Elevated Tidal Disruption Rates in Post-Starburst Galaxies

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MODEST-18 6/29/18

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A View to a Kill

Face-On

Face-On

Edge-On

Edge-On

$M_{BH}=10^6M_\odot$, $a_{BH}=0.9$, $i=90^\circ$

$N_{SPH}=100000$

(PN-SPH)

(Hayasaki, NCS & Loeb 16)
Tidal Disruption Events

- **Empirically:**
  - Rare multiwavelength (radio -> hard X-ray) transients
  - Dozens of strong candidate flares (most optical/X-ray)

- **Applications:**
  - Tools to measure SMBH demography (mass, maybe spin)
  - Super-Eddington accretion laboratories
  - Probes of jet launching physics
  - Rates encode stellar dynamical processes

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Figure 3

Spectral energy distribution. Spectral energy distribution of PS1-10jh during nearly simultaneous GALEX ultraviolet and PS1 optical observations (with the host galaxy flux removed) at two epochs, with 1σ error bars and labeled by their time in rest-frame days from the peak of the flare. Flux densities have been corrected for Galactic extinction of E(B−V) = 0.013 mag. The ultraviolet and optical SED from −19 to 247 d is fitted with a 3 × 10^4 K blackbody. Orange solid lines show blackbodies with this temperature scaled to the NUV flux density. Open symbols show the GALEX and PS1 flux densities corrected for an internal extinction of E(B−V) = 0.08 mag, and dotted blue line shows the 5.5 × 10^4 K blackbody fit to the de-reddened flux densities. The upper limit from the Chandra DDT observation on 2011 May 22.96 UT assuming a Γ = 2 spectrum typical of an AGN is plotted with a thick black line. The X-ray flux expected from an AGN with a comparable NUV flux is plotted for comparison with a thick grey line. Also shown are the u, g, and r band flux densities measured from aperture photometry with the Liverpool Telescope on 2011 Sep 24 UT, after subtracting the host galaxy flux measured by SDSS. Note that the observed continuum temperature, and even the maximum temperature allowed by possible de-reddening, are considerably cooler than the temperature of ≈ 2.5 × 10^5 (MBH/10^6 M⊙)^{1/12}r^{-1/2} ⋆ m^{-1/6} ⋆ K expected from material radiating at the Eddington limit at the tidal radius 4. This discrepancy is also seen in AGN and may imply that the continuum we see is due to reprocessing of some kind.

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements

We thank H. Tananbaum for approving our Chandra DDT request, and the entire

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Figure 2

Ultraviolet and optical light curve. The GALEX NUV and PS1 gP1, rP1, iP1, and zP1 band light curve of PS1-10jh (with the host galaxy flux removed) with 1σ error bars and in logarithmic days since the time of disruption determined from the best fit of the rP1-band light curve to the numerical model 20 for the mass accretion rate of a tidally disrupted star with a polytropic exponent of 5/3 (shown with solid lines scaled to the flux in the GALEX and PS1 bands). The GALEX and PS1 photometry at t > 240 rest-frame days since the peak is shown binned in time in order to increase the signal-to-noise. The dates of multiple epochs of MMT spectroscopy are marked with an S, and the date of the Chandra X-ray observation is marked with an X. Grey line shows an n = 5/3 power-law decay from the peak. Arrows show 3σ upper limits.
TDE Rates

- TDE rates set by passage of stars into **loss cone**

- Loss cone easily described in terms of angular momentum space
  - Full vs empty loss cone?
  - Relaxation (two-body) refills loss cone, sets TDE rate

- **Rate discrepancy?**
  - $\Gamma_{\text{theory}} \approx 2-10 \times 10^{-4}/\text{gal/yr} \gg \Gamma_{\text{obs}} \approx 1 \times 10^{-5}/\text{gal/yr}$ (NCS & Metzger 16)
  - Theoretical estimates ~conservative, few dynamical solutions (Lezhnin & Vasiliev 16)
  - Resolution probably luminosity function (van Velzen 18)

(Freitag & Benz 02)
The Post-Starburst Preference

Fig. 1.—Spectra of the eight optical/UV TDE host galaxies, in order of increasing strength of their Hδ A index. Also shown is the lower-resolution host galaxy spectrum of the high energy TDE Swift J1644. Strong Balmer absorption, Ca II H+Hϵ absorption, and a lack of strong emission lines are characteristic of post-starburst galaxies. Both SDSS J0748 and Swift J1644 were selected differently from the rest of the sample, although the optical spectrum of the TDE itself in SDSS J0748 appears similar to the other optical/UV TDEs.

