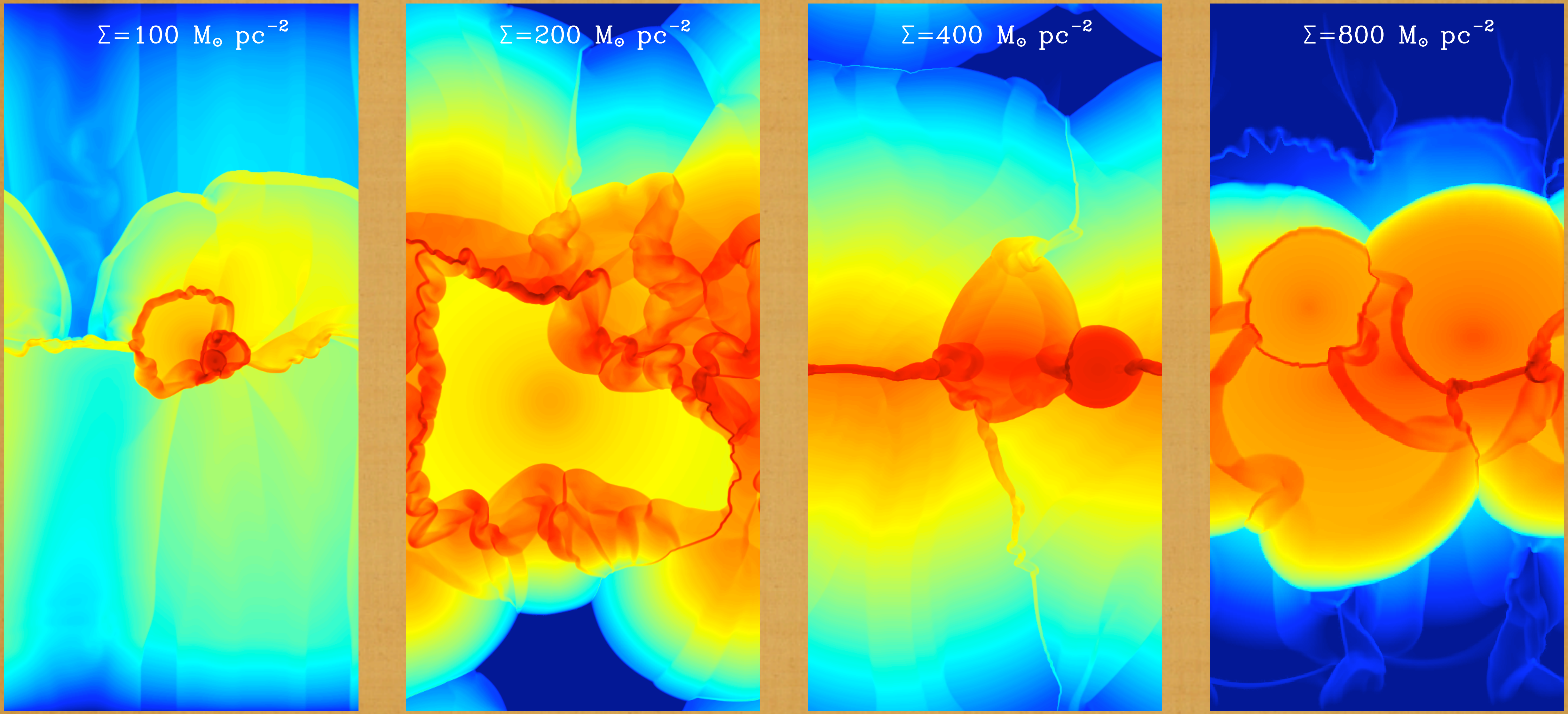
Starburst Regulation via Feedback Driven Turbulence

Rahul Shetty[1] & Eve Ostriker[2]



[1]Institute für Theoretische Astrophysik, Universität Heidelberg
[2]University of Maryland

