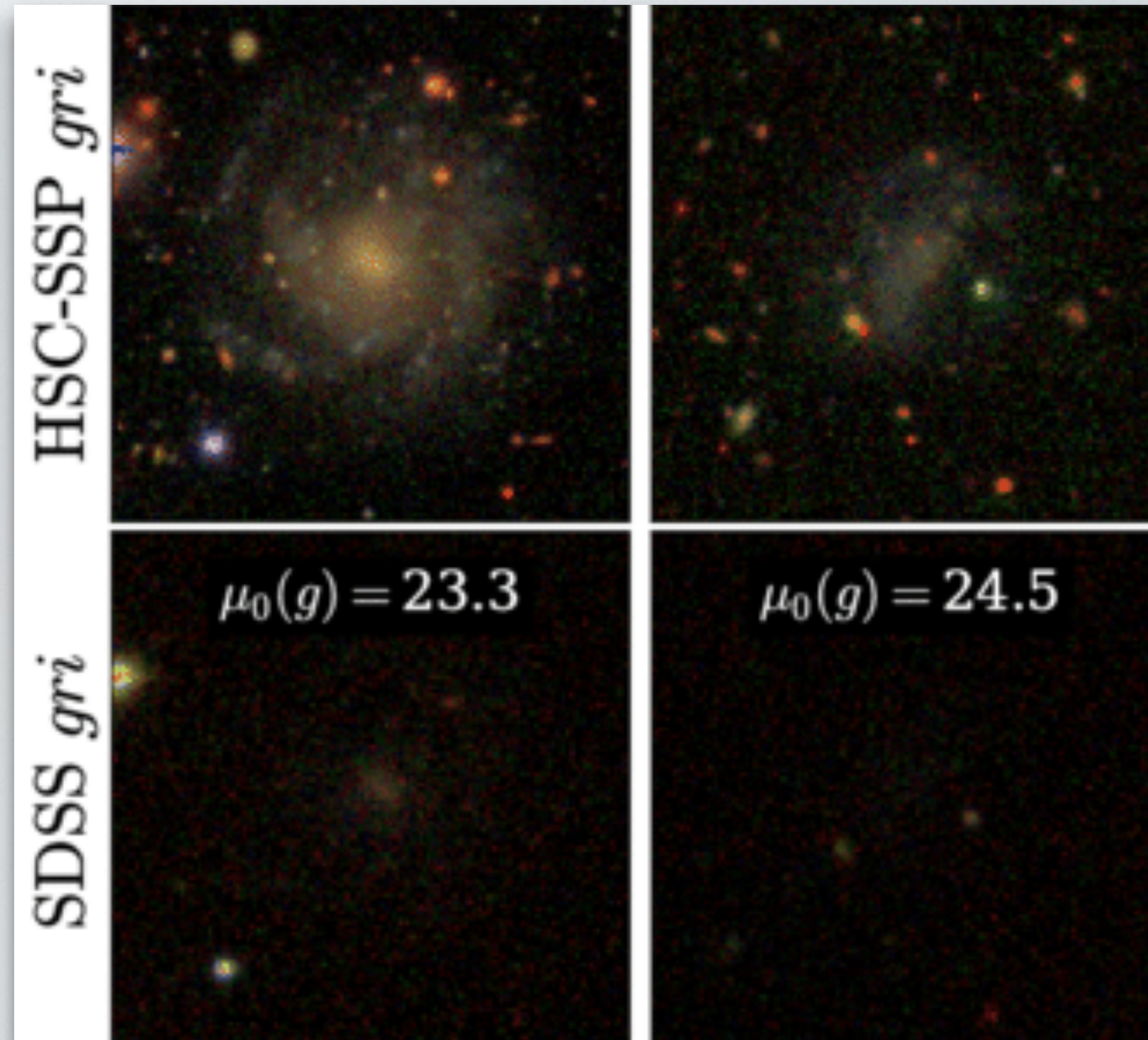
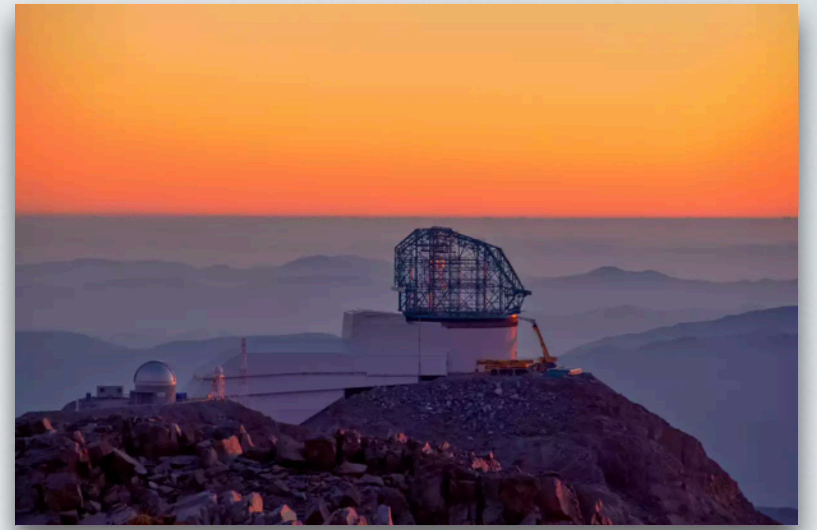
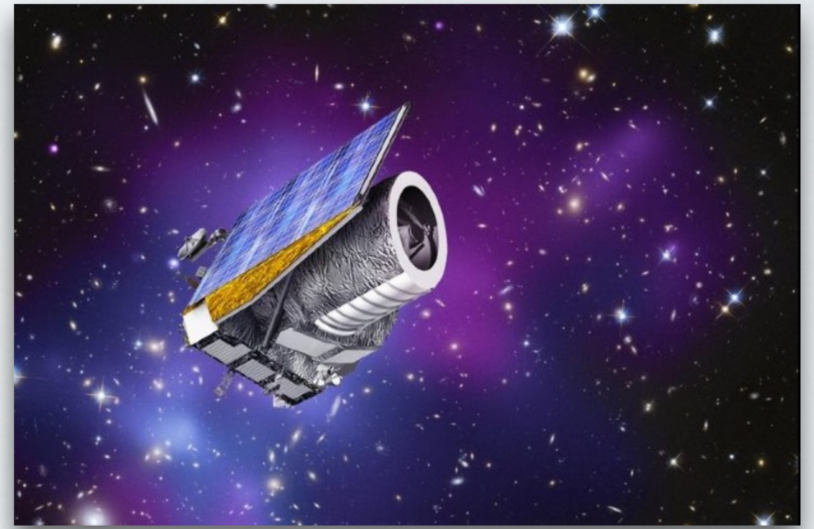


Image: Song Huang • Greco et al. 2017

Future surveys

- SDSS observed about 1 million galaxies
- Newest surveys have covered 300 million galaxies
- Vera Rubin Observatory
  - Will observe 20 billion galaxies
  - 20 TB / night
- Euclid Satellite (ESA)
  - 1 billion galaxies
  - To redshift ~2 (10 billion years ago!)





Part 3: Making stars

What happens when dark matter collapses?

- While collapsing, even cold dark matter acquires velocity
- Velocity means the dark matter cannot collapse into a point
- Halos cannot get rid of the dark matter’s velocity (or kinetic energy) and thus stay extended instead of collapsing further

Participation: Gas vs. dark matter

TurningPoint:
What quantity is relevant for gas but not for dark matter?

