Accretion Physics for The First Massive Black Holes

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First Stars and Galaxies: Challenges for the Next Decade

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z ~ 6 Quasars

$M_{BH} \sim 10^9\ M_{sun}$

$M_{halo} \sim 10^{12}\ M_{sun}$

stellar cluster + gas + dust

$V_{escape} \sim 10^3$ km s^{-1}

z ~ 20+ Seeds (Pop III *or* Pop II)

$M_{BH} \sim 100\ M_{sun}$

$M_{halo} \sim 10^8\ M_{sun}$

dark matter + H, He + first SN

$V_{escape} \sim$ few 10 km s^{-1}

$M_{halo} \sim 10^{11}\ M_{sun}$ (z ~ 9)

$M_{halo} \sim 10^{10}\ M_{sun}$ (z ~ 13)

$M_{halo} \sim 10^9\ M_{sun}$ (z ~ 18)

$M_{halo} \sim 10^8\ M_{sun}$ (z ~ 24)

* * *

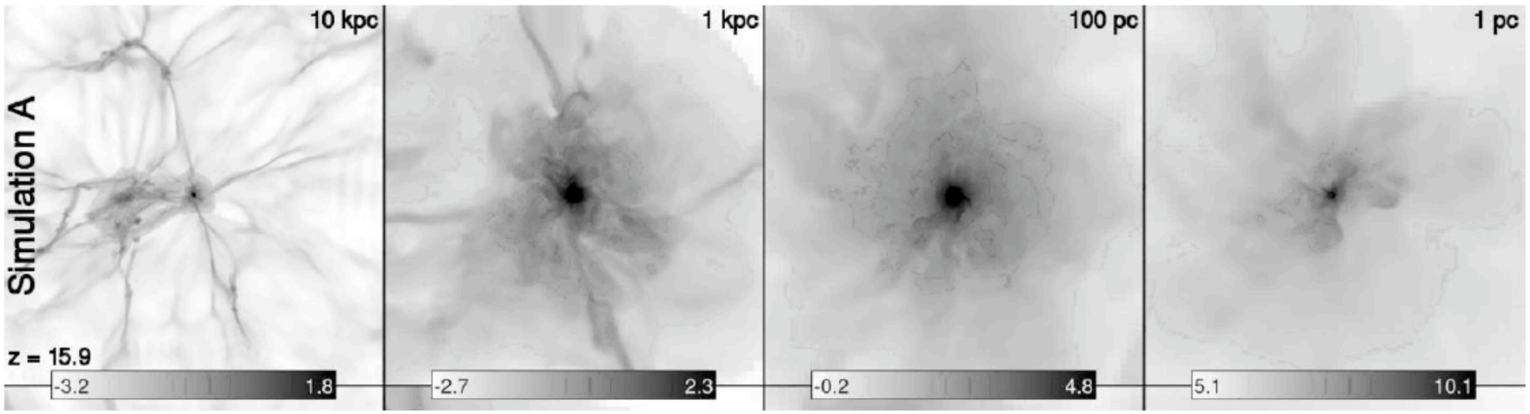
$n \sim 10^{-2}$–10^{-1} $(\mathrm{Mpc}/h)^{-3}$

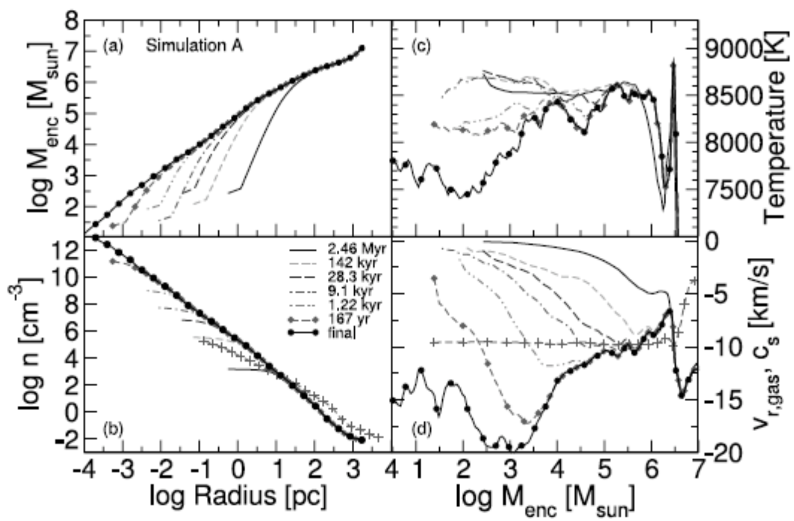
Show begins?

Standard Phrasing of the Question:

(E.g., Haiman & Loeb 2001)

- ★The accretion is radiatively-efficient (the energy liberated by accretion diffuses out of the accreting gas).
- ★Balance radiation pressure and gravity (the Eddington limit): the mass-doubling time >~ 5×10^7 years = Salpeter time
- ★From "seed" size, the black hole must double mass over 20 times.
- ★The minimum time required is 6×10^8 years.
- ★The universe was < 1 Gyr old.
- ★The black hole must grow at ~100% of its maximum growth rate.
- ★Can dense gas be present to feed the black hole 100% of the time?
- ★*What are observational strategies?*
- ★*When does the $M_{BH} - \sigma$ relation set in?*

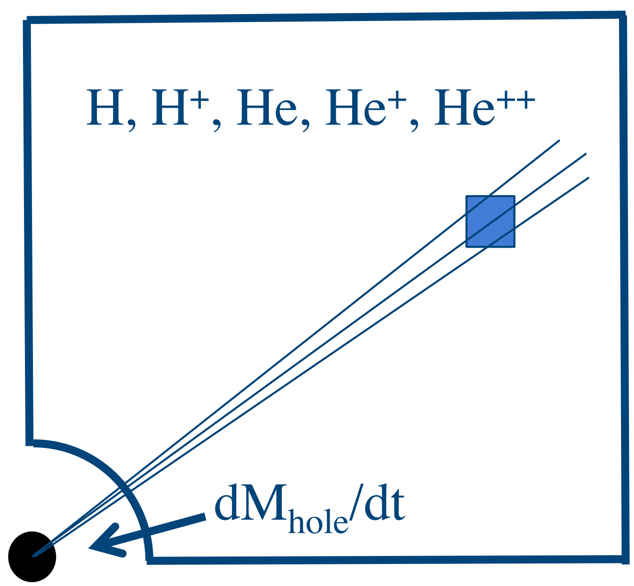




Wise, Turk, & Abel 2008
(similar densities:
Bromm & Loeb 2003,
Regan & Haehnelt 2009;
Shang, Brian, Haiman 2010)

The centers of 10^8 M_{sun} halos can receive lots of gas with modest amounts of angular momentum. Can the black hole grow by Bondi-like accretion?

Radiatively Efficient Accretion in a Dense Primordial Cloud



$M_{hole} \sim 100\ M_{sun}$

$R_{hole} \sim 10^{14}$ cm

$$\int_{\nu_{\min}}^{\nu_{\max}} L_\nu d\nu = \epsilon \dot{M}_{\rm hole} c^2$$

$$F_\nu = \frac{L_\nu}{4\pi r^2} \frac{\sum_{k=1}^{N_{\rm rays}} \exp\left(-\tau_\nu^{(k)}\right)\left[1 - \exp\left(-\hat{\tau}_\nu^{(k)}\right)\right]}{\sum_{k=1}^{N_{\rm rays}} \hat{\tau}_\nu^{(k)}}$$

