The Star Formation Rate

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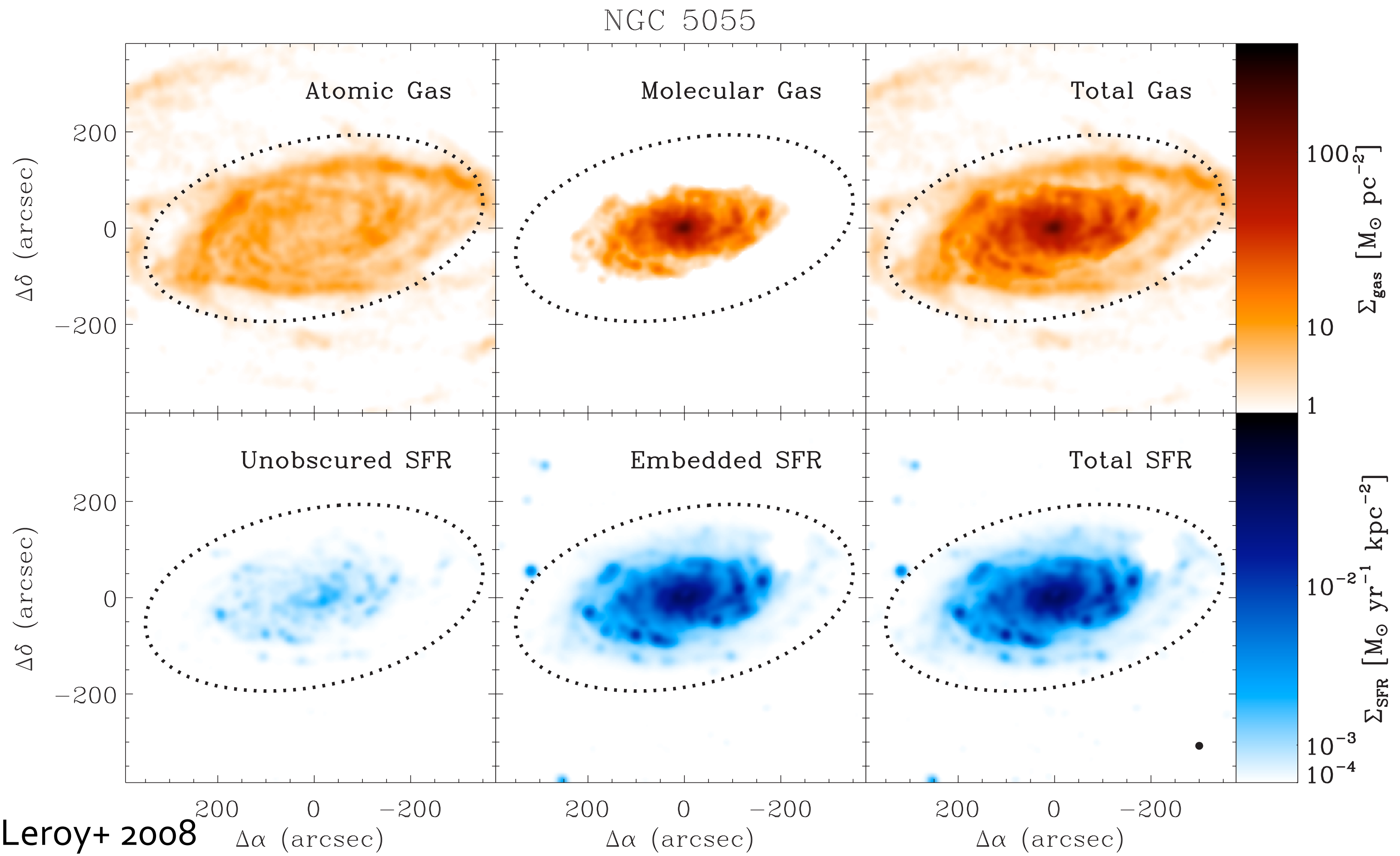
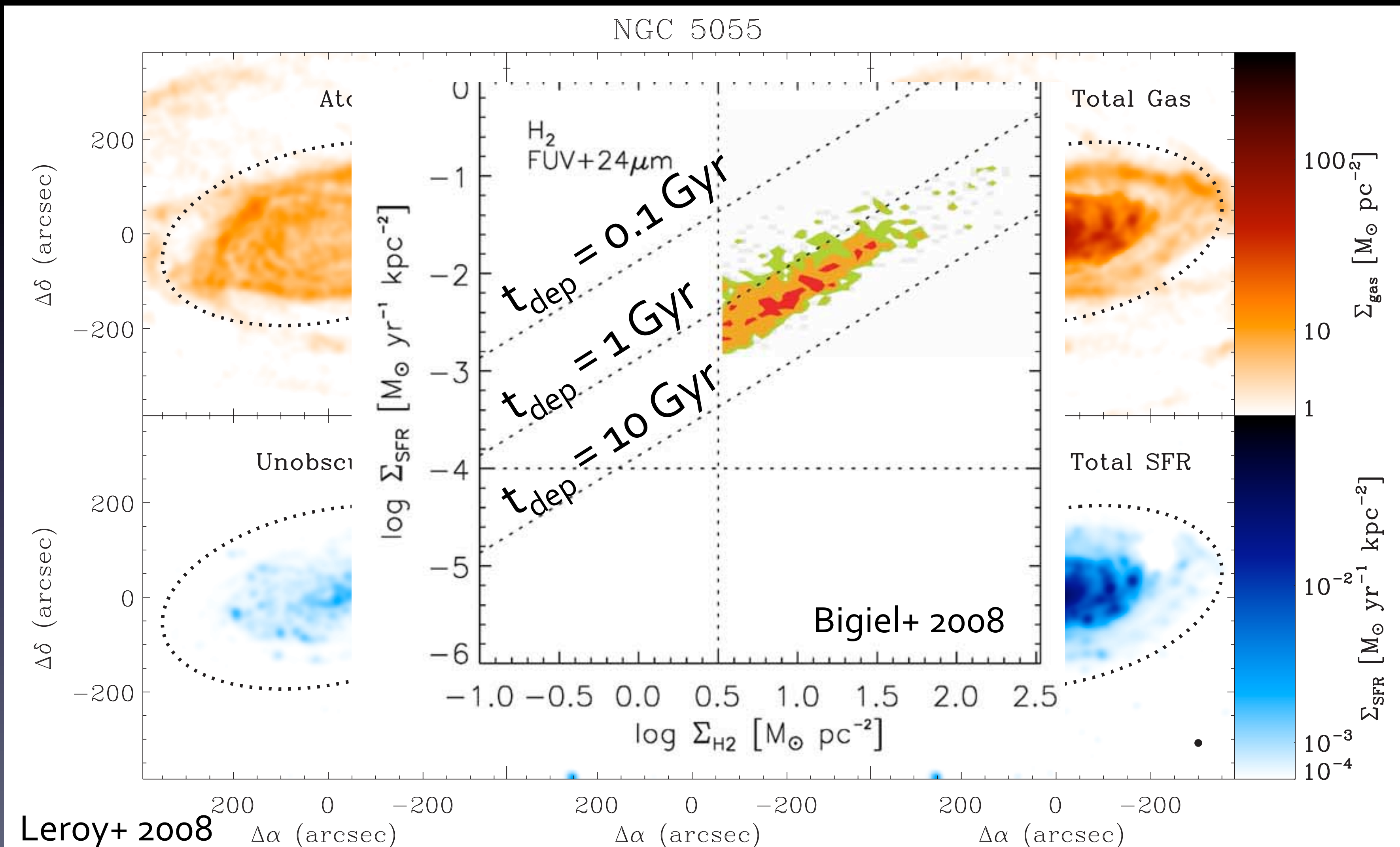
SF Laws on Galactic Scales

