J. Tan

Star Formation: From Local Regions to Extreme Starbursts

I review the star formation process as we understand it from studies of nearby Galactic regions, including infrared dark clouds, embedded clusters, and the local volume of the Milky Way. I then discuss how the various physical processes are expected to change as we go to more extreme proto star clusters and more extreme circumnuclear disks.

Star Formation:

From Local Regions to Extreme Starbursts

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Stefan O’Dougherty (UF)
Michael Butler (UF)
Audra Hernandez (UF)
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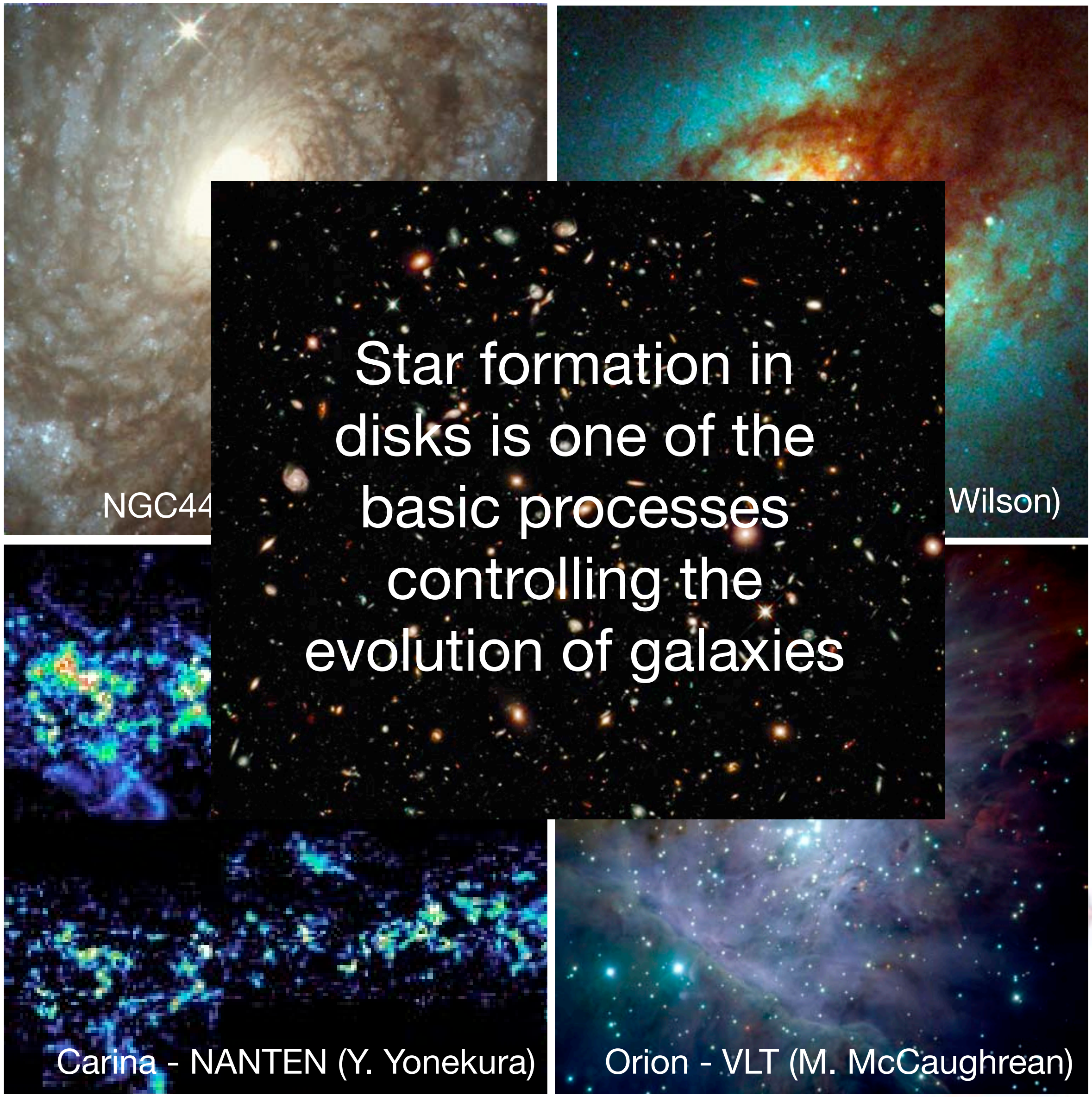
Elizabeth Tasker (McMaster)
Sven Van Loo (UF)
Desika Narayanan (CfA)
Greg Bryan (Columbia)

Peter Barnes (UF)
Paola Caselli (Leeds)
Izaskun Jimenez-Serra (CfA)
Francesco Fontani (IRAM)

Mark Krumholz (UCSC)
Chris McKee (UCB)
Britton Smith (Colorado)



Star formation in disks is one of the basic processes controlling the evolution of galaxies

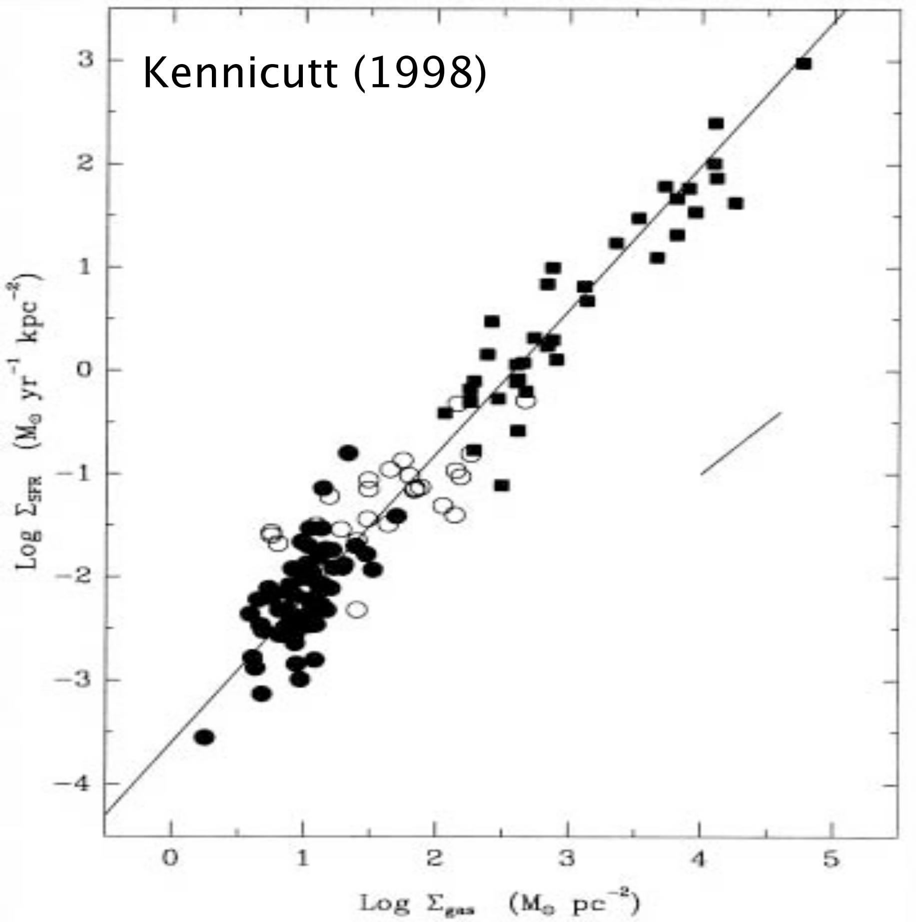
NGC44

Wilson)

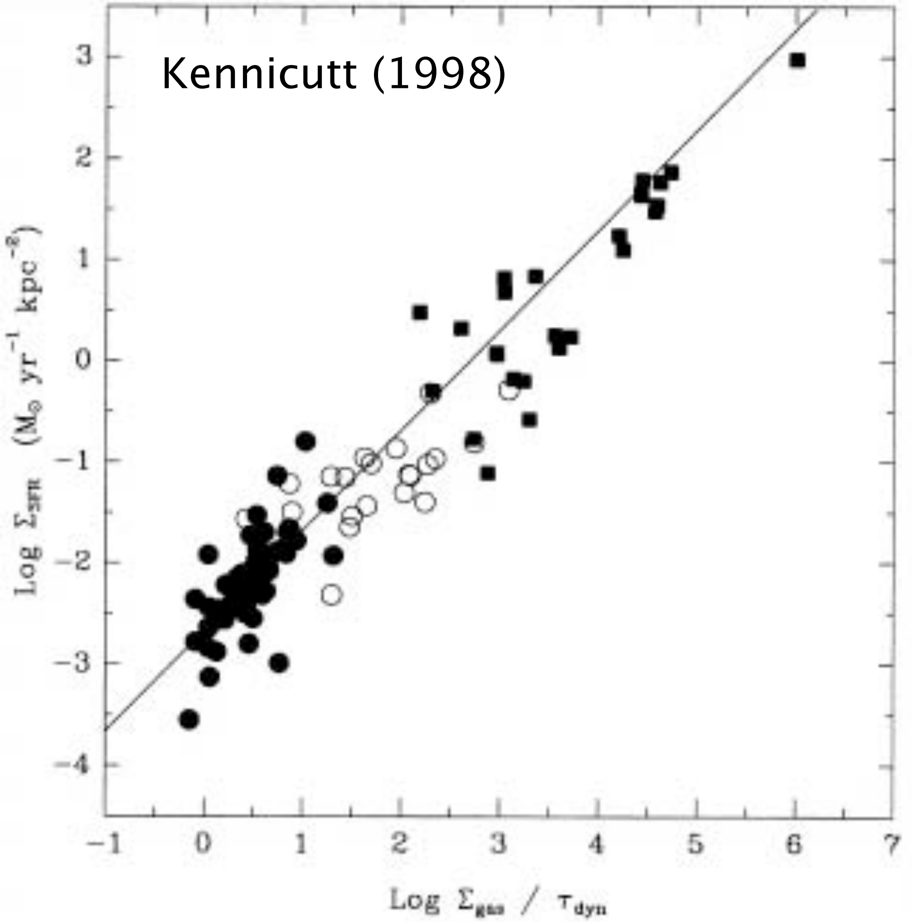
Carina - NANTEN (Y. Yonekura)

Orion - VLT (M. McCaughrean)

Global SFRs correlate with **gas content** and **orbital timescale**:


Kennicutt (1998)

