[Sculpting the Galactic Centre]

The missing cusp and a rapid evolving region

Pau Amaro Seoane

Outline

- Distribution of stars around MBHs: Missing cusps?
- Dearth of red giants at the GC (questions?)
- A rapid evolving region at the GC

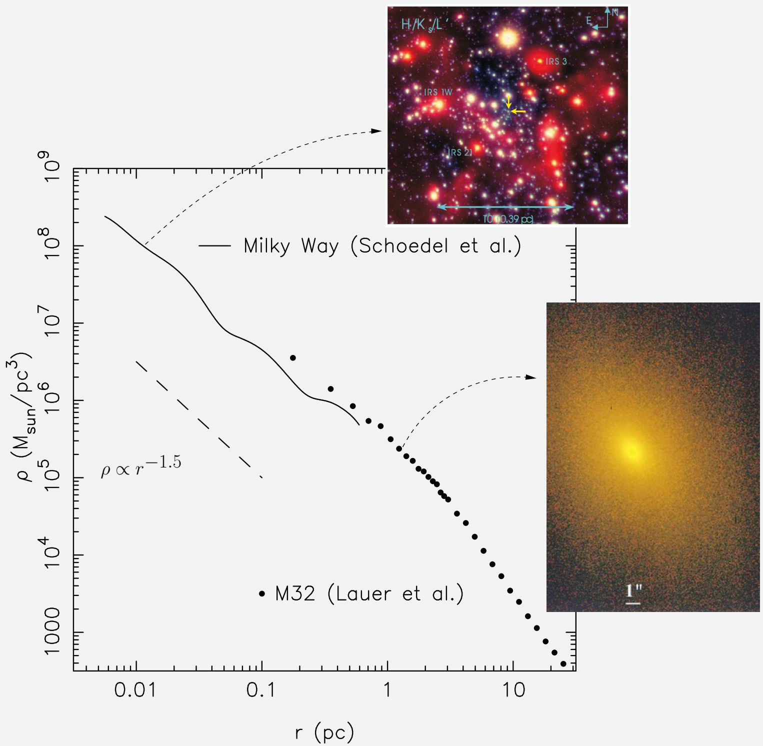
Based on:

1. Amaro-Seoane & Chen, ApJ Letts 2014
2. Chen & Amaro-Seoane, submitted to ApJ Letts 2014
3. Amaro-Seoane, Living Review Relativity 2014
4. Amaro-Seoane, Sopuerta & Freitag, MNRAS 2013
5. Brem, Amaro-Seoane, Sopuerta, MNRAS 2013
6. Preto & Amaro-Seoane 2010 ApJ Letts
7. Amaro-Seoane & Preto 2011 CQG
8. Amaro-Seoane, Brem, Cuadra & Armitage, ApJ Letts 2012

Distribution of stars around MBHs

Artist's (wrong) impression of funghi porcini

- ⋆ How many stars? How do they distribute?
- ⋆ **Very few observations**
- ⋆ R_h difficult to resolve
- ⋆ To study inner region have to assume underlying pop
- ⋆ Deproject observation
- ⋆ Assume observed star is tracing invisible pop
- ⋆ Considerable amount of modelling
- ⋆ Coincidence?



(Adapted from Merritt 2006)

Outline
Mass segregation
Cusps in distress
How do you ...
Isocore ... regrowth
The RER
Extra material
The missing RGs
Close

Mass segregation

- Classical problem in stellar dynamics
- Statistical thermal equilibrium $f(E) \propto e^{-E/\sigma^2}$ must be violated close to the MBH (R_t, R_Schw, R_coll)
- Peebles 1972 : Steady state with net inward flux of stars and energy
- Well within R_h but far from R_t, stars should have nearly-isotropic velocities
- Hence, if **single-mass**: quasi-steady solution takes power-law form (isotropic DF) $f(E) \sim E^p$, $\rho(r) \sim r^{-\gamma}$, with $\gamma = 3/2 + p$
- Bahcall & Wolf 1976 : Detailed kinematic treatment for **single-mass**
- $\gamma = 7/4$ and $p = \gamma - 3/2 = 1/4$

> Only a fool tries to solve a complicated problem when
> he does not even understand the simplest idealization – Donald Lynden-Bell

- Properties of multi-mass systems poorly reproduced by single-mass models
- Next integer after 1 is 2
- Models extending to 2-mass components; **B&W argued heuristically for a scaling relation** $p_L = m_L/m_H \times p_H$ that depends on the star's mass ratio only

- Hopman & Alexander 2009: **Two branches for the solution**, parametrized by

$$\Delta = \frac{D_{HH}^{(1)} + D_{HH}^{(2)}}{D_{LH}^{(1)} + D_{LH}^{(2)}} \approx \frac{N_H m_H^2}{N_L m_L^2} \frac{4}{3 + m_H/m_L}$$

  (measure for H's self-coupling relative to L's)

