Black hole feeding rates in post-merger galaxies

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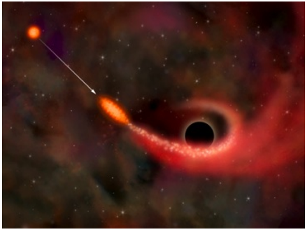
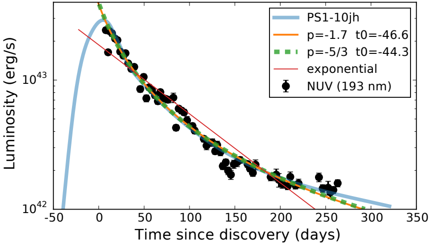
Stellar aggregates, Bad Honnef, 9 December 2016

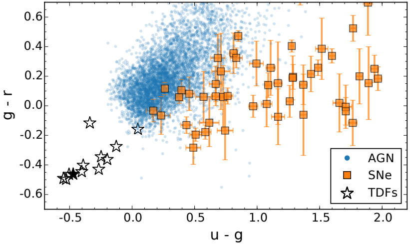
Tidal disruptions: observational status



- Occur in quiescent galactic nuclei;
- Observed as X-ray, UV and optical transients;
- Have distinct lightcurves and spectra;
- A few dozen of events registered so far

[see reviews by Komossa (1505.01093), Kochanek (1601.06787)].





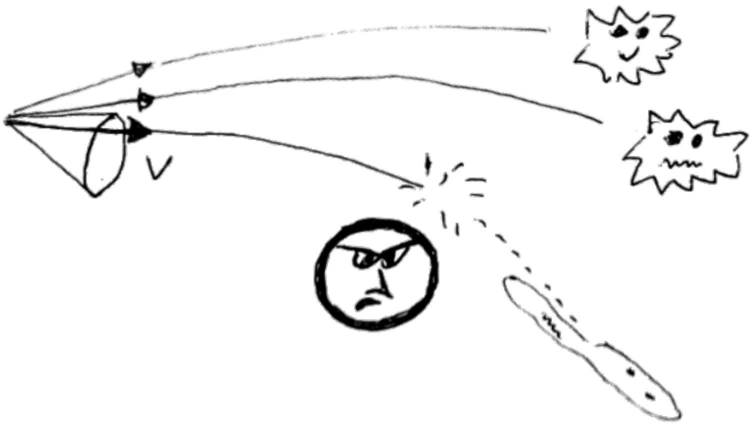
[from van Velzen+ 2016]

Tidal disruptions and the loss-cone theory

Tidal disruption radius: $r_t \simeq \left(\frac{M_\bullet}{M_\star}\right)^{1/3} R_\star$.

Direct capture occurs when $r_t \leq 4r_{\rm schw} = 8GM_\bullet/c^2$.

Critical angular momentum: $L_t \equiv \sqrt{2GM_\bullet r_t}$.



The classical loss-cone theory

Distribution function of stars: $\mathcal{N}(E, L, t)$.

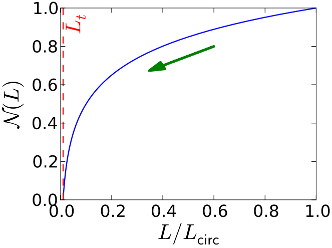
Two-body relaxation leads to the diffusion of stars in the phase space;

The Fokker–Planck equation for the diffusion in angular momentum:

$$\frac{\partial \mathcal{N}(E,L,t)}{\partial t} = \frac{\partial}{\partial L}\left(\mathcal{D}_1(L)\, \mathcal{N}(E,L,t) + \mathcal{D}_2(L)\, \frac{\partial \mathcal{N}(E,L,t)}{\partial L} \right).$$

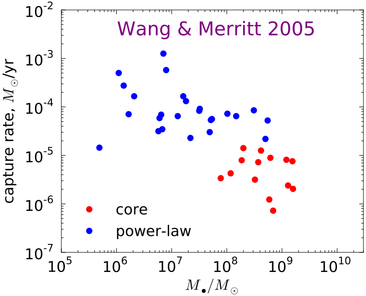
Steady-state profile: $\mathcal{N}(E, L) \propto A(E) + B(E) \ln(L/L_t)$
and the corresponding flux into the black hole $\mathcal{F}(E)$.

