The Star Formation/ISM Connection: Feedback and Self-Regulation

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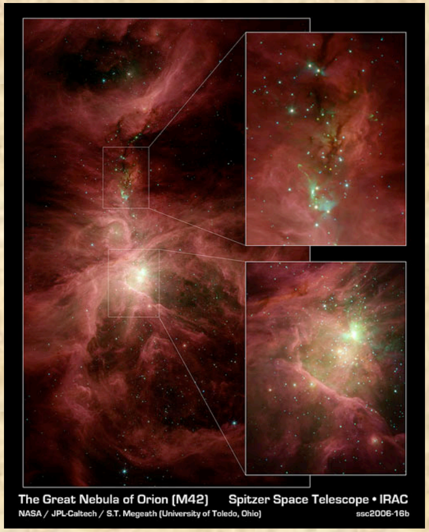
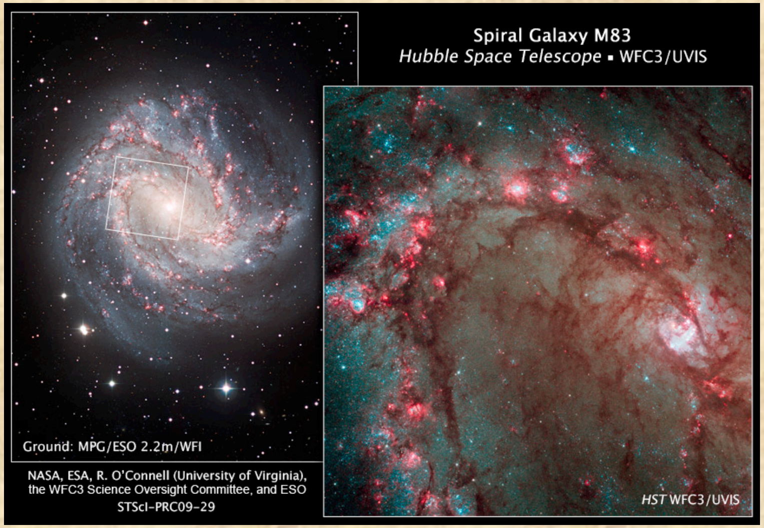
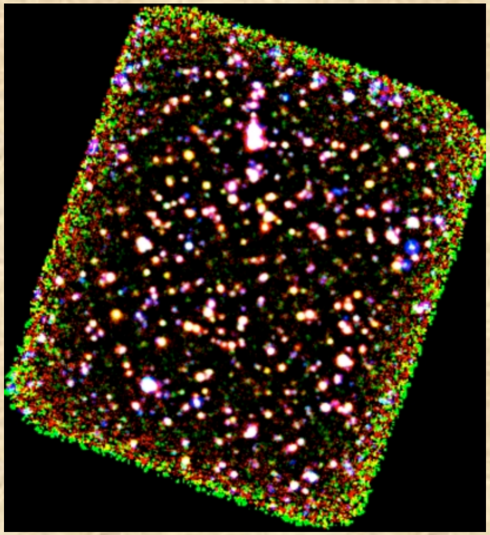
I. Star formation observations

SF Regulation: a range of time/space scales

- Cosmic infall and internal gas accretion influence long term SF rates, whole-galaxy correlations
  - supply, distribution of gaseous "fuel" within galaxy
  - SF evolution determines stellar distribution (disk/bulge…)
- Keys to setting short term ($\lesssim t_{orb}$), local rates:
  - local amount of gaseous "fuel"
  - gravity in the disk from gas, stars, DM
  - feedback from SF (heating, momentum injection)







Empirical Star Formation Rates

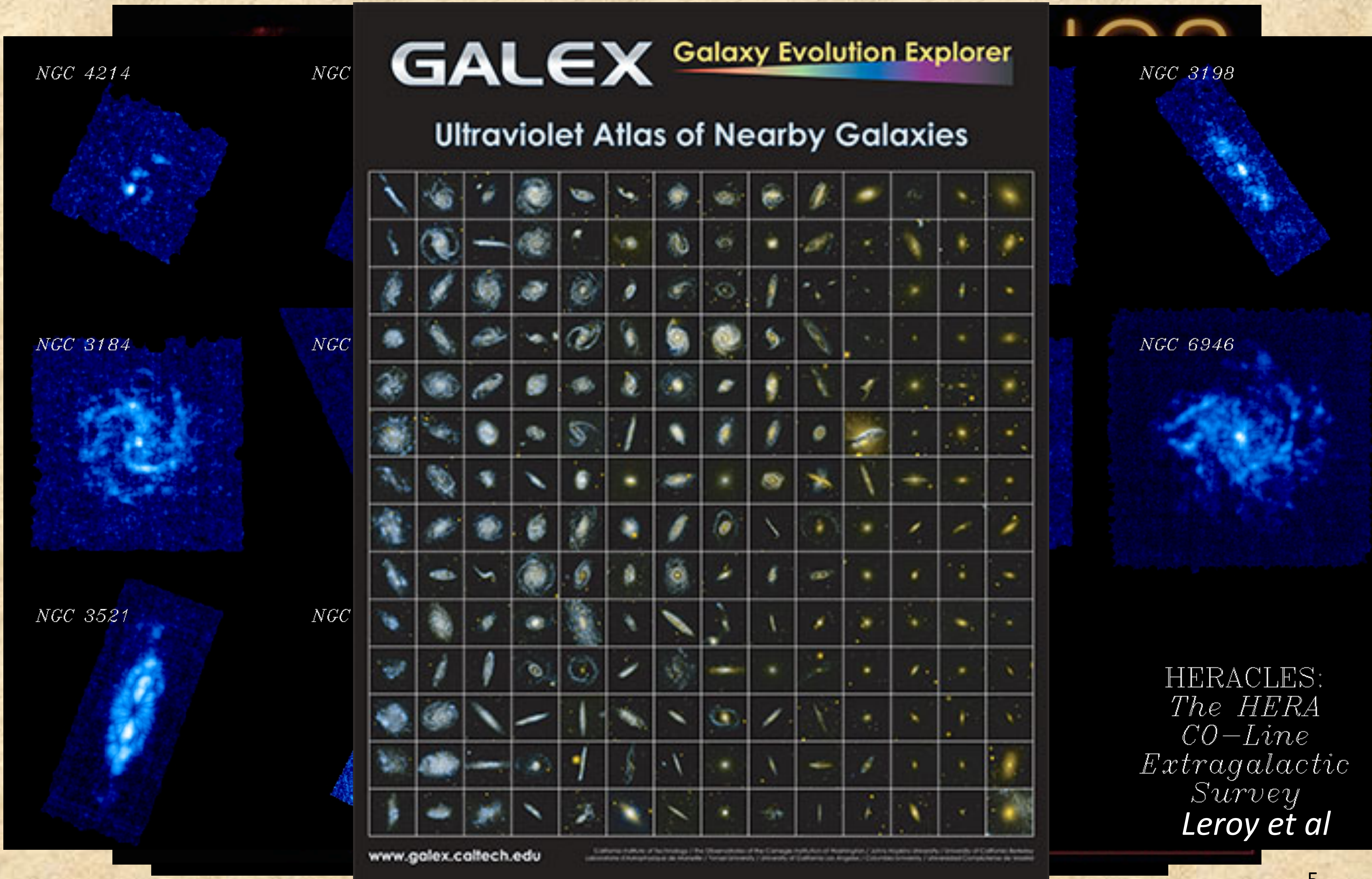
- On large (kpc →galaxy) scales, the details of SF are averaged into a mean SFR
- Observations of SFRs are often described by empirical Kennicutt-Schmidt (KS) laws:

  $\Sigma_{SFR} = A\,\Sigma_{gas}^{1+p}$ for $\Sigma_{gas} = \Sigma_{HI}$, Σ_{H2}, or $\Sigma_{HI} + \Sigma_{H2}$
- index p corresponds to $t_{SF,gas} = \Sigma_{gas}/\Sigma_{SFR} \propto \Sigma_{gas}^{-p}$

Kennicutt 1989,1998; Wong & Blitz 2002; Kennicutt et al 2007; Bigiel et al 2008,2010,2011; Leroy et al 2008, 2013; Blanc et al 2009; Genzel et al 2010;Daddi et al 2010; Schruba et al 2011

- Other correlations that have been explored:
  - SFR and orbital time (Ω)
  - SFR and stellar density, surface density (ρ_*, Σ_*)
  - SFR and ISM pressure, density ($P = \rho\sigma_z^2 \approx \Sigma_{gas} g_z/2$, $t_{ff}(\rho)$)

Spatially-resolved gas and SFR



Three regimes of star formation

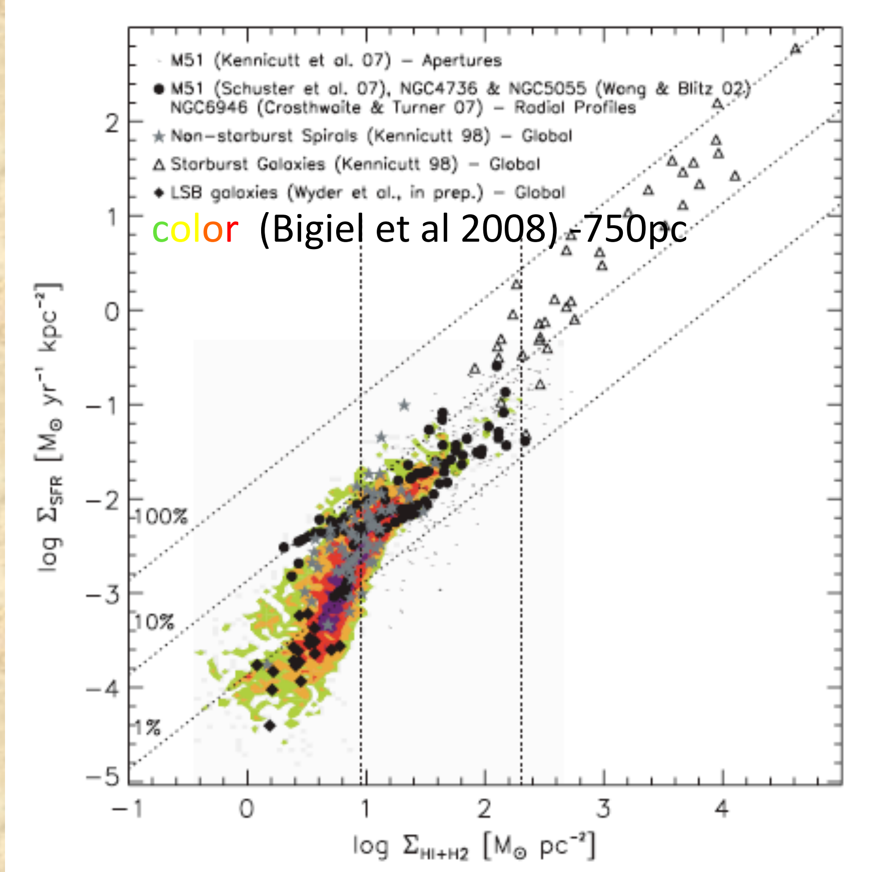
- Increase of Σ_{SFR} with

  $\Sigma_{gas} = \Sigma_{HI} + \Sigma_{H2}$:

  - Superlinear at low, high ends
    - $\Sigma_{gas} \approx \Sigma_{HI} \lesssim 10 M_{\odot}\,pc^{-2}$
    - $\Sigma_{gas} \approx \Sigma_{H2} \gtrsim 100\, M_{\odot}\,pc^{-2}$
  - Close to linear for

    $10 M_{\odot}\,pc^{-2} \lesssim \Sigma_{gas} \approx \Sigma_{H2} \lesssim 100\, M_{\odot}\,pc^{-2}$

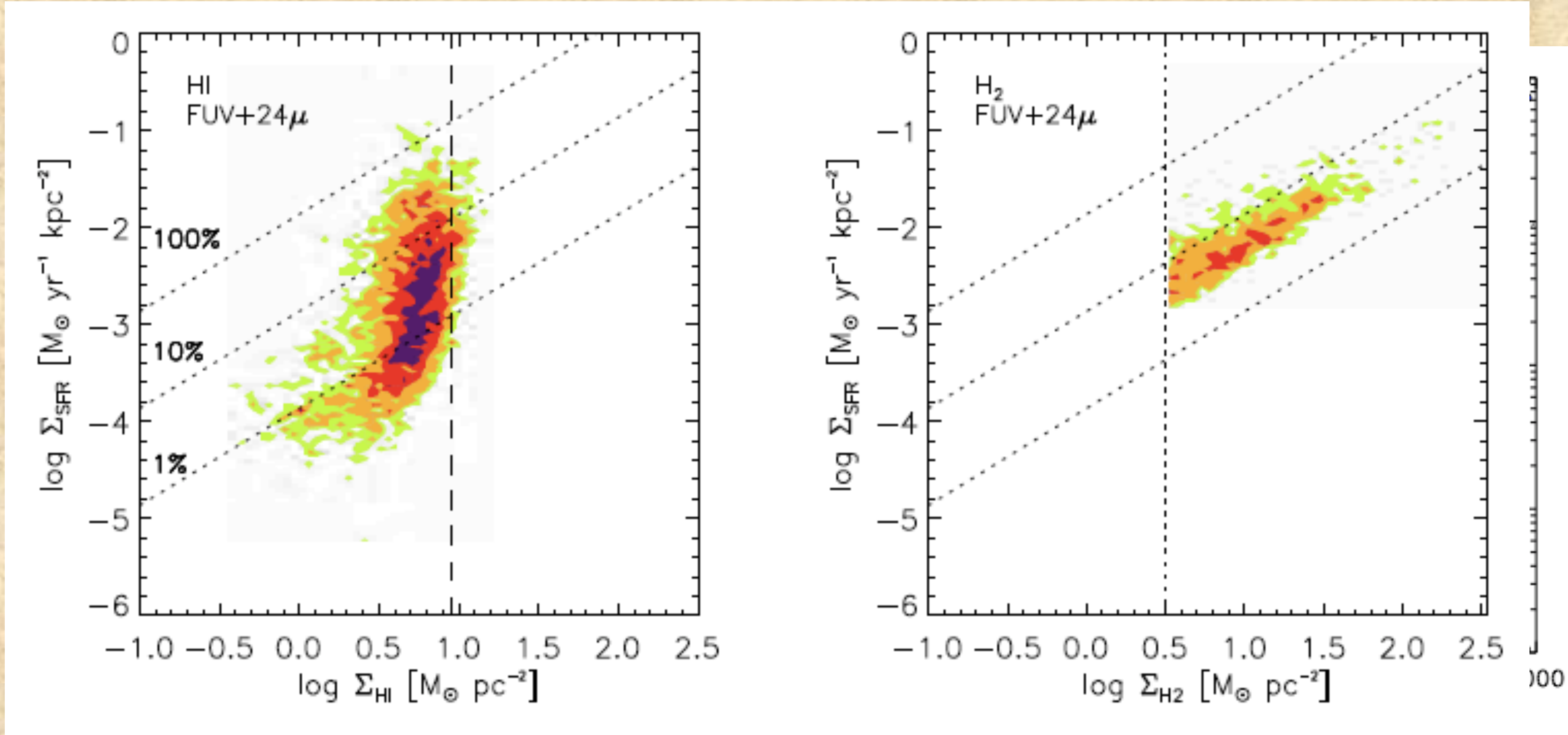
    with $t_{SF,H2} = 2\times10^{9}$ yr
- Significant scatter for HI-dominated regime
  - $\Sigma \lesssim 10 M_{\odot}\,pc^{-2}$



Local and global Kennicutt-Schmidt relations

⇒ *parameter other than Σ_{gas} is important!*

Σ_{SFR} vs. Σ_{HI}, Σ_{H2}

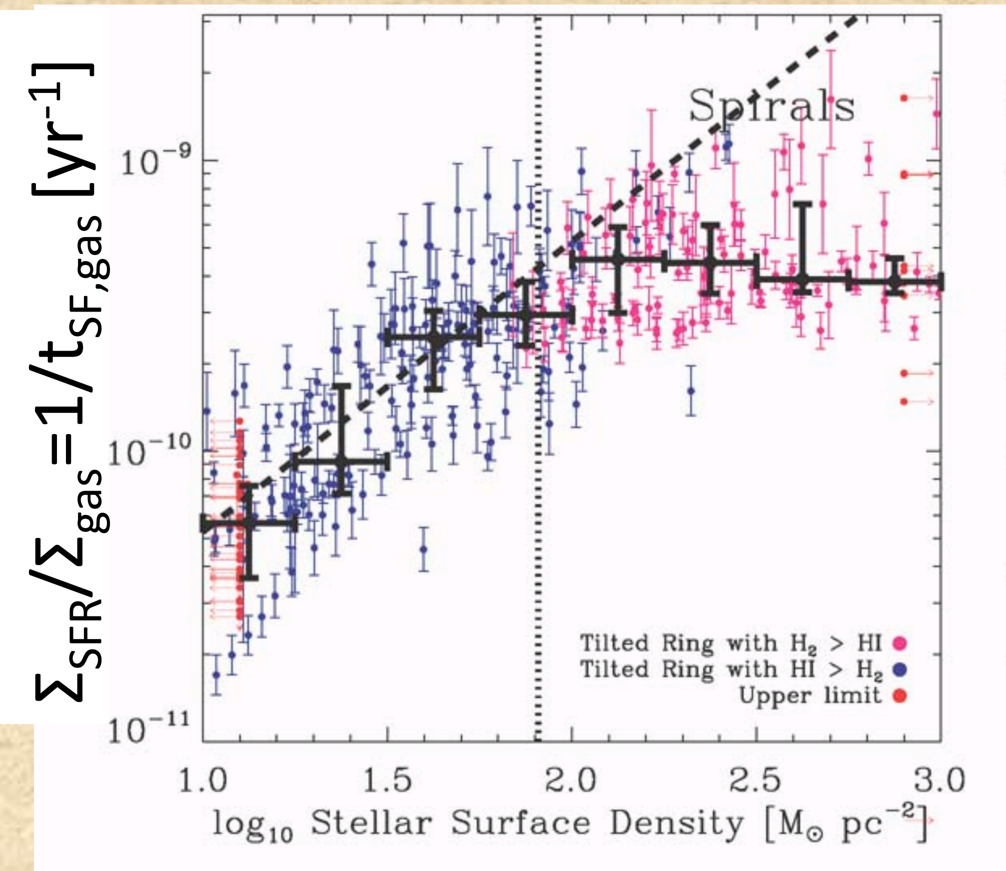


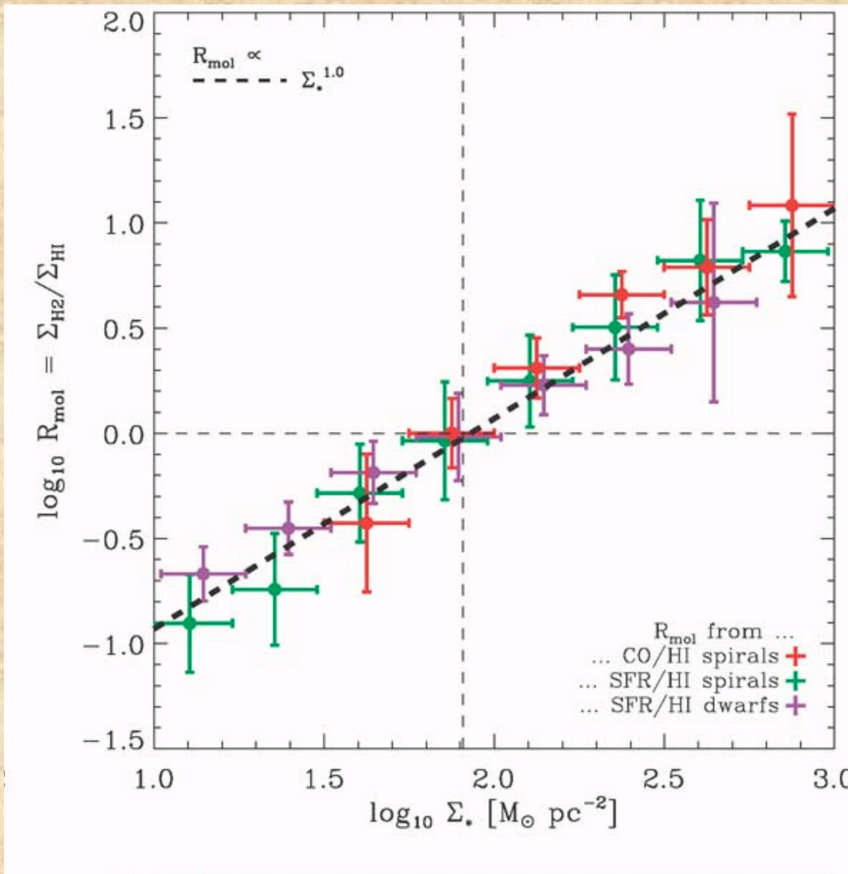
Schruba et al (2011)
Bigiel et al (2008)

- HI saturates at ~10 $M_\odot$ pc^{-2} (Wong & Blitz 2002)
- SFR linear in the molecular gas at moderate $\Sigma_{H2} \lesssim 100 M_\odot$ pc^{-2}, even in HI-dominated regime:

$\Sigma_{SFR} = \Sigma_{H2}/t_{SF}(H_2)$ with $t_{SF}(H_2) = 2\times10^9$ yr

SFR and H_2/HI correlations with stellar content





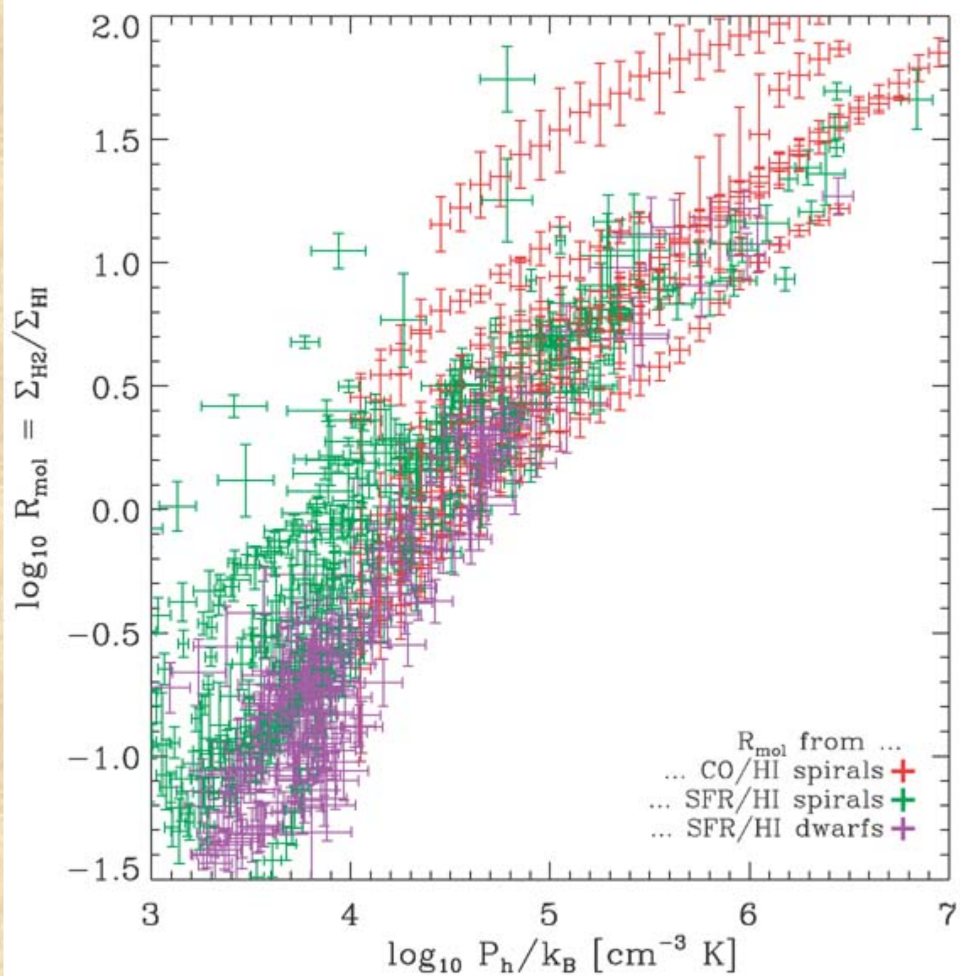
Leroy et al (2008)

Observed Σ_{H2}/Σ_{HI} - pressure relation

- Blitz & Rosolowsky (2006) found that $R_{mol}=\Sigma(H_2)/\Sigma(HI)$ increases with galactic gas and stellar density as

$$R_{mol} = \left[\frac{P_{ext}/k}{(3.5 \pm 0.6) \times 10^4}\right]^{0.92\pm0.07}$$

- BR P_{ext} is estimate of midplane pressure, assuming vertical equil.
- Leroy et al (2008) found similar relation, for both spirals and dwarfs

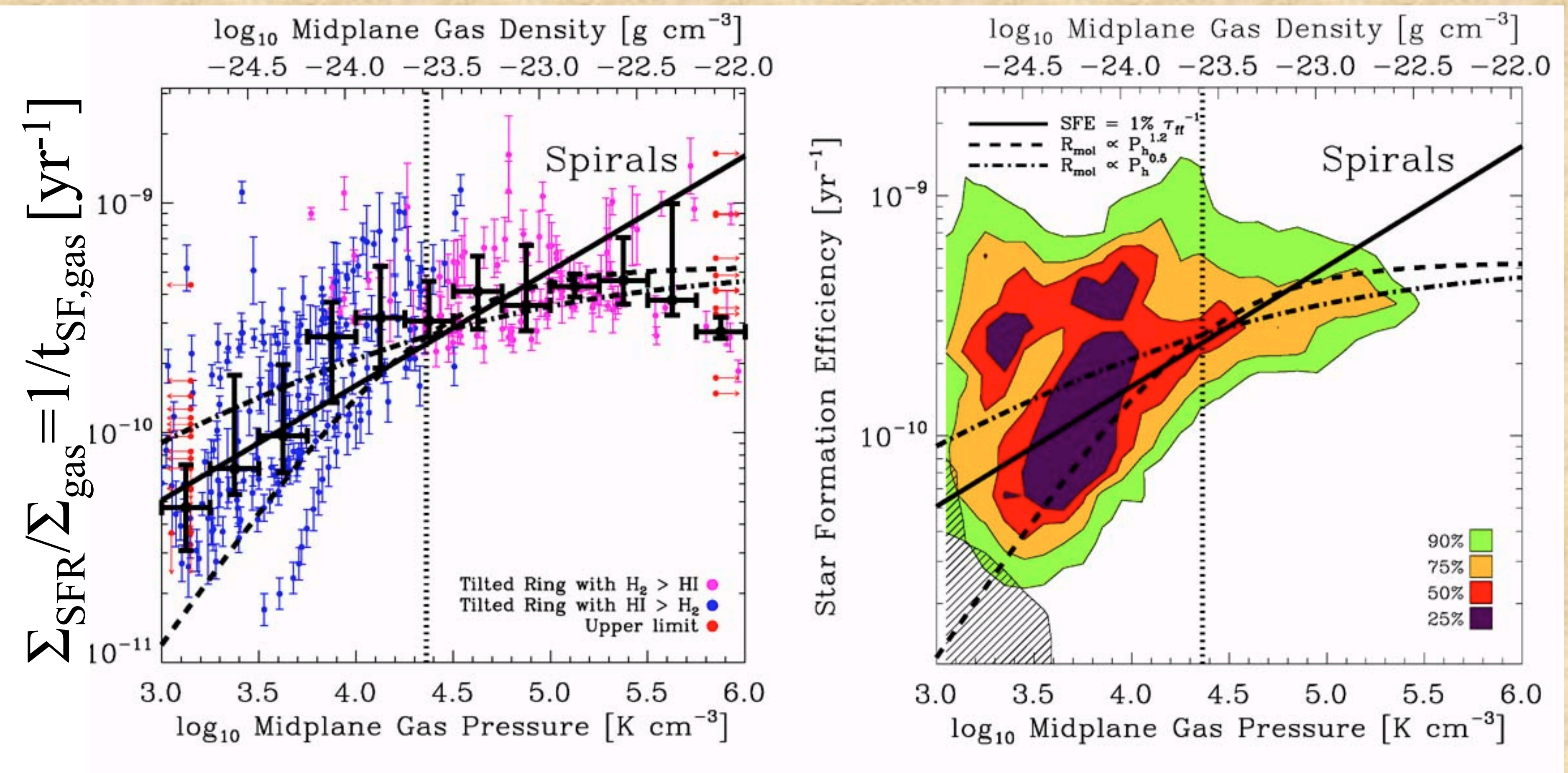


$$P_{ext} = 0.84(G\Sigma_\star)^{0.5}\Sigma_g \frac{v_g}{(h_\star)^{0.5}}.$$

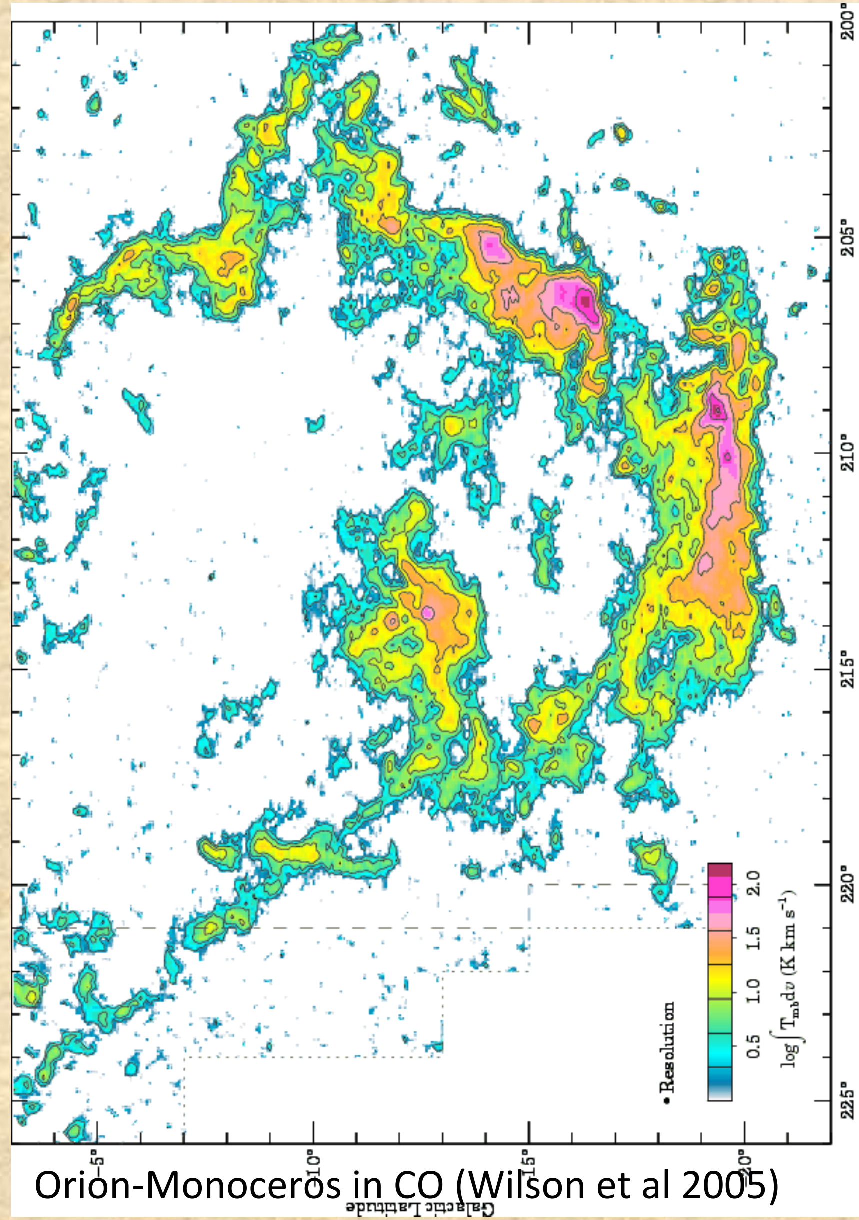
Leroy et al (2008)

Blitz & Rosolowsky (2006)

SFR and pressure correlation



Leroy et al (2008)



Orion-Monoceros in CO (Wilson et al 2005)

Why does star formation increase with pressure?

because…

Pressure increases with star formation!

Why does star formation increase with "hydrostatic" pressure?

because…

Thermal + turbulent pressure increases with star formation!

Σ_{SFR} vs. Σ_{H2} in starburst regime

- Gas dominated by H_2
- Steeper KS slopes than in mid-disks
- Regime of steeper KS slope corresponds to

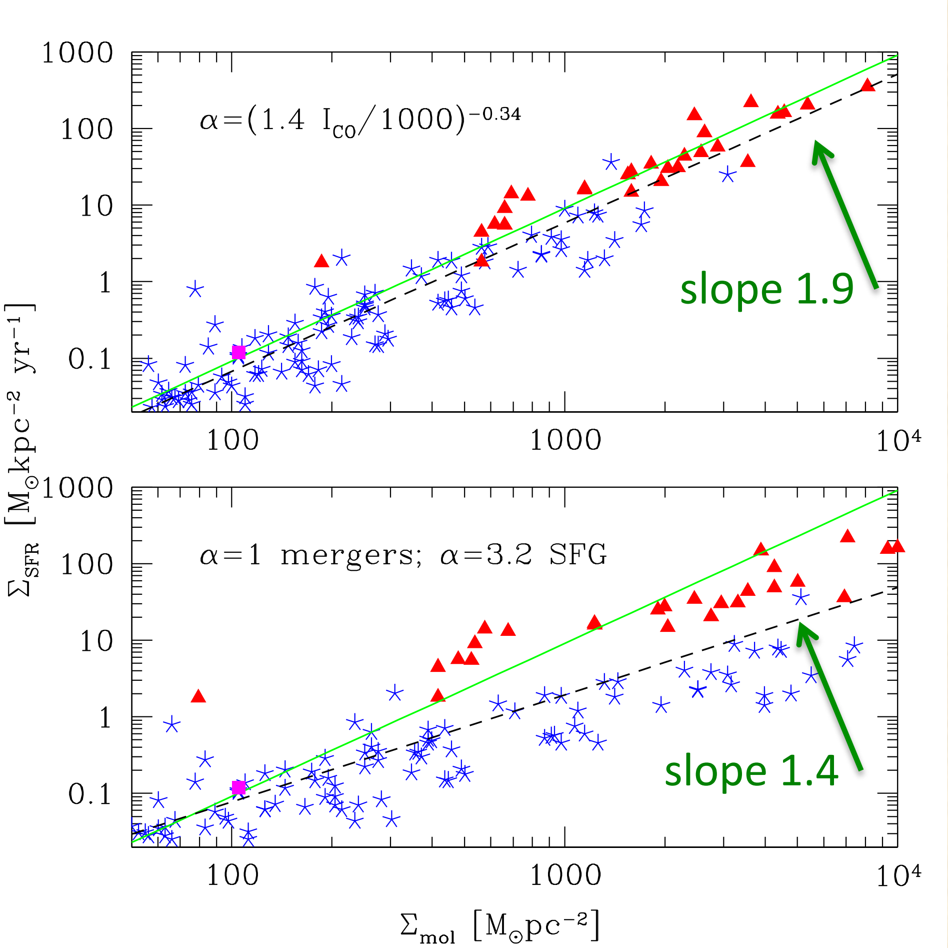
  $\Sigma_{gas} > \Sigma_{GMC} \sim 100\ M_\odot\ pc^{-2}$

  for resolved GMCs as observed in Local Group

  Blitz et al 2007, Sheth et al 2007, Bolatto et al 2008

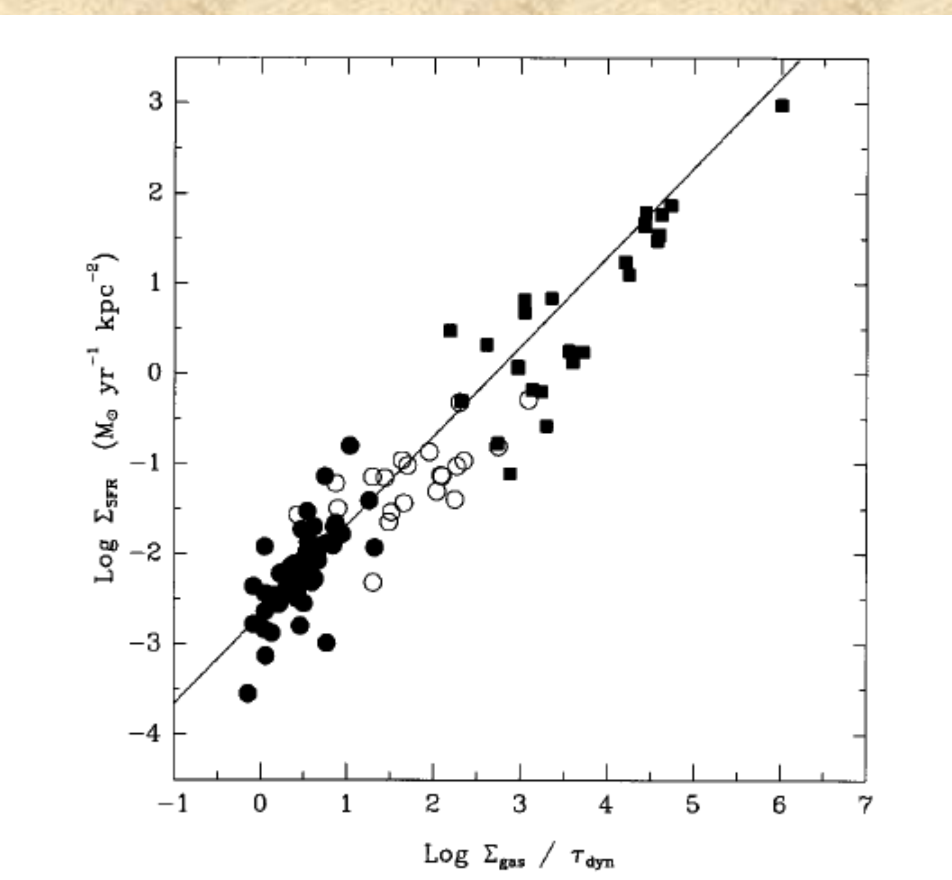
  ⇒ *"overlapping" GMCs*
- KS slope ~ 1.5 to 2, depending on CO →H_2 conversion

→ See Shetty et al 2011a,b and Narayanan et al (2011,2012) for X_{CO} dependencies

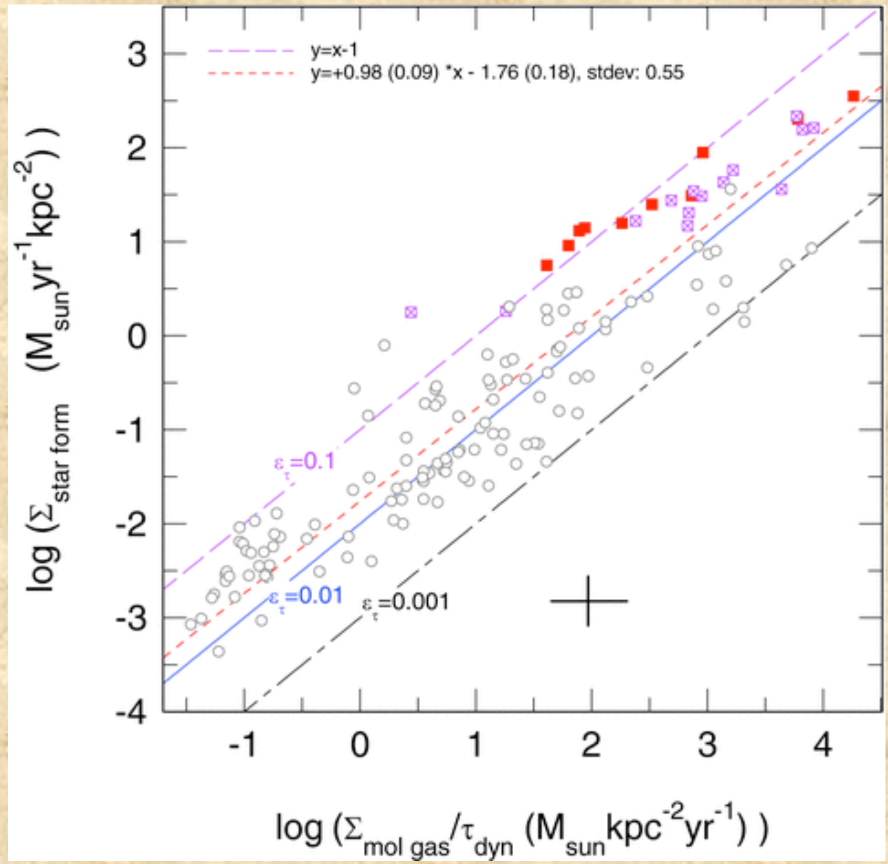


Data from Genzel et al (2010) sample; two different CO →H_2 conversion factors α

SF and orbital time



Kennicutt (1998)



Genzel et al (2010)

$$\Sigma_{SF} \sim 0.1\ \Sigma_{gas}/t_{orbit}$$

Gas consumption efficiency

- Interpretation of $t_{SF}(H_2)$= const. at $\Sigma_{H2} \lesssim 100 M_\odot\ pc^{-2}$:
  "isolated" GMCs have ~uniform properties and SFE independent of local environment

  $t_{SF}(H_2) = 2\times10^9$ yr requires $\varepsilon_{GMC} = 0.01$ if $t_{GMC} = 20$ Myr,

  $\varepsilon_{ff} = 0.003$ if $\langle n_H \rangle \sim 50\ cm^{-3}$
- Interpretation of $t_{SF}(H_2)$ decreasing in starbursts:
  where GMCs "overlap," density increases and relevant dynamical timescales are shorter
- Gas consumption timescale $t_{SF,gas} \equiv \Sigma_{gas}/\Sigma_{SFR}$:
  - ~10% efficiency per orbital time $t_{orb} = 2\pi/\Omega$
  - Lower efficiency over

    $t_{ff} = (3\pi/32G\rho_{gas})^{1/2} \sim 0.2\ t_{orb}$, $t_{ver} = H/v_z \sim 0.05\ t_{orb}$
- Star formation is *inefficient at consuming gas* over timescales relevant to the ISM dynamics

Questions for theory

- Why does the slope of $\Sigma_{SFR} = A\,\Sigma_{gas}^{1+p}$ change in different regimes?
- What is the origin of the R_{mol} -pressure relation?
  - Why does the "old" stellar component matter for SF?
  - What is the role of the multiphase ISM?
- Why is gas consumption so inefficient?
- How does energy and momentum feedback from massive stars affect the ISM and SFR?
- Can observed SFR relations be captured with simplified theoretical models?
- Can simulations reproduce observed SF relationships?