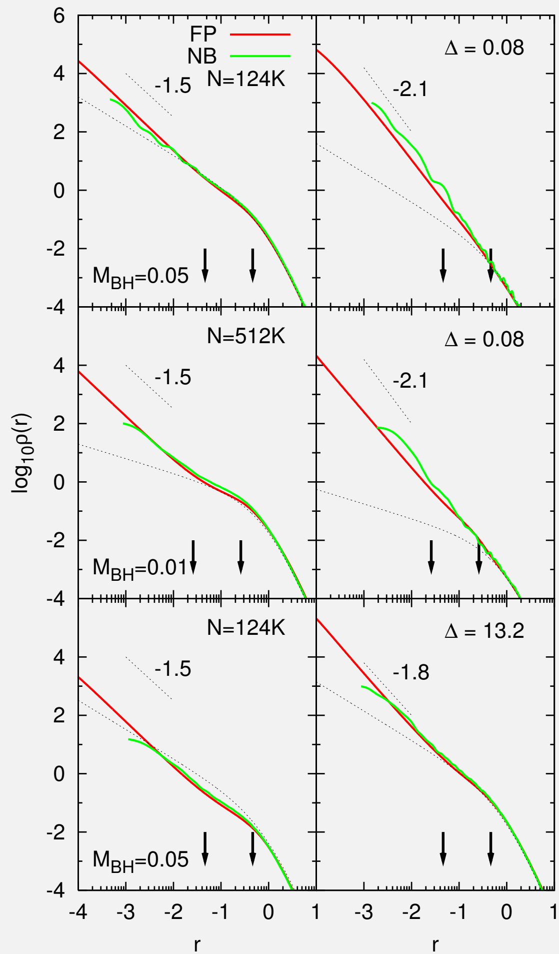
- **The "weak" branch** – $\Delta > 1$ corresponds to the scaling relations found by Bahcall & Wolf 1977

- **The "strong" branch** – $\Delta < 1$

- Preto & Amaro-Seoane 2010, Amaro-Seoane & Preto 2011:
  Validation of assumptions inherent to the Fokker-Planck (FP) approximation with N-body
  (scattering is dominated by uncorrelated, 2-body encounters and dense stellar cusps are robust against ejections)

- Not a priori trivial: For a BW $\gamma = 7/4$, stellar velocity high – fraction of stars with speeds close to $v_{\rm esc}$ in cusp very large

- $T = 0$ Dehnen profile with $\gamma = 1$ (top & bottom) and $\gamma = 1/2$ (middle)
- $\rho_{\rm L,H}(r)$ (left/right) after $\approx 0.2 T_{\rm rlx}(r_{\rm h})$
- $R = 10$, $f_H = 2.5 \times 10^{-3}$, $f_H = 0.429$
- γ_H from $\gtrsim 2$ to $\approx 7/4$ when moving from strong to weak branch
- $\gamma_L \approx 3/2$ throughout
- Arrows point to r_h and $0.1 r_h$
- **Agreement between both methods is quite good**
- FP validation – Advantages are clear: Much faster calculations



