On the Timescale for Star Formation in Galaxies

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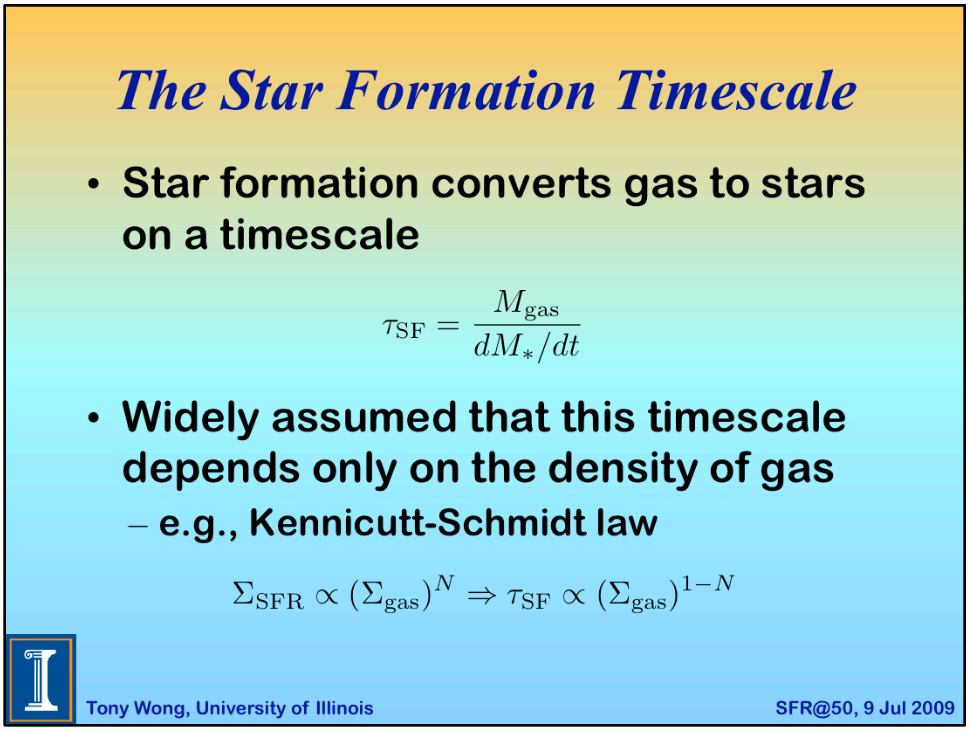
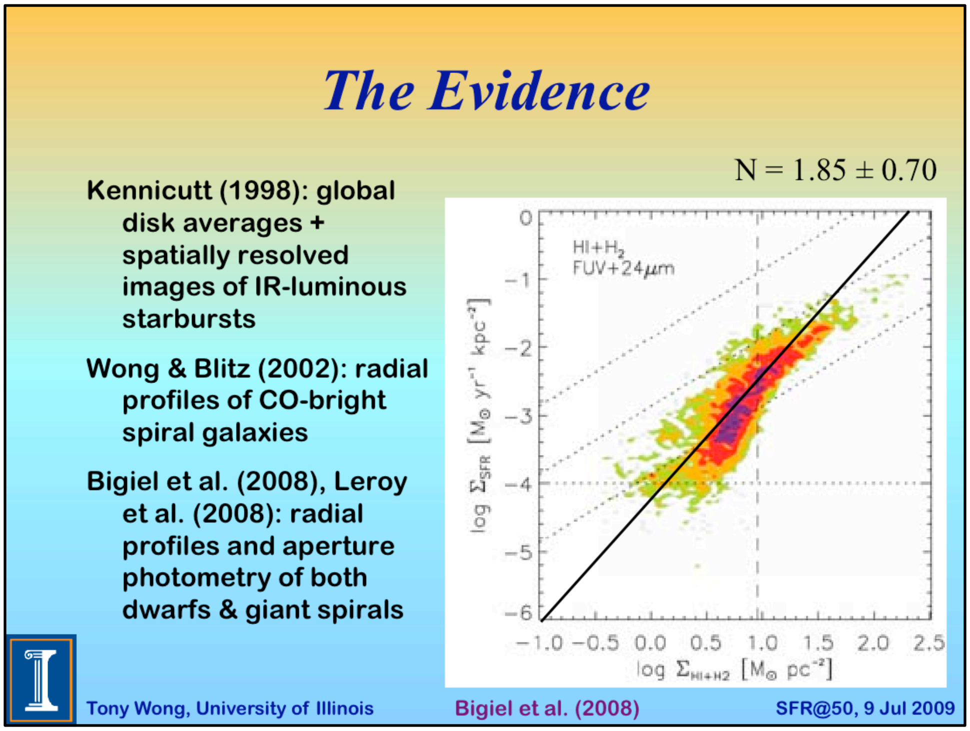


We define the SF timescale as simply the time over which the current SFR would turn all of the available cold gas into stars. The most common assumption is that this timescale depends only on the gas density or surface density For instance the KS law shown here leads to a SF timescale that scales as a negative power of the gas surface density for N>1.



The K-S law is attractive because of its simplicity, and it has been the subject of numerous observational studies, especially since CO imaging of external galaxies became available in the 1990's. I'll just mention here the seminal paper by Rob, which established the overall correlation on global scales, the study I did in my thesis work on the radial Schmidt law in CO-bright galaxies, and the more recent works by Frank Bigiel, Adam Leroy, and collaborators examining both the radial and local Schmidt law in a wider variety of galaxies. The overall correlation has a power law index of about 1.85, but with considerable scatter, especially at the low-density end, as we heard on Monday.

