Gas inflows in galaxy mergers: circumnuclear disks and massive seed black holes via direct gas collapse

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Outline

(a) Circumnuclear disks from central gas inflows and massive BH binaries

(b) Formation of massive BH seeds via direct gas collapse: intro

(c) Gas–rich galaxy mergers as a trigger to direct gas collapse
Multi-scale gas inflows in galaxies required to grow SMBHs

At all scales need to lose angular momentum (See Quataert’s talk)

Scale of circumnuclear disk
(1 pc - 100 pc)

- crucial, it feeds the accretion disk, hence the actual accretion flow directed to the black hole
- interplay with large scale dynamics and thermodynamics of galactic scale gas (and stars) because fed by large scales

Picture From Alex Hobbs (2012)
The observational perspective

- Circumnuclear disks of gas and stars (100-500 pc in size) ubiquitous in photometric + spectroscopic observations of interacting galaxies/mergers (Downes & Solomon 1998)

- Circumnuclear disks found in Seyfert galaxies (gas-rich spirals as typical hosts), with much higher incidence relative to non-active gas-rich spirals (Hicks et al. 2013)

- Recent observations (photometry and spectroscopy) have high enough resolution (~tens of pc) to characterize a circumnuclear disks at least in the low z Universe (Medling et al. 2013 - OSIRIS IFU spectroscopy at Keck II aided by Laser Guide Stars, LIRGs and ULIRGs from GOALS sample)
The simulations perspective

- Circumnuclear disks first found and studied by Barnes (2002) in set of major mergers --> gas with residual angular momentum not dissipated via shocks or gravitational torquing finds a centrifugal barrier at some radius

- Kazantzidis et al. (2005) found circumnuclear gas disks of ~ 100-300 pc scale in a wide range of merger remnants of nearly equal mass gas-rich galaxies (1:1 to 1:4), including counterrotating with external disks for retrograde mergers

- Mayer et al. (2007, 2008) - multi-scale SPH simulations with 10 pc and 2 pc resolution, equal mass mergers of Milky-Way type galaxies (10% gas fraction in disk) ----> circumnuclear disk of ~ $10^9$ Mo, ~ 100 pc size forms in less than 1 Myr after merger

- Chapon, Mayer & Teyssier (2013) confirm SPH results with AMR Ramses simulations of galaxy mergers reaching 0.1 pc resolution (polynomial EOS, no star formation and feedback)
Circumnuclear disk formation in cosmological simulations

(Fiacconi et al., in prep.)

Last stage of major merger (~1:3) between two z ~ 4.5 galaxies in zoom-in cosmological simulation (gas mass resolution 2000 M₀, spatial resolution 0.1 pc, SPH/Gasoline with particle splitting)

Shown is color-coded density map, starting when the larger scale portion of the galactic disks have been already disrupted by the interaction
In gaseous circumnuclear disks rapid binary SMBH formation

Fast BH binary formation confirmed by AMR/Ramses simulations --> hardening down to 0.1 pc separation in less than $10^6$ yr (Chapon, Mayer & Teyssier, 2013) – dynamical friction by gas dominates over that from stars/dm (Gravitational waves take over at separation $< 10^{-2}$ pc)
Direct gas collapse model for BH seeds

Rapid formation of massive BH seed --- mass $M_{\text{BH}} \sim 10^5 - 10^9 \text{ Mo}$

If early ($z \sim 8-10$) can explain high-$z$ QSOs ($M_{\text{BH}} > 10^9 \text{ Mo}$ at $z > 7$) without requiring continuous accretion at Eddington limit (or above) needed in scenarios with small BH seeds ($<~100 \text{ Mo}$) from Pop III stars (Madau & Rees 2001; Volonteri & Rees 2006) -

See talk by Bromm on how Pop III seeds are bound to accrete sub-Eddington due to radiative feedback (Johnson & Bromm 2006; Wise et al. 2008)

