Formation of Spirals Galaxies
(and more on Ellipticals)

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Elliptical Galaxies (cont.)

Formation of ellipticals in galaxy simulations

https://www.youtube.com/watch?v=rBC3FZIUIrw

Scaling relations of ellipticals

Because the relaxation times of elliptical galaxies are much longer than a Hubble time, these galaxies "remember" their formation.

Scaling relations tell us something about the formation process(es)

We'll start with scaling relations between structural parameters, like luminosity, velocity dispersion, and surface brightness...

One of the earliest known structural scaling relations was the Faber-Jackson relation:

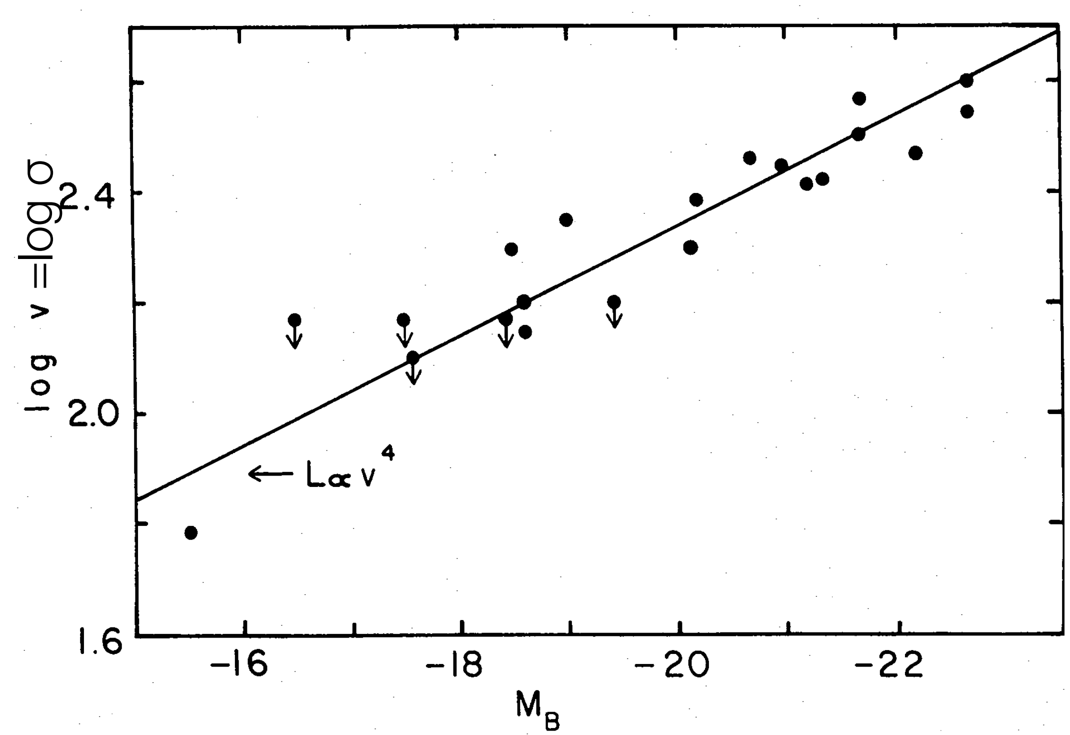
$$L \propto \sigma^4$$

strong correlation between luminosity (L) and central velocity dispersion (σ)

A natural consequence of the virial theorem.

Plenty of scatter, and the slope of the relation is different than the virial theorem.

This was assumed to indicate a missing parameter… and there was originally a lot of debate about what was the missing parameter..



Faber & Jackson 1976 ApJ, 204, 668

The fundamental plane for ellipticals

A break through in understanding of scaling laws came from large homogeneous data sets (from CCDs & long-slit spectroscopy), and the application of statistical tools.

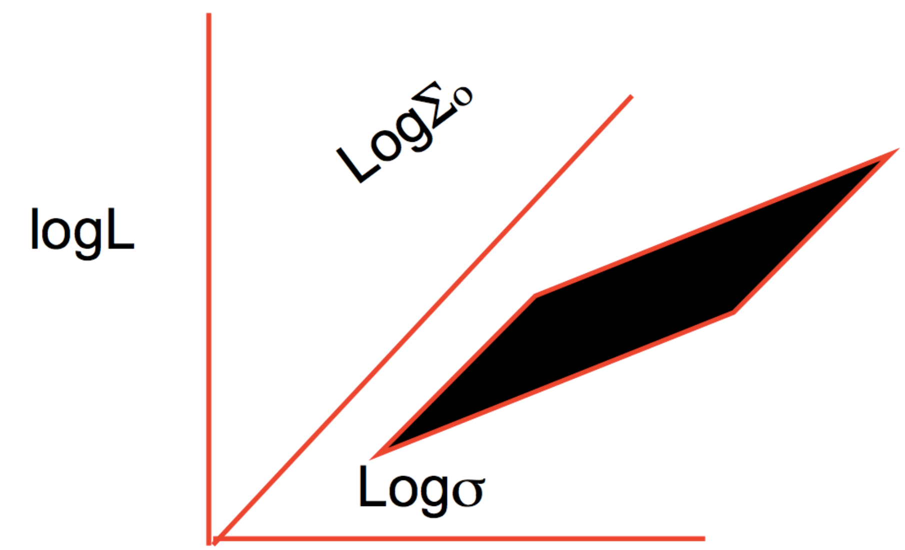
plane - means correlation in a 3D space and we see this space with three parameters that "see" the correlation from different angles.

$$R \propto \sigma^{1.24} \langle I \rangle_e^{-0.82}$$

Size

Velocity Dispersion

Luminosity



The mass-to-light ratios of ellipticals increases as they become more luminous (or more massive)

Likely because larger galaxies are older

The fundamental plane for ellipticals (cont.)

