# Star Formation and Feedback II: The IMF and the SFR

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30th Jerusalem Winter School on Theoretical Physics

January 1, 2013

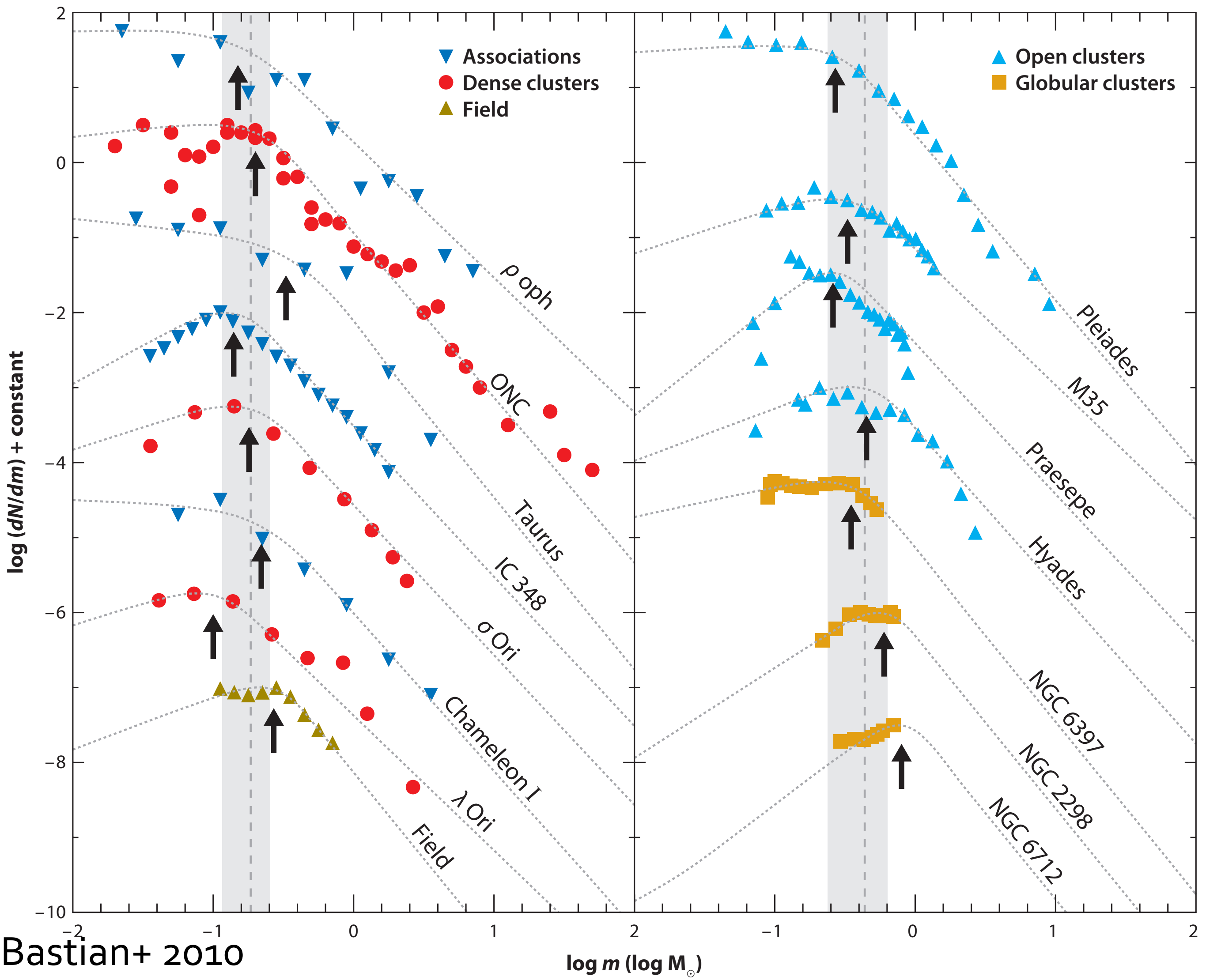
# Outline

- The IMF
  - Observations
  - Theoretical approaches
    - The peak and the isothermal conundrum
    - The tail
- The SFR
  - Observations
  - Theoretical approaches
    - The top-down approach
    - The bottom-up approach

# Why the IMF Matters

- Nearly all extragalactic measurements (e.g. masses, SFRs) implicitly assume an IMF
- IMF determines strength of stellar feedback
- IMF determines element production

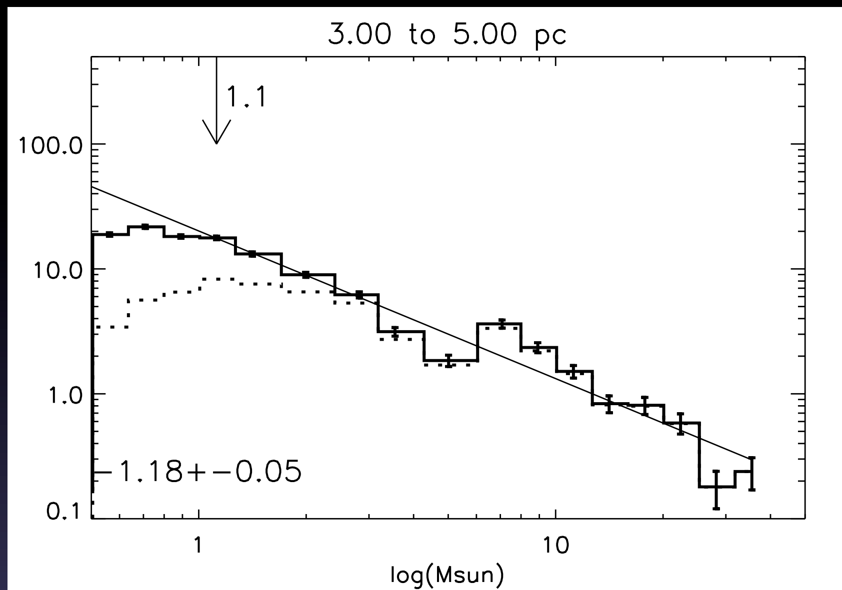
# IMFs in MW Regions



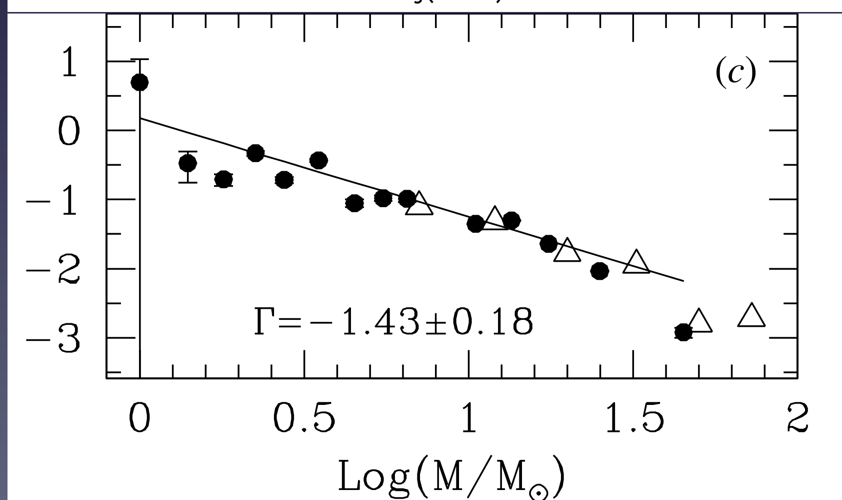

Bastian+ 2010

# IMFs in Magellanic Clouds

dn / d ln m + const

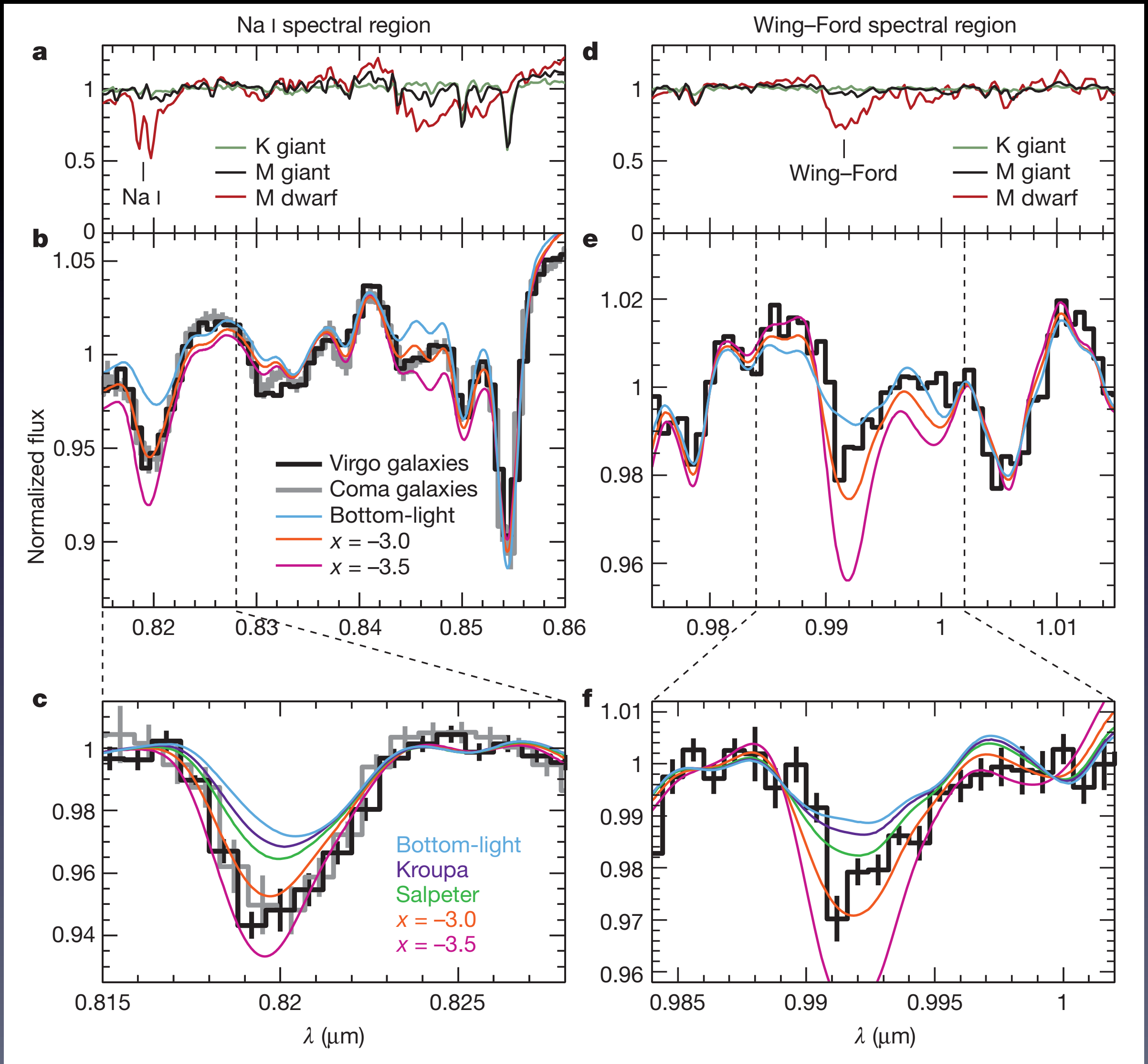



IMF in the 30 Doradus region, a starburst cluster in the LMC (Andersen+ 2009)




IMF in NGC 346 in the SMC, at 1/5 Solar metallicity (Sabbi+ 2008)

# Variation (?) in Giant Ellipticals




Spectra of nearby ellipticals in the vicinity of dwarf-sensitive features

van Dokkum & Conroy (2010)

# Properties of the IMF

- MW IMF shows a peak at 0.1 – 1 $M_{\odot}$, plus a powerlaw w/slope ~ −2.3 at higher masses
- LMC / SMC data indicate no variation with density, metallicity, dwarf vs. spiral
- Evidence for a bottom-heavy IMF in giant ellipticals, but only from integrated light – suggestive, but not absolutely certain

# The Peak: the Usual Story

- Gas clouds fragment due to Jeans instability

$$M_J \approx \sqrt{\frac{c_s^3}{G^3 \rho}}$$

$$\approx 0.4 M_\odot \left(\frac{T}{10\,\mathrm{K}}\right)^{3/2} \left(\frac{n}{10^5\,\mathrm{cm}^{-3}}\right)^{-1/2}$$

- Problem: GMCs have T ~ constant, but n varies a lot

# Isothermal Gas is Scale Free

$$\mathcal{M} = \frac{\sigma}{c_s} \propto \sigma$$

$$\beta = \frac{8\pi\rho c_s^2}{B^2} \propto \rho B^{-2}$$

$$n_J = \frac{\rho L^3}{c_s^3/\sqrt{G^3\rho}} \propto \rho^{3/2} L^3$$

$$\mathcal{M}_A = \mathcal{M}\sqrt{\frac{\beta}{2}}$$

$$\mu_\Phi = \frac{M}{M_\Phi} = \sqrt{\frac{\pi\beta}{2}}\, n_J^{1/3}$$

$$n_{J,\mathrm{turb}} = \frac{n_J}{\mathcal{M}^3}$$

$$\alpha_{\mathrm{vir}} = \frac{5\sigma^2 L}{2GM} = \frac{5}{6\pi}\left(\frac{\mathcal{M}}{n_J}\right)^2$$

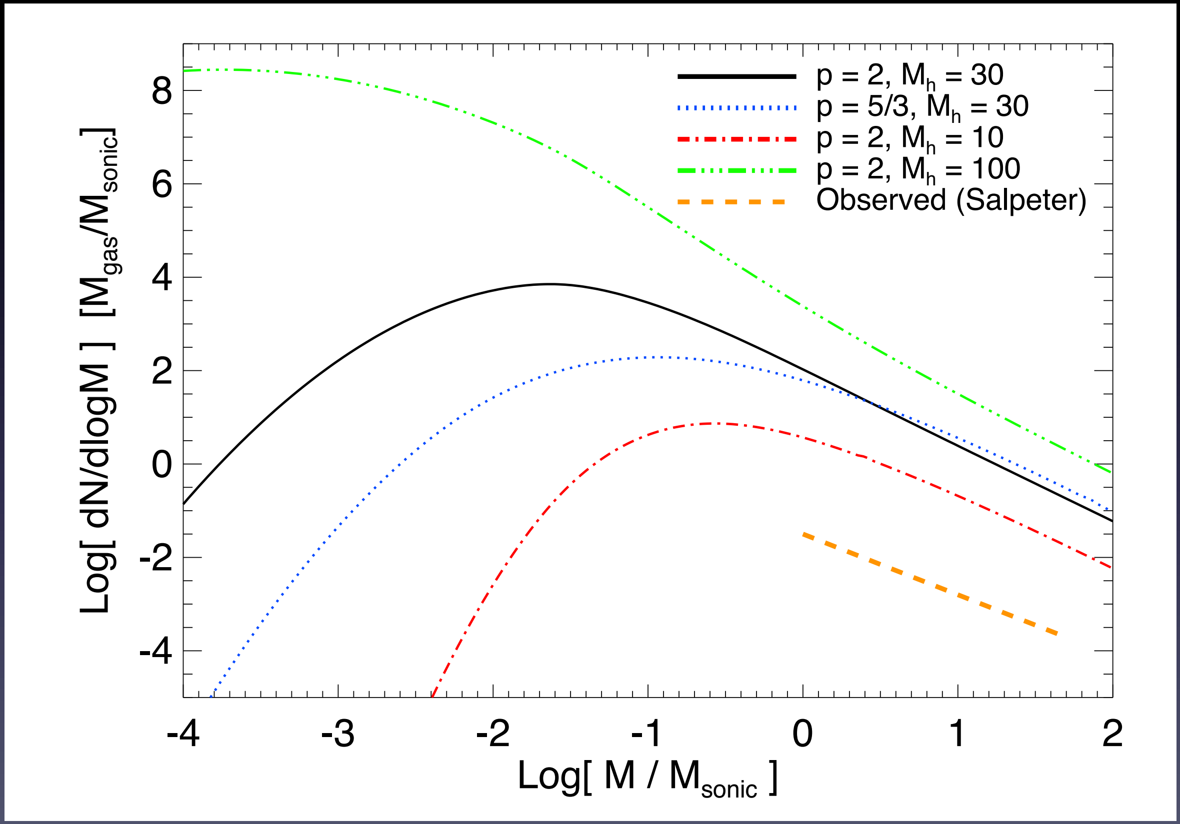
All dimensionless numbers invariant under $\rho \rightarrow x\rho$, $L \rightarrow x^{-1/2}L$, $B \rightarrow x^{1/2}B$, but $M \rightarrow x^{-1/2}M$

Non-isothermality **required** to explain IMF peak!

