Gravitational Instability and the Kennicutt-Schmidt Law

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Collaborators

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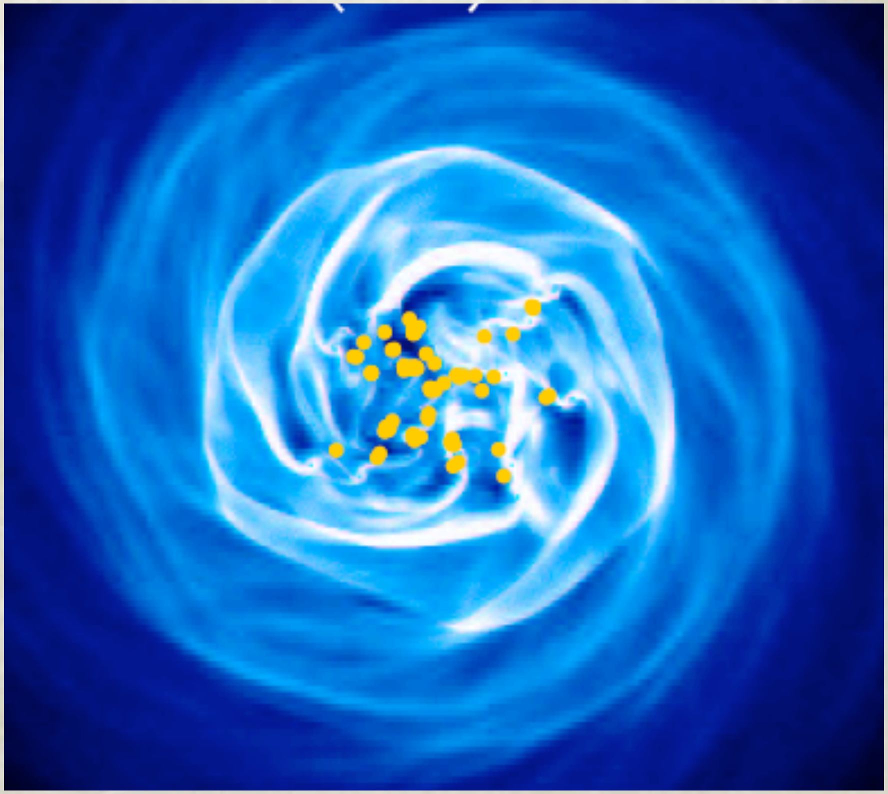
Numerical Experiments

dark matter

stars ➔

gas



Control: initial gravitational instability

Measure: star formation properties

Technical details

- **Code**: GADGET v1.1 (Springel, Yoshida & White 2001) + sink particles (Bate et al. 95, Jappsen, Klessen, Li, Mac Low 04) created when $n > 10^3$ cm^{-3}, interact gravitationally
- **Galaxy model**: DM halo + disk of stars & isothermal gas (Mo, Mao, White 98, Springel & White 99, Springel 00).
- **Initial conditions**:
  - Rotational velocities $50 < V_{rot} < 220$ km s^{-1}
  - Gas fractions 5-90% of disk mass
  - sound speeds 6 km s^{-1} (LT) , 15 km s^{-1} (HT)

Approximations

- Fast molecular cloud formation
- Isothermal gas
- Neglect of magnetic fields

Each of these approximations has been addressed with local computational models.

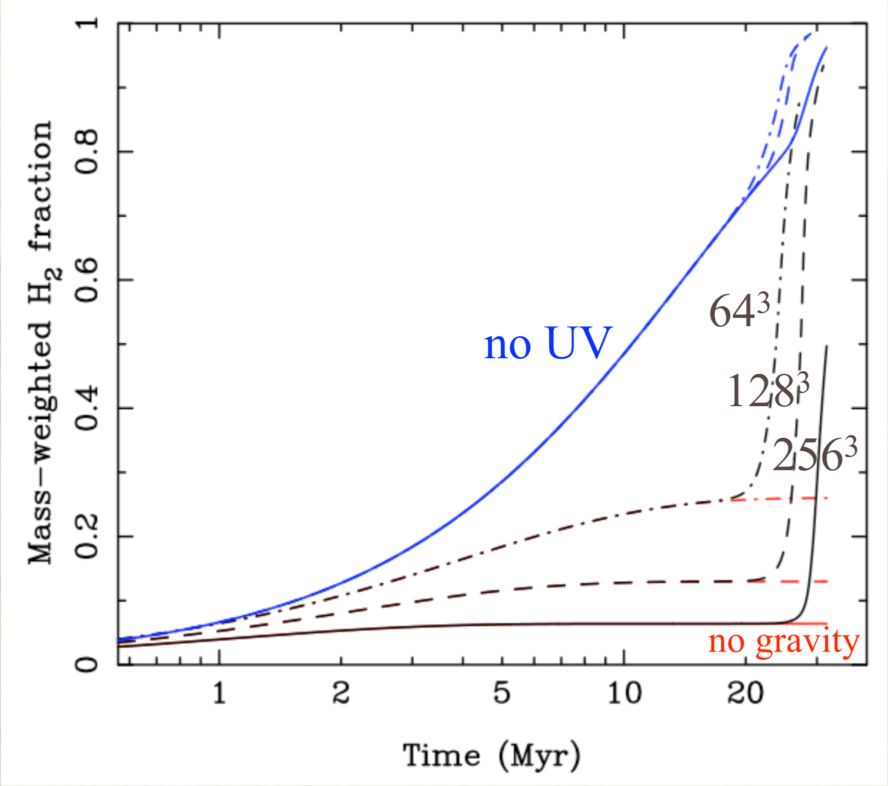
Approximations

- **<u>Fast molecular cloud formation</u>**
  - Follow non-equilib. abundances of H_2 and H^+ following Rosen & Smith (2004), fixed abundances of other species (CII, OI, SiII)
  - Radiative cooling, including H_2 ro-vib, CII, OI, SiII fine structure, dust-gas transfers
  - Photoelectric, cosmic ray, photodissoc. heating
  - Local approximation for H_2 self-shielding
  - Up to 512^3 MHD models with ZEUS-MP (Norman 2000)
- Isothermal gas
- Neglect of magnetic fields

