ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 22 • The Milky Way in context: Galaxy evolution

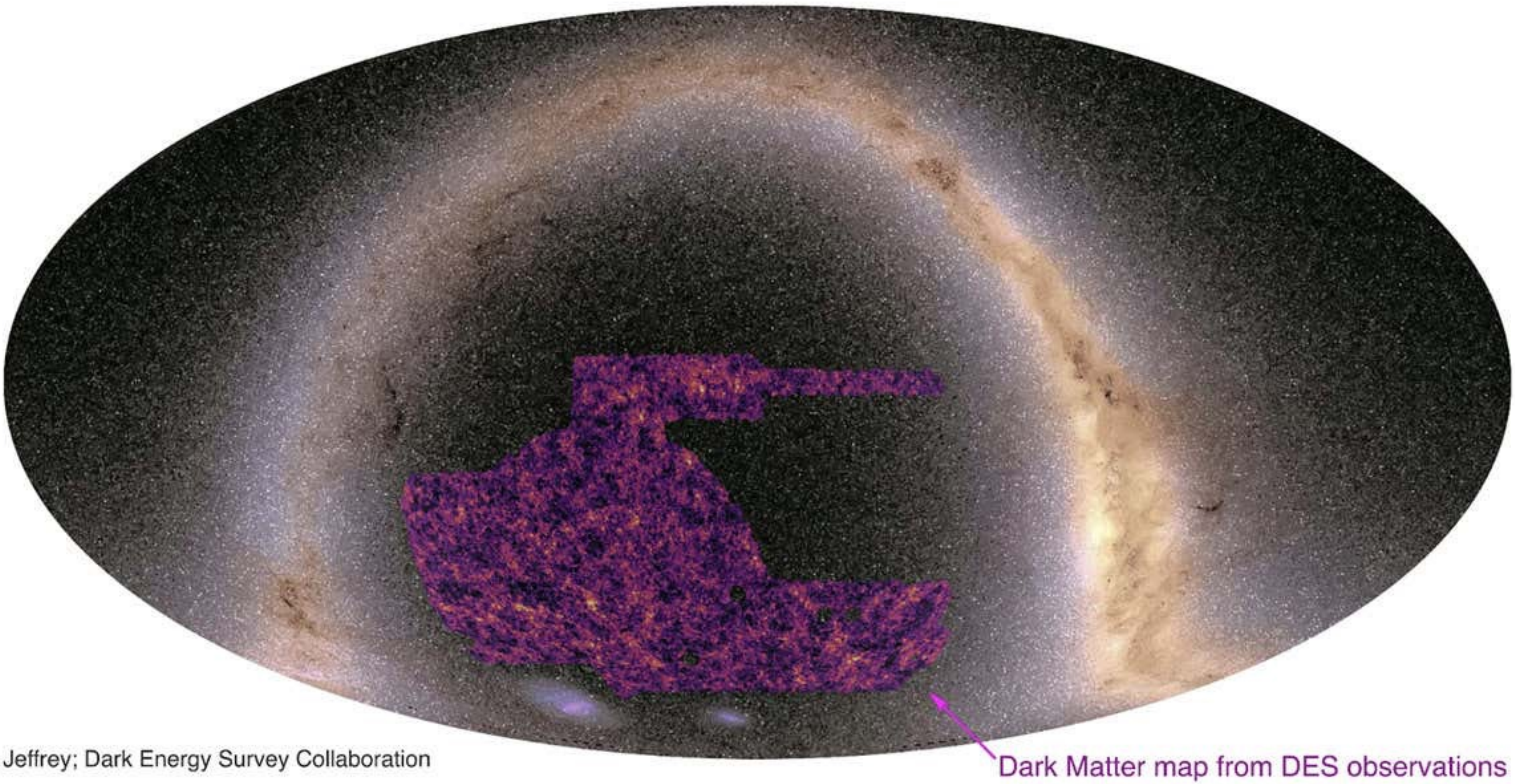
11/18/2021

Logistics

- Midterm solutions are online
- Please bring a laptop next time!

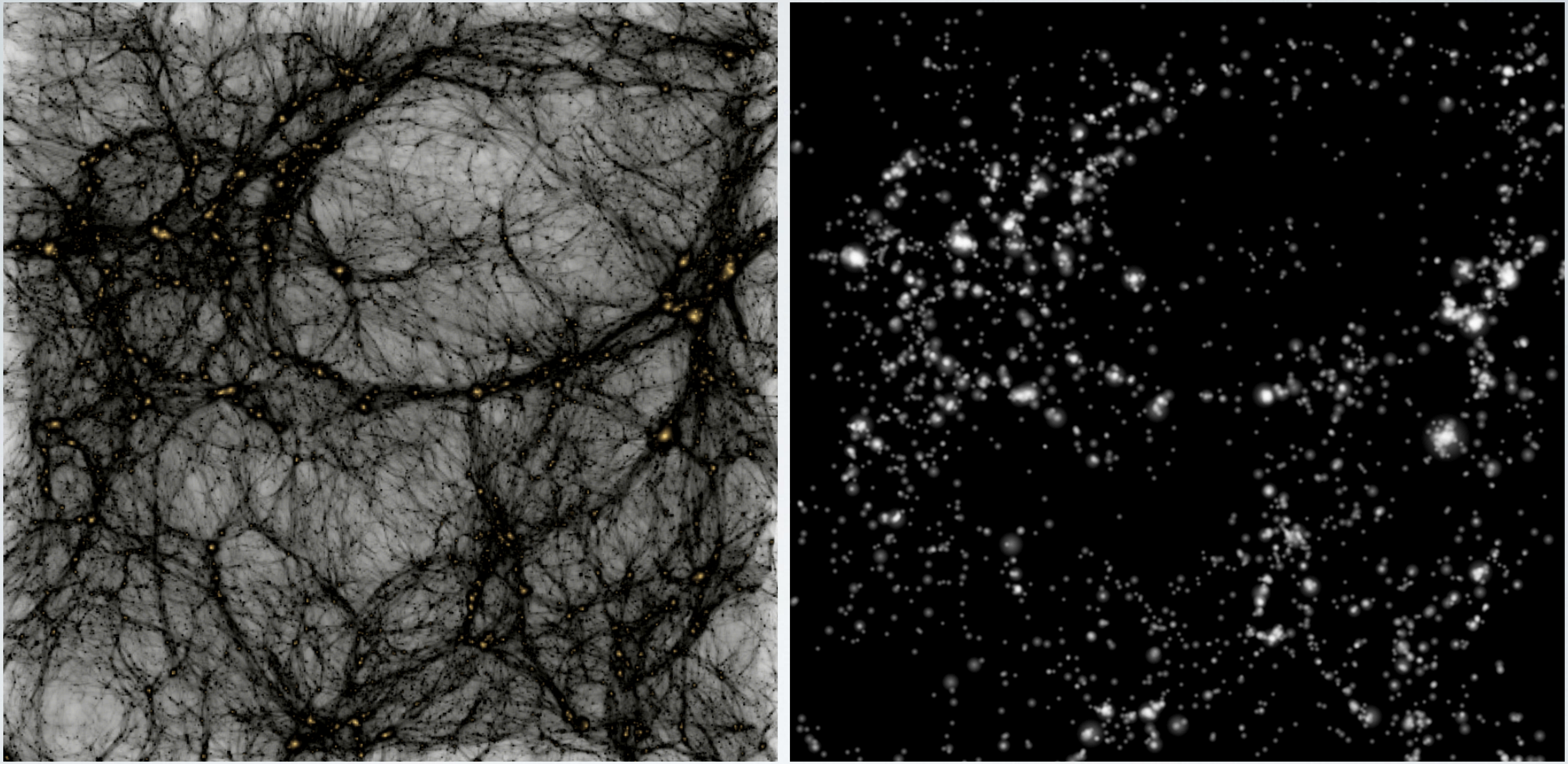
Recap

Weak lensing map of dark matter



N. Jeffrey; Dark Energy Survey Collaboration

Galaxy-halo connection

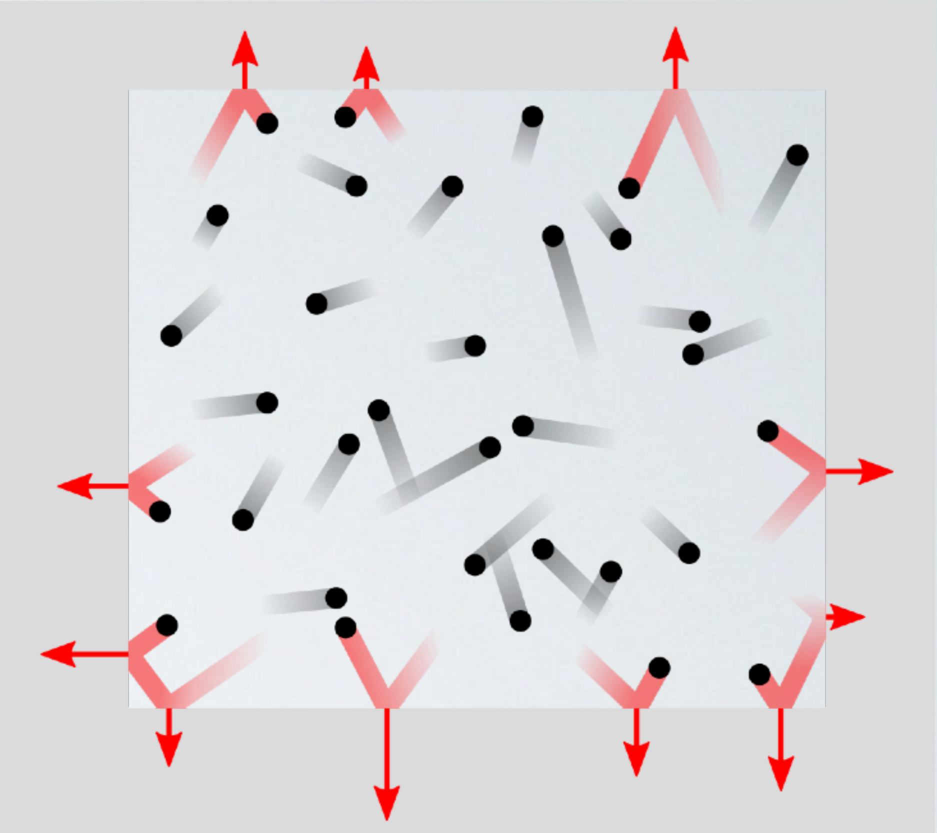


- Simple recipe: **measure galaxy luminosities**, count how many galaxies are how luminous
- **Find halos** in simulation of cosmic web
- Assign **largest luminosity to biggest halo**, second-largest luminosity to second-biggest and so on
- Very simplistic! There are more complicated methods as well

Wechsler & Tinker 2018

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

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

Participation: Recap #1

TurningPoint:
What is the Jeans mass (for gas of a given density and temperature)?

Session ID: diemer

30 seconds

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

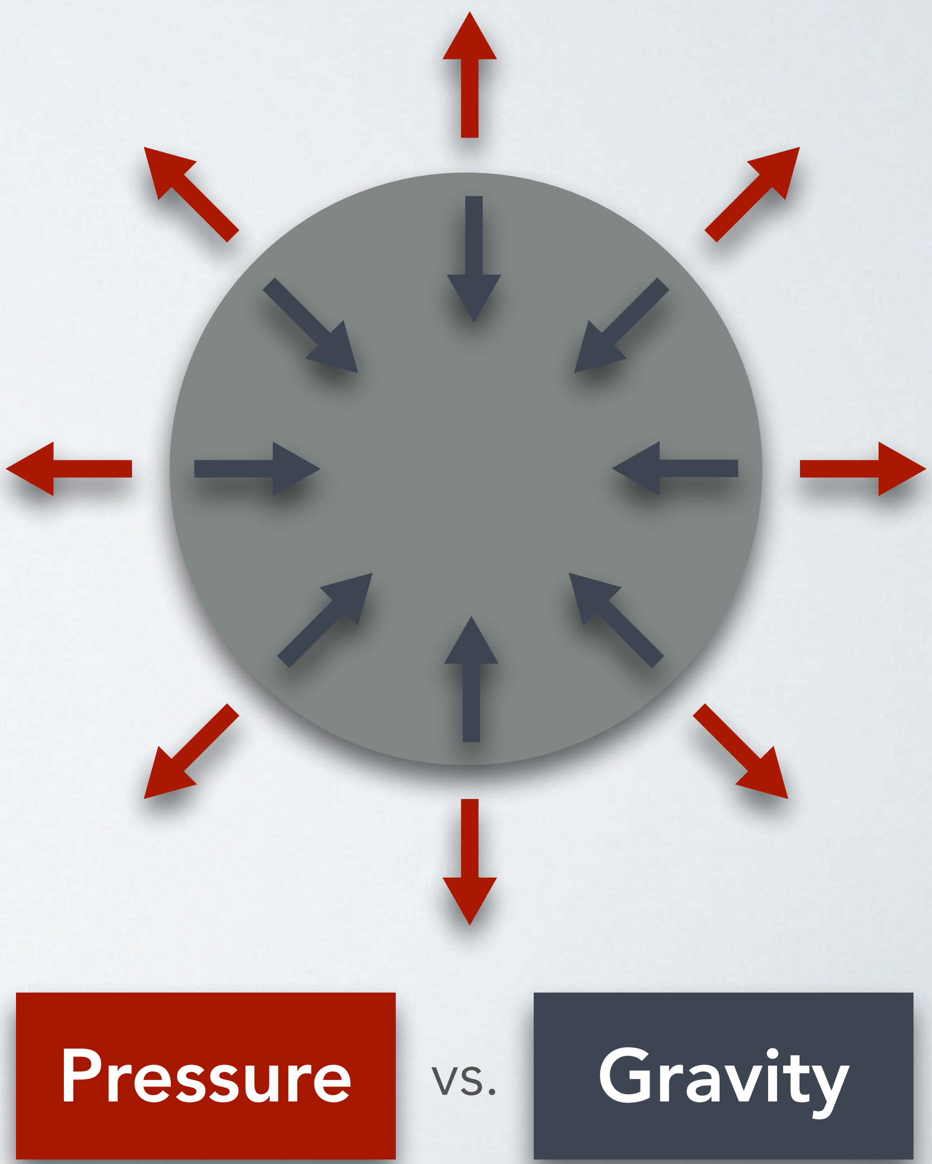
$$L_J = \sqrt{\frac{5\pi}{3} \frac{k_B T}{G\, m_p\, \rho}}$$

$$M_J = \frac{4\pi}{3}\left(\frac{L_J}{2}\right)^3 \rho \implies M_J = \frac{\pi^{5/2}}{6}\left(\frac{5k_B T}{3Gm_p}\right)^{3/2} \rho^{-1/2} = 2.7 \times 10^{23}\ \mathrm{g} \left(\frac{T}{K}\right)^{3/2} \left(\frac{\rho}{\mathrm{g/cm^3}}\right)^{-1/2}$$

$\rho,\ T$ 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



Participation: Recap #2

TurningPoint:

How does gas in galaxies reduce its pressure and collapse?

Session ID: diemer

30 seconds

What happens when gas collapses?