Two of the optical/UV TDE host galaxies (PTF09djl and PS1−10jh) lie in the SDSS footprint, and have absolute magnitudes comparable to the other six host galaxies, but are too faint for the SDSS spectroscopic sample due to their slightly higher redshifts (z = 0.1696, 0.184). No significant galaxy evolution from z ∼ 0.2 to 0.01 is observed.
Unusual Host Galaxy Preferences

• Many TDEs in **rare post-starburst/E+A galaxies** (Arcavi+14, French+16, 17, Law-Smith+17, Graur+17)

• Dynamical explanations:
  - **Binary SMBHs**; chaotic 3-body scatterings (Arcavi+14)
  - **Central overdensities**; short relaxation times (NCS & Metzger 16)
  - **Radial anisotropies**: low angular momentum systems (NCS+17)
  - **Nuclear triaxiality**: collisionless effects (Merritt & Poon 04)
  - **Eccentric nuclear disks**: secular instabilities (Madigan 17)

• Useful discriminant: delay time distributions (NCS+17)
Radial Orbit Anisotropies?

• Simple possibility: anisotropic velocities with radial bias
• Consider constant anisotropy $\beta = 1 - T_\perp / 2 T_r$
  * $\beta < \beta_{ROI} \sim 0.6$ to avoid radial orbit instability
• Solve 1D Fokker-Planck equation in angular momentum space:

$$\frac{\partial f}{\partial \tau} = \frac{1}{4j} \frac{\partial}{\partial j} \left( j \frac{\partial f}{\partial j} \right)$$

• TDE rate $\Gamma \propto t^{-\beta}$ in an isotropizing cusp
Anisotropic Delay Time Distributions

\[ \beta_0 = 0.6 \]

\[ \beta_0 = 0.4 \]

\[ \beta_0 = 0.2 \]

\[ 10^6 \]

\[ 10^7 \]

\[ 10^8 \]

\[ 10^9 \]

\[ 10^{10} \]

\( t \) [yr]

Rate Enhancement

Tadhunter+17 ?? \( \beta_0 = 0.6 \)

French+17

(NCS+17)
Stellar Overdensities?

- Suggestive evidence: color gradients in E+As (Pracy+13, Law-Smith+17)
- Overdense nuclei - $\rho(r) = \rho_{\text{infl}}(r/r_{\text{infl}})^{-\gamma}$ - can have short two-body relaxation times if overconcentrated or ultrasteep
- Overconcentrated ($r_{\text{infl}}$ low):
  - High, slowly evolving TDE rate
- Ultrasteep ($\gamma$ large):
  - If $\gamma > 7/4$, profile flattens with time (Bahcall & Wolf 76)
  - If $\gamma > 9/4$, TDE rate diverges inward
  - TDE rate $\Gamma \propto t^{-(4\gamma-9)/(2\gamma-3)} / \ln(t)$
Overdense Delay Time Distributions

\( \gamma = 1.75 \)
\( \gamma = 2.25 \)
\( \gamma = 2.50 \)
\( \gamma = 2.75 \)

10^6
10^7
10^8
10^9
10^{10}

Rate Enhancement

\( t \) [yr]

French+17

Tadhunter+17

(NCS+17)
Host Masses

- Host mass distribution uncertain, but useful secondary test
- Observed TDE mass function bottom-heavy
  - In agreement with overdensity scenario
  - In serious tension with radial anisotropies
- Caveat - masses estimated indirectly
NGC 3156: Modeling

- Optimal target: 22 Mpc, $M_{BH} = 3 \times 10^6 M_\odot$

- We fit an I(R) model to archival HST observations
  - NGC 3156 major outlier in central profile: $I(R) \propto R^{-1.3} \rightarrow \rho(r) \propto r^{-2.3}$

- TDE rate $\Gamma \sim 1 \times 10^{-3}$/yr!
  - Currently testing with recent HST observations
Conclusions

