Physical Origins of the Star Formation Law

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The SFR in a Nutshell

- Stars form only in molecular gas.
- In molecular gas, a (nearly) constant fraction ε_{ff} of the gas forms stars per t_{ff}

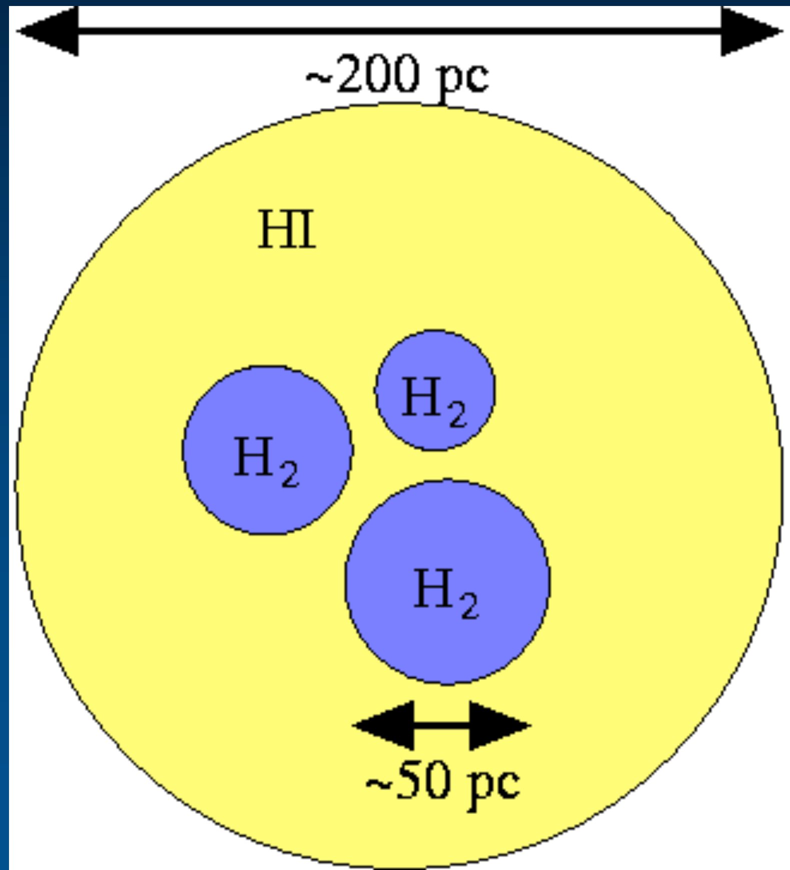
Computing the SFR therefore requires:

1. Computing the H_2 mass fraction
2. Computing t_{ff} in the molecular gas
3. Computing ε_{ff}

That's it.

Step 1: Computing the Molecular Fraction

- Molecules reside in giant molecular clouds (GMCs) that are the inner parts of atomic-molecular complexes
- The outer parts are dissociated by interstellar Lyman-Werner photons
- Goal: compute HI and H_2 mass fractions



Dissociation Balance in Atomic-Molecular Complexes

(Krumholz, McKee, & Tumlinson 2008a; McKee & Krumholz 2009)

The basic equations for this system are *chemical equilibrium* and *radiative transfer*.

$$
\begin{aligned}
n_{\mathrm{HI}} n \mathcal{R} &= n_{\mathrm{H_2}} \int d\Omega \int d\nu \, \sigma_{\mathrm{H_2}} f_{\mathrm{diss}} I_\nu / (h\nu) \\
\hat{e} \cdot \nabla I_\nu &= -(n_{\mathrm{H_2}} \sigma_{\mathrm{H_2}} + n \sigma_{\mathrm{d}}) I_\nu
\end{aligned}
$$

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Idealized problem: spherical cloud of radius *R*, density *n*, dust opacity σ_d, H_2 formation rate coefficient $\mathcal{R}$, immersed in radiation field with LW photon number density E_0^*, find fraction of mass in HI and H_2.

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Formation on grains = Photodissociation

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

Decrease in radiation intensity =

Absorptions by H2 molecules + dust grains

Idealized problem: spherical cloud of radius *R*, density *n*, dust opacity σ_d, H_2 formation rate coefficient $\mathcal{R}$, [illegible] radiation field with LW photon number density E_0^*, find fraction of mass in HI and H_2.

Calculating Molecular Fractions

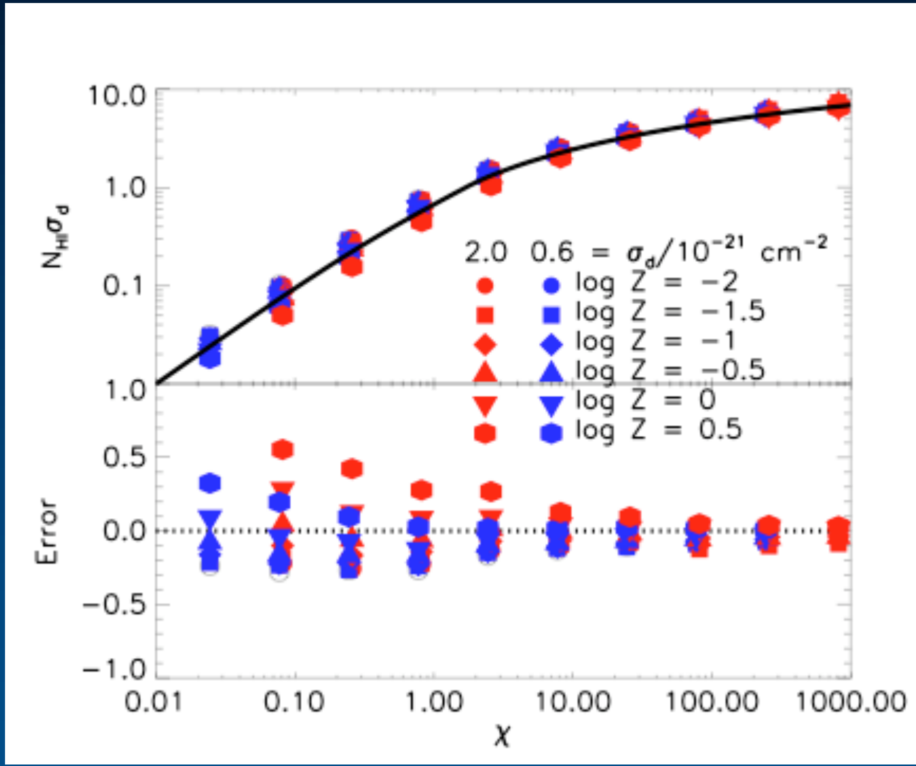
To good approximation, solution only depends on two numbers:

$$\tau_R = n\sigma_d R$$

$$\chi = \frac{f_{diss}\sigma_d E_0^*}{n\mathcal{R}}$$

A semi-analytic solution can be given from these parameters.