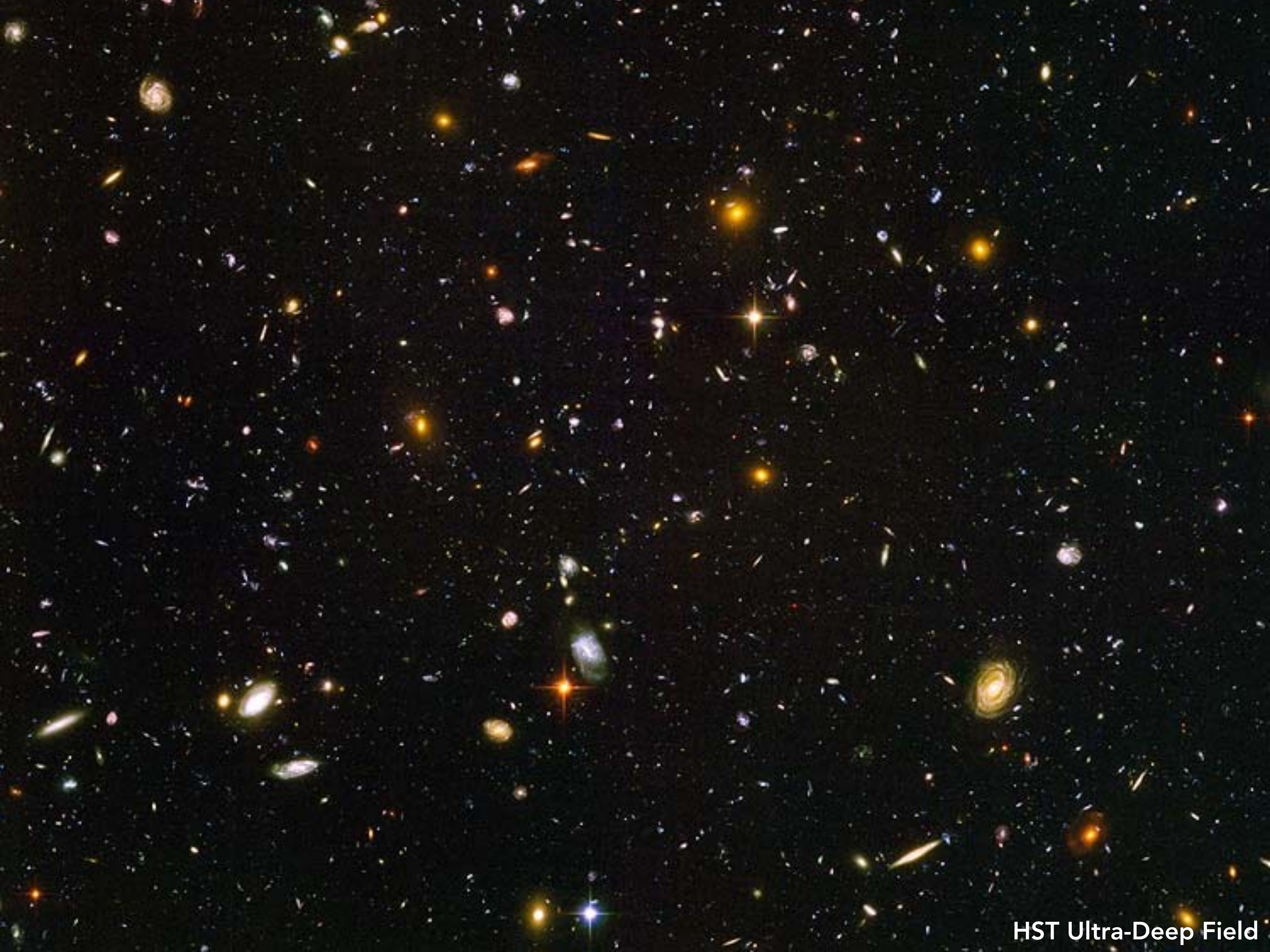
- In the Universe as a whole, we can work out the Jeans mass of gas right after recombination: $M_{\mathrm{J,recombination}} \approx 10^6 M_\odot$
- To further collapse, the **gas must cool**
- Galaxies cool by **emitting radiation** from the gas
- But most of the gas in galaxies remains relatively hot,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

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

Today

- The galaxy population
- Making galaxies
- Satellites, mergers, clusters
- The Milky Way and the Local Group

Part 1: The galaxy population


HST Ultra-Deep Field

Hubble Fork

- Classification scheme for galaxies
- Criteria: **shape**, prominence of **spiral arms**, **bars**
- Spirals tend to be blue, ellipticals red
  (but this is a sliding scale, and there are exceptions)

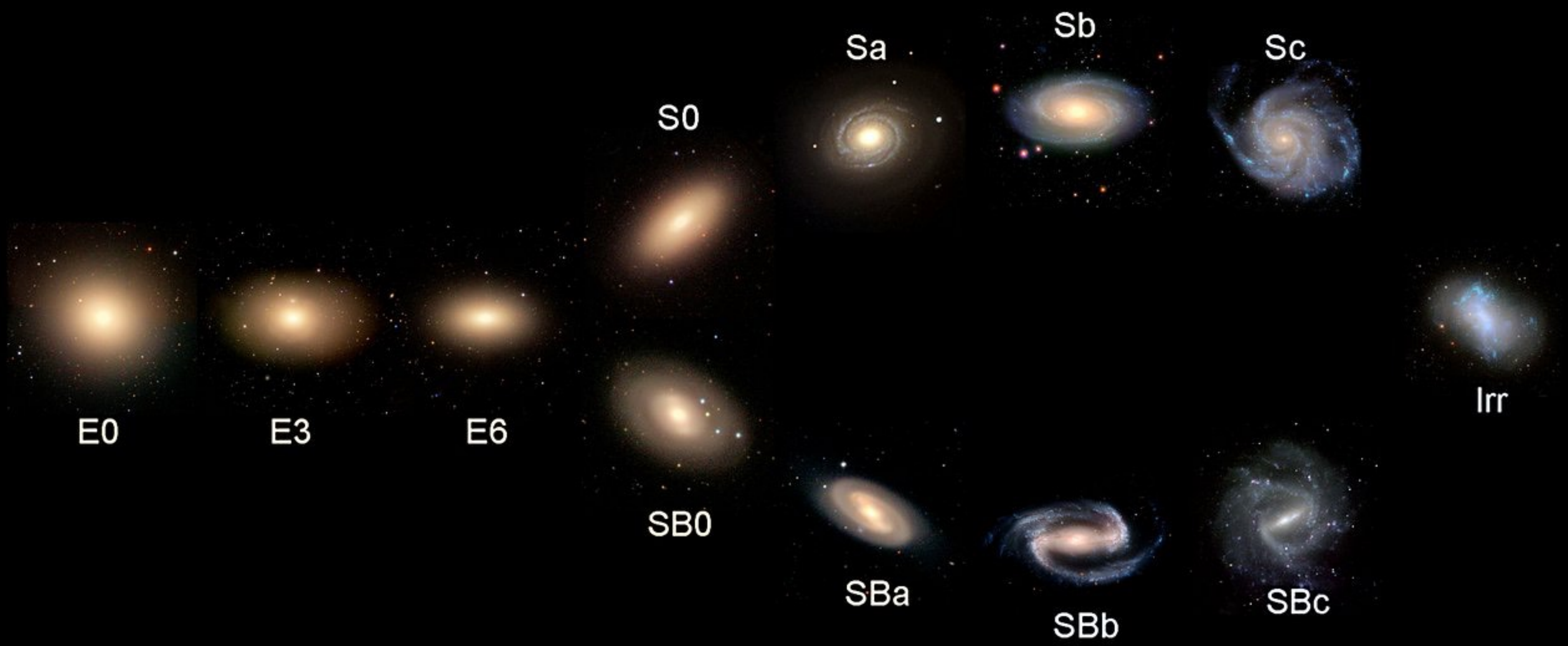


Image: Zooniverse

Participation: Galaxy color

TurningPoint:
What might the color tell us about a galaxy?

