The Molecular ISM, Star Formation, and Dwarf Galaxies

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Challenges for Low-Mass Galaxy Formation

1) The faint-end slope of the luminosity is flat: $\alpha <\sim 1.3$

2) The mass-to-light ratio is inferred to increase rapidly at $\log_{10} M < 11.5$ (i.e., the halo mass function is steep).

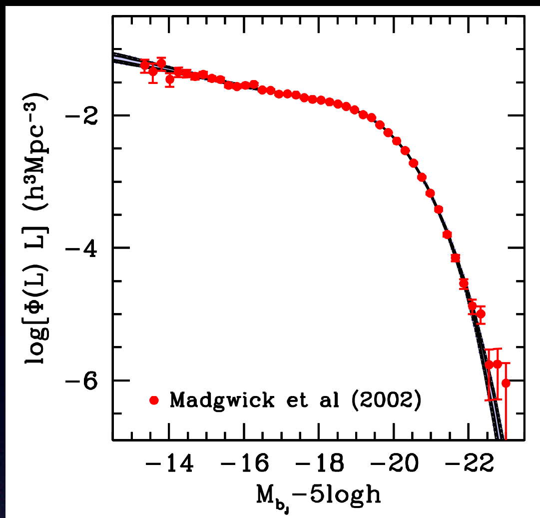
3) The stellar mass Tully-Fisher (1977) relation may break at faint magnitudes, but the baryonic TF relation apparently does not.

4) The baryon content of faint dwarfs is comparable to large disks (i.e., many small galaxies are gas rich).

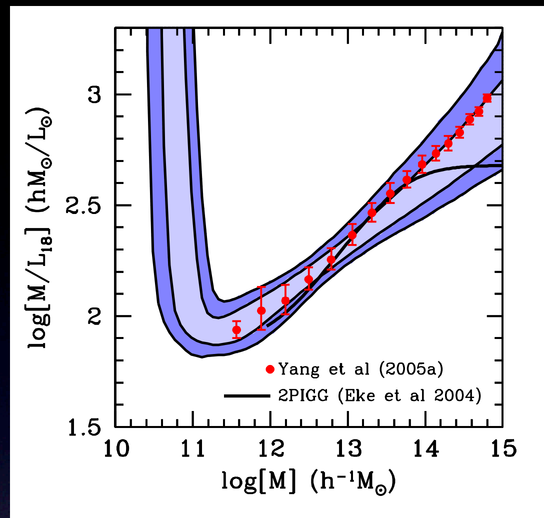
Star formation efficiency is a complicated function of halo mass.

Strong feedback has been a common recourse for attempting to addressing these challenges, but may not solve all outstanding issues.

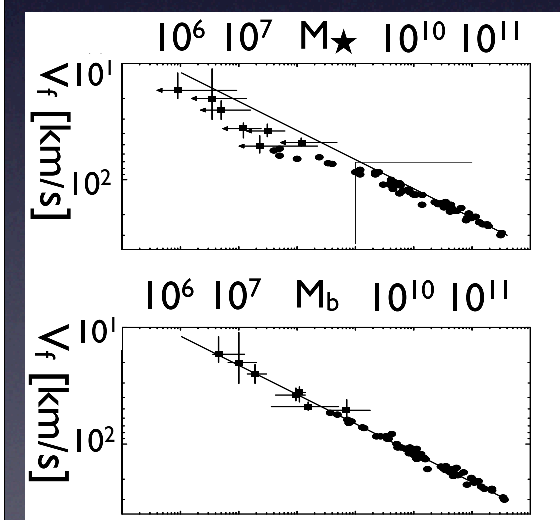
Let's revisit what we know observationally about star formation efficiency in quiescent galaxies and apply that knowledge to our models of star formation on galactic scales.



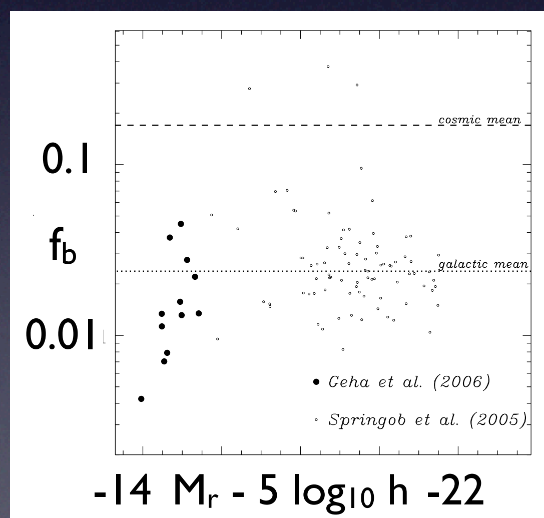
Madgwick et al. (2002)



van den Bosch et al. (2007)



McGaugh (2005)



Blanton et al. (2007)

Star formation rates in disks: the standard lore

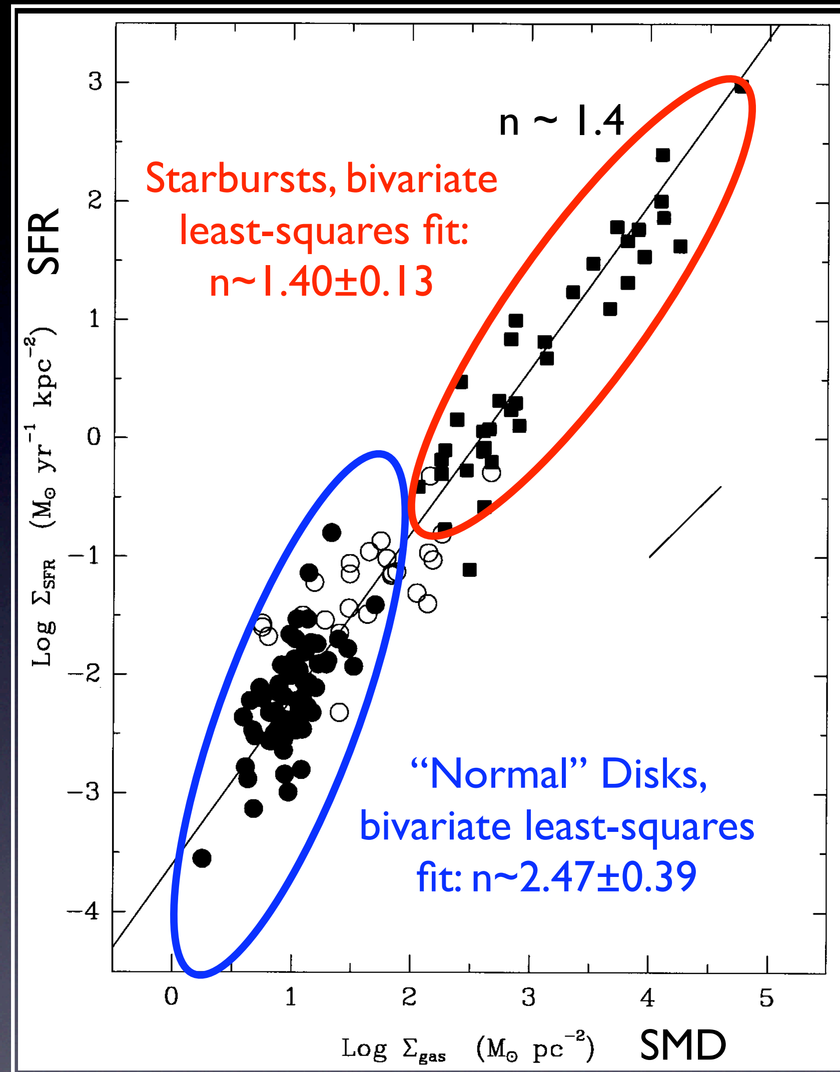
Schmidt (1959): Star formation rate has a power-law dependence on the local gas density

$$\dot{\rho}_\star \propto \rho_g^n$$

Kennicutt (1989,1998): Disk-averaged star formation rate surface density has a power-law dependence on the total gas mass surface density

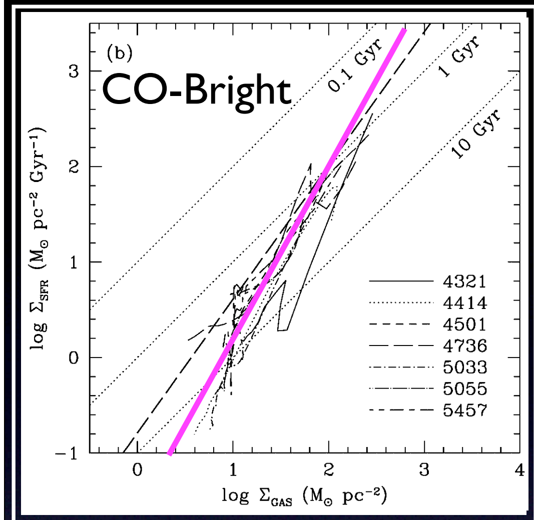
$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.4\pm0.15}$$

Theoretical prescriptions for star formation that convert gas mass into stars on a dynamical timescale date at least to Larson (1969). In simulations of galaxy formation, Katz (1992) and Navarro & White (1993) were among the first to adopt such prescriptions.