II. The multiphase ISM

ISM phases/structure

In galactic disks, the raw material for star formation is the neutral ISM:

- Atomic gas:
  - Warm atomic gas ($T \sim 10^4$ K; $n \sim 0.3$ cm^{-3} in Solar neighborhood)
    diffuse; fills much of volume near Galactic midplane
  - Cold atomic gas ($T \sim 100$ K; $n \sim 30$ cm^{-3} in Solar neighborhood)
    organized in dense clouds, sheets, & filaments; $L \sim 1$-10pc
  - Warm and cold phases coexist, in pressure equilibrium (FGH 1969)
  - Primary component in outer galaxies; saturated in inner galaxies:
    $\Sigma_{HI} \leq 10\ M_\odot\ pc^{-2}$ ($N_H \sim 10^{21}\ cm^{-2}$)
- Molecular gas:
  - Cold ($T \sim 10$ K) and dense ($n > 100$ cm^{-3})
  - Collected in gravitationally bound, turbulent clouds (GMCs)
  - Requires shielding from dissociating UV to exist
  - Primary component in inner galaxies: Σ_{H2} up to 10^2-10^3 $M_\odot\ pc^{-2}$

Other phases:

- Warm ionized gas ($T \sim 10^4$; heated/ionized by stellar UV)
- Hot ionized gas ($T \sim 10^6$K ; heated by supernova shocks)

Two-phase Thermal Equil.

- In Solar neighborhood,

  $P_{th,0} \approx P_{two\text{-}phase} \equiv (P_{min,cold} P_{max,warm})^{1/2}$

  ≈ 3000 k K cm^{-3} (Wolfire et al 2003)

- Dependence of $P_{two\text{-}phase}$:

$$\frac{P_{two-phase}}{k} = \left[n_{min} T_{min} n_{max} T_{min}\right]^{1/2}$$

$$= \Gamma\left[\frac{T_{min} T_{max}}{\Lambda(T_{min})\Lambda(T_{max})}\right]^{1/2}$$

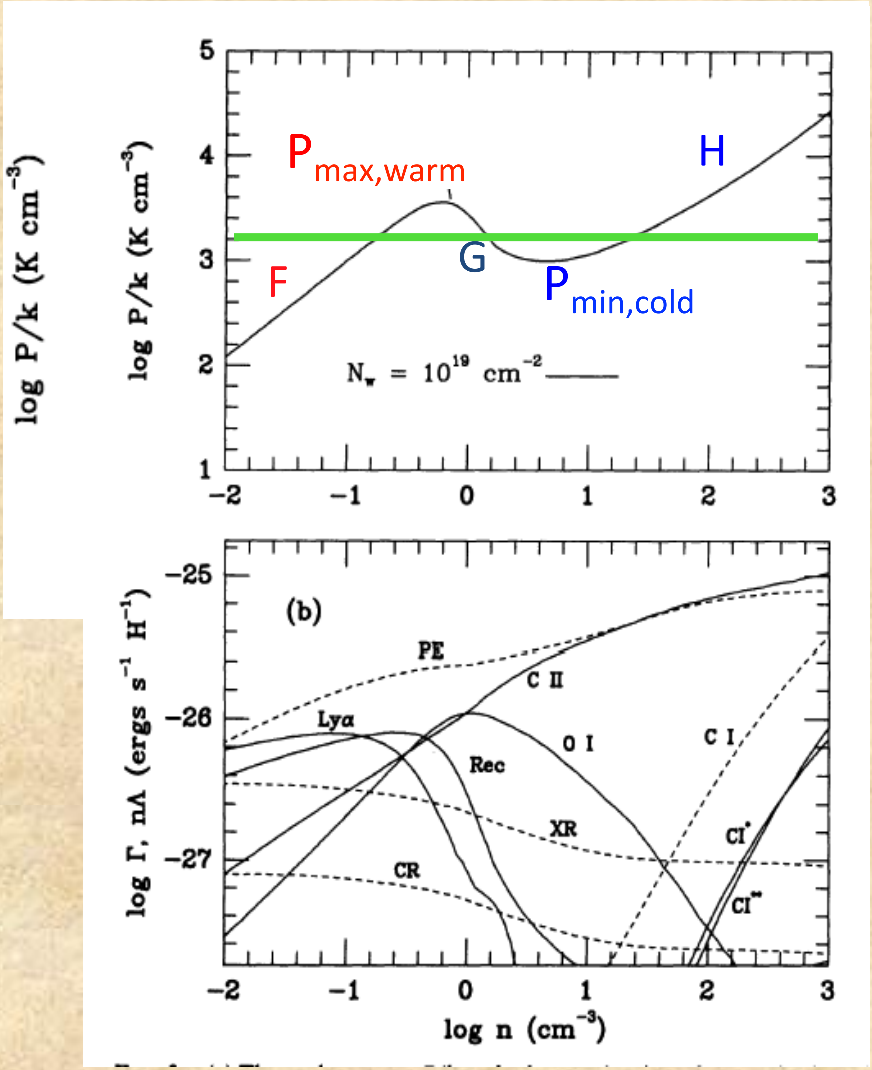
- T_{min}, T_{max} ~ const.; $\Gamma \propto Z_d J_{FUV}$, $\Lambda \propto Z_g \Rightarrow$

- $P_{two\text{-}phase} \propto J_{FUV} Z_d / Z_g$

  $\propto f_{rad} \Sigma_{SFR}$

  Larger f_{rad} at low Z_d :

  further UV propagation in diffuse ISM



Wolfire et al (1995)

equilibrium: $n\Lambda = \Gamma$

Molecular fraction in a cloud

Sternberg (1988);Krumholz, McKee, & Tumlinson 2009a,b; McKee & Krumholz 2010

- A cloud of cold gas exposed to external UV begins to become molecular (H_2)when

$$\Sigma_{cloud} > 11 M_\odot \, \mathrm{pc}^{-2} / Z'^{0.8}$$

  – lower metallicity Z′ requires a larger shielding column of HI
- For spherical clouds, $\frac{M_{HI}}{M_{H2}} \approx \left[Z'^{0.8} \left(\frac{N_{H,cloud}}{2 \times 10^{21}} \right) - 0.7 \right]^{-1}$
- Clouds are mostly-molecular at high columns
  – only gravitationally-bound clouds have high columns in outer galaxies
  – Most gas is molecular in inner galaxies

III. Self-regulated star formation

ISM energetics

- Timescales for cooling and turbulent dissipation in the neutral ISM are short
- For equilibrium, energy must be replenished
- High-mass stars efficiently:
  - heat the ISM with photoelectric effect from far-UV
  - drive turbulence in the ISM with expanding SN remnants
  - also: destroy parent GMCs through radiation, winds, SNe
- Midplane pressure $\propto$ energy density must support weight of diffuse ISM
  - pressure is dominated by turbulence for most of ISM
  - weight depends on gravity of gas, stars, dark matter
- *ISM equilibrium **demands** a certain level of feedback*

Thermal and dynamical equilibrium

- Thermal equilibrium:

$$n\Lambda(T) = \Gamma \Rightarrow P_{th}\,\Lambda(T)/T \propto J_{FUV} \Rightarrow P_{th} \propto \Sigma_{SFR}$$

- Turbulent equilibrium:

$$P_{turb} = \rho v_z^2 \sim v_z^2 \Sigma/H \sim v_z \Sigma/(H/v_z) \sim (\text{momentum/area})/t_{ver}$$

dissipation=driving ⇒

$$P_{turb} \sim (1/4) p_* \Sigma_{SFR}/m_* \quad \Rightarrow P_{turb} \propto \Sigma_{SFR}$$

- Vertical hydrostatic equilibrium:

$$P_{turb} + P_{th} \approx P_{DE} = \Sigma \langle g_z \rangle /2 \approx \Sigma (2G\,\rho_*)^{1/2} \sigma_z + \pi G \Sigma^2/2$$

$$\Rightarrow P_{DE} \approx P_{th} + P_{turb} \propto \Sigma_{SFR}$$

Application to starburst regions

Ostriker & Shetty (2011)

- Cold "diffuse" molecular gas: $\Sigma_{gas} > \Sigma_{GMC} \sim 100\ M_\odot\ pc^{-2}$
- Star formation rate from balancing weight with pressure (turbulence and trapped IR radiation):

$$\Sigma_{\rm SFR} = \frac{2\pi G}{f_p p_*/m_*}\Sigma^2_{\rm gas}\frac{1+\chi}{1+\tau/\tau_*}$$

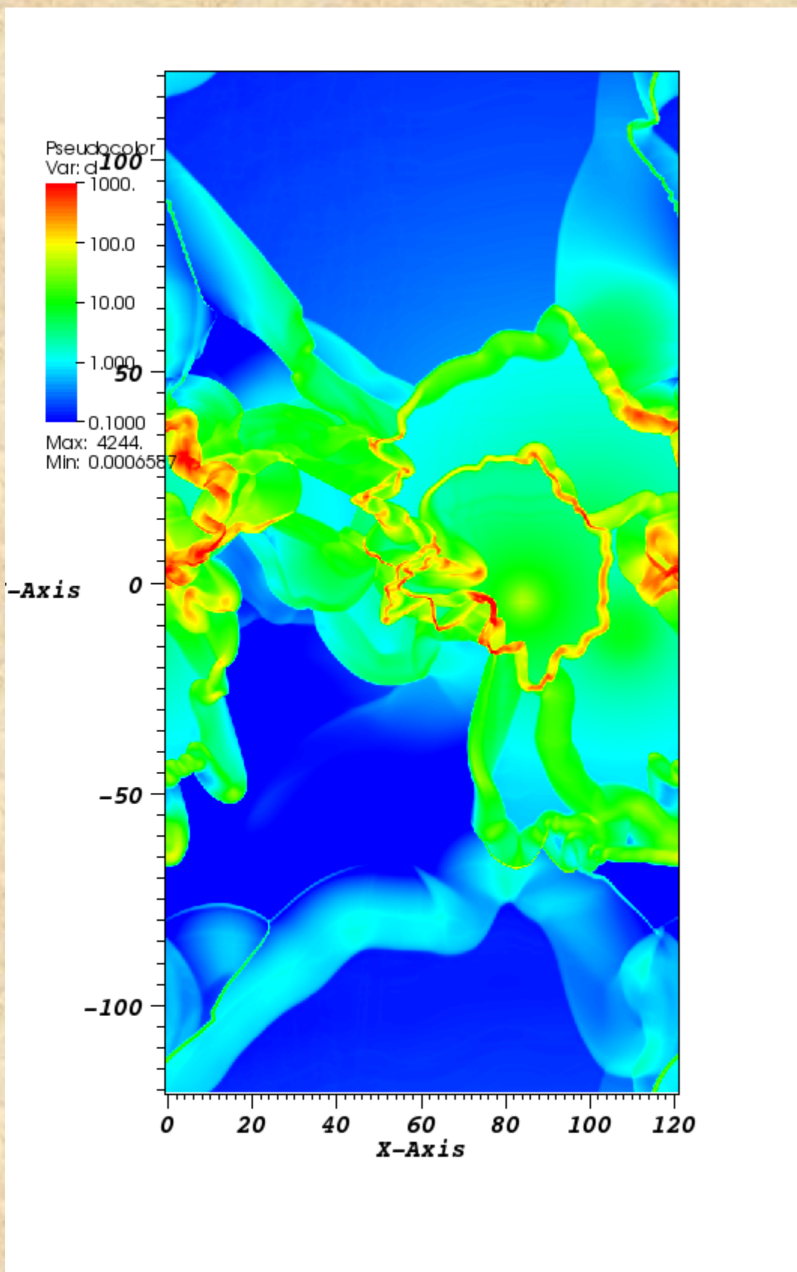
  - Self-gravity dominates stellar disk, bulge: $\chi \rightarrow 0$
  - SN-driven turbulent pressure > radiation pressure for $\Sigma_{gas} \lesssim 10^4\ M_\odot\ pc^{-2}$:

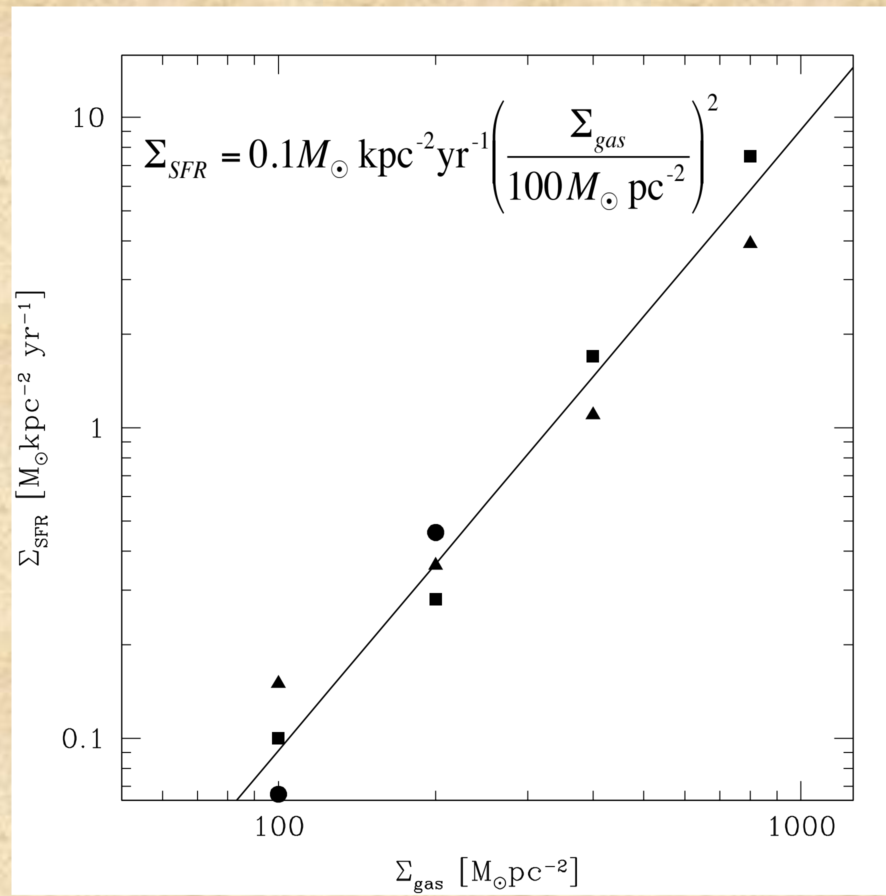
$$\frac{\tau}{\tau_*} = 0.008\frac{\Sigma_{gas}}{100 M_\odot {\rm pc}^{-2}}\frac{\kappa}{10cm^2/g}\left(\frac{p_*/m_*}{3000km/s}\right)^{-1}\left(\frac{\varepsilon_*}{10^{-3}}\right)^{-1}$$

- Radiative SN remnants (Cioffi et al 1988; Blondin et al 1998):

$$\frac{p_*}{m_*} \approx 3000{\rm km\,s^{-1}}\left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right)^{0.94}\left(\frac{n_0}{1{\rm cm}^{-3}}\right)^{-0.12}\left(\frac{m_*}{100M_\odot}\right)^{-1}$$

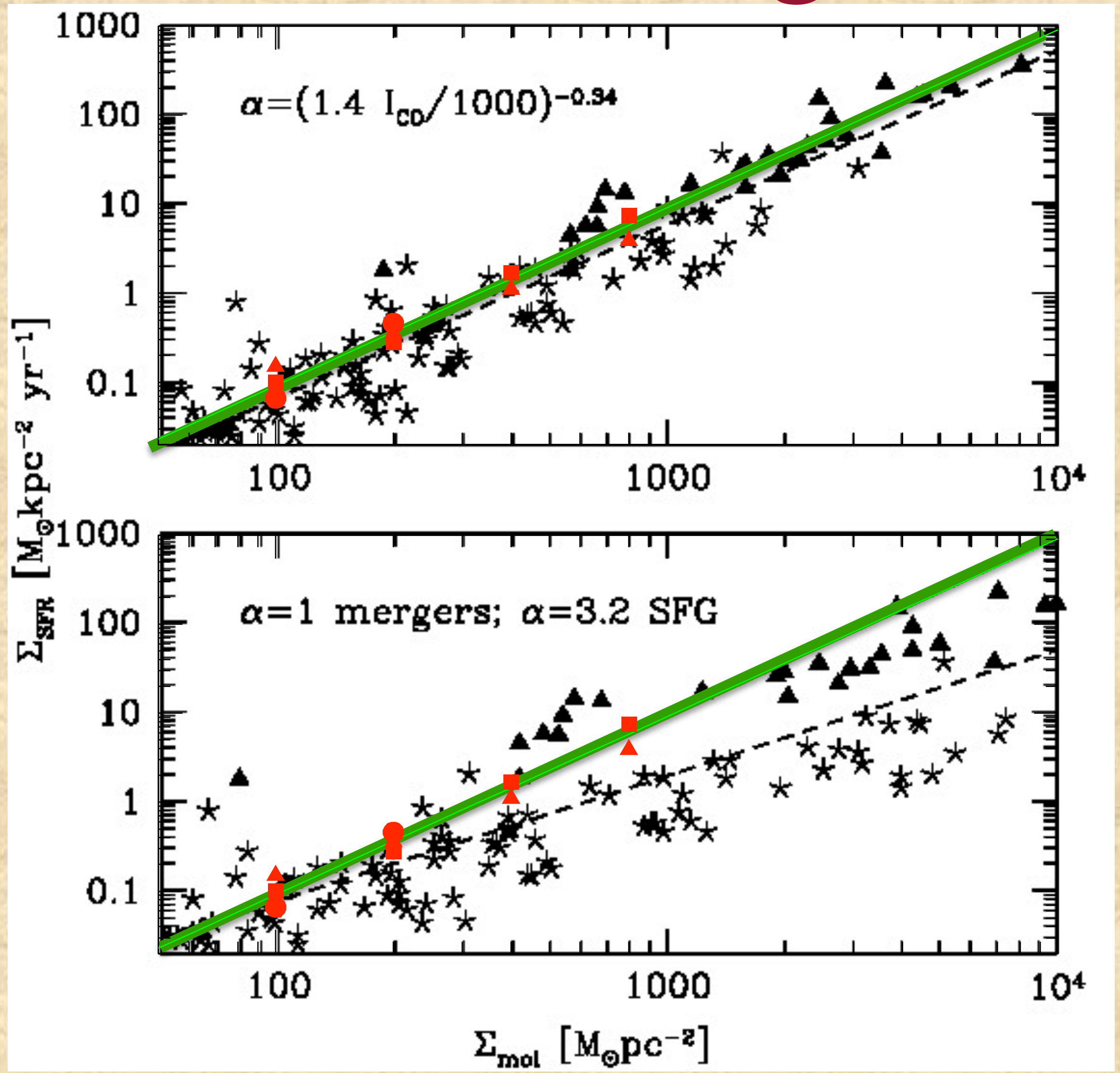
$$\Rightarrow \quad \boxed{\Sigma_{\rm SFR} = 0.1 M_\odot {\rm kpc}^{-2}{\rm yr}^{-1}\left(\frac{\Sigma_{\rm gas}}{100M_\odot{\rm pc}^{-2}}\right)^2}$$





Ostriker & Shetty (2011)

Starburst regions



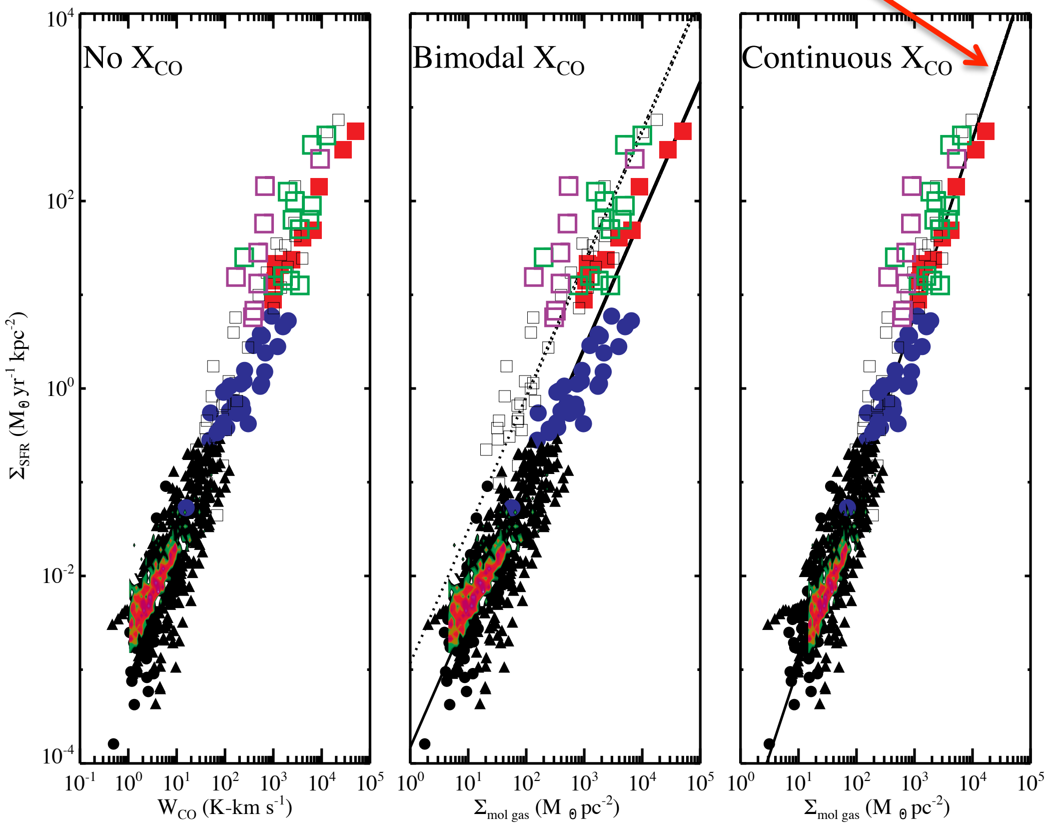
Ostriker & Shetty (2011)