# Option 1: Galactic Properties

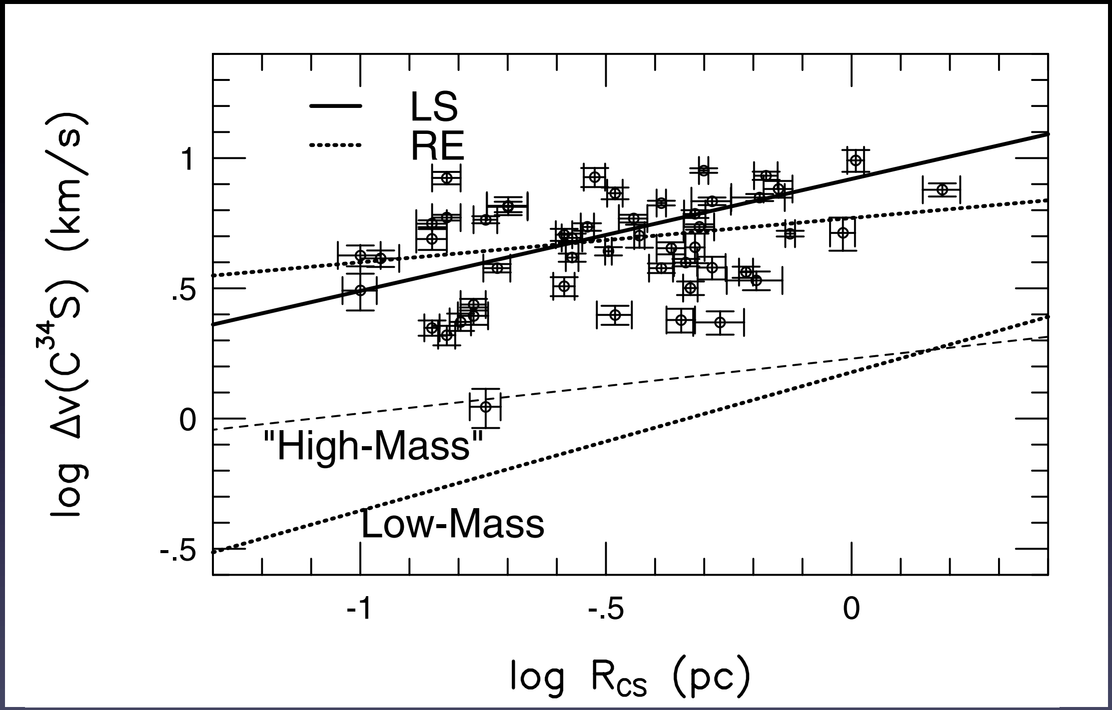
- GMCs embedded in a galaxy-scale non-isothermal medium
- Set IMF peak from Jeans mass at mean density (e.g. Padoan & Nordlund 2002, Narayanan & Dave 2012a,b)
- … or from linewidth-size relation
  $\sigma = c_s\ (\ell\ /\ \ell_s)^{1/2}$ (e.g. Hennebelle & Chabrier 2008, 2009; Hopkins 2012)

# Example: the Sonic Mass




IMF derived from excursion set model (Hopkins 2012); the IMF peak is proportional to the sonic mass, $M_{sonic} \approx c_s^2 \ell_s / G$

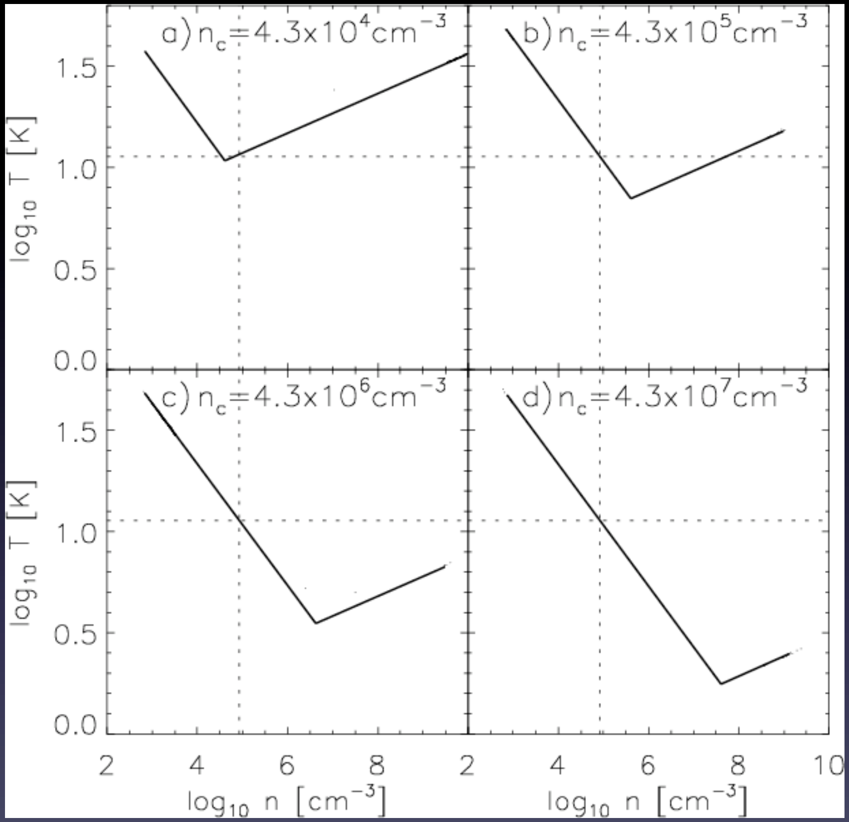
# Problem: LWS Non-Universal

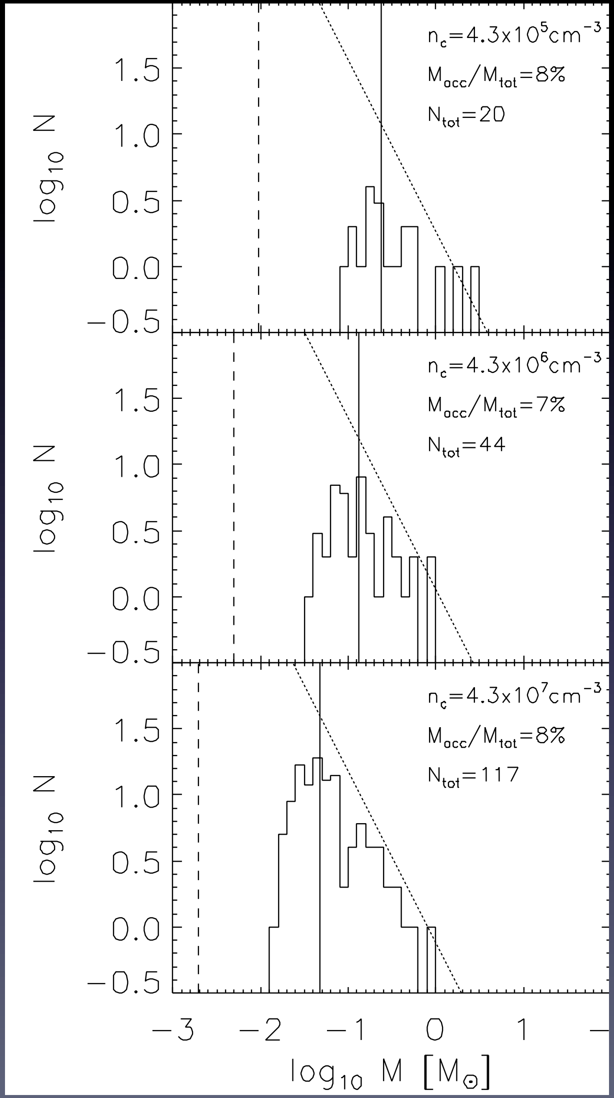



Linewidth-size relation low and high mass star-forming regions (Shirley+ 2003)

…so why is doesn't the IMF vary wildly from region to region in the MW and the Magellanic Clouds?

# Option 2: Local Non-Isothermality

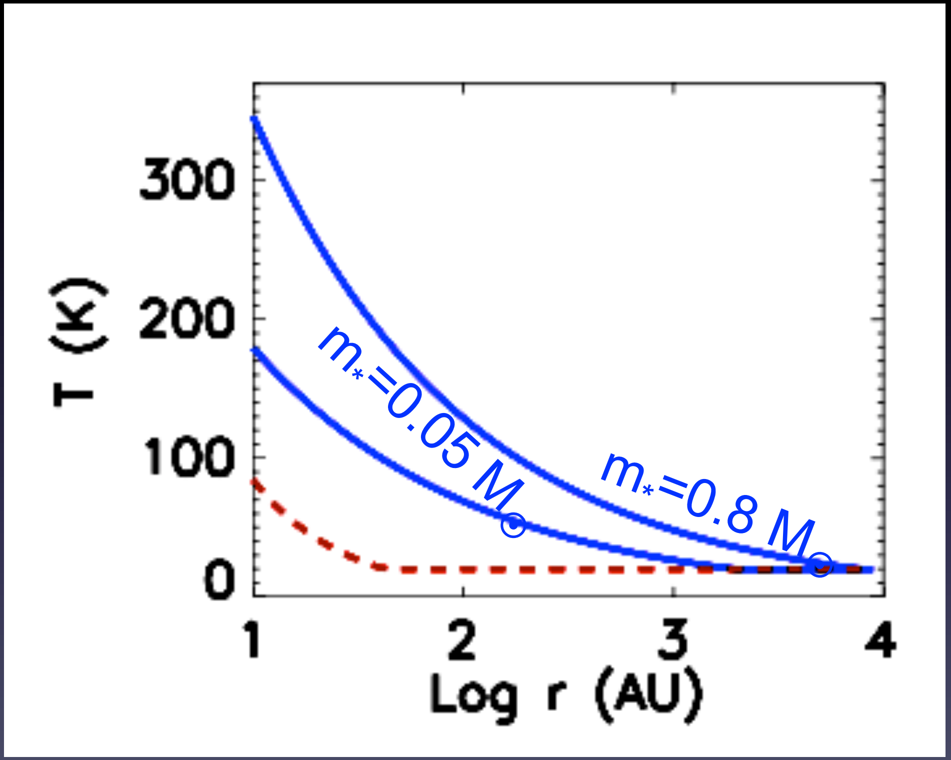



Above: EOS's used in simulations by Jappsen+ (2005); also see Larson (2005)
Left: fragment mass distributions for different EOS's

# What Breaks Isothermality?

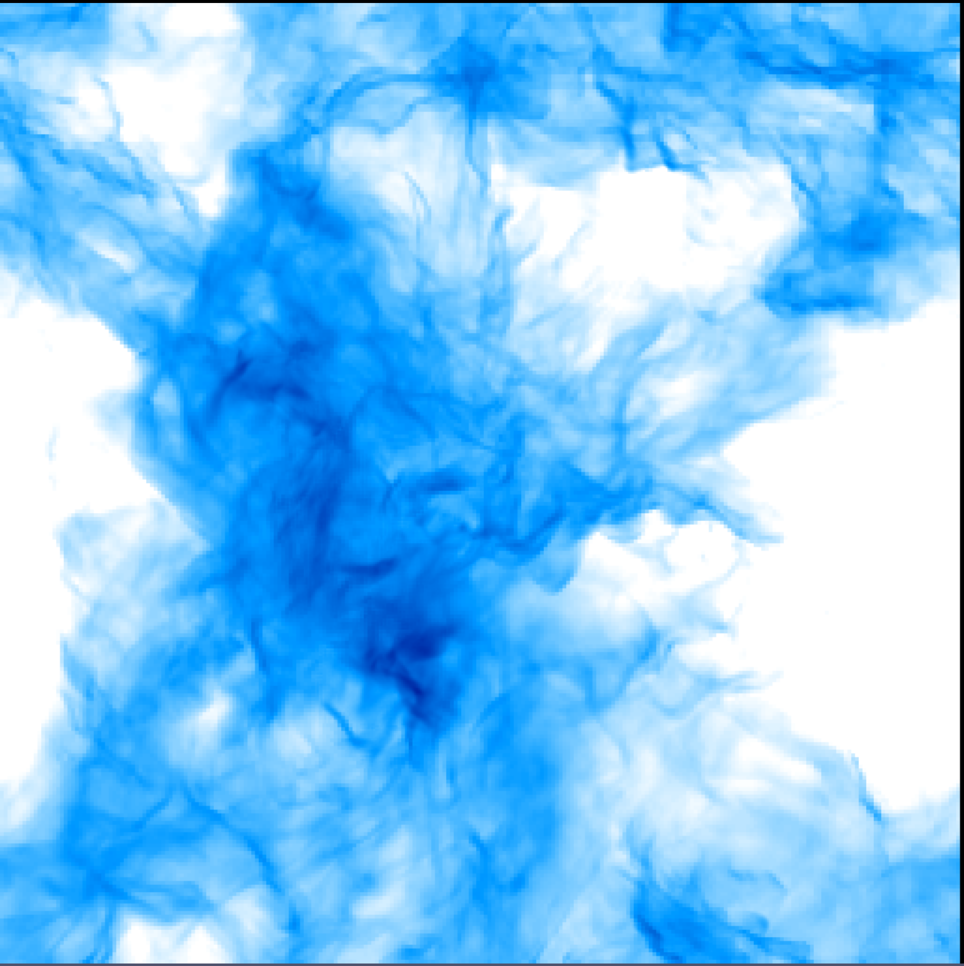
- Dust-gas coupling strong for $n \gtrsim 10^4\ \mathrm{cm}^{-3}$
- Accreting stars very bright ($L \sim 100\ L_\odot$ for $M = M_\odot$) ➔ easy to heat dust




Temperature vs. radius before (red) and after (blue) star formation begins in a 50 $M_\odot$, 1 g $\mathrm{cm}^{-2}$ core (Krumholz 2006)

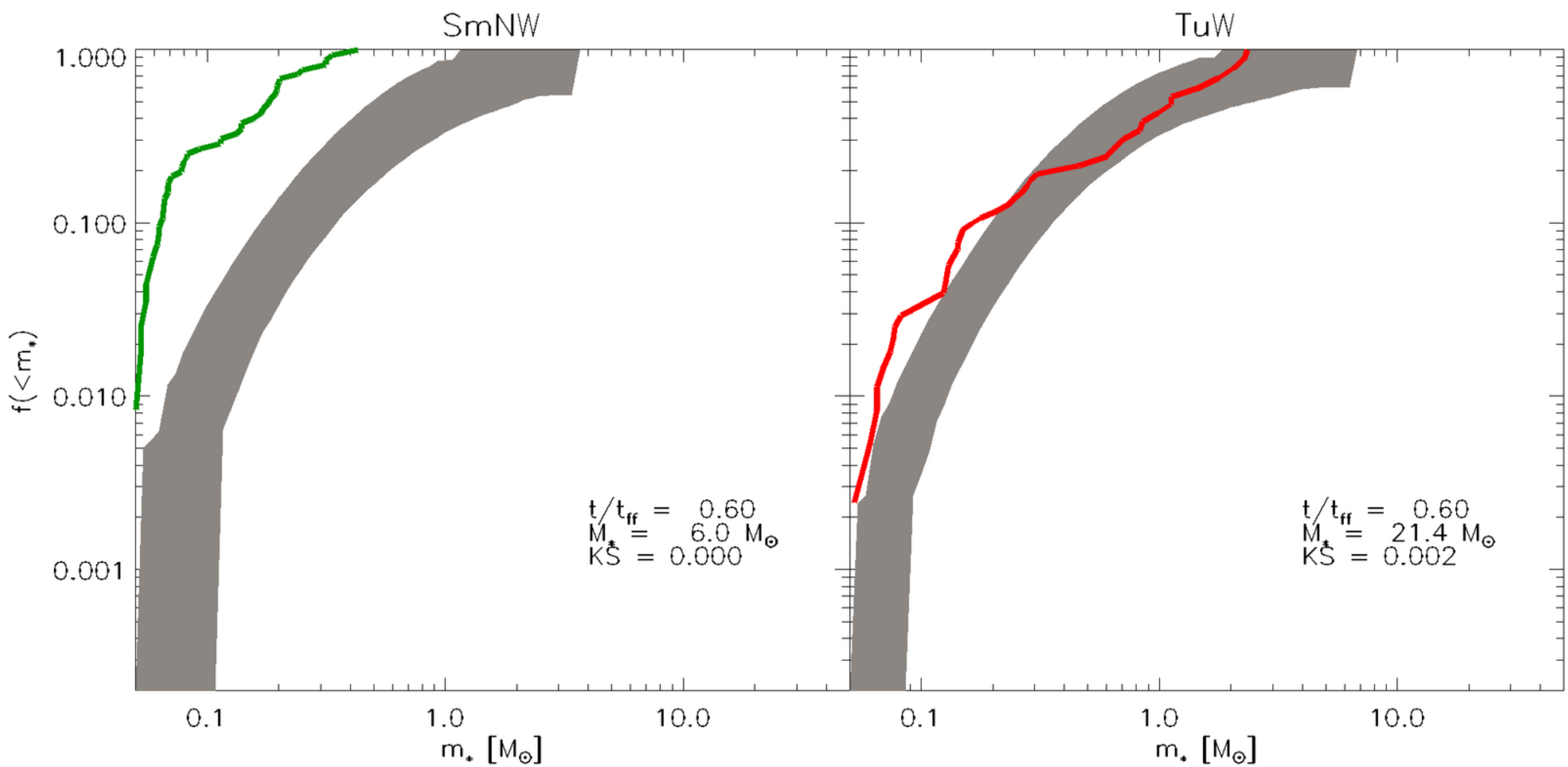
# Radiation-Hydro Simulation

(Krumholz+ 2012; also see Bate 2012)