<u>Virial Theorem</u>: for a stable, self-gravitating, spherical distribution, the total kinetic energy is equal to minus 1/2 times the total gravitational potential energy.

Where does the Fundamental Plane of elliptical galaxies come from?

Assume the Virial Theorem holds, then the mass is $M = V^2 R/G$

Divide this by the area to get the mass surface density: $\eta = \frac{M}{\pi R^2} \propto \frac{V^2}{R}$

The surface brightness is this divided by the mass-to-light ratio: $I = \eta \left(\frac{M}{L}\right)^{-1}$

combining this: $I \propto \frac{V^2}{R(M/L)}$

$$I_e = \frac{L}{2\pi R_e^2}$$

Rewrite this in terms of the radius R_e=R and identifying the velocity V as the velocity dispersion σ, we have

$$R_e \propto \left(\frac{M}{L}\right)^{-1} \sigma^2 \langle I \rangle_e^{-1}$$

But note the <u>observed</u> coefficients aren't 2 & -1 (they range from 1 to1.4 and from -0.75 to -0.9) and so this implies

observed relation:

$$R \propto \sigma^{1.24} \langle I \rangle_e^{-0.82}$$

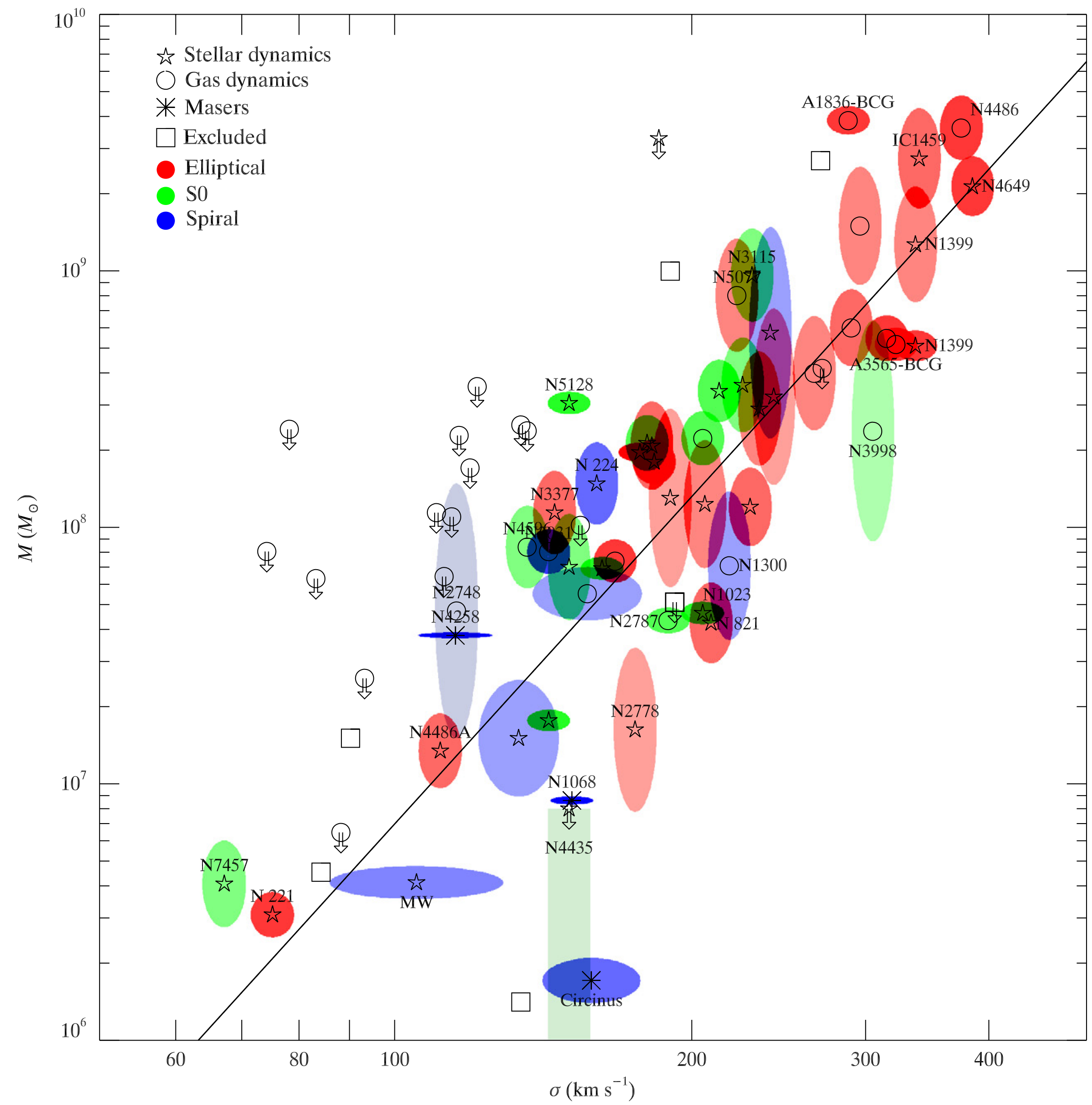
$$\boxed{\frac{M}{L} \propto L^{1/4}}$$

The more luminous Ellipticals have higher M/L

The black-hole mass/bulge-velocity relation

It is likely that every elliptical galaxy — even every spheroidal system, including bulges — has a super massive black hole (SMBH)

