

## A RAPIDLY EVOLVING REGION IN THE GALACTIC CENTER: WHY S-STARS THERMALIZE AND MORE MASSIVE STARS ARE MISSING

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### ABSTRACT

The existence of “S-stars” within a distance of  $1''$  from Sgr A\* contradicts our understanding of star formation, due to Sgr A\*’s forbiddingly violent environment. A suggested possibility is that they form far away and were brought in by some fast dynamical process, since they are young. Nonetheless, all conjectured mechanisms either fail to reproduce their eccentricities—without violating their young age—or cannot explain the problem of “inverse mass segregation”: the fact that lighter stars (the S-stars) are closer to Sgr A\* and more massive ones, Wolf–Rayet (WR) and O-stars, are farther out. In this Letter we propose that the mechanism responsible for *both* the distribution of the eccentricities and the paucity of massive stars is the Kozai–Lidov-like resonance induced by a sub-parsec disk recently discovered in the Galactic center. Considering that the disk probably extended to a smaller radius in the past, we show that in as short as (a few)  $10^6$  yr, the stars populating the innermost  $1''$  region would redistribute in angular-momentum space and recover the observed “super-thermal” distribution. Meanwhile, WR and O-stars in the same region intermittently attain ample eccentricities that will lead to their tidal disruptions by the central massive black hole. Our results provide new evidences that Sgr A\* was powered several millions years ago by an accretion disk as well as by tidal stellar disruptions.

*Key words:* Galaxy: center – Galaxy: kinematics and dynamics – methods: analytical – stars: massive – stars: Wolf–Rayet

*Online-only material:* color figures

### 1. INTRODUCTION

Observations of the Galactic center (GC) going back as far as 20 yr ago (see Genzel et al. 2010 for a review) reveal three facts: (1) an isotropic cusp of young O/B and Wolf–Rayet (WR) stars, starting at a distance of  $30''$  from Sgr A\* and extending inward to about  $1''$  ( $1'' \simeq 0.04$  pc), (2) a mildly thick stellar *disk* of about 100 WR and O-type stars, spanning from an inner radius of  $1''$  to an outer radius of about  $10''$ , and (3) a population of B stars, commonly referred to as “S-stars,” populating the innermost region, within  $1''$  from Sgr A\*, but *no* WR/O stars. A single star-formation (SF) episode may explain the formation of disk and cusp stars (Lu et al. 2013); the S-stars, however, could not have been born in this scenario because the violent environmental conditions within  $1''$  of Sgr A\* do not allow in situ SF. One way of populating that region is by dynamical friction, but the associated timescale is too long. For this reason, the problem is called the “paradox of youth” (Morris 1993; Ghez et al. 2003).

This issue led to the idea that S-stars could have formed at larger radii and later brought in by an efficient dynamical mechanism. One possibility is the tidal separation of binaries (Hills 1991; Gould & Quillen 2003; Ginsburg & Loeb 2006). A binary, formed at larger radius, can be set in such an orbit that at periaapsis it will be tidally separated by the central massive black hole (MBH), leaving one star, which could be a B star, bound to the MBH at a typical radius of  $\lesssim 1''$ . However, the captured stars would have very high eccentricities, typically about 0.93–0.99 (see the original work of Hills 1991 and Amaro-Seoane 2012 for a review). It would require some 20–50 Myr for them to achieve the observed near-thermal distribution (e.g., Perets et al. 2009; Antonini & Merritt 2013; Zhang et al. 2013) with the aid of a very dense cusp of segregated old stars which is in contradiction with current observations (Buchholz et al. 2009; Do et al. 2009).

Even in the presence of a dense cusp, there are two additional issues: (1) the same process would work for WR/O stars, and we do *not* see them within  $\lesssim 1''$  (Alexander 2011) and (2) the oldest O/WR stars are  $\lesssim 10$  Myr, so there has to be at least two SF episodes, since S-stars inside  $1''$  need  $\geq 20$  Myr to thermalize.

