EXTRAGALACTIC ASTRONOMY

The Universe of Galaxies

ASIAA Summer Student Program 2026

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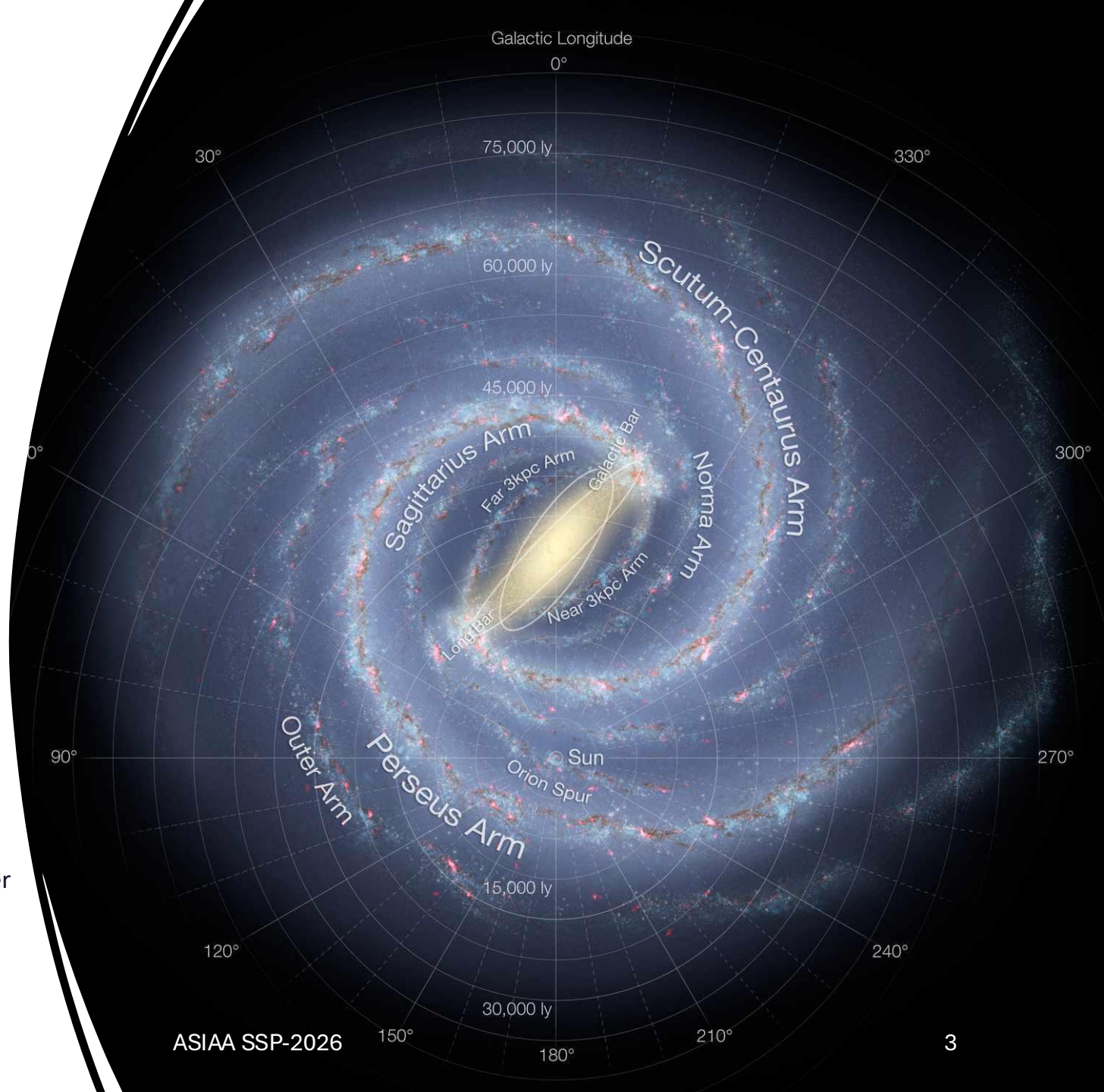
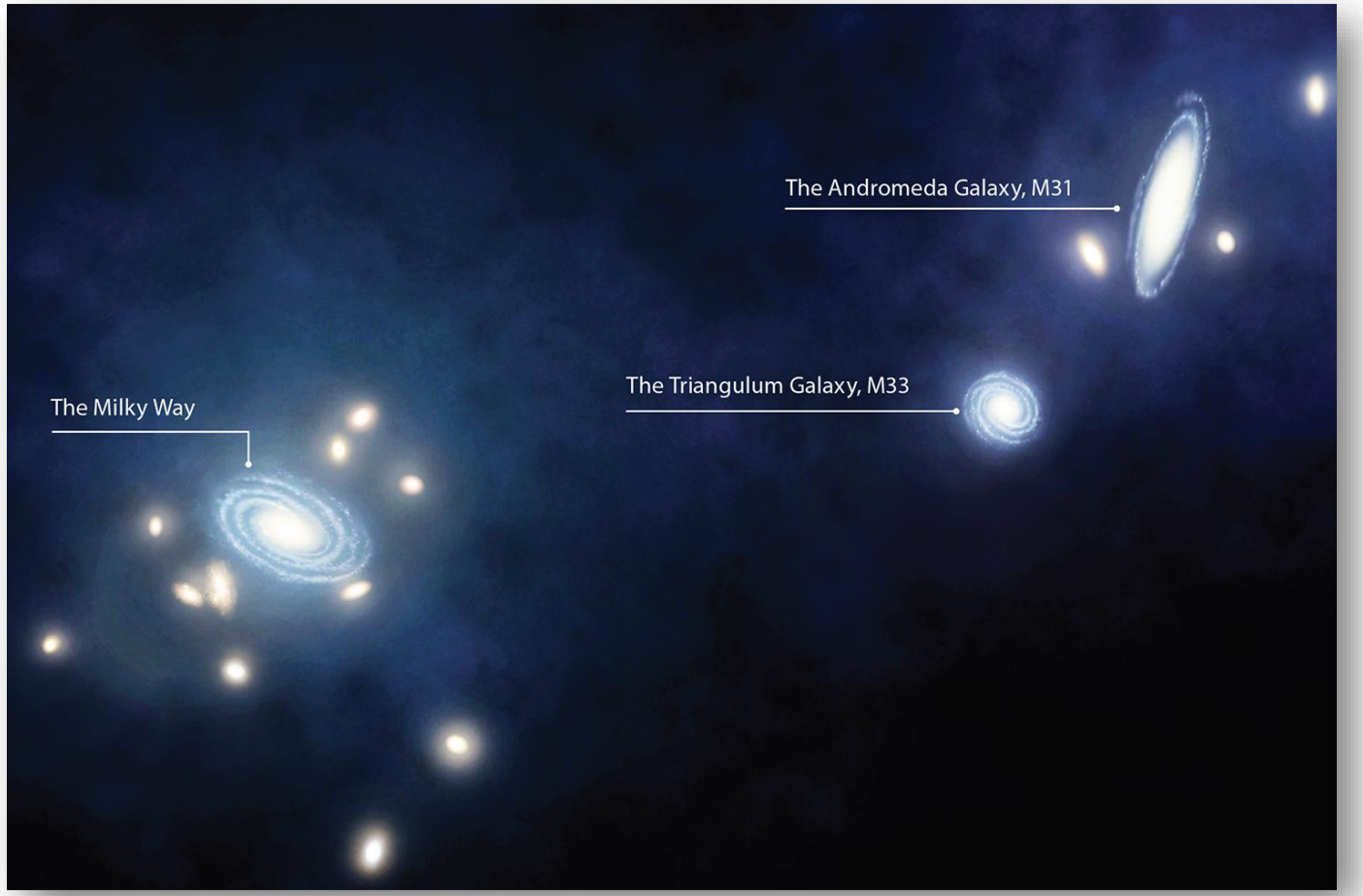
Milky Way

- Bulge
- Bar
- Disk
- Spiral arms

Type	Barred spiral (SBbc)
Stars	~200–400 billion
Diameter	~100,000 light-years
Sun's distance	~26,000 ly from center
Orbit time	~230 million years
Dark matter	~10× more than stars

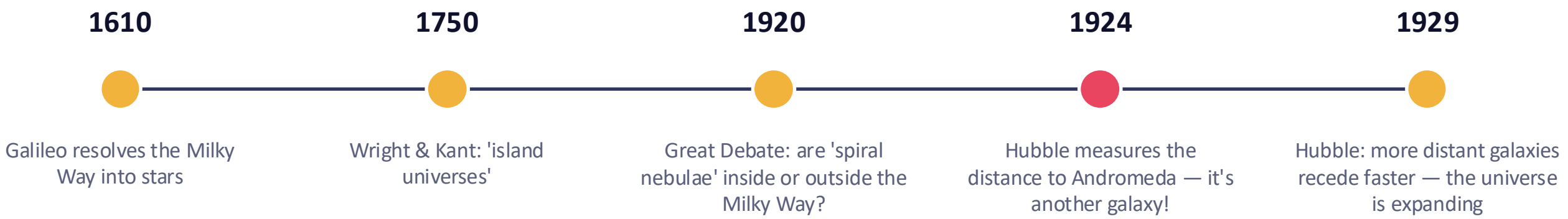


Local Group of Galaxies




~2'x1'

