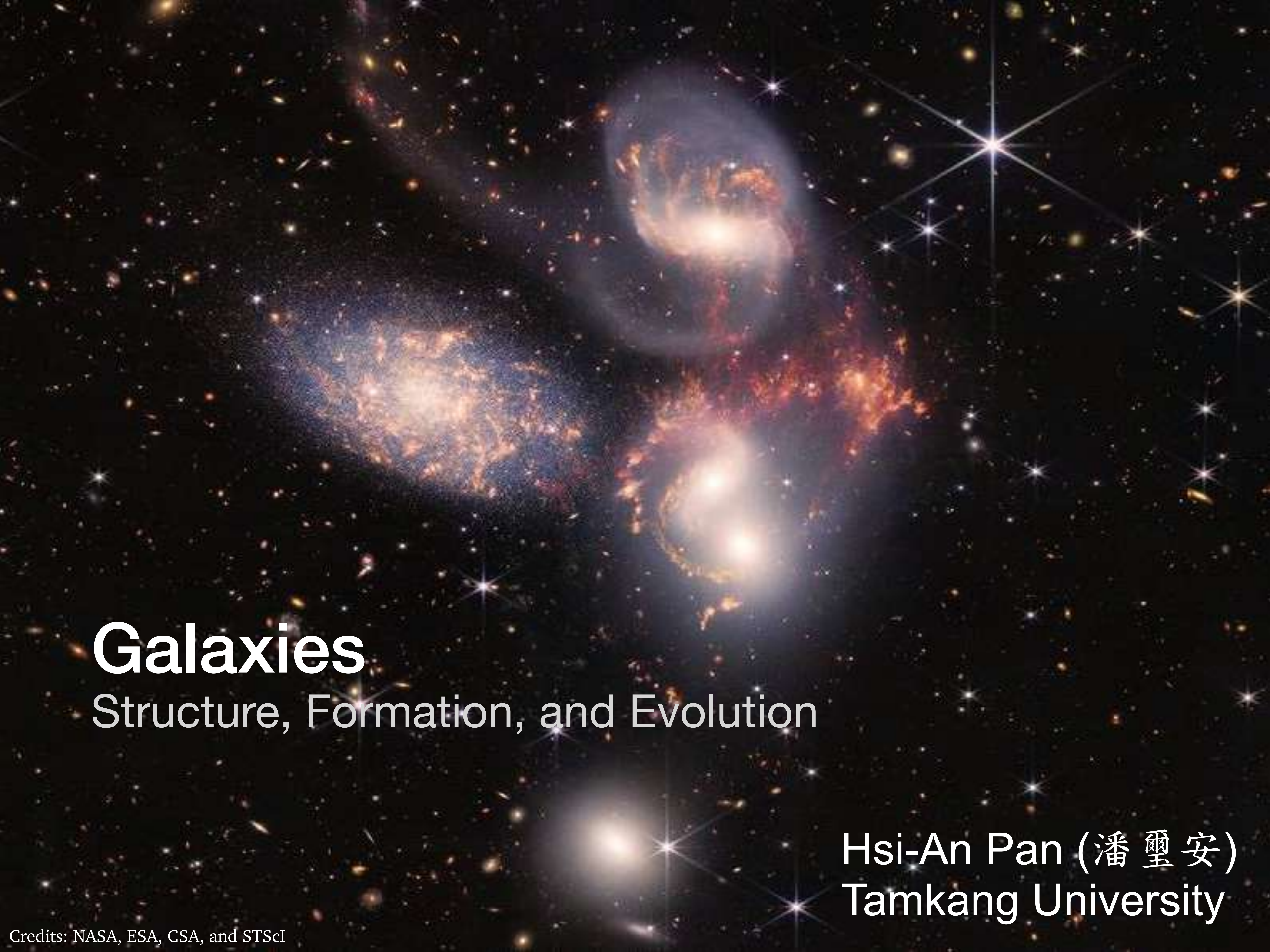


Galaxies

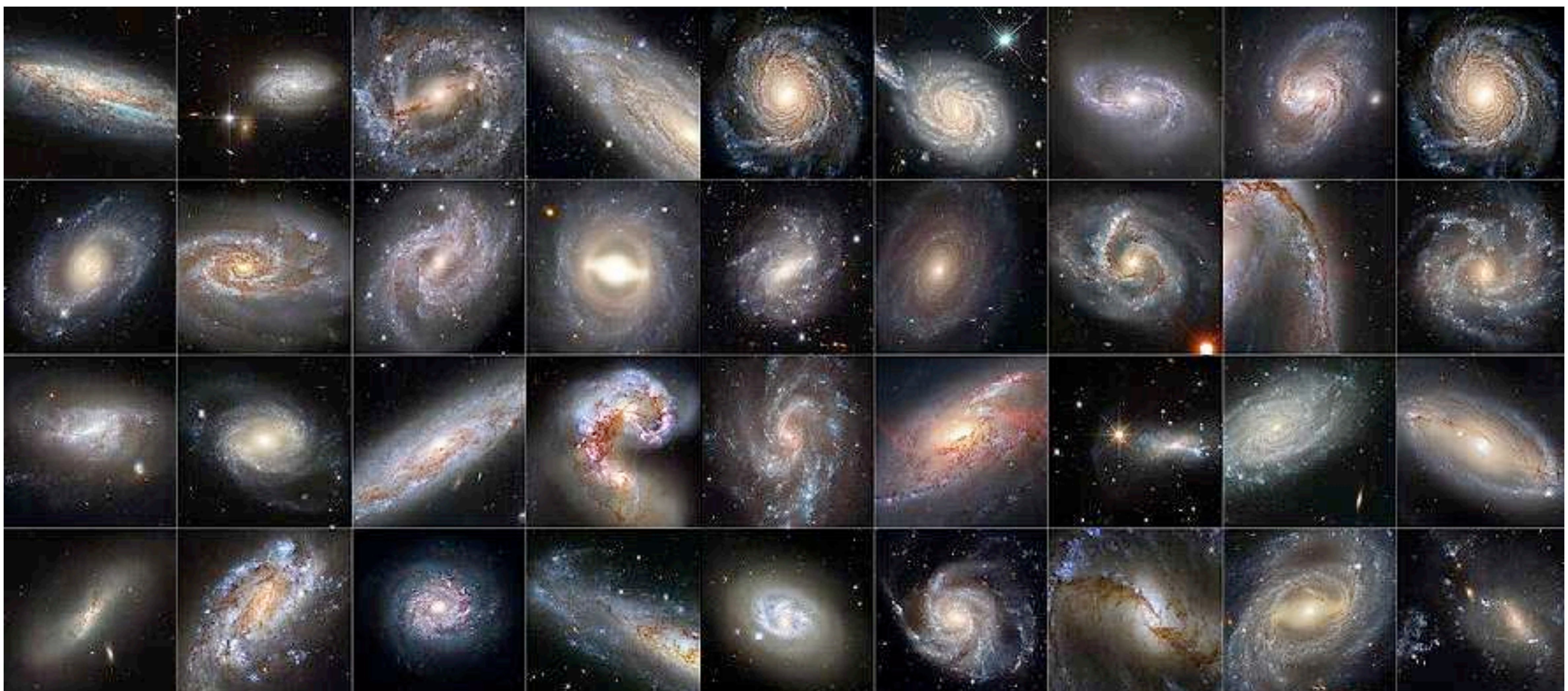
Structure, Formation, and Evolution

Hsi-An Pan (潘璽安)
Tamkang University

Credits: NASA, ESA, CSA, and STScI

What is a Galaxy?

- A galaxy is a gravitationally bound system.
    - Stars – from a few million to hundreds of billions
    - Gas and Dust – the interstellar medium (ISM)
    - Dark Matter – invisible mass dominating the galaxy's total mass
    - Sometimes: a central supermassive black hole



NASA, ESA, ADAM G. RIESS (STSCI, JHU)

Why Study Galaxies?

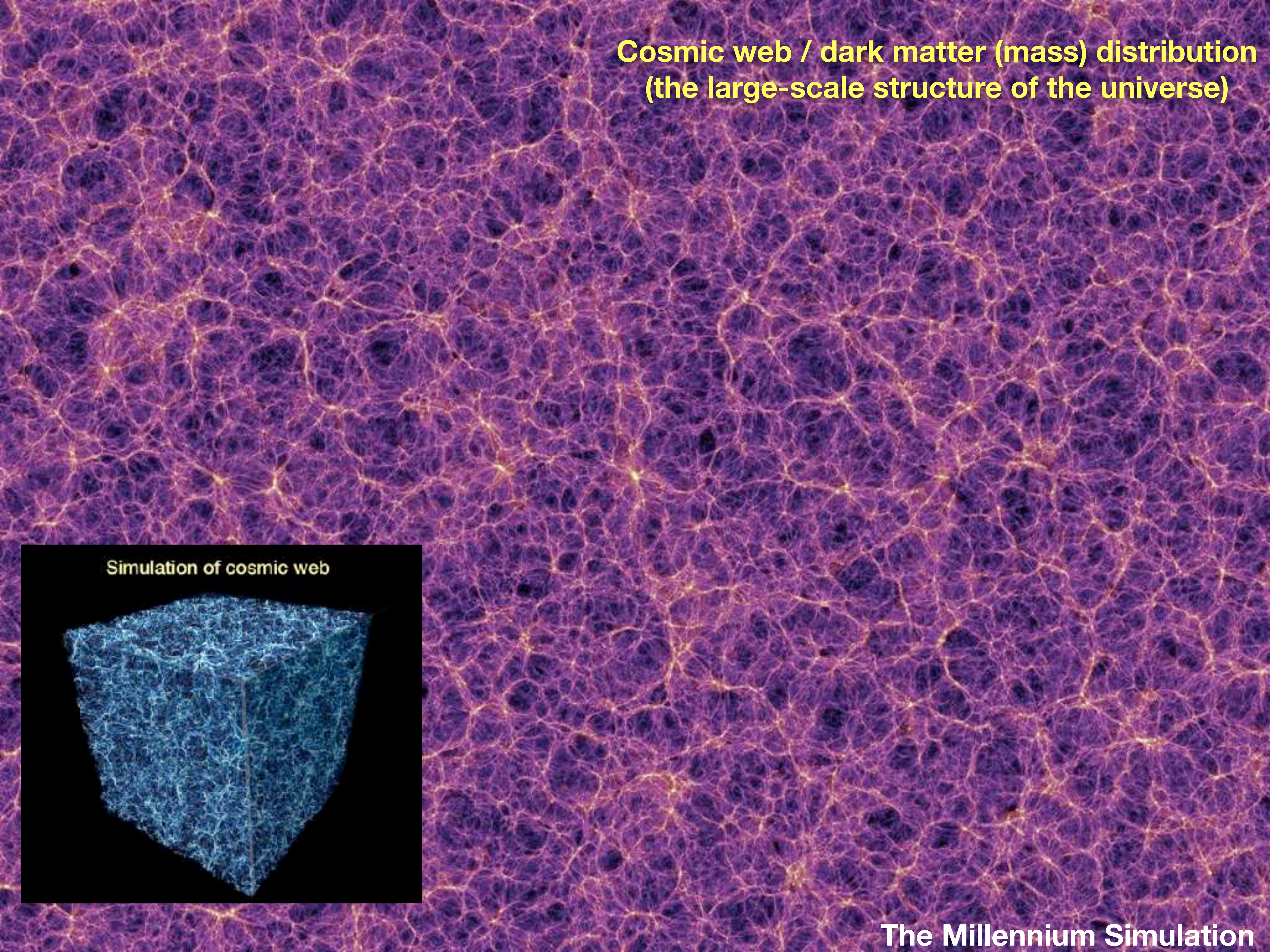
- **Galaxies contain most of the visible matter in the Universe.**
  - Contain the stars, planets, and gas where all astrophysical processes happen; therefore, they act as **cosmic laboratories** for studying star formation, black holes, and chemical evolution.
- **Astrophysical processes happen inside galaxies**
  - Star formation, stellar evolution, chemical enrichment, and black hole activity all take place within galaxies, making them the key sites of astrophysical phenomena.


ESA/Hubble

Why Study Galaxies?

Credit: NSF-DOE Vera C. Rubin Observatory

Cosmic web / dark matter (mass) distribution
(the large-scale structure of the universe)



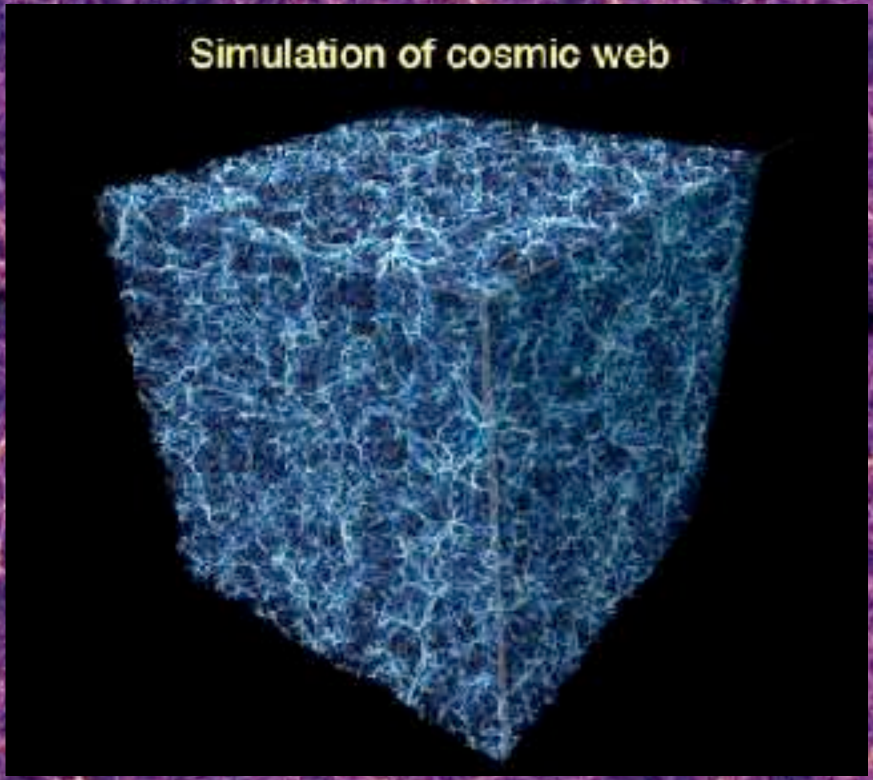
The Millennium Simulation

Why Study Galaxies?

- **Galaxies contain most of the visible matter in the Universe.**
  - Contain the stars, planets, and gas where all astrophysical processes happen; therefore, they act as **cosmic laboratories** for studying star formation, black holes, and chemical evolution.
- **Galaxies form the large-scale structure of the Universe**
  - On cosmic scales, galaxies are not randomly scattered, they cluster into groups, clusters, and filaments, tracing the cosmic web shaped by dark matter and the expanding Universe.

Cosmic web / dark matter (mass) distribution
(the large-scale structure of the universe)

What if mass were perfectly uniform in the universe?



The Millennium Simulation

I. Galaxy Types & Classification

II. Galaxy Formation & Evolution

III. ISM Cycle and Feedback Processes

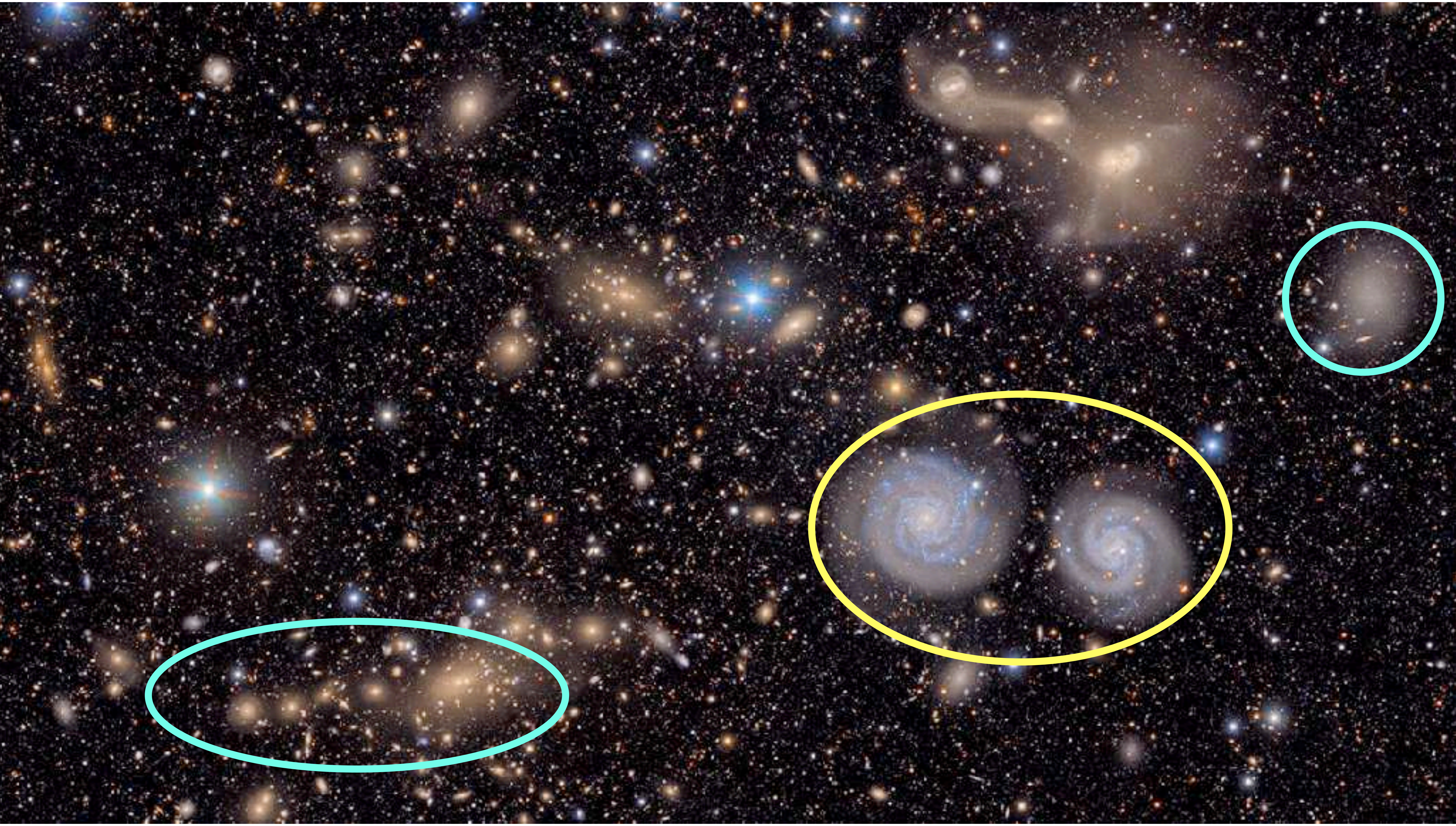
IV. How Do We Study Galaxies?

I. Galaxy Types & Classification

Galaxy Types & Classification

Credit: NSF-DOE Vera C. Rubin Observatory

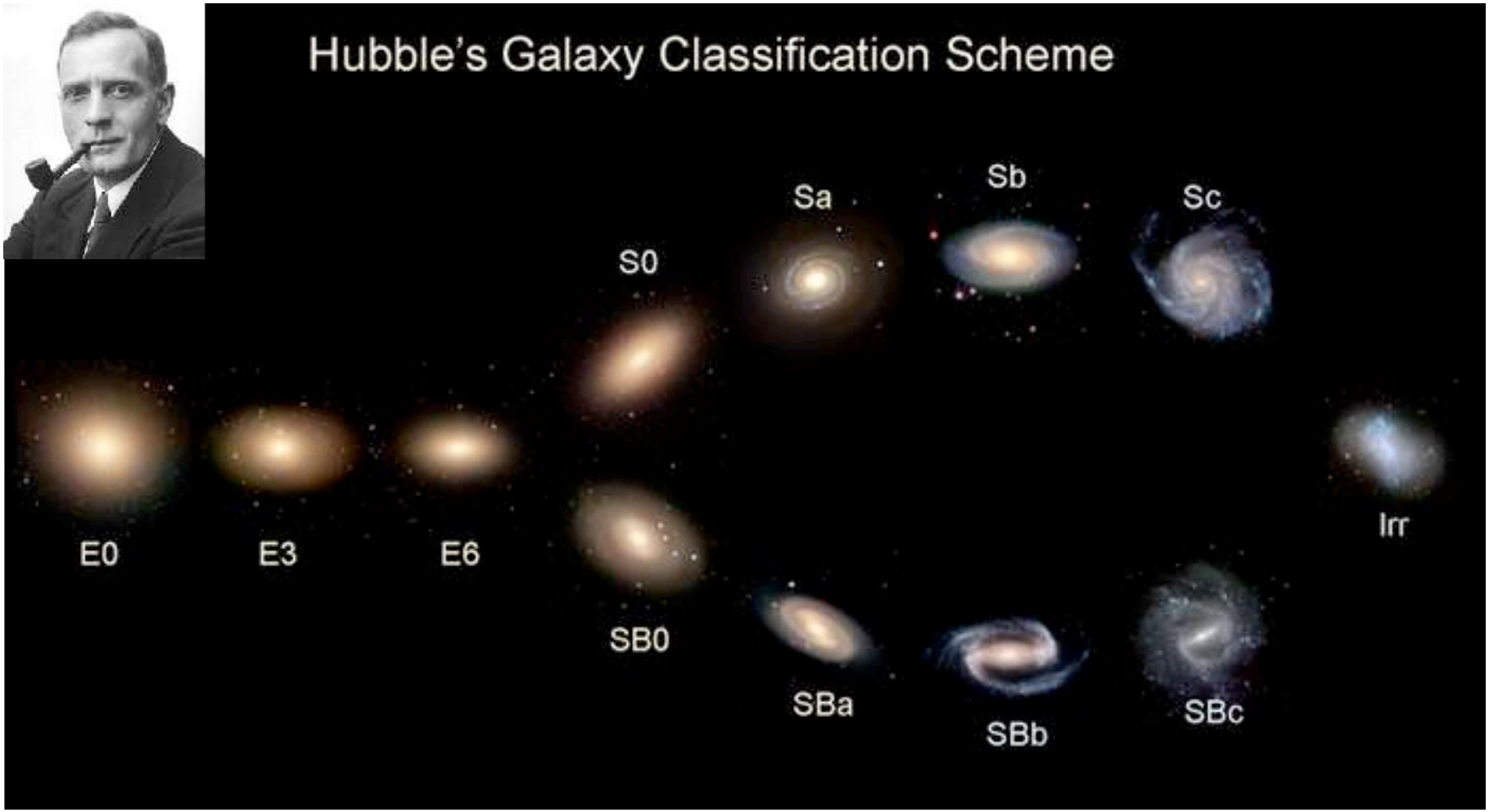
Galaxy Types & Classification



Credit: NSF-DOE Vera C. Rubin Observatory

Galaxy Types & Classification

- Galaxies are classified according to their appearance.



Spiral Galaxies

- Spiral galaxies are characterized by arched lanes of stars, just as is our own Milky Way Galaxy.
- The spiral arms contain young stars, indicating ongoing star formation.

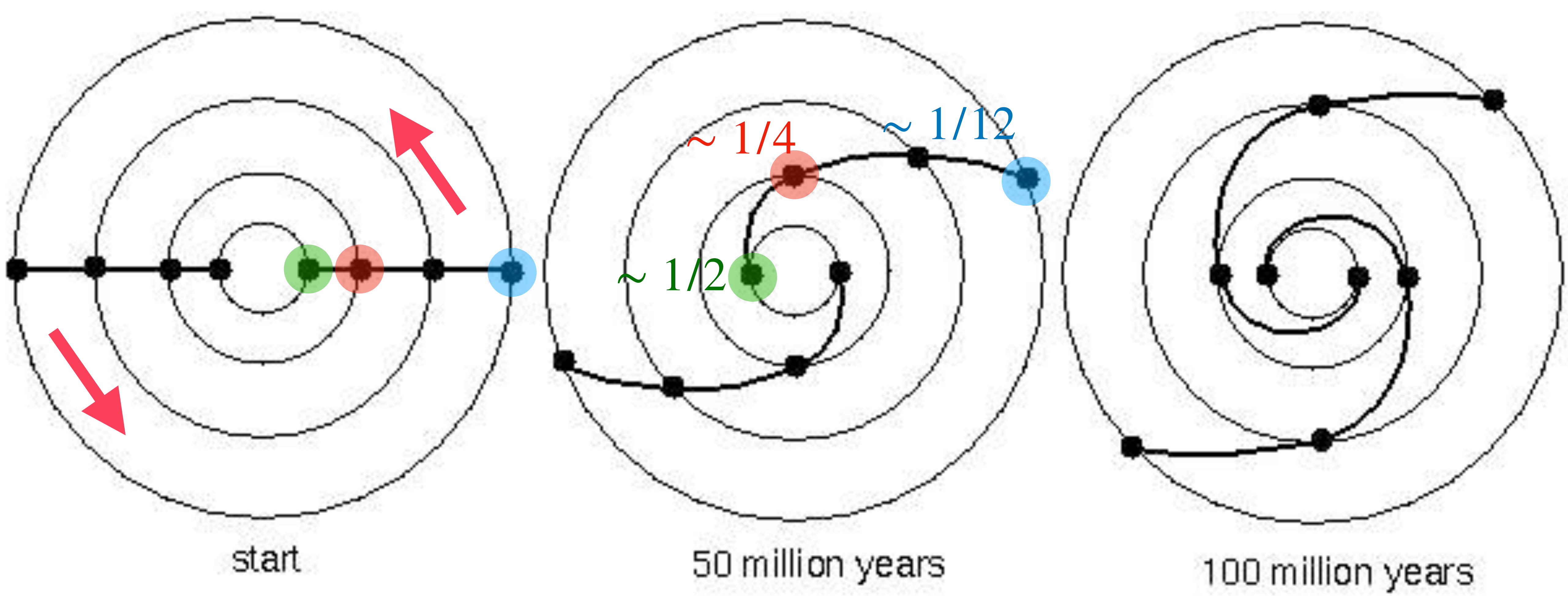
(a) Sa (NGC 1357) (b) Sb (M81) (c) Sc (NGC 4321)

R I V U X G

a: Adam Block/Steve Mandel/Jim Rada and Students/NOAO/AURA/NSF; b: Robert Gendler/Stocktrek Images/Science Source; c: ESO

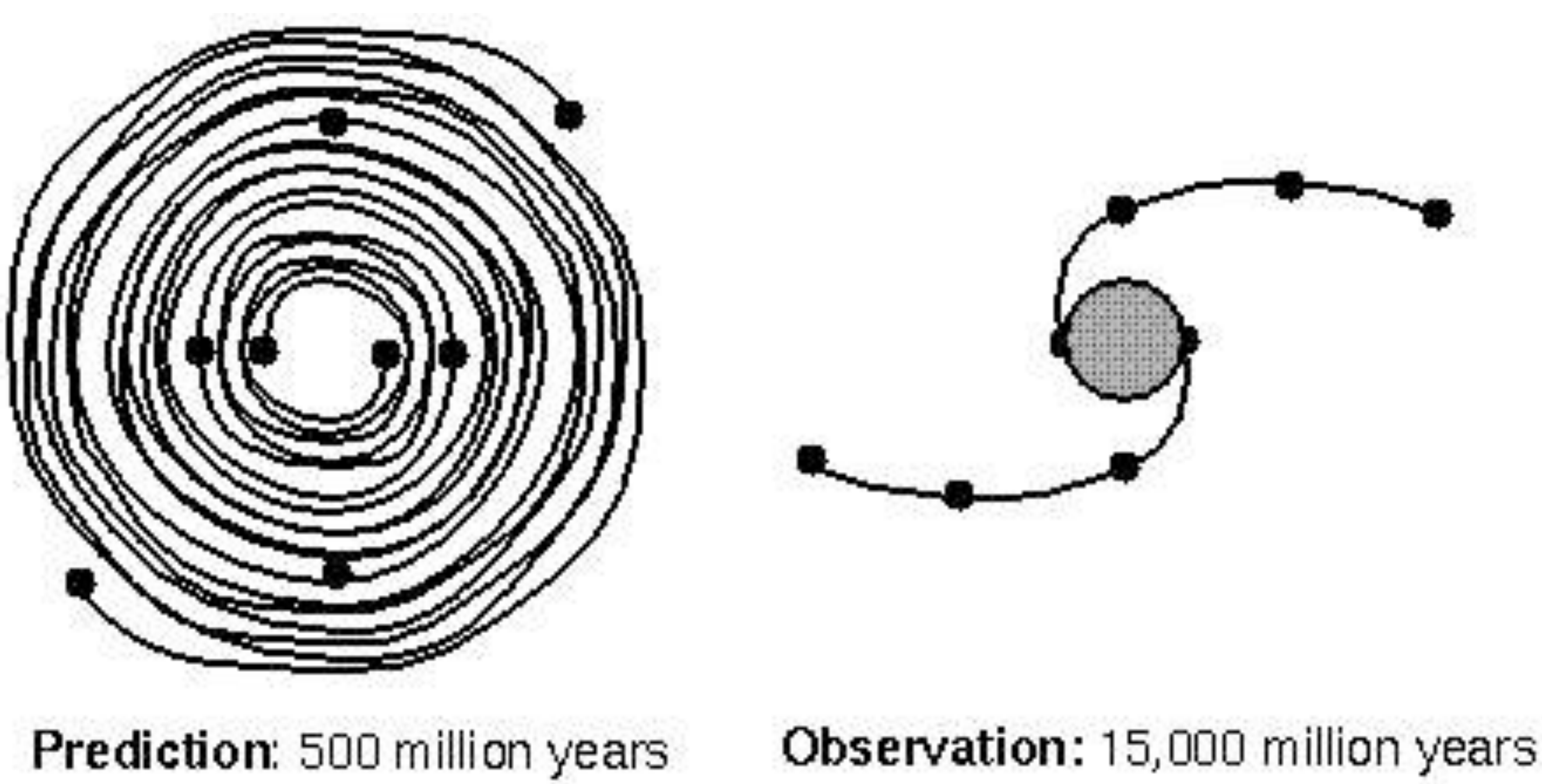
Spiral Galaxies

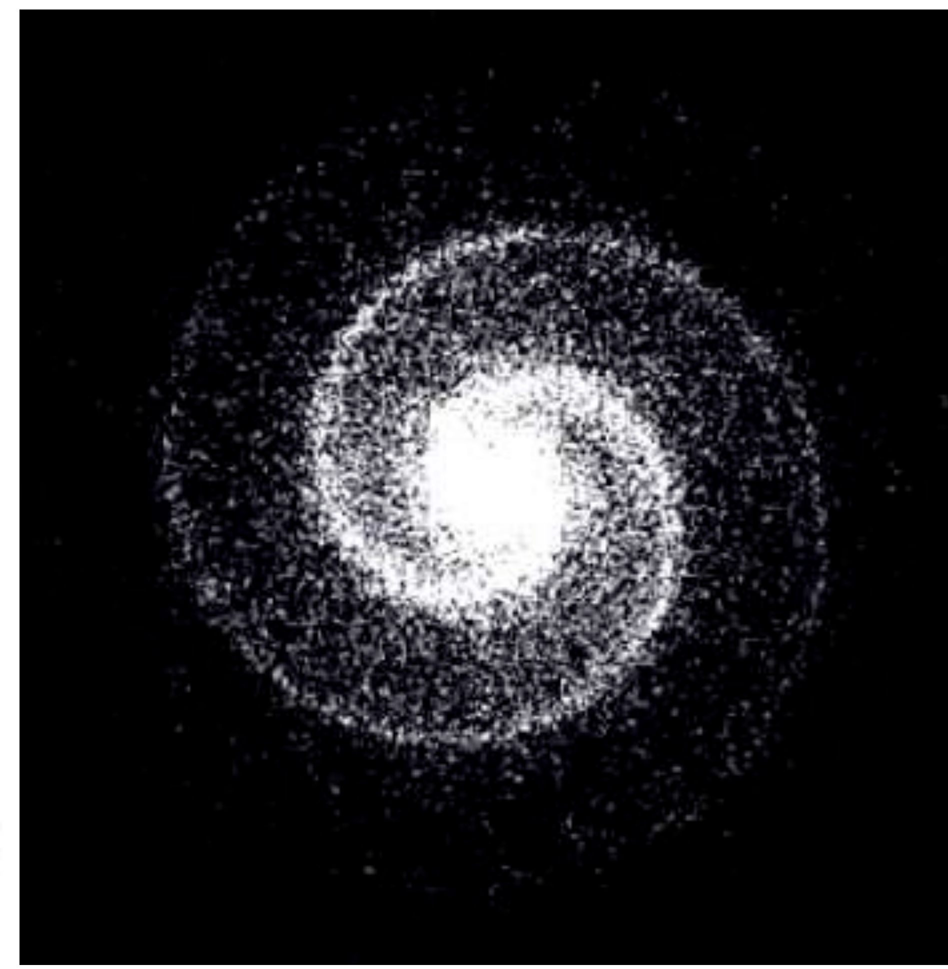
- **Differential rotation** provides an easy way to produce a spiral pattern in the disk.
- Most spiral galaxies have constant circular velocity ($v(r)$) at different radii (r). But angluar veloicity is $\Omega(r) = \dfrac{v(r)}{r}$, so the **angular veloicity** is dfferent at different radii.



