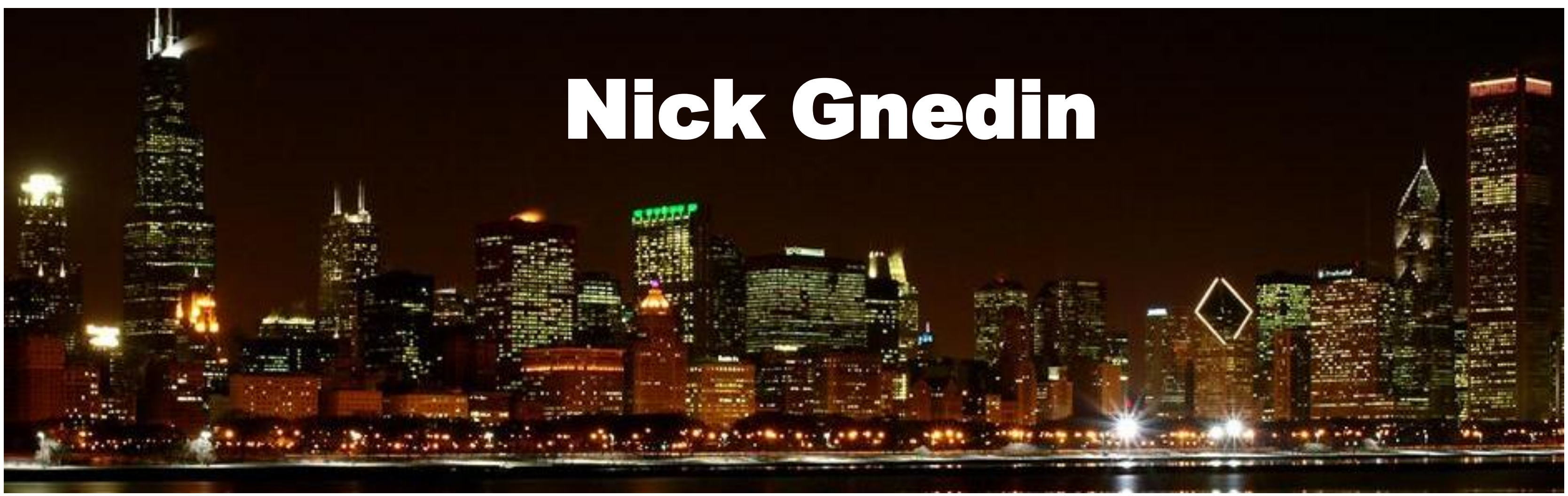
Emergence of the Kennicutt-Schmidt Relation



Nick Gnedin

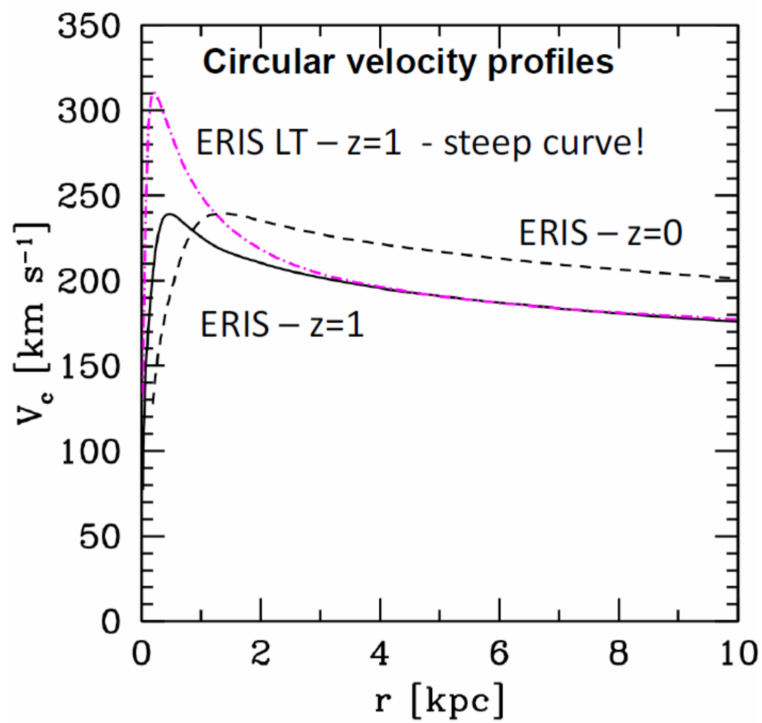
Fermilab

THE UNIVERSITY OF CHICAGO

A Lesson From History

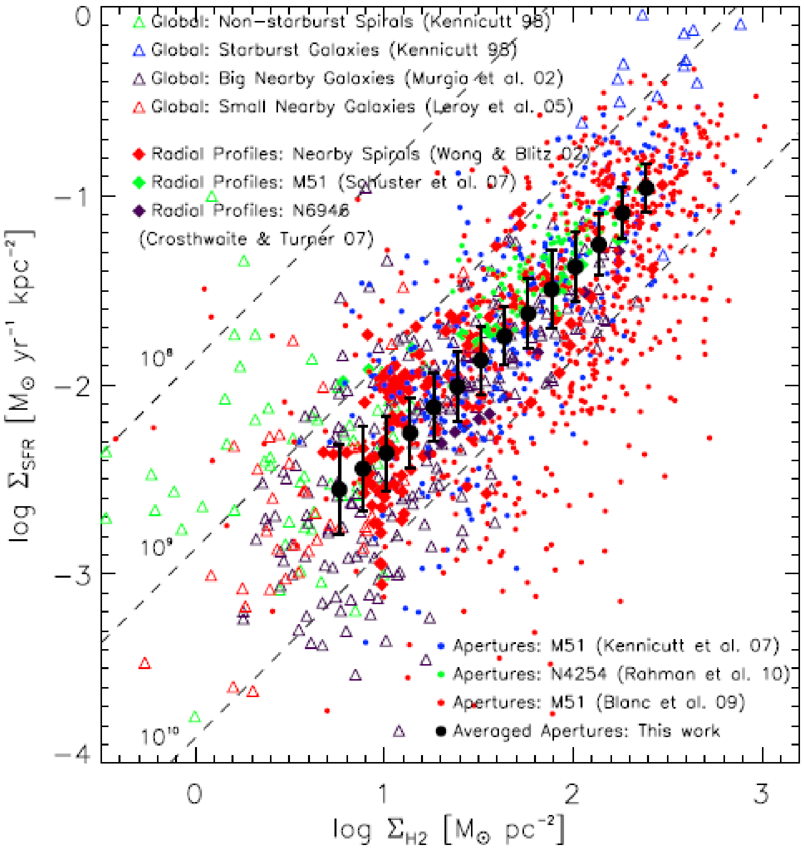
- 1993: Frank Summers comes up with the SF recipe that uses a density threshold of n_H=0.1/cc. ***Reasonable*** variations of that parameter had only modest effect.

- 2010: Governato et al: high density threshold (>10/cc) makes a ***large*** difference.

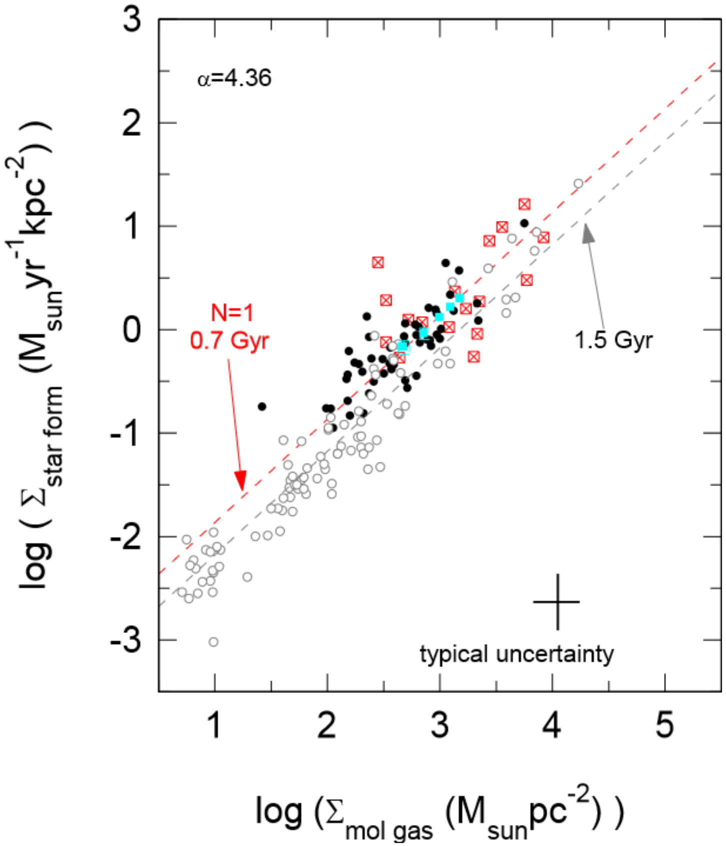


What We Know About Star Formation

Star formation correlates well with molecular gas…



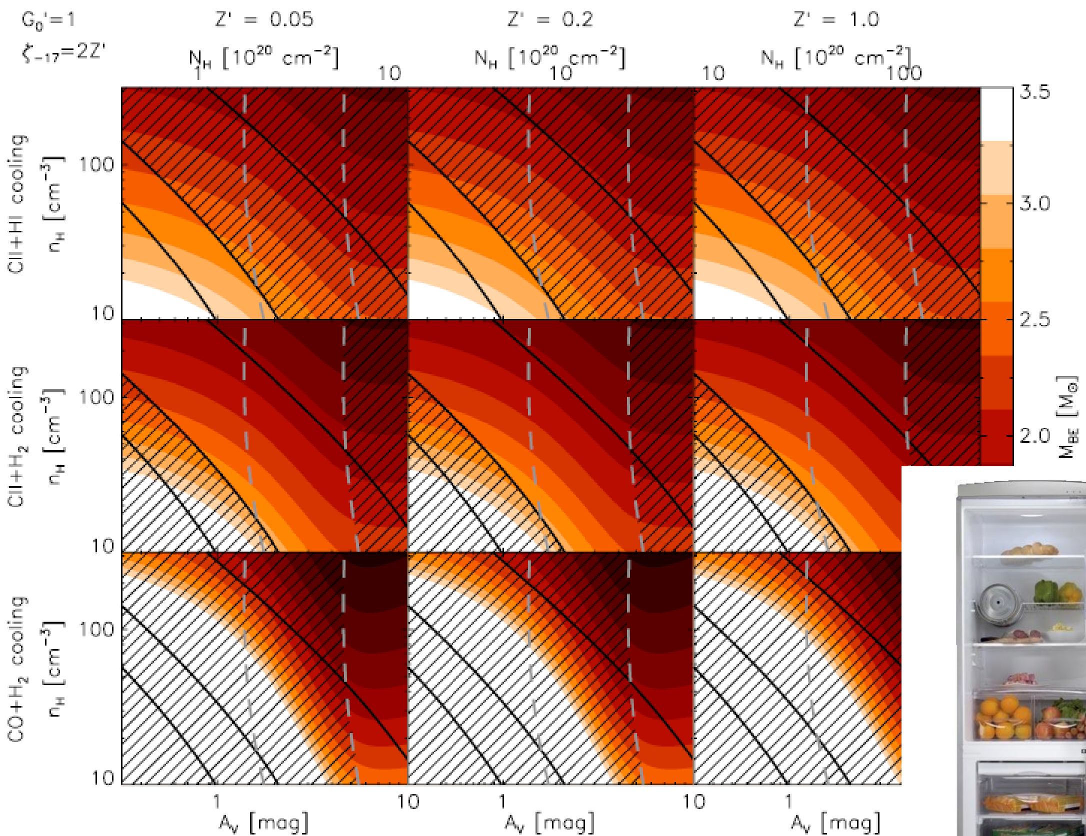
z=0 (Bigiel et al 2011)

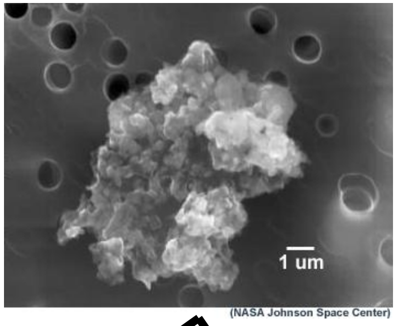


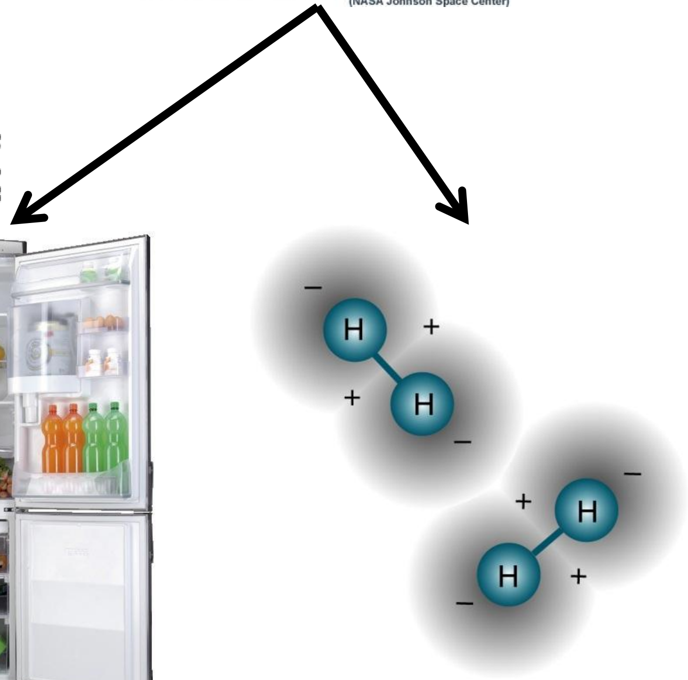
High z (Tacconi et al 2013)

What We Know About Star Formation

… for a simple physical reason.







