

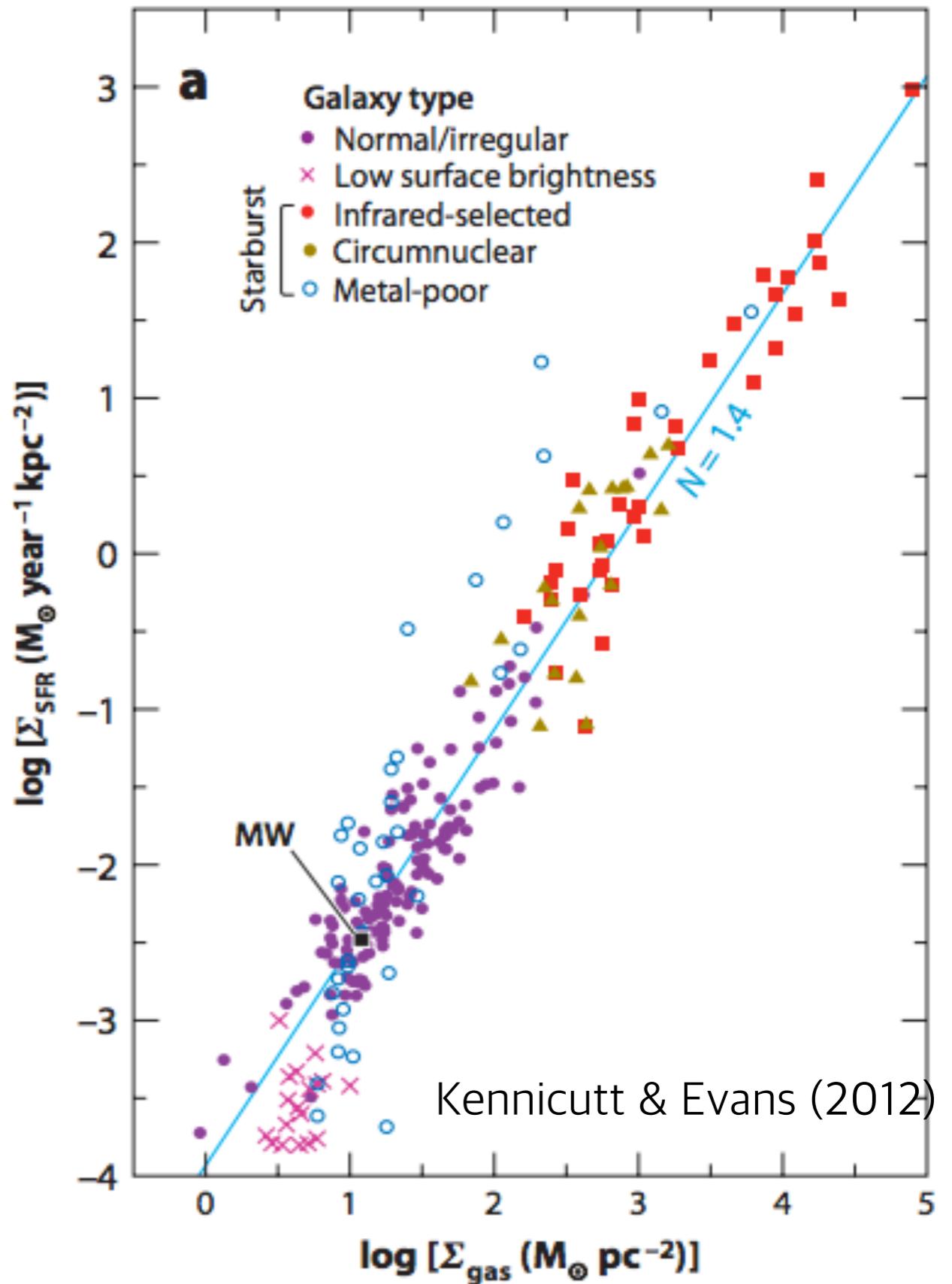
How do Supernovae Regulate Star Formation and (Winds) in Galaxies?

Chang-Goo Kim and Eve Ostriker
Princeton University

What determines the SFR in galaxies?

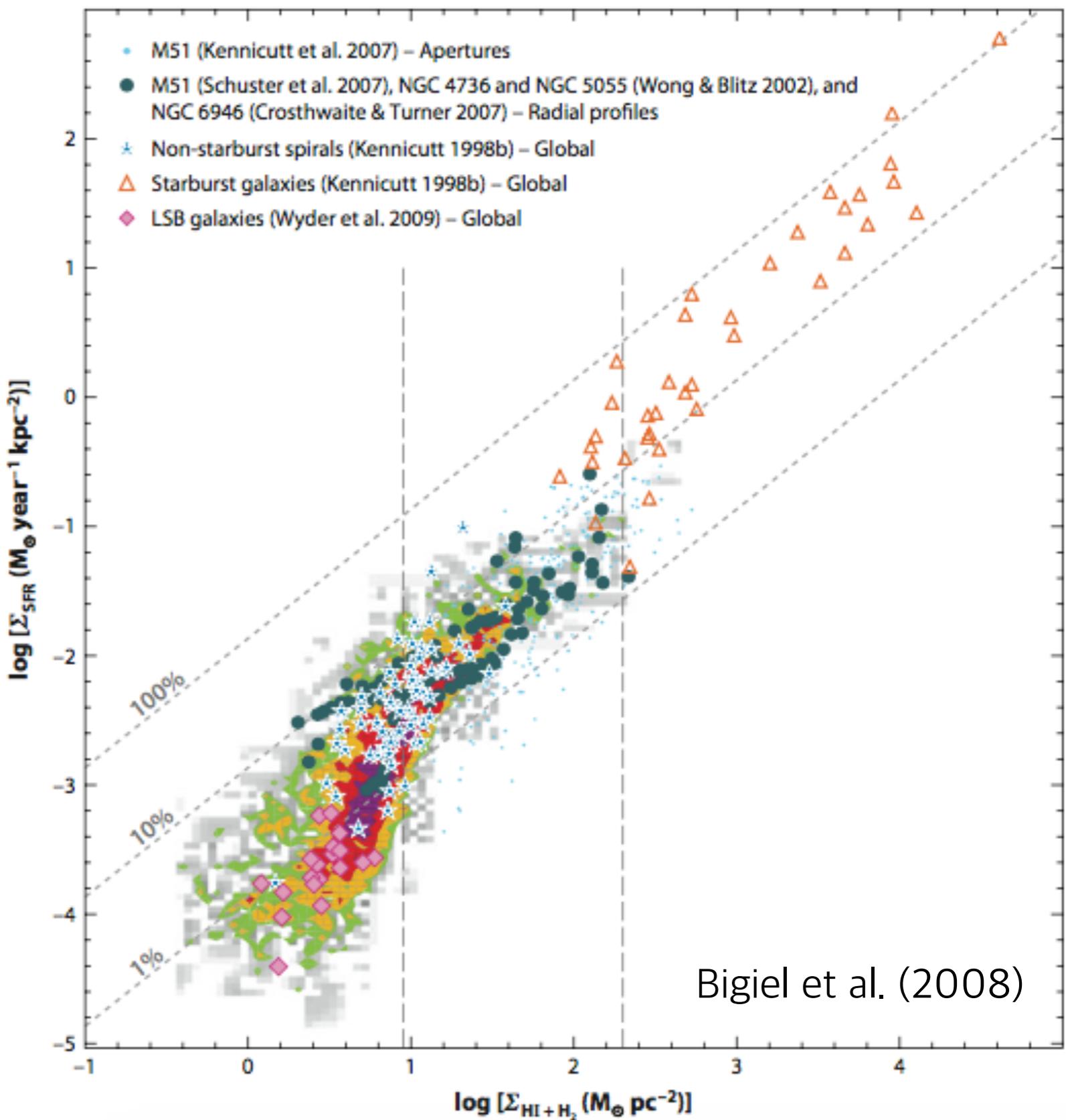
Classical Star Formation Law

- KS-relation
 - $\Sigma_{\text{SFR}} \propto \Sigma^{1+p}$
 - $p \sim 0.4$ (Kennicutt 1998)
 - $t_{\text{dep}} = \Sigma / \Sigma_{\text{SFR}} \propto \Sigma^{-p}$



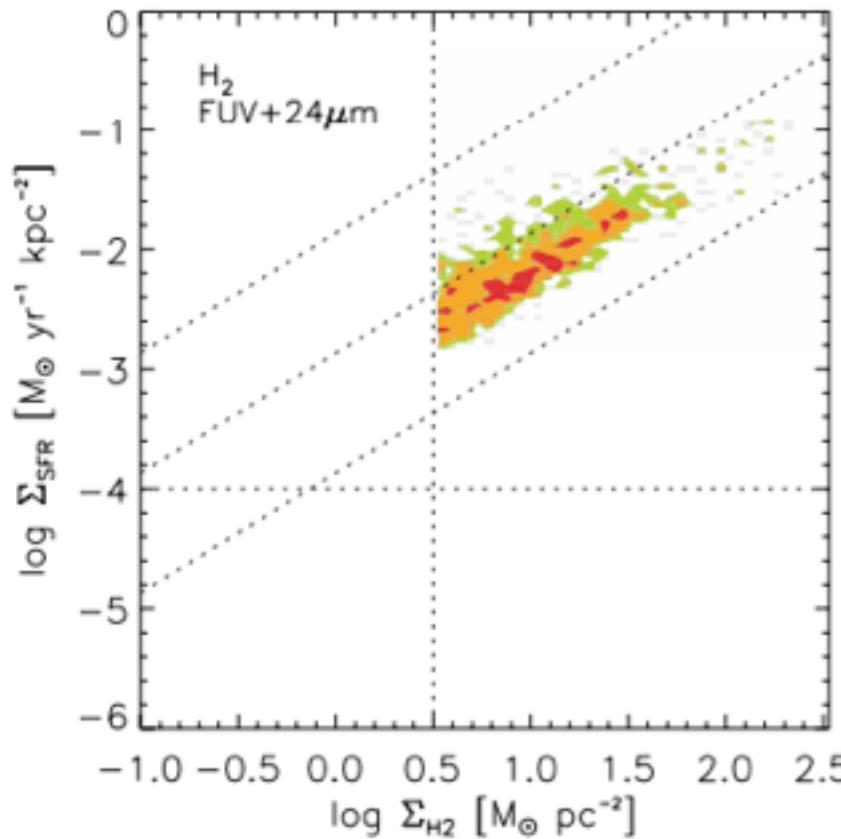
Modern Star Formation Law

- superlinear ($p > 0$) at low, high ends
- nearly linear ($p \sim 0$) for intermediate regime with $t_{\text{dep,mol}} \sim 2 \text{ Gyr}$
- significant scatter for HI-dominated regime
- Σ_{gas} is not the only control parameter

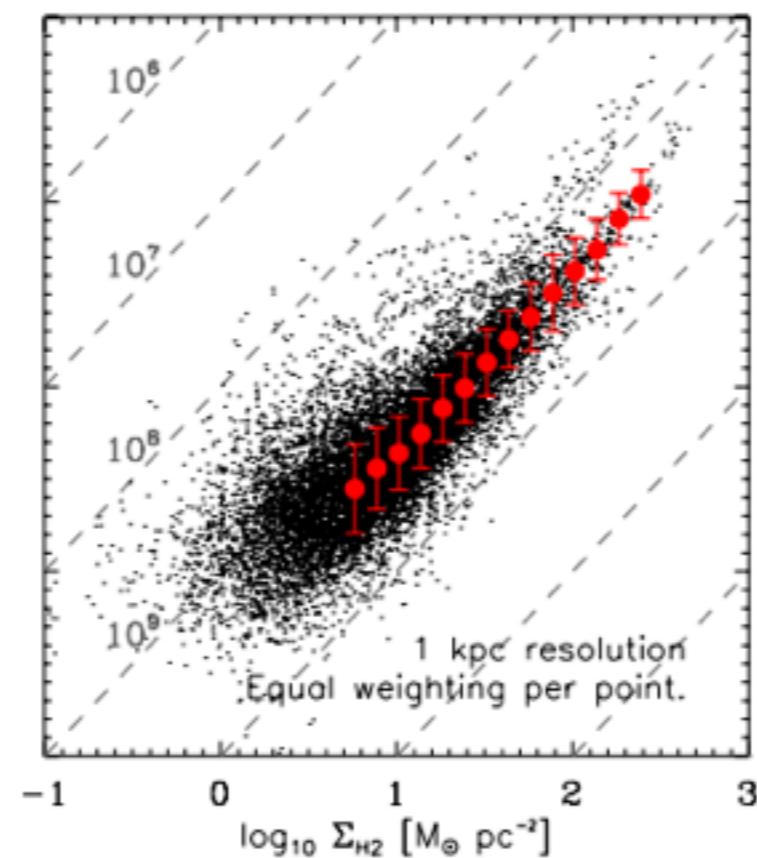


Molecular Star Formation Law

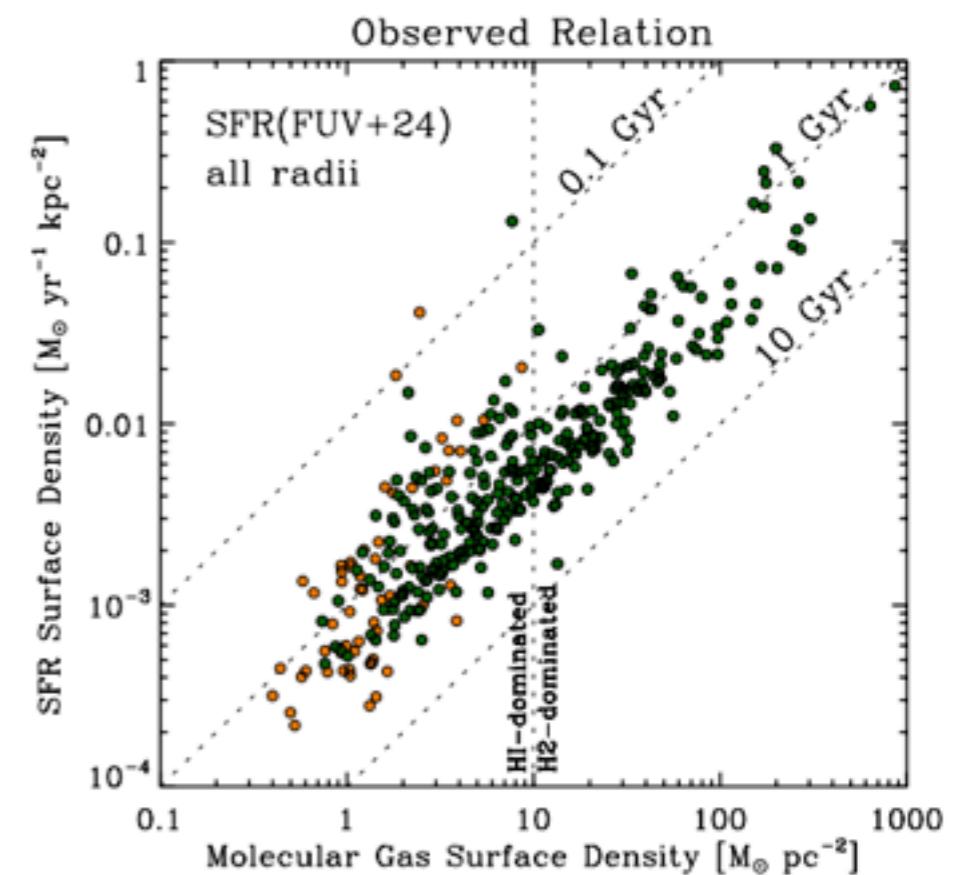
Bigiel et al. (2008)



Bigiel et al. (2011)



Schruba et al. (2011)



- $\Sigma_{\text{SFR}} \sim \Sigma_{\text{mol}} / t_{\text{dep}}$; $t_{\text{dep}} \sim (1-2) \text{ Gyr}$
- SF can be more efficient (t_{dep} is shorter) at less dense gas (Usero et al. 2015; Bigiel et al. 2016)
- SF is still inefficient at consuming gas; t_{dep} is longer than t_{dyn}

