galaxy formation theory

lecture 4

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outline of the course

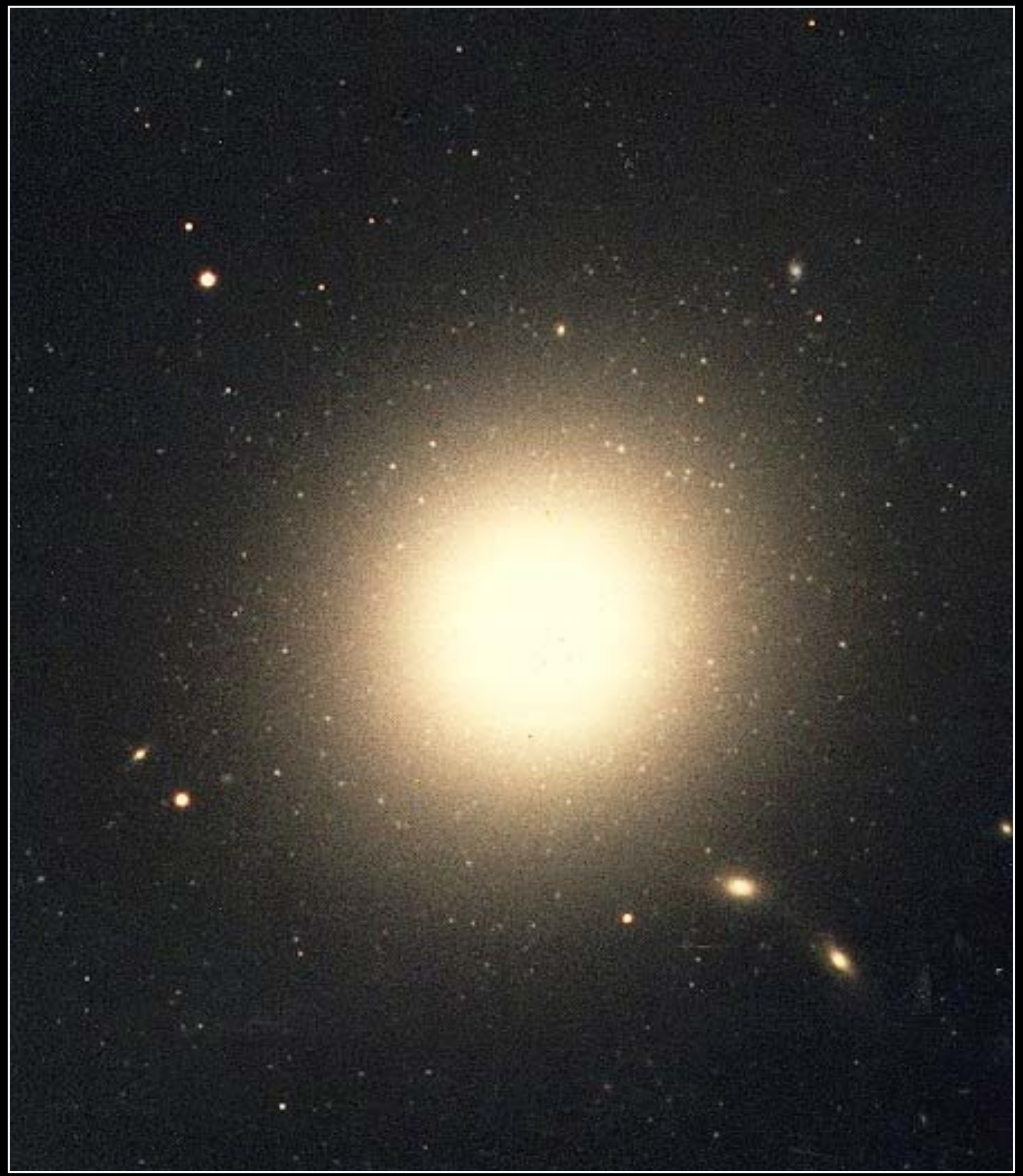
- a brief review of the observational background
- assembly of dark matter haloes
- gas cooling
- angular momentum
- star formation
- feedback
- galaxy mergers & morphology
- evolution of supermassive black holes