(Krumholz, Leroy, McKee 2011)

How We Actually Think About Star Formation

$$\dot{\rho}_* = \frac{\rho_{H_2}}{\tau_{SF}}$$

$$\tau_{SF} = \tau_{SF}(\rho_{H_2})$$

Density is only defined on a particular spatial scale.

The density in this room is:

A. 0.001 g/cm^3

B. 0.1 g/cm^3

C. 1 g/cm^3

D. 10^{14} g/cm^3

How We Should Think About Star Formation

- Take some spatial scale ***L***
- Average all densities on this scale - only those are meaningfully defined

$$\langle \dot{\rho}_* \rangle_L = \frac{\langle \rho_{\mathrm{H_2}} \rangle_L}{\tau_{\mathrm{SF}}}$$

- Even that is not enough!

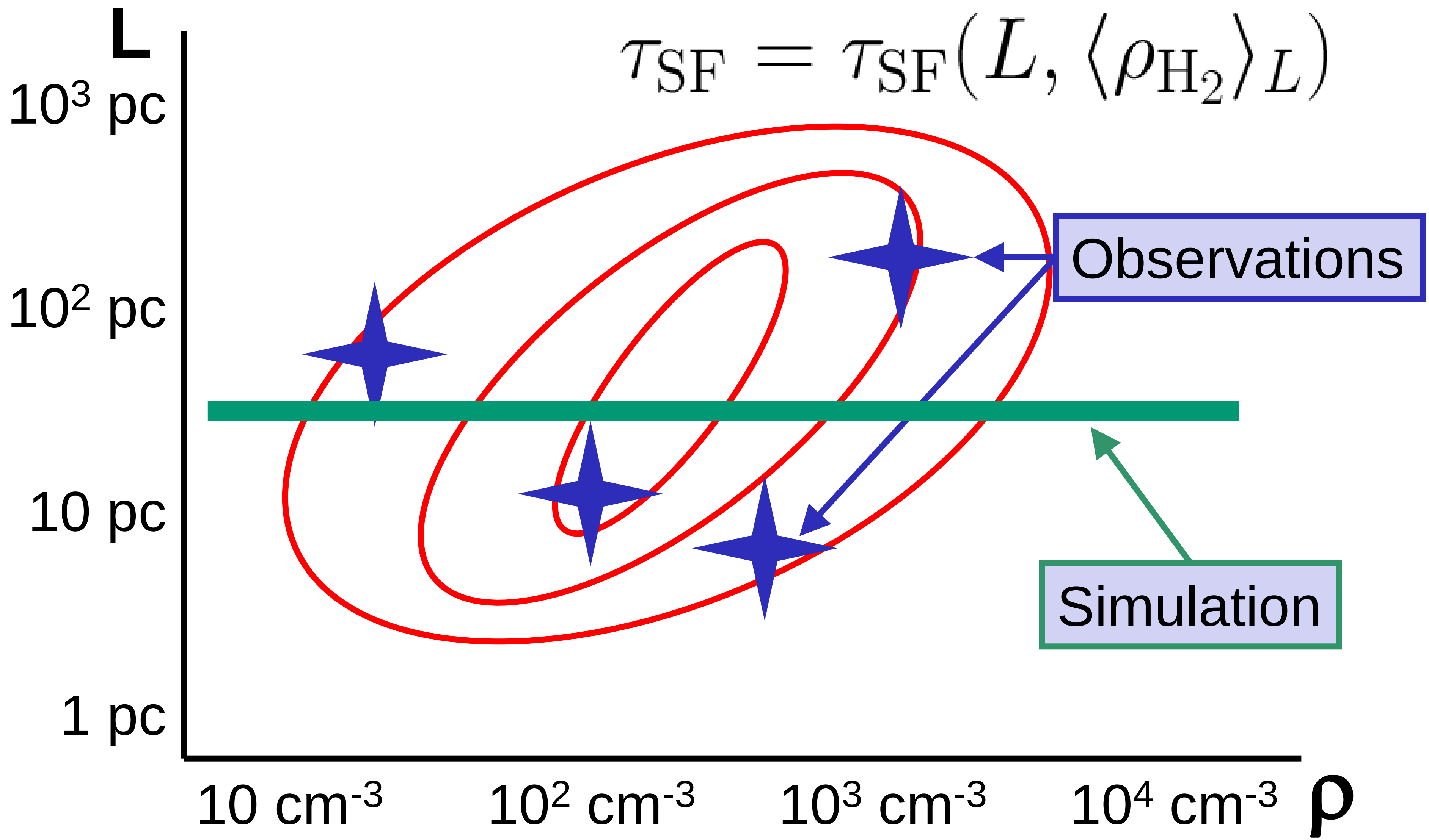
How We Should Think About Star Formation

- Star formation is stochastic.
- Let's start with the "*expectation value of the instantaneous SFR surface density*" on scale *L* (EVISFRD).

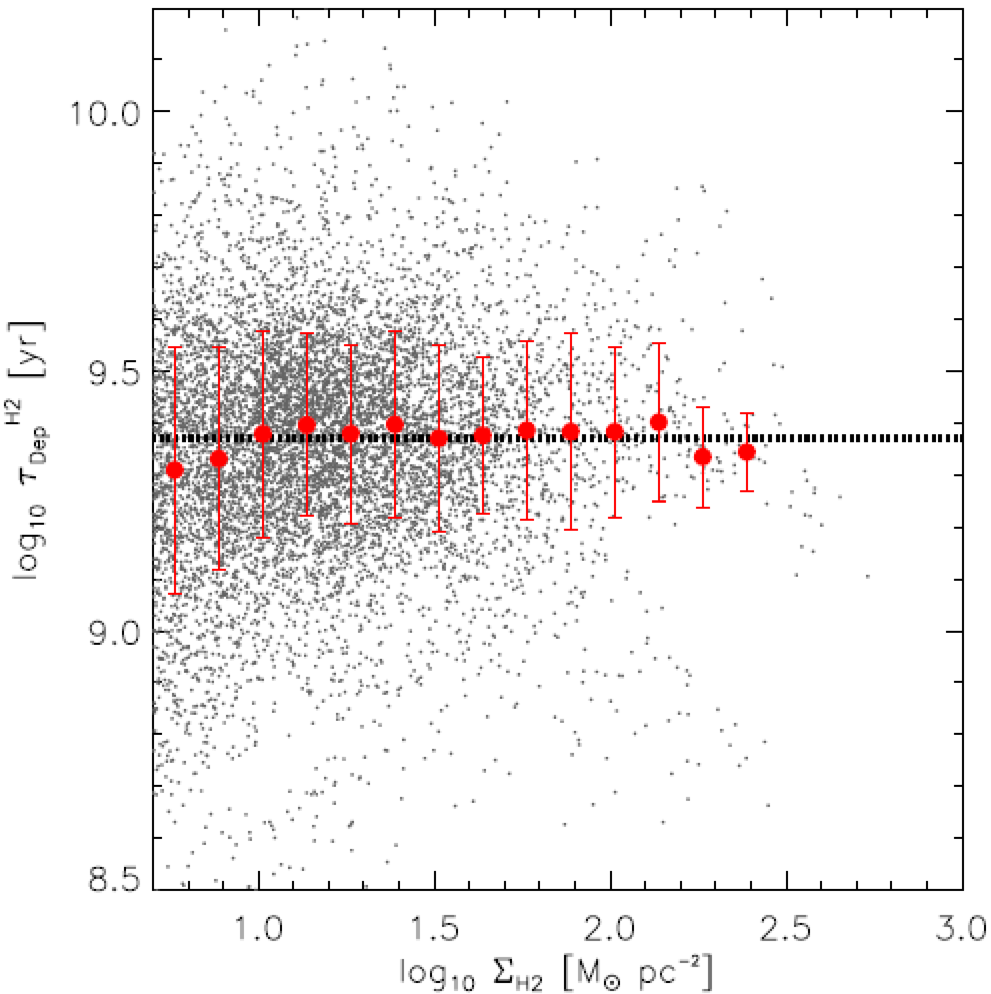
$$\overline{\langle \dot{\rho}_* \rangle_L} = \frac{\langle \rho_{\mathrm{H_2}} \rangle_L}{\tau_{\mathrm{SF}}}$$

$$\tau_{\mathrm{SF}} = \tau_{\mathrm{SF}}(L, \langle \rho_{\mathrm{H_2}} \rangle, \ldots)$$

Let's Think in 2D!



Large Scales (all z)



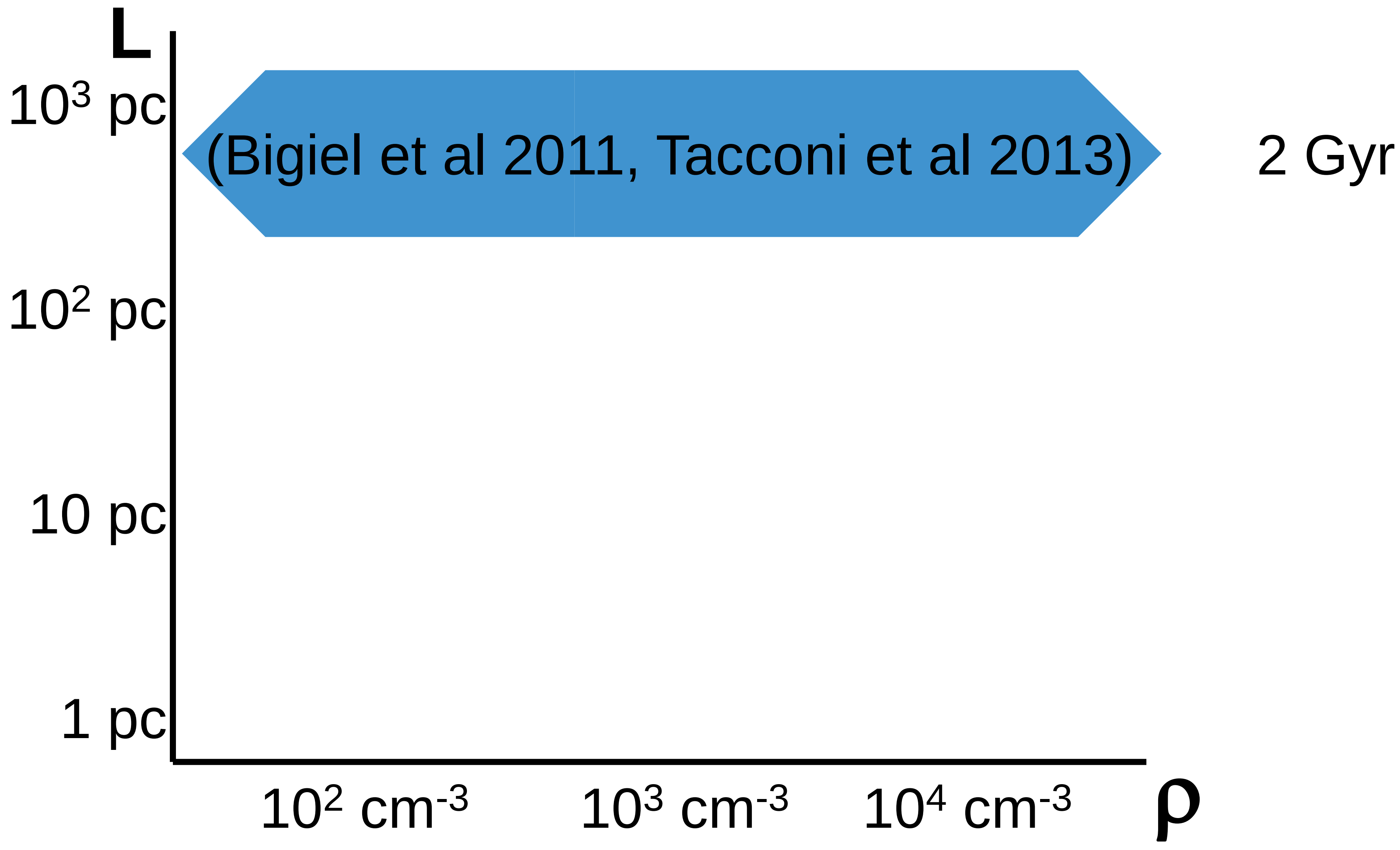
(Bigiel et al 2011)