Moreover, there is a reasonable correlation between the mass of the SMBH and the velocity dispersion of the spheroid:



$$\log(\mathcal{M}_{\rm BH}/M_\odot) = 4.24\log(\sigma/200\,\mathrm{km\,s^{-1}}) + 8.12$$

Formation of Spiral Galaxies

See e.g. chapter 10 in Cimatti et al. book

The formation of a disk galaxy

- Gas cools in halos / filamentary structure is visible also in gas

- At high-z: starbursts/SNe drive gas out of proto-galactic mini-haloes.

- z ~ 3: Disk(s) start to appear

- The disk is harassed by many accretion events, until about z ~ 1.4
  (these events contribute cold gas and stars)

- After that disk settles and grows more quiescently with an ocassional accretion event

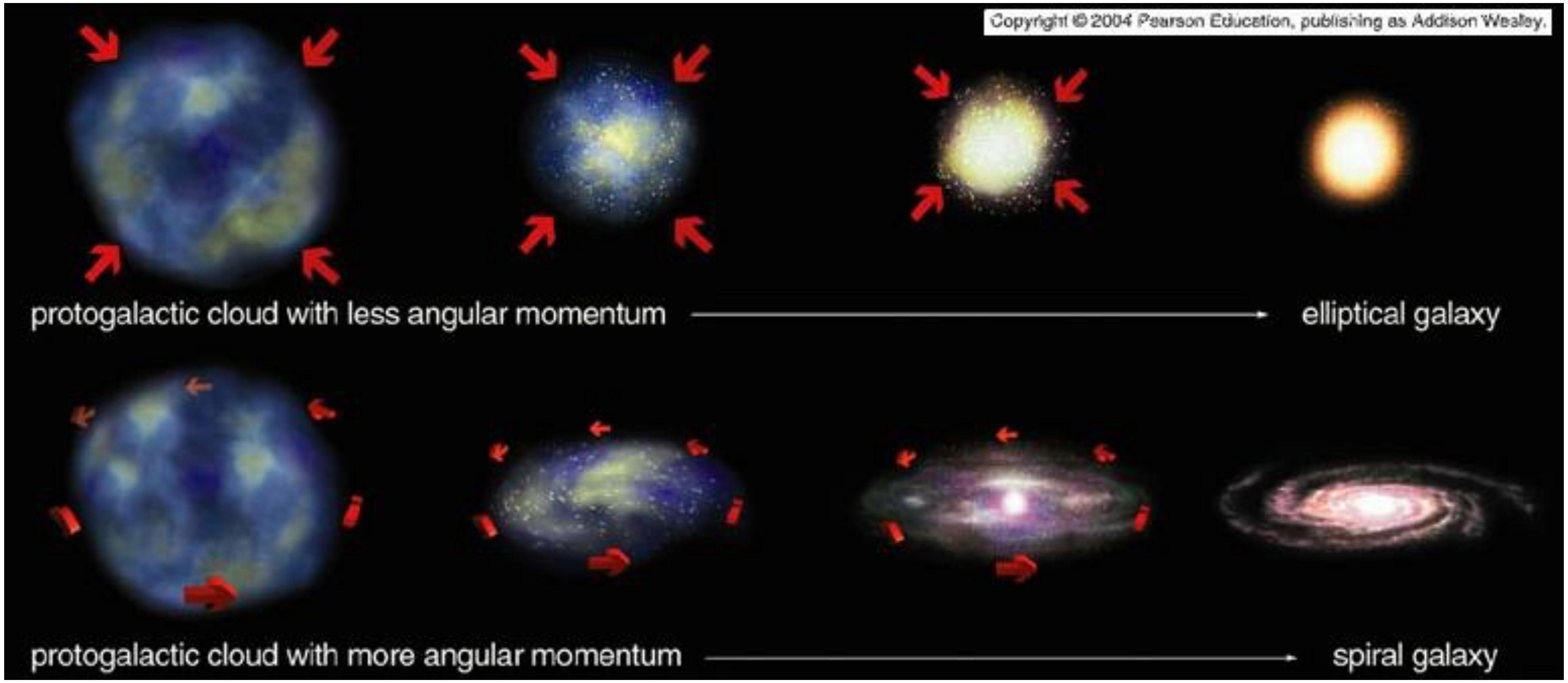
- It is at centre of a “cooling halo” which feeds the galaxy with new gas

Disc Formation

Discs are ‘rotation-supported’ (while ellipticals are ‘pressure-supported’)

Main assumption: baryons experience same gravitational field and specific torques (per unit of mass) as dark-matter haloes

Size of the formed disc is roughly proportional to its specific angular momentum



Dissipative collapse - angular momentum problem

Dark matter collapses preserving total energy

Instead, collapsing gas dissipates energy through radiation, but still preserves angular momentum -> a disc is formed

Efficient gas cooling leads to a centripetally supported disc, which rotates at characteristic circular speed v_c

The disc size $R = j_0/v_c$ is determined by the original specific angular momentum j_0

Until ten years ago, galaxy formation models struggled to reproduce the observed sizes pf galaxy discs (they were too small in comparison with reality)

global angular momentum problem

Lack of resolution made simulations to contain large gas clouds that transferred too much angular momentum to their host haloes because of dynamical friction

Why do discs have exponential light profiles?

