GR Precession and Debris Circularization in TDEs

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HAYASAKI, STONE & LOEB 2013

STONE, HAYASAKI & LOEB
(IN PREP.)

Tidal Disruption of Stars

- Laboratory for accretion/ jet astrophysics
  - Super-Eddington flows
  - Jet launching mechanisms
- Unique probe of quiescent galactic nuclei
  - SMBH mass, spin from *lightcurve, SED*
  - Stellar dynamics from *rate, inferred pericenter*

(Wikimedia Commons)

Tidal Disruption Basics

- Tidal radius: $R_t = R_* \sqrt[3]{M_{BH}/M_*}$
- Only SMBHs with $M_{BH}<10^8\ M_\odot$ can disrupt solar-type stars
  - Unless the SMBH is spinning rapidly (Kesden 11)

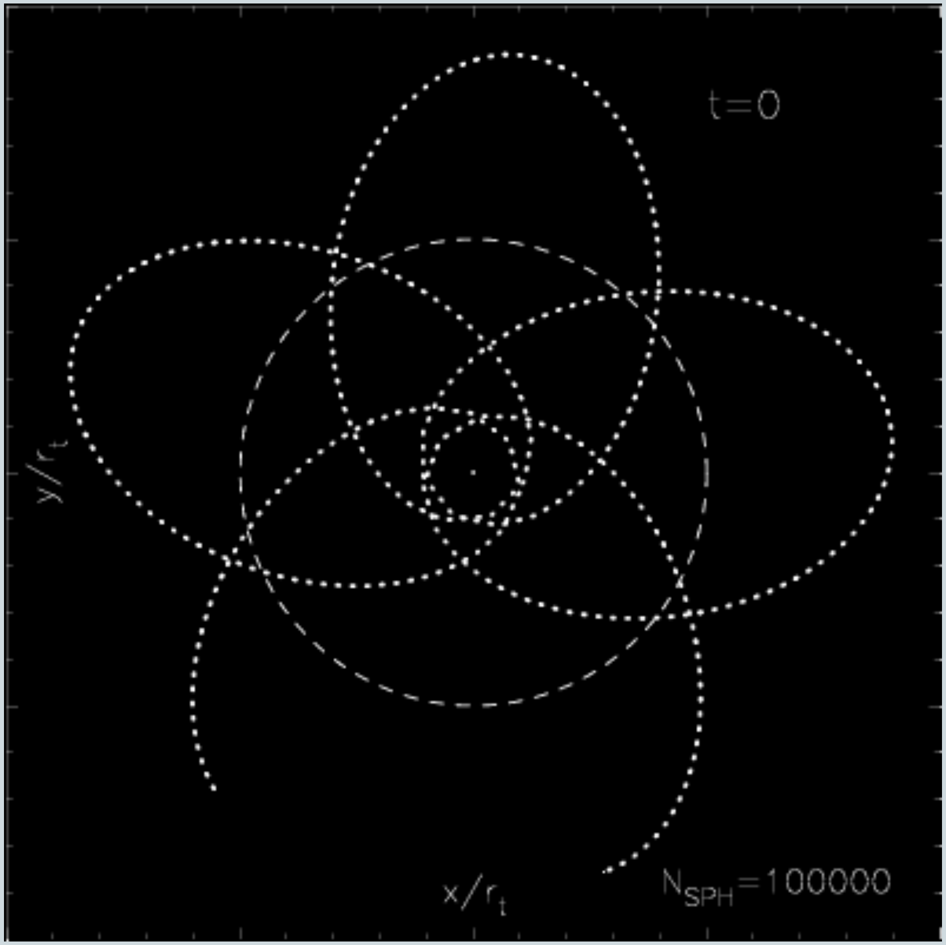
- Strength of tidal encounter defined by penetration factor $\beta=R_t/R_p$
  - $1<\beta<47$ for SMBHs; equivalently $1<R_p/R_g<47$

- Lightcurve often assumed to follow: $L \propto \dot{M} \propto t^{-5/3}$
  - At early times, numerical models for dM/dt necessary (Lodato+09, Guillochon & Ramirez-Ruiz 13)
  - dM/dt encodes stellar parameters

