The tale of angular momentum transport in primordial galaxies and the formation of massive BH seeds

with:

Pedro Capelo (Zurich)
Rafael Souza Lima (Zurich)
Tomas Tamfal (Zurich)
Hongping Deng (Zurich)
Lorenz Zwick (Zurich)
Jakob Stegmann (Zurich)
Elisa Bortolas (Zurich)

Silvia Bonoli (Bilbao)
Lionel Hammerle (Geneva)
Sijing Shen (University of Oslo)

Lucio Mayer
Center for Theoretical Astrophysics and Cosmology
Institute for Computational Science
University of Zurich
The puzzle of high-z Quasars

Bright Quasars (<L > 10^{47} \text{ erg/s}) < 700 million years after Big Bang (z > 6) \( M_{BH} > 10^9 \text{ Mo} \) (see X. Fan’s talk - Mortlock et al. 2011; Banados et al. 2016; 2019)

**PROBLEM:** is there enough time to grow these early SMBHs?

\[
\dot{M}_{\text{Edd}} = \frac{4\pi GM_\bullet}{\eta \kappa c}
\]

Eddington rate: maximum (spherical) accretion rate set by balance between gravity and pressure force of radiation

\[
M_\bullet(t) = M_\bullet(t_0)e^{(t-t_0)/\tau_{\text{Salp}}}
\]

“Growth equation”

\[
\tau_{\text{Salp}} \approx 4.4 \times 10^7 \left( \frac{f_{\text{Edd}}}{1} \right)^{-1} \text{ yr } \times (\eta/0.1) \text{ radiative efficiency}
\]

High-z QSO rare (~10^{-8} h^3 \text{ Mpc}^{-3}), 4 orders of magnitude less abundant than their z=0 counterparts. Abundance and clustering suggest their hosts rare massive halos (\( M_{\text{halo}} > \sim 10^{12} \text{ Mo} \) — see Volonteri & Rees 2006; Sijacki et al. 2010)

(Courtesy of Marta Volonteri)
High-z QSOs hardly from Eddington-limited accretion of Pop III BH seeds as seed mass should be $>\sim 10^4$ Mo

Alternative scenarios:

1. **Direct gas collapse into black hole seeds ($10^4$-$10^5$ Mo)**

Formation of massive BH from collapse of massive gas cloud, with a prior stage as a supermassive star (SMS) and/or quasi-star (Begelman 2010), or even directly into a BH via GR radial instability (“dark collapse” see Mayer & Bonoli 2019; Hammerle et al. 2019)
Regime: *radiatively inefficient accretion* in large optical depth medium ($\tau \gg 10^3$) with highly viscous-driven accretion flow $t_{\text{diff}} \gg t_{\text{advection}}$.

Prototypical model is SLIM disk by Sadowski et al. (2011;2013).

**Low radiative efficiency** ($\sim 0.1\%$, as opposed to $\gg 10\%$ in standard $\alpha$-disk accretion), no energy loss via winds.

More recent 3D MHD-RT accretion disk simulations by Jiang et al. (2015;2018) using VET method for RT show enhanced radiative losses in turbulent non-axisymmetric flow with **radiative efficiency of 1-5\%**, sustaining $\dot{M} \sim 25-150 \dot{M}_{\text{edd}}$ (+winds).
In both direct gas collapse and Super-Eddington accretion a challenge is to supply the gas at sufficiently high rates to sub-nuclear scales ($< 10^{-2} \cdot 1$ pc — scales of supermassive protostellar cloud in direct collapse scenarios or the accretion disk in super-Eddington scenarios).

For example, for SMS formation ($M^* > 10^4$ Mo) $M_{\text{dot}} > 0.1-1$ Mo/yr is required (Hosokawa et al. 2014; Woods et al. 2019). For Super-Eddington accretion onto light Pop III BH seeds ($<1000$ Mo) (Madau & Rees 2000) smaller $M_{\text{dot}}$ required at the beginning then larger as seed grows (Regan et al. 2019). For dark collapse into a massive BH even larger $M_{\text{dot}} \geq 100$ Mo/yr is required (Hammerle, Meynet, Mayer et al. 2019).

Need to feed from gas reservoir in galactic-scale disk. Which angular momentum transport mechanism(s) can feed the sub-nuclear galactic region efficiently enough?
A GENERAL MECHANISM FOR ANGULAR MOMENTUM TRANSPORT: GRAVITATIONAL TORQUES

Toomre parameter $Q = \frac{\kappa c_s}{\pi G \Sigma}$
(balance centrifugal force, pressure and gravity)

THREE REGIMES

(a) $Q \approx 1$ locally unstable to collapse, fragmentation (eg star formation) on a dynamical timescale ($t_{dyn}$).

