Observational Support for Massive Black Hole Formation Driven by Runaway Stellar Collisions in Galactic Nuclei.

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ABSTRACT

We explore here an scenario for massive black hole formation driven by stellar collisions in galactic nuclei, proposing a new formation regime of global instability in nuclear stellar clusters triggered by runaway stellar collisions. Using order of magnitude estimations, we show that observed nuclear stellar clusters avoid the regime where stellar collision are dynamically relevant over the whole system, while resolved detections of massive black holes are well into such collision-dominated regime. We interpret this result in terms of massive black holes and nuclear stellar clusters being different evolutionary paths of a common formation mechanism, unified under the standard terminology of being both central massive objects. We propose a formation scenario where central massive objects more massive than $\sim 10^8 M_\odot$ will be too dense (in virial equilibrium) to be globally stable against stellar collisions and most of its mass will collapse towards the formation of a massive black hole. Contrarily, this will only be the case at the core of less dense central massive objects leading to the formation of black holes with much lower black hole efficiencies $\epsilon_{BH} = \frac{M_{BH}}{M_{CMO}}$, with these efficiencies $\epsilon_{BH}$ drastically growing for central massive objects more massive than $\sim 10^7 M_\odot$, approaching unity around $M_{CMO} \sim 10^8 M_\odot$. We show that the proposed scenario successfully explain the relative trends observed in the masses, efficiencies and scaling relations between massive black holes and nuclear stellar clusters.

For more than half a century evidence was accumulated for the existence of Massive Black Holes (MBHs) in galactic nuclei with masses $\sim 10^6\sim 9 M_\odot$ (1-4), but only recently arrived definite support in favor of their existence (5). The origin of such ‘monsters’ puzzled theorists soon after their discovery (6), however, is still a mystery their dominant formation process (7). With the advent of the gravitational wave astronomy, specially with the future
LISA experiment (8, 9), it is expected to have definite answers on the formation of MBHs in the universe.

Several pathways have been proposed for MBH formation (6, 7, 10), which can be briefly summarized into 3 channels: i) Direct collapse of a primordial cloud onto a MBH (11-13) ii) Growth by gas accretion and/or mergers of a stellar/intermediate mass BH up to the mass range of MBHs (14, 15) and iii) Formation of a MBH by catastrophic stellar collisions in dense stellar clusters (6, 16, 17). However, all of them faced severe problems to fulfill the constraints set by observations, such as the physical conditions needed to sustain atomic cooling halos are unclear to be fulfilled (i; 18-20), problems for explaining the highest redshift quasars by lower mass BHs grown thru Eddington-limited accretion (ii; 21-24) and that simulations of stellar collisions in dense clusters are able to form only BHs of lower masses in the intermediate mass regime (iii; 25-28).

Besides the problems faced by the different formation scenarios, galactic centers are arguably the most favorable places for MBH formation. Any gaseous (and stellar) material that eventually loses its orbital support falls on to this preferential place (29, 30), which corresponds to the deepest part of the galactic gravitational potential. Multiple processes produces strong inflows at galactic scales funneling large amount of gaseous material (up to $10^{10} M_\odot$) to this preferential place, that includes gravitational torques in galaxy mergers (31-33), bars within bars (34, 35), clump migration by dynamical friction (36, 37), etc. These processes are expected to be even more dramatic in the case of proto-galactic material at high z, because of the higher gas fractions and the absence of AGN feedback from preexisting MBHs (38). Therefore, in the absence of feedback limiting factors (23, 39), the amount of material funneled into galactic nuclei has (in principle) no upper limit externally set by processes at galactic scales and thus, we expect to be the hosting place of the densest gaseous and stellar configurations in the universe. The straightforward question is then, if such material it does not ends up forming a MBH, that corresponds to gravity’s final triumph, which other stable physical configuration at intermediate densities it could be?

The hypothetical scenario under very efficient heating mechanisms ($T_{\text{vir}} \geq 10^4$K) has been extensively studied (11-13), where fragmentation is suppressed on smaller scales and directly leads to the formation of a single Very Massive quasi-Star (VMS; 40, 41) at the center, which afterwards collapses onto a MBH due to post-Newtonian instability (42, 43). Contrarily, in the absence of efficient heating the gaseous material funneled to the galactic center efficiently cools (44, 45), eventually becomes unstable and fragments in a broad range of scales (46, 47), leading to the formation of a dense stellar cluster (48, 49). Such dense stellar configurations are indeed observed, being called Nuclear Stellar Clusters (NSCs; 50-53), which even in some cases coexists with a MBH (54, 55), thus having possibly a joint
formation event. Therefore, a more realistic scenario reduces to how dense such stellar system it can be before becoming globally unstable, leading it again to the formation of a MBH.