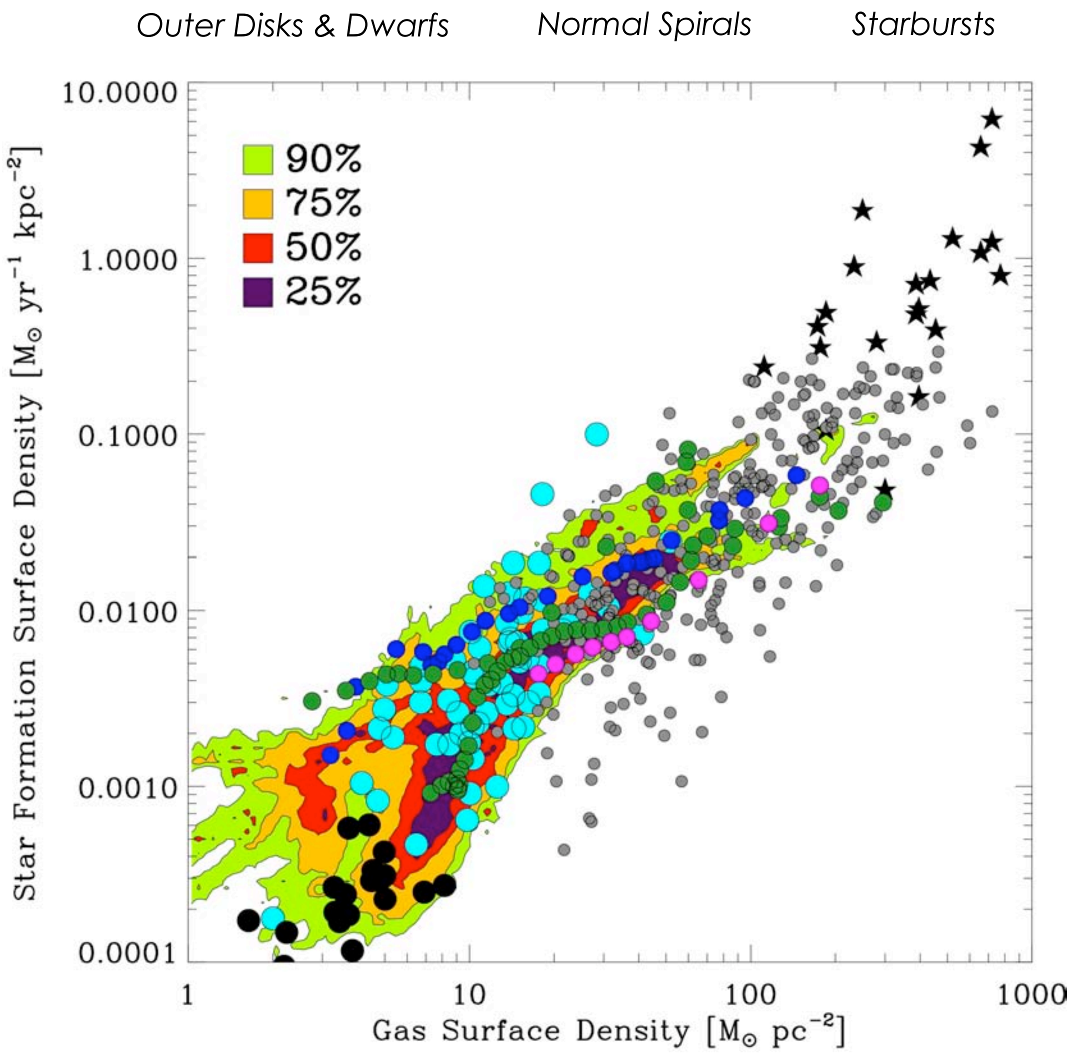
$$\Sigma_{\rm SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{1\ M_\odot\ {\rm pc}^{-2}} \right)^{1.4 \pm 0.15} M_\odot\ {\rm yr}^{-1}\ {\rm kpc}^{-2}$$


Kennicutt (1998)

$$\Sigma_{\rm SFR} \simeq 0.017 \Sigma_{\rm gas} \Omega_{\rm gas}$$

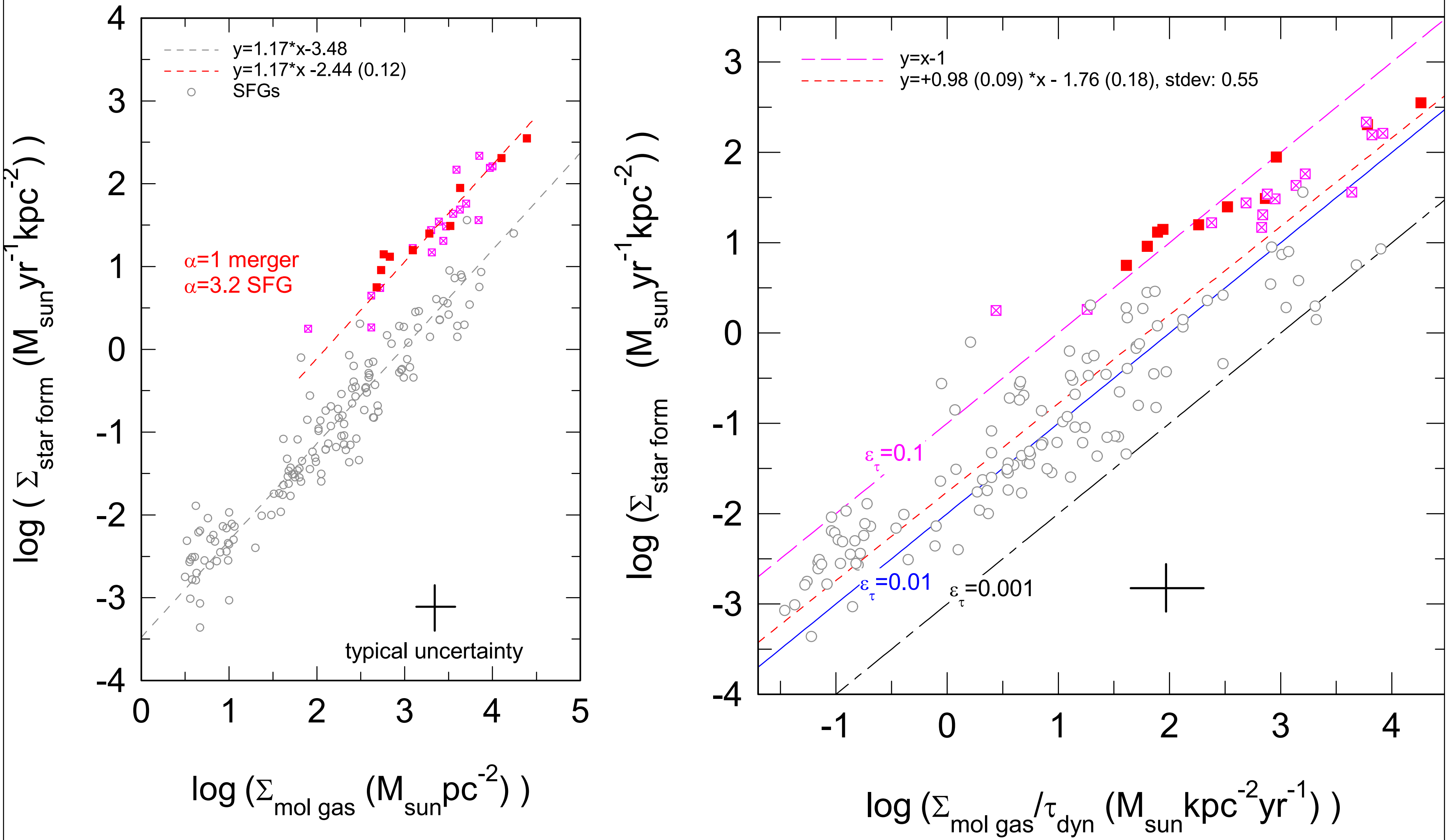
$$\varepsilon_{\rm orbit,outer} = 0.11$$

Also: Schmidt (1959), Wong & Blitz (2002), Boissier et al. (2003), Kennicutt et al. (2007), Leroy et al. (2008), Bigiel et al. (2008)



Kennicutt (1998) spirals and ★bursts; Wong & Blitz (2002); Schuster et al. (2007)
Wyder et al. (2007); Kennicutt et al. (2007); Crosthwaite & Turner (2007)

From Frank Bigiel

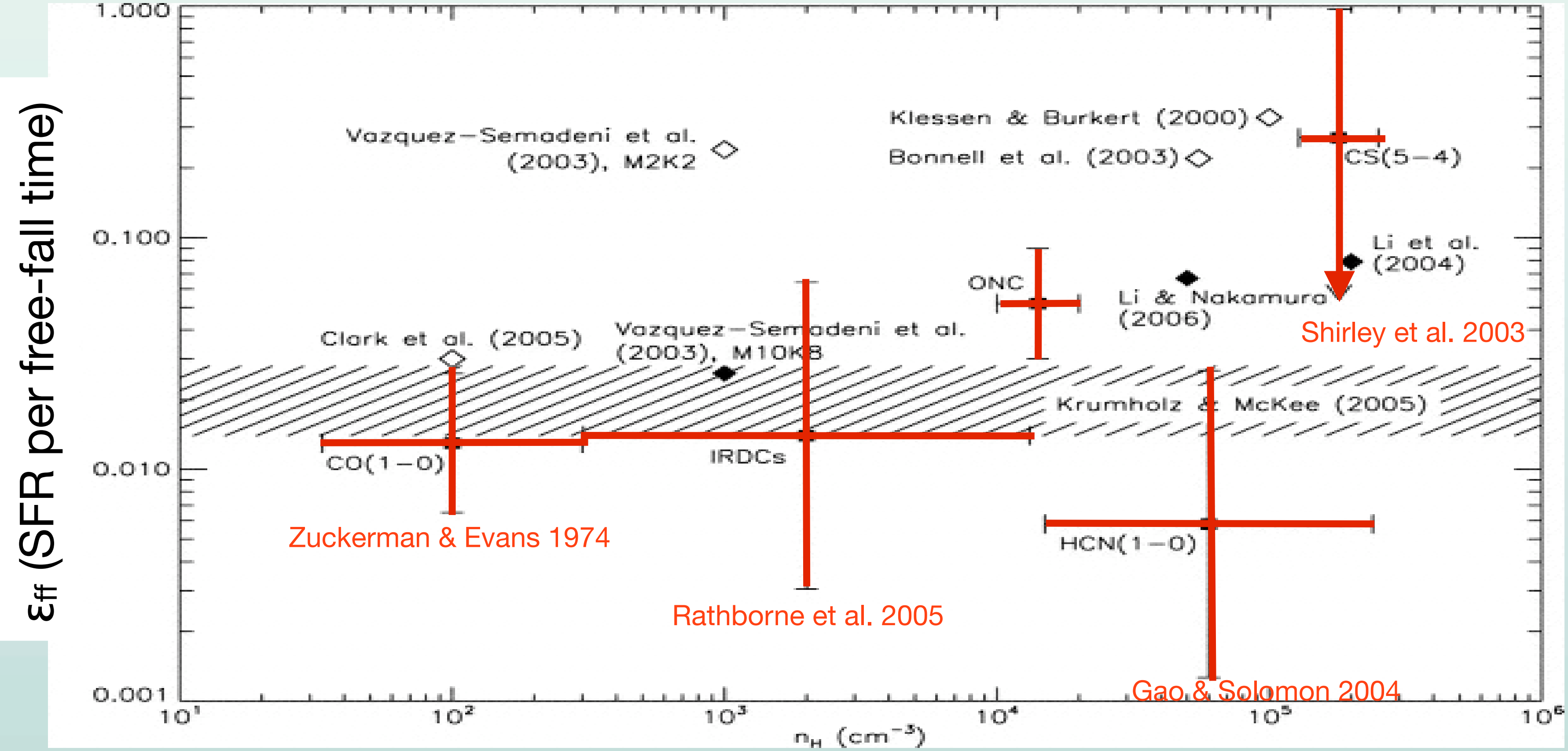


Genzel et al. 2010

Star Formation is Inefficient, Slow and Clustered

$\varepsilon_{\rm orbit} = 0.04$ in H_2 dominated regions of 12 disk galaxies (Tan 2010)

$\varepsilon_{\rm ff} \sim 0.01$ in Galactic GMCs (Zuckerman & Evans 1974)
and dense IRDCs (Krumholz & Tan 2007)



