# The Secret Lives of Molecular Clouds

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Back to the Galaxy II

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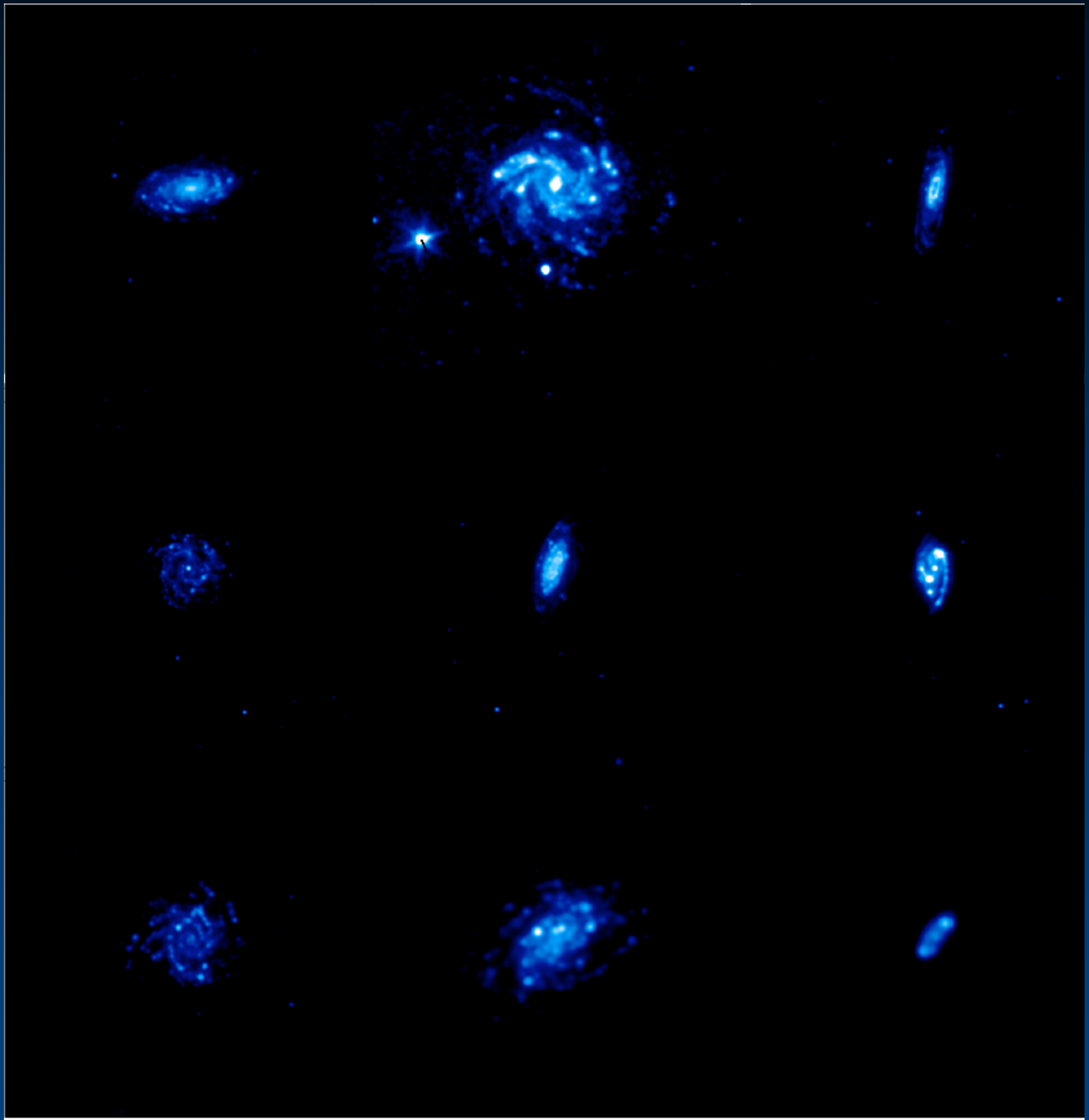
# Outline

- Embarrassing observational facts about star formation
- Turning gas into stars
  - Making molecular clouds
  - Turning molecular clouds into stars
  - Feedback in molecular clouds

# Observations

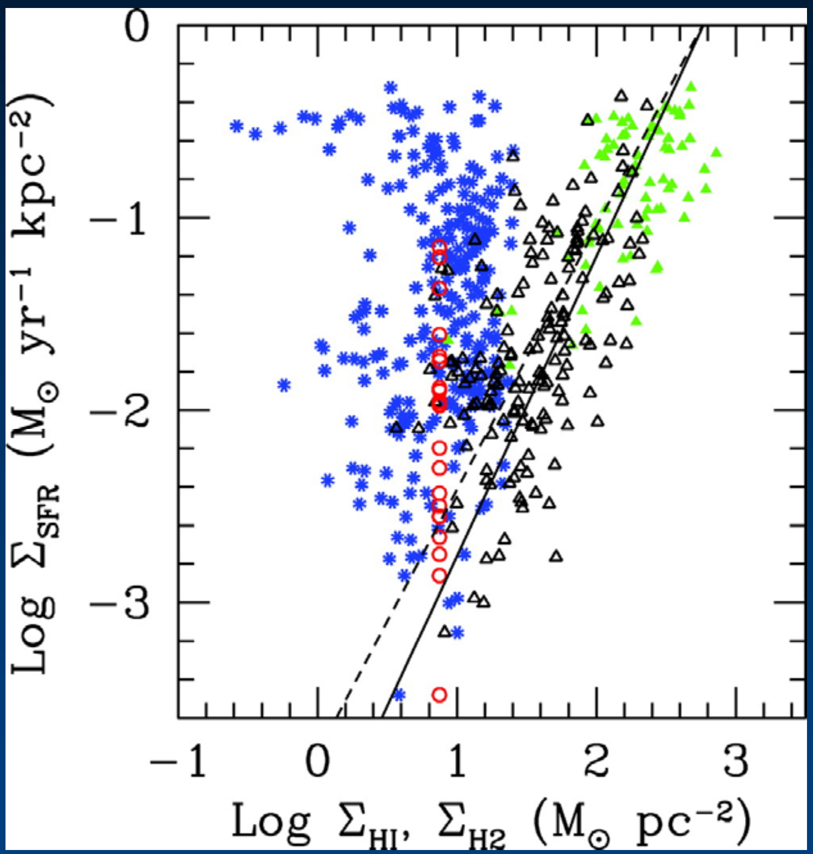
# Stars Do Not Form in Gas



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)

