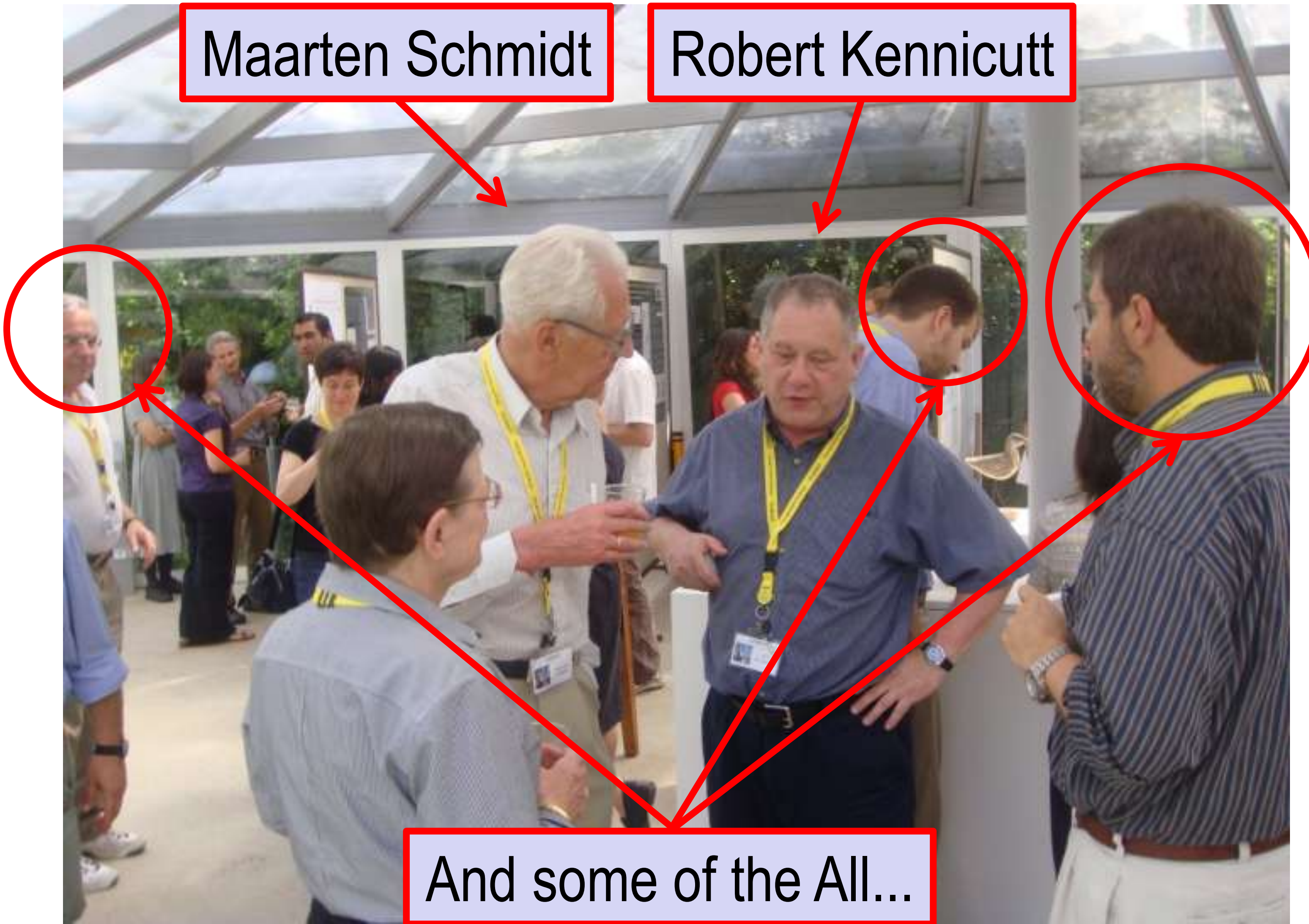
PART IV

Star Formation

1. Kennicutt-Schmidt and All, All, All



WARNING!

Anyone calling KS relation a "law" will be immediately forcefully removed from the lecture room.

History: Why KS?

THE ASTROPHYSICAL JOURNAL, 498:541–552, 1998 May 10

THE GLOBAL SCHMIDT LAW IN STAR-FORMING GALAXIES

ROBERT C. KENNICUTT, JR.[1]
Steward Observatory, University of Arizona, Tucson, AZ 85721
Received 1997 October 6; accepted 1997 December 23

THE STAR FORMATION LAW IN GALACTIC DISKS

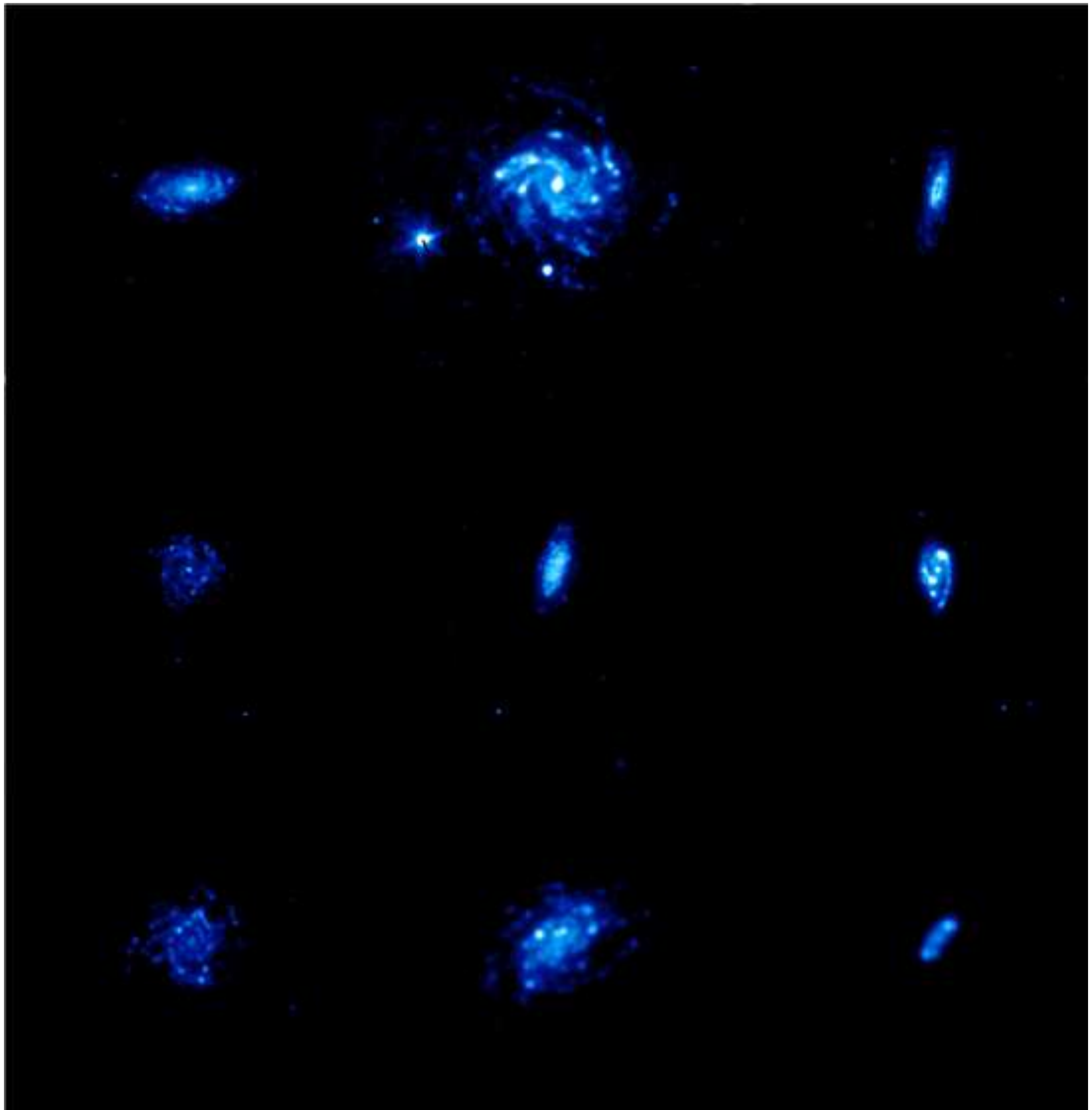
ROBERT C. KENNICUTT, JR.[1]
Steward Observatory, University of Arizona
Received 1988 November 29; accepted 1989 February 23

VOLUME 129 MARCH 1959 NUMBER 2

THE RATE OF STAR FORMATION

MAARTEN SCHMIDT*
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received October 29, 1958

What Stars Form From?

