The Dynamics of Close Interactions Between Stars and a Massive Black Hole

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Outline

- Close interactions with a MBH
  - Tidal disruption (MBH feeding, tidal disruption flares, detonation)
  - Tidal capture, heating (MBH feeding, "squeezars")
  - Gravitational waves from inspiraling remnants (EMRIs)
  - Captured stars around SgrA* (S-cluster, Eisenhauer et al 2005)
  - Hyper-velocity stars (HVSs in Galactic halo, Brown et al 2005, 2006)
  - Stellar capture by massive accretion disk

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  - Binary interactions (3-body exchanges)

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  - The relaxation bottle-neck (many assumptions / approximations)

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  - Binary interactions (3-body exchanges)
- Loss-cone dynamics
  - The relaxation bottle-neck (many assumptions / approximations)
- Efficient relaxation
  - Resonant relaxation
  - Massive perturbers

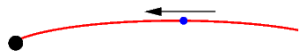
Strong star-MBH interactions

Direct infall

Feeding, Tidal disruption, detonation, flares

Absorption / Annihilation

Γ_{infall}



Alexander & Livio 2001; Alexander & Hopman 2003; Alexander & Morris 2003; Alexander & Livio 2004

Strong star-MBH interactions

Direct infall

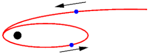
Absorption / Annihilation

Γ_{infall}

Inspiral

Meta-stable decay vs collisional ionization

Gravity waves, Tidal capture ("Squeezars") $\Gamma_{\mathrm{inspiral}} \sim 10^{-2}\Gamma_{\mathrm{infall}}$



Strong star-MBH interactions

Direct infall — *Absorption / Annihilation*

Γ_{infall}

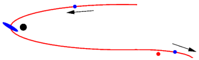
Inspiral — *Meta-stable decay vs collisional ionization*

$\Gamma_{\mathrm{inspiral}} \sim 10^{-2}\Gamma_{\mathrm{infall}}$

Tidal scattering — *Deep inelastic scattering*

"Weird" stars

$$\Gamma_{\mathrm{scatter}}(<r) \sim \Gamma_{\mathrm{infall}}\left[(r/q)^{\delta} - 1\right] \sim \mathcal{O}(\Gamma_{\mathrm{infall}})$$



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Tidal scattering

Deep inelastic scattering

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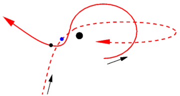
3-body exchange

Charge exchange

Orbital capture, Hyper-velocity stars

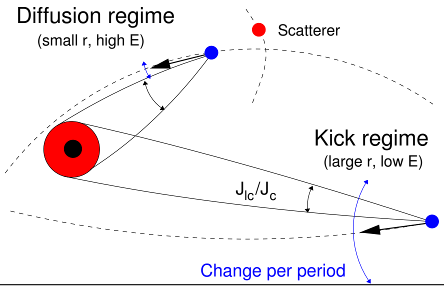
$$\Sigma \simeq \underbrace{\left[1 + A\frac{2M_\star(m+M_\bullet)}{mM_\bullet V^2}\right]}_{\text{Grav. focusing}} \underbrace{B\left(\frac{M_\bullet+M_\star}{m+M_\bullet+M_\star}\right)^2 \pi a^2}_{\text{Capture radius}} \underbrace{\left[\left(\frac{M_\star}{M_\bullet}\right)^{7/4}\left(\frac{m+M_\bullet}{m+M_\star}\right)^{1/4}\right]}_{\text{Phase space volume}}$$



Alexander & Livio 2001; Alexander & Hopman 2003; Alexander & Morris 2003; Alexander & Livio 2004

Loss-cone replenishment

- Incoherent 2-body relaxation of J $\quad t_J \sim J/\dot{J} \sim (J/J_c)^2 t_{relax}$



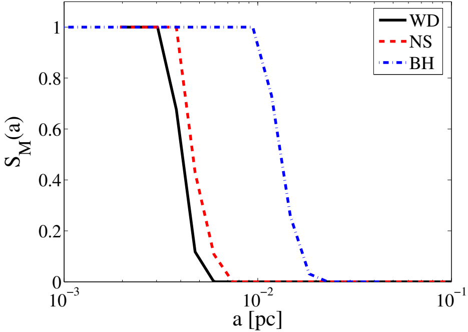
Hills 1975
Frank & Rees 1977
Lightman & Shapiro 1977
Cohn & Kulsrud 1978
Shapiro & Marchant 1978

