Regulation of Star Formation Rates in Multiphase Galactic Disks:

Numerical Tests of the Thermal/Dynamical Equilibrium Model

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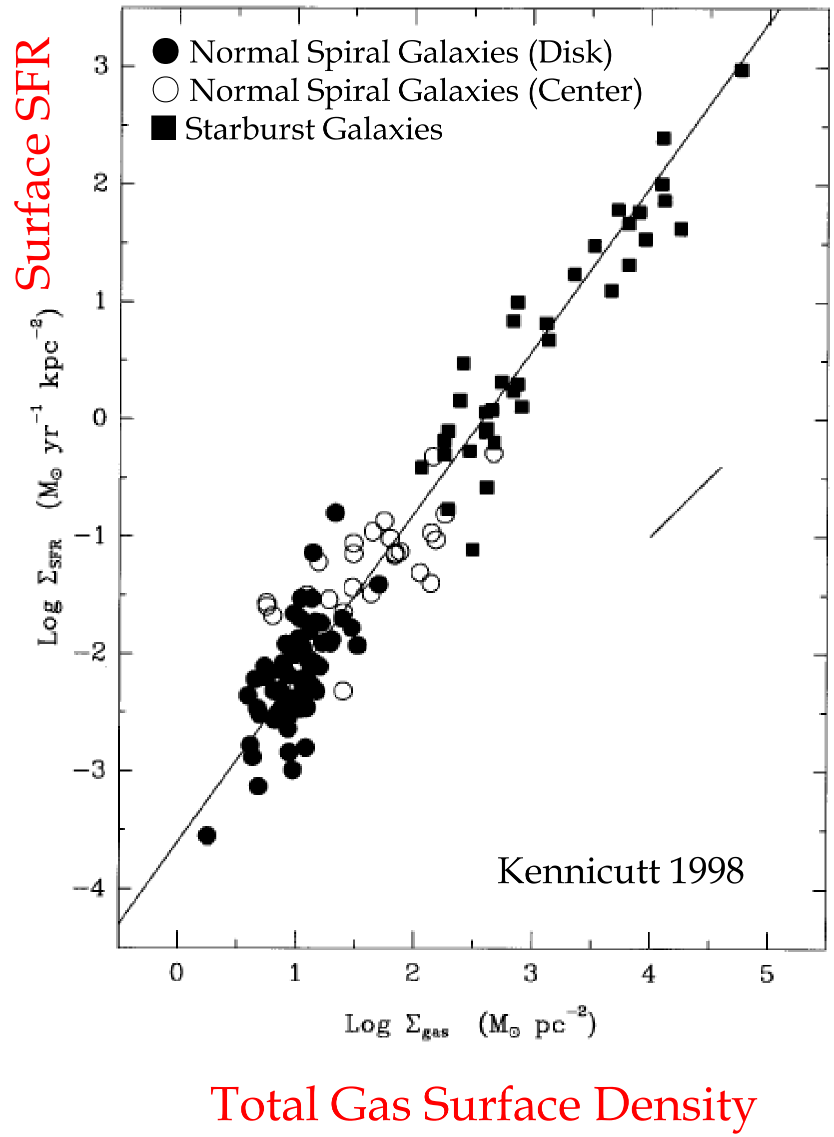
Star Formation Laws

- Schmidt Law (Schmidt 1959, 1963)
  - $\Sigma_{SFR} \propto \Sigma^N$
  - Σ_{SFR}: star formation rate per unit area [$M_\odot yr^{-1} kpc^{-2}$]
  - Σ: total (atomic + molecular) gas surface density

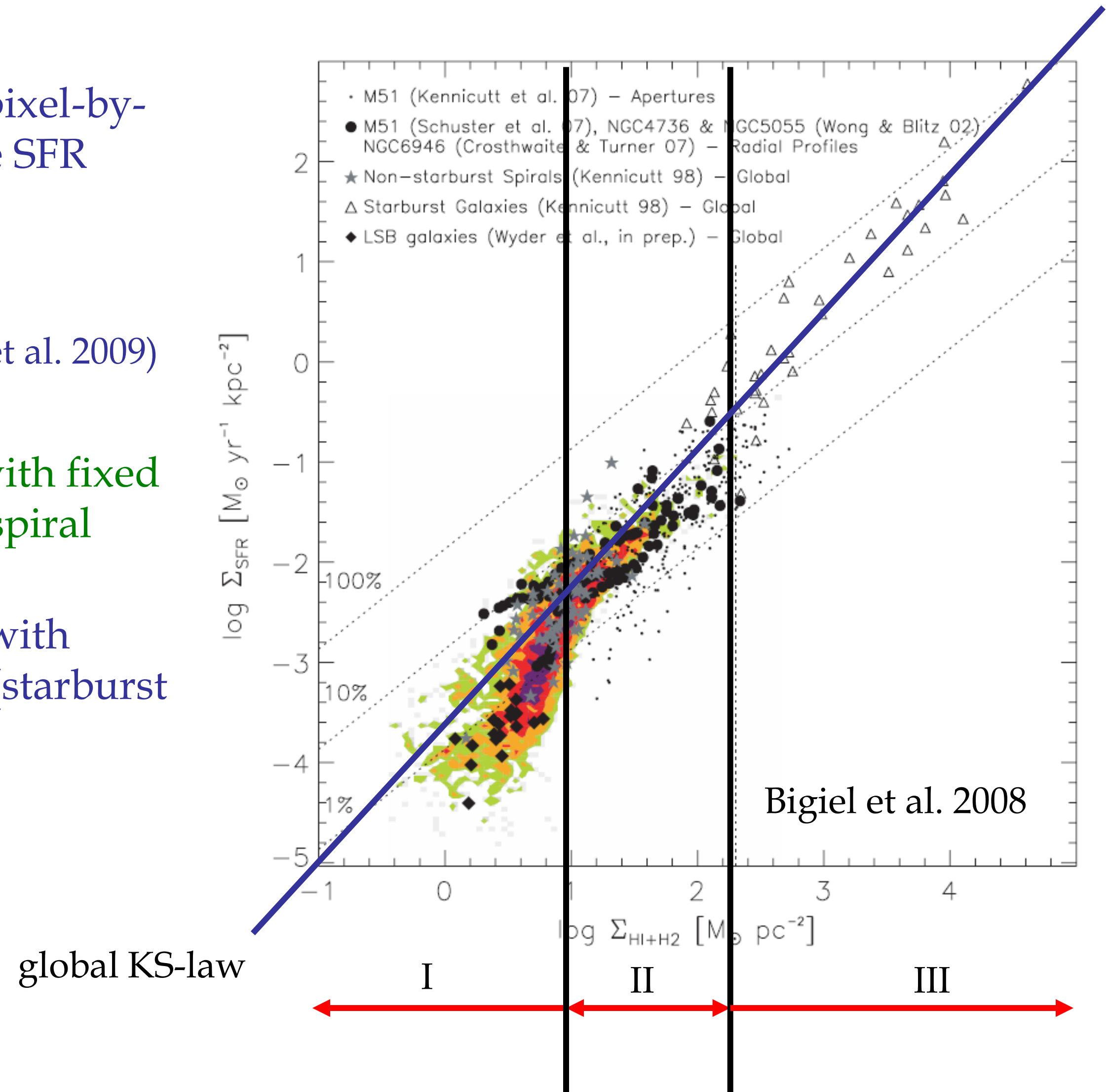
- Kennicutt-Schmidt Law (Kennicutt 1989, 1998)
  - $N=1.4\pm0.15$
  - single power law from normal to starburst spiral galaxies



Star Formation Laws

- Bigiel et al. (2008)
  - high resolution (~750pc) pixel-by-pixel measurements of the SFR
  - no single Schmidt law

