ASTR 610
Theory of Galaxy Formation

Lecture 16: Star Formation

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Yale University, Fall 2022

Star Formation

In this lecture we discuss the formation of stars. After describing the structure of Giant Molecular Clouds (GMCs), we describe two competing theories for regulating the star formation efficiencies in individual GMCs. Next we describe how GMCs form, followed by a describtion of empirical star formation laws and star formation thresholds..

Topics that will be covered include:

- Giant Molecular Clouds (GMCs)
- ambipolar diffusion
- supersonic turbulence
- Formation and Destruction of H_2
- the formation of GMCs
- Star Formation Laws
- Star Formation Thresholds

The Challenges of Star Formation

- Stars form out of Giant Molecular Clouds (GMCs), which have densities ~100 cm^{-3}, and sizes of tens of parsecs. Stars have sizes of ~10^{-7} pc, and densities of ~1 g cm^{-3}

  ⇒ Hence, during the process of star formation, densities have to increase by ~22 orders of magnitude

- Molecular clouds usually rotate due to differential rotation in the disk in which they form (in MW, $\Omega \sim 10^{-15}$ s^{-1}). If collapse would conserve angular momentum, this would imply rotation periods of the stars of well below 1 s.

  ⇒ Angular momentum has to be transferred out during collapse.

- Potential energy of the clouds ($E_{\rm pot} \propto -\frac{GM^2}{r}$) has to be released. For the Sun, this corresponds to 3.8x10^{48} erg, equivalent to ~3x10^{7} yrs of Solar luminosity...

  ⇒ This energy must be radiated/transported away despite the high opacities of the surrounding medium.

Giant Molecular Clouds

Observational Fact: all stars form inside Giant Molecular Clouds.

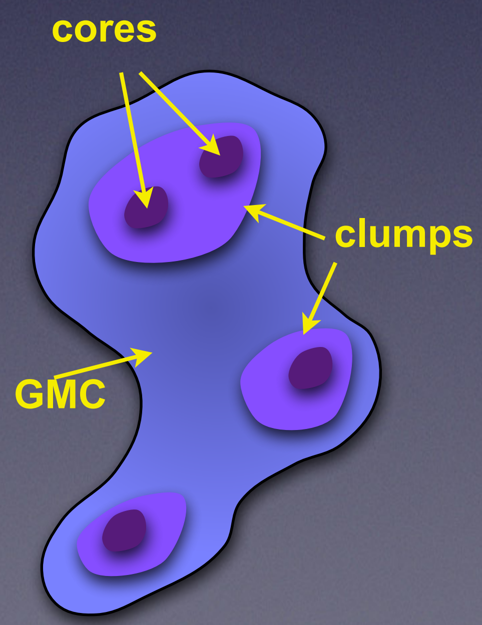
Understanding star formation consists of two components:

- understanding the formation of Giant Molecular Clouds
- understanding how stars form inside Giant Molecular Clouds

We start with addressing the second component; how do stars form inside GMCs

The Structure of Giant Molecular Clouds

GMCs have an extremely clumpy structure. They consist of molecular clumps, which themselves consist of molecular cores (also called proto-stellar cores).



structure	mass	density (n_H)
GMC	10^5 - 10^6 $M_\odot$	100 - 500 cm^{-3}
clump	10^2 - 10^4 $M_\odot$	10^2 - 10^4 cm^{-3}
core	0.1 - 10 $M_\odot$	> 10^5 cm^{-3}

Observational Fact:
temperature of GMCs is ~10K, similar to that of the clumps and cores. Hence, the various components of a GMC are not in thermal pressure equilibrium...

Giant Molecular Clouds

Observational Fact: GMCs are strongly correlated with young stars ($t < 10^7 \mathrm{yrs}$), but little correlation with older stars.

the lifetime of GMCs is of the order of $t_{\rm GMC} \simeq 10^7 \mathrm{yrs}$

For comparison, the free-fall time of GMCs is

$$t_{\rm ff} = \left(\frac{3\pi}{32\,G\,\rho}\right)^{1/2} \simeq 3.6 \times 10^6\,\mathrm{yrs}\,\left(\frac{n_{\rm H}}{100\,\mathrm{cm}^{-3}}\right)^{-1/2}$$

Since this is significantly smaller than the GMC lifetime, we infer that GMCs must somehow be supported against gravitational collapse...

But, if that is the case, then how/why/when do GMCs collapse to produce stars??

We can define the star formation efficiency of a GMC as $\varepsilon_{\rm SF,GMC} \equiv \frac{t_{\rm ff,GMC}}{t_{\rm SF,GMC}}$

where SF time scale for GMC is defined by $t_{\rm SF,GMC} \equiv M_{\rm GMC}/\dot{M}_*$

Observations indicate that $\varepsilon_{\rm SF,GMC} \simeq 0.002$

Key Question: why is the SF efficiency of GMCs so low?

Giant Molecular Clouds

If we ignore external pressure, we can use the virial theorem, according to which

$$\boxed{\frac{1}{2}\frac{\mathrm{d}^2 I}{\mathrm{d}t^2} = 2K + W}$$

and collapse will occur if $2K + W < 0$

Using that $c_{\rm s}^2 = (\partial P/\partial \rho)_S = k_{\rm B}T/\mu m_{\rm p}$ and assuming that GMCs are spheres with uniform density, we have that

$$K = \frac{3}{2}\,N\,k_{\rm B}\,T = \frac{3}{2}\,M\,c_{\rm s}^2 \qquad\qquad W = -\frac{3}{5}\,\frac{G\,M^2}{r_{\rm cl}}$$

Using that $\bar{\rho} = 3M/4\pi r^3$, the collapse condition for GMC based on virial theorem becomes

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

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

Giant Molecular Cloudss

NOTE: the thermal Jeans mass derived above ignores external pressure, which may not be very appropriate for GMCs. For an isothermal sphere in pressure equilibrium with its surroundings, the equivalent of the Jeans mass is the Bonnor-Ebert (BE) mass

$$\boxed{M_{\rm BE} \simeq 1.182 \frac{c_{\rm s}^3}{(G^3\,\rho)^{1/2}}}$$

which is almost identical to Jeans mass....(external pressure has little impact overall)

Thus, we have that $M_{\rm GMC} \gg M_{\rm J} \sim M_{\rm BE}$ and even $M_{\rm clump} \gg M_{\rm J} \sim M_{\rm BE}$, indicating that they ought to be collapsing on the free-fall time, unless they are supported by some other source of pressure...

On the scale of molecular cores, though, $M_{\rm core} \sim M_{\rm J} \sim M_{\rm BE}$ suggesting that they are stable against gravitational collapse in the absence of cooling...

In what follows we first discuss the old paradigm (often called `Standard Theory') that was largely developed during the 1980s, and according to which, GMCs are supported against gravitational collapse by magnetic fields...

The Standard Theory

Equating potential energy of cloud to its magnetic energy yields a characteristic mass

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

where the magnetic field, $\vec{B}$, is assumed to be uniform across the cloud (Spitzer 1986)

- If $M > M_\Phi$ the magnetic field cannot prevent gravitational collapse, and the cloud is said to be magnetically super-critical.

- If $M < M_\Phi$ the cloud is prevented from collapsing by magnetic forces, and the cloud is said to be magnetically sub-critical.

In order for GMCs to be sub-critical (stable) they need $B \sim 10 - 100\mu G$

As you can see, M_Φ is large. If $M > M_\Phi$ collapse occurs, which causes the density to increase. This should lower M_Φ resulting in fragmentation. However, while the cloud contracts, as long as the ionization level is sufficiently high, the magnetic field is `frozen' to the matter ➡ contraction conserves the magnetic flux $\Phi = \pi R^2 B$, to the extent that the ratio M/M_Φ remains fixed ➡ no fragmentation can occur...

Ambipolar Diffusion

This gives rise to a problem: how can (low-mass) stars ever form???

Solution: ambipolar diffusion

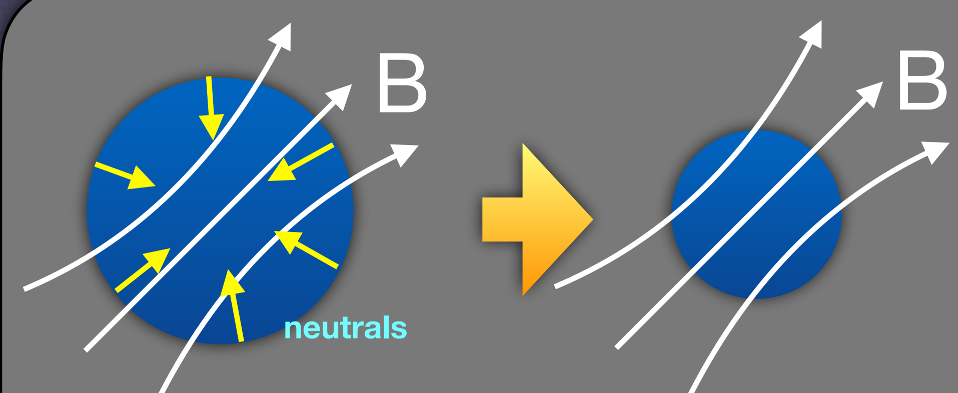
For a cloud consisting of both neutral and ionized particles, the neutrals are only indireclty coupled to the magnetic field via collisions with the ionized particles. For a sufficiently low ionized fraction, the neutral particles can diffuse through the magnetic field, resulting in a contraction on the ambipolar diffusion time:

$$t_{\rm ad} \sim 2 \times 10^7 \,{\rm yrs} \left(\frac{n_{\rm H_2}}{100\,{\rm cm}^{-3}}\right)^{3/2} \left(\frac{B}{30\,\mu G}\right)^{-2} \left(\frac{R}{10\,{\rm pc}}\right)^{2}$$

defined as time scale over which neutrals diffuse a distance R against the ions.