Static collapse

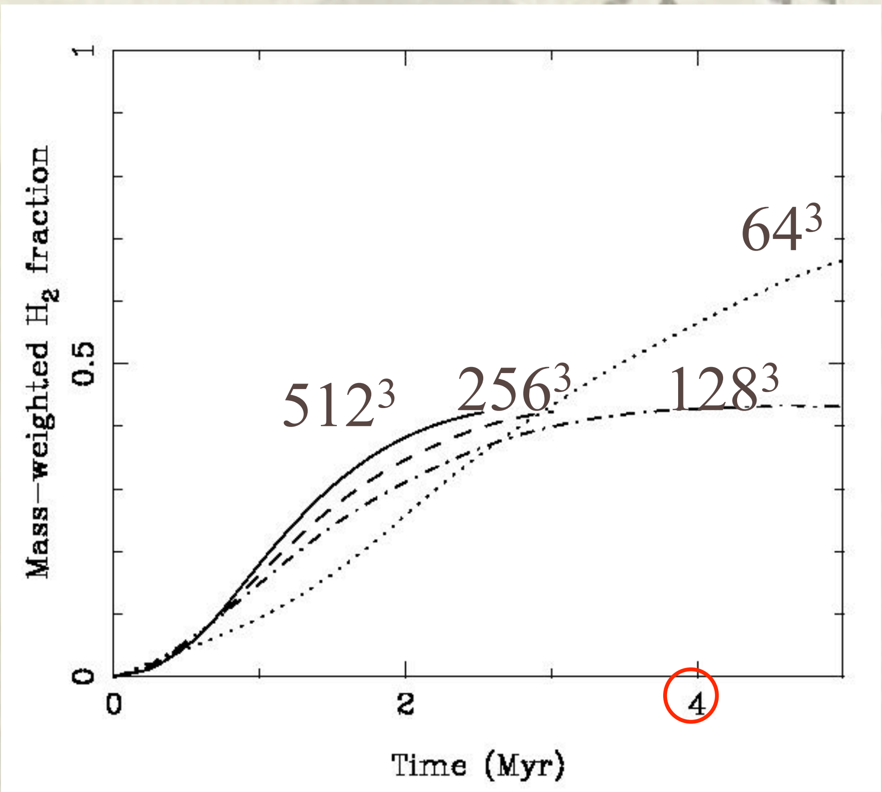
Turbulent flow

Glover & Mac Low 2006a

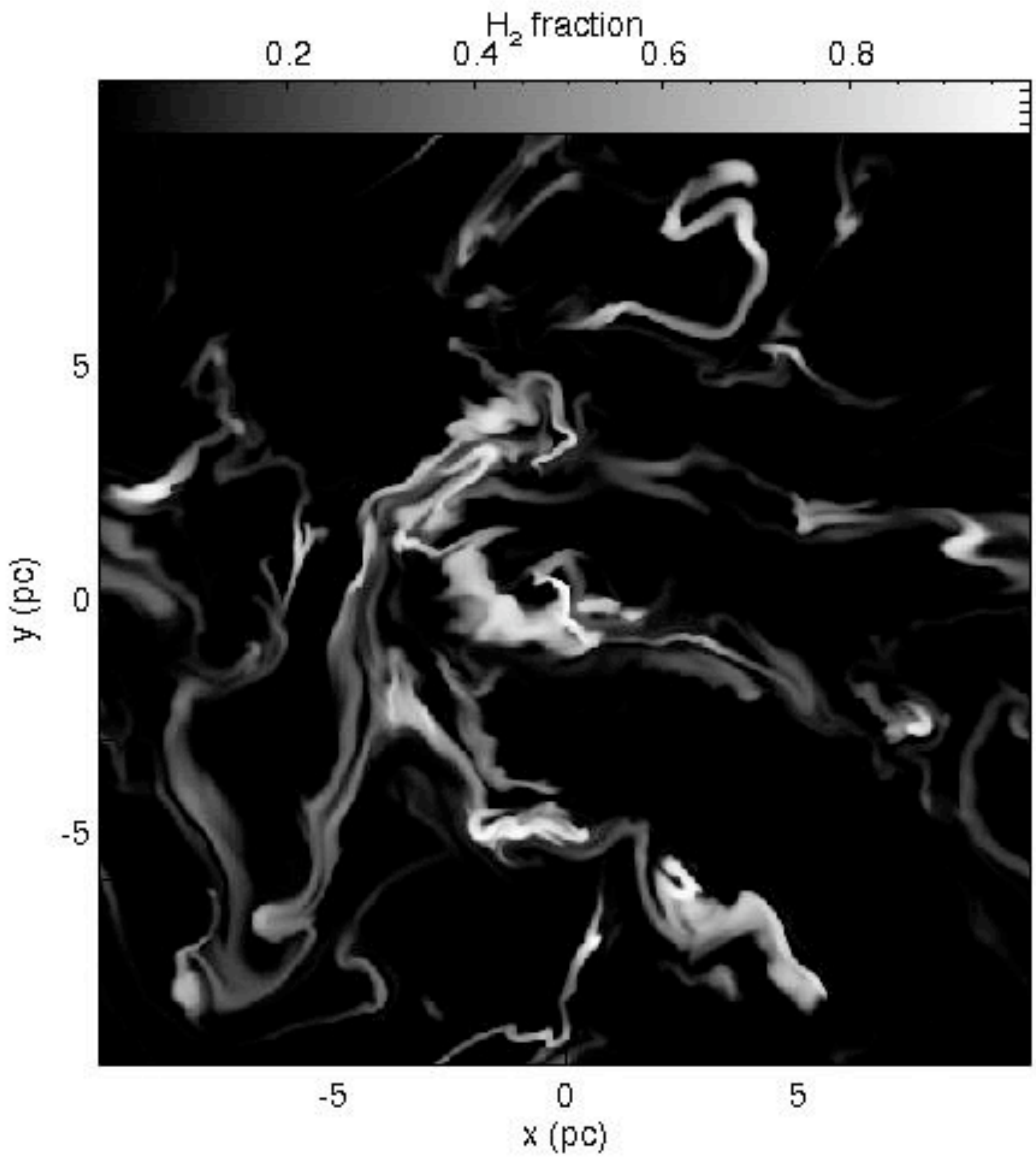


$L = 40$ pc, $B_0 = 5.85\ \mu G$, $v_{rms} = 0.0$

Glover & Mac Low 2006b



$L = 20$ pc, $B_0 = 5.85\ \mu G$, $v_{rms} = 10$ km/s



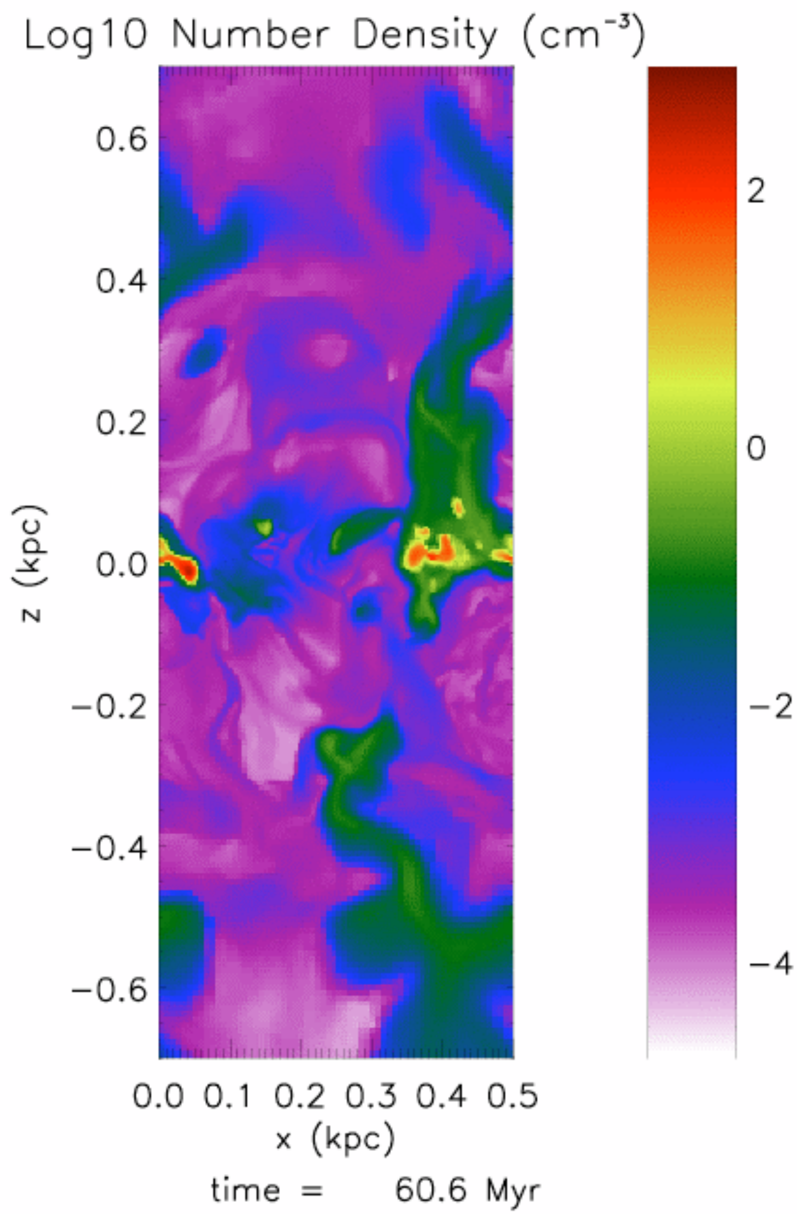
Glover & Mac Low 2006b

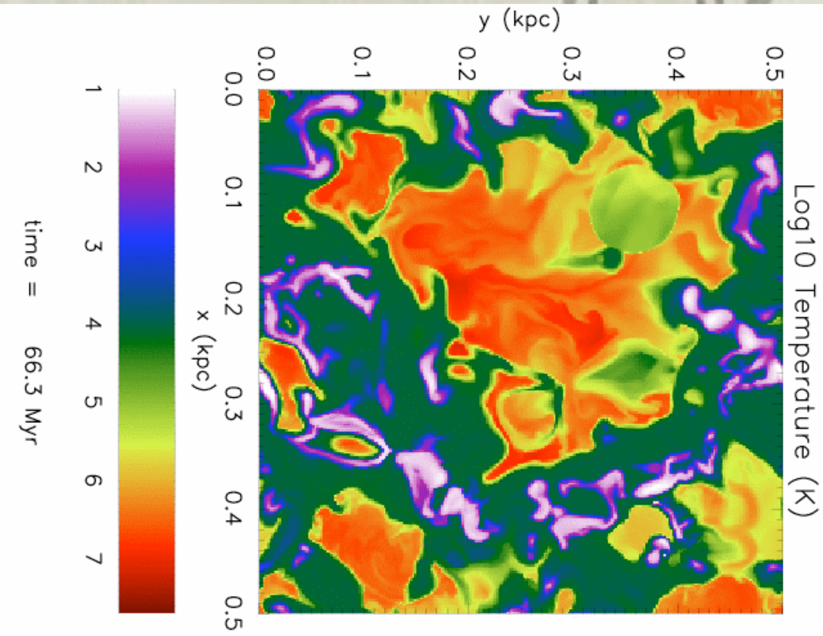
Molecular gas forms quickly in a turbulent medium once densities exceed 100 cm^{-3}.

We form sink particles at densities of 1000 cm^{-3} in our global disk models. Therefore our assumption that mass in sink particles is primarily molecular appears justified.

Approximations

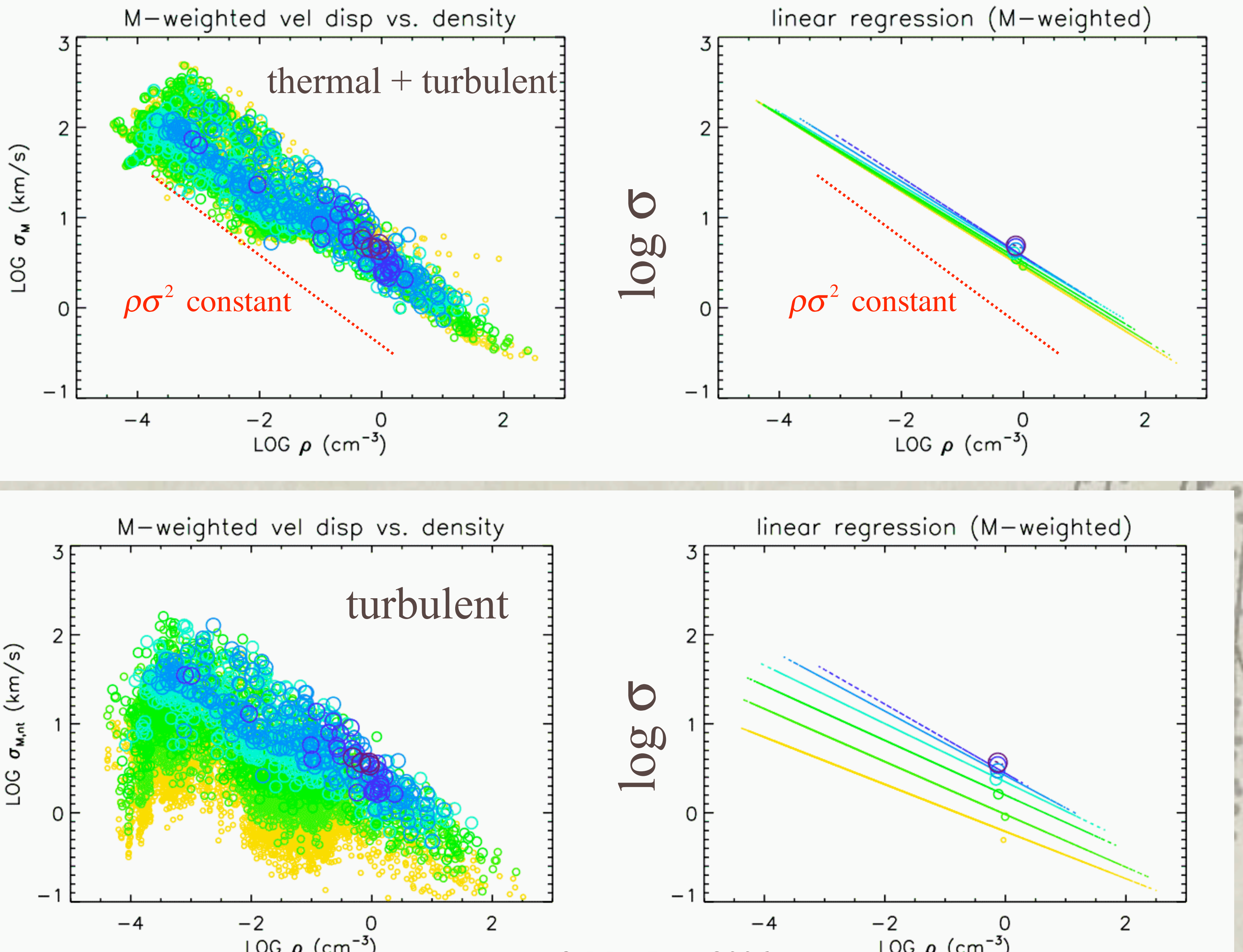
- Fast molecular cloud formation
- **Isothermal gas**
  - We used $T = 10^4$ K to model uniform velocity dispersion in gas in global models
  - Test by comparing with (500 pc)^2 x 10 kpc local models of SN driven ISM turbulence (Joung & Mac Low 2006), using Flash AMR hydro code (Fryxell et al 2001).
  - Models include discrete SNe, photoelectric heating and radiative cooling, static gravitational potential
  - Δx_{min}= 1.95 pc in region ±200 pc from plane
- Neglect of magnetic fields