Circularization of Tidal Debris

- Has not been simulated for e=1 TDEs around SMBHs
  - Critical for understanding early phase of light curve
- Two hypothesized shock formation mechanisms:
- Nozzle at pericenter (vertical shocks)
  - Seen in e=1 star-IMBH TDEs (Ramirez-Ruiz & Rosswog 09, Guillochon+13)
- Relativistic precession, debris stream self-intersection (Rees 88)
  - Semi-analytic model – Kochanek 94
  - Seen in e=0.8 star-SMBH SPH simulations (Hayasaki, **Stone** & Loeb 13)

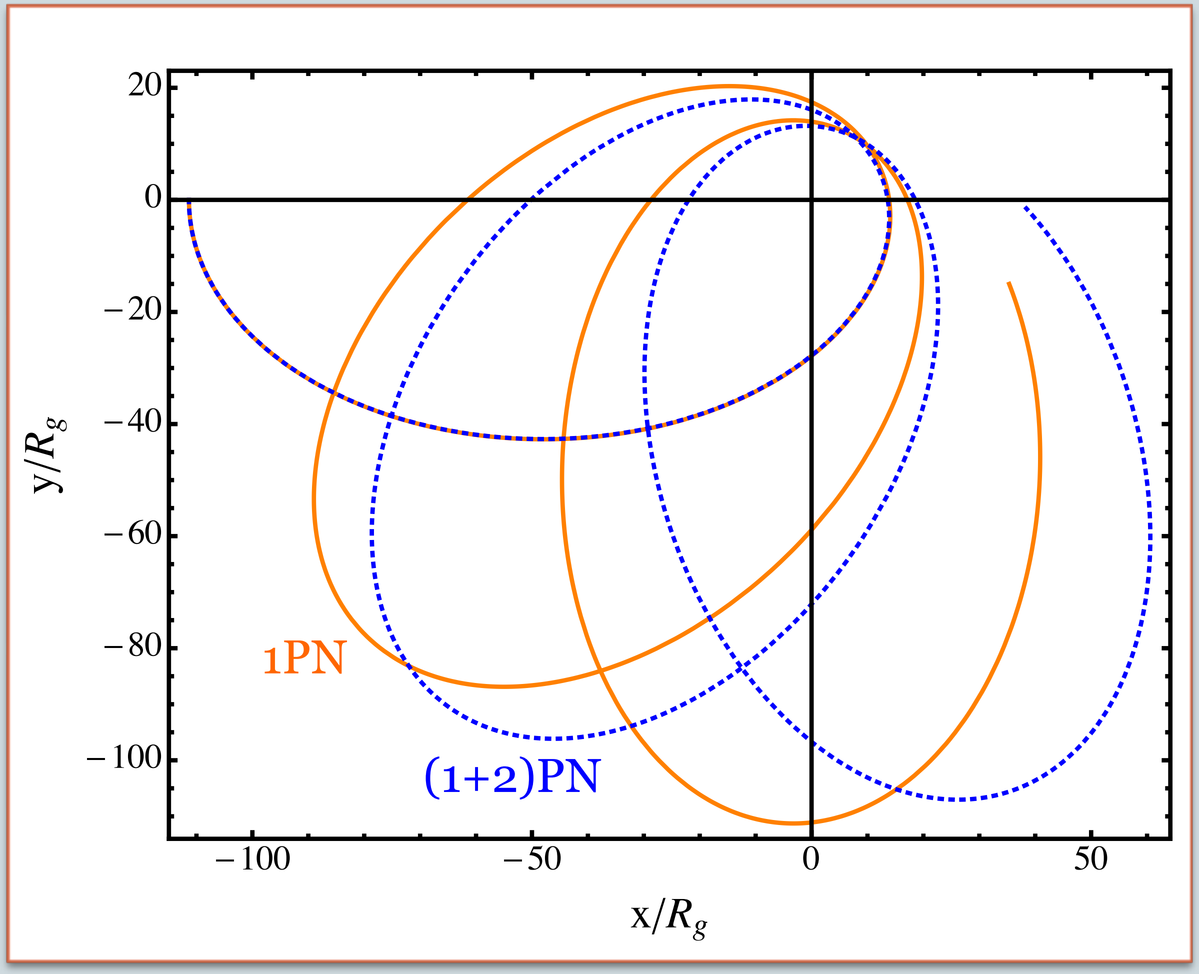
Results: Wegg Potential



(Hayasaki, **Stone** & Loeb 13)

