The Nature of Star Formation in z ~ 2 Galaxy Disks

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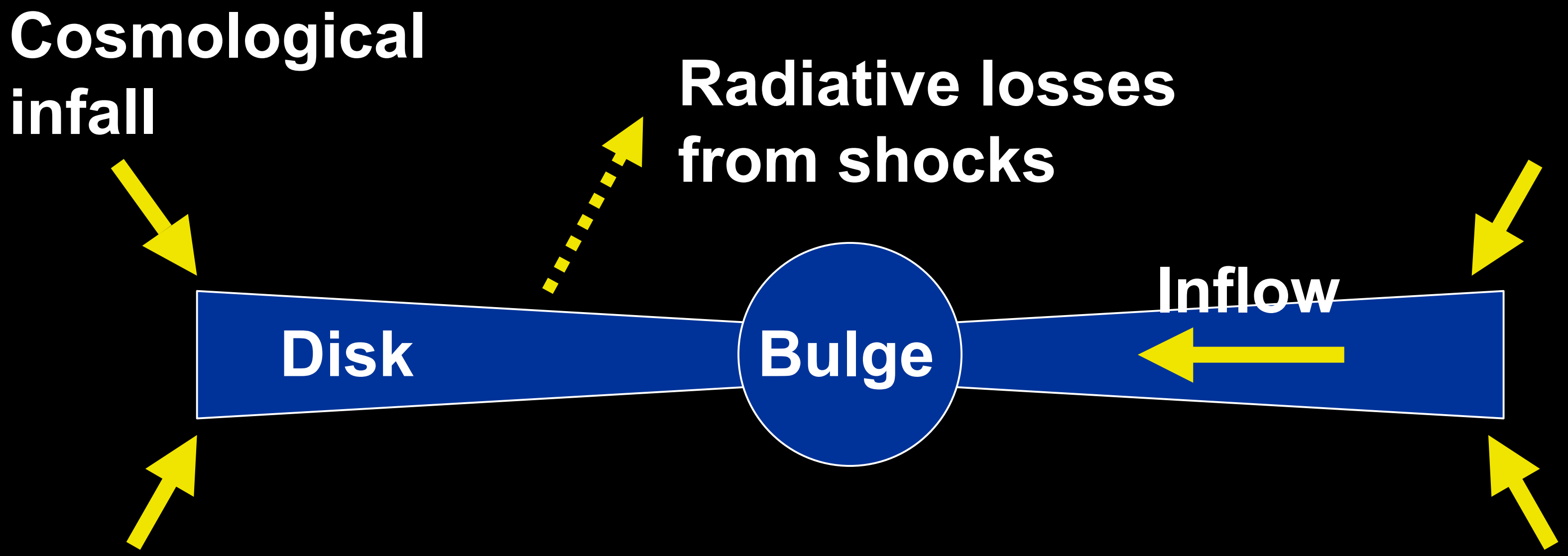
Outline

- Theory of gravitational instability-dominated disks
- Formation of giant clumps and clusters
- Feedback in giant clumps

Why Consider GI in High z Galaxy Disks?

- Observed velocity dispersions are $\sigma \sim 50$ km s^{-1} (e.g. Cresci+ 2009), but SNe unable to drive σ >~ 20 km s^{-1} (Joung & MacLow 2009)
- Turbulence no weaker in outer disks with no SF than in inner disks with SNe
- Accretion rates larger at z ~ 2 by a factor of ~100 $\Rightarrow$ much larger contribution to energy budget

Energy Balance in Q ~ 1 Disks



- Accretion onto disk edge raises surface density (Q ↓)
- Radiative shocks reduce velocity dispersion (Q ↓)
- Gravitational instability transports *j* out, mass in, and generates turbulent motion (Q ↑)
- Gas turns into stars (almost no effect on Q)

Formal System

(Krumholz & Burkert 2010)

[illegible]

$$\frac{\partial}{\partial t}\Sigma + \frac{1}{r}\frac{\partial}{\partial r}(r\Sigma v_r) \quad = \quad -\dot{\Sigma}_*$$

Continuity

$$\Sigma\left(\frac{\partial j}{\partial t} + v_r\frac{\partial}{\partial r}j\right) \quad = \quad \frac{1}{2\pi r}\frac{\partial}{\partial r}\mathcal{T}$$

Angular momentum

$$\frac{1}{2}\Sigma\left[\frac{\partial}{\partial t}\left(v_\phi^2 + 3\sigma^2\right) + v_r\frac{\partial}{\partial r}\left(v_\phi^2 + 3\sigma^2 + 2\psi\right)\right]$$

$$+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Sigma v_r\sigma^2\right) \quad = \quad \frac{1}{2\pi r}\frac{\partial}{\partial r}(\Omega\mathcal{T}) - \mathcal{L},$$

Energy

$$\frac{\partial}{\partial t}\left[\frac{\kappa\sigma}{\pi G(\Sigma + \Sigma_*)}\right] \quad = \quad 0$$

Marginal stability

Marginal stability equation determines $\mathcal{T}$, which in turn determines evolution of all other quantities