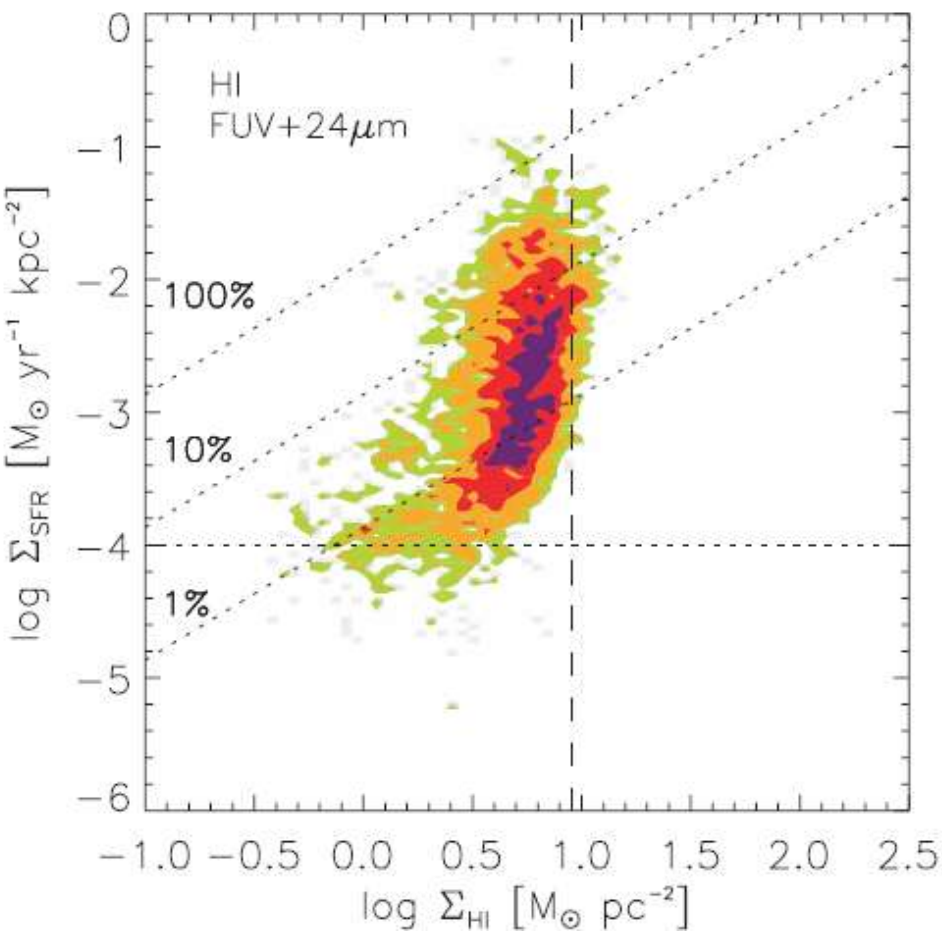


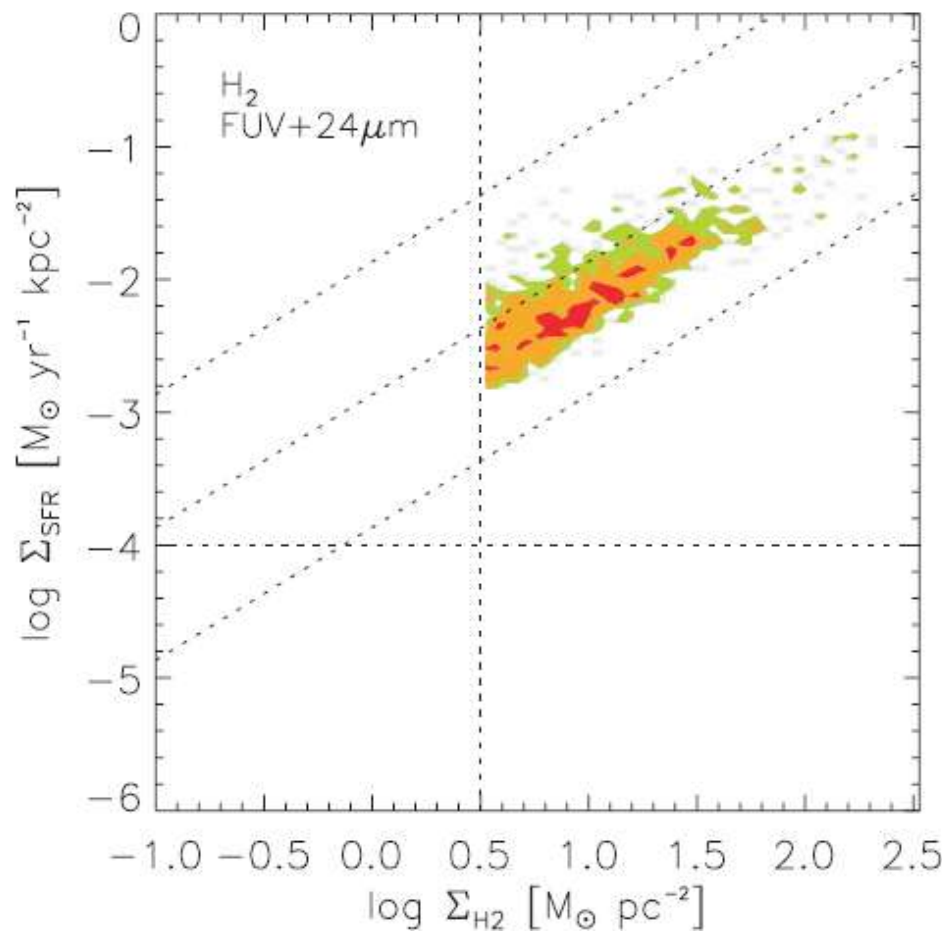
SFR distributions from 24 μm SINGS + GALEX

F. Walter &
The HI Nearby
Galaxy Survey

Why THINGS Matter

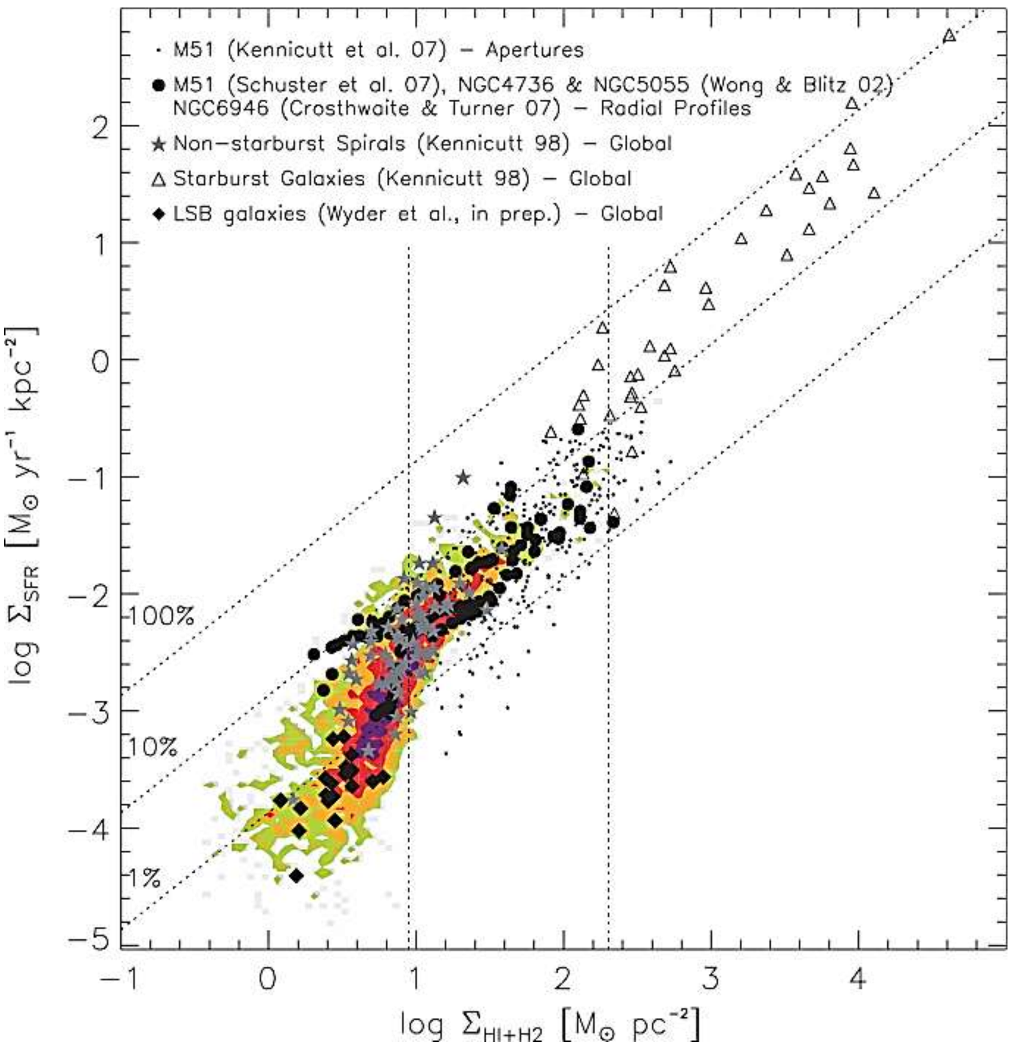
- The THINGS survey unambiguously proved what everyone knew in their hearts: ***stars form from molecular gas***.



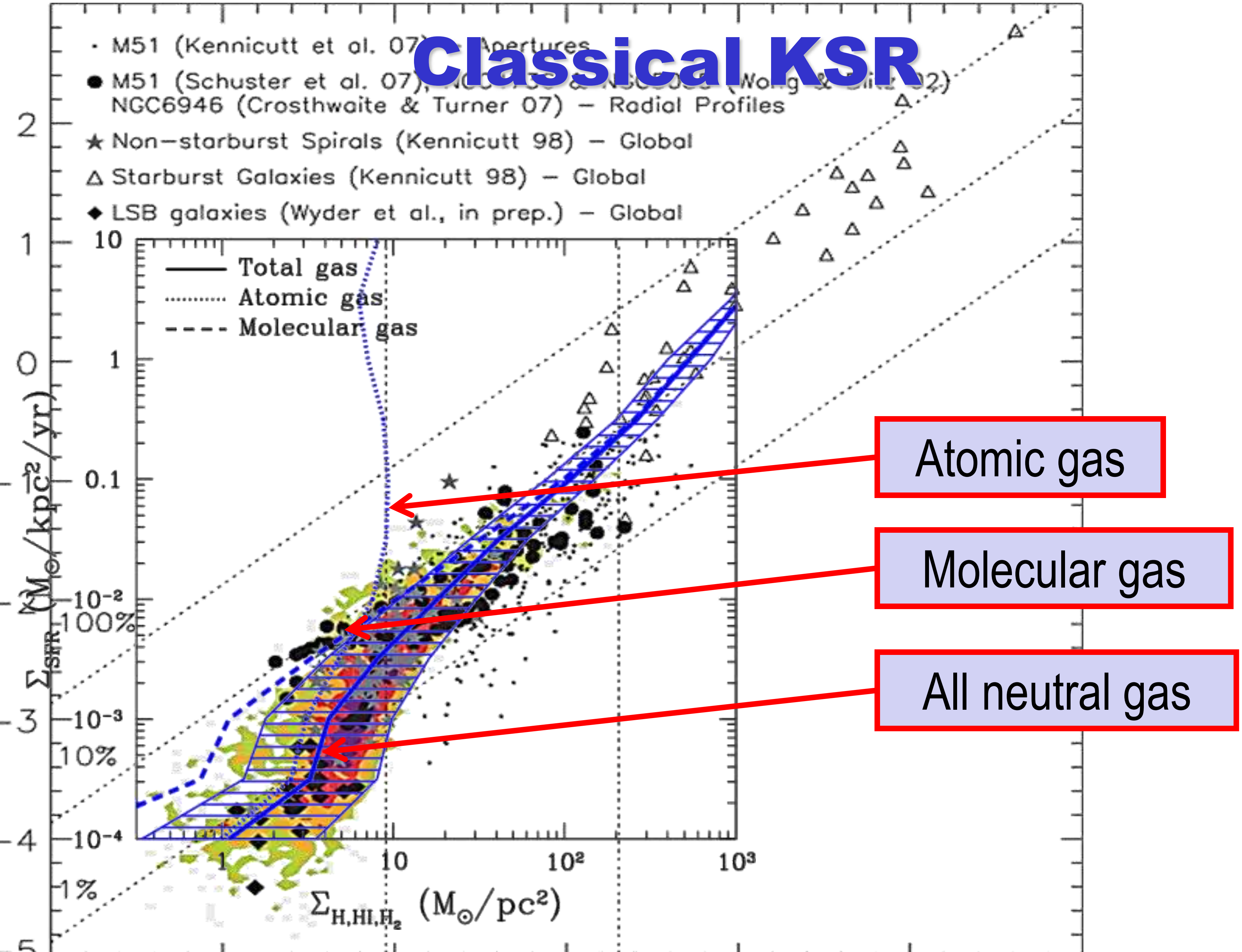


Classical KSR

- The one and only plot of the classical KSR in this course!



Classical KSR



Depletion Time

- It is convenient to think about star formation on large scales in terms of the *gas depletion time* τ_{SF} :

$$\Sigma_{\mathrm{SFR}} \equiv \left. \frac{d\Sigma_*}{dt} \right|_{\mathrm{SF}} = \frac{1.36\Sigma_{\mathrm{H_2}}}{\tau_{\mathrm{SF}}}$$

Quiz: This whole thinking is wrong. Why?