Since the stellar disk must initially be gaseous, the migration of B stars toward the disk’s center has been proposed as another possibility (Levin 2007; Griv 2010). However, (1) this cannot explain the eccentricities of the S-stars because the migrating stars will remain on near-circular orbits (Perets et al. 2009; Madigan et al. 2011; Antonini & Merritt 2013), and (2) WR/O stars would have migrated toward the center due to the same mechanism, but we do not observe them there. Once SF is over (no more gas), the stars in the disk, including the WR/O stars, would secularly torque each other and drift away from nearly circular orbits to rather eccentric ones (Madigan et al. 2009), and hence at periaapsis they would populate the central  $1''$ , but, still, we do not see WR/O stars there either.

In this Letter we show that, provided the disk was heavier and more extended in the past (Nayakshin et al. 2007; Wardle & Yusef-Zadeh 2008; Bonnell & Rice 2008; Hobbs & Nayakshin 2009; Alig et al. 2011; Mapelli et al. 2012), it created a rapidly evolving region (RER) inside  $1''$ , where the angular momenta of stars rapidly redistribute because of a Kozai–Lidov (KL) like resonance. This RER can explain both the eccentricities of S-stars and the absence of WR/O-stars because the latter are tidally disrupted.

### 2. DISK-DRIVEN EVOLUTION

#### 2.1. Timescales

To understand the effect of the disk, we first analyze the torque exerted by a wire of mass  $\delta m$  and radius  $R$  on a background star

of semi-major axis  $a$  (Ivanov et al. 2005; Šubr & Karas 2005; Löckmann et al. 2008). Chen et al. (2011) showed that the timescale for the wire to change the angular momentum of the star by a full cycle, i.e., to vary the eccentricity  $e$  of the star from its minimum value to the maximum and back, is

$$T_K = \begin{cases} \frac{2}{3\pi} \frac{M_\bullet}{\delta m} \left(\frac{a}{R}\right)^{-3} P(a), & \text{Kozai-Lidov, } a \leq R/2, \\ \frac{16\sqrt{2}}{3\pi} \frac{M_\bullet}{\delta m} \left(\frac{a}{R}\right)^{1/2} P(a), & \text{Non-determ., } a > R/2, \end{cases} \quad (1)$$

where  $M_\bullet = 4 \times 10^6 M_\odot$  is the mass of the MBH, and  $P(a) = 2\pi(a^3/GM_\bullet)^{3/2} \simeq 1.4 \times 10^3(a/[0.1 \text{ pc}])^{3/2} \text{ yr}$  is the orbital period of the star. The reason for  $R/2$  is the requirement to have all orbits within the radius of the wire, including the most eccentric ones,  $R_{\text{apo}} = a(1+e) \sim 2a$ , with  $R_{\text{apo}}$  the apocenter distance. Equation (1) is a generalization of the secular KL timescale (see Naoz et al. 2013, and references therein): (1) in the regime  $a \leq R/2$  we recover this well-known secular phenomenon but (2) when  $a \gtrsim R/2$ , i.e., when stellar orbits cross a sphere with the same radius as the wire, it provides a good approximation for the non-deterministic, but not necessarily chaotic, evolution of the stellar orbit.

Assuming that an extended disk is a superposition of wires, one can derive the corresponding timescale  $T'_K$  for the sum of torques to change the orbital elements of a star in a full cycle (Chang 2009):

$$1/T'_K = \int_{R_{\text{in}}}^{R_{\text{out}}} d(1/T_K), \quad (2)$$

where  $R_{\text{in}}$  and  $R_{\text{out}}$  denote the inner and outer radii of the disk,  $d(1/T_K) \propto \delta m = 2\pi \Sigma_d(R) R dR$ , and  $\Sigma_d(R)$  is the surface density of the disk. During  $T'_K$ , when secular evolution predominates, a star typically oscillates a full cycle between the maximum and minimum eccentricities, which are predetermined by three orbital parameters, namely, eccentricity, position angle of periaxis ( $\omega$ ), and inclination angle relative to the disk ( $\theta$ ). At any intermediate stage of that cycle, the ‘‘instantaneous’’ evolution timescale, defined as  $t_K(l) \equiv l/|\dot{l}|$ , can be derived from

$$t_K(l) \simeq lT'_K(a) \quad (3)$$

(e.g., Chang 2009; Chen et al. 2011), where  $l \equiv \sqrt{1-e^2}$  is the dimensionless angular momentum and the dot denotes the time derivative. The linear dependence on  $l$  reflects the coherence of the disk torque during  $t_K(l)$ .