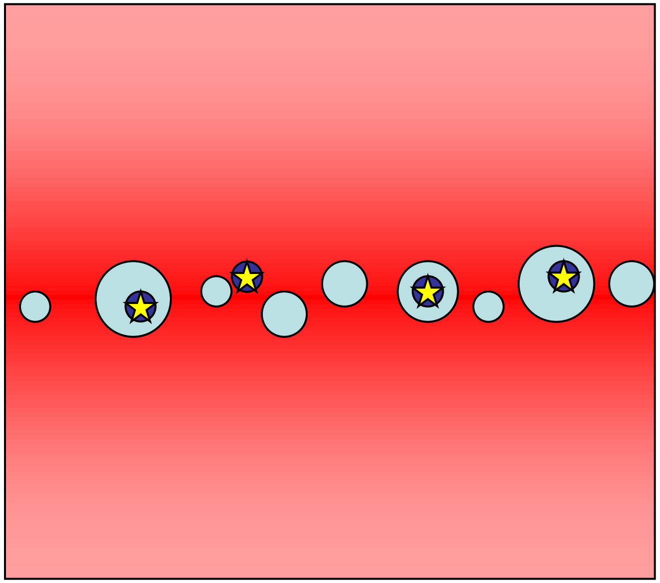
- Three regimes (c.f. Krumholz et al. 2009)
  - I: HI-dominated region
  - II: H_2-dominated region with fixed GMC properties (normal spiral galaxies)
  - III: H_2-dominated region with variable GMC properties (starburst galaxies)



Thermal/Dynamical Equilibrium Model

Ostriker, McKee, & Leroy (2010, OML)

- Gas components
  - diffuse gas: WNM + CNM
  - gravitationally bound clouds (GBCs): self-gravitating



Thermal/Dynamical Equilibrium Model

Ostriker, McKee, & Leroy (2010, OML)

- Vertical Dynamical Equilibrium

- Thermal Equilibrium

- Equilibrium Star Formation Rate

Thermal/Dynamical Equilibrium Model

Ostriker, McKee, & Leroy (2010, OML)

- effective Hydrostatic Equilibrium (HSE) of diffuse gas
  - horizontally- and temporally-averaged, vertically-integrated vertical momentum equation

$$P_{\rm th}\left(1+\frac{v_t^2}{c_w^2\tilde{f}_w}\right)=\frac{\pi G}{2}\Sigma_{\rm diff}^2+\pi G\Sigma_{\rm GBC}\Sigma_{\rm diff}+2\pi\zeta_d G c_w^2\tilde{f}_w\frac{\rho_{\rm sd}\Sigma_{\rm diff}^2}{P_{\rm th}}.$$

thermal+turbulent midplane pressure

weight of diffuse gas in the gravitational field associated with

diffuse gas

GBCs

stars and dark matter

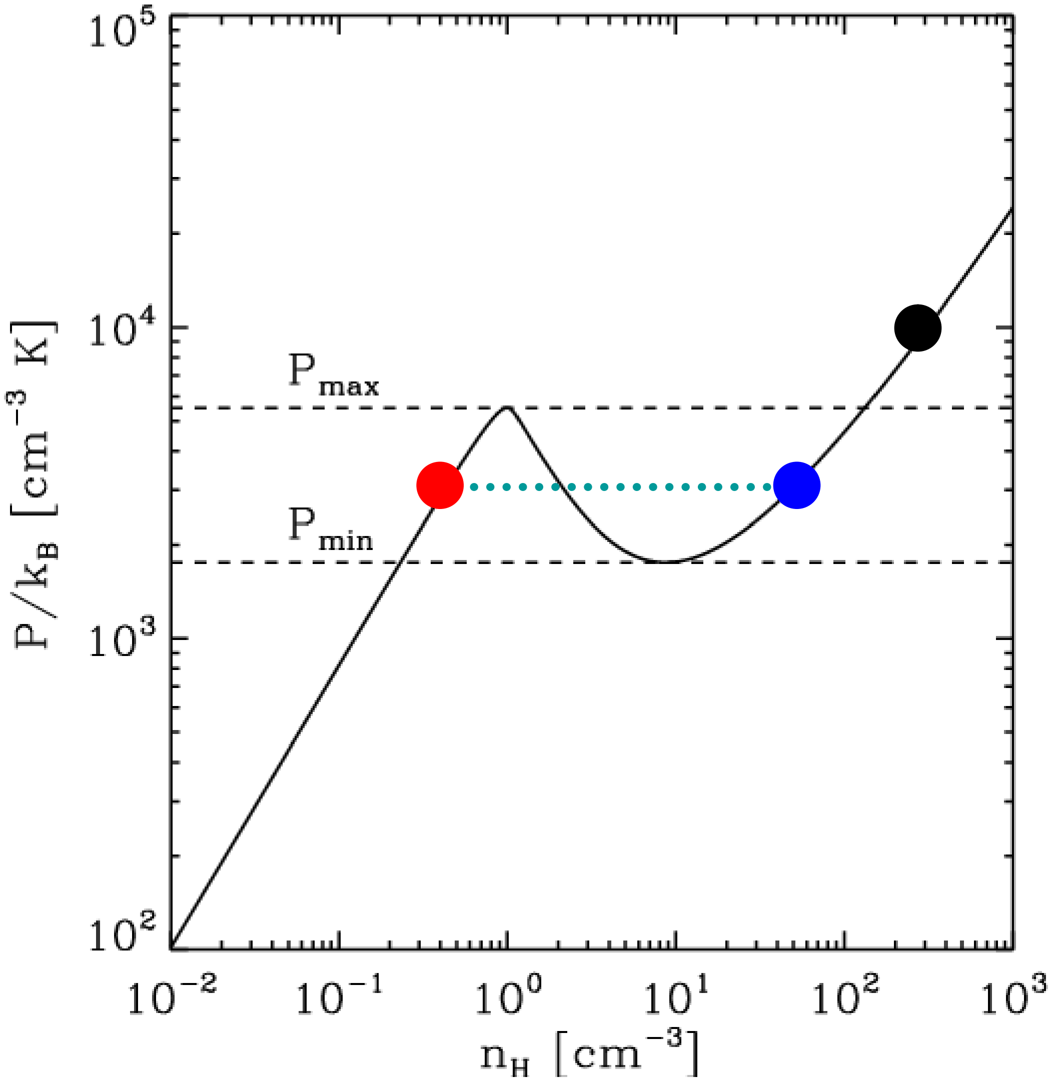
  - midplane thermal pressure estimated by effective HSE

$$P_{\rm HSE}=\frac{\pi G\Sigma_{\rm diff}^2}{4\alpha}\left\{1+2\frac{\Sigma_{\rm GBC}}{\Sigma_{\rm diff}}+\left[\left(1+2\frac{\Sigma_{\rm GBC}}{\Sigma_{\rm diff}}\right)^2+\frac{32\zeta_d c_w^2\tilde{f}_w\alpha}{\pi G}\frac{\rho_{\rm sd}}{\Sigma_{\rm diff}^2}\right]^{1/2}\right\}.$$

Thermal/Dynamical Equilibrium Model

Ostriker, McKee, & Leroy (2010, OML)

