Turbulence, Feedback, and Slow Star Formation

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KITP Seminar

5 October 2007

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Outline

- Embarrassing observational facts
- Turbulence-regulated star formation
- Star formation-regulated turbulence
- Conclusions

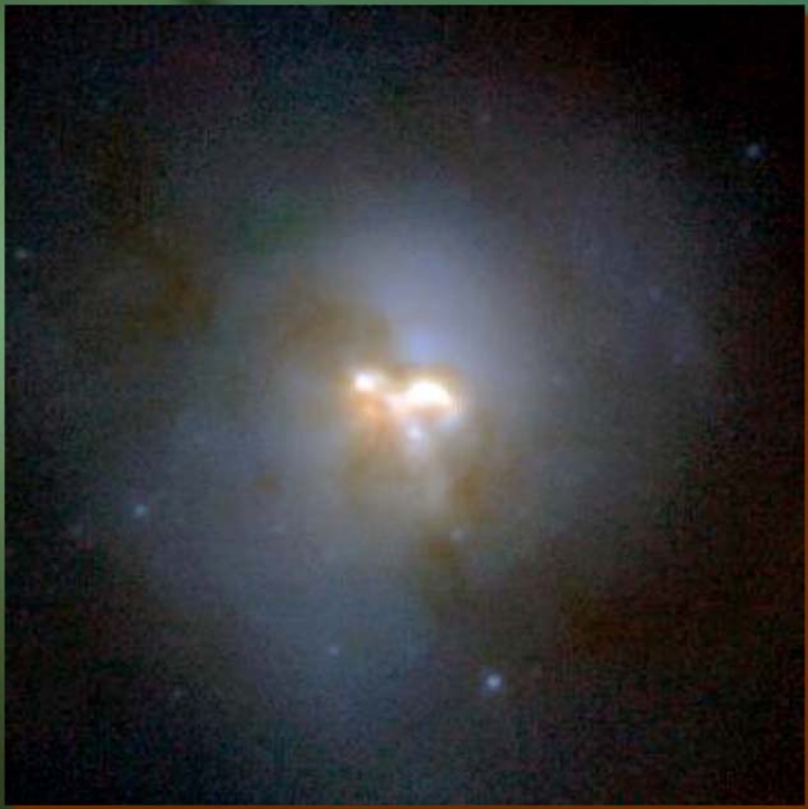
Observations

Star Formation is Slow…

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

- The Milky Way contains $M_{mol} \sim 10^9$ $M_\odot$ of gas in GMCs (Bronfman et al. 2000), with $n \sim 100$ H cm^{-3} (Solomon et al. 1987), free-fall time $t_{ff} \sim 4$ Myr
- This suggests a star formation rate $\sim M_{mol} / t_{ff} \sim 250\ M_\odot$ / yr
- Observed SFR is $\sim 3\ M_\odot$ / yr (McKee & Williams 1997)
- Numbers similar in nearby disks

…even in starbursts…



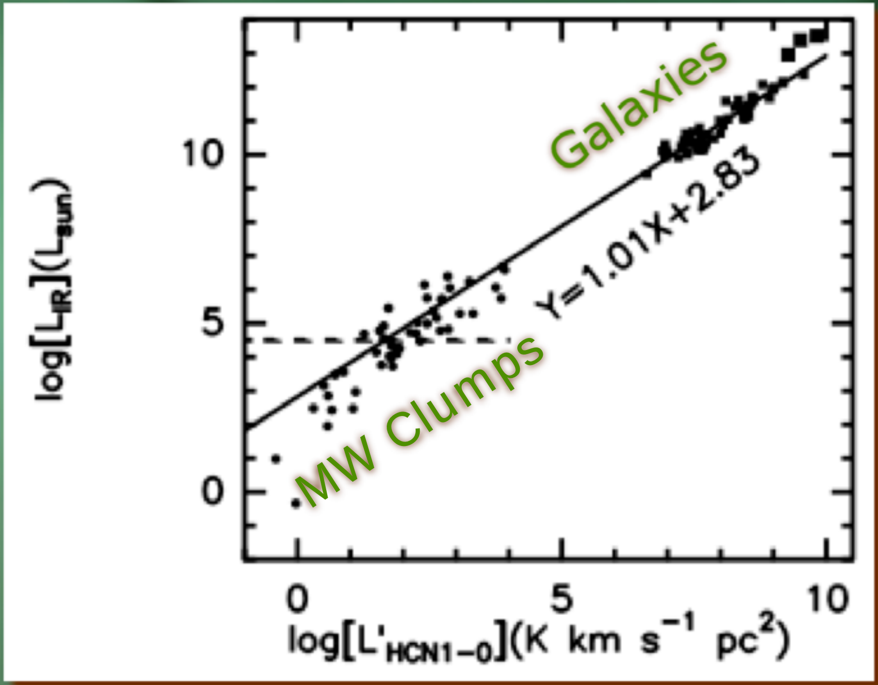
HST/NICMOS image of Arp 220, Thompson et al. 1997

- Example: Arp 220
- Measured properties: $n \sim 10^4$ H cm^{-3}, $t_{ff} \sim$ 0.4 Myr, $M_{mol} \sim 2 \times 10^9\ M_\odot$ (Downes & Solomon 1998)
- Suggested SFR ~ M_{mol} / t_{ff} ~ 5000 $M_\odot$ / yr
- Observed SFR is ~ 50 $M_\odot$ / yr (Downes & Solomon 1998): still too small by a factor of ~100

...even in dense gas...