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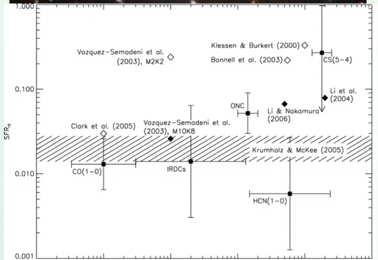

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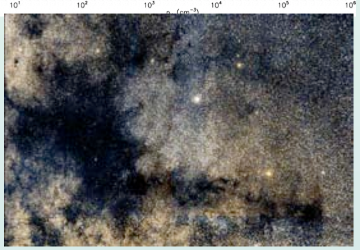
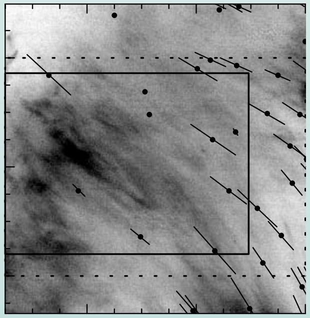
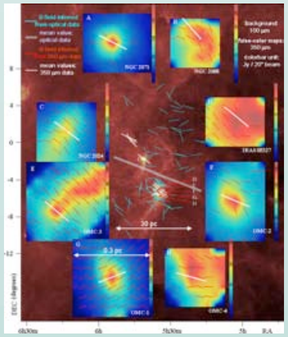


$\varepsilon_{ff} << 0.01$ in most gas in GMCs ($A_V<10$)
Pipe Nebula with M_g~$10^4 M_\odot$ (Forbrich et al. 2009)
$\varepsilon \sim 0.0006$
$\varepsilon_{ff} \sim 0.0006$ (assuming $t_{cloud}=1t_{ff}$)

Magnetic fields appear to be strong:



Ordered B-field vectors in Taurus (Heyer et al. 2008)



Correlation of B-field vectors from ~100pc to <1pc scales (Hua-bai Li et al. 2009)

Star Formation is Inefficient, Slow and Clustered

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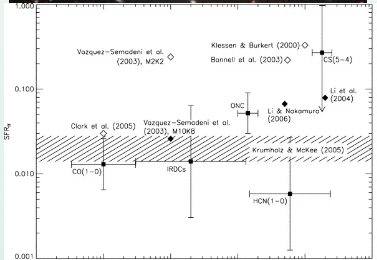

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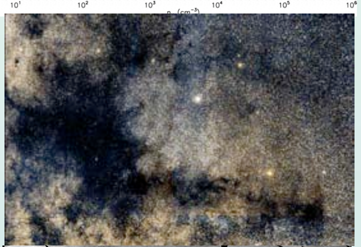

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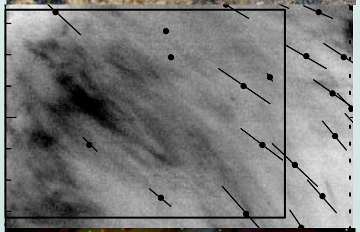


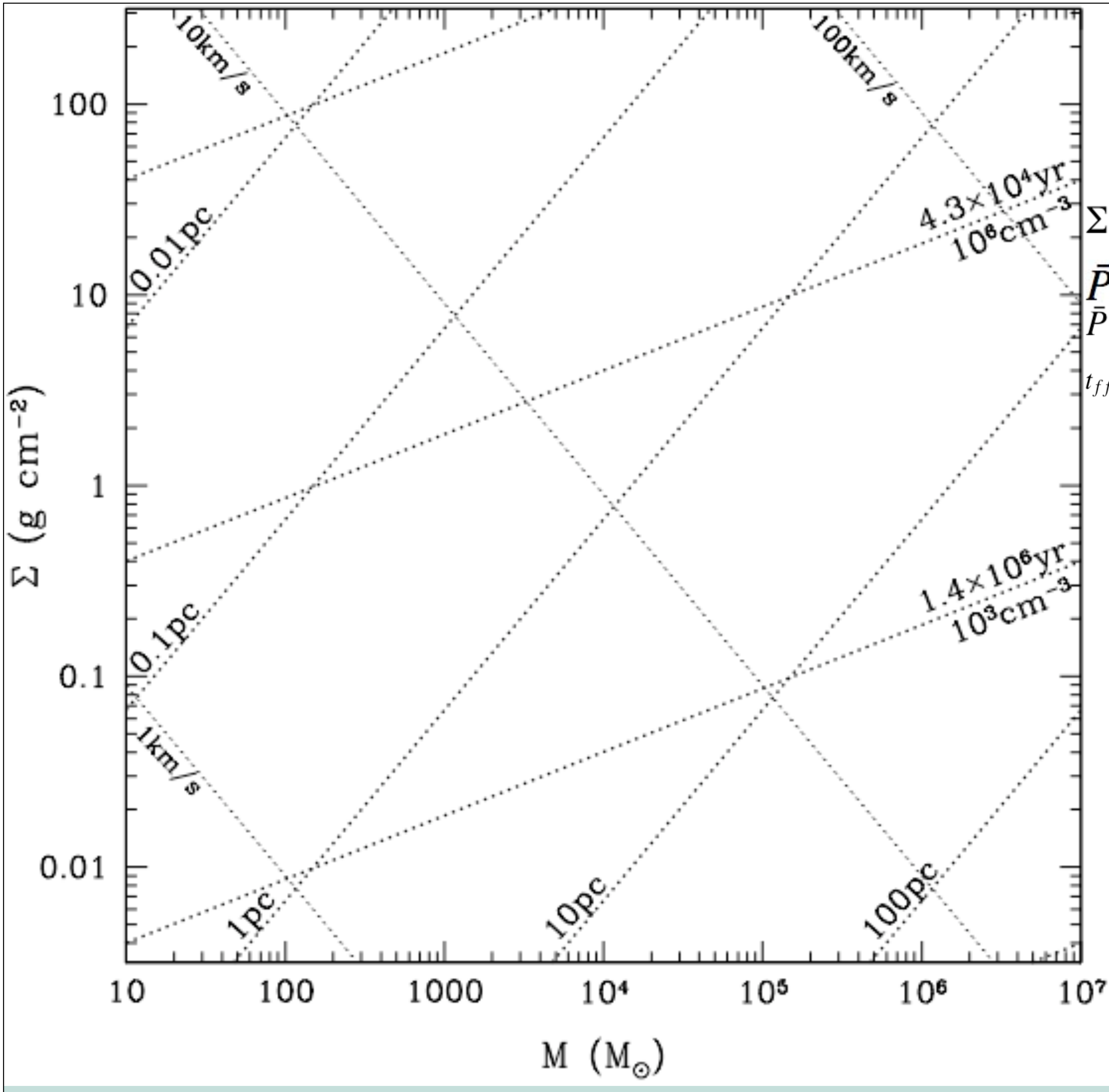
Magnetic fields appear to be strong:

Column density threshold for star formation may be due to regulation of ambipolar diffusion by photoionization (McKee 1989).

Star formation is highly clustered, occurring in star-forming clumps:

(Lada & Lada 2003; Gutermuth et al. 2009)
$\epsilon_{ff} \sim 0.01$, $\epsilon \sim 0.1\text{-}0.5 \rightarrow t_{form} >> t_{ff}$
slow star cluster formation (Tan, Krumholz, McKee 2006)

Overview of Physical Scales



$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2 \, K \, cm^{-3}$$

$$t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

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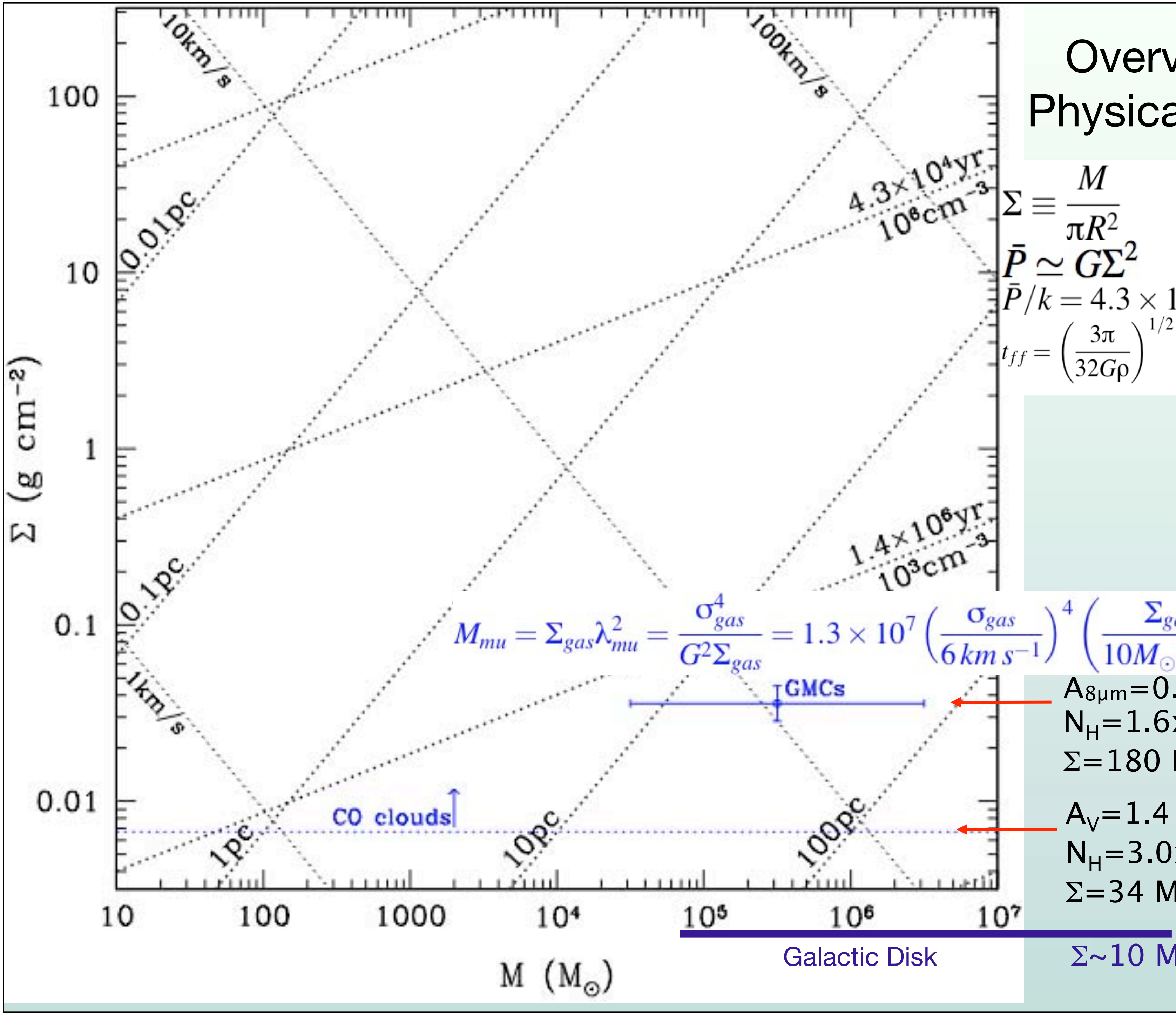

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$$M_{mu} = \Sigma_{gas}\lambda_{mu}^2 = \frac{\sigma_{gas}^4}{G^2\Sigma_{gas}} = 1.3 \times 10^7 \left(\frac{\sigma_{gas}}{6\,km\,s^{-1}}\right)^4 \left(\frac{\Sigma_{gas}}{10 M_\odot pc^{-2}}\right)^{-1} M_\odot$$