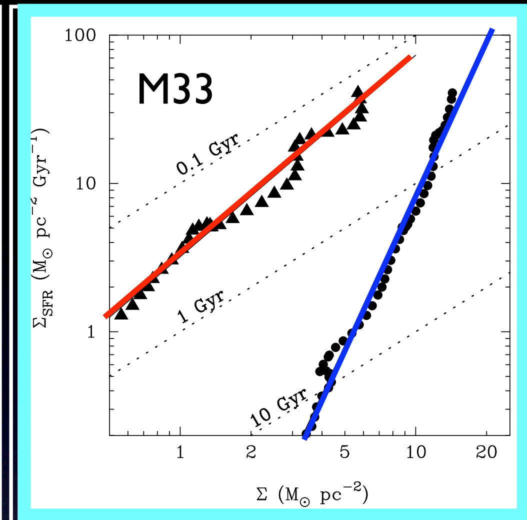


Kennicutt (1998)

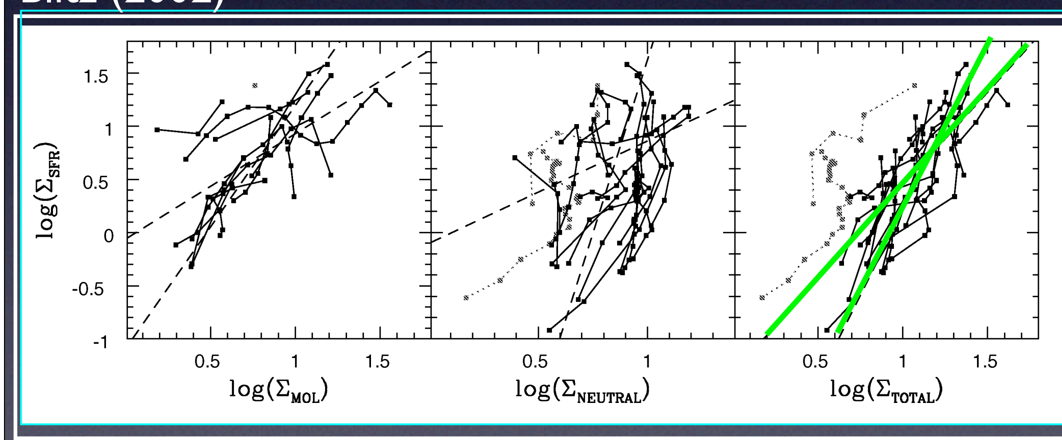
Spatially-dependent determinations of the Schmidt Law



Wong & Blitz (2002)



Heyer et al. (2004)



Boissier et al. (2003)

16 systems with abundance gradients, v_{circ}~100-300 km/s

Wong & Blitz (2002), CO-Bright:

$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.7\pm0.3}$$

Heyer et al. (2004), M33 Total Gas:

$$\Sigma_{SFR} \propto \Sigma_{gas}^{3.3\pm0.1}$$

Heyer et al. (2004), M33 H_2:

$$\Sigma_{SFR} \propto \Sigma_{H2}^{1.36\pm0.08}$$

Boissier et al. (2003), Z vs. N_H:

$$\Sigma_{SFR} \propto \Sigma_{gas}^{(1.96-3.55)}$$

Is $\dot{\rho}_\star \propto \rho_{\rm g}/t_{\rm dyn}$ the whole story?

SFR vs. Total Gas:

$n_{\rm gas} \approx 1.29 - 3.55$

SFR vs. Molecular Gas:

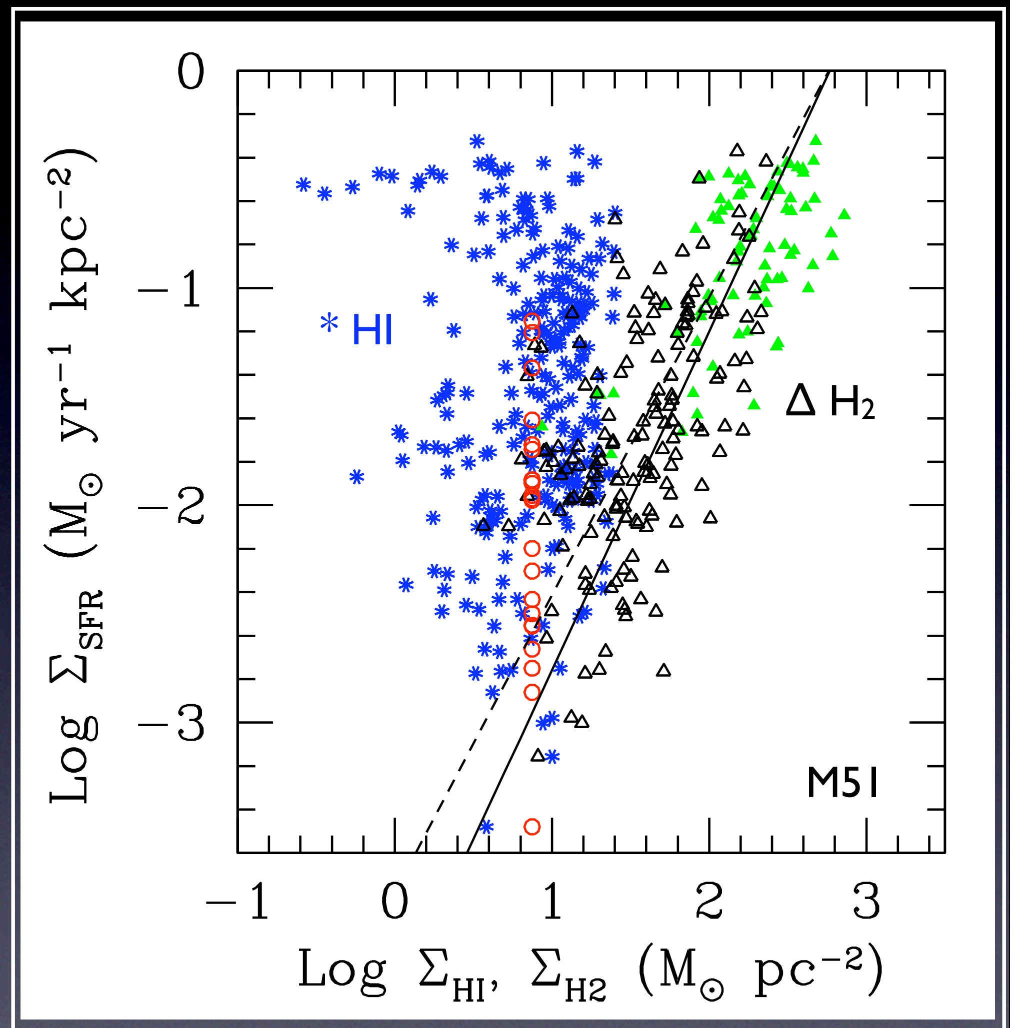
$n_{\rm H2} \approx 1.3 - 1.7$

Observations suggest:

1) The total gas Schmidt Law for quiescent galaxies is scale-dependent.

2) SF in molecular gas + efficiency ∝ $t_{\rm dyn}^{-1}$ is consistent.

Perhaps it's time to consider a model for star forming gas in simulations of galaxies that explicitly follows the evolution of the molecular ISM and ties the SFR to the molecular gas properties.