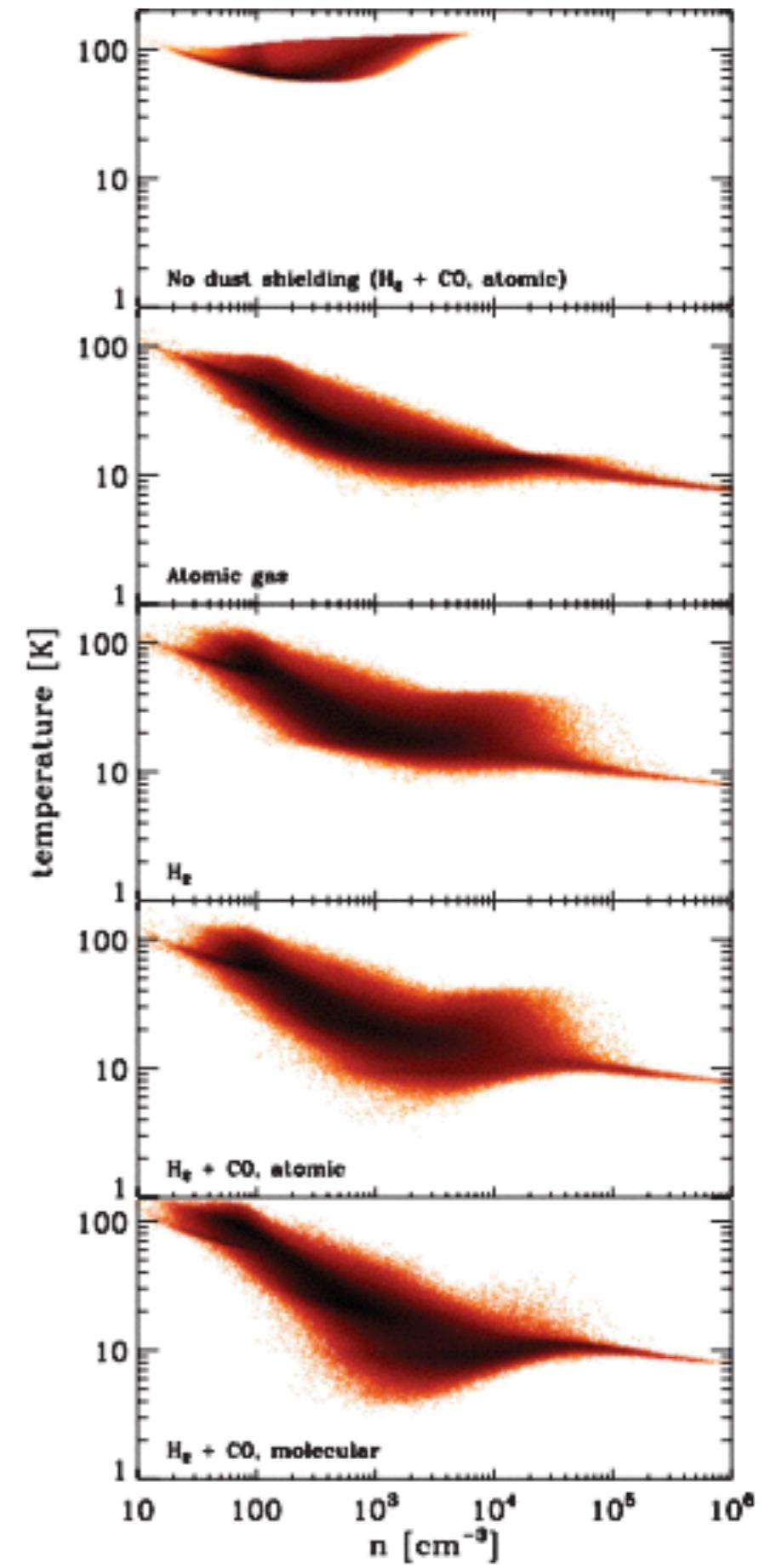
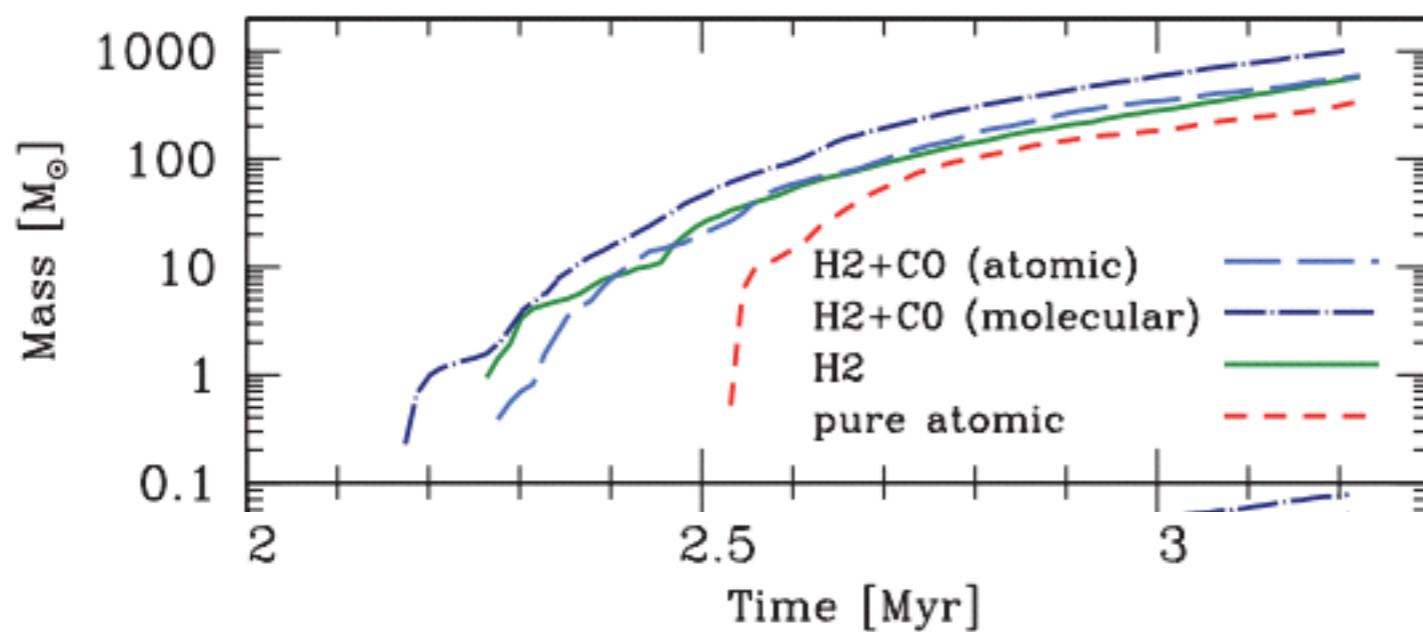
Empirical Star Formation Law

- SFR vs. Gas content:
 - $\Sigma_{\text{SFR}} \propto \Sigma^{1+p}$ or $\Sigma_{\text{SFR}} \propto \Sigma_{\text{mol}}$
 - Schmidt (1959, 1963); Kennicutt (1998); Schuster et al. (2007); Kennicutt (2007); Bigiel et al. (2008, 2010, 2011); Leroy et al. (2008, 2011); Schruba et al. (2011); Rahman et al. (2011, 2012)...
 - low SF efficiency $\sim 1\%$ per free fall time

Causality?

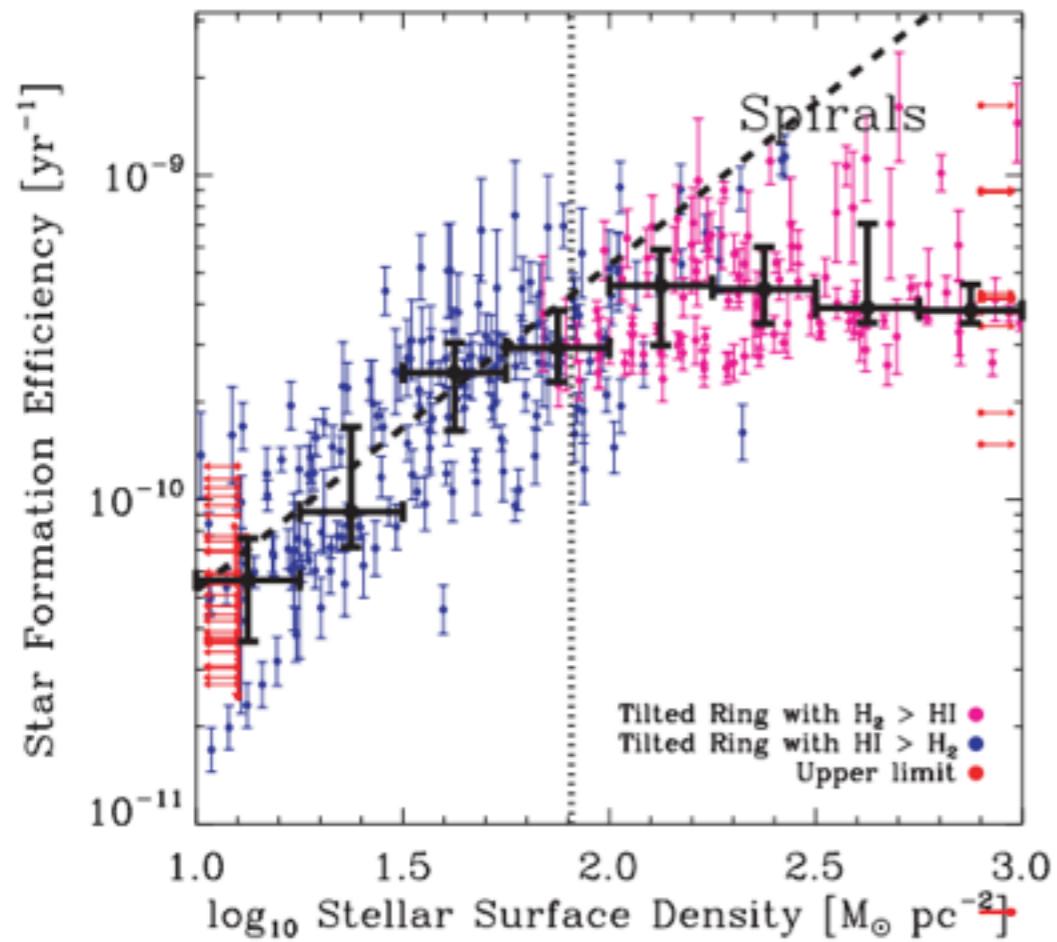
Glover & Clark (2012)

- molecular gas is not crucial
- dust shielding is essential to get high density and low temperature

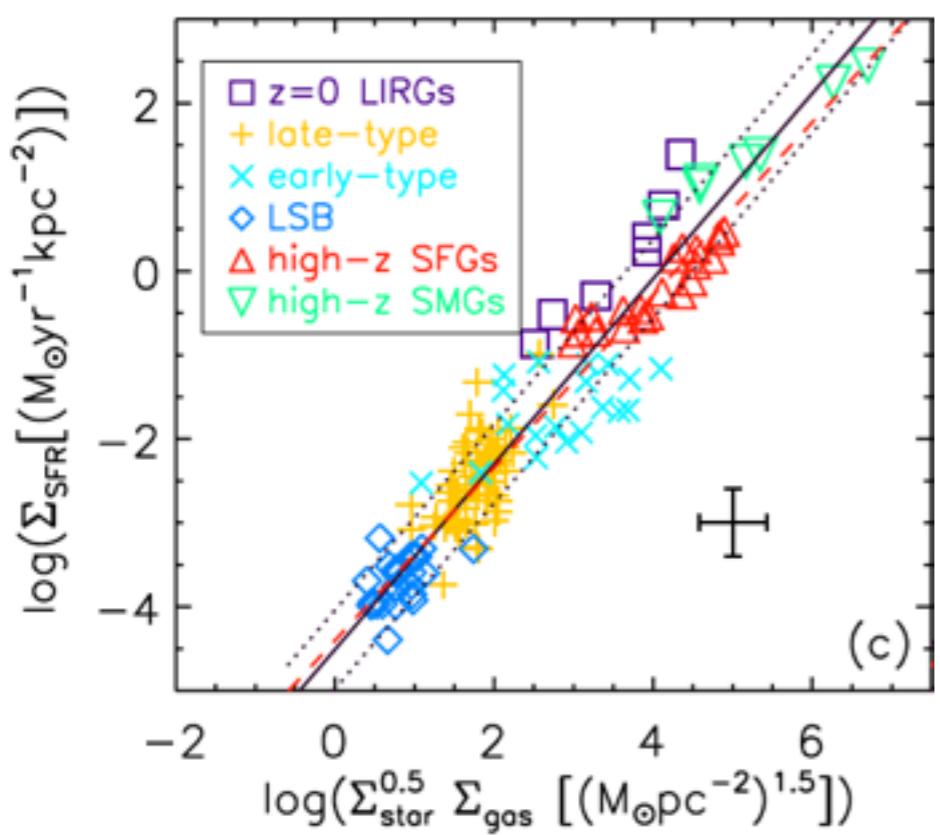
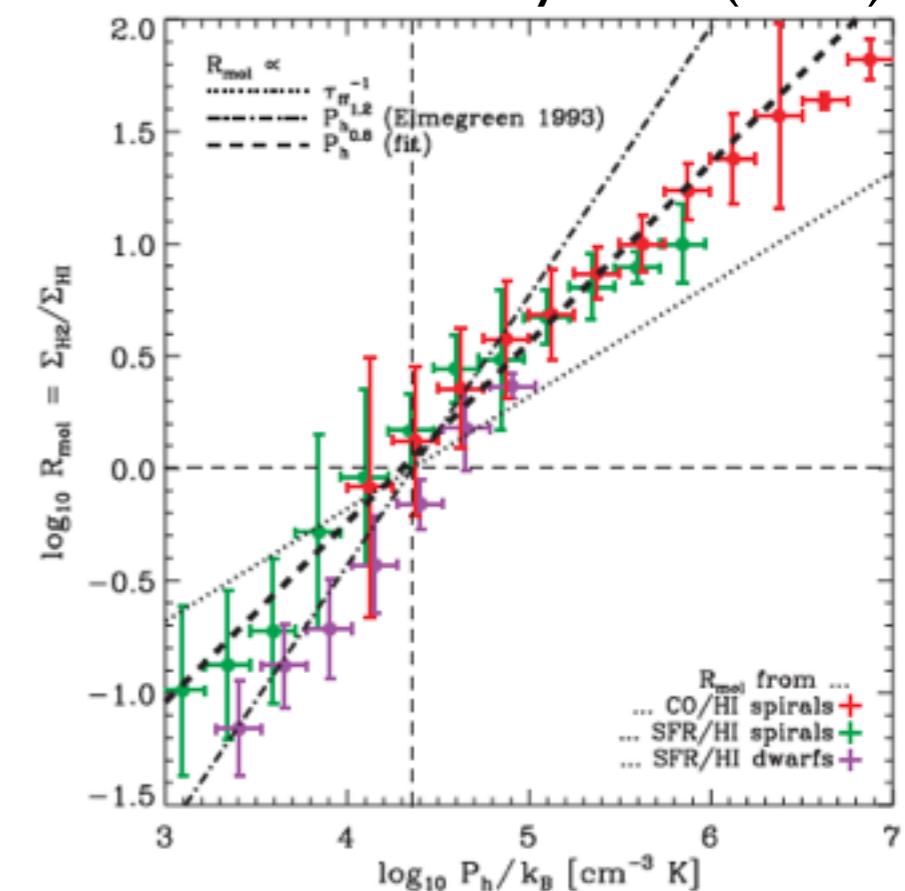


Molecular gas just trace the star forming gas, while SFR is set by other processes.

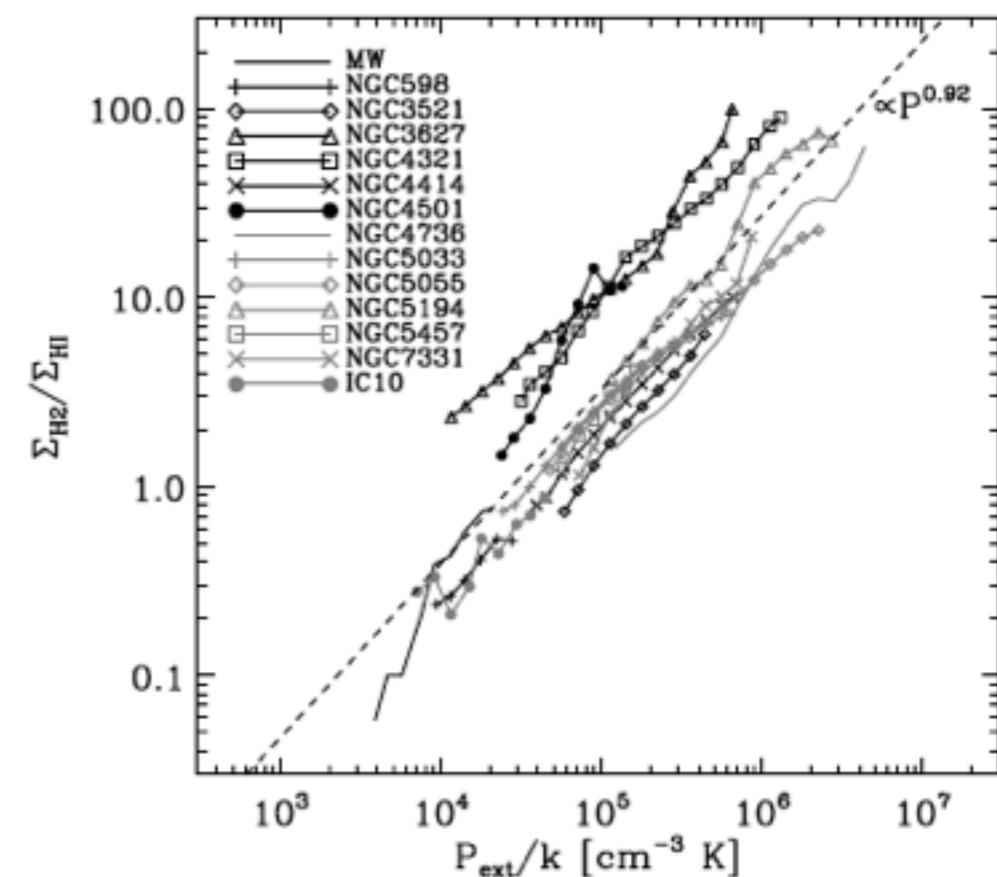
Leroy et al. (2008)



Leroy et al. (2008)



Shi et al. (2011)

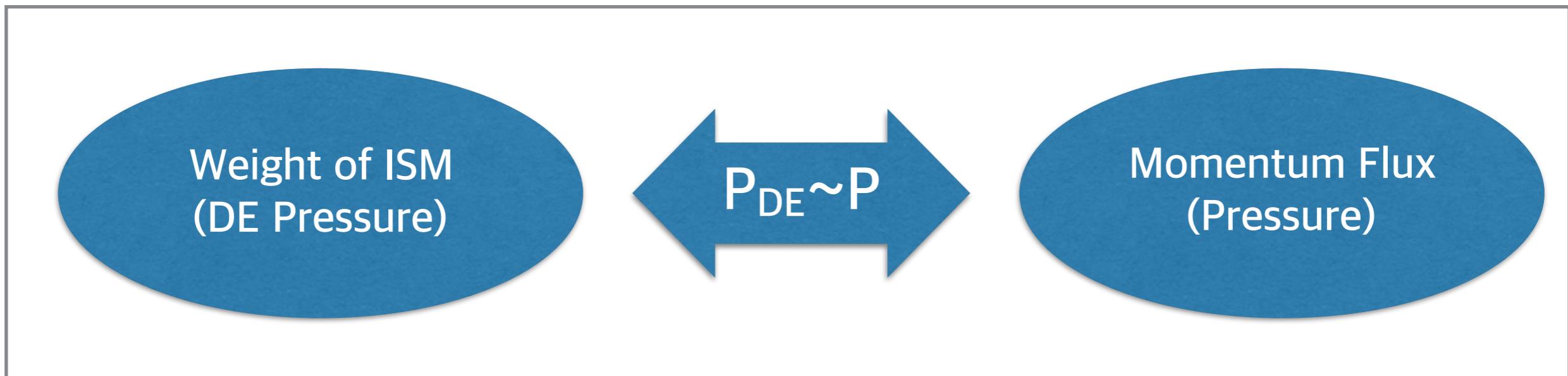
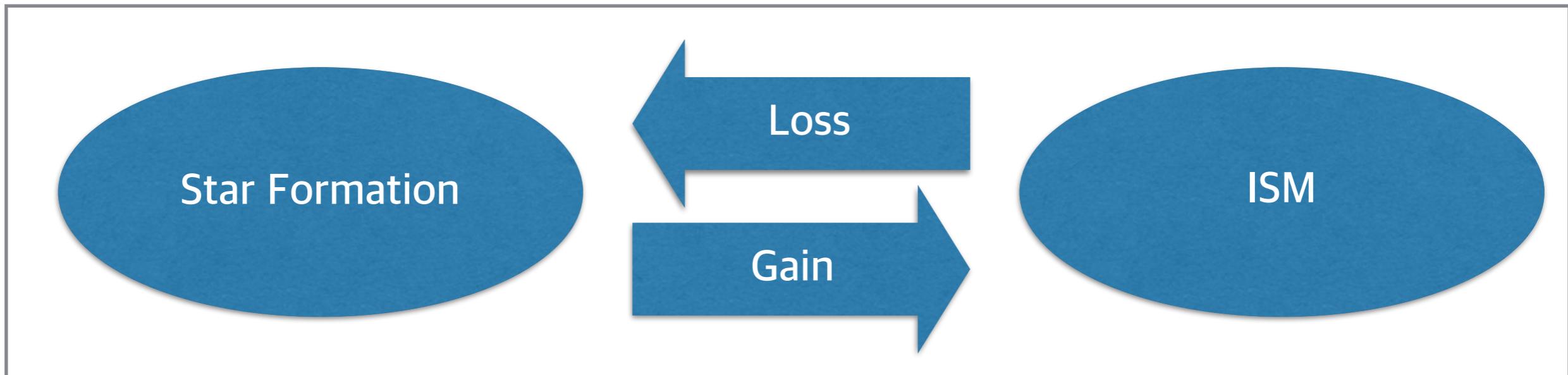


