Modeling the circumnuclear medium around quiescent SMBHs.

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Motivation for studying circumnuclear medium (CNM):

1. Observational constraints on BH occupation fraction.
   - Miller et al. (2014) find empirical relationship between x-ray luminosity, L_x, and galaxy mass, $M_{\rm gal}$.
   - Combine with upper limits in L_x for small $M_{\rm gal}$ to infer occupation fraction less than unity for small galaxies
   - Is this appropriate?
2. Emission from relativistic TDE jets (*Swift* J1644+57)
   - Are TDEs radio quiet due to dense CNM?
3. To what extent can properties of CNM of quiescent galaxies be understood by considering just the stellar mass loss from stars?
   - X-ray luminosity scaling with galaxy properties.
4. Is a steady state gas density profile possible?
   - Thermal instability?

Results-Profiles and $\dot{M}$.

1. Collect winds inside of stagnation radius r_s (where v=0).
2. $r_s \simeq \frac{7}{2} G M_\bullet / v_w^2$
3. r_s sets $\dot{M}$ and ρ
   a) $\dot{M} = \eta M_*(r_s)/t_h$
   b) M_* stellar mass inside r_s
4. Thermal instability.
   a) Sets in for $v_{w,0} \lesssim 300$ km/s
   b) Global--cooling rate is greater than heating rate. Monolithic cooling of solution.
   c) Local--$t_{\rm cool} \lesssim t_{\rm ff}$. (the cooling time is less than the free-fall time. Clouds condense out of hot gas. (see e.g. McCourt et al. 2012)

Fig. 1 Radial profiles of ρ, T, and v. $M_\bullet = 10^7 M_\odot$. $v_{w,0}$=300, 600, 1200 km/s. $\rho_* \sim r^{-1-\gamma}$. r_s is marked on each profile by a square.