Session ID: diemer

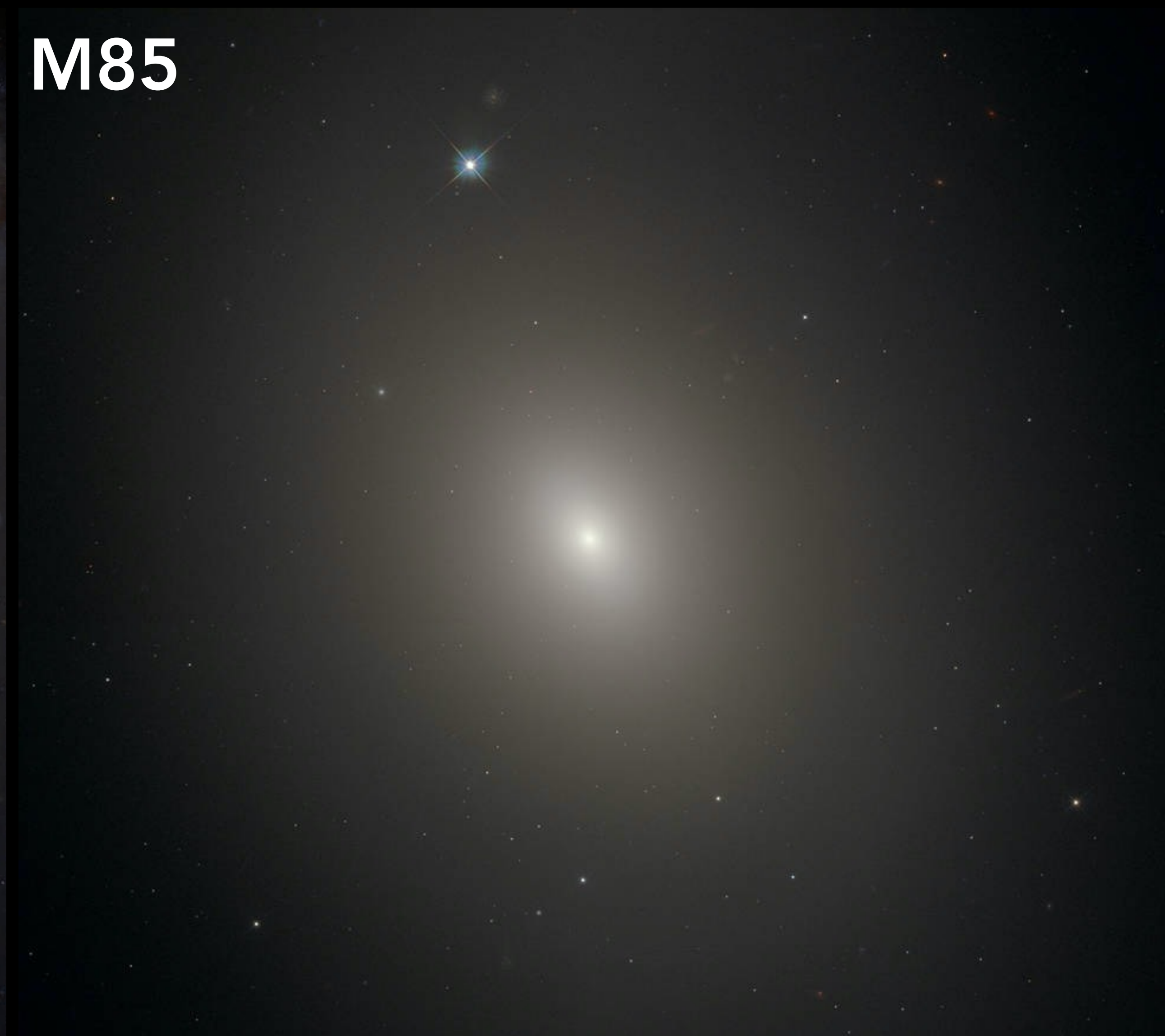
30 seconds

Observed spiral (disk) galaxies

M102

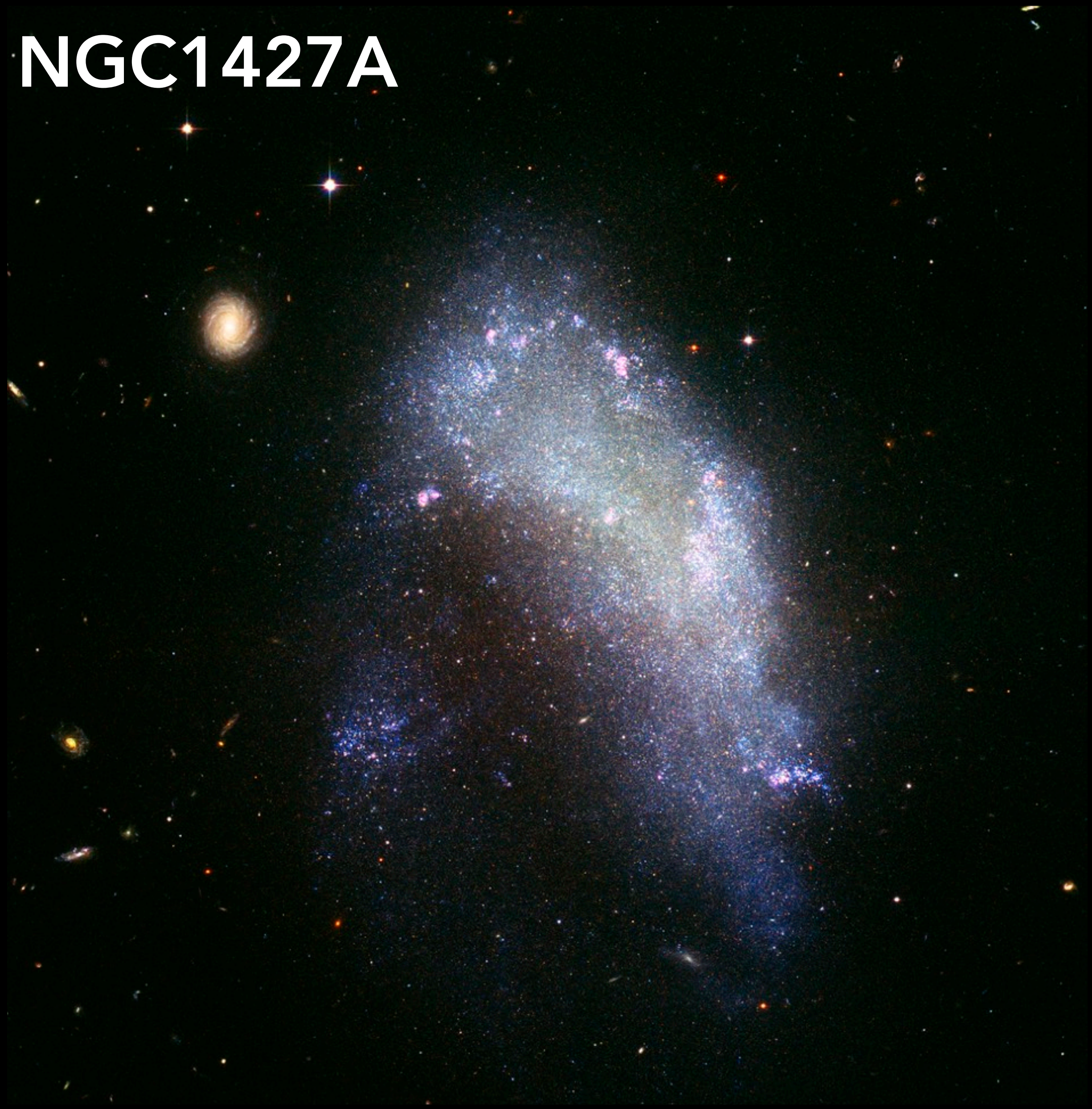
Hubble Space Telescope

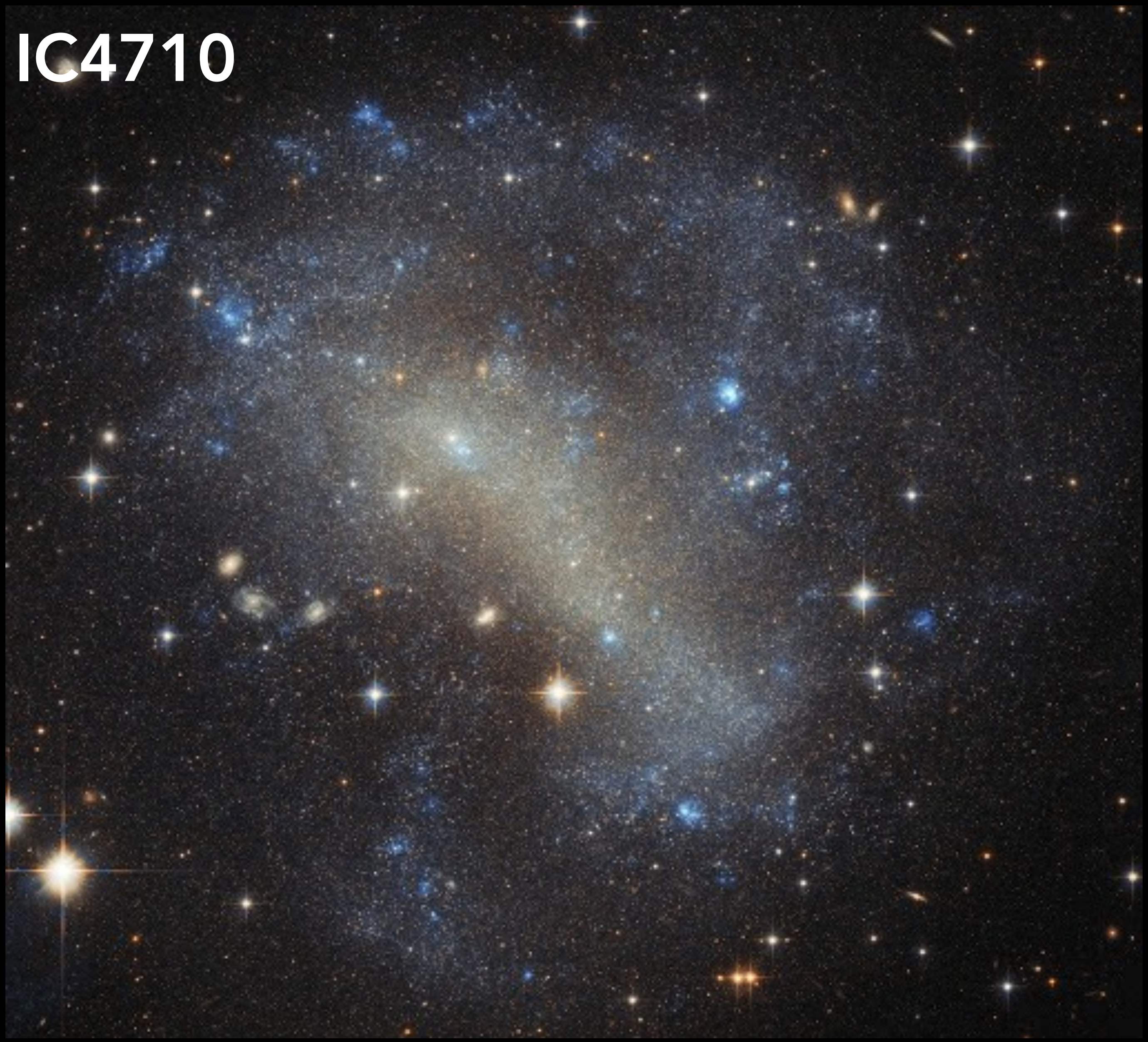
Observed elliptical galaxies



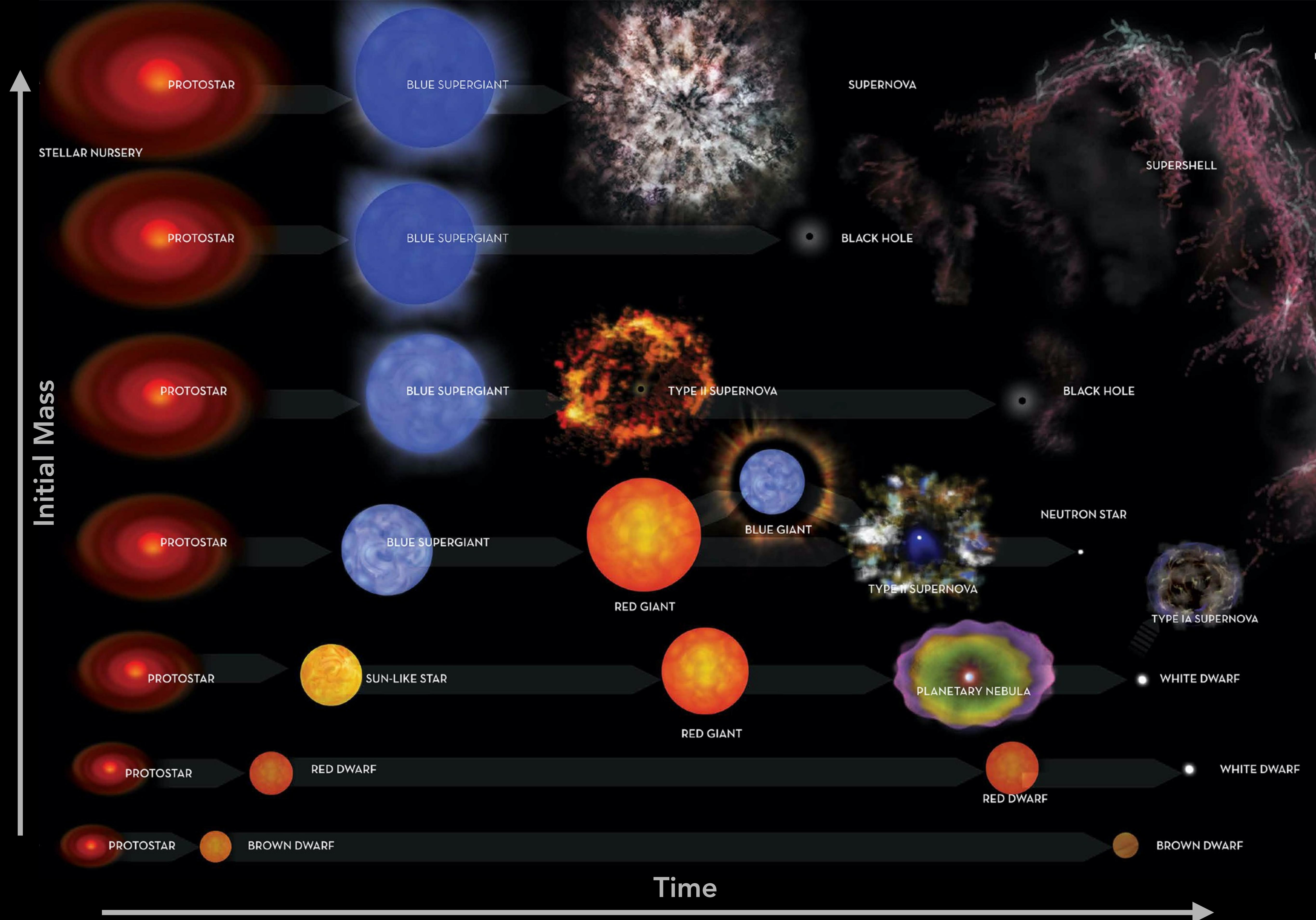
Hubble Space Telescope

Observed elliptical galaxies





Hubble Space Telescope



Summary of stellar evolution

NASA

Spiral vs. elliptical, red vs. blue

- **Shape**
  - **Spirals** tend to be very disk-like; this happens when the stars have high angular momentum
  - In **ellipticals**, the orbits of the stars are not in a disk
  - Ellipticals and spirals are sometimes called "**early**" and "**late**" types (meaning **old** and **young**)
- **Color**
  - Smaller stars are redder and live longer, bigger stars are bluer and live shorter (explode as Supernovae)
  - Thus, **as a stellar population ages, it gets more red** ("red and dead")
  - Blue galaxies are actively forming stars whereas red galaxies are not
- There are **intermediate stages** to all of these classifications: red spirals, blue-ish ellipticals/irregulars, the "green valley" in between red and blue, etc.

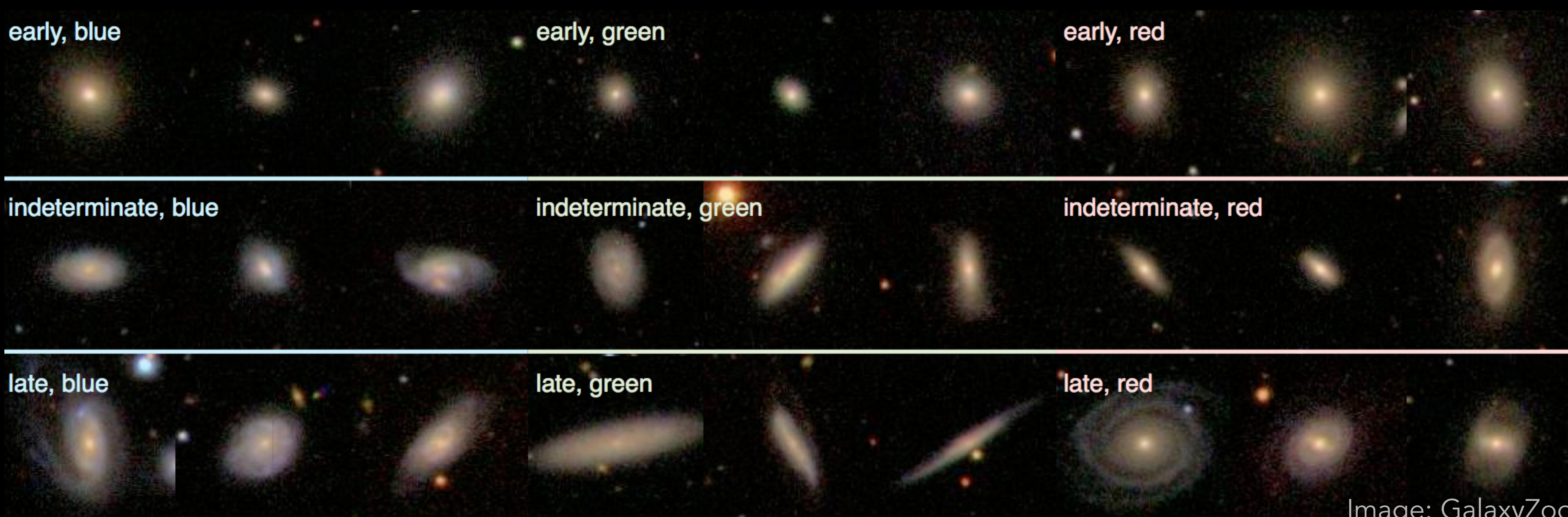
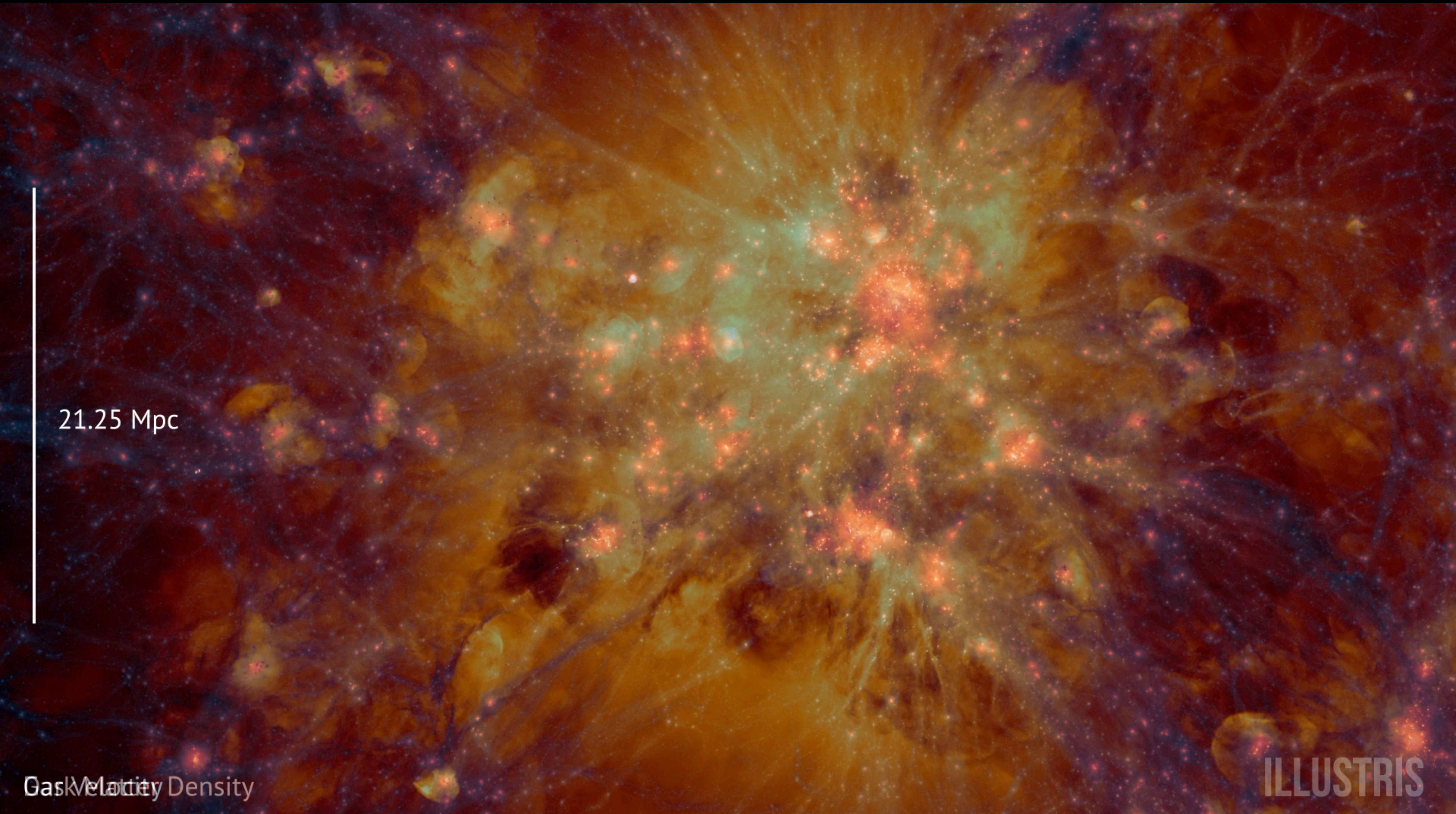


Image: GalaxyZoo

Part 2: Making galaxies

Simulation of galaxy formation



Illustris simulation: Vogelsberger et al. 2013, 2014ab • Torrey at al. 2014 • Genel et al. 2014 • Sijacki et al. 2015

IllustrisTNG simulation: Nelson et al. 2019

IllustrisTNG

- Multiple simulations that follow up to **30 billion particles**
- Particles represent **dark matter, gas, stars, and black holes**
- Up to 160 million CPU hours per simulation!

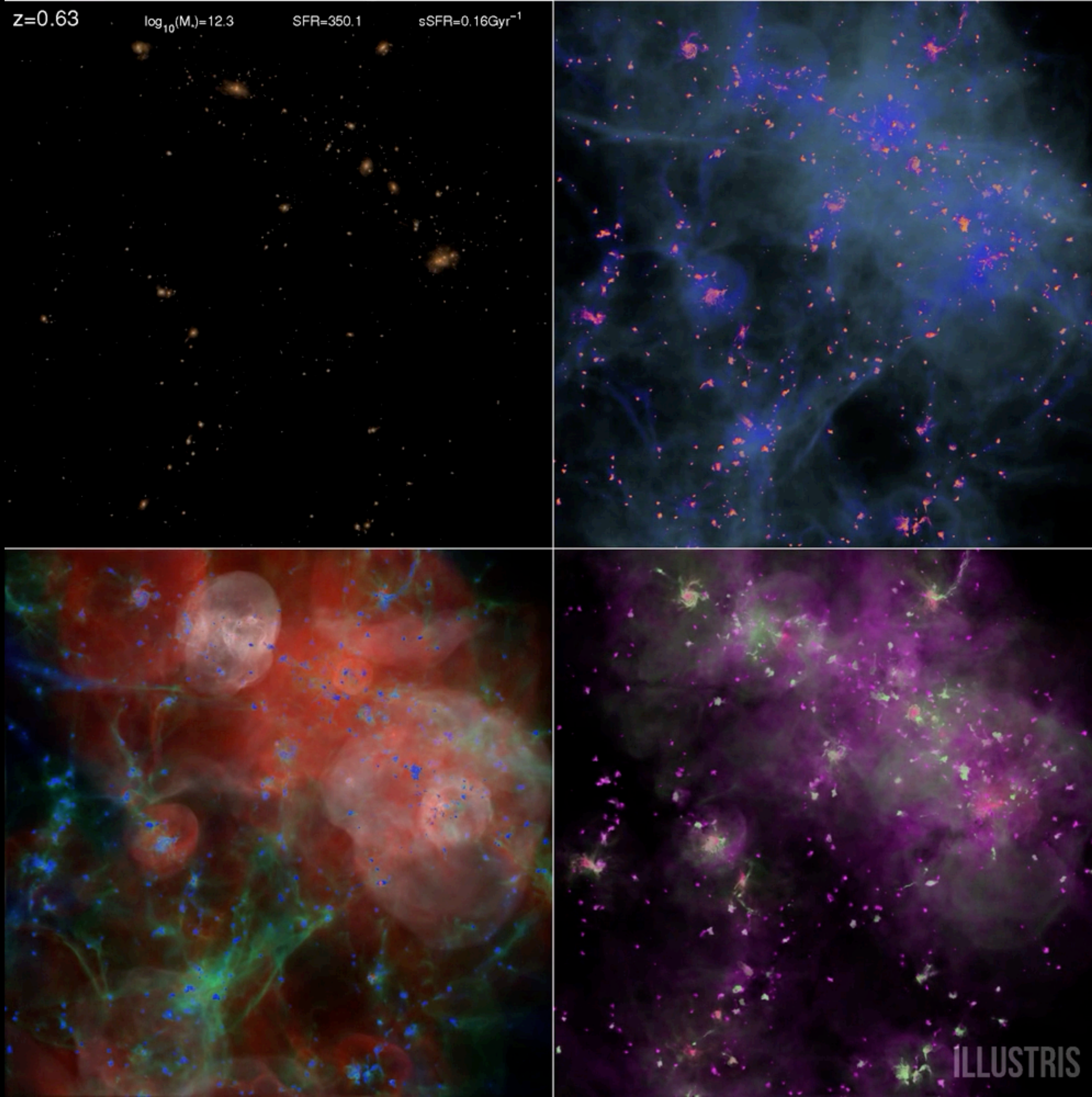
Hazel Hen, Stuttgart

Formation of spiral galaxy (simulation)