7. galaxy mergers & morphology

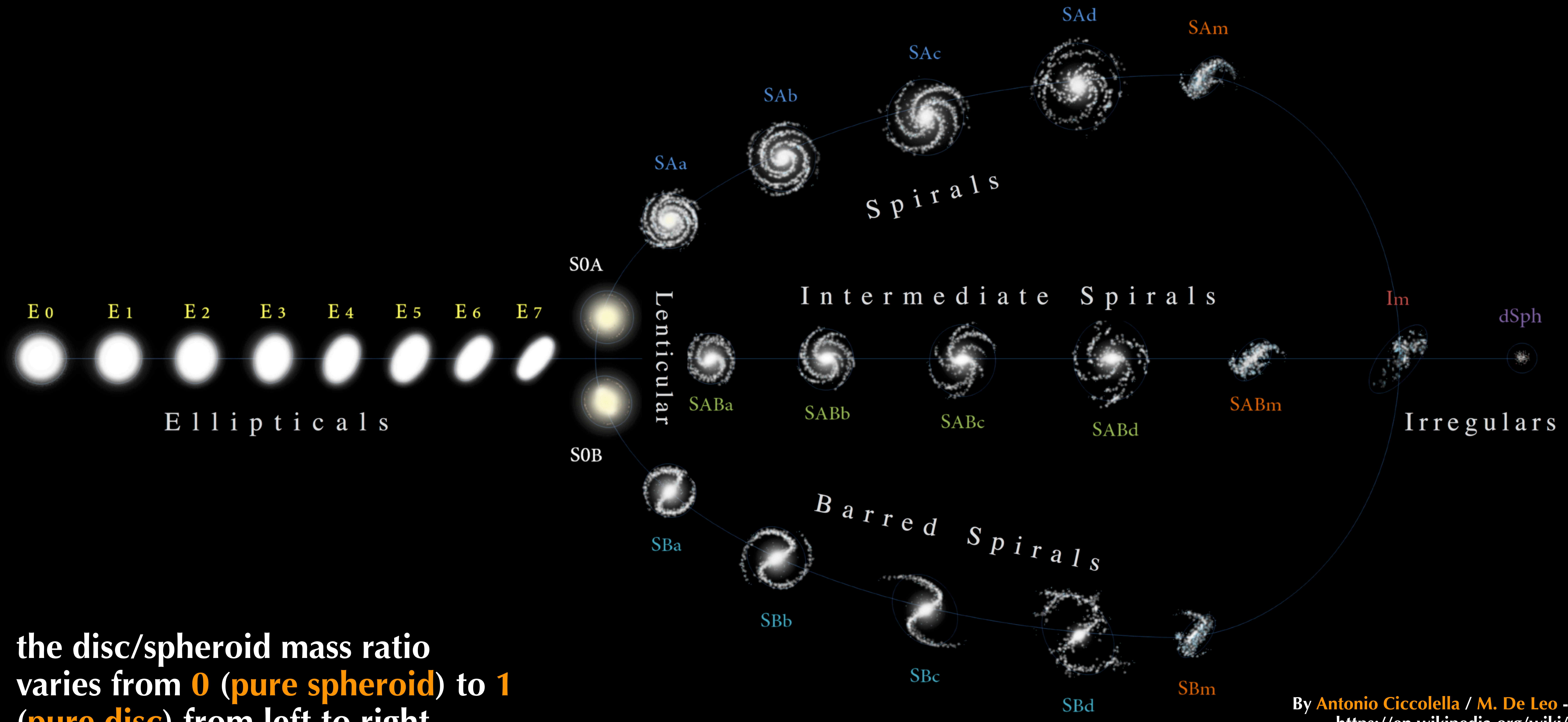
a broad **classification** of galaxy morphologies

discs

spheroids



HUBBLE-DE VAUCOULEURS DIAGRAM



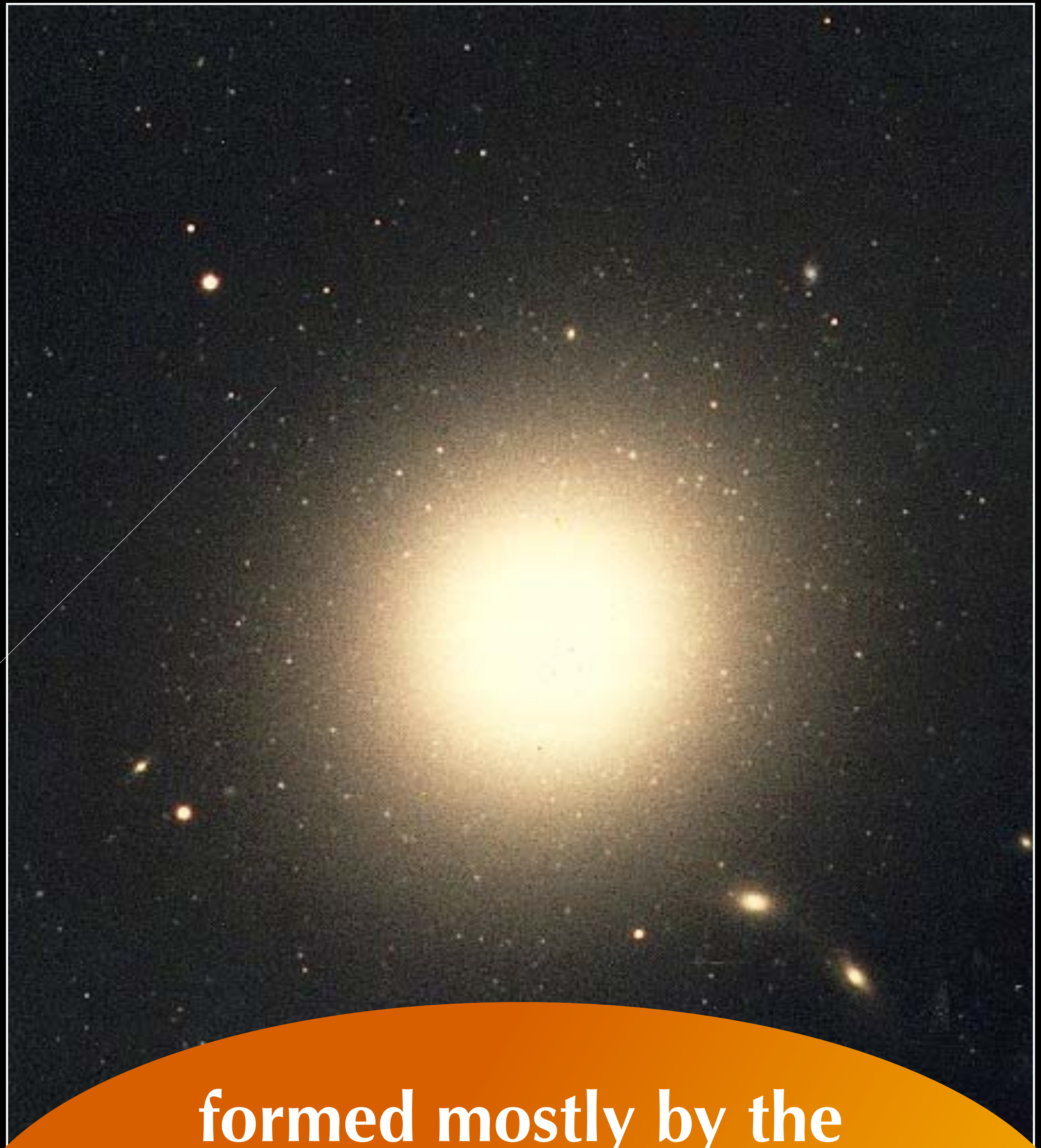
the disc/spheroid mass ratio varies from 0 (pure spheroid) to 1 (pure disc) from left to right

