Can’t Stop the Music!

DOES STAR FORMATION ONLY QUENCH WHEN GAS IS EXHAUSTED?

Mordecai-Mark Mac Low

Department of Astrophysics

AMERICAN MUSEUM OF NATURAL HISTORY

What Quenches SF?

- Many possibilities:
  - Ionization
    - local
    - remote
  - Tidal stripping
  - magnetic fields
  - SMBH jets
  - Supernovae
  - Lack of gas
- I will mainly consider the last two.

Need for Quenching

- Star formation is not as efficient as predicted by simple models (White & Frenk 1991) with:
  - baryon cooling
  - uniform star formation efficiency in cold gas

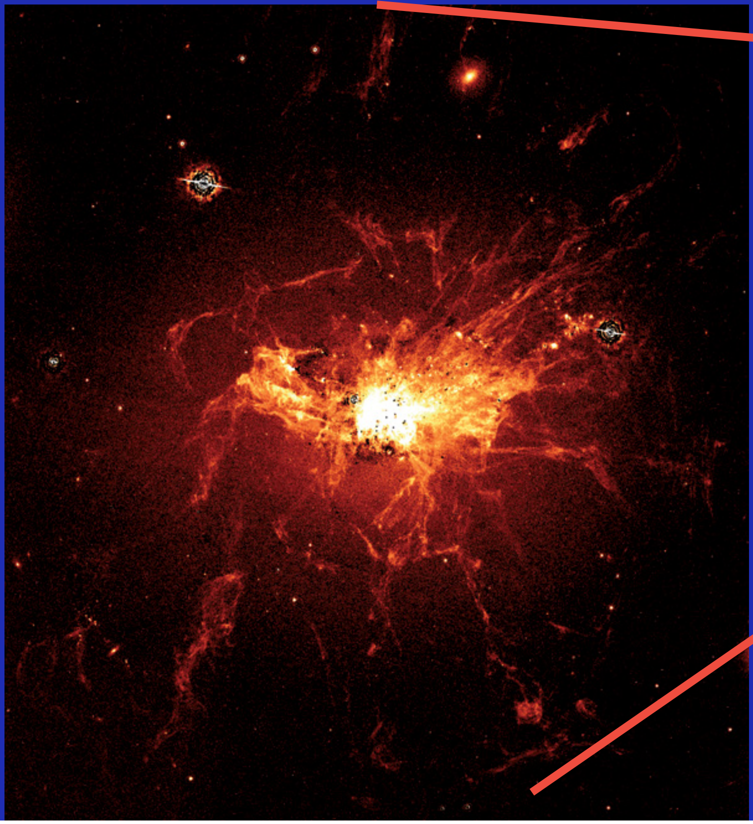
- high masses
  - X-ray emission suggests cooling flows around massive galaxies
  - high rate of gas cooling should drive star formation that is not observed

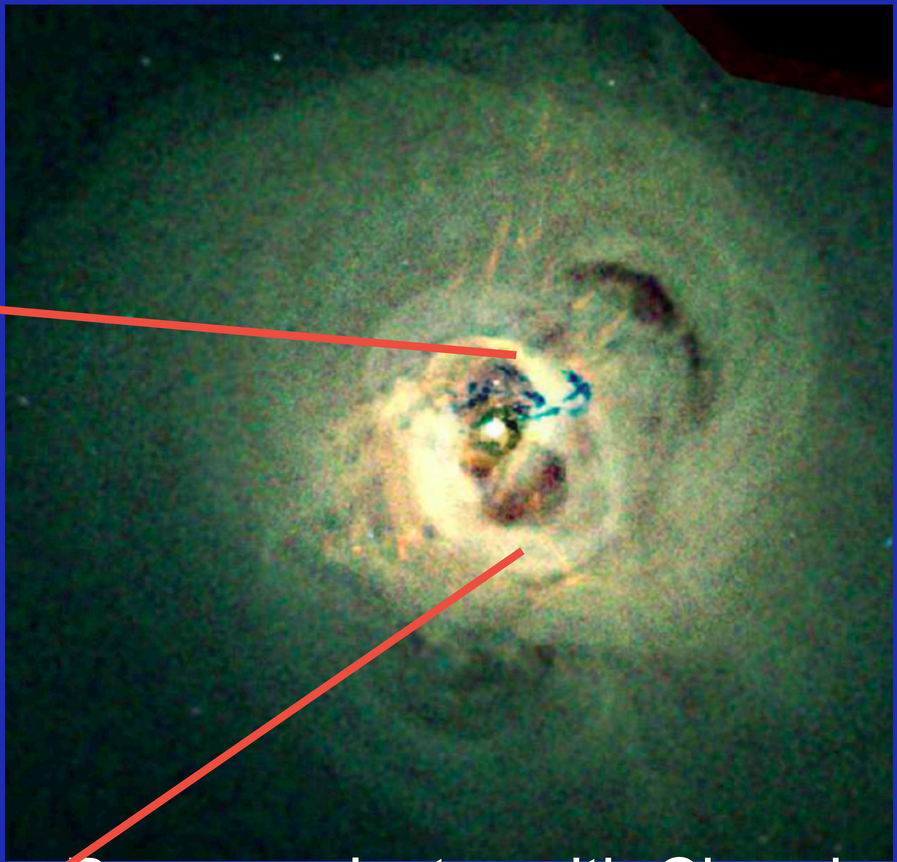
- low masses
  - too many dwarfs predicted (Klypin+ 99, Moore+ 99)
  - even with recent SDSS discoveries, observed luminosity function overpredicted

High Masses

- AGN outflows appear to heat cluster gas

magnetic support in center? (Fabian et al 08)





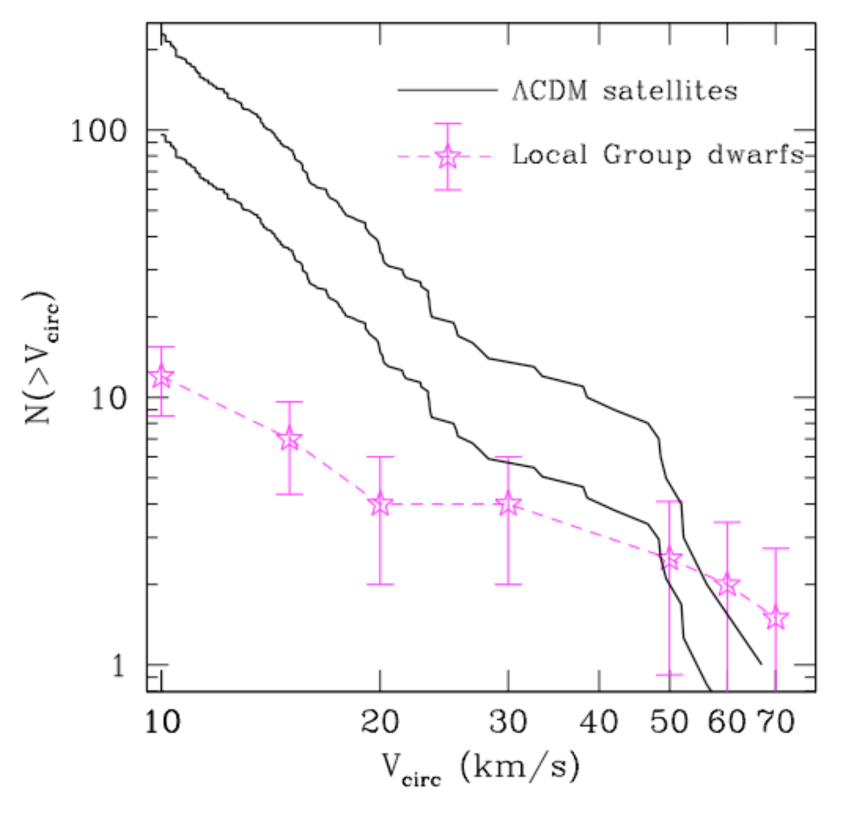
Perseus cluster with Chandra
Fabian et al 06

Hα

Low Masses

- outflows
  - scaling arguments: (Larson 1974; Dekel & Silk 1986) suggested outflows could explain low observed dwarf abundance
- thresholds
  - reduced SF efficiency at low masses may be sufficient to explain observations (e.g. Kravtsov 09)

the problem



Kravtsov 09

Outflows

- Fast galactic winds
- Cold gas at high velocities (Martin 05, Rupke + 05)
- Murray + 05 proposed radiation driven winds
- conserve momentum

$$v_w \propto \sigma \qquad \dot{M} \propto \frac{1}{\sigma}$$

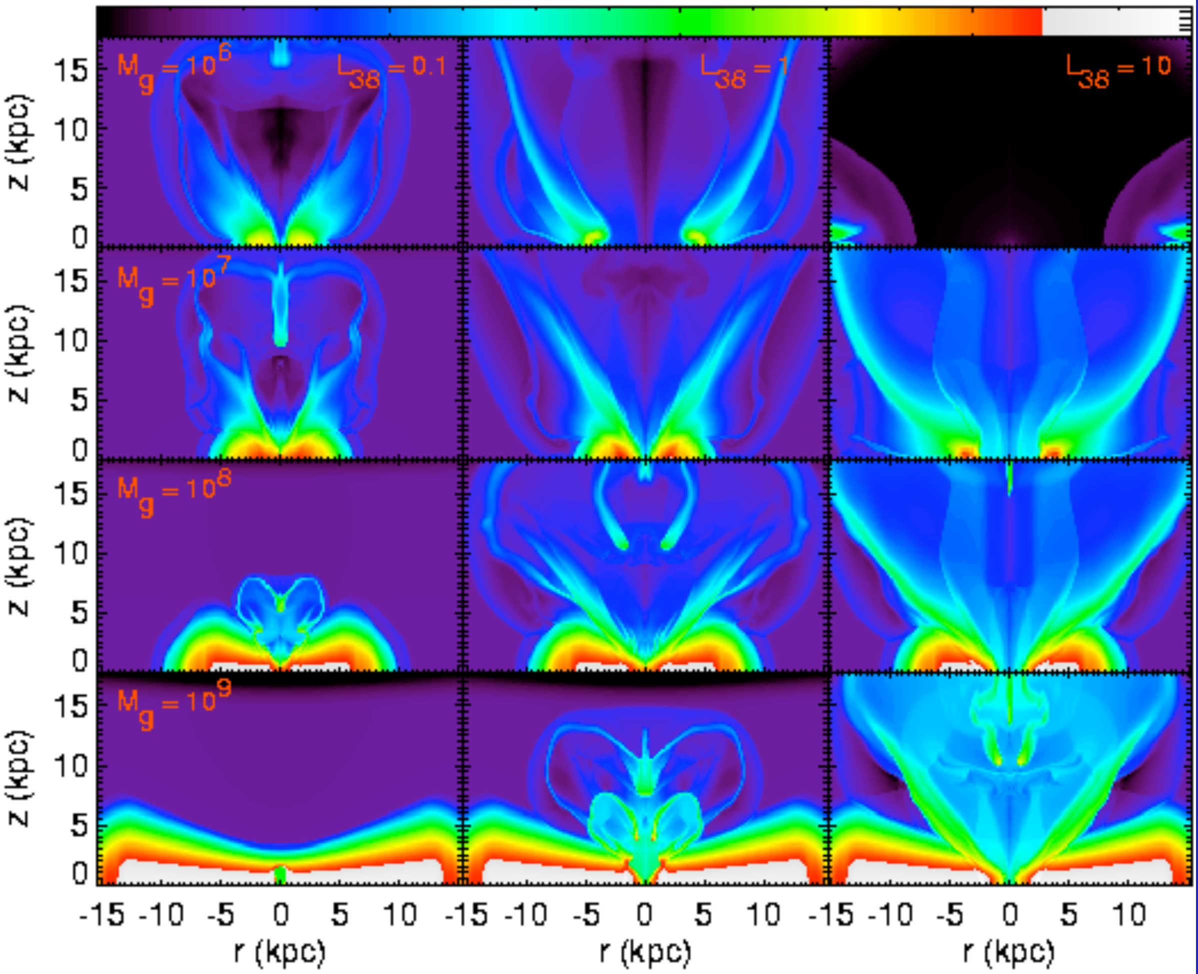
smaller galaxies lose more mass

- (perhaps could be driven by SNe?)
- Davé & Oppenheimer 08 show that assuming momentum-driven mass loss leads to reasonable dwarf galaxy spectrum

