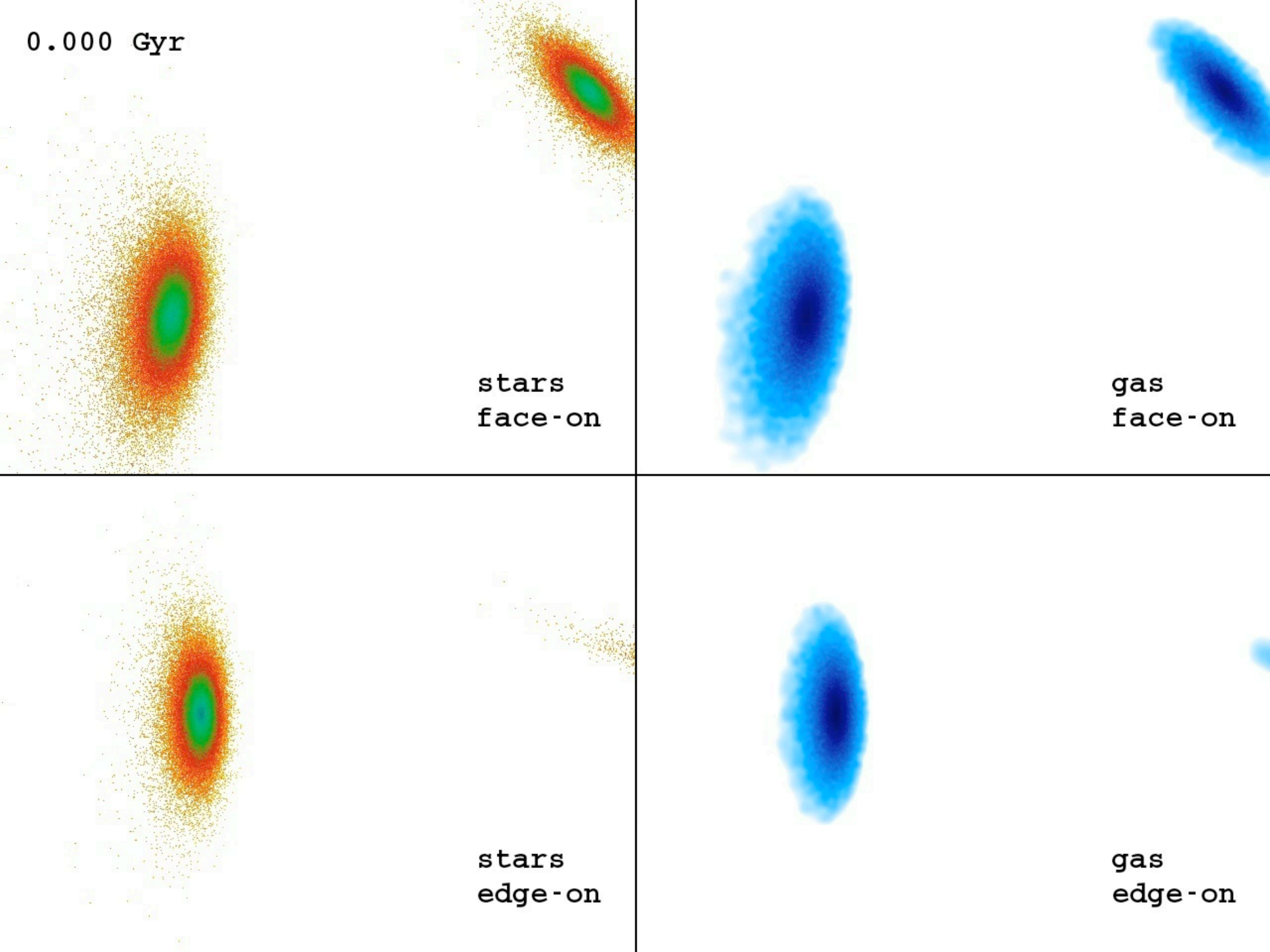

0.000 Gyr
stars
face-on
gas
face-on
stars
edge-on
gas
edge-on

2010 HIPACC Astro-Computing Summer School

# *Galaxy Simulations Using the N-Body/SPH code GADGET*

T.J. Cox (Carnegie Observatories)

# Outline

1. ~~Who am I and what am I doing here? My perspective, my science, and where my focus will be this week~~
2. ~~An overview of GADGET projects (+other practical - I hope - information)~~
3. ~~A brief overview of GADGET~~
4. Adding "Astrophysics" to GADGET
5. Loose Ends ... data structures, analysis, and visualization (w/ P. Hopkins)
6. What's next? (higher resolution, new models, and Arepo: the next generation of code)

# 4. Adding Astrophysics to Gadget

4.1 Cooling and Star formation

4.2 Sink Particles (both stars and BHs)

4.3 Feedback

4.4 Additional Odds and Ends ...

# 4. Adding Astrophysics to Gadget

4.1 Cooling and Star formation

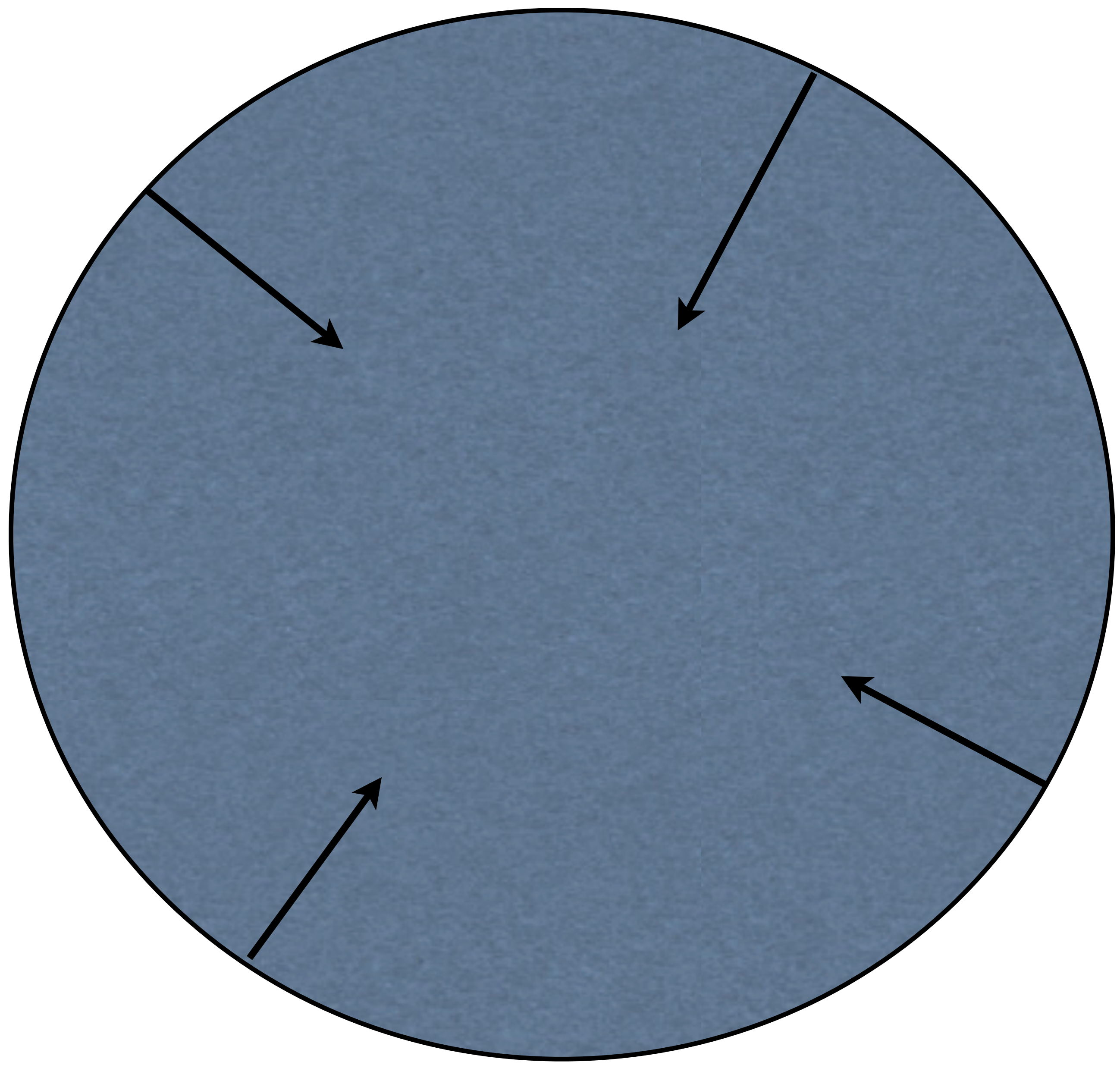
4.2 Sink Particles (both stars and BHs)

4.3 Feedback

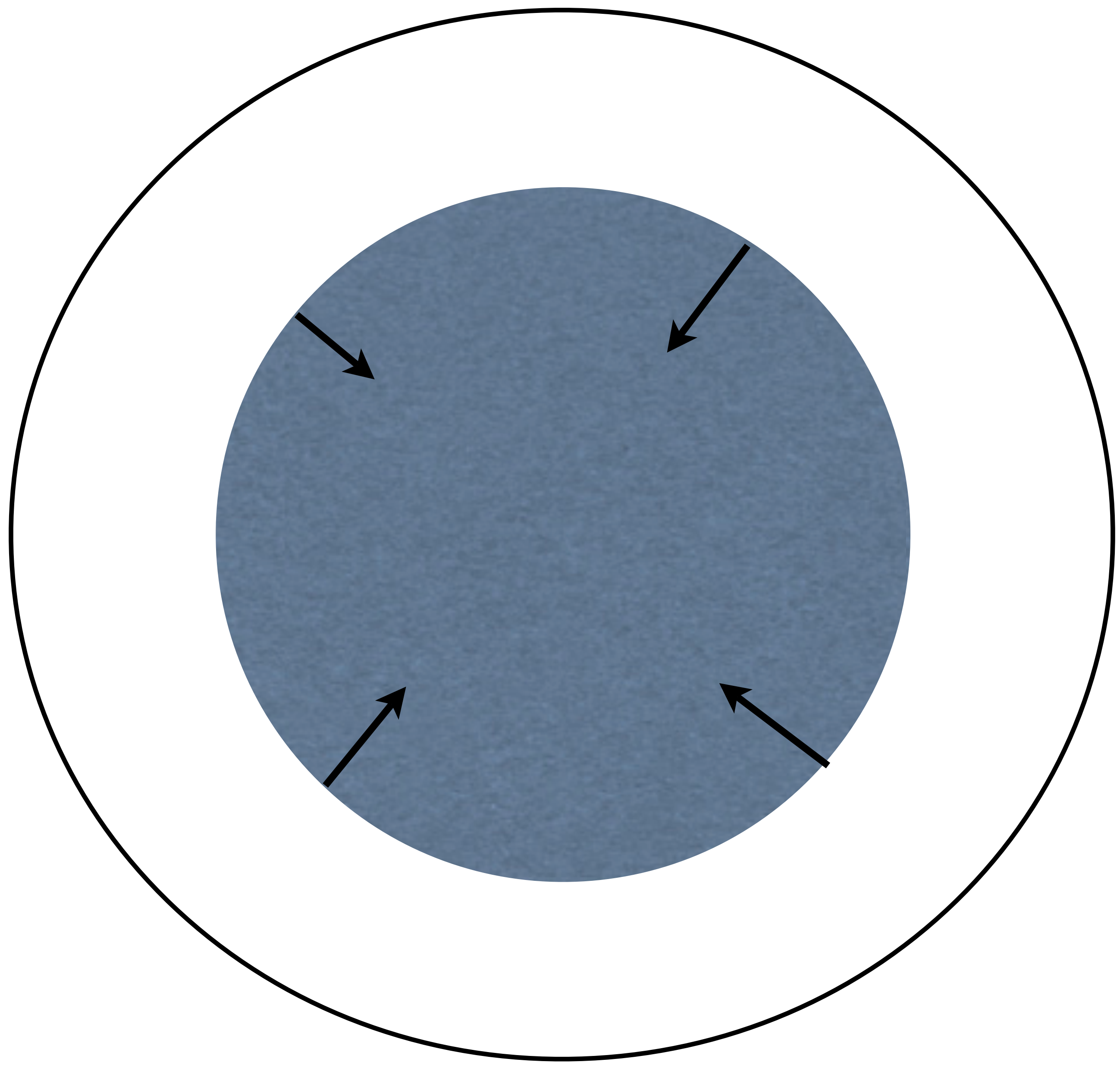
4.4 Additional Odds and Ends ...

Disclaimer: This is NOT a comprehensive review, and will focus primarily on SPH codes, techniques, and past results