Blitz & Rosolowsky (2006)

New Star Formation Law: Equilibrium View

- SFR vs. Dynamical Pressure:
 - Empirical (indirect; R_{mol} vs Pressure): Wong & Blitz (2002); Blitz & Rosolowsky (2004, 2006); Leroy et al. (2008); Yim et al. (2011, 2014)
 - Theoretical: Ostriker, McKee, Leroy (2010); Ostriker & Shetty (2011); CGK, Kim, Ostriker (2011)
 - Numerical: CGK, Kim, Ostriker (2011); Shetty & Ostriker (2012); CGK, Ostriker, Kim (2013); CGK & Ostriker (2015b)
- $\Sigma_{\text{SFR}} \propto P_{\text{tot}} \sim W (= \Delta P_{\text{DE}}) \sim \Sigma \langle g_z \rangle / 2$

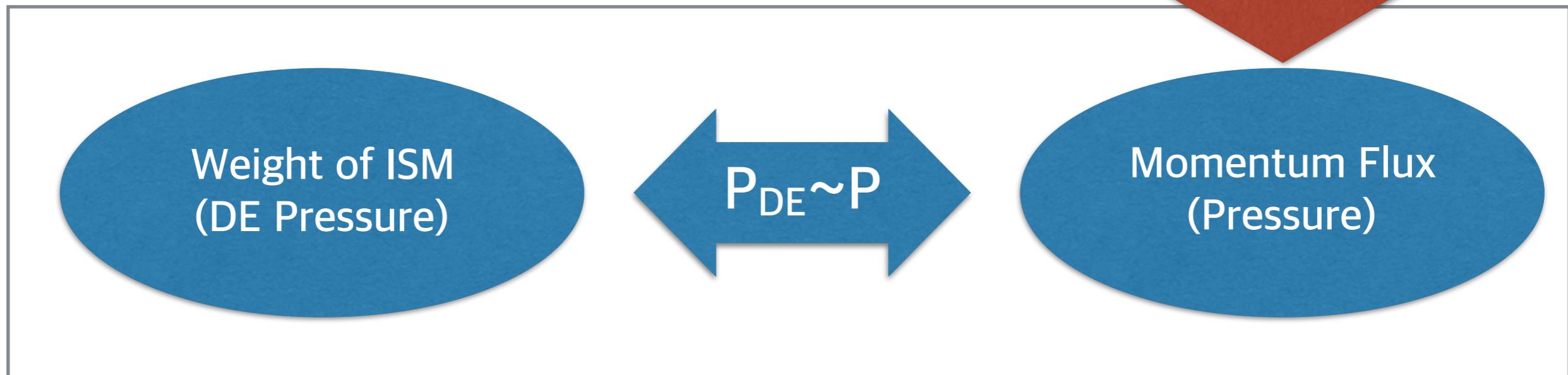
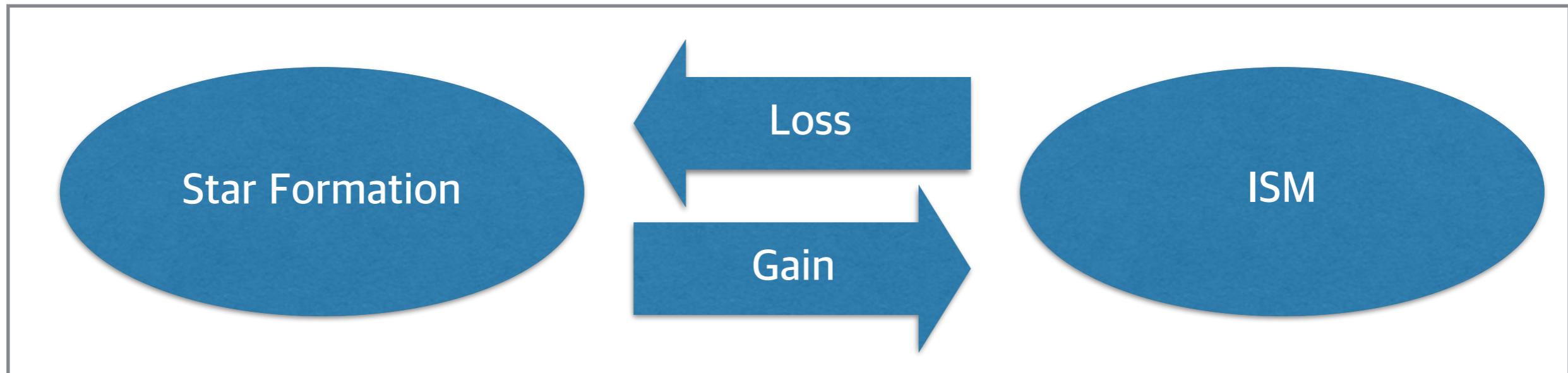
Energy and Momentum Equilibrium



Vertical Dynamical Equilibrium (HSE)

Ostriker, McKee, Leroy (2010); Ostriker & Shetty (2011); CGK, Kim, Ostriker (2011)

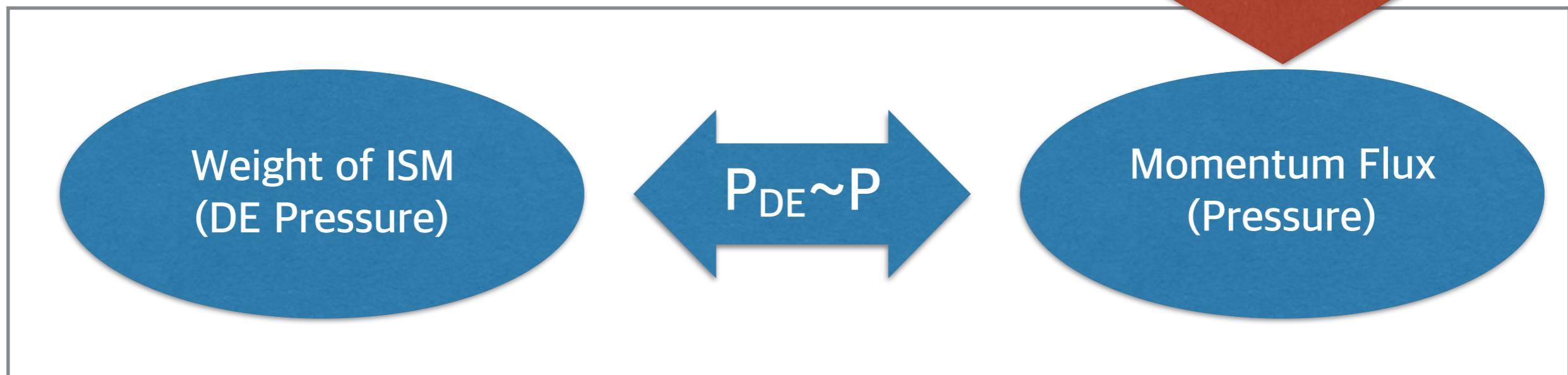
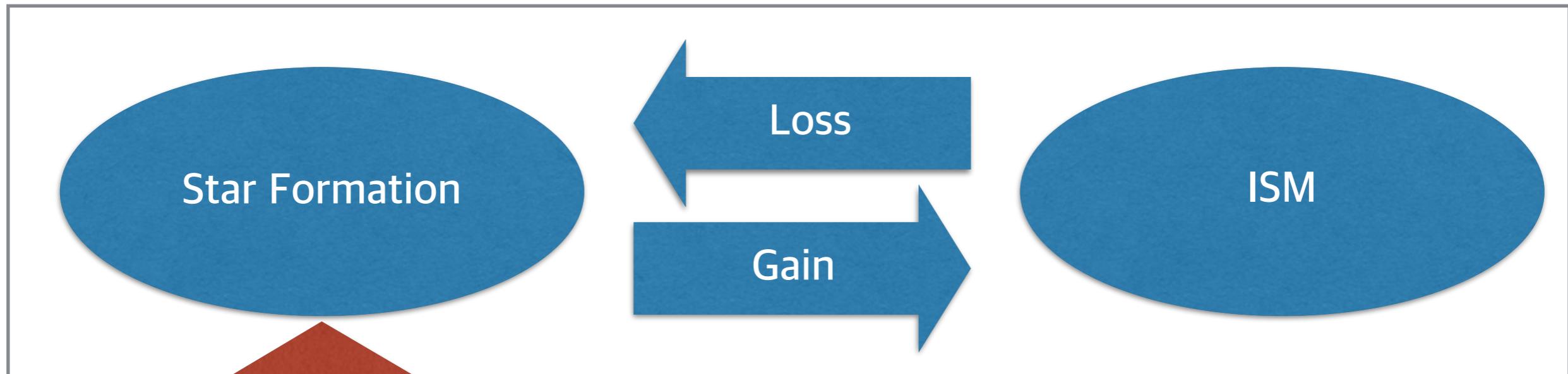
Energy and Momentum Equilibrium



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Energy and Momentum Equilibrium



Vertical Dynamical Equilibrium (HSE)

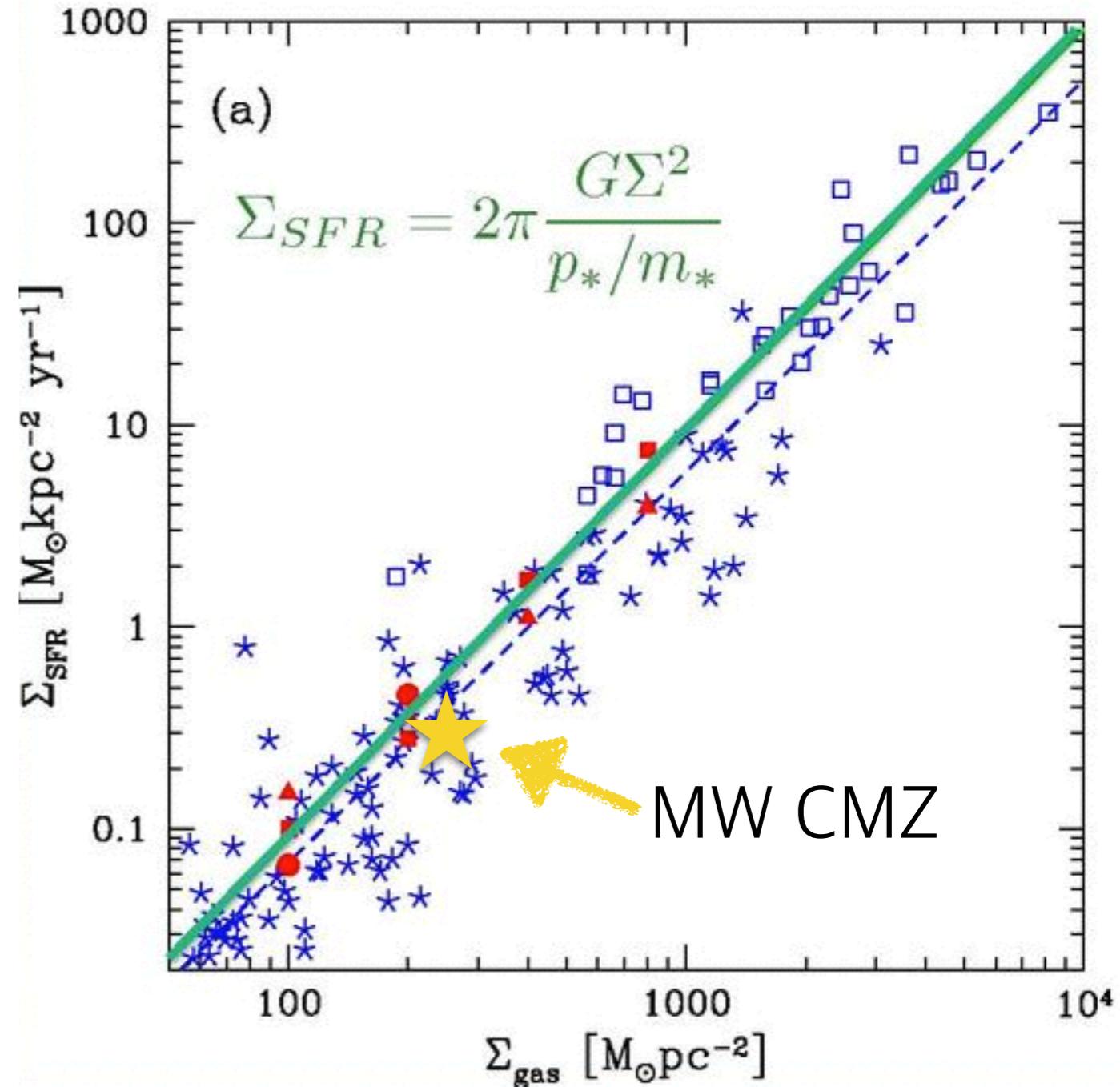
Ostriker, McKee, Leroy (2010); Ostriker & Shetty (2011); CGK, Kim, Ostriker (2011)

Simplest Case

- Turbulence dominates pressure support
 - total radial momentum injected per feedback event: p_*
 - total mass of new star per feedback event: m_*
 - momentum injection rate per volume: $(p_*/m_*)\Sigma_{\text{SFR}}/H$
 - momentum dissipation rate per volume: $\rho\sigma/t_{\text{diss}} \sim \rho\sigma^2/H$
 - $P_{\text{turb}} = (p_*/m_*)\Sigma_{\text{SFR}}/4$
- Gaseous self-gravity dominates gravity
 - $P_{DE} = \pi G \Sigma^2 / 2$

Simplest Case

- $P_{\text{turb}} = P_{\text{DE}} \rightarrow \Sigma_{\text{SFR}} = 2\pi G \Sigma^2 / (3000 \text{ km/s})$
- symbols: Genzel et al 2010 (with variable α_{CO})
- line: Ostriker & Shetty 2011
- can be applicable to starbursts
- MW CMZ (Kennicutt & Evans 2012):
 $\Sigma_{\text{SFR}} = 0.3 M_{\text{sun}}/\text{Myr}/\text{kpc}^2$;
 $\Sigma_{\text{gas}} = 250 M_{\text{sun}}/\text{pc}^2$



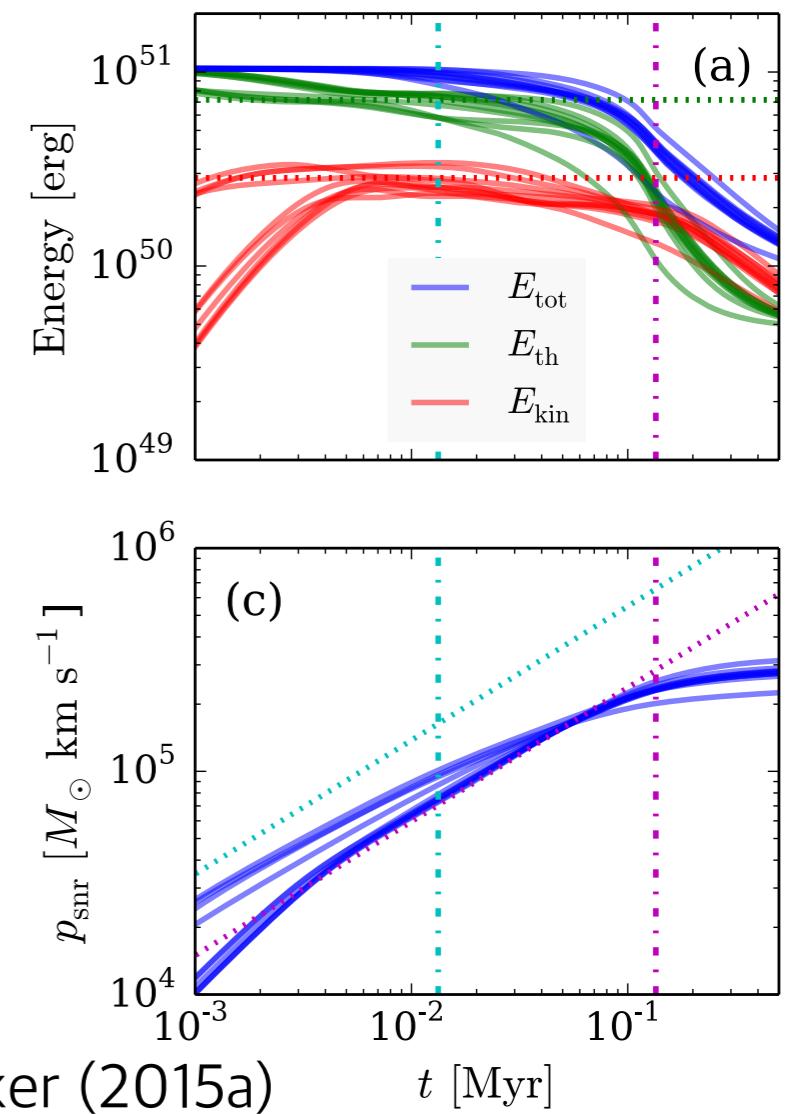
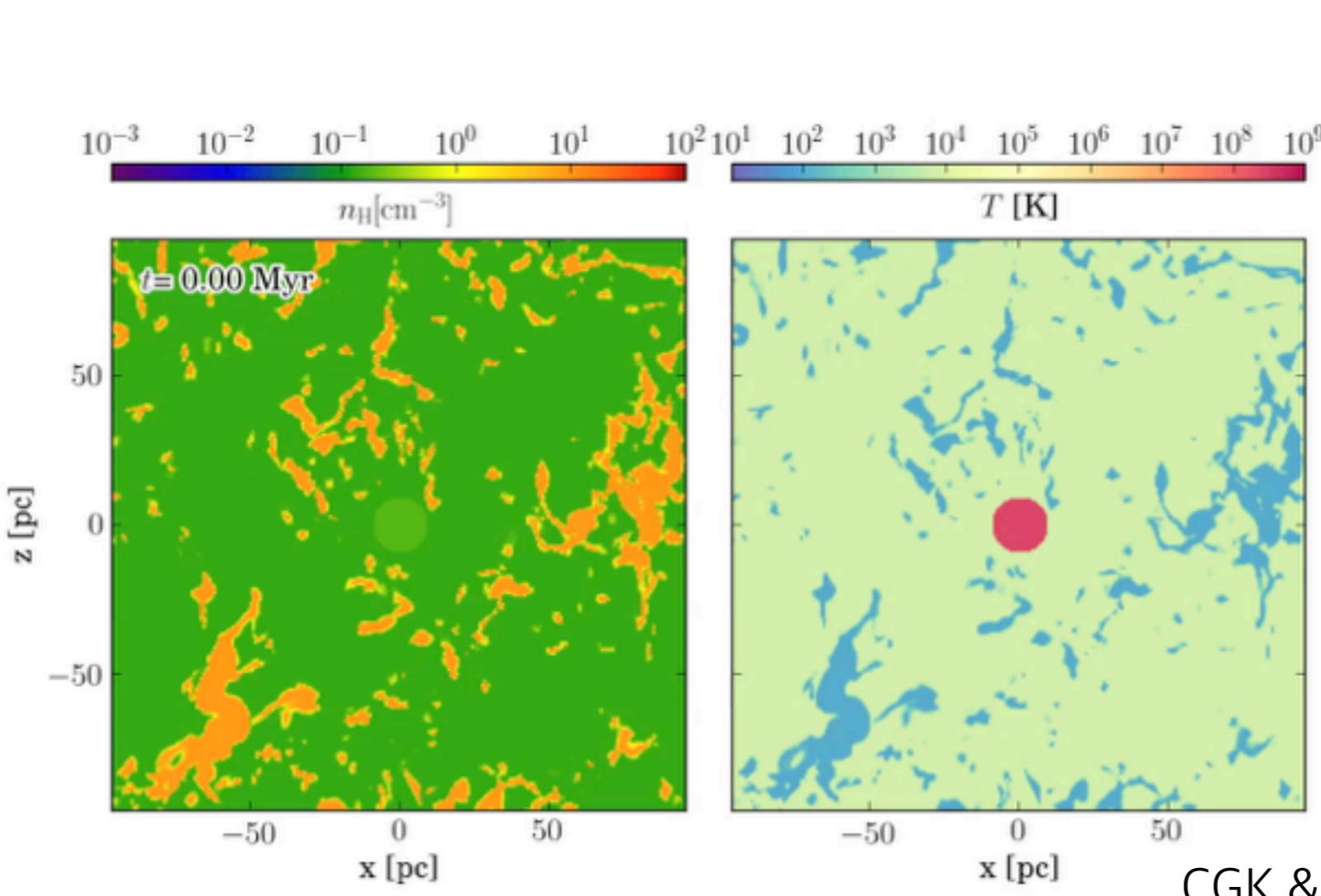
Ostriker & Shetty (2011)