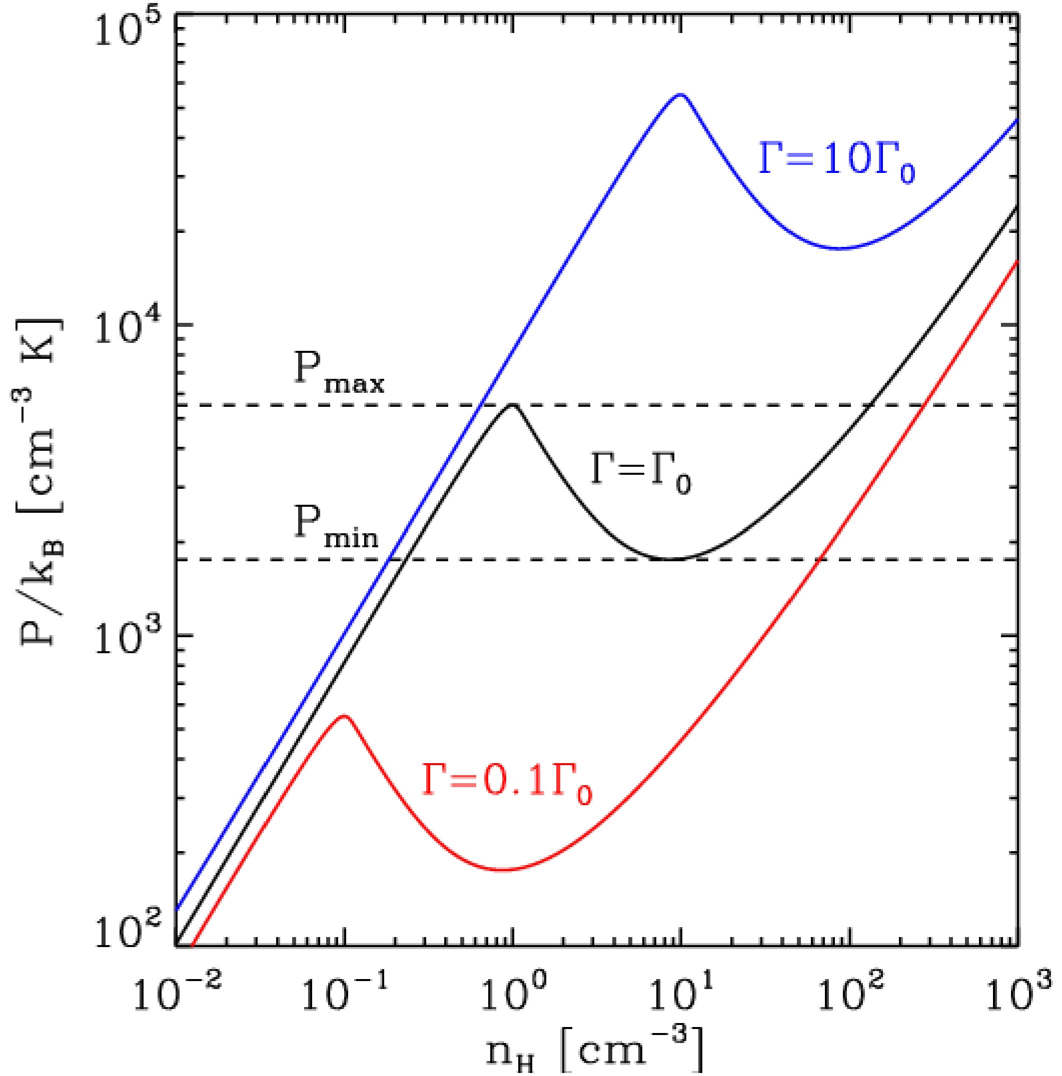
- Thermal Equilibrium
  - for two-phase ISM, $P_{min} < P_{mid} < P_{max}$



Thermal/Dynamical Equilibrium Model

Ostriker, McKee, & Leroy (2010, OML)

- Thermal Equilibrium
  - for two-phase ISM, $P_{min} < P_{mid} < P_{max}$
  - P_{min} and P_{max} are proportional to the heating rate (Γ)
  - Γ is proportional to the FUV intensity (J_{FUV})
  - J_{FUV} is proportional to the surface SFR (Σ_{SFR})
  - OML have assumed $P_{mid} = P_{two\text{-}phase} \equiv (P_{min} P_{max})^{1/2}$



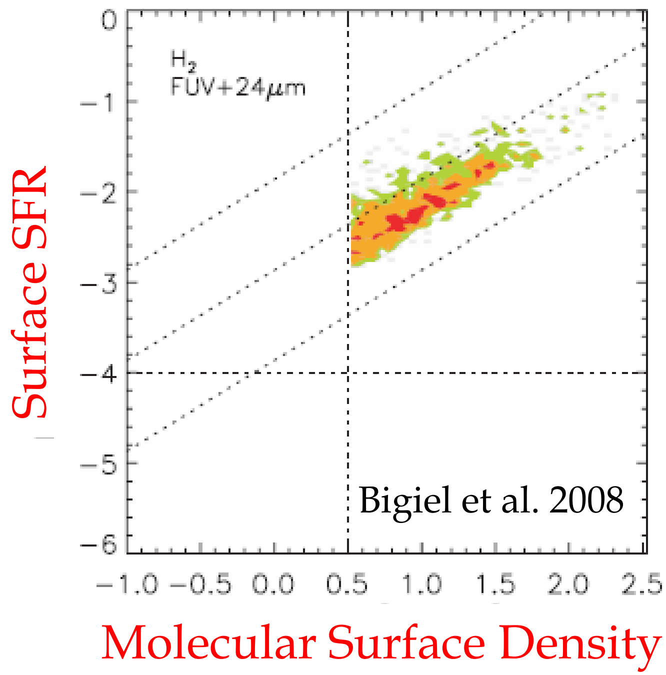
Thermal/Dynamical Equilibrium Model

Ostriker, McKee, & Leroy (2010, OML)

- Star Formation Rate

$$\Sigma_{\rm SFR} = \frac{\Sigma_{\rm GBC}}{t_{\rm SF,GBC}} = \frac{\Sigma - \Sigma_{\rm diff}}{t_{\rm SF,GBC}},$$

  - the typical timescale to convert GBCs to stars, $t_{SF,GBC}$=2Gyr



Thermal/Dynamical Equilibrium Model

Ostriker, McKee, & Leroy (2010, OML)

- Vertical Dynamical Equilibrium (P_{mid}=P_{HSE})

$$P_{HSE} = \frac{\pi G \Sigma_{\rm diff}^2}{4\alpha}\left\{1 + 2\frac{\Sigma_{\rm GBC}}{\Sigma_{\rm diff}} + \left[\left(1 + 2\frac{\Sigma_{\rm GBC}}{\Sigma_{\rm diff}}\right)^2 + \frac{32\zeta_d c_w^2 \tilde{f}_w \alpha}{\pi G}\frac{\rho_{\rm sd}}{\Sigma_{\rm diff}^2}\right]^{1/2}\right\}.$$

- Thermal Equilibrium (P_{mid}=$P_{two\text{-}phase}$)

$$P_{\rm two-phase}/k_{\rm B} = 12000\,{\rm cm}^{-3}\,{\rm K}\frac{\Sigma_{\rm SFR}/\Sigma_{\rm SFR,0}}{1 + 3Z_d'(\Sigma/\Sigma_0)^{0.4}},$$

