Relativistic loss-cone dynamics: Implications for the Galactic Center

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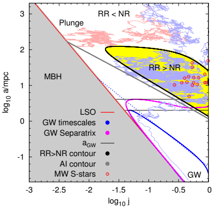
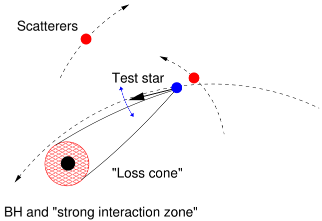


Bar-Or & TA 2015

The stellar dynamical loss-cone problem:

How do stars in a galactic nucleus interact *strongly* with a massive black hole (MBH) and/or fall into it, and at what rates?



Implications

Plunge processes:
Tidal disruption flares[1,2], tidal detonation[3], tidal scattering[4], gravitational wave (GW) flares

Inspiral processes:
GW extreme mass ratio inspirals (EMRIs)[1,2,5], tidal squeezars[6], accretion disk capture

Exotic stellar populations near MBHs[7,8,9]

MBH+stars formation and evolution[10,11,12,13]

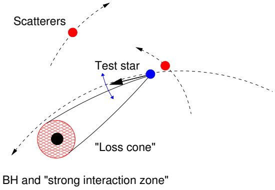
How do galactic nuclei randomize and relax?

1:TA & Hopman 2003 2:Bar-Or & TA 2015 3: TA 2005 4:TA & Livio 2001 5:Hopman & TA 2005, 2006a, 2006b 6:TA & Morris 2003 7:TA 1999 8:TA & Livio 2004 9:Perets, Hopman & TA 2007 10:TA & Hopman 2009 11:TA & Kumar 2001 12:Bar-Or & TA 2014 13:Bregman & TA 2012

Relaxation near a MBH

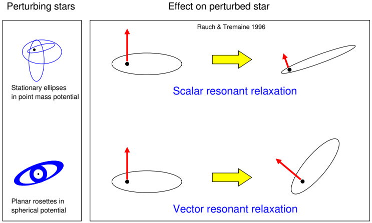
Non-coherent relaxation (NR: E, J)

Point—point interactions



Resonant relaxation (RR: J)

Orbit-orbit interactions



$Q = M_\bullet / M_\star$

$$T_{NR} \sim [Q^2 P / N_\star] / \log Q$$

$1/\log Q$: relaxation boost from close encounters

$$T_{RR} \sim [Q^2 P / N_\star] P / t_{\mathrm{coh}}$$

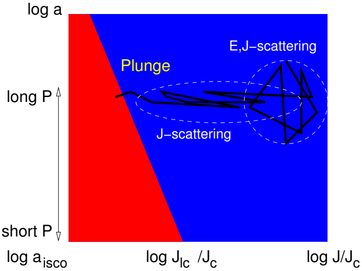
P/t_{coh}: relaxation boost from long coherence

Near MBH: $T_{RR}/T_{NR} \sim \log Q (P/t_{\mathrm{coh}}) \ll 1$

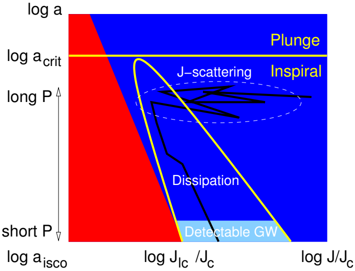
Fast evolution to $J \to 0$: Strong interaction with the MBH

The "classical" (pre-RR) loss-cone: Plunge vs inspiral

Loss primarily by by J-relaxation:  $T_J \sim j^2 T_E$ $\quad j = J/J_c(E)$



(Lightman & Shapiro 1977; Cohn & Kulsrud 1978)



(TA & Hopman 2003; Hopman & TA 2005)

