Regulation of Galactic Star Formation: Dynamical Effects

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Outline

- Introduction
- Toomre *Q* parameter and SF/disk regulation
- Schmidt laws in turbulent, multiphase disks
- SFR recipes from mean conditions?
- R_{mol} and vertical equilibrium of the ISM

Dynamical Effects on ISM

- disk shear
- disk rotation ⇒ Coriolis forces
- stellar disk: vertical gravity, spiral pattern, self-gravity
- gas self-gravity
- thermal pressure gradients
- heating & cooling ⇒cloudy density structure
- turbulence + other Reynolds stresses
- magnetic stresses
- cosmic ray pressure
- radiation pressure
- *spatial scales:* <pc to >10kpc
- *time scales:* $<10^6$ yr to $>10^9$ yr

Very complex system!   Proceed deliberately…

Star formation schematic

- Diffuse gas (HI and/or H_2) collects into self-gravitating GMCs
- Turbulence within GMCs creates (& disperses) overdense structures
- Densest cores collapse to make stars
- Feedback from SF (HII regions, winds, radiation pressure, SN blasts) destroys GMCs

$$\Sigma_{SFR} = \varepsilon_{GMC} \frac{\Sigma_{GMC}}{t_{GMC}} \rightarrow \varepsilon_{GMC} \frac{\Sigma_{diff}}{t_{diff}} \quad \textit{OR} \quad \Sigma_{SFR} = \varepsilon_{ff,dense} \frac{\Sigma_{dense}}{t_{ff,dense}}$$

- Proportion of gas in each component, timescales for GMC formation and destruction, efficiency over lifetime or over free-fall time… all depend on ISM dynamical processes
- Consider GMC formation first in a simple case…

GMC formation via self-gravitating instabilities

- Instabilities in rotating disks:
  - Limited on small scales by thermal pressure (sound waves)
  - Limited on large scales by angular momentum (Coriolis forces)
- Dispersion relation for axisymmetric perturbations:

$$\omega^2 = \boxed{\kappa^2} + \boxed{k^2 v_{th}^{\ 2}} - \frac{2\pi G\Sigma}{1+kH}k \qquad \text{for} \qquad \kappa^2 = \frac{1}{R^3}\frac{\partial(\Omega^2 R^4)}{\partial R} \rightarrow 2\Omega^2$$

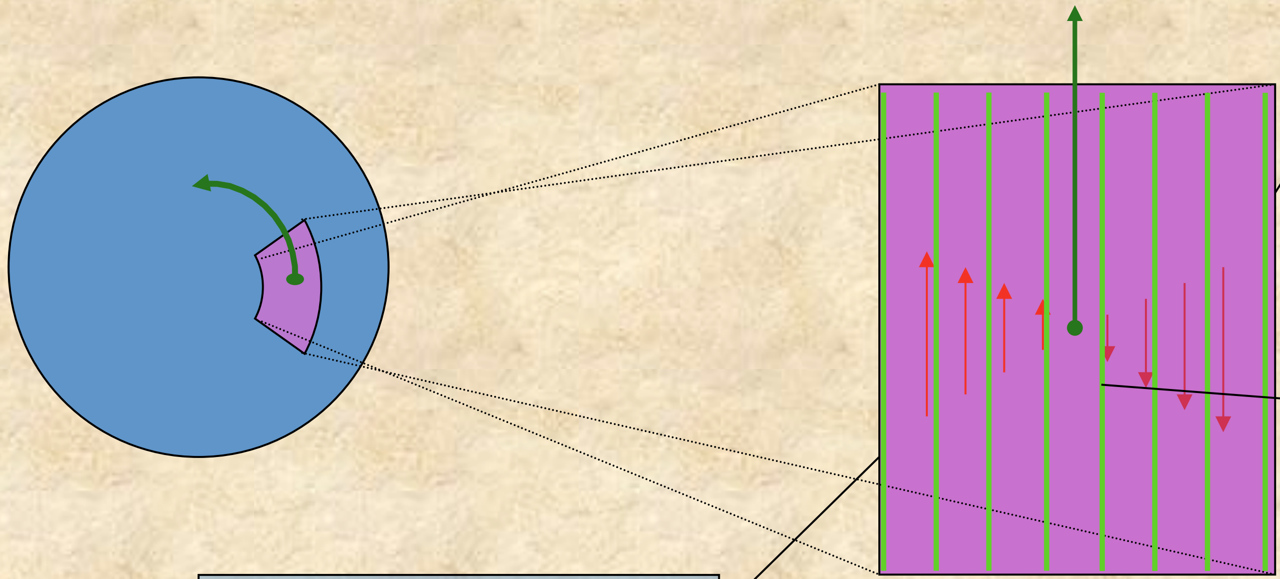
  - Mass $\lambda^2\Sigma \sim 10\, v_{th}^{\ 4}/(G^2\Sigma) \sim 10^7\, M_\odot\, (\Sigma_{gal}/10\, M_\odot\, pc^{-2})^{-1}$
- Need low Toomre parameter $Q \equiv \kappa v_{th}/\pi G\Sigma_{gal}$ for instability

$$Q = 1.5\left(\frac{v_{th}}{7kms^{-1}}\right)\left(\frac{V_c}{200kms^{-1}}\right)\left(\frac{R}{10kpc}\right)^{-1}\left(\frac{\Sigma_{gal}}{10M_\odot pc^{-2}}\right)^{-1}$$

- Nonaxisymmetric perturbations to make GMCs are also limited by shear, but they can grow via the swing amplifier if Q is sufficiently low

Large-scale dynamics with shear

For moderate-scale ISM dynamics (L>H), must include background sheared rotation. May consider a local patch of the disk:

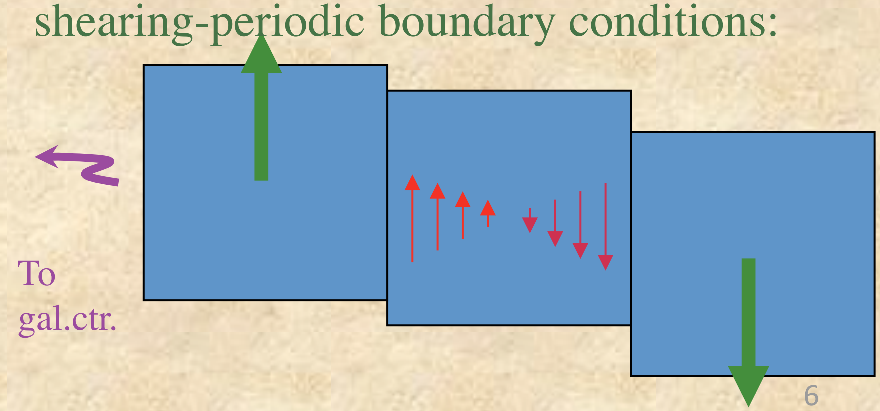


Exterior rotation is slower for “normal” shear

Mean magnetic fields are predominantly toroidal

Interior rotation is faster for “normal” outer-disk shear

For simulations with local model, apply shearing-periodic boundary conditions:



Similar approach may also be used when spiral arms are present (Roberts 1969)

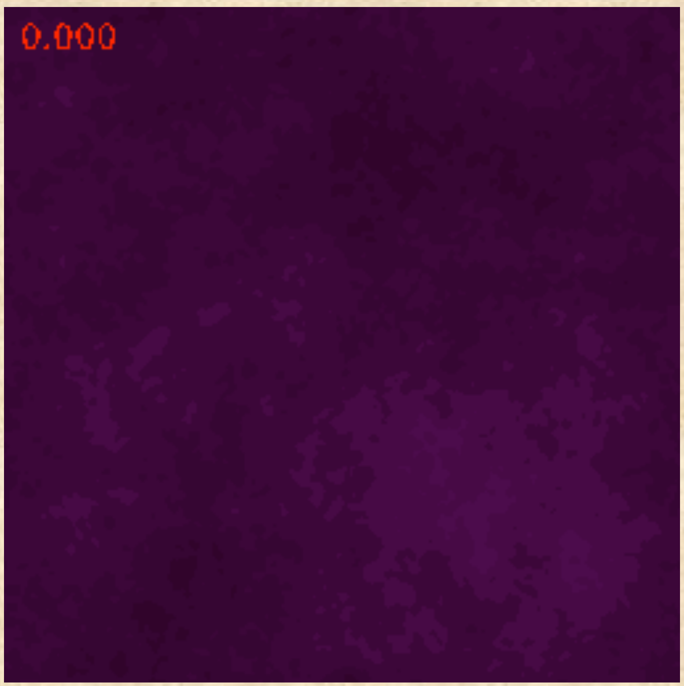
Nonlinear development of swing amplifier

- Thresholds for nonlinear instability :
  - Q_{th} =1.2-1.4 unmagnetized and magnetized cases, thin disk
  - Q_{th} <1 unmagnetized case, thick disk
  - Q_{th}~ 1.4 including stellar disk; unmagnetized thick disk
  - Q_{th}~1 strongly magnetized case, thick disk
  - Q_{th}~1.6 weakly magnetized case, thick disk
- Growth times: $t \sim t_{orb}$
- Characteristic cloud mass $M \sim M_J \Rightarrow \sim 10^7 M_\odot (\Sigma_{gal}/10\ M_\odot\ pc^{-2})^{-1}$

Kim & Ostriker (2001, 2007)

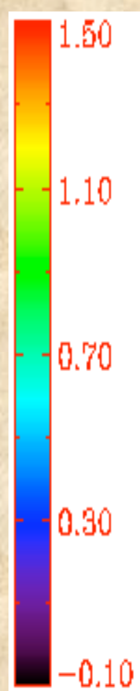
Kim, Ostriker, & Stone (2002, 2003)