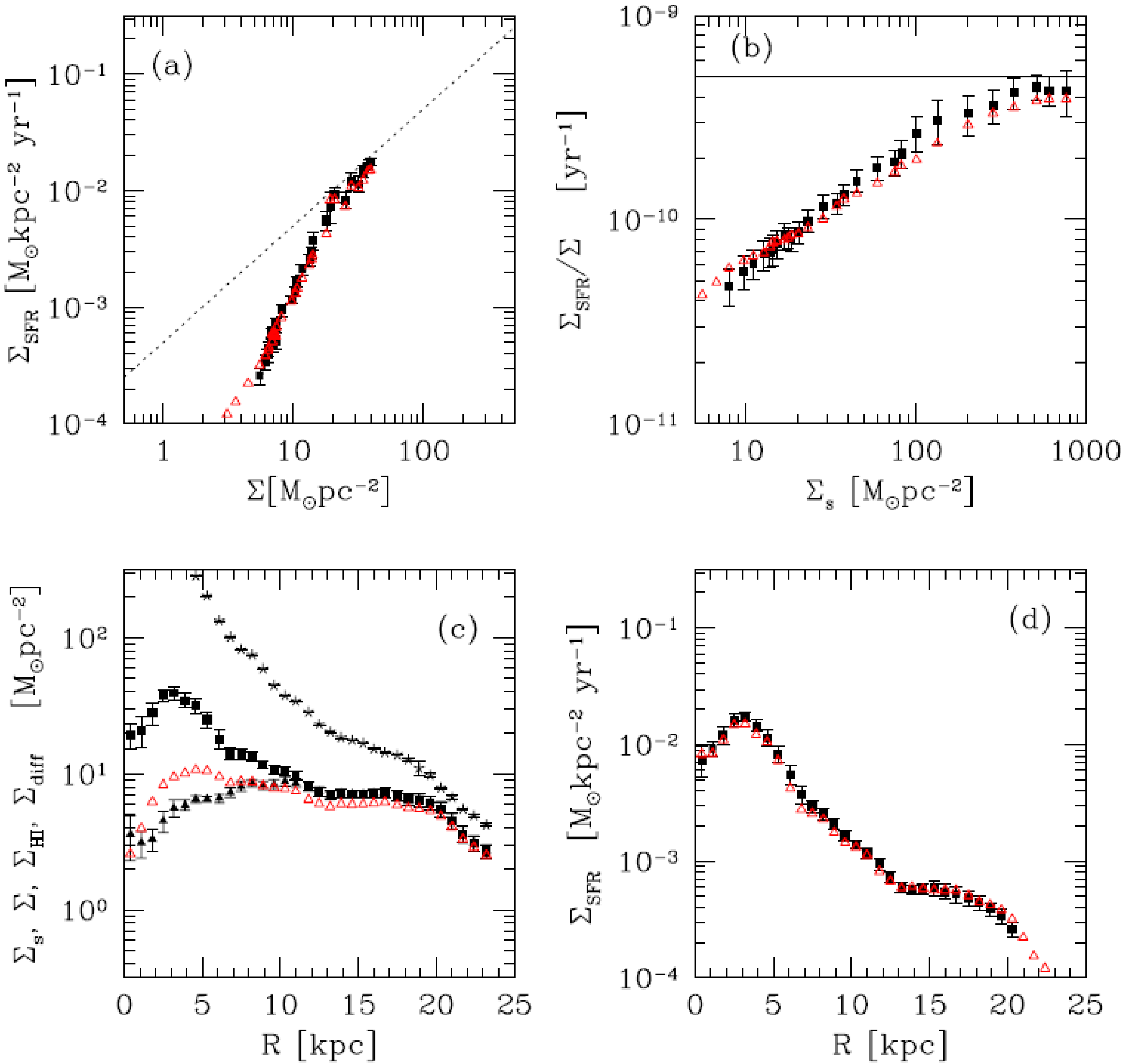
- Equilibrium Star Formation Rate

$$\Sigma_{\rm SFR} = \frac{\Sigma_{\rm GBC}}{t_{\rm SF,GBC}} = \frac{\Sigma - \Sigma_{\rm diff}}{t_{\rm SF,GBC}},$$

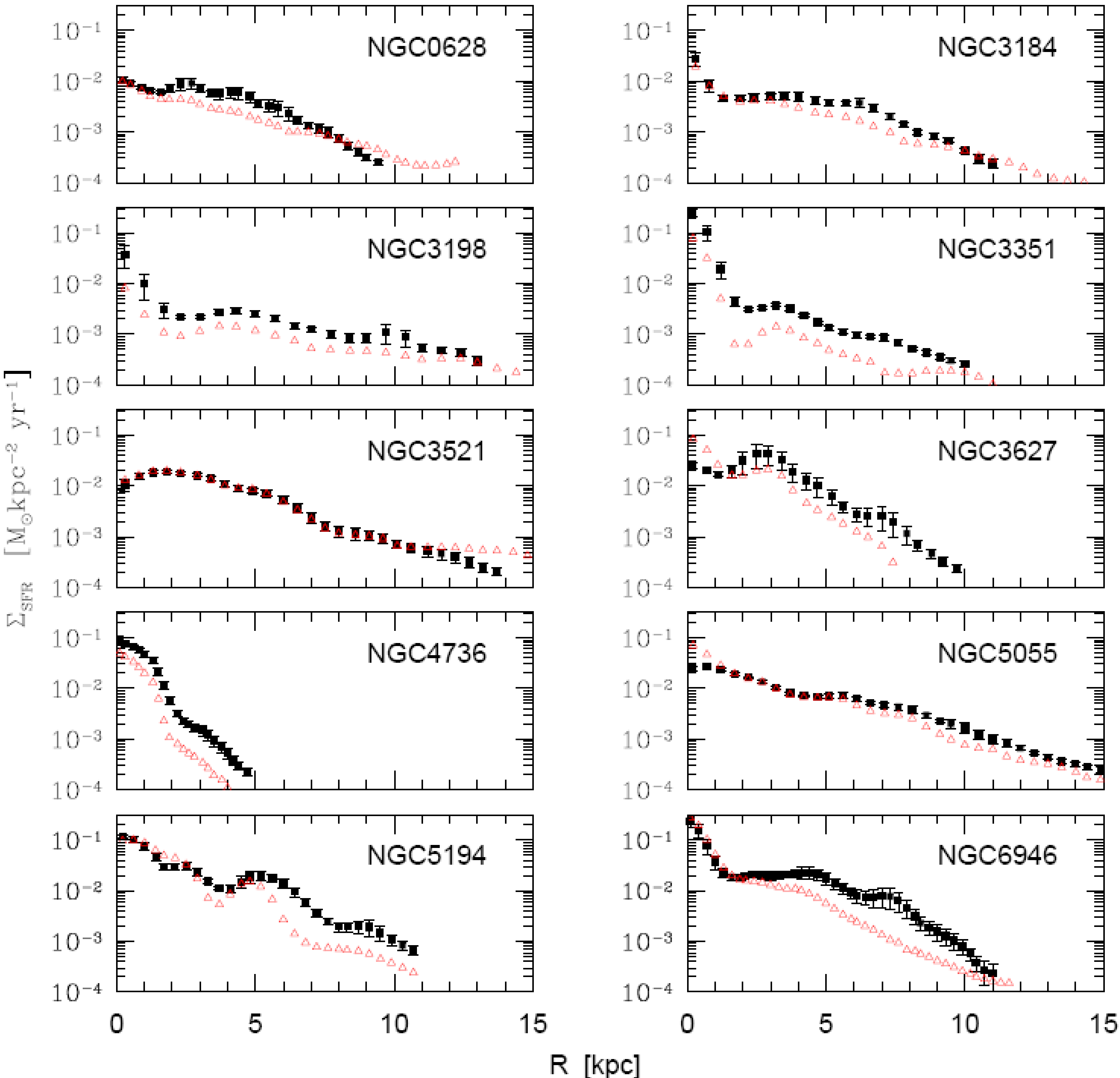
- [Σ, ρ_{sd}, Z_d'] → [Σ_{SFR}, Σ_{diff}]

Thermal/Dynamical Equilibrium Model

Ostriker, McKee, & Leroy (2010, OML)



- NGC 7331
- black: observation from Leroy et al. (2008)
- red: theory
  - α=5
  - f_w=0.5
  - $t_{SF,GBC}$=2Gyr


NGC0628
NGC3184
NGC3198
NGC3351
NGC3521
NGC3627
NGC4736
NGC5055
NGC5194
NGC6946
Σ_{SFR} $[M_\odot kpc^{-2} yr^{-1}]$
R [kpc]

Thermal/Dynamical Equilibrium Model

Ostriker, McKee, & Leroy (2010, OML)

- Q1. Is HSE really valid for turbulent, multiphase galactic disks? or $P_{mid}=P_{HSE}$?

- Q2. What is the consequence of thermal equilibrium? or $P_{mid}=P_{two\text{-}phase}$?

