Self-regulation in Starbursts and the Molecular Schmidt Law

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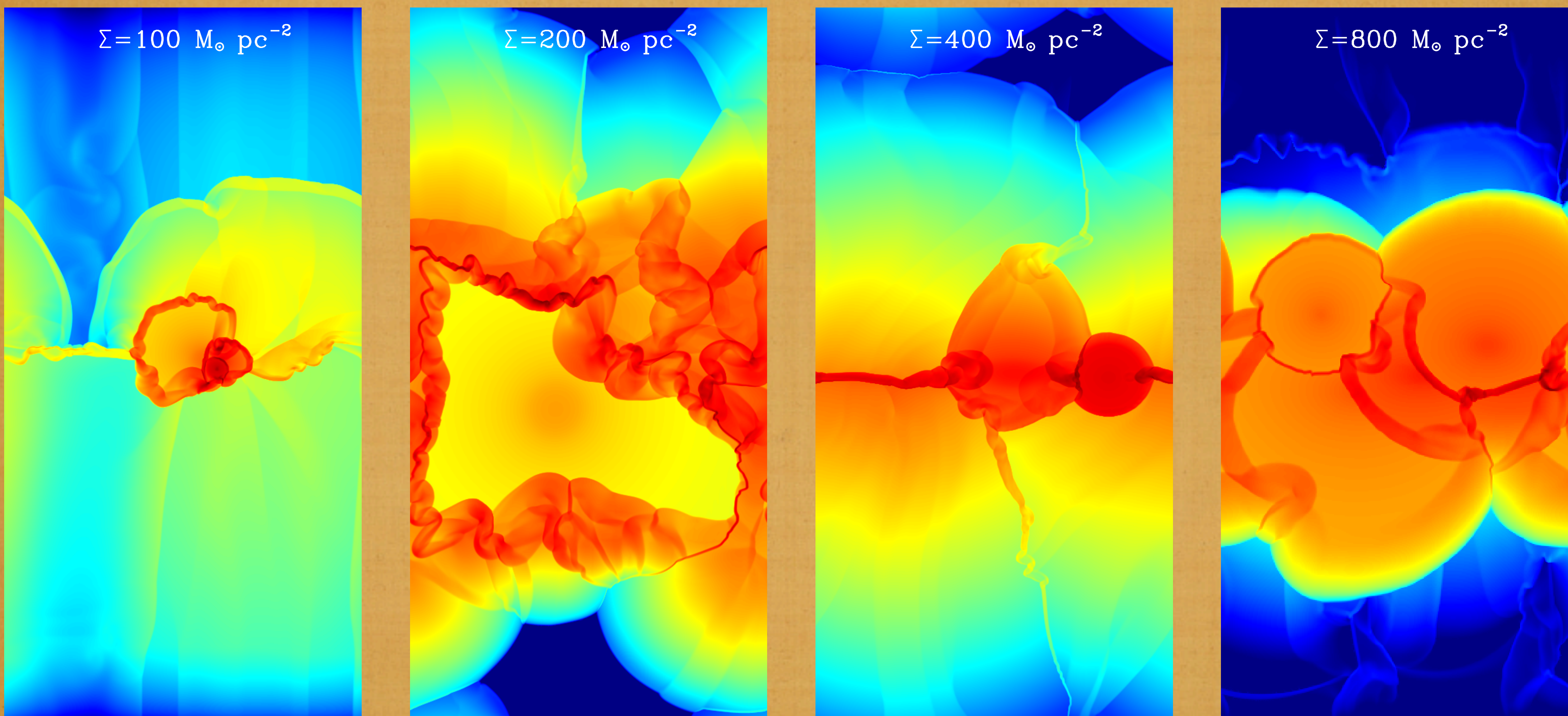

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SFB 881

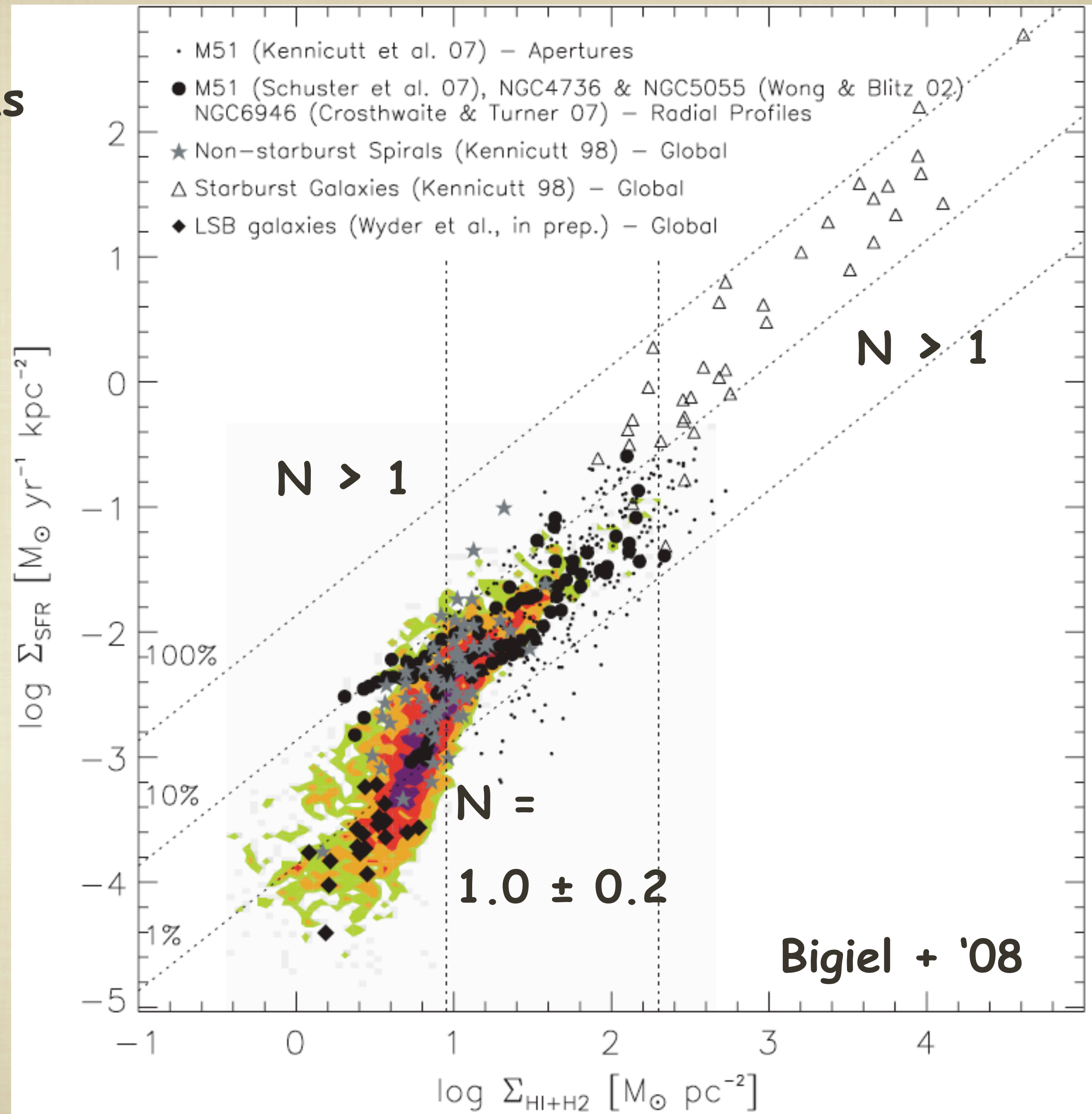
Overview

- 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
- Inferring the Σ_{SFR} - Σ_{mol} relationship
- Summary

SF: Observations

- $\Sigma_{SFR} \propto \Sigma^N_{gas}$

Schmidt '59
Buat + '89
Kennicutt '89
Kennicutt '98
Hunter + '98
Boselli + '02
Wong & Blitz '02
Boissier + '03
Heyer + '04
Leroy + '05
Kennicutt + '07
Leroy + '08
Bigiel + '08
Blanc + '09
Verley + '10
Daddi + '10
Genzel + '10
...