If star formation is regulated by ambipolar diffusion,

then $$\varepsilon_{\rm SF,GMC} = \frac{t_{\rm ff}}{t_{\rm ad}} \sim 0.05 - 0.1$$



neutrals, which are not frozen to B-field, can undergo gravitational collapse

Ambipolar Diffusion

Over the last two decades, it has become clear that this `standard theory' (according to which GMCs are supported by magnetic fields, and dissipate due to ambipolar diffusion), faces a number of serious problems:

- observations suggest that most clouds are magnetically super-critical, i.e., the magentic fields observed are not sufficient to prevent collapse
- the implied star formation efficiency of GMCs, $\varepsilon_{\rm SF,GMC} = t_{\rm ff}/t_{\rm ad} \sim 0.05$ is too high by almost an order of magnitude. Put differently, $t_{\rm ad} > t_{\rm GMC}$ indicating that GMCs do not live long enough for ambipolar diffusion to matter.

Supersonic Turbulence

Since the 1990s, a new paradigm has largely replaced the `standard theory'. In this new paradigm, GMCs are not supported by magnetic fields, but by supersonic turbulence.

In presence of turbulence, the sound speed in the Jeans mass can simply be replaced by an effective sound speed

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

Using the Jeans criterion, we see that a GMC will be stabilized against gravitational collapse if $\sigma_v > 6\,{\rm km/s}$, roughly consistent with the observed line-widths of GMCs

→ **GMCs are largely supported by turbulence** ⚠

Given that GMCs have a temperature T~10K, which corresponds to a thermal sound speed of $c_{\rm s} \simeq 0.2\,{\rm km/s}$, it is clear that the (turbulent) motions revealed by the observed line-widths are supersonic.

→ **turbulence in GMCs is supersonic** ⚠

Supersonic Turbulence

Turbulence is driven at some (large) scale, and then decays to smaller scales until the turbulent energy is dissipated on some small dissipation scale...

Let the power spectrum of the turbulent velocity field, on scales between the driving and the dissipation scales, be $P_v(k) \propto k^{-n}$

negligible compression	n = 11/3	(classical Kolmogorov theory)
strong compression	n = 4	(supersonice turbulence)

If $P_v(k) \propto k^{-n}$ then the velocity dispersion on scale l scales as $\sigma_v(l) \propto l^q$ with $q = \frac{n-3}{2}$

For n=4, one thus expects $\sigma_v \propto l^{1/2}$, which is in excellent agreement with the observational scaling relation of GMCs, according to which $M \propto R^2$ and $\Delta v \propto R^{1/2}$

\`Larson scaling relations' (Larson 1981)

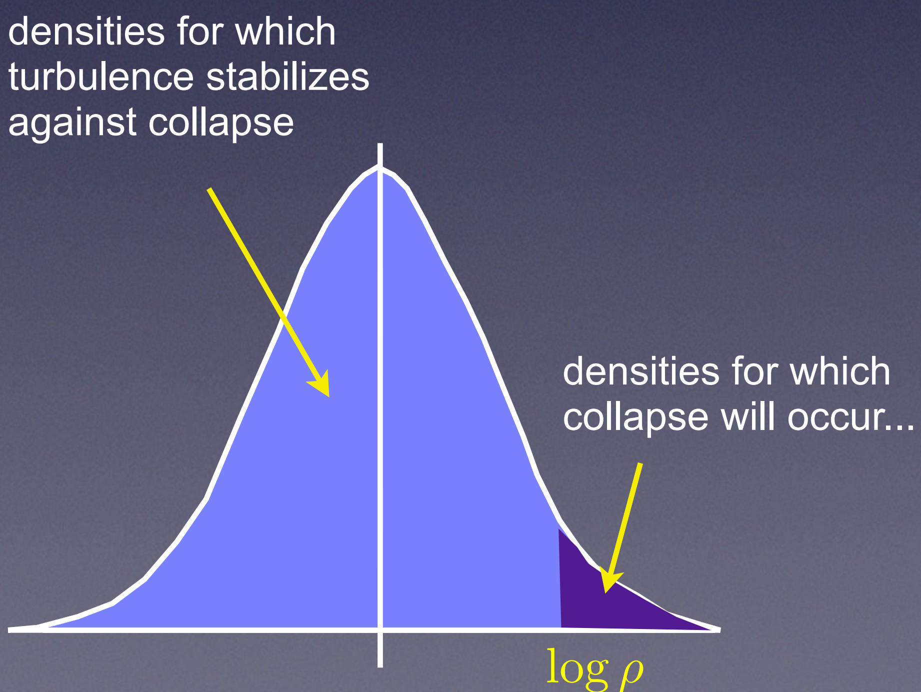
Since turbulence impacts the (effective) sound speed of the gas, as well as its density (at areas of compression, the density is boosted by the Mach number $\mathcal{M}$ squared), the Jeans mass in the presence of turbulence scales as

$$\boxed{M_{\rm J} \propto \frac{(c_{\rm s}^2 + \sigma_v^2)^{3/2}}{\mathcal{M}\,\rho^{1/2}}}$$

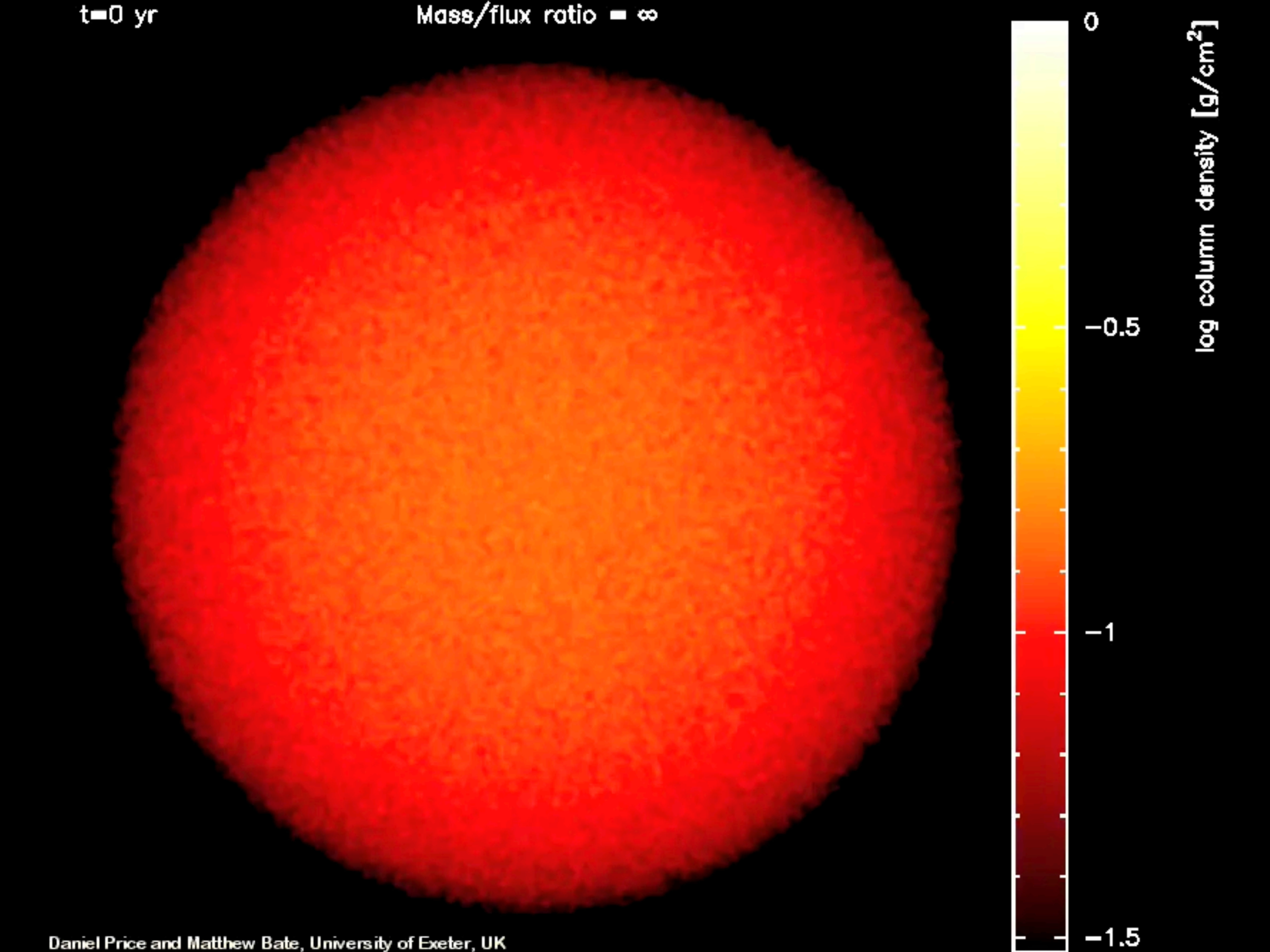
Supersonic Turbulence

$$M_{\rm J} \propto \frac{(c_{\rm s}^2 + \sigma_v^2)^{3/2}}{\mathcal{M}\,\rho^{1/2}} \qquad\qquad \sigma_v \propto R^{1/2}$$

- On large scales, $\sigma_v \gg c_{\rm s}$, and turbulent motions increase the effective pressure, preventing collapse (i.e., preventing star formation on the scale of the entire GMC)
- On small scales, $\sigma_v < c_{\rm s}$, and turbulent compression now boosts the gas densities locally, pushing them `over the edge', causing them to collapse; on small scales turbulence promotes collapse.



Numerical simulations & models of supersonic, self-gravitating turbulence reveal a log-normal distribution for the density distribution. Combined with the Jeans mass above, this gives a natural explanation of why only a small fraction of GMC partakes in SF at any given time. (and hence why $\varepsilon_{\rm SF,GMC}$ is so low)...


t=0 yr
Mass/flux ratio = ∞
0
−0.5
−1
−1.5
log column density [g/cm²]
Daniel Price and Matthew Bate, University of Exeter, UK

Supersonic Turbulence

The turbulence picture is fairly succesful, but it poses the question:

what drives the turbulence?