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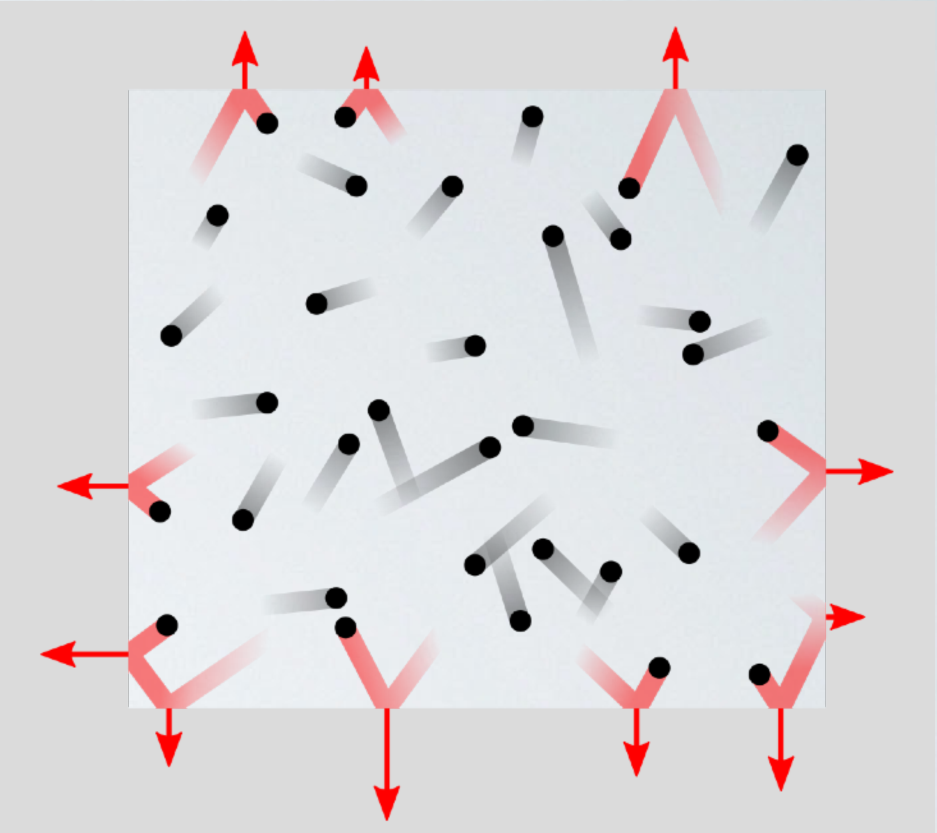
30 seconds

What happens when gas collapses?



- **Pressure** prevents gas from collapsing to a point mass
- Ideal gas law: **pressure is proportional to density times temperature**

Ideal gas law:

$$P = N_A k_B \, \rho T$$

$N_A = 6.0 \times 10^{23}/\mathrm{mol}$ Avogadro Number

$k_B = 1.38 \times 10^{-16} \frac{\mathrm{erg}}{K}$ Boltzmann constant

The Jeans Mass

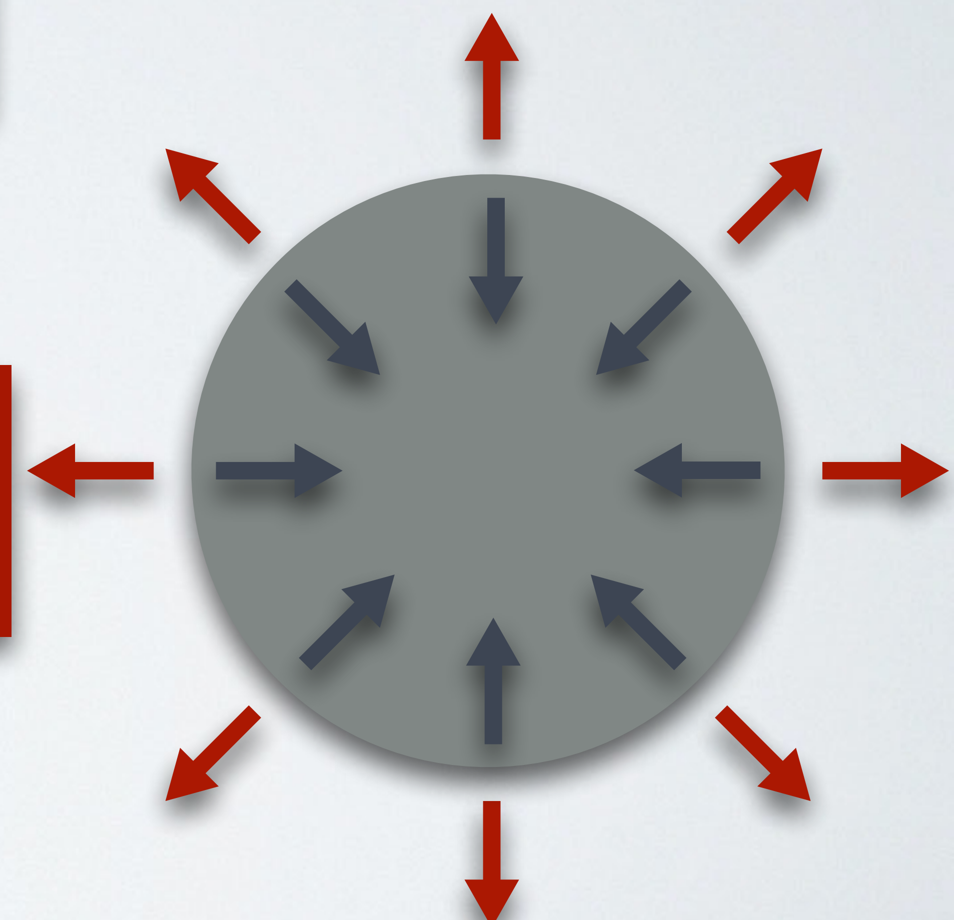

Sir James Hopwood Jeans

- Gravity tries to collapse gas
- Pressure resists collapse
- Gravity wins if cloud is larger than Jeans length, or has mass larger than Jeans mass

$$L_J = \sqrt{\frac{5\pi}{3}\frac{k_B T}{G\ m_p\ \rho}} \qquad = 8.0 \times 10^7\ \mathrm{cm} \left(\frac{T}{K}\right)^{1/2} \left(\frac{\rho}{\mathrm{g/cm^3}}\right)^{-1/2}$$

$$M_J = \frac{4\pi}{3}\left(\frac{L_J}{2}\right)^3 \rho \implies$$

$$M_J = \frac{\pi^{5/2}}{6}\left(\frac{5k_B T}{3Gm_p}\right)^{3/2} \rho^{-1/2} = 2.7 \times 10^{23}\ \mathrm{g} \left(\frac{T}{K}\right)^{3/2} \left(\frac{\rho}{\mathrm{g/cm^3}}\right)^{-1/2}$$



$\rho,\ T$	Gas density, temperature
$k_B = 1.38 \times 10^{-16} \frac{\mathrm{erg}}{K}$	Boltzmann constant
$m_p = 1.67 \times 10^{-24}\ \mathrm{g}$	Proton mass