a broad classification of galaxy morphologies

discs

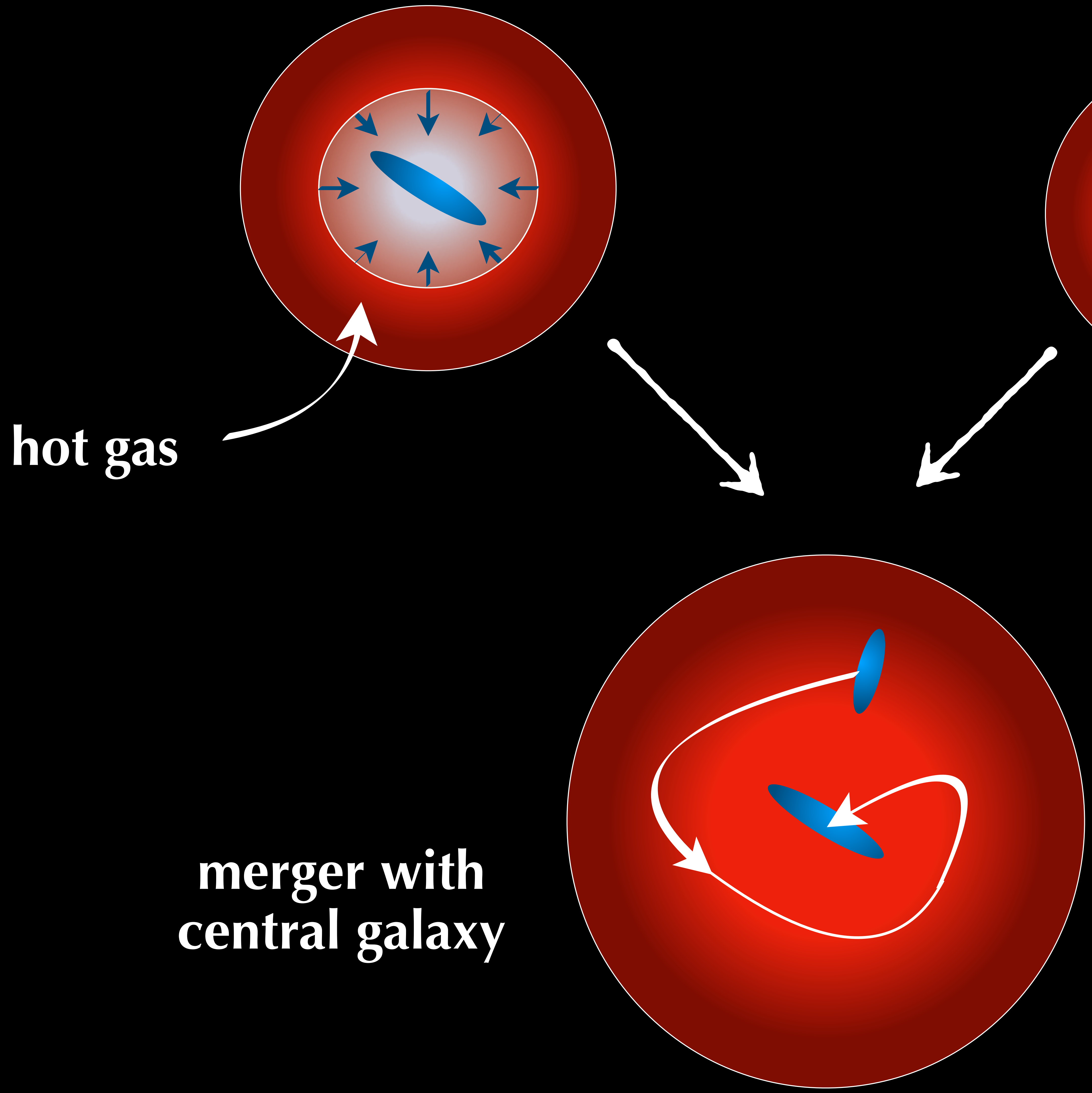
formed by the collapse of gas with angular momentum in DM haloes, following radiative cooling (lecture 2)

spheroids



formed mostly by the mergers of galaxy discs; some form by dynamical instabilities in galaxy discs

how do galaxy mergers happen?

