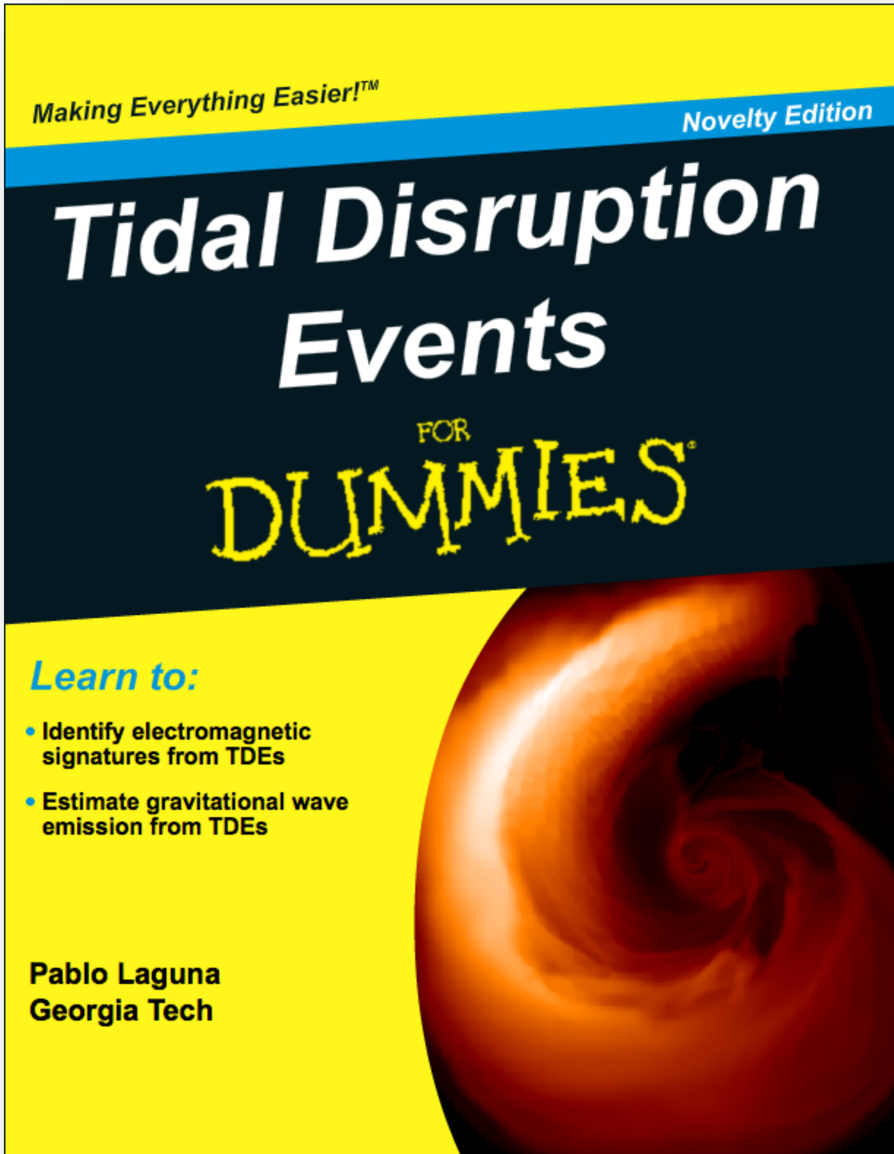
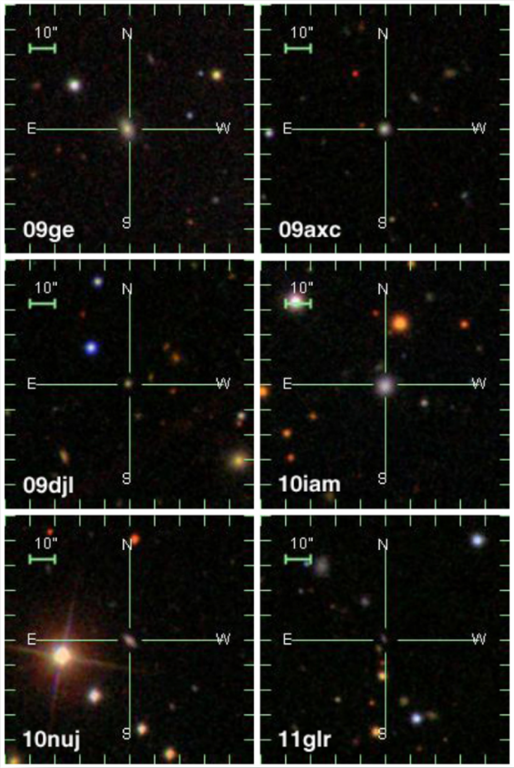


Georgia Tech

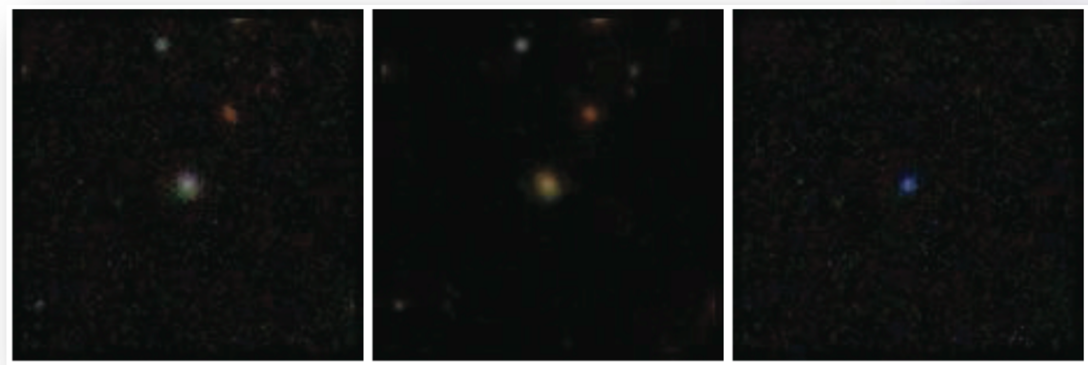
Pablo Laguna
Center for Relativistic Astrophysics
School of Physics
Georgia Tech, Atlanta, USA

The Transient Sky

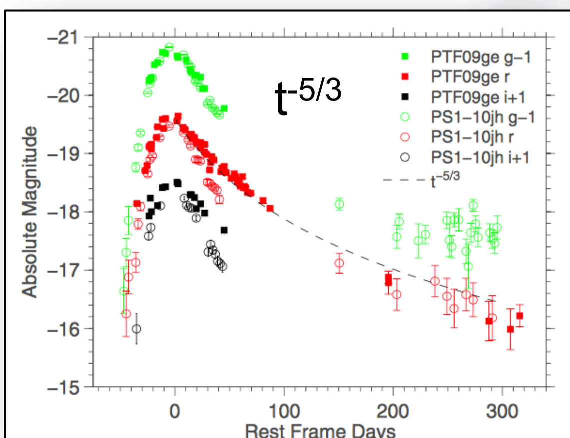
SN, GRBs, AGN or TDEs?



Arcavi et al. 2014, ApJ, 793, 38



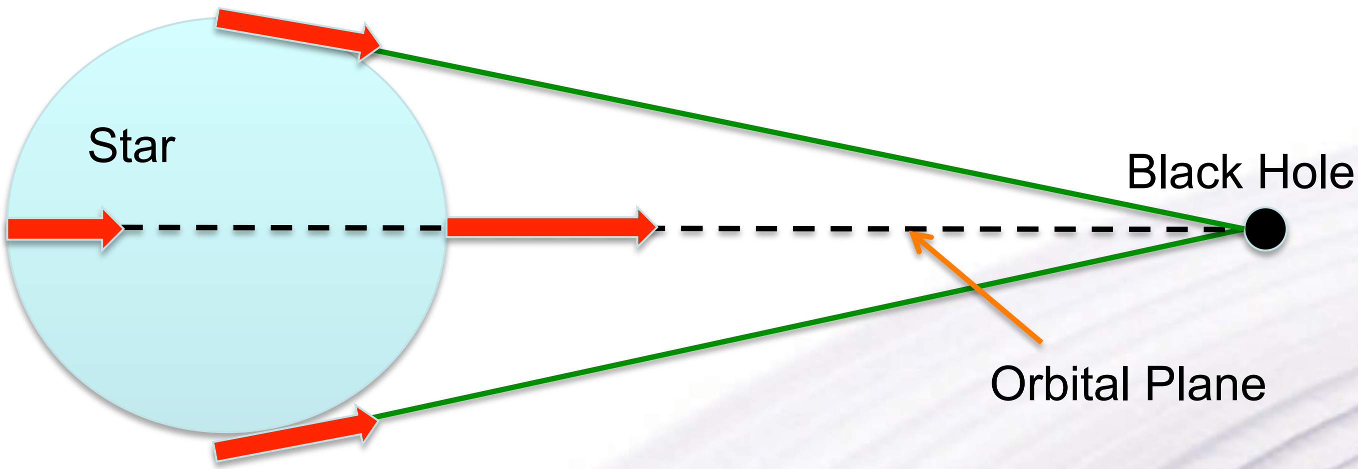
van Velzen et al. 2011, ApJ, 741, 73



If TDEs, we will learn about

- Demographics of MBHs in quiescent galaxies
- Constraints on low mass galaxies hosting MBHs
- Growth of MBHs by accreting gas at super-Eddington rates
- Stellar dynamics in the neighborhood of MBH

