Galaxies

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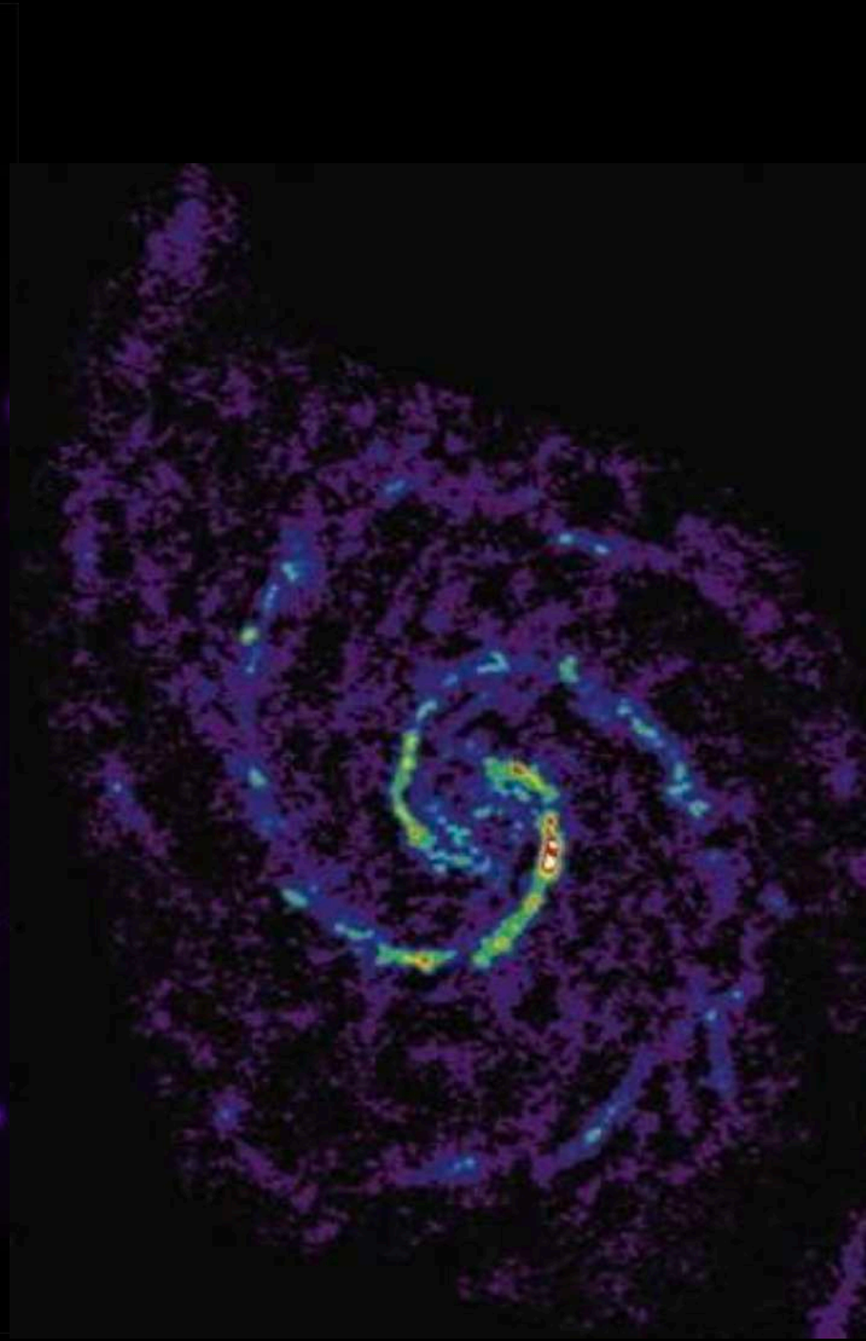
Galaxies: basic concepts

(1) Huge collections of stars and gas

- not like stars, which is a hot gas ball
- can be 100 billion of stars
- and/or the same amount of gas
- plus a little bit of dust
- and a supermassive black hole



M51 (& M51b)

Visible (stars), X-ray (hot gas), mm (cold gas)

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(2) Small smuges of normal matter in a huge dark matter halo

- ~x50 more dark matter than stars

z=0.0

80 kpc

Dark Matter

Via Lactea project

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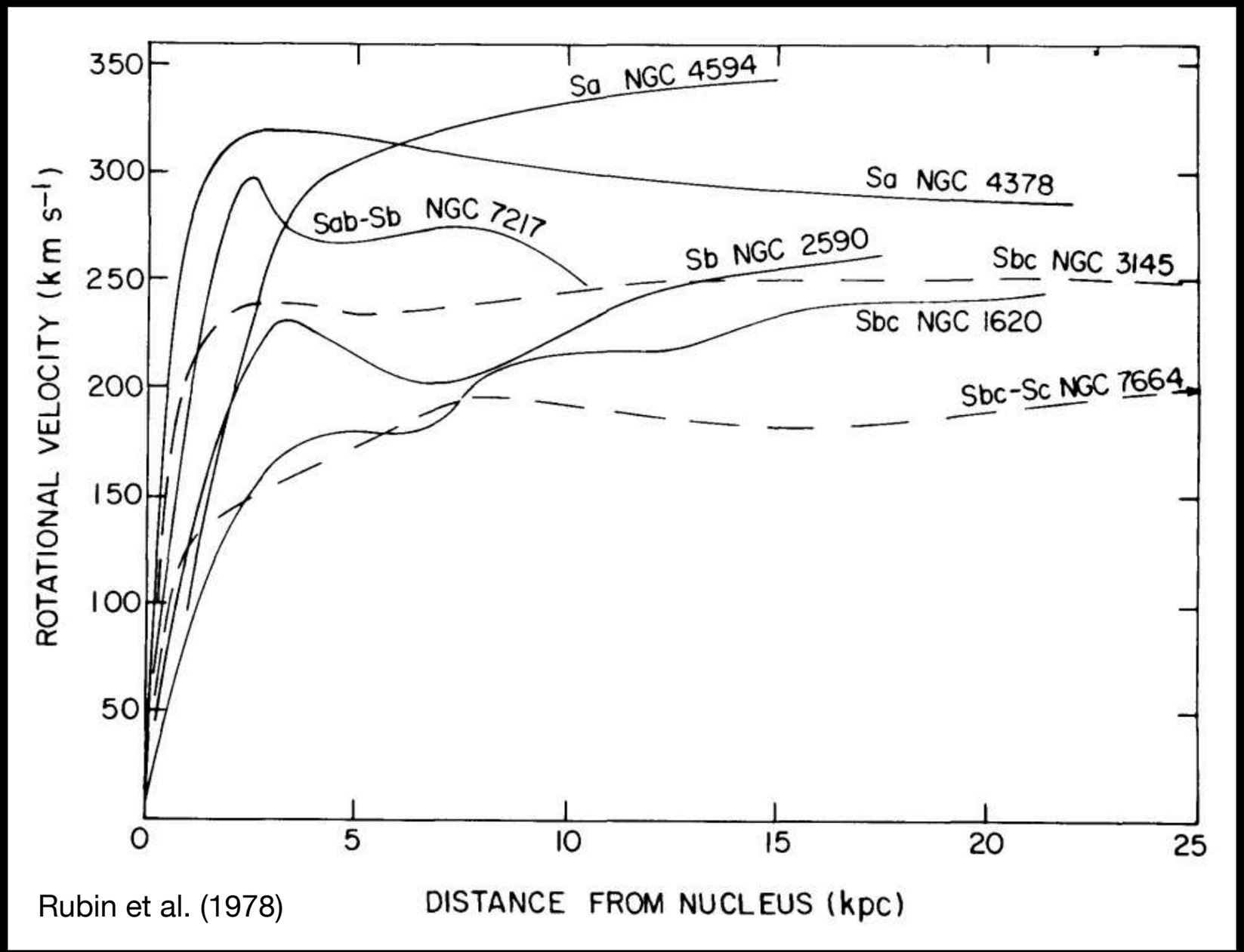
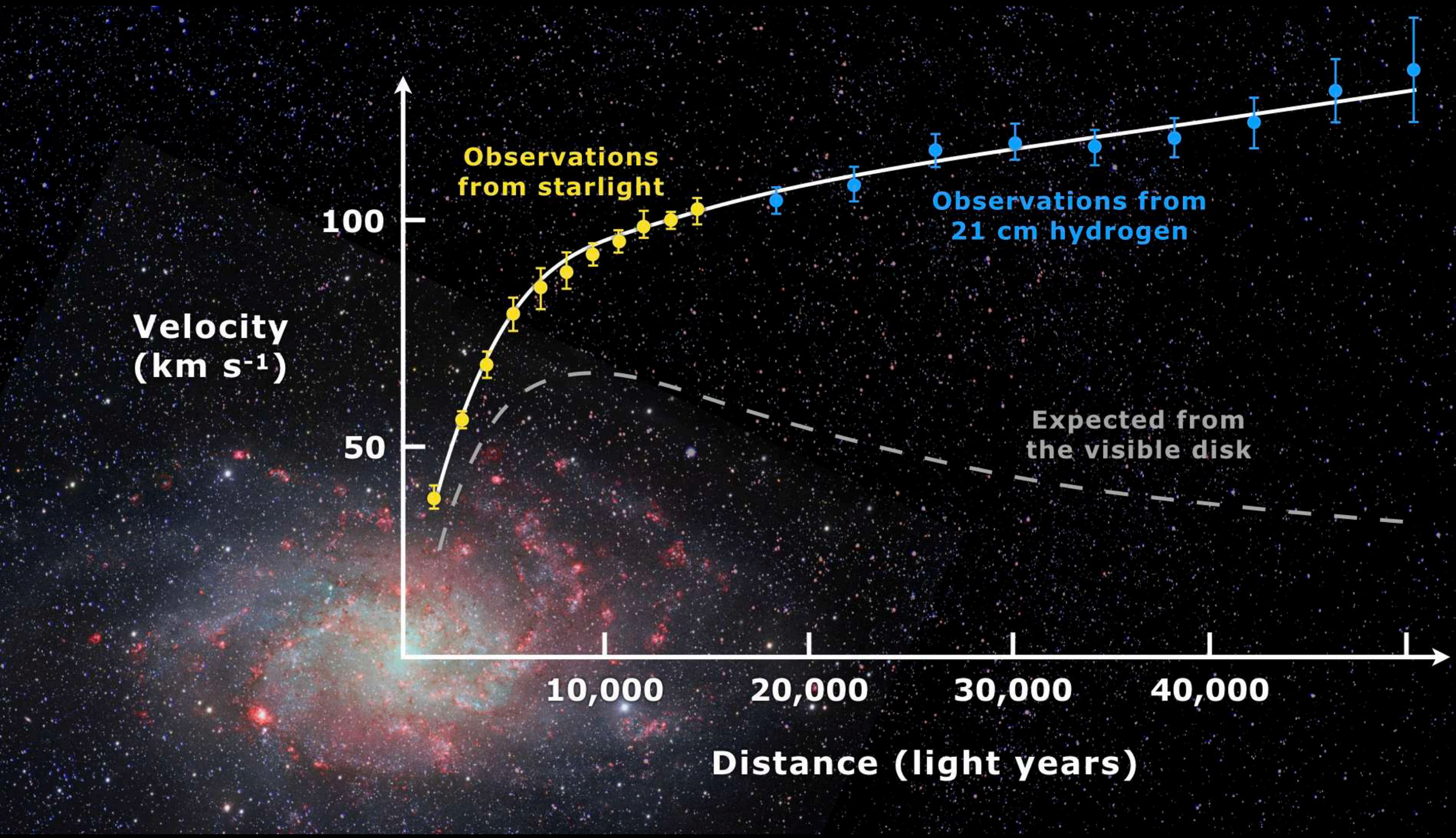
How do we know?

Galaxies rotate “too fast”



Rubin et al. (1978)

Galaxies: basic concepts



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Galaxies: basic concepts

Galaxy evolution is driven at all spatial/time scales

- Super massive black hole: ~ days / light days
- Star formation: ~10 pc / ~Myr
- Galaxy dynamics: ~ 10 kpc / ~100 Myr
- Large-scale strcuture: >Mpc / Hubble time

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> 10^9 difference in spatial scales

Galaxy is a terribly complicated problem!

Basic Properties

Galaxies

M51 (& M51b)
72’ (1.8m) Leviathan of Parsonstown, sketch, 1845

Galaxies

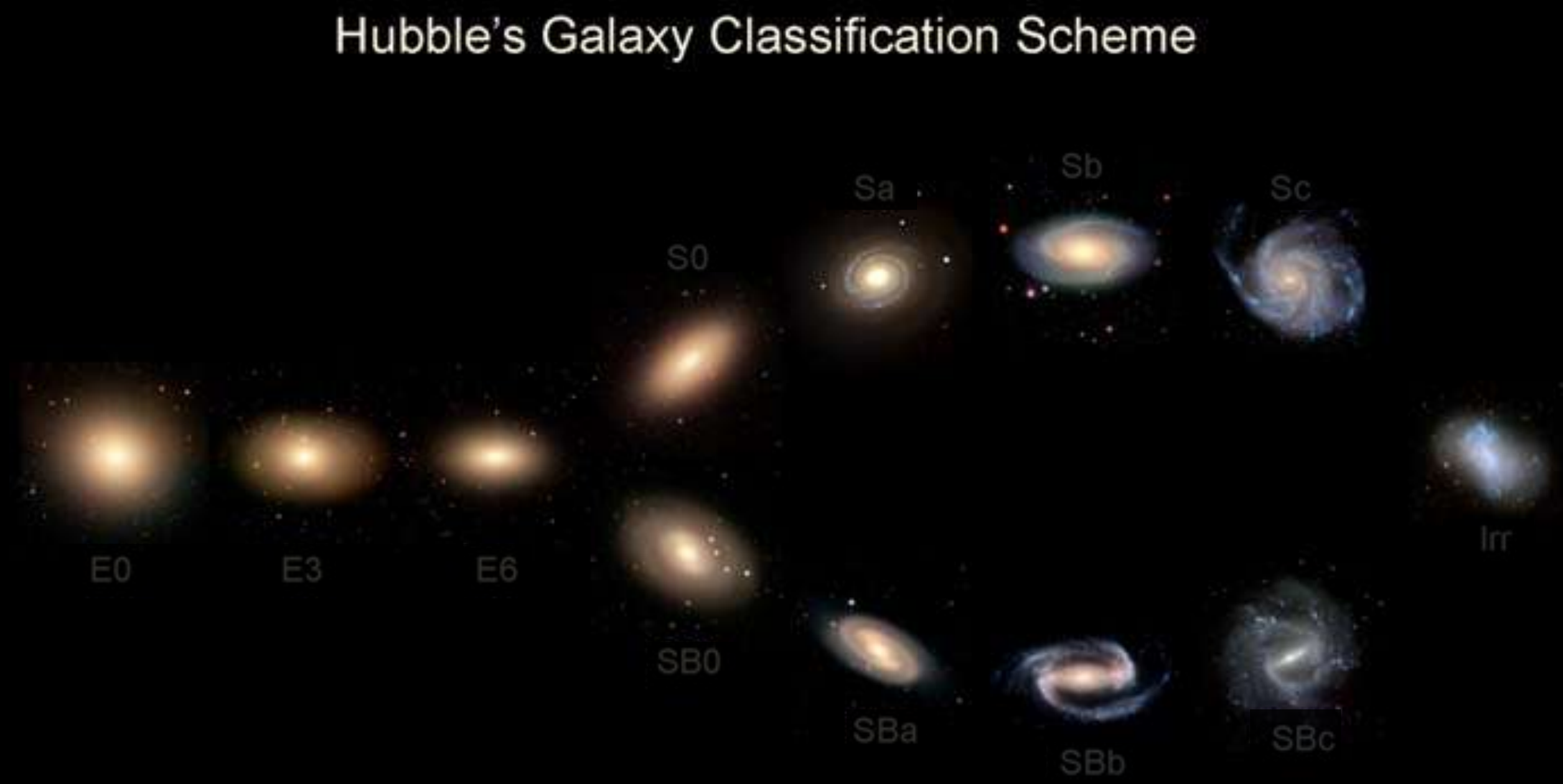
Galaxy were thought to be “nebulae” in the Milky Way

- 1924, Edwin Hubble measured the distance to M31
- Outside Milky Way
- Size is larger than Milky Way

The “Universe” is beyond our own Milky Way!

