Tidal disruption events (TDEs): properties & models

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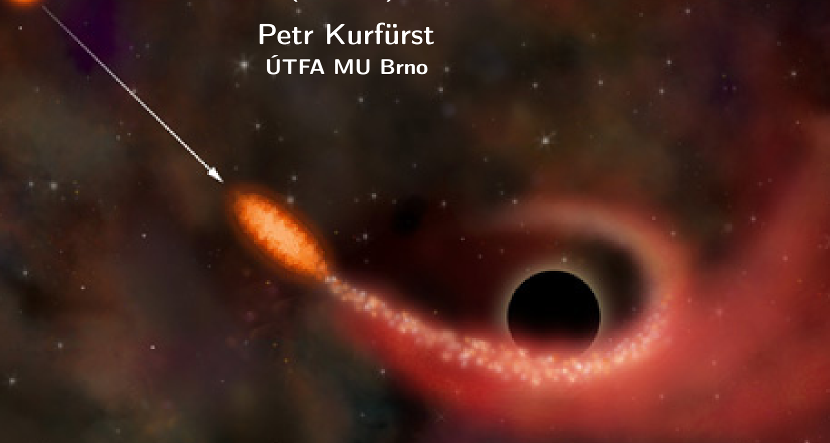
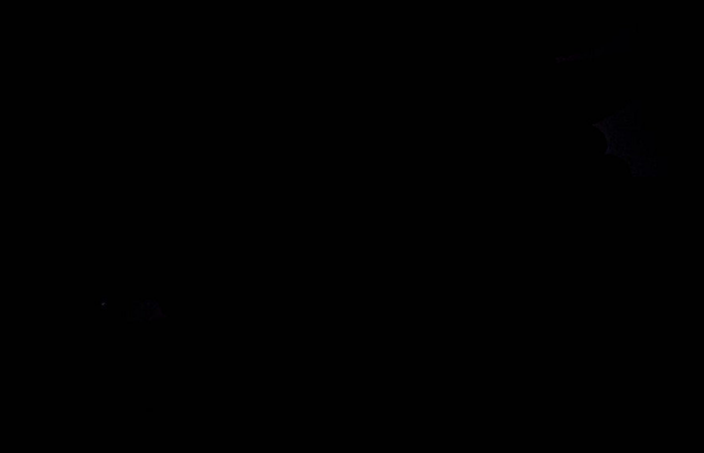


Astronomical transients

Selected chapters from astrophysics, fall semester, 2022

TDE phenomenon

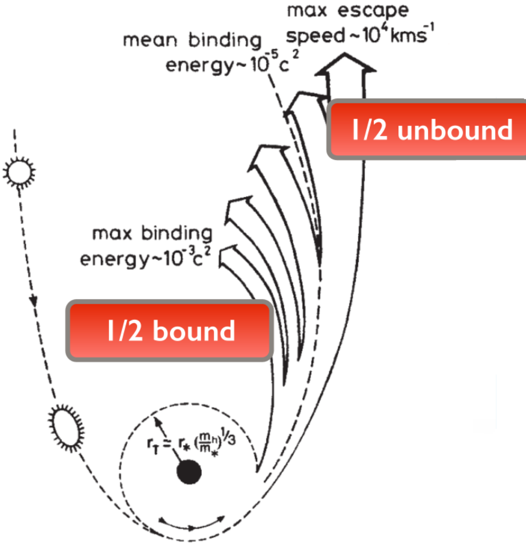
cf. T. Piran's &
E. M. Rossi's talk on 35HUJI



Credit: Stephan Rosswog 2006

TDE phenomenon

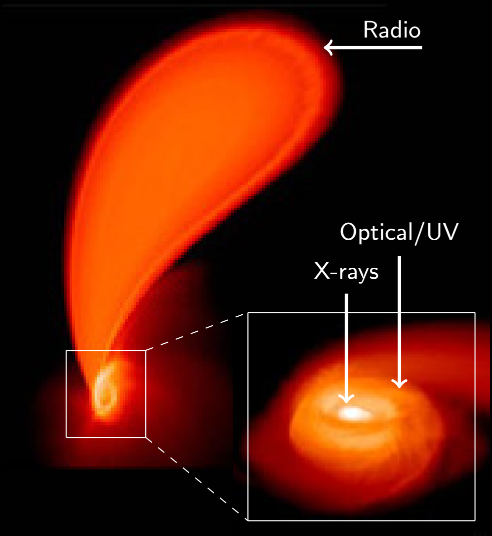
- Tidal disruption occurs when the tidal gravitational field has comparable magnitude to the self-gravity of the star, occurring at a radius given by
$$R_t \approx R_\star \left(\frac{M_{BH}}{M_\star}\right)^{1/3}$$
- Gas particles are then ejected on nearly ballistic orbits
- Disrupted stars are typically on approximately parabolic orbits
- Half of the material is bound while the other half forms an unbound collimated stream