Tidal Forces



$$\frac{GmM_*}{R_*^2} = \frac{GmM_h}{(R_t - R_*)^2} - \frac{GmM_h}{(R_t + R_*)^2} \approx \frac{GmM_h R_*}{R_t^{\ 3}}$$

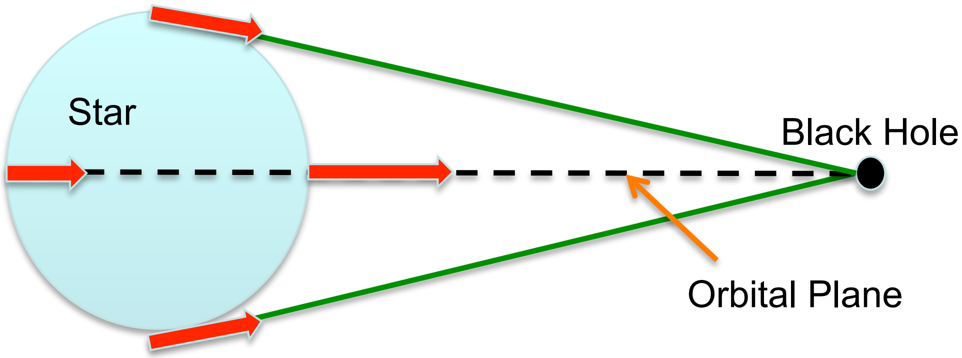
$$\frac{M_*}{R_*^2} \approx \frac{M_h R_*}{R_t^{\ 3}}$$

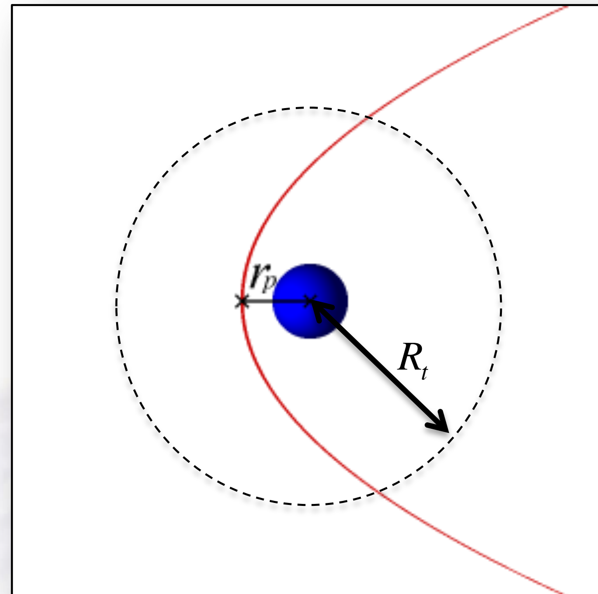
- Stretching along the orbital plane
- Compression perpendicular to the orbital plane

$$R_t \approx R_* \left(\frac{M_h}{M_*} \right)^{1/3}$$

Tidal Radius

Tidal Radius and Penetration Factor





$$R_t = R_* \left(\frac{M_h}{M_*} \right)^{1/3}$$

Tidal Radius

$$\beta \equiv \frac{R_t}{R_p}$$

Penetration Factor

Main Sequence

$$\frac{R_t}{M_{bh}} \simeq 47 \left(\frac{R_{ms}}{R_\odot} \right) \left(\frac{M_{ms}}{M_\odot} \right)^{-1/3} \left(\frac{M_{bh}}{10^6 M_\odot} \right)^{-2/3}$$

White Dwarf

$$\frac{R_t}{M_{bh}} \simeq 22 \left(\frac{R_{wd}}{0.95 R_\oplus} \right) \left(\frac{M_{wd}}{M_\odot} \right)^{-1/3} \left(\frac{M_{bh}}{10^4 M_\odot} \right)^{-2/3}$$

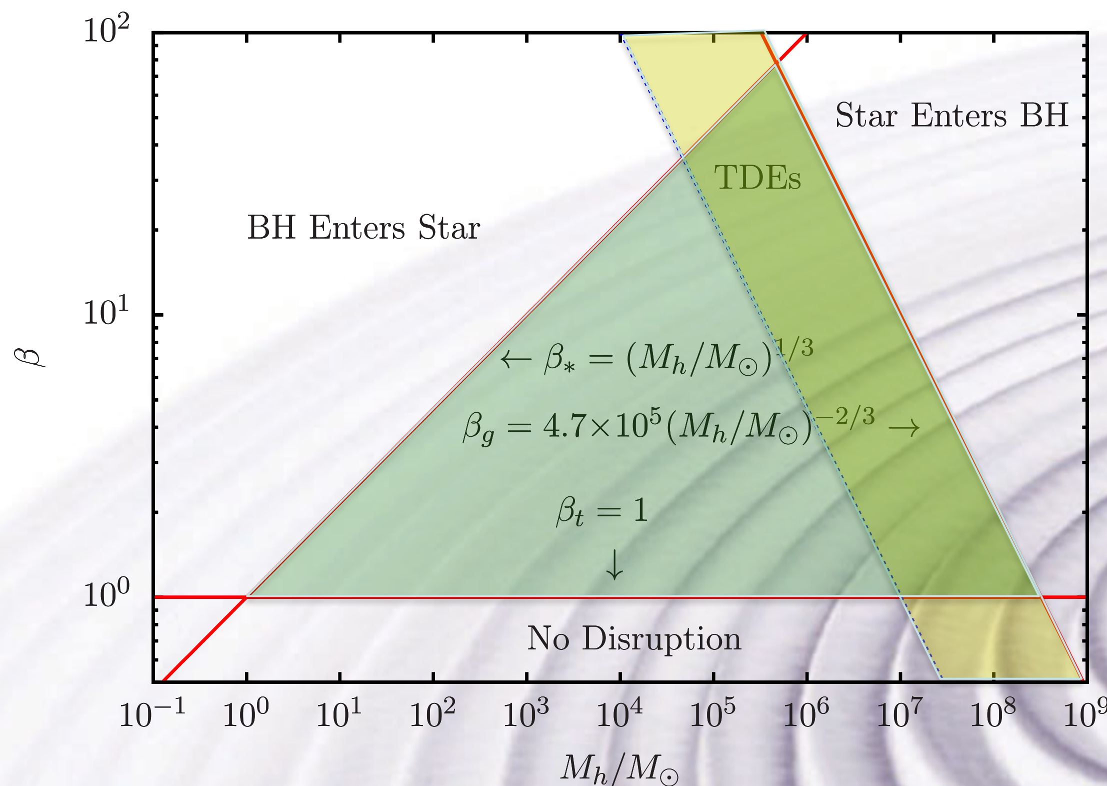
Triangle of Astrophysical Relevance

Tidal Radius

$$R_t \equiv R_* \left(\frac{M_h}{M_*}\right)^{1/3}$$

Penetration Factor

$$\beta(R_p) \equiv \frac{R_t}{R_p} = \frac{R_*}{R_p}\left(\frac{M_h}{M_*}\right)^{1/3}$$



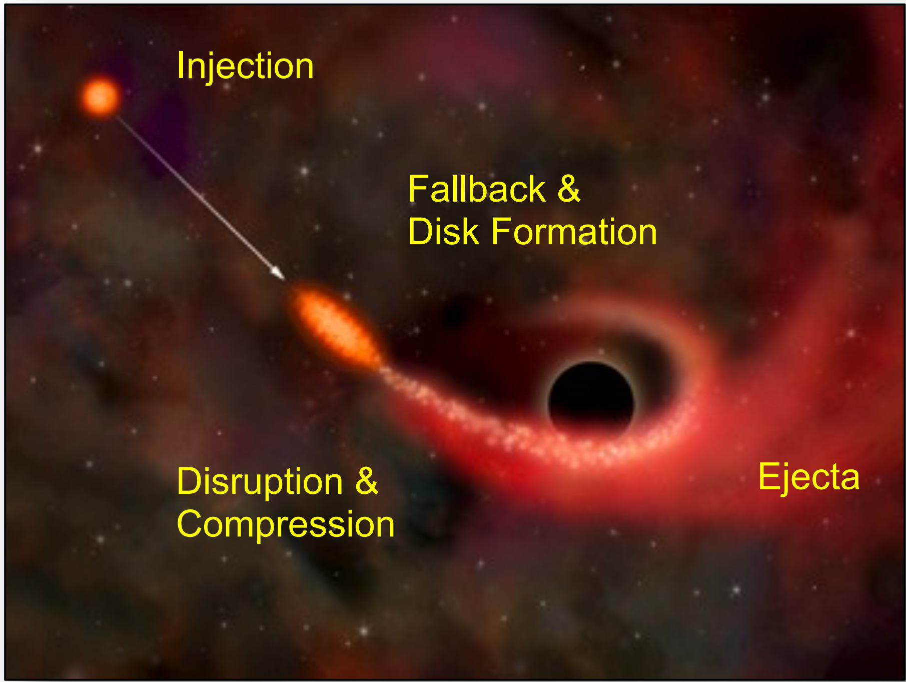
$$\beta_t = \beta(R_t) = 1$$

$$\beta_* = \beta(R_*) = \left(\frac{M_h}{M_*}\right)^{1/3}$$

$$\beta_g = \beta(R_g) = \frac{R_*}{G M_* / c^2}\left(\frac{M_h}{M_*}\right)^{-2/3}$$