τ_R depends only on galaxy Σ, Z $\Rightarrow$ can be measured directly



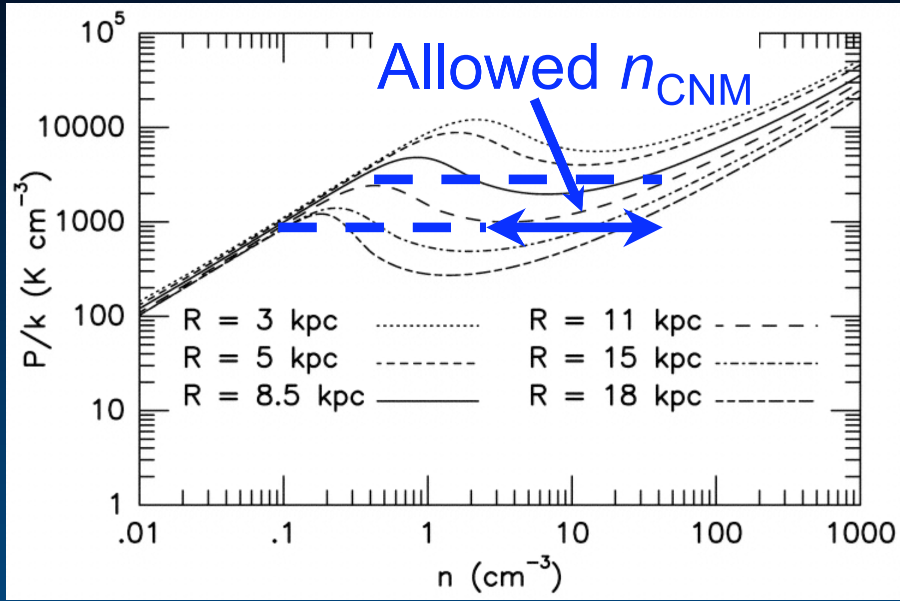
Analytic solution for location of HI / H_2 transition vs. exact numerical result

Shielding Layers in Galaxies

(Krumholz, McKee, & Tumlinson 2009)

What is $\chi \propto (\sigma_d / \mathcal{R})\ (E_0^* / n)$?

- Dust opacity σ_d and H_2 formation rate $\mathcal{R}$ both $\propto$ Z, so $\sigma_d / \mathcal{R} \sim$ const
- CNM dominates shielding, so n is the CNM density



FGH curves for MW (Wolfire et al. 2003)

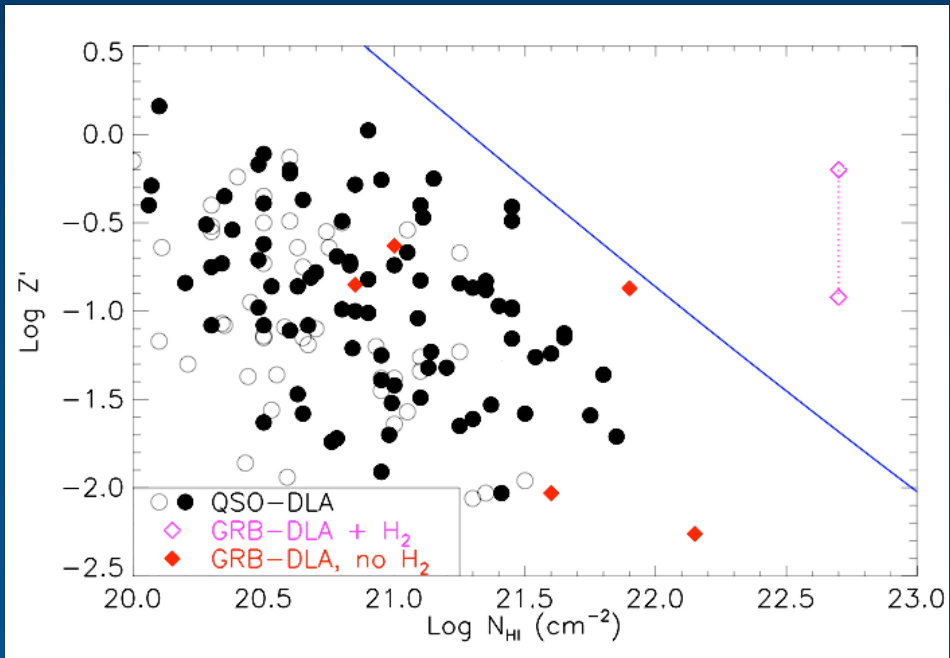
- CNM density set by pressure balance with WNM, and $n_{CNM} \propto E_0^*$, with weak Z dependence.

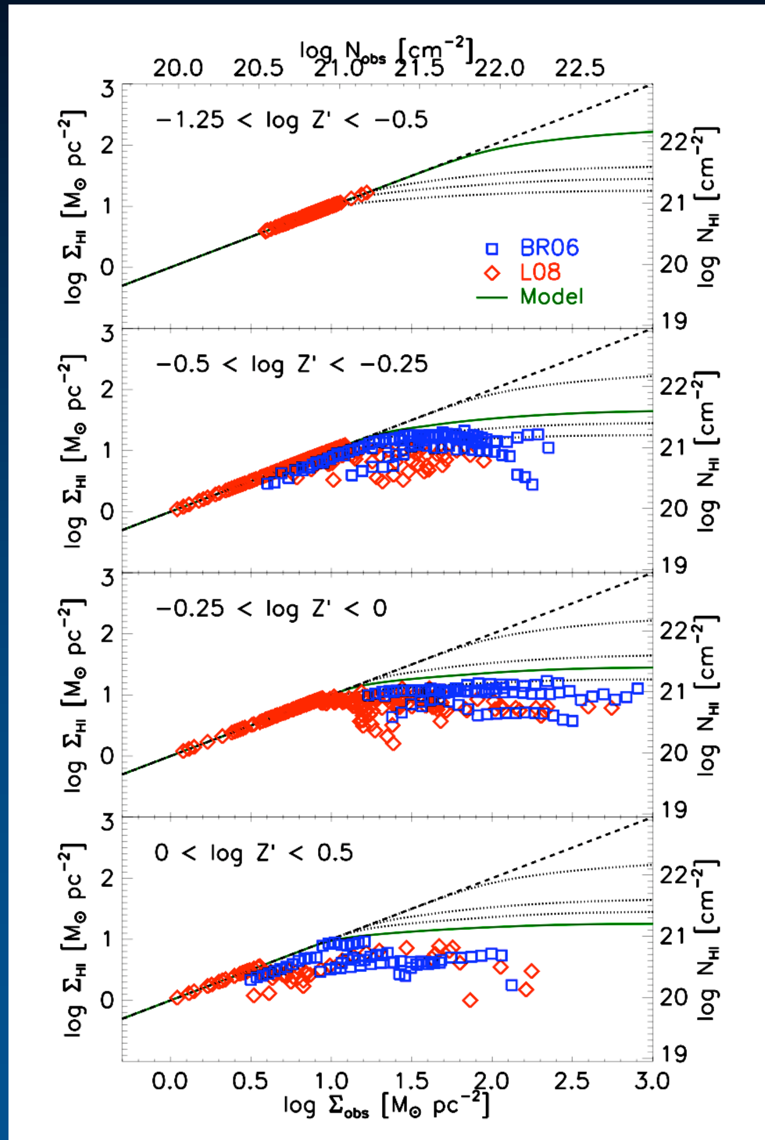
$\Rightarrow$ $\chi \propto (\sigma_d / \mathcal{R})\ (E_0^* / n) \sim 1$ in all galaxies!

$\Rightarrow$ $f_{H2}(\Sigma, Z)$ given by an analytic fitting formula!