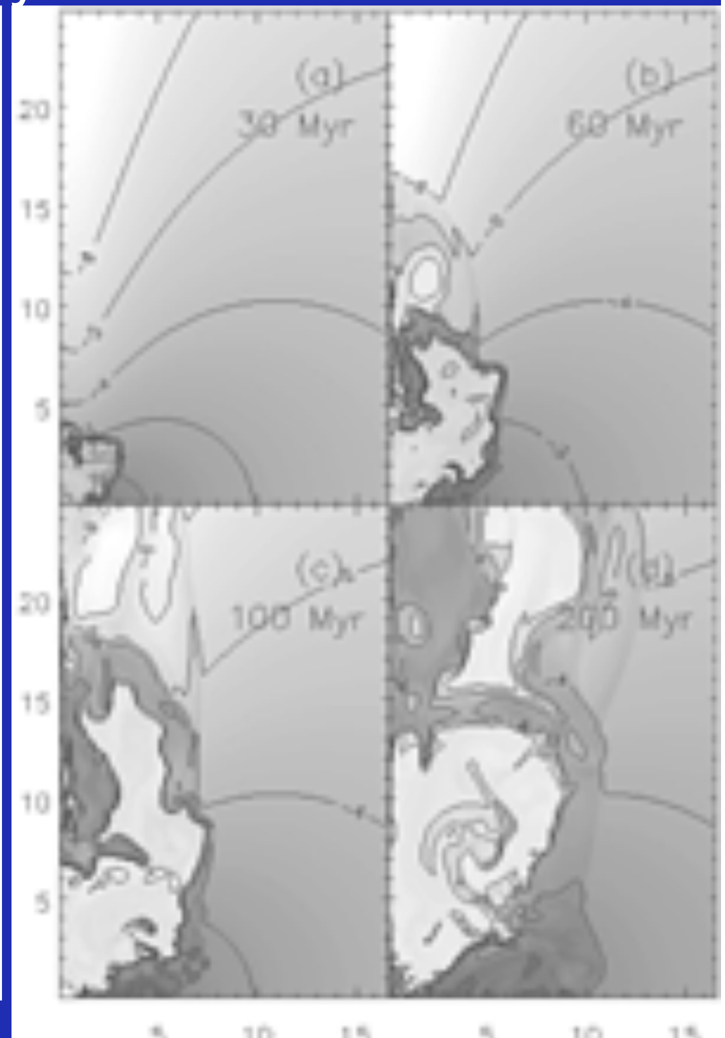
Isolated Dwarfs

easy to blow metals out, much harder to blow gas away

1 SN / 3 Myr 300 Kyr 30 Kyr



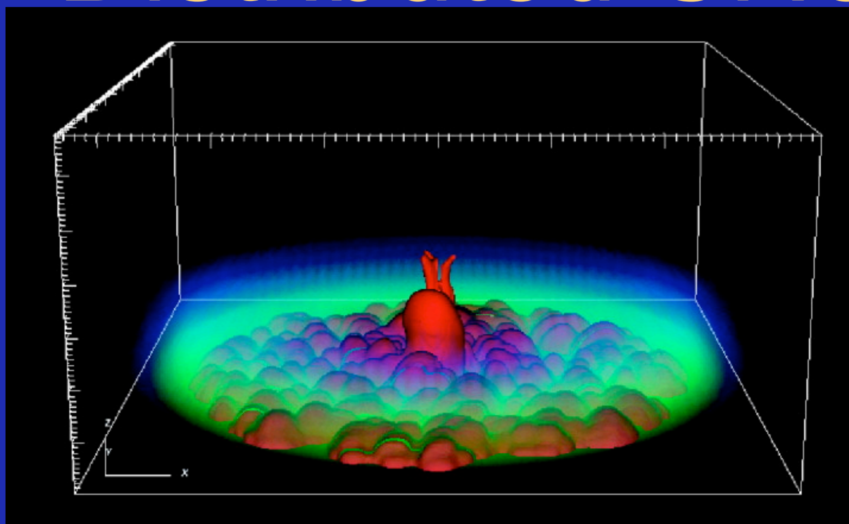
Mac Low & Ferrara 1999



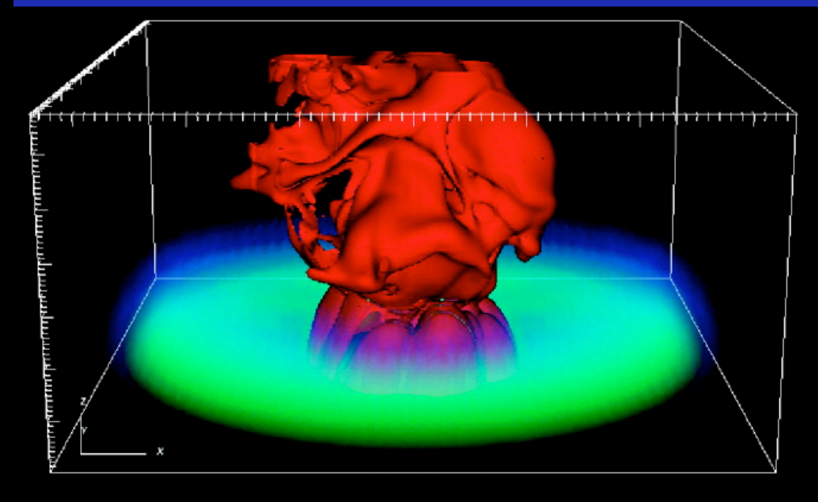
D'Ercole & Brighenti 1999

Distributed SNe

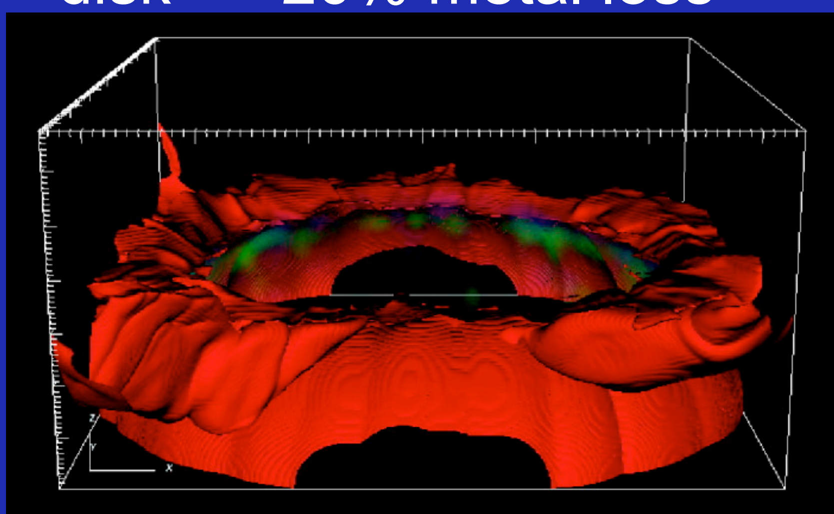
Fragile+ 04



SNe distributed over 80% of disk => 20% metal loss



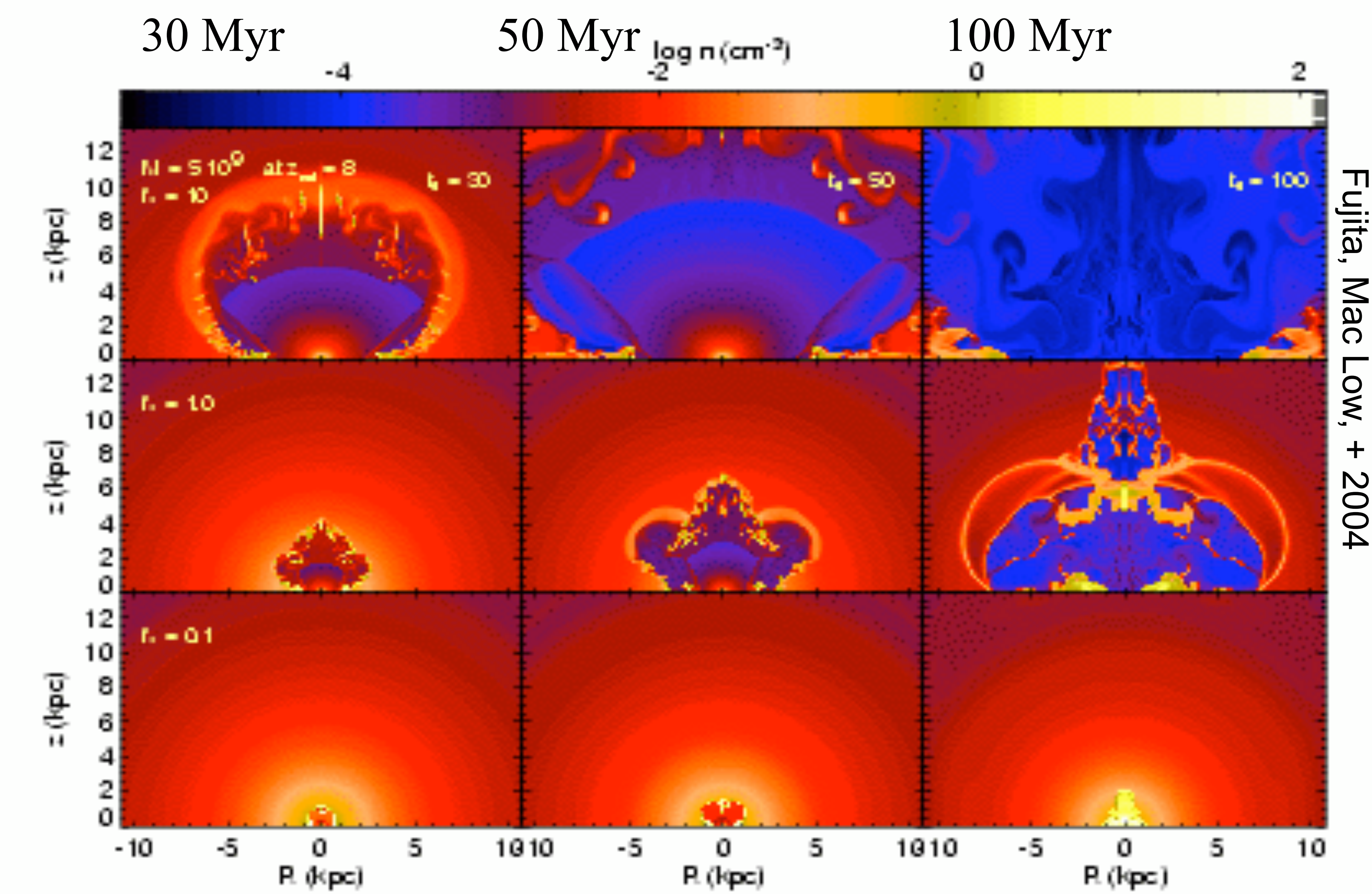
SNe distributed over 30% of disk => 60% metal loss



complete mass loss only for 10^{41} erg s^{-1} (1 SN / 300 yr) distributed over 80% of a 10^9 $M_{\odot}$ gas disk