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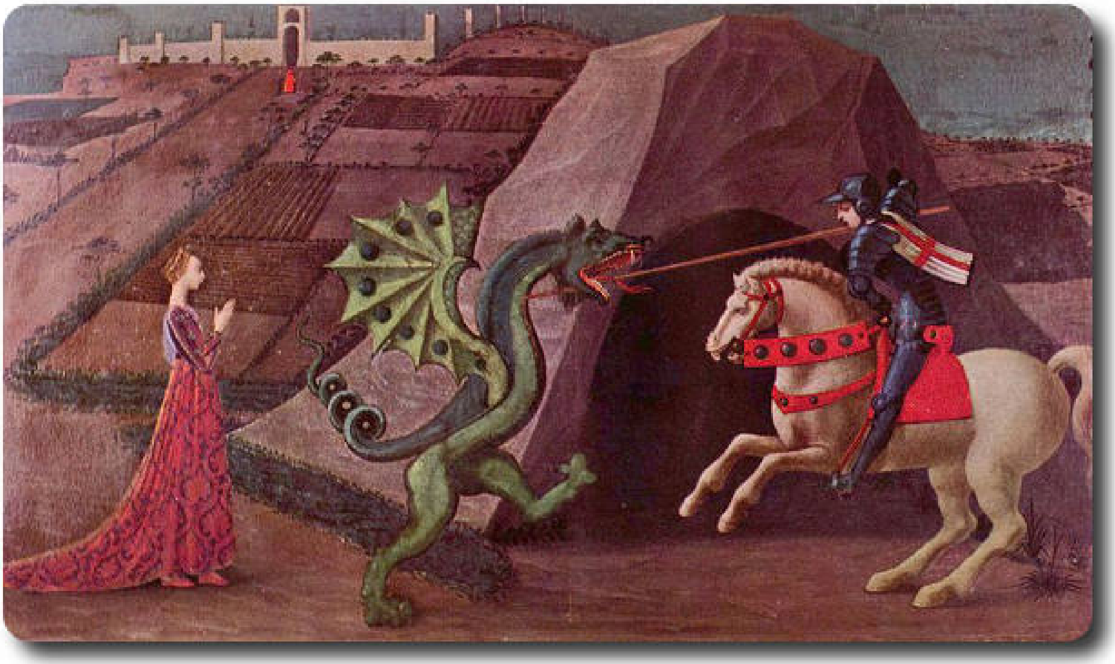
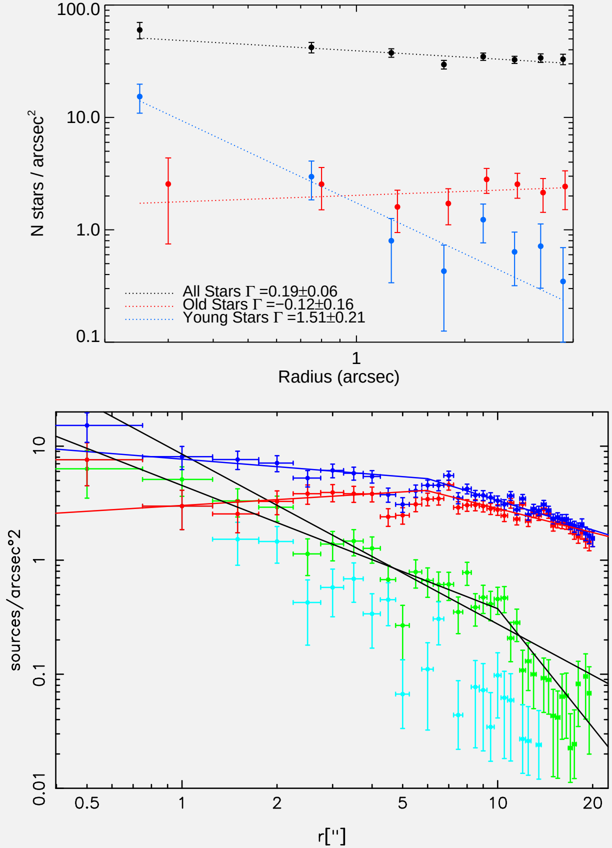
Cusps in distress



Paolo Ucello: Saint George and the Dragon

Cusps in distress

- Do et al. 2009, Buchholz et al 2009: Deficit of old stars based on number counts of spectroscopically identified, old stars in sub-parsec SgrA^* (down to magnitude $K = 15.5$)
- Schödel et al 2009: Best fits seem to favor slopes $\gamma < 1$
- Possibility of a core with $\rho_\star$ decreasing, $\gamma < 0$
- Note: detectable stars (essentially late-type giants) are still a small fraction, slope of the density profile is still weakly constrained and such a fit is only marginally better than one with $\gamma \sim 1/2$



(Do et al 2009, Buchholz et al 2009)

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How do you carve a hole at the GC?

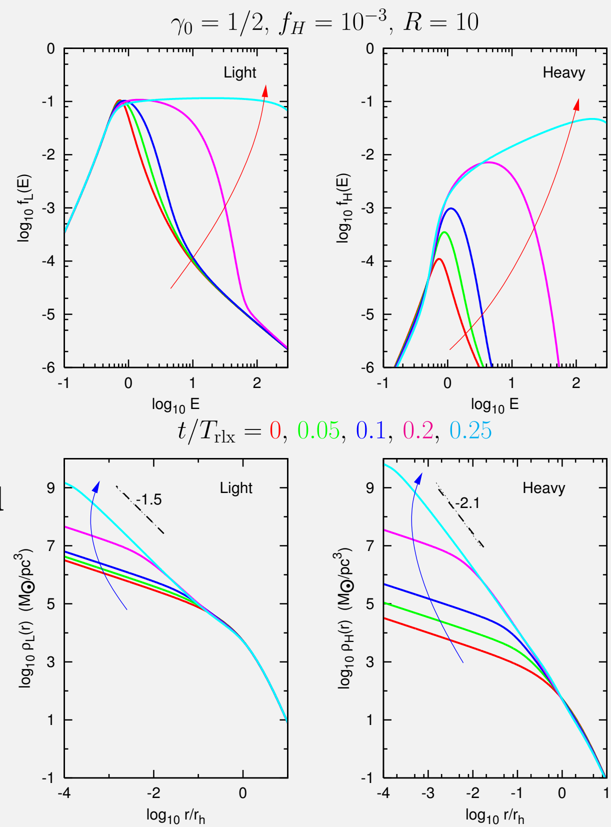
Which mechanisms could carve out a hole in the cusp?