Data from Genzel et al (2010) sample; two different CO →H_2 conversion factors α

→ See Shetty et al 2011a,b and Narayanan et al (2011,2012) for X_{CO} dependencies

$$\Sigma_{SFR} = 0.1 M_{\odot}\,\mathrm{kpc^{-2}yr^{-1}}\left(\frac{\Sigma_{gas}}{100\,M_{\odot}\,\mathrm{pc^{-2}}}\right)^2$$

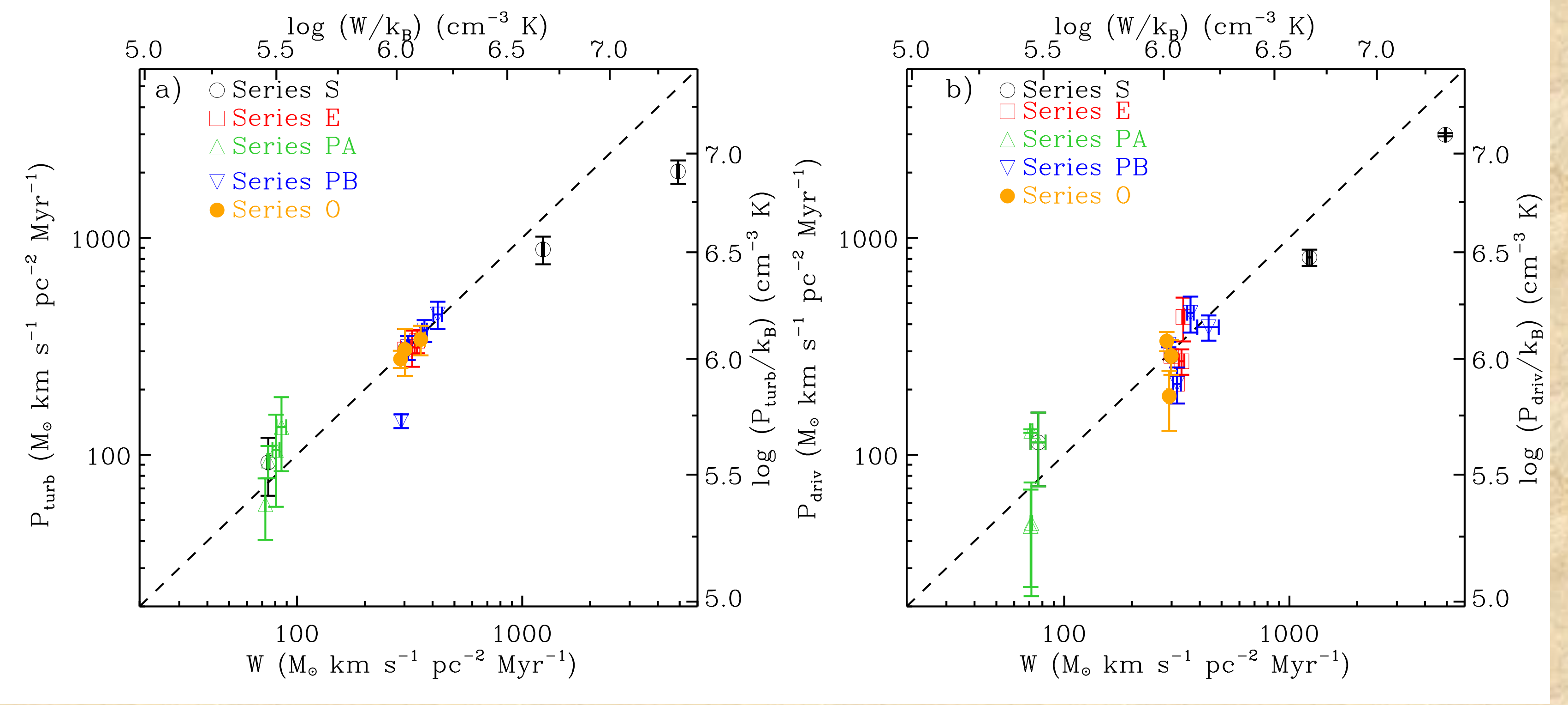
$$\Sigma_{SFR} = 0.1 M_{\odot}\ \mathrm{kpc}^{-2}\mathrm{yr}^{-1}\left(\frac{\Sigma_{gas}}{100\, M_{\odot}\ \mathrm{pc}^{-2}}\right)^{2}$$



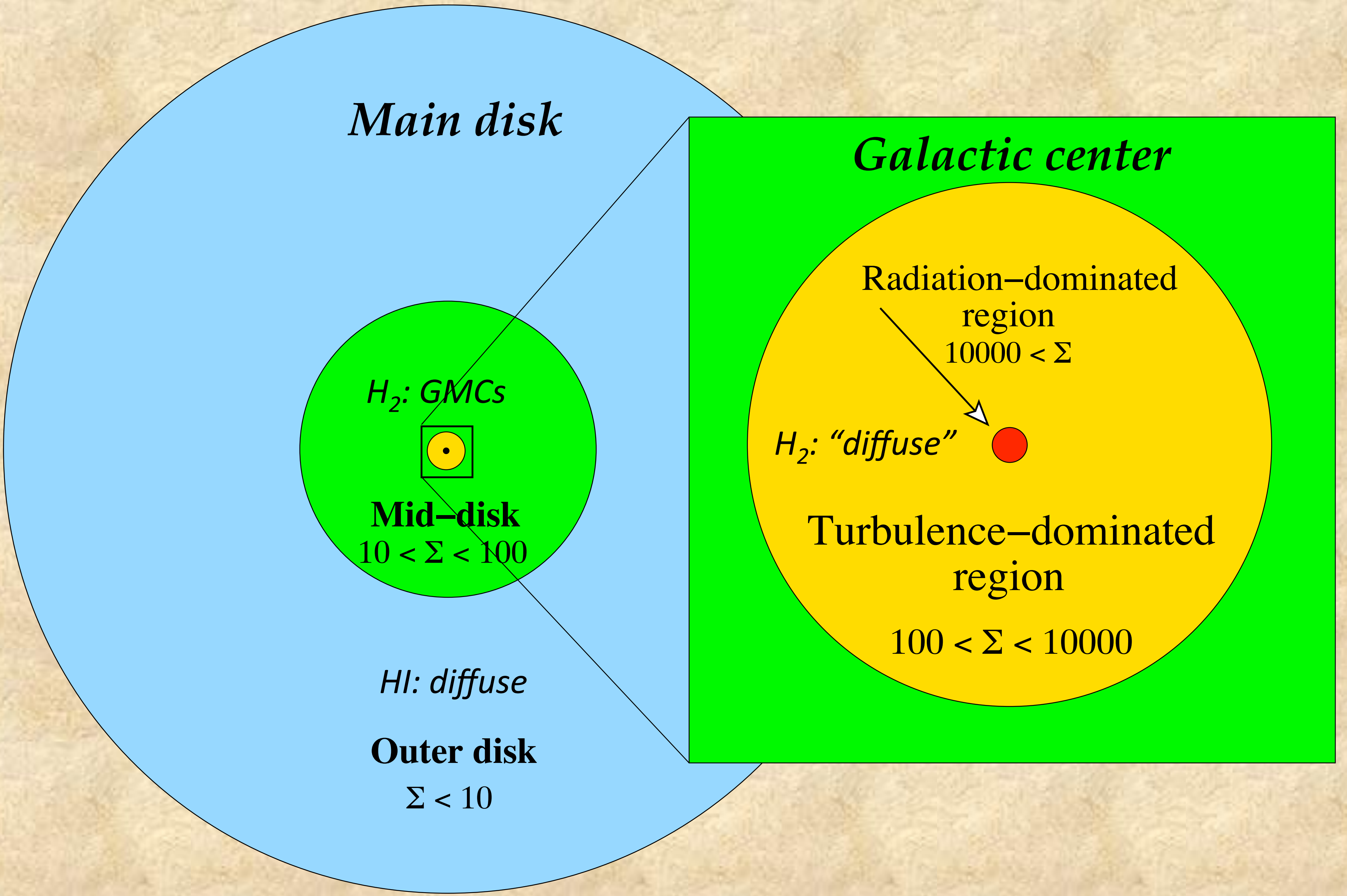
Narayanan, Krumholz, Ostriker, & Hernquist (2012)

Starburst regime simulations

- Feedback-driven, turbulence-dominated equilibrium:
  - $P_{turb} \approx W \approx \pi G \Sigma^2/2 \approx (1/4)(p_*/m_*)\Sigma_{SFR}$
  - ε_{ff}~0.005-0.01 insensitive to other conditions
  - v_z~ 5-10 km/s $\propto p_*/m_*$



Shetty & Ostriker (2012)


Main disk
H2: GMCs
Mid–disk
10 < Σ < 100
HI: diffuse
Outer disk
Σ < 10
Galactic center
Radiation–dominated region
10000 < Σ
H2: "diffuse"
Turbulence–dominated region
100 < Σ < 10000

Mid/outer disks

Ostriker, McKee, & Leroy (2010)

- ISM surface density Σ_{gas} has two parts: gravitationally-bound clouds Σ_{gbc} and diffuse atomic gas $\Sigma_{diff}=\Sigma_{gas}-\Sigma_{gbc}$
- SF is in GBC component, with timescale $t_{SF,gbc}$ (~2Gyr):
  - $\Sigma_{SFR} = \Sigma_{gbc}/t_{SF,gbc} = (\Sigma_{gas}-\Sigma_{diff})/t_{SF,gbc}$
- Diffuse gas is in vertical dynamical equilibrium
  – vertical gravity is from gas, stars, dark matter

$$P_{tot} = P_{th} + P_{turb} = P_{DE} = \frac{\Sigma_{diff}}{2}\langle g_z\rangle \approx \frac{\Sigma_{diff}}{2}\left[\pi G(\Sigma_{diff} + 2\Sigma_{gbc}) + 2(2G\rho_*)^{1/2}\sigma_z\right]$$

- Diffuse gas is in thermal equilibrium, consistent with two-phase (warm+cold) atomic medium: $P_{th} \propto \Sigma_{SFR}$
- Diffuse gas is in turbulent equilibrium, with dissipation on crossing time balanced by driving from SNe: $P_{turb} \propto \Sigma_{SFR}$
- *Feedback relations + hydrostatic equilibrium give cubic equation to solve for Σ_{SFR}, given Σ_{gas} and ρ_**

Mid/outer disks: results

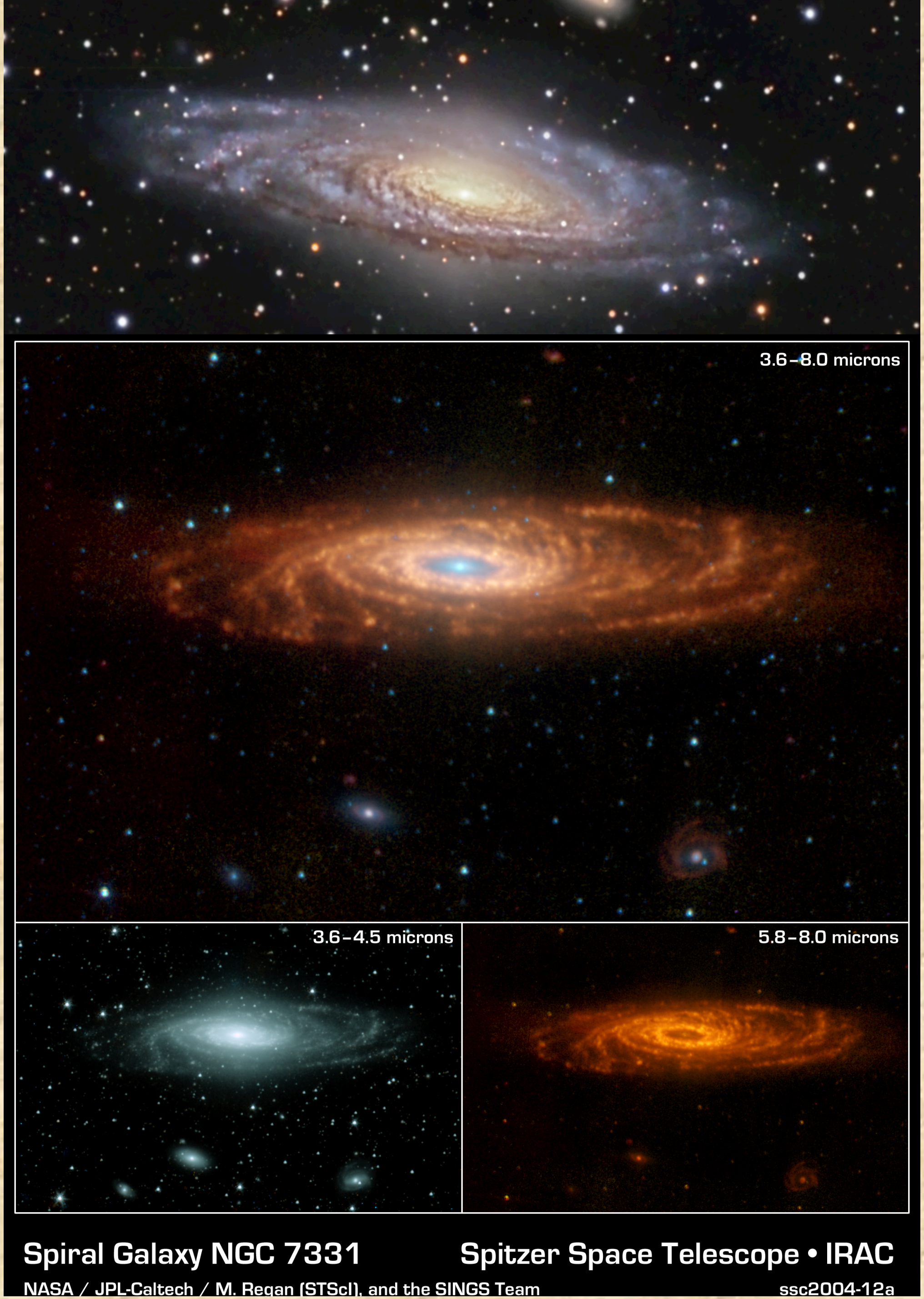
- Star formation rate:
  - At high Σ_{gas}, ρ_* : $\Sigma_{gas} \approx \Sigma_{gbc} \gg \Sigma_{diff} \Rightarrow \Sigma_{SFR} = \Sigma_{gas} / t_{SF,gbc}$
  - At low Σ_{gas}, ρ_* : $\Sigma_{gas} \approx \Sigma_{diff} \gg \Sigma_{gbc} \Rightarrow$

$$\Sigma_{SFR} \approx \frac{\Sigma_{SFR,0}}{P_{tot,0}} P_{tot} \approx \frac{\Sigma_{SFR,0}}{P_{th,0}} \frac{\Sigma_{diff}}{\alpha} \left[\frac{\pi G \Sigma_{diff}}{2} + \pi G \Sigma_{gbc} + \left(2G\rho_*\right)^{1/2} \sigma_z \right]$$

- Self-gravitating-to-diffuse ratio:

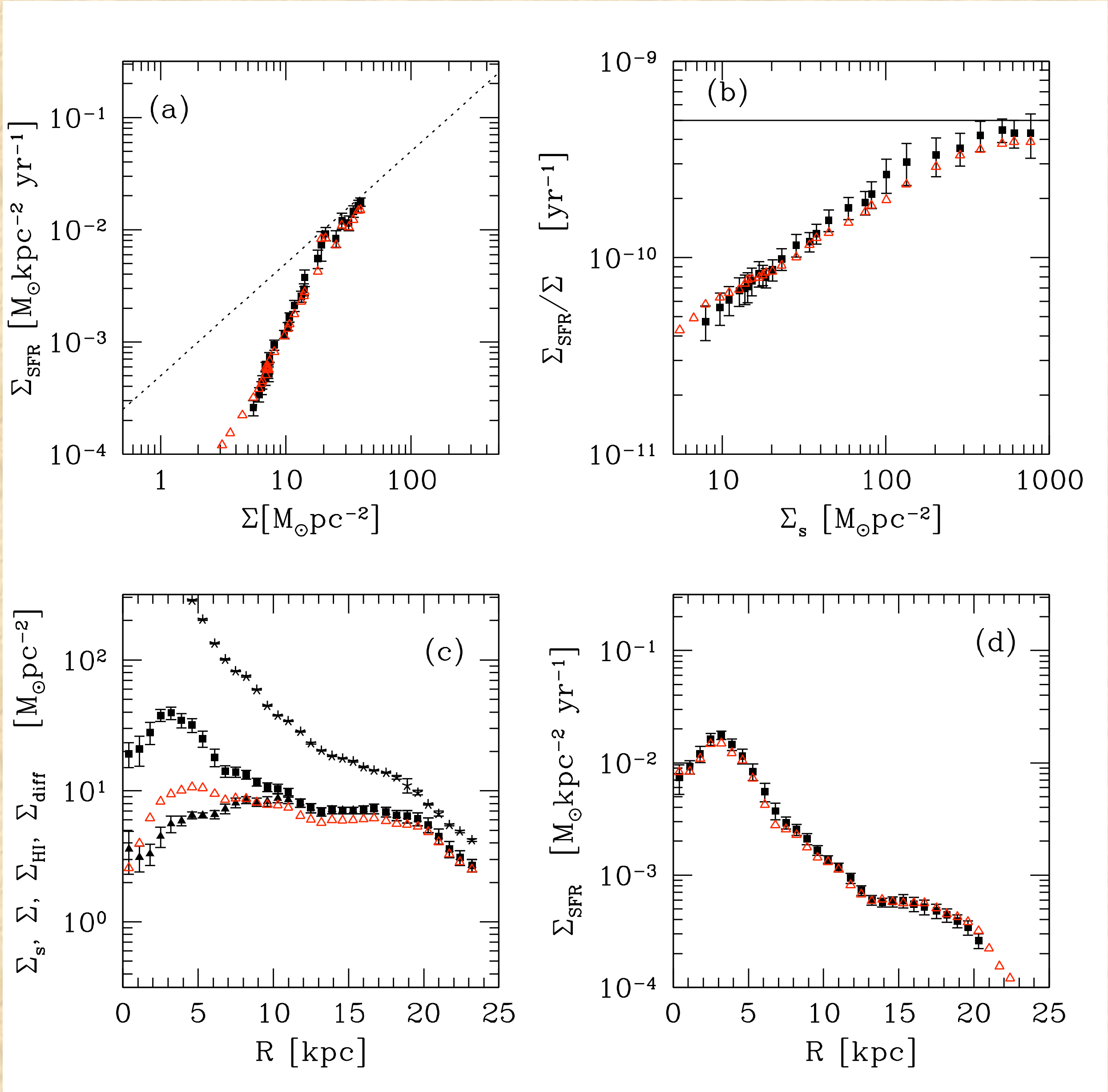
$$\frac{\Sigma_{gbc}}{\Sigma_{diff}} = \frac{\langle g \rangle_z}{1.3 \text{pc Myr}^{-2}} \propto \left[\frac{\pi G \Sigma_{diff}}{2} + \pi G \Sigma_{gbc} + \left(2G\rho_*\right)^{1/2} \sigma_z \right]$$