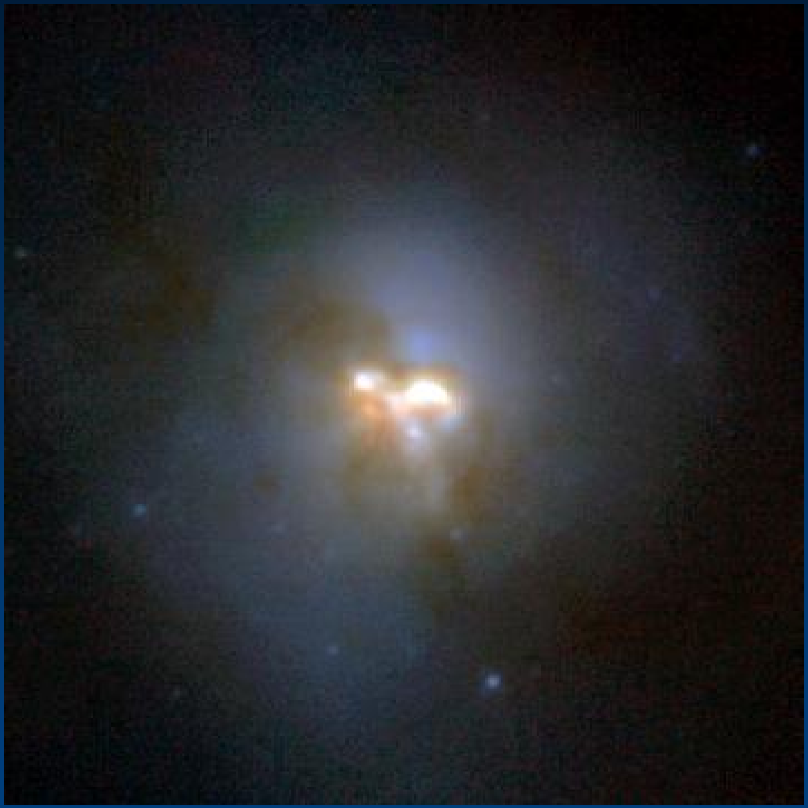
# Even once $H_2$ forms, SF is slow…

(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…

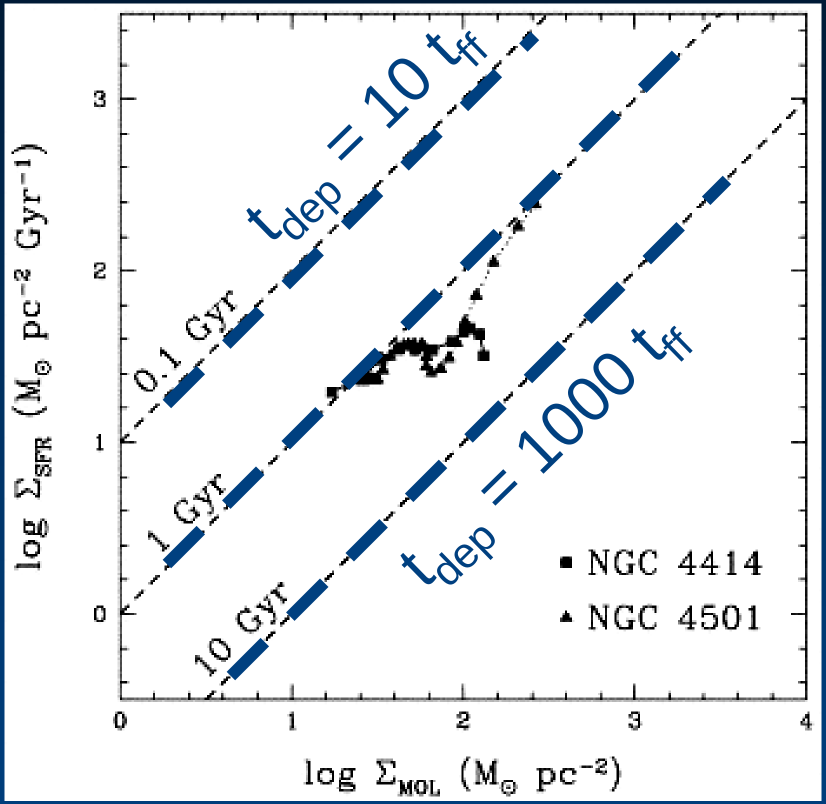
(Downes & Solomon 1998)

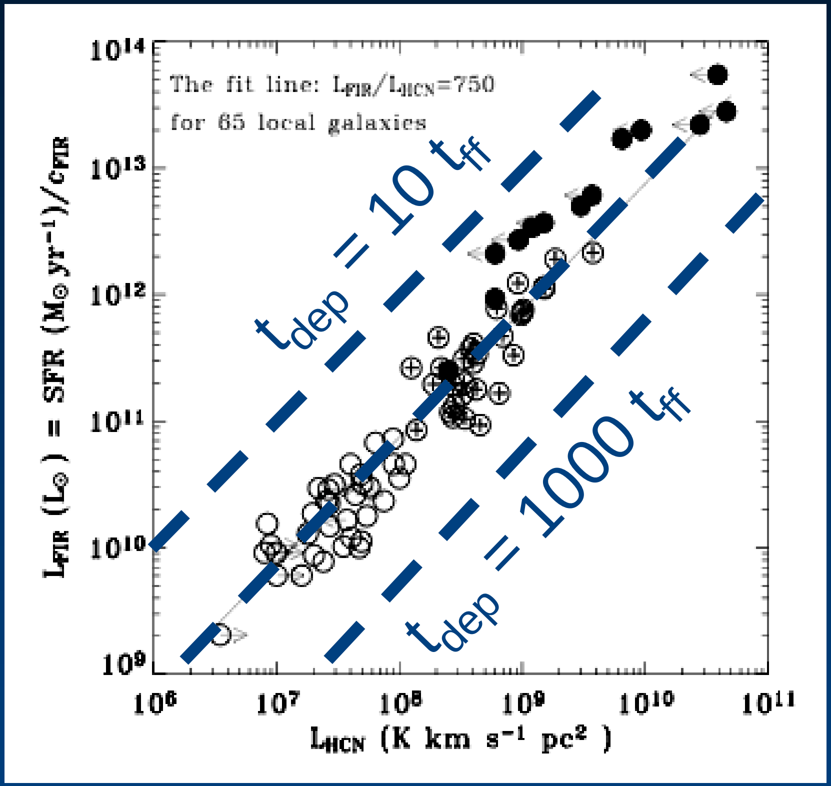


Arp 220 imaged by HST/NICMOS, Thompson et al. 1997

- 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...