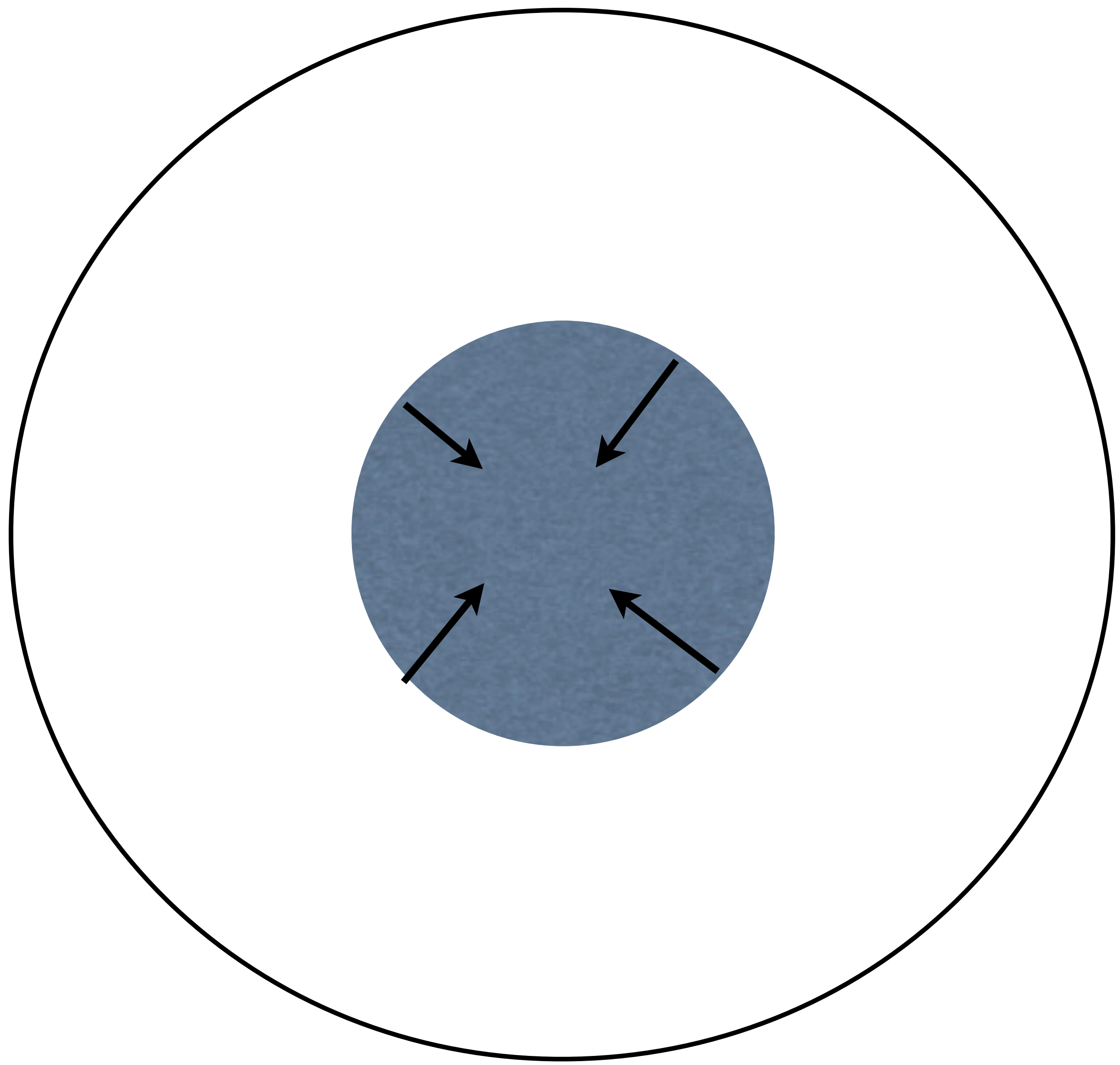
# 4.1 Cooling and Star Formation



# 4.1 Cooling and Star Formation



# 4.1 Cooling and Star Formation



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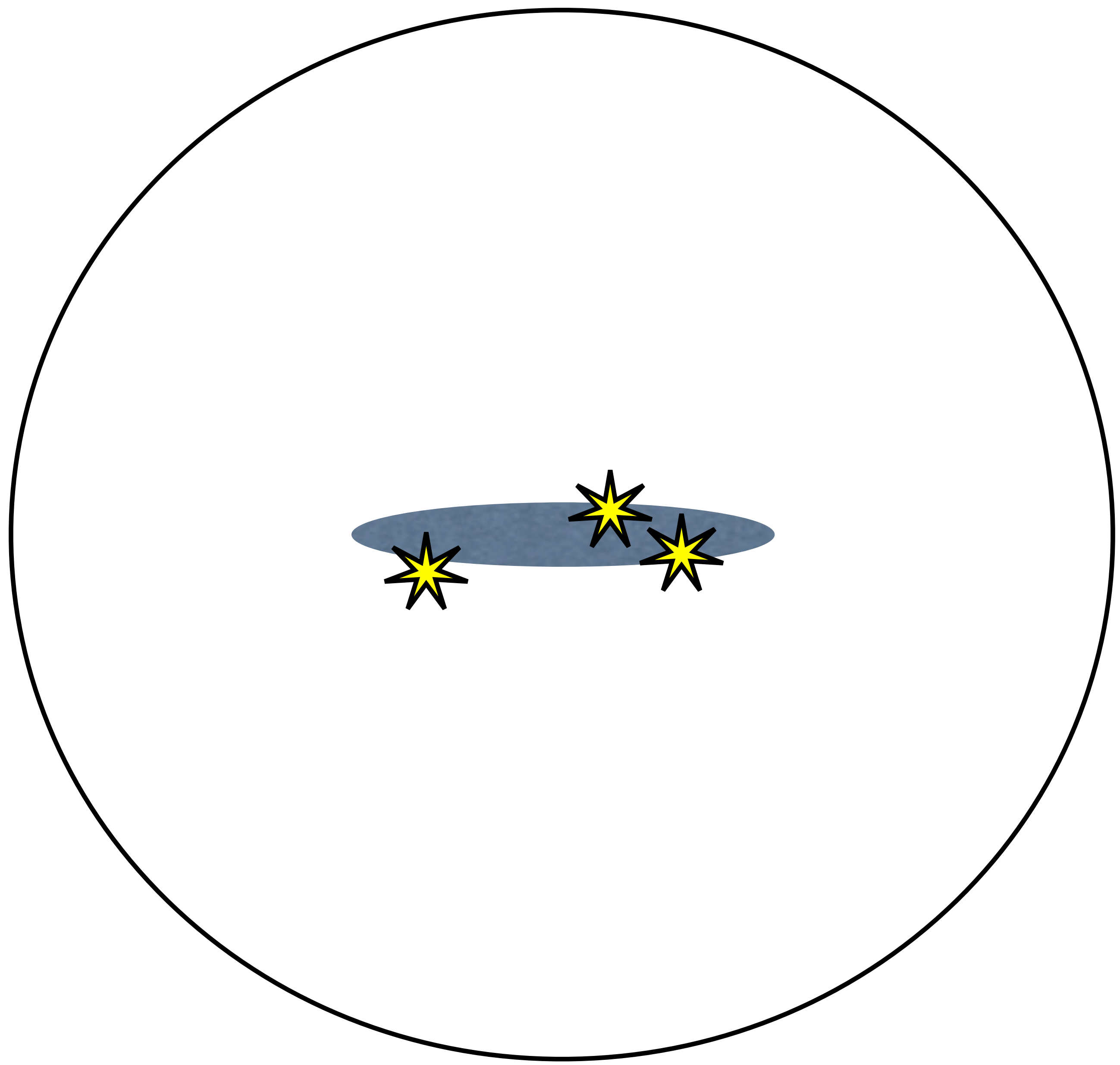
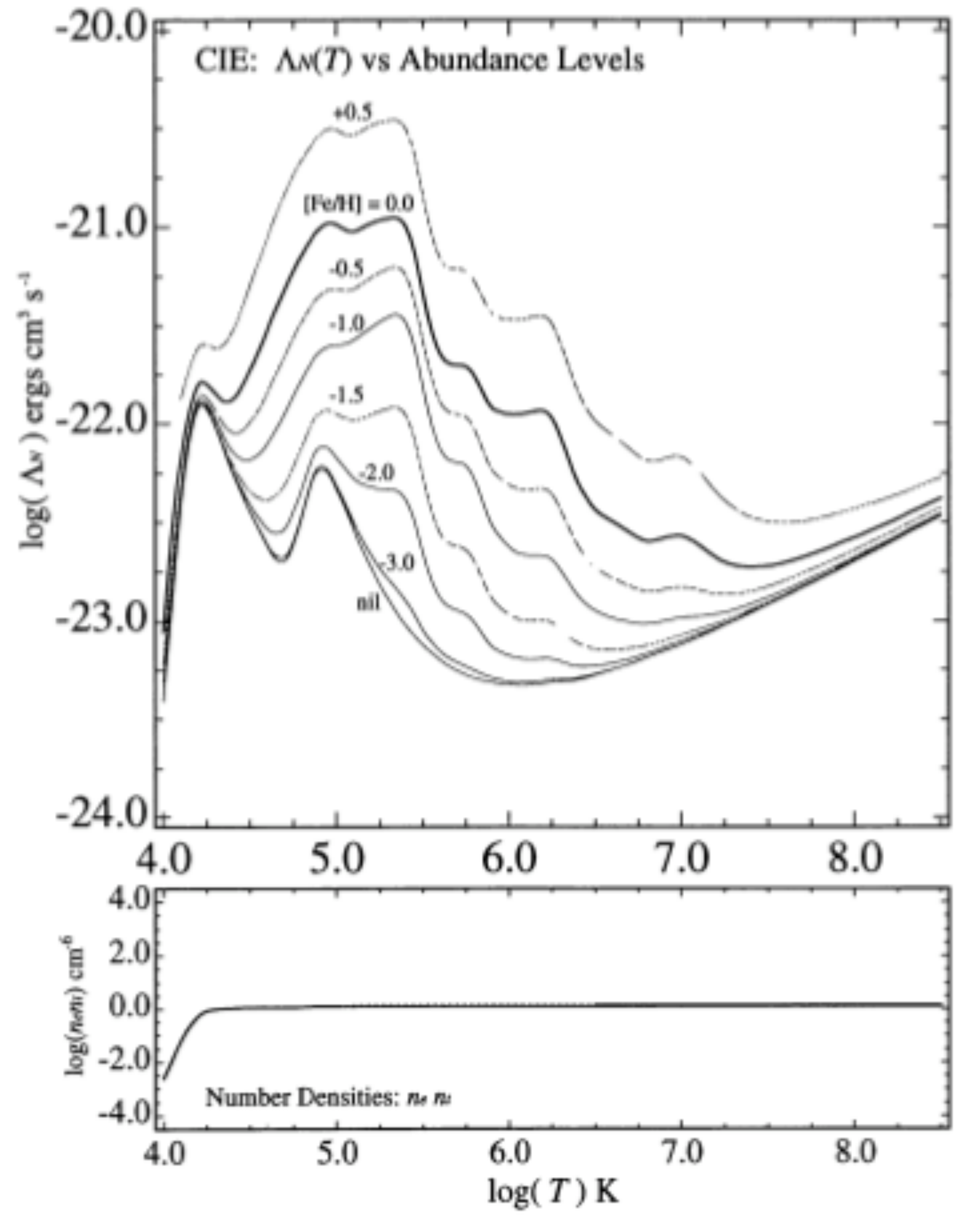


# 4.1 Cooling and Star Formation

* Tabulated cooling curves: H/He/Z from Sutherland & Dopita (1993)

* Explicitly track the ionization state and cooling rate (see, e.g., Weinberg et al. 1997)

* Tabulated cooling rate including molecules, ISRF, and metals from CLOUDY (Ferland et al.1998)



# 4.1 Cooling and Star Formation

$$\frac{\mathrm{d}u_i}{\mathrm{d}t} = \frac{1}{2}\sum_{j=1}^{N} m_j \left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} + \Pi_{ij}\right) \mathbf{v}_{ij} \cdot \nabla_i \overline{W}_{ij} - \frac{\Lambda_{\mathrm{net}}(\rho, T)}{\rho}$$

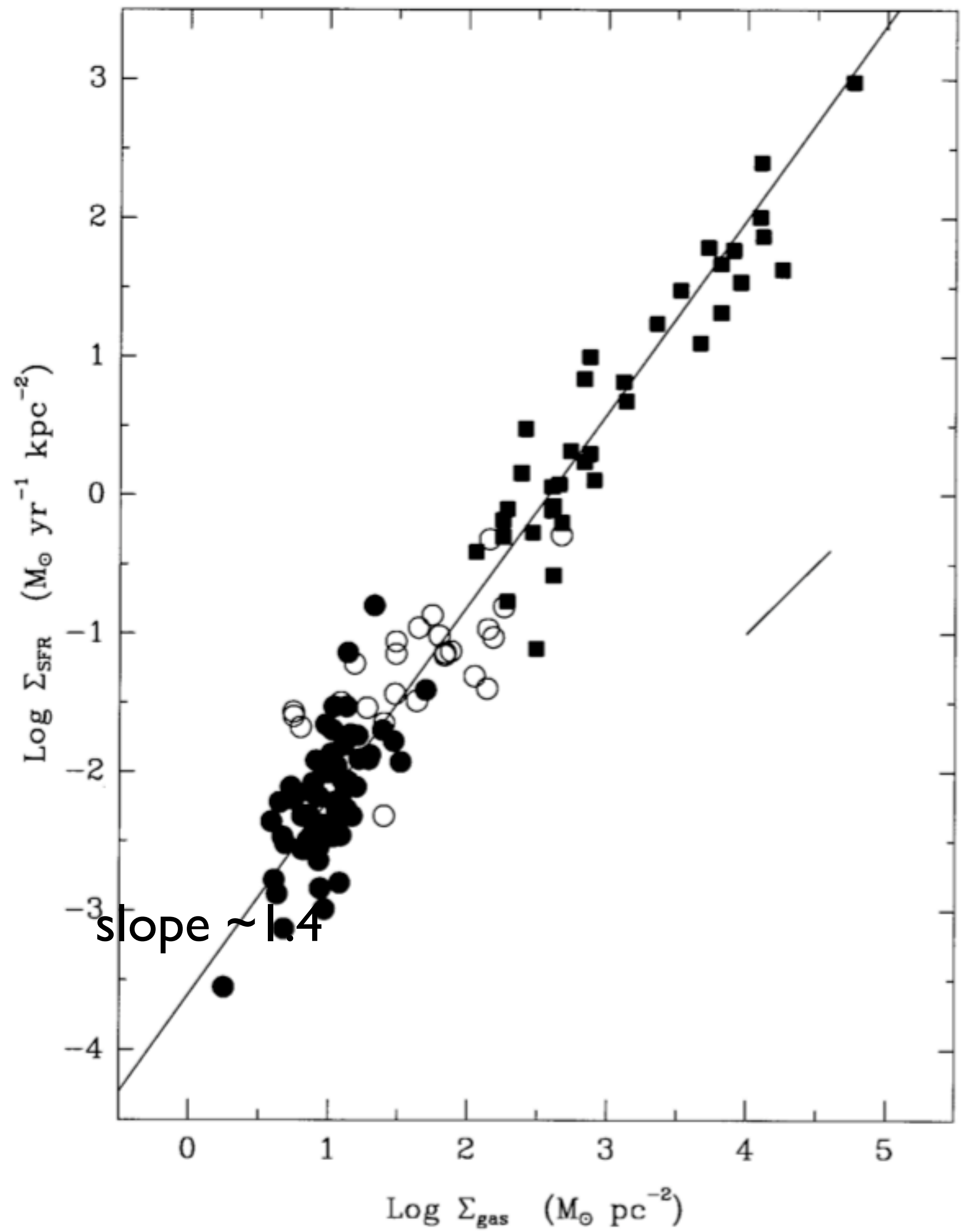
simply becomes an additional term in the energy (or entropy) equation

# 4.1 Cooling and Star Formation

* Relation holds for all environments, and physical conditions probed and spans many orders of magnitude

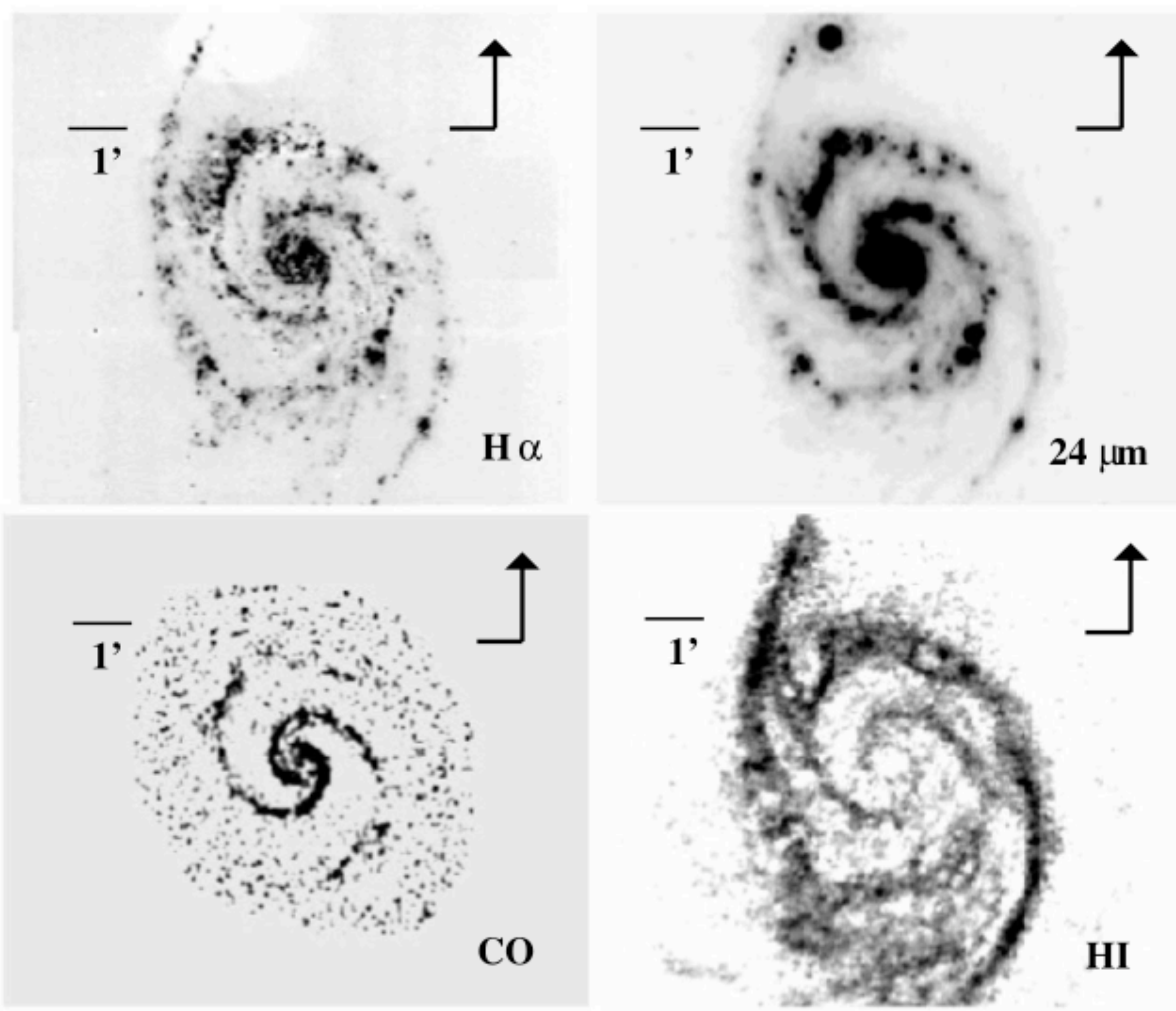
* Large scatter

* Evidence that the relation holds at high redshift (see, e.g., work by Bouche,Daddi,Genzel)

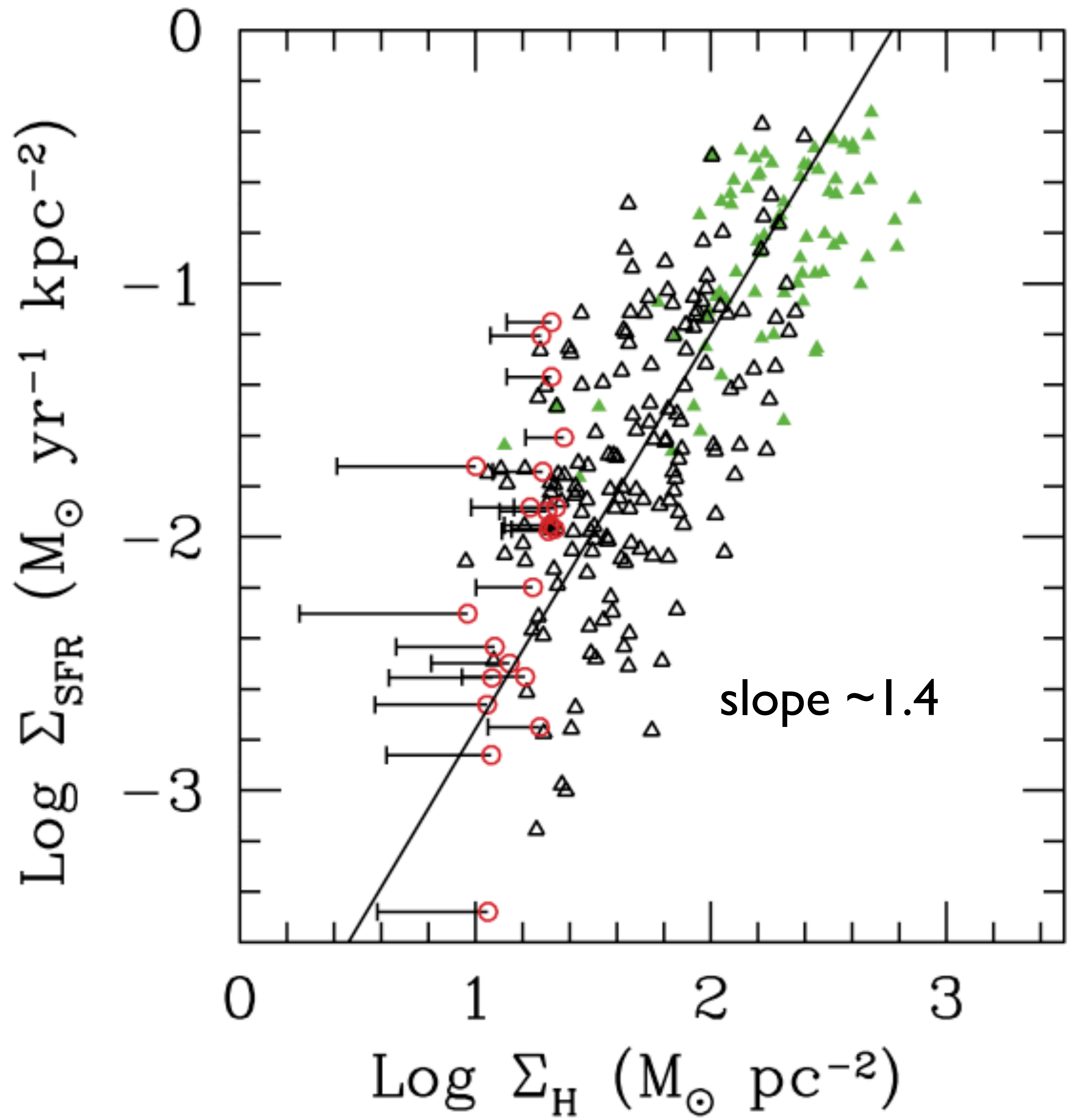



Kennicutt (1998)

# 4.1 Cooling and Star Formation




M51/SINGS survey (Kennicutt et al. 2007)