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, '07, 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 regions)

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

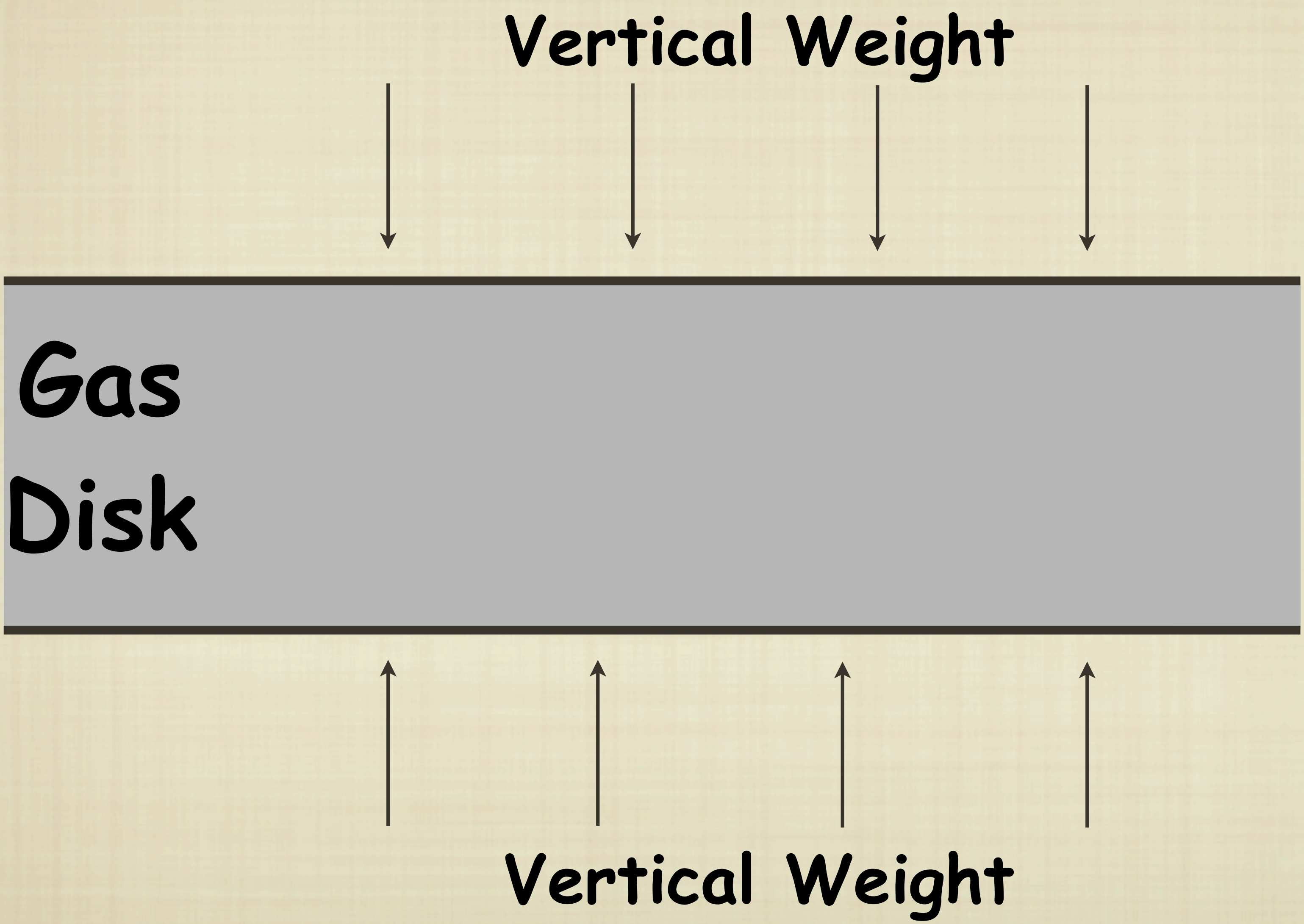
- Gravity (gas, stars, DM...) also plays role in cloud formation, and sets disk thickness
- ISM throughout vertical extent of disk (i.e. thickness) also important for SF?
- If SF self-regulated, for a multi-phase ISM, thermal and vertical dynamical equilibrium may determine the ISM characteristics (Ostriker+ '10)
- For molecular dominated regions, only vertical and dynamic equilibrium governs SF (Ostriker & Shetty '11)