Spiral Galaxies

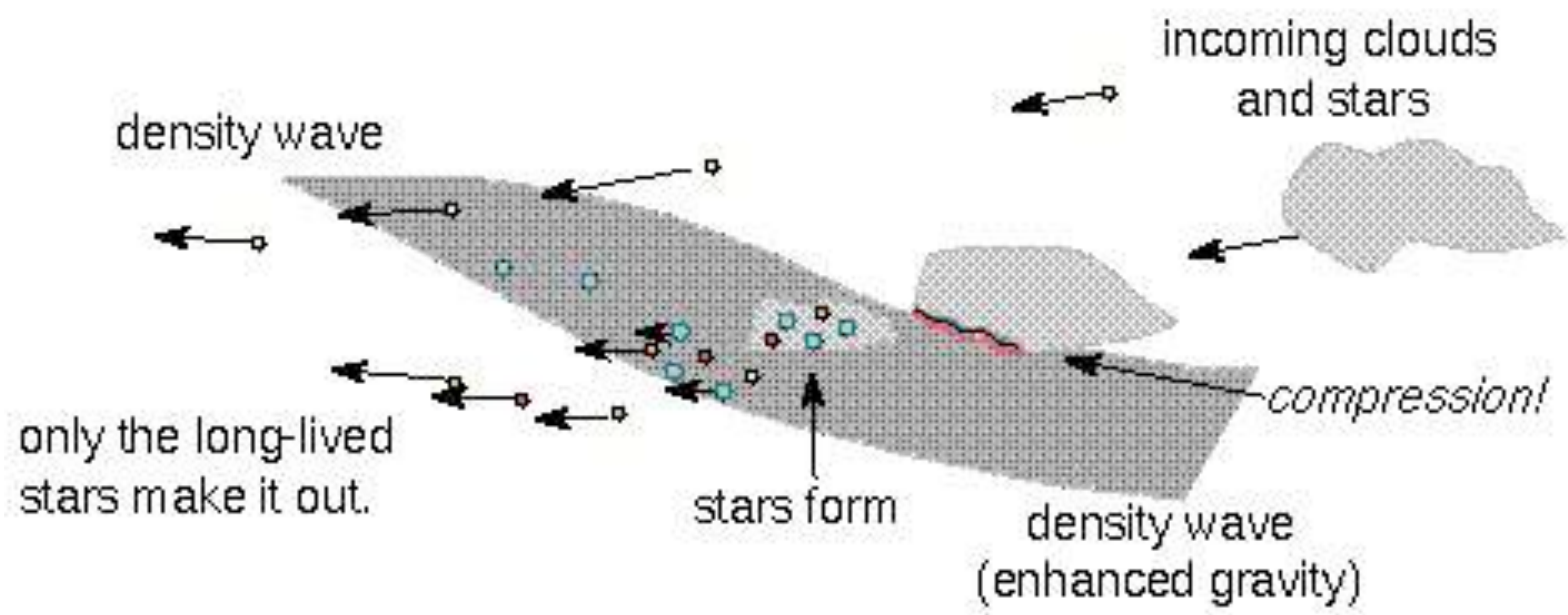
- The arms would wind up tighter and tighter over time. But observations show spiral arms that are not tightly wound. This is called **winding problem**.





Spiral Galaxies

- One popular theory says that the **spiral structure is a wave** that moves through the disk causing the stars and gas to clump up along the wave — the density wave.
- Spiral arms are regions of higher density that move more slowly than individual stars and gas, i.e., spiral arm is a **pattern**, not a fixed set of stars.



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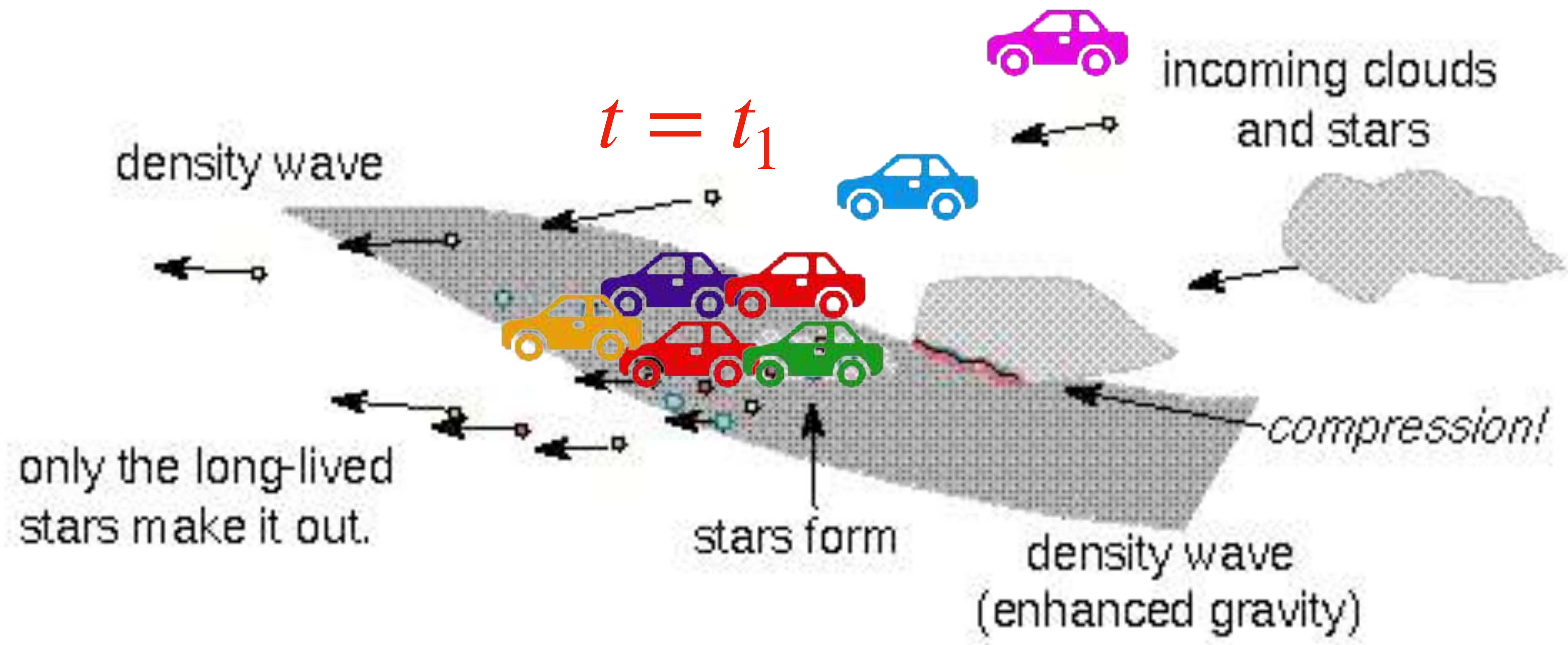

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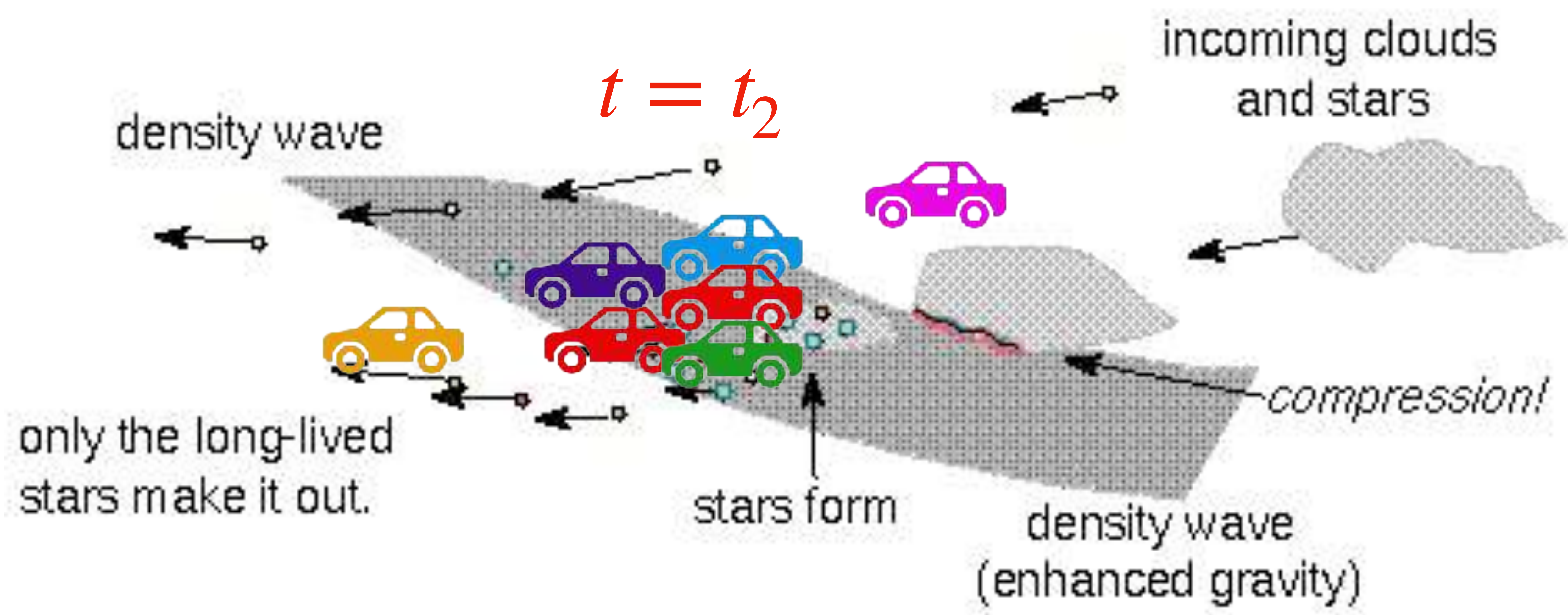

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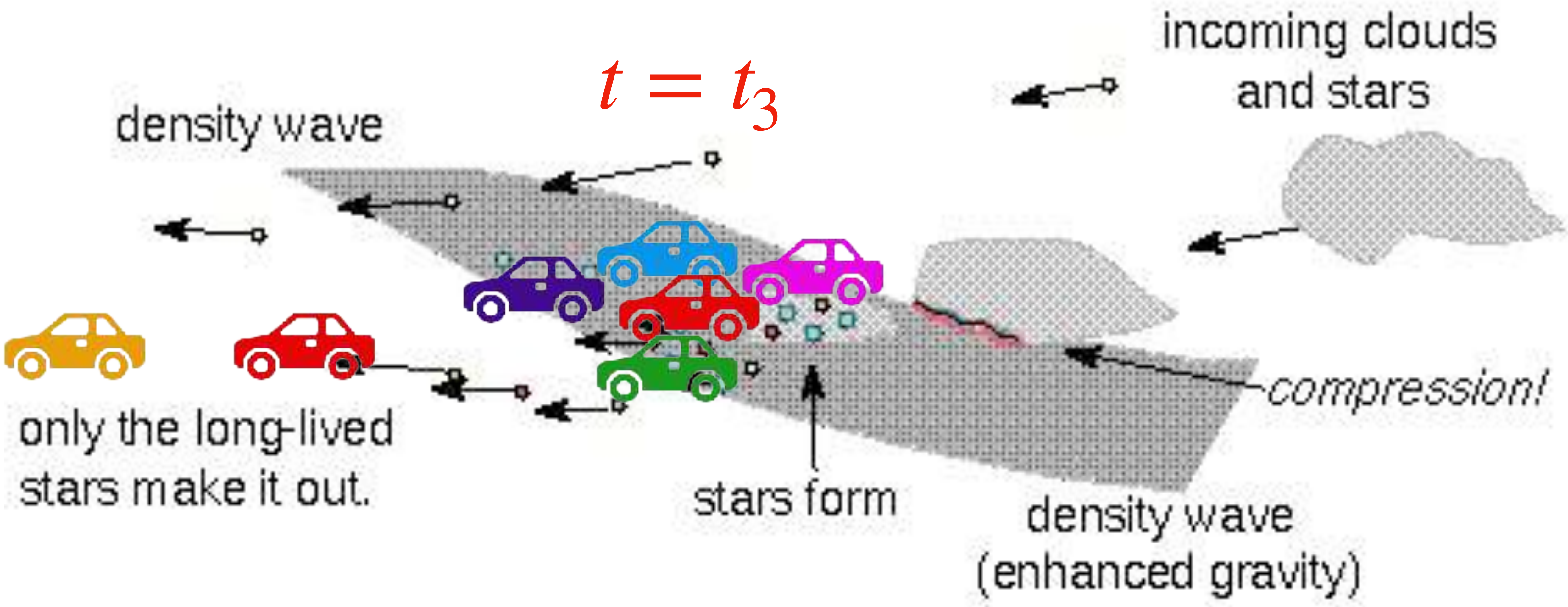

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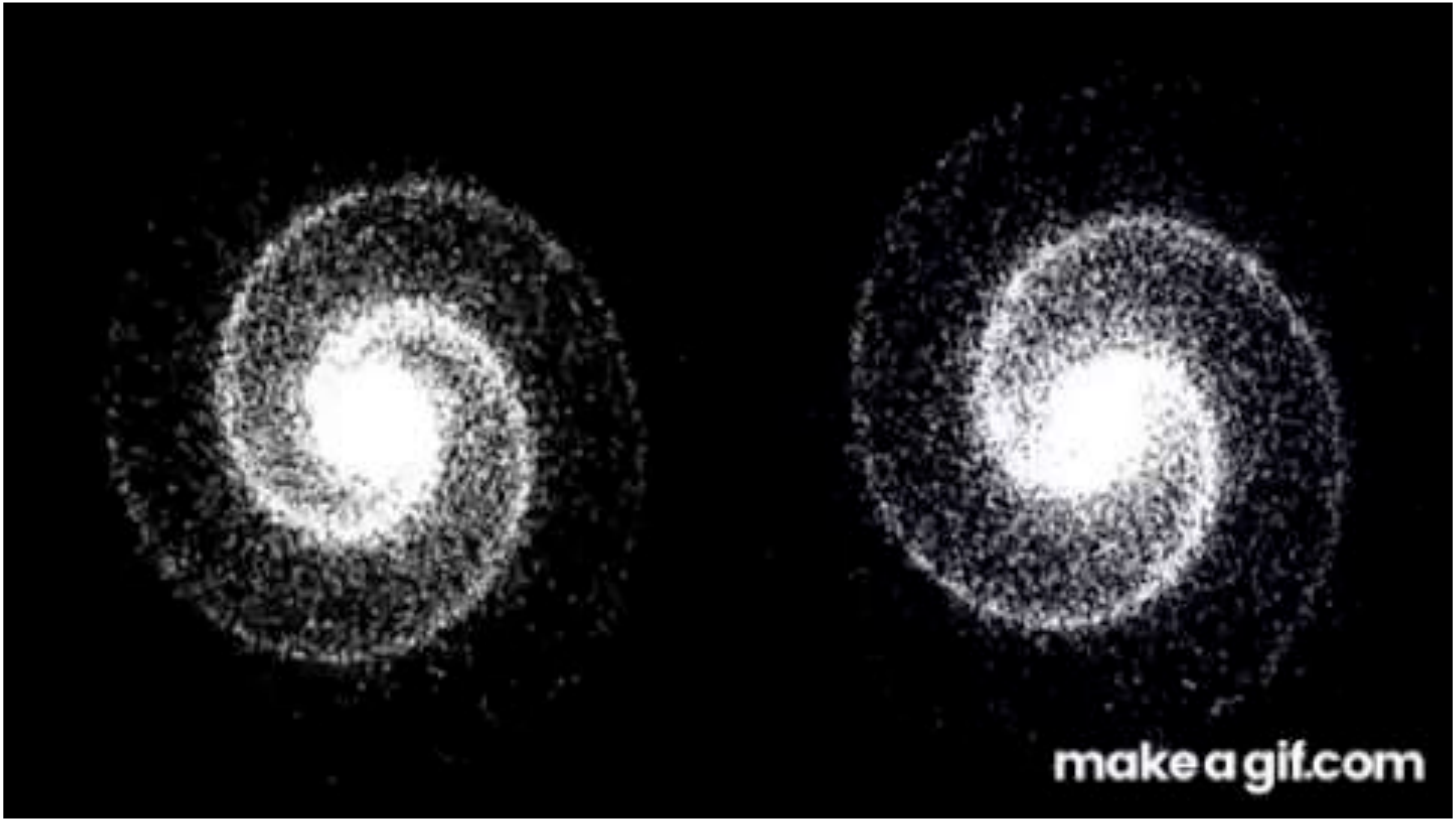

Spiral Galaxies

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Galaxy Types & Classification

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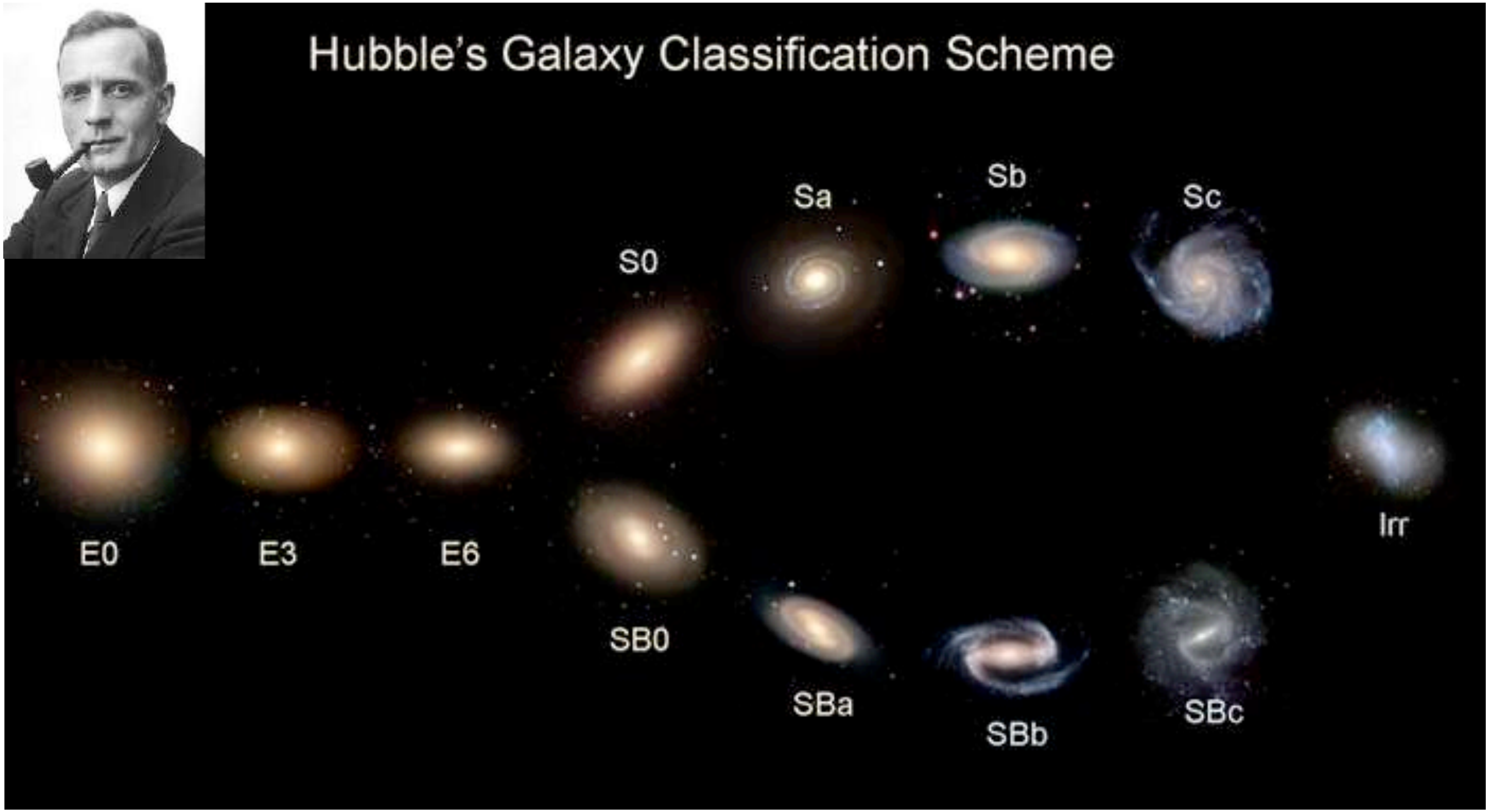

Barred-spiral Galaxies

- In some galaxies, the spiral arms originate at the ends of a bar-shaped region running through the galaxy's nucleus rather than from the nucleus itself. These are barred-spiral galaxies.

(a) SBa (NGC 1291)

R I V U X G

(b) SBb (M83)

(c) SBc (NGC 1365)

a: NASA/JPL-Caltech/CTIO; b, c: ESO

Barred-spiral Galaxies

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Non-barred galaxy

Barred galaxy

Galaxy Types & Classification

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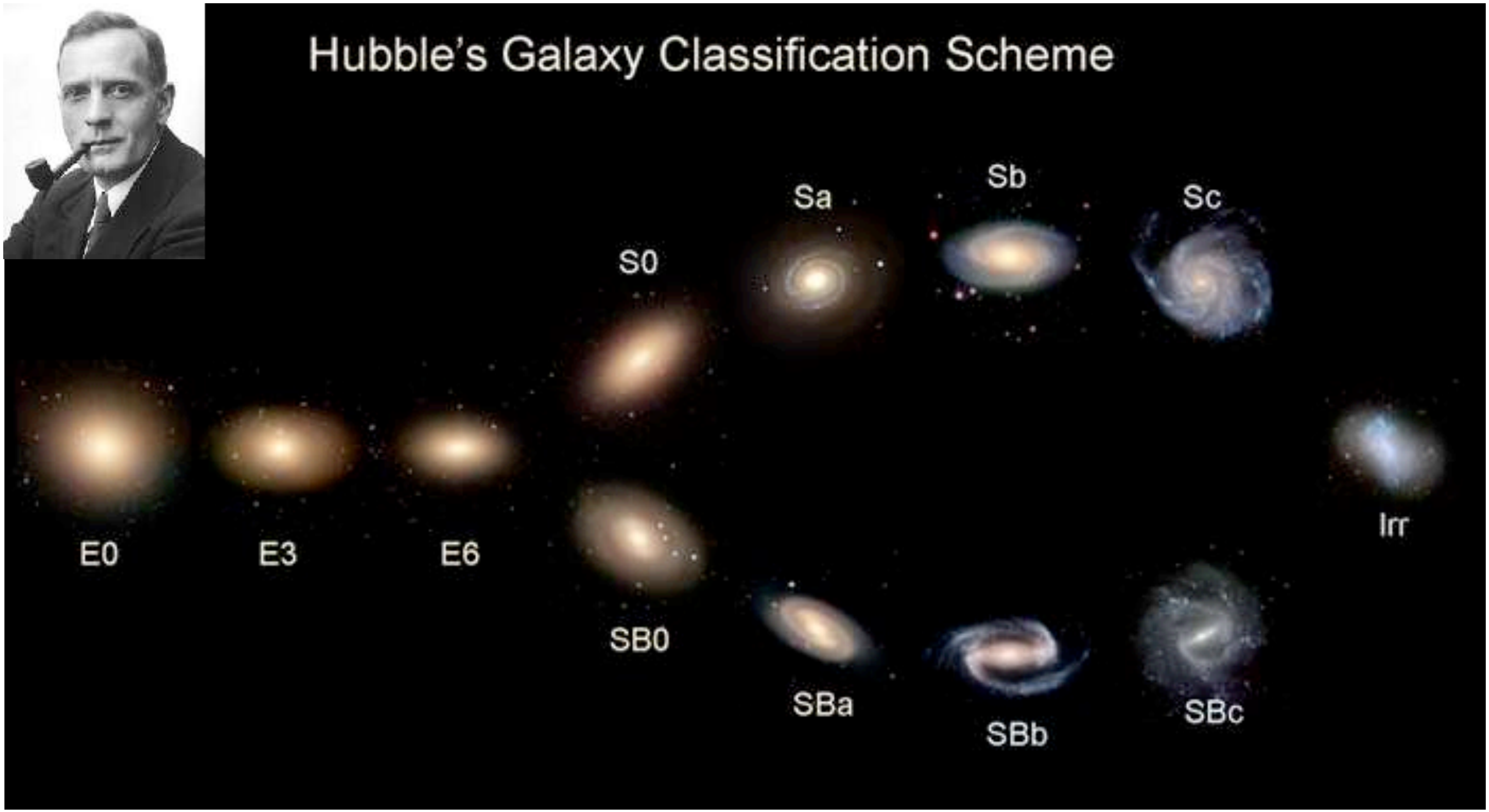

Elliptical Galaxies

- Elliptical galaxies, so named because of their distinctly elliptical shapes, have no spiral arms.

(a) E0 (M105) (b) E3 (NGC 4406) (c) E6 (NGC 3377)

a: Karl Gebhardt [University of Michigan], Tod Lauer [NOAO], and NASA; b: Jean-Charles Cuillandre, Hawaiian Starlight, CFHT; c: Karl Gebhardt [University of Michigan], Tod Lauer [NOAO], and NASA

Galaxy Types & Classification

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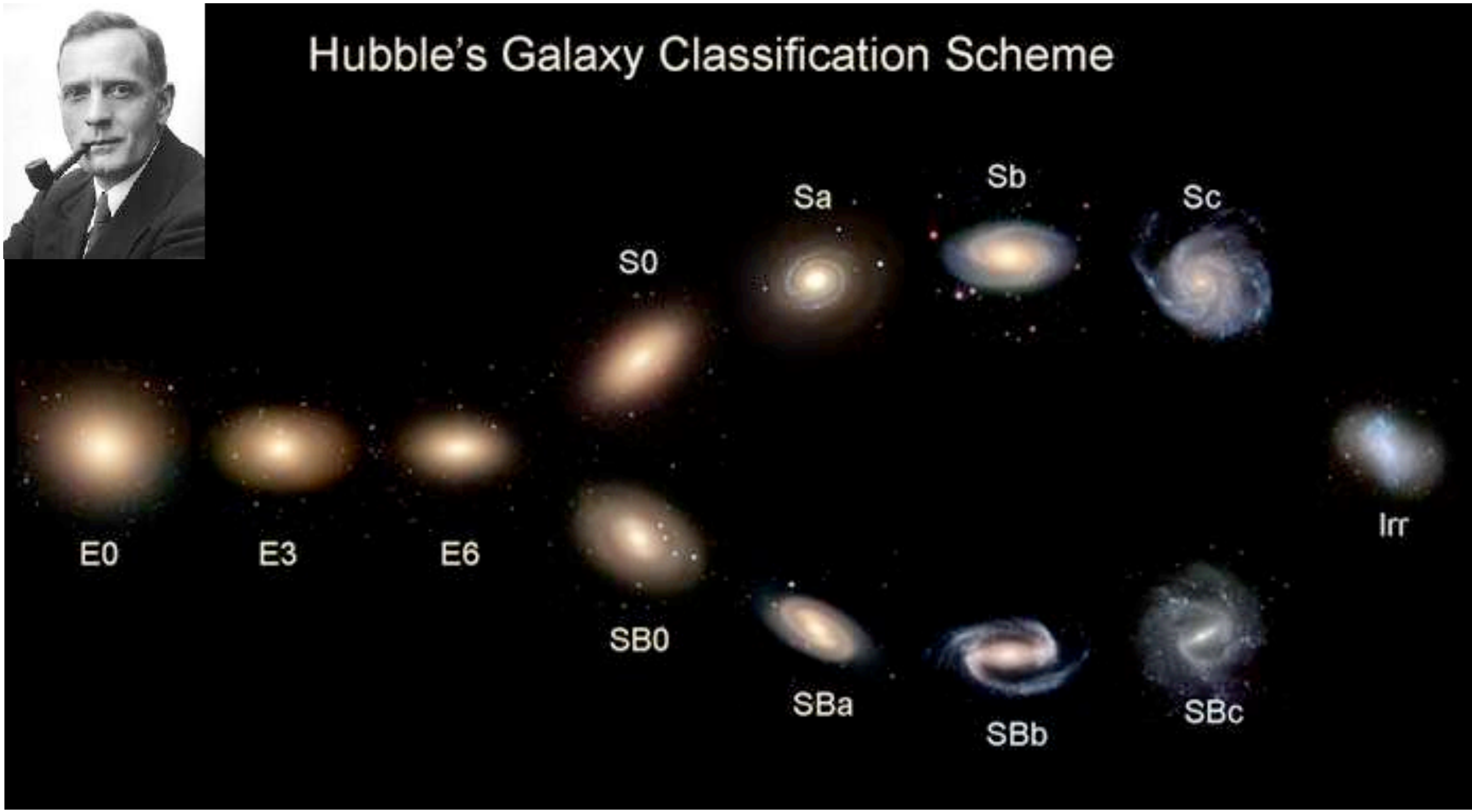
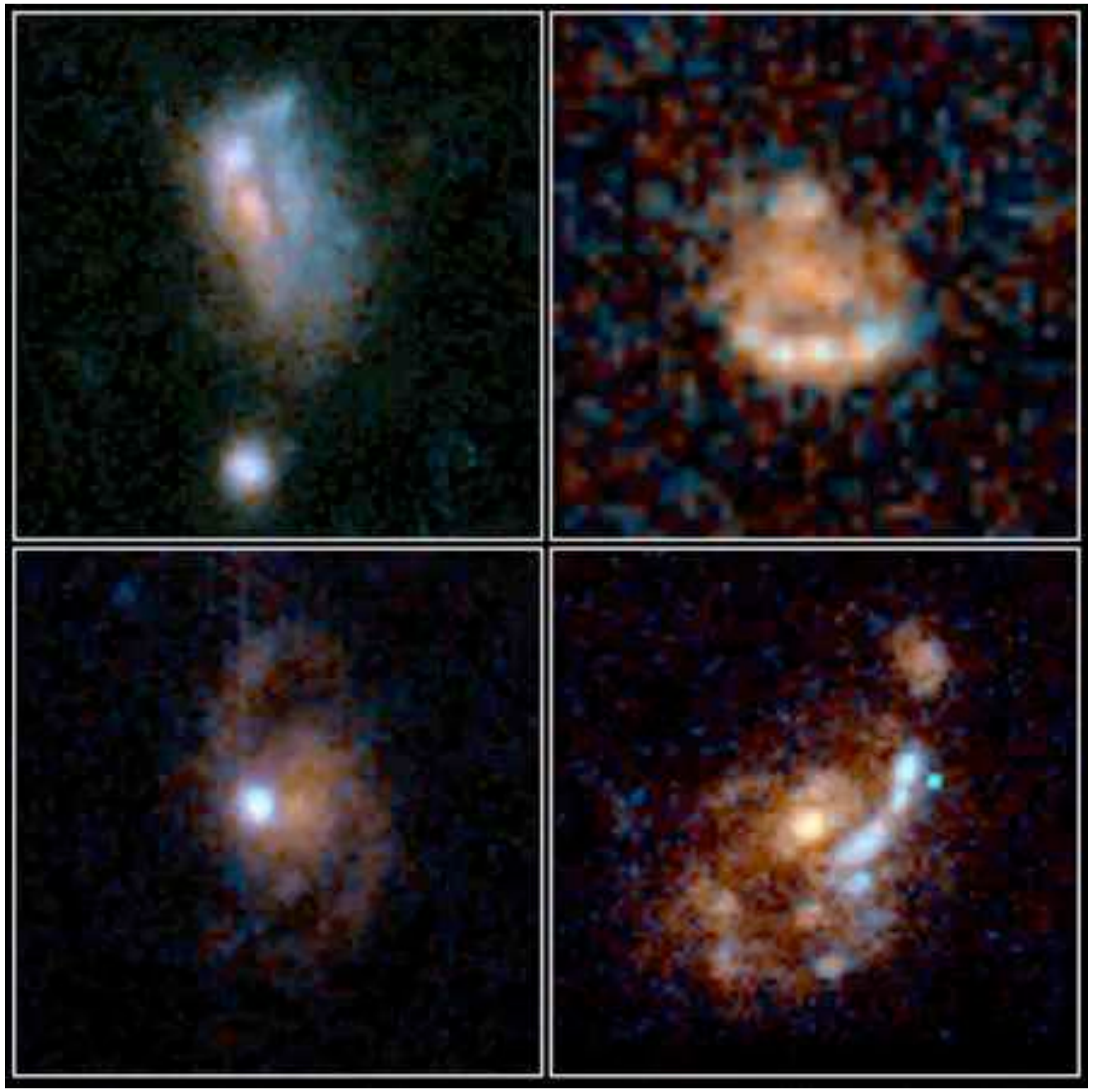


Irregular Galaxies

- Galaxies that do not fit into the scheme of spirals, barred spirals, and ellipticals are usually referred to as irregular galaxies.