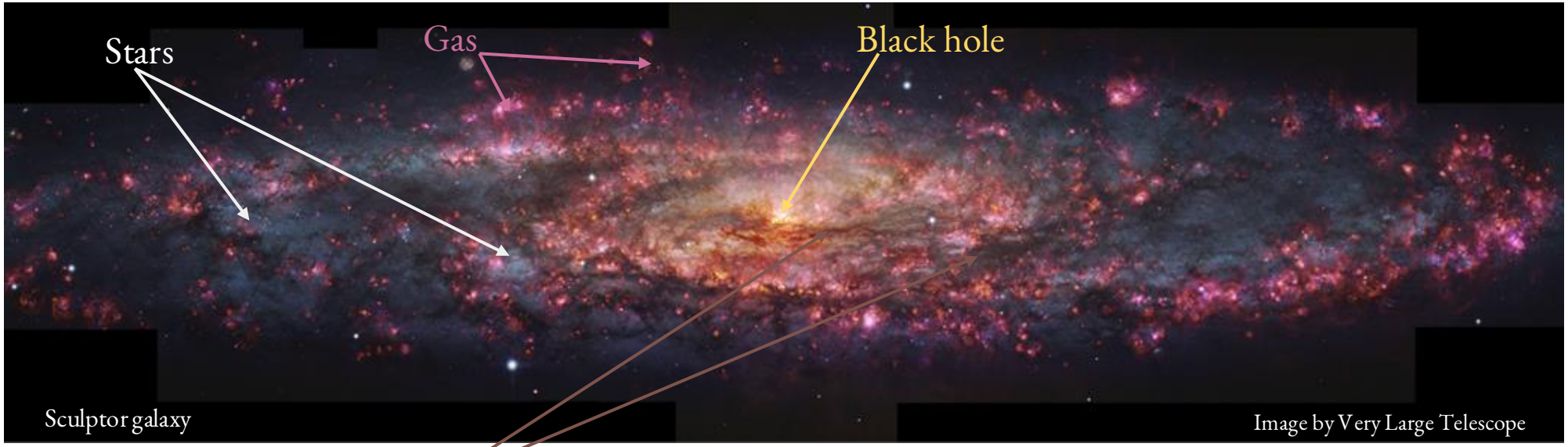
Galaxies were discovered surprisingly recently



In one human lifetime we went from 'our galaxy is the entire universe' to 'there are 2 trillion galaxies'.

Why study galaxies?

- They are the building blocks of the universe
  - Almost every star, planet, and atom you've heard of lives inside one.
- They are time machines
  - Light from a distant galaxy left it billions of years ago — we literally see the past.
- They link the very small to the very large
  - Quantum physics of star formation up to cosmology of the entire universe.
- They are still mostly a mystery
  - We don't fully understand how galaxies grow, why they stop forming stars, or what dark matter is.



Dark Matter: 85-95% !!!