There are a wide variety of sources:

external

- Galaxy Formation itself (cold flows, mergers, tidal interactions)
- Supernova explosions (outside of the GMC)
- Spiral arms
- Instabilities (gravitational, thermal, magnetodynamical)

internal

- Proto-stellar outflows
- Stellar winds
- Ionizing radiation

External processes are believed to be most important for the formation of GMCs.

Internal processes are believed to be most important for maintaining GMCs.

Self-Regulation

In addition to turbulence, the overall star formation efficiency (SFE) of GMCs may also be influenced by the presence of star formation itself...

- Feedback from proto-stellar winds are believed to regulate the star formation efficiency of the stellar cores.
- GMCs as a whole are believed to be destroyed by energy feedback from massive OB stars (photo-evaporation by HII regions, stellar winds, SN explosions)

NOTE: it may also be the case that GMCs are transient structures, both formed and destroyed by turbulence. In this picture GMCs never reach virial equilibrium but will be dispersed again over the timescale on which the large scale turbulent flows change direction.

- Star formation may also provoke star formation (positive feedback). Shock waves associated with supernovae, stellar winds and ionization fronts may compress neighboring gas, therefore triggering star formation. The overall importance of this induced mode of star formation is still unclear...

The Formation of Molecular Hydrogen

Having addressed the star formation within individual GMCs, we now turn to the issue of the formation of GMCs. Clearly, understanding the formation of GMCs is closely linked to understanding the formation of molecules. By far the most abundant molecule in interstellar space is H_2, which forms via two processes:

- Via recombination of pairs of adsorbed H atoms on the surface of dust grains. For a dust-to-gas mass ratio of 1:100 (typical for low density clouds in MW), the time scale for H_2 formation on dust grains is

$$\boxed{t_{\rm form} \simeq 1.5 \times 10^7\,{\rm yr}\left(\frac{n}{100\,{\rm cm}^{-3}}\right)^{-1}}$$

- Via gas-phase reactions such as

$$H_0 + e^- \rightarrow H^- + \gamma \qquad H^+ + H_0 \rightarrow H_2^+ + \gamma$$
$$H^- + H_0 \rightarrow H_2 + e^- \qquad H_2^+ + H_0 \rightarrow H_2 + H^+$$

Overall, forming H_2 via these gas-phase reactions is far less efficient than via dust-grains.

⇒ gas-phase H_2 formation is only important in absence of dust (metals); e.g., the formation of Pop III stars (see MBW App B1.4)

The Destruction of Molecular Hydrogen

The main destruction mechanism for molecular hydrogen is photo-dissociation.

Without going into details (see e.g., Kouchi et al. 1997), the photo-dissociation rate of H_2 in the unattenuated interstellar radiation field is

$$\boxed{k_{\rm pd} \simeq 5 \times 10^{-11} {\rm s}^{-1}}$$

⇒ the life time of a typical H_2 molecule is ~600 yrs.

However, molecular clouds cause self-shielding: dust and molecular hydrogen in outer layers of cloud cause continuum and line attenuation, respectively. Hence, the inner regions of GMCs are prevented from photo-dissociation.

Detailed calculations of formation & destruction rates show that

$$\boxed{\mathcal{R}_{\rm mol} \equiv \frac{n_{\rm H_2}}{n_{\rm HI}} \propto P_{\rm ext}^{2.2}\, J^{-1}}$$

external pressure

radiation intensity

⇒ H_2 forms where external pressure is high, and radiation intensity is low

The Star Formation Efficiency

Before we focus on the formation of GMCs let us first examine the overall efficiency of SF within galaxies (rather than within individual GMCs).

time scale for star formation

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

For disk galaxies: $t_{\rm SF} \sim (1-5) \times 10^9\,{\rm yrs} \gg t_{\rm ff}$

For starbursts: $t_{\rm SF} \sim 10^7 - 10^8\,{\rm yrs} \sim t_{\rm ff}$

Question: Why is SF in disk galaxies so inefficient? In particular, in those haloes where $t_{\rm cool} < t_{\rm ff}$, why doesn't all the gas collapse and form stars?

Angular Momentum: Gas does not collapse all the way to the center of the potential well. Cooling is isotropic, and therefore conserves angular momentum. Conservation of angular momentum causes a spin up of the cooling gas, resulting in the formation of a disk galaxy in centrifugal equilibrium...

However, this is not the entire story; not all gas is in GMCs, and since stars only form out of molecular gas, part of the inefficiency of SF is related to the (in)efficiency of forming GMCs.

The Formation of GMCs

Molecular gas can form wherever pressure is sufficiently high, and radiation intensity is sufficiently low. But why is molecular gas clumpy, distributed in Giant Molecular Clouds?

Instabilities

- thermal
- gravitational
- Parker (magnetic buoyancy)

These instabilities can be triggered by a wide variety of phenomena.

Triggers

- Galaxy Formation (accretion of matter)
- Large Scale Turbulence
- Spiral arms (grand-design)
- Star formation itself
- Mergers & interactions

In addition, one instability may trigger another; for example, thermal instability may trigger gravitational instability, etc.

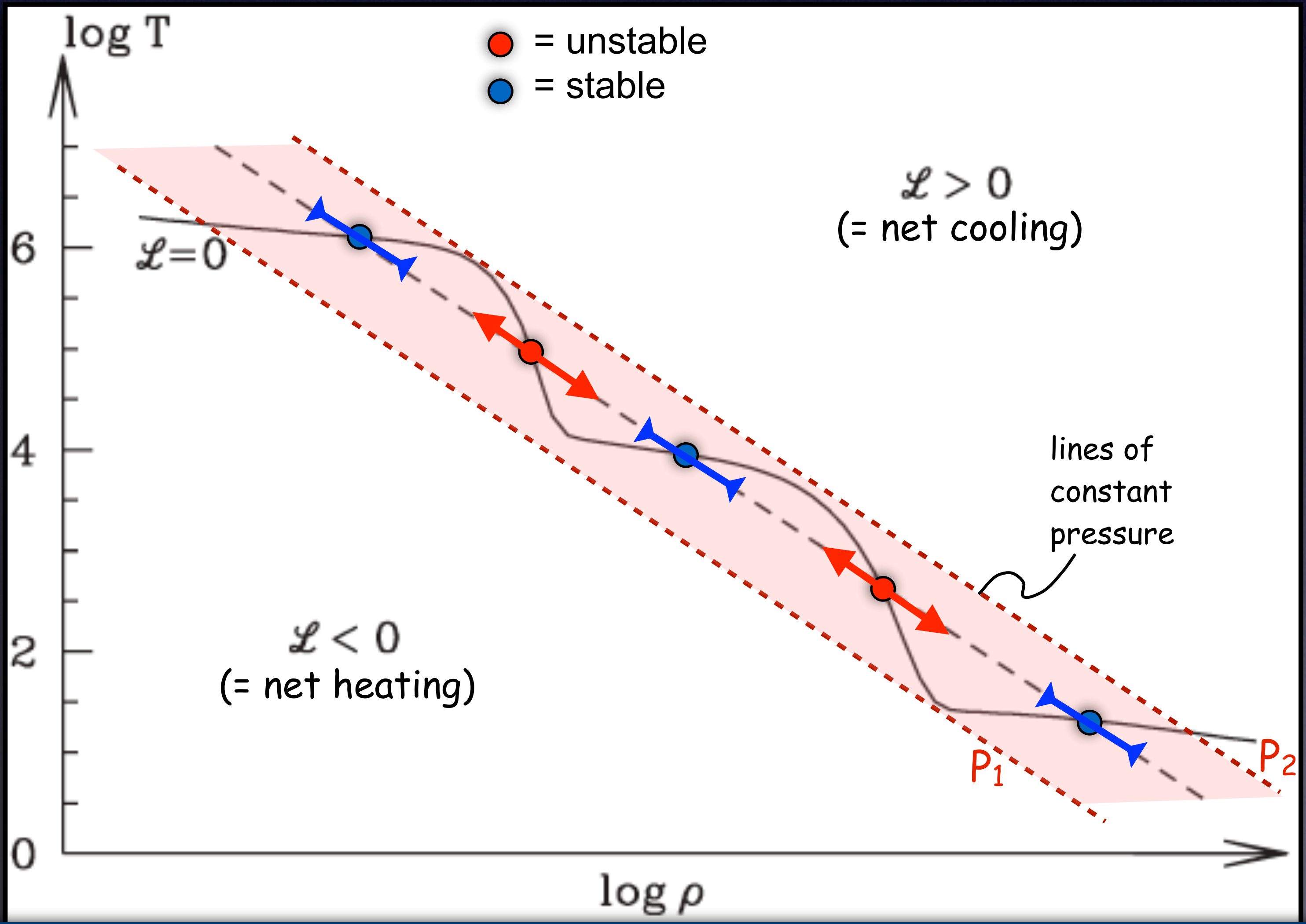
We now discuss the three instabilities mentioned above in turn, followed by brief discussion of some of the possible triggers...

Thermal Instability

A gas is said to be in thermal equilibrium if $\boxed{\mathcal{L} \equiv (\mathcal{C} - \mathcal{H})/\rho = 0}$

Since both $\mathcal{C}$ and $\mathcal{H}$ depend on n and T (for given composition and radiation field), thermal equilibrium defines a curve in the density-temperature plane.

For pressures $P_1 < P < P_2$ gas at multiple phases can coexist in pressure equilibrium. Only three of the five phases are stable, which are a hot phase ($T \sim 10^6$ K), a warm phase ($T \sim 10^4$ K), and a cold phase ($T \sim 10\text{-}100$ K).