Credit: Martin Rees 1988

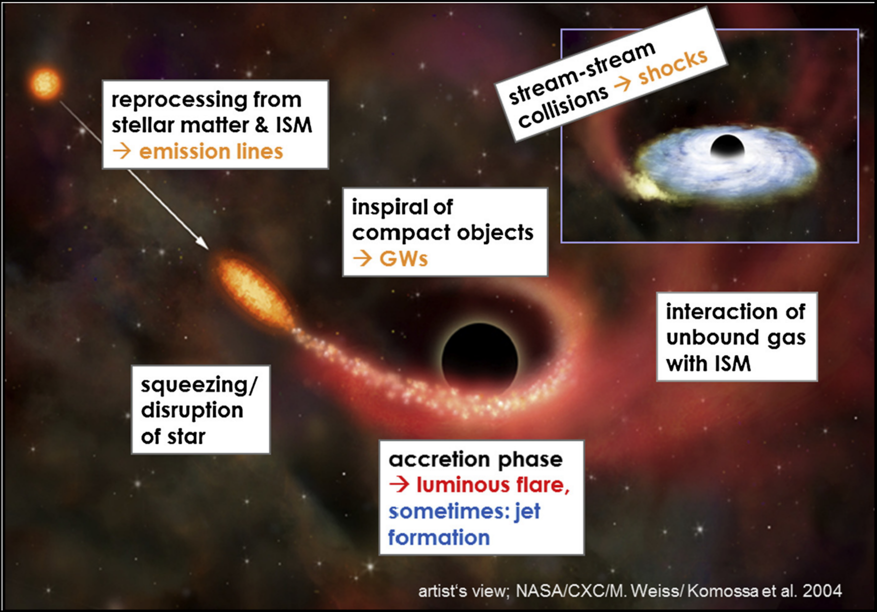
TDE phenomenon

- Radio → interaction zone of debris with CSM → very similar to GRB afterglows (see previous lecture)
- Differences → not relativistic & very far from spherical → the role of shock waves basically similar
- Optical/UV comes from the central blob of matter → from the distance $\sim 10^{15}$ cm out of the center; from the region where the two streams interact
- The X-rays come from the very tiny region of the accretion process around the center



Credit: Rosswog+ 2009

TDE phenomenon



TDE process

- Tidal radius:

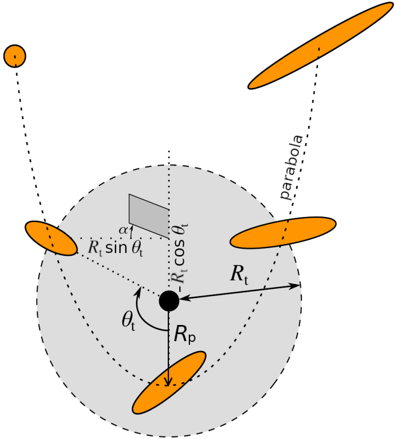
$$R_\mathrm{t} \sim R_\star \left(\frac{M_\mathrm{BH}}{M_\star}\right)^{1/3} \approx 30 \text{ (will derive later)}$$

- Energy E_t necessary to bring the star to R_t from "infinity":

$$E_\mathrm{t} \approx \frac{G M_\mathrm{BH} M_\star}{R_\star} \sim \frac{M_\star c^2}{R_\mathrm{t}/R_\mathrm{schw}} \approx 10^{52}\,\mathrm{ergs}$$

- Hydrodynamic timescale τ_h to disrupt the star:

$$\tau_\mathrm{h} \sim \left(\frac{G M_\star}{R_\star^3}\right)^{-1/2} \approx 10^3\text{ - }10^4\,\mathrm{s}$$



Credit: Bonnerot+ 2017

- The specific energy ΔE necessary to disrupt the star:

$$\Delta E \sim \pm \frac{G M_\mathrm{BH}}{R_\mathrm{t}^2} R_\star \text{ (will derive later)} \sim 10^{20}\,\mathrm{erg} \sim \frac{v_\infty^2}{2} \Rightarrow v_\infty \sim 10^4\,\mathrm{km\,s^{-1}}$$

Dynamics & rates → TDEs

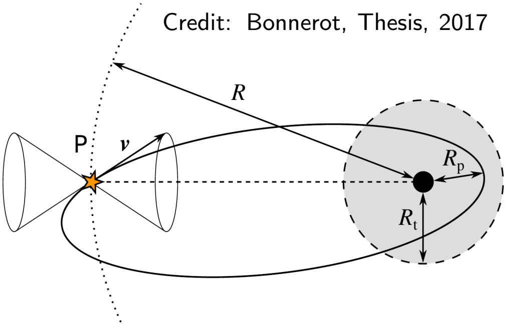
cf. Re'em Sari's talk on 35HUJI

- Dynamic processes near a galactic center leading to TDEs
- Rates: Loss cone ⇒ full/empty
- Relaxation timescale → 2-body (resonance relaxation)
- Evaluating the ratio $\frac{\mathcal{R}_{\mathrm{TDE}}}{\mathcal{R}_{\mathrm{EMRI}}}$ (Extreme-Mass-Ratio-Inspiral: stars orbiting around BH emitting GWs → get closer to the BH via slowly inspiralling on ∼circular orbits)
- Distribution of stars around BH: Bahcall-Wolf (BW) cusp → $\rho \sim r^{-7/4}$ → may affect the loss cone rates
- Galactic central BH mass: $M_{\mathrm{BH}} = 4 \times 10^6\, M_\odot \Rightarrow R_{\mathrm{schw}} = \frac{2GM_{\mathrm{BH}}}{c^2} \approx 0.1\,\mathrm{AU}$
- Radius of influence R_{inf}: radius of a sphere where the mass of stars equals the $M_{\mathrm{BH}} \Rightarrow M_{\mathrm{tot}}(r < R_{\mathrm{inf}}) = 2M_{\mathrm{BH}}$; $R_{\mathrm{inf}} \sim 2\,\mathrm{pc}$ in our galaxy $\Rightarrow \frac{R_{\mathrm{inf}}}{R_{\mathrm{schw}}} \approx 4 \times 10^6$

Loss cone: full/empty

Credit: Bonnerot, Thesis, 2017

- We now ignore the fact that stars have different masses $\Rightarrow$ $\langle M_\star \rangle \cong 1\, M_\odot \rightarrow$ # of stars within the $R_{\rm inf} \cong 4 \times 10^6$
- Circular Keplerian orbital period P at $R_{\rm inf} \approx 10^5$ yrs



- Tidal (residual) differential acceleration exerted by BH on a star with mass $M_\star = M_\odot$ and radius $R_\star = R_\odot$, at a distance $r \gg R_\star$:

$$a_t = \frac{GM_{\rm BH}}{r^2} - \frac{GM_{\rm BH}}{(r+R_\star)^2} \approx \frac{2GM_{\rm BH}R_\star}{r^3}$$

