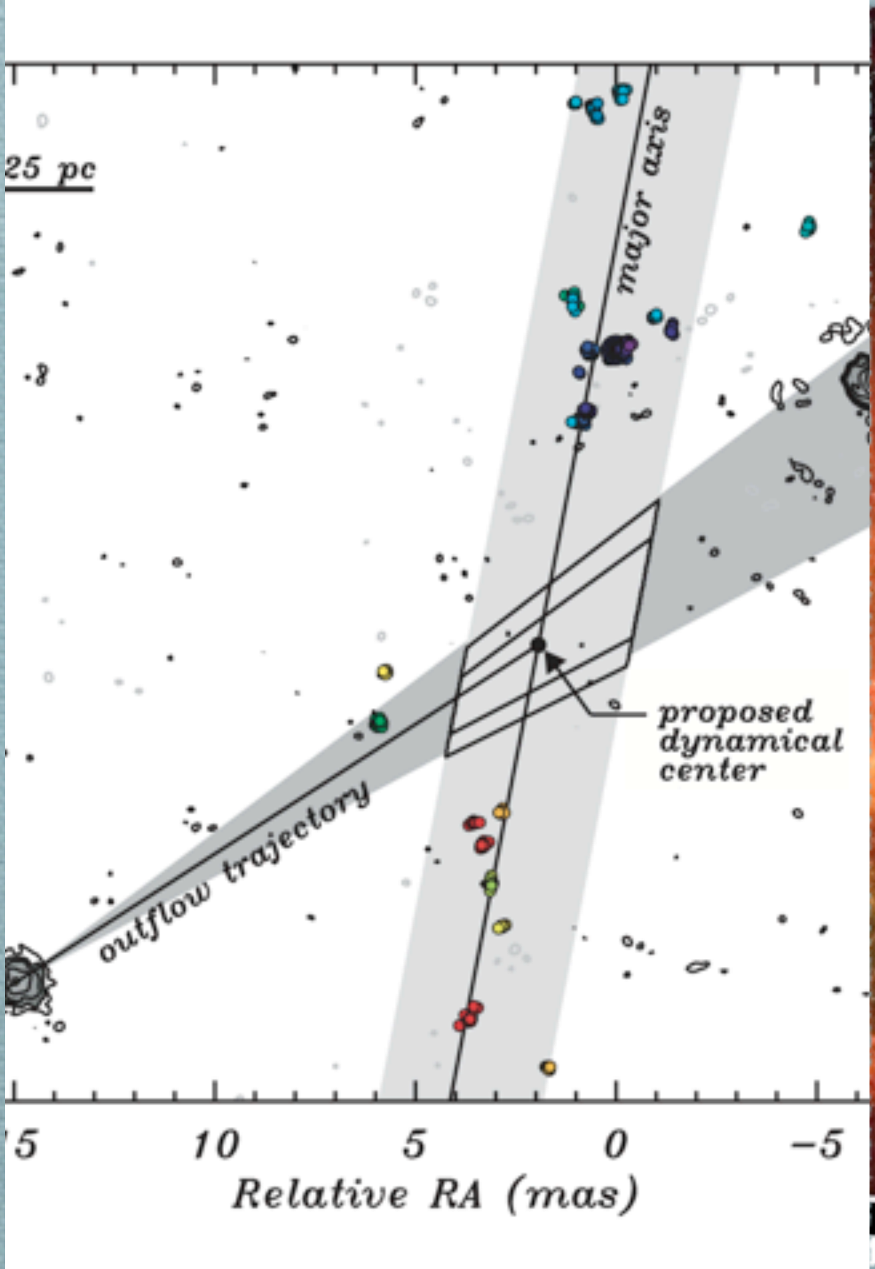
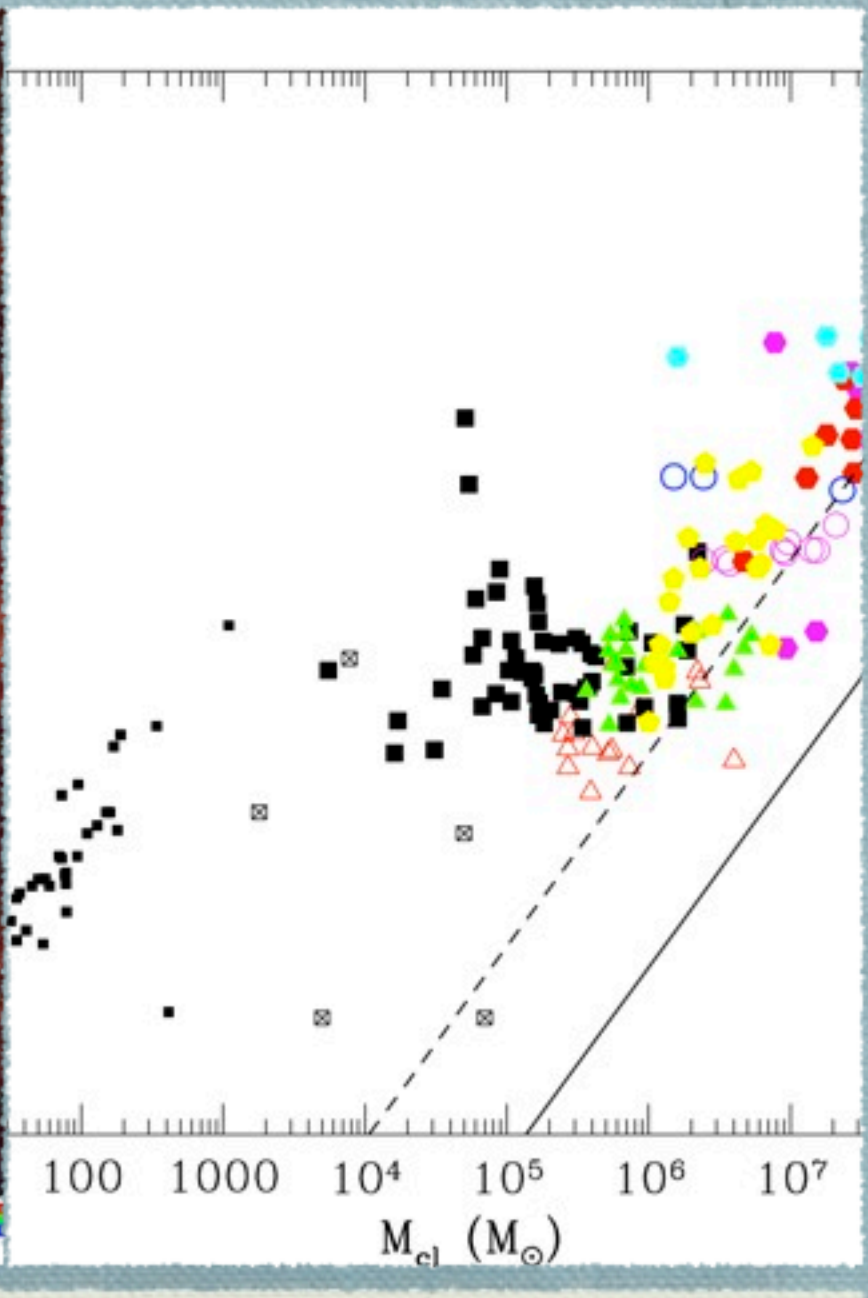