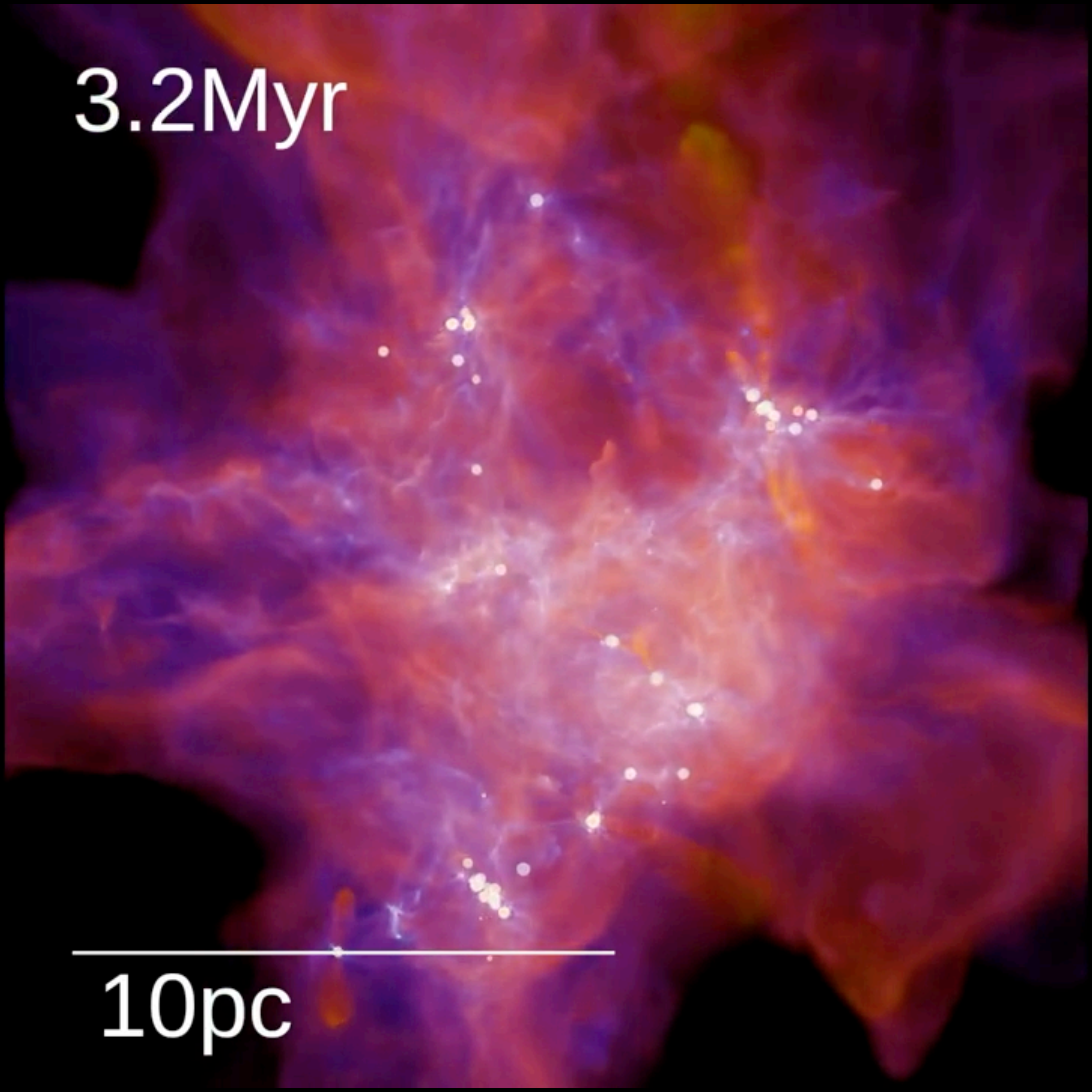
Pressure vs. **Gravity**

What happens when gas collapses?

- In the Universe as a whole, we can work out the Jeans mass of gas right after recombination: $M_{\mathrm{J,recombination}} \approx 10^6 M_\odot$
- To further collapse, the **gas must cool**
- Galaxies cool by **emitting radiation** from the gas
- But most of the gas in galaxies remains relatively hot, about 10,000 K
- Some gas cools further to make **denser clouds that collapse to stars**

$$M_\mathrm{J} = \frac{\pi^{5/2}}{6}\left(\frac{5k_\mathrm{B}T}{3Gm_\mathrm{p}}\right)^{3/2}\rho^{-1/2}$$