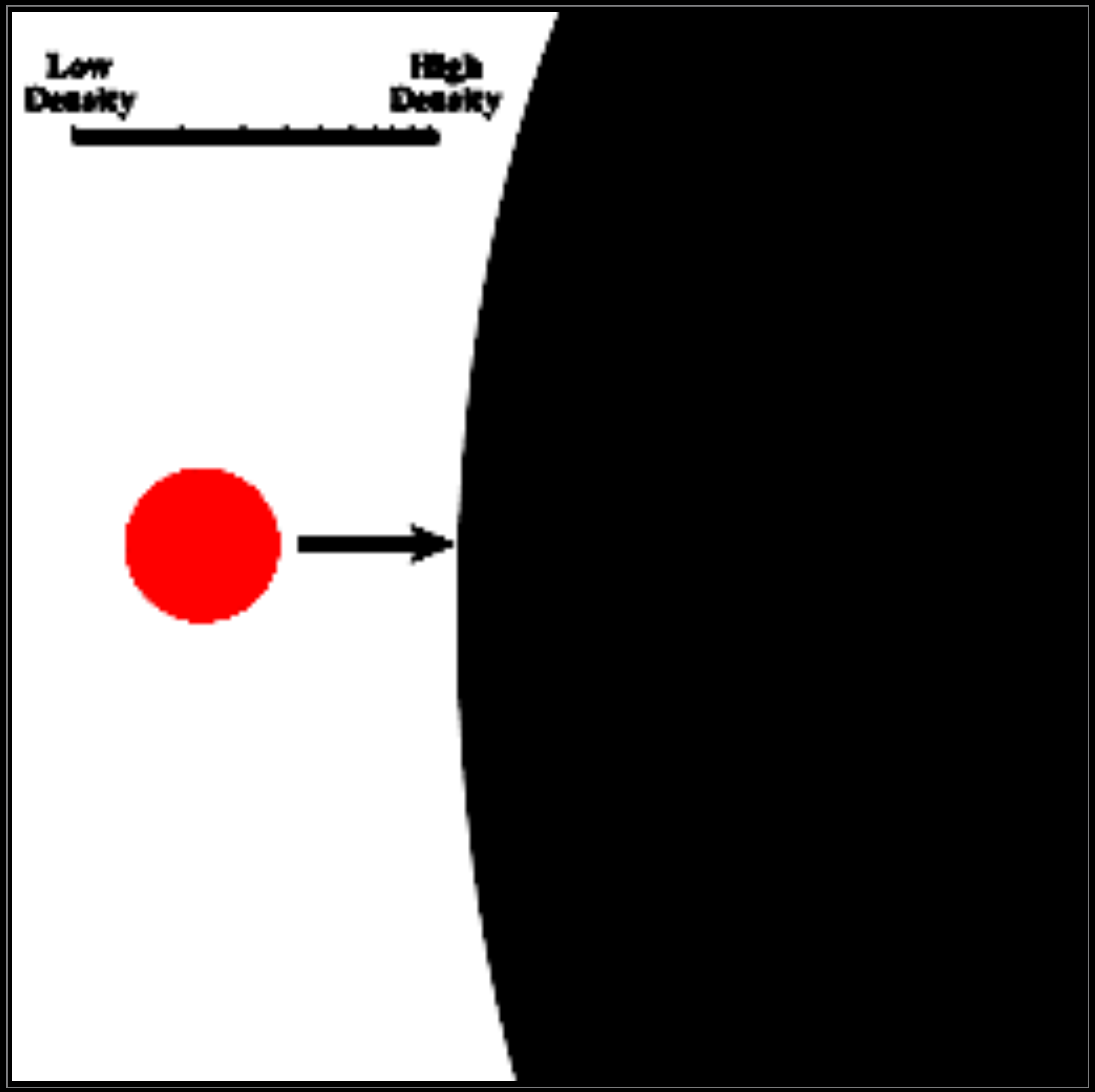


discs form in
progenitor haloes

satellite galaxy
orbit decays by
dynamical friction

galaxy mergers are a
natural outcome of
hierarchical models of
structure formation.
mergers between galaxies
take place within a
common halo, following
halo mergers

dynamical **friction**



credit: https://astronomy.swin.edu.au/cosmos/*/Dynamical+Friction

a massive body of **mass**, M, moving at **speed**, v, through a **background** of lighter particles of **density**, ρ, and **velocity dispersion**, σ, experiences a purely **gravitational** drag force due to a wake that is formed behind the moving body

$$\mathbf{F}_{df} = M\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{4\pi G^2 M^2 \rho \ln \Lambda}{v^3}\left[\operatorname{erf}(X) - \frac{2X}{\sqrt{\pi}}e^{-X^2}\right]\mathbf{v}$$

$$X = \frac{v}{\sqrt{2}\sigma}$$

Chandrasekhar (1943)

$X \sim 1$ for a body on a bound orbit in a system in dynamical equilibrium

galaxy merger timescale in a DM halo

a galaxy orbiting in a dark matter halo feels dynamical friction against the halo, which causes its orbit to shrink. over time, the satellite shrinks to the centre

for an object on a circular orbit with radius r, orbiting inside a halo with an isothermal density profile $\rho = \dfrac{V_c^2}{4\pi G r^2}$

$$\frac{\mathrm{d}r}{\mathrm{d}t} = -\frac{0.43 \ln\Lambda}{r}\frac{GM_{\rm sat}}{V_c}$$

$t_{\rm orb} = r_i / V_c$

so, a satellite galaxy sinks from $r = r_i$ to $r = 0$ over a timescale:

$$\cancel{t_{\rm fric} = \frac{1.17}{\ln\Lambda}\frac{r_i^2 V_c}{GM_{\rm sat}}} = \frac{1.17}{\ln\Lambda}\frac{M_{\rm halo}\left(< r_i\right)}{M_{\rm sat}}\, t_{\rm orb}$$