$\Gamma_{plunge} \sim N_\star(< r_h)/\left\langle \log(J_c/J_{lc}) T_E \right\rangle$ $\qquad \Gamma_{\mathrm{inspiral}} \sim N_\star\left[< r_{\mathrm{crit}}(T_E)\right]/\left\langle \log(J_c/J_{lc}) T_E \right\rangle$

$$\Gamma_{\mathrm{inspiral}} \sim O(0.01)\Gamma_{\mathrm{plunge}}$$

The "danger" of unquenched RR: No inner cusp

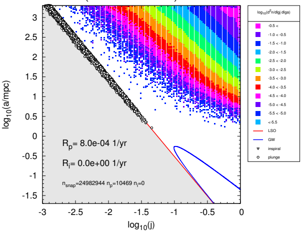
(No GR stars, no GW EMRIs, no . . .)

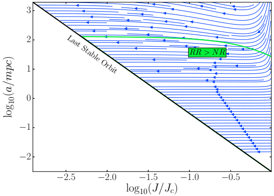
The "fortunate coincidence" conjecture:

(Hopman & TA 2006)

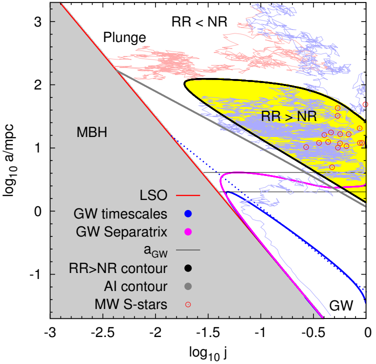
- Unquenched, RR drives all stars to plunge orbits (no EMRIs!).
- $\mathcal{O}(\beta^2 j^{-2})$ GR in-plane Schwarzschild precession becomes significant before $\mathcal{O}(\beta^{5/2} j^{-7} Q^{-1})$ GW dissipation.
- GR precession quenches RR and allows EMRIs to proceed unperturbed, decoupled from the background stars.

(Bar-Or & TA 2015)





The relativistic loss-cone



(Bar-Or & TA 2015)

The η-formalism

Stellar dynamics in the presence of correlated noise

(Ben Bar-Or's talk)

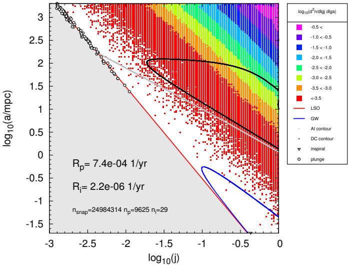
- **Adiabatic invariance$^{(\star)}$ quenches RR at low-j**
- **NR dominates evolution on long time scales**
- **Dynamical modeling of the relativistic loss-cone**

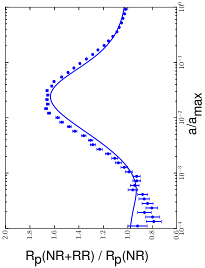
Effective RR diffusion that express correlated noise and secular precessions, together with NR diffusion and GW dissipation, provide a powerful scalable Monte Carlo tool for modeling long-term dynamics and loss-rates of galactic nuclei in the realistic $N_\star \gg 1$ limit$^{(\dagger)}$.

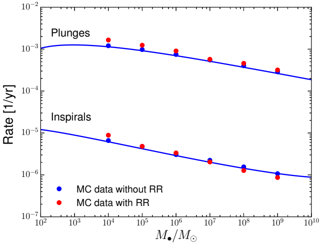
$\star$ Correct form and interpretation of the "Schwarzschild Barrier" (Merritt, TA, Mikkola & Will 2011).

$\dagger$ Validated against N-body results in the low-$N_\star$regime.

GW EMRI and tidal disruption rates in steady state



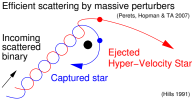


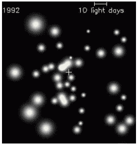


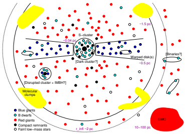
Galactic nucleus model ("MWEG")

- GR+mass precession
- GW+NR+RR
- Smooth noise+mass quenching
- Adiabatic invariance saves EMRIs: "Fortunate coincidence" validated.