IllustrisTNG Collaboration

Star light

Gas temperature



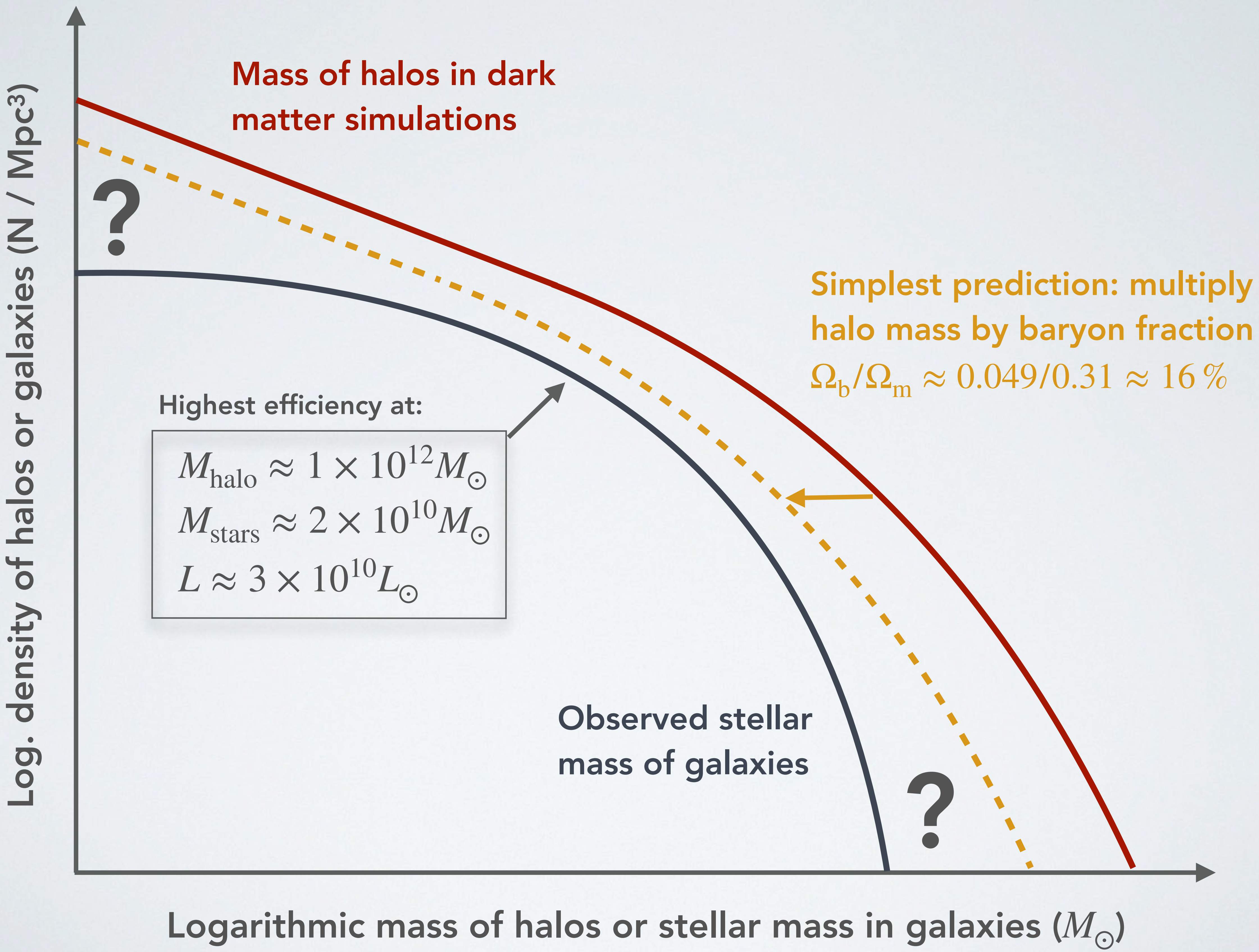
Gas density

Heavy elements in gas

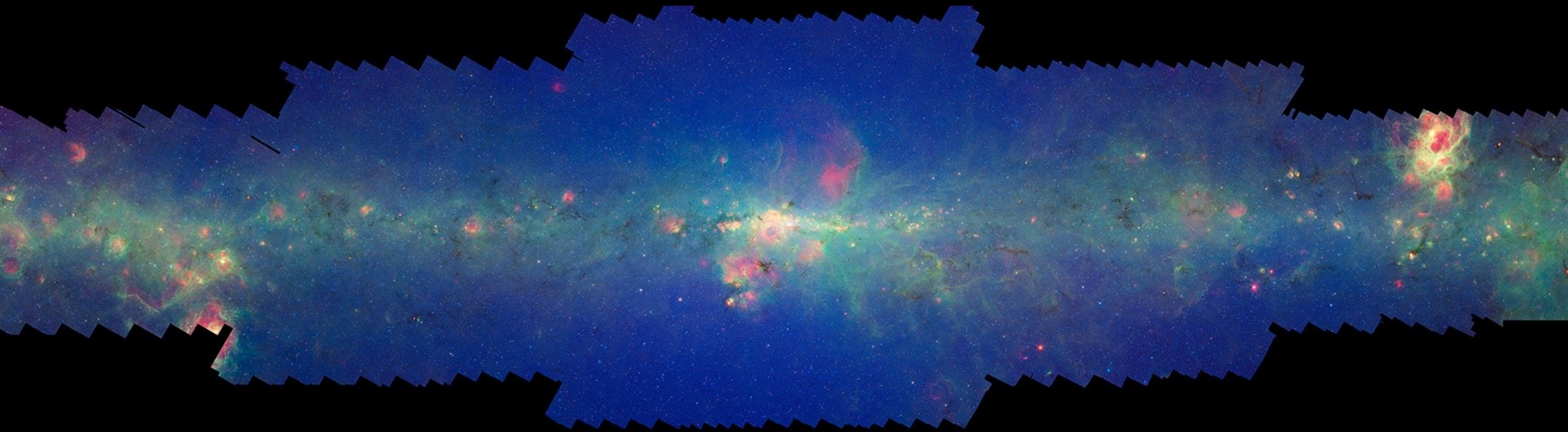
Illustris simulation: Vogelsberger et al. 2013, 2014ab

See also **EAGLE** (Schaye et al. 2015 • **SIMBA** (Dave et al. 2019)

Why feedback?

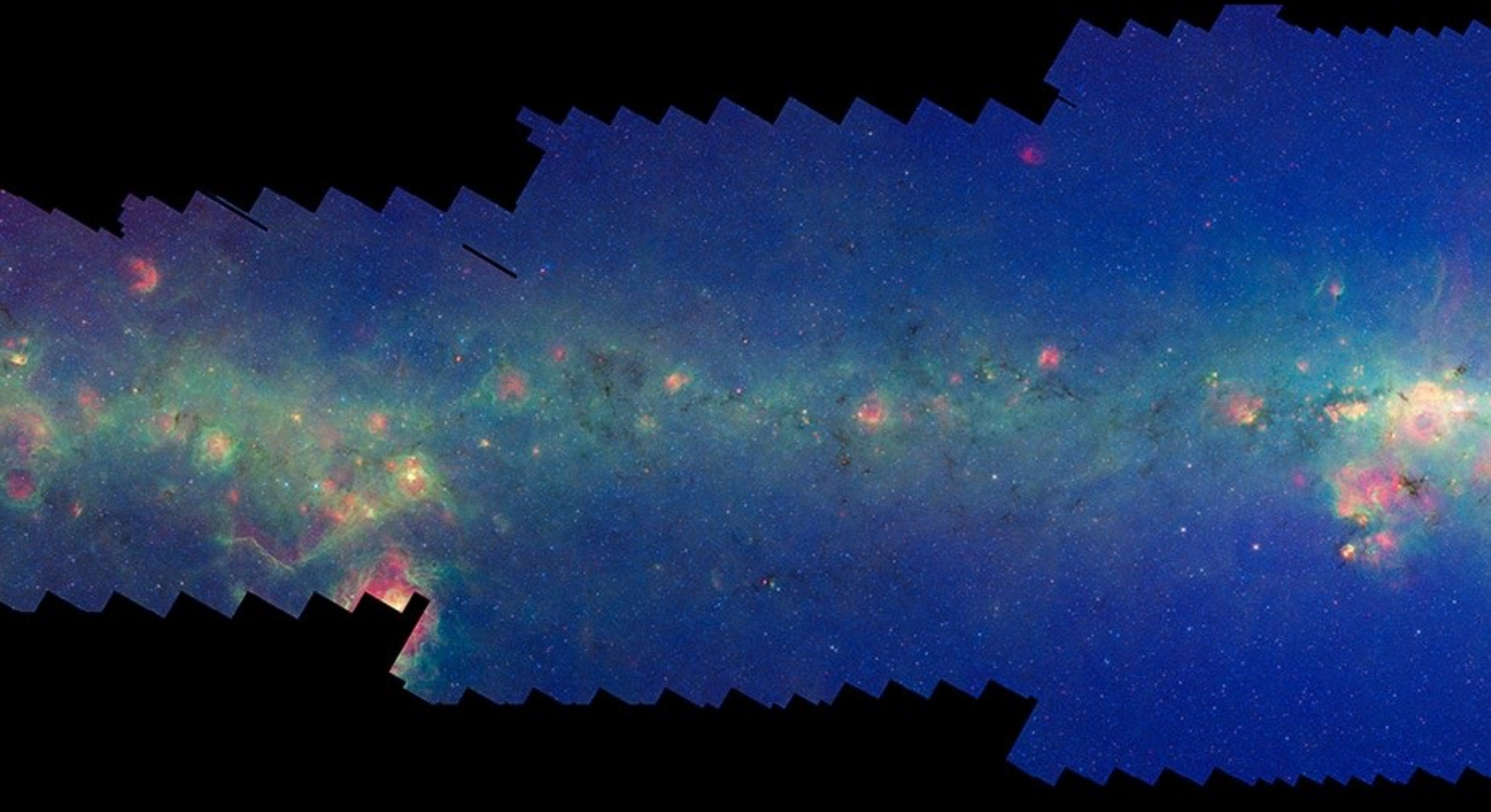


Star-forming clouds in the Milky Way disk



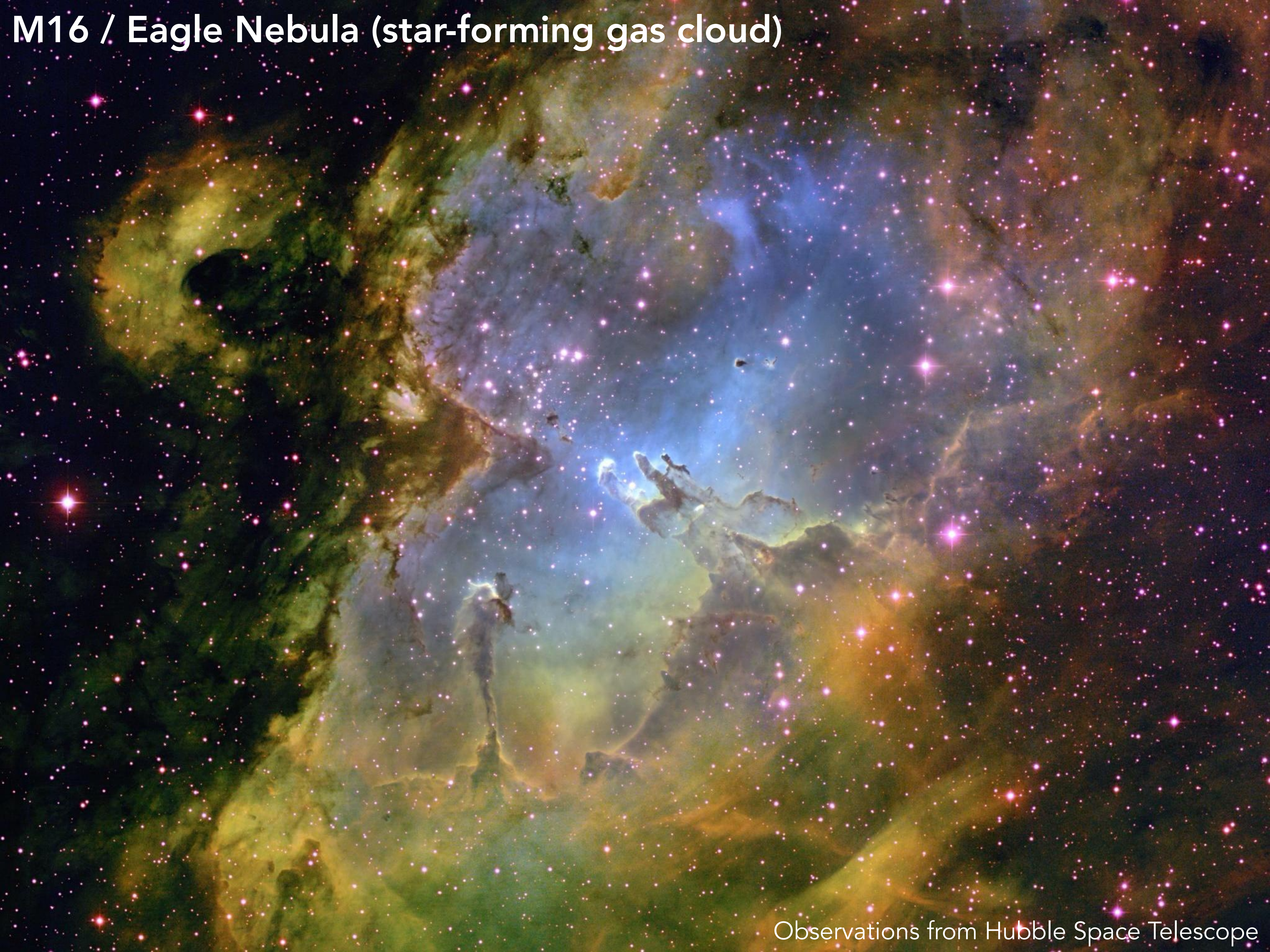
Observations from Spitzer Space Telescope

Star-forming clouds in the Milky Way disk

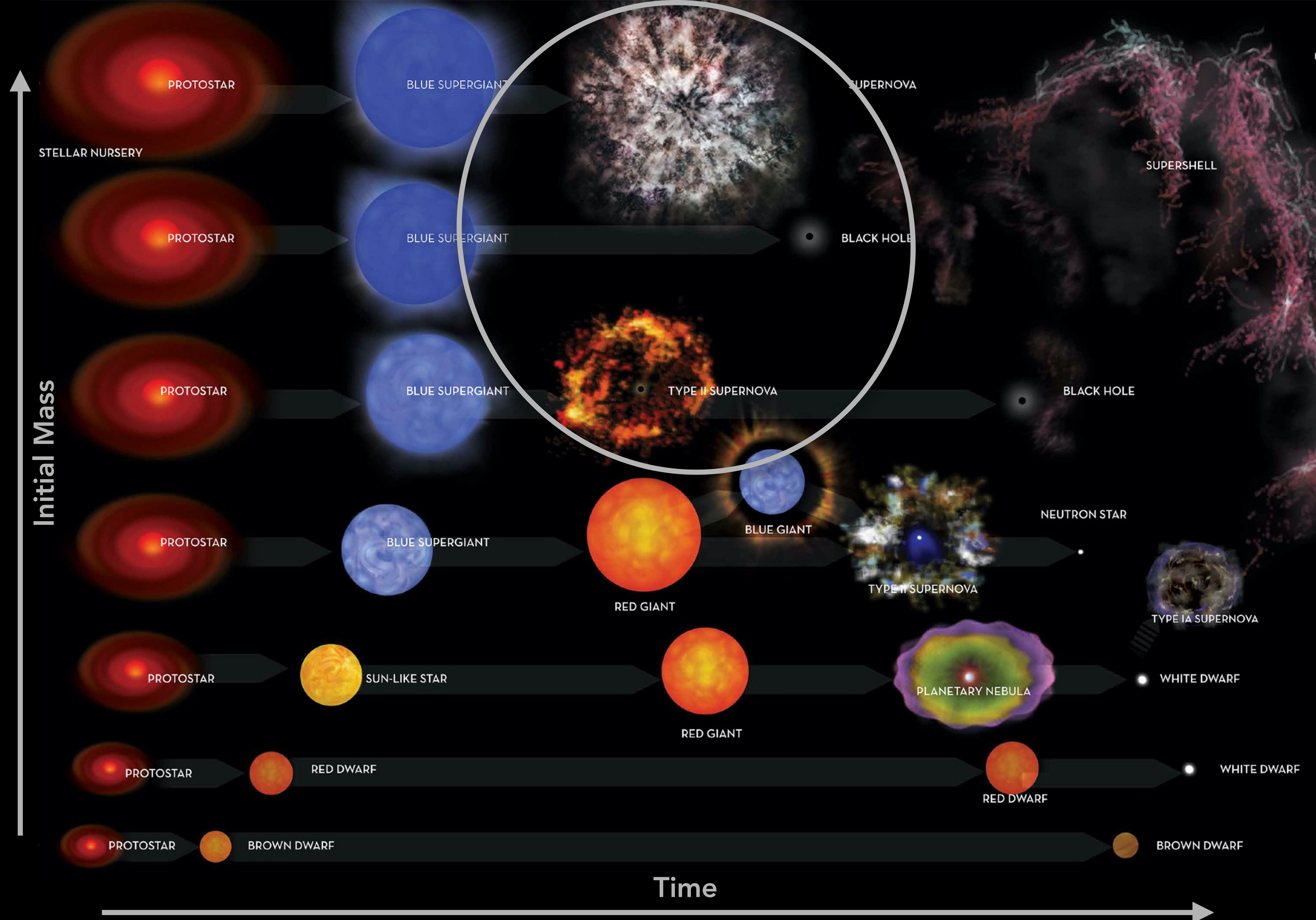


Observations from Spitzer Space Telescope

M16 / Eagle Nebula (star-forming gas cloud)



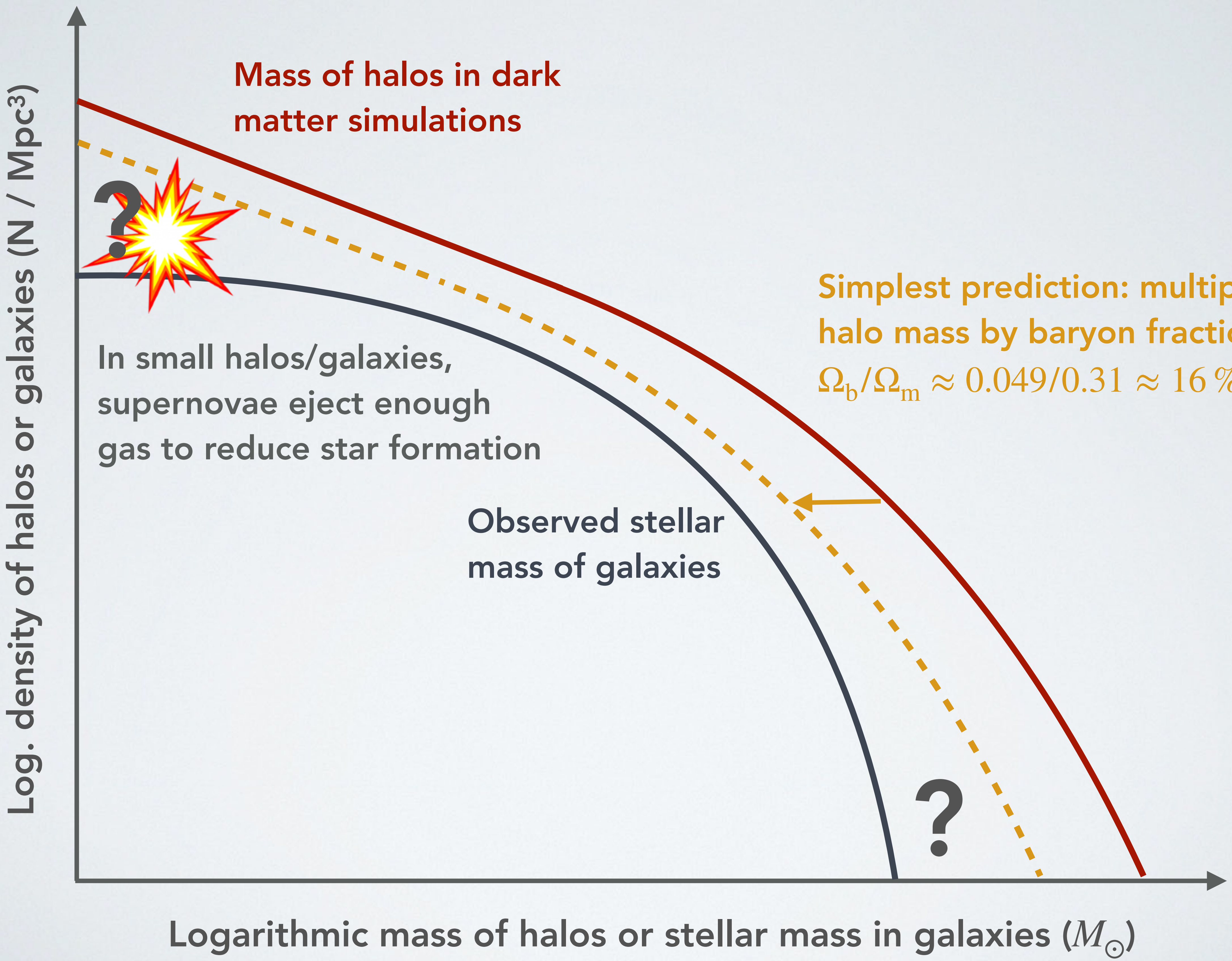
Observations from Hubble Space Telescope