# 4.1 Cooling and Star Formation

$$\frac{\mathrm{d}\rho_\star}{\mathrm{d}t} = c_\star \frac{\rho_{\rm gas}}{t_{\rm dyn}}$$

$$t_{\rm dyn} = (4\pi G \rho_{\rm gas})^{-1/2}$$

$\longrightarrow$

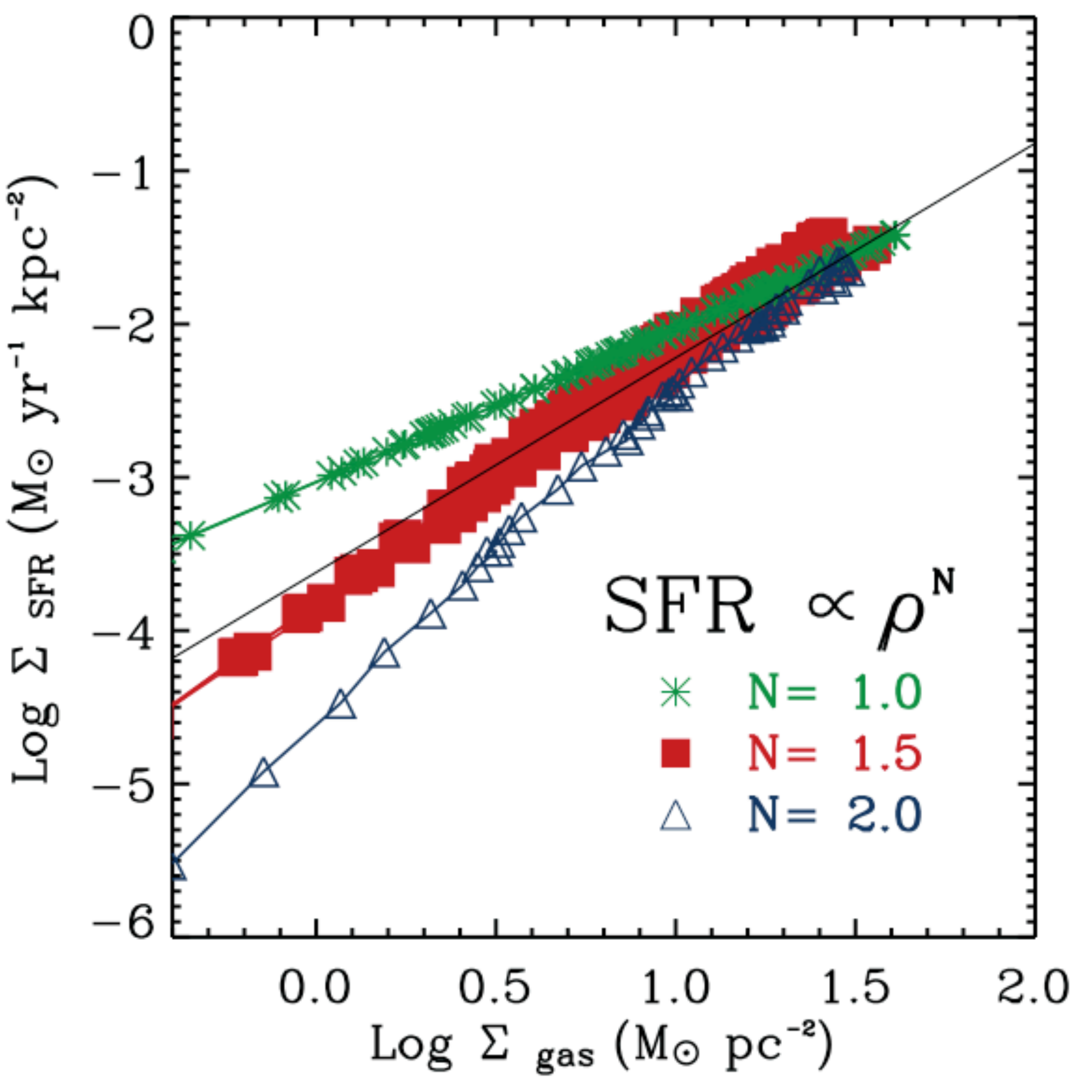
$$\frac{\mathrm{d}\rho_\star}{\mathrm{d}t} = C\,\rho_{\rm gas}^{N}$$

N=1.5

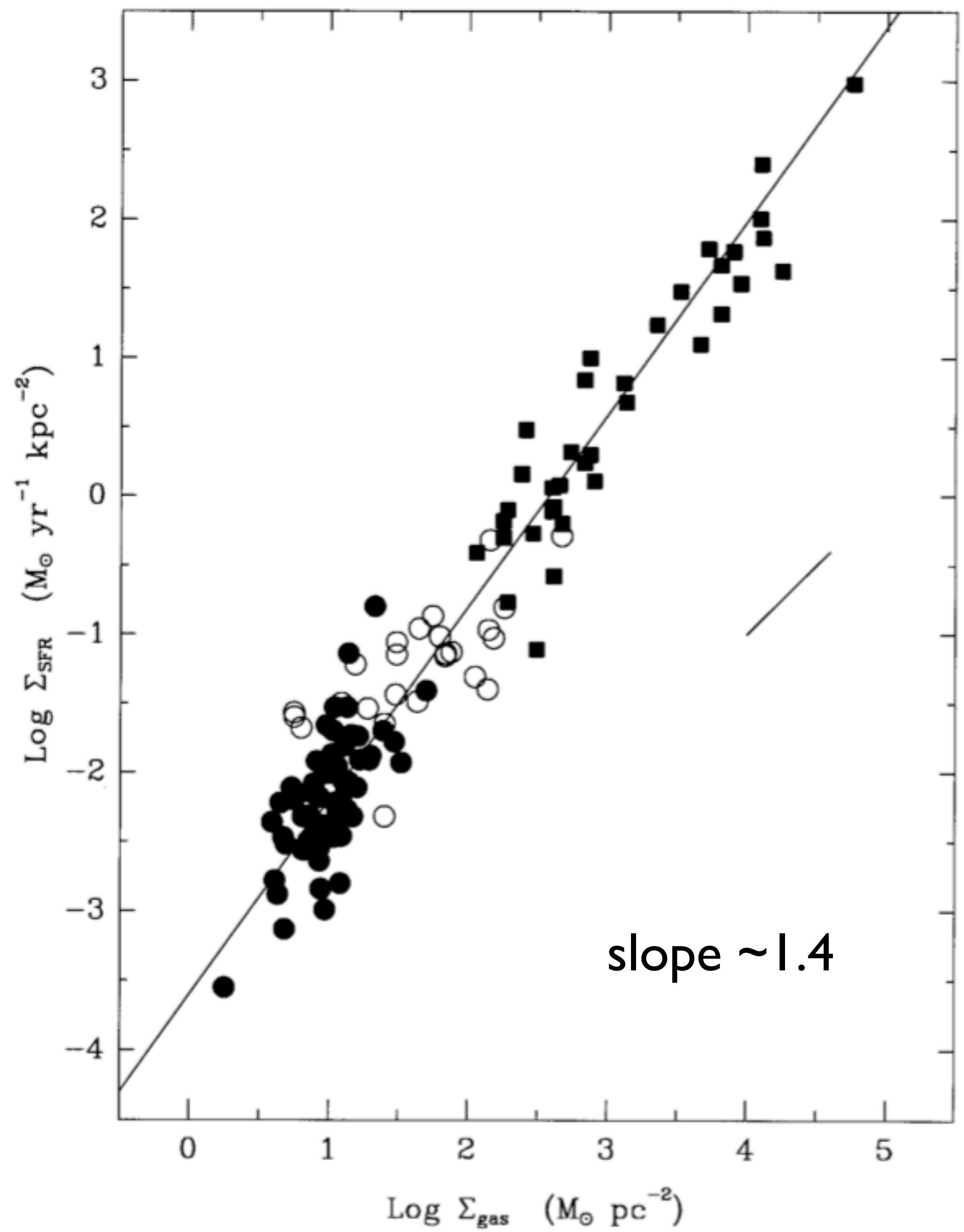
* A gas particle is then converted to a star particle probabilistically (i.e., star formation itself does not factor into the dynamics of the simulations - later we'll talk about feedback, which does).

# 4.1 Cooling and Star Formation

* SF implemented in a volumetric manner, but it still satisfies the observed surface density relation




Cox et al. (2006)




Kennicutt (1998)

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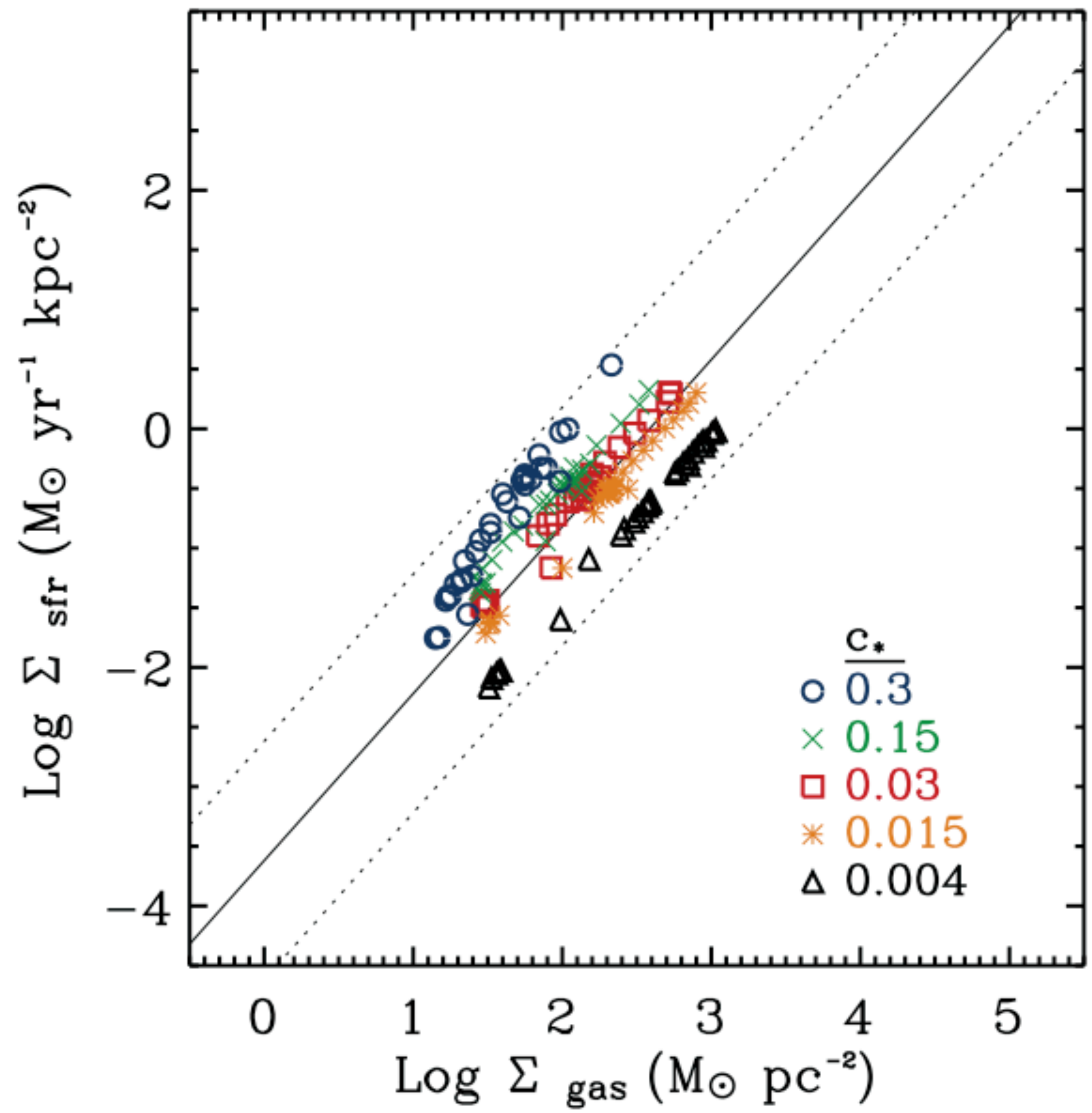
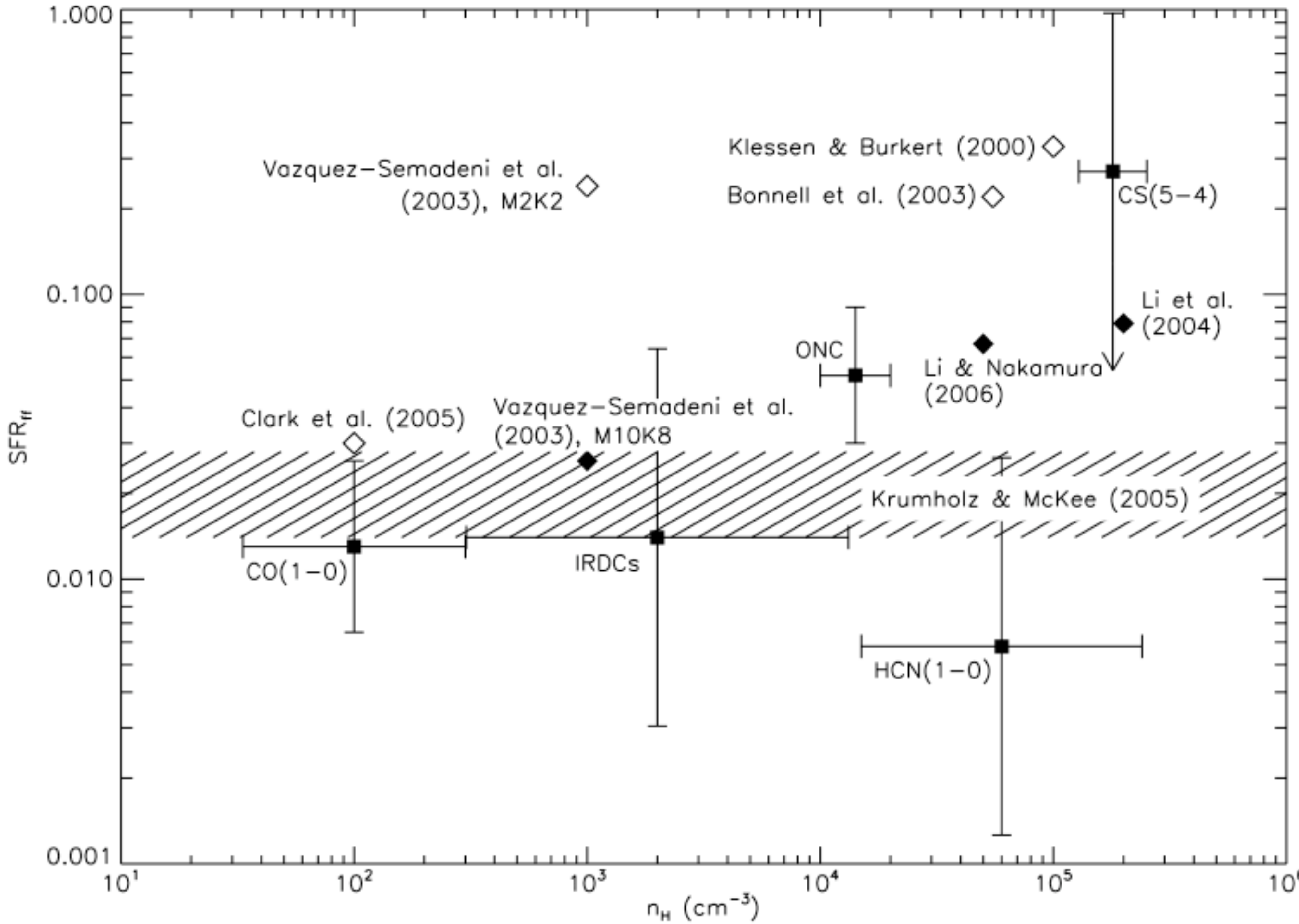


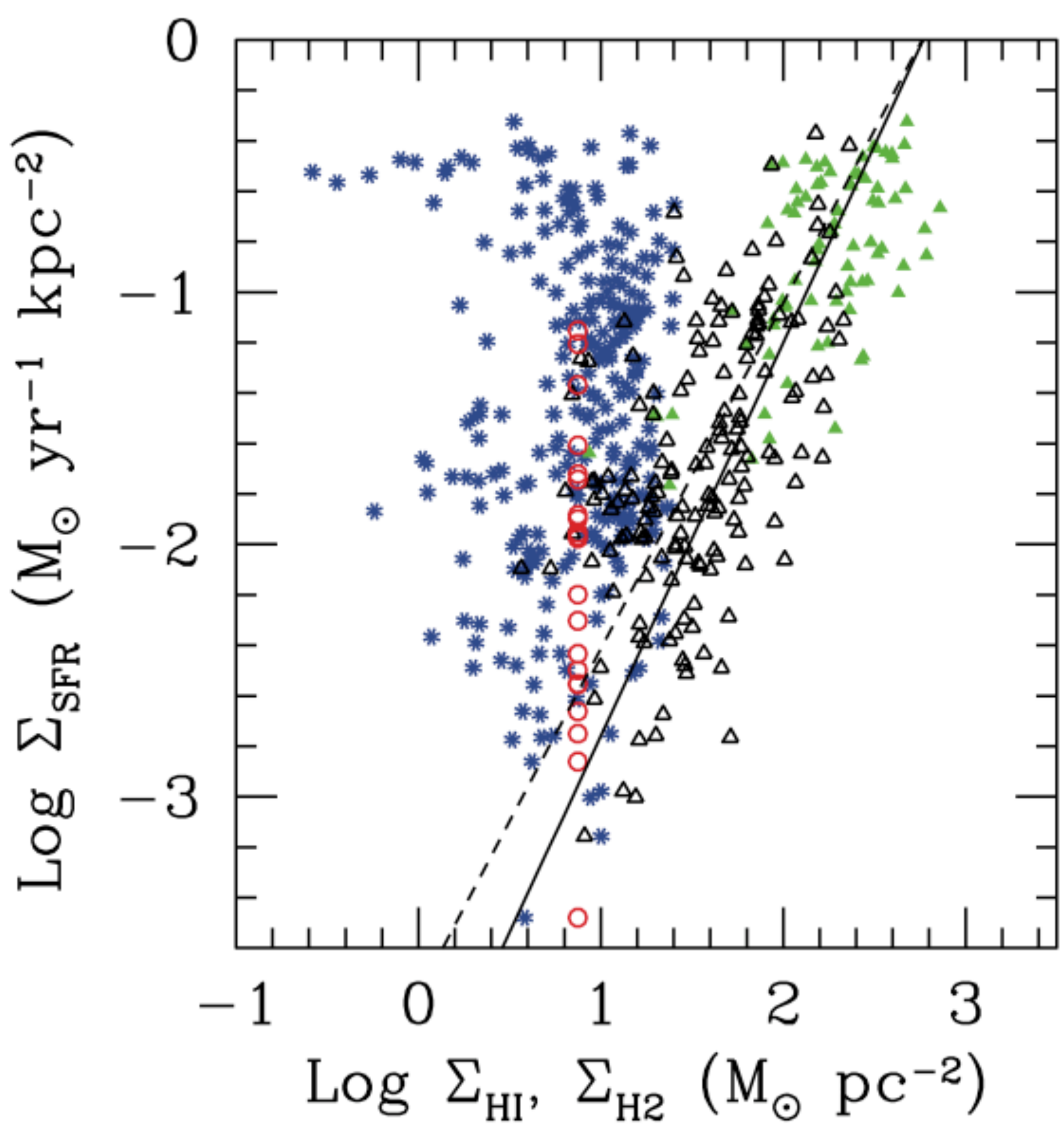

Cox et al. (2006)

# 4.1 Cooling and Star Formation




Krumholz & Tan (2007)

# 4.1 Cooling and Star Formation




Kennicutt et al. (2007)