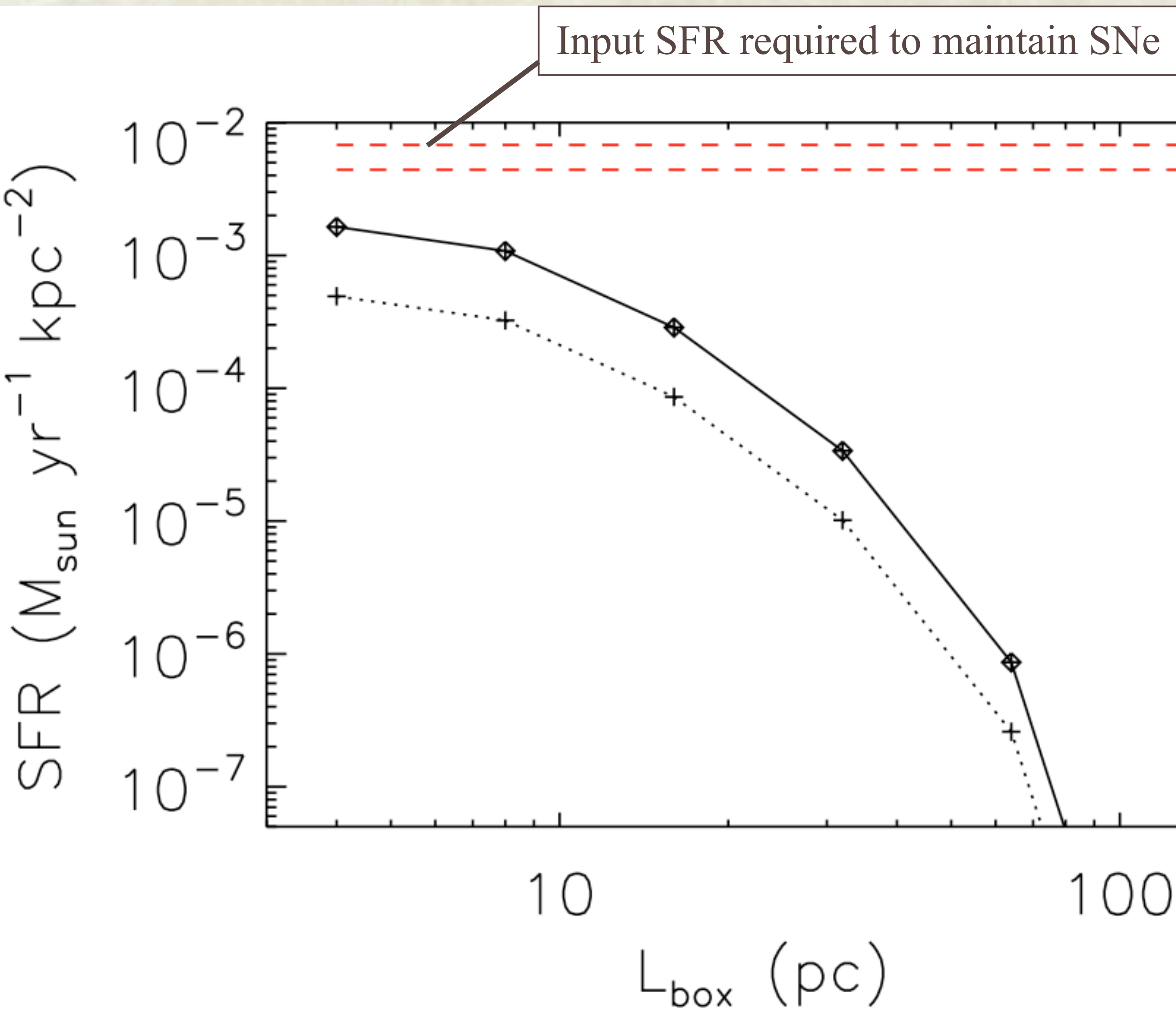


Temperature

Joung & Mac Low 2006



Joung & Mac Low 2006



Joung & Mac Low 2006

Isothermal EOS is a conservative assumption! Real ISM is even more compressible.

Barotropic equations of state are not required to prevent unrealistically high SF rates.

The most important effect this will have on our models is probably to change the mass spectrum (eg Li, Klessen & Mac Low 2003) from log-normal. Perhaps to something more like the observed power law?

Approximations

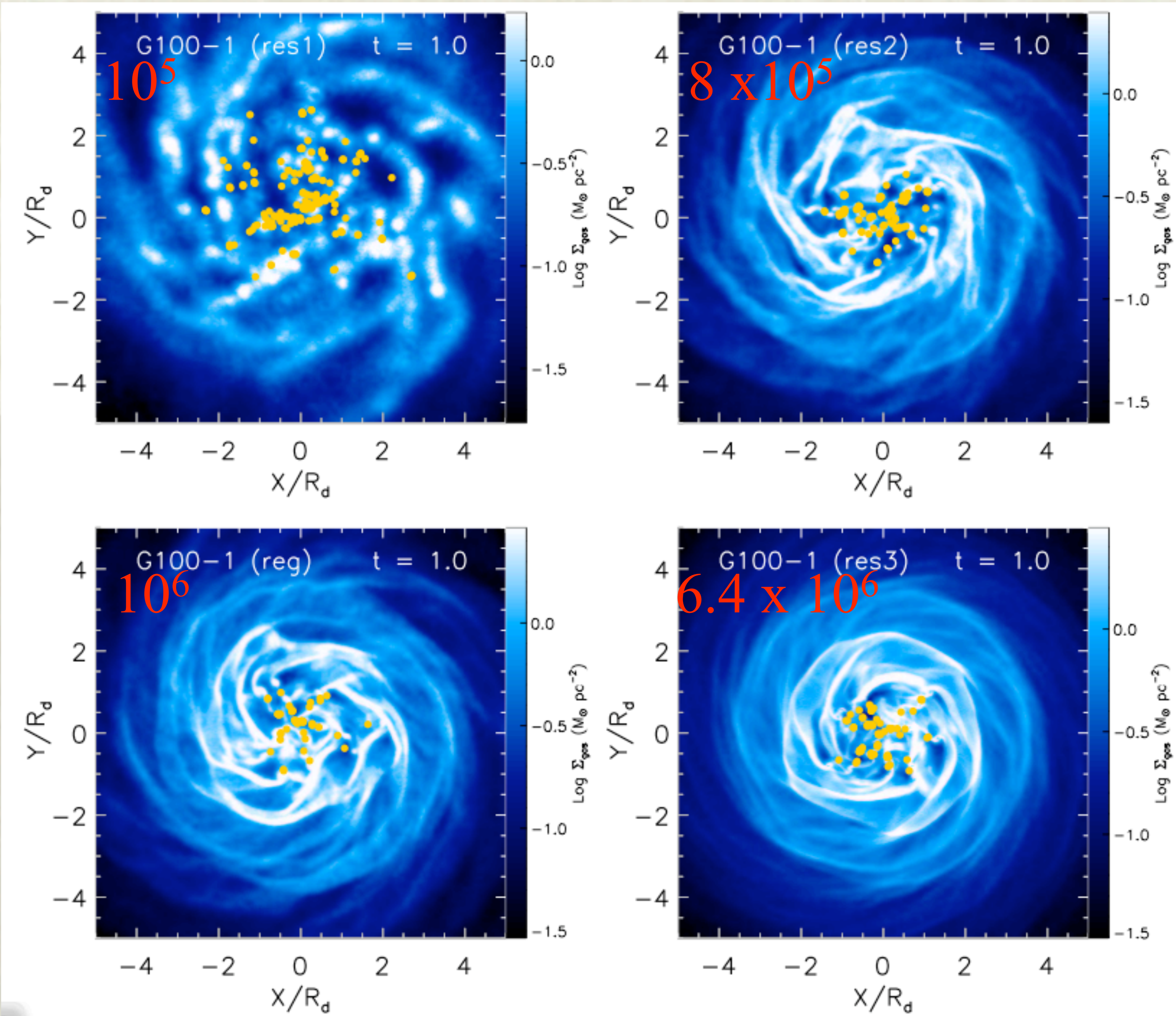
- Isothermal gas
- Fast molecular cloud formation
- **Neglect of magnetic fields**
  - B fields unlikely to support against collapse at these scales
  - B fields appear not to maintain turbulence.
  - They may slow collapse, make it less efficient.
  - ZEUS models summarized in Mac Low & Klessen (2004), P. Li et al. (2004)

Numerical Criteria

- *Jeans* for mass resolution (Bate & Burkert 97, Truelove et al. 97)
- *Gravity-hydro balance* for gravitational softening length (Bate & Burkert 97)
- *Equipartition* between gas, collisionless particle masses (Steinmetz & White 97).

Resolution study

Increasing linear res by factor of 2 between each frame.



Li, Mac Low, & Klessen 2005

Gravitational Instability

Linear analysis of axisymmetric radial gravitational instability:

- collisionless stars (Toomre 64)
- collisional gas (Goldreich & Lynden-Bell 65)

Q instability parameters:

Stars: $Q_s = \kappa\sigma_s / (3.36 G\Sigma_s)$ Gas: $Q_g = \kappa c_g / (\pi G \Sigma_g)$

Stars & gas (Rafikov 2001):

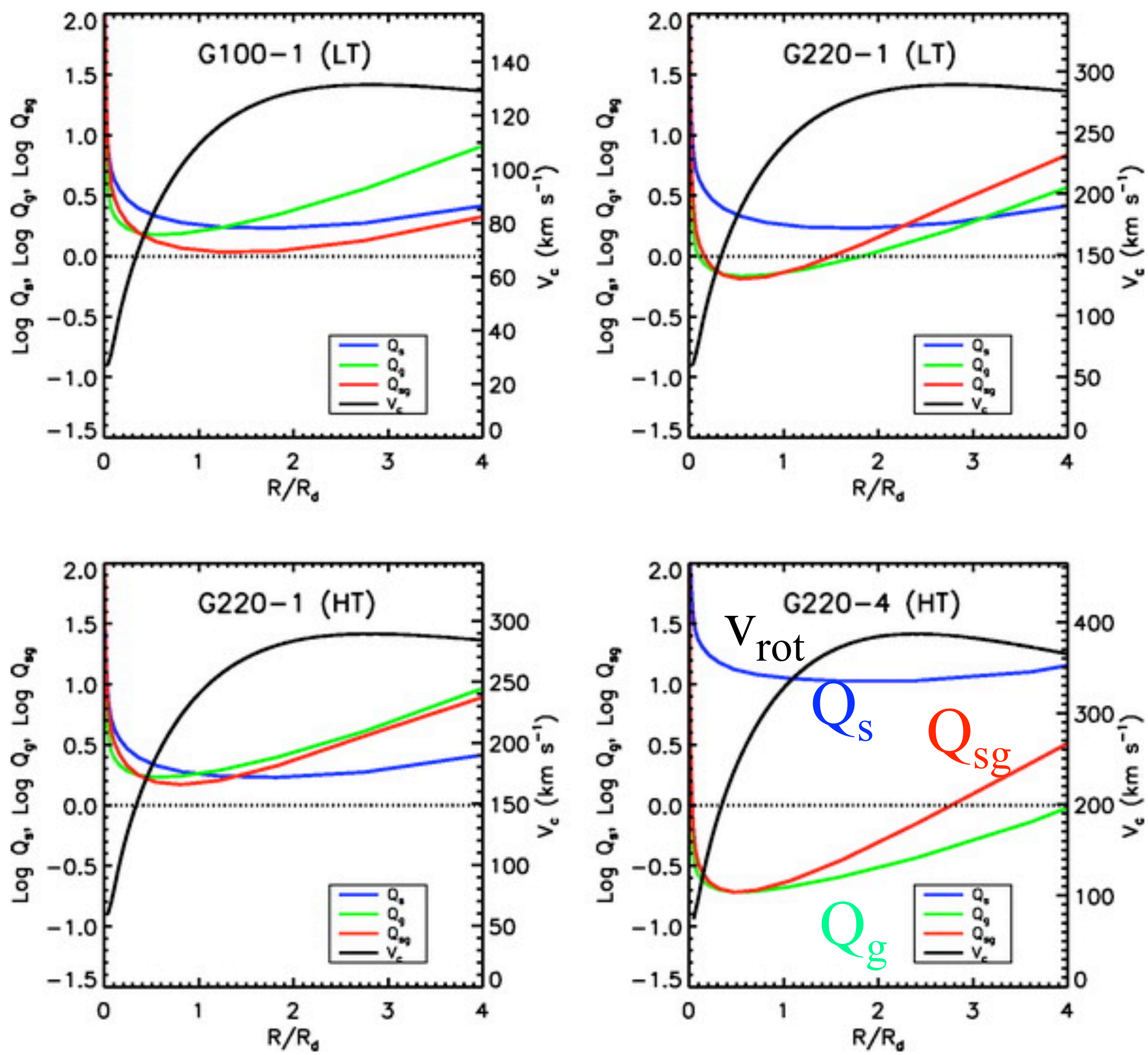
$$\frac{1}{Q_{sg}} = 2\frac{\left[1 - e^{-q^2} I_0\left(q^2\right)\right]}{qQ_s} + \frac{2qR}{Q_g\left(1 + q^2R^2\right)}$$

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

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

Instability when $Q_{sg} < 1$.