Dynamic Equilibrium

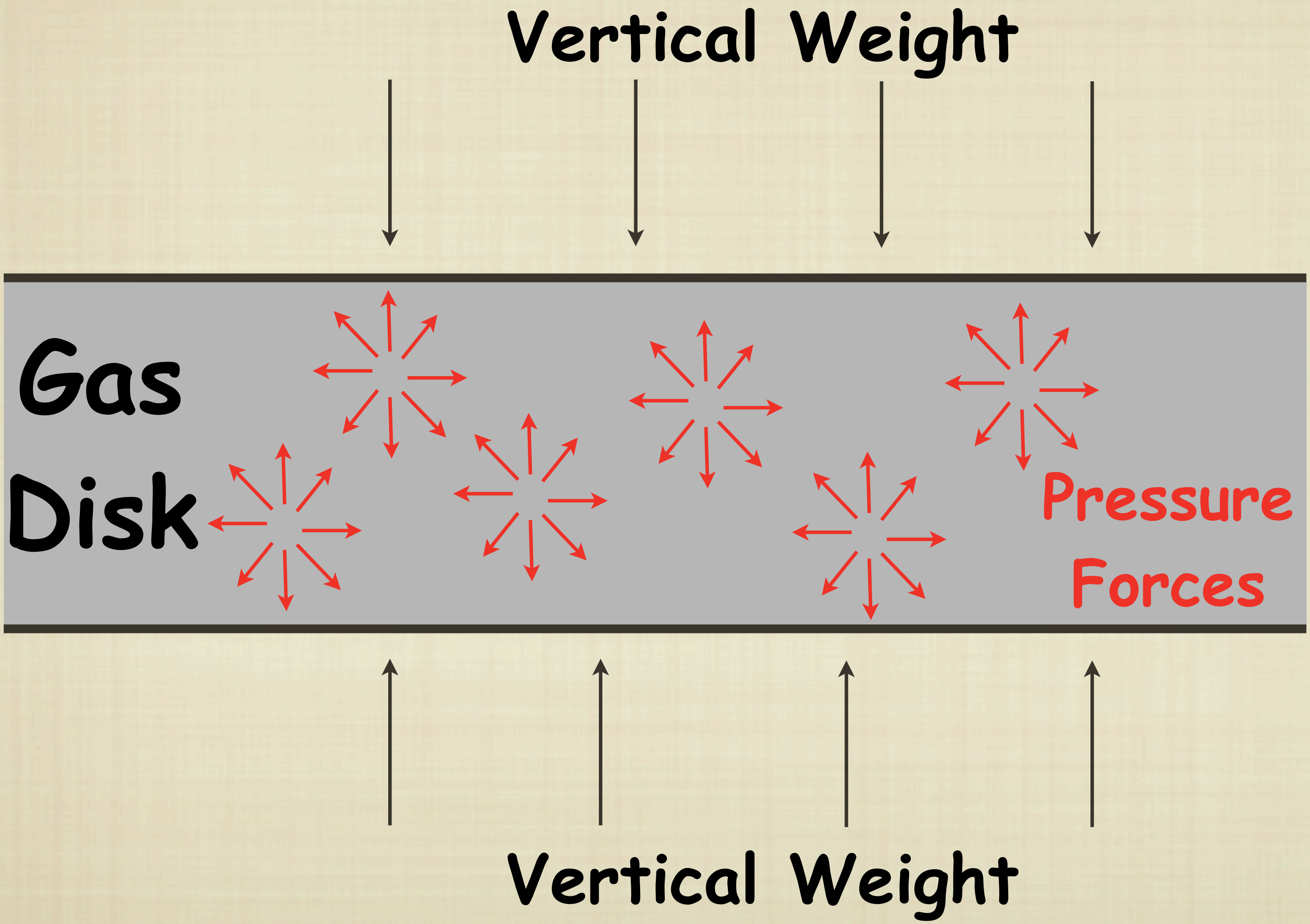
Gas

Disk

Dynamic Equilibrium



Dynamic Equilibrium



Vertical Dynamical Equilibrium sets SF?

Ostriker & Shetty '11,
Shetty & Ostriker '12

- 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 '12

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

$$\approx \rho \sigma^2_z$$

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

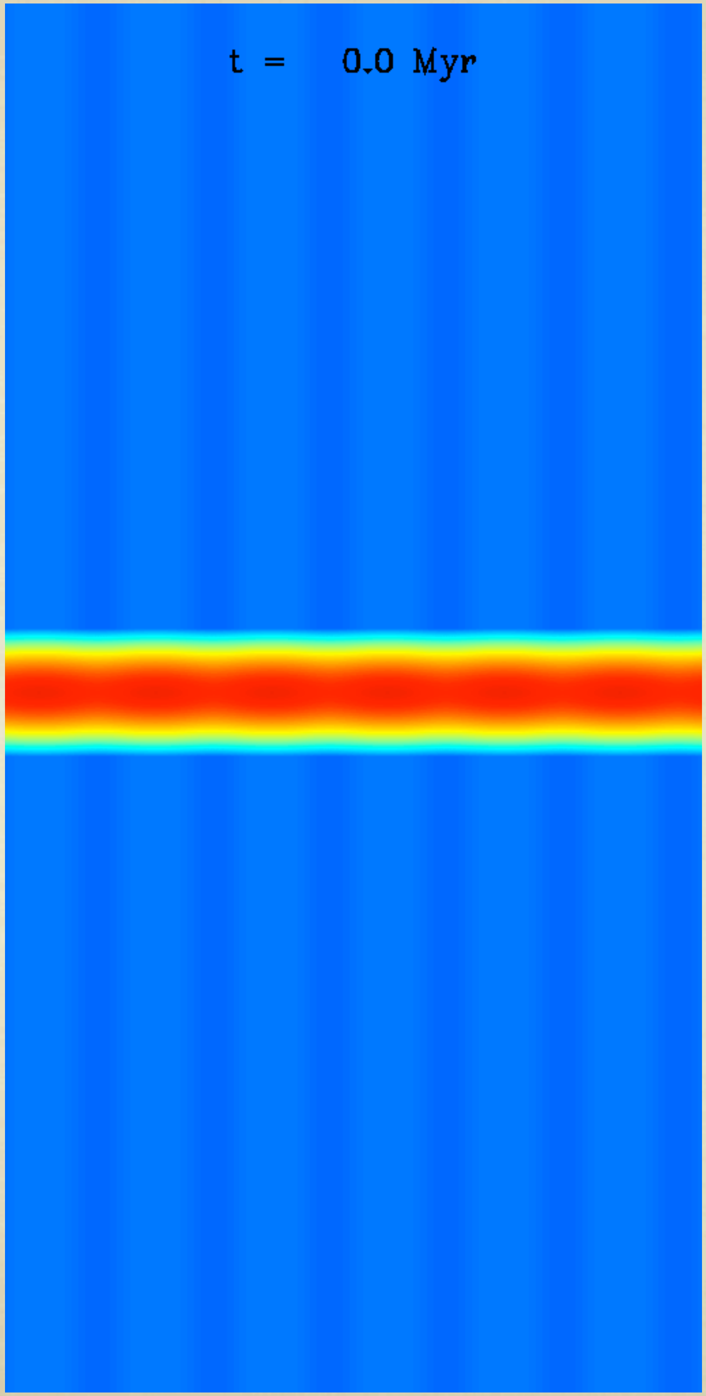
$$W_{tot} \approx P_{drive} \Longleftrightarrow \approx f_p \, (p_* / 4m_*) \, \Sigma_{SFR}$$

Testing Self-Regulation: Numerical Simulations

Shetty & Ostriker '12

- Physics included: hydrodynamics, self-gravity, rotation and external potential
- supernovae to disperse collapsing clouds (Shetty & Ostriker '08)
- High resolution 2D (r,z) simulations: 60x120 pc^2, 512x1024 zones $(0.15\ pc)^2$/zone
- *ATHENA* hydrodynamics code (Stone + '08)
- Main user-defined parameters: Σ, $\varepsilon_{ff}(n_{th})$, p_*, Ω