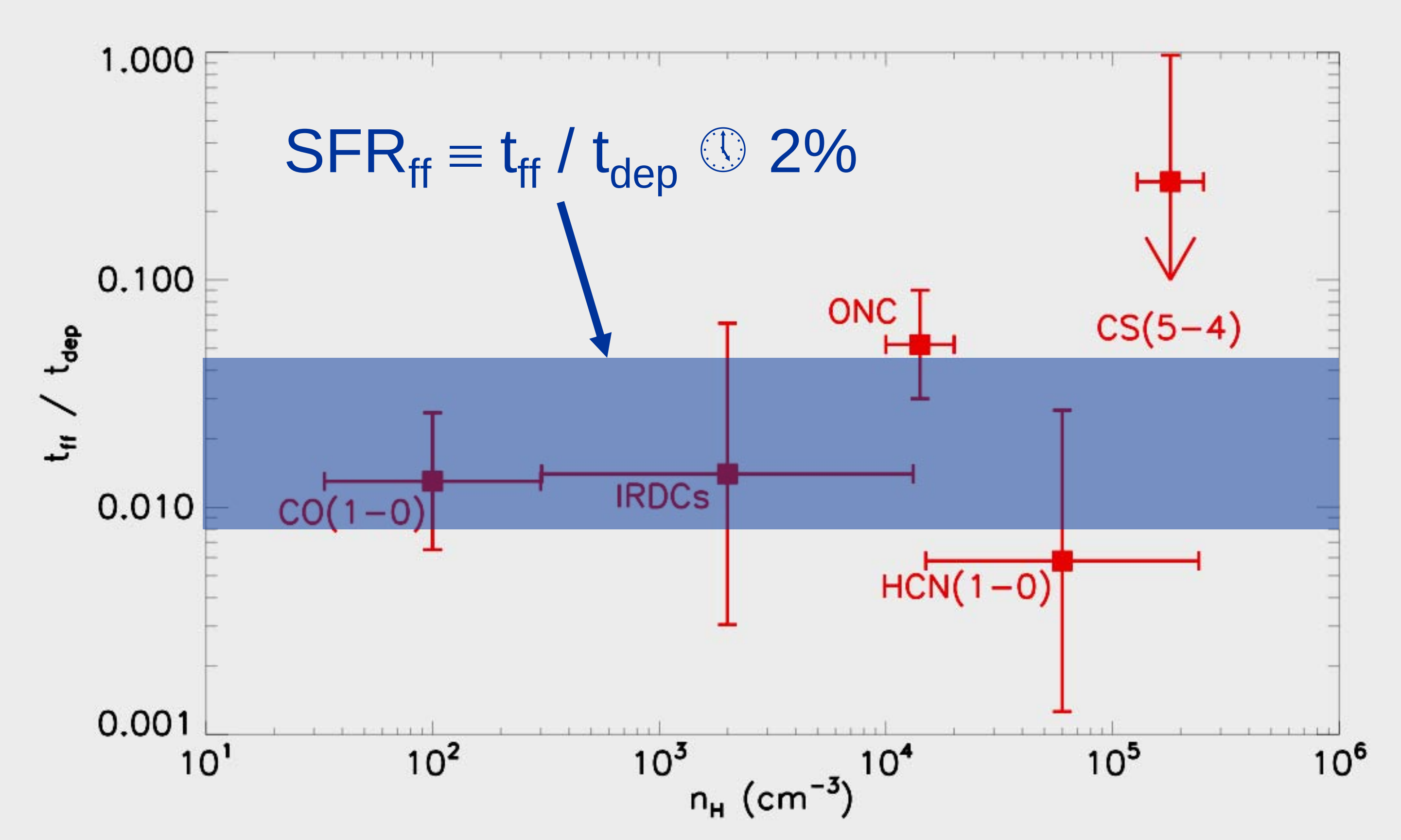


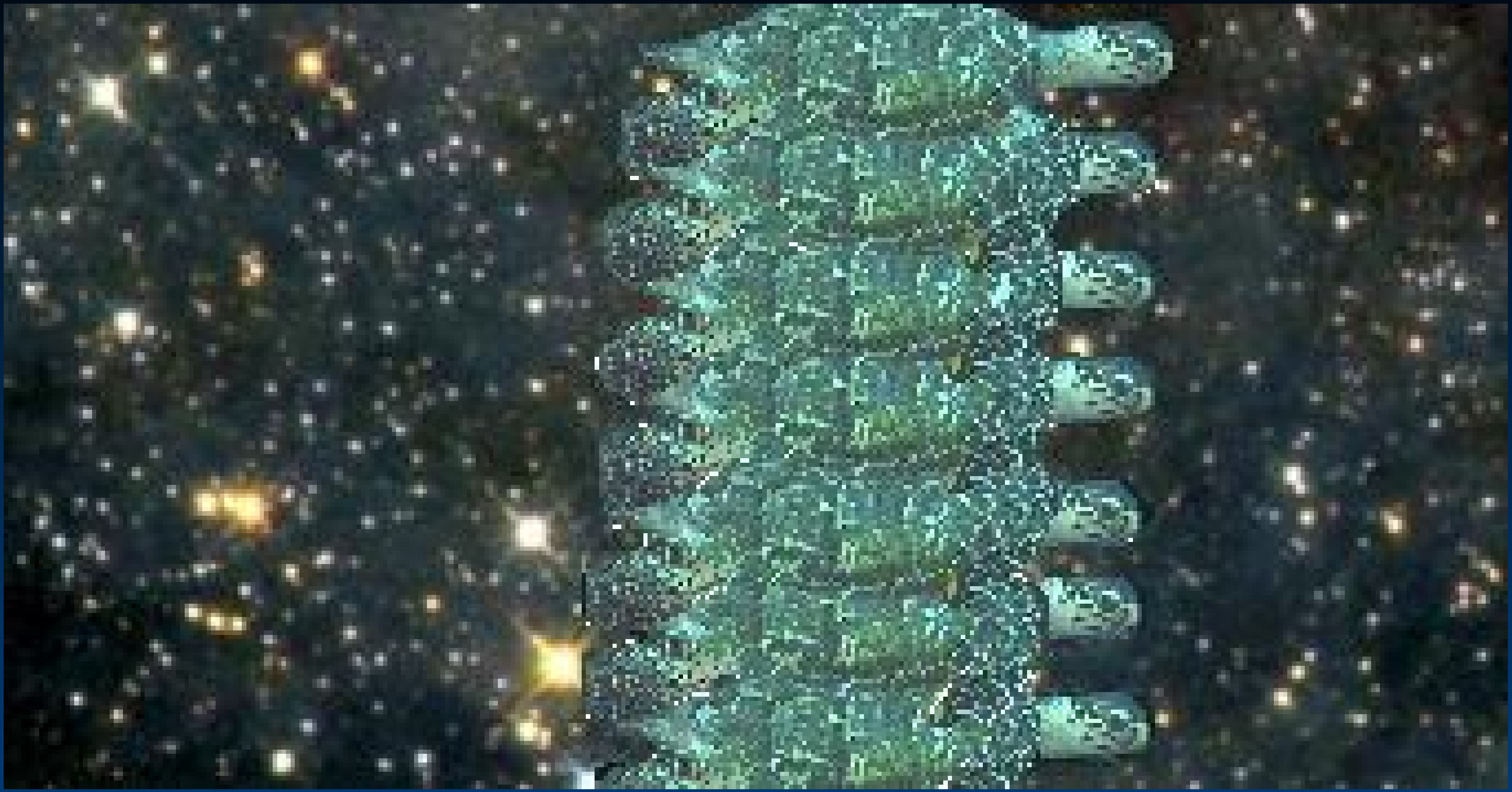




Depletion time as a function of $\Sigma_{H2}$ for 2 local galaxies (left, Wong & Blitz 2002) and as a function of $L_{HCN}$ for a sample of local and z ~ 2 galaxies (below, Gao et al. 2007)