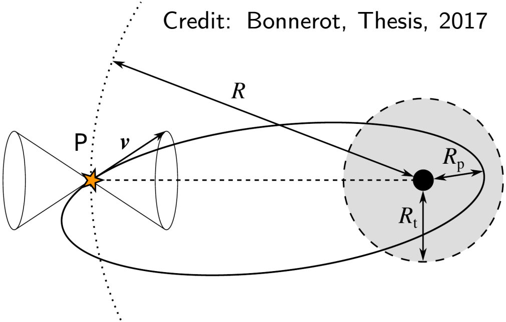
- We expect that if $a_t \geq g_\star$, the star will be tidally disrupted: we define the tidal radius $r = R_t$ where $a_t = g_\star \equiv GM_\star/R_\star^2$,

$$R_t \approx R_\star \left(\frac{2M_{\rm BH}}{M_\star}\right)^{1/3} \approx 1\,{\rm AU} \Rightarrow \frac{R_t}{R_{\rm schw}} \approx 10 \quad \text{(in our galaxy)}$$

Loss cone: full/empty

Credit: Bonnerot, Thesis, 2017

- Let's assume all 4×10^6 stars concentrated in or at $R_{\rm inf}$ with isotropic distribution of velocity v : how many stars will have the pericenter distance $R_{\rm p}$ of their elliptical orbits below $R_{\rm t}$?



- Conservation of angular momentum: $j = V_{\rm orb} R_{\rm inf} = \sqrt{GM_{\rm BH} R_{\rm inf}}$ for a star orbiting at $R_{\rm inf}$ with the Keplerian orbital velocity, per unit mass

- Angular momentum on an Keplerian orbit scales as $\sim \sqrt{r} \Rightarrow$ only stars in the point P with j lower by $\sqrt{R_{\rm t}/R_{\rm inf}}$ compared to $j_{\rm circ}$ can get below $R_{\rm t} \Rightarrow$ only a fraction of orbits $f_{\rm orb}\left(j < \sqrt{\frac{R_{\rm t}}{R_{\rm inf}}}\, j_{\rm circ}\right) = \frac{R_{\rm t}}{R_{\rm inf}}$ (2D cone section!)

- The latter ratio $= (4 \times 10^{-5})^{-1} \Rightarrow$ from the # of isotropically moving stars in the point P, only 10 may have sufficiently small j

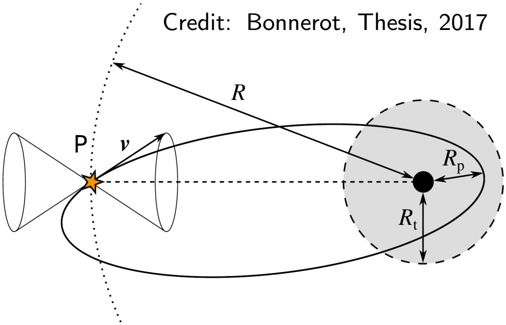
Loss cone: full/empty

- This means: every 10^5 years ($P_{\rm orb}$ on $R_{\rm inf}$), we will have 10 TDEs $\Rightarrow$ **full loss cone**:

$$\mathcal{R}_{\rm TDE} = \frac{N_\star \frac{R_{\rm t}}{R_{\rm inf}}}{P} = \frac{M_{\rm BH}}{M_\star} \frac{R_{\rm t}}{R_{\rm inf}} \frac{1}{P}$$

- $\mathcal{R}_{\rm TDE} \sim 10/P \rightarrow$ but: only in case of **no interactions** between orbits!

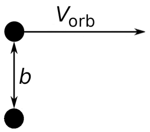
Credit: Bonnerot, Thesis, 2017



- After some time will all stars within this cone in velocity space be tidally destroyed: we obtain the **empty loss cone** $\Rightarrow \mathcal{R}_{\rm TDE} = 0$

- **Next step**: how quickly the stars scatter each other to refill the loss cone that the BH evacuated?

Loss cone: full/empty



- 2 stars moving absolutely randomly at or near $R_{\rm inf}$: one passes the other with velocity $v_{\rm orb}$, with an impact parameter b; the change in j is given by mutual gravity times the timescale of the interaction $b/v_{\rm orb}$, times $R_{\rm inf}$:

$$\Delta j = \boxed{\frac{GM_\star}{b^2}\frac{b}{v_{\rm orb}}} R_{\rm inf} = \frac{GM_\star}{b\,v_{\rm orb}} R_{\rm inf}$$

$gt = v$

- What is the **rate** of interactions at a distance b? A cylinder with a volume $V = 1/\rho \to$ a cross-section $S = \pi b^2$ and a length Δx:

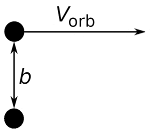
$$\frac{1}{t} = \frac{\rho S \Delta x}{t} \approx \pi b^2 \frac{N_\star}{R_{\rm inf}^3} v_{\rm orb} = \pi b^2 \frac{M_{\rm BH}}{M_\star}\frac{1}{R_{\rm inf}^3} v_{\rm orb}$$

- What will be the value of $b \to$ to deflect an orbit by 90°? Change in the "red" velocity gt will be $v_{\rm orb}$ (in case of 180° deflection $\to 2v_{\rm orb}$ - see the 5th lecture):

$$b_{\rm min}\!: \ \frac{GM_\star}{b\,v_{\rm orb}} = v_{\rm orb} \Rightarrow b_{\rm min} = \frac{GM_\star}{v_{\rm orb}^2} \equiv \frac{M_\star}{M_{\rm BH}} R_{\rm inf}$$

- So, over the timescale for which these interactions occur, the velocity distribution will be completely reconfigured $\to$ "isotropised"

Loss cone: full/empty



- What will be the **timescale** of these interactions? The inverse of the rate of interactions with b_{min} will be the **relaxation time** (+ a small logarithmic factor added later):

$$T_{relax} \sim \left[b^2 \frac{M_{BH}}{M_\star} \frac{1}{R_{inf}^3} v_{orb} \right]^{-1} = \frac{M_{BH}}{M_\star} P \quad (\sim 10^{11}\,\text{yrs}\,?)$$

- We have to correct this time by a logarithmic factor that comes from the fact that most of interactions are weaker even if more frequent:

$$T_{relax} \sim \frac{M_{BH}}{M_\star} P \frac{1}{\ln \frac{M_{BH}}{M_\star}} \quad (\sim 10^{10}\,\text{yrs} \approx \text{age of Galaxy})$$