(Gao & Solomon 2004, Wu et al. 2005, Krumholz & Tan, 2007, ApJ, 654, 304)

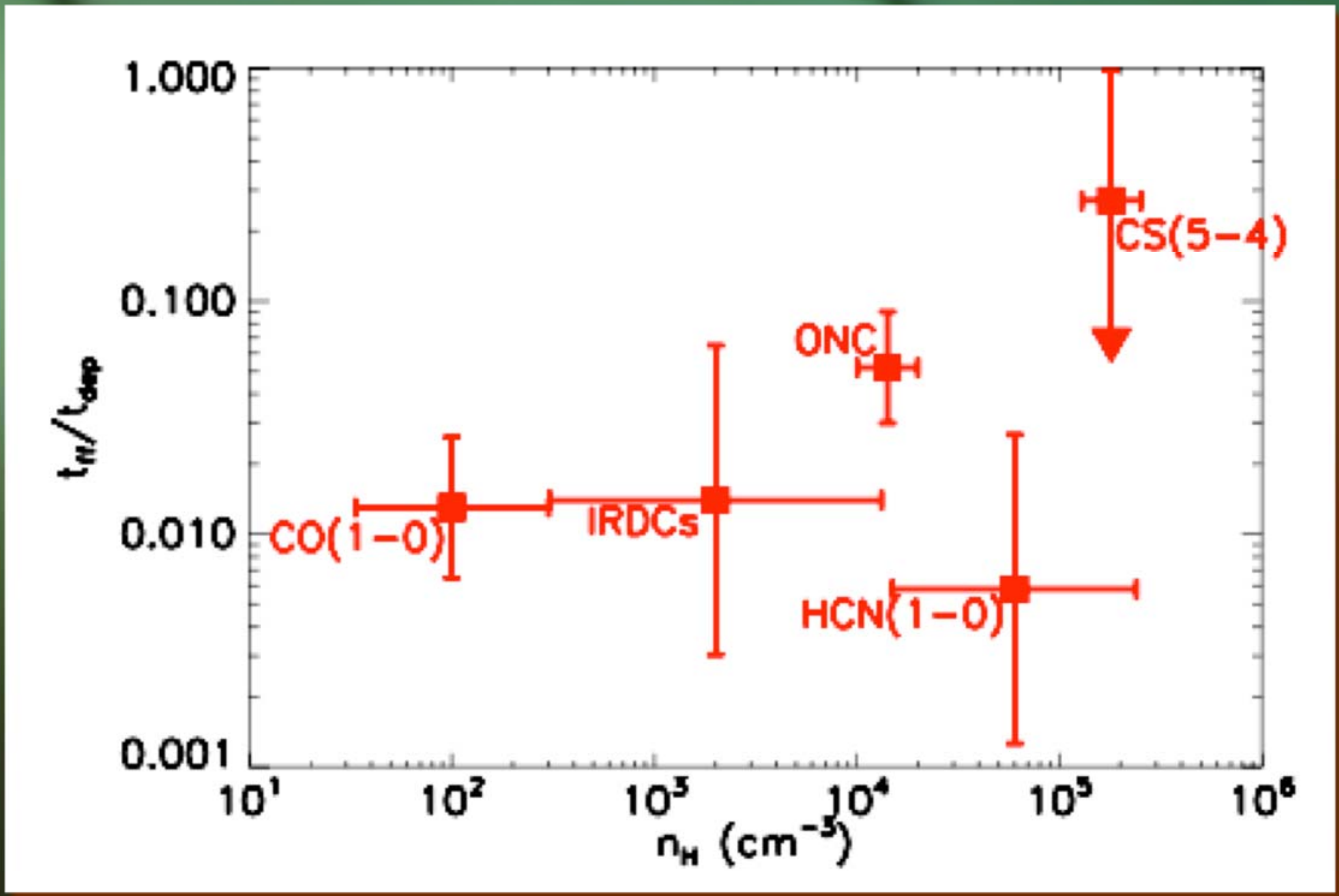
- Example: HCN observations show $L_{IR}/L_\odot \approx 900\ L_{HCN}$/K km s^{-1} pc^{-2}
- This implies a SFR ~ M_{HCN} / 30 Myr
- Critical density ~ 10^5 cm^{-3} ⇒ t_{ff} ~ 0.2 Myr
- Again, SFR too small by factor of ~100