Kennicutt et al. (2007)

A cartoon of molecular ISM processes

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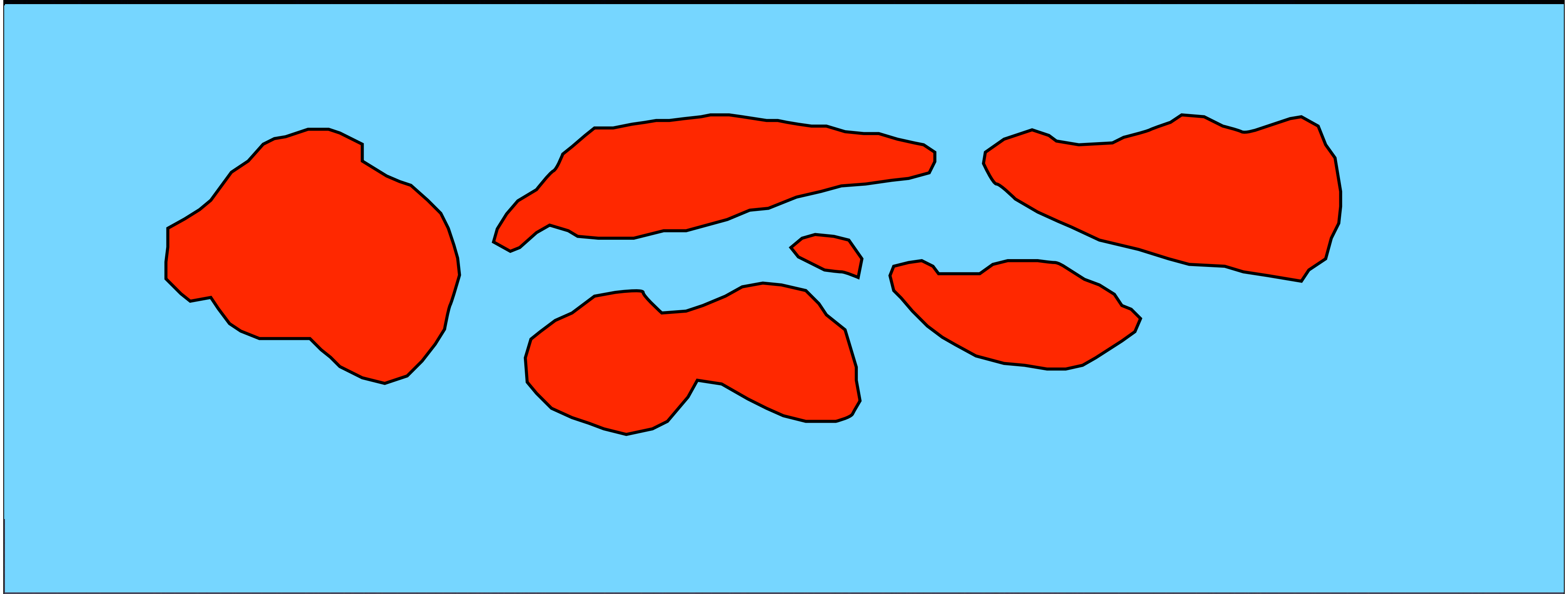
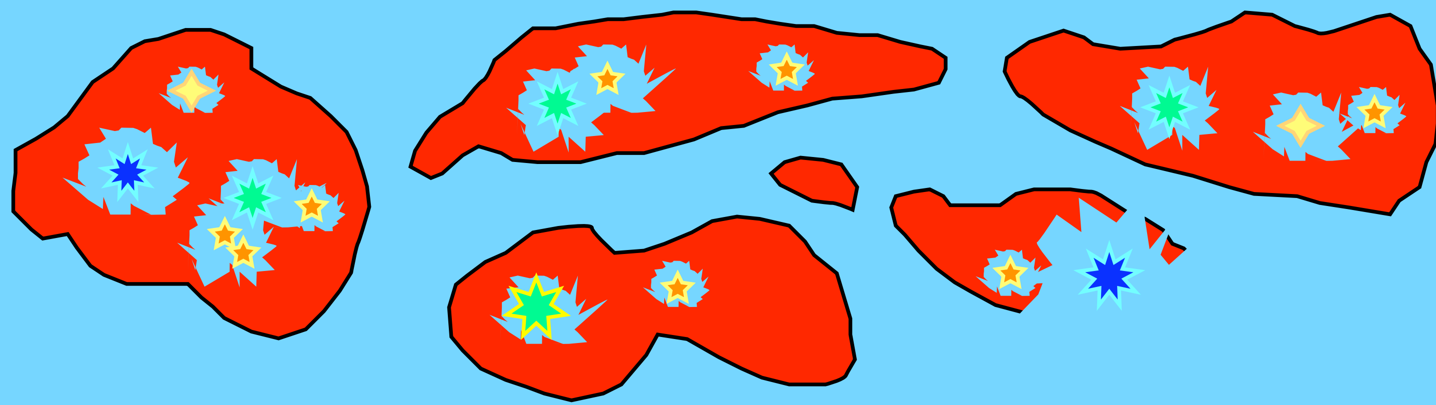


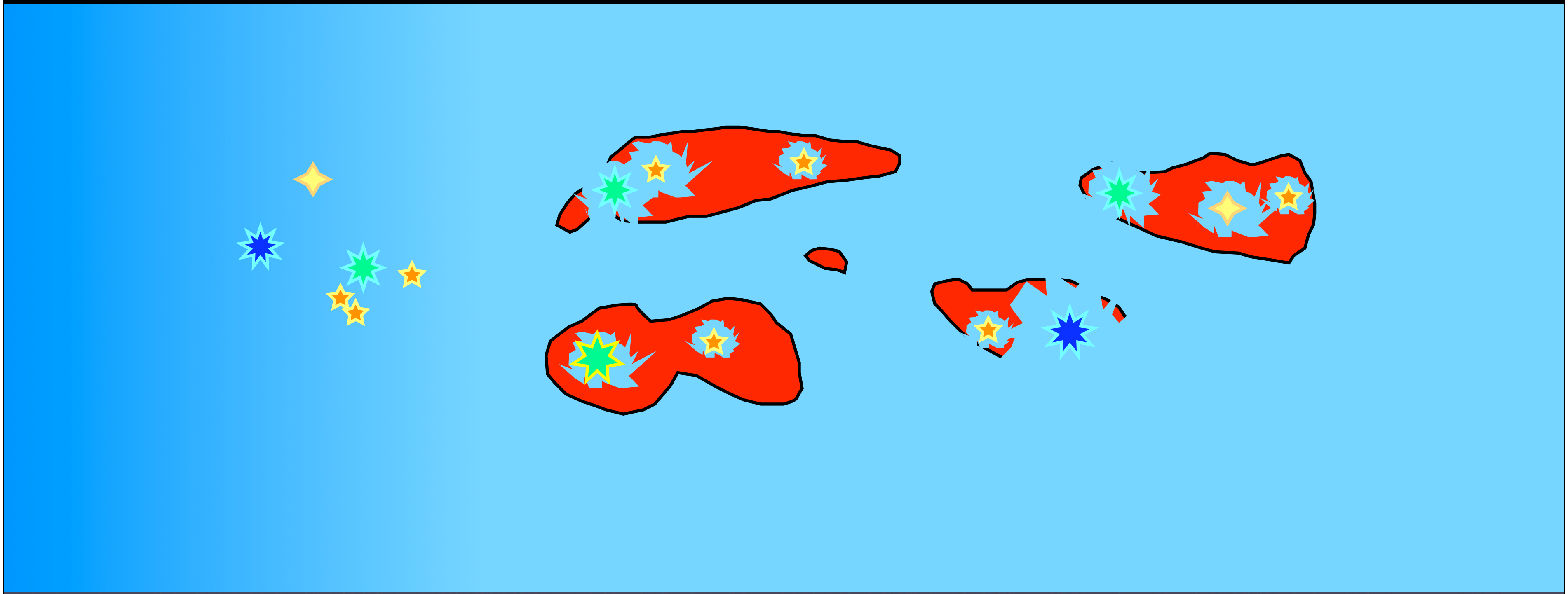
At sufficiently high gas densities, low-temperature coolants will allow molecular gas to condense from the hot ambient medium. The molecular gas fraction is determined by the equation of molecular equilibrium.