# 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.

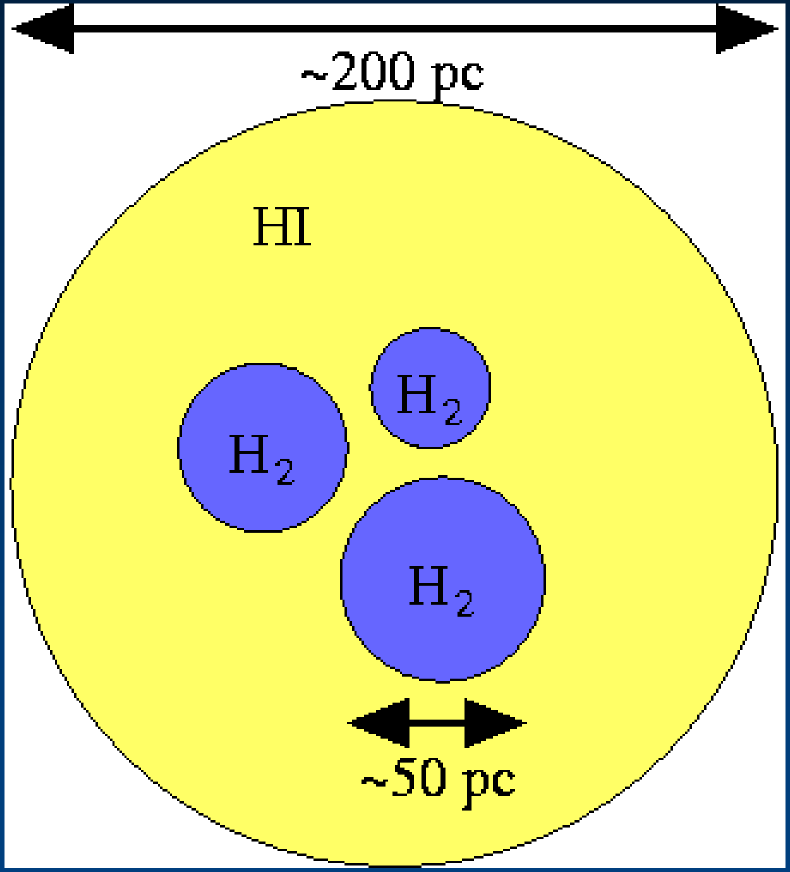
# Implications of Slow Star Formation, Part II

- 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

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

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

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

Decrease in radiation intensity =

Absorptions by H2 molecules + dust grains

# Calculating Molecular Fractions

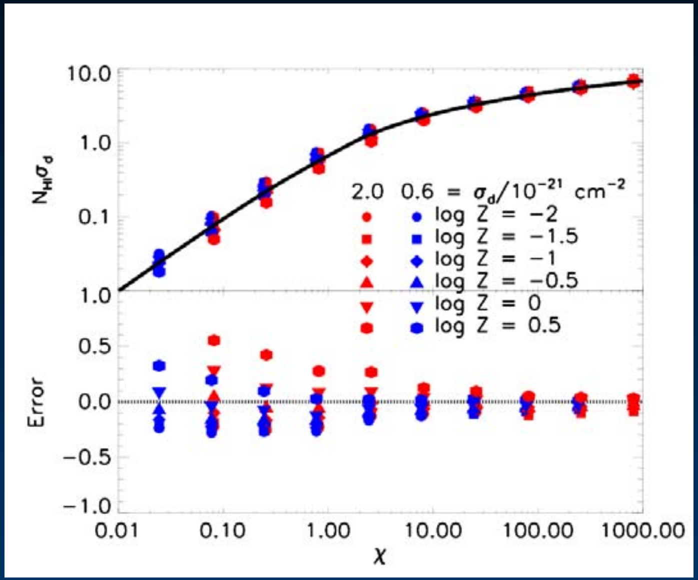
To good approximation, solution only depends on two dimensionless numbers:

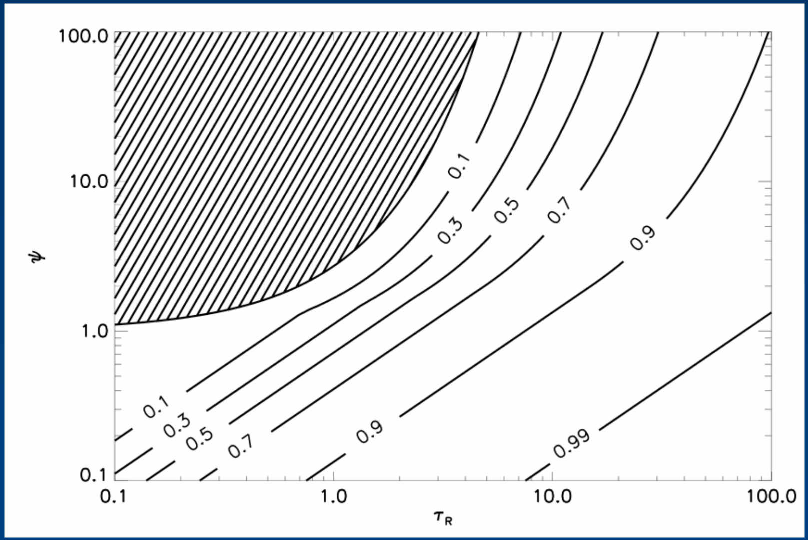
$$\tau_R = n\sigma_d R$$

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

Approximate solution:

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




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

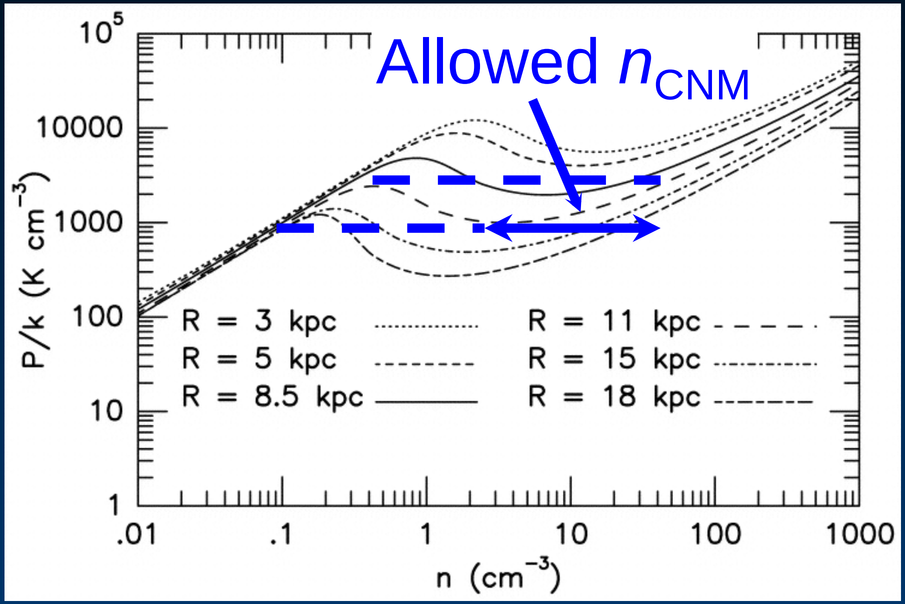
Bottom: $H_2$ volume fraction vs. $\psi$, $\tau_R$

# Shielding Layers in Galaxies

(Krumholz, McKee, & Tumlinson, 2008b, submitted)

What is $\psi \propto \sigma_d E_0^* / nR$?

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




FGH curves for MW (Wolfire et al. 2003)

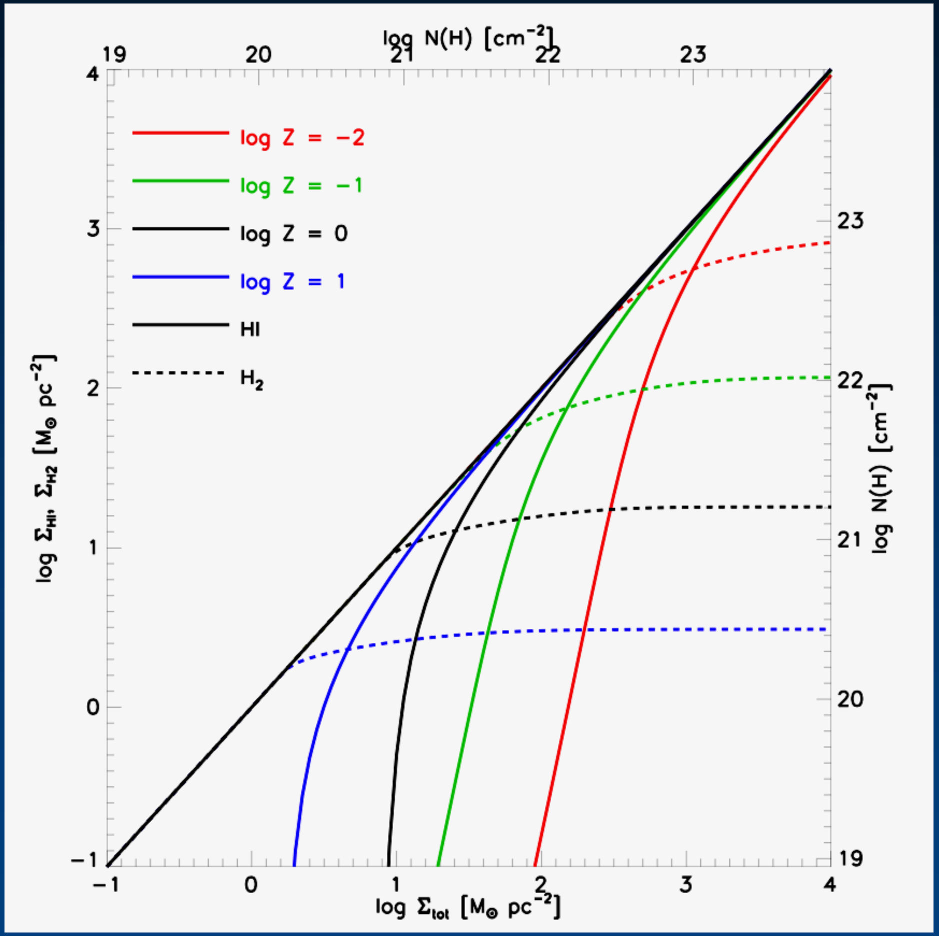
- CNM density set by pressure balance with WNM, and $n_{CNM} \propto E_0^*$, with weak Z dependence.

$\Rightarrow \psi \propto \sigma_d E_0^* / nR \sim 1$ in all galaxies!

# Predictions for $H_2$ Content

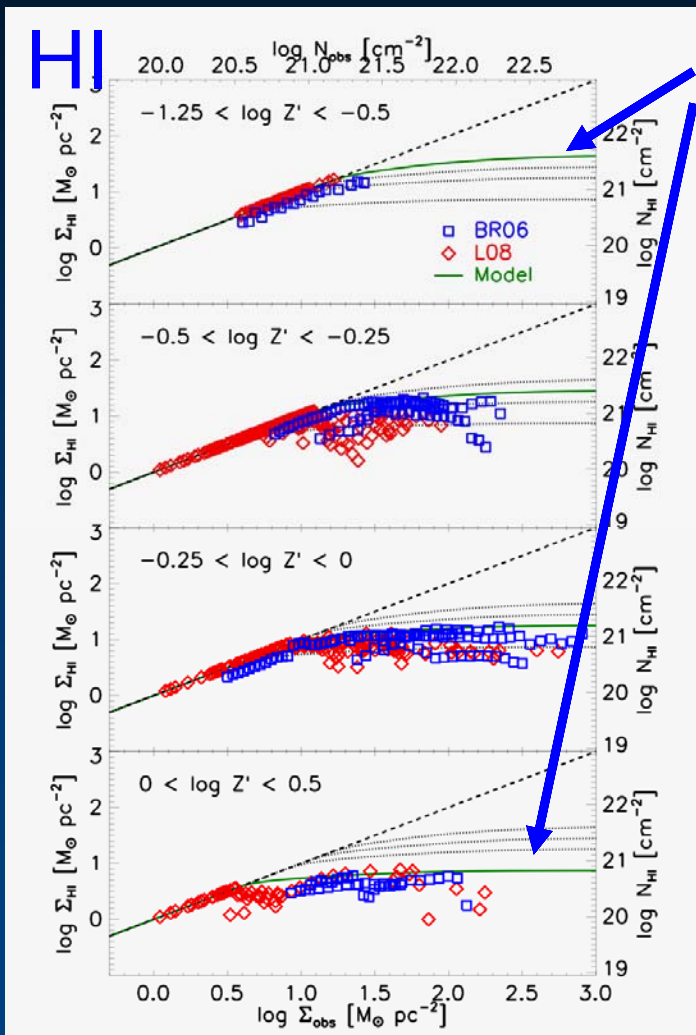
Compute $\tau_R$ from column density $\Sigma$, metallicity Z, and pressure balance between molecules and CNM.