- Slow diffusion into the loss-cone $\quad \Gamma \sim n_\star / \log(J_c/J_{lc}) t_{relax}$
- Is faster relaxation possible?
  - ▷ Non-spherical potentials
  - ▷ Chaotic orbits

Magorrian & Tremaine 1999

Norman & Silk 1983
Gerhard & Binney 1985
Merritt & Poon 2004
Holley-Bockelmann et al 2002

A critical energy / distance for inspiral

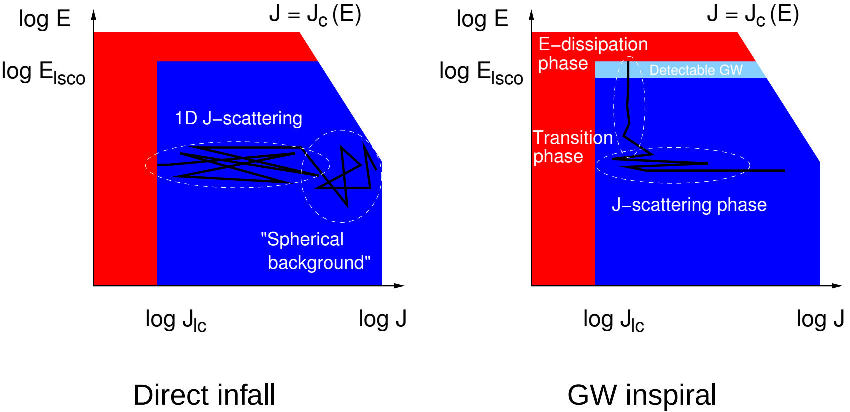


Hopman & Alexander 2005, 2006

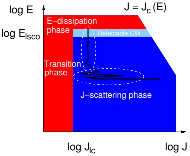
Implications:

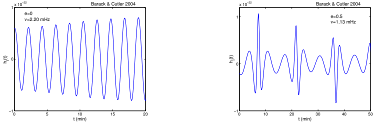
1. Inspiral very inefficient compared to direct infall.
2. Mass segregation very important for EMRI GW rates.
3. Stellar BHs dominate EMRIs ($\gtrsim 10^{-7}\,\mathrm{yr}^{-1}$ per galaxy).

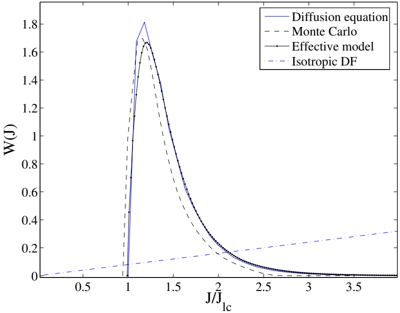
Infall and inspiral in the diffusion limit