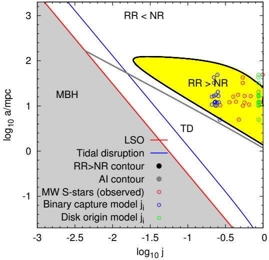
Puzzles of the Galactic center: Origin of the S-stars? Where's the old stellar cusp?

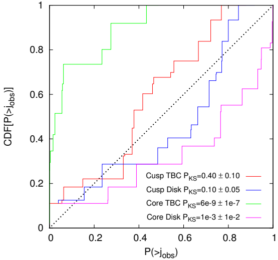






Disk formation and migration (Levin 2007)





Sabsovich, Bar-Or & TA 2016, in prep.

Conclusions: 1. RR is essential for S-stars post-capture/migration randomization.

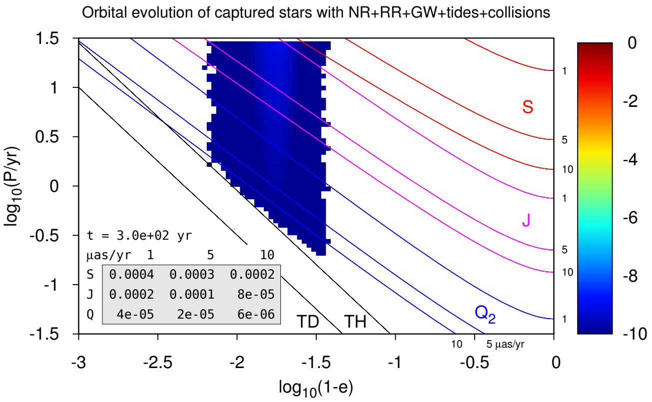
2. Best fit model: Tidal capture in dense old cusp of stellar remnants.

The hunt for relativistic stars for testing strong gravity[1,2,3]

- Option 1: No old cusp in inner Galactic center (inner RG cusp missing[4,5,6])
  - All young stars inside $\lesssim 0.01$ pc observed—none strongly relativistic.
  - Low stellar density $\Rightarrow$ very slow dynamical evolution.
  - $\Rightarrow$ No *local* stellar targets for tests of strong GR.
- Option 2: Dark cusp of stellar remnants + old stars further out
  - Rapid *e*-evolution (RR), but slower *a*-evolution (NR).
  - Stellar destruction ($\overline{T}_\star \sim 5 \times 10^7$ yr) faster than T_E at $\mathcal{O}(1\,\mathrm{pc})$.
  - Strong depletion of *local* strongly relativistic stars.
- Option 3: Dark cusp of stellar remnants + tidally-captured stars
  - Low-mass equivalents of S-stars / Hyper-velocity B-stars.
  - Fast, continuous supply rate if scaled by S-stars.

1:Zucker, TA, Gillessen et al 2006 2:Will 2008 3:Merritt, TA, Mikkola & Will 2010 4:Buchholz et al 2009 5:Do et al 2009 6:Bartko et al 2010

Evolution of tidally-captured relativistic stars in a dark cusp



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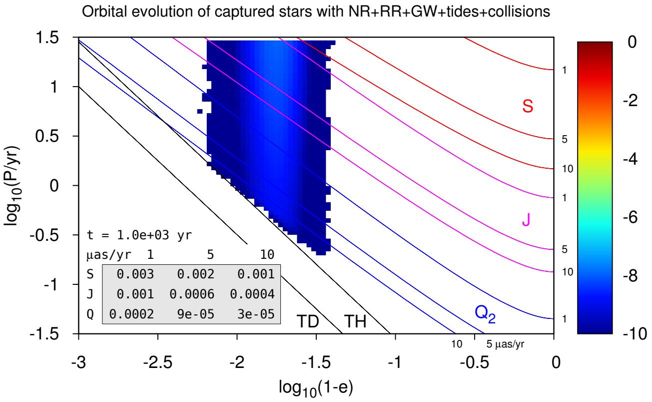