$A_{8\mu m}=0.30$

$N_H=1.6\text{x}10^{22}cm^{-2}$

$\Sigma=180\ M_\odot\ pc^{-2}$

$A_V=1.4$

$N_H=3.0\text{x}10^{21}cm^{-2}$

$\Sigma=34\ M_\odot\ pc^{-2}$

Σ~$10\ M_\odot\ pc^{-2}$

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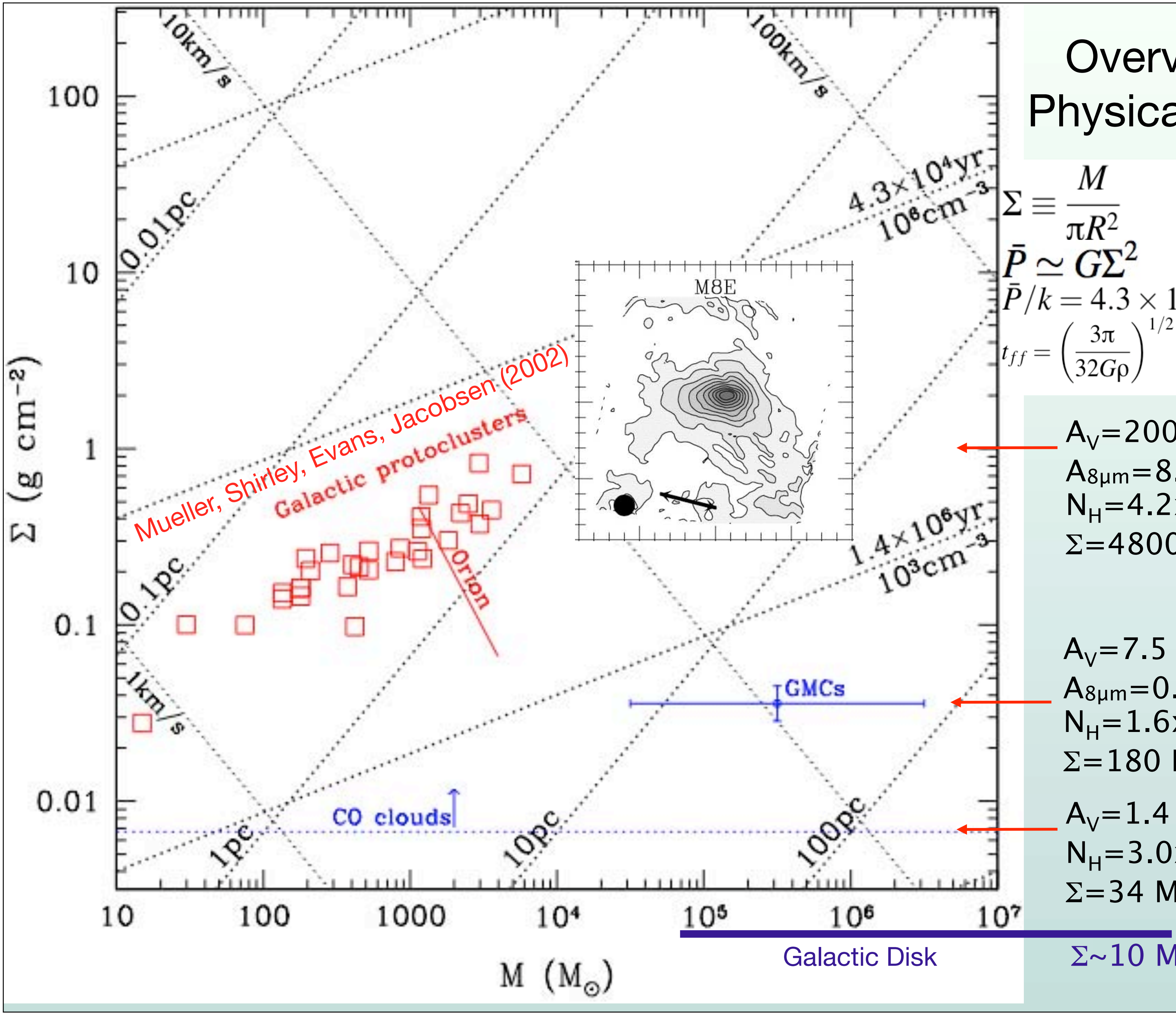

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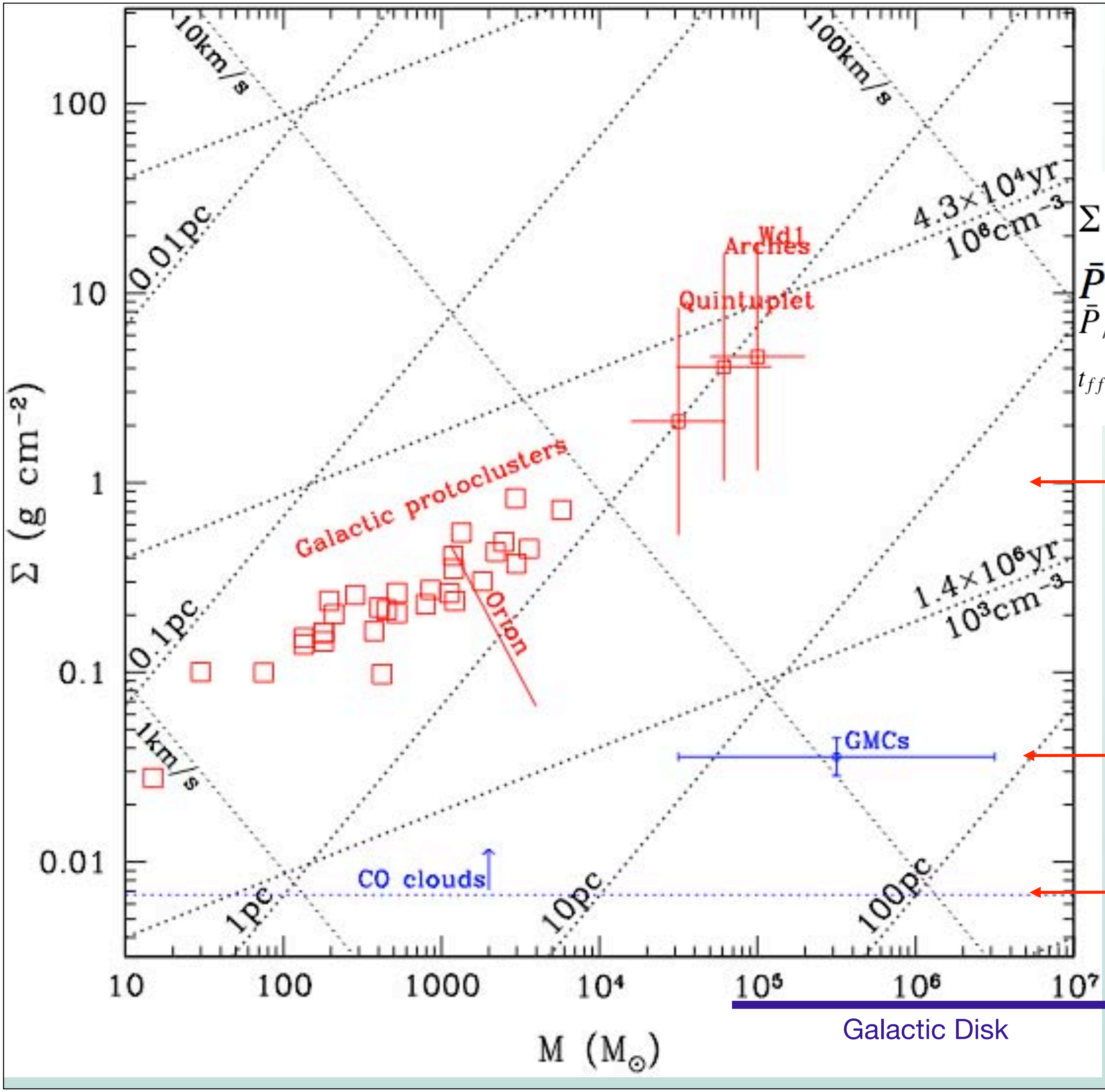

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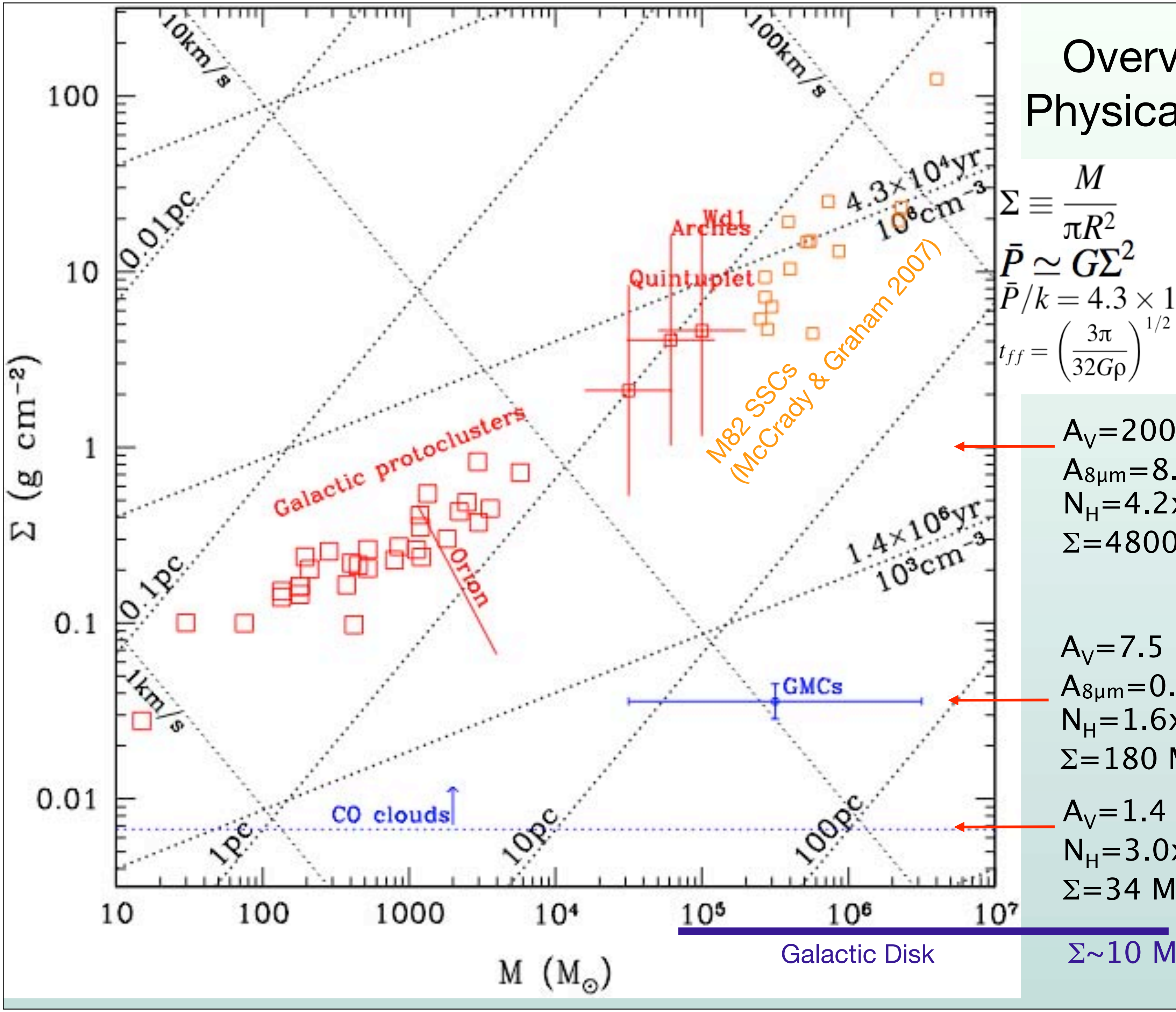

