The Secret Lives of Molecular Clouds

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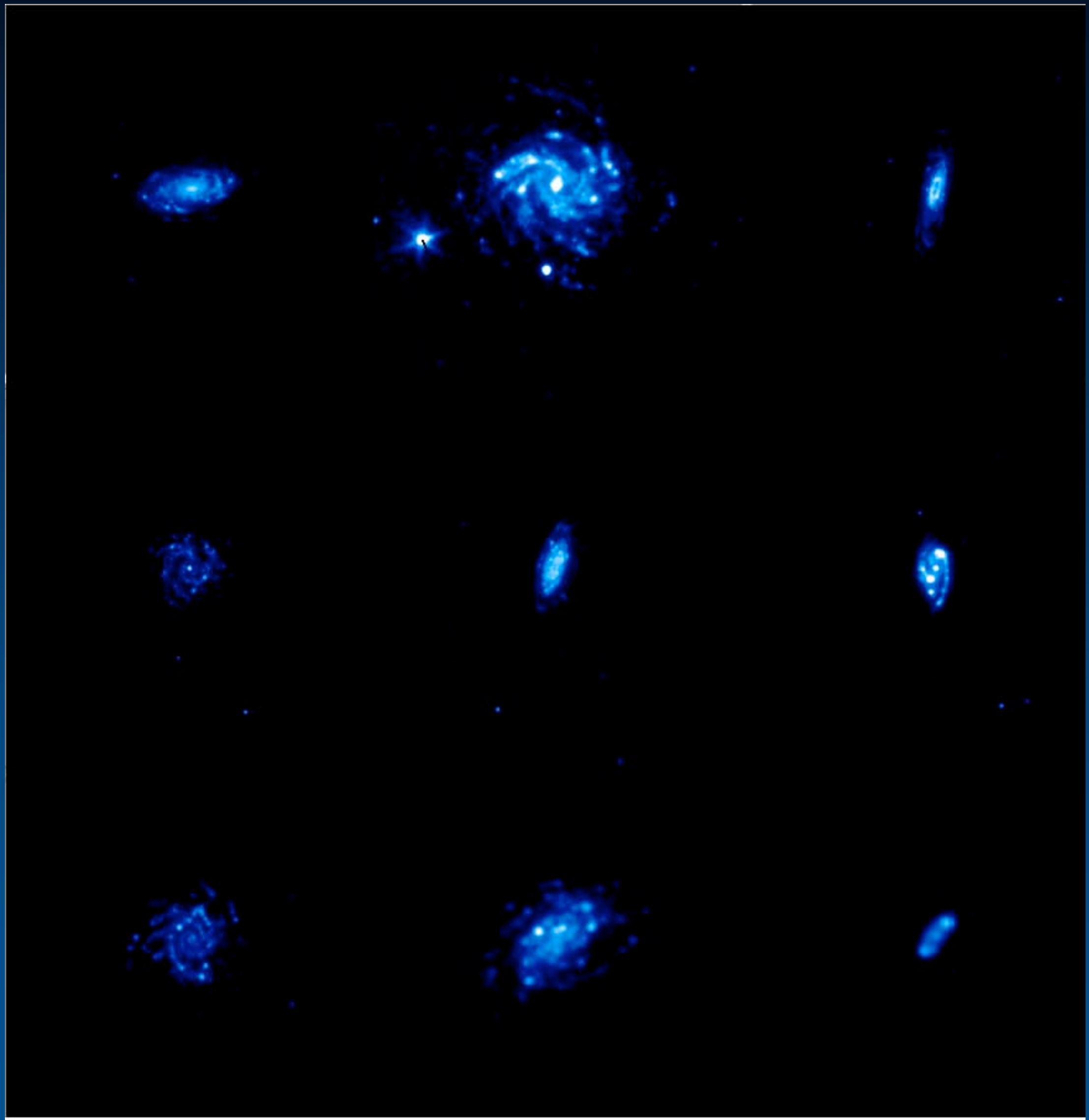
Outline

- Embarrassing observational facts about star formation
- Turning gas into stars
  - Making molecules
  - From molecules to stars
  - Stellar Feedback
- Problems for the future

Observations

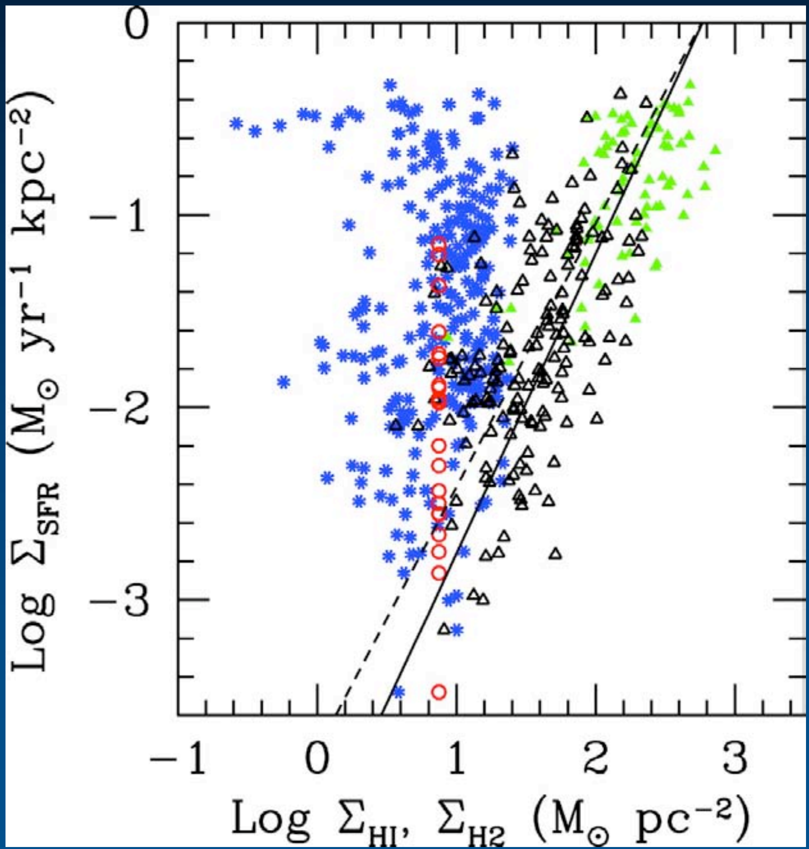
Stars Do Not Form in Gas



SFR distributions from 24 μm SINGS + GALEX

SINGS + GALEX + THINGS + SONG (animation borrowed from N. Gnedin)

Stars Form in Molecular Gas



The SFR in a galaxy correlates well with the molecular gas surface density, and only poorly with the HI.

SFR vs. surface densities of HI (blue asterisks) and H_2 (black and green triangles) in M51a (Kennicutt et al. 2007)

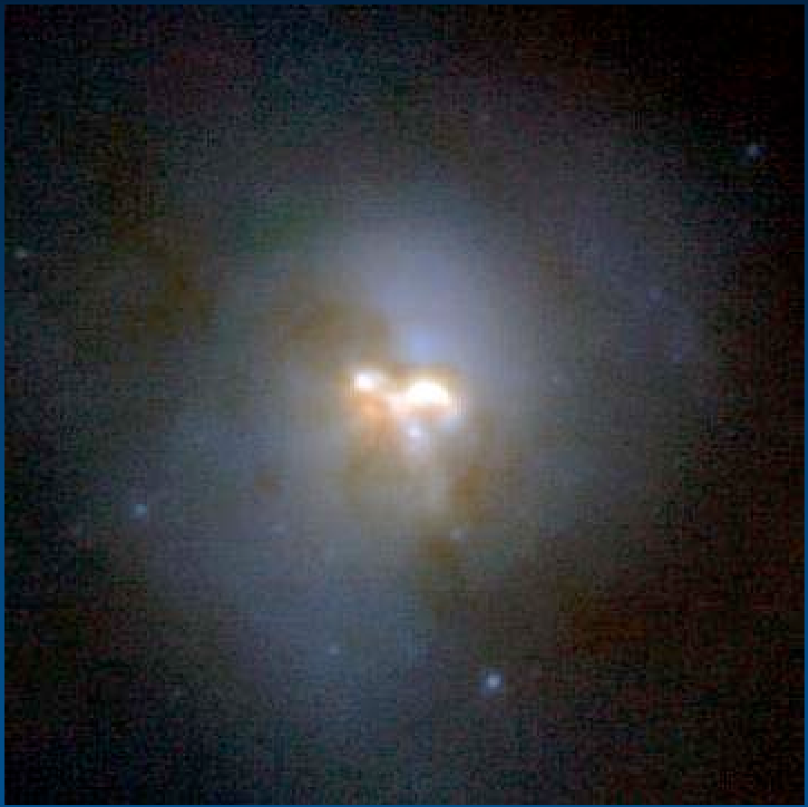
Even once H_2 forms, SF is slow…

(Zuckerman & Evans 1974; Rownd & Young 1999; Wong & Blitz 2002)

- The MW disk contains ~10^9 $M_\odot$ of gas in giant molecular clouds
- GMCs have n_H ~ 100 cm^{-3}, t_{ff} ~ 4 Myr
- If GMCs were collapsing, the SFR would be ~10^9 $M_\odot$ / 4 Myr = 250 $M_\odot$ / yr
- Observed SFR in MW is ~ 3 $M_\odot$ / yr, lower by a factor of ~100
- Numbers similar in nearby galaxies

