Numerical Modeling of Multiphase, Turbulent Galactic Disks with Star Formation Feedback

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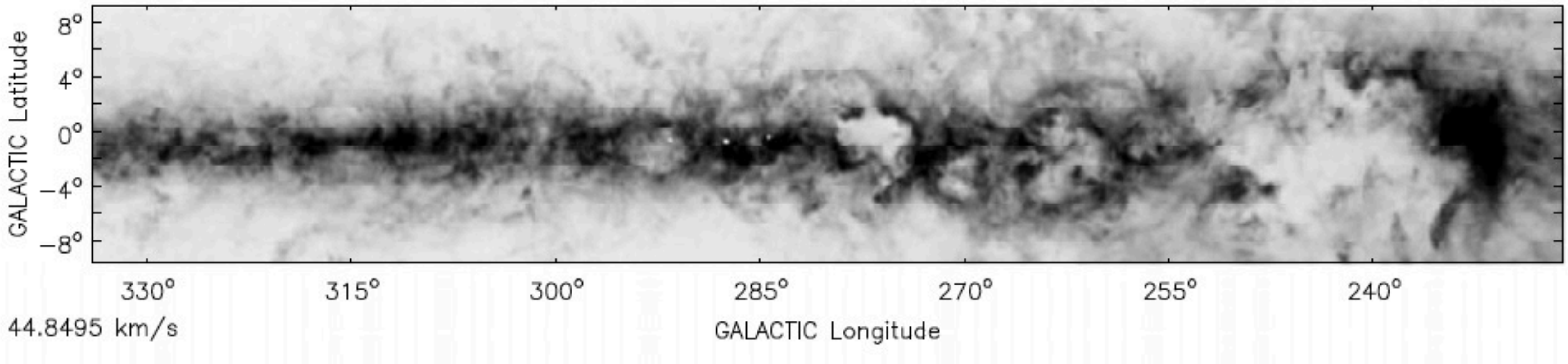
IAU GA XXVIII - Beijing, August 2012 - SpS12 - Modern Views of the ISM

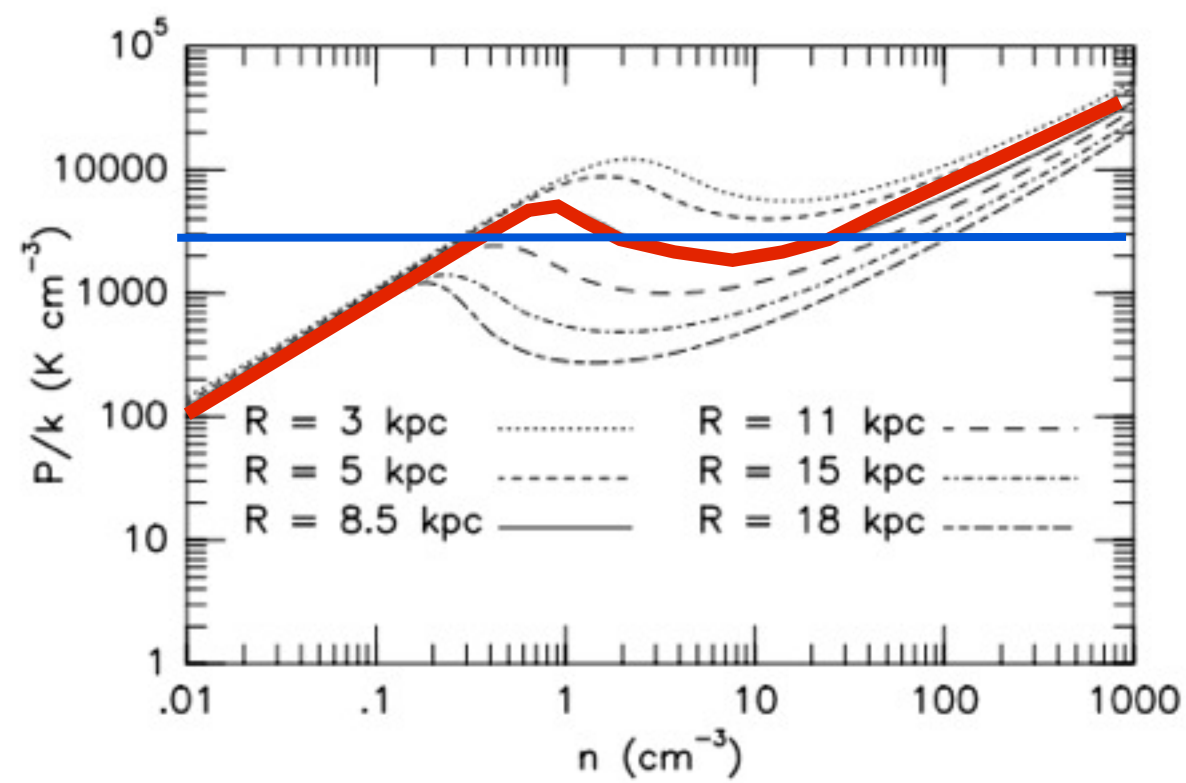
How does the ISM look like?



The frothy ISM; GASS (McClure-Griffith 2012)

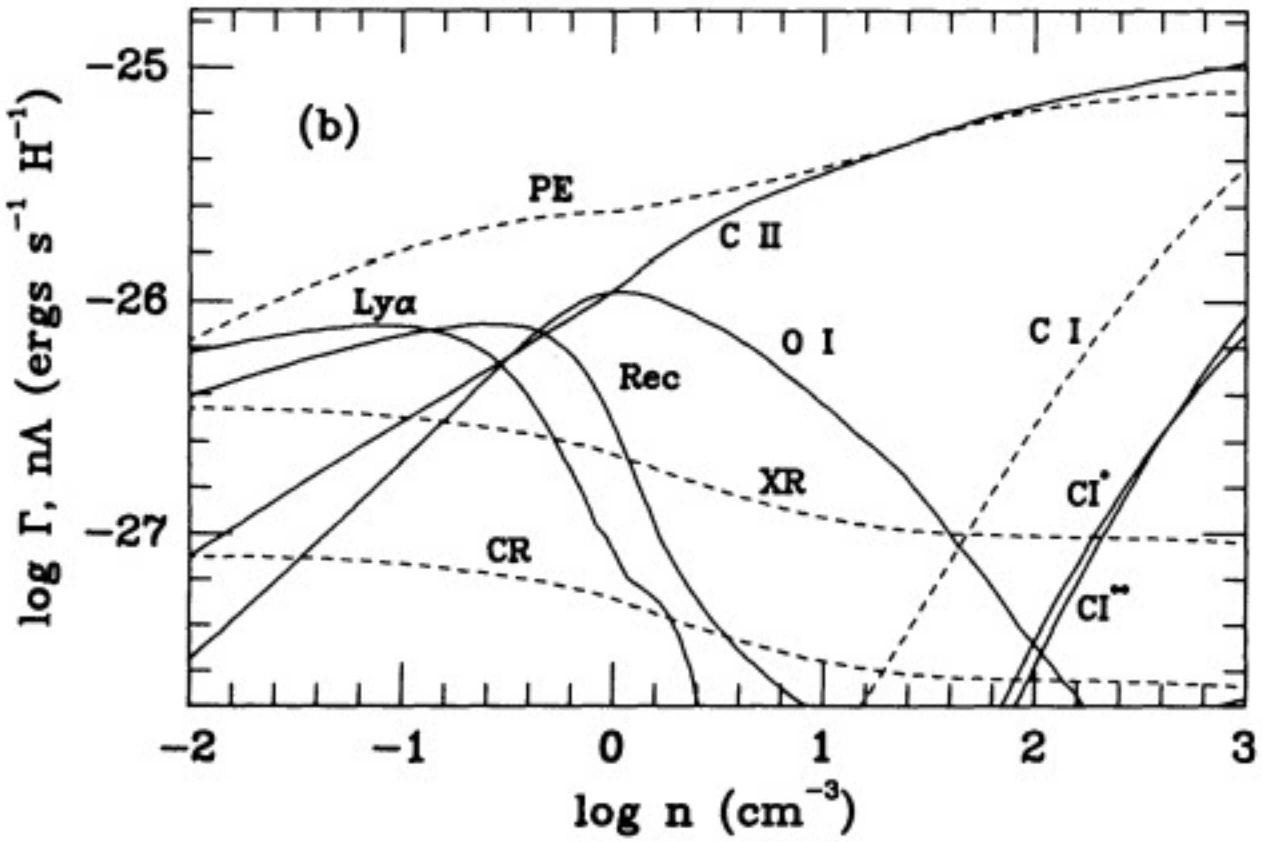
Atomic ISM (FGH 1969; Wolfire+ 1995)

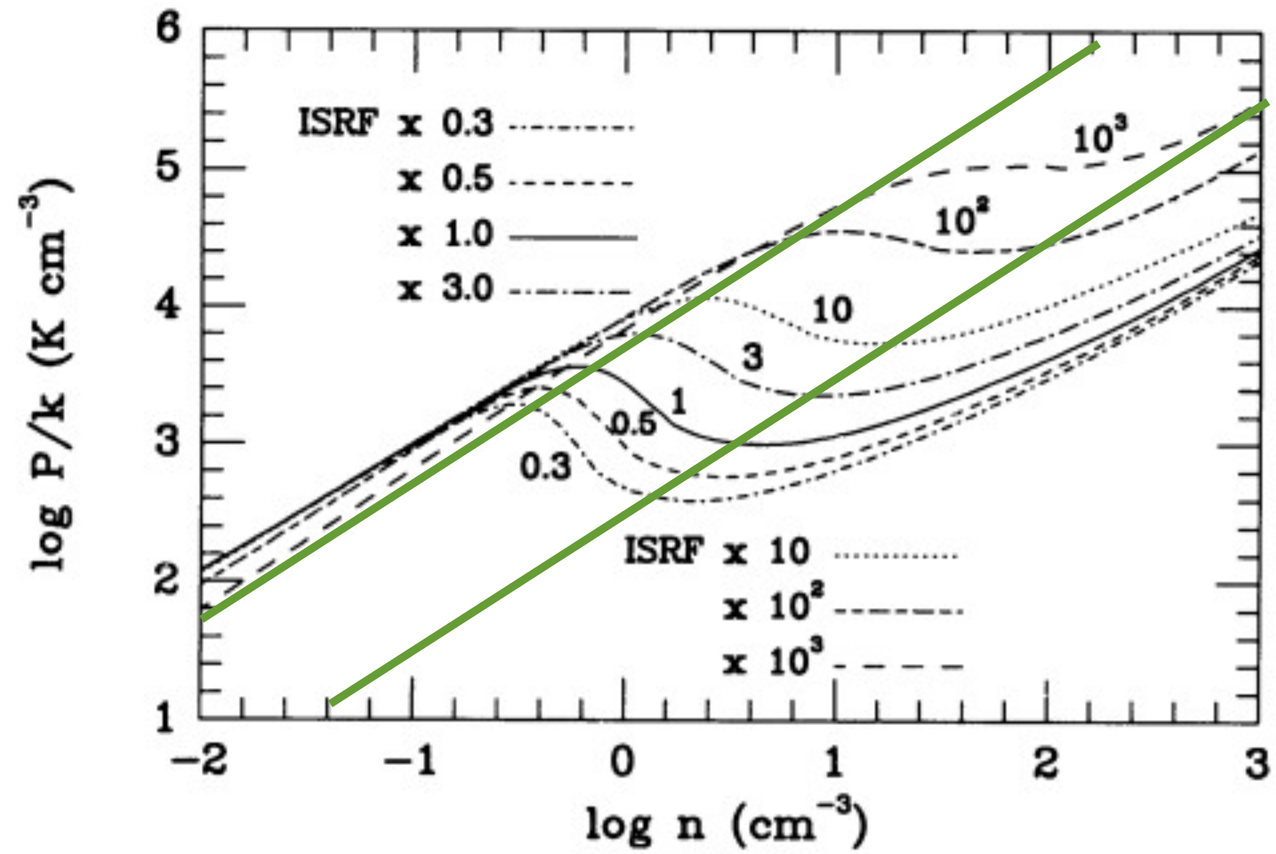
- WNM: $n \sim 0.3 cm^{-3}$; $T \sim 8000K$
- CNM: $n \sim 30 cm^{-3}$; $T \sim 80K$
- coexist in pressure equilibrium



Wolfire et al. (2003)

Wolfire et al. (1995)





cooling

- fine structure line cooling by CII - low T
- Ly-alpha radiation and e-recombination - high T

heating

- photoelectric heating by FUV radiation

$$\Gamma \propto J_{\rm FUV} \propto f_{\rm rad}\Sigma_{\rm SFR}$$

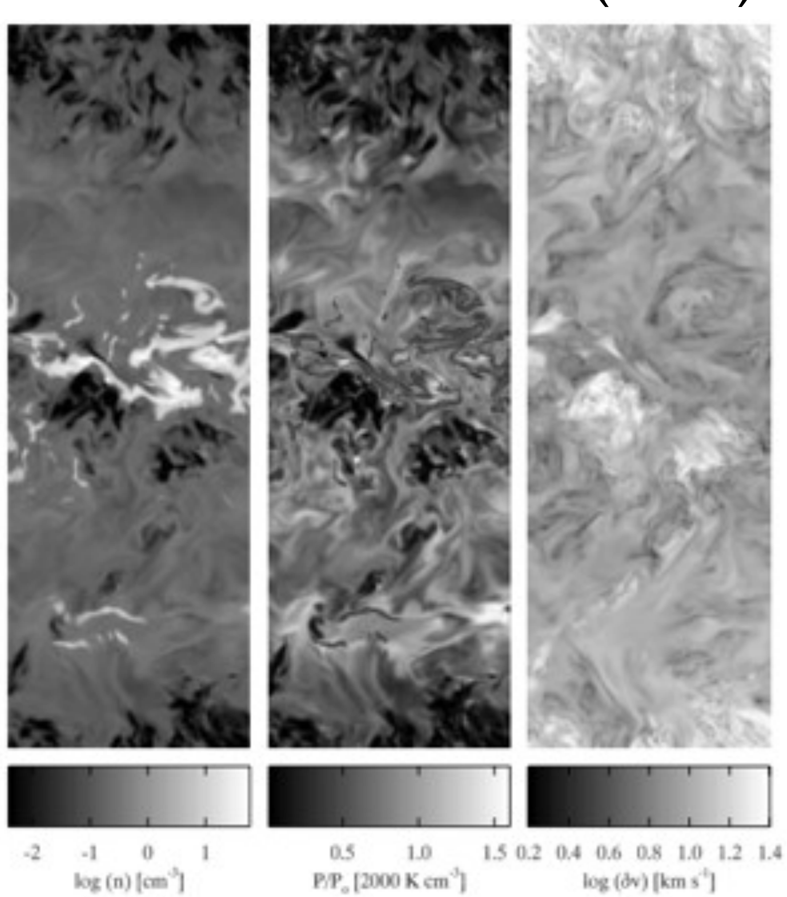
ISM is turbulent - non-thermal line width of ~7-10 km/s (e.g., Heiles & Troland 2003)

energy driving sources - necessary for sustaining supersonic turbulence (Stone et al. 1998; Mac Low et al. 1998)