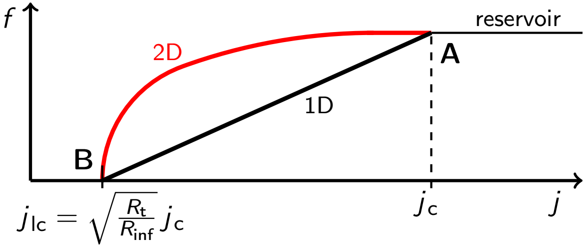
- But: for our purpose, I do not need to isotropise the j of all stars but only of a tiny fraction of them that is necessary to refill the loss cone:

$$T_{relax,LC} = \frac{R_t}{R_{inf}} T_{relax} \approx P$$

- This holds **if** the edges of the loss cone are sharp $\rightarrow$ they are diluted so you have to "bring" stars from farther away $\rightarrow$ $T_{relax} \approx P \times \ln \frac{M_{BH}}{M_\star} \approx 10\,P$

Alternative approach - j diffusion

- I can regard the previous also as a diffusion flux in 2D in a j space $\rightarrow$ pointing out that the 1st Fick's law in 2D has a specific property



- We try to diffuse a quantity $f(j)$ from the point A where it has a constant distribution to the point B where it is cleaned

- Why in 2D: only 2 components of v contribute to j (the 3rd - radial - does not)
- The 1st Fick's law in 1D: $D\dfrac{\partial f}{\partial j} = \mathrm{const.}$ $\rightarrow$ the flux is linear (black line)
- The 2D 1st Fick's law: $j\,D\dfrac{\partial f}{\partial j} = \mathrm{const.} \Rightarrow f \propto \ln \dfrac{j}{j_{\mathrm{lc}}}$ $\rightarrow$ particles (stars) have to diffuse through inwardly smaller ring areas that becomes "harder" (red line)

BW cusp

- What will be the **rate** of 2B interactions in case of any given distance r:

$$\frac{1}{t} \sim b_{\min}^2 \frac{N_\star(r)}{r^3} v(r) = \frac{G^2 M_\star^2}{v(r)^3} \frac{N_\star(r)}{r^3} = \frac{G^2 M_{\rm BH}^2}{v(r)^3} \frac{N_\star(r)}{r^3} \left(\frac{M_\star}{M_{\rm BH}}\right)^2 =$$

$$= N_\star(r) \frac{G M_{\rm BH}}{r^3} \frac{r}{v(r)} \left(\frac{M_\star}{M_{\rm BH}}\right)^2 = N_\star(r) \left(\frac{M_\star}{M_{\rm BH}}\right)^2 \frac{1}{P(r)} \quad \text{(+ the log factor...)}$$

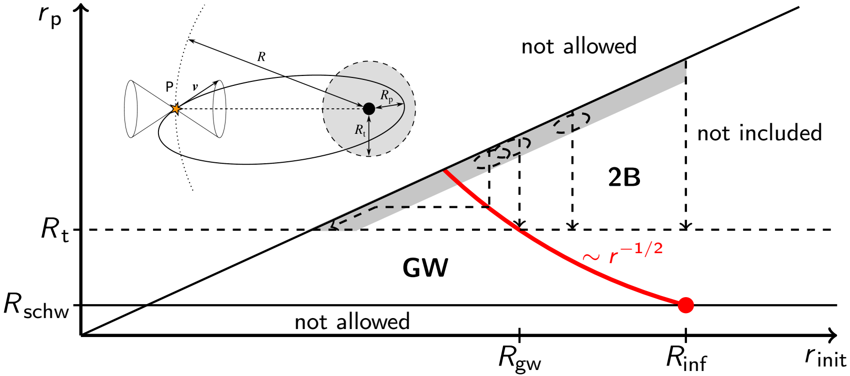
- Peebles: BH absorbs stars that arrive as a constant diffusion flux at a timescale given by the latter; we denote $N_\star(r)$ the number of stars within each radius r $\rightarrow$ # of stars evacuated from a given r with the above rate (per unit time) is constant (wrong argument):

$$N_\star^2(r) \left(\frac{M_\star}{M_{\rm BH}}\right)^2 \frac{1}{P(r)} = \text{const.} \Rightarrow \rho_\star(r) \propto r^{-9/4}$$

- Bahcall & Wolf: Energy $\sim M_\star/r$ evacuated from a given r with the above rate (per unit time) is constant (correct argument):

$$\frac{N_\star^2(r)}{r} \left(\frac{M_\star}{M_{\rm BH}}\right)^2 \frac{1}{P(r)} = \text{const.} \Rightarrow \rho_\star(r) \propto r^{-7/4}$$

TDEs/EMRIs



- Initial position of a ★ within the gray strip near the diag line (circular orbits → 45° if properly scaled); they may accidentally diffuse around their j equilibria within the strip; some refill the loss cone → diffuse "vertically" down to R_t
- ★ with $r_{init} < R_{gw}$ diffuse "vertically" down only to the red line ($\sim r^{-1/2}$ dividing the "2-body region" from the "GW region"), then move "horizontally" to the diagonal line, and then along it to R_t: the ratio $\frac{\mathcal{R}_{TDE}}{\mathcal{R}_{EMRI}} = \frac{R_{inf}}{R_{gw}} = \left(\frac{R_t}{R_{schw}}\right)^2$

TDEs/EMRIs

- Breakup of binaries may alter this "picture" $\rightarrow$ "story" for a separate lecture
- For any significantly eccentric orbit, we do not need to change it much because the pericenter is already close to BH: the time-rate to change the pericenter is smaller by j^2 (where $j \sim \sqrt{r_\mathrm{p}}$) $\rightarrow \frac{1}{t} \sim N_\star(r) \left(\frac{M_\star}{M_\mathrm{BH}}\right)^2 \frac{1}{P(r)} \frac{r_\mathrm{p}}{r} \rightarrow$ with $N_\star(r)$ given from the BW cusp
- The timescale at which GWS can bring any orbit r to a smaller r_p:

$$T_\mathrm{gw} = \frac{R_\mathrm{schw}}{c} \frac{M_\mathrm{BH}}{M_\star} \left(\frac{r_\mathrm{p}}{R_\mathrm{schw}}\right)^4 \frac{r_\mathrm{p}}{r} \left(\frac{r}{r_\mathrm{p}}\right)^{3/2},$$