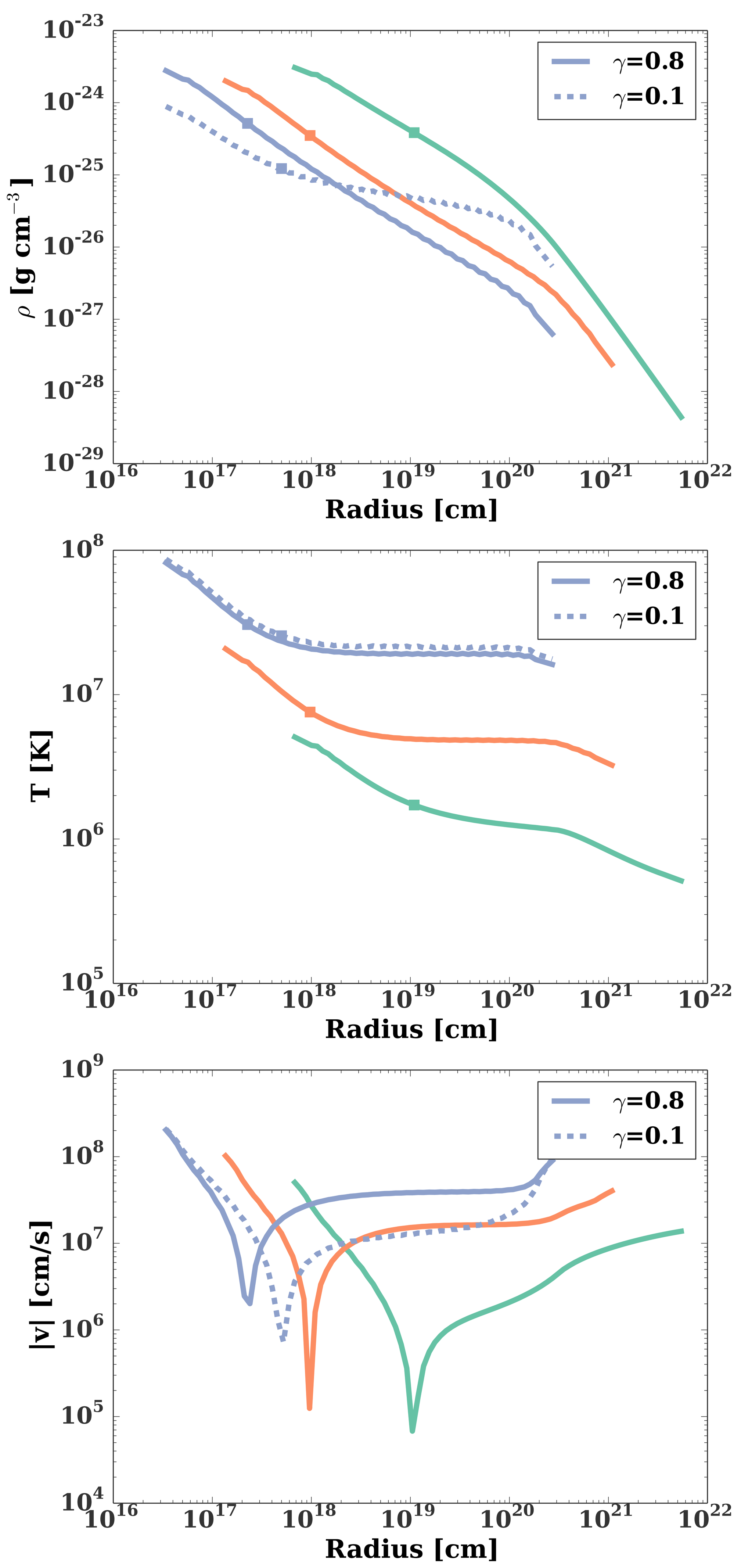


Fig.2 $\dot{M}/\dot{M}_{\rm Edd}$ versus $M_\bullet$ for cores (γ=0.1, *) and cusps (γ=0.8, ▸).

Solid (γ=0.8) and dashed lines (γ=0.1) are approximate analytic expressions.