$t_{\rm fric}/t_{\rm orb} \sim 1$ for $M_{\rm sat}/M_{\rm halo} \sim 1$

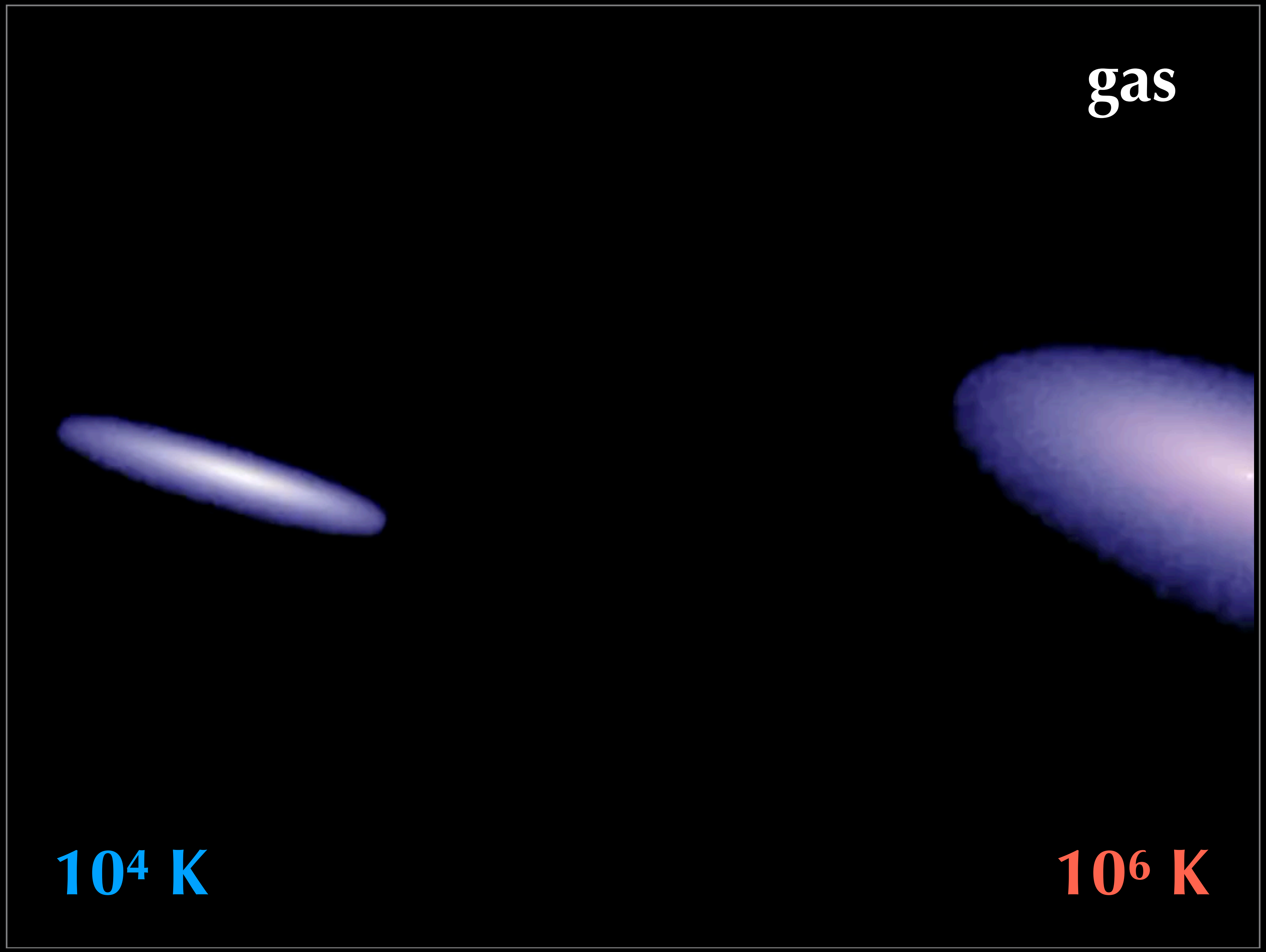
$t_{\rm fric}/t_{\rm orb} \gg 1$ for $M_{\rm sat}/M_{\rm halo} \ll 1$

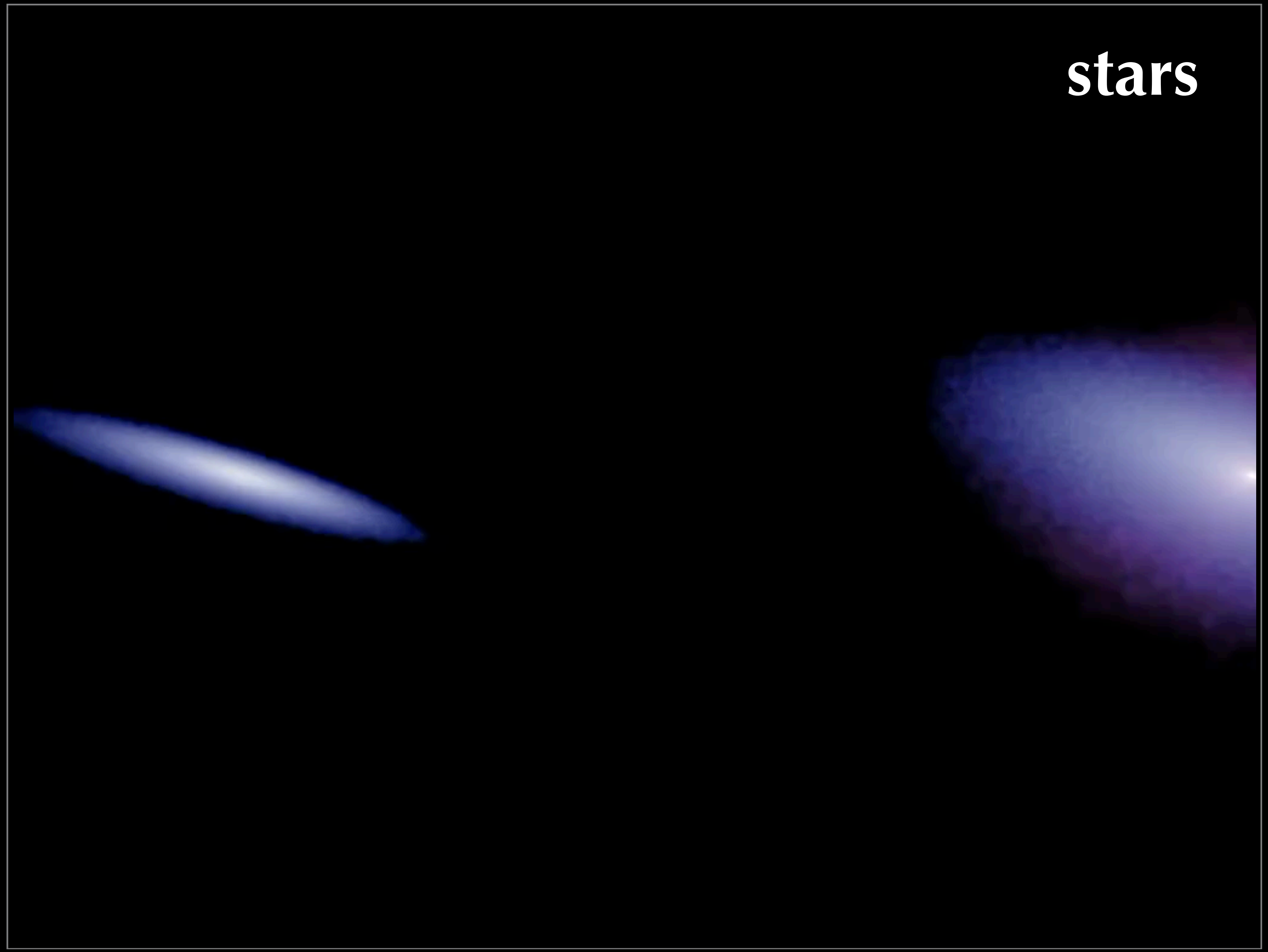
$\ln\Lambda \sim \ln\left(1 + M_{\rm halo}/M_{\rm sat}\right)$