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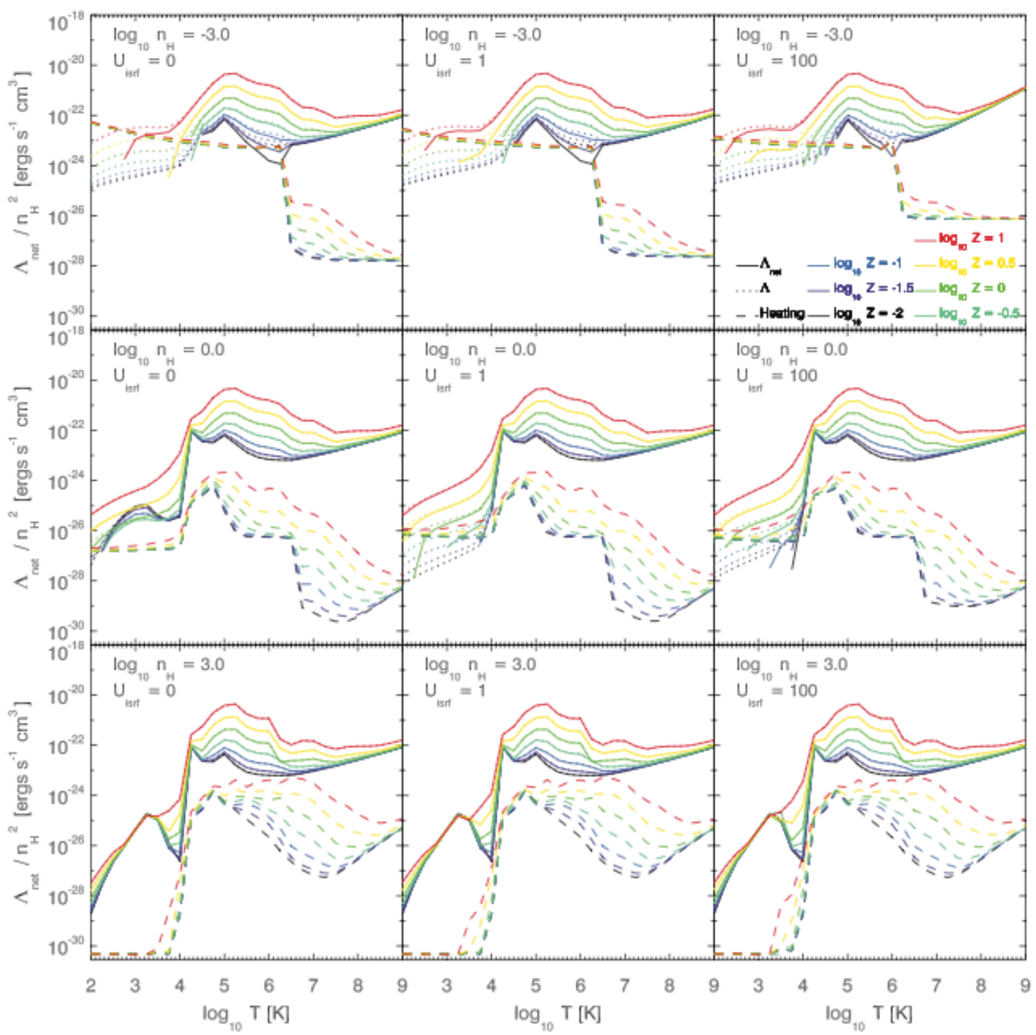
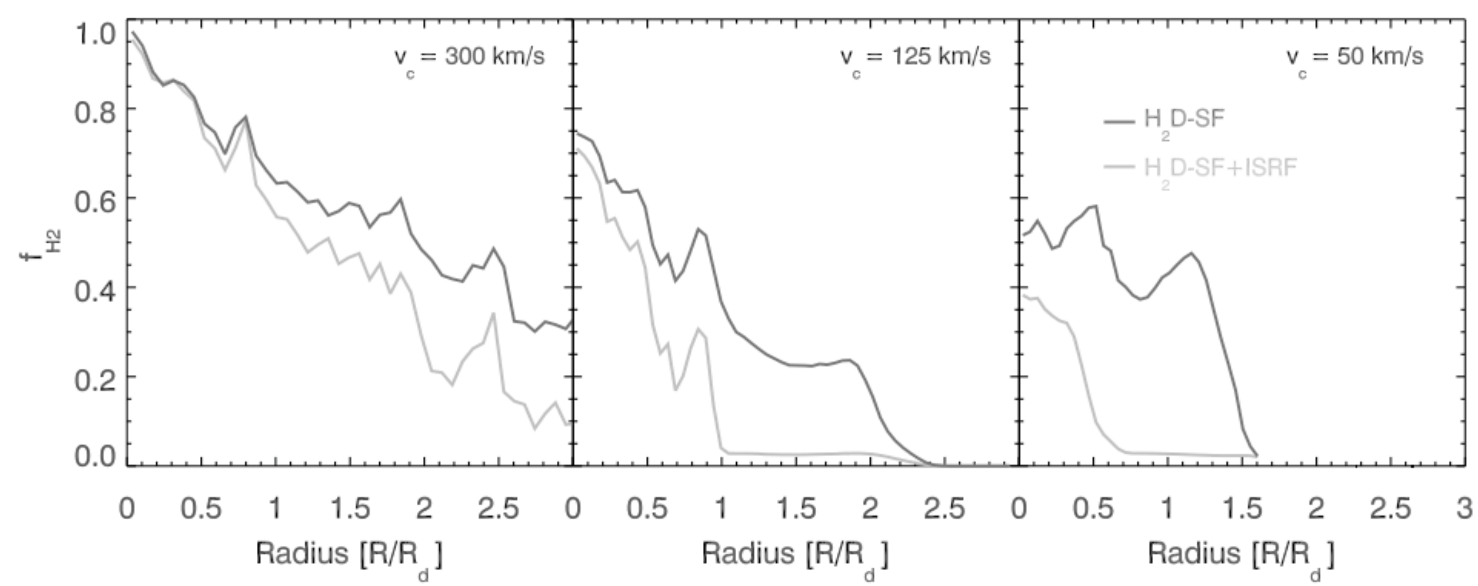
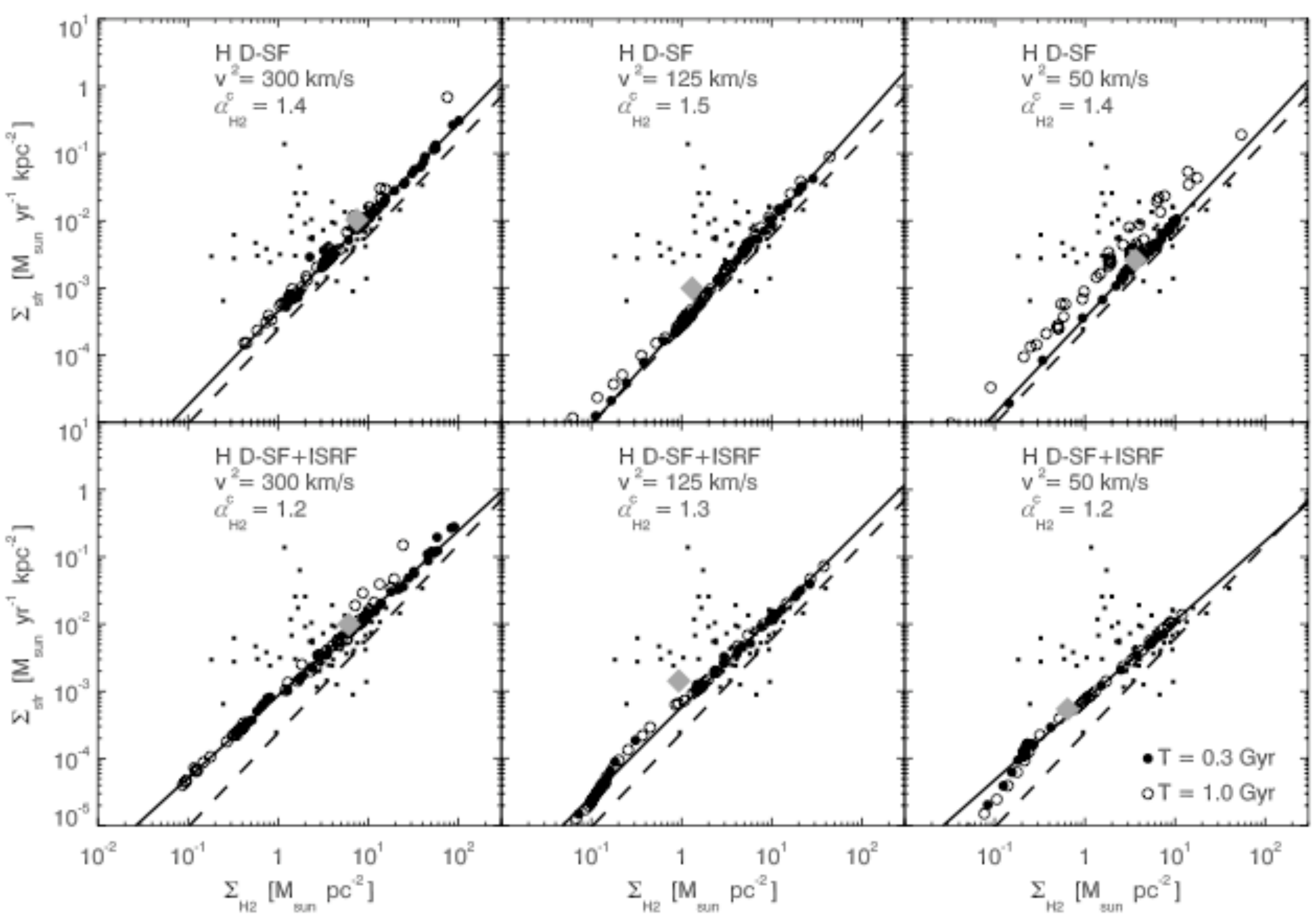


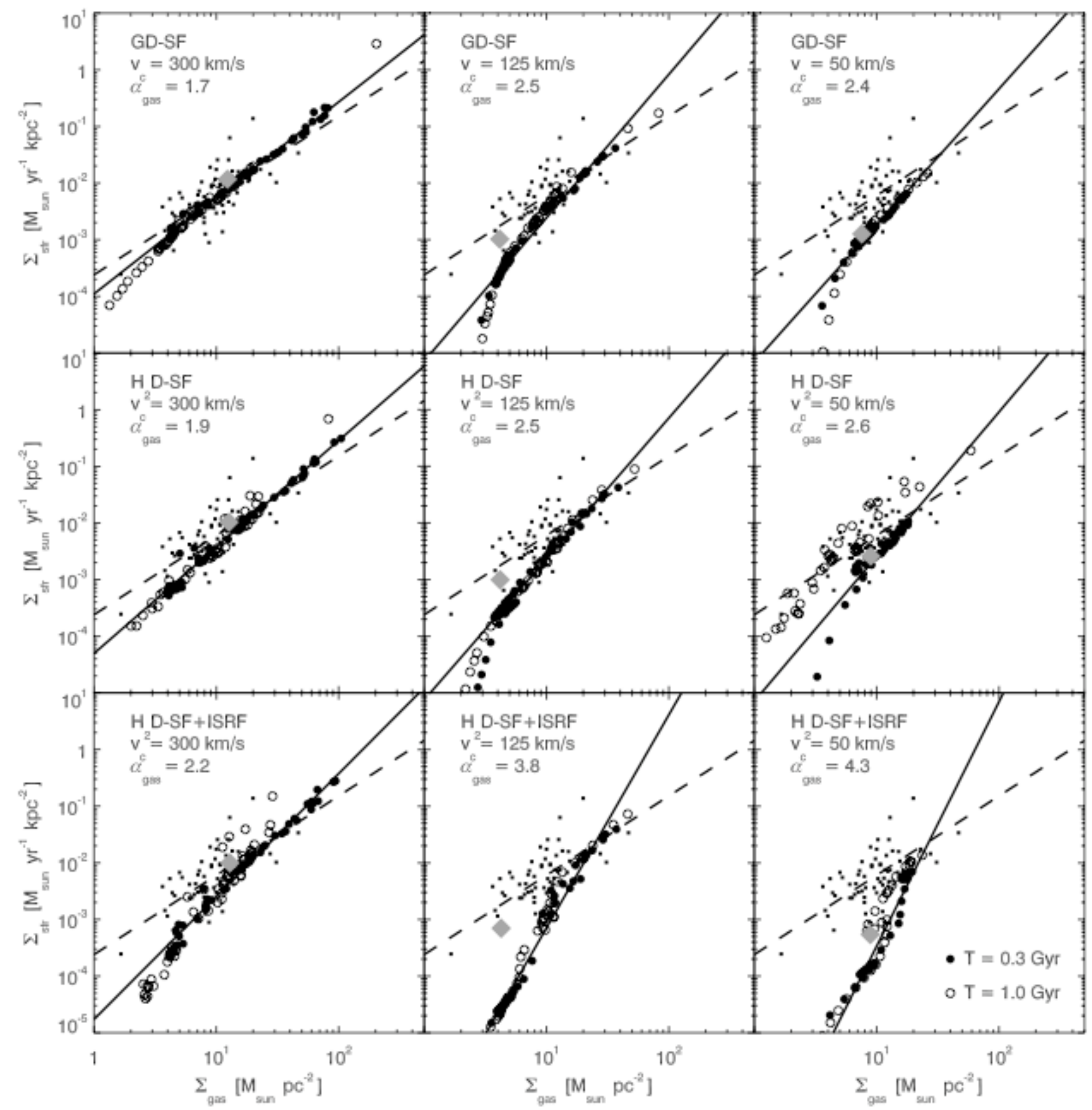

Robertson & Kravtsov (2008)

# 4.1 Cooling and Star Formation

$$\dot{\rho}_\star = (1-\beta) f_{\mathrm{H_2}} \frac{\rho_g}{t_\star} \left( \frac{n_{\mathrm{H}}}{10h^2\ \mathrm{cm}^{-3}} \right)^{0.5}$$




CO surface density

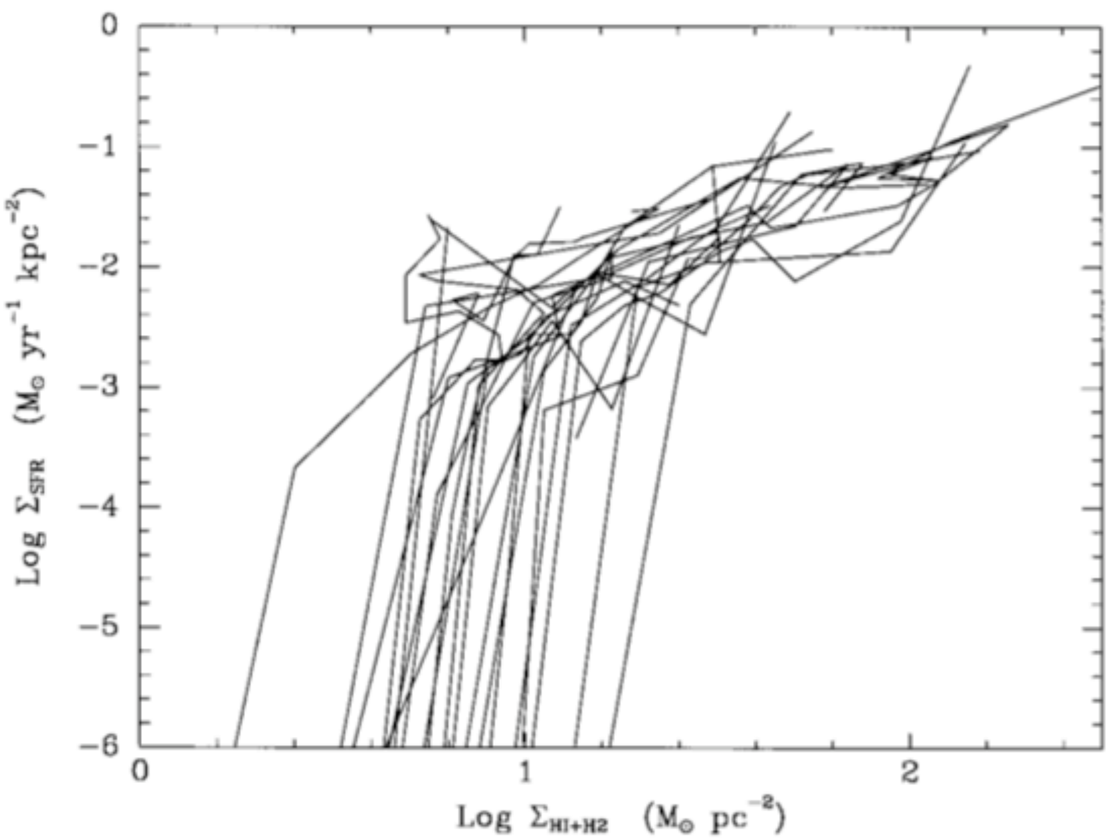



total gas surface density

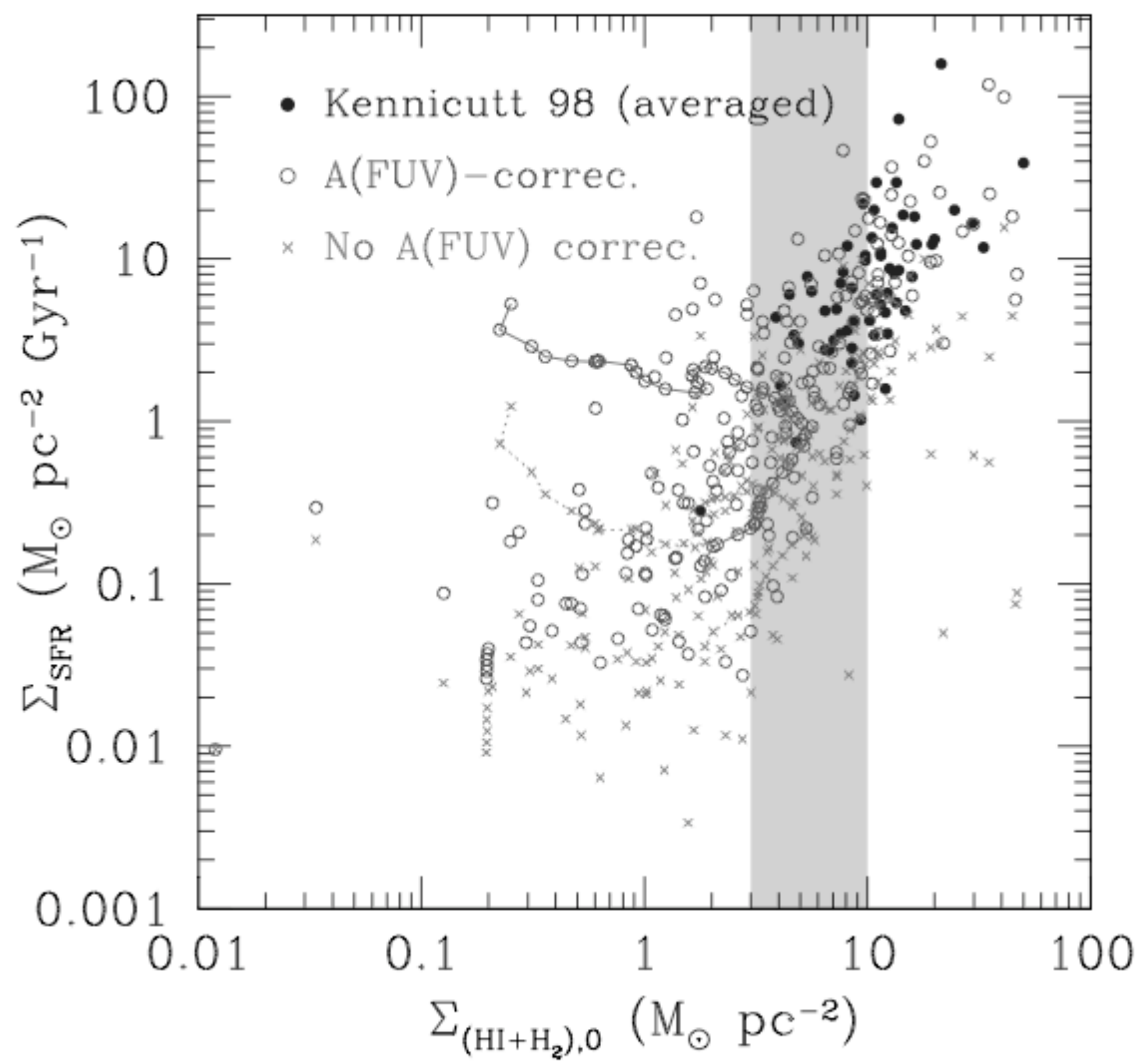
Robertson & Kravtsov (2008)

# 4.1 Cooling and Star Formation

* Should the star formation drop at low densities, i.e., is there a threshold for star formation?