Density is only defined on a particular spatial scale.

$$\rho = \frac{M}{V} = \frac{M}{L^3}$$

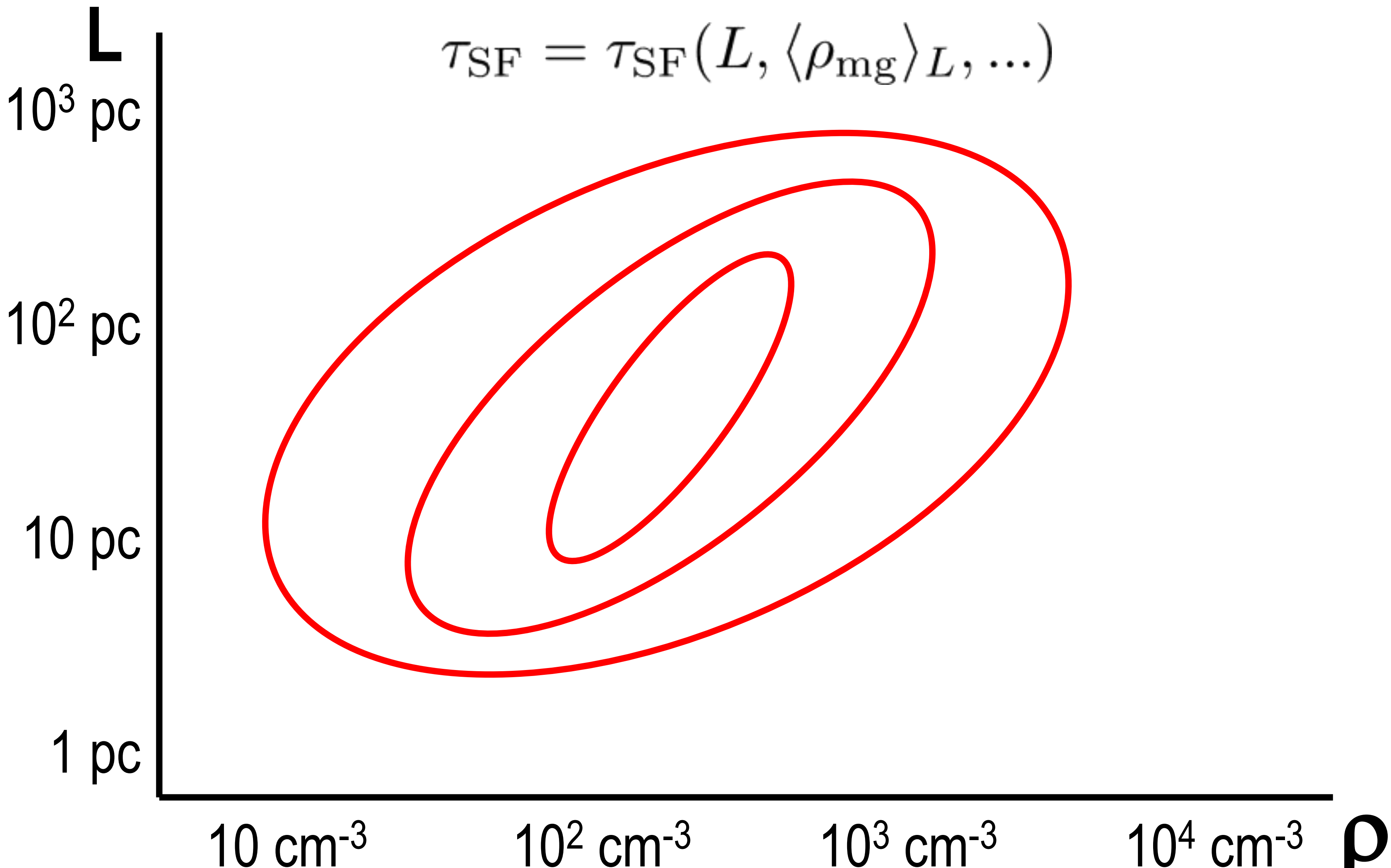
How We Should Think About Star Formation

- Take some spatial scale L.
- Average all densities on this scale - only them are meaningfully defined.

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

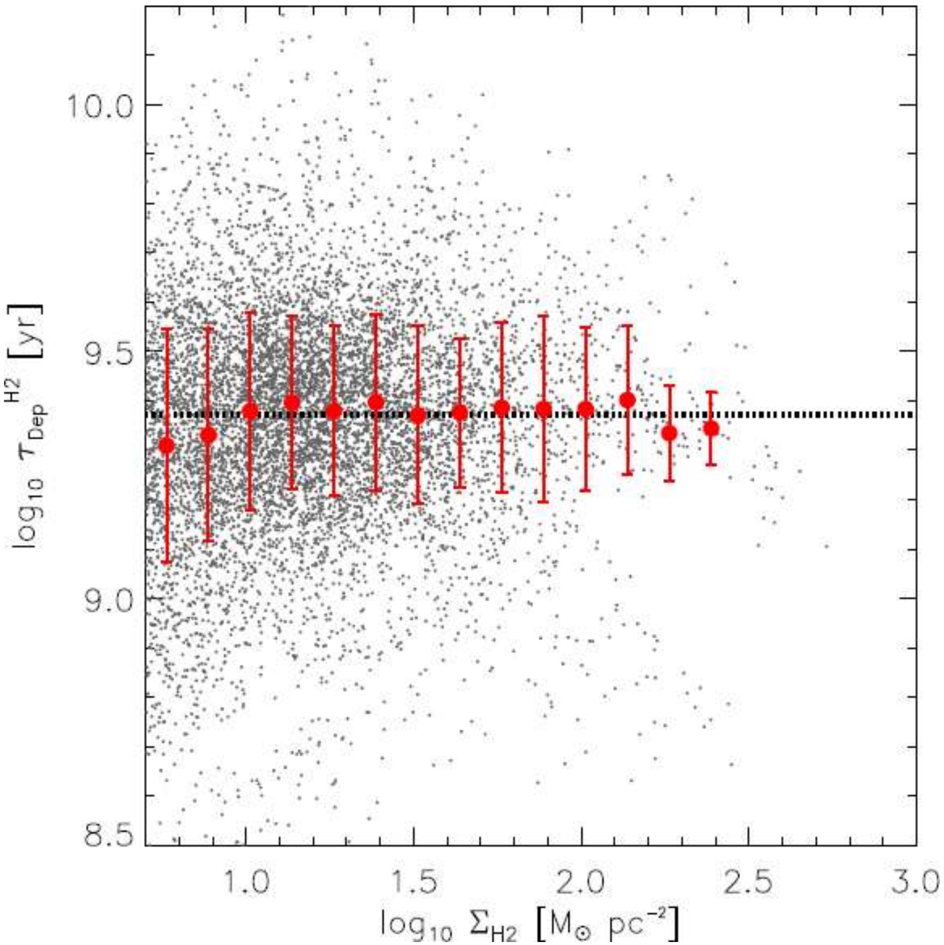
- With $\tau_{\rm SF} = \tau_{\rm SF}(L, \langle \rho_{\rm mg} \rangle_L, \ldots)$.

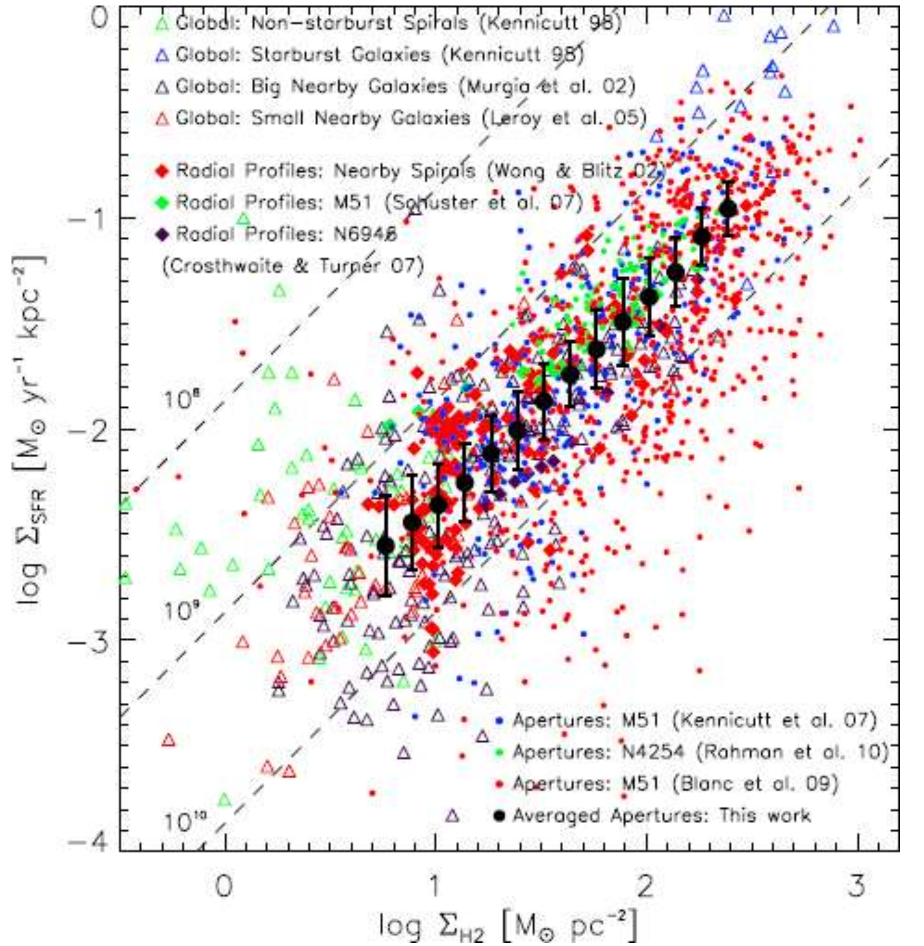
Let's Think in 2D!



Large Scales, z~0

- THINGS galaxies: $L > 500\mathrm{kpc}, \tau_{\mathrm{SF}} \approx 2\mathrm{Gyr}.$





A Side Note

- For a log-normal distribution with a median μ and dispersion σ:

$$p(x)dx = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln(x) - \ln(\mu))^2}{2\sigma^2}\right) \frac{dx}{x}$$

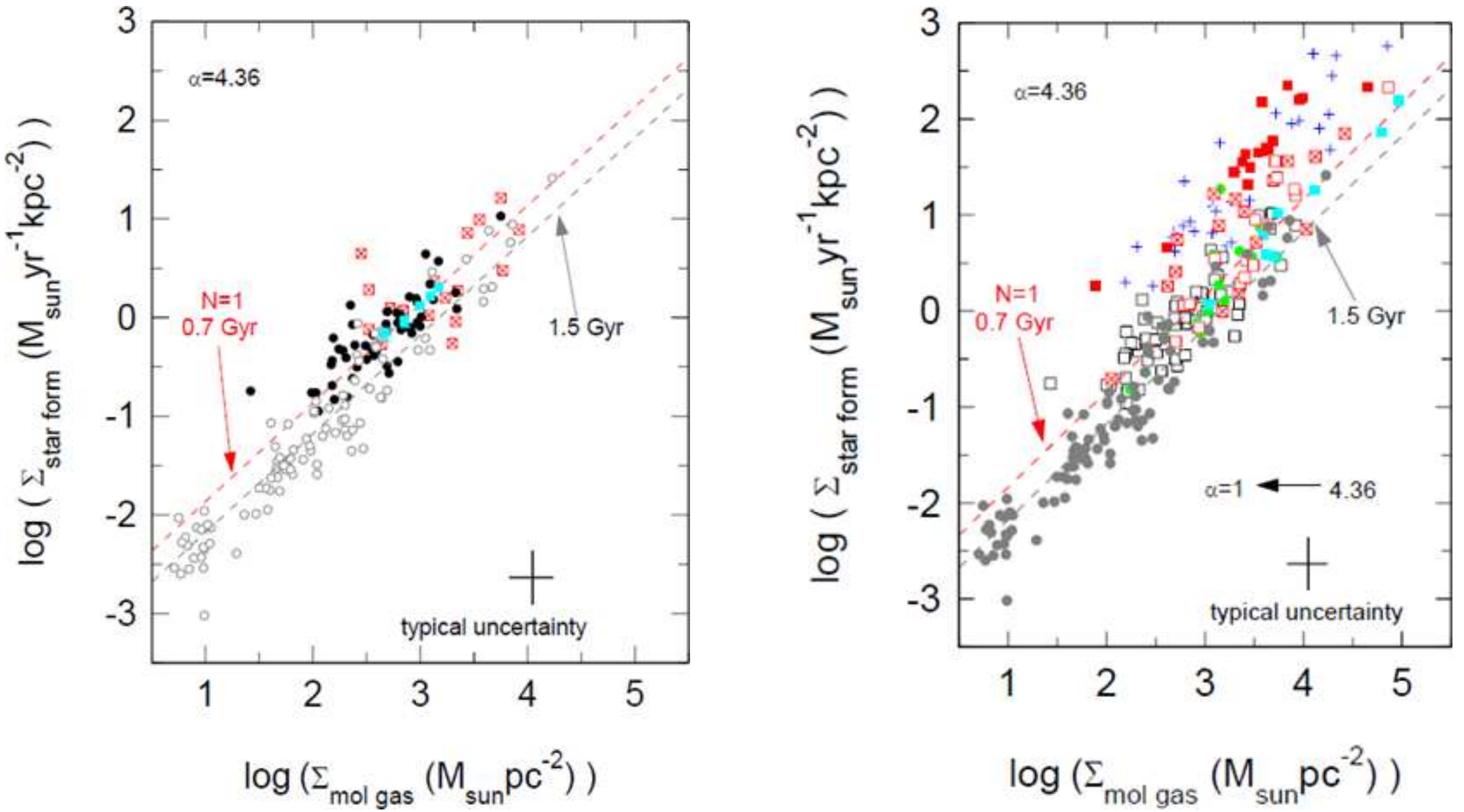
$$\bar{x} \equiv \int xp(x)dx = \mu \exp(\sigma^2/2)$$