Galaxies

Galaxies can be very different……

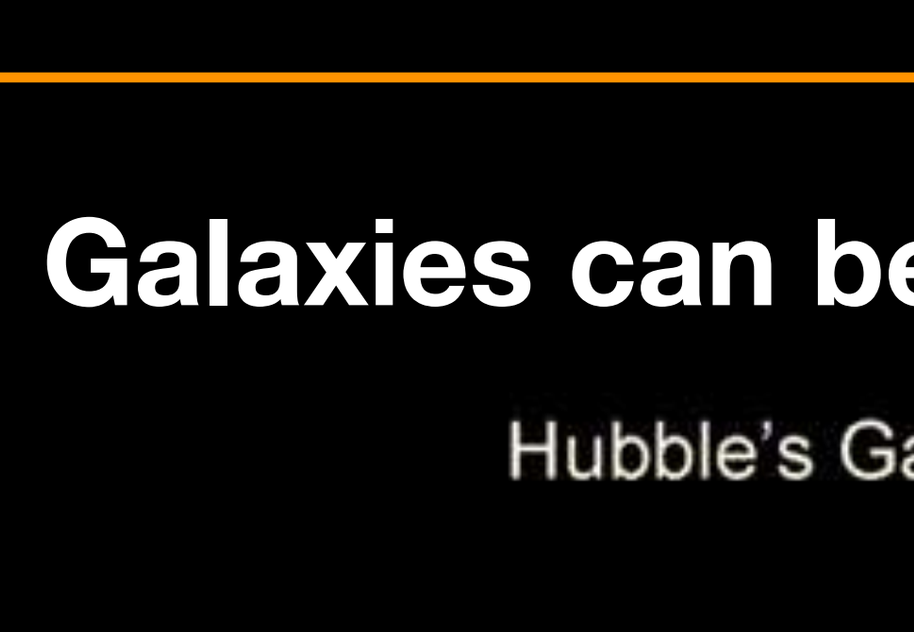


Galaxies

Galaxies can be very different……

Hubble's Galaxy Classification Scheme

Elliptical



Disk/Spiral

Irregular

Galaxies

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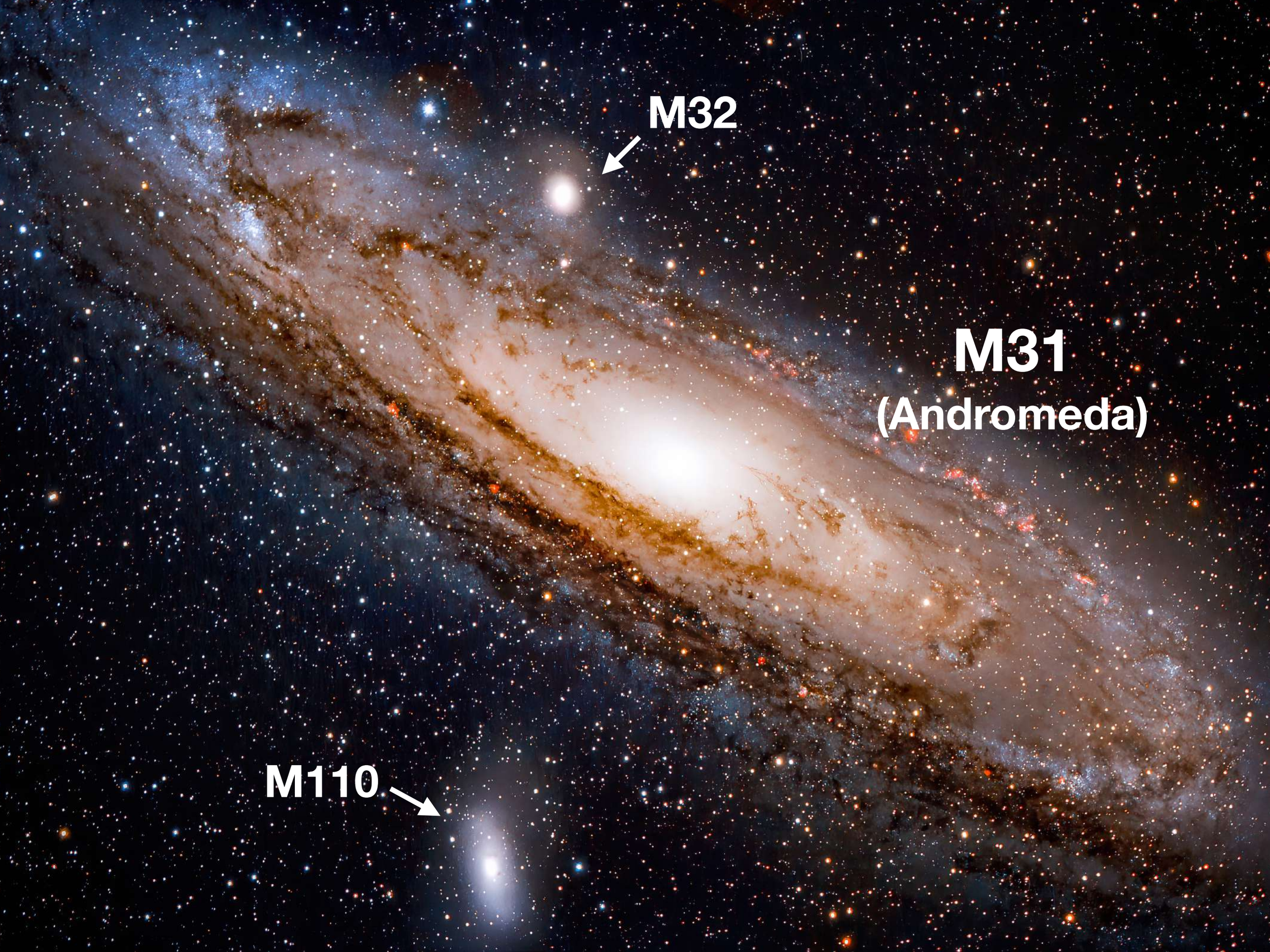
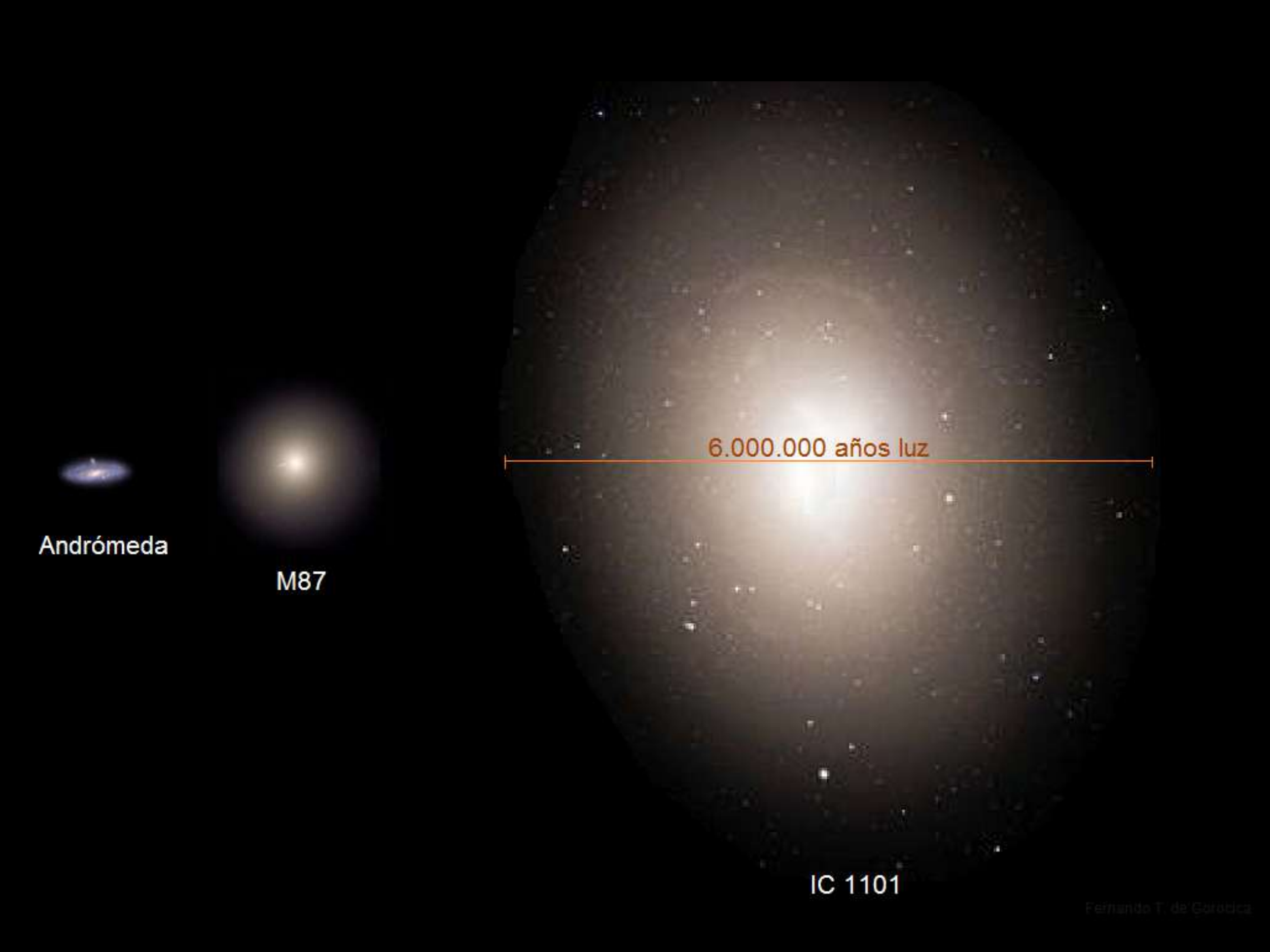

M32
M31
(Andromeda)
M110


6.000.000 años luz
Andrómeda
M87
IC 1101

Galaxies

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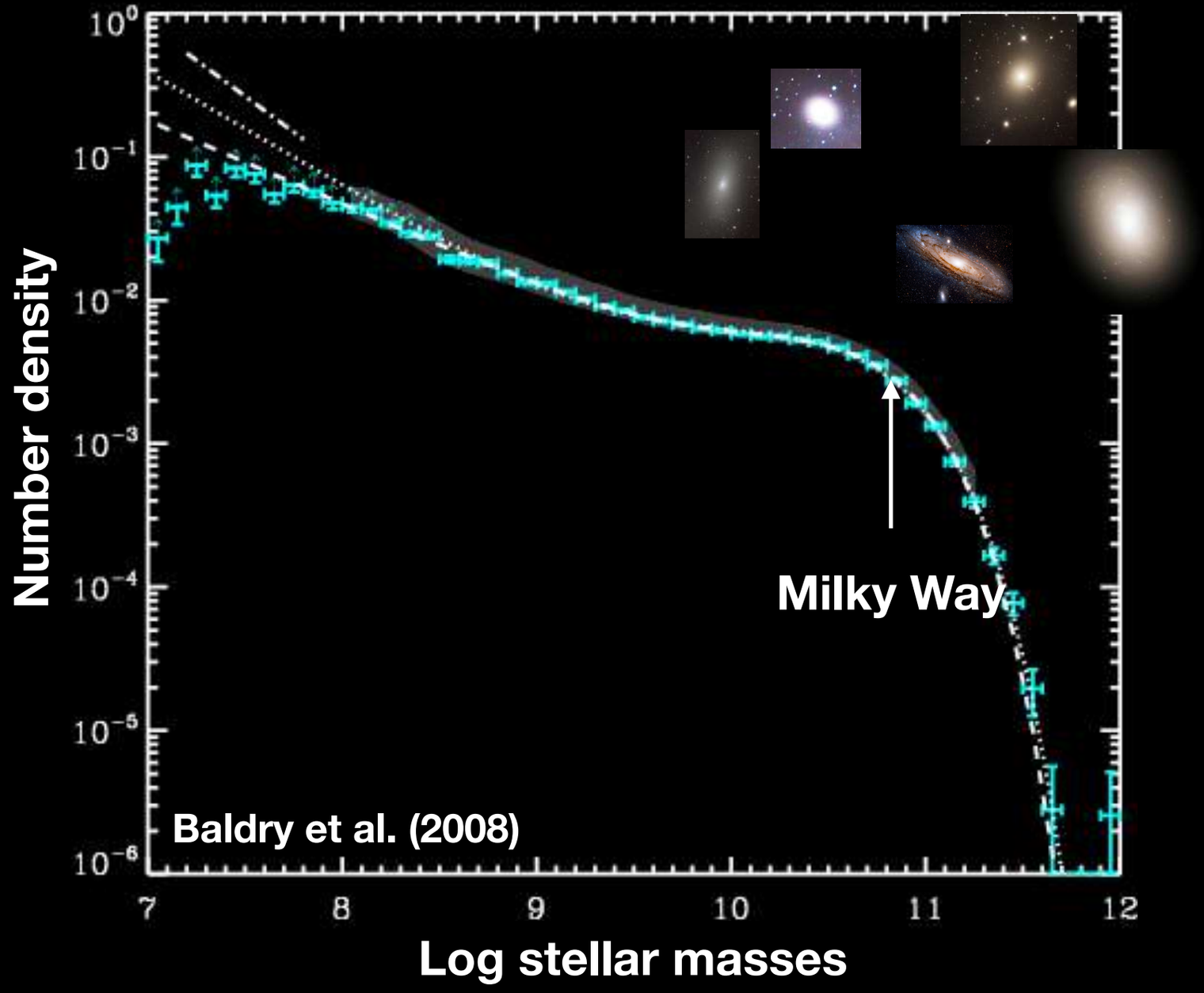

Galaxies

Galaxies can be very different……

But also *extremely* well-regulated

Tell me the stellar mass of a galaxy, I can predict:
— The size to a factor of 2
— The rotation velocity / velocity dispersion to ~30%
— The super massive black hole mass to a factor of 3
— The total halo mass to a factor of 2
— and more, e.g., the age, chemical composition, etc
(across ~3 orders of magnitudes in M_stars)

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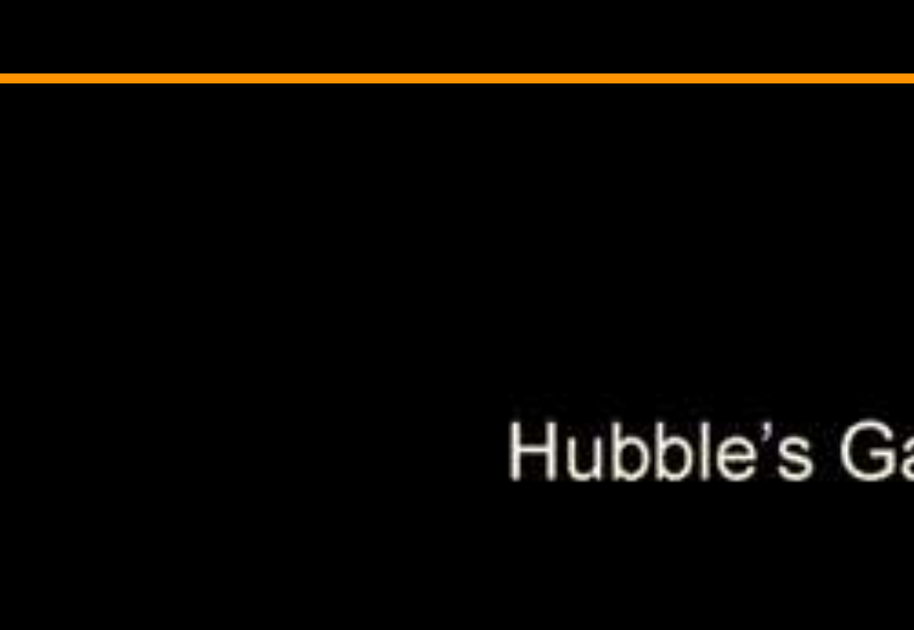
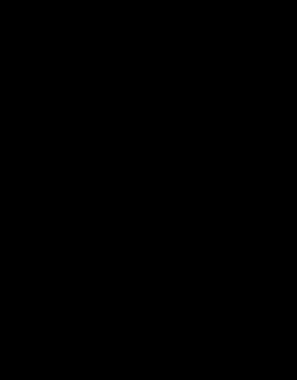
Galaxies: Highly regulated complex systems

Mystery!