…similar to empirical R_{mol} –P relation

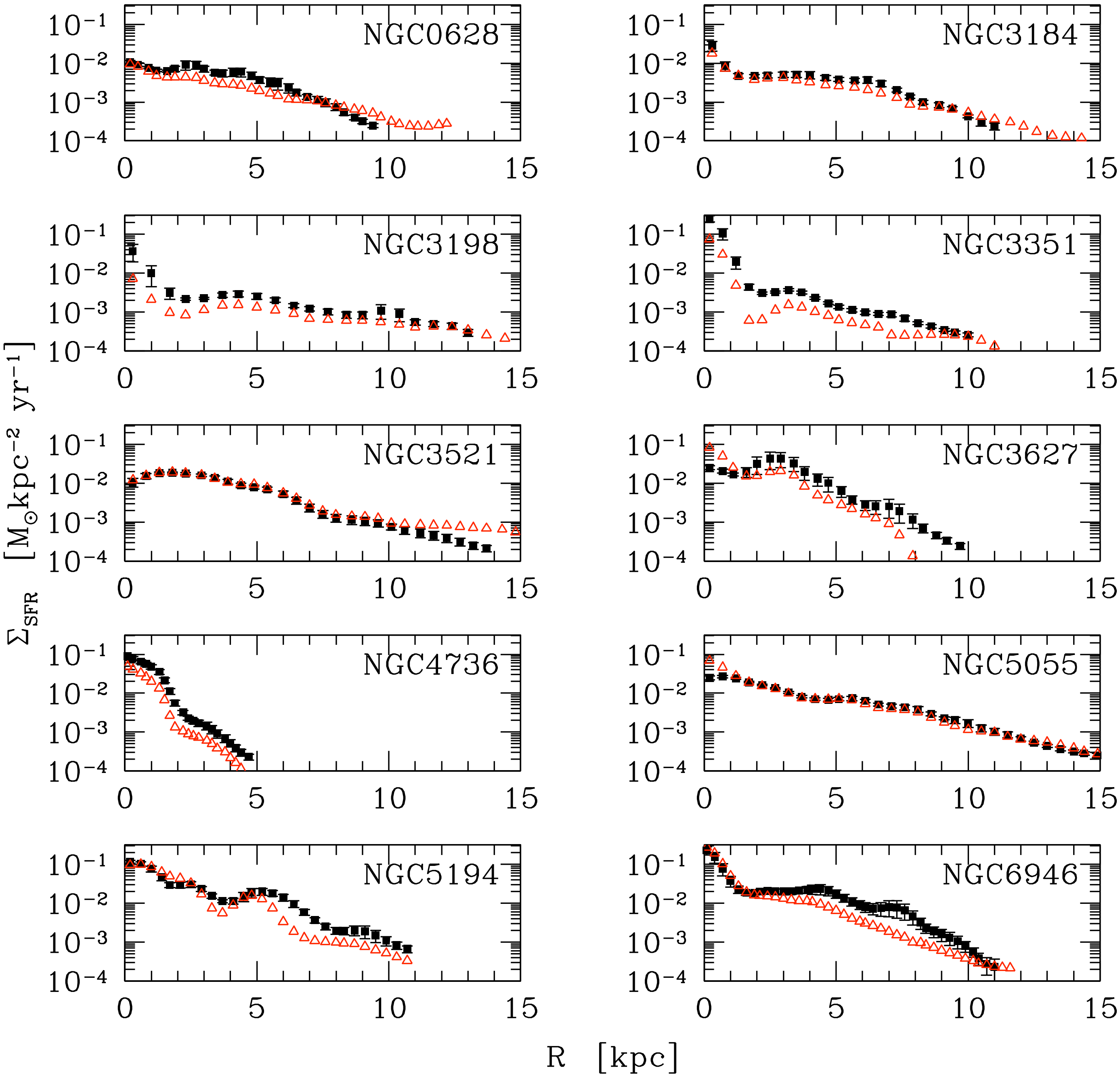

3.6–8.0 microns
3.6–4.5 microns
5.8–8.0 microns
Spiral Galaxy NGC 7331
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / M. Regan (STScI), and the SINGS Team
ssc2004-12a

R.J. Gabany

NGC 7331 – thermal/dynamical equilibrium model



Ostriker, McKee, & Leroy (2010)



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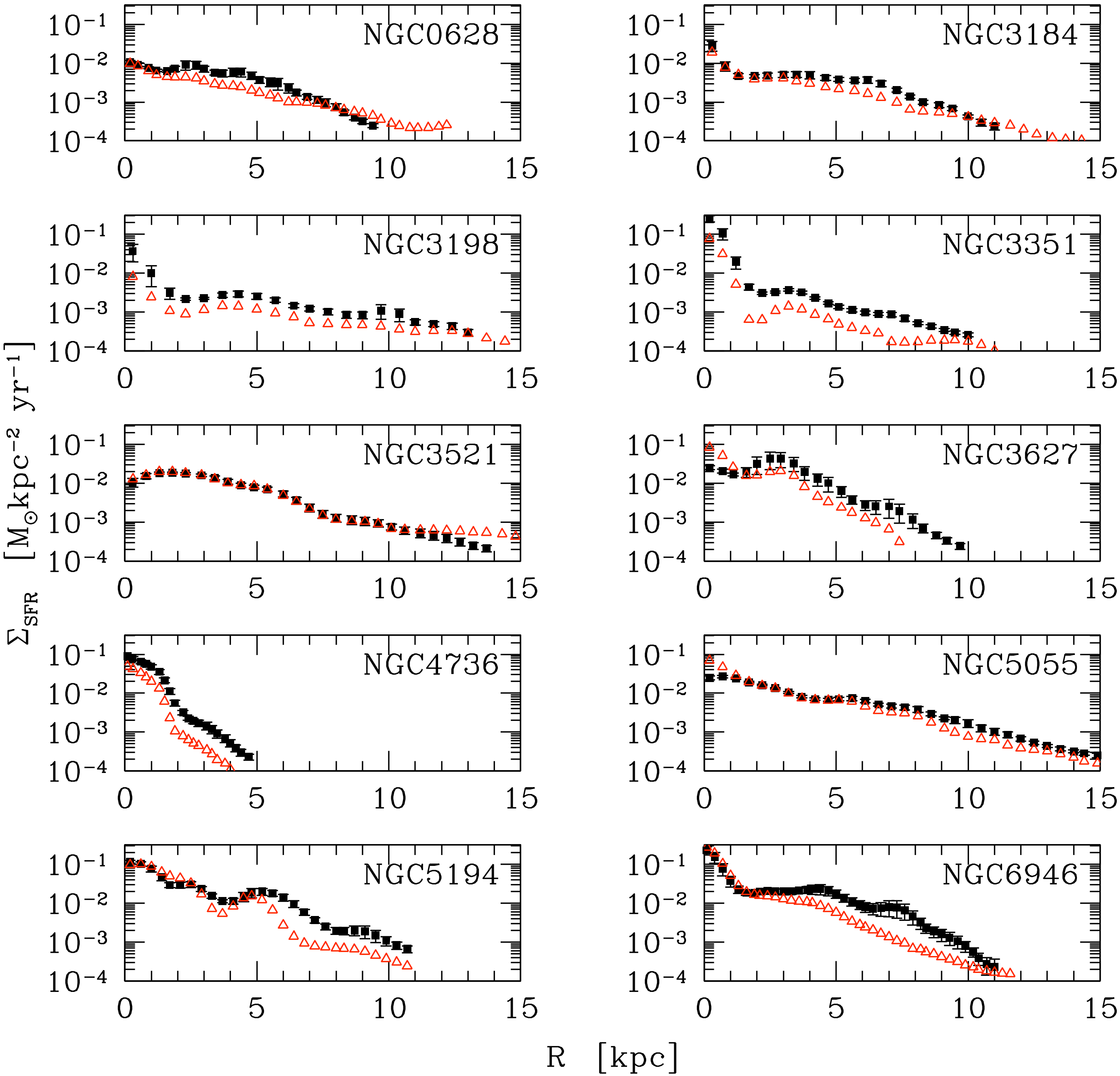


Ostriker, McKee, & Leroy (2010)

Approach to SF Equilibrium

- If diffuse gas fraction is high…
- From vertical dynamics,

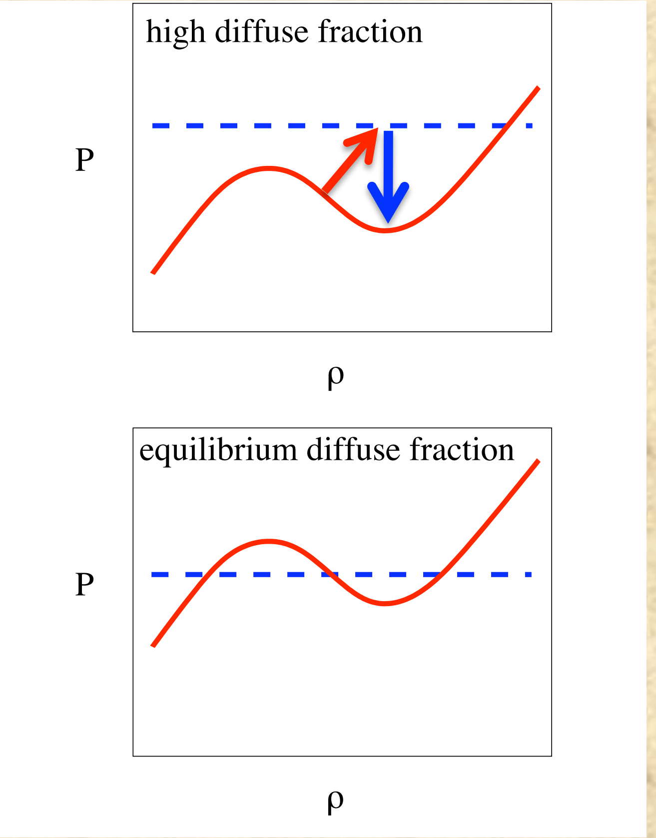
$$P_{th} \sim \Sigma_{diff} (2G\rho_*)^{1/2} \frac{\sigma_{z,diff}}{\alpha}$$

is high

- $\Sigma_{gbc} = \Sigma_{gas} - \Sigma_{diff}$ is low $\Rightarrow \Sigma_{SFR}$ low

$$P_{two\text{-}phase} / k \sim 10^6 \mathrm{K\ cm^{-3}} \frac{\Sigma_{SFR}}{M_\odot \mathrm{\ kpc^{-2} yr^{-1}}}$$

is low

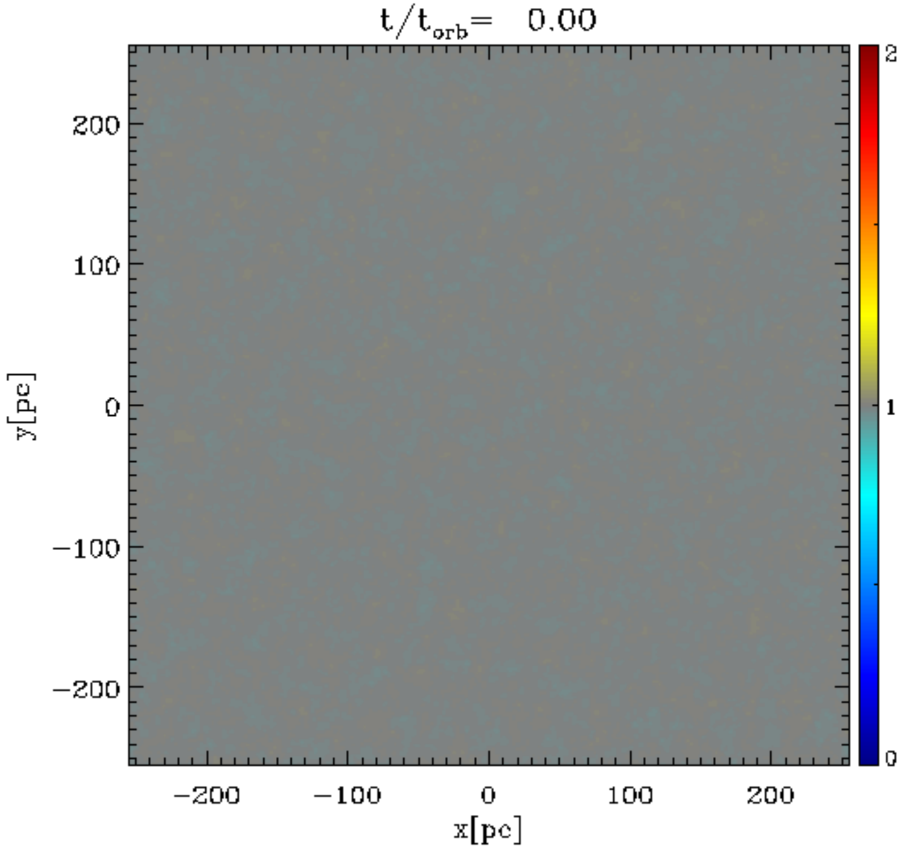


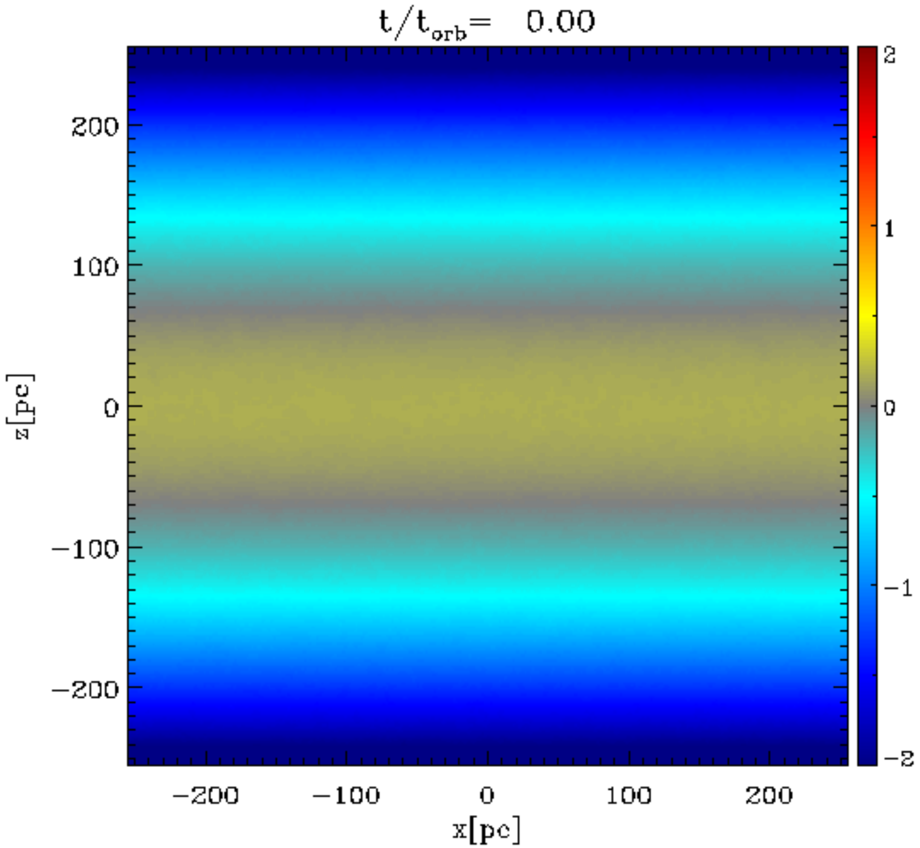
- *Warm medium cools and condenses to make cold clouds*
- *Cold clouds collect into GBCs; lowers Σ_{diff} and P_{th}*
- *Increase in Σ_{gbc} raises Σ_{SFR}*
- *Higher Σ_{SFR} raises $P_{two\text{-}phase}$*

Simulations with radiative and turbulent feedback

- Test & calibrate thermal/ dynamical equilibrium model:
- Kim, Kim, & Ostriker (2011,2013)
  - include turbulent driving from SN
  - include dependence of heating rate on star formation rate
  - simulations use the *Athena* code

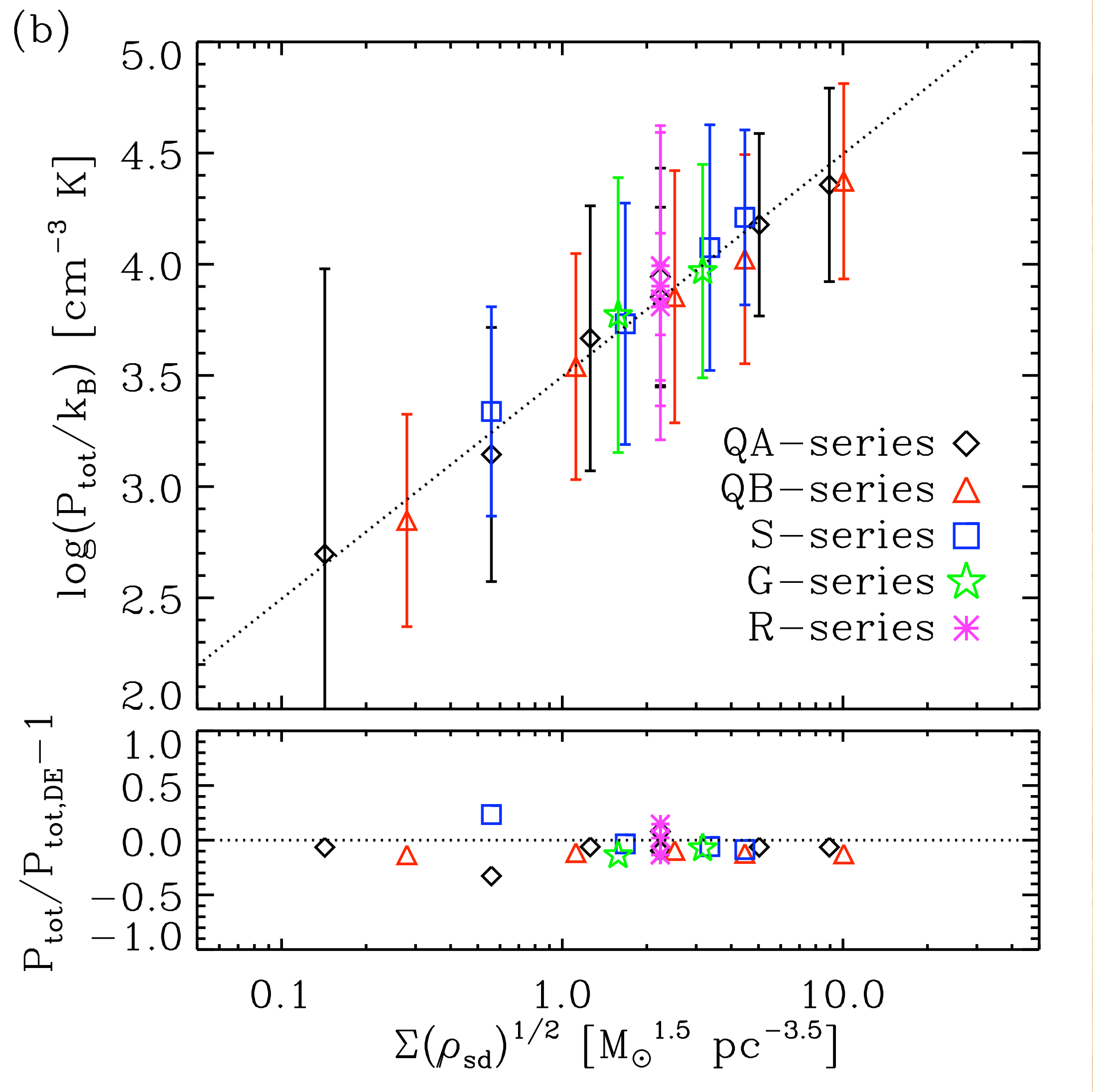
- Does weight=midplane pressure?
- Does heating, thermal equilibrium yield P_{th} close to $P_{two\text{-}phase}$?
- Does turbulent driving/dissipation yield P_{turb} close to $P_{driv,SN}$?
- What is resulting SFR behavior?