- Hence, for $\sigma \approx 0.25\mathrm{dex}$

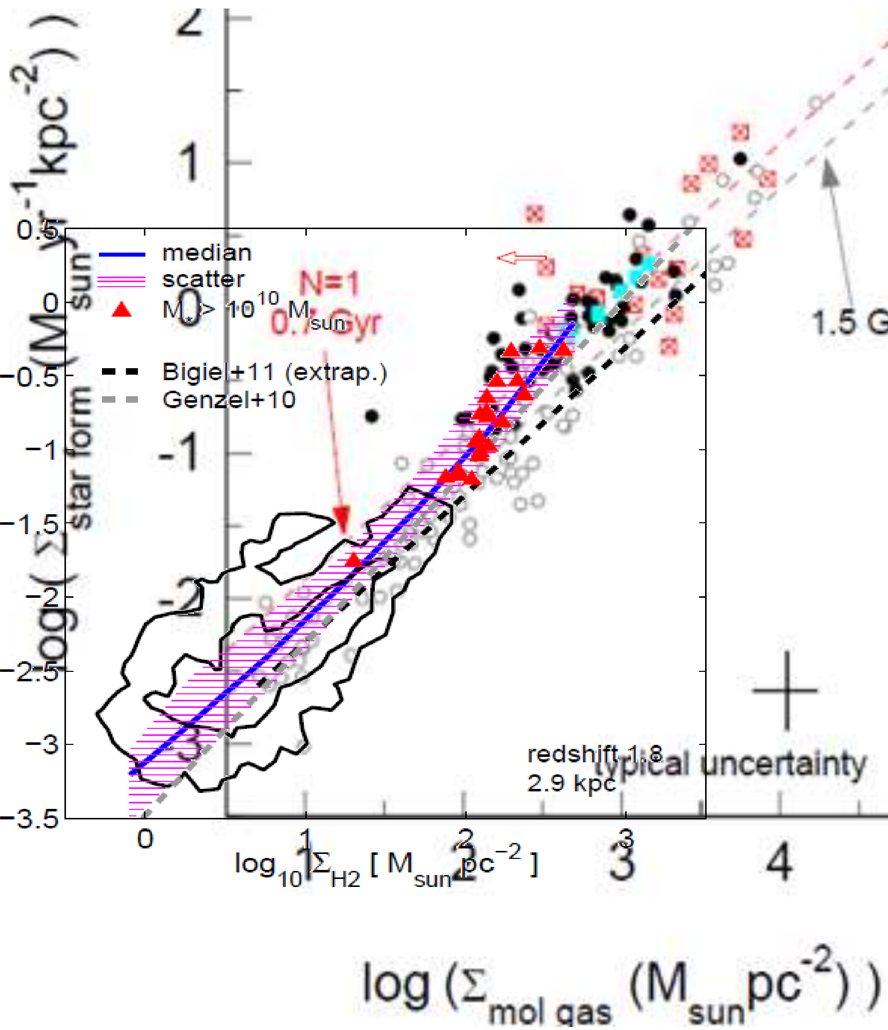
$$\bar{\tau}_{\mathrm{SF}} \approx 0.8\tau_{\mathrm{SF,med}}$$

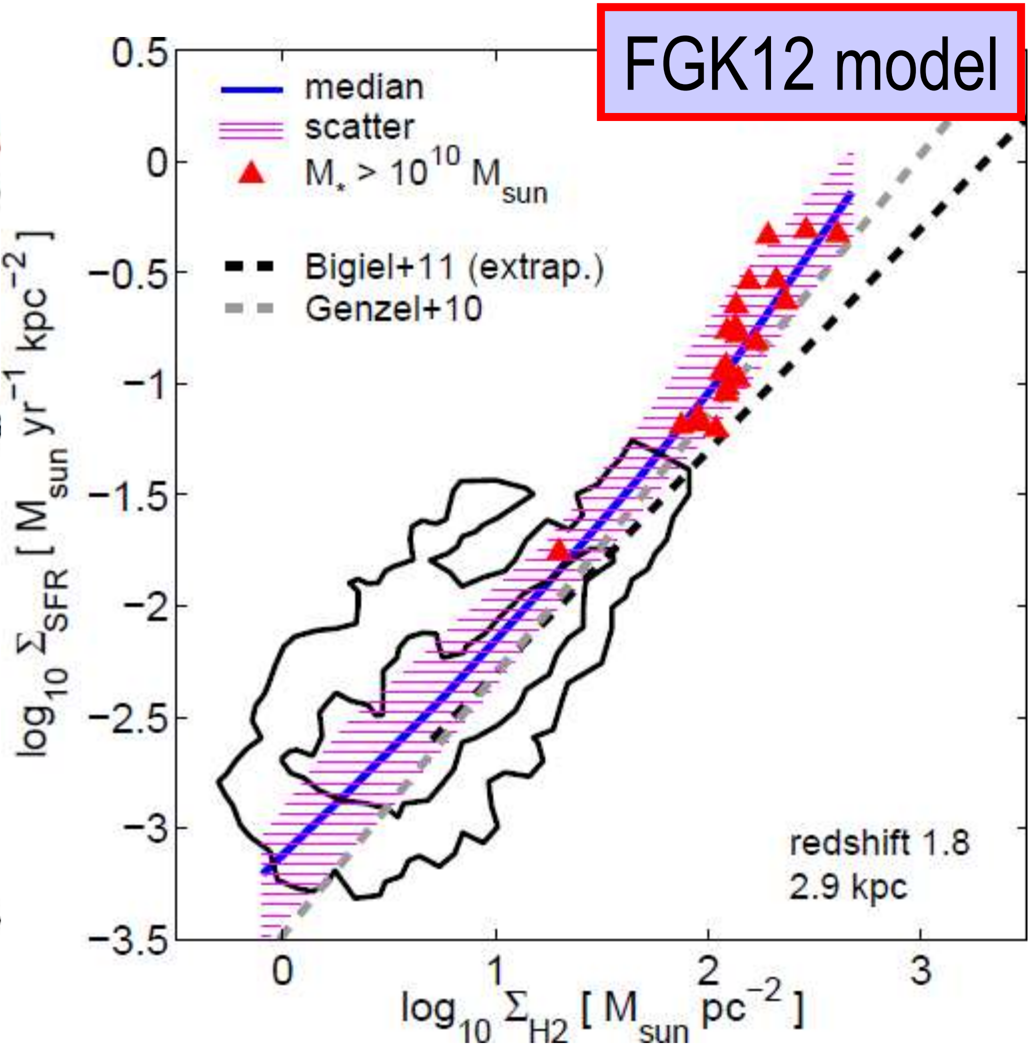
High Redshift, z~2-3

- At high redshifts the depletion time is also constant, although may be a factor ~2-3 shorter.



Variable Depletion Time or X_{co}?

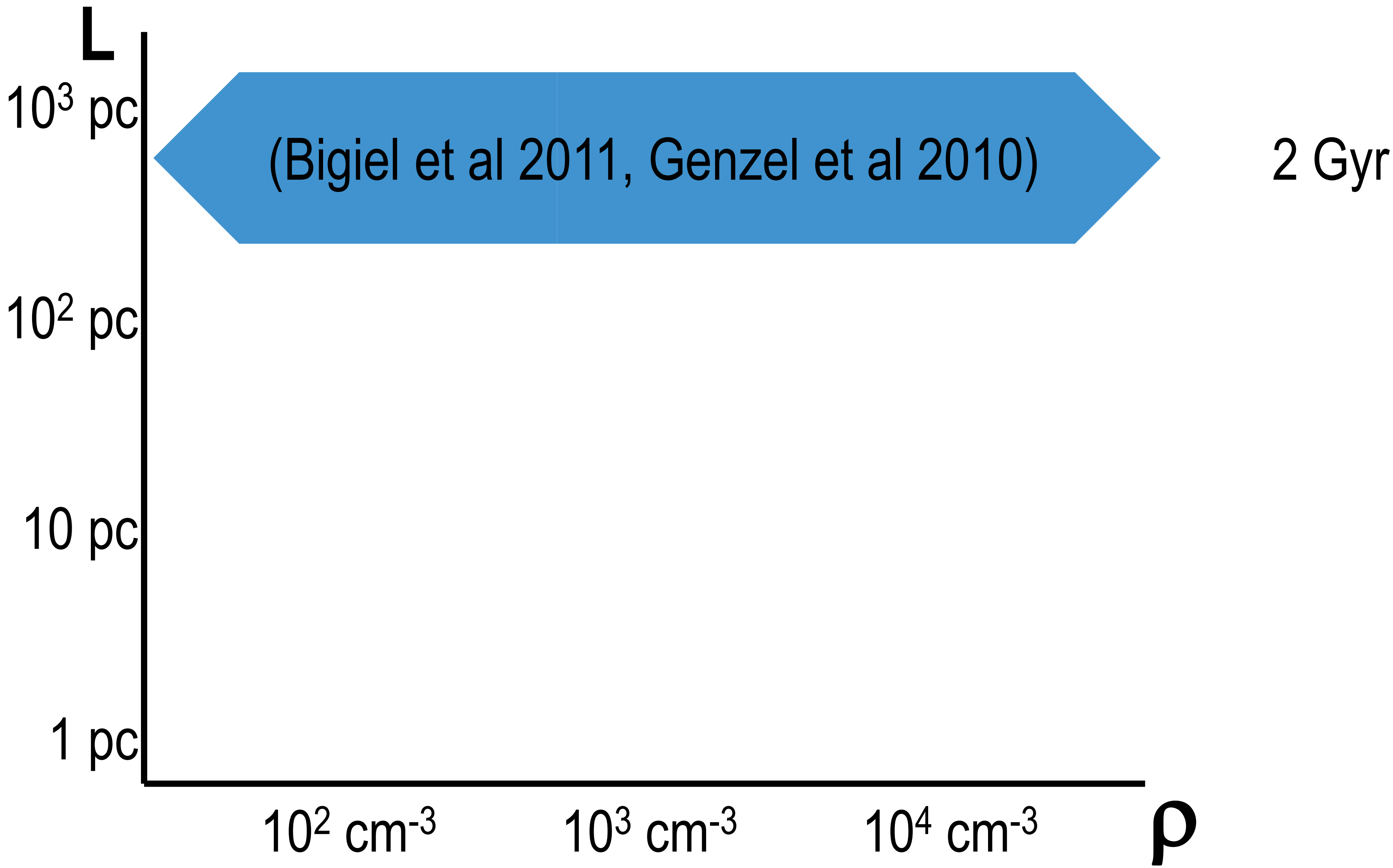




Variable Depletion Time or X_{CO}?

- High-redshift galaxies have higher SFR per unit CO luminosity.
- Whether this reflects a higher X_{CO} factor or a shorter τ_{SF} is a big open question.

Let's Think in 2D!