$$L \sim 500\,\mathrm{pc}$$

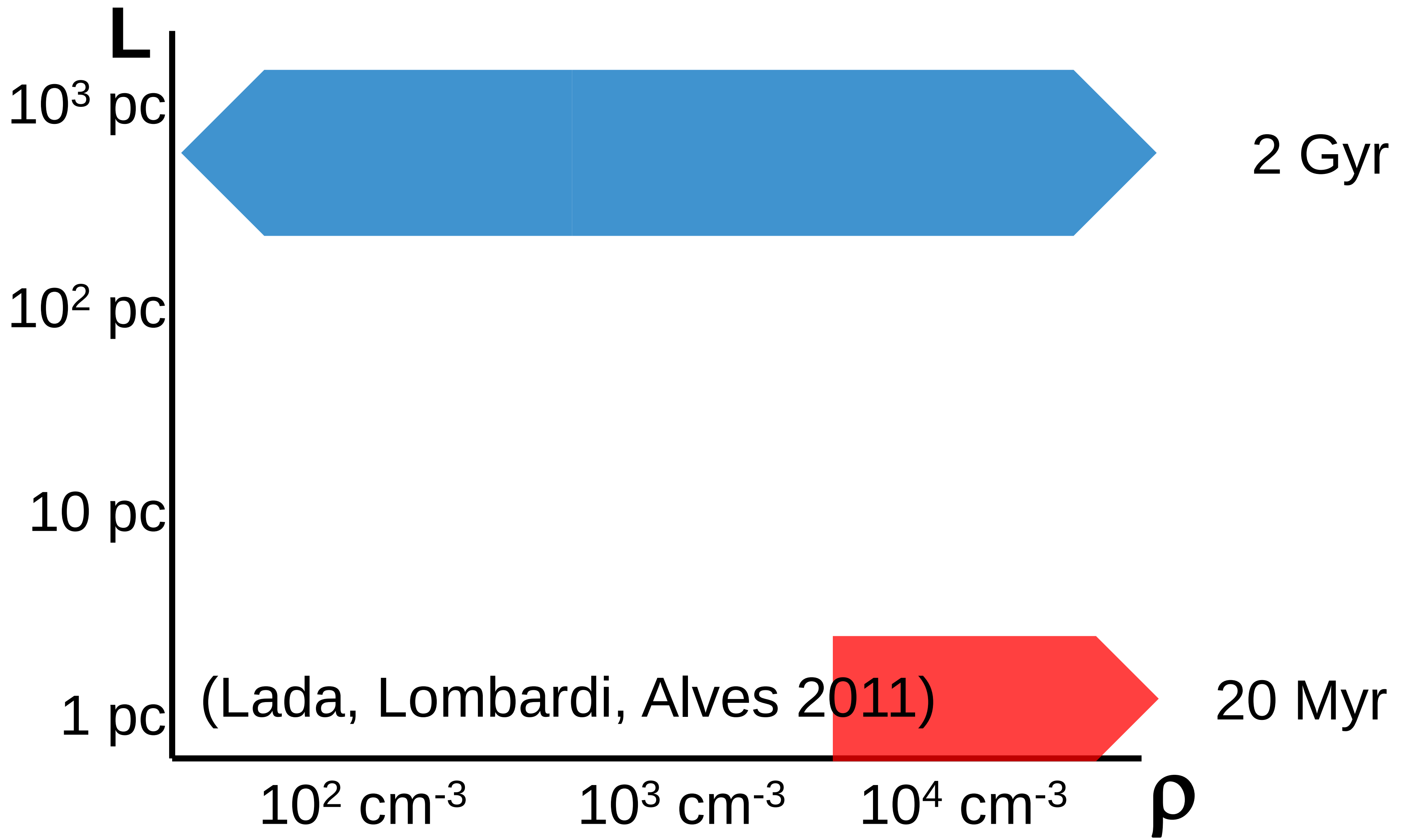
$$\tau_{\mathrm{SF}} \approx 2\,\mathrm{Gyr}$$

- Constant time-scale
- Linear SF recipe

Let's Think in 2D!

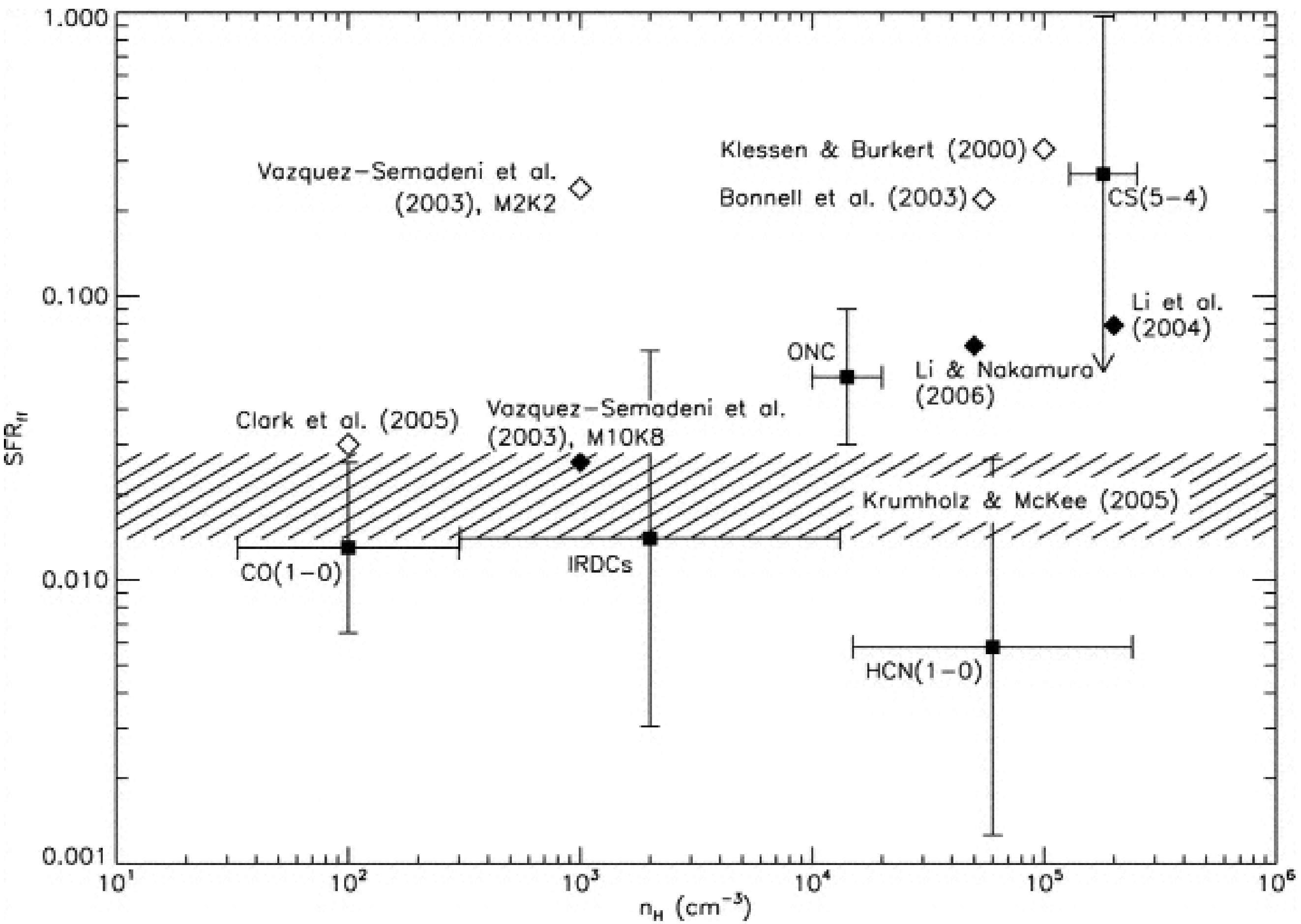


Let's Think in 2D!

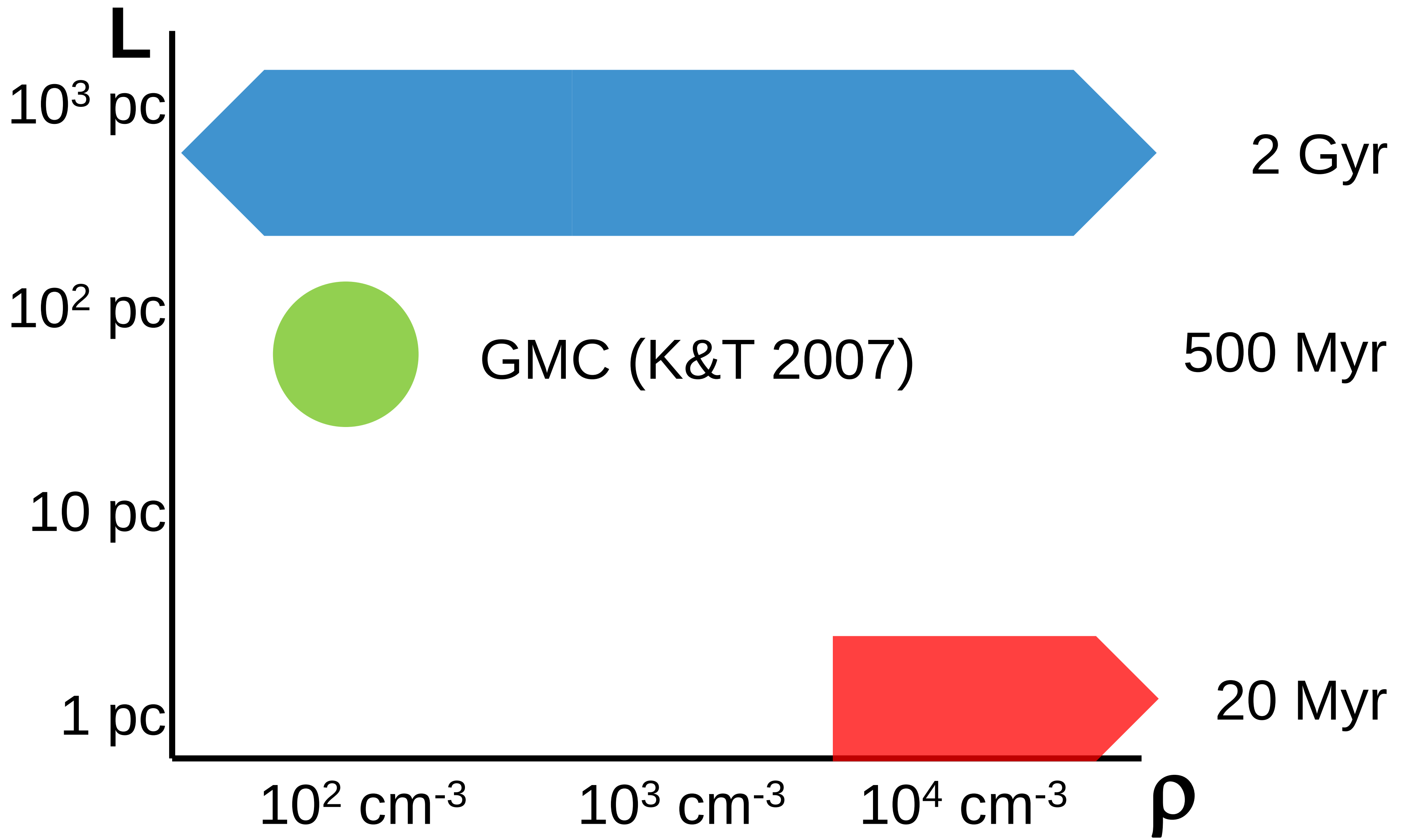


“Don’t Be Hasty...”