AGN Fueling:
massive star cluster formation in dense environments

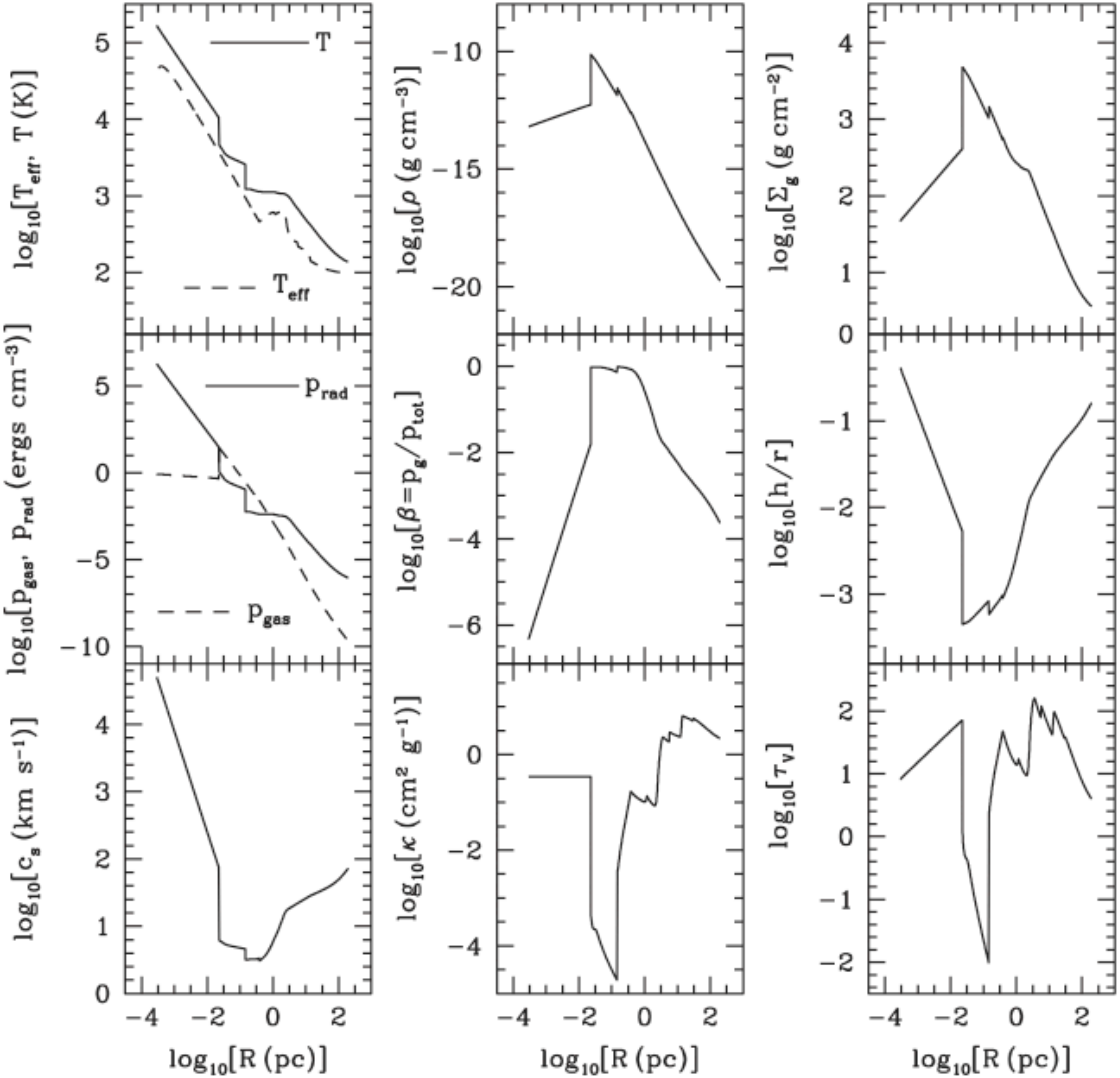
Eliot Quataert , Todd Thompson, Mubdi Rahman, Libby Harper-Clark

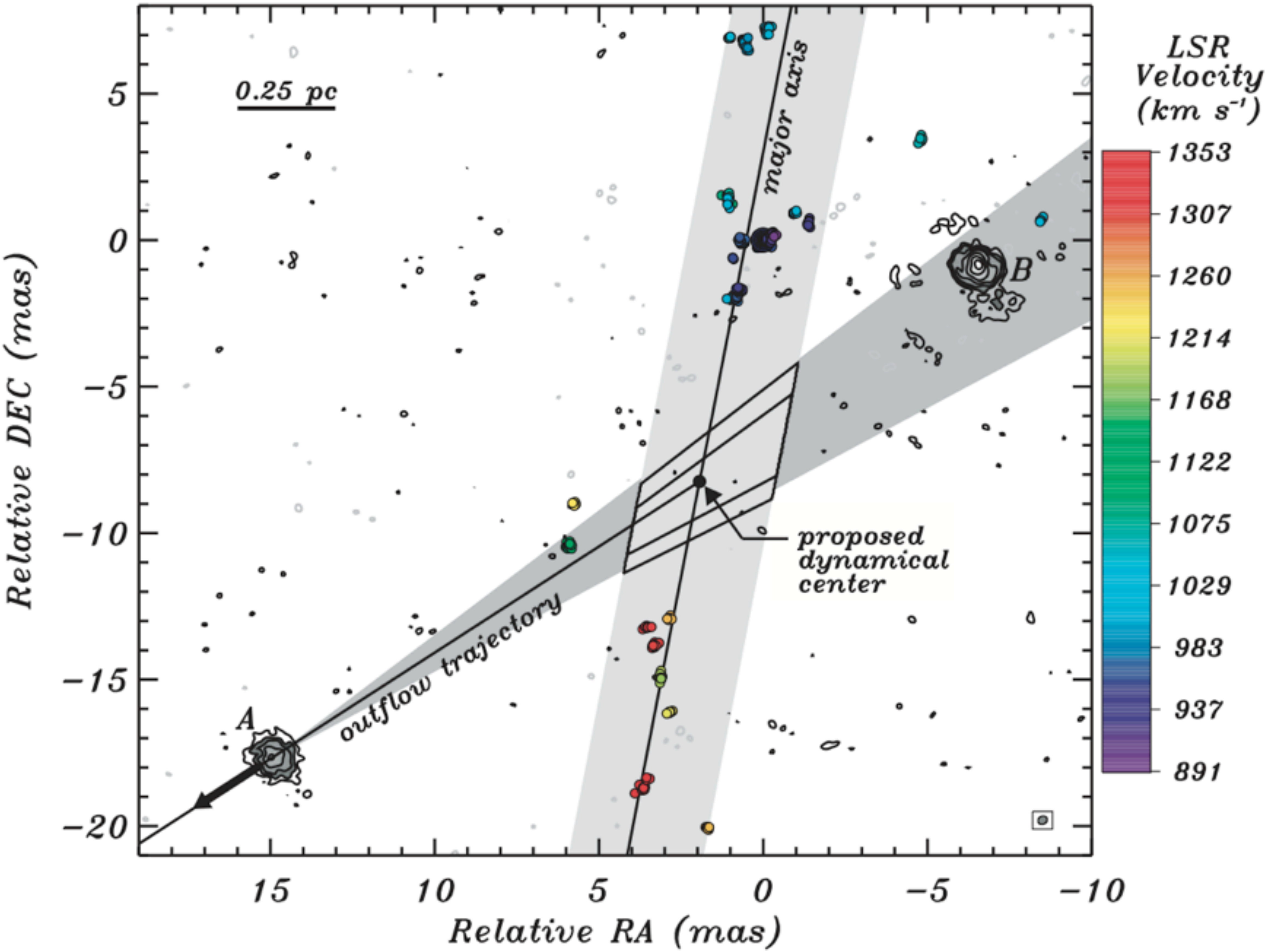
Outline

- Requirements for fueling AGN
- Observations of gas surface density, turbulent velocity, T
    - Q~1
    - Star formation
- Simulations---bars, spiral arms, eccentric disks
- Star clusters
    - mass-radius relation
- Stellar feedback
- Star formation versus accretion onto AGN
- AGN feedback
- Conclusions