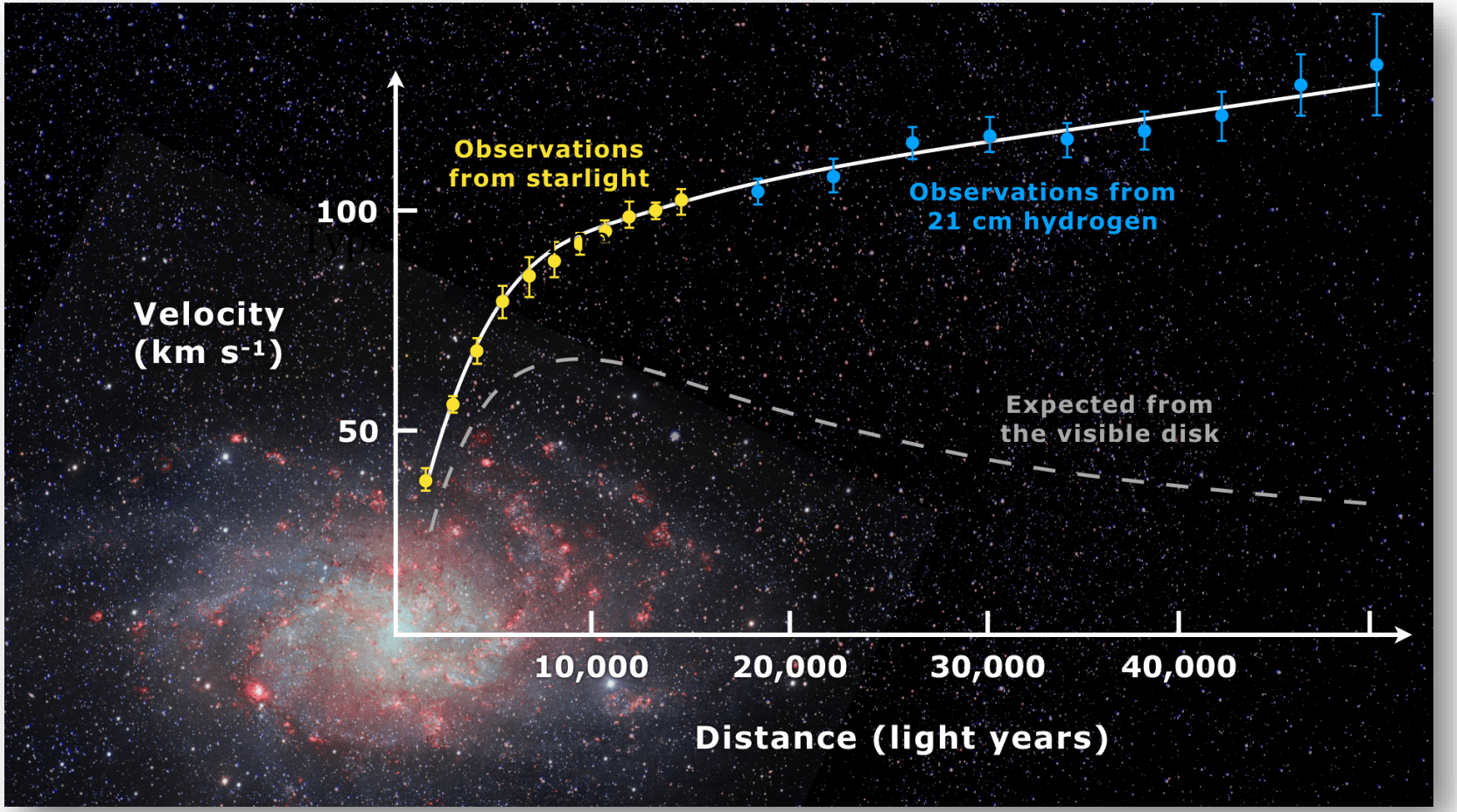
Black holes & dark matter

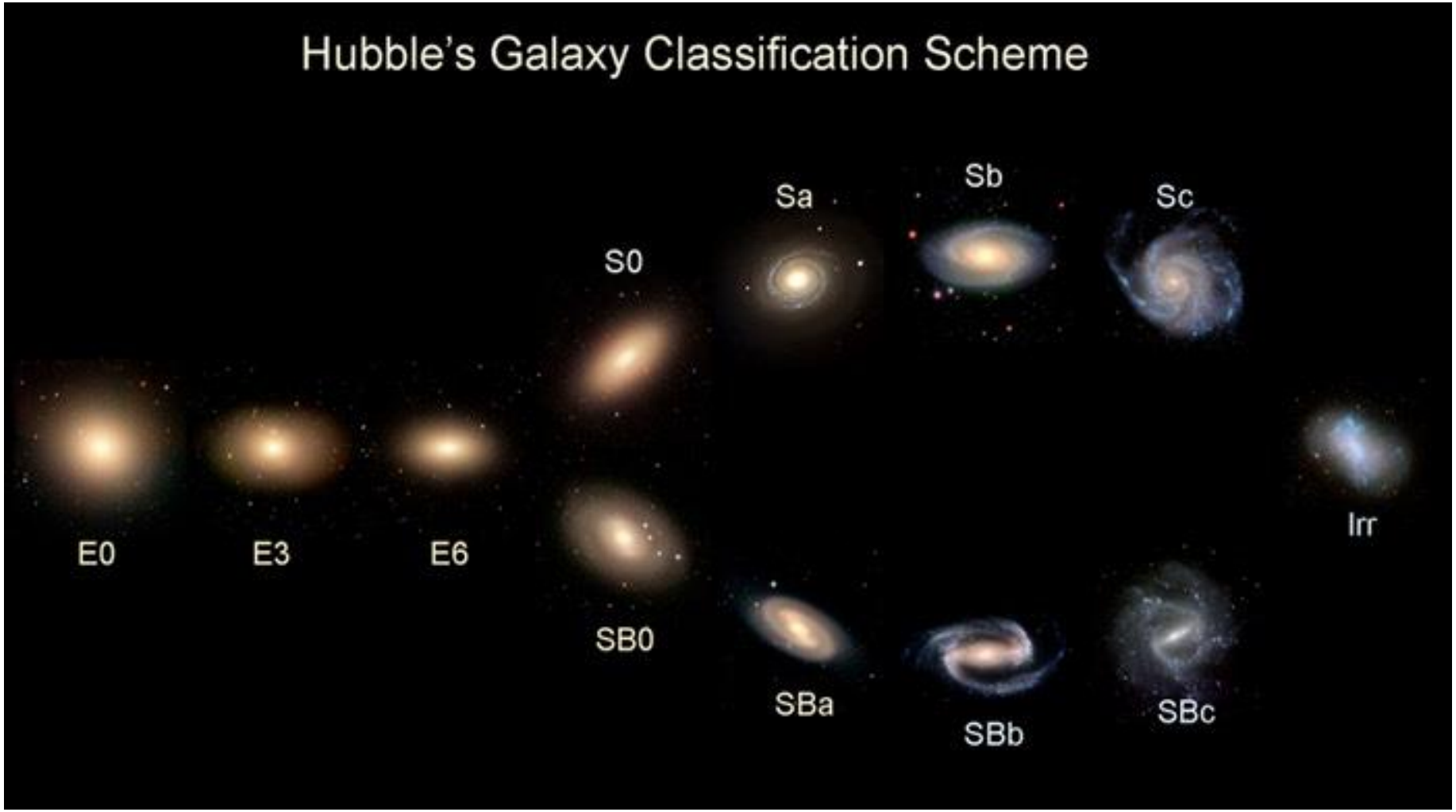
$$v = \sqrt{\frac{G.M(r)}{r}}$$

Galaxy Rotation curves

&

stellar movements




Hubble's Galaxy Classification Scheme
E0
E3
E6
S0
Sa
Sb
Sc
Irr
SB0
SBa
SBb
SBc

Spiral galaxies

Star-forming

Shape: Flat rotating disk

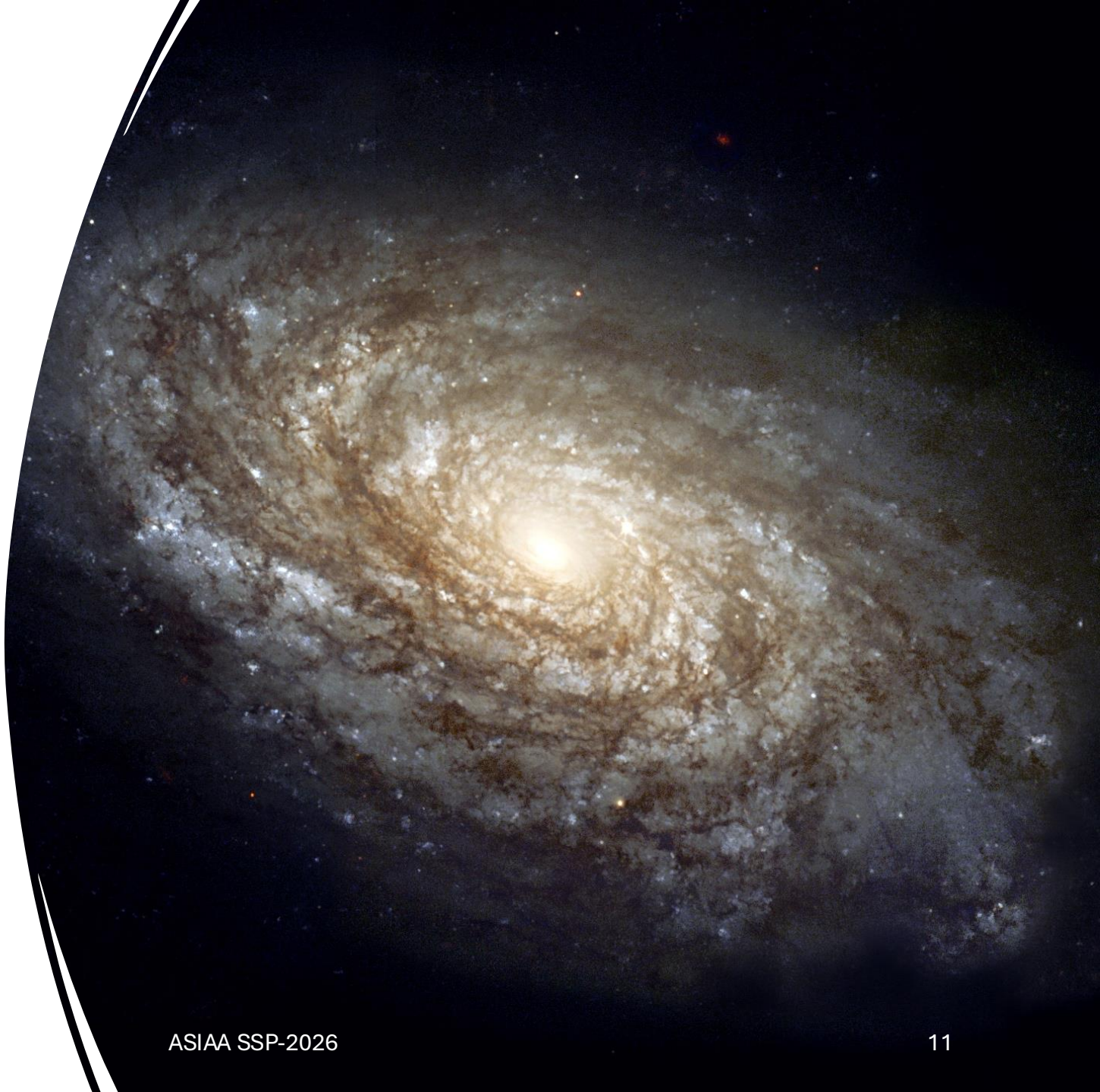
Color: Blueish – disk full of hot young stars

Gas & Dust: Plenty

Motion: Rotational

Examples: Milky Way, Andromeda, Whirlpool

Fraction: ~60% of nearby galaxies



Elliptical galaxies

Quiescent (quenched/dead)

Shape: Smooth featureless

Color: Reddish – old cool stars

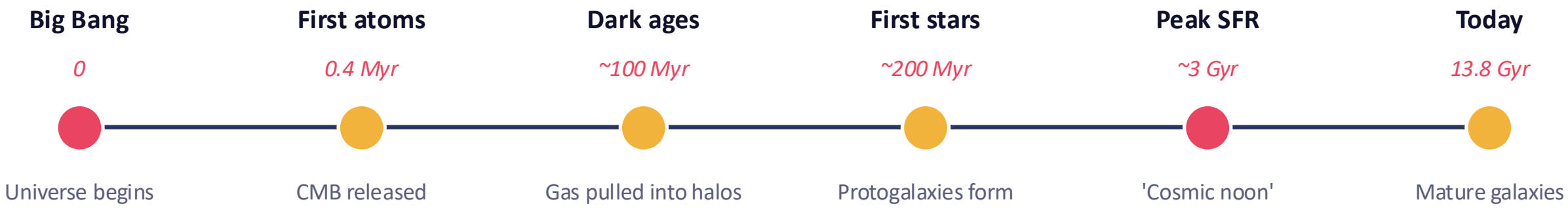
Gas & Dust: Very little

Motion: Random orbits

Examples: M87, M32

Where: Common in dense galaxy clusters

How did galaxies form?

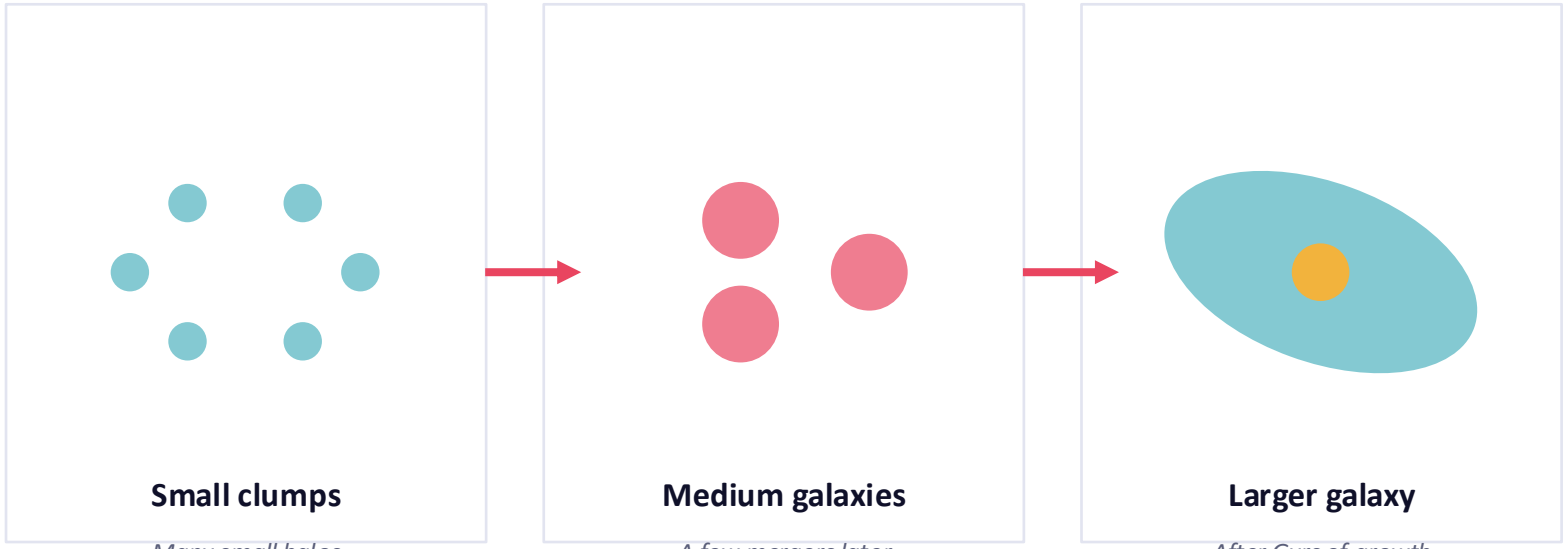


The big picture:

Dark matter clumps first → gas falls into the clumps → gas cools and forms stars → stars and clumps merge and grow.

Hierarchical assembly

Galaxies grow by merging

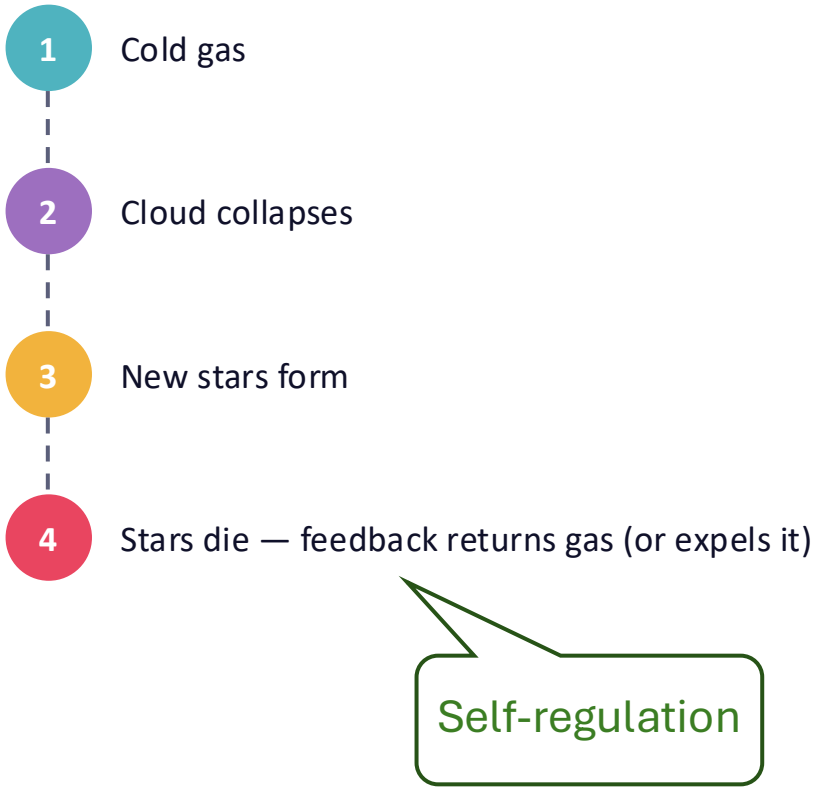


Mergers transform spirals into ellipticals

Test for cosmological models

The Milky Way is still eating dwarf galaxies right now — Sagittarius dwarf, Magellanic Stream, etc.