At high pressure, the only phase in thermal equilibrium is the cold phase

ideal for GMC formation

At low pressure, the only phase in thermal equilibrium is the hot phase

no molecular gas can form

Gravitational Instability

The Jeans criterion is not the proper gravitational instability criterion to use in a disk galaxy. After all, in a disk the differential rotation makes perturbations to feel a coriolis force, which causes the perturbations to start rotating.

⇒ centrifugal force provides support against collapse

Toomre Stability Parameter

$$\boxed{Q \equiv \frac{c_s\,\kappa}{\pi\,G\,\Sigma}}$$

Here κ is the epicycle frequency:

$$\kappa = \sqrt{2}\left[\frac{V_c^2}{R^2} + \frac{V_c}{R}\frac{\mathrm{d}V_c}{\mathrm{d}R}\right]^{1/2}$$

Toomre Stability Criterion: a disk is stable against gravitational collapse if Q > 1

If Q < 1 then perturbations with size $\lambda = \lambda_{\rm crit}$ will collapse

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

For a MW-like disk galaxy, $\lambda_{\rm crit} \simeq 1\,\mathrm{kpc}$, which implies a mass

$$\boxed{M_{\rm crit} = \pi\left(\frac{\lambda_{\rm crit}}{2}\right)^2 \Sigma \simeq 2.4\times10^7\,M_\odot\left(\frac{\Sigma}{30\,M_\odot\mathrm{pc}^{-2}}\right)}$$

Gravitational Instability

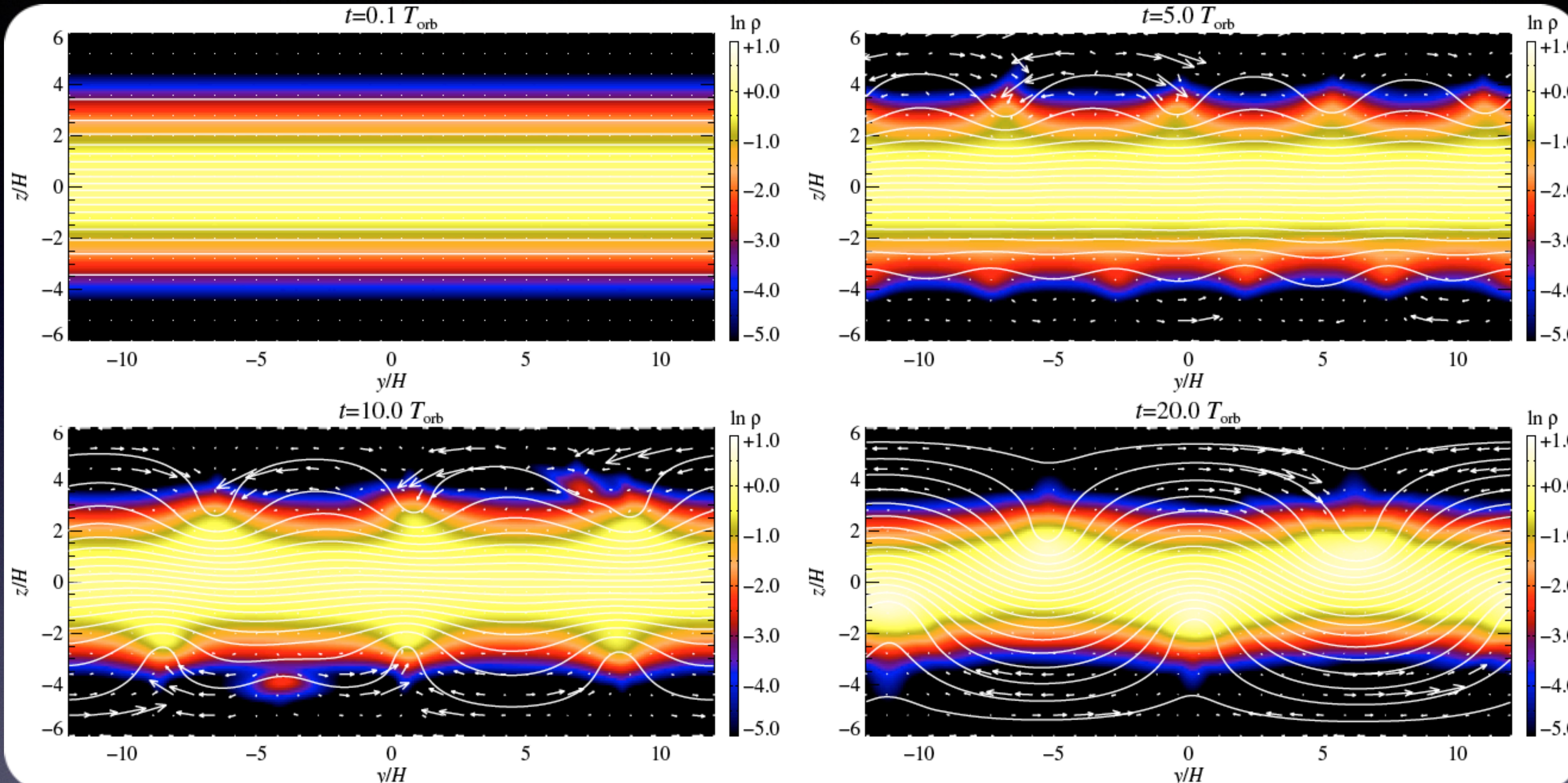
$$M_{\rm crit} = \pi \left(\frac{\lambda_{\rm crit}}{2}\right)^2 \Sigma \simeq 2.4 \times 10^7 \, M_\odot \left(\frac{\Sigma}{30 \, M_\odot {\rm pc}^{-2}}\right)$$

- If the disk becomes gravitational unstable the masses of the objects that will start to collapse are significantly more massive than typical GMCs: $M_{\rm crit} \gg M_{\rm GMC}$

Hence, mass scale of GMCs is unlikely to be directly related to gravitational instability. However, it is still possible that GMCs form via fragmentation of objects that becomes gravitational unstable.

Alternatively, in order for the mass scale of GMCs to be gravitational unstable, the disk needs to be far from stability, i.e., $Q < 0.1$. This can be accomplished if the sound-speed of the disk is sufficiently low ($c_s \sim 0.2$ km/s), which corresponds to a temperature of $T \sim 10$ K. Hence, the thermal instability may be required here...

The Parker Instability



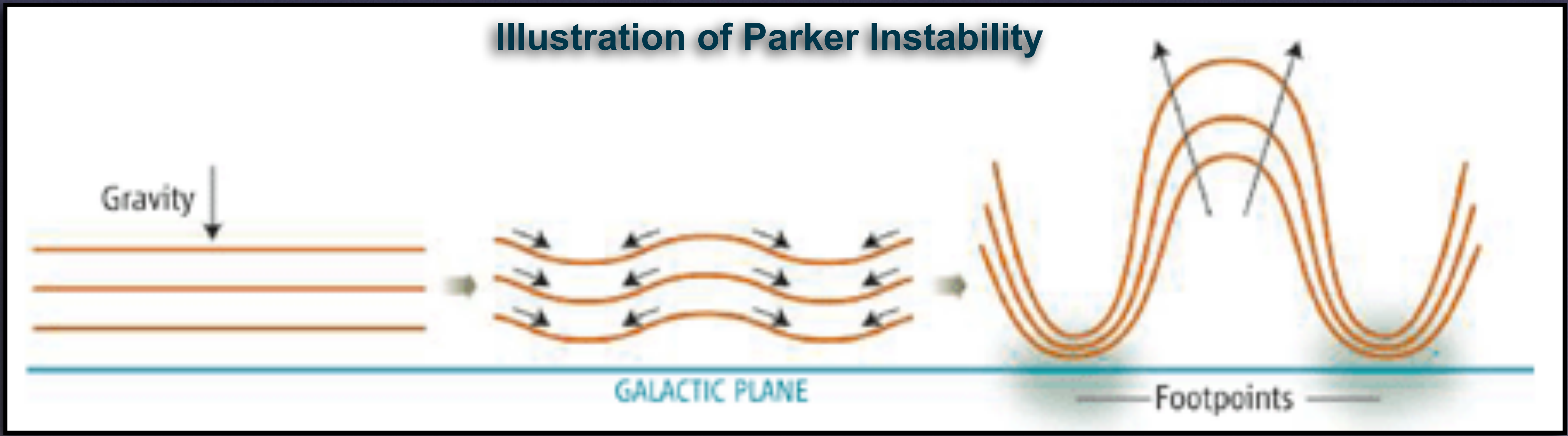
Source: Johansen & Levin, 2008, A&A, 490, 501

The Parker Instability (aka Magnetic Buoyancy Instability) works as follows: Consider a uniform, vertically stratified gas disk, coupled to a magnetic field <u>parallel</u> to the disk. Suppose dynamical equilibrium under the balance of gravity & pressure (thermal & magnetic). A small perturbation which causes field lines to rise/sink in certain parts of disk is amplified, because gas loaded onto the field lines slides of the peaks and sinks to valleys, causing further `compression’ of field lines....