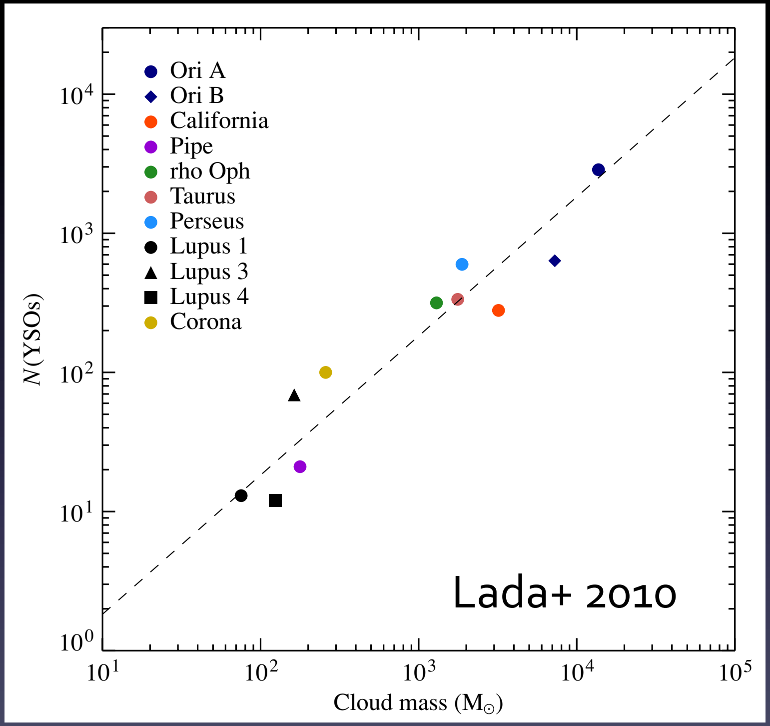


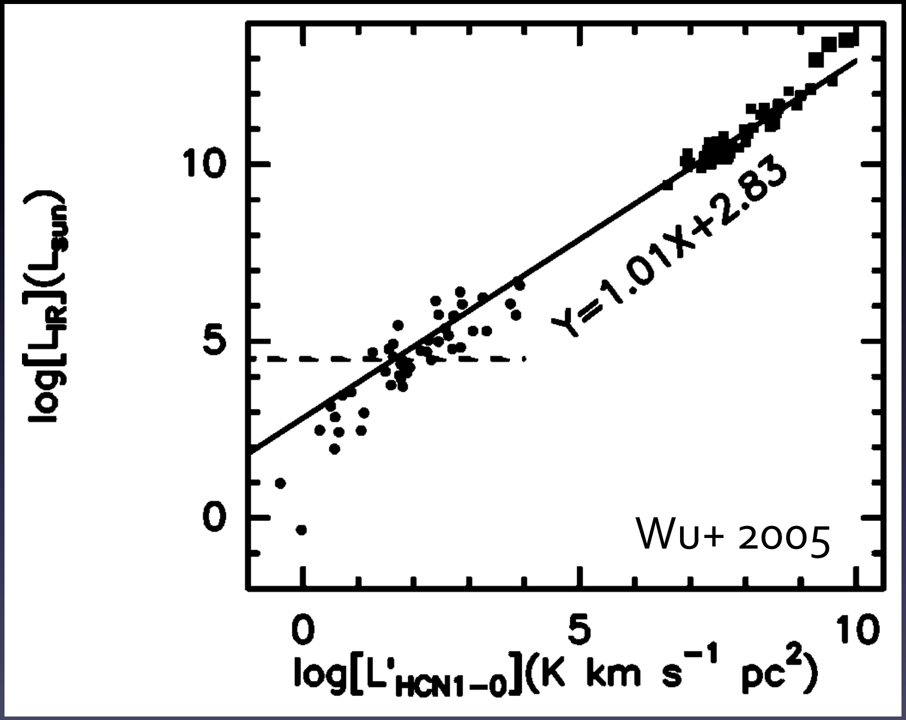
Leroy+ 2008

SF Laws on Galactic Scales

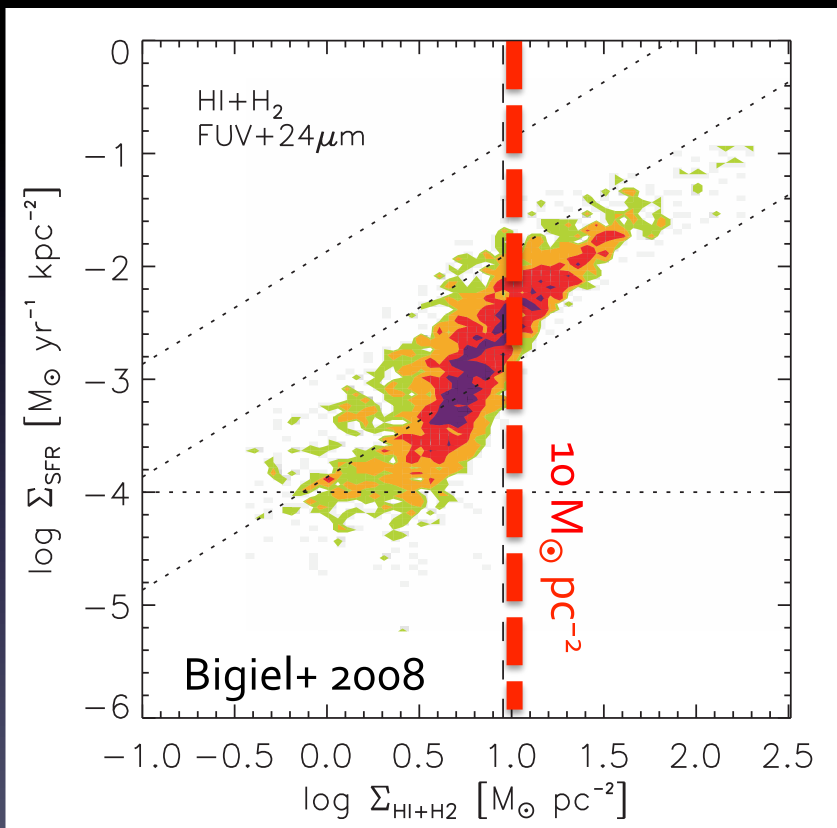


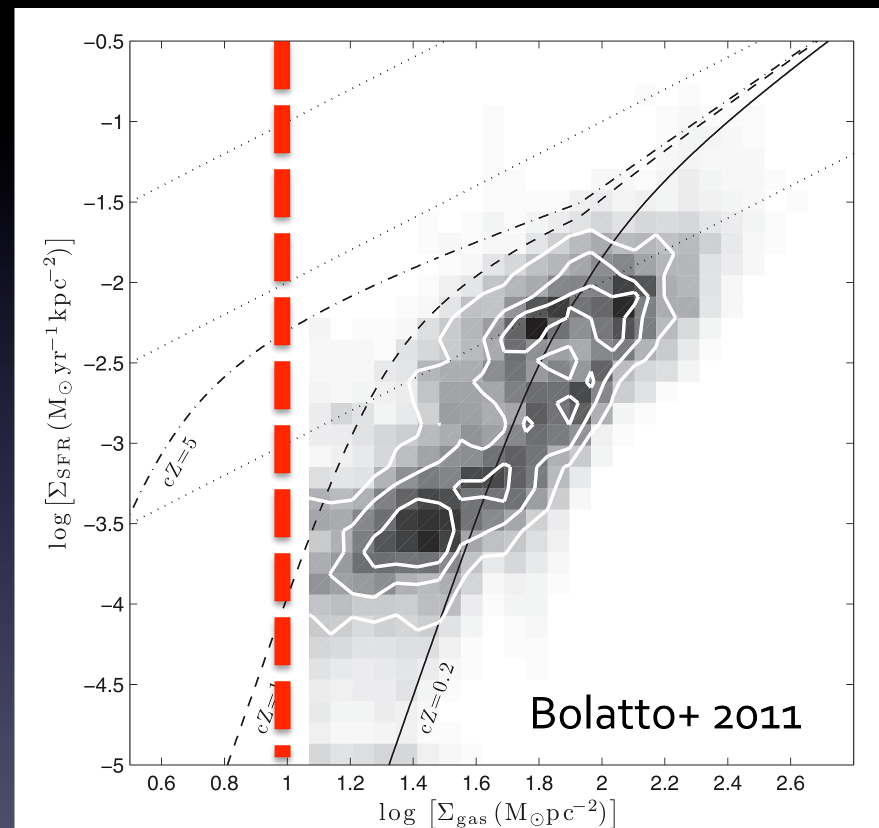
SF Laws on Sub-Galactic Scales



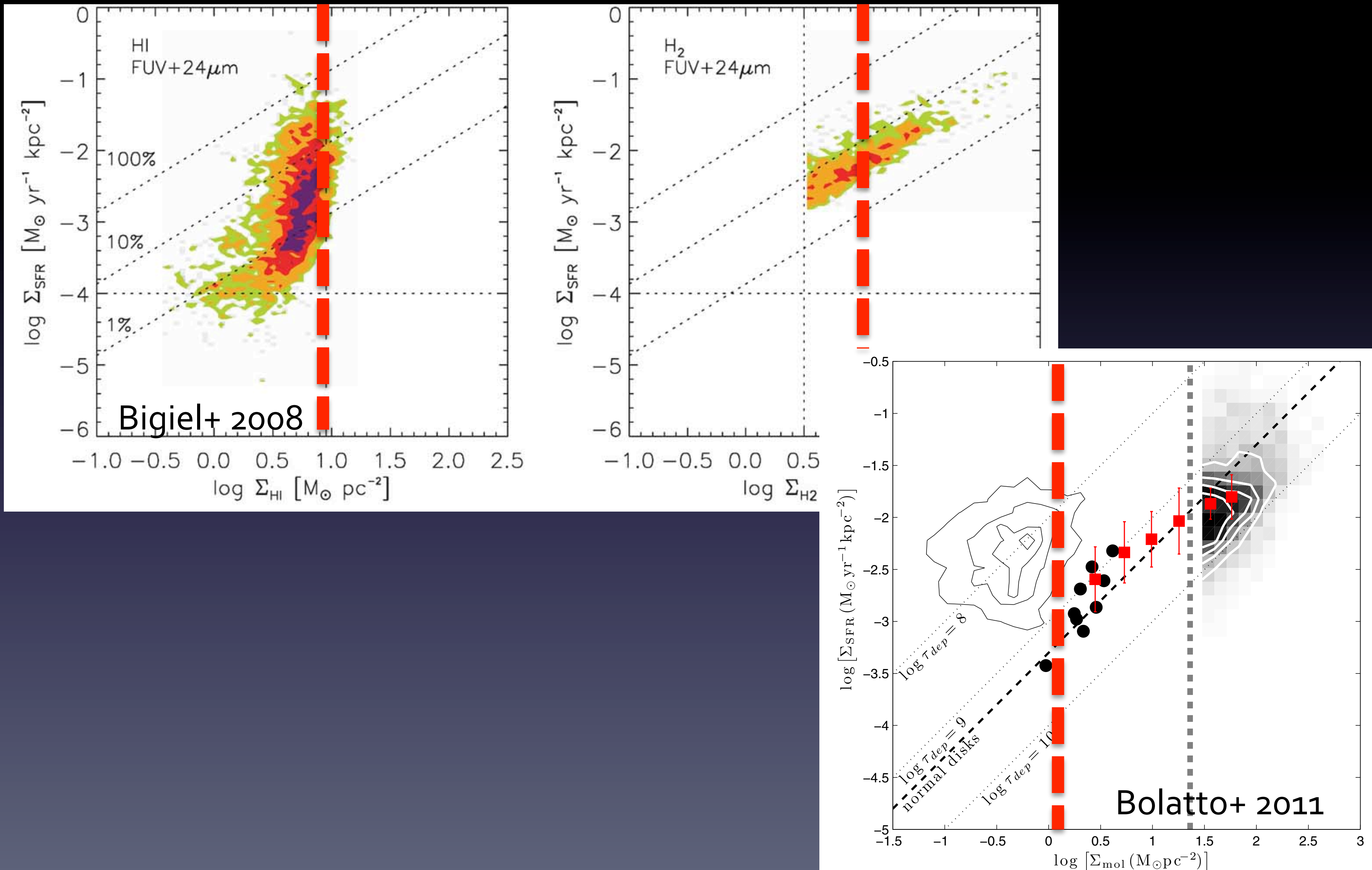


Metallicity-Dependence





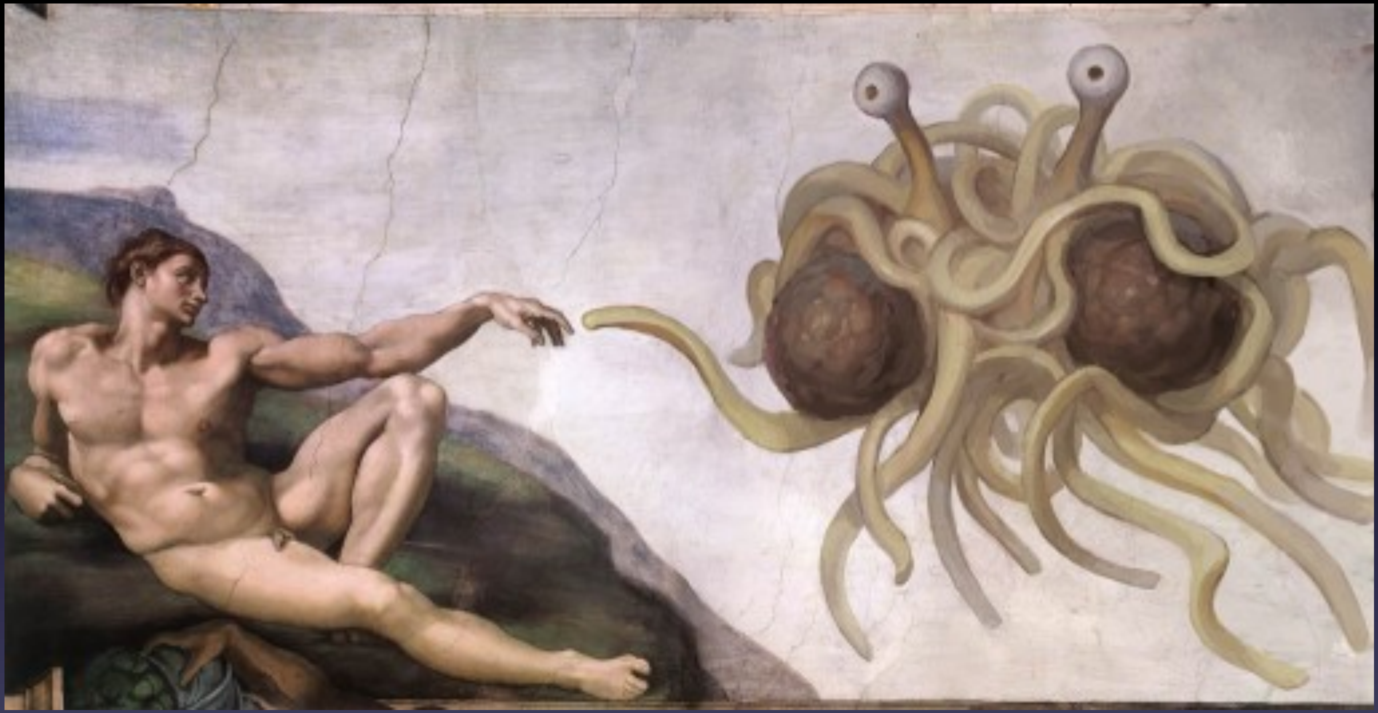
Phase-Dependence



The Theoretical Challenge

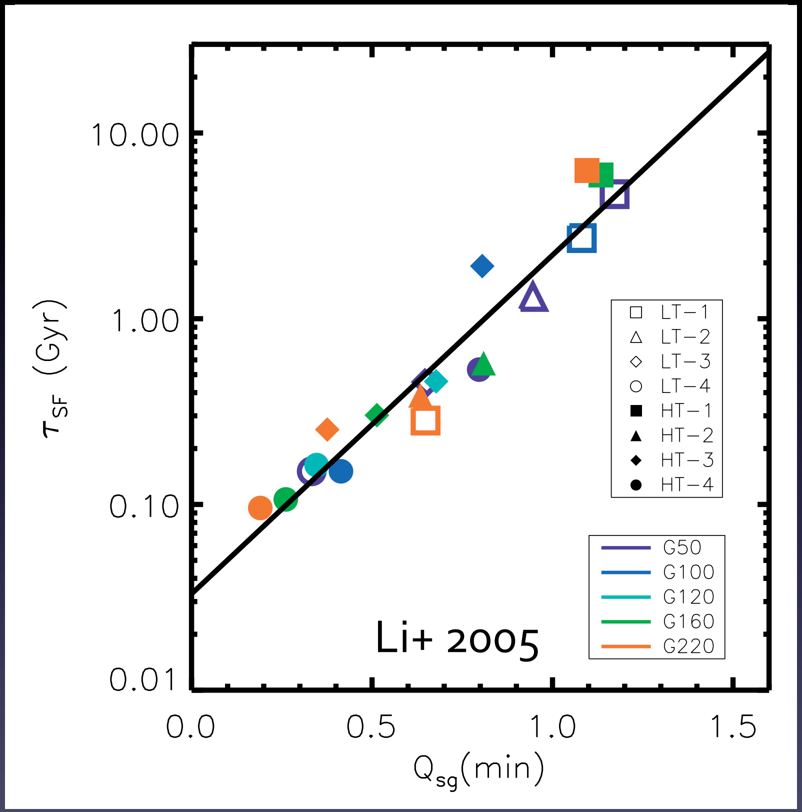
- Which laws are the fundamental ones, the local or the galactic-scale? Both? Neither?
- Can we unify the different sets of laws (at different scales, for different phases) within a single theoretical framework?

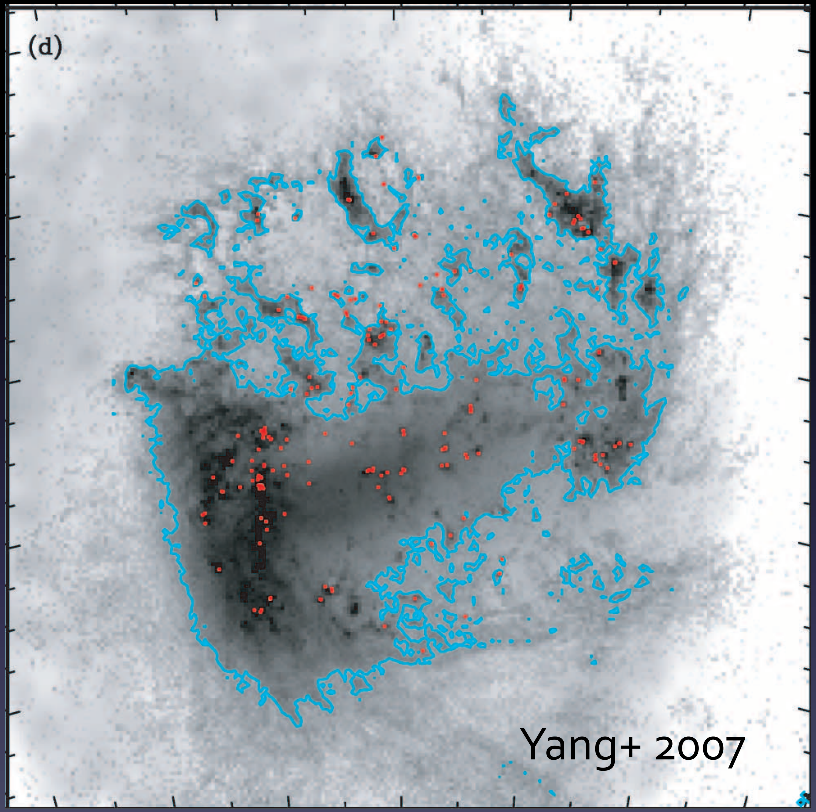
SF Laws: the Top-Down Approach



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.