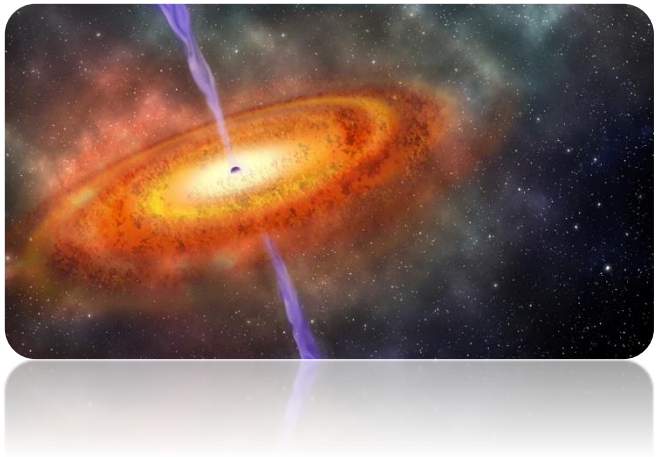
Star formation: gas → stars



Why this matters

- How fast a galaxy forms stars (its SFR) is a very useful number to describe it.
- Star formation needs cold gas — without fresh gas a galaxy slowly fades.
- Massive stars explode as supernovae, blowing hot gas back out — 'stellar feedback'.
- Without feedback, galaxies would form ~10× too many stars (this is a real, unsolved tension).

Feedback Mechanisms

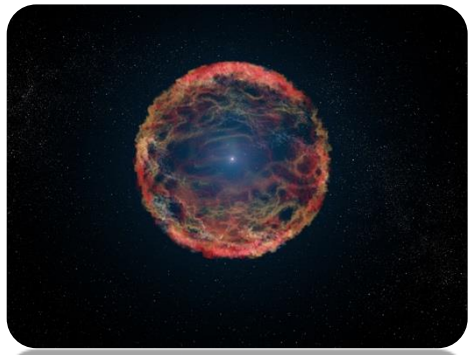


Stellar Feedbacks

Massive stars end up as supernovae

Eject gas and inject heat

Small galaxies



AGN Feedback

Supermassive blackholes (10^6-$10^{10}M_\odot$)

Active galactic nucleus (AGN)

Quasars: most extreme AGN

Eject gas and heat up gas

Massive galaxies

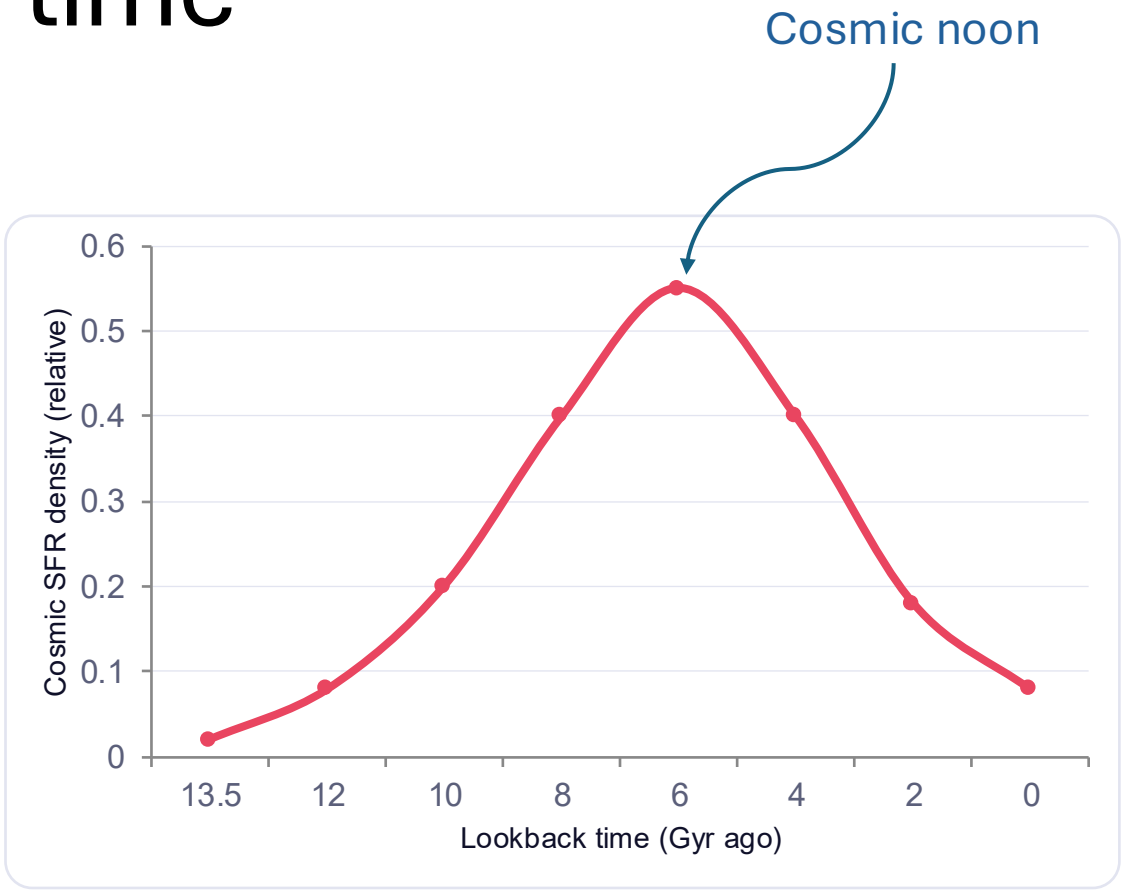
Which came first:
SMBH or galaxy?

Why do galaxies stop forming stars?

- Some galaxies are actively forming stars
- But some do not
- Stopping of SF: **quenching**
- Quenched: **Quiescent** Galaxies
- Reasons for quenching:
  - Feedback
  - Morphology/structure
  - Environment
    - Mergers & interactions
    - Starvation

Galaxies through cosmic time

- ~10× more stars/yr ~10 Gyr ago
- Galaxies grew rapidly, then settled down.
- Modern surveys trace this history directly.