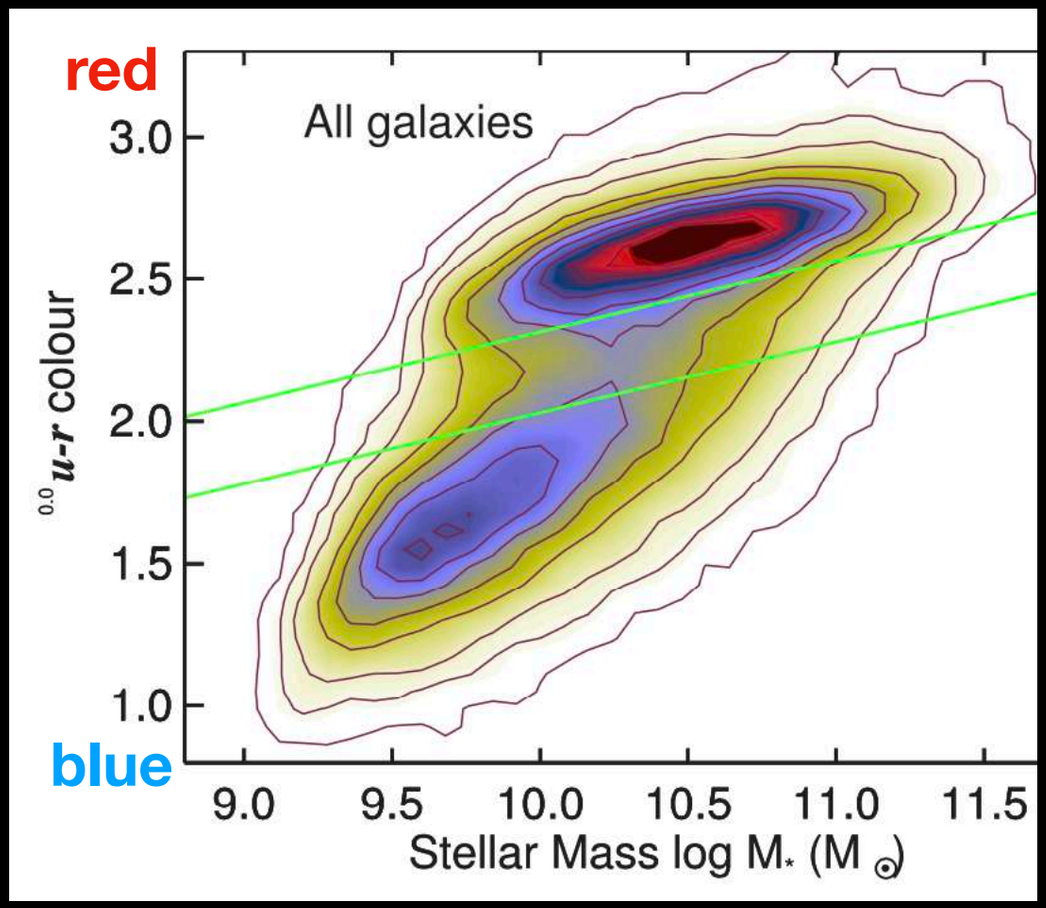
Galaxies

Hubble's Galaxy Classification Scheme



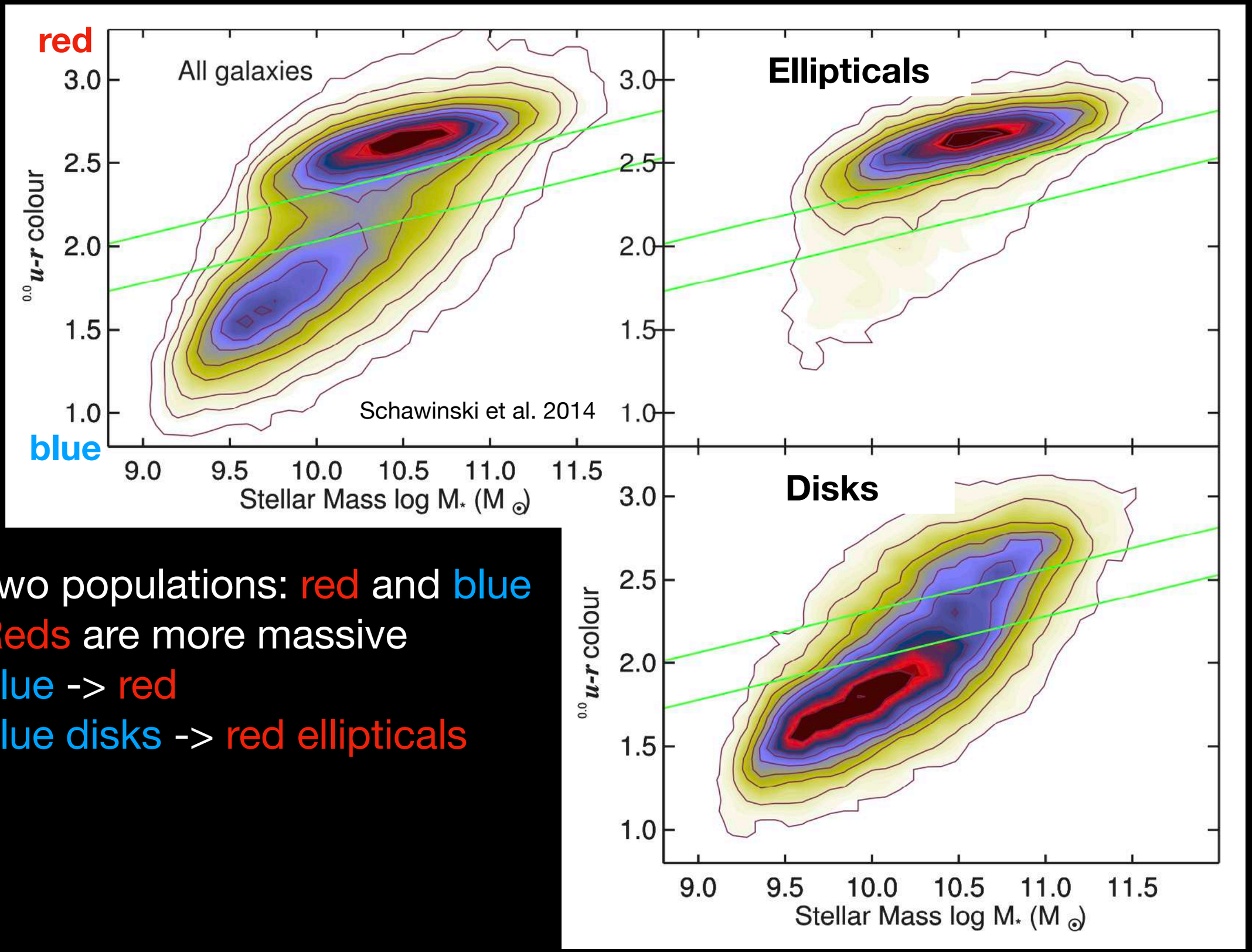


Galaxies



- Two populations: red and blue
- Reds are more massive
- blue -> red

Galaxies



- Two populations: red and blue
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- blue -> red
- blue disks -> red ellipticals

Formation of galaxies

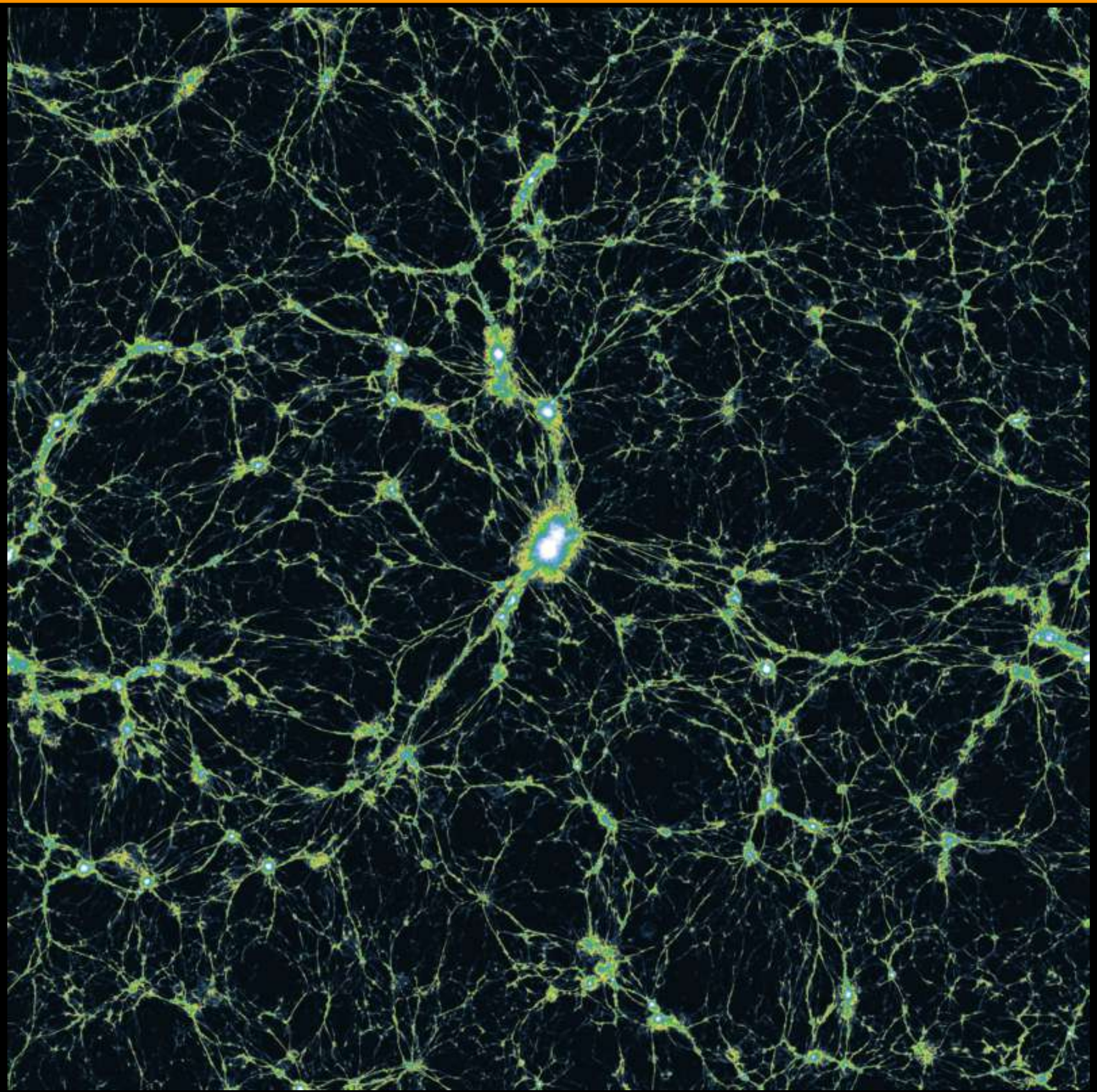
Formation of galaxies

Key concept:

- Gas infall
- Gas cooling
- Star formation
- Feedback

Of course, gravity always pulls material in.

Formation of galaxies: gas infall



Formation of galaxies: gas cooling

Heated to T > 10^6 K

Too hot to form stars.
Recall from Day 1, at what T would star formation happen?

Gas cools down through collision
— collision excites atoms; it decays, emits a photon
— free electron recombines with an ion, emits a photon
— charge particles collide and accelerate, emit a photon
(a.k.a. free-free or Bremsstrahlung emission)

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- Happening at all temperatures
- more efficient at high T

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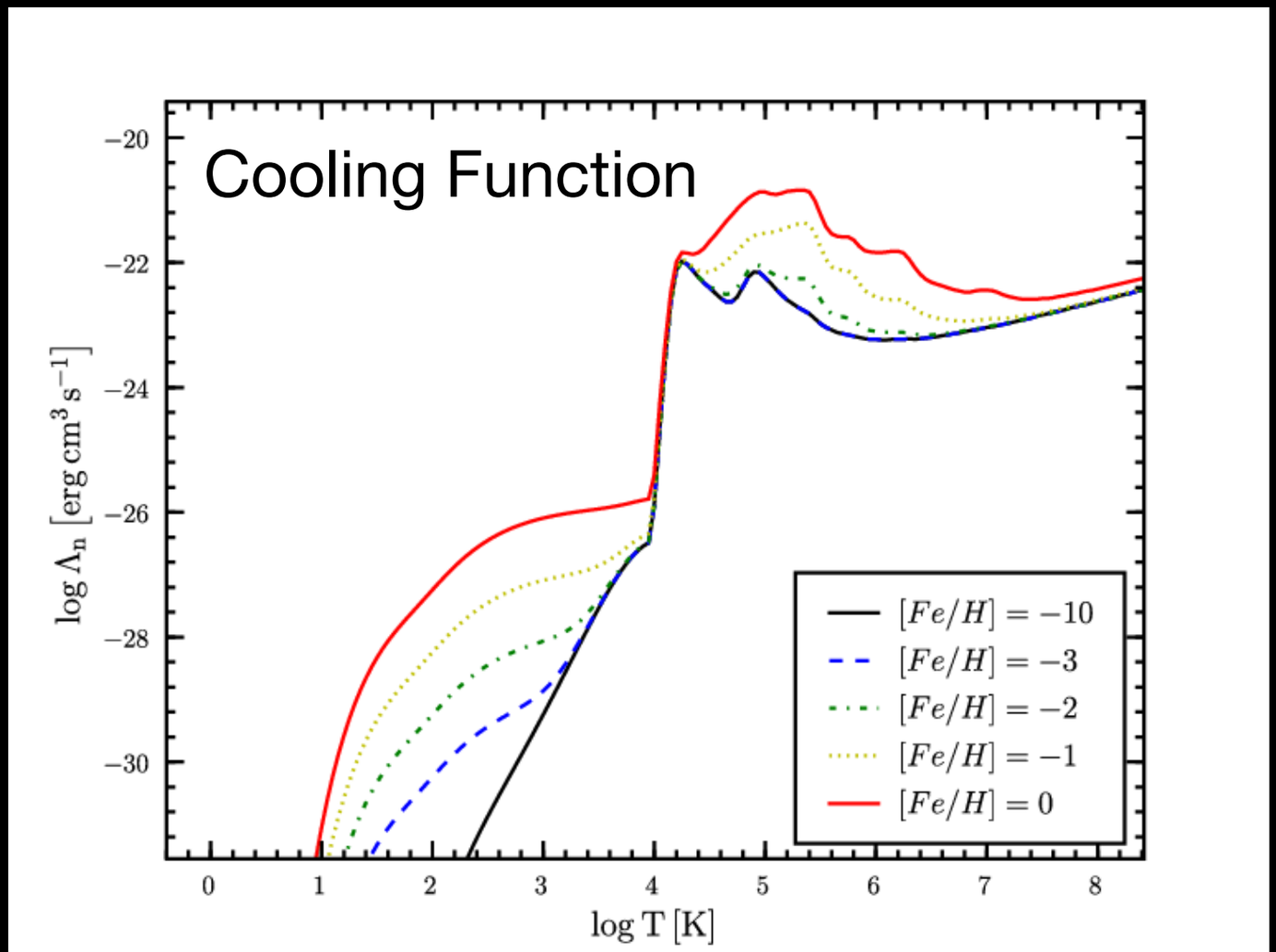
— Depending on the chemical composition
— Metals are efficient coolent.
— Dominate at T ~< 10^7 K