Successful Model Predictions

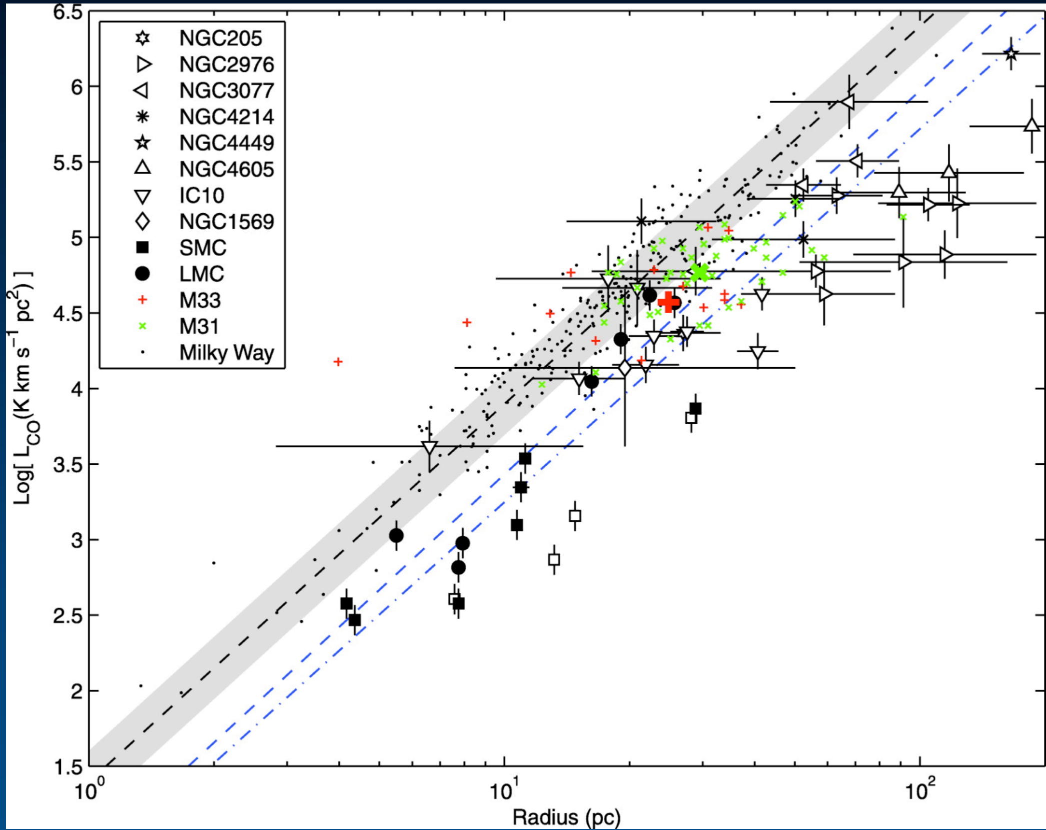
- H_2 fractions seen by THINGS (Krumholz, McKee, & Tumlinson 2009)
- Maximum HI columns of DLAs (Krumholz et al. 2009)
- When ram-pressure stripping causes galaxies to lose H_2 (Fumagalli et al. 2009; poster here)





Step 2: t_{ff} in GMCs

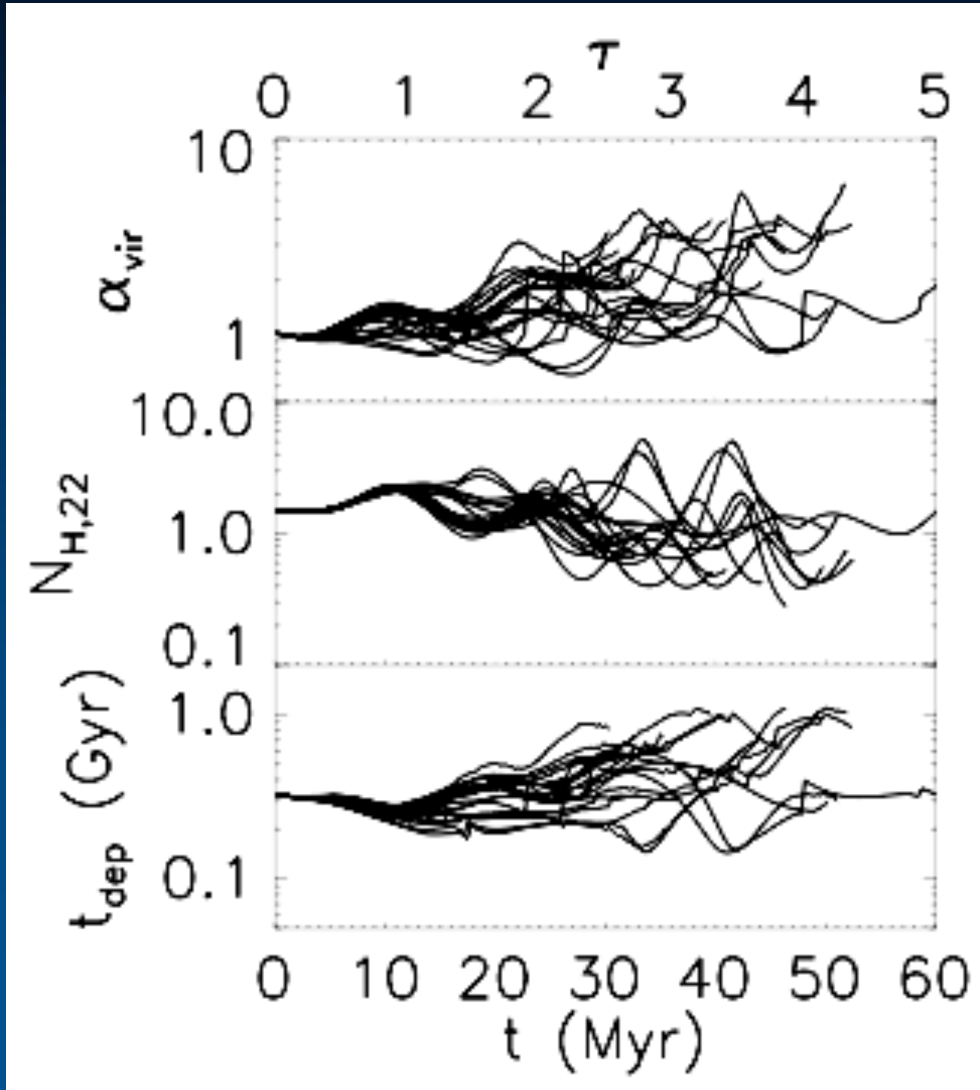
- GMCs in nearby galaxies all have $\Sigma_{GMC} \sim 100\ M_\odot\ pc^{-2}$ ($N_H \sim 10^{22}$) (Bolatto et al. 2008)



Luminosity (∝mass) vs. radius for galactic and extragalactic GMCs (Bolatto et al. 2008)

Step 2: t_{ff} in GMCs

- GMCs in nearby galaxies all have $\Sigma_{GMC} \sim 100\ M_\odot\ pc^{-2}$ ($N_H \sim 10^{22}$) (Bolatto et al. 2008)
- HII region feedback naturally keeps GMCs at this surface density (Krumholz, Matzner, & McKee 2006)



Evolution of GMC virial ratio, column density, and depletion time in semi-analytic models

Including the Starburst Regime

(Krumholz, McKee, & Tumlinson 2009)