…even in starbursts…

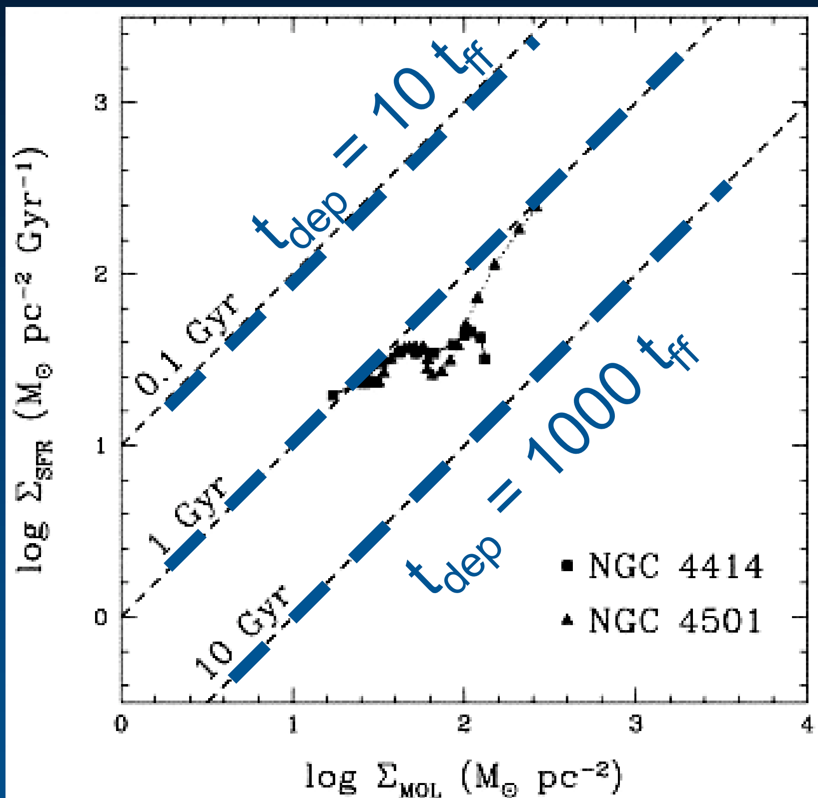
(Downes & Solomon 1998)

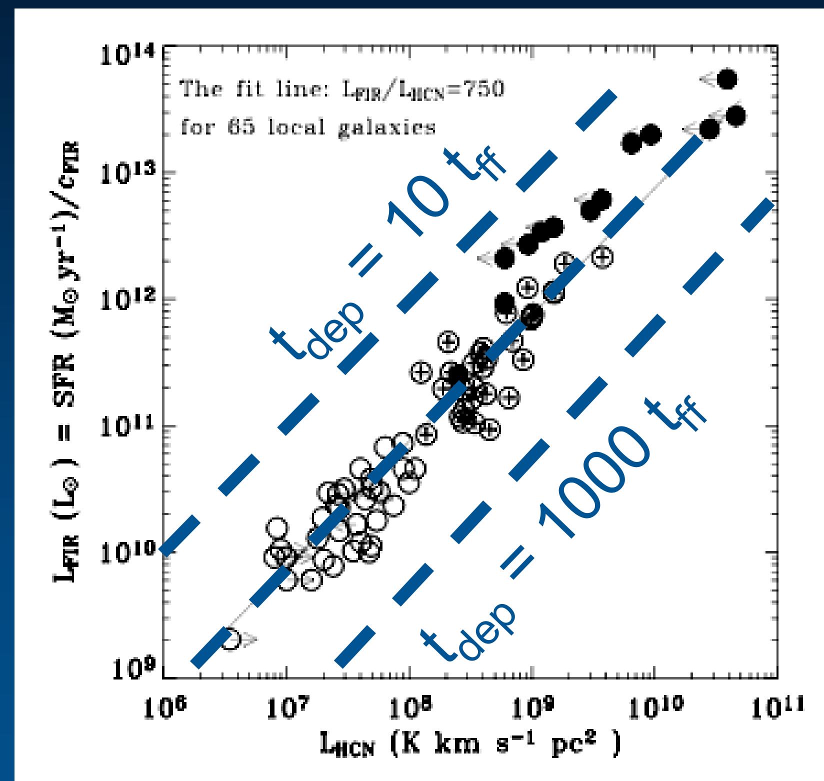


Arp 220 imaged by HST/NICMOS, Thompson et al. 1997

- Example: Arp 220
- ISM mass 2 x 10^9 $M_\odot$ in molecular gas
- ISM density 10^4 cm^{-3}, t_{ff} ~ 0.4 Myr
- Suggested SFR ~ 5000 $M_\odot$ / yr
- Actual SFR ~ 50 $M_\odot$ / yr : too small by factor of 100