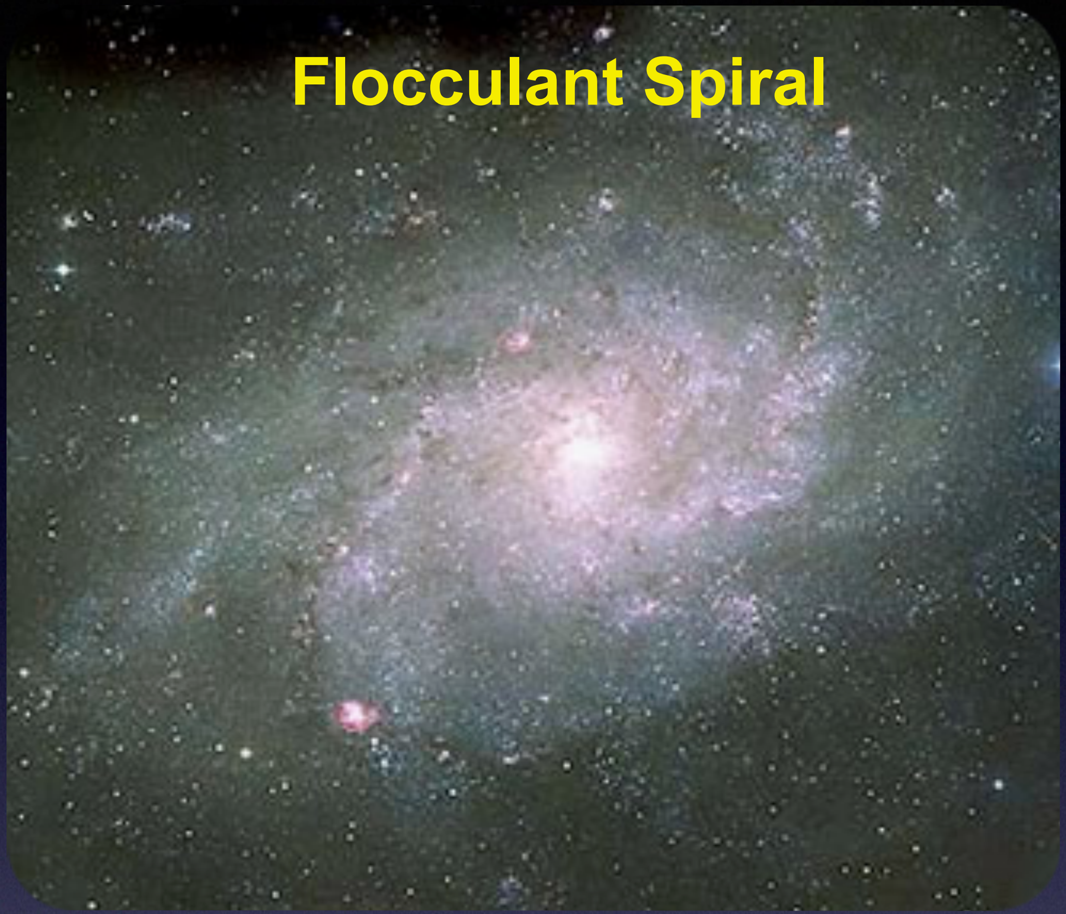
The Parker Instability

The characteristic scale for the Parker instability is ~4πH, were H is the scale height of the diffuse component of the disk. For the Milky Way, H~150 pc, and thus the Parker instability causes perturbations on scales of ~1-2 kpc.

Numerical simulations show that the density contrast generated by the Parker instability saturates when it reaches order unity. This implies that Parker instability on its own may not be sufficient to drive gravitational collapse on large scales, but it may be an important trigger in an otherwise marginally stable disk... It may also act as a source of turbulence.



Spiral Arms

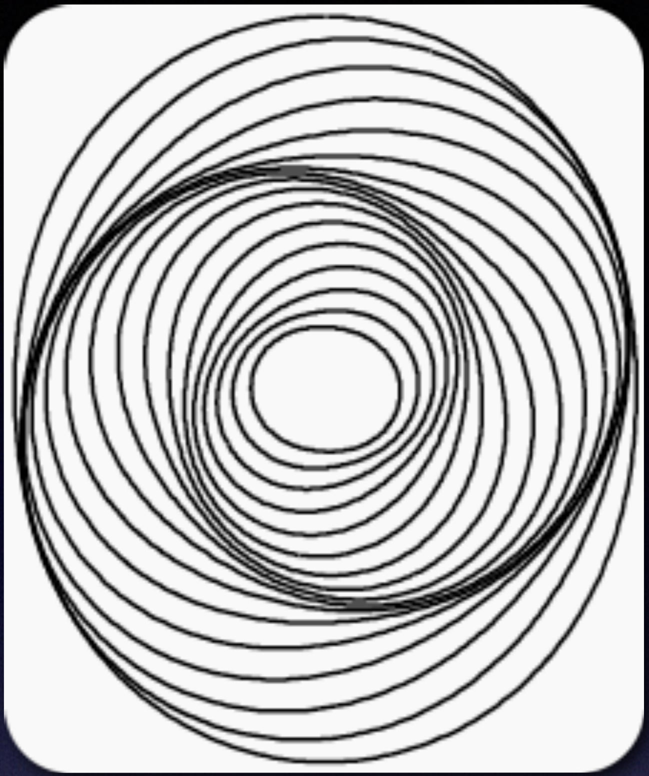


Grand-Design Spirals are believed to be density waves that rotate around center with certain pattern speed. Whenever a gas cloud moves through such a spiral arms, it is compressed, which triggers star formation. Here the spiral arms trigger star formation...

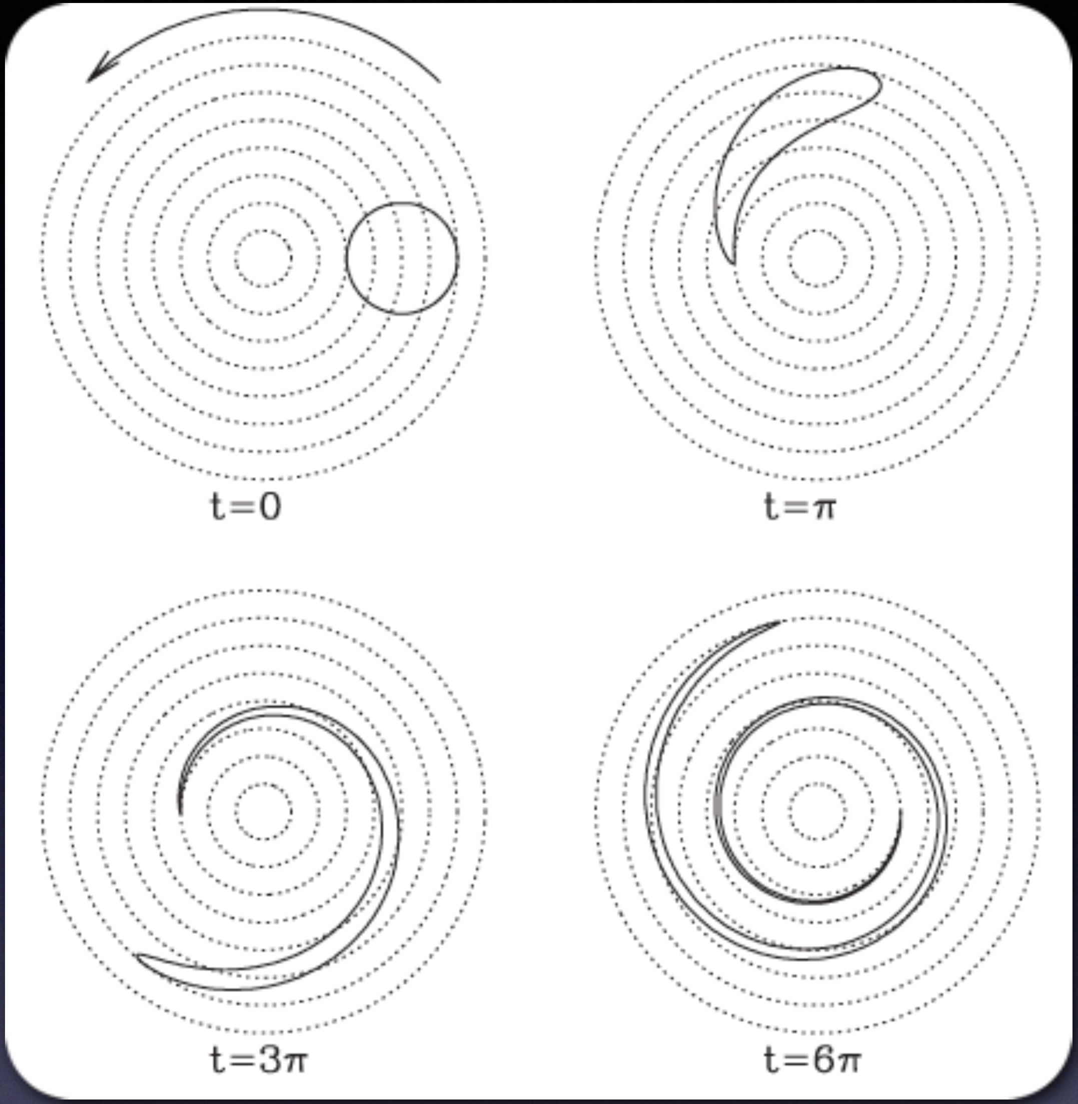
Flocculant spirals are believed to be short-lived, transient features that form due to differential rotation that results in shearing of local instabilities. These spirals are a consequence of local instabilities...