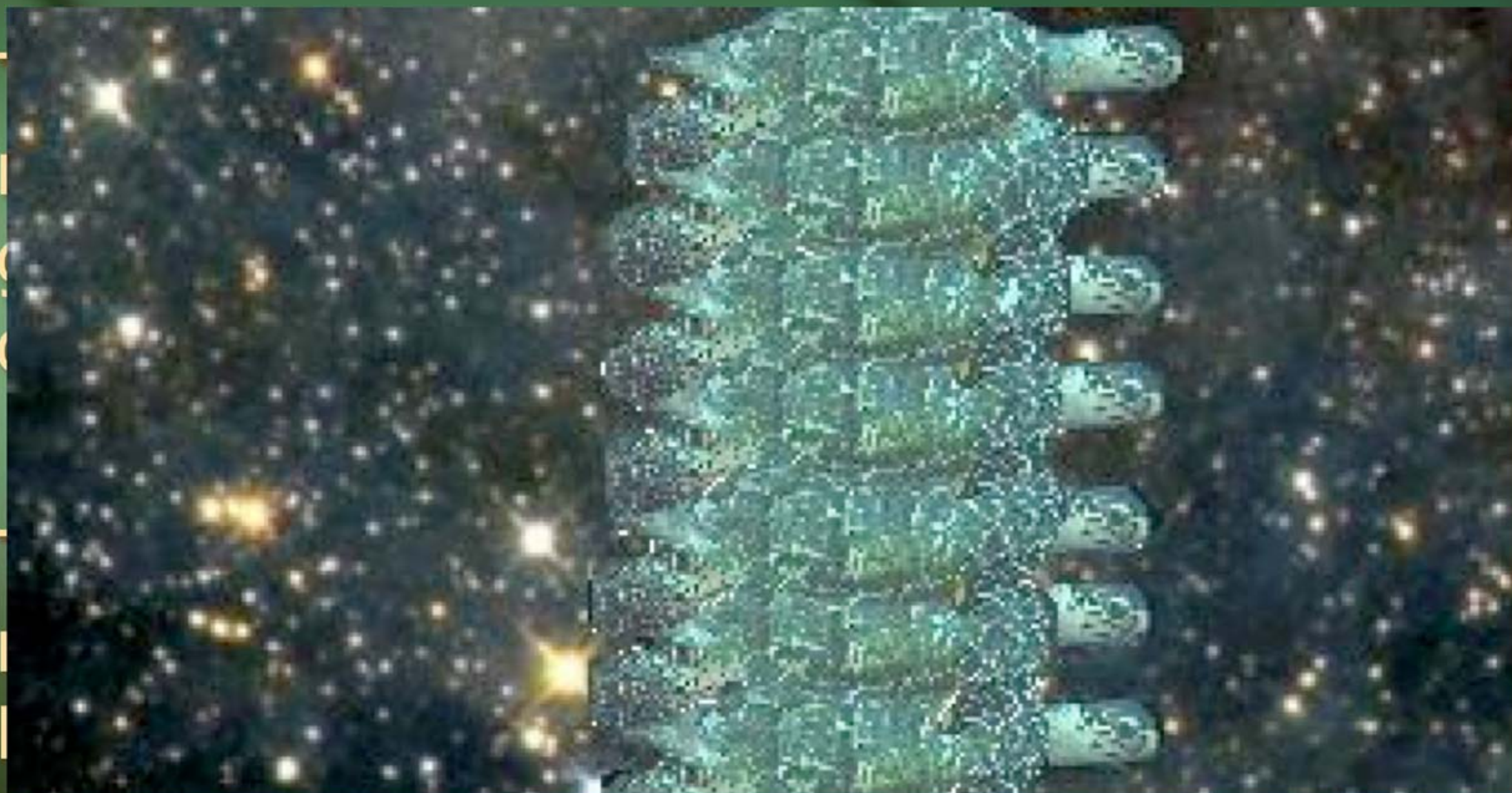
Observed IR-HCN correlation, (Wu et al. 2005)

All Observed Star Formation is Slow!

(Tan, Krumholz, & McKee, 2006, ApJL, 641, 121; Krumholz & Tan, 2007, ApJ, 654, 304)



Rant #1



regions containing a few percent of the mass, exactly as for the CO clouds.

In other words: it's turtles all the way down!