t/t_{orb} unstable



v_A/c_s=0.3, *Q*=1.0

logΣ

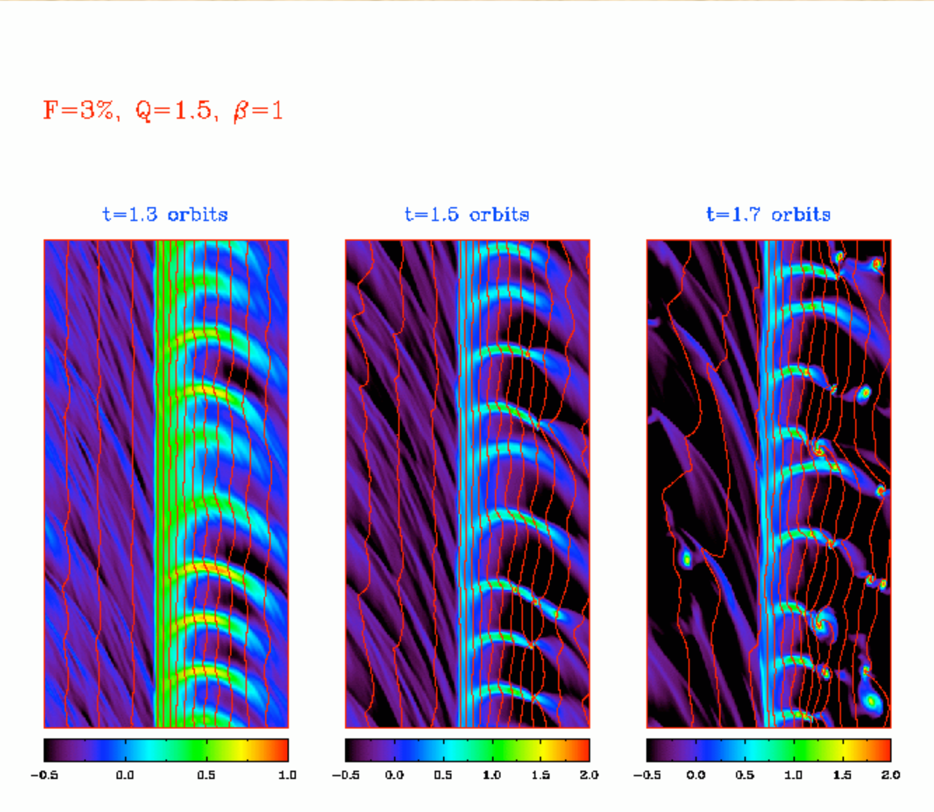


t/t_{orb} stable

v_A/c_s=0.3, *Q*=1.5

With spiral structure…

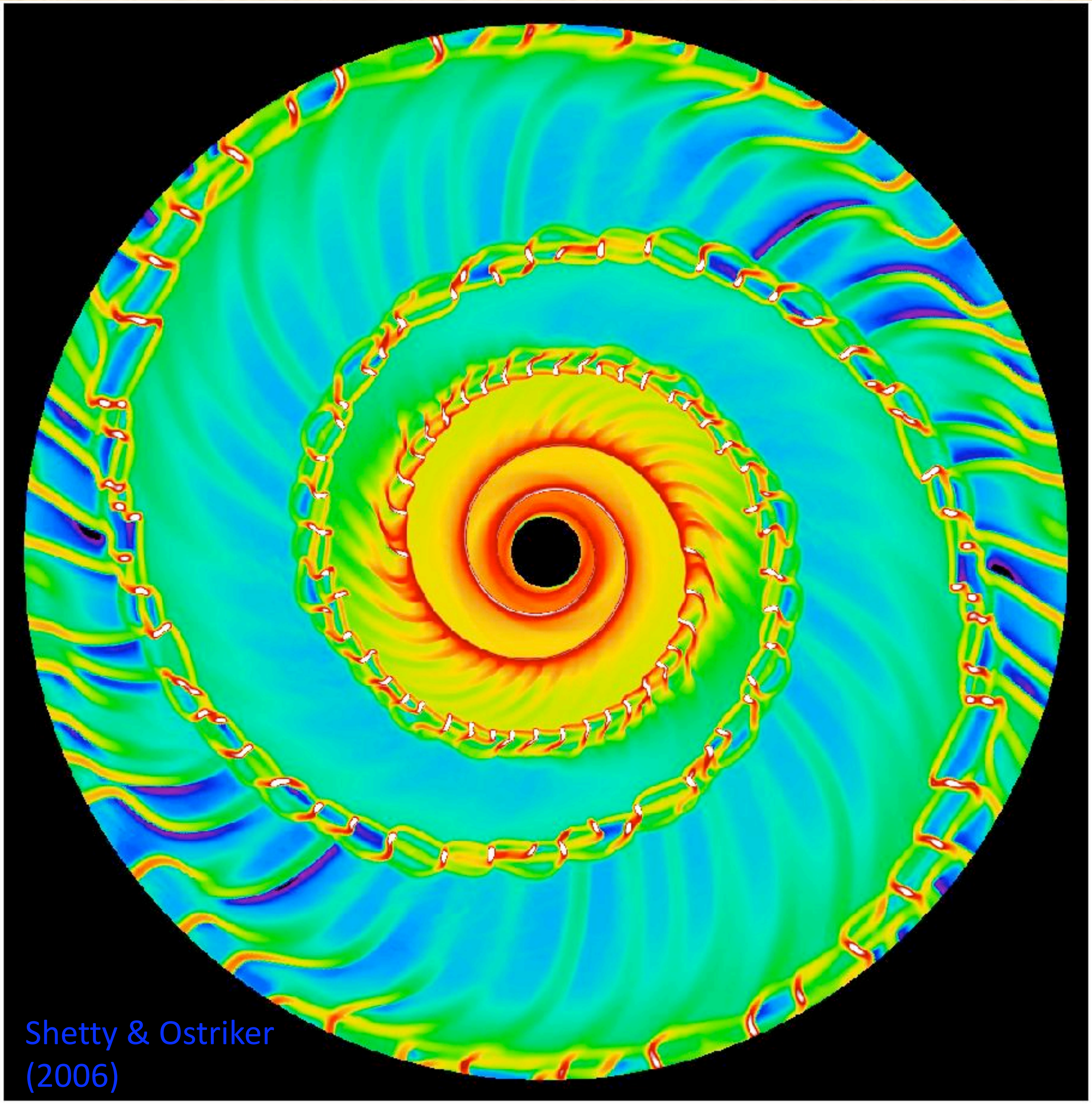
- Jeans mass and Jeans time lower in spiral arms, due to shock compression of gas
- Self-gravity leads to growth of spiral-arm spurs
- Clouds form in arm if shock is strong
- Clouds form downstream if shock is weaker
- Magnetic field is important for maintaining arm integrity
- Cloud masses 10^6-10^7 $M_\odot$
- Magnetic braking removes spin angular momentum from clouds
- Internal turbulence is required to fragment massive GMAs into lower-mass GMCs.



Kim & Ostriker (2002)

see also Kim, Bonnell talks

Spurs and clouds in global model



Shetty & Ostriker (2006)

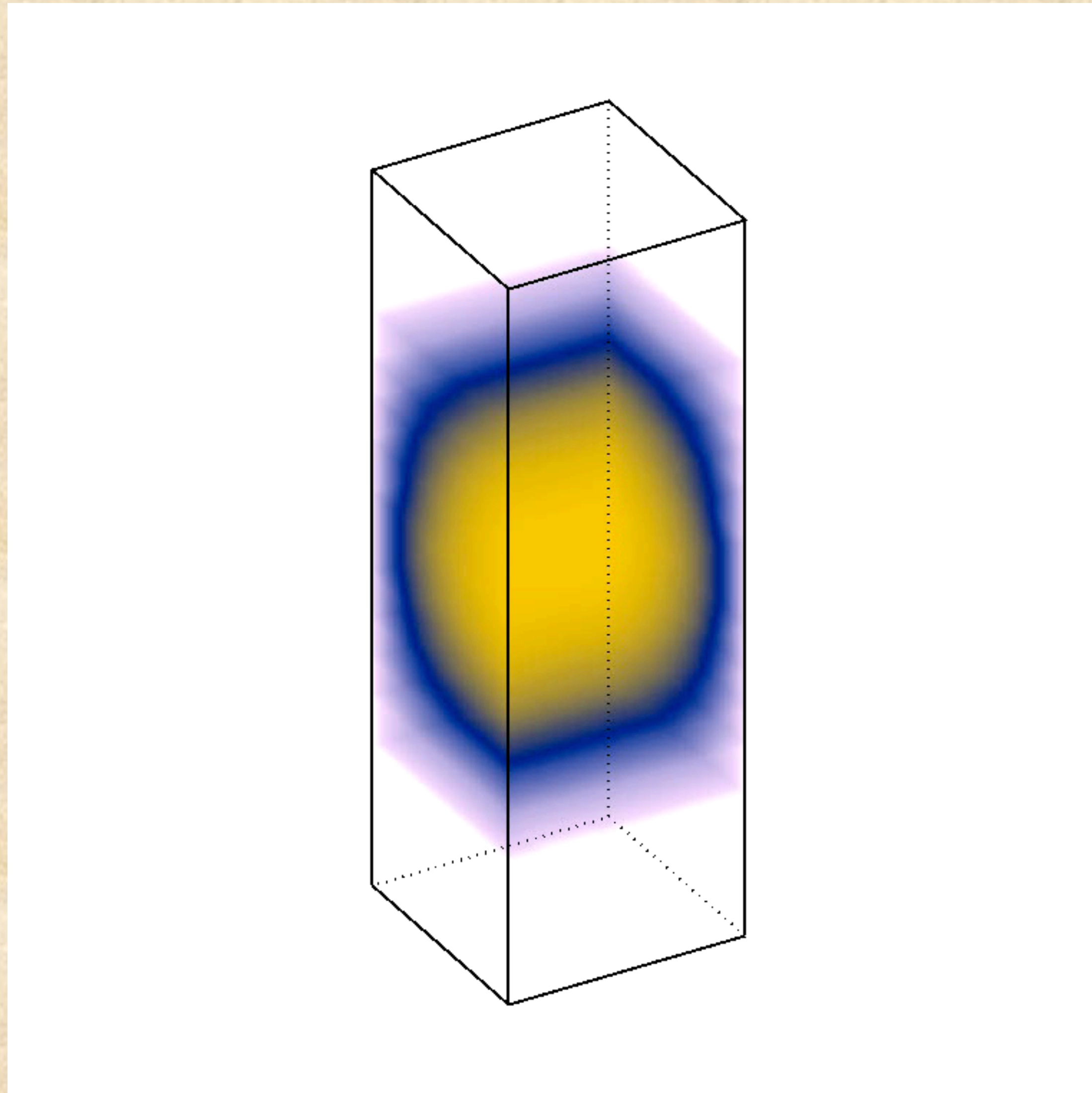
HST-ACS/WFC (S. Beckwith)

Spitzer-IRAC (R. Kennicutt)

Herschel-PACS

Real ISM: multiphase, turbulent!

- Is gravitational stability of multiphase ISM regulated by Q_{eff} with v_{turb} and v_{therm} contributions from all components?
- Does control of v_{turb} from energetic feedback yield self-regulated Q_{eff} and *SFR*?
- What is the role of disk substructure and the vertical gas distribution in setting the SFR?



Two-phase turbulent ISM model Piontek & Ostriker (2007)

Disk thickness/multiphase effects?

- Consider vertically-averaged timescale for self-gravity:

$$t_g = (G\bar{\rho})^{-1/2} = \left(\frac{G\Sigma_{gas}}{2H_{gas}}\right)^{-1/2}$$

- For disk in vertical equilibrium with $Q_{gas}/Q_{*}=const$,
  $H_{gas} \sim v_z^2/(G\Sigma_{gas}) \Rightarrow t_g \sim v_z/(G\Sigma_{gas})$

- *If* $\Sigma_{SFR} \propto \Sigma_{gas}/t_g$, then $\Sigma_{SFR} \propto \Sigma_{gas}^2/(G\, v_z) \Rightarrow$

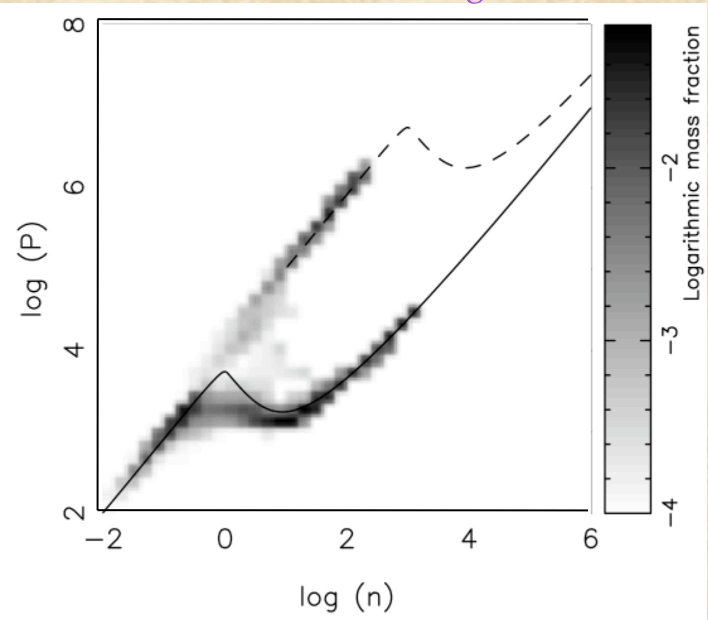
Schmidt Law would be $\Sigma_{SFR} \propto \Sigma_{gas}^{2}$ for $v_z \sim const$

Schmidt Law would be $\Sigma_{SFR} \propto \Sigma_{gas}^{1.5}$ for $H_{gas} \sim const.$, $v_z \propto \Sigma_{gas}^{0.5}$

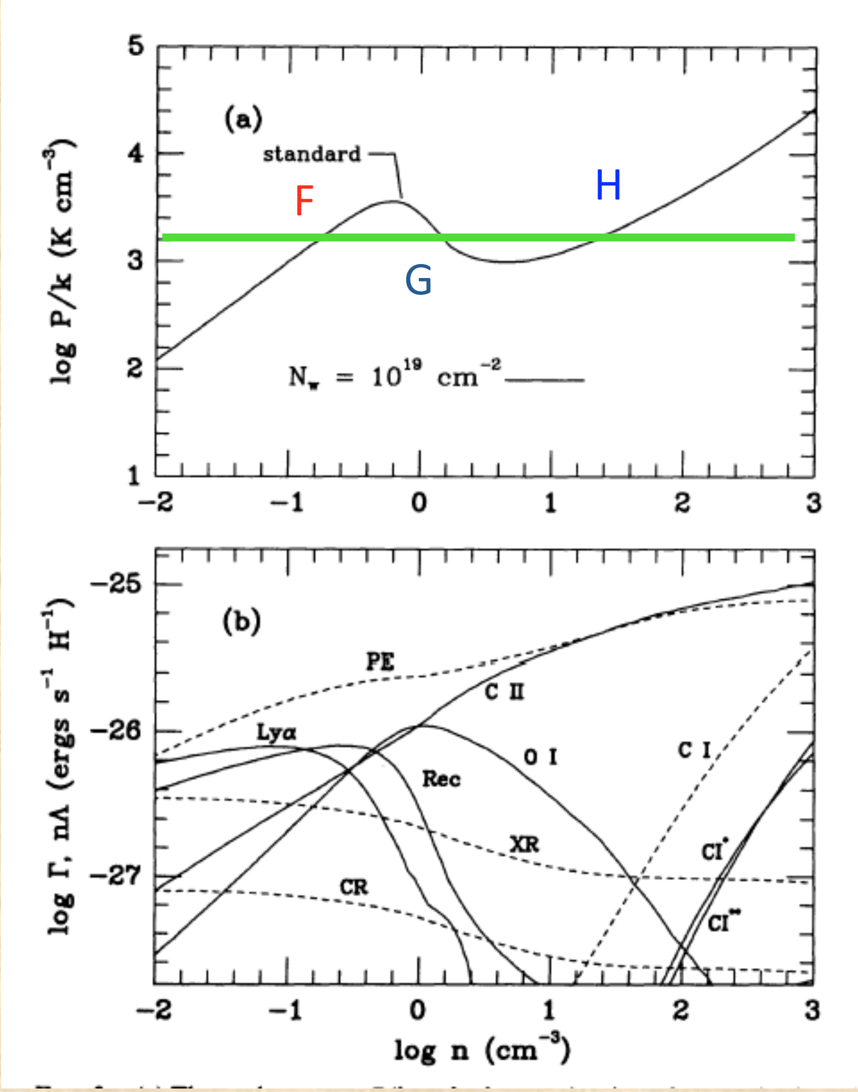
- But for multiphase disk, t_g from the vertically-averaged (volume-weighted) density may not represent t_g in most of the gas…