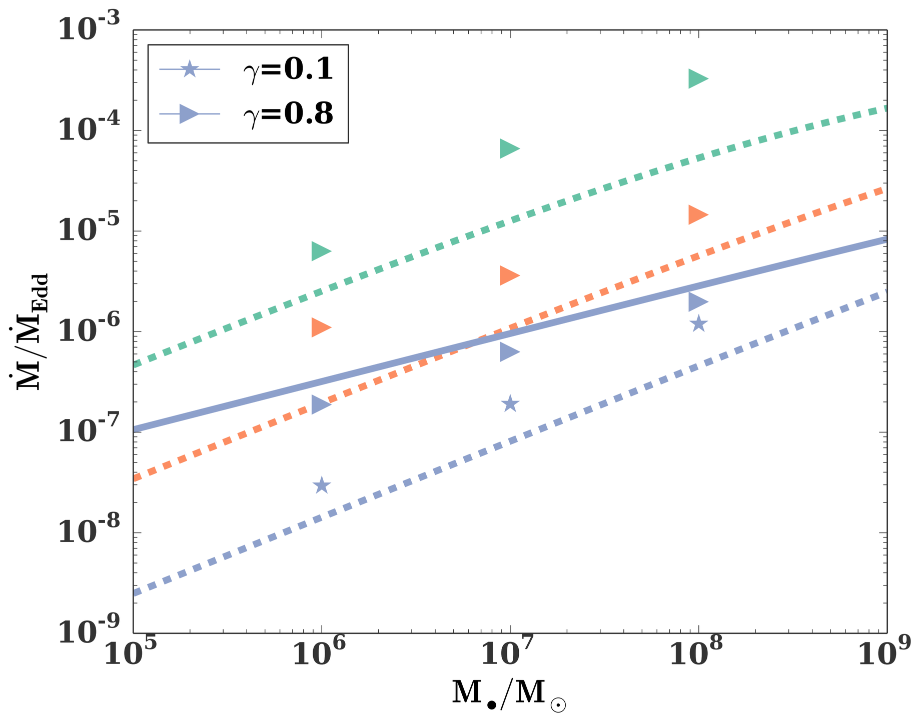
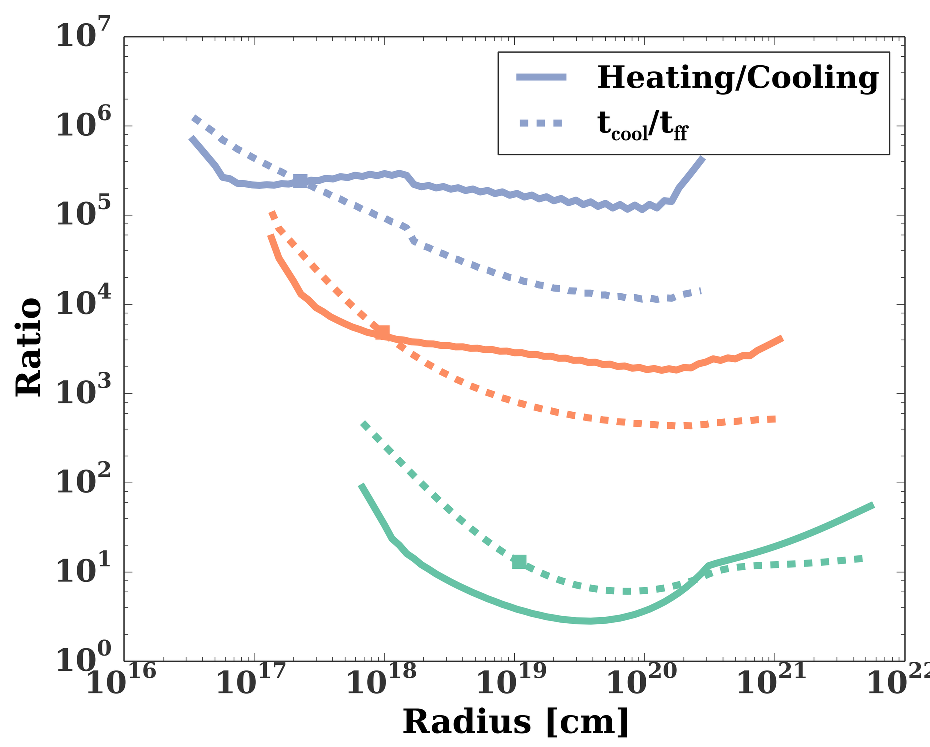


Fig. 3 Heating/Cooling and $t_{\rm cool}/t_{\rm ff}$. $v_{w,0}$=300, 600, 1200 km/s.

As $v_{w,0}$ decreases:

a. $t_{\rm cool}/t_{\rm ff}$ decrease
b. Heating/Cooling decreases
c. Thermal instability ($v_{w,0}$=300 km/s).



Model

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho r^2 v\right) = \overbrace{q}^{\eta\rho_*/t_h}$$

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r}\right) = -\frac{\partial p}{\partial r} - \rho\frac{G M_{\rm enc}}{r^2} - qv$$

$$\rho T\left(\frac{\partial s}{\partial t} + v\frac{\partial s}{\partial r}\right) = q\left[\frac{v^2}{2} + \frac{v_w^2}{2} - \frac{\gamma}{\gamma-1}c_s^2\right]$$

1. Mass source is proportional to ρ_*, the stellar density
2. $v_w = \sqrt{\sigma^2 + v_{w,0}^2}$ --heating
   a. σ --from stellar velocity dispersion
   b. $v_{w,0}$--free parameter for other sources (e.g. Stellar winds, SNe Ia etc.)
3. Look for steady state solutions
4. Neglect cooling/conduction; post-hoc checks
5. Spherical symmetry
6. See e.g. Holzer and Axelford (1970) and Quataert (2004)