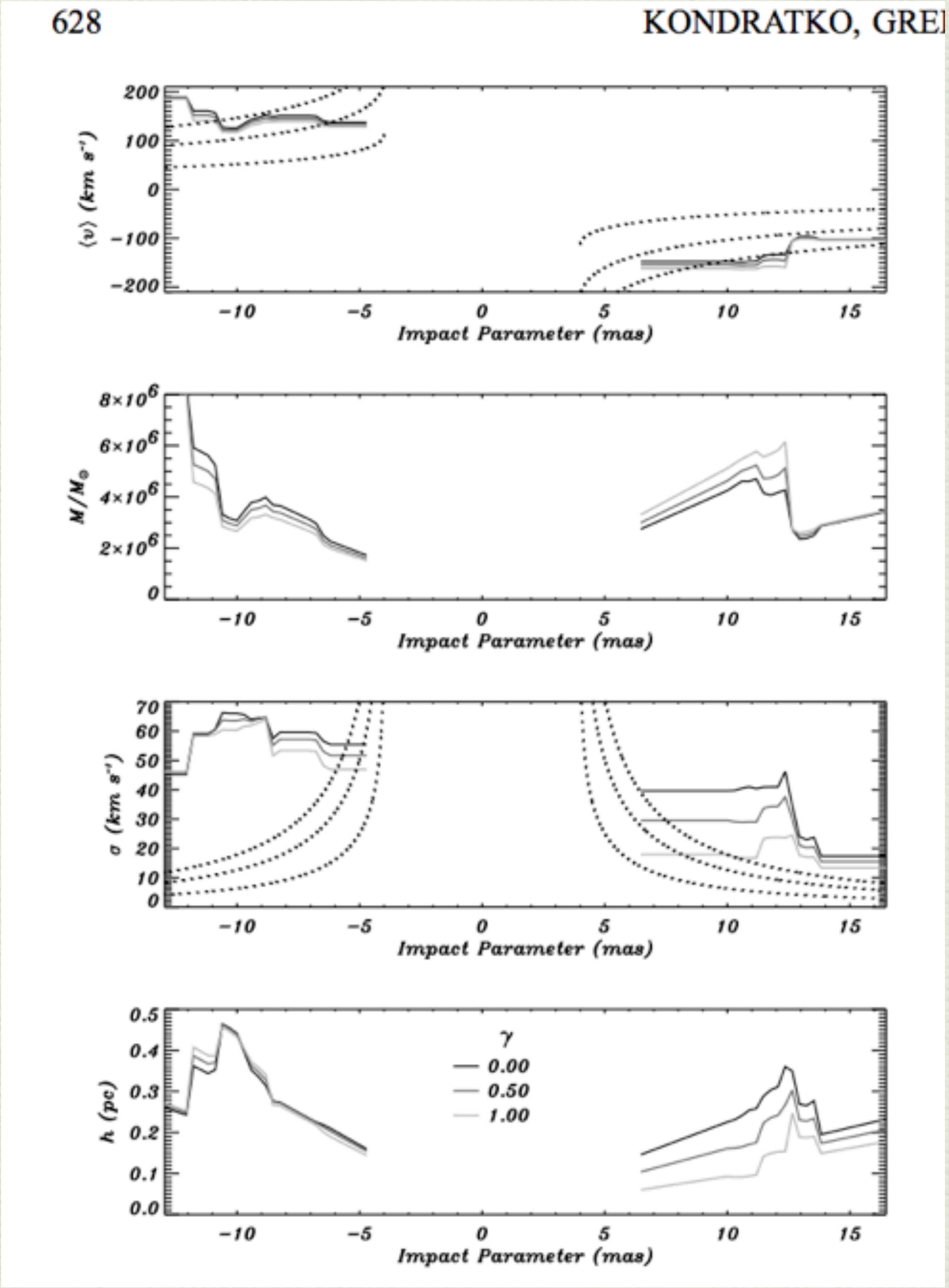
Feeding a QSO

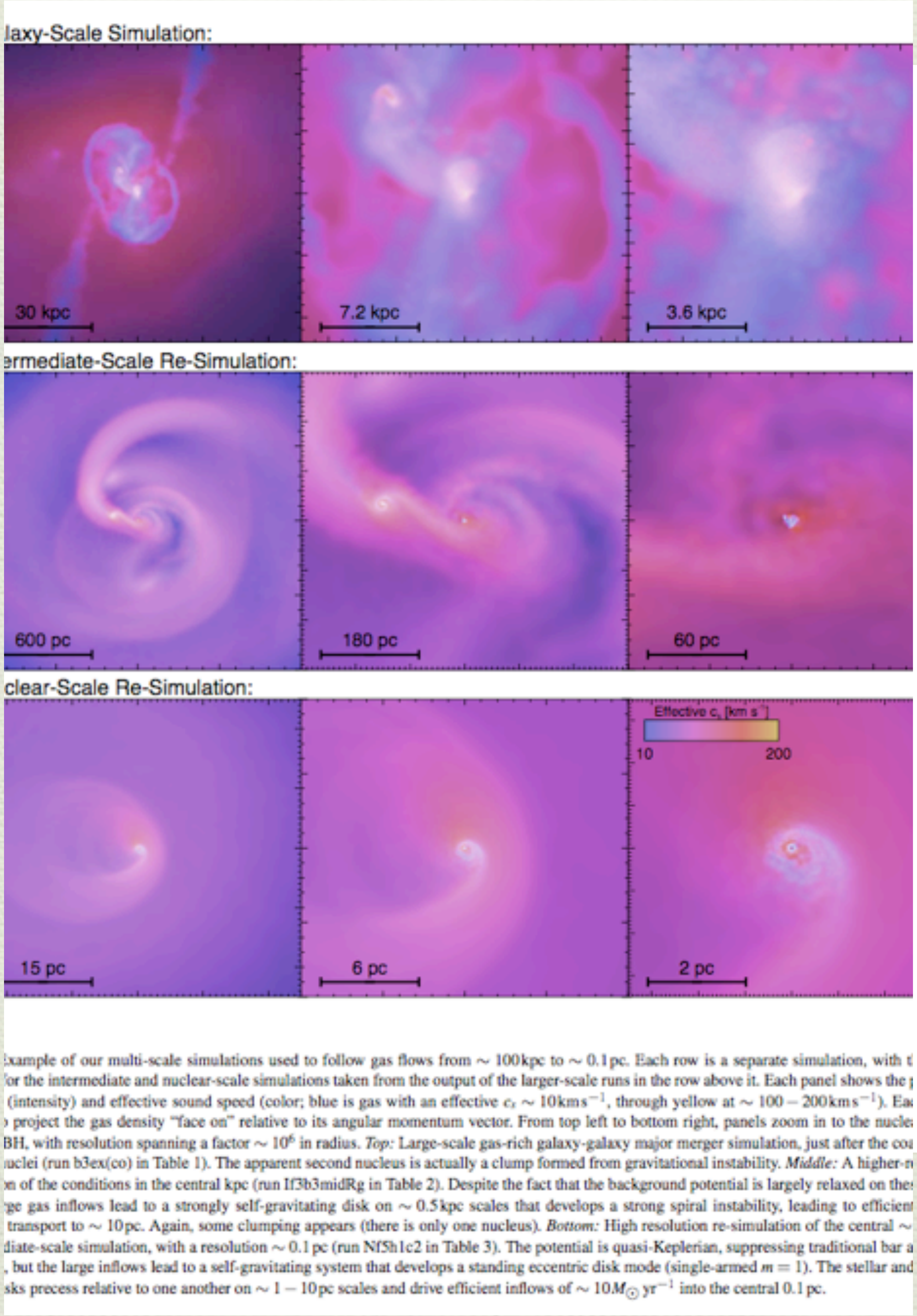
- QSO $L \sim 10^{46}$ erg/s => dM/dt~2 solar masses/year
- $dM/dt = 2\pi r\, v_r \Sigma_g \sim 2\pi r\, v_c \Sigma_g (v_r/v_c) \Rightarrow \Sigma_g \sim 1\text{-}100\ (1\text{pc}/r)$ g cm^{-2}
- $M_{BH} \sim 10^9\ M_{sun}$ $\sigma \sim 300$km/s $r_{BH} \sim 50$pc
- $Q = v_c c_s / \pi G \Sigma$ $(c_s \Rightarrow v_T)$
- $Q < 1$ for $r > 0.1$pc


T
T_eff
log10[T_eff, T (K)]
2
3
4
5
log10[ρ (g cm^-3)]
−10
−15
−20
log10[Σ_g (g cm^-2)]
0
1
2
3
4
p_rad
p_gas
log10[p_gas, p_rad (ergs cm^-3)]
5
0
−5
−10
log10[β=p_g/p_tot]
0
−2
−4
−6
log10[h/r]
−1
−2
−3
log10[c_s (km s^-1)]
0
1
2
3
4
log10[κ (cm^2 g^-1)]
0
−2
−4
log10[τ_V]
2
1
0
−1
−2
−4
−2
0
2
log10[R (pc)]
log10[R (pc)]
log10[R (pc)]



0.25 pc
major axis
outflow trajectory
proposed dynamical center
A
B
LSR Velocity (km s⁻¹)
1353
1307
1260
1214
1168
1122
1075
1029
983
937
891
Relative DEC (mas)
Relative RA (mas)
5
0
−5
−10
−15
−20
15
10
5
0
−5
−10


628 KONDRATKO, GRE



xample of our multi-scale simulations used to follow gas flows from ~ 100kpc to ~ 0.1pc. Each row is a separate simulation, with t or the intermediate and nuclear-scale simulations taken from the output of the larger-scale runs in the row above it. Each panel shows the (intensity) and effective sound speed (color; blue is gas with an effective $c_s \sim 10\,\mathrm{km\,s^{-1}}$, through yellow at $\sim 100-200\,\mathrm{km\,s^{-1}}$). Ea project the gas density "face on" relative to its angular momentum vector. From top left to bottom right, panels zoom in to the nucle BH, with resolution spanning a factor $\sim 10^6$ in radius. *Top:* Large-scale gas-rich galaxy-galaxy major merger simulation, just after the coa uclei (run b3ex(co) in Table 1). The apparent second nucleus is actually a clump formed from gravitational instability. *Middle:* A higher-r n of the conditions in the central kpc (run If3b3midRg in Table 2). Despite the fact that the background potential is largely relaxed on the ge gas inflows lead to a strongly self-gravitating disk on ~ 0.5kpc scales that develops a strong spiral instability, leading to efficien transport to ~ 10pc. Again, some clumping appears (there is only one nucleus). *Bottom:* High resolution re-simulation of the central $\sim$ diate-scale simulation, with a resolution ~ 0.1pc (run Nf5h1c2 in Table 3). The potential is quasi-Keplerian, suppressing traditional bar a , but the large inflows lead to a self-gravitating system that develops a standing eccentric disk mode (single-armed $m = 1$). The stellar and sks precess relative to one another on $\sim 1-10$pc scales and drive efficient inflows of $\sim 10 M_{\odot}\,\mathrm{yr^{-1}}$ into the central 0.1 pc.