How to explain N=2?

- **Jeans rate: natural growth rate for disk instabilities**

$$\omega_{\rm J} = \frac{\pi G \Sigma_g}{c_g} = \frac{\kappa}{Q} \quad \Rightarrow \quad \Sigma_{\rm SFR} \propto \Sigma_g \omega_{\rm J} \propto \frac{\Sigma_g^2}{c_g}$$

- **Since κ ~ Ω in real galaxies (to within a factor of 2), orbital rate also works:**

$$\omega_{\rm J} = \Omega\, Q^{-1} \quad \Rightarrow \quad \Sigma_{\rm SFR} \propto \Sigma_g \Omega \qquad \text{if Q ~ const.}$$

- **Free-fall rate at midplane density also similar:**

$$\omega_{\rm ff} \sim (G\rho_0)^{1/2} \sim \left(\frac{G\Sigma_g}{H}\right)^{1/2} \qquad H = \frac{c_g^2}{\pi G \Sigma_g} \Rightarrow \omega_{\rm ff} \sim \frac{G\Sigma_g}{c_g} \sim \omega_{\rm J}$$

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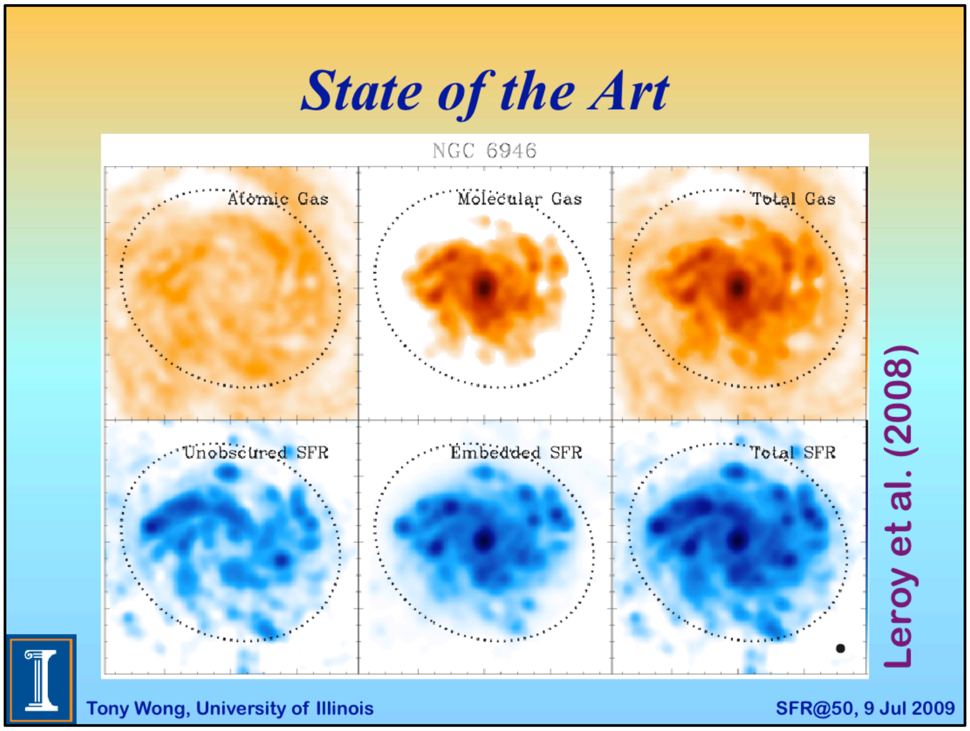
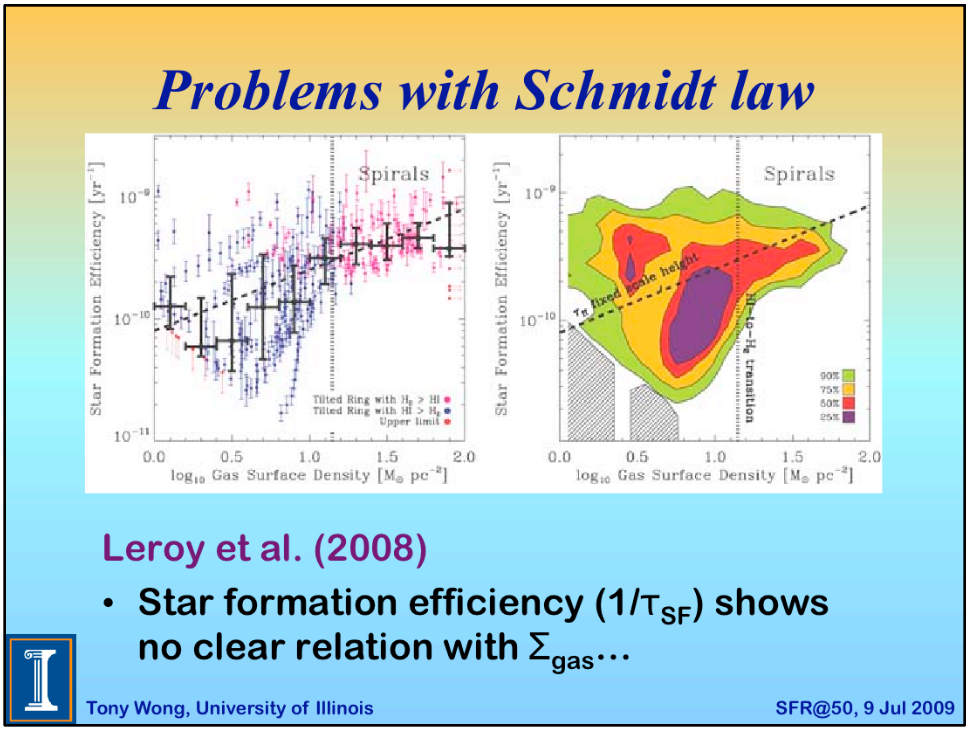
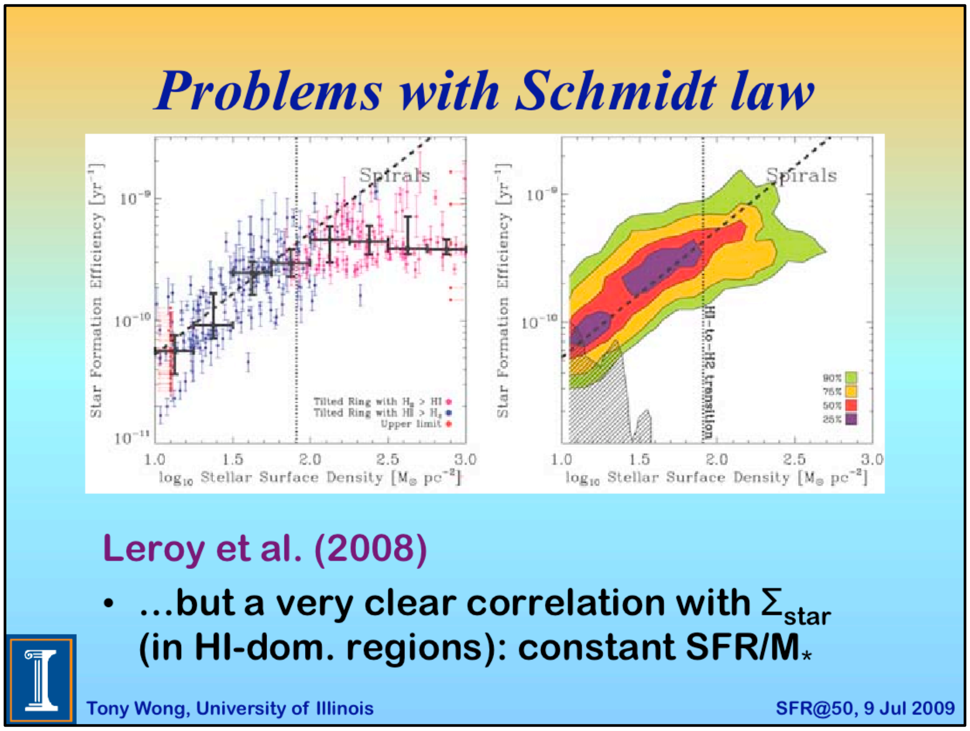
In fact there is good theoretical motivation for a KS index of around 2. The natural growth rate for gravitational instabilities in a disk is the Jeans rate, which is proportional to Sigma_g for a constant gas velocity dispersion. If gas converts to starts at a rate proportional to the Jeans rate, then N=2 follows. Since for a constant Q parameter, as is often assumed, the Jeans rate is proportional to the rotation rate, an alternative star formation law involving the orbital rate is more or less equivalent. Finally, if you calculate the free-fall rate at the expected midplane density, you also get the same rate. So the KS law seems fairly robust, much to the consternation of the theorists.