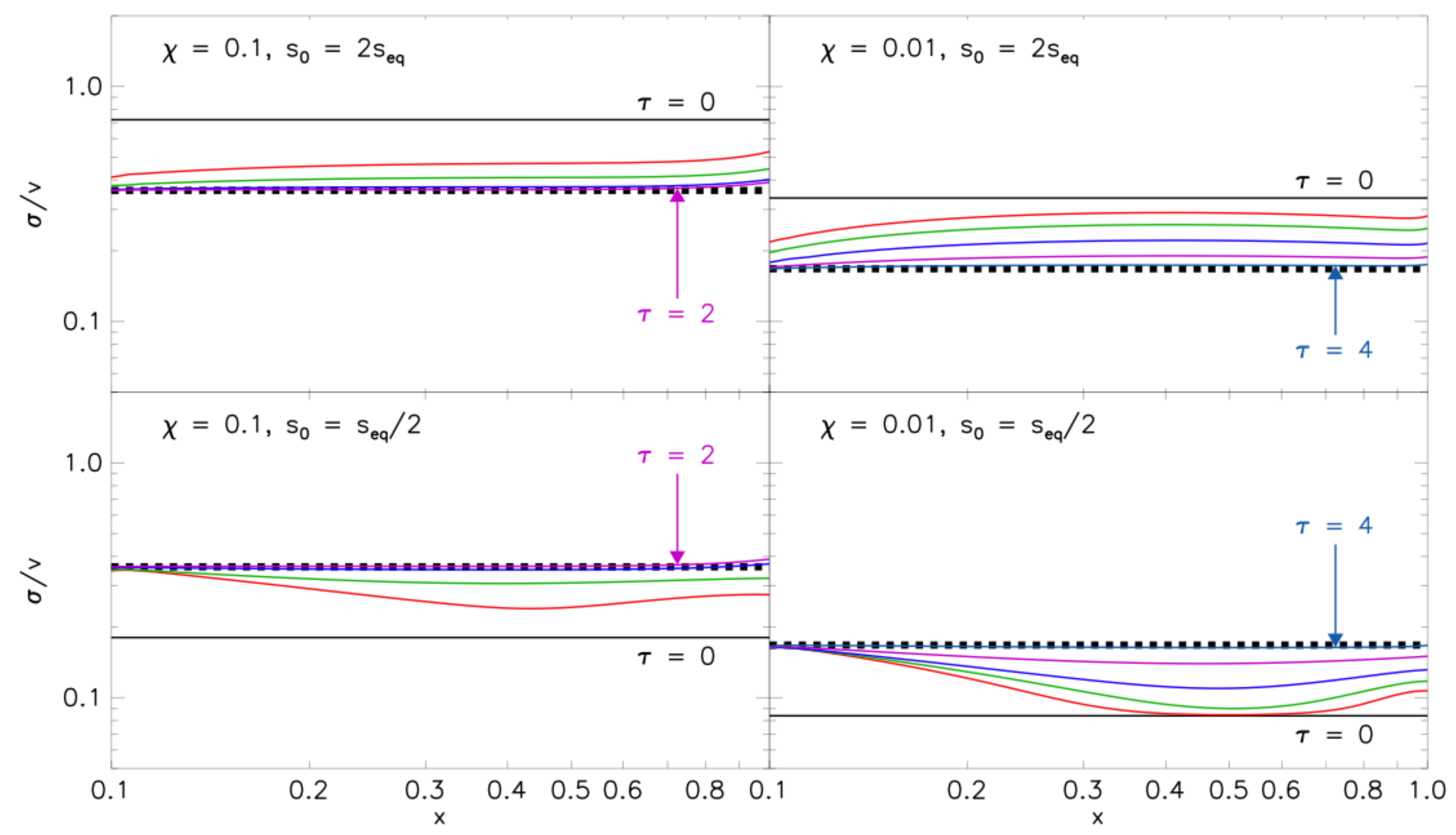
Steady State Disks

- For powerlaw rotation curves, family of steady-state solutions exists
- Solution depends on gas fraction and accretion rate; for flat rotation curve:

$$\sigma = \frac{1}{\sqrt{2}}\left(\frac{3G\dot{M}_{\mathrm{ext}}}{2f_g}\right)^{1/3}$$

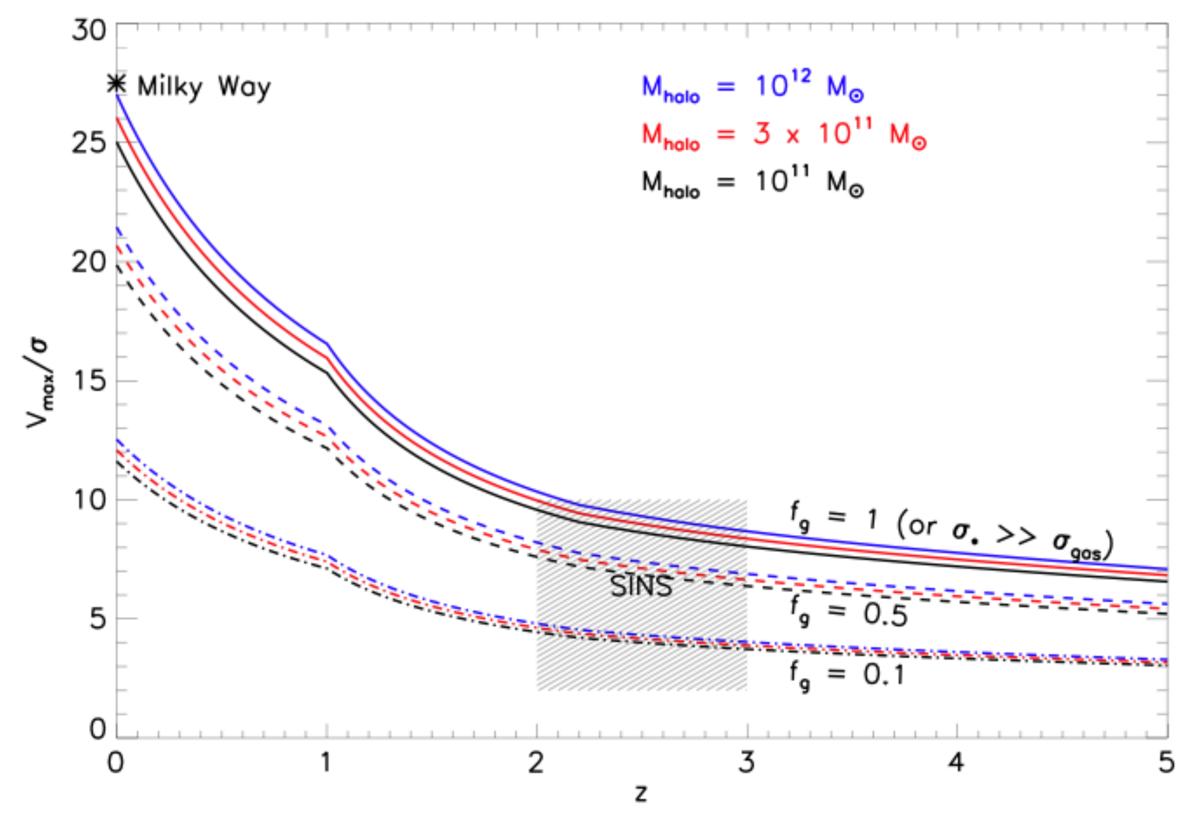
- Velocity dispersion set by accretion rate and gas fraction only, and gas fraction relevant only if $\sigma_* \approx \sigma_{\text{gas}}$