Then use solution for $H_2$ fraction vs. $\psi$, $\tau_R$ to compute molecular content as a function of $\Sigma$, Z



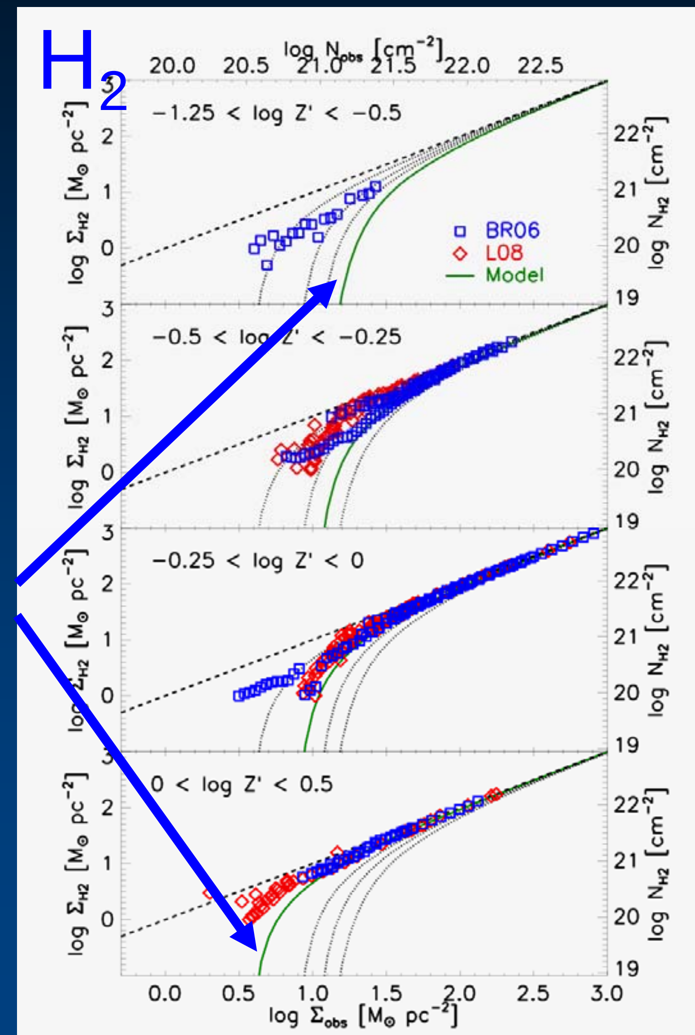
# Reality Check…

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




Matches observed saturation of HI at ~10 $M_\odot$ pc$^{-2}$, with higher $\Sigma_{HI}$ at low metallicity!

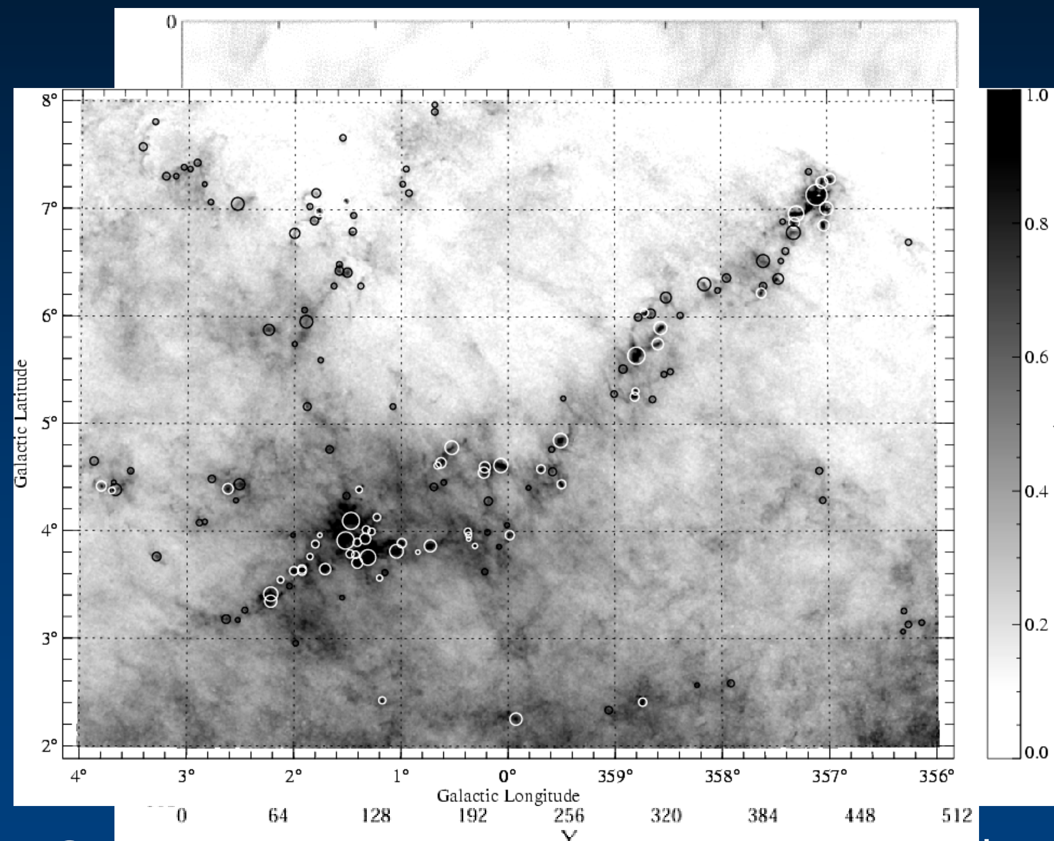
Matches column needed for molecules to appear, with higher $\Sigma$ at lower metallicity!