i.e. merger timescales long/short for small/large satellites

the merger of two spiral galaxies

credit: Volker Springel





mergers cause much of the gas to shrink to the centre of the final galaxy (energy dissipation), triggering rapid star formation ⇒ starbursts

galaxy mergers in the real Universe

credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University), K. Noll (STScI), and J. Westphal (Caltech)

minor mergers

credit: Phil Hopkins

during **major** mergers ($M_1 \sim M_2$), discs are completely disrupted, producing a stellar spheroid

during **minor** mergers ($M_2 \ll M_1$), the small satellite galaxy falling into the stellar disc does not destroy it, but makes it thicker

rough dividing line:
$M_2/M_1 \sim 1/3$

credit: P.-A. Duc (CEA), J.-C. Cuillandre (CFHT) et al. 2013, IAUS, 295, 358

QSO MC2 1635+119
Hubble Space Telescope • ACS/WFC

NASA, ESA, and G. Canalizo (University of California, Riverside)

STScI-PRC07-39

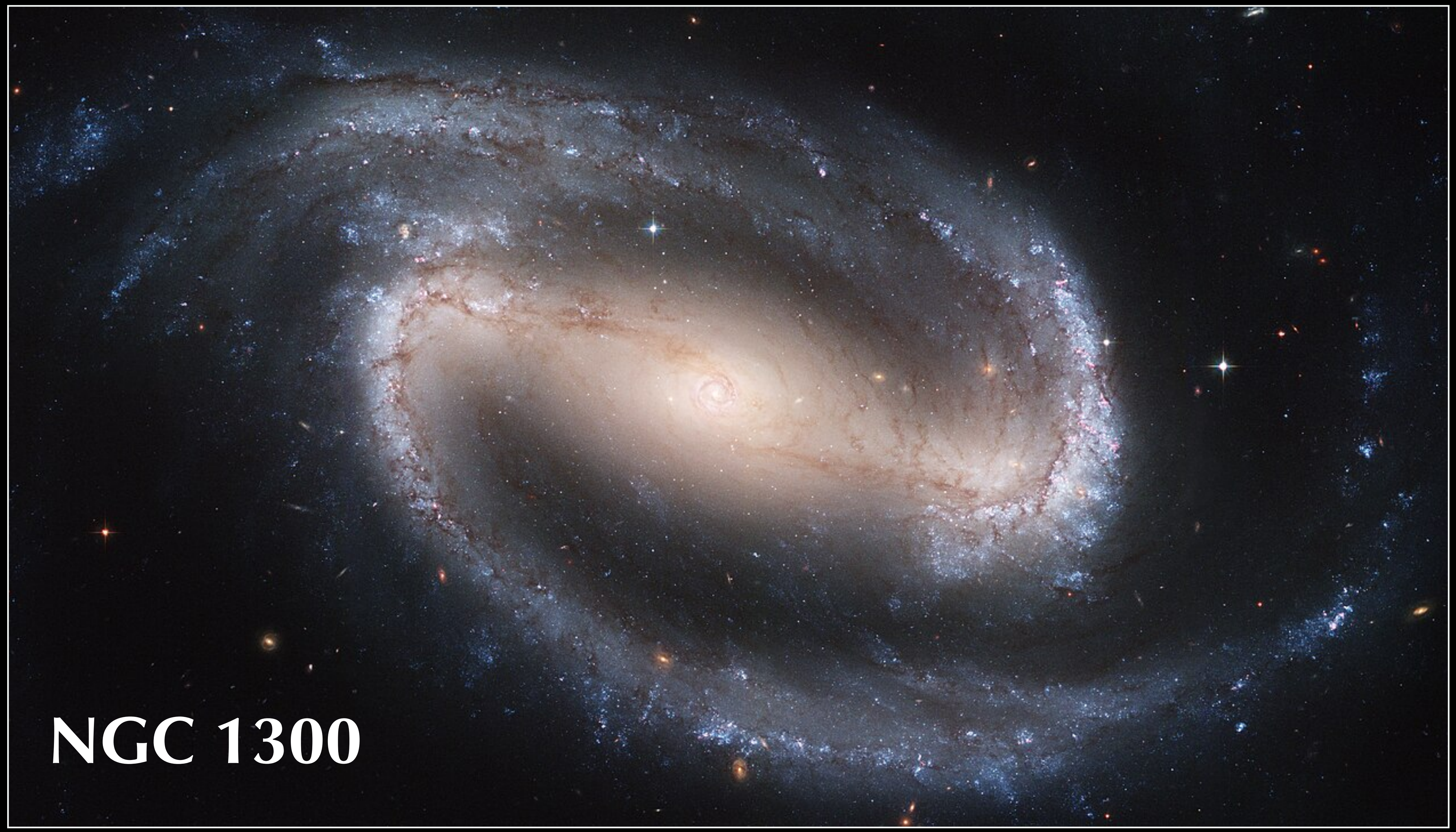
bonus: secular (internally-driven) dynamical evolution

(see Francesca's course on Secular Evolution for an in-depth exploration of this topic)