Non-Steady GI Disks



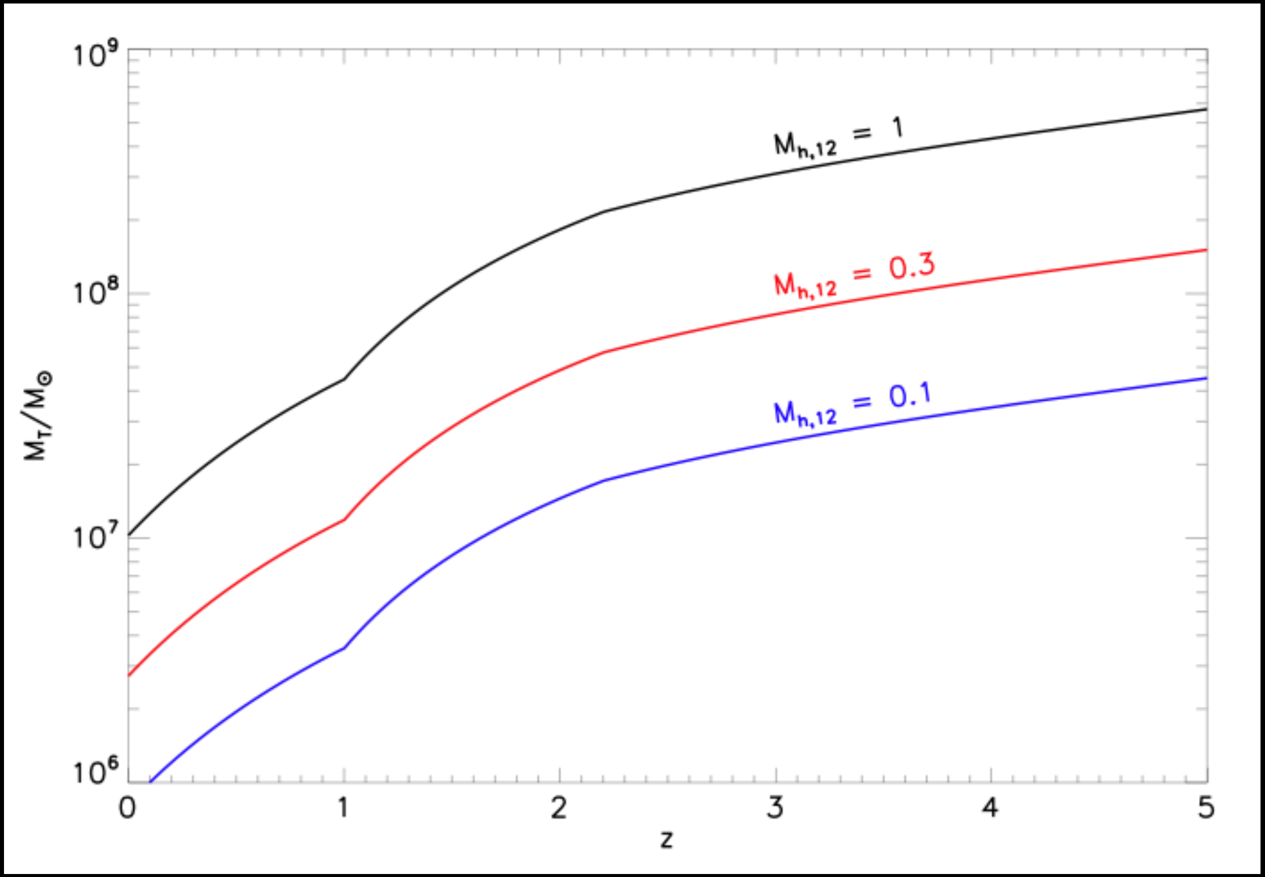
Numerical result: disks out of steady state evolve into the steady state solution in ~1 viscous time

Evolution of Velocity Dispersions with z



From typical accretion rate as a function of halo mass and z (Bouche+ 2009), we can compute v/σ

Evolution of Toomre Mass



Toomre mass $M_T = \sigma^4 / G^2\Sigma \Rightarrow$ higher accretion rate at high z produces higher σ, higher $M_T \Rightarrow$ giant clumps

