Enhanced Star Formation Rates in Starburst Galaxies

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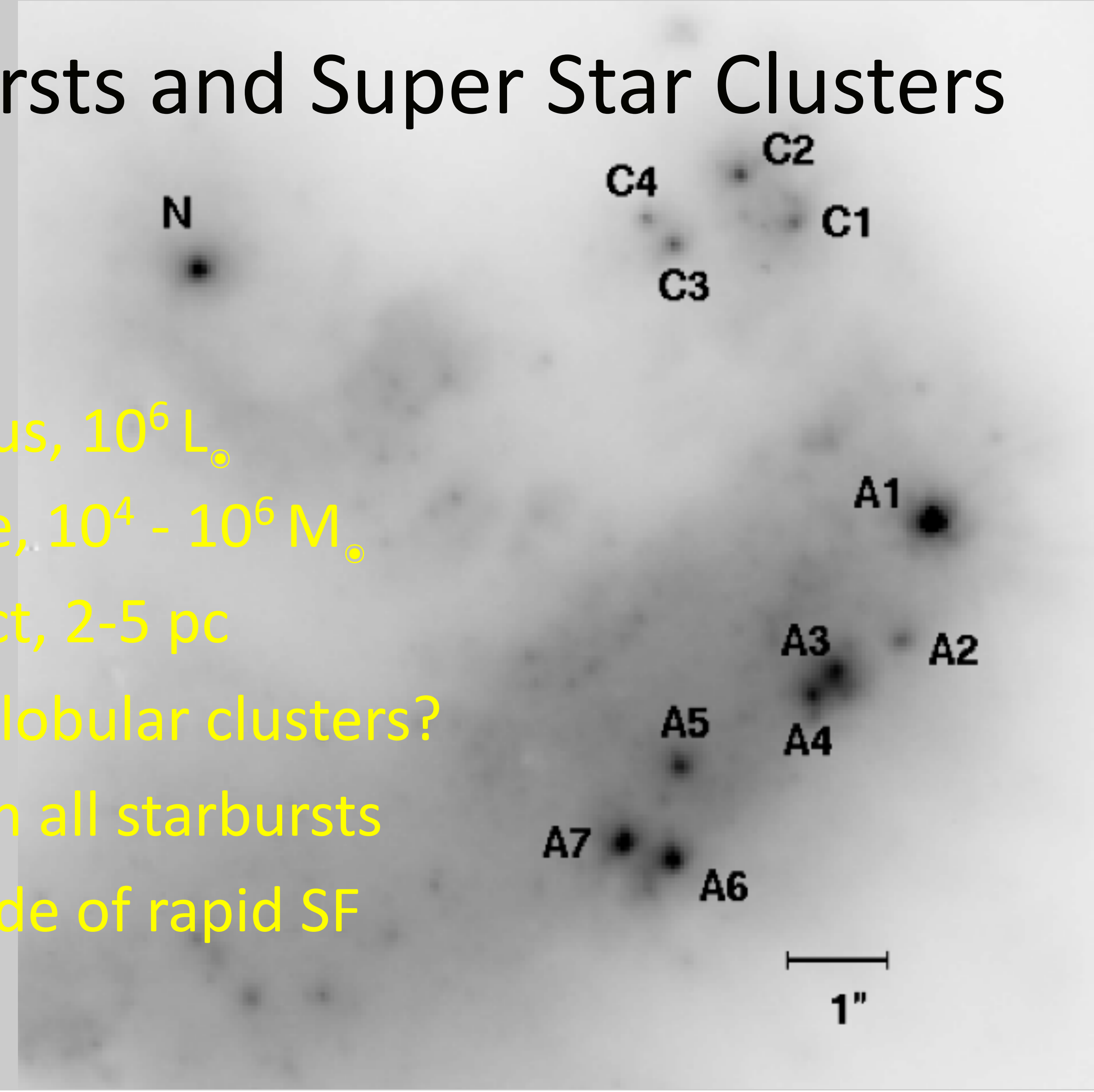
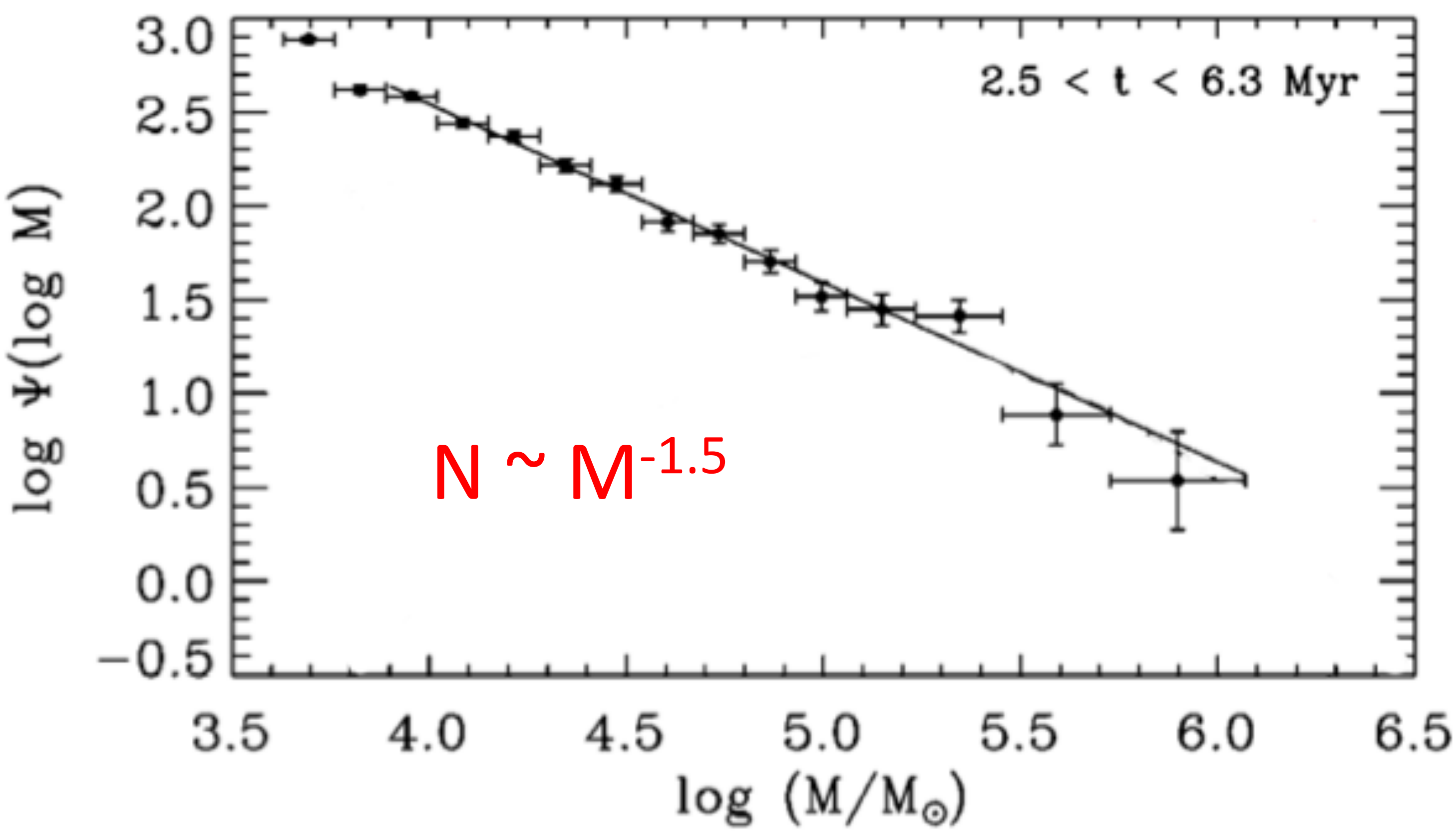
Starbursts and Super Star Clusters

- luminous, $10^6 L_\odot$
- massive, $10^4 - 10^6 M_\odot$
- compact, 2-5 pc
- proto-globular clusters?
- found in all starbursts
- the mode of rapid SF



Mass function of SSC same as GMCs



Zhang & Fall 1999

Convert one GMC into one SSC in high pressure environment

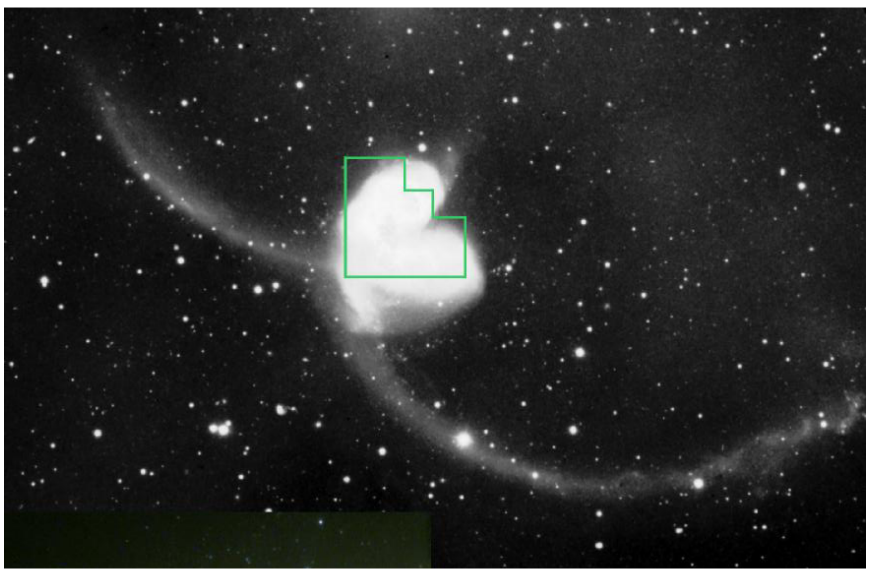
- Hypotheses:

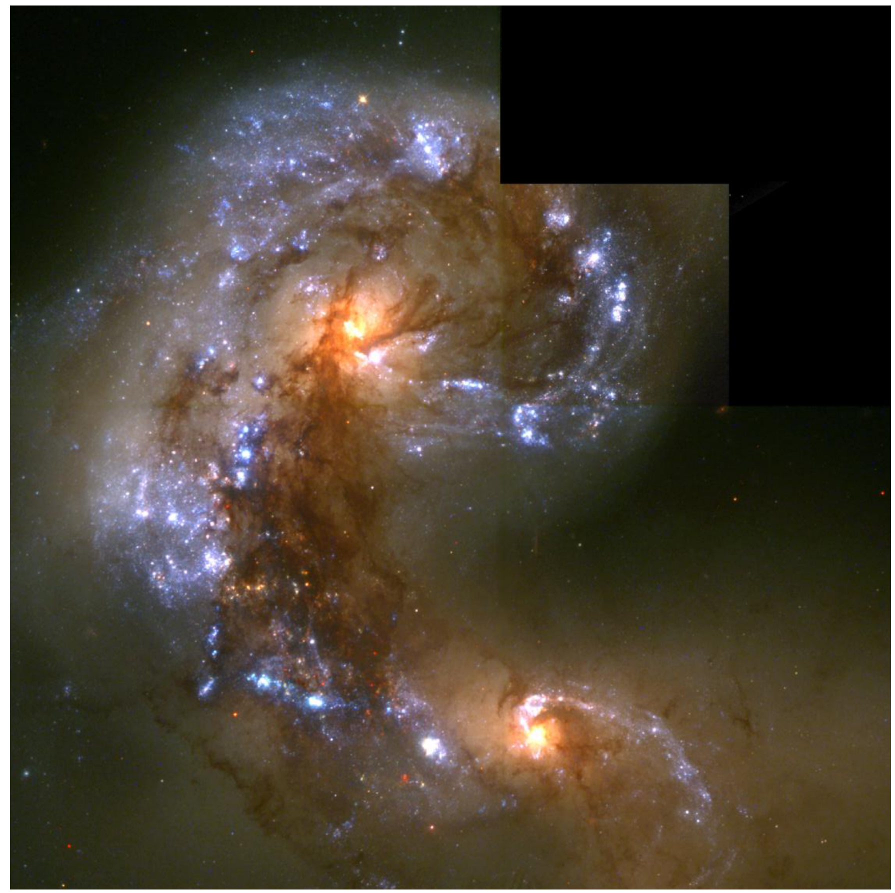
- Slow compression inside a super giant molecular (10^8 $M_\odot$) cloud.
    - Harris & Pudritz 1994

- Fast compression by shocks ?
    - Colliding HI clouds ionize and compress embedded molecular clouds
        - Jog & Solomon 1992

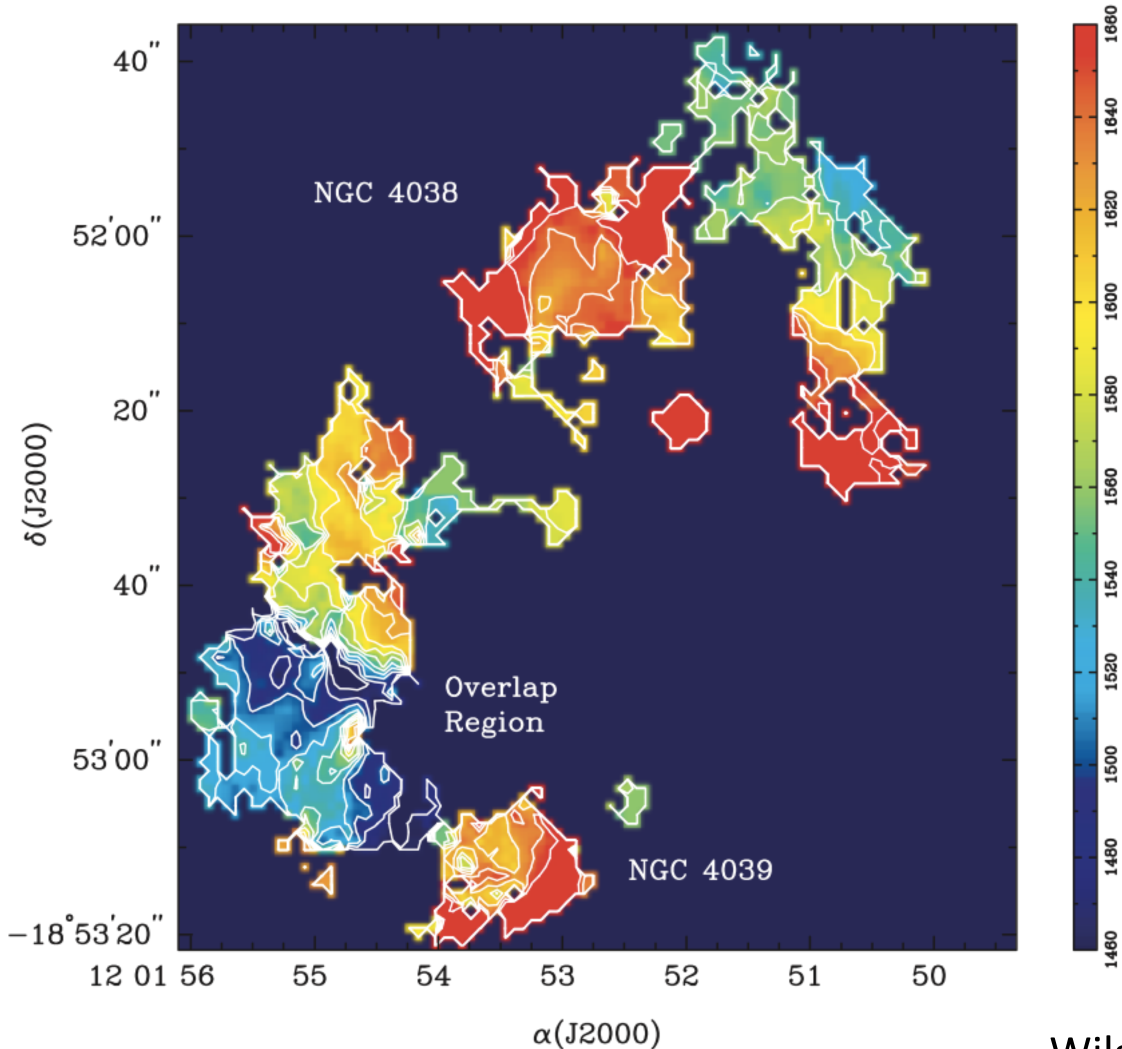
Some observational evidence for both hypotheses