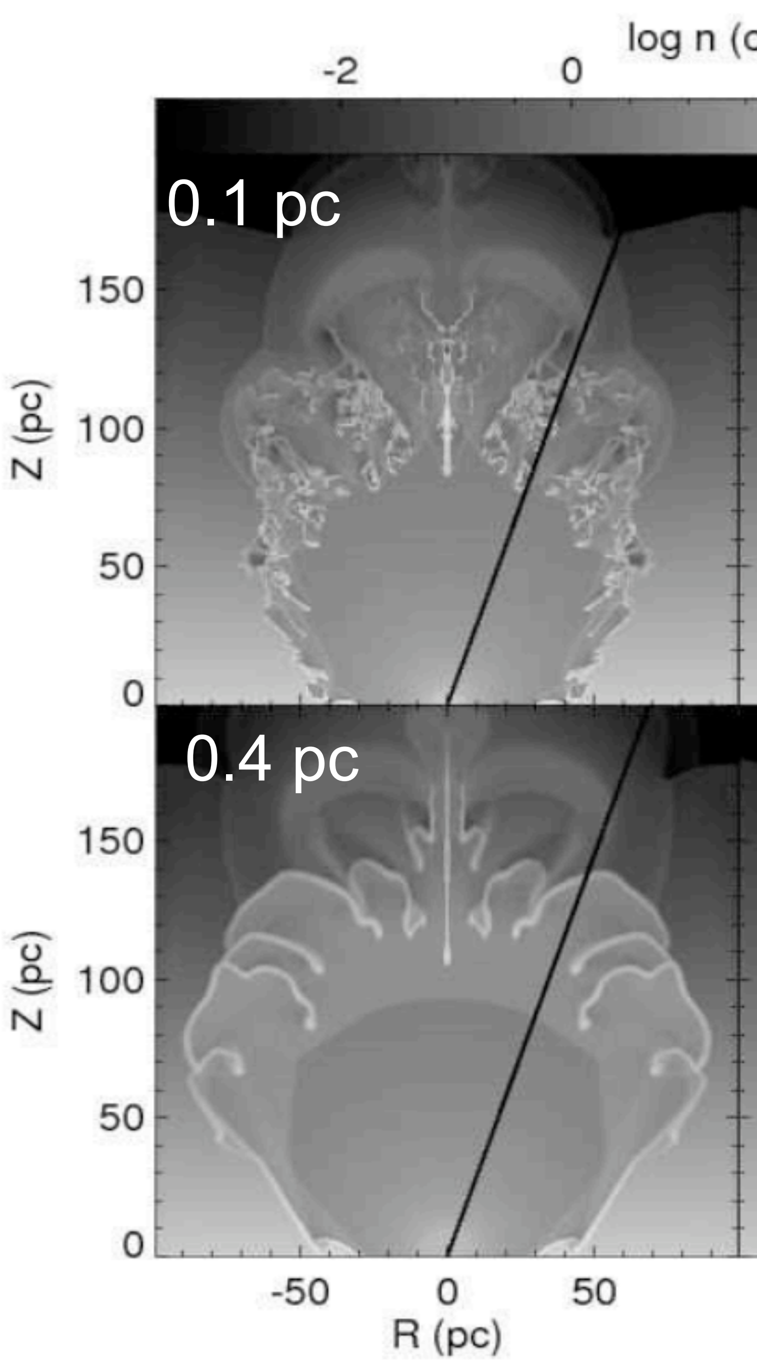
Dwarfs with Halos

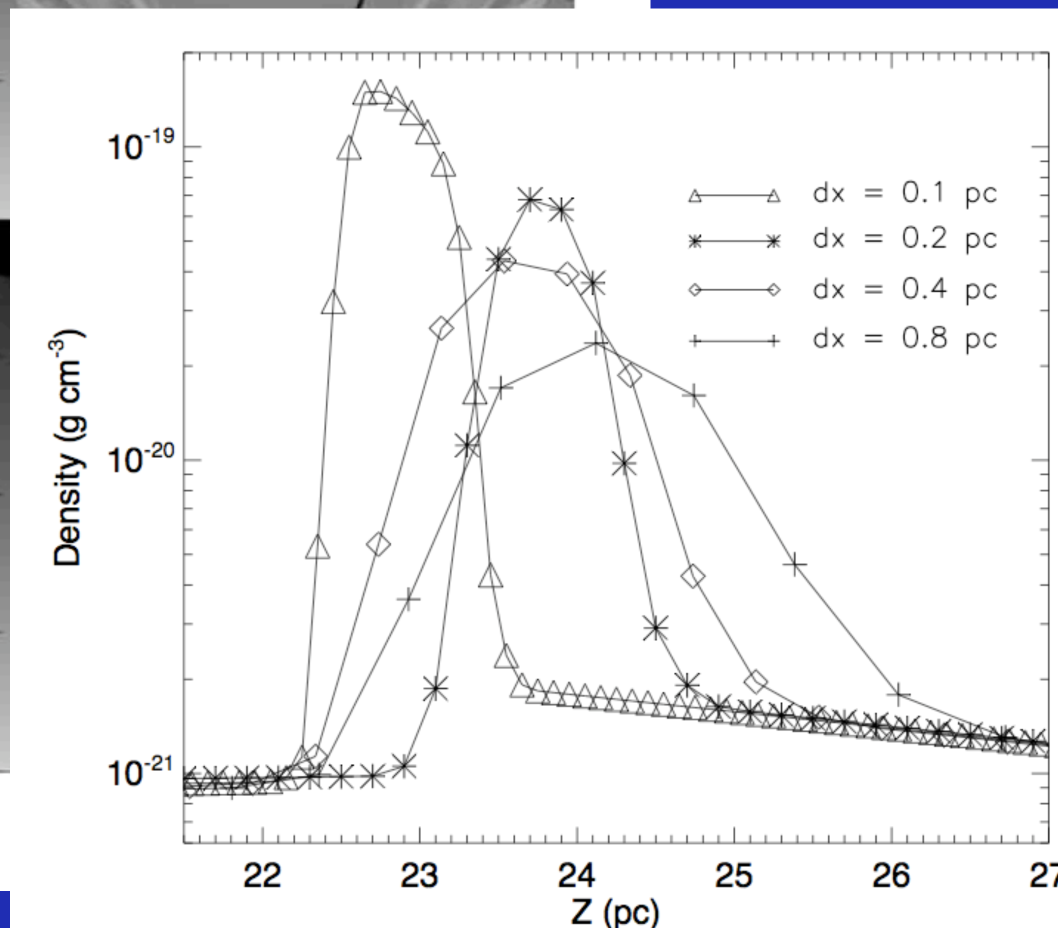
only very high efficiency SF blows away gas!



Fujita+ 09

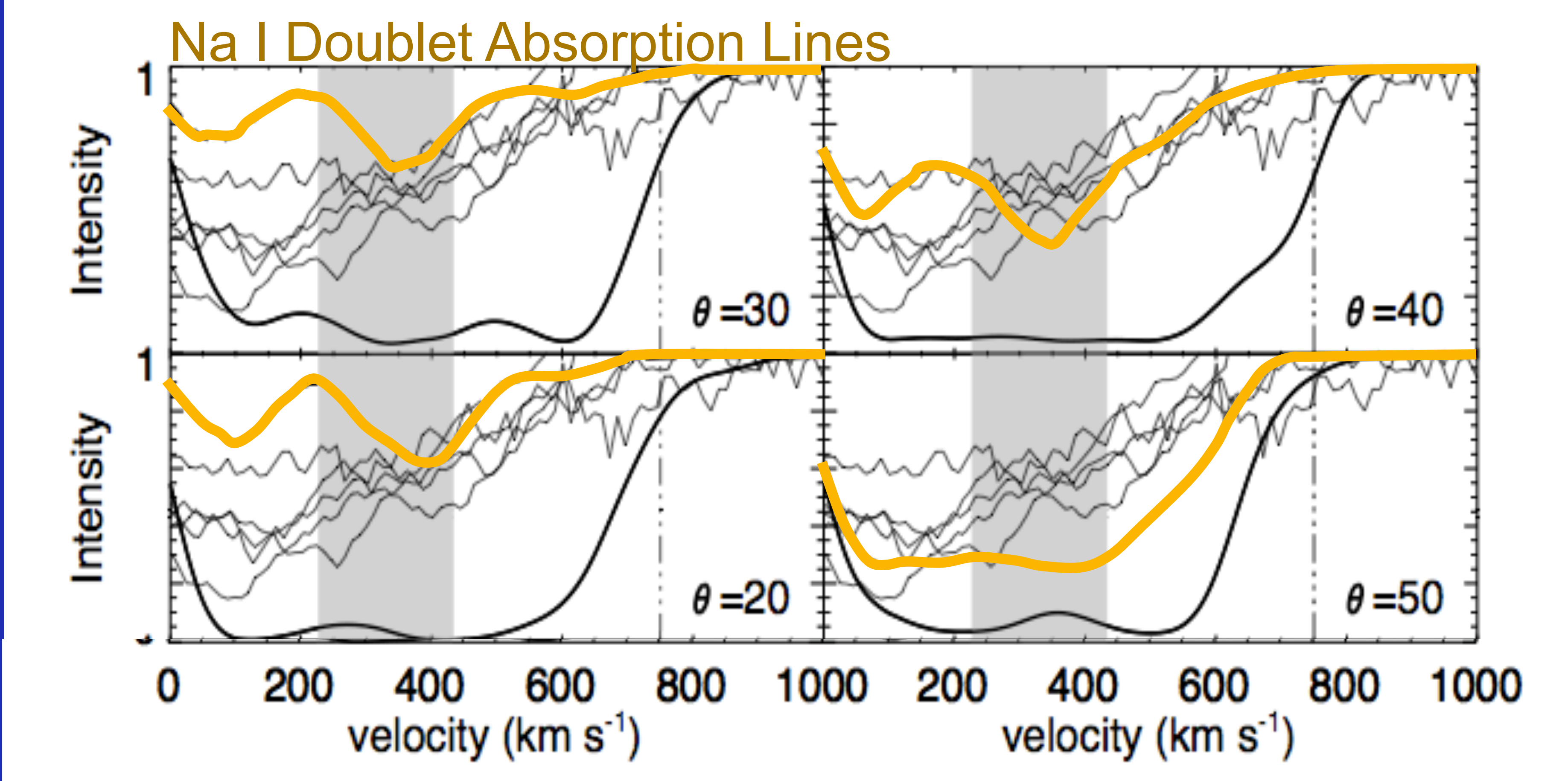
ULIRG winds can accelerate cold gas





Fast Cold Gas from SN Wind

Fujita+ 09



but little mass loss!

observations from Martin 05

Gravitational Instability

Does this offer a robust threshold mechanism?

linear analysis of axisymmetric, radial gravitational instability

Stars: $Q_s = \kappa\sigma_s / (3.36 G\Sigma_s)$ (Toomre 64)

Gas: $Q_g = \kappa c_g / (\pi G \Sigma_g)$ (Goldreich & Lynden-Bell 65)

Stars & gas together (Rafikov 2001):