(b) $1 < Q < 2$ locally stable, globally unstable to non-axisymmetric disturbances (spiral modes, bar-like modes)
Angular momentum transport (on $\sim t_{orb}$ timescale) via spiral density waves (Lynden Bell & Pringle 1979; Lin & Pringle 1987; Laughlin & Adams 2000)
Mass/angular momentum transport can be parametrized with (local) ‘alpha disk” (effective “alpha” large $\lesssim 0.1$).
$\rightarrow$ Nonlinear regime, hydro simulations needed

(c) $Q > 2$ locally and globally stable - dynamically uninteresting (remains close to axisymmetric)
1 < Q < 2 is the “useful” regime for sustained angular momentum transport

The cooling timescale controls in which Q regime the disk will settle. IF $t_{\text{cool}} < t_{\text{orb}} \rightarrow Q < 1 \rightarrow$ fragmentation (Gammie 2001; Rice et al. 2004; Deng et al. 2017)

**How can one enforce $t_{\text{cool}} > t_{\text{orb}}$?**

**Conventional route:** inefficient radiative cooling by ansatz — metal-free gas plus dissociation of H$_2$ by Lyman-Werner ionising radiation field from nearby star forming galaxies—-> atomic cooling halos at $z \sim 15$-20 (eg Wyse et al. 2019)

Example of protogalactic disk simulation in metal-free stomic cooling halo Latif et al. (2013)

Jeans unstable clump ($M \sim 10^4 M_\odot$)

$M_{\dot{}} \sim 1 M_\odot/yr$

$M_{\text{clump}} \sim 10^3$-4 $M_\odot$

(still too small BH seed?)
Alternative route direct collapse route: nuclear inflows in mergers of massive metal-enriched galaxies at $z \sim 8-10$ (Mayer et al. 2010; 2015; Mayer & Bonoli 2019) ($M_{\text{vir}} \sim 10^{12} \text{ M}_\odot$, 4-5σ peaks)

The inner 200 pc region a few Myr before final merger: the remnants of the two galaxy cores are shown
Parsec-scale dense nuclear disk forms which keeps accreting matter infalling supersonically (Mdot > 1000 Mo/yr). Disk core is warm and stable to fragmentation due to dynamical heating by shocks in accretion flow and disk (Mayer et al. 2015)

$\simeq 10^9$ Mo inside $\sim 2$ pc in only $\sim 10^4$ yr after galaxy merger
Any direct collapse pathway possible, including “dark collapse” (Hammerle et al. 2019)
A novel regime: Magnetised Gravitoturbulent Nuclear Disk

Increased stability against fragmentation? New pathway for enhanced angular momentum transport?

Test case: self-gravitating protoplanetary disk

Assume some prior amplification of B field by turbulent dynamo during gravitational collapse or merger (eg Schober et al. 2013; Grete et al. 2019) —> Initial seed $B_z$ field in the range 0.1-1 Gauss

Regime initially studied in 3D magnetised self-gravitating protoplanetary disk simulations (Deng, Mayer et al. 2019)
Gravitational instability with magnetic dynamo: stabilising effect (Q rises) PLUS enhanced turbulent mass transport

Disk models with a range of cooling rates, from a few to 10 orbital times

\[ \alpha \sim \frac{\langle H_{r\phi} + M_{r\phi} + G_{r\phi} \rangle}{\langle P \rangle} \]

Stresses (hydro, magnetic and gravitational)

Turbulent viscosity \( \alpha \sim 0.2-0.3 \)

In non-magnetised self-gravitating disks \( \alpha \ll 0.1 \)
Field amplification driven by dynamo mechanism

Dynamo generated by vertical circulation around spiral density wave intensity maxima

Shown is vertical slice through disk

Magnetic energy grows $\sim 10$ times larger than in identical, non-self gravitating disk with MRI (plasma $\beta \sim 7-10$ rather than $\beta >\sim 100$)
First local shearing box simulations by Riols and Latter 2017;2018) with PLUTO code uncovered gravitational instability (GI) driven spiral dynamo loop:

(I) radial compression of B field by spiral density waves + (II) lifting and folding of B field by vertical rolls generates new radial field + (III) shearing of new radial field back into toroidal by differential rotation (toroidal —> poloidal —> toroidal loop with net mean field growth)
Preliminary results: field amplification in self-gravitating nuclear disk in high-z merger remnant in Mayer et al. (2015)

Caution: current simulation *adiabatic* without cooling gravitational instability weakens over time —→ weaker dynamo trigger

Will need to add cooling to assess increased stability against fragmentation