Colliding pair NGC 4038/39
Antennae galaxies





Compression in overlap region seen in CO velocities



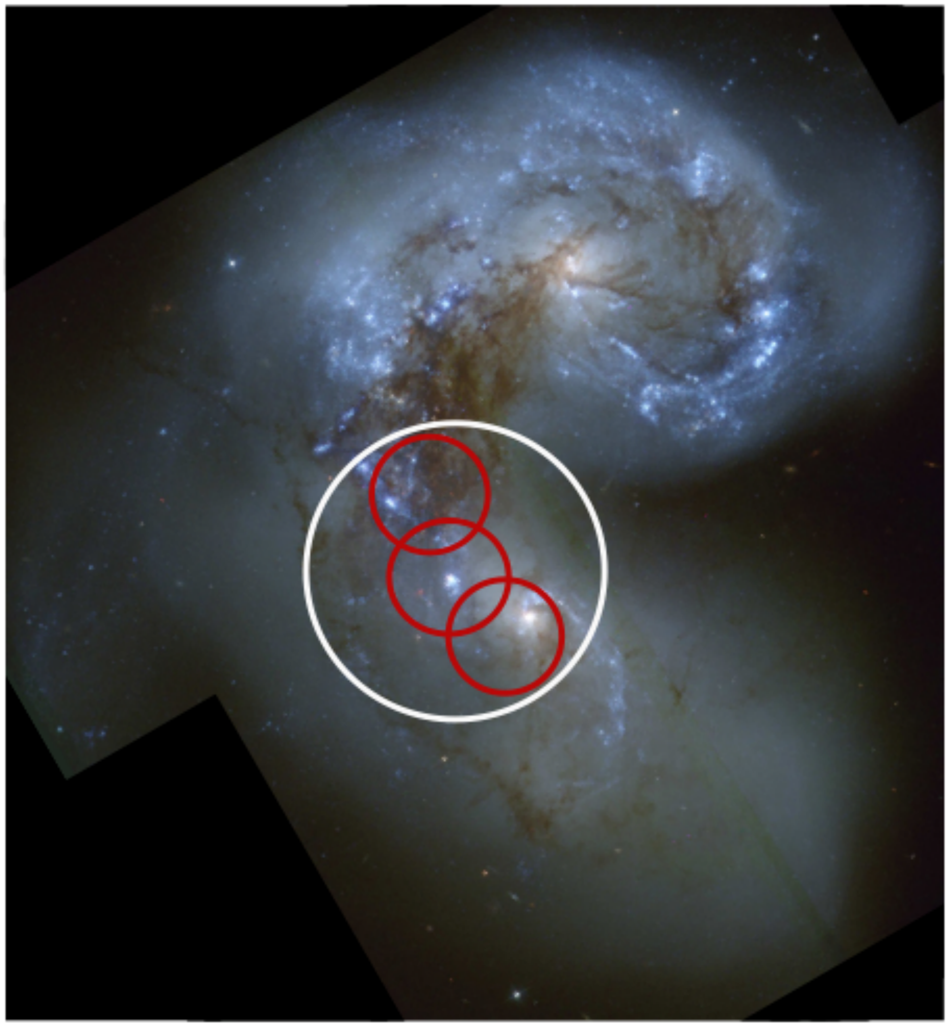
Wilson et al 2003

SGMCs in Antennae Galaxies

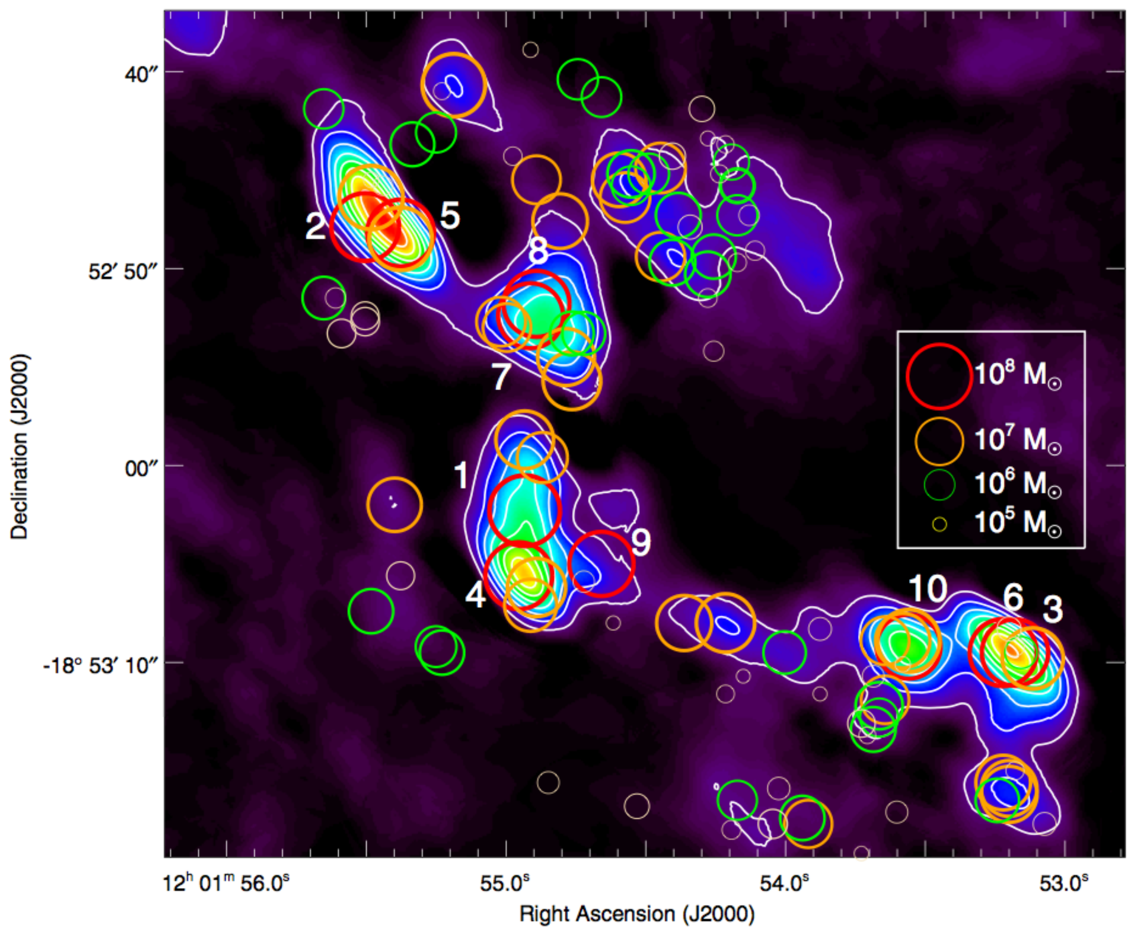
- Super giant molecular clouds up to $10^8\ M_\odot$?
  - Artifact of low spatial resolution 4.5” = 480 pc ?
    - (Wilson et al 2003)

- 1.5” = 160 pc at 22 Mpc from PdBI
    - (Wei, Keto, Lo 2012)

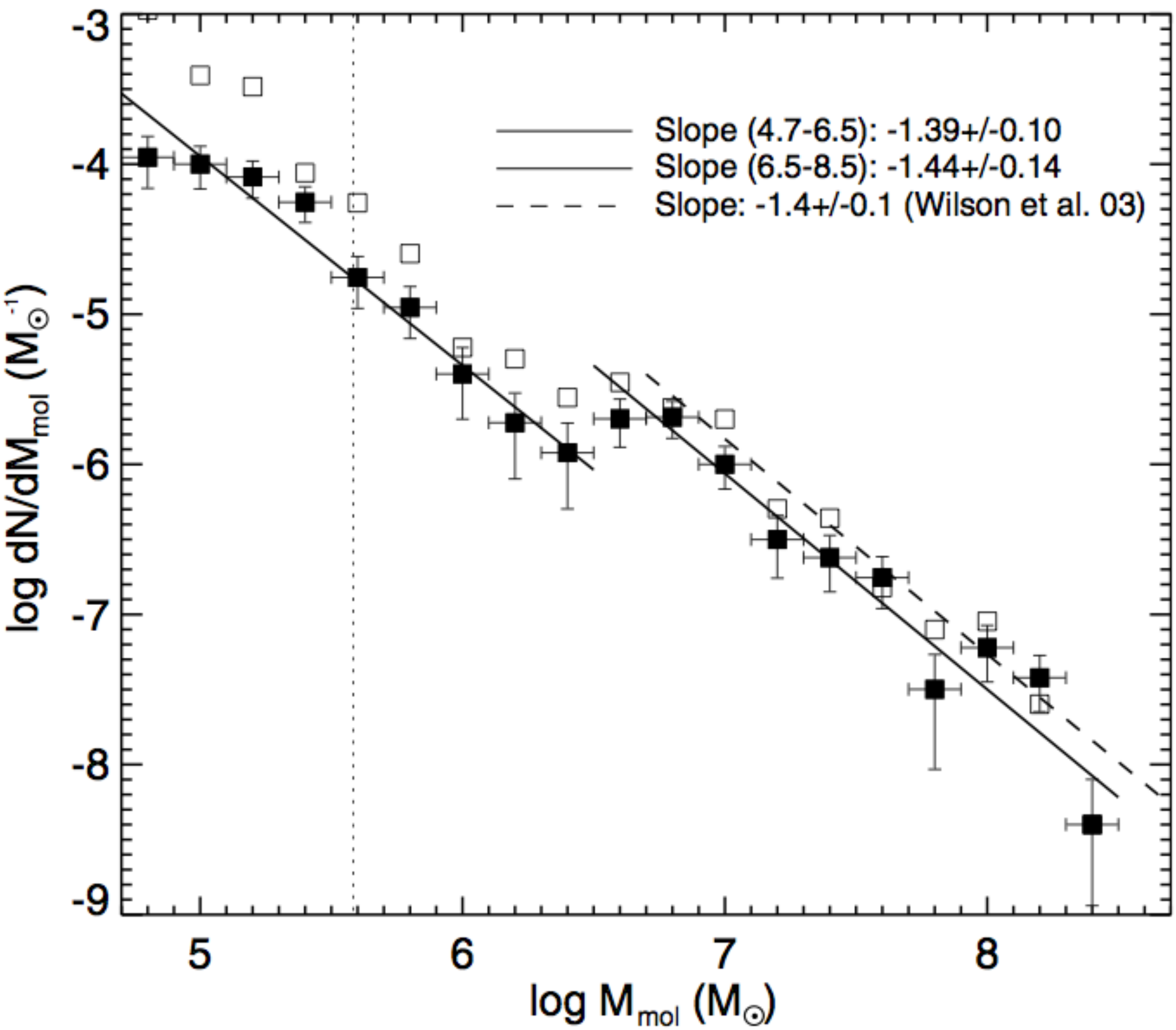
Colliding pair NGC 4038/39
Antennae galaxies



Found several SGMCs



SMGCs in Antennae



A problem with time scale?

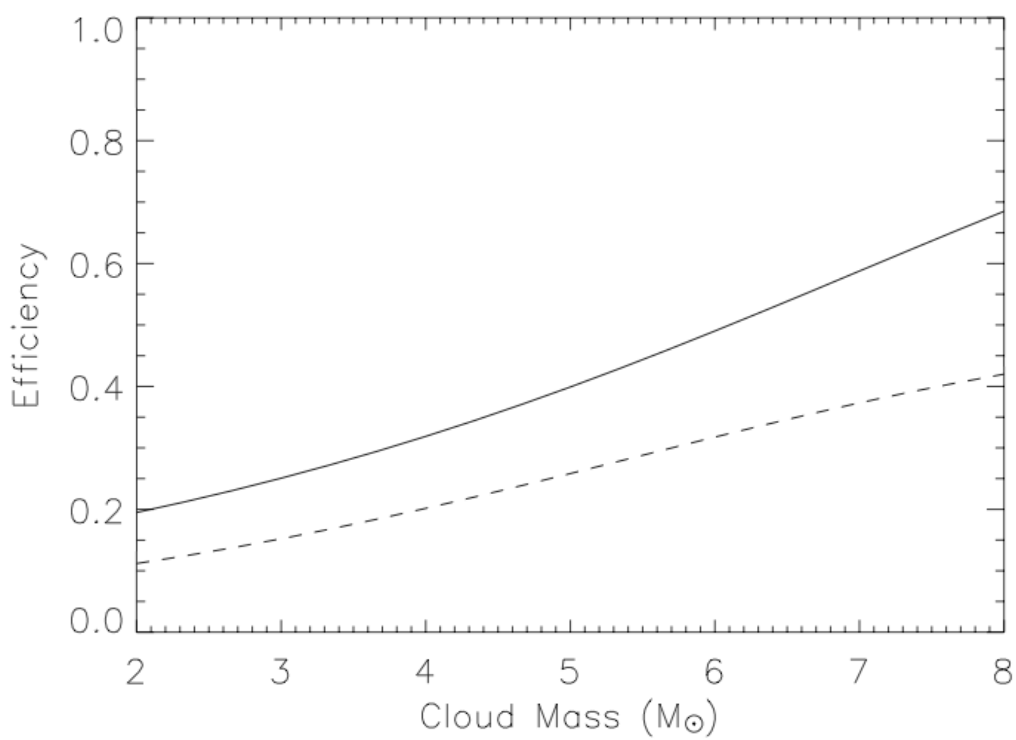
- Need to form the cluster < gas crossing time
- And
- Convert most of the gas mass into stars
  - > 50 % efficiency