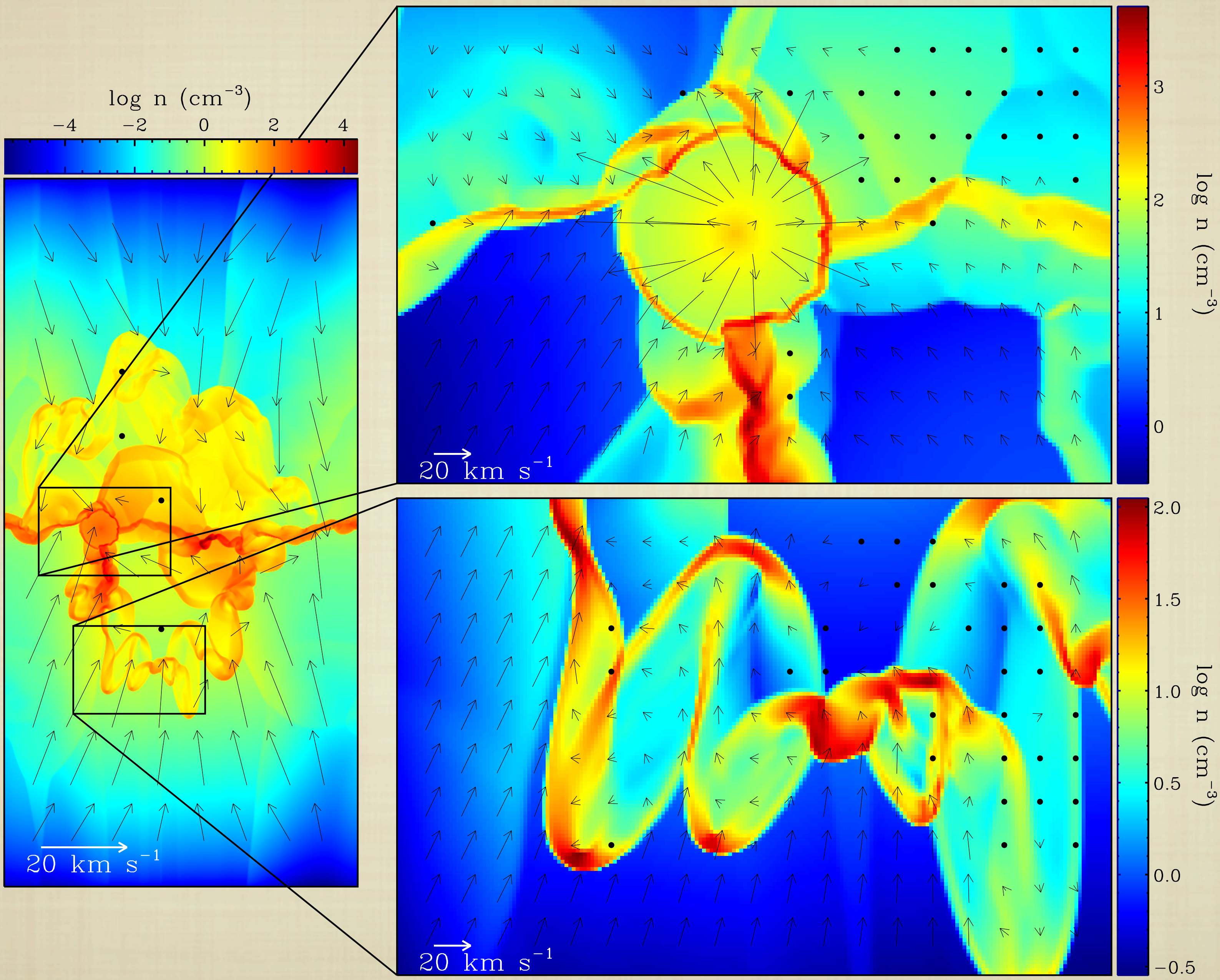
Simulations: Time Evolution



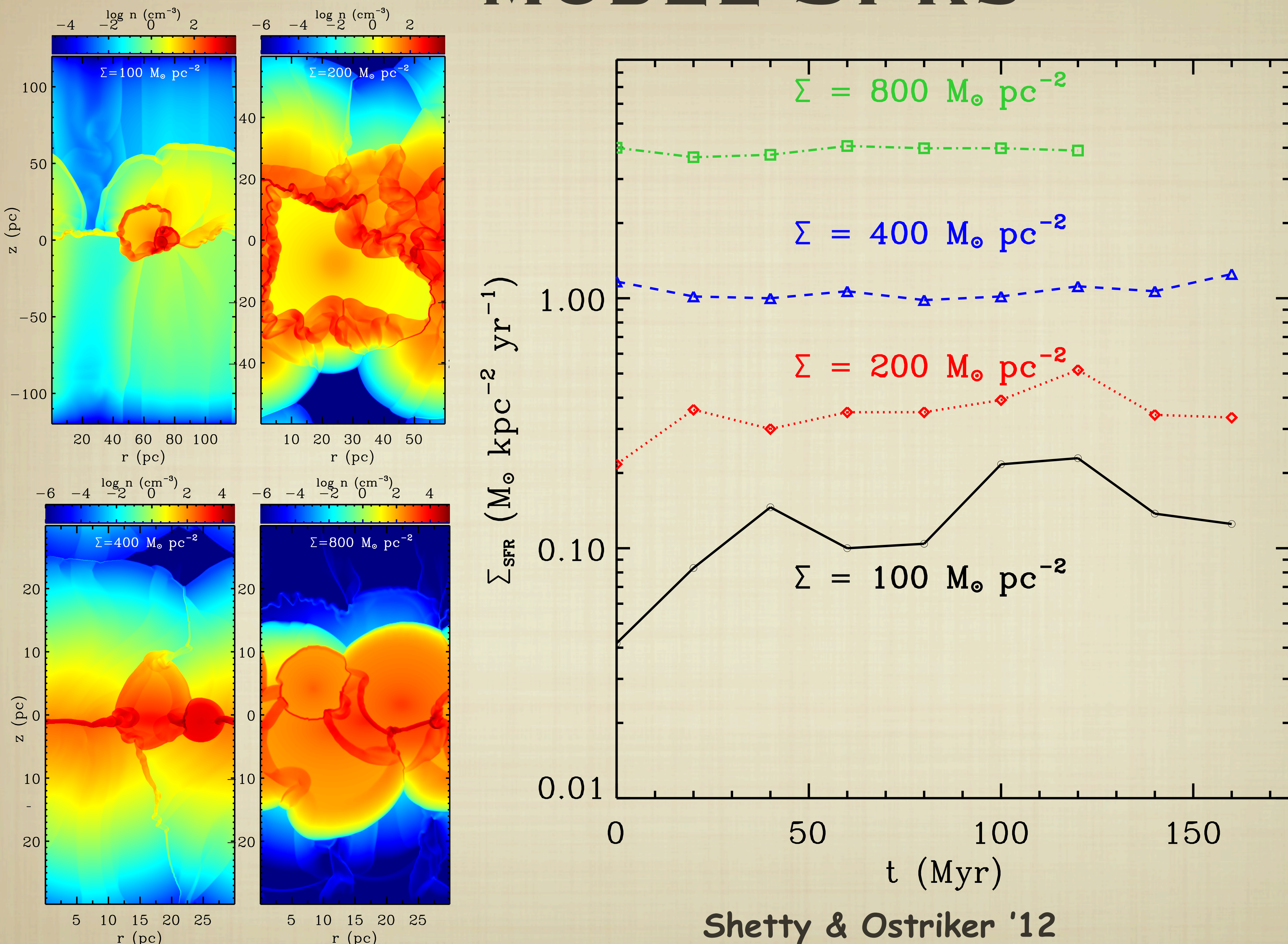
60 x 120 pc^2

Σ_{gas} = 100 $M_\odot$ pc^{-2}

Numerical Simulations II



Model SFRs

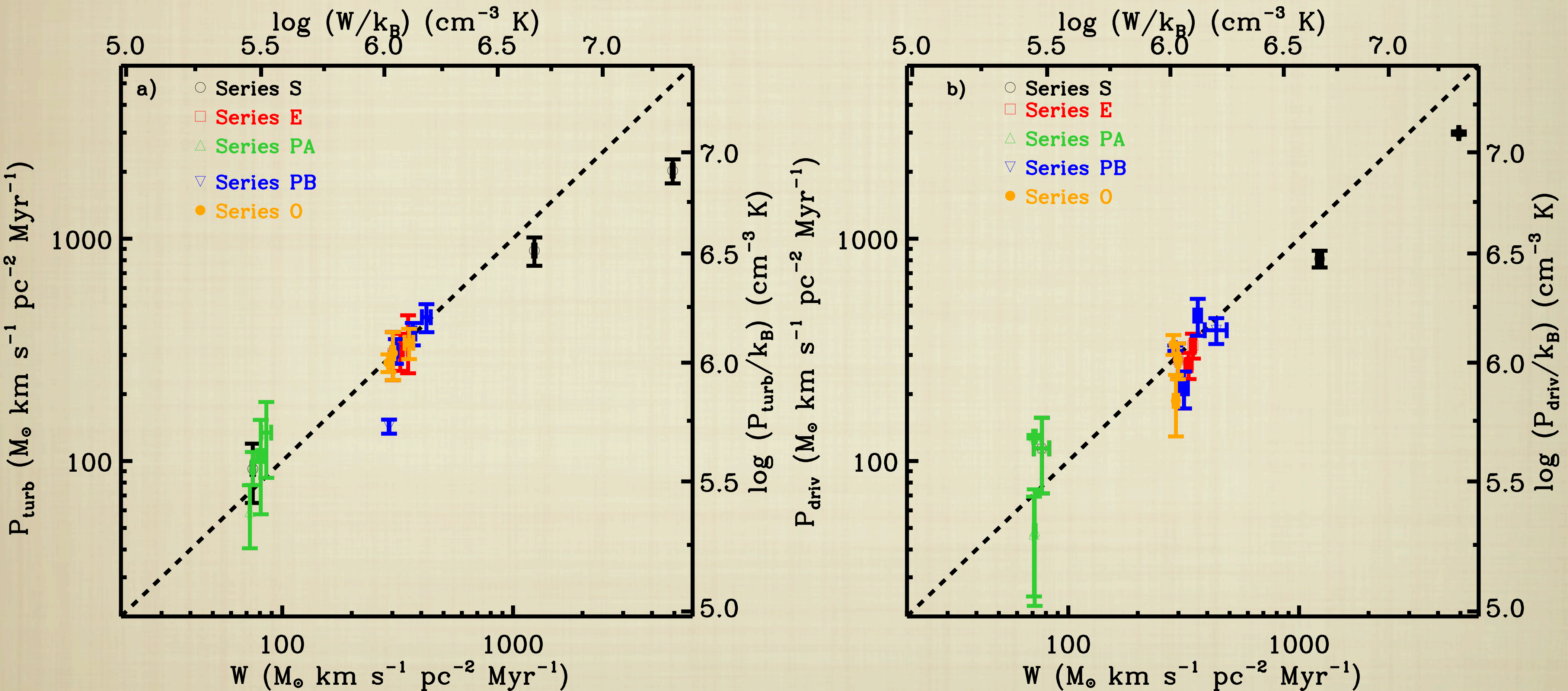


Shetty & Ostriker '12