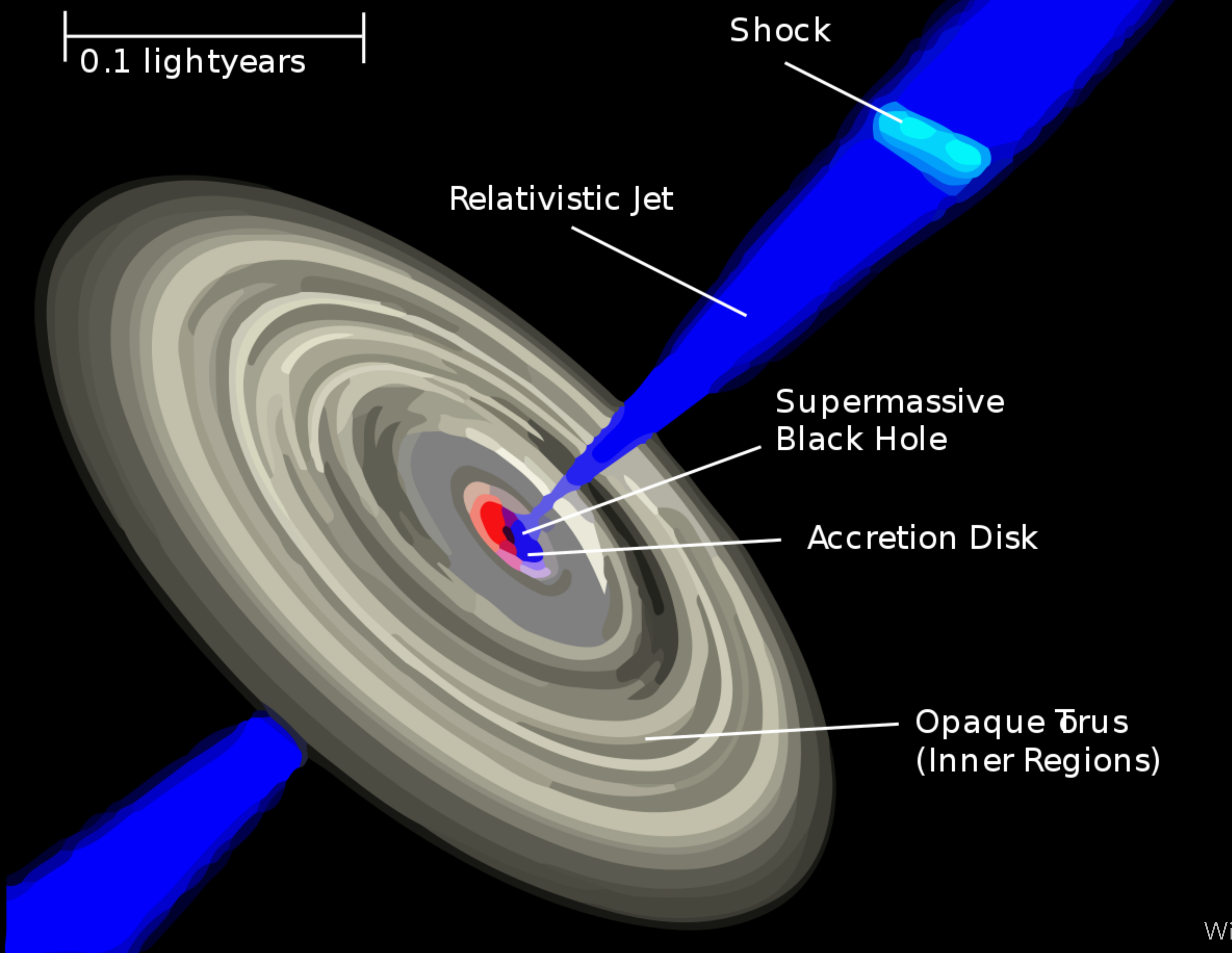
Summary of stellar evolution

NASA

Why feedback?

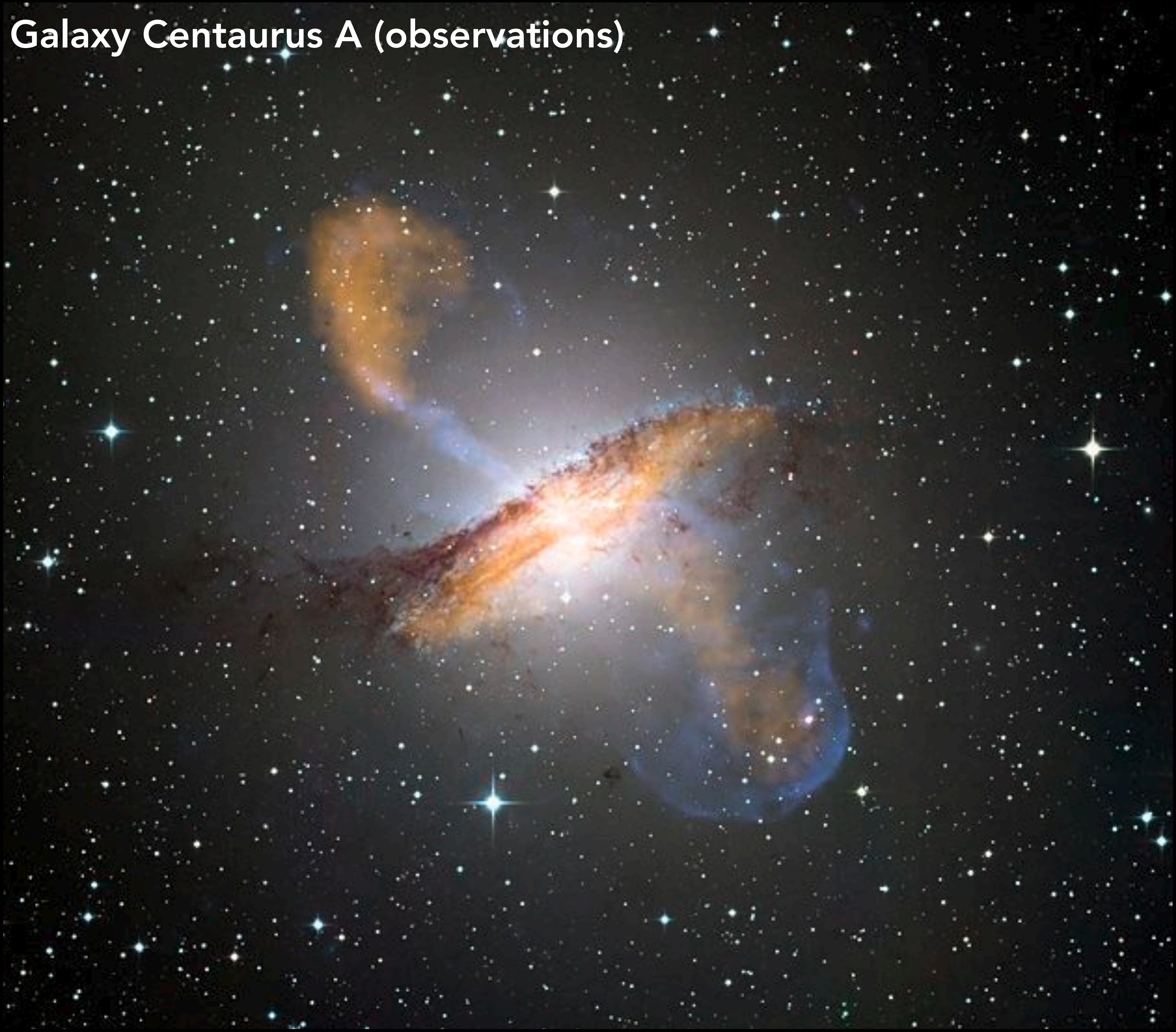


Active Galactic Nuclei (AGN)



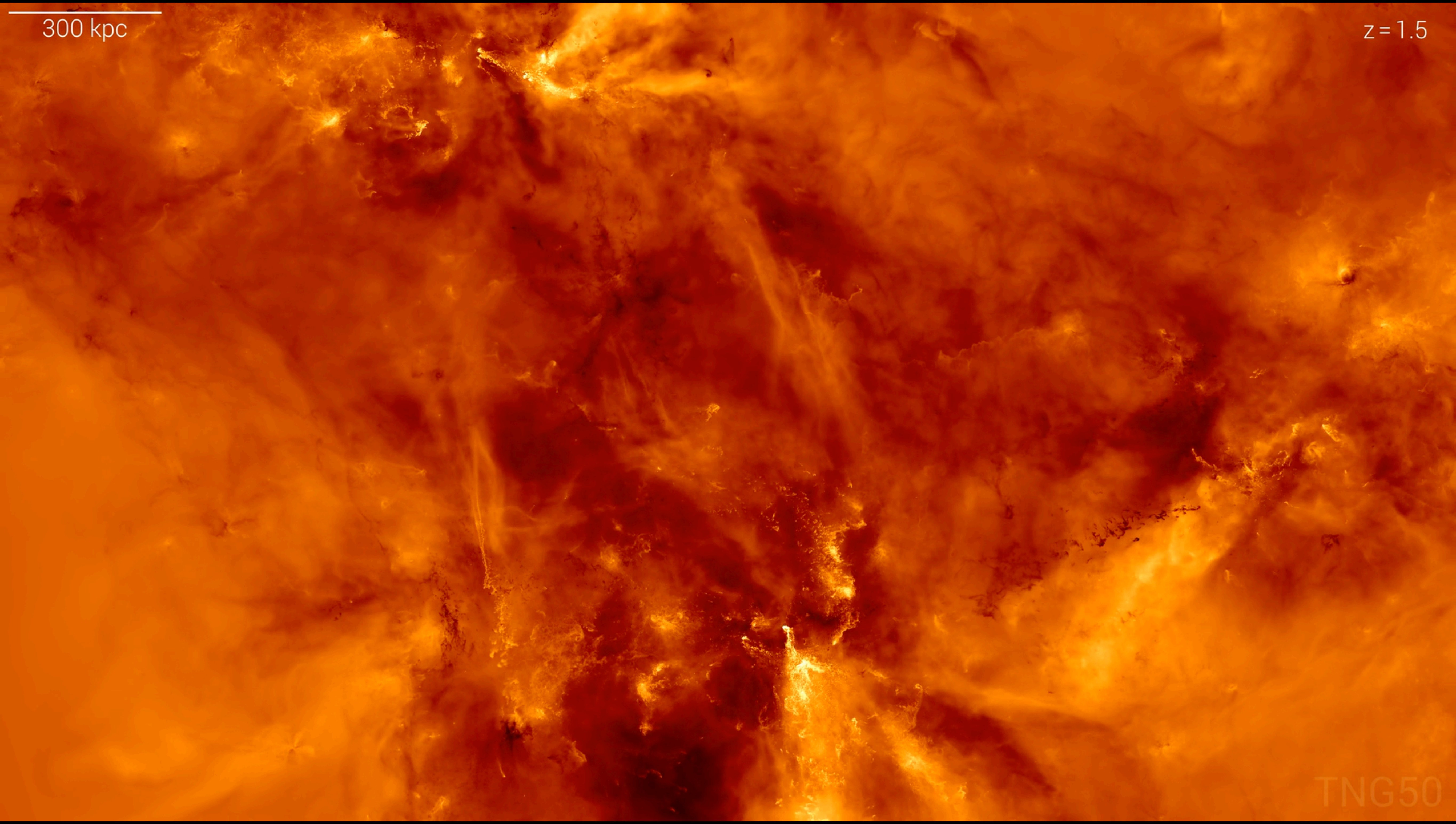
Wikipedia

Active Galactic Nuclei (AGN)



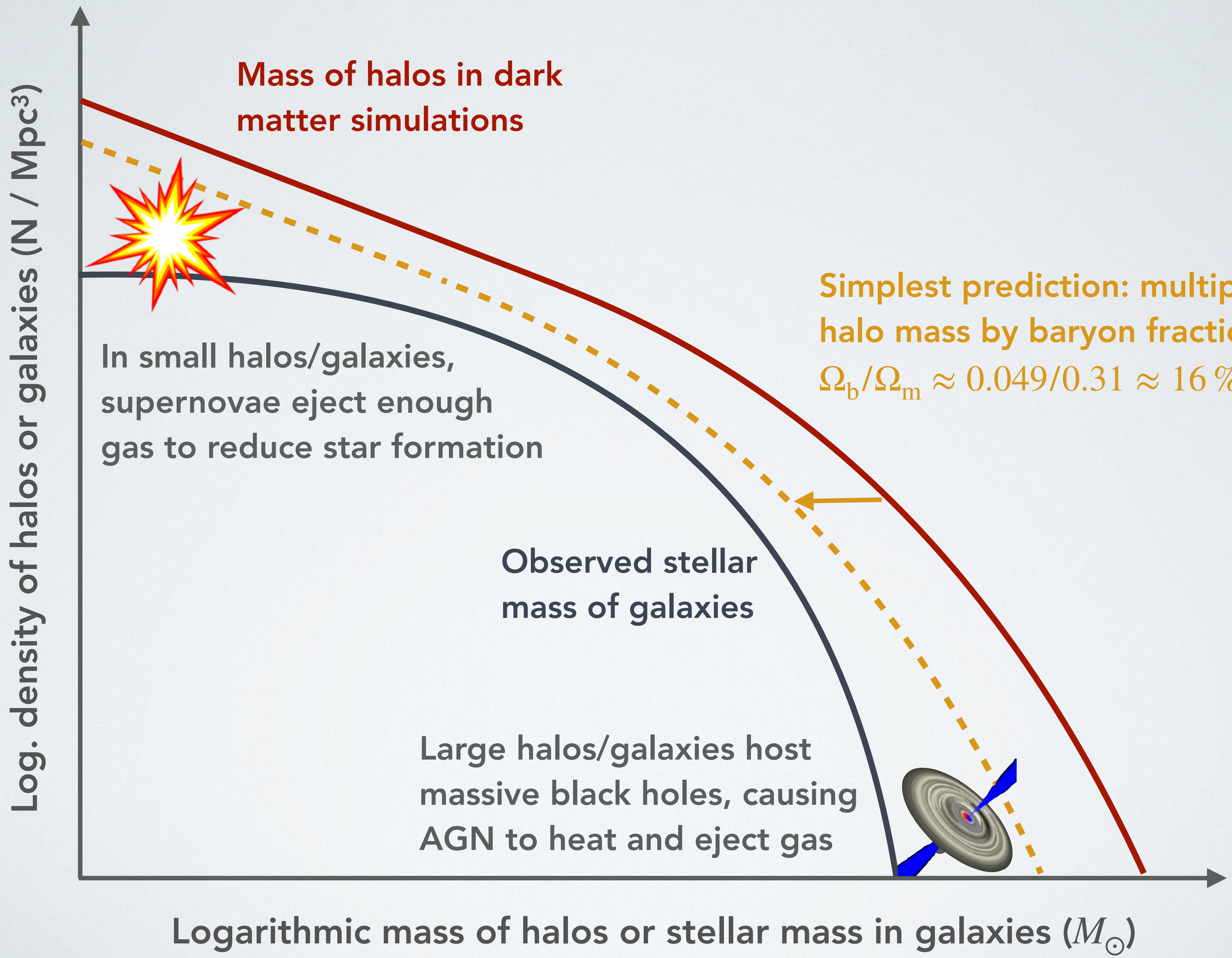
ESO / NASA / MPIfR

Gas flows around forming galaxies (simulation)



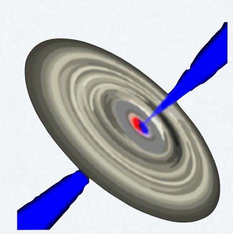
Illustris TNG50 • Pillepich et al. 2019 • Nelson et al. 2019

Why feedback?