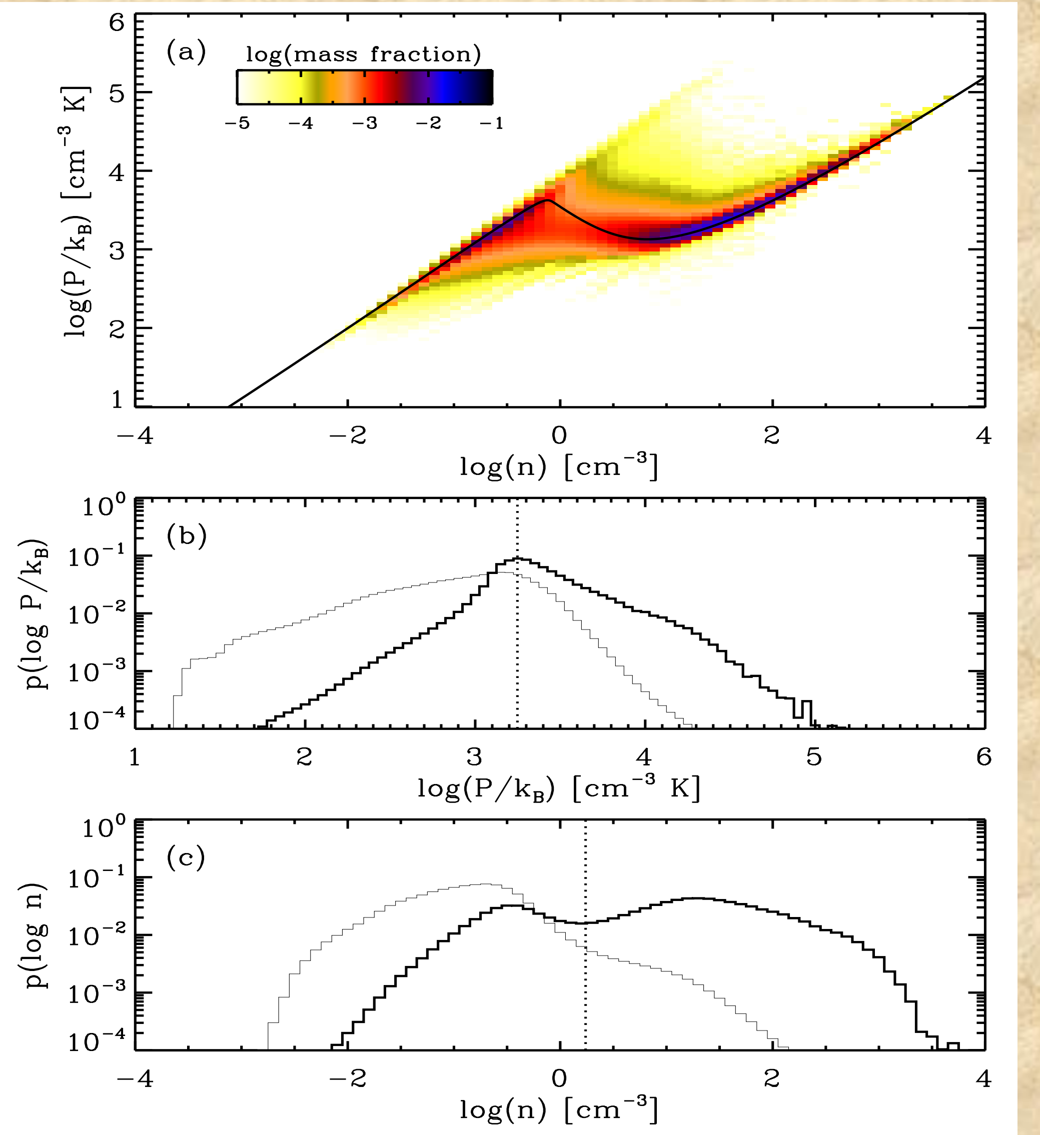
Test of equilibrium assumptions

Kim, Kim, & Ostriker (2011)



Vertical dynamical equilibrium: $P_{tot} \propto P_{tot,DE} \propto \Sigma\, g_z$

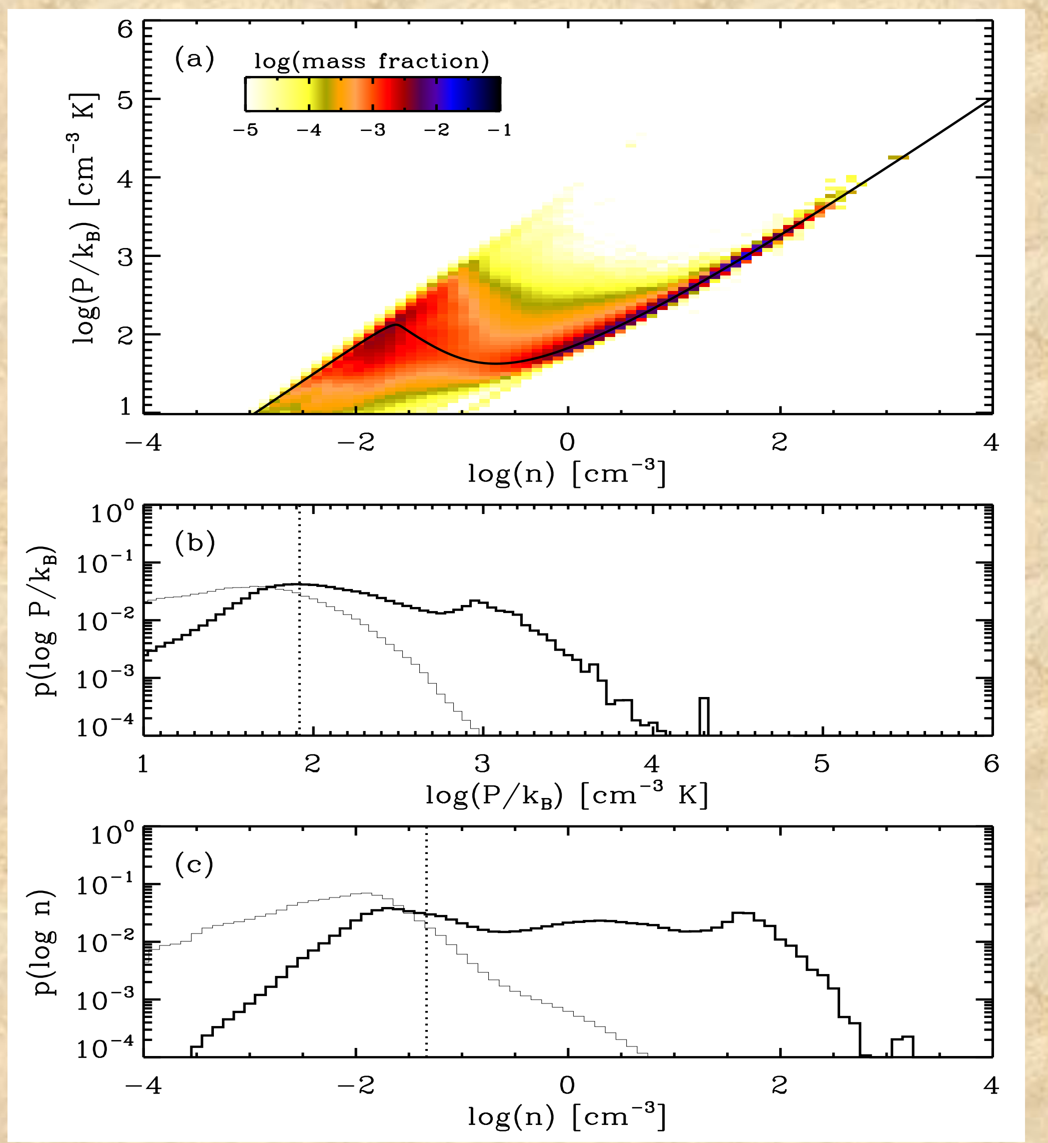
Thermal state of gas



Kim, Kim, & Ostriker (2011)

Solar neighborhood model: Σ_{gas} =10 $M_{\odot}$ pc^{-2}

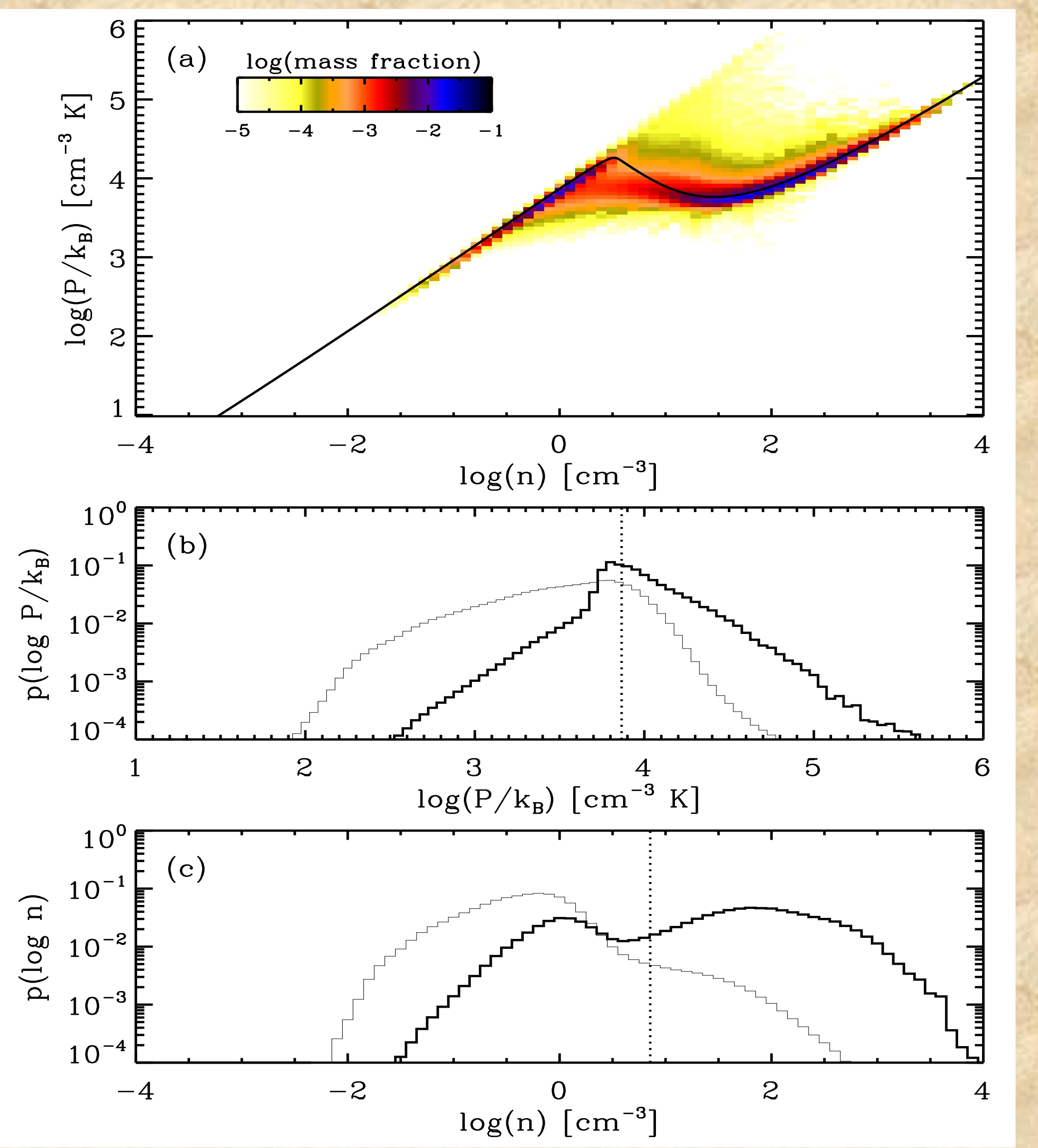
Thermal state of gas



Kim, Kim, & Ostriker (2011)

Outer galaxy model: $\Sigma_{gas} = 2M_{\odot}\,pc^{-2}$

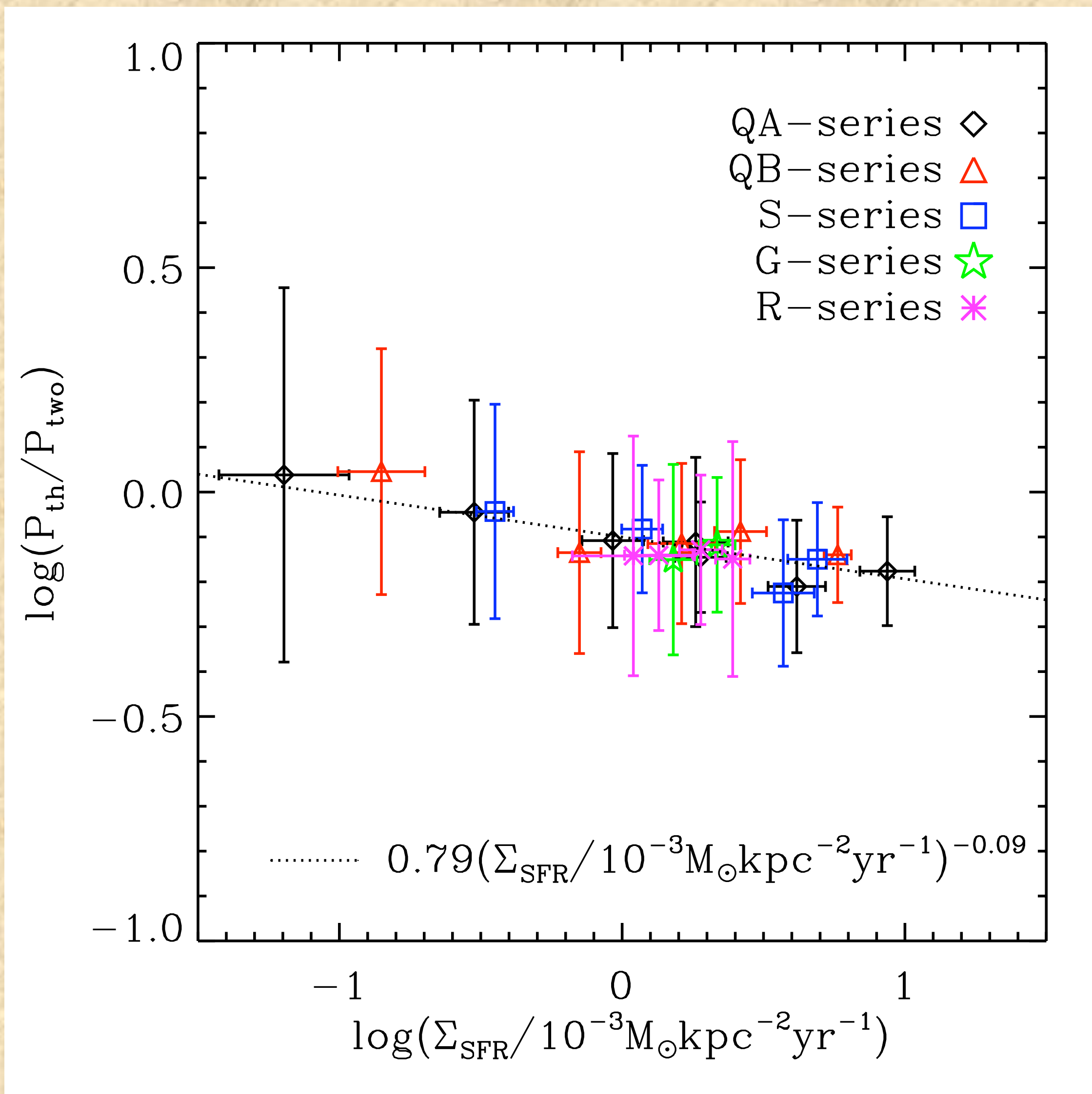
Thermal state of gas

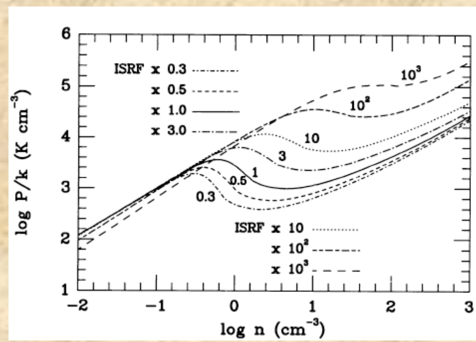


Kim, Kim, & Ostriker (2011)

Mid-disk model: $\Sigma_{gas} = 20 M_{\odot}\ pc^{-2}$

Test of equilibrium assumptions



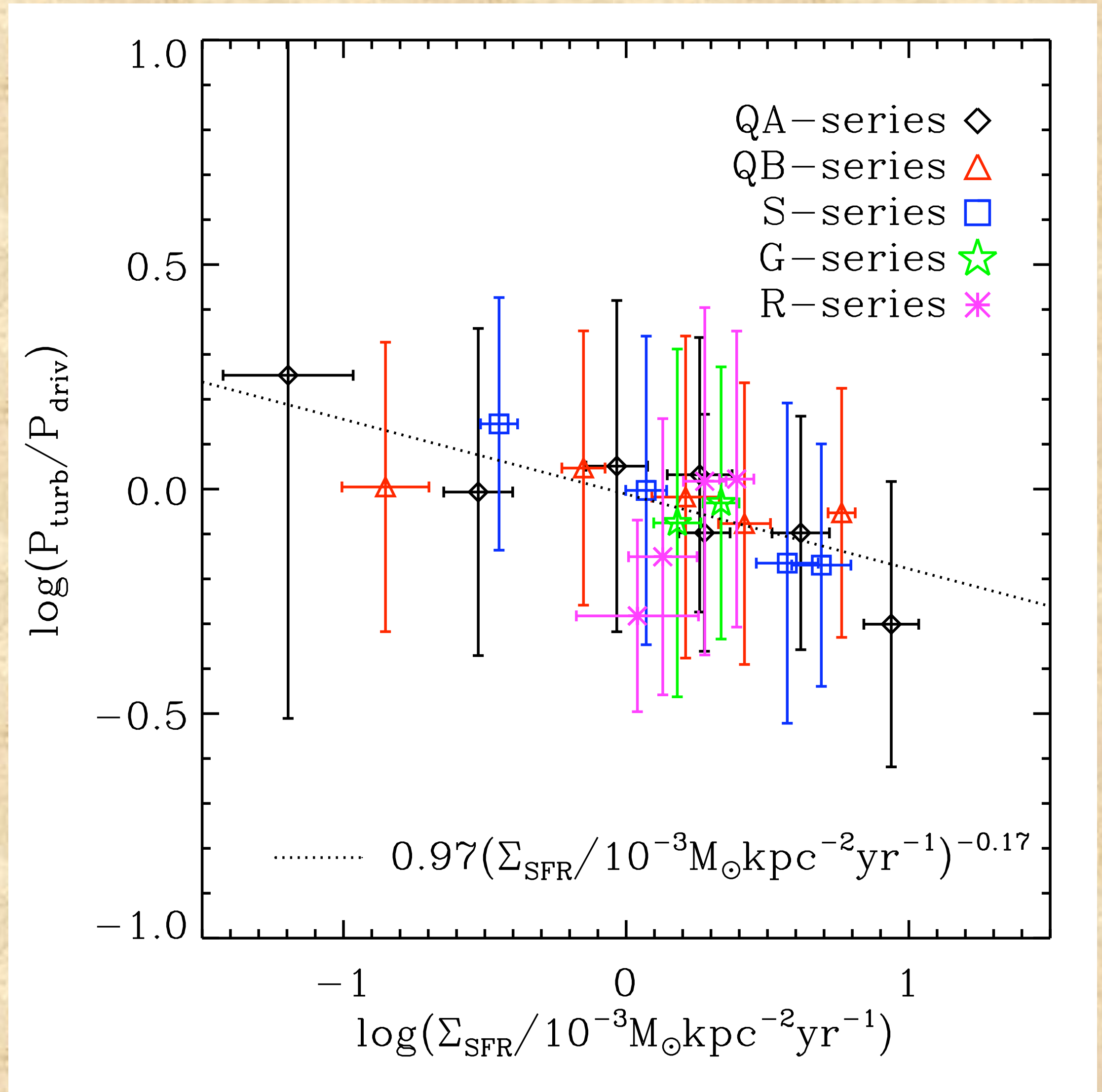


Kim, Kim, & Ostriker (2011)

Thermal equilibrium with feedback: $P_{th} \propto P_{two} \propto \Sigma_{SFR}$

Test of equilibrium assumptions

Kim, Kim, & Ostriker (2011)



Turbulent equilibrium with feedback: $P_{turb} \propto P_{driv} \propto \Sigma_{SFR}$

Turbulent state of the gas

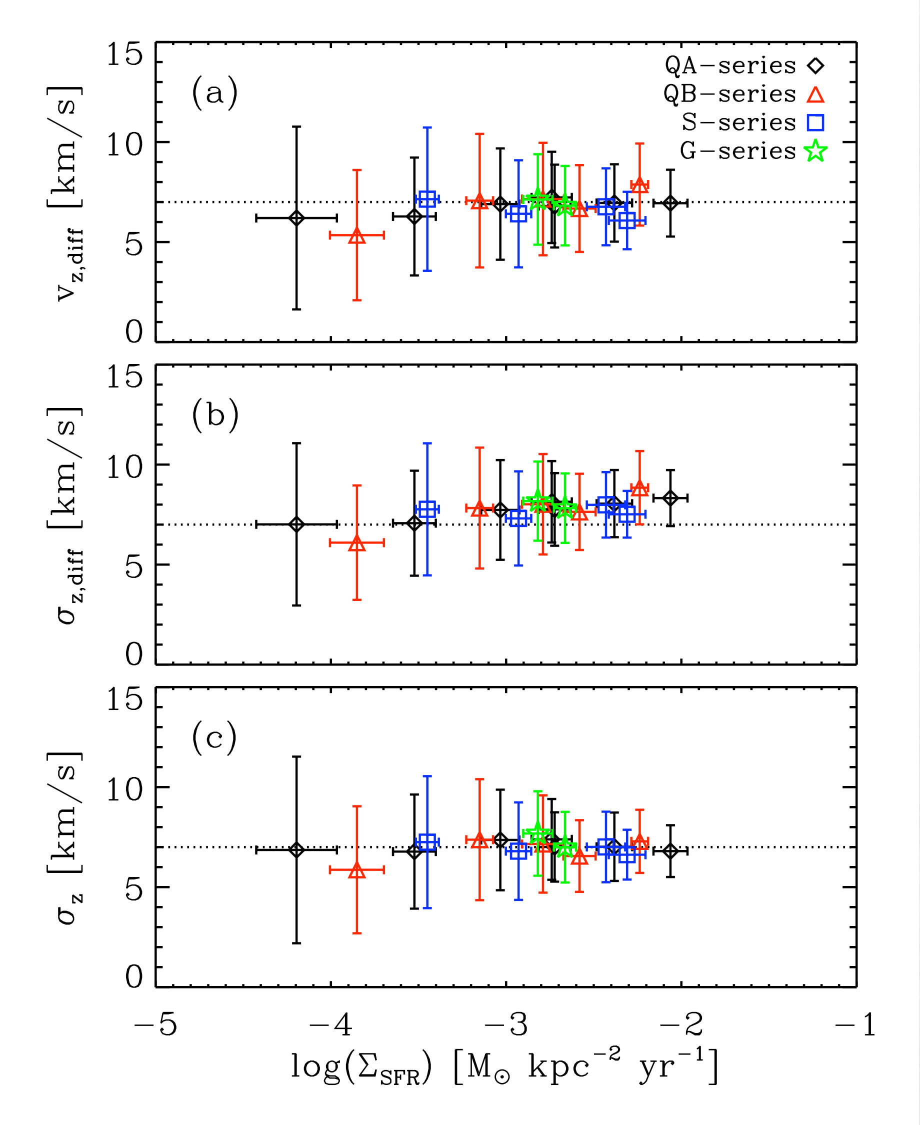
- Vertical turbulent velocity dispersion $v_z \approx 7$ km/s
- Consistent with previous numerical results:

  de Avillez & Breitschwerdt 2005, Dib et al 2006, Shetty & Ostriker 2008, Agertz et al 2009, Joung et al 2009

- Consistent with observations of turbulent velocities in MW and nearby face-on galaxies:

  Heiles & Troland 2003, Dickey et al 1990, van Zee & Bryant 1999, Petric & Rupen 2007, Kalbera & Kerp 2009