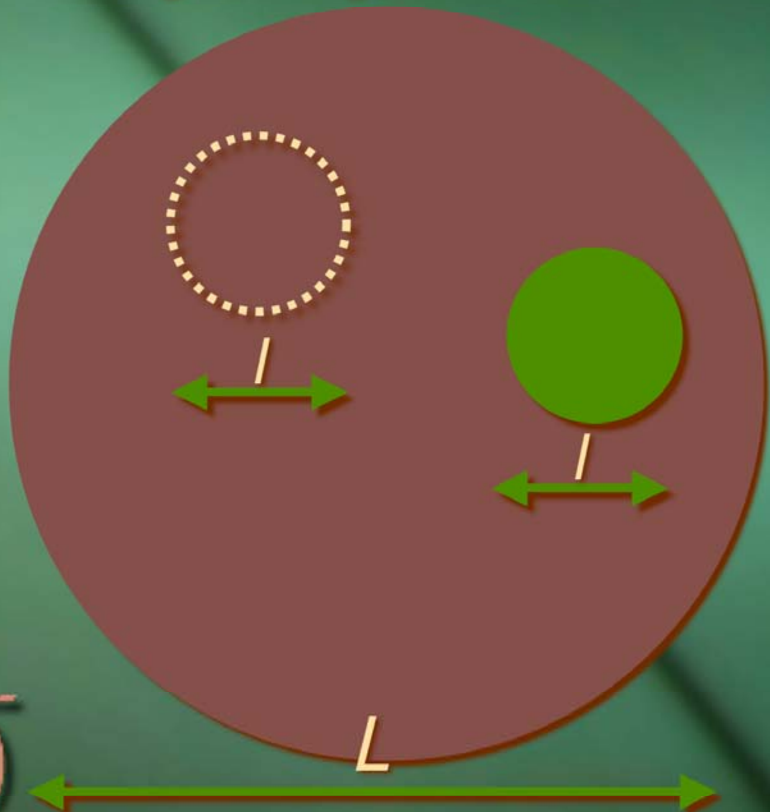
Implications of Slow Star Formation

- For galaxy modelers:
  - Bad news: unless you can resolve > 10^5 cm^{-3}, you cannot avoid subgrid models.
  - Good news: setting SFR ~1% / t_{ff} in cold gas is a good model for any maximum ρ.
- For SF theorists:
  - A big question is: why SF is so slow?
  - The answer for the SF rate (as opposed to threshold) must be at small scales (it's not cloud formation, spiral arms, etc.).

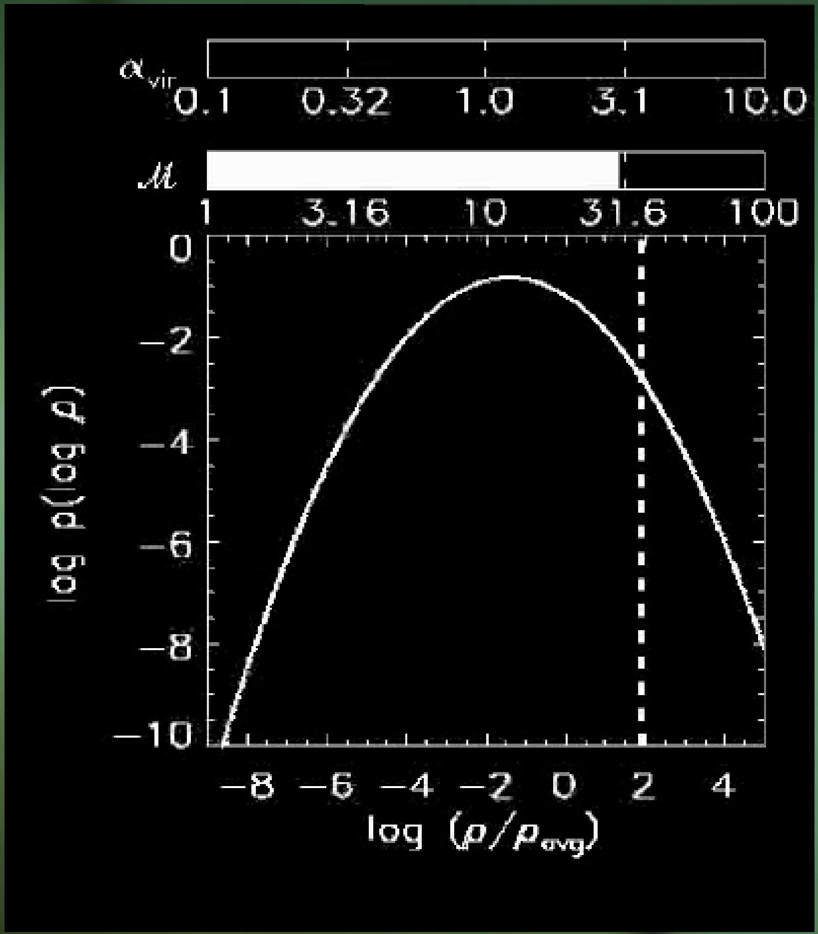
Turbulence-Regulated SF

(Krumholz & McKee, 2005, ApJ, 630, 250)