Hubble-Lemaître Law

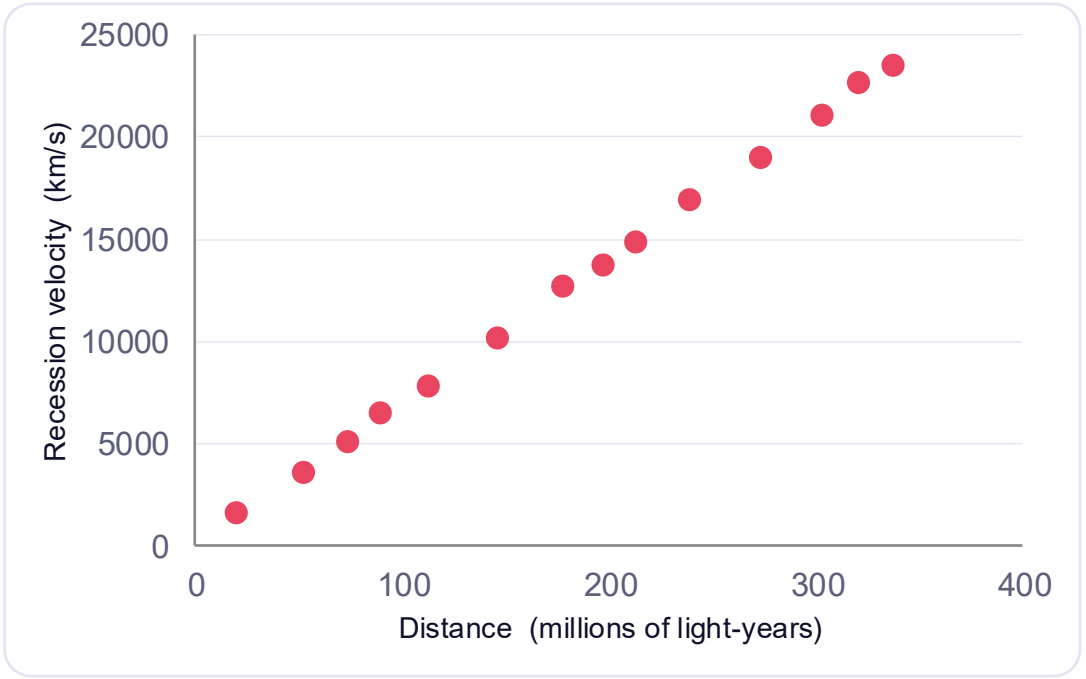
Galaxies are moving away

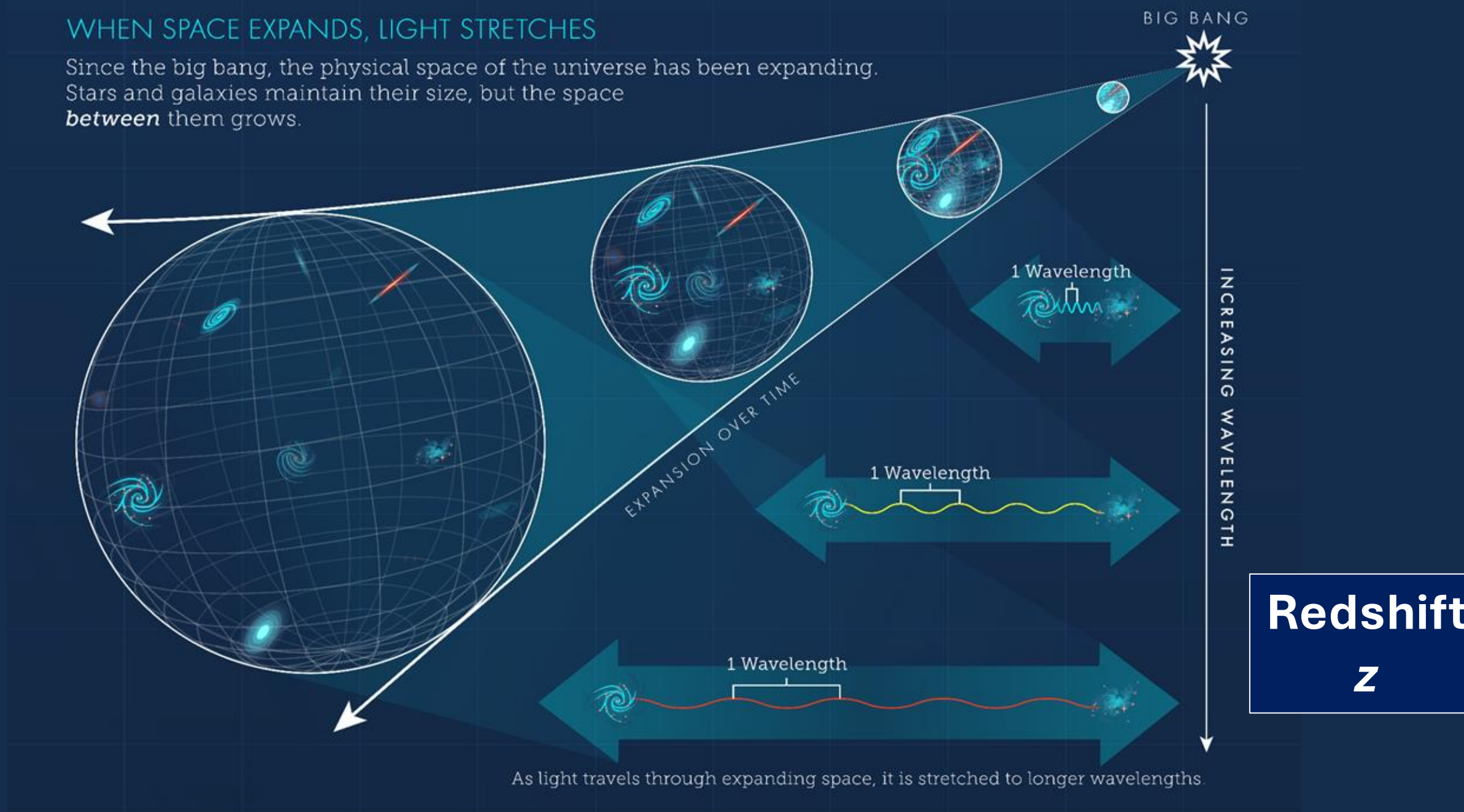
More distant galaxies recede faster

Slope of the line = Hubble constant H_0

~70 km/s/Mpc

Universe is expanding!

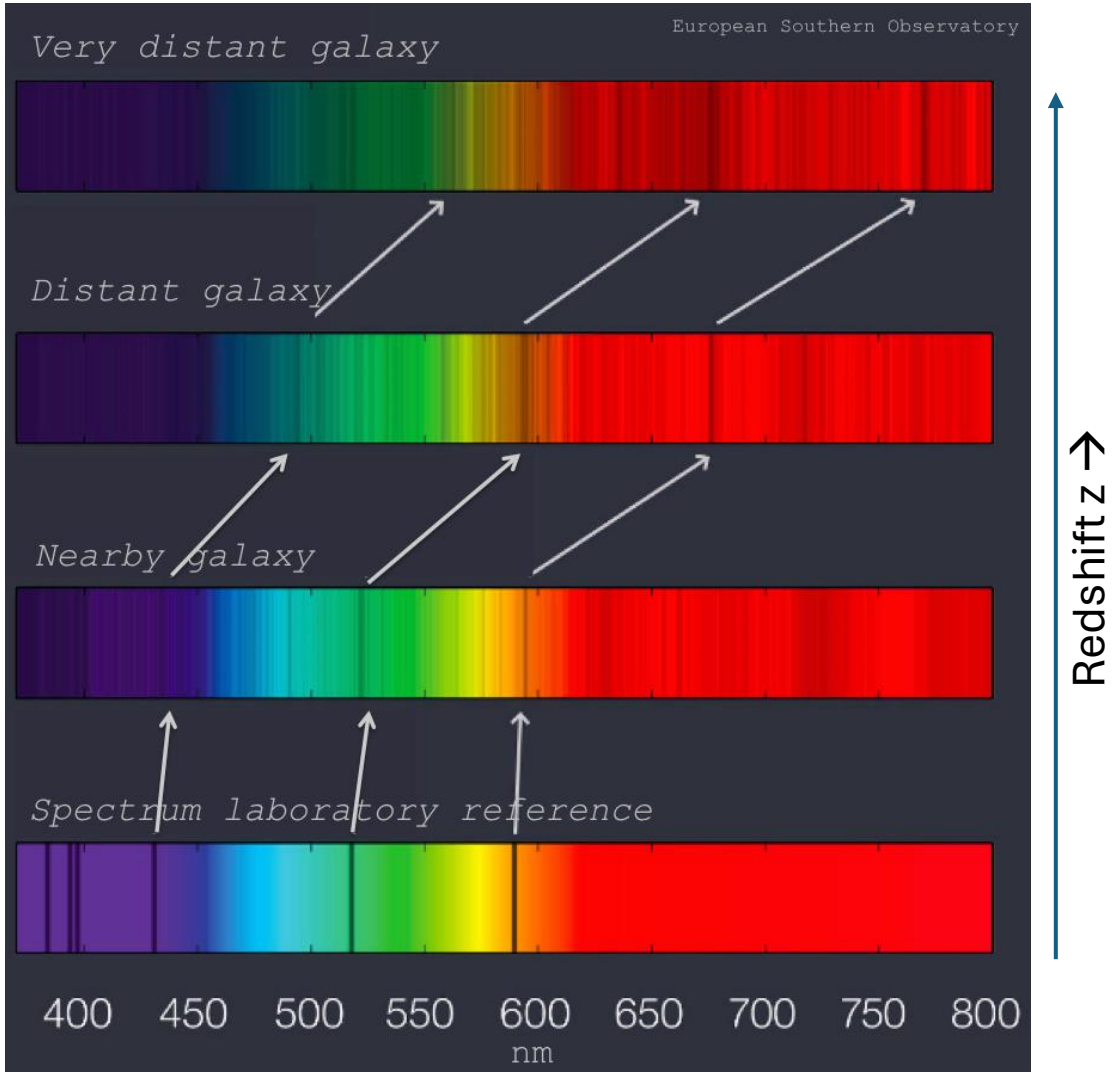



WHEN SPACE EXPANDS, LIGHT STRETCHES
Since the big bang, the physical space of the universe has been expanding.
Stars and galaxies maintain their size, but the space
between them grows.
BIG BANG
EXPANSION OVER TIME
1 Wavelength
1 Wavelength
1 Wavelength
INCREASING WAVELENGTH
As light travels through expanding space, it is stretched to longer wavelengths.

Redshift
z

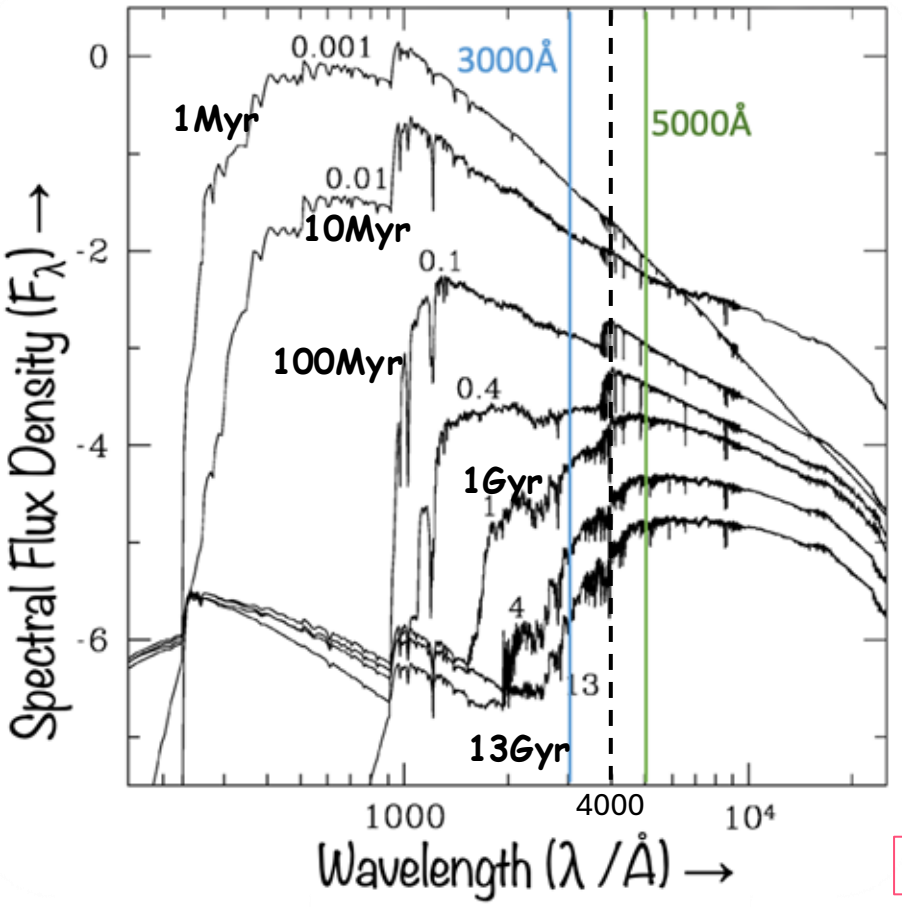
Rest-frame wavelength

- Observed wavelength changes with redshift (z)
- Correct for this change
- Rest-frame wavelength