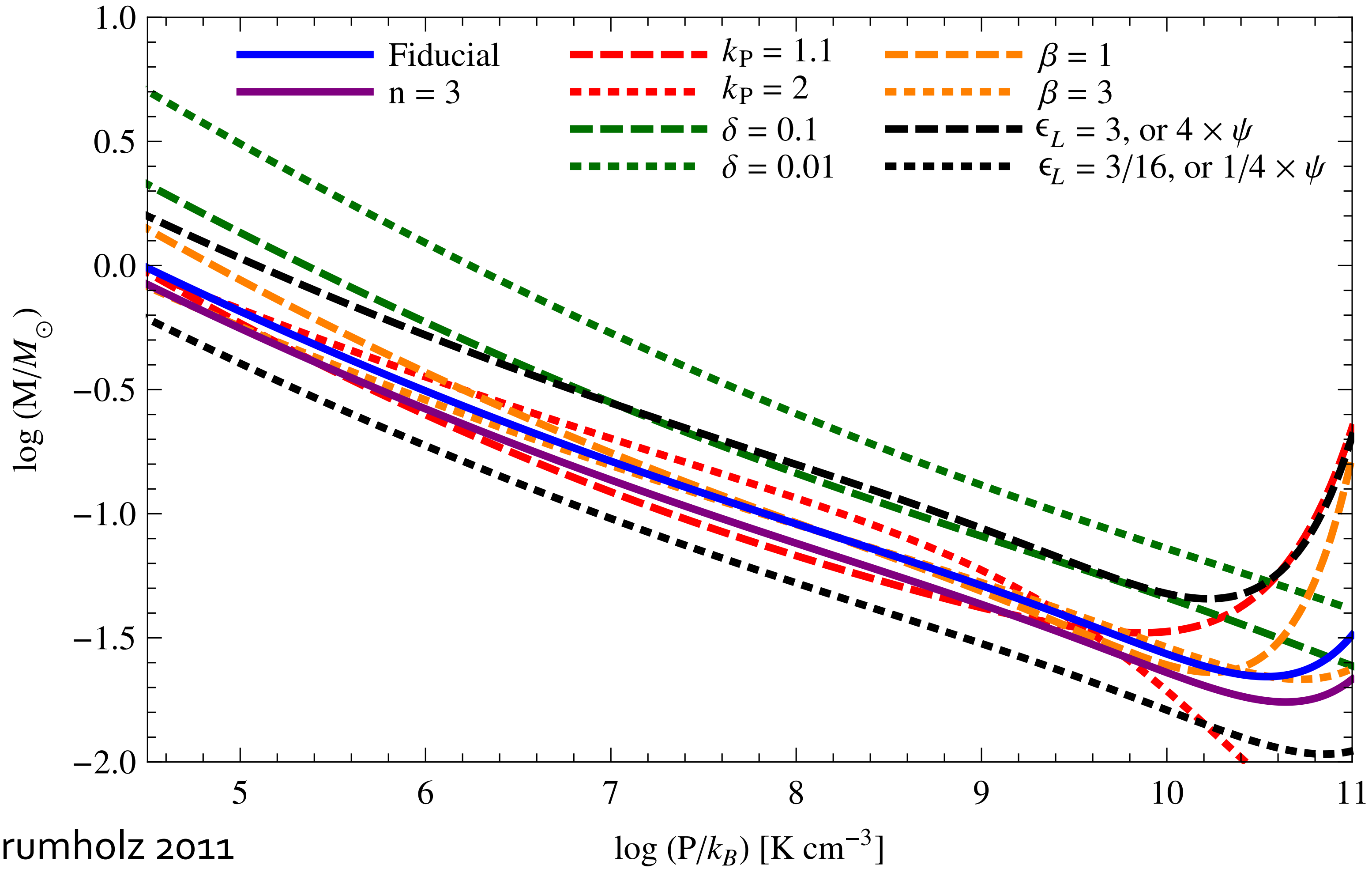


Left: projected density; right: projected temperature; simulation also includes protostellar outflows

# IMF from RHD Fragmentation



# What Does Peak Depend On?

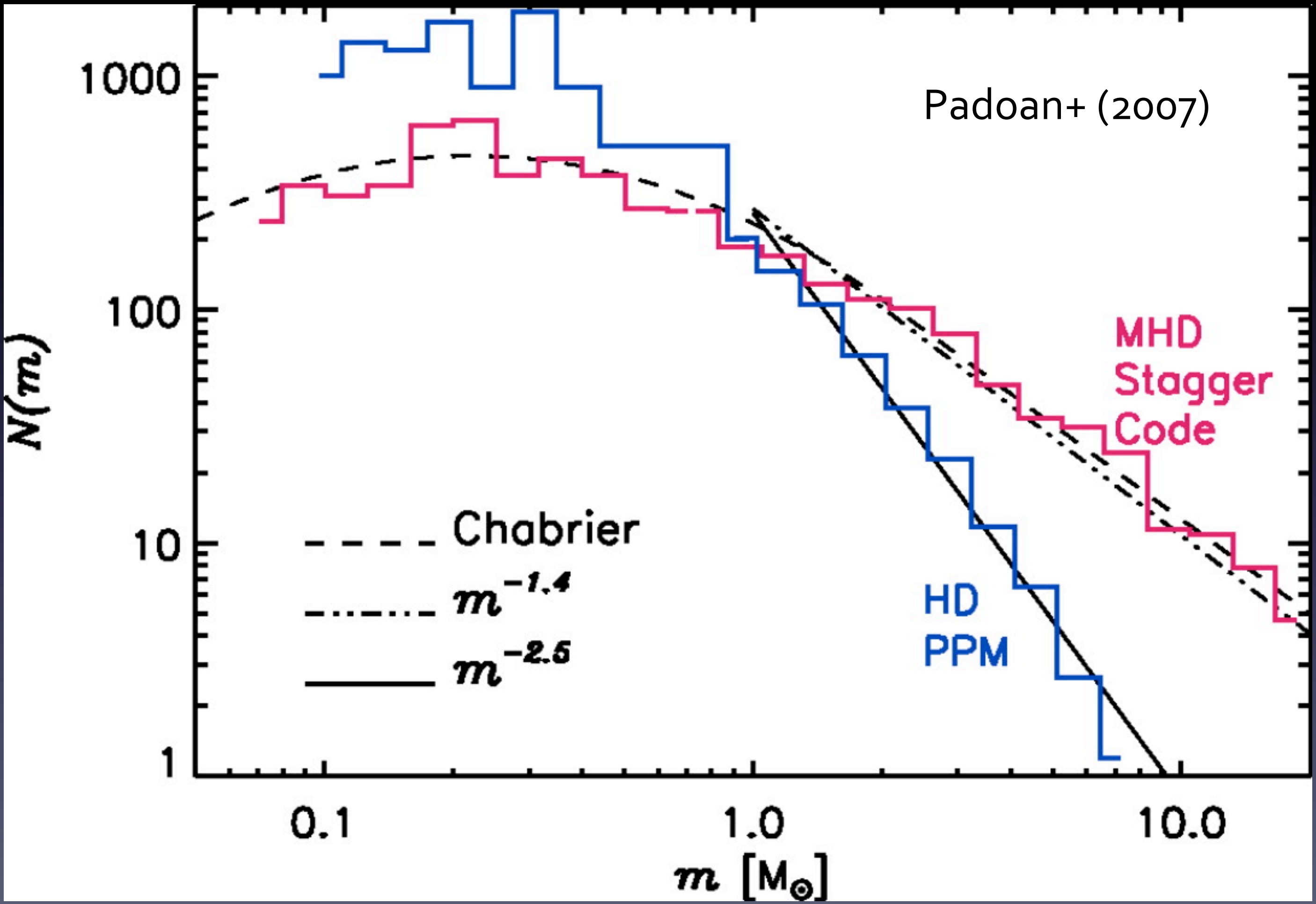



Krumholz 2011

# The Tail: Turbulence

- At masses above the peak, IMF is a powerlaw of fixed slope
- A powerlaw is scale-free, so isothermal approach is probably ok
- Universality of slope suggests a universal origin, likely in the physics of turbulence

# Numerical Results



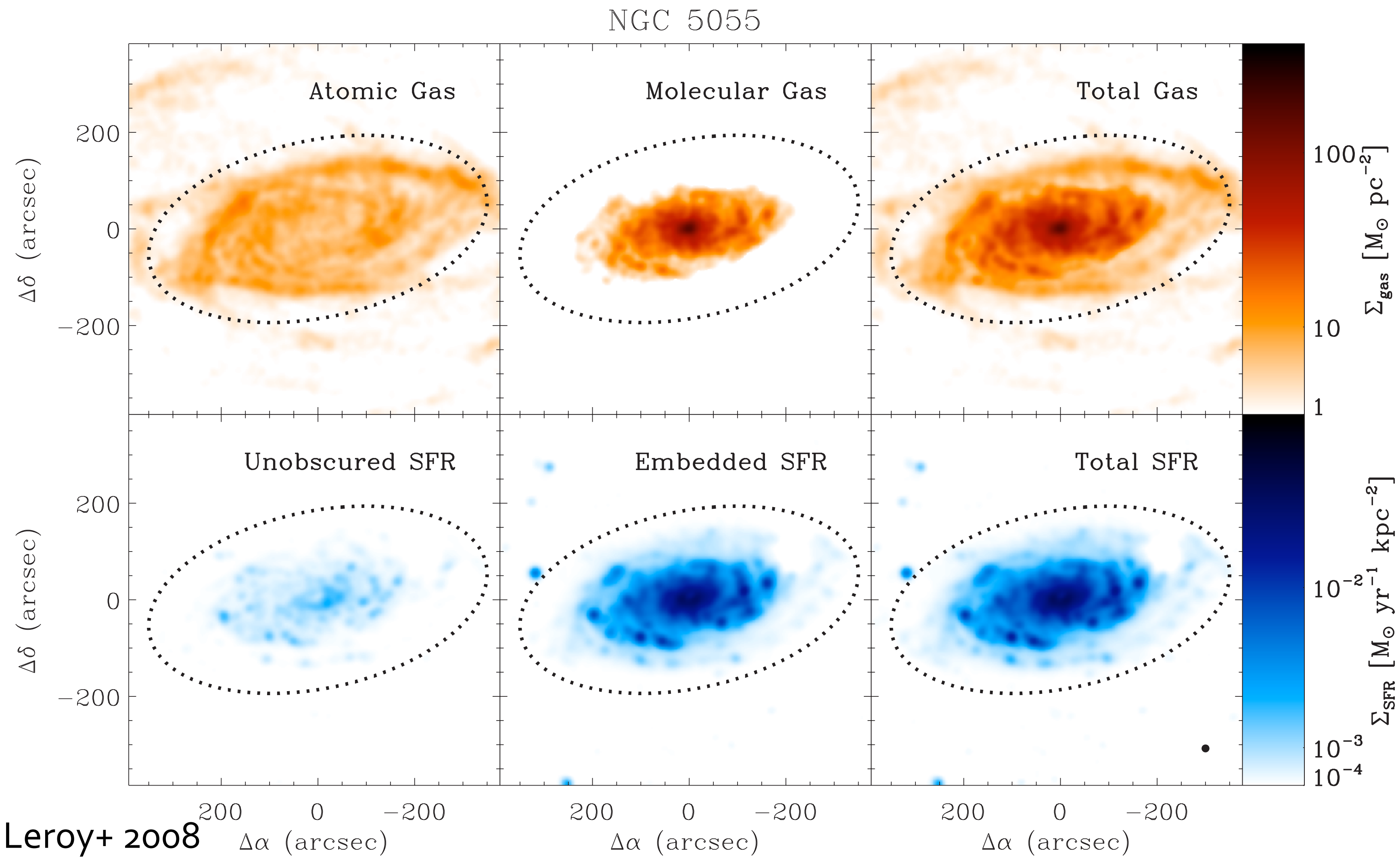
# Analytic Results

- Analytic derivations: twiddle arguments (Padoan & Nordlund 2002, 2007), PS-like model (Hennebelle & Chabrier 2008a,b), excursion set model (Hopkins 2012)
- Basic idea: turbulent power spectrum P(k) ➔ scale-dependent density variance σ(M) ➔ mass spectrum of bound objects
- $P(k) \sim k^{-(1.7-2)}$ ➔ $dN/dM \sim M^{-2.3}$
- Caveat: all models assume ρ, v uncorrelated, which is clearly not true

# The Star Formation Rate

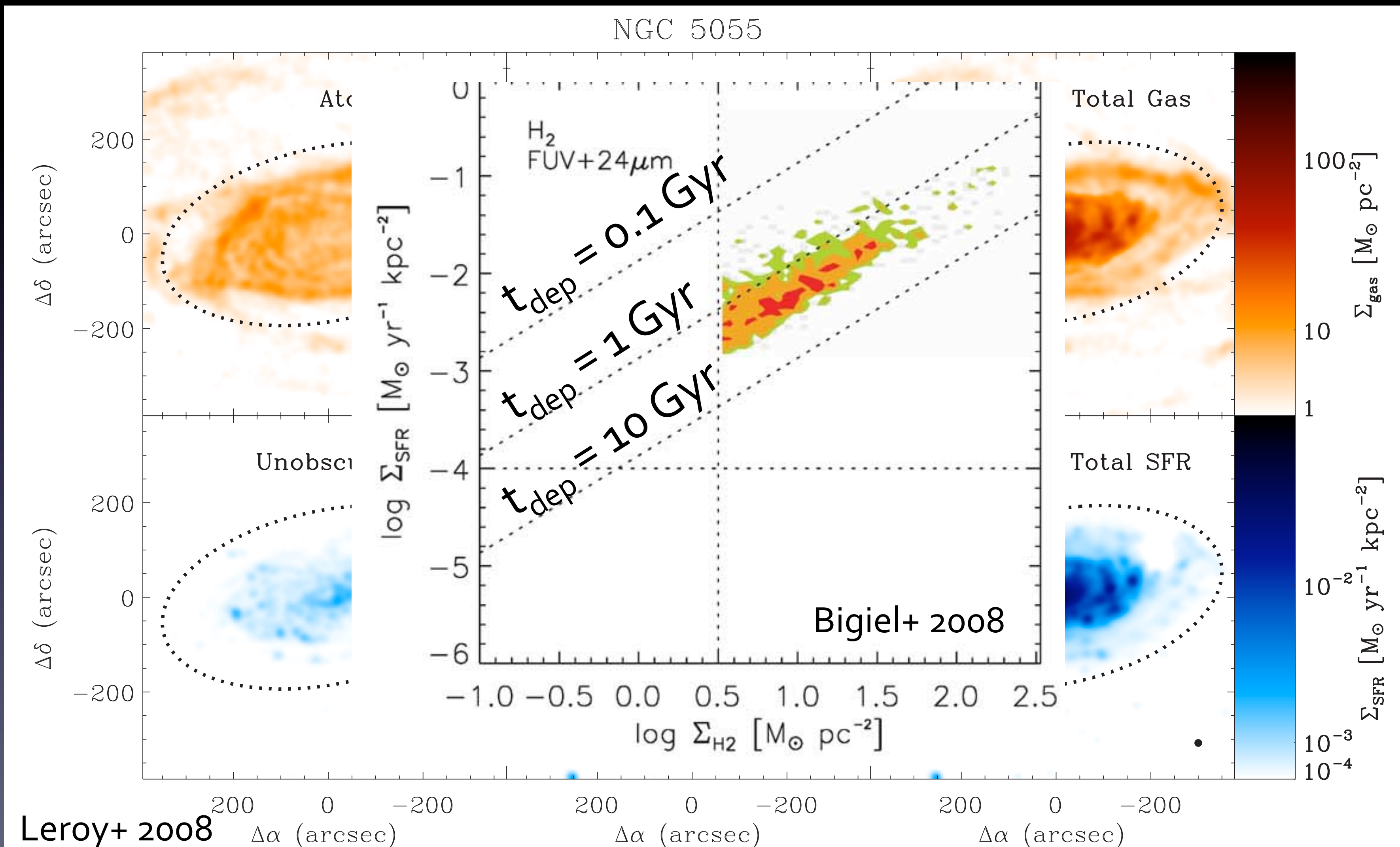
- As long as $t_{SF} << t_H$, SFR (mostly) set by gas inflows / outflows
- However, $t_{SF} >\sim t_H$ for most galaxies in the early universe, and in sub-$L_*$ galaxies today
- Even when, , $t_{SF} << t_H$ SFR determines gas content of galaxies, important for galactic structure