A natural candidate for triggering instability in stellar clusters are collisions between stars since it is an efficient mechanism for loosing orbital energy support, because physical collisions between stars are a dissipative source on a fluid interpretation of a cluster, being able to convert energy in kinetic motions into internal heat of stars and otherwise, without collisions the energy in stellar motions behaves adiabatically. However, it is generally believed that physical collisions between stars are considered an exotic phenomena that rarely happen in the universe (56), restricted to only be relevant in the cores of dense stellar configurations like Globular Clusters systems (57), where it is well established that the cores of such dense stellar systems are unstable to suffer catastrophic runaway stellar collisions (25). Numerical experiments have shown that runaway collisions of the most massive stars could lead to the formation of Intermediate-Mass Black Holes (IMBHs) in the centers of typical globular clusters (BH masses $\sim 10^3 M_\odot$) can be build up before the first supernova explodes; 25-27, 58). Nevertheless, it is unclear what could happen in the more extreme conditions of proto-galactic nucleus, because of the lack of detailed N-body simulations that includes the effects of the higher densities and velocity dispersions, that in addition to gas dissipation should define a density limit for NSCs before becoming globally unstable to catastrophic stellar collisions.

An order of magnitude estimate that quantifies the occurrence of collisions in any system with large number of particles, is to compute a collision timescale given by $t_{\text{coll}} = \lambda / \sigma$, where $\sigma$ is the characteristic (dispersion) velocity of the system and $\lambda$ is the particle (star) mean free path (56). From the equation $n\Sigma_o \lambda = 1$ a mean free path can be probabilistically defined (59, 60), where $n$ is the number density of stars and $\Sigma_o$ the effective cross section, giving a collision rate of $t_{\text{coll}}^{-1} = n\Sigma_o \sigma$. Assuming that the stellar system is virialized, the dispersion velocity is $\sigma = (GM/R)^{1/2}$, where $M$ is the total mass and $R$ the characteristic radius of the system. This result is generally valid in any stellar system in virial equilibrium and is also valid for systems with a relevant dark matter component, using the empirically calibrated formula of (61), where the velocity dispersion is $\sigma = (GM/5f_g R)^{1/2} \approx (GM/R)^{1/2}$ for $f_g = 0.16$ (62). Therefore, in any virialized stellar system the collision timescale is given by

$$t_{\text{coll}} = \frac{1}{n\Sigma_o \sqrt{\frac{R}{GM}}}.$$  

In an uniform system, composed only by solar mass stars, the number density is $n = 3M/4\pi R^3 M_\odot$. The effective cross section $\Sigma_o$, due to gravitational focusing, is for a solar mass star approximately $100 \pi R_\odot^2$ (i.e. using Eq 7.195 in 56). Under these assumptions, neglecting radial concentrations, initial mass functions and other dimensionless factors of
order unity, collisions will be relevant in the dynamics (and possibly becoming unstable) of a given system with a characteristic age \( t_H \), if its age is comparable or longer than the collision time, \( t_{\text{coll}} \leq t_H \), which is equivalent to the following condition:

\[
\hat{\rho}_{\text{crit}} \equiv \left( \frac{4M_\odot}{300R_\odot^2 t_H G^{1/2}} \right)^{2/3} \leq MR^{-7/3},
\]

where \( \hat{\rho}_{\text{crit}} \) is a critical mass density, an intermediate density between the surface density \( (\propto R^{-2}) \) and a volumetric one \( (\propto R^{-3}) \). The largest relevant value for \( t_H \) is the age of the universe, which is of the order of \( \sim 10^{10} \) years that gives critical mass density \( \hat{\rho}_{\text{crit}} \sim 10^7 M_\odot \text{pc}^{-7/3} \), but galactic centers can be one order of magnitude younger \( (t_H \sim 10^9 \text{yr}) \). Within geometrical factors of order unity, such boundary is set by a combination of a fundamental constant \( (G) \), with typical parameters of our universe such as its current age \( (t_H) \) and the properties of the sun \( (M_\odot, R_\odot) \), which it is considered to be an average star in the Universe, defining the critical density of stable stellar systems for our current cosmic parameters. Also, we arrive to such criterion without ad-hock assumptions, being the only assumption to be virialized, which is only a requirement for being an stationary stellar system.