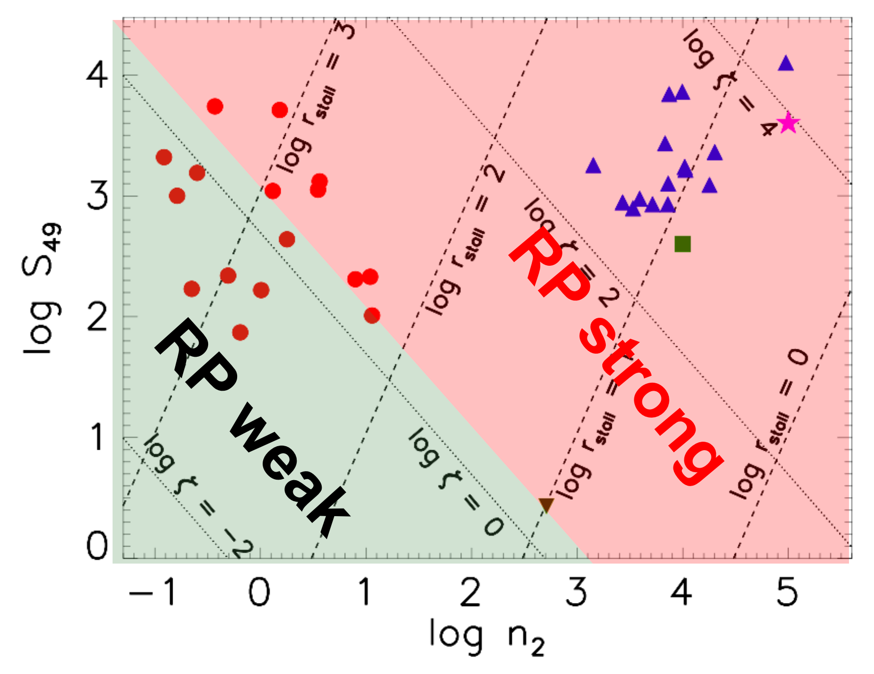
Feedback in Giant Clumps

(Krumholz & Dekel 2010)

- Supernovae insufficient to disrupt ~10^9 $M_\odot$ clumps (Dekel+ 2009)
- Winds, ionized gas unable to produce σ ~ 20 km s^{-1} needed for virial balance
- Fraction of GC mass turned into stars determined by stellar radiation pressure (Krumholz & Matzner 2009; Murray, Quataert, & Thompson 2009; Fall, Krumholz, & Matzner 2010)

When is Radiation Pressure Important?

(Krumholz & Matzner 2009)



Importance of RP in clusters in M82 (blue), Antennae (red), Orion (brown), Arches (green)

- RP force >> gas pressure force when

$$\zeta = 6.2 \times 10^{-2} n_2^{2/3} S_{49}^{2/3} \gg 1$$

- RP-driven expansion stalls at radius

$$r_{\rm st} = 8.9 n_2^{-1/2} S_{49}^{1/4} \ {\rm pc}$$

- Ex. R136: $n_2 \sim 10^3$, $S_{49} \sim 10^2 \Rightarrow \zeta \sim 100$, $r_{st} \sim 1$ pc

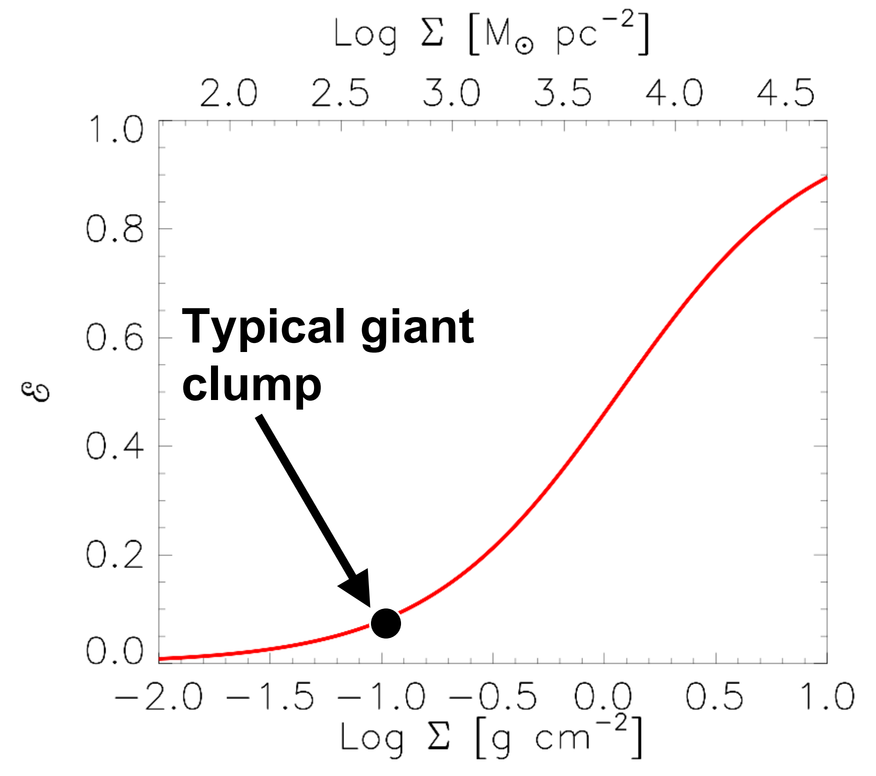
Star Formation Efficiency from Radiation Pressure

(Fall, Krumholz, & Matzner 2010)