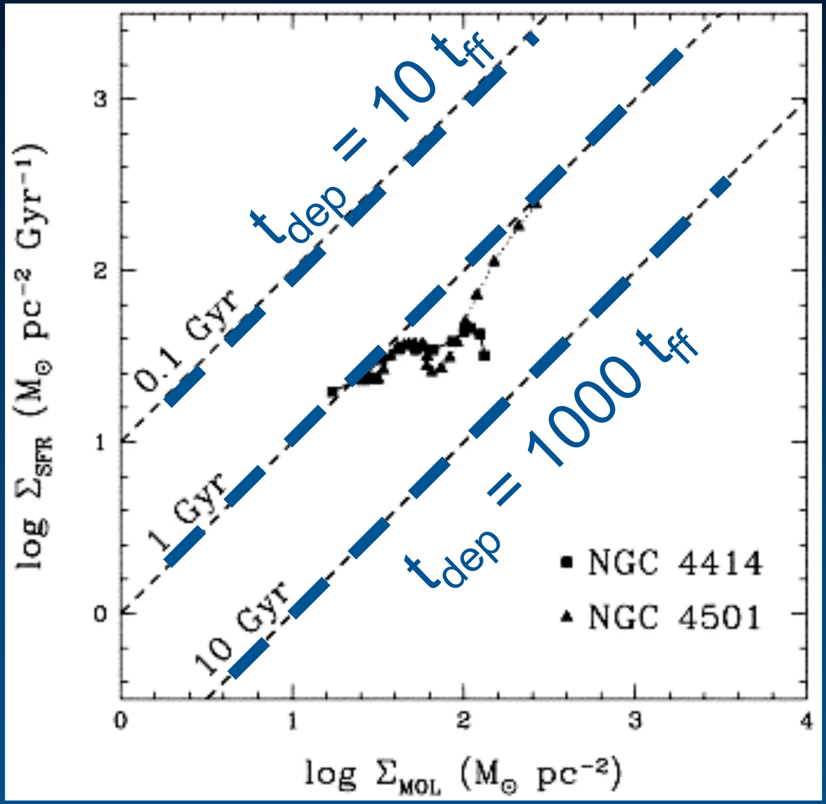
- Invariance of Σ_{GMC} breaks down when $\Sigma_{gal} > \Sigma_{GMC} \Rightarrow$ $\Sigma_{\rm GMC} = \max(85\, M_\odot\ {\rm pc}^{-2}, \Sigma_{\rm gal})$
- Most GMC mass is in objects with mass ~ galactic Jeans mass $\Rightarrow$

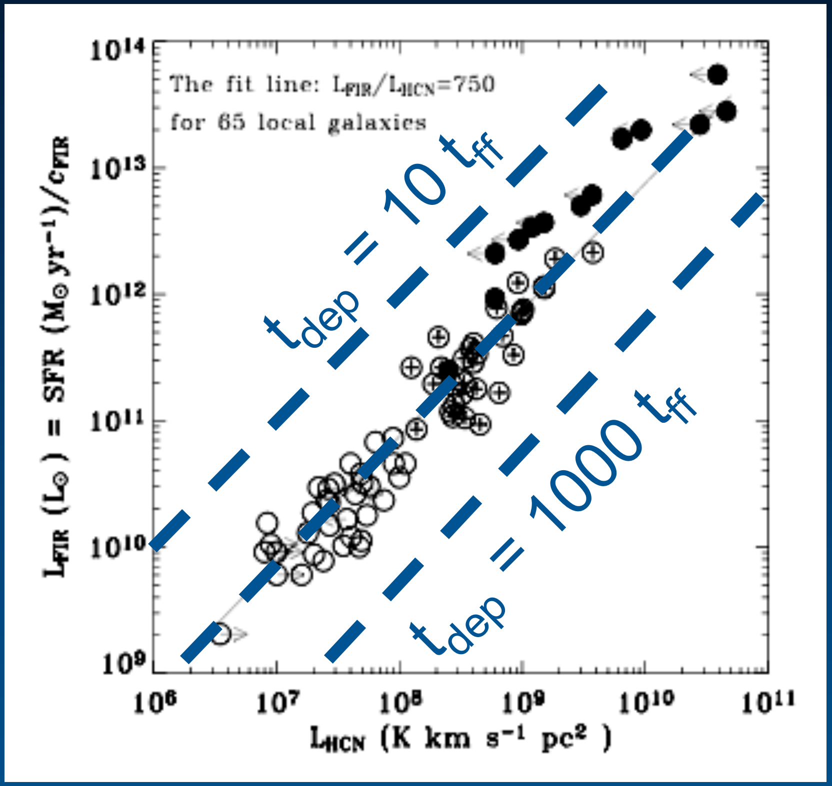
$$M_{\rm GMC} = 3.7 \times 10^7\, M_\odot \left(\frac{\Sigma_{\rm GMC}}{85\, M_\odot\ {\rm pc}^{-2}}\right)$$

- Combining:

$$t_{\rm ff} = 20\ {\rm Myr} \left[\left(\frac{\Sigma_{\rm gal}}{85\, M_\odot\ {\rm pc}^{-2}}\right)^{1/4}, \left(\frac{\Sigma_{\rm gal}}{85\, M_\odot\ {\rm pc}^{-2}}\right)^{-1/2}\right]$$

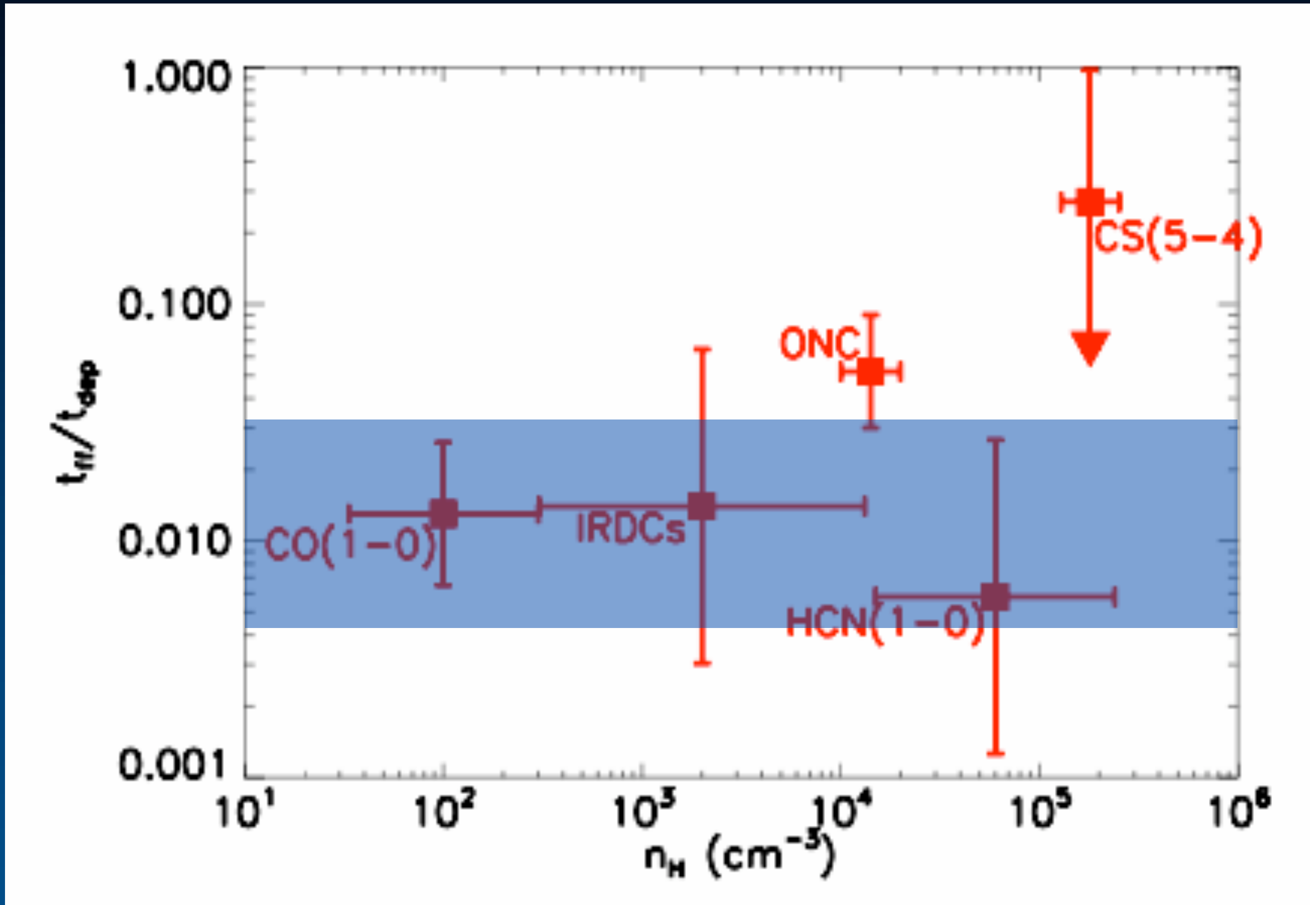
Step 3: Compute ϵ_{ff}





Depletion time as a function of Σ_{H2} for 2 local galaxies (left, Wong & Blitz 2002) and as a function of L_{HCN} for a sample of local and z ~ 2 galaxies (right, Gao & Solomon 2004, Gao et al. 2007)