Lada, Margulis, Dearborn 1984

- Otherwise
  - Gas (most of the mass) will disperse
  - Stars in the cluster inherit the original KE of the gas
  - Cluster will be unbound (not an SSC or globular)

High efficiency to prevent dispersal by stellar feedback

$$dM_c / dt = -dM_s / dt - AL / c_t^2$$



Keto, Ho, Lo 2005 modified from Elmegreen & Efremov 1997

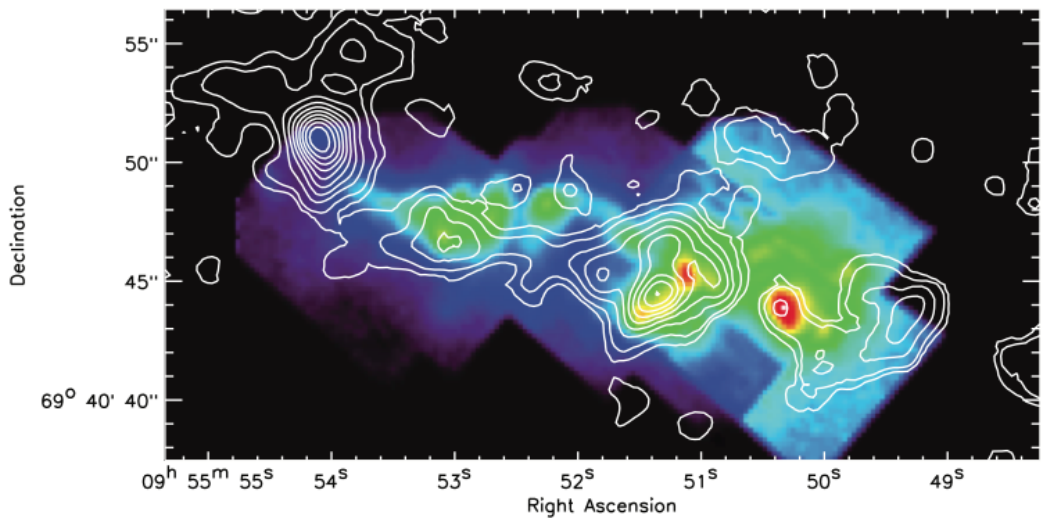
> 50 % efficiency
Lada, Margulis, Dearborn 1984

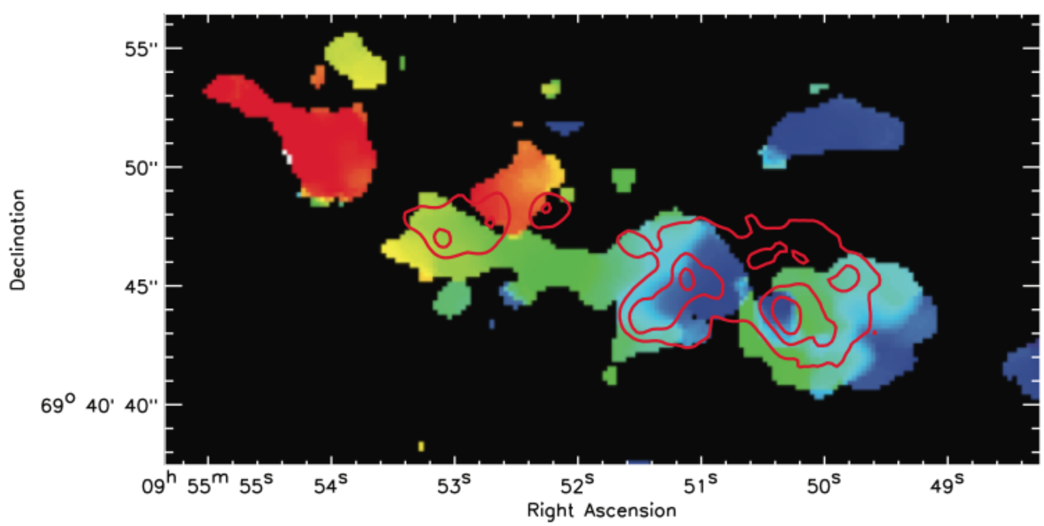
Observational evidence for fast compression in M82

- Observations of molecular cloud precursors to Super Star Clusters able to resolve an extragalactic GMC
- 1" = 17 pc at 3.5 Mpc
- CO(2-1) from OVRO

  – Keto, Ho, Lo 2005

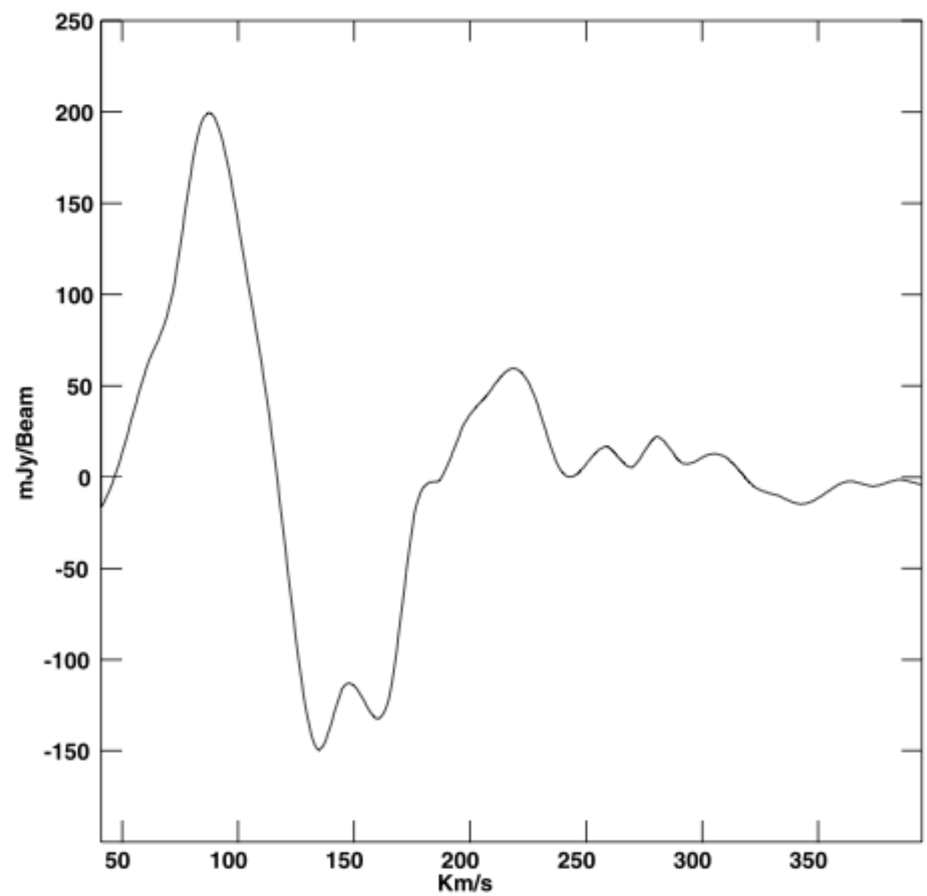
SF (mid-IR) correlated with Velocity not column density