- As SF proceeds and SFE rises, S_{49} rises, n_2 drops, r_{st} rises
- When $r_{st} > R_{cl}$, mass is ejected
- Result:

$$\mathcal{E} = \frac{\Sigma}{\Sigma + \Sigma_{\rm crit}}$$

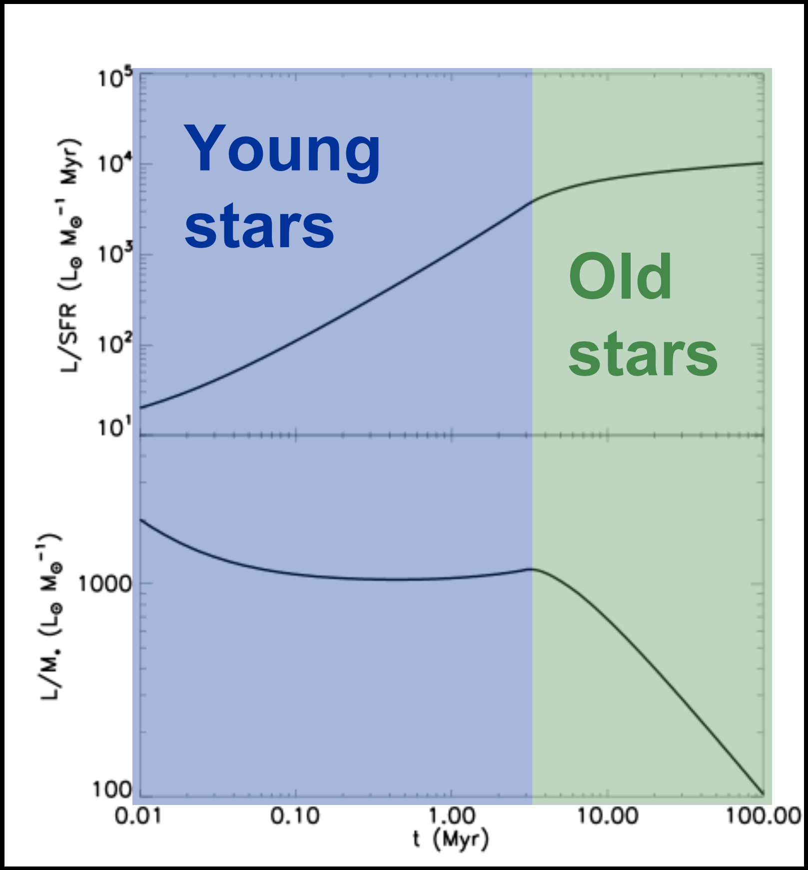
$$\Sigma_{\rm crit} \approx \frac{10\langle L/M_* \rangle}{3\pi G c}$$



SFE vs. Σ, computed using RP feed-back for the <L/M*> value for a zero age stellar population

Old Stars, Young Stars

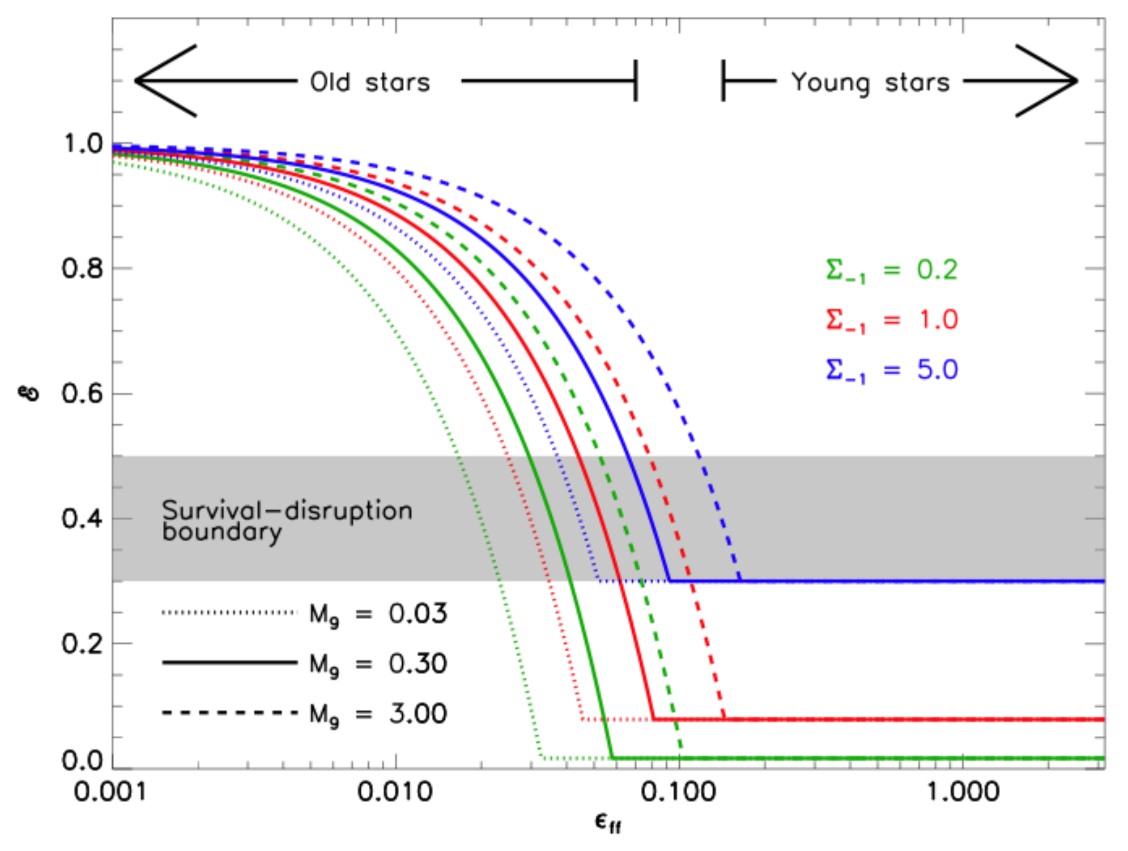
- $<L/M_*>$ ~ constant for ~3 Myr, then declines
- $<L/SFR>$ ~ rises for ~3 Myr, then remains constant
- In a giant clump, t_{cr} ~ 15 Myr ⇒ $<L/SFR>$ constant, $<L/M_*>$ declining: old stars limit; not like modern SF