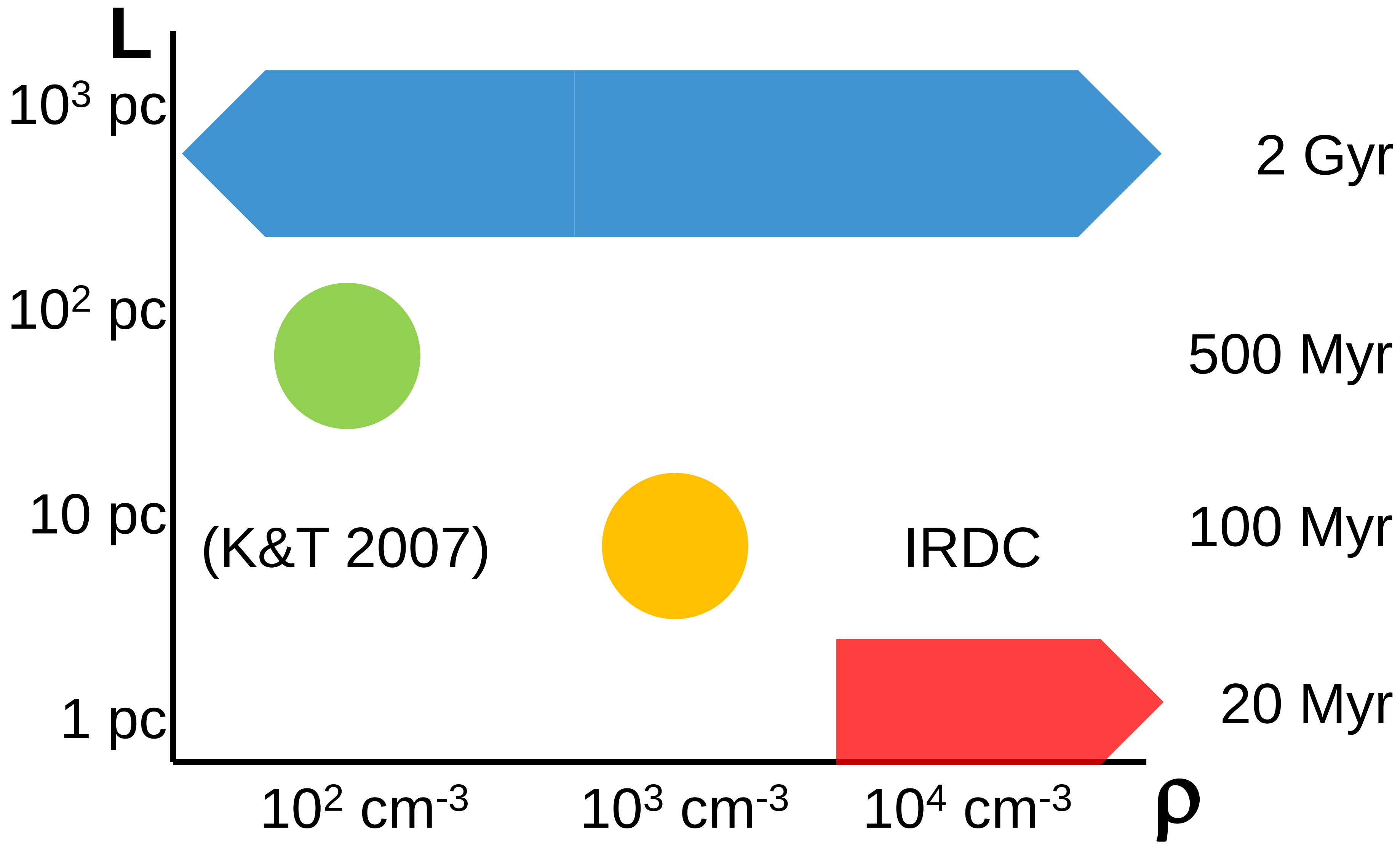
Krumholz & Tan (2007): $\tau_{\rm SF} \propto \tau_{\rm ff} \propto \rho^{-1/2}$



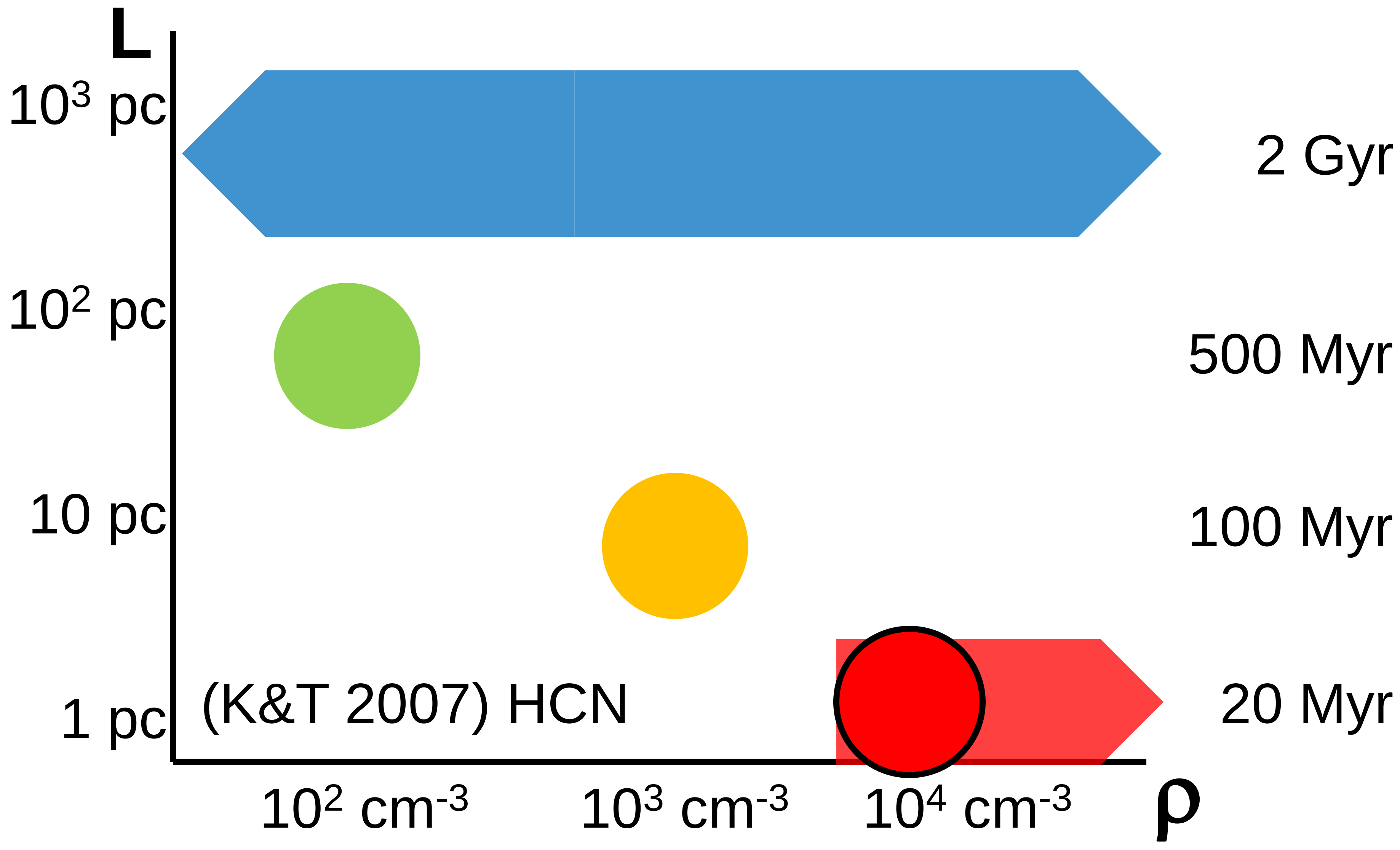
Let's Think in 2D!



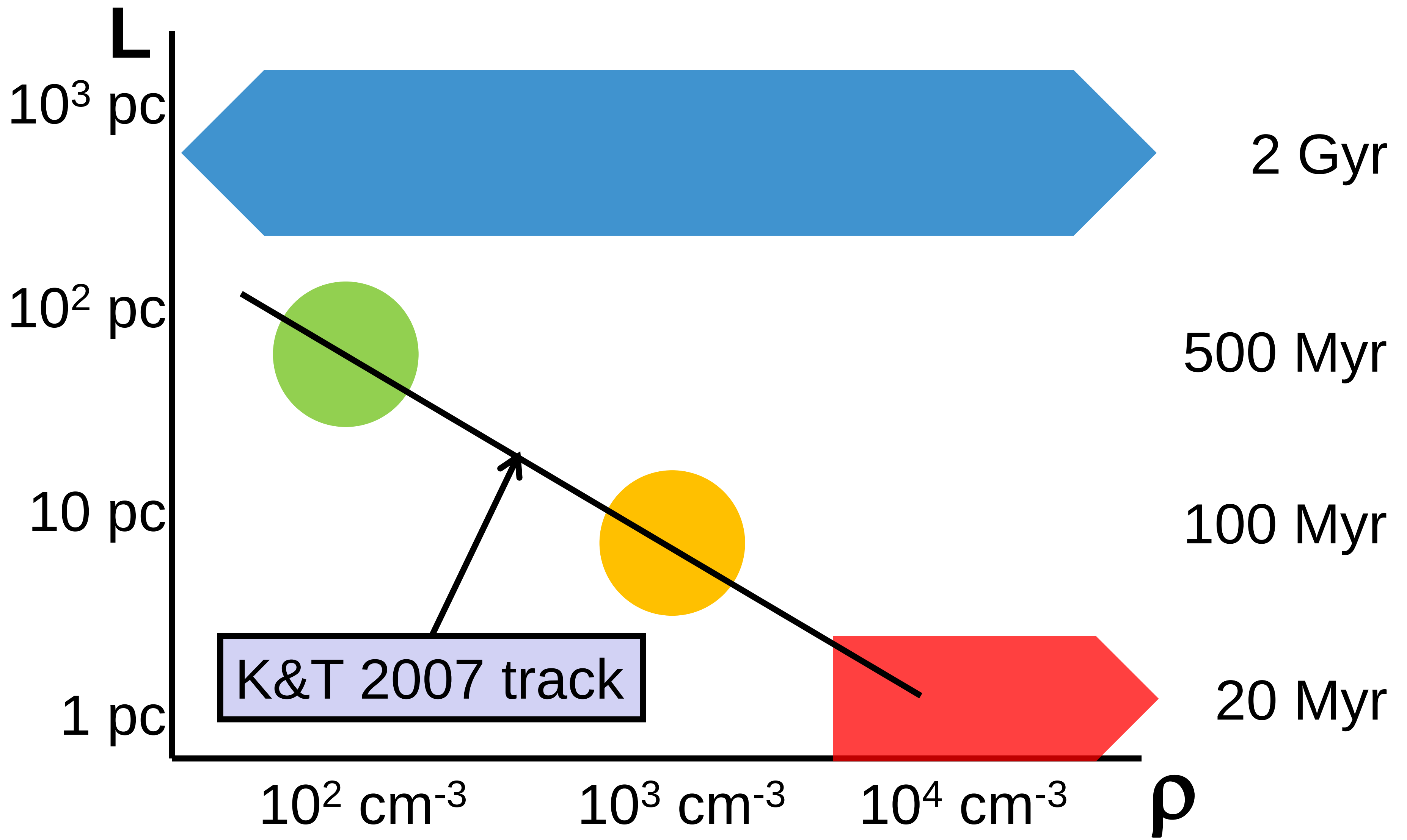
Let's Think in 2D!