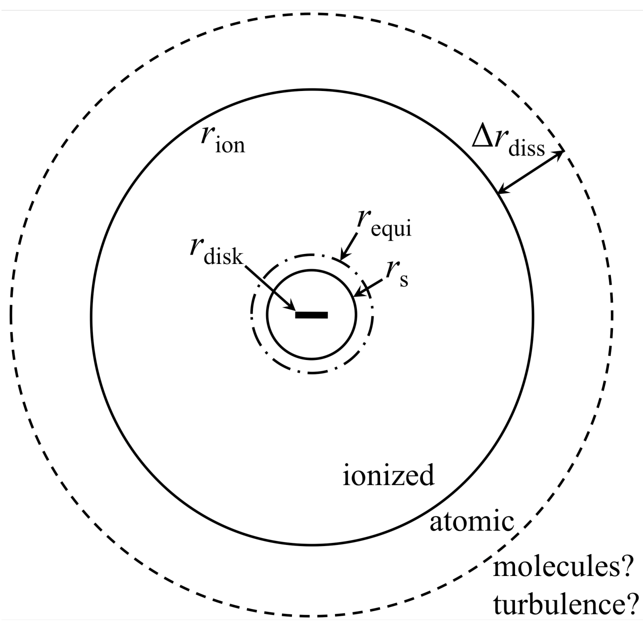
see, e.g., Mellema et al. 2006

FLASH2.5, 2D cylindrical

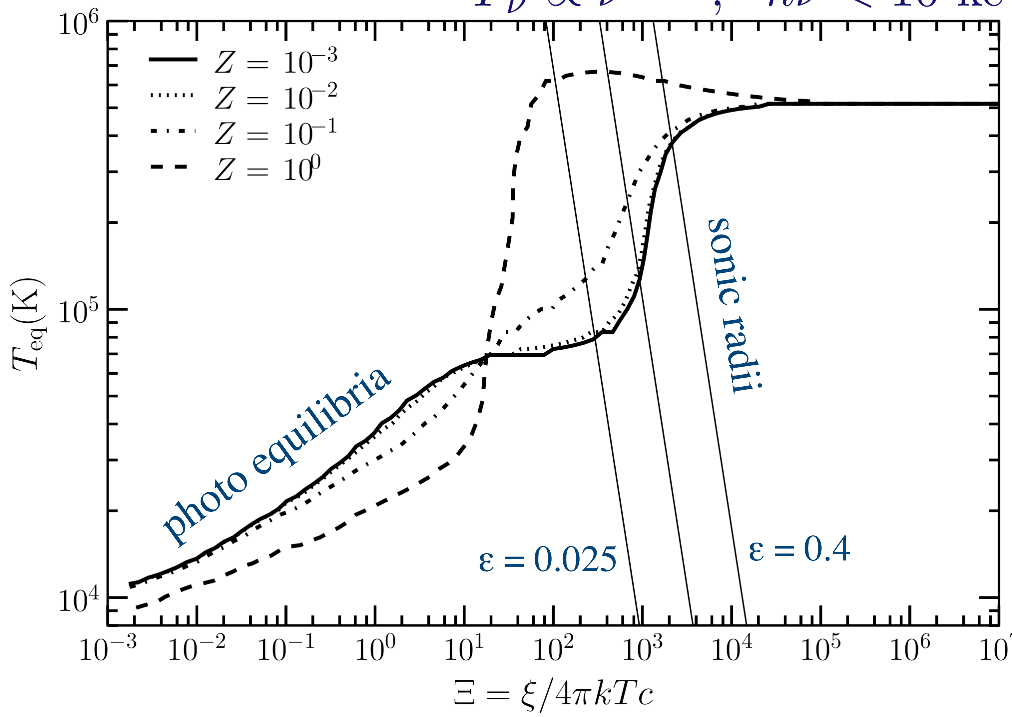
In quasiradial, "Bondi" accretion, the steady-state accretion rate is fixed by the conditions at the sonic radius:

$$r_{\rm s} \sim 3 \times 10^{15} \; \frac{M_2}{T_{{\rm s},4}} \; {\rm cm}$$

If the accretion flow is radiatively efficient, the temperature at the sonic radius is set by photoheating:



$F_\nu \propto \nu^{-1.5}, \quad h\nu < 10$ keV

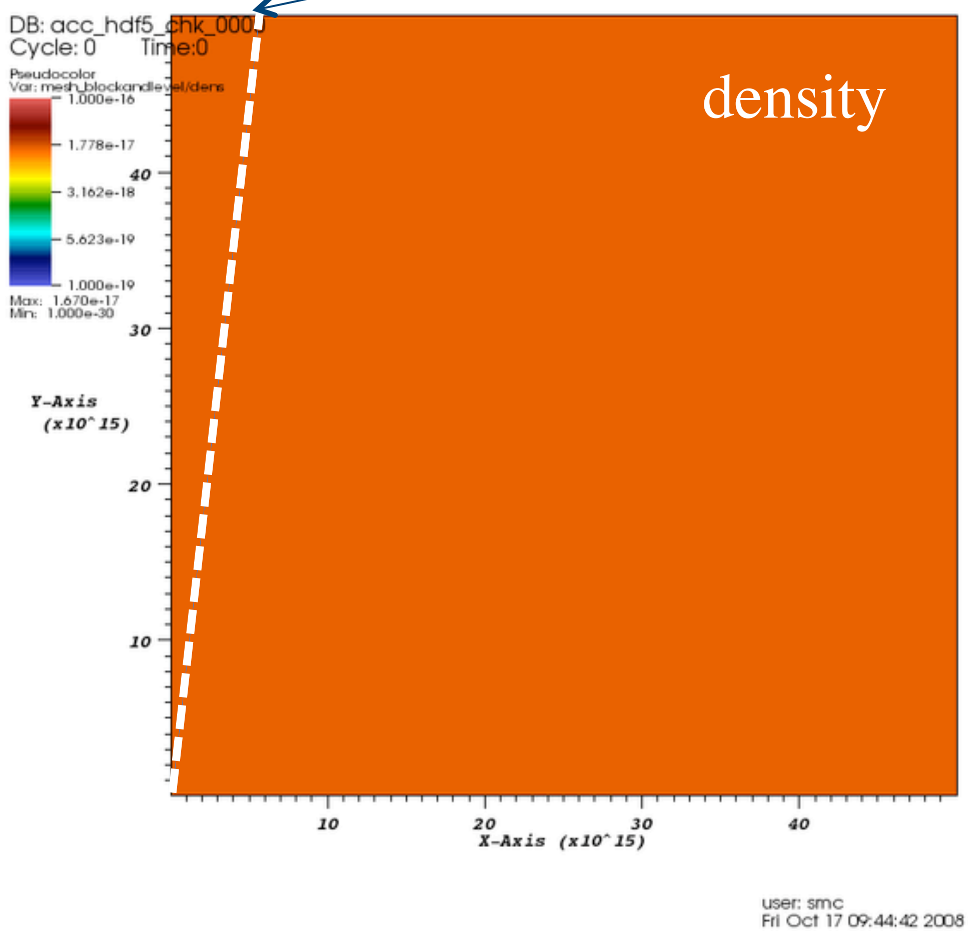


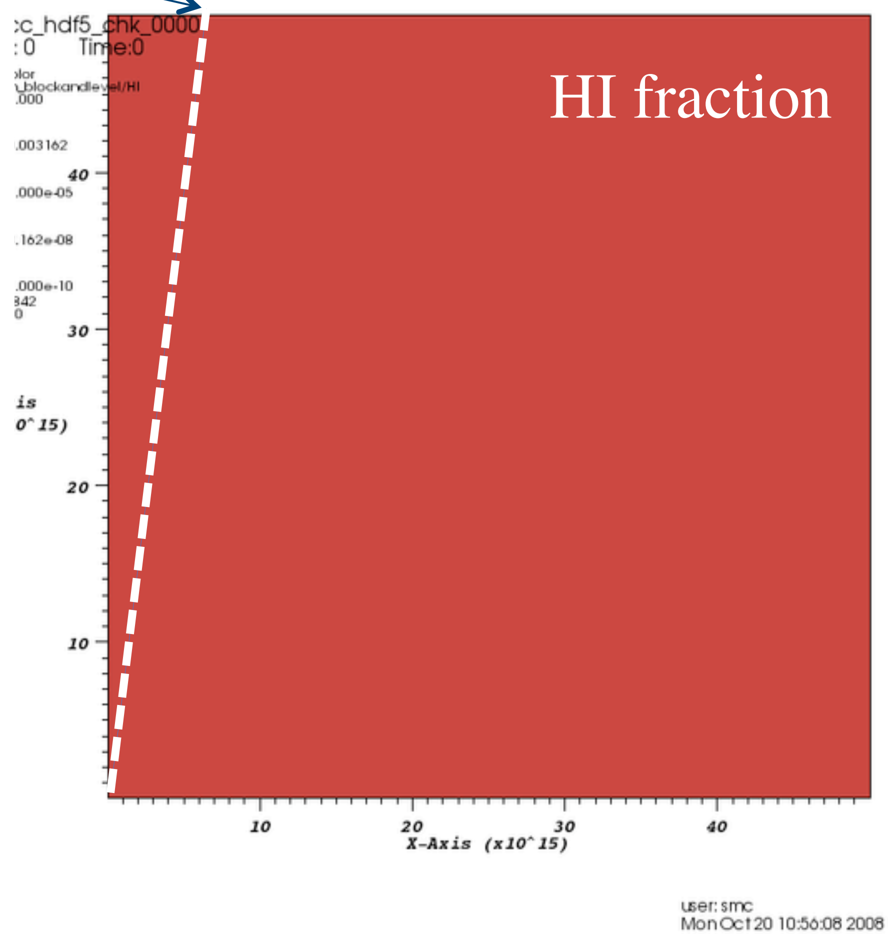
10/07/09

MM, Bromm, Couch, Oh, ApJ 2009

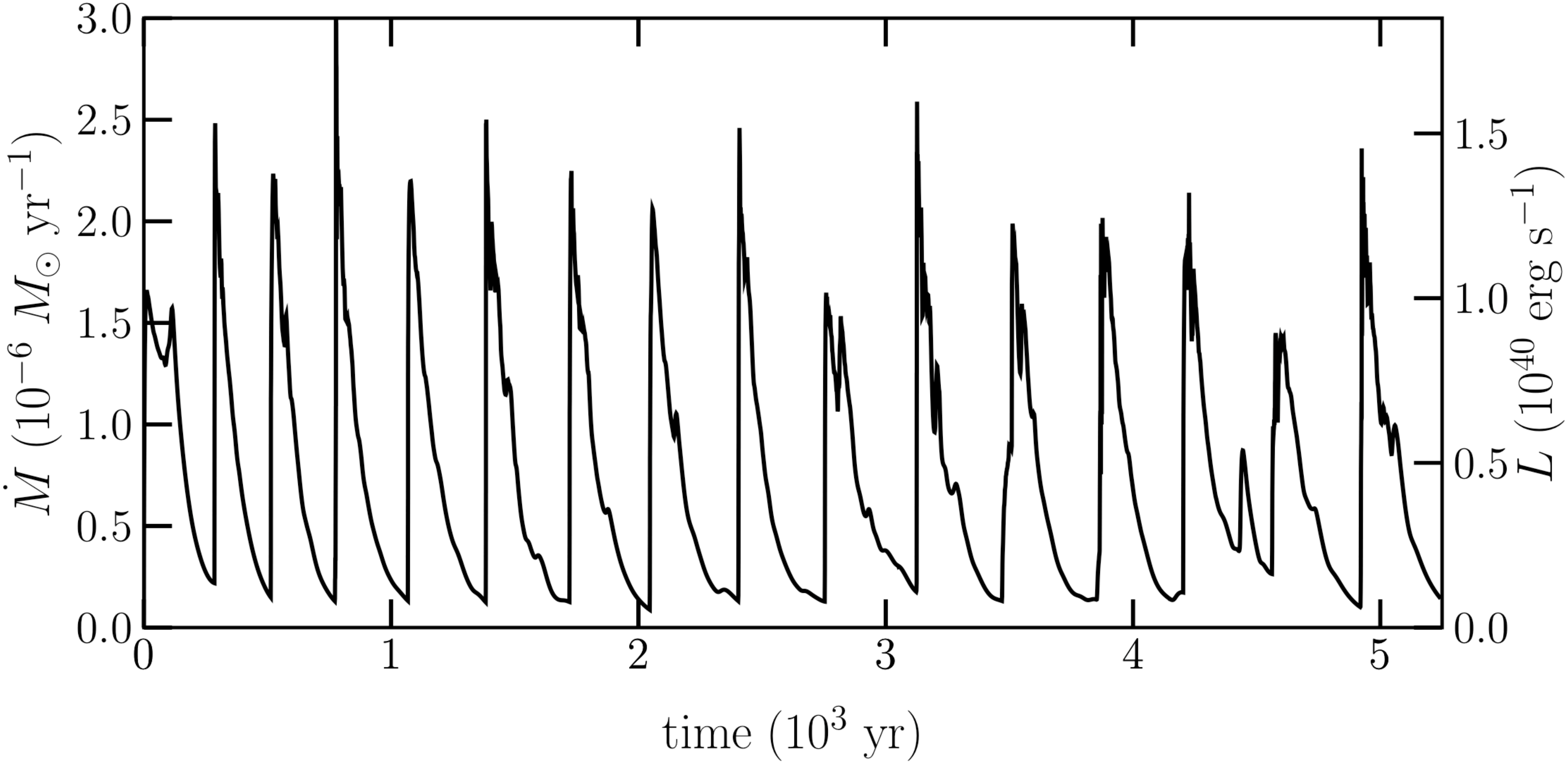
deliberate numerical artifact: $\tau = 0$, ignore

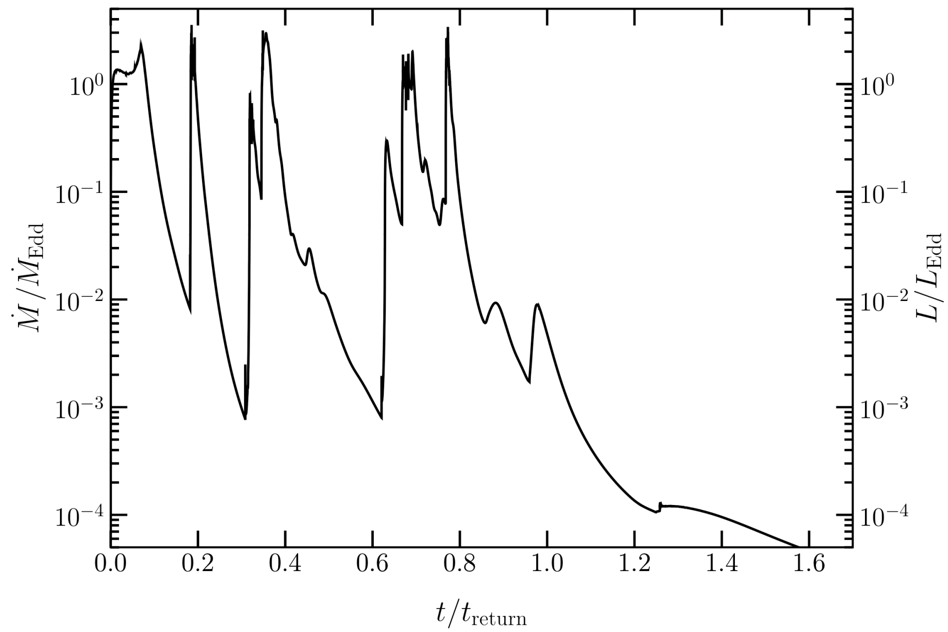
MM, Couch, & Bromm 2009





MM, Couch, & Bromm 2009





Moderate mass clouds ($M_{gas} \sim M_{BH}$) are blown away.

The sphere of influence must be resupplied *many more times* for small black holes to accrete their own mass:

$R_{BH} \sim M_{BH} / (c_s^2+v^2)$

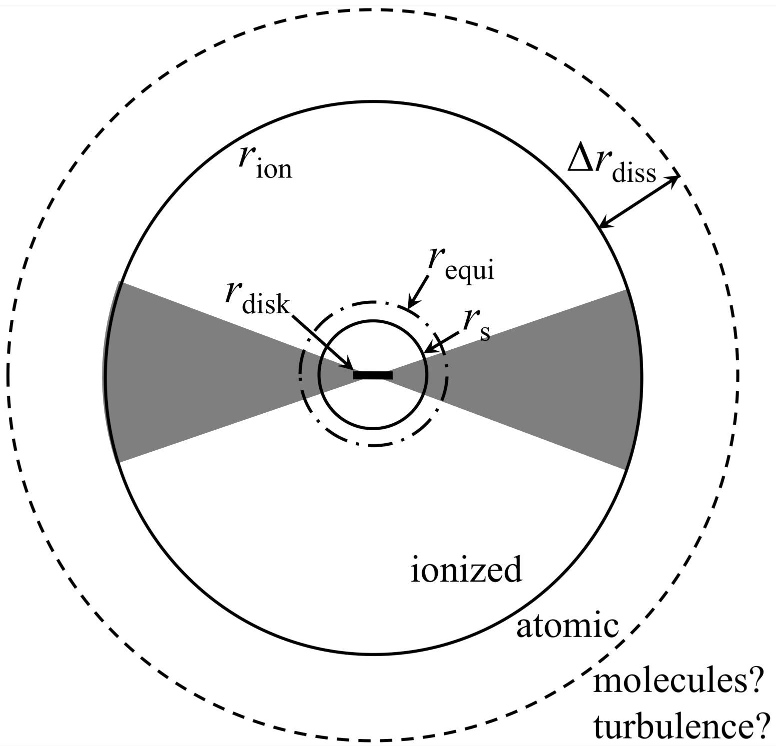
$M_{gas} \sim \varrho\, R_{BH}^3$

$M_{gas} / M_{BH} \sim \varrho\, M_{BH}^2 / (c_s^2+v^2)^3$

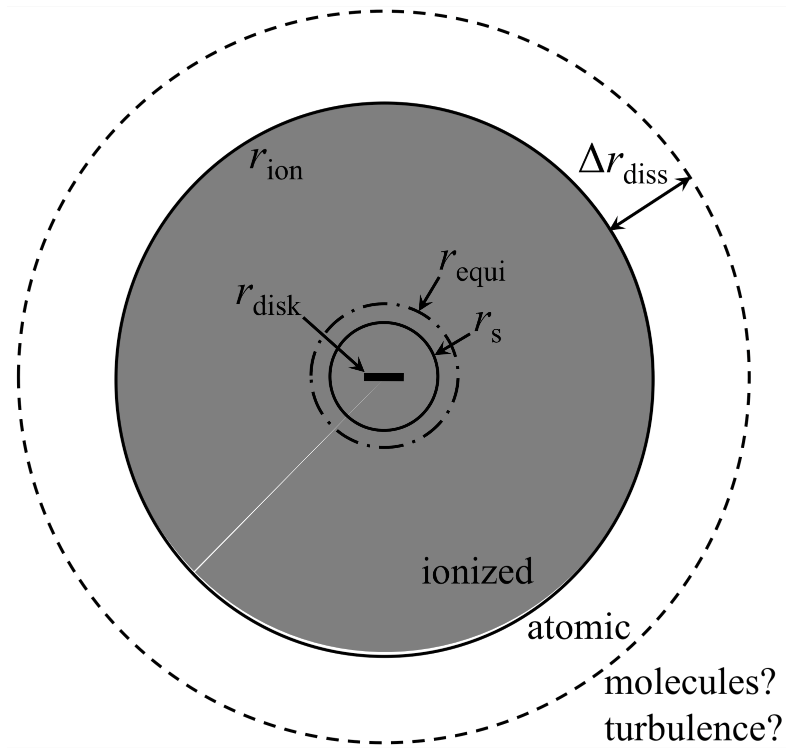
Can substantial mass be stashed in a disk or torus around the black hole? The mass of standard, non-self-gravitating, atomic/ionized disks is limited: $M_{disk} < 10^{-6} (M_{BH} / 100\, M_{\odot})^2\, M_{\odot}$

Couch, MM, Bromm, in prep.

disk shadow

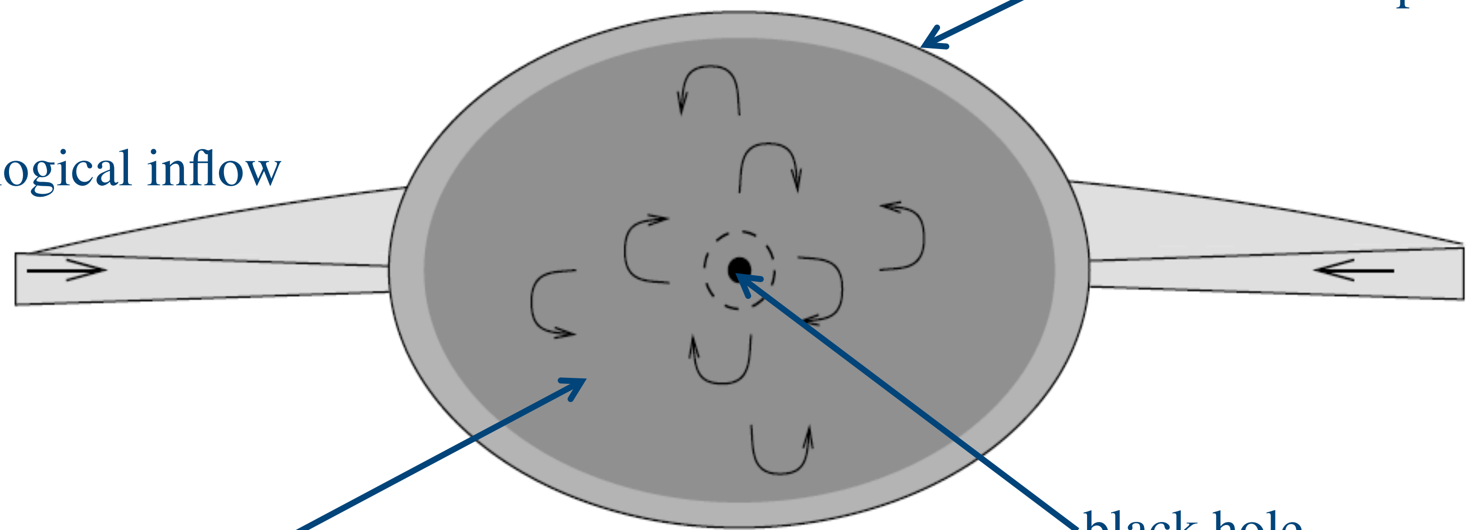


trapped radiation?



Quasi-Stars?

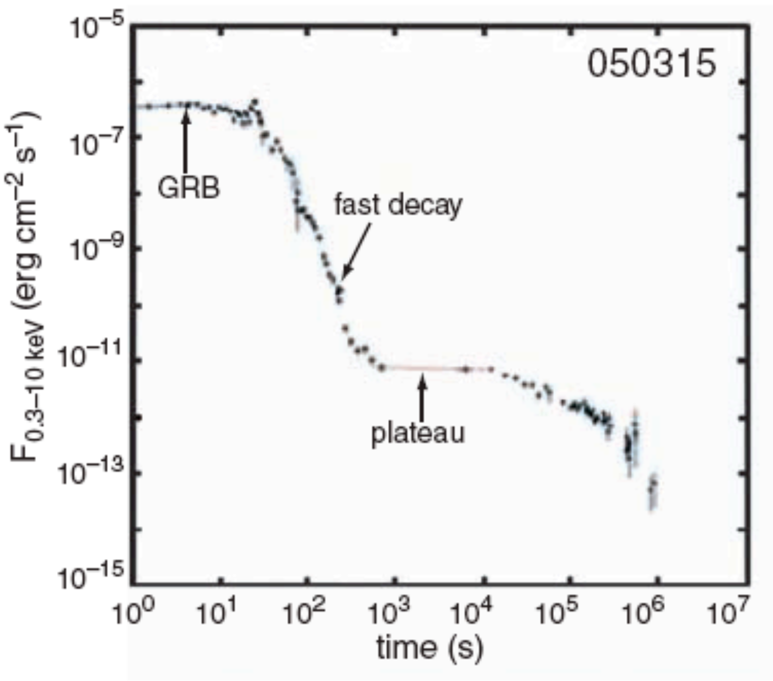
Begelman, Volonteri, & Rees 2006; Begelman, Rossi, & Armitage 2008; Begelman 2009



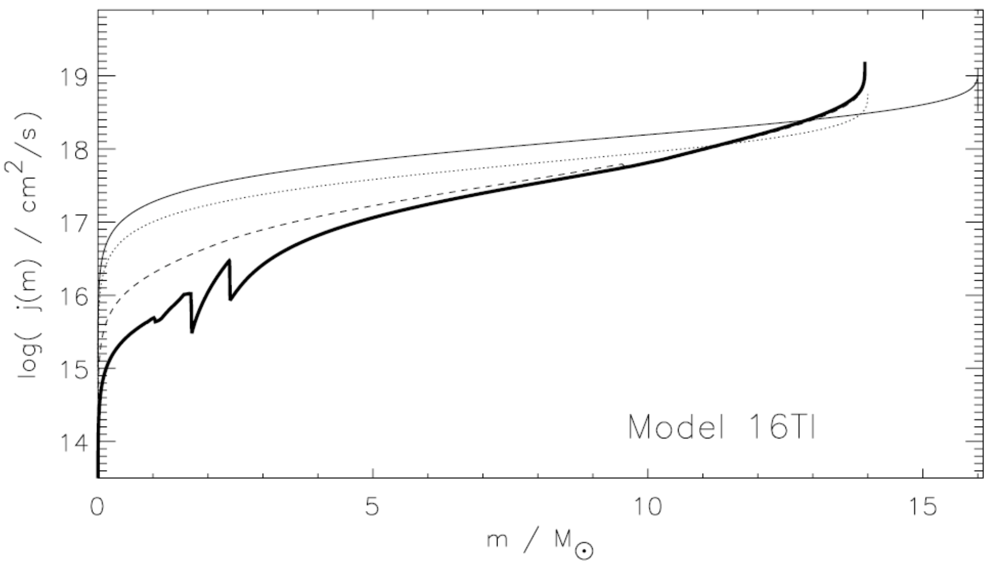
The basic idea: the radiative envelope can remain bound for $L > L_{Edd}(M_{BH})$ as long as $L < L_{Edd}(M_{star})$.