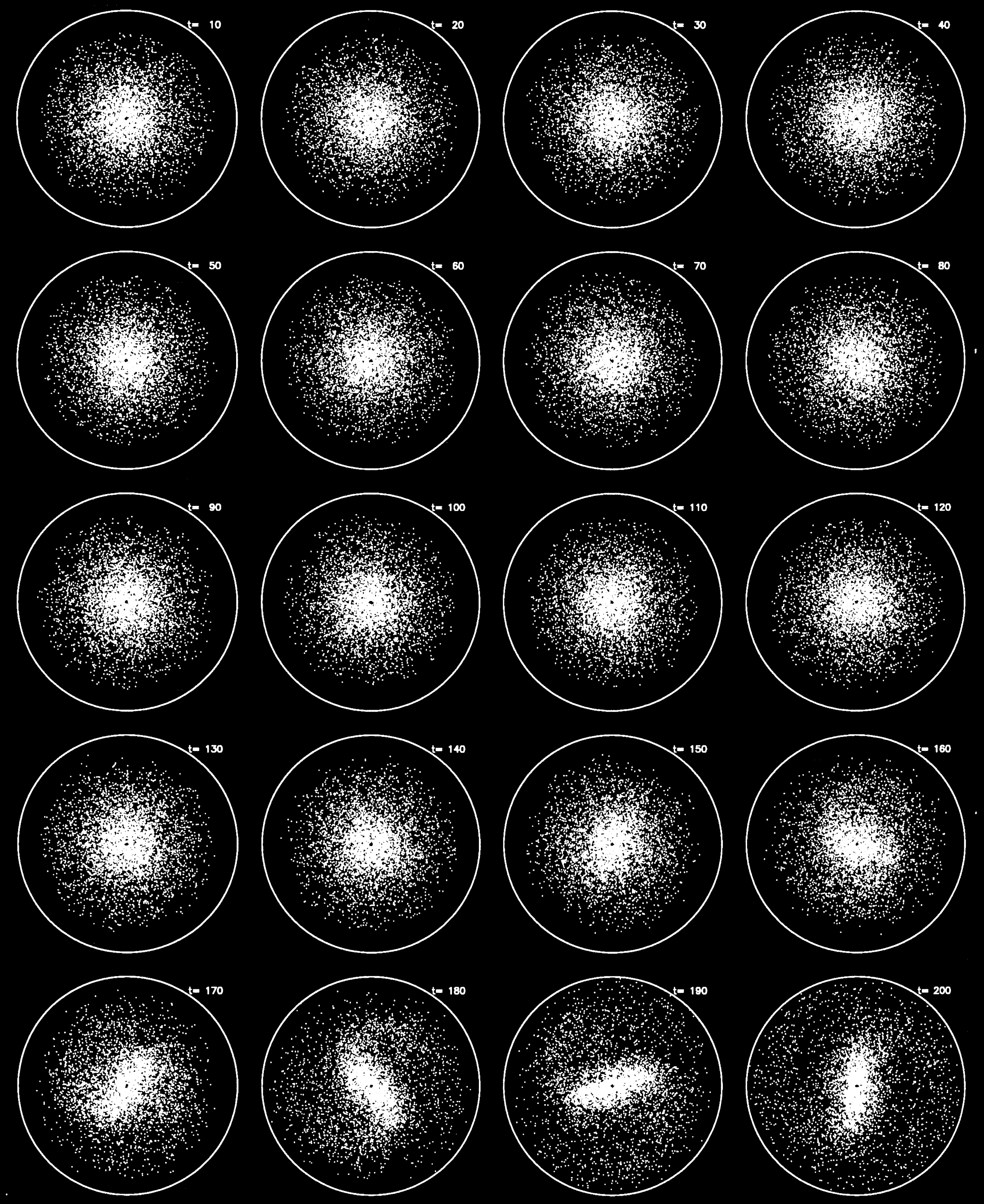
spiral and bar structures in galaxies

spirals

barred spiral



dynamical instabilities in stellar discs – spirals & bars



the stellar discs of galaxies are unstable to various dynamical instabilities if the velocity dispersion of the stars is too low:

— spiral structure (milder)

— bar instability (stronger)

Sellwood & Carlberg (1984)

Sellwood (1993)

gravitational stability of a rotating disc

the local stability of a thin, rotating gas disc with surface density, $\Sigma_{\rm gas}$, and velocity dispersion, $\sigma_{\rm gas}$, depends on the following ratio (Toomre 1964):

essentially balancing the competing effects of gravity, gas pressure, and rotation

$$\boxed{Q = \frac{\kappa\,\sigma_{\rm gas}}{\pi G \Sigma_{\rm gas}}}$$

$$\kappa = \left(R\frac{\mathrm{d}\Omega^2}{\mathrm{d}R} + 4\Omega^2 \right)^{1/2}$$