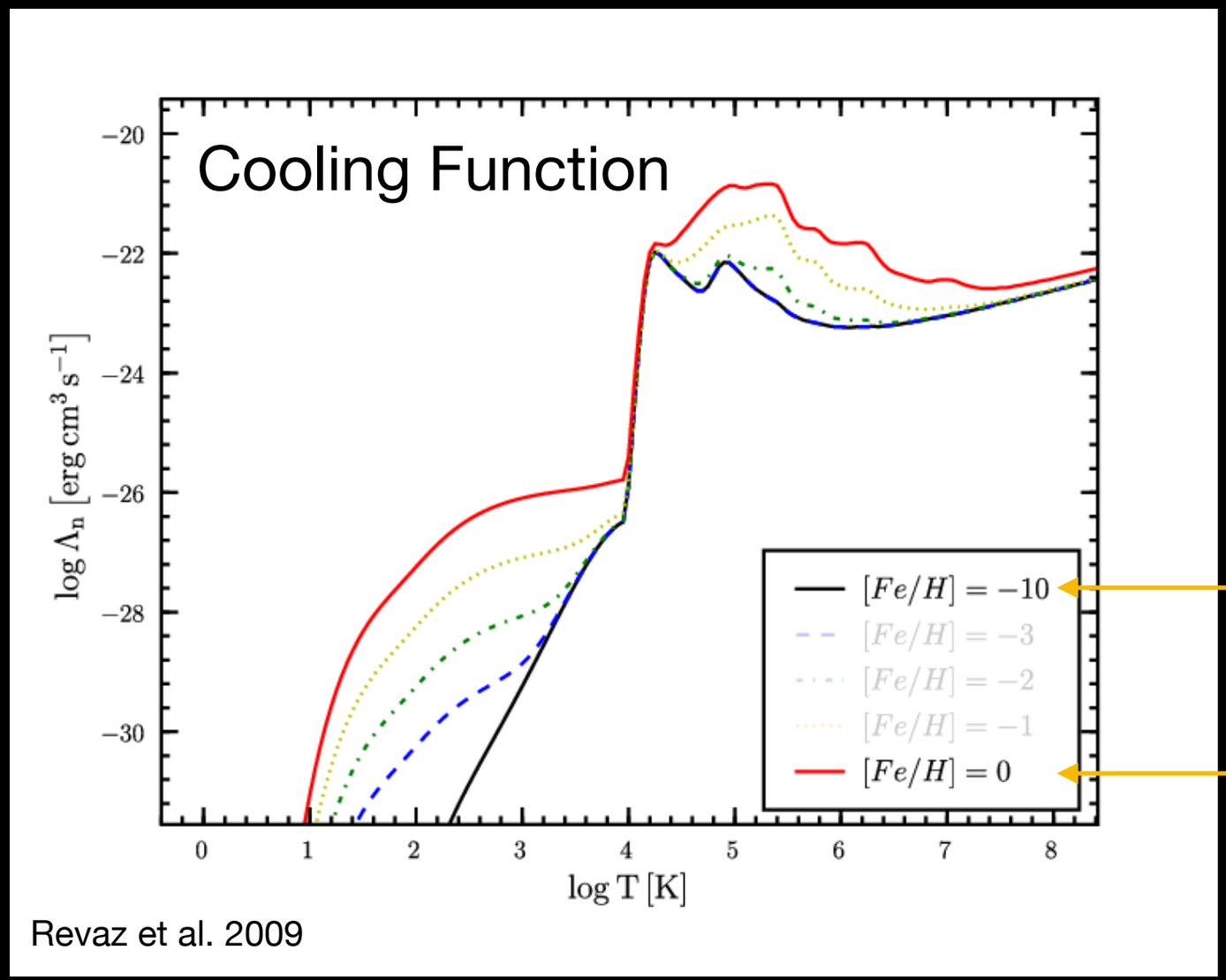
Formation of galaxies: gas cooling

Gas cooling $\propto n^2 \Lambda(T)$



Revaz et al. 2009

Formation of galaxies: gas cooling



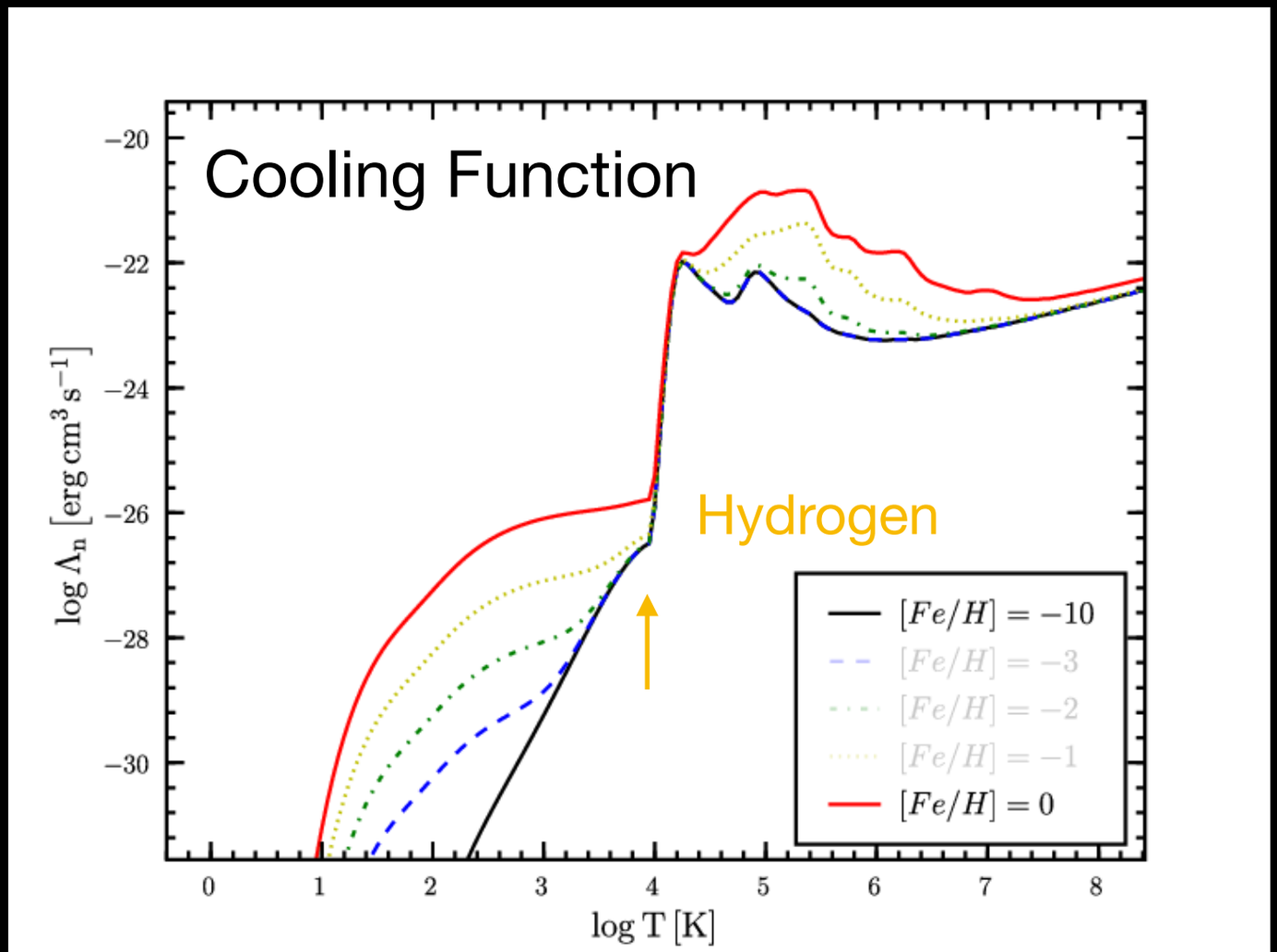
Revaz et al. 2009

Gas cooling $\propto n^2 \Lambda(T)$

10^{-10} of the Sun, ~ 0

"metal" content like the Sun
— Everything other than H, He
— C, N, O, Fe, etc
— a few %

Formation of galaxies: gas cooling



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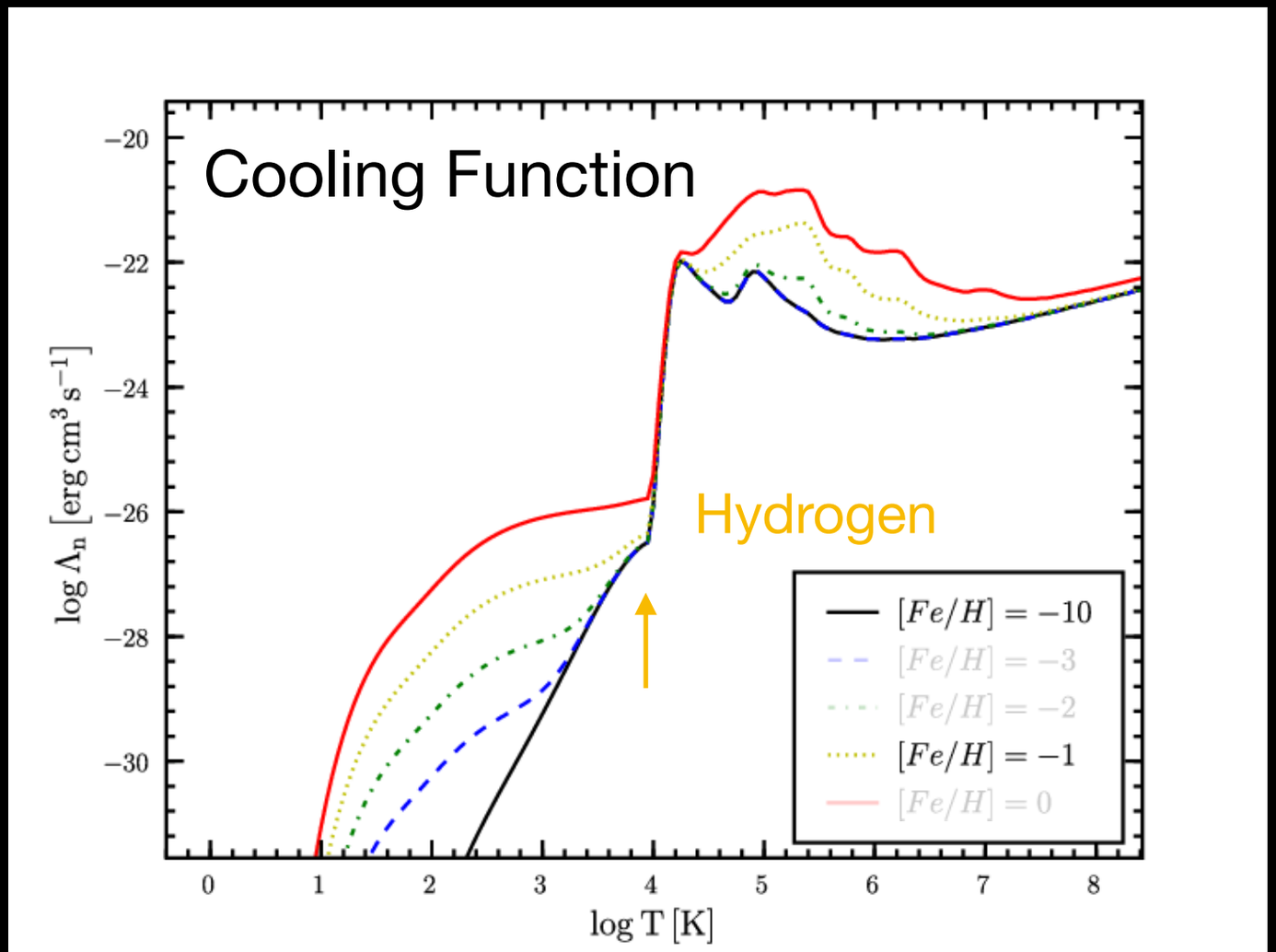
Gas cooling $\propto n^2 \Lambda(T)$

— Below ~10^4 K, Hydrogen cooling becomes inefficient

Formation of galaxies: gas cooling



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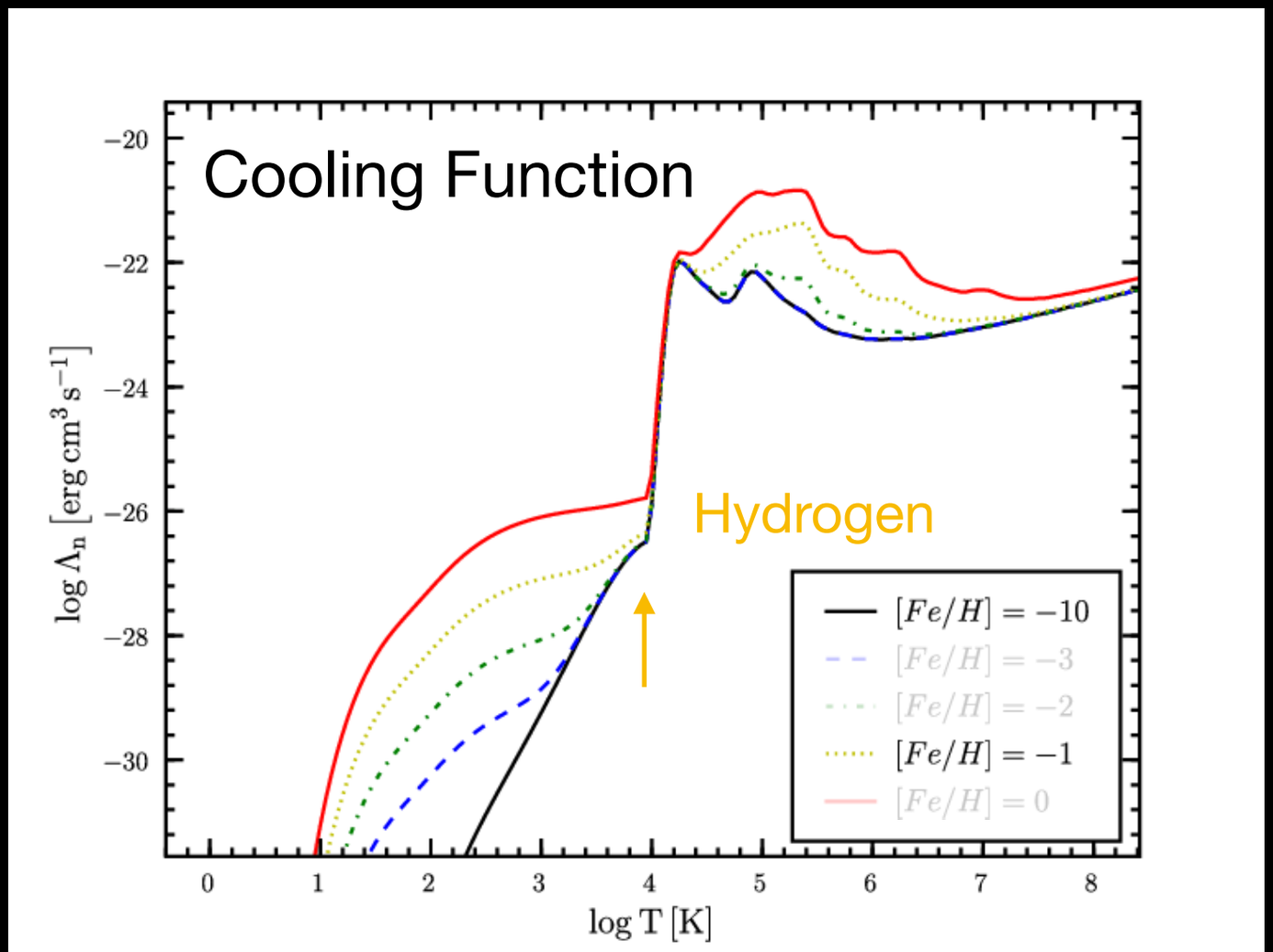
— Need metals/molecules as coolent

— more energy states

— a little helps a lot

Formation of galaxies: gas cooling



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— Once gas gets cool (and dense) enough, SF happens. (Go back to Day 1)

Formation of galaxies: star formation

What is happening in the process?

Formation of galaxies: star formation

What is happening in the process?

