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Little Red Dots Are Tidal Disruption Events in Runaway-collapsing Clusters

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Abstract

I hypothesize a physical explanation for the "little red dots" (LRDs) discovered by the James Webb Space Telescope (JWST). The first star formation in the Universe occurs in dense clusters, some of which may undergo runaway collapse and form an intermediate mass black hole. This process would appear as a very dense stellar system, with recurring tidal disruption events (TDEs) as stellar material is accreted by the black hole. Such a system would be compact, UV-emitting, and exhibit broad Hα emission. If runaway collapse is the primary mechanism for forming massive black hole seeds, this process could be fairly common and explain the large volume densities of LRDs. In order to match the predicted number density of runaway collapse clusters, the tidal disruption rate must be on the order of 10^{-4} per year. A top-heavy stellar initial mass function may be required to match observations without exceeding the predicted ΛCDM mass function. The TDE LRD hypothesis can be verified with follow-up JWST observations looking for TDE-like variability.

Unified Astronomy Thesaurus concepts: High-redshift galaxies (734); Intermediate-mass black holes (816); Galaxy formation (595); Tidal disruption (1696); Active galactic nuclei (16)

1. Introduction

The objects known as little red dots (LRDs) discovered by the James Webb Space Telescope (JWST) have been mystifying our community (J. E. Greene et al. 2024; D. D. Kocevski et al. 2024; V. Kokorev et al. 2024; J. Matthee et al. 2024). They exhibit features common to both star-forming galaxies and active galactic nuclei (AGNs), but their emission cannot be modeled robustly by either (or a combination). Their number density at high redshift is also higher than expected compared to similar galaxy populations. If they are dominated by star formation, they are more compact than anything ever seen before (C. A. Guia et al. 2024) and exceed the predicted stellar mass function allowed by ΛCDM (M. Boylan-Kolchin 2023; H. B. Akins et al. 2024; J. F. W. Baggen et al. 2024). If they are dominated by AGN emission, their existence implies an almost 100% AGN fraction in high-redshift galaxies (J. E. Greene et al. 2024). Both of these possibilities are difficult to reconcile with any cosmic evolution model.

LRDs have been discovered mostly at redshifts $5 < z < 8$, and often exhibit a "V-shaped" spectral energy distribution (SED). The bottom of the "V" is at the Balmer break (D. J. Setton et al. 2024), with rising luminosity both in the UV and red wavelengths. They have broad Hα emission lines, but the broadness is not seen in Hβ (M. Brooks et al. 2024; R. Maiolino et al. 2024). They are X-ray undetected or weak (M. Yue et al. 2024) and are also undetected in the far-infrared (P. G. Pérez-González et al. 2024; C. C. Williams et al. 2024; I. Labbe et al. 2025). This lack of emission not only makes the SEDs very difficult to characterize and bolometric luminosities hard to determine, but also means there is an overall struggle to pinpoint the source of the emission at all.

One of the many reasons LRDs are fascinating is their potential to shed light on the formation and evolution of supermassive black holes (SMBHs). The formation mechanism of SMBH seeds, often thought to be intermediate mass black holes (IMBHs) of some variety, is highly unconstrained, as is their subsequent growth into SMBHs. Seeds may be "light" (i.e., the remnants of the first stars, e.g., V. Bromm & A. Loeb 2003), "heavy" (i.e., direct collapse black holes, e.g., M. C. Begelman et al. 2006), or in between (i.e., remnants of runaway cluster collapse, e.g., B. Devecchi & M. Volonteri 2009), and are likely to undergo at least some phases of super-Eddington growth to reach supermassive size. Observations of the earliest galaxies could untangle this quandary—or at least, we thought so.

In this Letter I explore the hypothesis that LRDs can be explained by black hole seeds in the making via tidal disruptions in runaway collapsing clusters. The resulting SED would somewhat resemble an AGN but with some key differences, many of which are consistent with LRD observations.