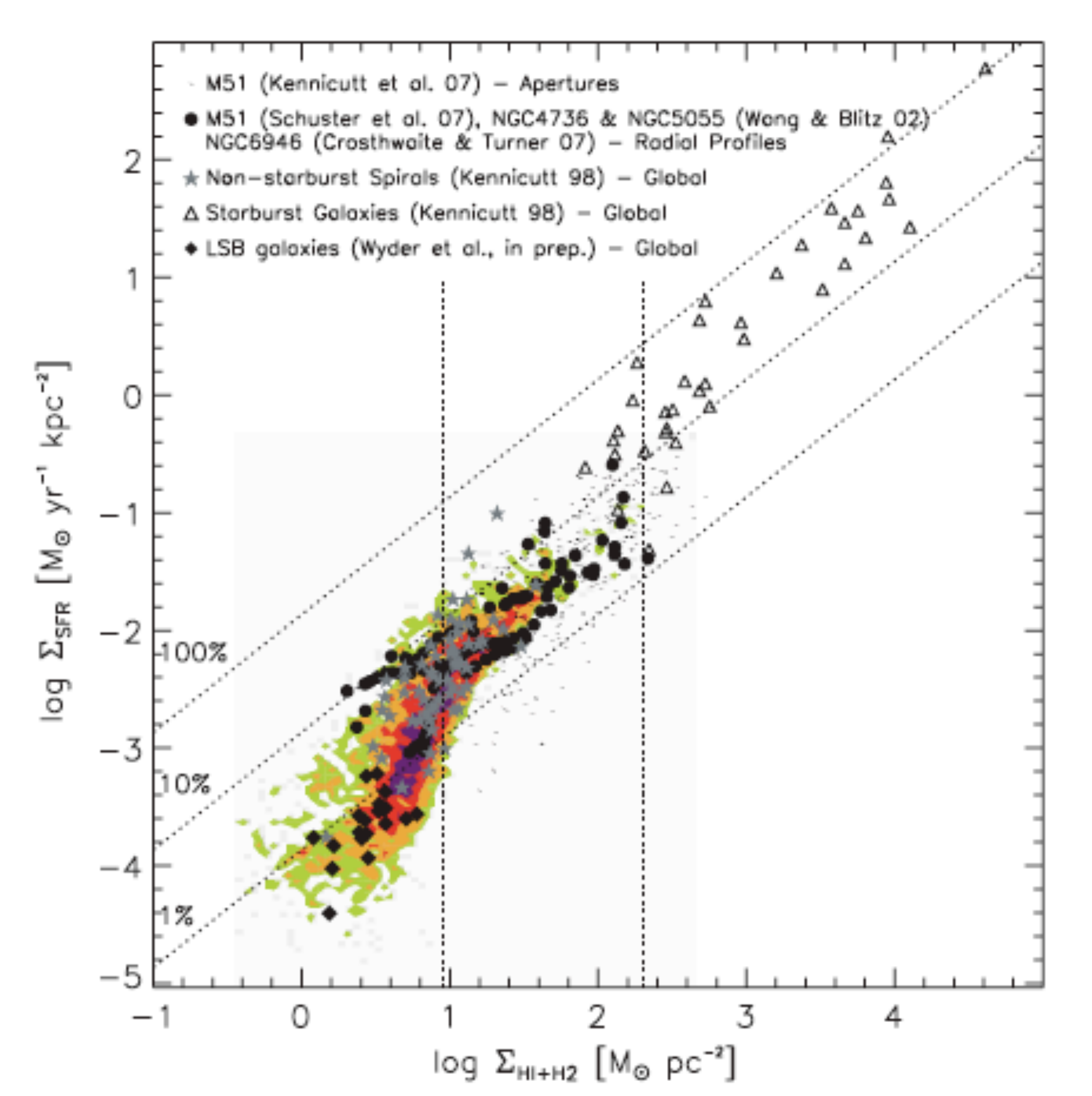
- Turbulence independent of Σ_{SFR}
  - $t_{diss} \sim t_{ver} = H/v_z \propto t_{sf}$
  - $v_z \approx \varepsilon_{ver}\, p_*/m_*$ for $\varepsilon_{ver} \sim 0.003$



Kim, Kim, & Ostriker (2011)

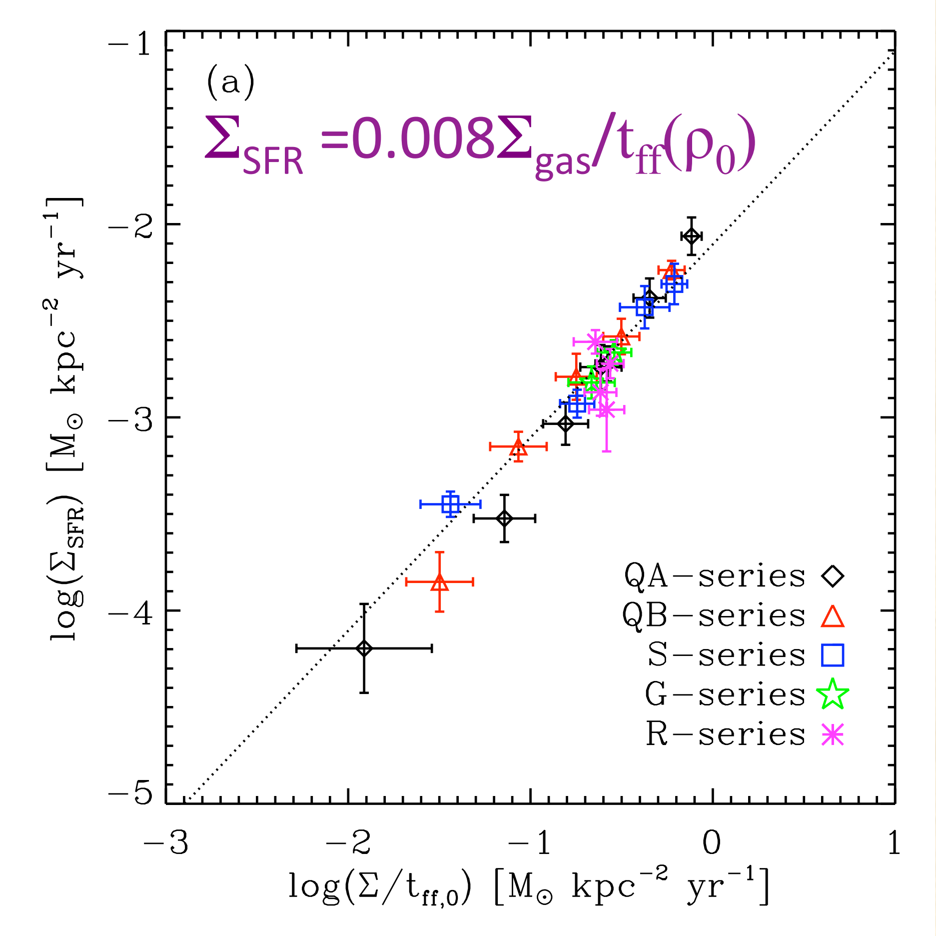
Σ_{SFR} vs. Σ_{gas}

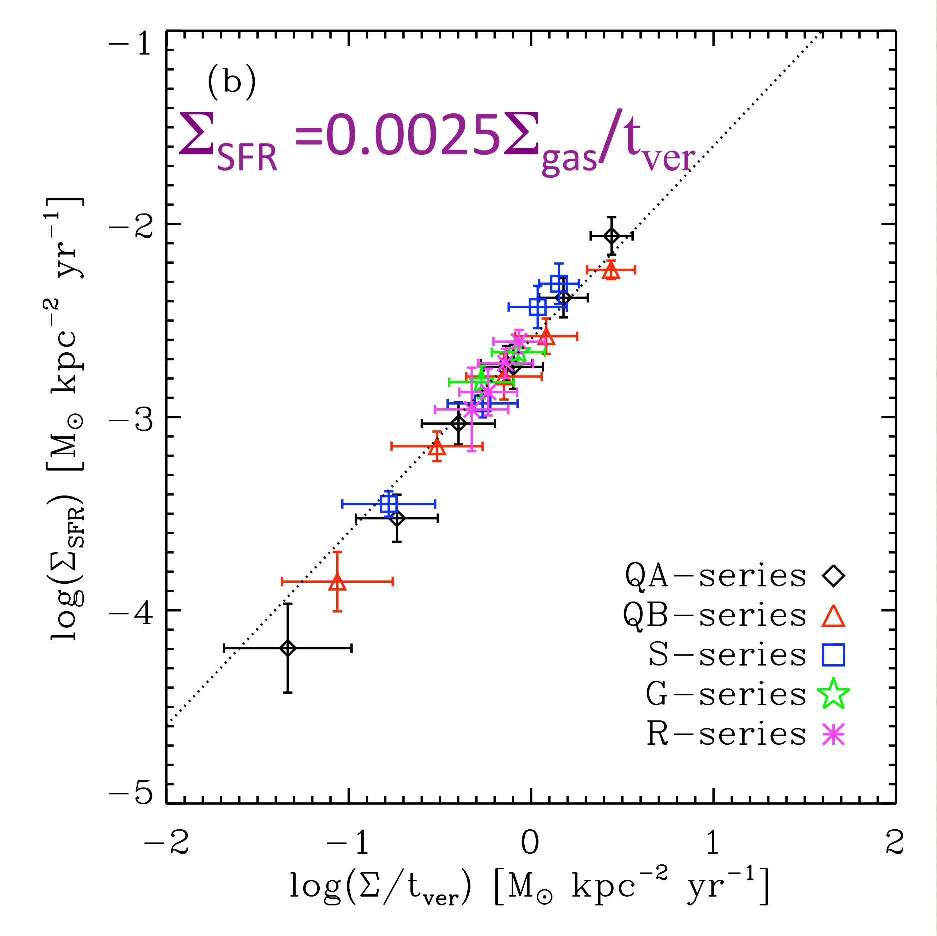
Kim, Kim, & Ostriker (2011)



Bigiel et al (2008, 2010)

Σ_{SFR} vs. Σ_{gas}/t_{ff} and Σ_{gas}/t_{ver}

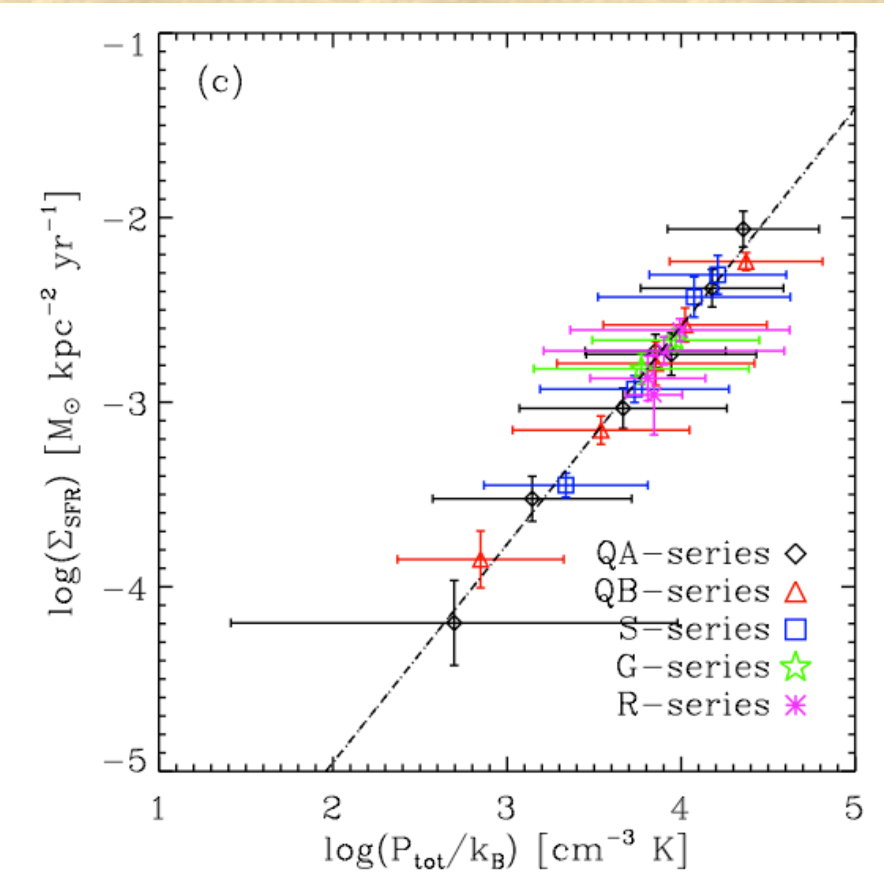


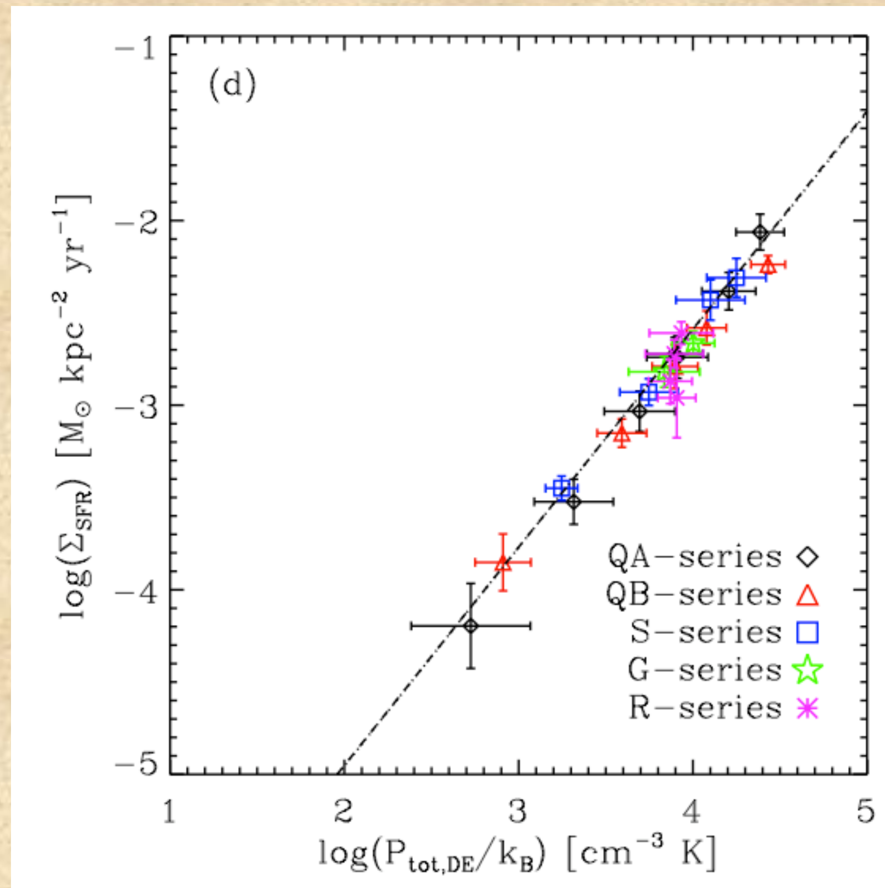


Kim, Kim, & Ostriker (2011)

Σ_{SFR} vs. total pressure

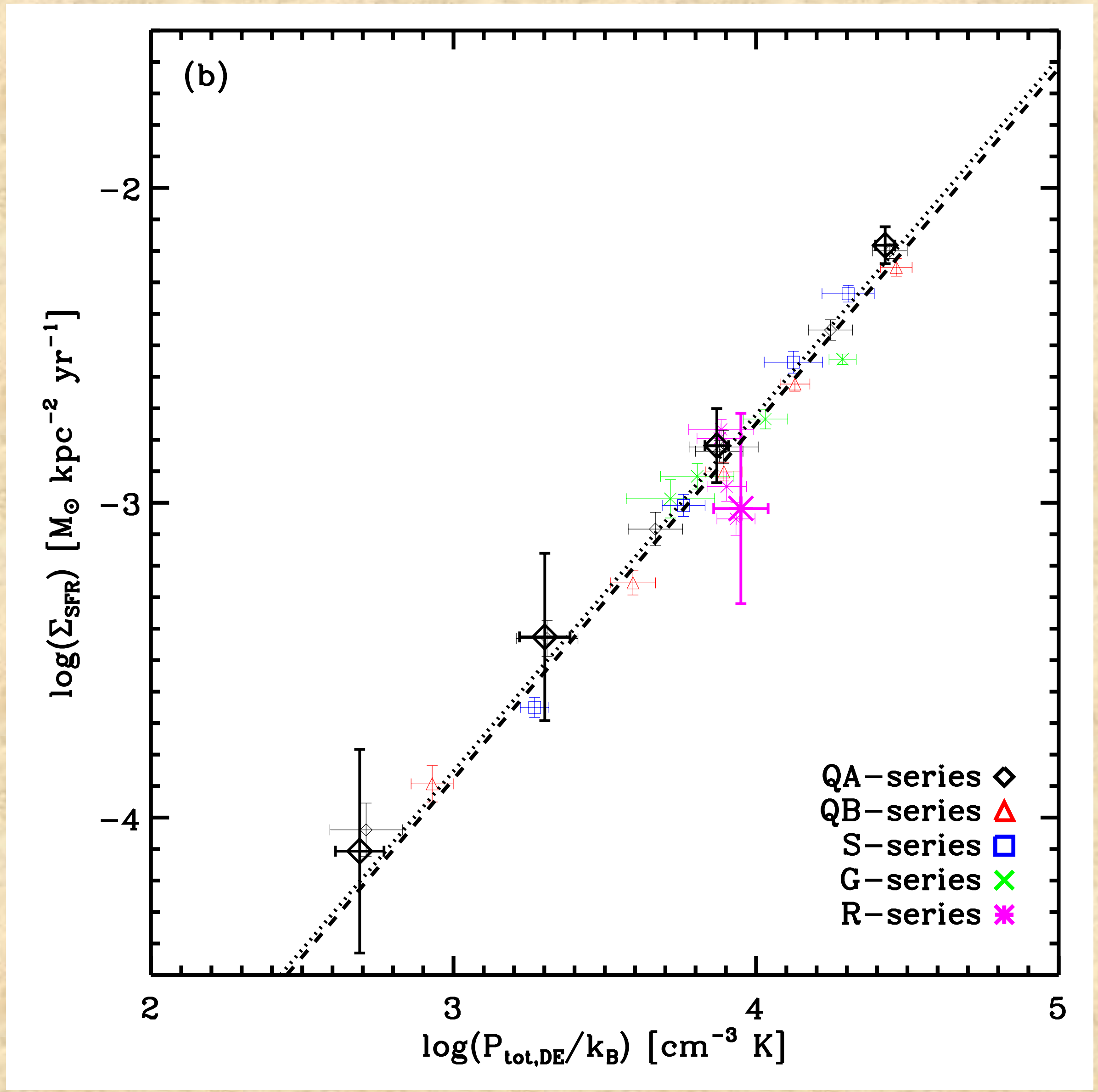
$$P_{tot} = P_{th} + P_{turb} ; P_{tot,DE} \approx \frac{\Sigma_{diff}}{2}\left[\pi G(\Sigma_{diff} + 2\Sigma_{gbc}) + 2\left(2G\rho_*\right)^{1/2}\sigma_z\right]$$





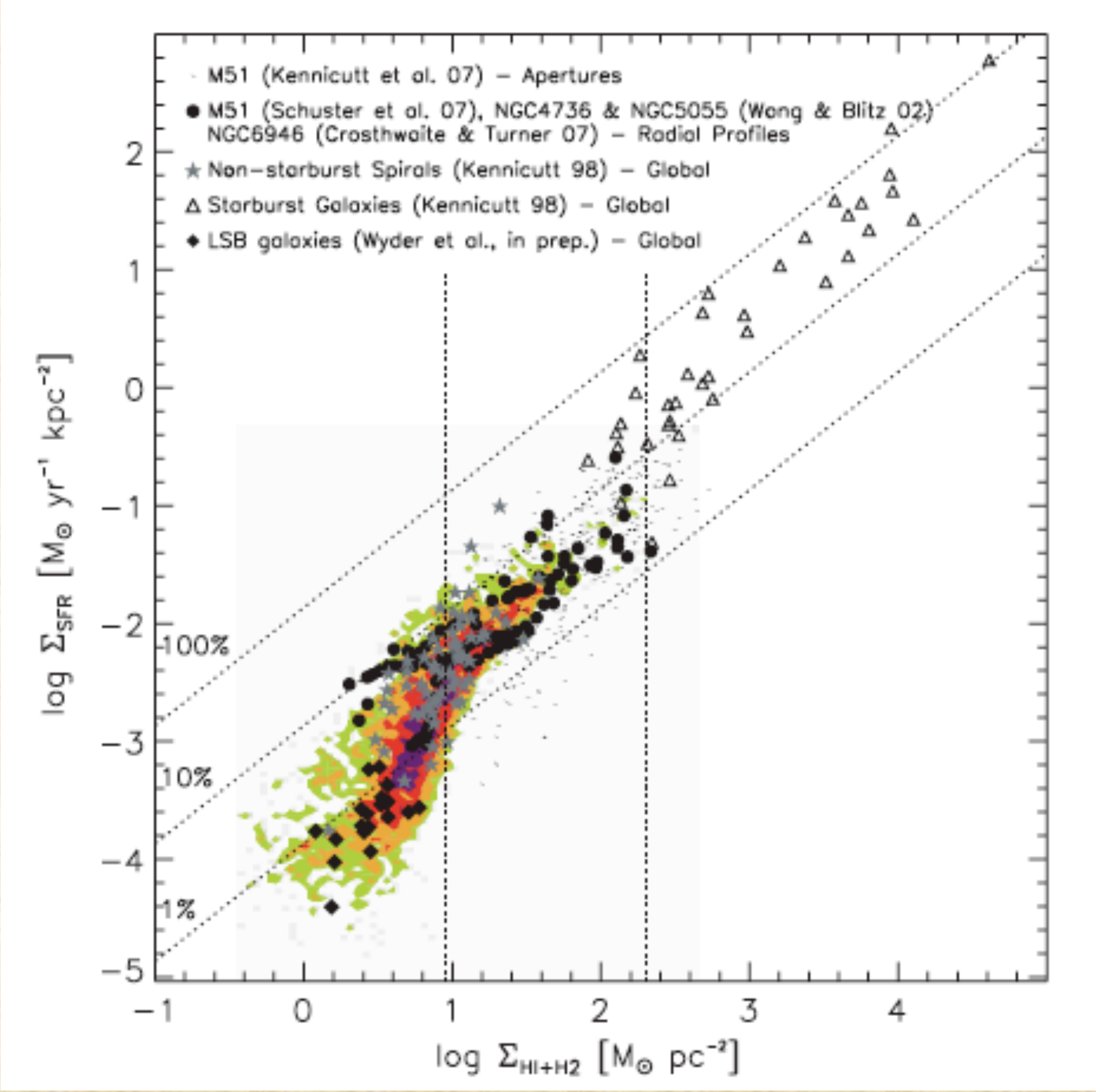
$$\Sigma_{SFR} = 2.6 \times 10^{-3}\, M_\odot\, \mathrm{kpc}^{-2}\mathrm{yr}^{-1}\left(\frac{P_{tot}/k}{10^4\,\mathrm{K\ cm}^{-3}}\right)^{1.2}$$

$$P_{tot} = P_{th} + P_{turb} \approx \frac{\Sigma_{diff}}{2}\left[\pi G(\Sigma_{diff} + 2\Sigma_{gbc}) + 2\left(2G\rho_*\right)^{1/2}\sigma_z\right]$$