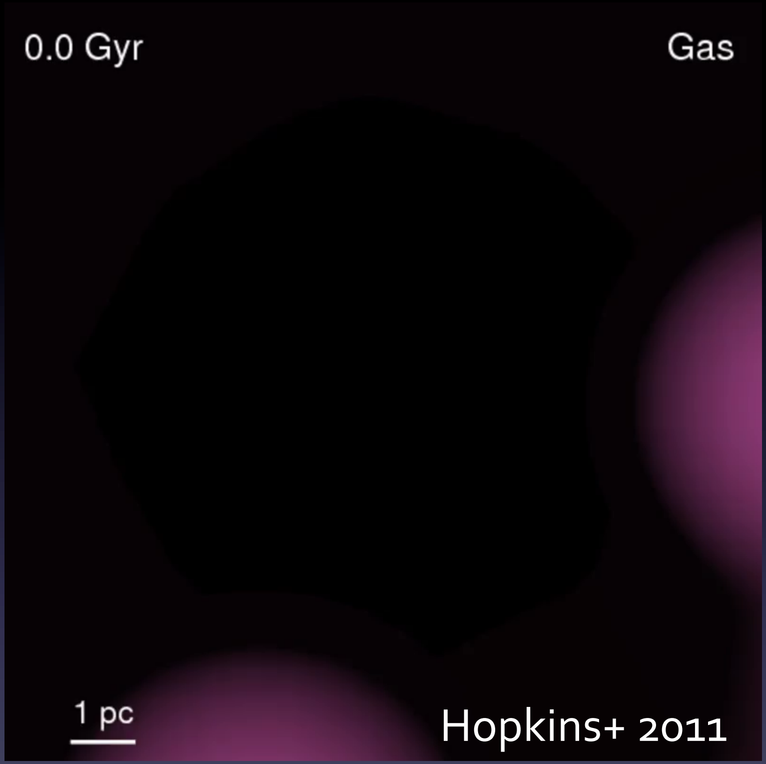
Q-Based Models

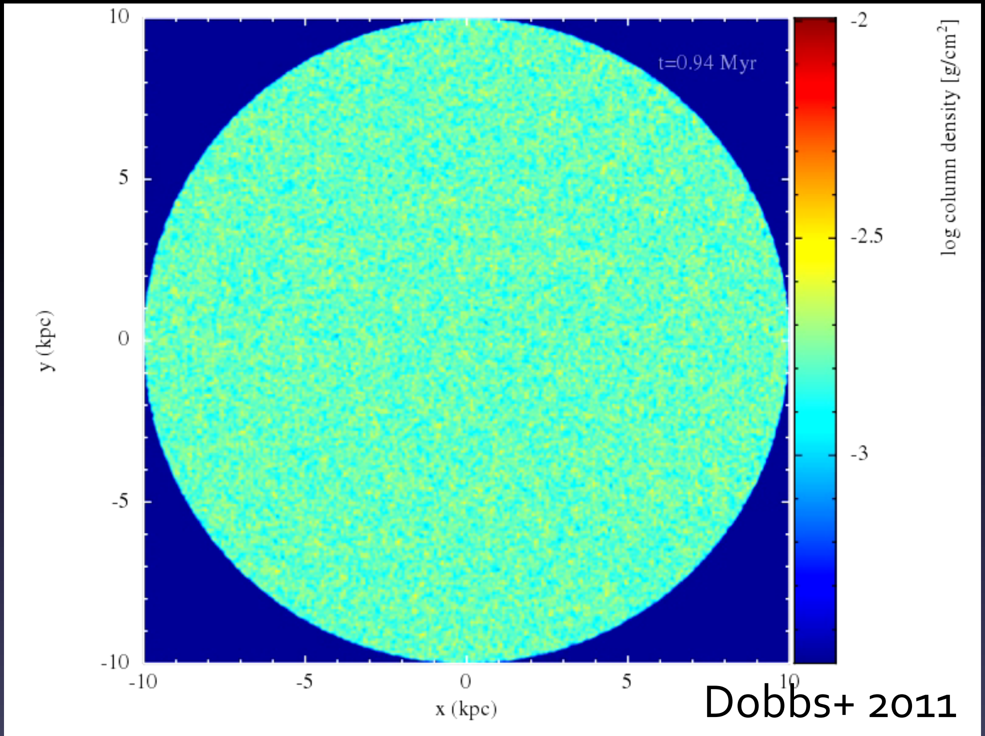




Basic idea: SFR is a function of Toomre Q in galaxy

Feedback Models

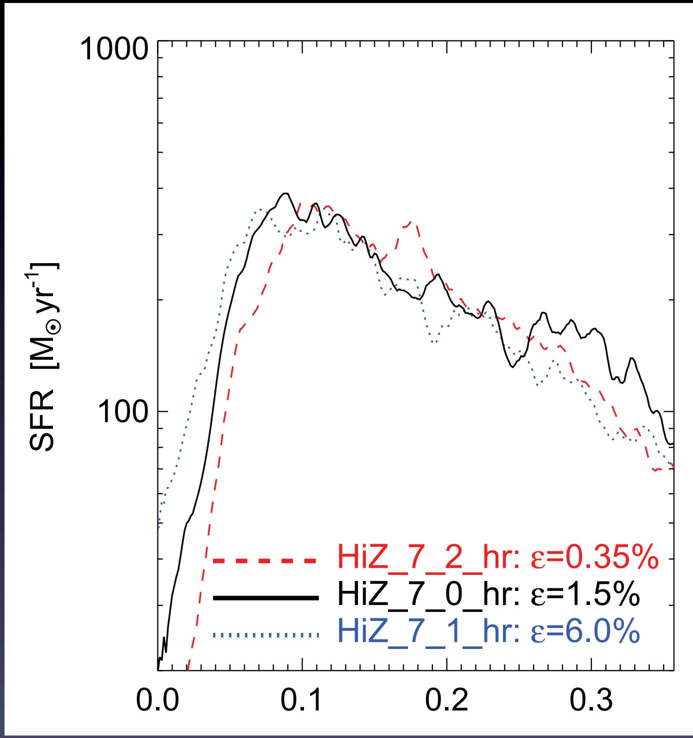


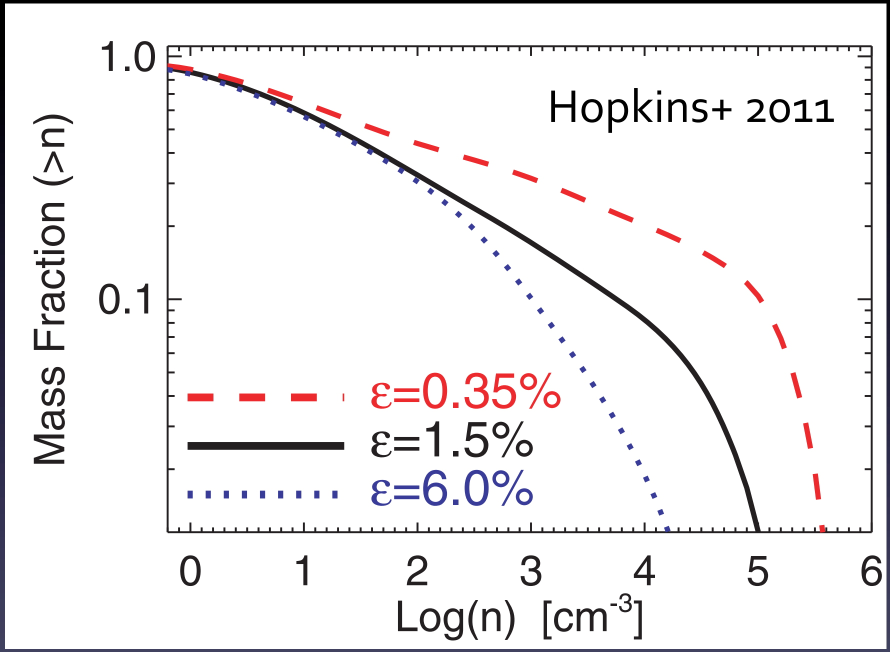


Also see Tasker (2011), E. Ostriker's talk

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

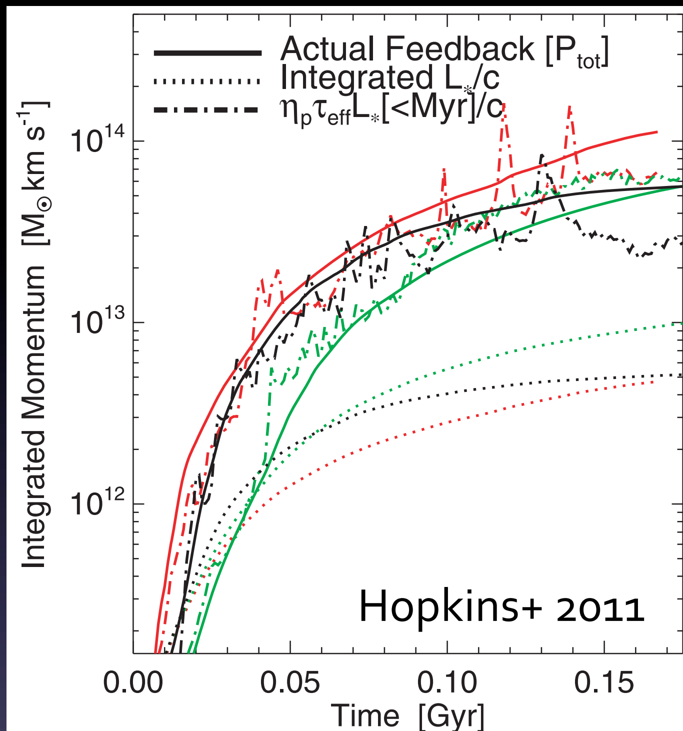
Characteristics of Top-Down Models

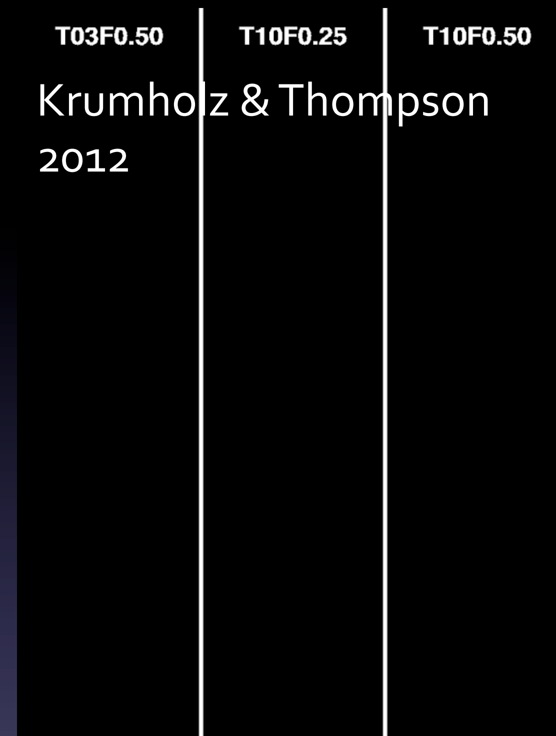




Changing the small-scale SF law does not change the SFR in the galaxy, but it does change the gas density distribution

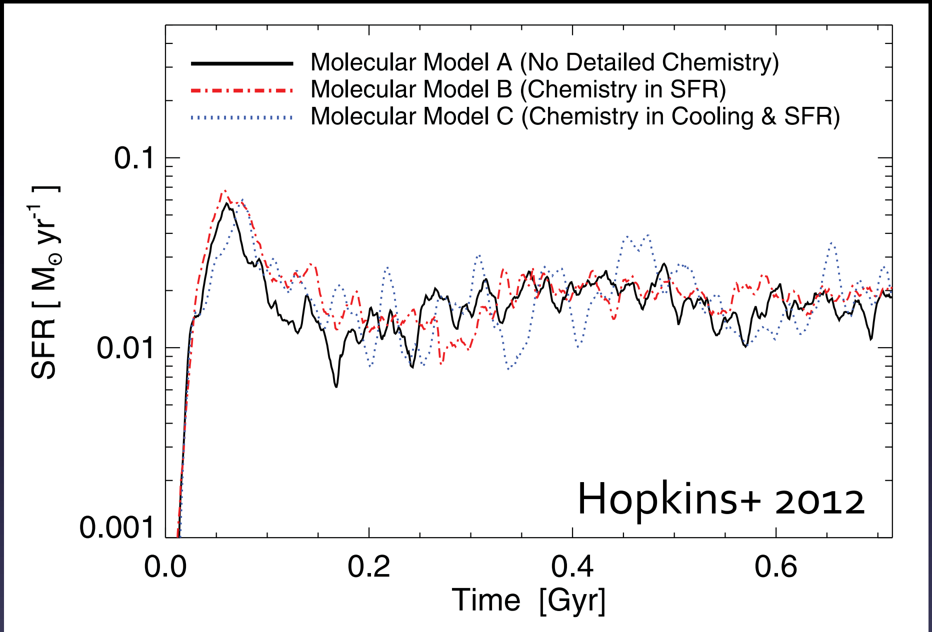
Top-Down Model Limitations

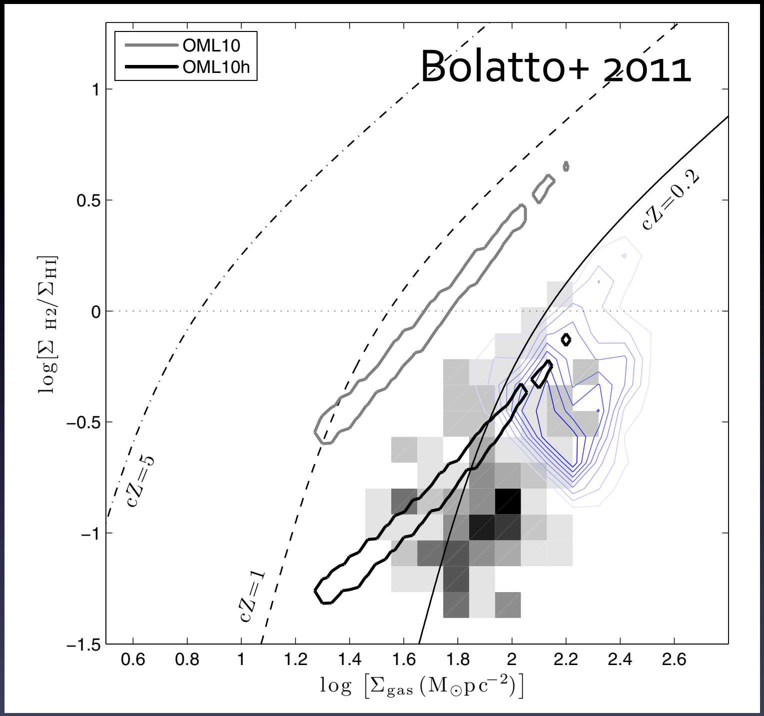




- Results depend strongly on subgrid feedback model (e.g. radiative trapping, SFE inside unresolved GMCs, UV heating per unit)
- No independent prediction for local SF laws

Metallicity in Top-Down Models



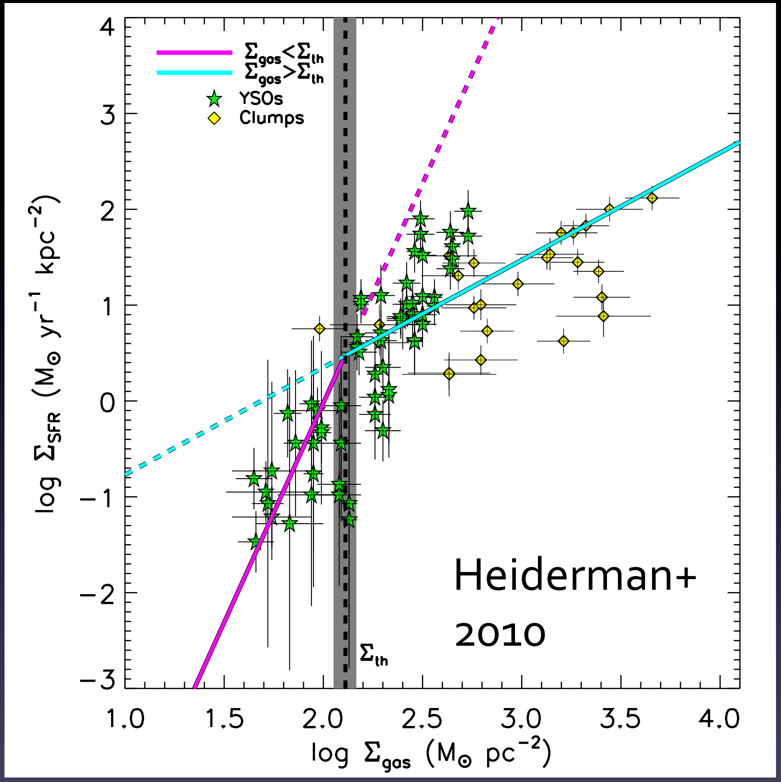


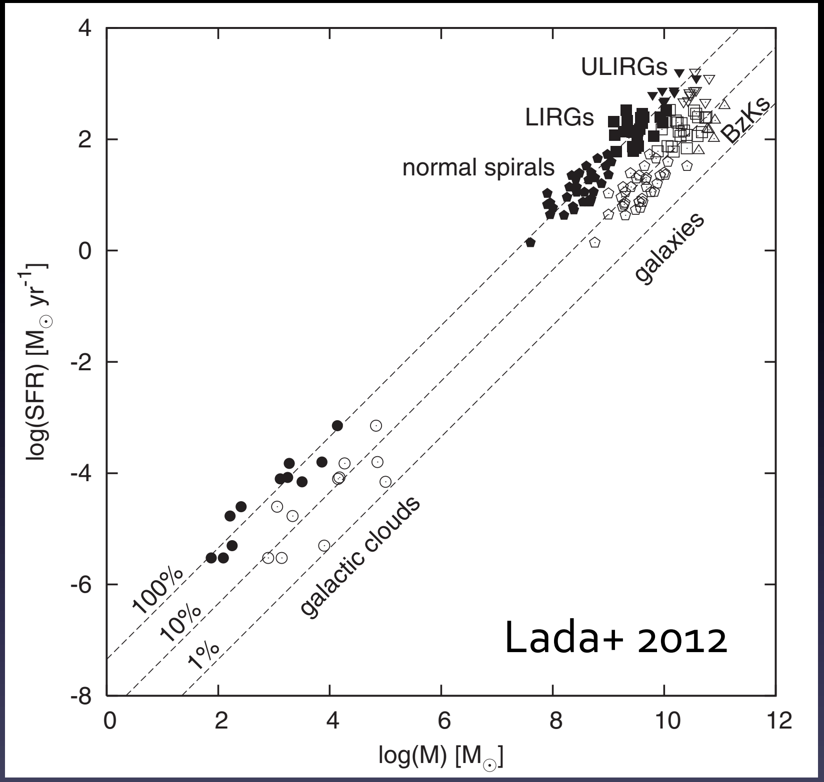
Top-down models most naturally predict SF laws that do not depend on metallicity or phase, strongly inconsistent with observations

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.

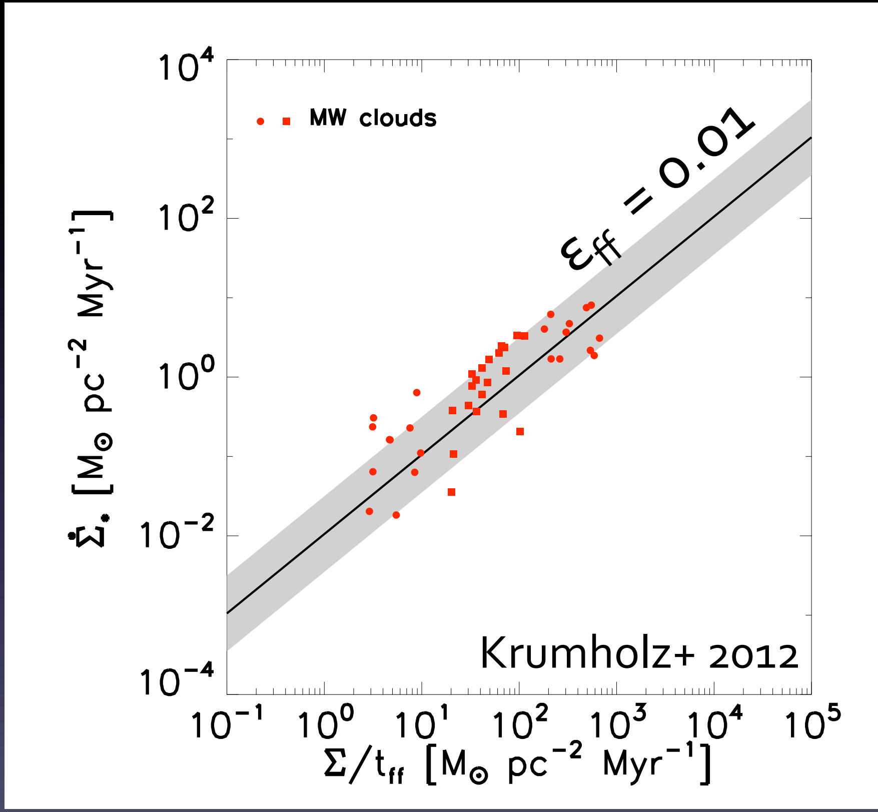
The "Dense Gas" Model

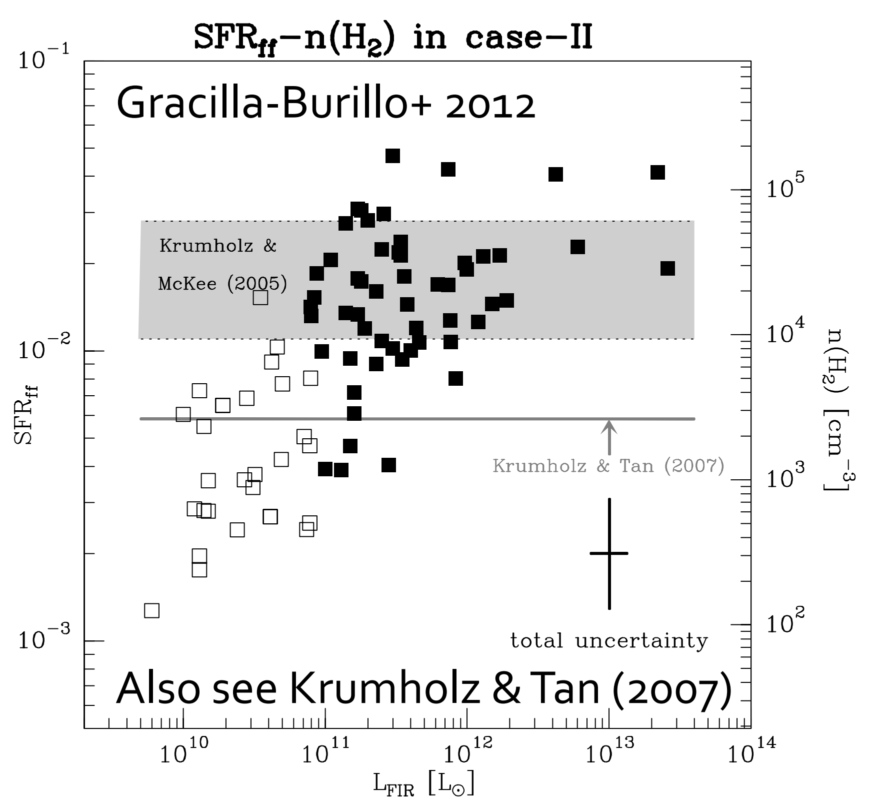




Basic idea: SFR = M(>ρ_{dense}) / t_{dense}, with ρ_{dense}, t_{dense} = const
Problems: no physical basis for values of ρ_{dense}, t_{dense};
evidence for threshold mixed

Observed Local SF Law



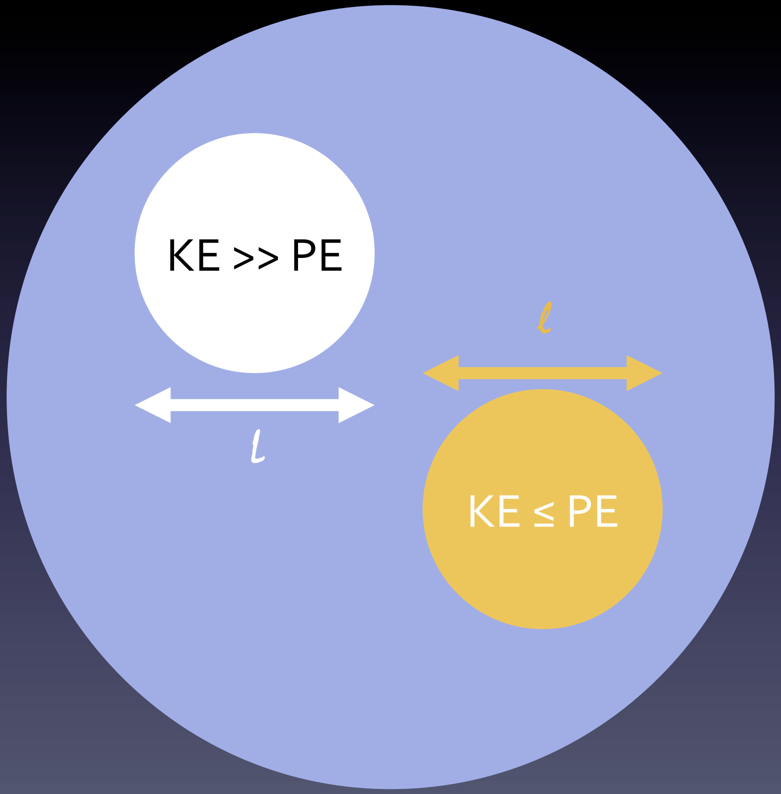


Local SF law: ~1% of gas mass goes into stars per free-fall time, independent of density or presence of massive stars