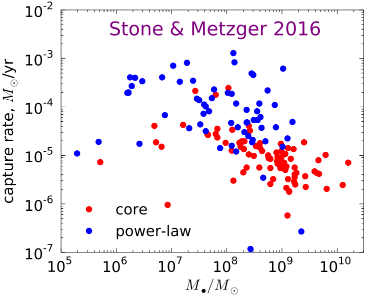
Analytic time-dependent solution
in terms of Bessel series
[Milosavljević & Merritt 2003, Lezhnin & Vasiliev 2015].



Steady-state tidal disruption rates

- Take a surface brightness profile of a galaxy nucleus $\Sigma(R)$;
- Assume a black hole mass $M_\bullet$ and mass-to-light ratio Υ;
- Deproject Σ to obtain the density profile $\rho(r)$;
- Compute the isotropic distribution function in energy $\mathcal{N}(E)$;
- Compute the diffusion coefficients $\mathcal{D}(E)$;
- Integrate the steady-state flux to obtain $N_{\mathrm{TDE}} = \int \mathcal{F}(E)\,dE$.

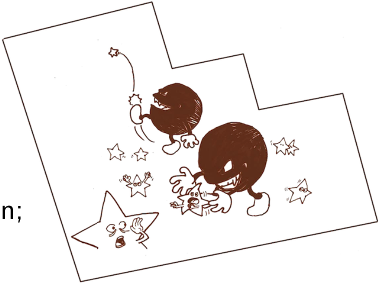




Theoretical predictions are higher than the observed rates!

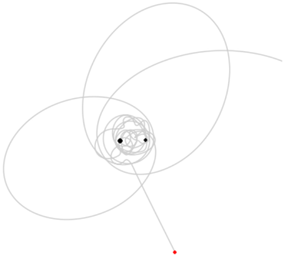
Galaxy mergers and binary supermassive black holes

- Binary SBH naturally created in galaxy mergers;
- The two SBHs spiral in and eventually coalesce due to gravitation-wave emission;
- On their way to coalescence, they eject stars from the galactic nucleus (the slingshot effect);
- As a result, a gap in the angular momentum distribution is formed;
- The flux of stars into a residual single SBH is suppressed until this gap is refilled.

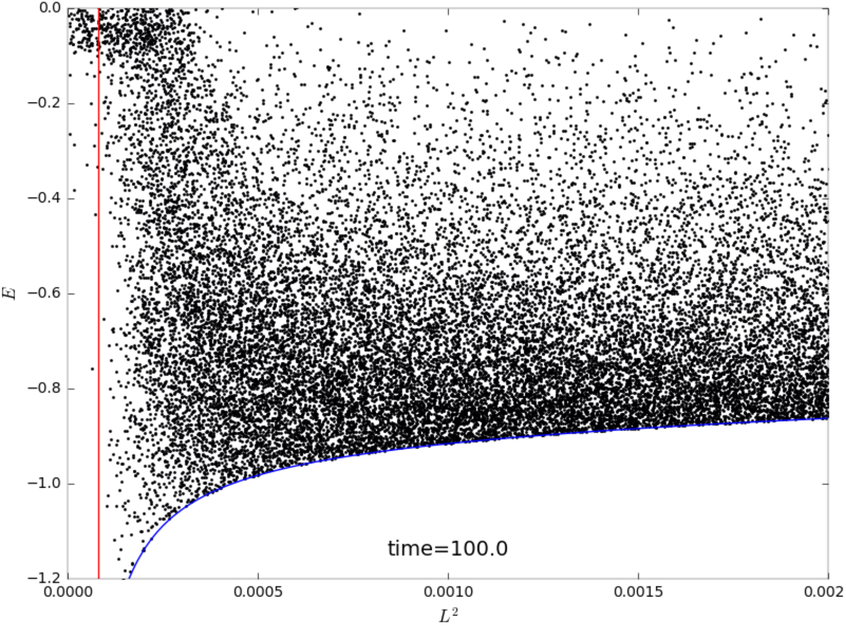


WFPC2 captures a SMBH binary kicking stars out of the bulge

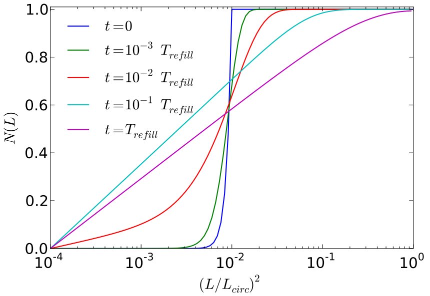
[image credit: Paolo Bonfini]