- Whole cloud: PE(L) ~ KE(L), (i.e. $\alpha_{vir} \sim 1$)
- Linewidth-size relation: $\sigma = c_s (l/\lambda_s)^{1/2}$
- In average region, PE(l) $\propto l^5$, KE(l) $\propto l^4$ ⇒ most regions have KE(l) » PE(l)
- Overdense regions can have PE(l) ~ KE(l)
- PE = KE implies $\lambda_J \approx \lambda_s$, where $\lambda_J = \sqrt{\pi c_s^2/(G\rho)}$
- This also implies that $P_{\rm th}(\rho) = P_{\rm ram}(\bar{\rho}, \sigma)$



The Turbulent SFR



- Turbulent gas has lognormal PDF of densities that depends on $\mathcal{M}$
- $\lambda_J \approx \lambda_s$ gives instability condition on density
- Gas above critical density collapses on time scale t_{ff}
- Result: an estimate

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

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

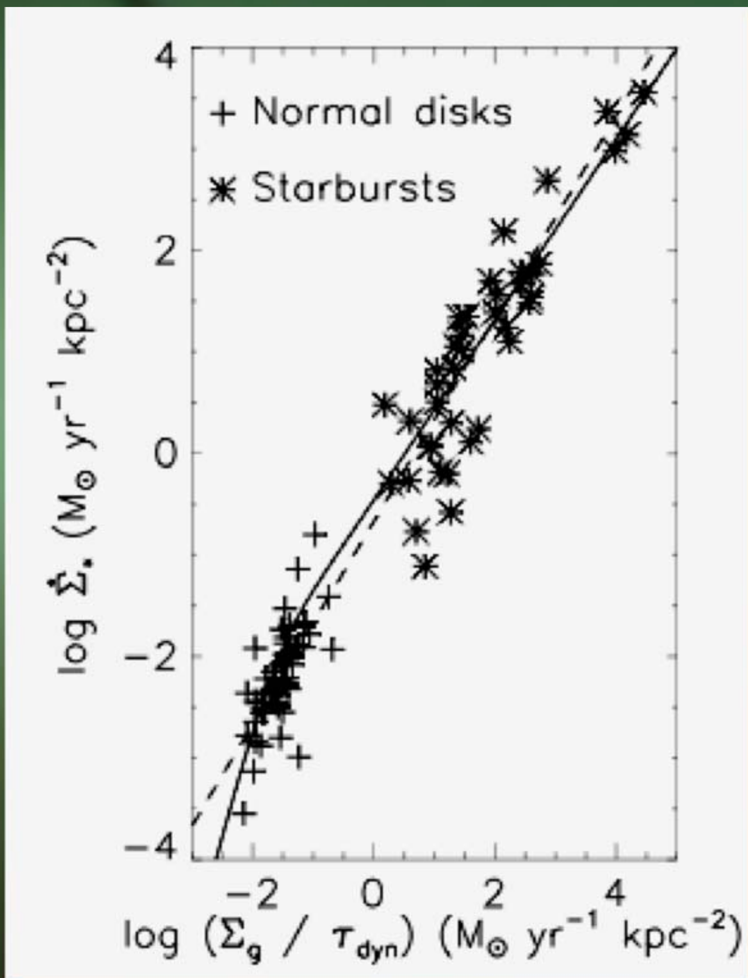
Comparison to Milky Way

- In MW, properties of GMCs observable
- Integrate over GMC distribution to get SFR:

$$\dot{M}_{*-pred} \approx \int_{M_6=0.01}^{M_6=6} \frac{\mathrm{SFR_{ff}}}{t_{\mathrm{ff}}} \frac{dN}{d\ln M} dM$$
$$= 5.3\, M_\odot\ \mathrm{yr}^{-1}$$

- Observed SFR ~ 3 $M_\odot$ / yr: good agreement!
- Also reproduce radial distribution (Luna et al. 2006)
- Direct test: repeat calculation once a comparable catalog is available for M33, M64, LMC.

SF Law in Other Galaxies



Theory (solid line, KM05), empirical fit (dashed line, Kennicutt 1998), and data (K1998) on galactic SFRs