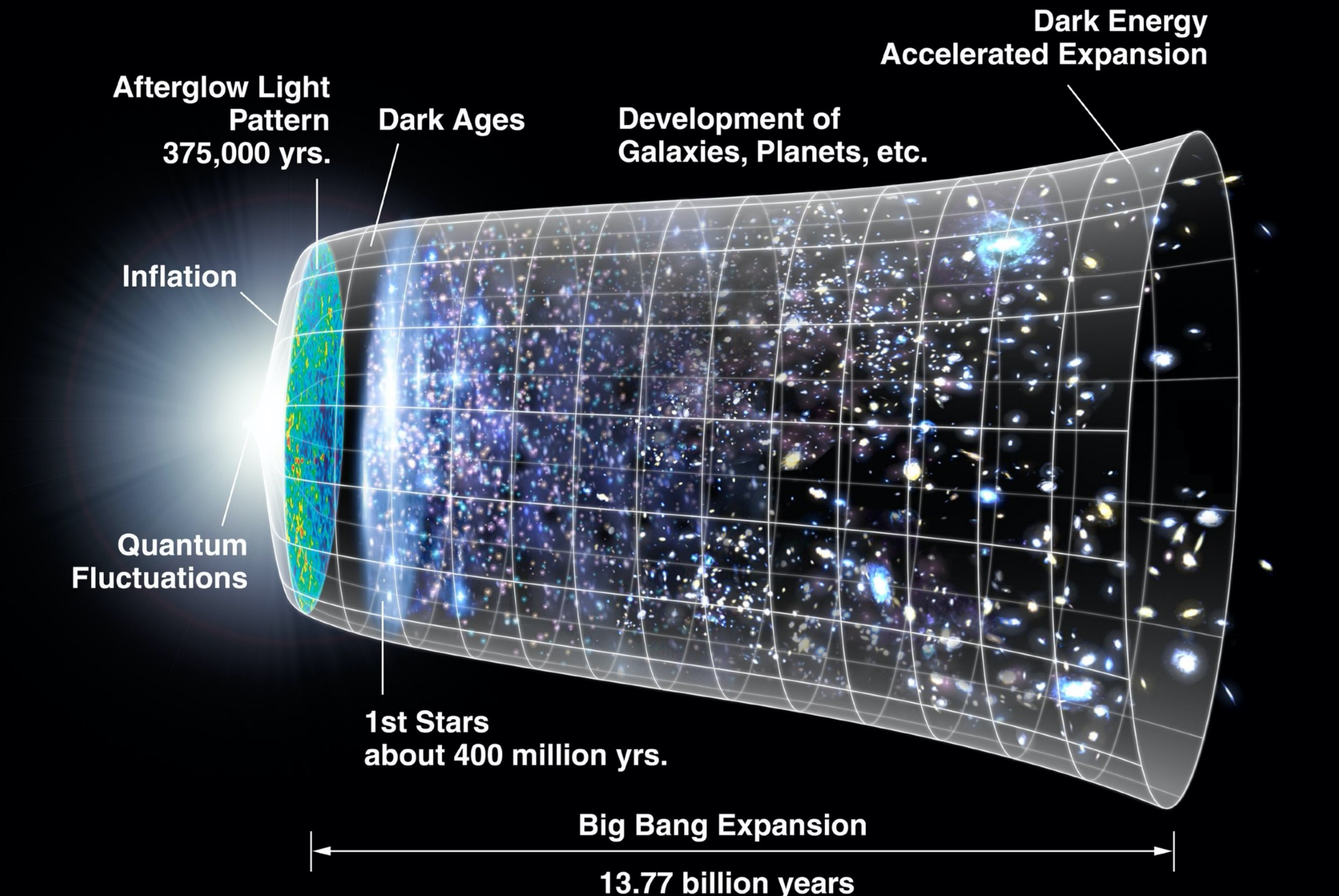
Star formation simulation



STARFORGE Collaboration

Part 4: The end of the dark ages

History of the Universe



NASA / WMAP

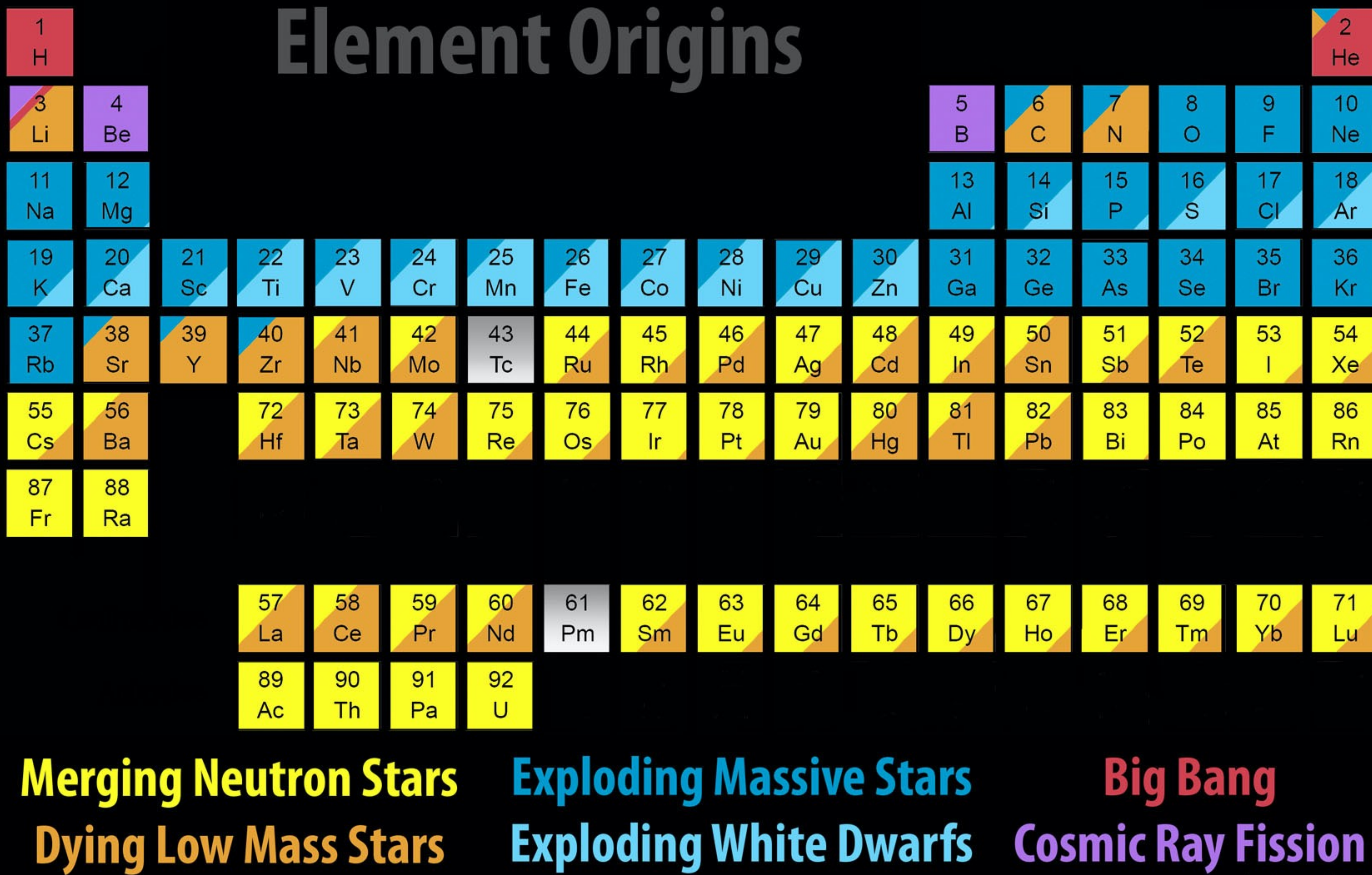
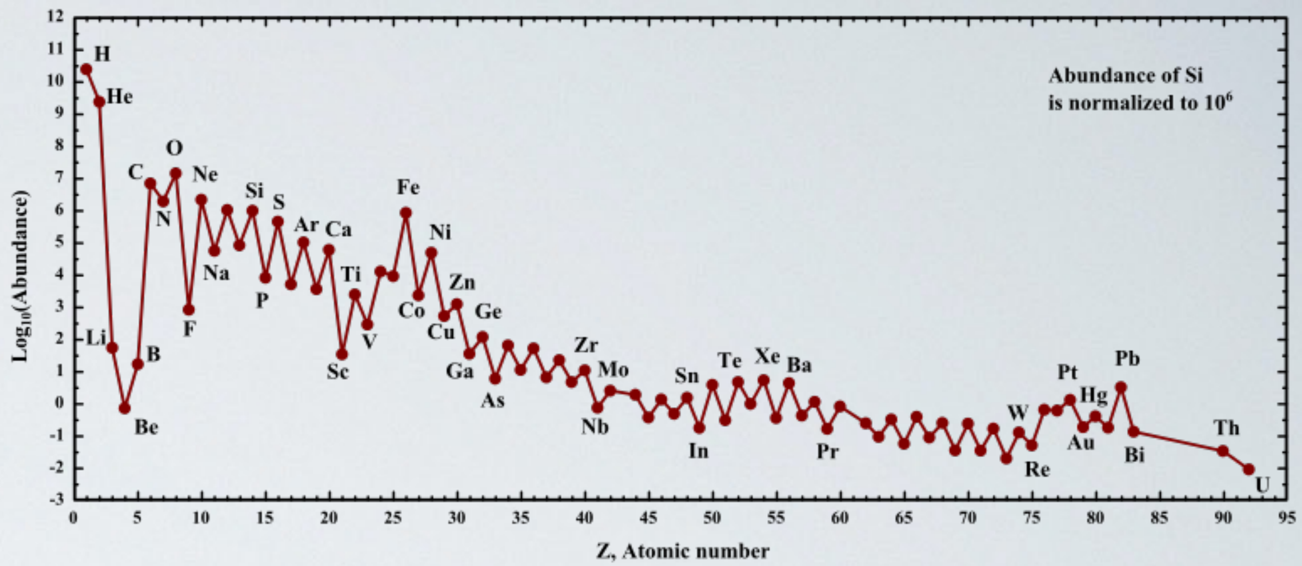