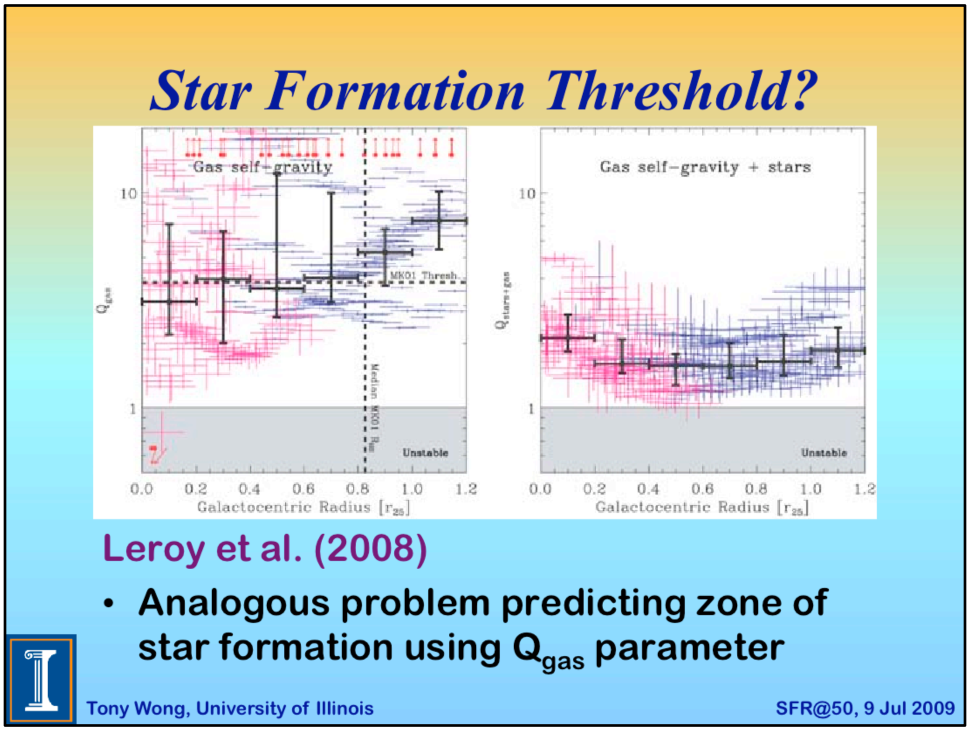
However, as Rob noted in his opening talk, the quality of the data is forcing us to look at the problem anew. Let me again highlight the THINGS dataset presented by Adam and Frank, which has synthesized the best available data: CO and HI for gas, FUV and 24-micron for the SFR.