$<L/SFR>$ and $<L/M_*>$ vs. time since onset of SF (Krumholz & Tan 2007)

Efficiency vs. SFR

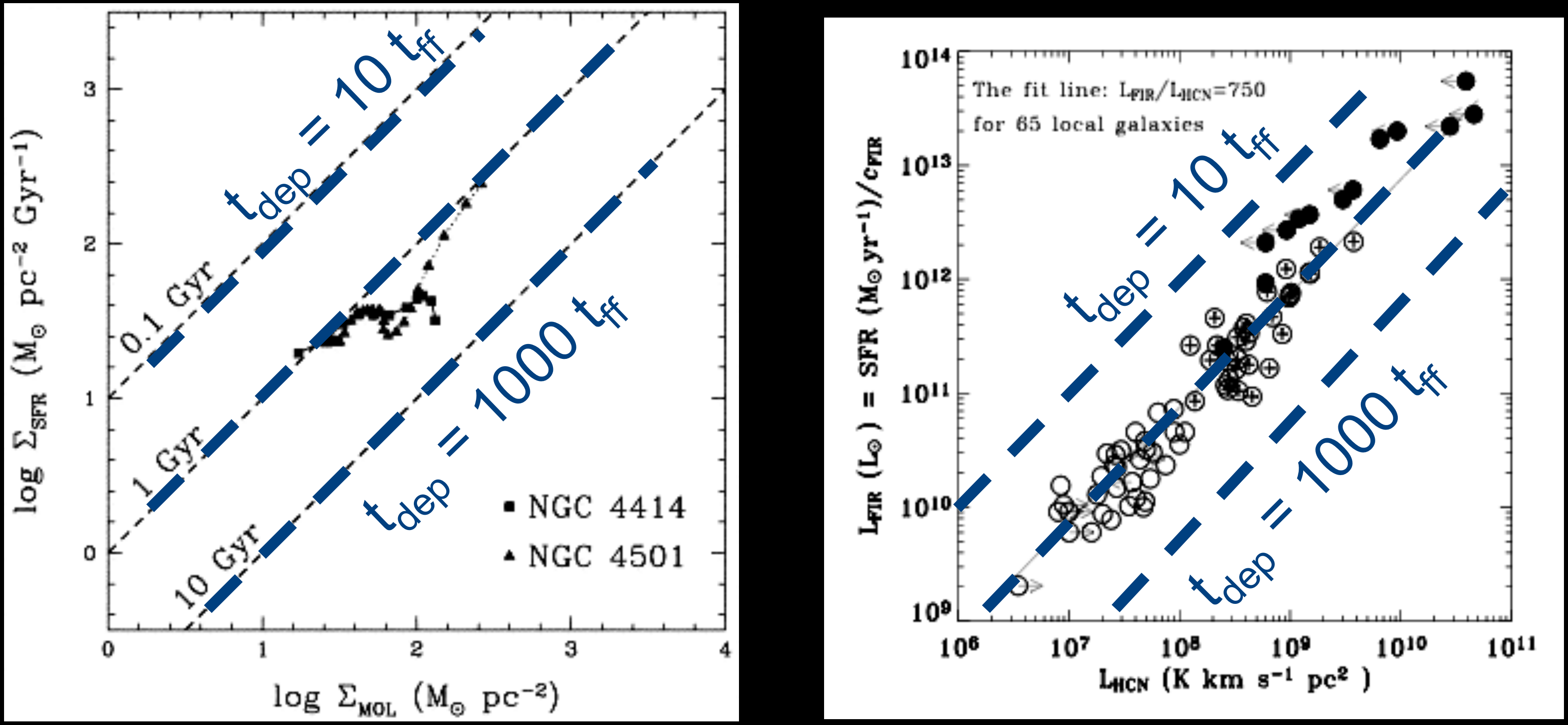
(Krumholz & Dekel 2010)



- $\mathcal{E}$ depends on $\langle L/M_* \rangle \propto$ SFR/M_* in old stars limit
- Low $\mathcal{E}$ and disruption likely only for large values of