“Long” Gamma-Ray Bursts

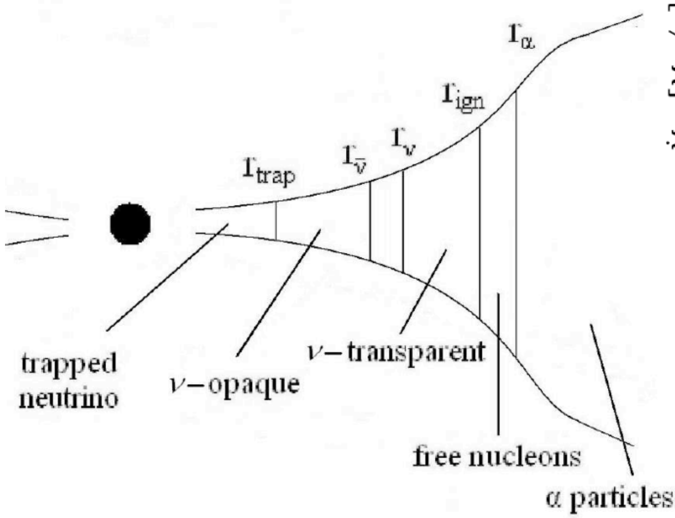
Fig. Kumar, Narayan, Johnson 2008



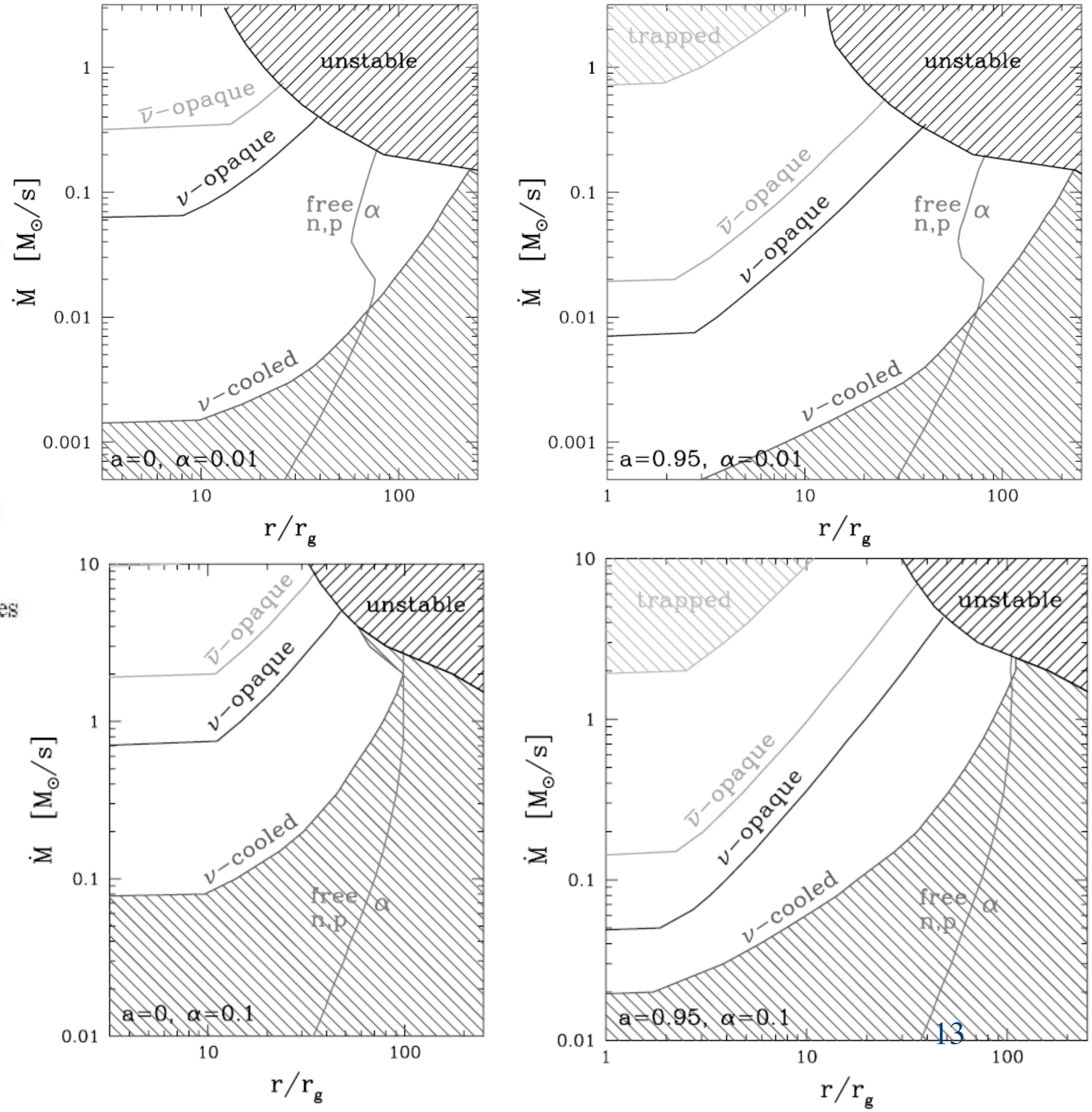
Woosley & Heger 2006

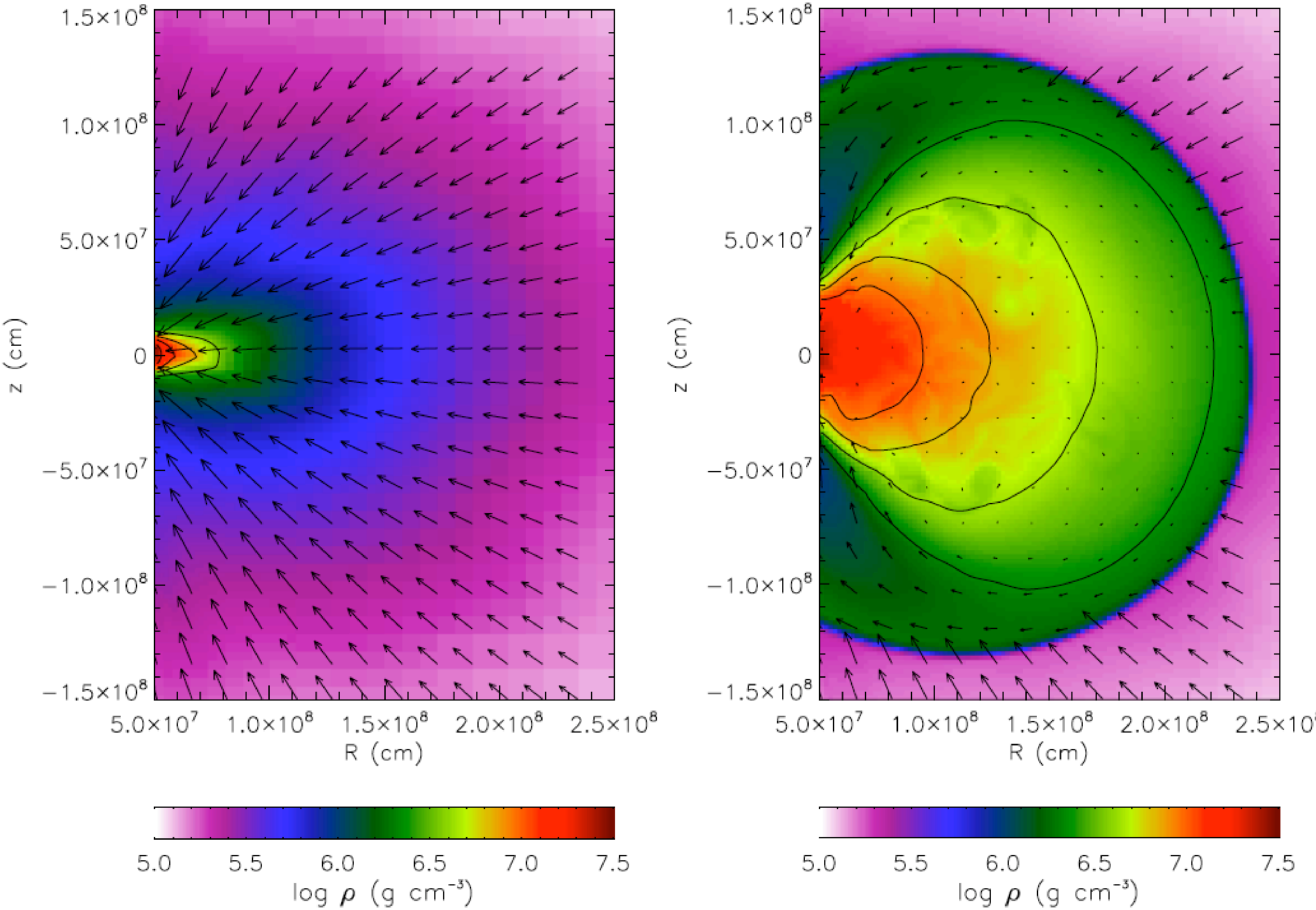


ν-Cooled Disks

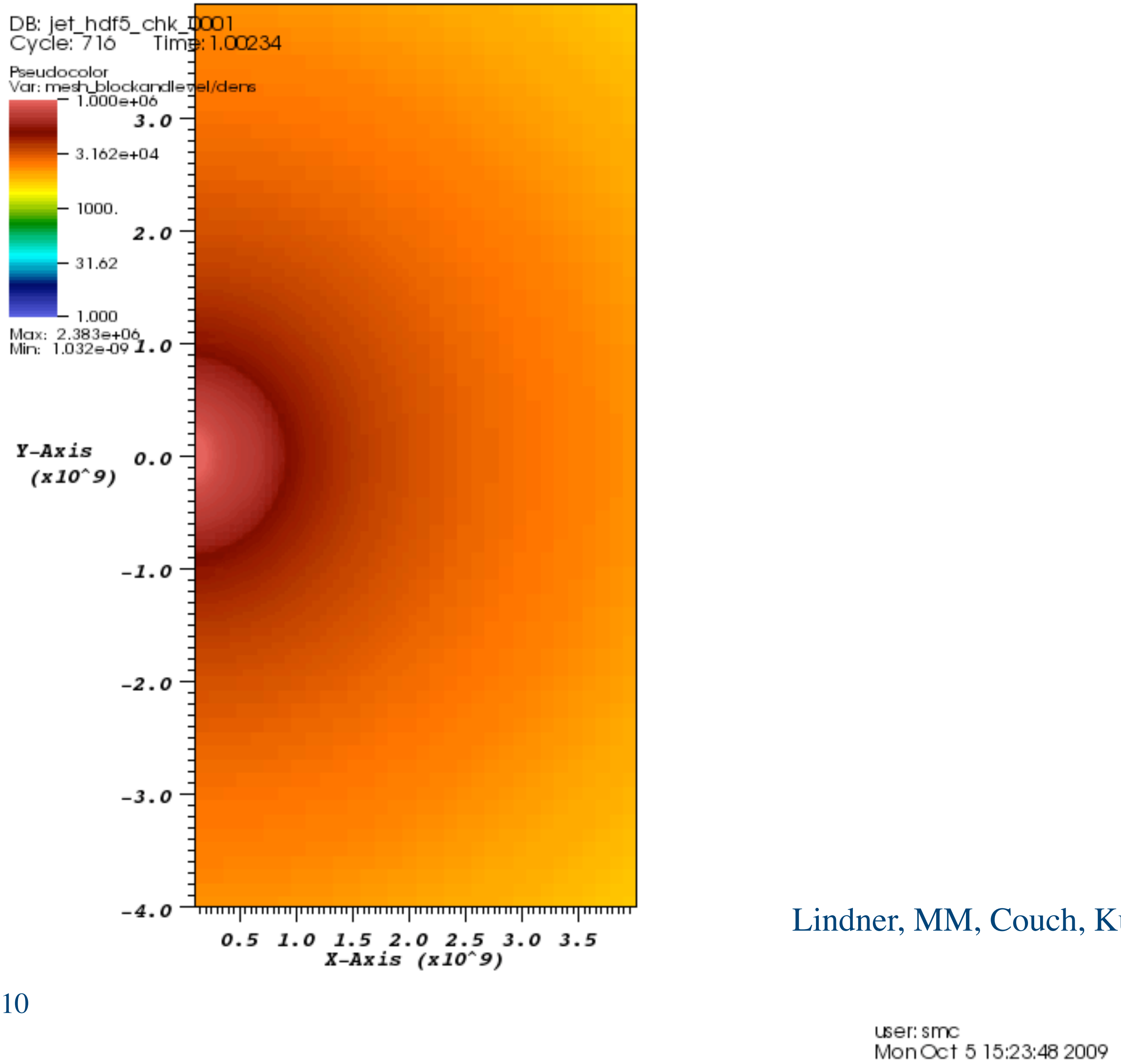