Halpha - Kennicutt (1998)

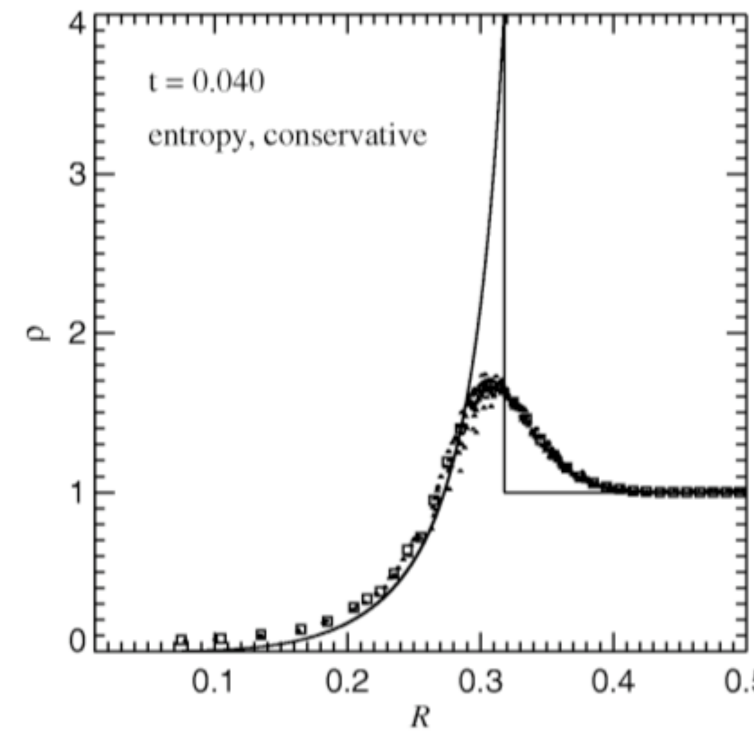


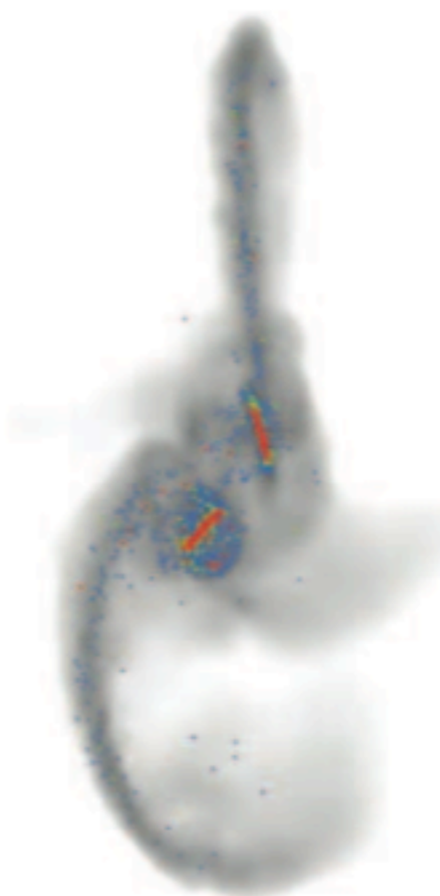

UV - Boissier et al. (2007)

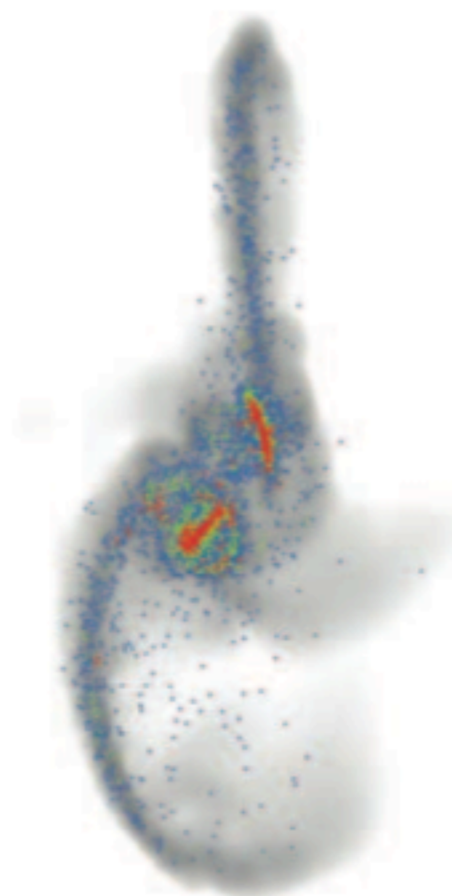
# 4.1 Cooling and Star Formation

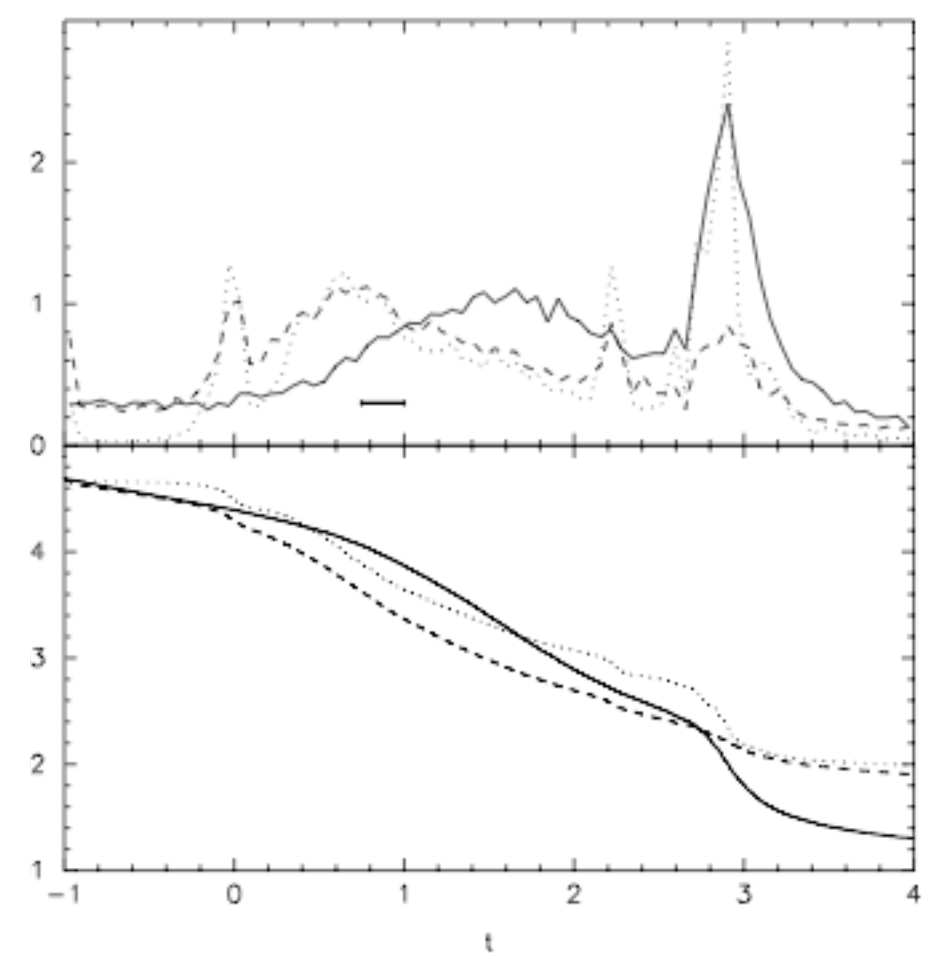
Shock-induced star formation (Barnes 2004)

$$\dot{\rho}_* = C_* \rho_g^n \mathrm{MAX}(\dot{u}, 0)^m$$





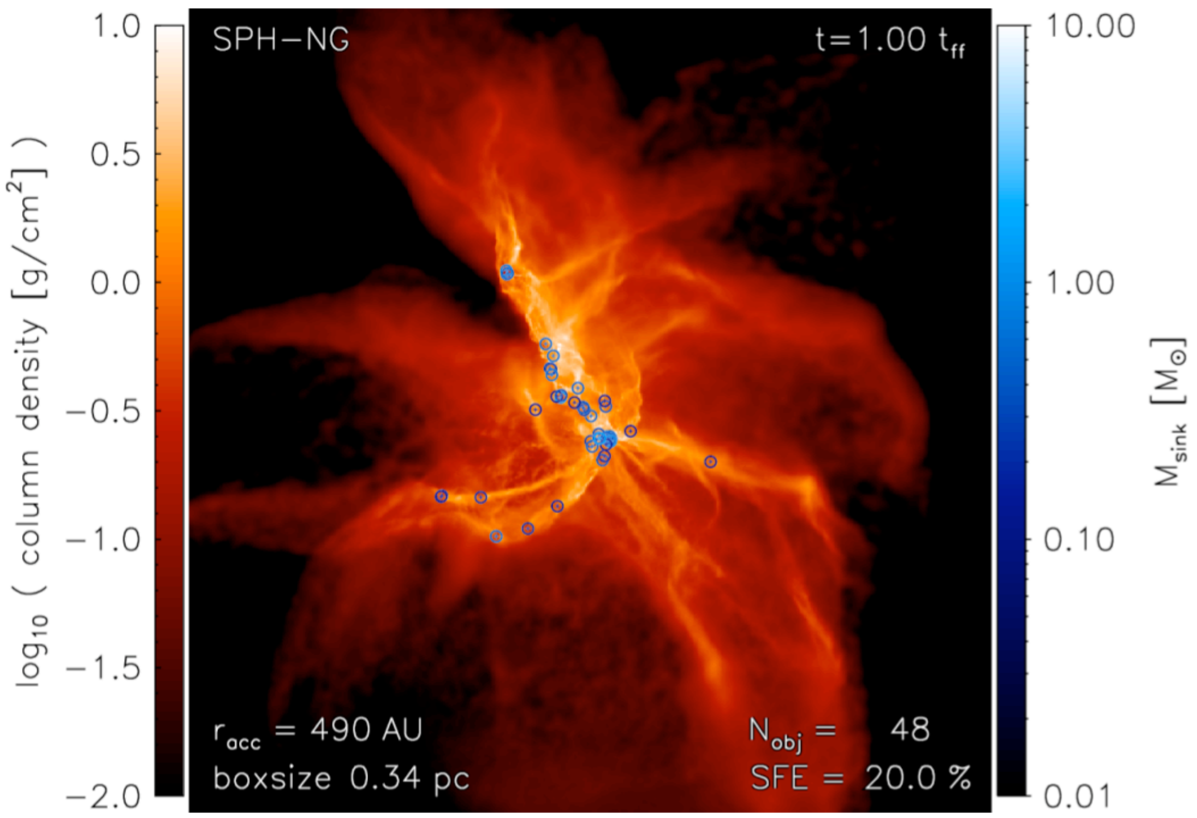


# 4.2 Sink Particles

* Based upon a specific set of criteria (density, converging flow, distinct from other sinks, etc.) an individual is wholly converted to a non-SPH "sink" particle.

* The sink particle can then accrete neighboring particles under certain conditions (r<r_accretion, bound)

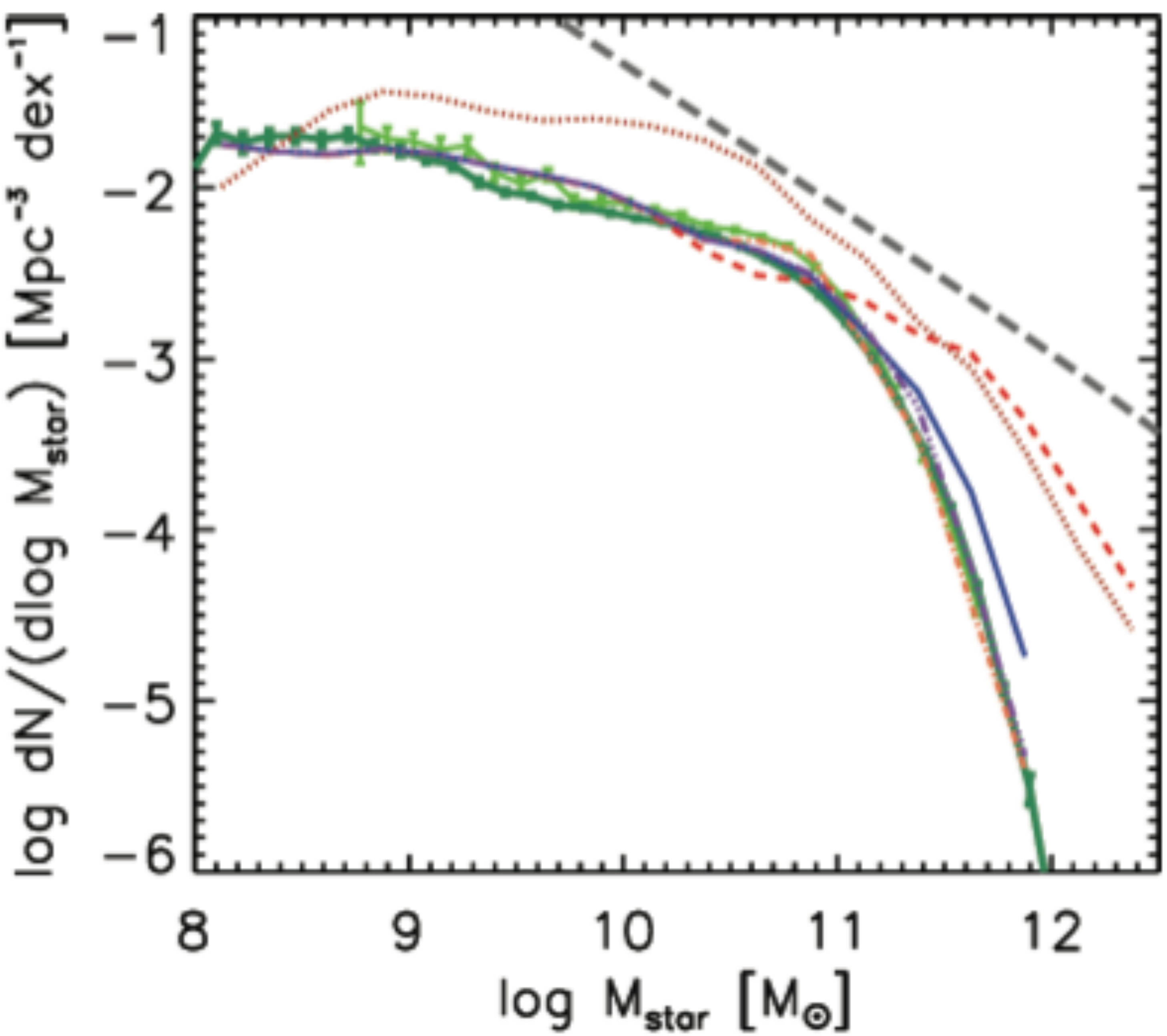
* BH's are modeled as sink particles that are still contain an SPH component and additionally inject energy into local particles




see, e.g., Bate et al. (1995), Jappsen et al. (2005)

# 4.3 Feedback

## 4.3 Feedback

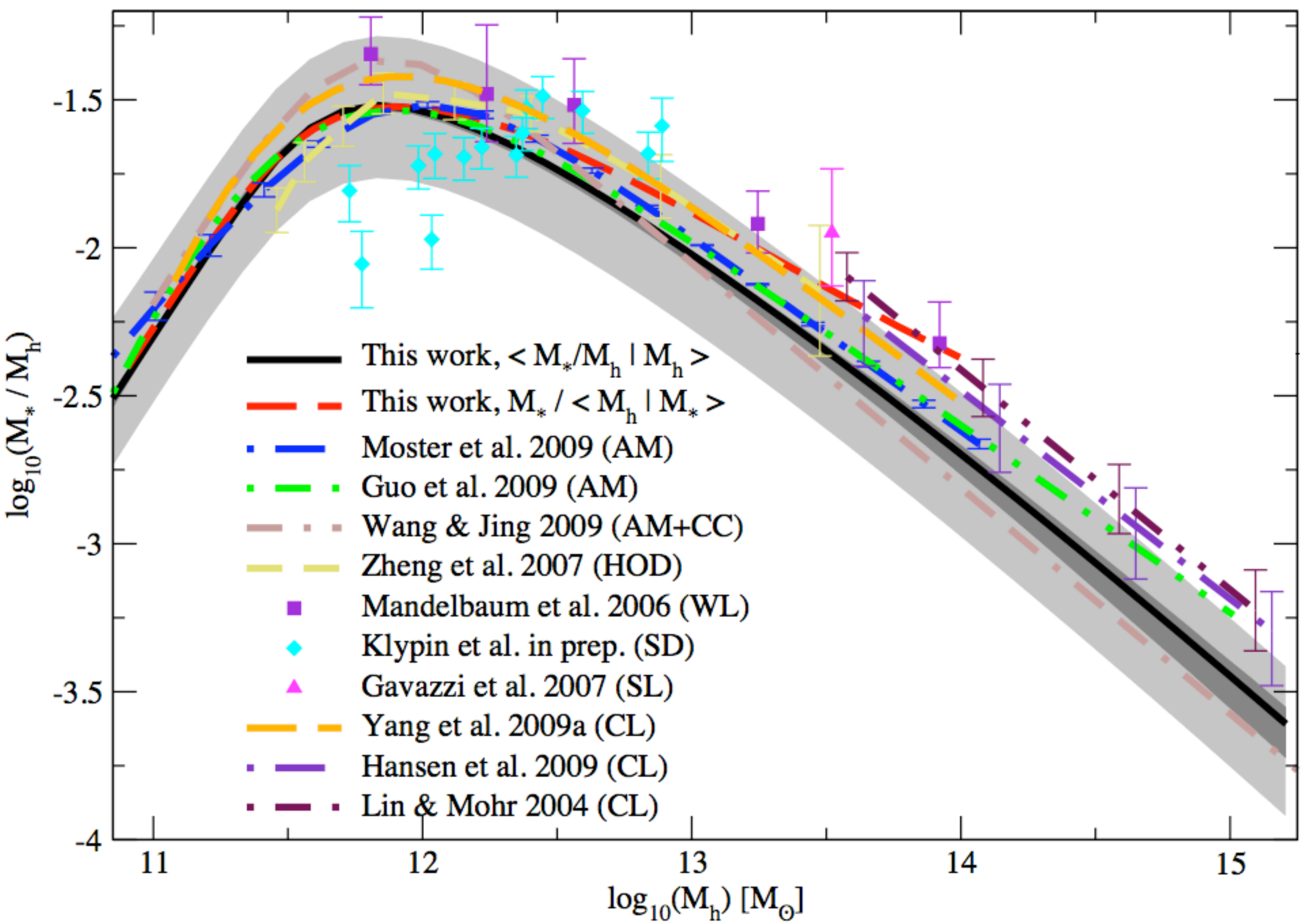



Somerville et al. (2008)

