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GALAXY FORMATION AND EVOLUTION

PAP 318, 5 op, autumn 2022
B119, Exactum

Lecture 9: Star formation and supernova feedback in galaxies

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On this lecture we will discuss

1. Star formation in molecular clouds.
2. The formation and stability of giant molecular clouds.
3. The self-regulation of star formation in galaxies.
4. Thermal and gravitational instabilities.
5. Empirical laws of star formation. Global and local relations.
6. Supernova feedback in galaxies. Ejection and heating of gas by supernovae.

The lecture notes correspond to:

- MBW: pages 393-397 (§8.5)
- MBW: pages 417-448 (§9.1-9.7)

9.1 Giant molecular clouds (GMCs)

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- Stars form in GMCs with n_{H2}~100-500 cm^{-3} (ϱ~10^{-22} gcm^{-3}, M~10^5-10^6 $M_\odot$), sizes of tens of parsecs and T~10 K.

- ***Molecular*** clouds rotate due to the differential rotation of the disk in which they form. During the collapse, a large fraction of the angular momentum must be transferred out to explain the relatively slow rotation periods of stars. In addition, the potential energy ($E_{pot} \propto -GM^2/r$) of the collapse must be released. E.g. for the Sun that'll correspond to 3×10^7 yr at $L_\odot$. So energy must also be radiated away.

- Stars have densities of ϱ~1 gcm^{-3} and sizes of 10^{-7} pc -> star formation involves a density increase of 22 orders of magnitude and a large temperature increase.

- The structure of GMCs is ***extremely clumpy*** and within the GMC we have high density clumps (n~10^2-10^4 cm^{-3}, M~10^2-10^4 $M_\odot$) with very dense cores (n>10^5 cm^{-3}, M~0.1-10 $M_\odot$), where star formation ultimately takes place.

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9.1.1 Star formation in GMCs

- **Observations suggest that GMCs are strongly correlated with young massive stars ($t<10^7$ yr) rather than with older stars. Hence, GMCs' lifetime is of the order of 10^7 yr.**

- **In the absence of pressure, a GMC will collapse on a free-fall time**

$$\tau_{\rm ff} = \left(\frac{3\pi}{32G\bar{\rho}}\right)^{1/2} \simeq 3.6\times10^6\,{\rm yr}\left(\frac{n_{\rm H_2}}{100\,{\rm cm}^{-3}}\right)^{-1/2}$$

- **Which is shorter than its lifetime, thus there must be some support against gravitational collapse.**

- **This raises an interesting question: how do GMCs collapse to form stars?**

- **In order to understand star formation, we need to understand GMCs.**

9.2 Models of GMCs

- **As a first step, it is useful to define a star formation efficiency parameter as $\varepsilon_{SF}=t_{ff}/t_{SF}$, where the star formation timescale $t_{SF}=M_{GMC}/SFR$.**

- **Observations indicate that $\varepsilon_{SF}=0.002$. But, why is star formation in GMCs so inefficient? In other words, why is the star formation scale 3 orders of magnitude larger than the free-fall timescale?**

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9.2.1 Dynamics of GMCs

- **For a sphere of uniform density, the virial theorem (assuming virial equilibrium and zero external pressure) can be written as**

$$2K + W = 0, \quad K = \frac{3}{2} N k_b T = \frac{3}{2} M c_S^2, \quad W = -\frac{3}{5} \frac{G M^2}{r_{\rm cl}}$$

- **From which we can derive a collapse condition (Jeans mass)**

$$M > M_J = \left(\frac{5 c_s^2}{G} \right)^{3/2} \left(\frac{3}{4 \pi \bar{\rho}} \right)^{1/2} \simeq 40 M_\odot \left(\frac{c_s}{0.2 \ {\rm km/s}} \right)^3 \left(\frac{n_{H_2}}{100 \ {\rm cm}^{-3}} \right)^{-1/2}$$

- **A decrease in temperature (i.e. the sound-speed) and/or an increase in density, causes a decrease in the Jeans mass, resulting in fragmentation of the cloud into smaller clumps.**

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9.2.2 Dynamics of GMCs

- **For a more realistic case, we can use an isothermal sphere in pressure equilibrium with its surroundings and derive the Bonnor-Ebert mass**

$$M_{\mathrm{BE}} = 1.182 \frac{c_s^3}{(G^3 \rho)^{1/2}} = 1.182 \frac{c_s^4}{(G^3 P_{\mathrm{th}})^{1/2}}$$

- **which more accurately describes GMCs.**
- **For clouds with**

$$M_{\mathrm{GMC}} \gg M_{\mathrm{J}} \sim M_{\mathrm{BE}}$$

- **thermal pressure is not enough to stop them from collapsing. So additional mechanisms must be affects GMCs.**

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9.2.3 Magnetic fields in GMCs

- A prime source for non-thermal pressure in GMCs is magnetic fields, which have assumed to be the critical stabilising force in classical star formation models. Equating the potential energy of a cloud with its magnetic energy yields

$$M_\Phi \equiv \frac{5^{3/2}}{48\pi^2}\frac{B^3}{G^{3/2}\rho^2} \simeq 1.6\times 10^5\,\mathrm{M}_\odot \left(\frac{n_{\mathrm{H}_2}}{100\,\mathrm{cm}^{-3}}\right)^{-2}\left(\frac{B}{30\mu\mathrm{G}}\right)^3$$

- which provides us with an additional collapsing criterion. If $M>M_\Phi$ the magnetic field cannot prevent the gravitational collapse, and the cloud is magnetically super-critical. If $M<M_\Phi$ the cloud is prevented from collapsing by magnetic forces and the cloud is magnetically sub-critical.

- To be stable (sub-critical) GMCs need typically B~10-100 μG.

9.2.4 Magnetic fields in GMCs

- **There are two main problems that the standard magnetic pressure theory for star formation has been facing**
  - **the observed magnetic fields are not sufficient to prevent collapse**
  - **the derived star formation efficiencies are ~10x higher**
- **The above problems have been realised since the early 90s, and a new theory in which GMCs are supported by supersonic turbulence instead of magnetic fields started to develop.**

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9.3 Supersonic turbulence

- **In this paradigm, the sound speed in the Jeans mass equation is replace by an effective sound speed that account for *turbulence***

$$c_{\mathrm{s,eff}} = \sqrt{c_s^2 + \frac{1}{3}\langle v^2 \rangle} = \sqrt{c_s^2 + \sigma_v^2}$$

- **For GMCs to be stabilised by turbulence σ_v>6 km/s is required, which is roughly consistent with the observed line-widths of GMCs.**
- **GMCs have low temperatures of T~10 K corresponding to sound speeds of ~0.2 km/s. Hence, turbulent motions in the GMCs are supersonic.**

9.3.1 Supersonic turbulence

- **Turbulence is driven at some large scale and then decays to smaller scales until the turbulent energy is dissipated at the dissipation scale.**
- **Turbulence affects both the effective sound speed of the gas and its density (at areas of compression the density is boosted by the Mach number squared)**

$$M_J \propto \frac{(c_s^2 + \sigma_v^2)^{3/2}}{\mathcal{M}\rho^{1/2}}$$

- **On large scales $\sigma_v \gg c_s$ turbulent motions increase the effective pressure hence prevents collapse, whilst on small scales $\sigma_v < c_s$ and turbulent compression boosts gas densities, hence promotes collapse.**

9.3.2 Drivers of turbulence

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- The turbulent picture of star formation is fairly successful, but the critical question remains: what drives turbulence?
- External processes: important for the formation of GMCs.