This plot from Leroy et al. (2008) has really been a revelation. It shows the reciprocal of the radially averaged SF timescale vs. gas density, and the same relation measured in individual apertures. The dashed line is the commonly used N=1.5 Schmidt law. It's not a good description of the data. Indeed, no power law relation involving Sigma_gas can be a good description of the data.



On the other hand, there is a good relationship between the SF timescale and the stellar surface density, indeed a fairly linear one. This had been hinted at by earlier HI work of Ryder & Dopita, and Hunter, Elmegreen, & Baker, but is now unambiguous, and clearly a property of the HI only.



The stars also seem to be important for any kind of gravitational instability. We used to think the Toomre Q parameter was regulated to be close to 1 in the inner disk, and a slight increase in the outer disk led to a cutoff in star formation. Now we know that measured Q parameters are all over the place, there is no outer disk cutoff for SF, and that it’s the combined instability parameter of gas and stars that appears to be kept close to 1.

Including Effect of Stars

- **modified Jeans rate (Talbot & Arnett 1975)**

$$\omega_{\rm J} = \pi G \left(\frac{\Sigma_*}{c_*} + \frac{\Sigma_g}{c_g} \right) = \frac{\pi G \Sigma_g}{c_g} \boxed{\left(1 + \frac{c_g}{c_*} \frac{\Sigma_*}{\Sigma_g} \right)}$$

correction factor

- **modified free-fall rate (Leroy et al. 2008)**

$$\omega_{\rm ff} = \left(\frac{32\pi}{3} G \rho_0 \right)^{1/2} = \frac{4\pi G \Sigma_g}{\sqrt{3} c_g} \left(1 + \frac{c_g}{c_*} \frac{\Sigma_*}{\Sigma_g} \right)^{1/2}$$

- **Orbital rate unchanged, but $\Omega/\omega_{\rm J}$ is now an effective Q (including stars):**

$$\omega_{\rm J} = \Omega(Q^{-1} + Q_*^{-1}) = \Omega\, Q_{\rm eff}^{-1}$$

Wang & Silk (1994)