Physical Picture: Schwarzschild SMBH

- Apsidal precession causes stream self-intersection at R_{si}
- Large angle shocks occur unless intersection $R_{si} \approx R_{apo}$

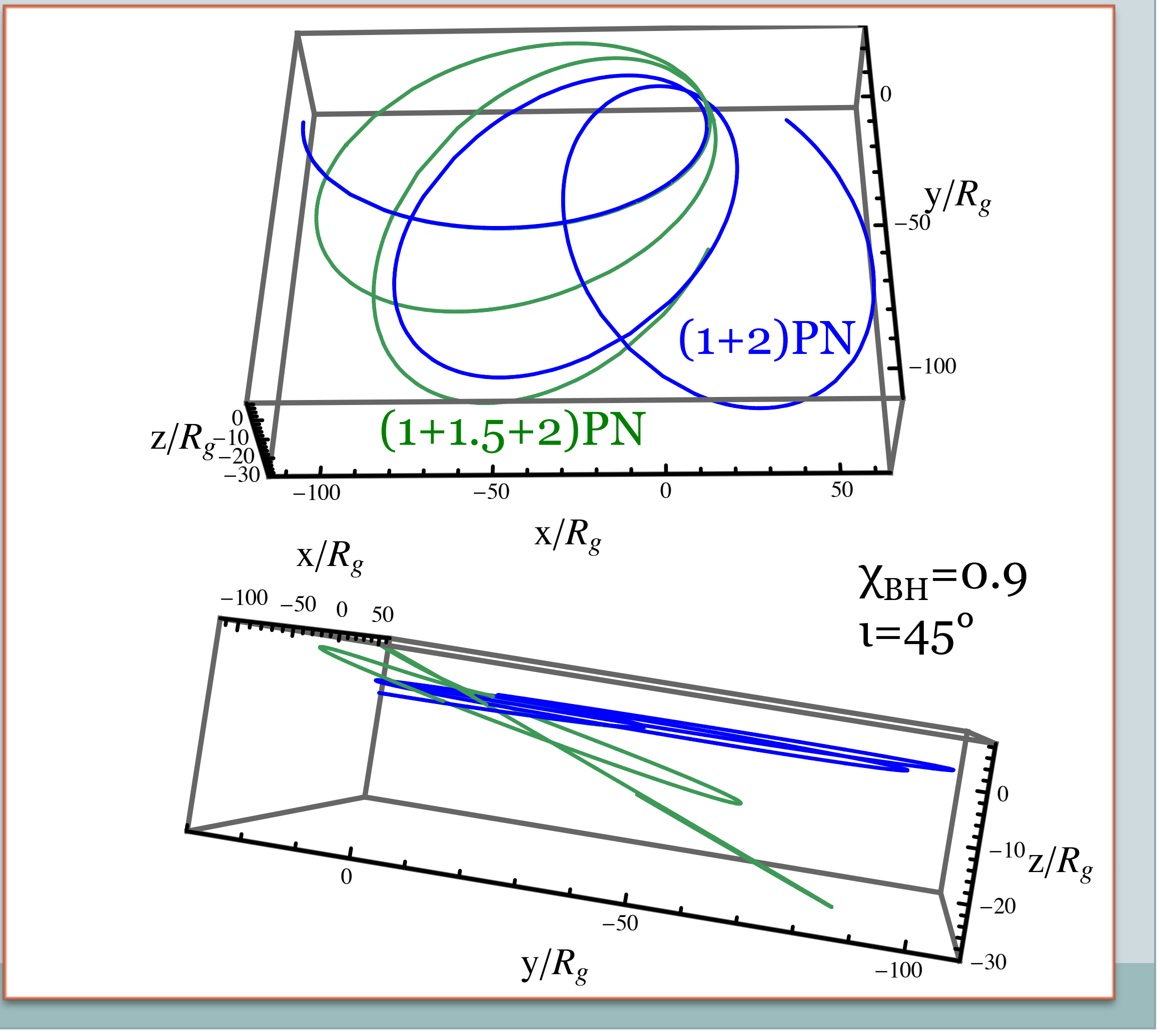


(**Stone**, Hayasaki & Loeb *in prep*)