Why is ε_{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 $\sigma_v \sim \ell^{1/2}$
- Scaling: $M \sim \ell^3$, $PE \sim \ell^5$, $KE \sim \ell^4$, so PE << KE, typical region unbound
- Only over-dense regions bound; integrating over lognormal PDF gives $\varepsilon_{ff} \sim 0.01$



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

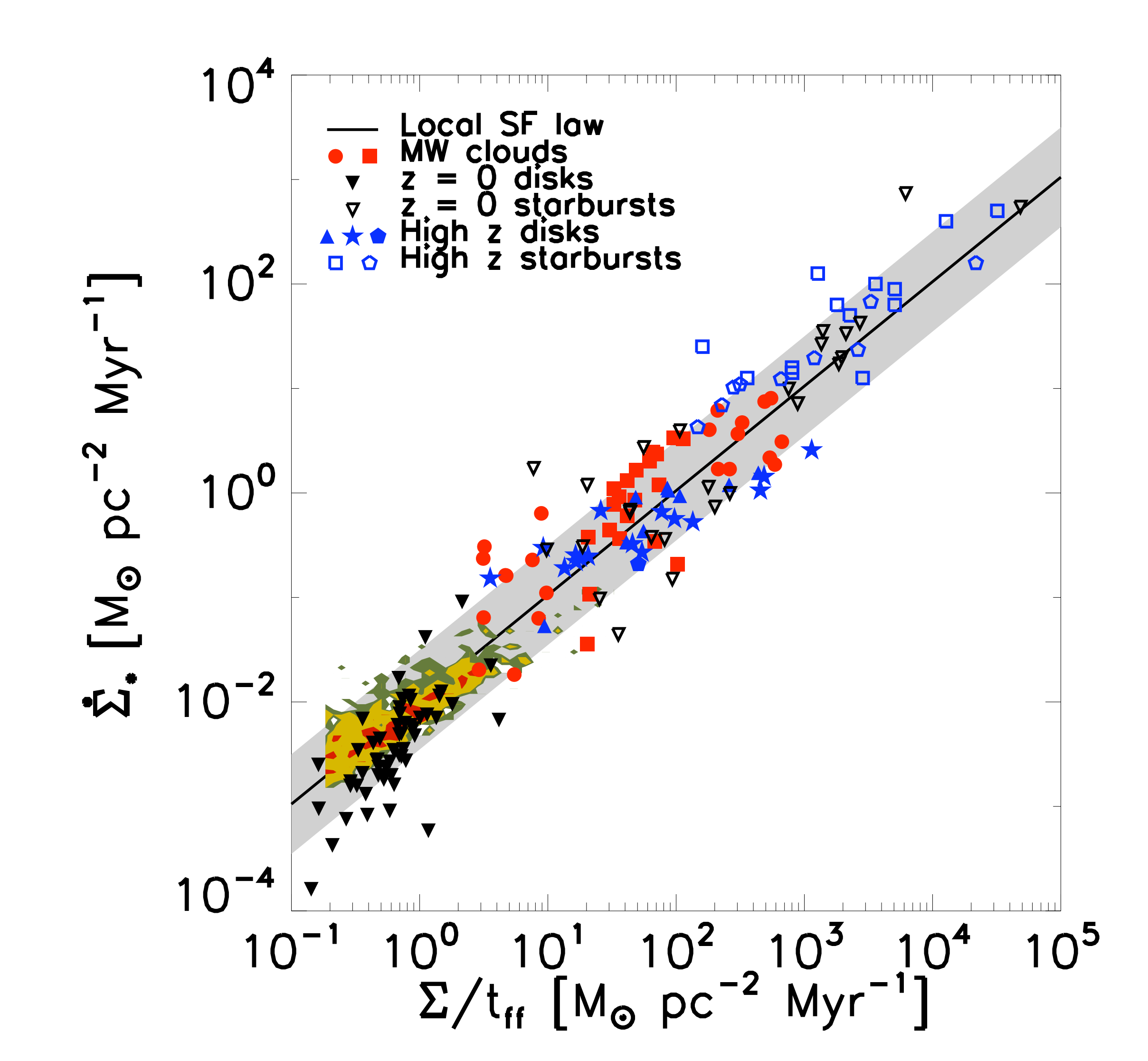
$$\rho_{\rm GMC} \sim G(\Sigma_{\rm GMC}^3 \Sigma_{\rm gal})^{1/4}/\sigma^2$$

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

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

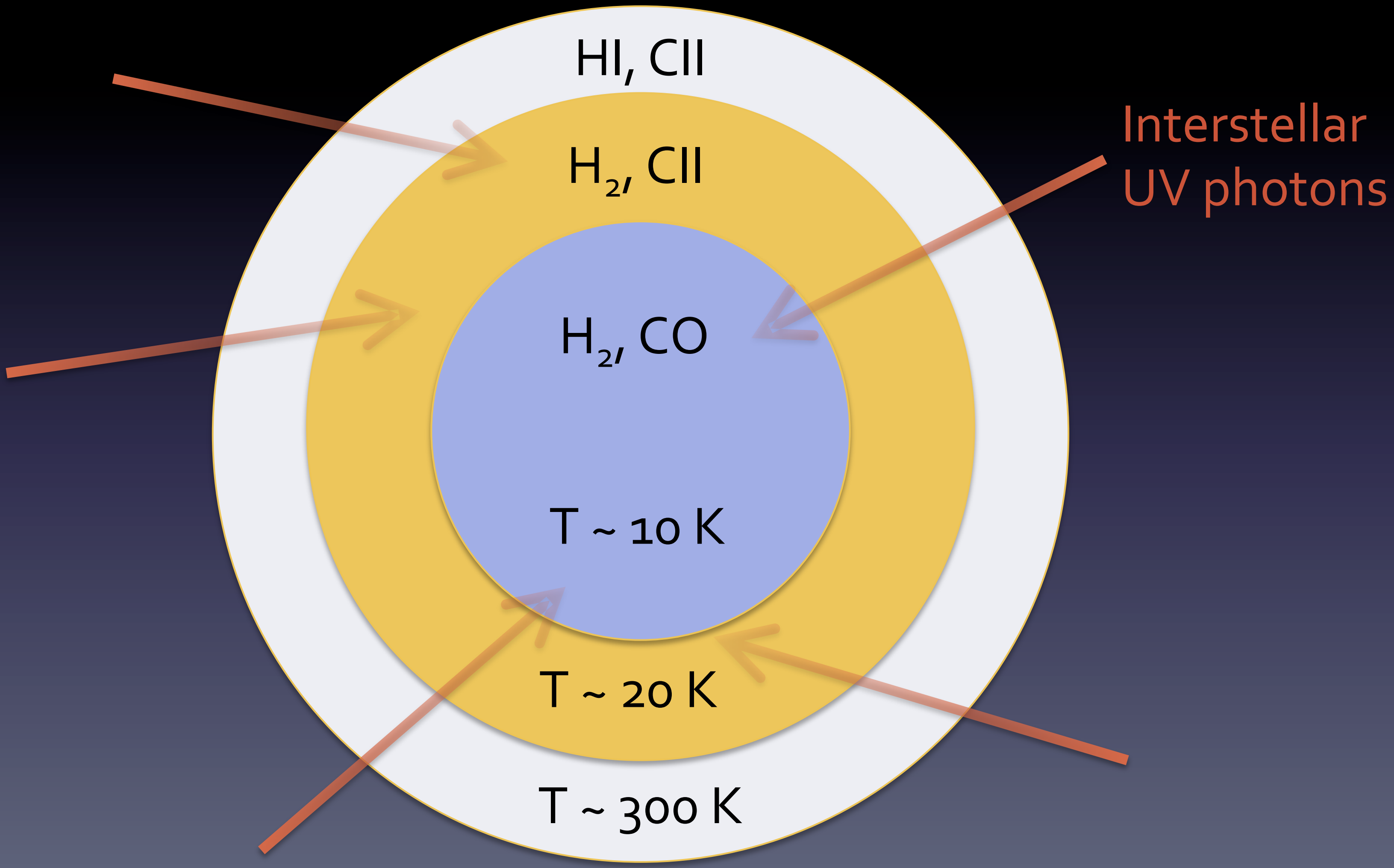
- Ansatz: $\rho = \max(\rho_T, \rho_{GMC})$

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

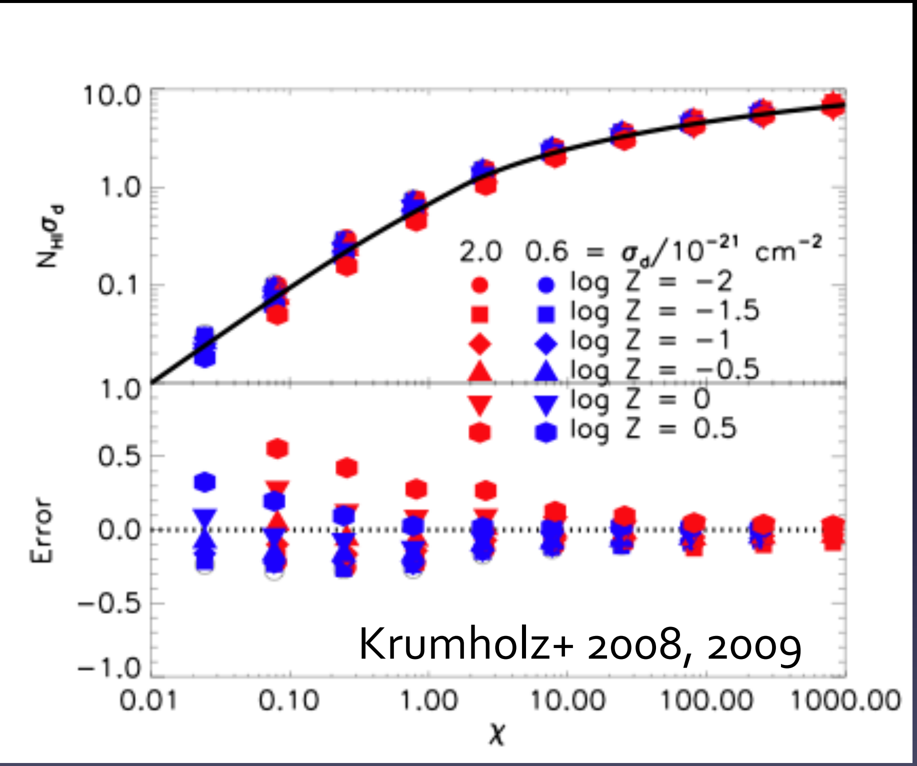
Calculating Molecular Fractions

To good approximation, solution only depends on two numbers:

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

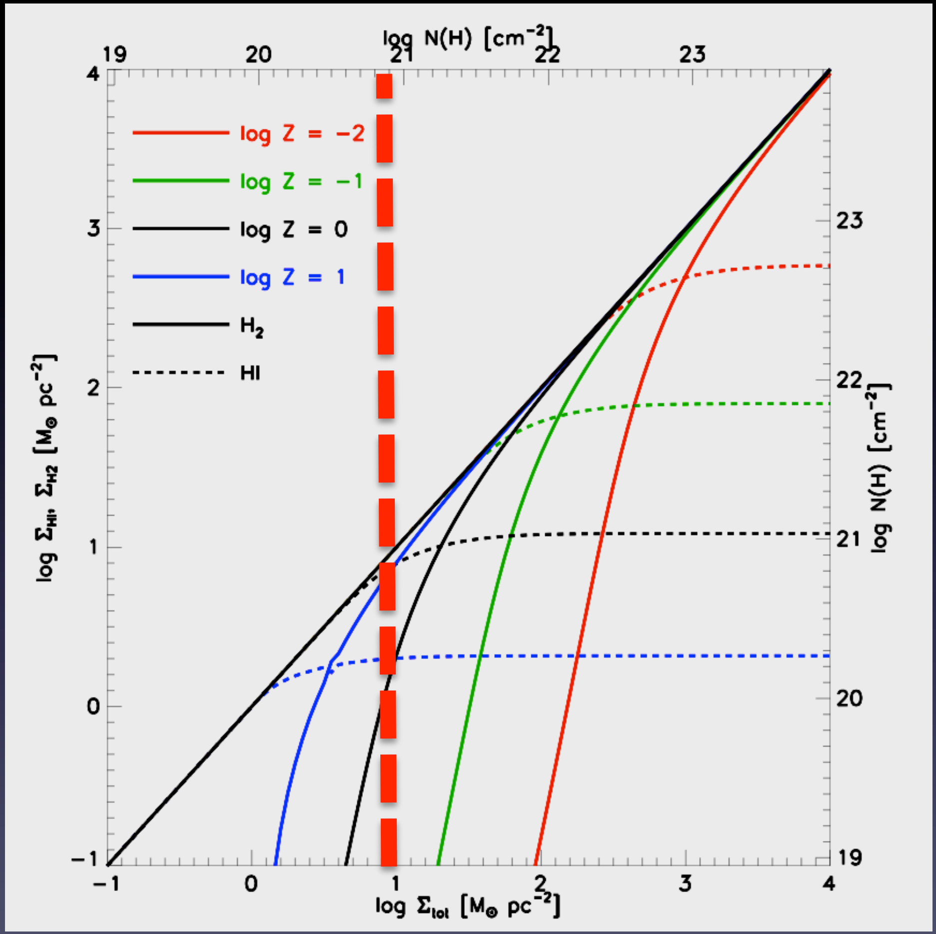
$$\chi = \frac{f_{\mathrm{diss}}\sigma_{\mathrm{d}}E_0^*}{nR}$$

An approximate analytic solution can be given from these parameters.



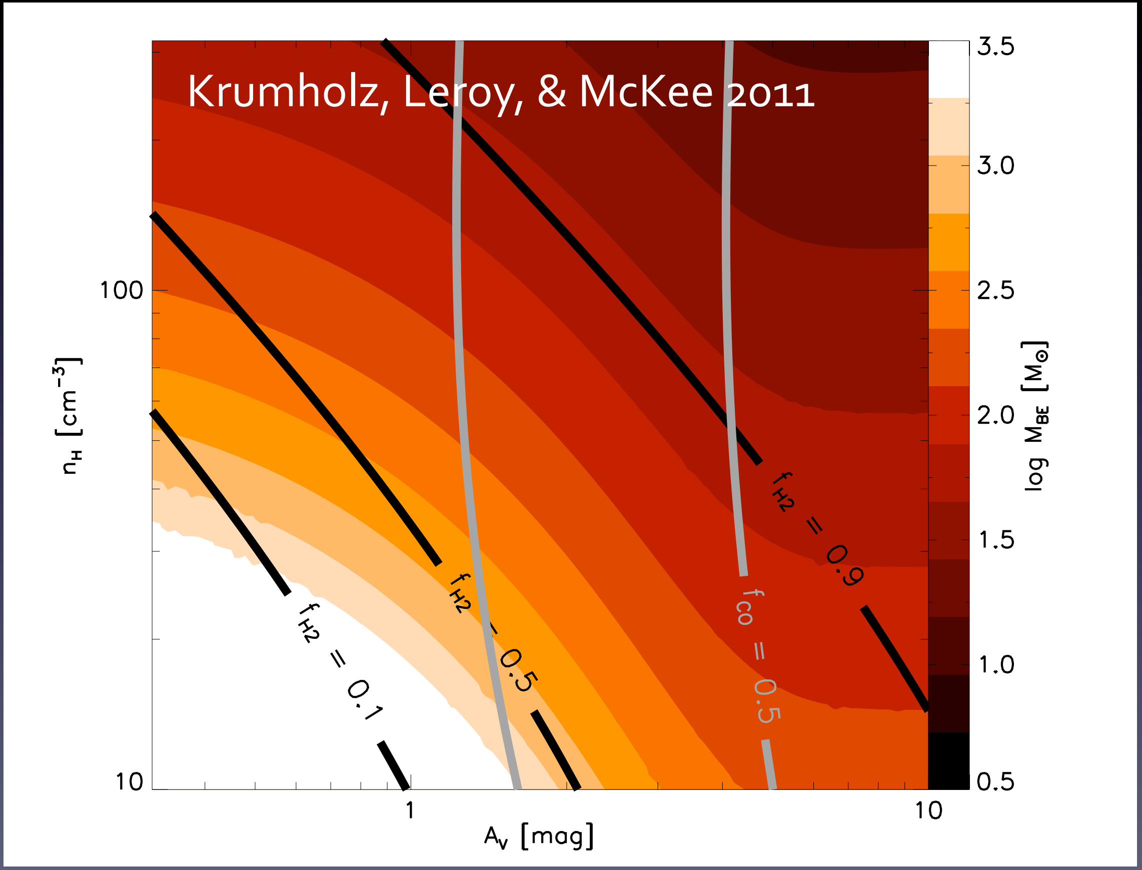
Analytic solution for location of HI / H_2 transition vs. exact numerical result