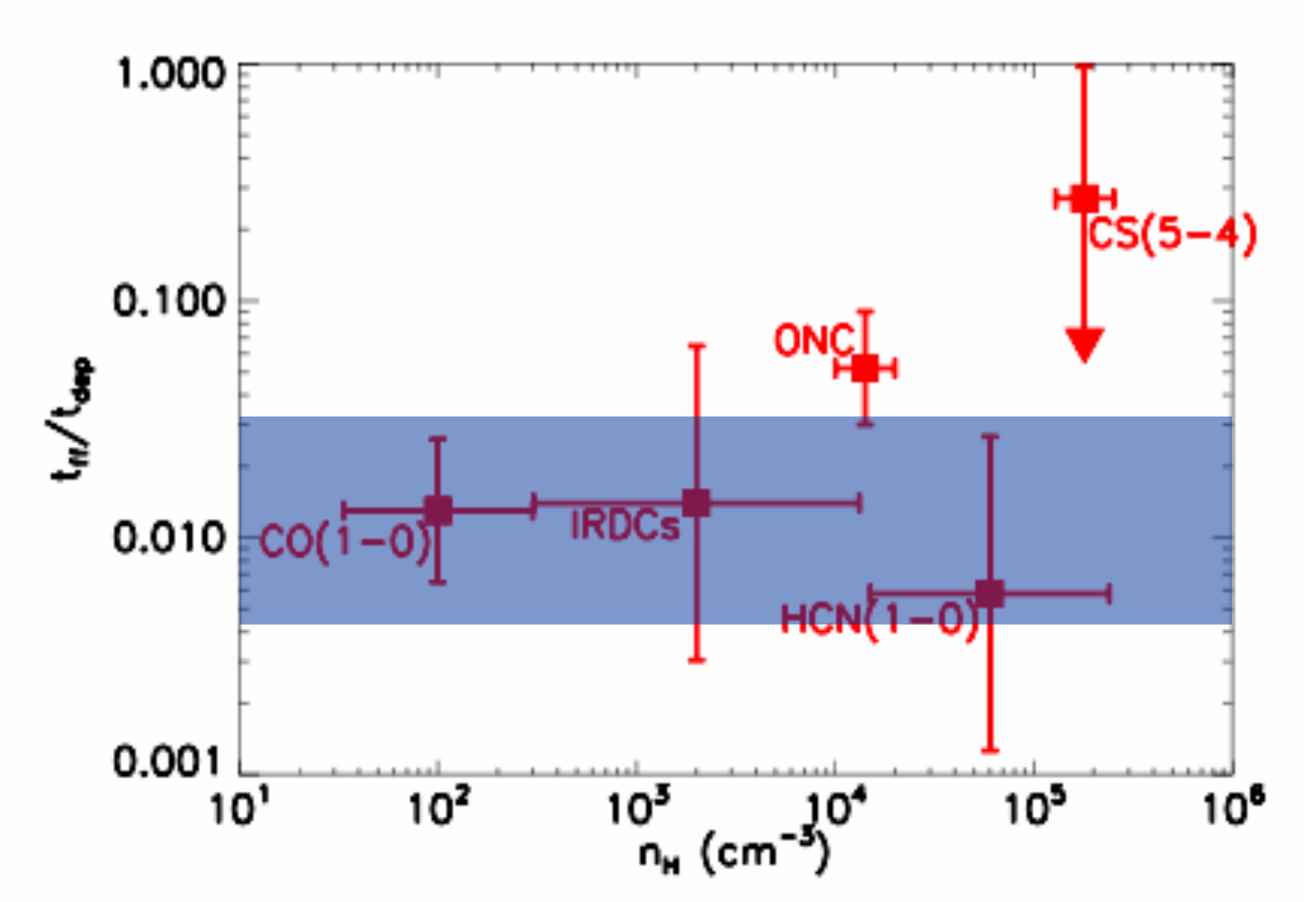
$$\epsilon_{\rm ff} \equiv \frac{\dot{M}_*}{M_{\rm gas}/t_{\rm ff}}$$

Measuring ε_{ff}



Depletion time as a function of Σ_{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 (right, Gao & Solomon 2004, Gao et al. 2007)