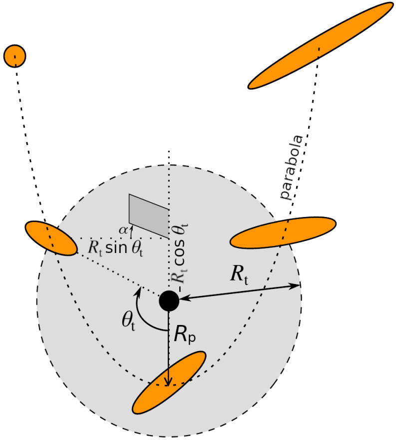
  where the 1st fraction is the timescale of two equal bodies at R_schw, the 2nd fraction $\rightarrow$ longer time due to the mass ratio, the 3rd term $\rightarrow$ the GR gives $t \sim r_\mathrm{p}^4$ to shrink the orbit from r_p to R_schw, the 4th term $\rightarrow$ the lowering of emitted E for much wider orbit $r > r_\mathrm{p}$, and the last one $\rightarrow$ the longer time due to lower velocity at r

TDE energy budget

- Let's describe the basic dynamics associated with the passage of the star at pericenter:
- The star starts to be deformed at a few R_t from the BH $\rightarrow$ stretched along an almost radial direction $\rightarrow$ stellar debris spread with (specific) $E_{\rm orb} = E = -GM_{\rm BH}/(R_t + R_\star)$:

$$E = E(R_t) + \Delta E \approx -\frac{GM_{\rm BH}}{R_t} + \frac{GM_{\rm BH}}{R_t^2} R_\star$$

- At R_t, ★ is confined between two orbital planes that intersect near pericentre, and ★ is progressively compressed into a "pancake"



Credit: Bonnerot+ 2017

- We introduce β as R_t/R_p, in the limit $\beta \gg 1$, the inclination angle between these two planes is $\alpha \approx R_\star/(R_t \sin\theta_t) \Rightarrow$ (parabola)

$$\cos\theta_t = \frac{2R_p}{R_t} - 1 \Rightarrow \sin\theta_t \approx \theta_t = \sqrt{\frac{R_p}{R_t}} \Rightarrow \alpha \approx \frac{R_\star}{\sqrt{R_p R_t}}$$

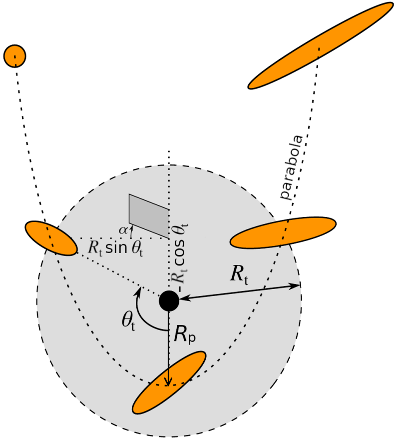
TDE energy budget

- At pericentre, in addition to shearing along the orbital plane, the star undergoes a vertical compression for a large β:

- The specific vertical "compression" energy $\Delta E_c = \frac{1}{2}\langle v_c^2 \rangle \Rightarrow$ the pericenter "compression" velocity $\sqrt{\langle v_c^2 \rangle} \approx \alpha v_p$ where $v_p = \sqrt{\frac{GM_{BH}}{R_p}}$ is the orbital velocity at R_p

- Substituting R_t and β, the latter gives

$$\langle v_c^2 \rangle \sim \Delta E_c = \beta^2 \frac{GM_\star}{R_\star}$$



Credit: Bonnerot+ 2017

TDE energy budget

- This strong vertical compression causes the formation of shocks that convert this energy ΔE_c into a compressive heat T_c

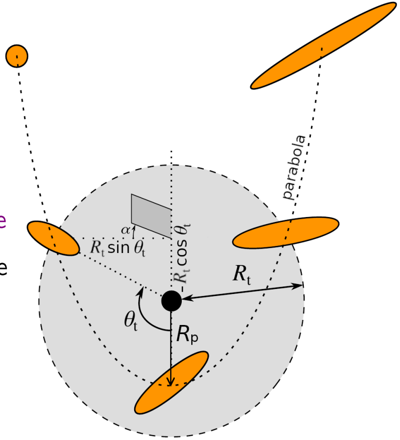
- Comparing $\dfrac{\Delta E_c}{\Delta E} \sim \beta^2 \left(\dfrac{M_\star}{M_{BH}}\right)^{1/3}$ $\Rightarrow$ can be ignored unless $\beta \gg 1 \Rightarrow$ the effectivity of the compression increases for smaller BHs

- From the previous and from the stellar structure and evolution theory $\rightarrow$ temperature at a stellar center $T_\star \sim \dfrac{GM_\star}{R_\star}$

$$\Rightarrow T_c \sim \beta^2 T_\star$$

  $\Rightarrow$ for MS stars with $T_\star \approx 10^7$ K $\Rightarrow \beta \approx 3$ can give He burning

- Increase in T in WDs can be explosive (He-flash)



Credit: Bonnerot+ 2017

Corresponding high compression not obtained numerically $\rightarrow$ a controversy? (Rossi+ 2017)

Fallback of matter on ballistic orbits

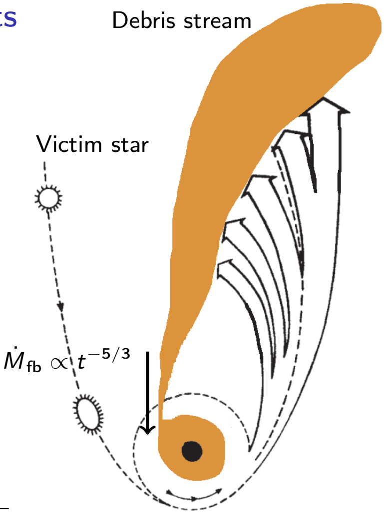
- About half of the debris stream produced by the disruption is bound to the BH $\rightarrow$ it comes back to the disruption site