• Two-body relaxation sets floor on per-galaxy TDE rate $\Gamma_{\text{theory}} \sim 10^{-4}/\text{gal/yr}$
  ✦ Discrepant with old $\Gamma_{\text{obs}} \sim 10^{-5}/\text{gal/yr}$; discrepancy may be resolved by broad TDE luminosity function

• Several dynamical explanations for the post-starburst preference
  ✦ Radial anisotropies promising for rates, temporal evolution, disfavored by mass function
  ✦ SMBH binaries generally disfavored
  ✦ Overdensity hypothesis most promising, but requires extreme parameter choices

• Delay time distributions powerful future tool - model selection and parameter extraction
The Wages of Spin

(Hayasaki, NCS & Loeb 16)
Observed TDEs

- First TDE candidates found with ROSAT (e.g. Komossa & Bade 99)
  - Later, XMM-Newton, Chandra
- Emission generally consistent with simple theory
  - Light curve follows $t^{-5/3}$
  - Thermal soft X-ray SED consistent with compact accretion disk
- Optical/UV TDEs first found in SDSS (van Velzen+11) and Pan-STARRS (Gezari+12)
  - Also PTF, ASASSN
- Thermal blackbody emission $>10^2 \times$ brighter than naive predictions

Figure 3
Spectral energy distribution. Spectral energy distribution of PS1-10jh during nearly simultaneous GALEX ultraviolet and PS1 optical observations (with the host galaxy flux removed) at two epochs, with $1\sigma$ error bars and labeled by their time in rest-frame days from the peak of the flare. Flux densities have been corrected for Galactic extinction of $E(B-V)=0.013$ mag. The ultraviolet and optical SED from $-19$ to $247$ days is fitted with a $3 \times 10^4 K$ blackbody. Orange solid lines show blackbodies with this temperature scaled to the NUV flux density. Open symbols show the GALEX and PS1 flux densities corrected for an internal extinction of $E(B-V)=0.08$ mag, and dotted blue line shows the $5.5 \times 10^4 K$ blackbody fit to the de-reddened flux densities. The upper limit from the Chandra DDT observation on 2011 May 22.96 UT assuming a $\Gamma=2$ spectrum typical of an AGN is plotted with a thick black line. The X-ray flux expected from an AGN with a comparable NUV flux is plotted for comparison with a thick grey line. Also shown are the u, g, and r band flux densities measured from aperture photometry with the Liverpool Telescope on 2011 Sep 24 UT, after subtracting the host galaxy flux measured by SDSS. Note that the observed continuum temperature, and even the maximum temperature allowed by possible de-reddening, are considerably cooler than the temperature of $\approx 2.5 \times 10^5 (\frac{M_{BH}}{10^6 M_\odot})^{1/12} \times \frac{1}{r^{-1/2}} K$ expected from material radiating at the Eddington limit at the tidal radius. This discrepancy is also seen in AGN and may imply that the continuum we see is due to reprocessing of some kind.
Realistic TDE Rates

• Theoretical rates calculated semi-empirically (Magorrian & Tremaine 99, Wang & Merritt 04, NCS & Metzger 16):
  ✦ Take sample of nearby galaxies
  ✦ Deproject I(R) -> \( \rho(r) \)  
    \[\text{[assumes sphericity]}\]
  ✦ Invert \( \rho(r) \) -> \( f(\epsilon) \)  
    \[\text{[assumes isotropy]}\]
  ✦ Compute diffusion coefficients \( <\Delta J^2(\epsilon)> \), loss cone flux \( \mathcal{A}(\epsilon) \)  
    \[\text{[assumes IMF]}\]

• Low mass galaxies dominate event rate
  ✦ \( \Gamma_{\text{theory}} \sim 2-10 \times 10^{-4}/\text{gal/yr} \)

(Lauer+05)
The Rate Discrepancy

- $\Gamma_{\text{obs}} \sim 1 \times 10^{-5}/\text{gal/yr} \ll \Gamma_{\text{theory}} \sim 2-10 \times 10^{-4}/\text{gal/yr}$
- Rate estimates **conservative**
  - See also Lezhnin & Vasiliev 16
- Explanations of discrepancy:
  1. Dynamical?
  2. Selection effects?
  3. TDE luminosity function

(NCS & Metzger 16)
Rate Discrepancy Resolved?