Importance of rest-frame wavelength

Young massive star

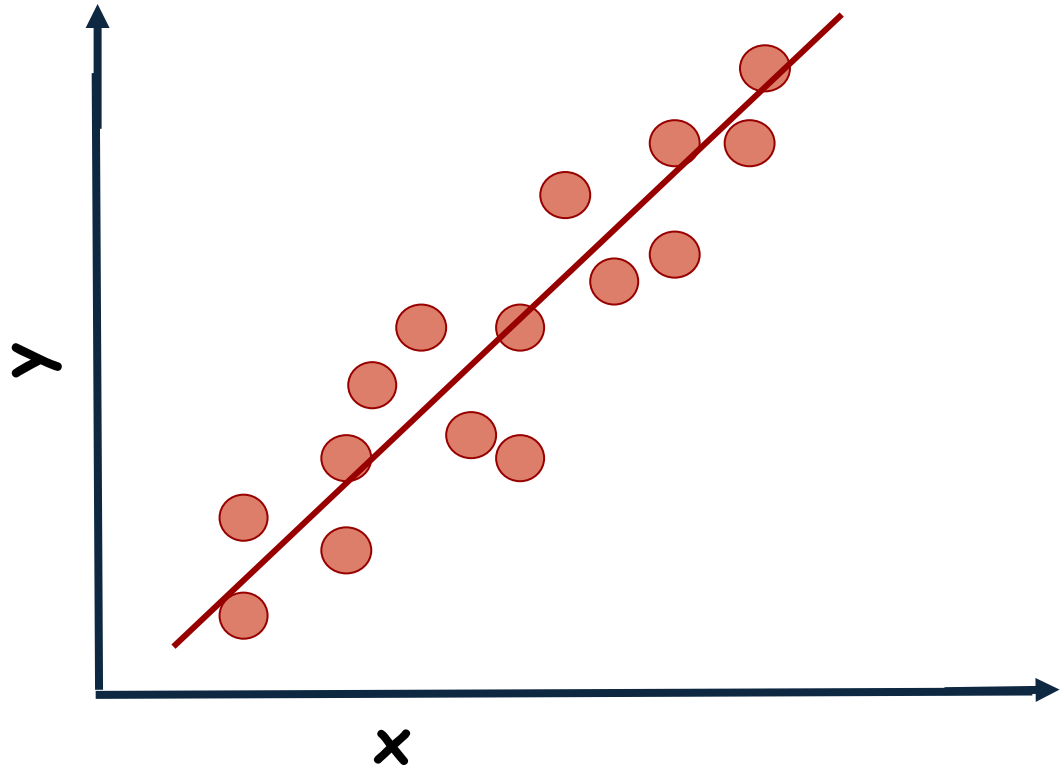


Bruzual & Charlot 2003

Old low-mass star

Galaxy Scaling Relations

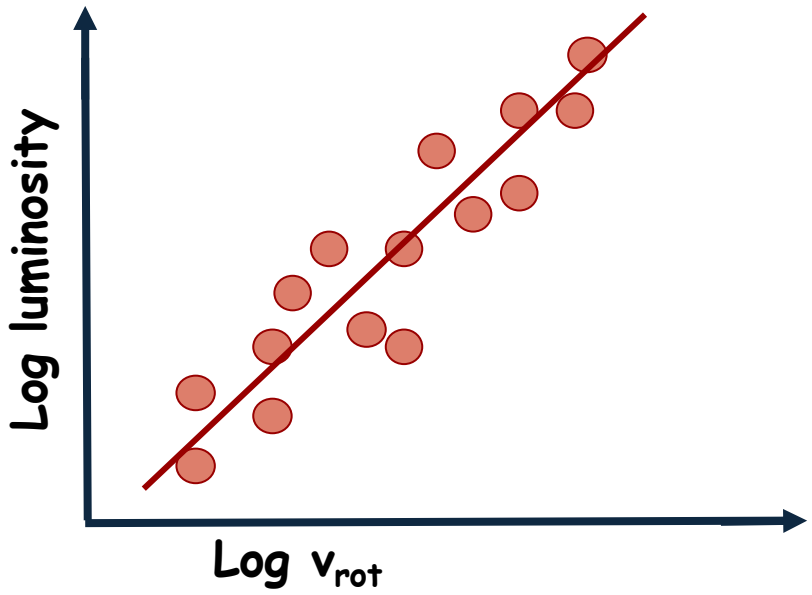
- Galaxy properties are correlated
- Testing models
- Understanding physics
- Predicting an unknown parameter



Galaxy Scaling Relations

- Tully Fisher Law
- Spiral galaxies
- Total luminosity (L) & rotational velocity (v_{rot})

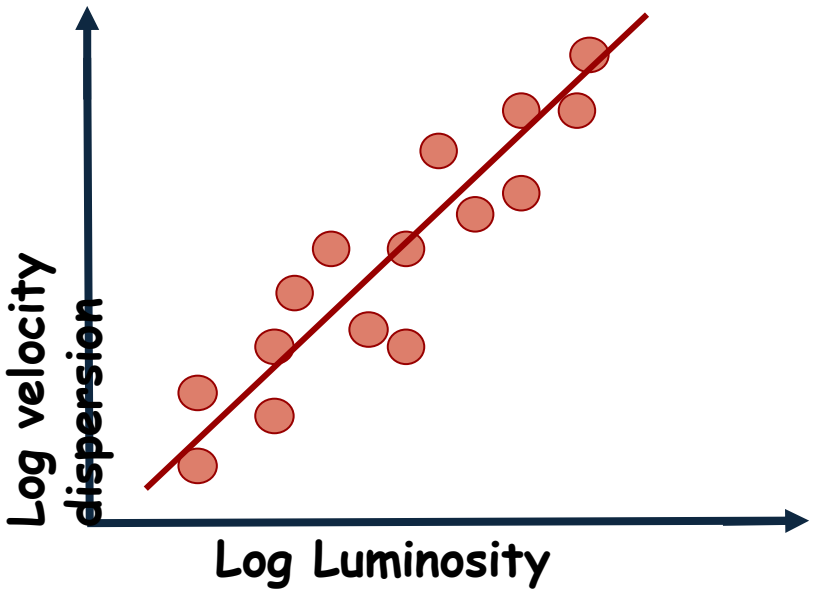
$$L \propto v_{rot}^{\alpha} \text{ where } \alpha = 3.5\text{-}4$$



Galaxy Scaling Relations

- Faber-Jackson Relation
- Elliptical galaxies
- Total luminosity (L) & central stellar velocity dispersion (σ)

$$L \propto \sigma^{\gamma} \text{ where } \gamma = 4$$

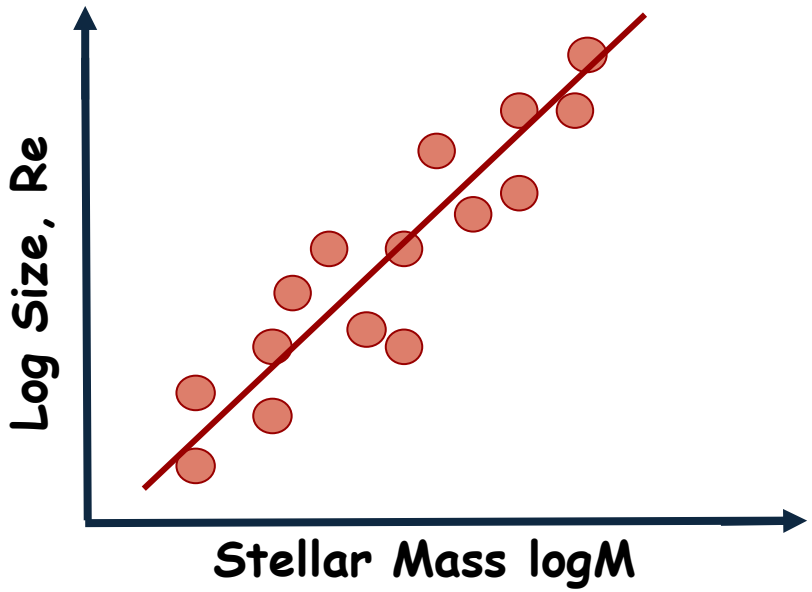


Galaxy Scaling Relations

- Size-Mass Relation
- All galaxies
- Effective radius (R_e) & stellar mass (M_*)

$$\log R_e \propto \log M_*$$

- It comes from **Fundamental Plane**: R_e, I_e, σ

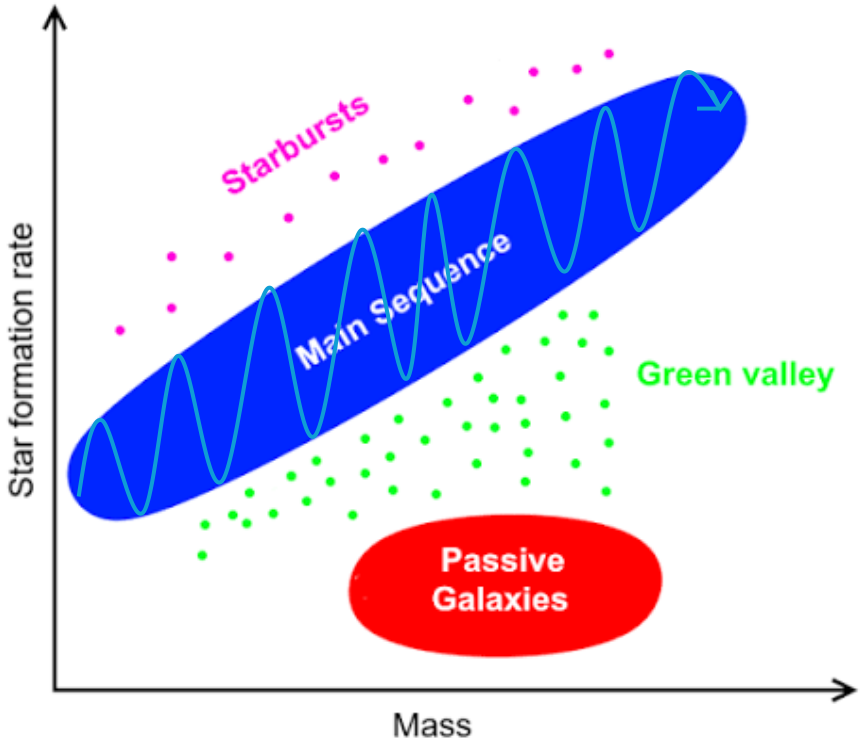


Galaxy Scaling Relations

- Star formation main sequence (SFMS)
- SFR & stellar mass (M_*)