# 4.3 Feedback

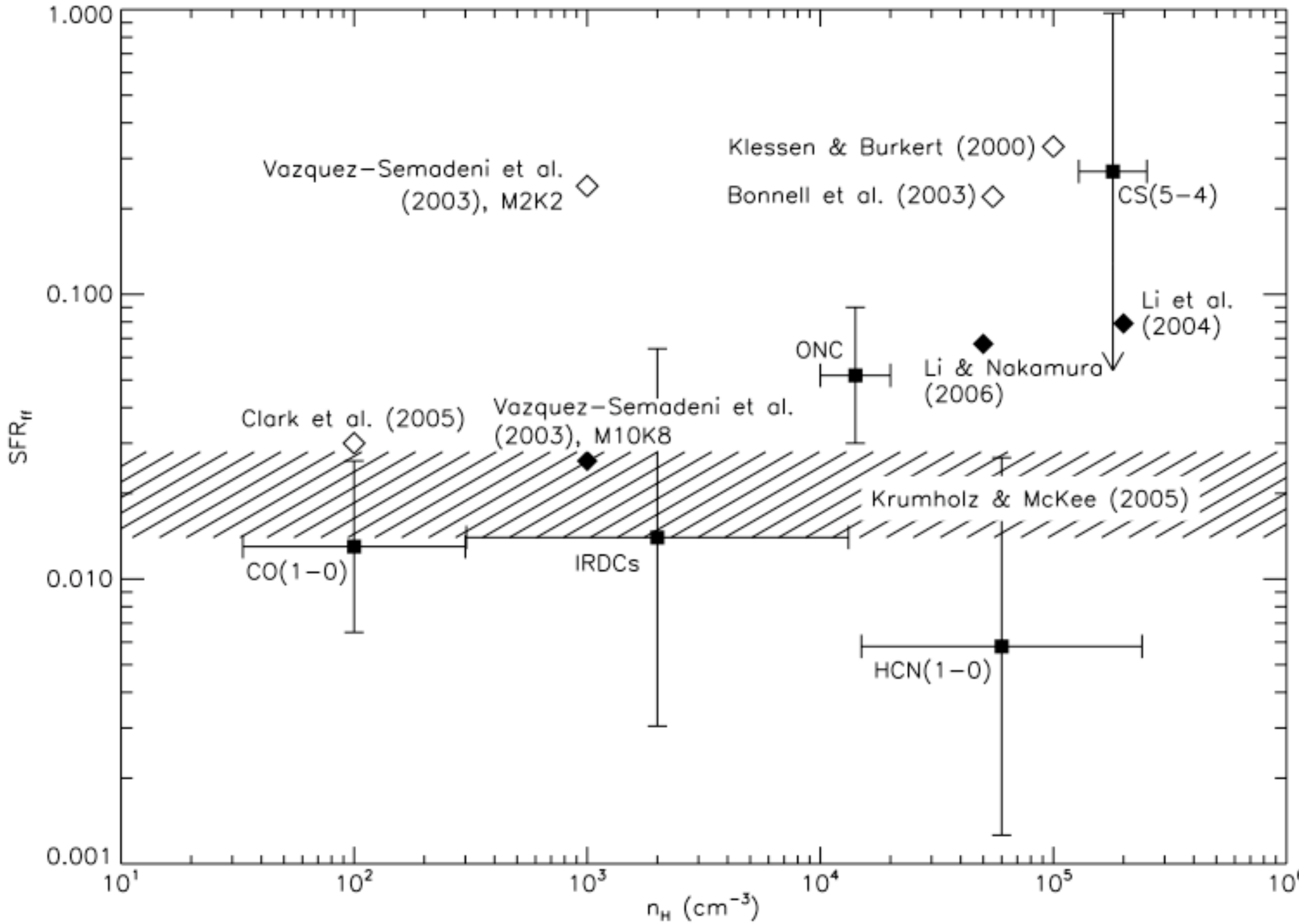
~0.03 at maximum

(about ~20% of the universal baryon fraction)




Behroozi, Conroy, & Wechsler (2010)

# 4.3 Feedback

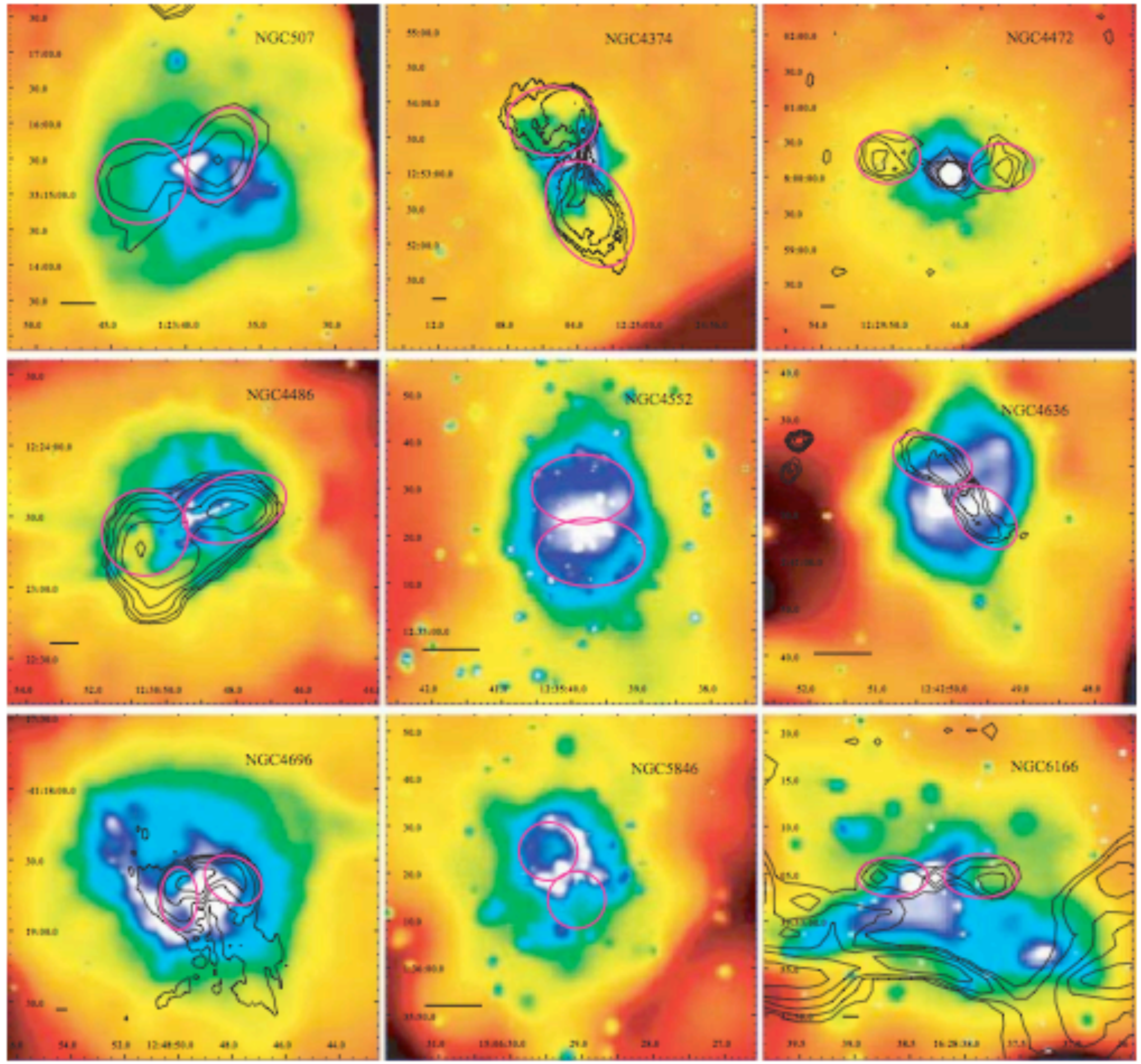



Krumholz & Tan (2007)

# 4.3 Feedback

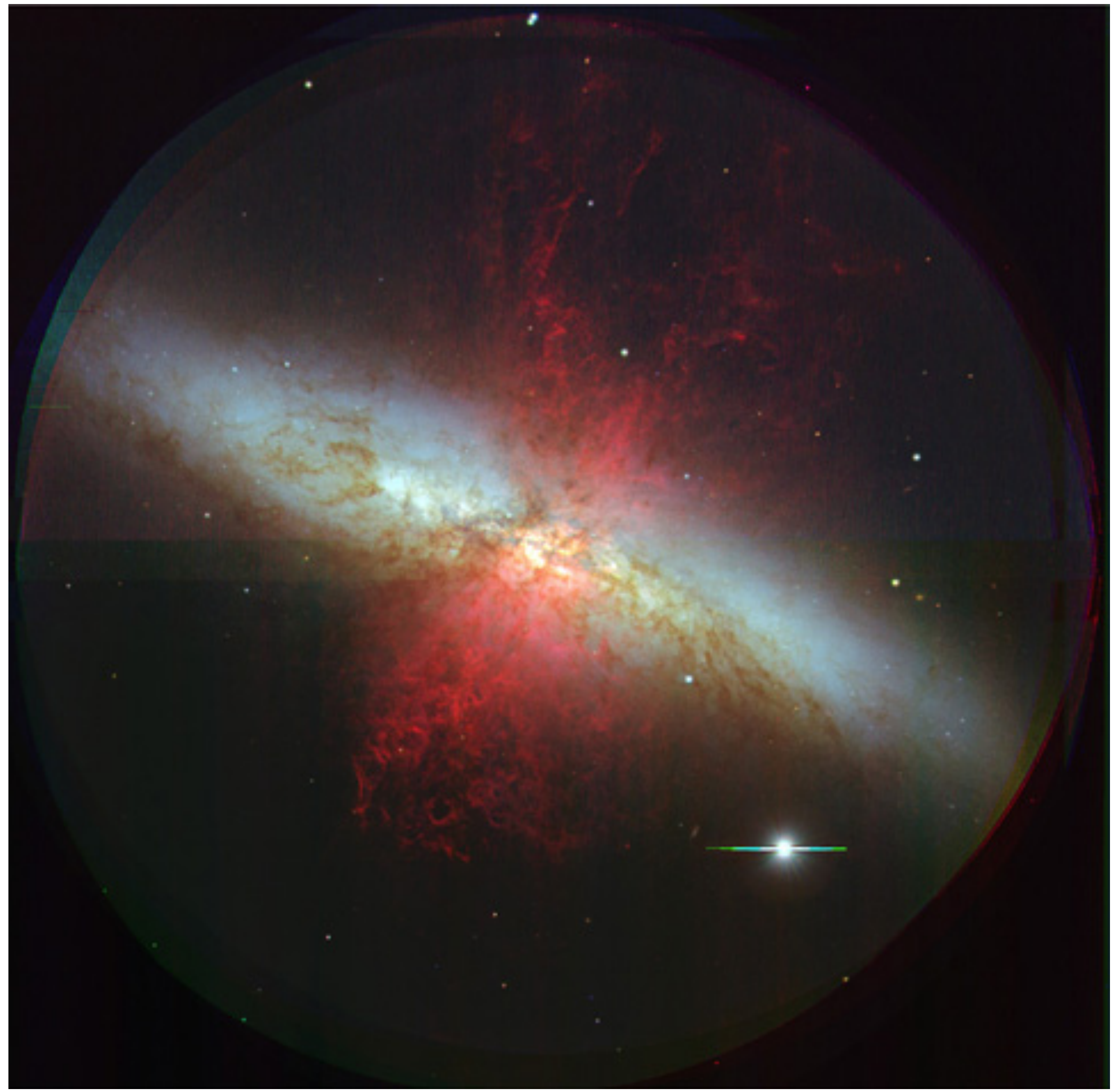
Bubble and jets in appear to offset the efficient cooling which should be occurring in clusters (see, e.g., Allen et al. 2006)

“radio-mode” AGN feedback



# 4.3 Feedback

* Galactics winds are ubiquitous (in high-z star-forming galaxies, local starbursts, and moderate-z post-starburst systems, see, e.g., Heckman, Strickland, Veilleux, Rupke, Martin, Tremonti, Weiner, Steidel, ..)



# 4.3 Feedback

types of feedback:

* Radiative: UV/X-rays from young stars and AGN

* Energetic: Outflows driven by SN, stellar winds, and AGN

* Mass, metals, and dust deposited by SN, stellar winds, AGB stars, AGN

# 4.3 Feedback

A multitude of models exist to include feedback in simulations (several of which you've heard about this week):

# 4.3 Feedback

A multitude of models exist to include feedback in simulations (several of which you've heard about this week):

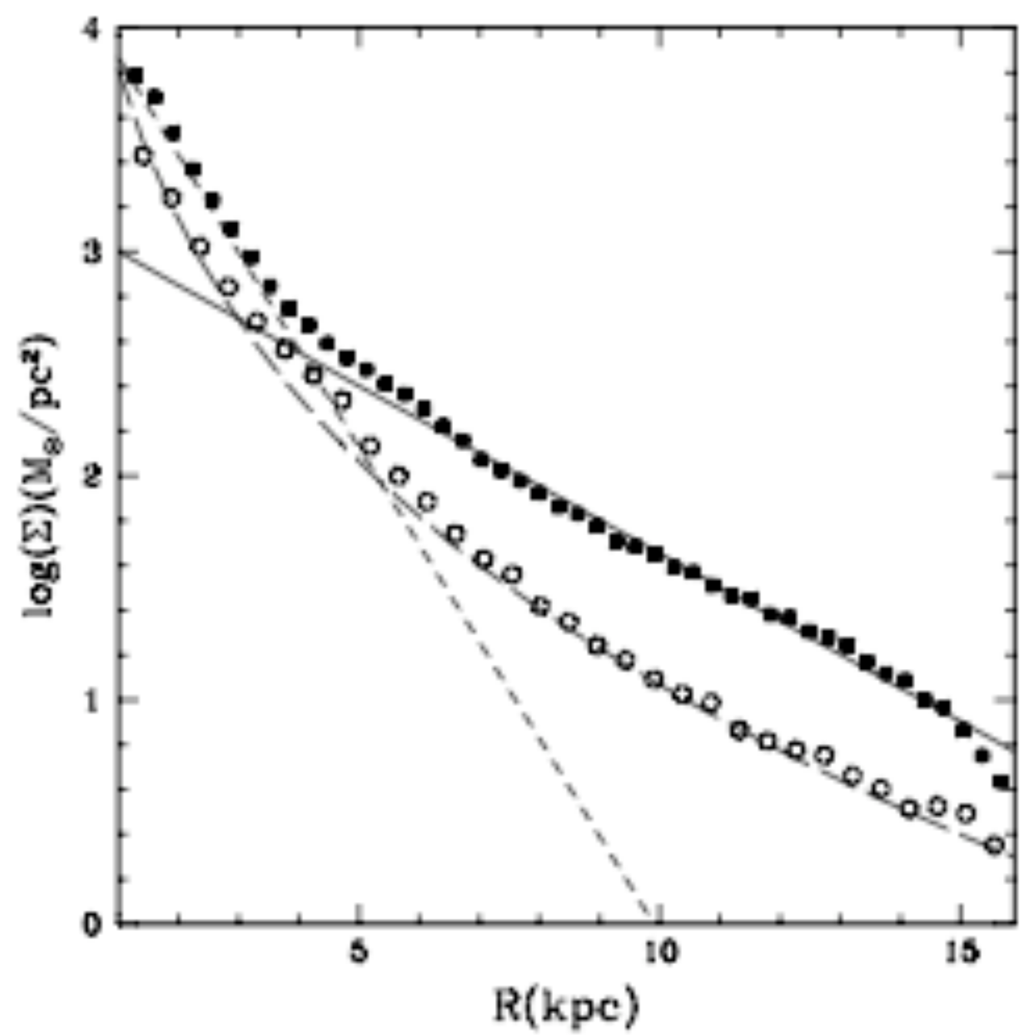
* Thermal feedback is generally ineffective (see, e.g., Katz 1992 - the cooling time is short in these high density regions and any addition SN energy is quickly radiated away)

$$\frac{\mathrm{d}u_i}{\mathrm{d}t} = \frac{1}{2}\sum_{j=1}^{N} m_j \left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2} + \Pi_{ij}\right) \mathbf{v}_{ij} \cdot \nabla_i \overline{W}_{ij} - \frac{\Lambda_{\mathrm{net}}(\rho, T)}{\rho} + \text{SN energy}$$

# 4.3 Feedback

A multitude of models exist to include feedback in simulations (several of which you've heard about this week):

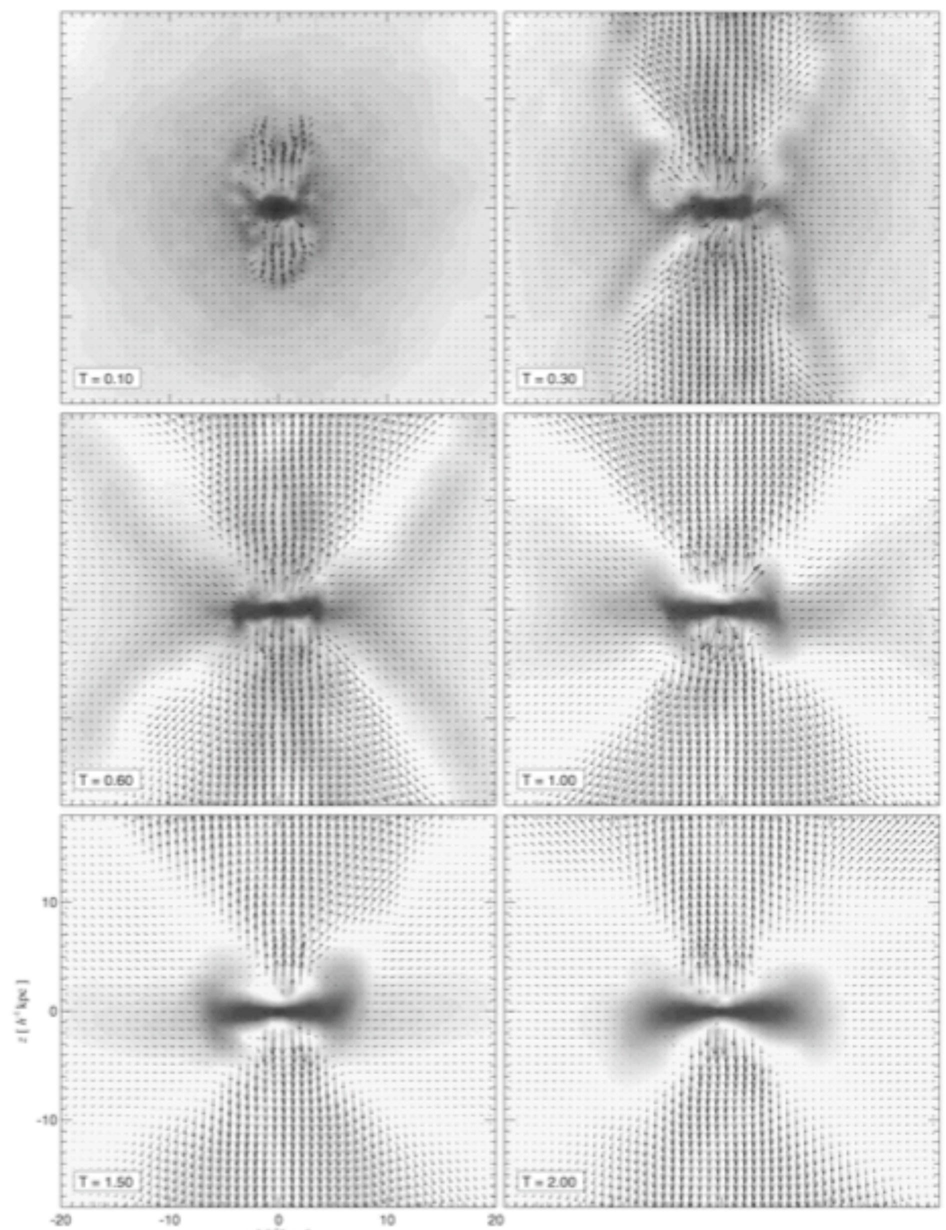
* turn off cooling for a period of time post-SF (see, e.g., Governato et al. 2004)