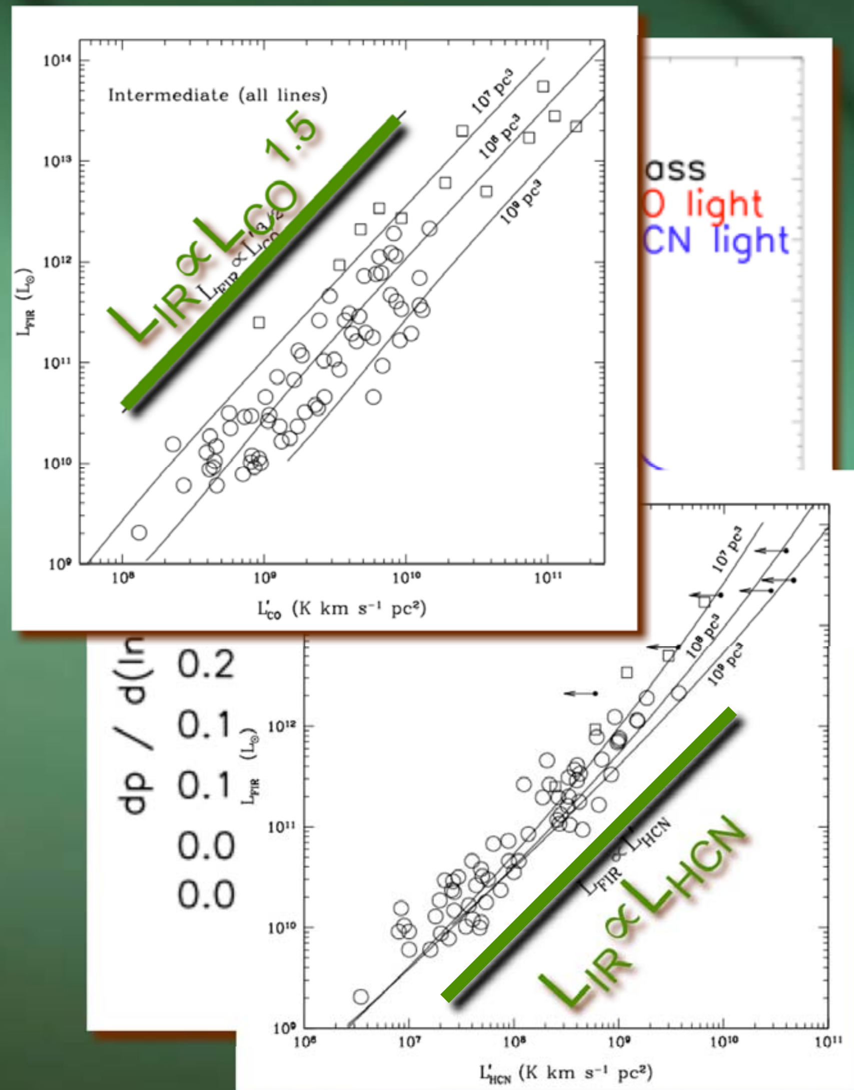
- For other galaxies, GMCs not directly observable
- Estimate GMC properties based on (1) pressure balance with ISM, (2) virial balance in GMCs

$$\dot{\Sigma}_* \approx 9.5 f_{\rm GMC} Q_{1.5}^{-1.32} \Omega_0^{1.32} \Sigma_{g,2}^{0.68}\, M_\odot\ {\rm yr}^{-1}\ {\rm kpc}^{-2}$$

SF Laws in Different Tracers

(Krumholz & Thompson, 2007, ApJ, in press, arXiv:0704.0792)

- SF law depends on tracer: SFR $\propto L_{CO}^{1.5}$, or SFR $\propto L_{HCN}^{1.0}$
- Depends on n_{crit}:
  - CO: low $n_{crit} \rightarrow$ all gas, varying n
  - HCN: high $n_{crit} \rightarrow$ dense gas, fixed n
- SFR ~ 0.01 M/t_{ff}; t_{ff} fixed for HCN, not CO, so CO gets extra power of 0.5



Star Formation-Regulated Turbulence

(Krumholz, Matzner, & McKee 2006, ApJ, 653, 361)

- Observed GMCs are turbulent, virialized, all have about same N_H
- Turbulence decays in ~1 crossing time (Stone, Ostriker, & Gammie 1998; Mac Low et al. 1998)
- Large GMCs live 20–30 Myr, ~3–4 t_{cr}, ~6–8 t_{ff}
- Need to explain cloud lifetimes and invariance of cloud properties