Heidelberg - October 18, 2011

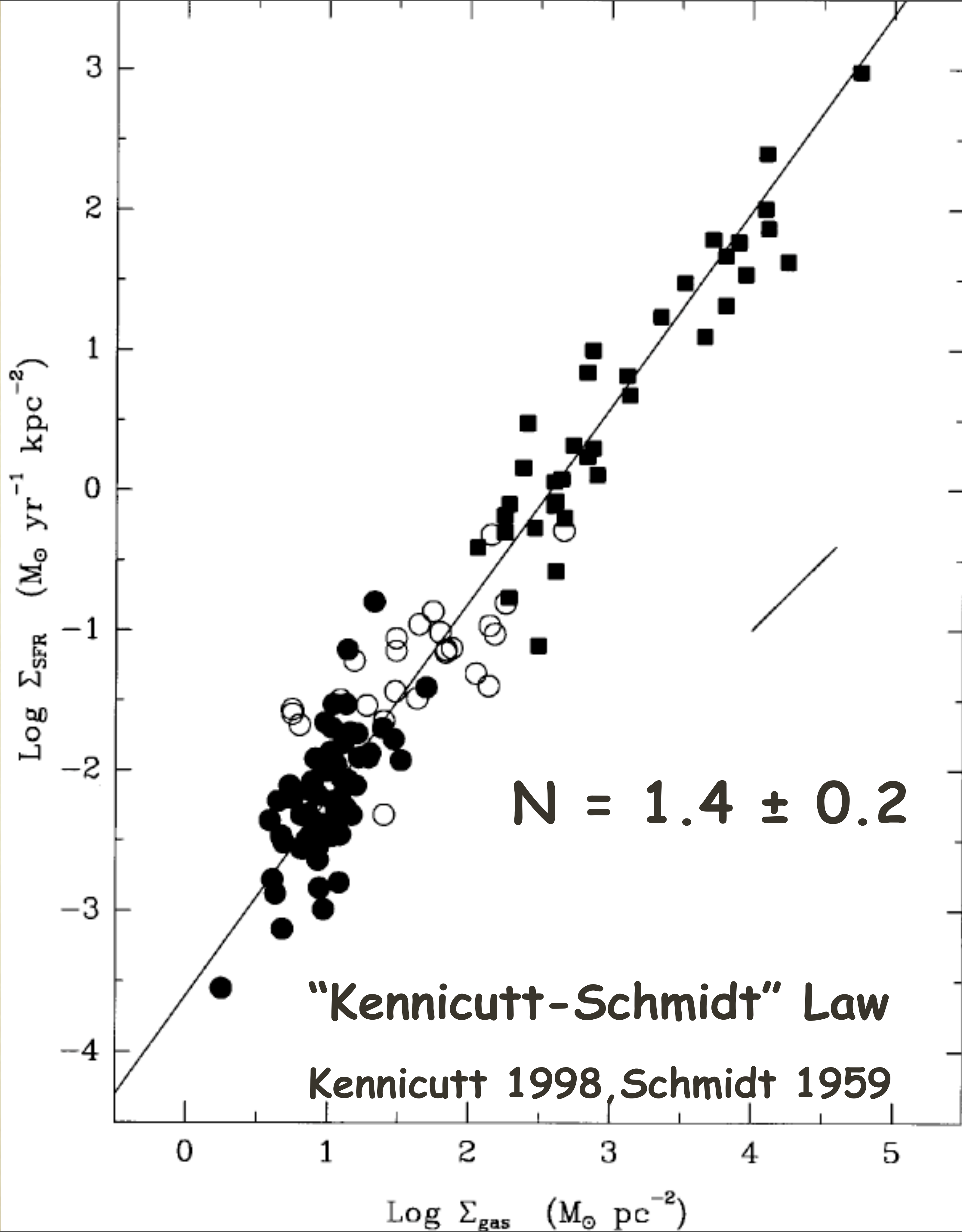
Overview

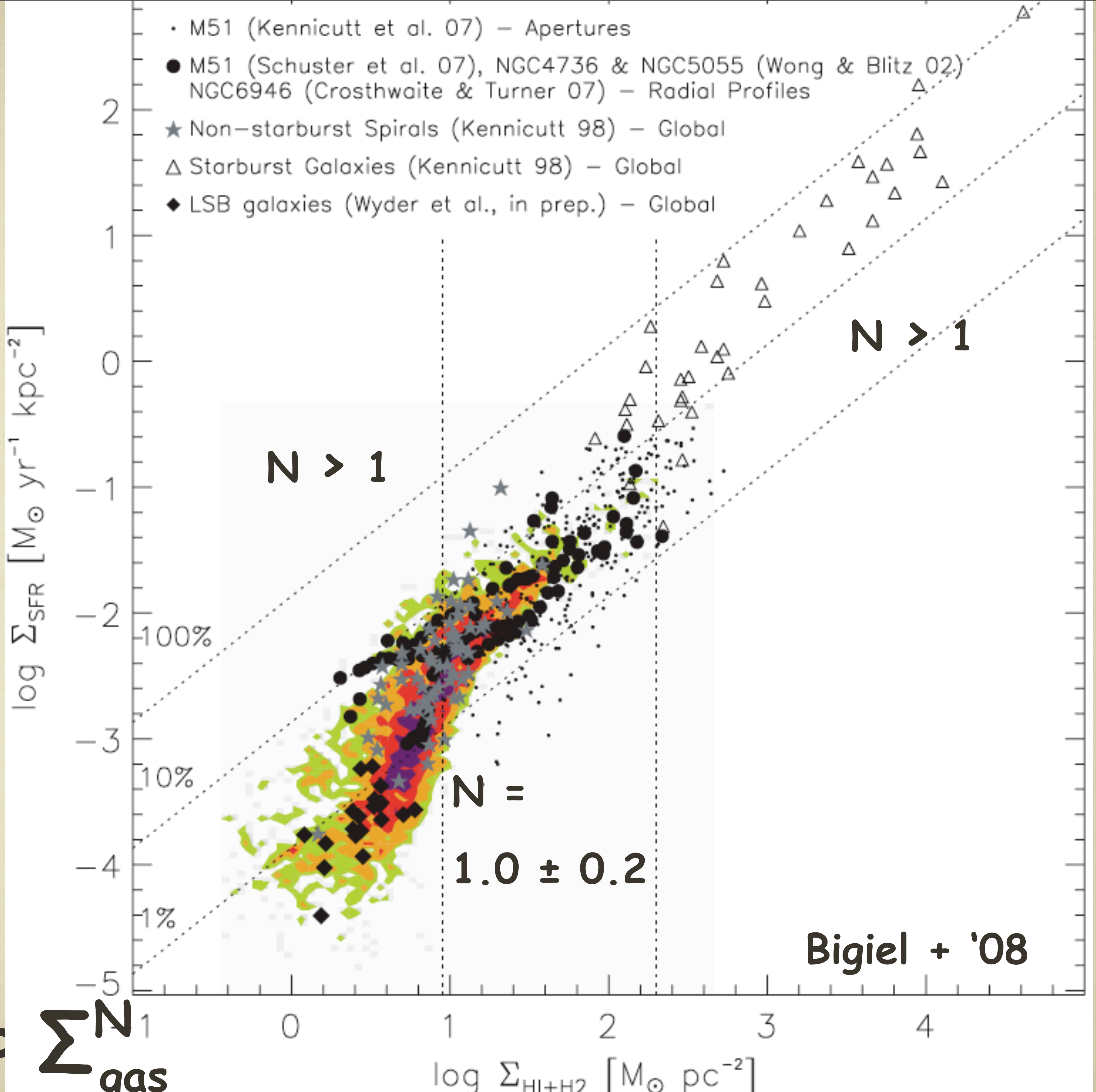
- Galactic Star Formation (SF)
  - Observational & Theoretical Perspective
- Theory of SF Self-Regulation
  - Focus on Galactic Center & [U]LIRGs
  - Analytical Predictions
  - Numerical Simulations
  - Comparison to Observations
- Future Work & Summary

SF: Observations

- FUV (extinction corrected by mid-IR) or Hα trace the Star Formation Rate Σ_{SFR}
- HI and CO lines, assuming an appropriate X factor, trace total gas surface density:
  - $\Sigma_{gas} = \Sigma_{HI} + \Sigma_{H2}$
- Observations generally find:
- $\Sigma_{SFR} \propto \Sigma_{gas}^{N}$

- $\Sigma_{SFR} \propto \Sigma_{gas}^{N}$





- $\Sigma_{SFR} \propto \Sigma_{gas}^{N}$

Theory of SF

- Dynamical or Kinematic Arguments
  - Local free fall time: $\rho_{SFR} \propto \frac{\rho_{gas}}{t_{ff}} \propto \rho_{gas}^{3/2}$
  - Orbital time: $\Sigma_{SFR} \propto \frac{\Sigma_{gas}}{t_{orb}} \propto \Sigma_{gas}\,\Omega$

  (Quirk 72, Kennicutt 89, 98, Elmegreen 94, Silk 97)