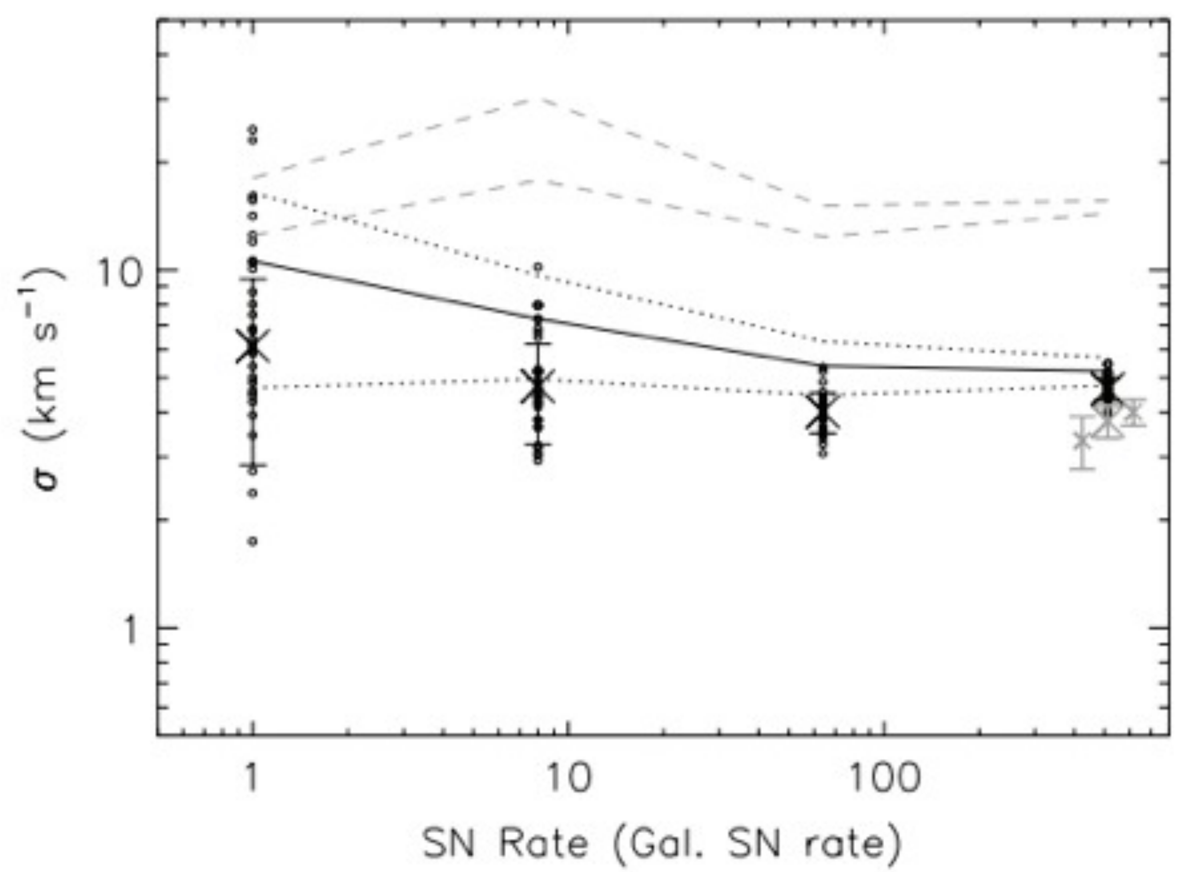
- stellar sources - stellar winds, outflows, supernovae
- non-stellar sources - gas dynamical instabilities (GI, TI, MRI, ...), galactic spiral shocks

SNe are dominant in terms of magnitude

Piontek & Ostriker (2007)

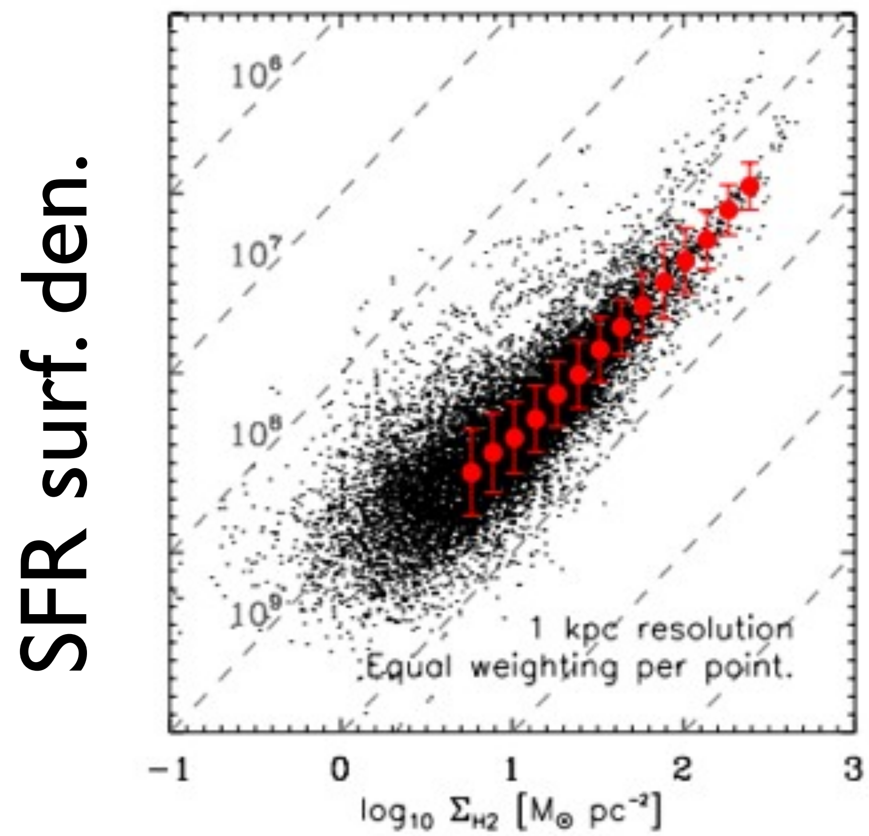


Joung et al. (2009)

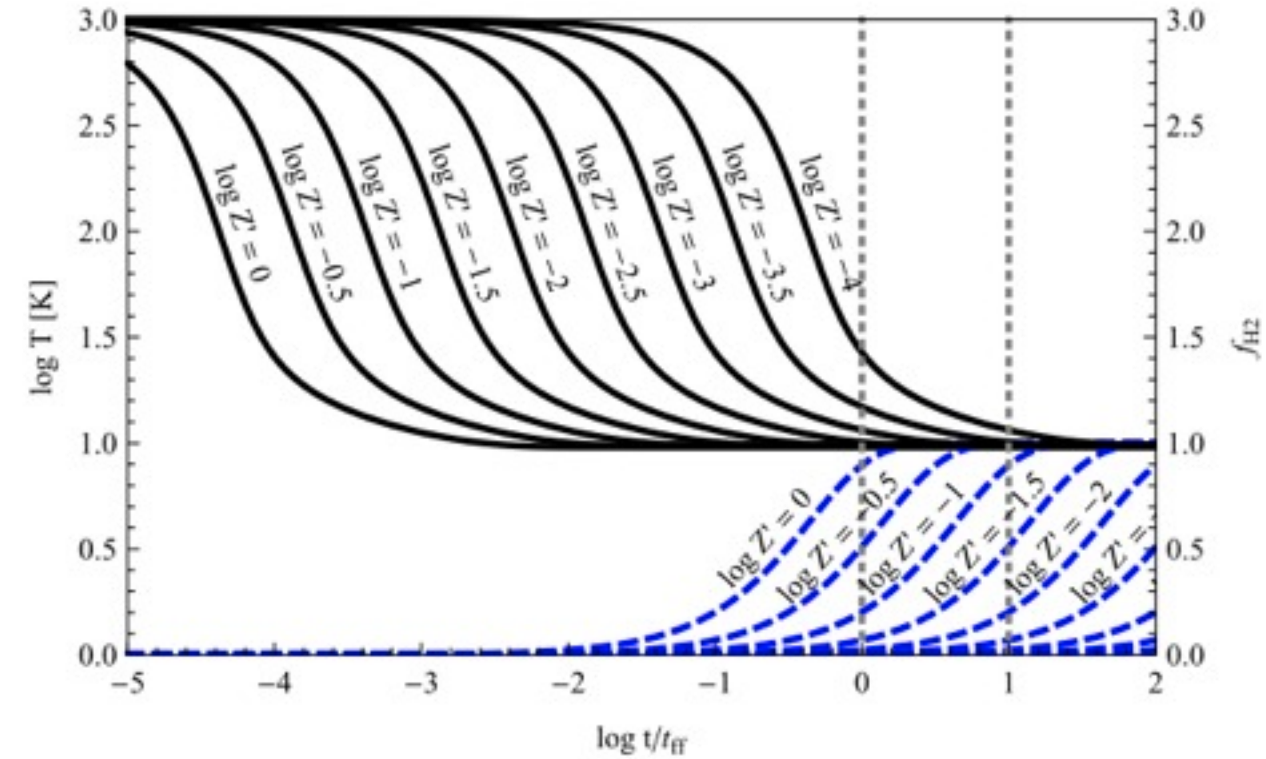


In addition...

Bigiel et al. (2011)



H_2 surf. den.



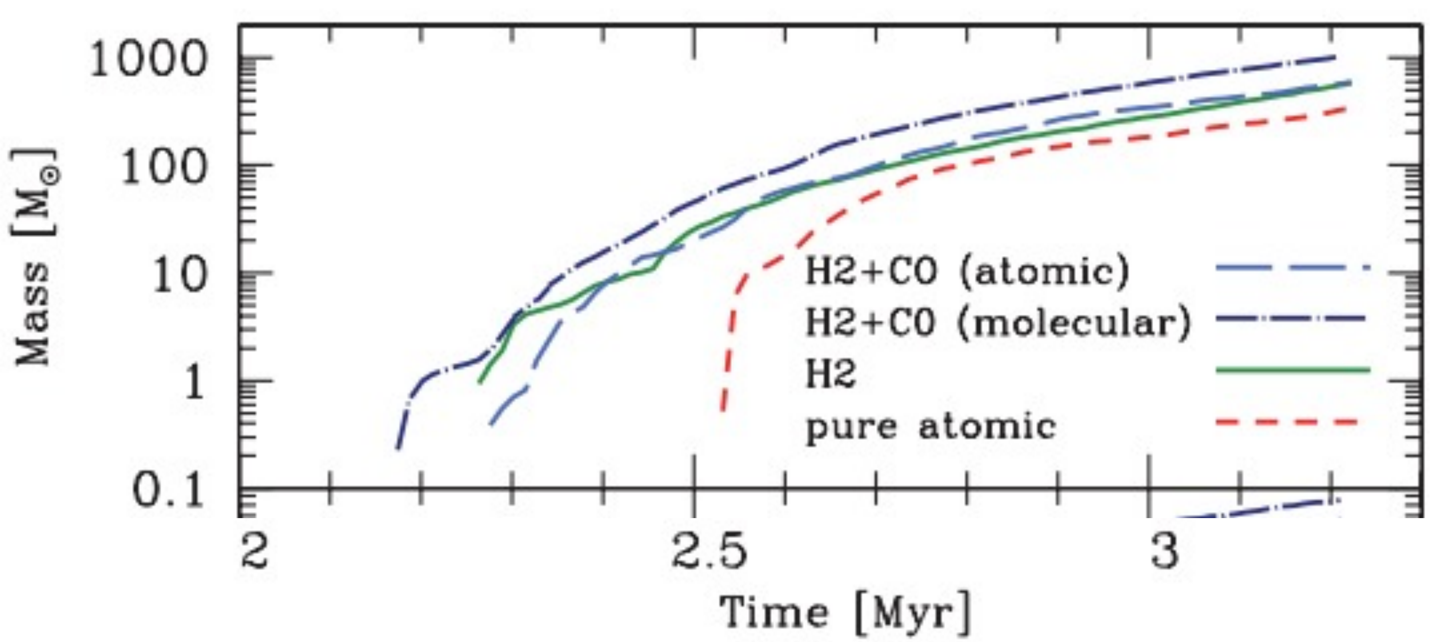
atomic gas can cool down rapidly even with low Z, but cannot become fully molecular within a free-fall time if Z<Z_solar (Krumholz 2012)

