Rapid black hole formation in the early universe

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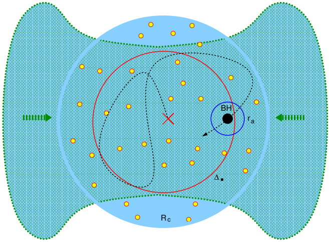


Overview

- Stellar mass BH seeds accrete quasi-spherically and grow supra-exponentially in the early universe in stellar clusters fed by dense cold-flows, and reach masses of $\gtrsim 10^4\, M_\odot$ by $z \sim 15$.
- Slow disk accretion can then grow them to the observed $M_\bullet \gtrsim 10^9\, M_\odot$ QSO at $z \sim 7$.
- The Eddington limit on the mass accretion rate does not apply.
- The angular momentum bottleneck is circumvented by the dynamics of the light BH seed in the birth cluster.
- New element: The accretor as a stochastic dynamical object.

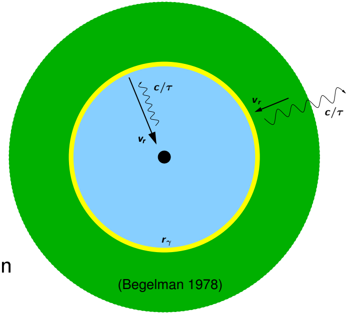
(Alexander & Natarajan, 2014, Science, 345, 1330)

Conventional statement of the problem

- Only *known* formation path: SN $\rightarrow \mathcal{O}(10\, M_\odot)$ BH.
- Early massive QSO: $M_{\bullet,f} \gtrsim 10^9\, M_\odot$ at $z_f \sim 7 \leftrightarrow t_f \sim 0.8$ Gyr (e.g. Mortlock et al 2011).
- *If* Eddington-limited accretion: $\dot{M}_E \sim L_E / c^2 \eta_{\rm rad}$.
  - *e*-folding time $t_E = 4.5 \times 10^7$ yr for $\eta_{\rm rad} = 0.1$.
- Example: for $z_i \sim 16 \leftrightarrow t_i \sim 0.25$ Gyr:
  $M_{\bullet,i} = M_{\bullet,f} / \exp[(t_f - t_i)/t_E] \sim 5000\, M_\odot$.
- Nature manages to create massive BH seeds, or exceed $\dot{M}_E$.

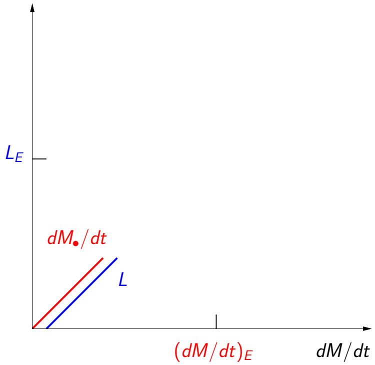
Correct restatement of the problem

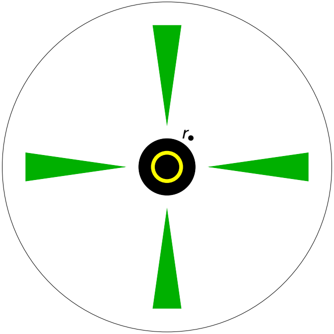
- The Eddington limit is *not* a problem.
  - $L \lesssim L_E$ but $\dot{M} \not< \dot{M}_E$,
    even for spherical accretion!
  - Arbitrary high $\dot{M}$ due to an
    effective horizon by photon trapping.
- Angular momentum *is* the problem!
  - Fast free-fall accretion only if circularization radius $r_c = J^2/GM_\bullet < r_\bullet$ (event horizon),
  - Otherwise, disk forms outside $r_c > r_\bullet$
    and slow viscosity-limited accretion.



Photon trapping

$$r_\gamma = \frac{\dot{M}\kappa}{4\pi c}\ ,\ \eta_{\rm rad} = \frac{GM_\bullet}{c^2\max(r_\bullet, r_\gamma)}\left[\propto \frac{1}{\dot{M}}\ \text{if}\ r_\gamma > r_\bullet\right] \Rightarrow L = \eta_{\rm rad}(\dot{M})\dot{M}c^2 \le \frac{4\pi Gc}{\kappa} = L_E$$





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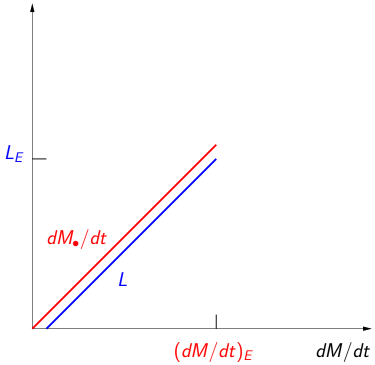