Vertically-resolved disk models

- Include:
  - sheared rotation (V_c=const),
  - heating and cooling with bistable thermal equilibrium
  - fixed stellar gravity
  - HII region feedback: intense local heating
  - gas self-gravity
- Explore a range of Σ_{gas}, Ω, and ρ_*

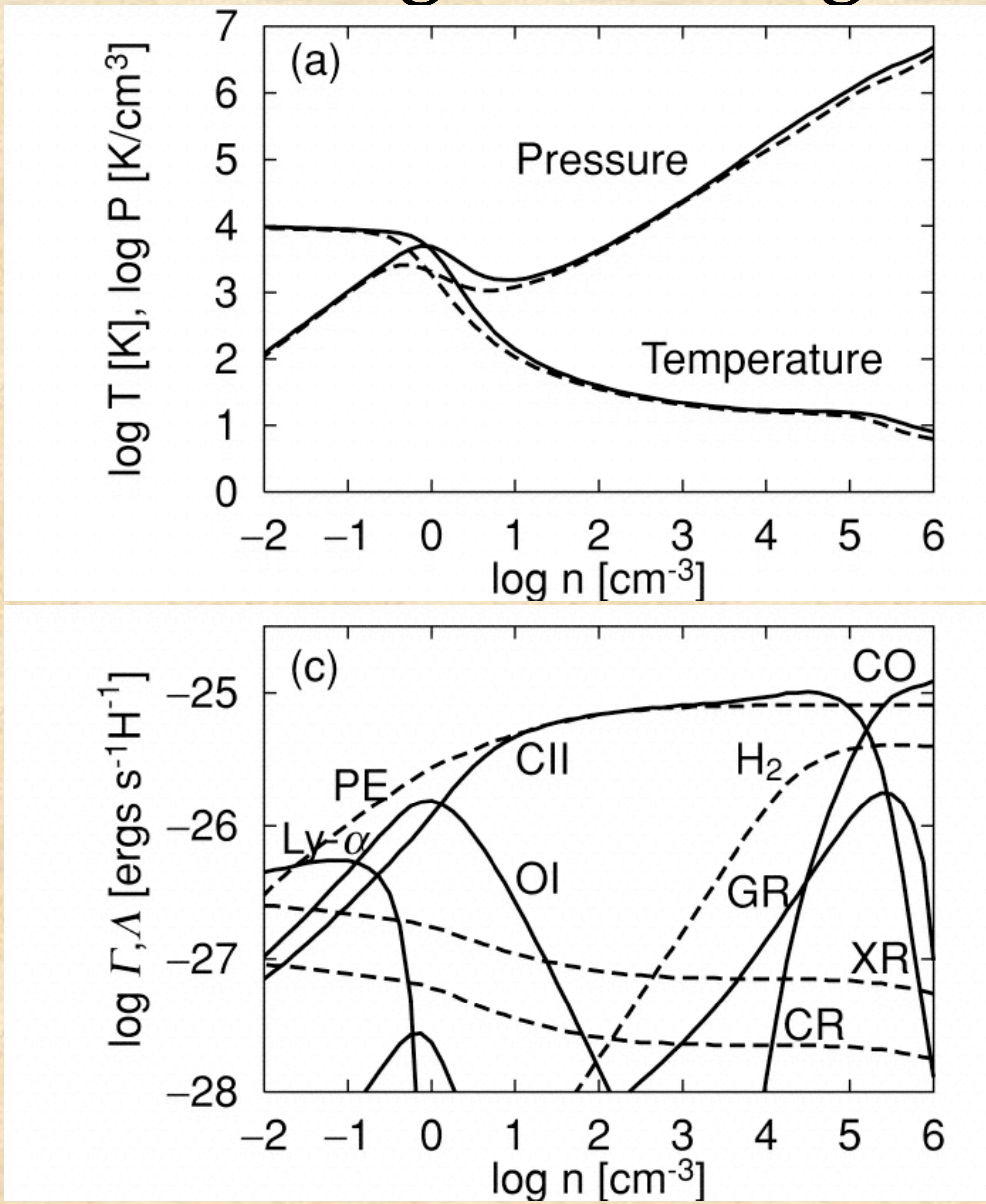


Koyama & Ostriker (2009a)



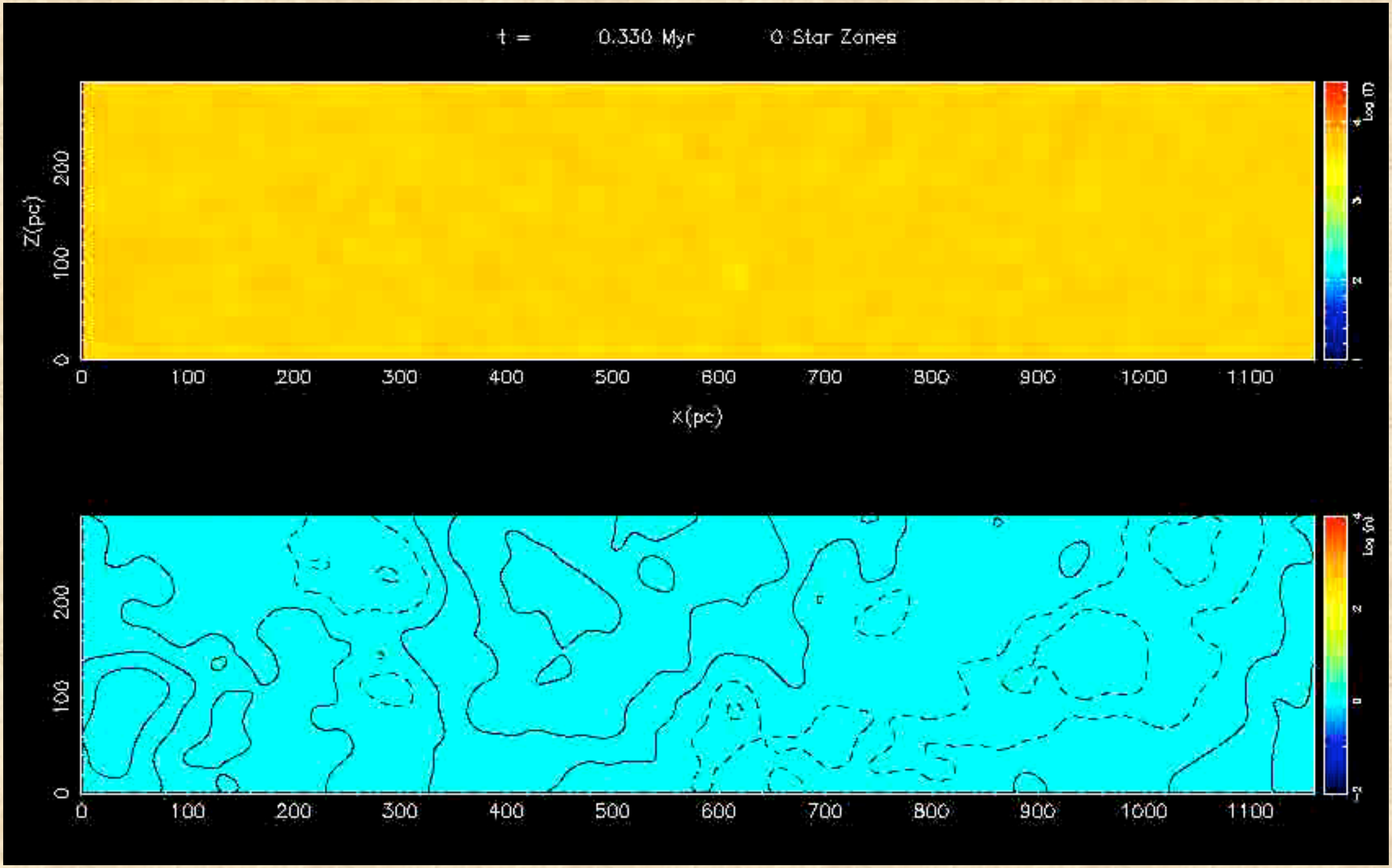
Wolfire et al (1995)

Heating & Cooling



Koyama & Inutsuka (2000)

Temperature and density -- evolution



T

n

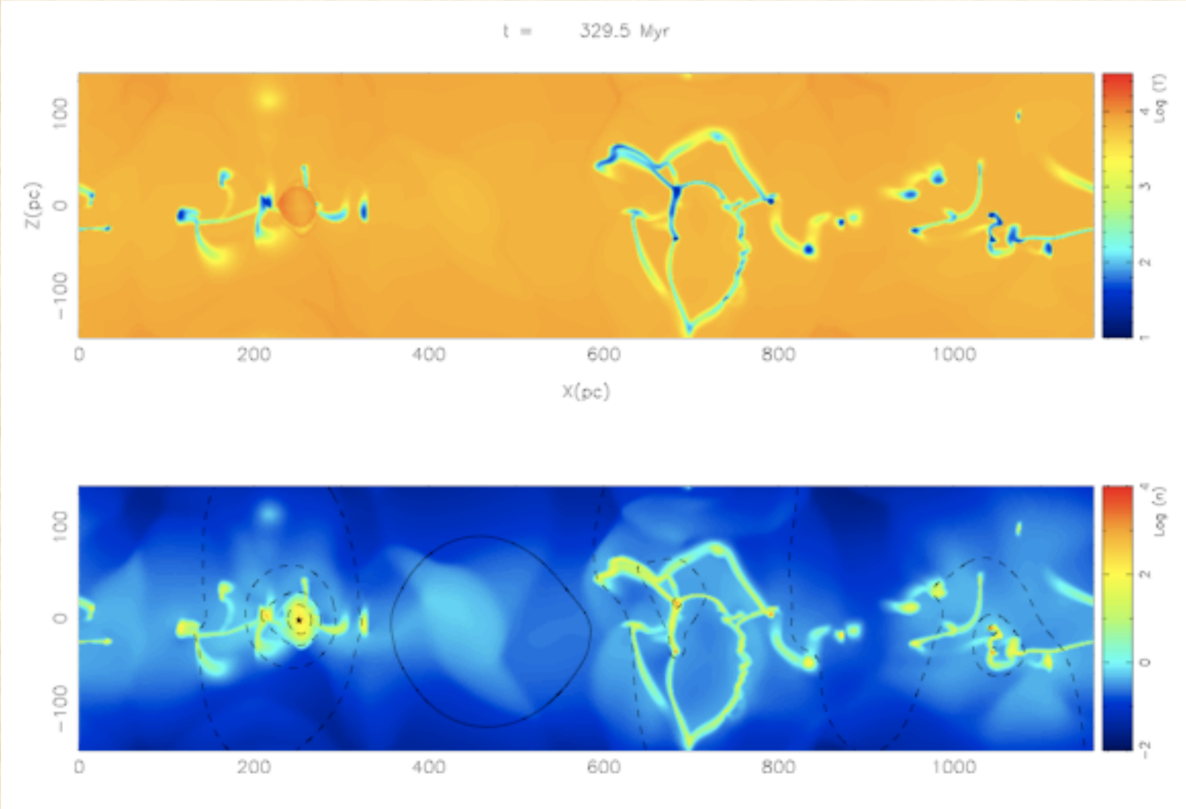
z

R

Koyama & Ostriker (2009)

Vertically-resolved disk models

- Independent environmental parameters: Σ_{gas}, Ω, and ρ_*
- Measure:
  - Toomre Q, including turbulent velocity dispersion
  - vertical velocity dispersion and disk thickness
  - virial parameters for gas components
  - midplane and mean pressure
  - proportions of dense gas ⇒ $\Sigma_{SFR} = \varepsilon_{ff,dense} \frac{\Sigma_{dense}}{t_{ff,dense}}$
- See: Koyama & Ostriker (2009a,b)