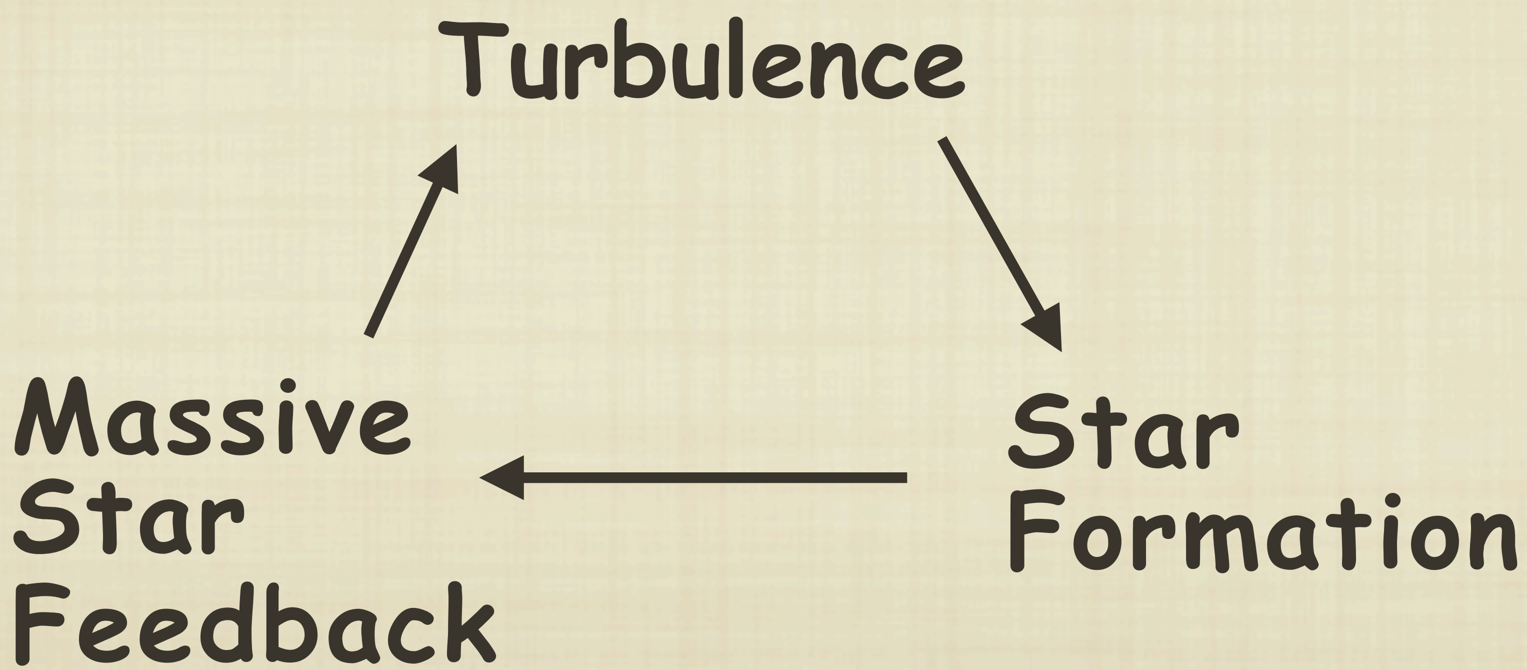
- Numerical Simulations: large scale gravitational instability (Li+'05, '06, Tasker+'06, '08, '09, Dobbs+'08, '09, '11, Shetty & Ostriker '08)

- Krumholz & McKee '05, +'09: SFR primarily determined by local processes (atom - molecular transition, turbulence due to HII region)

SF Self Regulation I

- Turbulence is ubiquitous, and must play a dominant role in regulating SF
  (Mac Low & Klessen '04, McKee & Ostriker '07)

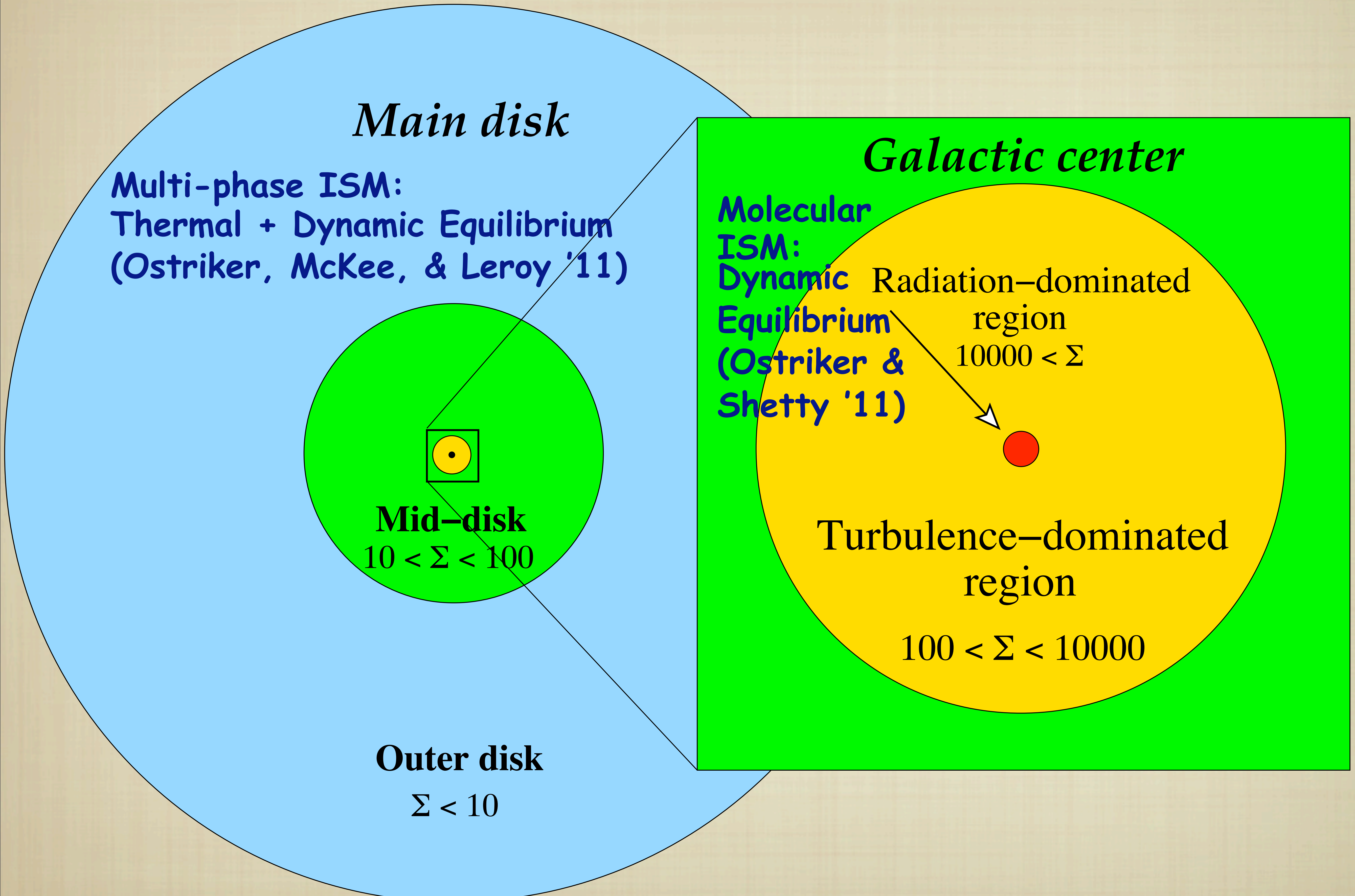
- Massive star feedback energizes the ISM, raising the velocity dispersion and thus the turbulent level



- Feedback loop leads to SF Self regulation?

SF Self Regulation II

- Gravity (gas, stars, DM...) also plays role in cloud formation, and sets disk thickness
- ISM throughout disk height also important for SF?
- If SF self-regulated, for a multi-phase ISM, thermal and vertical dynamical equilibrium may determine the ISM characteristics (Ostriker+ '11)
- For molecular dominated regions, only vertical and dynamic equilibrium governs SF (Ostriker & Shetty '11)


Main disk
Multi-phase ISM:
Thermal + Dynamic Equilibrium
(Ostriker, McKee, & Leroy '11)
Mid–disk
10 < Σ < 100
Outer disk
Σ < 10
Galactic center
Molecular ISM:
Dynamic Equilibrium
(Ostriker & Shetty '11)
Radiation–dominated region
10000 < Σ
Turbulence–dominated region
100 < Σ < 10000

Vertical Dynamical Equilibrium sets SF?