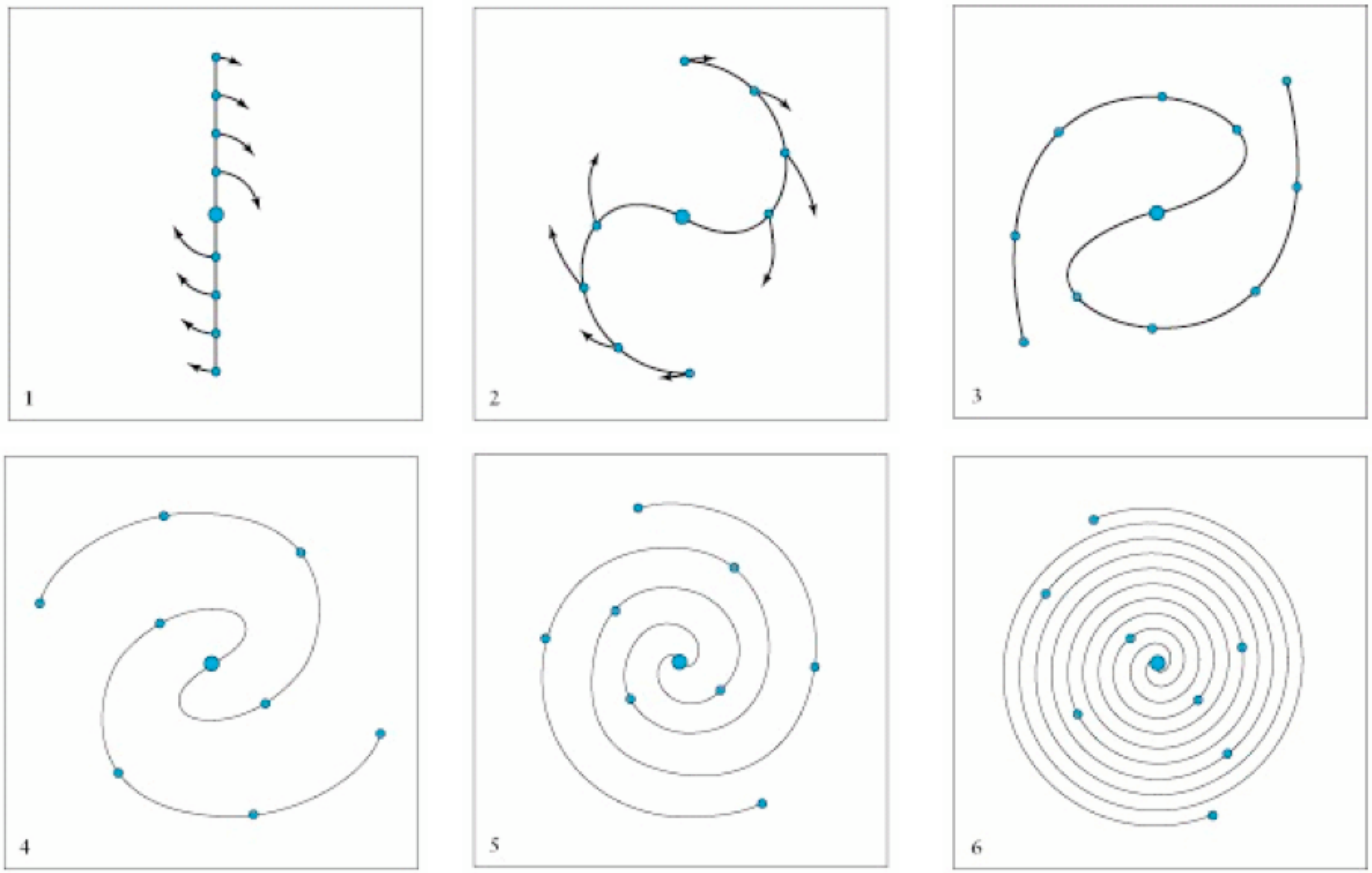
Exponential light profiles are common in discs - independent of mass

Exponential profiles are followed by both molecular and atomic gas

Galaxy models can explain the exponential profiles through a combination of efficient SF and feedback that removes low angular-momentum material from the galaxy centre, with inefficient SF in the outskirts.

Alternatively, exponential profiles can be explained through radial stellar migrations facilitated by the spiral arms