The MBH and cusp stars affect the KL-like evolution by perturbing the orbital parameters ( $e$ ,  $\omega$ ,  $\theta$ ). We must distinguish two regimes: (1) at *high*  $e$ ,  $\omega$  is significantly perturbed, because of the induced relativistic (GR) precession rate,

$$\dot{\omega}_{\text{GR}} = 3(GM_\bullet)^{3/2}/(l^2 c^2 a^{5/2}), \quad (4)$$

with  $c$  the speed of light. It may even exceed the KL precession rate,

$$\dot{\omega}_K \simeq 2\pi/(T'_K l) \quad (5)$$

(e.g., Chang 2009). When this happens, the disk coherence is broken and the KL cycle quenched, hence it defines a boundary to the region in phase space where the evolution is driven by the disk. In some loose sense, this boundary is analogous to the Schwarzschild barrier in galactic nuclei (Merritt et al. 2011;

Brem et al. 2014). (2) At *low*  $e$ , the perturbation on  $\omega$  originates from the total stellar mass  $M_*(a)$  enclosed by the orbit. The Newtonian precession rate

$$\dot{\omega}_M \simeq 2\pi l M_*(a)/[M_\bullet P(a)] \quad (6)$$

may exceed  $\dot{\omega}_K$  in this regime, which imposes a second boundary (Chen et al. 2011).

Outside these boundaries, the evolution of angular momentum will be determined by either two-body relaxation, with a characteristic timescale of

$$t_{2b}(l) \equiv |l/\dot{l}| \simeq l^2 (M_\bullet/m_*)^2 P(a)/(N \ln \Lambda) \quad (7)$$

(e.g., Kocsis & Tremaine 2011), or (scalar) resonant relaxation (RR; Rauch & Tremaine 1996), on a timescale of

$$t_{\text{RR},s}(l) \equiv \left| \frac{l}{\dot{l}} \right| \simeq \frac{l^2}{1-l^2} \left( \frac{M_\bullet}{m_*} \right)^2 \frac{P^2(a)}{N t_\omega} \quad (8)$$

(Gürkan & Hopman 2007, who studied the dependence on  $e$ ). In Equations (7) and (8),  $m_*$  denotes the average mass of one star,  $N = M_*(a)/m_*$  is the number of stars enclosed by the stellar orbit,  $\ln \Lambda = \ln(M_\bullet/m_*)$  is the Coulomb logarithm, and  $t_\omega = 2\pi/|\dot{\omega}_M - \dot{\omega}_{\text{GR}} - \dot{\omega}_K|$  is the joint precession timescale combining Newtonian, GR, and KL precessions (Chen & Liu 2013).

Between the two boundaries is the RER: any star in it cycles between the maximum and minimum eccentricities predetermined by ( $e$ ,  $\omega$ ,  $\theta$ ). Moreover, the two extrema are evolving. The corresponding timescale is given by vectorial RR (Rauch & Tremaine 1996), which changes  $\theta$  on a timescale of