Applications-Galaxy scaling relations

1. $v_{w,0}$ related to star formation rate (SFR).
2. SFR is related to $M_\bullet$.
3. $M_\bullet \rightarrow SFR \rightarrow v_{w,0}$
4. Insufficient heating from SF, to stabilize gas to cooling above $M_\bullet \gtrsim 5\times10^7 M_\odot$
5. Steady state is possible for smaller masses
6. Tension with observations? Miller et al. (2014) find $L_x \sim M_\bullet^{0.7-0.8}$.
   a) $\dot{M}/\dot{M}_{\rm Edd} \sim M_\bullet^{-0.2}$ if $L_x \sim \dot{M}$.
   b) $\dot{M}/\dot{M}_{\rm Edd} \sim M_\bullet^{-0.6}$ if $L_x \sim \dot{M}^2$.
   c) We find $\dot{M}/\dot{M}_{\rm Edd}$ increases with $M_\bullet$ (Fig. 6).
   d) However, note much of Miller sample is in thermally unstable region of parameter space.
   e) Could potentially explain discrepancy.

Fig. 4 Star formation rate vs. z for different $M_\bullet$. Assuming $M_\bullet \sim M_{\rm halo}^{1.55}$ from Bandara et al. (2012), and using fitting formulas from Moster et al. (2013).

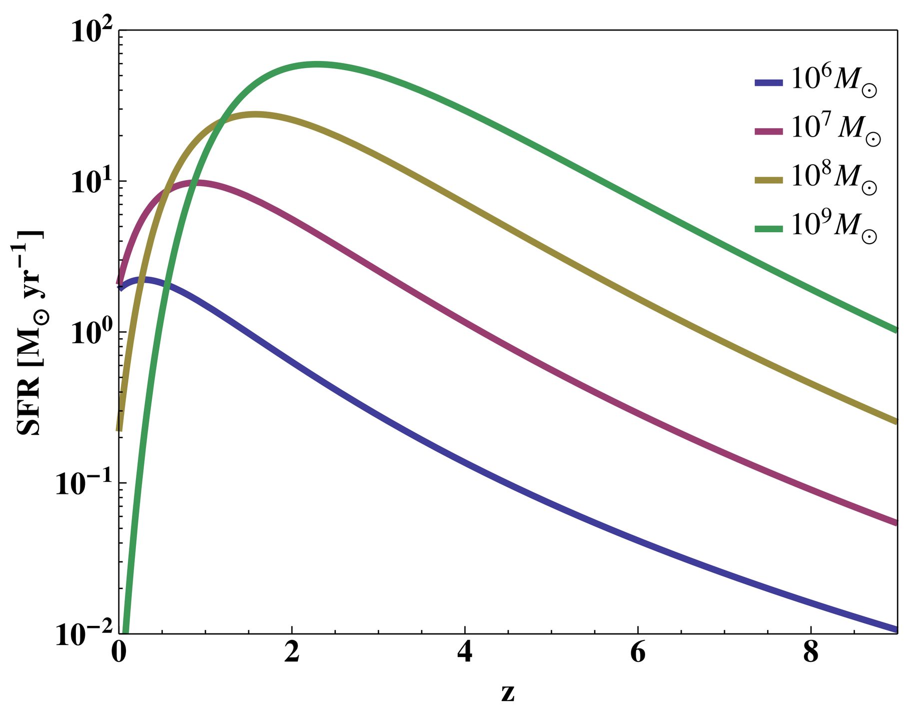


Fig. 5 Given above SFRs can calculate the $v_{w,0}$ as a function of $M_\bullet$. Heating sources include SNe Ia, Stellar winds, Millisecond pulsars (MSPs), and feedback from the black hole itself.

In this plot (and two on right) dashed vertical line indicates $v_{w,0}$ is too small to prevent thermal instability.