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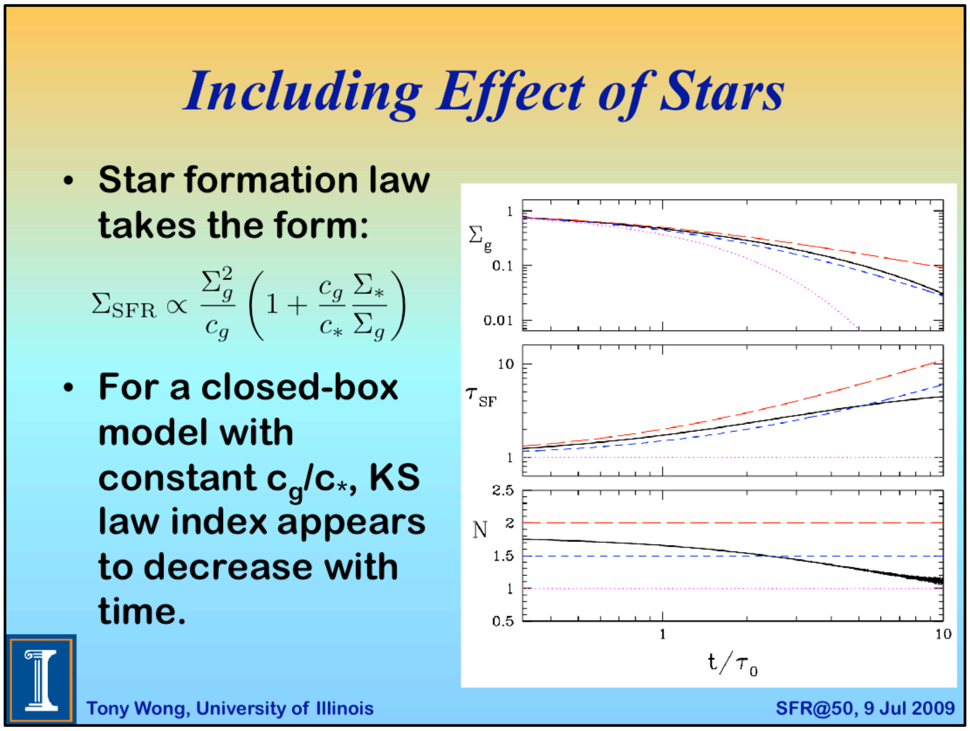
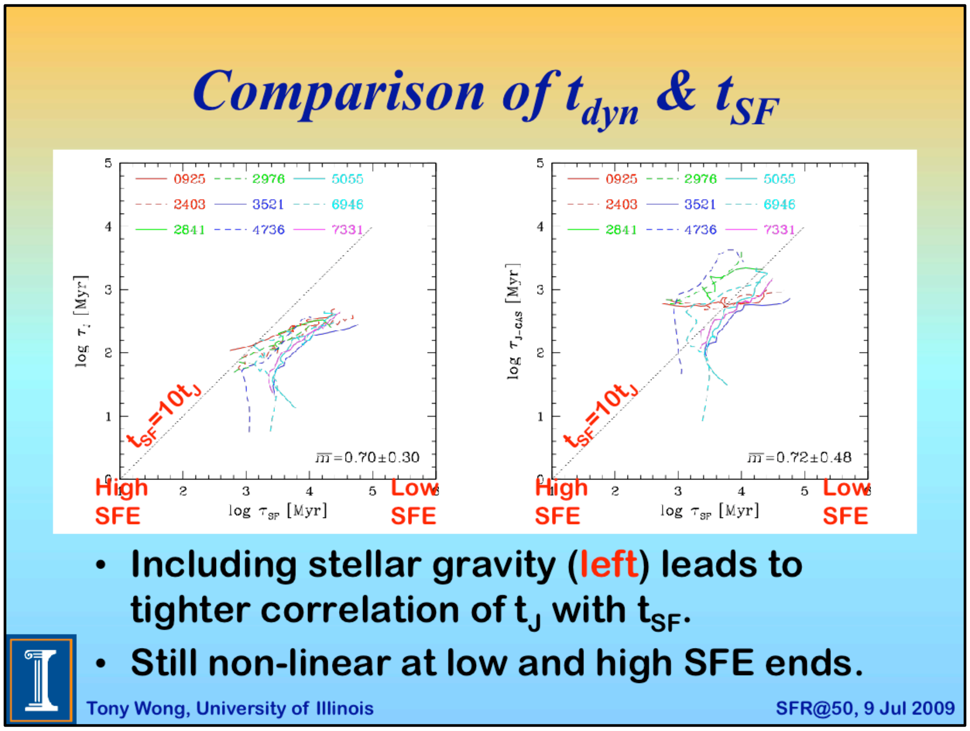
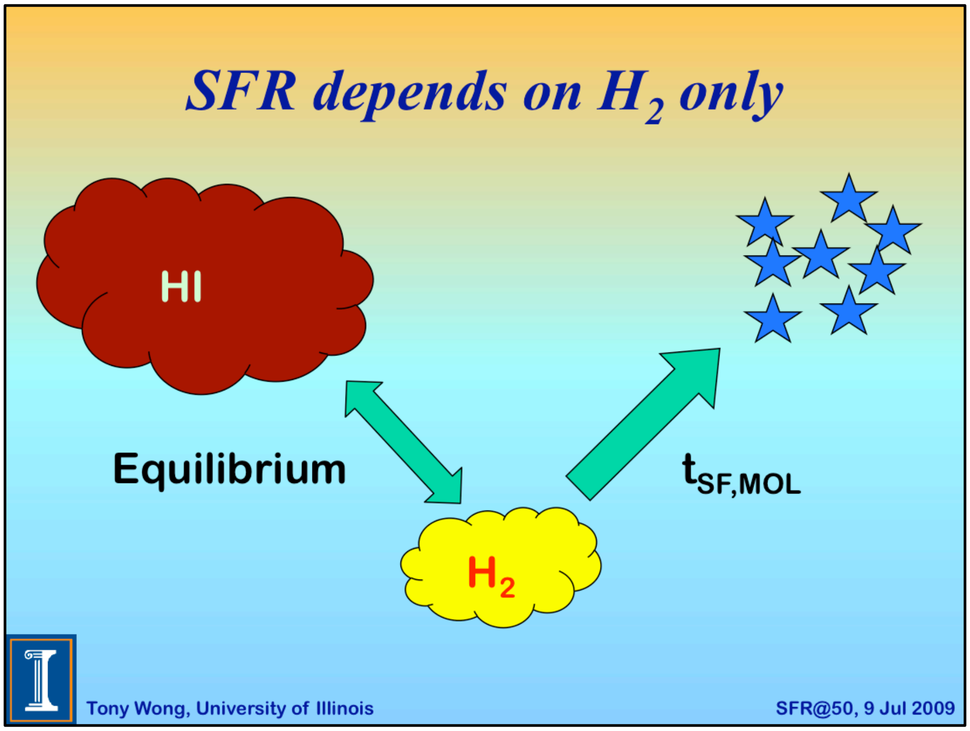
How do we include the effect of stars? One simple way is to simply add a term to the Jeans rate, as done by Talbot & Arnett, which leads to a correction factor as shown here. You'll note that this correction factor tends to reduce the Schmidt law index below 2, as expected from most observations. I should also point out that there are analogous timescales based on the free-fall rate, as given by Leroy et al., and, the orbital rate, which is still the same as the Jeans rate if the effective Q parameter including stars is close to 1.