Figure 1 displays the observed masses and effective radius for nuclear stellar clusters in both late- and early-type galaxies (red circles) taken from (55). The solid blue line in Fig 1 displays the condition given by Eq. 2 for \( t_H = 1.4 \times 10^{10} \) years (62) and the dashed blue lines, are respectively \( t_H = 10^8, 10^6 \) and \( 10^4 \) years, for comparison purposes. The measured properties of NSCs (red circles) shows a clear avoidance of the regions in which collisions could be globally relevant in the internal dynamics of a cluster, with collision timescales always larger than the age of the universe (right side of the solid blue line). The only clear exception is NGC 1507, with its \( \geq 10^7 M_\odot \) in only 0.1 pc of effective radius, however, this last measurement has estimated errors over 2000% (effective radius up to 2.3 pc that moves NGC 1507 to right side of the blue line). It is important to note that these are average collision timescales, relevant for global stability against collisions, that it can be considerably shorter at the core and therefore, these globally stable NSCs can still coexist with an unstable core which is expected to be triggered by Spitzer’s instability (25, 63-64).

In addition, we plot in Fig 1 the measured masses and resolution radius \( (=0.5d_{\text{resol}} \text{, where } d_{\text{resol}} \text{ is the observation spatial resolution}) \) for MBH candidates, but we differentiate them between ‘well-resolved’ MBHs with influence radius \( R_{\text{inf}} \) larger than 3 spatial resolutions (black circles) and ‘unresolved’ ones \( (R_{\text{inf}} < 3 \text{ } d_{\text{resol}}) \) with white circles, both from the sample of (65). Contrarily to the case of nuclear clusters, in the case of MBH candidates we see two clear trends: the properties of resolved MBHs are in the region that clearly passed to the collision-dominated regime (left side of the solid blue line) and the unresolved ones, still
Fig. 1.— Measured masses and effective radius for nuclear stellar clusters (red circles), ‘well-resolved’ MBHs (black circles) and ‘unresolved’ MBHs (white circles). The measurement of M87’s black hole shadow (5) is denoted by the black star, which is the closest to the black line that represents positions of the Schwarzschild radius as a function of mass. The solid blue line represents the condition given by Eq. 2 for $t_H = 1.4 \times 10^{10}$ years ($\rho_{\text{crit}} \sim 10^7 M_\odot \text{pc}^{-7/3}$) and the dashed blue lines, the same condition for respectively $t_H = 10^8, 10^6$ and $10^4$ years. The horizontal green line represents the condition implied by Eq. 3 ($\sim 3.5 \times 10^8 M_\odot$) in order to be in agreement with the observed scaling relation for NSCs (54). The positions of NSCs are restricted within the boundaries defined by the collisional stable region for NSCs, denoted by the thicker blue and green lines.

avoids the collision-dominated regime and coexist with the NSCs.

The trend for unresolved MBHs positions can be easily understood taking into account that the properties of MBHs are diluted due to resolution. For the unresolved MBHs, this means a decrease in densities down to values comparable to stellar densities in the nuclear regions of their host. Therefore, the unresolved MBHs can be taken as better estimates of the properties of the stellar background within $R_{\text{int}}$ than of MBHs itselfs and in some sense, they can be considered also like stellar systems. Taking this into account, the properties of NSCs clearly differs from the ones of resolved MBHs, with NSCs avoiding the collision-dominated region and resolved MBHs passing such limit, with a sharp transition from NSCs to resolved
MBHs around $t_{\text{coll}}$ of the order of the age of the universe.

Moreover, in a virialized system, $R = GM/\sigma^2$, the condition given by Eq. 2 can be rewritten as:

$$\sqrt{\frac{4R_\odot}{300\sigma_\odot t_H}} \leq \frac{M_\odot}{M} \left(\frac{\sigma}{\sigma_\odot}\right)^{3.5},$$

with $\sigma_\odot = \sqrt{\frac{GM_\odot}{R_\odot}} \sim 400$ km s$^{-1}$. If this condition is combined with the empirical scaling relation that constrains the properties for observed NSCs, $\frac{M_{\text{NSC}}}{10^{6.9}M_\odot} = (\frac{\sigma}{128\text{km/s}})^{2.73} \sim (\frac{3\sigma}{\sigma_\odot})^{2.73}$ (54), gives that NSCs will be unstable for masses larger than $\sim 3.5 \times 10^8 M_\odot$ (for a $t_H$ again of the order of the age of the universe). This condition is denoted by the horizontal green line in Fig. 1 showing again good agreement with the value of the most massive NSCs. Therefore, besides these conditions being order of magnitude estimations with simplifications, the positions of NSCs are suggestively restricted within the boundaries defined by the collisional stable region, denoted by the thicker blue and green lines in Fig. 1.