We don’t really deal with the physical processes……

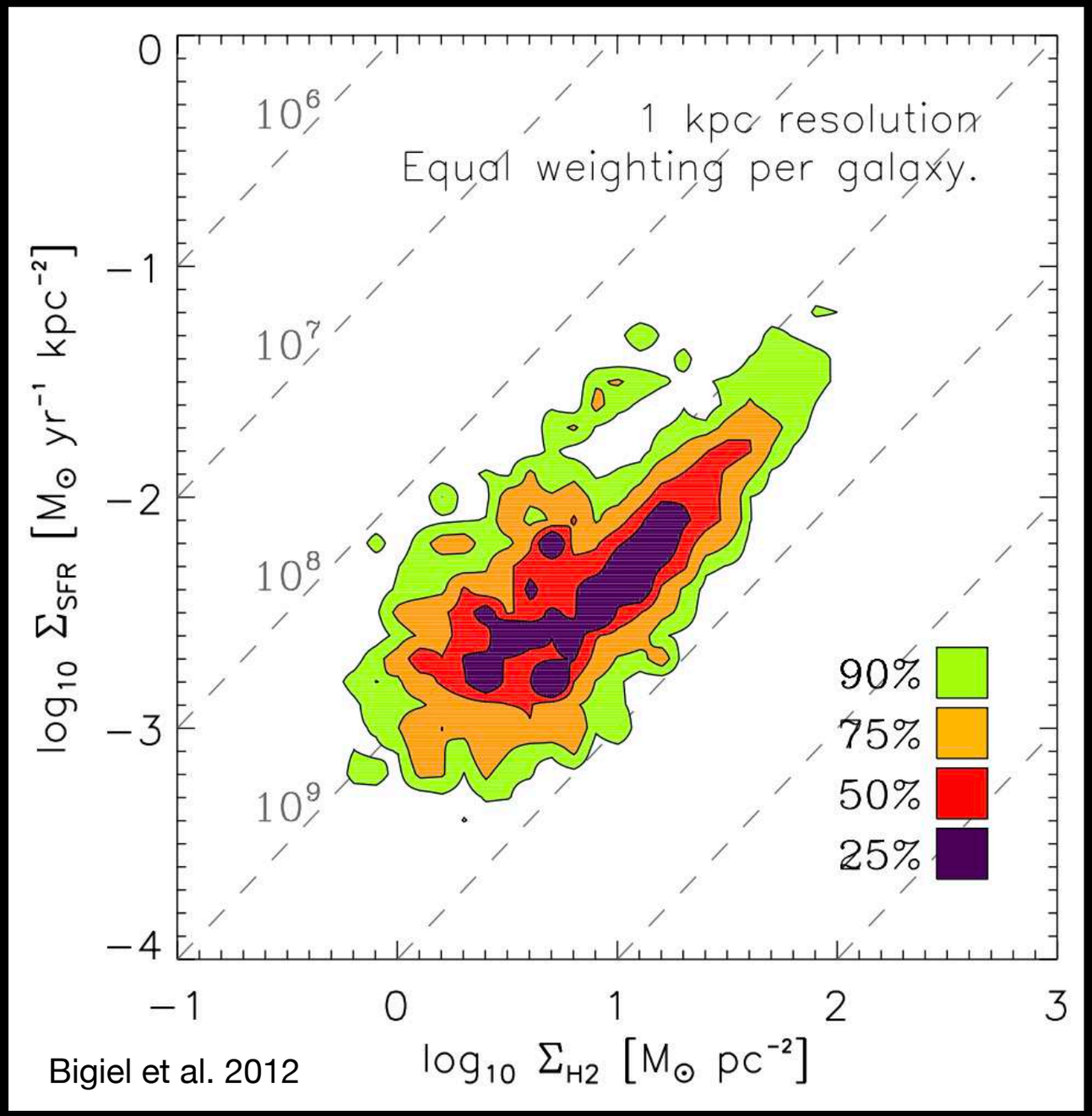
Physical picture:
— Ionized gas —> atomic gas —> molecular gas —> star formation

Empirical star-formation “law”

$$\Sigma_{SFR} \propto \Sigma_{gas}^{N}$$

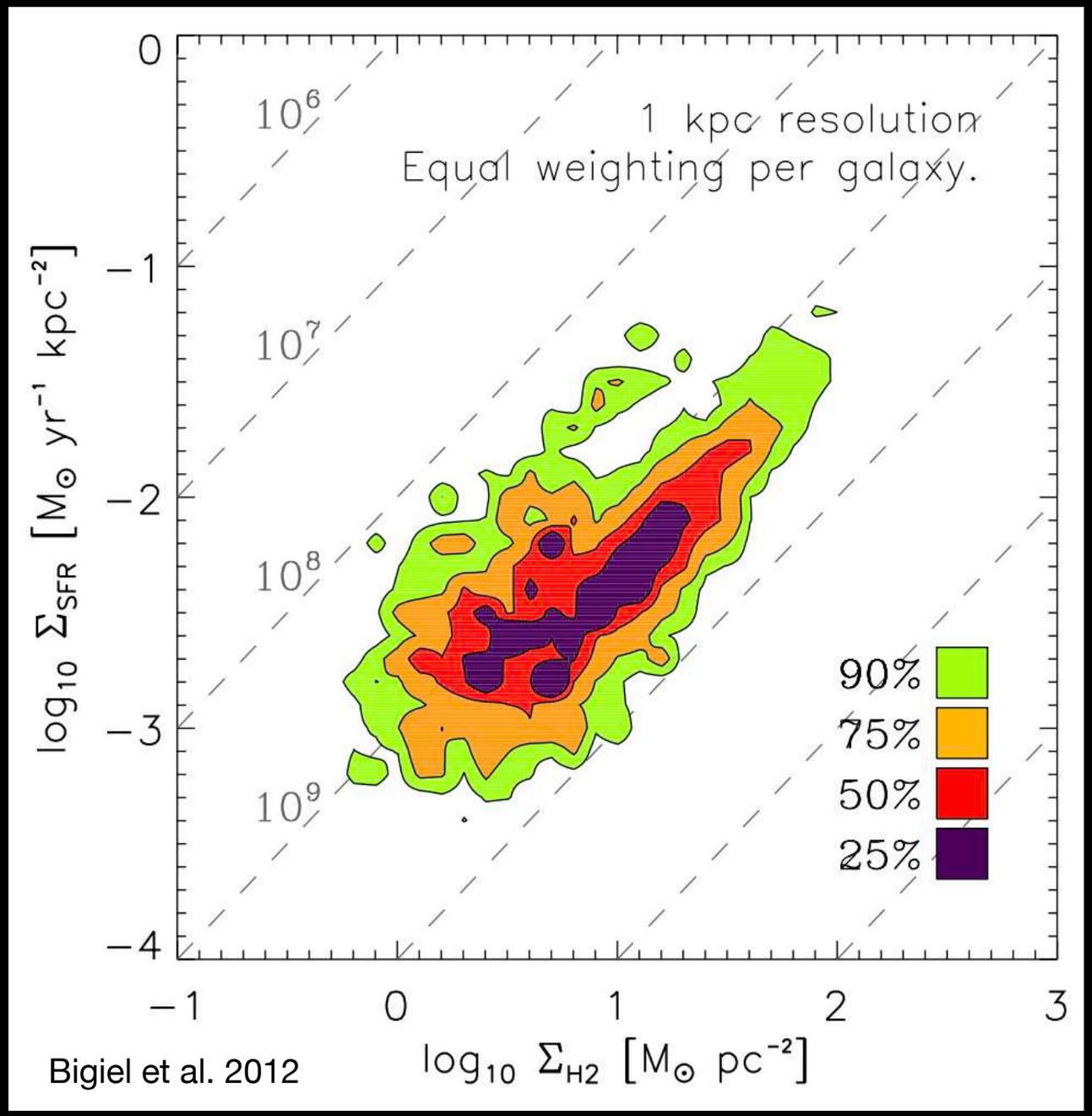
gas: “cold” gas

Formation of galaxies: star formation



Bigiel et al. 2012

Formation of galaxies: star formation



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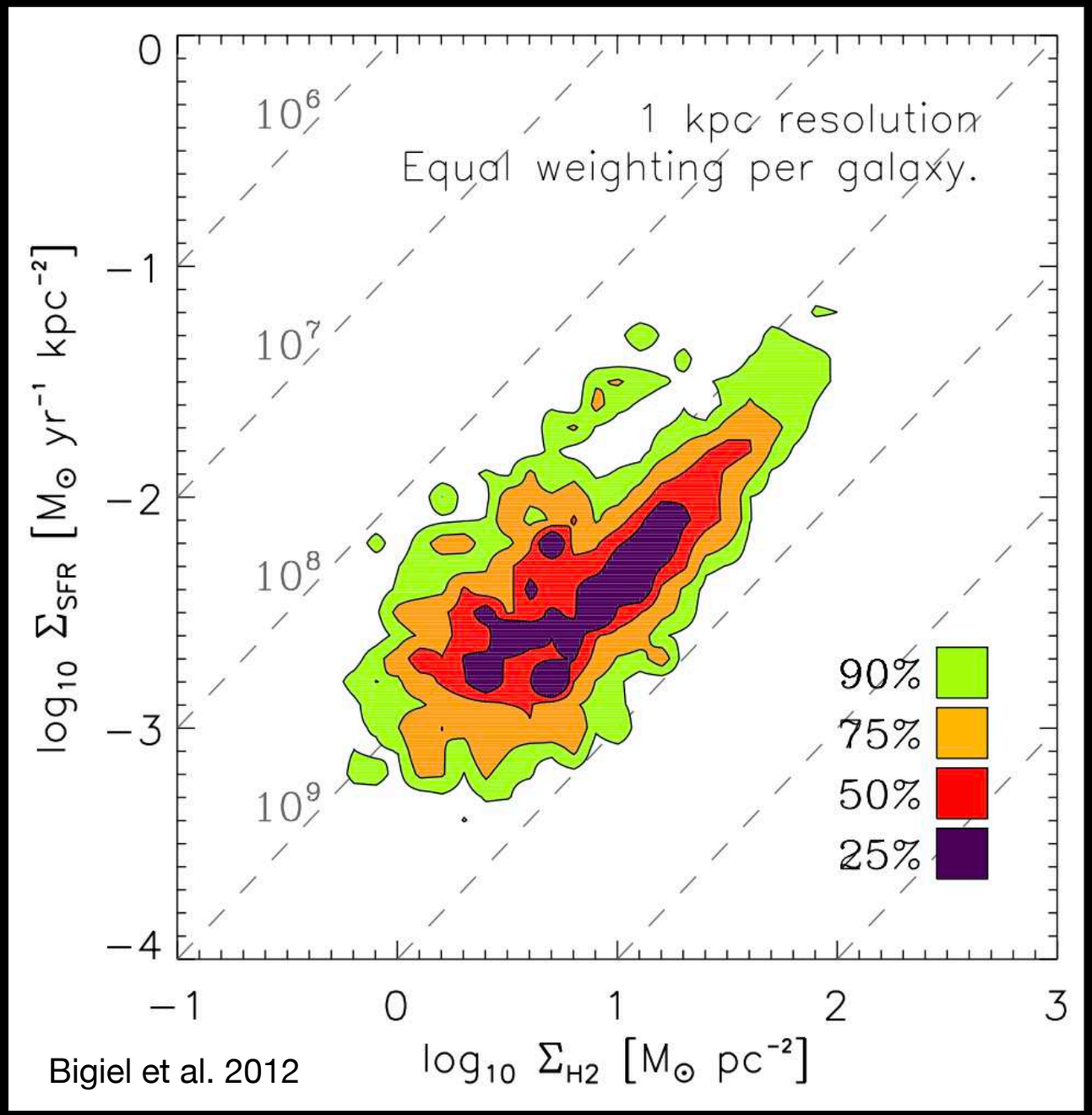
$$\frac{M_{H2}}{SFR} \simeq 2\ Gyr$$

Formation of galaxies: star formation



Bigiel et al. 2012

$$\frac{M_{H2}}{SFR} \simeq 2\ Gyr$$

Question:
Why do we still see galaxies forming stars now, ~13.7 Gyr after the Big Band?

Formation of galaxies: feedback

Feedback

- Energy/material from stellar winds / SN / SMBH
- Return metals into the interstellar medium
- Regulating star formation
  - make gas hotter & more turbulent, eject gas

M82

Red: H_alpha

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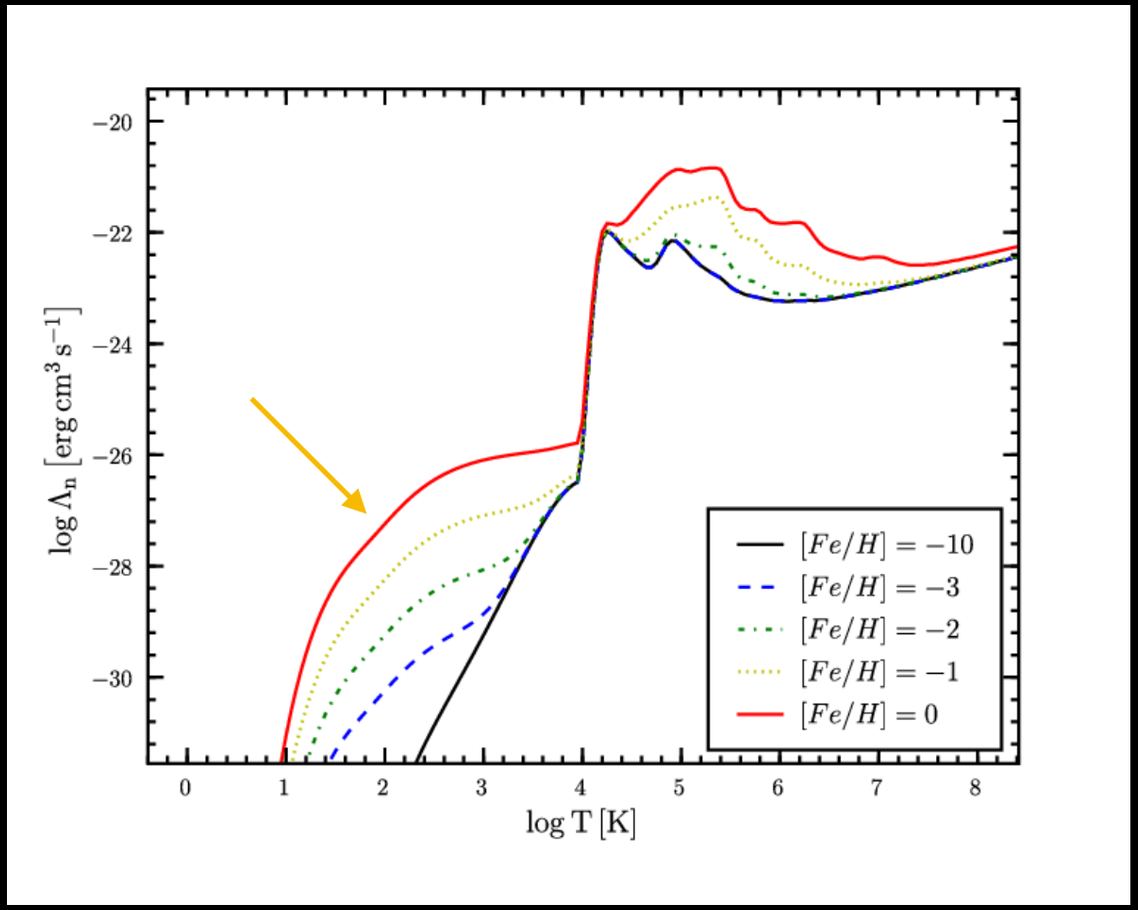