…even in dense gas…

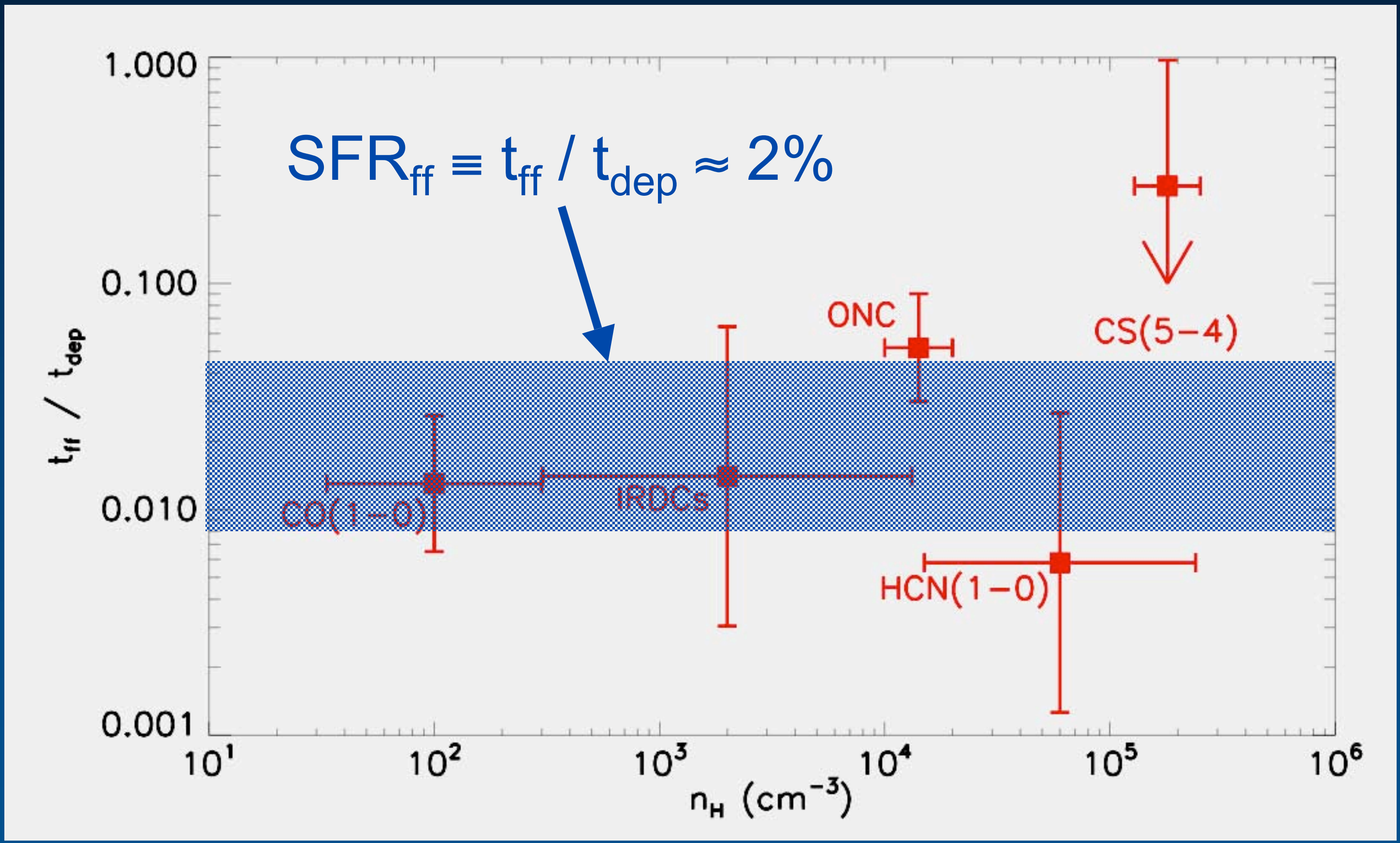


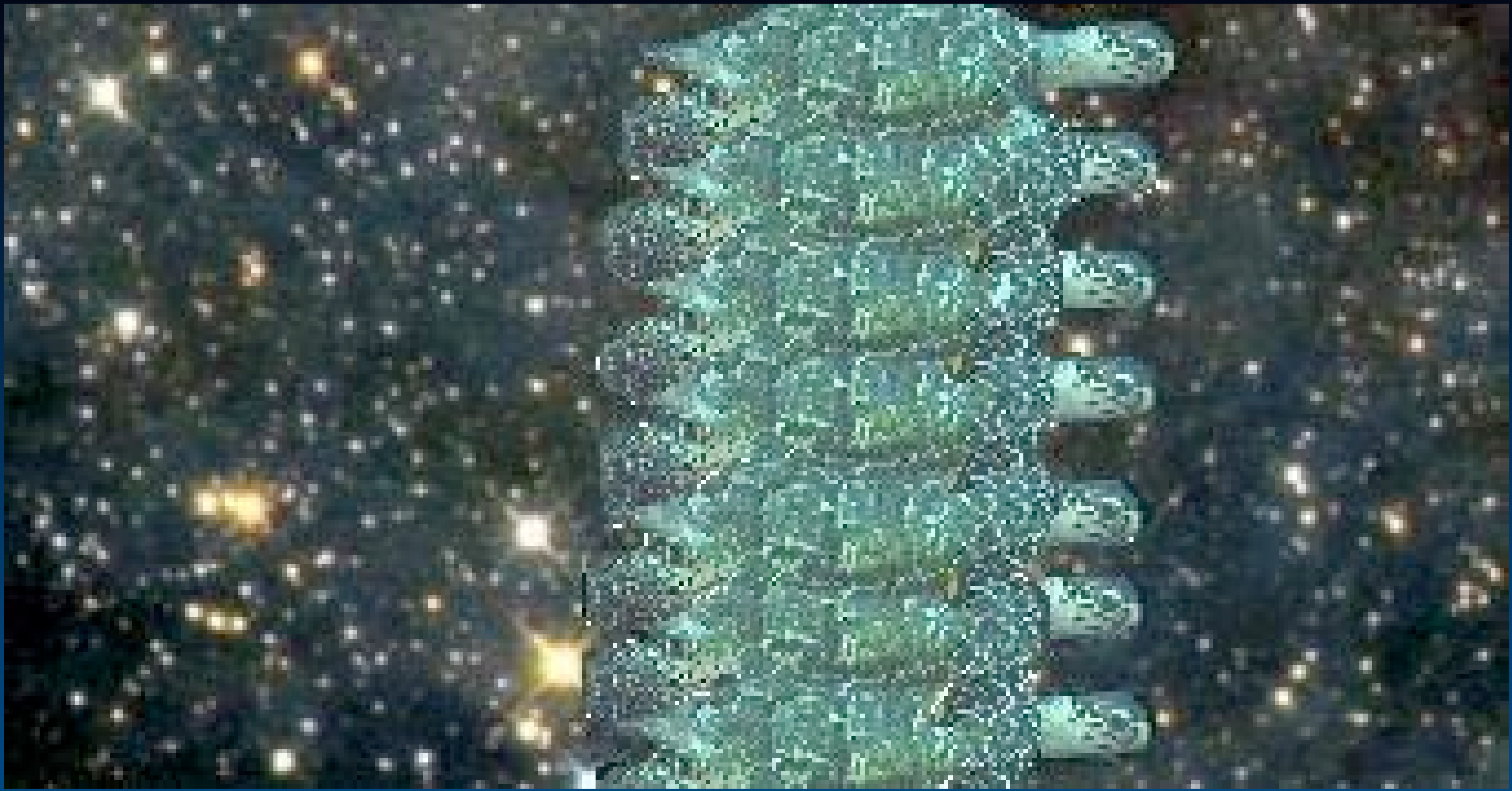


Depletion time as a function of Σ_{H2} for 2 local galaxies (left, Wong & Blitz 2002) and as a function of L_{HCN} for a sample of local and z ~ 2 galaxies (below, Gao et al. 2007)

Now the Good News: There is a Universal SFR!

(Tan, Krumholz, & McKee 2006; Krumholz & Tan 2007)





In other words:

so far it's turtles all the way down…

Implications of Slow Star Formation

- For people who care about galaxies:
  - Bad news: you can simulate formation of GMCs with an approximate treatment of H_2 formation, but the SFR in GMCs is set at very small scales. Galaxy-scale simulations are stuck with subgrid models for that.
  - Good news: once molecules form, the SFR seems to follow a universal law that ~ 1 – 5% of the gas goes into stars per t_{ff}, independent of density.

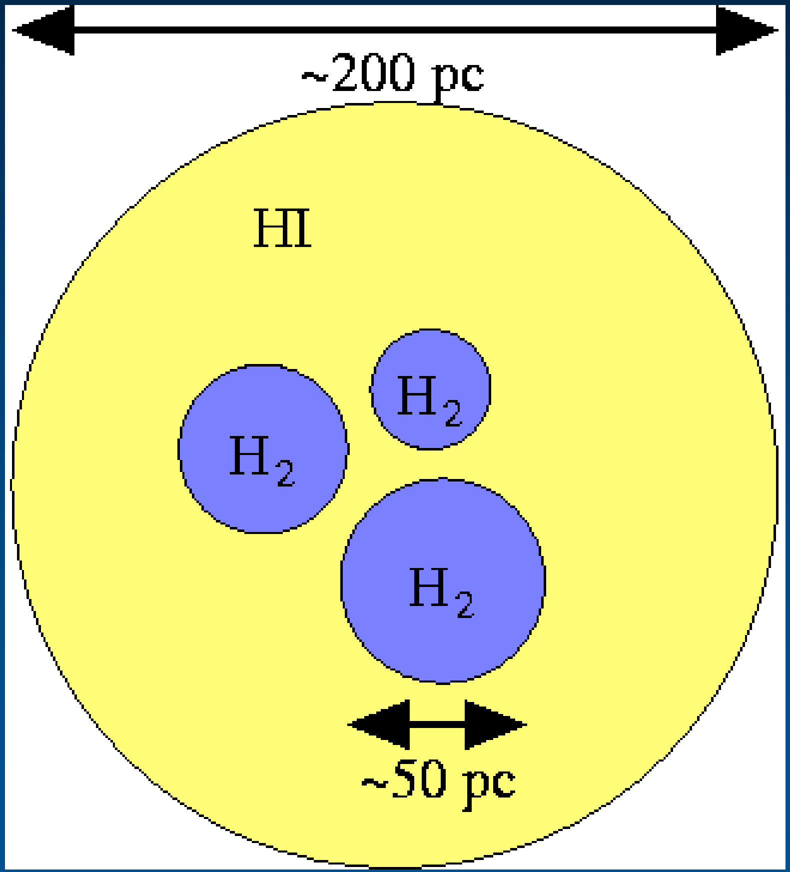
Implications of Slow Star Formation, Part II

- For star formation theorists:
  - Task 1: figure out what determines what fraction of the gas will form molecules, since this controls which gas is "eligible" for form stars
  - Task 2: understand what sets the universal few percent per t_{ff} in the molecular gas

From HI to Stars

Step 1: Making Molecules

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



Dissociation Balance in Atomic-Molecular Complexes

(Krumholz, McKee, & Tumlinson, 2008a, ApJ, in press)

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

Formation on grains = Photodissociation

$$n_{\mathrm{HI}} n \mathcal{R} = n_{\mathrm{H}_2} \int d\Omega \int d\nu \, \sigma_{\mathrm{H}_2} f_{\mathrm{diss}} I_\nu / (h\nu)$$

$$\hat{e} \cdot \nabla I_\nu = -(n_{\mathrm{H}_2} \sigma_{\mathrm{H}_2} + n \sigma_{\mathrm{d}}) I_\nu$$

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 $\mathcal{R}$, immersed in radiation field with LW photon number density E_0^*, find fraction of mass in HI and H_2.

Calculating Molecular Fractions

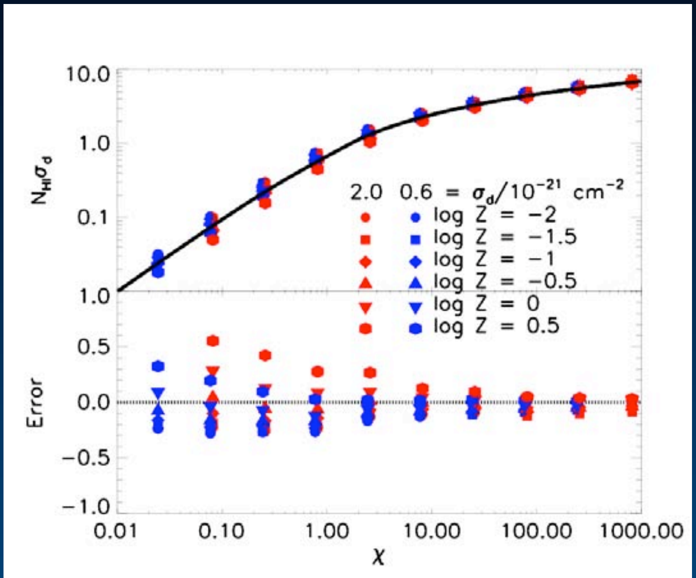
To good approximation, solution only depends on two dimensionless numbers:

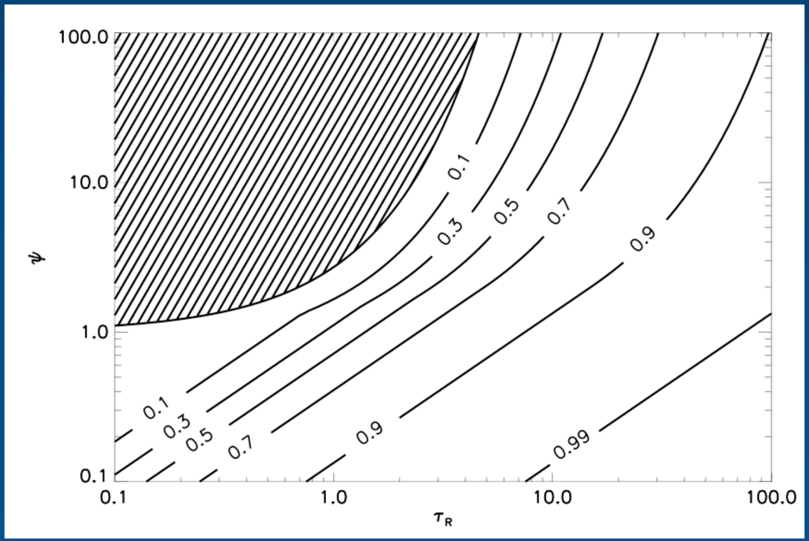
$$\tau_R = n\sigma_d R$$

$$\psi = \phi \frac{f_{\mathrm{diss}}\sigma_d E_0^*}{nR}$$

Approximate solution:

$$f_{H_2,\mathrm{vol}} \approx 1 - \frac{3\psi}{4(\tau_R + 0.2\psi)}$$





Top: analytic solution for location of HI / H_2 transition vs. exact numerical result