There is a Universal SFR

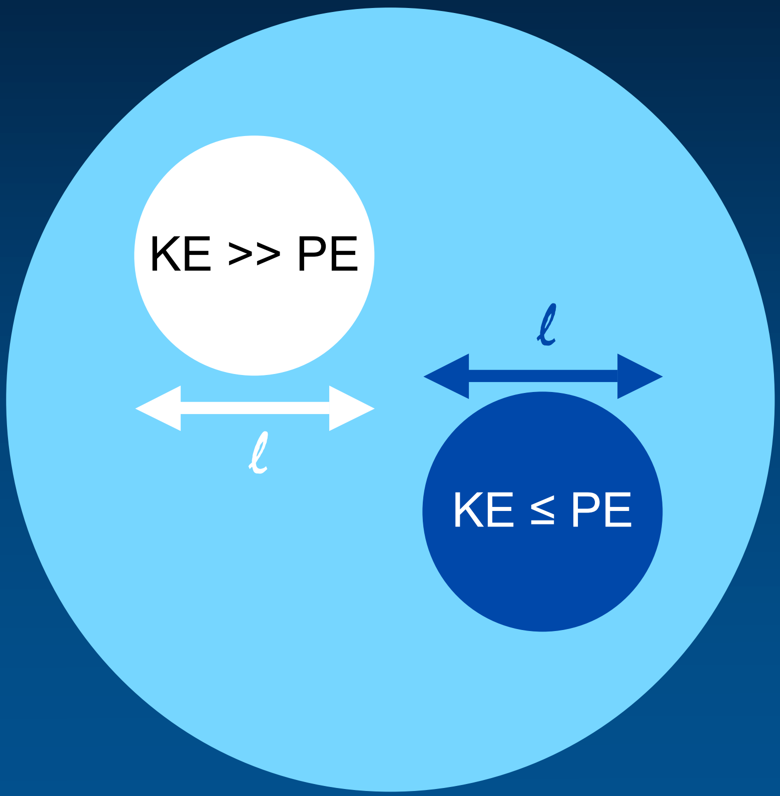


Clouds convert ε_{ff} ~1% of their mass to stars per t_{ff}, regardless of density or environment (Tan, Krumholz, & McKee 2006; Krumholz & Tan 2007)

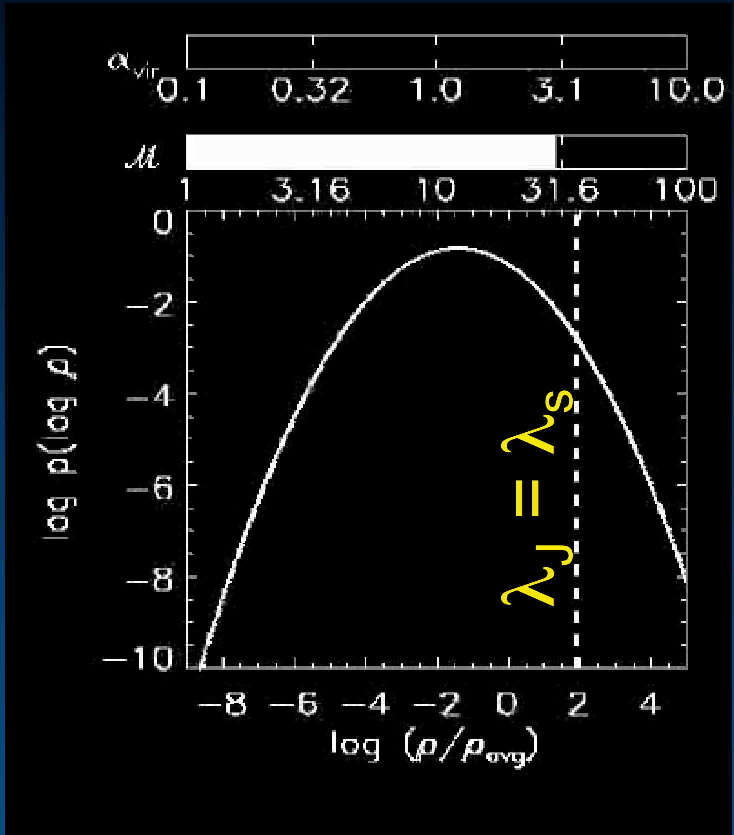
Where Does ε_{ff} Come From?

(Krumholz & McKee 2005)

- On large scales, GMCs have $\alpha \approx 1$ (i.e. PE $\approx$ KE)
- Linewidth-size relation: $\sigma_v \approx c_s (\ell / \lambda_s)^{1/2}$
- In average region, $M \propto \ell^3$
  $\Rightarrow$ KE $\propto \ell^4$, PE $\propto \ell^5$
  $\Rightarrow$ KE >> PE
- Hypothesis: SF only occurs in regions where PE $\geq$ KE and $P_{th} \geq P_{ram}$
- Only overdense regions meet these conditions
- Required overdensity is given by $\lambda_J \leq \lambda_s$, where $\lambda_J = c_s [\, \pi / (G\rho) \,]^{1/2}$



Calculating the SFR



- Density PDF in turbulent clouds is lognormal; width set by $\mathcal{M}$
- Integrate over region where $\lambda_J \leq \lambda_s$, to get mass in "cores", then divide by t_{ff} to get SFR
- Result:

$$\varepsilon_{ff} \approx 0.015\, \alpha^{-0.68} (\mathcal{M} / 30)^{-0.32}$$

ε_{ff} ~ 1% for any turbulent, virialized object

Putting it Together: The Total Gas Star Formation Law

(Krumholz, McKee, & Tumlinson 2009)

$$\dot{\Sigma}_* = f_{\mathrm{H_2}}(\Sigma_{\mathrm{gal}}, Z)\frac{\Sigma_{\mathrm{gal}}}{2.6\ \mathrm{Gyr}} \times \begin{cases} \left(\frac{\Sigma_{\mathrm{gal}}}{85\ M_\odot\ \mathrm{pc}^{-2}}\right)^{-0.33}, & \Sigma_{\mathrm{gal}} < 85\ M_\odot\ \mathrm{pc}^{-2} \\ \left(\frac{\Sigma_{\mathrm{gal}}}{85\ M_\odot\ \mathrm{pc}^{-2}}\right)^{0.33}, & \Sigma_{\mathrm{gal}} > 85\ M_\odot\ \mathrm{pc}^{-2} \end{cases}$$