Galaxy Formation & Evolution

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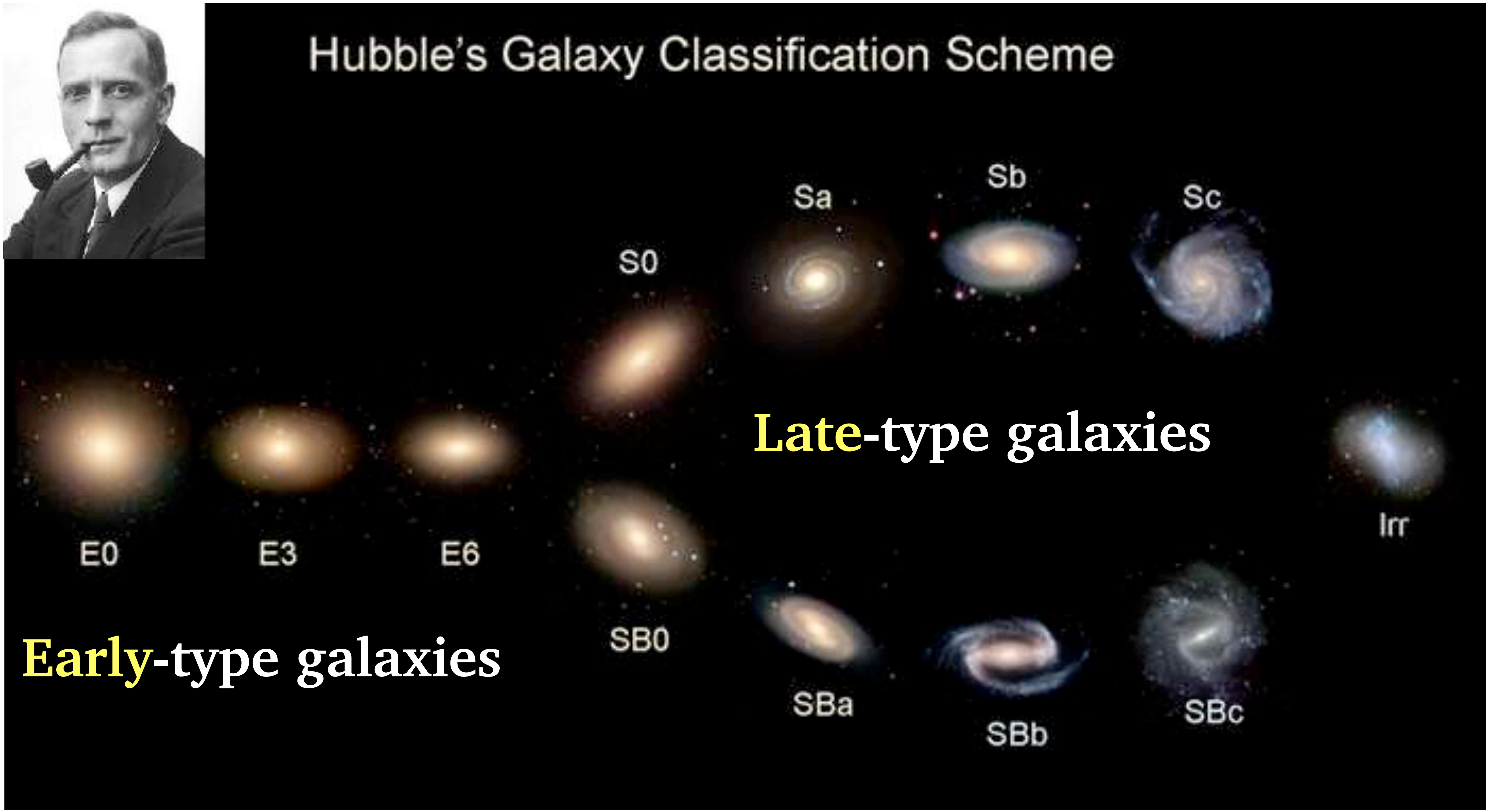
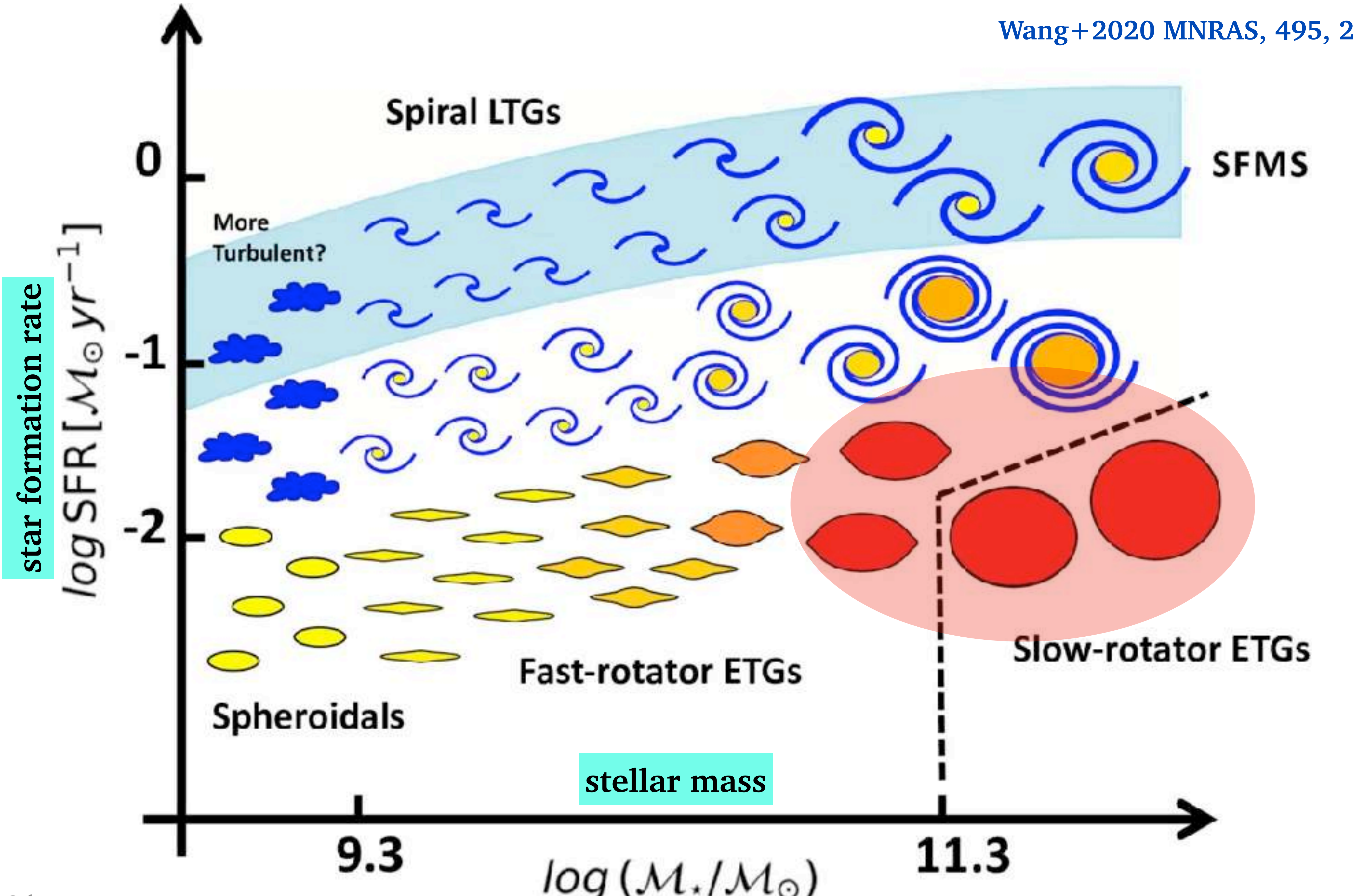


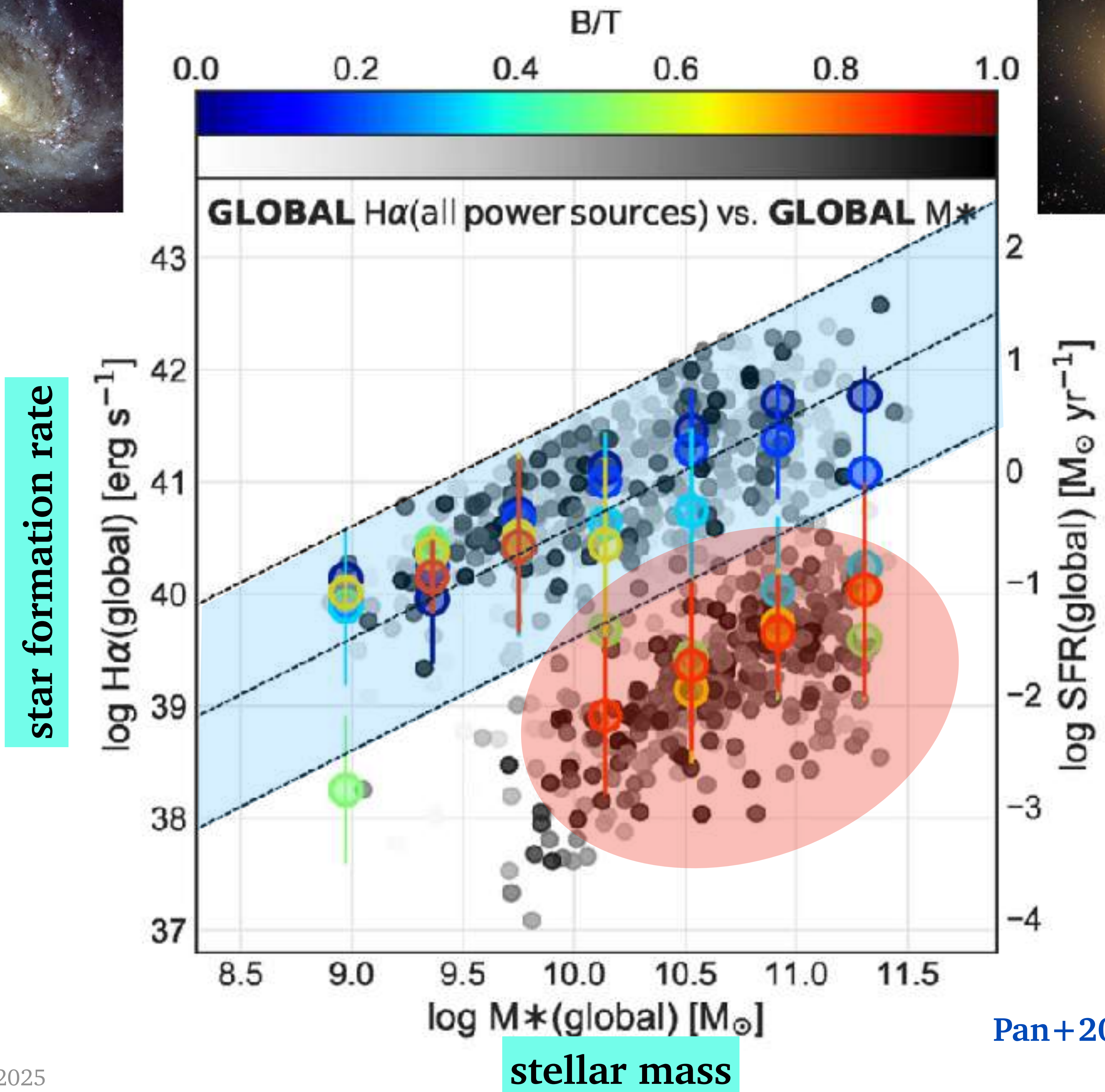
II. Galaxy Formation & Evolution

Galaxy Formation & Evolution

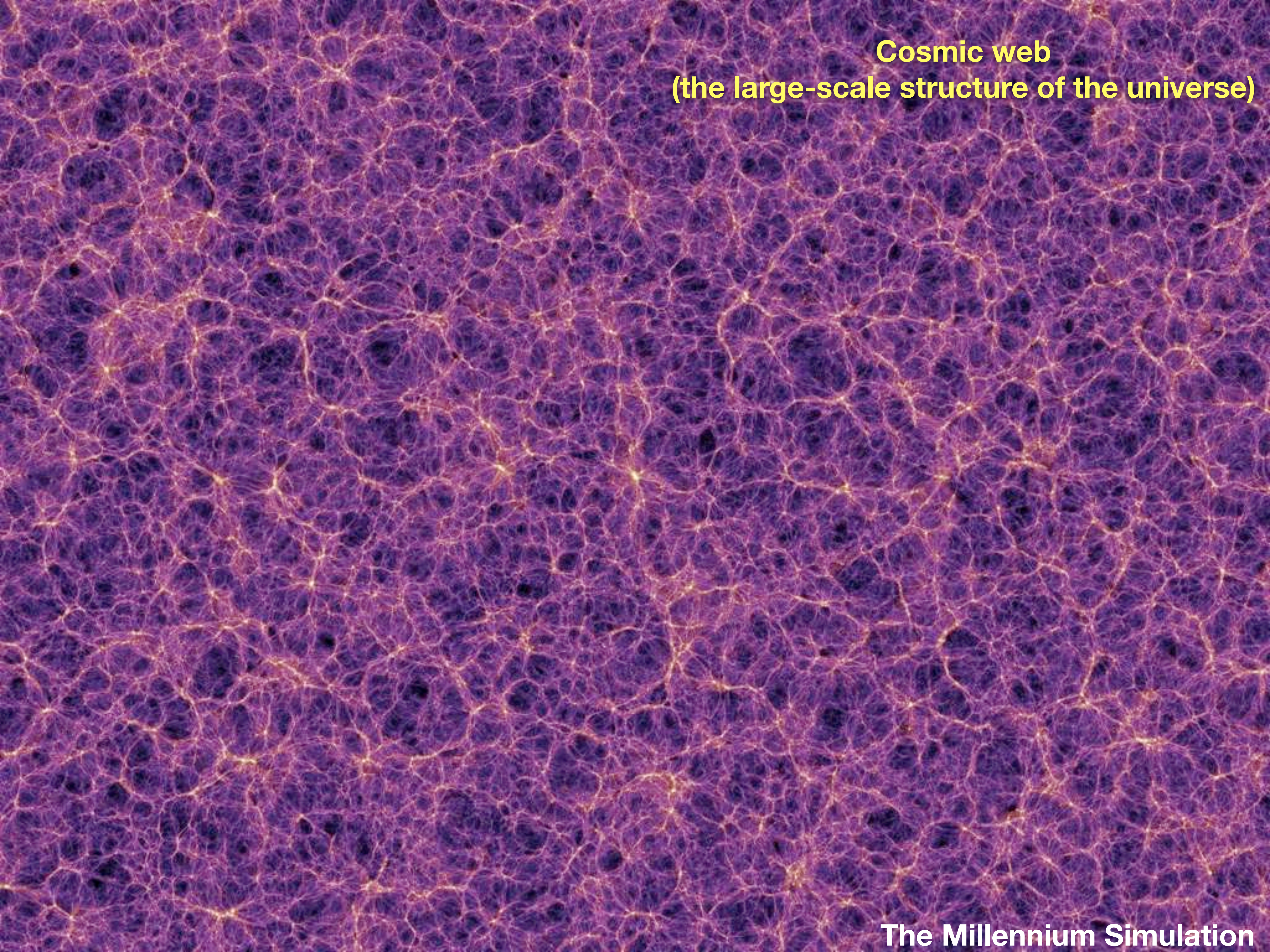
Wang+2020 MNRAS, 495, 2



Galaxy Formation & Evolution

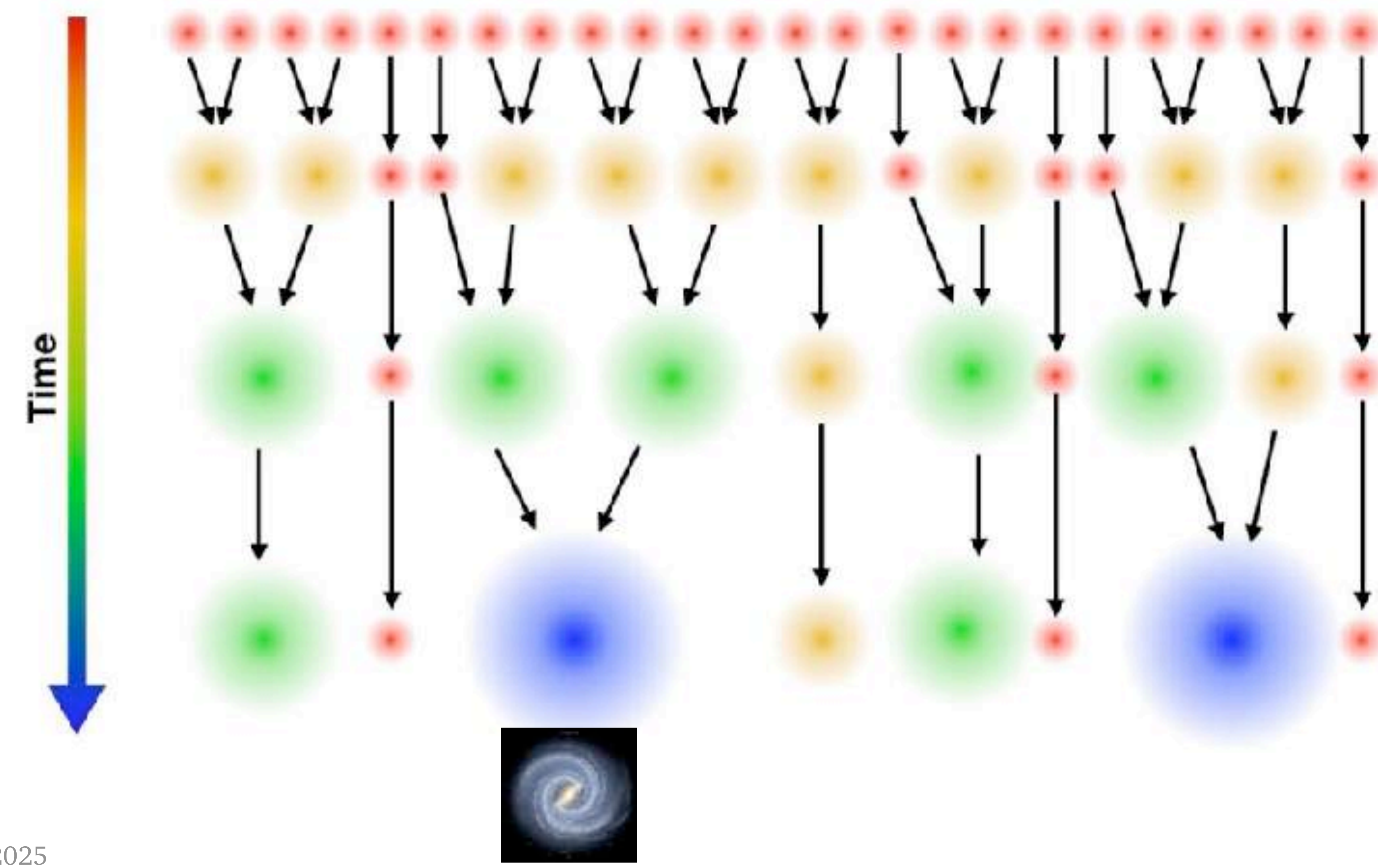


Pan+2018 ApJ, 854, 2


Cosmic web
(the large-scale structure of the universe)
The Millennium Simulation

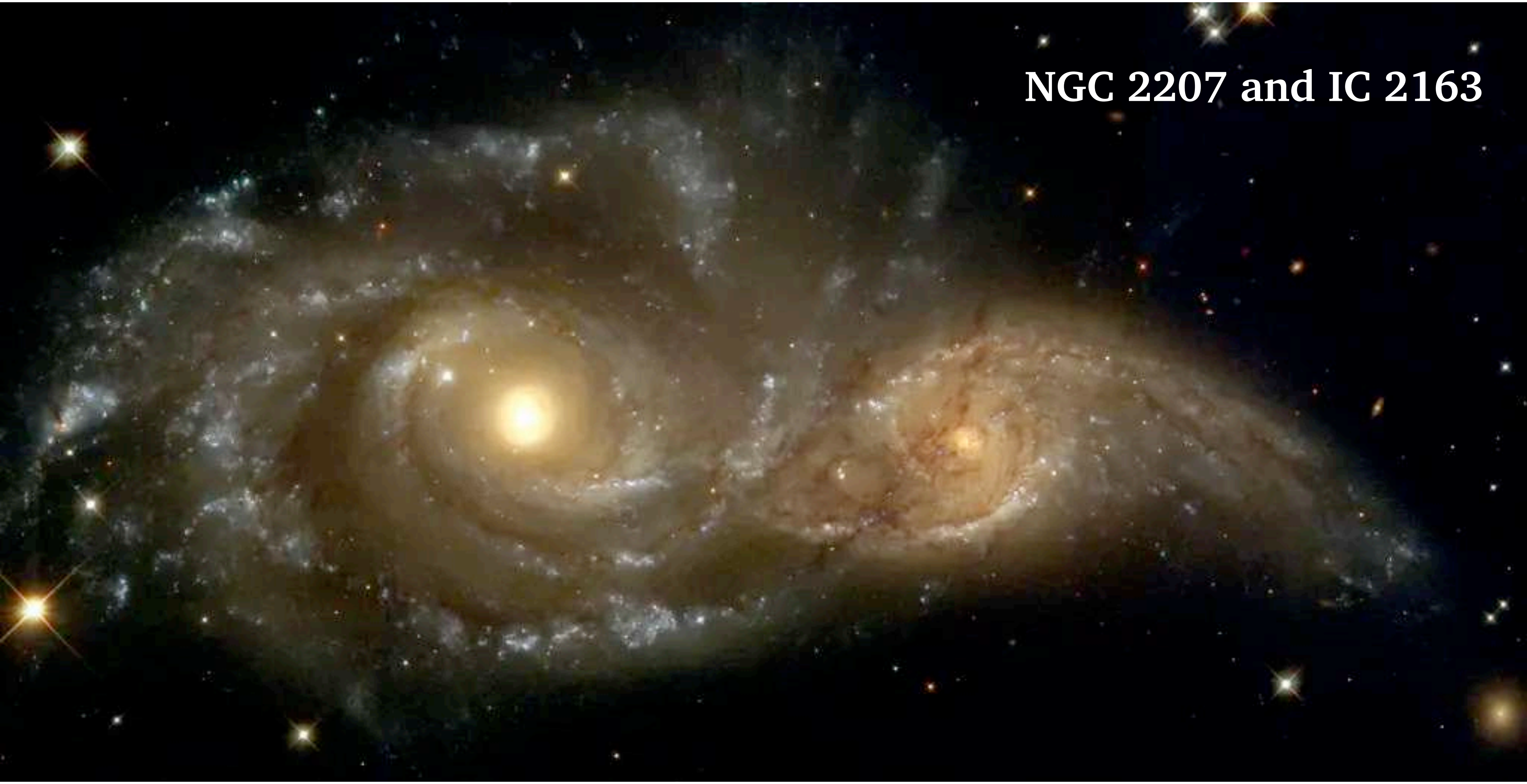
The Hierarchical Model of Galaxy

- **What is "hierarchical formation"?**
  - Small structures form first.
  - Larger galaxies build up over time by merging and accreting smaller ones.
  - This is often summarized as "**bottom-up**" structure formation.

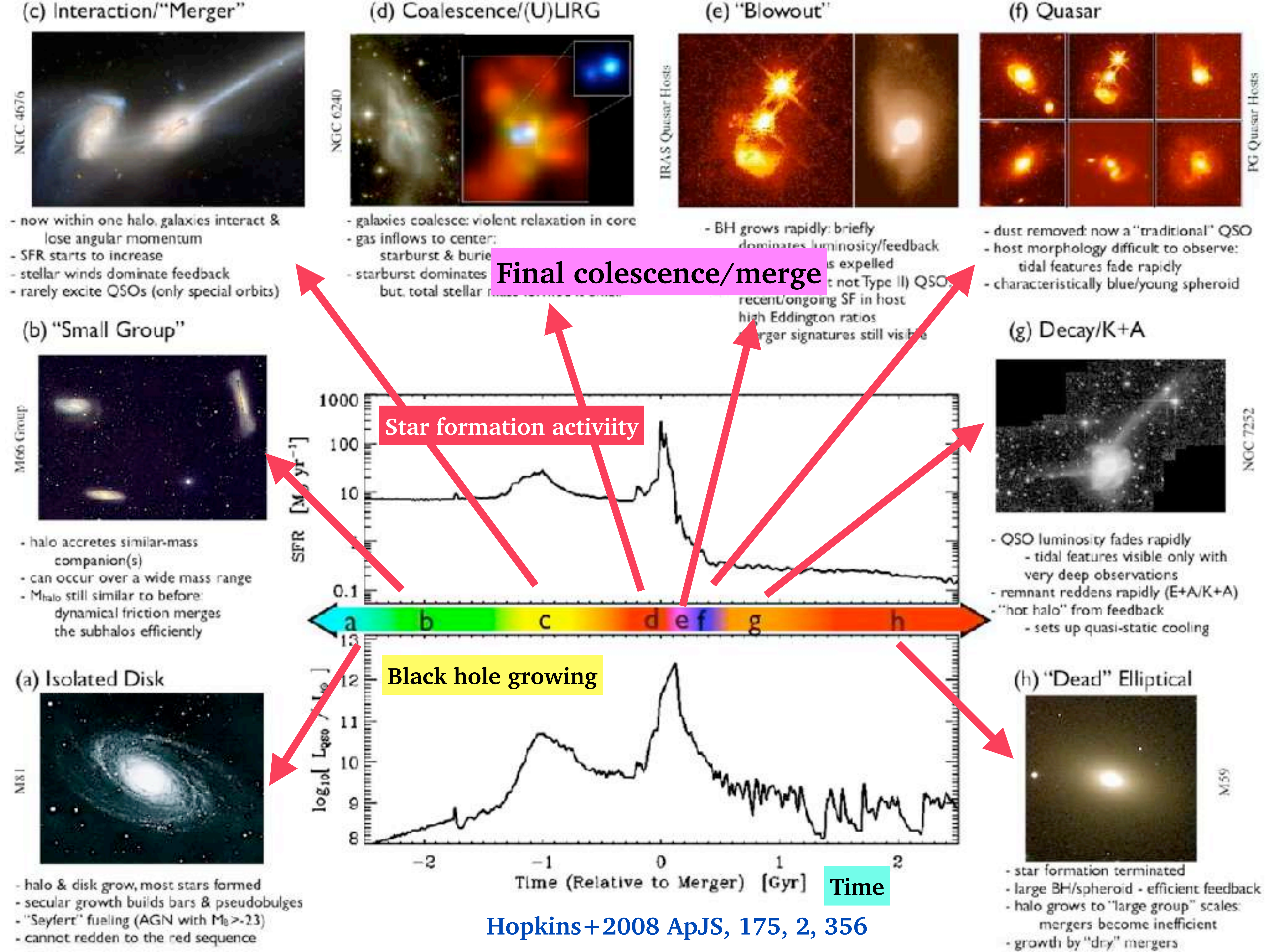


The Hierarchical Model of Galaxy

- In the local Universe, ~20% to ~50% of galaxies are in pairs/ mergers (e.g., Nevin+2023 MNRAS, 521, 1).



NASA, ESA, and The Hubble Heritage Team (STScI)



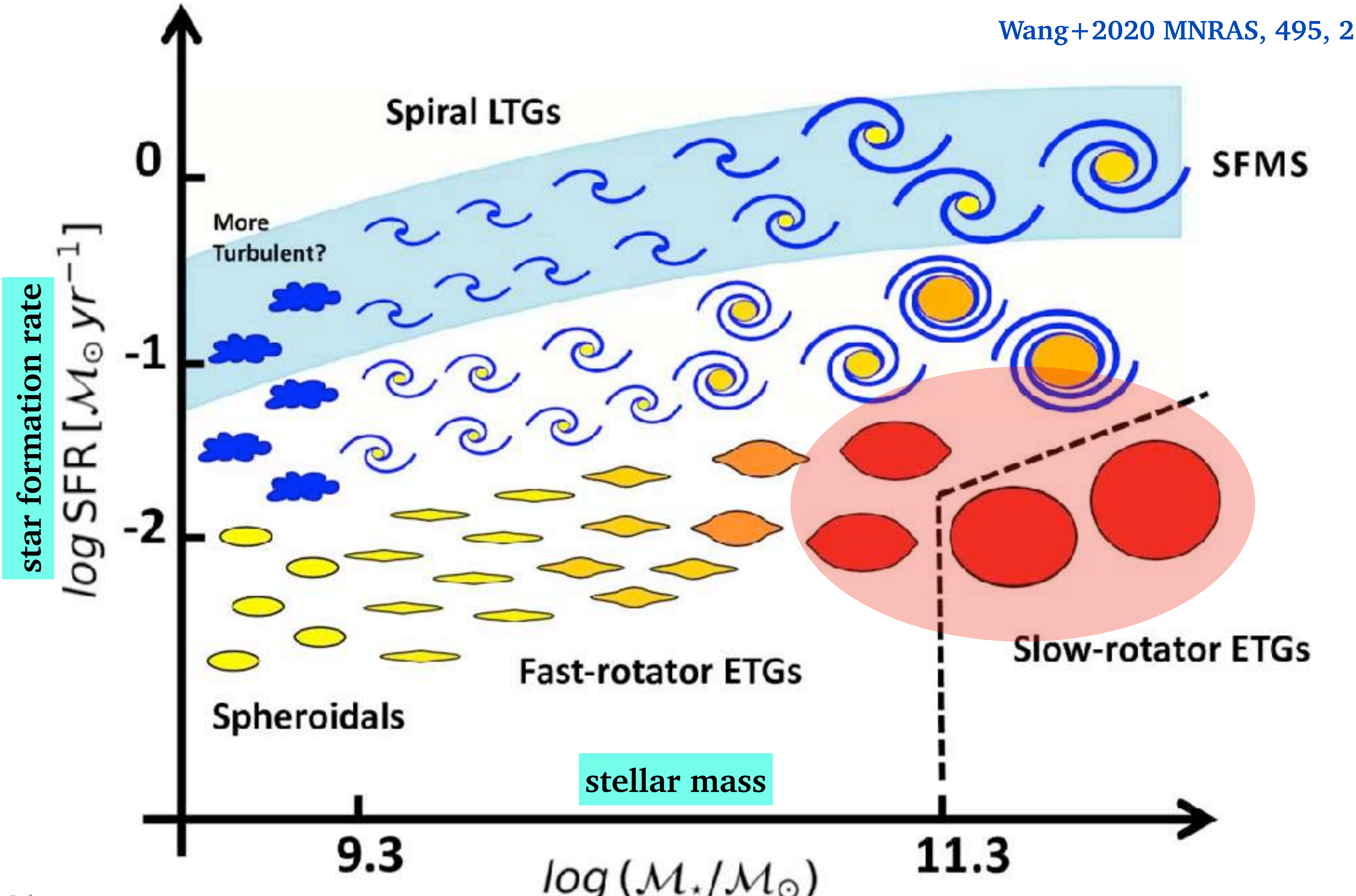
Hopkins+2008 ApJS, 175, 2, 356

The Hierarchical Model of Galaxy

Visualization Credit: NASA, ESA, and F. Summers (STScI)
Simulation Credit: NASA, ESA, G. Besla (Columbia University), and
R. van der Marel (STScI)

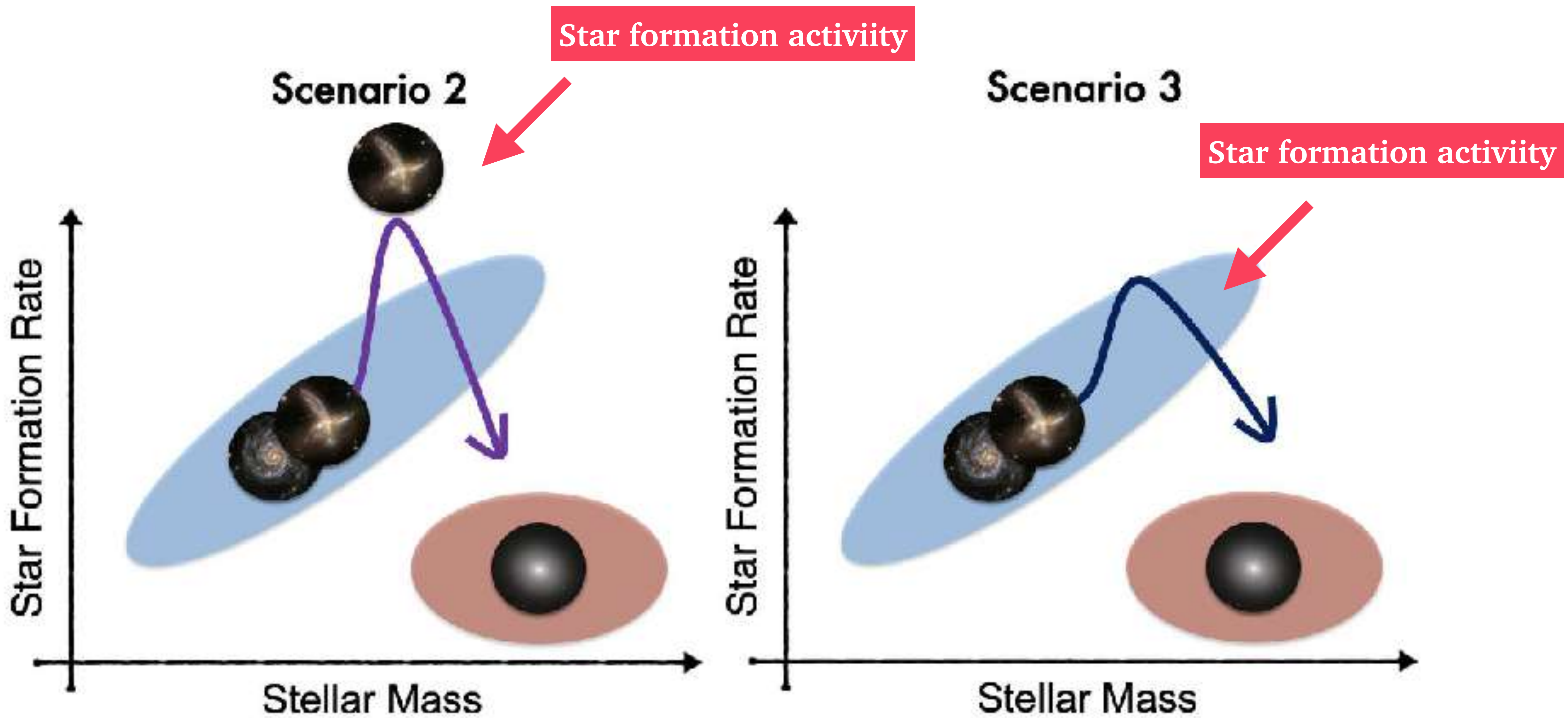
Galaxy Formation & Evolution

Wang+2020 MNRAS, 495, 2



Galaxy Formation & Evolution

- Spirals can evolve into ellipticals when two spiral galaxies merge.