A cartoon of molecular ISM processes



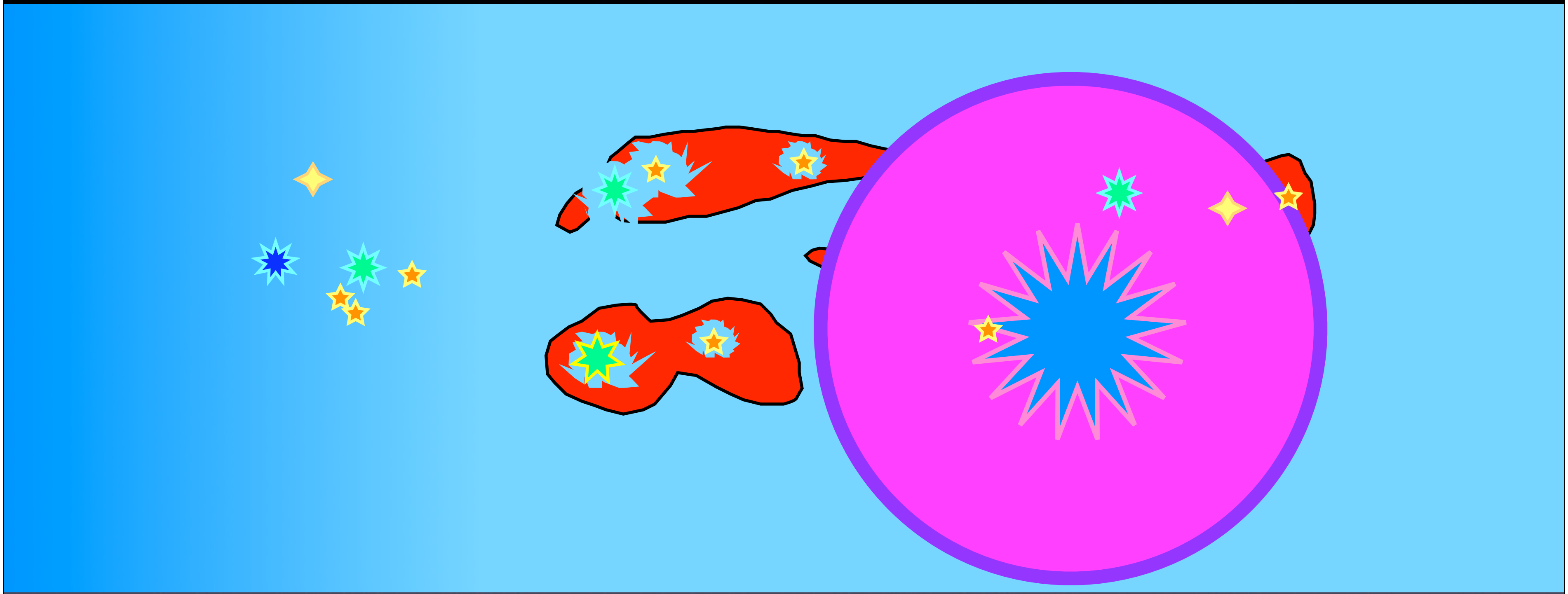
Stars form from the molecular clouds, and the local interstellar radiation field increases. Soft UV photons in the ISRF can begin to photodissociate the molecular clouds.

A cartoon of molecular ISM processes



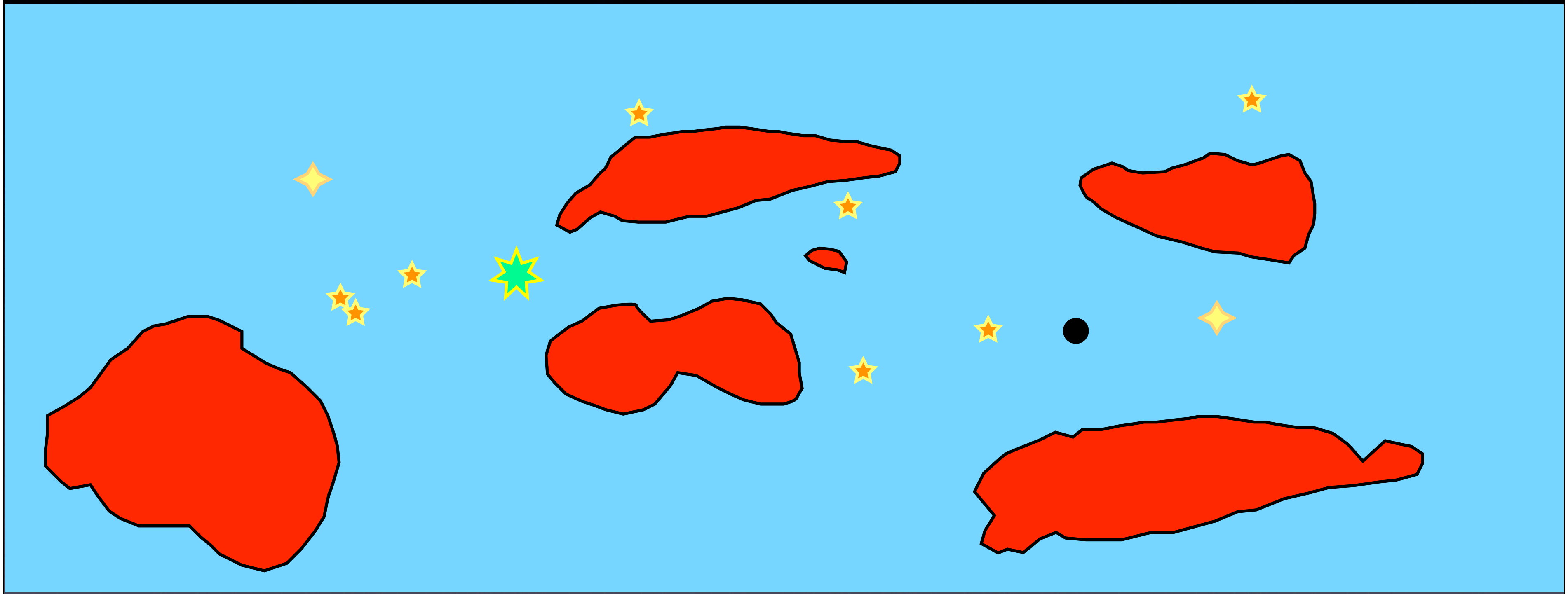
In the presence of an ISRF, the molecular density at moderate ISM densities is suppressed. In some regions of the ISM, the local ISRF can destroy all molecular gas, removing low-temperature coolants and increasing the gas temperature. The destruction of H_2 by the ISRF acts as a feedback mechanism to regulate star formation, and is efficient even as the local cooling time is short.

A cartoon of molecular ISM processes



Additional feedback mechanisms, such as supernovae from massive stars, may still operate.

A cartoon of molecular ISM processes



After the young stars die the ISRF may abate, allowing the molecular ISM to reform and the star formation cycle to start again.

A new model for the molecular ISM and star formation

Star formation is tied to the local molecular density and dynamical time

$$\dot{\rho}_\star = C_\star f_{\rm H2}(1-\beta)\rho_{\rm gas}^{1.5}$$

The molecular fraction is a function of density, temperature, metallicity, and ISRF strength

$$f_{\rm H2} = f_{\rm H2}(\rho_{\rm gas}, T, Z, U_{\rm ISRF})$$

The local ISRF strength tracks the local star formation rate density

$$U_{\rm ISRF} = U_\odot(\nu) \times \left(\frac{\Sigma_{\rm SFR}}{\Sigma_{\rm SFR,\odot}}\right)$$

The thermal evolution of ISM gas depends on the supernovae heating and the net atomic and molecular cooling rates

$$\rho_{\rm gas}\frac{{\rm d}u}{{\rm d}t} = \epsilon_{\rm SN}\dot{\rho}_\star - \Lambda_{\rm net}$$