More Realistic Case

- Pressure supports
 - turbulence + thermal + (turbulent) magnetic + ?
- Gravity
 - gas + stellar + dark matter: $P_{DE} \sim \pi G \Sigma^2 / 2 + \Sigma (2G\rho_{sd})^{1/2} \sigma_z$

Turbulence: Supernovae

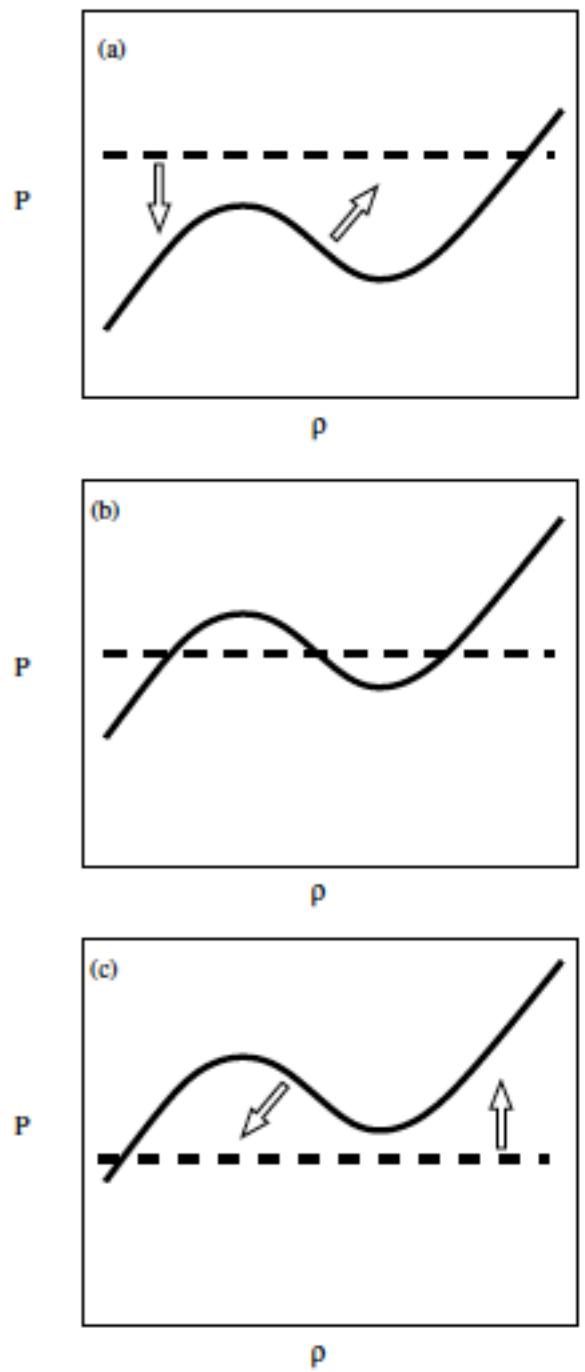
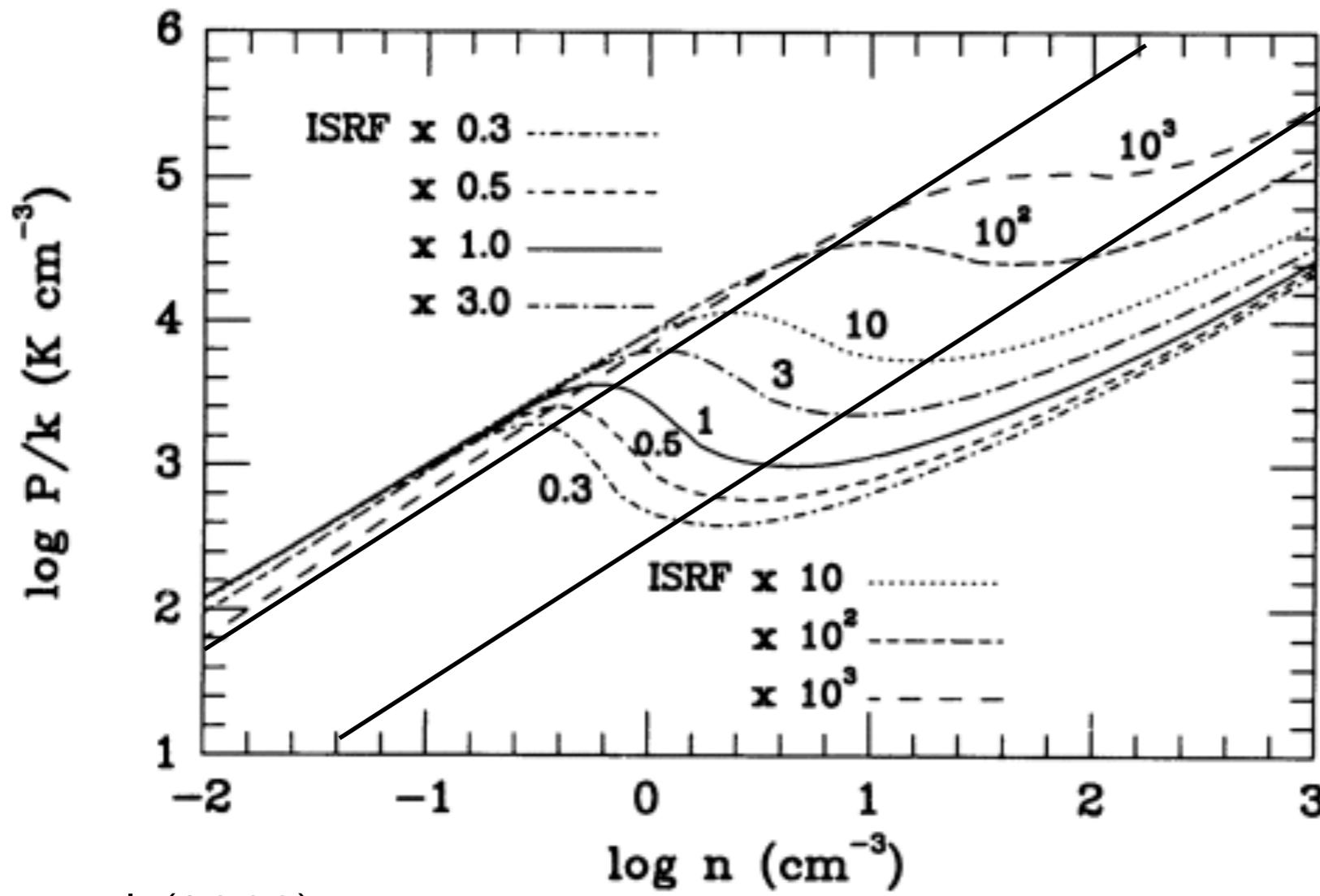
- p_* can be 10 times larger than other feedback
- $p_* = 2.8 \times 10^5 \langle n/1\text{cm}^{-3} \rangle^{-0.17} M_{\text{sun}} \text{ km/s}$ (CGK & Ostriker 2015a; see also Martizzi et al. 2015; Walch & Naab 2015; Iffrig & Hennebelle 2015)



CGK & Ostriker (2015a)

Thermal Pressure: FUV heating

- FUV heating is proportional to the SFR
- $n^2\Lambda(T)=n\Gamma \rightarrow P_{th} \sim nkT \sim [kT/\Lambda(T)]\Gamma \propto \Sigma_{SFR}$



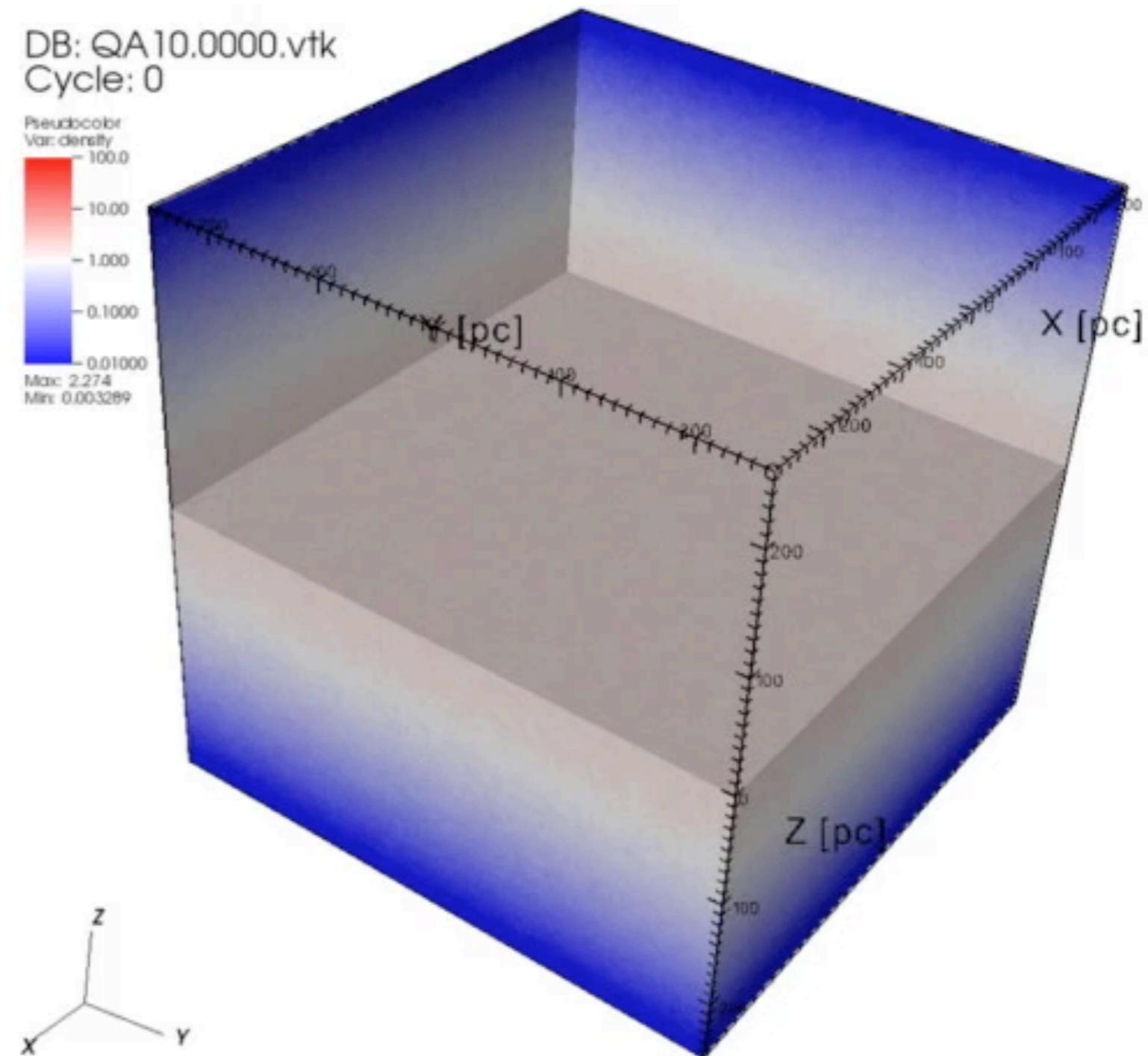
Ostriker, McKee, Leroy (2010)

Does this equilibrium really hold?

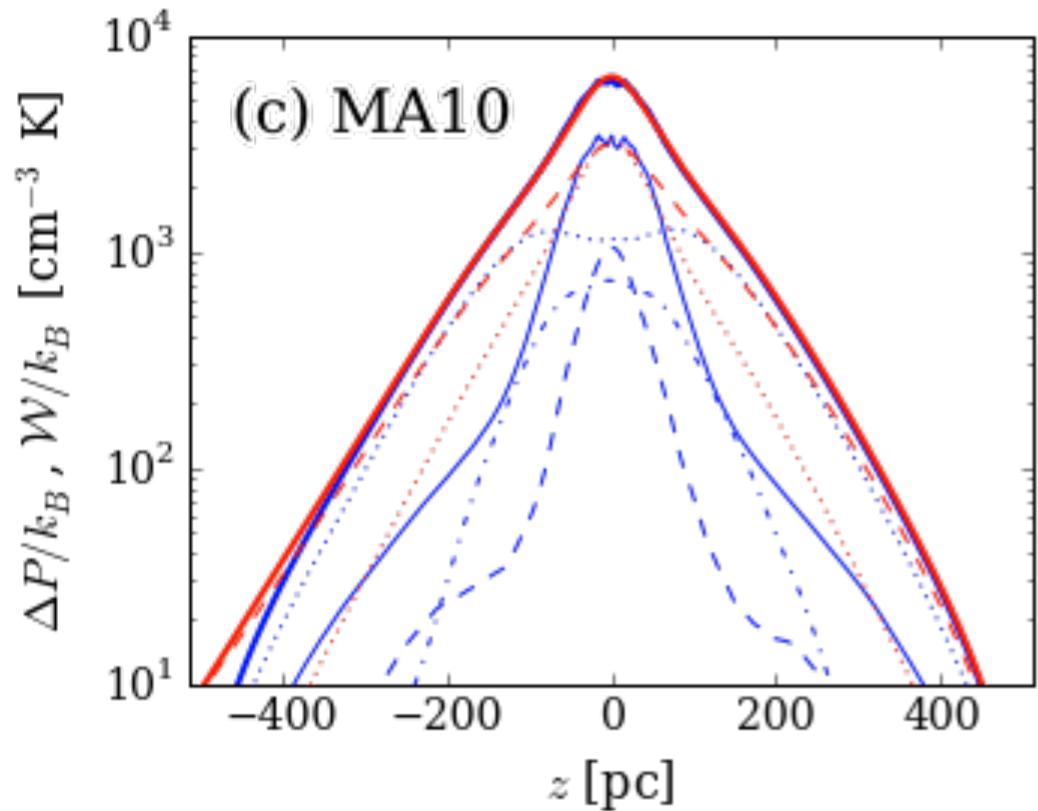
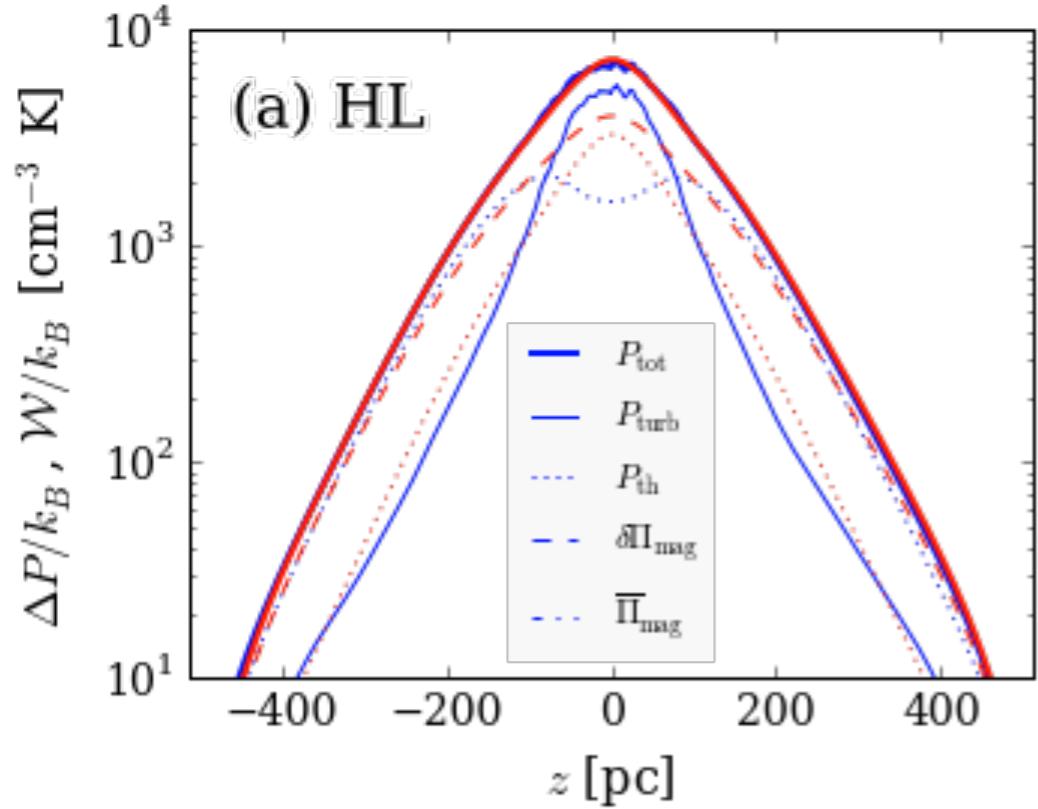
Simulations with self-consistent SN and FUV heating

CGK, Kim, Ostriker (2011); CGK, Ostriker, Kim (2013); CGK & Ostriker (2015b)

- momentum injection for SN (fixed p_*/m_*)
- SFR dependent heating rate
- external gravity
- self-gravity
- diff. rotation
- MHD (KO15b)



Vertical Force Balance (HSE)