Gómez-Guijarro+2022 A&A, 59, A196

Galaxy Formation & Evolution

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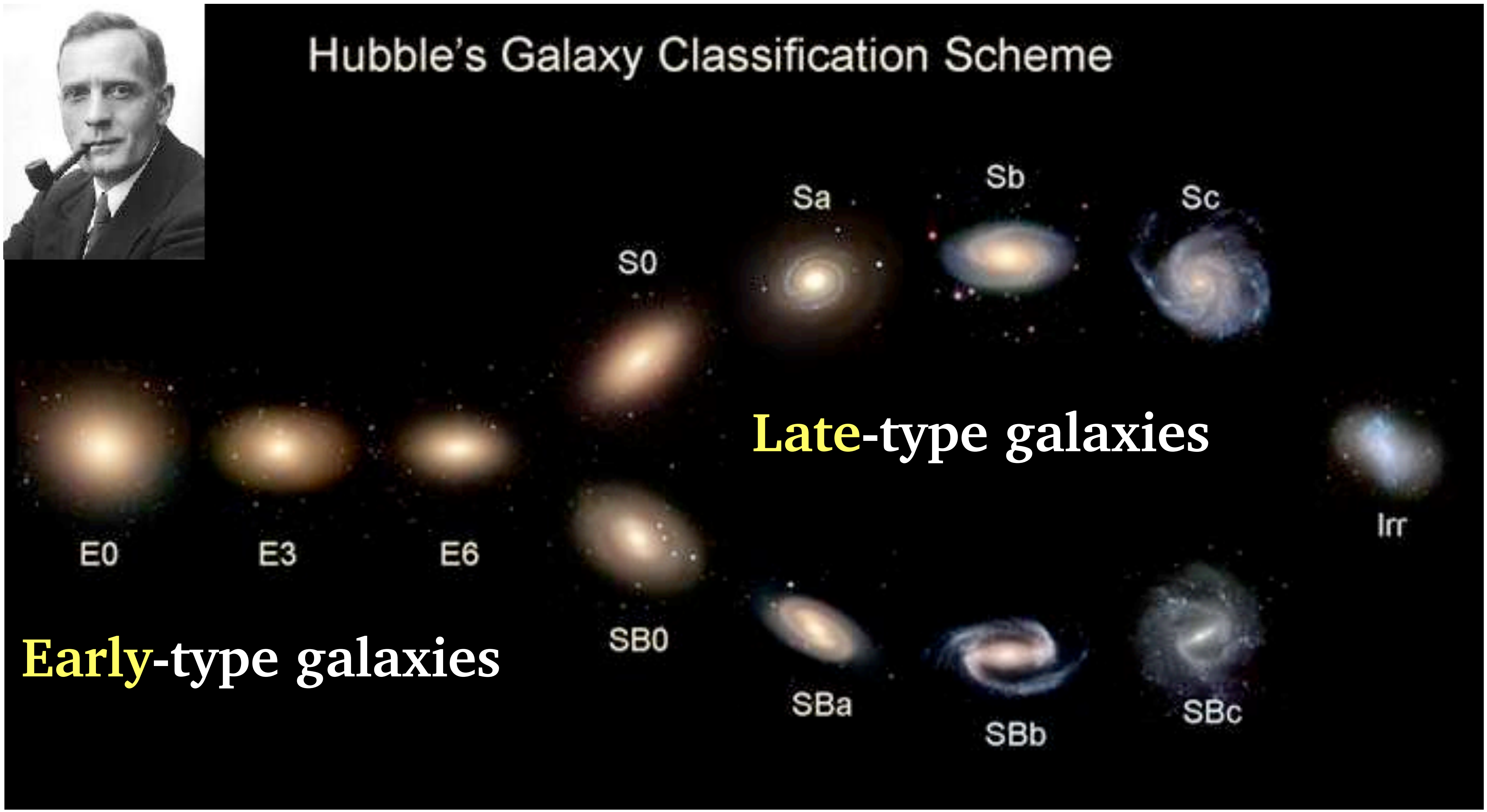
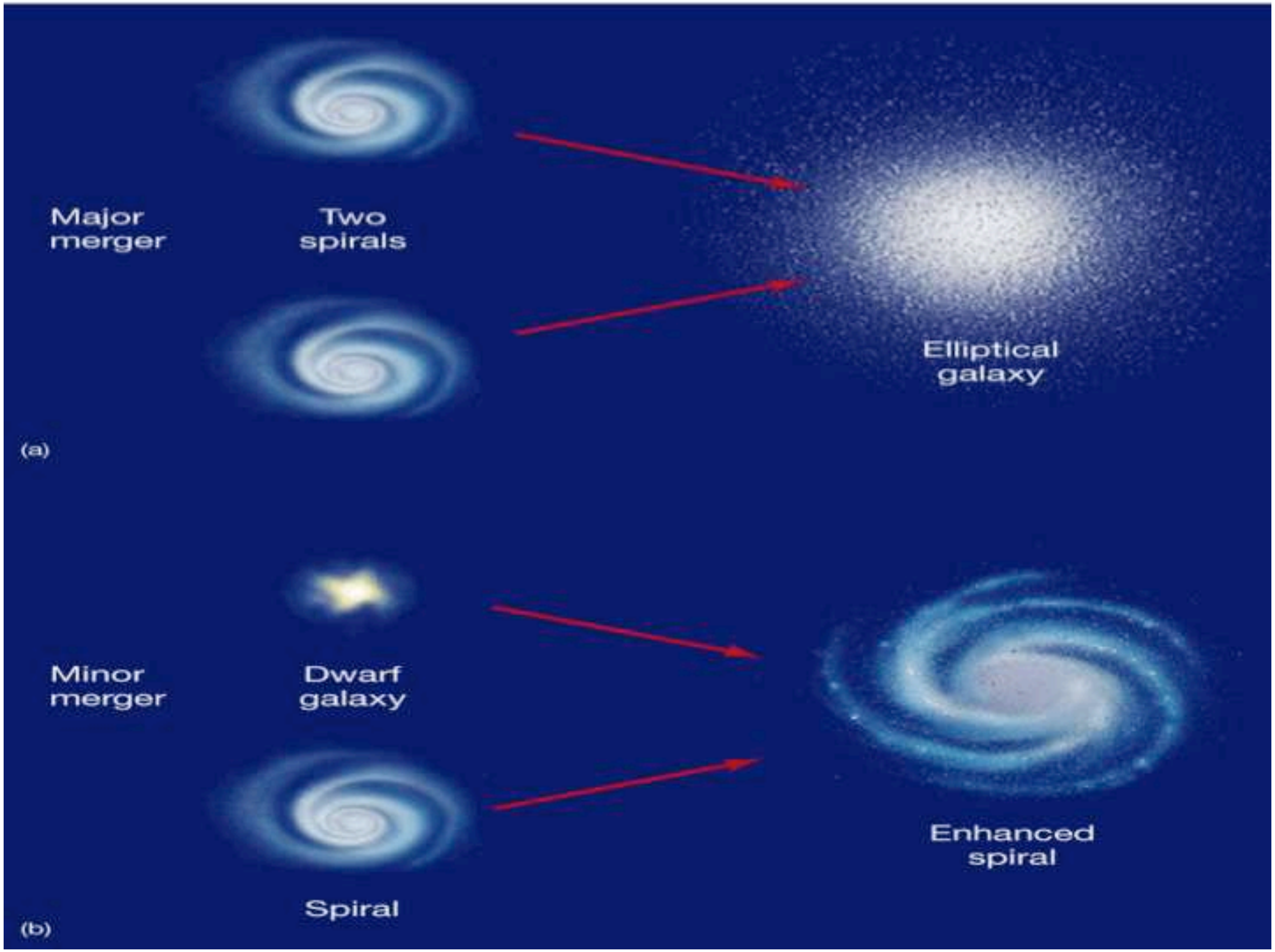


Evolution?

The Hierarchical Model of Galaxy

- Not all galaxy mergers efficiently lead to the formation of elliptical galaxies; only specific configurations, such as major mergers between gas-rich, similarly sized galaxies tend to disrupt disk structures.



III. ISM Cycle and Feedback Processes

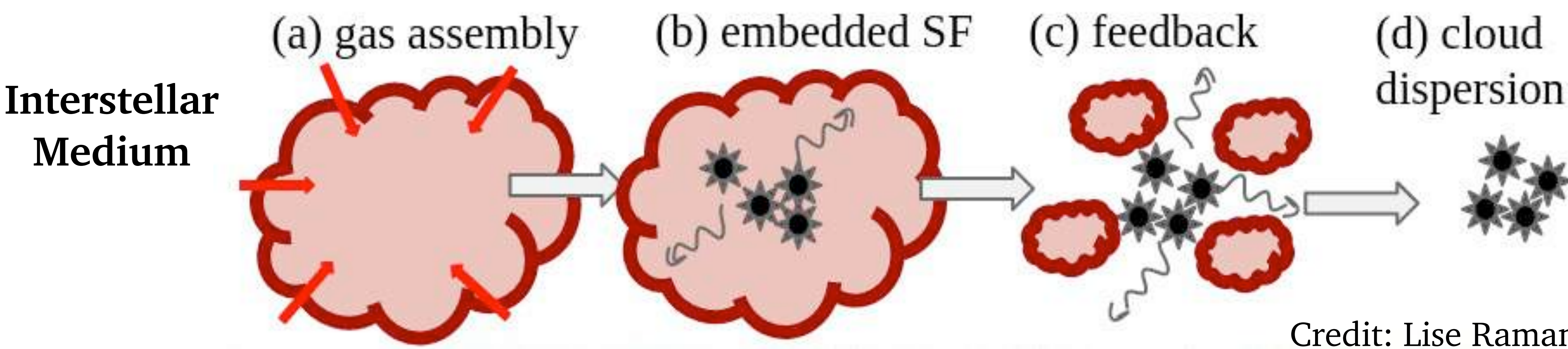
ISM Cycle and Feedback Processes

- Interstellar Medium (ISM)
  - **“ISM is anything not in stars” (Osterbrok 1984)**
    - Matter: Gas
    - Matter: Dust
    - Energy: Interstellar Radiation Field

NASA, ESA, CSA, STScI

ISM Cycle and Feedback Processes

- One of the most important processes in a galaxy (ISM) is star formation.

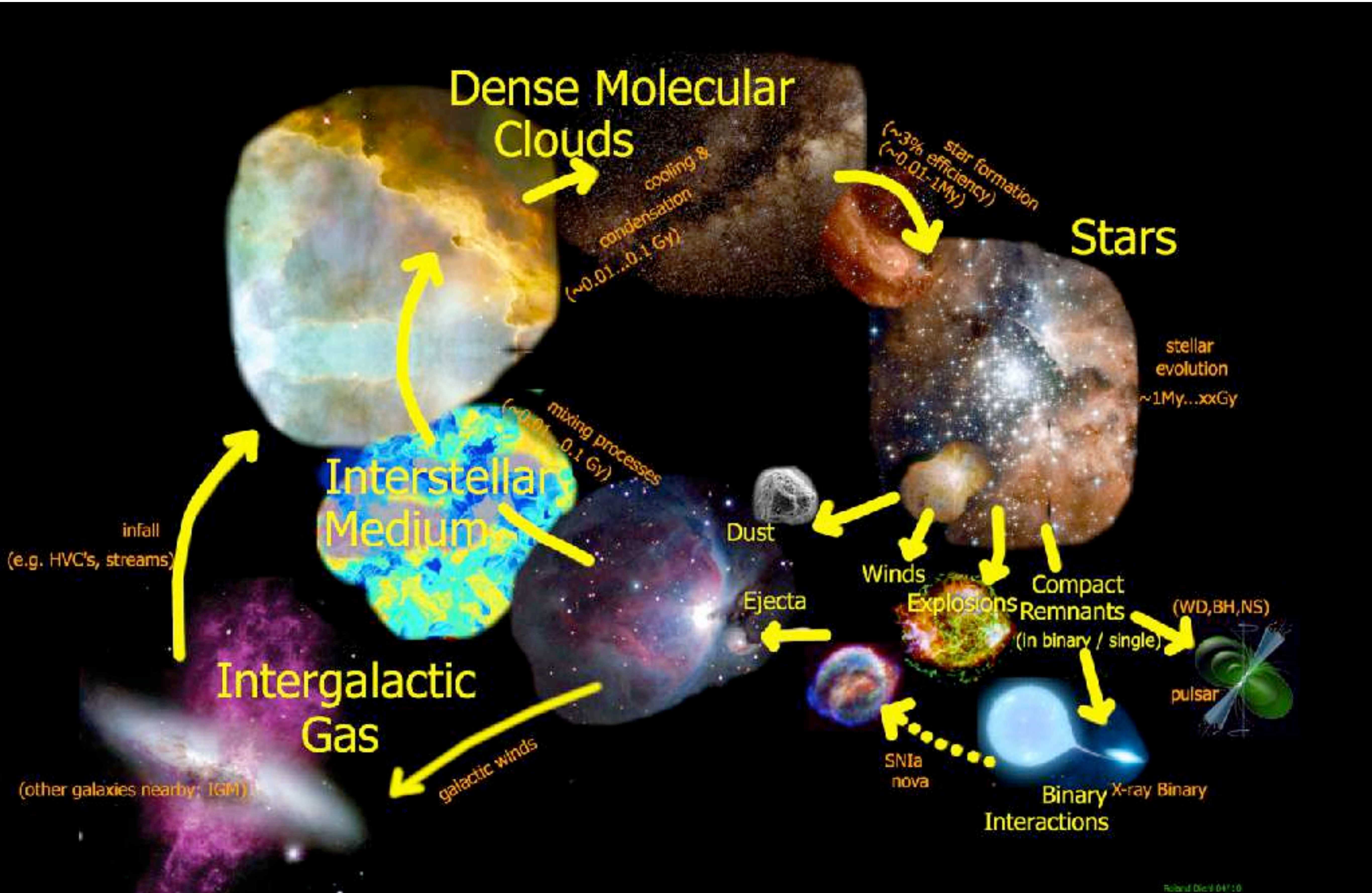


Credit: Lise Ramambason

- These stars form in dense regions (molecular clouds) of the interstellar medium.

- As stars evolve and die, they don't simply fade away—but what impact do they leave behind?

ISM Cycle and Feedback Processes



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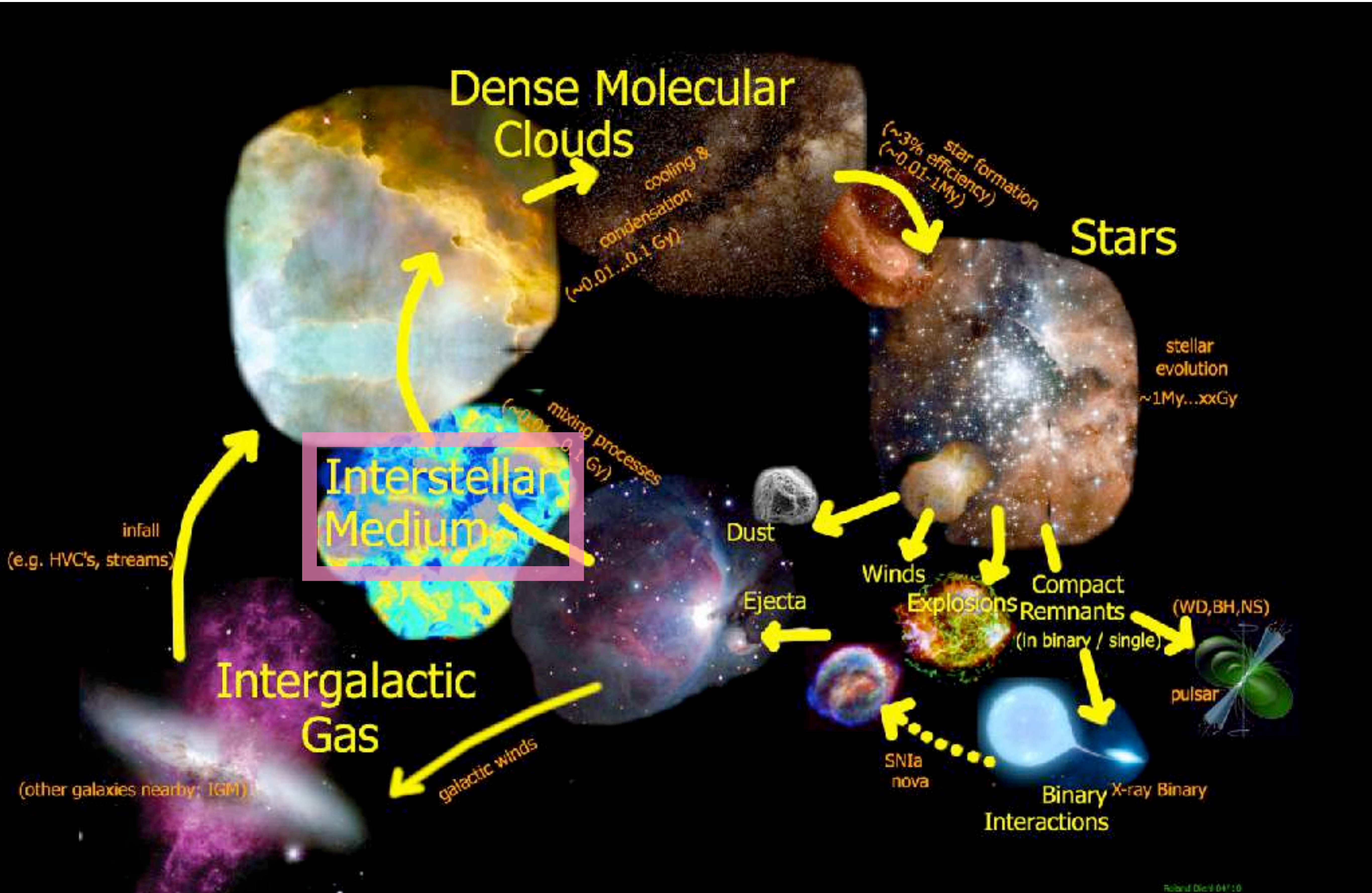
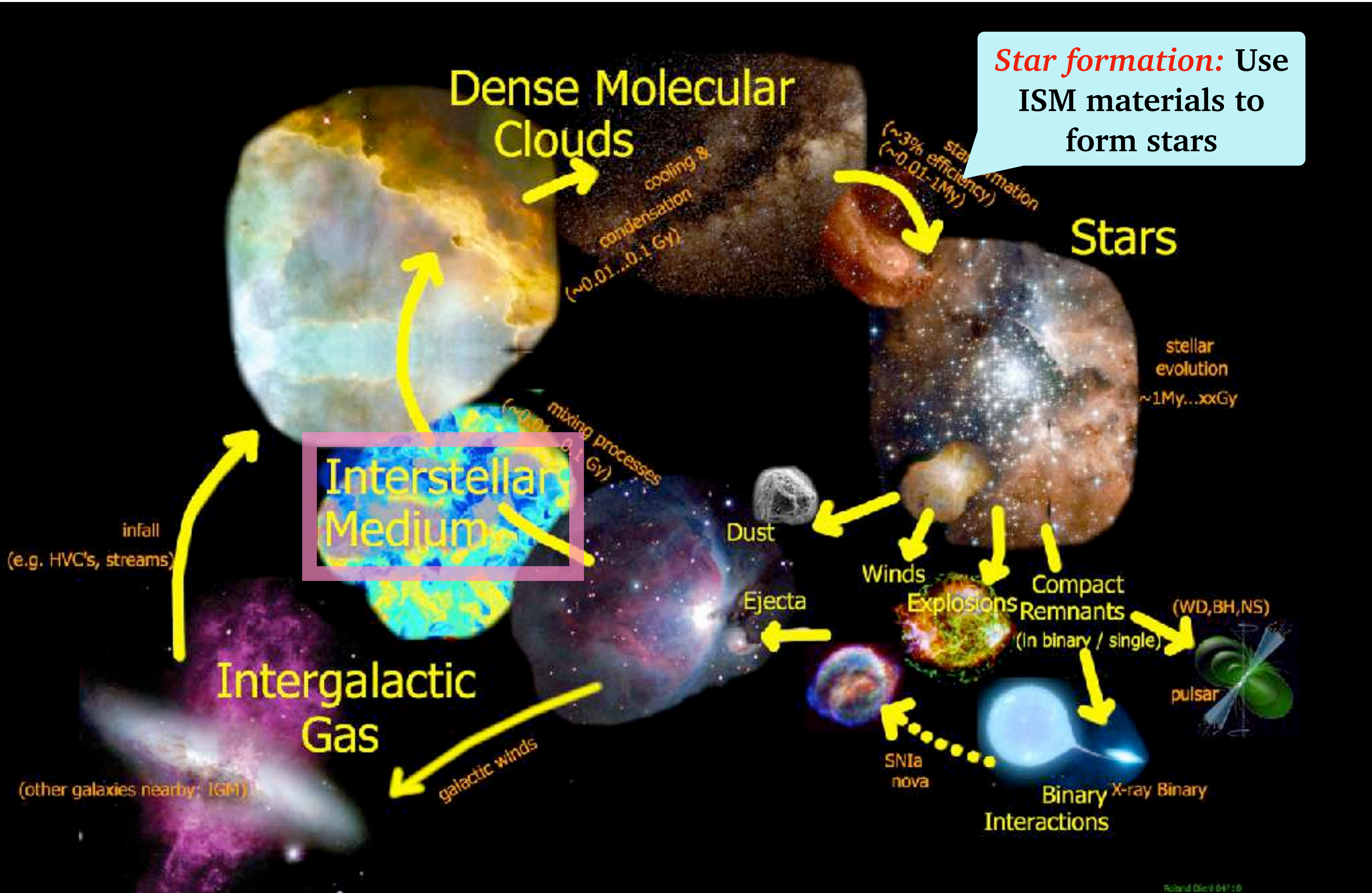
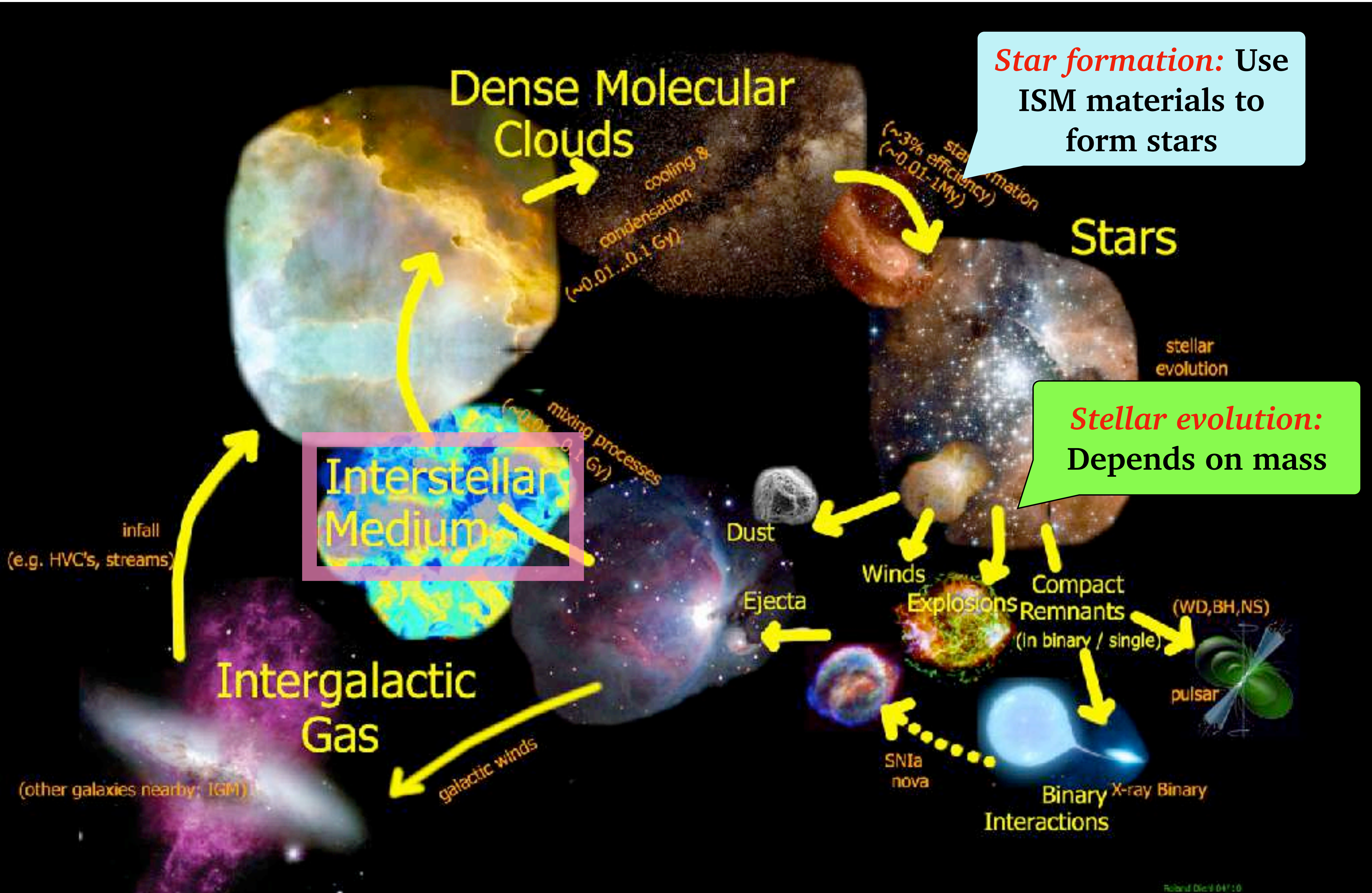


ISM Cycle and Feedback Processes



Star formation: **Use ISM materials to form stars**

ISM Cycle and Feedback Processes



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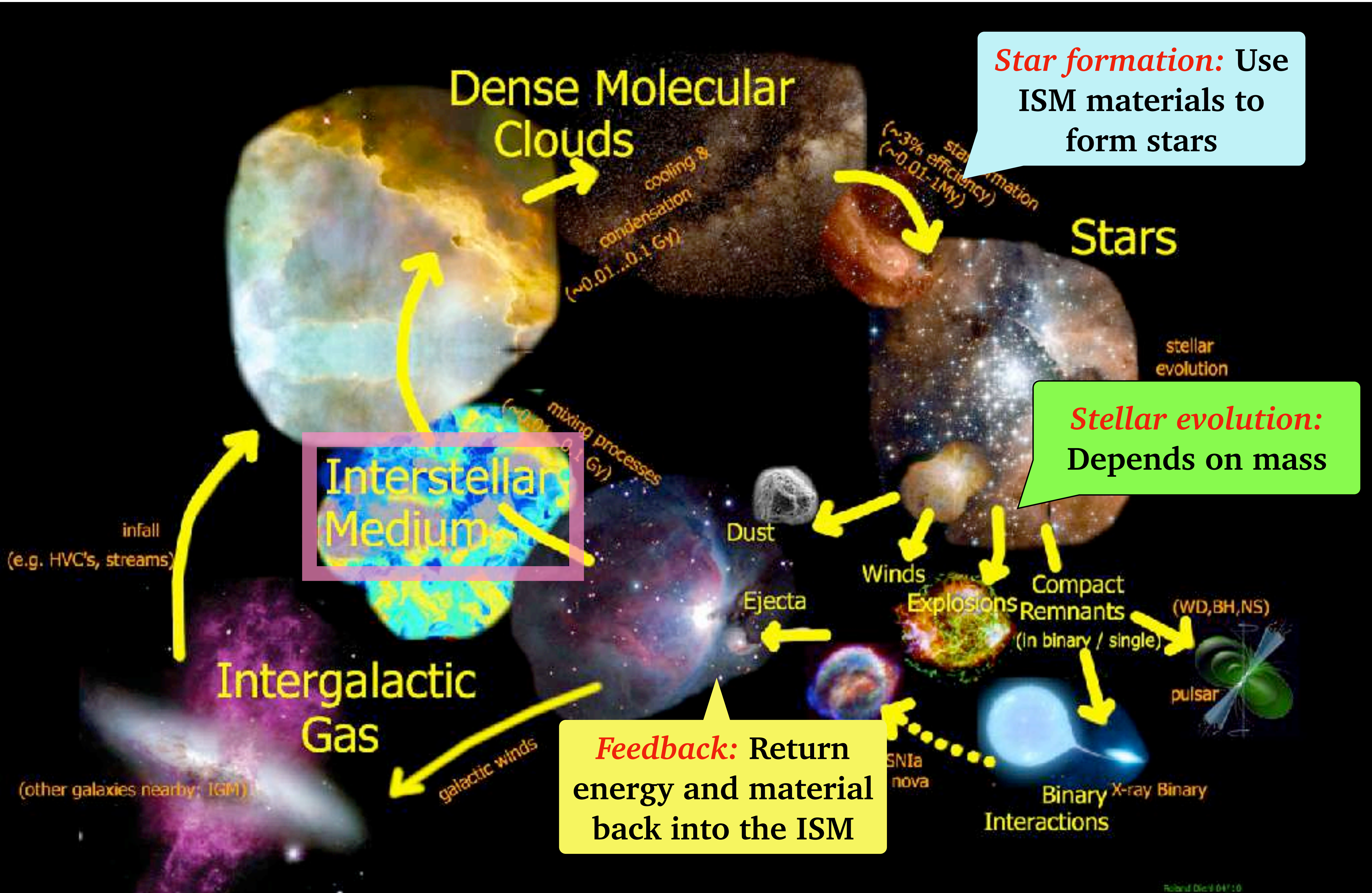

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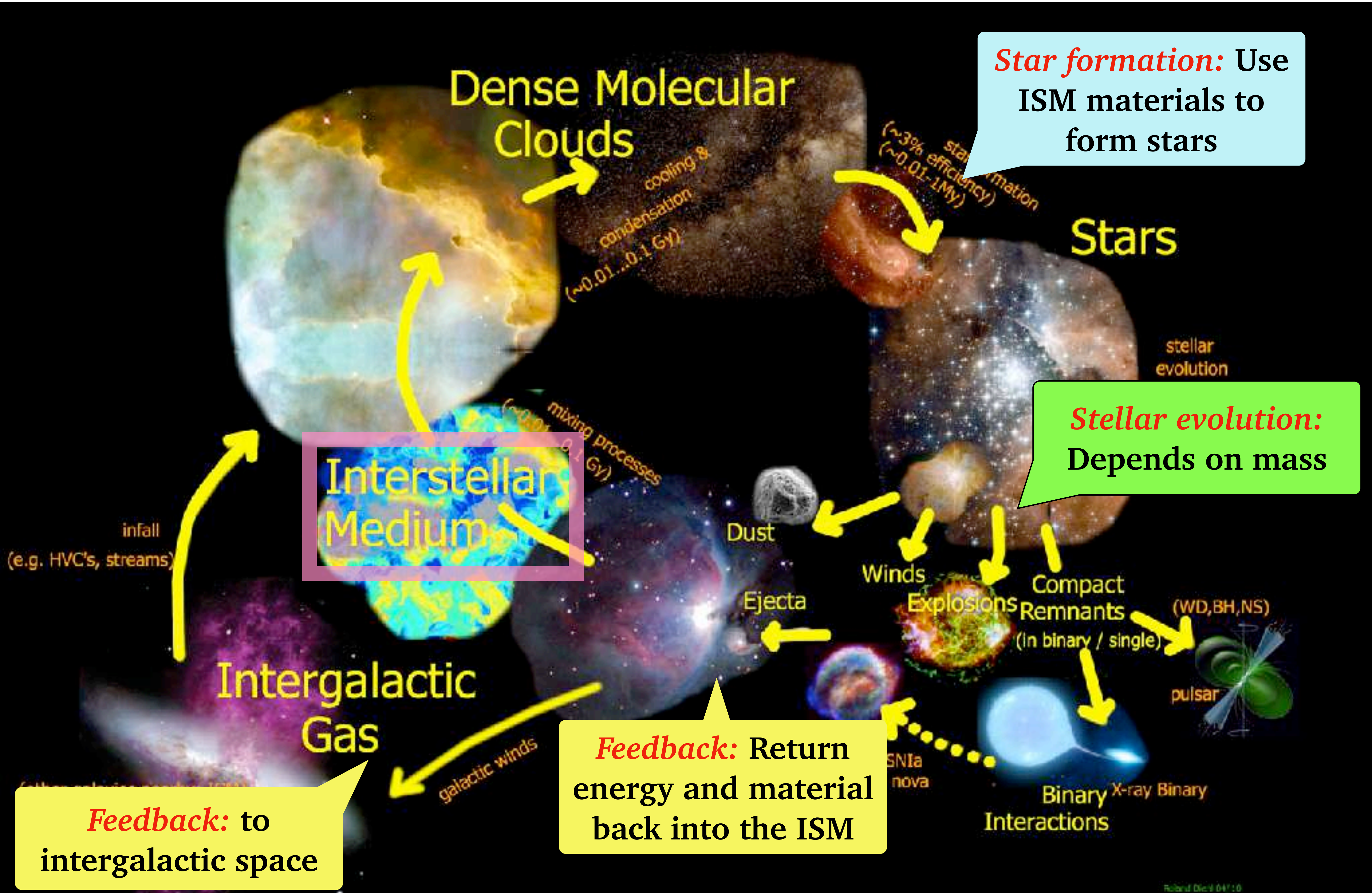

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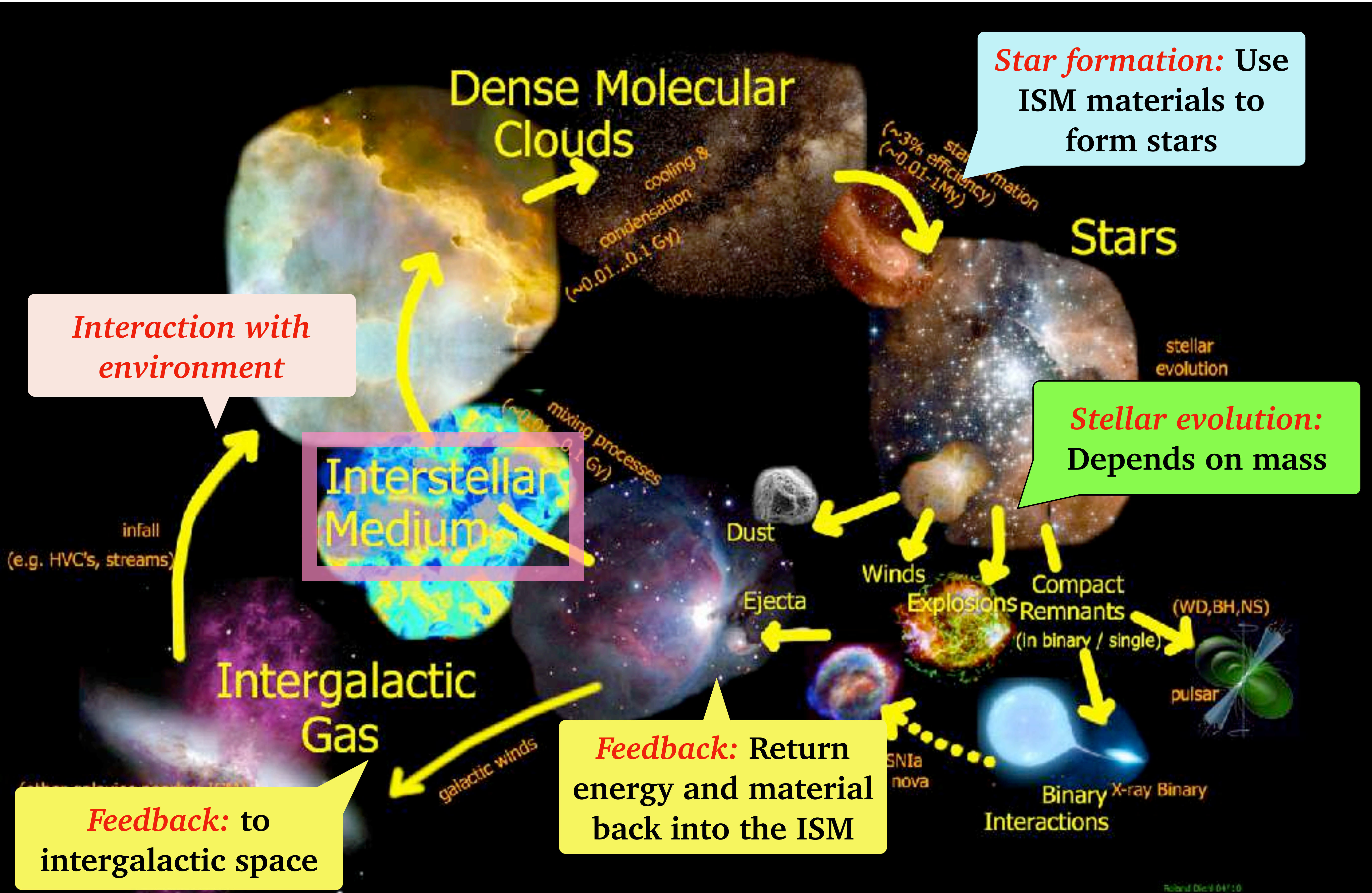