14 *Hopkins and Quataert*

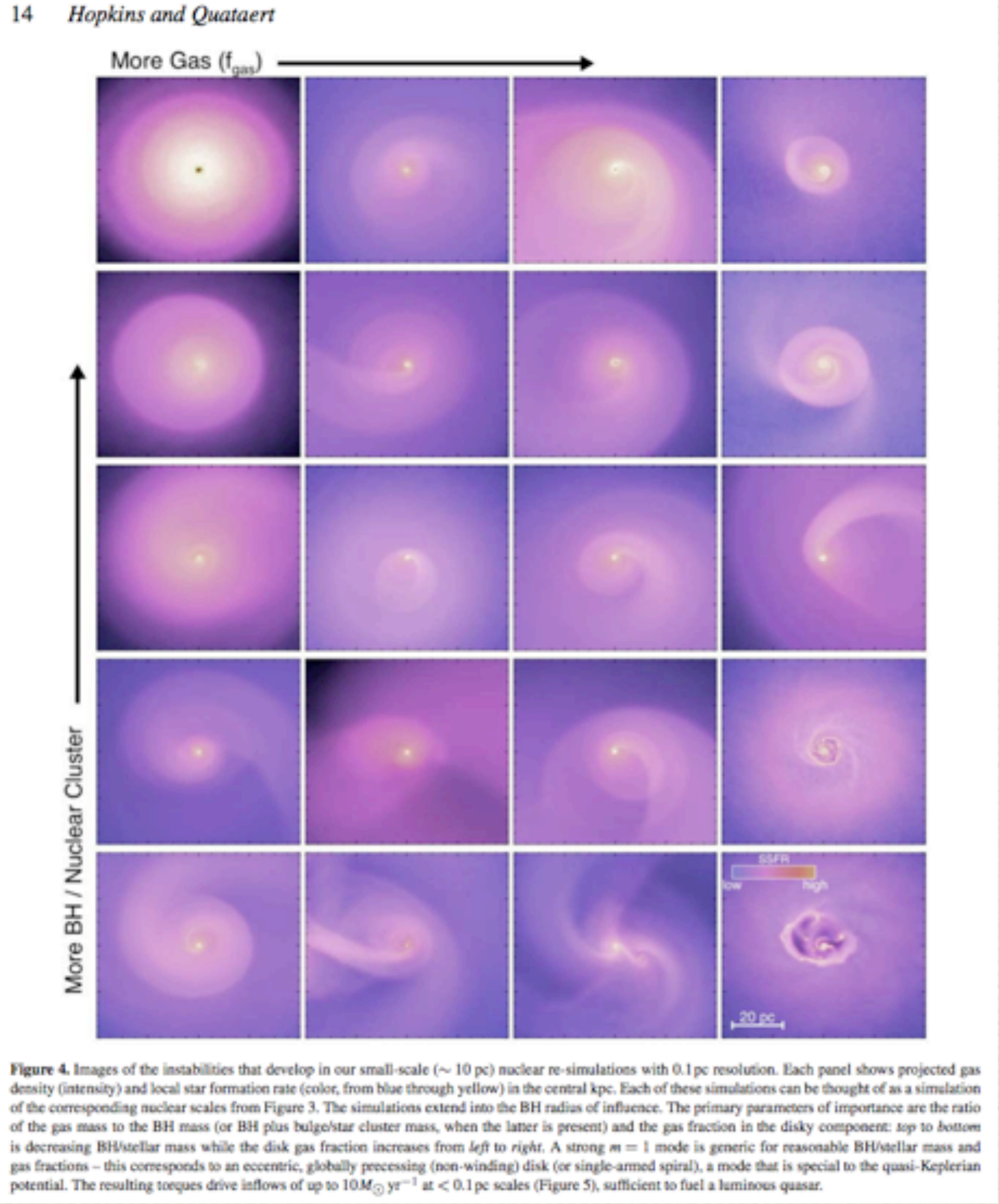


Figure 4. Images of the instabilities that develop in our small-scale (~ 10 pc) nuclear re-simulations with 0.1 pc resolution. Each panel shows projected gas density (intensity) and local star formation rate (color, from blue through yellow) in the central kpc. Each of these simulations can be thought of as a simulation of the corresponding nuclear scales from Figure 3. The simulations extend into the BH radius of influence. The primary parameters of importance are the ratio of the gas mass to the BH mass (or BH plus bulge/star cluster mass, when the latter is present) and the gas fraction in the disky component: *top* to *bottom* is decreasing BH/stellar mass while the disk gas fraction increases from *left* to *right*. A strong $m = 1$ mode is generic for reasonable BH/stellar mass and gas fractions – this corresponds to an eccentric, globally precessing (non-winding) disk (or single-armed spiral), a mode that is special to the quasi-Keplerian potential. The resulting torques drive inflows of up to $10 M_{\odot}\,\mathrm{yr^{-1}}$ at < 0.1 pc scales (Figure 5), sufficient to fuel a luminous quasar.

Giant Molecular Cloud (GMC) and star cluster masses:

Toomre mass

$$M_{Toomre} = \pi H^2 \Sigma_g \tag{1}$$

$$H = \left(\frac{v_T}{v_c}\right) R \tag{2}$$

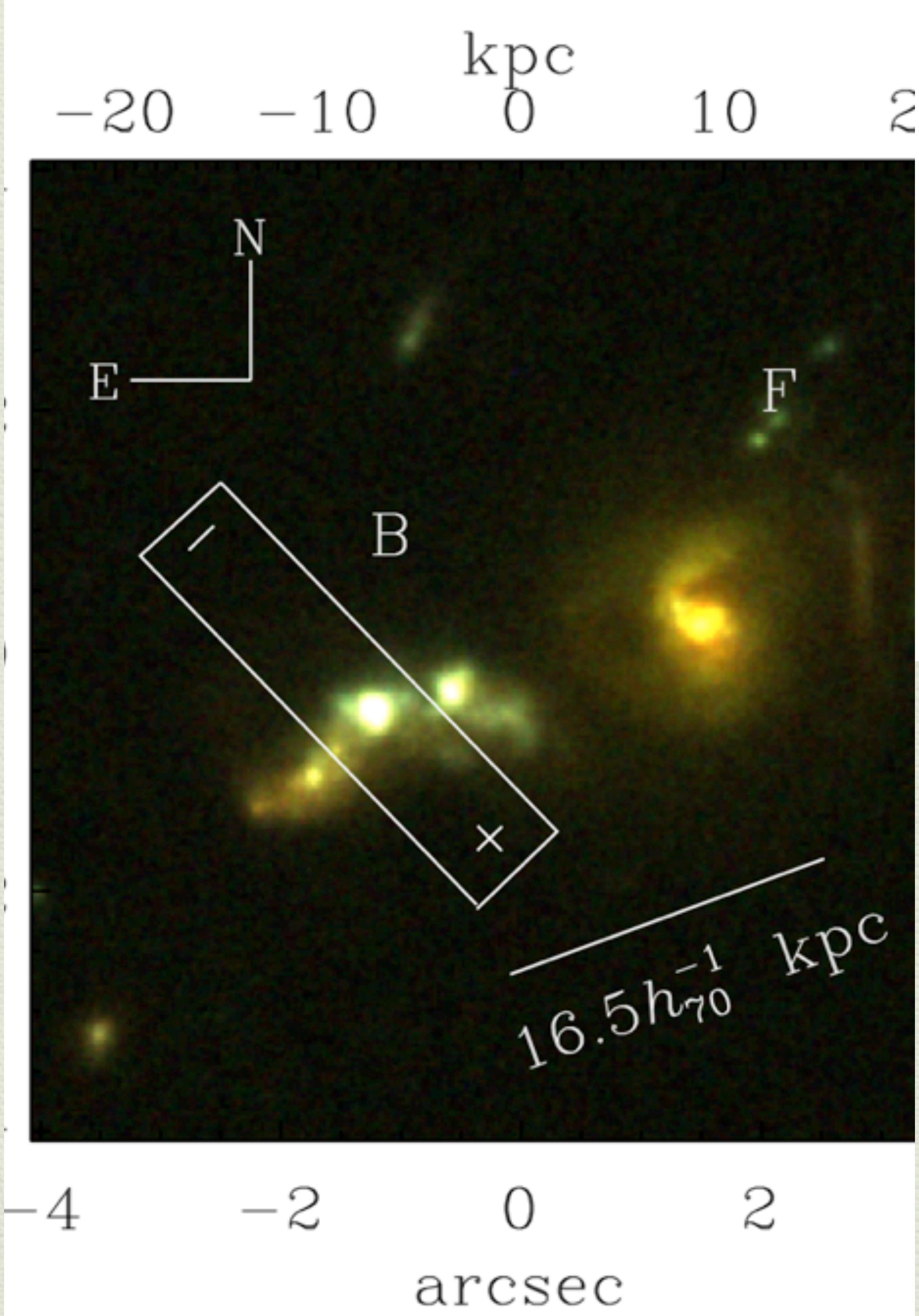
This is consistent with observed GMC masses in both the Milky Way and nearby spirals.