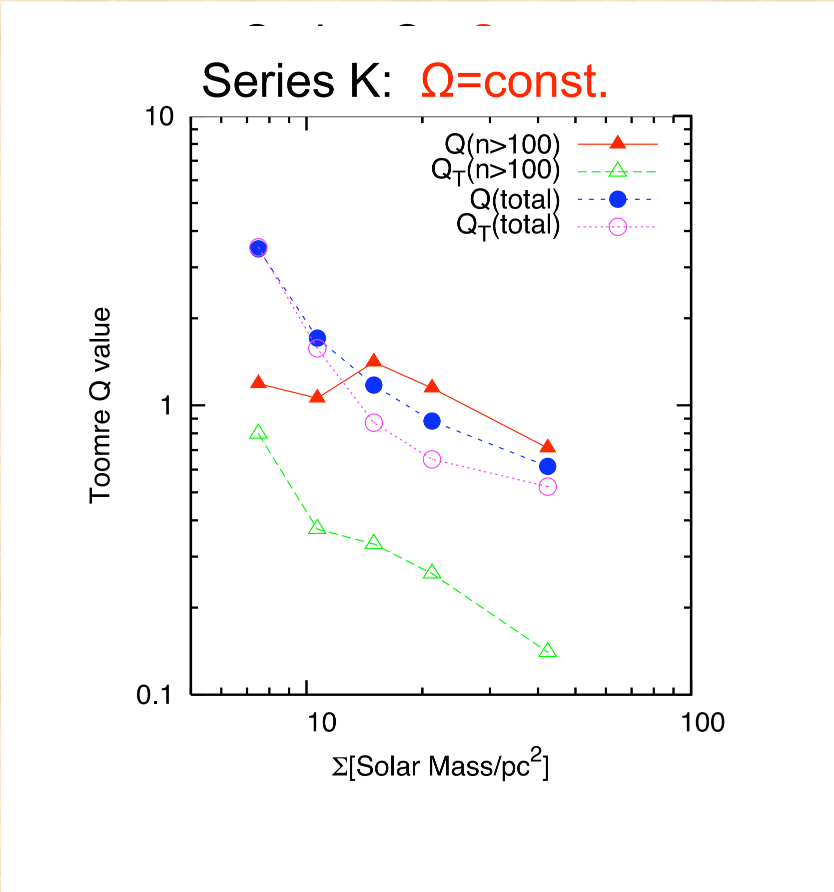
Toomre parameter

- Self-regulation of SF is clear:

  turbulence driven by feedback from SF raises Q
  - important in cold, dense gas
- However, leverage of turbulent feedback on SFR is limited…

$$Q = 0.15\left(\frac{v_{eff}}{7\,kms^{-1}}\right)\left(\frac{V_c}{200\,kms^{-1}}\right)\left(\frac{R}{10\,kpc}\right)^{-1}\left(\frac{\Sigma_{gas}}{100\,M_{\odot}pc^{-2}}\right)^{-1}$$

- Main evolutionary response in galaxies may be converting gas to stars until $Q \sim Q_{crit}$



Koyama & Ostriker (2009a)

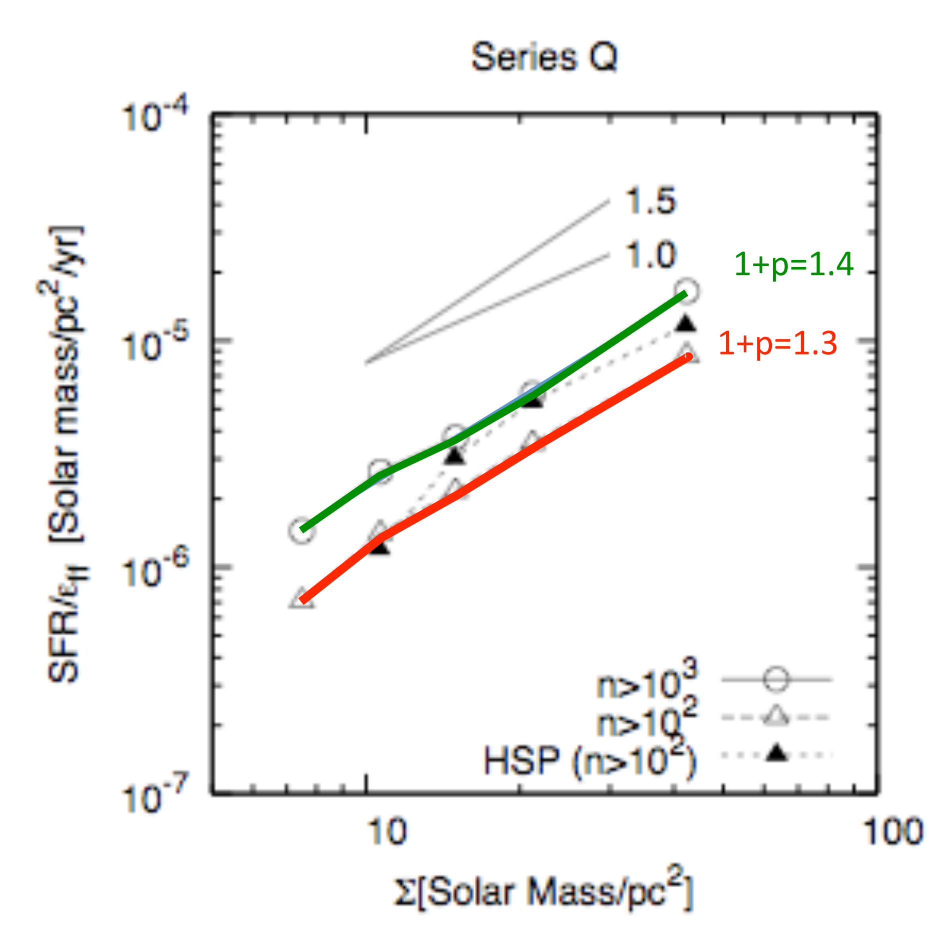
Averaging Star Formation

- Observations of SF are often described by empirical Schmidt laws: $\Sigma_{SF} = A\,\Sigma_{gas}^{1+p}$
- Index p corresponds to $t_{SF} = \Sigma_{gas} / \Sigma_{SF} \propto \Sigma_{gas}^{-p}$
  - Different tracers have different t_{SF}
  - $p = 0$ implies constant t_{SF} for a given tracer
  - $p > 0$ implies t_{SF} decreases with increasing Σ_{gas}
  - Observations show a range $1+p = 1-2 \Rightarrow p = 0-1$, depending on tracer, averaging scale

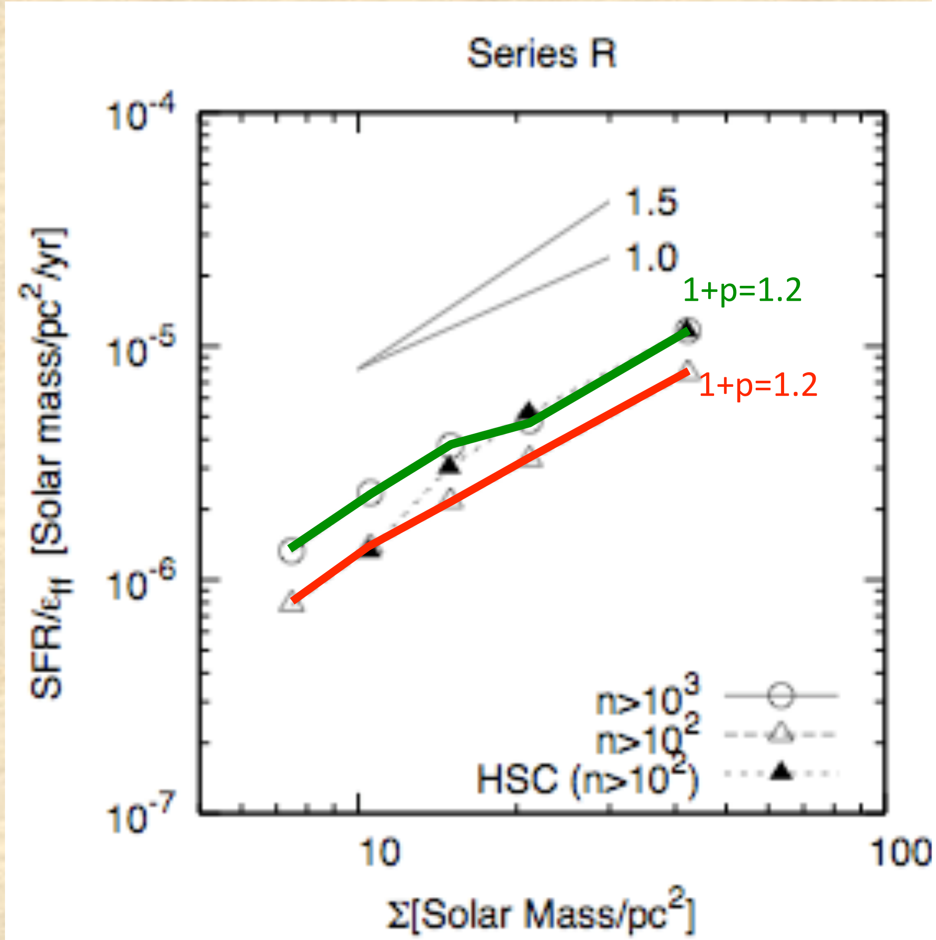
❖ Questions:
  - Can simulations reproduce observed gas-SF relationships?
  - How does including environmental parameters other than Σ_{gas} change the relationship?
    e.g.: Σ_*, Ω, σ_{gas}, σ_*
  - Are observed relationships “fundamental”, or a result of galactic evolution?
  - Can SF-gas relations be captured with simplified models?

Schmidt laws in vertically-resolved turbulent, multiphase models with $\Omega \propto \Sigma_{gas}$