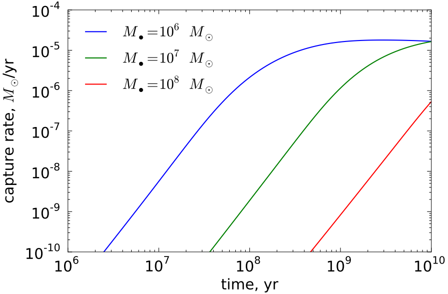


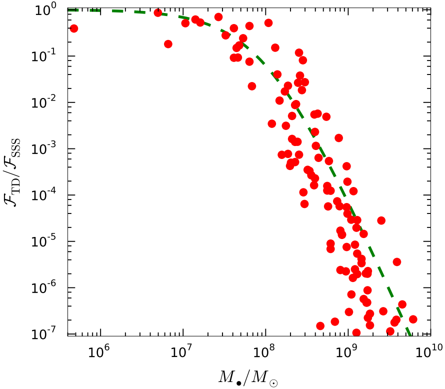
A gap in stellar distribution at low angular momentum



The gap takes a while to refill





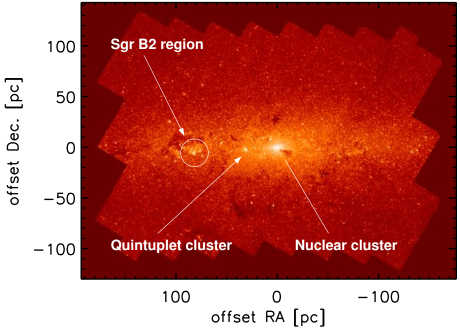


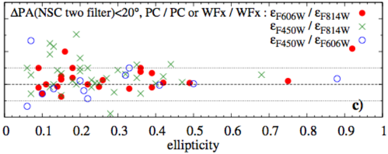
Ratio between time-dependent (suppressed) and stationary capture rates for a sample of nearby galaxies with estimated black hole masses.

The capture rate is still suppressed after 10 Gyr for galactic nuclei with $M_\bullet \gtrsim 10^{7.5}\ M_\odot$.

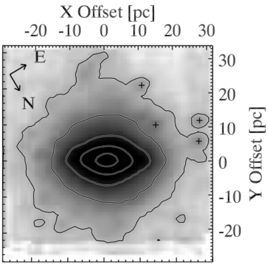
Non-spherical galactic nuclei

[Milky Way NSC, Schödel+ 2014]





[NSC catalog of Georgiev & Böker 2014]

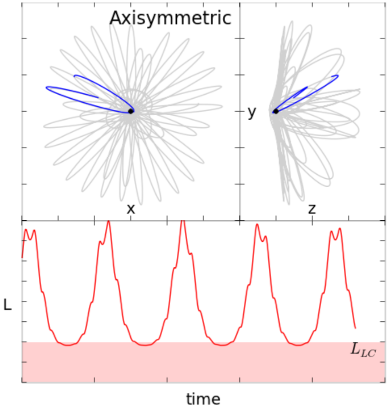


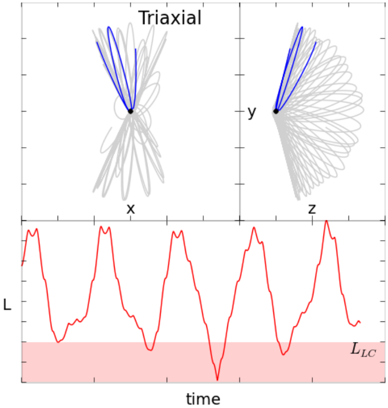
[NGC 4244 NSC, Seth+ 2008]