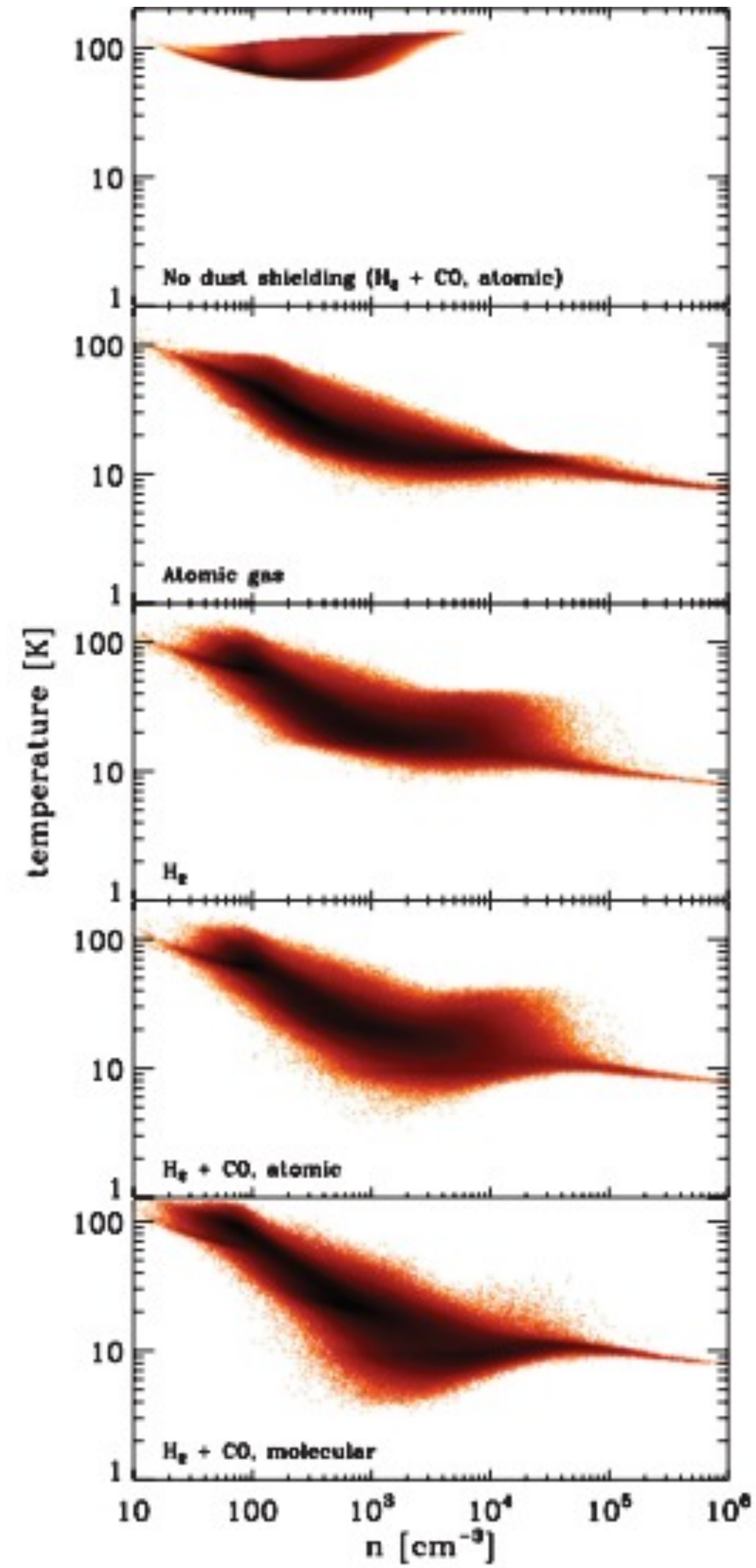
Molecular ISM?

- very well correlate with the SFR (but not the cause)
- shielding is necessary
- good tracer for gravitationally bound entities (not for low Z gas)

Glover & Clark (2012)

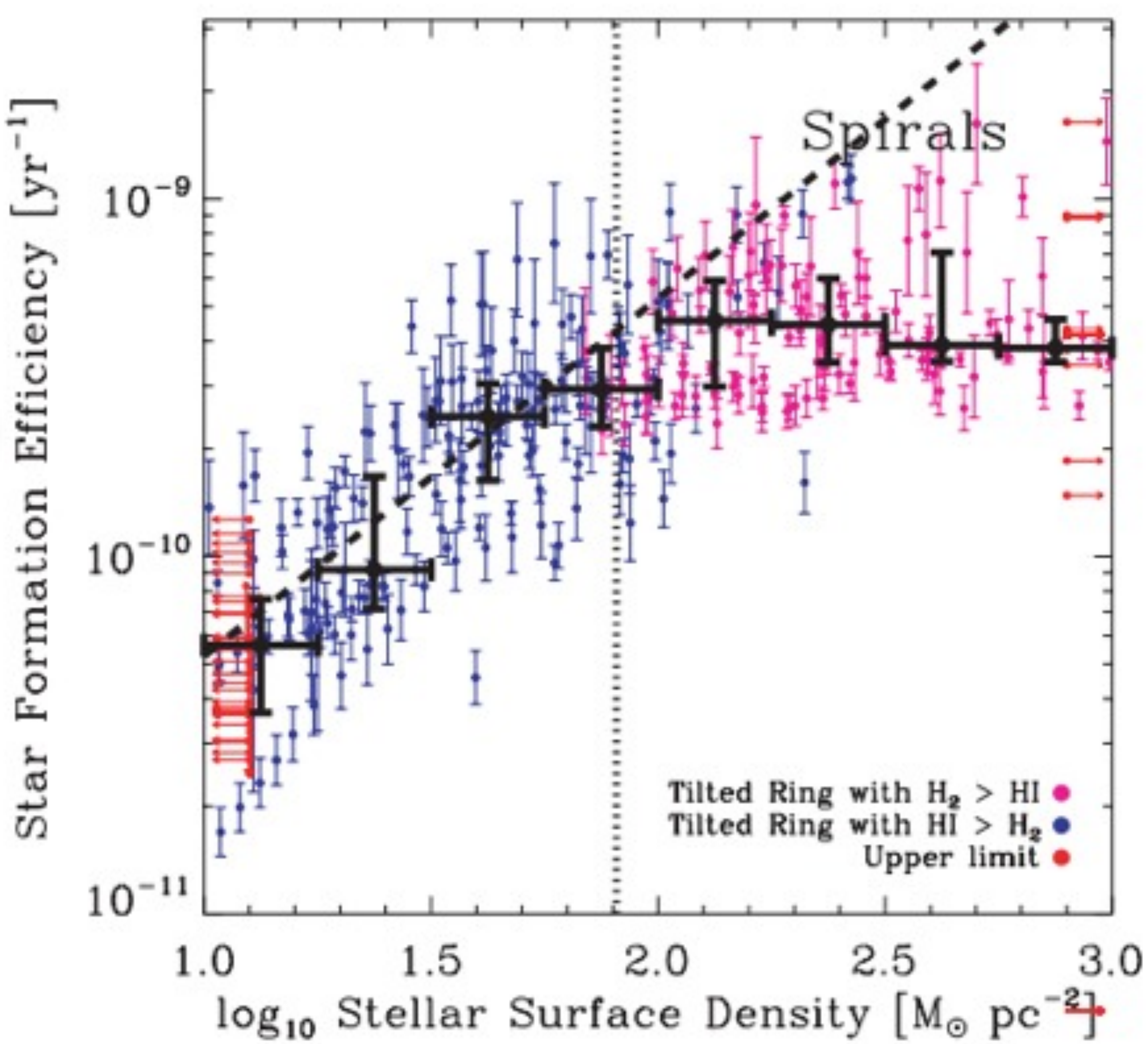
- molecular gas is not crucial
- dust shielding is essential to get high density and low temperature gas to form stars





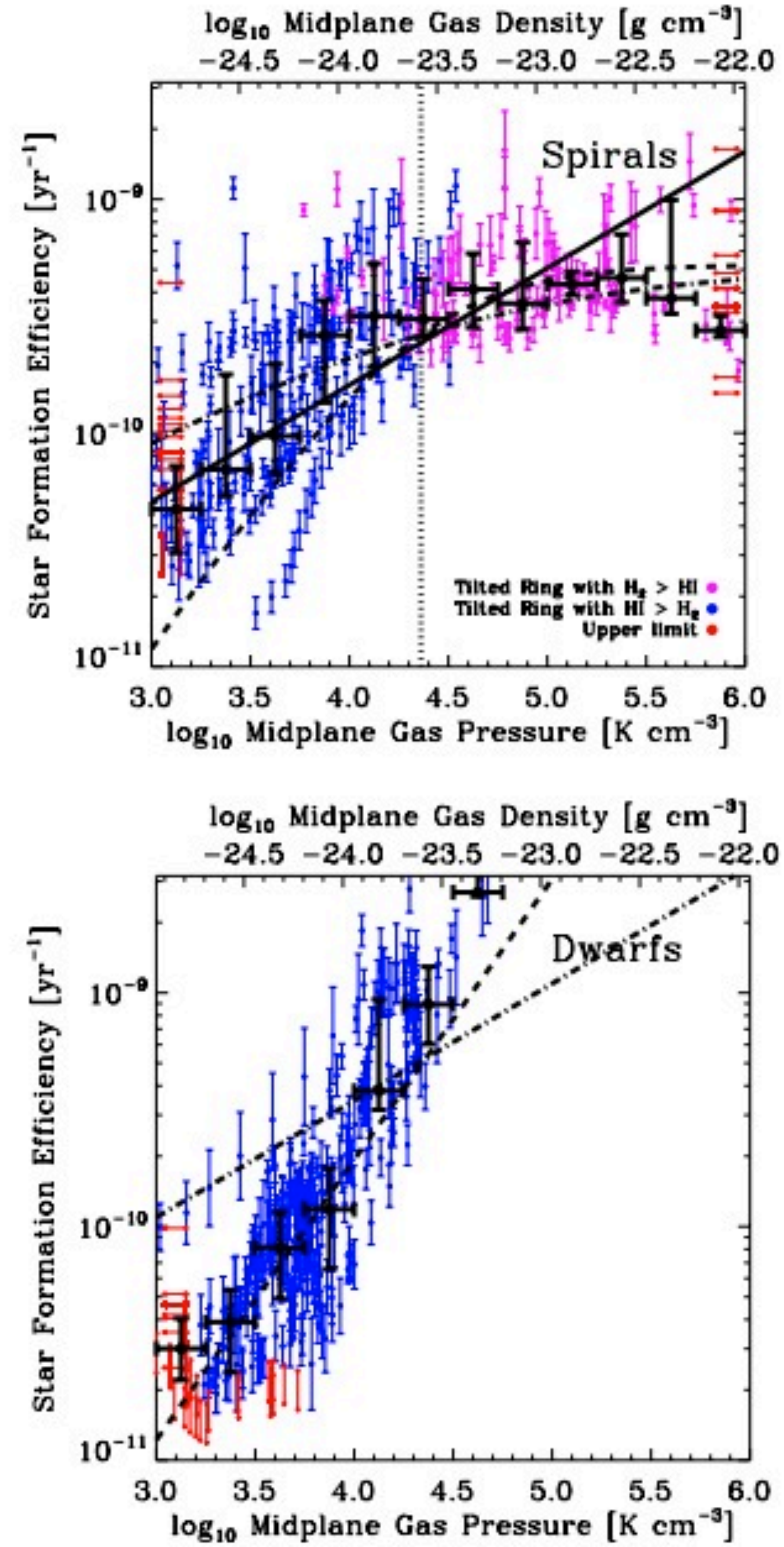
Leroy et al. (2008)