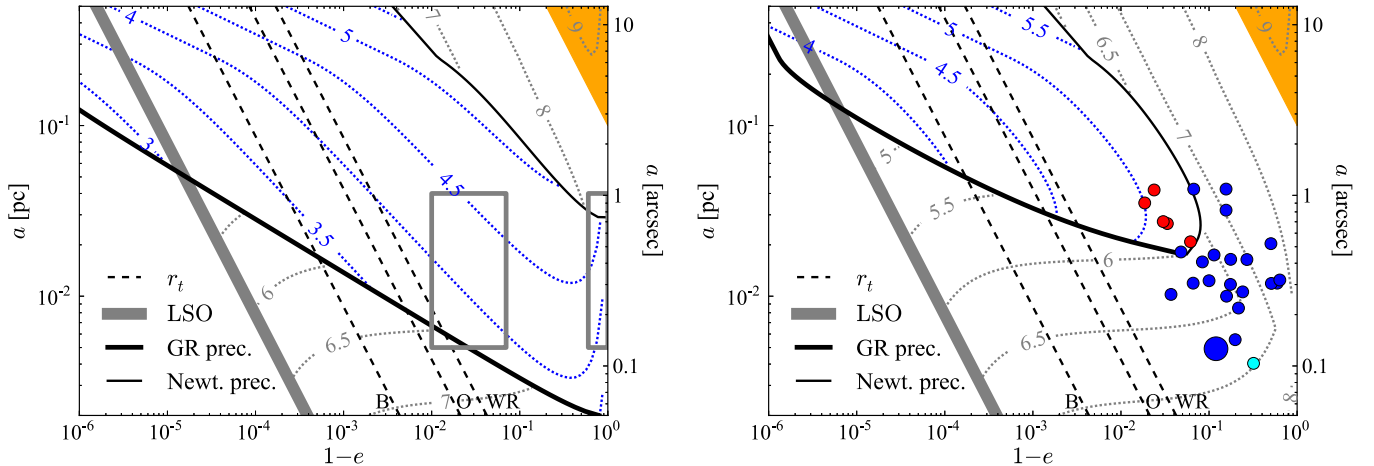
$$t_{\text{RR},v} \equiv \left| \frac{1}{\dot{\theta}} \right| \simeq \frac{0.3}{(0.5+e^2)^2} \frac{M_\bullet P(a)}{m_* \sqrt{N}} \quad (9)$$

(Gürkan & Hopman 2007; Eilon et al. 2009). Inside RER,  $t_{\text{RR},v}$  is longer than the Newtonian and GR precession timescales, so the vectorial RR does not impact the boundaries. Its role is to characterize the required time for a star to explore in random-walk fashion the range of maxima and minima in eccentricities fenced in by the boundaries of the RER.

## 2.2. A Receding Disk

The boundaries of the RER are changing because the properties of the disk have changed during the past (1–10) Myr. We can distinguish two stages in the evolution of the disk.

1. An early phase in which the disk was mostly gaseous and its inner edge reached the innermost stable circular orbit (ISCO) at about  $6GM_\bullet/c^2 \simeq 10^{-6} \text{ pc}$  (Nayakshin & Cuadra 2005; Levin 2007). This disk contained at least  $10^4 M_\odot$  of gas, triggering fragmentation and SF (Nayakshin & Cuadra 2005), and it could have been as massive as  $(3-10) \times 10^4 M_\odot$  according to recent simulations (Nayakshin et al. 2007; Bonnell & Rice 2008; Hobbs & Nayakshin 2009; Mapelli et al. 2012). We will adopt a disk mass of  $M_d = 3 \times 10^4 M_\odot$  for this phase. It is worth noting that stars that formed in the outer disk may migrate inward (Levin 2007; Griv 2010), so the disk inside  $R = 0.04 \text{ pc}$  could contain both gas and stars.
2. Today, after some (1–10) Myr, the central 0.04 pc of the disk is no longer present, because the gas is consumed by either SF (Levin & Beloborodov 2003; Nayakshin & Cuadra