Both MBHs and NSCs are observed to coexist in the nuclei of galaxies (54, 55) suggesting to be a generic byproduct of their formation and evolution, being these two completely distinct type of objects unified into the terminology of being a Central Massive Object (CMO; 66). MBHs dominates in galaxies with masses larger than $10^{12} M_\odot$ and similarly occurs with NSCs for galaxies less massive than $10^{10} M_\odot$, with both coexisting in the intermediate mass regime (55). If they are indeed different evolutionary stages of a common formation mechanism, the simplest interpretation of their different locations in Fig 1 is in terms of MBHs and NSCs being CMOs with different final fates. CMOs that are too dense to be globally stable against stellar collisions will collapse towards the formation of a MBH, contrarily, this will only be the case at best in the core of less dense clusters, being globally stable in the form of a NSC (probably coexisting on its center with a lower mass BH formed in the unstable core).

Simulations of globular-type stellar clusters ($<10^6 M_\odot$) shows that cores are unstable to suffer catastrophic runaway stellar collisions of massive stars due to Spitzer’s instability (25), as long as the cluster is enough massive and concentrated, with core collapse (relaxation) times less than those set by the evolution of their massive stars ($<3$-$25$ Myr). A central most massive object is generically formed with efficiencies ranging from 0.1% (25-27) up to a few percentage of the cluster mass (67, 68), depending on multiple physical parameters such as stellar radius, (initial) stellar mass distribution, etc. The central most massive object is expected to have similar fate of a VMS, being typically out of thermal equilibrium with Kelvin-Helmholtz timescale larger than the collision timescale (28) and also, expected to collapse to an IMBH due to post-Newtonian instability (42, 43).
Unfortunately, direct N-body simulations do not explore either the regime of larger clusters in the NSC mass range (> $10^6 M_\odot$) or the more extreme regime of globally unstable clusters, not only because its properties are more exotic but also, because they are numerically much more expensive. The few exceptions are restricted to either Monte Carlo calculations (58, 69) or self-consistent Fokker-Planck models of galactic nuclei (70, 71) but their results are already quite suggestive, finding that in large N systems (> $10^7$ stars, which corresponds to cluster masses larger than $10^7 M_\odot$ assuming solar mass stars) three-body binary heating is unable to reverse core collapse before the onset of runaway collisions and then are vulnerable to a ‘merger instability’, which may lead to the formation of a central black hole (70, 71). Since in this regime the collision runaway started well before core collapse and for a system with (initially) equal mass stars (70, 71), without even requiring Spitzer’s instability, it is reasonable to expect in those systems efficiencies $M_{BH}/M_{\text{cluster}}$ higher than the few percentage found in N-body simulations of globular-type stellar clusters. Therefore, NSCs are indeed expected to be the most favorable places for stellar collisions in the Universe.

Fig 1 is supporting evidence that in addition of NSCs being the most favorable places for stellar collisions, the most massive and denser NSCs that forms in the Universe might exist only temporarily, being globally unstable to collapse to a MBH. This should be eventually triggered by runaway stellar collisions at some density limit, regardless if it is at the $\rho_{\text{crit}}$ defined by Eq. 2 or another one that includes processes not taken into account (gas dissipation, etc). It is then possible to visualize the following transition in the properties of CMOs: for objects denser than some critical limit, which from Eq 3 seems to be the case for $M_{CMO} > 10^8 M_\odot$ in order to fulfill the observed scaling relation for NSCs (54), most of the CMO mass will be in the form of a MBH. On the opposite mass limit, the bulk of mass in the CMO will stay in the stars of the NSC, even some cases with an undetectable MBH at its center, with black hole efficiencies $\epsilon_{BH} = M_{BH}/M_{CMO}$ probably in the range of star cluster simulations from 0.1% up to a few percent (25-27, 67-68) until it approaches to a second critical mass ($M_{CMO} \sim 10^7 M_\odot$; according to 70, 71), where the black hole efficiency should have a drastic change, rapidly growing towards $\epsilon_{BH}$ close to 1.