1. Galaxy formation itself (cold flows, mergers, tidal interactions).
2. Supernova explosions (outside of the GMC).
3. Spiral arms in disk galaxies.
4. Instabilities (gravitational, thermal, magneto-dynamical).

- Internal processes: important for maintaining the GMCs.

1. Proto-stellar outflows.
2. Stellar winds.
3. Ionising radiation.

9.4 Self-regulated star formation

- **In addition to turbulence, the overall star formation efficiency of GMCs can also be influenced by star formation itself. This is called self-regulation.**

- **For example, feedback from proto-stellar winds are believed to regulate star formation efficiency of the stellar cores.**

- **GMCs as a whole are also believed to be ultimately destroyed by energetic feedback from massive OB stars (photo-evaporation by HII regions, stellar winds and supernova explosions).**

- **Star formation may also promote star formation (positive feedback). Shock waves associated with supernovae, stellar winds and ionisation fronts may compress neighbouring gas and thus induce star formation.**

9.5 Star formation efficiency

- **Before we study further the formation of GMCs, it's useful to have an idea of how efficient star formation is in galaxies. We can define the star formation timescale**

$$t_{\rm SF} = \frac{M_{\rm gas}}{\dot{M}_*}$$

- **which for disc galaxies is ~10^9 yr and for starburst galaxies ~10^7-10^8 yr.**
- **Since the value for disc galaxies is >> than the free-fall timescale, a question arises: why are disc galaxies so inefficient at forming stars?**
- **Angular momentum needs to be conserved during the process of forming a disc structure from a cloud that's isotropically cooling and collapsing. This results in a spin up of the disc of cool gas that prevents it from reaching the centre of the potential well.**
- **Also, not all gas is in GMCs which the material from which stars form.**

9.6 Formation and destruction of molecular hydrogen

- **Understanding the formation of GMCs is closely linked to understanding the formation of molecules. By far the most important and abundant molecule in interstellar space is H_2 which can form via two processes:**
  - **Via recombination of pairs of adsorbed H atoms on the surface of dust grains.**
  - **And directly via gas-phase reactions, which is much less efficient than the formation via dust-grains. The gas-phase formation of H_2 is only important in the absence of dust, e.g. the formation of the first stars in the Universe (Pop III stars).**
- **The main destruction mechanism of H_2 is photo-dissociation. An unattenuated radiation field would destroy the molecules rapidly. Need dense gas and self-shielding in the GMCs.**

9.7 Formation of GMCs

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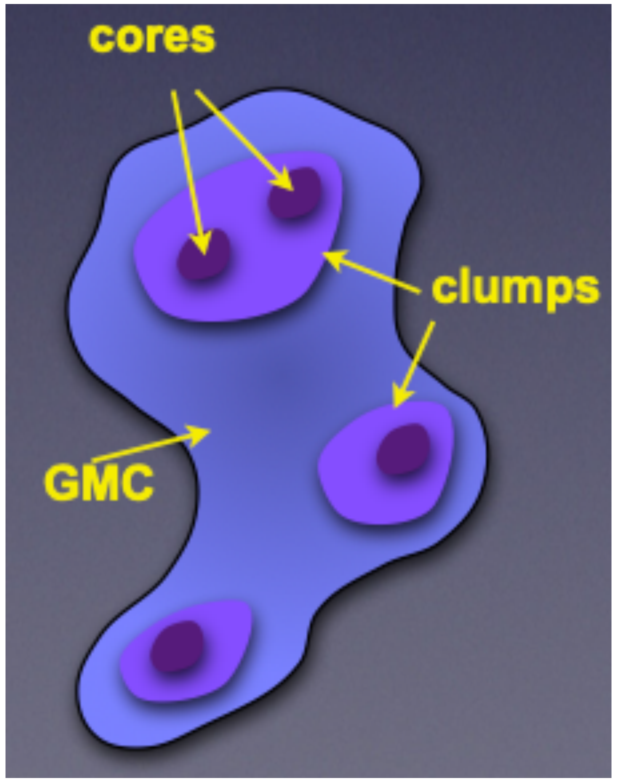
- Molecular gas can form wherever pressure is sufficiently high, and radiation intensity is sufficiently low.
- But we find molecular gas clumped together into GMCs.
- So what are the physical mechanisms behind this clumpiness?



9.7.1 Thermal instabilities

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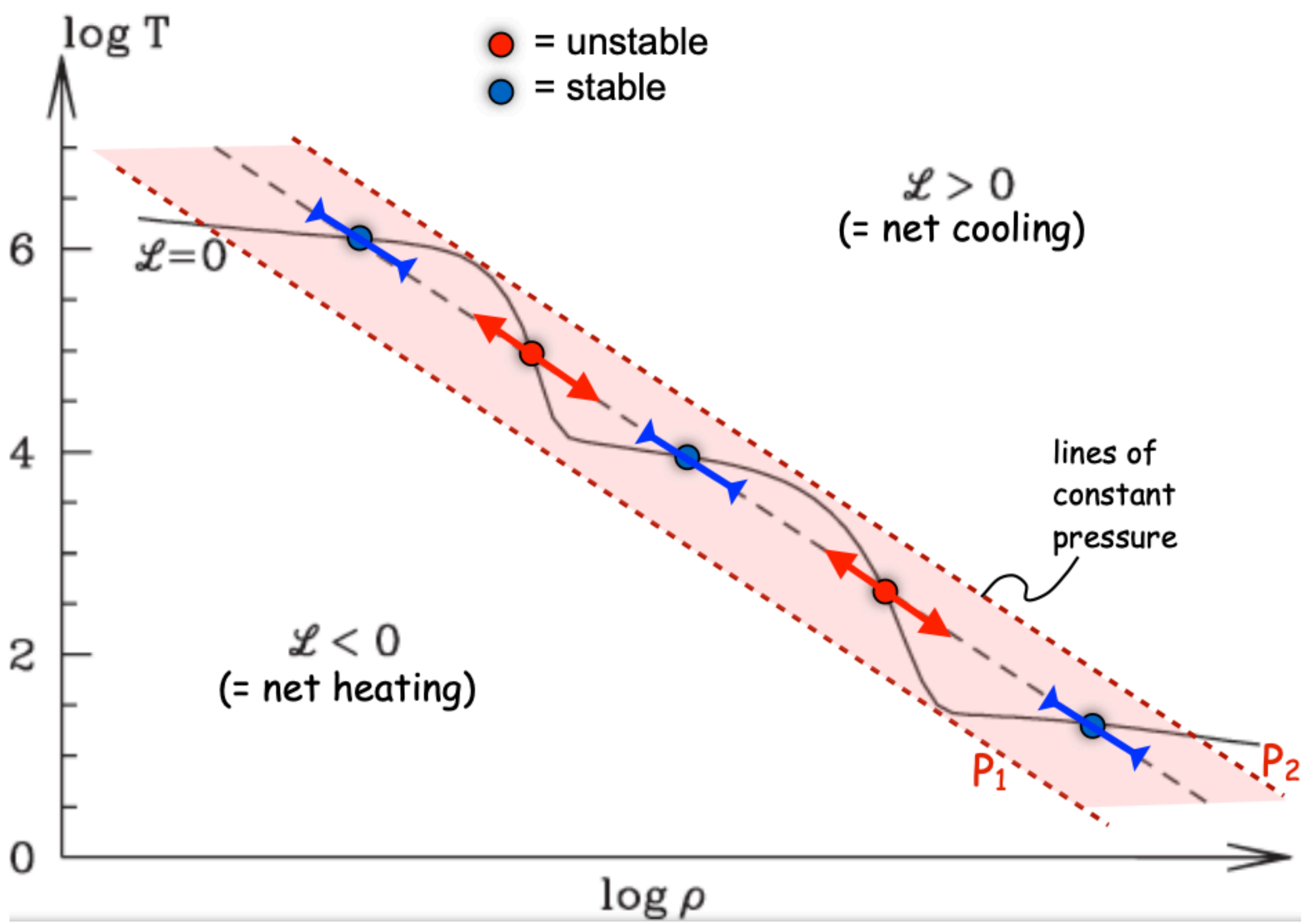
- Gas in thermal equilibrium implies $\Lambda=(C-H)/\varrho=0$.
- Since Λ is a function of T and ϱ, thermal equilibrium can be defined as a curve in the density-temperature plane.
- For pressures $P_1<P<P_2$ gas at multiple phases can coexist in pressure equilibrium. However, only three phases are stable.