Ostriker & Shetty '11, Shetty & Ostriker '11 (in prep)

- Vertical weight due to gas self-gravity:

  $W_g = \int \rho (d\Phi/dz) dz = \pi G \Sigma^2/2$

- Vertical weight due to external potential:

  $W_{tot} = W_g + W_{ext} = 0.5\pi G \Sigma^2 \,(1 + X)$

- ISM Pressure:

  $P_{eff} = P_{turb} + P_{th} + \Delta P_{mag} + \Delta P_{cr} + \Delta P_{rad} \equiv \rho \sigma^2{}_z \,(1 + \mathcal{R})$

- SN driven momentum flux:

  $P_{drive} = f_p \,(p_* /4m_*)\, \Sigma_{SFR}$

- In equilibrium, SF regulated by:

$P_{drive} = P_{turb}$

$P_{turb} = W_{tot}$

$W_{tot} = P_{drive}$

Vertical Dynamical Equilibrium sets SF?

Ostriker & Shetty '11, Shetty & Ostriker '11 (in prep)

$$P_{drive} \approx P_{turb} \Longleftrightarrow f_p (p_* / 4m_*) \Sigma_{SFR} \approx \rho \sigma^2_z$$

$$P_{turb} \approx W_{tot} \Longleftrightarrow \approx \pi G \Sigma^2 / 2$$

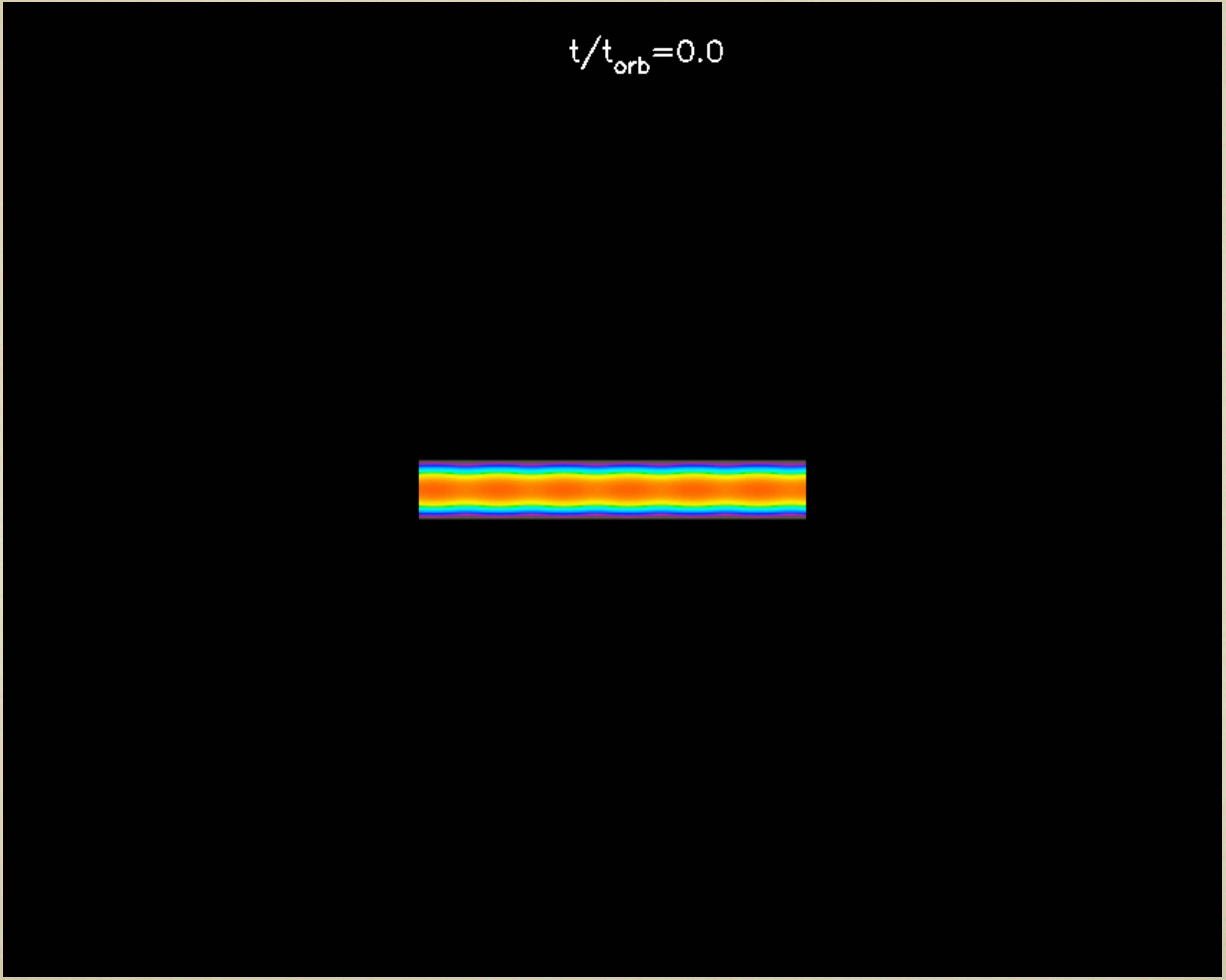
$$W_{tot} \approx P_{drive} \Longleftrightarrow \approx f_p (p_* / 4m_*) \Sigma_{SFR}$$

Testing Self-Regulation: Numerical Simulations

Shetty & Ostriker '11 (in prep)

- Physics included: hydrodynamics, self-gravity, rotation and external potential
- supernovae to disperse collapsing clouds (Shetty & Ostriker '08)
- High resolution 2D (r,z) simulations: 60×120 pc^2, 512×1024 zones $(0.15\ \mathrm{pc})^2$/zone
- *ATHENA* hydrodynamics code (Stone + '08)
- Main user-defined parameters: Σ, $\epsilon_{ff}(n_{th})$, p_*, Ω