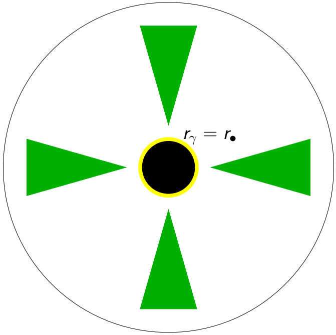

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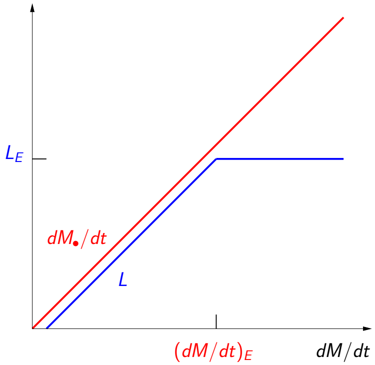
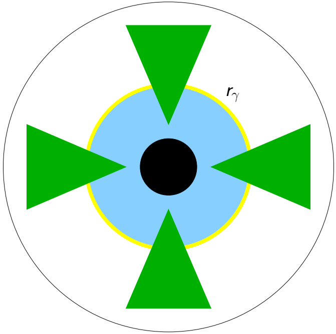




Zero-angular momentum accretion

- Bondi-Hoyle-Lyttleton (spherical / wind) accretion :

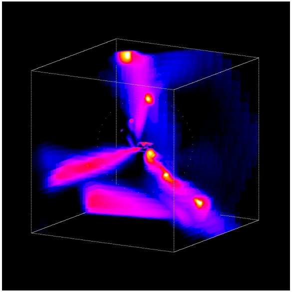
$$\dot{M} \sim \pi r_a^2 v_\infty \rho_\infty \propto M_\bullet^2 \,, \qquad r_a = \frac{2GM_\bullet}{v_\infty^2} \,, \qquad v_\infty^2 = c_\infty^2 + v_\bullet^2$$

- Divergence in a finite time (supra-exponential):

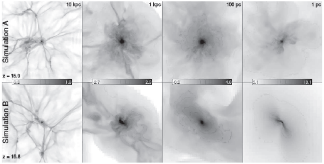
$$M_\bullet(t) = \frac{M_{\bullet,i}}{1 - t/t_\infty} \,, \qquad t_\infty \simeq \frac{3}{\sqrt{2}\pi} \frac{c_\infty^3}{G^2 M_i \rho_\infty} \quad (\star)$$

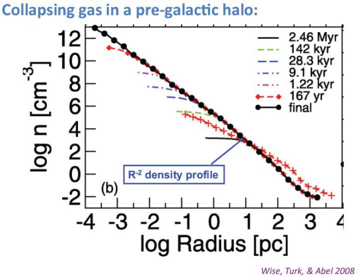
* Including $\mathcal{O}(1)$ increase in Bondi's t_∞ due to radiation back-pressure (Begelman 1978).

Initial conditions: Dense cold-flows in the early universe



Dekel et al 2009



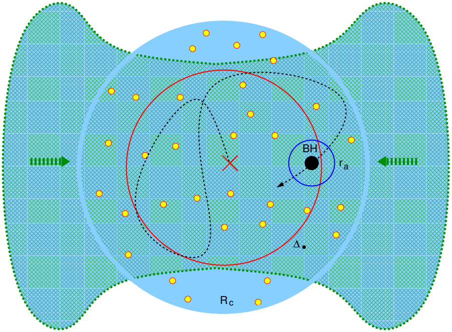


Wise, Turk & Abel 2008

BELR-like densities on sub-pc scale without a central MBH!

Demonstration of concept

Compact cluster in cold flow node



Alexander & Natarajan 2014

$$
\begin{aligned}
z &\gtrsim 15 \\
M_\bullet &= 10\ M_\odot \\
M_\star &= 1\ M_\odot \\
R_c &= 0.25\ \text{pc} \\
M_c &= M_g + M_s = 4 \times 10^4\ M_\odot \\
M_g &= 2 \times 10^4\ M_\odot \\
M_s &= N_\star \times M_\star = 2 \times 10^4\ M_\odot \\
t_\infty &= 3.5 \times 10^7\ \text{yr} \quad (< t_\text{E}!)
\end{aligned}
$$

The challenges of a low mass BH seed

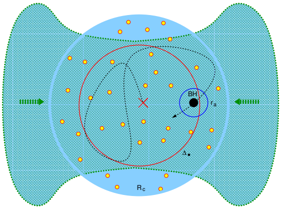
1. More growth needed to reach $\gtrsim 10^9\, M_\odot$.
2. Unavoidable acceleration of low mass BH in the cluster induces angular momentum in the flow in its non-inertial rest-frame:
   - Acceleration-induced velocity gradient

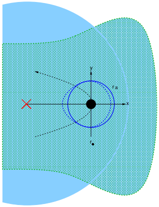
     $$j_a \sim \Omega_c r_a^2 > 0$$

   - Density-induced gradient

     $$j_a \sim \frac{\mathrm{d}\log\rho}{\mathrm{d}\log r}\Omega_c r_a^2 < 0$$

   - In hydrostatic equilibrium and dynamical equipartition, near-universal $j_a(M_\bullet/M_\star)$.