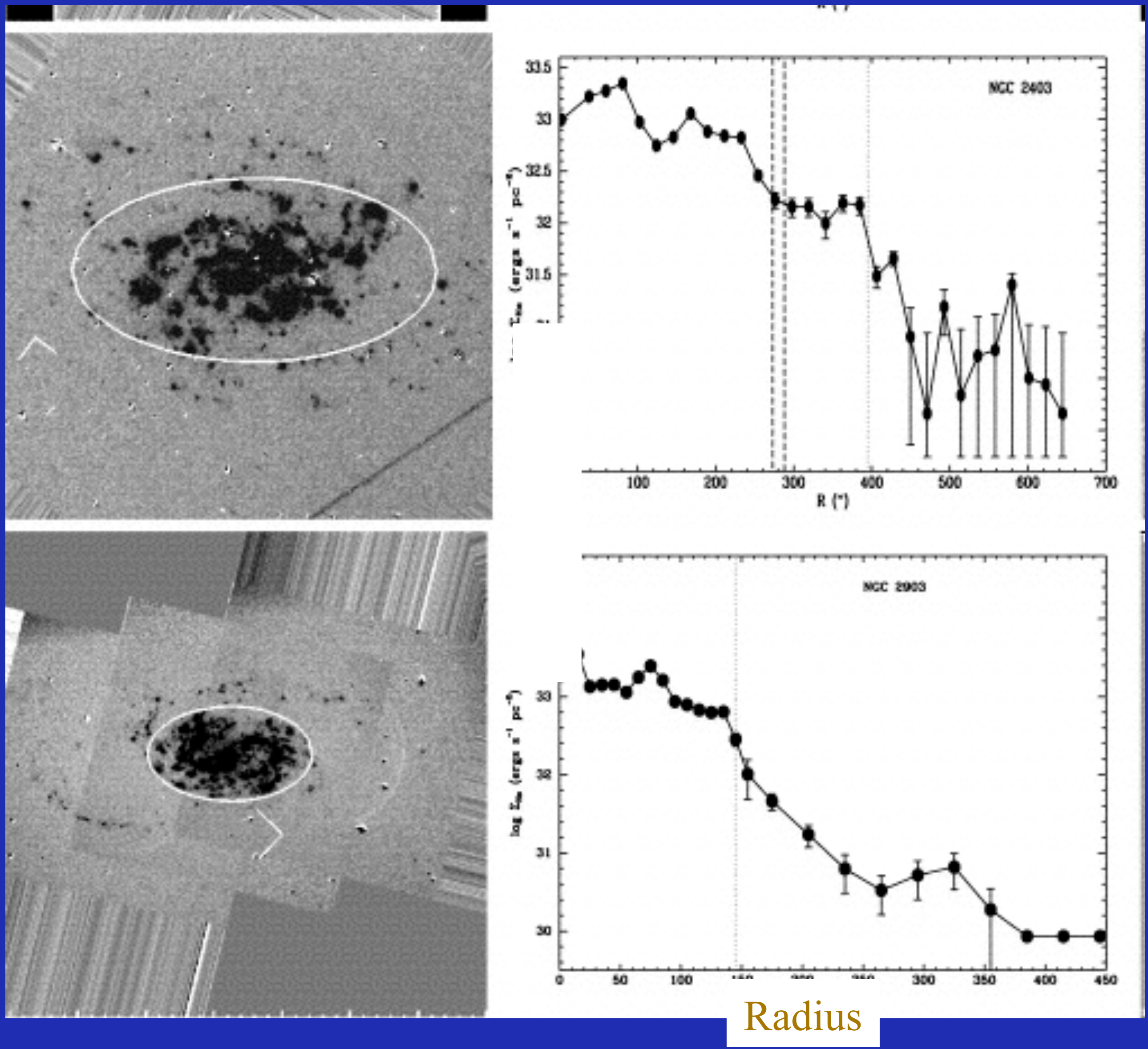
$$\frac{1}{Q_{sg}} = 2\frac{\left[1 - e^{-q^2} I_0\left(q^2\right)\right]}{q Q_s} + \frac{2qR}{Q_g\left(1 + q^2 R^2\right)}$$

κ -- epicyclic frequency
I_0 -- Bessel fcn of order 0,
$q = k\sigma_s / \kappa$, $R = c_g / \sigma_s$.

Σ_s, Σ_g -- star, gas surf. den
σ_s -- radial stellar vel disp
c_g -- isotherm gas sound spd

Instability when $Q_{sg} < 1$.

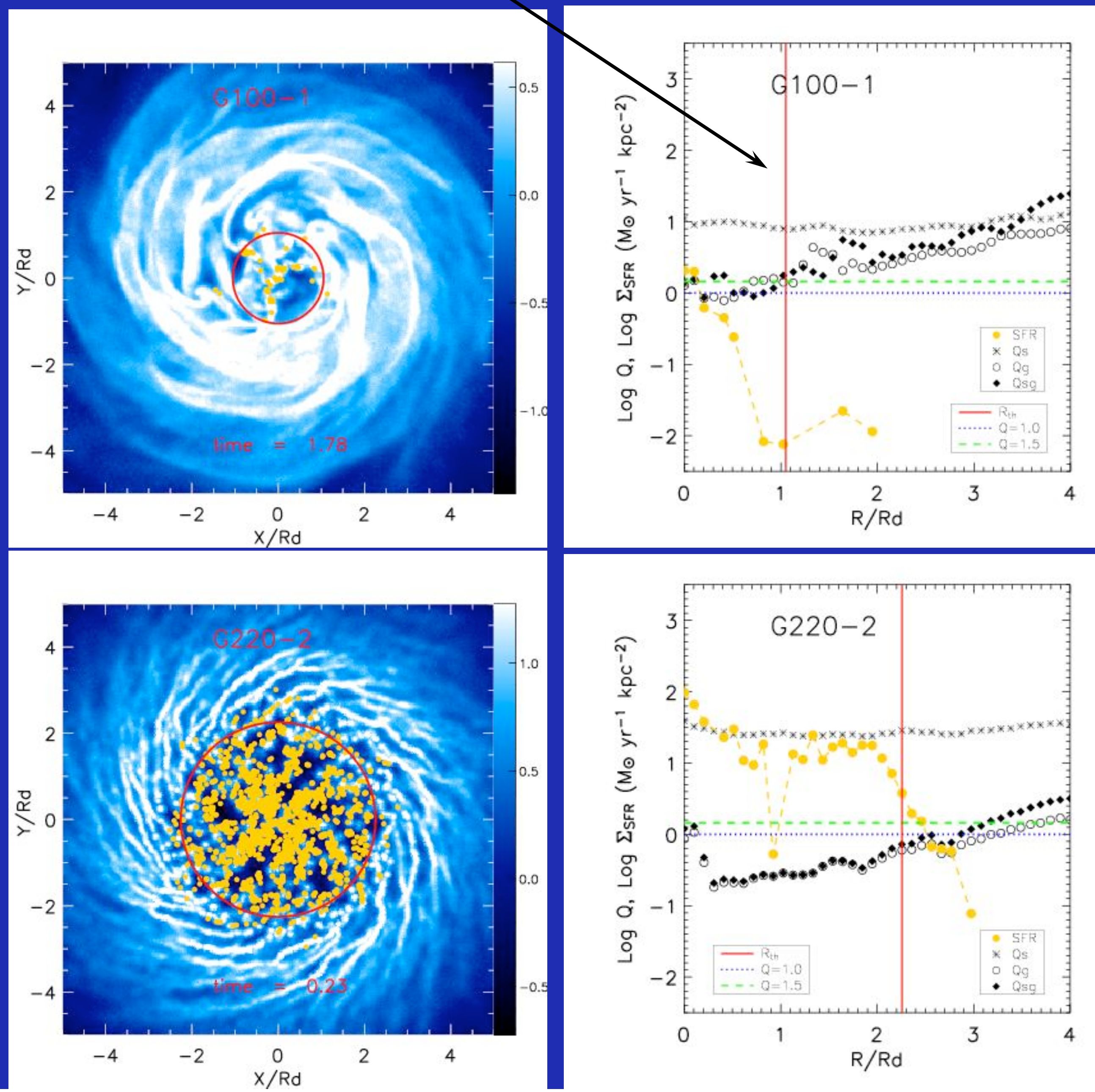
Star Formation Thresholds



Martin & Kennicutt 01

Star Formation Thresholds

90% of star formation

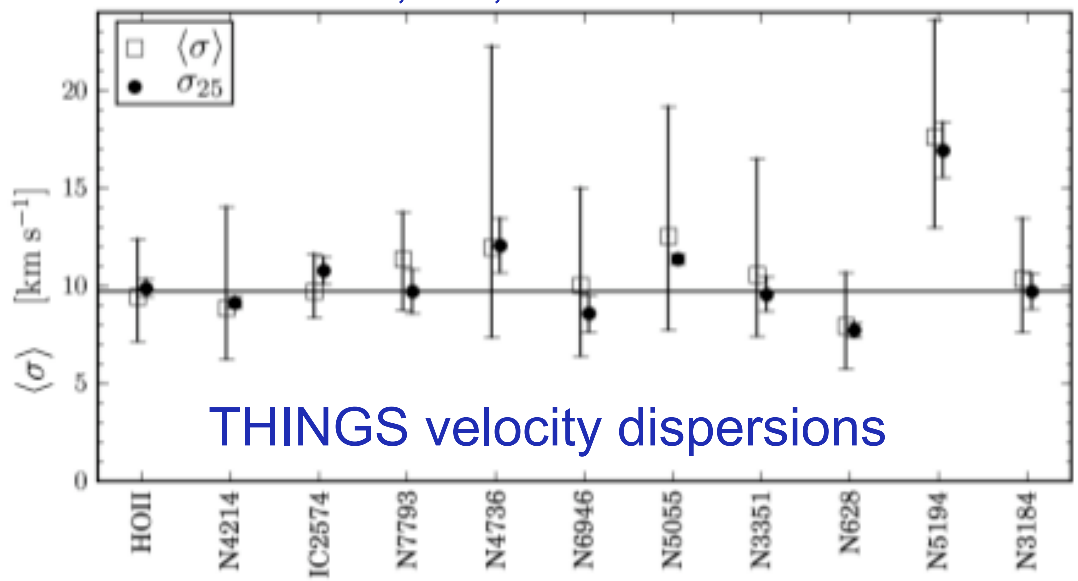


Threshold occurs near where Q_{sg} exceeds threshold

Model using constant velocity dispersion.

Li, Mac Low, & Klessen 05a

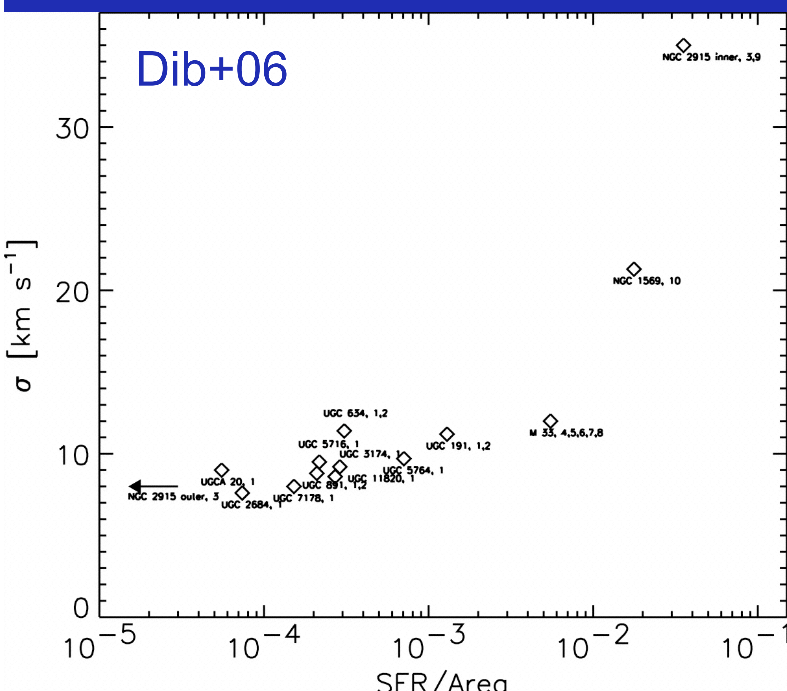
Tamburro, Rix, Mac Low + 09

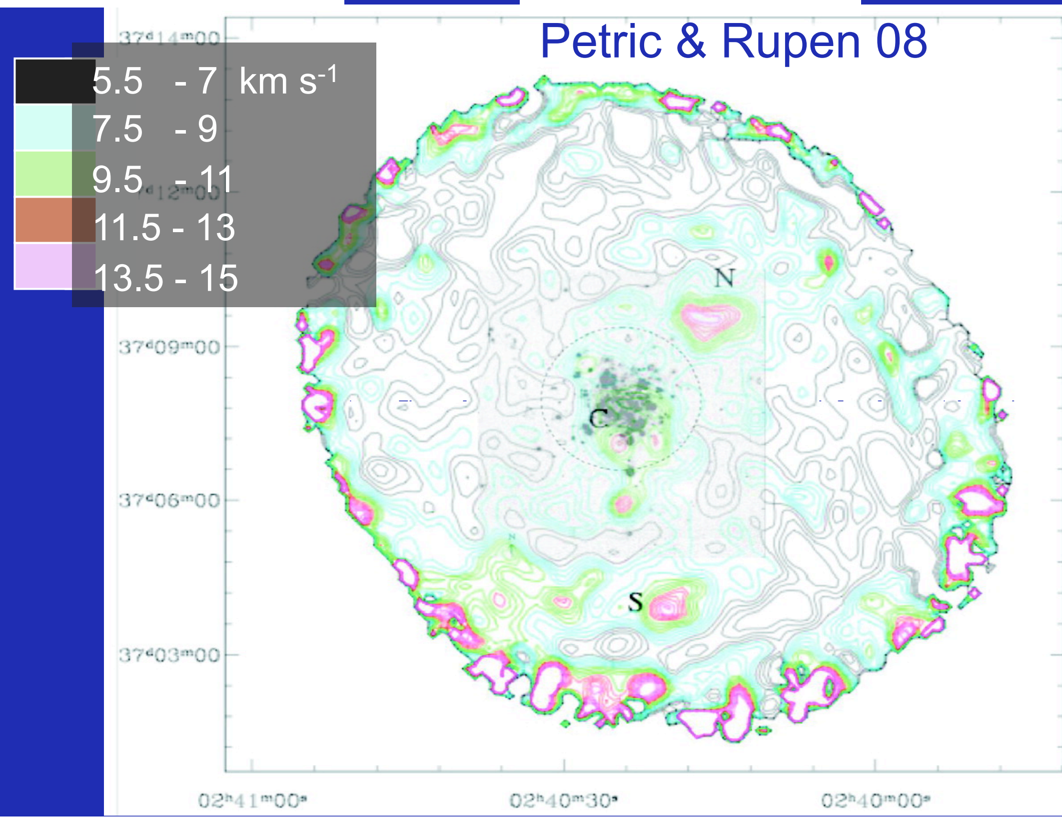


Why constant velocity dispersion in H I?