Initial Gravitational Instability

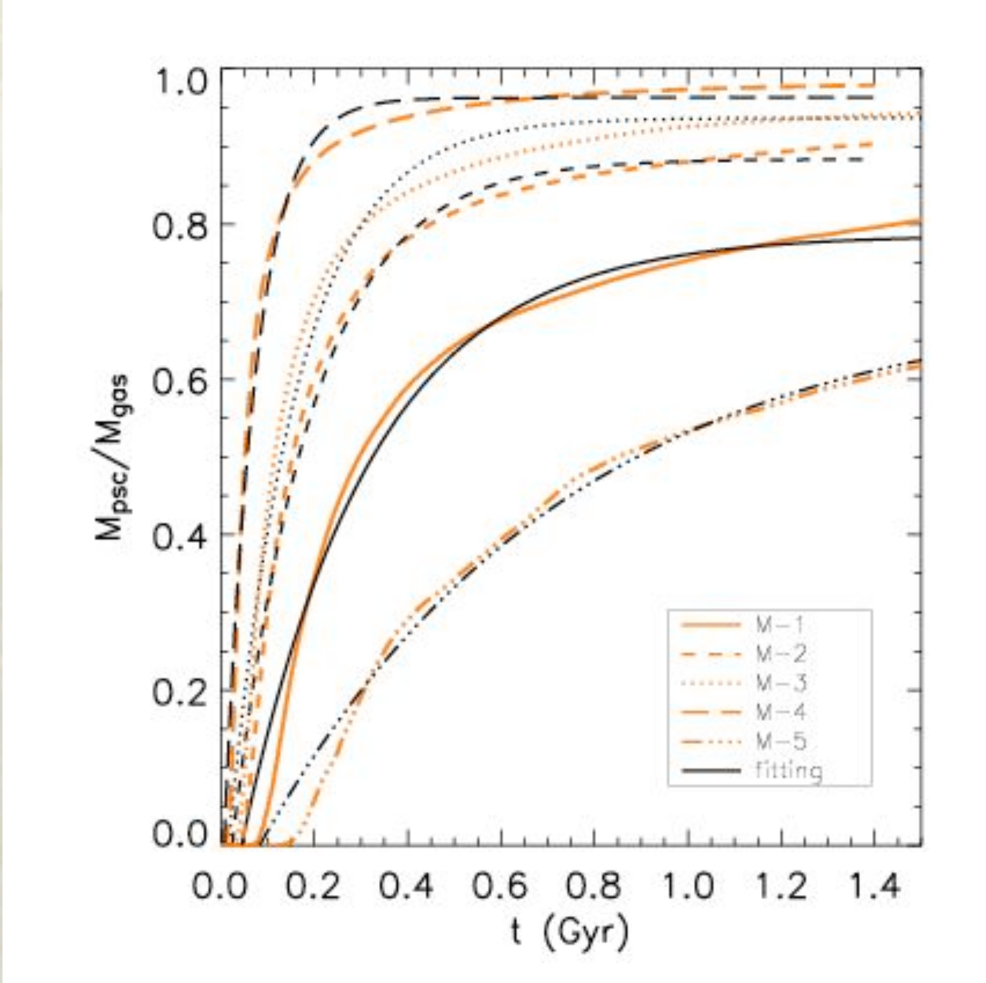


Higher mass
Higher gas frac

More unstable

Li, Mac Low, & Klessen 2005, ApJ

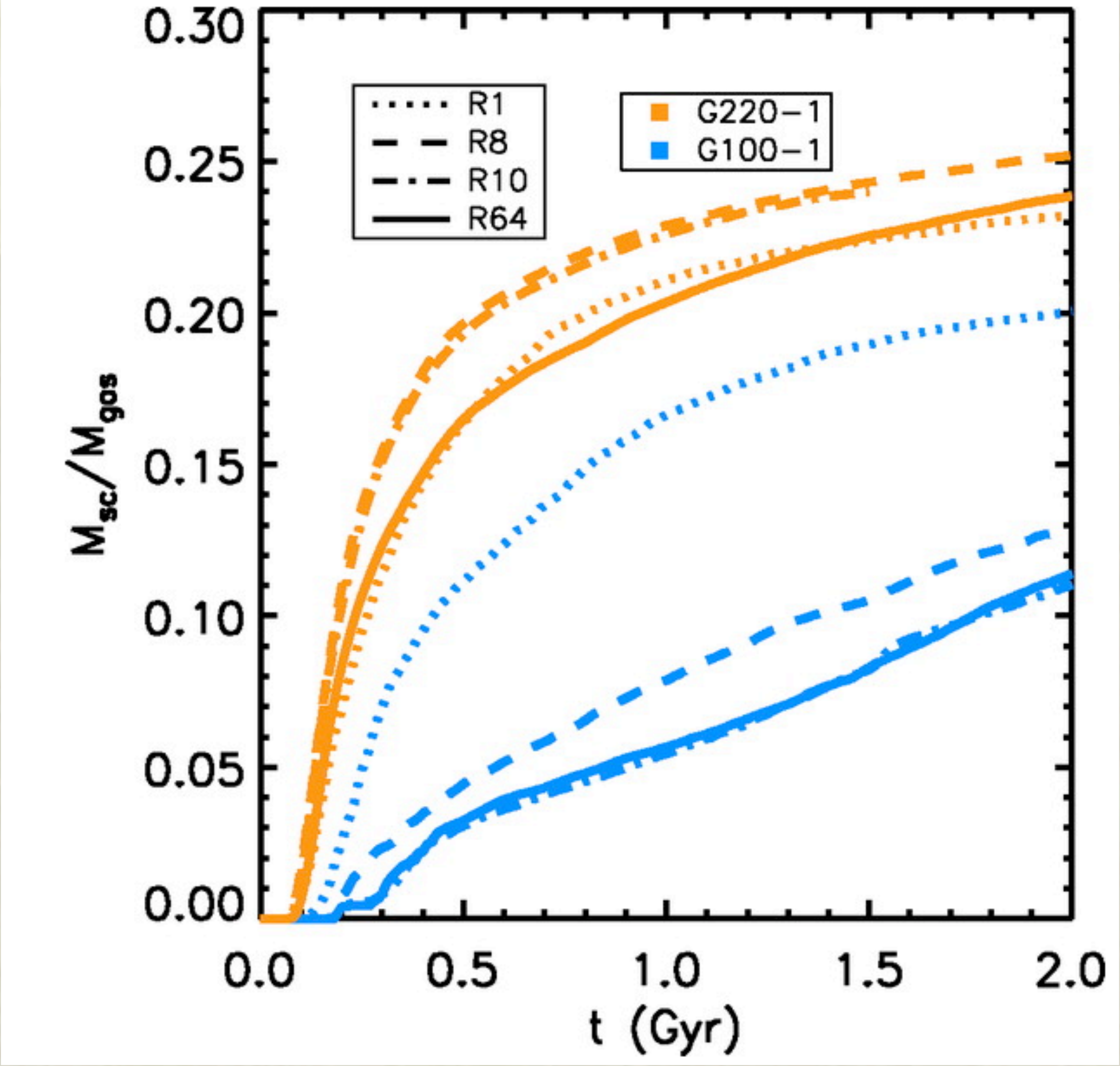
Collapse Timescale



Li, Mac Low, & Klessen 2005, ApJ

$$M_* = M_0\left(1 - \exp\left[-t/\tau_{sf}\right]\right)$$

Resolution Study

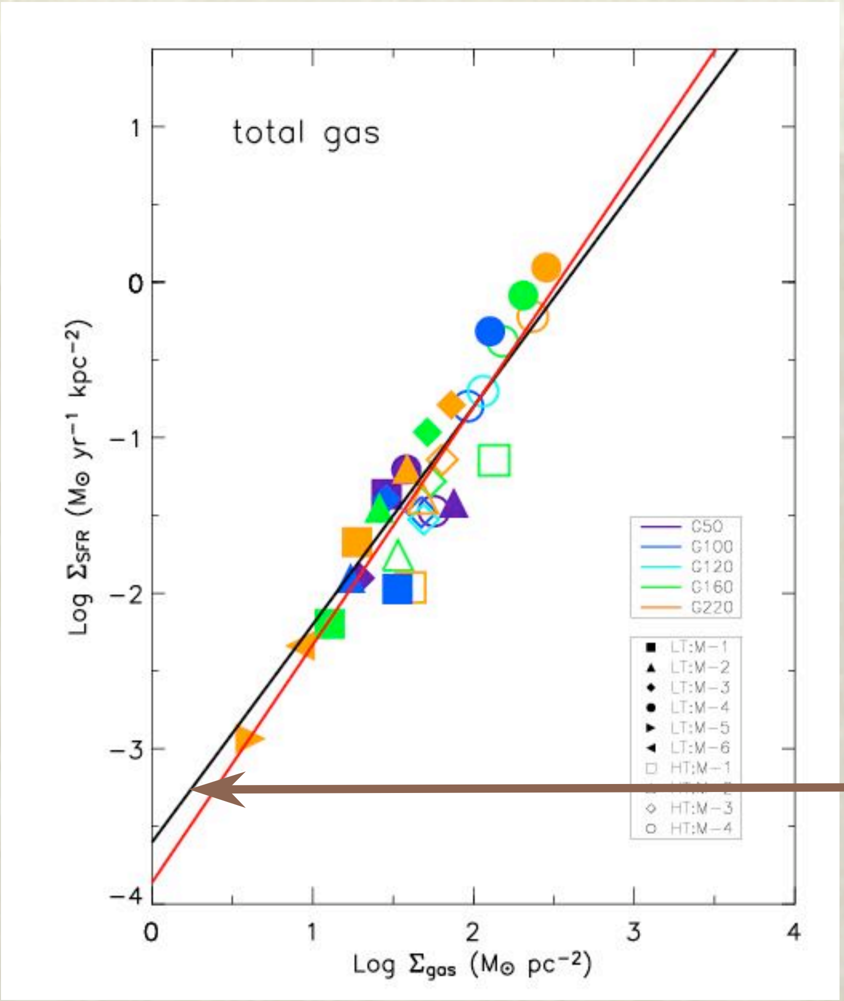


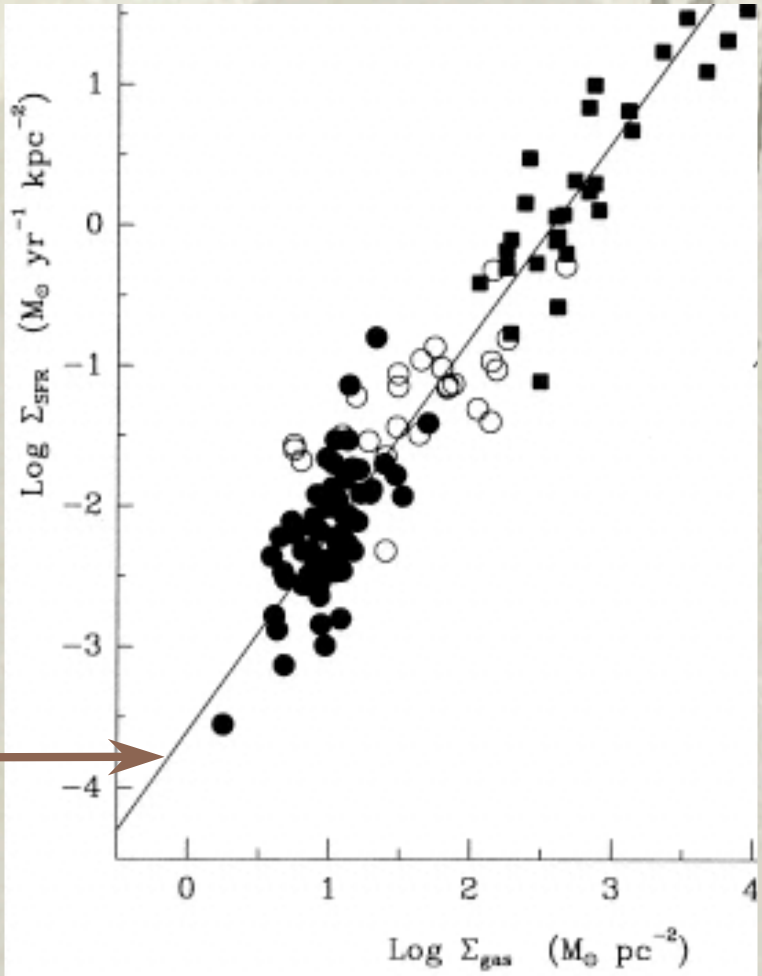
Li, Mac Low, & Klessen 2005, ApJ

Global Schmidt Law

models

observations

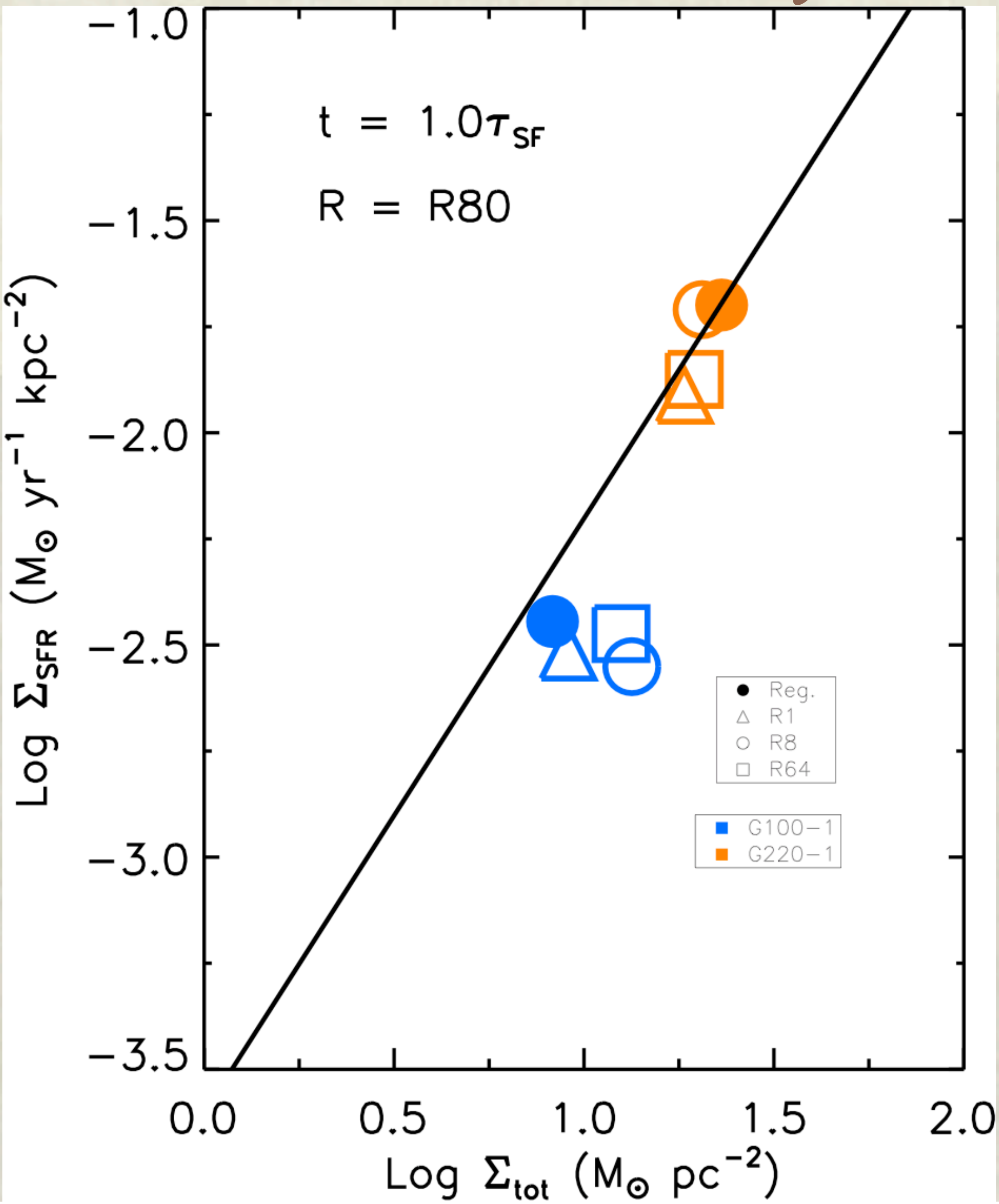




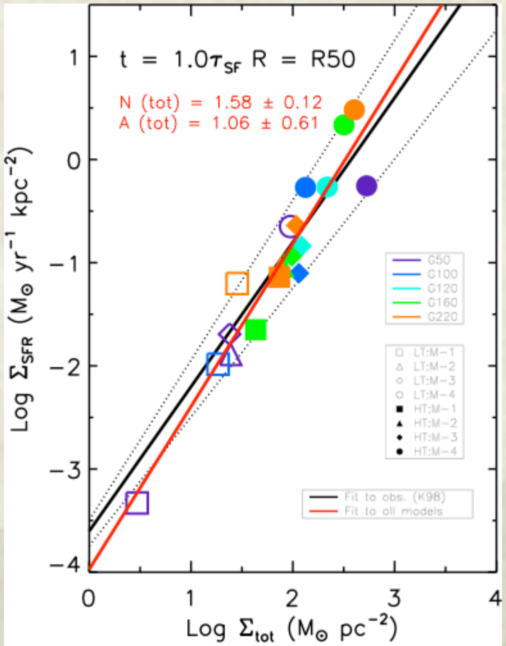