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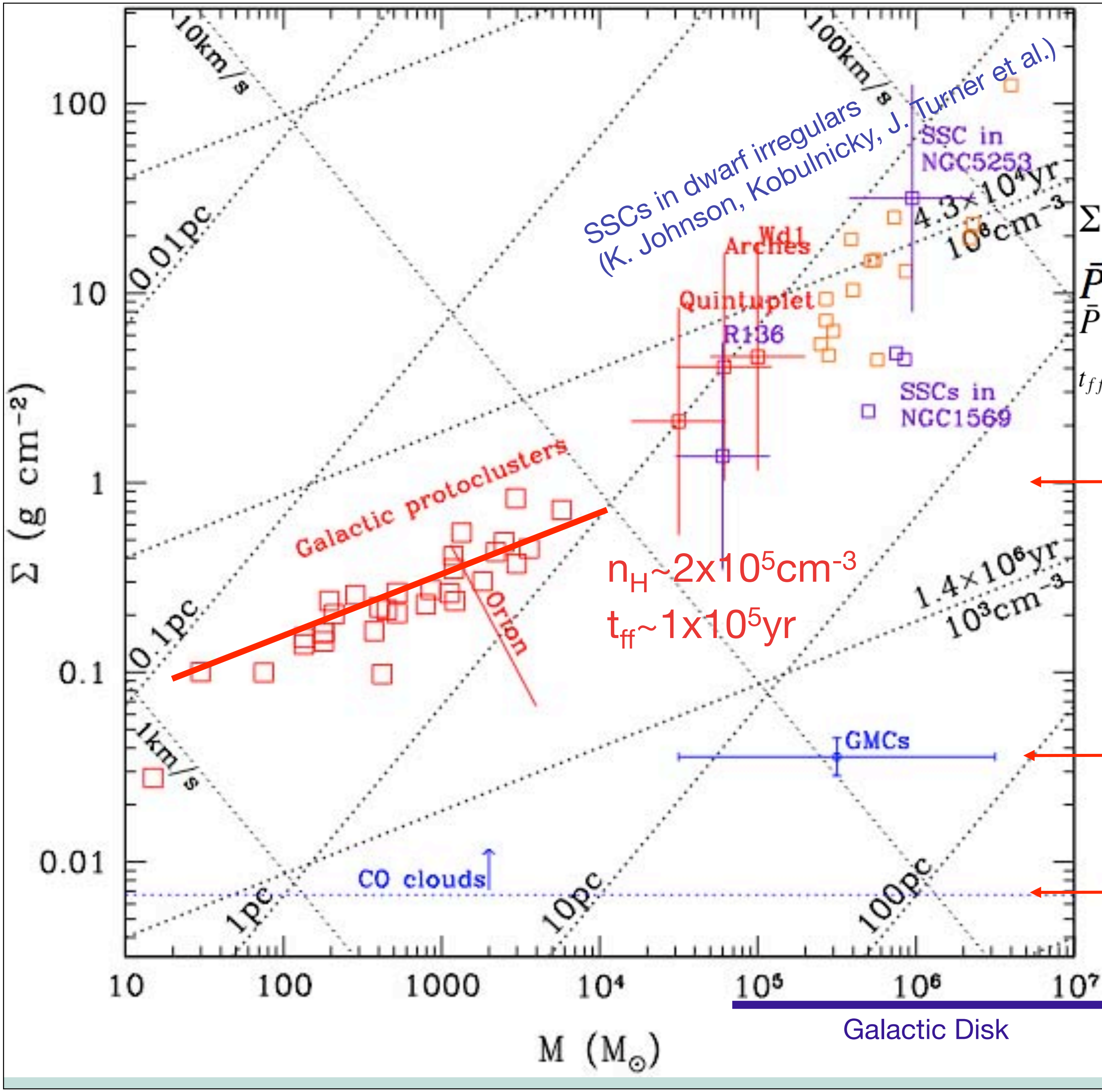

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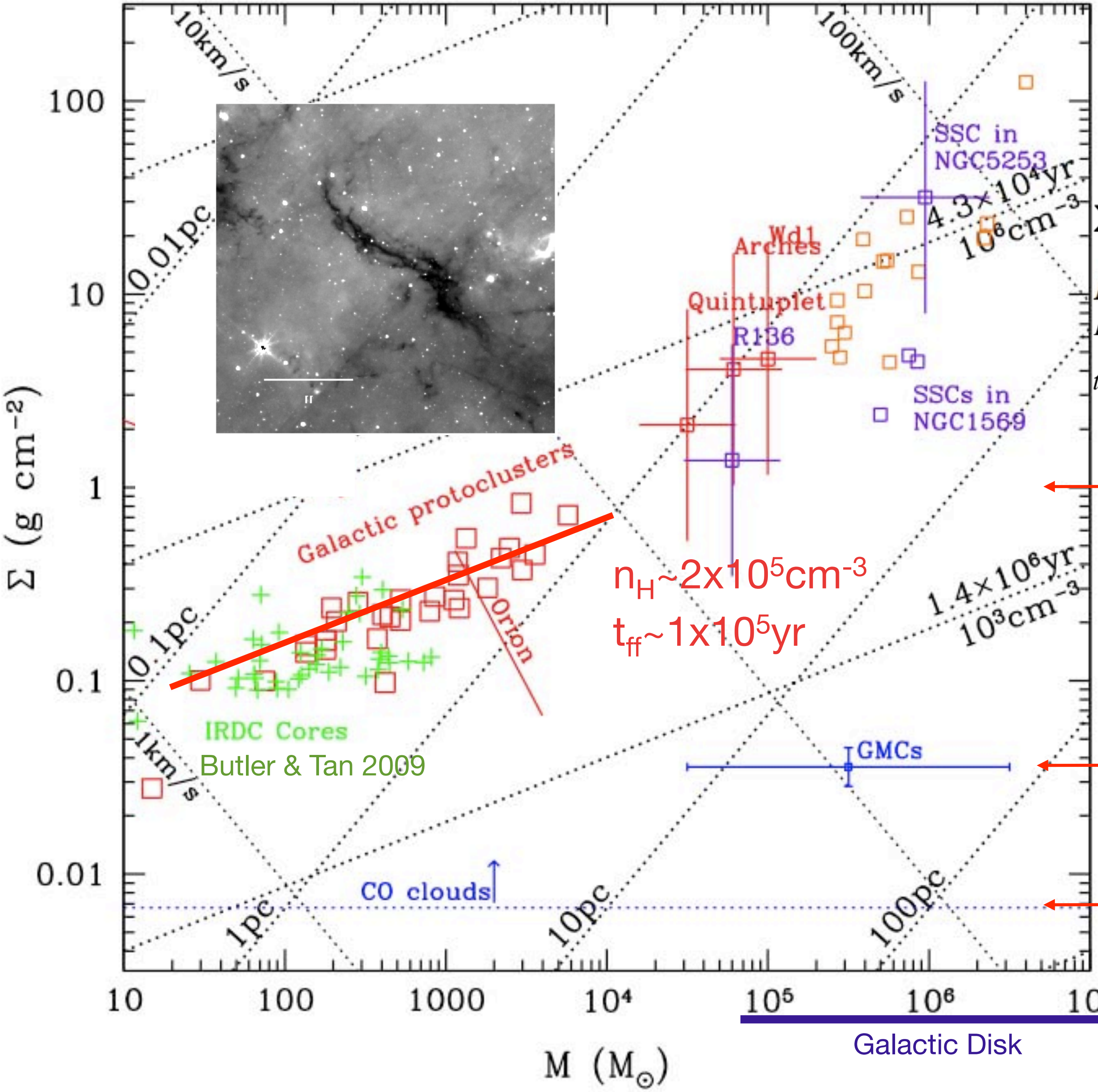

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Star Formation Driven by GMC Collisions

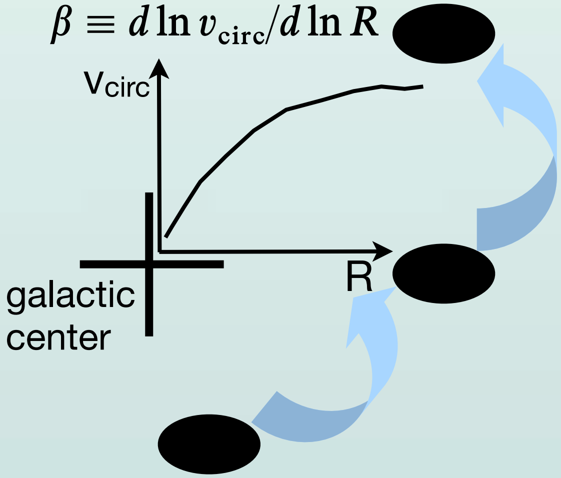
Tan (2000)

In regions of galaxies dominated by molecular gas, a large fraction of the total gas is in gravitationally bound clouds (GMCs & associated HI).

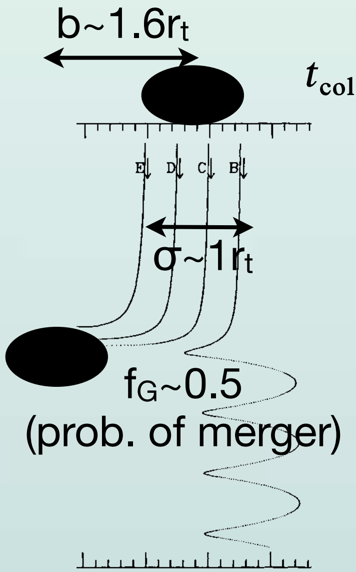
Formation of GMCs is not the rate limiting step for star formation, but rather formation of magnetically supercritical star-forming clumps ($A_V>10$) within GMCs.
(c.f. “building block” model of Wu, Evans et al.)