# SF Laws on Galactic Scales

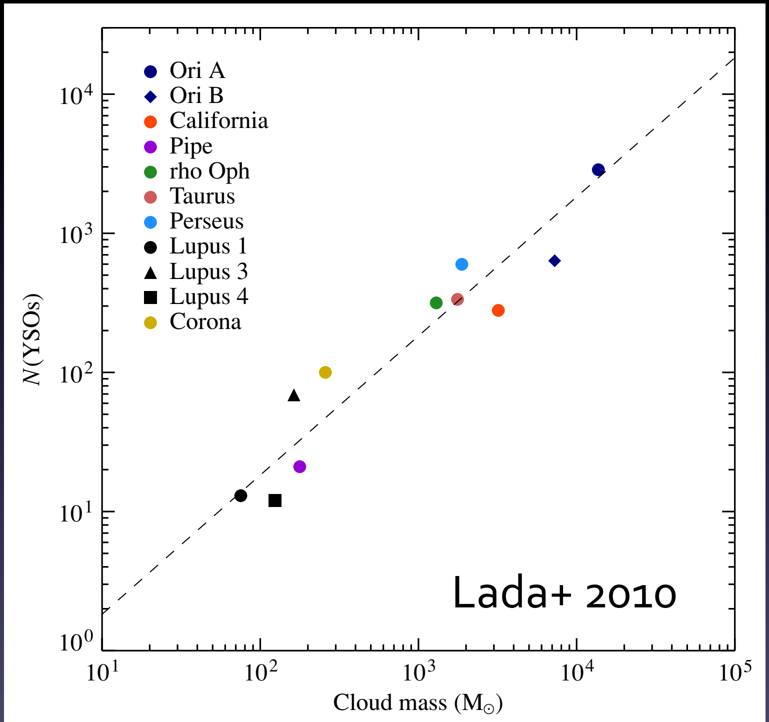


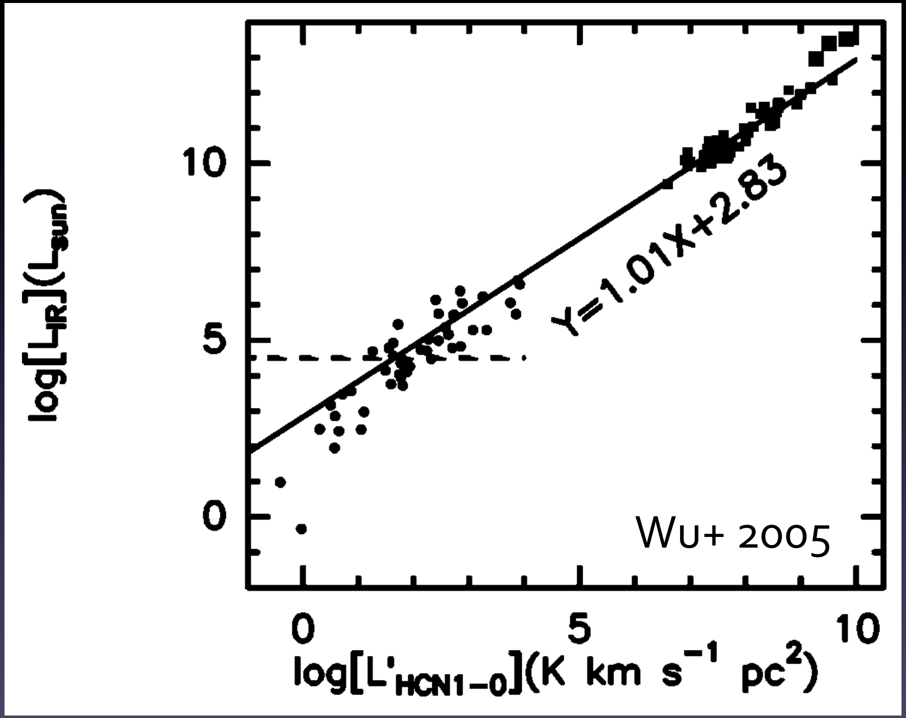

Leroy+ 2008

# SF Laws on Galactic Scales

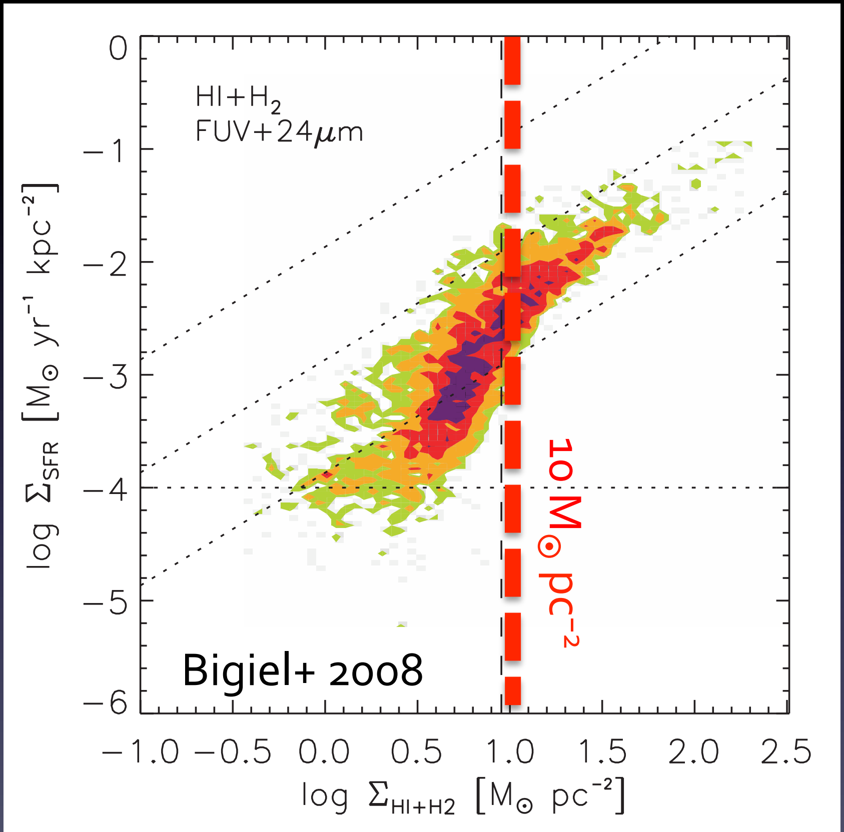


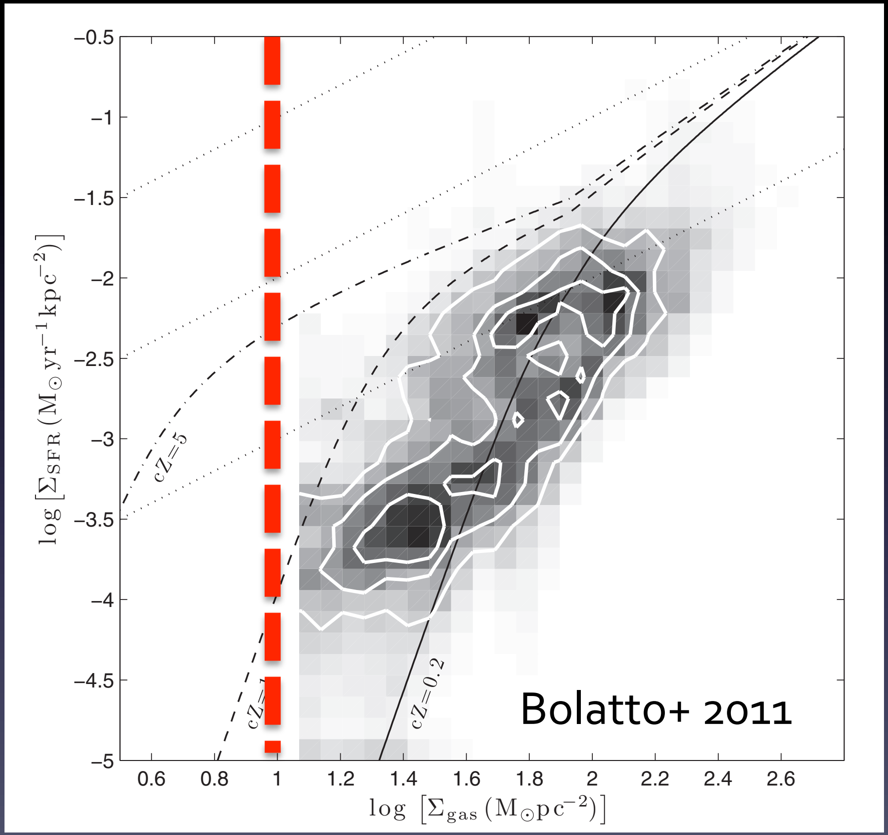
# SF Laws on Sub-Galactic Scales



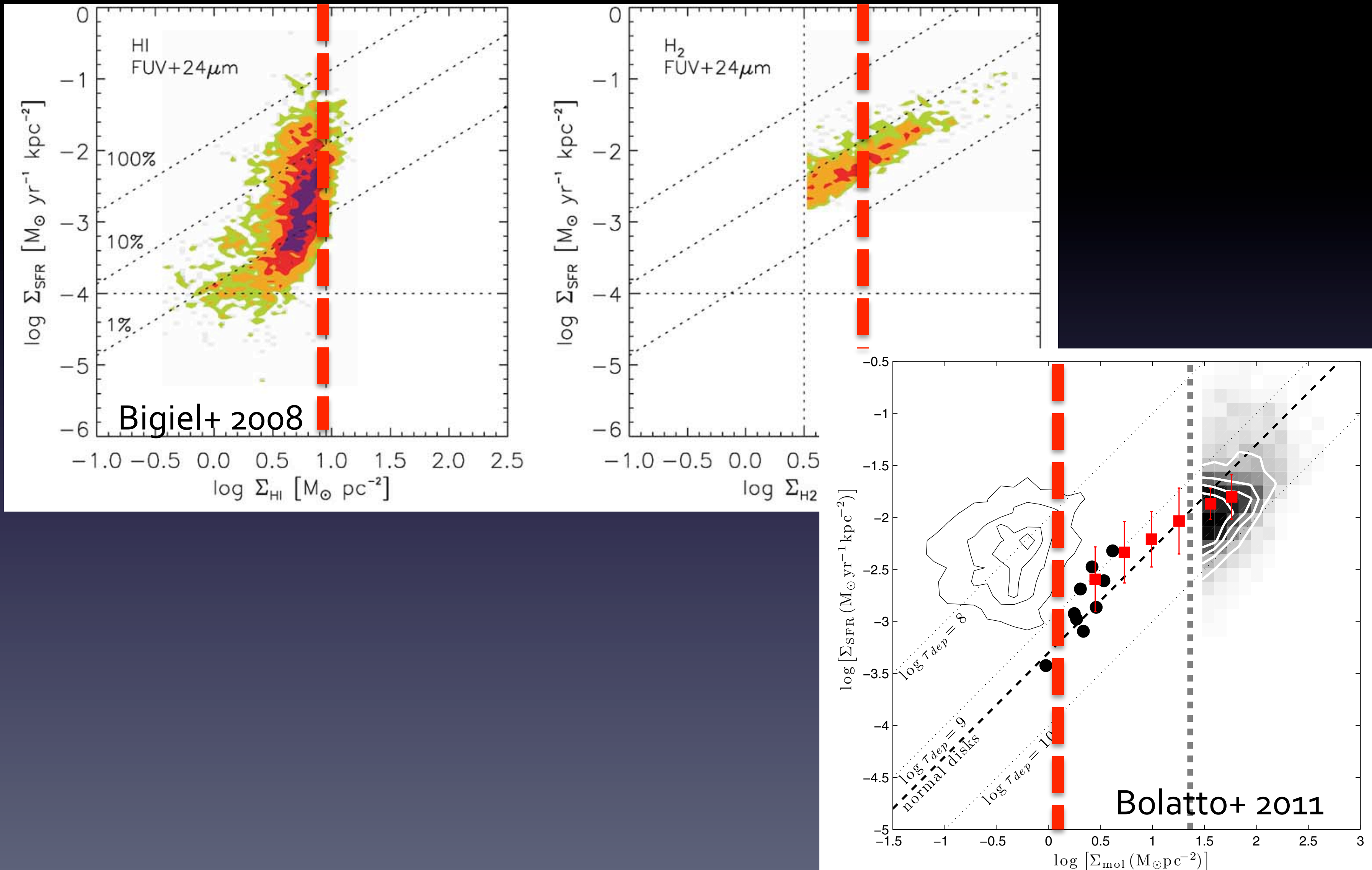



# Metallicity-Dependence



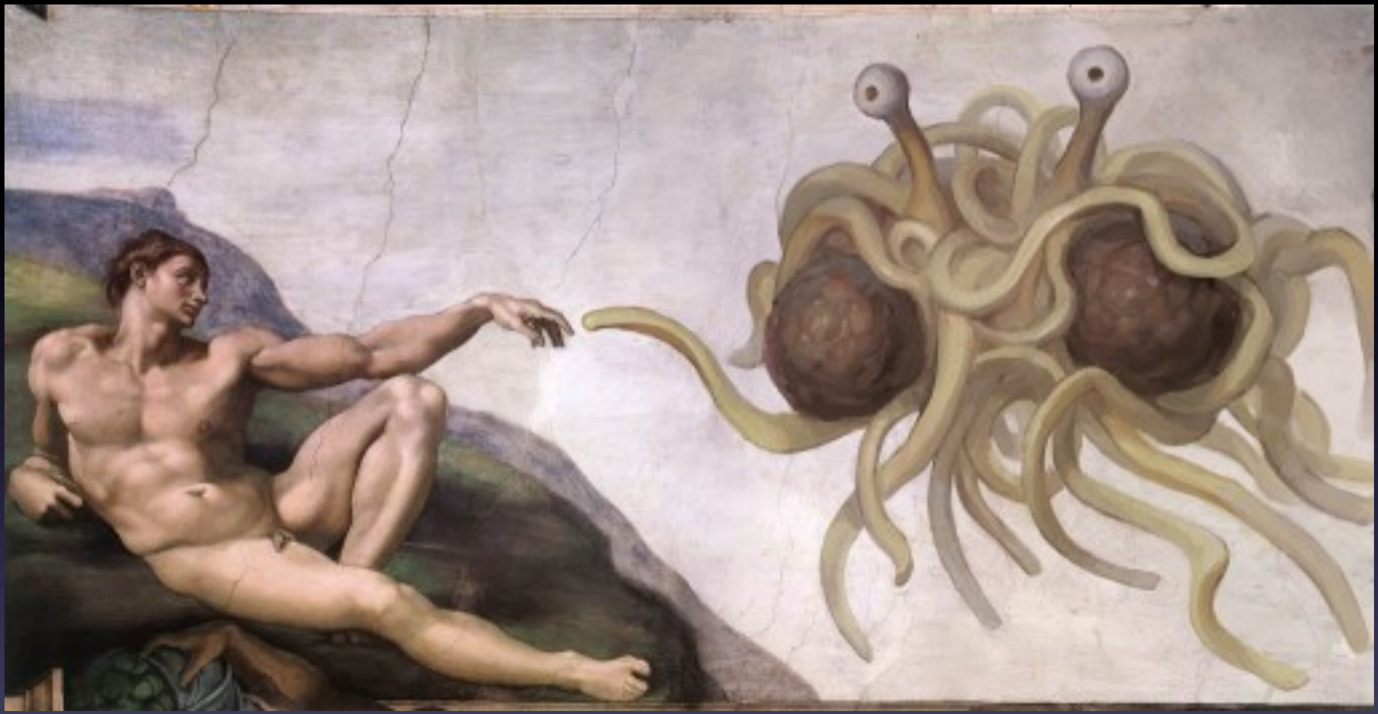
# Phase-Dependence



# The Theoretical Challenge

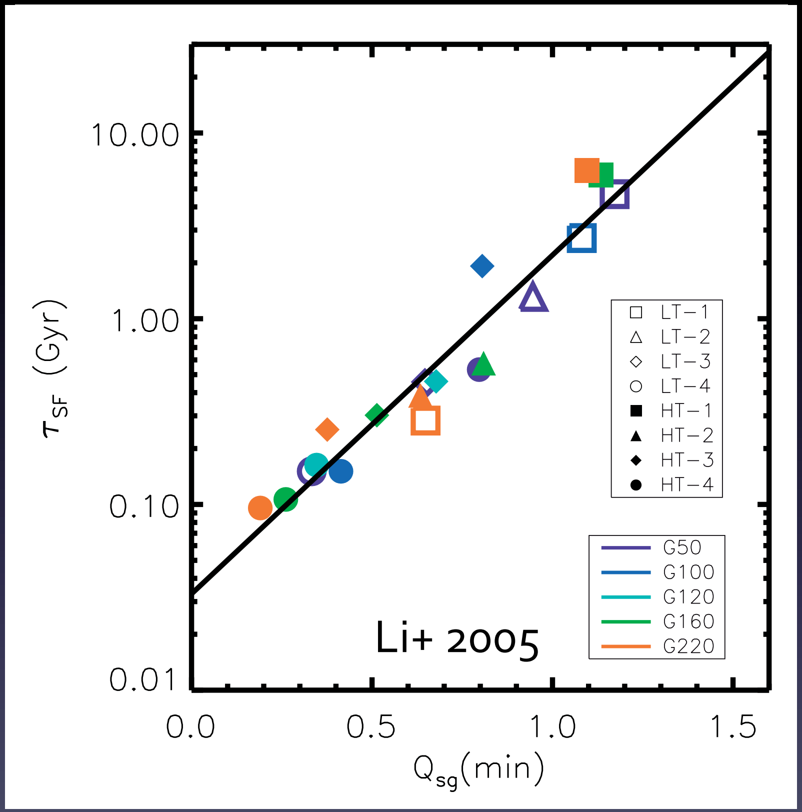
- Which laws are the fundamental ones, the local or the galactic-scale? Both? Neither?
- Can we unify the different sets of laws (at different scales, for different phases, for different lines) within a single theoretical framework?