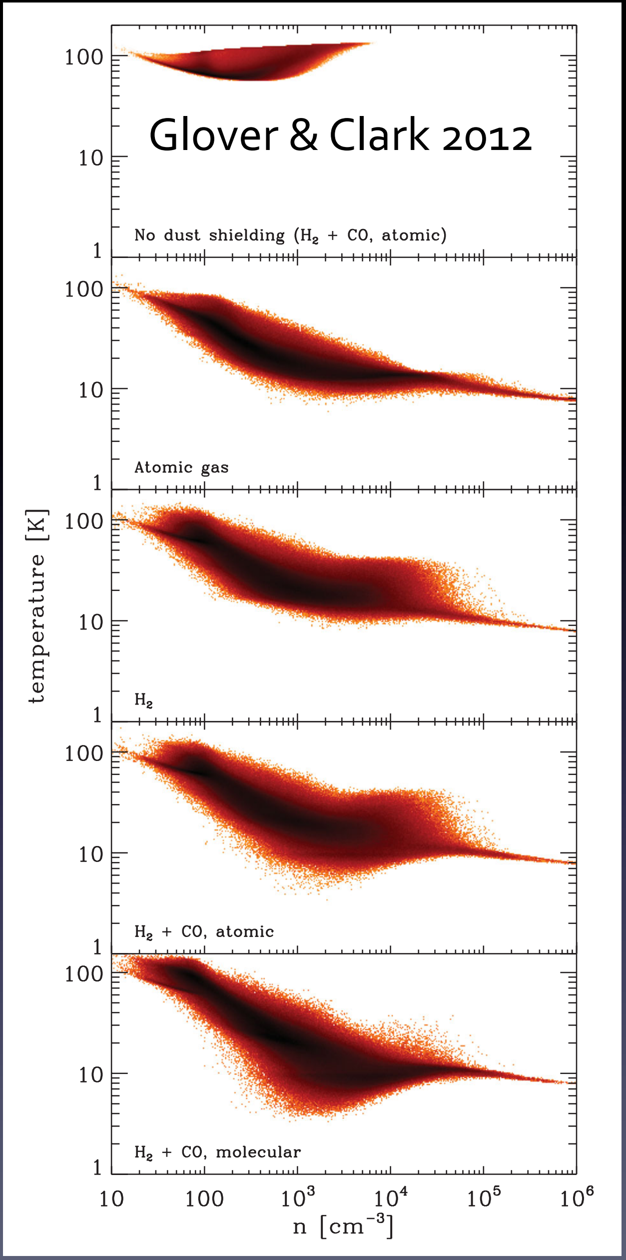
Calculating f_{H_2}



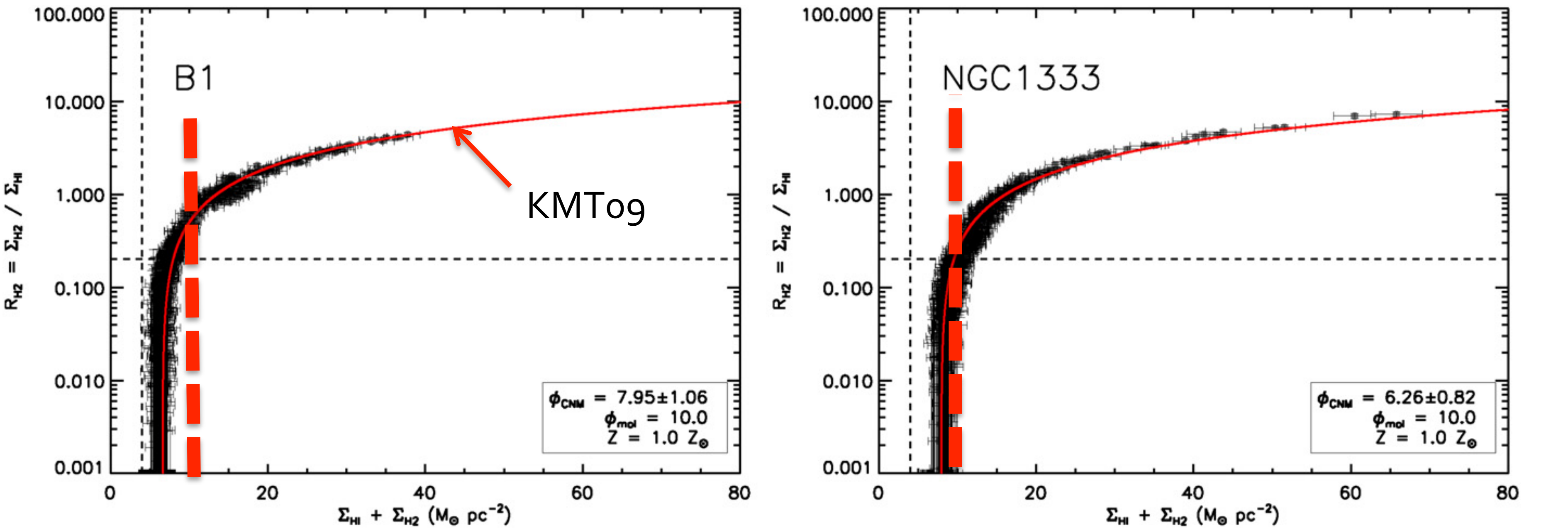
Qualitative effect: f_{H_2} goes from ~0 to ~1 when $\Sigma Z \sim 10\ M_\odot\ \mathrm{pc}^{-2}$

Why Does SF Follow H_2?



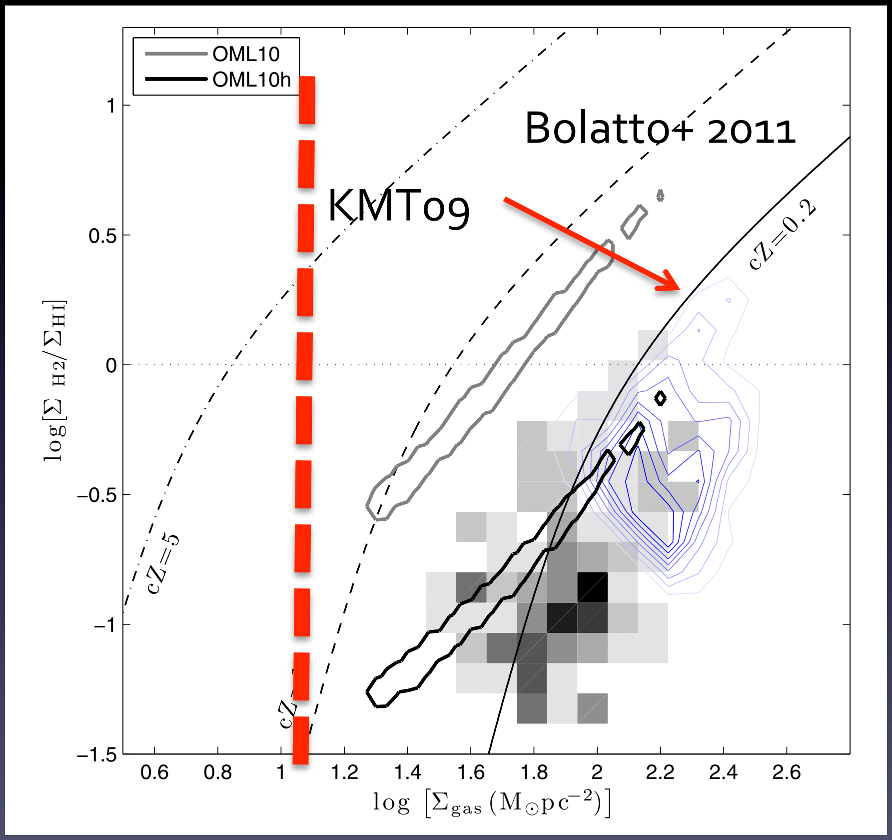


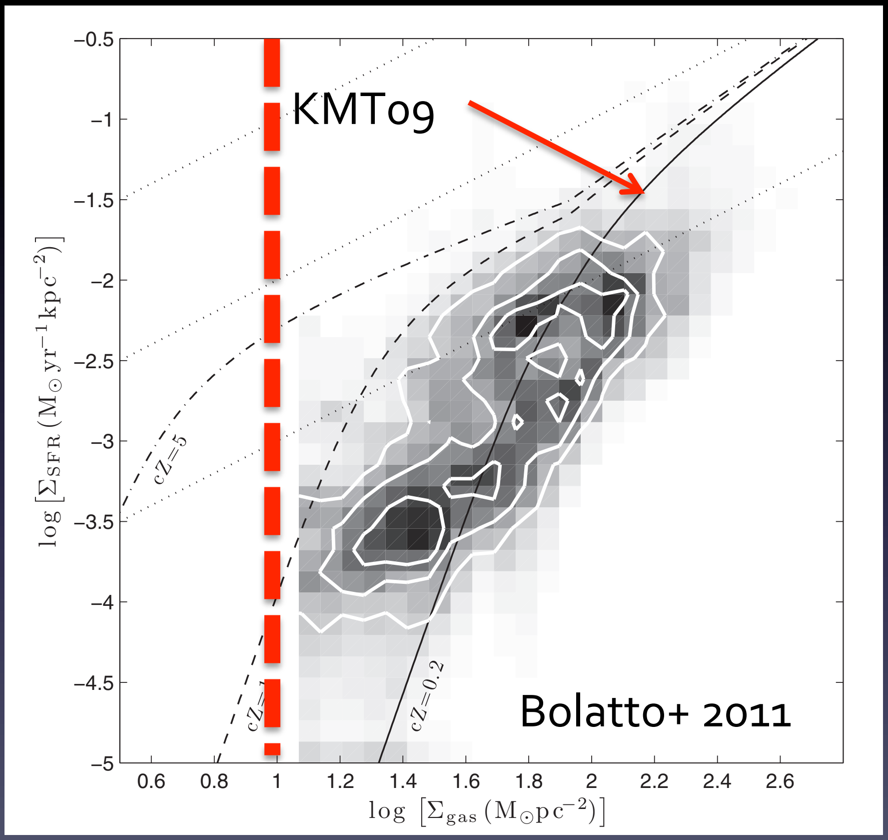
The Local HI – H2 Transition



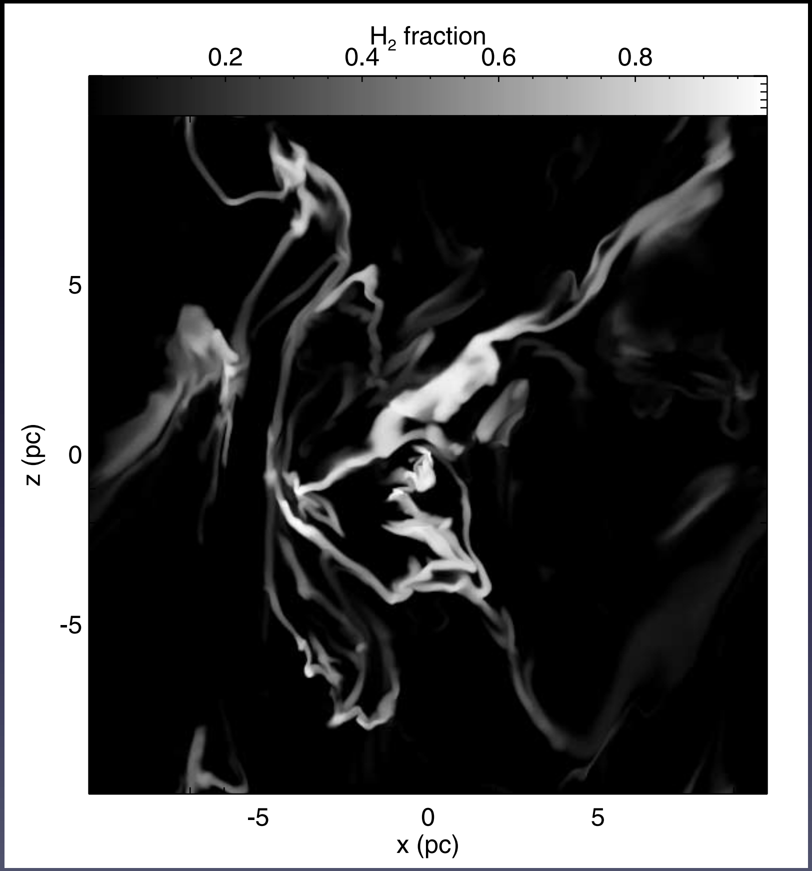
Lee+ 2012

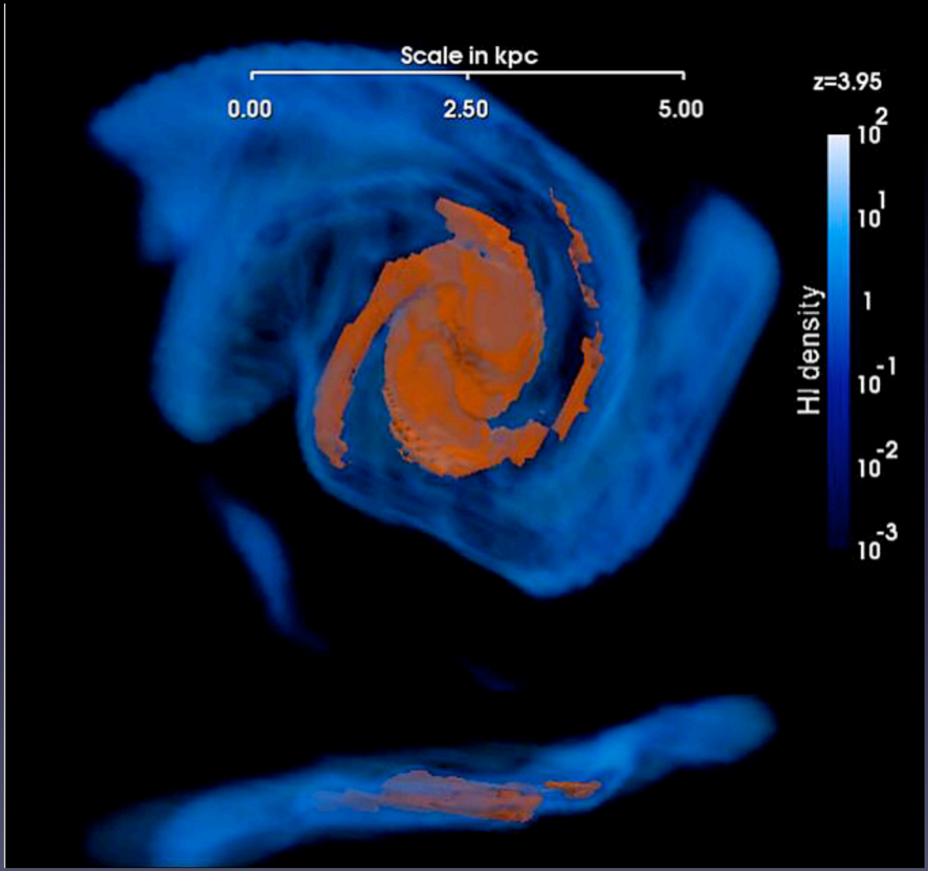
Extra-Galactic Phase Dependence





Non-Equilibrium Effects



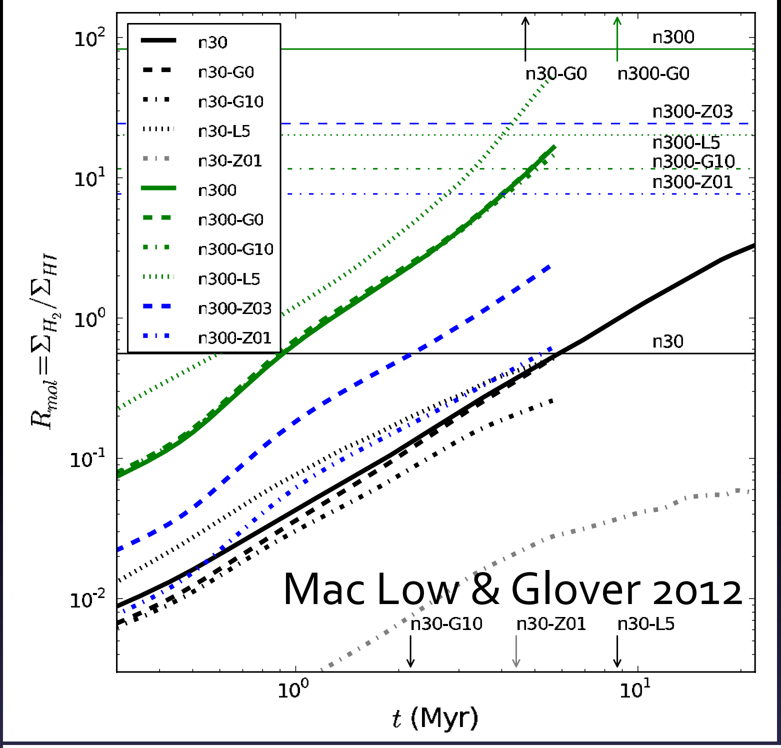


L ~ 10 pc; Glover & Mac Low 2007

L ~ 1 kpc; Gnedin+ 2009

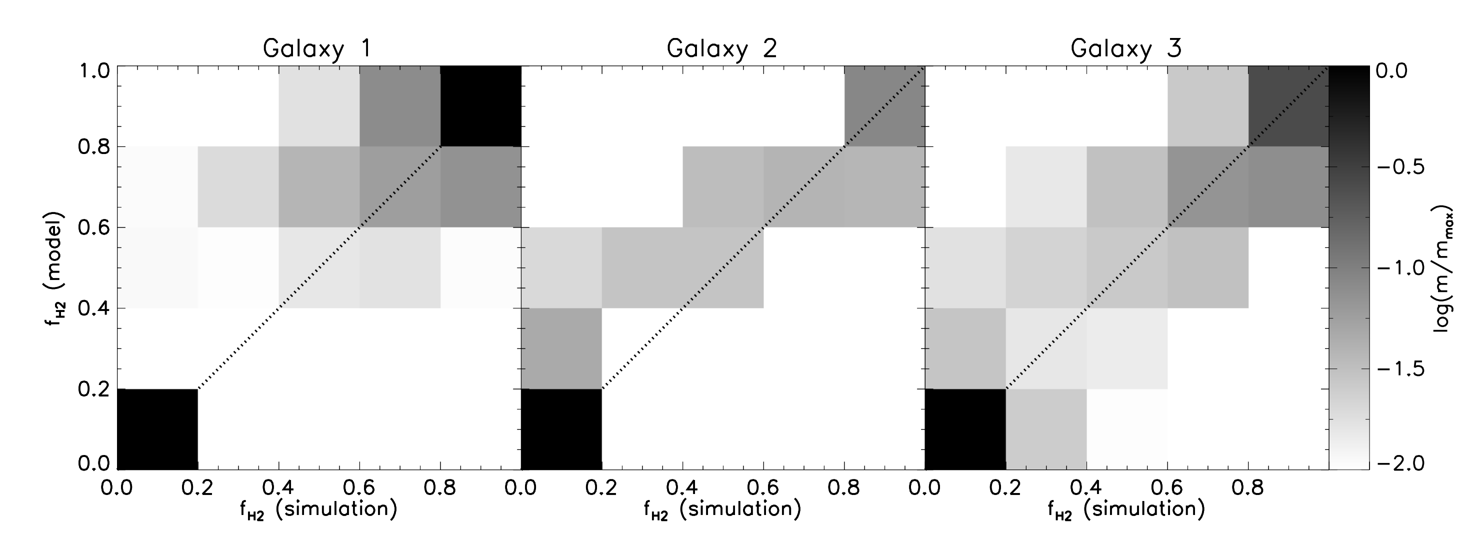
See also Pelupessy+ 2009, Christensen+ 2012

Is H_2 in Equilibrium?