HII region in 30 Doradus, MCELS team

A Semi-Analytic GMC Model

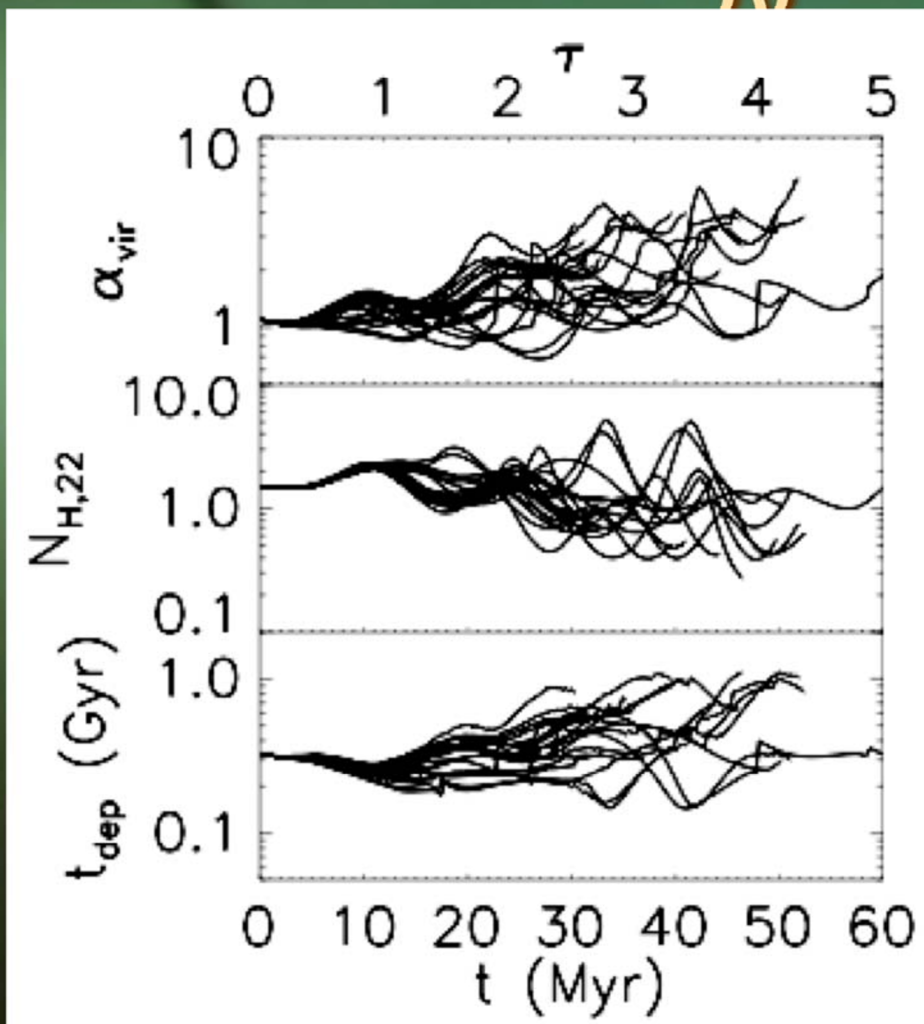
M_g, M_*,
R, dR/dt, σ

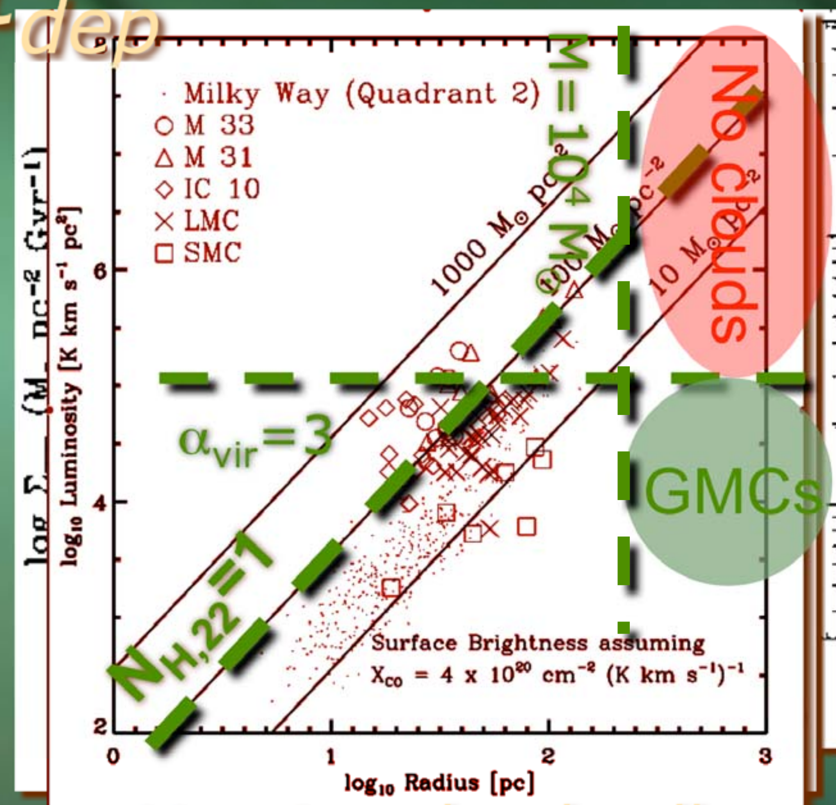
- Goal: model GMC energy and momentum budget, including decay of turbulence, turbulent driving and mass loss due to HII regions
- Evolution eqns: non-equilibrium virial theorem and energy conservation

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

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

Clouds Stay Near Observed Values of α_{vir}, N_H, t_{dep}





Massive clouds all have α_{vir} = 0.5 – 3 (Heyer et al. 2001)

Galactic and LG clouds have N_H ~1 10^{22} cm^{-2} (Blitz et al. 2006)

Depletion time constant ~2 Gyr (Wong & Blitz 2002)