SFR/total gas mass



stellar surface density

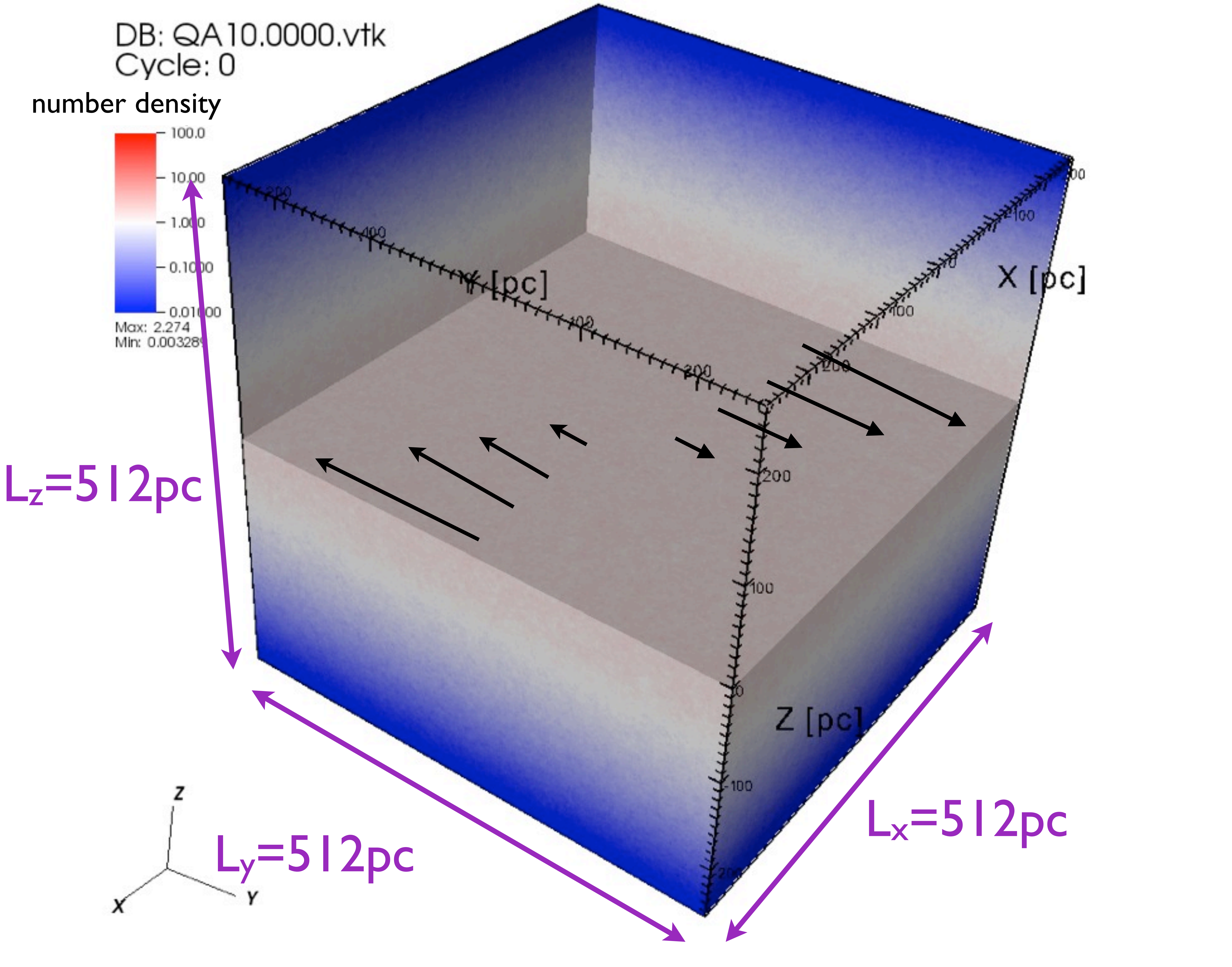
SFR/total gas mass



midplane Pressure

Physical Ingredients

- ✓ ISM cooling and heating
- ✓ star formation feedback (momentum, radiative heating)
- ✓ external gravity (fixed potential)
- ✓ vertically-resolved disks
- ✓ self-gravity
- ✓ galactic differential rotation (flat rotation)
- \- magnetic fields
- \- hot gas
- \- molecule formation and destruction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Cycle: 0
number density
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10.00
1.000
0.1000
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Max: 2.274
Min: 0.003289
Y [pc]
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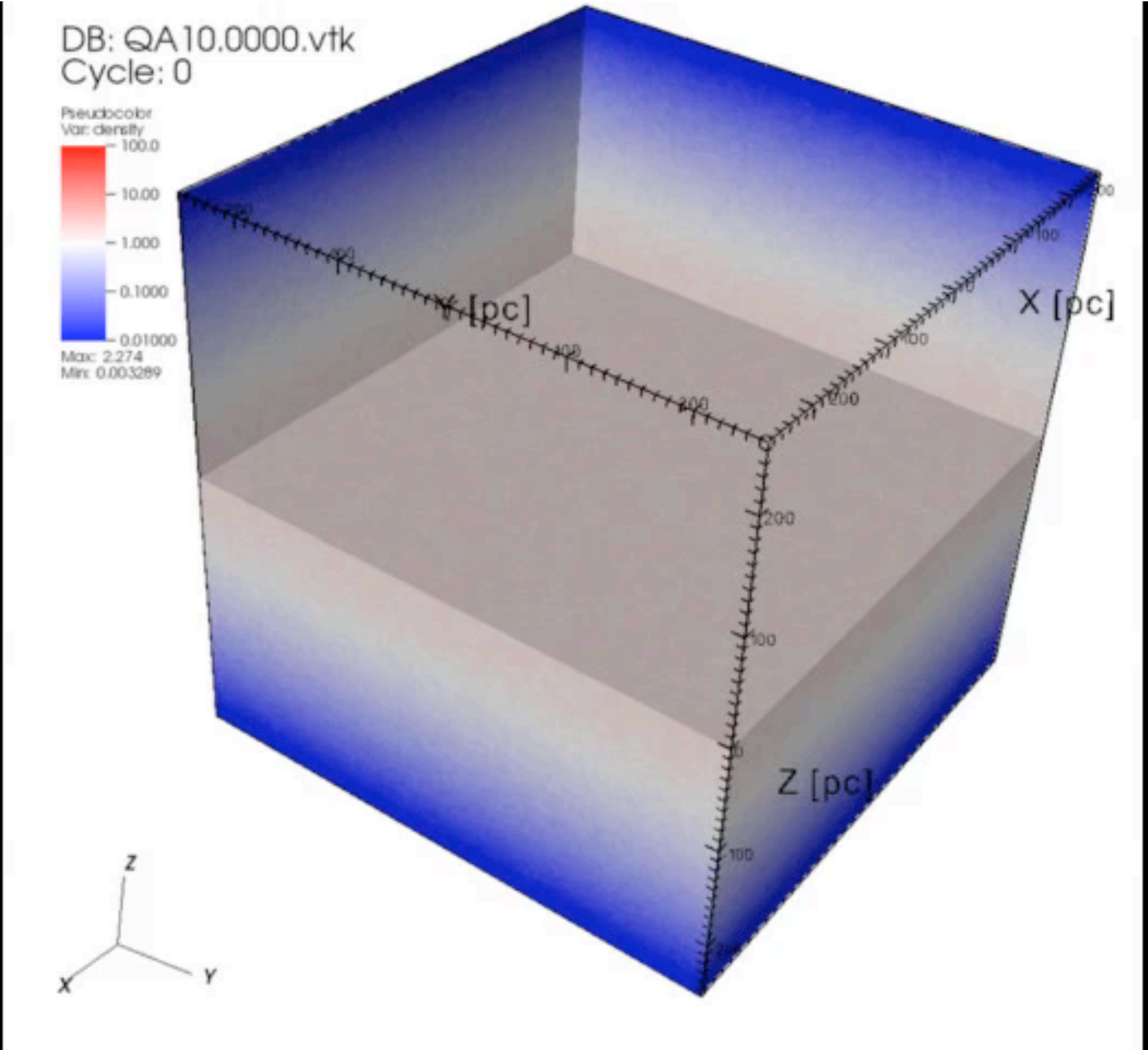
Lz=512pc
Ly=512pc
Lx=512pc
Z
X
Y


DB: QA10.0000.vtk
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Max: 2.274
Min: 0.003289
Y [pc]
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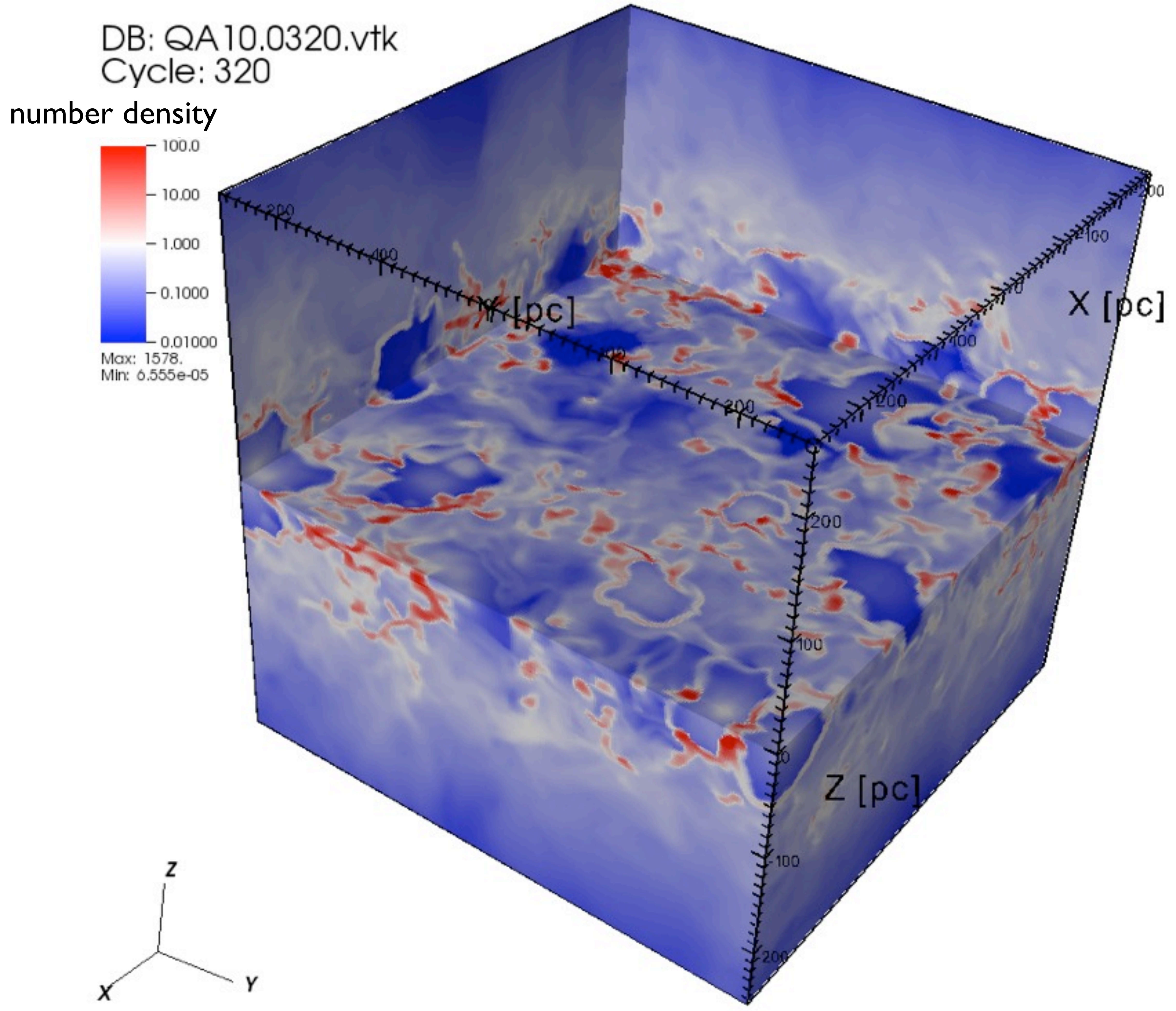
Z [pc]
Z
X
Y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Cycle: 320
number density
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1.000
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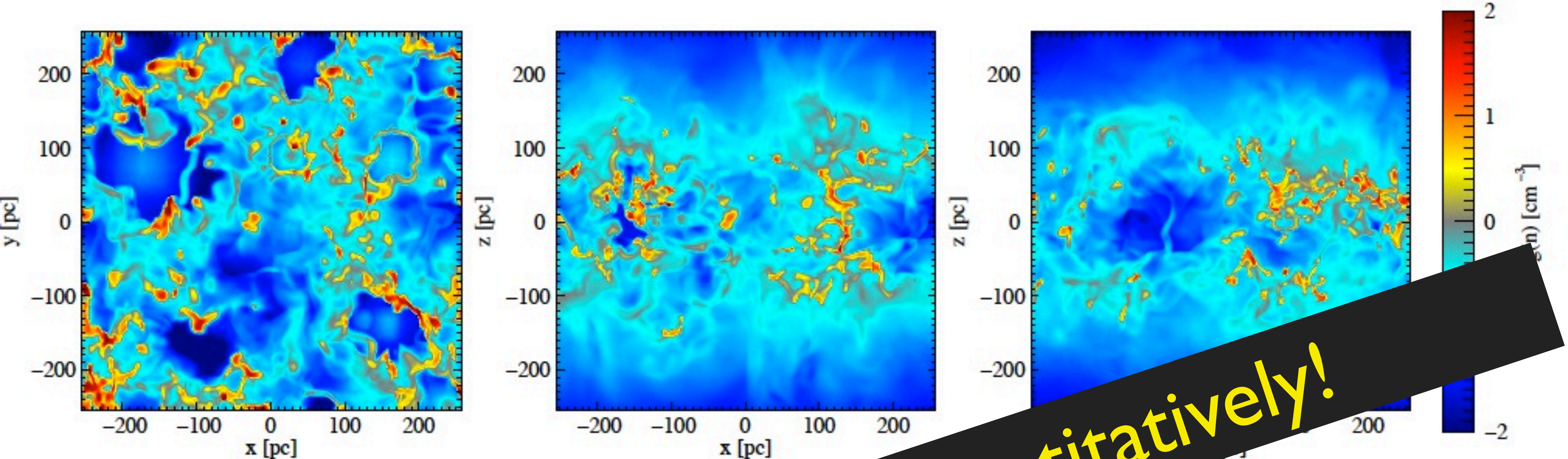
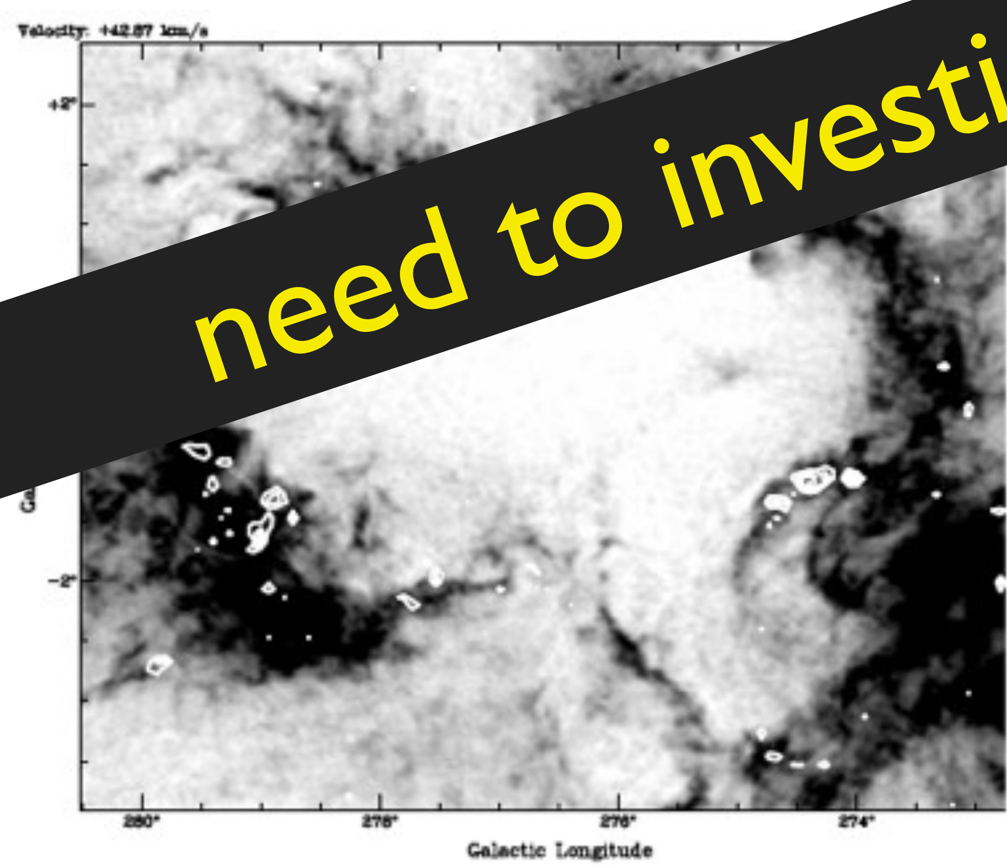
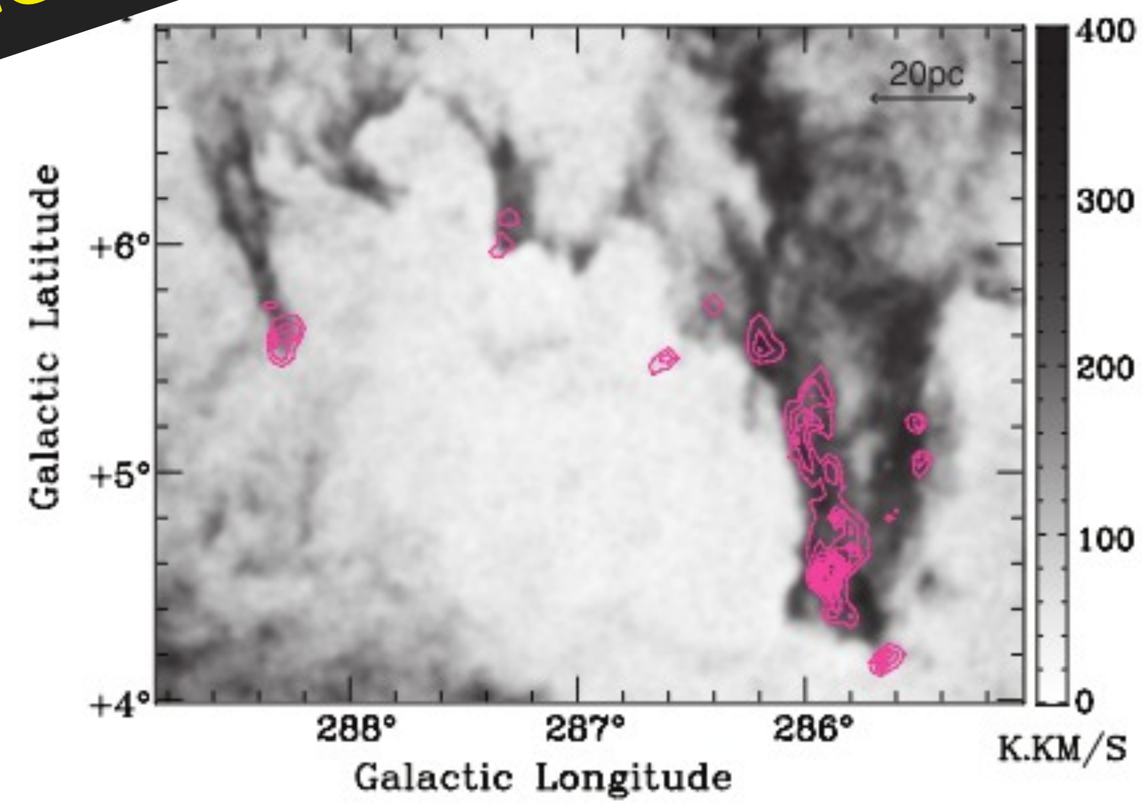
Y [pc]
X [pc]
Z [pc]
Z
X
Y