Stage I - Gas inflow in galaxy from kpc to $\sim 1 \text{ pc}$ scales to form BH precursor, eg bound supermassive gas cloud ($M > 10^6 \text{ Mo}$) - need efficient loss of gas angular momentum over many spatial scales (eg Lodato & Natarajan 2006)
Stage II - Depending on mass and rotational energy of supercloud (Trot/W) two pathways:

(a) low Trot/W (< 0.01) - supermassive star arises (see Yoshida's talk). Global collapse into massive black hole with $M_{BH} \sim M_{\text{star}}$ due to radial GR radial instability (Fowler & Hoyle 1966; Zeldovitch & Novikov 1972; Baumgart & Shapiro 1999; Shibata & Shapiro 2002; Saijo & Hawke 2009) --> direct formation of SMBH

(b) high Trot/W -- no global dynamical collapse, halted by rotation. Cloud can evolve into short-lived (>~ Myr) supermassive star that collapses into BH only at the center due to e.g. catastrophic neutrino cooling (Begelman et al. 2006; Begelman 2008; Begelman & Volonteri 2010; Dotan & Shaviv 2012). BH initially only 10-100 Mo accretes super-Eddington from a pressure-supported, <~0.1 pc scale convective envelope powered by BH accretion energy ("Quasi-star" - accretion still below the Eddington limit of the envelope)

BH can reach > $10^4$-5 Mo before cloud dispersal (in a few Myr) as long as quasi-star mass > $10^7$ Mo (Dotan, Rossi & Shaviv 2012)

--- direct formation of massive BH seed

This talk: how can Stage I be achieved?
TIMESCALE FOR SUPERMASSIVE CLOUD/STAR ASSEMBLY: REQUIRED GAS INFLOW RATE

Simple argument: a supermassive star ($M_{\text{star}} > \sim 10^7 \text{ Mo}$) has short lifetime ($t_{\text{life}} \sim 10^6 \text{ yr}$) must be assembled on $t_{\text{form}} < t_{\text{life}}$

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\rightarrow$ Characteristic gas inflow rate to feed the cloud $dM_g/dt > \sim M_{\text{star}}/t_{\text{life}} \sim 10 \text{ Mo/yr}$ for $M_{\text{star}} > \sim 10^7 \text{ Mo}$ (Begelman 2008; Dotan et al. 2012)

HOW DO WE GET SUCH HIGH GAS INFLOW RATES IN GALACTIC NUCLEI DOWN TO $\sim \text{ pc scales (\sim scale of Quasi-star)}$?
Gravitational torques in self-gravitating, marginally unstable protogalactic disk
(bars-in-bars, spiral modes, see eg Begelman et al. 2006, Lodato & Natarajan 2006; Levine et al. 2009)

Needs massive but “warm” disk (Toomre Q ~ 1.5–2, tcool > torb)
If gas cools efficiently (tcool < torb) and reaches Q < 1 then widespread fragmentation ---> switch to star formation dominated regime

How do we keep the disk “warm” and stable?
Standard argument: suppress molecular cooling and metal cooling below 10^4 K to keep Q > 1, avoiding gas makes stars rather than BH seed --- star formation bottleneck

-- potentially can work at very high redshift (z > 15) with very low metallicity gas (< 10^-5 solar, for higher values dust cooling already very effective in driving fragmentation, see Omukai et al. 2008) + likely requires proximity with massive star forming galaxies shining with high LW flux to dissociate H_2 (Dijikstra et al. 2009; Agarwal et al. 2012)

BUT at z >~ 15 characteristic host protogalaxy mass small (~ < 10^8 Mo), a potential problem since inflow rate dM_gas/dt ~ V_{halo}^{-3}G ~ M_{halo}/G ~< 1 Mo/yr neglecting effect of angular momentum (roughly consistent with simulations of Wise et al. 2008, Regan & Haenhelt 2009)
A DIFFERENT SCENARIO:
MASSIVE MULTI-SCALE GAS INFLOWS IN GALAXY MERGERS

- Galaxy mergers are known to trigger the strongest gas inflows in galaxies at 100 pc–1 kpc scales (due to tidal torques and shocks extracting angular momentum) ----> simulations show $\frac{dM}{dt} > 100 \text{ Mo/yr}$ (eg Kazantzidis et al. 2005; Li et al. 2006), can sustain high SF rates in ULIRGs and sub-mm galaxies (eg Hopkins et al. 2008; Bournaud et al. 2012).