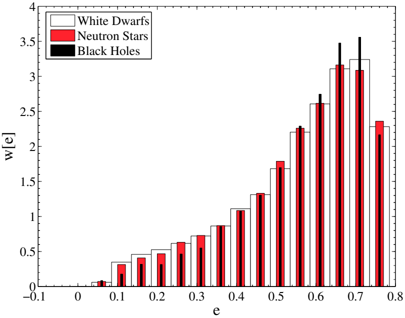


Eccentricity distribution of GW EMRI sources



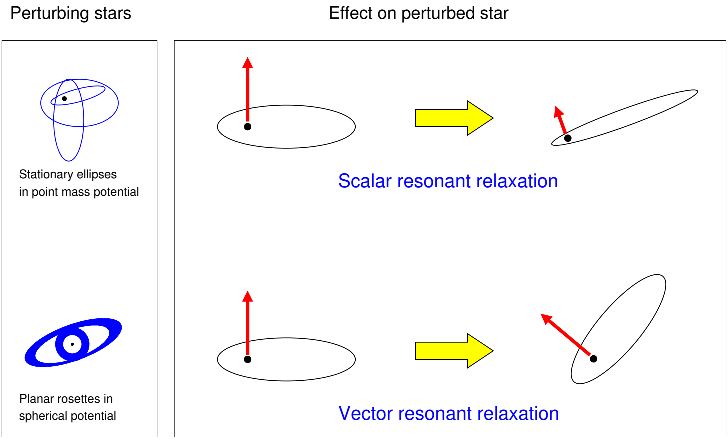






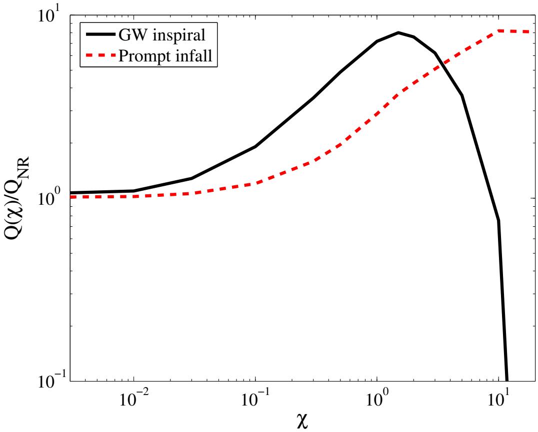
Hopman & Alexander 2005

Resonant relaxation



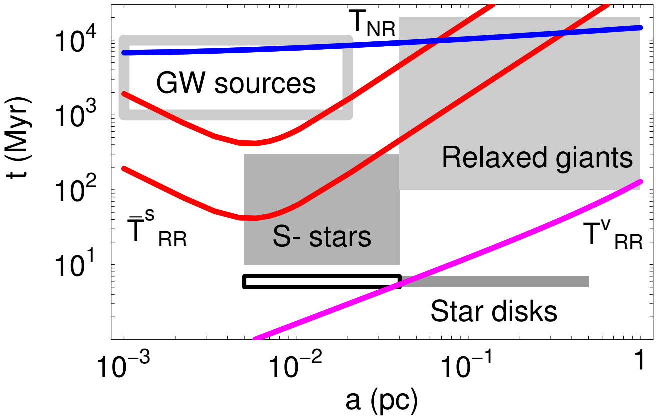
Rauch & Tremaine 1996

Uncertain RR efficiency (χ): effect on GW EMRI rates



Hopman & Alexander 2006

Resonant relaxation near the Galactic black hole



Hopman & Alexander 2006

Accelerated relaxation by massive perturbers

Large-angle deflection: $v^2 \sim 2GM/r_c$
Deflection rate: $\Gamma \sim nvr_c^2 \sim nM^2/v^3$

(Zhao, Haehnelt & Rees 2002)

Obs. MPs in central 100 pc
$\sim 10^8$ stars of $1\,M_\odot$
$\sim 10^2$ MPs of $10^{3-5}\,M_\odot$

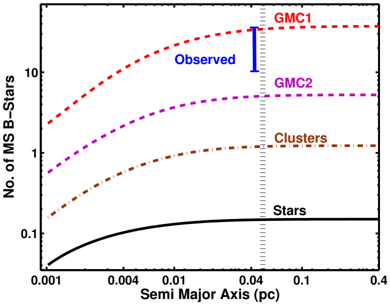
Example:
$(nM^2)_{GMC} \sim 3 \times 10^3\,(nM^2)_\star$

Implications:

1. Massive perturbers accelerate relaxation in the Galactic Center and plausibly in late-type galaxies generally.

2. MPs accelerate close interactions only when loss-cone is large and refilling by stellar relaxation is inefficient: 3-body exchanges, binary MBH coalescence.

Massive perturbers in the Galaxy



Perets, Hopman & Alexander 2006

Results:

- Efficient exchange capture of young stars near SgrA*

  (Gould & Quillen 2003)

- Steady supply of high-v stars

  ▷ Tens of $v > 500$ km/s, 3-5 $M_\odot$ stars, tens of kpc from GC

  (Brown et al 2006)

- Rapid binary MBH mergers

  ▷ $2 \times 10^6\,M_\odot + 2 \times 10^6\,M_\odot$ merger in Galactic Center in $\sim 10^9$ yr

Summary

- Classification of close interaction dynamics
  - Infall
  - Inspiral
  - Scattering
  - Exchange
- Inspiral: interplay of scattering and dissipation
  - Gravitational waves from high-e EMRIs
  - Mass segregation important ($\times$10 enhancement)
- Efficient relaxation mechanisms
  - Resonant relaxation near MBH
  - Massive perturbers far from MBH