1. **Infalling clusters** carve a hole but need a steady inflow of one at roughly every 10^7 years (Baumgardt et al 2006, Portegies Zwart et al 2006)
2. **SgrA^* is a binary MBH** – But then there must have been a more or less recent major merger involving the Milky Way

- Too early to conclude for the inexistence of a segregated cusp?
- **Let's play the game:** Time necessary for cusp growth if at some point a central core is carved?
- Choose as initial condition a model with $\gamma = 1/2$ – Isotropization time is $\ll T_{rlx}(r_h)$ **(Merritt 2009)**

Isocore … regrowth

- By $t \sim 0.25\, T_{rlx}(r_h)$, cusps **fully developed** (~ 0.02 pc if scaled to MW)
- Enough to re-growth very steep cusp of SBHs if carving happened more than 6 Gyr ago
- Disagreement with Merritt 2009 : Different approach: Neglection of H-H and H-L scattering, valid long as $\rho_H \ll \rho_L$. Limited to early evolution (Hs only minor perturbation on Ls)
- Results reproduced by independent research: Gualandris & Merritt 2011



Close

A rapid evolving region (RER)

Picture by Gregory Deryckere

Facts about the GC

- An isotropic cusp of young stars: O/B, WR starting at ~ 1 pc from SgrA* and extending to $1''$
- Mildly thick stellar *disk* of ~ 100 WR and O-type stars from $1''$ to $10''$
- Within $1''$: Population of B stars –S-stars– but *no* WR/O (Tal Alexander: "inverse mass segregation")
- A single SF episode can explain the formation of disk and cusp stars
- But S-stars cannot be born there
- Environmental conditions within $1''$ are violent for in-situ SF
- DF timescale too long for bringing there the S-stars
- "Paradox of youth" (Morris 1993; Ghez et al. 2003)

Tidal separation of binaries?

- ⋆ Hills 1991: Binary tidally separated, bound S-star + HV star
- ⋆ Initial eccentricity too large: Would take 20 – 50 Myrs to get to the observed near-thermal distribution *with the help of an old segregated cusp, currently missing*
- ⋆ And: This would also work for O/WR stars, but we don't see them $\lesssim 1''$
- ⋆ The oldest O/WR stars are $\lesssim$ 10 Myrs: Need at least 2 SF episodes because we have to thermalize the S-stars
- ⋆ Huge uncertainties: Massive perturbers, IMBHs, very hard binaries, binary fraction... to mention a few

Planetary-like migration?

- Disk must have initially been gaseous
- B stars migrated in it (Levin 2007; Griv 2010)
- But: Cannot explain the eccentricities of the S-stars . Leads to $e \sim 0$ (Perets et al. 2009; Madigan et al. 2011; Antonini & Merritt 2013)
- WR/O would migrate too, and we don't see them

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Provided the disk was heavier and more extended in the past (supported by a number of numerical works), it created a rapid evolving region (RER) inside $1''$ because of a Kozai-Lidov-like resonance, that can both explain the distribution of eccentricities of the S-stars and the absence of WR/O-stars.

For a wire to change the eccentricity e of the star from its minimum value to the maximum and back (Chen et al. 2011, Naoz et al. 2013):

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

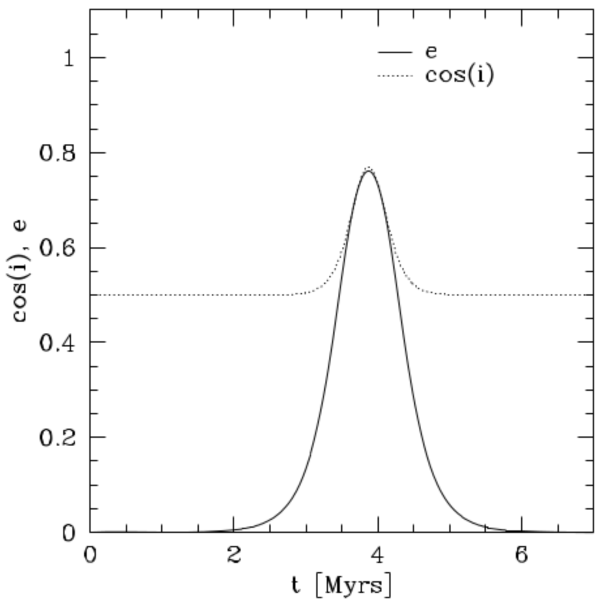
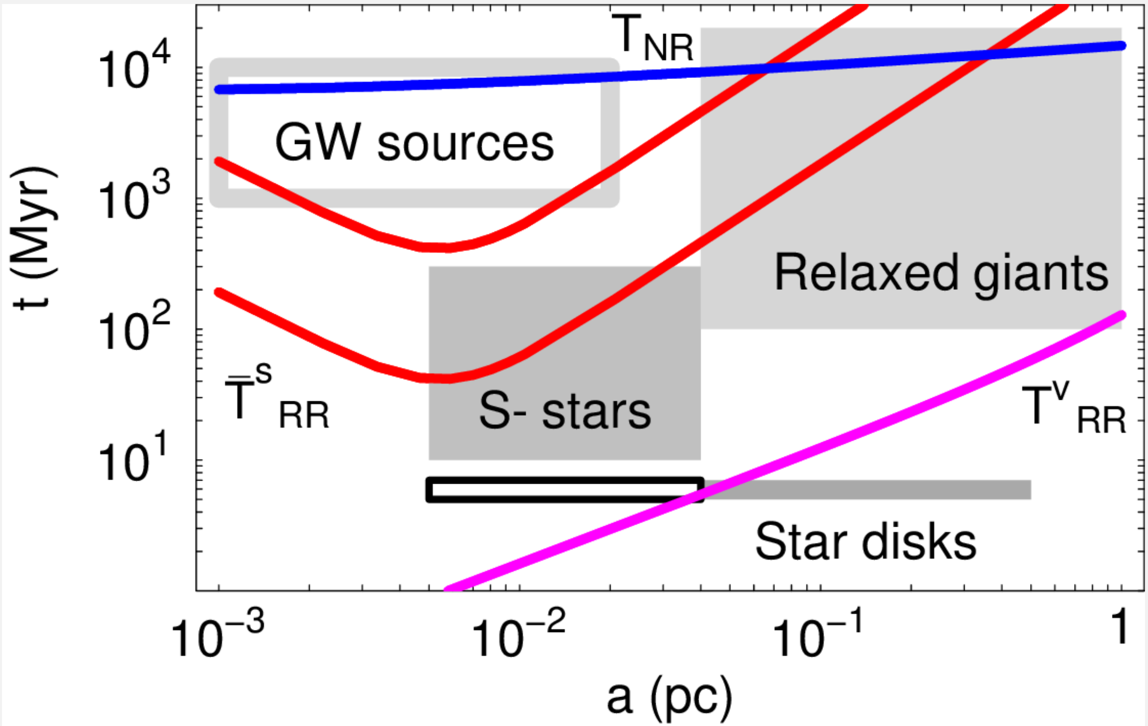