# 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

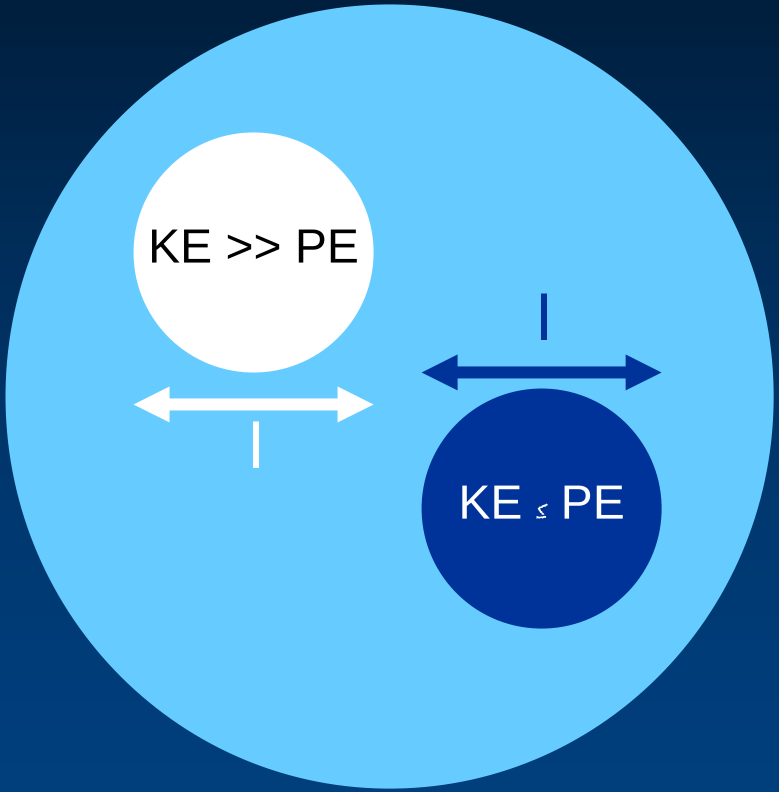



Column density map of the Pipe Nebula, with cores circled; Alves, Lombardi, & Lada 2007

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 ≈ KE)
- Linewidth-size relation: $\sigma_v \approx c_s (l / \lambda_s)^{1/2}$
- In average region, $M \propto l^3$
  $\Rightarrow$ KE $\propto l^4$, PE $\propto l^5$
  $\Rightarrow$ KE >> PE
- Hypothesis: SF only occurs in regions where PE $\gtrsim$ KE and $P_{th} \gtrsim P_{ram}$
- Only overdense regions meet these conditions
- Required overdensity is given by $\lambda_J \lesssim \lambda_s$, where $\lambda_J = c_s [\pi / (G\rho)]^{1/2}$



# Calculating the SFR

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

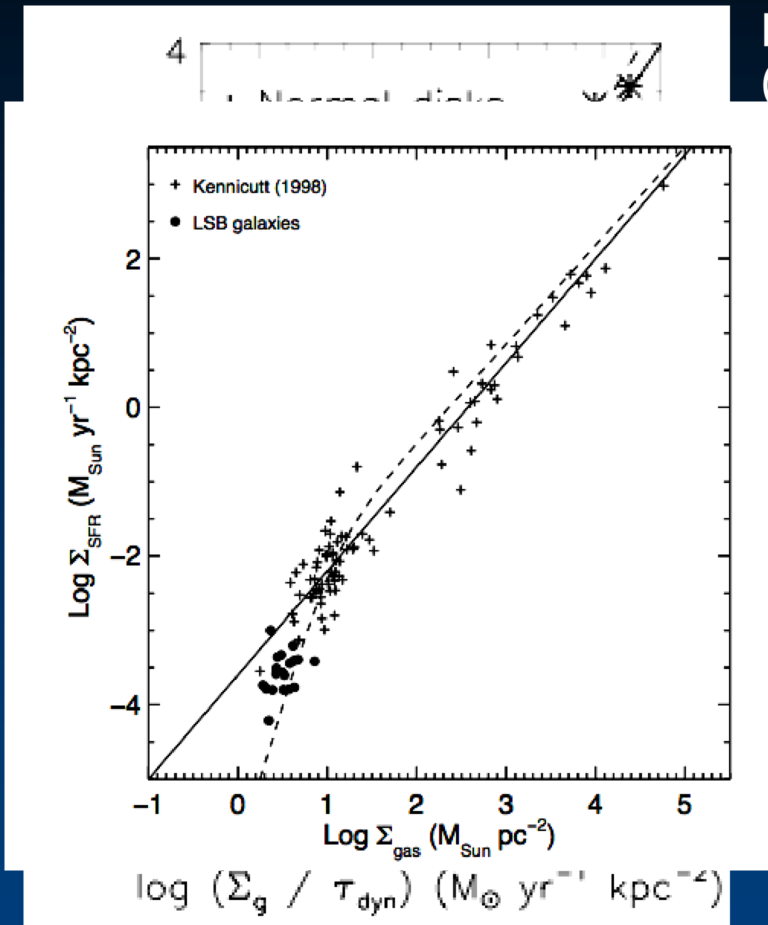
$\lambda_J = \lambda_s$

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

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

$\mathrm{SFR}_{ff}$ ~ 1-5% for any turbulent, virialized object

# Predicting the Kennicutt Law




Data and dashed line: Kennicutt (1998), solid line: KM05 model

Plus signs, solid line: Kennicutt 1998
Circles: LSBs, Wyder et al. 2008
Dashed line: KM05 model

- We don't know $t_{ff}$, $\mathcal{M}$ in GMCs in other galaxies
- Estimate by assuming
  - GMC mass ~ Jeans mass
  - GMCs are virialized
  - GMC internal pressure balances weight of ISM
- Result: a Kennicutt law in terms of observables

$$\frac{\dot{\Sigma}_*}{M_\odot/\mathrm{yr}/\mathrm{kpc}^2} = 130 f_{\mathrm{mol}} \left(\frac{\Omega}{\mathrm{Myr}^{-1}}\right)^{1.3} \left(\frac{\Sigma_g}{\mathrm{g}/\mathrm{cm}^2}\right)^{0.7}$$

# Step 3: Stellar Feedback

(Krumholz, Matzer, & McKee 2007)

30 Doradus HII region, MCELS

- All observed GMCs turbulent, $\alpha \approx 1$
- GMC lifetime is ~ 30 Myr (Blitz et al. 2007), $t_{cr}$ ~ 7 Myr $\Rightarrow$ need energy injection
- GMCs in have very similar properties in all nearby galaxies
- Hypothesis: SF feedback regulates GMC density and virial balance