- The stream moves ballistically around BH $\rightarrow$ the most tightly bound debris has an orbital energy $-\Delta E \approx -GM_{\rm BH}/2a$ (Virial $\rightarrow E_k$ cancels half of E_p), which corresponds to a semi-major axis $a_{\rm min}$ and orbital period $t_{\rm min}$ (using the Kepler law $t^2 \propto a^3$ and assuming $\mathrm{d}M/\mathrm{d}E = \mathrm{const.}$):

$$\frac{GM_{\rm BH}}{R_\star \left(\frac{M_{\rm BH}}{M_\star}\right)^{2/3}} = \frac{GM_{\rm BH}}{2a} \Rightarrow$$

$$a_{\rm min} = \frac{R_\star}{2}\left(\frac{M_{\rm BH}}{M_\star}\right)^{2/3} \Rightarrow t_{\rm min} \sim R_\star^{3/2}\frac{\sqrt{M_{\rm BH}}}{M_\star} \Rightarrow$$

$$\Delta E \sim M_{\rm BH}^{2/3} t^{-2/3} \rightarrow \dot{M} = \frac{\mathrm{d}M}{\mathrm{d}E}\frac{\mathrm{d}E}{\mathrm{d}t} \sim t^{-5/3}$$



- But: Stellar structure can modify dM/dE (Lodato+ 2009; Guillochon & Ramirez-Ruiz 2013)

Circularisation

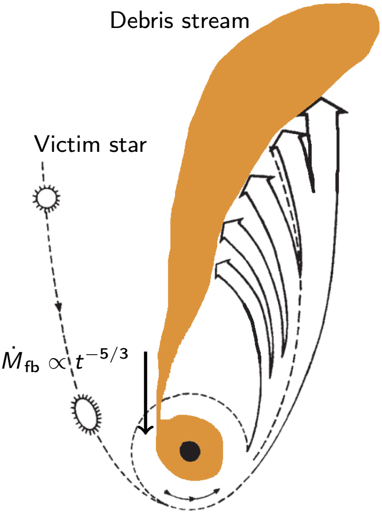
- It is commonly believed that most of the electromagnetic emission detected from TDEs originates from the dissipation of the debris orbital energy when the stream comes back to BH

- We can evaluate j at $R_{\rm p}$ by comparing the specific energies

$$\frac{1}{2}v^2 = \frac{GM_{\rm BH}}{R_{\rm p}} \Rightarrow j_{\rm p} \approx \sqrt{2GM_{\rm BH}R_{\rm p}}$$

- From the conservation of j, we define the circularisation radius $R_{\rm circ}$ where most of the disrupted debris is settled at a circular orbit within a standard accretion disk:

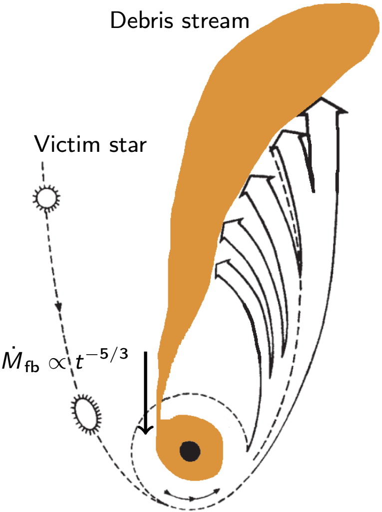
$$j_{\rm p} = j_{\rm circ} \approx \sqrt{GM_{\rm BH}R_{\rm circ}} \Rightarrow R_{\rm circ} = 2R_{\rm p}$$



- The loss of orbital energy is then $\Delta E_{\rm circ} \approx \dfrac{3GM_{\rm BH}}{4R_{\rm p}}$

Circularisation

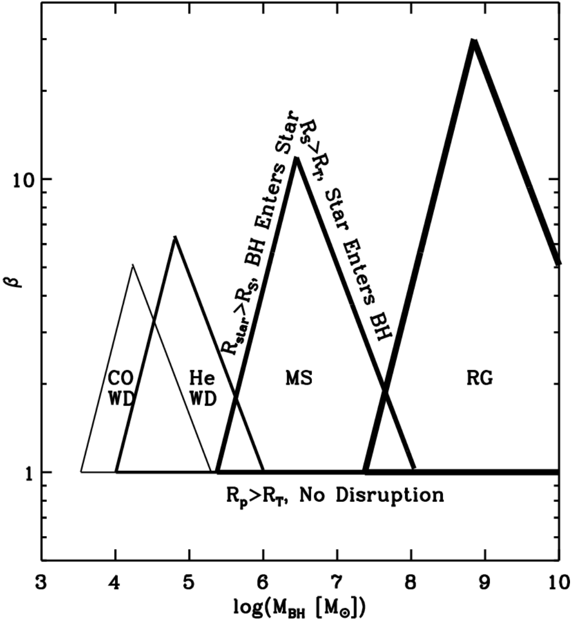
- Comparing the loss of circular energy ΔE_{circ} with the compression energy ΔE_{c}:
$$\frac{\Delta E_{\mathrm{circ}}}{\Delta E_{\mathrm{c}}} \sim \beta \left(\frac{M_{\mathrm{BH}}}{M_\star}\right)^{1/3} \approx 10^2$$
- Assuming that a fraction η of the available rest mass energy is dissipated and radiated locally, the associated L can be larger than the L_{Edd} by a factor (Bonnerot 2017)
$$\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}} = \frac{\eta \dot{M} c^2}{L_{\mathrm{Edd}}}$$
- This ratio exceeds unity initially as long as the black hole mass is $M_{\mathrm{BH}} \lesssim 3 \times 10^7 M_\odot$ $\rightarrow$ then decreases with time and becomes lower than one for $t \geq t_{\mathrm{Edd}}$ with $t_{\mathrm{Edd}}/t_{\mathrm{min}} \equiv (\dot{M}/\dot{M}_{\mathrm{Edd}})^{3/5}$ (Bonnerot 2017):
$$L_{\mathrm{acc}} \approx L_{\mathrm{Edd}} = 10^{44}\,\mathrm{erg\,s^{-1}} \left(\frac{M_{\mathrm{BH}}}{10^6\,M_\odot}\right)$$