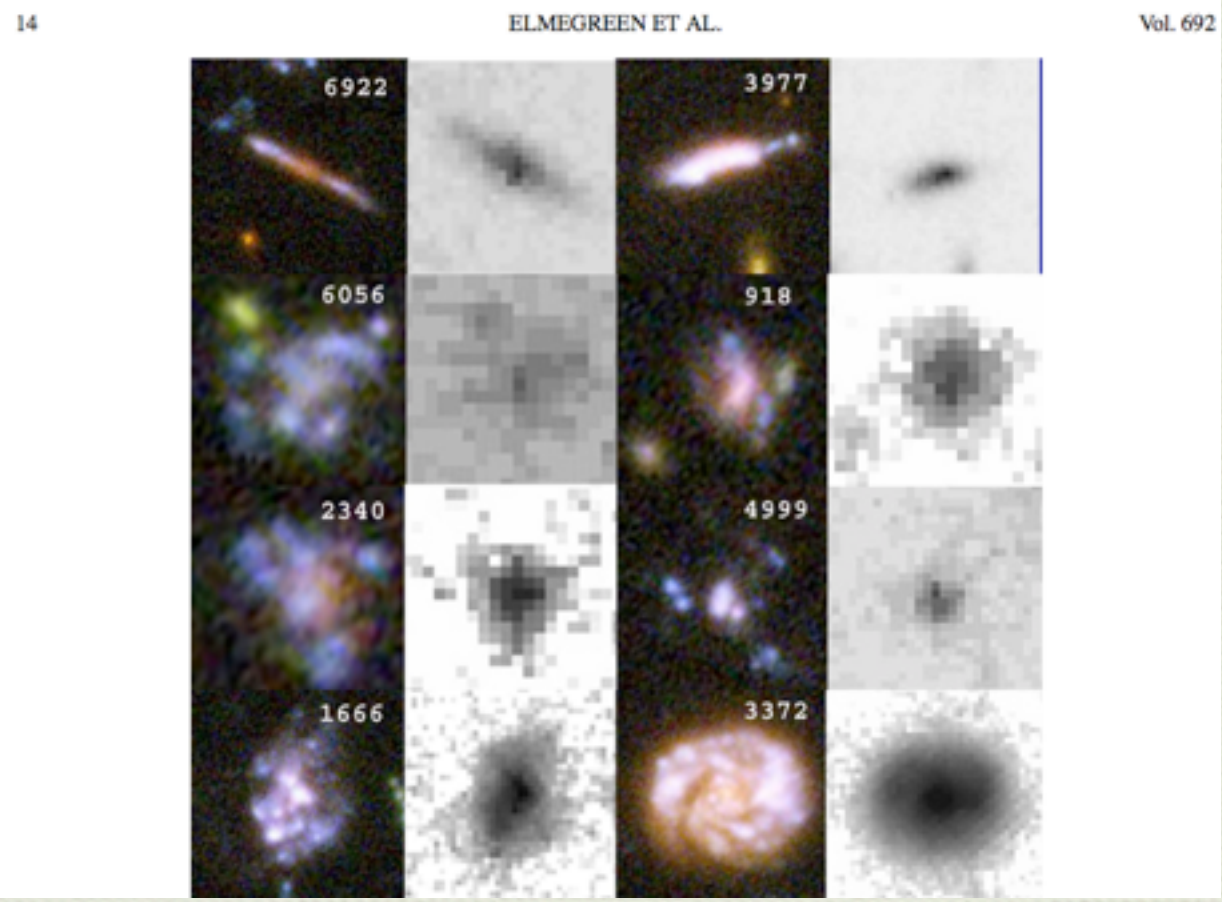
Stellar cluster mass appears to be given by the Eddington limit:

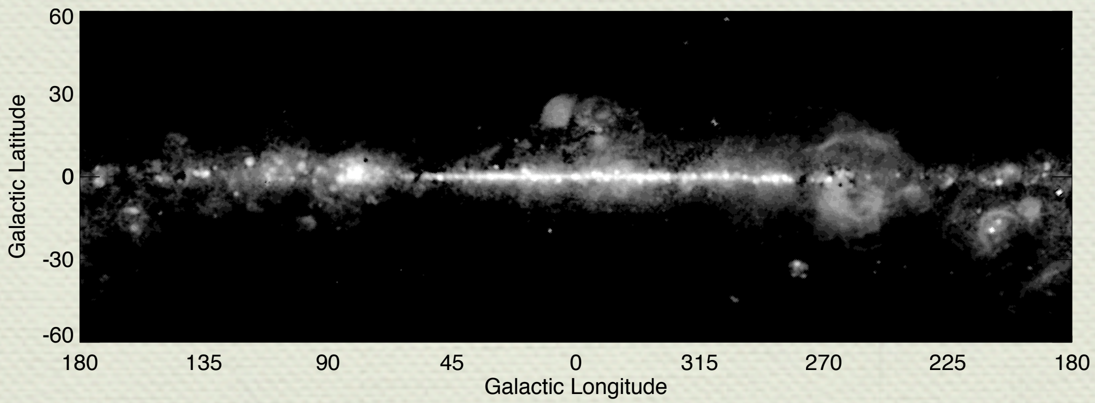
$$\frac{G M_{GMC} M_{GMC}}{R_{GMC}^2} = \frac{L}{c} = \left(\frac{L}{M_* c}\right) M_* \tag{3}$$

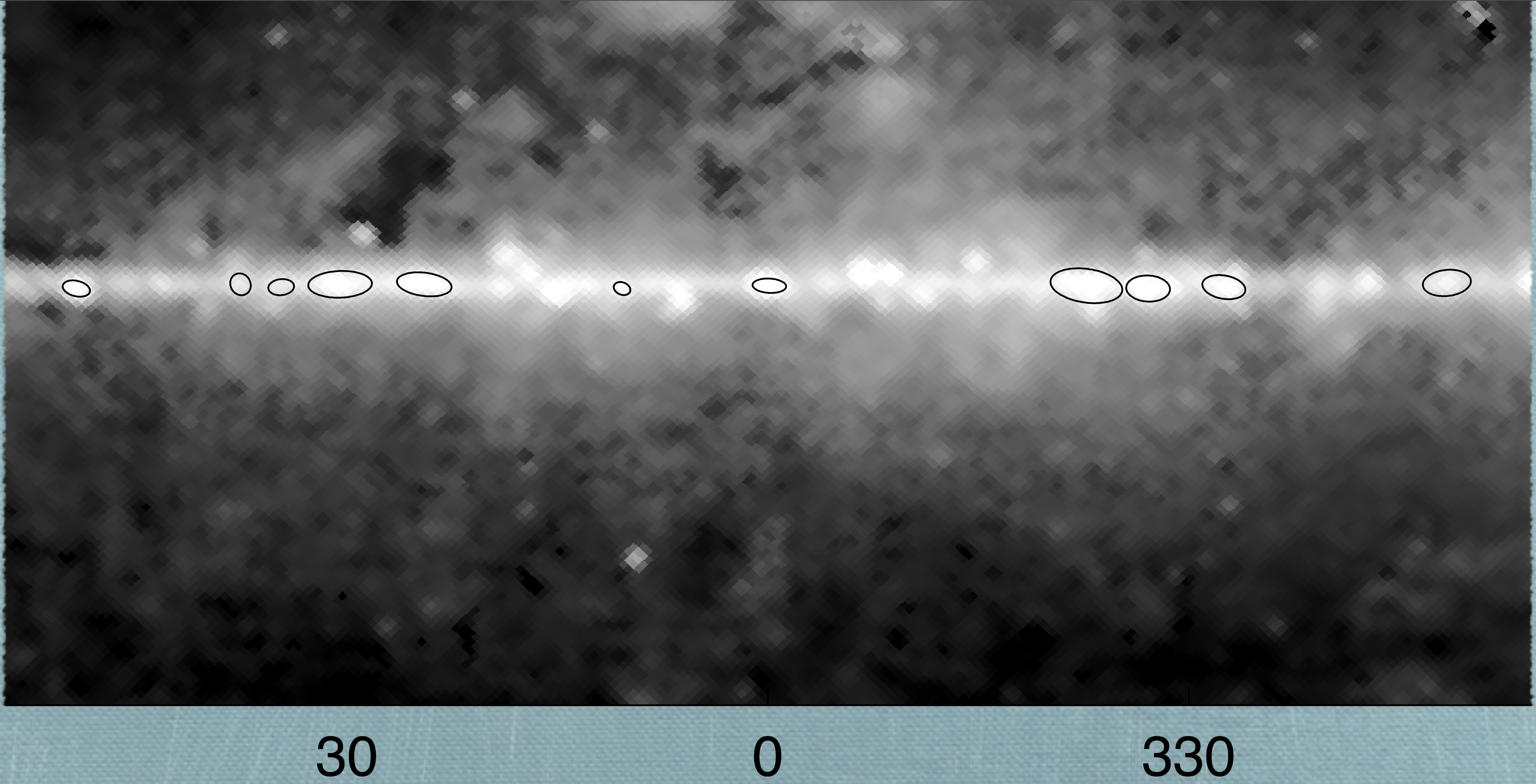
so

$$\epsilon_{GMC} \equiv \frac{M_*}{M_{GMC}} = \left[\frac{4\pi G}{c}\left(\frac{L}{M_*}\right)\right] \Sigma_{GMC} \approx \Sigma_{GMC} \tag{4}$$