9.7.2 Gravitational instabilities

- **In a disk galaxy with differential rotation the Jeans criterion is not the proper criterion for gravitational instability. The centrifugal force due to rotation provides additional support against collapse.**

- **The Toomre stability criterion can be derived for a rotating disk, where the velocity shear makes the disk stable against gravitational collapse, i.e. the disk is stable if Q>1:**

$$Q = \frac{c_s \kappa}{\pi G \Sigma}, \qquad \kappa = \sqrt{2}\left[\frac{v_c^2}{R^2} + \frac{v_c}{R}\frac{dv_c}{dR}\right]^{1/2}$$

- **Here c_s is the sound speed, $\varkappa$ is the *epicyclic frequency* and Σ is the surface mass density. For Q<1 perturbations of the size λcrit will grow:**

$$\lambda_{\rm crit} = \frac{2\pi^2 G \Sigma}{\kappa^2}$$

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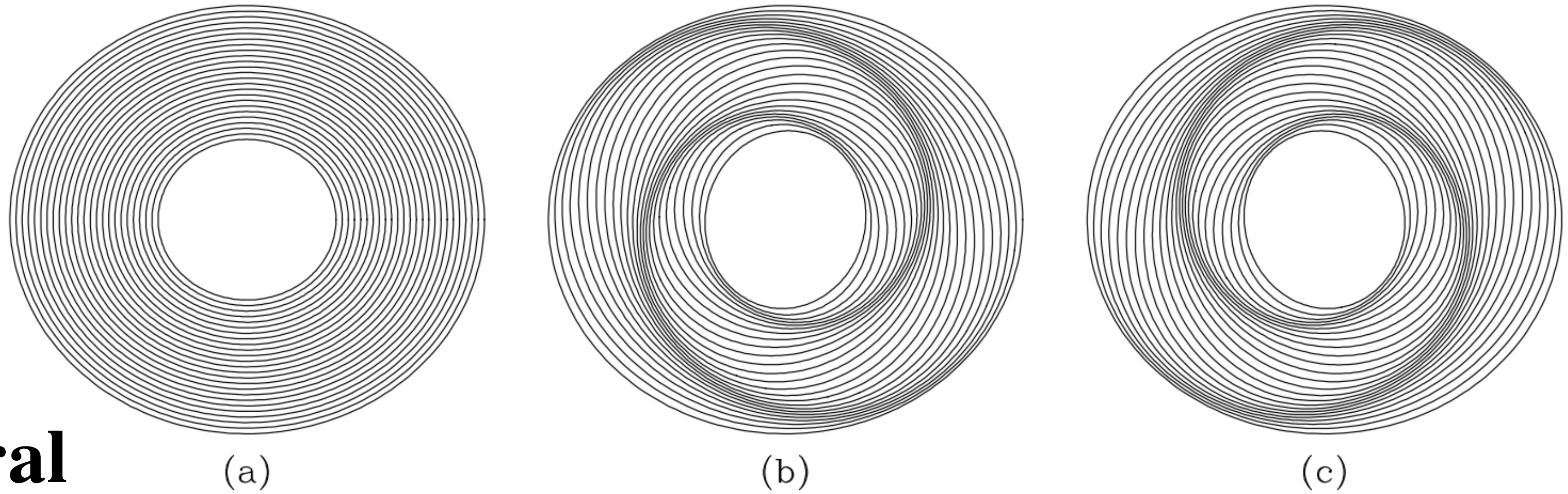
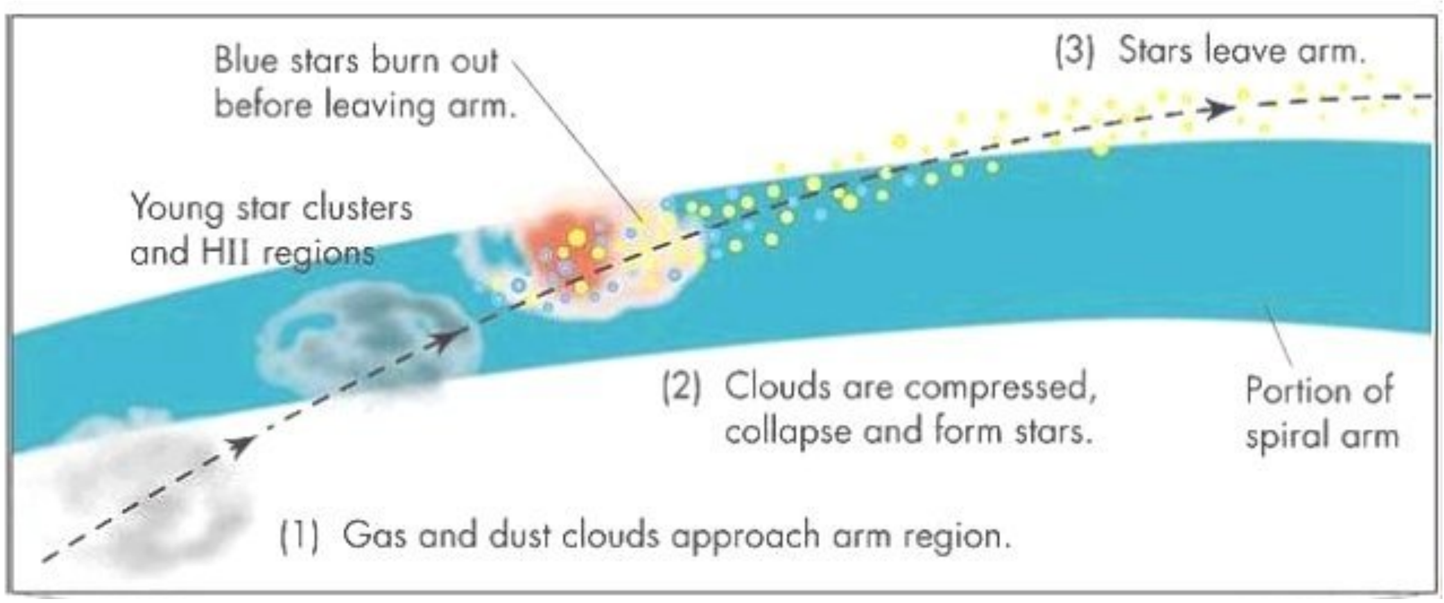
9.7.3 Spiral arms