Loss cone in non-spherical stellar systems

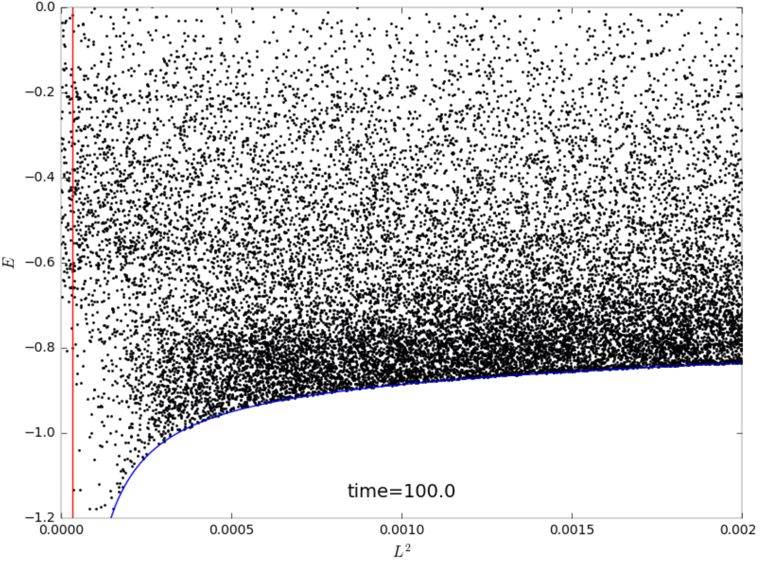
Angular momentum L of any star is not conserved, but experiences oscillations due to torques from non-spherical distribution of stars.

Many more stars can attain low L and enter the loss cone.





The gap is much less prominent in non-spherical systems



This is the reason that the "Final-parsec problem" does not exist [Vasiliev+ 2015, Gualandris+ 2016].

The Monte Carlo method for non-spherical systems

- Galactic nuclei have $N_\star \gg 10^6$ – not amenable to direct N-body simulations.
- Difficult or impossible to properly scale the simulations with affordable N in the presence of both collisional (N-dependent) and collisionless (N-independent) processes.
- Conventional Fokker–Planck or Monte Carlo methods restricted to spherical symmetry.

- Solution:

  use the Monte Carlo approach,
  but without orbit-averaging.

The Monte Carlo method for non-spherical systems

- **Gravitational potential:**

  spherical-harmonic expansion of an arbitrary density profile
  (similar to the self-consistent field method of Hernquist & Ostriker 1992).

- **Orbit integration:**

  adaptive-timestep, all particles move independently in the global potential.

- **Two-body relaxation:**

  local diffusion coefficients in velocity $\langle \Delta v_{\|}^2 \rangle, \langle \Delta v_{\perp}^2 \rangle (r, v)$ computed from the smooth distribution function $f(E)$ (spherical isotropic background), *with adjustable amplitude* (assigned independently of N);
  perturbations to velocity applied after each timestep.

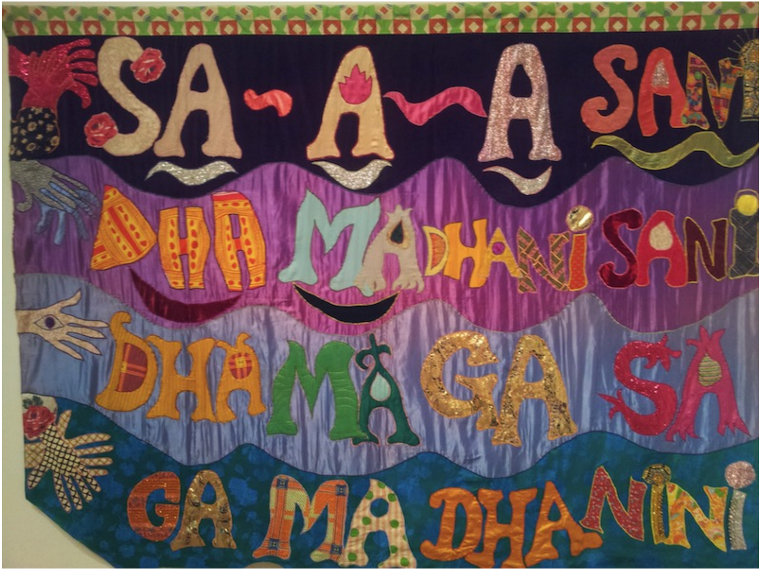
- **Massive black hole(s):**

  capture of stars with $r < r_{\rm t}$, three-body scattering by a massive BH binary.

- **Temporal smoothing:**

  potential and diffusion coefficients updated after an interval of time $\gg T_{\rm dyn}$, but $\ll T_{\rm rel} \implies$ reduced parasitic noise (+trajectory oversampling).