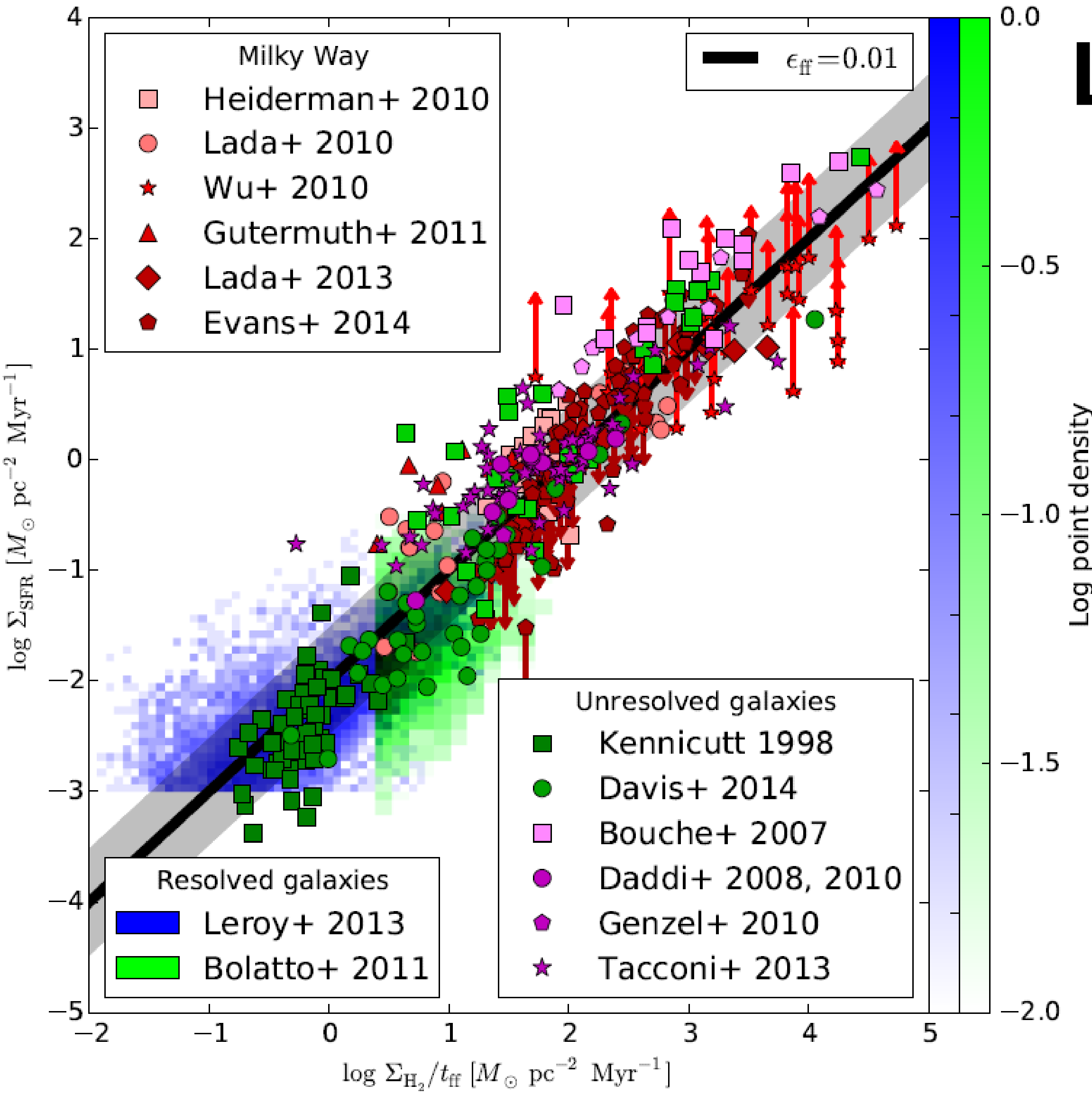
Let's Think in 2D!

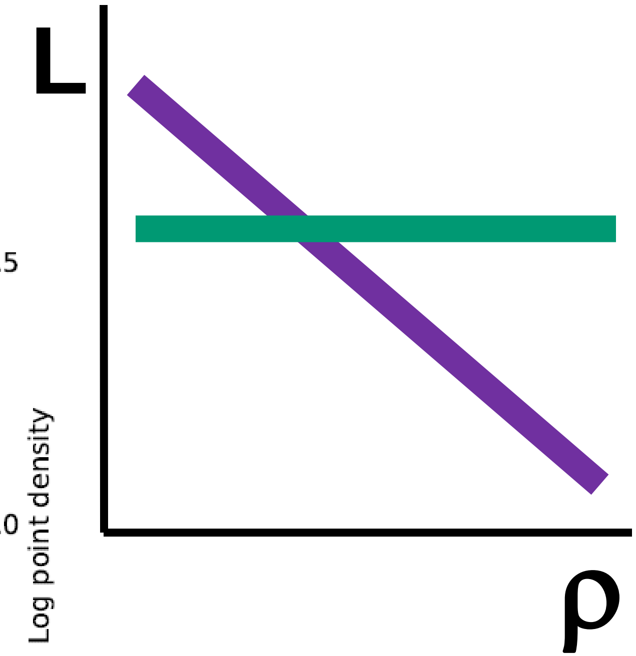


Let's Think in 2D!



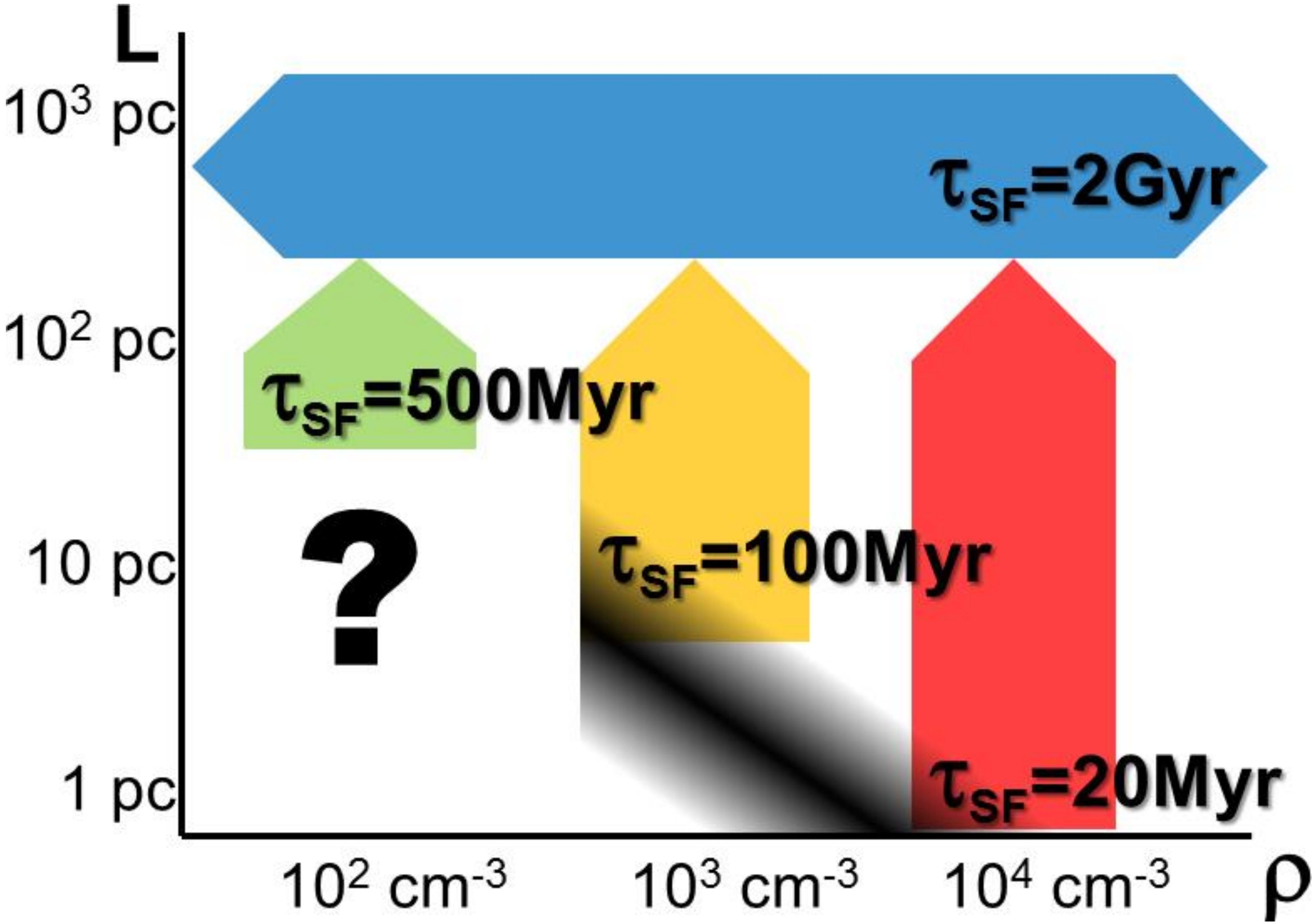
Not Wrong, Just Irrelevant



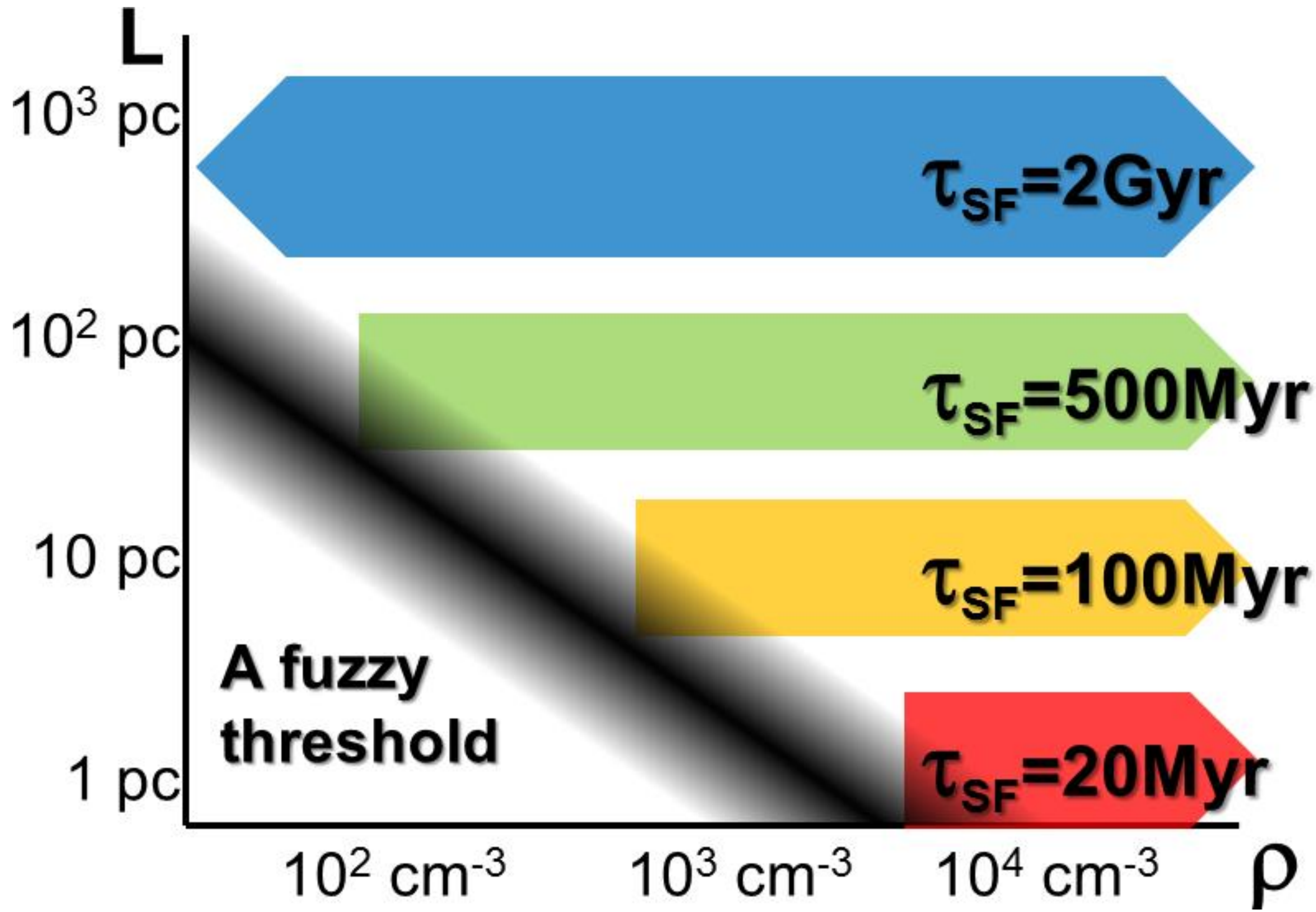


(Krumholz 2014)