# 4.3 Feedback

A multitude of models exist to include feedback in simulations (several of which you've heard about this week):

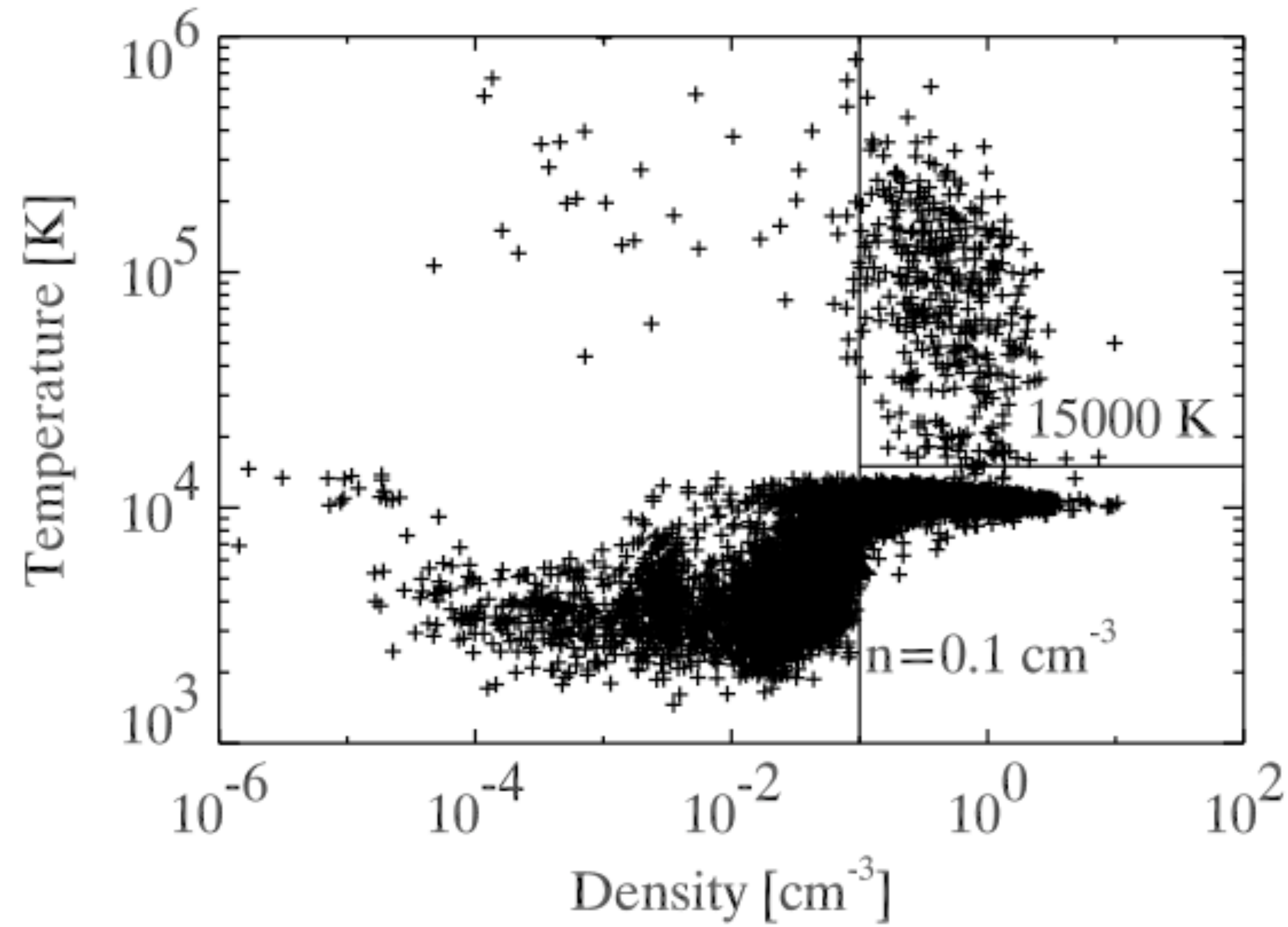
* deliver the energy in a kinetic fashion, rather than thermally (e.g., Navarro et al. 1993, Mihos & Hernquist 1994, Springel & Hernquist 2005, Oppenheimer & Dave 2006)



# 4.3 Feedback

A multitude of models exist to include feedback in simulations (several of which you've heard about this week):

* Stinson et al. (2006) - energy comes from star-particles, not star-forming gas, and come from SN II, Ia, and stellar winds, but it still adopts a similar restriction on the cooling



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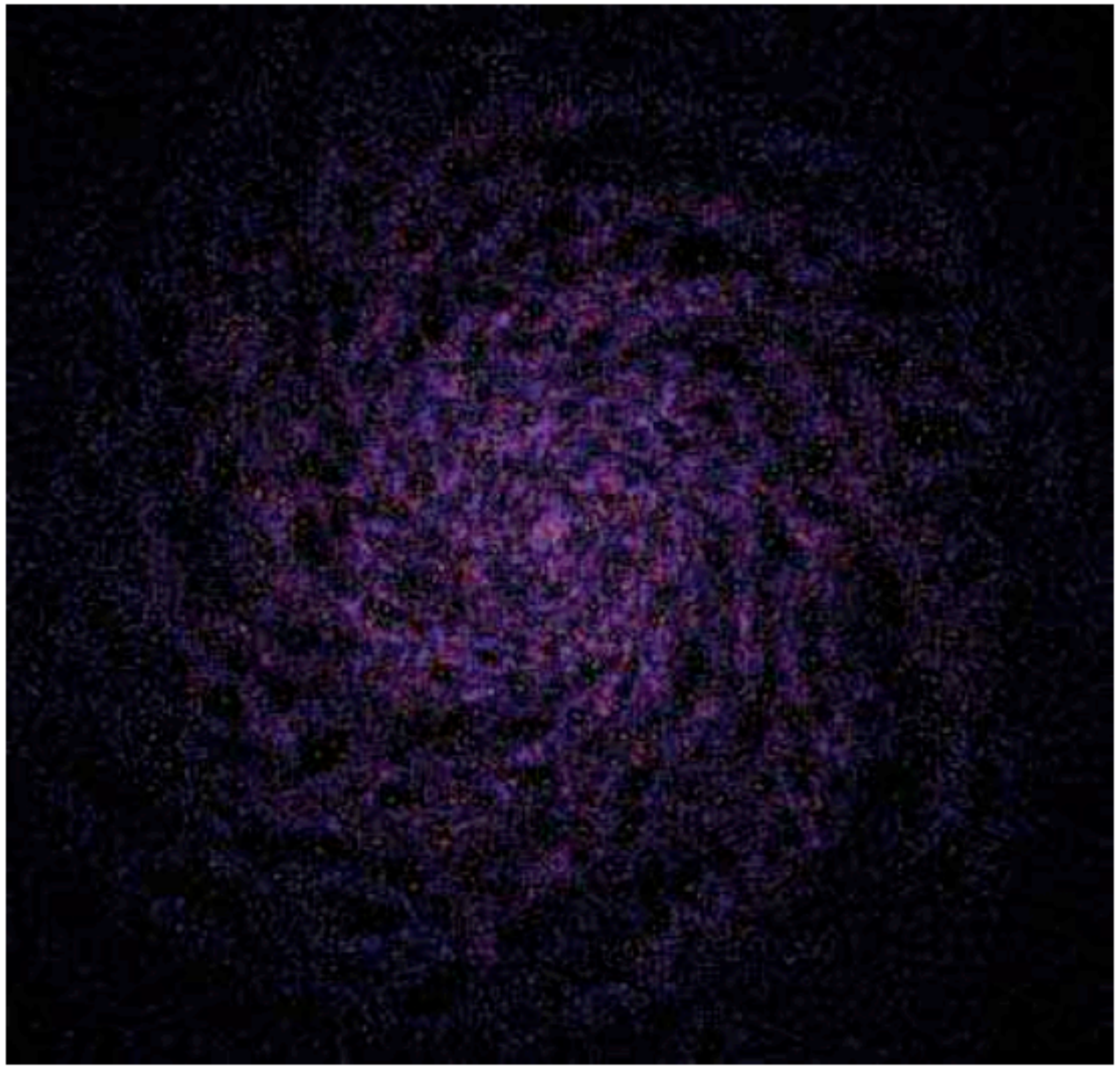
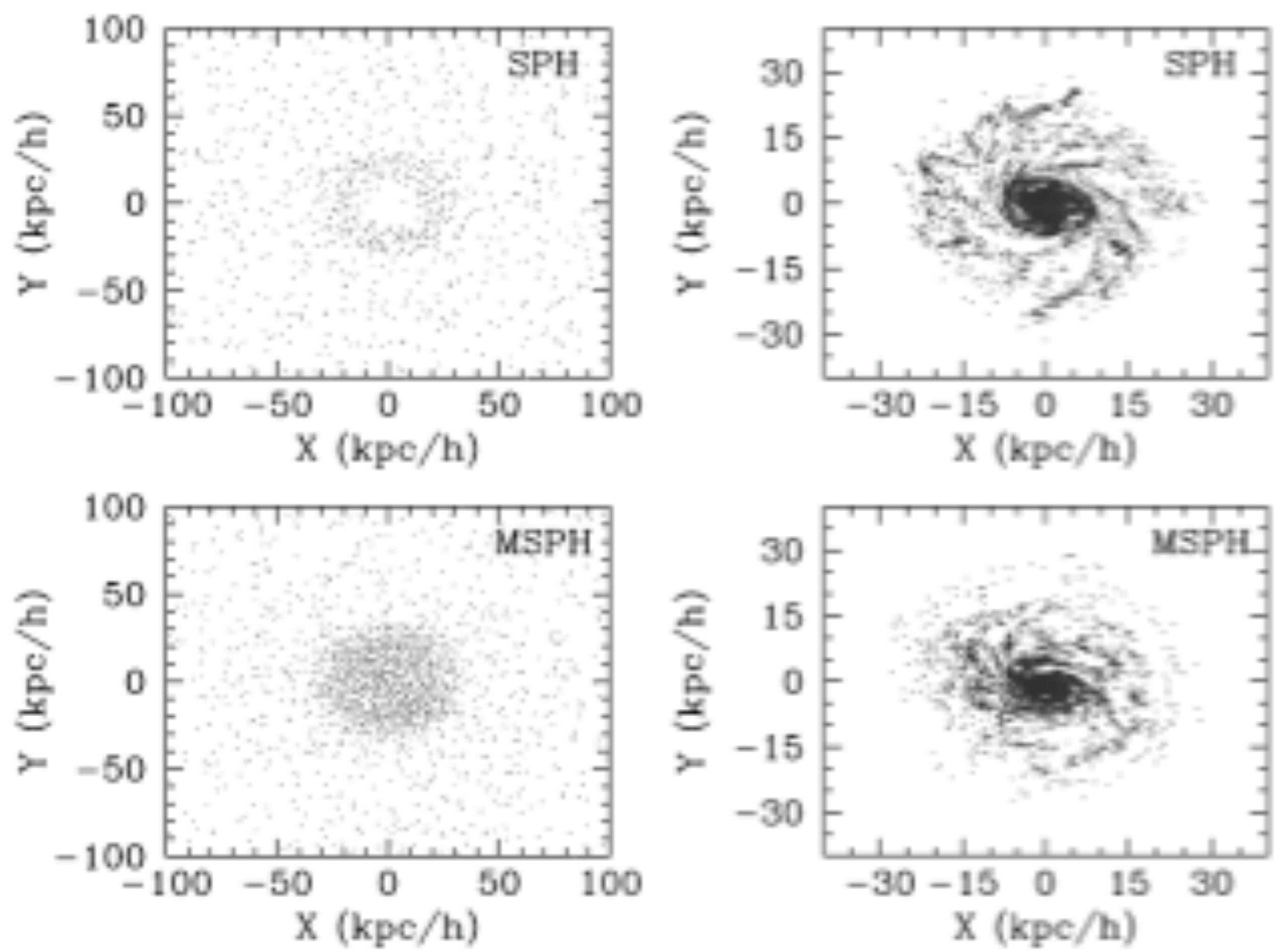


# 4.3 Feedback

A multitude of models exist to include feedback in simulations (several of which you've heard about this week):

* Models which try to explicitly track a multiphase ISM (see, e.g., Yepes et al. 1997, Hultman & Pharasyn 1999, Springel & Hernqsuit, Marri & White 2004) and some even treat cold material differently within the SPH calculation.



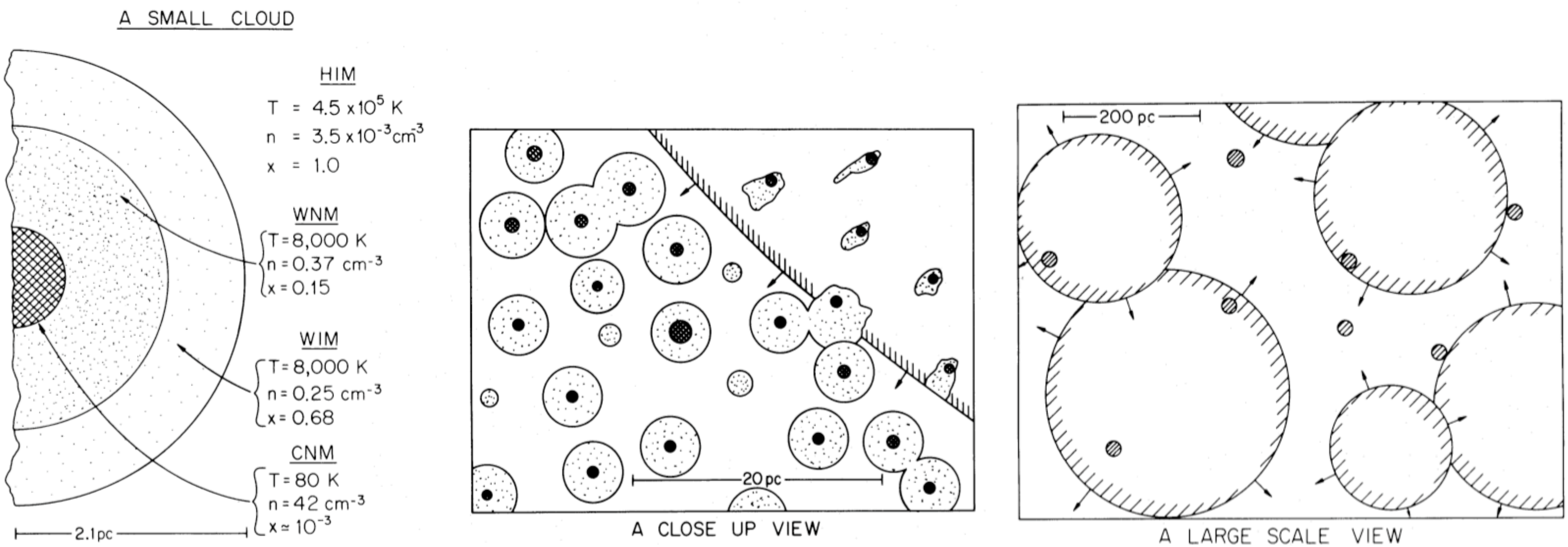
## 4.3 Feedback

A multitude of models exist to include feedback in simulations (several of which you've heard about this week):

In practice, many of the aforementioned models simply act to artificially push or pressurize the ISM for a period of time after a star-formation event.

# 4.3 Feedback

The McKee & Ostriker (1978) view of the ISM:



# 4.3 Feedback

A simplified picture of McKee & Ostriker (1978) within Gadget (Springel & Hernquist 2003, see also Yepes et al. 1997)

$$\frac{d\rho_c}{dt} = -\frac{\rho_c}{t_\star} - A\beta\frac{\rho_c}{t_\star} + \frac{1-f}{u_h - u_c}\Lambda_{net}(\rho_h, u_h),$$

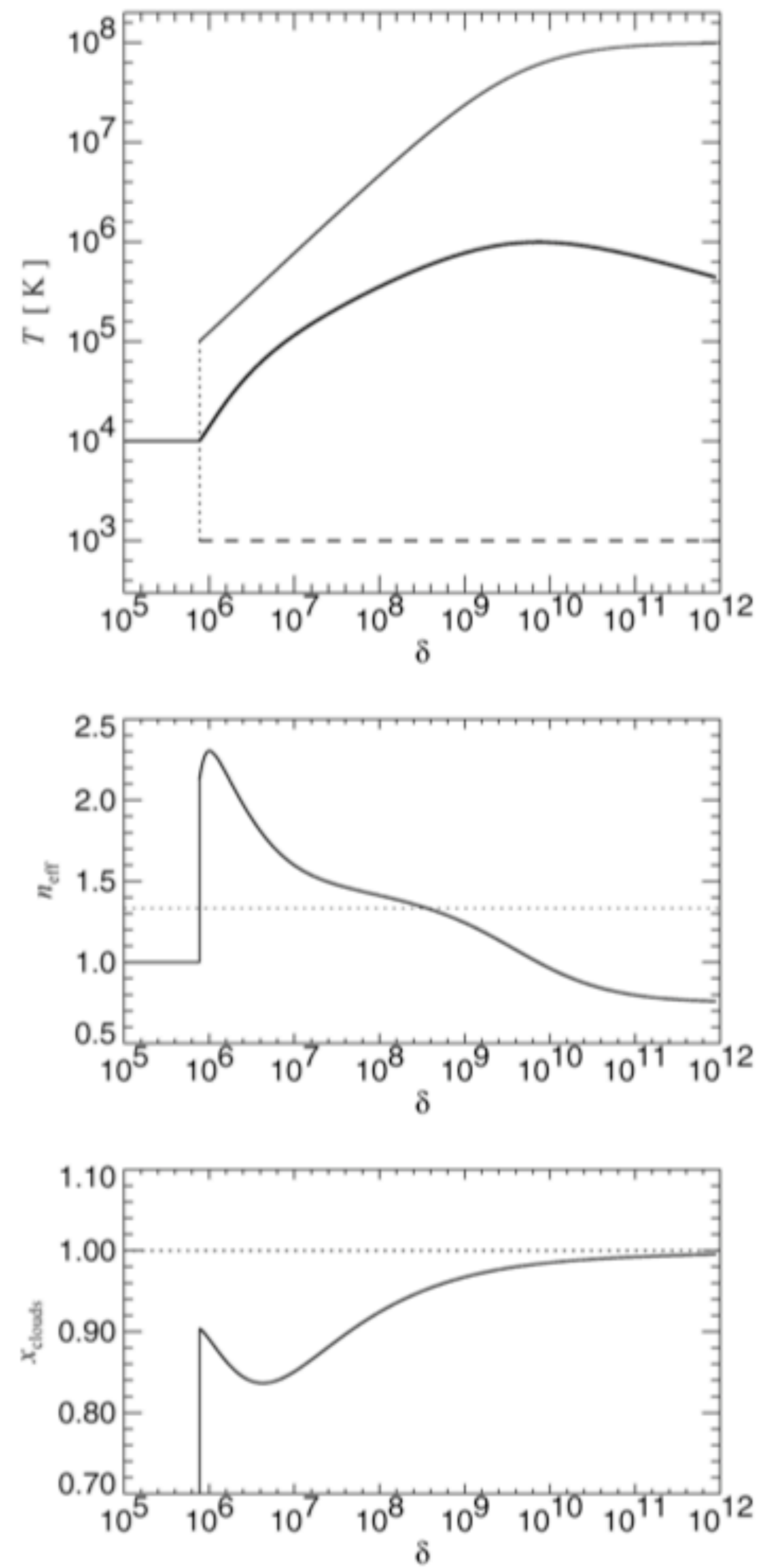
$$\frac{d\rho_h}{dt} = \beta\frac{\rho_c}{t_\star} + A\beta\frac{\rho_c}{t_\star} - \frac{1-f}{u_h - u_c}\Lambda_{net}(\rho_h, u_h).$$