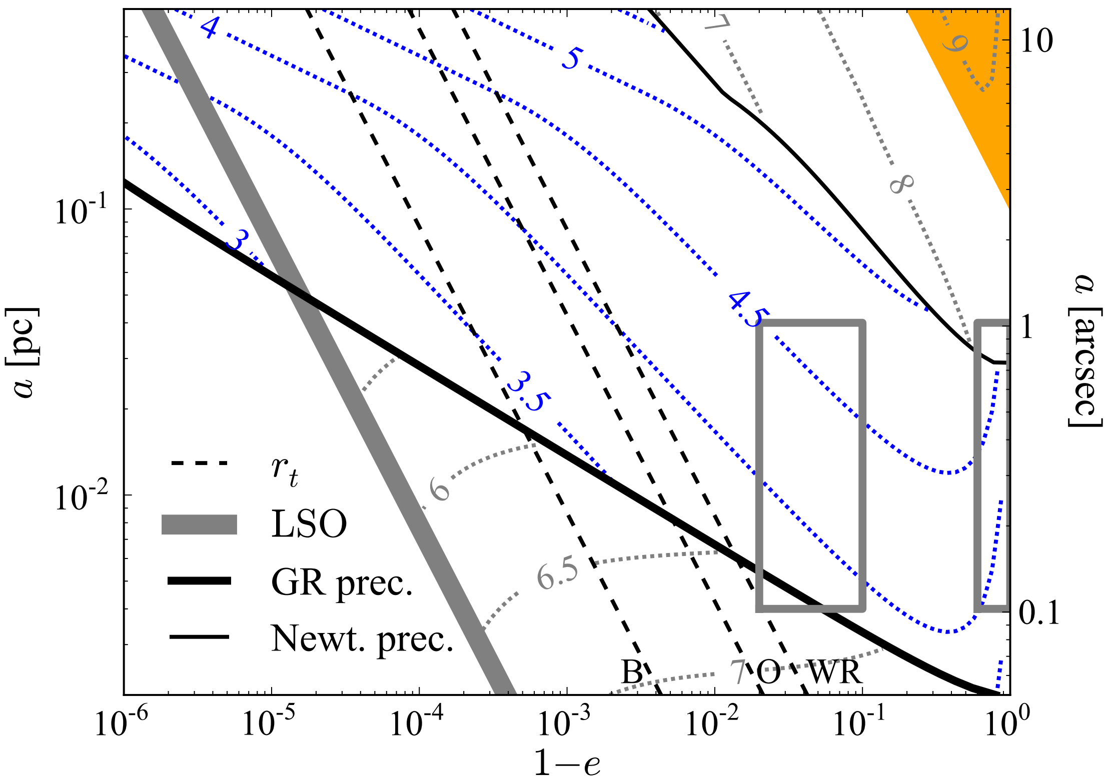
Figure 1. Simple illustration of the Kozai oscillation for one disc of mass, $M_{\rm eff} = 2 \times 10^3\,{\rm M}_\odot$ for a test particle (star) with an initial inclination of 60° relative to the plane of the disc. The test particle's eccentricity and inclination are shown as a solid and dotted lines, respectively. The precession from general relativity and the stellar bulge potential are ignored in this case.