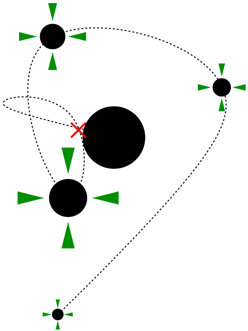




Overcoming the angular momentum barrier (1)

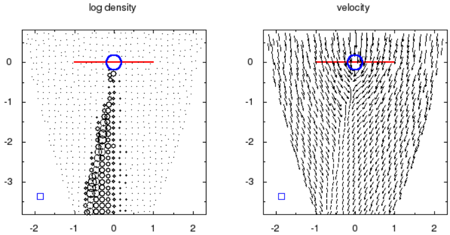
- Rapid randomization of the motion of the BH.
  - Resonant relaxation of orbital orientation.
- Deceleration by accretion drag.
  - When $t_{acc} < t_{rlx}$ ($M_\bullet \sim 25\, M_\odot$),

    BH decouples from the cluster .



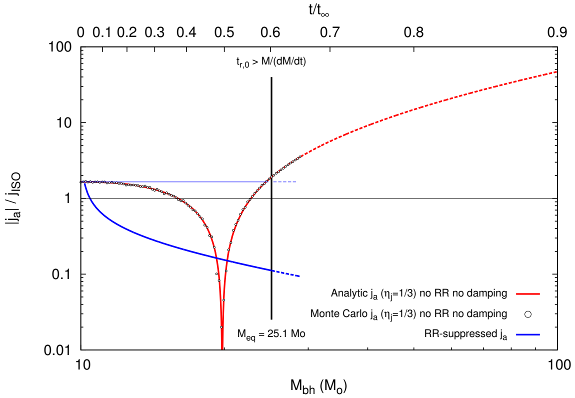
Overcoming the angular momentum barrier (2)

- Initial cancellation of the induced angular momentum.
  - Density gradients cancel velocity gradients ($M_\bullet \sim 20\, M_\odot$).
- Low efficiency of angular momentum accretion.
  - Self-regulating capture from inhomogeneous wind: $\eta_j \sim 1/3$.



Fleischer & Alexander, 2015, in prep.

Angular momentum evolution

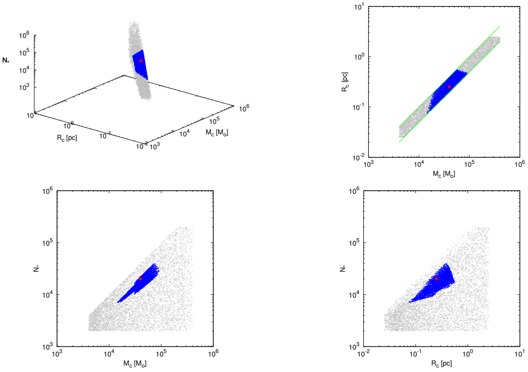


To do: Calibrate and combine all j_a-reducing effects.

Conclusions

- Stellar BHs in very dense cold flows at redshifts $z > 15$ can be launched by stellar dynamical processes into a phase of supra-exponential accretion.
- The growth is supply limited: stellar BHs grow rapidly in a few $\times\, 10^7$ years into $\gtrsim 10^4\, M_\odot$ intermediate mass BHs.
- Subsequent slower growth by disk accretion suffices to produce the supermassive BHs that power the brightest early quasars.
- Only $\mathcal{O}(0.01)$ of DM halos where the first stars form need undergo this process to account for the $z > 6$ quasars.

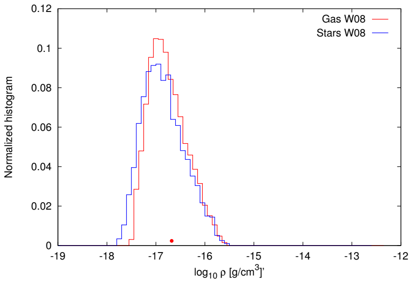
Appendix: The phase-space for supra-exponential accretion



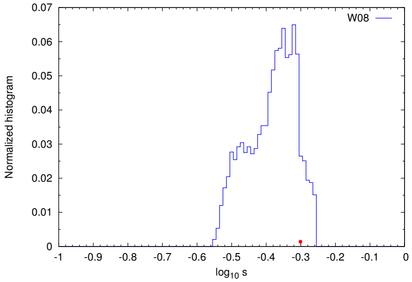
Conditions for efficient supra-exponential accretion:

1. Physical scales consistent with simulations.
2. SE divergence faster than cluster / cold-flow lifetimes.
3. $j_a(M_\bullet) \to 0$ near $M_\bullet \sim M_{\rm dec}$.
4. Efficient j_a cancellation by resonant relaxation orbital flips

Appendix: The phase-space for supra-exponential accretion



Gas, stars density



Stellar mass fraction

Only $\mathcal{O}(0.01)$ of DM halos where the first stars form ($\sim$3.5σ density peaks at z>15) need undergo this process to account for the $z > 6$ quasars ($\sim 4\sigma - 5\sigma$ density peaks).

Alexander, Natarajan & Rossi, 2015, in prep.