Depends on size scale and gas metallicity:

- > 100 pc scales: yes on average
- ~10 pc scales: maybe; simulations suggest no, but observations suggest yes,

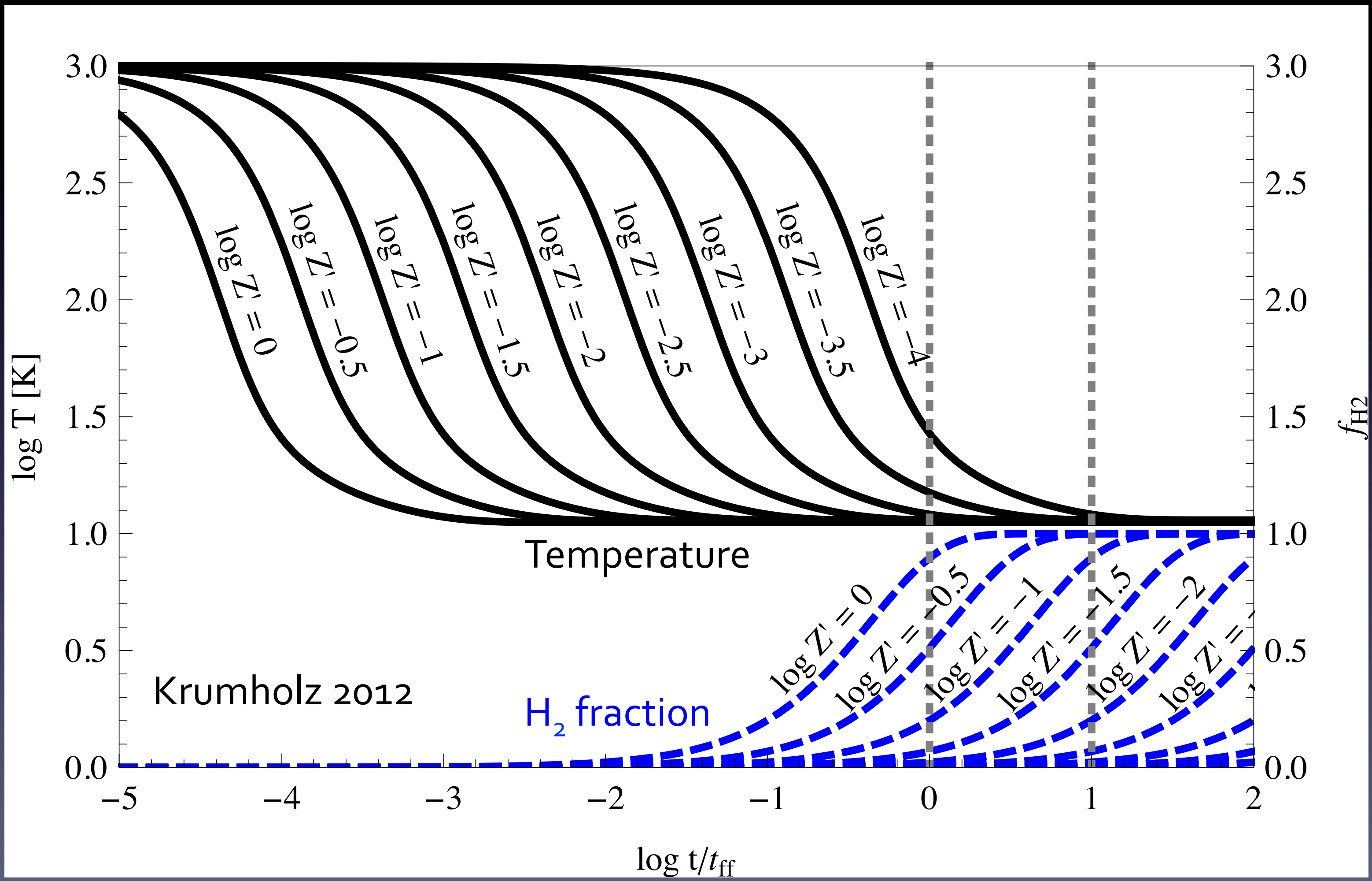


Krumholz & Gnedin 2011

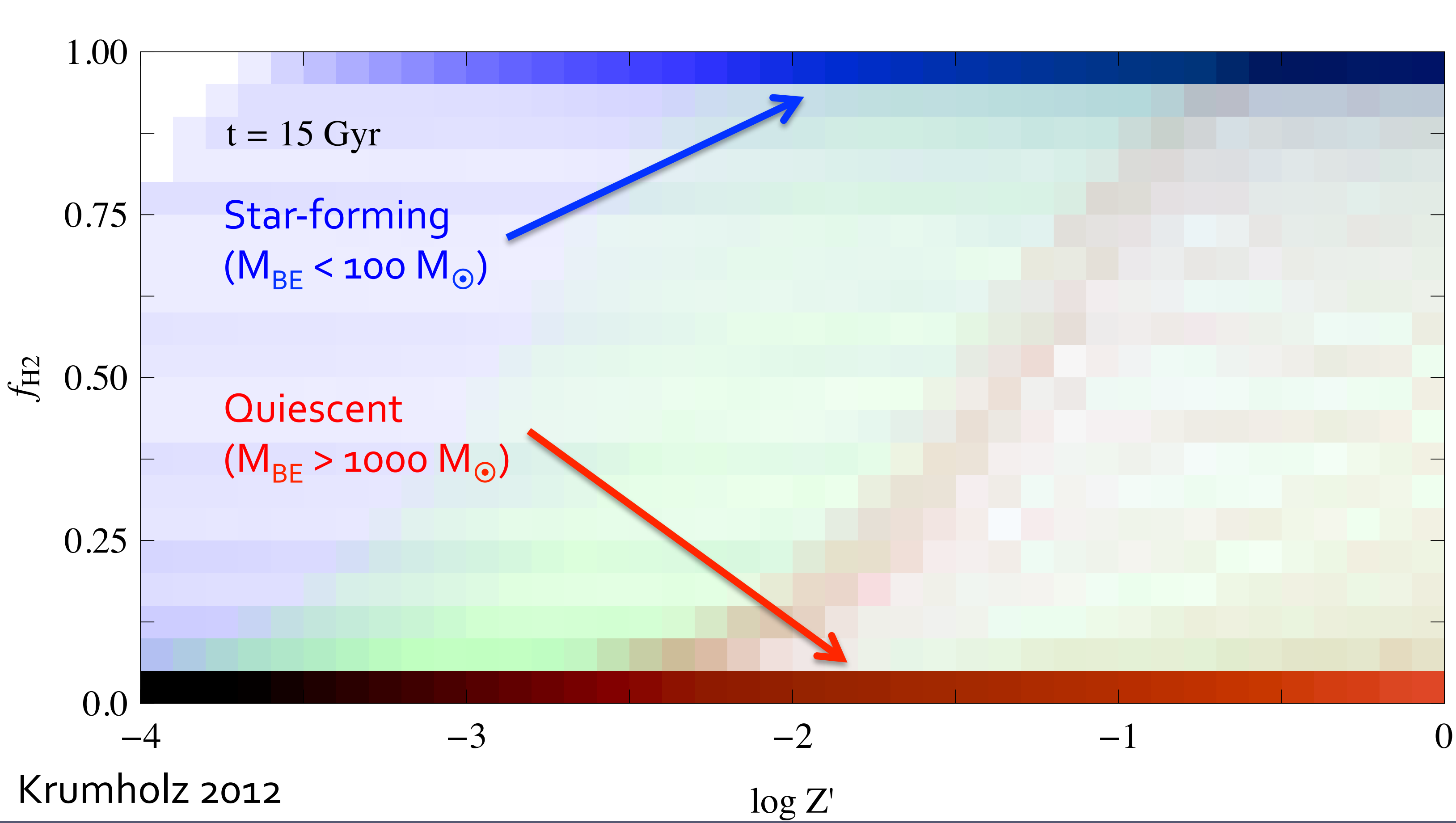
Equilibrium Timescales

- H_2 forms slowly: $t_{H_2} \sim 1/n\mathcal{R} \approx 100$ Myr$/n_1 C$ Z'
- Gas cools quickly: $t_{cool} \sim (T/91\ K)\ /\ k_{CII\text{-}H}\ \delta_C\ n =$ $0.04/n_1 C$ Z' $(T/91\ K)\ \exp(91\ K/T)$ Myr
- At low Z', can have $t_{cool} << t_{ff} << t_{H_2}$ ➔ SF should take place before bulk of gas forms H_2

Equilibrium Timescales



Implication: SF in HI!



Krumholz 2012

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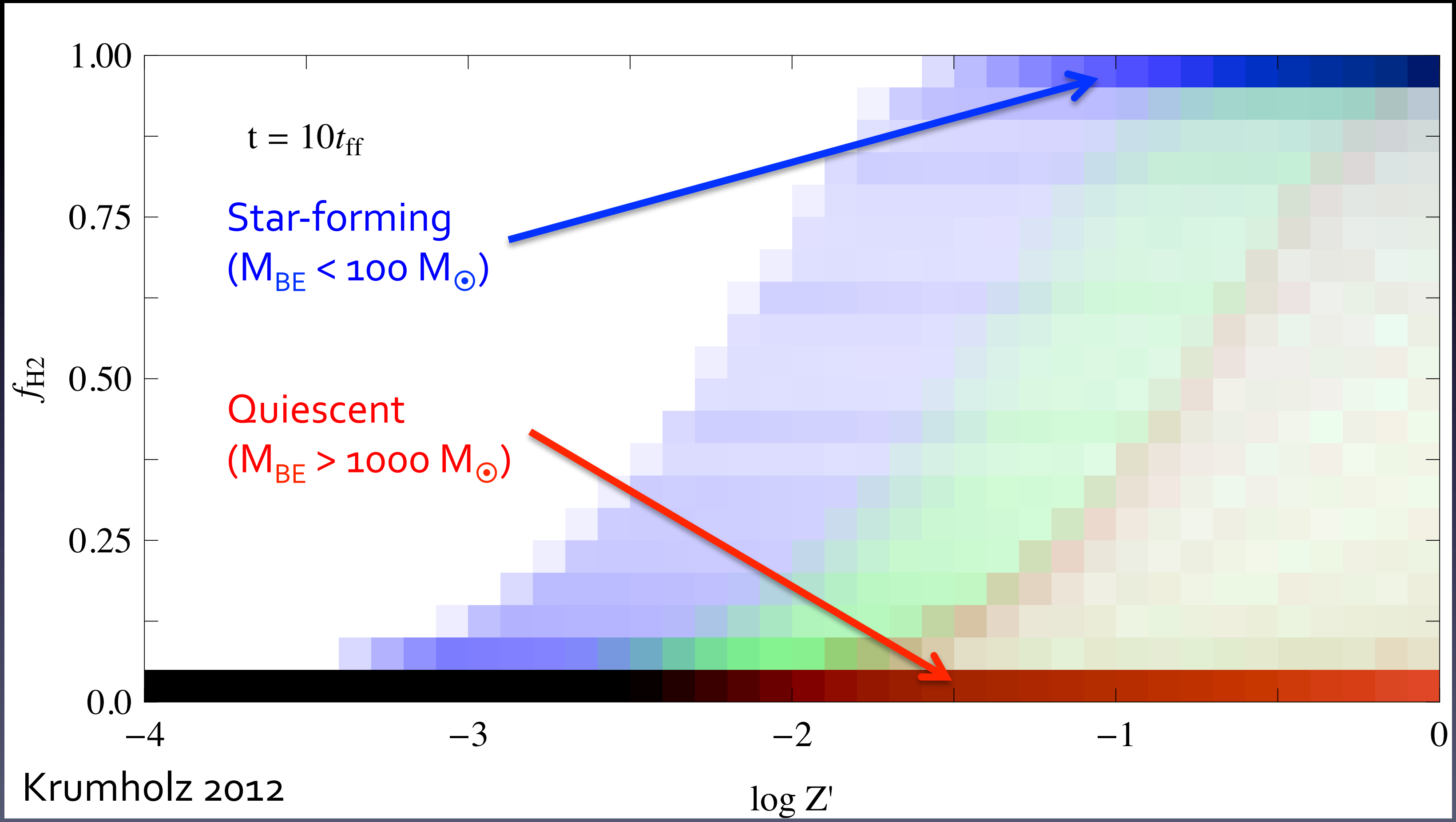