**Figure 1.** Mapping evolution timescales in the  $a-(1-e)$  plane. The thick gray line on the left-hand side corresponds to the last stable orbit (LSO) around Sgr A\*. The thick solid black curve is the result of equating the KL precession rate,  $\dot{\omega}_K$ , to its relativistic equivalent,  $\dot{\omega}_{GR}$ . Above that curve, dynamical evolution is determined by the KL effect up to the next solid black curve, which comes from equating  $\dot{\omega}_K$  to  $\dot{\omega}_M$ , the precession rate induced by the enclosed stellar mass. The dashed black parallel lines crossing the figures from top to bottom indicate the typical tidal-disruption radii for B, O, and WR stars. The blue dotted isochrones, fenced in the region where the evolution is governed by the KL mechanism, are associated with the logarithms of the two-body-relaxation or RR timescales, whichever is shorter. The gray dotted isochrones are associated with the logarithms of the two-body-relaxation or RR timescales, whichever is shorter. The small orange triangles at the top right corners depict the loci of the red giants in the GC. In the left panel, the two gray boxes depict the expected birth places of S-stars in the binary-separation and migration-in-disk models (also see Antonini & Merritt 2013). In the right panel, the dots correspond to: S-stars not associated with the young stellar disk (small-blue, Gillesen et al. 2009), the infalling G2 object (also called DSO; see Eckart et al. 2013 for a different interpretation of its nature) measured at different times or different wavelengths (small-red, Gillesen et al. 2013), S2/S0-2 (big-blue, the brightest S-star, Ghez et al. 2003; Eisenhauer et al. 2003), and S102/S0-102 (small-cyan, Meyer et al. 2012), the S-star with the shortest period known.

(A color version of this figure is available in the online journal.)

2005) or black-hole accretion (Alexander et al. 2012), and the stars have had time to be scattered out of the disk plane due to the vectorial RR (Hopman & Alexander 2006; Kocsis & Tremaine 2011). For this reason, we say the inner edge of the disk has *receded* from the ISCO to the current location of  $R_{in} \simeq 1'' \simeq 0.04$  pc (e.g., Paumard et al. 2006), while the outer edge is still the same, at  $R_{out} \simeq 12'' \simeq 0.5$  pc. The present mass of the disk is  $M_d = 10^4 M_\odot$  (Paumard et al. 2006; Bartko et al. 2010).

In both situations, we modeled the disk surface density as a power law  $\Sigma_d(R) \propto R^{-1.4}$  (Bartko et al. 2010), which leads to a mass of  $6 \times 10^3 M_\odot$  at  $10^{-6}$  pc  $< R < 0.04$  pc in the early phase. To derive  $M_*(a)$  and  $N$  in Equations (6)–(9), we adopted the broken-power-law model from observations (Genzel et al. 2010), whose density slope is  $\gamma = 1.3$  for the inner 0.25 pc. We assumed an average stellar mass of  $m_* \simeq 10 M_\odot$  (also see Kocsis & Tremaine 2011 for discussions). In this model, we have  $t_{RR,v} \simeq 1.5 \times 10^6 (0.5 + e^2)^{-2} (a/1'')^{0.65}$  yr for stars in the central arcsec of the Galaxy.

### 3. SCULPTING THE GALACTIC CENTER

#### 3.1. Rapidly Evolving Region

In Figure 1 we display the boundaries of the RER. The left panel corresponds to  $R_{in} = 10^{-6}$  pc and the right one to  $R_{in} = 0.04$  pc. In this  $(1-e)-a$  plane, at any location, we can estimate the instantaneous evolution timescale as

$$\left| \frac{1-e}{\dot{e}} \right| = \frac{e(1-e)}{l^2} t_K(l) \simeq \frac{e(1-e)}{l} T'_K(a). \quad (10)$$

We can then identify the lines with constant evolution timescales, i.e., the contours. We call them “isochrones,” and depict them as blue dotted curves. Outside the RER the isochrones

are shown in gray and determined by either two-body scattering,  $e(1-e)t_{2b}(l)/l^2$ , or RR process,  $e(1-e)t_{RR,s}(l)/l^2$ , whichever timescale is shorter.

Two striking conclusions from a first look at this figure are (1) stars in the RER evolve on very short timescales, of the order of  $10^{3-5.5}$  yr, to complete a full KL cycle. As discussed previously, after a time of  $t_{RR,v}$ , any star at  $a < 1''$  would have *fully* explored the angular-momentum range within the RER. (2) As the disk recedes, the boundaries come closer and the RER shrinks. Any star that finds itself out of the RER will be “frozen” from the point of view of another star which is still in it: the timescales outside the RER are long.