So if we take the modified Jeans rate as determining the SFR, the K-S takes this form. What would the consequences be for galaxy evolution? Well, for a simple closed-box model the evolution is easily determined. Gas is consumed similar to what you'd find for an N=1.5 Schmidt law, and the instantaneously observed Schmidt law index decreases with time, from around N=2 to N=1. Of course, real galaxies are not closed boxes, but this calculation underscores the need for caution in applying the K-S law to relatively young systems.

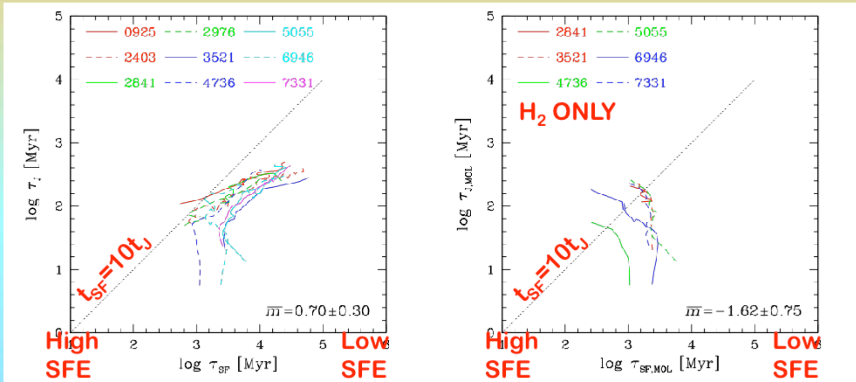


How well does this new prescription actually work? I show here a comparison between the Jeans timescale and the star formation timescale for 9 galaxies in the Leroy et al. sample, both HI and H_2 dominated. Including the correction factor as we've done in the left panel clearly improves the correlation, but does not make it linear. The dashed line here indicates that the SF timescale is 10 times the dynamical timescale. Compared to the Jeans timescale, the SF timescale is too long, both in the inner disks of H_2-dominated galaxies and the outer disks of HI-dominated galaxies. Similar problems occur for the free-fall and orbital rates, as Leroy et al. have pointed out. It's possible that the molecular content in the inner disk is overestimated, due to a change in the XCO factor, and that some of the outer HI is not involved in SF. But at face value, the simple dynamical argument doesn't seem to account for the data.



Let's briefly look at a couple of alternatives. First, suppose that some equilibrium in the HI to H_2 ratio has been established, and the SF timescale only reflects what's happening in the molecular gas. Does the dynamical timescale explain this timescale?

Two-Phase Model (I)



- **Counting only H_2: no correlation with t_{SF}!**
- **If SF only involves H_2, its rate must be set by other factors.**

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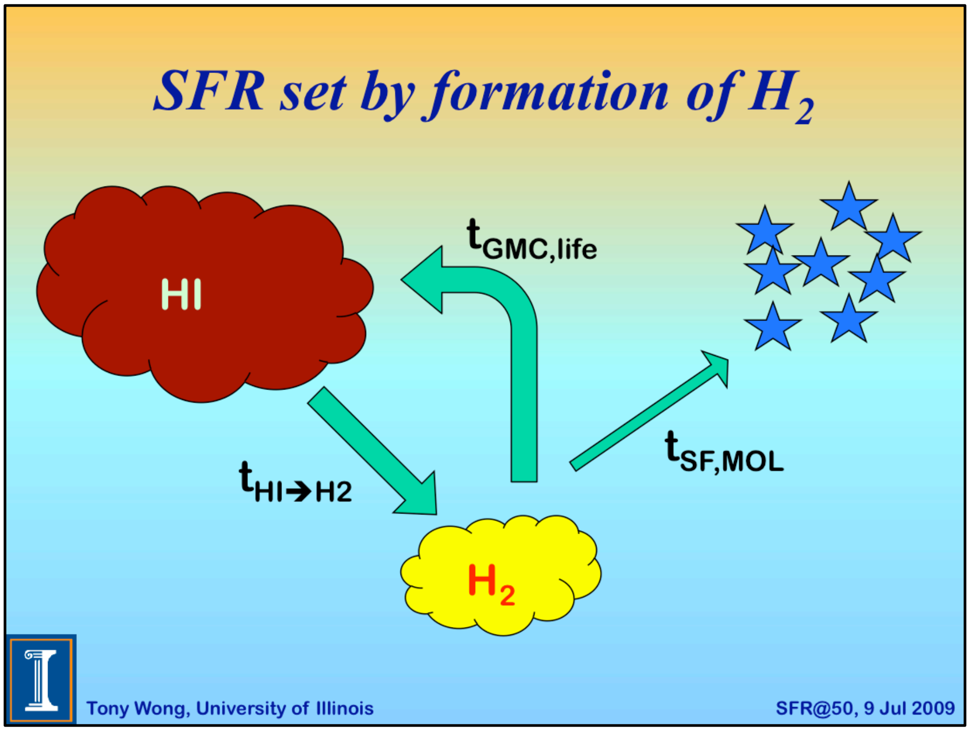
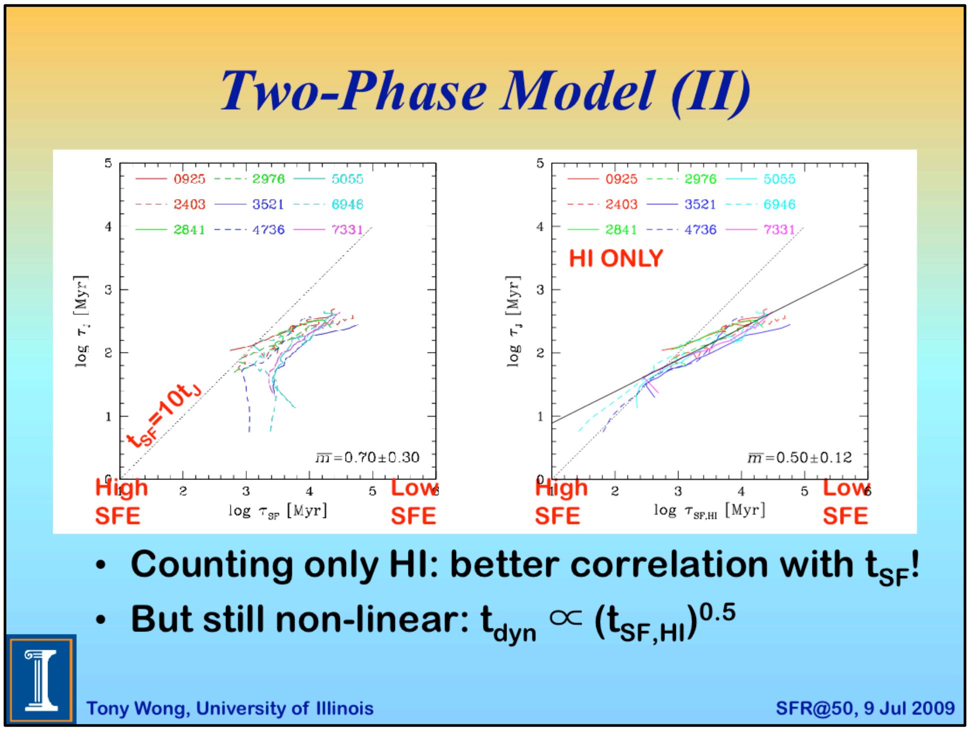
The answer is no: as we've seen, the SF timescale in molecular gas is relatively constant at around 2 Gyr, whereas the dynamical timescale varies considerably with radius. So if SF only involves molecular gas, its timescale must be determined by other factors. Of course, the obvious candidate is that it's the dynamical time on the scale of a GMC, rather than on galactic scales, which is the controlling factor.