Image: Jennifer Johnson

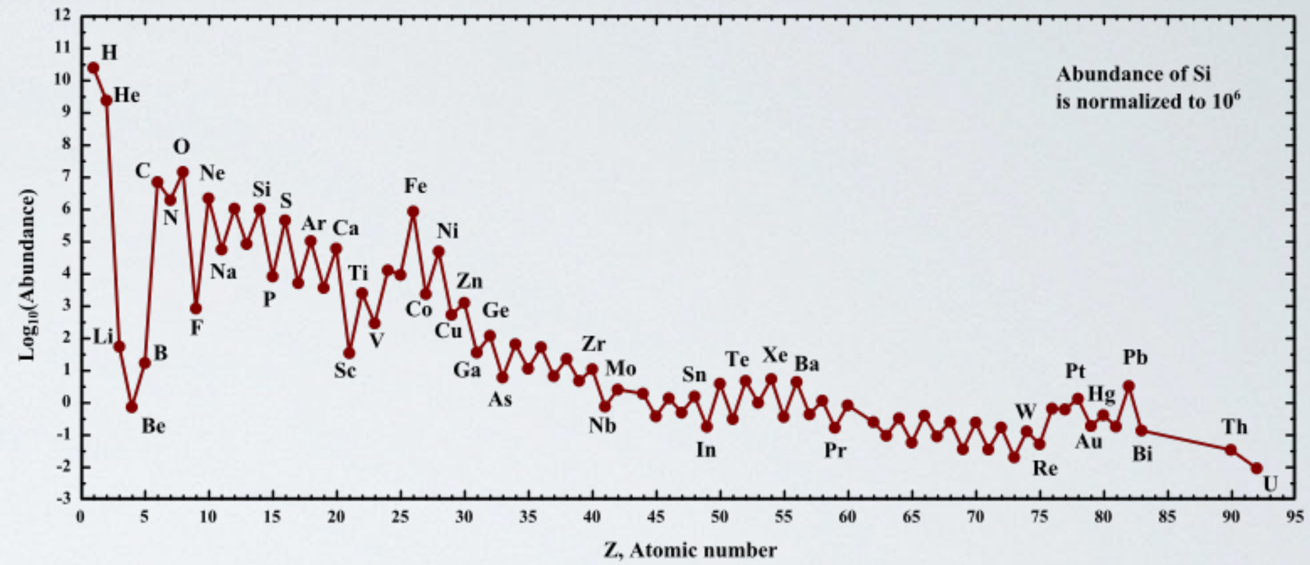
Stellar populations



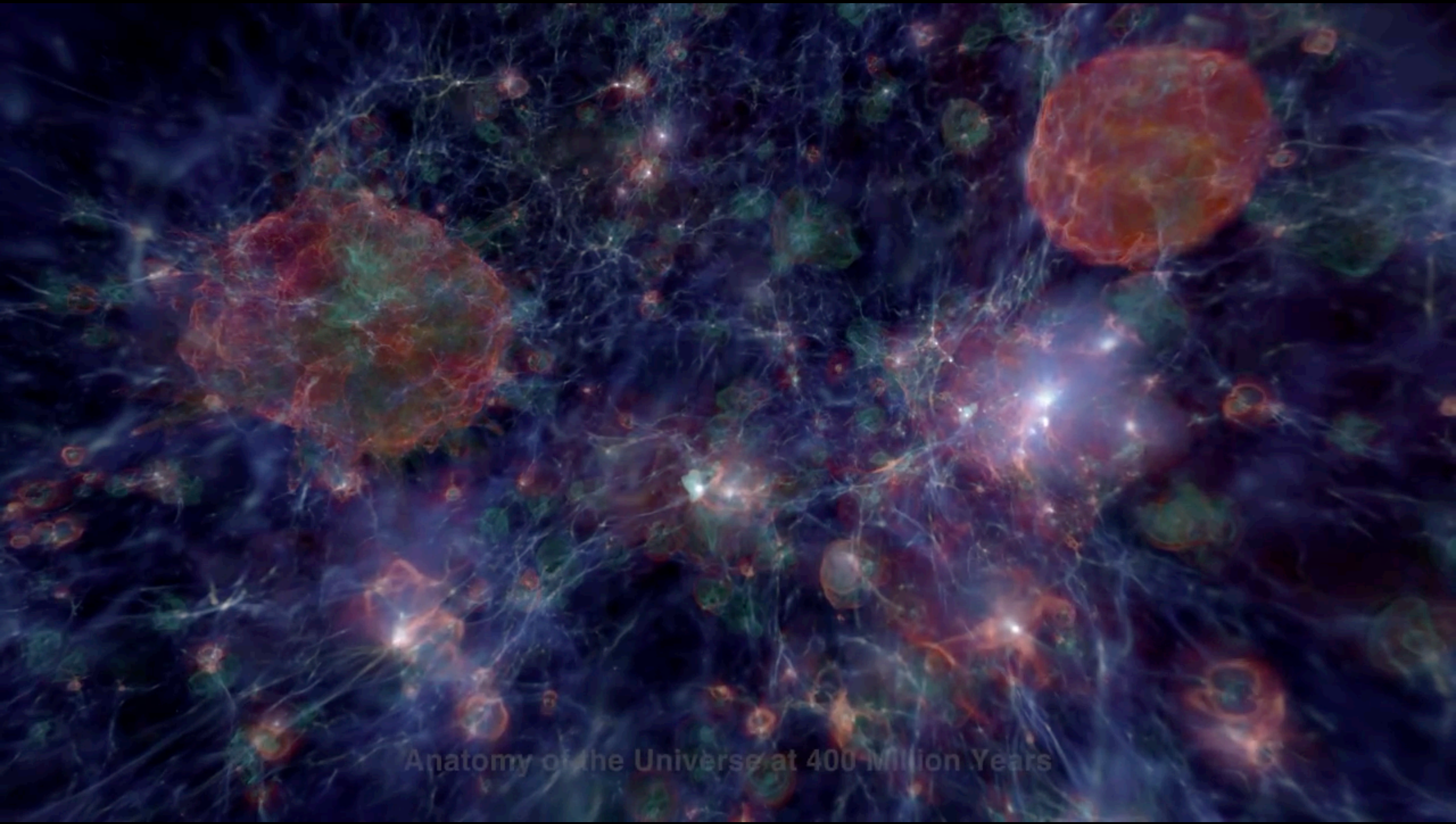
- **Pop I stars**
  - Normal stars like the Sun (composed by 2%-3% “metals” by mass)
- **Pop II stars**
  - Old, very deficient in heavy elements (about 0.1% metals by mass)
  - Found in the globular clusters, galactic bulge, galactic halo
- **Pop III stars**
  - The first stars with no metals
  - The compositionis set by Big Bang Nucleosynthesis:
    H, He, Li (with traces of B and Be)
  - Were likely very massive and extremely bright
  - Very short-lived (explode as Supernovae)
  - Reason: gas clouds without metals cannot cool efficiently,
    so have to be very massive to collapse in the first place
  - Could be seeds for supermassive black holes?

Oldest observed star

- Record holder:
  SMSS J031300.36−670839.3
- 13.6 billion years old
- Metallicity < -7, meaning 10 million times less iron than in Sun!
- Often found in globular clusters



First galaxies lighting up the Universe (simulation)



Simulation by M. Norman et al.

Reionization

- Gas is neutral (atoms) after recombination at z~1100
- Massive stars produce ultraviolet radiation
- Radiation will escape from galaxies and reionizes the hydrogen/helium gas in the Universe

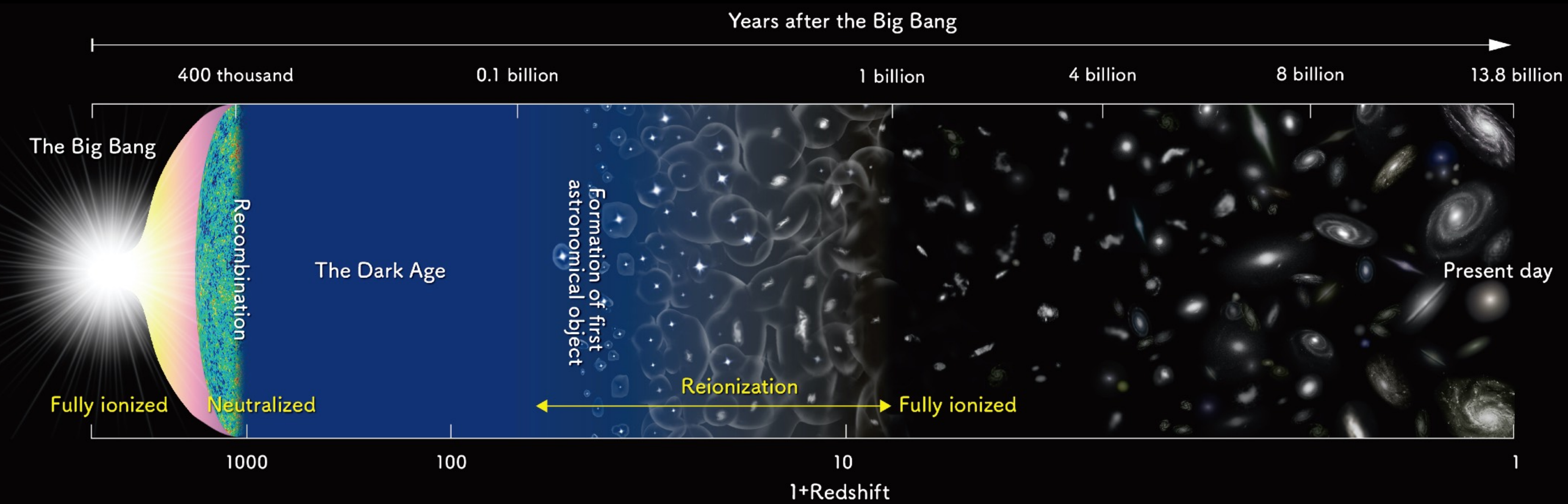
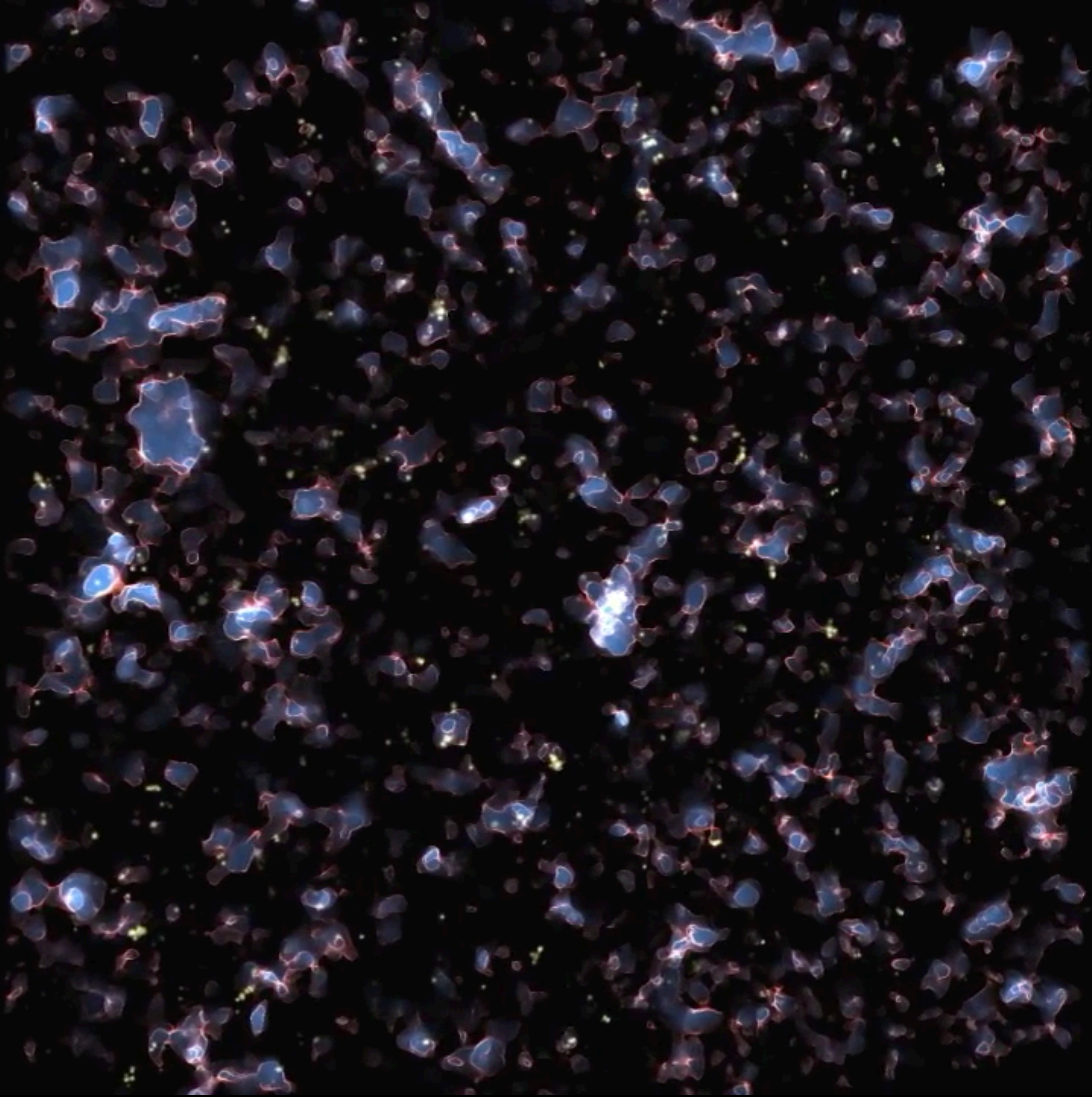


Image: NAOJ


M. Alvarez, R. Kaehler, T. Abel

Participation: Highest-z galaxy

TurningPoint:
How far back can we see galaxies (measured in years since the Big Bang)?