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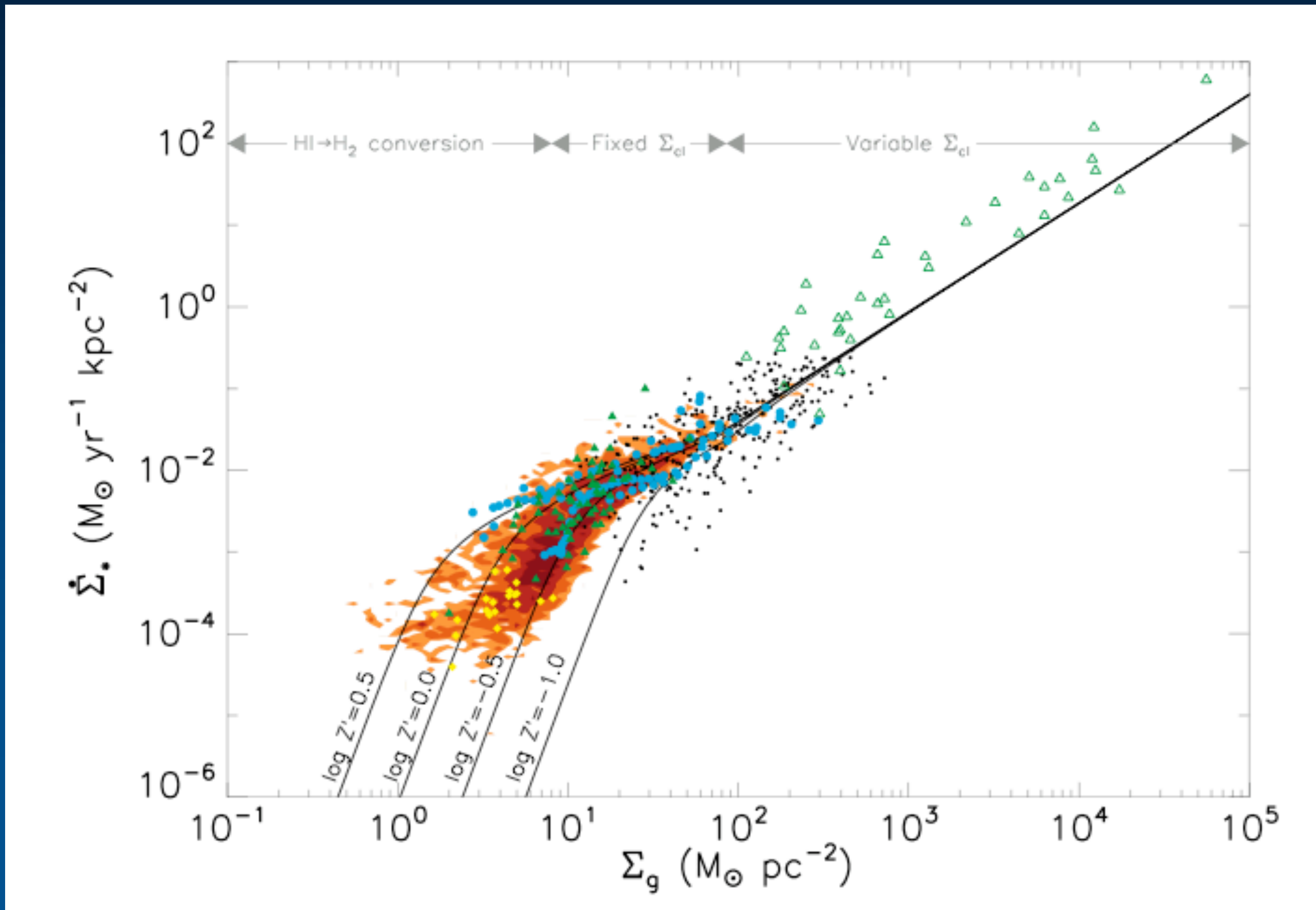

Lines:
theory

Contours:
THINGS, Bigiel et al. 2008

Symbols:
literature data compiled by Bigiel et al. 2008

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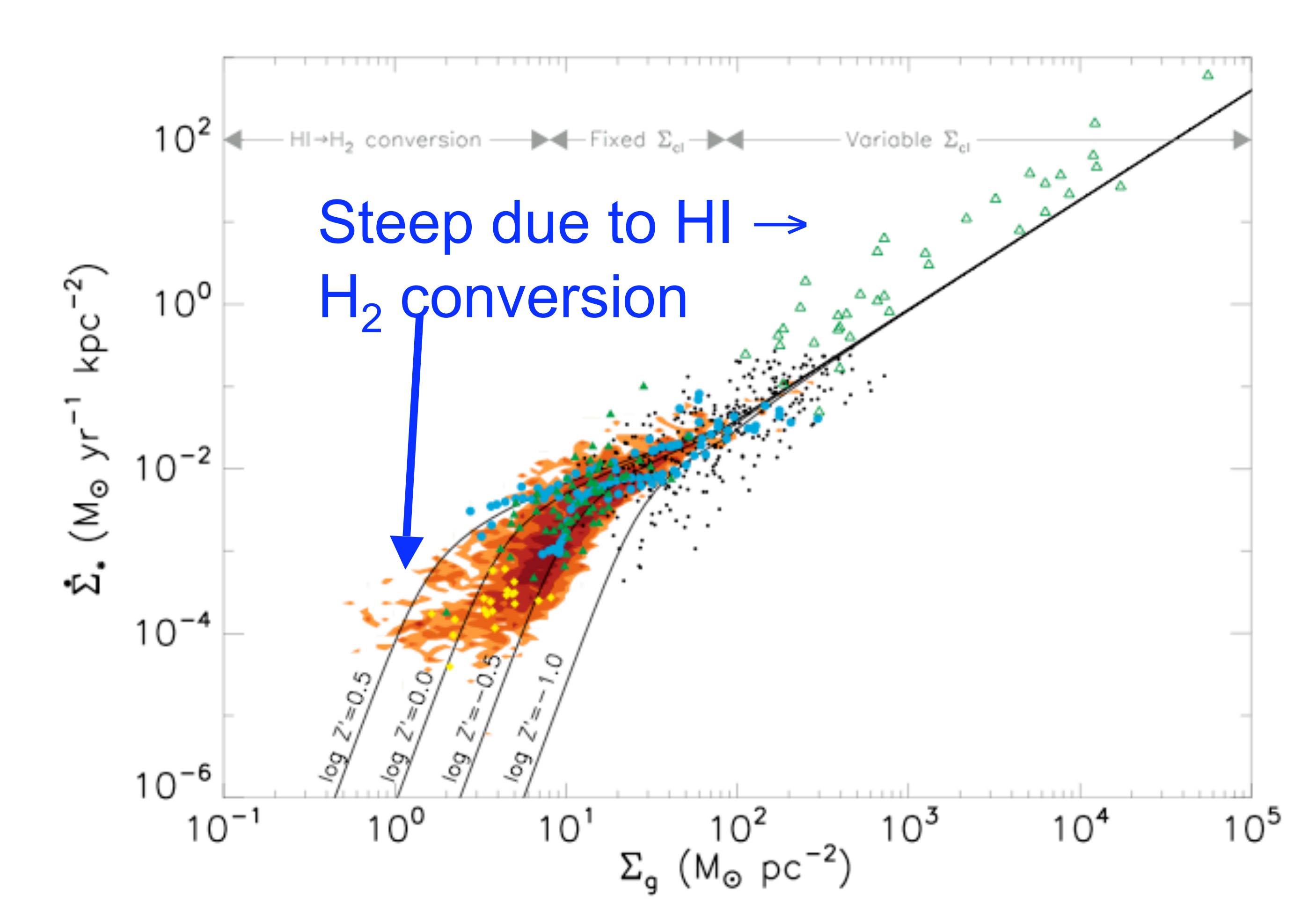