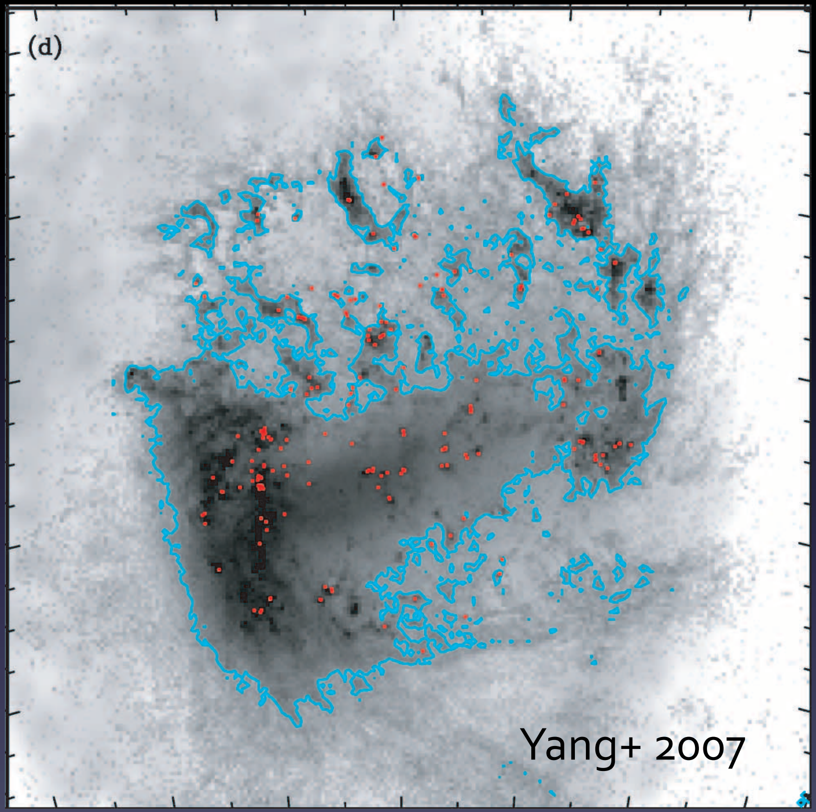
# SF Laws: the Top-Down Approach



The idea in a nutshell: the SFR is set by *galactic-scale* regulation, independent of the local SF law. The local law is to be explained separately.

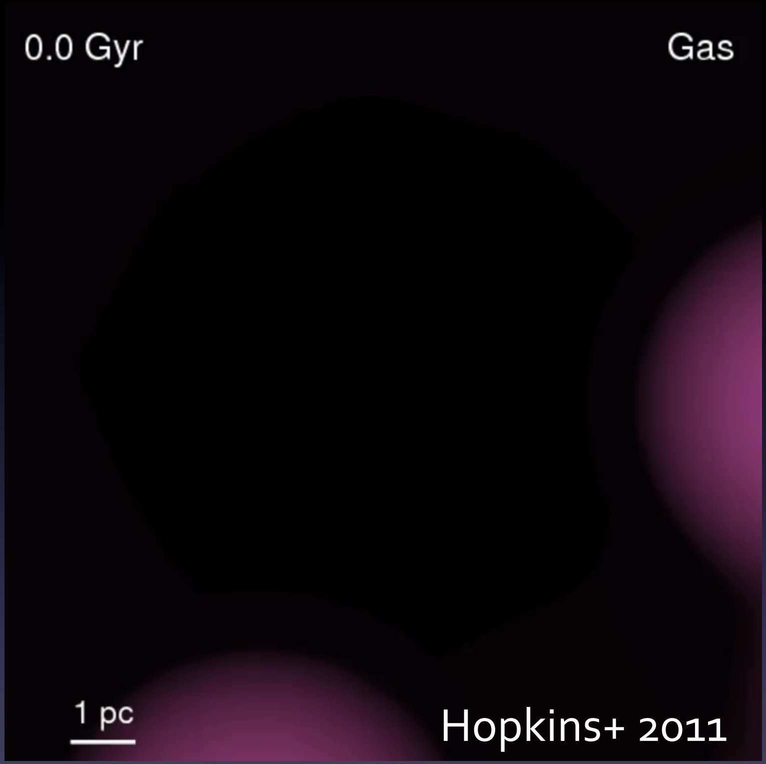
# Q-Based Models

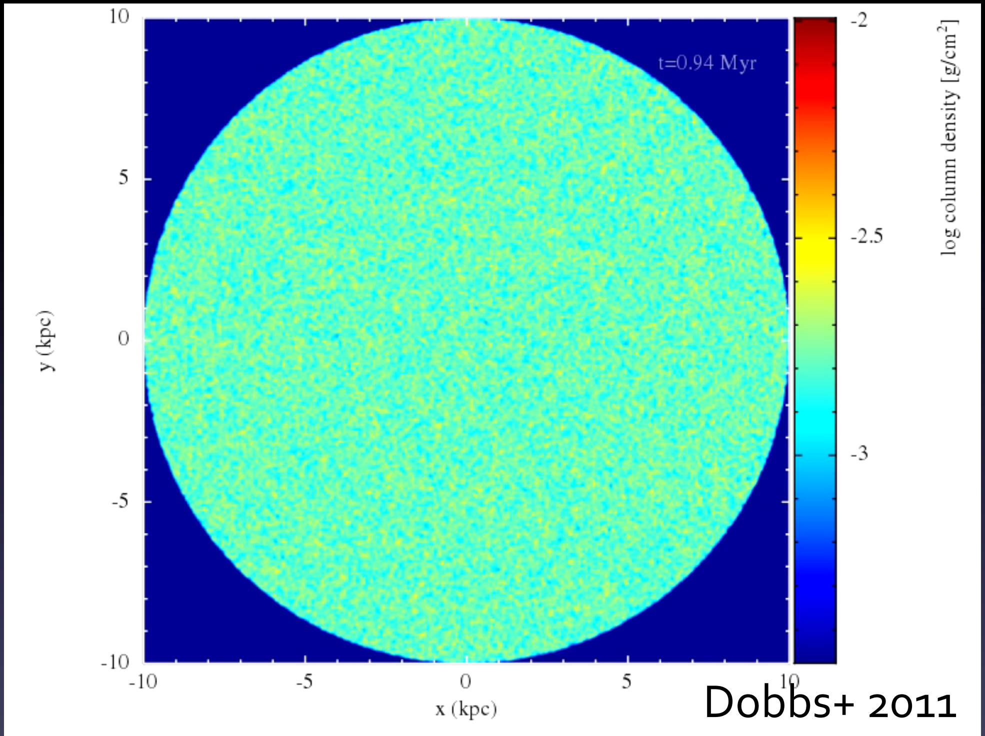



Basic idea: SFR is a function of Toomre Q in galaxy

# Feedback Models

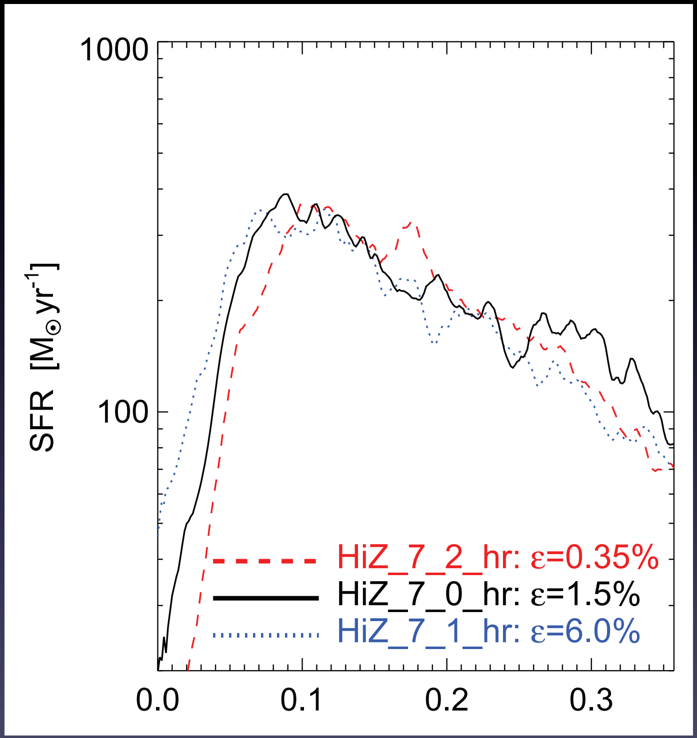


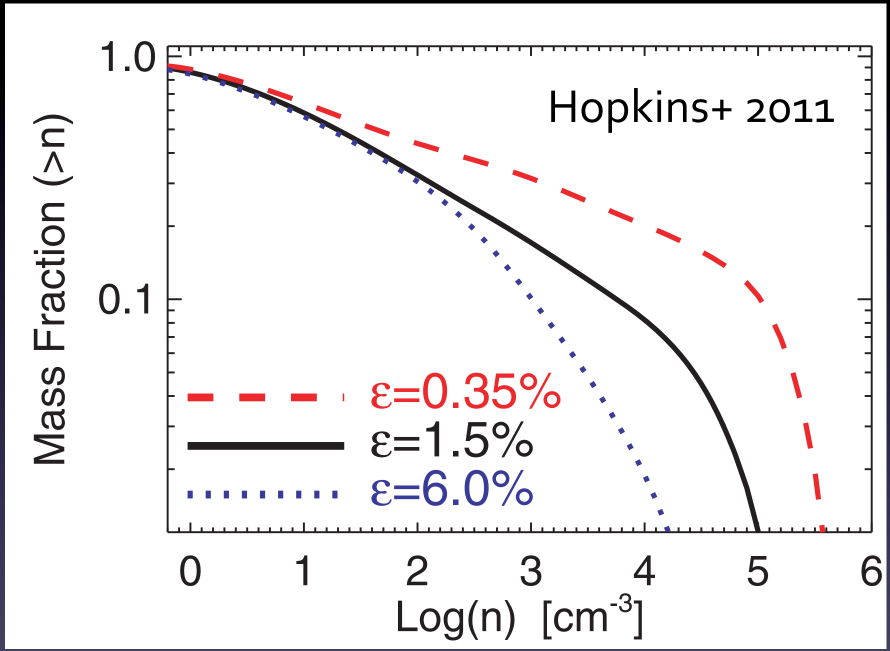




Also see Ostriker+ (2010), Tasker (2011)

Mechanisms that regulate SF rate: supernovae, radiation pressure, ionized gas pressure, FUV heating

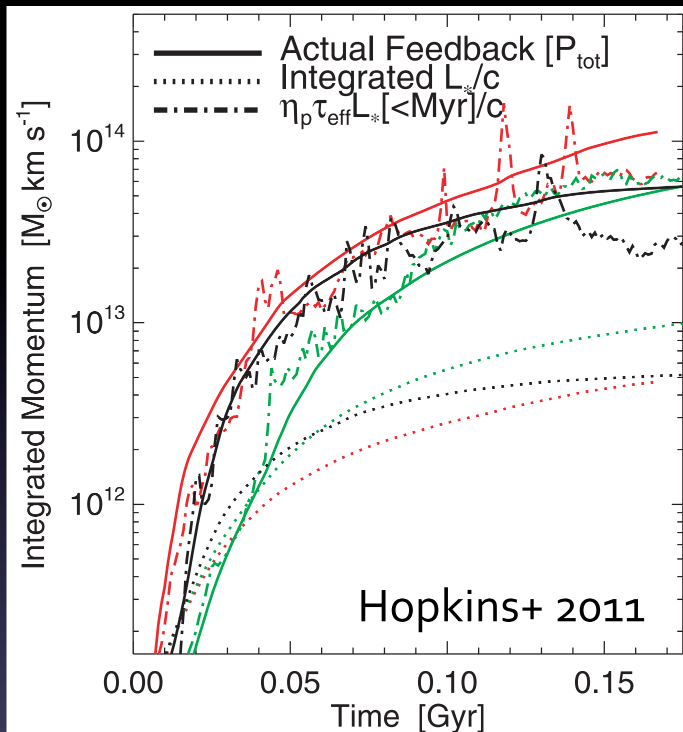
# Characteristics of Top-Down Models

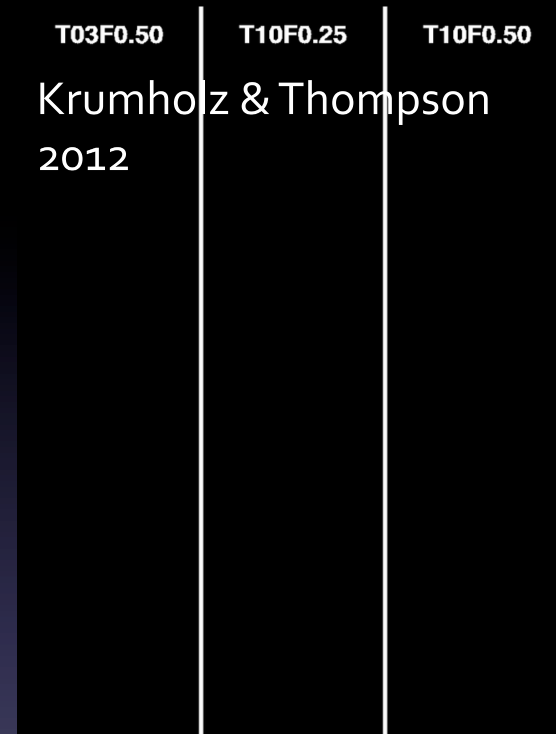



Changing the small-scale SF law does not change the SFR in the galaxy, but it does change the gas density distribution

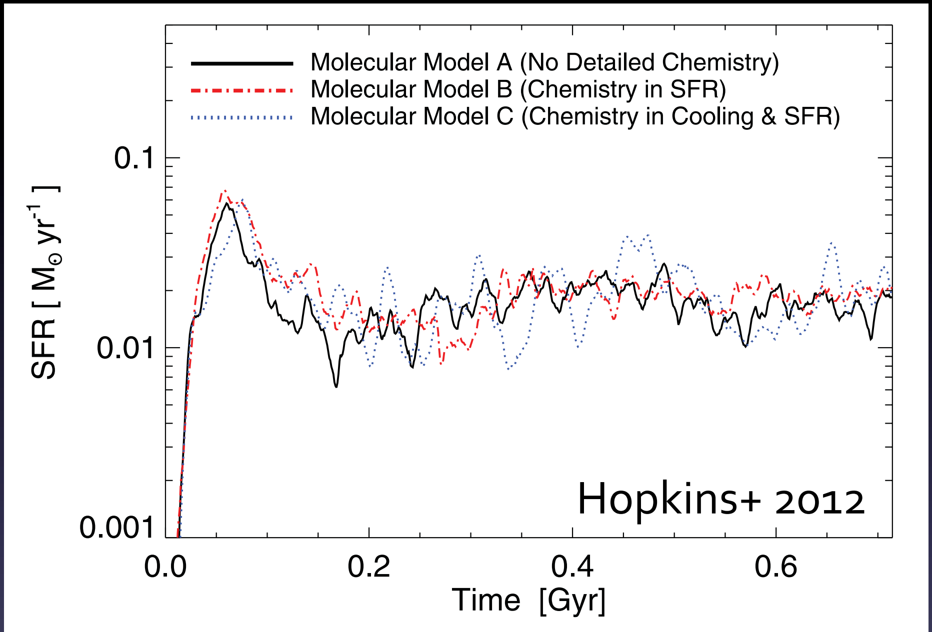
# Top-Down Model Limitations

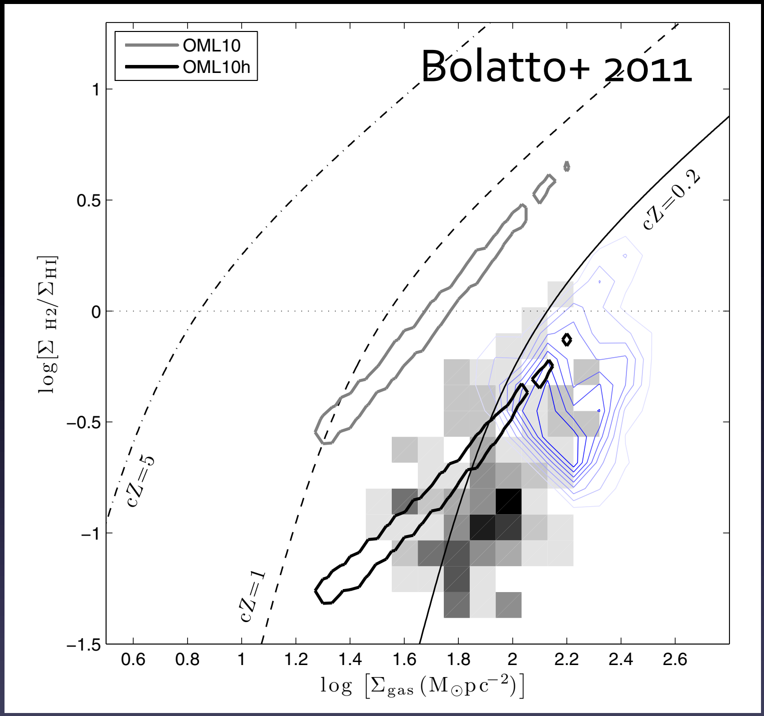



- Results depend strongly on subgrid feedback model (e.g. radiative trapping, SFE inside unresolved GMCs, UV heating per unit)
- No independent prediction for local SF laws