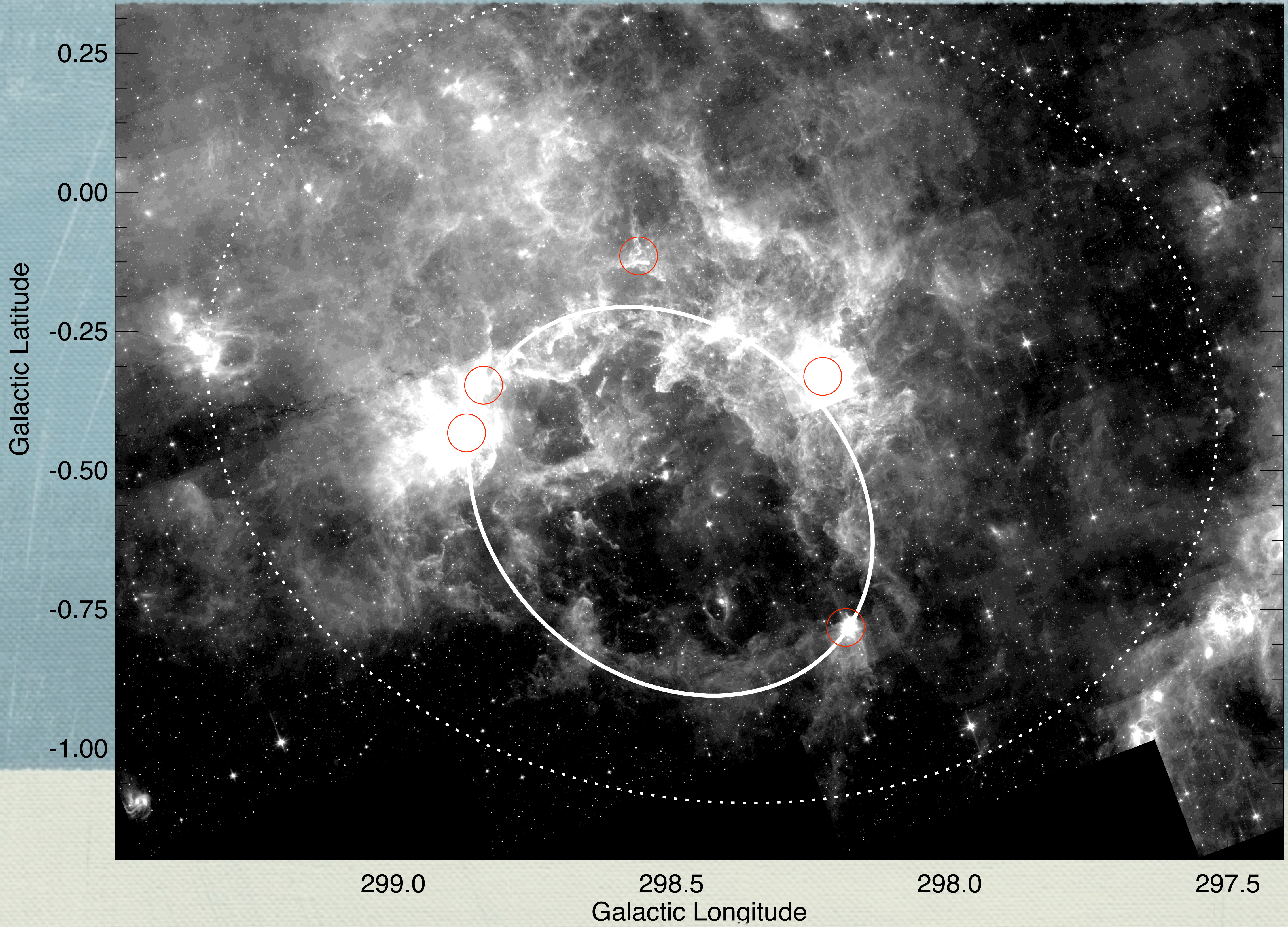



14 ELMEGREEN ET AL. Vol. 692

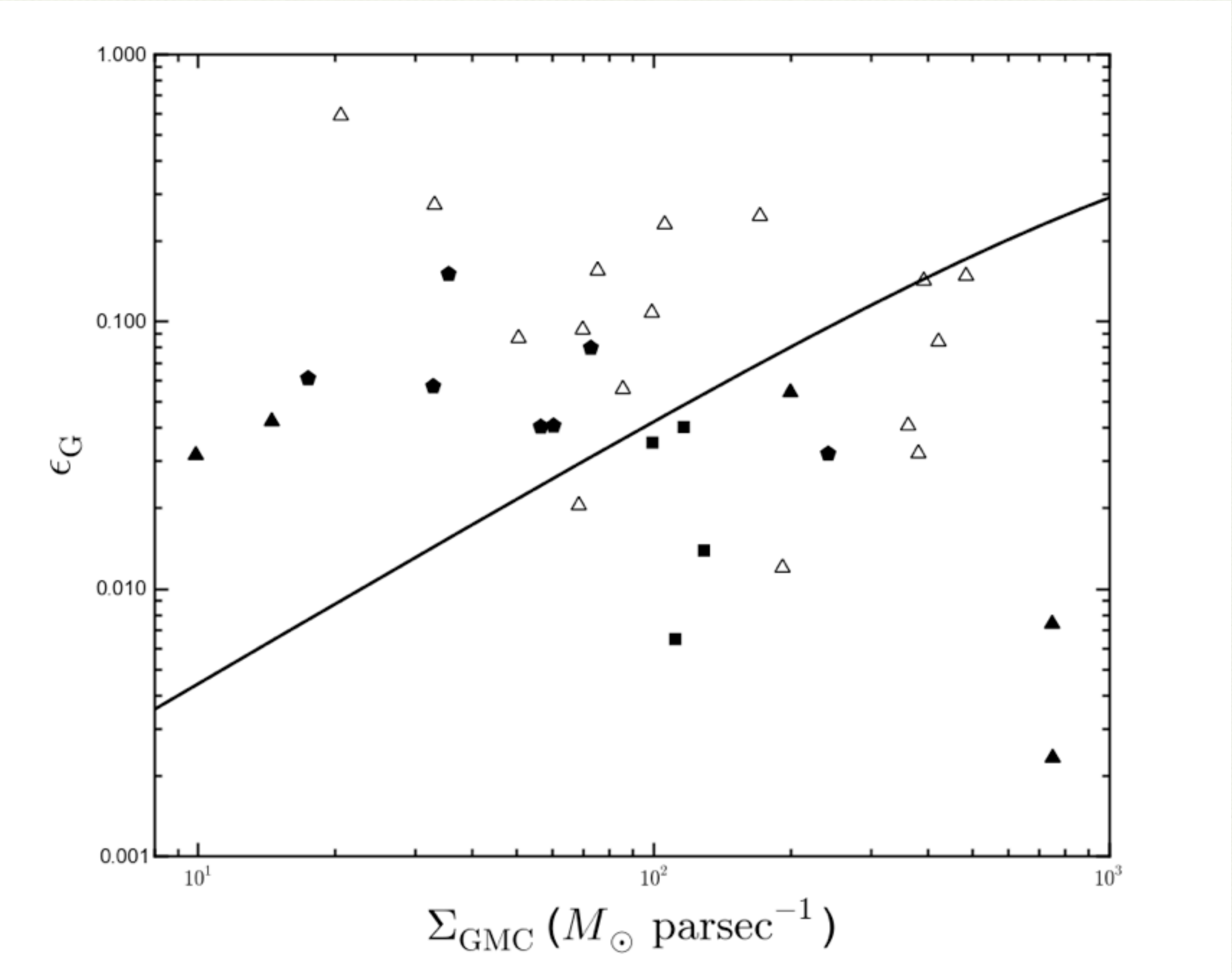




Finding Milky Way Clusters With WMAP



Star Cluster Masses


1.000
0.100
0.010
0.001
ϵ_G
10^1
10^2
10^3
$\Sigma_{\rm GMC}\,(M_\odot\ {\rm parsec}^{-1})$

Star Cluster Radii

Simple force balance for a ball of gas collapsing under its own gravity:

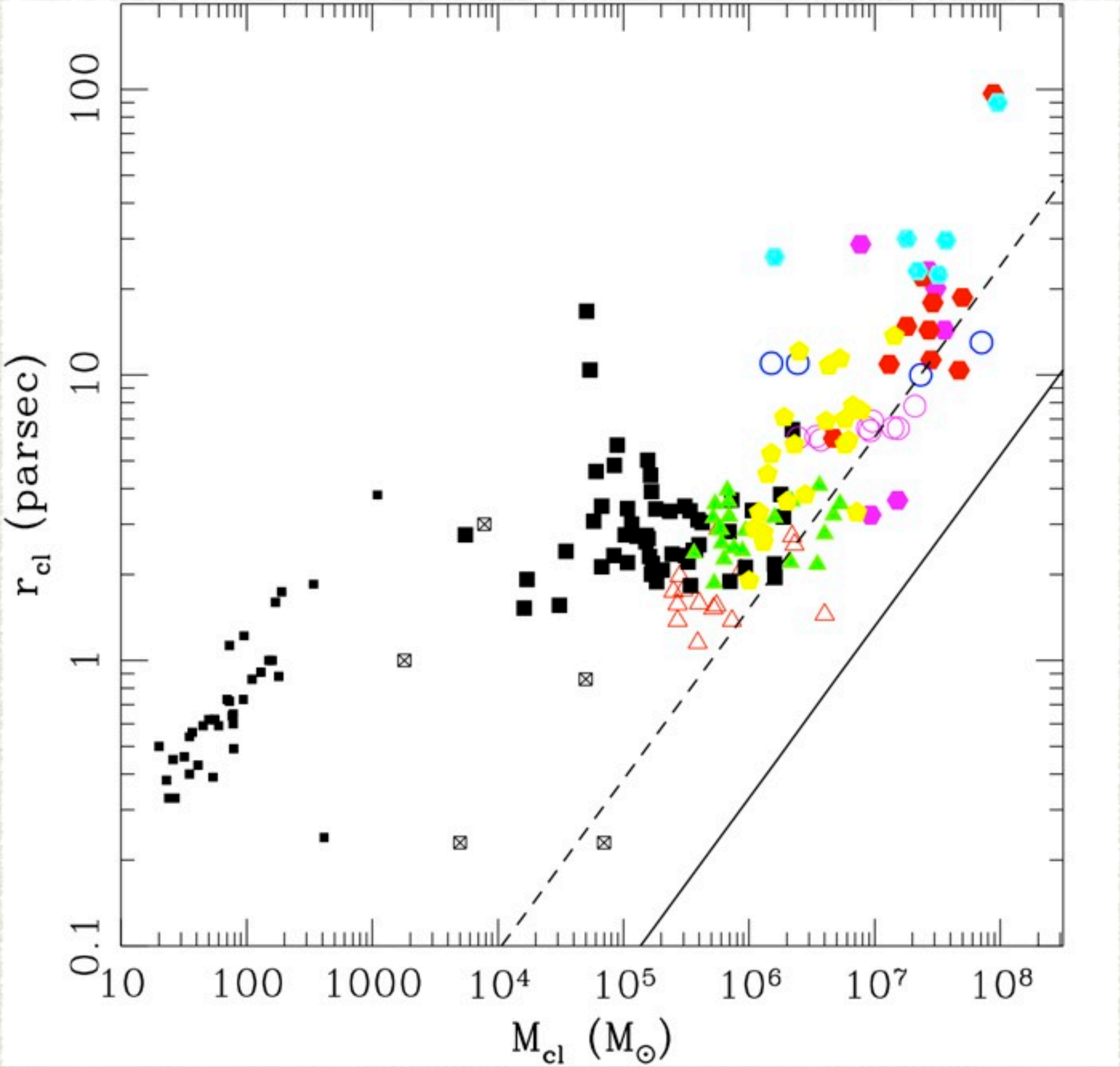
$$\begin{aligned} F_{grav} &\approx \frac{GMM}{r^2} \\ F_{rad} &= \frac{\tau L}{c} \end{aligned}$$