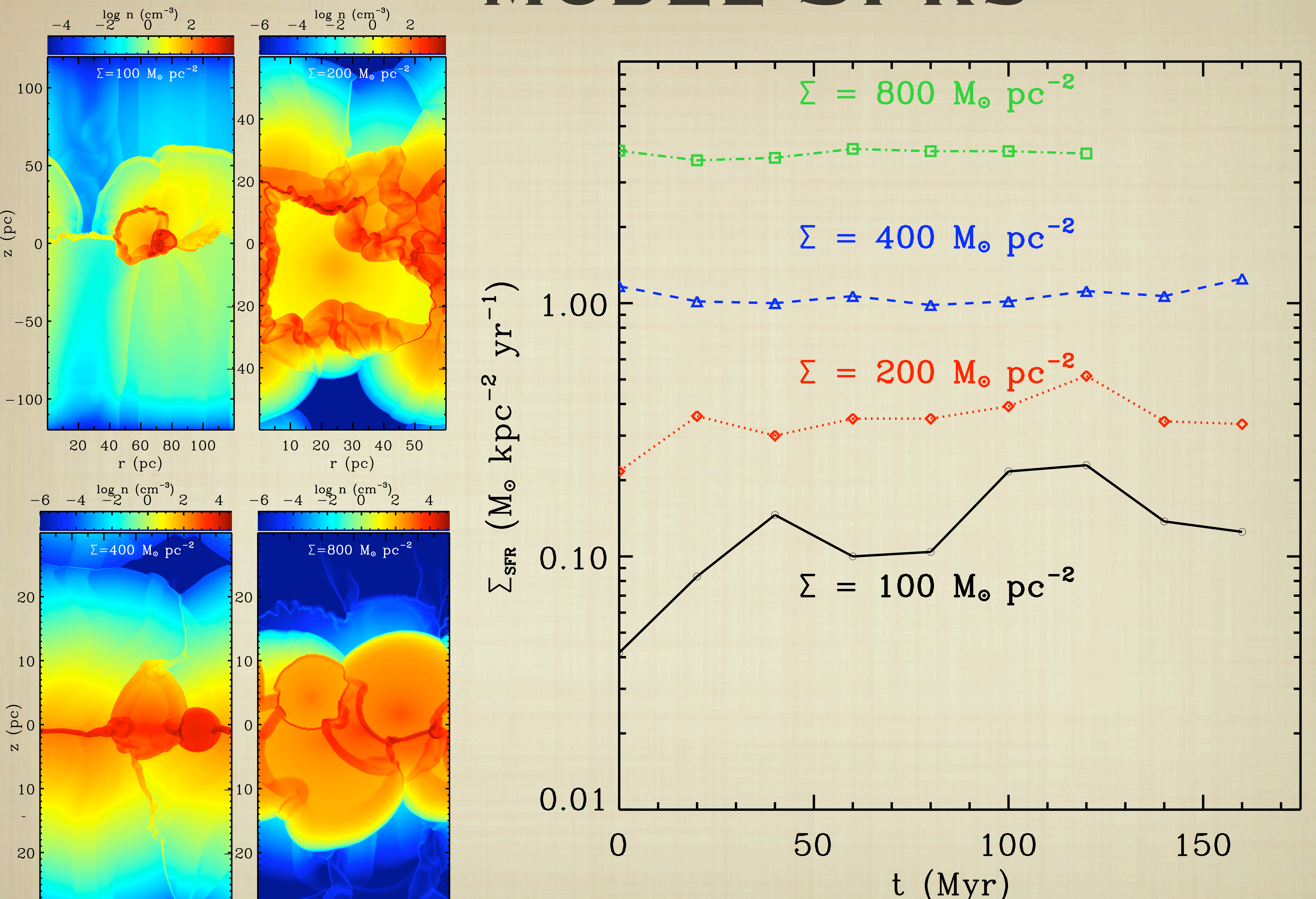
Numerical Simulations



Disk Properties

- Disk properties compared to predictions from self-regulation
- Thickness: $H^2 = \sum\rho z^2 / \sum\rho$
- Vertical velocity dispersion: $\sigma^2 = \langle v_z{}^2 \rangle = \sum\rho v_z{}^2 / \sum\rho$
- SF rate: $\Sigma_{SFR} = m_* N_{SN} / (L_r L_\phi \Delta t_{bin})$
- SF efficiency: $\epsilon_{ff}(n_0) = \Sigma_{SFR}\, t_{ff}(n_0) / \Sigma$ to be compared to chosen efficiency $\epsilon_{ff}(n_{th})$

Model SFRs

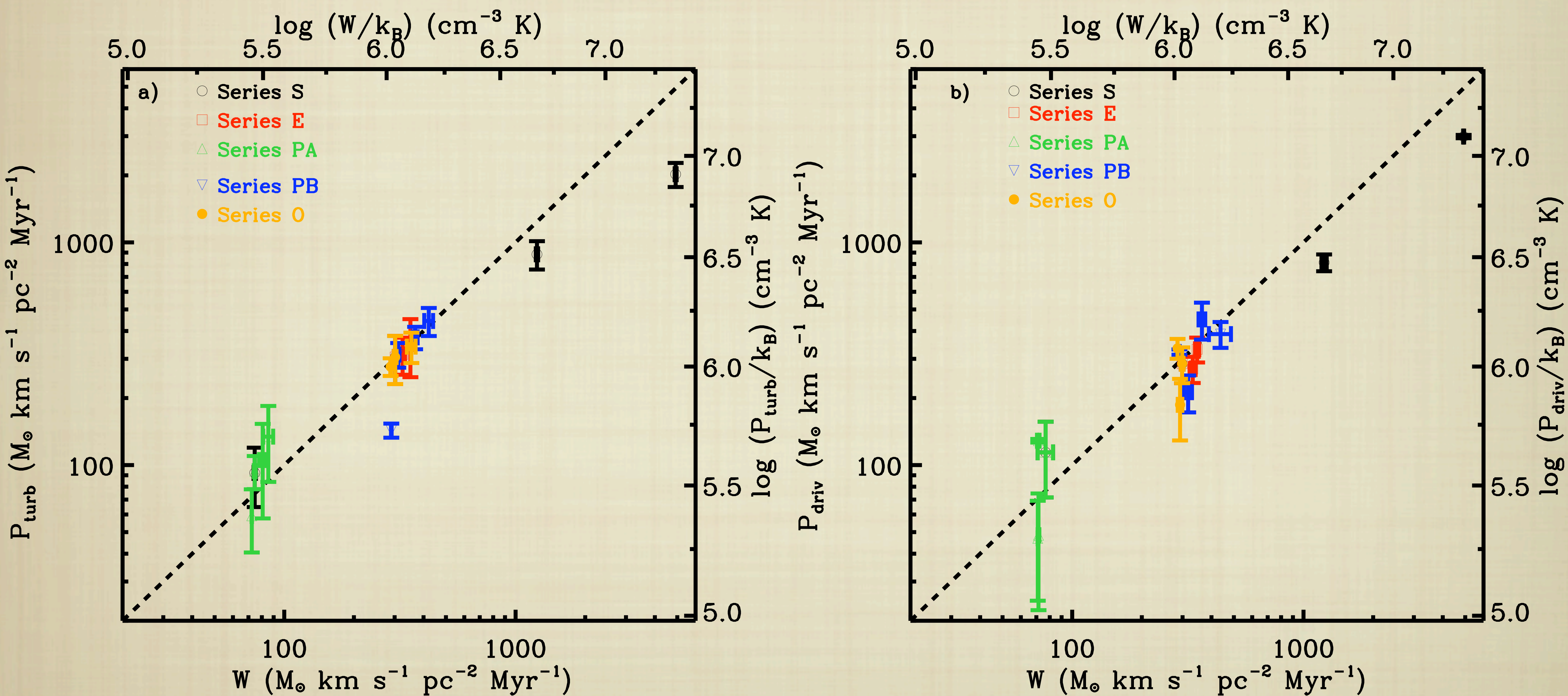


Shetty & Ostriker '11 (in prep)

Momentum Flux Balanced?