* f=1 when thermally unstable

* cold temp= 1000 K

* assume that the two components are in pressure equilibrium

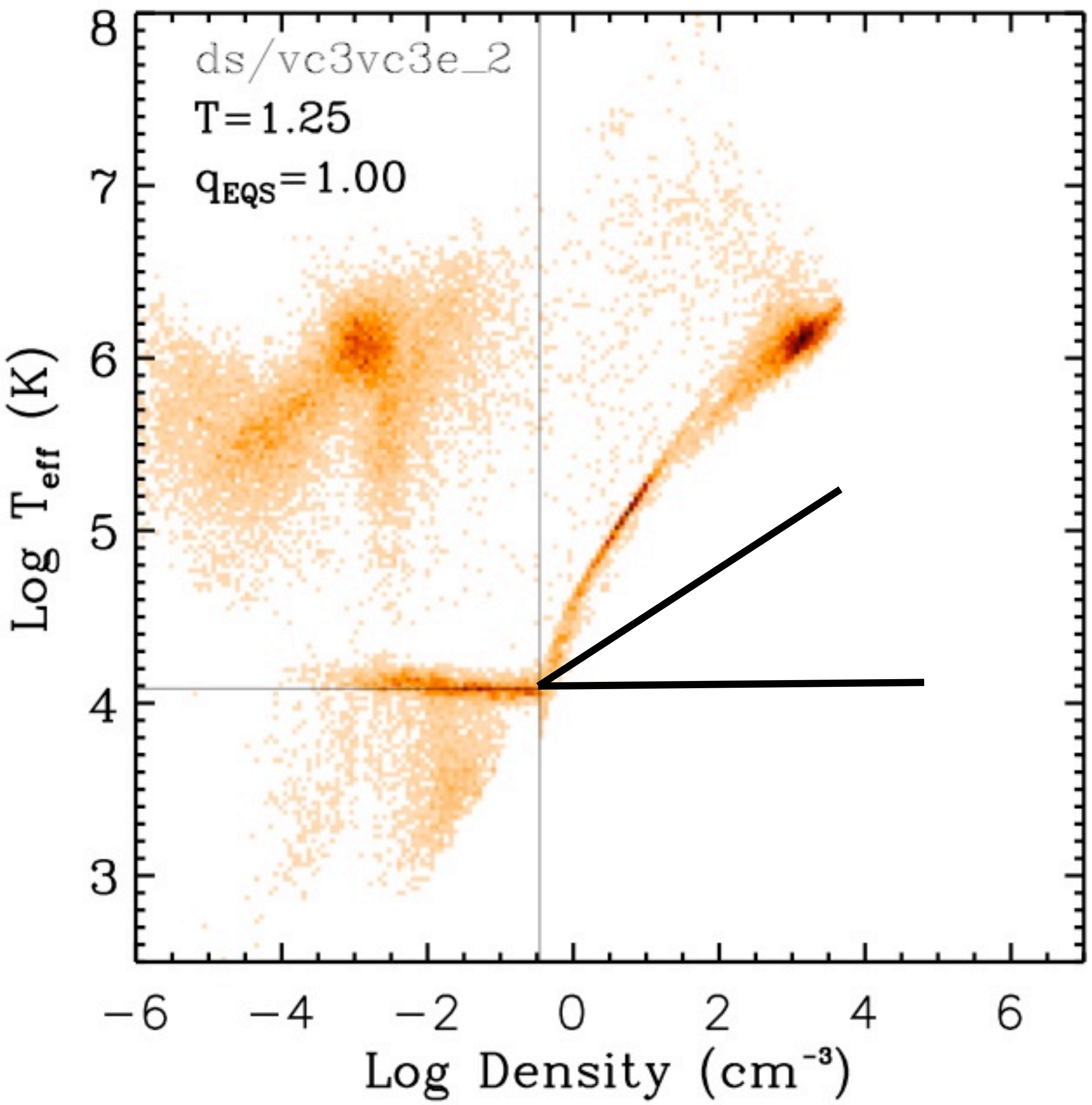
* leads to a self-regulated model for the ISM when the thermal instability is operating



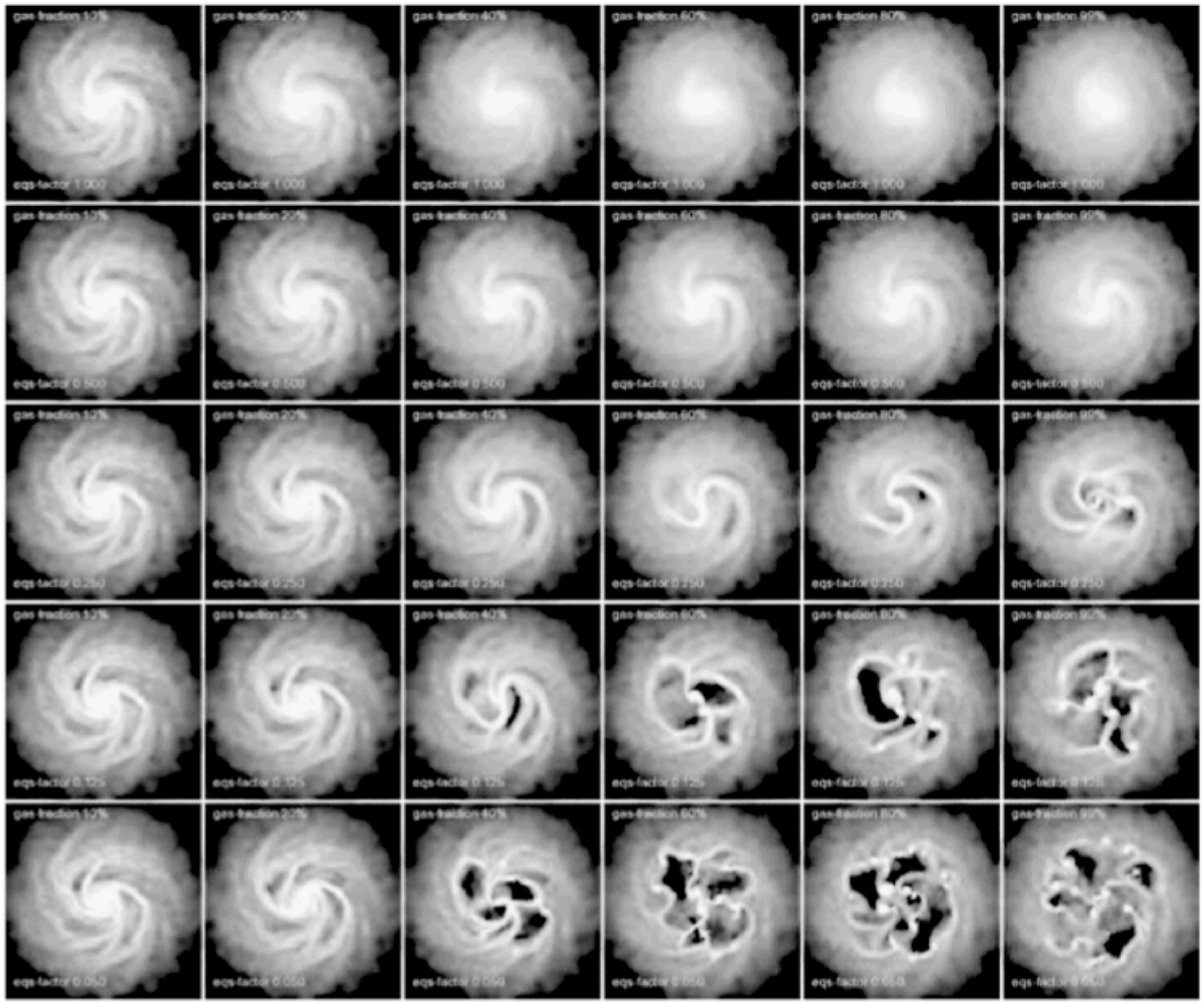
# 4.3 Feedback

Gas is "pressurized" in the star-forming regime.

The amount of pressurization can be modulated by a simple interpolation with 10^4 K



# 4.3 Feedback



Springel & Hernquist 2003

in triton:/home/hipacc-5/Gadget_sffb

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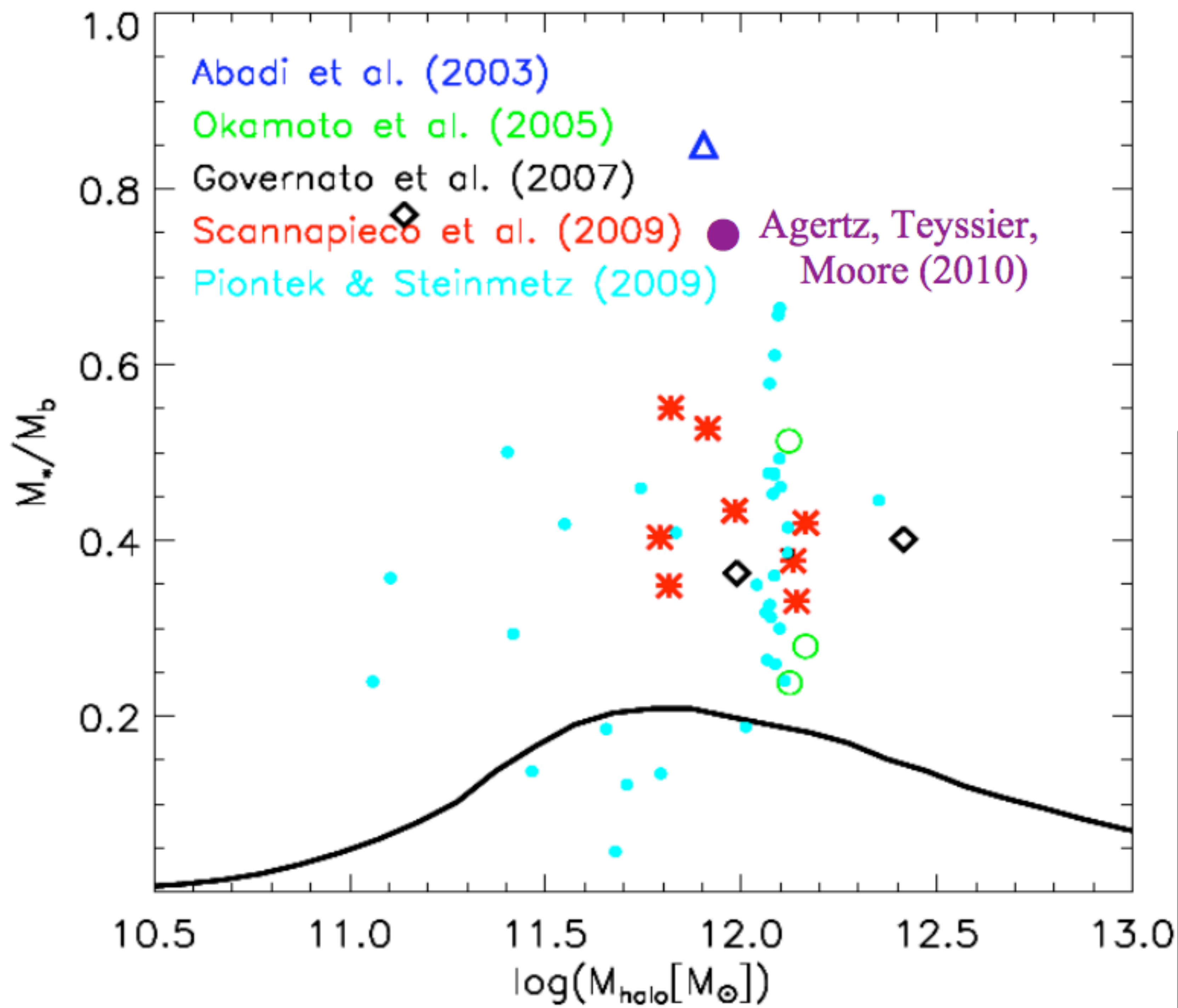
computes accelerations

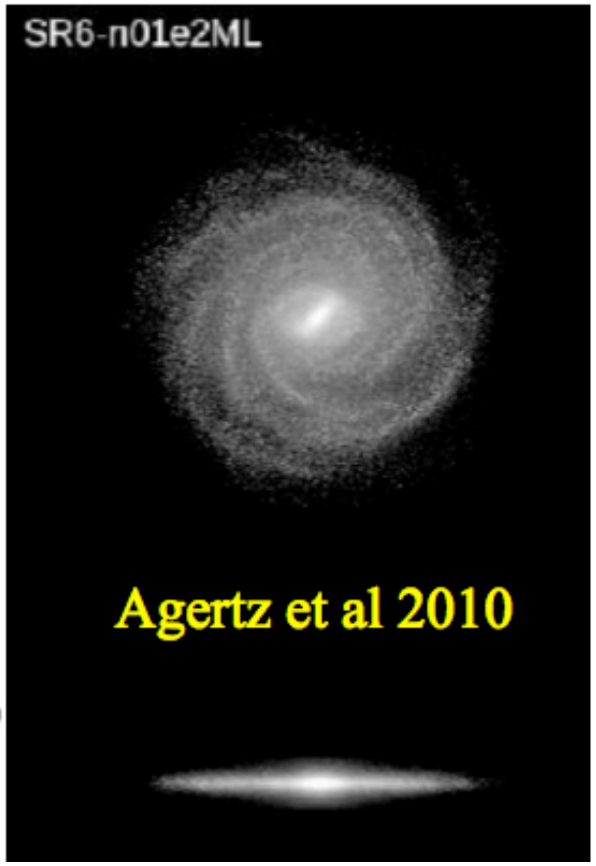
(accel.c)

- compute gravitational acceleration in gravtree.c
- determine SPH density in density.c
- compute hydrodynamic forces in hydra.c
- do cooling and star formation (sfr_eff.c and cooling.c)

=> Additional compile-time options and parameter file options.

# 4.3 Feedback: we've made progress but still work to do



# 4.3 Questions and Comments

* Will our SF model hold as we go to higher resolution?

* What should the SF law be at low densities? Tracking CO is a necessity, but will that reproduce the GALEX observations?

* What, if any, is the best feedback model?

* Theory (Murray et al.) suggests that radiation pressure may dominate the feedback over thermal or kinetic effects, don't we need to include this? And B, and CR, and ....

* What tests can we perform to address the above question?

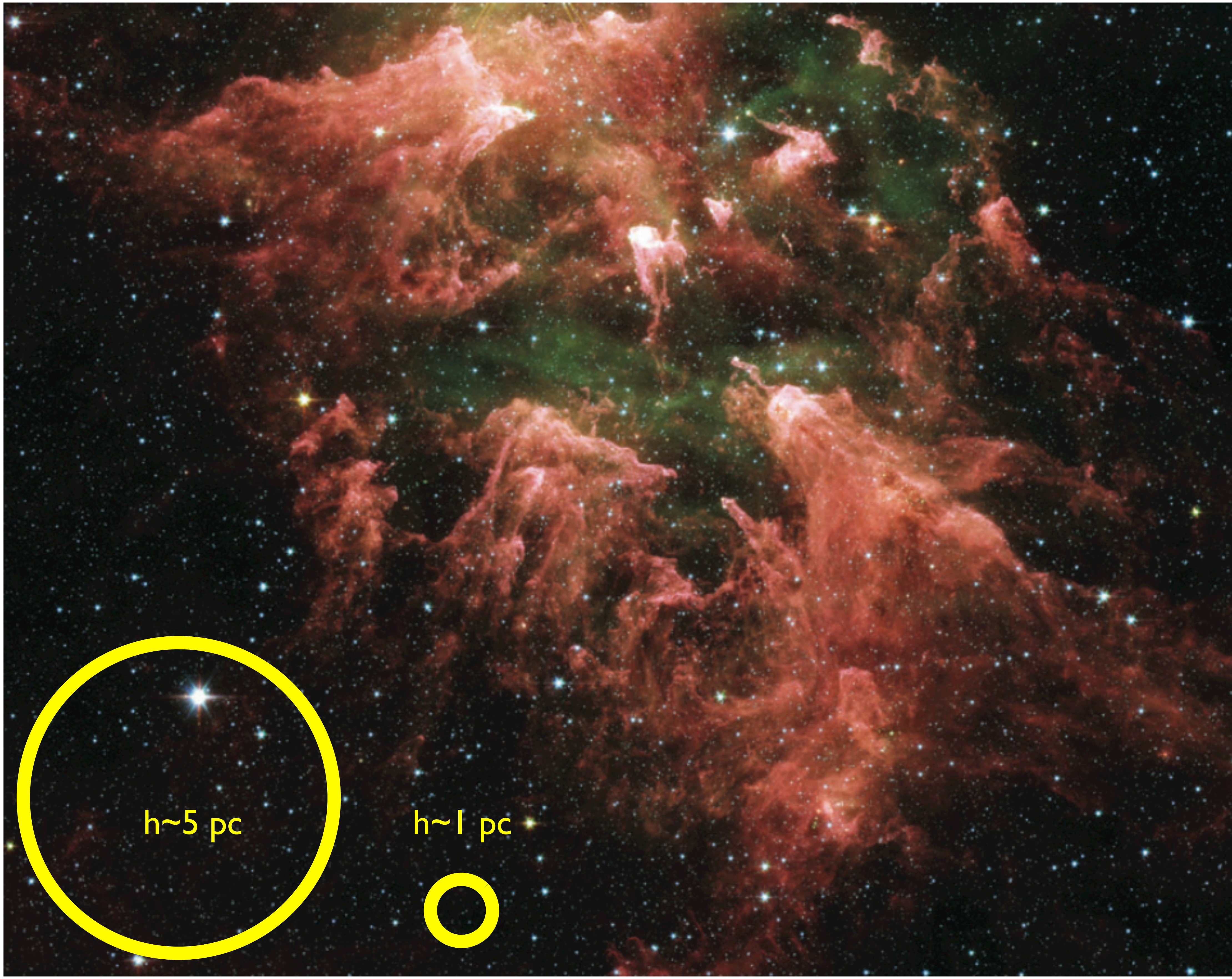
* Can we use our existing models as we go to higher resolution?

* Will a sub-grid model always be required, even if we can resolve some form of multiphase structure within the ISM?

* ....

IRAC 3.6/5/8 um image of a 40 pc region of the Carina Nebula containing 10^5, <10^5, ~10^4 M_solar of atomic, molecular, and young stellar objects.

Eta Carinae and ~70 O stars are just above this image.




McKee & Ostriker 2007 (image: Spitzer/Smith)