Hypothesis: GMC collisions & mergers compress gas that is already molecular, dense, and prone to gravitational instability, creating star-forming clumps.

$$\beta \equiv d\ln v_{\rm circ}/d\ln R$$



2D monolayer of GMCs in galactic disk



Gammie et al. (1991)

$$t_{\rm coll} \sim \frac{1}{2}\frac{\lambda_{\rm mfp}}{v_s(\sim 1.6 r_t)} \sim \frac{1}{3.2 r_t(\Omega - dv_{\rm circ}/dR)\mathcal{N}_A r_t f_{\rm G}}$$

$$\mathcal{N}_A \simeq \frac{\Sigma_{\rm gas}}{M_c} = \frac{\alpha\kappa\sigma_{\rm gas}}{\pi G Q M_c} \simeq (1+0.3\beta)\frac{0.7\alpha}{Q r_t^2}$$

$$\boxed{t_{\rm coll} \simeq \frac{Q}{9.4 f_{\rm G}(1+0.3\beta)(1-\beta)}\, t_{\rm orb} \quad \rightarrow 0.2\, t_{\rm orb} \qquad (\beta=0)}$$

Star Formation Driven by GMC Collisions

$$t_{\rm coll} \simeq \frac{Q}{9.4 f_{\rm G}(1+0.3\beta)(1-\beta)}\, t_{\rm orb}$$

The collision time is short because:

1. GMCs are in a near 2D distribution
2. Gravitational focusing boosts cross section to be ~tidal radius, ~100pc
3. Interaction velocity is shear velocity at impact parameter ~2 tidal radii, ~10km/s, rather than velocity dispersion, ~6 km/s

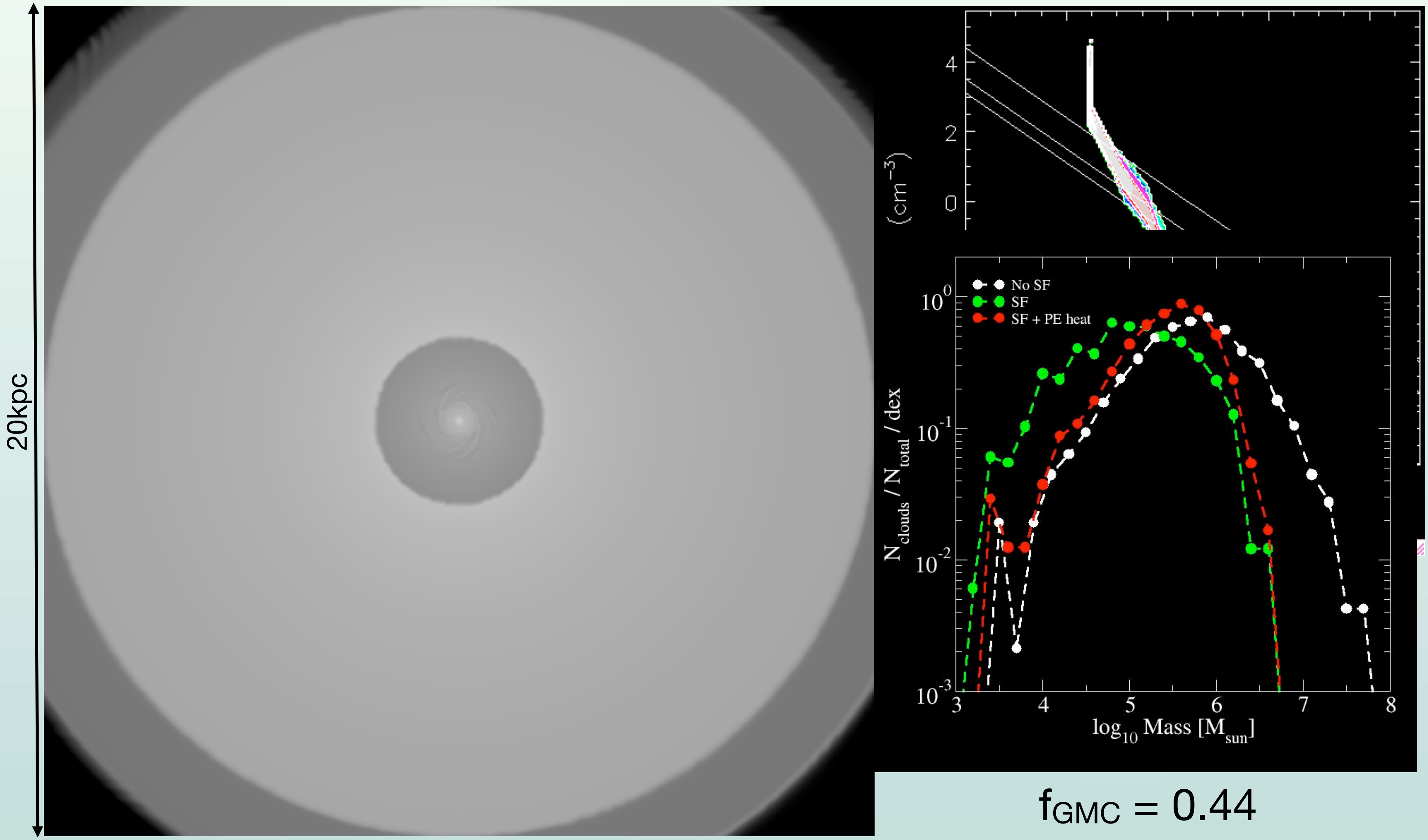
$$\Sigma_{\rm SFR} = \frac{\epsilon f_{\rm sf}\, \mathcal{N}_A M_c}{t_{\rm coll}} \simeq \frac{\epsilon f_{\rm sf}\, \Sigma_{\rm gas}}{t_{\rm coll}}$$

$$\Sigma_{\rm SFR} \simeq 1.5 \underset{\overset{\uparrow}{0.02}}{\epsilon} \underset{\overset{\uparrow}{0.5}}{f_{\rm sf}}\, \underset{\overset{\uparrow}{0.5}}{f_{\rm G}}\, \underset{\overset{\uparrow}{1}}{Q}^{-1} \Sigma_{\rm gas}\, \Omega(1-0.7\beta) \rightarrow 7.5\mathrm{x}10^{-3}\, \Sigma_{\rm gas}\, \Omega\, (1\text{-}0.7\beta)$$

A simulated idealized disk galaxy

Tasker & Tan (2009),
Tasker & Tan, in prep.

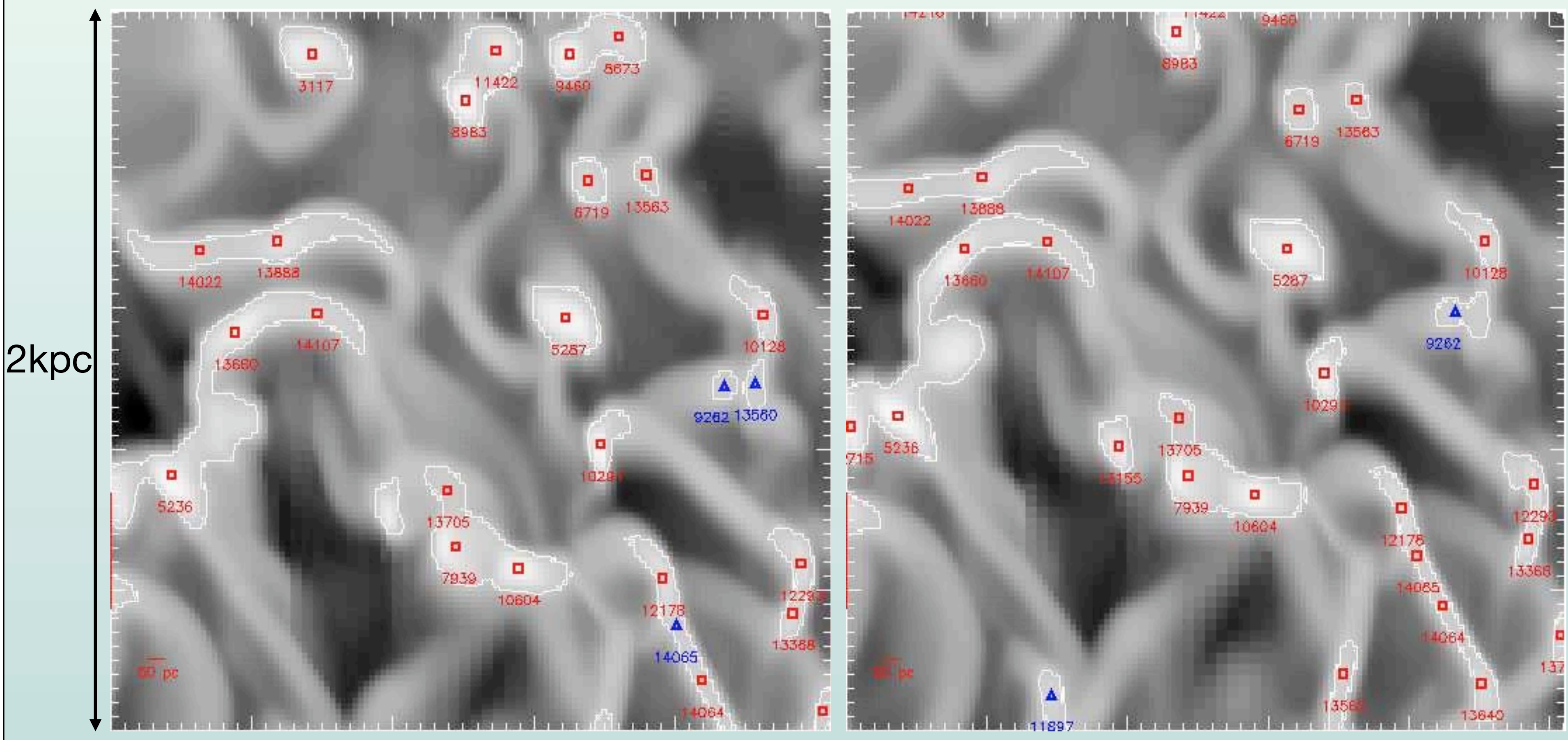
Flat rotation curve, axisymmetric fixed background potential (old stars & DM), Q=1 (for σ=6km/s) from 2-10kpc. ENZO AMR 3D Hydro Atomic Cooling to 300K, 8pc resolution, “GMCs” identified as regions with $n_H > 100 cm^{-3}$, $\varepsilon_{ff} = 0.02$ in “GMCs” (Krumholz & Tan 2007), FUV heating appropriate for Milky Way (Wolfire et al. 2003)



$f_{GMC} = 0.44$

GMC Tracking

Follow cloud birth, merger, destruction



t=160Myr

t=161Myr

Implications of Frequent GMC Collisions

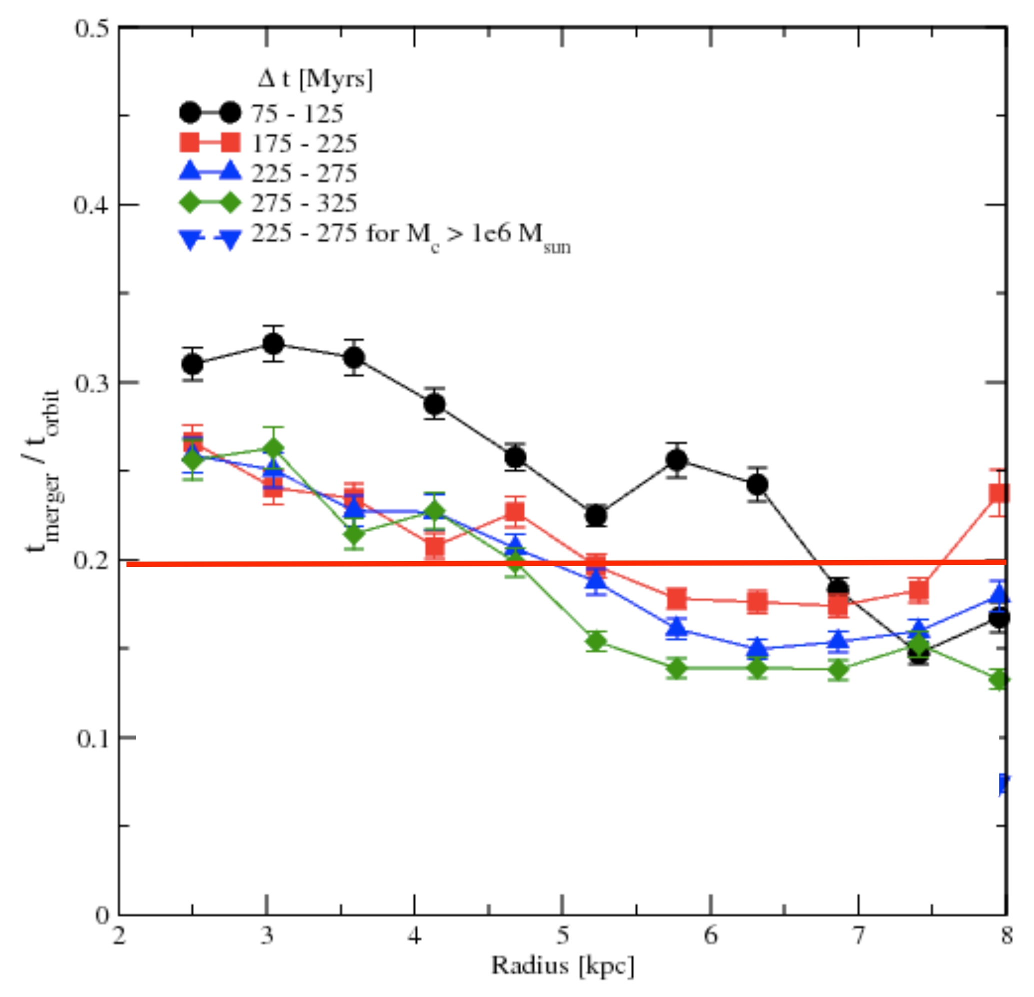
We find GMCs suffer frequent mergers. A typical GMC merges every 0.2 orbital times, i.e. ~20-30Myr.