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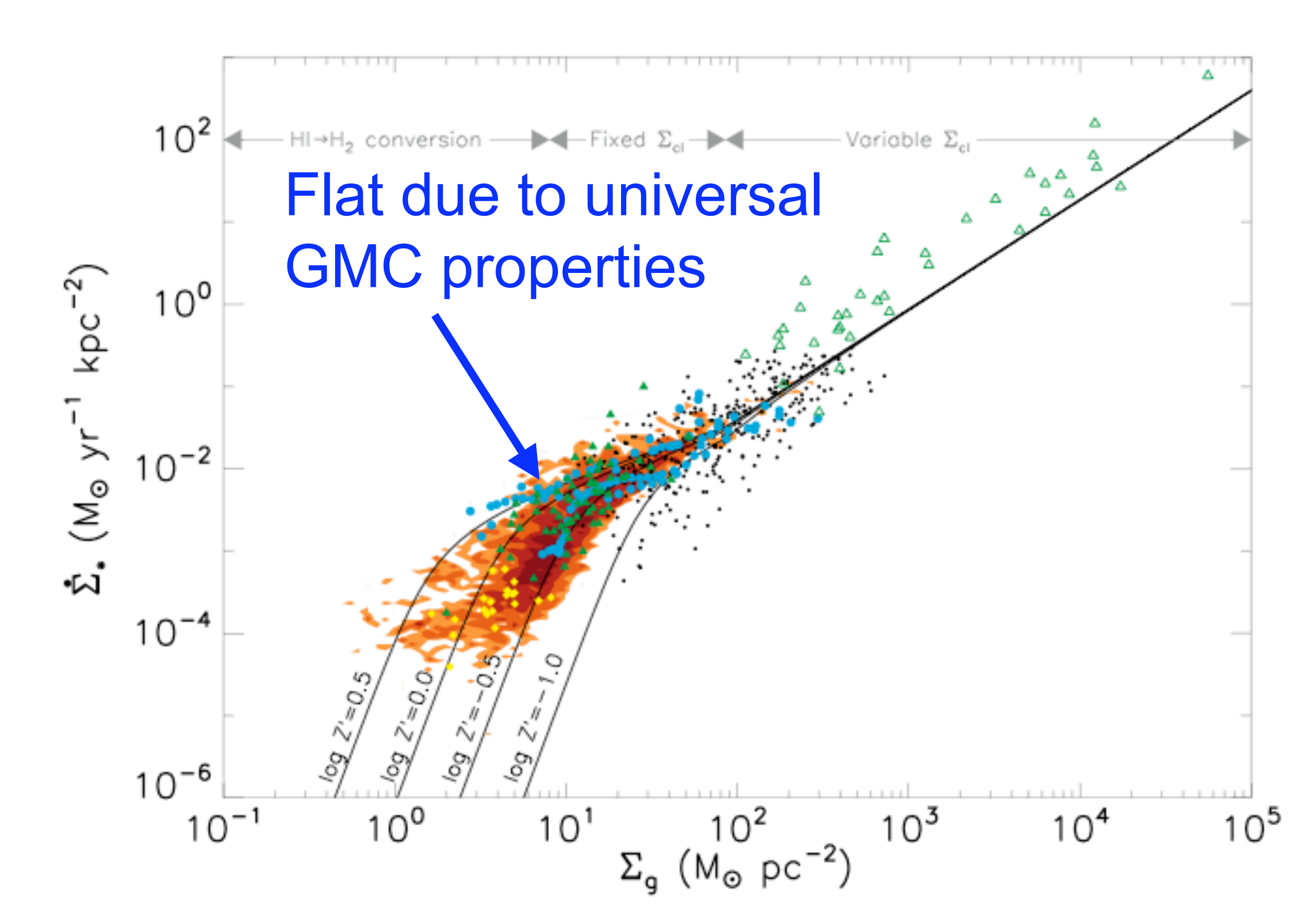

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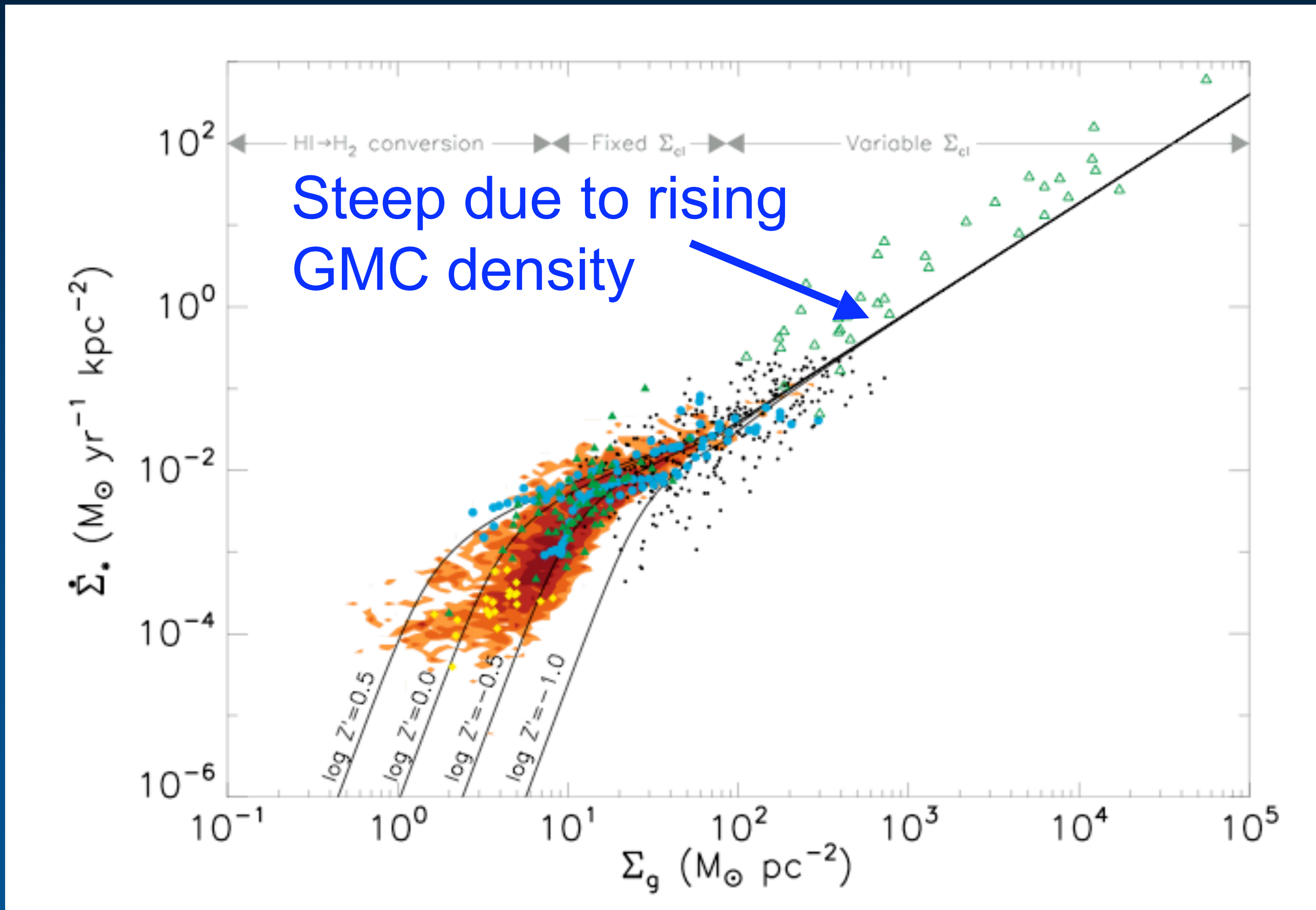