Feedback Proccess

- Feedback refers to how stars and black holes return energy and material into their host galaxy, affecting future star formation.
- **Why it matters:**
  - Regulates star formation
  - Drives galaxy evolution
- **Two main types:**
  - Stellar Feedback (from stars & supernovae)
  - AGN Feedback (from supermassive black holes)

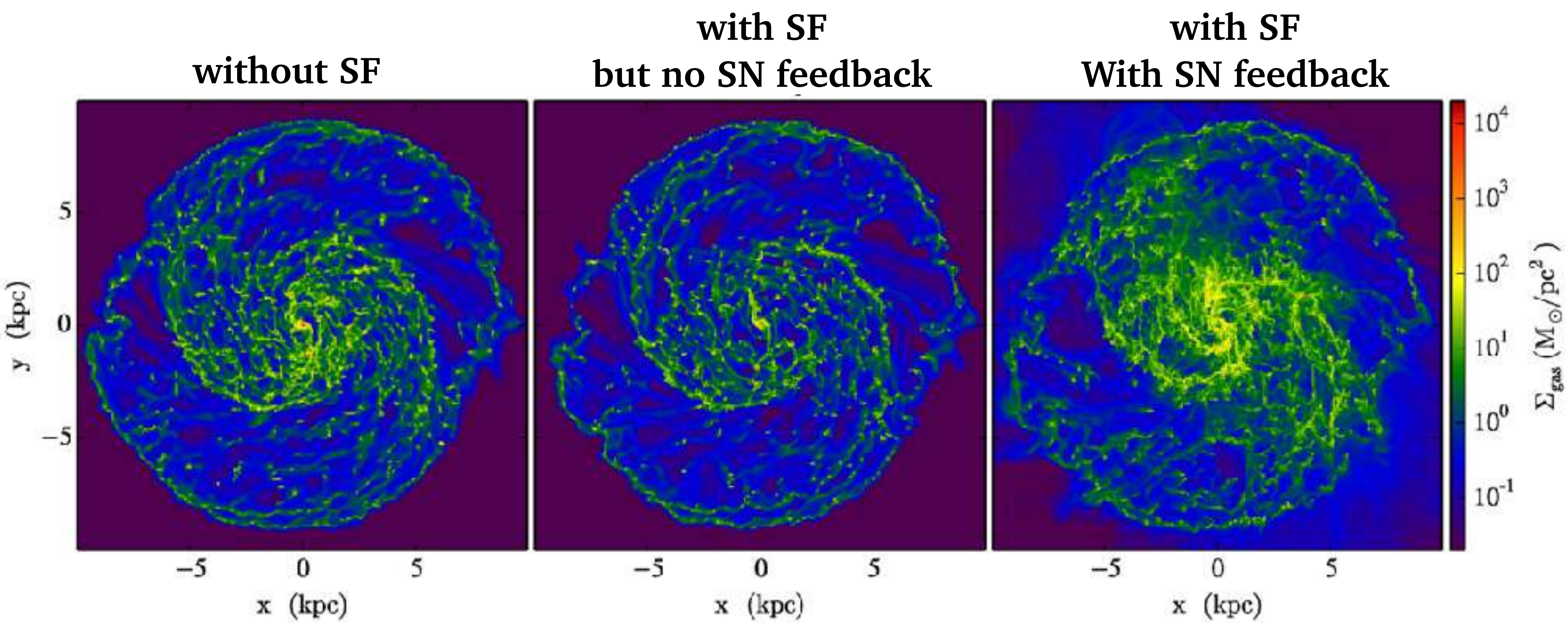
Stellar Feedback

- **What causes it?**
  - Stellar winds from massive stars
  - Radiation from young stars
  - Supernova explosions

- **Effects on the galaxy:**
  - Heats the interstellar medium (ISM) ➙ **prevents future SF**
  - Blows (stirs up) gas (out of) galaxies ➙ **prevents/triggers future SF**
  - Compress ISM ➙ **triggers future SF**

Stellar Feedback

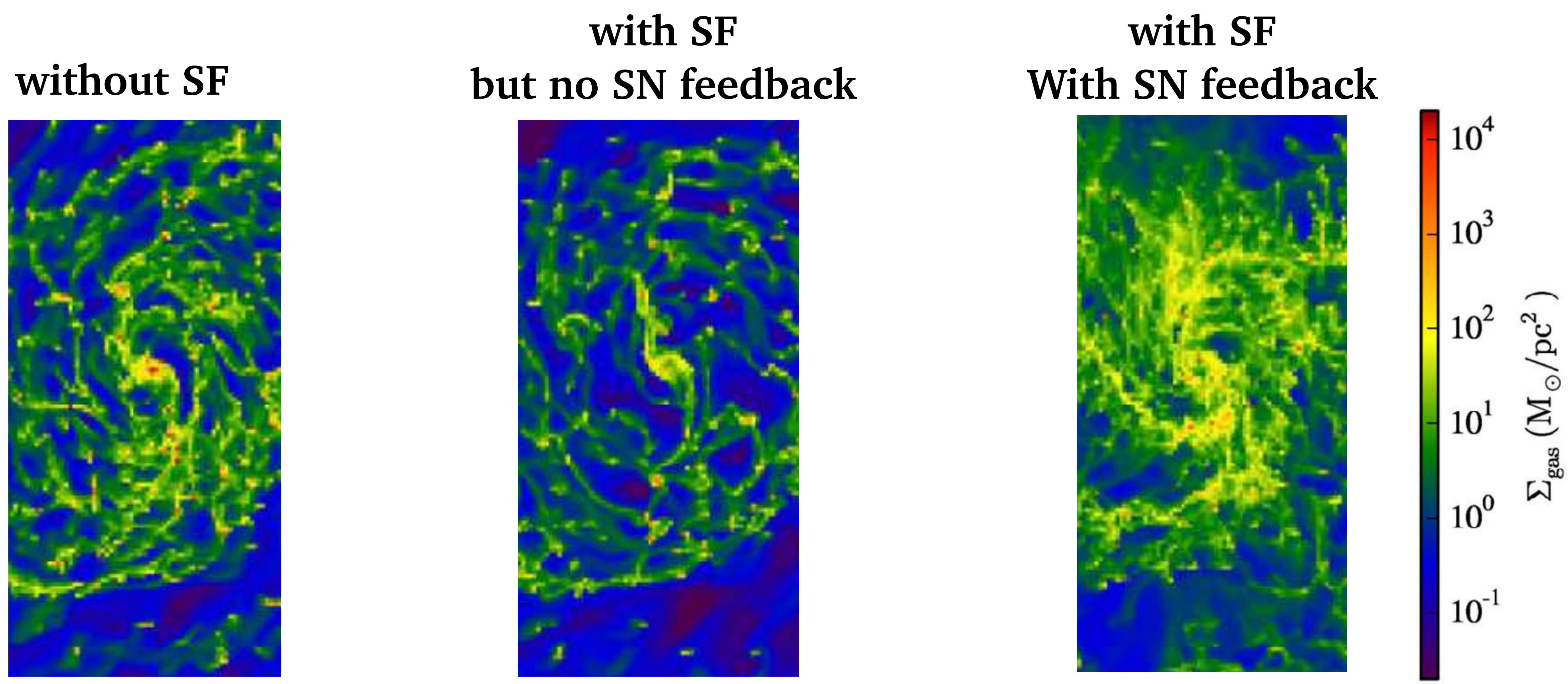
- Compariosn of **gas stucture** in simulated galaxies:



Fujimoto+2014 MNRAS, 461, 1684

Stellar Feedback

- Compariosn of **gas stucture** in simulated galaxies:



Fujimoto+2014 MNRAS, 461, 1684

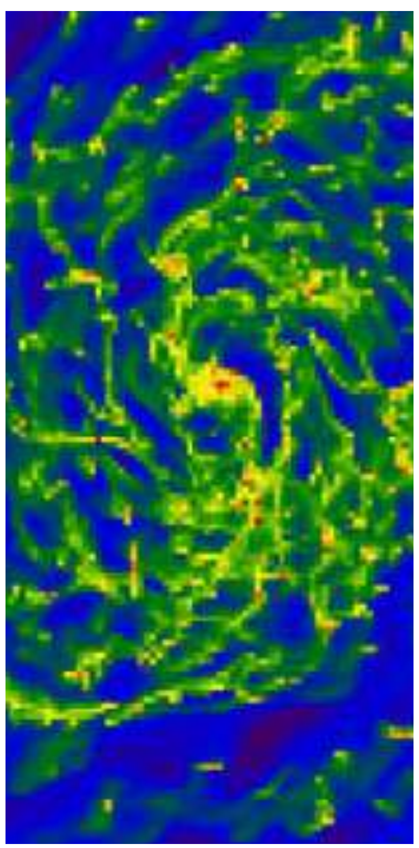
Stellar Feedback

The gas structure (distribution) is altered, which in turn affects the location of future star formation.

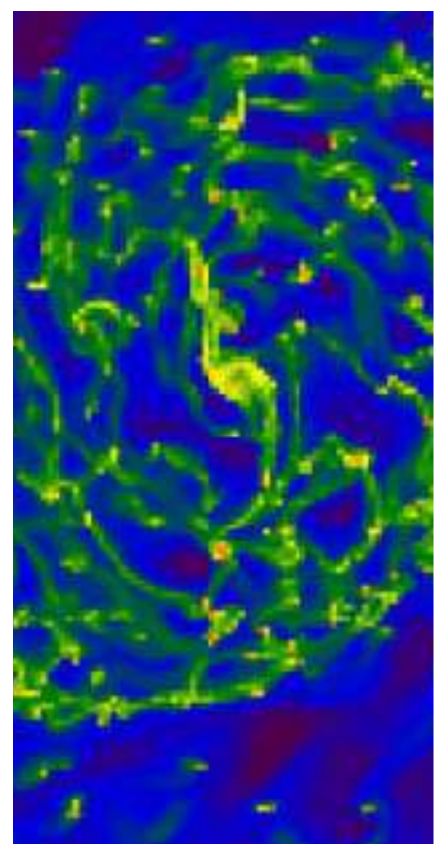
- Compariosn of **gas stucture** in simulated galaxies:

Supernovae blow material (gas) away, making the gas appear more extended.

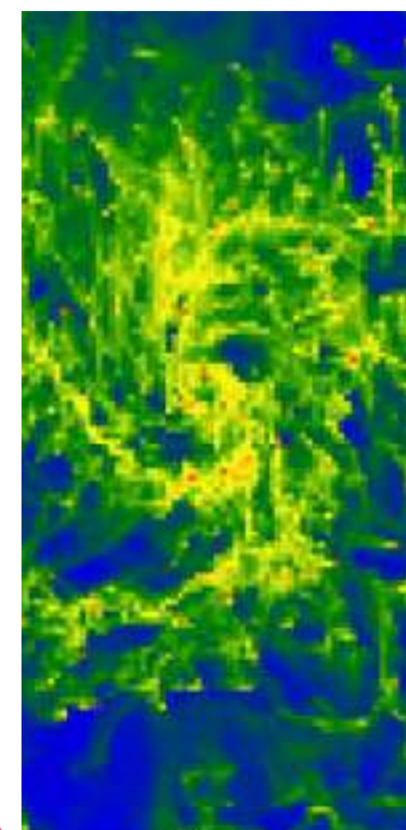
without SF



with SF
but no SN feedback

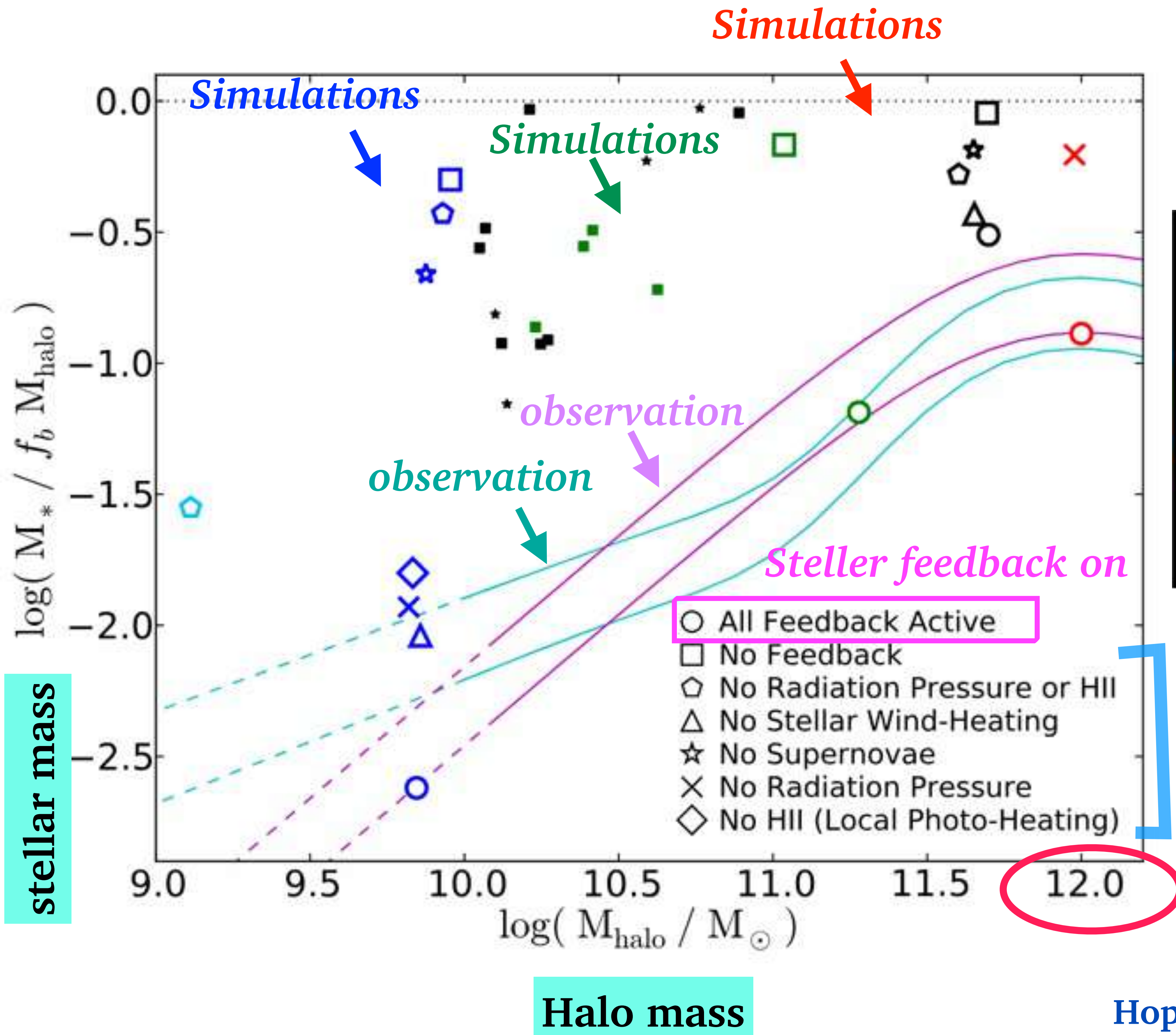


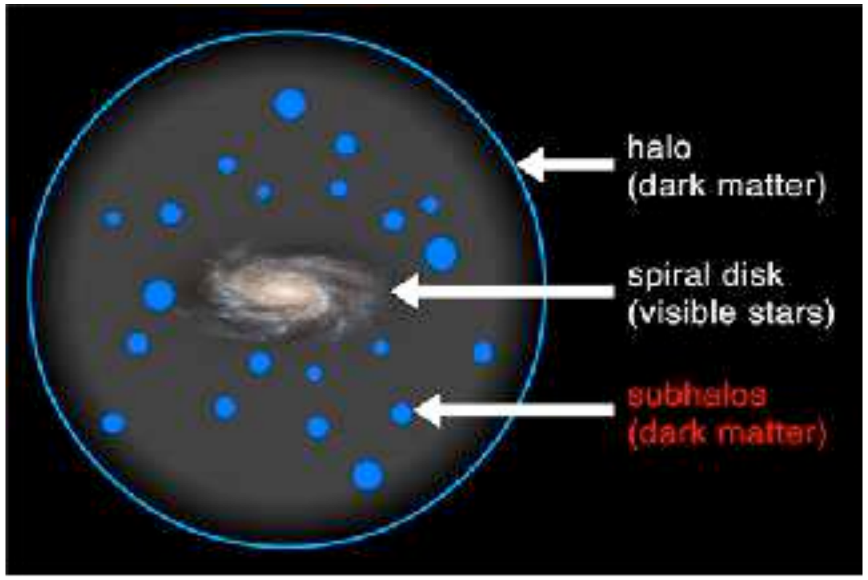
with SF
With SN feedback



Fujimoto+2014 MNRAS, 461, 1684

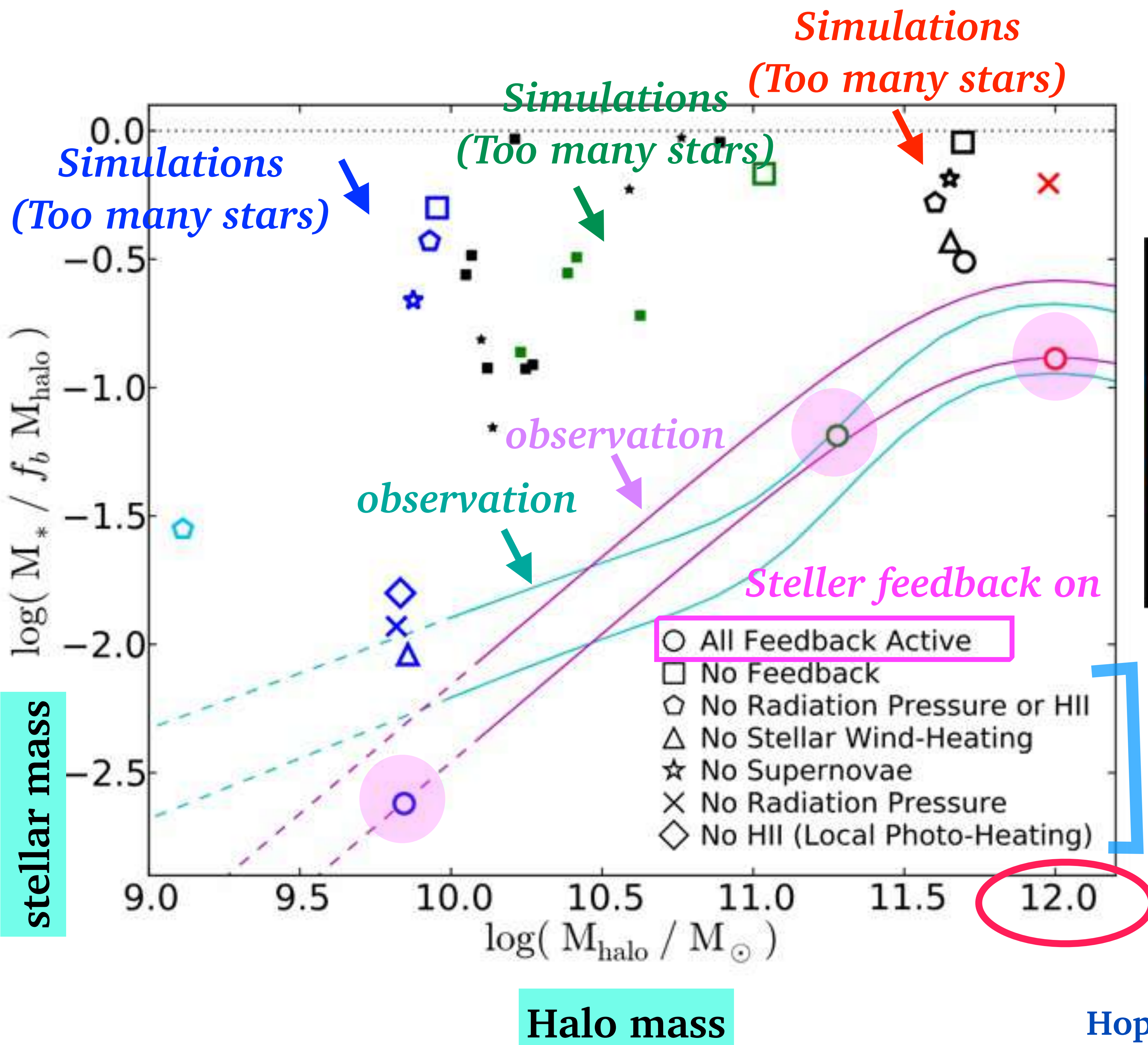
Stellar Feedback

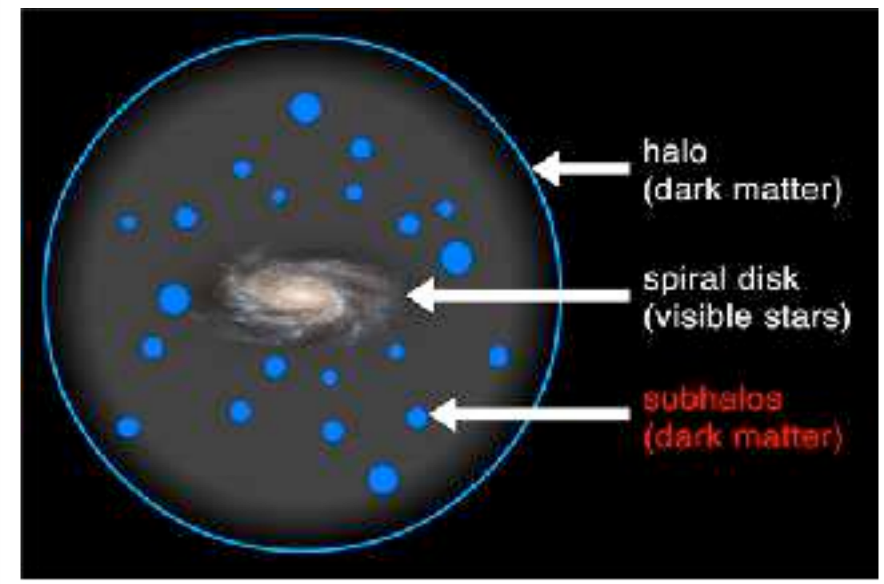




Hopkins+2014 MNRAS, 445, 581

Stellar Feedback



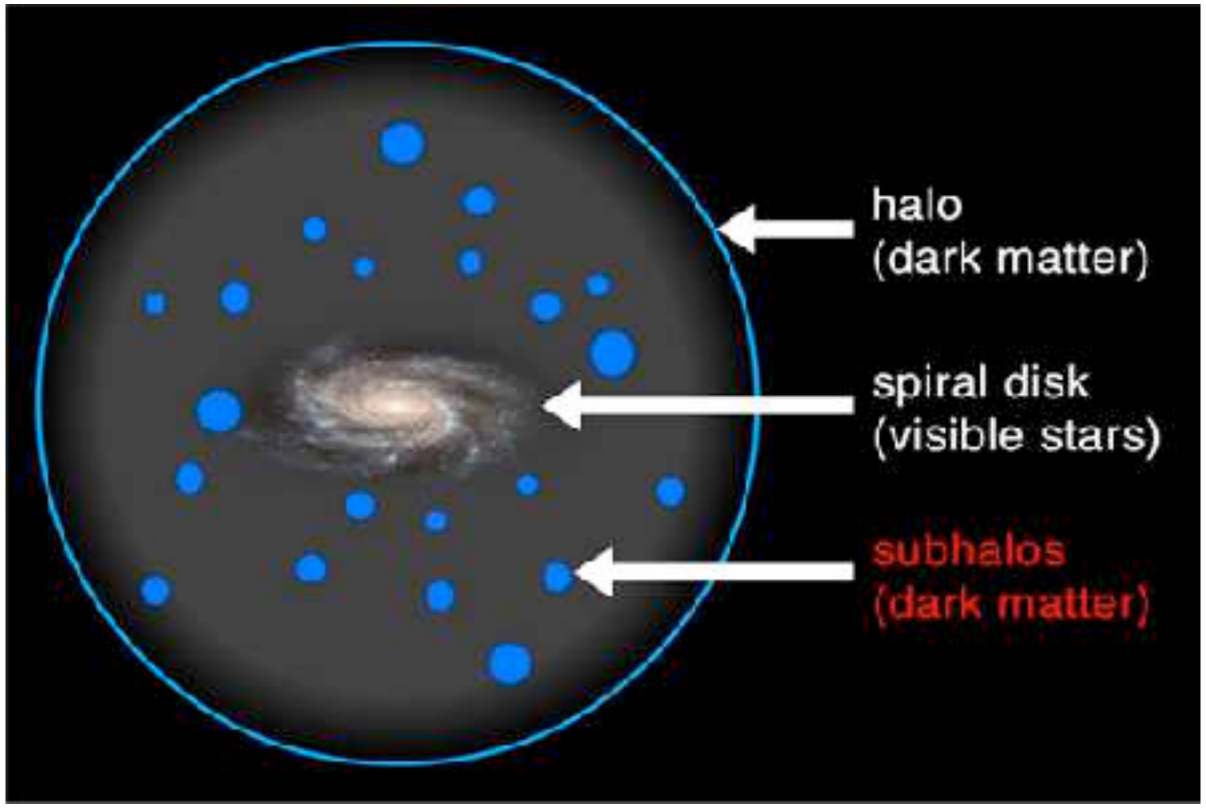


Steller feedback off

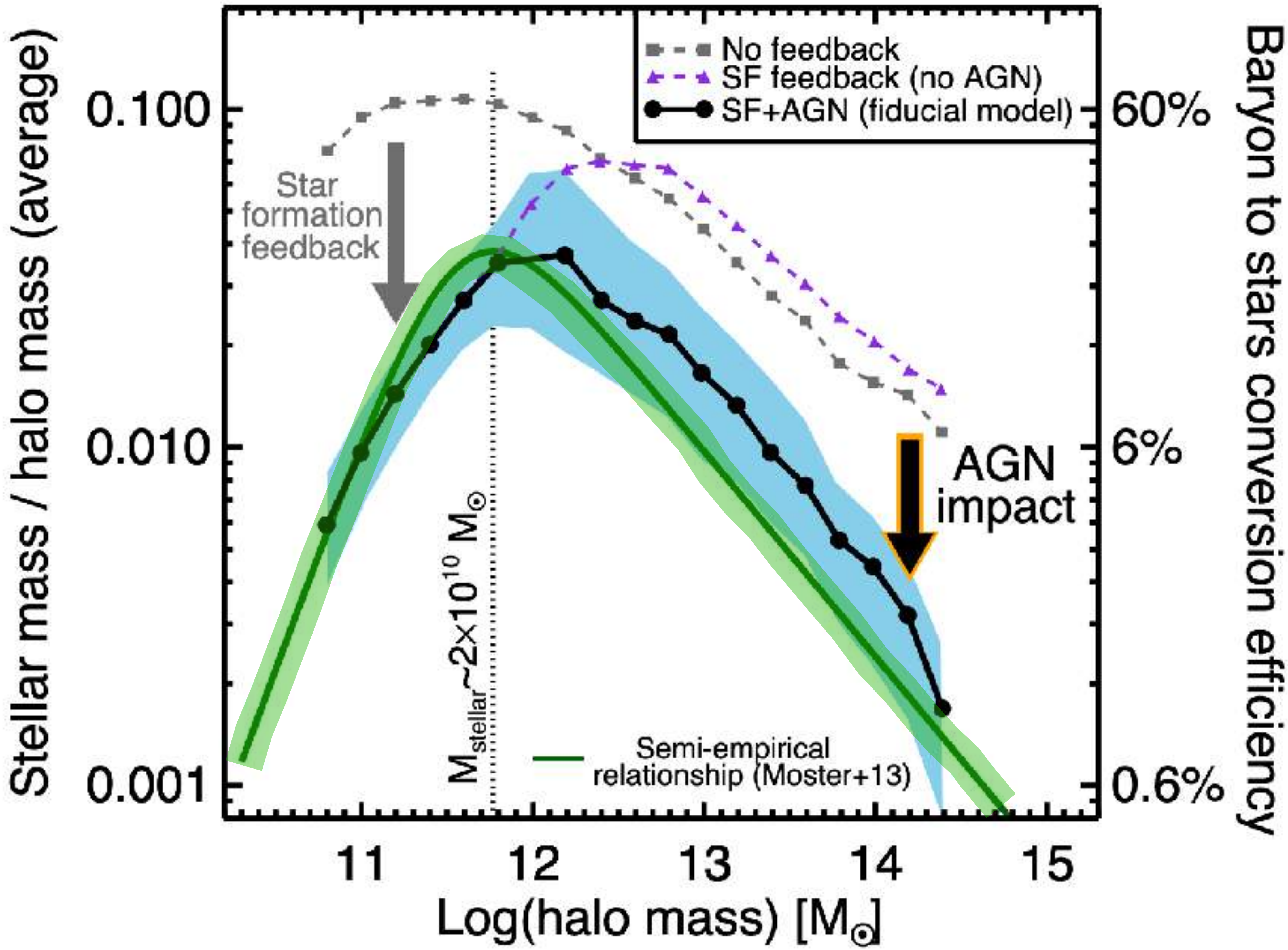
Hopkins+2014 MNRAS, 445, 581

AGN Feedback

- **What causes it?**
  - Energy released as gas falls into a supermassive black hole
  - AGN can launch jets/winds/outflows
- **Effects on the galaxy:**
  - Heats or ejects cold gas
  - Can shut down star formation in massive galaxies
  - Helps explain why massive galaxies are “red and dead”.