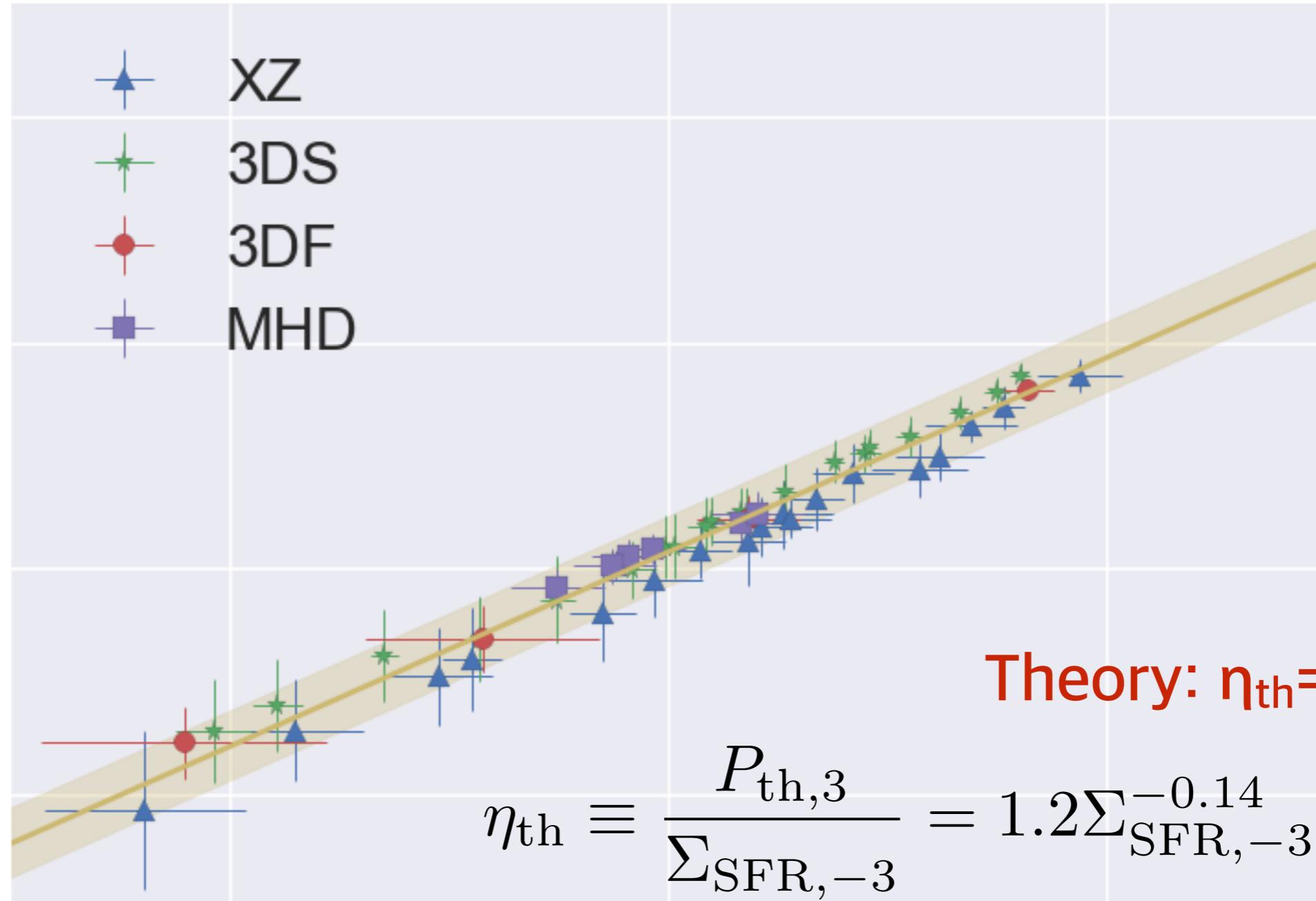
total pressure (thick blue)
turbulent (solid)
thermal (dotted)
turb. mag. (dashed)
mean mag. (dot-dashed)

II

total weight (thick red)
self (dotted)
external (dashed)

$\Sigma_{\text{SFR}} \rightarrow \text{Heating} \rightarrow P_{\text{th}}$

$$P_{\text{th},3}/k_B = \left(\frac{P/k_B}{10^3 \text{ cm}^{-3} K} \right) 10^2$$



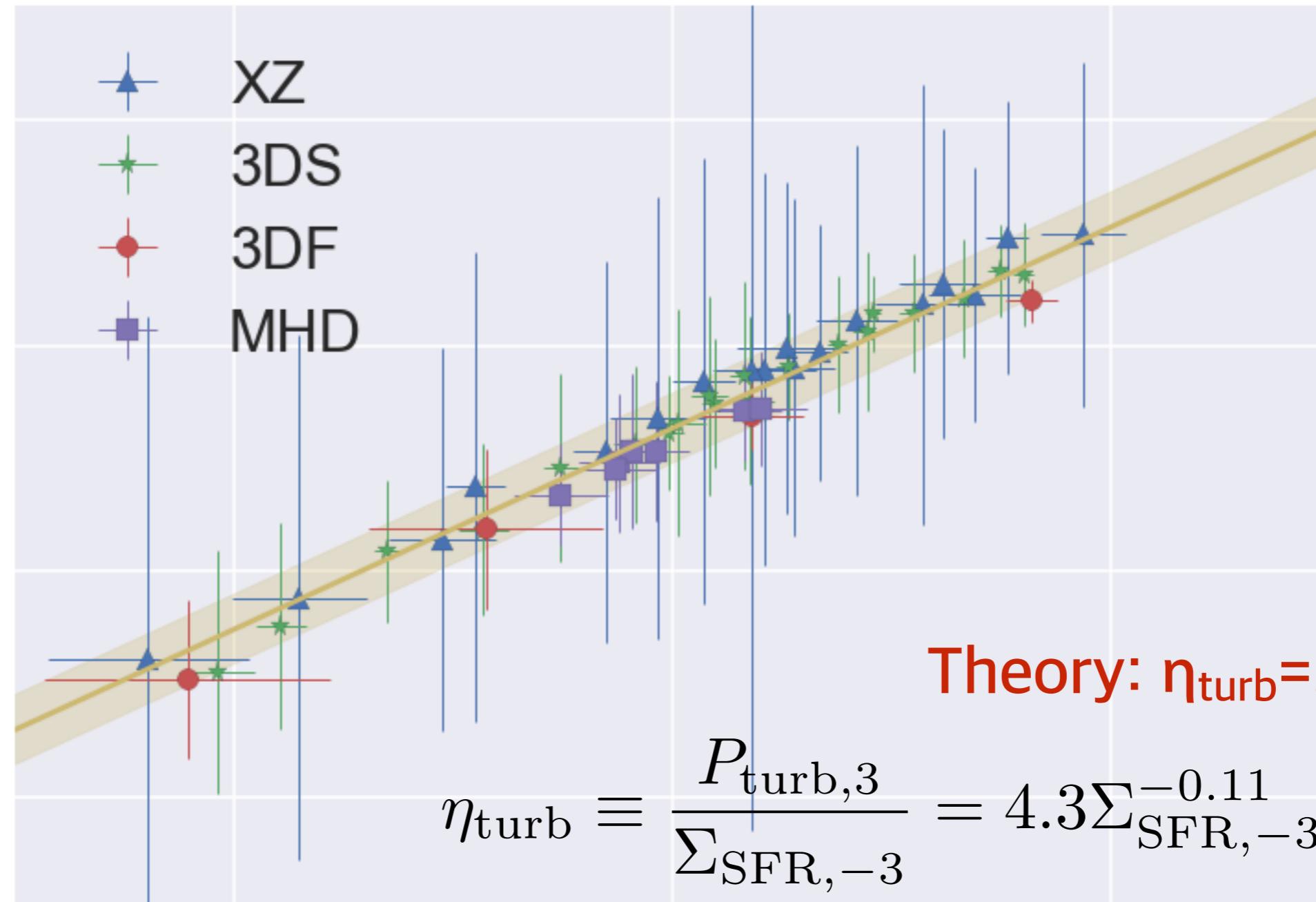
Theory: $\eta_{\text{th}}=1.2$

$$\eta_{\text{th}} \equiv \frac{P_{\text{th},3}}{\Sigma_{\text{SFR},-3}} = 1.2 \Sigma_{\text{SFR},-3}^{-0.14}$$

$$\Sigma_{\text{SFR},-3} = \left(\frac{10^1 \Sigma_{\text{SFR}}}{10^{-3} M_{\odot} \text{kpc}^{-2} \text{yr}^{-1}} \right)^{-1}$$

$\Sigma_{\text{SFR}} \rightarrow \text{Turbulence Driving} \rightarrow P_{\text{turb}}$

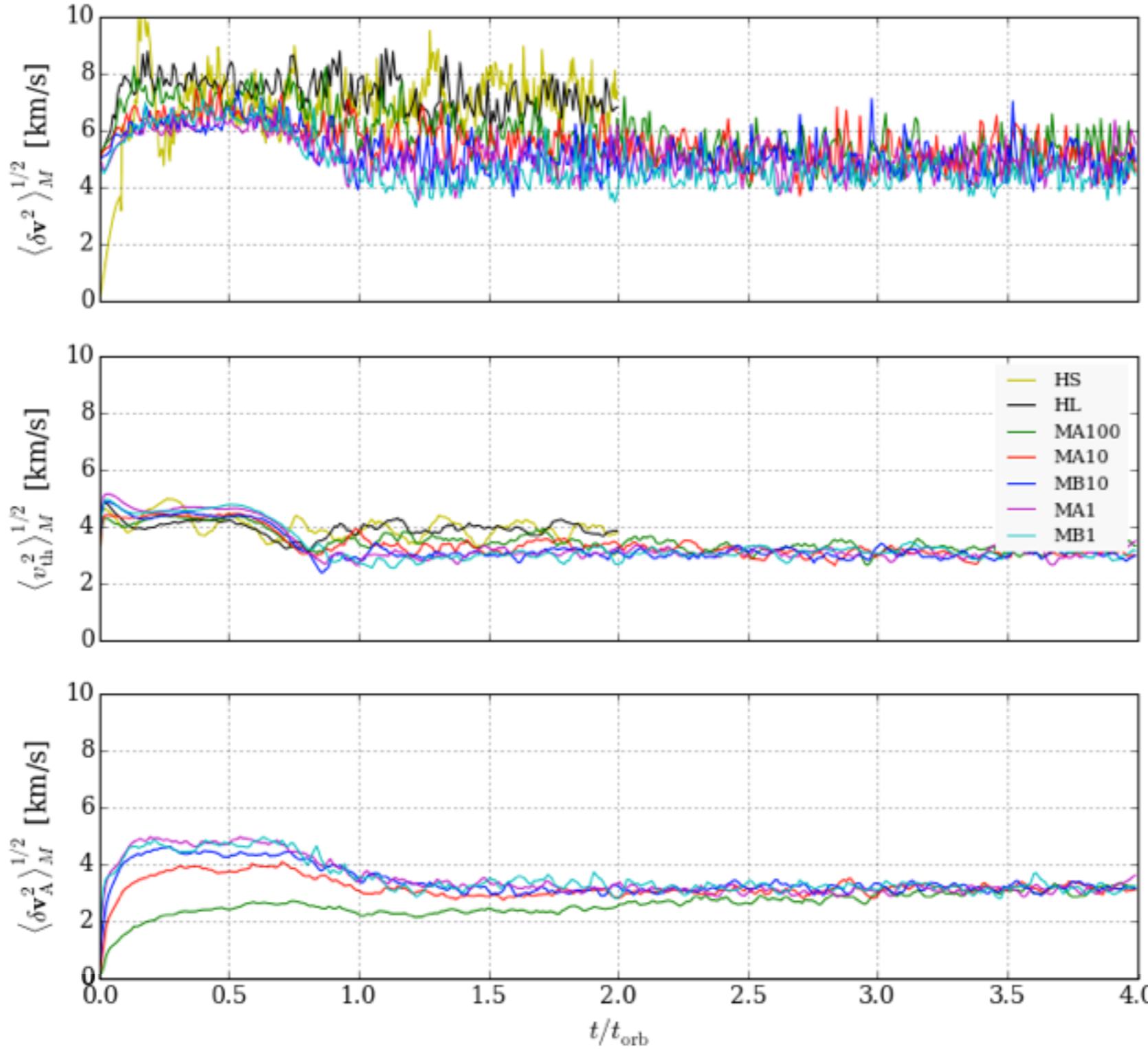
$$P_{\text{turb},3}/k_B = \left(\frac{P/k_B}{10^3 \text{ cm}^{-3} \text{ K}} \right)$$



$$\eta_{\text{turb}} \equiv \frac{P_{\text{turb},3}}{\Sigma_{\text{SFR},-3}} = 4.3 \Sigma_{\text{SFR},-3}^{-0.11}$$

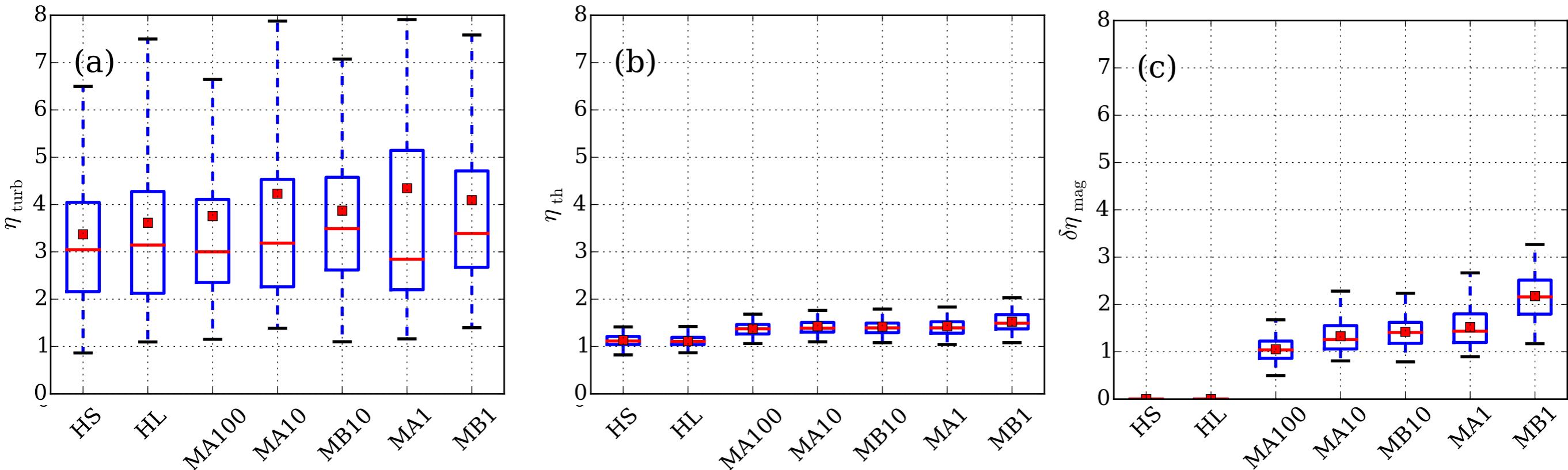
$$\Sigma_{\text{SFR},-3} \equiv \left(\frac{10^1 \Sigma_{\text{SFR}}}{10^{-3} M_{\odot} \text{kpc}^{-2} \text{yr}^{-1}} \right)^{-1}$$

Turbulent Magnetic Pressure: dynamo



- turbulent magnetic fields grow and saturate rapidly

$\Sigma_{\text{SFR}} \rightarrow \text{Turbulence} \rightarrow \text{Dynamo} \rightarrow \delta\Pi_{\text{mag}}$



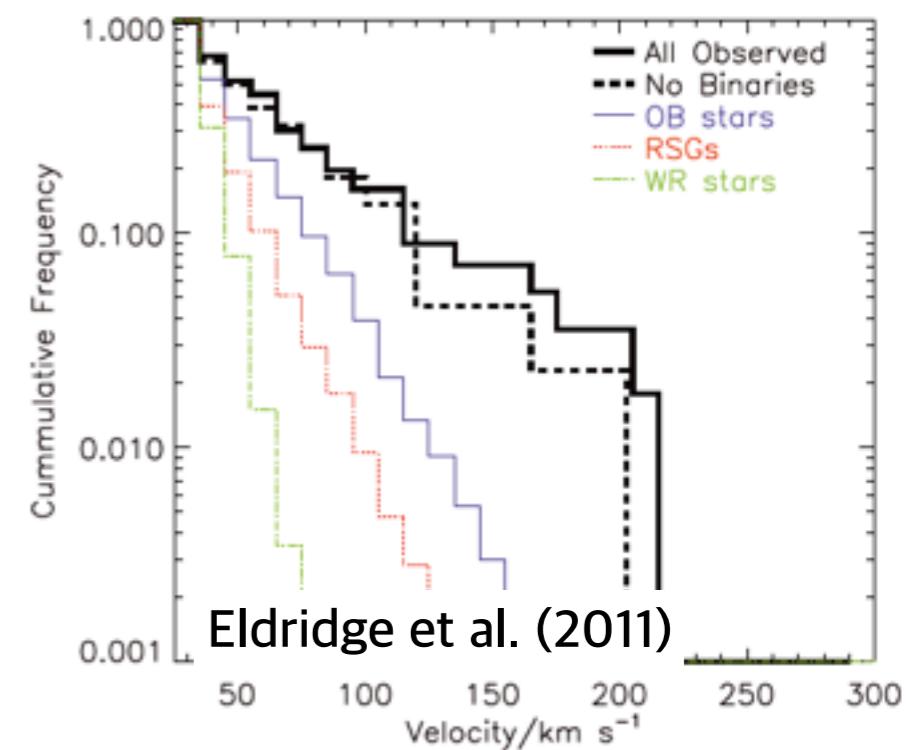
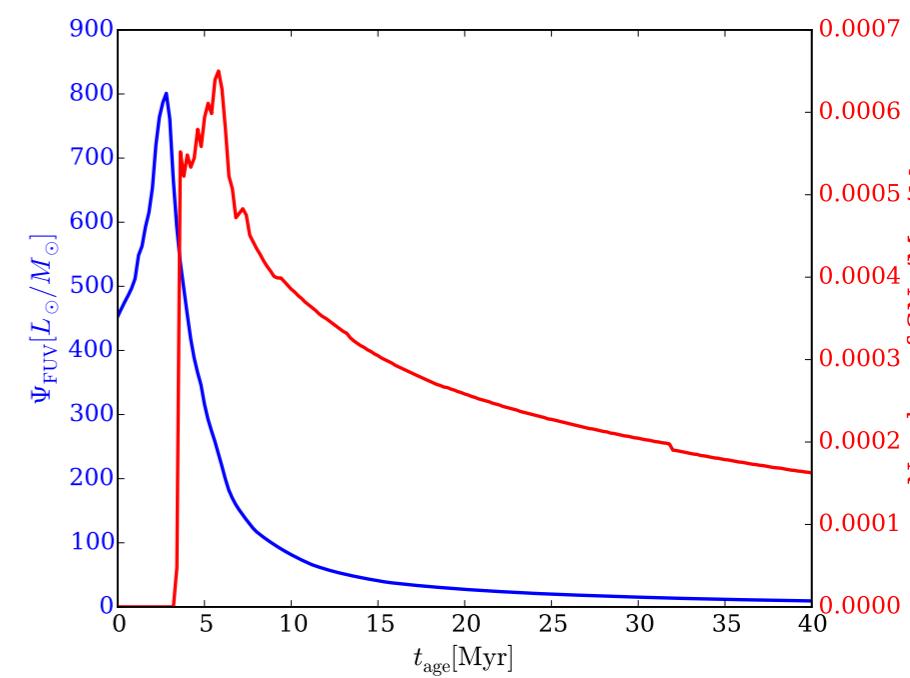
$$\eta \equiv \left(\frac{P/k_B}{10^3 \text{cm}^{-3} K} \right) \left(\frac{\Sigma_{\text{SFR}}}{10^{-3} M_\odot \text{kpc}^{-2} \text{yr}} \right)^{-1}$$