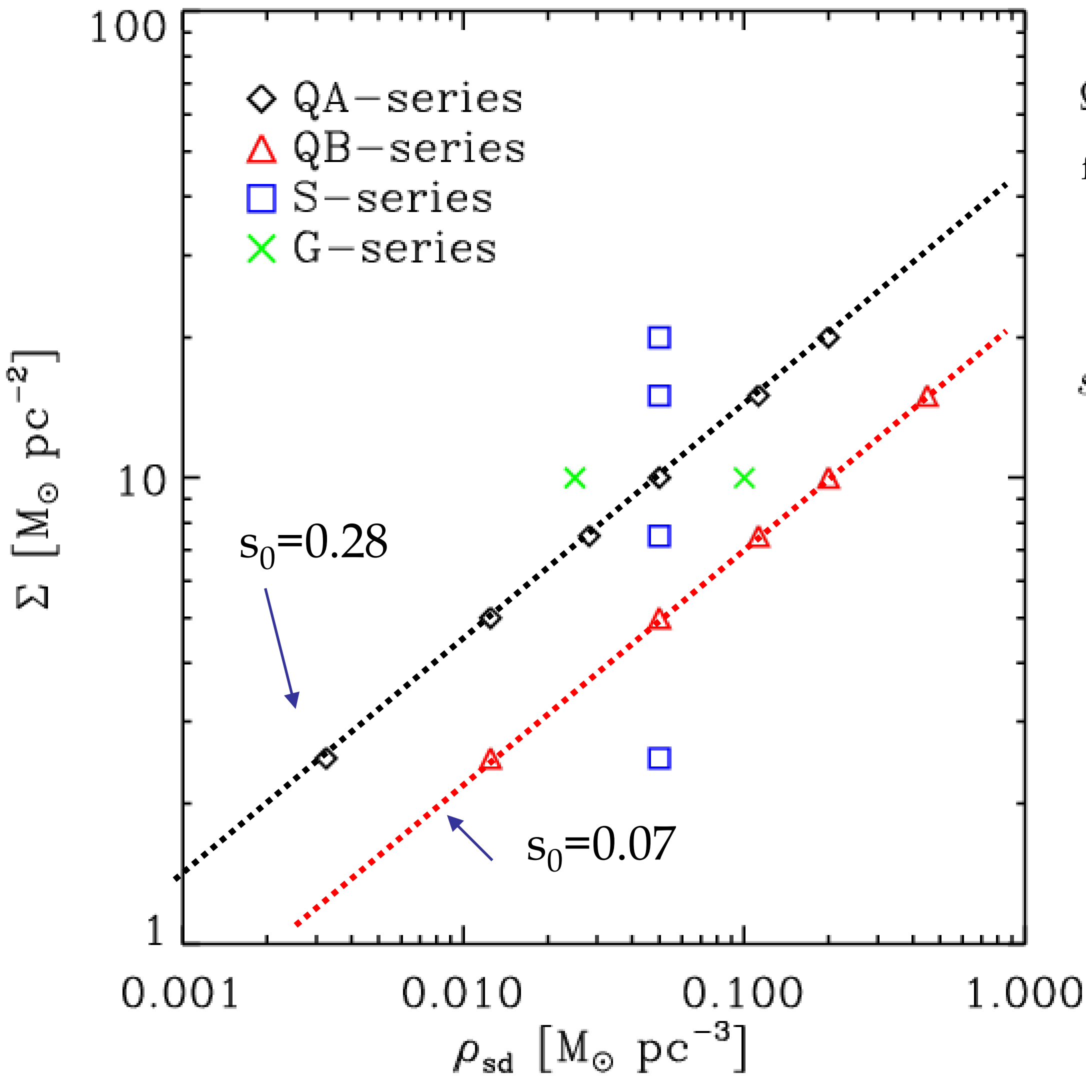
- Q3. What are the most probable ranges of α and f_w?

Method

- Local 2.5D (radial-vertical; XZ) hydrodynamic simulations
  - self-gravity (Σ)
  - vertical stratification (ρ_{sd}; stellar +DM halo)
  - galactic rotation (Ω; flat rotation)
  - cooling and heating (Koyama & Inutsuka 2002)
  - SF mechanical feedback (SN explosion → turbulent ISM)
  - SF radiative feedback ($\Gamma \propto \Sigma_{SFR}$ → regulation of SFR)

- Athena Code (Stone et al. 2008; Stone & Gardiner 2009)
  - HLLC, PLM, van Leer integrator
  - Boundary conditions
    - X: shearing-periodic
    - Z: periodic with vacuum BC for gravitational potential (Koyama & Ostriker 2009)
  - FFT Poisson solver in a disk geometry (Koyama & Ostriker 2009)
  - Implicit cooling solver

Models



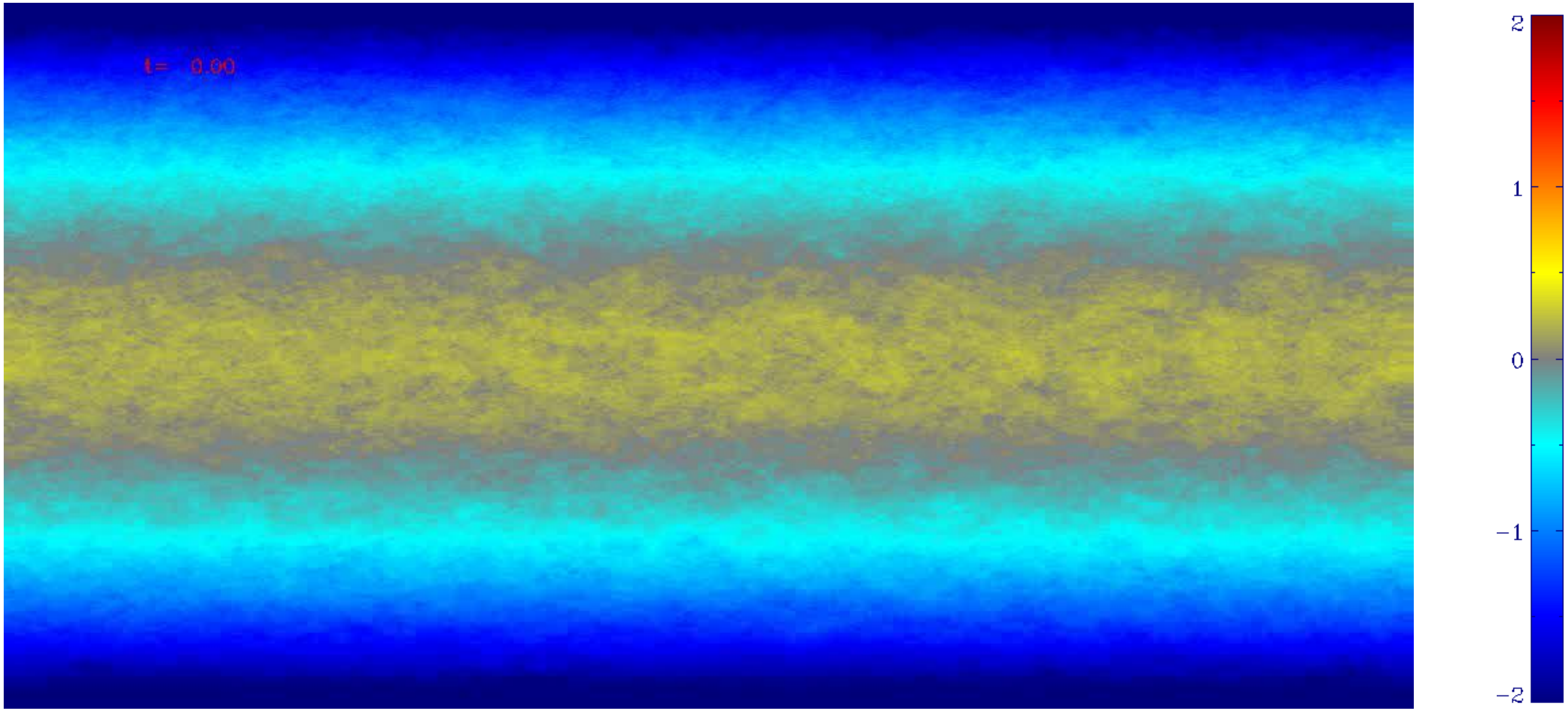
$$\Omega = 28\,\mathrm{km\,s^{-1}}(\Sigma/10\,M_\odot\,\mathrm{pc^{-2}})$$