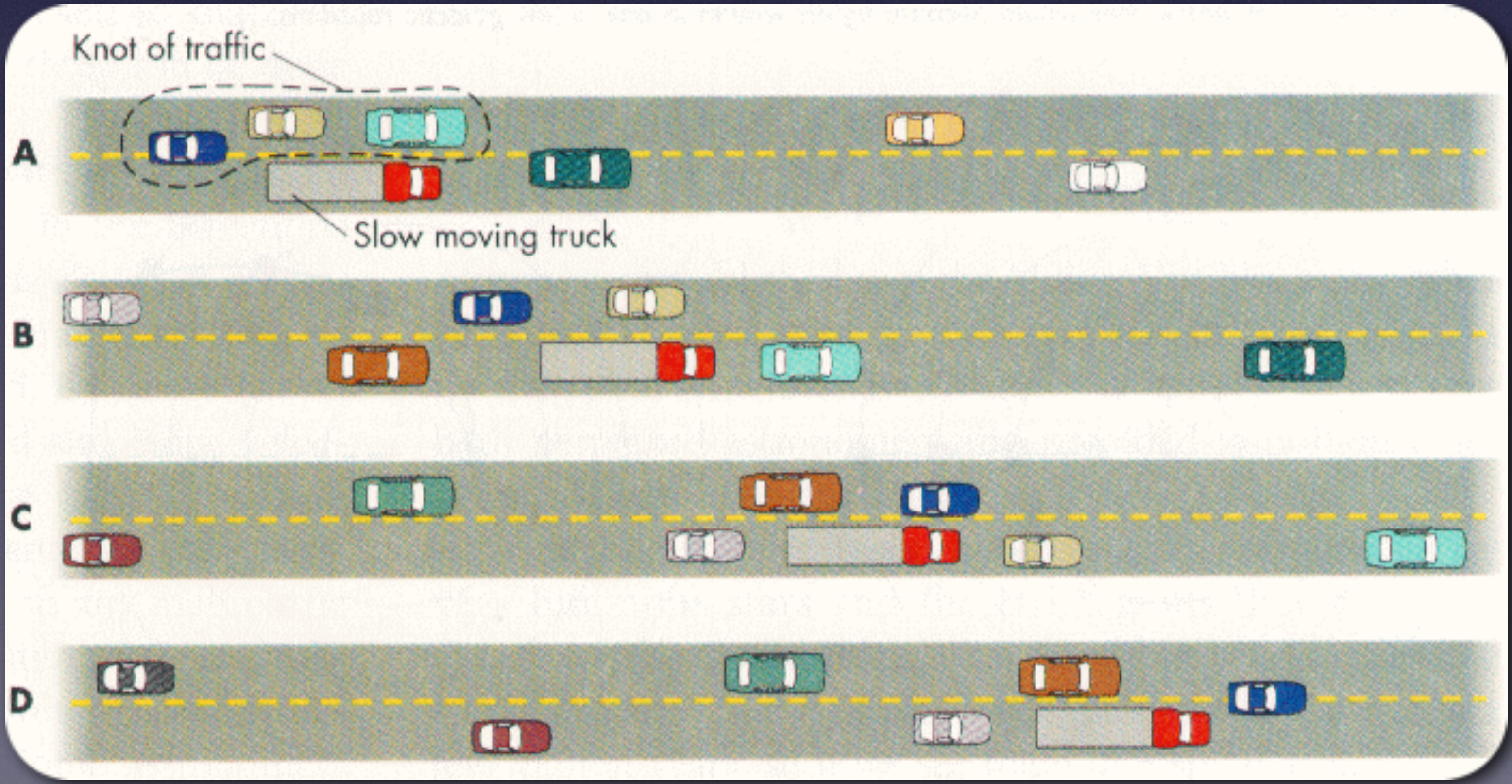
(Students: read MBW §11.6 for details)

Spiral Arms



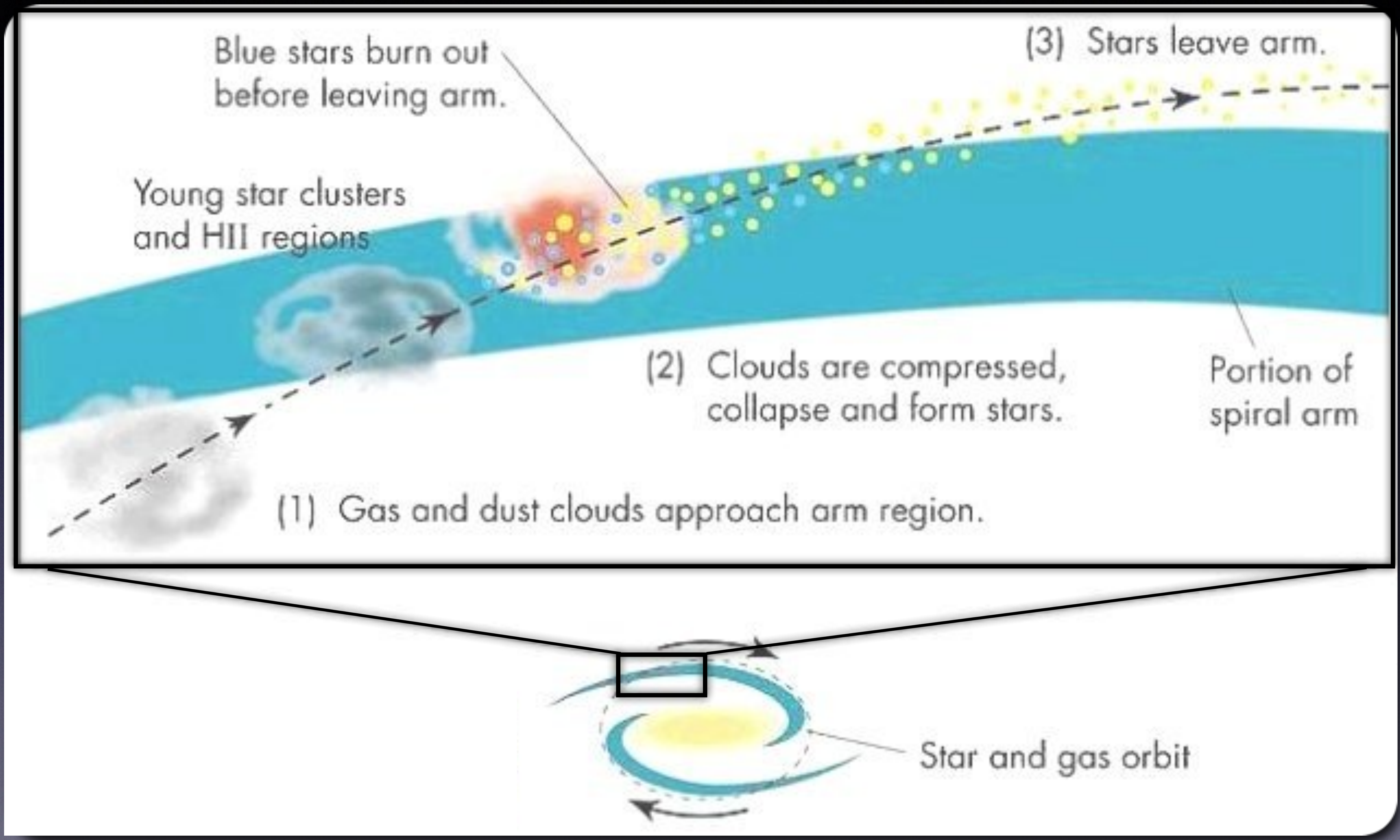
Spiral density waves are a manifestation of orbit crowding; Stars and gas clouds overtake (or are overtaken) by the density wave, but are not continuously part of it. Analogy: traffic crowding around slow moving truck....





For comparison, flocculant spirals are always made-up out of the same material. Hence, they are also called material arms. Because of winding, they are short-lived (transient) features...

Triggering SF with Density Waves

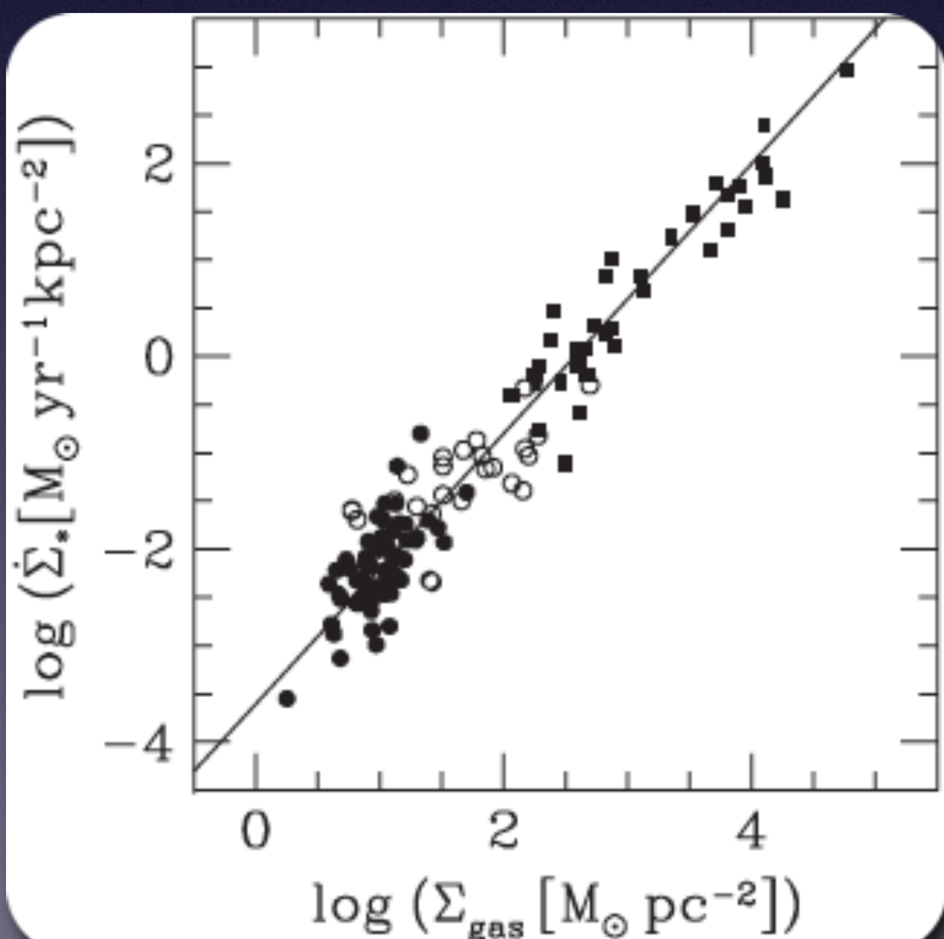


Empirical Star Formation Laws

In galaxy formation modeling, we rarely if ever resolve the ~20 orders of magnitude in density relevant for SF. Since we lack proper theory of SF, one typically resorts to (empirical) star formation laws, which are scaling relations between the SFR and global properties such as the gas density, temperature, metallicity etc.