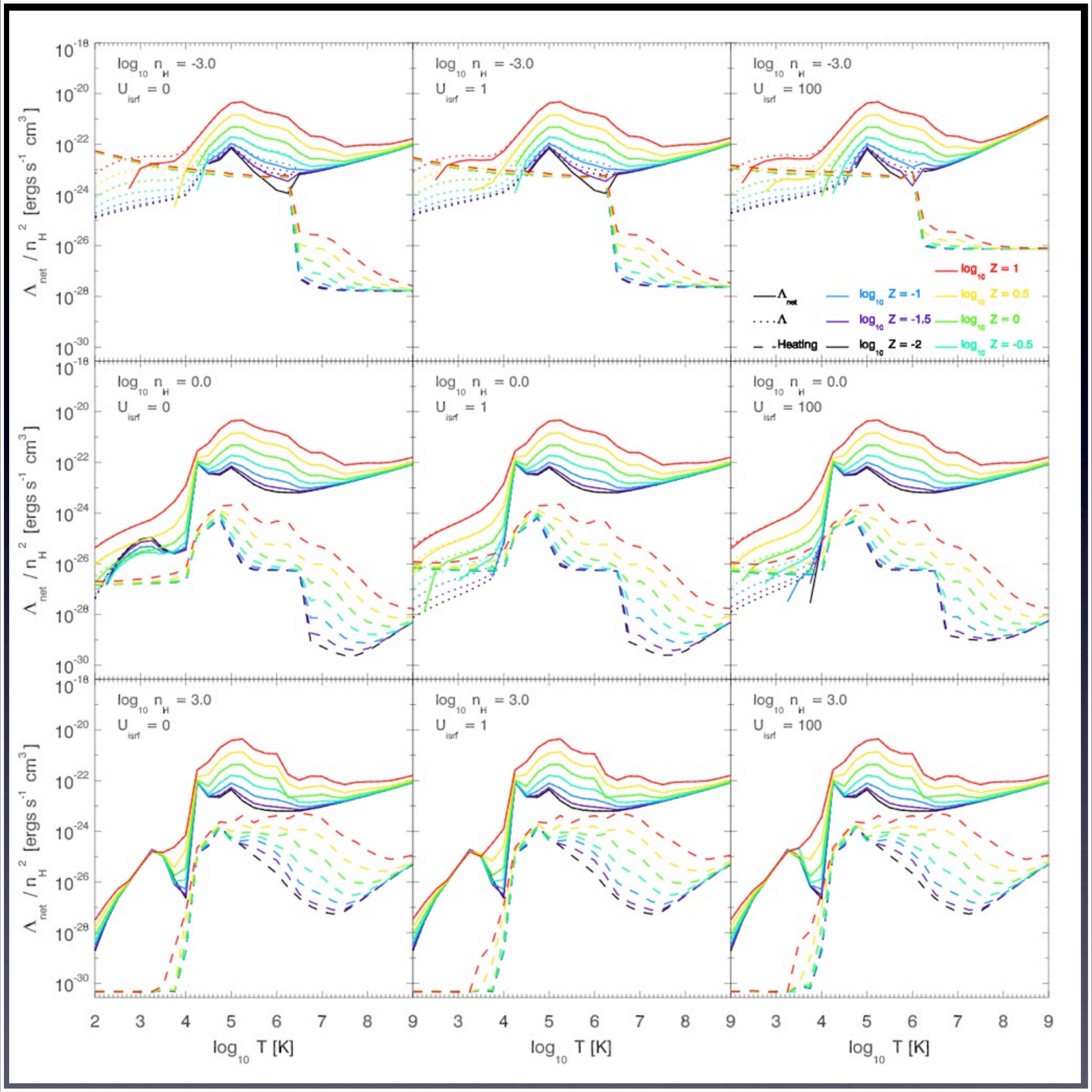
The net atomic and molecular cooling rates depend on density, temperature, metallicity, and ISRF strength

$$\Lambda_{\rm net} = \Lambda_{\rm net}(\rho_{\rm gas}, T, Z, U_{\rm ISRF})$$

Implemented in the N-body/SPH code GADGET2

Robertson & Kravtsov (2007, in prep)

A new model for the molecular ISM and star formation



Robertson & Kravtsov (2007, in prep)

T, ρ, Z, and ISRF-dependent Cooling + Heating rates calculated with the photoionization code Cloudy

Tabulate the molecular fraction f_{H2}, the ionization fraction, and the molecular weight + interpolate

Molecular gas may be photodissociated by soft UV photons. Include the presence of an interstellar radiation field (Mathis et al. 1983), and vary its strength with the local SFR density.

Isolated disk star formation efficiency

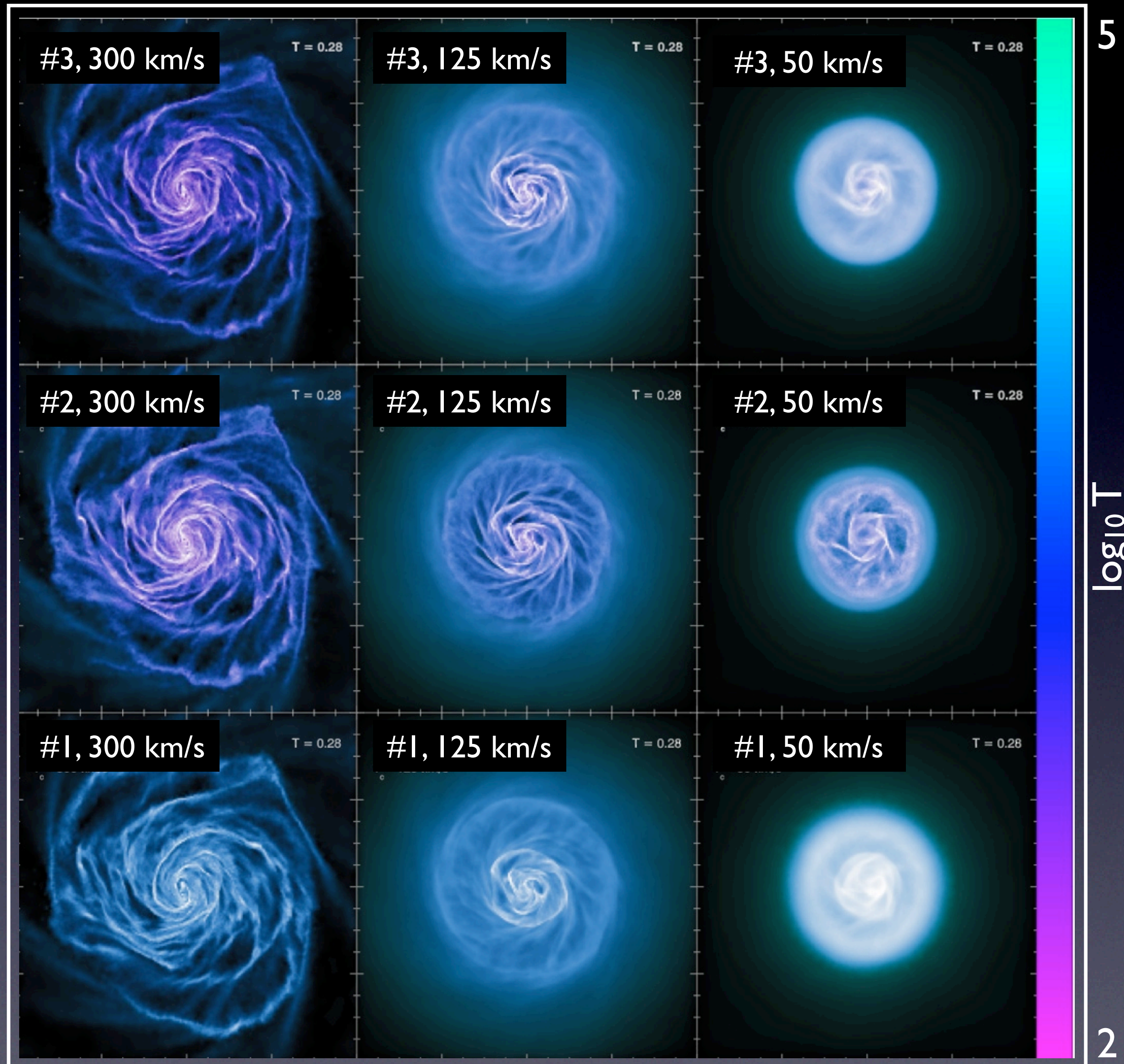
Characterize the SF efficiency in disks with v_{circ}~50-300 km/s, modeled after DDO154, M33, and NGC 4501.

Compare and contrast three ISM + SF models:

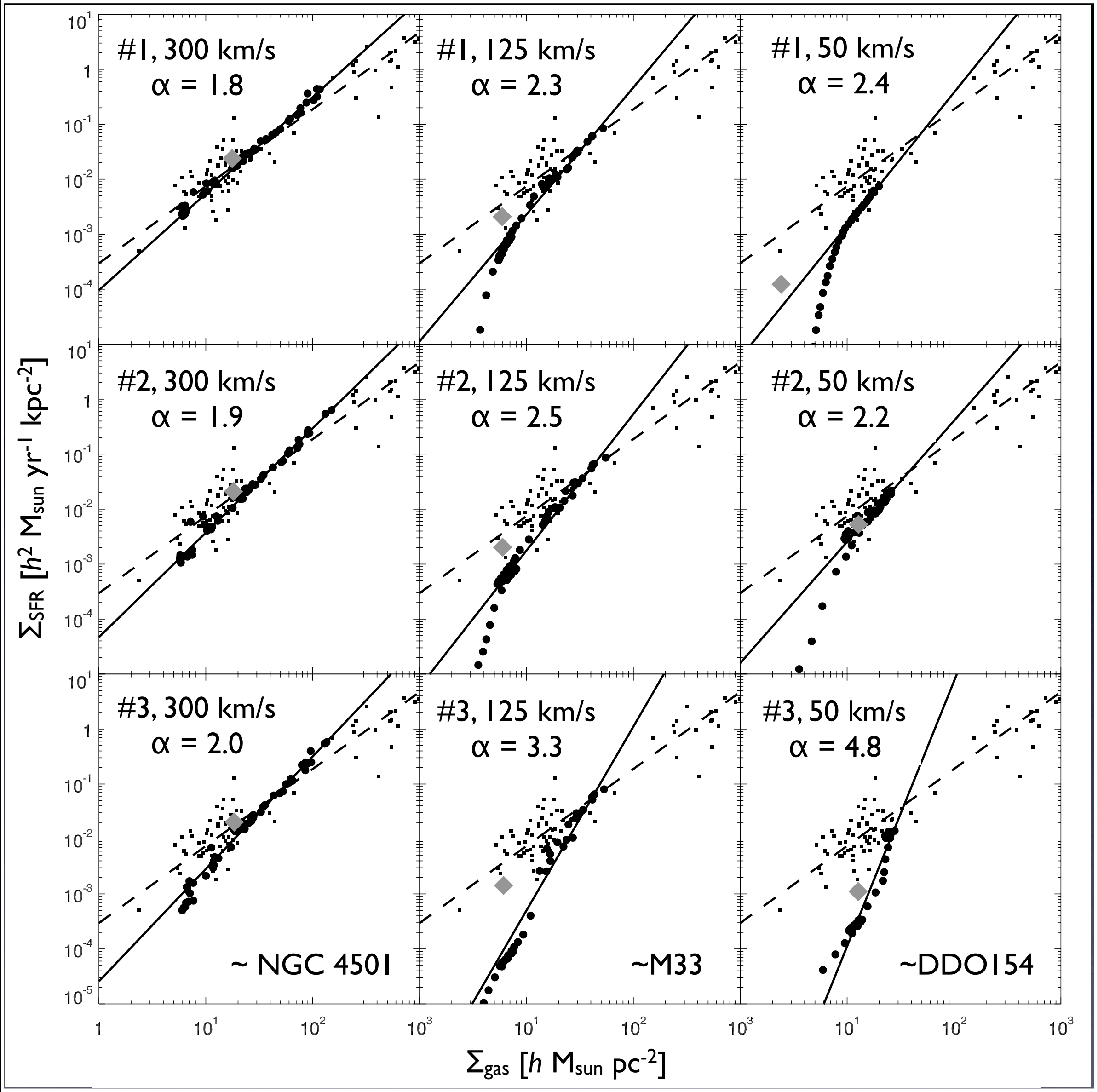
#1) "Standard" atomic cooling + total gas density SF scaling + SF threshold model

#2) New atomic & molecular cooling + molecular density SF scaling w/o ISRF

#3) New atomic & molecular cooling + molecular density SF scaling w/ ISRF



Robertson & Kravtsov (2007, in prep)



Results: Total Gas Schmidt Law

SFR density vs. total gas surface density averaged over annuli

SF timescale chosen to match disk-averaged Schmidt Law (Kennicutt 1998, dashed line) at high densities.

Molecular ISM model shows scale-dependence owing to $\Sigma_{H2}(\Sigma_{gas})$

Molecular ISM + ISRF model produces a much stronger dependence of SF efficiency on the galaxy mass scale.

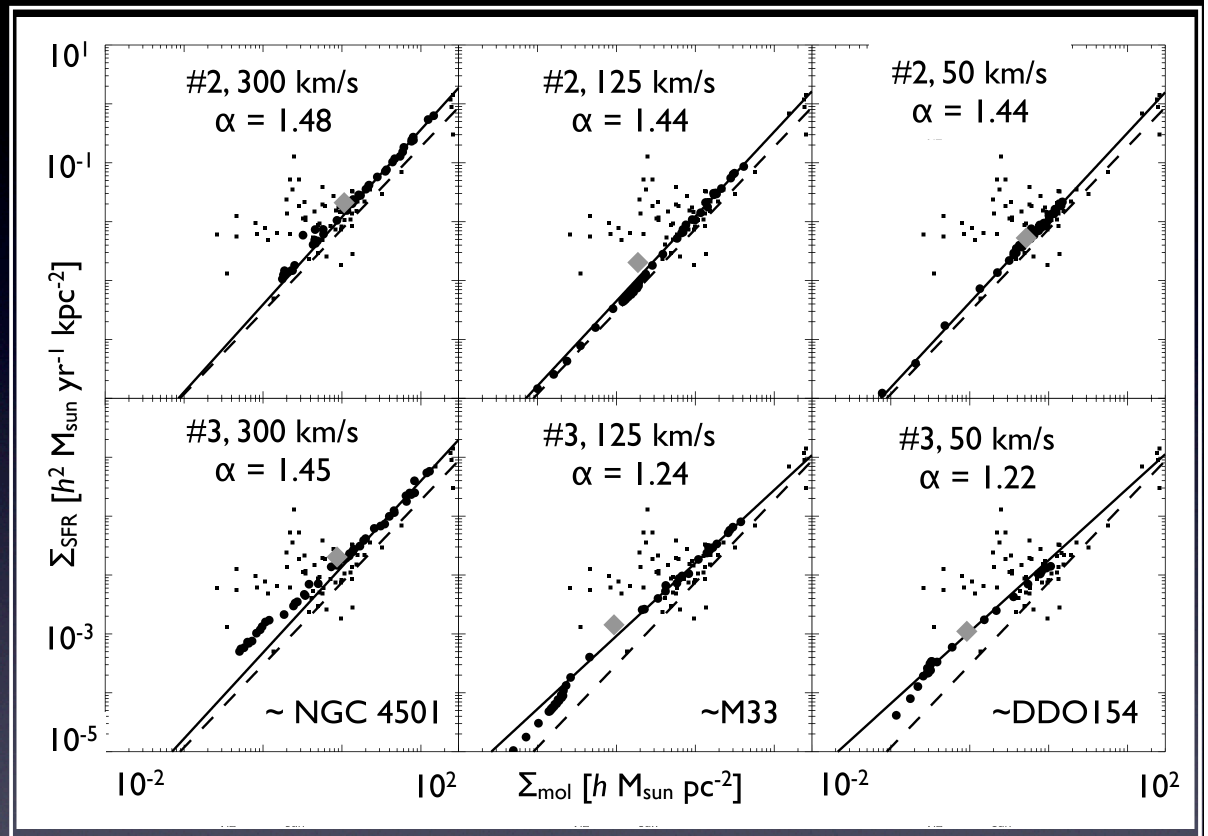
Robertson & Kravtsov (2007, in prep)

Results: Molecular Gas Schmidt Law

SFR density vs. molecular gas surface density averaged over annuli

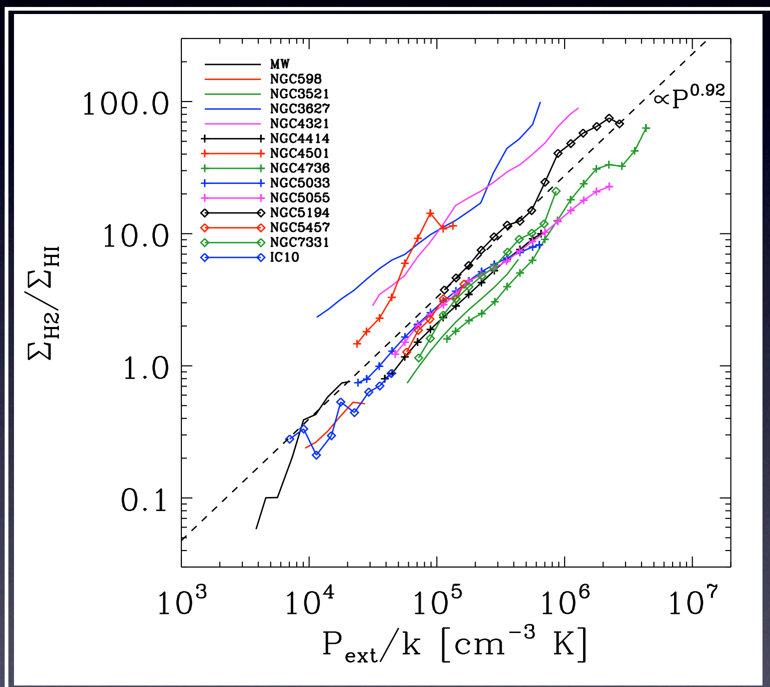
Molecular ISM + ISRF model produces a slightly shallower dependence of SFR on molecular gas surface density than does the model without an ISRF.