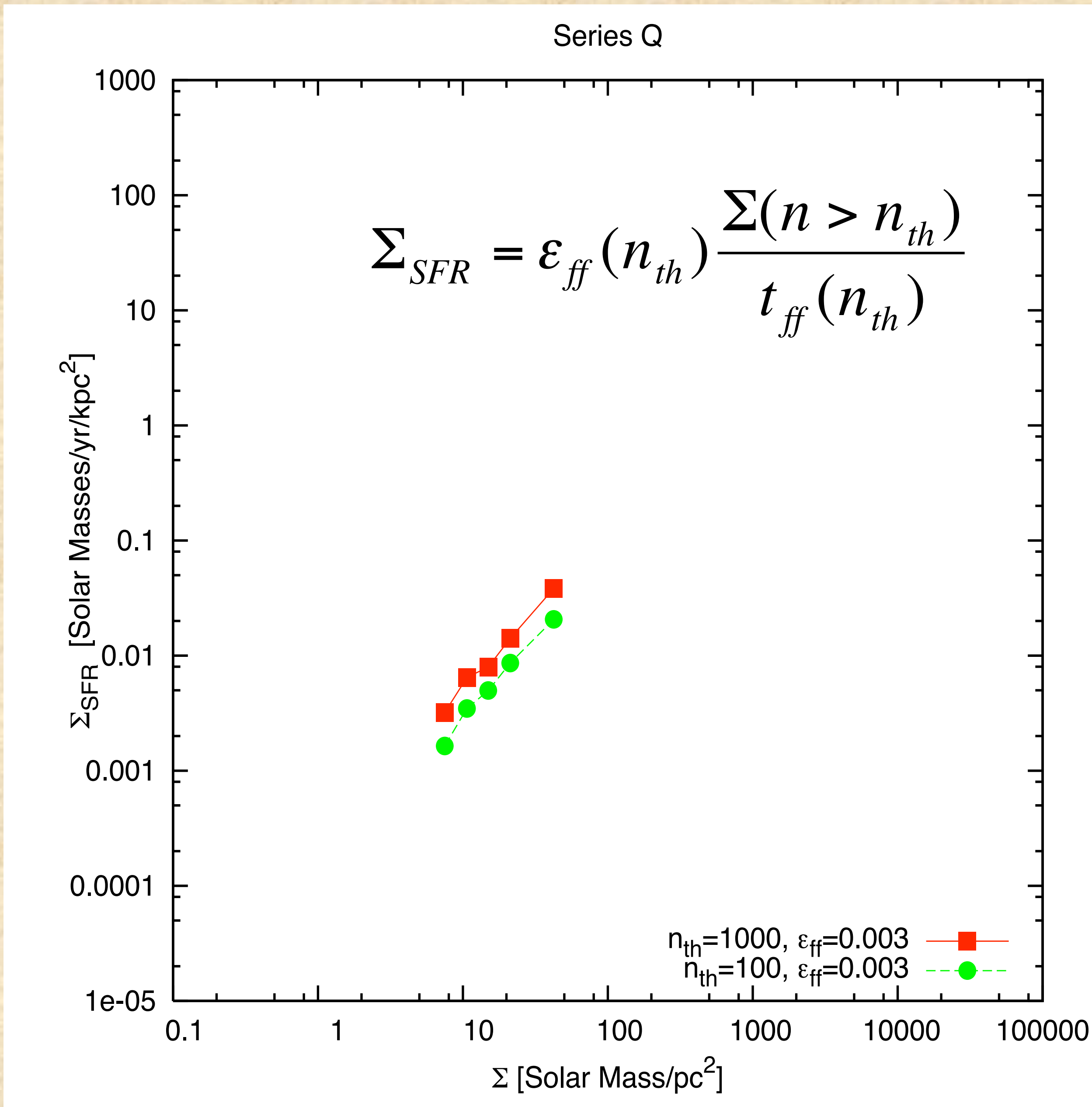
Q series: Q_{gas}=const, Q_*=const

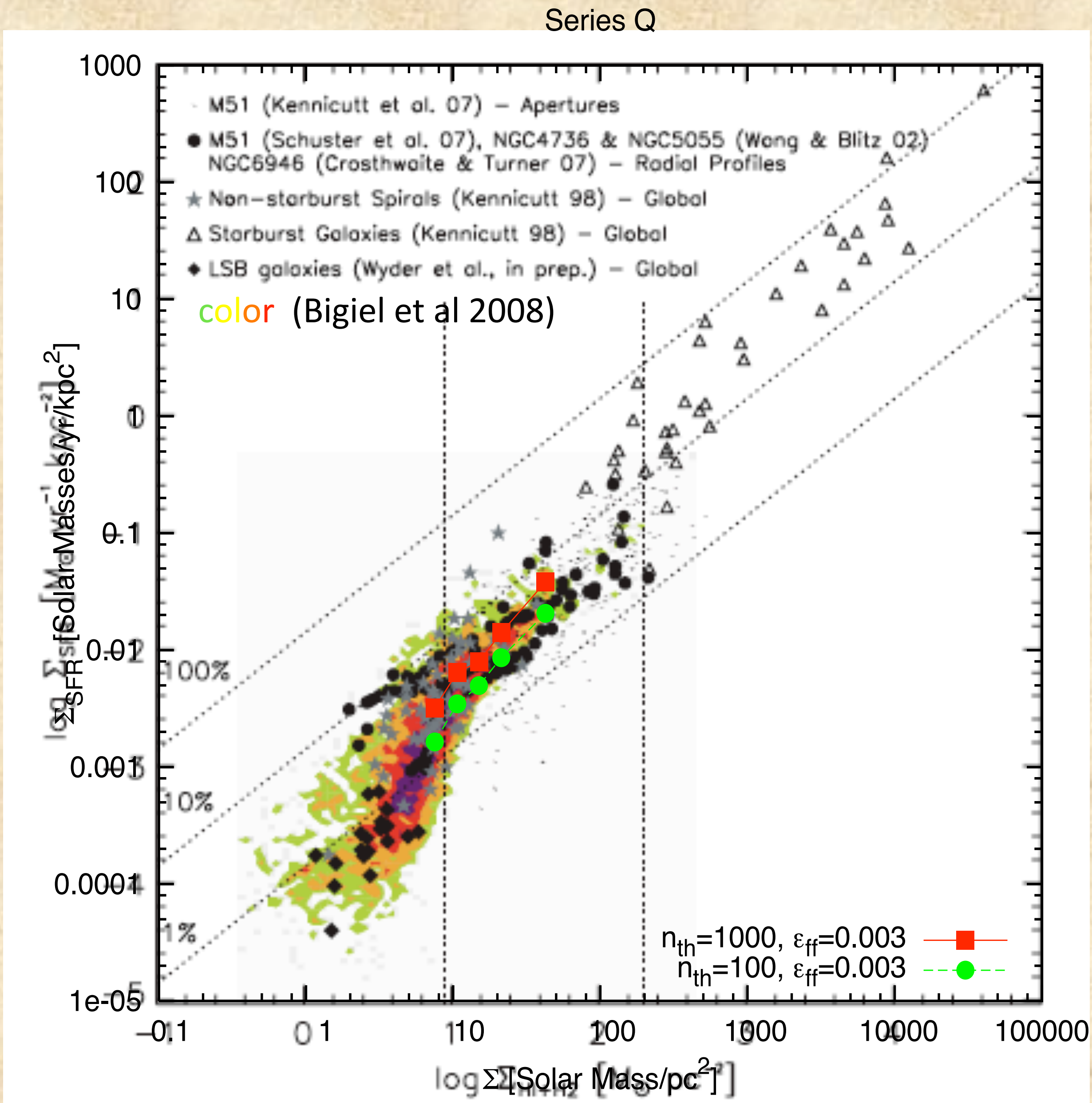


R series: Q_{gas}=const, ρ_*=const

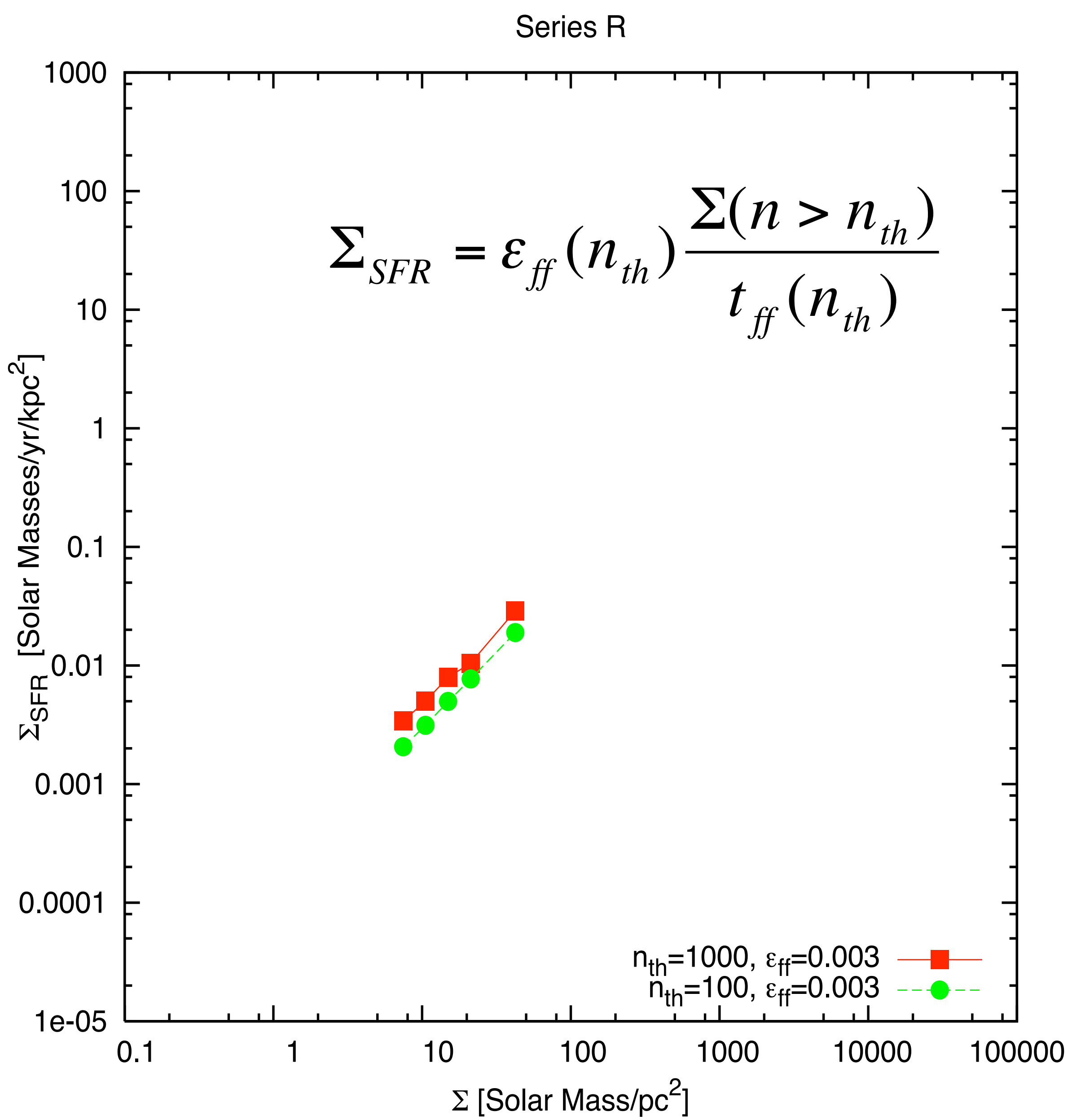


require ϵ_{ff}=0.001-0.01 to match observations


Series Q
$$\Sigma_{SFR} = \varepsilon_{ff}(n_{th}) \frac{\Sigma(n > n_{th})}{t_{ff}(n_{th})}$$
Σ_{SFR} [Solar Masses/yr/kpc^2]
Σ [Solar Mass/pc^2]
n_{th}=1000, ε_{ff}=0.003
n_{th}=100, ε_{ff}=0.003
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-05
0.1
1
10
100
1000
10000
100000

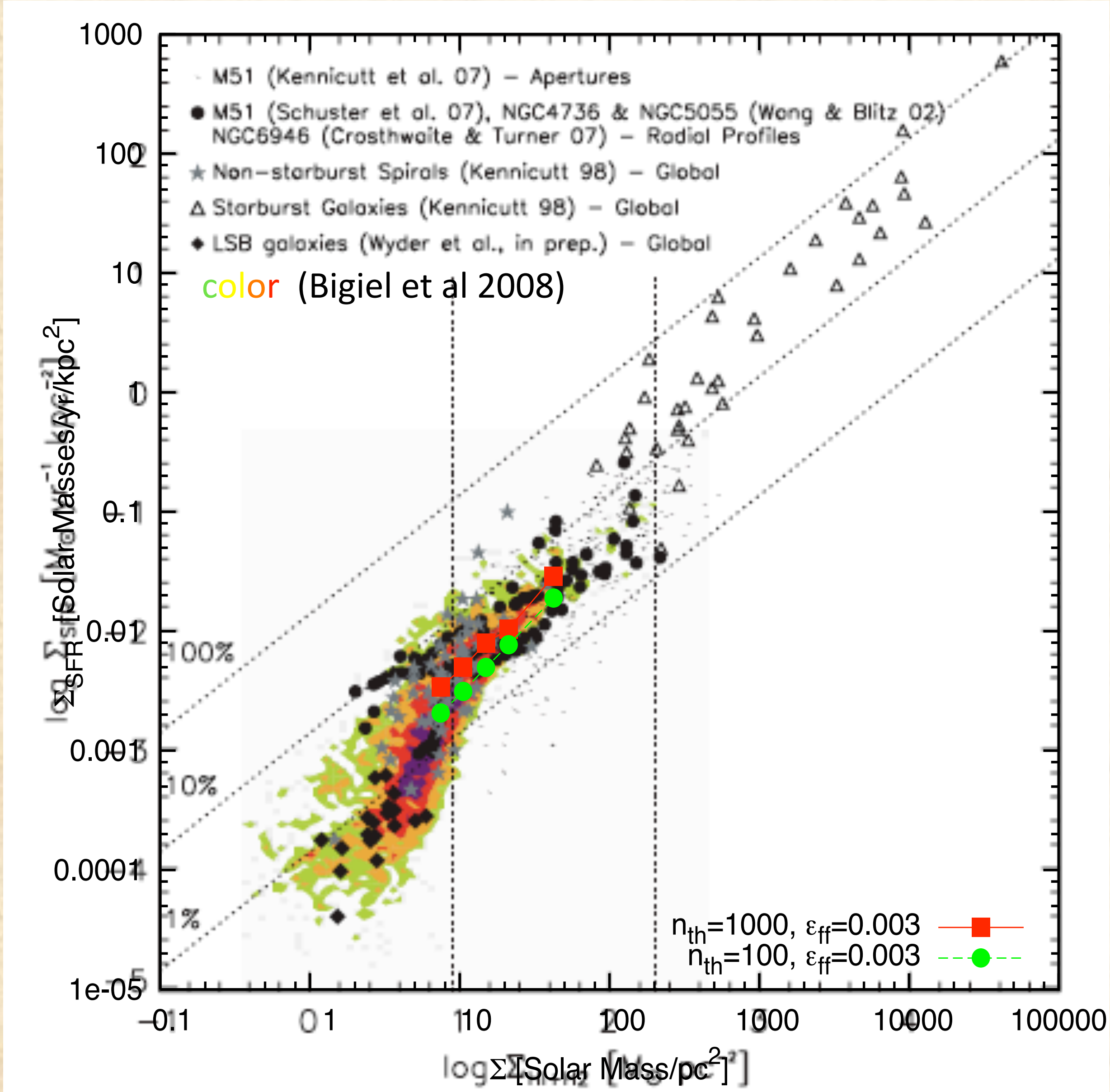


Series Q
M51 (Kennicutt et al. 07) – Apertures
M51 (Schuster et al. 07), NGC4736 & NGC5055 (Wong & Blitz 02)
NGC6946 (Crosthwaite & Turner 07) – Radial Profiles
Non–starburst Spirals (Kennicutt 98) – Global
Starburst Galaxies (Kennicutt 98) – Global
LSB galaxies (Wyder et al., in prep.) – Global
color (Bigiel et al 2008)
100%
10%
1%
n_{th}=1000, ε_{ff}=0.003
n_{th}=100, ε_{ff}=0.003
Σ_{SFR}[Solar Masses/yr/kpc^2]
Σ[Solar Mass/pc^2]
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-05
0.1
1
10
100
1000
10000
100000