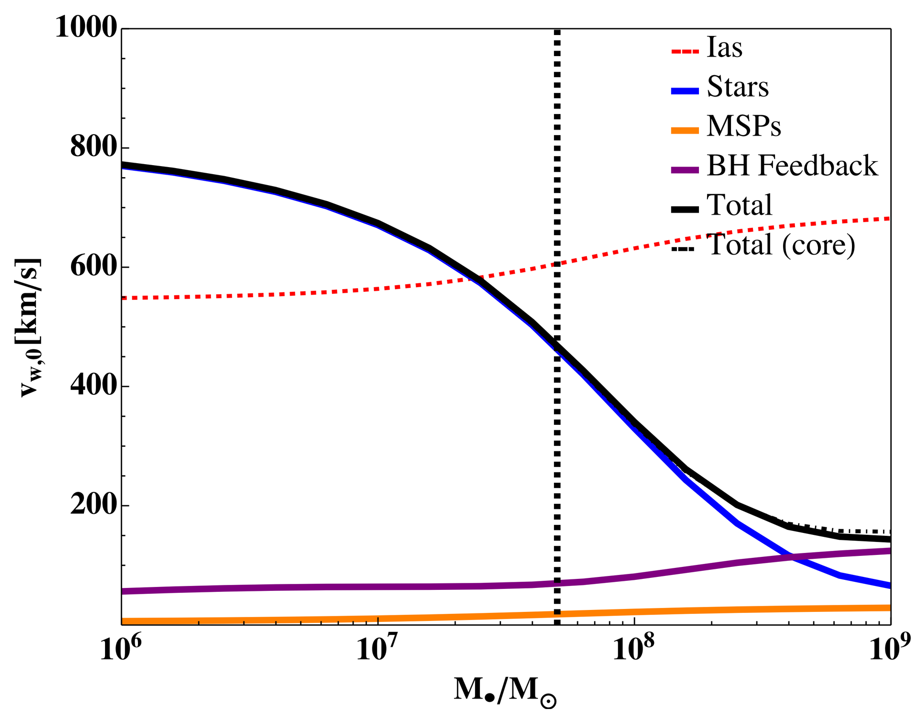


Fig. 6 $\dot{M}/\dot{M}_{\rm Edd}$ versus $M_\bullet$ calculated using the result for $v_{w,0}$ versus $M_\bullet$ in **Fig. 5**