Chen & Beloborodov 2007

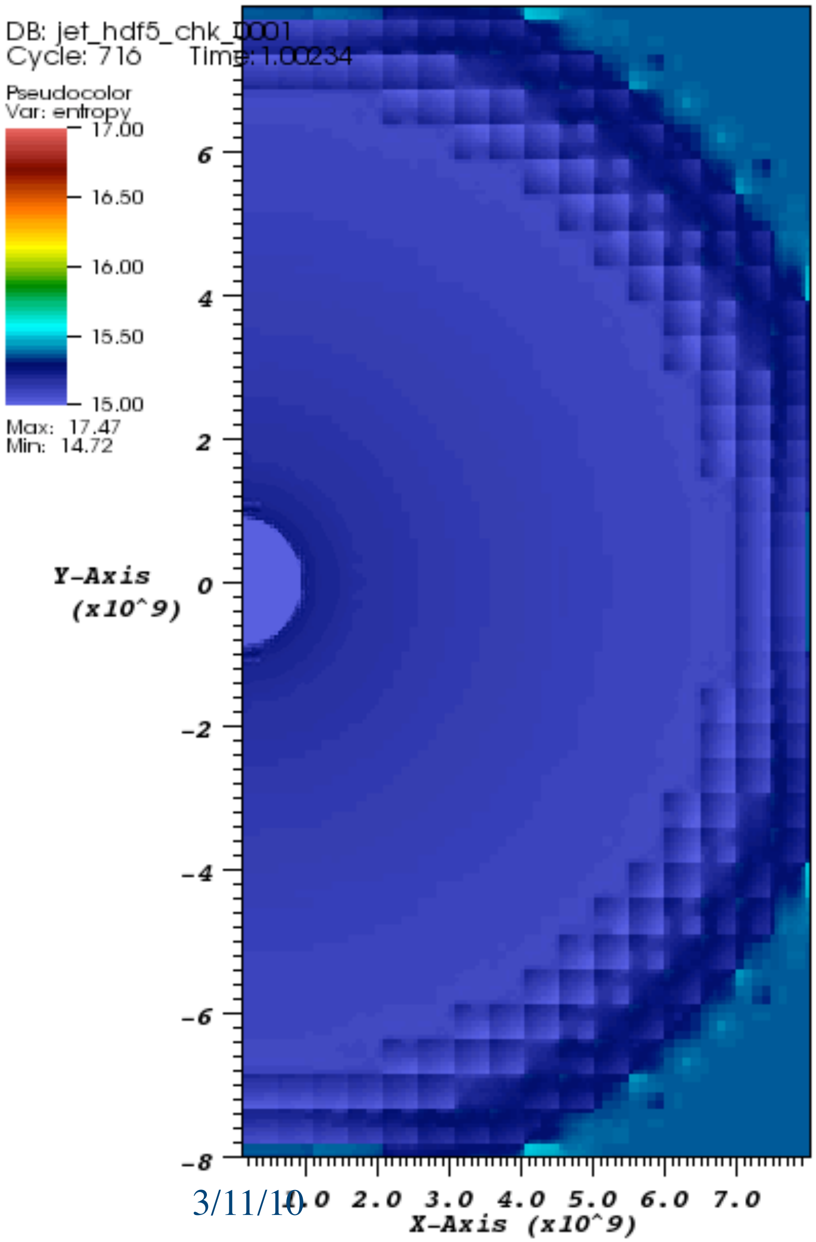




Lindner, MM, Couch, Kumar 2009



Lindner, MM, Couch, Kumar 2009



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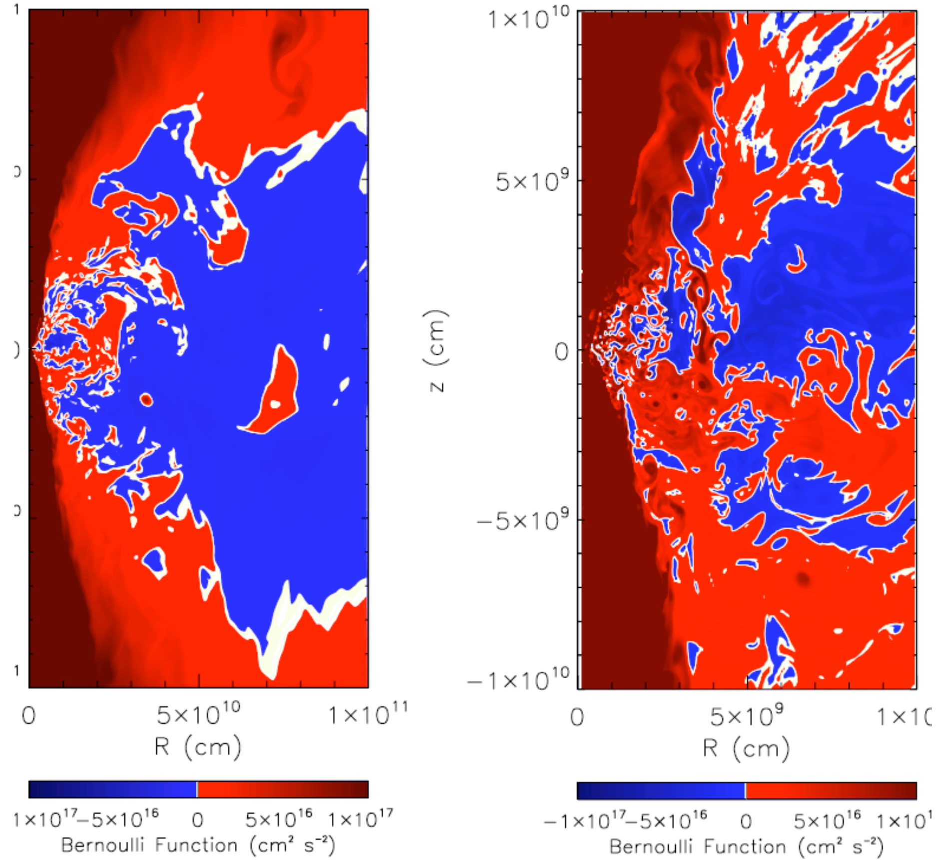
Lindner, MM, Couch, Kumar 2009