![Graph showing the volumetric rate of TDFs host galaxies compared to the galaxy mass function.](van Velzen 17)
Birth of a Bahcall-Wolf Cusp

\[ \rho \propto r^{-2.75} \]

\[ \rho \propto r^{-1.75} \]
and $q$ is the short-to-long axis ratio of the stellar figure [61]. A substantial fraction of stars with $\ell < \ell_{lc}$, and with instantaneous angular momenta less than $\sim \epsilon_{1/2}$ will pass eventually within $r_{lc}$. If the population of low-$\ell$ orbits is not too different from the population in an isotropic, spherical galaxy having the same radial mass distribution, the fraction of stars at any $E$ that are destined to pass within $r_{lc}$ is

$$\sim \int_{\ell=0}^{\ell_{lc}} d\ell \int \sqrt{\epsilon_{0}} d\ell \approx \sqrt{\epsilon \ell_{lc}} \ (41)$$

compared with the smaller fraction $\sim \ell_{lc}^2$ in a spherical galaxy. The timescale over which these orbits are drained is the longer of the radial period and the period, $t_{prec}$, associated with precession through a full cycle in $\ell$ or $\cos i$; the latter time is roughly $\sim \epsilon^{-1/2}$ times the "mass precession time" $t_M \approx P_M \cdot /M$, i.e. the time for apsidal precession of an orbit due to the (spherically) distributed mass. Near the influence radius, $M \approx M \cdot$, and in a nucleus of moderate flattening, $\epsilon^{-1/2} t_M$ will be of order or somewhat longer than $P(r_h)$. While longer than the time required for loss-cone draining in spherical galaxies, this time is still short enough that the saucer orbits within $\sim r_h$ would probably be drained soon after the SBH is in place.

Figure 7. Two important types of orbit that exist near SBHs in axisymmetric or triaxial nuclei. Left: saucer orbit; right: pyramid orbit. Each figure shows the surface of the three-dimensional volume filled by the orbit; the SBH is at the origin and the short ($z$) axis of the nucleus is indicated by the vertical line. Saucer orbits are present both in axisymmetric and triaxial nuclei; their excursions in $L$ are limited to $L \geq L_{min}$, where $L_{min}=L_z$ in the axisymmetric case. Pyramid orbits exist only in the triaxial geometry; they reach zero angular momentum at the corners of the pyramid. Both types of orbit have counterparts obtained by reflection about a symmetry plane of the potential.

Saucer-like orbits exist also in triaxial nuclei [53], but much of the phase space in triaxial potentials is occupied by an additional family of orbits: the pyramid orbits [38],

Pyramid Orbit: $J \geq 0$

Triaxial Potential

Axisymmetric Potential

Saucer Orbit: $J \geq J_z$

Pyramid Orbit: $J \geq 0$
Eccentric Stellar Disks?

Figure 1: Physics of orbital oscillations within a stable eccentric disk. The entire disk (black) precesses in the prograde direction (counter-clockwise in this figure). If an orbit (red) moves ahead of the disk (left panel), it feels a gravitational pull towards the bulk of the disk. This torques the orbit, decreasing its angular momentum and thus increasing its orbital eccentricity ($e^2/(1-e^2)$). This lowers the orbit's precession rate, allowing the bulk of the disk to catch up with it. The reverse happens for an orbit which lags behind the bulk of the disk (right panel). The overall effect is to stabilize the disk: any orbit which is perturbed off the disk is driven back toward it by torques and differential precession. The mechanism inducing this stability leads to oscillations in eccentricity.