need to investigate quantitatively!

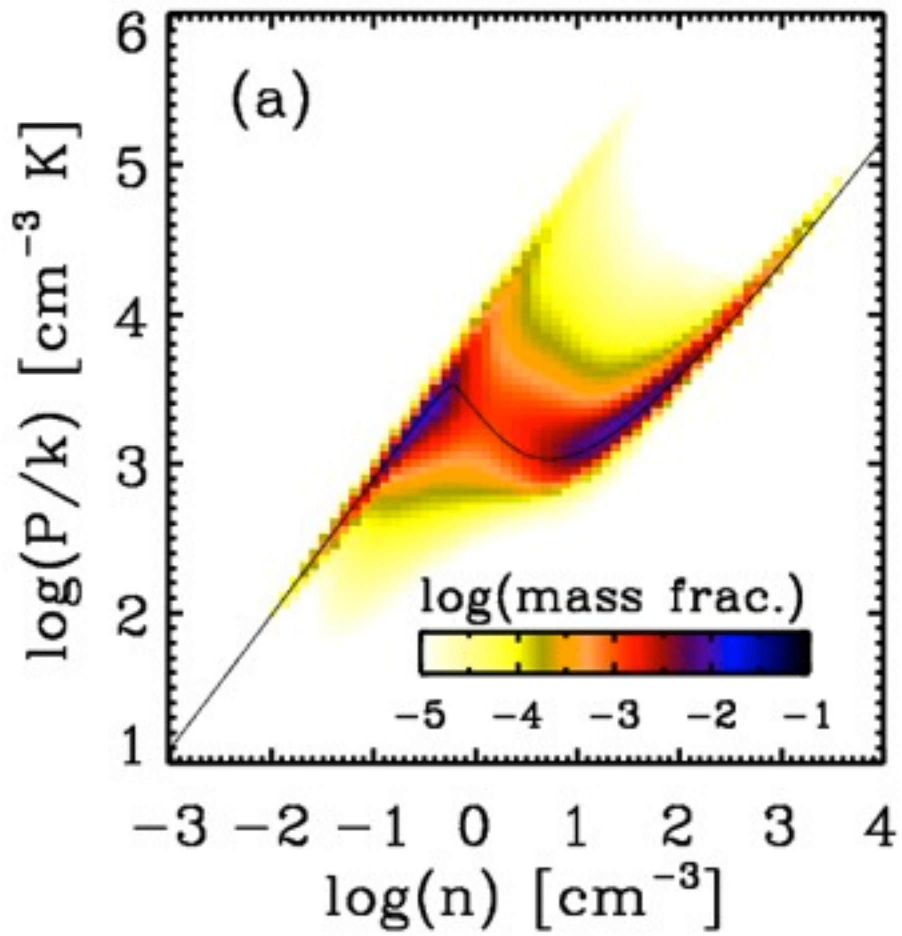


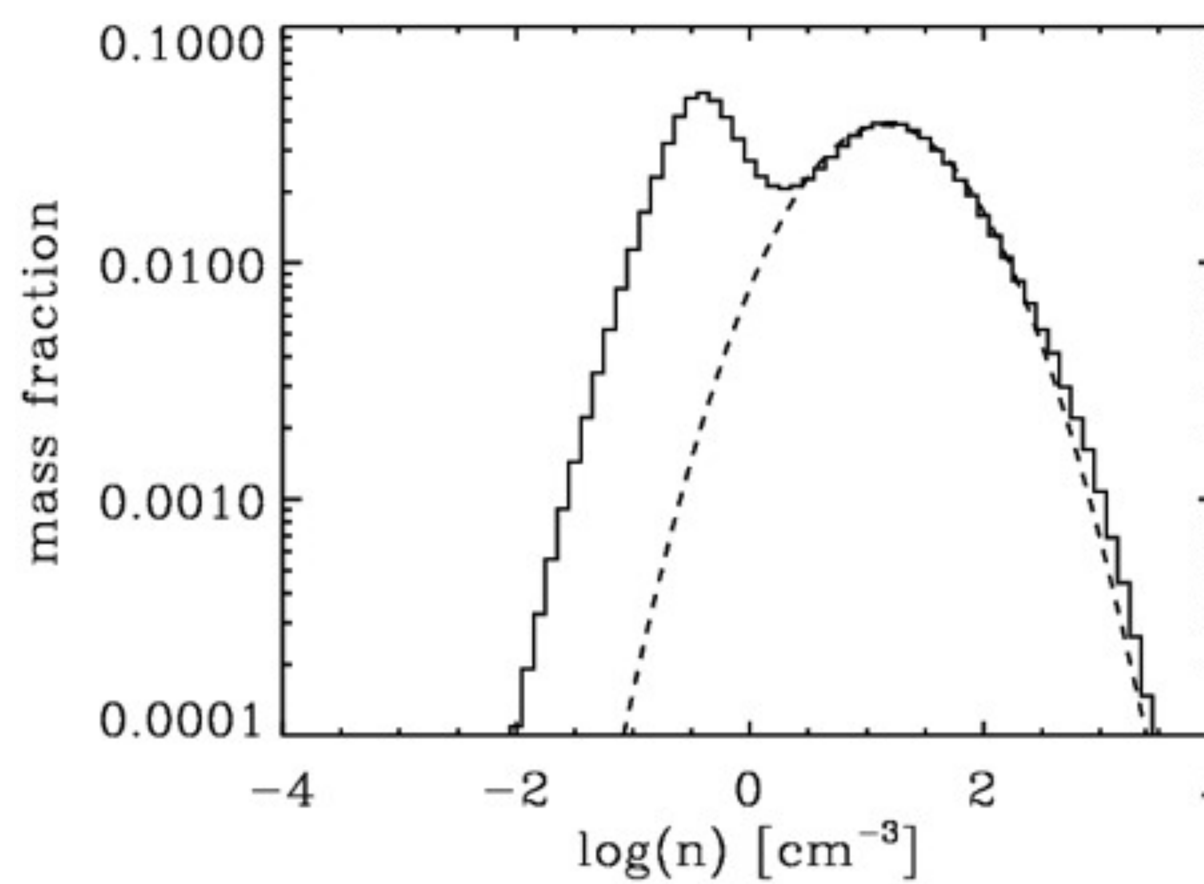
McClure-Griffith (2012)



Dawson et al. (2011)

- both warm and cold phases reside mostly at thermal equilibrium curve
- unstable (out-of-equilibrium) gas exists (~25-30%)
- density PDF of cold gas follows log-normal distribution very well as isothermal supersonic turbulence





Glover & Clark (2012)