- **Grand-design spiral arms are believed to be spiral density waves.**
- **Whenever a gas cloud moves through such a spiral arms, it gets compressed.**
- **This compression can cause gravitational instabilities which trigger star formation.**

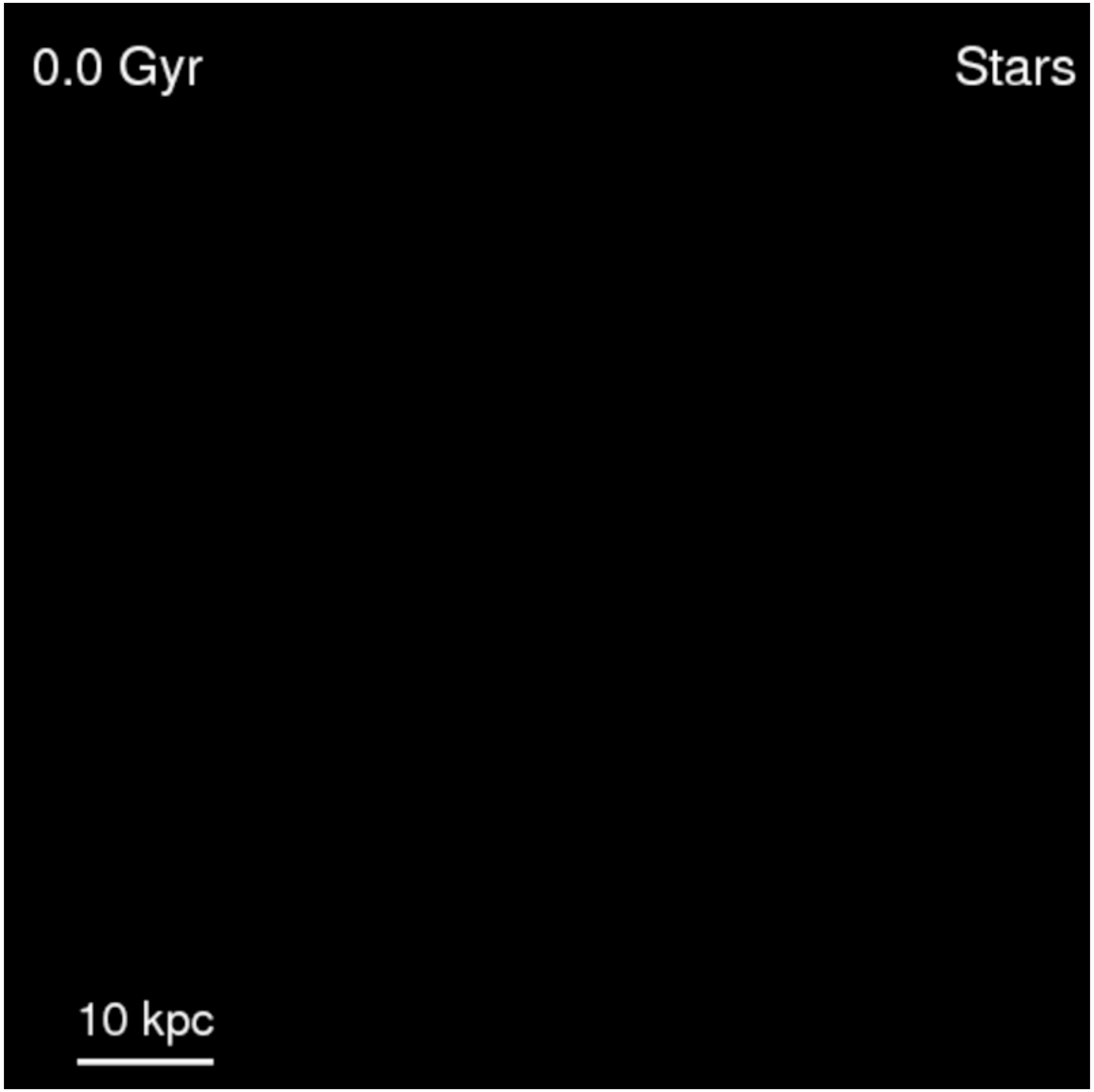




9.7.4 Mergers

Video link: http://www.tapir.caltech.edu/~phopkins/movies/sbcn_hr_f_stars_c.mp4

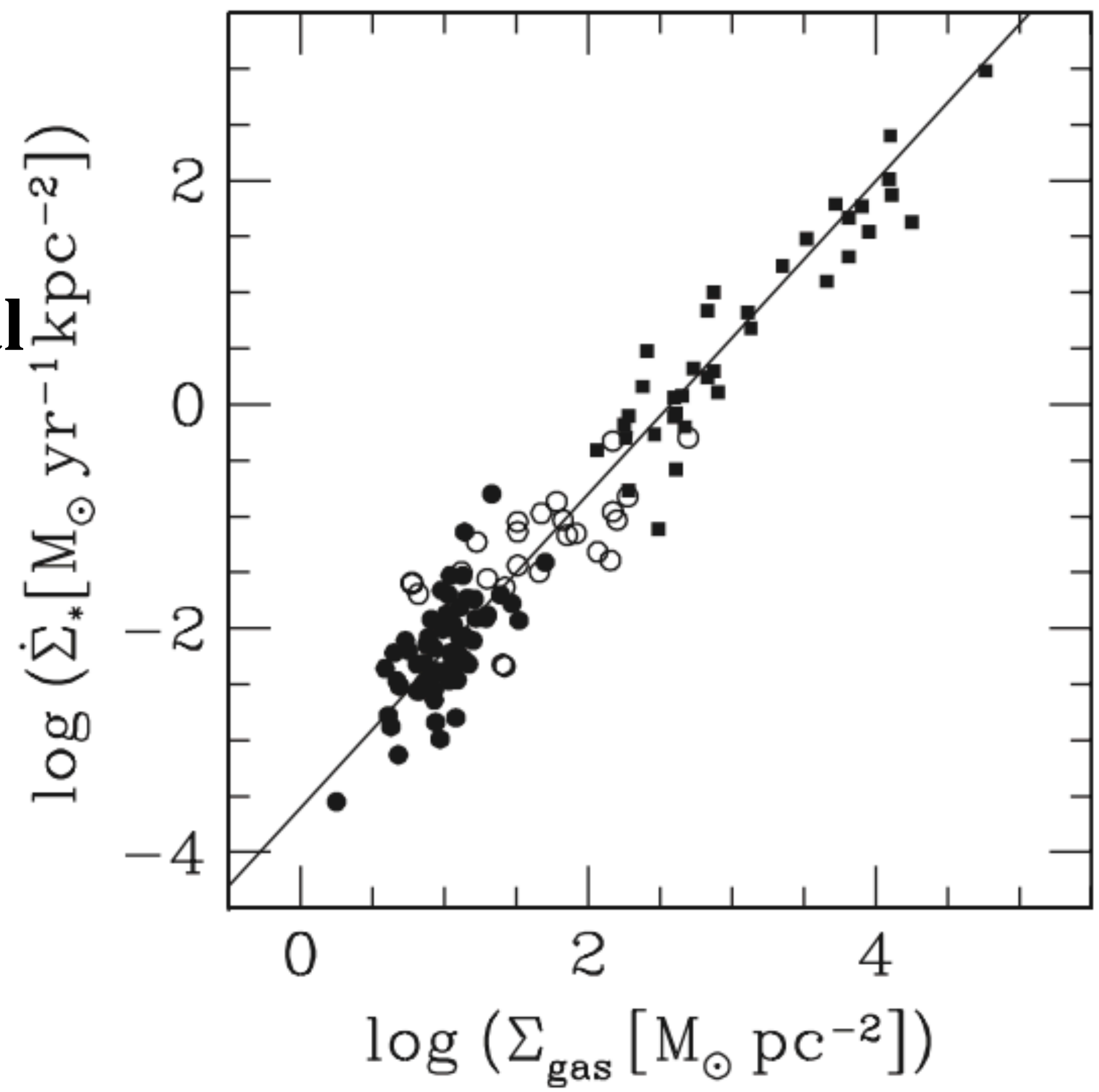
- **Gas can be compressed by shocks as two galaxies merge, and be energised as the energy in the merger is converted into turbulent motion.**