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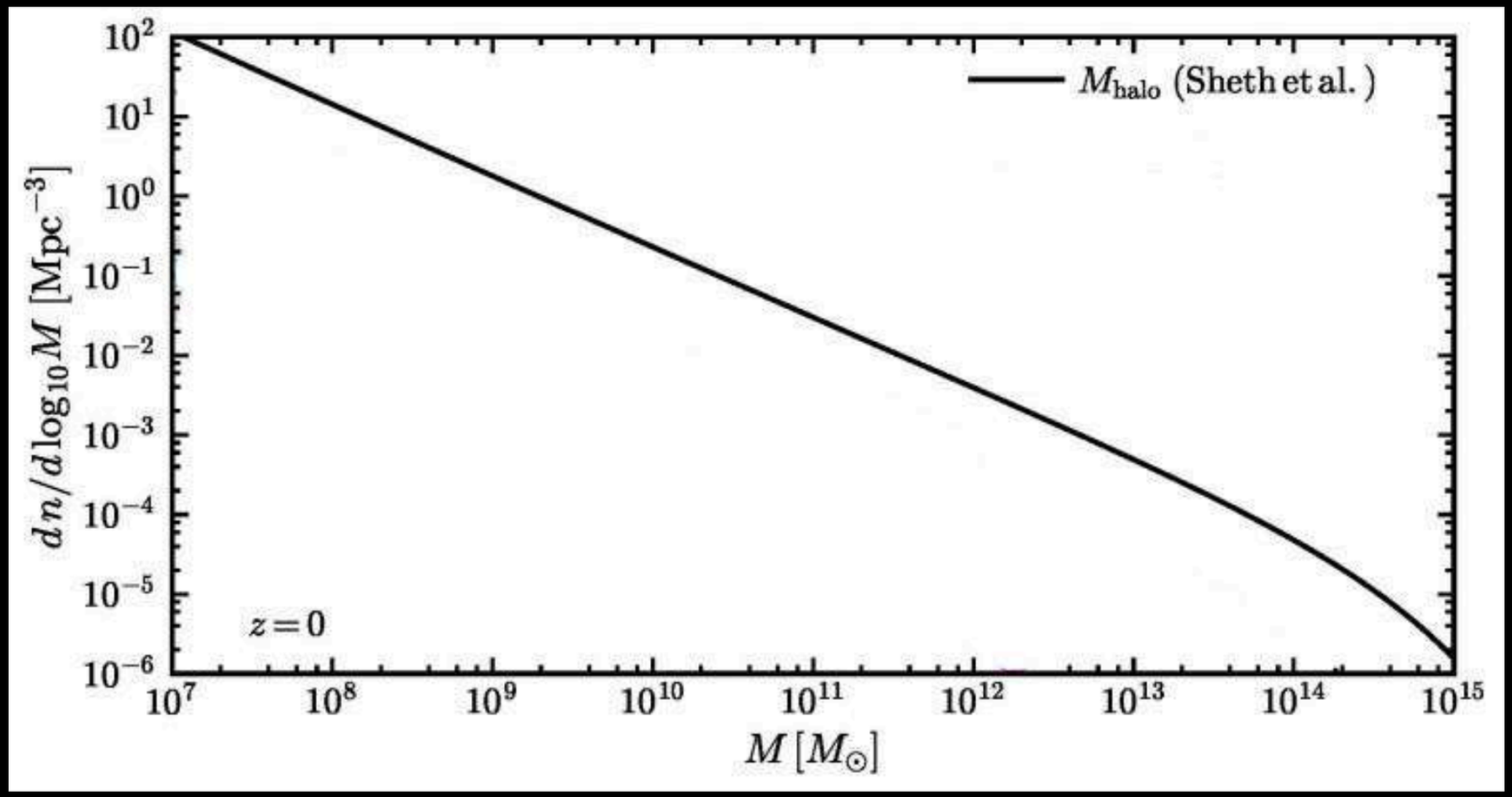

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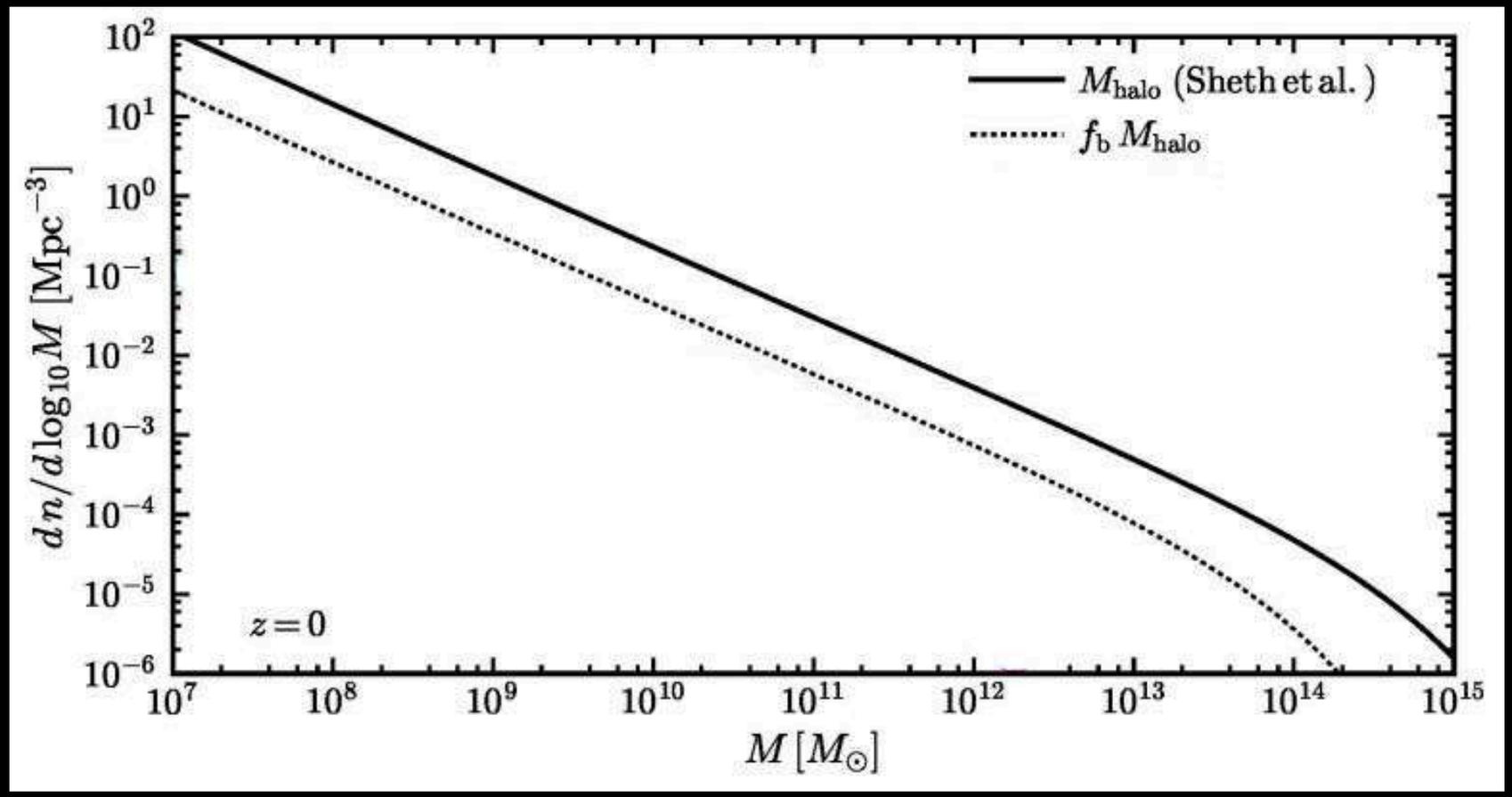

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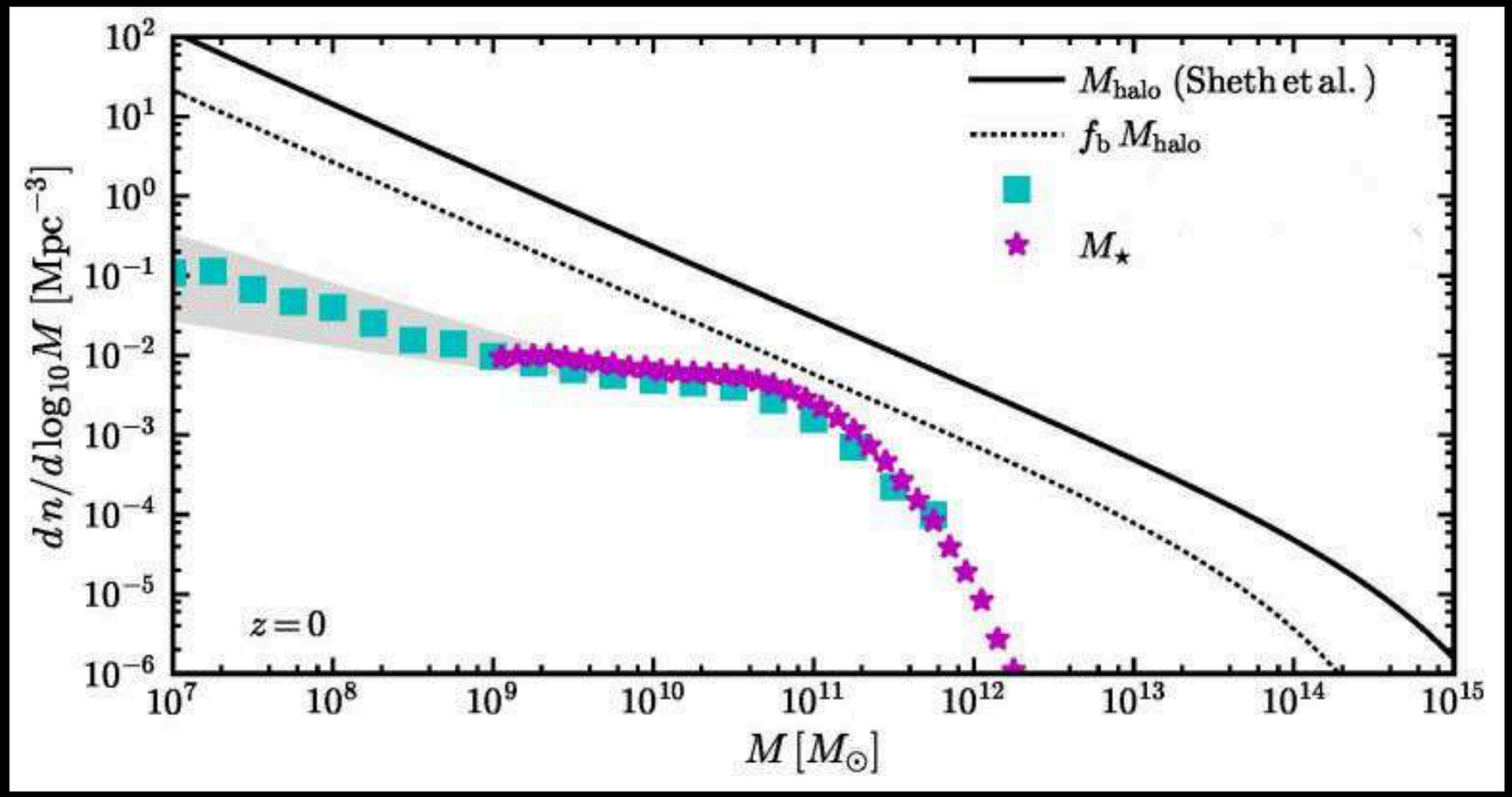

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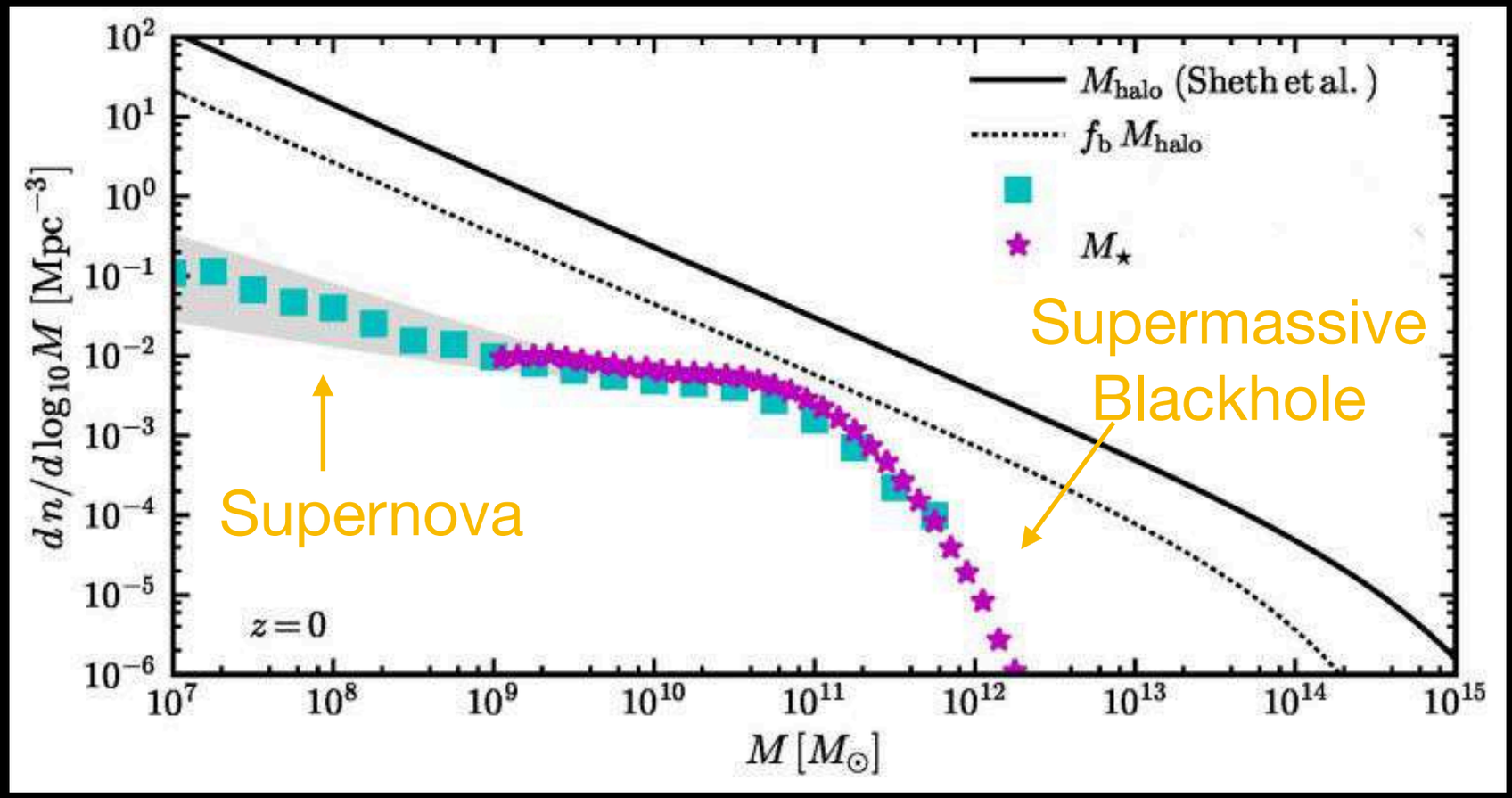

Formation of galaxies

Key concept:

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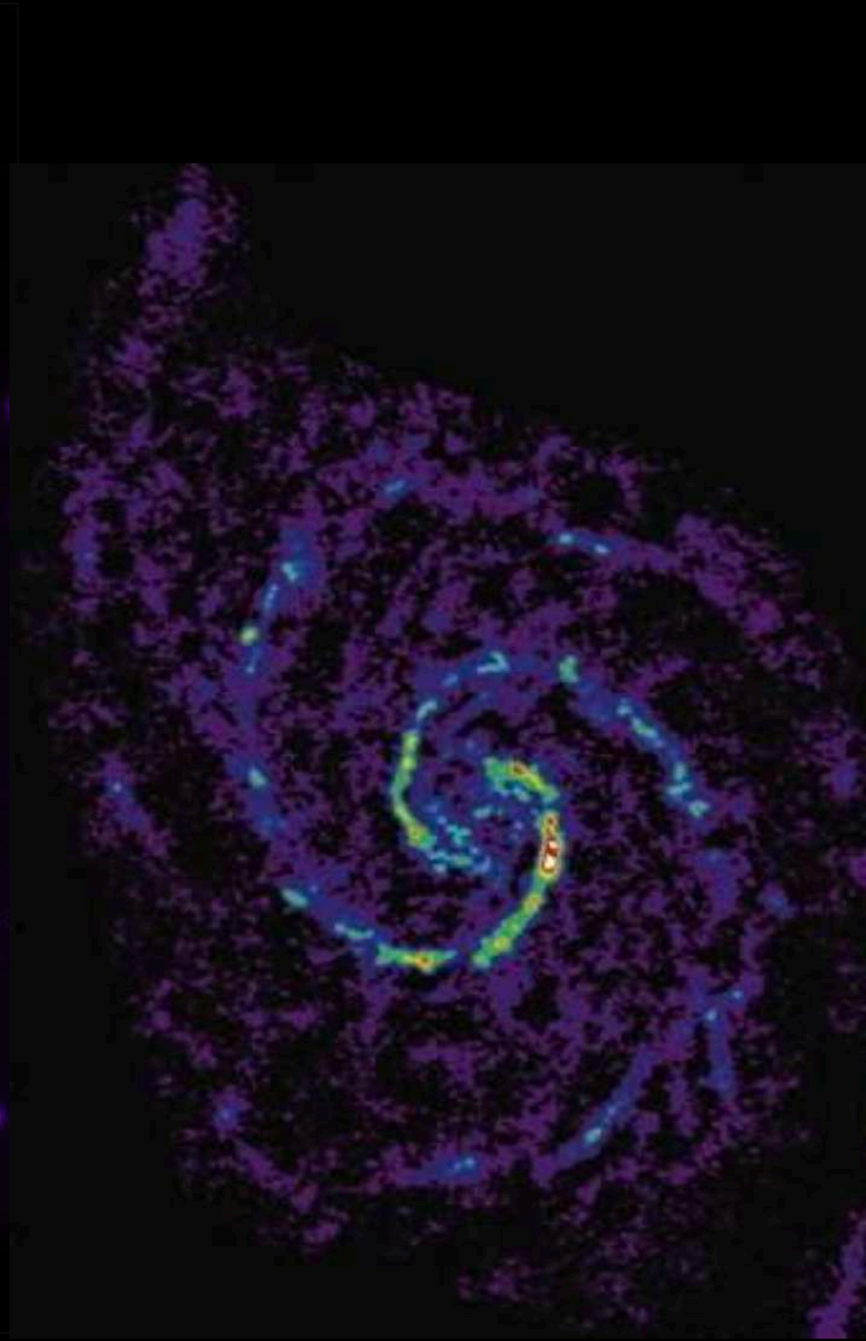
And more……