– relaxation in any geometry



[Moki Cherry, "Raga", 1970s]

Implementations of the Monte Carlo method

Name	Reference	relaxation treatment	timestep	1:1[1]	BH[2]	remarks
Princeton	Spitzer&Hart(1971), Spitzer&Thuan(1972)	local dif.coefs. in velocity, Maxwellian background $f(r, v)$	$\propto T_{dyn}$	−	−	
Cornell	Marchant&Shapiro (1980)	dif.coef. in E, L, self-consistent background $f(E)$	indiv., T_{dyn}	−	+	particle cloning
—	Hopman (2009)	same		−	+	stellar binaries
Hénon	Hénon(1971)	local pairwise interaction, self-consistent bkgr. $f(r, v_r, v_t)$	$\propto T_{rel}$	−	−	
—	Stodołkiewicz(1982) Stodołkiewicz(1986)	Hénon's	block, $T_{rel}(r)$	−	−	mass spectrum, disc shocks binaries, stellar evolution
Mocca	Giersz(1998)	same	same	+	−	3-body scattering (analyt.)
	Hypki&Giersz(2013)	same	same	+	−	single/binary stellar evol., few-body scattering (num.)
Cmc	Joshi+(2000)	same	$\propto T_{rel}(r=0)$	+	−	partially parallelized
	Umbreit+(2012), Pattabiraman+(2013)		(shared)	+	+	fewbody interaction, single/binary stellar evol., GPU
Me(ssy)[2]	Freitag&Benz(2002)	same	indiv.$\propto T_{rel}$	−	+	cloning, SPH physical collis.
—	Sollima&Mastrobuono-Battisti(2014)	same		−	−	realistic tidal field
Raga	Vasiliev(2015)	local dif.coef. in velocity, self-consistent background $f(E)$	indiv.$\propto T_{dyn}$	−	+	arbitrary geometry

[1] One-to-one correspondence between particles and stars in the system

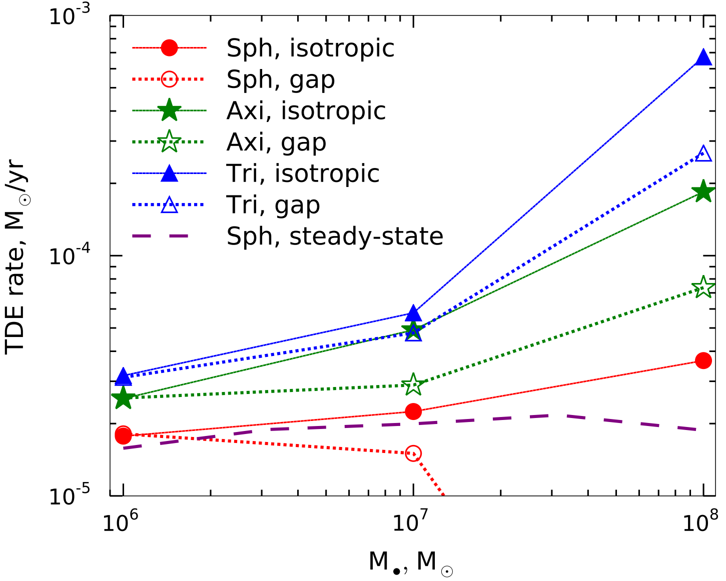
[2] Massive black hole in the center, loss-cone effects

Features of the रागा Monte Carlo code

- − Single-mass systems;
- − No binaries;
- − No stellar evolution;
- − No few-body interactions;
- + Central black hole(s);
- + Non-spherical systems;

vs.

Results: capture rates in post-merger galaxies



Summary

- Tidal disruptions probe the demographics of massive black holes.
- Galaxy mergers lead to non-spherical remnant shapes and a gap in the angular-momentum distribution of stars.
- The increase in tidal disruption rates due to non-spherical shape is more important than the suppression due to the gap.
- The rates are higher than simple spherical steady-state estimates by a factor $2 \div 10$.
- Discrepancy with observationally inferred rates still exists!

References:

E.Vasiliev, CQG, 31, 244002, 2014.
K.Lezhnin & E.Vasiliev, ApJL, 808, 5, 2015.
K.Lezhnin & E.Vasiliev, ApJ, 831, 84, 2016.

The Raga code is available at `http://td.lpi.ru/~eugvas/raga`