9.8 Empirical star formation laws: global relations

- **In galaxy formation modelling it is in practise impossible to resolve the ~20 orders of magnitude relevant for star formation. Instead one can use empirical star formation laws.**

- **The most known empirical star formation law is the Schmidt-Kennicutt law that relates the global averaged star formation density to the surface-gas density (atomic+molecular):**



$$\dot{\Sigma}_* \simeq 2.5 \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{M_\odot {\rm pc}^{-2}} \right)^{1.4} M_\odot {\rm yr}^{-1} {\rm kpc}^{-2}$$

9.8.1 Empirical star formation laws: global relations

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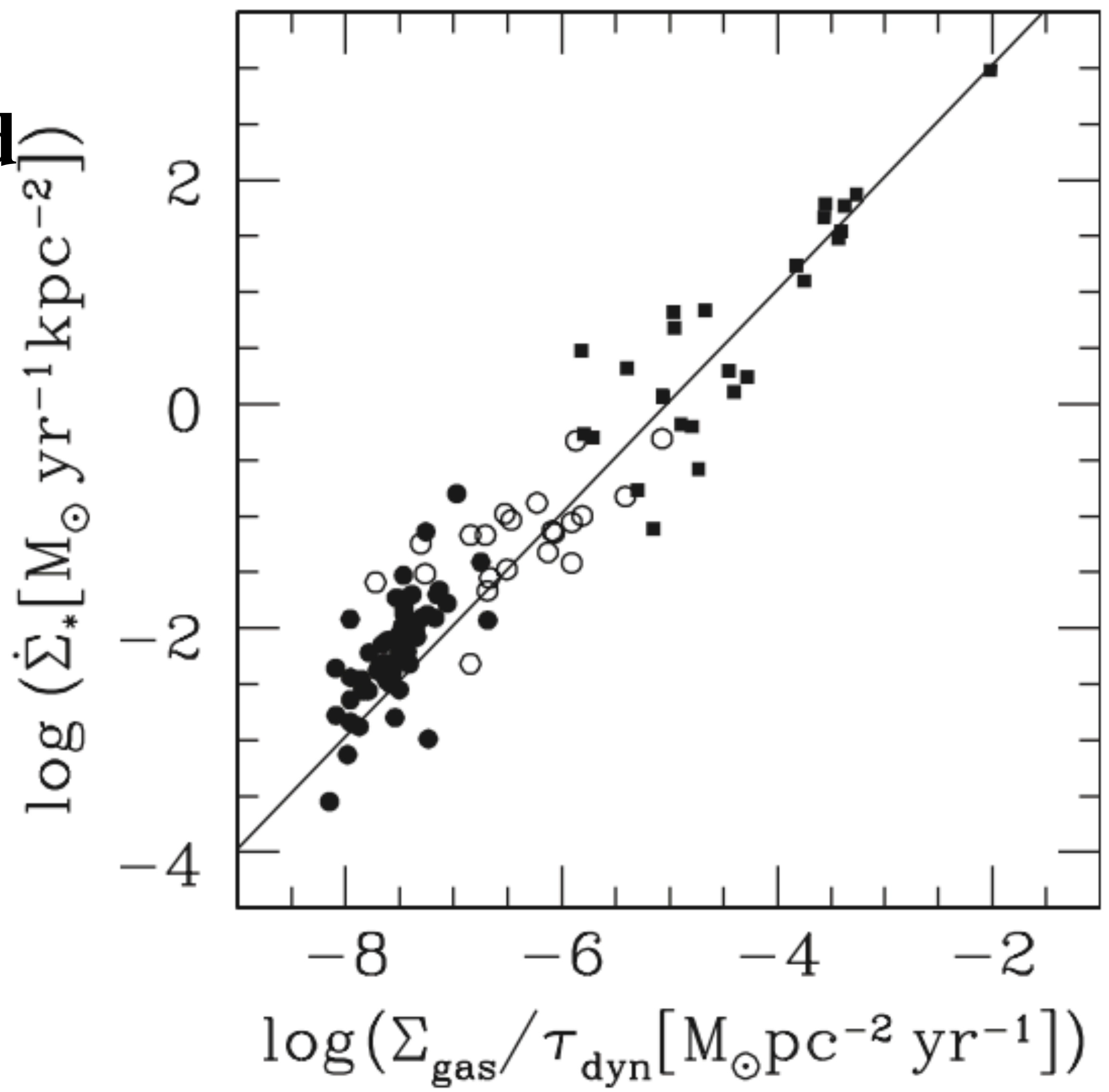
- **The KS-law also reveals a tight correlation between the surface SFR and Σ_{gas}/τ_{dyn}, where $\tau_{dyn}=2\pi R/V(R)$ and R is the outer edge of the star-forming disk.**

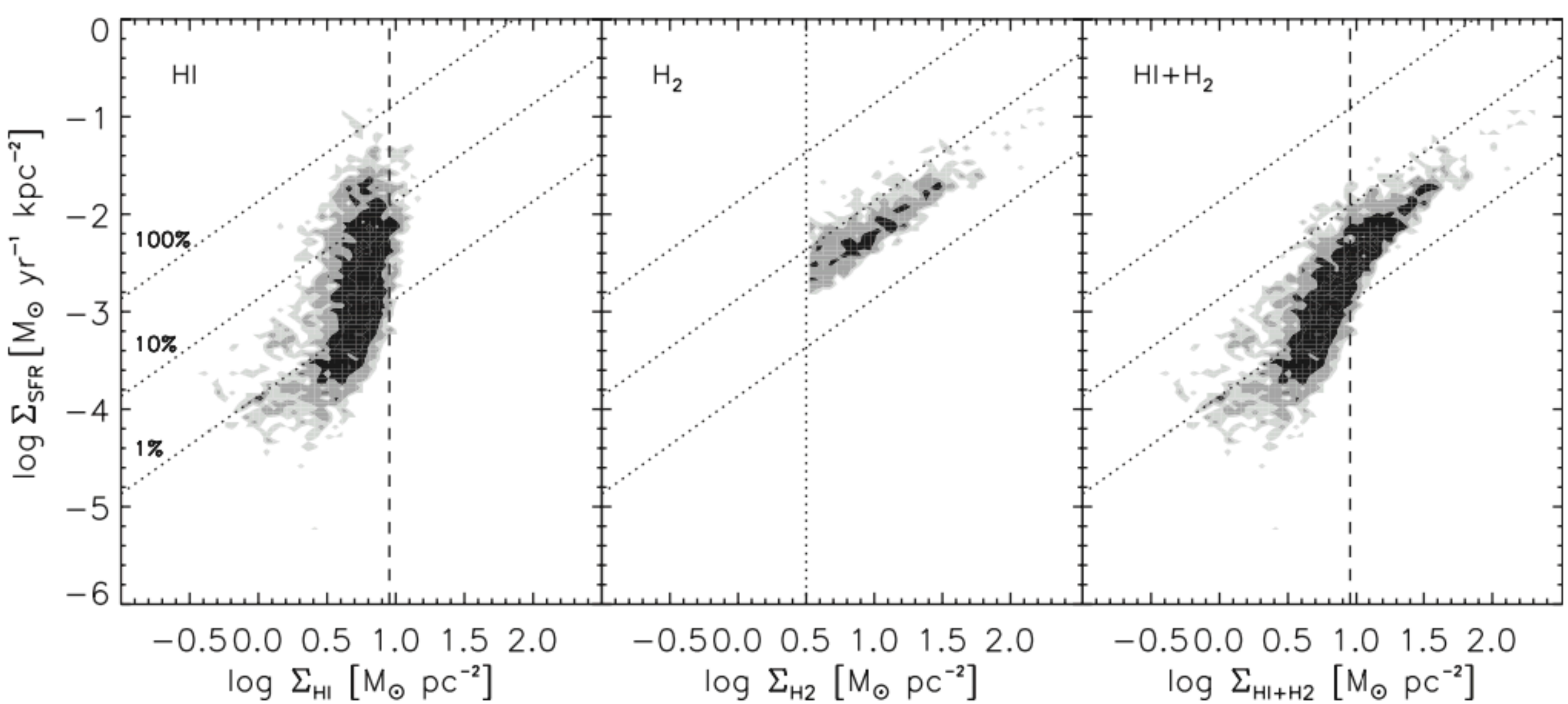
$$\dot{\Sigma}_* \simeq 0.017\Sigma_{\rm gas}\Omega, \quad \Omega = V_{\rm rot}(R)/R$$