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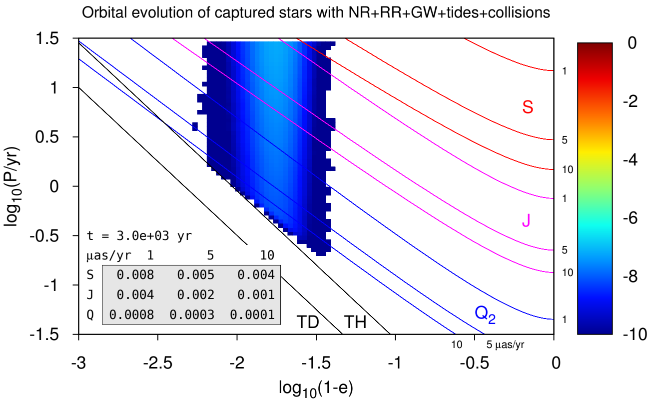

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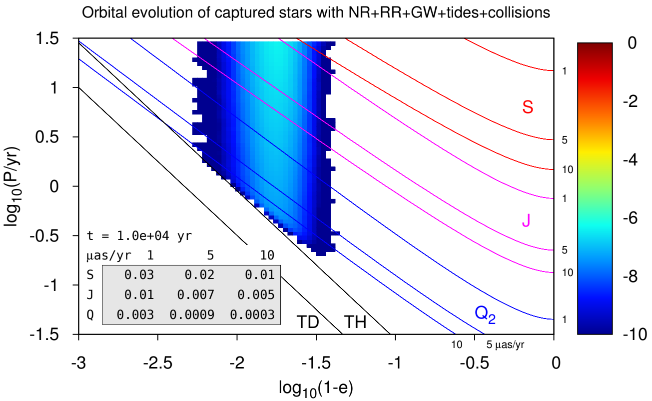

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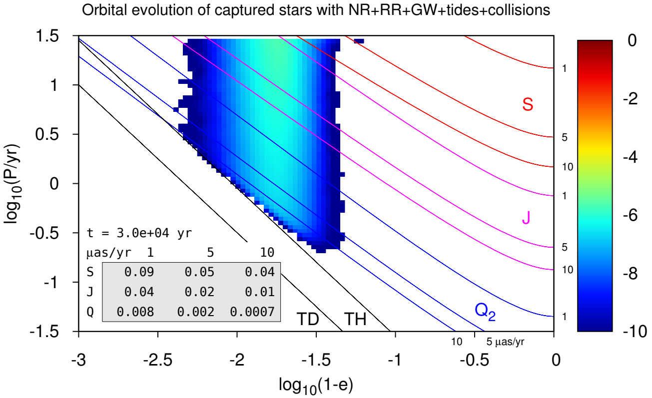

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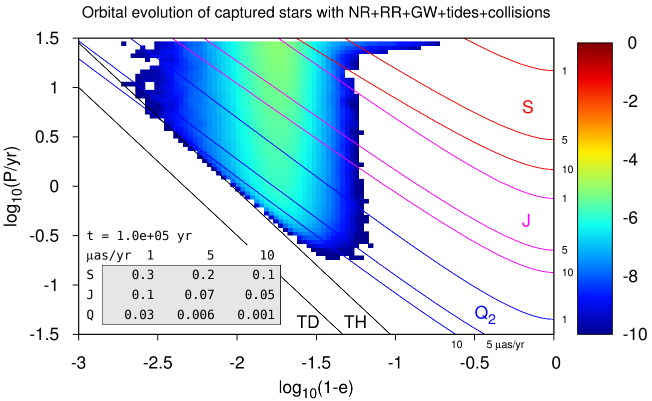