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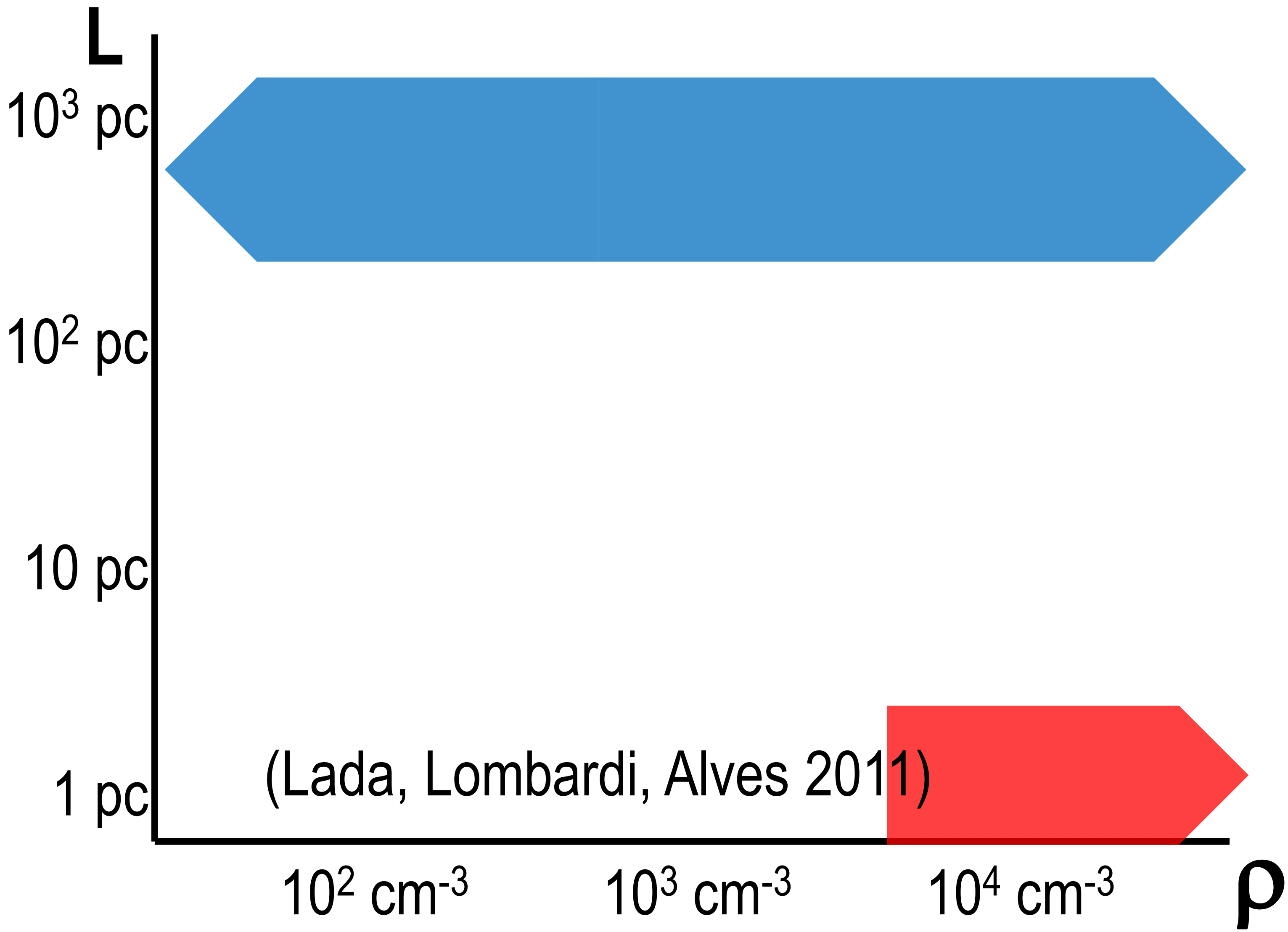


Constant Efficiency per Free-Fall Time

- The most common ansatz used in modern simulations is the *constant efficiency per free-fall time*:

$$\tau_{\rm SF}(L, \langle\rho_{\rm mg}\rangle_L, \ldots) \to \frac{\tau_{\rm ff}(\langle\rho_{\rm mg}\rangle_L)}{\epsilon_{\rm SF}} = \epsilon_{\rm SF}^{-1}\sqrt{\frac{3\pi}{32G\langle\rho_{\rm mg}\rangle_L}}$$

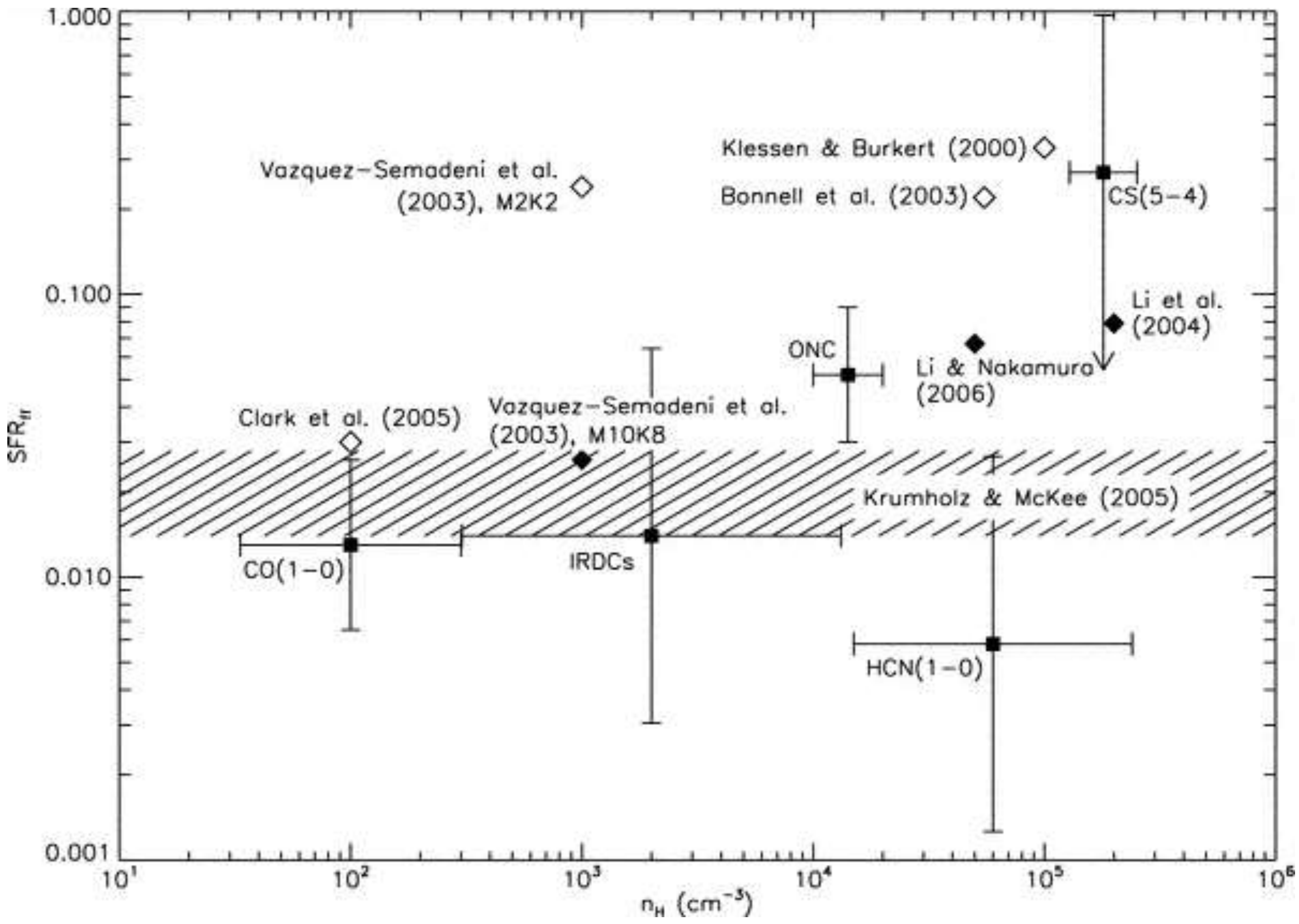
- or, in a more familiar form:

$$\langle\dot{\rho}_*\rangle_L = \epsilon_{\rm SF}\frac{\langle\rho_{\rm mg}\rangle_L}{\tau_{\rm ff}} = \epsilon_{\rm SF}\frac{\langle\rho_{\rm mg}\rangle_L^{3/2}}{\sqrt{3\pi/(32G)}}$$

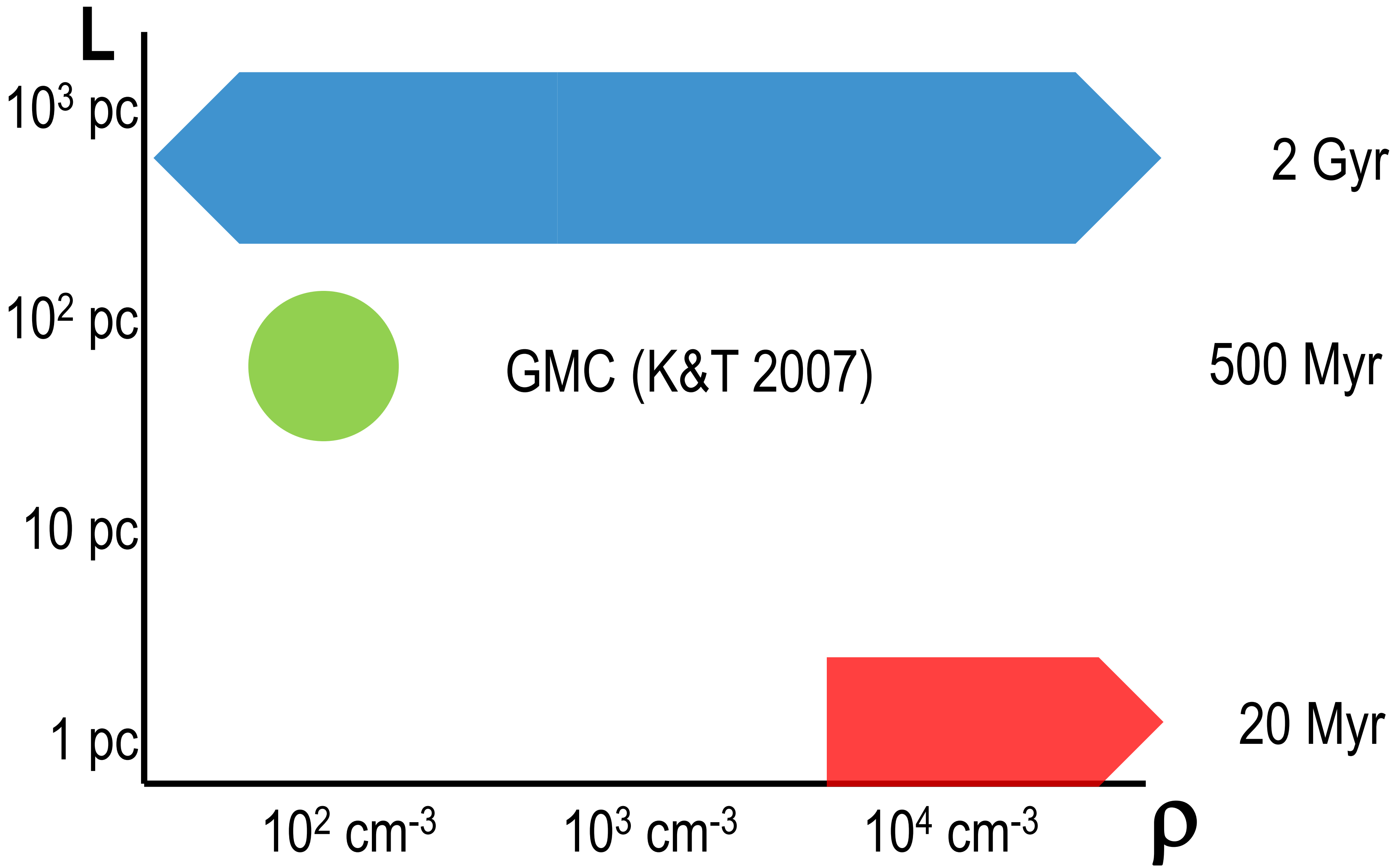
- This is just an **ansatz**: molecular clouds are turbulent and the free-fall time is meaningless on scales above molecular cores (~0.1pc).