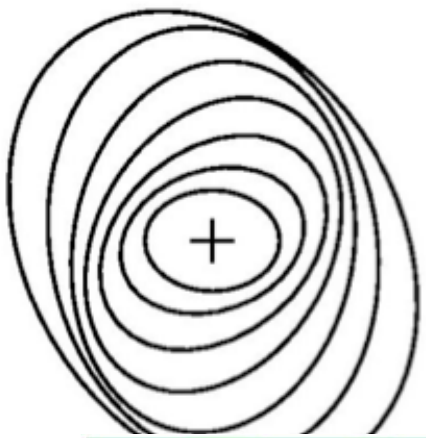
Formation of spiral arms



Density waves

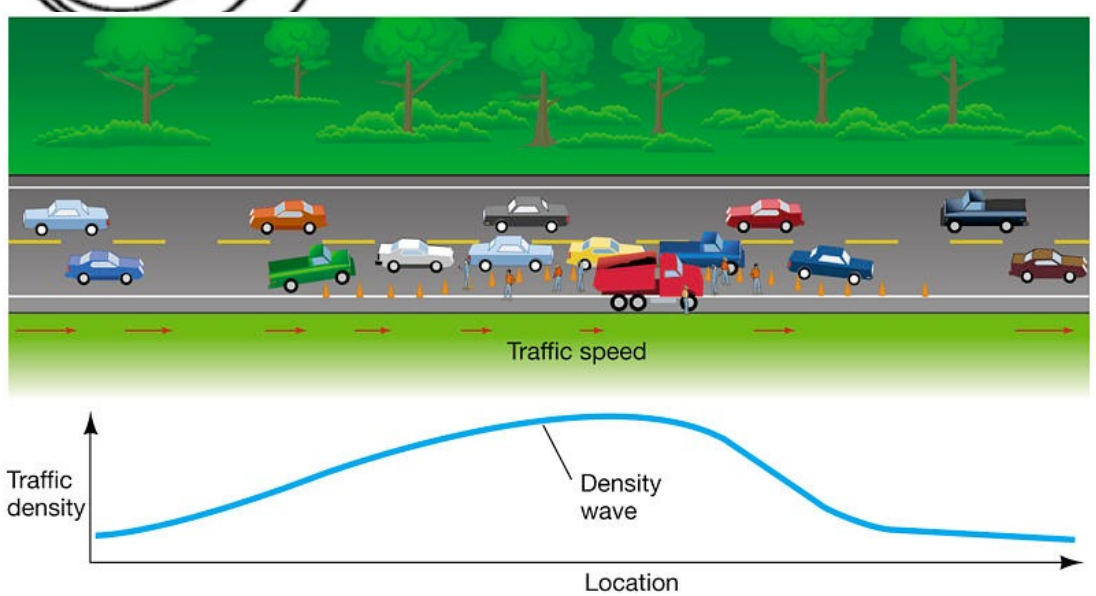
It seems likely that spiral arms are created by a density perturbation that moves along at a speed different from the objects around it. The density wave resists the spiral's tendency to wind up and causes a rigidly rotating spiral pattern. Like slow moving traffic on the highway.

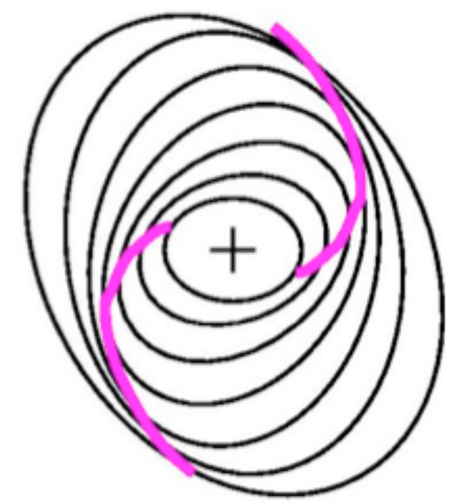
Pattern Speed - fixed angular speed of density wave rotating through galaxy.



There is an initial "seed" perturbation in the spiral disc. These come from either initial asymmetries in the disk and/or halo (galaxy formation processes), or induced via galaxy encounters.

Thus there are regions of slightly higher density than their surroundings. The higher density accelerates matter into the wave.