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30 seconds

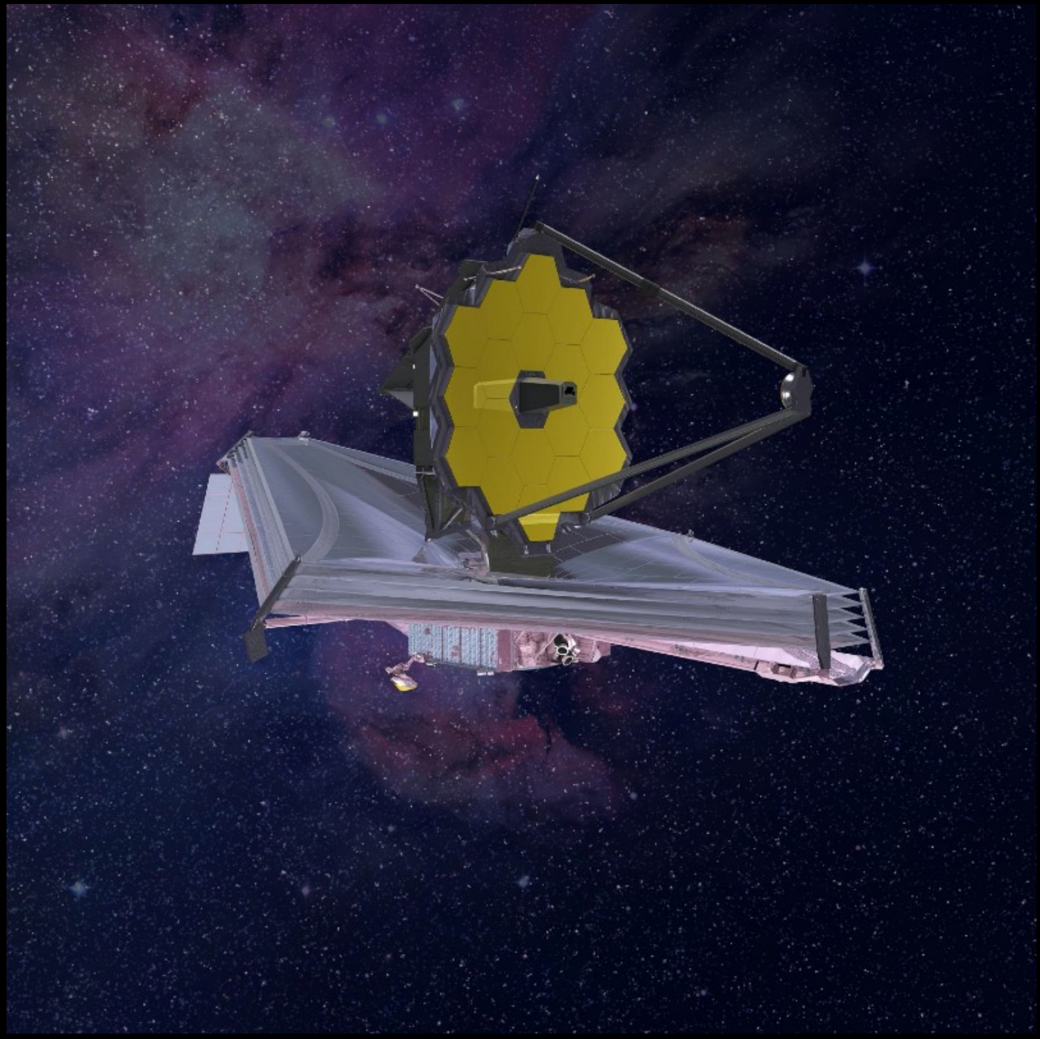
Highest redshift galaxy

- GN-z11, observed with Hubble Space Telescope
- Redshift ~11 (400 million years after Big Bang)