2. Runaway Collapse

One prominent theory for the formation of black hole seeds is the runaway collapse of dense star clusters. It is thought to create seeds of $\sim 1000\,M_\odot$ and may or may not be redshift dependent, depending on whether metallicity is an important factor. The phenomenon of runaway collapse involves a dynamical instability resulting in the collapse of the cluster core. The ensuing runaway collisions in these nuclear star clusters may result in the creation of a supermassive star (S. F. Portegies Zwart et al. 1999; T. Ebisuzaki et al. 2001; S. F. Portegies Zwart et al. 2004; B. Devecchi & M. Volonteri 2009), which then evolves into an IMBH. This phenomenon has been demonstrated in Monte Carlo (M. A. Gürkan et al. 2004; M. Freitag et al. 2006) and N-body (A. Rantala & T. Naab 2025) simulations, and runaway collapse may be enhanced in clusters with low metallicities and higher masses (U. N. Di Carlo et al. 2021) and/or high binary fractions of

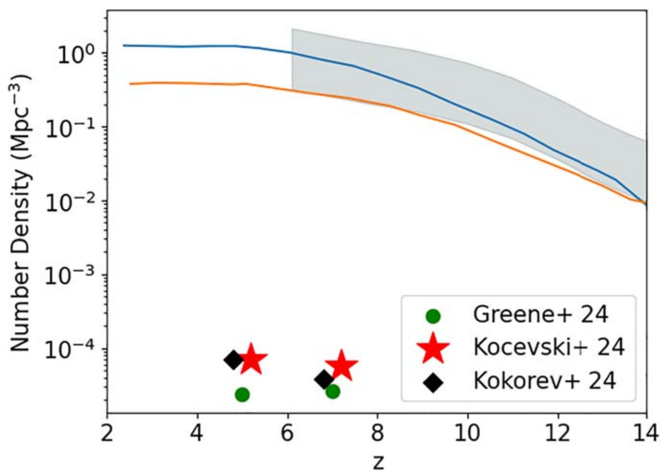

Figure 1. Comoving number density of runaway collapse black hole seeds vs redshift. Predictions from numerical simulations vary based on whether a delayed cooling model is used with supernova feedback (blue line) or not (orange line; M. Habouzit et al. 2017). Analytic predictions using variable seed masses are shown in the gray shaded area (B. Devecchi et al. 2012). Data points represent JWST LRD observations from J. E. Greene et al. (2024; green dots), D. D. Kocevski et al. (2024; red stars), and V. Kokorev et al. (2024; black diamonds). The data are ∼4 orders of magnitude below the predicted densities.

massive stars (E. González et al. 2021). Other works suggest IMBH formation may involve a preexisting black hole that rapidly accretes surrounding objects in the cluster (M. C. Begelman & M. J. Rees 1978; M. B. Davies et al. 2011). Regardless of the precise order of operations, a dense cluster surrounding a massive black hole will be an efficient environment for tidal disruption events (TDEs). In fact, T. Alexander & B. Bar-Or (2017) suggest that IMBHs should not exist at all because growth from TDEs is so efficient that the minimum SMBH mass is $10^5\,M_\odot$.

There have been very few calculations of the number density of such seeds with cosmic time, likely because the conditions for runaway collapse happen on a much smaller scale than that of, e.g., cosmological simulations. Estimates have been made by B. Devecchi et al. (2012; analytic) and M. Habouzit et al. (2017; numerical), which I show in Figure 1. The gray shaded area represents an adaptation of the prediction from B. Devecchi et al. (2012) for a range of seed masses (300–3000 $M_\odot$). The solid lines are from a cosmological hydrodynamic simulation using a subgrid model with star formation–based IMBH formation (M. Habouzit et al. 2017). The blue line shows a model with delayed cooling after supernova explosions, while the orange represents regular kinetic or thermal supernova feedback. Their model includes a combination of a cluster-based model, which is based on the formation of a supermassive star as described in the previous paragraph, and seeds from Population III stars. This model specifically aims to create seeds based on the formation of the first stars and nuclear star clusters. Both types of seeds are formed by finding dense pristine clumps of gas with an average mass of $\sim 1000\,M_\odot$. Their results do not differentiate the two threads of seed formation, so the data in Figure 1 may be taken as an upper limit. Also included in this figure are observational results of LRDs from JWST: J. E. Greene et al. (2024; green dots), D. D. Kocevski et al. (2024; red stars), and V. Kokorev et al. (2024; black diamonds). The observed points are about 4 orders of magnitude below the predicted density of black hole seeds formed through cluster collapse. A canonical TDE has a peak bolometric luminosity of $\sim 10^{44}\,\mathrm{erg\,s^{-1}}$ and remains observable for about 1 yr (S. Gezari 2021). Therefore, a TDE rate of 10^{-4} per year could explain the fraction of observed LRDs versus the occupation of black holes in galaxies.