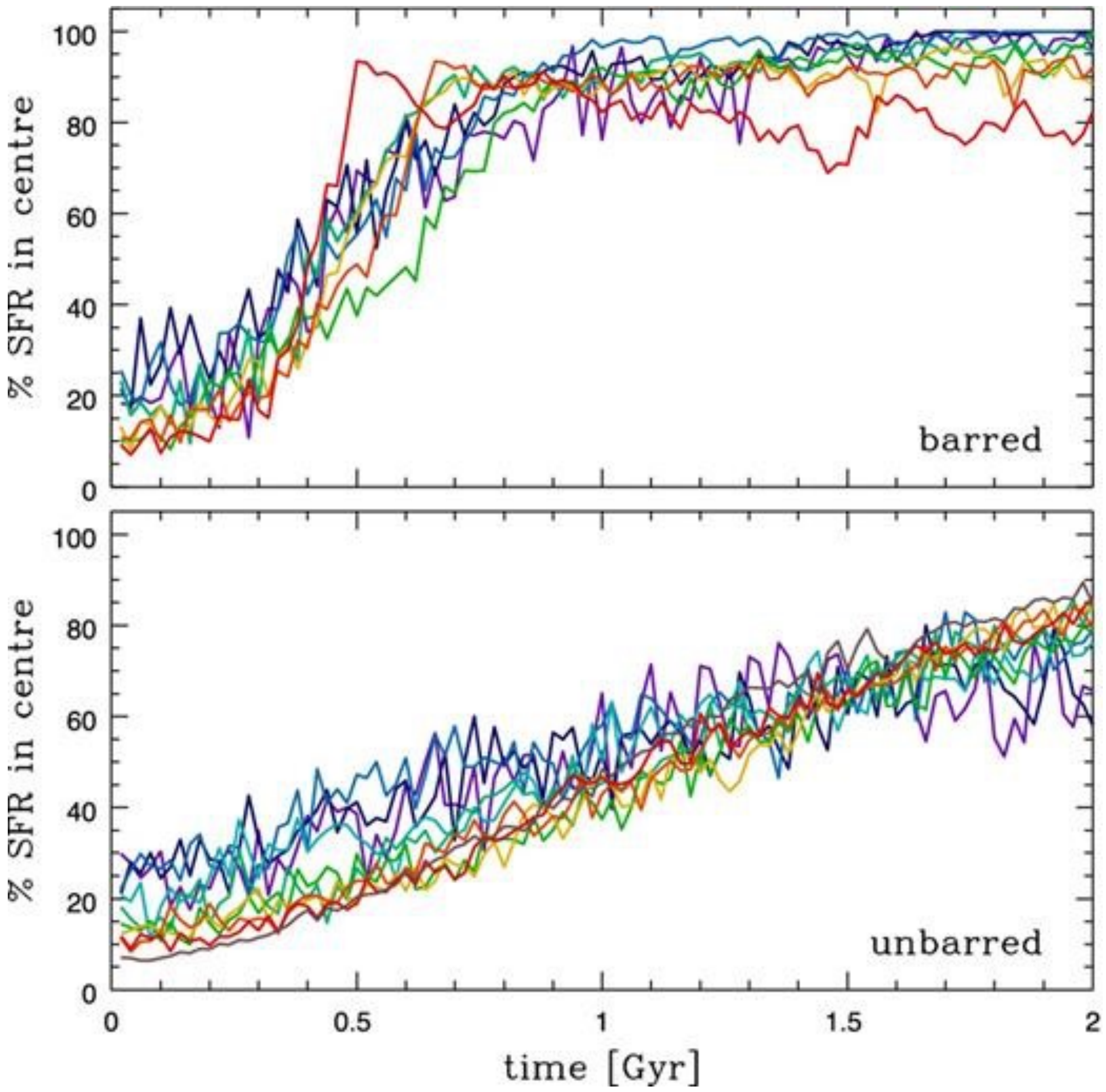




Spiral arm pattern is amplified by resonances between the epicyclic frequencies of the stars (deviations from circular orbits) and the angular frequency of the spiral pattern

Bars in Spiral Galaxies

Bars facilitate inflows of gas toward the galactic centre and often produce starbursts (especially in most massive galaxies)



Carles et al. (2016)

Formation of bars and pseudo-bulges

Bars are the product of *global* disc instabilities -
due to internal processes (like in formation of arms) or external processes (galaxy encounters)

Bar formation is relatively easy and takes only a few Gyr

Still, only ~ 60% of spirals contain bars at z=0 and fraction is lower at higher z

Massive dark matter haloes and high gas fractions in the disc tend to suppress bar formation

Bars are prone to *buckling instability:* when the thin disc suffers distortions out of the plane, bars tend to be destroyed and a **pseudo-bulge** is formed

Formation of galaxy stellar haloes

Stellar haloes are diffuse, low-density stellar components in the outskirts of spiral and ellipticals

Stellar haloes are composed of diffuse stars, globular clusters and stellar streams

Stars are typically old - likely formed before the host galaxy

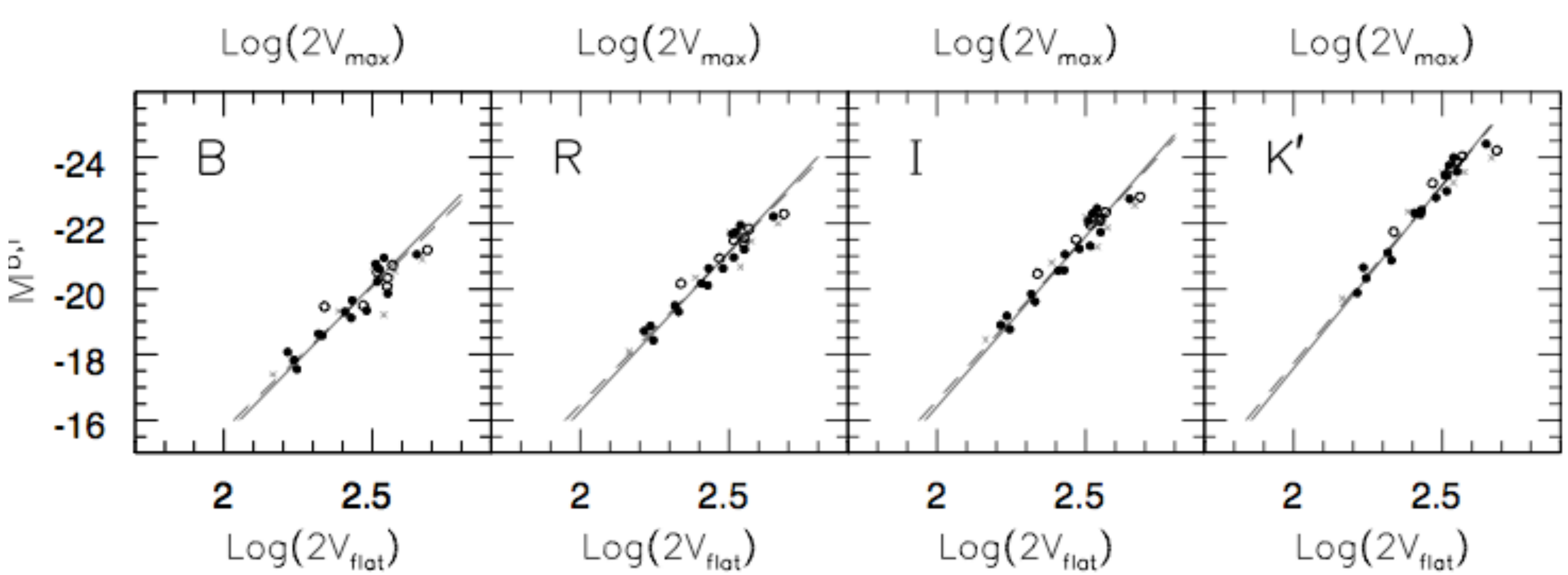
Satellite accretion likely a main process to form stellar halo