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 '12

Simulation vs Analytic Sol'ns

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

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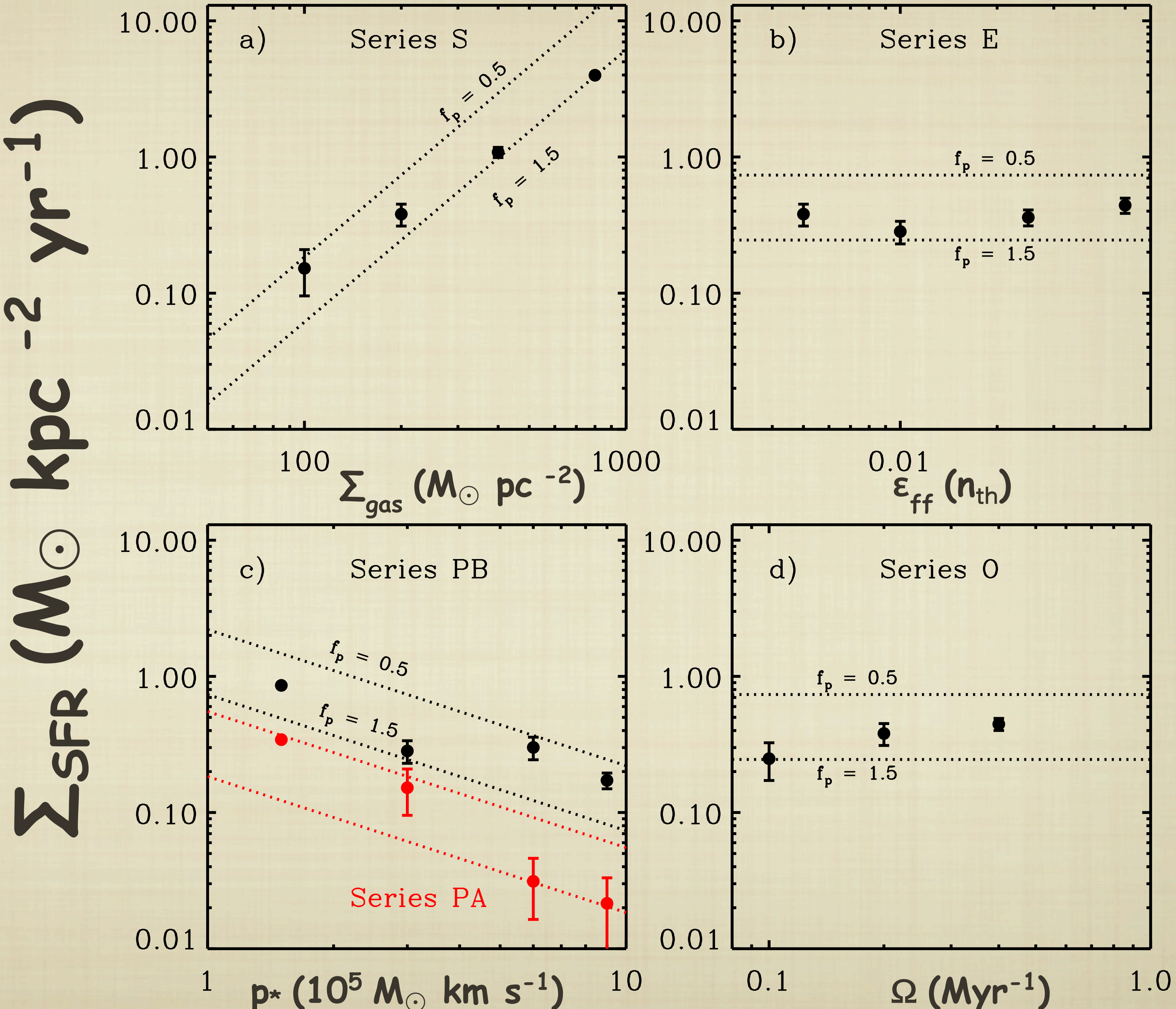
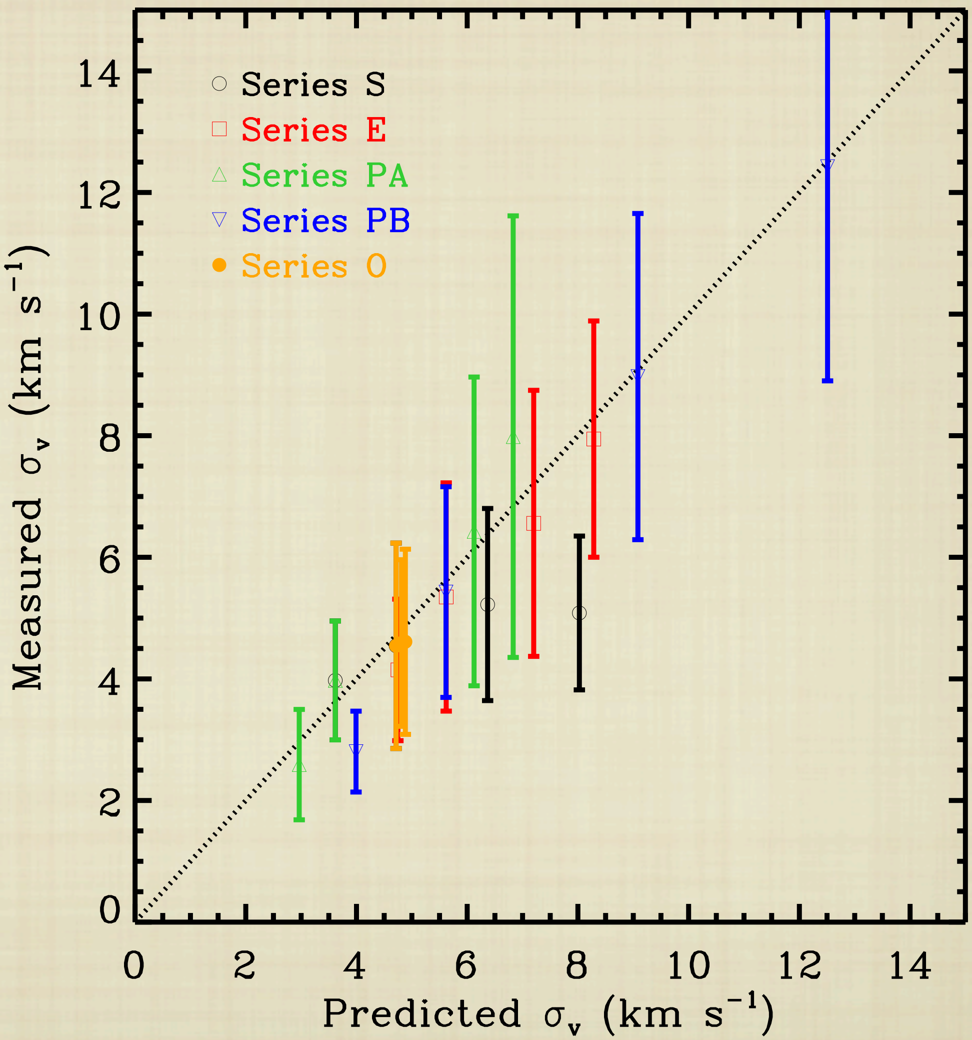