Series R
$$\Sigma_{SFR} = \varepsilon_{ff}(n_{th}) \frac{\Sigma(n > n_{th})}{t_{ff}(n_{th})}$$
Σ_{SFR} [Solar Masses/yr/kpc^2]
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-05
0.1
1
10
100
1000
10000
100000
Σ [Solar Mass/pc^2]
n_{th}=1000, ε_{ff}=0.003
n_{th}=100, ε_{ff}=0.003

Series R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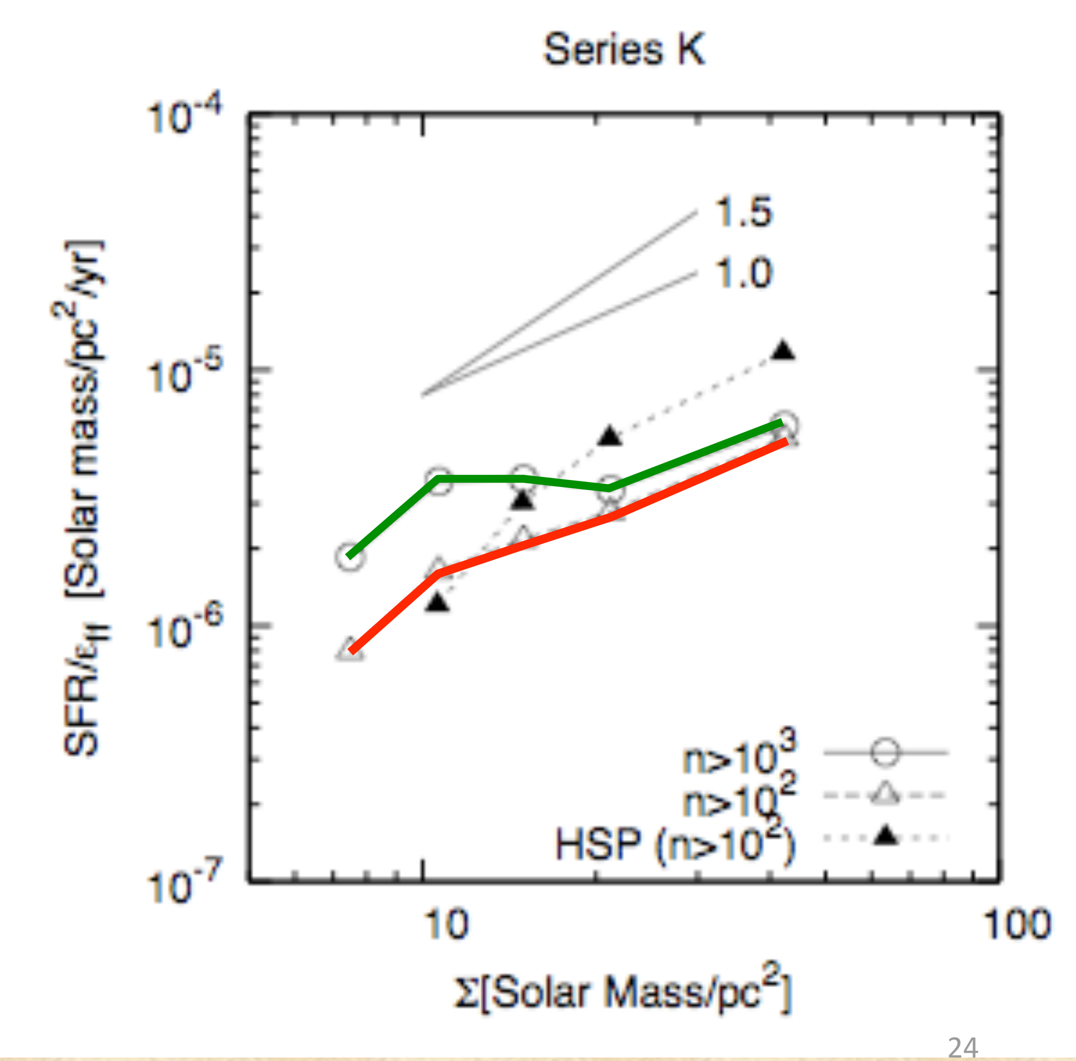
100
1000
10000
100000
Σ_{SFR}[Solar Masses/yr/kpc^2]
Σ[Solar Mass/pc^2]

but if Ω=constant…

- Σ_{SFR} *vs* Σ_{gas} is not power-law; not independent of density threshold
- Conclusion: SFR is inherently dependent on environment including rotation, not just the available supply of gas
- Observed Schmidt laws suggest evolutionary selection effect:

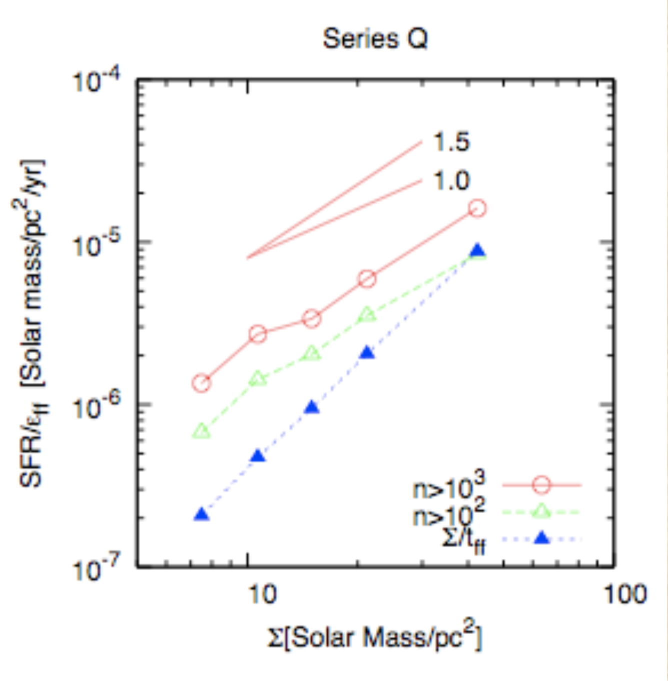
  Σ_{gas} decreases to make $Q = \kappa\,\delta v / (\pi G \Sigma_{gas}) \sim 1$

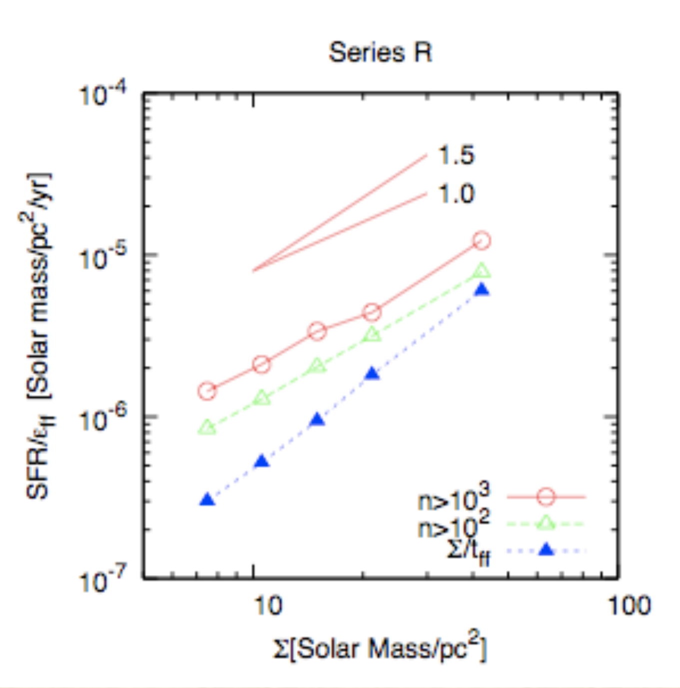
K series: κ =const.



SF predictions?

- Simple SF recipes are often based on large-scale timescales, e.g.:
  - $\Sigma_{SFR} \propto \Sigma_{gas}/t_{orb}$
  - $\Sigma_{SFR} \propto \Sigma_{gas}/t_{ff}$ ($\varrho_{ave}=\Sigma_{gas}/H$)
- These yield too-steep profiles
- Need to resolve vertical disk structure and turbulent, multiphase warm/cold gas to obtain accurate SFR in simulations





Observed H_2/HI

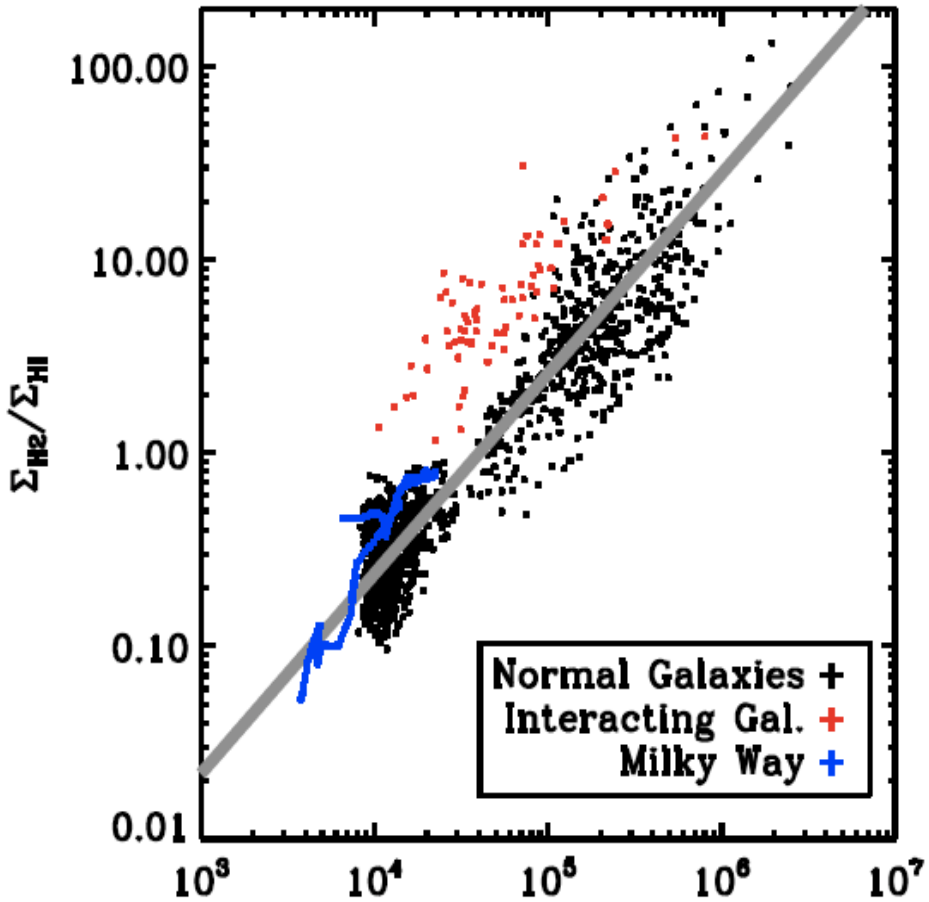
- Blitz & Rosolowsky (2006) found that

  $R_{mol}=\Sigma(H_2)/\Sigma(HI)$

  increases with galactic gas and stellar density as

$$R_{mol} = \left[\frac{P_{ext}/k}{(3.5 \pm 0.6) \times 10^4}\right]^{0.92 \pm 0.07}$$

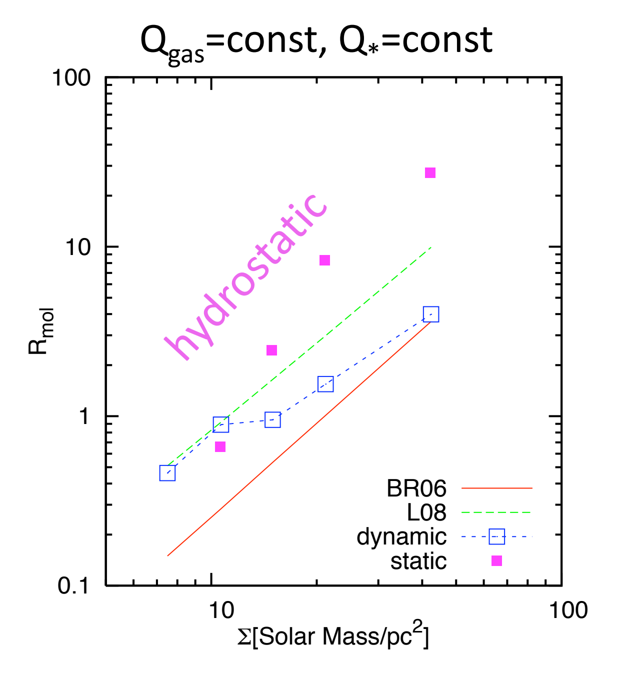
- BR P_{ext} is estimate of midplane pressure
- Leroy et al (2008) find similar relation