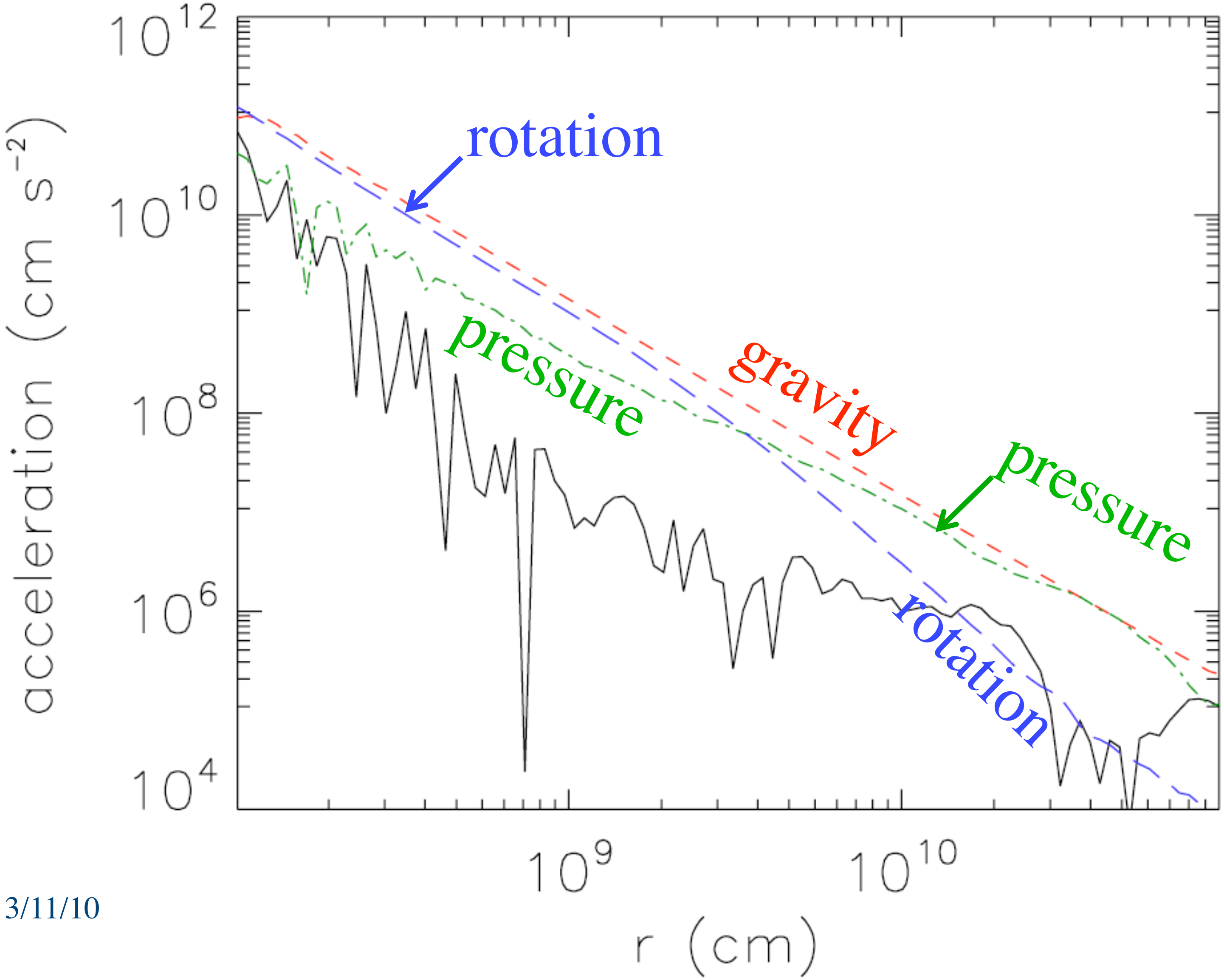


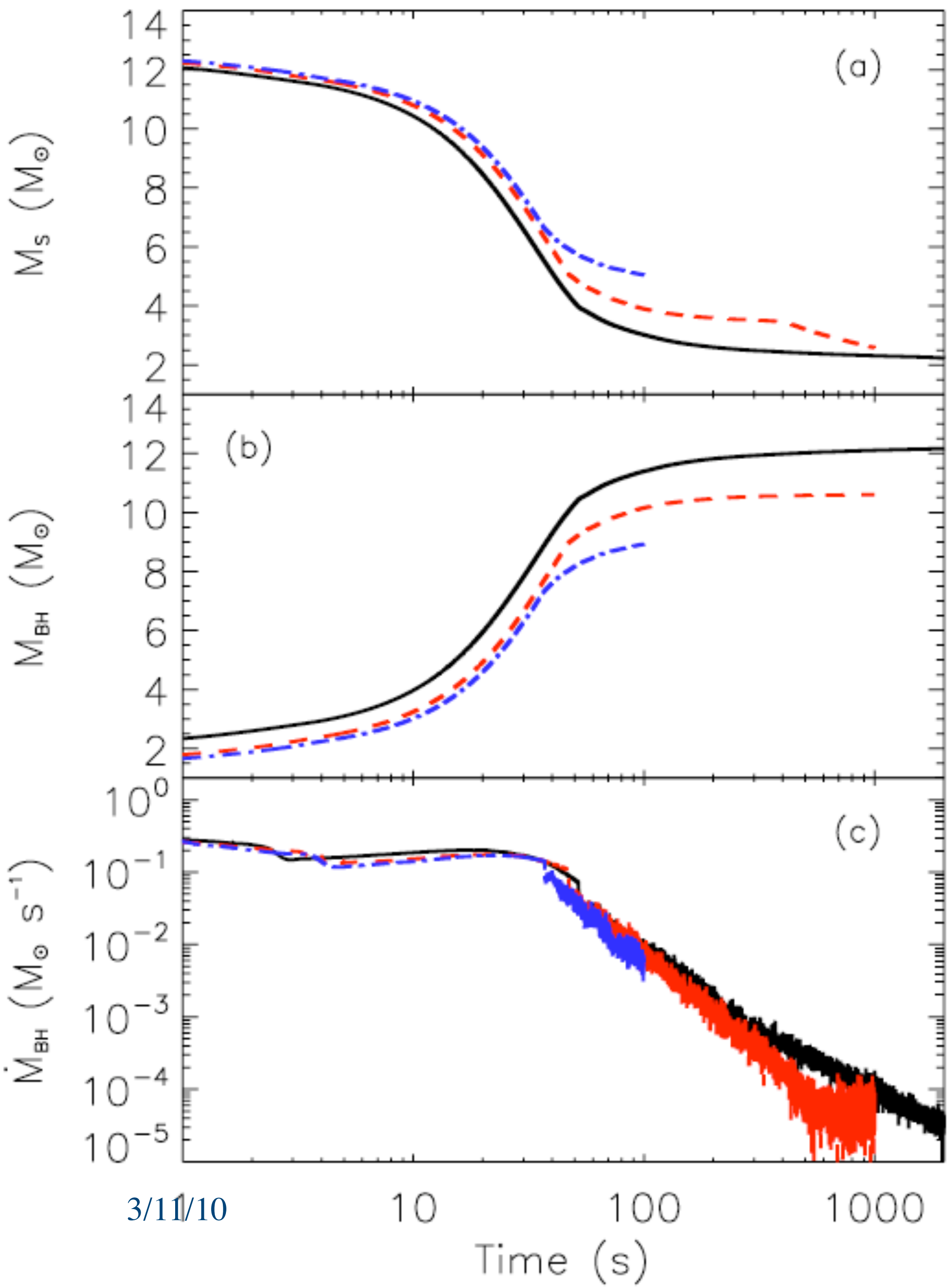
blue: bound fluid

red: unbound fluid

RIAF = ADIOS

Structure of the Accretion Flow





If the MeV gamma-ray and X-ray luminosities track the rate with which material is accreting onto the black hole, the prompt gamma-ray emission lasts while infall is straight into the black hole, or the matter circularizing where neutrino cooling is very efficient.

Circularization outside the black hole without highly efficient neutrino cooling necessitates accretion-powered shock expansion (e.g., v_{shock} ~ 1,000-5,000 km/s). This leads to a precipitous decline of central density and central accretion rate, just as during the early X-ray afterglow.

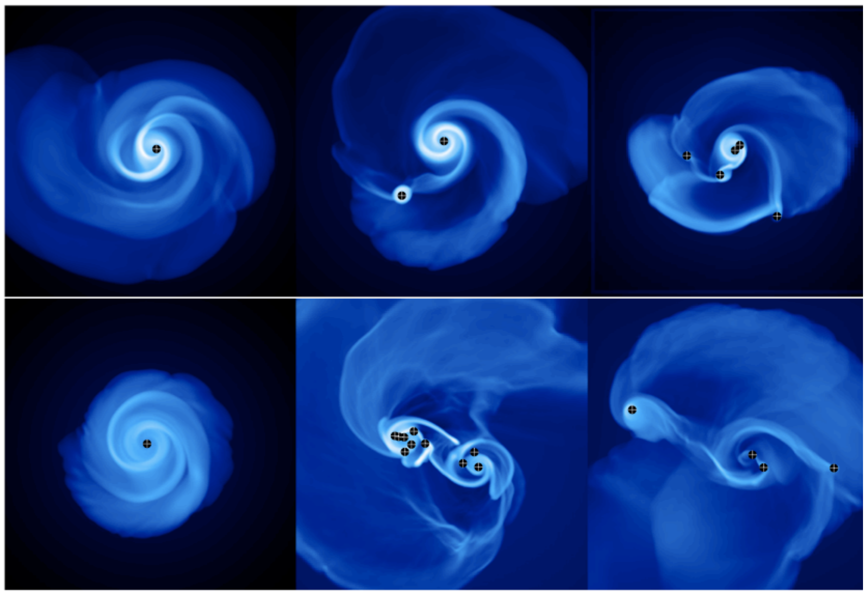
- Can the accretion-powered shock be fast enough to produce a SN Ic, just like the SNe concomitant to long GRBs? [Work in progress: parameter space search; neutrino and nuclear processes are of essence.]
- What is the final black hole mass if the progenitor (first star, supermassive star, quasistar) is rapidly rotating? Are there observational signatures?
- Fundamental questions: What controls the amount of mass ultimately accreting onto the black hole in radiatively-inefficient accretion flows? What is the structure of the outflow?
- Can a quasar-progenitor "seed" black hole, if fed by galactic gas, transition into the radiatively-inefficient regime and accrete at a sustained, supercritical rate?

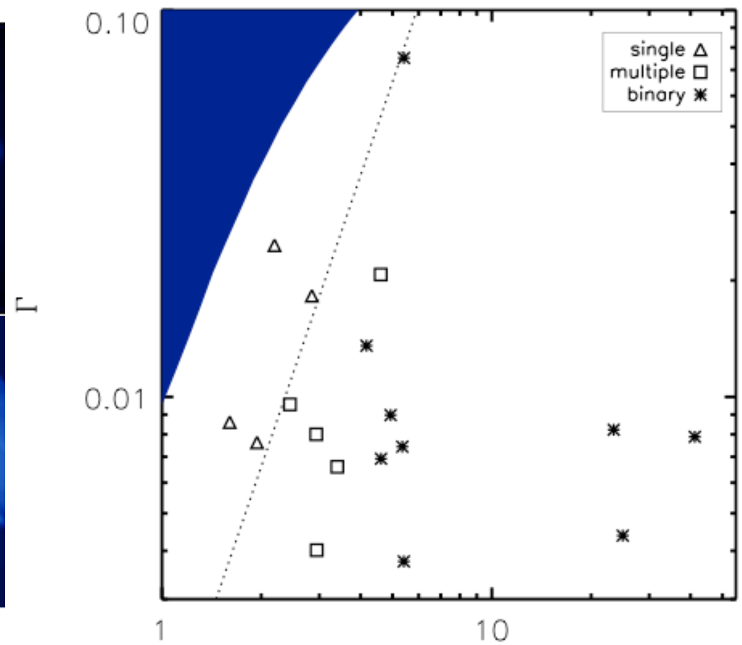
- QSO progenitor halo, e.g., 10^9 M_{sun} @ z=18.
- Halo mass exponentiates in ~ 20 Myr
- Cold accretion (Dekel & Birnboim, etc.) delivers gas a fraction into the inner < 100 pc.
- The gas passes ~100 km/s shock and circularizes in the halo (the first disks, e.g., van den Bosch, Abel, Herquist 2003)
- The shocked gas cools rapidly by H_2 or fine structure lines (Safranek-Shrader, Bromm, MM 2010, see poster).
- Get a turbulent, globally-self-gravitating disk.