- Despite increase of gas density due to inflow most of nuclear gas does not turn into stars. ----> From observations SF rate $\sim \frac{\epsilon_{\text{sf}} M_{\text{gas}}}{t_{\text{dyn}}}$, with $\epsilon_{\text{SF}} \ll 0.1$, occurring in high z merging systems (see eg Genzel et al. 2010, Tacconi et al. 2012).

- Circumnuclear disks in nearby LIRGs and ULIRGs (various evolutionary stages) often have inferred gas fractions > 50% within 100–500 pc (from H2 and CO observations, eg Medling et al. 2013).

$\rightarrow$ gas consumption timescale slower than inflow timescale $\frac{t_{\text{dyn}}}{\epsilon_{\text{SF}}} \gg t_{\text{dyn}} \sim t_{\text{inflow}}$
Can the merger-driven gas inflow continue all the way from 100 pc to << pc scales and form a precursor of a massive BH?

NOTE: we DO NOT assume suppression of cooling and star formation -- gas has non-zero metallicity because we start at z < 10
I - Gas-rich major mergers of massive proto-disk galaxies
(Mdisk ~ 6 x 10^{10} Mo, ~6 x 10^{9} Mo of gas at merger time) in 10^{12} Mo halos at z ~8
Resolution 0.1 pc and 3000 Mo in ~ 30 kpc volume
Galaxy halo mass consistent with abundance of high-z SDSS QSOs (Fan et al. 2006, Morlock et al. 2010)
i.e. rare 3-4σ peaks at z > 6 (Volonteri & Rees 2006; Li et al.2007; Sijacki et al. 2009)

60% of total gas mass accumulated within 200 pc due to tidal torques and shocks

Zoom in in the inner 200 pc region a few Myr before final merger: the remnants of the two galaxy cores are shown

Gas thermodynamics with effective equation of state (EOS) : polytropic with effective adiabatic index in the range 1.1-1.4

EOS based on NUCLEAR STARBURST model with solar metallicity gas by Spaans & Silk 2005 (also Klessen et al. 2007) calibrated with radiative transfer calculations

-- Accounts for thermal equilibrium between atomic/molecular line cooling and heating (UV, IR from dust, cosmic rays), including steady-state ionization of species
-- for density range 10 to 10^7 atoms/cc in dusty starburst (SFR >~ 30 Mo/yr) with metal enriched gas (metallicity solar).
Multi-stage gas inflow down to sub-pc in gravitationally unstable circumnuclear gas disk formed by major merger

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rapid formation of supermassive ($> 10^8 \text{M}_\odot$) sub-pc scale gas cloud in only $\sim 10^5$ years after merger (SMBH precursor)

Below logarithmic density map spanning $10^5$ yr after merger


Large scale $m=2$ mode imprinted by galaxy collision starts inflow in nuclear disk

Secondary spiral instabilities assist inflow at $< 10$ pc scale and further increase central density

Central region then undergoes Jeans collapse $\rightarrow$ formation of supermassive cloud ($M > 10^8 \text{M}_\odot$, $N_{\text{sph}} > 10^9$) $\rightarrow$ SMBH precursor?
• Supercloud Jeans unstable at resolution limit – further collapse (a) via supermassive star + quasi-star route or (b) directly into $>10^8$ Mo SMBH via post-newtonian instability (route (b) requires $R \sim 640GM/c^2 \sim 0.02$ pc for $M \sim 10^8$ Mo from numerical GR simulations results if angular momentum is negligible (Shibata et al. 2002; Saijo et al. 2009), for us $R_{\text{cloud}} \sim 0.5$ pc)