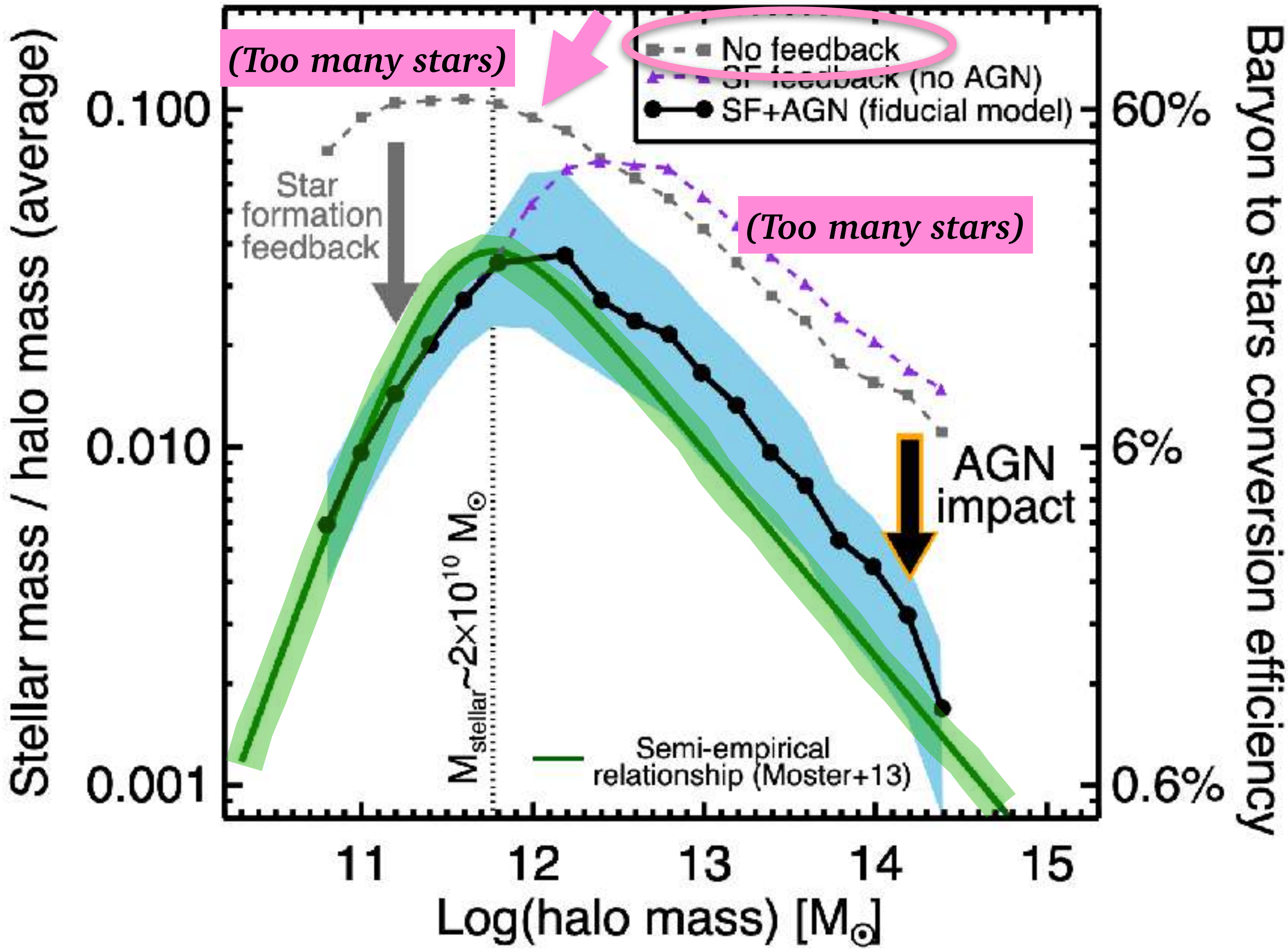


AGN Feedback



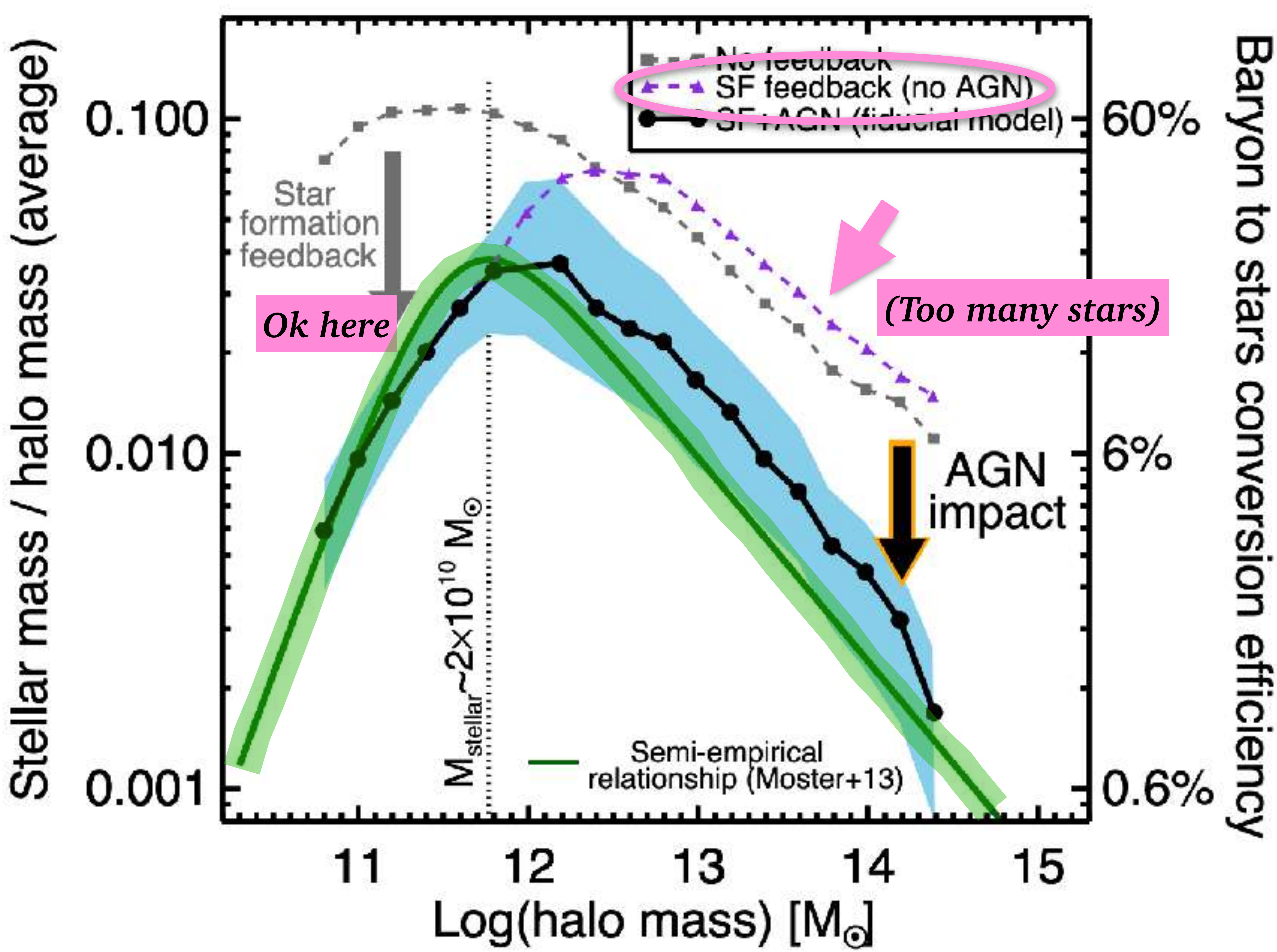
Werner+2019 Space Science Reviews, 215, 1

AGN Feedback



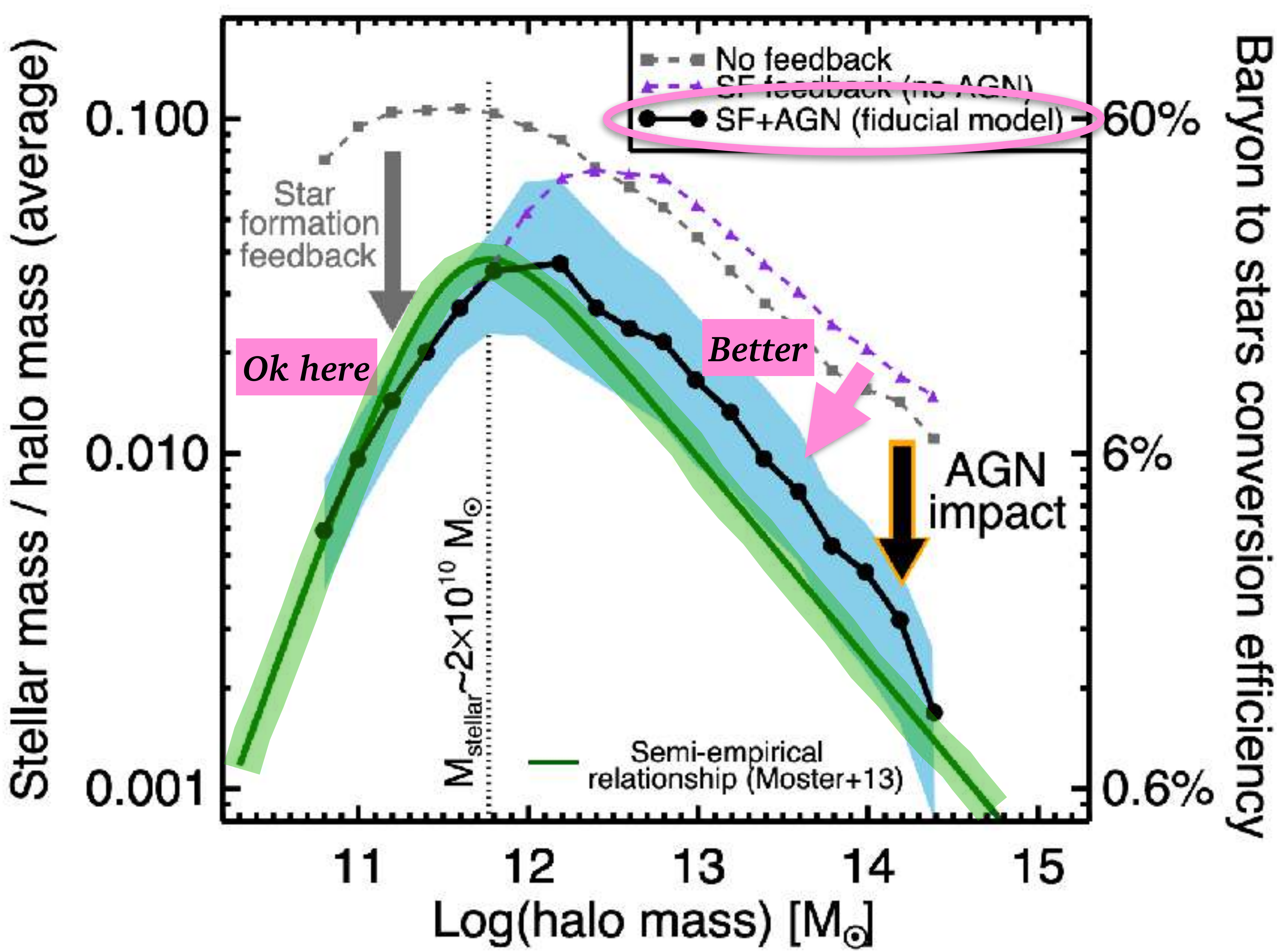
Werner+2019 Space Science Reviews, 215, 1

AGN Feedback



Werner+2019 Space Science Reviews, 215, 1

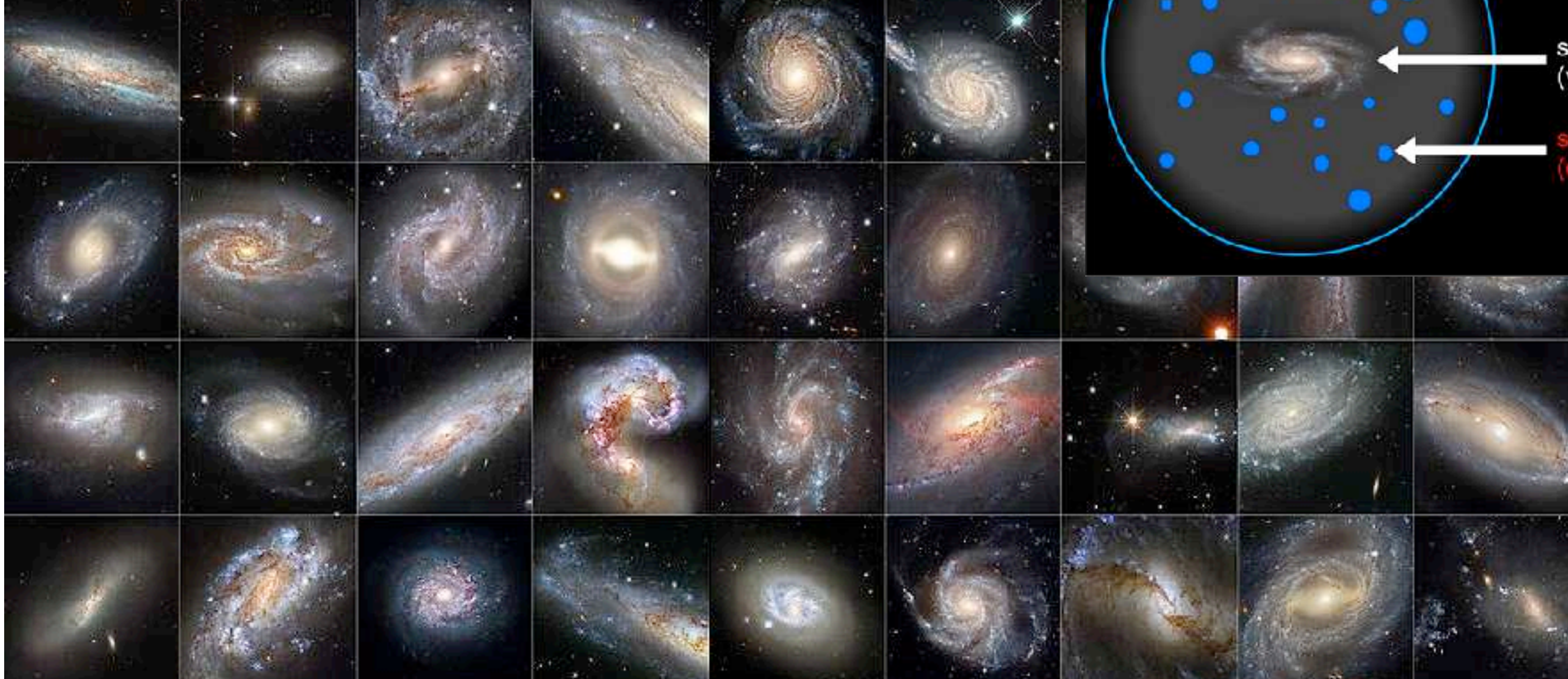
AGN Feedback

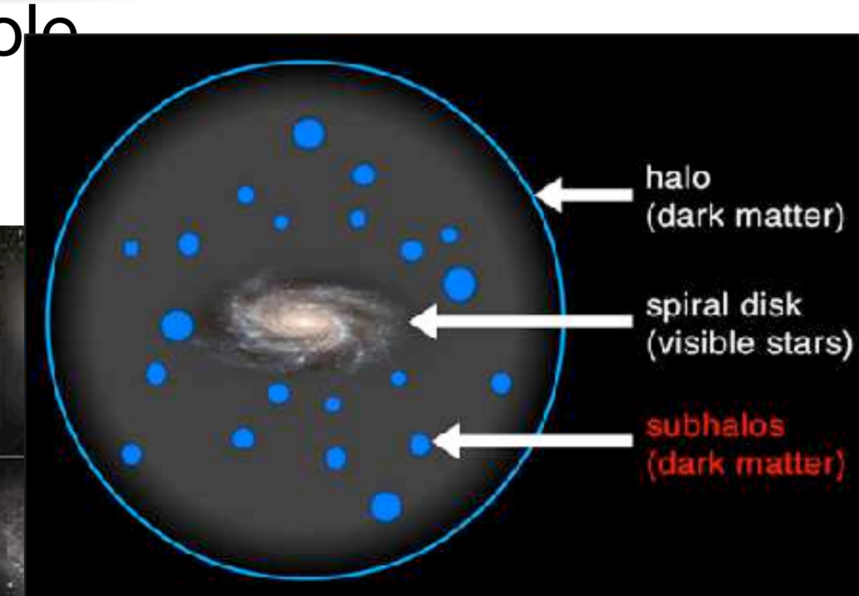


Werner+2019 Space Science Reviews, 215, 1

What is a Galaxy?

- A galaxy is a gravitationally bound system.
  - Stars – from a few million to hundreds of billions
  - Gas and Dust – the interstellar medium (ISM)
  - Dark Matter – invisible mass dominating the galaxy's total mass
  - Sometimes: a central supermassive black hole





What Is Dark Matter?

- Dark matter is a form of matter that:
  - Does not emit, absorb, or reflect light
  - Interacts primarily through gravity
  - Makes up about 80% of the matter in the universe

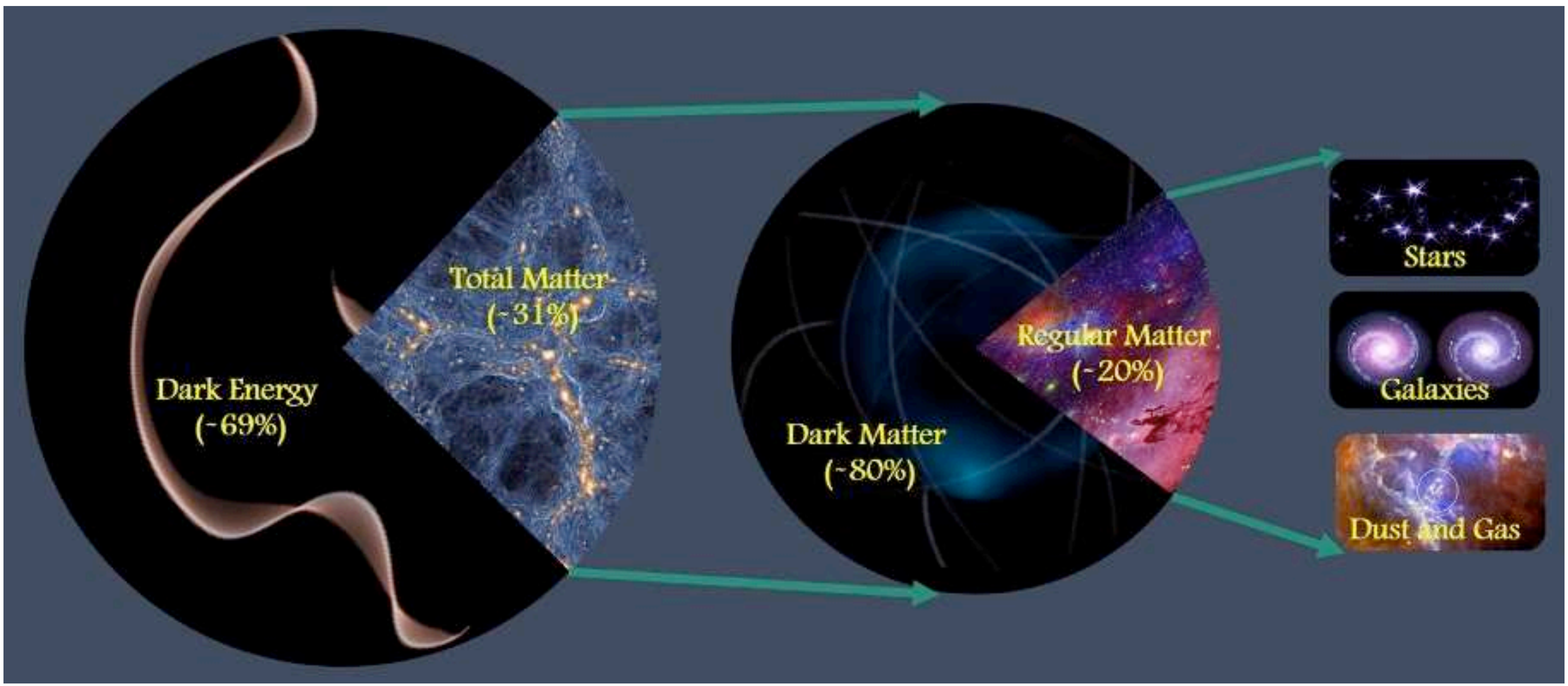


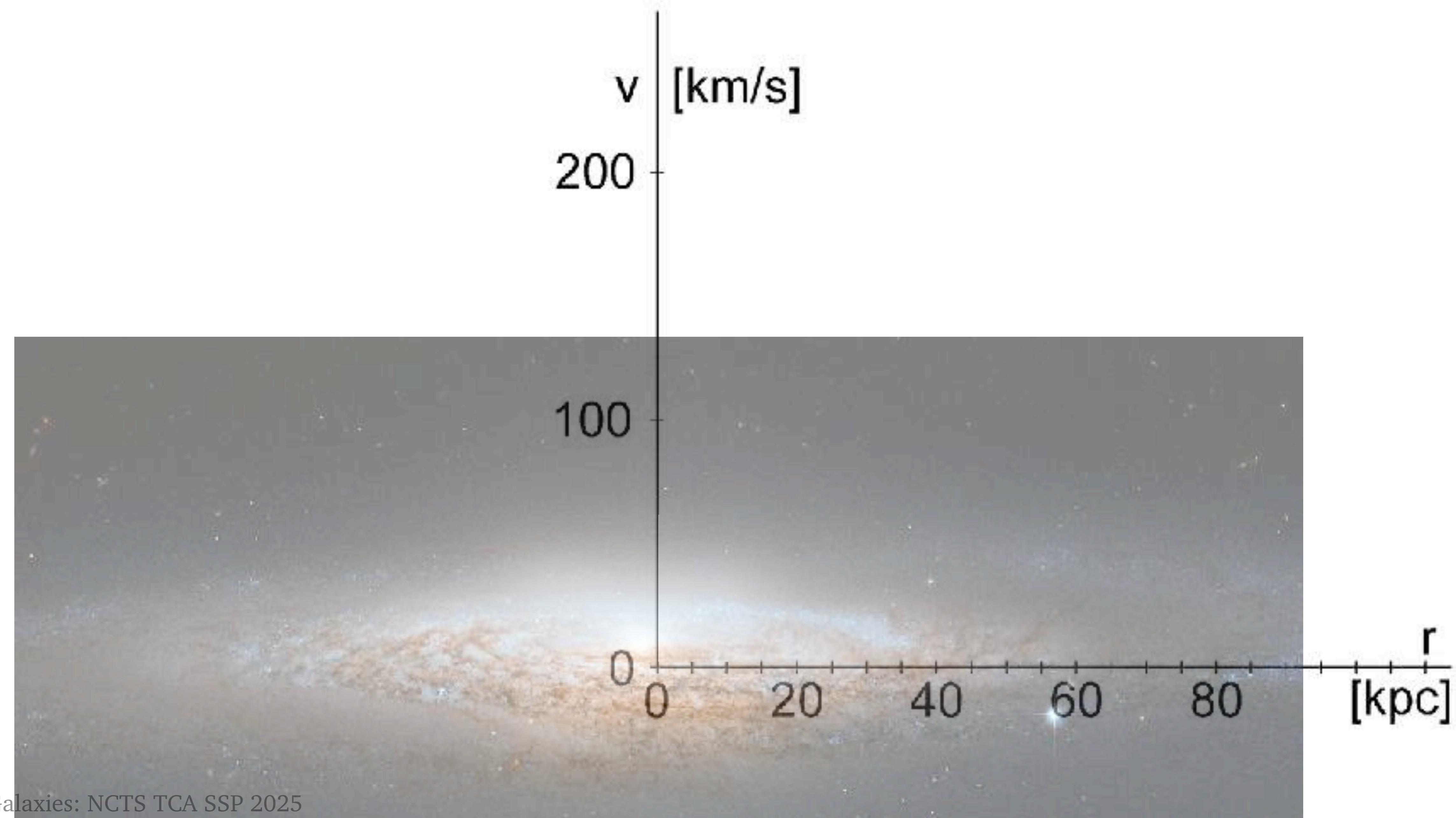
Image credit: UCR/Mohamed Abdullah

Dark Matter

- Why do we believe in dark matter?

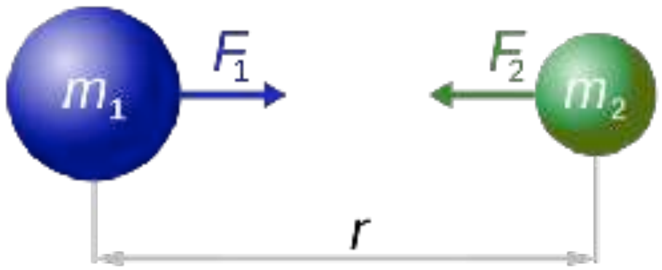
Dark Matter

- Why do we believe in dark matter?
- **Rotation curve** of a galaxy:
    - A rotation curve is a plot showing how the orbital velocity of stars or gas in a galaxy changes with distance from the galactic center.

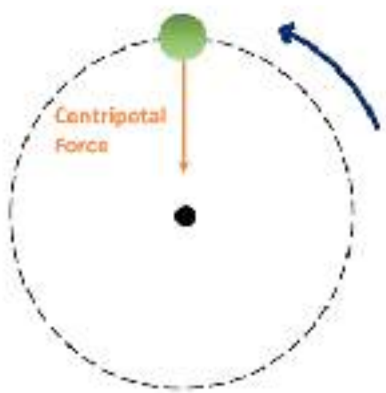


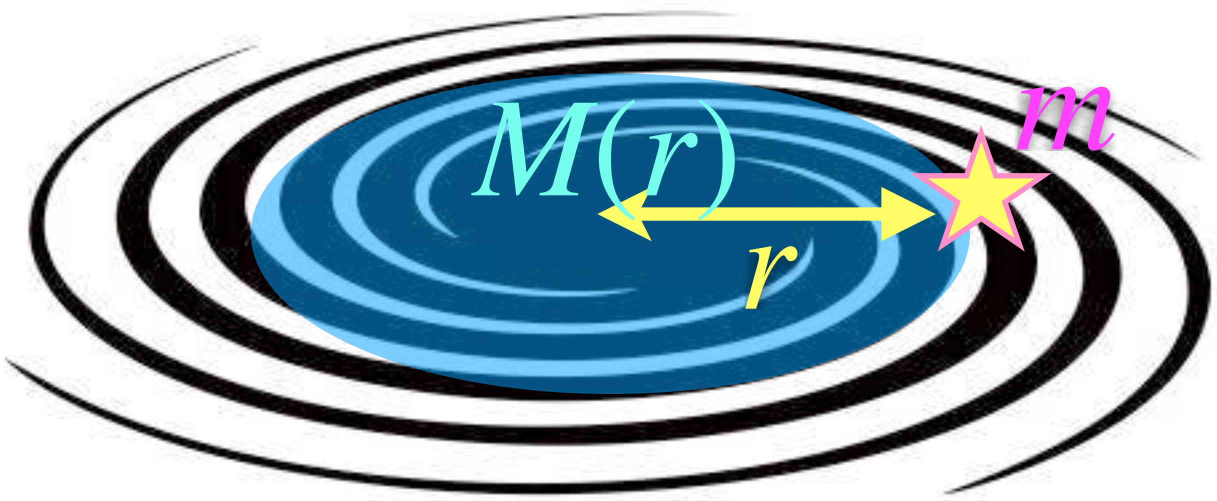
Dark Matter

- The gravitational force between two masses is:
  - $$F = \frac{GMm}{r^2}$$



- For an object in circular orbit, the centripetal force needed to keep it in orbit is:
  - $$F = \frac{mv^2}{r}.$$





- Set the gravitational force equal to the centripetal force:
  - $$v(r) = \sqrt{\frac{GM(r)}{r}}$$
  - This is the basic rotation curve for a test mass orbiting a point mass or spherically symmetric mass distribution.

Dark Matter

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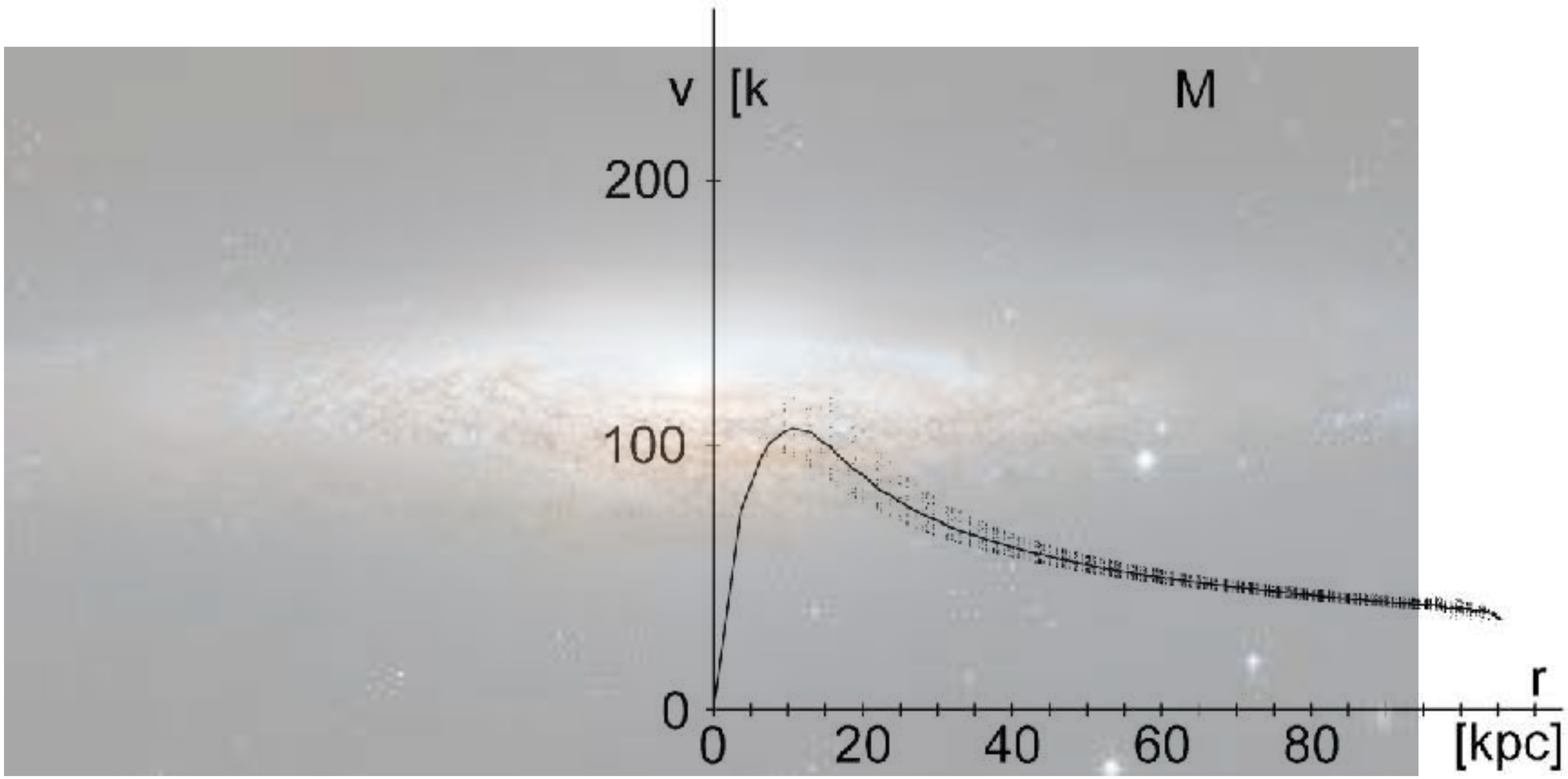
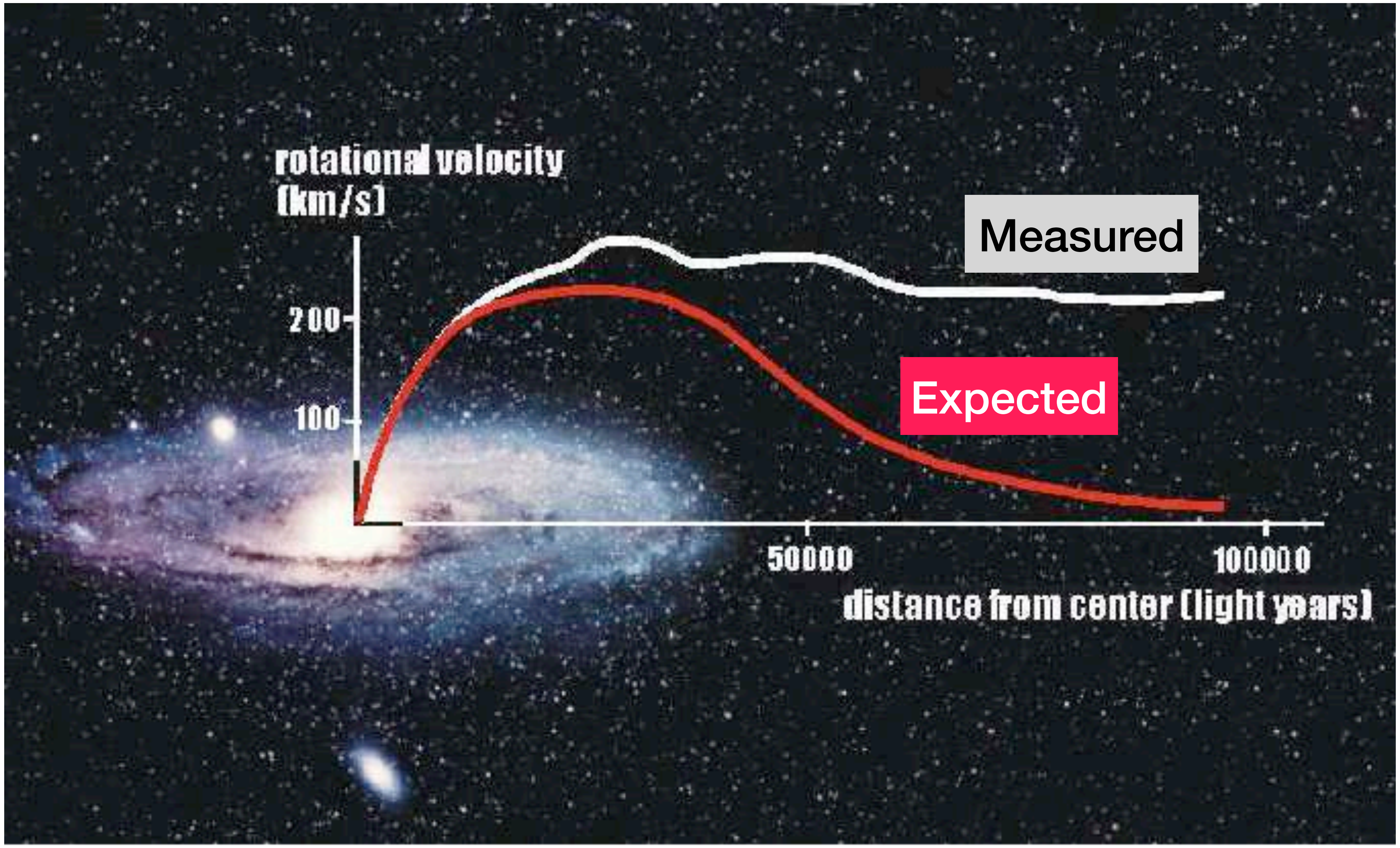


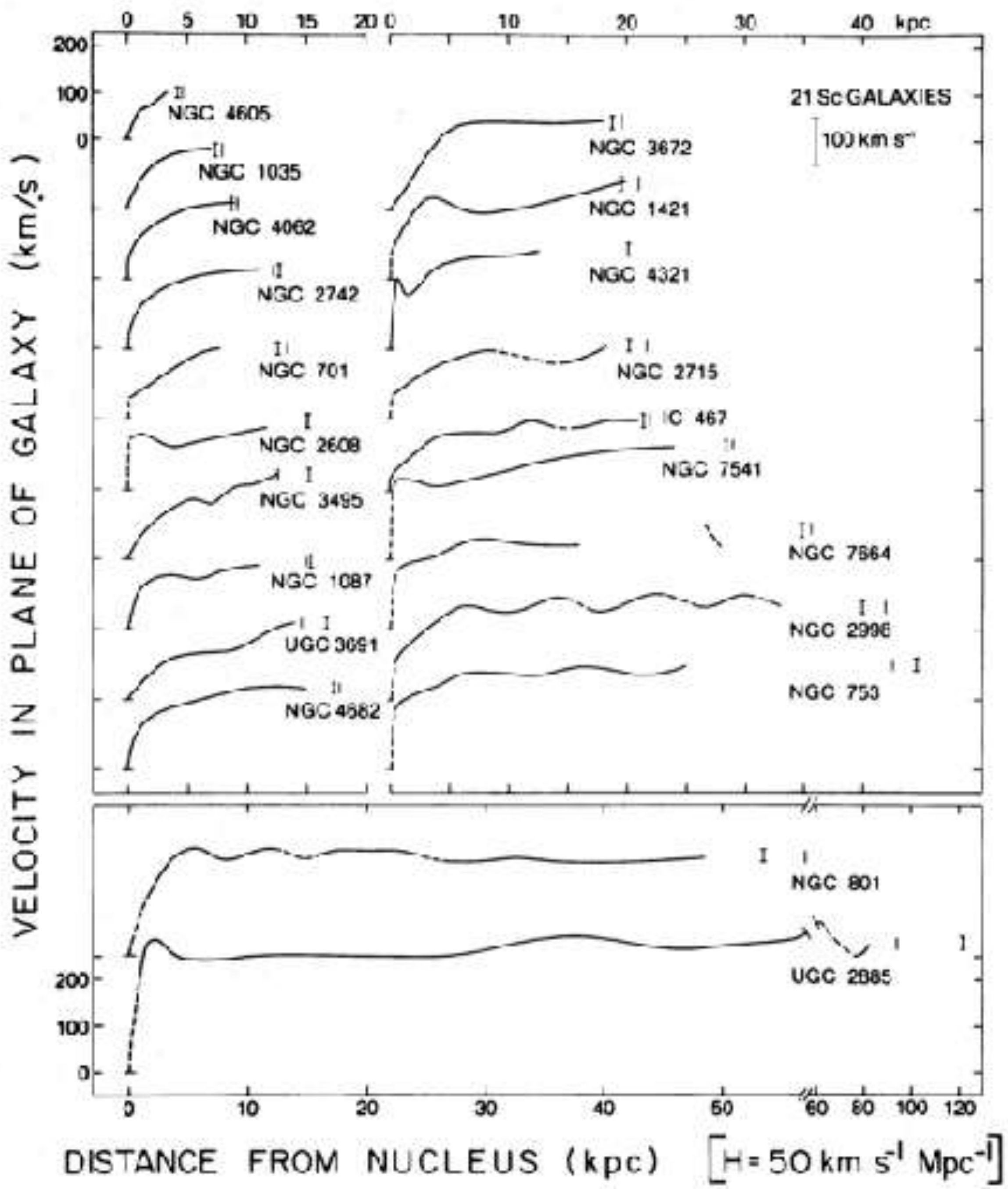
Dark Matter

- $v(r) = \sqrt{\dfrac{GM(r)}{r}}$
- Rotation curve reveals the underlying mass distribution and provides strong evidence for dark matter, especially when the curve stays flat at large radii where visible matter is sparse.