W idely observed in local universe.

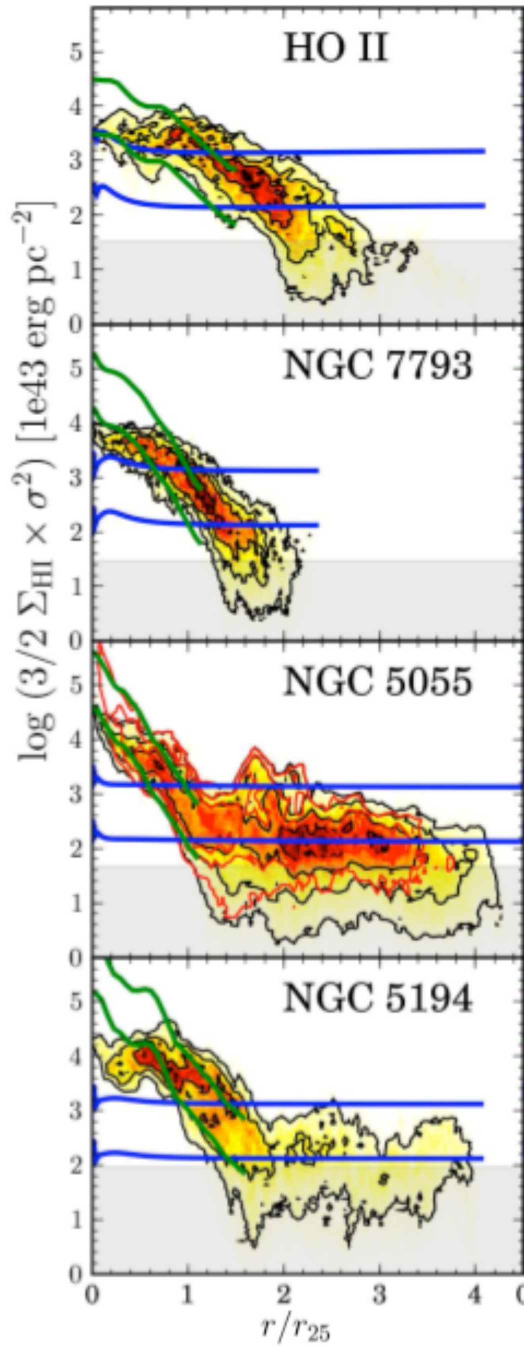
NGC 1058





is transition real story?

Tamburro, Rix, Mac Low + 2009



Kinetic Energy vs Radius

SNR

$$E_k = \eta \times (\epsilon_{\rm SN}\, 10^{51}\ {\rm erg})\tau_D$$

$$\eta = \frac{\rm SFR}{\langle m \rangle} \times f_{*\rightarrow{\rm SN}}$$

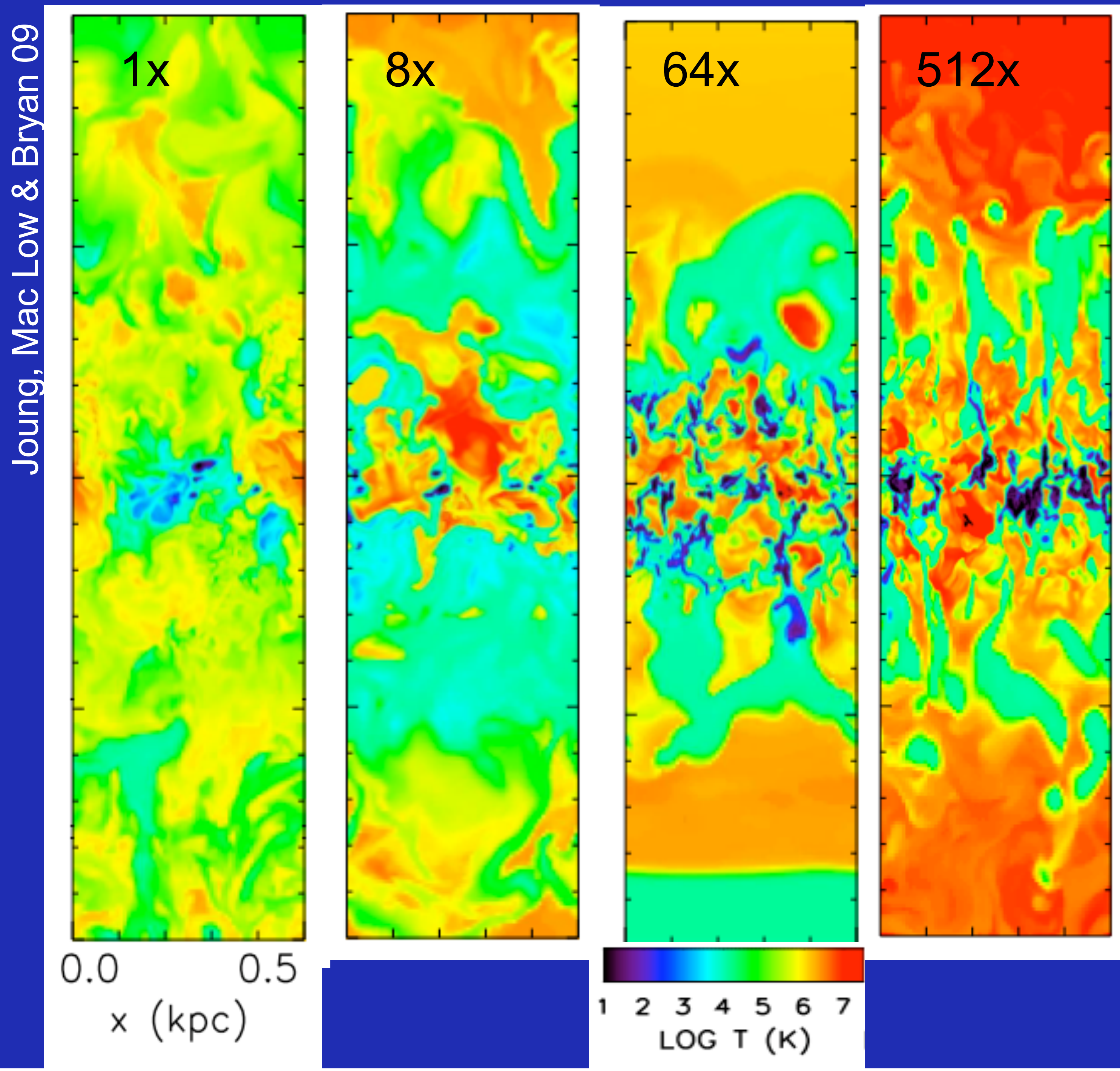
$$\tau_D \simeq 9.8\ (\lambda_{100}/\sigma_{10})\ {\rm Myr}$$

MRI

$$\dot{E}_{\rm MRI} = 3.7 \times 10^{-8}\ {\rm erg\ cm^{-2}\ s^{-1}} \times \left(\frac{h_z}{100\ {\rm pc}}\right) \left(\frac{B}{6\ \mu{\rm G}}\right)^2 \frac{\Omega}{(220\ {\rm Myr})^{-1}}$$

Sellwood & Balbus 99, Mac Low & Klessen 04
see sims by Piontek & Ostriker 04, 05, 07

Schaye 04 argues for UV heating maintaining outer disk KE => no cold phase there.