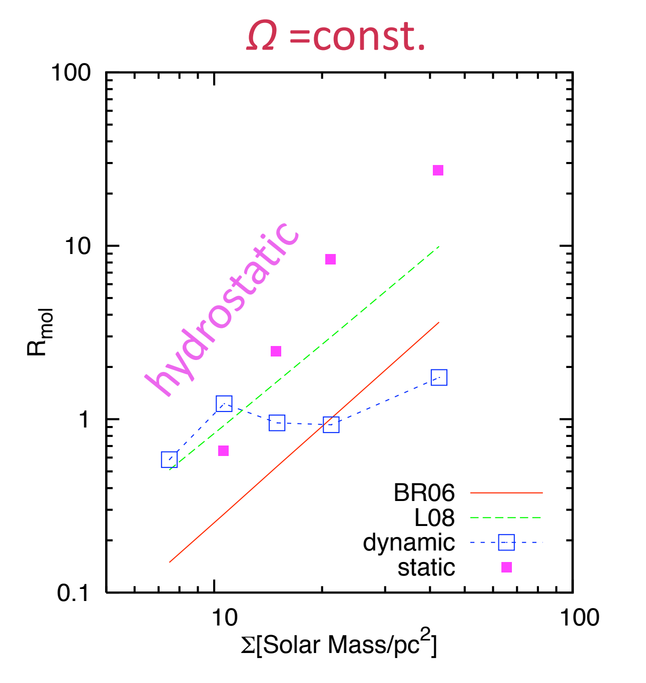


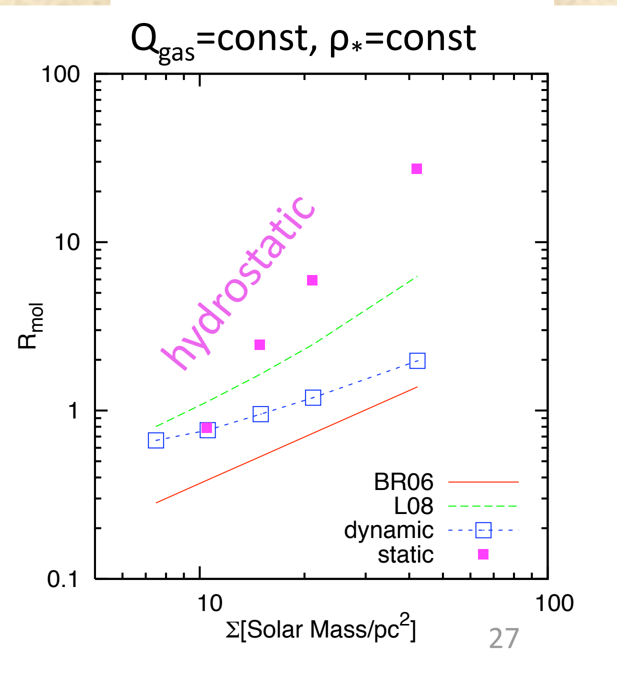
$$P_{ext} = 0.84(G\Sigma_\star)^{0.5}\Sigma_g \frac{v_g}{(h_\star)^{0.5}}.$$

R_{mol} in simulations

- vertically-resolved, multiphase, turbulent simulations have R_{mol} consistent with observations if $\Omega \propto \Sigma_{gas}$
- …but not if Ω =const
- Hydrostatic models have R_{mol} much larger than observed values







Origin of R_{mol} relation?

- In vertical equilibrium, for multiphase, turbulent disk (Koyama & Ostriker 2009b)

$$P_{0,tot} \equiv \sigma_z^2 \rho_0 = (c_s^2 + v_z^2)\rho_0 = \Sigma_{gas}\left(G\Sigma_{gas} + \left[\left(G\Sigma_{gas}\right)^2 + 2G\rho_* \sigma_z^2 \right]^{1/2} \right)$$

- Atomic gas midplane thermal pressure is $\rho_0 c_s^2 \approx P_{min,cold}$

$$P_{\min,cold} = c_s^2 \rho_0 = \frac{c_s^2}{c_s^2 + v_z^2}\rho_0 = \frac{c_s^2}{\sigma_z^2}\Sigma_{HI}\left(G\Sigma_{HI} + \left[\left(G\Sigma_{HI}\right)^2 + 2G\rho_* \sigma_z^2 \right]^{1/2} \right)$$

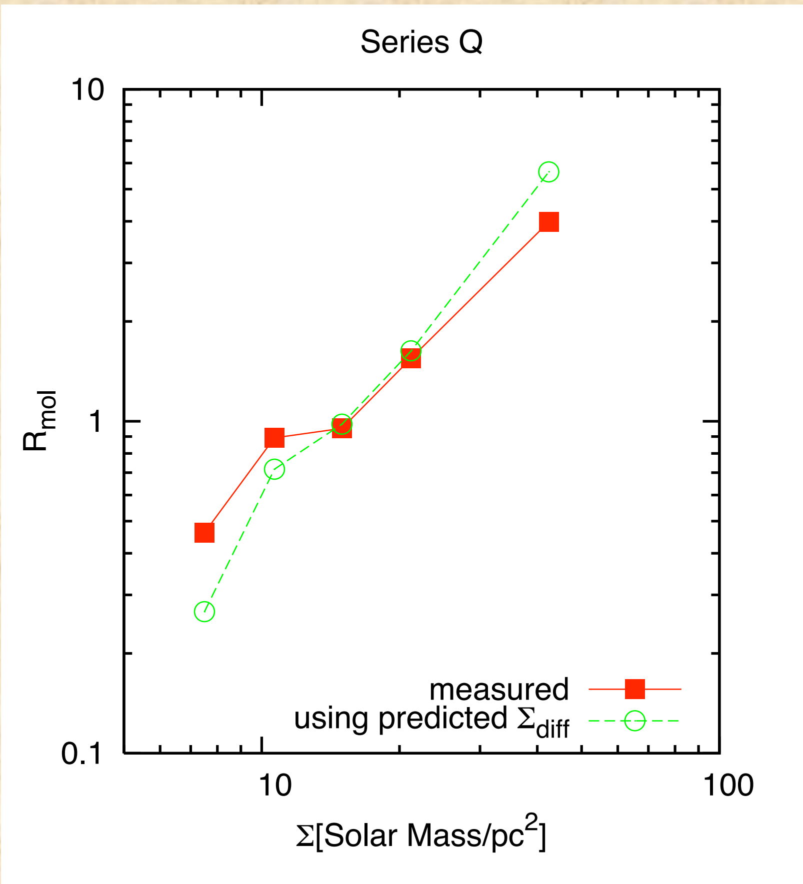
$\Rightarrow$

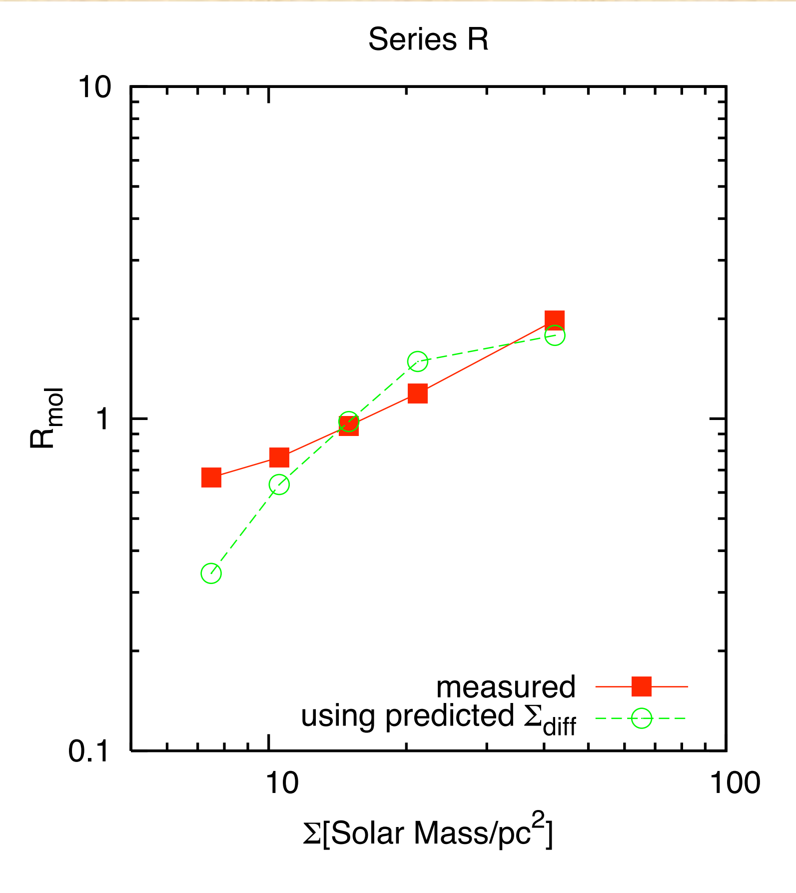
$$\Sigma_{HI} = \left(\frac{P_{\min,cold}}{2G} \right)^{1/2} \frac{\sigma_z / c_s}{\left[1 + \frac{\rho_* c_s^2}{P_{\min,cold}} \right]^{1/2}}$$

- Predicted molecular-to-atomic ratio is

$$\frac{\Sigma_{H2}}{\Sigma_{HI}} = \Sigma_{H2}\left(2G\rho_*\right)^{1/2} \frac{c_s^2/\sigma_z}{P_{\min,cold}} \left[1 + \frac{P_{\min,cold}}{\rho_* c_s^2} \right]^{1/2} \sim \frac{P_{BR}}{const.}$$

R_{mol} comparison using simulation





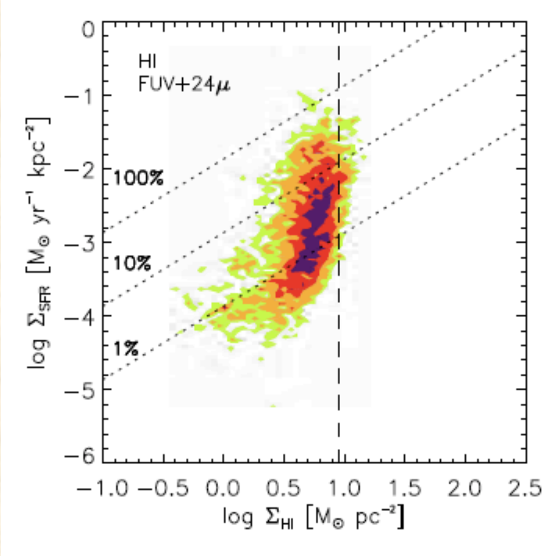
HI saturation?

- With $$\Sigma_{HI} = \left(\frac{P_{\min,cold}}{2G}\right)^{1/2} \frac{\sigma_z / c_s}{\left[1 + \frac{\rho_* c_s^2}{P_{\min,cold}}\right]^{1/2}}$$, the maximum

value of Σ_{HI} is ~ $(P_{\min,cold}/G)^{1/2} \approx 10\ M_\odot\ pc^{-2}$

- Relatively insensitive to metallicity, radiation field; from Wolfire et al (2005),

$$\frac{P_{\min}}{k} \equiv 1.1 n_{\min} T_{(\min)} \simeq 8500 \frac{G_0' \left(Z_d'/Z_g'\right)}{1 + 3.1 \left(G_0' Z_d' / \zeta_t'\right)^{0.365}}\ \mathrm{cm}^{-3}\ \mathrm{K}\ ,$$



Bigiel et al (2008)

- May contribute to observed HI "saturation" (Wong & Blitz 2002, Bigiel et al 2008)