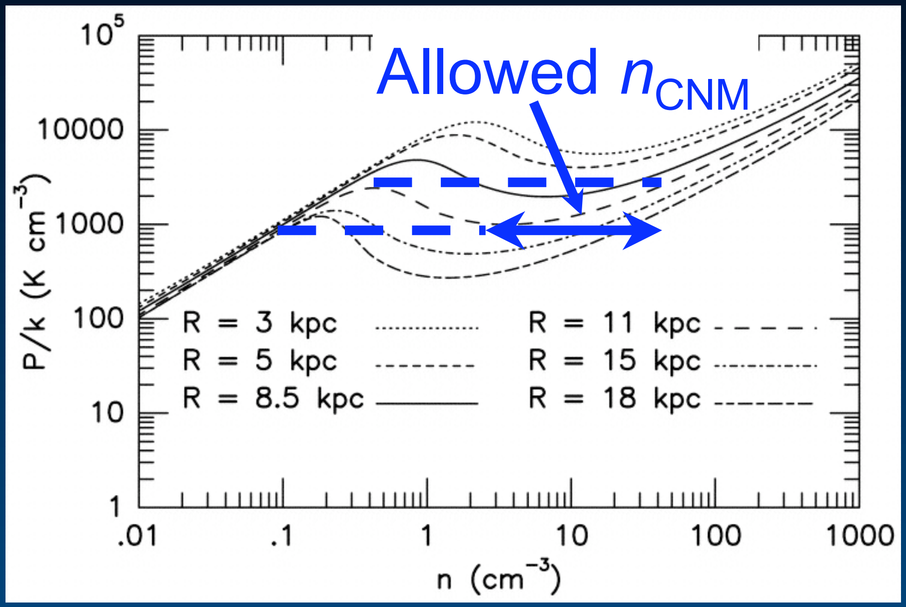
Bottom: H_2 volume fraction vs. ψ, τ_R

Atomic Shielding in Galaxies

(Krumholz, McKee, & Tumlinson, 2008b)

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

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



FGH curves for MW (Wolfire et al. 2003)

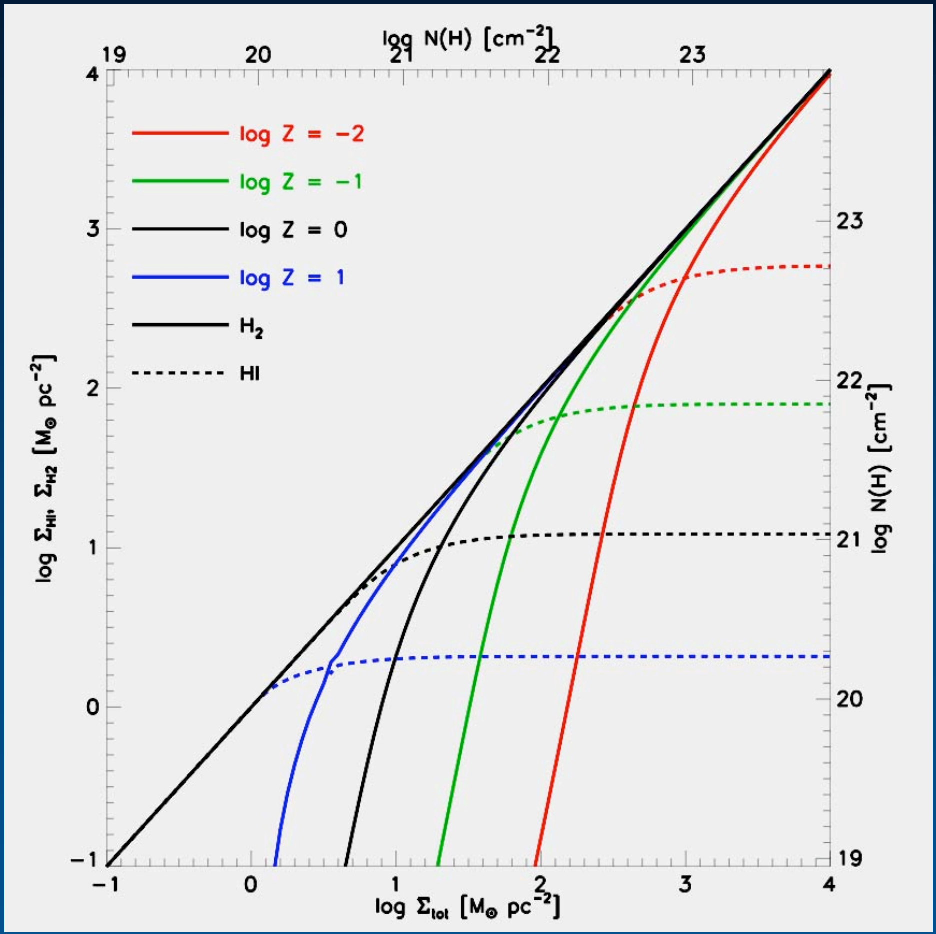
- CNM density set by pressure balance with WNM, and $n_{CNM} \propto E_0^*$, with weak Z dependence.

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

Predictions for H_2 Content

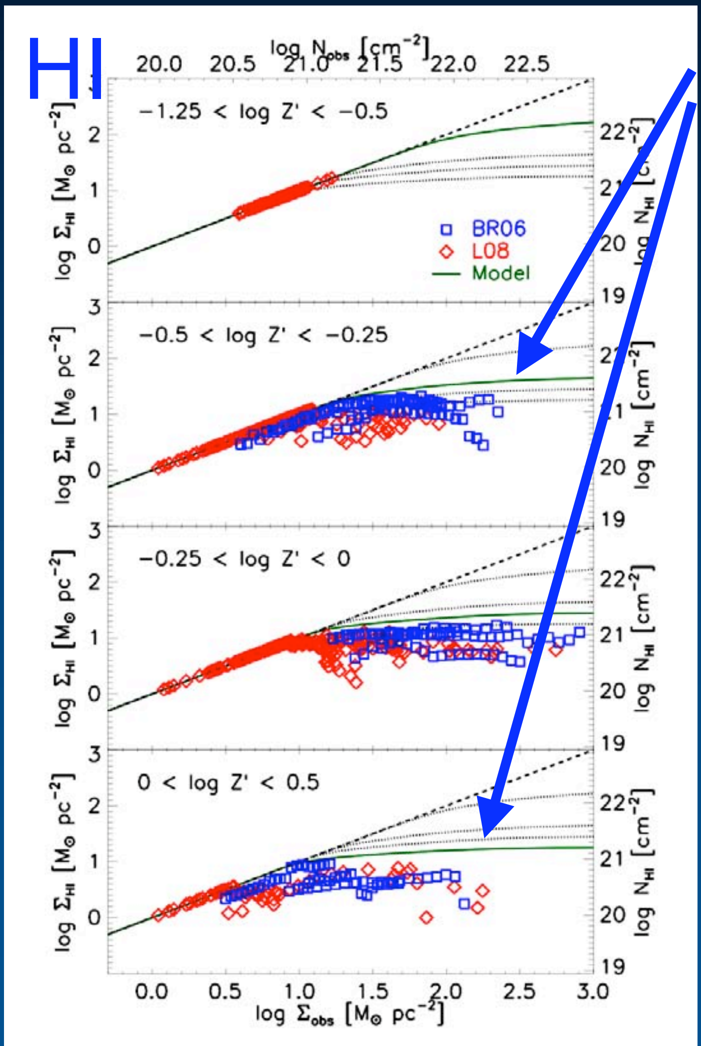
Compute τ_R from column density Σ, metallicity Z, and pressure balance between molecules and CNM.

Then use solution for H_2 fraction vs. ψ, τ_R to compute molecular content as a function of Σ, Z



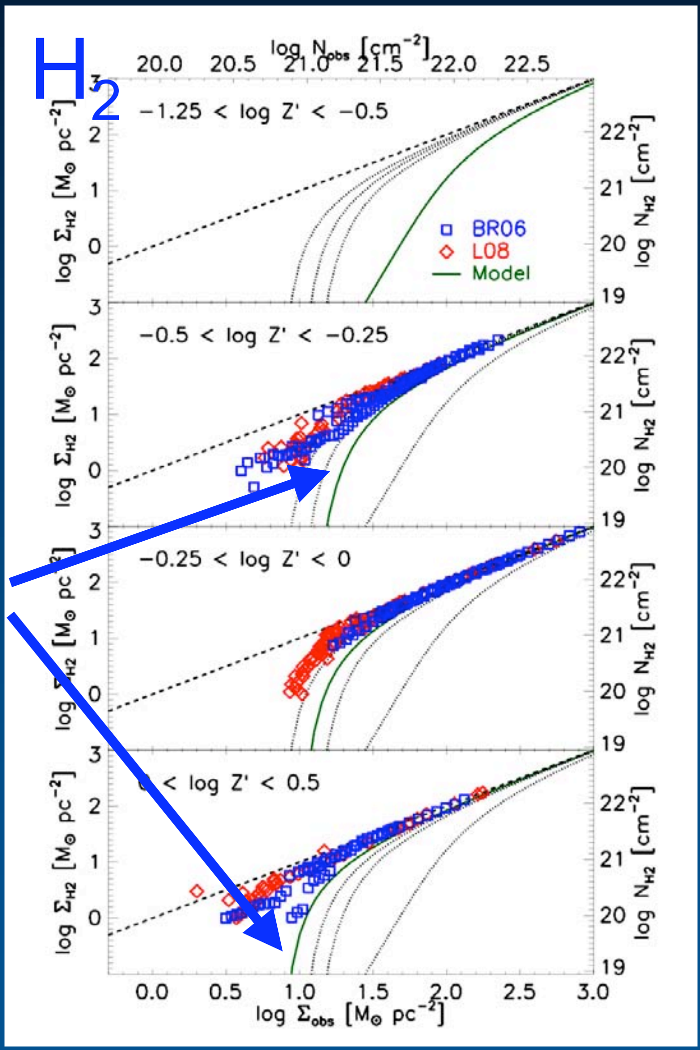
Reality Check…

Compare model to BIMA SONG (Blitz & Rosolowsky 2006) and HERA / THINGS (Leroy et al. 2008) surveys, with galaxies binned by metallicity