# Metallicity in Top-Down Models



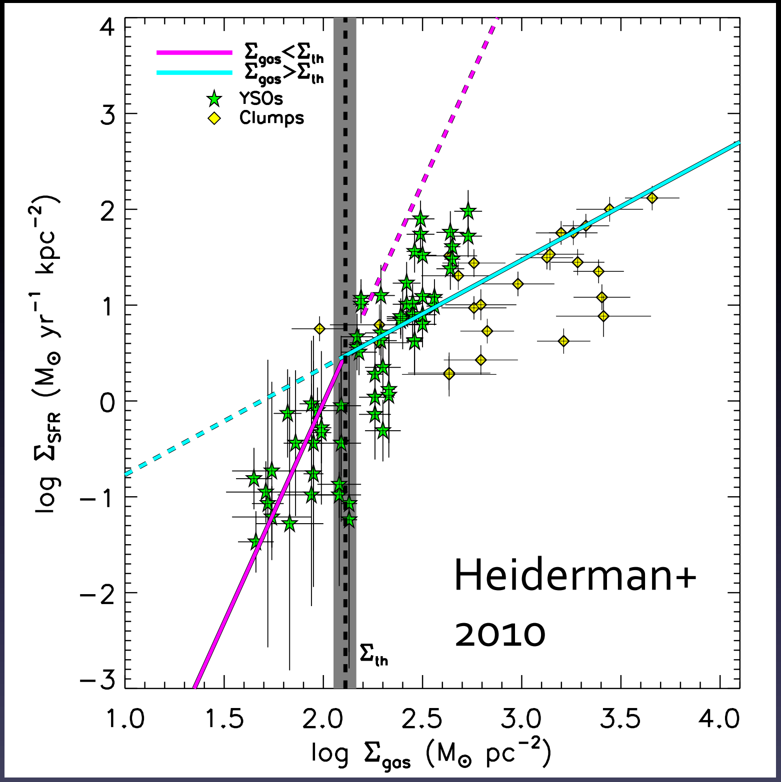



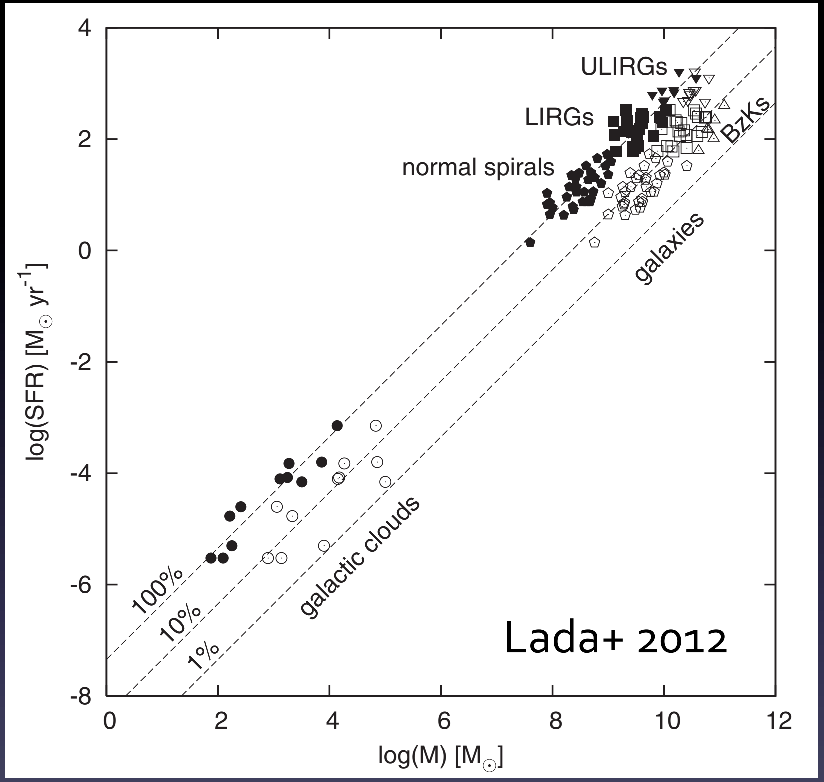

Top-down models most naturally predict SF laws that do not depend on metallicity or phase, strongly inconsistent with observations

# SF Laws: the Bottom-Up Approach

The idea in a nutshell: the SFR is set by a *local* SF law, plus a galactic-scale distribution of gas.

# The "Dense Gas" Model

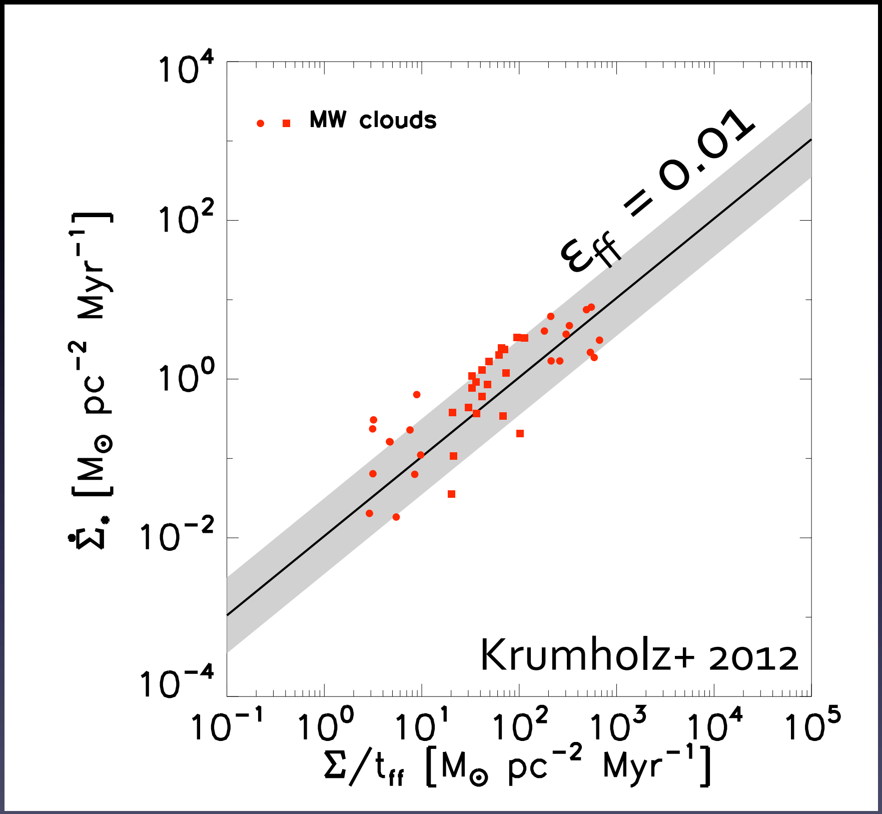


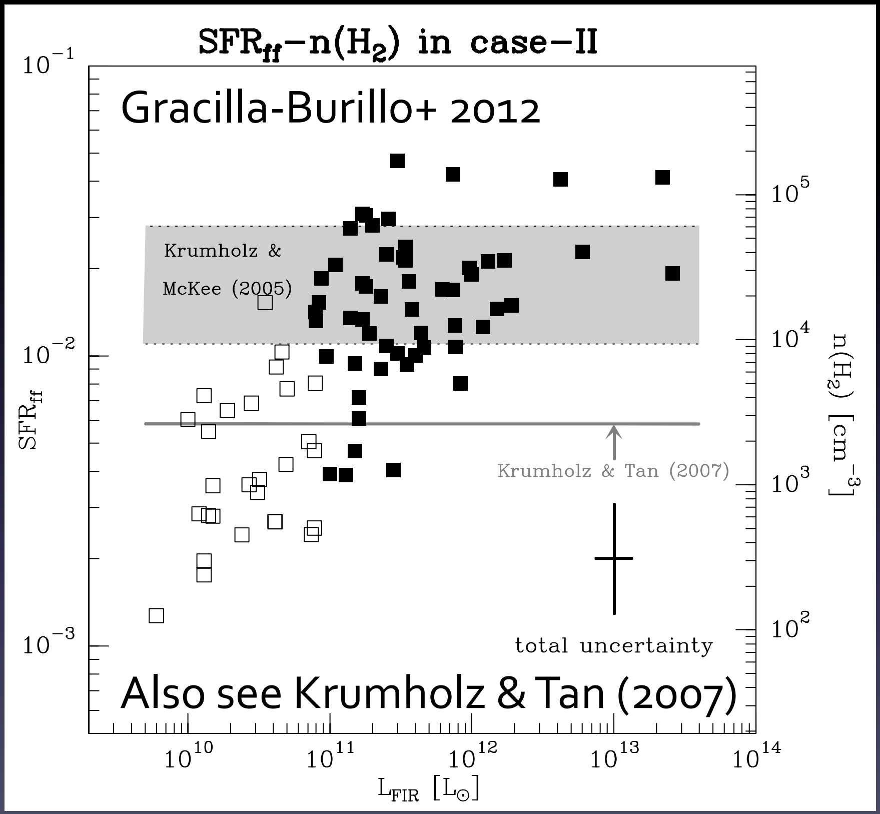




Basic idea: SFR = $M(>\rho_{dense}) / t_{dense}$, with $\rho_{dense}$, $t_{dense}$ = const

Problems: no physical basis for values of $\rho_{dense}$, $t_{dense}$; evidence for threshold mixed

# Observed Local SF Law



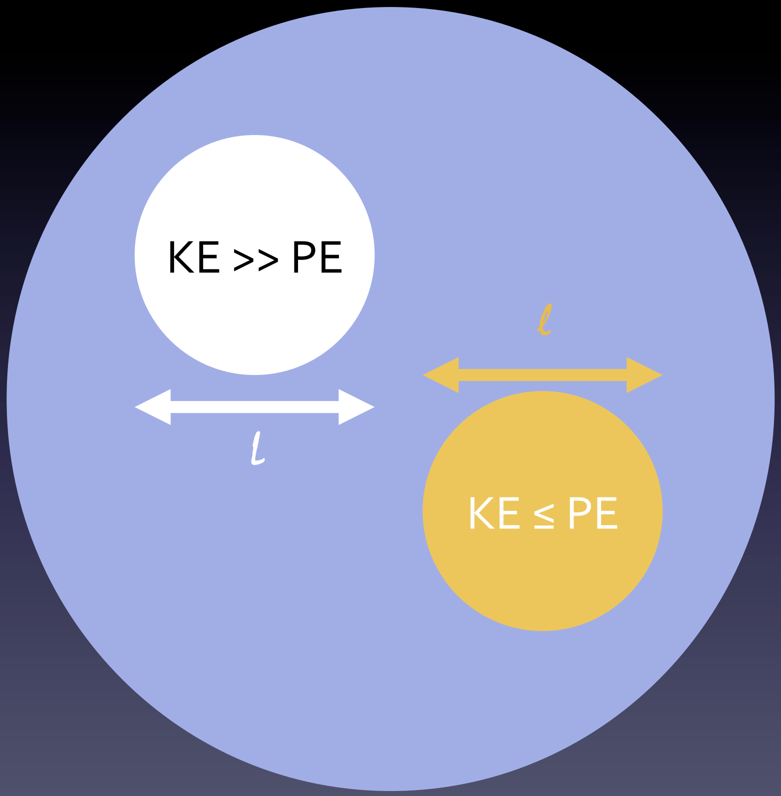




Local SF law: ~1% of gas mass goes into stars per free-fall time, independent of density or presence of massive stars

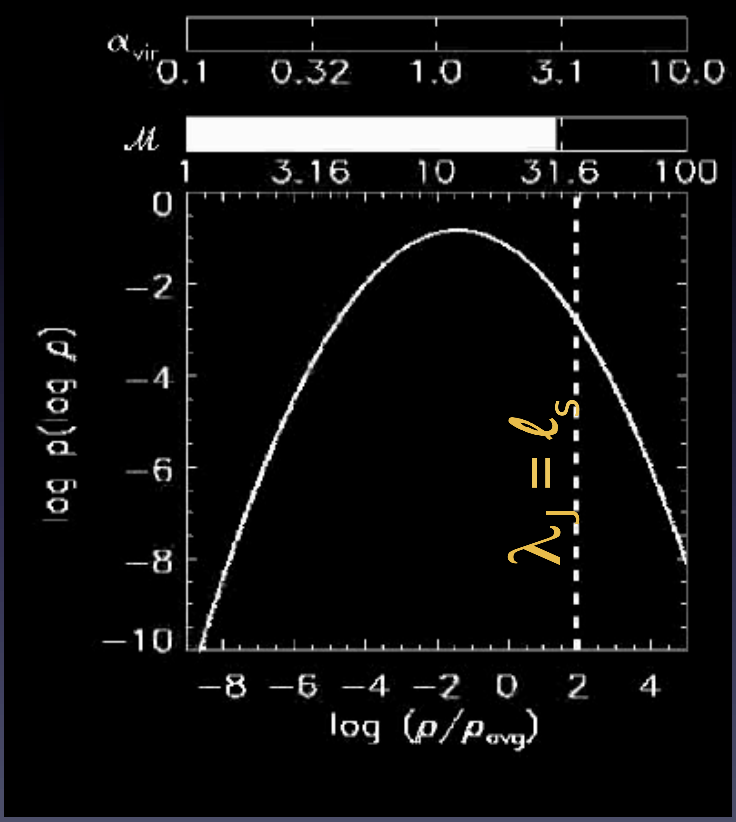
# Why is $\varepsilon_{ff}$ Low?