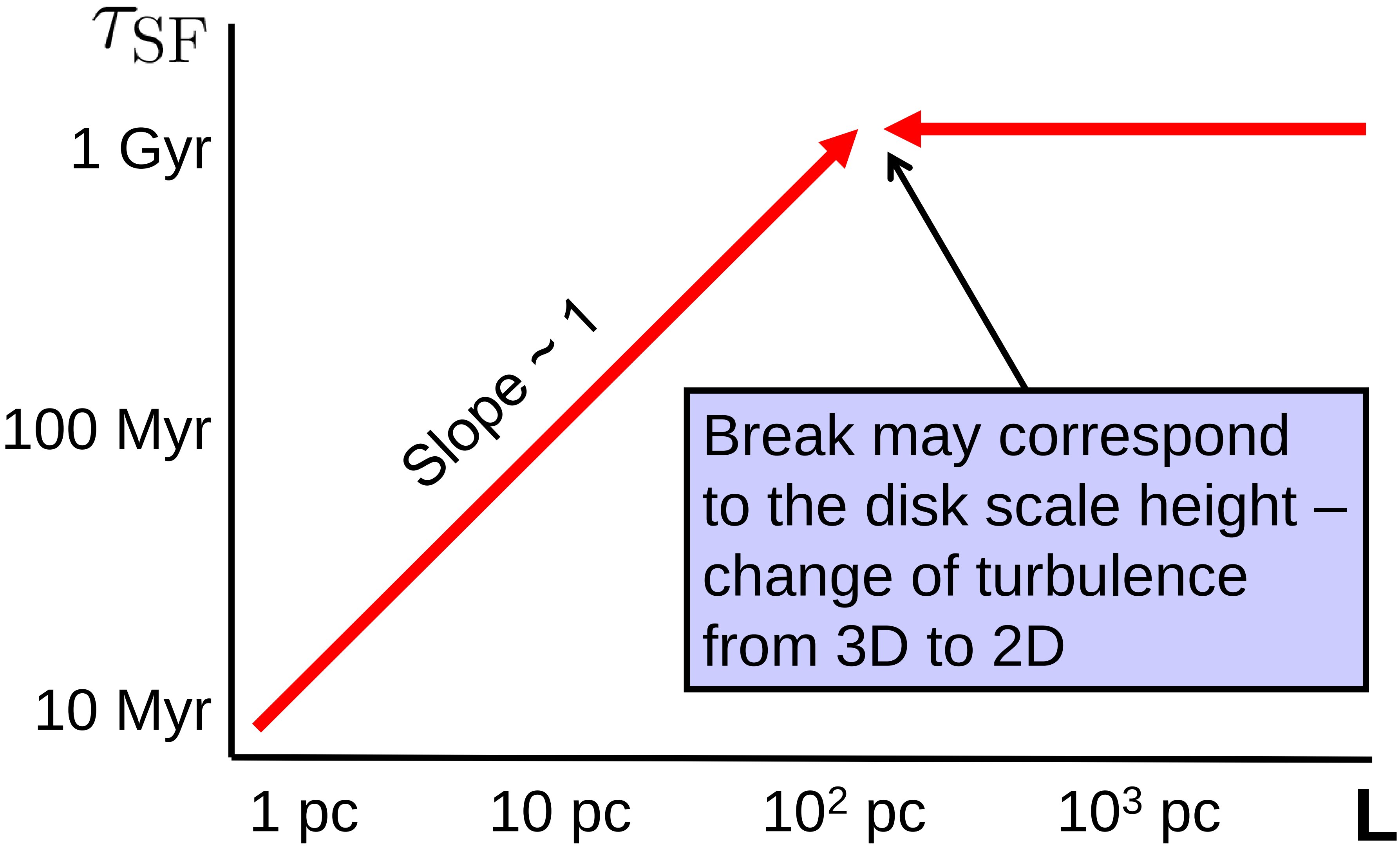
Case I: "3/2" Model



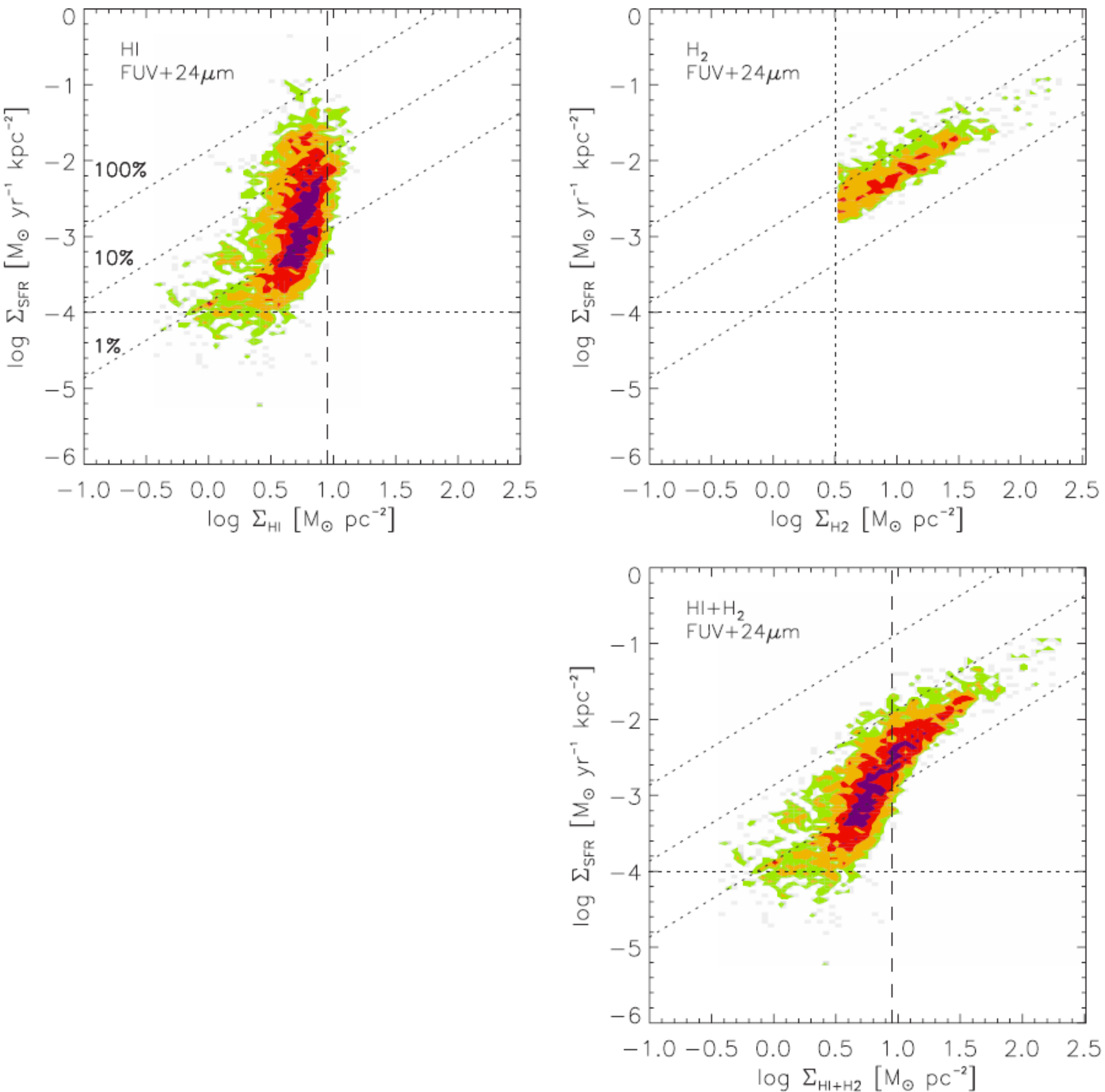
Case II: Linear Model



Linear Model



Refresher: KS Relation



Plotting

$\Sigma_{\rm SFR}$ vs $\Sigma_{\rm gas}$

instead of

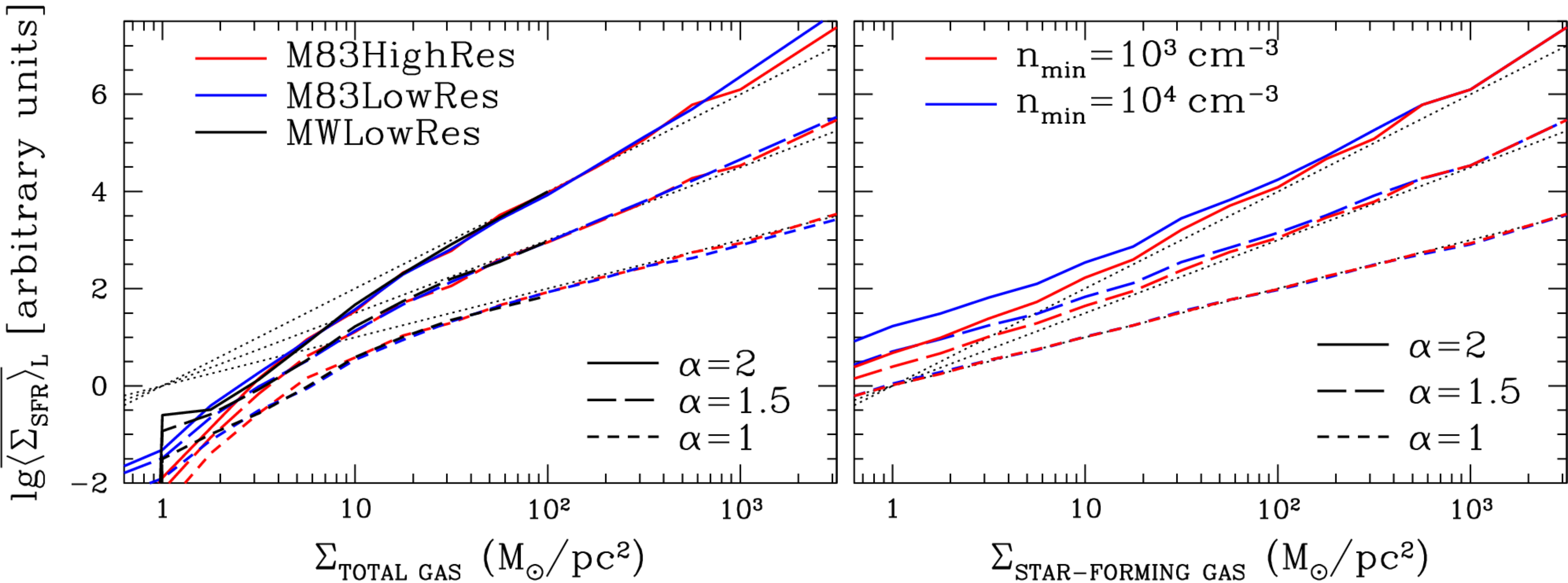
$\Sigma_{\rm SFR}$ vs $\Sigma_{\rm H_2}$

is just slacking.
(And yes, there are several fitting formulae you can use!!!)