Observed Value of ε_{ff}

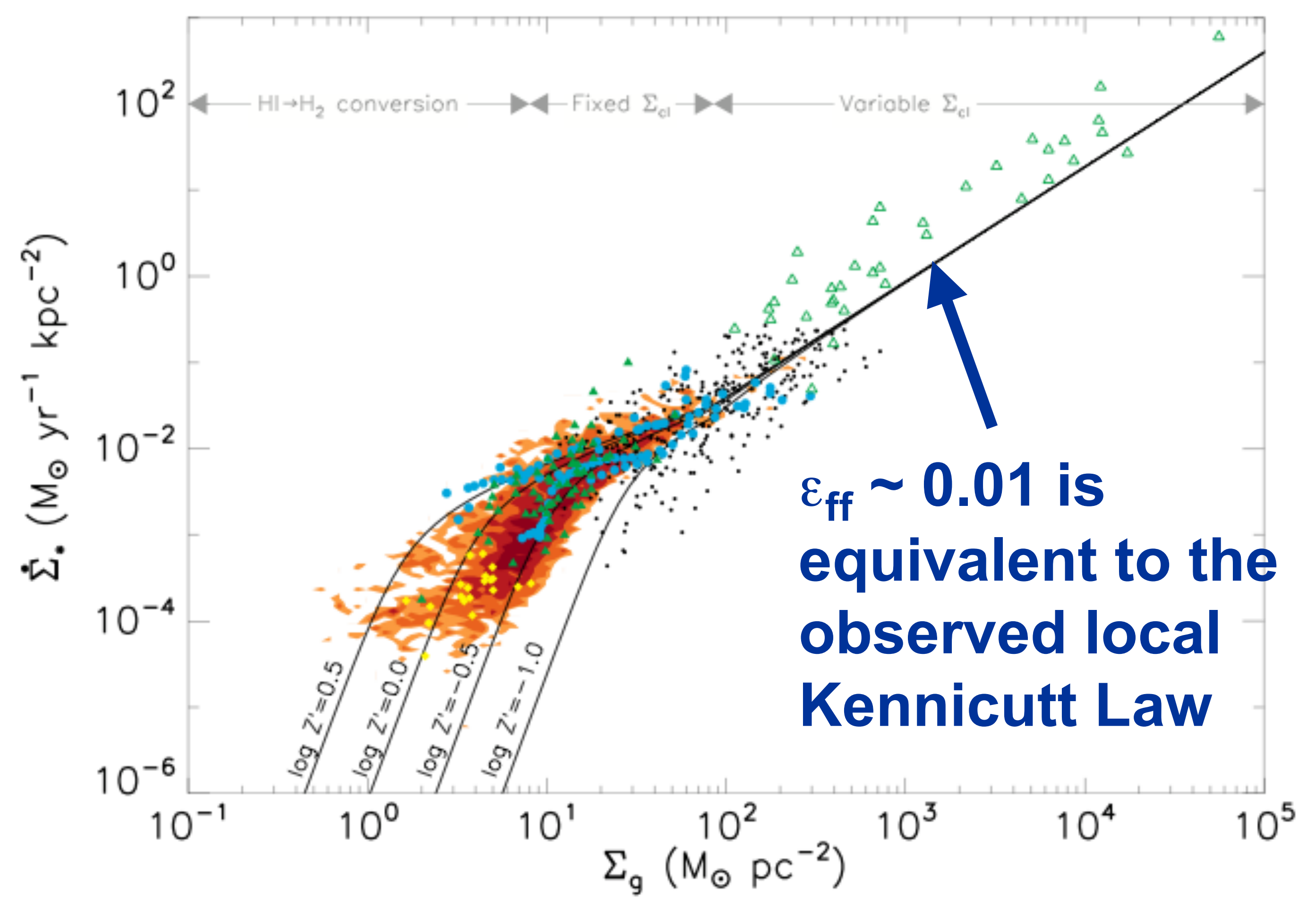


Clouds convert ε_{ff} ~1% of their mass to stars per t_{ff}, regardless of density or environment

(Tan, Krumholz, & McKee 2006; Krumholz & Tan 2007; Evans et al. 2009)

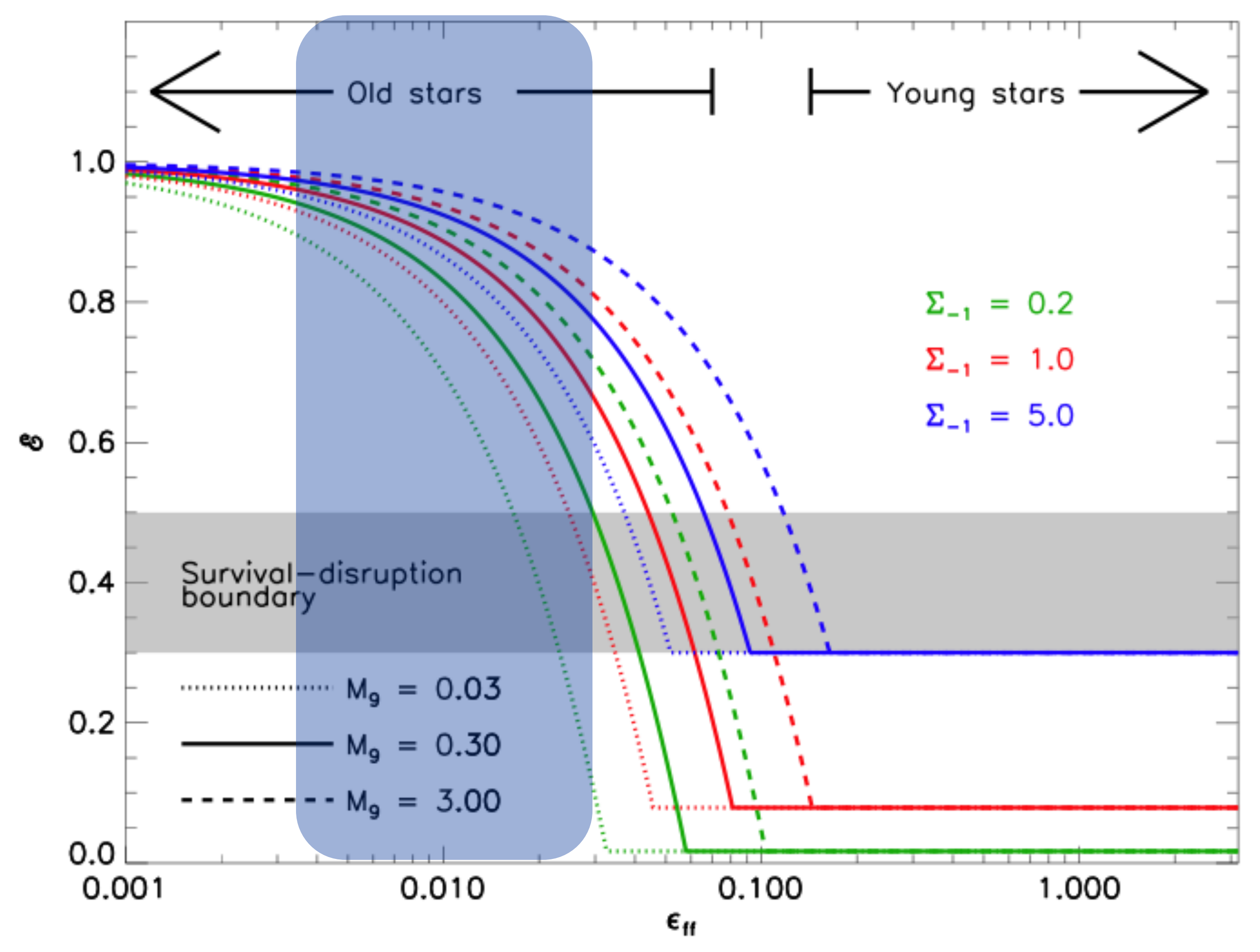
ε_{ff} and the Kennicutt Law

(Krumholz, McKee, & Tumlinson 2009)



ε_{ff} ~ 0.01 is equivalent to the observed local Kennicutt Law

Implication for Giant Clumps



Summary

- Disks likely dominated by GI over most of galaxy formation
- Velocity dispersion and clumping scale set by GI
- Resulting giant clumps at $z \sim 2$ are resistant to disruption unless SF at high z is unlike any in the local universe, and is off the Kennicutt law