The concordance of this scenario for CMOs evolutionary paths, with the observed relative masses in MBHs and NSCs can be easily tested. Assuming that is the total mass in CMOs the mass reservoir for which competes MBHs and NSCs in galactic nucleus, $M_{CMO} = M_{NSC} + M_{BH}$; for a black hole formation efficiency $\epsilon_{BH}$ the central black hole mass is $M_{BH} = \epsilon_{BH} M_{CMO}$ and the mass of the surrounding nuclear cluster is then $M_{NSC} = (1 - \epsilon_{BH}) M_{CMO}$, both related to the efficiency as $\epsilon_{BH} = (1 + M_{NSC}/M_{BH})^{-1}$, which then it can be directly estimated by measuring the masses $M_{NSC}$ and $M_{BH}$. Also, assuming that is total mass in central massive objects $M_{CMO}$ the one that correlates with the total mass of the host spheroid ($M_{CMO} = \epsilon M_{sph}$, with $\epsilon \sim 0.1\%; 72$), it is straightforward to realize that
in both limiting cases (either only a MBH or a NSC), the observed (individual) relations are automatically fulfilled \( M_{\text{NSC}} \sim \epsilon_{\text{sph}} \) for \( \epsilon_{\text{BH}} \sim 0 \) and \( M_{\text{BH}} \sim \epsilon_{\text{sph}} \) for \( \epsilon_{\text{BH}} \sim 1 \).

![Graph showing black hole formation efficiency](image)

Fig. 2.— Observed black hole formation efficiency \( \epsilon_{\text{BH}} = (1 + \frac{M_{\text{NSC}}}{M_{\text{BH}}})^{-1} \) as a function of the total mass in central massive objects \( M_{\text{CMO}} = M_{\text{NSC}} + M_{\text{BH}} \), with both quantities computed using the MBHs and NSCs masses from two independent datasets represented by white (73) and black circles (74). The efficiency displayed in the figure has two dominant values for black hole efficiencies (\( \epsilon_{\text{BH}} \leq 0.15 \) at \( M_{\text{CMO}} \leq 10^7 M_\odot \) and \( \epsilon_{\text{BH}} \geq 0.9 \) for \( M_{\text{CMO}} \geq 10^8 M_\odot \)) and a transition close to a step function of the mass.

Fig 2 displays the efficiencies \( \epsilon_{\text{BH}} = (1 + \frac{M_{\text{NSC}}}{M_{\text{BH}}})^{-1} \) plotted against the total mass in central massive objects \( M_{\text{CMO}} = M_{\text{NSC}} + M_{\text{BH}} \), both quantities computed using the measured masses from two independent datasets denoted by the white (73) and black circles (74; assuming \( M_{\text{NSC}} = 10^5 M_\odot \) for 12 ‘core galaxies’ with no NSC detections). The data in Fig 2 clearly displays three regimes: a) \( \epsilon_{\text{BH}} \leq 0.15 \) for \( M_{\text{CMO}} \leq 10^7 M_\odot \), b) \( \epsilon_{\text{BH}} \geq 0.9 \) for \( M_{\text{CMO}} \geq 10^8 M_\odot \) and c) a transition regime between \( 10^7 M_\odot \leq M_{\text{CMO}} \leq 10^8 M_\odot \) with rapidly growing \( \epsilon_{\text{BH}} \). This trend is clear and suggestively in agreement with the proposed formation scenario for CMOs, with the transition regime limited on the expected boundaries defined by the ‘merger instability’ found in Fokker-Planck models of galactic nuclei (\( \sim 10^7 M_\odot \); 70-71) and the upper limit given by Eq 3 to fulfill the scaling relation for NSCs (\( \sim 10^8 M_\odot \); 54). This can be contrasted, for example, with black hole efficiencies \( \epsilon_{\text{BH}} \) that are randomly distributed.
between 0 and 1, which could be the case on a different formation scenario, where most (75%) of the measurements should be in the interval $\epsilon_{BH} = [0.15, 0.9]$ and where there is a total absence of points in regimes a) and b) of Fig 2. Moreover, a sharp transition is also seen around to $M_{CMO} \sim 10^8 M_\odot$, suggesting again that this is the limit for (collision-driven) global collapse, where most of the mass ends up into a single MBH and that naturally explains the lack of NSCs around MBHs for $M_{BH} > 10^8 M_\odot$ (55).