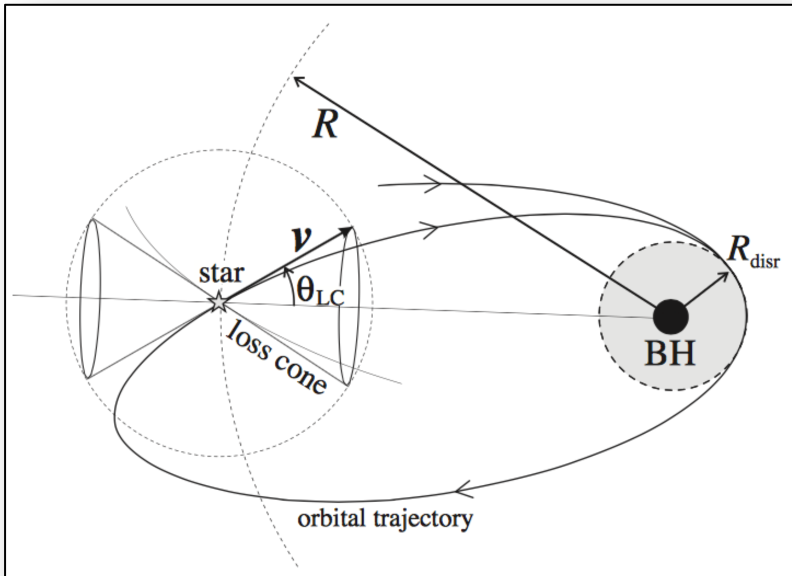
Luminet & Pichon (1989)

The Disruption of a Star:
What to Look For



- Near periapsis, the star disrupts and compresses. Detonation, multiple bounces, and gravitational waves are possible outcomes.
- Fallback material yields an accretion disk (soft x-rays), with super-Eddignton outflows (optical/UV) and relativistic jets (radio/x-rays)
- Unbound material could also yield emission lines if irradiated by the disk

TDE: The Capture



Freitag & Benz

Loss Cone: Set of orbital directions that leads to capture or disruption

Event rate depends on how the *Loss Cone* gets populated

Stars enter the *Loss Cone* via collisions with other stars or relaxation

Stars can also be ejected from the Loss Cone via collisions.

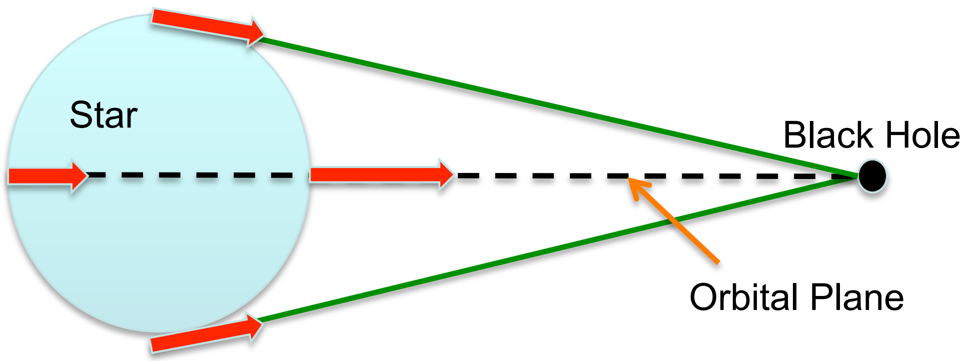
Event rate ~ 10^{-4} yr $^{-1}$

$$L \leq L_{LC} \approx \sqrt{2 G M_h R_{LC}}$$

$$\text{If } R_{LC} \approx R_h \approx \frac{G M_h}{\sigma^2} \text{ star is captured}$$

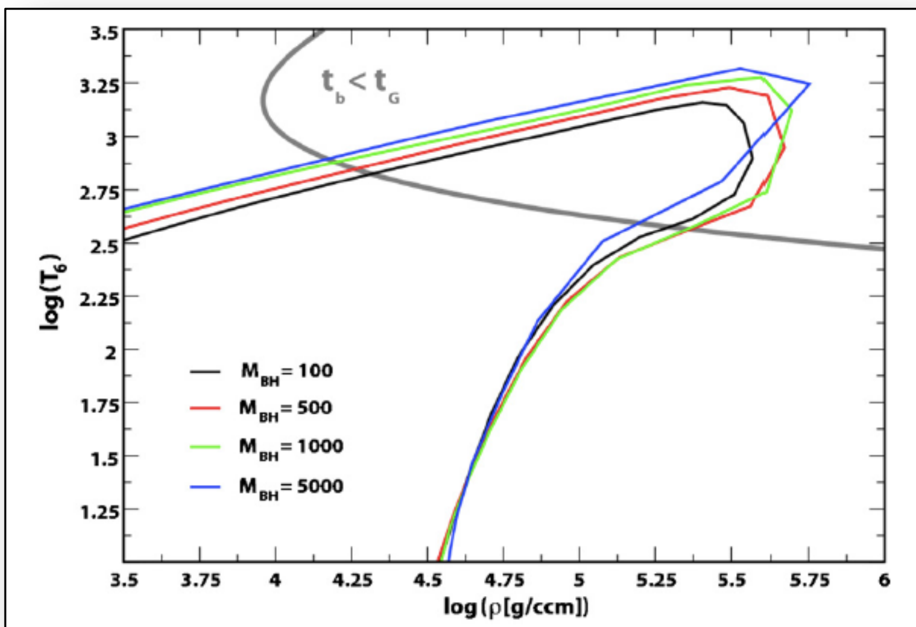
$$\text{If } R_{LC} \approx R_t \approx R_* \left(\frac{M_h}{M_*}\right)^{1/3} \text{ star is disrupted}$$