Dynamic Equilibrium: $W_{tot} \approx P_{drive} \approx P_{turb}$

$$\pi G \Sigma^2/2 \approx f_p\,(p_*/4m_*)\,\Sigma_{SFR} \approx \rho \sigma^2_z$$



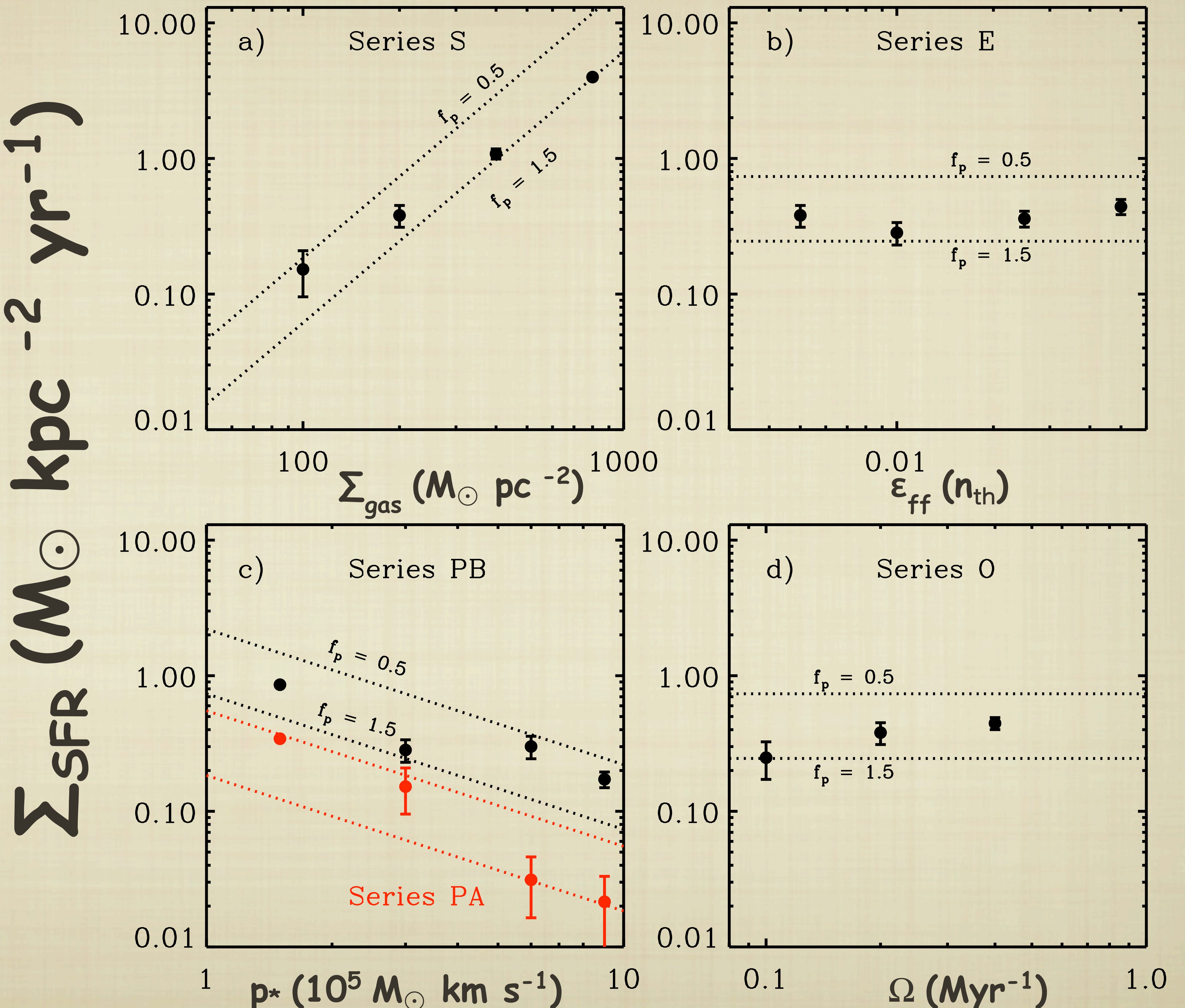
Shetty & Ostriker '11 (in prep)

Simulation vs Analytic Sol'ns

$$\Sigma_{SFR} = \frac{2\pi G}{f_p} (1+x) (p_* / m_*)^{-1} \Sigma^2$$

Simulation vs Analytic Sol'ns

$$\Sigma_{SFR} = \frac{2\pi G}{f_p} (1+x) (p_* / m_*)^{-1} \Sigma^2$$

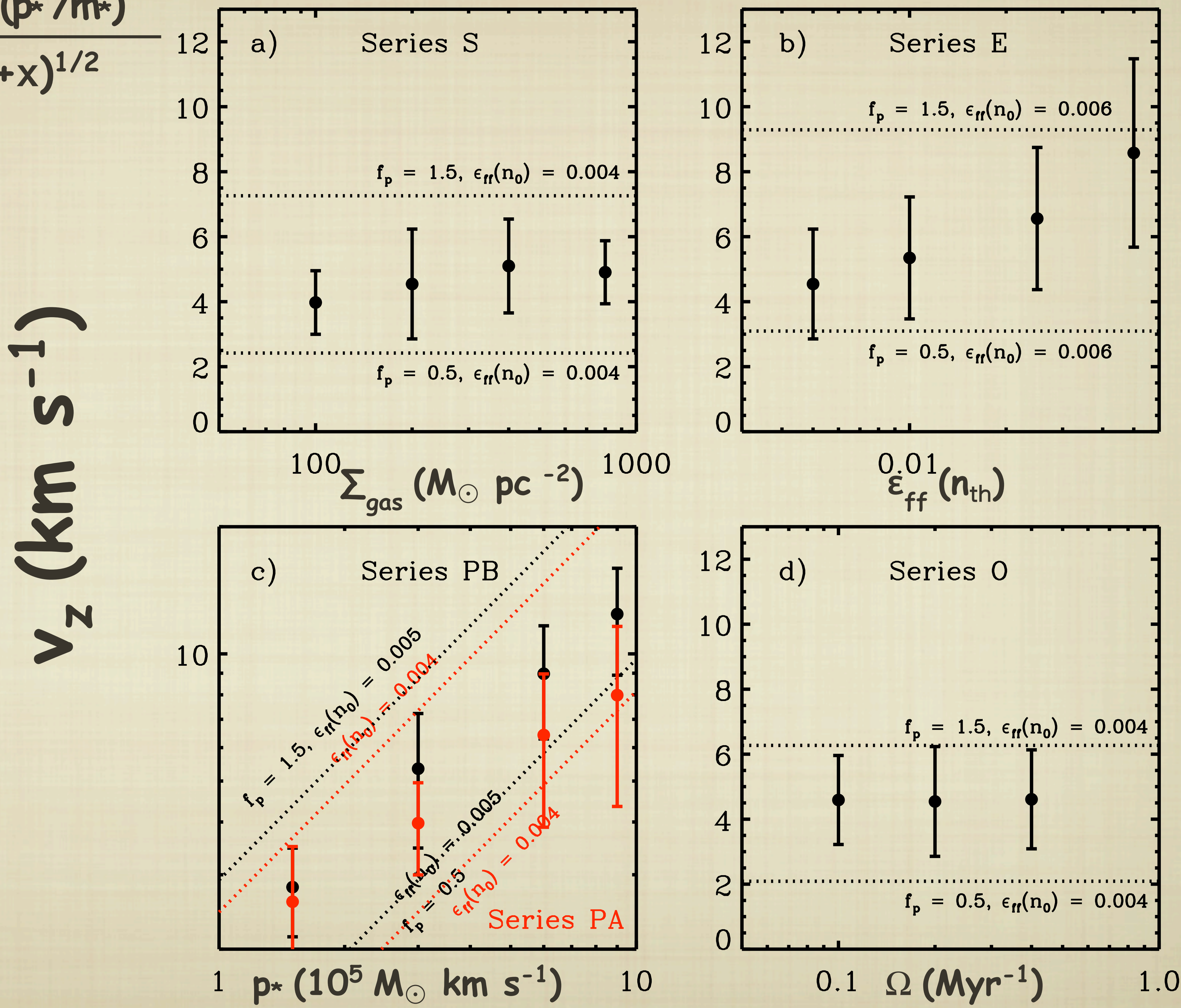


Simulation vs Analytic Sol'ns

$$v_z = \frac{2 f_p \varepsilon_{ff}(n_0)(p_* / m_*)}{\sqrt{3}\,\pi(1+x)^{1/2}}$$