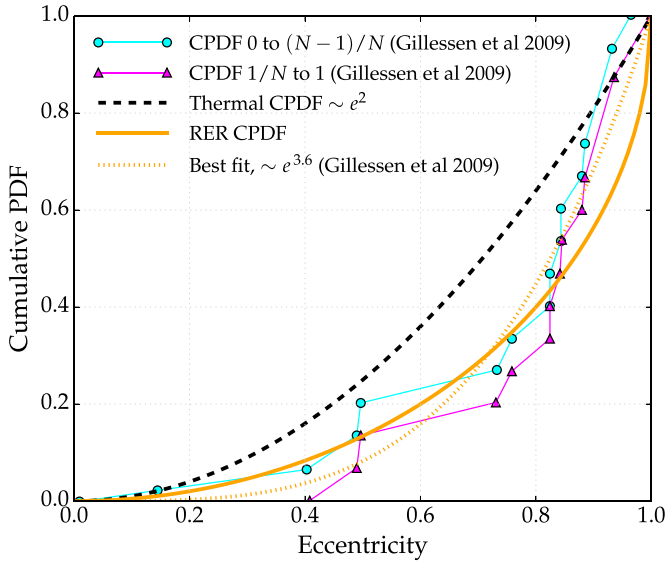
Since a short evolution timescale leads to low probability of stellar distribution, today (right panel of Figure 1), the absence of S-stars within the RER boundaries may be plausible corroborating observational evidence that the RER does exist at the GC. At present, the only measured object within the RER boundaries is G2 (red dots; Gillesen et al. 2013). From its nearby isochrones, we see that G2 must have been formed less than  $10^{5.5}$  yr ago.

#### 3.2. A Close Thermalization of the S-stars

The two more successful scenarios of B stars being deposited close to the GC, i.e., binary separation and disk migration, place these stars well within the RER (left panel of Figure 1). These stars are able to sufficiently mix in angular-momentum space, on a timescale of  $t_{RR,v} \simeq 0.7$  Myr in the binary-separation scenario and of  $t_{RR,v} \simeq 6$  Myr in the disk-migration one. The latter mechanism (disk migration) requires a much longer time to reach the superthermal distribution in eccentricities because of the  $e$  dependence of Equation (9). We note that these timescales are at least 10 times shorter than those from the earlier models, which neglected the RER.

The fully mixed eccentricities do not necessarily have a thermal distribution (P. Brem et al., in preparation).





**Figure 2.** Cumulative probability distribution functions of the eccentricities of S-stars, derived from observations (cyan and purple), thermal distribution ( $e^2$ , black-dashed), our RER model ( $1 - \sqrt{1 - e^2}$ , orange-solid), and best fit to observational data (orange-dotted).

(A color version of this figure is available in the online journal.)

Following the argument that a longer evolution timescale correlates with a higher probability distribution, we have  $dN/de \propto dt/de$ , and substituting Equation (10) for  $dt/de$ , we can derive  $dN/de \propto dt/de \propto e/l$ . This distribution function is steeper than a thermal one,  $dN/de \propto e$ . The steepness stems from the linear dependence of the evolution timescale ( $l/\dot{l}$ ) on the orbital angular momentum  $l$ , whereas in the case of two-body relaxation and RR, the evolution time scales with  $l^2 = 1 - e^2$ .

Figure 2 compares various cumulative probability distribution functions for  $e$ , derived from two theoretical models—a thermal one and our RER model—as well as from observations. It is clear that compared to the thermal distribution, the RER one is in better agreement with the observations.

### 3.3. Depleting WR/O Stars

For a star of mass  $m_*$  and radius  $r_*$ , if its eccentricity becomes so high that the orbital pericenter distance from Sgr A\* becomes smaller than the tidal radius

$$r_t \simeq r_* \left( \frac{M_\bullet}{m_*} \right)^{1/3} \simeq 4 \times 10^{-6} \text{ pc} \left( \frac{r_*}{R_\odot} \right) \left( \frac{m_*}{M_\odot} \right)^{-1/3}, \quad (11)$$

it will be tidally disrupted (Rees 1988). In Figure 1 we show the typical  $r_t$  associated with B, O, and WR stars. Once stars cross it from right to left, they are lost. This drain is enhanced in the RER by the increasingly shorter timescales, as the stars progressively move to the left.