Turbulent Velocities

- Turbulent velocities measured higher in the Galactic Center
- Similar linewidth-size exponent to Milky Way disk, but with larger coefficient



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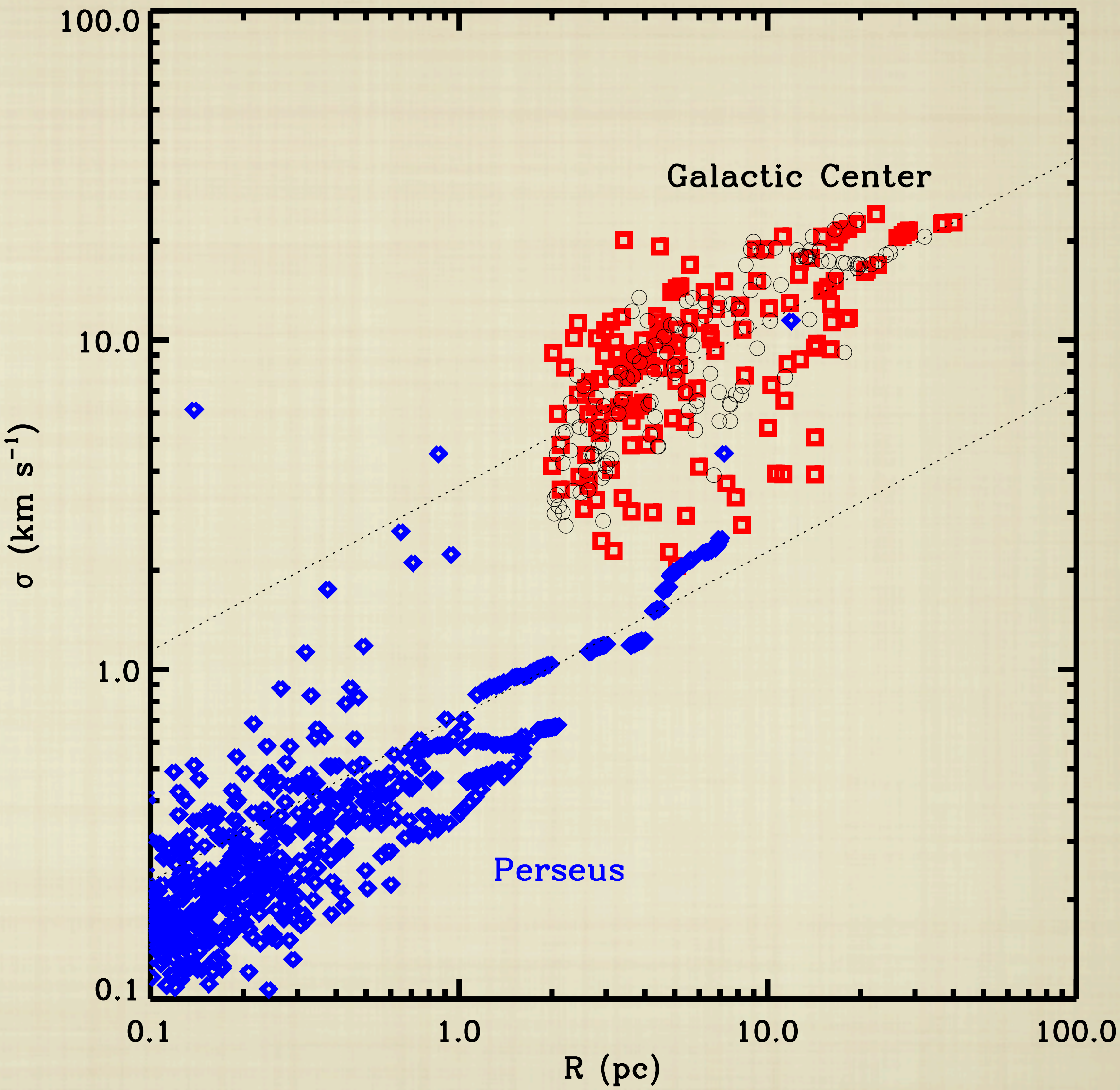
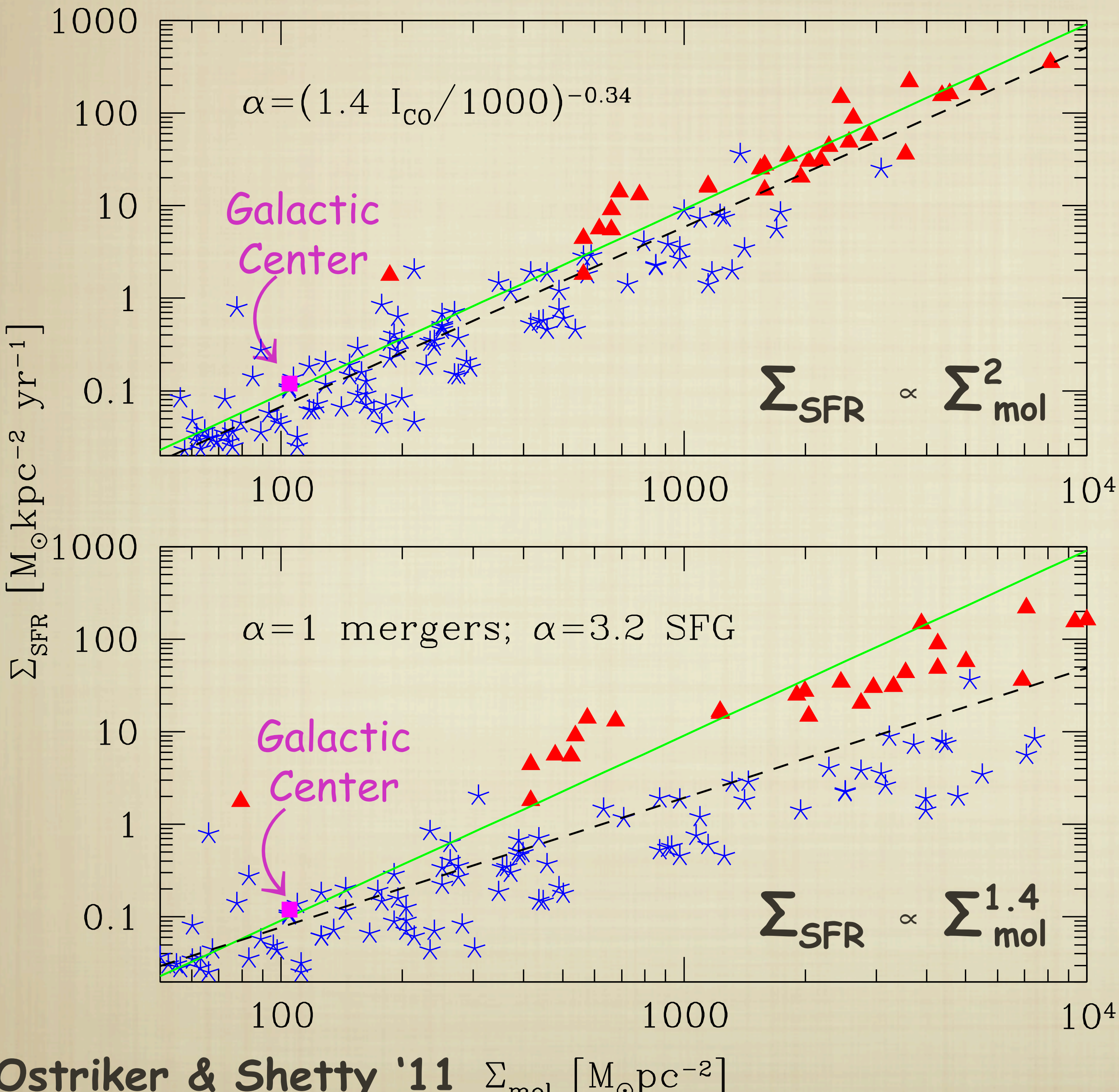