- **This implies that about 10% of the available gas is consumed by star formation per orbital time.**



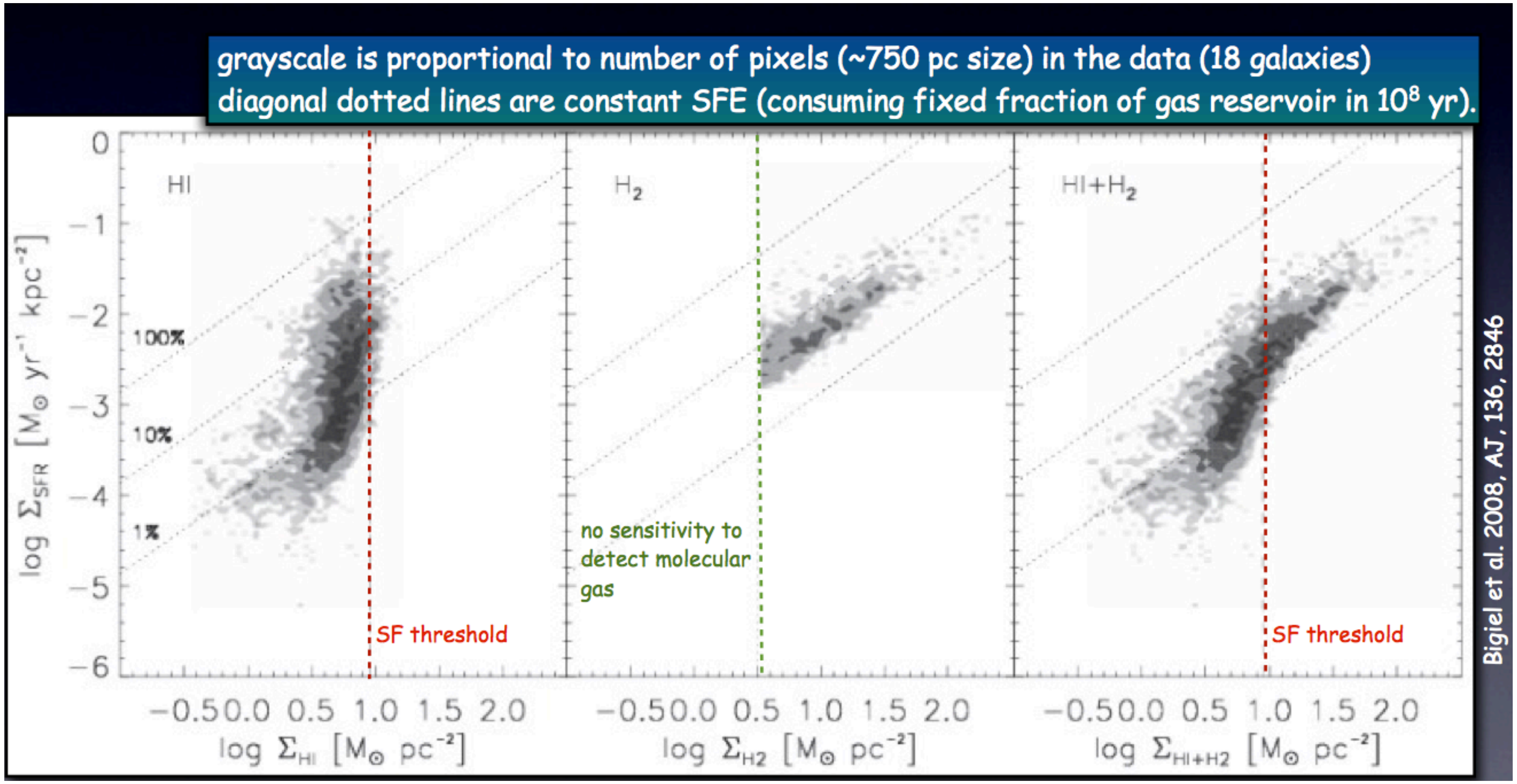
9.8.2 Empirical star formation laws: local relations

- **Instead of global measurements (i.e. averaged over the entire galaxy), when the resolution allows, one can measure the SFR, Σ_{gas} and Ω locally pixel by pixel.**
- **Observations show that locally the SF efficiency has little to do with the local orbital time, contrary to the global quantities.**



9.8.3 Empirical star formation laws: local relations

- **The high resolution measurements of the small-scale local data have revealed that an equivalent to the KS-law is valid with one modification. There is a pronounced break in the power-law behaviour near $\Sigma_{gas} \sim 10\ M_{\odot}\ pc^{-2}$.**



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9.9 Feedback

- **One of the most important problems in galaxy formation is the overcooling problem discussed in Lecture 8. Preventing overcooling requires some heat input.**
- **According to the current paradigm the main heating mechanisms are feedback from supernovae and AGN feedback from supermassive black holes (see Lecture 13).**

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9.9.1 Supernova feedback

- **To eject gas from a galaxy requires an energy of E_{ej}=1/2$M_{ej}V^2_{esc}$, where V_{esc} depends on the total mass and mass profile of the galaxy and its dark matter halo. The energy available for supernova feedback is:**

$$E_{\rm fb} = \epsilon_{\rm SN} \zeta M_* E_{\rm SN}$$

  - **$\varepsilon_{SN} \leq 1$= fraction of SN energy available for feedback (not radiated away).**
  - **z=0.01 $M_{\odot}^{-1}$= number of SN produced per solar mass (IMF dependent).**
  - **$E_{SN} \sim 10^{51}$ erg= energy supplied by SN.**

- **Equating the feedback energy with the required ejection energy from a NFW halo with concentration parameter c we get:**

$$\frac{M_{\rm ej}}{M_\star} \simeq 0.4 \epsilon_{\rm SN} \left(\frac{c}{10}\right)^{-1} \left(\frac{V_{\rm vir}}{200~{\rm km/s}}\right)^{-2}$$