Shape of stellar streams resembles tidal streams produced in galaxy interactions

Scaling relations in late-type galaxies

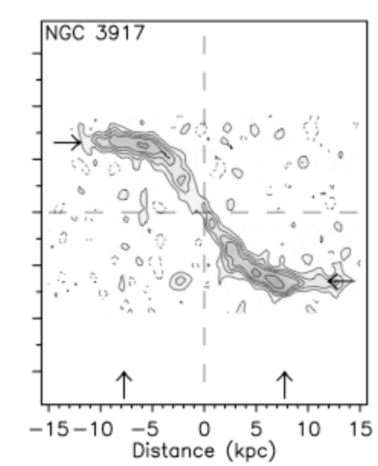
Tully-Fisher relation

A relationship exists between the luminosity of a spiral galaxy and its maximum rotation velocity.



$$L \propto V_{\max}^4$$

amplitude of flat part of HI rotation curve



More scatter in B due to stellar population effects

The exponent changes with bandpass

Link between the stellar mass (luminosity) of a disc and the mass of the Dark Matter halo.

Verheijen 2001

Tully & Fisher 1977

The Tully-Fisher relation - physical arguments

More luminous galaxies rotate faster

How does this come about?

Circular velocity and mass are related through $v^2 = \frac{GM}{r} \longrightarrow M \propto rv^2$

The flux and luminosity are related $I = \frac{L}{4\pi r^2} \longrightarrow r \propto \left(\frac{L}{I}\right)^{1/2}$

Assuming that M/L is constant $M = L \times \left(\frac{M}{L}\right) \propto rv^2 \propto \left(\frac{L}{I}\right)^{1/2} v^2$

$$L^{1/2}\left(\frac{M}{L}\right) \propto I^{-1/2}v^2 \longrightarrow L \propto v^4 \left(\frac{M}{L}\right)^{-2} I^{-1}$$

Assuming that M/L and I are constant $\boxed{L \propto v^4}$

Stars & Dark Matter are linked…

Formation of disks in galaxy simulations

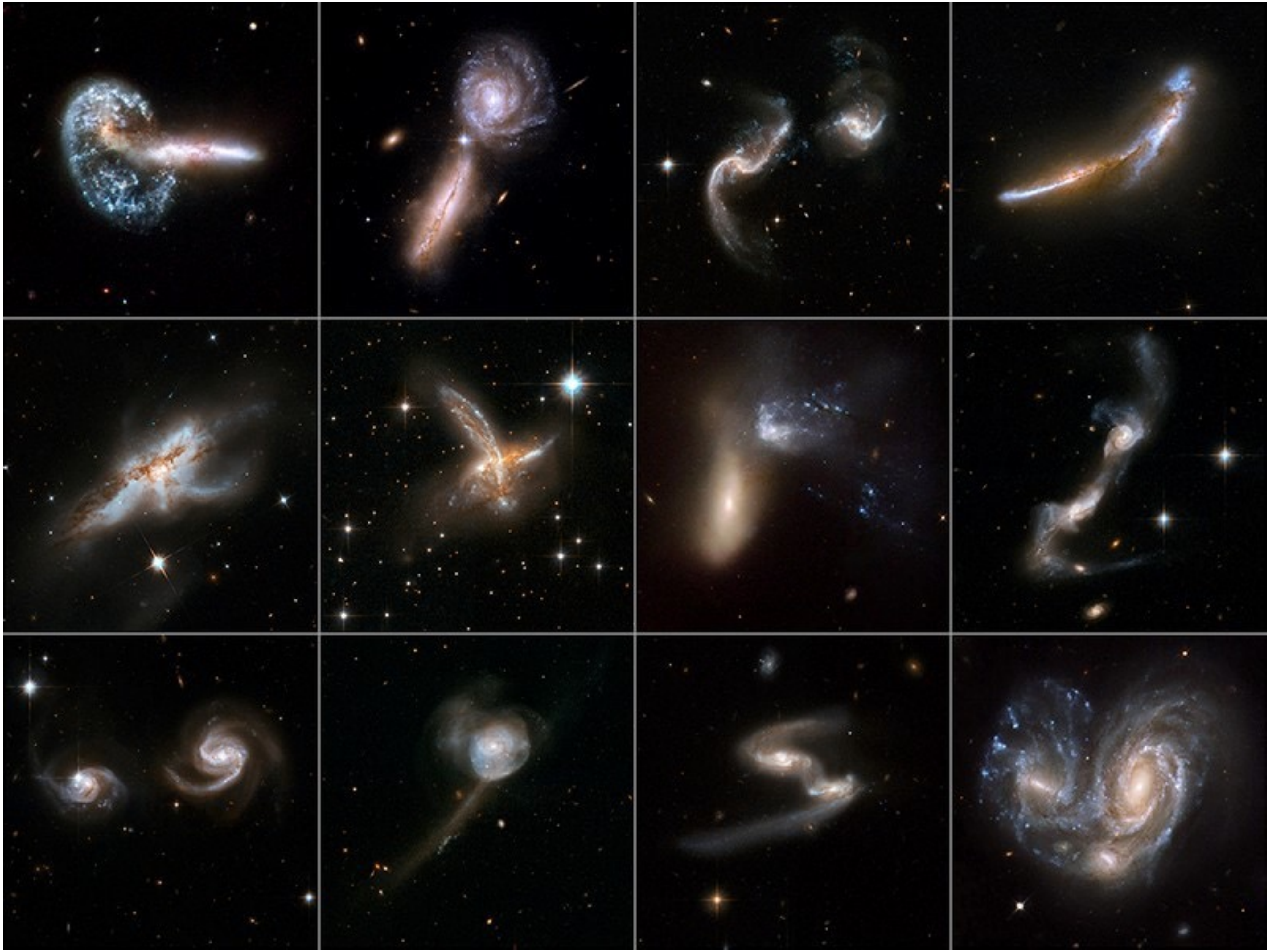
https://www.youtube.com/watch?v=O674AZ_UKZk