Tidal Compression

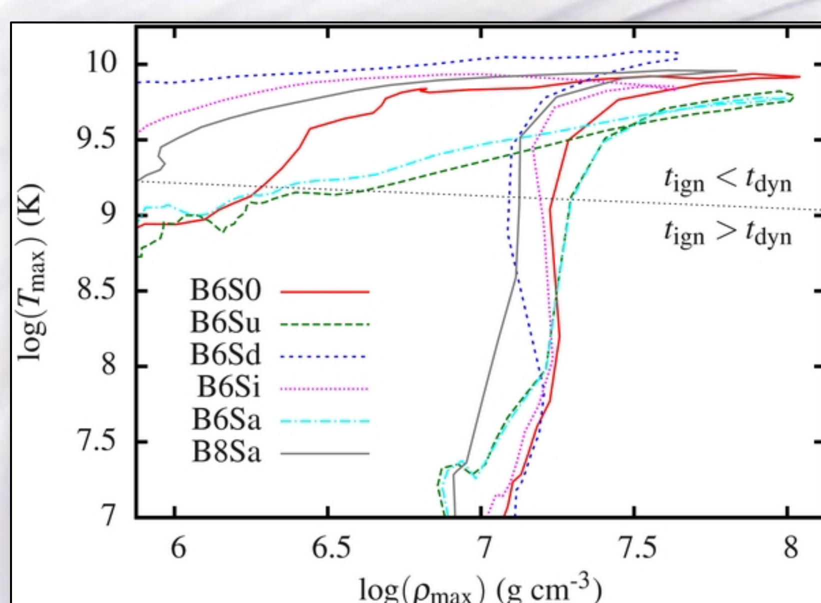


$$\rho_{max} \sim \rho_* \beta^3$$
$$T_{max} \sim T_* \beta^2$$

Carter & Luminet 1993

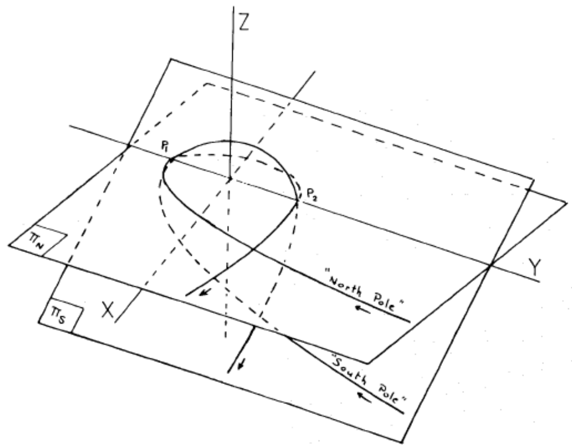


Rosswog, Ramirez-Ruiz, Hix

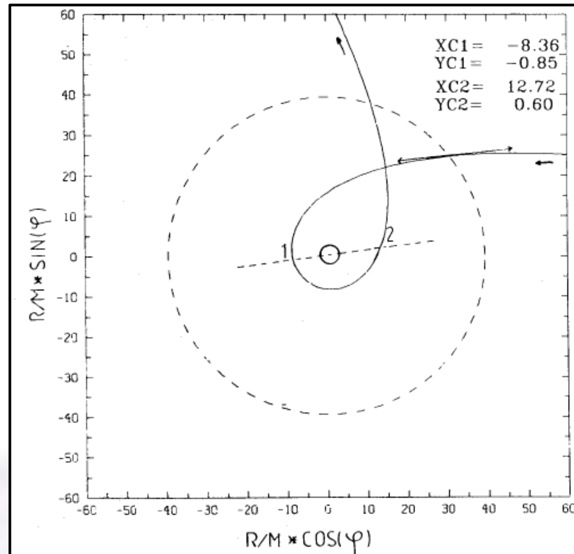


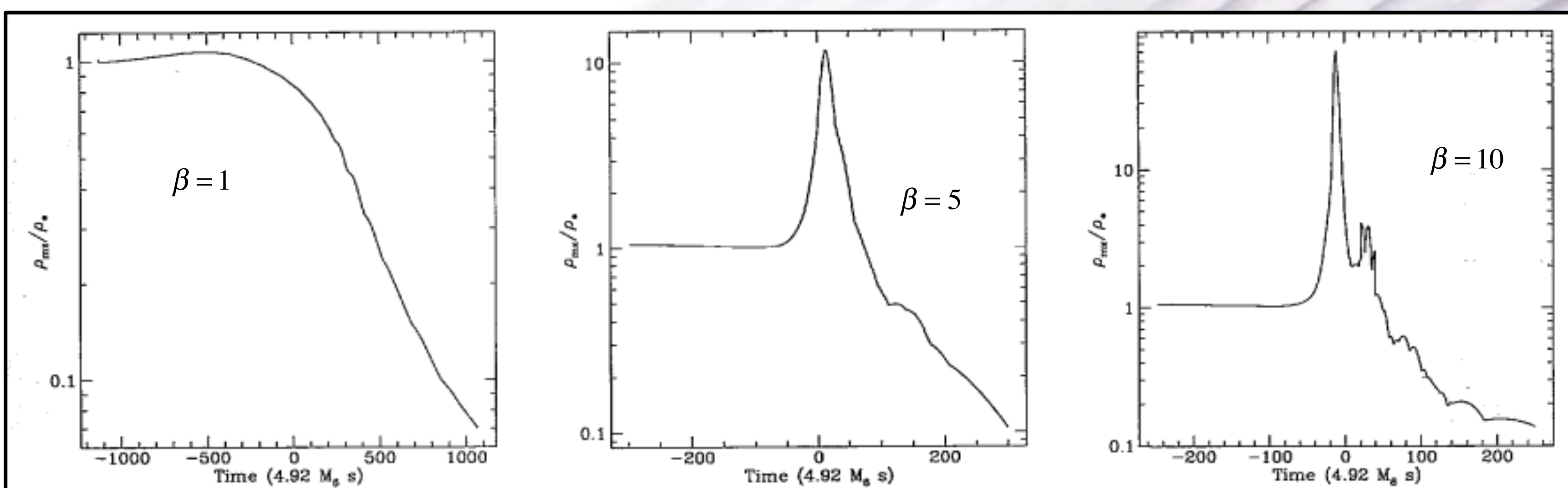
Haas, Shcherbakov, Bode, PL

Multiple Tidal Compression



Luminet & Marck, 1985, MNRAS, 212, 57

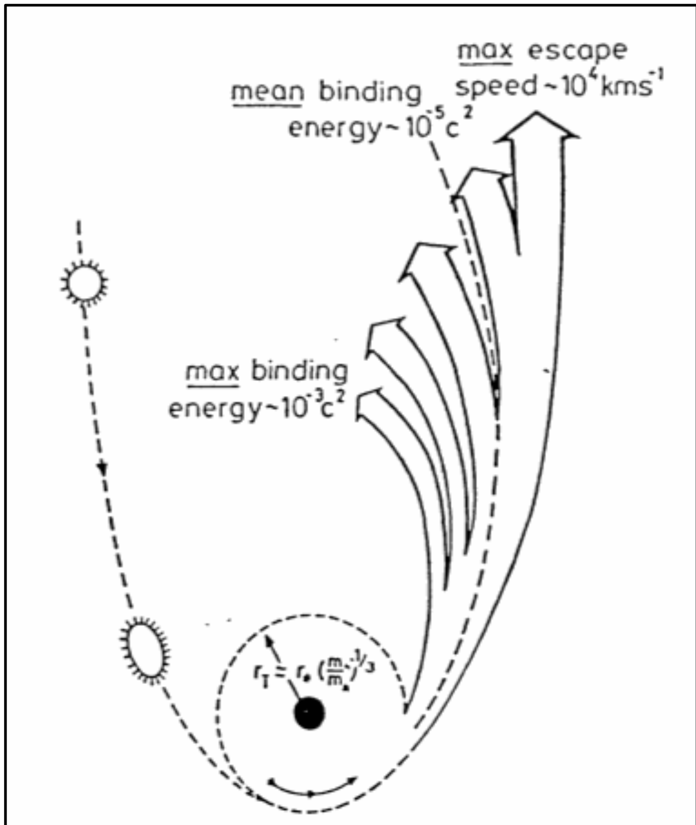




Laguna, Miller, Zurek & Davies 1993, ApJL 410, 83

Fallback Material

$$\dot{M} = \frac{dM}{d\epsilon}\frac{d\epsilon}{dt} \propto \frac{d\epsilon}{dt} \quad \text{if} \quad \frac{dM}{d\epsilon} \approx \text{const}$$



Rees 1988

Recall

$$\epsilon \sim \frac{M_{bh}}{a}$$

$$P \propto a^{3/2}$$

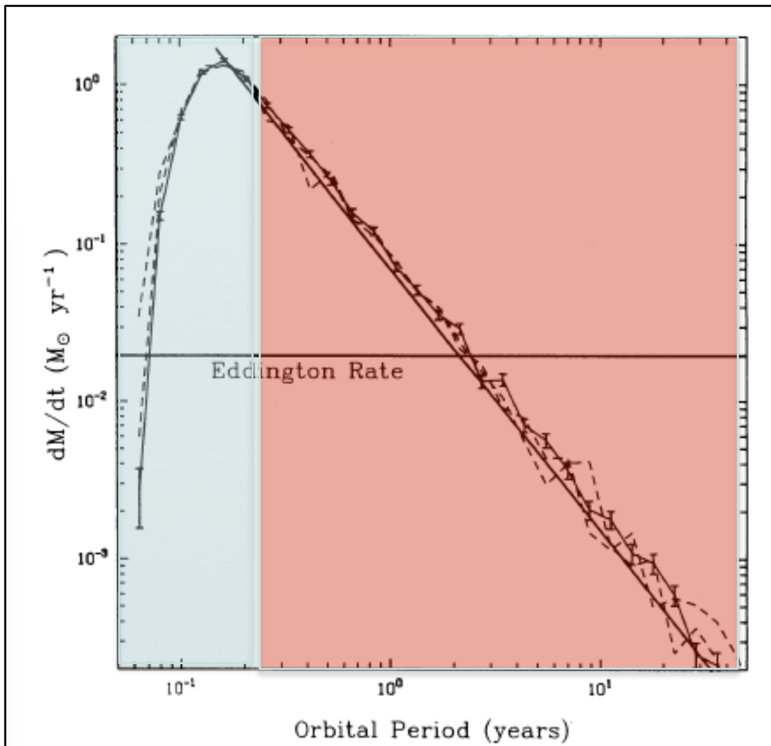
$$\epsilon \sim P^{-2/3}$$

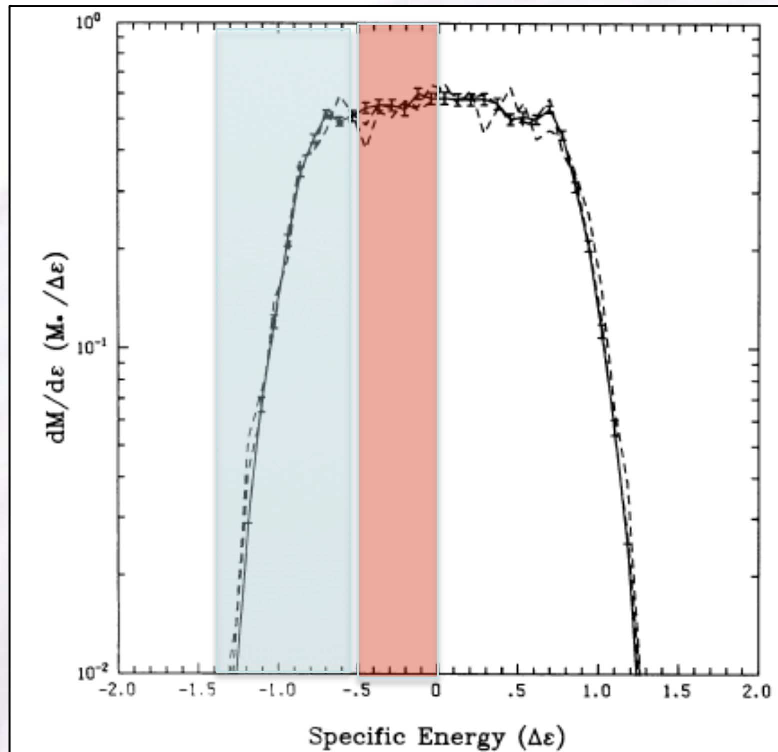
$$\frac{d\epsilon}{dt} \propto t^{-5/3}$$