(Original model: Krumholz & McKee 2005;
updates by Padoan & Nordlund 2011, Hopkins 2012, Federrath & Klessen 2012)

- Properties of GMC turbulence: $\alpha_{vir} \sim 1$, density PDF lognormal, LWS relation $\sigma_v = c_s\,(\ell/\ell_s)^{1/2}$
- Scaling: $M \sim \ell^3$, $PE \sim \ell^5$, $KE \sim \ell^4$, so PE << KE, typical region unbound
- Only over-dense regions bound; required overdensity given by $\lambda_J = c_s[\pi/(G\rho)]^{1/2} < \ell_s$



# Calculating $\varepsilon_{ff}$




- Density PDF in turbulent clouds is lognormal; width set by $\mathcal{M}$
- Integrate over region where $\lambda_J \leq \ell_s$, to get mass in "cores", then divide by $t_{ff}$ to get SFR
- Result: $\varepsilon_{ff}$ ~ few% for any turbulent, virialized object

# Building a Galactic SF Law from a Local One

- Need to estimate characteristic density
- In MW-like galaxies, GMCs have $\Sigma_{GMC} \sim 100$ $M_\odot$ $pc^{-2}$, $M_{GMC} \sim \sigma^4 / G^2 \Sigma_{gal}$; this gives

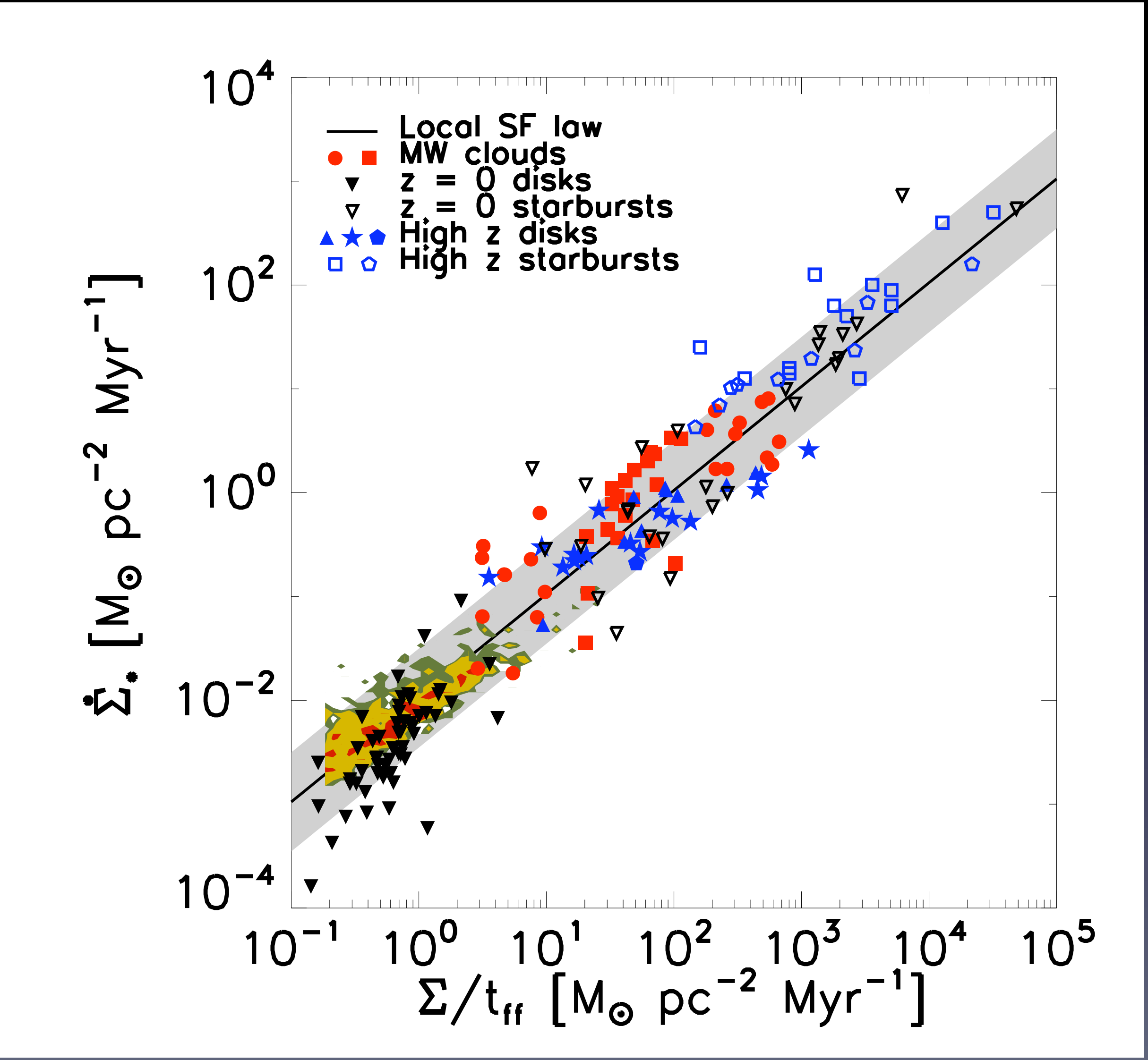
$$\rho_{\rm GMC} \sim G(\Sigma_{\rm GMC}^3 \Sigma_{\rm gal})^{1/4}/\sigma^2$$

- In SB / high-z galaxies, Toomre stability gives

$$\rho_{\rm T} \sim \Omega^2/GQ^2$$

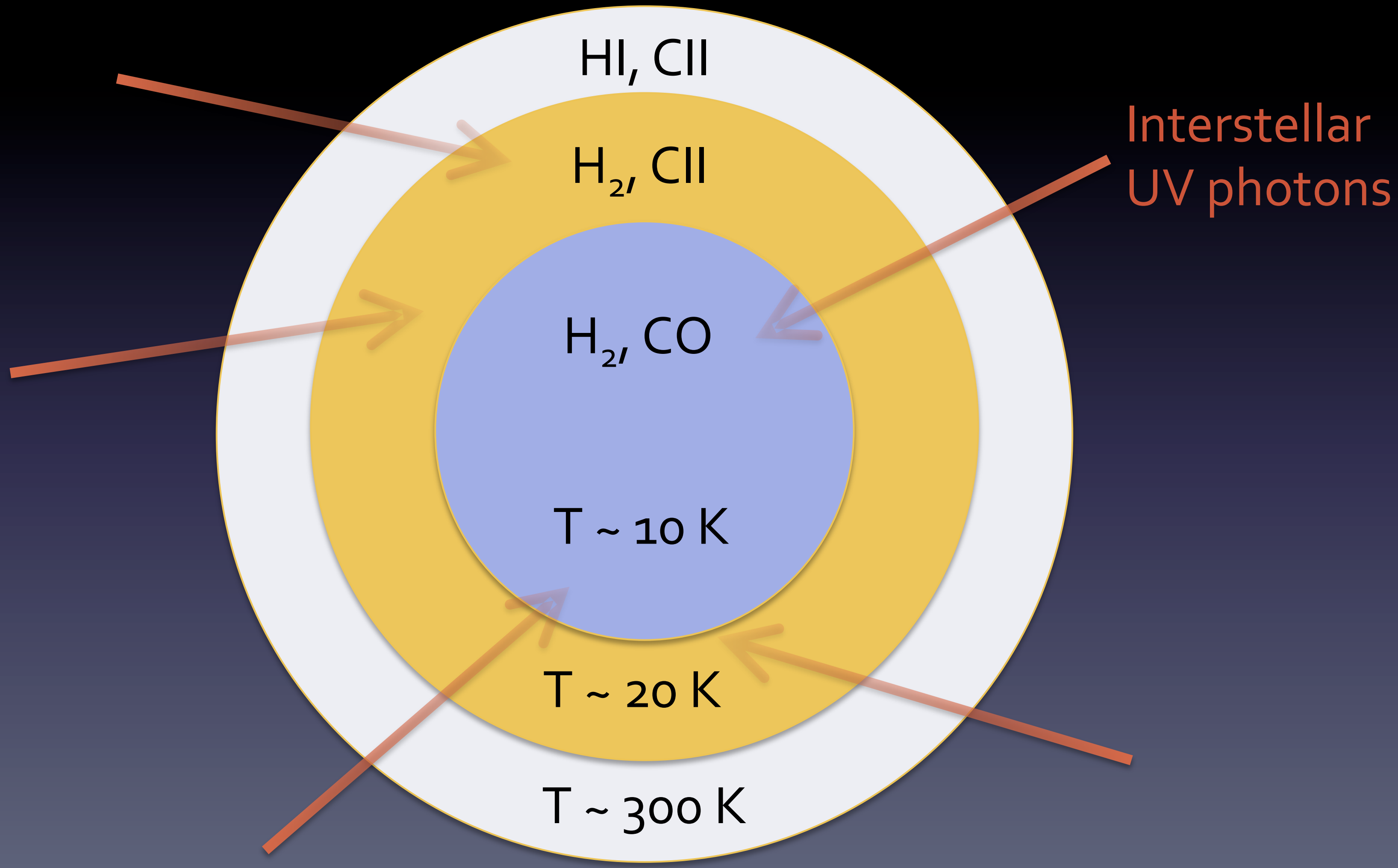
- Ansatz: $\rho = \max(\rho_T, \rho_{GMC})$

# Combined Local-Galactic Law




Krumholz, Dekel, & McKee 2012

# Metallicity / Phase-Dependence



# Chemical and Thermal Balance

$H_2$ formation

$H_2$ photodissociation

$$n_{\rm HI} n \mathcal{R} \quad = \quad n_{\rm H_2} \int d\Omega \int d\nu \, \sigma_{\rm H_2} f_{\rm diss} I_\nu / (h\nu)$$

$$\hat{e} \cdot \nabla I_\nu \quad = \quad -(n_{\rm H_2} \sigma_{\rm H_2} + n \sigma_{\rm d}) I_\nu$$

Decrease in rad. intensity

Absorption by dust, $H_2$

Line cooling

Photoelectric heating

$$n^2 \Lambda = n \int d\Omega \int d\nu \, \sigma_d E_{\rm PE} I_\nu / (h\nu)$$

$$\hat{e} \cdot \nabla I_\nu = -n \sigma_d I_\nu$$

Decrease in rad. intensity

Absorption by dust

Caveat: this is assumes equilibrium, which may not hold

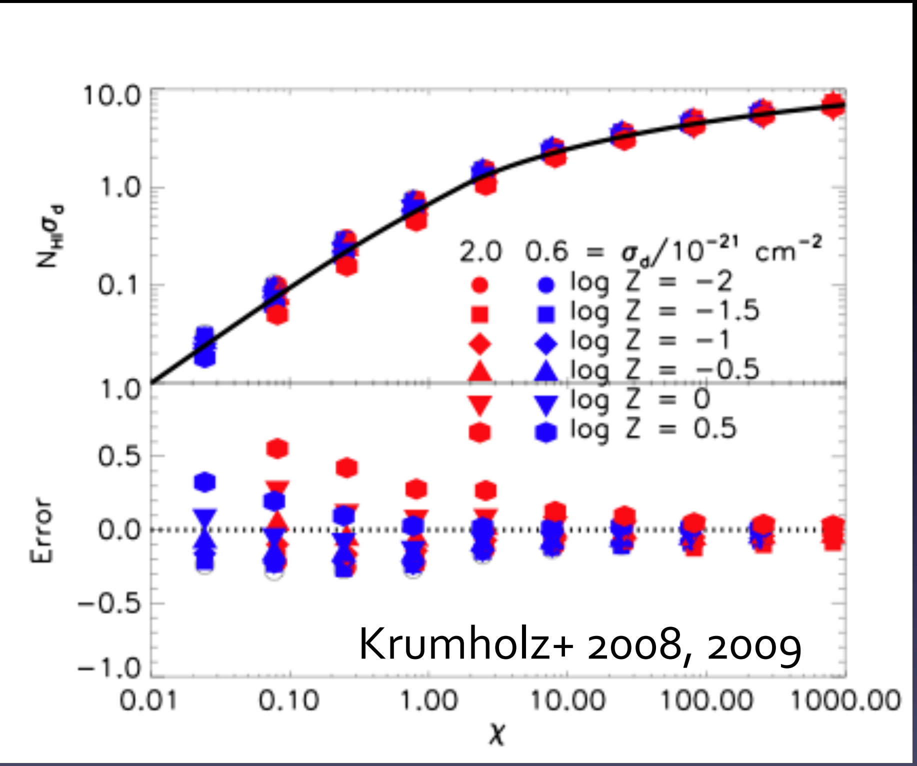
# Calculating Molecular Fractions

To good approximation, solution only depends on two numbers:

$$\tau_{\mathrm{R}} = n\sigma_{\mathrm{d}}R$$

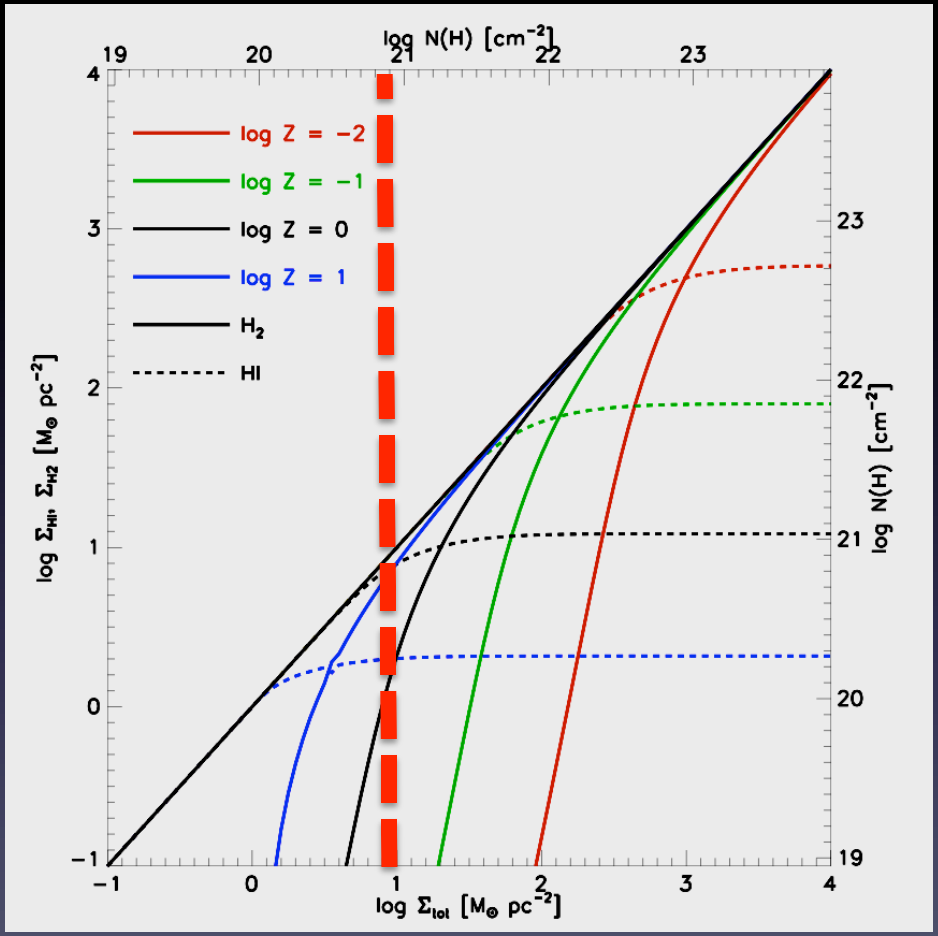
$$\chi = \frac{f_{\mathrm{diss}}\sigma_{\mathrm{d}}E_0^*}{nR}$$

An approximate analytic solution can be given from these parameters.



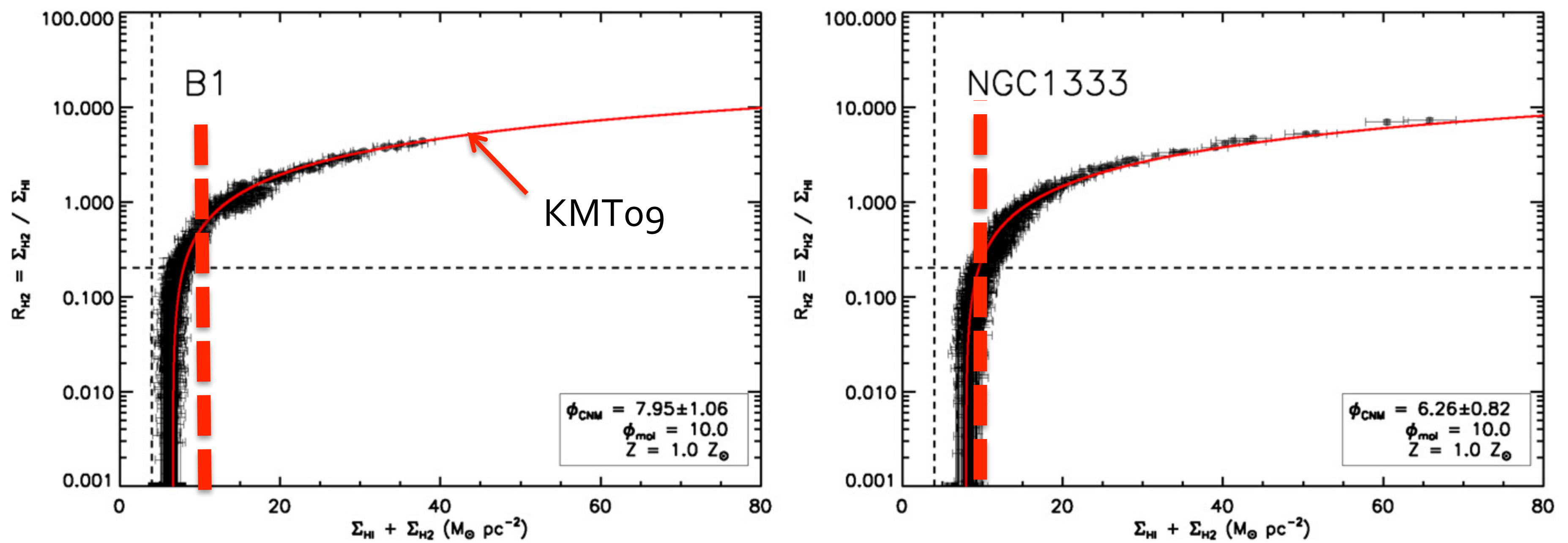

Analytic solution for location of HI / $H_2$ transition vs. exact numerical result