Li, Mac Low, & Klessen 2005, ApJLett, 2006, ApJ

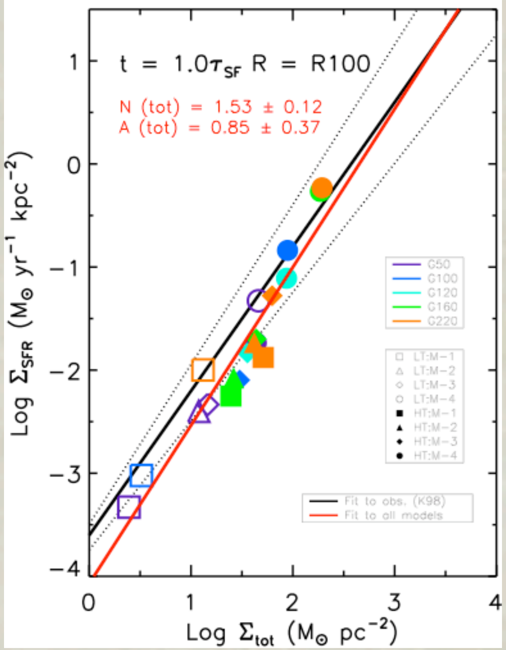
Kennicutt 1998

Resolution Study



Li, Mac Low, & Klessen 2006,





Variations

Observed

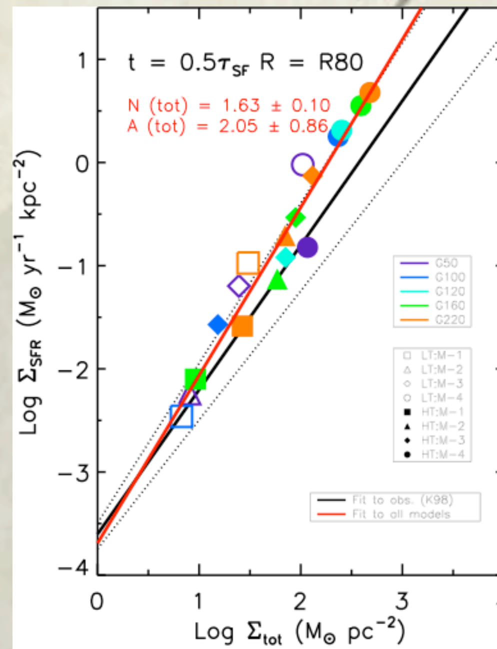
$$\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{gas}}{1\ M_\odot\ \mathrm{pc}^{-2}} \right)^{1.4 \pm 0.15} M_\odot\ \mathrm{year}^{-1}\ \mathrm{kpc}^{-2},$$

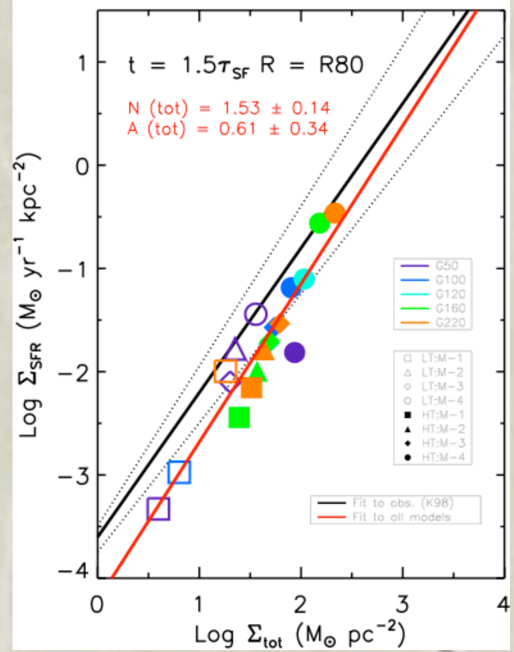
That is,

$A = 2.5 \pm 0.7$
$N = 1.4 \pm 0.15$

Varying SFE:

- $\varepsilon = 0.1 \Rightarrow A = 0.7 \times 10^{-4}$
- $\varepsilon = 0.9 \Rightarrow A = 3.2 \times 10^{-4}$