• Assume route (b) and, conservatively, that $>10^5$ Mo BH forms from ultimate collapse of SMS ( < 0.1 % of supercloud mass!), then:
Seed forming at $z \sim 8$ can grow at $>0.7 \times$ Eddington rate to $10^9$ Mo in $<3 \times 10^8$ yr, i.e by $z \sim 7$

In first $10^5$ yr after merger:

(a) Mass inflow rate
$\sim10^4$-$10^5$ Mo/yr (>> “free-fall” rate in halo potential well $dM/dt \sim Vc^3/G \sim 30$ Mo/yr used in previous direct collapse models, eg Lodato & Natarajan 2006)

(b) Star formation rate
($\sim0.1 \times M_g/T_{\text{orb}}$)
$\sim 10^3$ Mo/yr

--- gas inflow up to 2 orders of magnitude higher than star formation rate
In low mass galaxies ($< 10^{11} \, \text{Mo}$) no SMBH precursor forms

1:1 mergers between galaxies with a range of masses

- Base run ($M_{\text{vir}} = 10^{12} \, \text{Mo}$)
- 5x lower mass ($M_{\text{vir}} = 2 \times 10^{11} \, \text{Mo}$)
- 40x lower mass ($M_{\text{vir}} = 2.5 \times 10^{10} \, \text{Mo}$)

$T_{\text{rot}}/W < 0.05$

$T_{\text{rot}}/W > 0.25$

No Jeans unstable cloud because inflow is weakly self-gravitating

Shown on left: Logarithmic gas density maps
Mergers with (optically thin) radiative cooling and star formation

Gas cools radiatively and turns into stars above a density of $10^4$ cm$^{-3}$, thermal supernovae feedback + pressurization of medium to avoid spurious fragmentation below local Jeans length (no radiative transfer so maximized fragmentation)

$< 10^5$ yr after the merger star formation has turned 30% of the nuclear gas disk into stars but $> 10^8$ Mo of gas still concentrates at < 0.5 pc in supermassive flattened cloud

--- even stronger inflow than with EOS model (strong angular momentum dissipation in gravitoturbulent regime, see also Begelman & Shlosman 2010)
We follow the cosmological evolution of galaxies and their black holes:

- **Light (Pop III) seeds** ($M = 1000 \, M_\odot$) populate ALL newly formed galaxies

- **Direct collapse seeds** ($M = 10^5 \, M_\odot$) are formed during major mergers (and replace PopIII black holes), IF certain conditions implied by our simulations are satisfied

Embedding our formation scenario in the LCDM galaxy formation paradigm (Bonoli, Mayer & Callegari 2012 + in prep.)

We use the semi-analytical Munich model of galaxy formation (Croton et al. 2006; Bonoli et al. 2009), applied to the outputs of the dark matter-only Millennium Cosmological Simulation ($500 \, \text{Mpc}$ volume with $\approx 10^9 \, M_\odot$ mass resolution, see Springel et al. 2005)

We have a full population of galaxies evolving in a cosmological framework that allows us to study the consequences of BH seeding models.
Conditions for the formation of massive seed black holes (from simulations)
✓ 1. Major merger (1:3) of gas-rich late-type galaxies (B/T < 0.2)
✓ 2. Host halo $M_h > 10^{11} M_{\text{Sun}}$
✓ 3. No pre-existing black hole of $M_{\text{BH}} > 10^6 M_{\text{Sun}}$ (because feedback would stop gas inflow)

Seed black hole of $10^5 M_{\text{Sun}}$, starts accreting from large gas reservoir

Self regulation: accretion stops once the energy released by the black hole unbinds the reservoir (assumed isotropic thermal feedback with 0.05 coupling efficiency). BH will continue grow Eddington limited during subsequent mergers in the same way as Pop III seeds (a la Croton et al. 2006)

Radius of the gas reservoir is a free parameter (0.1-1pc), determines its binding energy
Properties of the BH mass function