- No big difference between HD and MHD for $\eta_{\text{turb}}, \eta_{\text{th}}$
- $\delta\Pi_{\text{mag}} \sim P_{\text{driv}}/4$; $\delta\eta_{\text{mag}} \sim 1.4$
- Total feedback yield is larger in magnetized disks, while vertical force balance demands the same total support. So, SFR can be reduced with magnetic fields.
- magnetized ISM is more efficient converter for star formation feedback

stronger initial B

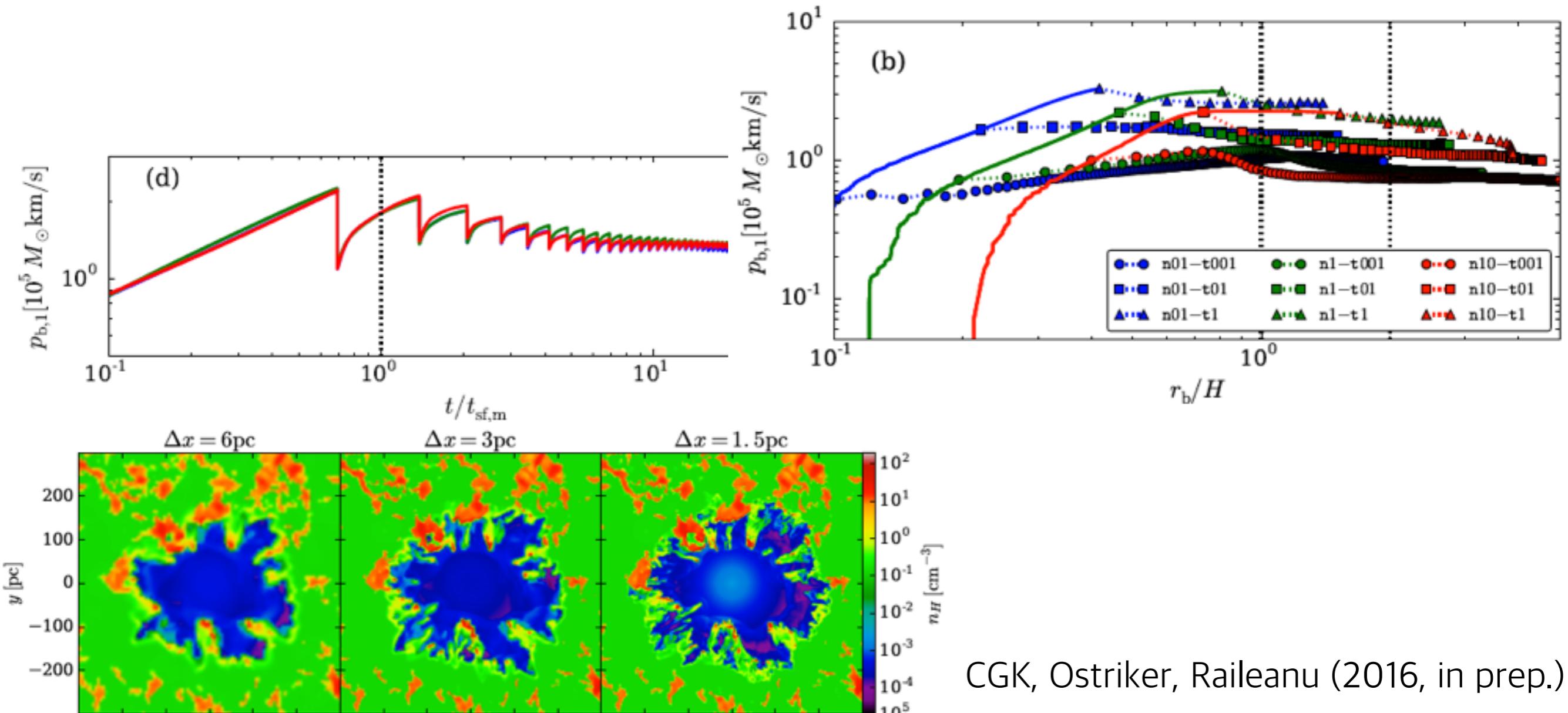
New Simulations

- **Self-consistent feedback from time-varying SFR**
 - Clusters: STARBURST99, fully sampled IMF, lifetime of 40Myr
 - Runaways: binary runaways, 1/3 of SNe
 - Resolved SN Feedback events (~90% in thermal energy; ~10% in momentum)
 - FUV heating (no radiative transfer)
- Magnetic fields with galactic differential rotation (Kim & Ostriker 15b)
- Long term evolution to reach self-regulated state ($\sim 3t_{\text{orb}} \sim 450 \text{ Myr}$)



Multiple, Correlated Supernovae

- p^* per SN $\sim (0.8\text{-}3) \times 10^5 M_{\odot} \text{ km/s}$
 - in contrast to 1D spherical result (Gentry et al. 2016)

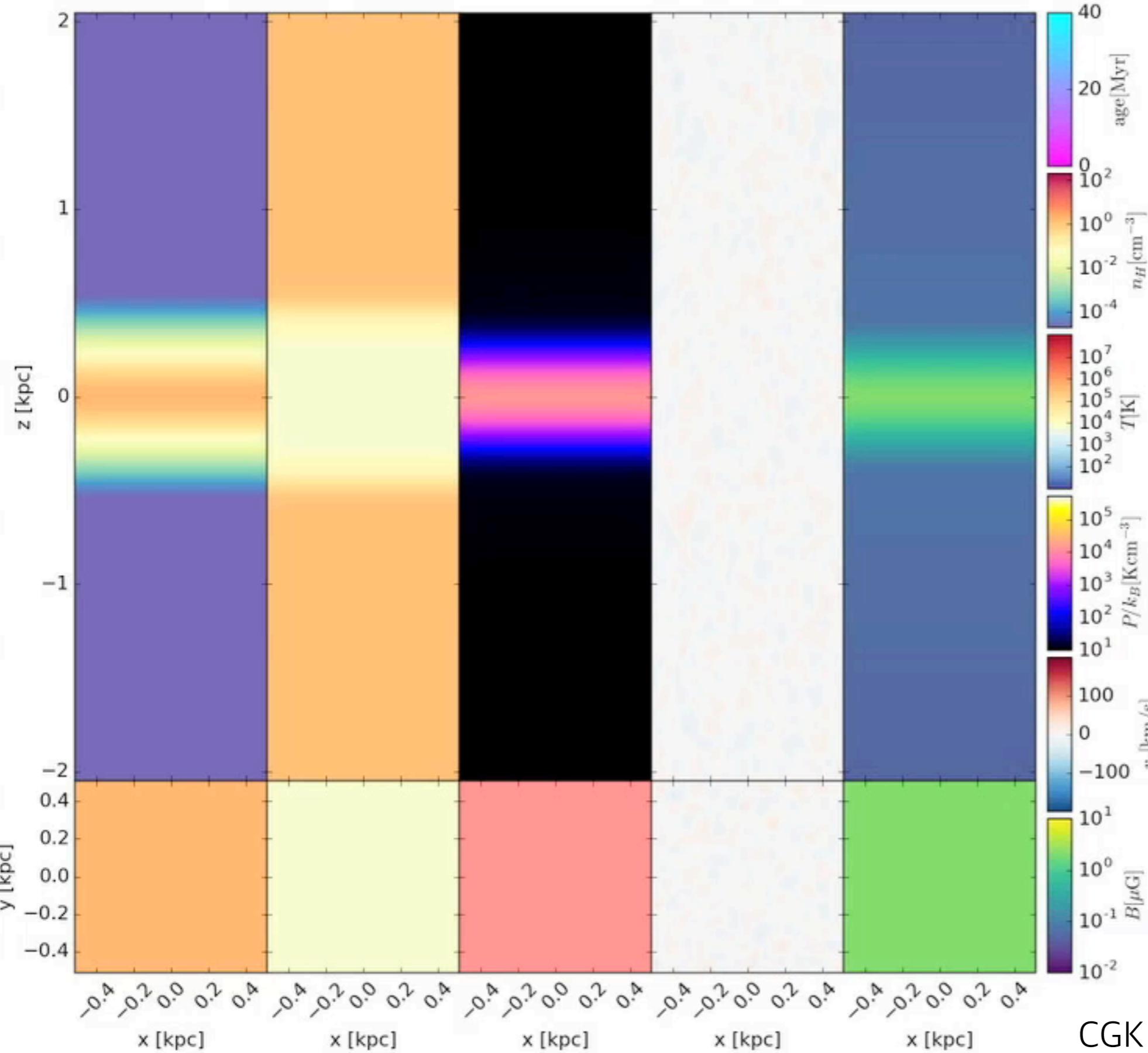


n_H

T

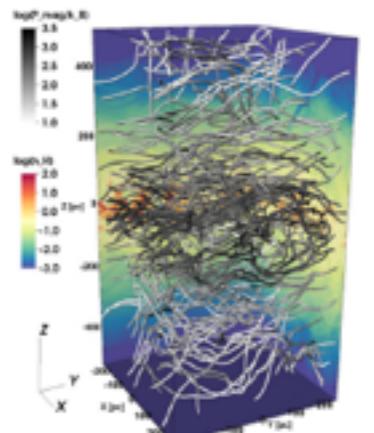
 P/k_B v_z

B

 $10^3 M_\odot$ $10^4 M_\odot$ $10^5 M_\odot$ 

Solar nbhd.
 $\Sigma \sim 10 M_{\text{sun}}/\text{pc}^2$
 $L_x = L_y \sim 1 \text{kpc}$
 $L_z \sim 4 \text{kpc}$
 $dx = 4 \text{pc}$

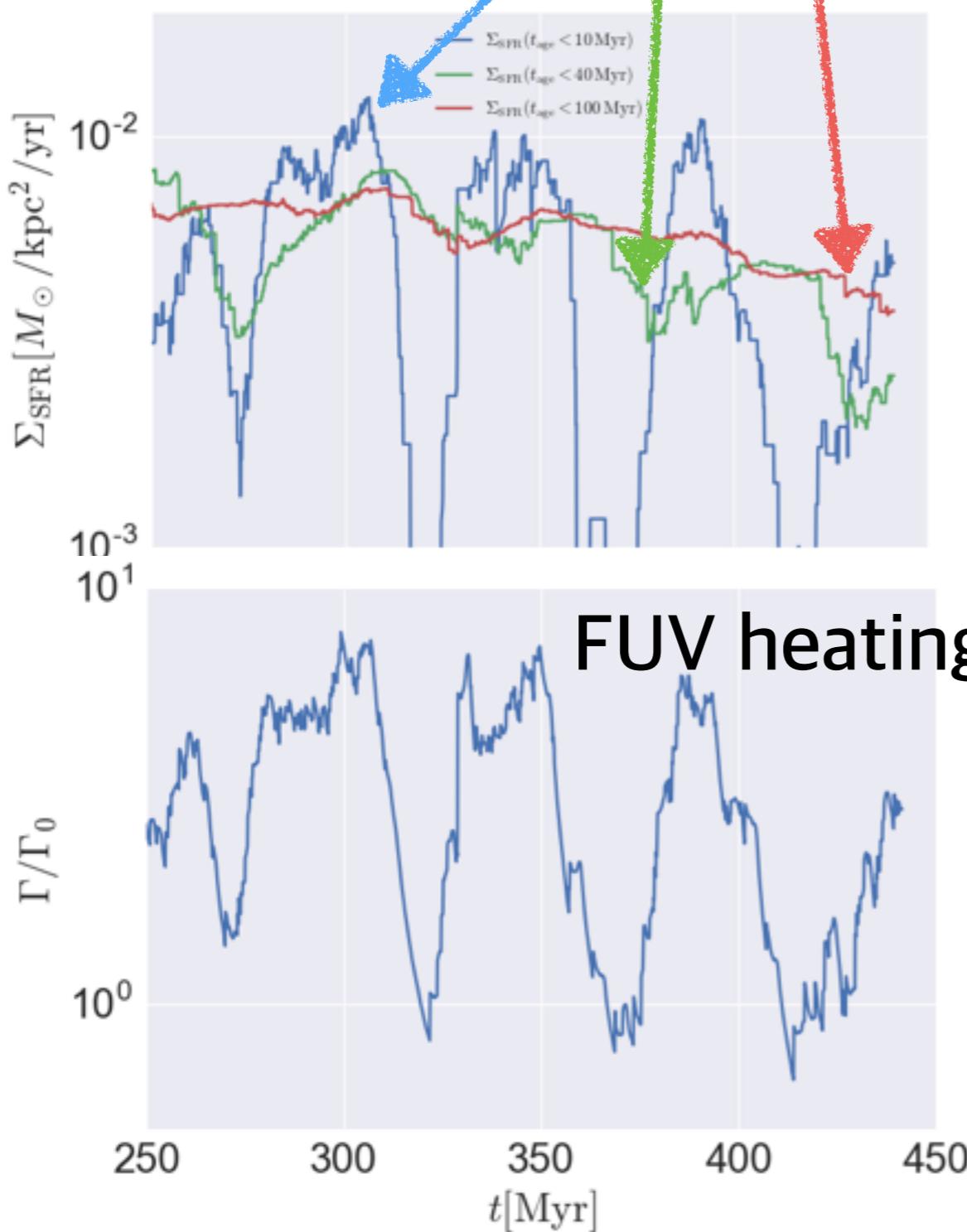
Athena MHD
uniform grid



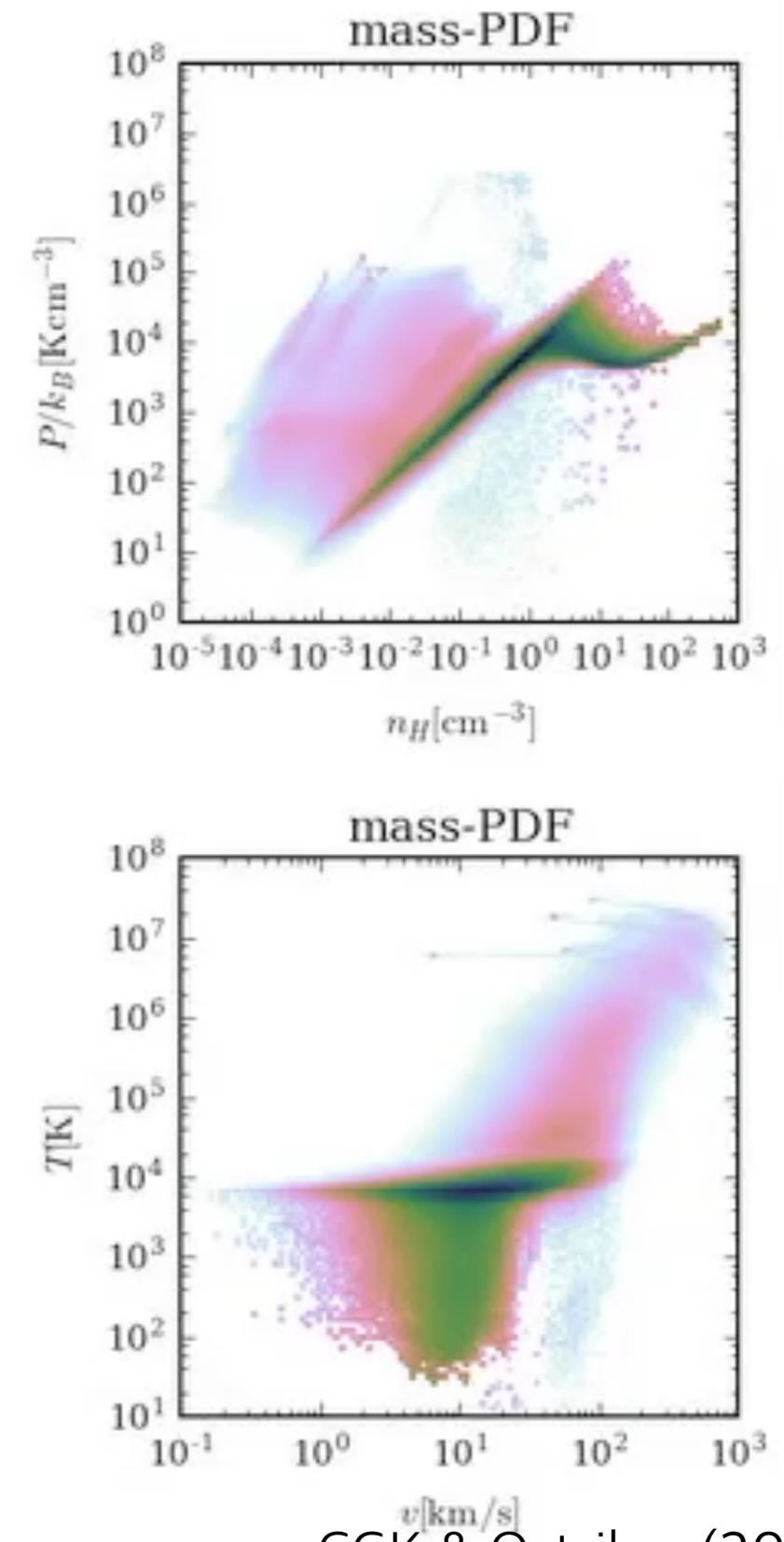
CGK & Ostriker (2016, in prep.)

SFR is self-regulated!