Constant Efficiency per Free-Fall Time

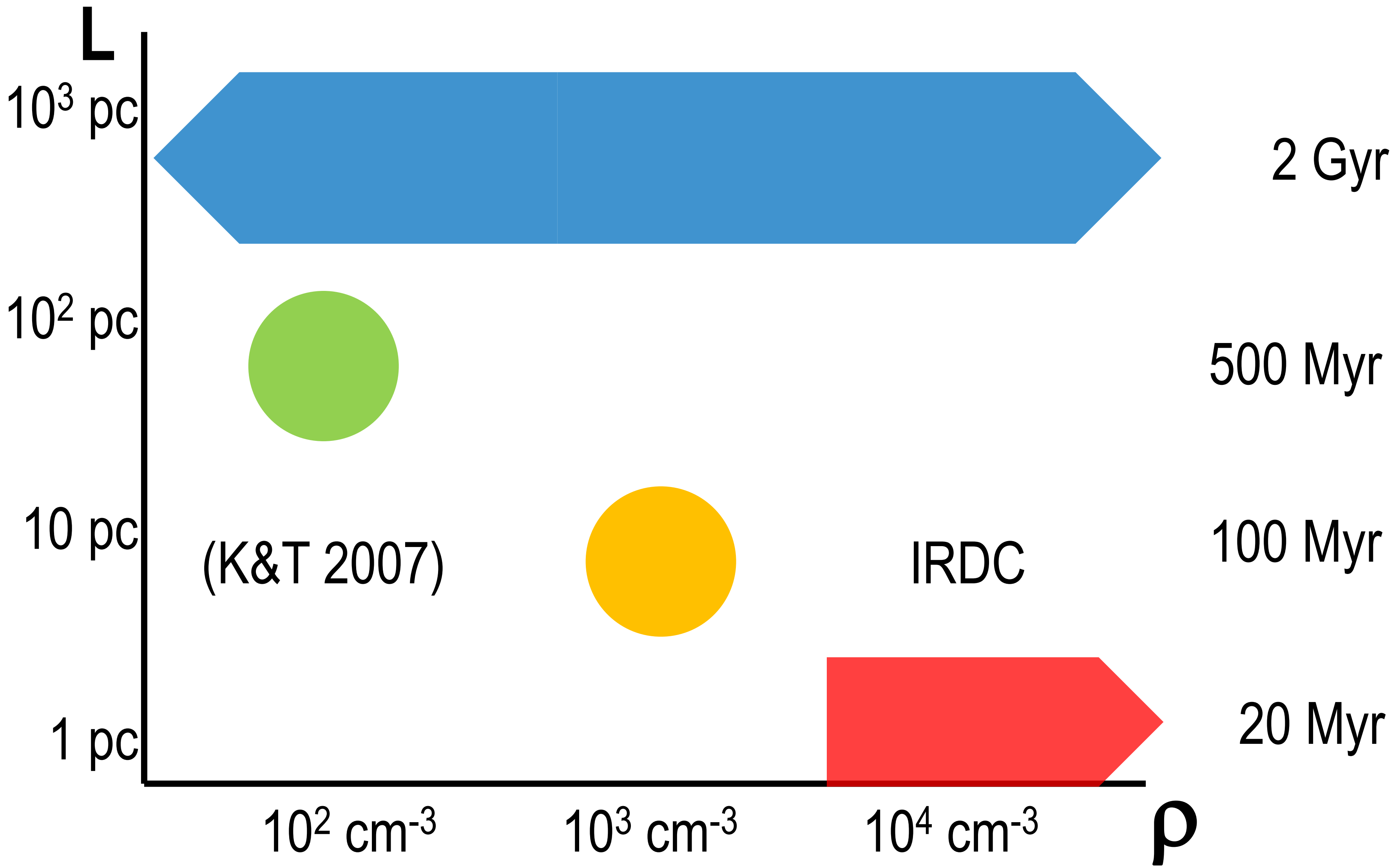
- Krumholz & Tan (2007) did not invent the “constant efficiency per free-fall” ansatz, but they advocated it strongly.



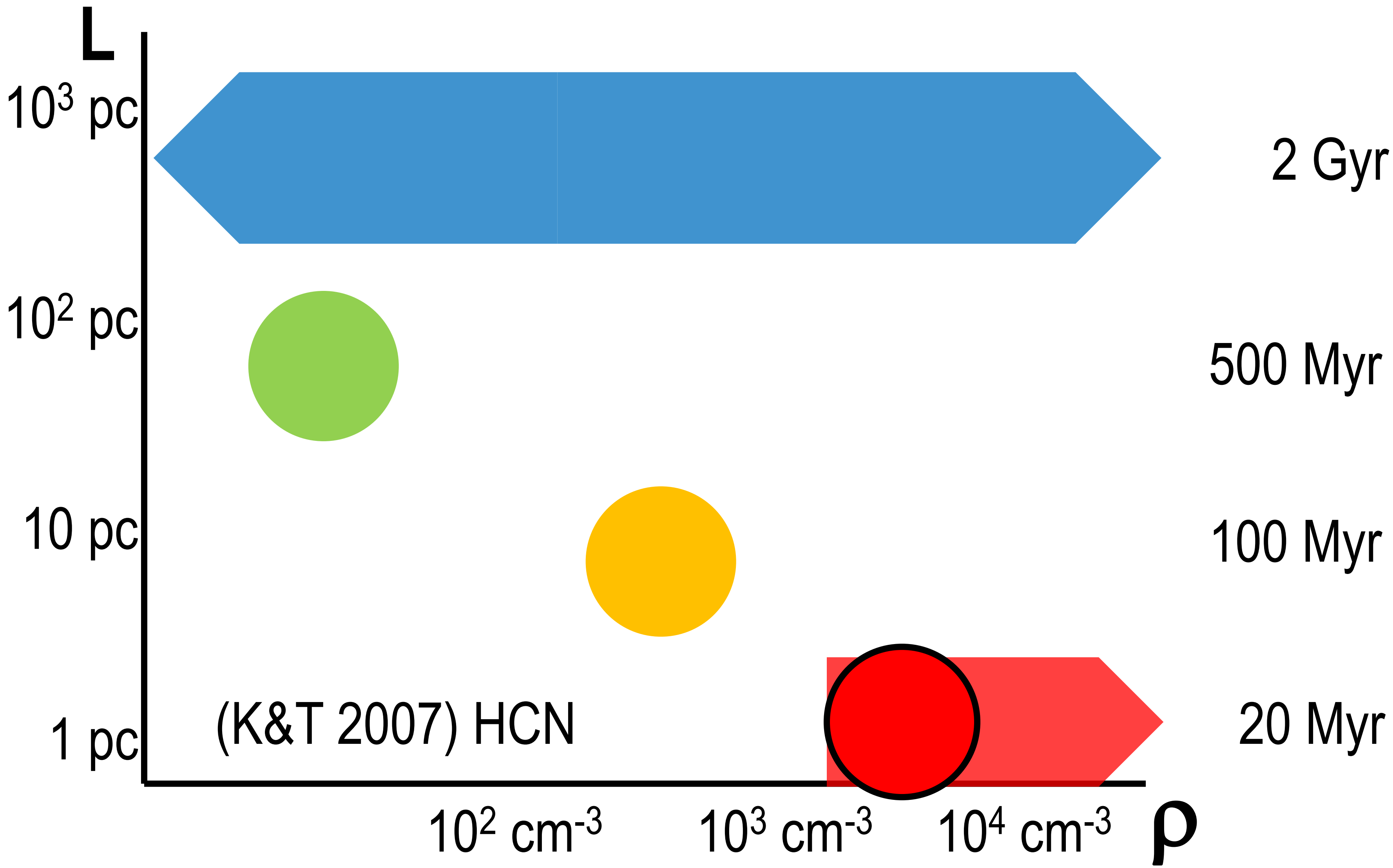
Let's Think in 2D!



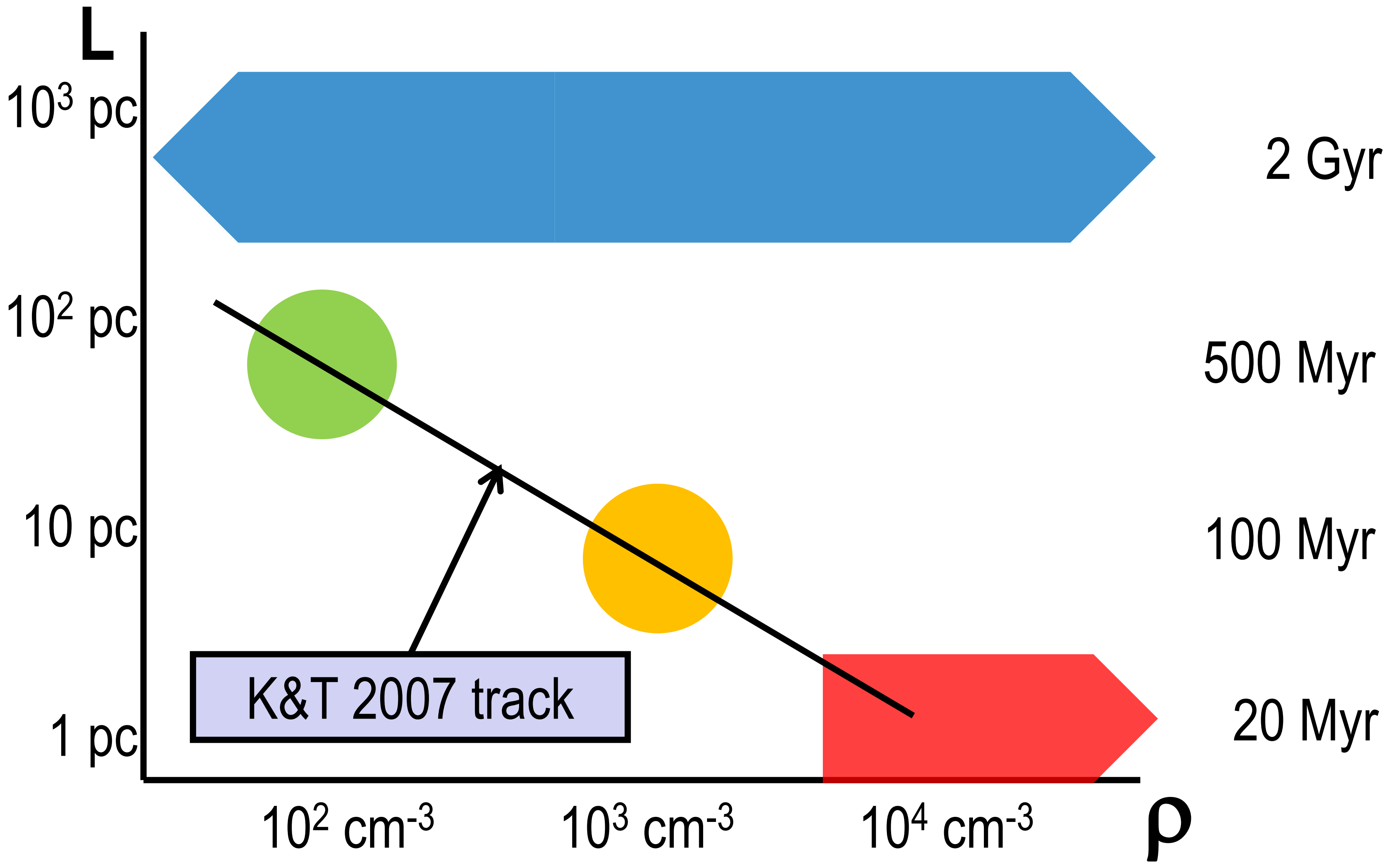
Let's Think in 2D!