Simulation vs Analytic Sol'ns

$$v_z = \frac{2 f_p \epsilon_{ff}(n_0)(p_* / m_*)}{\sqrt{3}\,\pi (1+x)^{1/2}}$$



Simulation vs Analytic Sol'ns

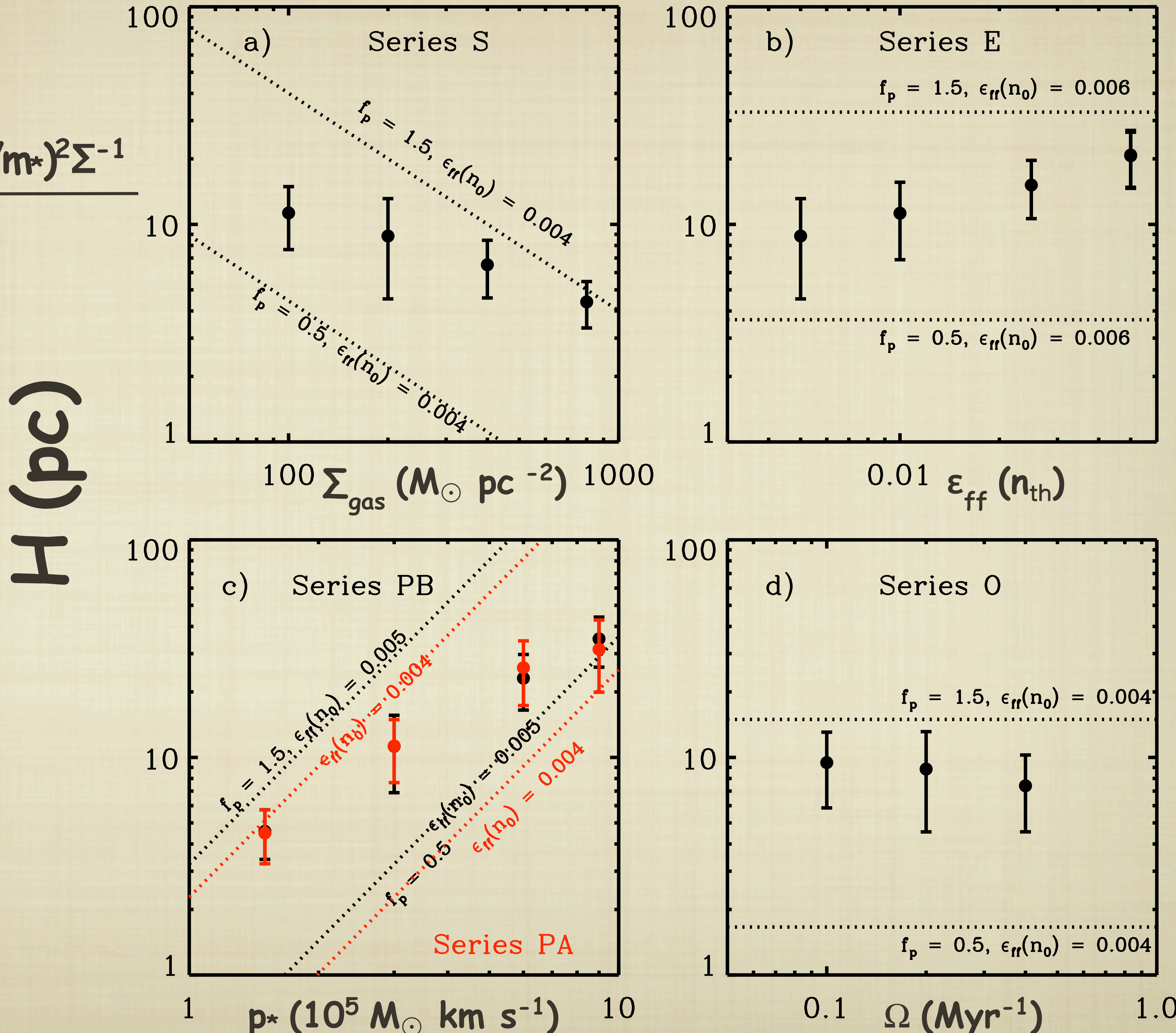
$$H = \frac{v_z^{\,2}}{\pi G \Sigma (1+x)}$$

$$\propto \frac{f_p^{\,2}\, \epsilon_{ff}^2(n_0)(p_* / m_*)^2 \Sigma^{-1}}{(1+x)^2}$$