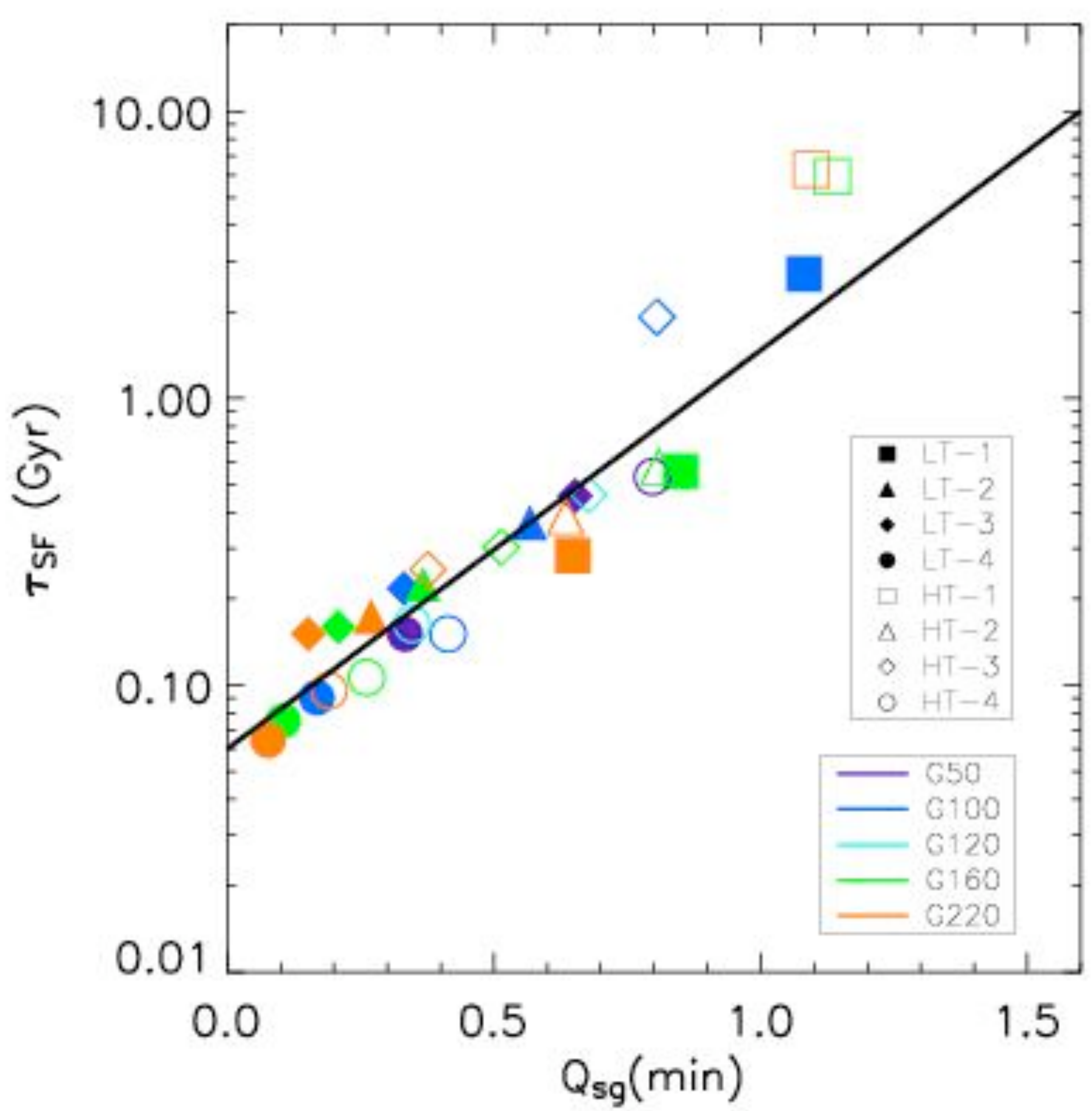




Instability drives SF

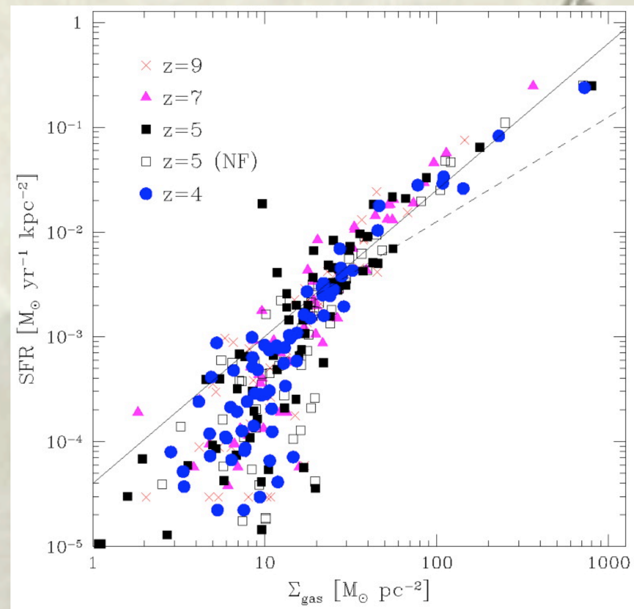
$$\tau_{SF} \propto e^{\alpha Q_{sg}}$$

$$\alpha \simeq 3$$



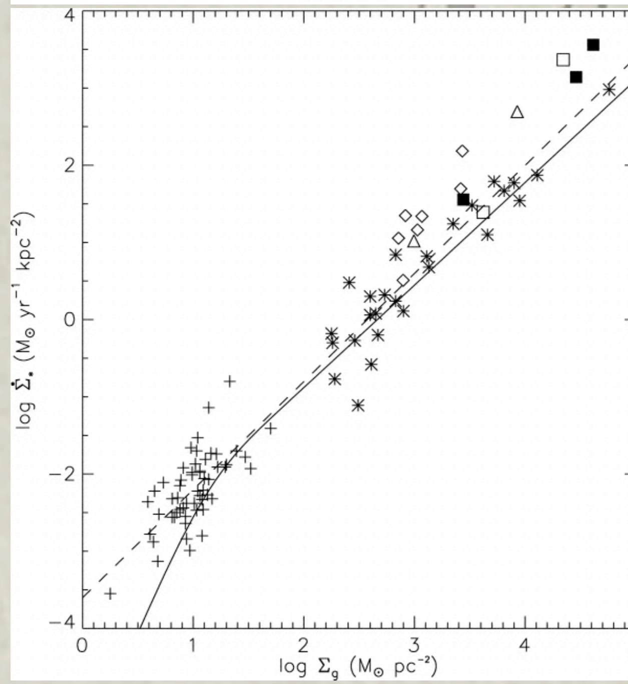
Complementary Derivations

- Kravtsov (2003):
  - Cosmological ICs
  - Star formation law $\dot{\rho}_* \propto \rho_g$
  - Measured SF in many galaxies in one model



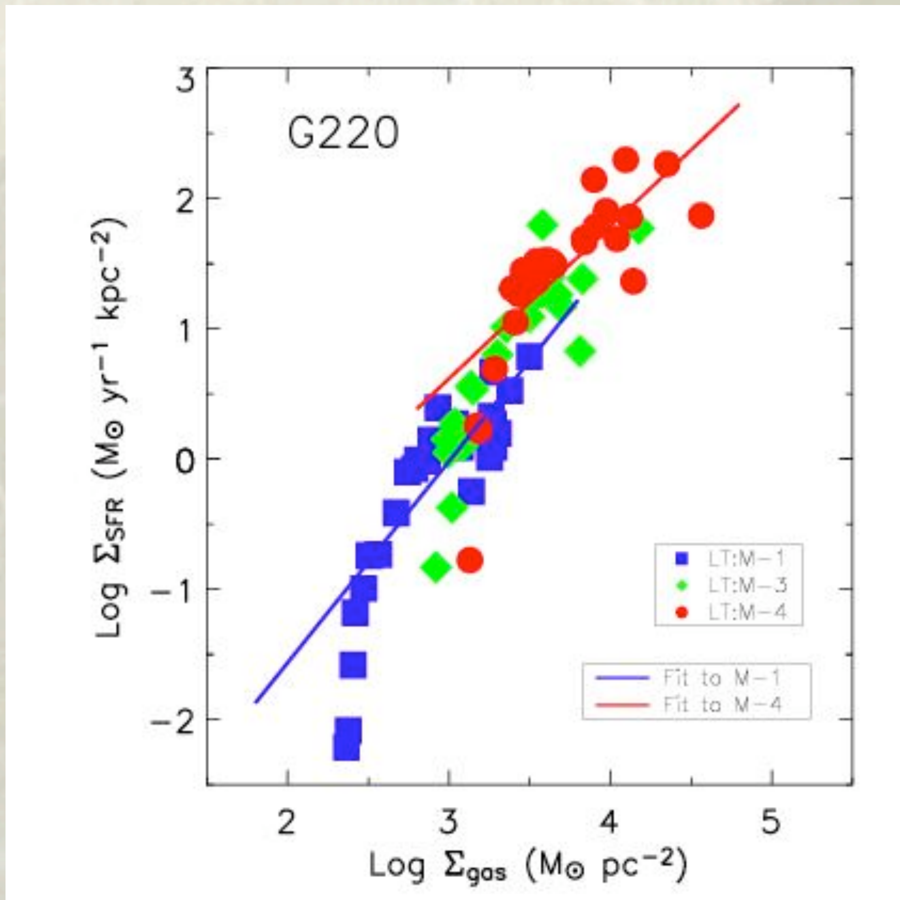
Kravtsov 2003

- Krumholz & McKee (2005):
  - Take observed distribution of GMCs, H II regions as *input*
  - GMCs in virial equilibrium
  - Derive Schmidt law (*solid*) from density PDF of supersonic turbulence (see Padoan & Nordlund)