Dark Matter

- The way galaxy rotate is strong evidence for the existence of dark matter.
- Who found this? Dr. Vera Rubin (1928-2016).



VIII. DISCUSSION AND CONCLU

We have obtained spectra and deter curves to the faint outer limits of 21 Sc g inclination. The galaxies span a range from 3×10^9 to 2×10^{11} $L_\odot$, a range 10^{10} to 2×10^{12} $M_\odot$, and a range in ra 122 kpc. In general, velocities are obta of the optical image (defined by 25 mag arcsec^{-2}), a greater distance than previously observed. The major conclusions are intended to apply only to Sc galaxies.

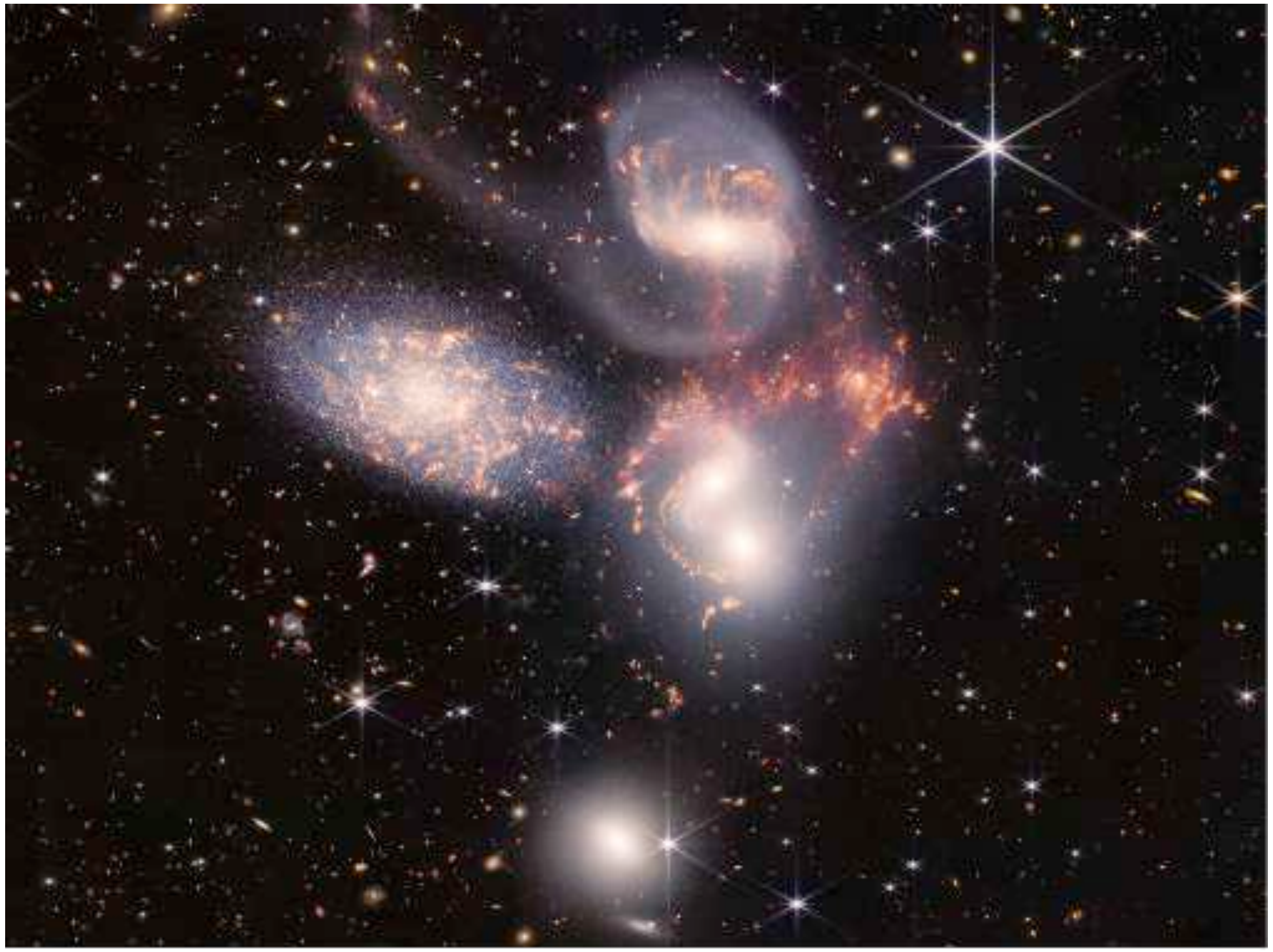
1. Most galaxies exhibit rising rotational velocities at the last measured velocity; only for the very largest galaxies are the rotation curves flat. Thus the smallest Sc's (i.e., lowest luminosity) exhibit the same lack of a Keplerian velocity decrease at large R as do the high-luminosity spirals. This form for the rotation curves implies that the mass is not centrally condensed, but that significant mass is located at large R. The integral mass is increasing at least as fast as R. The mass is not converging to a limiting mass at the edge of the optical image. The conclusion is inescapable that non-luminous matter exists beyond the optical galaxy.

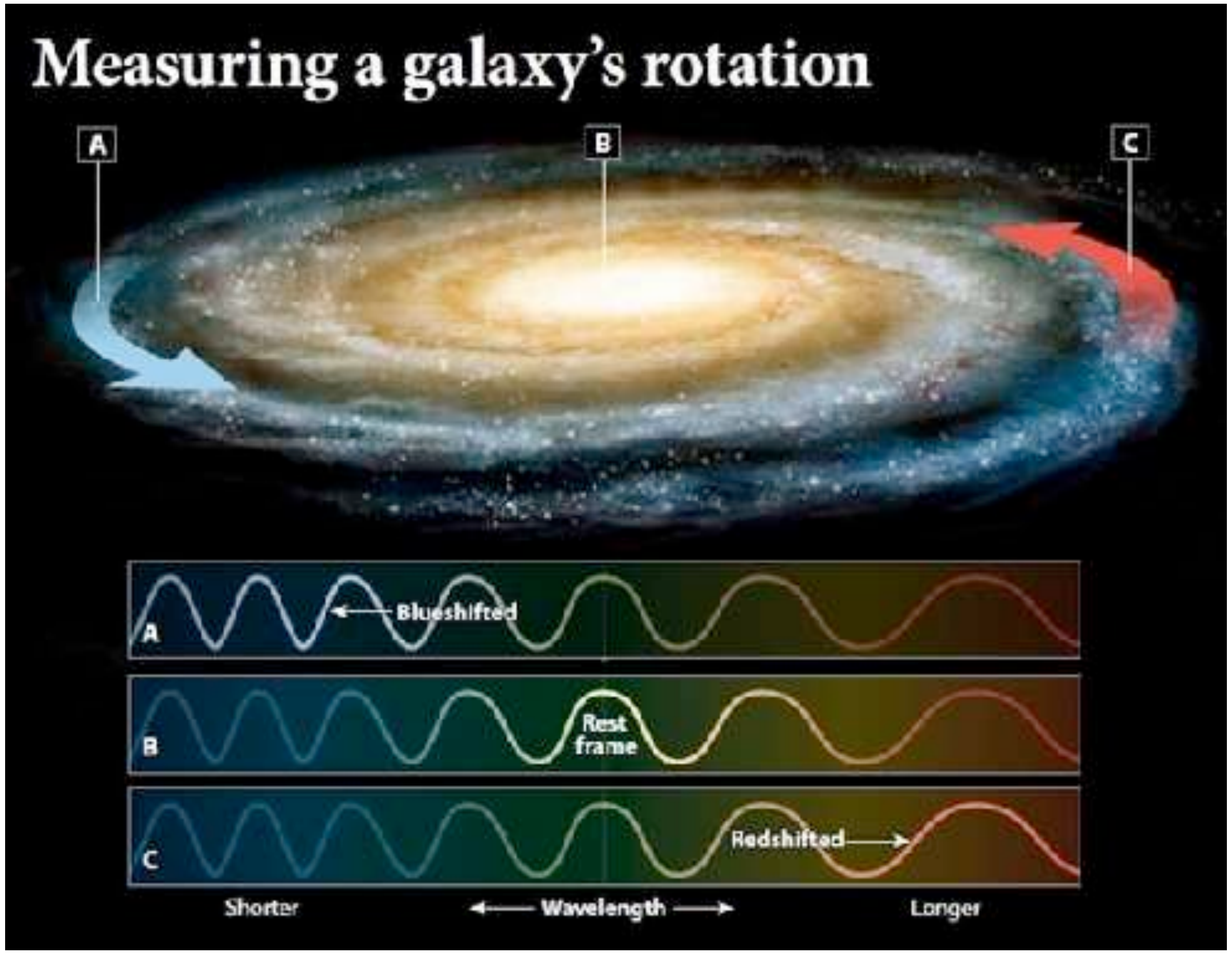
Rubin et al. 1980, ApJ, 238, 471

IV. How Do We Study Galaxies?

How Do We Study Galaxies?

- Light (electromagnetic radiation)
- Spectra
- Simulations (based on physics and gravity)

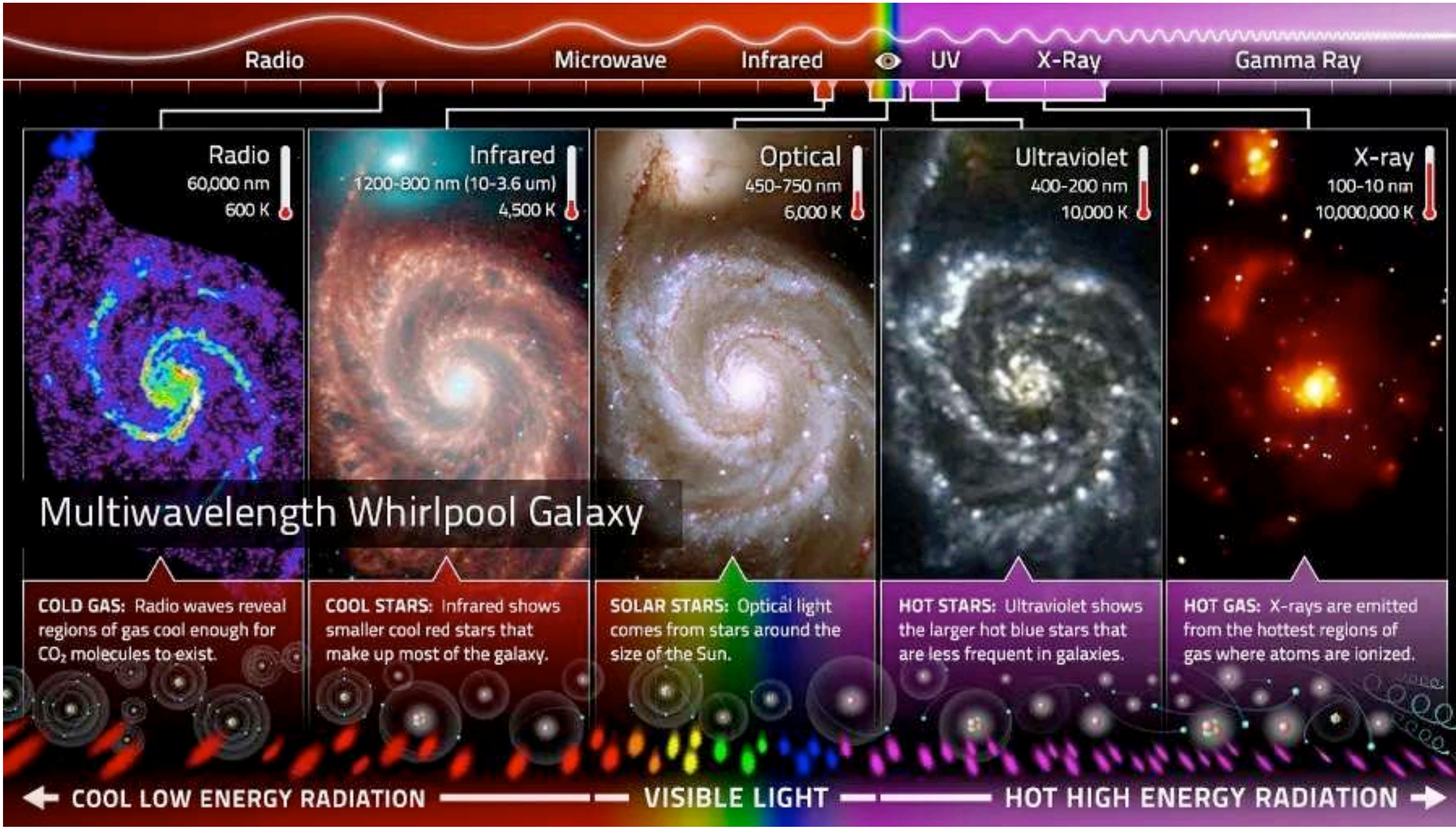




Doppler effect

Multi-wavelength Light From Galaxies

increasing eneergy

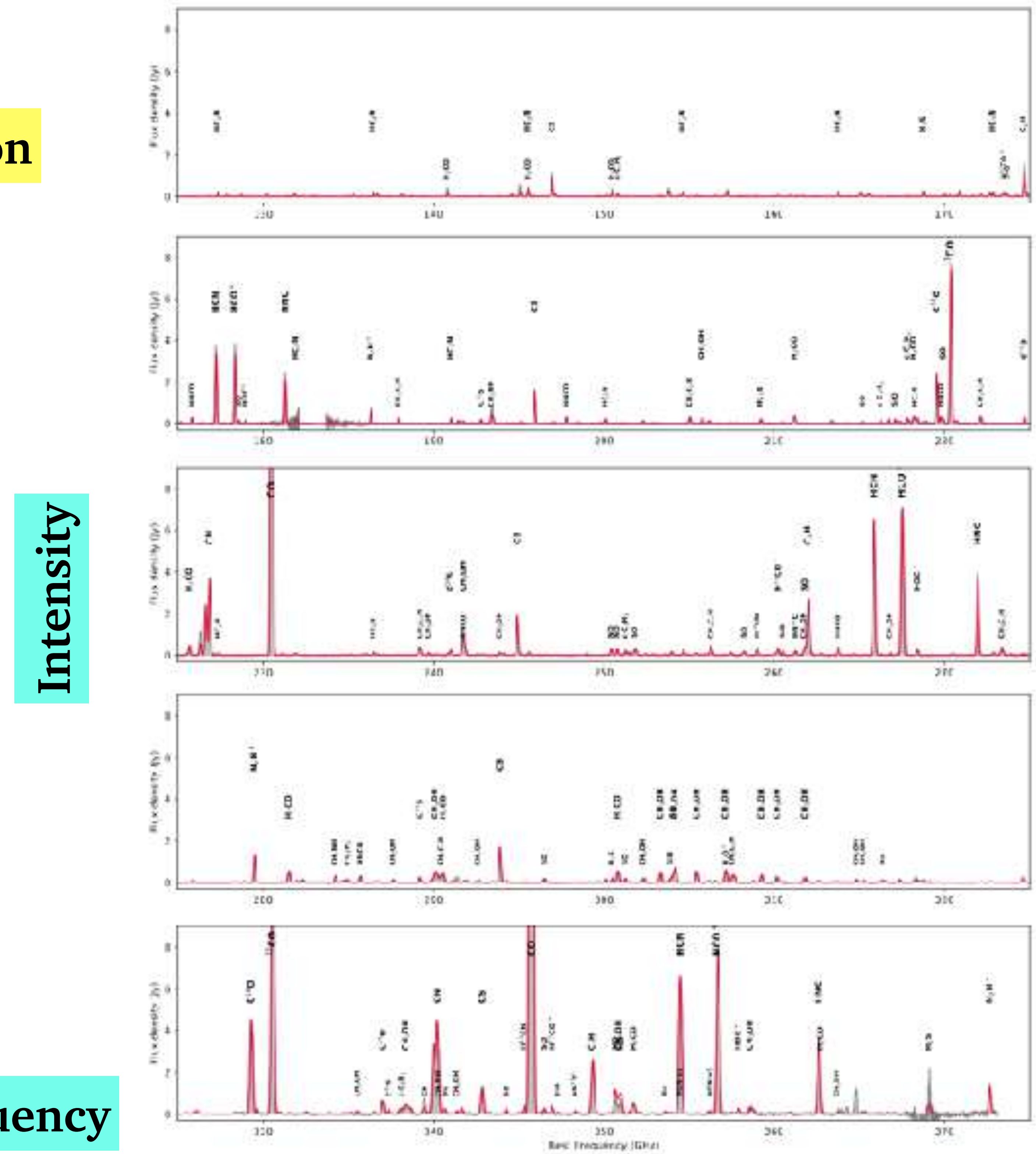


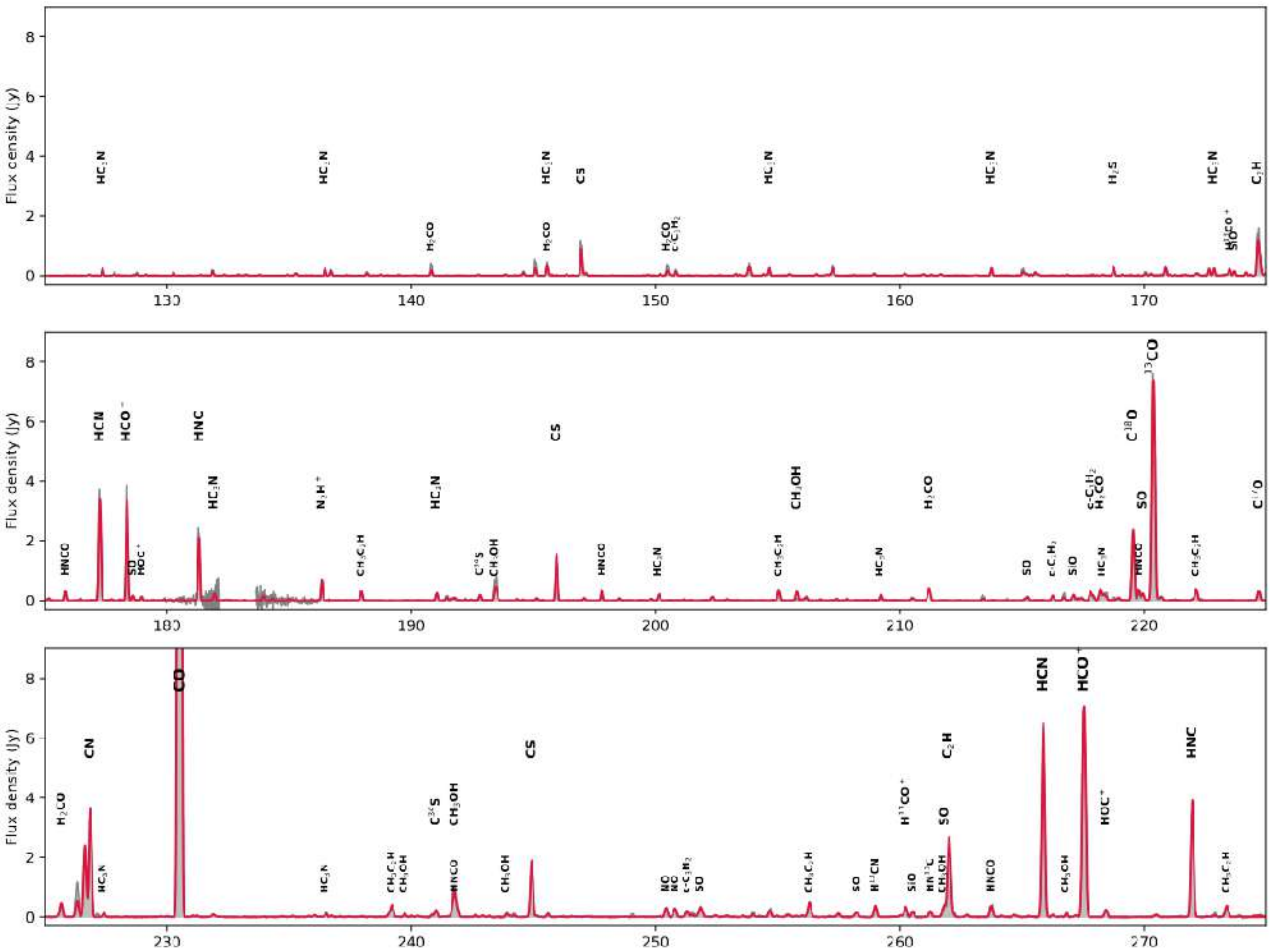
Multi-wavelength Spectra

- The spectrum of a galaxy is the combined light from its billions of stars and all other radiating matter in the galaxy, such as gas and dust.

Example 1: chemical composition

Martin et al. 2021, A&A, 656, A46





Flux density (Jy)
0
2
4
6
8
130
140
150
160
170
HC$_3$N
CS
H$_2$CO
c-C$_3$H$_2$
H$_2$S
C$_2$H
SiO
H^{13}CO$^+$
Flux density (Jy)
180
190
200
210
220
HNCO
HCN
HCO$^+$
SO
HOC$^+$
HNC
HC$_3$N
N$_2$H$^+$
CH$_3$C$_2$H
C^{34}S
CH$_3$OH
CS
H$_2$CO
SiO
c-C$_3$H$_2$
C^{18}O
^{13}CO
C^{17}O
Flux density (Jy)
230
240
250
260
270
H$_2$CO
CN
HC$_3$N
CO
CH$_3$C$_2$H
CH$_3$OH
C^{34}S
HNCO
CS
NO
c-C$_3$H$_2$
SO
H^{13}CN
H^{13}CO$^+$
SiO
HN^{13}C
C$_2$H
HCN
HCO$^+$
HOC$^+$
HNC

Multi-wavelength Spectra

- In a galaxy, only the youngest, **most young massive stars** in a galaxy are hot enough to excite hydrogen gas to emit **Hα (H-alpha)** photons, making the **Hα** line a tracer of recent star formation.

Example 2: Star Formation Rate (SFR)

Balmer series:

Hα: $n = 3 \rightarrow 2$ **(6562.8 Ångströms)**

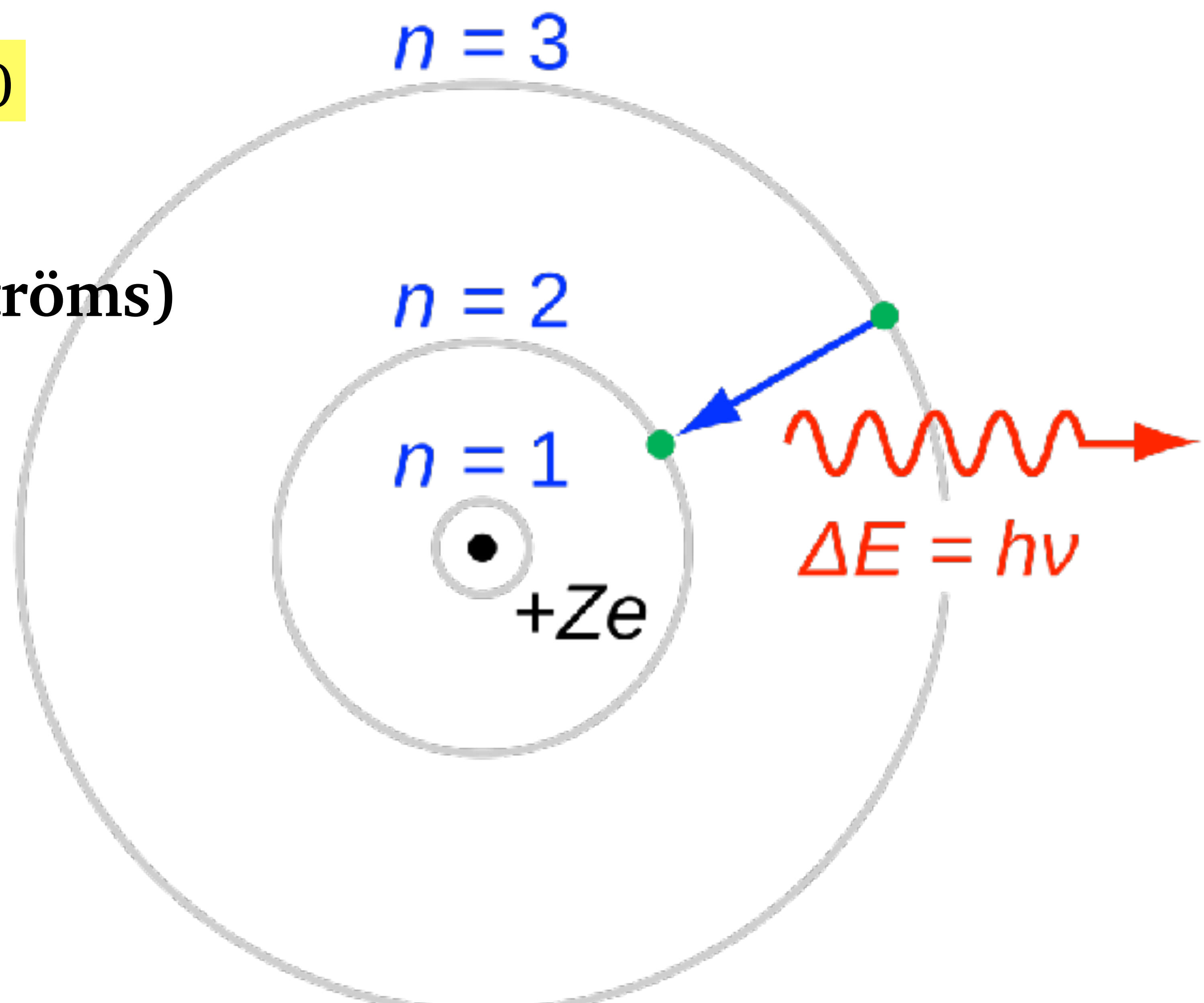
Hβ: $n = 4 \rightarrow 2$

Hγ: $n = 5 \rightarrow 2$

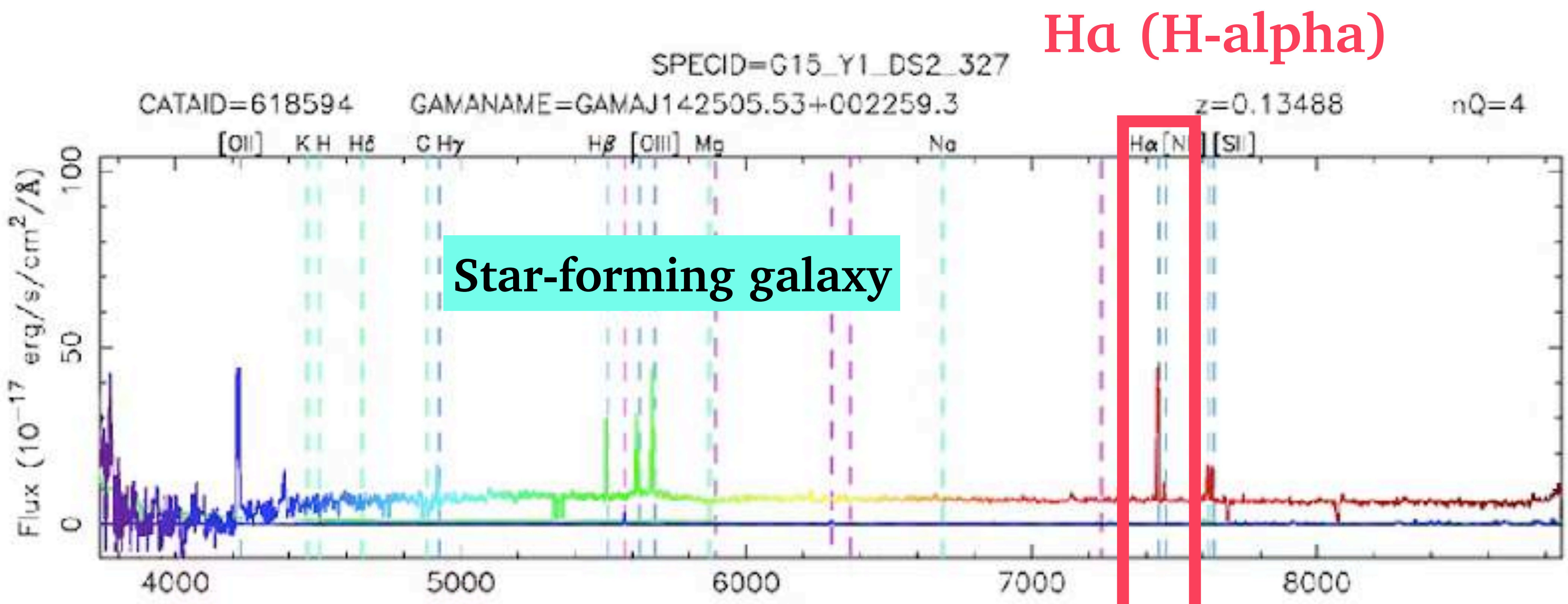
Lyman series:

Lα: $n = 2 \rightarrow 1$

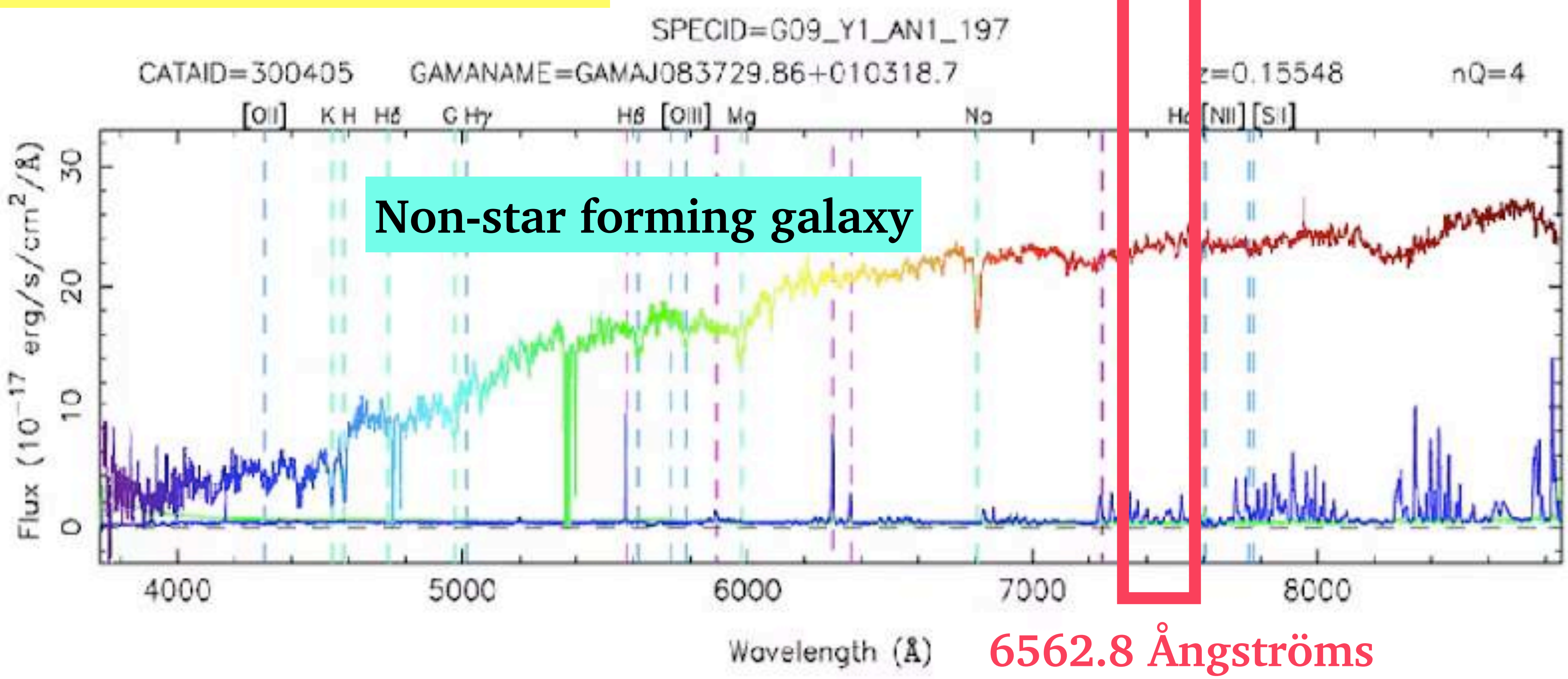
Lβ: $n = 3 \rightarrow 1$



Multi-wavelength Spectra



Example 2: Star Formation Rate (SFR)