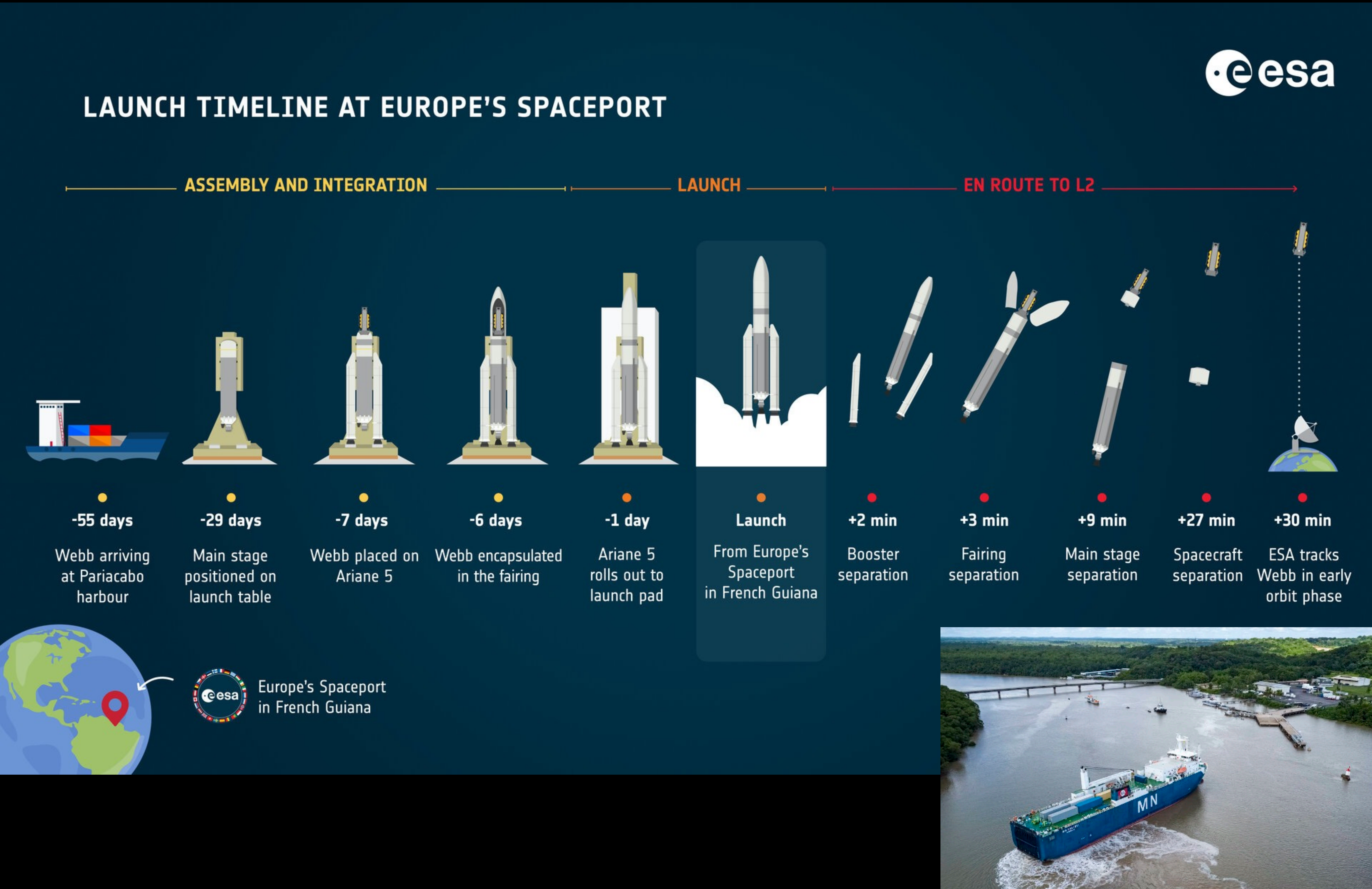
NASA / HST

James Webb Space Telescope

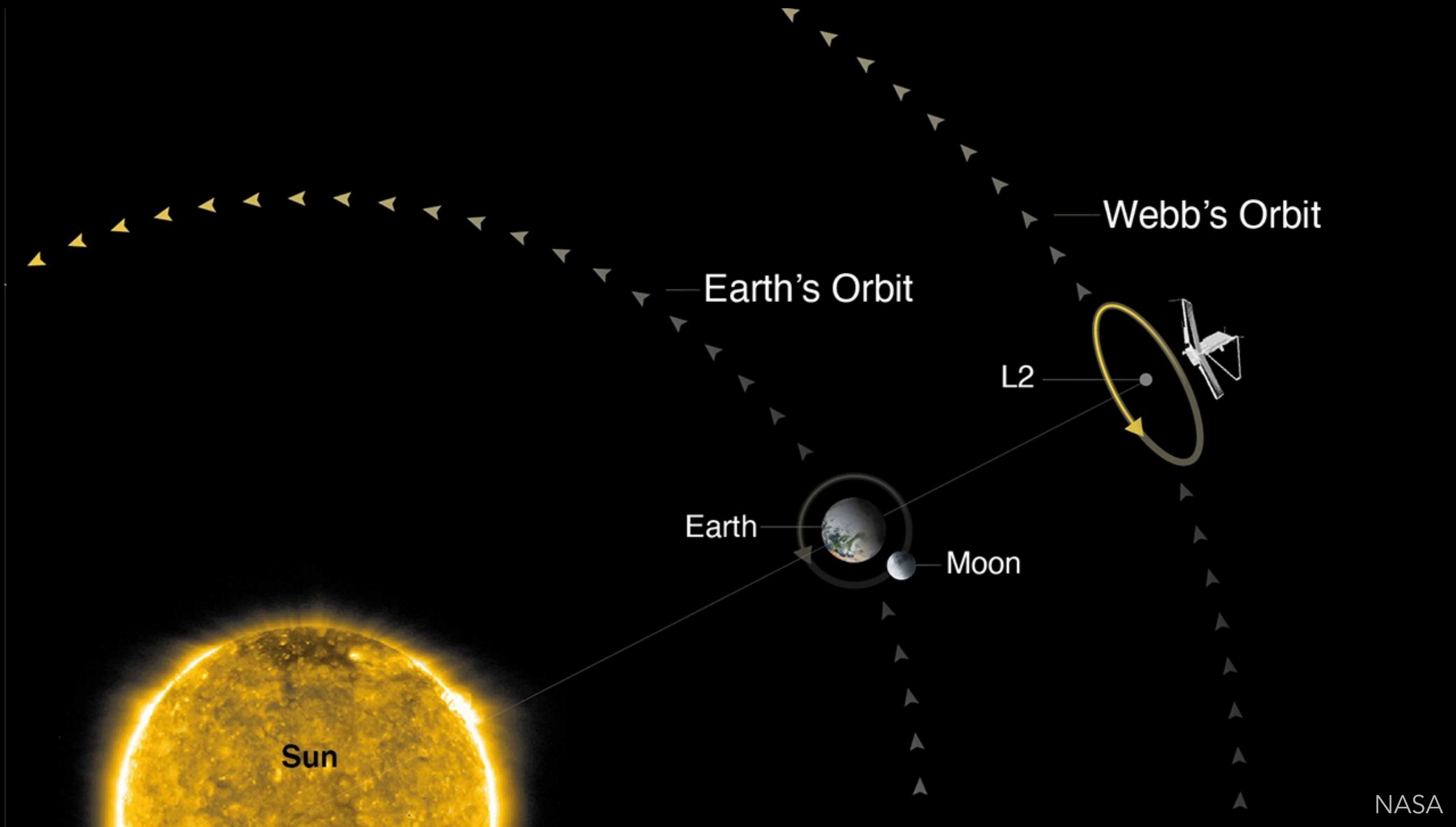
- James Webb Space Telescope (JWST) will be high-resolution infrared telescope in space
- Cost: $11 billion (oops!)
- Will perhaps see the first galaxies?