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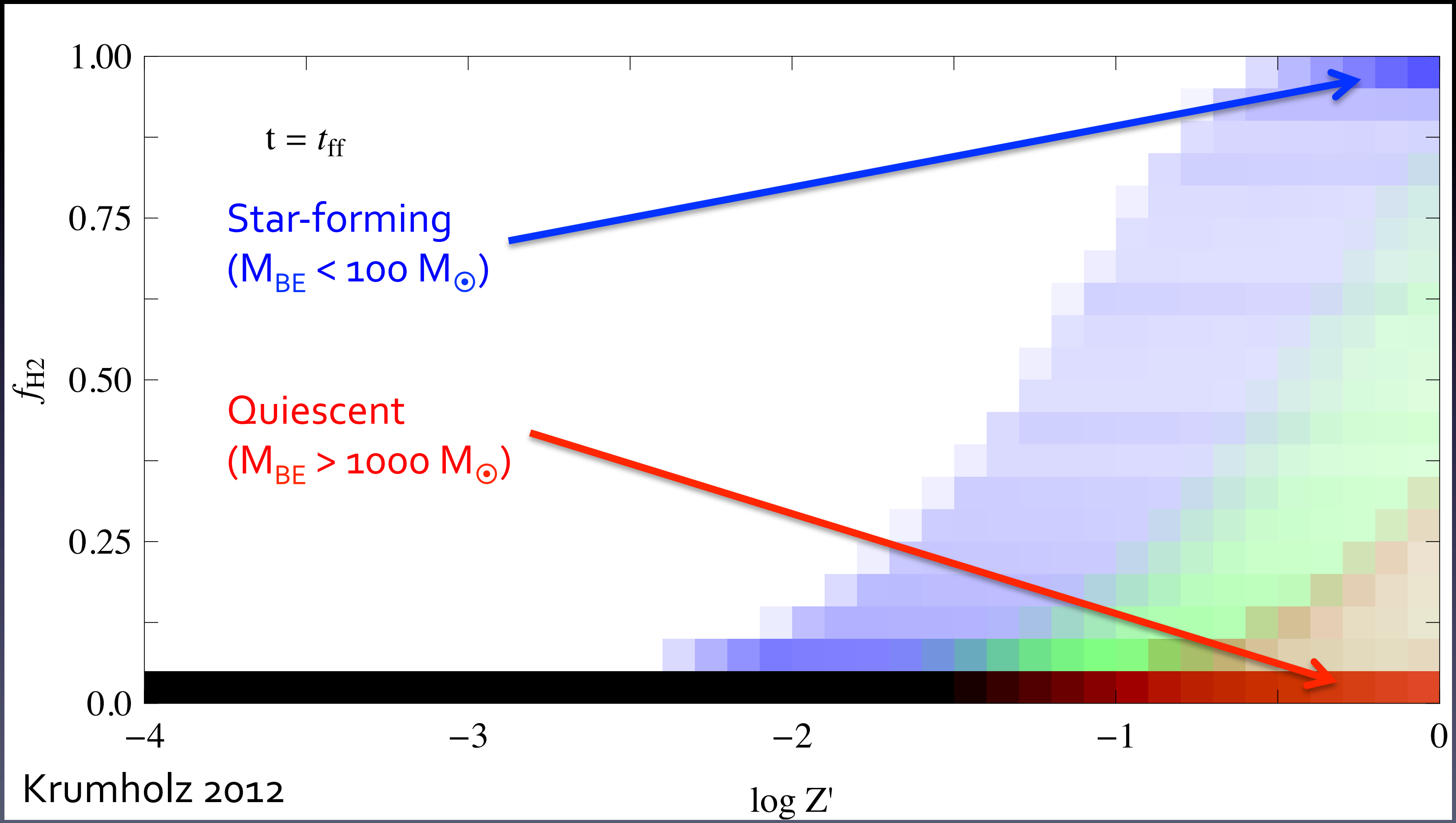
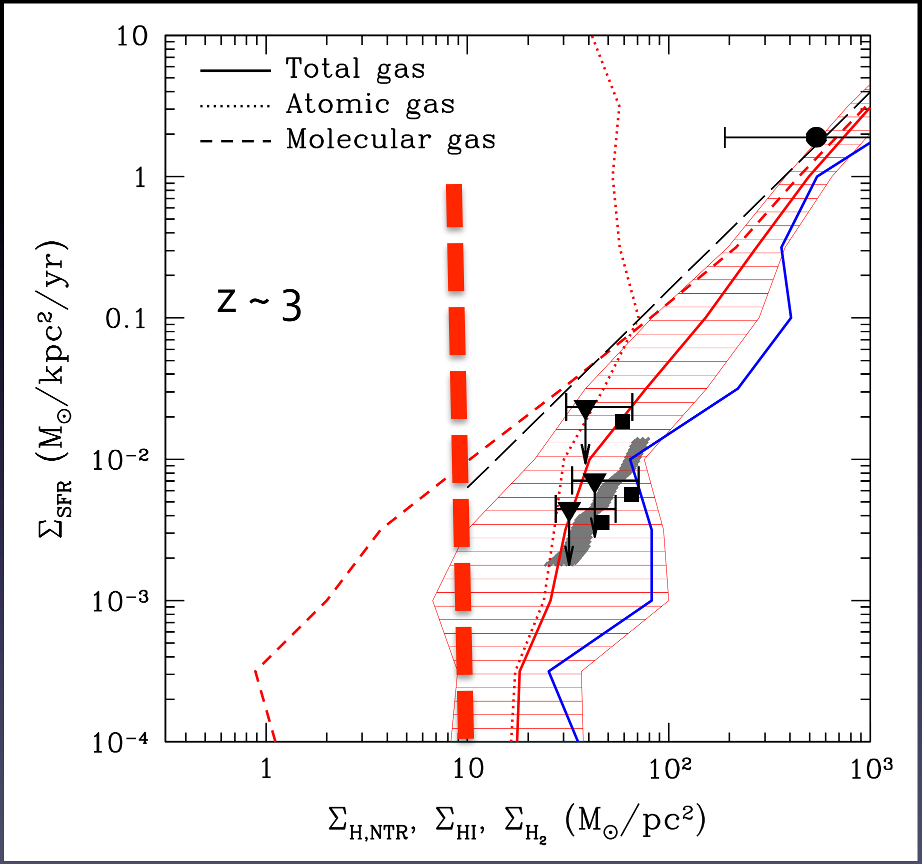
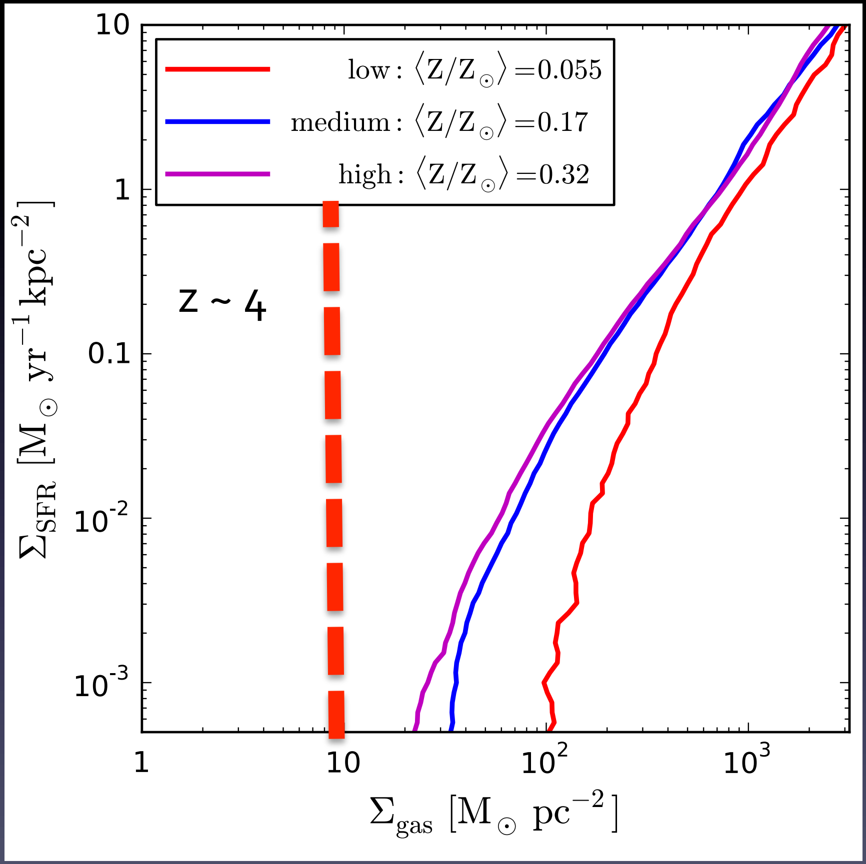


Cosmological Implications

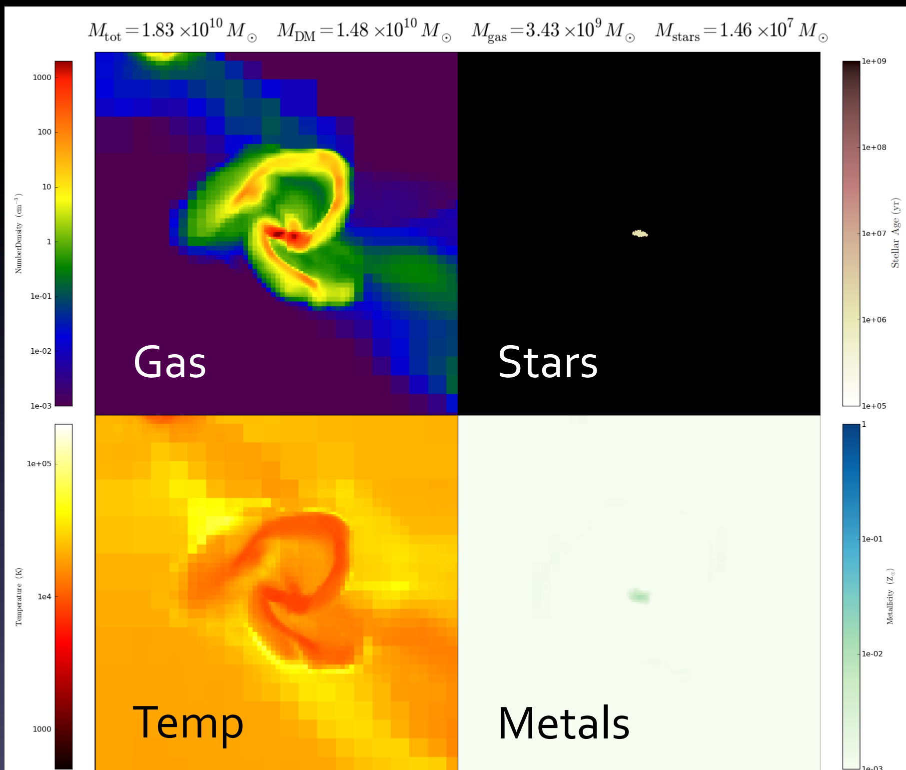


Gnedin & Kravtsov 2010

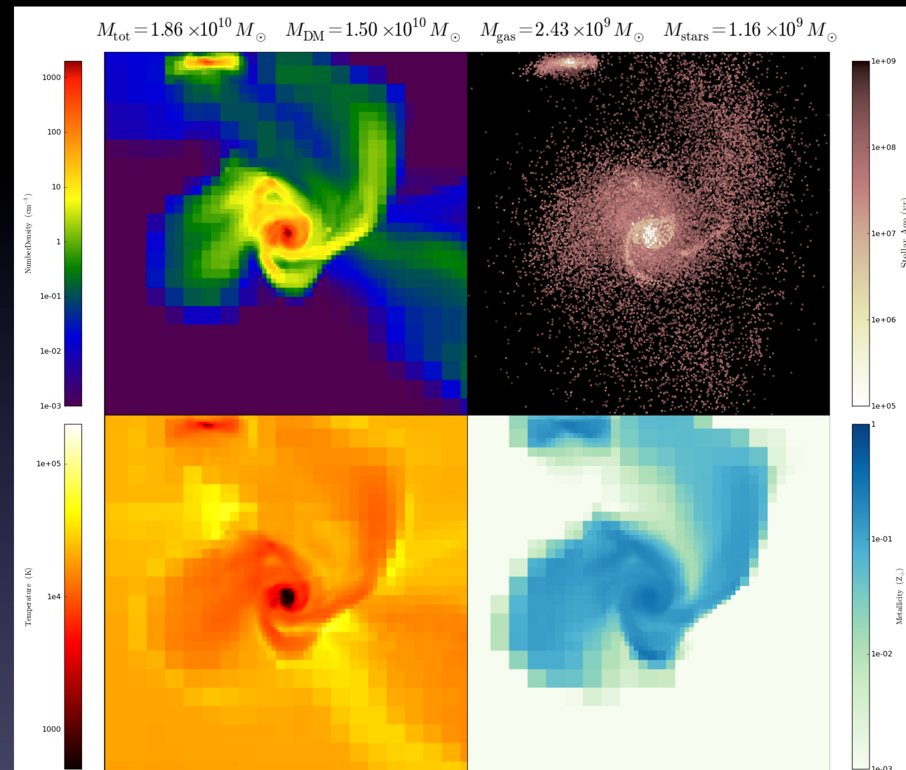


Kuhlen+ 2012

Metallicity-Regulated SF



Metallicity-dependent SF

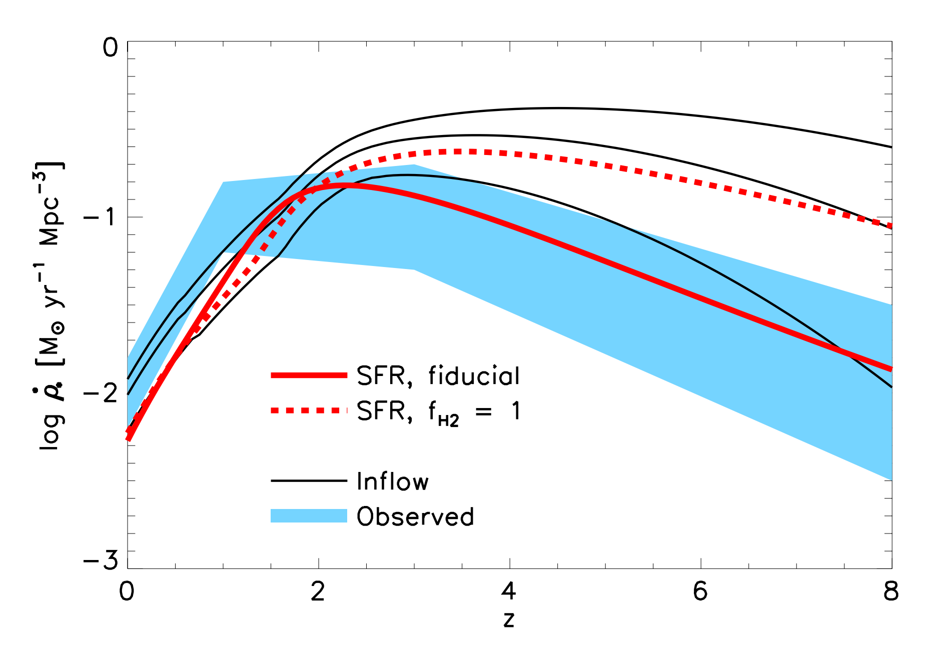


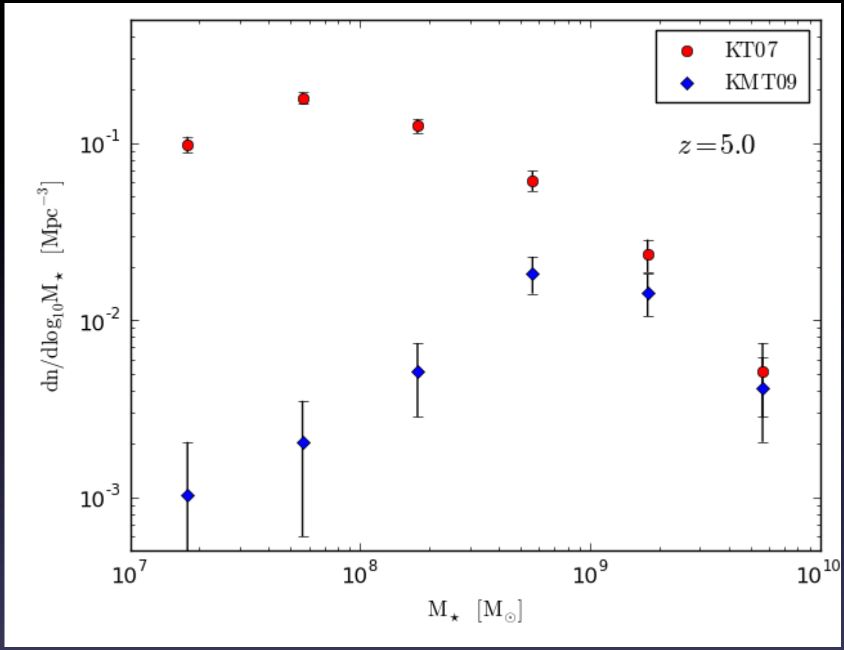
Metallicity-independent SF

Same halo (~10^{10} $M_\odot$, z~5) in two simulations with different SF recipes (Kuhlen+ 2012)