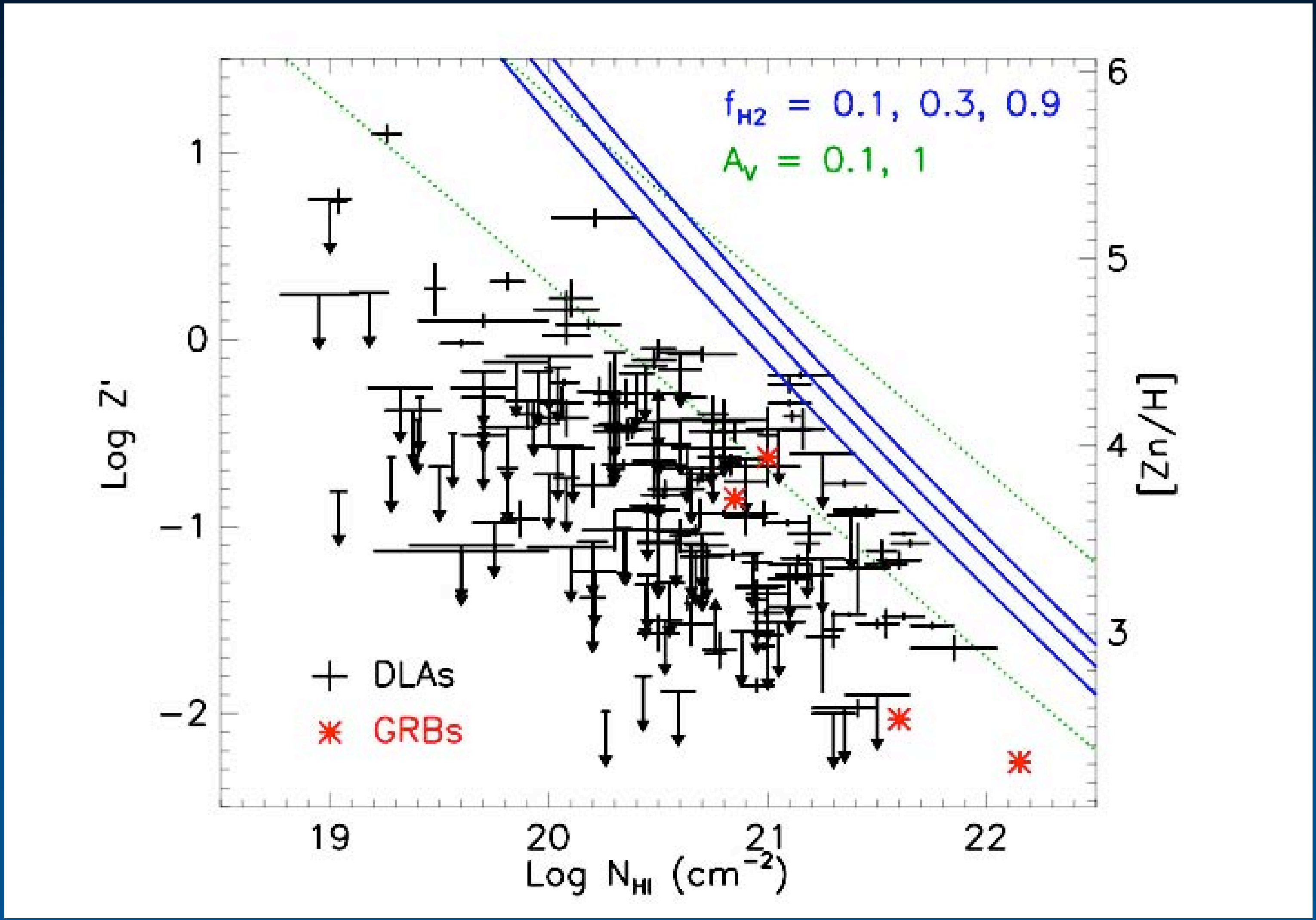
Matches observed saturation of HI, with higher Σ_{HI} at low metallicity!

Matches column needed for molecules to appear, with higher Σ at lower metallicity!



Another Application: DLAs

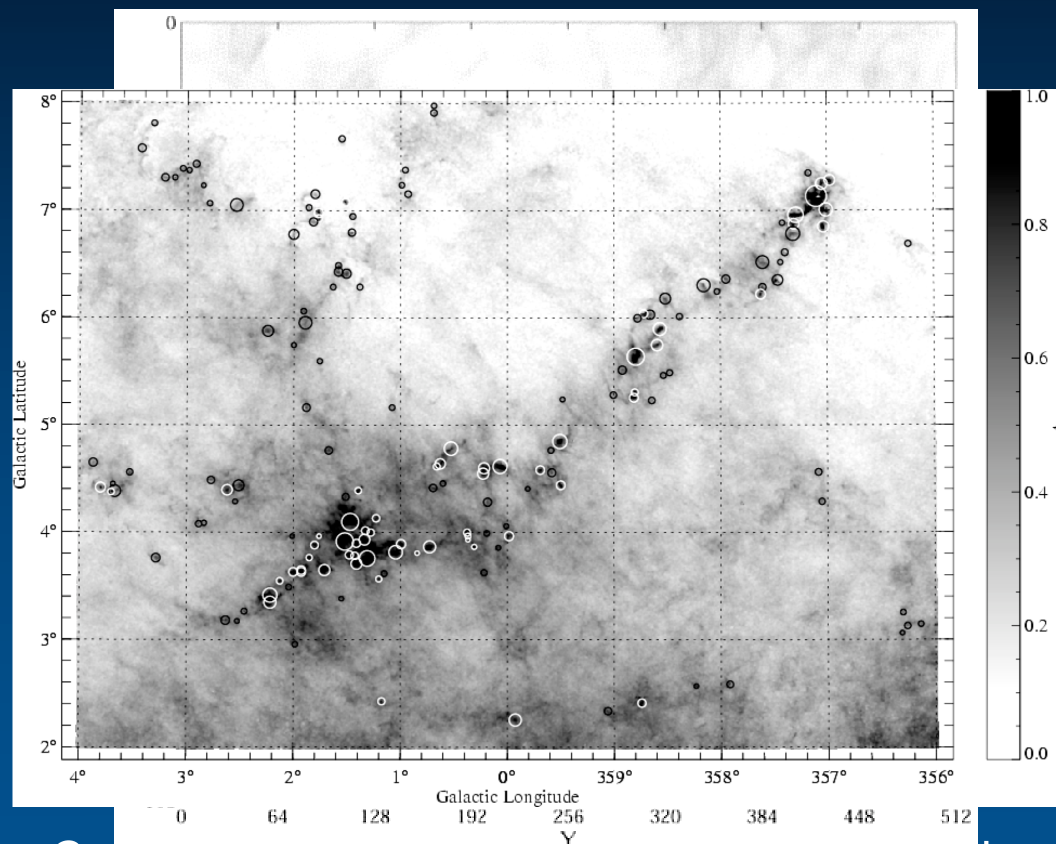
(Krumholz, Ellison, Prochaska, McKee, & Tumlinson, 2009, in preparation)



Step 2: Turning Molecules into Stars (Slowly)

(Krumholz & McKee 2005)

- Most GMC gas is in low density "envelopes", not dense "cores"
- GMCs are very turbulent, $\mathcal{M} \sim 30$
- Simulations of turbulence give core-envelope structure

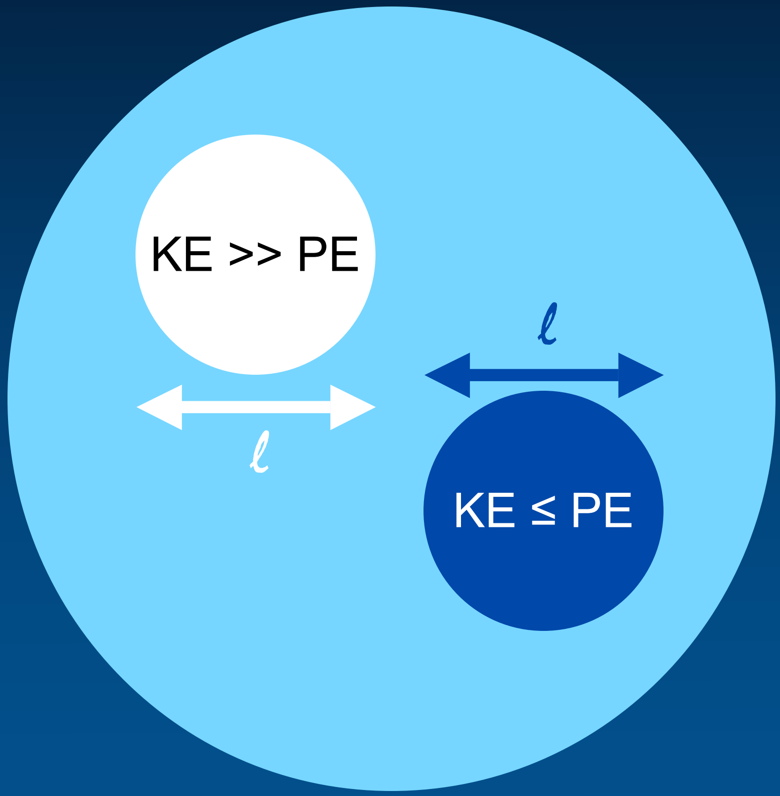


Column density map of the Pipe Nebula, with cores circled, Alves, Lombardi, & Lada 2007