Frequent mergers can explain the retrograde rotation of GMCs.

Frequent mergers can be an important source of turbulence in GMCs.

Frequent mergers redefine the notion of GMC lifetimes.

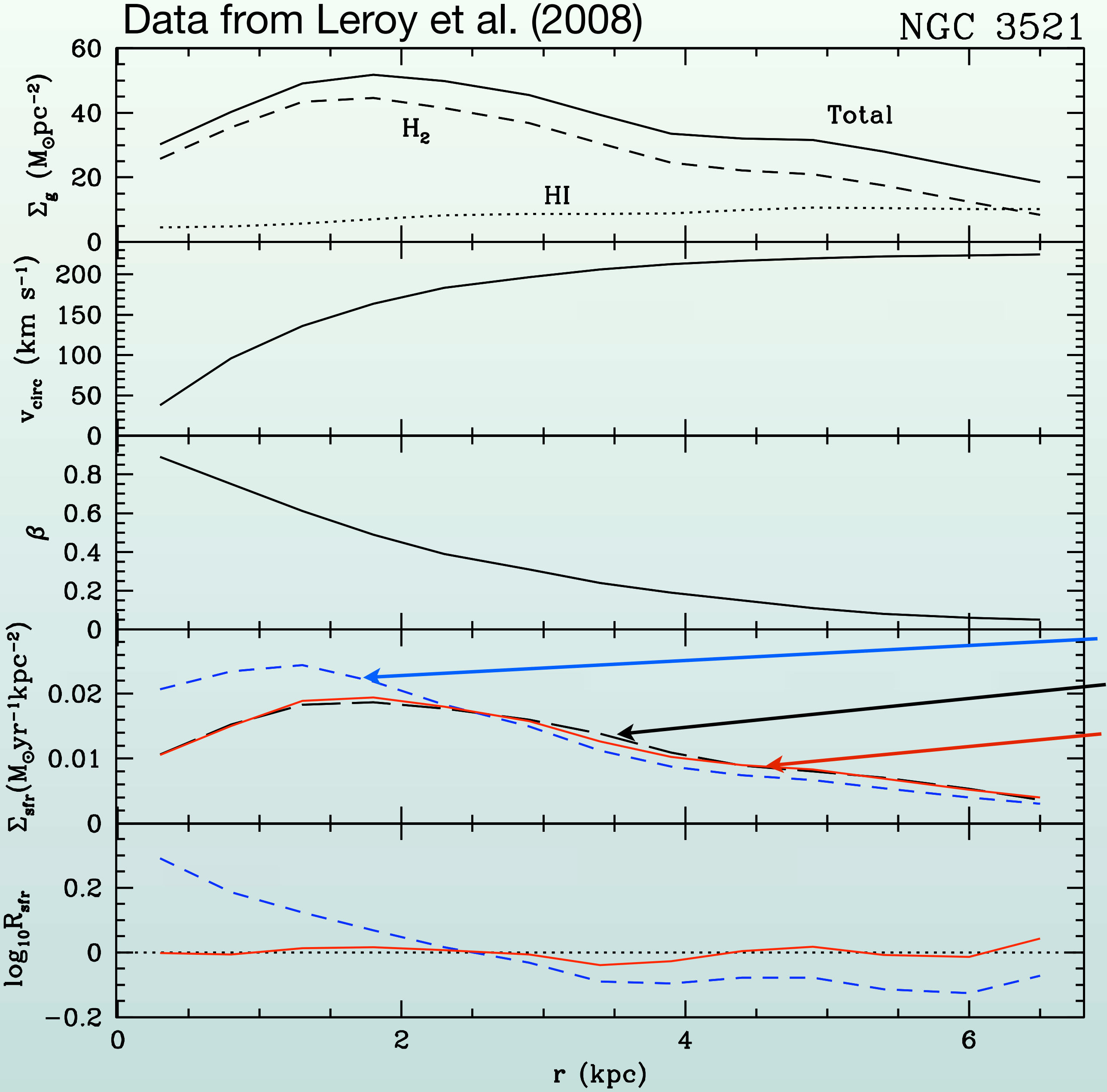
This process could trigger star formation and be the link between global galactic dynamics and star cluster formation.



A test of SF Laws: Empirical Effect of Shear on Σ_{sfr}

Tan (2010)

Data from Leroy et al. (2008)



$\Sigma_{sfr} = B\ \Sigma_g\ \Omega$

Observed Σ_{sfr}

$\Sigma_{sfr} = B\ \Sigma_g\ \Omega(1\text{-}0.7\beta)$

Comparison of 6 SF laws in 12 galaxies:

Schmidt-Kennicutt power law:

$$\Sigma_{\rm sfr} = A_g \Sigma_{g,2}^{\alpha_g},$$

Kennicutt Omega law:

$$\Sigma_{\rm sfr} = B_\Omega \Sigma_g \Omega$$

Constant molecular law:

$$\Sigma_{\rm sfr} = A_{\rm H2} \Sigma_{\rm H2,2},$$

8.0x10^{-3}

GMC collisions law (Tan 2000):

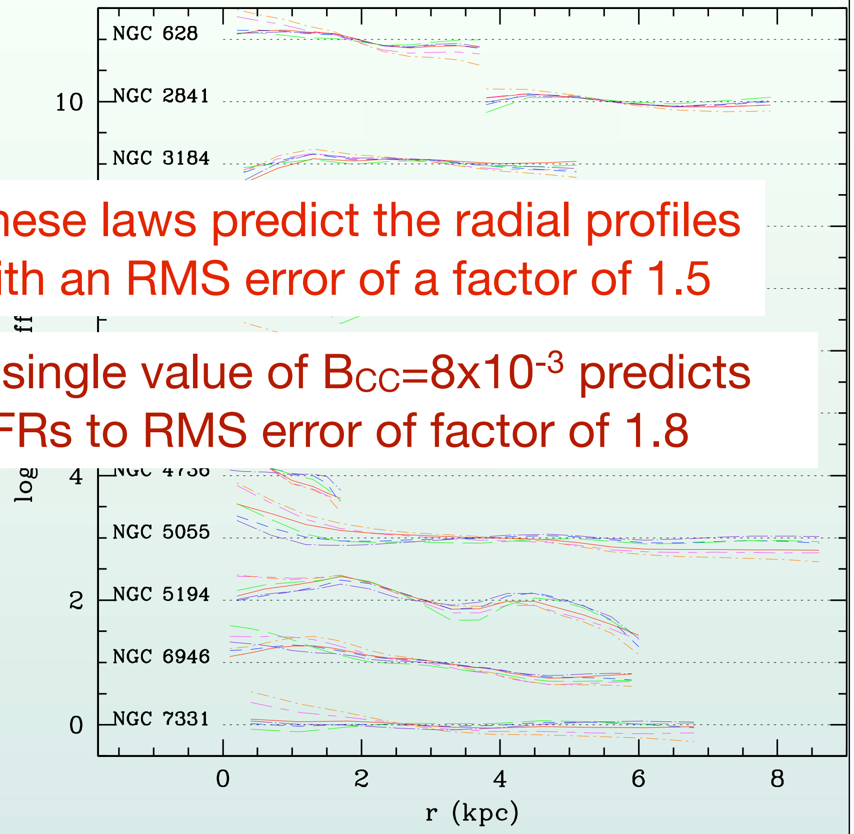
$$\Sigma_{\rm sfr} = B_{\rm CC} Q^{-1} \Sigma_g \Omega (1 - 0.7\beta), \quad (\beta \ll 1)$$

Krumholz-McKee (2005) turbulence law:

$$\Sigma_{\rm sfr} = A_{\rm KM} f_{\rm GMC} \phi_{\bar{P},6}^{0.34} Q_{1.5}^{-1.32} \Omega_0^{1.32} \Sigma_{g,2}^{0.68}$$