# Calculating $f_{H_2}$



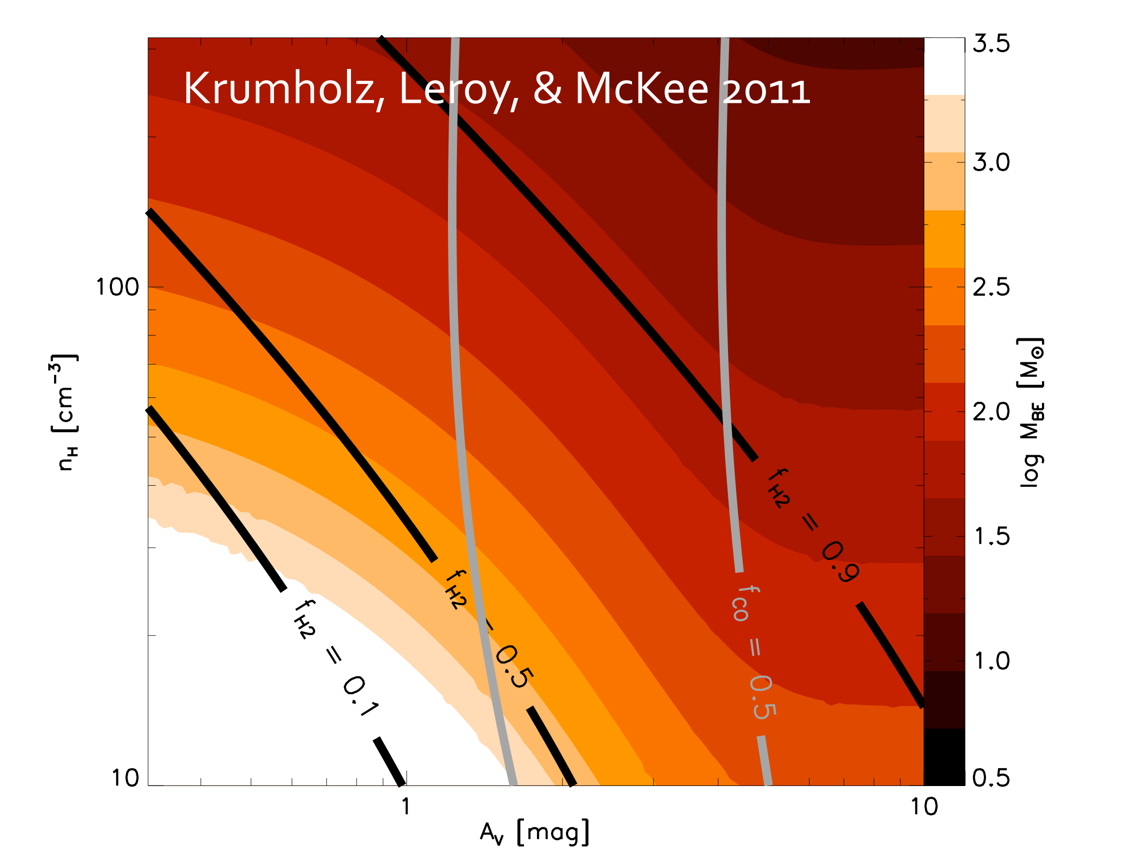

Qualitative effect: $f_{H_2}$ goes from ~0 to ~1 when $\Sigma Z \sim 10\ M_\odot\ pc^{-2}$

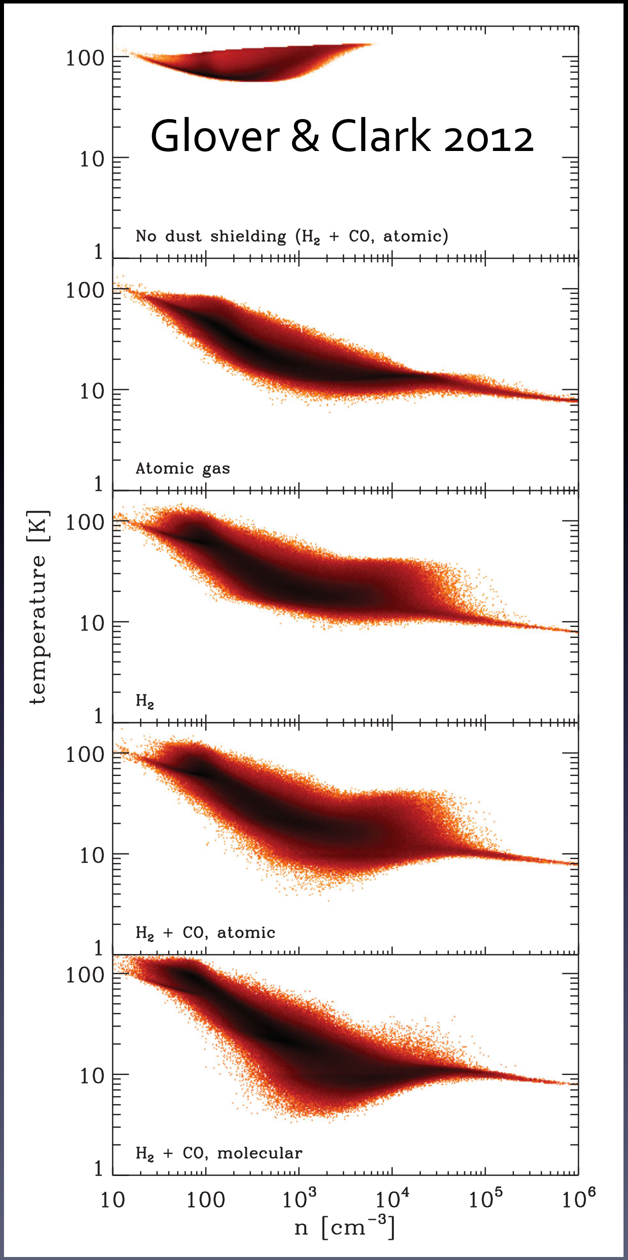
# The Local HI – H2 Transition



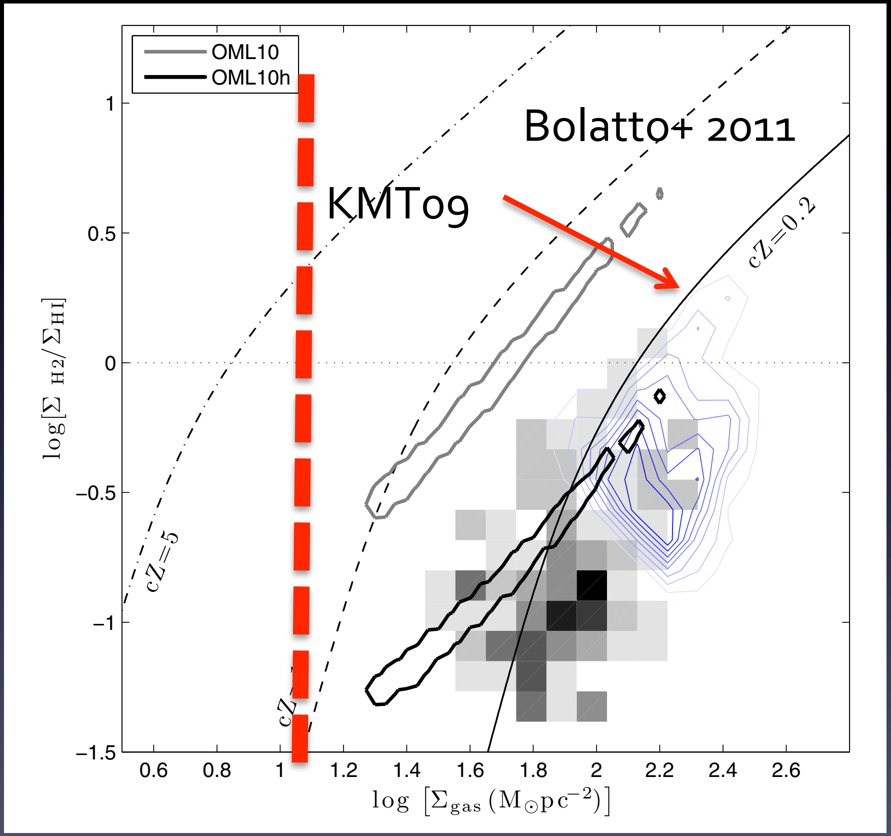

Lee+ 2012

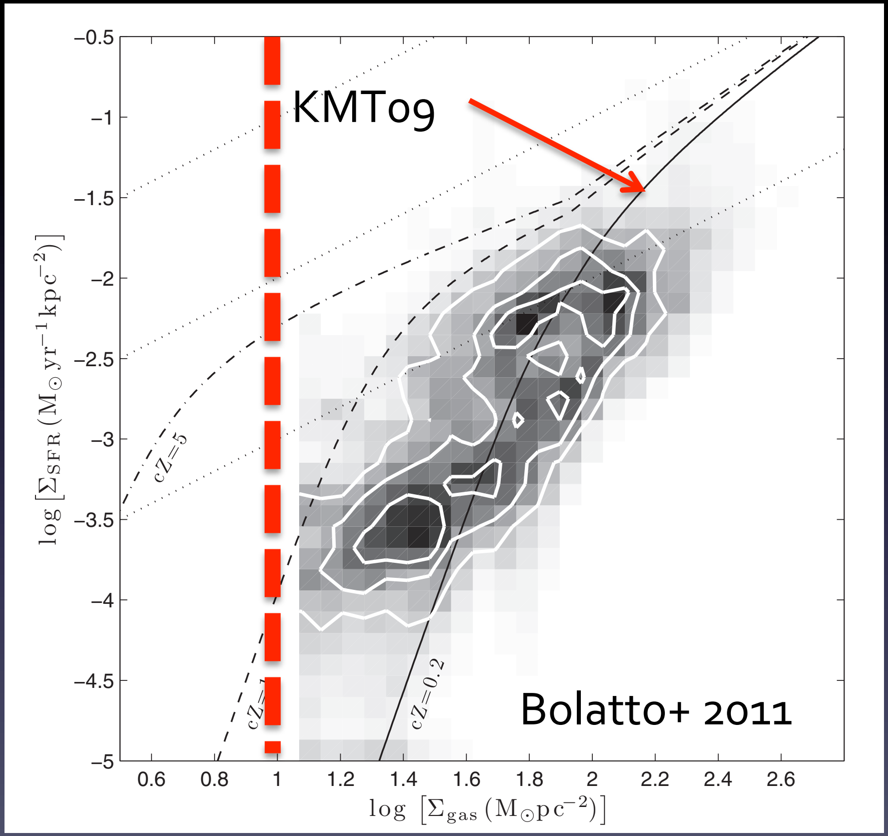
# Why SF Follows $H_2$



# Extra-Galactic Phase Dependence

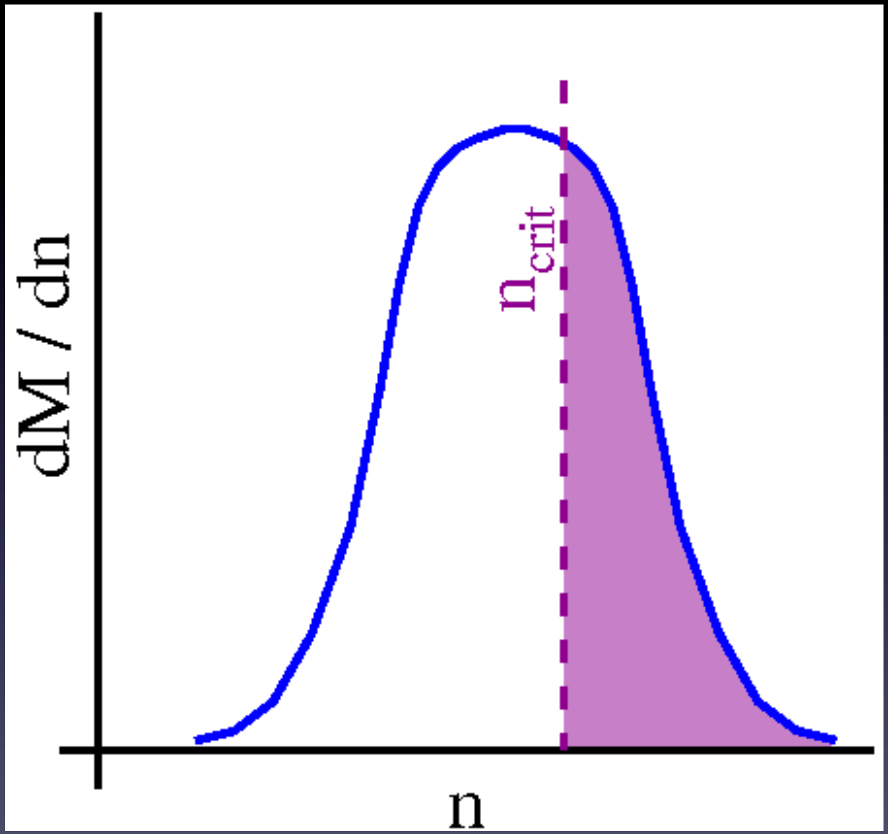


# SF Laws in Other Lines

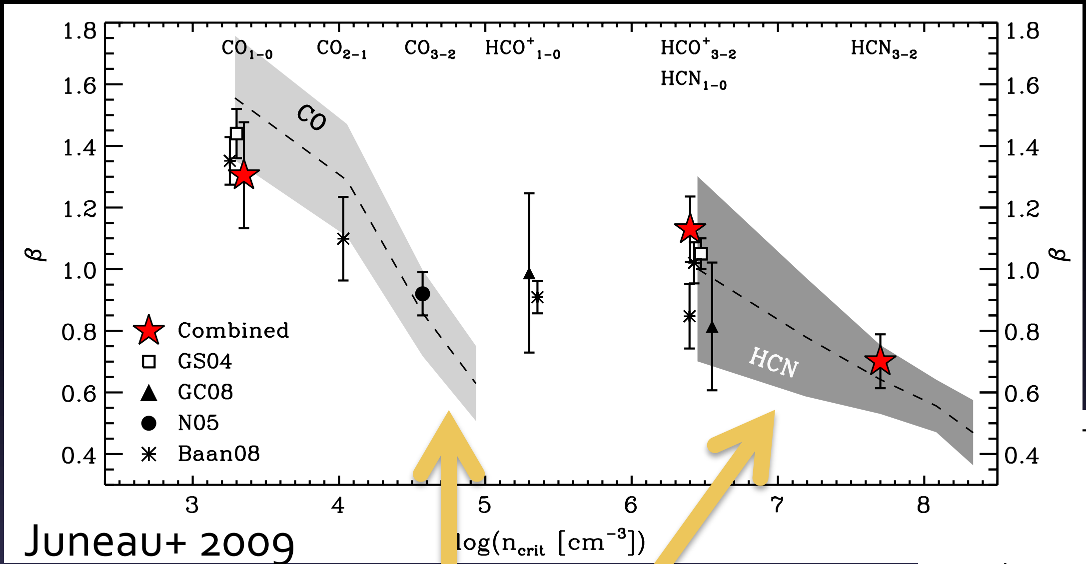
(Krumholz & Thompson 2007; see also Narayanan+ 2008)

- SFR is a fixed mass fraction per free-fall time, so for density n, $SFR \propto L_{IR} \propto n^{3/2}$
- Line luminosity depends on mass above $n_{crit}$
- Low $n_{crit}$ (e.g. CO 1-0) $\Rightarrow L_{line} \propto n^1$
- High $n_{crit}$ (e.g. HCN 1-0) $\Rightarrow L_{line} \propto n^p$, $p > 1$



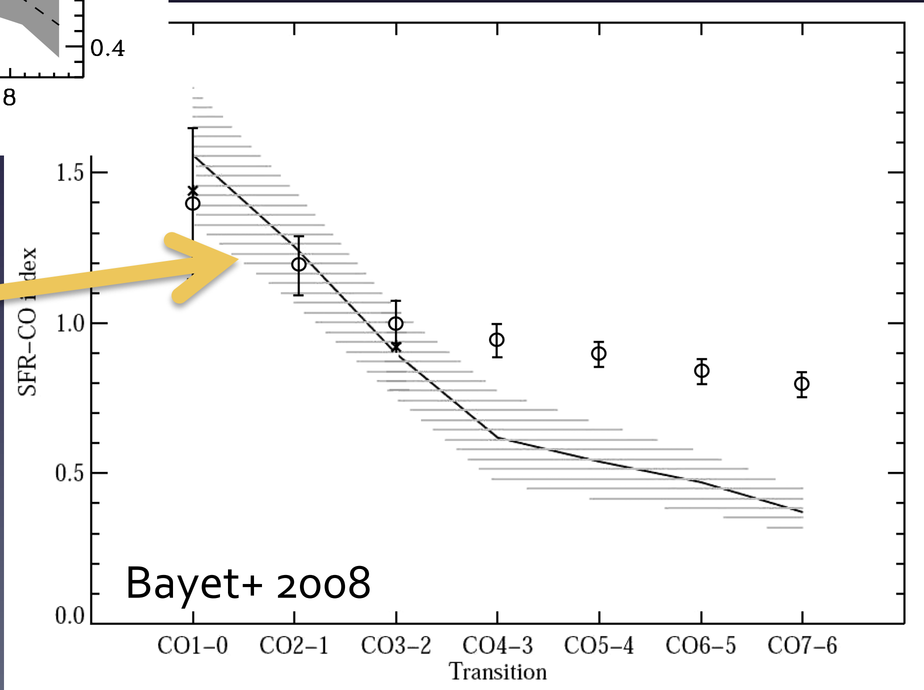

$SFR \propto L_{line}^{3/2}$ for low $n_{crit}$
$SFR \propto L_{line}^{q}$, $q < 3/2$, for high $n_{crit}$

# Multi-Line Models




Juneau+ 2009

Models: Narayanan+ (2008)

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