"epicyclic" frequency

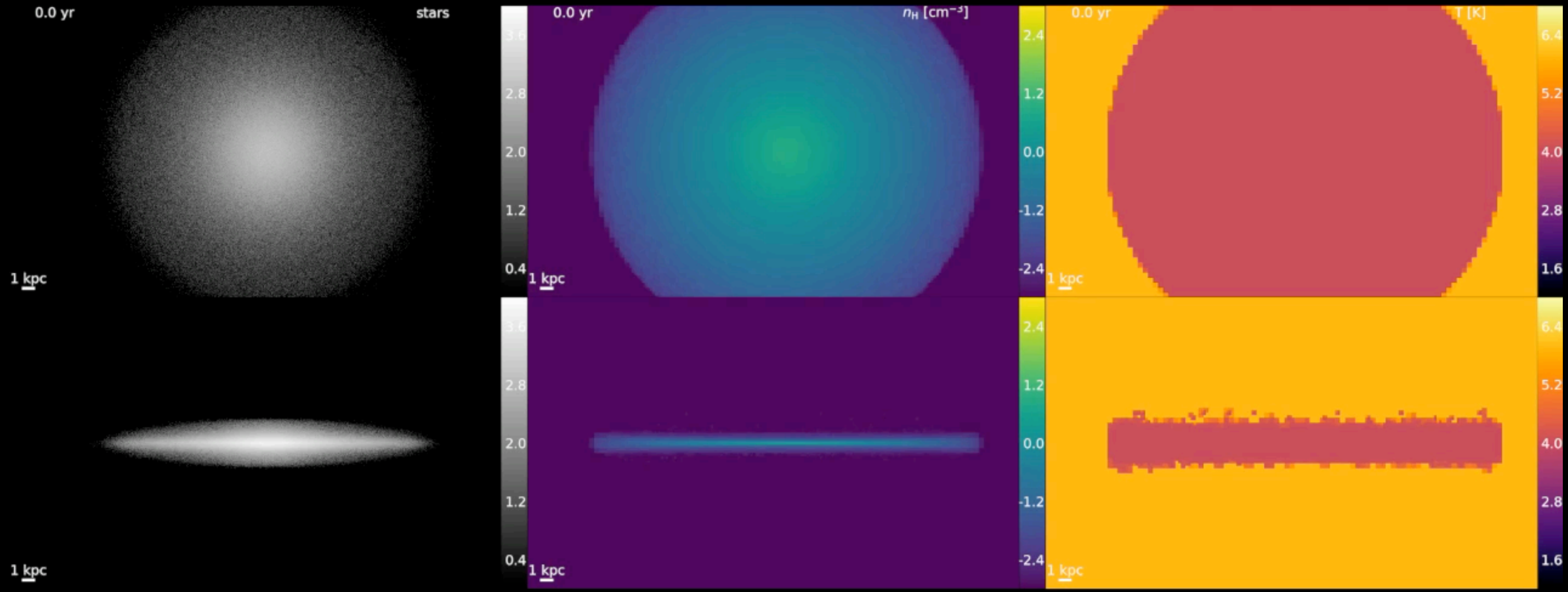
$Q < 1 \Rightarrow$ locally unstable

$Q > 1 \Rightarrow$ locally stable for axisymmetric perturbations

similar result for stellar discs:

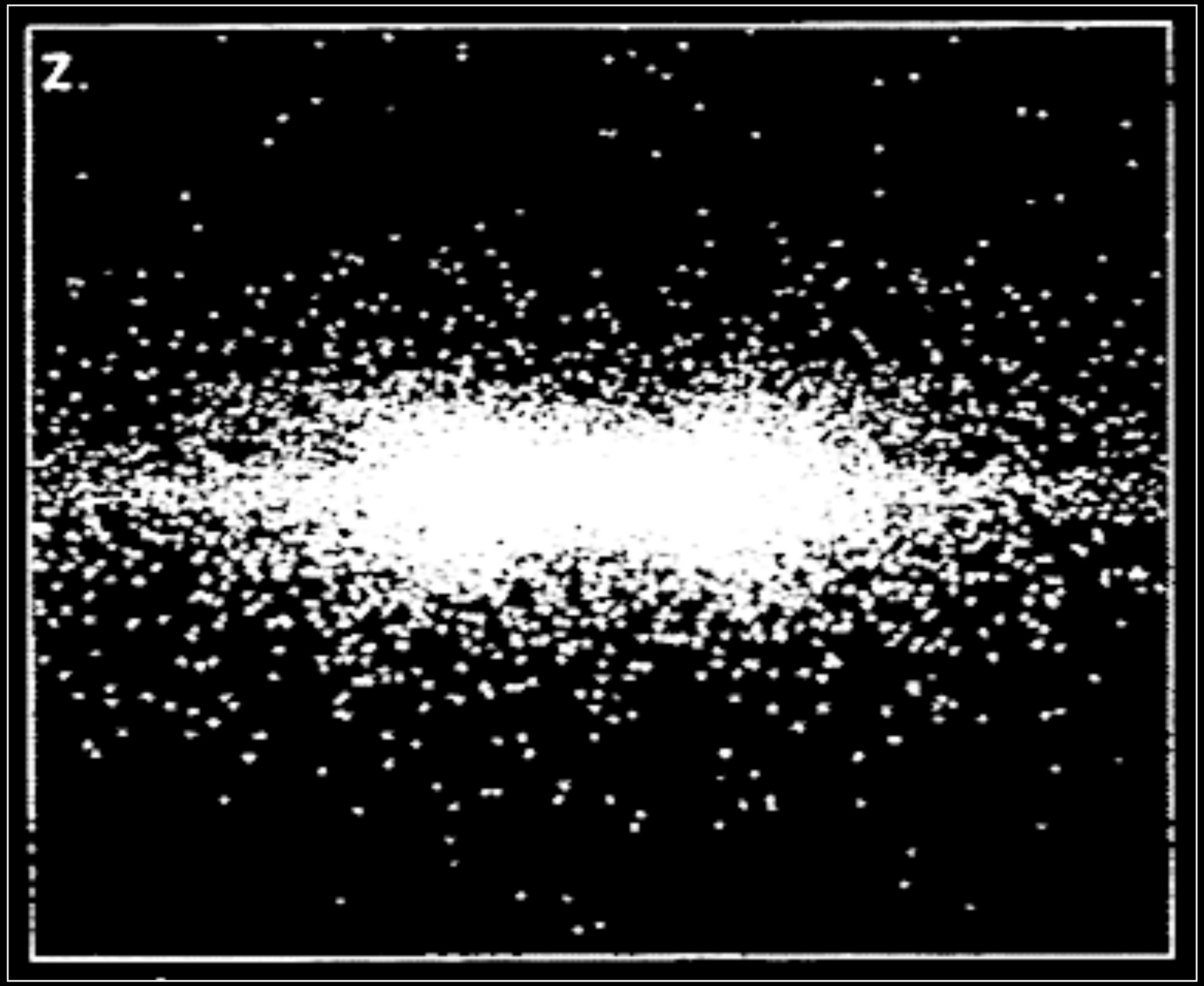
$$Q = \frac{\kappa\,\sigma_\star}{3.36\, G \Sigma_\star}$$

in practice, $Q > 2 - 3$ seems to be needed in order to be stable against the formation of spiral structure and bars credit: Francesca Fragkoudi



the bar drives gas to the galaxy centre ⇒ this results in a starburst and feeds the central black hole

vertical instabilities of bars



Combes & Sanders (1981)

buckling instabilities cause bars to thicken in the vertical direction , forming a pseudo-bulge

so, there are at least two pathways for forming spheroids/bulges: galaxy mergers & bar instabilities