SFR for last 10, 40, 100 Myr



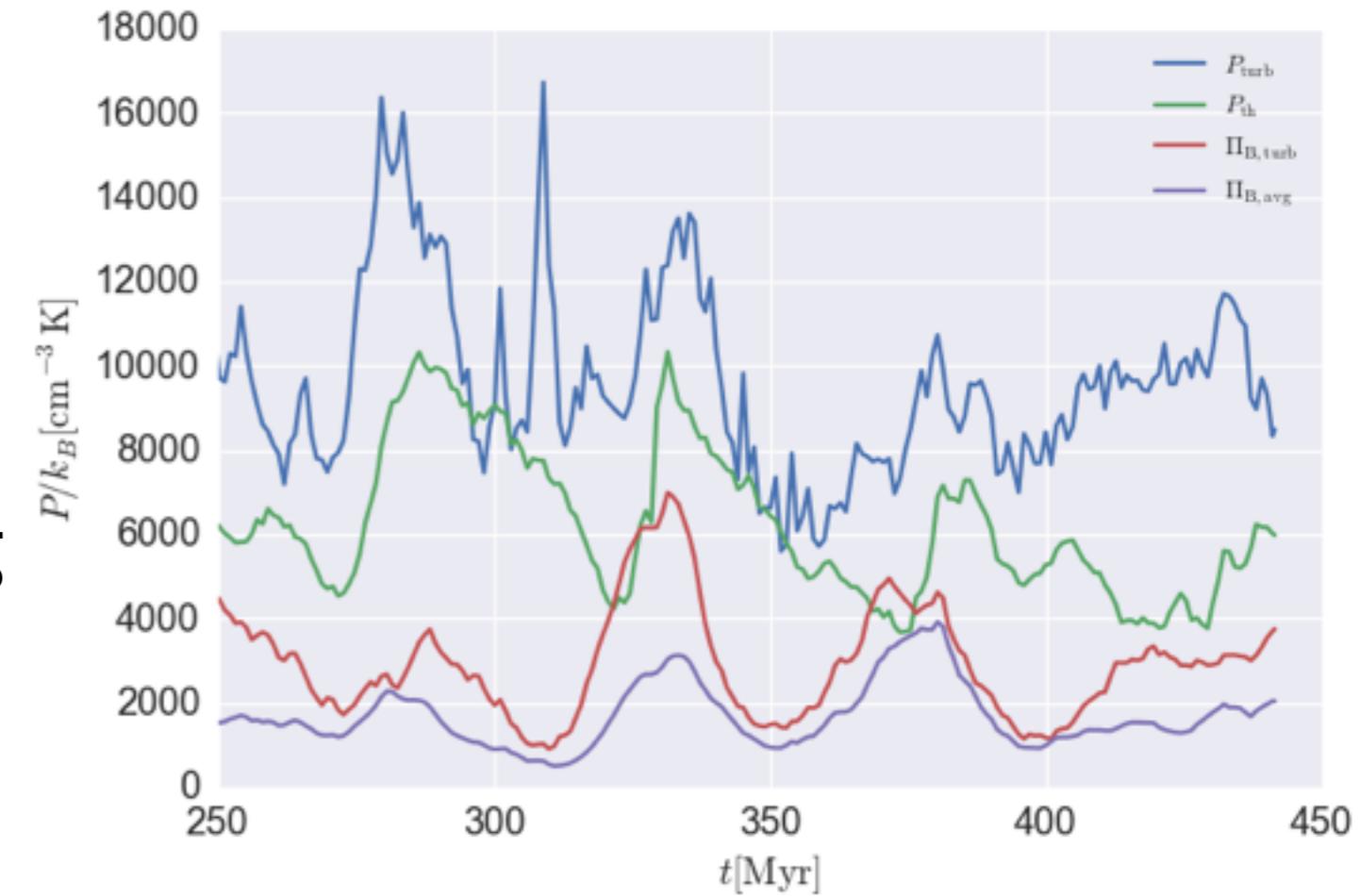
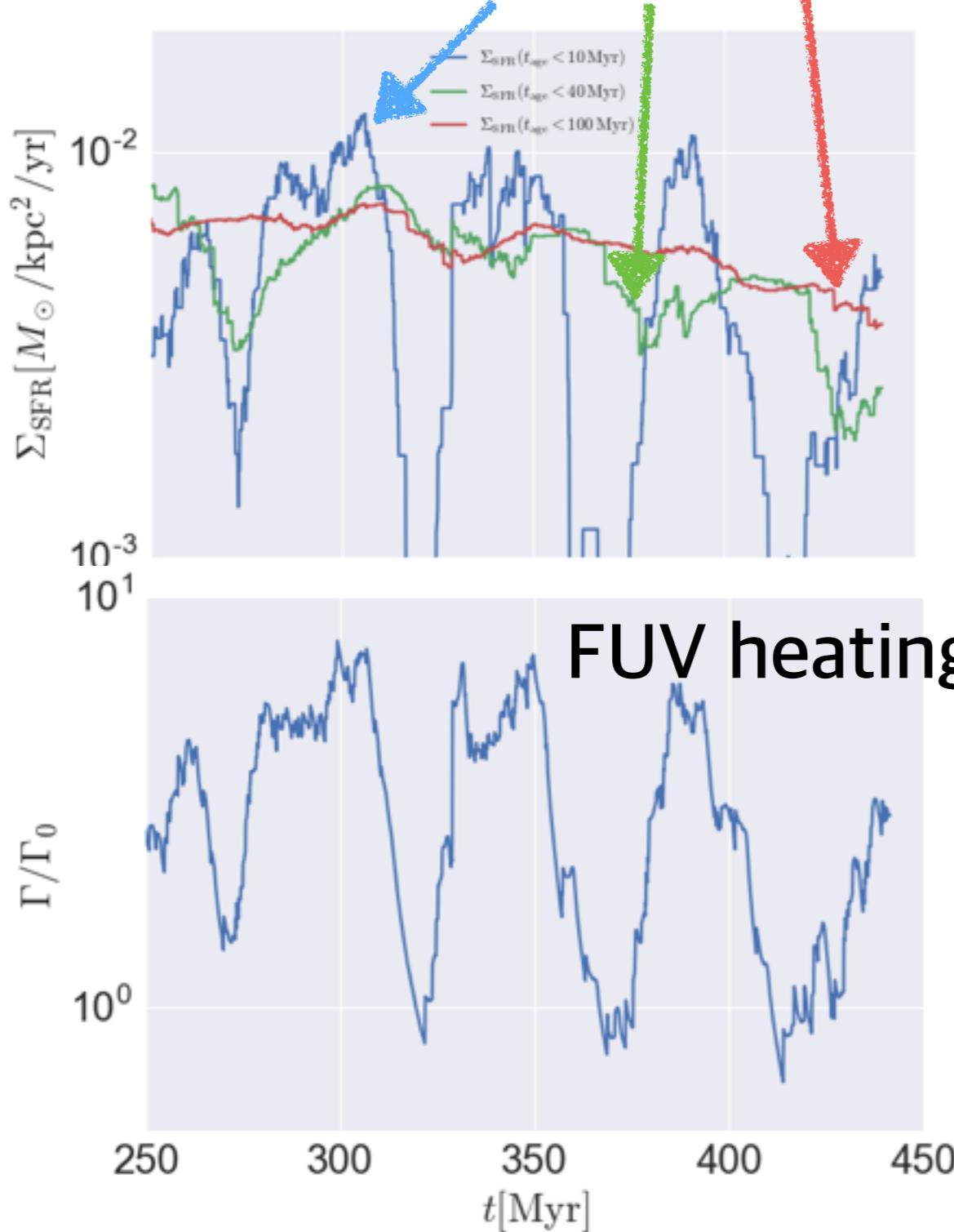
FUV heating



CGK & Ostriker (2016, in prep.)

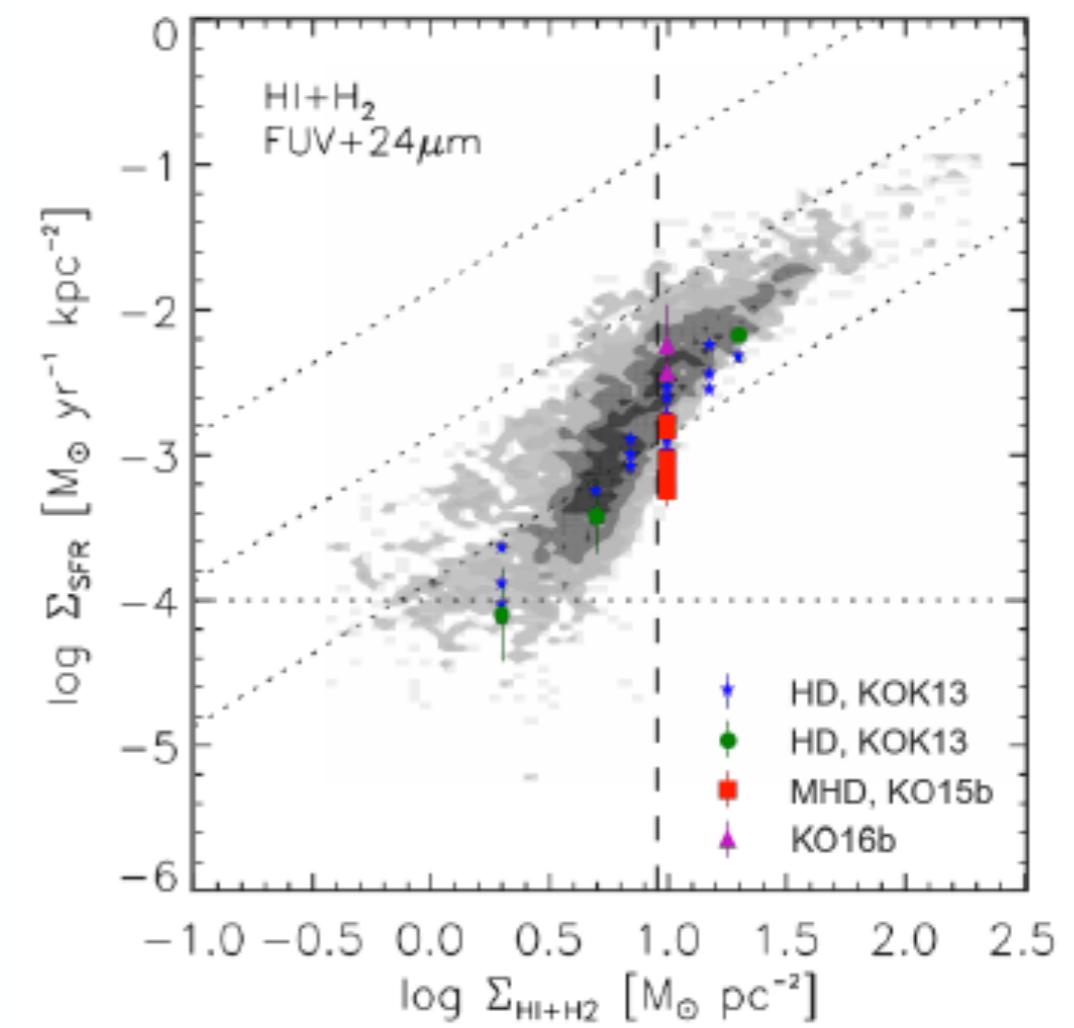
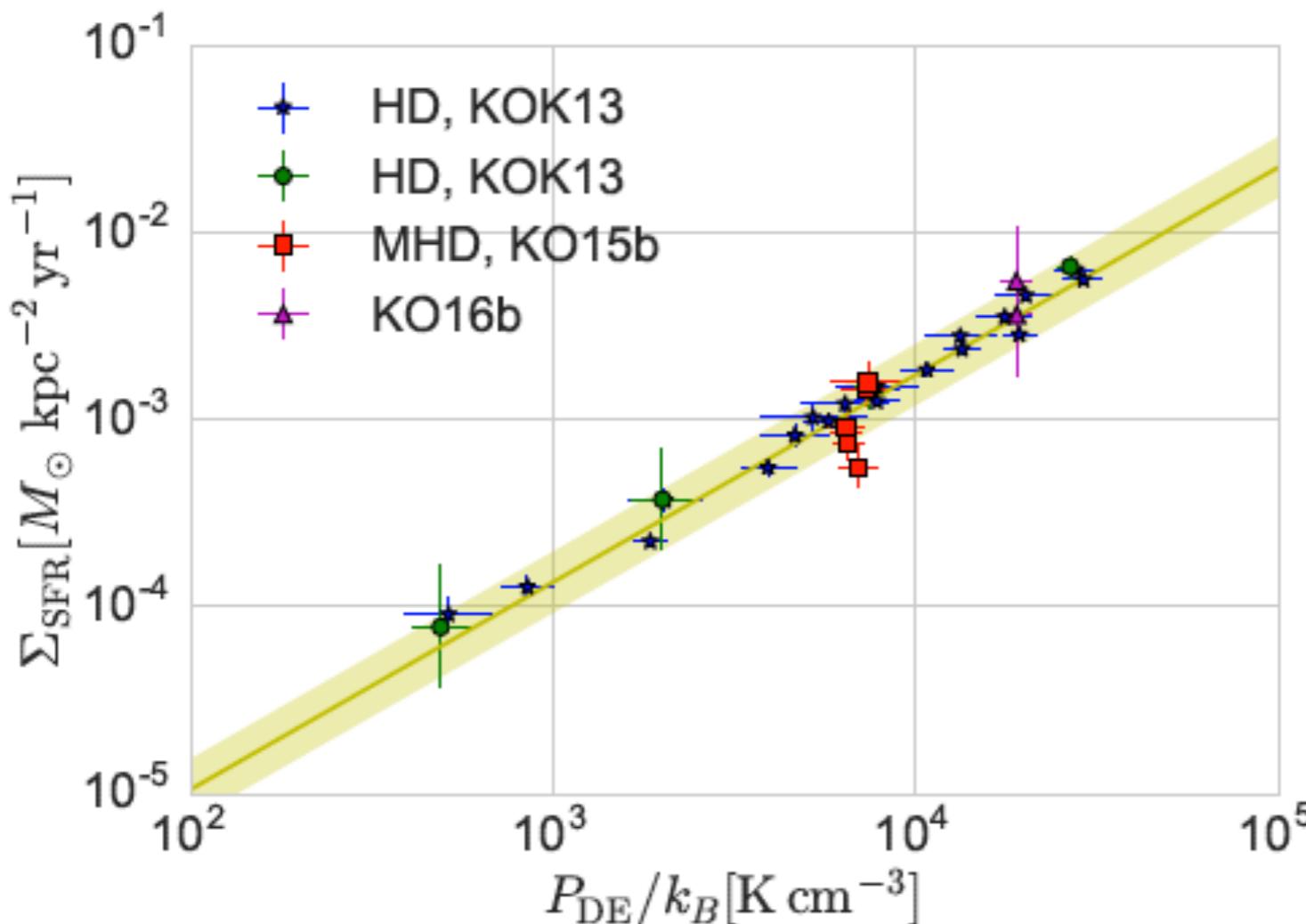
SFR is self-regulated!

SFR for last 10, 40, 100 Myr



$\Sigma_{\text{SFR}} - P$ vs $\Sigma_{\text{SFR}} - \Sigma$

- New simulation gives more realistic ISM properties as well as Σ_{SFR} ; but new and old simulations hold the same $\Sigma_{\text{SFR}} - P_{\text{DE}}$ relationship with $\eta_{\text{tot}} \sim 1000 \text{ km/s}$ (~ 5 in our units)

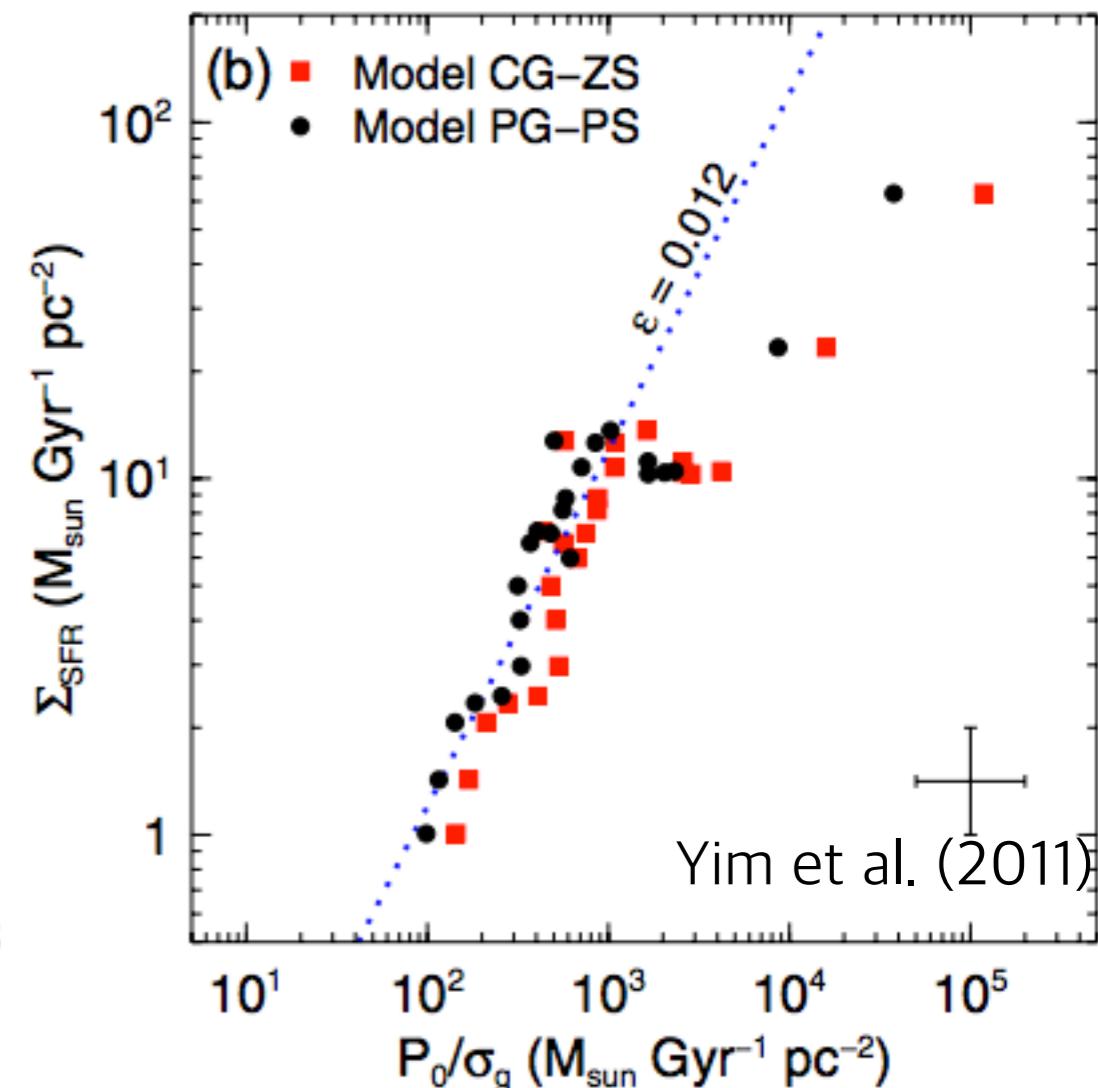
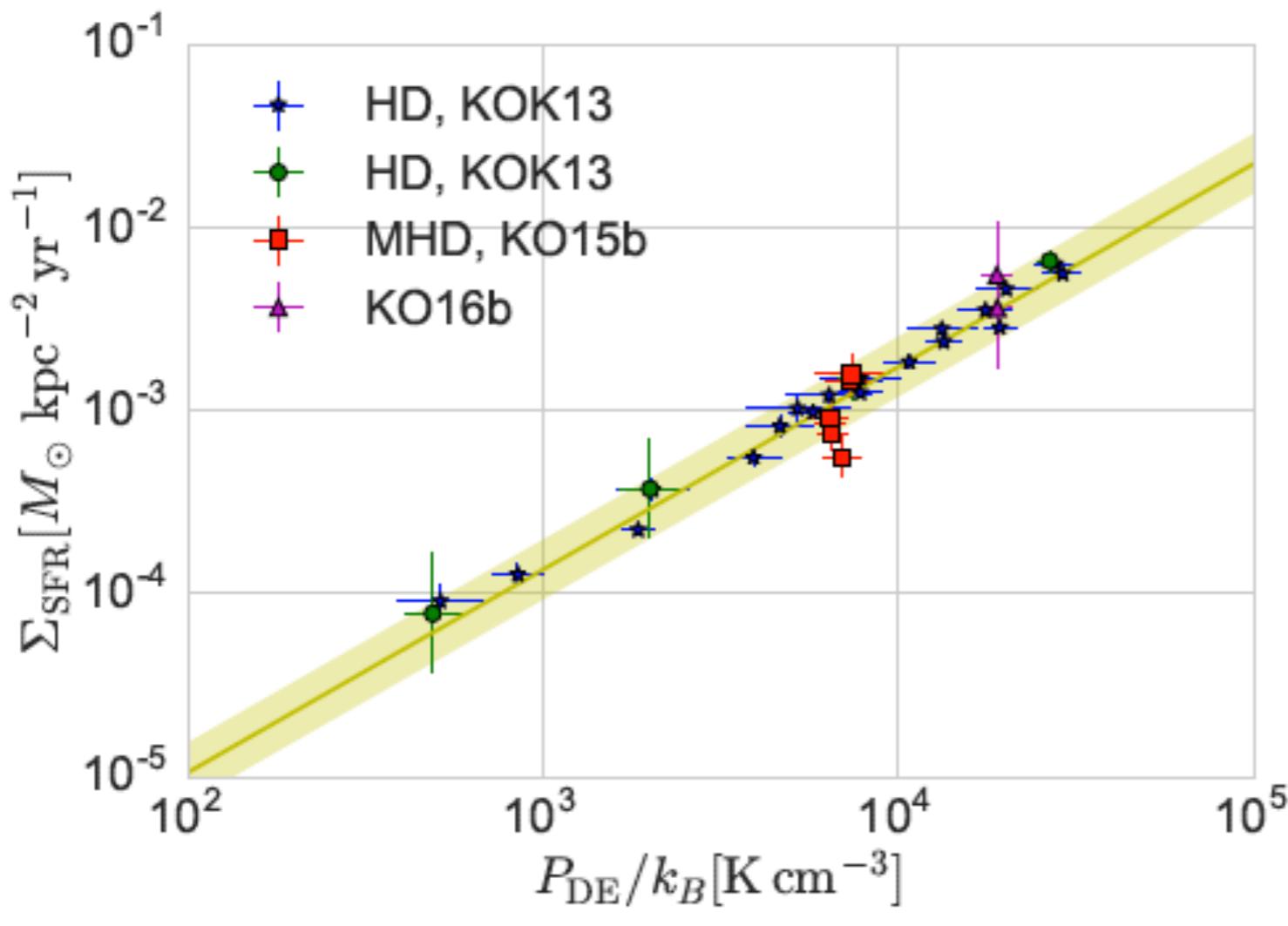


How Galaxies form Stars (locally)?