Keto, Ho, Lo 2005

CO spectra show compression

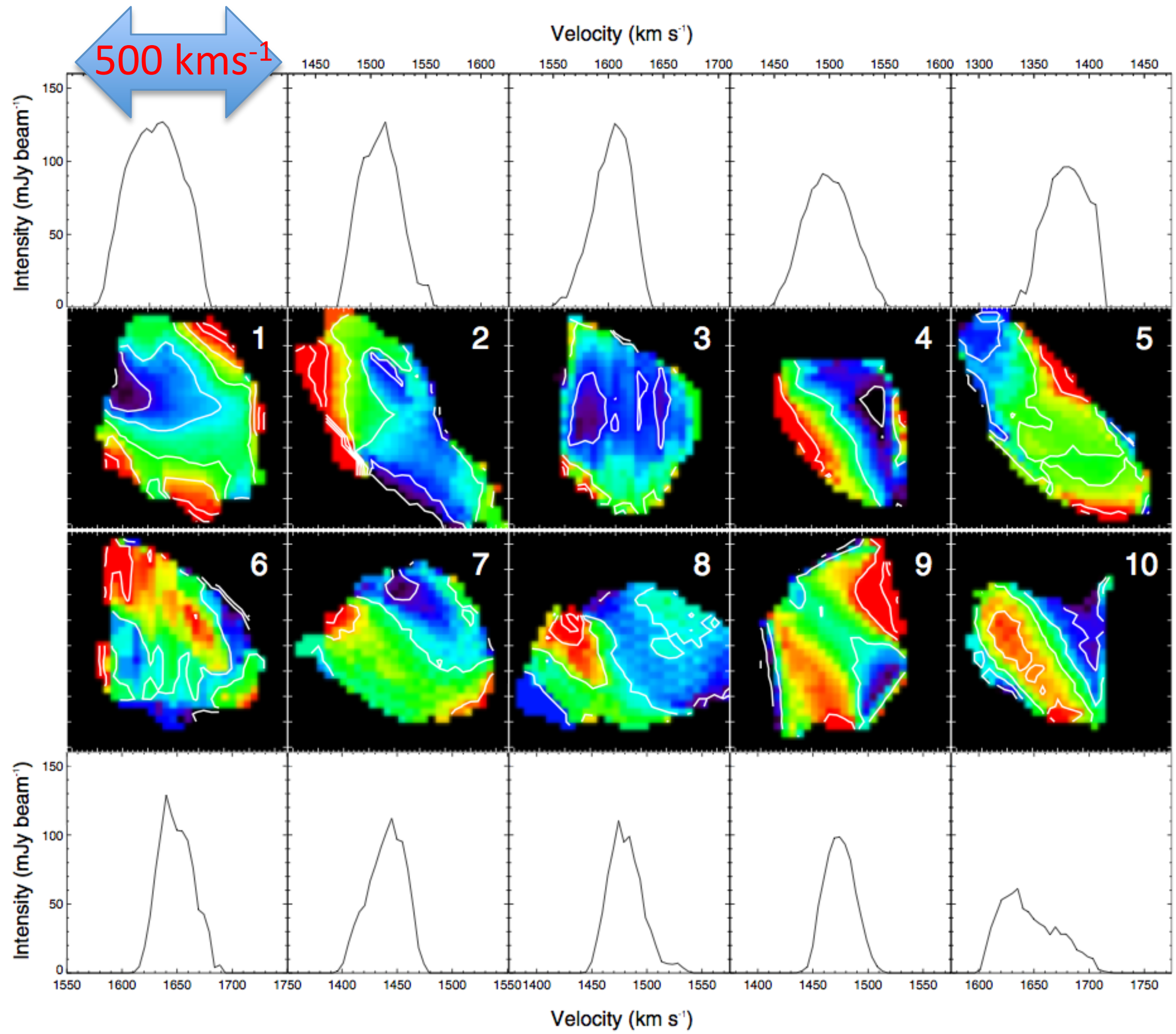


Rapid compression by surrounding ionization probably not viable

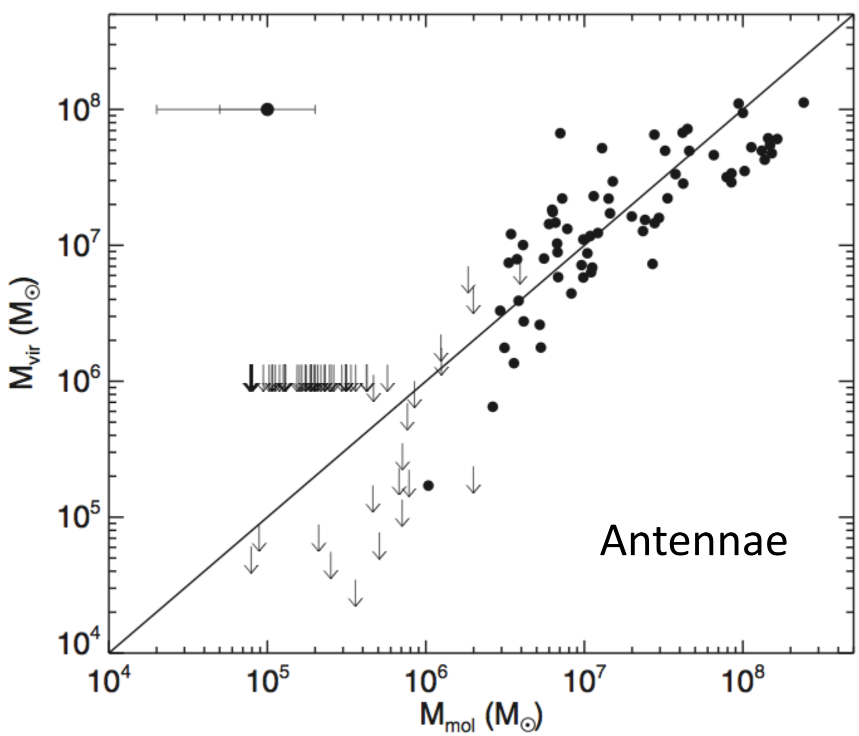
- Cooling time of 10^6 K gas is 1000 years
- Crossing time of molecular cloud is 10^5 years

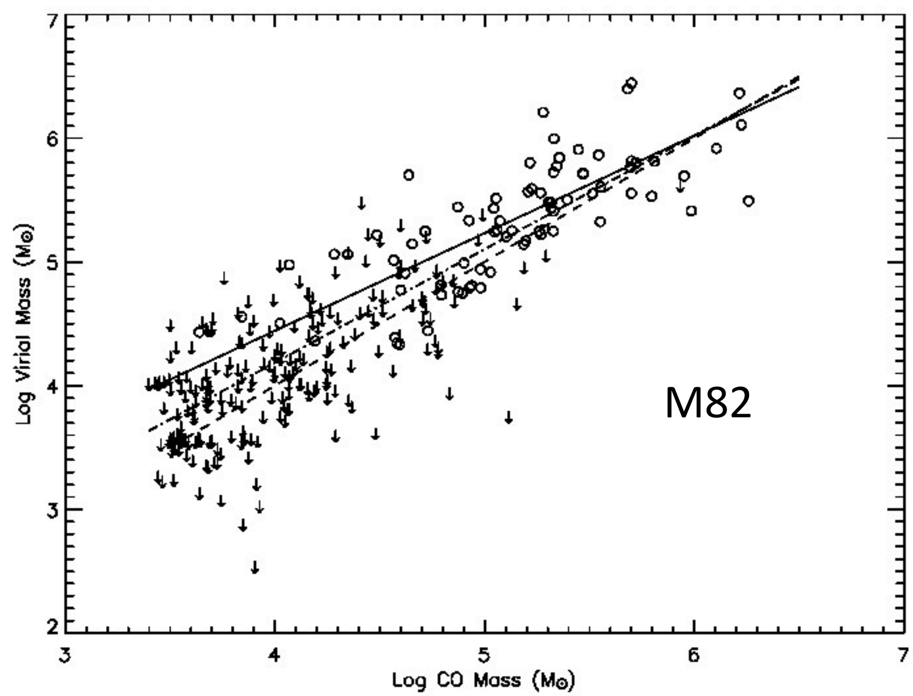
- At best, drive a shock into the cloud to start a wave of propagating star formation

Very high ΔV (100 kms^{-1})
(No correlation of SFR with ∇V)

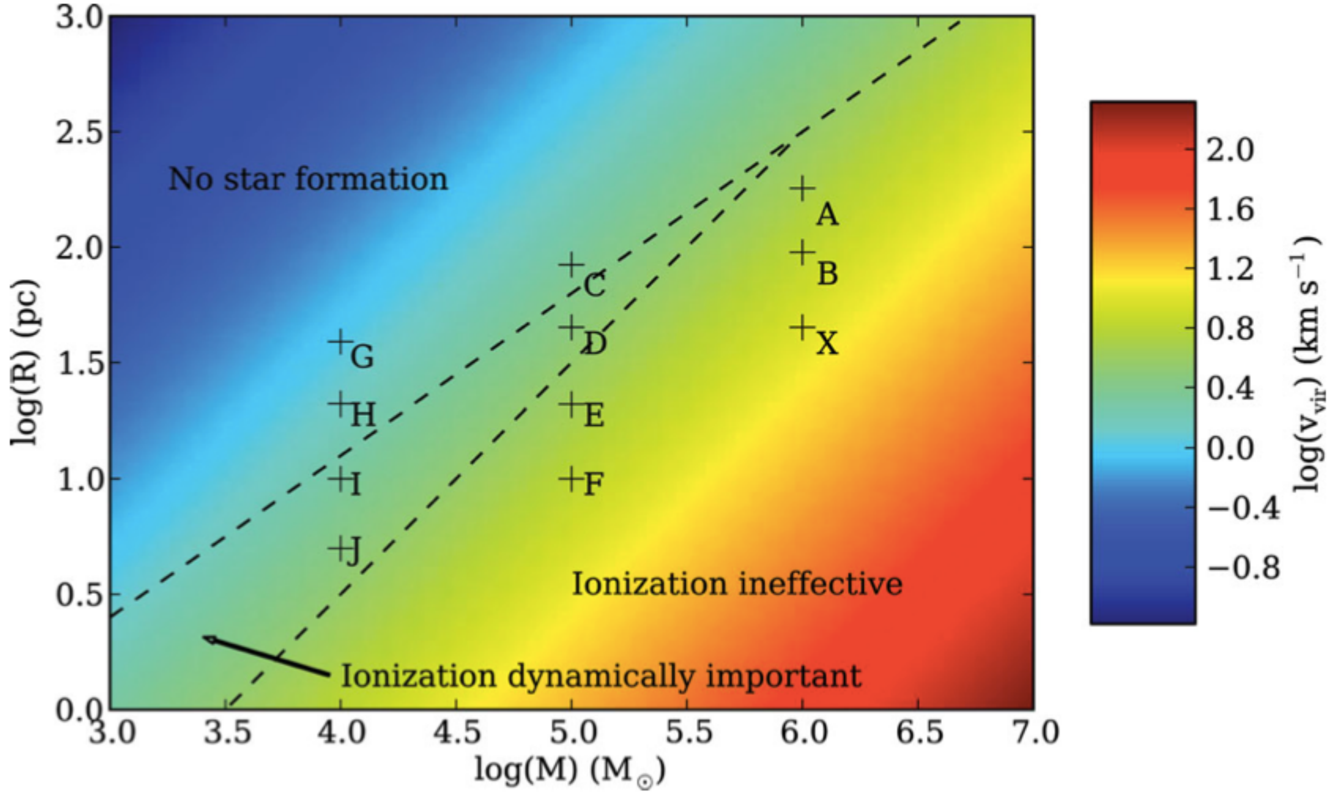


Gas is gravitationally bound with $\Delta V \sim 100\ kms^{-1}$ (10^6 K)