Galaxy mergers

Credit: ESA/Hubble & NASA, A. Adamo et al.

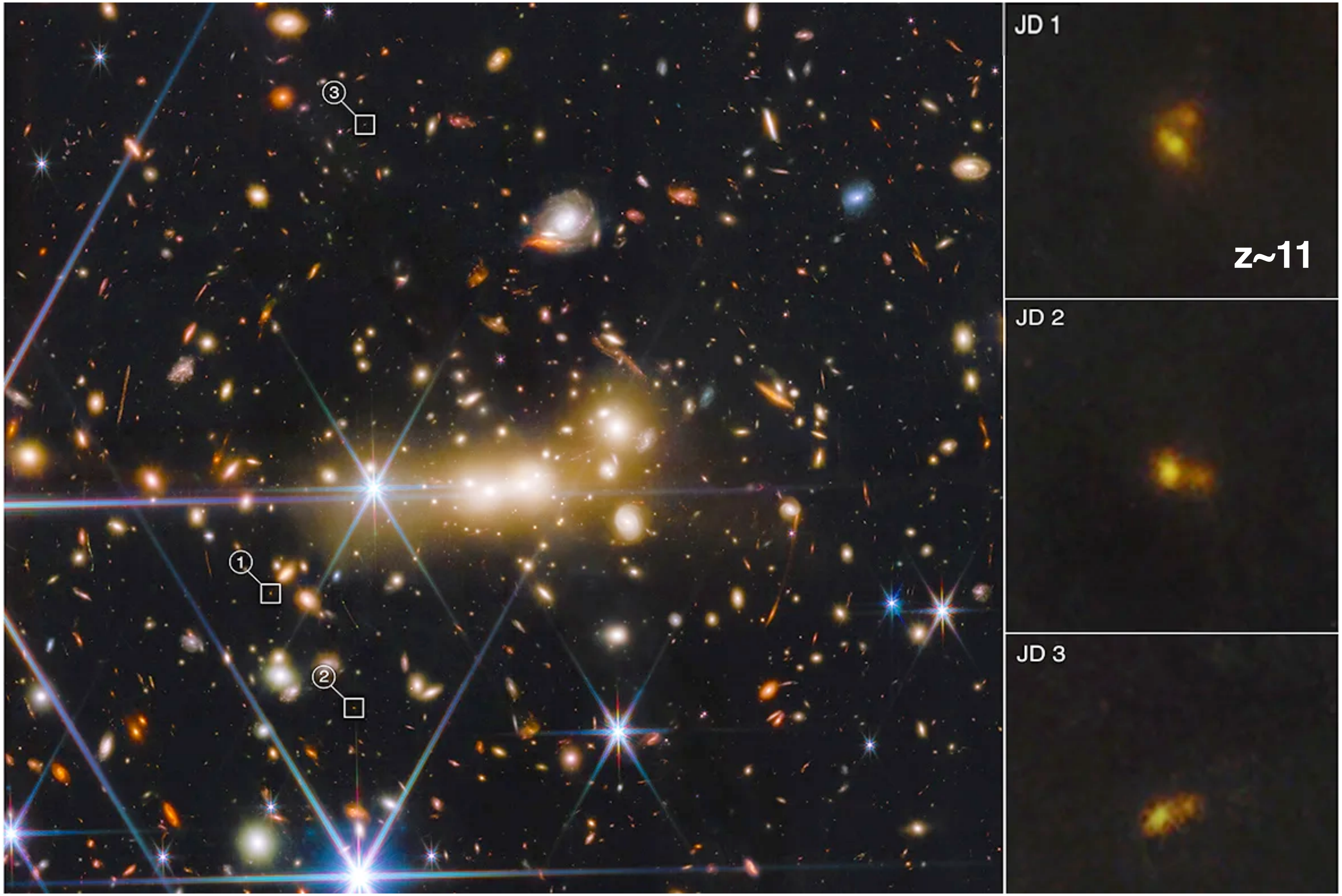
https://www.esa.int/ESA_Multimedia/Images/2021/01/Hubble_showcases_6_galaxy_mergers

Galaxy mergers (more examples)



Credit: ESA/Hubble & NASA, C. Conselice et al.

Galaxy mergers in the very early Universe



Credit: NASA/ESA/CSA/Dan Coe (STScI)/Rebecca Larson (UT Austin)/Yu-Yang Hsiao (JHU)