- But: some discrepancies with the models $\rightarrow$ much higher T_{eff} then observed ($\sim 10^6$ K / 50 000 K)

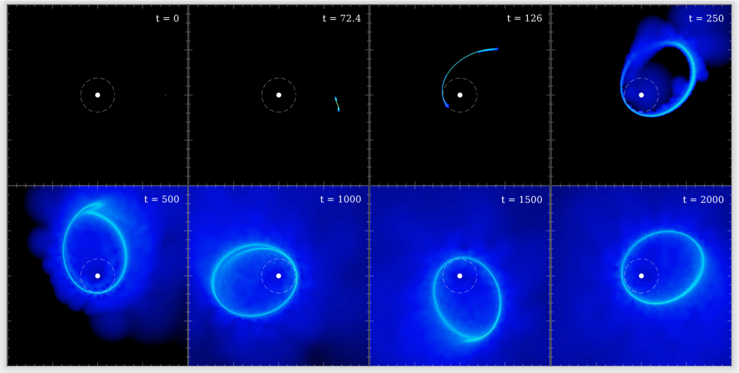
TDE models

- Allowable region for the TDEs of stars of different evolutionary states: a $0.6\,M_\odot$ CO WD, a $0.17\,M_\odot$ He WD, a $1\,M_\odot$ MS star, and a $1.4\,M_\odot$ RG, bounded by the conditions that $R_p < R_t$, $R_\star < R_{schw}$, and $R_t > R_{schw}$ for a TDE to be observable, as a function of M_{BH}, and $\beta \equiv R_t/R_p$



Credit: Rosswog, Ramirez-Ruiz & Hix 2009

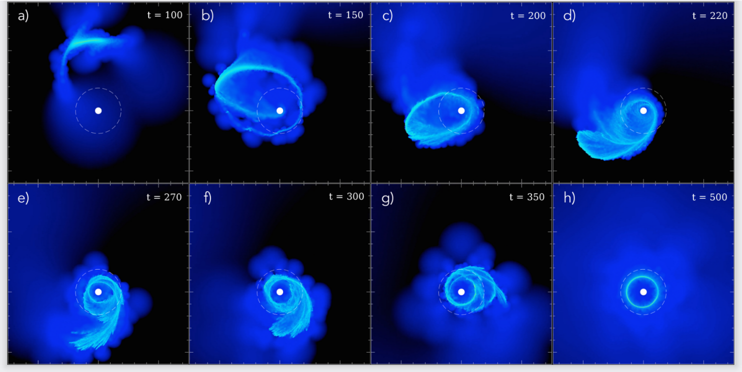
TDE models



Credit: Clerici & Gomboc 2020

- Two behaviours of the circularisation of the debris, depending on the initial orbital e and β: (a) shocks and higher precessing angles allow the debris to form a circular disc quickly and (b) the shocks are not impactful enough to allow fast circularisation $\rightarrow$ the debris follows elliptical orbits $\rightarrow$ Figure: the debris does not circularise efficiently and a disc is not formed (quickly)

TDE models

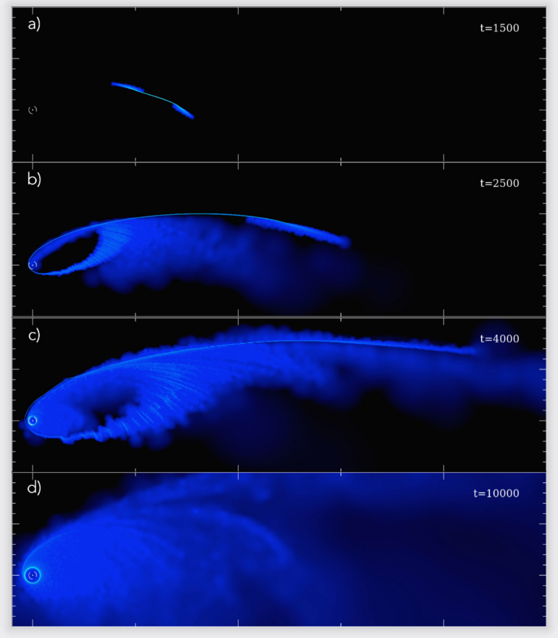


Credit: Clerici & Gomboc 2020

- Circularisation of the stellar debris: the debris quickly and efficiently circularises, mainly through self-crossings and shocks, and forms a disc with no debris falling back

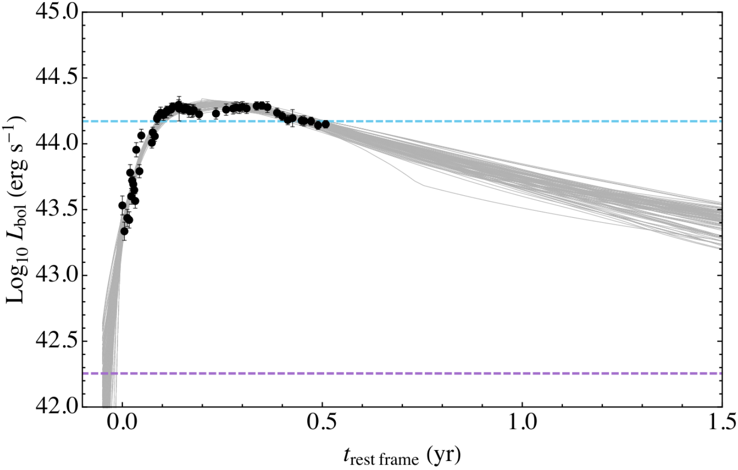
TDE models

- Circularisation of the stellar debris: the debris circularises relatively quickly and forms a disc while there is still debris falling back