$$L \propto \dot{M} \propto t^{-5/3}$$

The TDE Smoking Gun

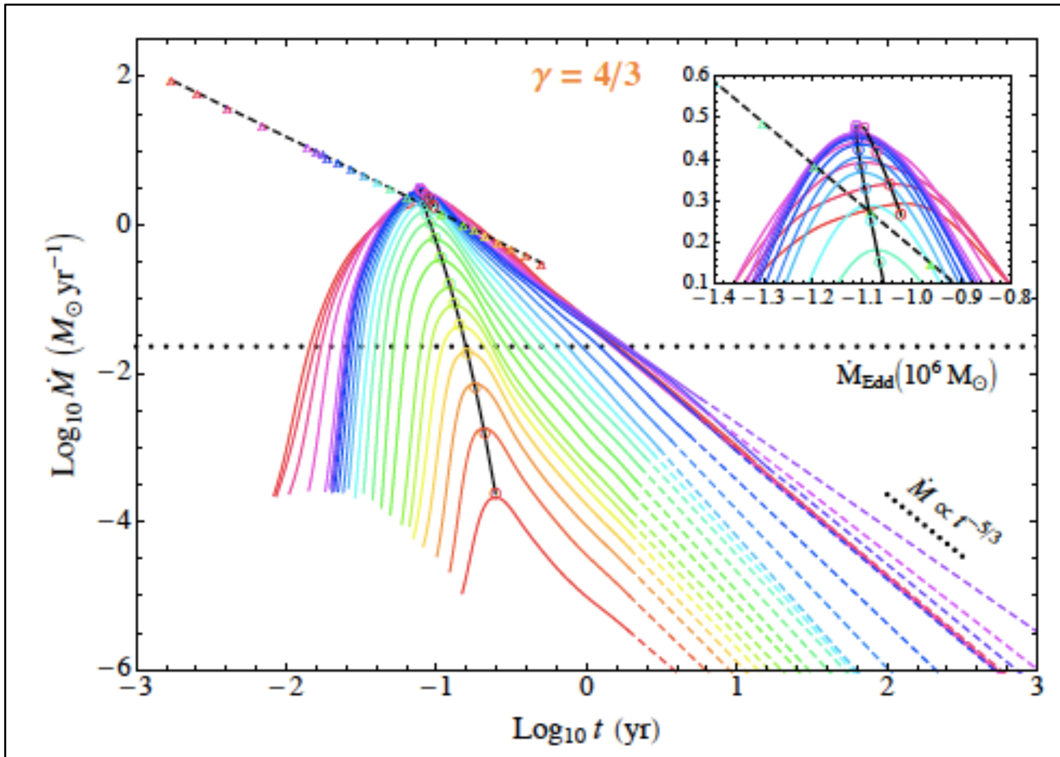
$$L \propto \dot{M} \propto t^{-5/3}$$





Evans and Kochanek 89

Deviations from $\dot{M} \propto t^{-5/3}$

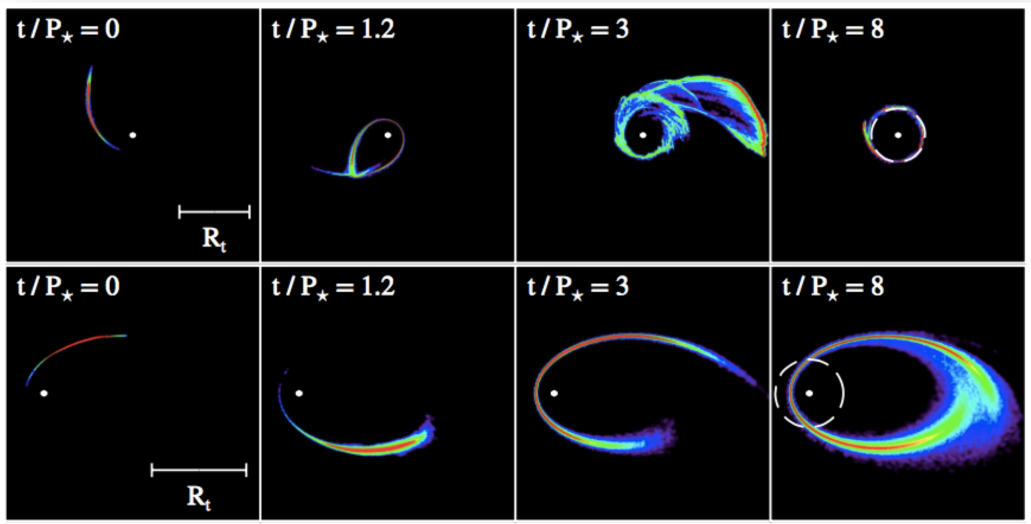


Guillochon et al

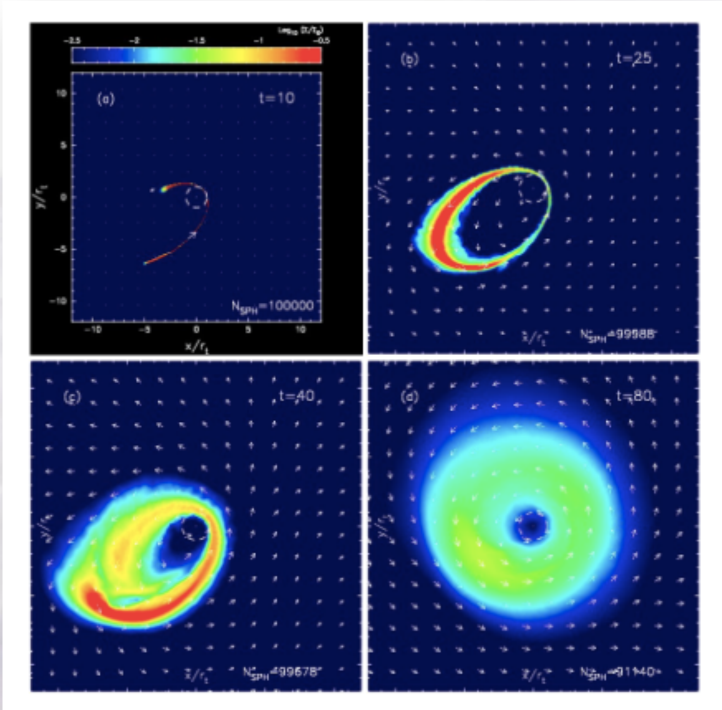
Not included:

- BH and stellar spin
- GR
- Partial disruption

Circularization & Disk Formation

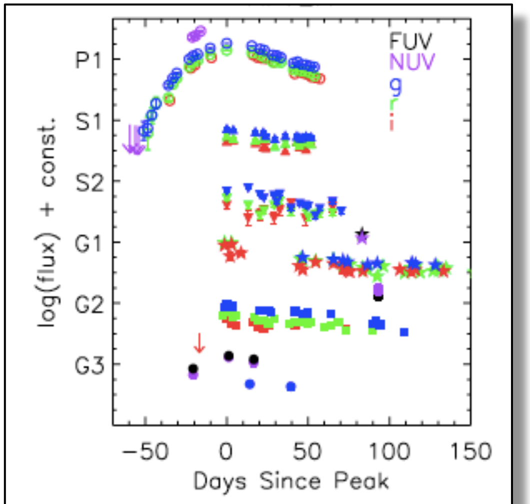


Relativistic precession could also assist in circularizing the bound debris. *Bonnerot et al*

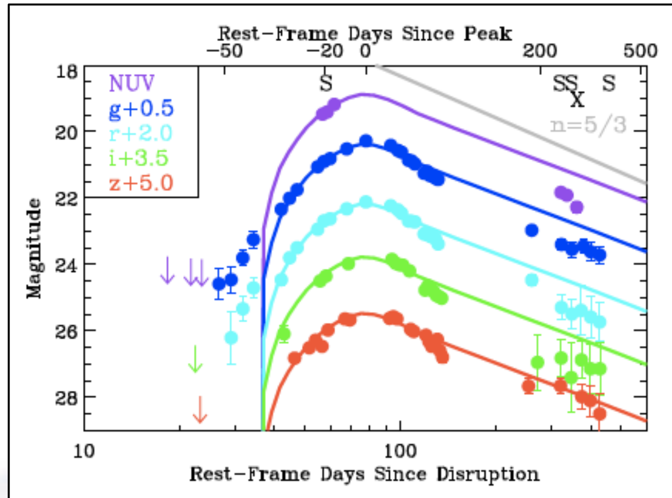


Circularization depends on the efficiency of radiative cooling. *Hayasaki, Stone & Loeb*

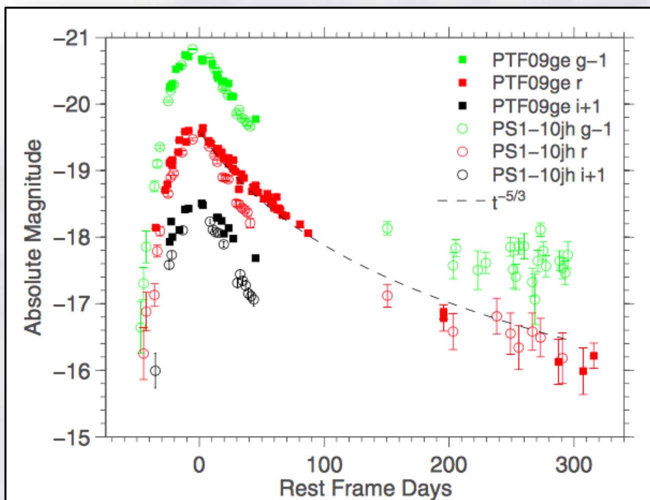
TDE Candidates



Gezari et al

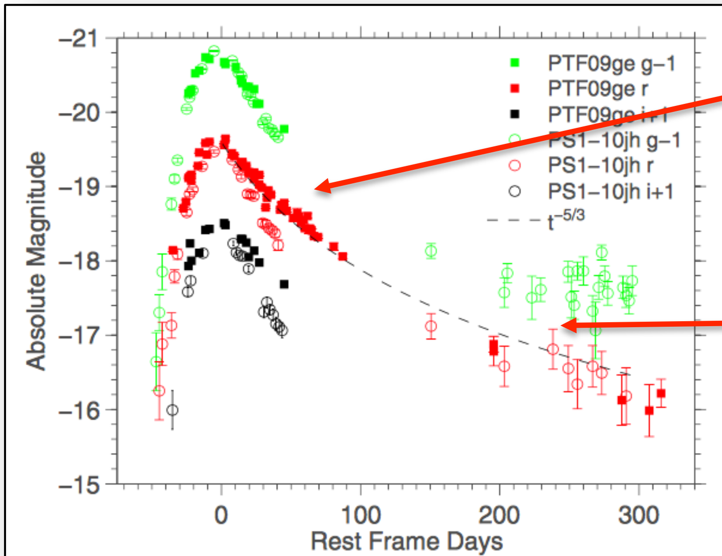


PS1-10jh



van Velzen et al. 2011, ApJ, 741, 73

Where is the emission produced?