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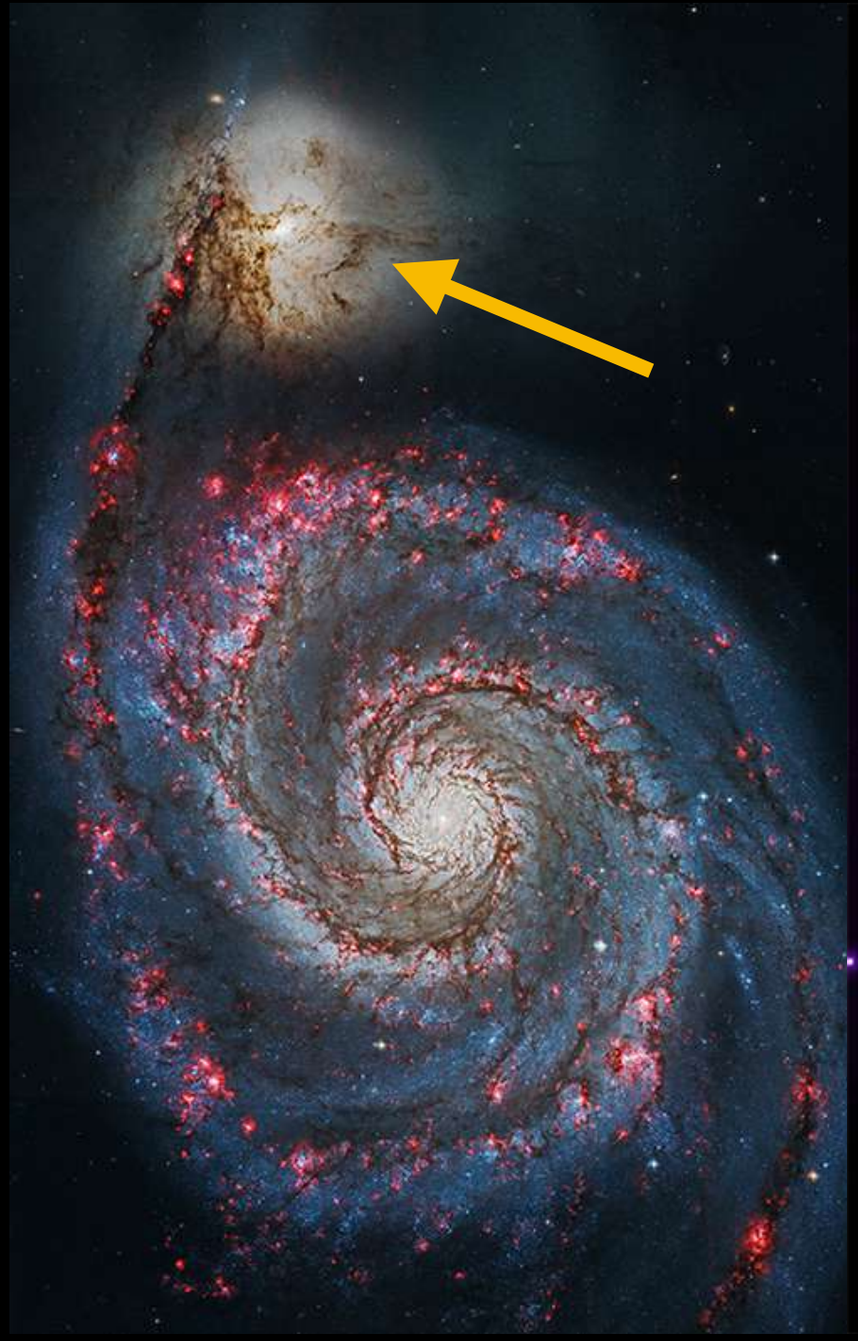

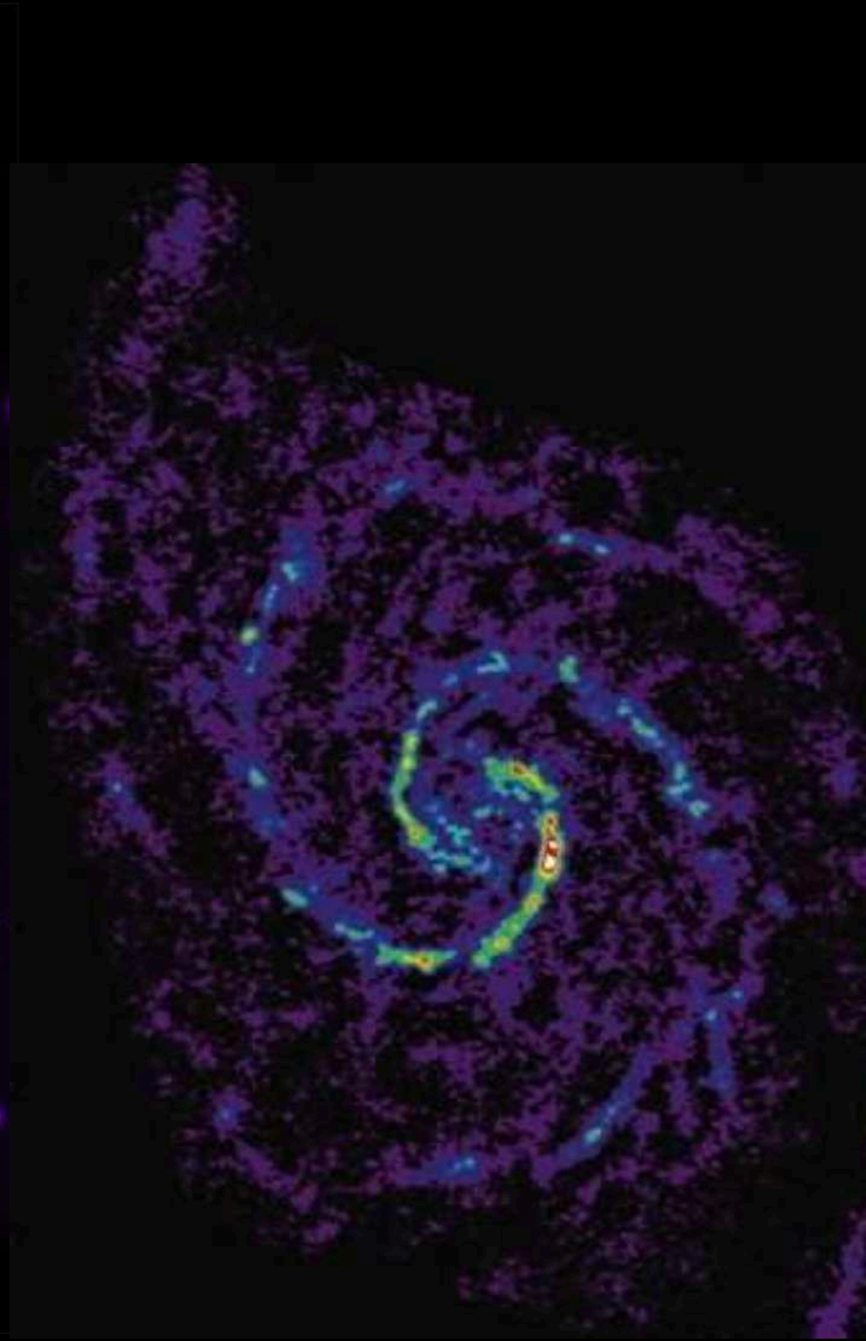

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Galaxy merger

NGC 4676

Arp 272

Arp 148

Formation of galaxies: merger

The effect of galaxy merging

(what could happen)

— Create spheroids
— Drive gas inflow, induce burst of star formation
— Induce feedback
— Produce massive galaxies

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Numerical simulation of stars when galaxies merger:

Formation of galaxies: merger

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Numerical simulation of gas when galaxies merger:

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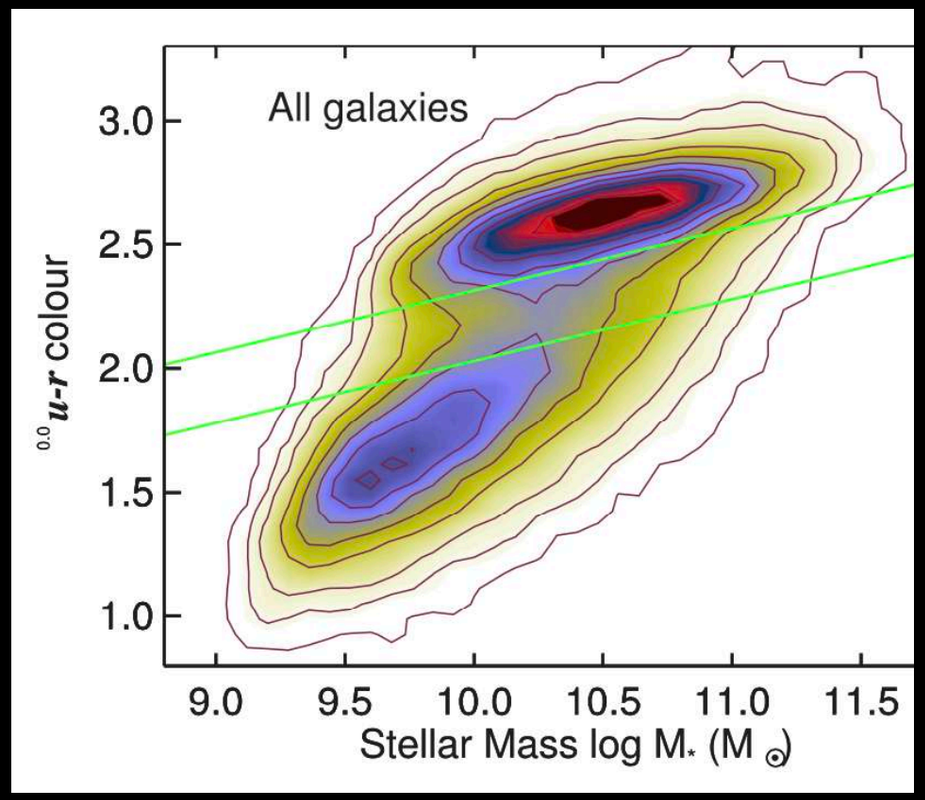

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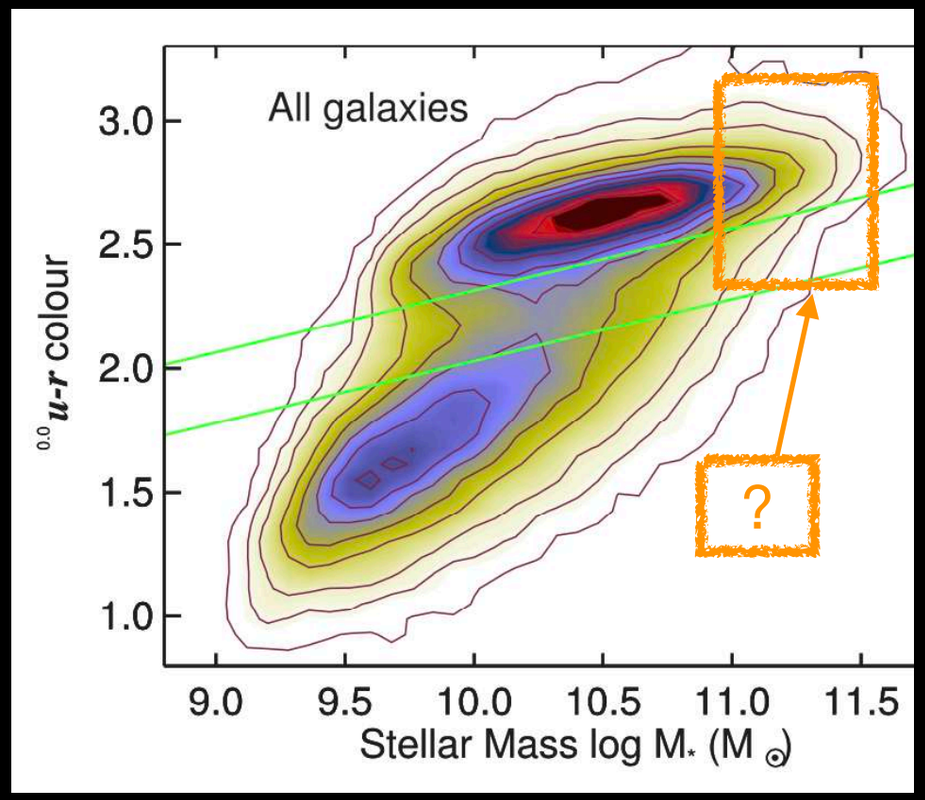

If no massive star-forming galaxies,
How can there be massive quiescent galaxies?

Formation of galaxies: merger

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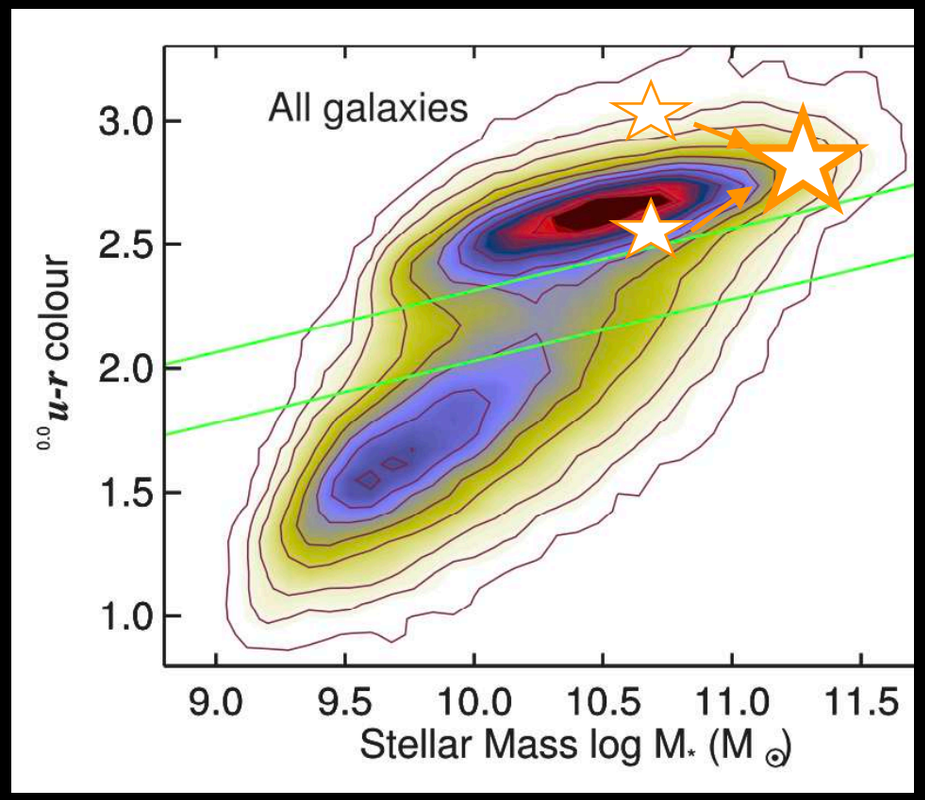


If no massive star-forming galaxies,
How can there be massive quiescent galaxies?