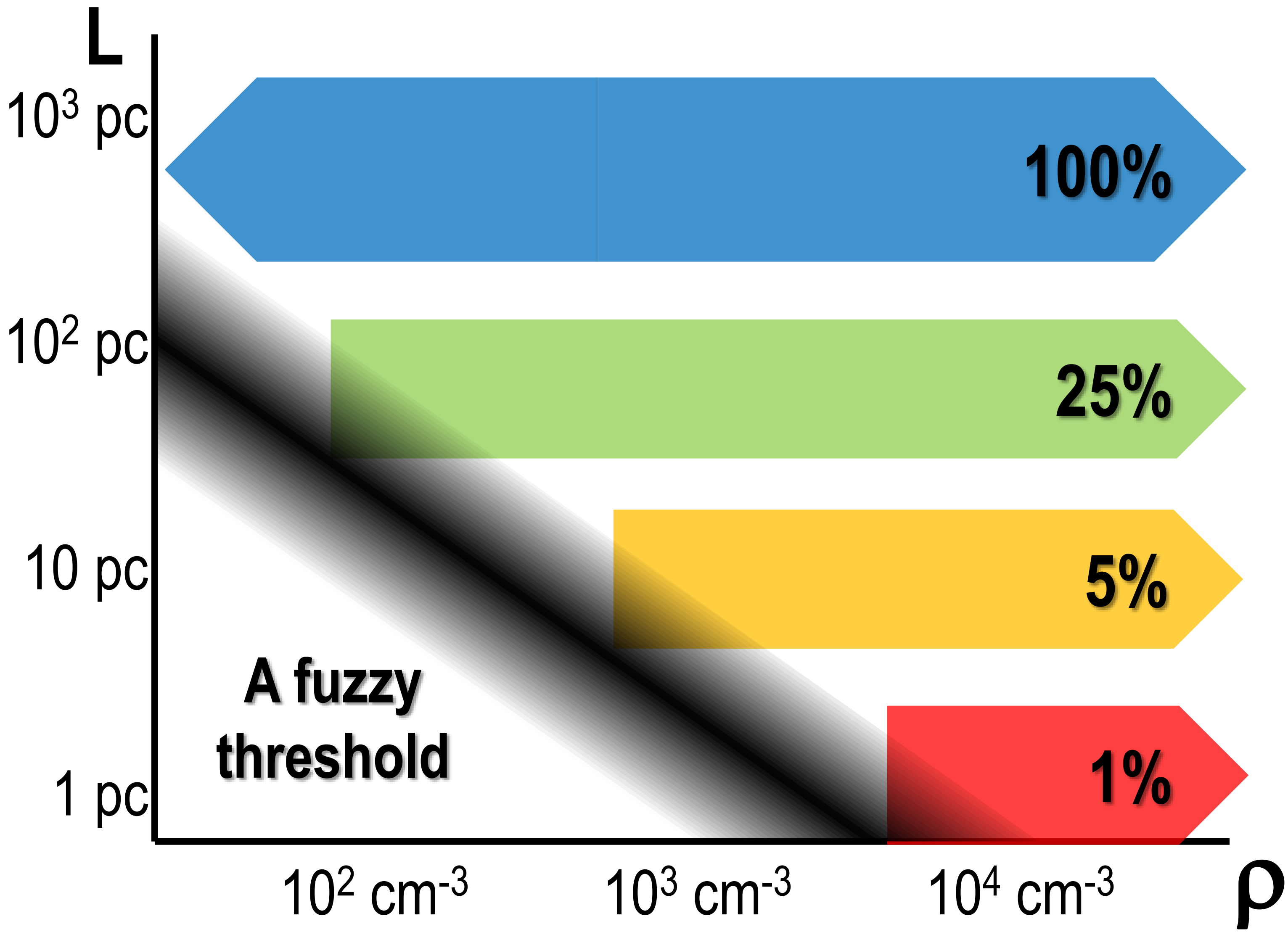
Let's Think in 2D!



Let's Think in 2D!



Is Life Simple?

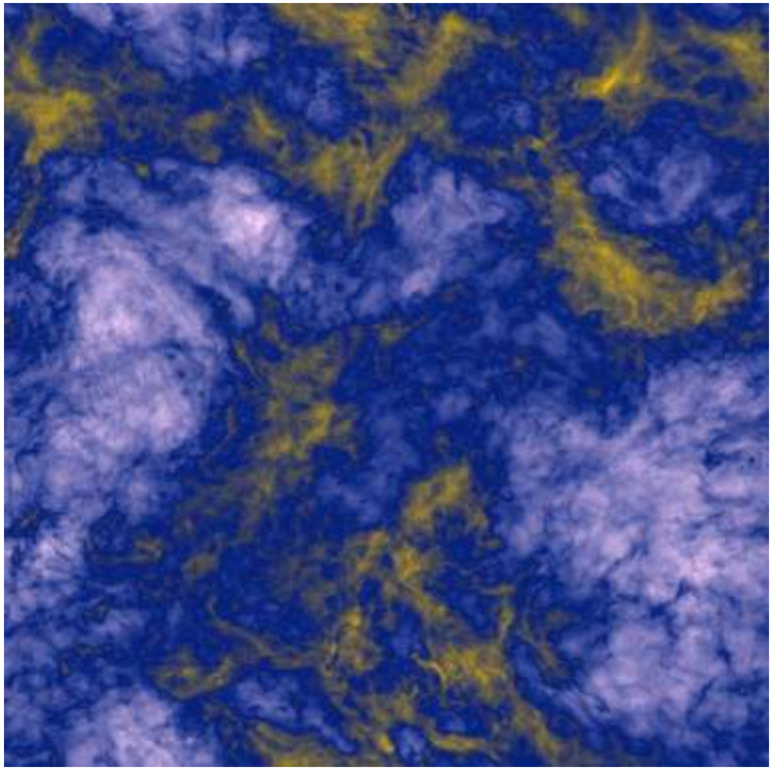


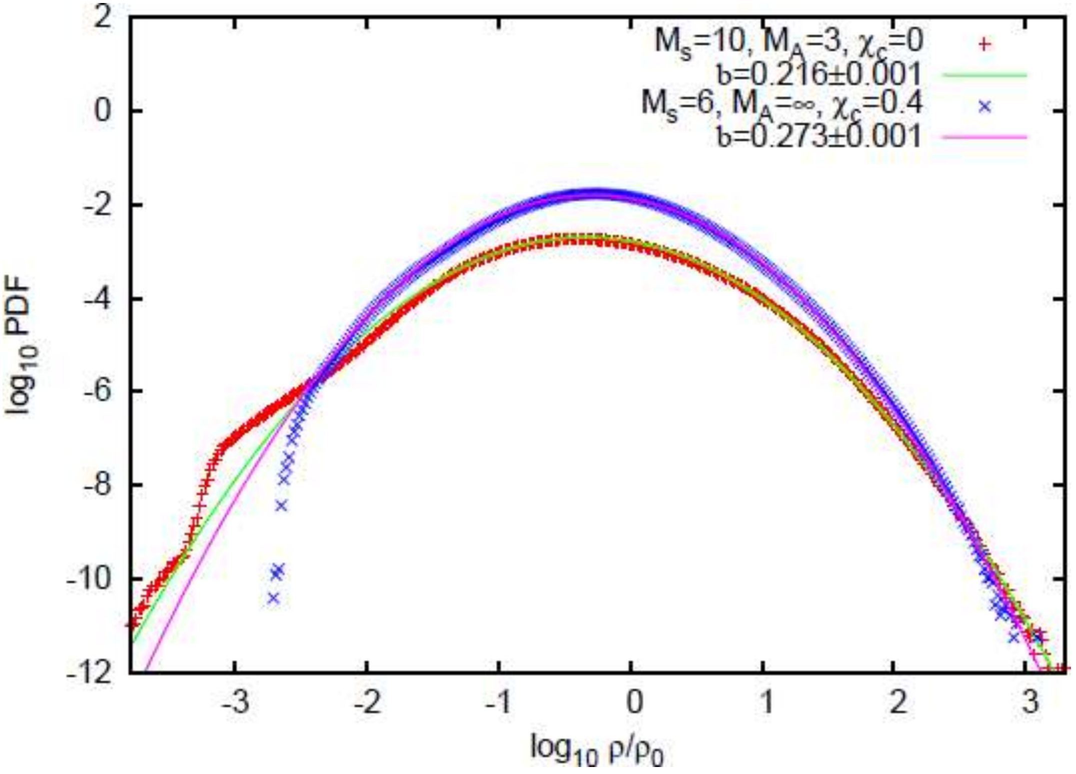
Summary

$$\langle \dot{\rho}_* \rangle_L = \frac{\langle \rho_{\rm mg} \rangle_L}{\tau_{\rm SF}}, \qquad \tau_{\rm SF} = \tau_{\rm SF}(L, \langle \rho_{\rm mg} \rangle_L, \ldots)$$

- Density is only defined on some scale, $\rho = M/V$.
- On large scale ($\ll 100{\rm pc}$) the depletion time is independent of density, but may depend on other factors (redshift, "normal" vs "merger" mode, etc).
- The "constant efficiency per free-fall" ansatz ($\dot{\rho}_* \propto \rho_{\rm mg}^{3/2}$) is just an **ansatz**, the free-fall time is not a relevant physical quantity in turbulent molecular clouds.
- Existing observational constraints are equally consistent with $\tau_{\rm SF} = \tau_{\rm SF}(L)$ ansatz.

2. Excursion Set Formalism in Star Formation





- Density distribution in simulations of supersonic turbulence is known to be closely approximated by log-normal.

ESF as a Theory of SF

- Started by Padoan & Norlund (2002, 2007), picked up by Hennebelle & Chabrier (2008) and developed further by Phil Hopkins in a recent series of papers.
- Builds on the analogy with cosmology: Gaussian linear density field of LSS vs Gaussian $\ln(\rho/\rho_0)$ field in molecular clouds.
- Just from the general principles, it is obvious to every cosmologist that such an approach cannot work...

Refresher: Excursion Set Formalism

- Also known as Press-Schechter formalism.
- Consider a box $B_1(L)$ of size L with some field $\delta(\vec{x})$ in it; the field is *random* if a value of δ in the same relative location in some other box $B_2(L)$ cannot be determined from the corresponding value of δ in B_1.
- Take Fourier transform of $\delta(\vec{x})$:

$$\delta_{\vec{k}} = \int d^3x \delta(\vec{x}) e^{i\vec{k}\vec{x}}$$

- The random field $\delta(\vec{x})$ is Gaussian with the *power spectrum* $P(k)$ if:

$$\langle \delta_{\vec{k}_1} \delta^*_{\vec{k}_2} \rangle = P(k_1) \delta^3_D(\vec{k}_1 - \vec{k}_2)$$

Refresher: Excursion Set Formalism

- Reversing the Fourier transform:

$$\delta(\vec{x}) = \int d^3k \sqrt{P(k)} \lambda_{\vec{k}} e^{-i\vec{k}\vec{x}} \tag{A}$$

- with

$$\langle \lambda_{\vec{k}_1} \lambda^*_{\vec{k}_2} \rangle = \delta^3_D(\vec{k}_1 - \vec{k}_2)$$

- Sometimes, $\lambda_{\vec{k}}$ are (incorrectly) called “phases”.