It is common to characterize the SFR in a galaxy in terms of the mass in stars formed per unit time per unit area (at least in disks): $\dot{\Sigma}_* = \dot{M}_*/\mathrm{area}$

A related quantity is the gas consumption timescale $\tau_{\rm SF} \equiv \Sigma_{\rm gas}/\dot{\Sigma}_*$



The most well-known empirical Star Formation Law is the

Kennicutt-Schmidt law:

atomic + molecular

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

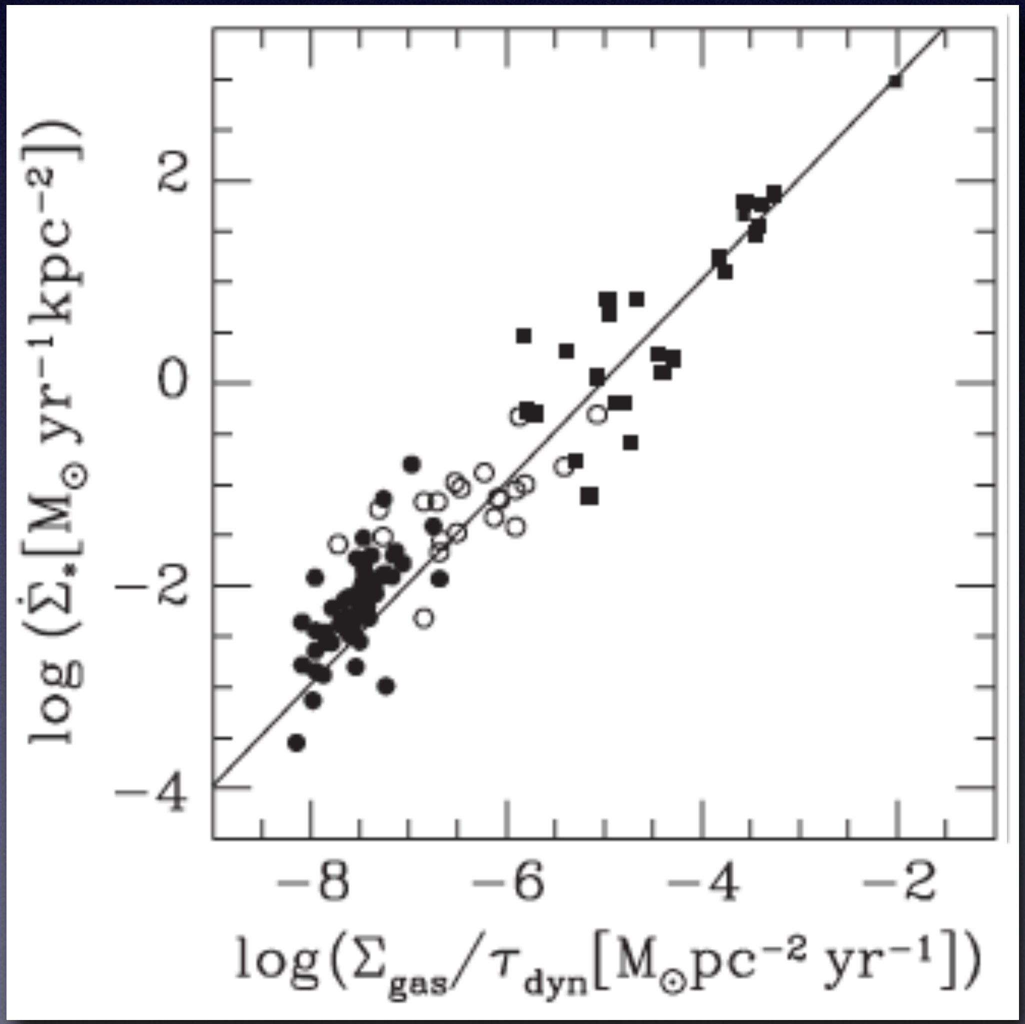
which is a good fit to the global (=averaged over entire galaxies) SFRs of galaxies over ~5 magnitudes in gas surface density (see fig to the left).

Note: a power-law relation $\dot{\Sigma}_* \propto \Sigma_{\rm gas}^n$ is called a Schmidt-law.

Empirical Star Formation Laws

Caution: the KS-law is often interpreted as indicating that SFR is controlled by self-gravity of the gas. In that case $\dot{\rho}_* = \epsilon_{\rm SF} \frac{\rho_{\rm gas}}{t_{\rm ff}} \propto \rho_{\rm gas}^{1.5}$, and if all galaxies have roughly similar scale-heights, this also implies that the SFR surface density $\dot{\Sigma}_* \propto \Sigma_{\rm gas}^{1.5}$. However, $\epsilon_{\rm GF} \ll 1$ which indicates that simple self-gravity can't be the entire picture...

Be careful using global, empirical SF laws to constrain physics of star formation: global properties integrate over many orders of magnitude in scales and physical processes....



For example, Kennicutt has shown that his data that implied the KS-law also reveals a tight correlation between $\dot{\Sigma}_*$ and $\Sigma_{\rm gas}/t_{\rm dyn}$.

Defining: $t_{\rm dyn} = t_{\rm orb} = 2\pi R/V_{\rm rot}(R)$ where R is chosen to be the outer edge of the star forming disk, Kennicutt found that

$$\boxed{\dot{\Sigma}_* \simeq 0.017\, \Sigma_{\rm gas}\, \Omega}$$

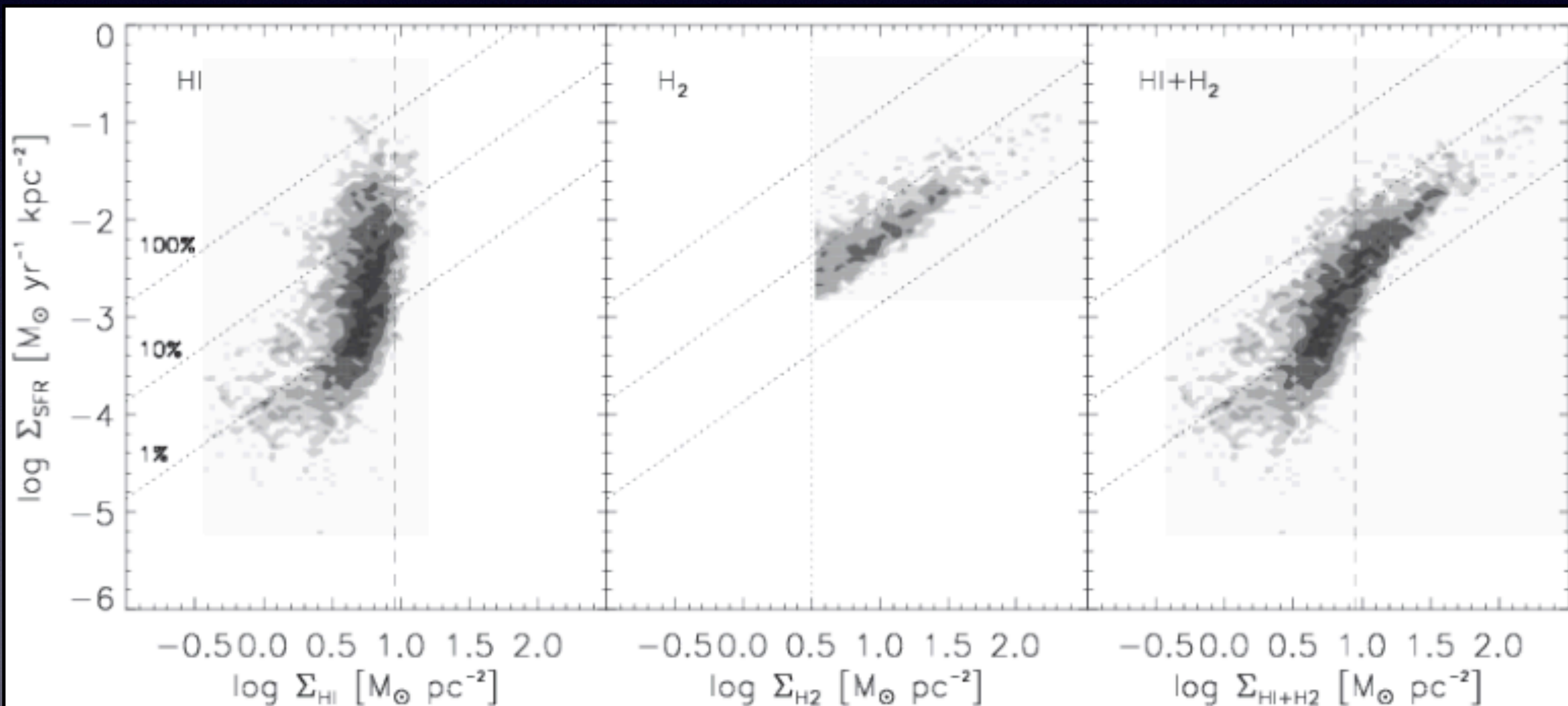
with $\Omega \equiv V_{\rm rot}(R)/R$ the orbital frequency.

~10% of gas is consumed by SF per orbital time

Local Star Formation Laws

Rather than measuring $\dot{\Sigma}_*$, $\Sigma_{\rm gas}$, Ω etc globally (i.e., averaged over entire galaxies), one can also measure these quantities locally (averaged over a narrow radial range, or even per pixel).