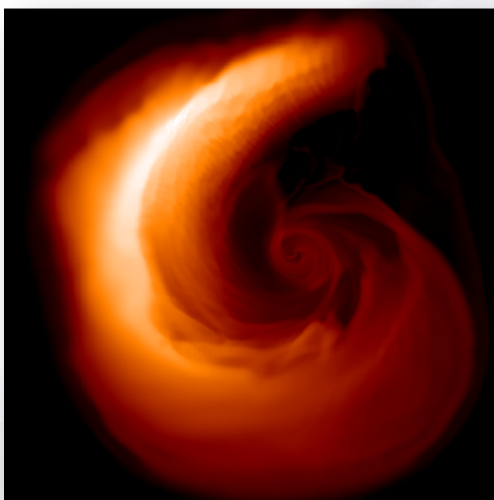


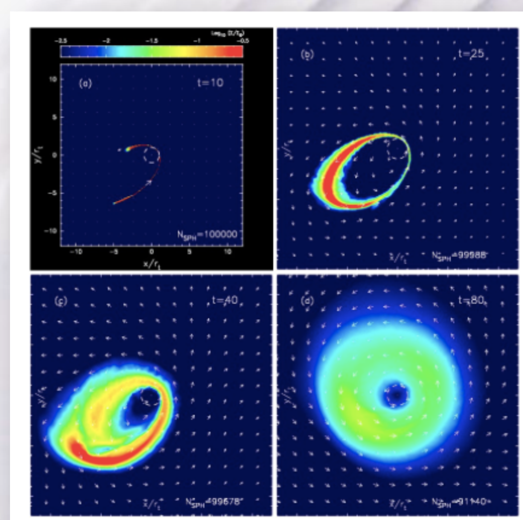
Flare:

- From self-intersection
- Prompt accretion

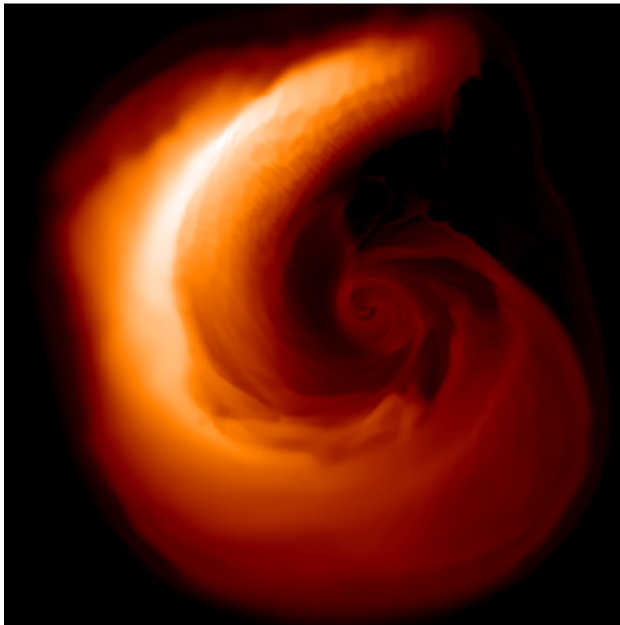
Power-law decay:

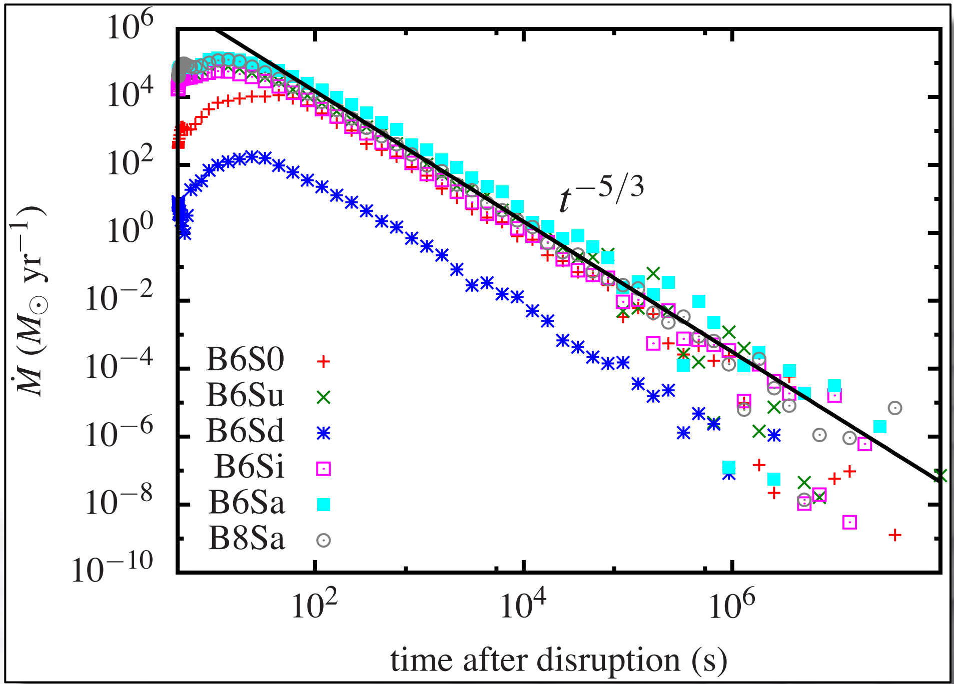
- From the disk?
- Direct accretion?





White Dwarf TD



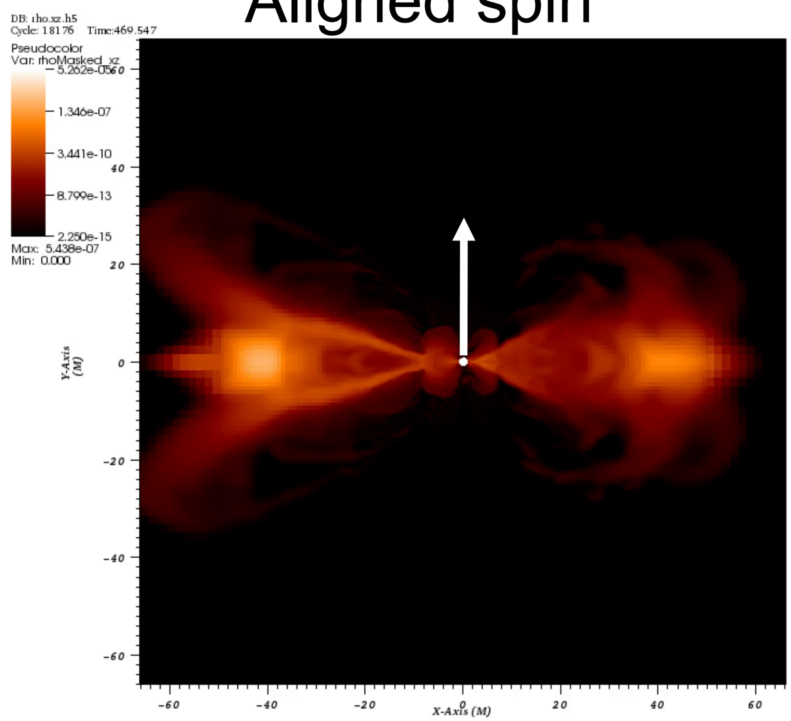


Haas et al 2012

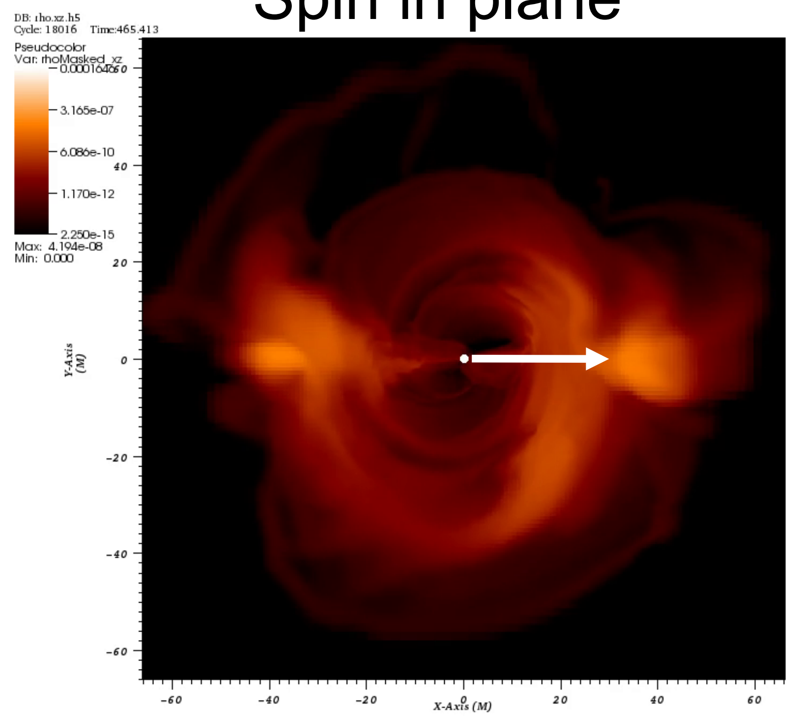
- WD disrupted by a 1,000 M_{solar} BH
- Eventually fallback rate settles down to $t^{-5/3}$
- Amplitude of accretion depends on spin and its orientation