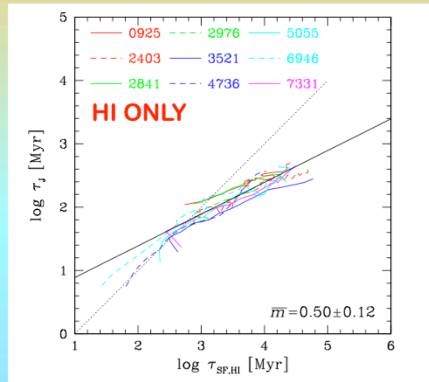
Let's consider an alternative description. Here we no longer assume that HI and H_2 are always in equilibrium: the timescale for converting one to the other is actually an important influence on the star formation time. Physically this is reasonable: crossing times are longer on larger scales, so the bottleneck for star formation may well be on those large scales. On the other hand, we've added complexity to the model by introducing two additional timescales: the timescale for forming molecular gas from atomic gas, and the timescale for molecular gas dispersal.



Unfortunately it's hard to observe the GMC formation time directly, so the best we can do is measure timescale for star formation to consume the HI, and hope that the SFR is proportional to the GMC formation rate. When we do that, we do see a good correlation with the dynamical timescale. But it's not linear: the dynamical timescale appears to scale with the square root of the HI-derived star formation time.

An HI-based SF Law

- $t_{dyn} \propto (t_{SF,HI})^{0.5}$ inconsistent with a steady state unless GMC lifetimes anticorrelate with dynamical time:



$$\frac{M_{\rm HI}}{t_{\rm HI\rightarrow H_2}} = \frac{M_{\rm H_2}}{t_{\rm GMC,life}} \propto \frac{\rm SFR}{t_{\rm GMC,life}}$$

$$t_{\rm SF,HI} = \frac{M_{\rm HI}}{\rm SFR} \propto \frac{t_{\rm HI\rightarrow H_2}}{t_{\rm GMC,life}} \Rightarrow \boxed{t_{\rm GMC,life} \propto (t_{\rm dyn})^{-1}}$$