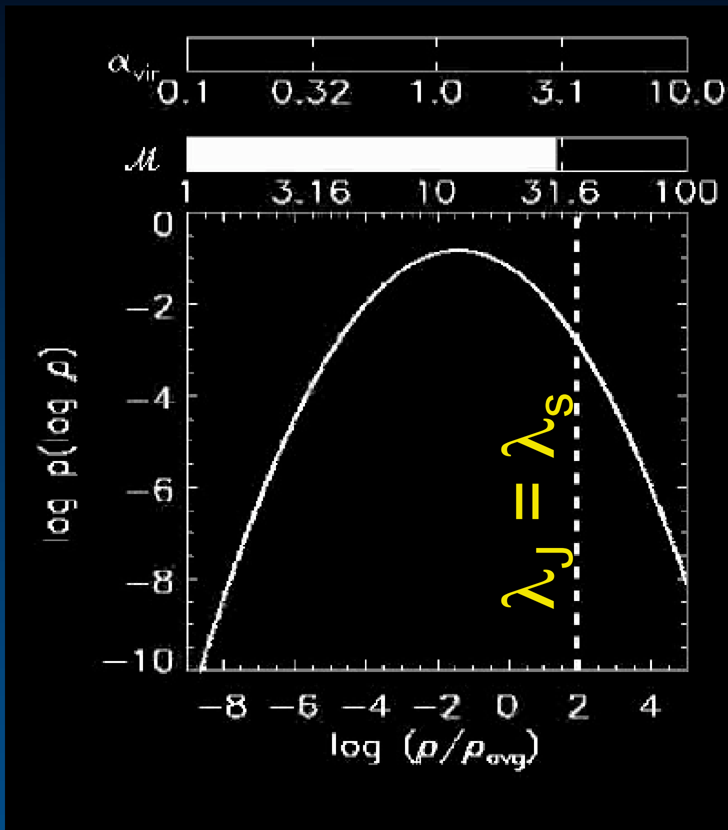
Column density map of a simulation of MHD turbulence with $\mathcal{M}$ = 10, Li et al. 2004

How Turbulence Sets the SFR

- 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



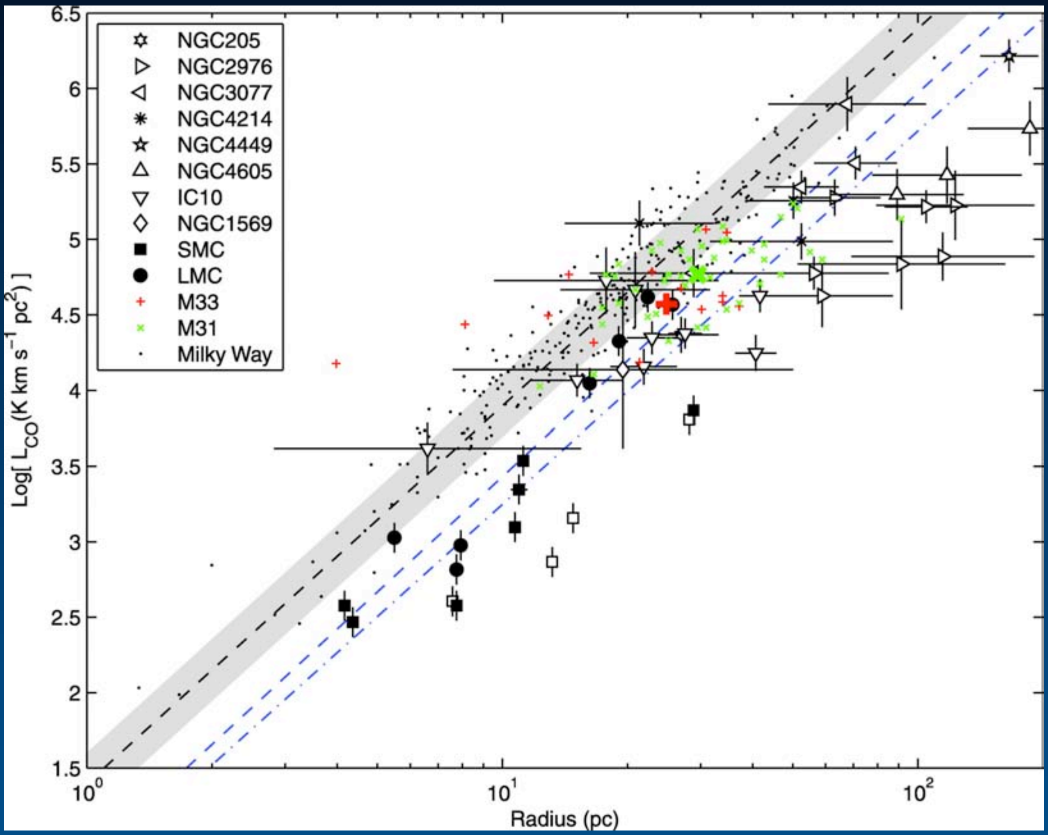
- Density PDF in turbulent clouds is lognormal; width set by $\mathcal{M}$
- Integrate over region where $\lambda_J \leq \lambda_s$, to get mass in "cores", then divide by t_{ff} to get SFR
- Result:

$$\mathrm{SFR}_{ff} \approx 0.073\, \alpha^{-0.68}\, \mathcal{M}^{-0.32}$$

SFR_{ff} ~ 1-5% for any turbulent, virialized object

A Remark on GMCs

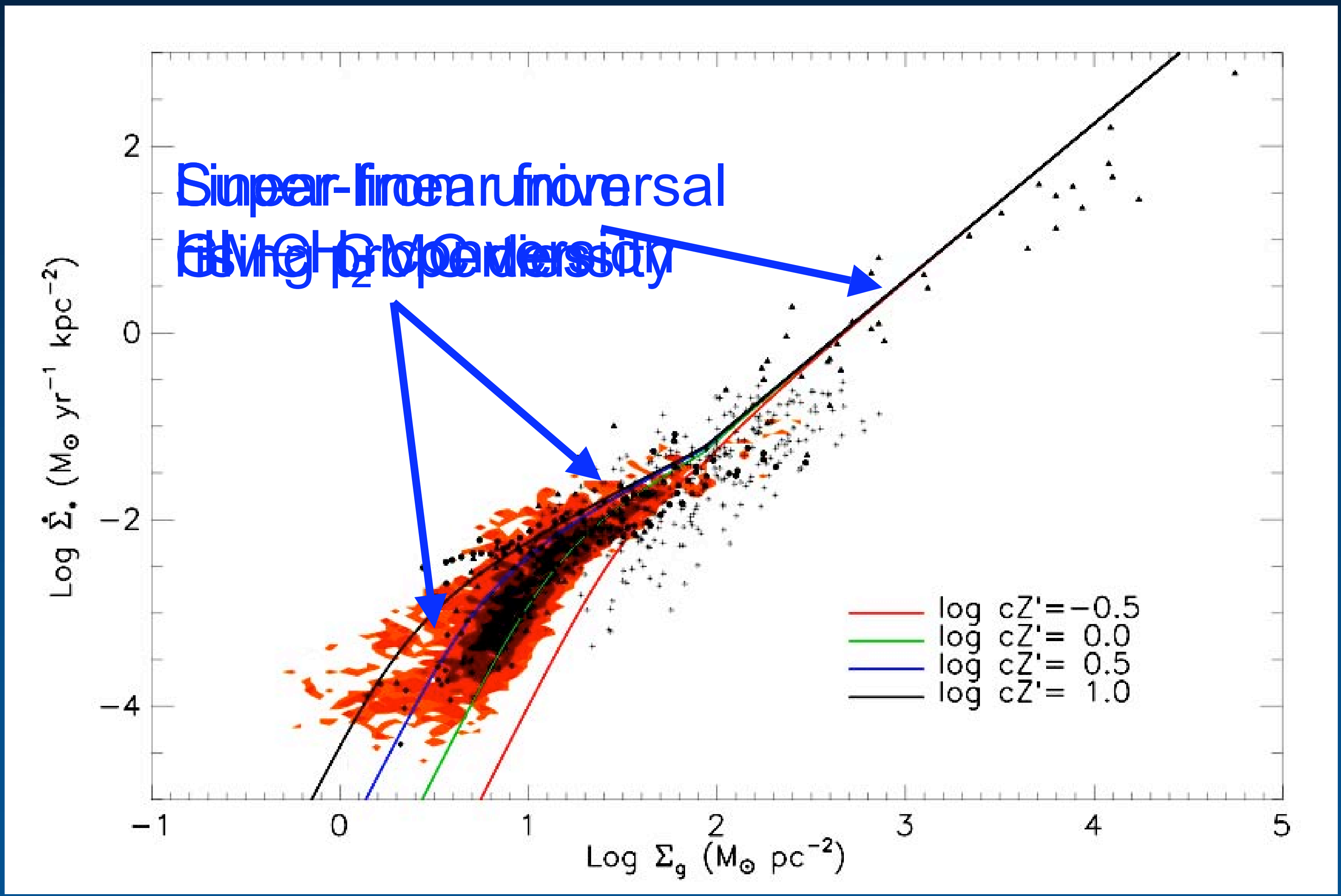
- SFR is simply ~0.01 × M_{mol} / $t_{ff\text{-}mol}$
- We can calculate M_{mol}, so we just need $t_{ff\text{-}mol}$!
- In low Σ galaxies, GMCs all have $\Sigma \sim 100\ M_{\odot}\ pc^{-2}$ (Bolatto et al. 2008)
- In high Σ galaxies, Σ_{GMC} must be $\geq \Sigma_{gal}$ to maintain hydrostatic balance



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

Putting it Together: The Total Gas Star Formation Law

(Krumholz, McKee, & Tumlinson, 2009, in preparation)