The stability of a disk depends entirely on direction of its $e$-vector precession. In Madigan, Levin & Hopman (2009), we focused on the case in which an eccentric stellar disk is embedded in a more massive symmetric nuclear star cluster (such as in the Milky Way Galactic center; Feldmeier et al., 2014). This additional gravitational potential leads to retrograde precession ($e_0 \cdot v_p < 0$ where $v_p$ is the velocity at periapsis). Retrograde precession, combined with mutual gravitational torques, results in an 'eccentric disk instability' which propels the orbits apart. Here we focus on the case in which the mass of the asymmetric eccentric disk is much greater than the background stellar potential (as is true for the M31 nucleus; Kormendy & Bender, 1999), such that the direction of precession for the bulk of the disk is reversed. Prograde precession ($e_0 \cdot v_p > 0$) leads instead to stability: orbits which precess ahead of the disk feel a gravitational pull toward the disk behind it. We show this in the left panel of figure 1. This gravitational force creates a torque $\tau_z < 0$ (see equation 1a) which decreases the angular momentum of the orbit. Specific angular momentum and energy are defined as $j^2 = GM \cdot a (1-e^2)$ (2a) and $E = GM \cdot 2a$ (2b). The torque does not affect the energy, or equivalently the semi-major axis, of the orbit. Hence the torque raises the orbital eccentricity of the orbit. Increasing the eccentricity slows its angular precession rate ($/f \cdot j/e$), stalling the orbit until it is reabsorbed by the mean body of the disk. A similar analysis shows that orbits which lag behind the disk decrease in eccentricity, precess more rapidly and are driven back towards the bulk of the disk (right panel of figure 1). This stability mechanism implies both that a coherent precessing eccentric disk maintains its shape in response to perturbations, and that perturbed orbits undergo oscillations in eccentricity and in orientation about the mean body of the disk. A similar analysis shows that sufficiently massive eccentric disks are stable to perturbations in inclination resulting from out-of-plane forces. Strongly perturbed and/or extremely eccentric orbits can flip their orientation however; see §3.4.
SMBH Binaries?

Fig. 1.— Grey scale images showing the full 100×100 MUSE field centered on PGC 043234 (RA=12:48:15.24, DEC=+17:46:26.5), the host galaxy of the nearby TDE ASASSN-14li. The left panel shows an image of the continuum emission at 5100 Å, just to the blue of the strong [O III] 5007 nebular line at the redshift of PGC 043234. The right panel shows an image at 5110 Å which includes [O III] 5007 nebular line emission at the redshift of PGC 043234, that clearly reveals the presence of extended [O III] 5007 emission. The extended source to the west of PGC 043234 is a background edge-on galaxy at z=0.15 (RA=12:48:14.18, DEC=+17:46:28.0) and the point source to the south of PGC 043234 is a foreground Galactic star (RA=12:48:15.21, DEC=+17:46:16.06).
SMBH Binaries

- Nascent SMBH binaries see increase in TDE rate:
  - Kozai effect (Ivanov+05)
  - Chaotic 3-body scatterings (Chen+11, Wegg & Bode 11)
- Enhancement huge ($\Gamma \sim 10^{-1}/yr$) but short-lived ($<10^6$ yr)
  - Occurs before final parsec problem
  - Unique lightcurves? (Coughlin talk)
- Possibly disfavored by:
  - Total rate fraction $\sim$3-25% (Wegg & Bode 11)
  - Fine-tuned timescales
  - Mass distribution

(Wegg & Bode 11)
SMBHB TDE Rates

\[ z = 1, z = 0.1 \]

\[ 1 \times 10^5, 5 \times 10^5, 1 \times 10^6, 5 \times 10^6, 1 \times 10^7, 5 \times 10^7, 1 \times 10^8 \]

\[ 1 \times 10^{-8}, 1 \times 10^{-7}, 1 \times 10^{-6}, 1 \times 10^{-5}, 1 \times 10^{-4} \]

\[ \dot{N}_{\text{TDE}} \, [\text{yr}^{-1}] \]

\[ M_\ast \, [M_\odot] \]

(NCS+17)
The particular choice of $M - \log L$ (resolved) sample used by McConnell & Ma (2013) relation by Kormendy & Ho (2009) for our sample is that several host galaxies harbour black which the relation was originally derived (see also Figure 4.2.3 Choice of $M - \log L$ for our sample. Therefore we compare these values with those obtained with the re-

Another issue that arises from using the $M - \log L$ relation at the low mass end. For example, Ferrarese & Ford (2005, 2013) versions published in the literature (\cite{Ferrarese2005, Ferrarese2013}). Each of these works has its particular sample se-

We note that the latter relation was explicitly derived for elliptical galaxies and is most likely not appropriate for our sample. We remark that our galaxies are not ellipticals and therefore it is unlikely that this relation is appropriate for the latter relation, we remark that our galaxies are not ellipticals

The solid line represents the best-fitting relation (Eq. 3) to illustrate the e

For example,\cite{Ferrarese2005, Ferrarese2013}; red triangles represent the TDE host black hole masses and various versions of SMBH masses in optical TDE hosts peaked just below 10