where

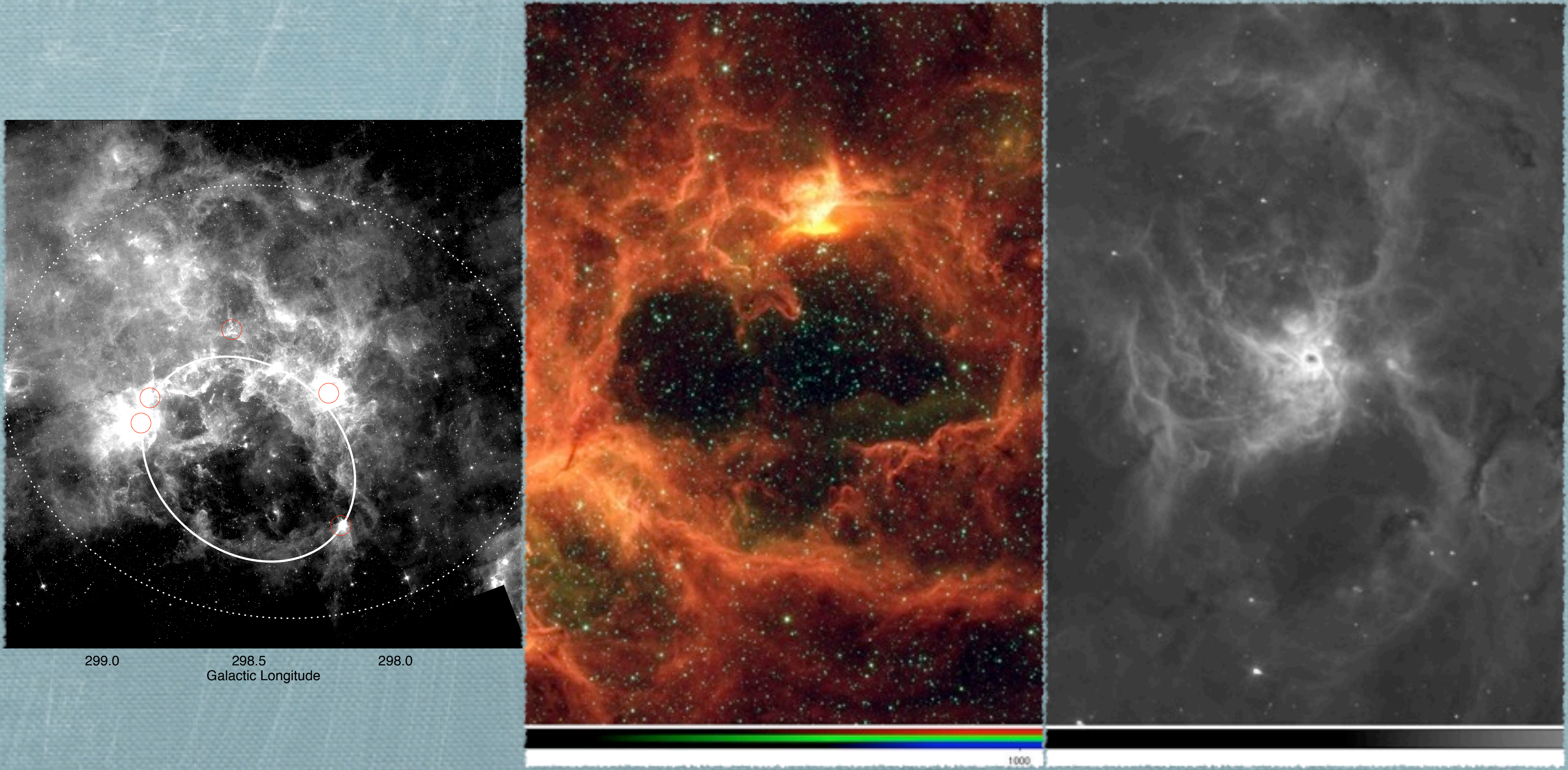
$$\begin{aligned} \tau &= \kappa \frac{M}{4\pi r^2} \\ L &= \frac{GM\dot{M}}{r} \approx \frac{GMM}{r^2 v} \end{aligned}$$

Combining all these and solving for r

$$r \approx \left(\frac{\kappa}{4\pi c}\right)^{2/5} G^{1/5} M^{3/5}$$



100
10
1
0.1
10
100
1000
10^4
10^5
10^6
10^7
10^8
r_{cl} (parsec)
M_{cl} ($M_\odot$)



Stellar Feedback

How Do Stars Affect (Feedback on) the ISM?

- Supernovae
- Stellar Winds --- Don't see associated x-ray emission
- HII regions ---- Irrelevant for starburst galaxies ($c_s << v_T$)
- Radiation Pressure

Feedback Continued

- The observational consequence of feedback is the suppression of star formation, and the ejection of gas
- Turbulent velocities, associated with suppressed star formation, appear to be powered by expanding bubbles in the Milky Way
  - $L_{Turb} = \pi R^2 H \varrho v_T^2 \; v_T / H = \pi R^2 \varrho v_T^3 \approx 2\text{x}10^{39}$ erg s^{-1}
- Supernovae are ineffective in ULIRGs and SMG
  - Too late to disrupt GMCs
  - $L_{SN} < L_{Turb}$