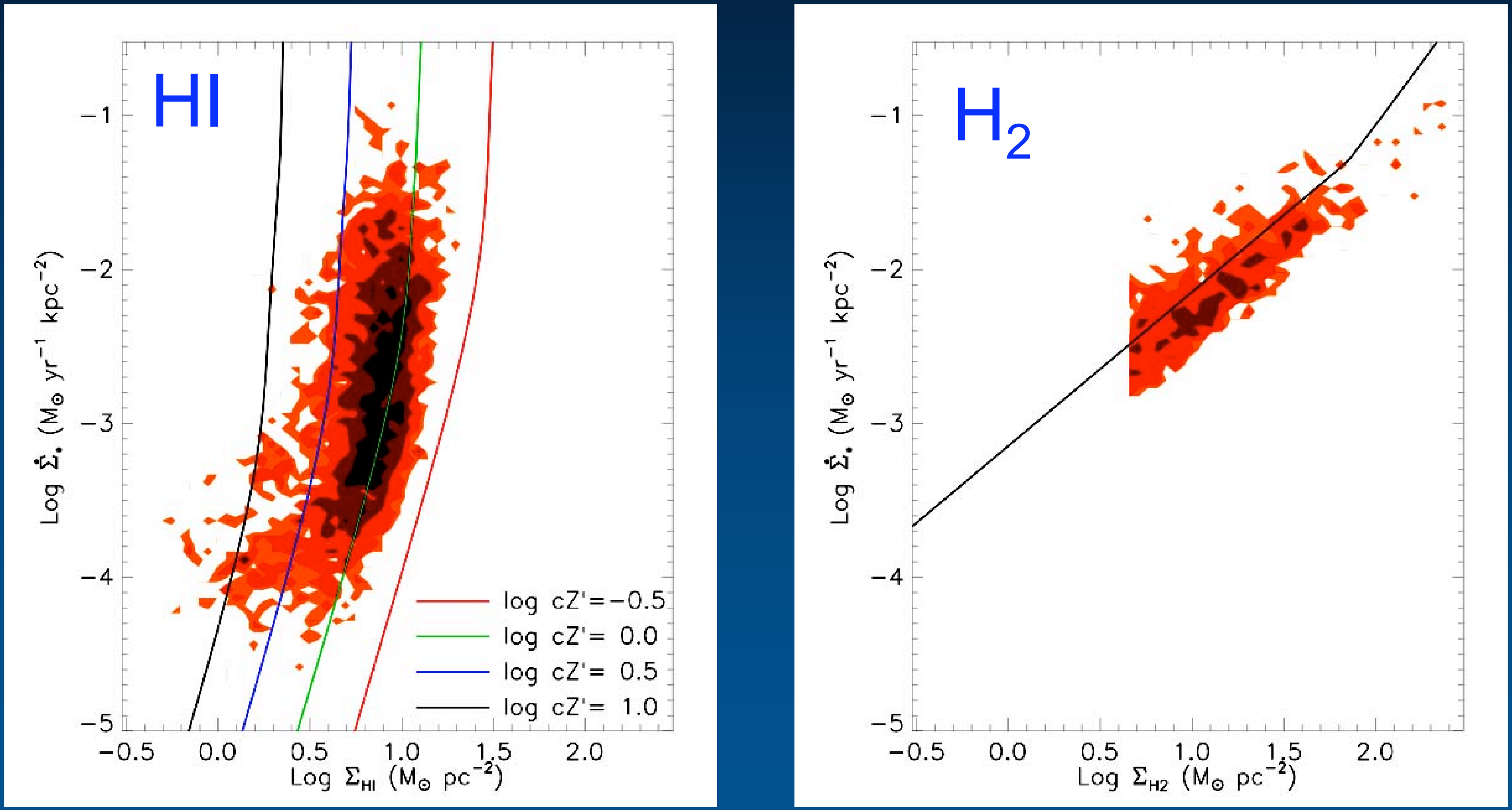


Lines:
theory

Contours:
THINGS, Bigiel et al. 2008

Symbols:
literature data compiled by Bigiel et al. 2008

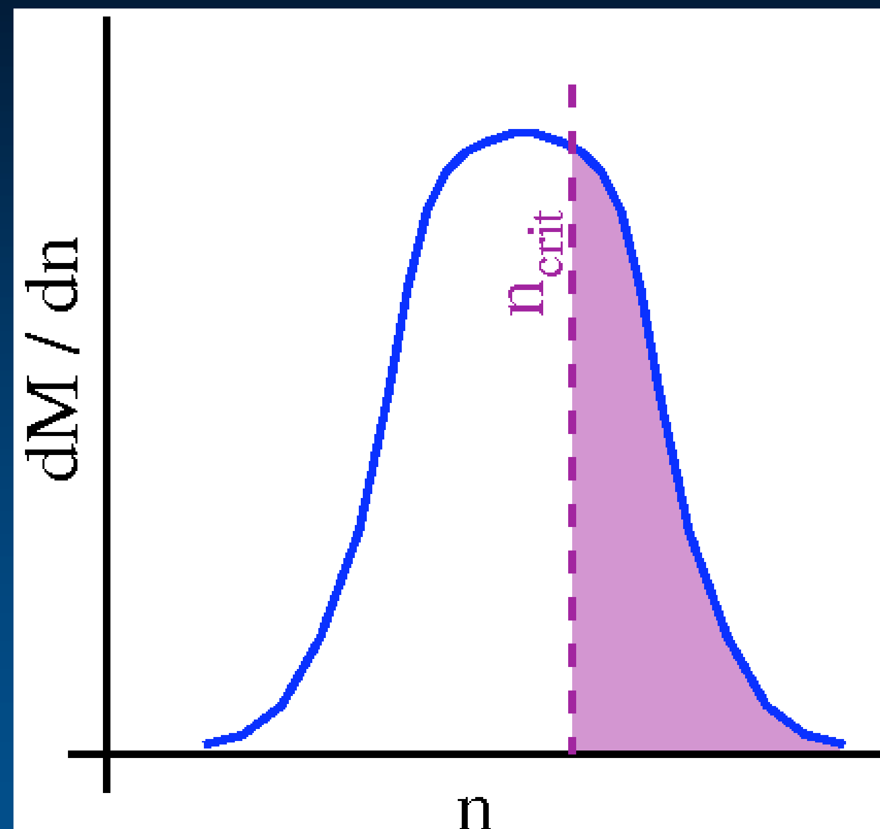
Atomic and Molecular Star Formation Laws



“Other” Kennicutt Laws

(Krumholz & Thompson 2007)

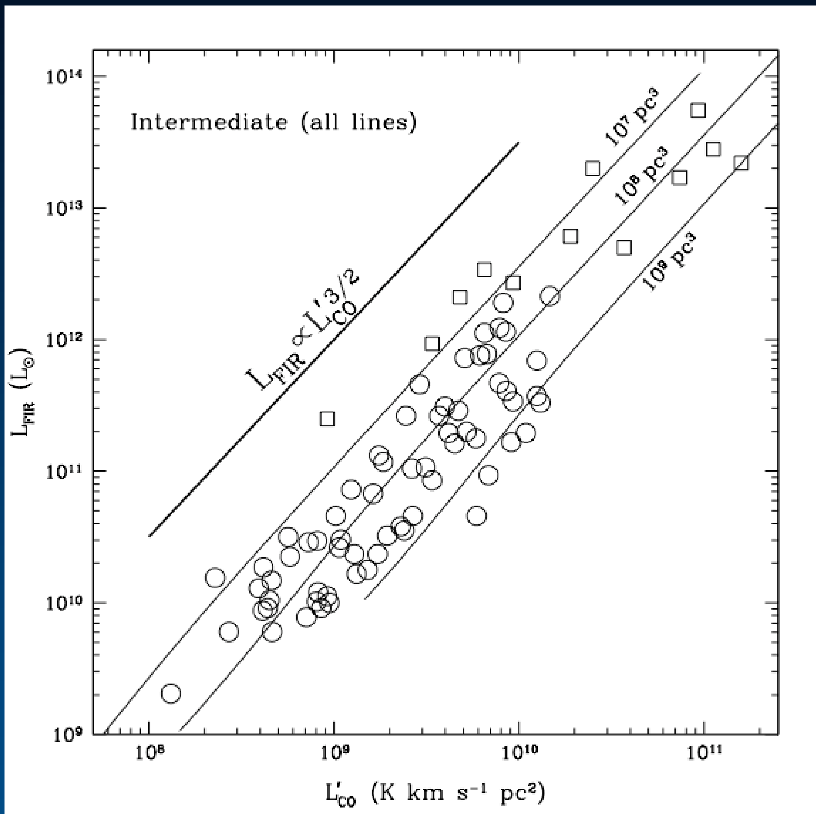
- SFR is a fixed mass fraction per free-fall time, so for density n, $SFR \propto L_{IR} \propto n^{3/2}$
- Line luminosity depends on mass above n_{crit}
- Low n_{crit} (e.g. CO 1-0) $\Rightarrow L_{line} \propto n^{1}$
- High n_{crit} (e.g. HCN 1-0) $\Rightarrow L_{line}$

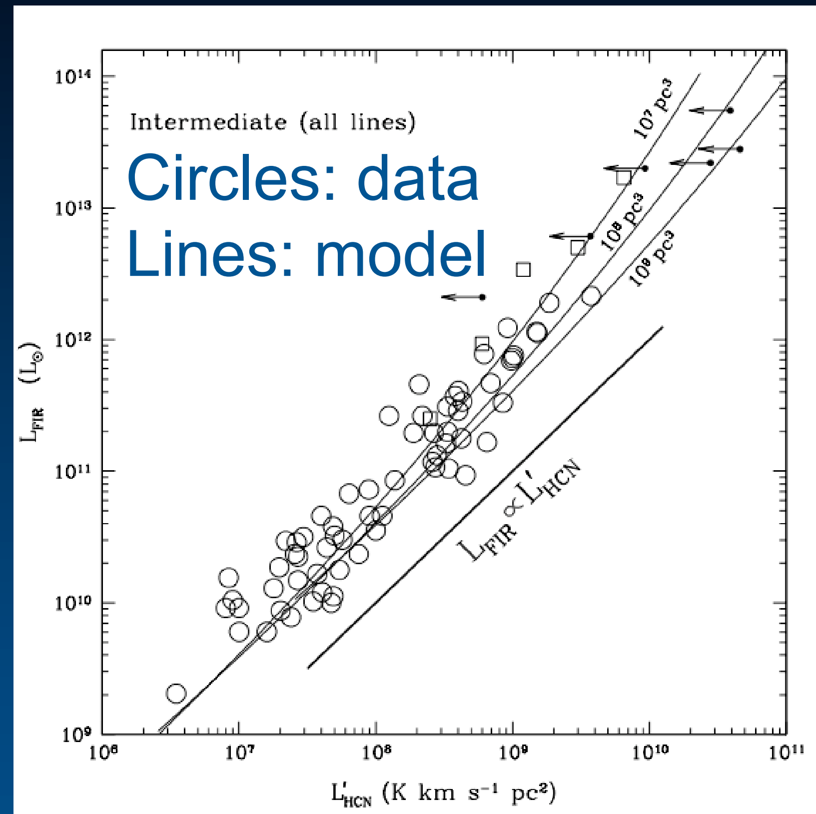


$SFR \propto L_{line}^{3/2}$ for low n_{crit}

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

Line Emission Model vs. Data





Calculation w / simple non-LTE radiation code reproduces slope and normalization of observed correlations, predicts new ones (e.g. IR-HCO^+)