Shetty + '12

Self-Regulation in Observed Systems?



Ostriker & Shetty '11

Star forming galaxies and merger systems from Genzel + '10

Galactic Center from Yusef-Zadeh + '09

Continuous X factor? (Shetty + 11a,b, Narayanan + 11, 12, Feldmann + '12)

Inferring the Molecular Schmidt Law

- Measurement uncertainties and intrinsic scatter may lead to biases in fitting a model to data (*e.g.* Weiner +2006, Kelly 2007).

- Hierarchical models allow for estimating the model parameters of individuals and for the group

- Bayesian inference is ideally suited for fitting hierarchical models, and accounting for uncertainties, through MCMC methods

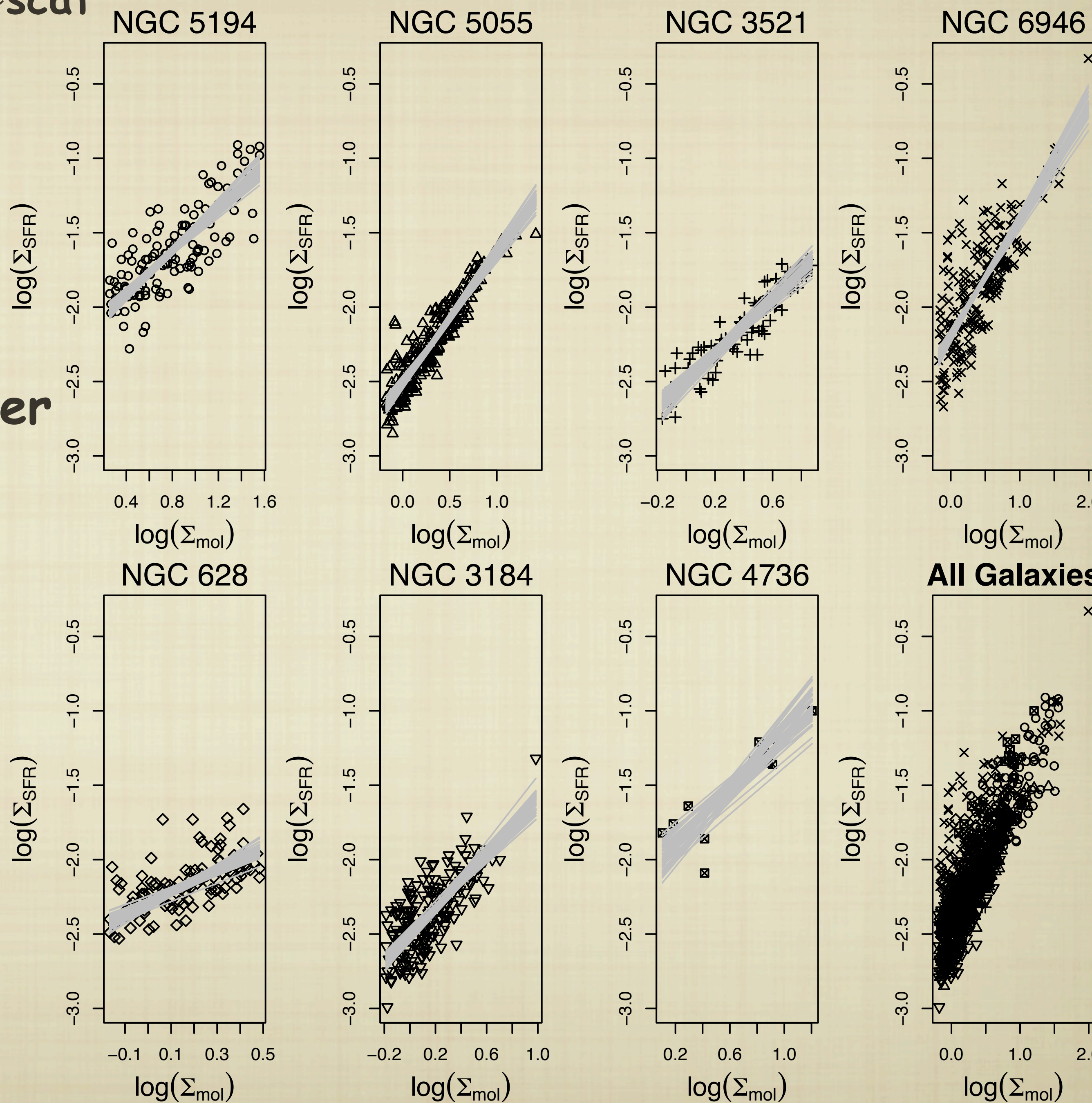
- Employ a hierarchical Bayesian method, with a full treatment of uncertainties to estimate Schmidt law parameters from the Bigiel + 2008 sample