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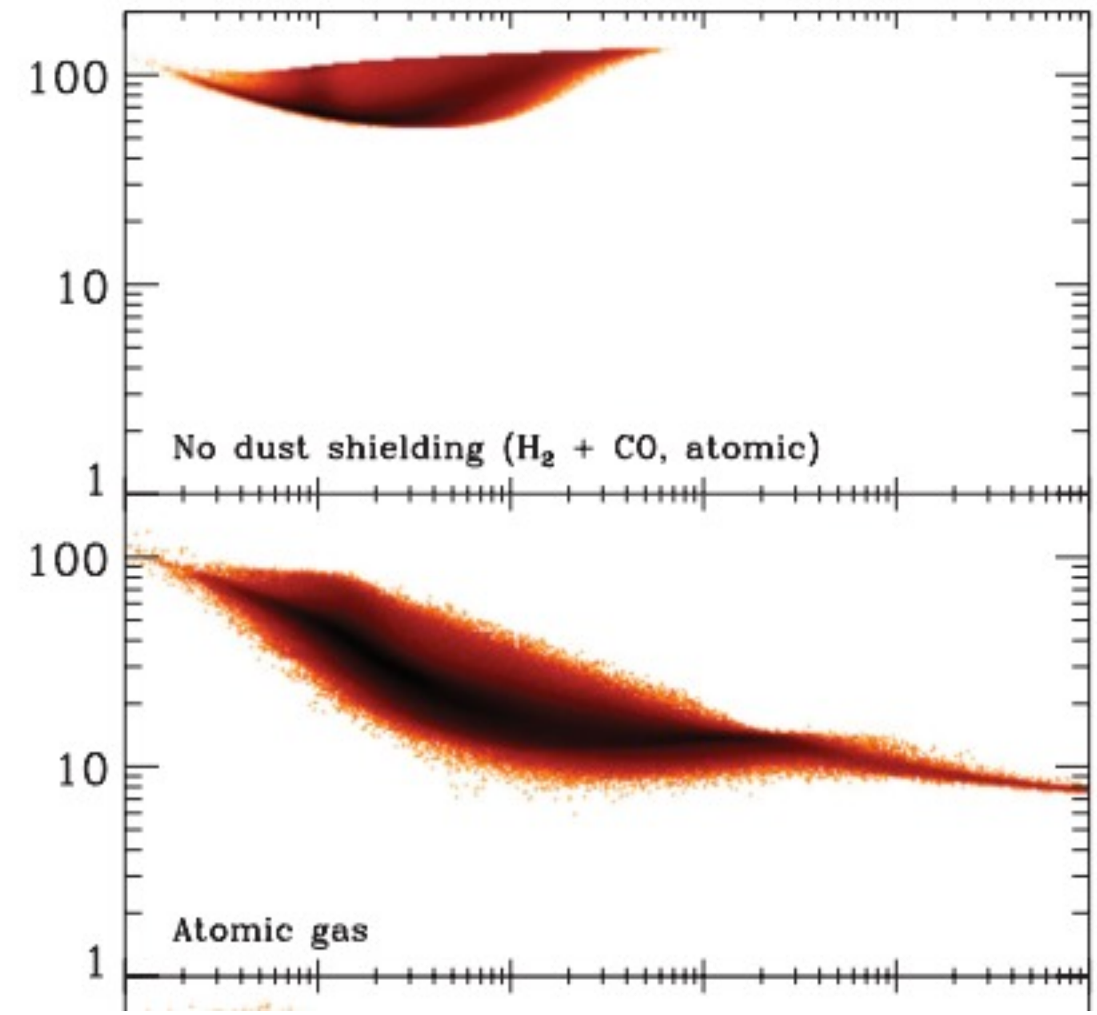
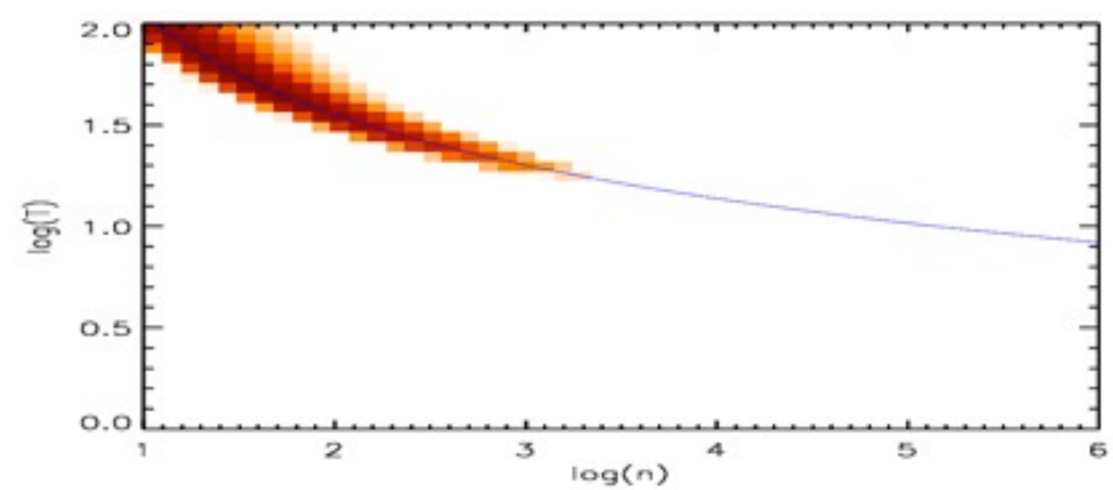
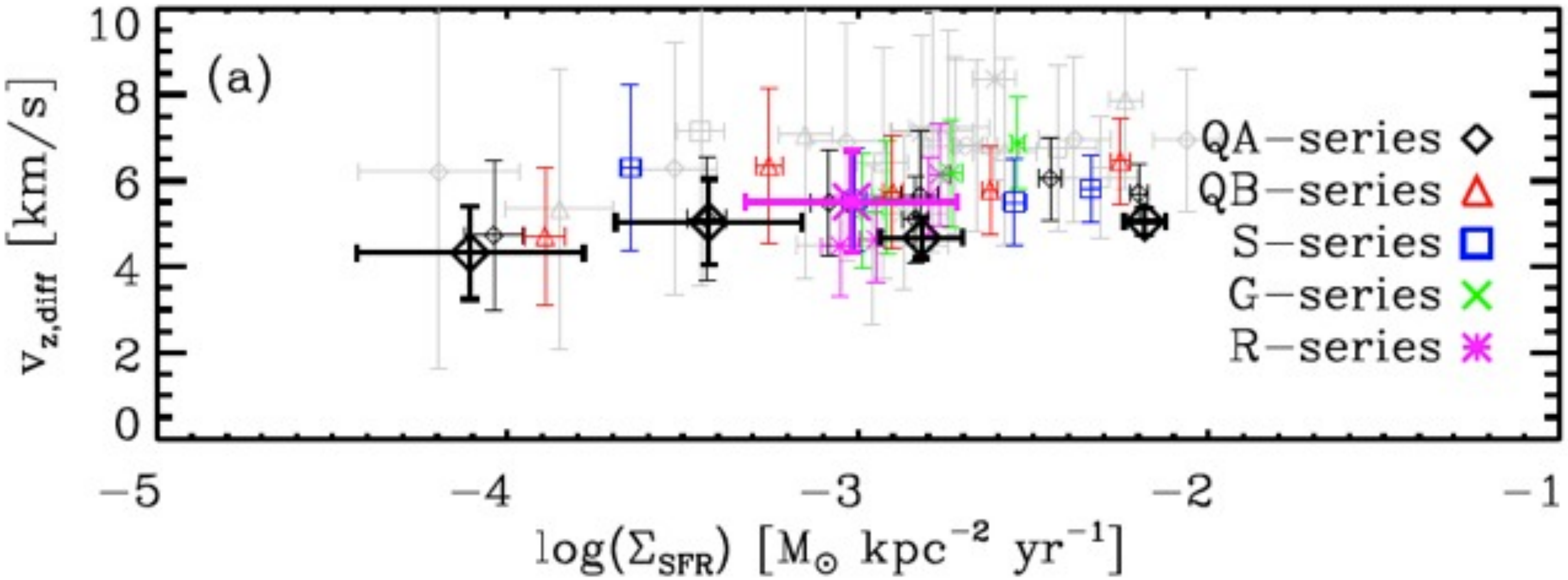


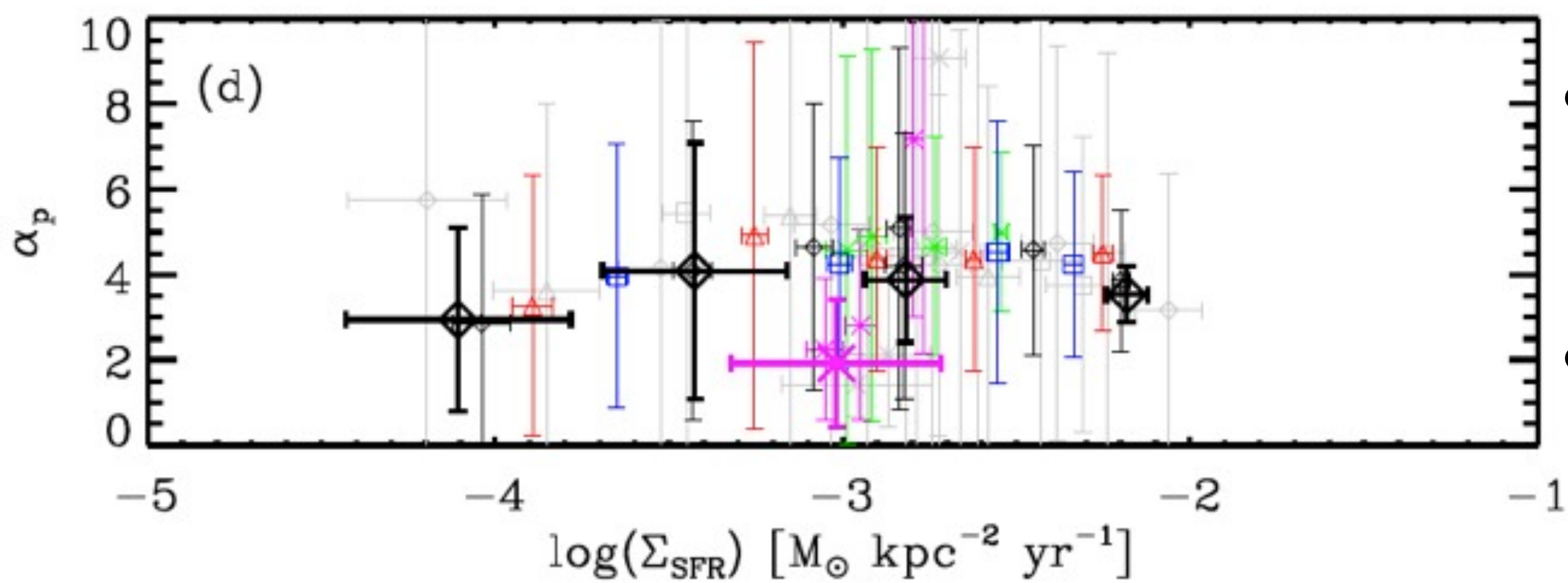
while our model (L~512 pc, dx~2pc) is unable to push the gas such a high density regime, the cold gas achieves reasonably low temperature at a given density





- ~6km/s, irrespective of SFR
- proportional to the injected momentum per stellar mass

p_*/m_*=3000 km/s in our model

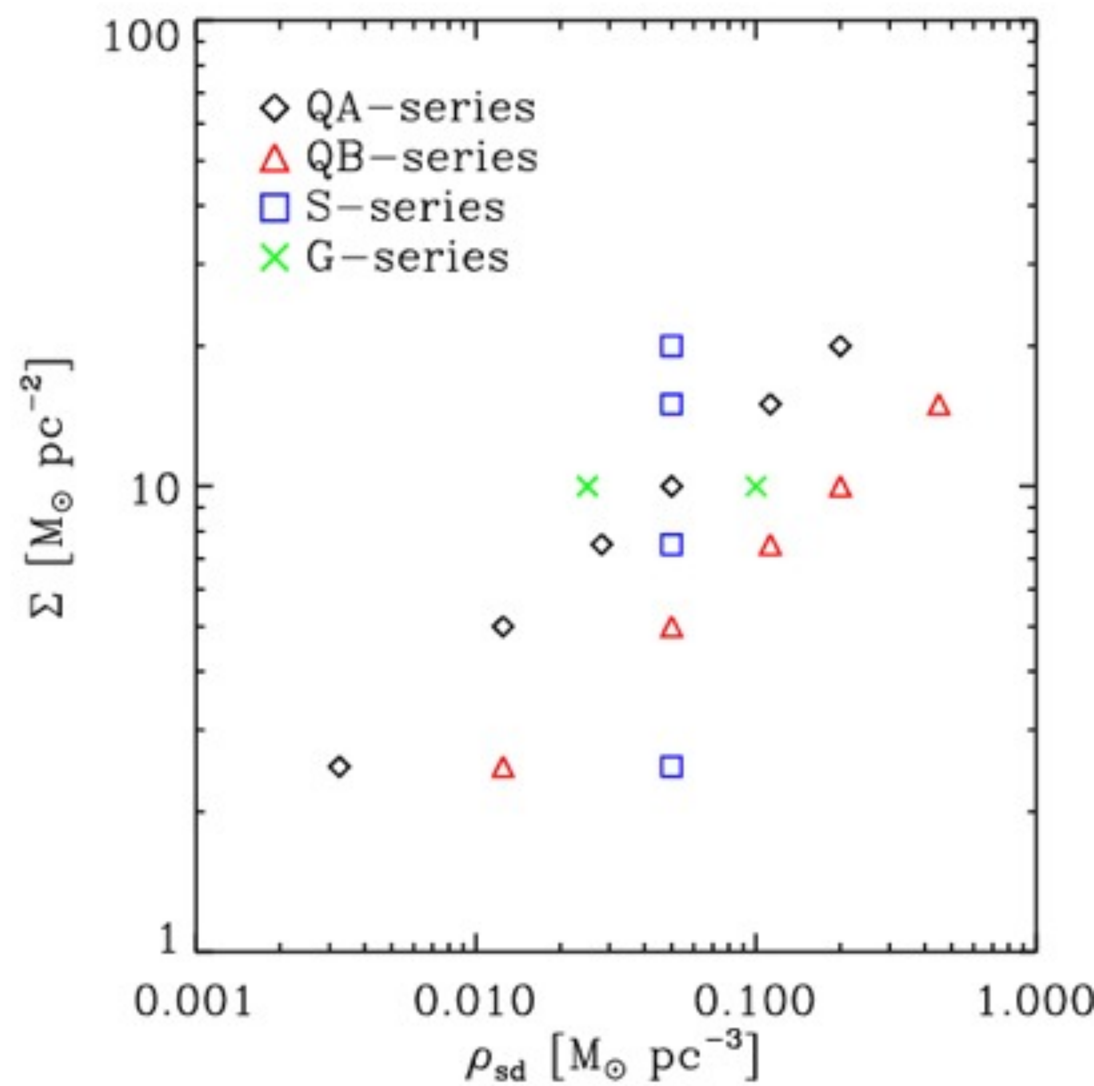


- ratio of midplane total-to-thermal pressure ~4-5, irrespective of SFR
- decreases as f_{rad} increases

Our model seems to resemble the multiphase, turbulent ISM in galactic disks quite well

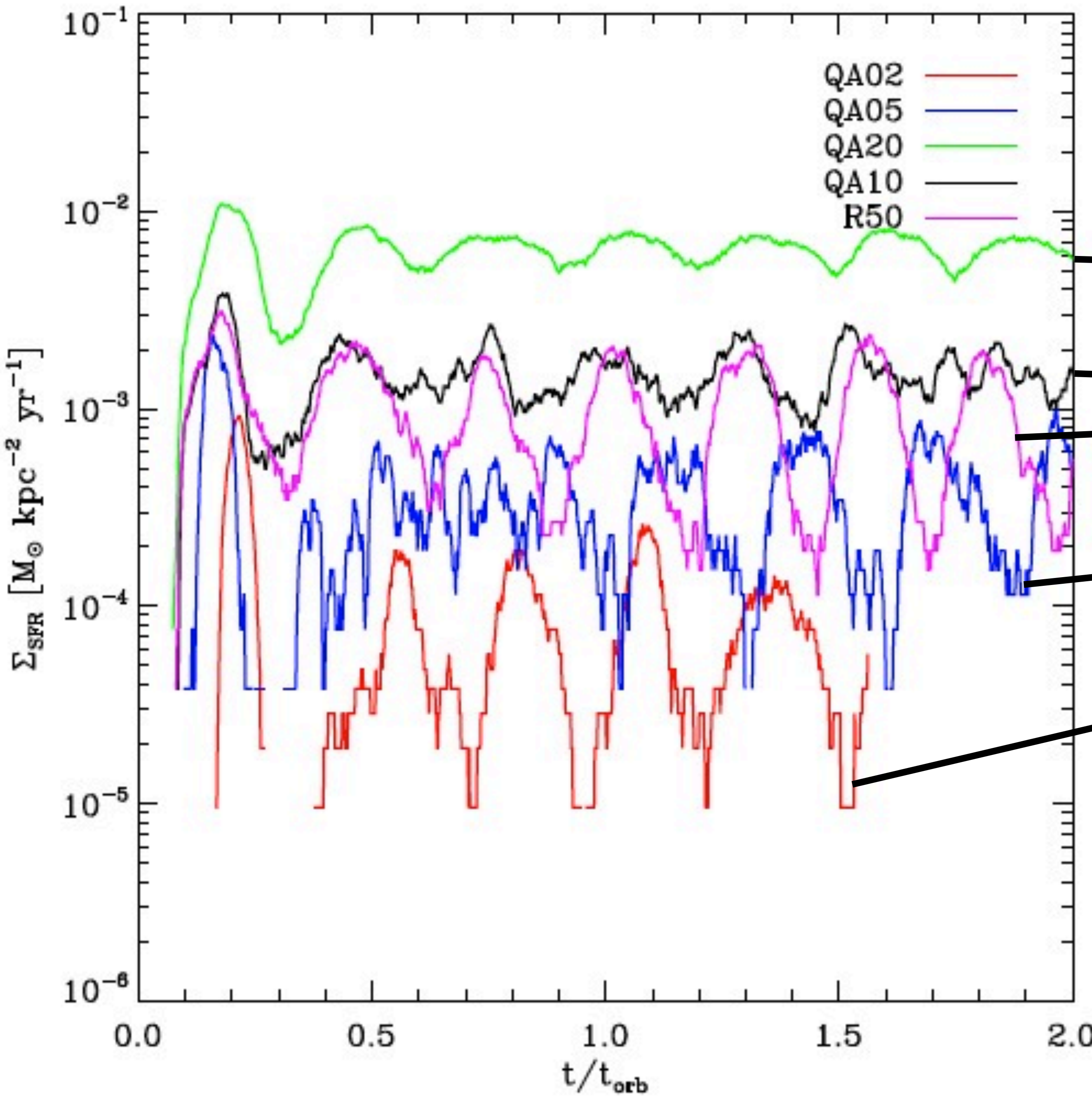
then...