Step 3: Stellar Feedback

(Krumholz, Matzer, & McKee 2007)

30 Doradus HII region, MCELS

- All observed GMCs turbulent, $\alpha \approx 1$
- Turbulence decays in ~1 crossing time
- Observed GMC lifetime is ~ 30 Myr (Blitz et al. 2007), t_{cr} ~ 7 Myr $\Rightarrow$ need driving to maintain turbulence
- Hypothesis: driver is SF feedback

A Semi-Analytic GMC Model

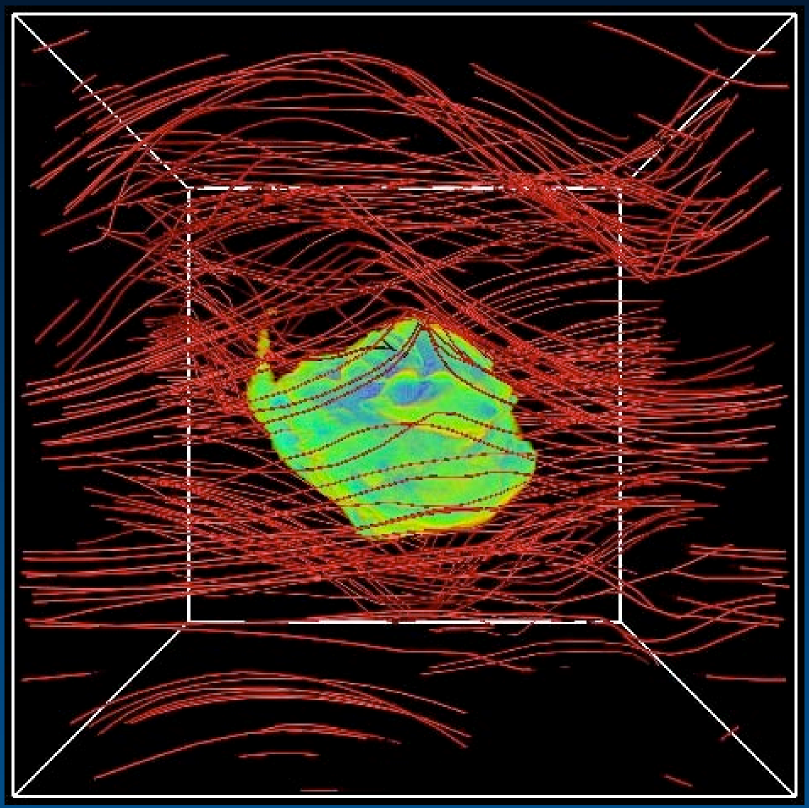
Follow evolution of:
M_{gas}, M_*,
R, dR/dt, σ

- Model GMC mass, energy, momentum budgets, with feedback and mass loss
- Use 1D model
  - Bad: real GMCs not spheres
  - Good: can solve exact equations: non-equilibrium virial, energy equations

$$\frac{\ddot{I}}{2} = 2(\mathcal{T} - \mathcal{T}_0) + \mathcal{W} + \mathcal{B} - \left(\frac{1}{2}\right)\frac{d}{dt}\int (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

$$\dot{E} + \int \rho \left(\frac{v^2}{2} + e + \phi + \frac{P}{\rho}\right) \mathbf{v} \cdot d\mathbf{S} = \Gamma - \Lambda$$

HII Region Feedback



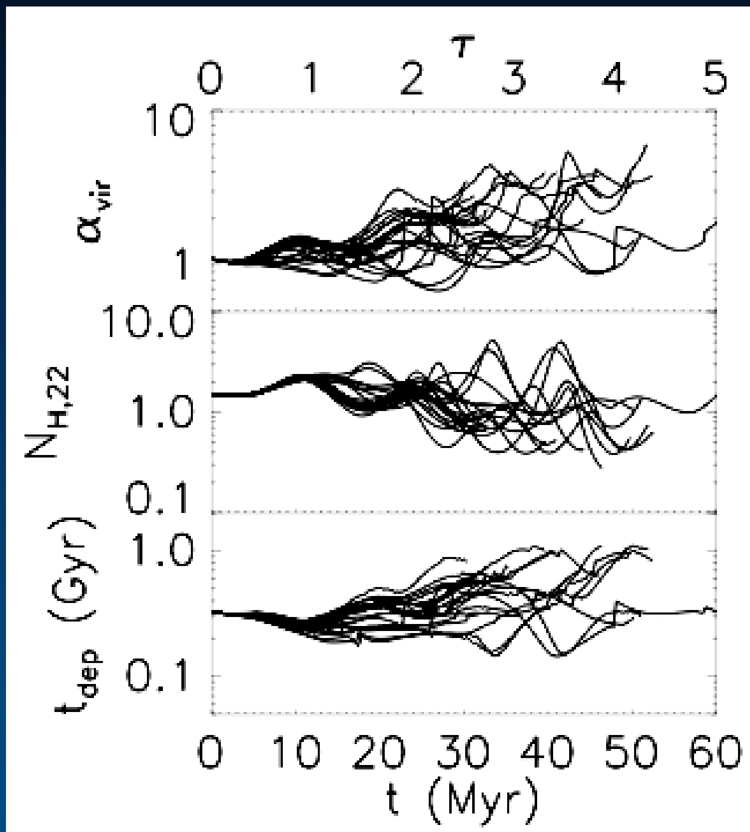
Simulation of HII region in a magnetized cloud, Krumholz & Stone 2008, in preparation

- HII regions dominate feedback (even beat SNe)
- Use modified Spitzer solution to get HII region expansion
- Assume all HII regions blister, lead to mass loss
- Compute energy injection assuming shells break up, merge with turbulence

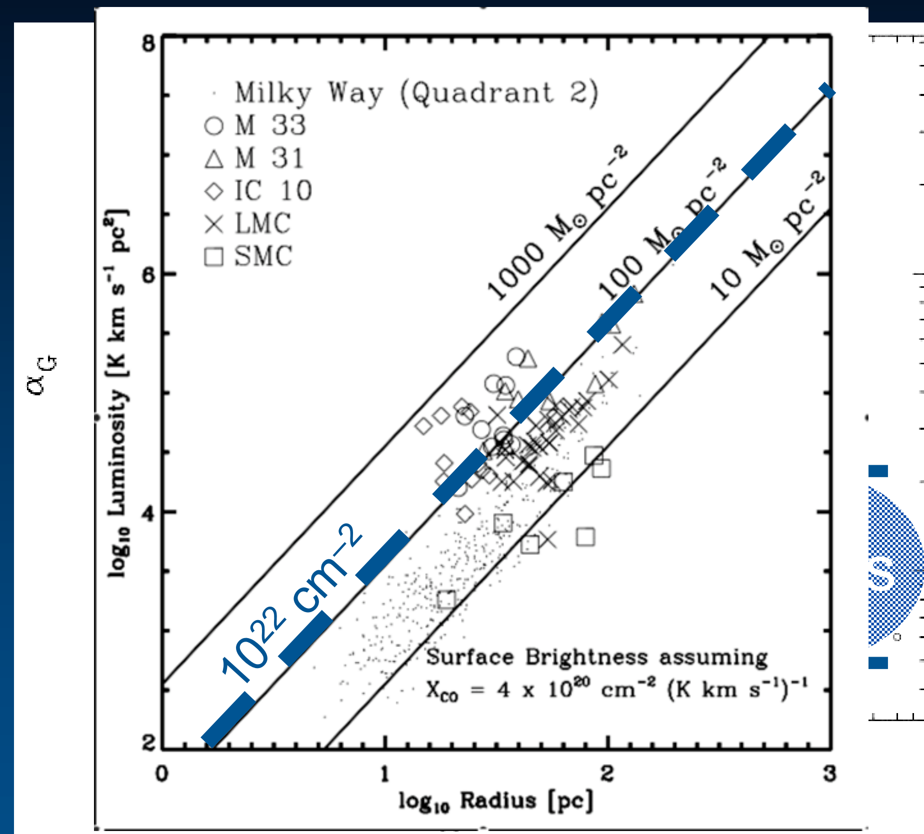
Model Runs

- Start clouds in equilibrium at observed column density $N_H \approx 10^{22}$ cm^{-2}
- Draw stars from cluster luminosity function, IMF to get HII region luminosity
- Run until cloud is unbound by HII regions or has N_H too low to remain molecular

Quasi-Equilibrium Clouds



Sample of runs for $M_{cl} = 5 \times 10^6\ M_\odot$



GMC mass vs. radius in the Local Group, Blitz et al. 2007

α vs. mass for GMCs, Heyer et al. 2001

Feedback keeps GMCs close to equilibrium (α ~ 1) at a preferred (column) density

Conclusions

- Star formation is slow because (1) only molecular gas makes stars; (2) even this gas forms stars at only ~2% per t_{ff}
- The molecular fraction is determined by column density and metallicity; low Z galaxies require very high Σ to make H_2
- The SFR in the H_2 is determined by turbulence driven by SF feedback
- Feedback energy balance imposes a column density $\sim 10^{22}$ cm^{-2} in GMCs