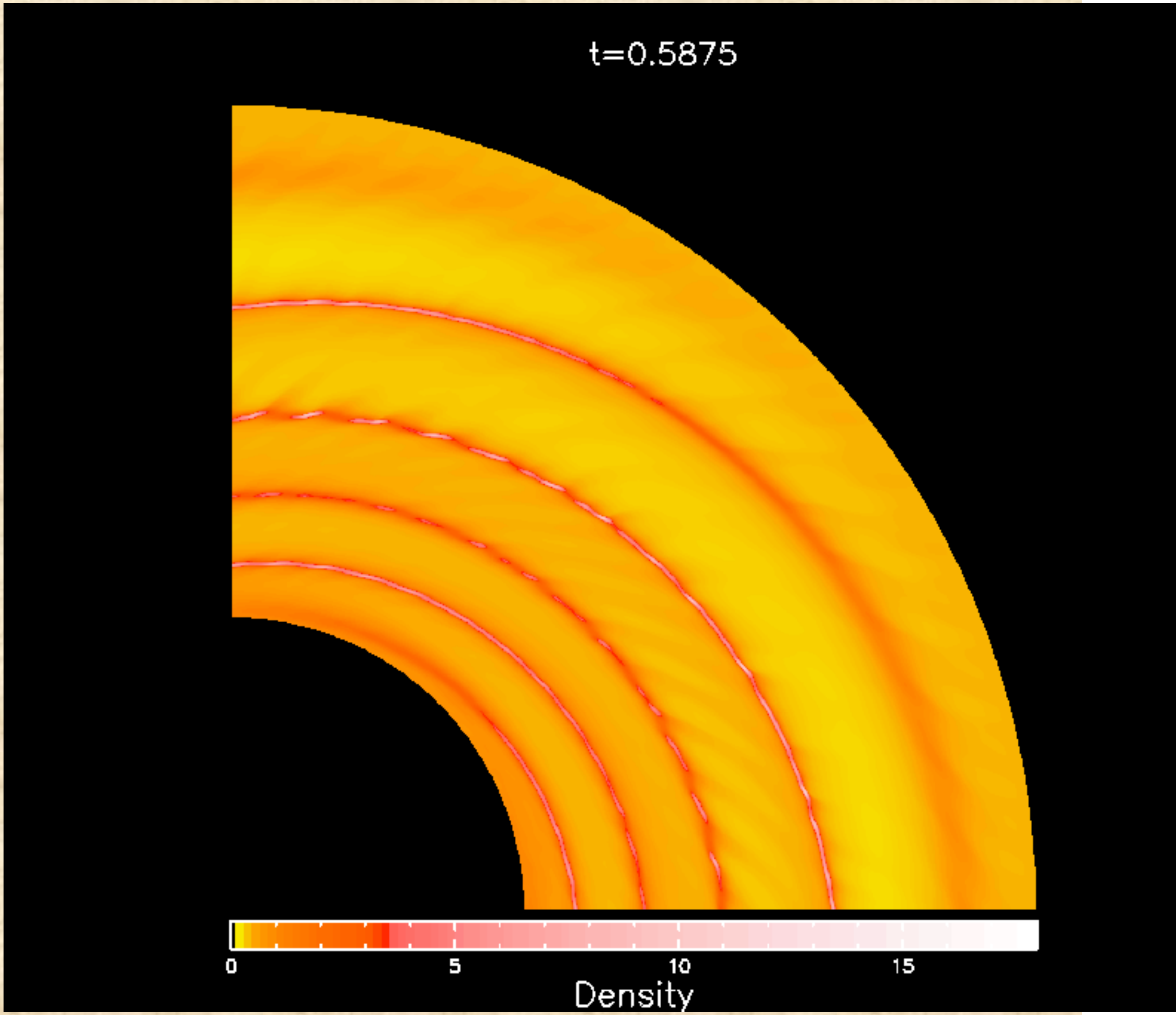
Summary

- Star formation is inherently affected by galactic environment:
  - galactic rotation (Ω) , shear, and ρ_* -- not just Σ_{gas}
  - detailed state of gas is also important…
- Including disk thickness, the stellar component, and turbulent magnetic fields, the threshold Toomre Q_{gas} is ≈1.5
- GMC formation in spiral arms is favored by high Σ_{gas}, and spiral-arm spurs enhance interarm GMC/star formation
- Feedback from star formation raises the turbulence level and Q_{eff}, but leverage on self-regulated SF may be limited
- Observed SF/gas relations may result from evolutionary selection: gas is depleted until Q increases to ~1
- Vertically-resolved simulations with feedback-driven turbulence, multiphase gas have Schmidt relations and R_{mol} consistent with observations provided Ω and Σ_{gas} increase together
- Simple SF recipes/unresolved disks yield too-steep Σ_{SFR} vs. Σ_{gas}
- Dynamics/thermodynamics may contribute to limiting Σ_{HI}

extra slides

Global model with "SN" feedback

- To measure SFR, require steady state of cloud formation and destruction
- $\Sigma_{SF} \propto \Sigma_{dense}$
- SN momentum input $\propto \Sigma_{SF}$
- SN-driven turbulence both creates and destroys dense clouds…

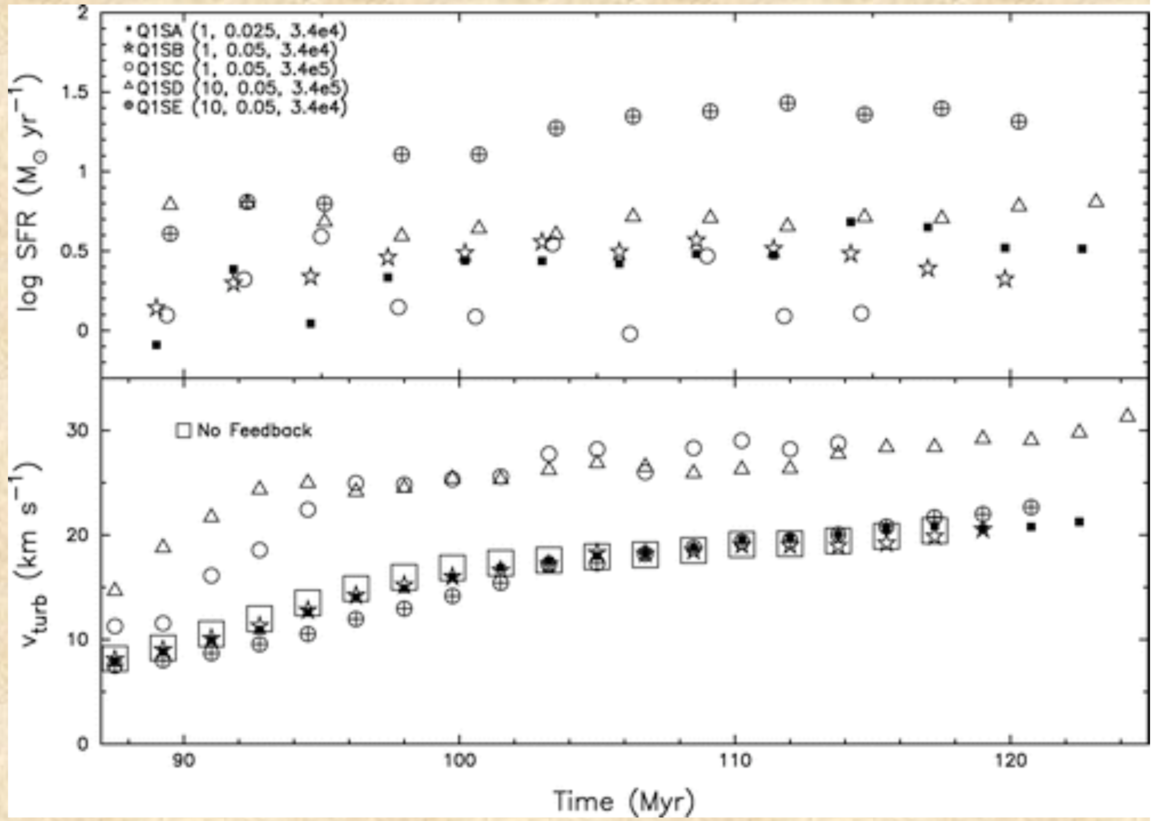


Shetty & Ostriker (2008)

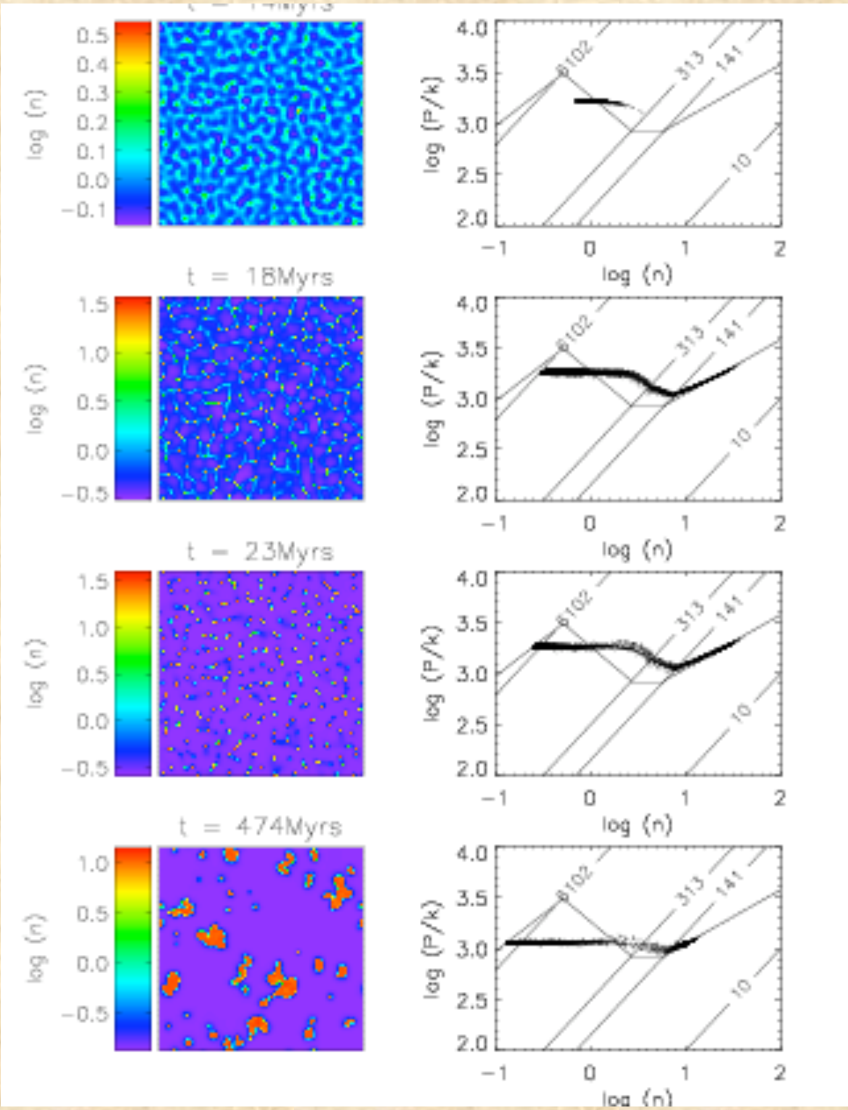
Q=1 "strong feedback" model

Global SFR in models with feedback

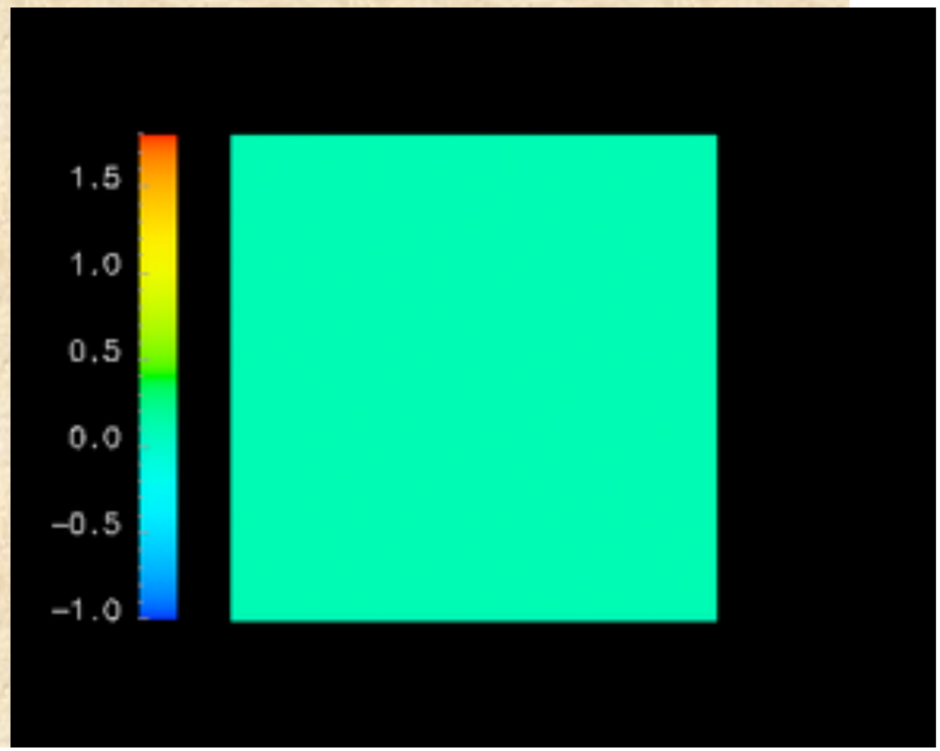
- Increase in E_{SN} at fixed $t_{SF,dense}$ lowers SFR
- Sub-linear increase in SFR with $1/t_{SF,dense}$ ⇒feedback reduces fraction of dense gas
- in net, *feedback reduces SFR*



Thermal Instability and HI structure



- Thermal instability develops due to bistable heating/cooling curve (Field 1965)
- Medium separates into cold clouds + warm intercloud gas
- Overall cooling towards $P_{min,cold}$



Piontek & Ostriker (2004)