for the same Toomre's Q parameter

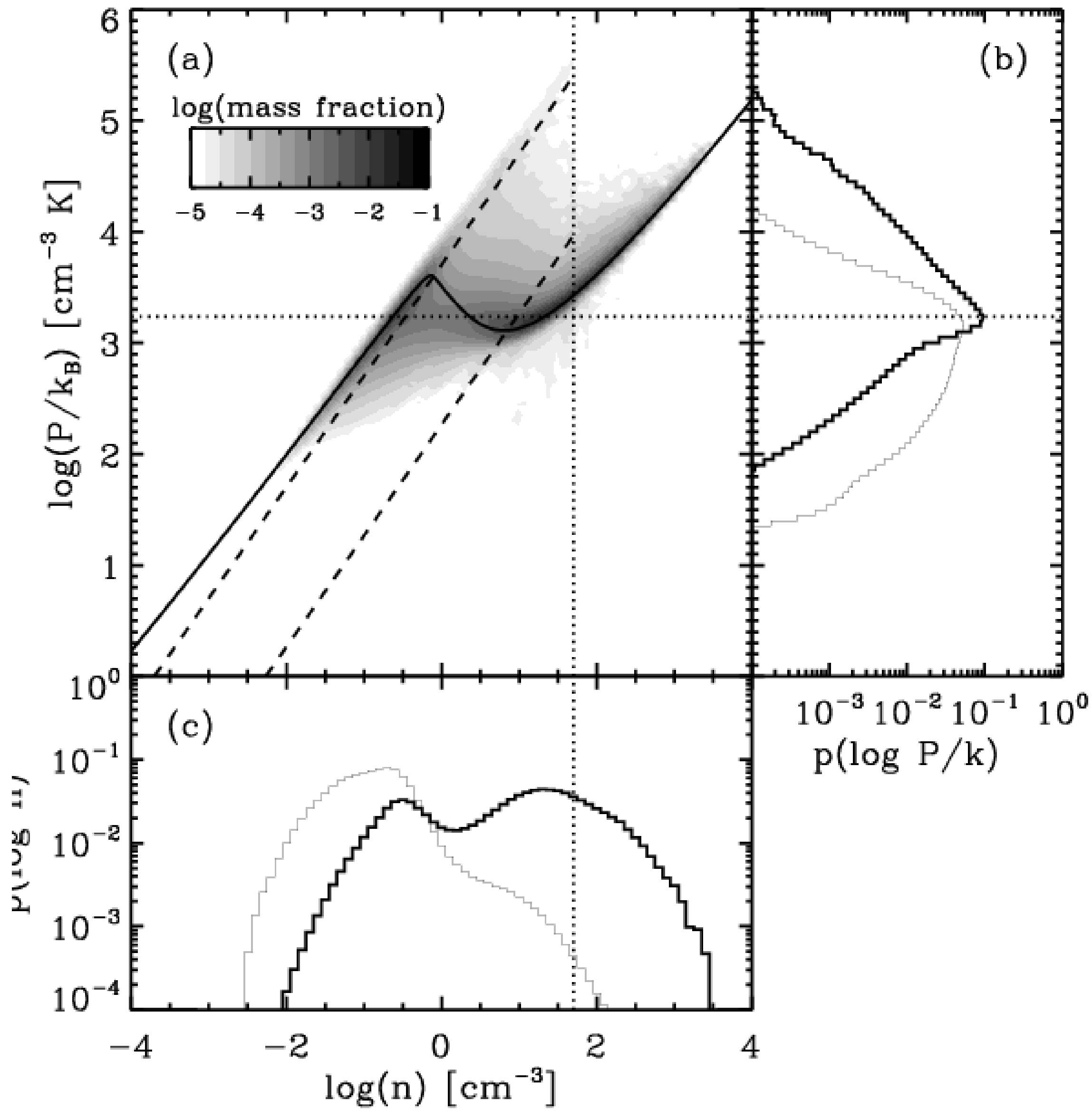
$$s_0 \equiv \frac{\pi G \Sigma^2}{2\sigma_z^2 \rho_{\rm sd}} = 0.28 \left(\frac{\Sigma}{10\,M_\odot\,\mathrm{pc^{-2}}}\right)^2 \left(\frac{\sigma_z}{7\,\mathrm{km\,s^{-1}}}\right)^{-2} \left(\frac{\rho_{\rm sd}}{0.05\,M_\odot\,\mathrm{pc^{-3}}}\right)^{-1}$$

Time Evolution

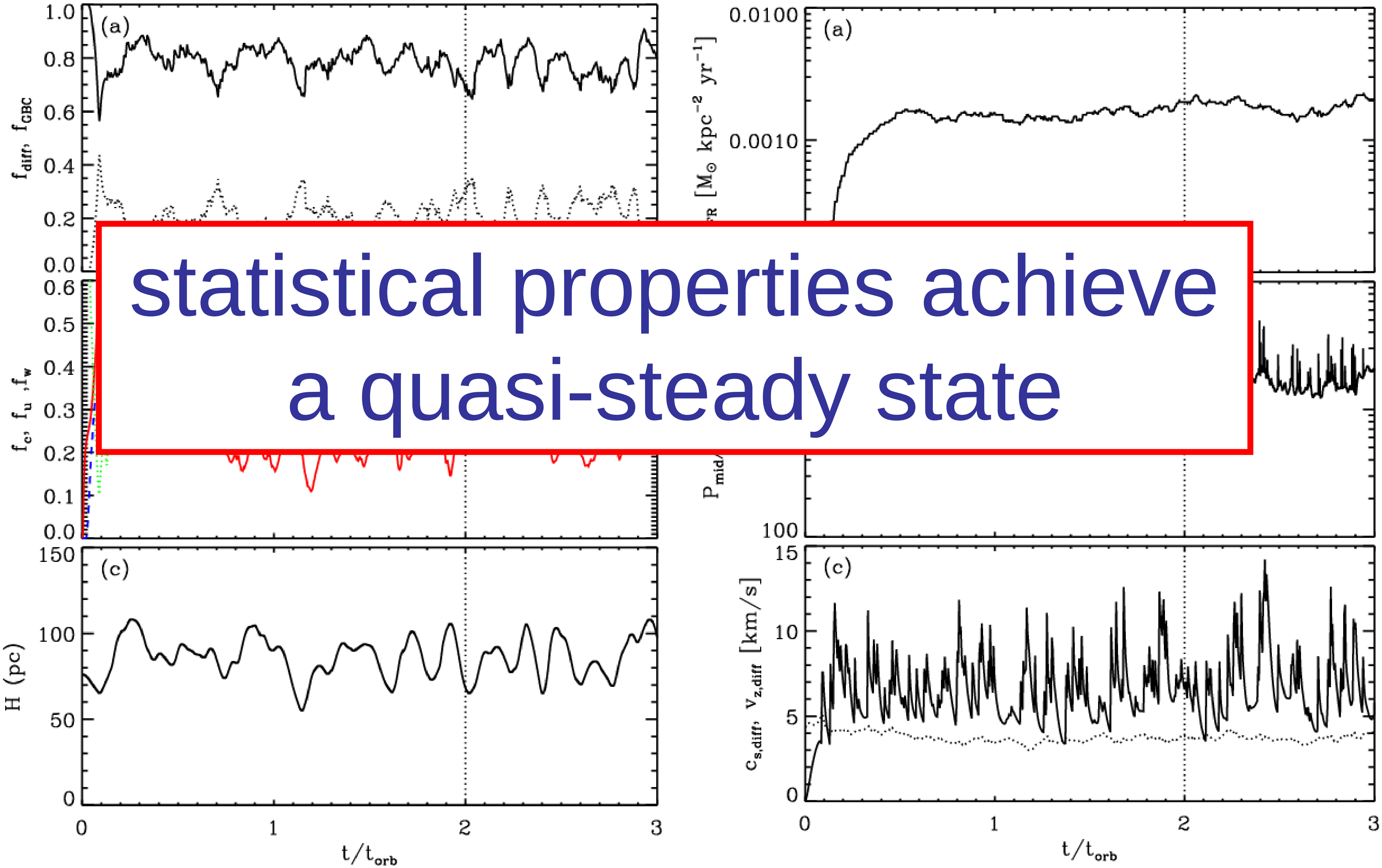
- Fiducial model
  - Σ=10 $M_{\odot}pc^{-2}$, ρ_*=0.05$M_{\odot}pc^{-3}$, Ω_0=28km/s/kpc
  - 1024pc X 512pc   dx=dz=1pc



PDFs


(a)
(b)
(c)
log(mass fraction)
−5 −4 −3 −2 −1
log(P/k_B) [cm^-3 K]
log(n) [cm^-3]
p(log P/k)
10^-3 10^-2 10^-1 10^0
10^0
10^-1
10^-2
10^-3
10^-4
−4 −2 0 2 4
6 5 4 3 2 1 0