# A Semi-Analytic GMC Model

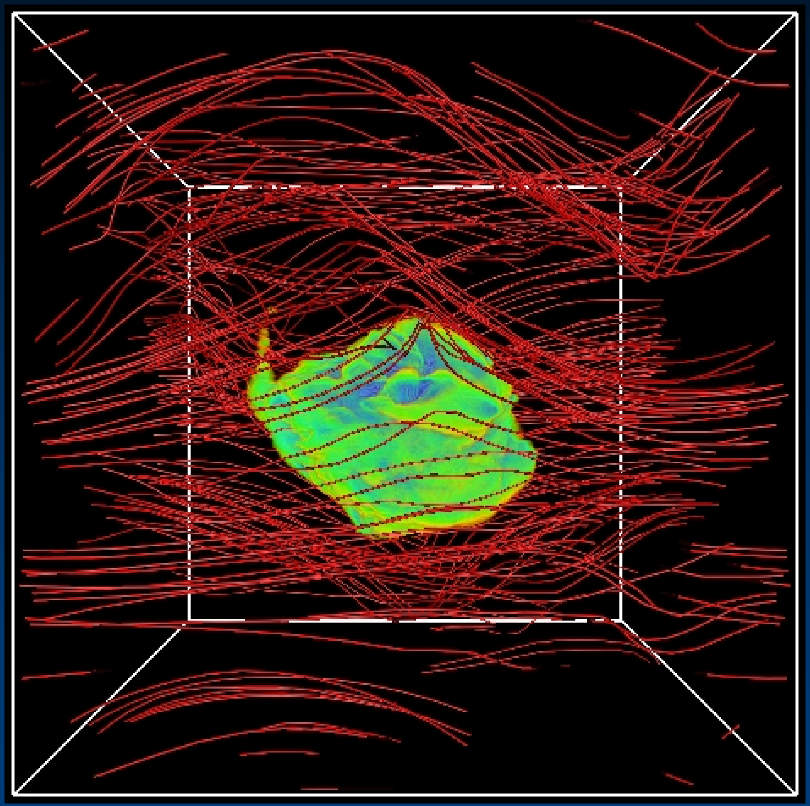
Follow evolution of:
$M_{gas}$, $M_*$,
R, dR/dt, σ

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

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

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

# HII Region Feedback



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

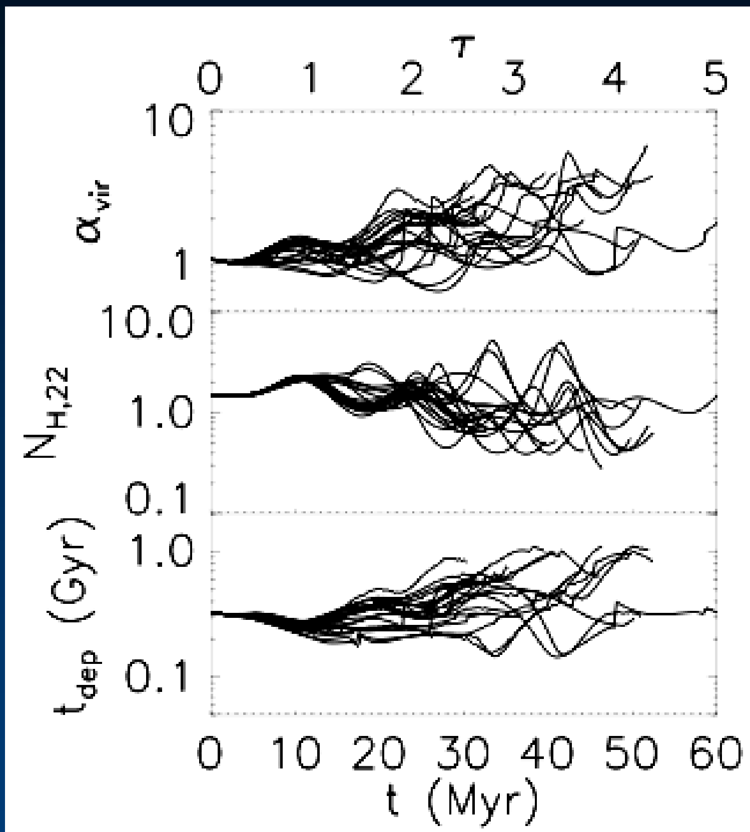
- HII regions dominate feedback (even beat SNe)
- Use modified Spitzer solution to get HII region expansion
- Assume all HII regions blister, lead to mass loss
- Compute energy injection assuming shells break up, merge with turbulence

# Simulation of HII Region Driving

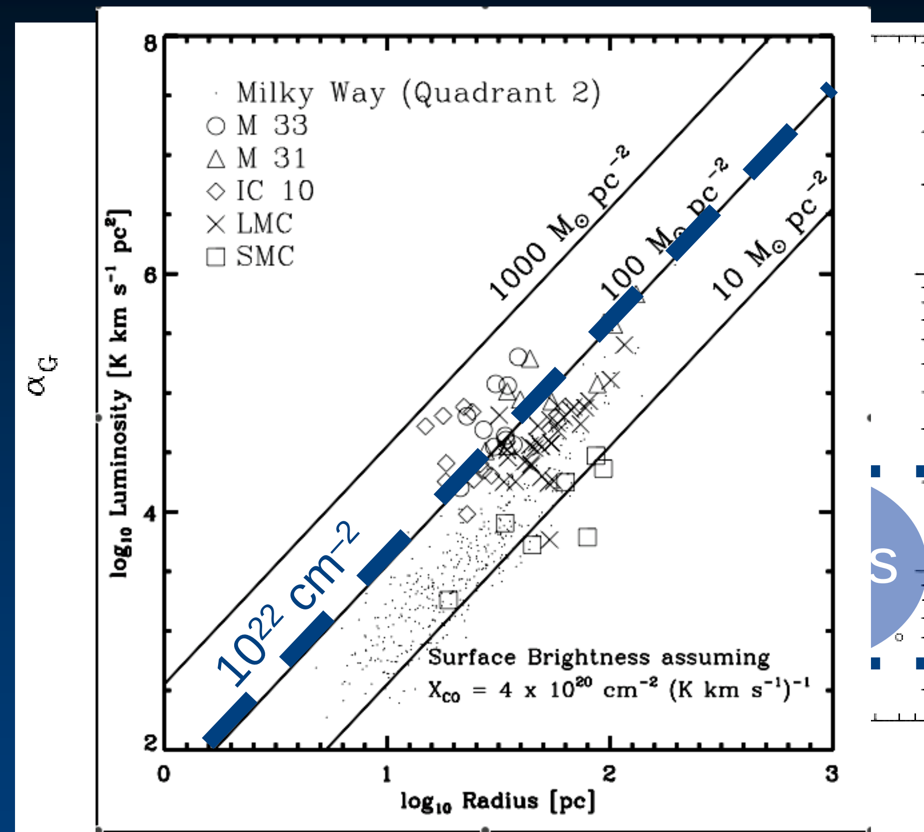
(Krumholz, Stone, & Gardiner 2007; Krumholz & Stone 2008, in preparation)

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

# Quasi-Equilibrium Clouds




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




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

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

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 $\Sigma$ 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 ~$10^{22}$ cm$^{-2}$ in GMCs