Hierarchical Bayesian Fitting of the Schmidt Law

- $\Sigma_{SFR} = A\Sigma^{N}_{mol} + \varepsilon_{scat}$

  fit individual and "group" parameters, with uncertainties

  Posterior is a PDF of each fit parameter



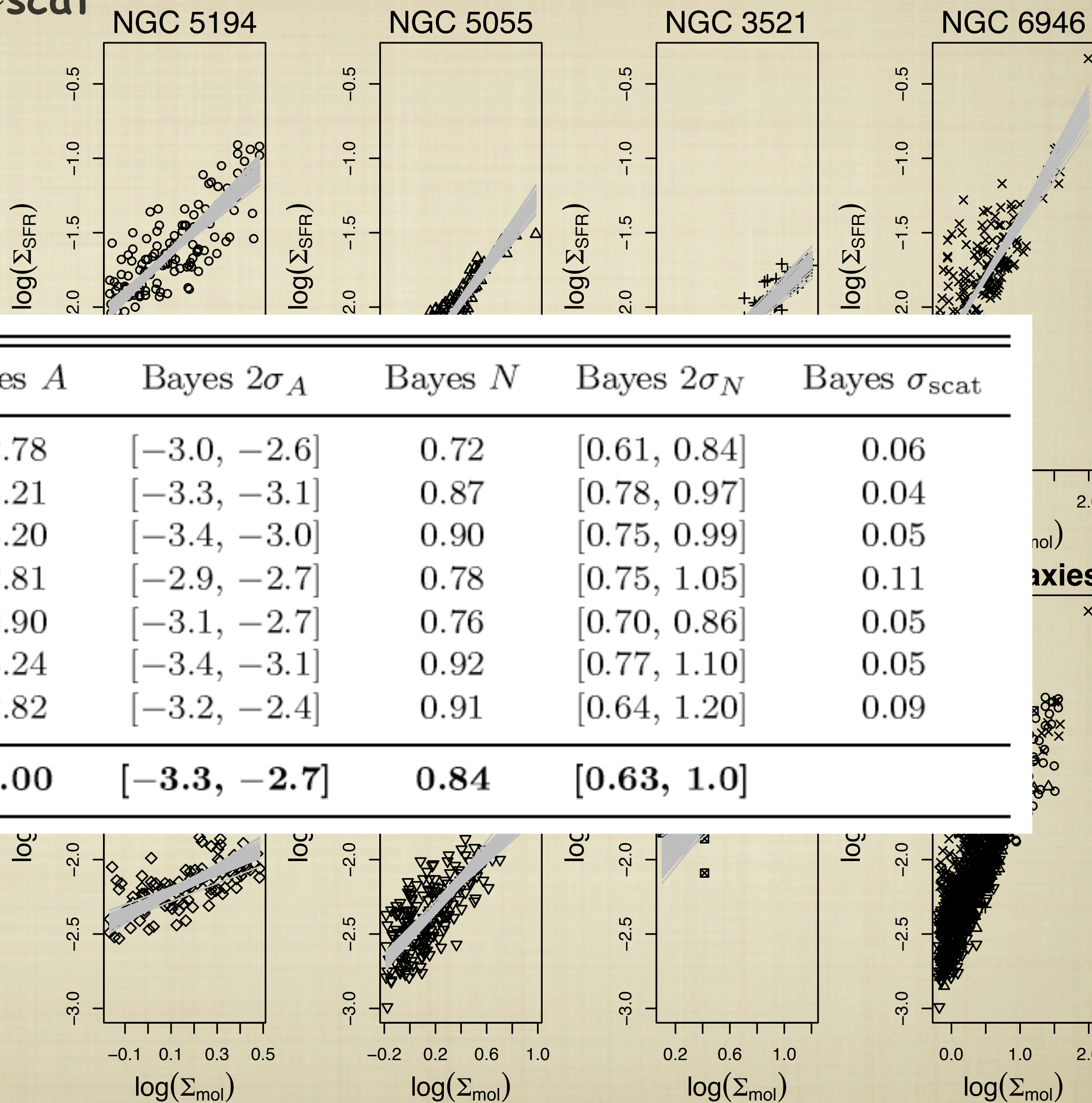
Bigiel+'08, '10

Shetty, Kelly, Bigiel In Prep

Hierarchical Bayesian Fitting of the Schmidt Law

- $\Sigma_{SFR} = A\Sigma^{N}_{mol} + \varepsilon_{scat}$

fit <u>individual</u> and "<u>group</u>" parameters, with <u>uncertainties</u>



Subject	Bayes A	Bayes $2\sigma_A$	Bayes N	Bayes $2\sigma_N$	Bayes $\sigma_{\rm scat}$
NGC 5194	−2.78	[−3.0, −2.6]	0.72	[0.61, 0.84]	0.06
NGC 5055	−3.21	[−3.3, −3.1]	0.87	[0.78, 0.97]	0.04
NGC 3521	−3.20	[−3.4, −3.0]	0.90	[0.75, 0.99]	0.05
NGC 6946	−2.81	[−2.9, −2.7]	0.78	[0.75, 1.05]	0.11
NGC 628	−2.90	[−3.1, −2.7]	0.76	[0.70, 0.86]	0.05
NGC 3184	−3.24	[−3.4, −3.1]	0.92	[0.77, 1.10]	0.05
NGC 4736	−2.82	[−3.2, −2.4]	0.91	[0.64, 1.20]	0.09
Group Parameters	**−3.00**	**[−3.3, −2.7]**	**0.84**	**[0.63, 1.0]**	

Bigiel+'08, '10

Shetty, Kelly, Bigiel
In Prep

Summary

- In starbursts (away from AGN), SN driven feedback balances vertical gravity, leading to star formation self-regulation.
- Self-regulation leads to $\Sigma_{SFR} \propto \Sigma^2_{gas}$ (for gravity dominated by Σ_{gas}), and strongly constrains v_z and H, confirmed by numerical simulations.
- Observations support $\Sigma_{SFR} \propto \Sigma^2_{gas}$ if X factor varies continuously. Other properties must also be verified.
- Hierarchical Bayesian modeling of molecular Schmidt relationship estimates an index < 1.