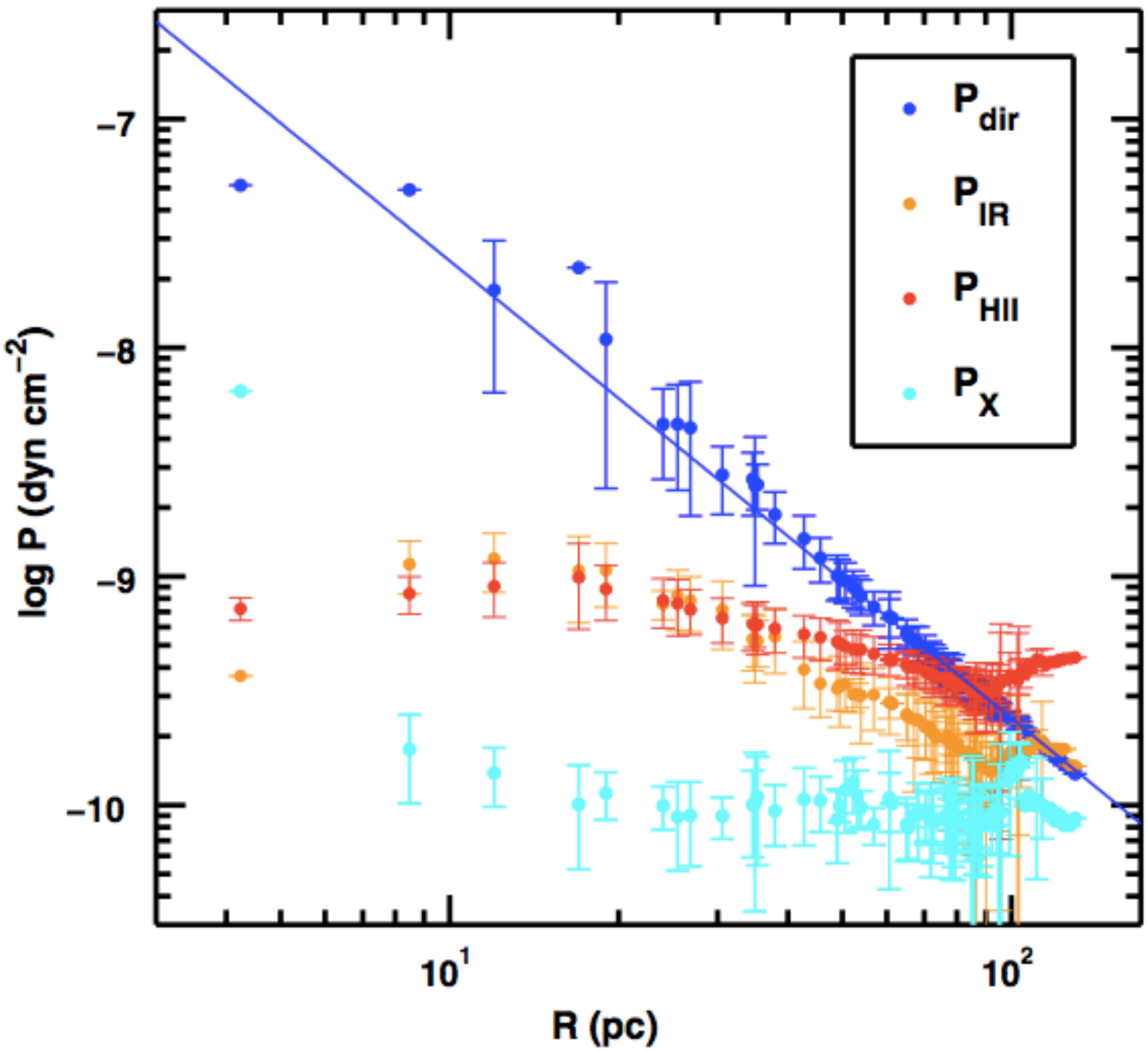
Most stellar feedback is insignificant



Theoretical modeling

Dale, Ercolano, Bonnell 2013

Direct radiation pressure from O stars may disperse the cluster



Observations of R136
Lopez 2011

Relaxed timescale

- O stars have very short timescales (10^6 yrs)
- Still need high efficiency
- How does pressure enhance star formation?

Normal state of the ISM

- Turbulent cascade in pressure-bound virial equilibrium

$$\frac{\ddot{I}}{2M} = 3\sigma^2 - \frac{\Gamma G M}{R} - \frac{4\pi P_e R^3}{M}$$

Source of pressure

- Either:
  - Dynamic
    - Converging flows
  - Thermal
    - Warm HI or warmer HII

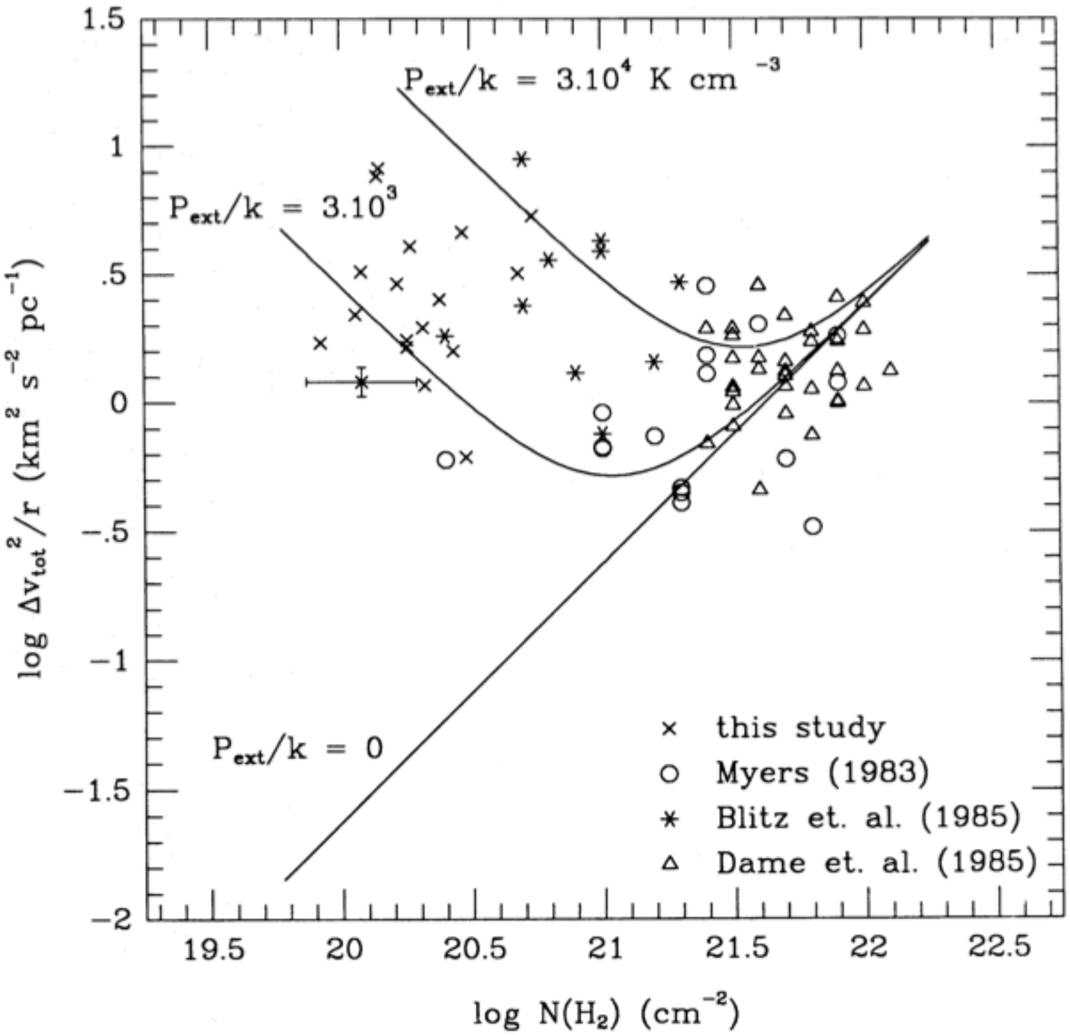
- Two examples from sub-cloud scales that may be extrapolated to extra-galactic scales

Virial equilibrium with external pressure

$$\frac{\ddot{I}}{2M} = 3\sigma^2 - \frac{\Gamma G M}{R} - \frac{4\pi P_e R^3}{M}$$

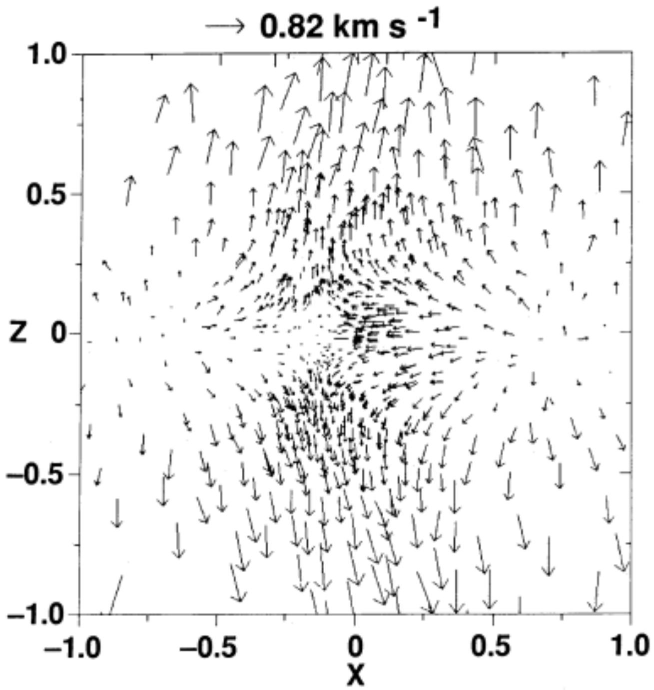
$$\frac{3\sigma^2}{R} = \Gamma G N + \frac{4\pi P_e}{N}$$