Mass Function and SF at High z

Krumholz & Dekel 2012

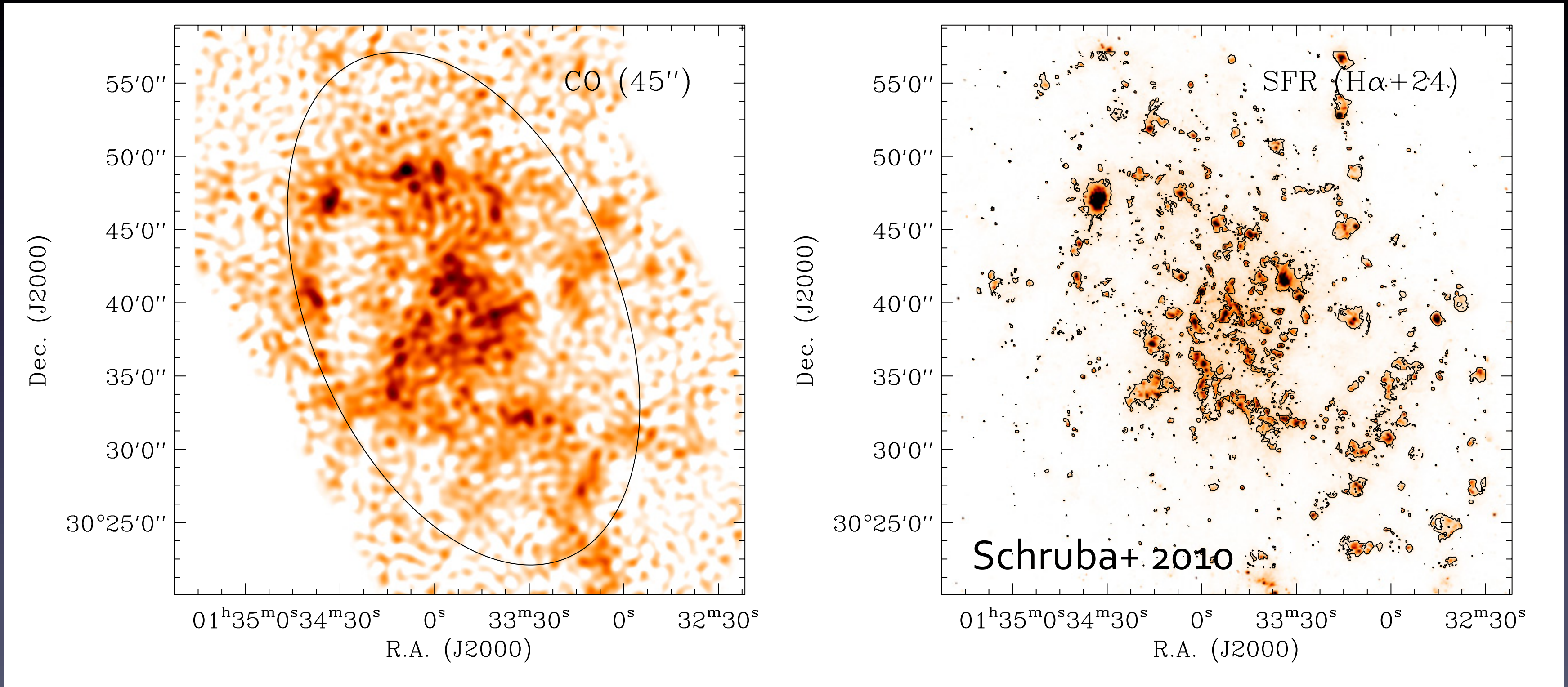




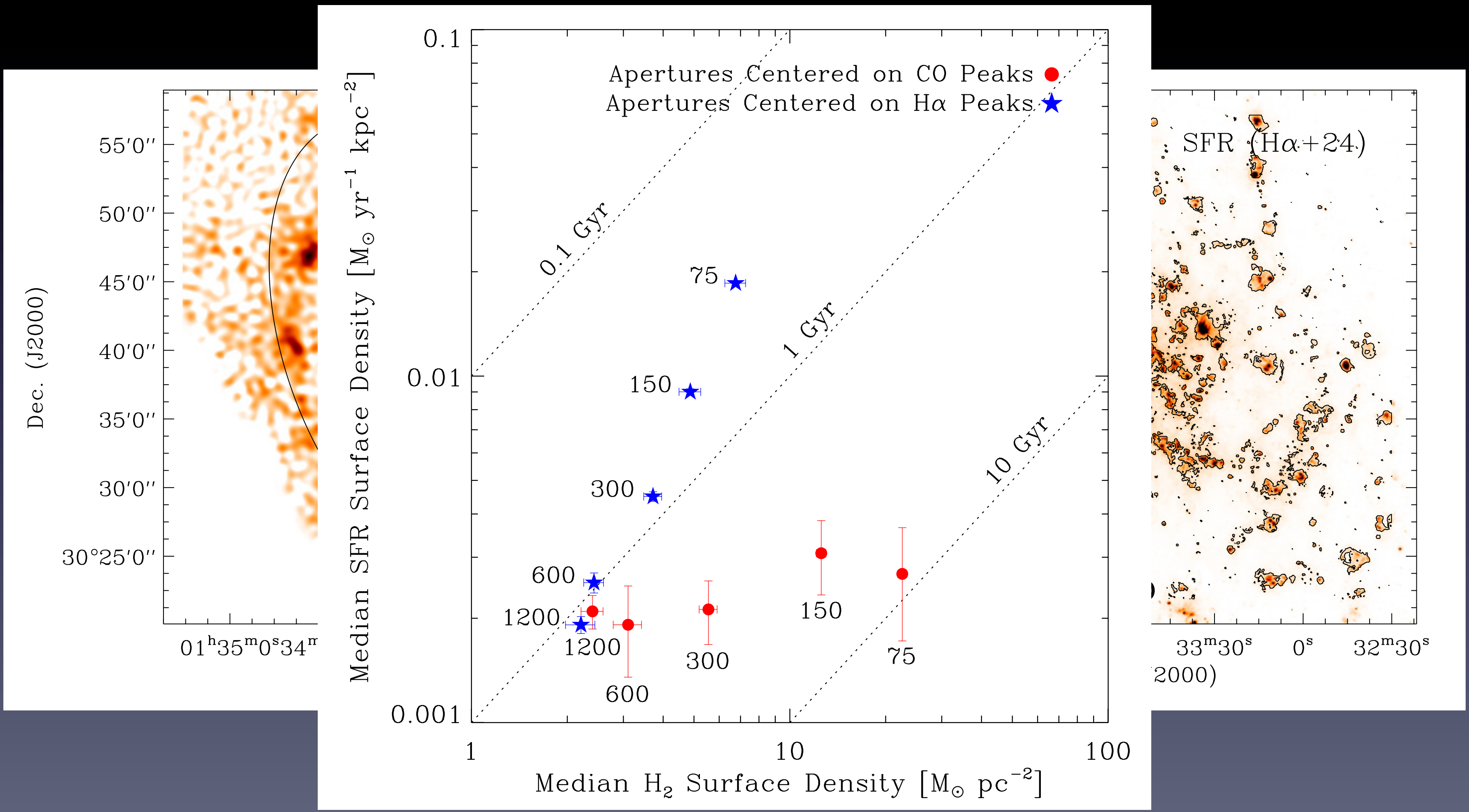
Kuhlen+ 2012

The Future: Mapping out the Space Between Local and Galactic

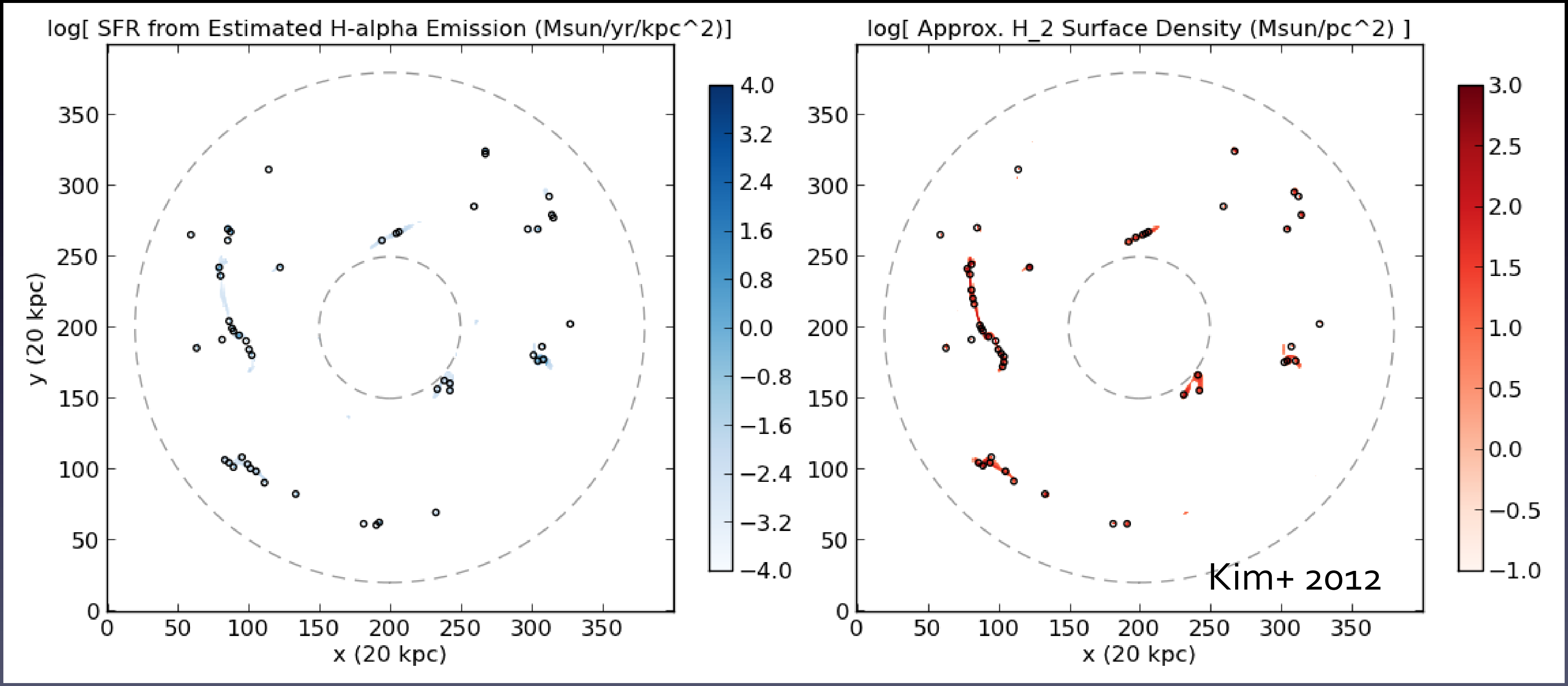
Extragalactic SF Laws at High Resolution



Extragalactic SF Laws at High Resolution



Comparison to Model



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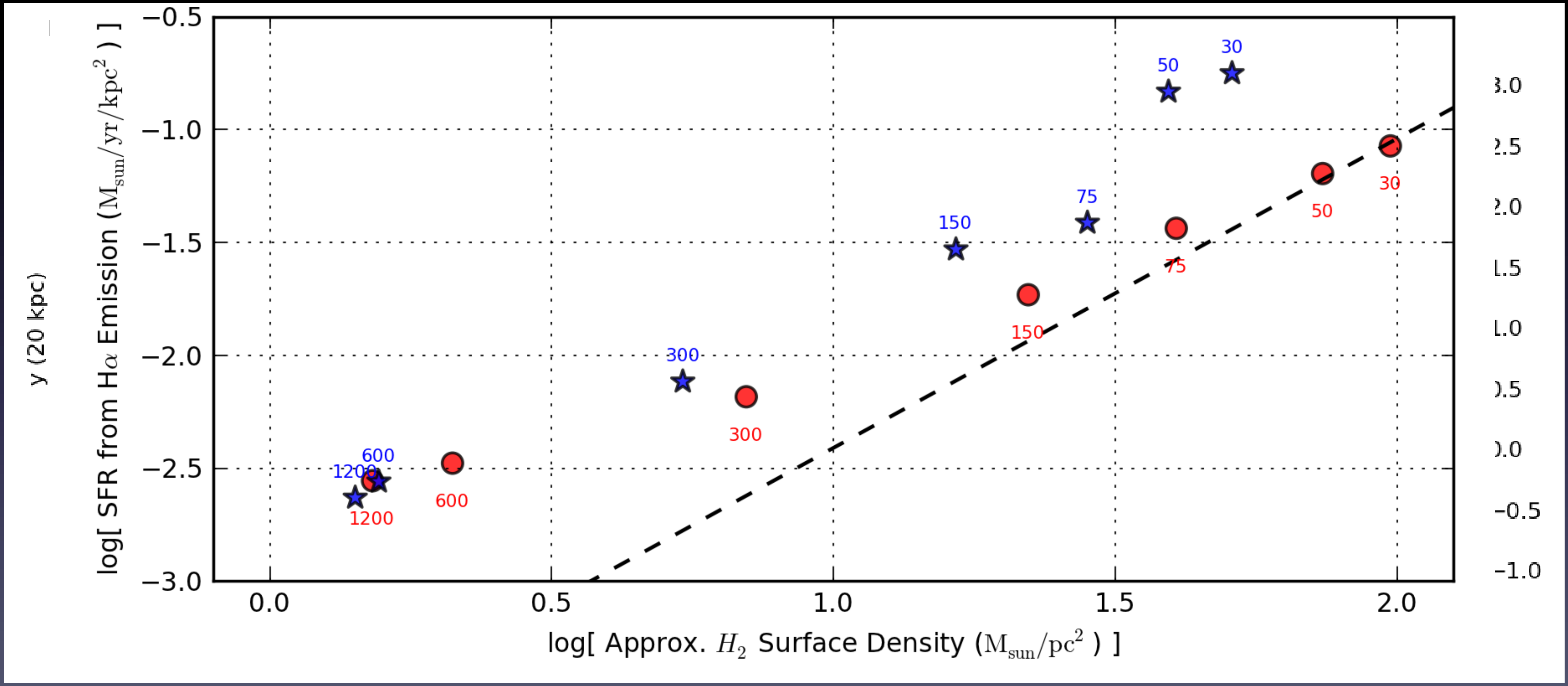
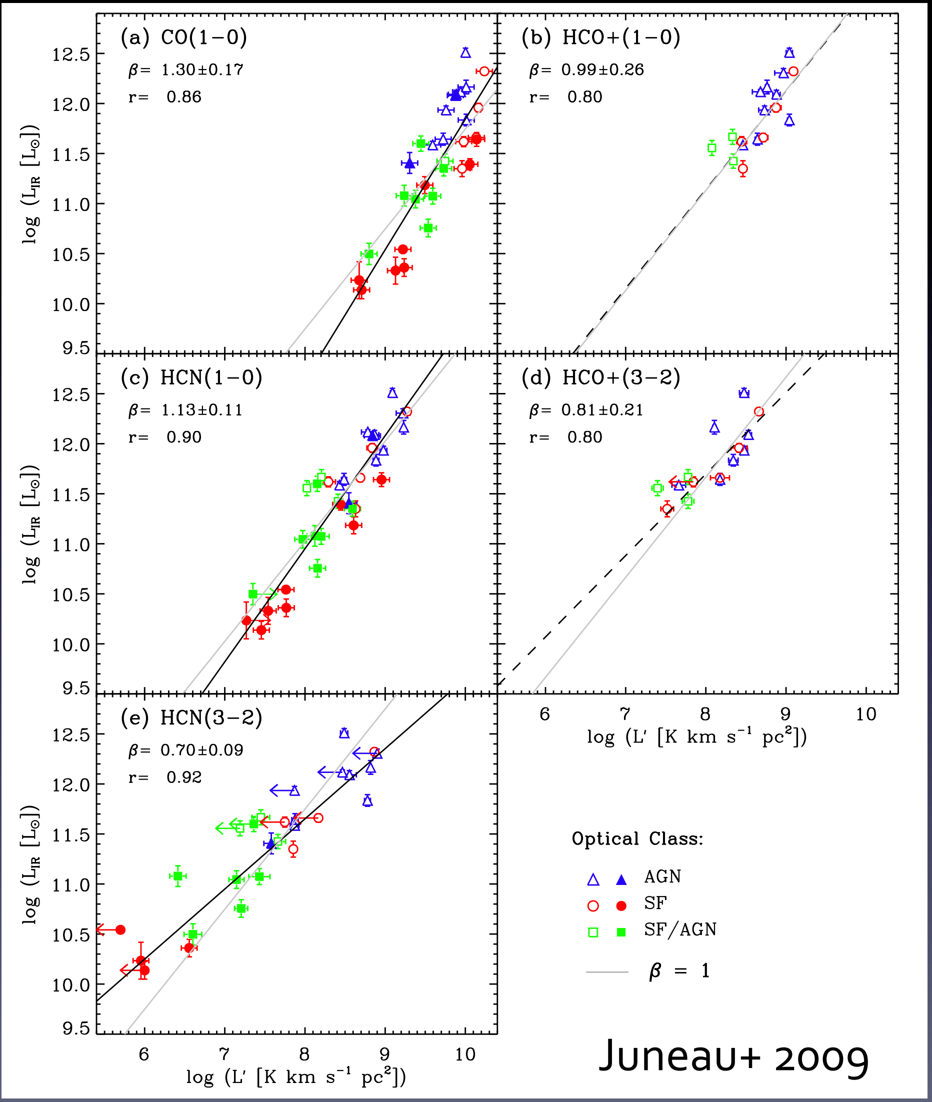
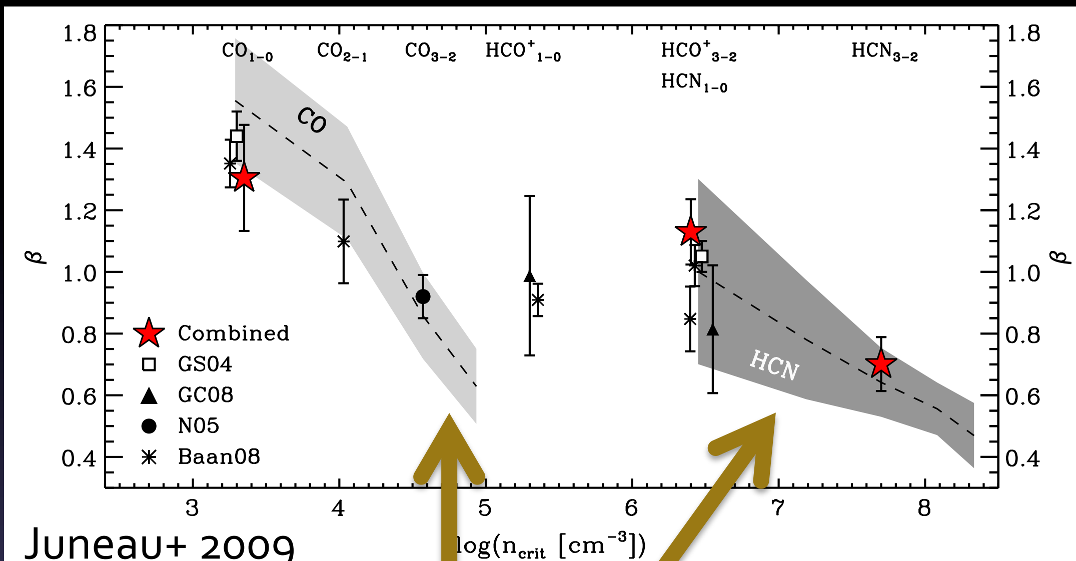


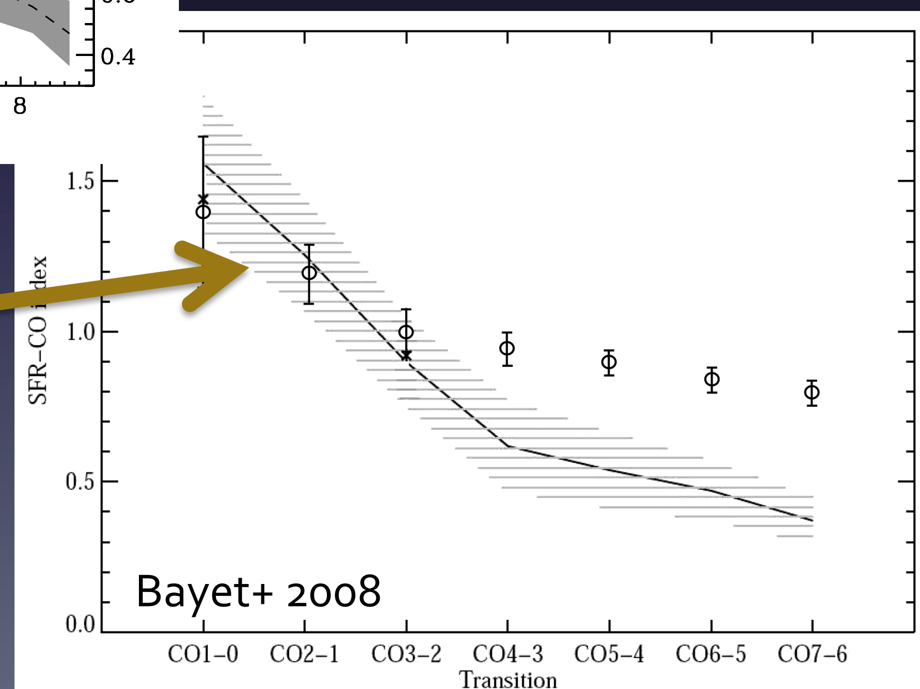
SF Laws in Many Lines



Juneau+ 2009

Comparison to Model





Models: Narayanan+ (2008)

Summary

- Can local and extra-galactic laws be unified? Depends on whether SF regulation is top-down or bottom-up
- Can laws for different phases / metallicities be unified with other laws? Yes, but this only happens naturally in a bottom-up framework.
- Promising approach: measure and predict SF laws at intermediate scales and densities