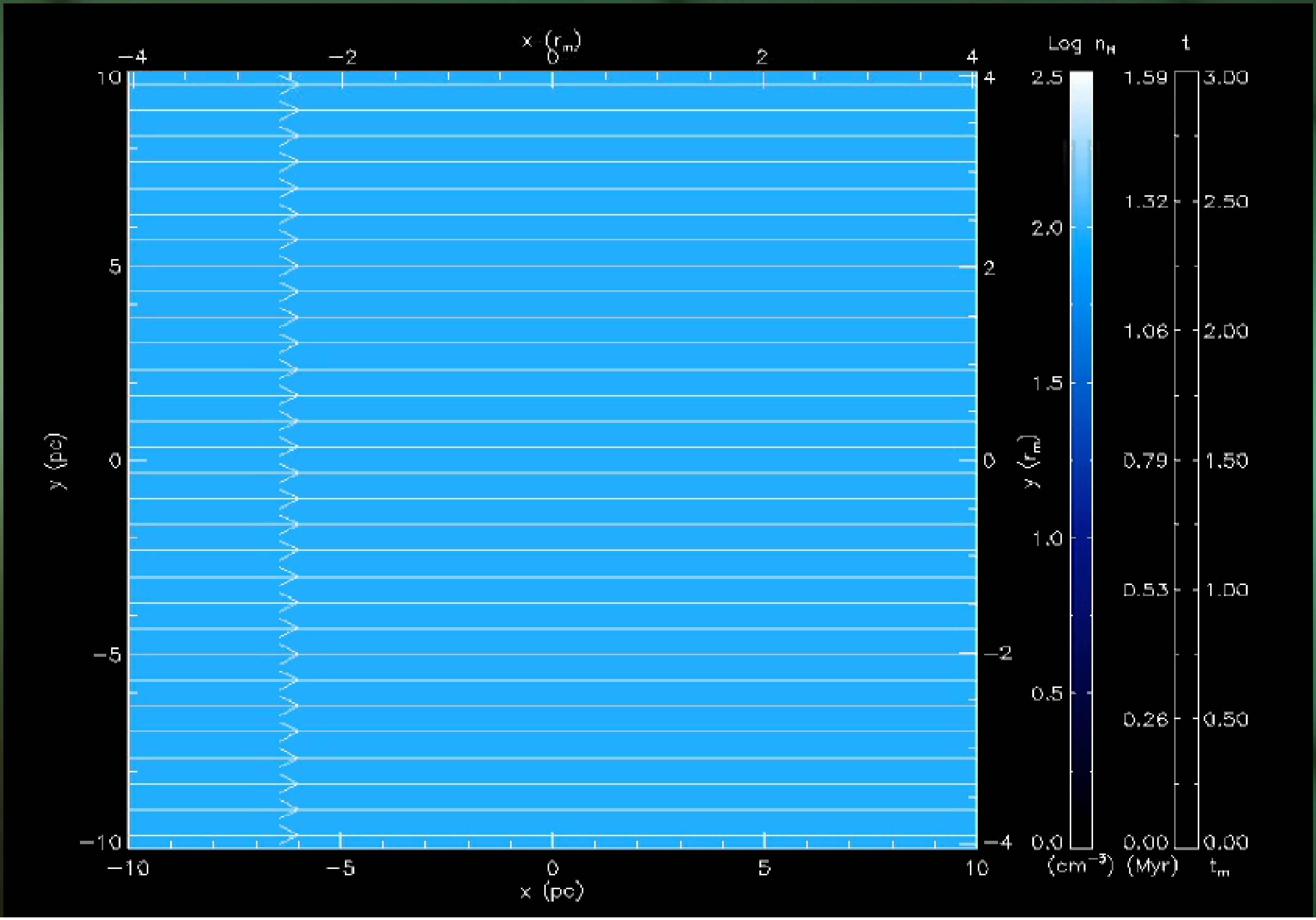
Global Results

Mass	Lifetime	SFE	Destroyed By?
2×10^5 $M_\odot$	9.9 Myr (1.6 t_{cr}, 3.2 t_{ff})	5.3%	Unbinding, dissociation by interstellar UV
1×10^6 $M_\odot$	20 Myr (2.2 t_{cr}, 4.4 t_{ff})	5.4%	Unbinding by HII regions
5×10^6 $M_\odot$	43 Myr (3.2 t_{cr}, 6.4 t_{ff})	8.2%	Unbinding by HII regions

- Large clouds quasi-stable, live 20-40 Myr: agrees with observed ~30 Myr lifetime of LMC GMCs (Fukui et al. 2007)!
- Small clouds live ~1 crossing time, consistent with small, local clouds

Next Step: Ionization MHD Simulations

(Krumholz, Stone, & Gardiner 2007, ApJ, in press, astro-ph/0606539)



Conclusions

- Star formation is SLOW on all scales, in all environments
- Feedback-driven turbulence can explain this observation
- This model explains / predicts:
  - Low SFR even in very dense gas
  - GMC lifetimes and properties
  - Rate of star formation in MW
  - Kennicutt Law and IR-HCN correlation