$$\text{if} \quad t_{\rm HI\rightarrow H_2} \propto t_{\rm dyn}$$

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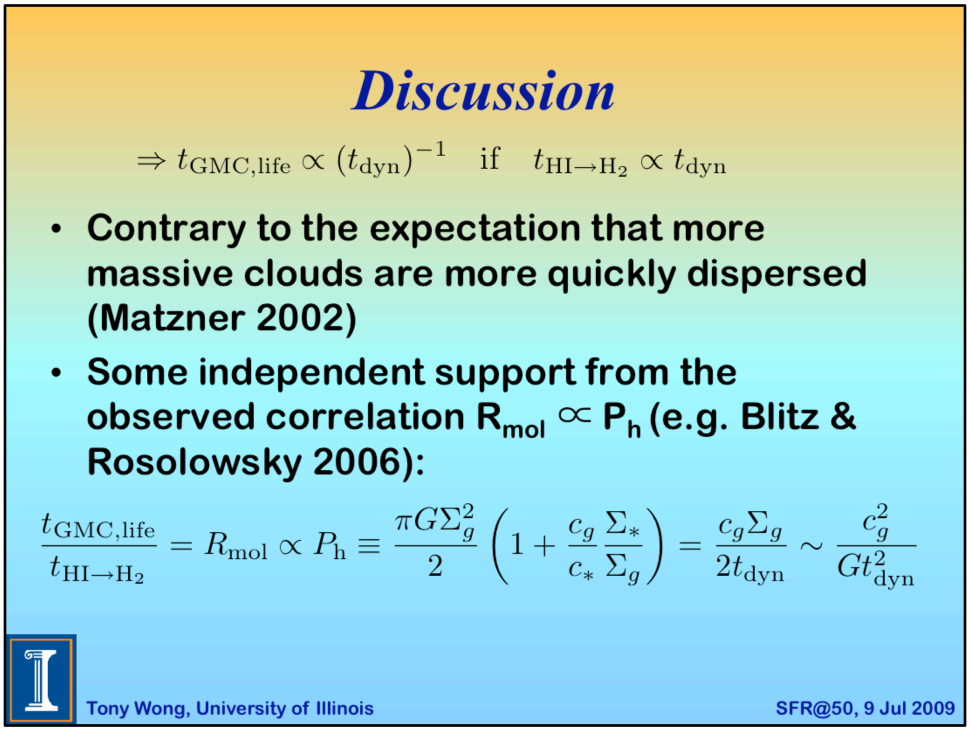
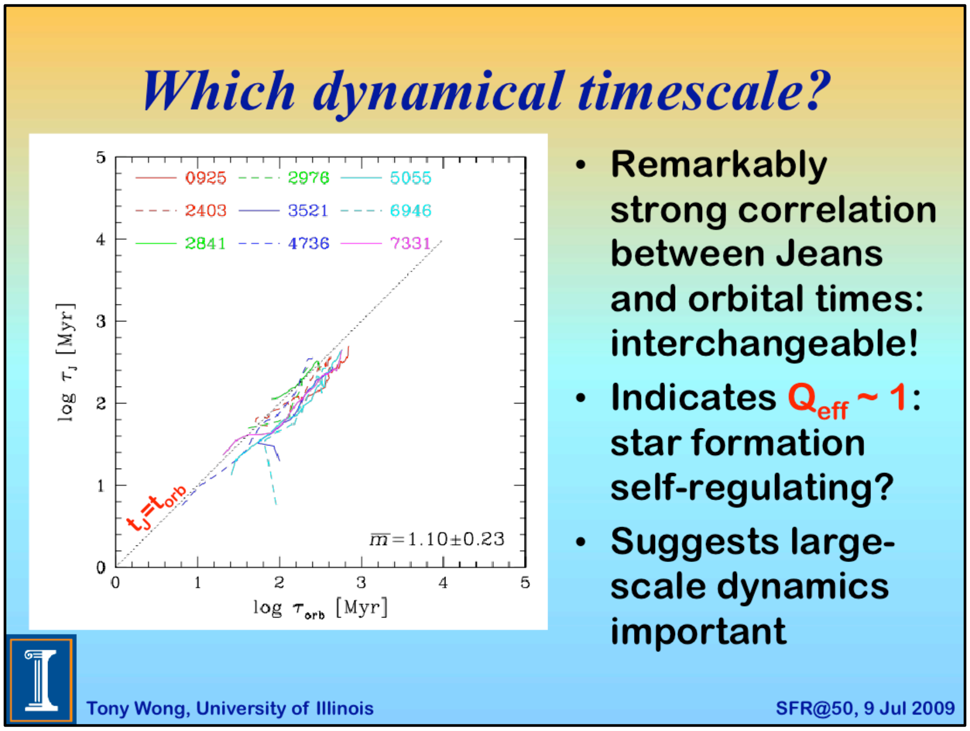
What does this mean? Well, if there's a complete and steady-state cycling between atomic and molecular gas, and if we identify the H_2 formation time with the dynamical time, then the observed relation can only be satisfied if the GMC lifetime scales inversely with the dynamical time.



This relationship is troubling. Dimensionally, it's incorrect. It's also contrary to the expectation that GMC lifetimes are set by stellar evolution, or that more massive clouds are more quickly dispersed. However, it does get some independent support from the observed correlation between the molecular to atomic ratio and the hydrostatic pressure, since the pressure scales as 1/tdyn^2 for a constant velocity dispersion, and the molecular to atomic ratio represents the ratios of these two timescales.



Perhaps by now you're thinking that by trying to relate star formation rates to large-scale dynamical rates, I'm trying to fit a square peg into a round hole. I would like to end by just noting an interesting equality of two of the basic dynamical timescales. Because the effective Q parameter is always close to 1, the Jeans and orbital timescales are equivalent; that's why I've been quite casually referring to the Jeans time as the dynamical time. Since this regulation probably involves star formation, I think it's hard to avoid the conclusion that large-scale dynamics is important, even if we don't have a full explanation for the observed star formation timescale.

Conclusions

- Star formation timescale increases with radius, but not as expected from classical Schmidt law.
- Including self-gravity of stellar disk in t_{dyn} tightens – but does not linearize – the correlation with t_{SF}.
- A 2-phase model, with GMC lifetimes inversely related to t_{dyn}, can satisfy current observational constraints.

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Here then is a summary of my conclusions.