3. TDE Rates in LRDs

TDEs happen when stars enter the tidal radius of a black hole. As a result, approximately half of the star's mass becomes unbound, and the remainder is stretched into streams before being eventually devoured by the black hole. These events likely result in super-Eddington accretion, and are UV bright but often X-ray weak. Broad Hα lines with widths of 3–13 $\times$ $10^4\,\mathrm{km\,s^{-1}}$ are common (S. Gezari 2021). Their brightness decays with a characteristic $t^{-5/3}$ power law and lasts on the order of hundreds of days. I now quantify whether the TDE rate estimated in the previous section is physically reasonable for powering black hole growth.

N. C. Stone et al. (2017) suggest that a combination of tidal capture and TDEs can grow a black hole quickly and efficiently. They give the following rate:

$$\dot{N} = n_\star \Sigma v_{\rm rel}, \tag{1}$$

where the number density of stars $n_\star = \rho/M_\star$ with a mean stellar mass of M_*, $v_{\rm rel}$ is the relative velocity between the black hole and the star (which I take to equal the velocity dispersion σ), and Σ is the tidal-capture cross section, given by

$$\Sigma = \pi R_t^2 \left(1 + \frac{2GM_{\rm tot}}{R_t v_{\rm rel}^2}\right). \tag{2}$$

Here, $M_{\rm tot}$ is the total mass ($M_{\rm BH} + M_*$), R_t is the tidal radius given by $R_t = r_\star (M_{\rm BH}/M_\star)^{1/3}$, and $r_\star$ is the solar radius multiplied by $M_*^{0.8}$. Tidal capture is likely dominant at lower black hole masses (e.g., $M < 10^3 M_\odot$) and would contribute minimal luminosity. A possible limitation of this model is that initial black hole growth may be delayed because tidally captured stars will inflate before being consumed, causing a slow build before runaway growth occurs. Therefore, it is uncertain whether this method will be fast enough to jump-start the growth of LRD black holes by the time they are observed. As the dominant process shifts to TDEs at higher masses, N. C. Stone et al. (2017) argue that in the full loss-cone approximation, the growth rate would remain similar and still scale as $M_{\rm BH}^{4/3}$. However, it is also unclear at which point, if any, the growth of the black hole transitions from being dominated by tidal captures to TDEs. The evolution of a collapsing cluster is dynamic and may include further gas inflow from the larger environment (and subsequent star formation), so it is likely that a full loss cone is an appropriate assumption.

In addition to the prior analytic estimate, I consider a rate developed using numerical simulations. F. P. Rizzuto et al. (2023) use the BIFROST code (A. Rantala et al. 2023) to study the growth of a black hole in a cluster using direct N-body methods, including post-Newtonian dynamics and a detailed TDE prescription. They devise the following formula, which matches their results:

$$\dot{N} = 1.1 F f_b \ln\left(0.22\frac{M_{\rm BH}}{M_*}\right)\left(\frac{M_{\rm BH}}{10^3 M_\odot}\right) \times \left(\frac{\rho}{10^7 M_\odot\ {\rm pc}^{-3}}\right)\left(\frac{100\ {\rm km\ s^{-1}}}{\sigma}\right)^3 {\rm Myr}^{-1},$$

where F is a numerical prefactor set to 0.8 and f_b is the fraction of bound stars, which is assumed to be 0.2. This analytic rate matches their simulations well, and while the simulations were only run for black hole mass growth up to $\sim 3000\,M_\odot$ for computational reasons, they suggest the mass growth will scale linearly with the TDE rate, which will remain as calculated above as long as the physical conditions (e.g., density, velocity dispersion) of the cluster are unchanging. These simulations assume old stellar ages and therefore do not include effects from supernovae or other stellar feedback in the cluster. They also do not include the effect of multiple black holes, which could increase (by increasing the cross section) or decrease (by scattering objects out of the cluster) the TDE rate. Overall, both rate estimates come from different rationales and are in rough agreement with each other, so they can be used as a guideline.

Using these two rate estimates, I compute expected TDE rates in LRD environments. The stellar densities in LRDs are estimated to be in the realm of 10^6–$10^8 M_\odot\,{\rm pc}^{-3}$, and I use 10^8 as a fiducial value (C. A. Guia et al. 2024). Using a canonical velocity dispersion for cluster collapse estimated at 40 km s^{-1} (M. C. Miller & M. B. Davies 2012) and a mean stellar mass of 1 $M_\odot$, I plot the TDE rate in Figure 2 as a function of black hole mass (top) and stellar velocity dispersion (bottom; thick lines). In the top plot, the velocity dispersion is fixed at 40 km s^{-1}, while the bottom plot has a fixed $M_{\rm BH} = 10^4\ M_\odot$. The rate estimate by N. C. Stone et al. (2017) is plotted in blue and the one by F. P. Rizzuto et al. (2023) in red. A rate of 10^{-4} per year is very reasonable within the range of $10^3 M_\odot < M_{\rm BH} < 10^5 M_\odot$ and/or velocity dispersions of 100–150 km s^{-1}. There are no direct constraints on stellar velocity dispersions in LRDs, but it is plausible that with such high densities the values would be large.