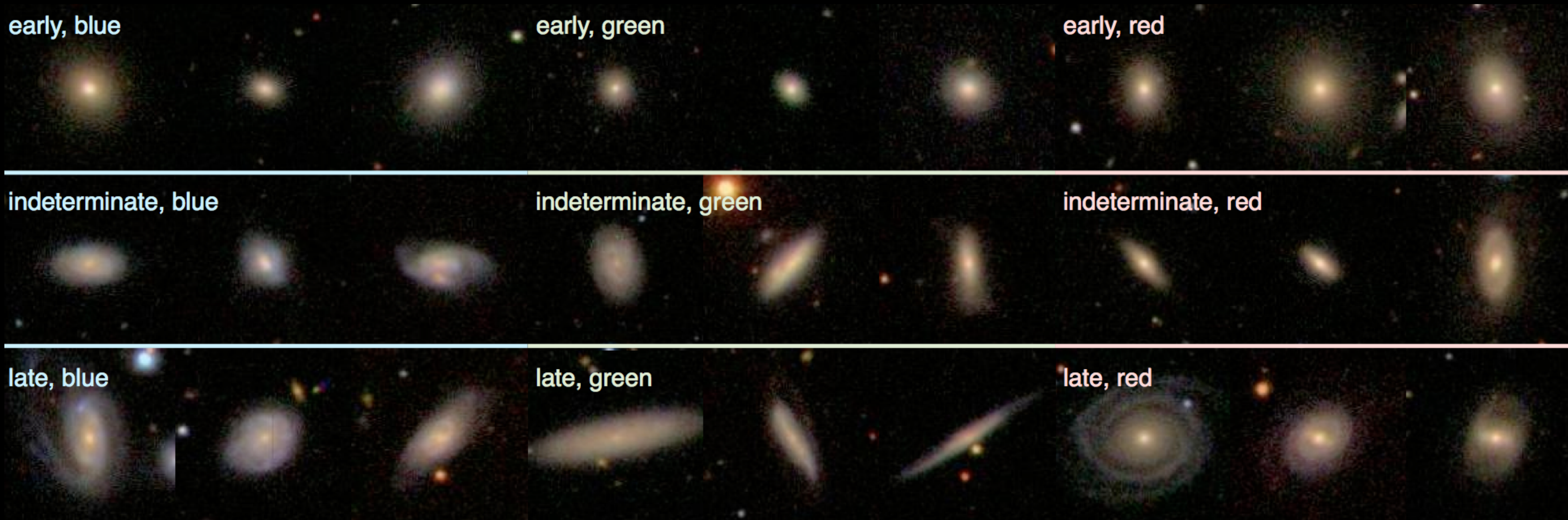


Feedback Summary

- The term "feedback" summarizes mechanisms that slow down star formation (by ejecting and/or heating gas)
- Reduces star formation
  - Especially at the low-mass end via **Supernovae**
  - Especially at the high-mass and via **Active Galactic Nuclei (AGN)**
- There are other mechanisms (e.g., stellar winds)

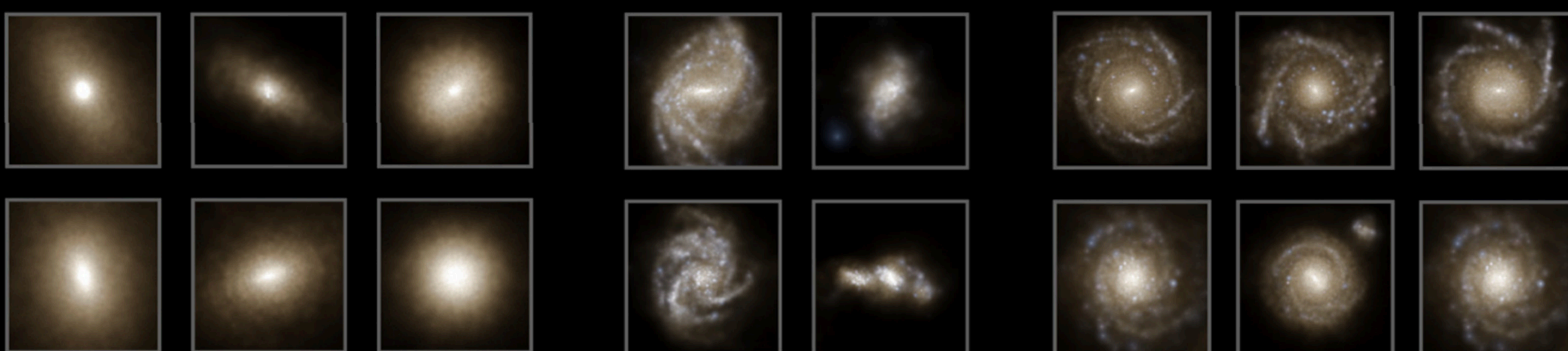


• • •



Observation ↑

↓ Simulation



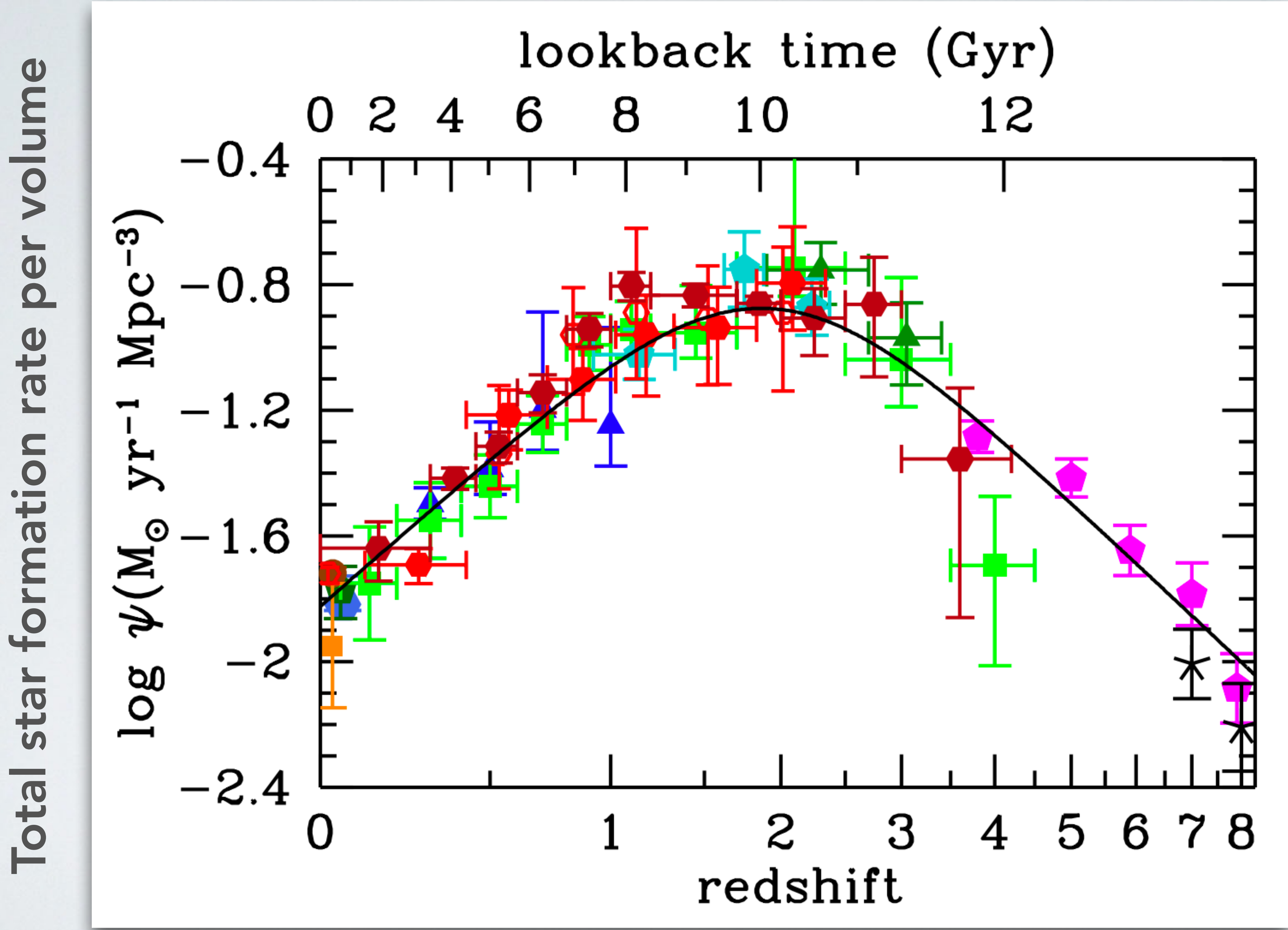
ellipticals

irregulars

disks / spirals

GalaxyZoo • IllustrisTNG Collaboration

Cosmic star formation history



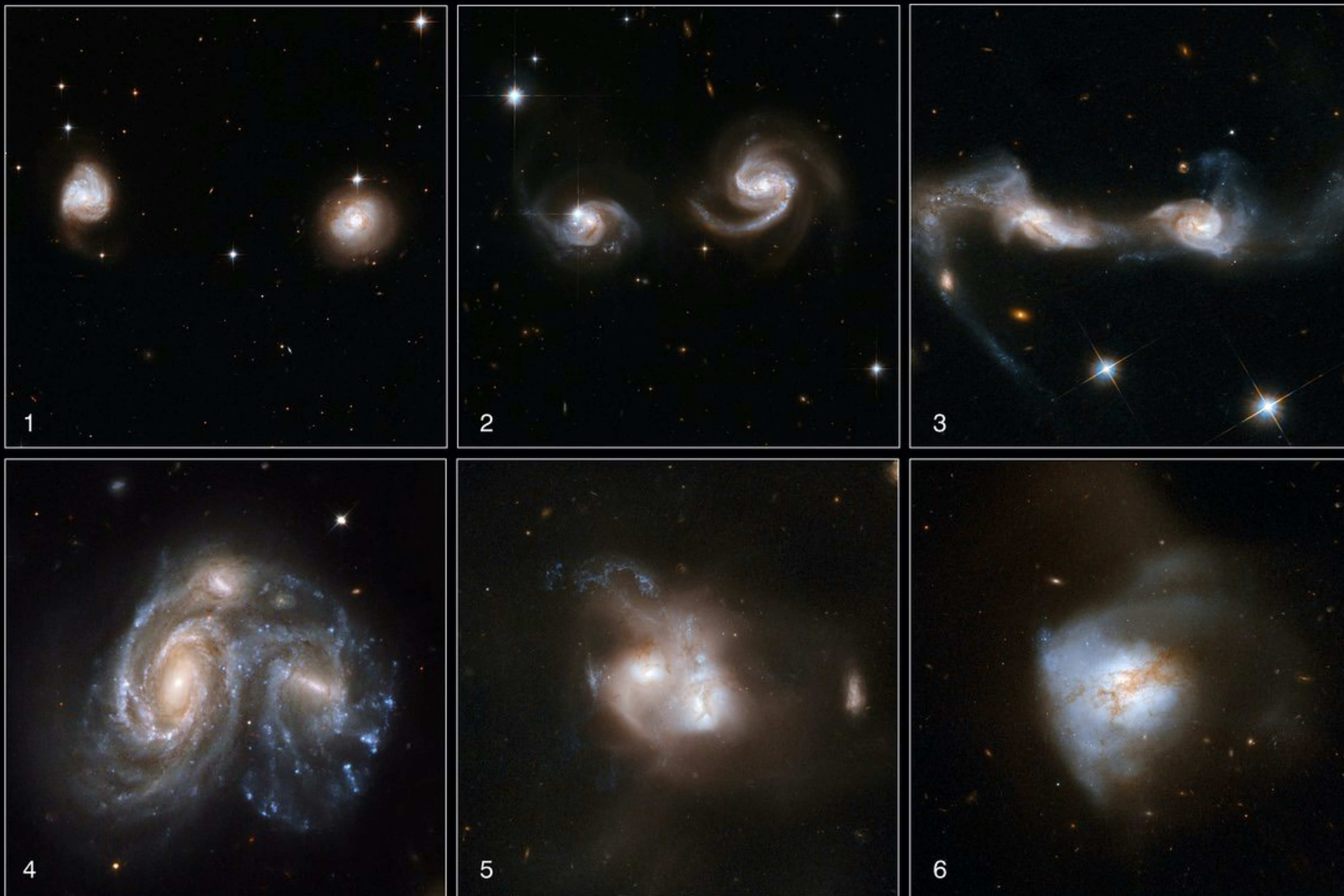
Madau & Dickinson 2014

Galaxy Evolution Summary

- Galaxies follow their halos: they **grow rapidly in the beginning** and **slow down** as the supply of fresh gas dries up
- Star formation was **most active around z = 2**, 10 billion years ago
- As fewer new stars are formed, **galaxies become redder** (older stellar population)
- Star formation will keep decreasing as galaxies run out of new gas; the Universe has already made the majority of its stars!

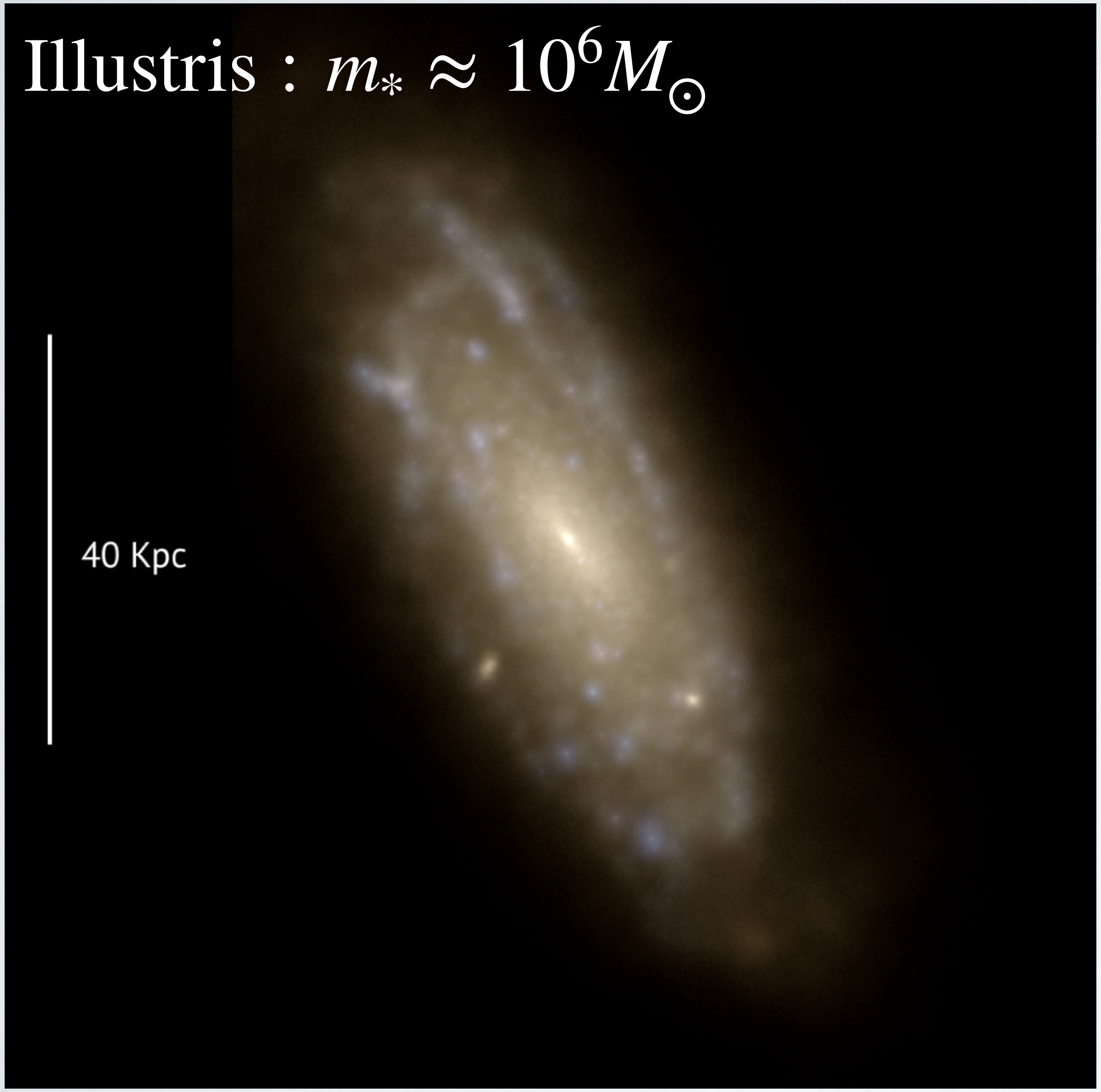
Part 3: Satellites, mergers, clusters

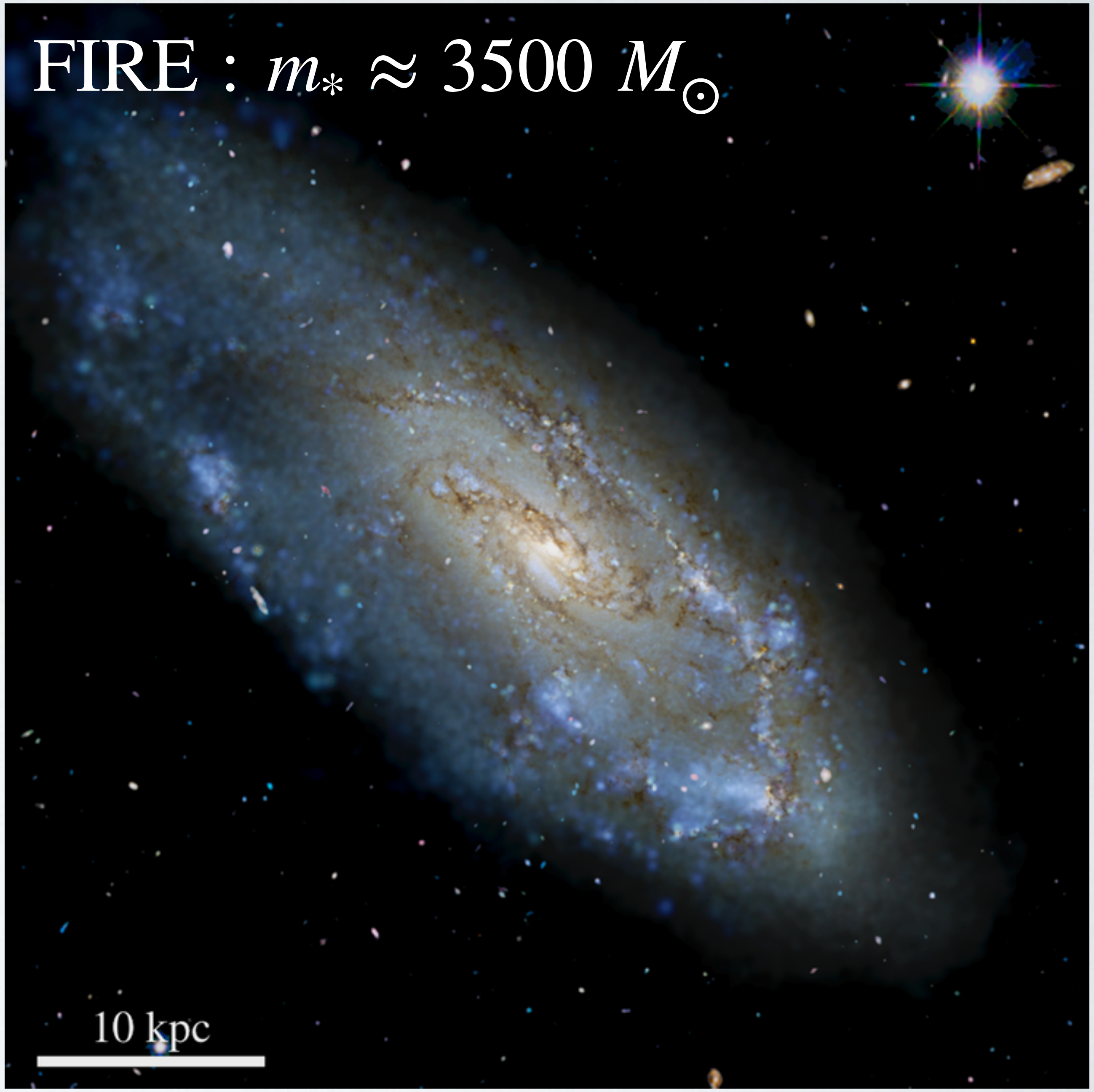
Merging galaxies (observations)