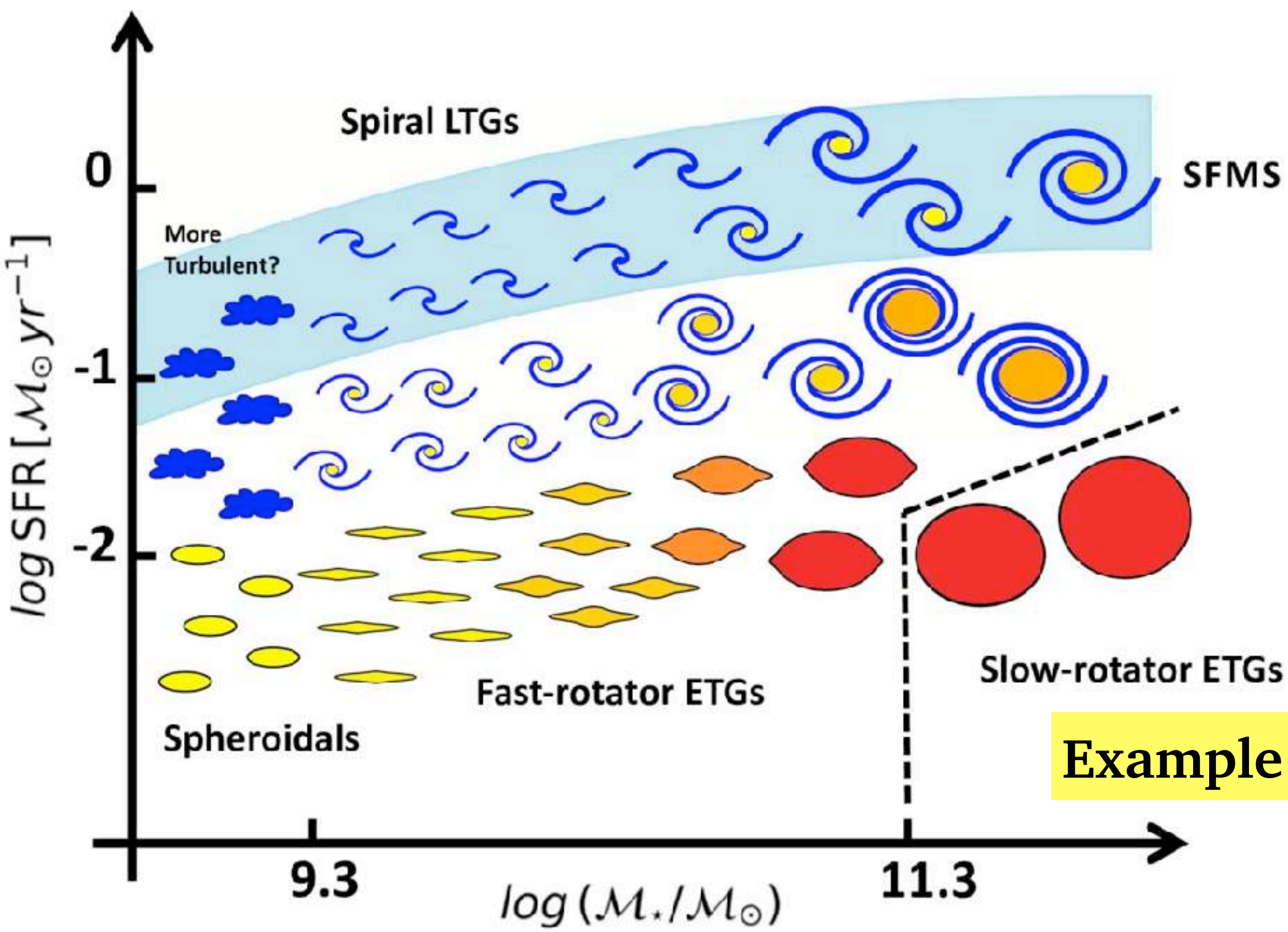


Multi-wavelength Spectra

- The star formation rate (SFR) is a measure of how quickly a galaxy (or a region within it) is forming new stars.
- Kennicutt (1998) provides a commonly used conversion:

$$\text{SFR }(M_\odot/\text{yr}) \approx 7.9 \times 10^{-42} \times L(\text{H}\alpha)\ (\text{erg/s})$$

star formation rate

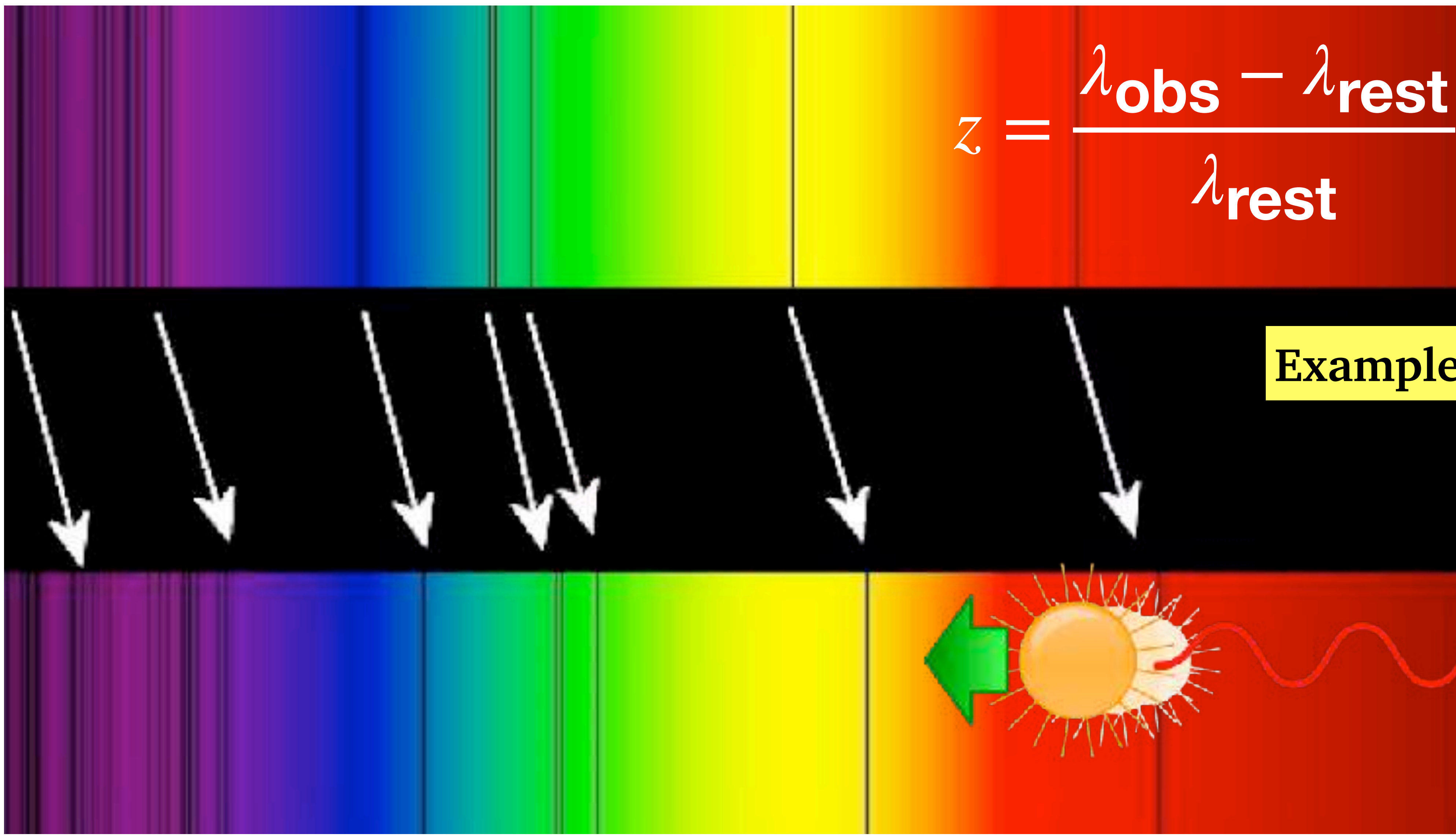


stellar mass

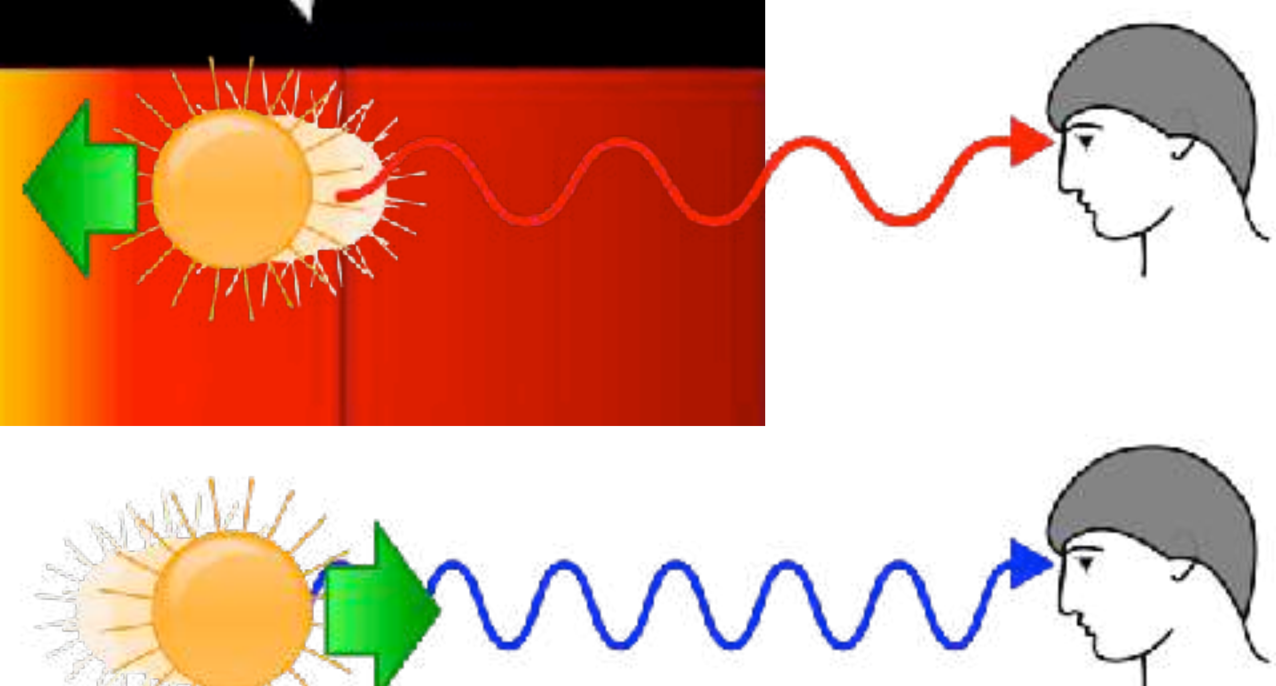
Example 2: Star Formation Rate (SFR)

Multi-wavelength Spectra

- A basic piece of information derived from a spectrum is the distance to the galaxy (redshift, z). Because the universe is expanding, the light emitted by the galaxy is stretched toward redder wavelengths as it innocently moves across space. We measure this as redshift.



Example 3: galaxy distance



Multi-wavelength Spectra

- If you observe the Hα line at $\lambda_{\text{obs}} = 7219.3\ \text{Å}$, and its rest-frame wavelength is $\lambda_{\text{rest}} = 6563\ \text{Å}$, then $z = \dfrac{7219.3 - 6563}{6563} \approx 0.10$

- This means the galaxy is receding from us, and its light has been stretched by 10%.

- Use Hubble's Law: $D \approx \dfrac{cz}{H_0}$, $D \approx\ 418\ \text{Mpc}.$

    - H_0: Hubble constant,

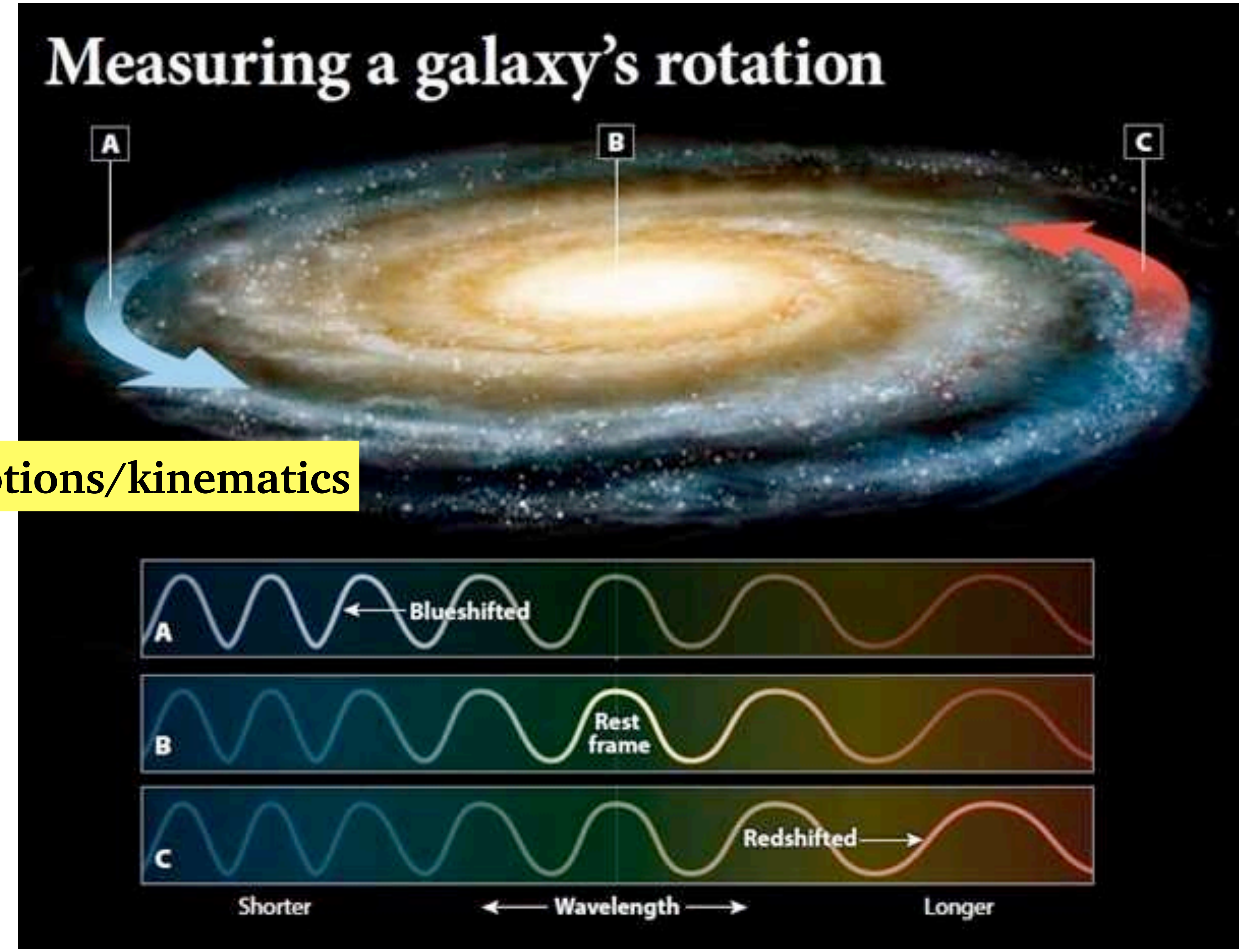
    - c: speed of light,

    - z: redshift.

Example 3: galaxy distance

Multi-wavelength Spectra

- By observing the Doppler shift of emission lines (e.g., Hα, HI 21 cm) at different positions across the galaxy, we can constrain the rotation of a galaxy.

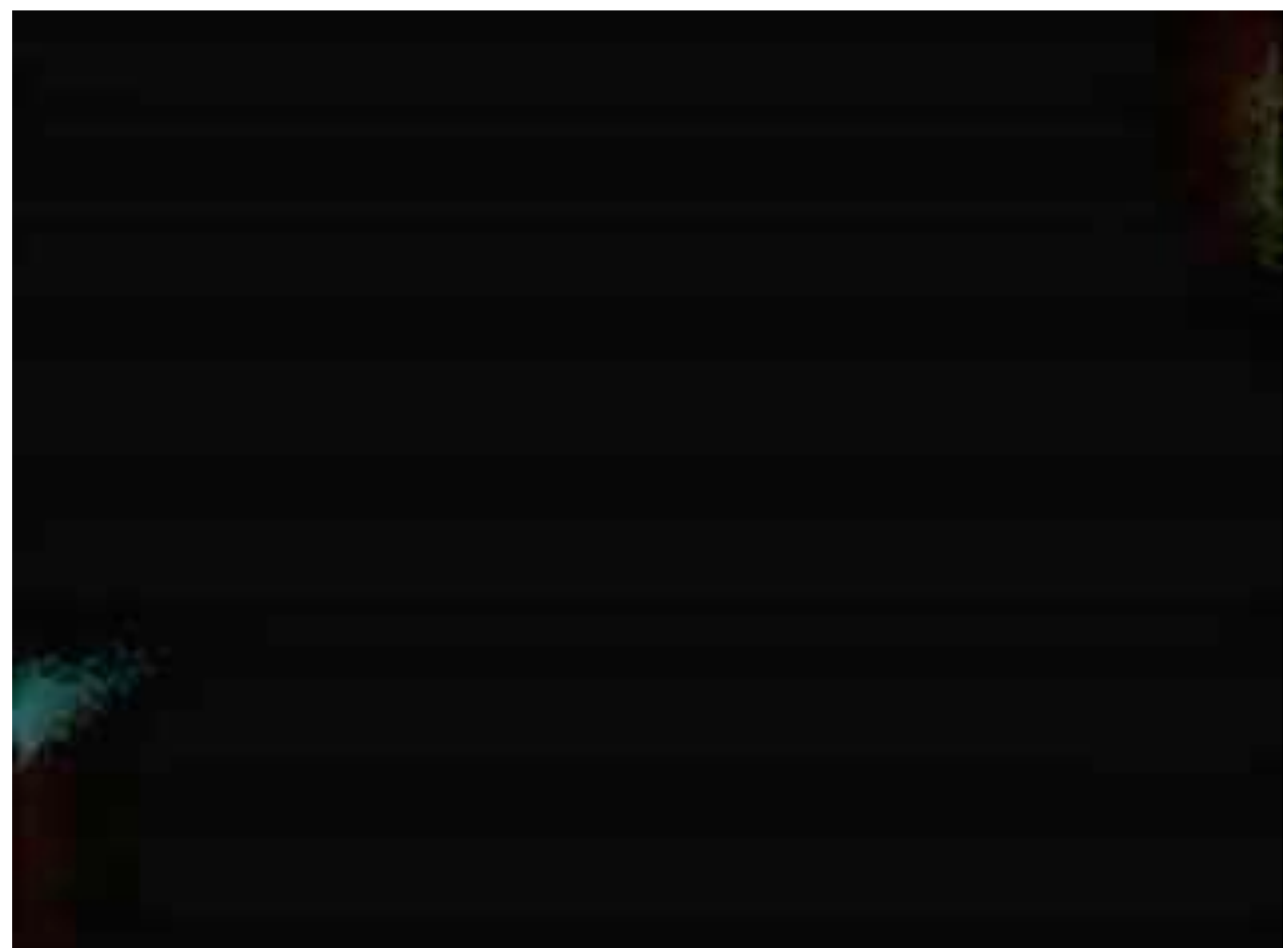


Example 4: motions/kinematics

Galaxy Simulations

- Observations show us galaxies as they are, but we want to understand **how galaxies form and evolve**.
- Simulations let us:
    - Recreate galaxies and test hypotheses
    - Compare directly with telescope data.

NGC 4676, or the Mice Galaxies
Credit: NASA



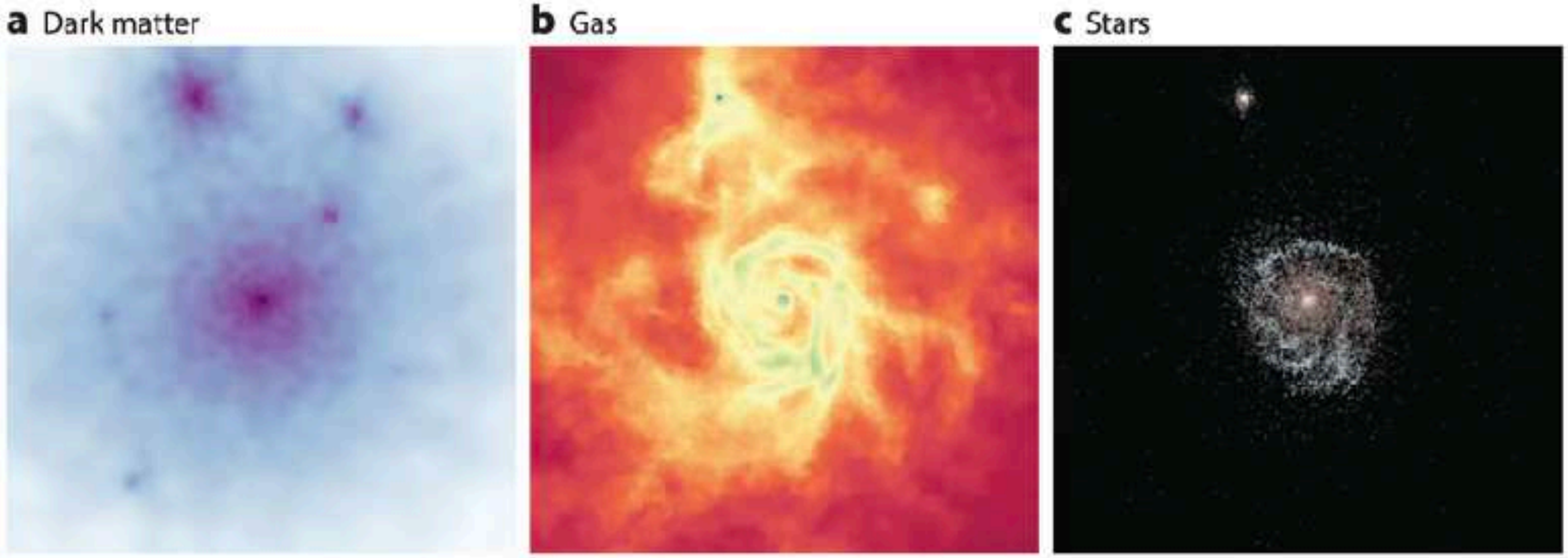
Credit: Josh Barnes (University of Hawaii) and John Hibbard (National Radio Astronomy Observatory)

Galaxy Simulations

- What **Physics / Chemistry** Goes into Galaxy Simulations?
  - **Gravity / Mass**
    - Pulls stars, gas, and dark matter together
    - Forms galaxies and holds them together
  - **Hydrodynamics**
    - Simulates how gas moves, flows, and gets compressed
    - Important for forming stars
  - **Radiative cooling/heating**
    - Gas can cool and collapse to make stars
    - Or get heated by energy from stars or black holes

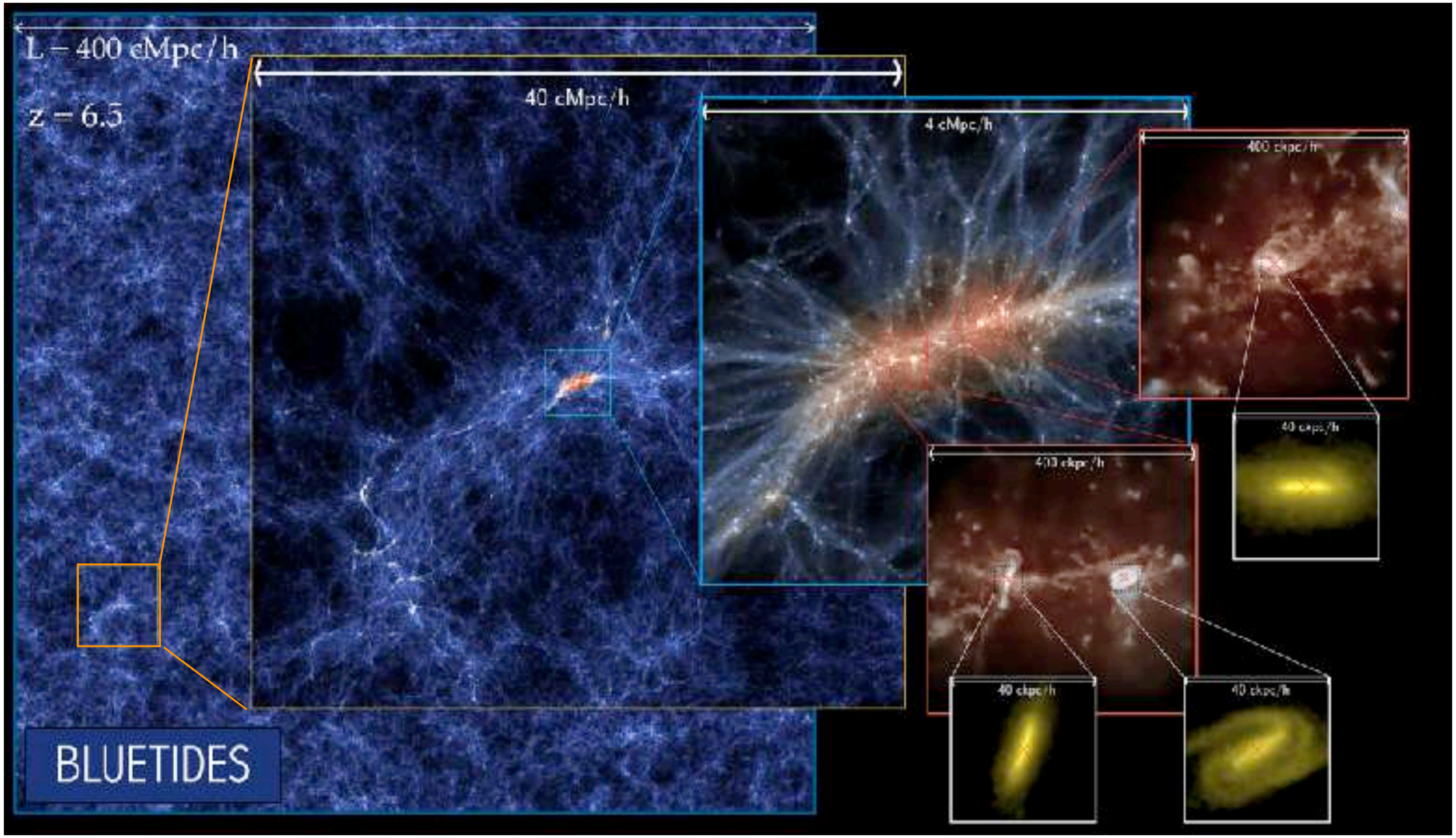
Galaxy Simulations

- **Star formation models**
  - When gas gets dense and cold, it can form stars
- **Feedback from stars & black holes**
  - Stars and black holes give off energy (like supernovae or jets)
  - This can blow gas out or stop more stars from forming
- **Chemical Process**
  - Formation of hearvy elements, molecules.



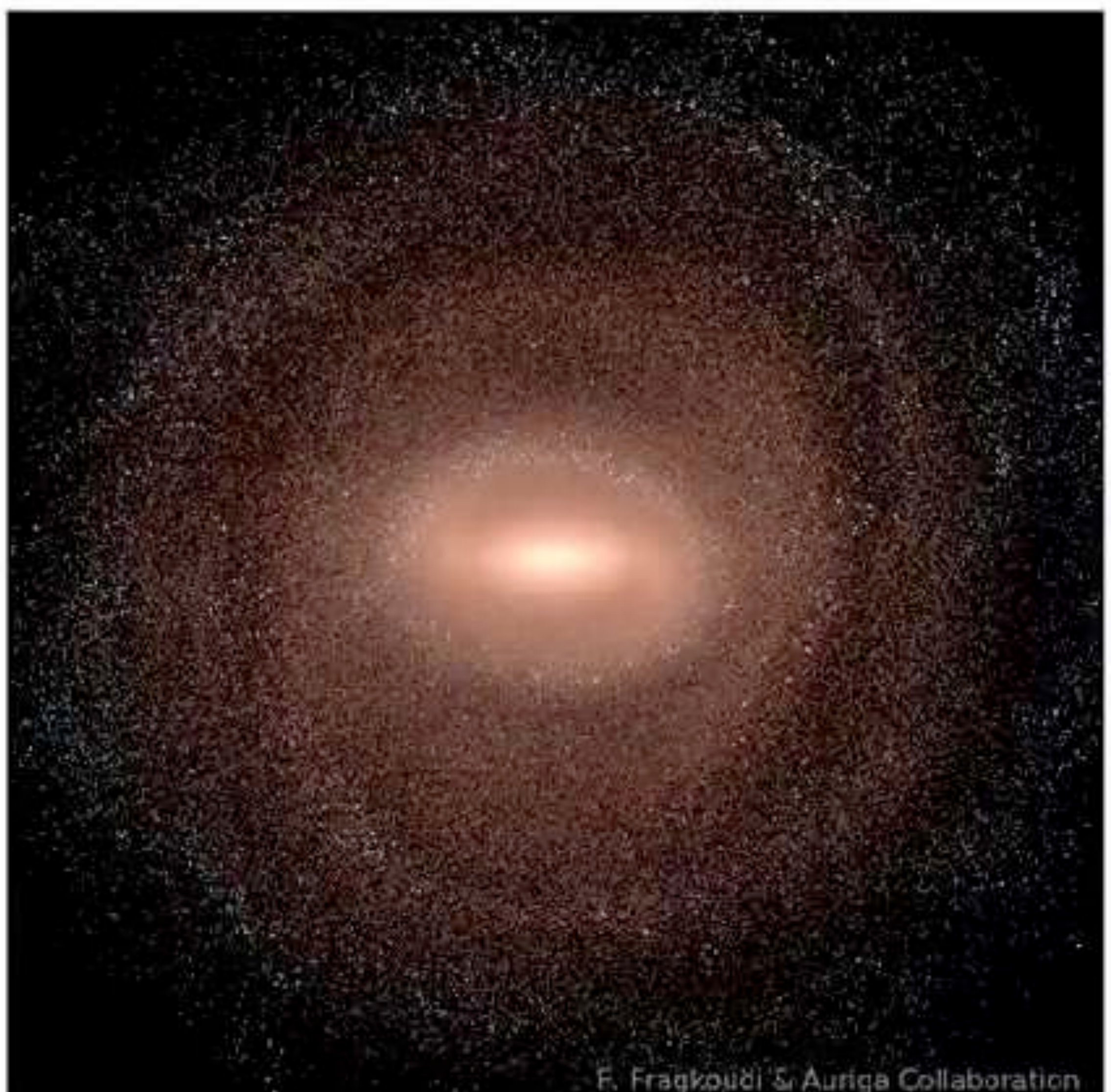
Types of Galaxy Simulations

- **Cosmological Simulations**
  - Simulate a large volume of the universe
  - Include many galaxies, dark matter, and cosmic structure
- Examples: Illustris(TNG), EAGLE, Millennium, SIMBA, BlueTides



Types of Galaxy Simulations

- **Zoom-in Simulations**
  - Simulate one (or a few) galaxy at a time in high resolution
  - Focus on individual galaxies in high detail
- Example: FIRE, NIHAO, Auriga



A simulated barred spiral galaxy from the Auriga simulations. Rotating the galaxy to view it face-on, edge-on and zooming in on its bar and boxy/peanut bulge. Credit: F. Fragkoudi & the Auriga Collaboration

Types of Galaxy Simulations

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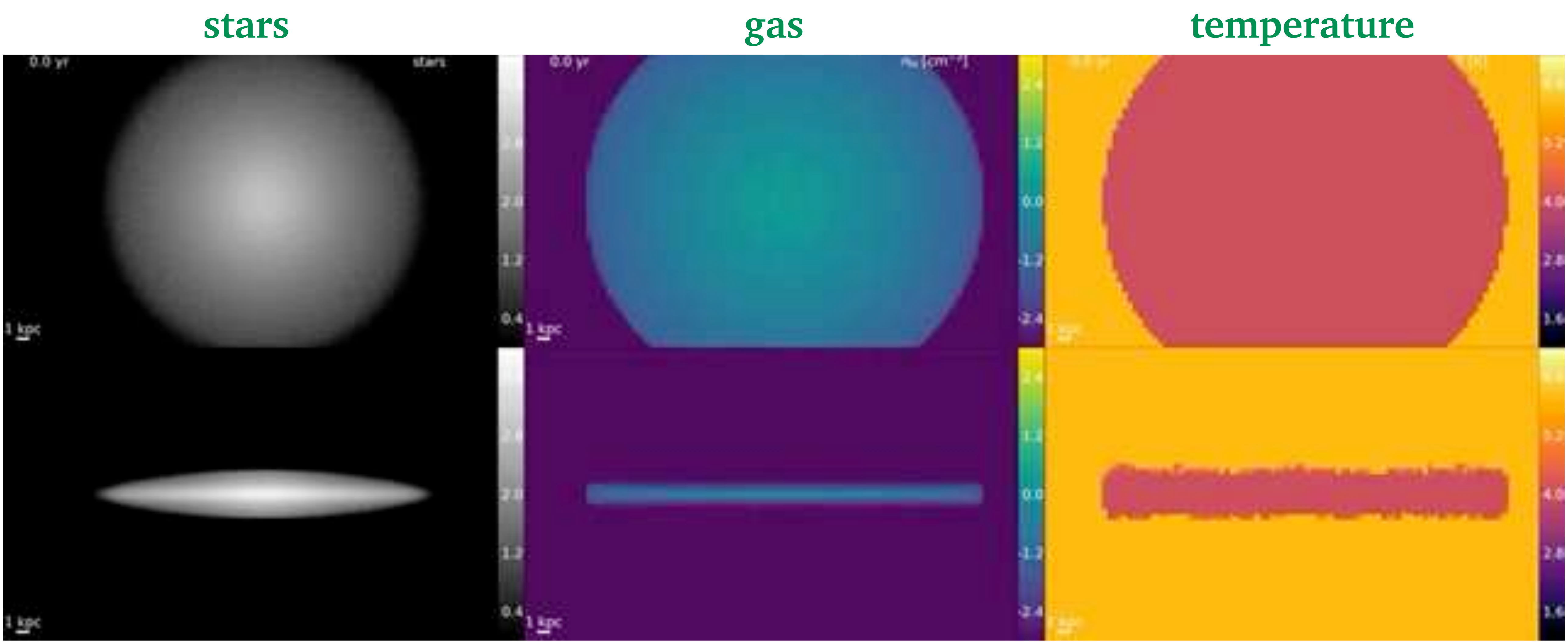
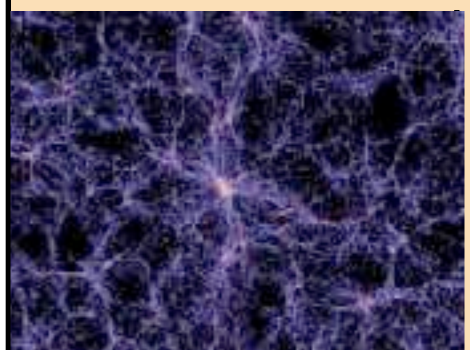
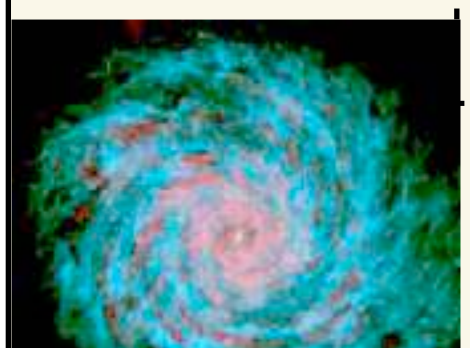


A simulated isolated barred spiral galaxy with star formation and supernova feedback. From left to right: stellar surface density, gas surface density, temperature of the gas. The top row shows the face-on projection and the bottom row shows the edge-on projection of the galaxy. From Fragkoudi & Bieri (in prep.).

Types of Galaxy Simulations

Cosmological simulations 	✓Pros	Large-scale structure (cosmic web) Lots of galaxies at once Good for statistics and environment effects
	✕ Cons	Lower resolution per galaxy Can't see fine details Star formation/feedback treated simply
Zoom-in simulations 	✓Pros	Very high resolution Detailed galaxy structure formation and evolution Better for gas, star formation, and feedback studies
	✕ Cons	Only a few galaxies at a time Not great for studying the big picture or rare events

Reading Material

- It is a long-standing, publicly accessible knowledgebase for **extragalactic astronomy and cosmology**.
- Some articles are outdated, but many still provide valuable foundational knowledge, and new articles continue to be added.
- https://ned.ipac.caltech.edu/level5/