A KL cycle induced by a disk (Chang 2009)

Close



Hopman & Alexander 2006, their figure 7



4
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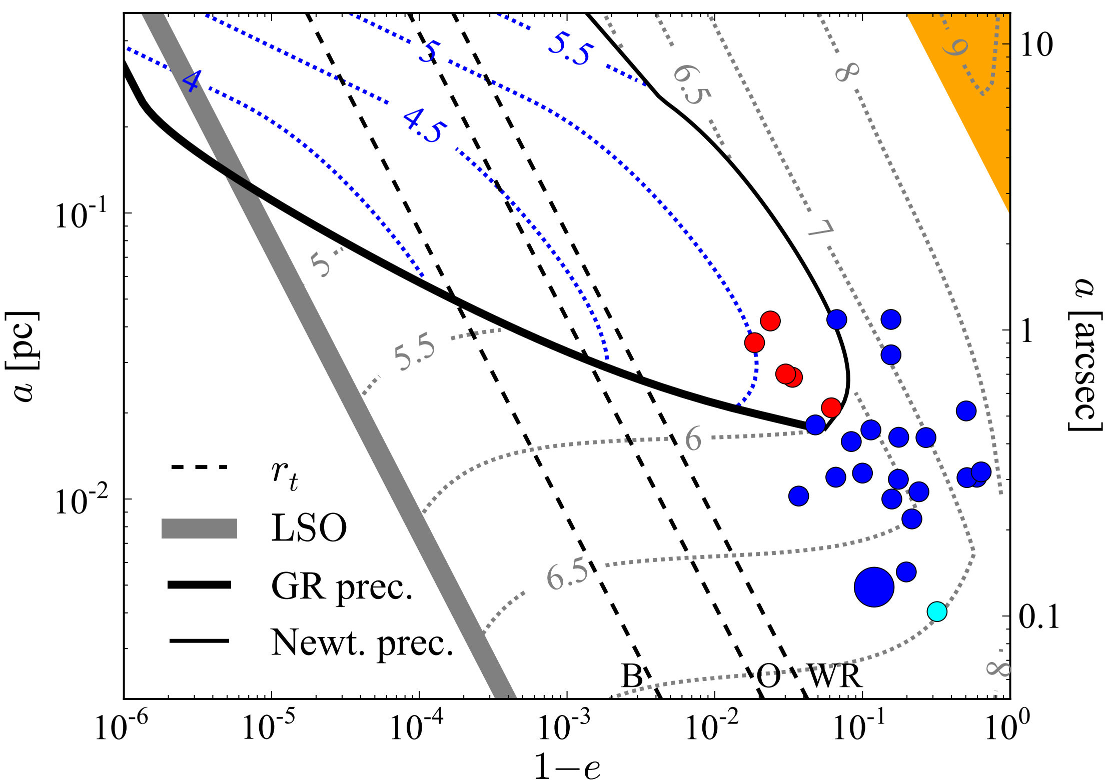
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– Instantaneous time evolution in the RER:

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

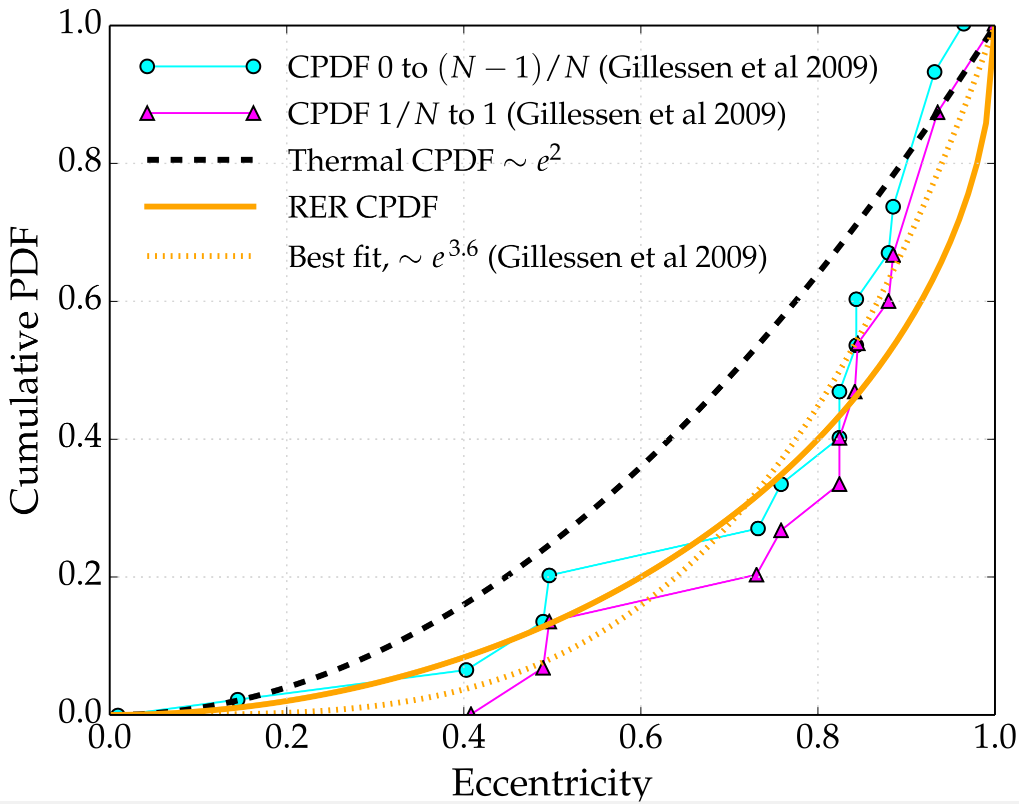
– Stars in the RER migrate on very short timescales, $10^{3.5-5.5}$ yrs, to complete a full KL cycle