- Global self-gravity (bars, massive spiral arms) transport angular momentum (e.g., Shlosman, Begelman).

- Time scales:
  - gas cooling: short
  - disk growth ~ halo growth ~ 20 Myr ~ $(1+z)^{-5/2}$
  - disk orbital period ~ $2\pi/\Omega$ ~ 30 Myr ~ $(1+z)^{-3/2}$
  - disk accretion ~ disk orbital period ~ 30 Myr ~ $(1+z)^{-3/2}$
  - disk star formation ~ $1/(0.01\Omega)$ ~ 500 Myr ~ $(1+z)^{-3/2}$
- At large z, disk remains self-gravitating, accretes on the orbital time: inflow ~ 5 M_{sun}/yr.
- $\Sigma(r) \sim r^{-1}$ (simulations show this in turbulence and rotation-supported flows)
- "Seed" black hole at the center dominates gravitational potential where $M_{disk}(r) = M_{BH}$, $r \sim 10^{-3}$ pc.

Disk Fragmentation

Turk, Abel, & O'Shea 2009; Stacy, Greif, & Bromm 2009; Kratter et al. 2010; Clark et al. this conference; Omukai et al. this conference





Kratter, Matzner, Krumholz, Klein 2010

$\xi \leftarrow \dfrac{G\dot{M}}{c_s^3}$

- Radiation trapping within the black hole's radius of influence: the gas mass in the torus encircling the black hole grows faster than radiation diffuses from the torus.
- The torus fragments into massive fragments (e.g., Goodman & Tan 2004), but the fragments migrate inward and *enhance* accretion within the torus (e.g., Goodman & Rafikov 2001; Wada et al. 200?; Kumar & Johnson 2010).
- Sustained supercritical accretion: A quasistar from scratch?
- RIAF = ADIOS in which most mass *escapes*; if 1,000 km/s wind, kinetic luminosity is > 10^{42} erg/s, significant feedback, X-rays, recombination radiation.

Conclusions

- Sustained quasispherical accretion ("Bondi") mediated by a thin disk is difficult to sustain because of radiation pressure.
- Collapsars—the long GRB progenitors are plausible examples of radiatively-inefficient supercritical accretion flows: real-world "quasistars".
- Can RIAF conditions emerge in the first galaxies? What are the consequences of RIAFs for astronomy? – Challenges for cosmological simulations.