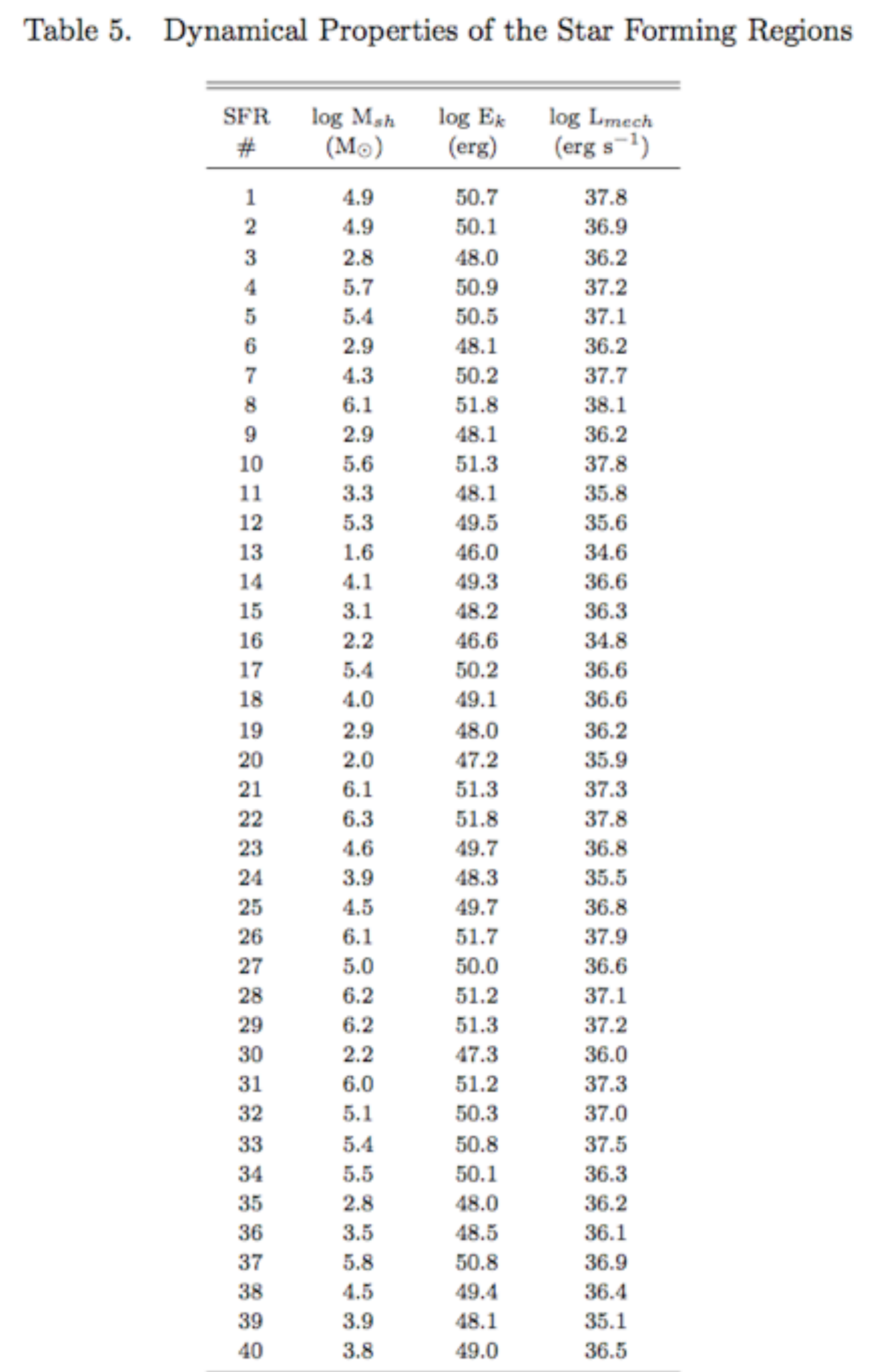


Table 5. Dynamical Properties of the Star Forming Regions

SFR #	log M_{sh} ($M_\odot$)	log E_k (erg)	log L_{mech} (erg s^{-1})
1	4.9	50.7	37.8
2	4.9	50.1	36.9
3	2.8	48.0	36.2
4	5.7	50.9	37.2
5	5.4	50.5	37.1
6	2.9	48.1	36.2
7	4.3	50.2	37.7
8	6.1	51.8	38.1
9	2.9	48.1	36.2
10	5.6	51.3	37.8
11	3.3	48.1	35.8
12	5.3	49.5	35.6
13	1.6	46.0	34.6
14	4.1	49.3	36.6
15	3.1	48.2	36.3
16	2.2	46.6	34.8
17	5.4	50.2	36.6
18	4.0	49.1	36.6
19	2.9	48.0	36.2
20	2.0	47.2	35.9
21	6.1	51.3	37.3
22	6.3	51.8	37.8
23	4.6	49.7	36.8
24	3.9	48.3	35.5
25	4.5	49.7	36.8
26	6.1	51.7	37.9
27	5.0	50.0	36.6
28	6.2	51.2	37.1
29	6.2	51.3	37.2
30	2.2	47.3	36.0
31	6.0	51.2	37.3
32	5.1	50.3	37.0
33	5.4	50.8	37.5
34	5.5	50.1	36.3
35	2.8	48.0	36.2
36	3.5	48.5	36.1
37	5.8	50.8	36.9
38	4.5	49.4	36.4
39	3.9	48.1	35.1
40	3.8	49.0	36.5

Star Formation vs. AGN

- To feed a Quasar, the accretion timescale must be comparable to the star formation timescale $\tau_{acc} \approx \tau_* = M_g/(dM_*/dt)$
    - Nobody has figured out how to do this!
- Bars within Bars (Shloshman & Begelman) is part of the story
- Eccentric disks?
- Break Kennicutt?
    - $d\Sigma_*/dt = 0.017\ \Sigma_g / \tau_{dyn}$
    - FIR optically thick star formation?

AGN Feedback

- Energy Feedback is popular, but it is hard to see how it can work during a starburst (when there is lots of gas around)
  - In addition, it predicts $M_{BH} \sim \sigma^5$
- Momentum feedback may work, but will not disrupt the host galaxy's ISM
  - Instead, it will limit the maximum mass of the hole

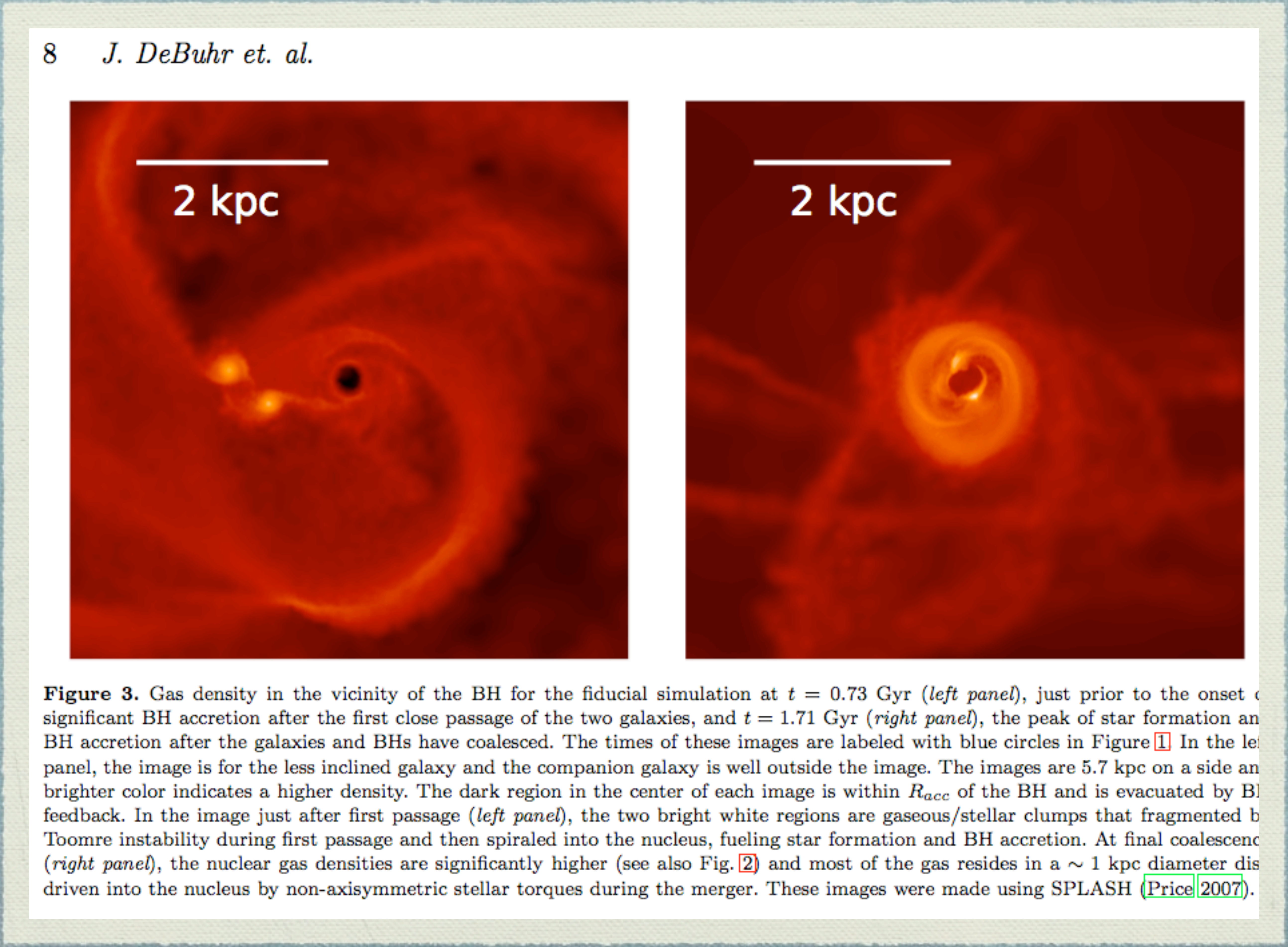


Figure 3. Gas density in the vicinity of the BH for the fiducial simulation at $t = 0.73$ Gyr (*left panel*), just prior to the onset significant BH accretion after the first close passage of the two galaxies, and $t = 1.71$ Gyr (*right panel*), the peak of star formation an BH accretion after the galaxies and BHs have coalesced. The times of these images are labeled with blue circles in Figure 1. In the le panel, the image is for the less inclined galaxy and the companion galaxy is well outside the image. The images are 5.7 kpc on a side an brighter color indicates a higher density. The dark region in the center of each image is within R_{acc} of the BH and is evacuated by B feedback. In the image just after first passage (*left panel*), the two bright white regions are gaseous/stellar clumps that fragmented b Toomre instability during first passage and then spiraled into the nucleus, fueling star formation and BH accretion. At final coalescenc (*right panel*), the nuclear gas densities are significantly higher (see also Fig. 2) and most of the gas resides in a ~ 1 kpc diameter dis driven into the nucleus by non-axisymmetric stellar torques during the merger. These images were made using SPLASH (Price 2007).

Conclusions

- We have a handle on the masses of GMCs, and on the resulting masses and radii of star clusters
- Stellar feedback appears to arise from radiation pressure on dust (at least in the Milky Way)
- This may lead to the slow rate of star formation given by Kennicutt
- We still don’t know how to feed quasars
    - But we are making progress