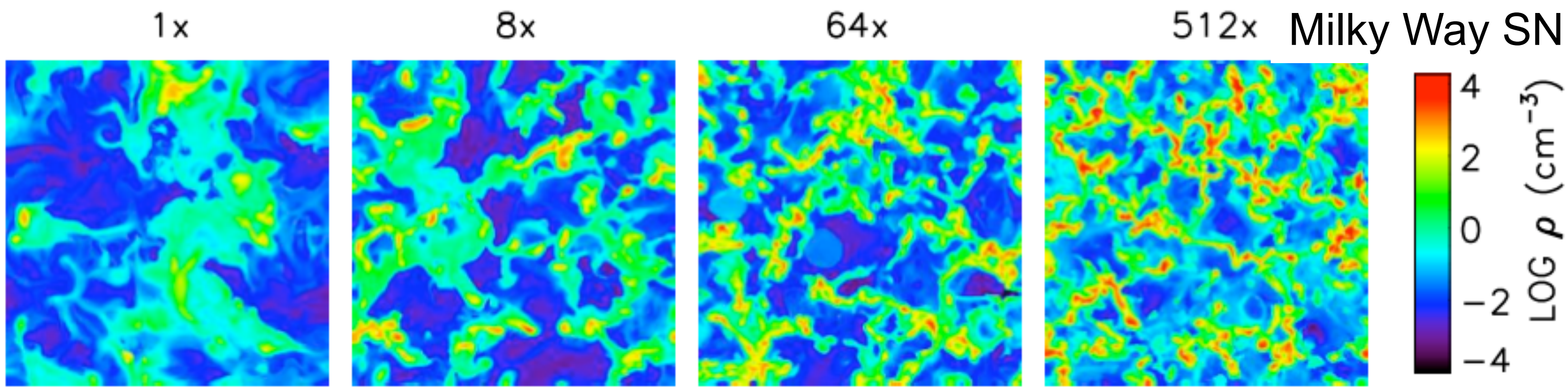


SN/SFR rates in Milky Way units

disk density following Kennicutt-Schmidt Law

$\Delta x = 2$ pc

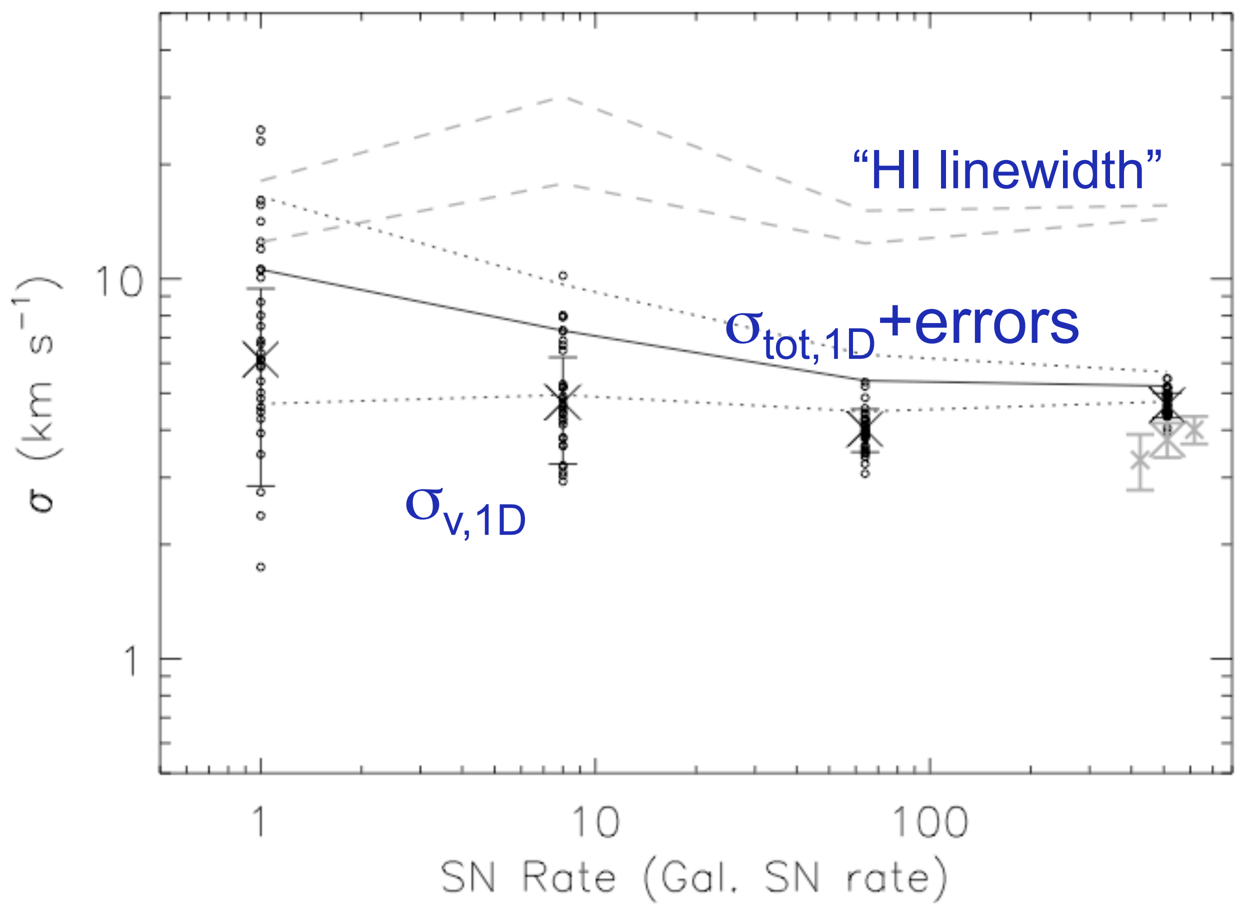
Joung, Mac Low & Bryan 09



assuming Kennicutt-Schmidt law for gas surface density.

SN feedback does NOT drive high HI velocity dispersions.

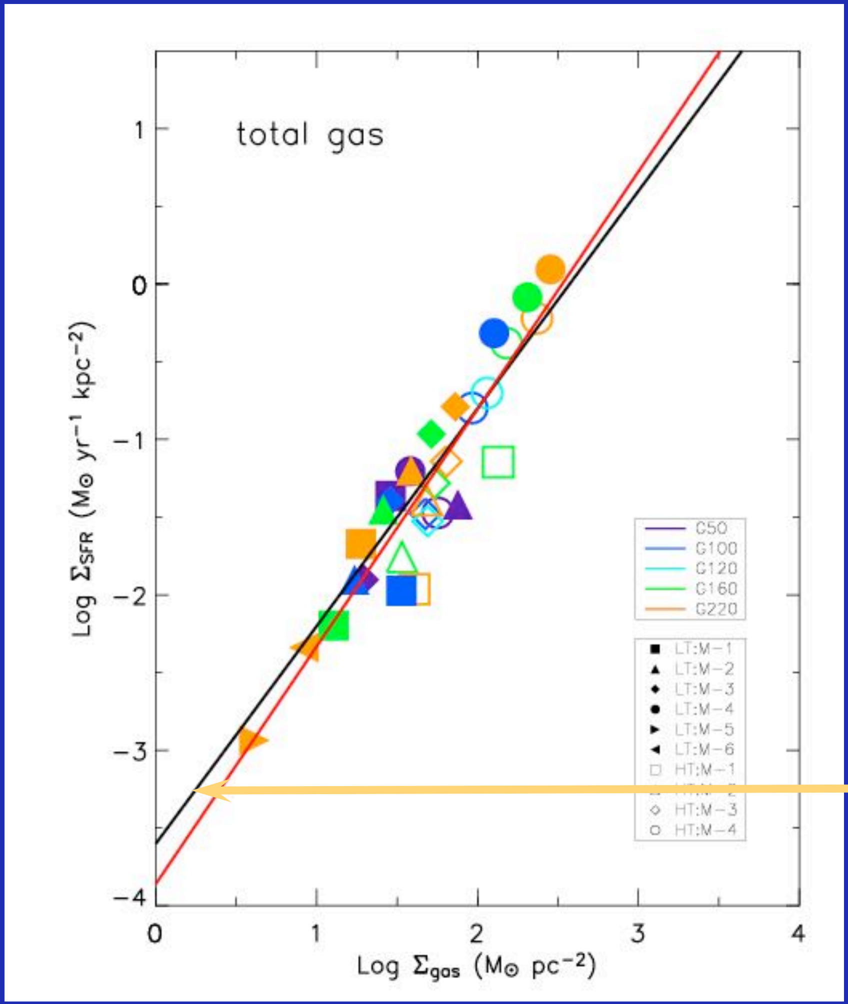
cf. Monaco 04a
Ceverino & Klypin 09



Global Schmidt Law

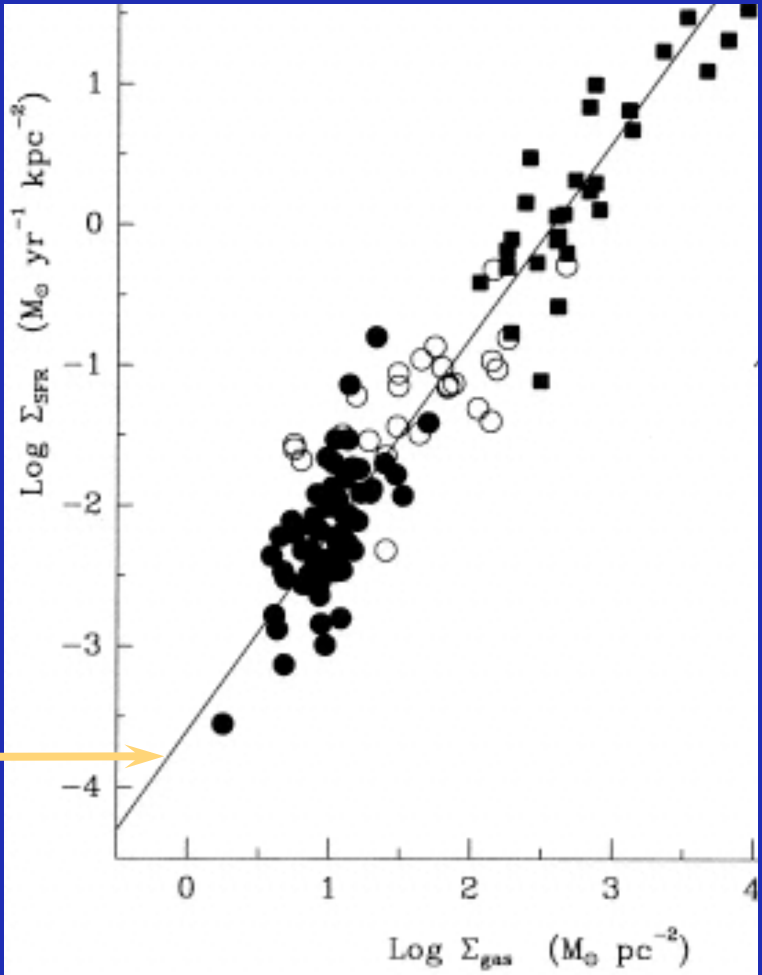
constant velocity dispersion can reproduce (too)