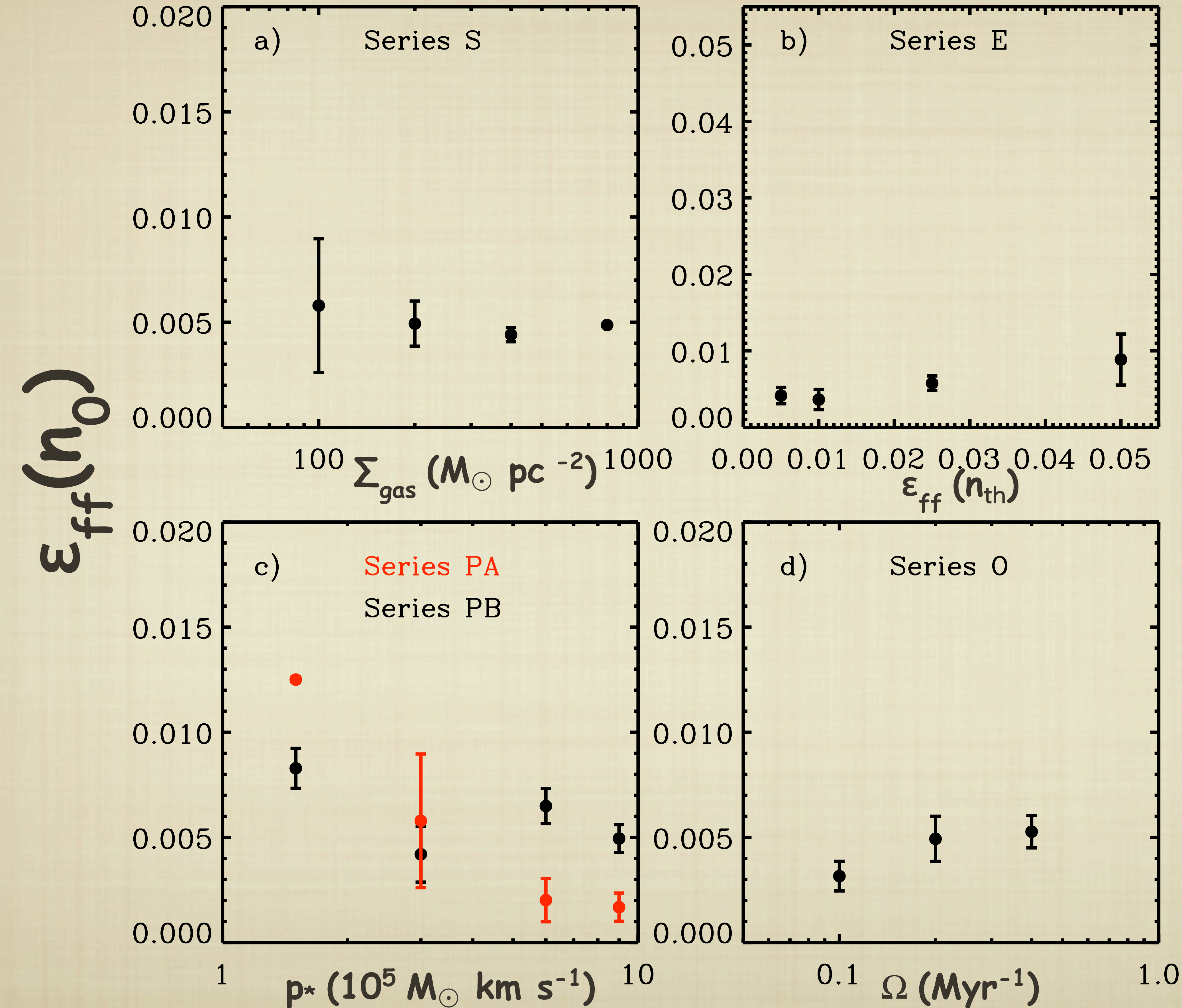
Simulation vs Analytic Sol'ns

$$H = \frac{v_z^2}{\pi G \Sigma (1+x)}$$

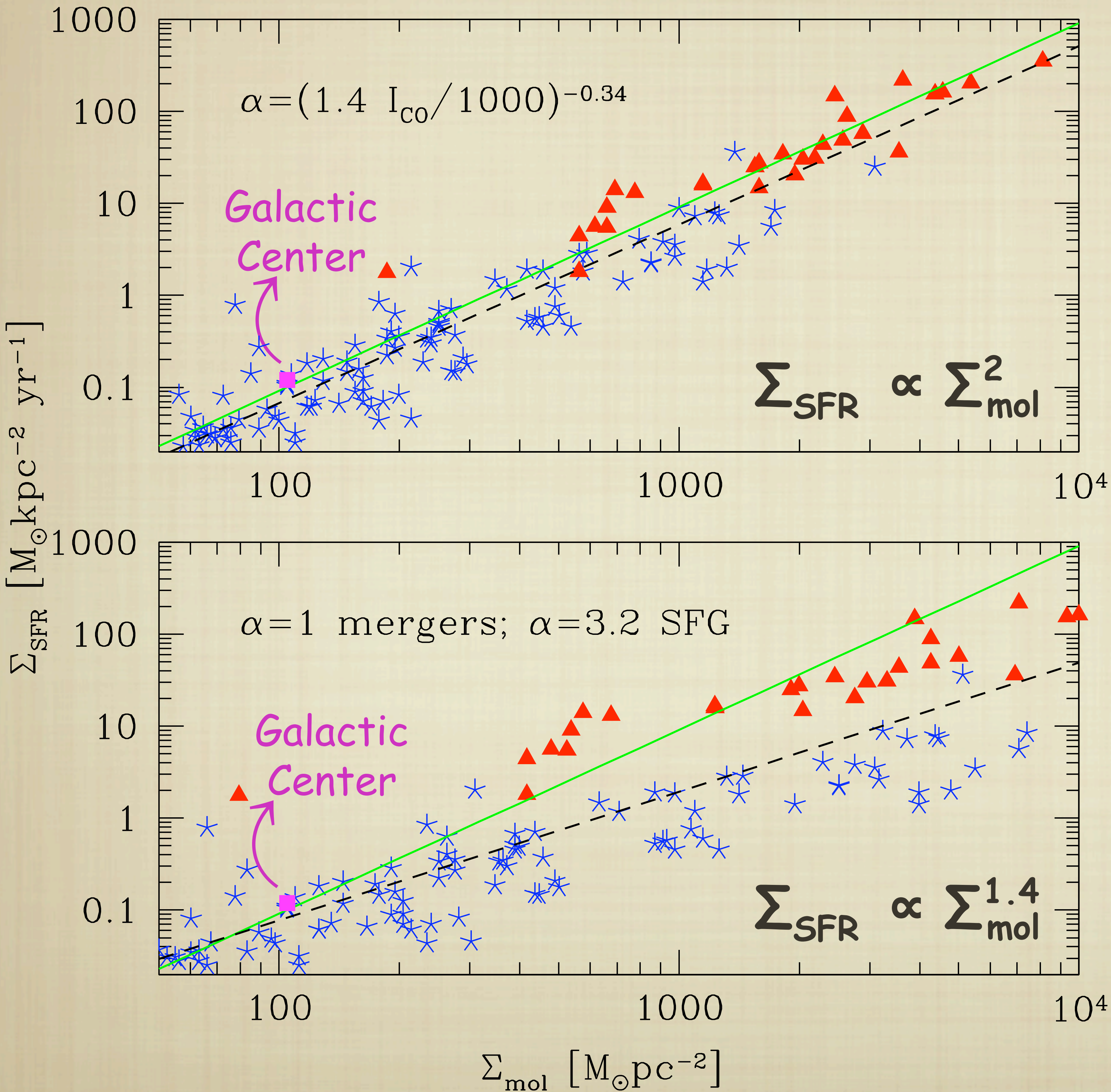
$$\propto \frac{f_p^{\,2}\, \varepsilon_{ff}^2(n_0)(p_*/m_*)^2 \Sigma^{-1}}{(1+x)^2}$$



$\varepsilon_{ff}(n_0)$ vs. $\varepsilon_{ff}(n_{th})$



Self-Regulation in Observed Systems?



Star forming galaxies and merger systems from Genzel + '10

Galactic Center from Yusef-Zadeh + '09

Continuous X factor? (Shetty + 11a,b, Narayanan + 11a,b)

Future Work

- 3D Simulations
- Comparison to Observations
- Modeling Radiative Feedback

Summary

- Explored the balance between vertical gravity and pressure forces
- If pressure dominated by turbulence injected by massive stars, star formation is self-regulated
- Self-regulation feasible in molecular dominated regions, e.g. Galactic Center & ULIRGS
- Self-regulation leads to $\Sigma_{SFR} \propto \Sigma_{gas}^2$ (for gravity dominated by Σ_{gas}), and strongly constrains v_z and H, confirmed by numerical simulations
- Observations support $\Sigma_{SFR} \propto \Sigma_{gas}^2$ if X factor varies continuously. Other properties must also be verified.