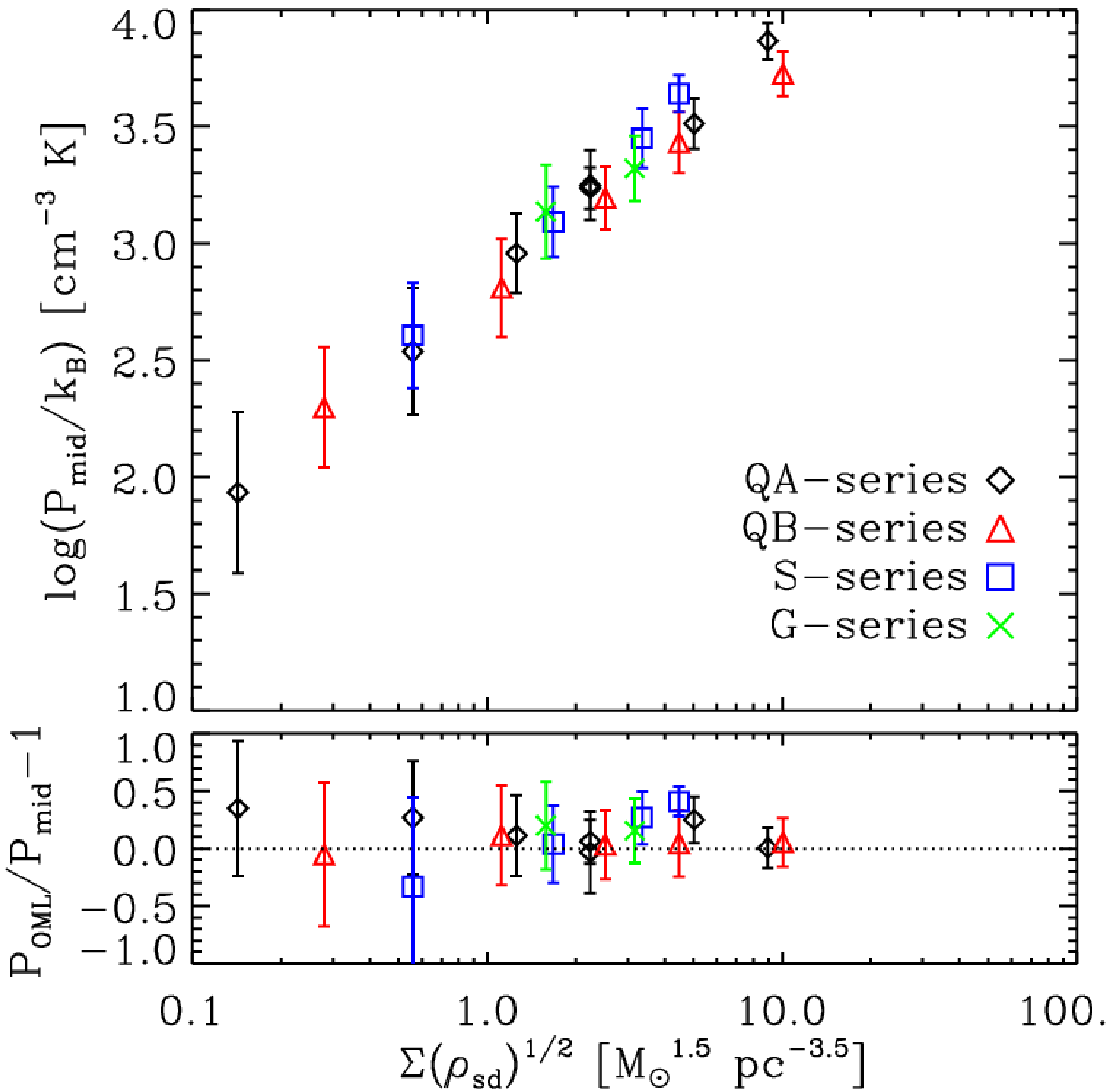
Time Evolution



statistical properties achieve a quasi-steady state

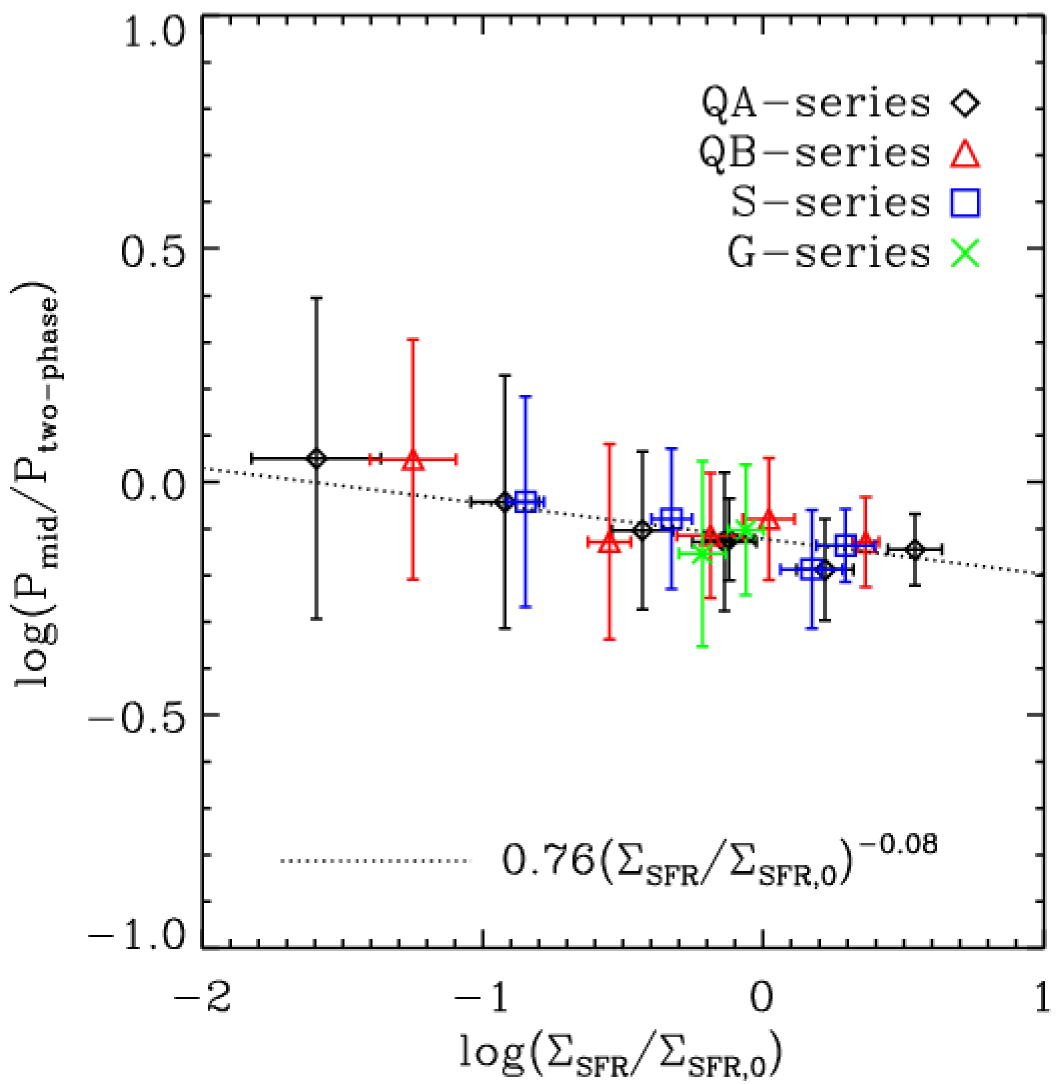
Vertical Dynamical Equilibrium

- Overall, HSE gives good estimations for the midplane thermal pressure (within ~15%)