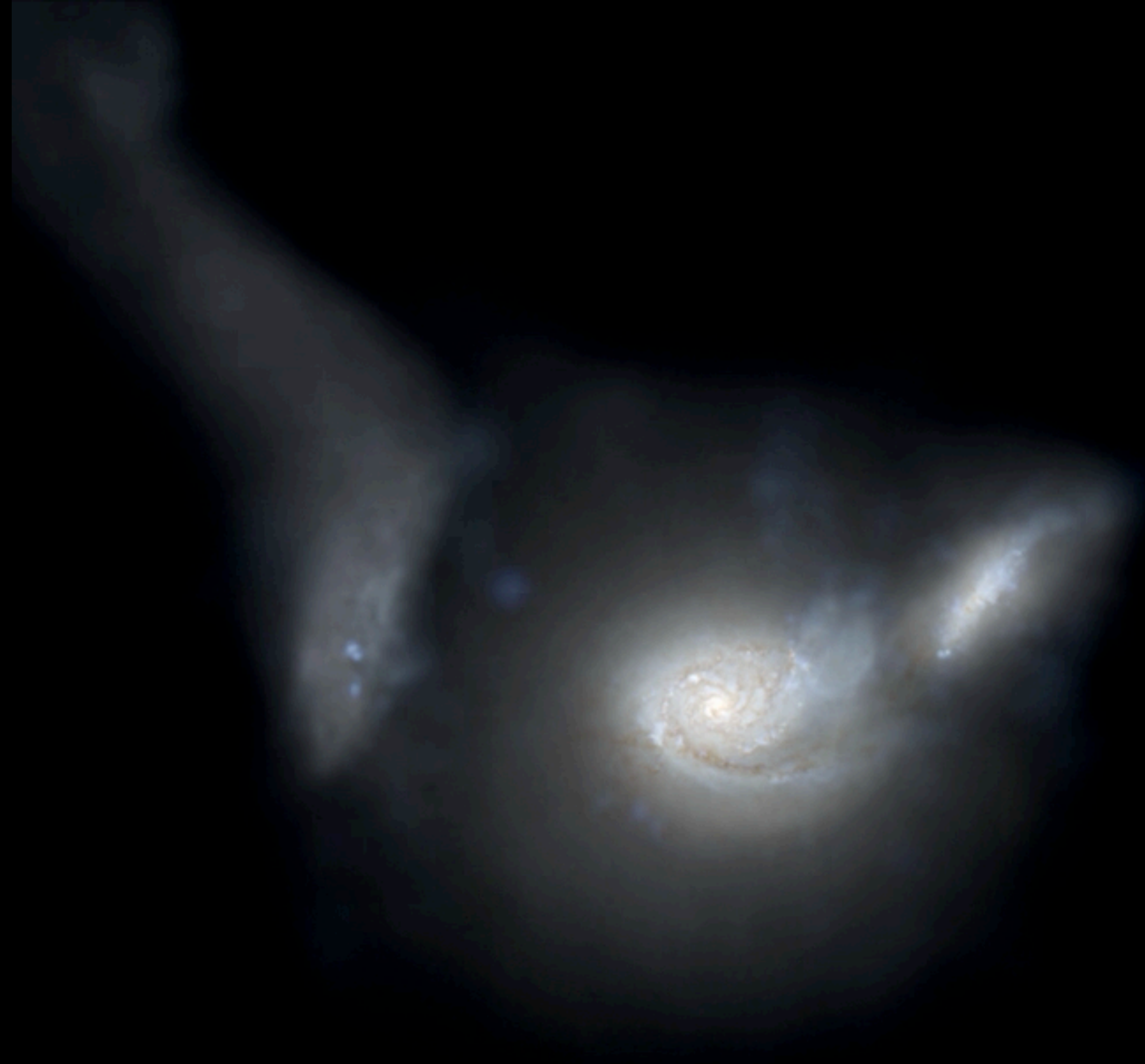
NASA, ESA, A. Evans, K. Noll, J. Westphal

High resolution vs. large volume in simulations



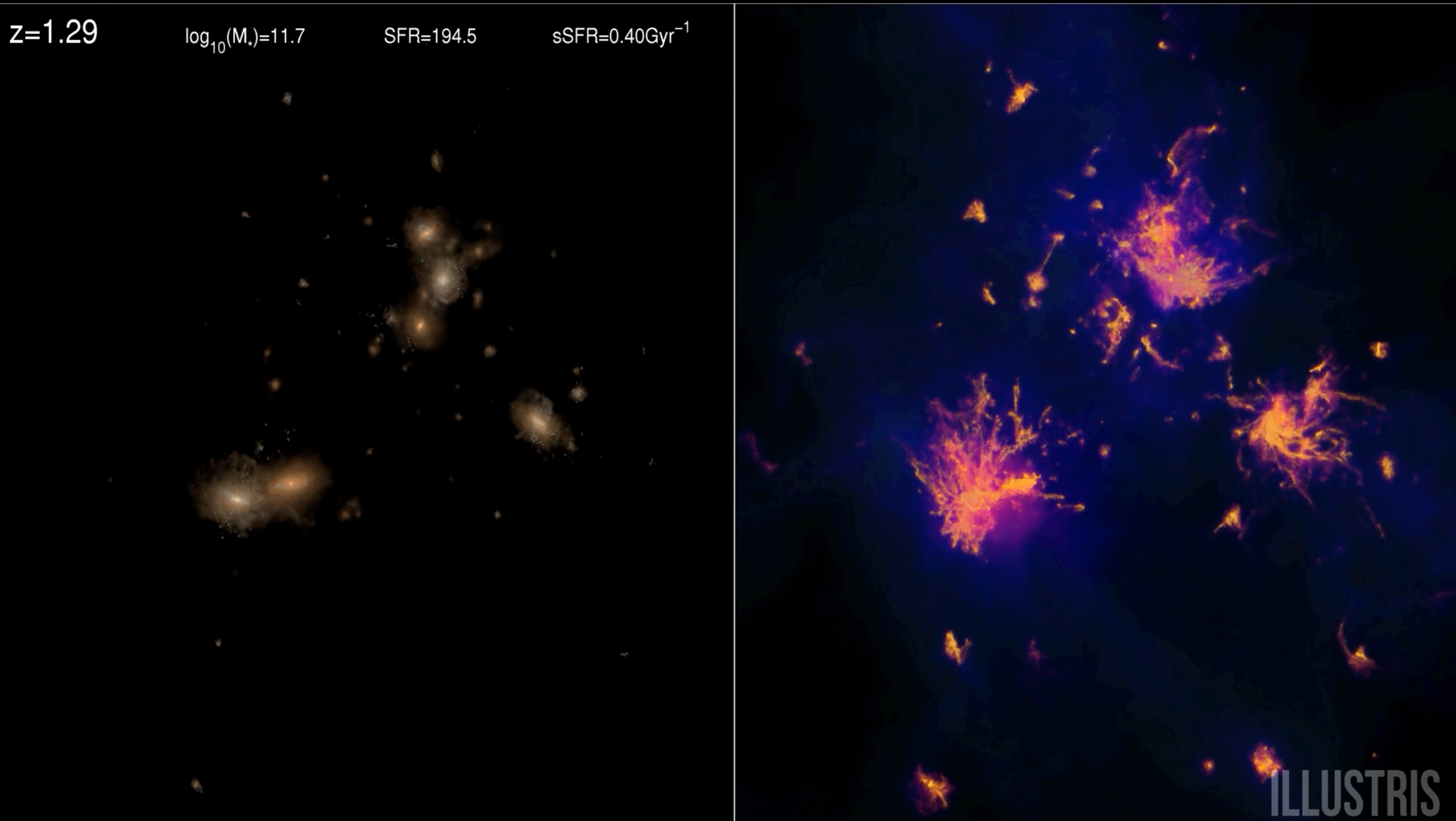


Illustris: Vogelsberger et al. 2013, 2014ab • **FIRE/FIRE-2:** Hopkins et al. 2014, 2017



Simulation by the FIRE Collaboration

Formation of an elliptical galaxy (simulation)



IllustrisTNG Collaboration

Formation of cluster (simulation)

Illustris TNG50 • Pillepich et al. 2019 • Nelson et al. 2019

Coma Cluster (observations)

Summary of mergers and clusters

- Galaxies **merge frequently**
- When disk galaxies merge, the stellar orbits get mixed up and the result is likely **more elliptical**
- Galaxy **clusters are large halos** with numerous subhalos and the **satellites** that live within them

Part 4: The Milky Way and the Local Group

Participation: Star formation rate

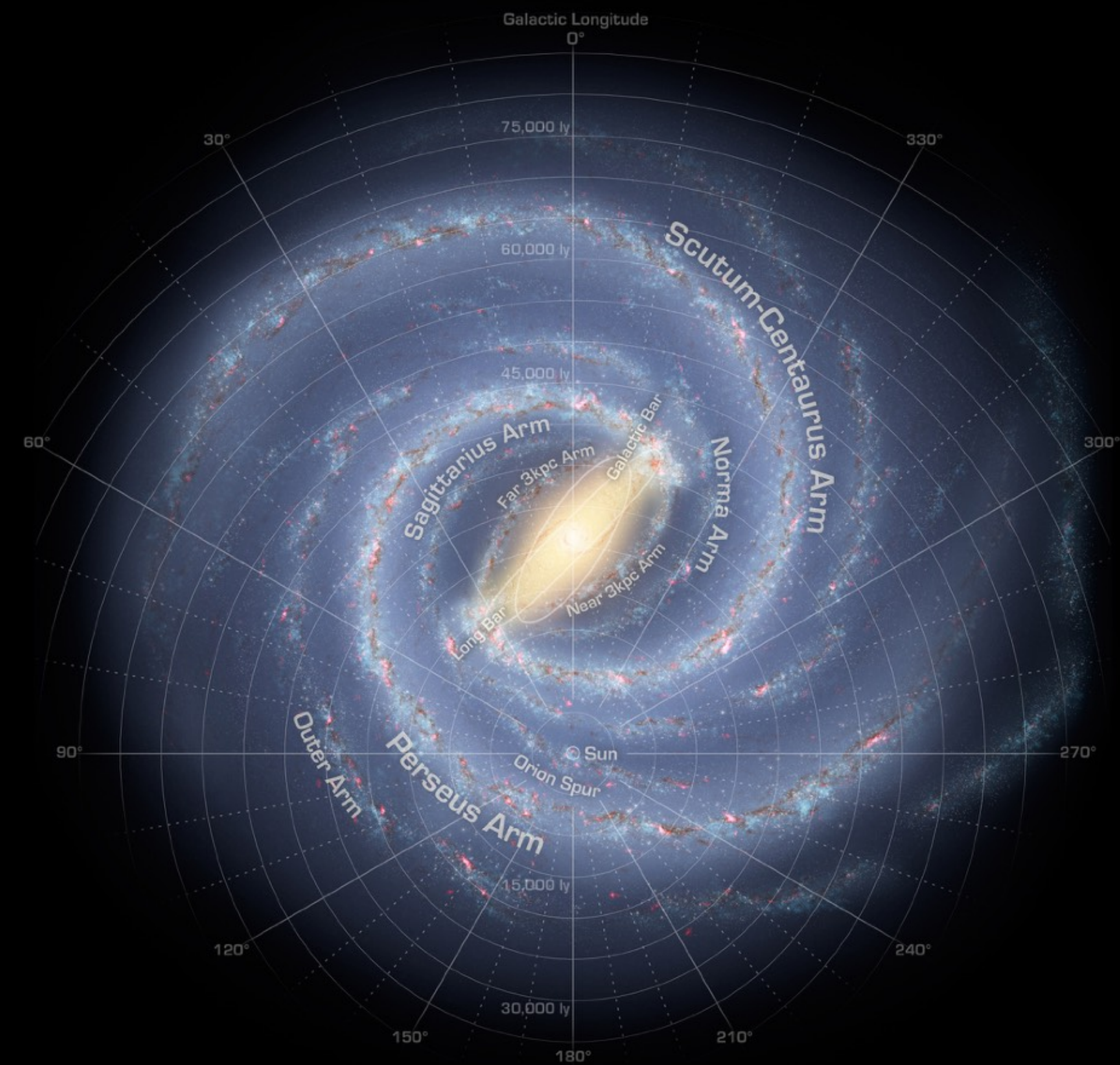
TurningPoint:
What is the star formation rate of the Milky Way, roughly?

Session ID: diemer

30 seconds

Milky Way

- Fairly typical spiral disk galaxy
- Probably has modest bar
- Stellar mass about $6 \times 10^{10}\ M_\odot$
- Forms about $1.5\ M_\odot/\mathrm{yr}$ in stars
- In "green valley" (neither red nor blue)
- Two relatively large satellites
  (large and small Magellanic clouds)