models



Li, Mac Low, & Klessen 05a, 06

observations

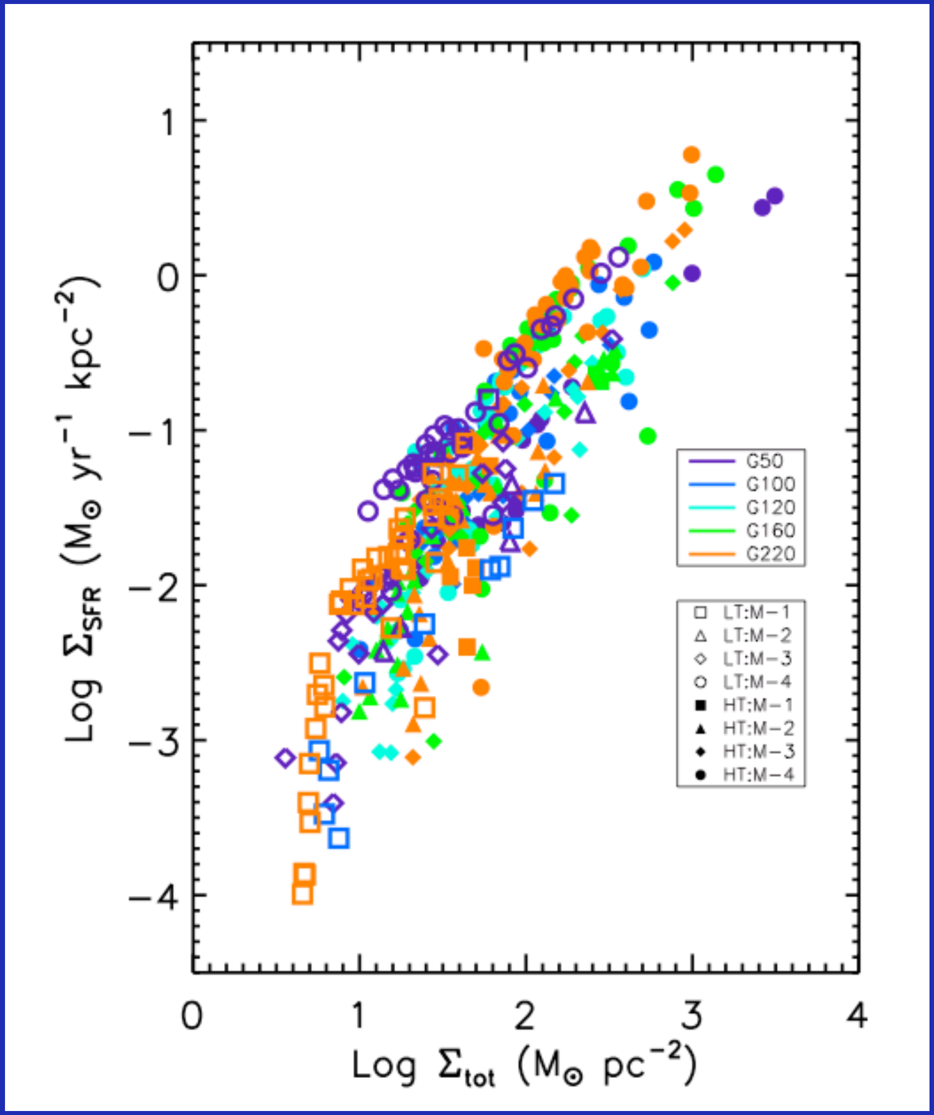


Kennicutt 98

Local Schmidt Law

threshold seen at outer edge from Toomre instability

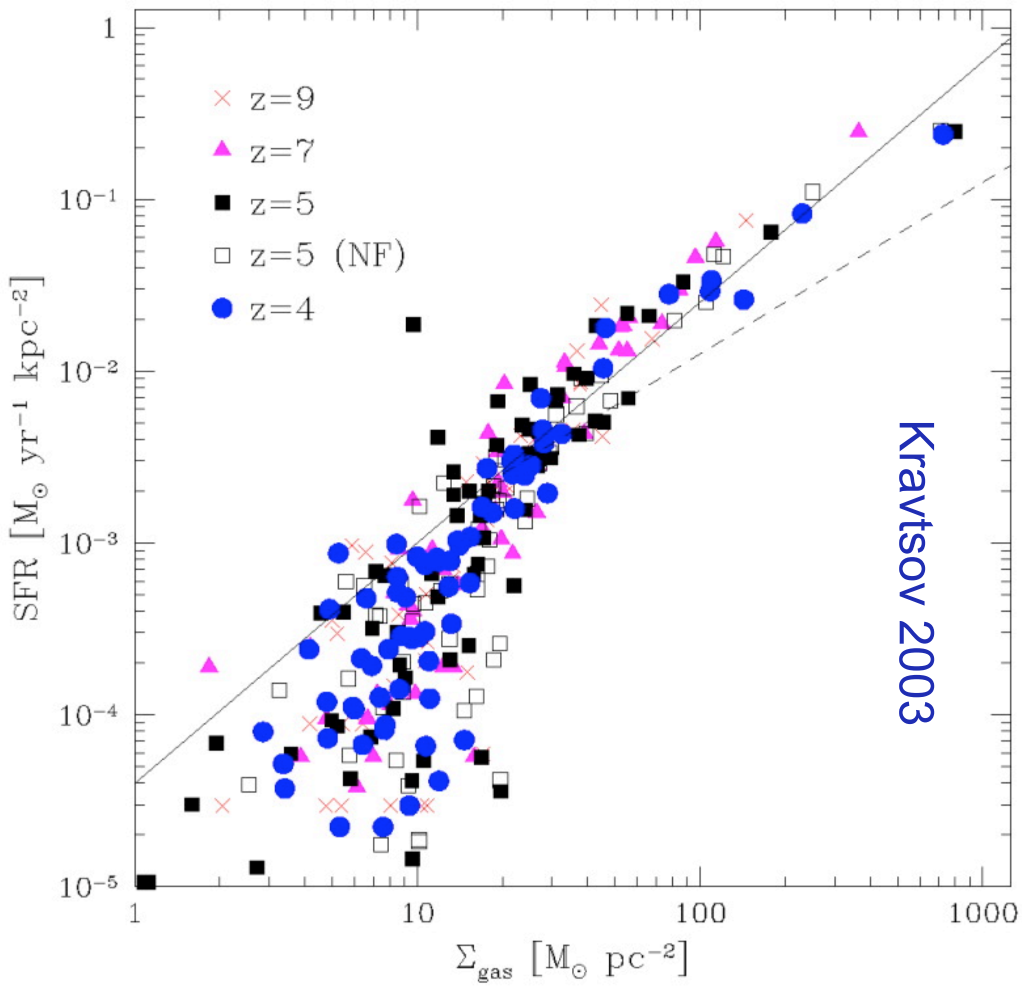
as seen by Bigiel + 08?



Li, Mac Low & Klessen 06

Cosmological Context

- Kravtsov (2003):
  - Cosmological ICs
  - Star formation law
    $$\dot{\rho}_* \propto \rho_g$$
  - No effective feedback
  - Measured SF in many galaxies in one model
  - Downturn seen by Wolfe & Chen 06 at z = 3? (Kravtsov talk)
  - see also Tassis + 09



Kravtsov 2003

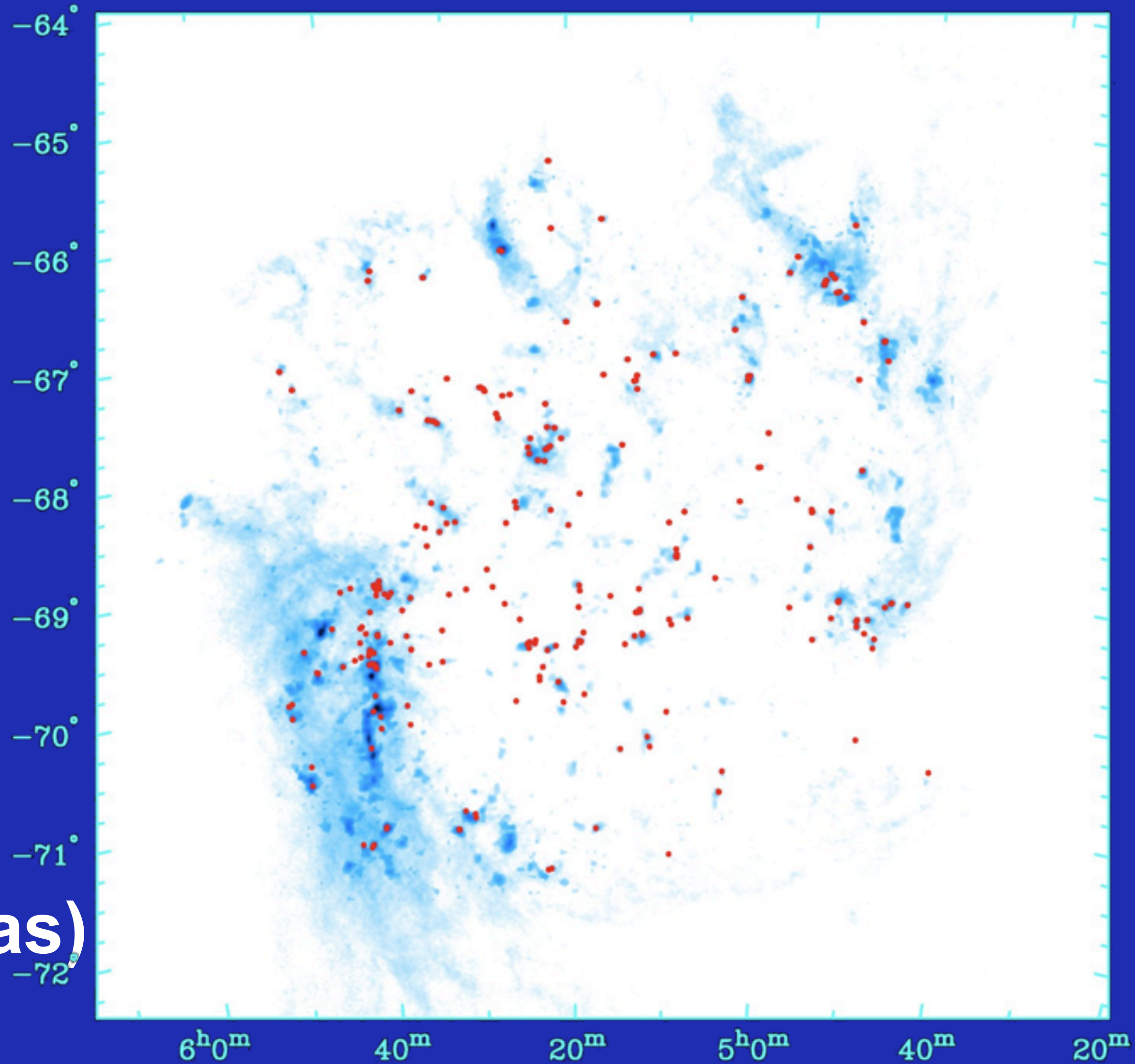
LMC Stability

Stars: Spitzer 3 μm,
constant σ_*
Atomic gas: HI (Kim +)
Molecules: CO (Fukui +)

YSOs: Spitzer 8 μm

Q_g : blue scale

YSOs: red dots



Yang, Gruendl, Chu, Mac Low & Fukui 07

gas only:

$$Q_g = \frac{\kappa c_g}{\pi G \Sigma_g}$$ **<1 (gas)**

LMC Stability

Stars: Spitzer 3 μm,
constant σ_*
Atomic gas: HI (Kim +)
Molecules: CO (Fukui +)

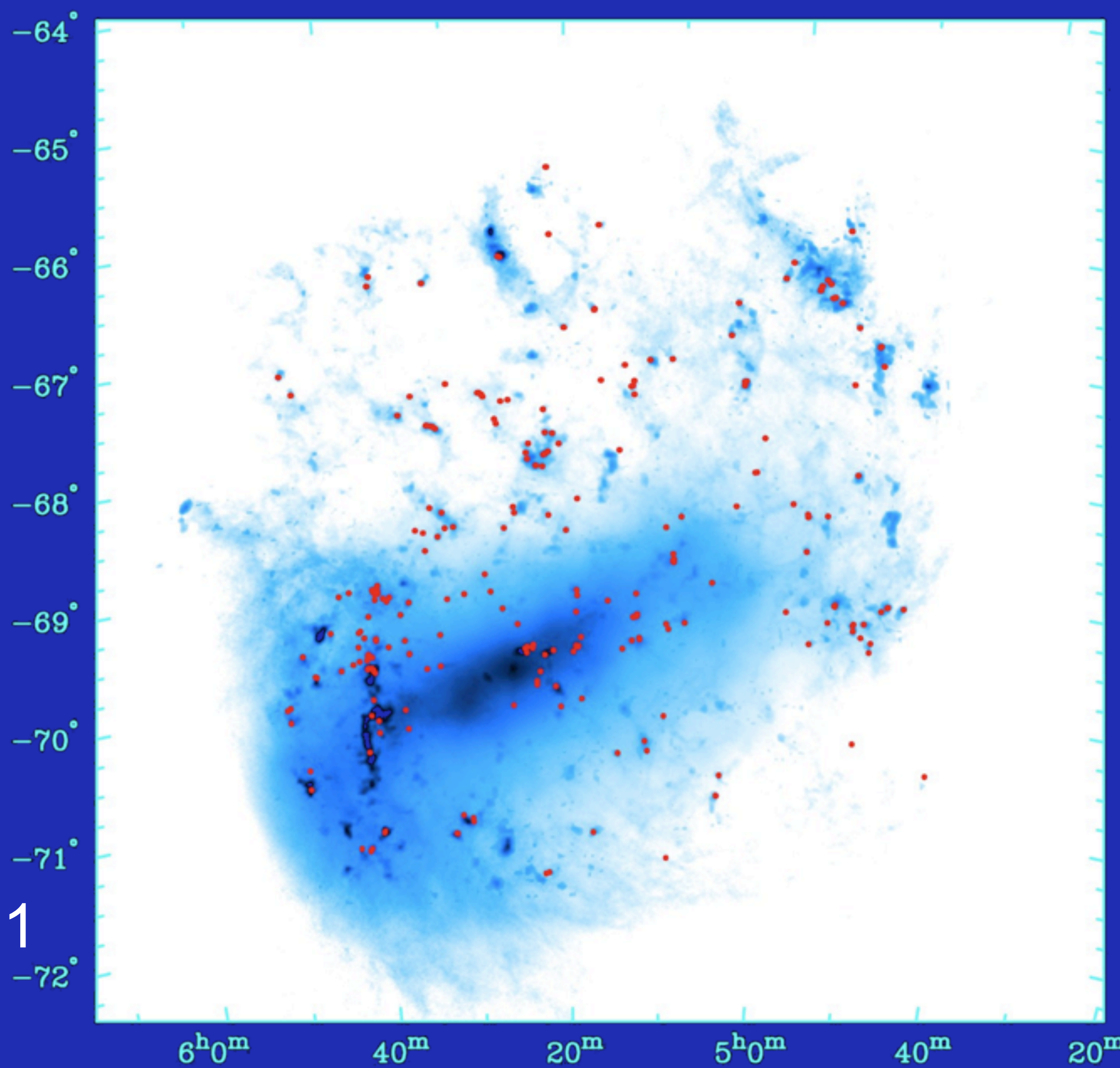
YSOs: Spitzer 8 μm

Q_{sg}: blue scale

YSOs: red dots

Stars & gas:

Q from Rafikov 01



Yang, Gruendl, Chu, Mac Low & Fukui 07

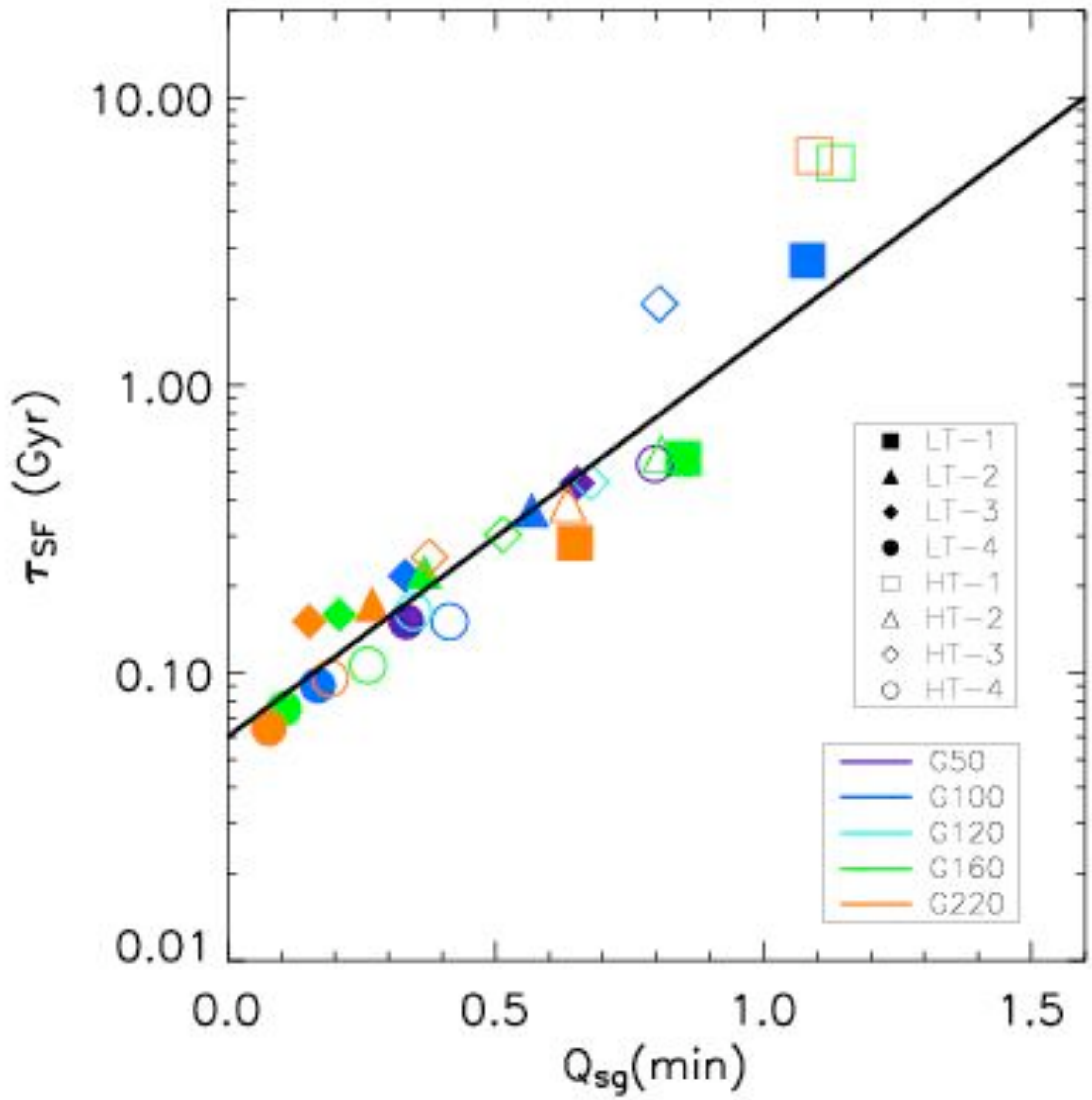
LMC Stability

- We assumed constant velocity dispersion $\sigma_* = 15$ km s^{-1} for stellar disk.
- Leroy + 08 argue that instead it is the stellar scale height that is constant, giving a velocity dispersion $\sigma_* \propto \Sigma_*^{1/2}$
- This would imply entire disk stable!
- Further observations of σ_* needed at large R (see upcoming work by Zasov +; Herrmann & Ciardullo; K. Jackson & Hunter;)

Instability drives SF

$$\tau_{SF} \propto e^{\alpha Q_{sg}}$$

$$\alpha = 4.2 \pm 0.2$$



Li, Mac Low, Klessen 05

Large Magellanic Cloud

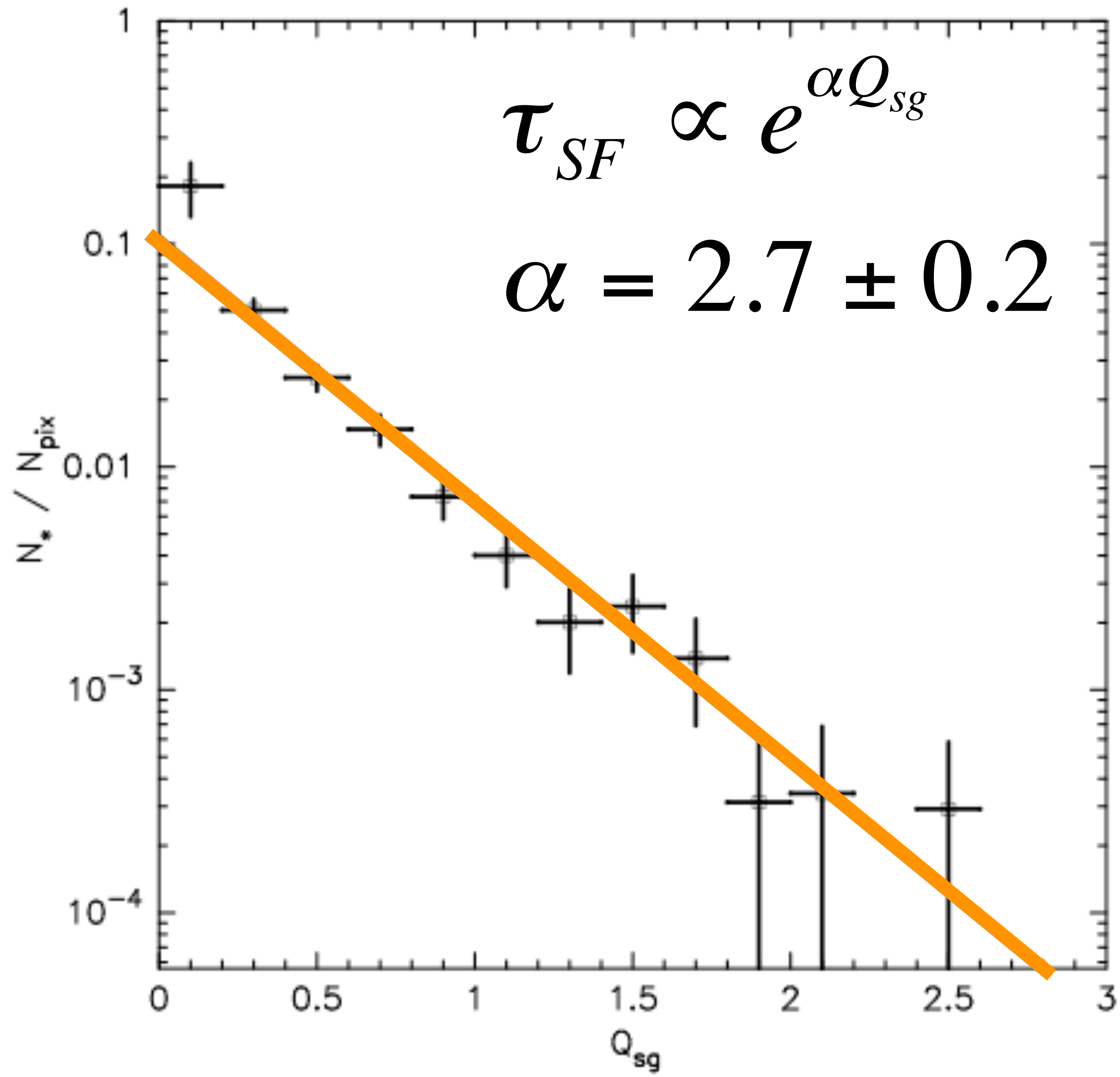
$$\frac{N_*}{N_{pix}} \propto \frac{1}{\tau_{SF}}$$

Assume IR bright young stars all about the same age.

Measure number of stars in different bins of Q_{sg}

Normalize by area of each bin on galaxy.

This gives a timescale.



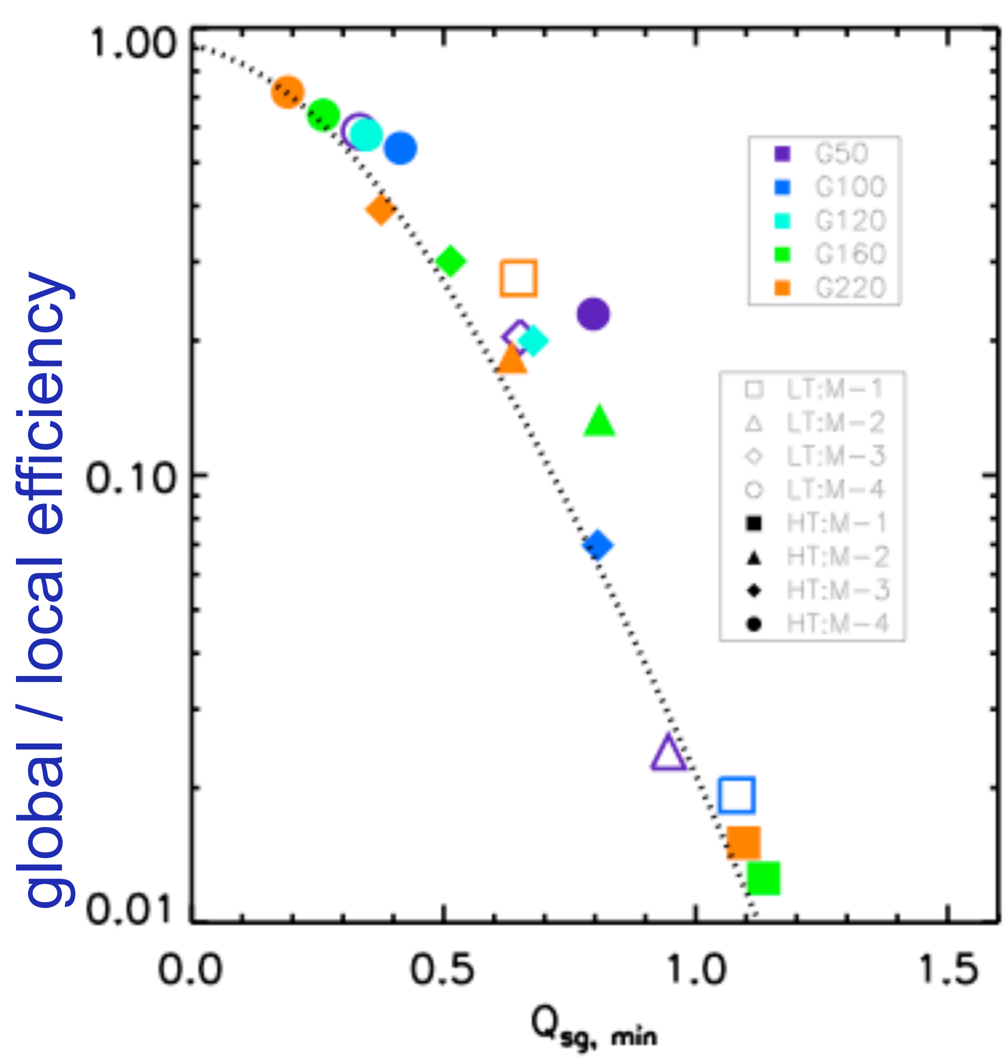
Yang, Gruendl, Chu, Mac Low & Fukui 07

Global SF Efficiency

$$\varepsilon_g = M_* / M_{init} = M_0 \left(1 - e^{-t/\tau_{SF}}\right) = f\left(Q_{sg,\min}\right)$$

constant local efficiency implies wide variation in global efficiency.

More stable galaxies have far lower global efficiency.



Li, Mac Low, & Klessen 06

Conclusions

- Supernova or AGN feedback effective at keeping hot gas hot, but not at heating up cold gas.
  - Primary effect in star forming regions of galaxies is likely to help maintain velocity dispersion.
  - Monster in bathtub must splash in the hot gas
- Nonlinear gravitational instability seems able to function as an exponential cutoff.
  - necessary but insufficient to explain decline in efficiency at low masses, particularly at high redshift.