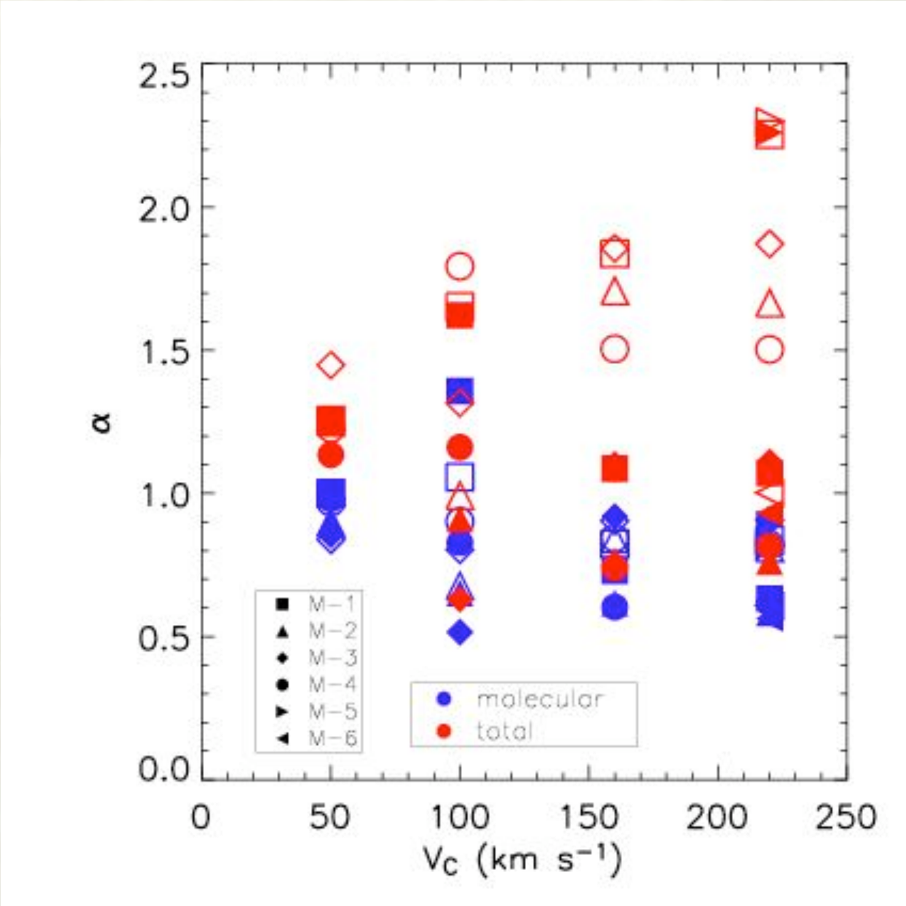


Krumholz & McKee 2006

Local Schmidt Laws

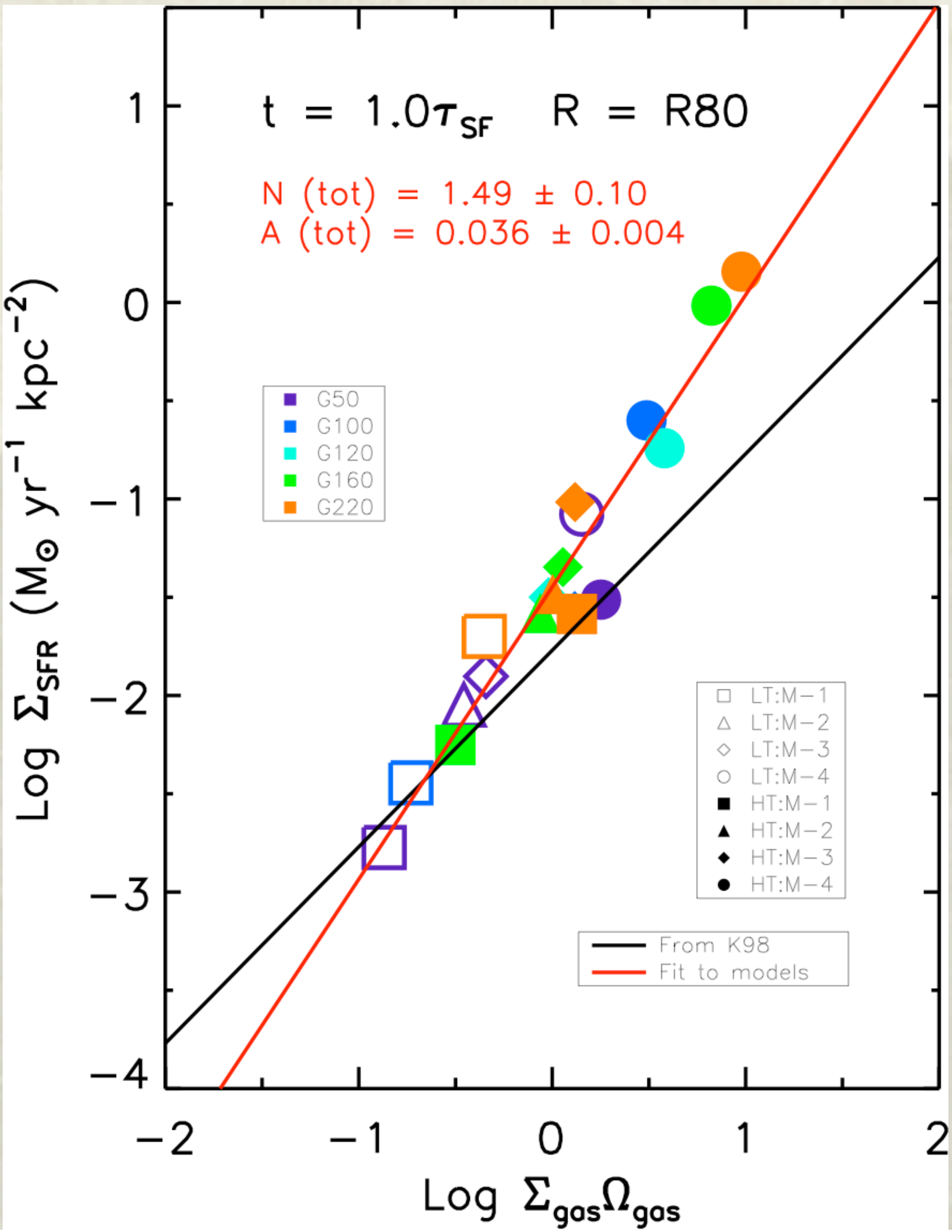


Local Schmidt Law Indices



Wyse-Silk Law disagrees?

Primarily for very gas-rich objects foreign to the local universe, though.



LMC Stability

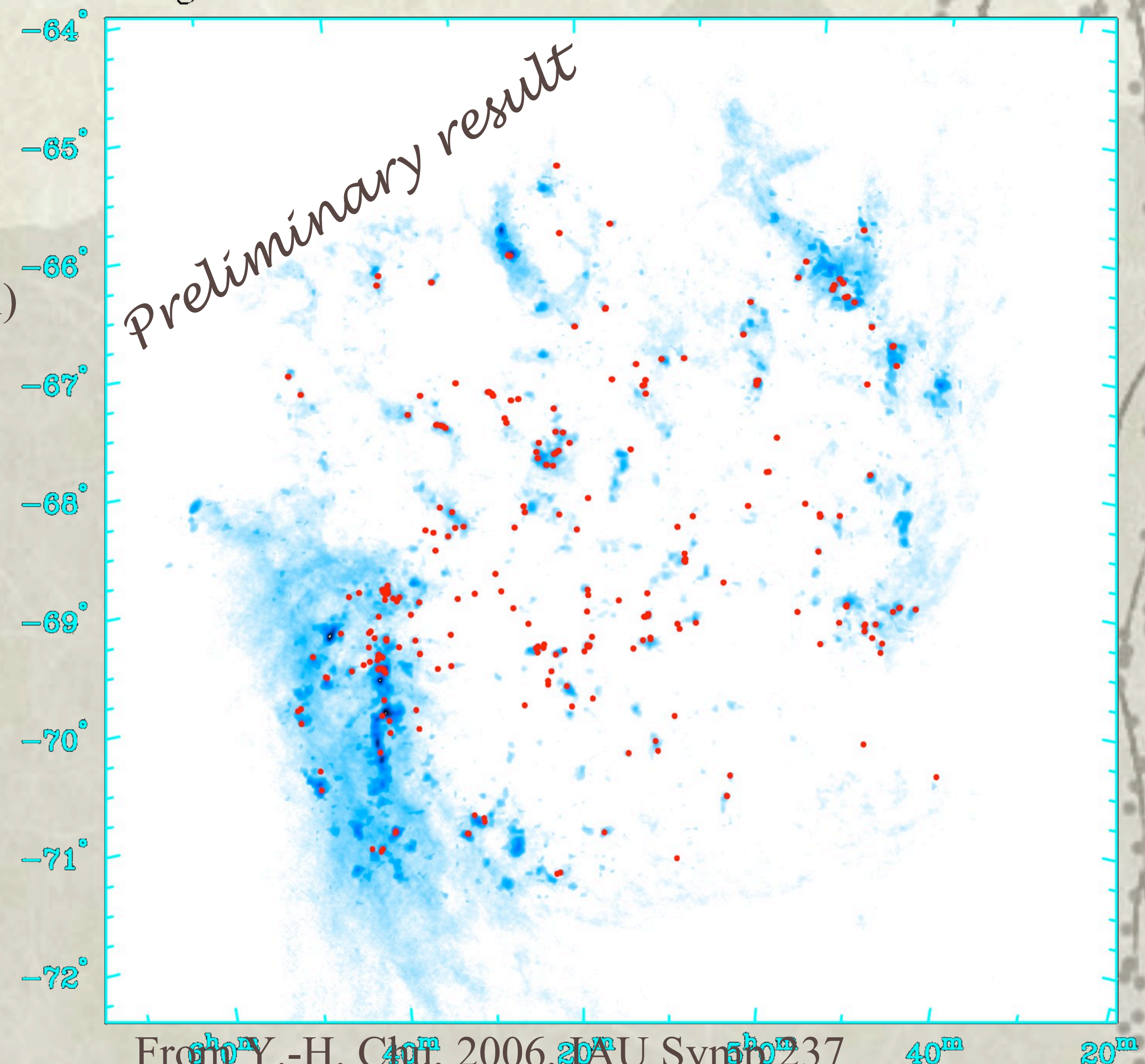
$$Q_g = \frac{\kappa c_g}{\pi G \Sigma_g} < 1 \quad \text{(gas)}$$

Atomic gas: HI (Kim et al)
Molecules: CO (Fukui et al)

YSOs: Spitzer 8 µm

Q_g: blue scale

YSOs: red dots



From Y.-H. Chu, 2006, IAU Symp 237

LMC Stability

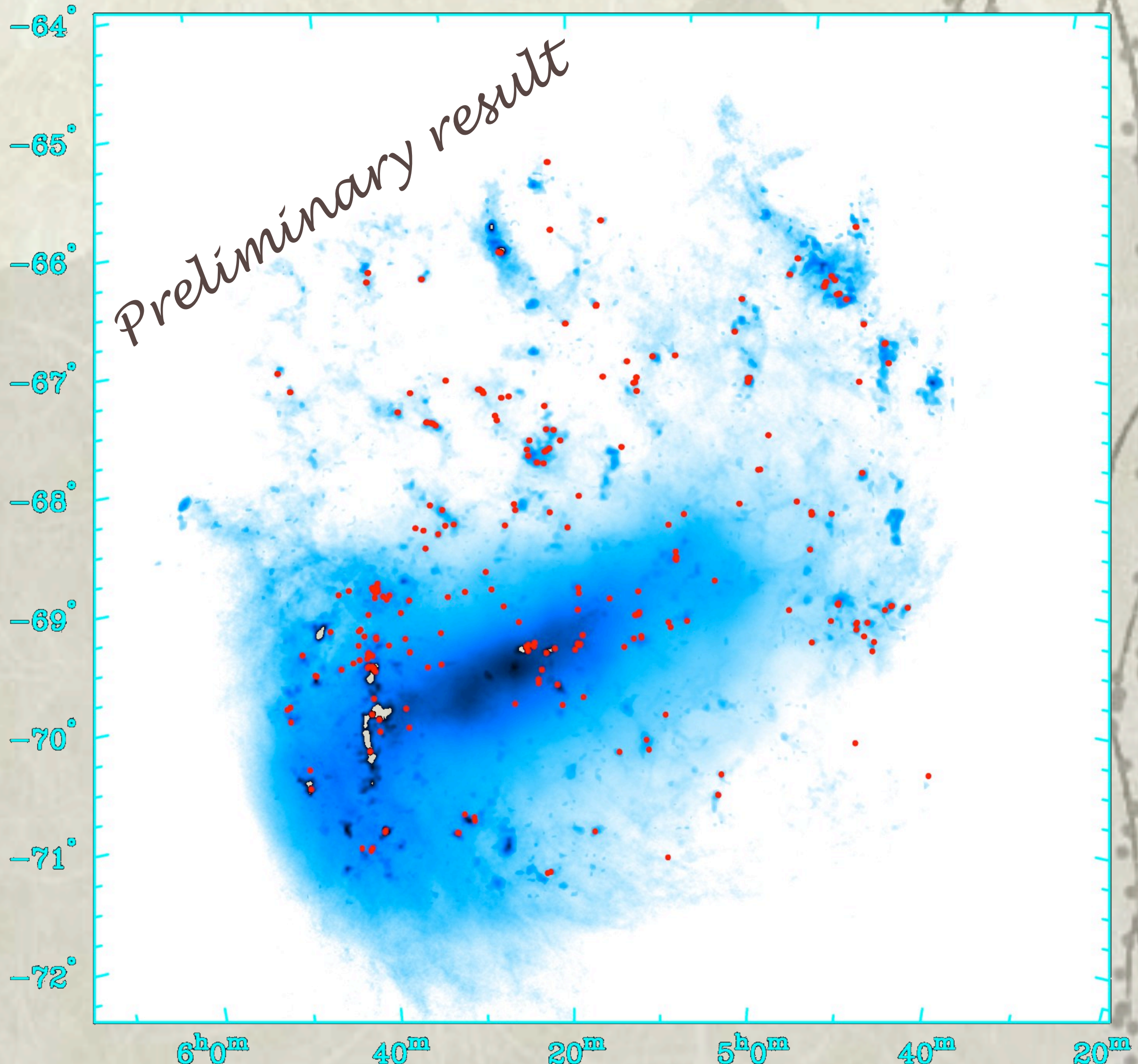
Stars: Spitzer 3 μm
Atomic gas: HI (Kim et al)
Molecules: CO (Fukui et al)