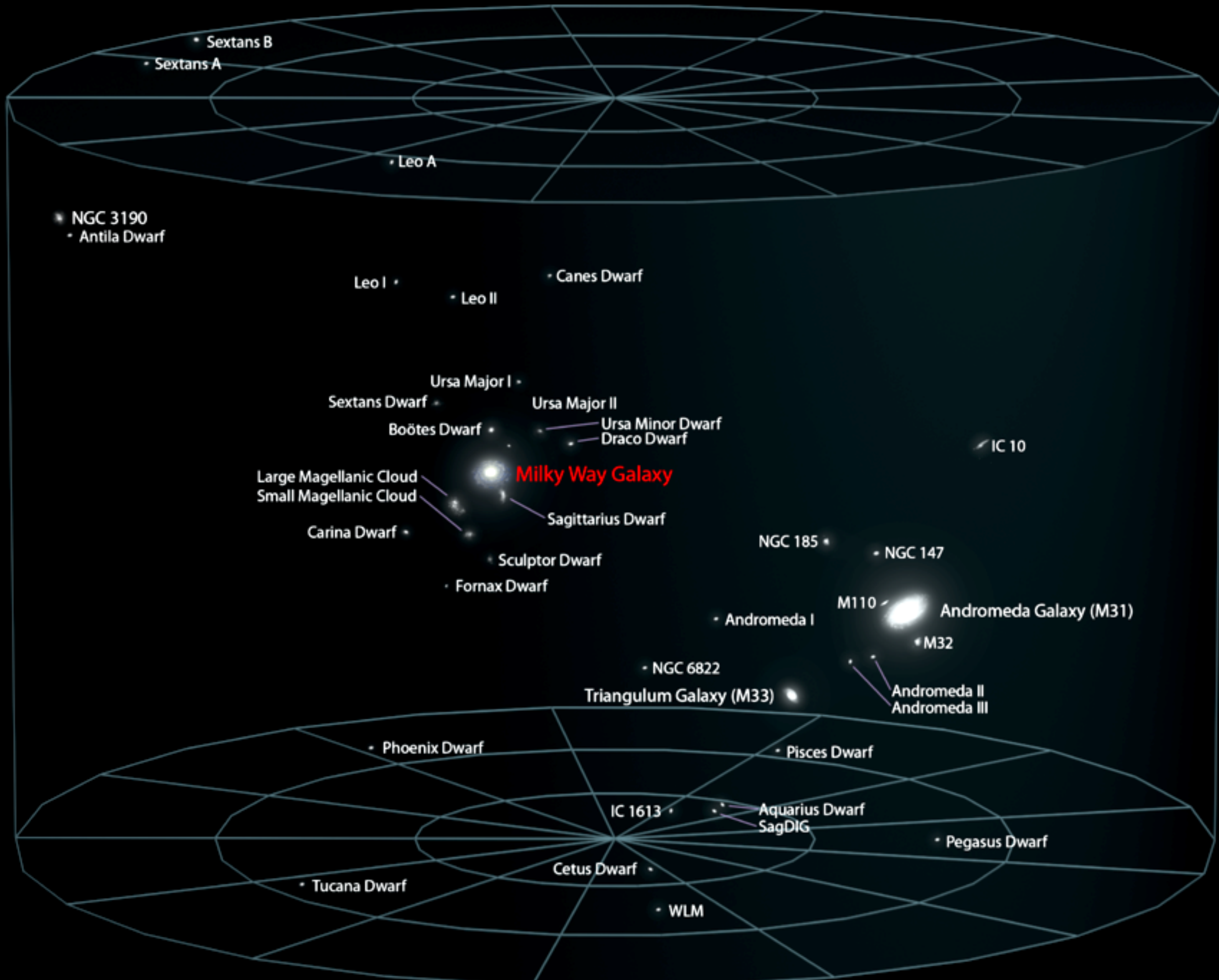


Image: A. Colvin

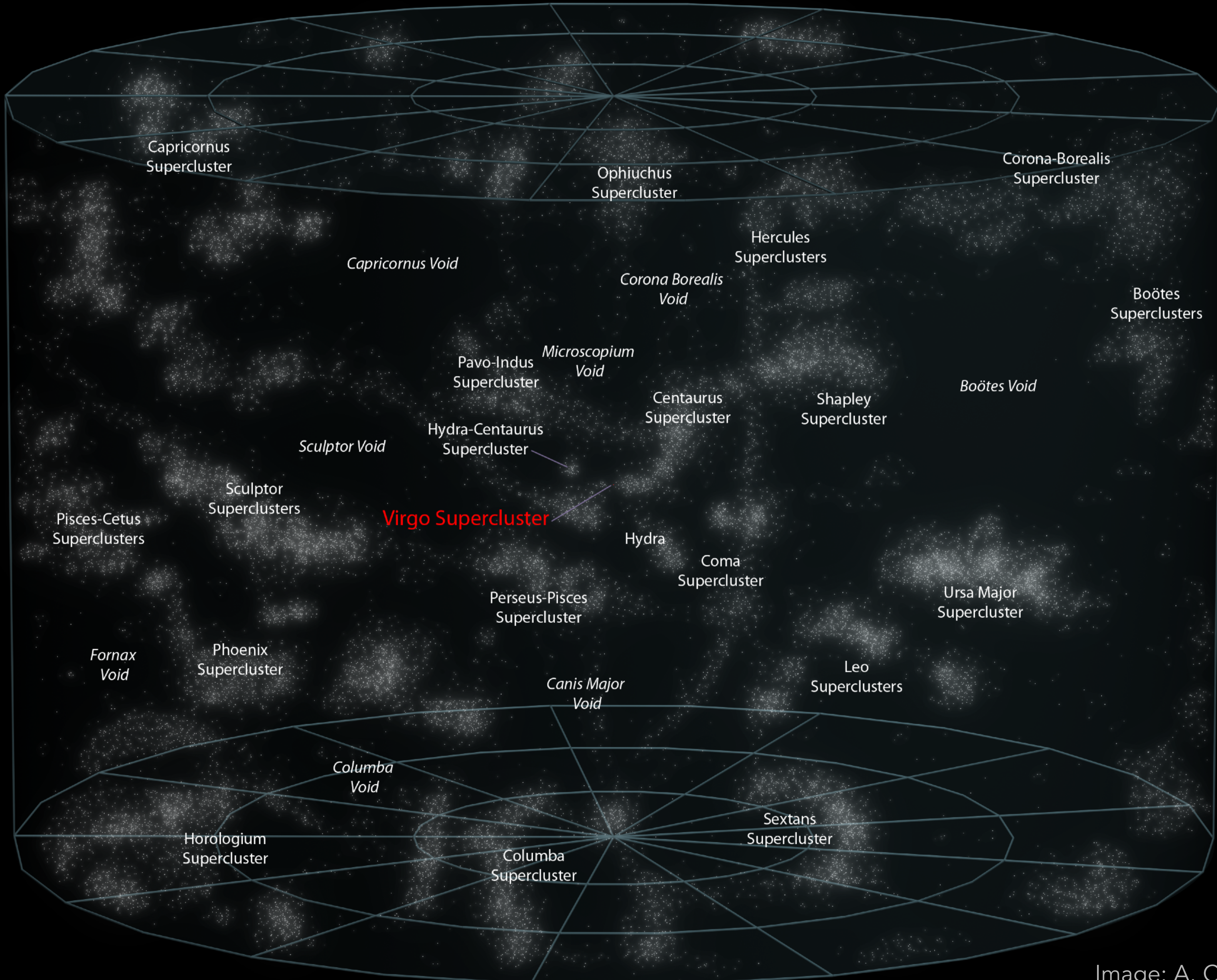
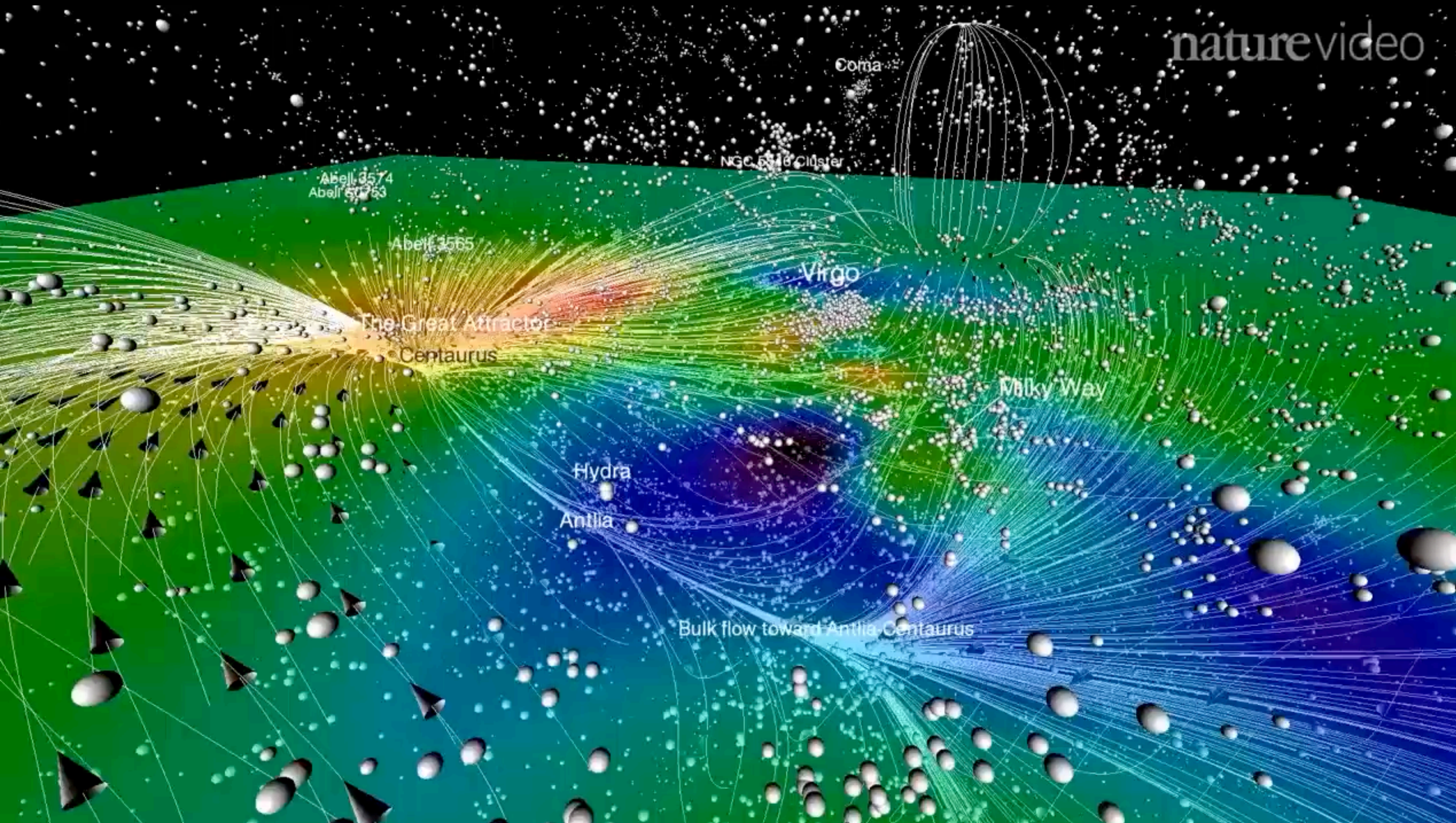


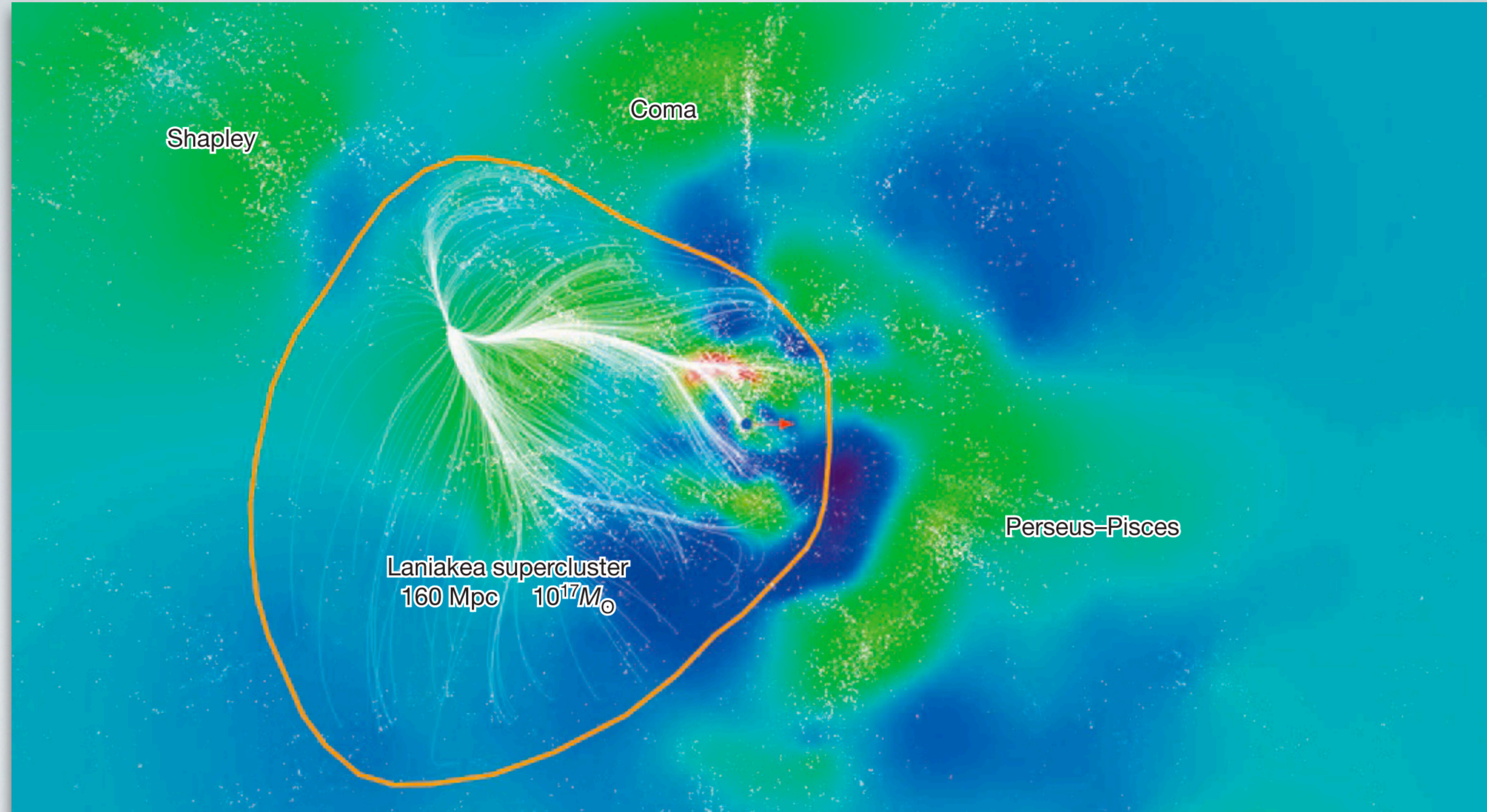
Image: A. Colvin

Laniakea Supercluster



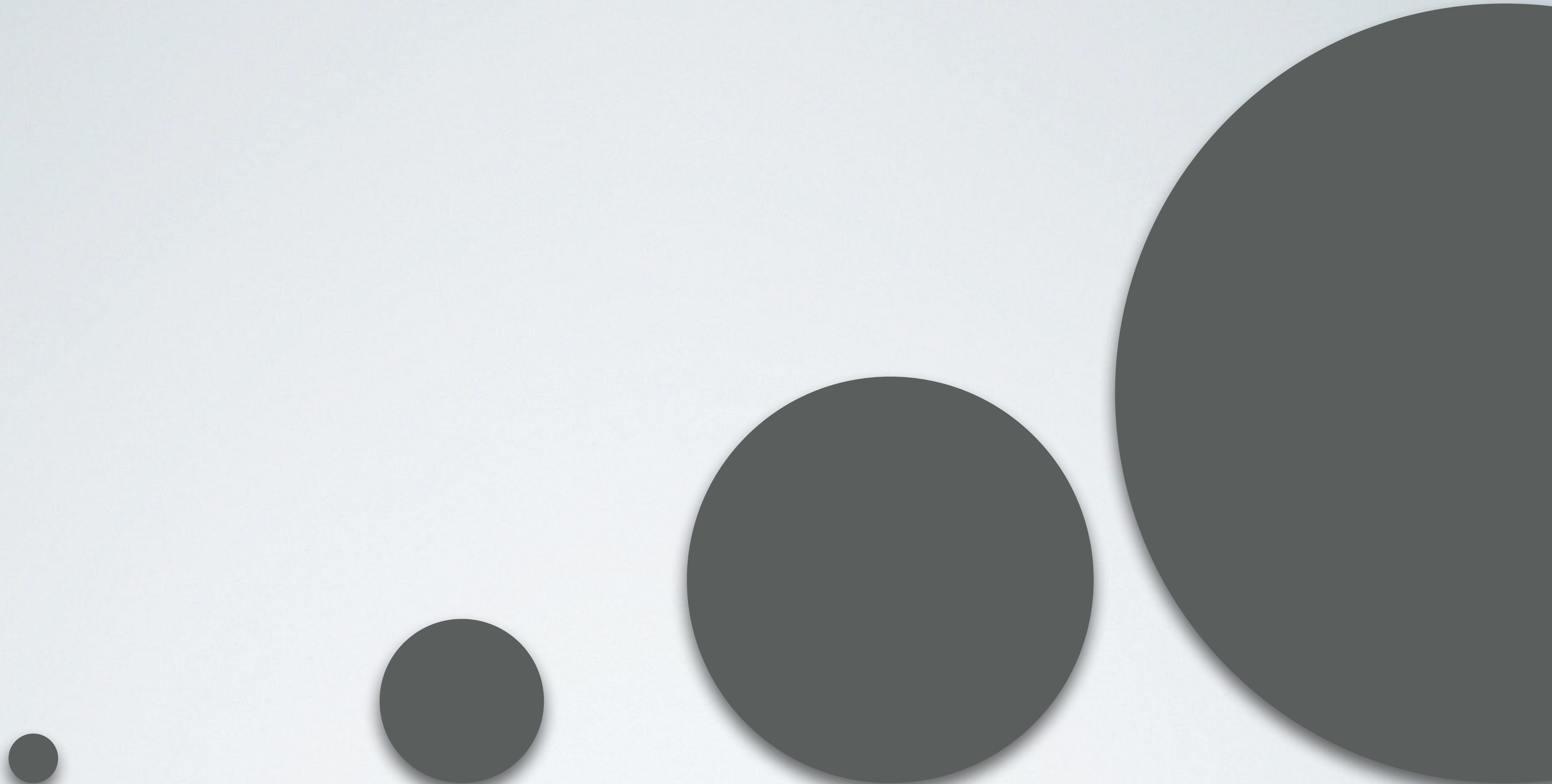
Nature • Tully et al. 2014

Laniakea



Tully et al. 2014

Halo masses for comparison



Large Magellanic cloud	Milky Way	Big clusters	Laniakea supercluster
$M \approx 10^{10}\ M_\odot$	$M \approx 10^{12}\ M_\odot$	$M \approx 10^{15}\ M_\odot$	$M \approx 10^{17}\ M_\odot$

Take-aways

- The most important characteristics of galaxies are **color** (red / blue, or old / young) and **shape** (disk / elliptical)
- The **evolution** of galaxies **follows their halos**: it typically starts fast and slows down as gas supply dries up
- **Feedback** from Supernovae, Active Galactic Nuclei, and other mechanisms reduces star formation
- Galaxies evolve both **internally** (aging stellar population) and **externally** (mergers, interactions)

Next time…

We'll talk about:

- Black holes

Assignments

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

Reading:

- H&H Chapter 9