Shown in the dashed, dotted, and dotted–dashed lines in Figure 2 are rates calculated bracketing a reasonable LRD parameter space. The dotted lines display a fiducial stellar density of $10^6 M_\odot\,{\rm pc}^{-3}$ rather than 10^8, and show that for the lower bound of estimated densities the TDE rate may still reach $10^{-4}\,{\rm yr}^{-1}$ but only for larger black holes and lower velocity dispersions. The dashed and dotted–dashed lines show extrema in velocity dispersion (150 km s^{-1}; upper panel) and black hole mass (10^3 and $10^5 M_\odot$, respectively; lower panel).

As mentioned above, the tidal-capture prediction of N. C. Stone et al. (2017) is only valid for the full loss-cone assumption. At some critical mass M_c the loss cone transitions from full to empty, at which point the rate of TDEs will scale as $M_{\rm BH}^{-11/12}$. I include this calculation in the form of light gray downward-sloping lines in Figure 2 for a range of M_c values. (I include them on the fiducial calculation only so as not to further distract from the results of the figure.) In many cases, the TDE rate increases with increasing black hole mass and decreasing velocity dispersion, and a rate of $10^{-4}\,{\rm yr}^{-1}$ is unlikely to be reached in a case of small black hole mass and/or high velocity dispersion.

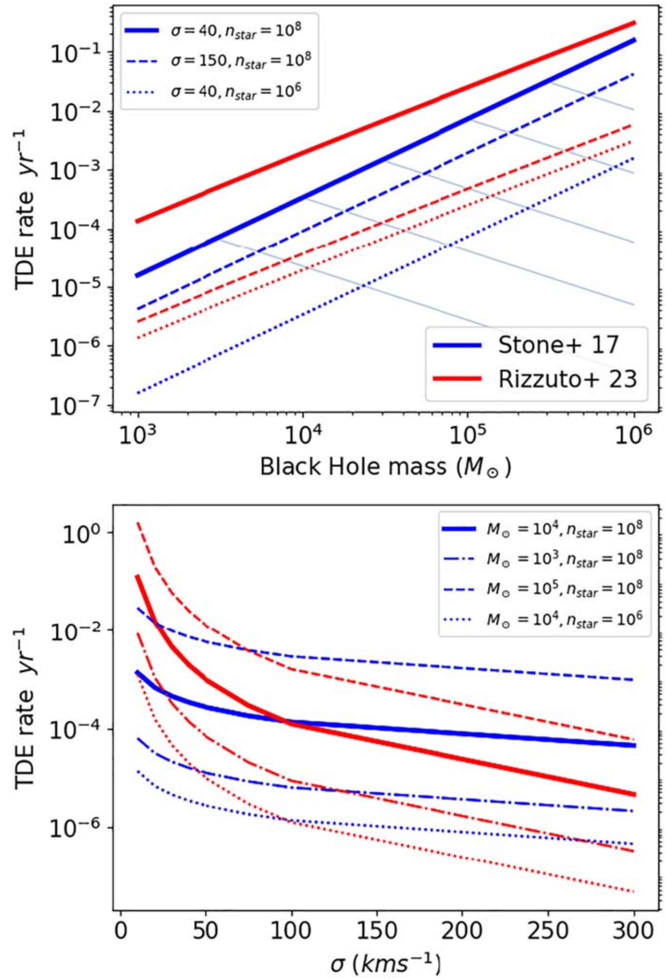

Figure 2. Rates of TDEs for models by N. C. Stone et al. (2017; blue) and F. P. Rizzuto et al. (2023; red). Fiducial models shown in thick lines. Top: TDE rate vs. black hole mass, with fixed velocity dispersion of $\sigma = 40$ km s^{-1} (thick solid lines), $\sigma = 150$ km s^{-1} (dashed lines), and with stellar density $n_{\rm star} = 10^6 M_\odot\,{\rm pc}^{-3}$ (dotted lines). Light gray lines extending from the fiducial blue model indicate the rate in the instance of a transition from a full to empty loss cone, for various values of the critical mass M_c. Bottom: TDE rate vs stellar velocity dispersion, with fixed black hole mass of $10^4\ M_\odot$ (thick solid lines), $10^5\ M_\odot$ (dashed lines), $10^3\ M_\odot$ (dotted–dashed lines), and stellar density $n_{\rm star} = 10^6 M_\odot\,{\rm pc}^{-3}$ (dotted lines).