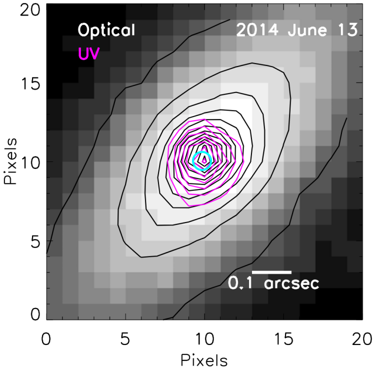
Credit:
Clerici & Gomboc 2020

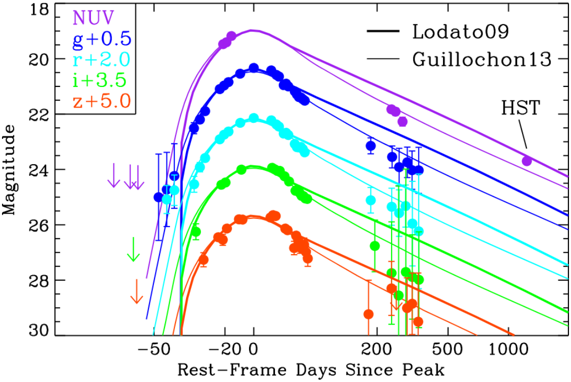
TDE models



- L_{bol} of TDE PS16dtm compared to an ensemble of models → dashed blue line shows L_{Edd} for fixed black hole mass of $10^6\ M_\odot$, the dashed purple line shows the AGN luminosity prior to the flare → the projected behavior of the flare suggests that it will remain bright for years (Blanchard+ 2017)

TDE observables





Credit: Gezari+ 2015

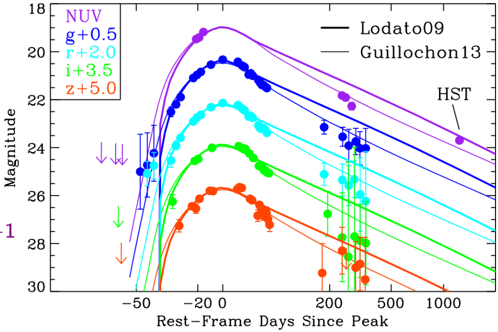
- PS1-10jh taken in the F225W (UV) and F625W (optical) filters. Grayscale and black contours show an optical image dominated by the host galaxy, and magenta contours show the UV point source associated with the fading transient
- UV/optical light curve of tidal disruption event candidate PS1-10jh as measured by GALEX in the NUV and PS1 in the g,r,i,z bands, 1250 rest-frame days since the peak of the flare. Models for the fallback rate of a tidally disrupted star from Lodato et al. (2009) are plotted with thick lines and from Guillochon & Ramirez-Ruiz (2013) are plotted with thin lines.

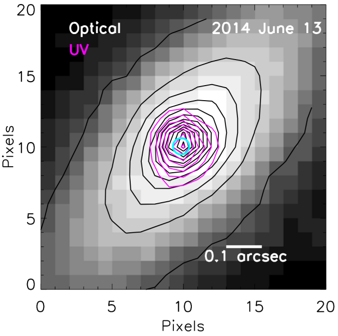
TDE observables

- **Parameters of PS1-10jh:**

- Peak luminosity: $\sim 10^{44}\,\mathrm{erg\,s^{-1}}$
- Temperature: $\sim 50\,000\,\mathrm{K}$
- Line width: $\sim 5000\,\mathrm{km\,s^{-1}}$
- Total energy: $\sim 10^{51}\,\mathrm{erg}$

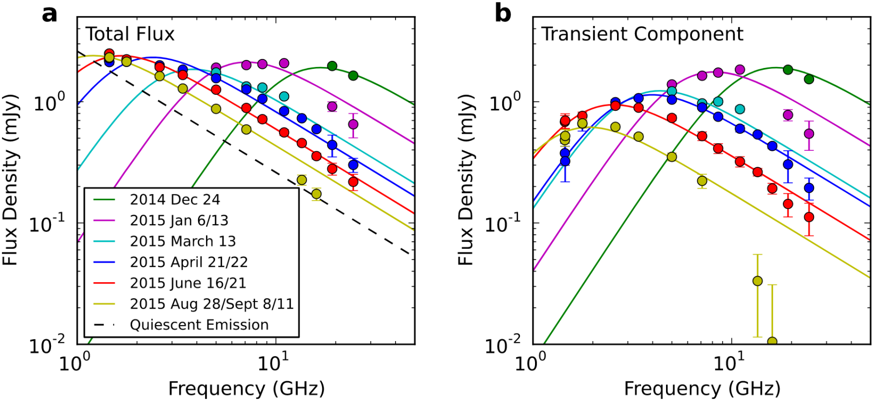
- R_{em}: $\sim 10^{15}\,\mathrm{cm} = \sim 1000\,R_{\mathrm{schw}}$





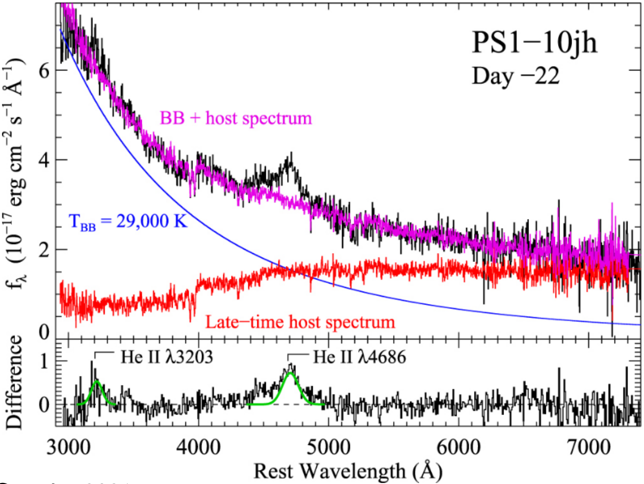
TDE observables

- **Radio TDEs**



Credit: Alexander et al. 2017

TDE observables



Credit: Gezari+ 2021

Detection of transient, broad He II line emission on top of the hot, thermal continuum 22 days before the peak of the flare in TDE PS1-10jh