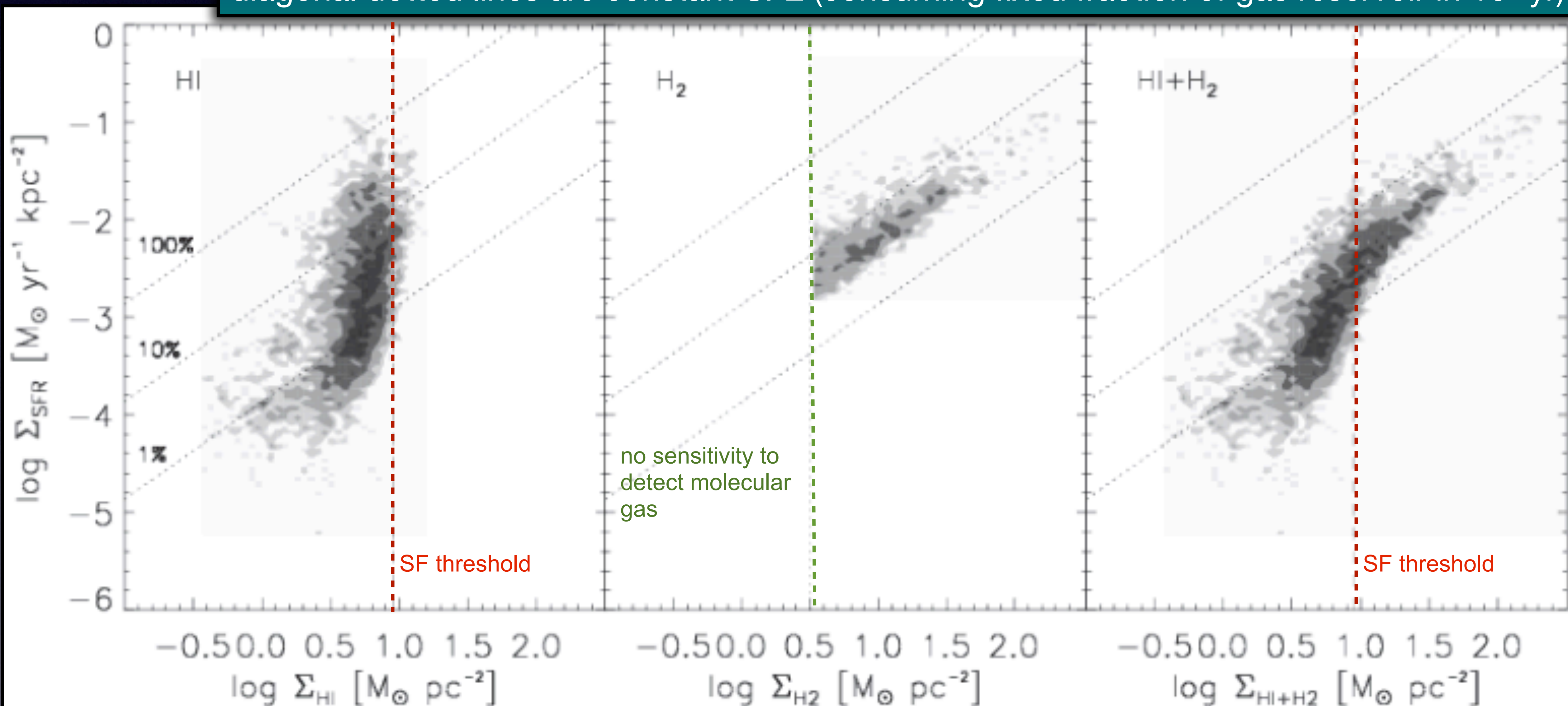
Such data has shown that there is no local equivalent of relation between $\dot{\Sigma}_*$, $\Sigma_{\rm gas}$ and Ω , indicating that the SF efficiency has little to do with the local orbital time.



Local Star Formation Laws

The local data does reveal an equivalent of the KS-law, but with one modification: there is a pronounced break in the power-law behavior near $\Sigma_{\rm gas} \simeq 10\, M_\odot {\rm pc}^{-2}$.
This break is interpreted as a SF threshold. By splitting gas in atomic and molecular, it is clear that threshold coincides with atomic-to-molecular transition...

grayscale is proportional to number of pixels (~750 pc size) in the data (18 galaxies)
diagonal dotted lines are constant SFE (consuming fixed fraction of gas reservoir in 10^8 yr).



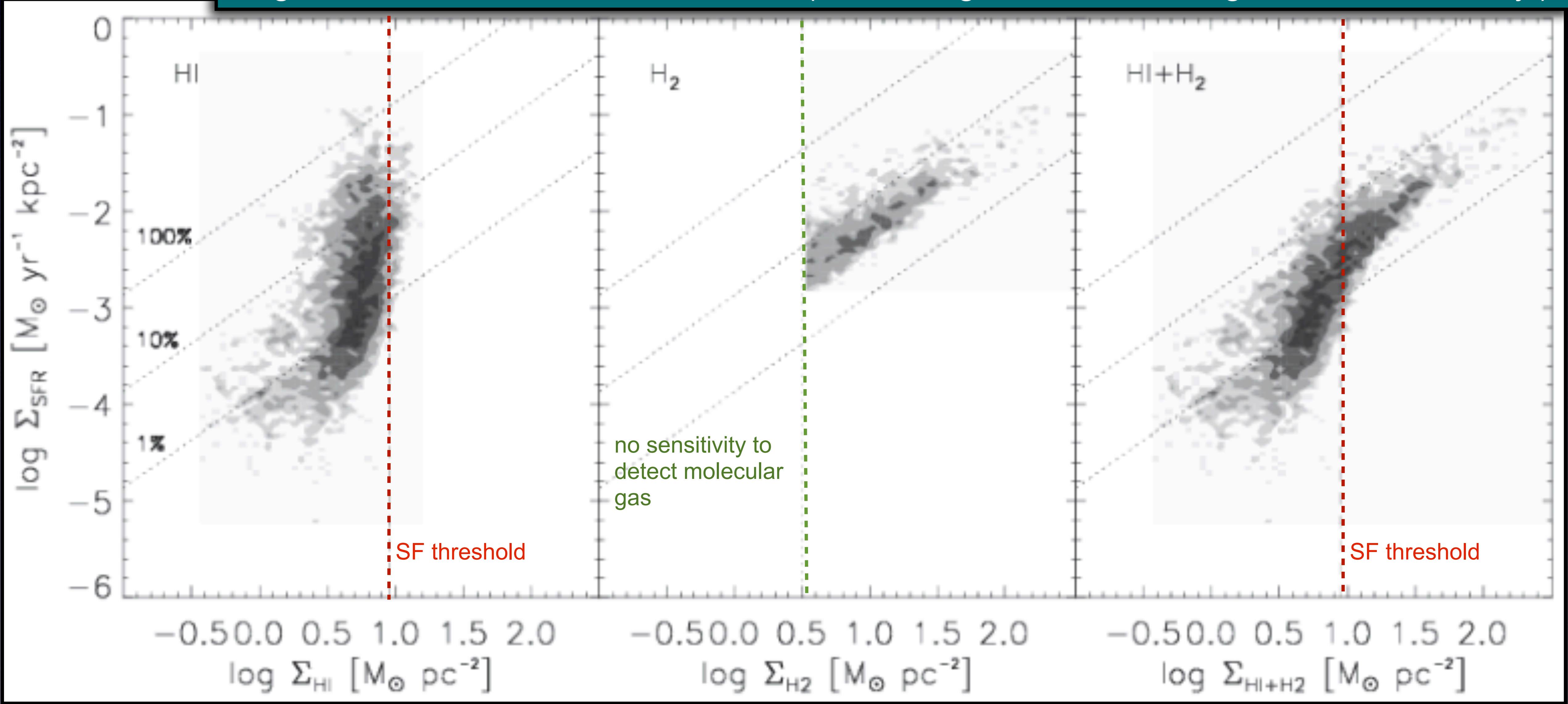
Source: Bigiel et al. 2008, AJ, 136, 2846

Local Star Formation Laws

Clearly, atomic gas is an extremely poor indicator of star formation. In the case of molecular gas, however, there is a well defined Schmidt law, with slope $n = 1.0 \pm 0.2$

$$\boxed{\dot{\Sigma}_* \simeq 7 \times 10^{-4} \left(\frac{\Sigma_{\rm H_2}}{M_\odot \, {\rm pc}^{-2}} \right)^{1.0} M_\odot \, {\rm yr}^{-1} \, {\rm kpc}^{-2}}$$

grayscale is proportional to number of pixels (~750 pc size) in the data (18 galaxies)
diagonal dotted lines are constant SFE (consuming fixed fraction of gas reservoir in 10^8 yr).



Source: Bigiel et al. 2008, AJ, 136, 2846

Star Formation in Semi-Analytical Models

The empirical SF laws discussed above are often used to "model" star formation in galaxy formation modeling. For example, many SAMs adopt

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

and set $\varepsilon_{\rm SF} \simeq 0.1$, in agreement with the empirical findings of Kennicutt, or they treat $\varepsilon_{\rm SF}$ as a free parameter, to be constrained by the data.

Some SAMs even go so far to adopt a scaling

$$\boxed{\varepsilon_{\rm SF} = \varepsilon_{\rm SF,0} \left(\frac{V_{\rm vir}}{200\,{\rm km/s}}\right)^{\alpha_{\rm SF}}}$$

where both $\varepsilon_{\rm SF,0}$ and $\alpha_{\rm SF}$ are treated as free parameters...

Some SAMs also include star formation thresholds, but this requires a model for how the gas is spatially distributed within a (disk) galaxy, which is not always modeled very rigorously...

Lecture 16 Summary

- At high gas densities ($\Sigma_{\rm gas} > 10\, M_\odot {\rm pc}^{-2}$) conditions are such that self-shielding becomes efficient, and molecular gas forms.

- Various mechanisms trigger instabilities, creating GMCs supported by supersonic turbulence.

- Turbulent compression creates clumps and cores; the latter are Jeans unstable and collapse to form stars.
  Overall SFE per GMC is low $\varepsilon_{\rm SF,GMC} \sim 0.002$

- At low gas densities ($\Sigma_{\rm gas} < 10\, M_\odot {\rm pc}^{-2}$) star formation is suppressed, due to inability for gas to self-shield (i.e., form molecules), and due to reduced self-gravity, which enhances stability.

- Mergers and tidal interactions cause efficient transport of angular momentum out (funneling gas in). This boosts efficiency of creating GMCs, so that galaxy enters starburst phase.

- Energy and momentum injection due to star formation process itself is likely to be important regulator of star formation efficiency in GMCs.

Merger Induced Starburst

Source: Phil Hopkins