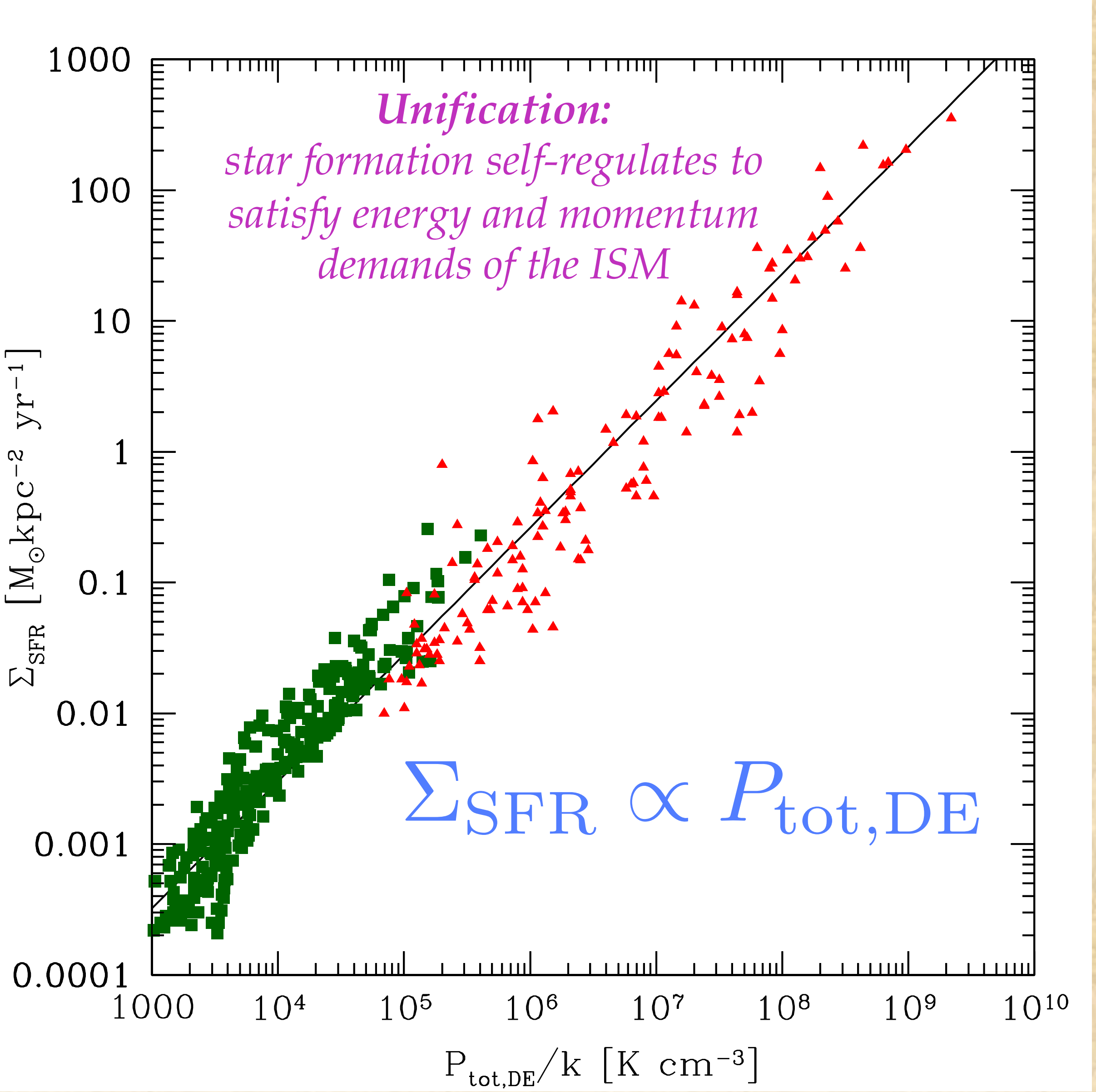
Kim, Kim, & Ostriker (2013)

Σ_{SFR} vs. Σ_{gas}



Bigiel et al (2008, 2010)

Σ_{SFR} vs. equilibrium pressure



Summary

- Recent observations at ~ kpc resolution in disk galaxies suggest (at least) three regimes of Σ_{SFR} vs Σ_{gas}
- SF is also correlated with *stellar* content at low Σ_{gas}
- Self-regulated star formation:
  - feedback of energy *and momentum* from massive stars/SNe prevents most of ISM from collapsing gravitationally on scales ≤ H
  - Σ_{SFR} increases, with $P_{diffuse} \propto \Sigma_{SFR}$ from feedback, until $P_{diffuse} = P_{DE}$
- In simultaneous thermal and dynamical equilibrium,

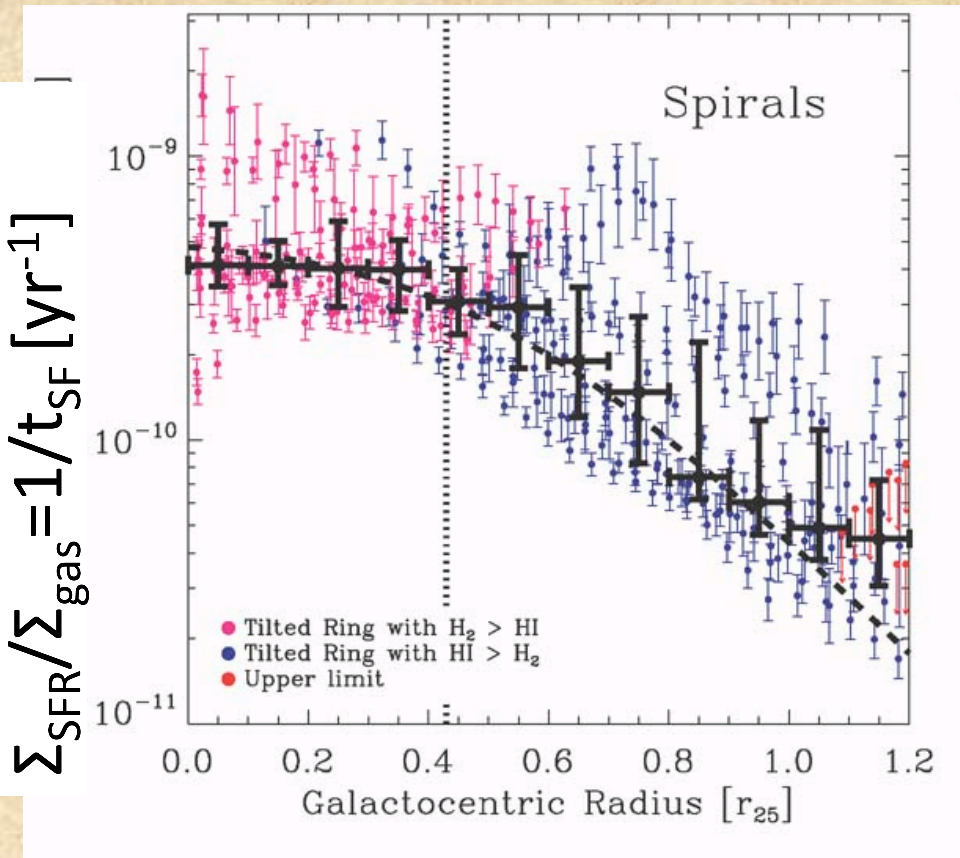
  $\Sigma_{SFR} \propto \Sigma \rho_*^{1/2} \sigma_z$ in outer (mostly atomic) disks
- Molecule-dominated starbursts have $\Sigma_{SFR} \propto \Sigma^2$
- Unified self-regulation law in both starbursts, outer disks:

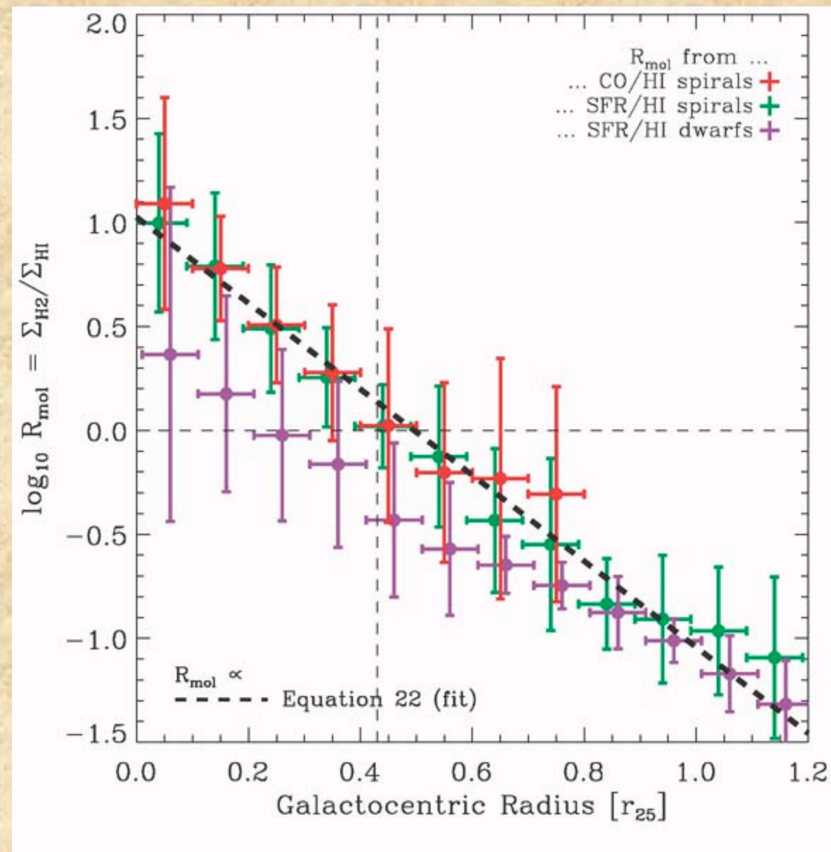
  $\Sigma_{SFR} \propto P_{DE}$; coefficient set by feedback yield
- Initial comparisons: theory, simulations, observations agree

ISM demands a certain rate of E, p input; star formation supplies it

Low mass consumption efficiency ↔ High energy production efficiency

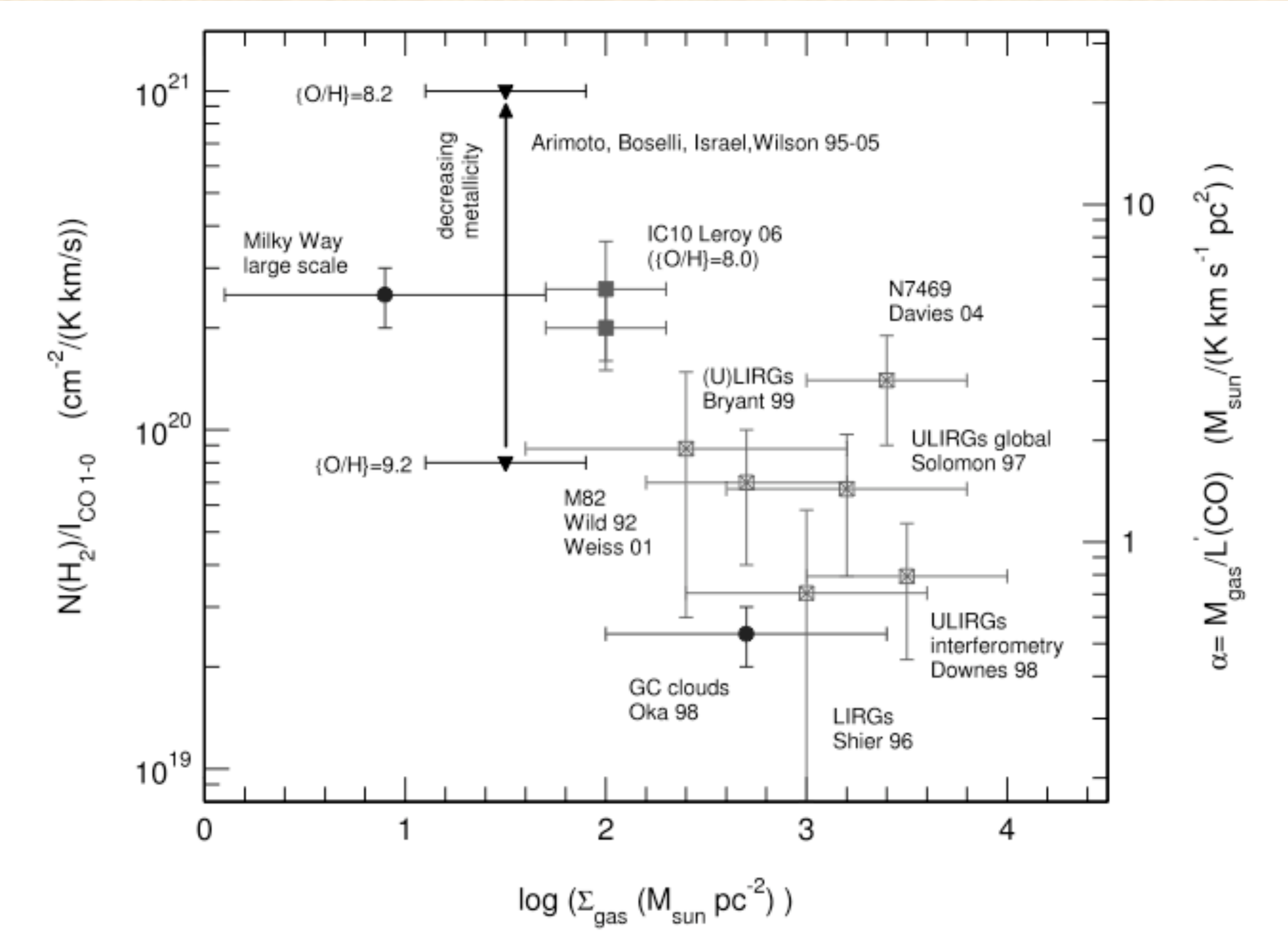
SFR and H2/HI correlations with galactic environment





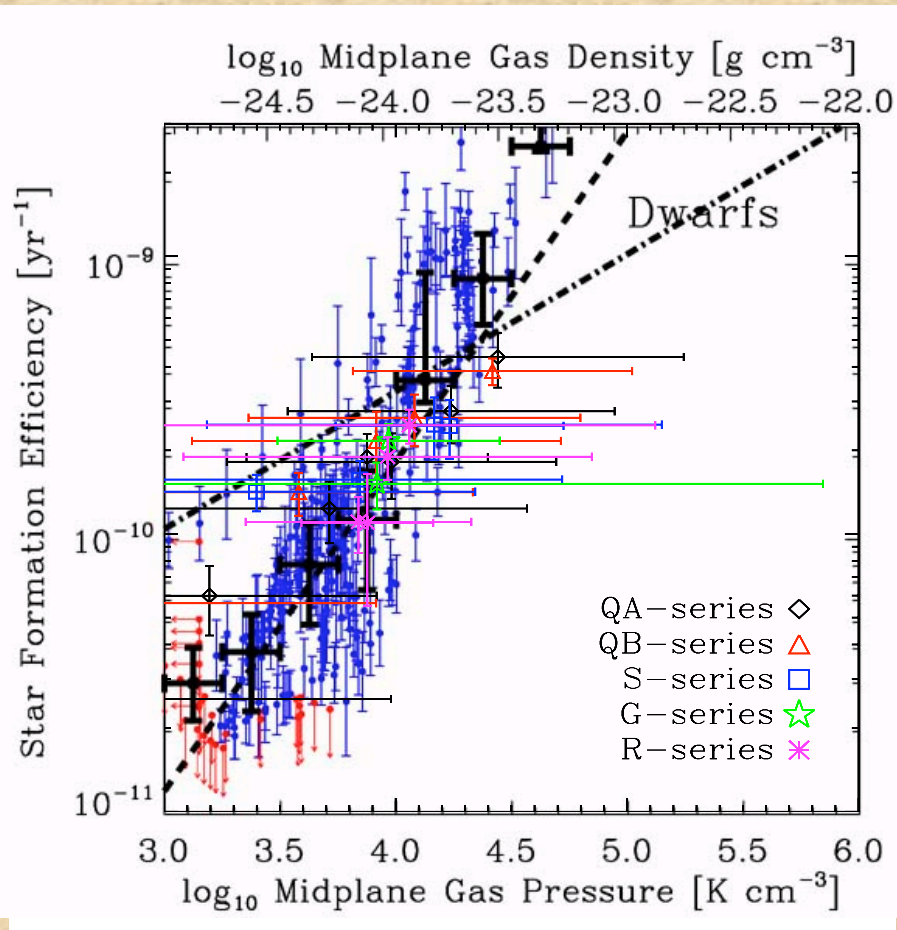
Leroy et al (2008)

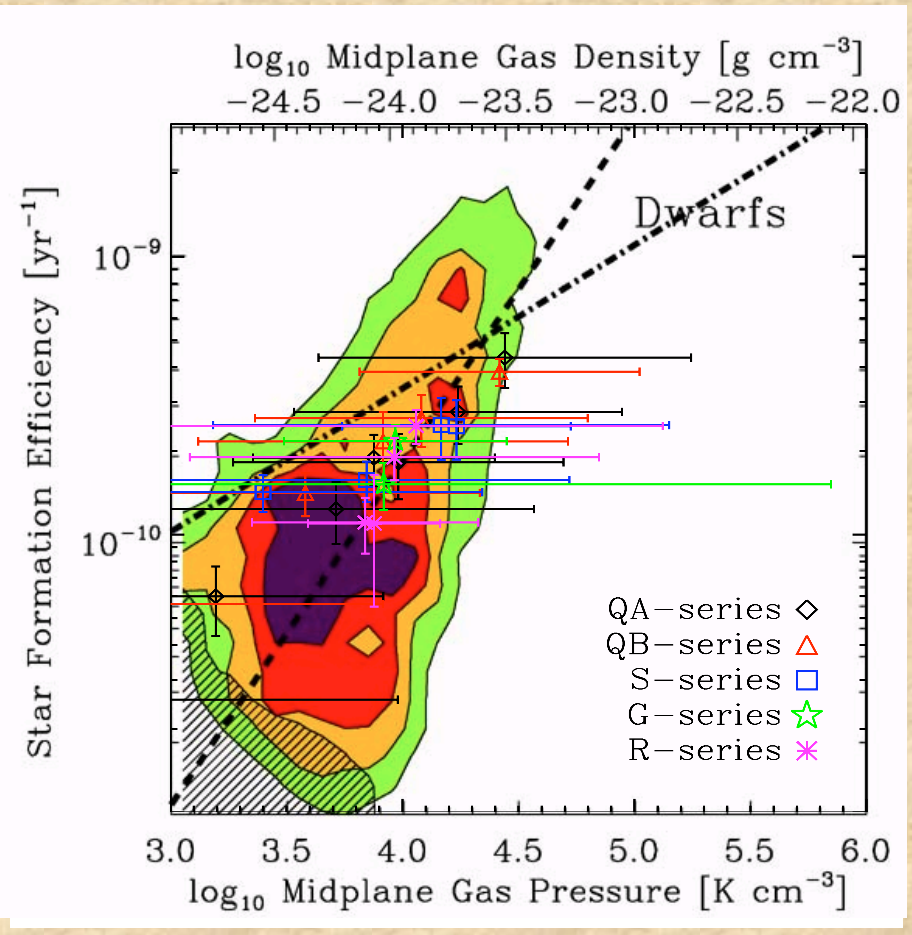
Dependence of X_{CO} on Σ_{H2}



Observations in different regimes:
Tacconi et al 2011

$\Sigma_{SFR}/\Sigma_{gas}$ vs. P_{tot} for dwarfs





Leroy et al (2008)