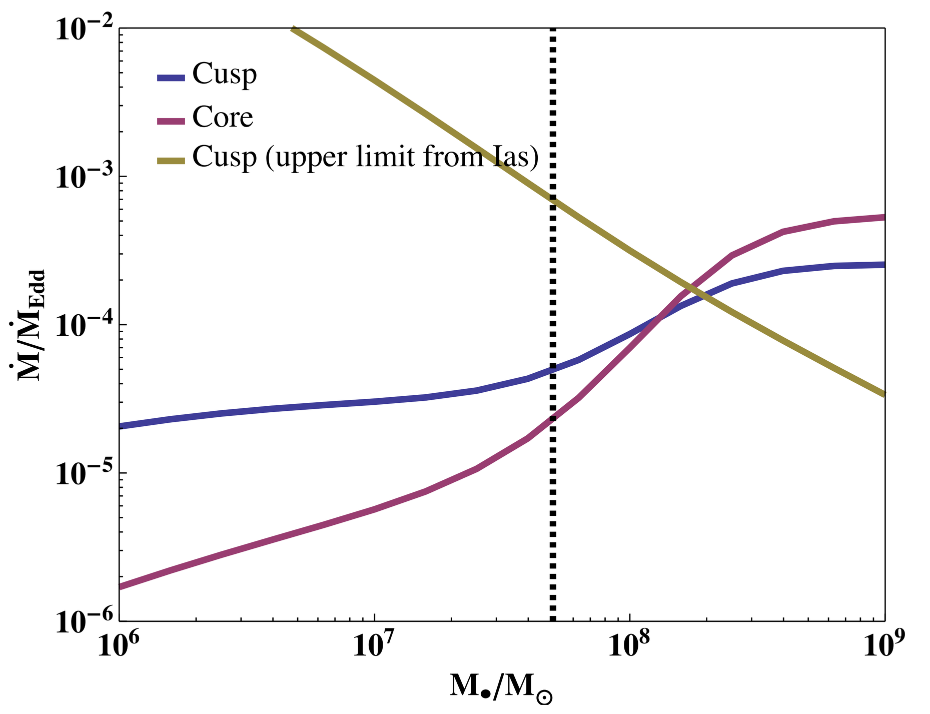
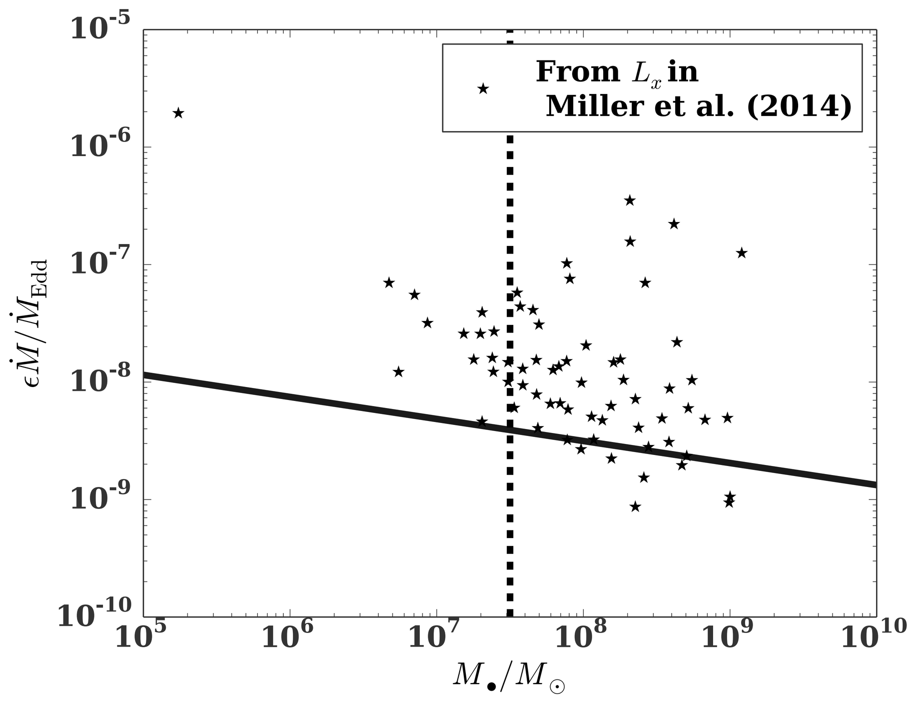


Fig. 7 Trend in $\dot{M}/\dot{M}_{\rm Edd}$ with $M_\bullet$ inferred from Miller et al. (2014) Assuming $L_x \sim \epsilon \dot{M} c^2$. Contrast with increasing trend above!

But note

a) Scatter
b) $M_\bullet > 5\times10^7 M_\odot$ don't expect model to apply due to cooling instability.



References
1. Bandara K., Crampton D., Simard L., 2009, ApJ, 704, 1135
2. Holzer T. E., Axford W. I., 1970, ARA&A, 8, 31
3. McCourt M., Sharma P., Quataert E., Parrish I. J., 2012, MN-RAS, 419, 3319
4. Miller B. P., Gallo E., Greene J. E., Kelly B. C., Treu T., Woo J.-H., Baldassare V., 2014, ArXiv e-prints
5. Moster B. P., Naab T., White S. D. M., 2013, MNRAS, 428,3121
6. Quataert E., 2004, ApJ, 613, 322