The efficiency displayed in Fig 2 with two dominant values for BH efficiencies and a transition with a form close to a step function of the mass, could also explain the origin in the change of scaling in the M-$\sigma$ relation from NSCs to MBHs, which has been taken as support that MBHs and NSCs may not share a common origin (54). The empirical evidence is that NSCs have a less steep scaling relation $M_{NSC} \propto \sigma^{2-3}$ (54, 75), compared with the scaling for MBHs that have steeper slopes of $M_{BH} \propto \sigma^{4-5}$ (76, 77). Assuming that CMOs have a single scaling relation originated in the galaxy formation process, for example, the scaling defined at the critical threshold given by Eq. 3 ($M_{CMO} \propto \sigma^{3.5}$), the step function efficiency $\epsilon_{BH}$ shown in Fig 2 bias the relation for the less massive MBHs, giving a steeper slope ($> 3.5$) for the MBH scaling relation and vice versa, $1 - \epsilon_{BH}$ bias the original relation for the more massive NSC giving a less steep slope ($< 3.5$). Therefore, this naturally reconcile an scenario of joint formation, with different M-$\sigma$ scaling relation for MBHs and NSCs.

This scenario also links naturally to the fact that the existence MBHs in galaxies is intimately related with their spheroidal/triaxial component (76, 77), which is supported by random motions and where collisions are much more frequent compared to the disk component of galaxies (for a given characteristic velocity), since disks are systems that are rotationally supported characterized by ordered motions that prevents collisions. In addition, this collision driven global instability in extreme stellar systems sets internally the upper mass limit of NSCs around $\sim 10^8 M_\odot$, something needed because at galactic scales the study of gravitational instabilities do not set externally an upper limit for the stellar cluster masses in galactic nuclei, since the size of the whole system is the largest unstable wavelength (78). Only when rotation becomes relevant (i.e. in the galactic disk), this sets a maximum mass scale for a gaseous collapsing cloud, ranging from $M_{\text{cloud}}^{\text{max}} \sim 10^6 M_\odot$ for MW type disks, upto the order of $\sim 10^8 M_\odot$ for ULIRGs nuclear disks (47). Those massive clouds in ULIRGs are expected to migrate and runaway merge in galactic nuclei (37), again lacking of a well defined upper limit.

The details in the exact evolution of the gaseous (and stellar) material funneled into galactic nuclei are still unclear under realistic conditions. Most probably the extremely dense, purely gas-free NSC discussed in this paper rarely exists in the Universe and most often (especially in the early Universe), an unstable NSC will collapse as a whole during its formation,
before evaporating its gaseous envelope (as might be suggested by the multiple stellar popu-
lations seen in surviving NSCs; 79). Also, we have neglected relevant secular processes such
as the role of preexisting MBHs binaries in the dynamics and formation of galactic nuclei
(80-82). Certainly, more realistic simulations (with and without gaseous components) are
needed to set these open issues, but the absence of NSCs in the collision-dominated regime,
with the sharp transition seen at the boundaries of the unstable region of Fig 1, suggests
that the fate of the unstable ones is unavoidably collapsing onto a MBH. Therefore, besides
all these uncertainties, the results in this work can be taken as supporting evidence that the
collapse leading to MBH formation is most probably triggered by runaway collisions, than
by suppressing fragmentation on smaller scales (or alternatively by the runaway growth of
a preferred IMBH on cosmological timescales). Also, this collision-driven BH formation is
a process that could happen even in the the earliest epochs of the Universe (83), without
imposing strict constraints on cosmological timescales.

Because it is hard to constrain MBH formation enough thru direct observations of such
objects by traditional electromagnetic detections, in addition of having more complex and
realistic simulations, definite answers will probably come from direct observations of the
final collapse by gravitational-wave observatories such as LISA (8). In the complex collision-
driven collapse scenario described in this letter, it is hard that the final collapsing VMS will
be close to spherically or axially symmetric, therefore, it is expected to be at least bar-shaped
or most probably, even more irregular and a gravitational wave signal it is expected from
galactic centers at the moment of MBH formation (6), that will be detectable in the LISA
band out to high redshift (84).
References and Notes

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