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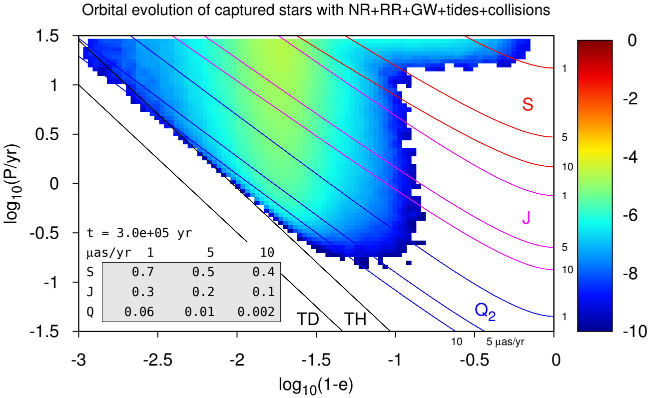

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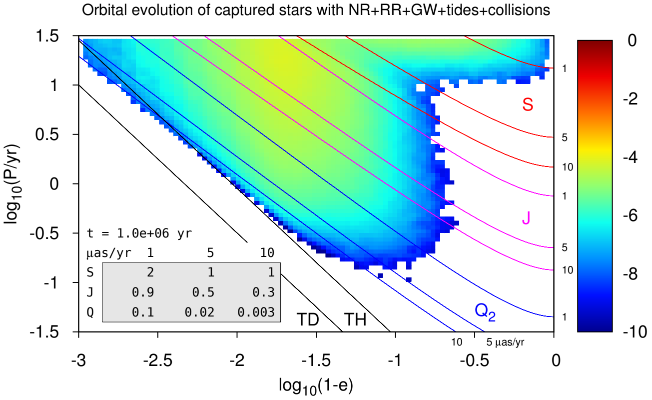

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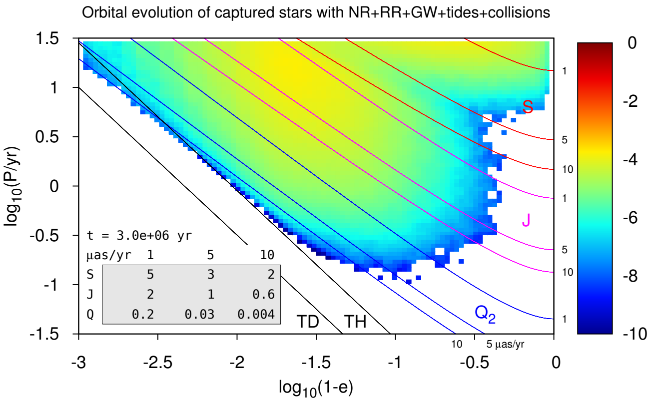

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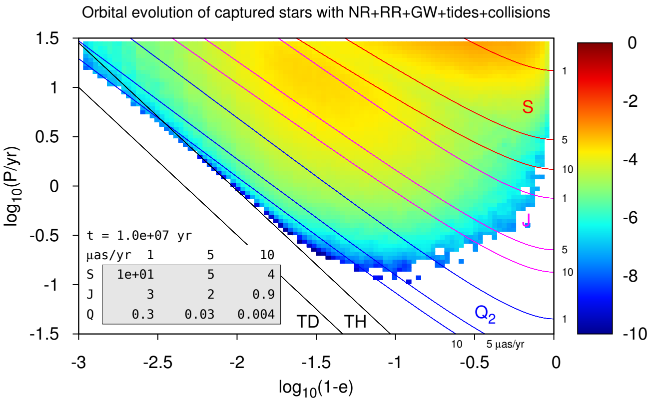