Need to growth by merging

Formation of galaxies: merger

The effect of galaxy merging

(what could happen)

— Create spheroids
— Drive gas inflow, induce burst of star formation
— Induce feedback
— Produce massive galaxies

We have seen the effect of merger

— Milky-Way-mass galaxies had experienced ~1 “major merger”
  — more frequent for “minor merger”
— Important to galaxy evolution
— But very complicated, huge parameter space

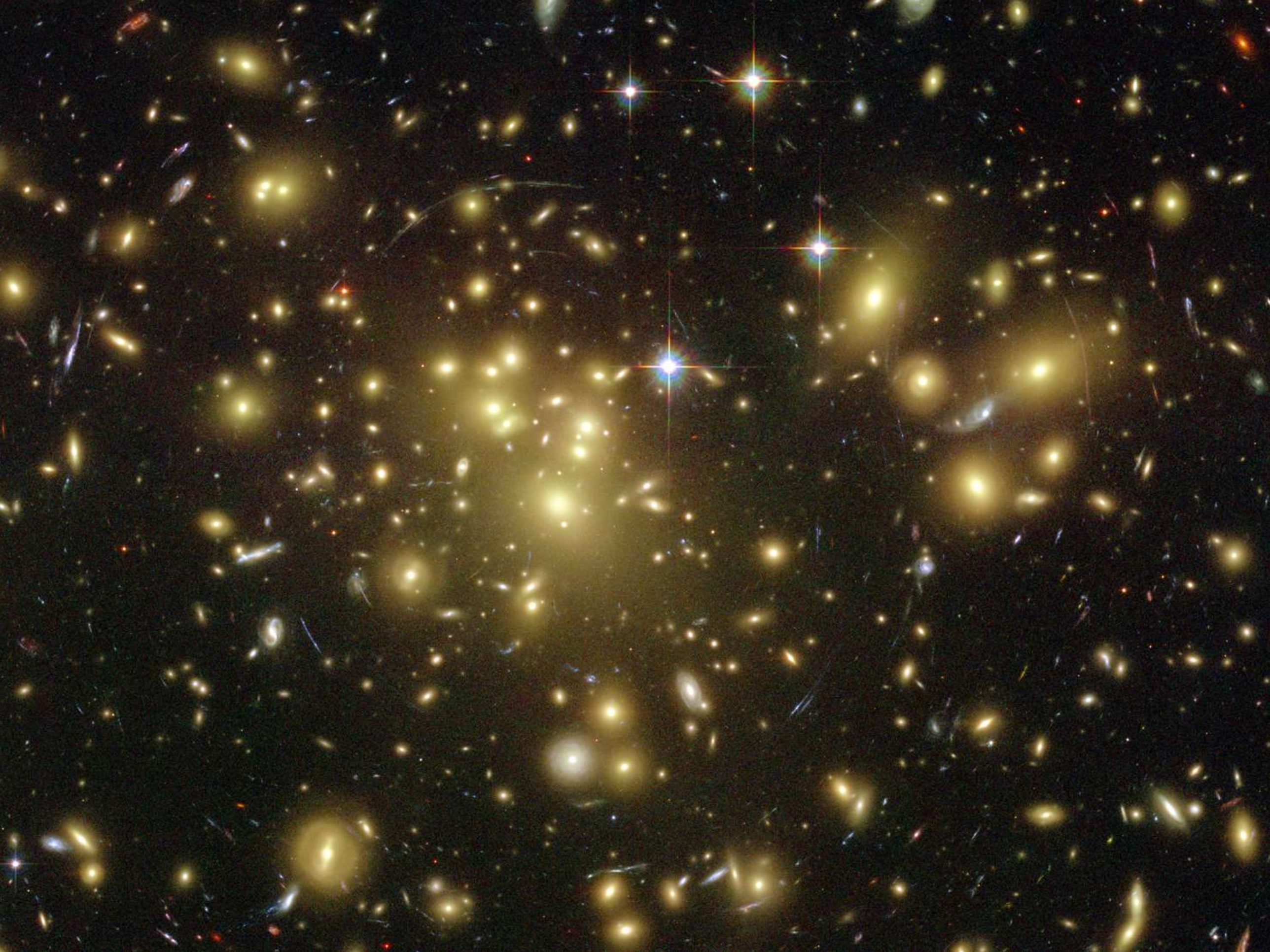
Formation of galaxies

Key concept:

- Gas infall
- Gas cooling
- Star formation
- Feedback
- Galaxy merger

And more……

Galaxies in galaxy clusters



Galaxies in galaxy cluster

(1) Strong effects from galaxy-galaxy interaction

- **gravitational interaction are common**
  - produce effects like galaxy merger, but weaker

- **(some regions in clusters) galaxy mergers are frequent**
  - galaxy number density is high
  - but relative velocity is also high, hard to be captured

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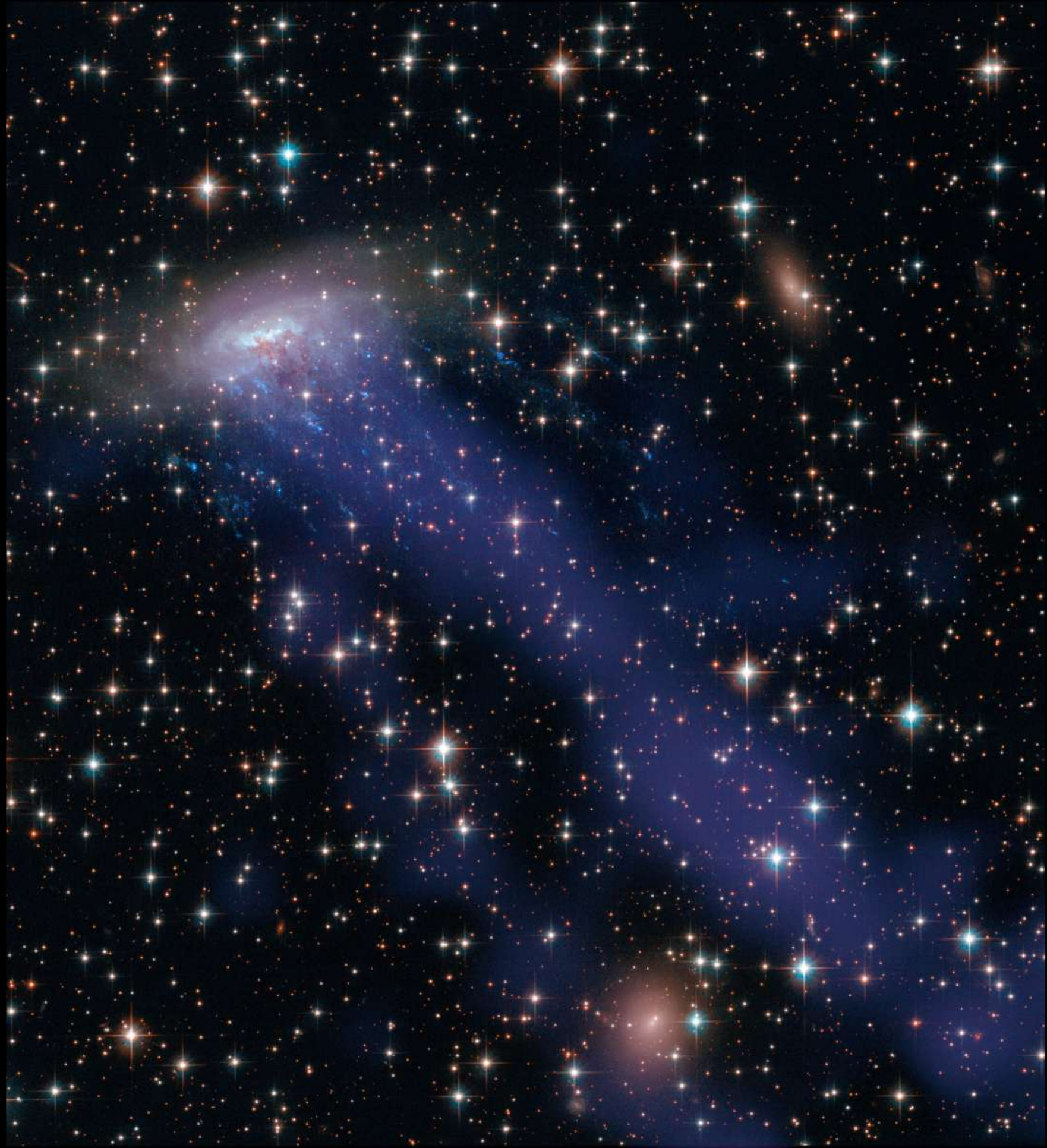
(2) Effects from galaxy-cluster interaction

- **“ram pressure stripping”: gas stripped when falling into clusters**
  - $P \sim \rho v^2$ ρ : ambient gas density : prefer center of massive clusters
  - If P > self gravity, gas is stripped : perfer low-mass galaxies

ESO 137-001
“Jellyfish galaxy”



Galaxies in galaxy cluster

What do we observe?

Galaxies in galaxy cluster

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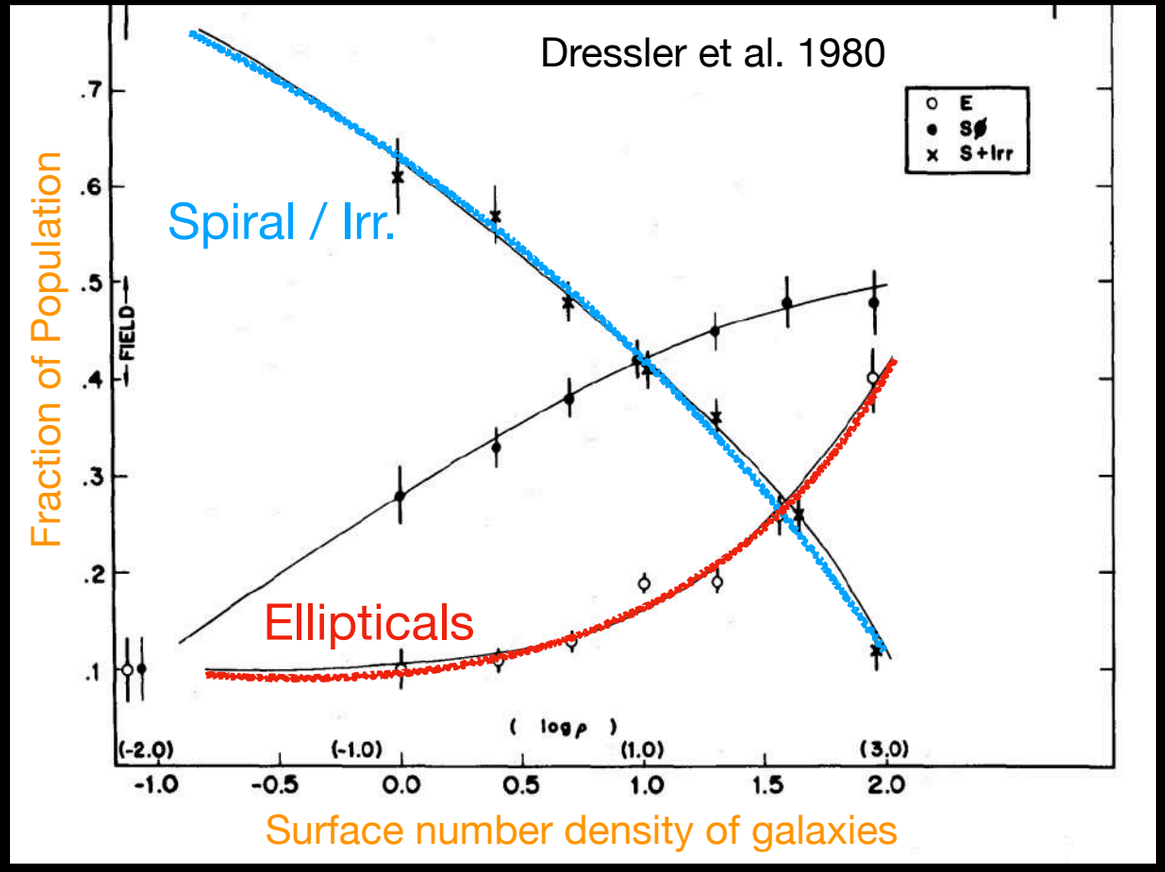
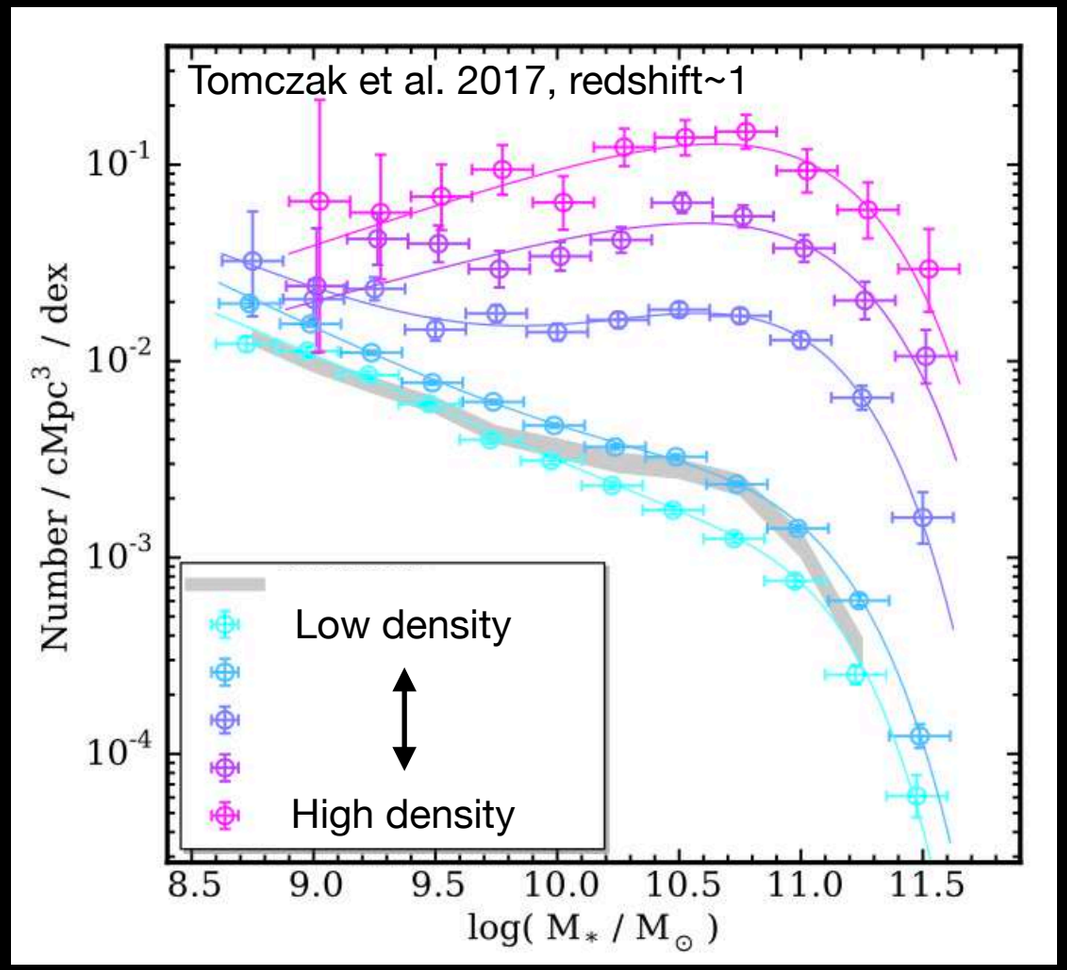
(1) Higher red/elliptical galaxy fraction



Galaxies in galaxy cluster

What do we observe?

(1) Higher red/elliptical galaxy fraction
(2) Relatively more high-mass galaxies



Formation of galaxies

Key concept:

- Gas infall
- Gas cooling
- Star formation
- Feedback
- Galaxy merger
- Galaxy clusters (large-scale structure)

Galaxies: summary

(1) Huge collections of stars and gas
(2) Small smuges of normal matter in a huge dark matter halo

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Terribly complicated but fun!