The scale dependency of SF efficiency vs. molecular gas surface density is *much* weaker than for the total gas density Schmidt Law, as required by observations.



Robertson & Kravtsov (2007, in prep)

f_{H2}-Pressure Correlation



Blitz & Rosolowsky (2006)

In 1993, Elmegreen calculated the relation between pressure, ISRF emissivity *j*, and molecular fraction as

$$f_{\rm H2} \propto P^{2.2} j^{-1}$$

Modeling the disk midplane pressure as

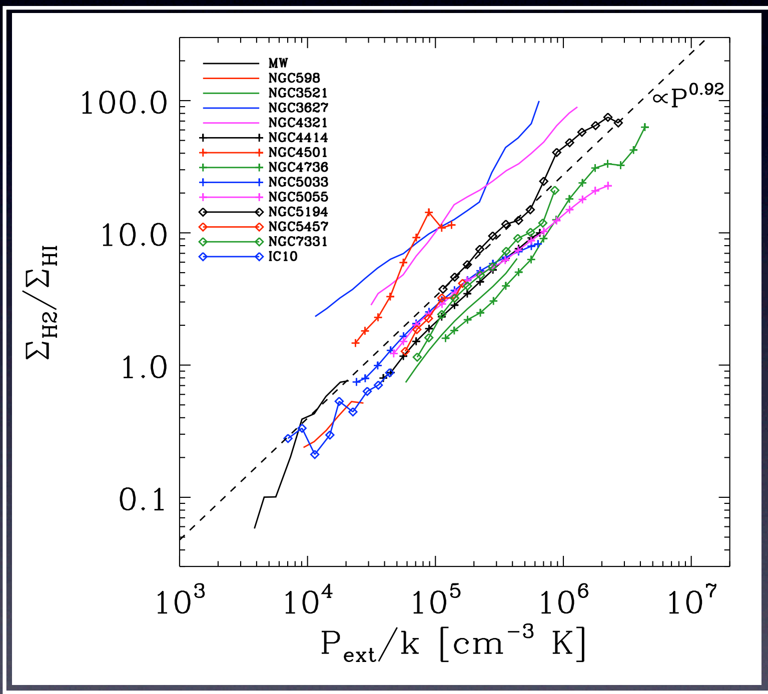
$$P \approx \frac{\pi}{2} G \Sigma_{\rm gas} \left(\Sigma_{\rm gas} + \frac{\sigma_{\rm gas}}{\sigma_\star} \Sigma_\star \right)$$

Wong & Blitz (2002) and Blitz & Rosolowsky (2006) find that

$$f_{\rm H2} \propto P^{0.8-0.9}$$

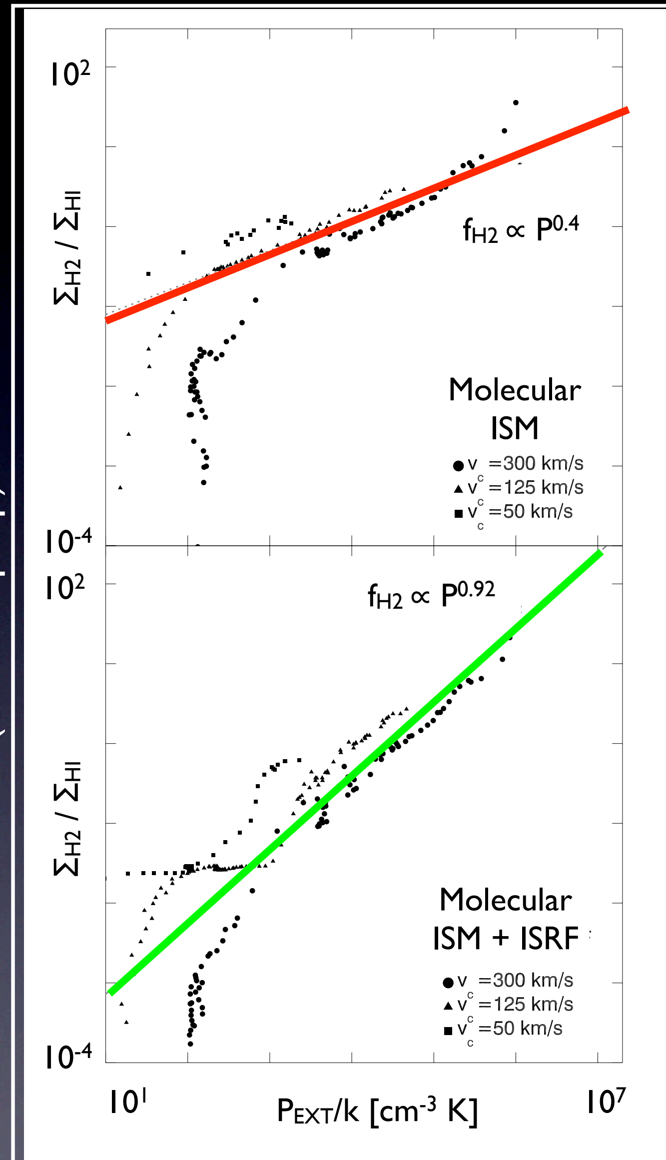
This proportionality is similar to the predicted proportionality if the ISRF emissivity scales with the stellar surface mass density.

f_{H2}-Pressure Correlation



Blitz & Rosolowsky (2006)

Robertson & Kravtsov (2007, in prep)



f_{H2}-Pressure Correlation

The disk galaxy models simulated with the molecular ISM + ISRF model successfully reproduce the Blitz & Rosolowsky (2006) pressure-molecular fraction trend.

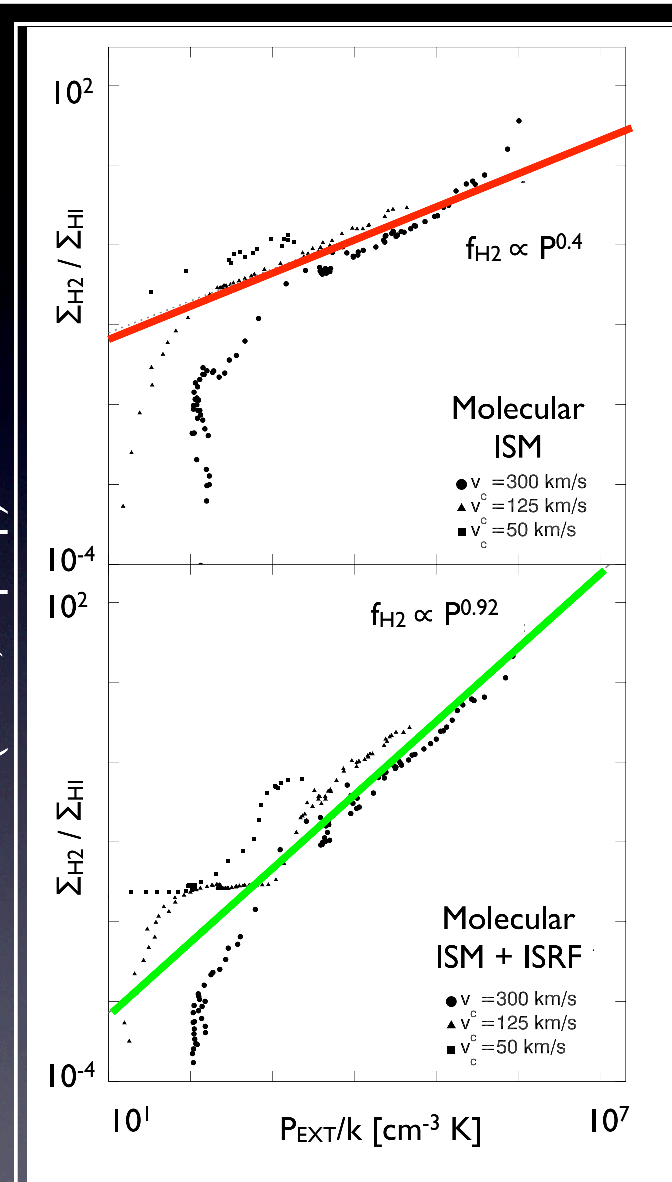
The disk galaxy models simulated without an ISRF do not reproduce the trend, but follow a weaker trend that reflects the lack of molecular photodissociation at low ISM densities.