(Non?) Emergence of KSR

- Tasker simulations
  (1.5 pc resolution, weak feedback):
  - ❖ Slope is preserved
  - ❖ Amplitude is not

$$\overline{\langle \dot{\rho}_* \rangle_l} \equiv \dot{\rho}_* \propto \begin{cases} \rho^\alpha, & \text{if } \rho \geqslant \rho_{\min} \\ 0 & \text{if } \rho < \rho_{\min} \end{cases}.$$



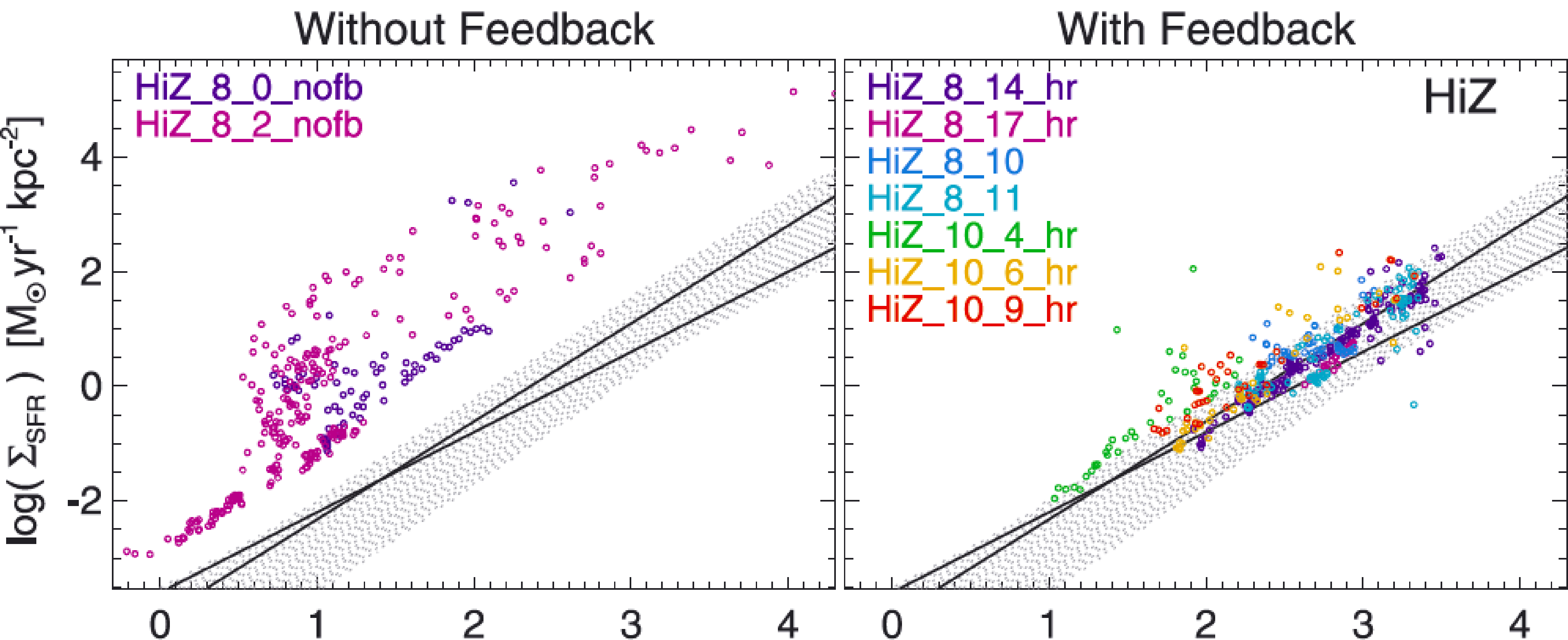
Strong Feedback Example #1

Self-regulated star formation in galaxies via momentum input from massive stars

Philip F. Hop
[1]Department of Astron 94720, USA
[2]Canadian Institute for ada

In our simulations, stars are assumed to form from dense gas with a constant efficiency ϵ per free-fall time $t_{\rm ff} = \sqrt{3\pi/32\,G\,\rho}$, above some minimum threshold ρ_0, i.e.

$$\dot{\rho}_* = \frac{\epsilon\,\rho}{t_{\rm ff}} \propto \rho^{3/2} \quad \text{for} \quad \rho > \rho_0. \tag{2}$$

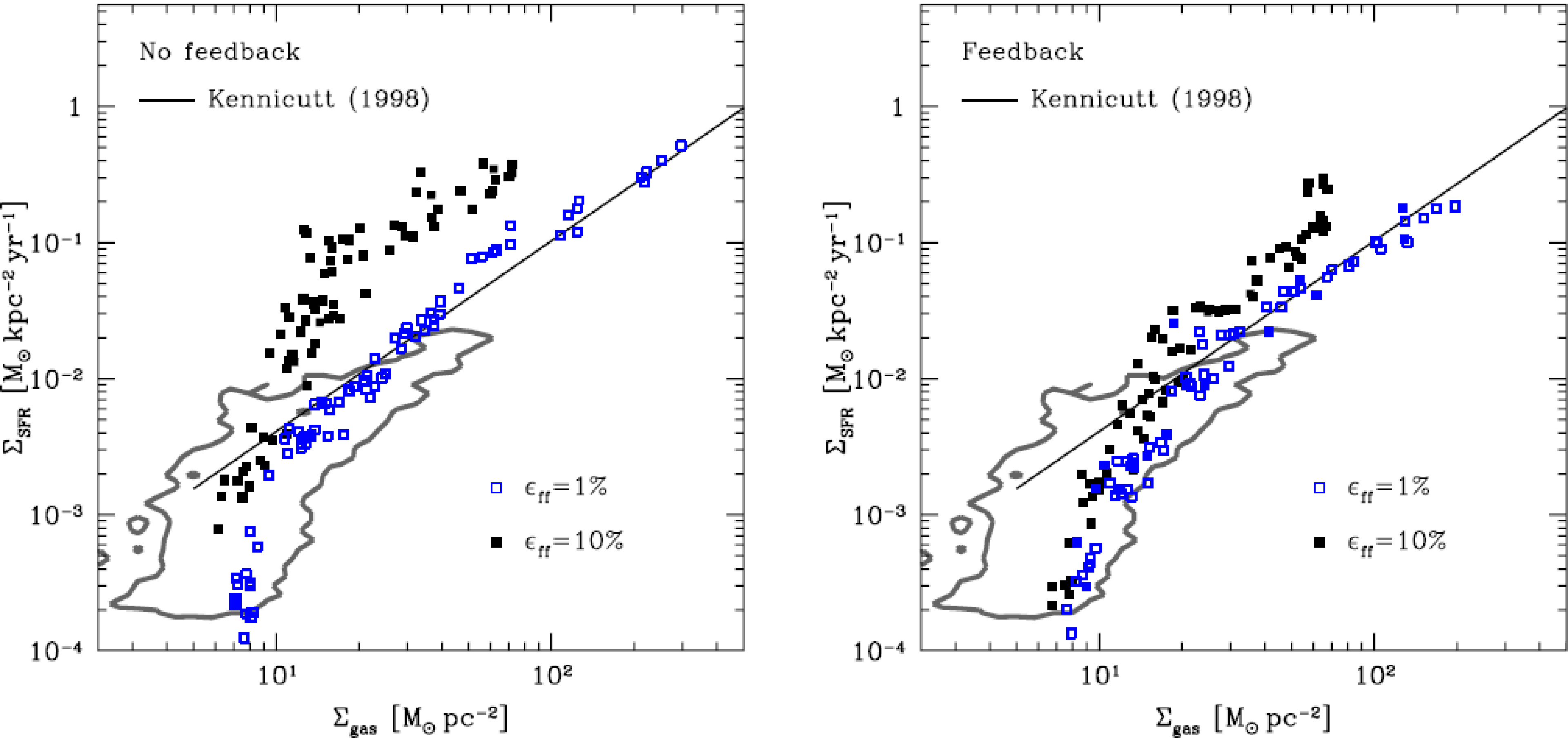


Strong Feedback Example #2

TOWARD A COMPLETE ACCOUNTING OF ENERGY AND MOMENTUM FROM

OSCAR AGE ... GNEDIN[1,2,5]

In this work we assume that $t_{SF} = t_{ff}/\epsilon_{ff}$, where $t_{ff} = \sqrt{3\pi/32G\rho}$ is the local gas free-fall time and ϵ_{ff} is the star formation efficiency per free-fall time. With this assumption Equation (21) enforces $\dot{\rho}_* \propto \rho^{1.5}$, which is close to the

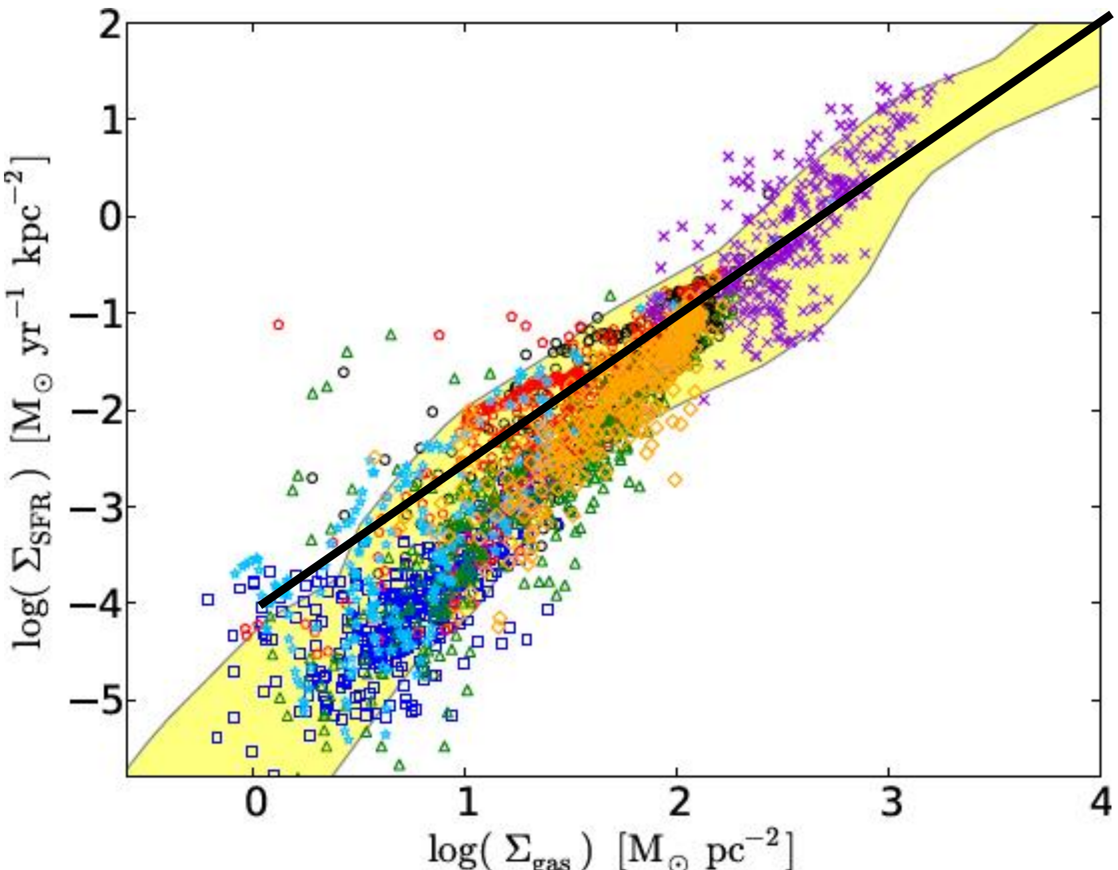


Strong Feedback Example #3

Galaxies on FIRE (Feedback In Realistic Environments): Stellar Feedback Explains Cosmologically Inefficient Star Formation

Philip F. Hopki … er-Giguère[2,5],
Eliot Quataert[2],

or smoothing length). This forms stars at a rate $\dot{\rho}_* = \rho_{\rm mol}/t_{\rm ff}$ (i.e. 100% efficiency per free-fall time); so that the galaxy and even kpc-