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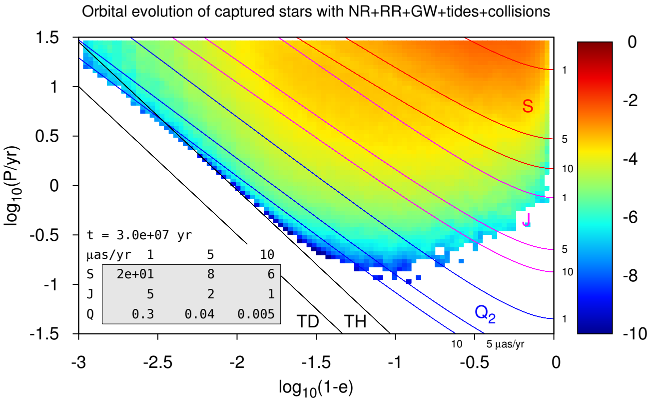

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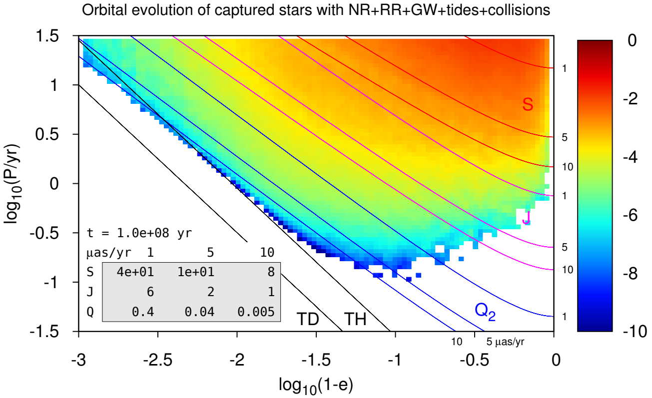

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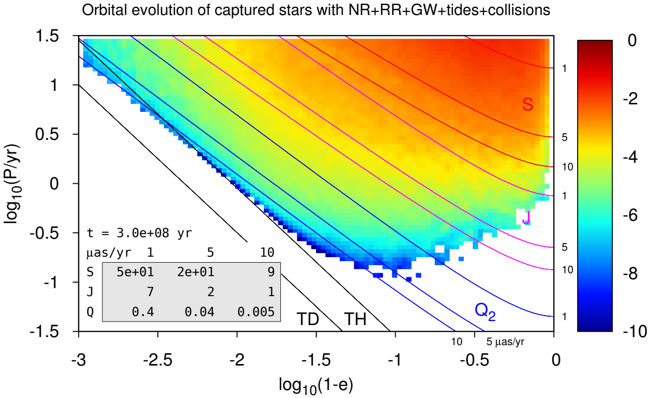

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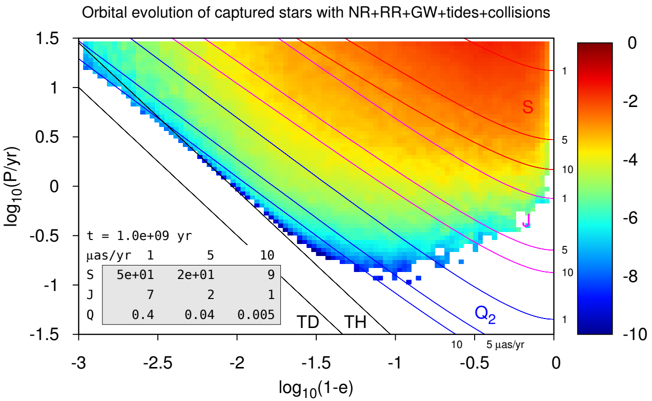

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Summary

- Theoretical results (more in Ben Bar-Or's talk)
  - NR, RR, GW dissipation and secular precession can be treated analytically as effective diffusion with correlated noise.
  - The steady state depends mostly on NR, which erases AI.
- General applications
  - Relativistic loss-cone modeling of galactic nuclei in $N_\star \gg 1$ limit.
  - Plunge / EMRI rates and branching ratios.
- Implications for the Galactic Center
  - Origin of S-stars: Dark cusp + binary capture favored.
  - $\mathcal{O}(100)$ captured low-mass relativistic stars may exist in GC, but strongly relativistic orbits suppressed by tidal interaction with MBH.