Krumholz-McKee-Tumlinson (2009) turbulence law

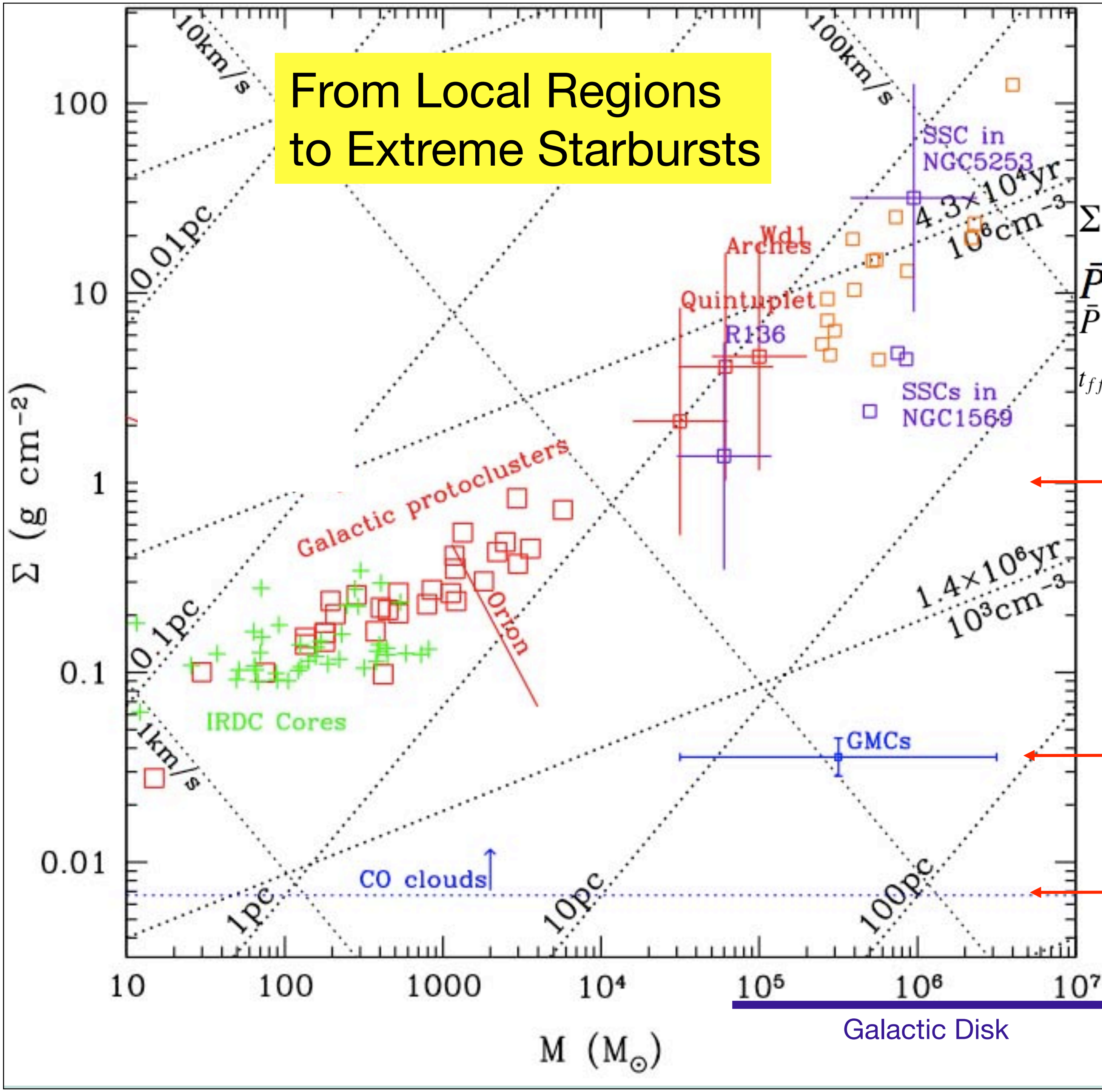
$$\Sigma_{\rm sfr} = A_{\rm KMT} f_{\rm GMC} \Sigma_{g,2} \times \begin{cases} \left(\Sigma_g/85 M_\odot {\rm pc}^{-2}\right)^{-0.33}, & \Sigma_g < 85\ M_\odot {\rm pc}^{-2} \\ \left(\Sigma_g/85 M_\odot {\rm pc}^{-2}\right)^{0.33}, & \Sigma_g > 85\ M_\odot {\rm pc}^{-2} \end{cases}$$



These laws predict the radial profiles with an RMS error of a factor of 1.5

A single value of B$_{\rm CC}$=8x10^{-3} predicts SFRs to RMS error of factor of 1.8

Overview of Physical Scales



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$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

$$t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

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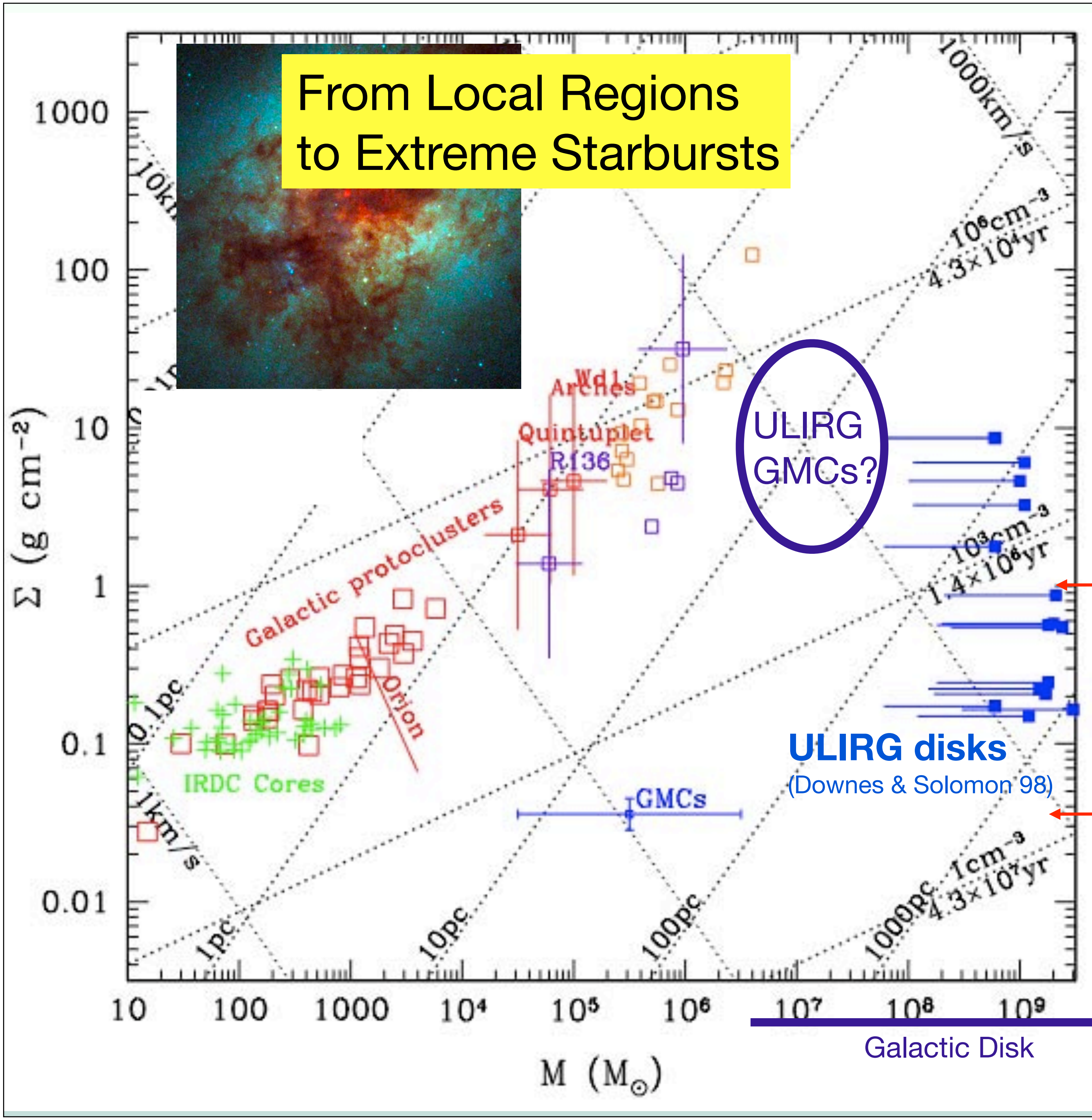

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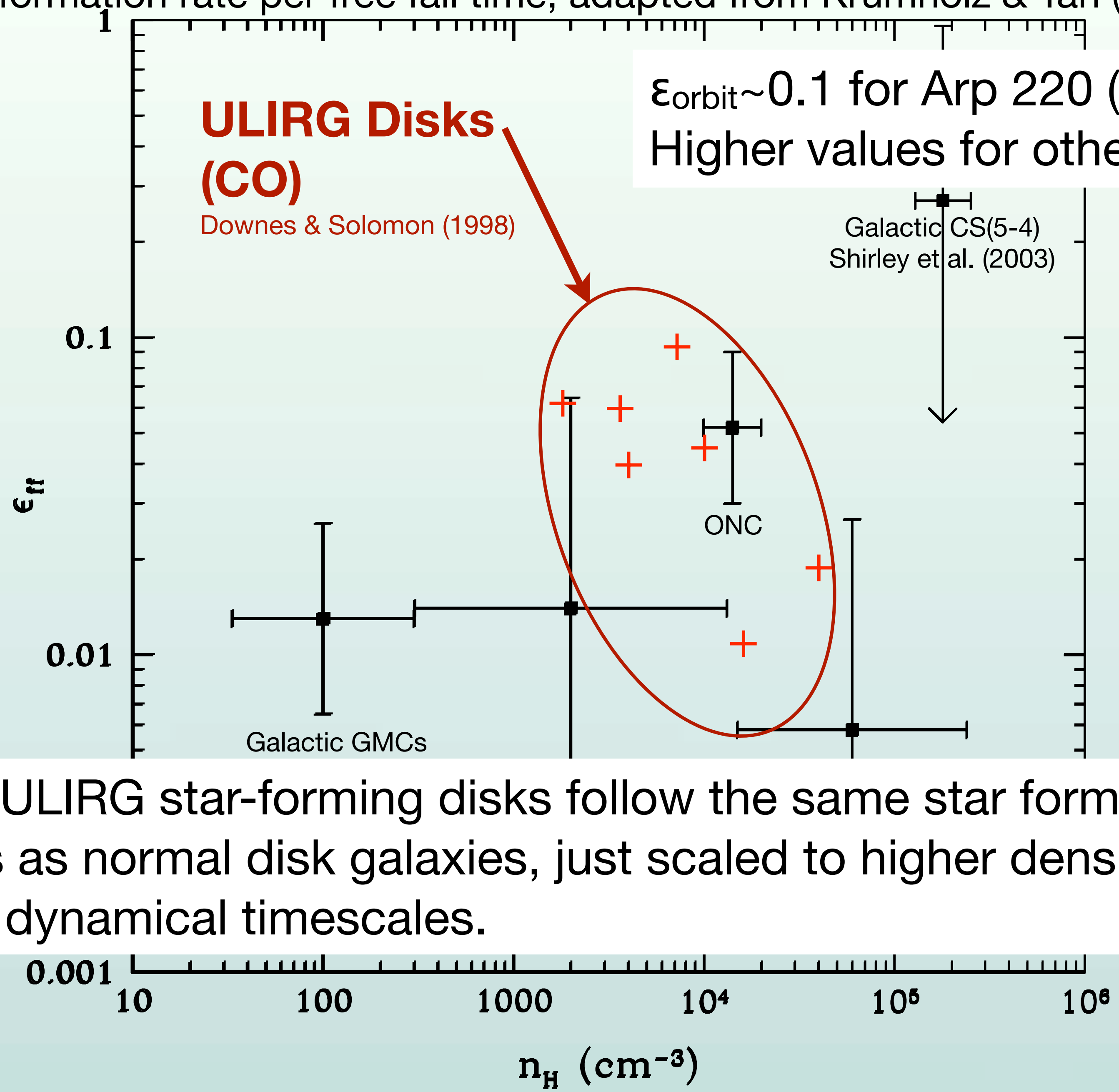
$\Sigma\sim10\ M_\odot\ pc^{-2}$

Star formation rate per free fall time, adapted from Krumholz & Tan (2007)



ε_{orbit}~0.1 for Arp 220 (E & W)
Higher values for other systems

Maybe ULIRG star-forming disks follow the same star formation physics as normal disk galaxies, just scaled to higher densities and shorter dynamical timescales.

Conclusions

To understand star formation in disk galaxies and circumnuclear starbursts:

~~Stars form from Gas~~

~~Stars form from Molecular Gas~~

Stars form from Magnetically Supercritical Molecular Gas at $A_V > 10$

Star formation is slow: $\varepsilon_{ff} \sim 0.01$-$0.05$ from n_H up to $\sim 10^5 \mathrm{cm}^{-3}$,
perhaps due to turbulence or magnetic support

Star formation is localized in ~parsec-sized star clusters
but knows about the global dynamical timescale of the disk

Star formation triggered by converging flows in galactic-shear-driven
GMC collisions can explain these local and global features

Maybe a single, self-similar model of a star-forming, self-regulated
(Q~1) disk can explain both disk galaxies and circumnuclear starbursts