– Stars mix fully in angular-momentum space after $t_{\mathrm{RR,\,v}} \sim 10^6\ (a/1'')^{0.65}$ yr

– eccentricities follow $dN/de \propto dt/de \propto e/l$

– Steeper than a thermal one, $dN/de \propto e$

– Any star out of the RER is “frozen”: Evolves at least 100 times more slowly



CPDF 0 to $(N-1)/N$ (Gillessen et al 2009)
CPDF $1/N$ to 1 (Gillessen et al 2009)
Thermal CPDF $\sim e^2$
RER CPDF
Best fit, $\sim e^{3.6}$ (Gillessen et al 2009)
Cumulative PDF
Eccentricity
0.0
0.2
0.4
0.6
0.8
1.0

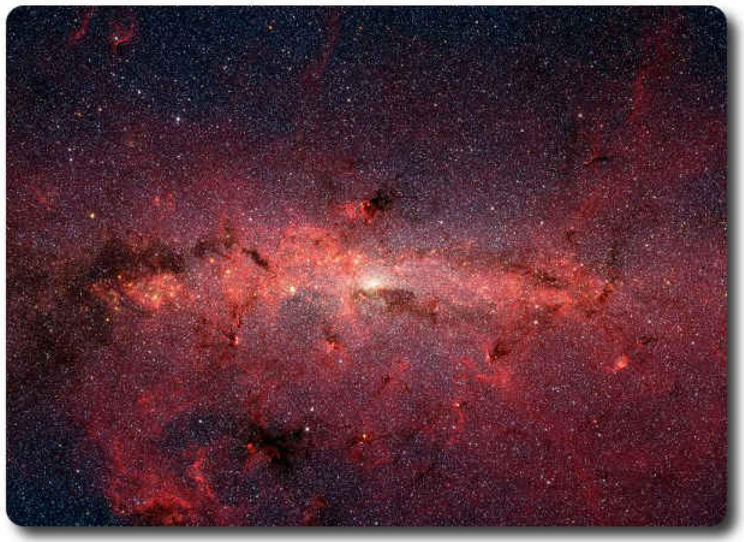
The RER: Conclusions

RER – Distribution of eccentricities of the S-stars and the absence of more massive stars within $1''$ of SgrA*, due to the torques exerted by the disk on the stellar population. Our *sole hypothesis* is that around $(1-6)$ Myr ago, the disk had extended down to $R \ll 0.04$ pc.

- Agrees with current observations about the nonexistence of an old segregated cusp in the GC
- Other scenarios crucially rely on the presence of the cusp to thermalize the S-stars (Perets et al. 2009; Madigan et al. 2011; Antonini & Merritt 2013)
- Our scenario is the only one which does not depend on the way the S-stars formed, provided they are deposited in the GC
- RER unifies S-stars eccentricities and the observed discontinuity of WR/O stars above and below $1''$
- We unify the origin of all the young stellar populations in the GC to *only one single SF episode*
- Corroborated with direct-summation $N-$body integrations, for the non-believers (AS et al, in prep)

Extra material

Testing mass segregation in our Galactic Center



MW – IR Spitzer

Challenging two-body relaxation

- (Possible) spherical core of RGs with a flat surface density profile (Buchholz et al. 2009, Do et al. 2009)
- If these RGs trace an underlying old stellar population, total mass of the old stars might be $\sim 10^5\ M_\odot$ (Merritt 2009)
- Presence of a mild thick young stellar disk, $H/R \simeq 0.1$, 2–7 Myr
- $\sim$ 100 Wolf-Rayet (WR) and O-type stars in near-circular orbits ($e < 0.4$)
- (Levin & Beloborodov (2003); Tanner et al. (2006); Paumard et al. (2006); Lu et al. (2006); Bartko et al. (2010))
- Total mass of $\sim 10^4\ M_\odot$
- Surface density profile of $\Sigma_d(R) \propto R^{-2}$
- $\sim R_{\rm in} \simeq 0.04$ pc and $R_{\rm out} \simeq 0.5$ pc