James Webb Space Telescope

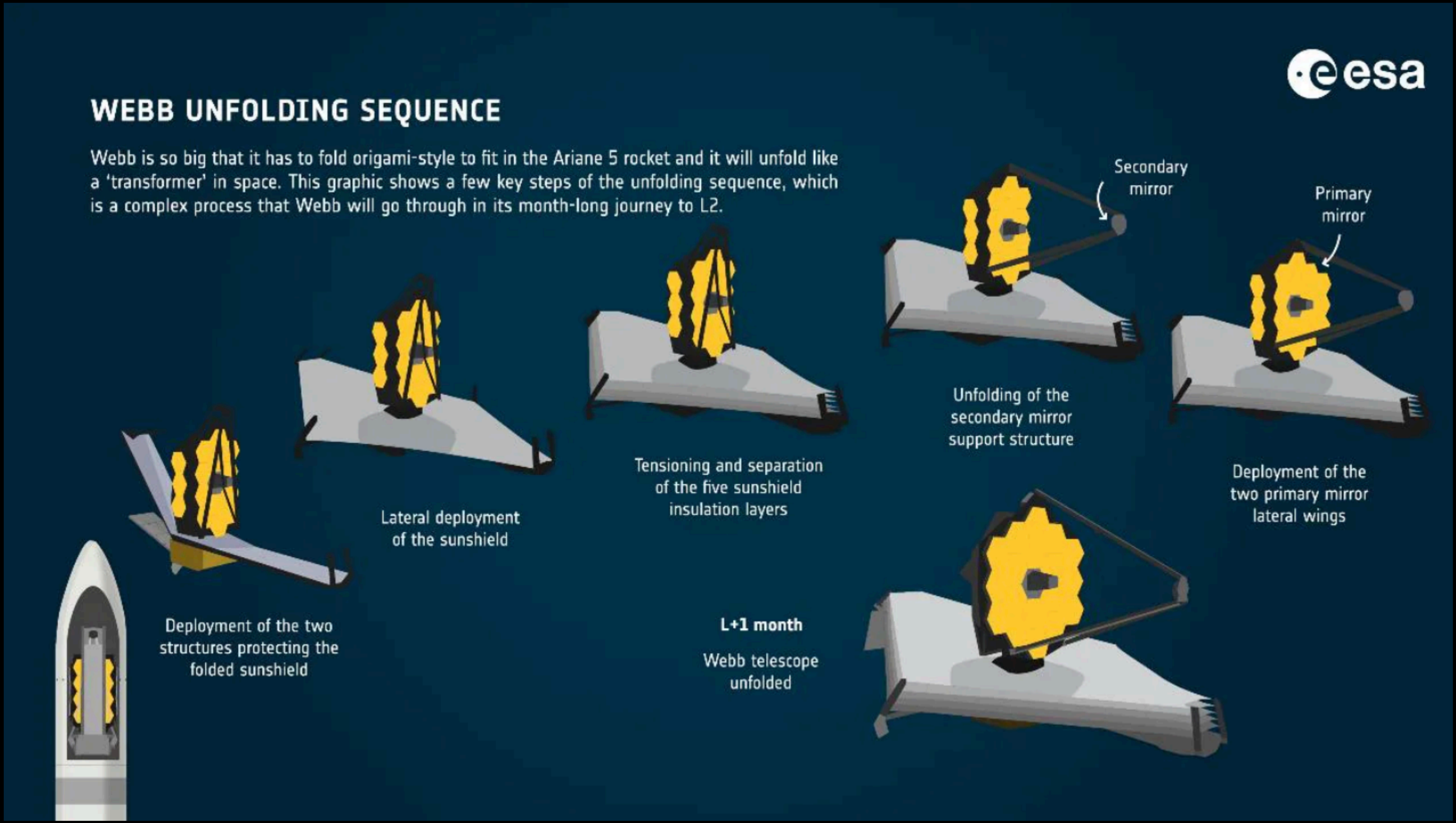


James Webb Space Telescope



NASA

James Webb Space Telescope



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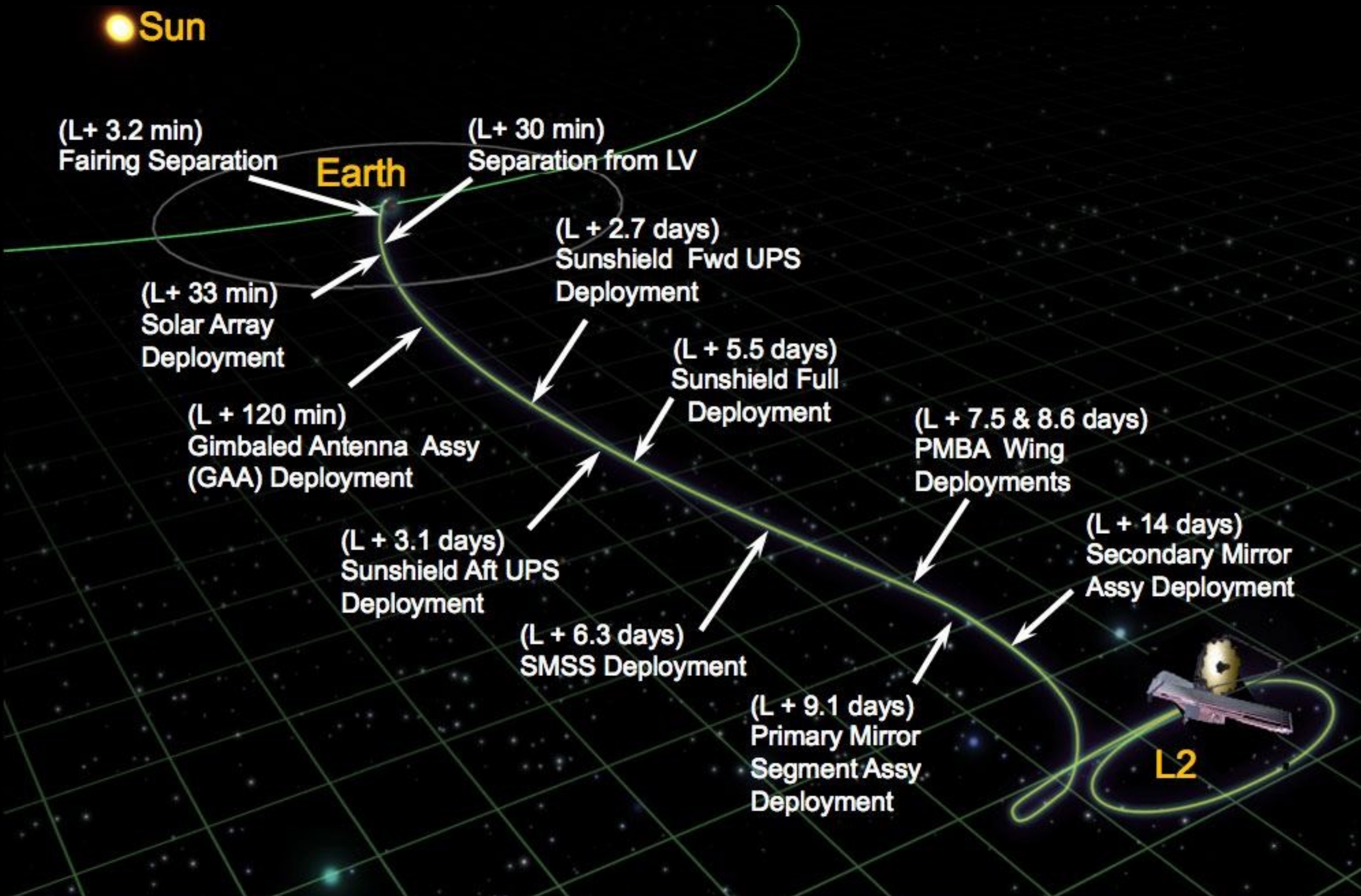
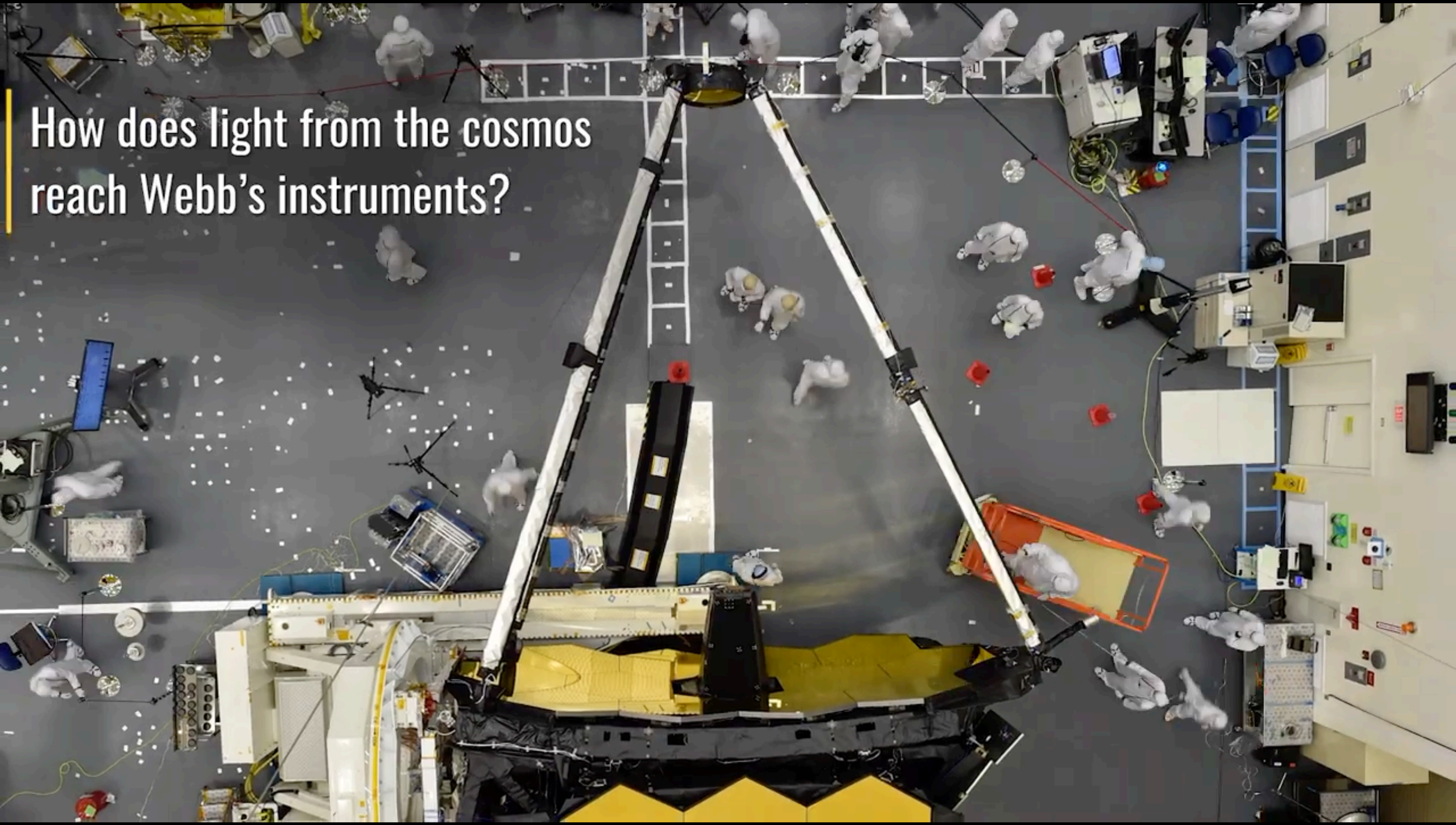
James Webb Space Telescope



NASA

James Webb Space Telescope



NASA

Take-aways

- We observe structure in the Universe via weak lensing and via **galaxy surveys**
- **Galaxies live at the centers of halos**; with some simple assumptions, dark matter simulations predict patterns of galaxies that are statistically like the real Universe
- Galaxies form through the gravitational collapse of gas, which is counteracted by **pressure**
- Gas can **cool** to form even denser clouds, which eventually colapse to make **stars**

Next time…

We'll talk about:

- Galaxy evolution

Assignments

- Post-lecture quiz (by tomorrow night)
- Homework 5 (by 12/2)

Reading:

- H&H Chapter 15