  $SFR \propto M_*^{\alpha}$ where $\alpha = 0.6\text{-}1.0$

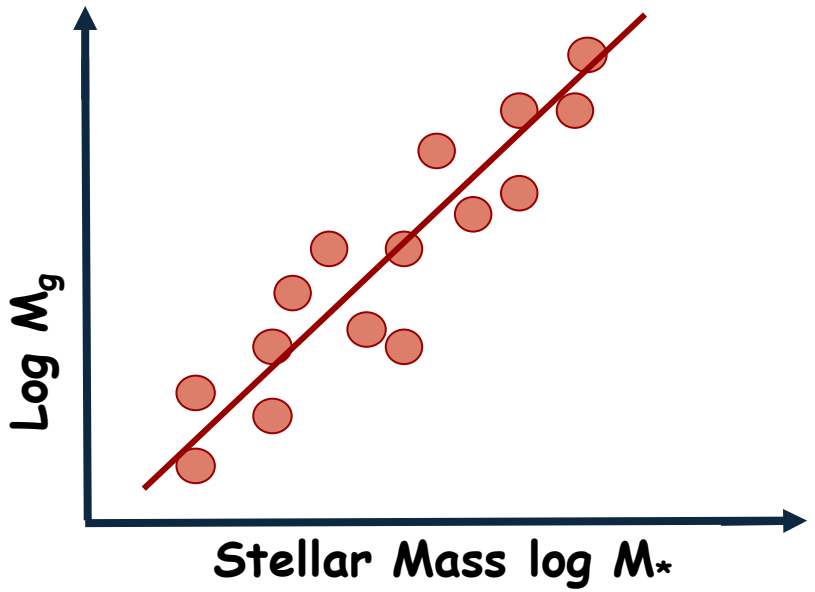
- Depending on distance galaxies are classified into:
  - Star-burst (above)
  - Star-forming (on)
  - Green valley/quenching (below)
  - Quiescent (way below)



Galaxy Scaling Relations

- Molecular Gas Main Sequence
- Molecular gas mass (M_g) & stellar mass (M_*)

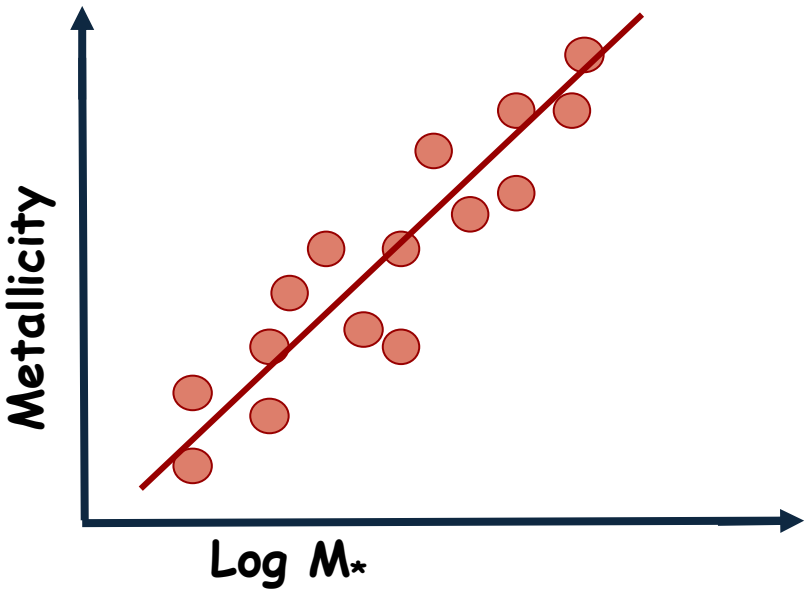
$$\log M_g \propto \log M_*$$



Galaxy Scaling Relations

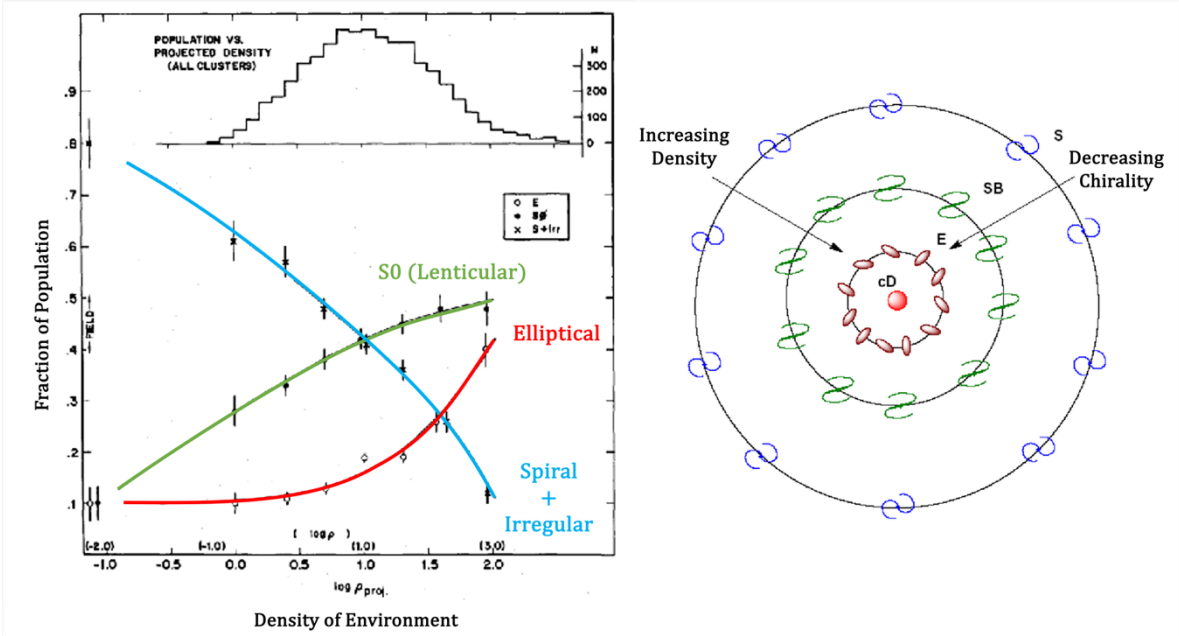
- Mass metallicity relation (MZR)
- Metals: elements heavier than Helium
- Stellar mass & gas phase metallicity

  $\log \text{Metallicity} \propto \log M_*$
- Chemical enrichment



Role of cosmic environment

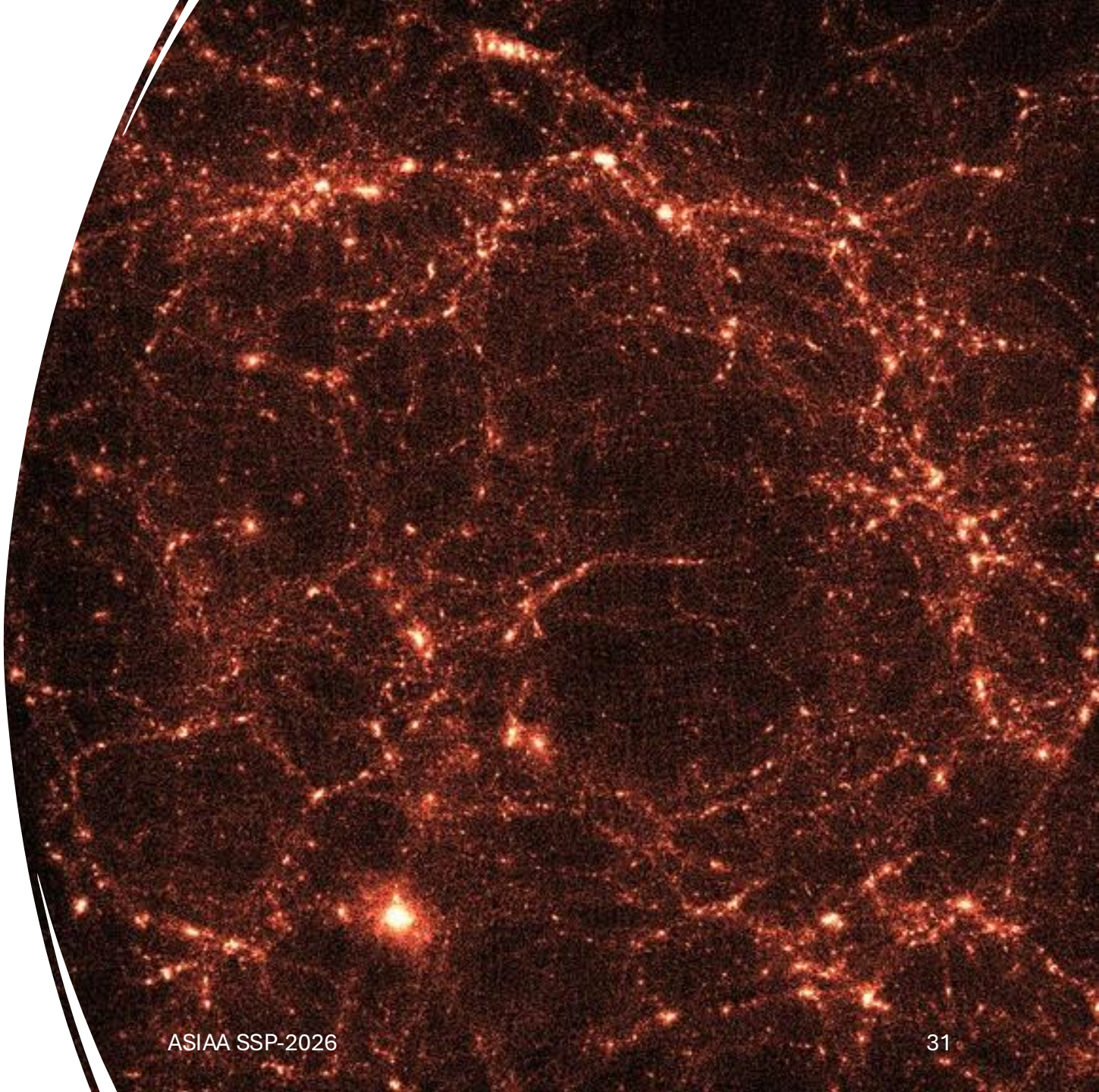
- Low density environments
  - Late-type galaxies (disky spirals)
- High density environments
  - Early-type galaxies (smooth ellipticals)