To calculate  $r_t$ , we assume  $m_* = (7, 25, 60) M_\odot$ , respectively, for the three types of stars (Zinnecker & Yorke 2007). Main-sequence stars less massive than  $7 M_\odot$  are below the current detection limit of observations. Correspondingly, we have adopted  $r_* = 4 R_\odot$  for main-sequence B stars, and  $r_* = 40 R_\odot$  and  $80 R_\odot$  respectively for O and WR stars. B stars can be envisaged as main-sequence stars, but O and WR stars are more massive, and shorter-lived. We hence adopt larger radii for them, 3–4 times larger than typical radii on the main-sequence, since they have evolved off the main sequence (Paumard et al. 2006; Bartko et al. 2010).

We can see in the left panel of Figure 1 that any WR star in a stripe defined between  $0'.15 \lesssim a \lesssim 0'.8$  and any O star in  $0'.2 \lesssim a \lesssim 0'.8$  will be tidally disrupted, because it will have explored all the  $(1 - e)$  space in  $\sim 10^6$  yr. Similarly, for B stars, the corresponding stripe is delimited by the narrower zone  $0'.5 \lesssim a \lesssim 0'.8$ . In fact, this predicted gap (for B stars) does occur in the current distribution of S-stars (right panel of Figure 1). If we had assumed a disk mass of  $M_d > 3 \times 10^4 M_\odot$ , this gap would have broadened to incorporate the region where  $a < 0'.5$ , and it would contradict current observations. Therefore, an upper limit to the disk mass can be derived, approximately  $3 \times 10^4 M_\odot$ .

By looking at the left panel again, we realize that only WR/O stars with  $a > 0'.8$  and low  $e$  can survive because they are always outside of the RER and cannot drift quickly enough to higher  $e$ . Indeed, WR/O stars have been discovered only at  $a \gtrsim 1''$  but not inside. In principle, our model cannot deplete WR/O stars at  $a < 0'.1$ , because at such small  $a$  the RER does not reach the tidal radii. Observations did not find any WR/O star there, maybe because the extrapolation of the disk density profile  $\Sigma(R) \propto R^{-1.4}$  results in  $< 1$  WR/O star at  $R < 0'.1$ .

## 4. DISCUSSIONS

In this Letter we have presented a picture that explains the distribution of the eccentricities of S-stars and the absence of more massive stars within  $1''$  of Sgr A\*. Our *sole* hypothesis is that around (1–10) Myr ago, the disk extended down to  $R \ll 0.04$  pc. We find that the torque exerted by the disk creates a region in the GC in which the dynamical evolution is significantly accelerated compared to other regions, by a factor ranging from 10 to 100 times; we call it the “RER.”

Our scenario agrees with current observations about the nonexistence of an old segregated cusp in the GC (Buchholz et al. 2009; Do et al. 2009), contrary to other works, which crucially rely on the cusp to thermalize the S-stars (Perets et al. 2009; Madigan et al. 2011; Antonini & Merritt 2013; Zhang et al. 2013). Because the time needed to randomize angular momentum is now shortened to (0.7–6) Myr, our model is able to accommodate various possibilities for the formation of S-stars, while other models rely heavily on when S-stars were brought to the GC (Perets et al. 2009; Antonini & Merritt 2013).

Moreover, our RER scenario unifies two observational facts that have been thought until now to be disconnected: we successfully populate the observed range of  $e$  for B stars and we can duplicate the observed discontinuity of WR/O stars above and below  $1''$ . Both of them will be established in as short as (0.7–6) Myr, so we can even unify the origin of all the young stellar populations in the GC to *only one single SF episode*. This unification does pose a problem for earlier models: if all B stars formed simultaneously with WR/O stars, since this must be less than 6 Myr ago (because WR/O stars cannot be older), two-body relaxation and RR will fail to explain the distribution of  $e$ .

At this stage, it is crucial to theoretically understand the dynamical response of the old stellar population to the RER and test it against observations of dimmer (than B-type), older stars. If they match, it would be robust evidence that the RER has indeed played a role in sculpting the GC.

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