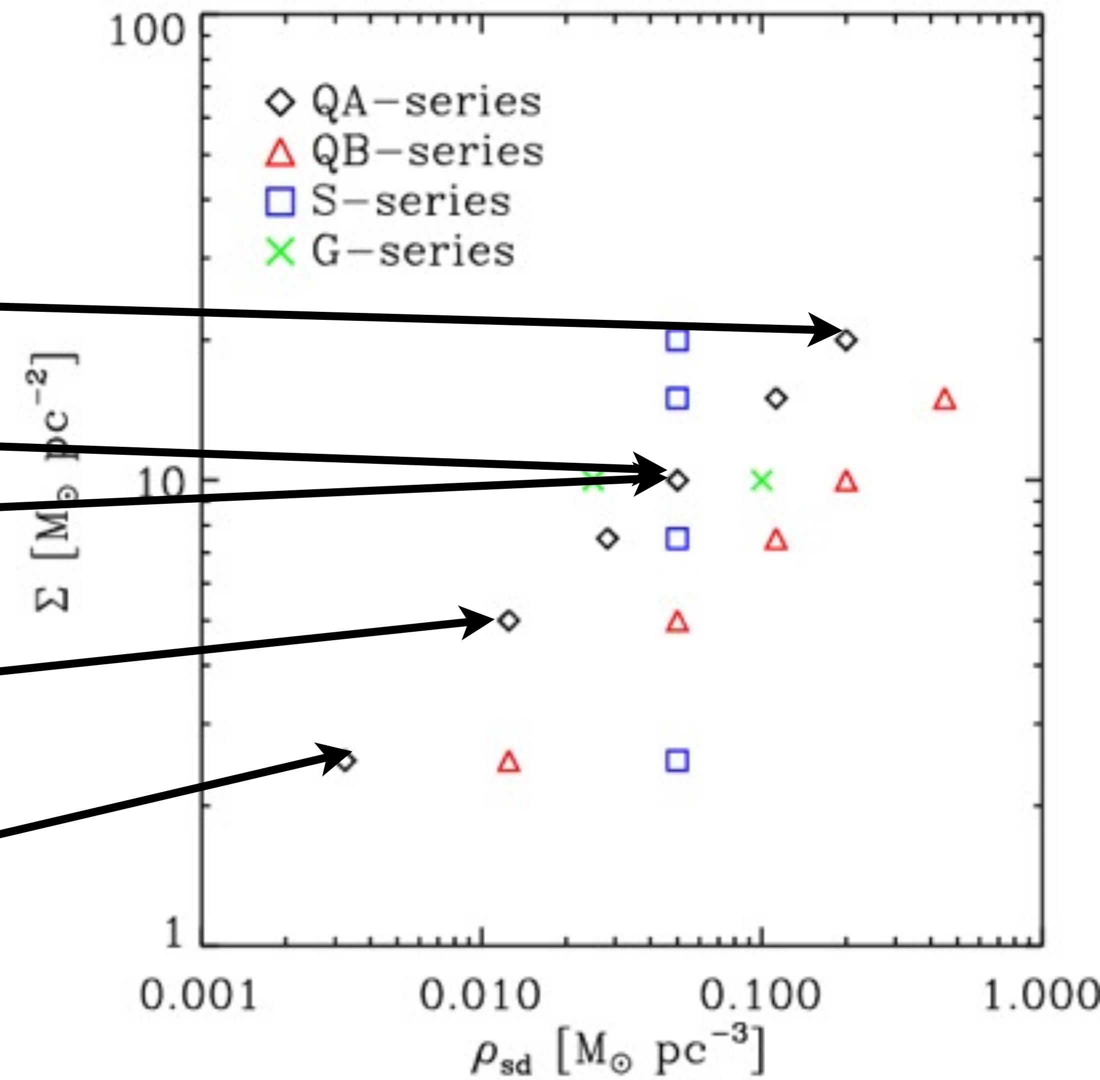
$$\Gamma \propto J_{\rm FUV} \propto f_{\rm rad}\Sigma_{\rm SFR}$$



- gas surface density
- external gravity
- heating efficiency

SFRs (and other physical properties) are well saturated after 1 or 2 vertical oscillations (~0.3-0.6 t_{orb})





- gas surface density
- external gravity
- heating efficiency

Regulation of SFR

Feedback from SF drives turbulence and heats the gas

➡ key ingredient to regulate SFR

demand of ISM

- turbulence dissipation

$$P_{\rm turb} \sim \frac{\Sigma v_z}{H/v_z} \sim \rho v_z^2$$

- atomic gas cooling

$$n\Lambda(T) = P_{\rm th}\Lambda(T)/T$$

supply from SF

- turbulence driving

$$P_{\rm driv} \sim \frac{p_*}{m_*}\Sigma_{\rm SFR}$$

- PE heating

$$\Gamma \propto J_{\rm FUV} \propto f_{\rm rad}\Sigma_{\rm SFR}$$

Ostriker et al. (2010); Ostriker & Shetty (2011)

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turbulence dissipation and/or cooling dominate ➜ lower velocity dispersion and more cold gas ➜ more stars form

Ostriker et al. (2010); Ostriker & Shetty (2011)

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- PE heating

$$\Gamma \propto J_{\rm FUV} \propto f_{\rm rad}\Sigma_{\rm SFR}$$

turbulence driving and/or heating dominate ➜ higher velocity dispersion and less cold gas ➜ less stars form

Ostriker et al. (2010); Ostriker & Shetty (2011)

demand of ISM

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$$P_{\rm turb} \sim \frac{\Sigma v_z}{H/v_z} \sim \rho v_z^2$$

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supply from SF

- turbulence driving

$$P_{\rm driv} \sim \frac{p_*}{m_*}\Sigma_{\rm SFR}$$

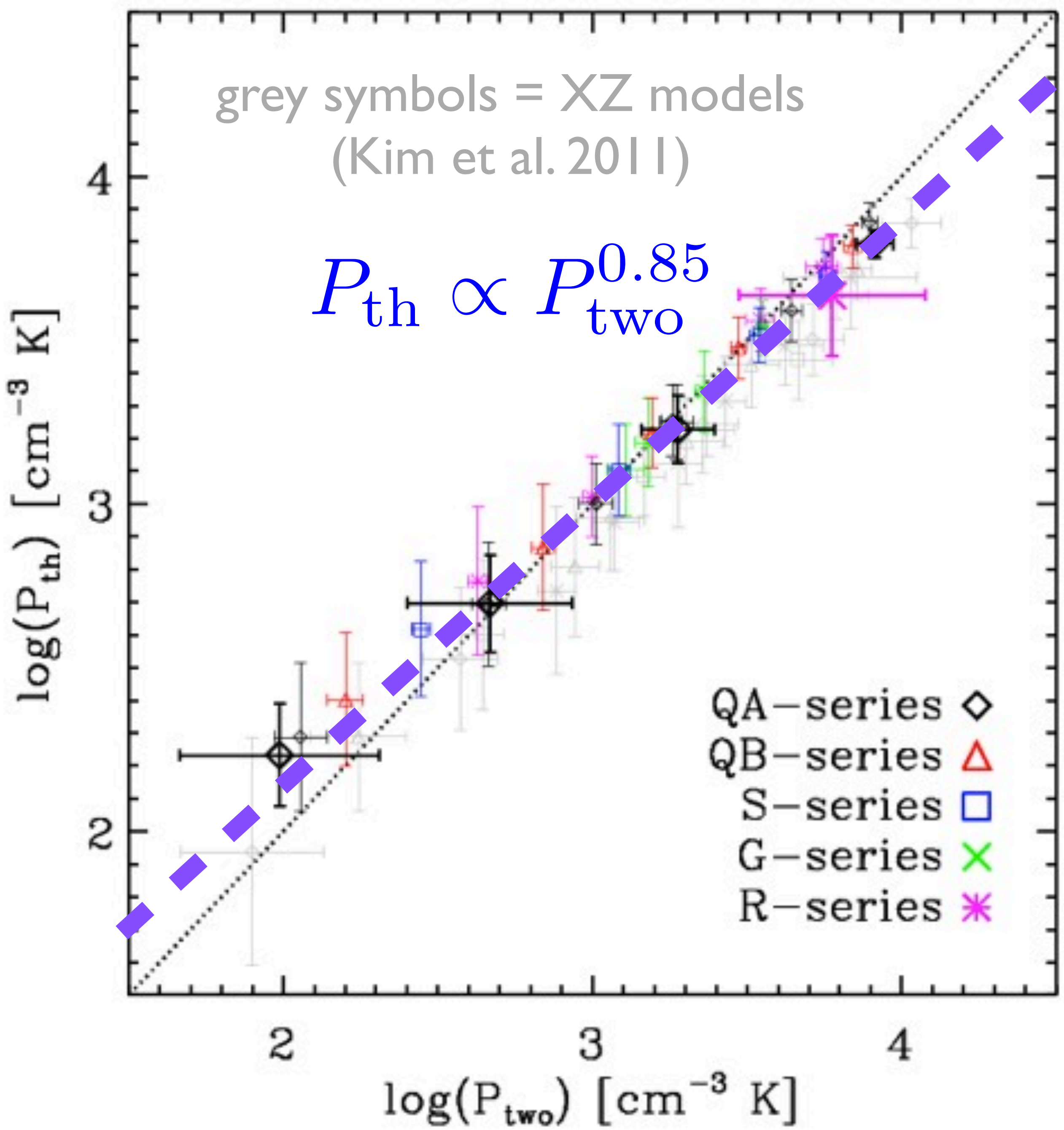
- PE heating

$$\Gamma \propto J_{\rm FUV} \propto f_{\rm rad}\Sigma_{\rm SFR}$$

- SFR is regulated until supply meets demand
- at the same time, vertical force balance (gravity vs. pressure) should be satisfied

$$P_{\rm th} + P_{\rm turb} \approx \Sigma(\sqrt{2G\rho_*}\sigma_z + \pi G\Sigma/2)$$

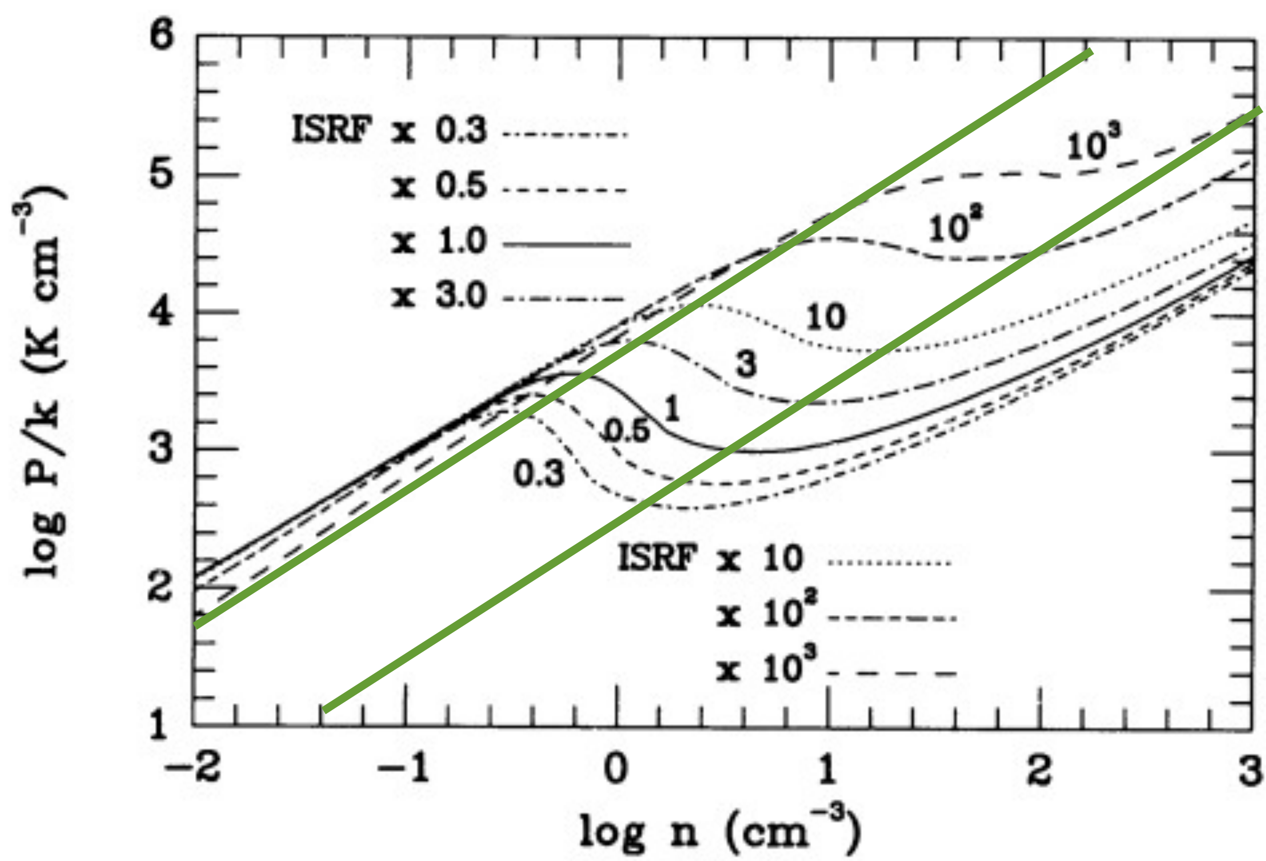
Ostriker et al. (2010); Ostriker & Shetty (2011)