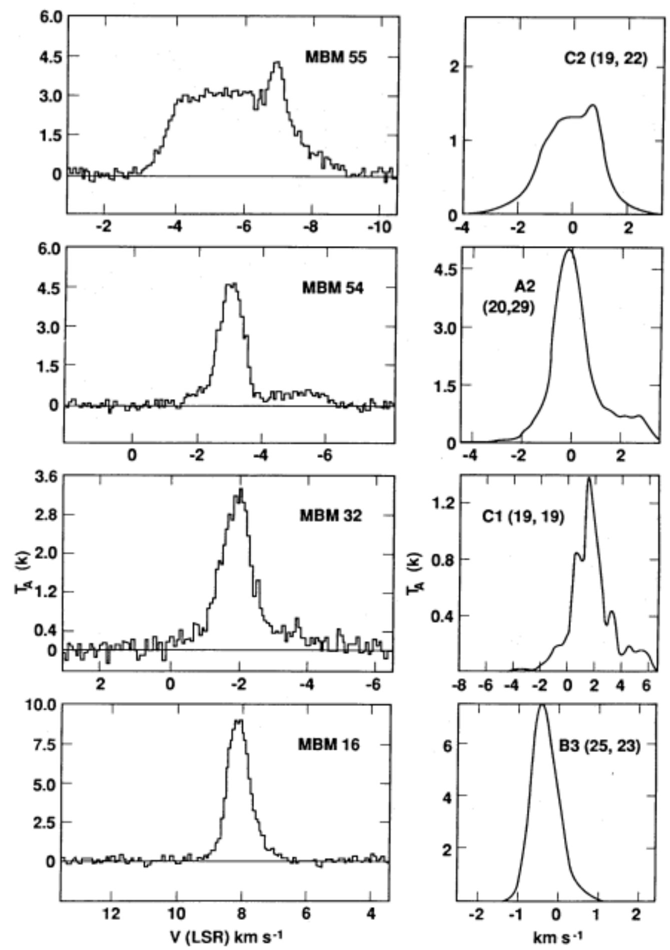
High Latitude Clouds



Keto & Myers 1986

HLCs as converging flows

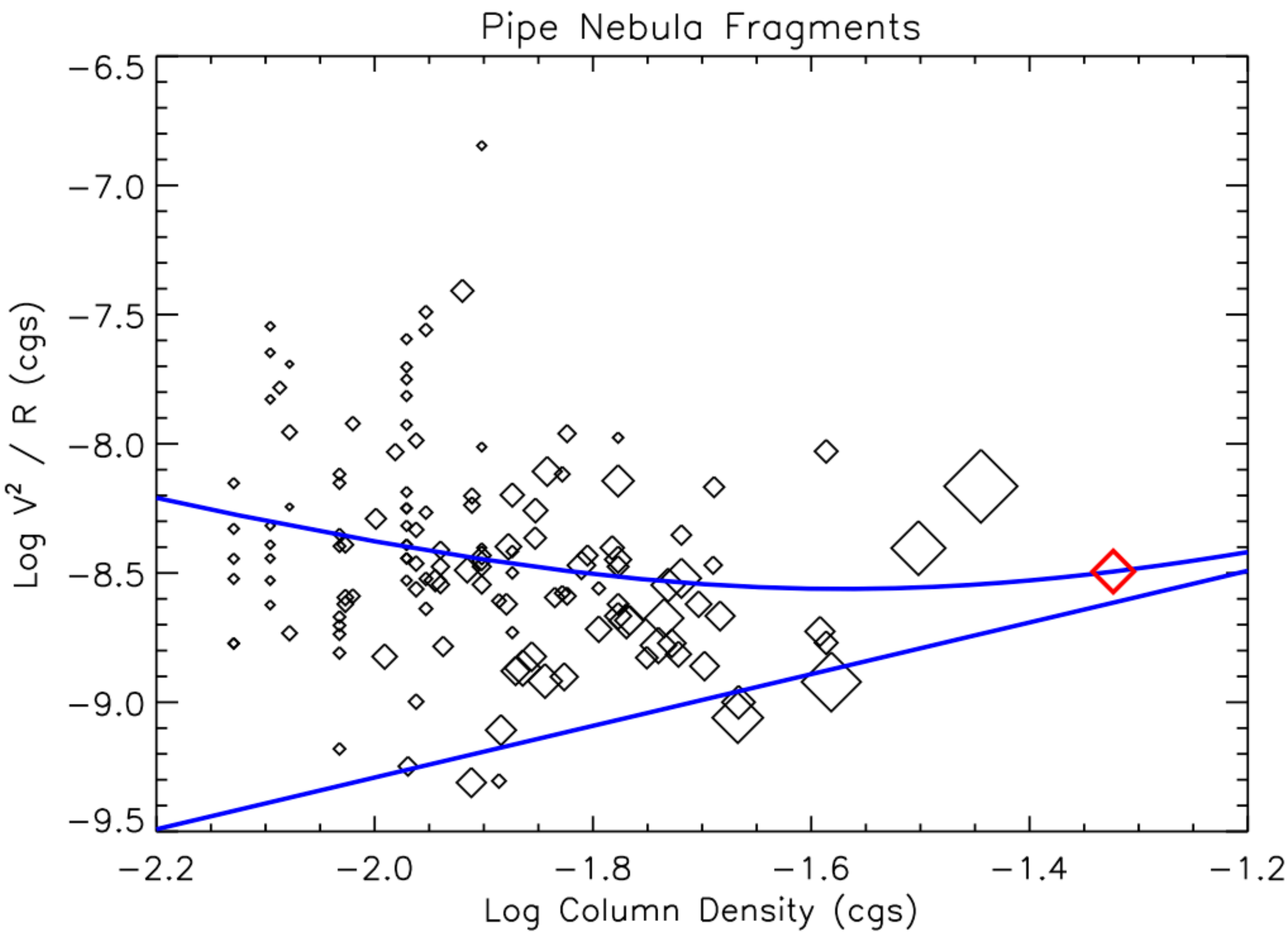




Keto & Lattanzio 1989
Data from Magnani, Blitz & Mundi 1985

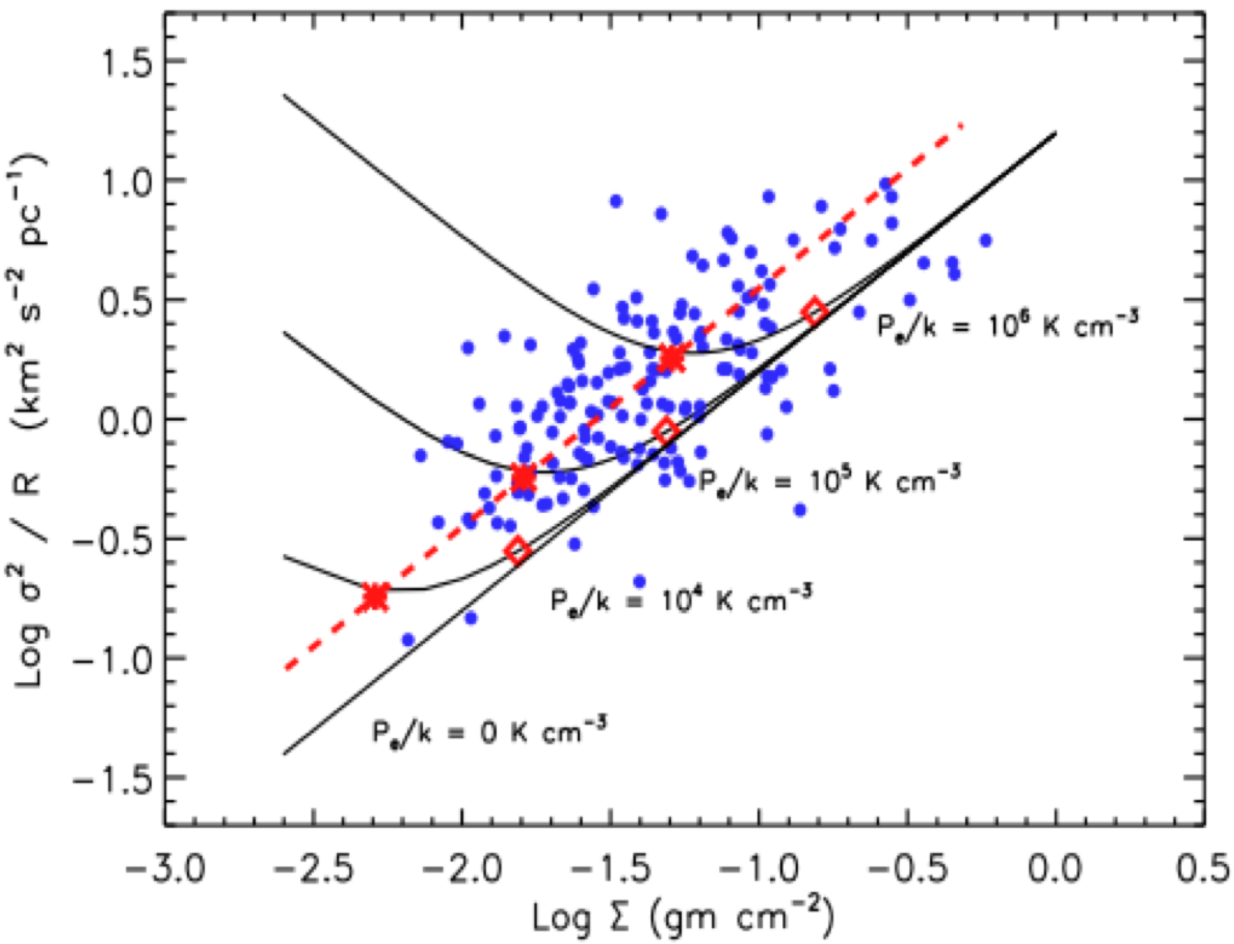
Pipe Nebula

Pressure confined cores in Pipe



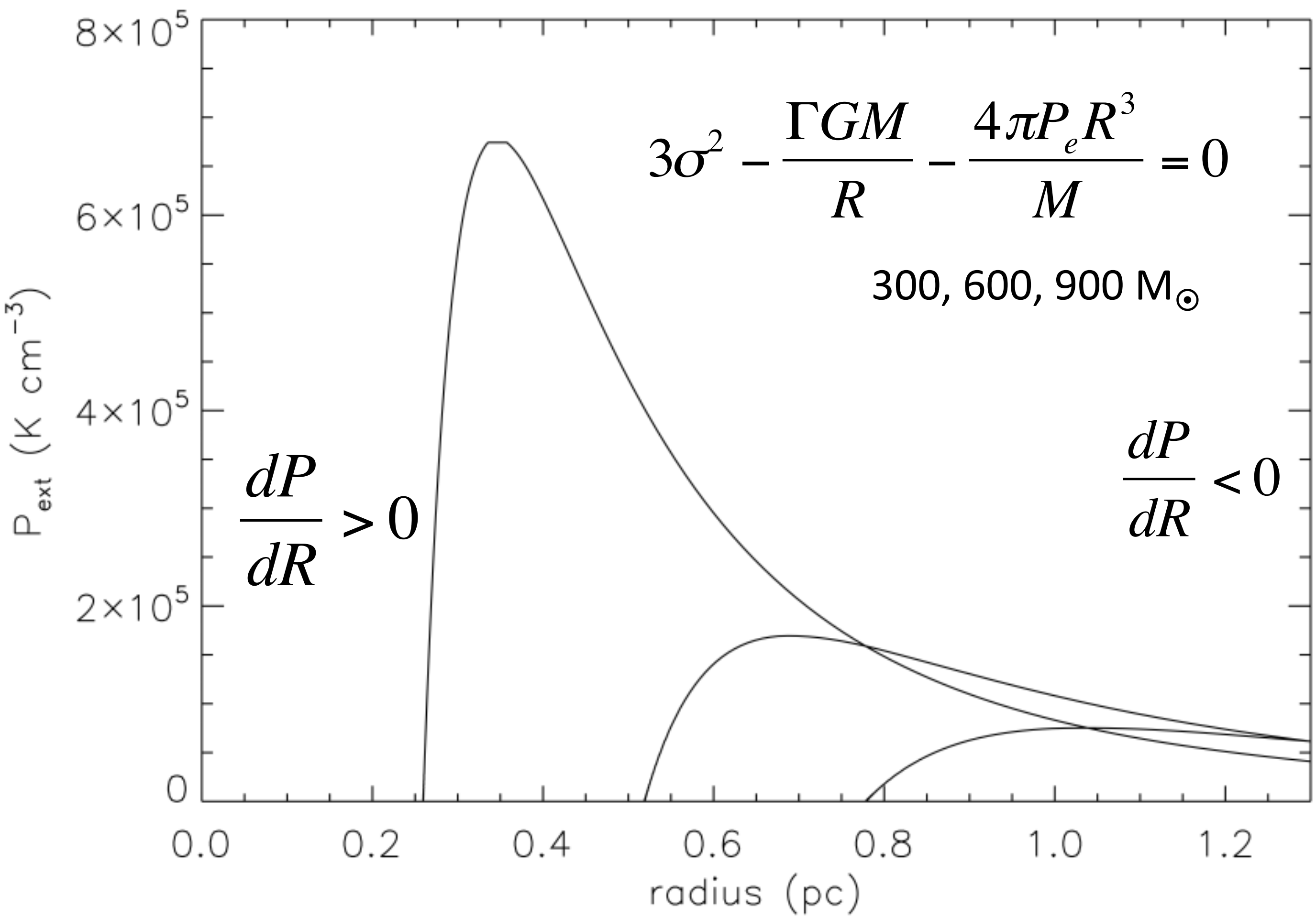
Data from Jill Rathborne, Charlie Lada, Jan Forbrich

Galactic clouds



Field, Blackman & Keto 2011
data from Heyer (2009)

Stable and unstable equilibria



Field, Blackman, Keto 2008, 2011

Mass cascade to smaller scales

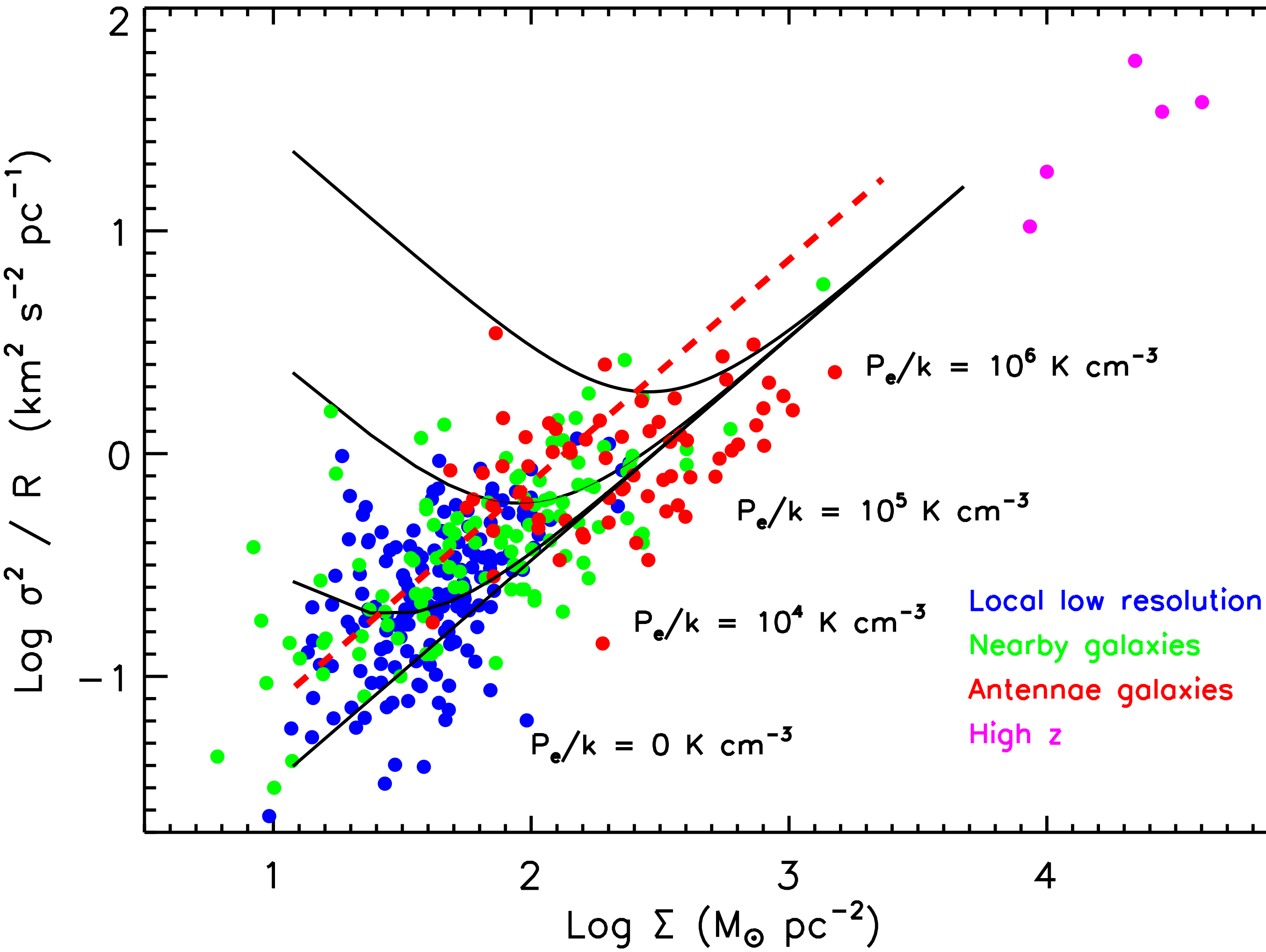
- For any σ^2, P_{ext} there is a critical max. mass
- As turbulence decays, $M_{critical}$ < $mass_{cloud}$
- Cloud must either fragment or collapse
- Lifetime of cloud is limited
  - lifetime of cascade can be steady state (if the cascade is fed from large scale)

2 Effects from an increase in external pressure

- Compress the clouds to higher density
  - Specifically, the clouds adjust to the new equlibrium following the virial equation

- More of the clouds find themselves above the critical mass

Higher pressure-density in starbursts



- Data compiled by Longmore & Kruijssen
- Heyer 2009, Bolatto et al 2008, Wei, Keto, Ho 2011

3 different descriptions of the same effect

- Analytic

- Numerical
  - SFR ~ $\exp(-t_{dyn} / t_{ff})$ (Padoan)

- Statistical
  - Stars form in the tail of density PDF above a critical density (Jeans mass – Toomre Q)
  - Enhanced star formation requires reformulation of the instability criteria with external pressure – or – definition of variation of mean density with the external pressure

Conclusions (Hypothesis)

- Despite problems with angular resolution, data indicate higher pressures in starbursts
- An external event increases the external pressure.
- Throws the fragmentation cascade out of equlibrium.
- Enhanced star formation on all spatial scales.