9.9.2 Supernova feedback

- **Rather than just ejecting gas from the halo, SN energy can also be used to reheat the gas: $E_{int}=3/2M_{gas}\,(k_BT/\mu m_p)$.**
- **Let us reheat gas from an initial temperature $T_{init}=10^4$ K to the virial temperature T_{vir}, this requires**

$$E_{\rm reheat} = \frac{3}{2} M_{\rm gas} \frac{k_B(T_{\rm vir} - T_{\rm init})}{\mu m_p} = \frac{3}{4} M_{\rm gas} V_{\rm vir}^2 \left(1 - \frac{T_{\rm init}}{T_{\rm vir}}\right)$$

- **Equating the reheating energy to the SN energy**

$$\frac{M_{\rm gas}}{M_\star} \simeq 17\epsilon_{\rm SN} \left(\frac{V_{\rm vir}}{200\ {\rm km/s}}\right)^{-2} \left(1 - \frac{T_{\rm init}}{T_{\rm vir}}\right)^{-1}$$

- **Reheating is more efficient than ejecting gas. $0.01<\varepsilon_{SN}<1$ and depends on the ISM and star formation conditions.**

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9.9.3 Mass loading

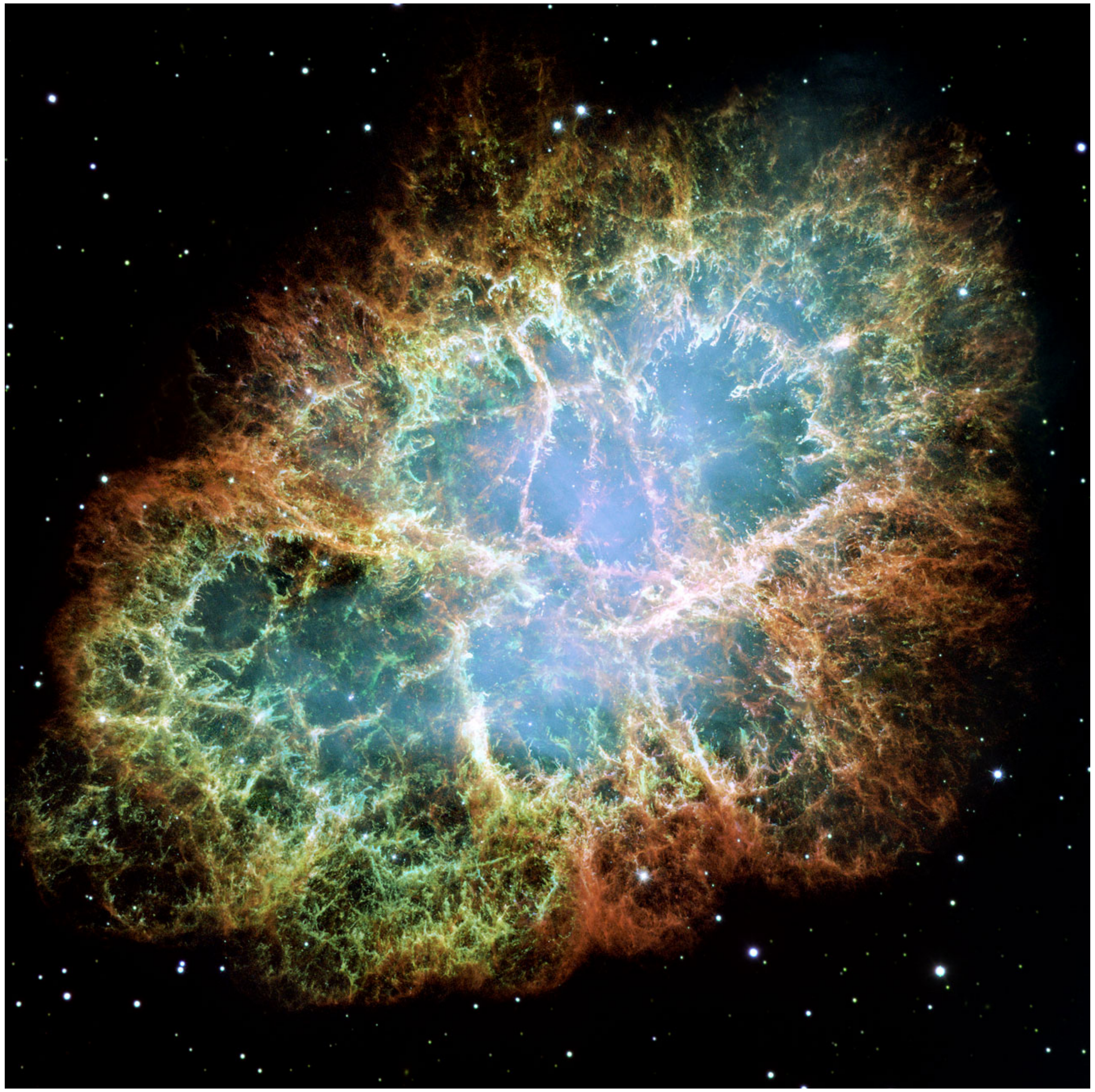
- **The ratio η is called the mass loading factor of the wind and is an important parameter for galaxy formation:** $\eta = \dot{M}_{\rm w}/\dot{M}_*$
- **Since we lack proper, theoretical understanding of galactic winds and numerical simulations lack the spatial resolution and physics to treat SN feedback from first principles, a number of heuristic approaches have been used in numerical simulations and semi-analytic models:**
  - **Energy-driven winds:** $v_w \propto V_{vir}$ $\eta \propto V_{vir}^{-2}$ **(energy conserved).**
  - **Momentum-driven winds:** $v_w \propto V_{vir}$ $\eta \propto V_{vir}^{-1}$ **(momentum conserved).**
  - **Constant winds models:** v_w=constant η=constant.
  - **Power-law wind models:** $v_w \propto V_{vir}$ $\eta \propto V_{vir}^{-\alpha}$.

9.9.4 Numerical simulations

- **Thermal feedback:**
  - **A fraction $\varepsilon_{SN} \leq 1$ of the SN energy is given to neighbouring gas particles in the form of thermal energy. A problem with this approach is that the gas in star-forming regions is very dense resulting in rapid cooling and consequently most of the SN energy is rapidly radiated away. A solution is to turn off cooling for a time period Δt to allow the thermal pressure to disperse the gas.**
- **Kinetic feedback**
  - **A fraction $\varepsilon_{SN} \leq 1$ of the SN energy is given to neighbouring gas particles in form of kinetic energy, the wind velocity has to be put in by hand. A problem is that the star-forming gas is dense preventing gas from escaping to large distances. A solution would be to turn off the hydrodynamics for wind particles for a time period Δt to allow the kinematic motion to disperse the gas.**

9.9.5 Rayleigh-Taylor instabilities

- **Realistic supernova winds are subject to Rayleigh-Taylor instabilities.**
- **This instability arises when lower density gas pushes higher density gas, i.e. when a hot bubble tries to disperse a shell of dense cold gas.**
- **Rayleigh-Taylor fingers appear that ultimately allow the hot gas to escape.**
- **If galactic winds consist of hot bubbles pushing shells of cold material outwards, mass loading factors are naturally restricted to $\eta \leq 1$.**



What have we leant?