Given the scalings of the radiation field strength with the SFR surface density in our simulations, one expects that

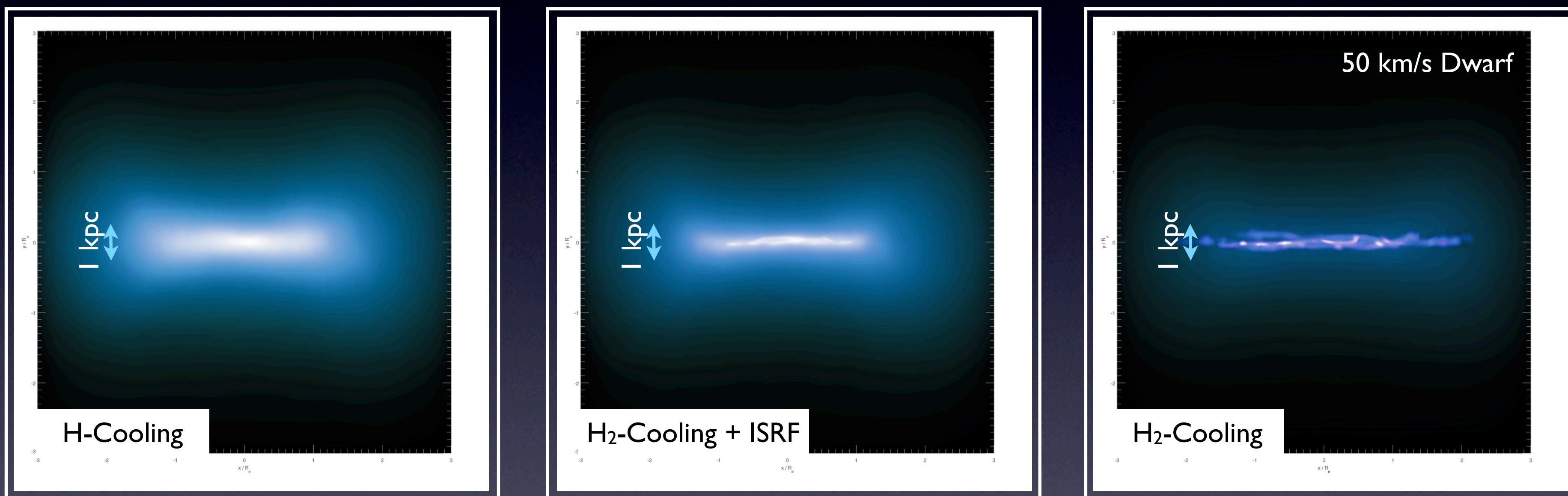
$$f_{\rm H2} \propto P^{0.87}$$

which closely matches the observe trend.

Robertson & Kravtsov (2007, in prep)



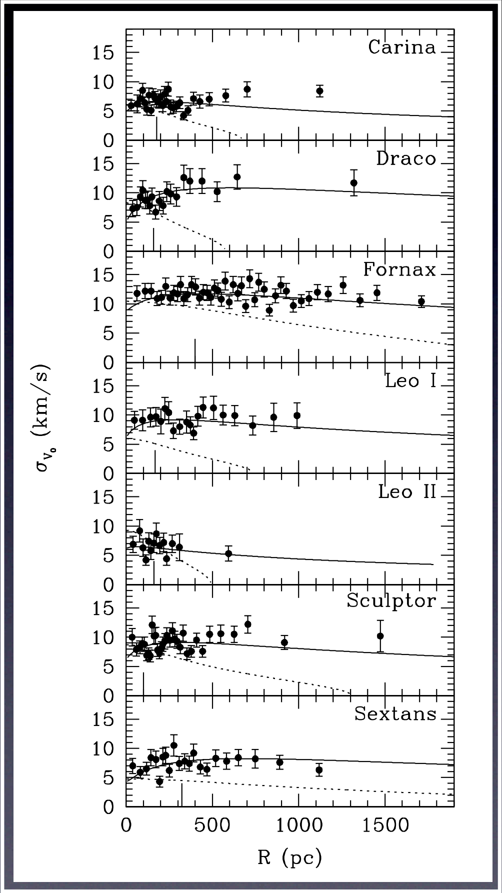
Results: Dwarf Galaxy Gas Disk Structure



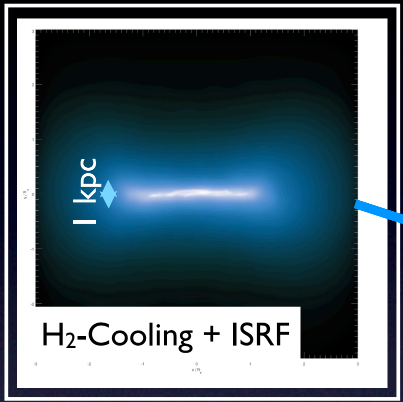
10^4 K ⟶ Mean Temperature of the ISM ⟶ 10^2 K

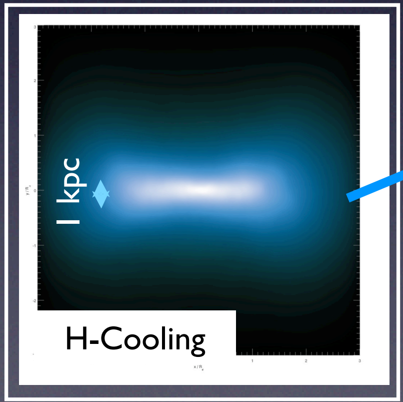
See also James Bullock's talk and Kauffman, Wheeler, and Bullock (2007)

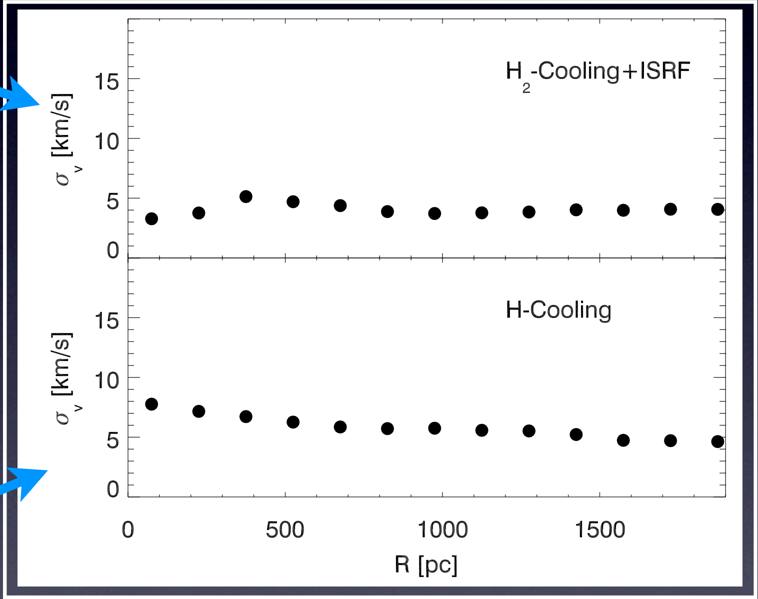
Final Aside: Dwarf Galaxy Velocity Dispersions



Walker et al. (2007)

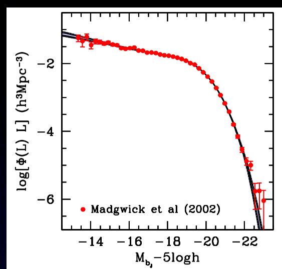




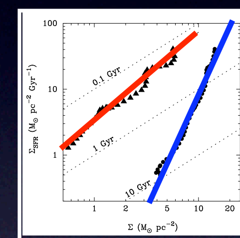


If dSph systems were originally disk galaxies, their velocity dispersions serve as constraints on models for their formation or evolution.

Summary

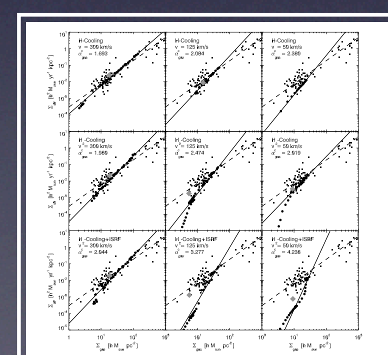


The scale-dependency of star formation efficiency has wide-ranging implications, from the luminosity function to the Tully-Fisher relation.



Observations suggest that the total gas Schmidt Law is scale-dependent, but the molecular gas Schmidt Law is consistent with n~1.5

Robertson & Kravtsov (2007, in prep) have developed a model of star formation and the ISM that includes T, ρ, Z, and ISRF-dependent Λ and f_{H2}, ties the SFR directly to the molecular gas density, and have implemented it in GADGET2.



Our model successfully reproduces the total gas Schmidt Law, the molecular gas Schmidt Law, and the f_{H2} - Pressure relation.