Effects of spin misalignment

Aligned spin

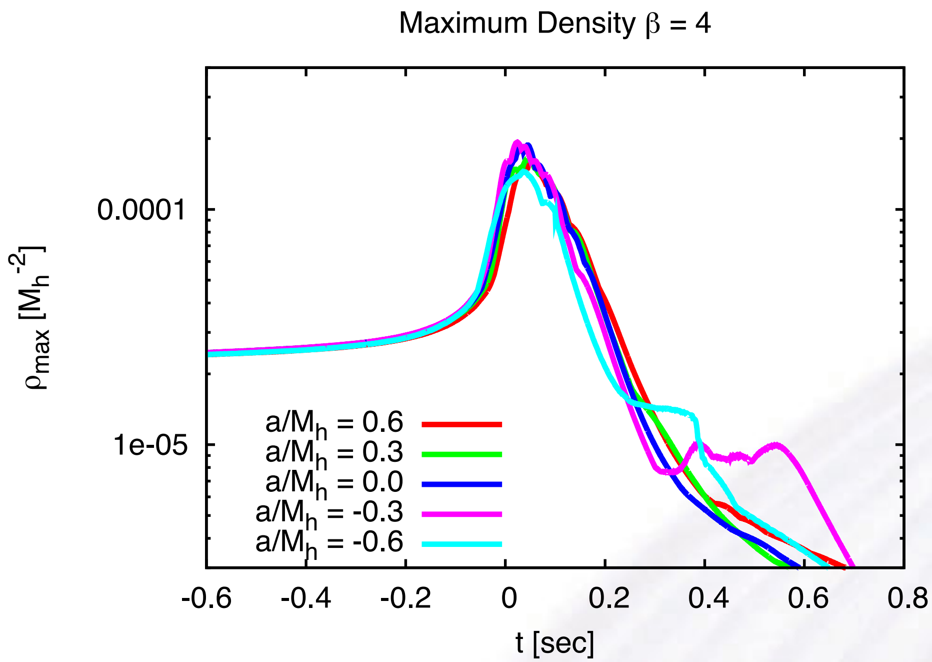


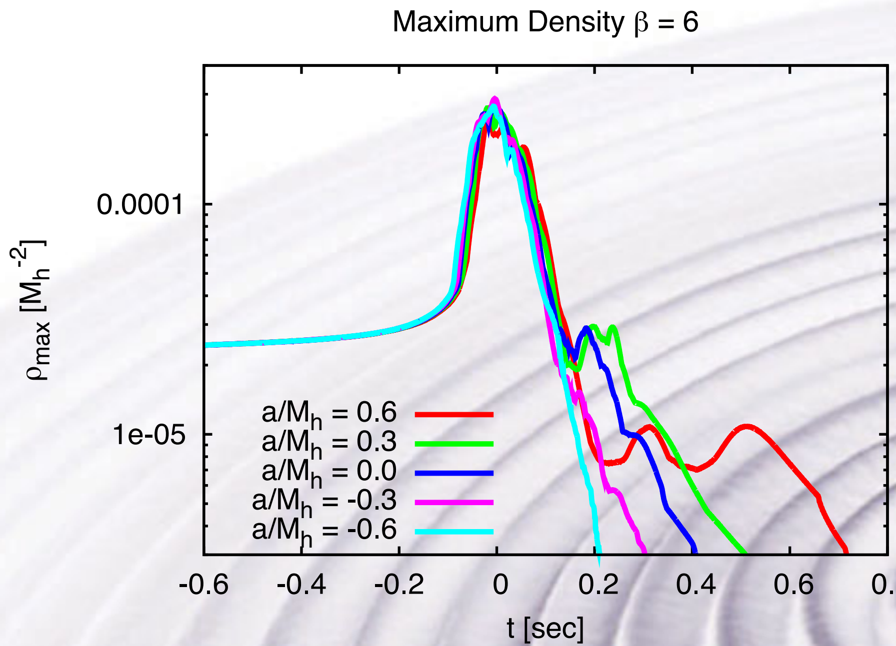
Spin in plane



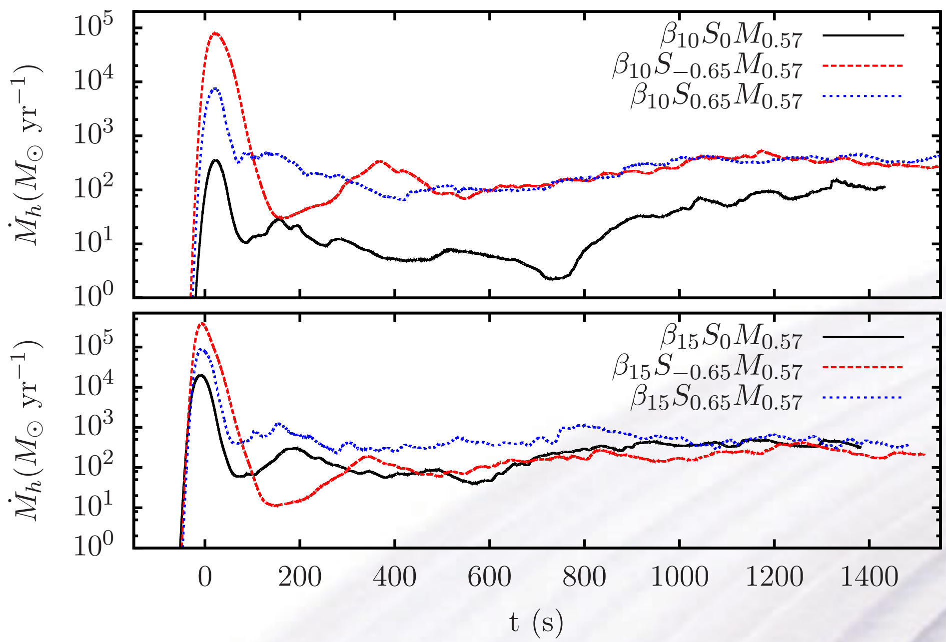
- Material is influenced by frame dragging
- Inner region obscured by debris

Density & Temperature @ Max Compression





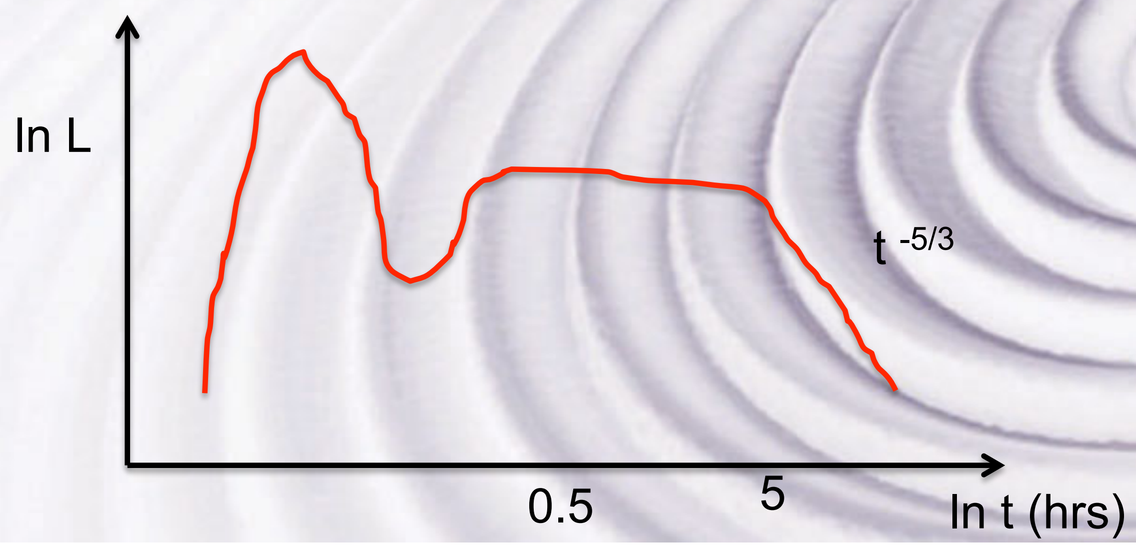
Accretion Rates



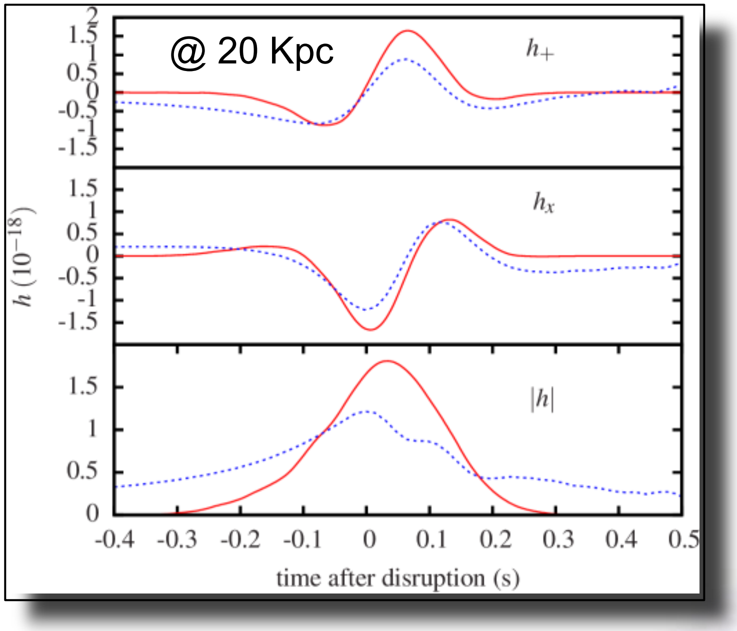
Time to swallow the bound debris:

$$T_* \approx \frac{0.5\,M_\odot}{10^3\,M_\odot\,\mathrm{yr}^{-1}} \sim 5\,\mathrm{hrs}$$