Refresher: Excursion Set Formalism

$$\delta(\vec{x}) = \int d^3k \sqrt{P(k)}\lambda_{\vec{k}} e^{-i\vec{k}\vec{x}} \qquad \text{(A)}$$

- For some $P(k)$ integral in (A) diverges for large k; then it is treated as a limit of the smoothed field

$$\delta(\vec{x}) \equiv \lim_{R\to 0} \delta(\vec{x}; R) = \int d^3k \sqrt{P(k)}\lambda_{\vec{k}} W(kR) e^{-i\vec{k}\vec{x}}$$

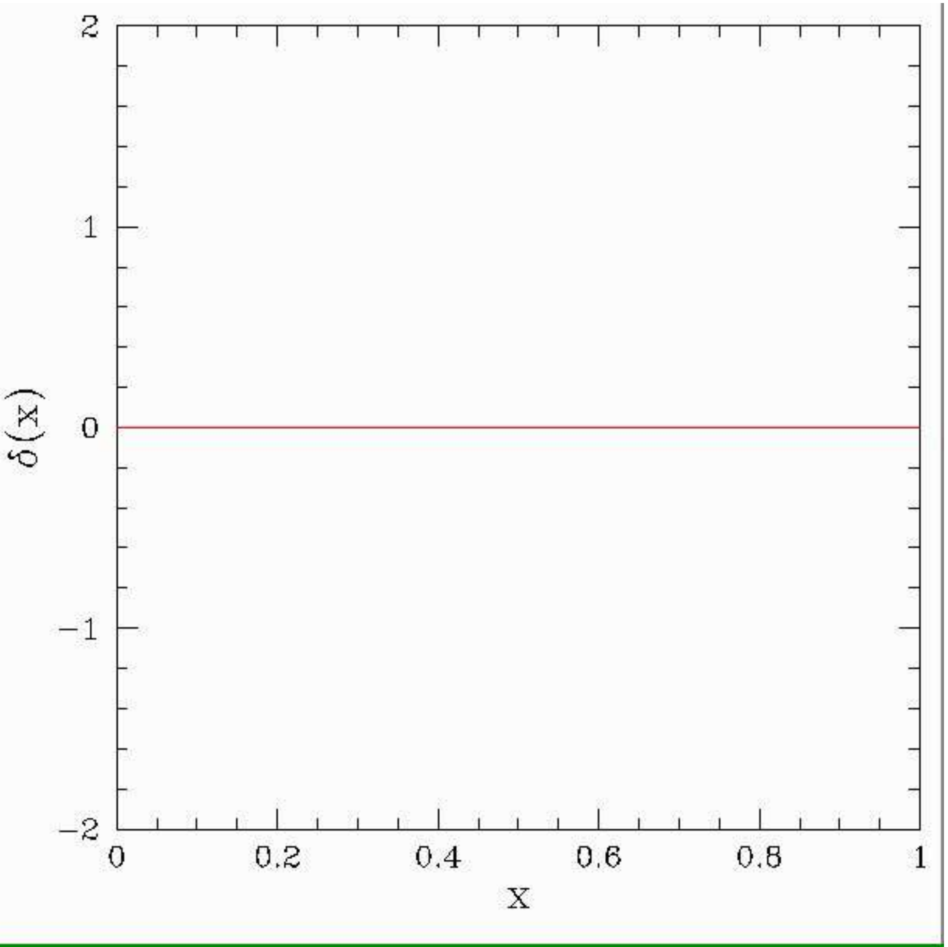
- where $W(kR)$ is a low-pass filter ($W(0) = 1$, $W(\infty) = 0$).

Refresher: Excursion Set Formalism

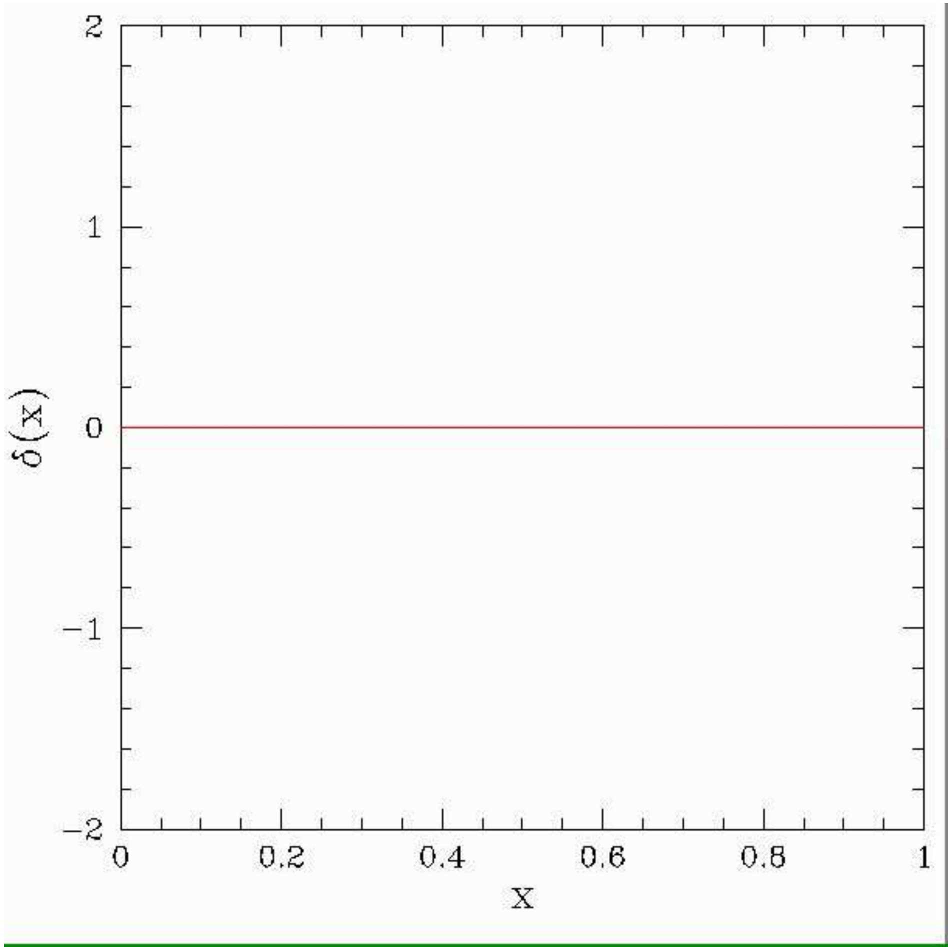
- Excursion Set formalism considers $\delta(\vec{x}; R)$ as a function of R and compares it with some "barrier" function $b(R)$.
- Obviously, $\delta(\vec{x}, R = \infty) = 0$.
- As R decreases, $\delta(\vec{x}; R)$ starts deviating from zero. For some value of R it may cross the barrier for the first time.
- The fraction of all $\delta(\vec{x}; R)$ that cross the barrier at R is called the "first crossing distribution".

Refresher:
Excursion Set Formalism

Smooth filter



Sharp filter



Refresher: Excursion Set Formalism

- For example, in the Press-Schechter formalism the barrier is constant, $b = \delta_L(t_f) = 1.69$.
- Then the first crossing distribution becomes (½ x) the mass function of dark matter halos with $M_h = 4\pi\bar{\rho}_m R^3/3$.
- Excursion Set formalism may be used for many other purposes (ask Sasha Kaurov about using it for modeling reionization).

ESF as a Theory of SF

- In modeling SF Excursion Set formalism can be used for several goals:
  - First crossing distribution gives the mass function of largest bound objects – molecular clouds.
  - Last crossing distribution* gives the mass function of smallest bound objects – molecular cores/stars.
  - It is useful for other purposes too: distribution of holes in the ISM, clustering of stars, etc.
- But wait, what should the barrier be?

* Guessing what it is is left as a home exercise.

Collapse Barrier

Quiz:

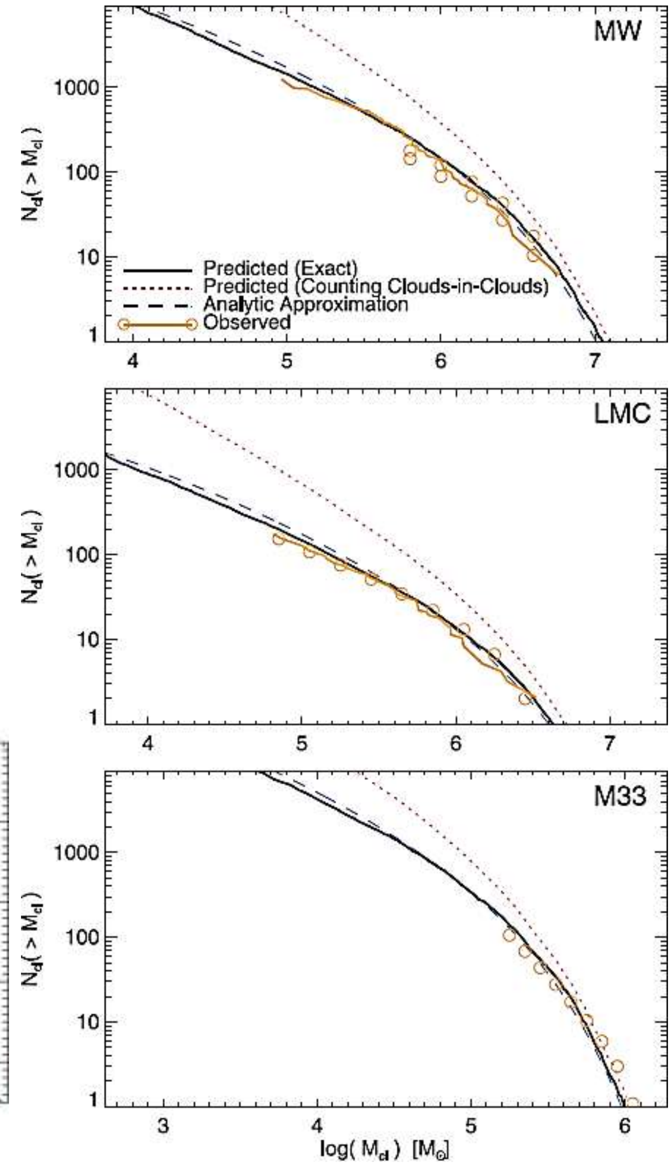
A. I **do** know what the collapse barrier is.
B. I do **not** know what the barrier could be.

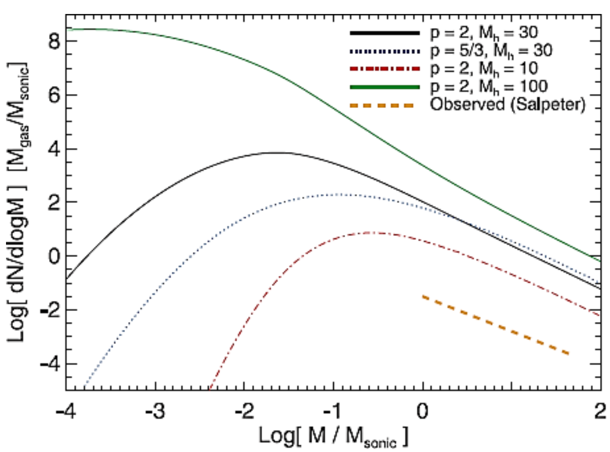
$$\omega^2 = \kappa^2 - 2\pi G \frac{\bar{\Sigma}|k|}{1+|k|h} + (\sigma_t^2(k) + c_S^2)k^2$$

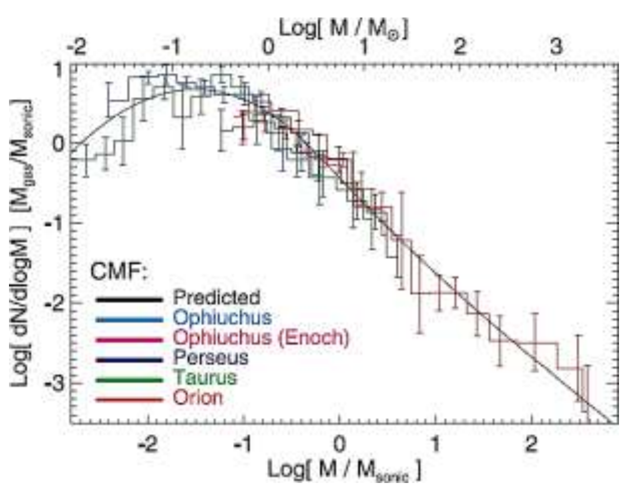
- The collapse barrier is simply the condition for gravitational instability for a disk of finite thickness (recall, the Jeans condition is hidden inside this one).

ESF as a Theory of SF

- Excursion Set formalism makes predictions that are computable "analytically" and match a large variety of observations unexpectedly well.
- The rest is for Ralf to explain...







The End