Recent theoretical work has used the observed sample of TDE candidates to analyze flare demographics (\cite{McConnell2013, McConnell2016}); who included only galax-

In Figure 6. The BH/bulge mass estimates used for these systems are needed to resolve this issue for less than 10

We have overplotted (dotted line) and \cite{Kormendy2005, Kormendy2004} relation, valid for early-type galaxies. Regarding the relation should show an increased scatter, possibly com-

It is subject to large uncertainties. Here we present a new and therefore the $M - \log L$ relation to lower masses. These authors did not find ev-

\cite{McConnell2013, McConnell2016} found that the relation derived for quiescent massive mass galaxies (\cite{Ferrarese2005, Ferrarese2013}); while the dashed line represents the

\cite{Barth2004} measure black hole masses combined with a flattening at low mass galaxies (\cite{Ferrarese2005, Ferrarese2013}); to illustrate the e

However, there is at present there is at present no conclusive evidence that corroborates these predictions. A black hole mass distribution for TDE host

Distribution of the observed black hole masses in our BH masses of optically/UV selected TDEs

Our mass distribution, presented in Figure 6. Observed TDE Hosts

\cite{Stone2016}. This is in contrast to fig. 12 of Metzger & Stone (2015). This is in contrast to fig. 12 of Metzger & Stone (2015). This is in contrast to fig. 12 of Metzger & Stone (2015). This is in contrast to fig. 12 of Metzger & Stone (2015). This is in contrast to fig. 12 of Metzger & Stone (2015). This is in contrast to fig. 12 of Metzger & Stone (2015). This is in contrast to fig. 12 of Metzger & Stone (2015). This is in contrast to fig. 12 of Metzger & Stone (2015). This is in contrast to fig. 12 of Metzger & Stone (2015). This is in contrast to fig. 12 of Metzger & Stone (2015).
General Relativistic Hills Masses

- Hills Mass: maximum SMBH mass that can produce a TDE
  - $R_t \approx R_\star (M_{BH}/M_\star)^{1/3}$, while $R_g = GM_{BH}/c^2$
  - Above $M_{Hill} \approx 9 \times 10^7 M_\odot$, TDEs impossible...
  - ...in Schwarzschild metric
- Quantifiable in exact GR with Fermi Normal Coordinates (Marck 83, Beloborodov+92)
  - Eigenvalues of $C_{ij}$ determine disruption
- $M_{Hill}$ increases a factor of $\sim 8$ as SMBH spin $a \to 1$ (Kesden 12)
  - Smaller IBSO (parabolic+inclined ISCO)
  - Stronger tidal tensor

(Kesden 12)
Angle of Approach

\(a = 0.00\)

\(a = 0.5\)

\(a = 0.9\)

\(a = 0.99\)

\(a = 0.9999\)

\(I_{10^8}\)

\(I_{10^9}\)

\(M_H [M_\odot]\)

(NCS & van Velzen in prep)
TDEs as Integrated Spin Constraints

(NCS & van Velzen in prep)
Does Metallicity Matter?

(NCS & van Velzen in prep)

$Z = 0.030 \, Z_\odot$

$Z = 0.075 \, Z_\odot$

$Z = 0.30 \, Z_\odot$

$Z = 0.60 \, Z_\odot$

$Z = 1.4 \, Z_\odot$

$Z = 2.2 \, Z_\odot$

$M_\odot = 1 \times 10^7$ to $2 \times 10^8$

$M_\text{H}(a=0) [M_\odot]$ vs. $M_\odot [M_\odot]$
Sometimes not...

(NCS & van Velzen in prep)
...and Sometimes Yes

(NCS & van Velzen in prep)
X-ray TDEs

- First TDE candidates found with ROSAT (e.g. Komossa & Bade 99)
  - Later, XMM-Newton, Chandra
- Emission generally consistent with simple theory
  - Light curve follows $t^{-5/3}$
  - Thermal soft X-ray SED consistent with compact accretion disk
- Cadence usually poor
- Surprises in nonthermal hard X-rays
  - Three jetted TDEs found by Swift
  - Occasional hard power-law in thermal TDEs
Stellar Dynamics and Tidal Disruption Event Rates

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Photo credit: Jean-Pierre Luminet