- **At high gas densities (Σ_{gas}>10 $M_{\odot}pc^{-2}$) conditions are such that self-shielding becomes important, and molecular gas forms.**
- **GMCs are supported by supersonic turbulence and turbulent compression creates clumps and cores that are Jeans unstable.**
- **Energy and momentum injection due to the star formation process itself is likely to be an important regulator of the star formation efficiency in GMCs.**
- **Supernova feedback is an essential ingredient in galaxy formation models. It helps explaining why the star formation efficiency overall is low and why galaxy formation if less efficient in lower mass haloes. In the numerical modelling of supernova feedback many challenges still remain.**

Extra slides

- **H -> (neutral) hydrogen aka in astronomy HI**
- **H_2 -> molecular hydrogen aka in astronomy H2**
- **H^+ -> singly-ionised hydrogen aka in astronomy HII**

Extra slides

Video link: https://esahubble.org/videos/heic1501f/

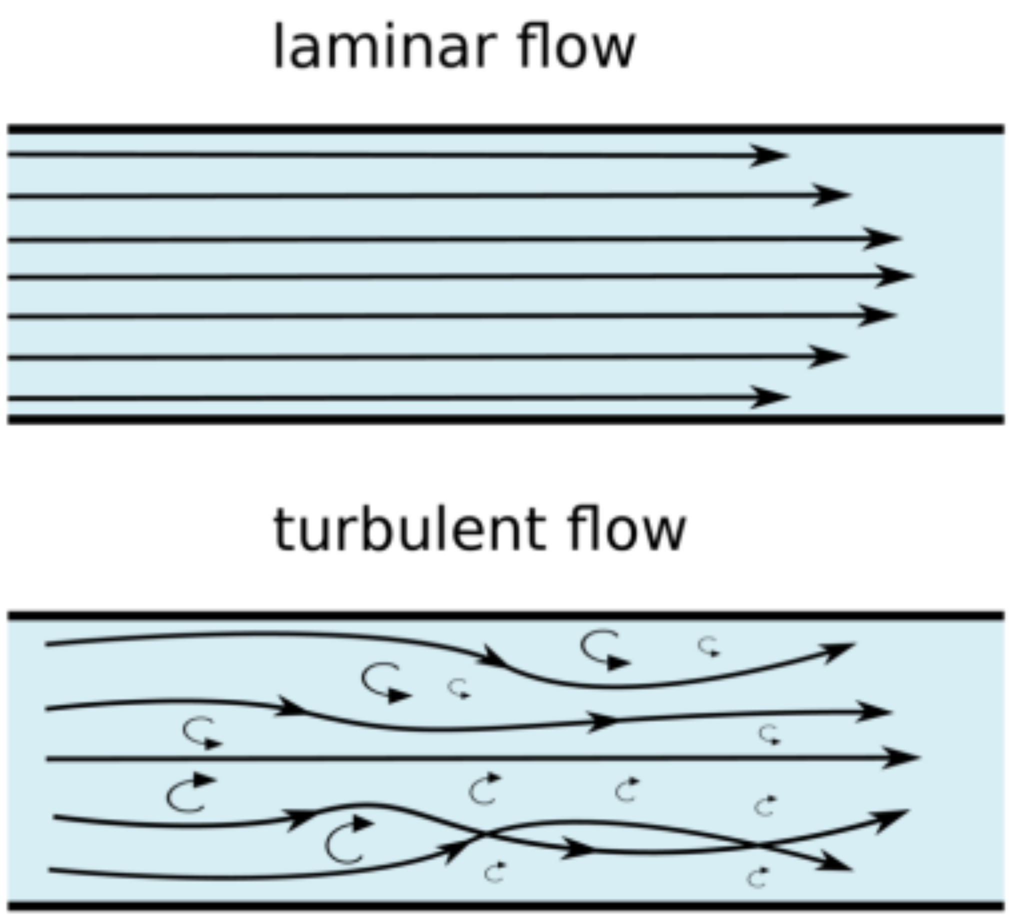
- **Sagittarius arm -> IC 4703 -> M16 -> Pillars of creation**

Extra slides

- Sagittarius arm -> IC 4703 -> M16 -> Pillars of creation

Extra slides

- **Laminar is a flow where fluid particles follow well-defined paths/ streamlines.**
- **Turbulent is a flow where fluid particles move is chaotic ways.**



Extra slides

- **Deviations from circular orbits are called epicycles.**
- **Epicyclic frequency: describes the frequency of an oscillation in the radial direction.**

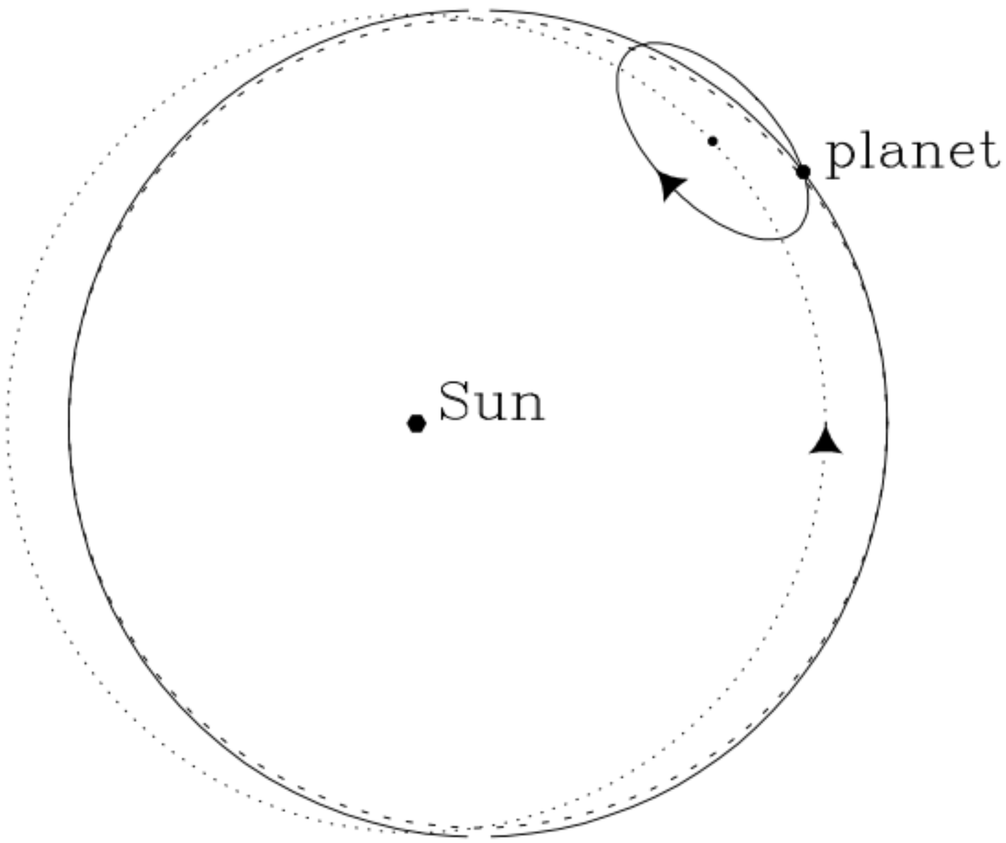


Figure 3.7 An elliptical Kepler orbit (dashed curve) is well approximated by the superposition of motion at angular frequency κ around a small ellipse with axis ratio $\frac{1}{2}$, and motion of the ellipse's center in the opposite sense at angular frequency Ω around a circle (dotted curve).