4. Conclusions and Caveats

The plethora of LRDs discovered by JWST has challenged models of black hole and galaxy evolution. In this Letter, I suggest that a primary origin for the emission from LRDs is due to TDEs occurring during the process of forming the seeds of SMBHs. The predicted number density of dense stellar clusters undergoing a runaway collapse is about 10^4 times higher than that of LRDs, implying a TDE rate of 10^{-4} per year. Other common attributes include a spectral rise in the UV/optical, broad Hα, and X-ray weakness. The broad Hα emission from TDEs is not correlated with black hole mass (unlike in AGNs), providing an explanation for the proposed overmassive nature of these high-redshift black holes relative to their host. The Hα lines also show absorption features (J. Matthee et al. 2024), which could be due to tidal streams of disrupted stars. X-ray weakness is thought to be a sign of super-Eddington accretion, likely combined with a viewing angle effect, and is thought to occur in TDEs. In addition, when

TDEs do show X-rays they are soft, which may be redshifted out of the Chandra detection range.

This model fails to directly address the red colors of LRDs. The red part of the SED is likely at least somewhat dominated by stellar light, as evidenced by a common feature of a Balmer break (D. J. Setton et al. 2024; although see K. Inayoshi & R. Maiolino 2025). LRDs do not characteristically show evidence of warm or hot dust (though see G. Barro et al. 2024), and therefore a standard AGN model (consisting of a torus) cannot apply. Another common thorn in the side of LRD scientists is the number densities of these objects. If LRDs are assumed to be dominated by AGNs, their number densities are not far from those of all galaxies in the Universe, implying a near 100% AGN occupation fraction at $z \sim 7$ for the brightest galaxies ($L_{\mathrm{bol}} > 10^{45}\ \mathrm{erg\ s^{-1}}$). Conversely, if most or all of the light is dominated by star formation, LRDs on their own reach or exceed the predicted stellar mass functions for all galaxies at high redshift in ΛCDM (M. Boylan-Kolchin 2023; H. B. Akins et al. 2024).

These issues can be avoided if one assumes a nonstandard initial mass function (IMF). A top-heavy IMF would result in higher-luminosity stars, and an overall decrease in stellar mass estimates. The IMF has been shown to vary with density and metallicity (M. Marks et al. 2012), which are both extreme in the case of LRDs. T. Jeřábková et al. (2017) have shown that star clusters with top-heavy IMFs can reach up to quasar luminosities (i.e., $10^{46}\ \mathrm{erg\ s^{-1}}$ for a stellar mass of $10^{9} M_{\odot}$), with a mass-to-light ratio of 10^{-3}, for the first 10 Myr of their lifetimes. Therefore, I propose that the source of the light is stellar, originating in the dense nuclear cluster surrounding the IMBH, and with a top-heavy IMF. The whole issue of too bright/too many stars is solved if there are actually fewer stars of higher masses. A top-heavy IMF from a metal-poor population could sufficiently produce the red stellar light, explain a lack of dust (if the environment is very metal-poor), and solve the number density problem. More massive stars would also result in more luminous TDEs. SED models of LRDs with varying IMFs are needed to confirm this suggestion.

LRDs are not all identical, and there is no need for one overarching theory to explain their existence. For example, some objects show strong AGN signatures (see I. Labbe et al. 2024; B. Wang et al. 2024), which likely dominate the SEDs. Therefore, TDEs occurring in runaway collapsing clusters may explain a subset of LRDs, and canonical AGNs and other phenomena the others. One way to verify the TDE hypothesis is to search for strong variability in the rest-frame UV (caused by TDE emission) but less in the rest-frame optical/near-infrared (dominated by stellar light). TDEs have well-known decays in their light curves, which can be confirmed fairly straightforwardly. TDEs have also been shown to exhibit decaying luminosity in coronal lines on timescales of ∼years (T.-G. Wang et al. 2012), which could be observed with spectroscopic follow-up. The caveat is that due to time dilation, timescales are lengthened by a factor of $(1 + z)$, so decays will occur approximately 6–8 times more slowly than seen in the local Universe. Initial searches for variability of LRDs have found none as of yet (M. Kokubo & Y. Harikane 2024; W. L. Tee et al. 2025), highlighting that these objects may have a diverse taxonomy. Follow-up with JWST at appropriate timescales is crucial for verifying the TDE hypothesis.

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