(z> 0 “observed” MF from Merloni & Heinz 2005, z=0 MF from Shankar 2004)

- Light seeds (Pop III)
- Massive seeds (DC)

1 pc reservoir

0.1 pc reservoir

- Light seeds (Pop III)
- Massive seeds (DC) active (>~10% fedd)
By z=0 becomes zoom-in region becomes small galaxy cluster, with central galaxy massive early type galaxy (see lower resolution simulations in Feldmann et al. 2010;2011)

Zoom-in cosmological simulation with modern SPH (GASOLINE)
-- Hi-res region 2 Mpc comoving
At z ~ 4.5 each massive galaxy (M_{vir} <~ 10^{11} Mo) as well resolved as the single galaxy in the Eris simulation (Guedes et al. 2011)
-- at z ~ 4.5-5 splitting of SPH particles in selected sub-volumes of most massive galaxies to increase resolution to ~ 2000 Mo in the gas phase (0.1 pc spatial).
-- sub-grid star formation and feedback model (delayed cooling) as in the Eris simulations which produce realistic massive spirals at z=0

By z=0 becomes zoom-in region becomes small galaxy cluster, with central galaxy massive early type galaxy (see lower resolution simulations in Feldmann et al. 2010;2011)
At the core of the action...

Polytropic EOS

Fully radiative, star formation, supernovae feedback, thermal and metal diffusion to allow mixing in SPH
Effect of star formation pre-merger

Mergers with cooling and SF not completed yet but possible issue in conditions pre-merger: \( \frac{M_{\text{gas}}}{M^*} \) within 100 pc \(<\sim 0.3\)

Will it be sufficient to produce central gas collapse?

Is this perhaps reflecting tendency to overproduce stellar masses in galaxy formation simulations at high-\(z\)? (see abundance matching problem, eg Moster et al. 2012)
Conclusions and open questions

Massive, dense circumnuclear disks of gas and stars are a natural consequence of gas-rich galaxy mergers, hence a common occurrence in galaxy formation (all galaxies were once gas-rich disks!). They are the galactic reservoir of gas for the BH accretion disk.

They drive naturally fast formation of massive BH binaries and their decay to sub-pc scales and possibly drive the formation of a central supermassive cloud precursor of a massive BH seed.

Does direct collapse into a SMBH really occur after formation of supermassive cloud and which path does it take? Global post-newtonian instability? Supermassive star + quasi-star? Or does the central inflow produce a mass-loaded massive nuclear star cluster which undergoes fast core collapse into BH seed (Davies et al. 2011)?

-- Modeling of cloud collapse at even higher resolution w/post-newtonian effects or interface with full General Relativistic simulations (ongoing with AEI Potsdam)
-- Better characterization of physical conditions of central gas inflow and cloud - need proper radiative transfer, neutrino diffusion in hot core etc..

How does our SMBH formation scenario depend on the structure/initial angular momentum content of merging galaxies?

What would change with a realistic multi-phase ISM in the circumnuclear disk?

Galactic disks at high z clumpier and more turbulent than our ICs! Gravitoturbulence could aid collapse via dissipation of angular momentum (eg Begelman & Shlosman 2010) -- cosmological simulations on the way (Fiacconi et al., in prep.)
Predictions for merger-driven massive BH seed formation (simulations combined with SAMs):

• BH formed by merger-driven collapse also at low z, and should have low clustering amplitude (those that form at high z are instead highly clustered as expected for high-sigma peaks) and preferentially found in bulge-dominated galaxies

• At z > 2 large deviations from local $M_{\text{bulge}}-M_{\text{BH}}$: SMBH already in place while bulge grows with the (slower) galaxy assembly

If quasi-star phase precedes BH seed formation could be observable with JWST (blackbody emission at a few microns), although only very few per JWST field expected (see also Volonteri & Begelman 2010). At low z such events about an order of magnitude less frequent but gamma ray and radio emission could be detected if jets develop in quasi-stars, perhaps explaining unidentified sources in gamma-ray catalogs (Czerny et al. 2012)