YSOs: Spitzer 8 μm

Q_{sg}: blue scale

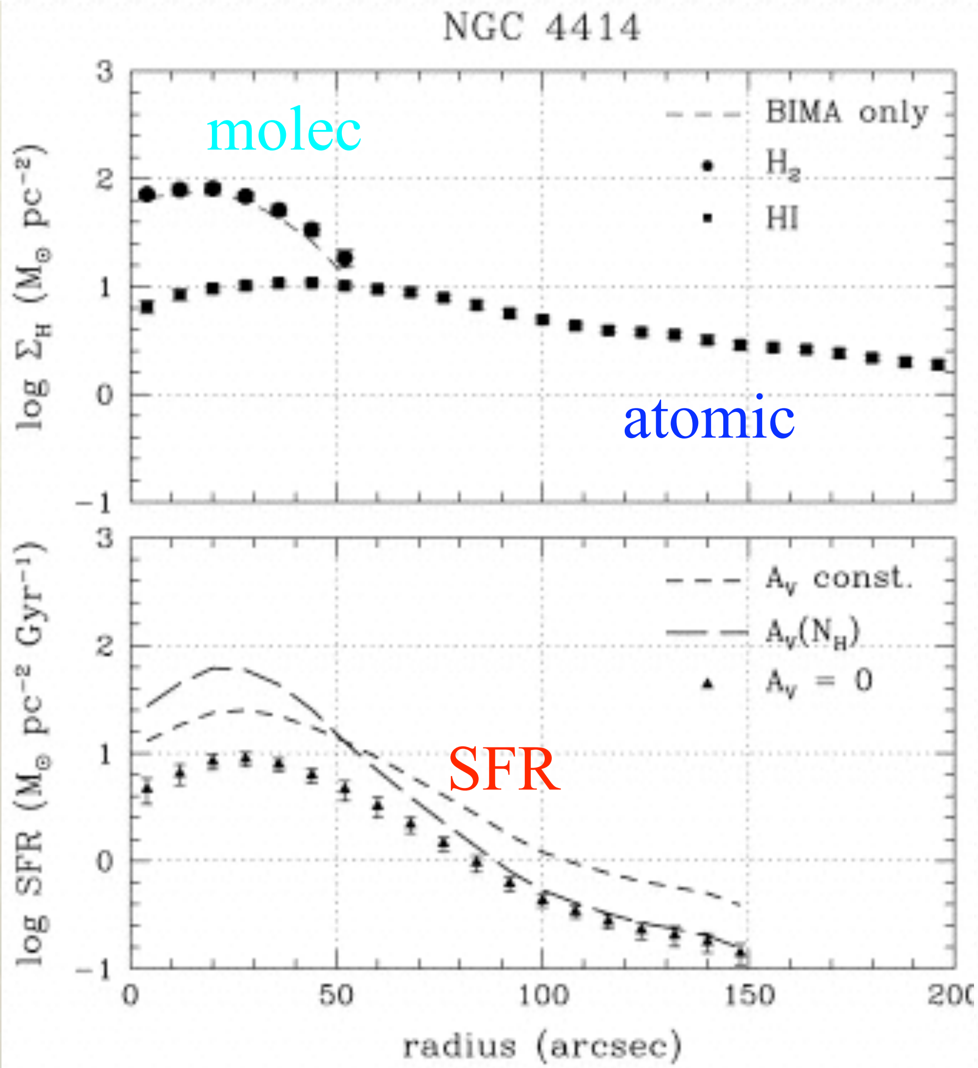
YSOs: red dots

Stars & gas

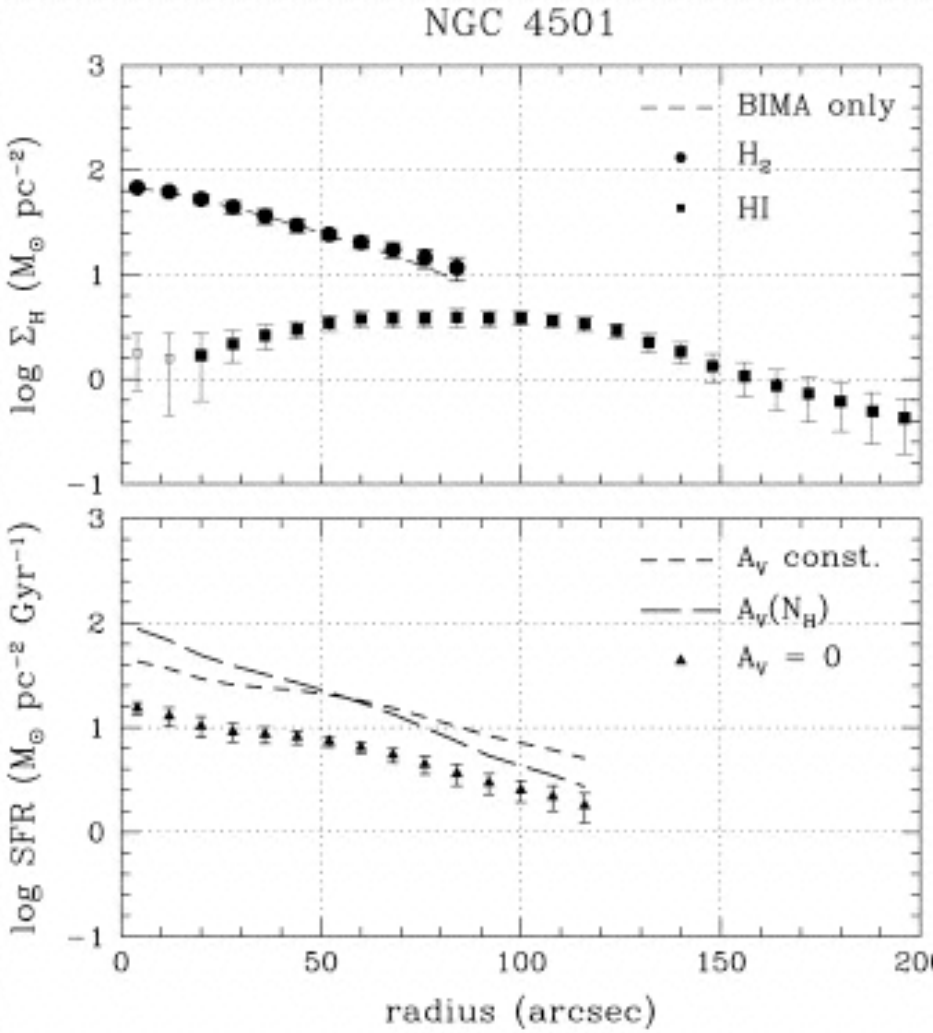


From Y.-H. Chu, 2006, IAU Symp 237

Observed radial distributions of gas



Wong & Blitz 2002

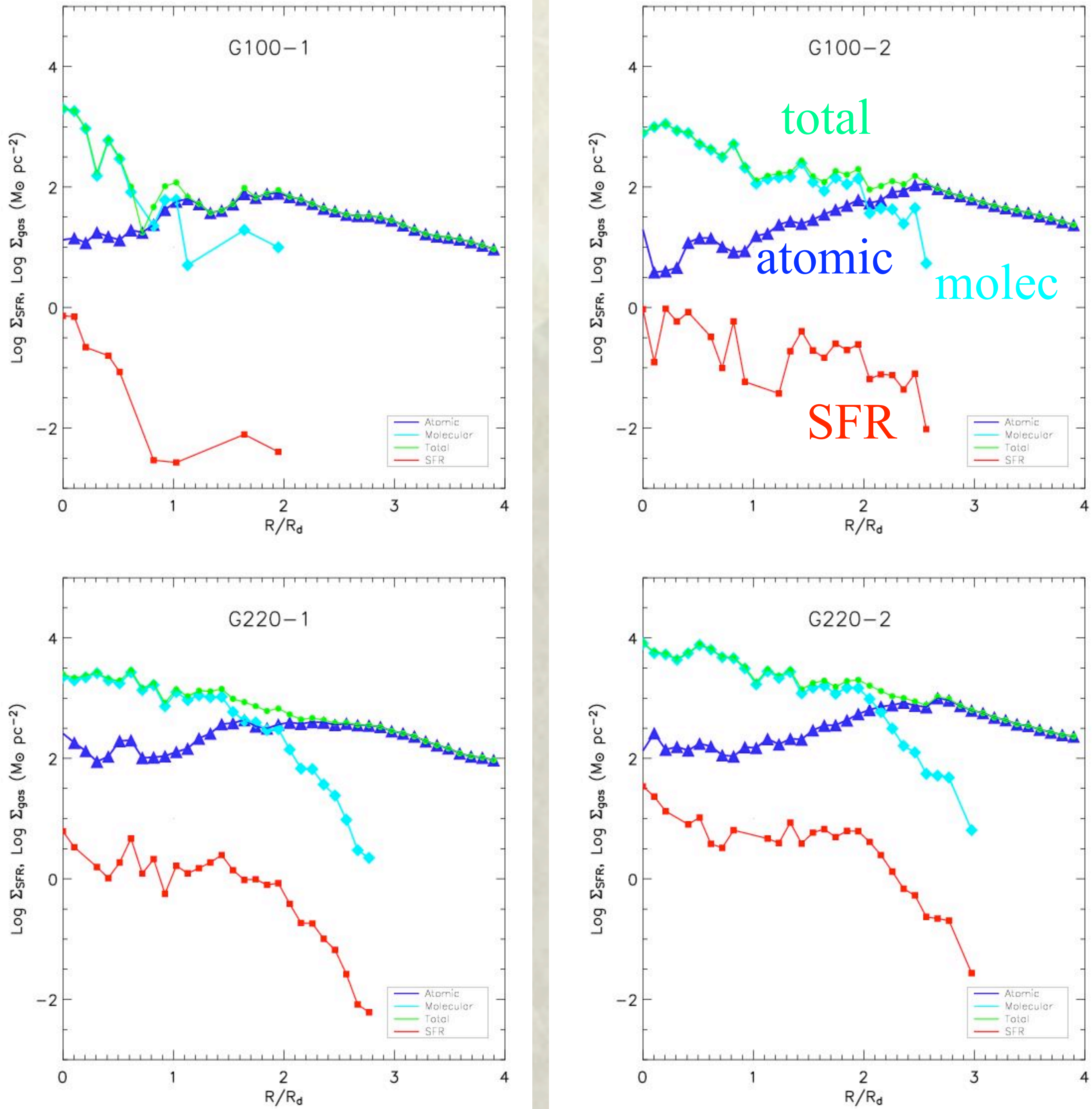


Model distributions, assuming sink particle mass goes

- 30% to stars
- 70% to molecules

Also cf. breaks in stellar profiles seen at threshold (Pohlen & Trujillo 2006, Elmegreen & Hunter 2006)

Li, Mac Low, & Klessen 2006



Conclusions

- Nonlinear development of gravitational instability appears sufficient to explain Kennicutt-Schmidt law.
- However, consistency between our models and the observed behavior of molecular clouds must still be tested.