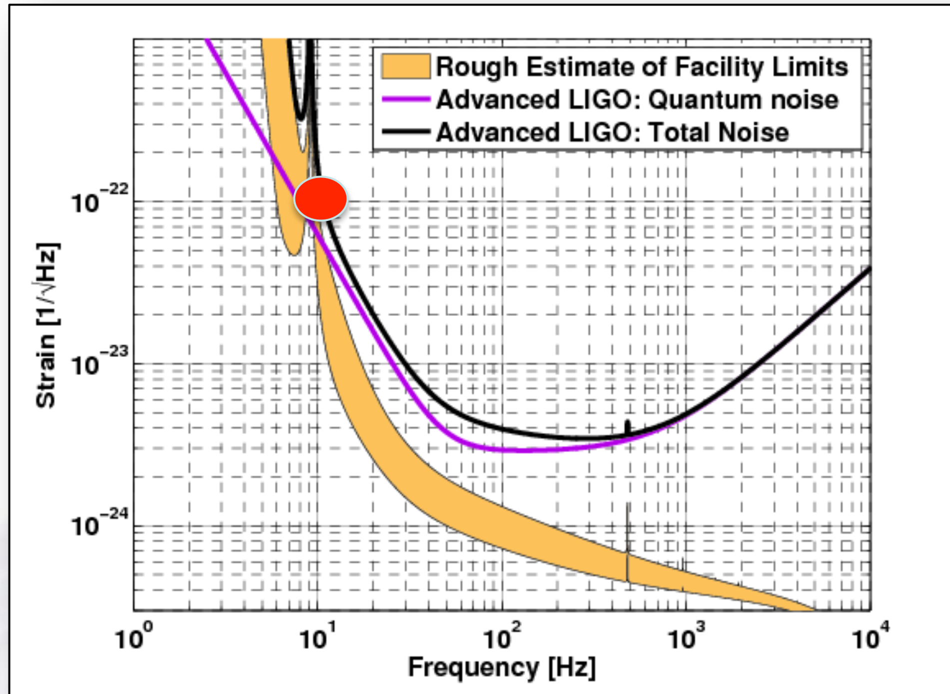
Simulation time ~ 0.6 hrs



Gravitational Waves from Star-BH System



Haas, Bode, Schervakov & PL 2004



$$h \sim \frac{M_* M_h}{D R_p} \sim \beta D^{-1} R_*^{-1} M_*^{4/3} M_h^{2/3}$$

$$\sim 10^{-22}\left(\frac{\beta}{10}\right)\left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1}\left(\frac{R_{ms}}{R_\odot}\right)^{-1}\left(\frac{M_{ms}}{M_\odot}\right)^{4/3}\left(\frac{M_h}{10^6 M_\odot}\right)^{2/3}$$

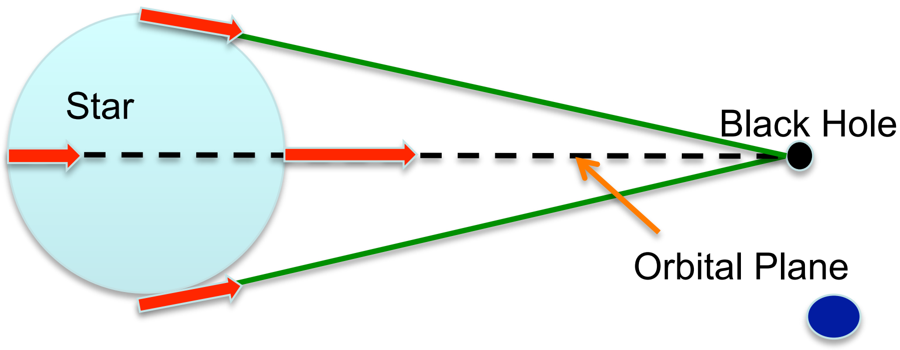
$$\sim 10^{-22}\left(\frac{\beta}{10}\right)\left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1}\left(\frac{R_{wd}}{R_\oplus}\right)^{-1}\left(\frac{M_{wd}}{M_\odot}\right)^{4/3}\left(\frac{M_h}{10^4 M_\odot}\right)^{2/3}$$

$$f \sim \left(\frac{M_{bh}}{R_p^3}\right)^{1/2} \sim \beta^{3/2} R_*^{-3/2} M_*^{1/2}$$

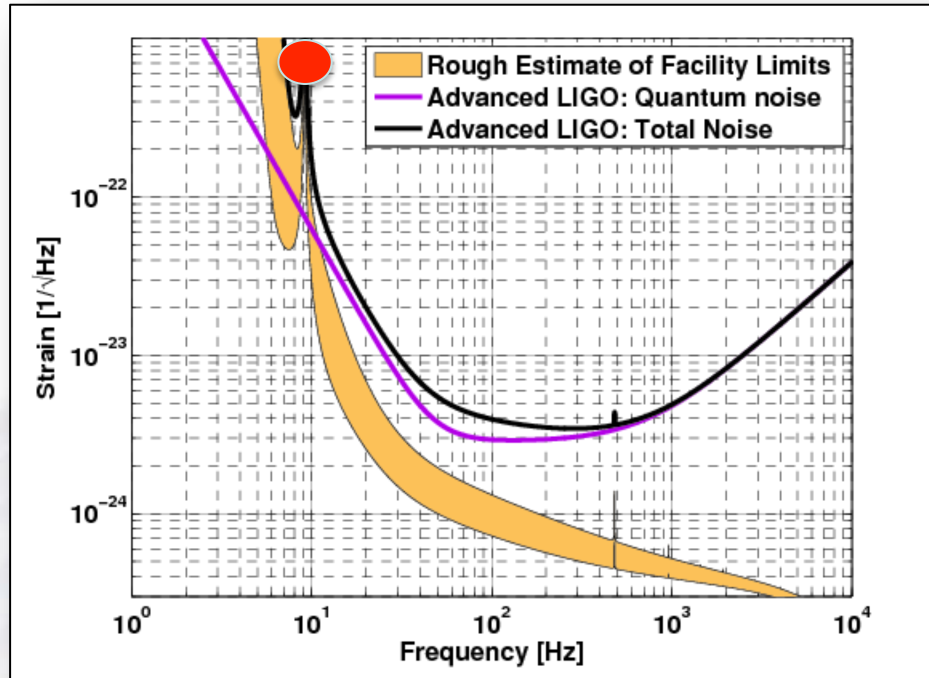
$$\sim 0.02\left(\frac{\beta}{10}\right)^{3/2}\left(\frac{R_{ms}}{R_\odot}\right)^{-3/2}\left(\frac{M_{ms}}{M_\odot}\right)^{1/2}\ \mathrm{Hz}$$

$$\sim 10\left(\frac{\beta}{10}\right)^{3/2}\left(\frac{R_{wd}}{R_\oplus}\right)^{-3/2}\left(\frac{M_{wd}}{M_\odot}\right)^{1/2}\ \mathrm{Hz}$$

Gravitational Waves from Star Compression



Guillichon et al 2008; Stone et al 2012



$$h \sim \frac{\beta^3 M_*^2}{D R_*}$$

$$\sim 10^{-23} \left(\frac{\beta}{10}\right)^3 \left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \left(\frac{R_{ms}}{R_\odot}\right)^{-1} \left(\frac{M_{ms}}{M_\odot}\right)^2$$

$$\sim 10^{-21} \left(\frac{\beta}{10}\right)^3 \left(\frac{D}{100\,\mathrm{Mpc}}\right)^{-1} \left(\frac{R_{wd}}{R_\oplus}\right)^{-1} \left(\frac{M_{wd}}{M_\odot}\right)^2$$

$$f \sim \beta^4 R_*^{-3/2} M_*^{1/2}$$

$$\sim 0.02 \left(\frac{\beta}{10}\right)^4 \left(\frac{R_{ms}}{R_\odot}\right)^{-3/2} \left(\frac{M_{ms}}{M_\odot}\right)^{1/2} \mathrm{Hz}$$

$$\sim 10 \left(\frac{\beta}{10}\right)^4 \left(\frac{R_{wd}}{R_\oplus}\right)^{-3/2} \left(\frac{M_{wd}}{M_\odot}\right)^{1/2} \mathrm{Hz}$$

Summary

- For ultra-close encounters ($R_t \sim R_{g)}$, the tools of numerical relativity are needed to get the correct gas dynamics to model TDEs
- Early accretion, outflow and fallback rate will tell us about the BH's spin
- TDEs with prompt accretion will help identifying IMBH
- Magnetic fields could provided models of jetted TDEs
- TDEs of WD by IMBH could potentially be candidates for multi-messenger observations

Questions

- What is the physics needed in TDE simulations to understand the observed luminosities beyond the estimates from accretion rates?
- Are there other ubiquitous signatures of TDEs besides the $t^{-5/3}$ accretion rate decay.
- Jetted TDEs?