Cosmic Web: Structure on the largest scales

Structure ladder

Galaxies	*10^{8}–10^{12} $M_{\odot}$*
Groups	*tens of galaxies*
Clusters	*100s–1000s of galaxies*
Filaments	*strings linking clusters*
Voids	*huge empty regions*



Open questions

- Quenching mystery
- What is the primary trigger that kills star formation?
  - AGN feedback?
  - Environmental starvation?

Open questions

- Missing baryons problem
- Bing Bang predicts roughly 5% of matter is baryonic
- ~2.5% is missing
- Where?
  - Circumgalactic medium (CGM)
  - Warm-hot intergalactic medium (WHIM)

Open questions

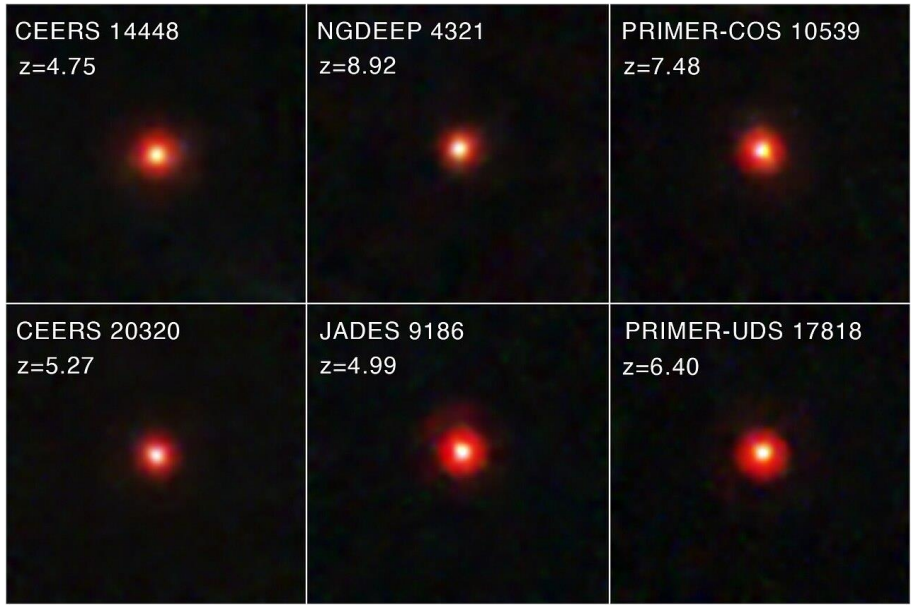
- Missing satellites problem
- Models predict hundreds of tiny satellites around galaxies
- We see only dozens
- Proposed solutions:
  - Invisible clumps of dark matter
  - Maybe DM is not cold?

Open questions

- How did the first galaxies form so fast?
- JWST found massive & evolved galaxies in the early Universe
- How?
  - High SFE in the early epochs
  - Broken ΛCDM?

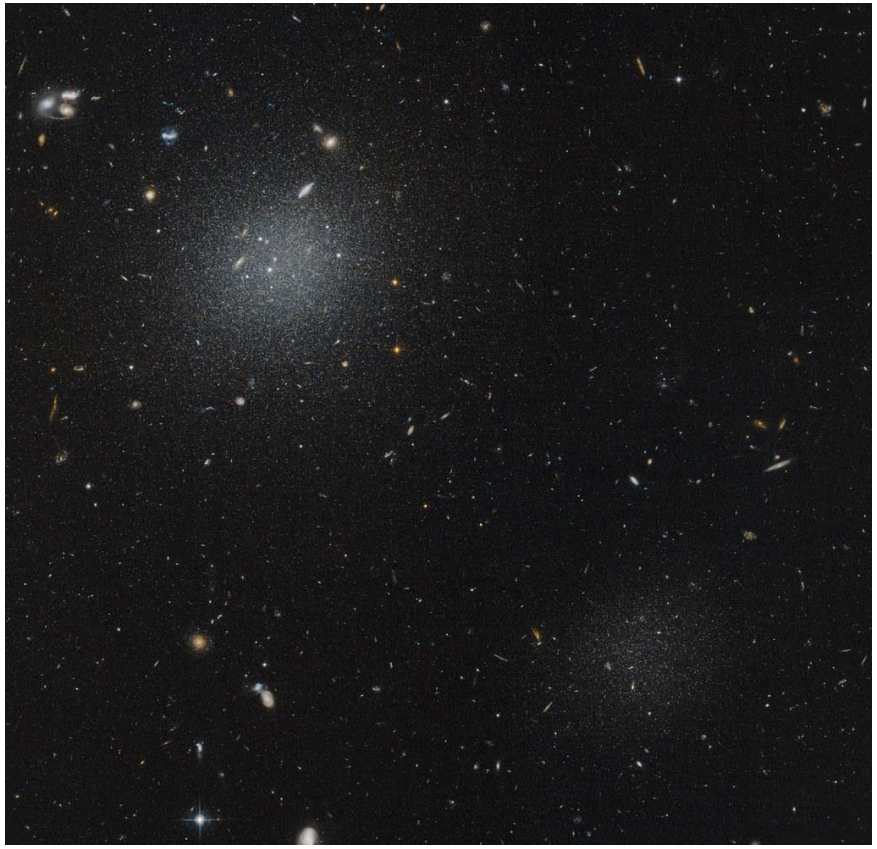
Open questions

- Little red dots (JWST discovery)
- Ultra compact and very red
- What are they?
  - Extreme starburst?
  - Monster blackhole?



Open questions

- Ultra-diffuse galaxies (UDGs)
- As large as Milky Way
- >1000 x fewer stars
- What are they?
  - Failed galaxies (puffed up)
- Dark matter puzzle
  - Some are mostly DM
  - Some have no DM
- Breaking the scaling relations



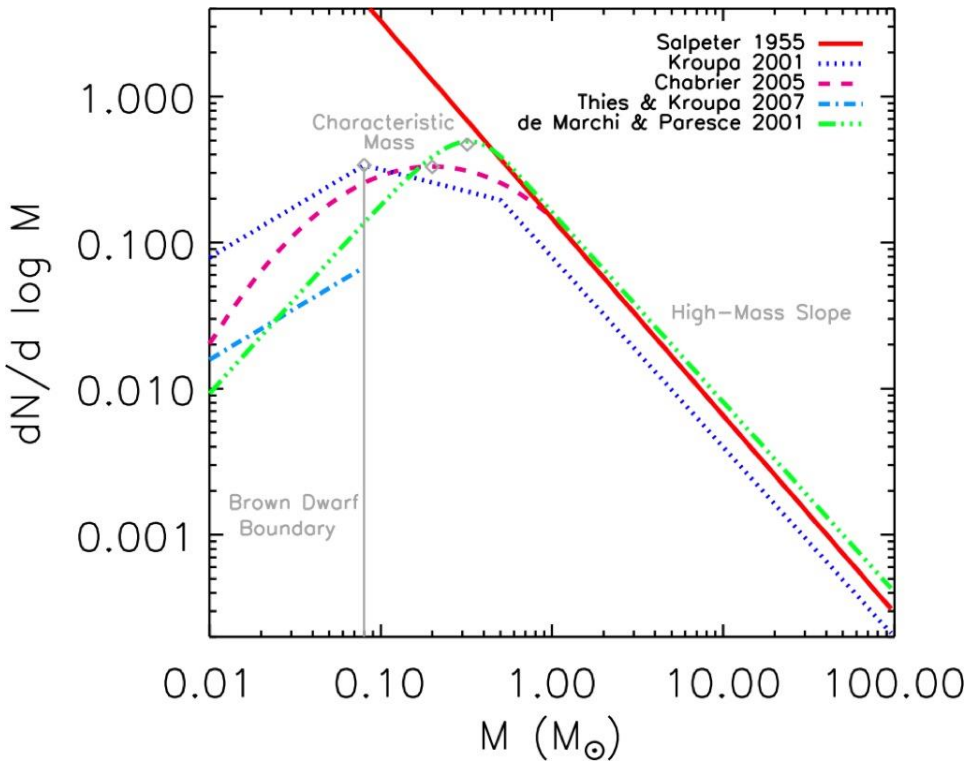
Open questions

Initial Mass function: is it universal?

- IMF describes initial stellar mass distributions

  $N(M) \propto M^{-x}$

- Life expectancy of stars vary
- IMFs are from Milky Way
- Can we assume it is true for all?
- Top heavy vs bottom heavy



Challenges

- Snapshot challenge
  - We can never observe a galaxy evolving!
  - Only statistical analysis
- Selection effects & Malmquist bias
  - Easier to detect bright things than faint ones
  - Galaxies get dimmer with distance
- Dust
  - Dust absorbs bluer wavelengths & re-emits in IR
  - We need dust correction formulas (but is it universal?)
- Dynamic Range
  - It is hard to combine
    - large scale impacts of gravity
    - small scale physics (gas, dust, feedback, ….)