A long story

- **Stellar collisions?**
- Depletion of stars in the RGB could be due to stellar collisions (Morris 1993, Genzel et al. 1996)
- Studied extensively, Davies et al. (1998); Alexander (1999); Bailey & Davies (1999); Dale et al. (2009)
- Cannot fully explain observations
- **A secondary massive BH?**
- BBH: three-body slingshots could scour out a core
- Baumgardt et al. 2006; Portegies Zwart et al. 2006; Matsubayashi et al. 2007; Löckmann & Baumgardt 2008; Gualandris & Merritt 2012
- Needs a secondary of at least $\sim 10^5\ M_\odot$
- MW should have had a recent major merger
- Does not look like that . . .
- **Infalling clusters?**
- Could steepen up density profile outside of $10''$

- The inner $10''$ would look like a core
- Kim & Morris 2003; Ernst et al. 2009; Antonini et al. 2012
- Mass segregation can rebuild the cusp in about $\sim (1/4)\, T_{\rm rlx}$ (Hopman & Alexander 2009, Preto & Amaro-Seoane 2010; Amaro-Seoane & Preto 2011)
- Would require a steady inflow of a cluster roughly every 10^7 years to avoid cusp regrowth

We propose a simple, new scenario in which the depletion of RGs is merely a consequence of the natural fragmentation phase that the gaseous disk experienced. We prove that the regions of overdensity in the star-forming disk easily removed the envelope of stars in the RGB after a rather low number of crossings through the disk.

We prove that the regions of overdensity that progressively form in the disk, referred to as "clumps", are dense enough to efficiently remove it completely and release the inner compact core of the RGs.

Amaro-Seoane & Chen 2014 ApJ Letts in press.

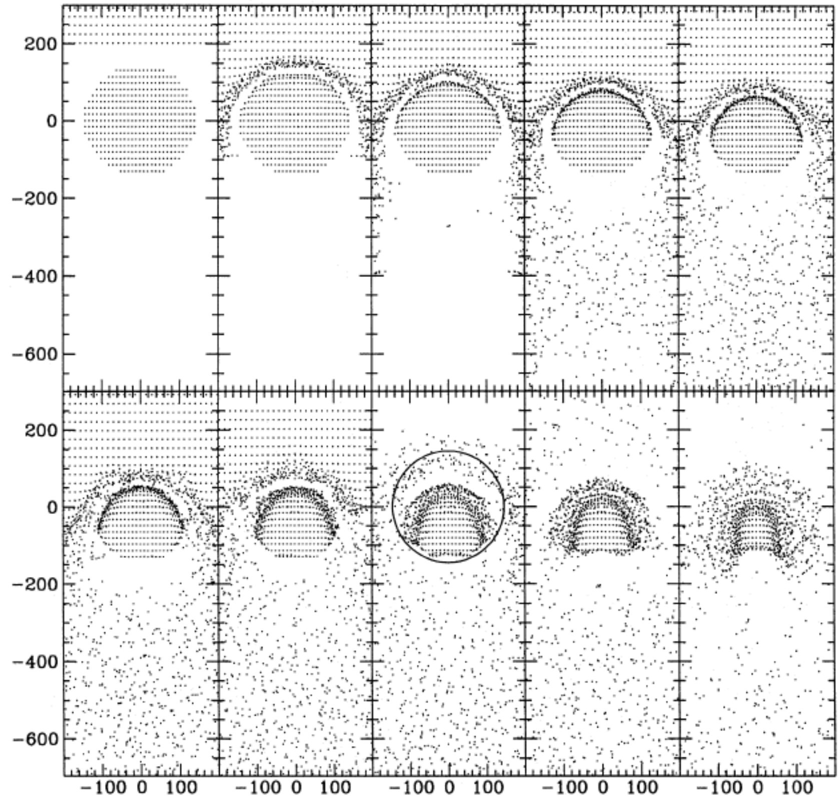


FIG. 4.—Snapshots of particle positions from the $v_* = 8000$ km s^{-1}, $\Sigma = 10^5$ g cm^{-2} simulation. Particles plotted are those within two smoothing lengths of the $y = 0$ plane. The panels are plotted at time intervals of 2.5×10^4 s; the spatial scales are in solar radii.

Armitage et al. 1996

Depletion of red giants: Conclusions

– Prediction: Released cores of the RGB stars populate GC

– Difficult to detect them in IR

– Core exhausts remaining of H envelope in a couple Mys: Very faint

– At the same time: Shift in their peak emission to shorter wavelengths, invisible in IR filters (Davies & King 2005)

– Need deeper spectroscopic observations and more complete photometric surveys down to the 18th K-magnitude

– **An old, segregated cusp is still a possibility**

– ... and it is *directly* linked to other properties of the GC