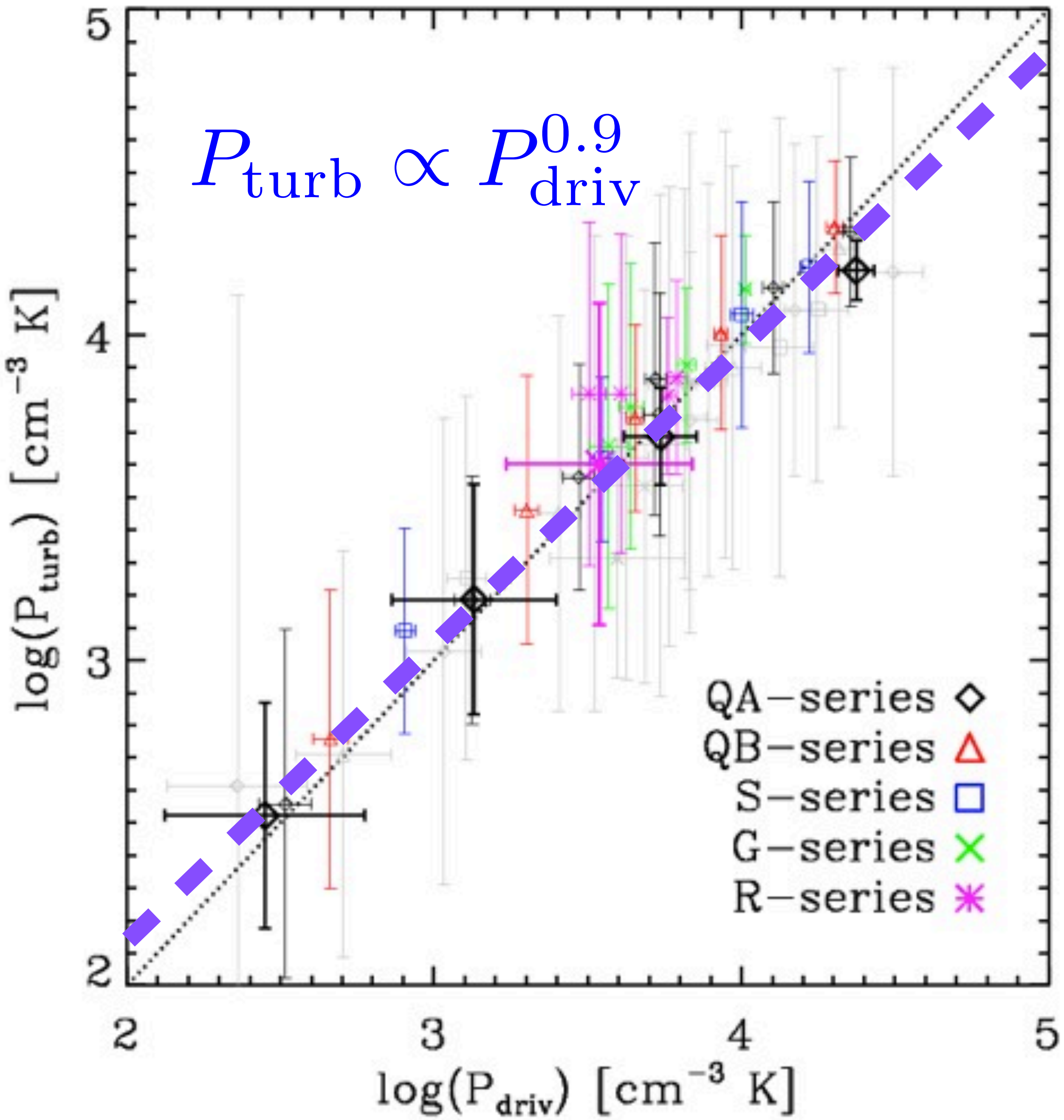


midplane thermal pressure is nearly linearly proportional to the SFR surface density

heating balances cooling

$$P_{\rm two}/k_B = 3,110\ {\rm K\ cm^{-3}} f_{\rm rad} \left(\frac{\Sigma_{\rm SFR}}{\Sigma_{\rm SFR,0}}\right)$$



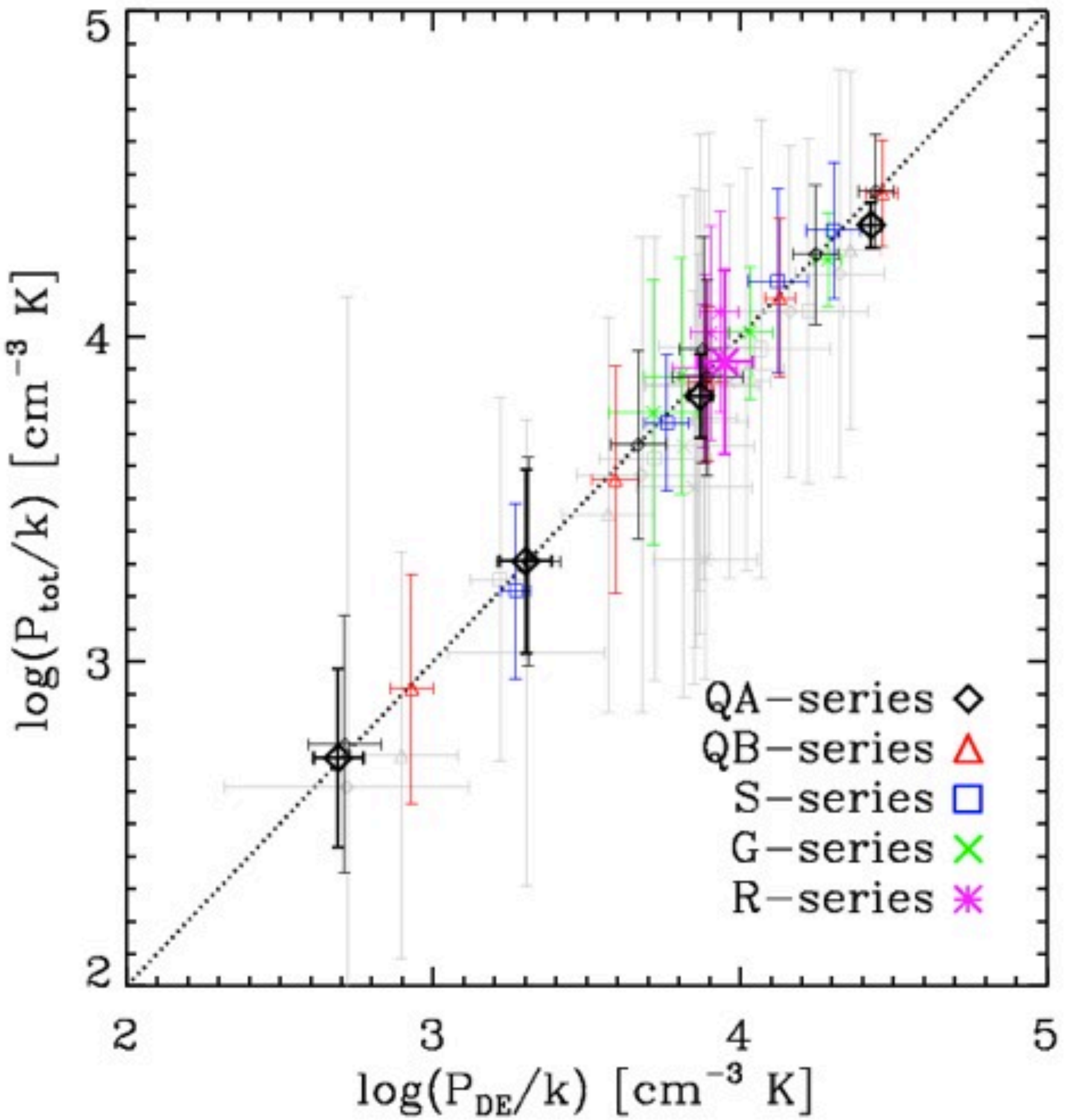


$$P_{\rm driv}/k_B = 8,990 \text{ K cm}^{-3} \left(\frac{\Sigma_{\rm SFR}}{\Sigma_{\rm SFR,0}}\right)$$

grey symbols = XZ models
(Kim et al. 2011)

midplane turbulent pressure is nearly linearly proportional to the SFR surface density

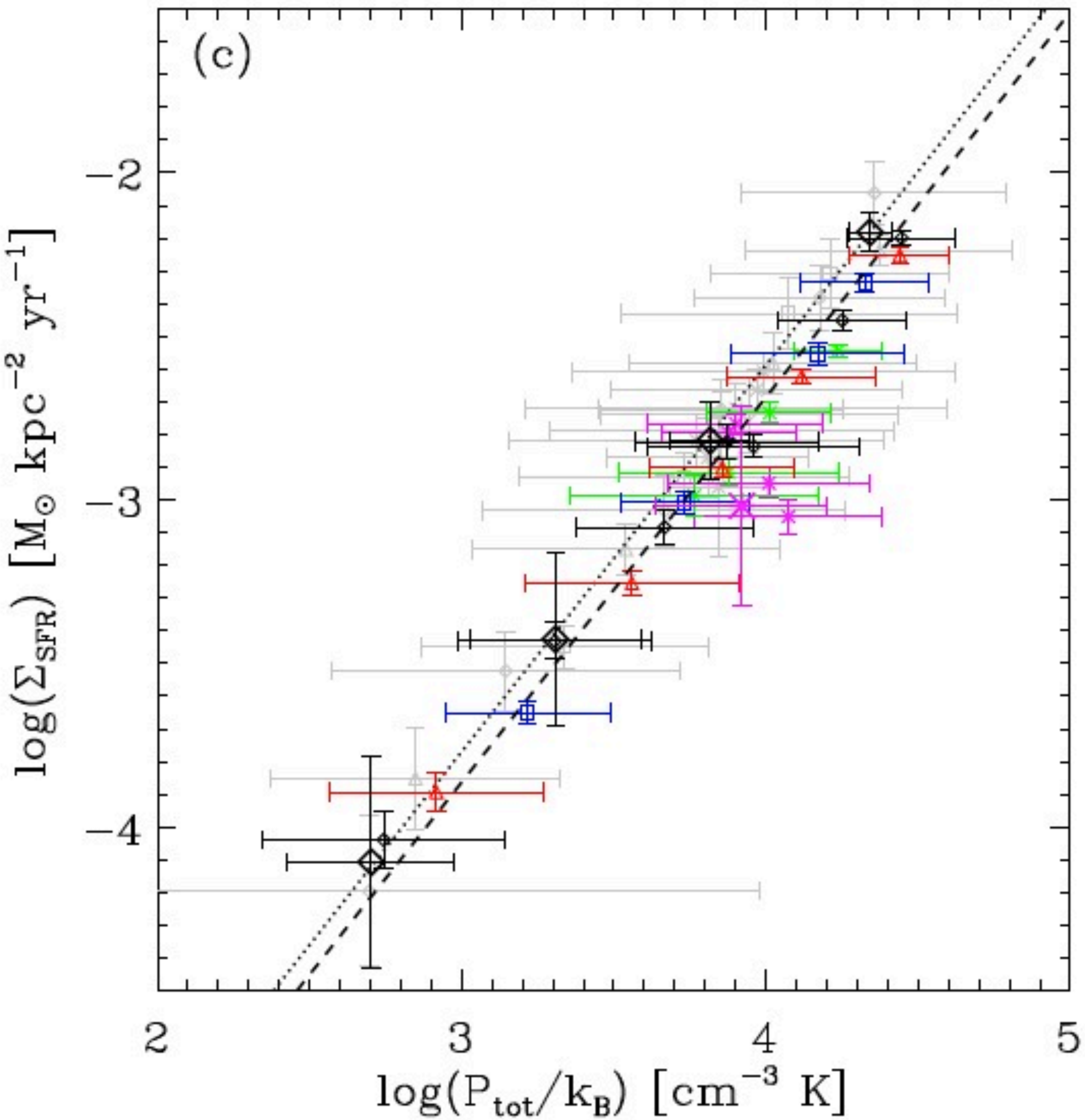
turbulence driving balances dissipation



grey symbols = XZ models
(Kim et al. 2011)

$$P_{\rm th} + P_{\rm turb} \approx \Sigma(\sqrt{2G\rho_*}\sigma_z + \pi G\Sigma/2)$$

on average sense, total pressure can be very well estimated by vertical dynamical equilibrium (rel. diff. is less than 12%)



grey symbols = XZ models
(Kim et al. 2011)

$$P_{\rm tot} \sim P_{\rm DE} \propto \Sigma\sqrt{\rho_{\rm sd}}$$

$$P_{\rm tot} \sim P_{\rm th} + P_{\rm turb} \sim P_{\rm two} + P_{\rm driv} \propto \Sigma_{\rm SFR}$$

Conclusions

- multiphase, turbulent nature of the atomic ISM is essential and should be captured for realistic numerical simulations
- SF feedback supplies energies in both turbulent and thermal forms very efficiently to meet ISM demands
- on average sense (scales larger than H), vertical, thermal, and turbulent equilibria indeed hold