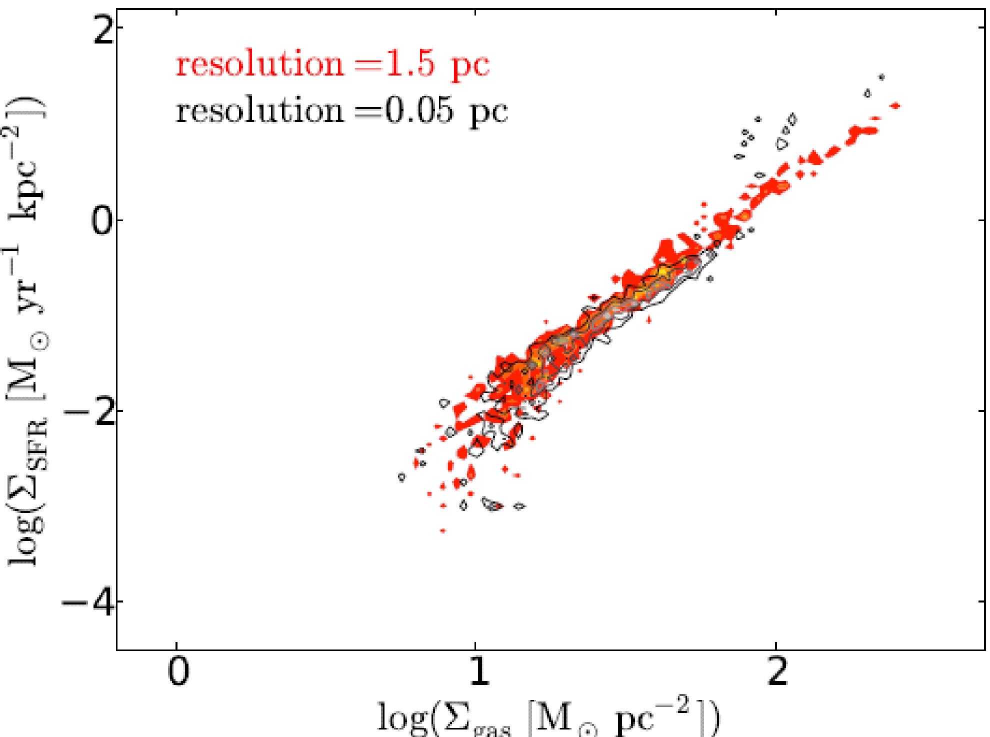
Strong Feedback Example #4

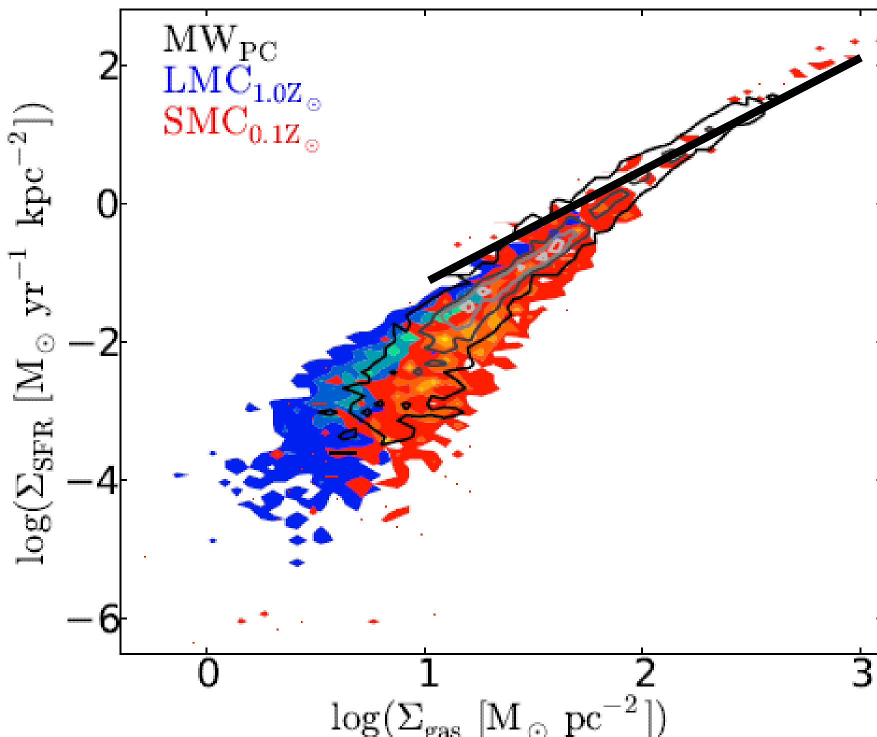
THE ROLE OF TURBULENCE IN STAR FORMATION LAWS AND THRESHOLDS

Katarina Kraljic, Florent Renaud, and Frédéric Bournaud
CEA, IRFU, SAp, F-91191 Gif-sur-Yvette Cedex, France
Insti… d

The SFR of a beam is estimated from the gas content of each cell by

$$\rho_\star = \epsilon \frac{\rho}{t_{\rm ff}} \propto \epsilon \rho^{3/2} \quad \text{for } \rho > \rho_0, \qquad (5)$$





Conclusions

- Star formation recipe depends on both ***scale*** and ***density***:

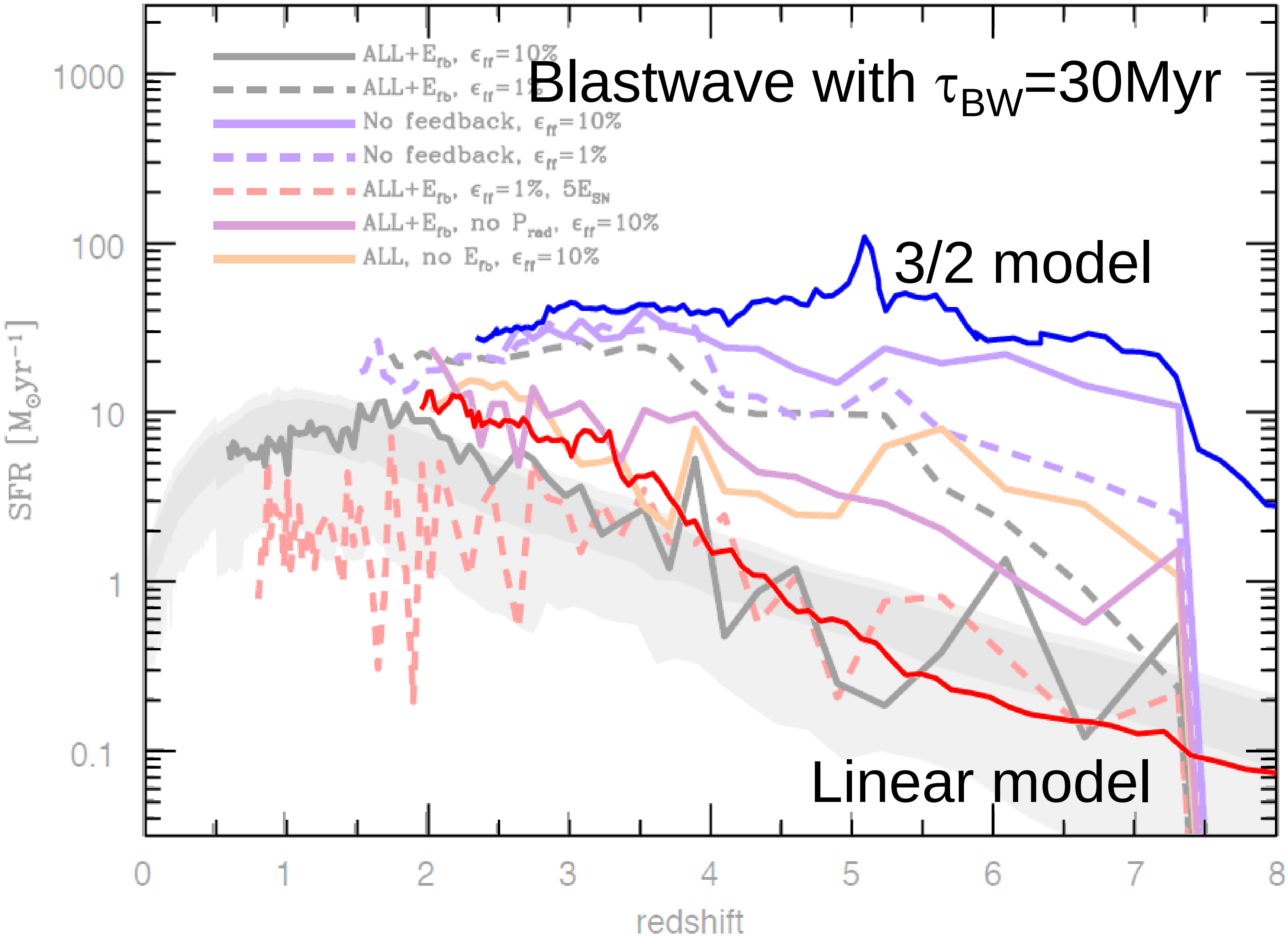
$$\overline{\langle \dot{\rho}_* \rangle_L} = \frac{\langle \rho_{\rm H_2} \rangle_L}{\tau_{\rm SF}}$$

- Many (may be all) existing simulations, with strong and weak feedback, are consistent with (partial) non-emergence of the KS relation: amplitude is emergent, but the slope is not (neighboring density bins are strongly correlated).

Conclusions From Conclusions

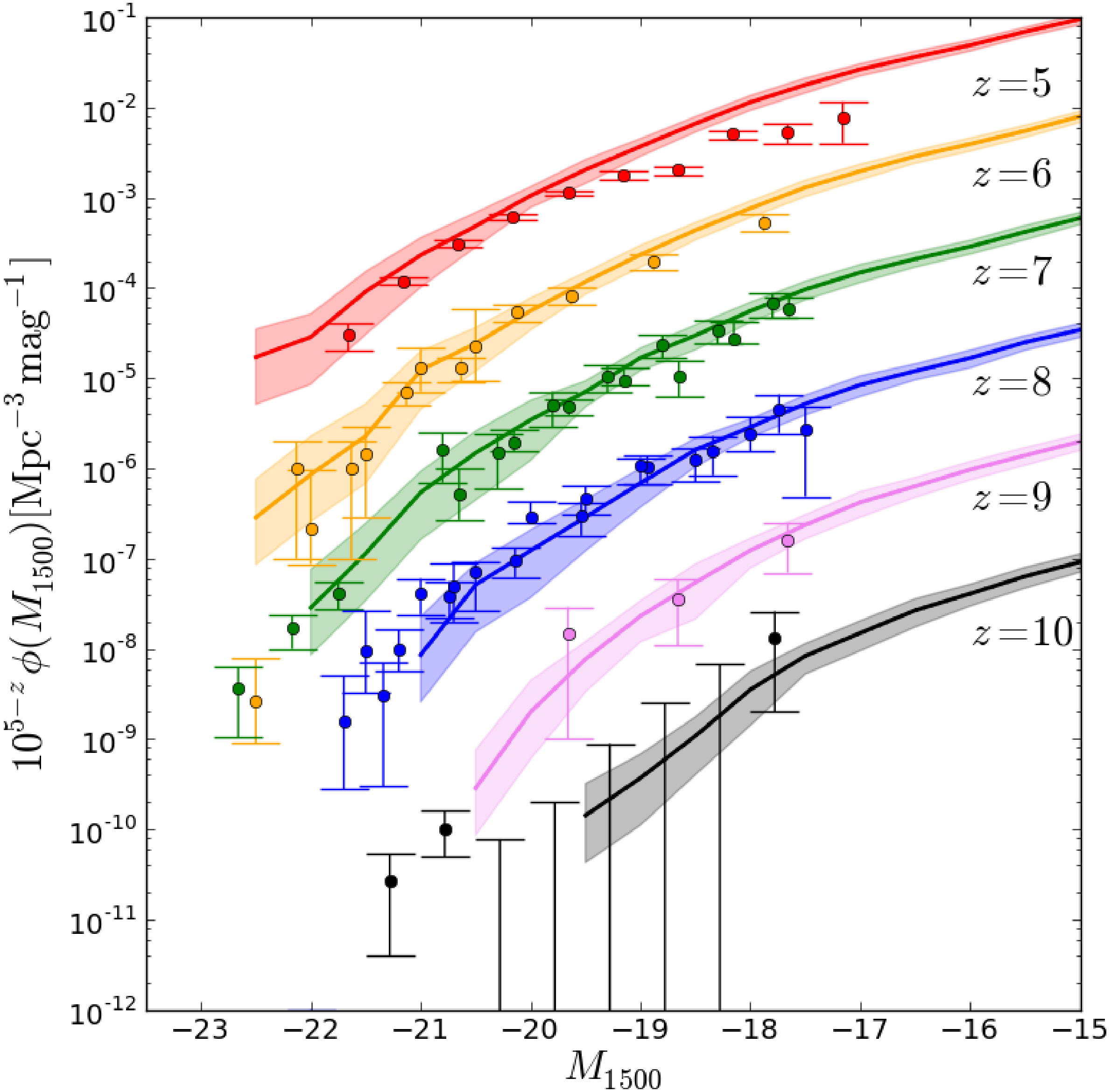
- It is important to break away from the “classical” 3/2 model and explore another “degree of freedom”: variation in the SF recipe (different slopes, stochasticity, non-trivial physical criteria, etc).
- These variations are degenerate with the feedback model – the need of ultra-strong feedback may be an artifact of assumed 3/2 SF model.

Afterword



ALL+E$_{fb}$, ϵ_{ff}=10%
ALL+E$_{fb}$, ϵ_{ff}=1%
No feedback, ϵ_{ff}=10%
No feedback, ϵ_{ff}=1%
ALL+E$_{fb}$, ϵ_{ff}=1%, 5E$_{SN}$
ALL+E$_{fb}$, no P$_{rad}$, ϵ_{ff}=10%
ALL, no E$_{fb}$, ϵ_{ff}=10%
Blastwave with τ_{BW}=30Myr
3/2 model
Linear model
SFR [$M_\odot yr^{-1}$]
1000
100
10
1
0.1
0
1
2
3
4
5
6
7
8
redshift

Afterword



$$\frac{d\rho_*}{dt} = \frac{\rho_{\mathrm{H_2}}}{\tau_{\mathrm{SF}}}$$

$$\tau_{\mathrm{SF}} = 1.5\mathrm{Gyr}$$

$$\tau_{\mathrm{BW}} = 10\mathrm{Myr}$$


GO
LINEAR