Thermal Equilibrium

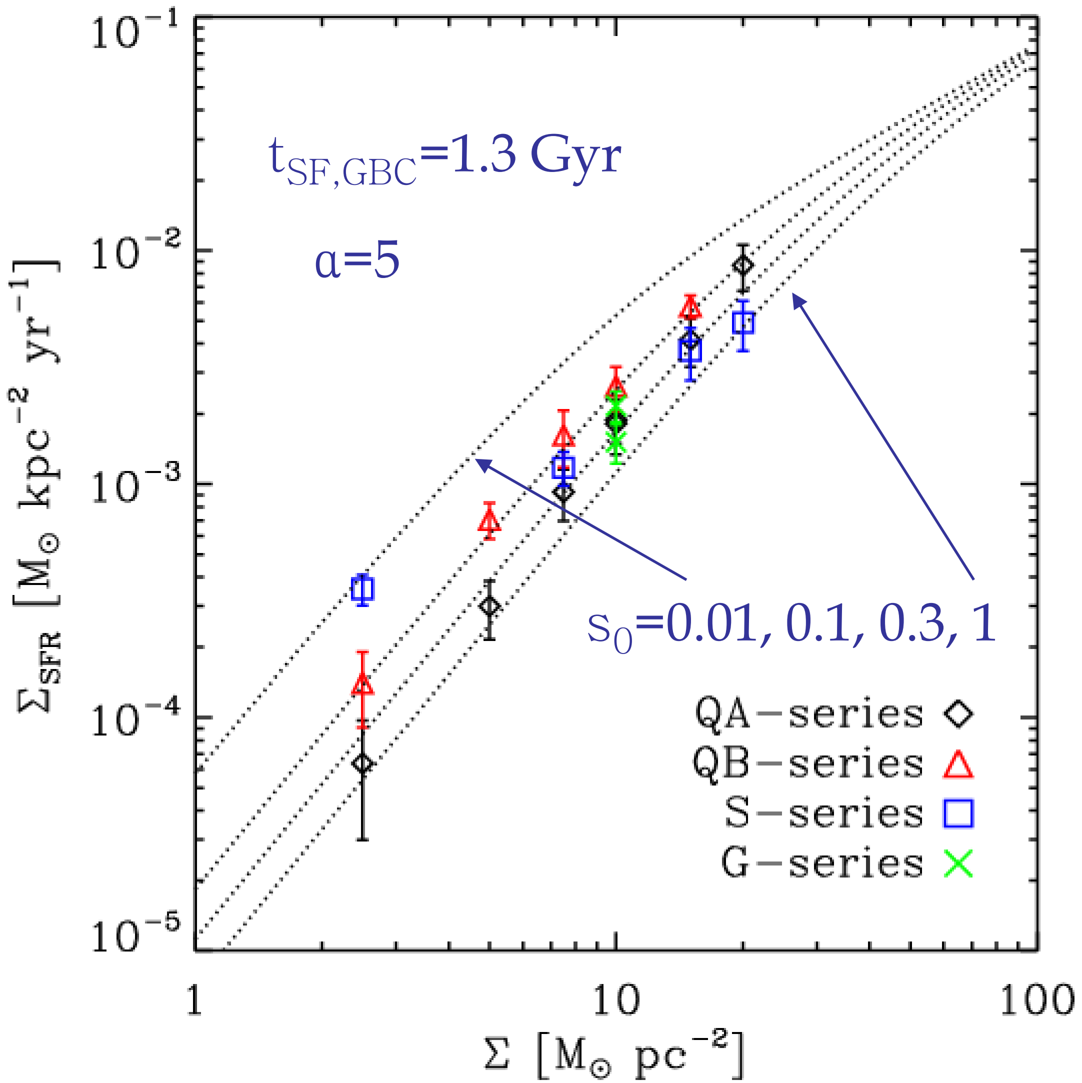
- $P_{\text{two-phase}} \propto \Sigma_{\text{SFR}}$
- P_{mid} has slightly shallower dependence and smaller value than $P_{\text{two-phase}}$
- The assumption made in OML theory is not bad as a first step for thermal constraint



Star Formation Law

- $t_{SF,GBC}$=1-1.5Gyr
- α=3-6 including some extreme cases or α=4-5 mostly.
- f_w varies from 0.2 to 0.5
- s_0=0.3 and 0.1 for QA- and QB-series, respectively.

$$s_0 \equiv \frac{\pi G \Sigma^2}{2\sigma_z^2 \rho_{sd}}$$



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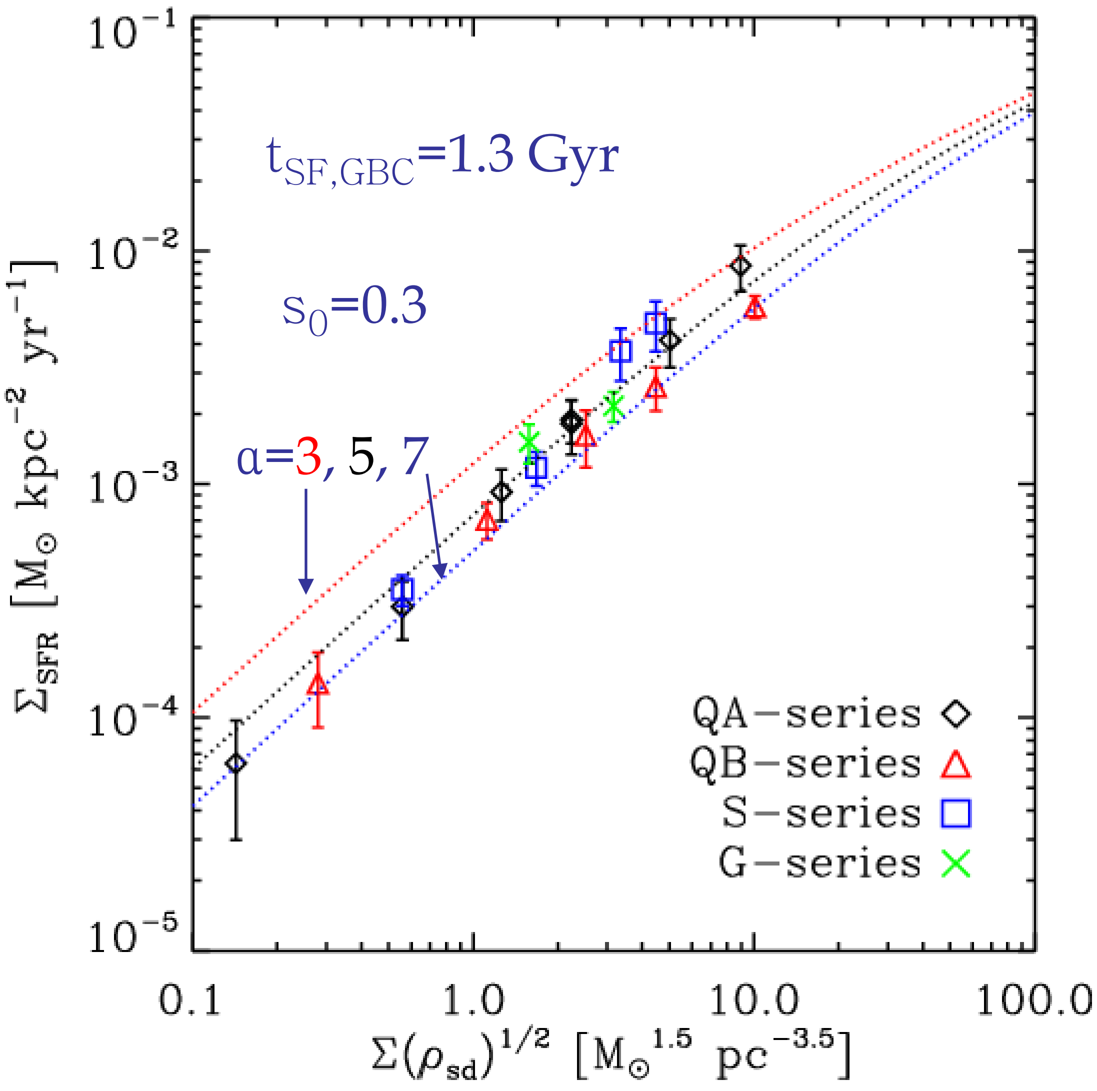

Summary

- Q1. Is HSE really valid for turbulent, multiphase galactic disks? or $P_{mid}=P_{HSE}$?
  - Yes! Gravities due to all components and turbulent (and magnetic) pressure should be taken into account.

- Q2. What is the consequence of thermal equilibrium? or $P_{mid}=P_{two\text{-}phase}$?
  - $P_{mid}=P_{two\text{-}phase}\,(\Sigma_{SFR}/\Sigma_{SFR,0})^{-0.09}$ is better. This may depend on the form of cooling and heating function.

- Q3. What are the possible ranges of α and f_w?
  - α varies from 3 to 6, but remains within a range of 4-5 mostly.
  - $t_{SF,GBC}$=1-1.5Gyr (consistent with the empirical result)
  - f_w varies from 0.2 to 0.5, so it is better use s_0 (or σ_z~7km/s) as a parameter.