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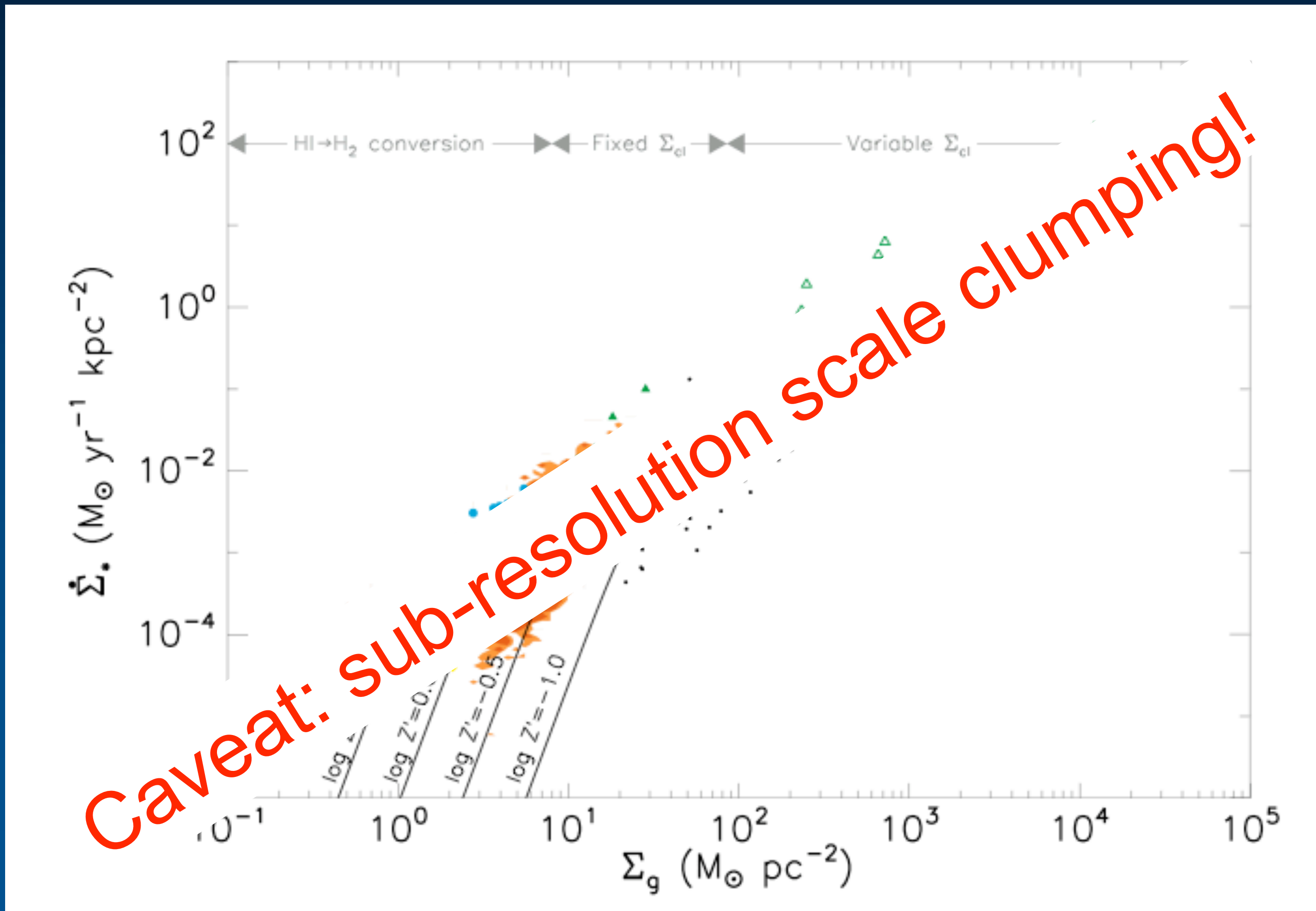

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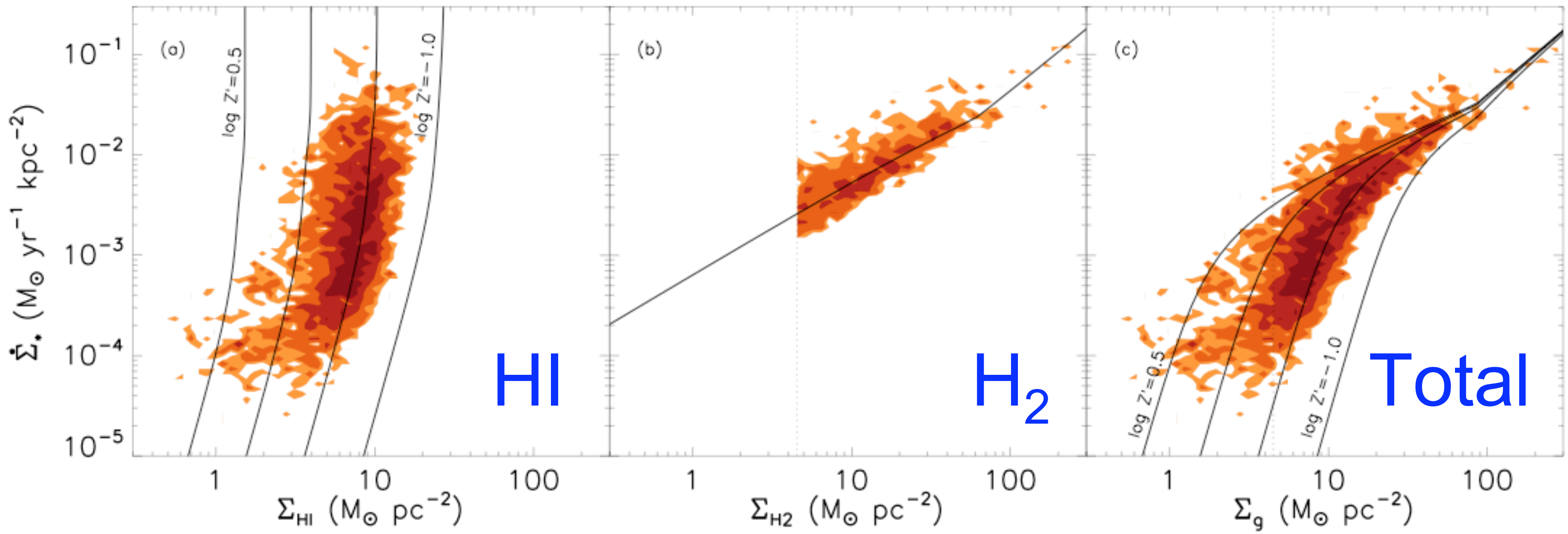
Atomic and Molecular Star Formation Laws



Contours: THINGS (Bigiel et al. 2008)
Lines: Theory for metallicities from 0.1 x solar to 3 x solar
(Krumholz, McKee, & Tumlinson 2009)

Summary

The SFR depends on:

1. The molecular fraction f_{H2} — determined by radiation and chemistry, depends on galaxy Σ, Z
2. The free-fall time in molecular clouds t_{ff} — determined by SF feedback in low Σ galaxies, by galaxy Σ in high Σ galaxies
3. The star formation rate per free-fall time ε_{ff} — this is always ~1% due to the physics of turbulence