Caution: I'm talking about local “galactic” scales,
not local “cloud” scales

Dynamical Pressure sets SFR

- ISM demands certain level of SFR to provide (vertical) pressure support against (vertical) gravity
- Measure dynamical pressure!



How Galaxies form Stars (globally)?

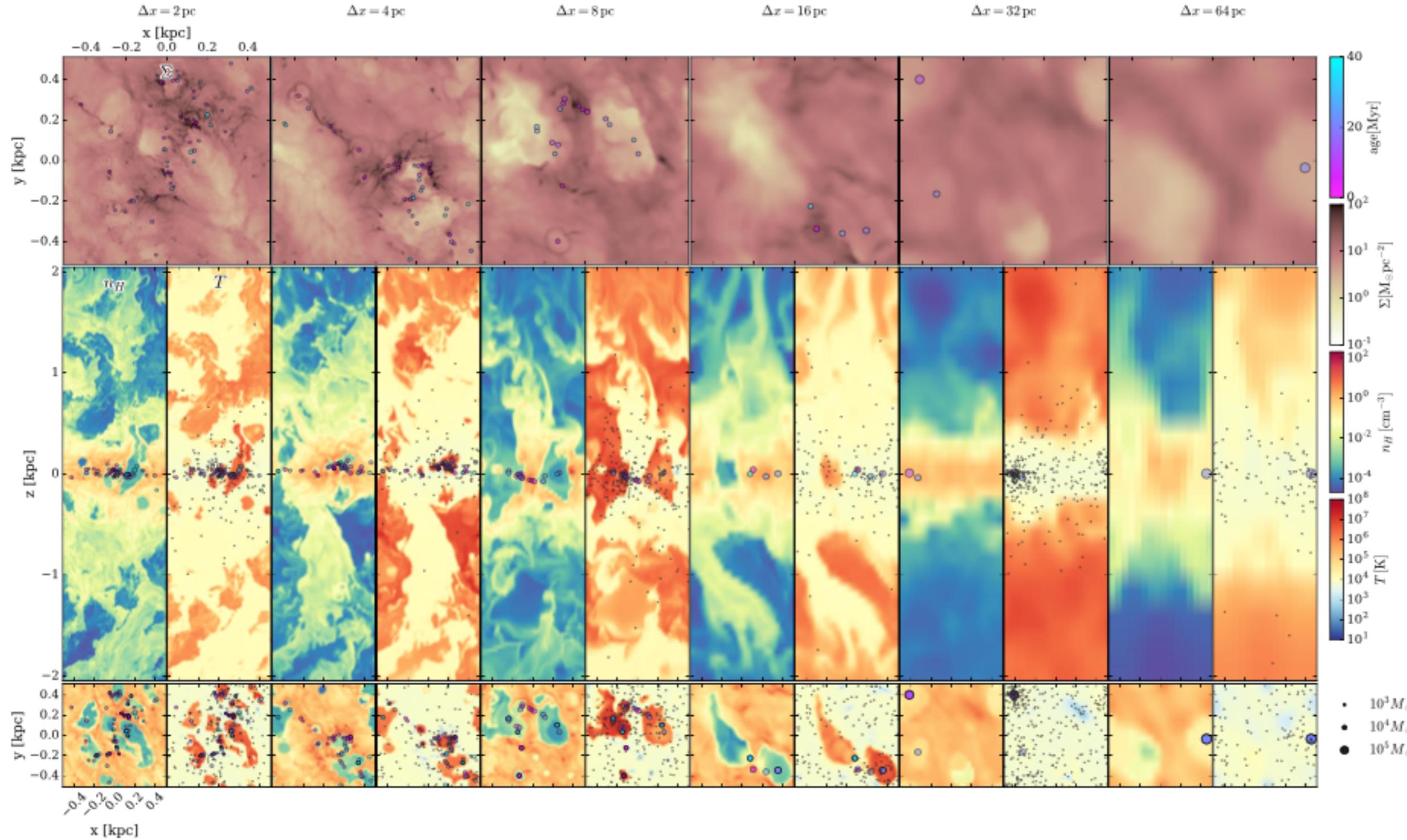
How the Universe Forms Stars?

- Need to understand both internal regulation and external gas exchanges (cosmic accretion and winds)
- What is the mass loading factor ($M_{\text{wind}}/M_{\text{SFR}}$)?
 - SAM
 - cosmological large volume simulations (EAGLE; Illustris)
 - cosmological zoom-in simulations

Caution for galaxy simulators

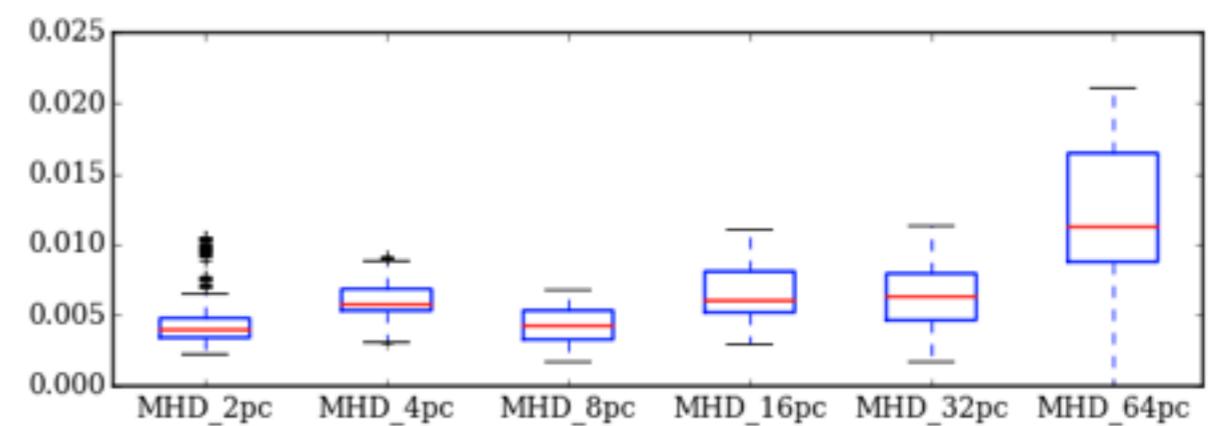
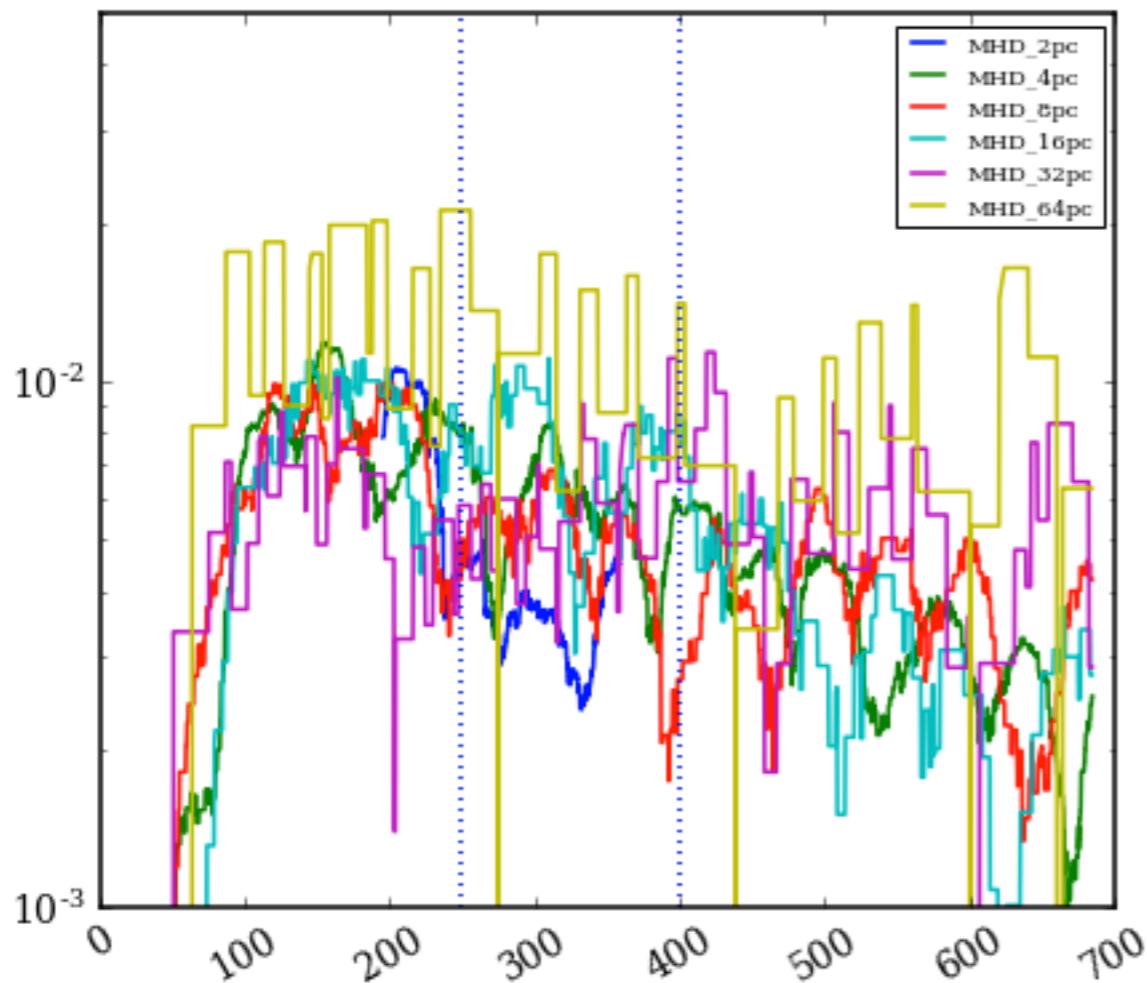
$\Delta x = 2 \text{ pc}$

$\Delta x = 64 \text{ pc}$



Caution for galaxy simulators

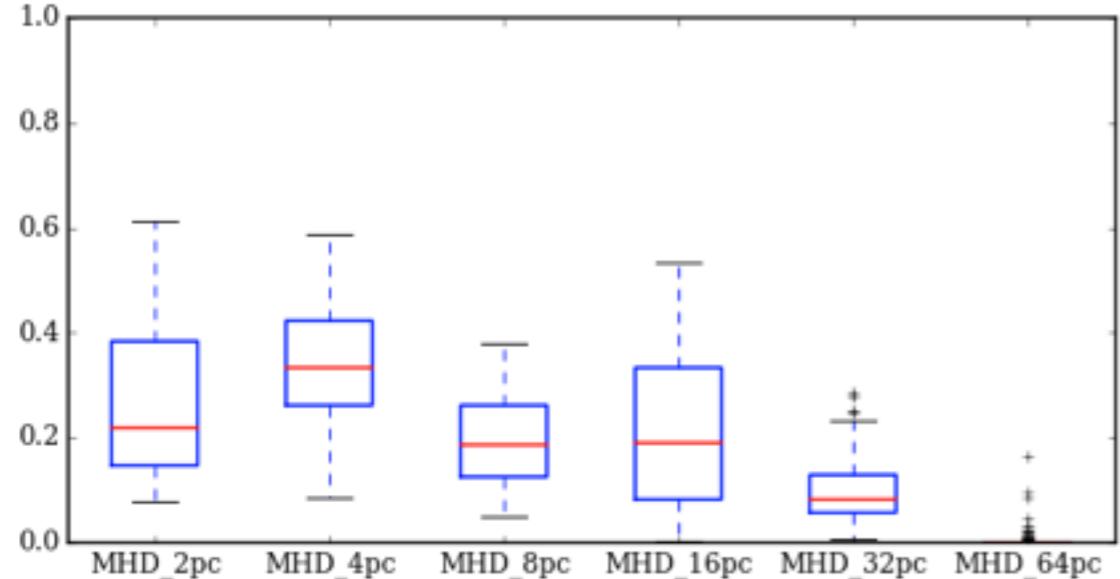
- If you do the right thing for feedback (in terms of total momentum injection), SFR is the easiest quantity to get right.



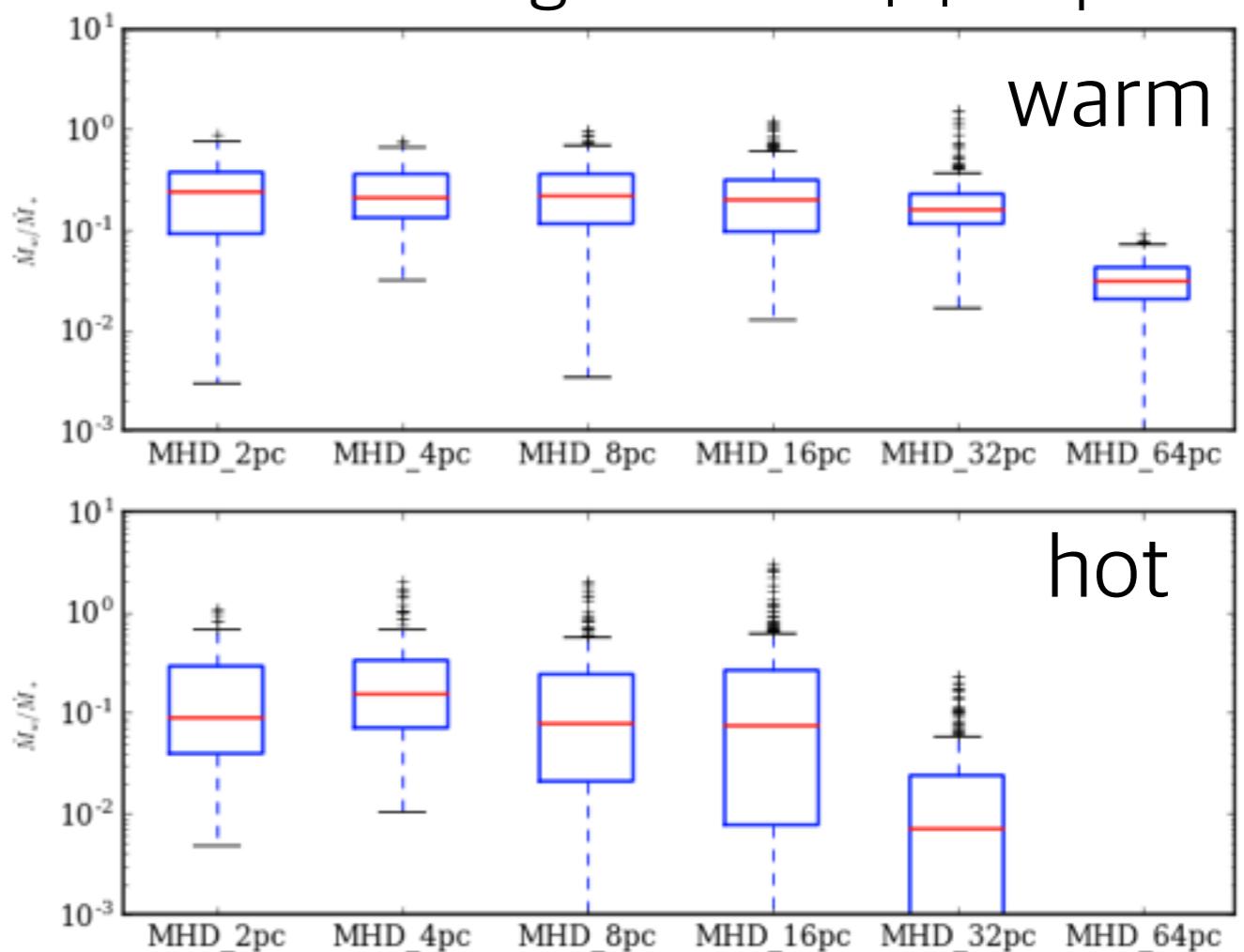
Caution for galaxy simulators

- If you do the right thing for feedback (in terms of total momentum injection), SFR is the easiest quantity to get right.
- Correct phase balance is the hardest.

Hot gas volume fraction at $|z|<0.5$ kpc



Mass loading factor at $|z|=2$ kpc



Summary

- Local galactic conditions demand certain level of SFR to provide proper pressure support.
 - different feedback will give you different pressure ratios
 - non-feedback pressure can reduce total SFR demands
- SF process is very efficient in energy and momentum generation so that inefficient in gas consumption.
- Connection to
 - larger scales require global modeling of galaxies in isolation and/or cosmological (zoom-in) simulations; caution that SF feedback has to be resolved. don't stop when you get “right” SFRs
 - smaller scales require more sophisticated simulations including radiation and chemistry with MHD.