Physical Picture: Kerr SMBH

- Misaligned SMBH spin χ_{BH} breaks orbital plane symmetry
- Lense-Thirring torques cause nodal precession of orbital plane
- Debris streams miss each other; shocks prevented

(**Stone**, Hayasaki & Loeb *in prep*)



Analytic Treatment: Schwarzschild

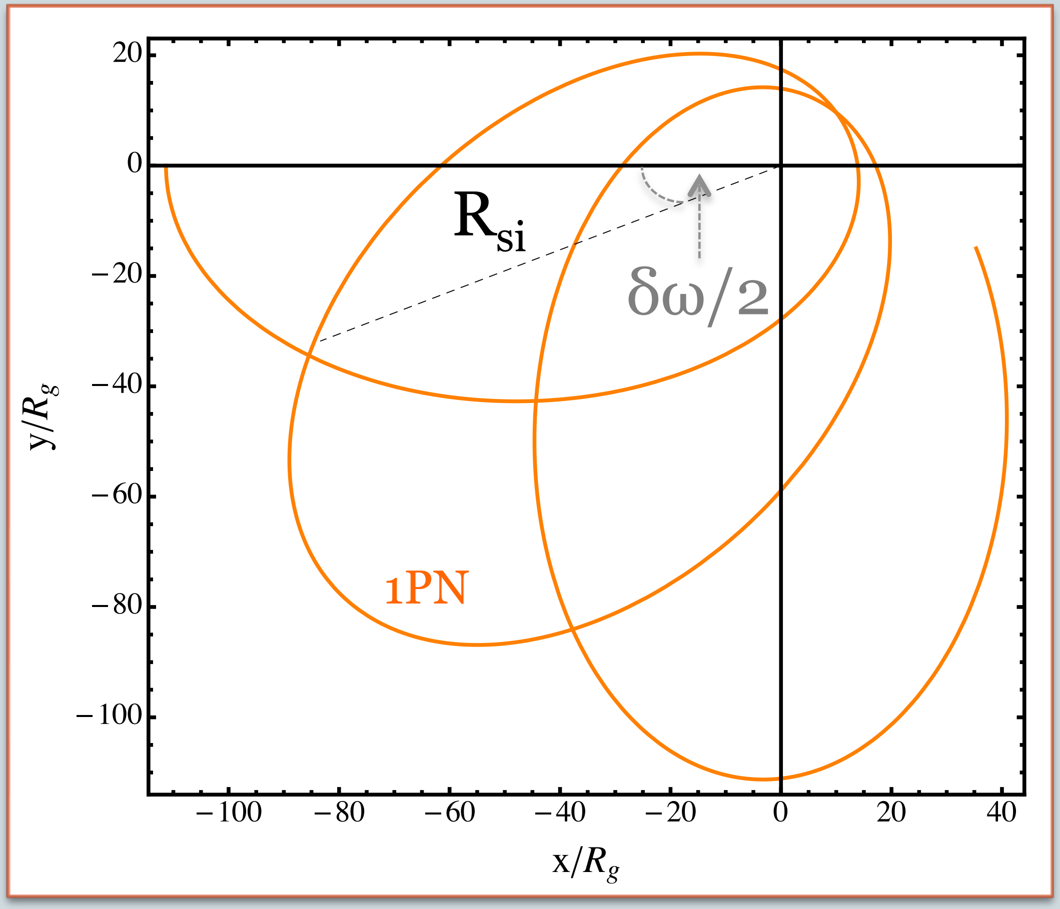
- Impulsive PN approximation: all precession at pericenter

$$\delta\omega = \frac{6\pi}{c^2}\frac{GM_{BH}}{a(1-e^2)}$$

$$\approx 11.5^\circ \left(\frac{\tilde{R}_p}{47}\right)^{-1}$$

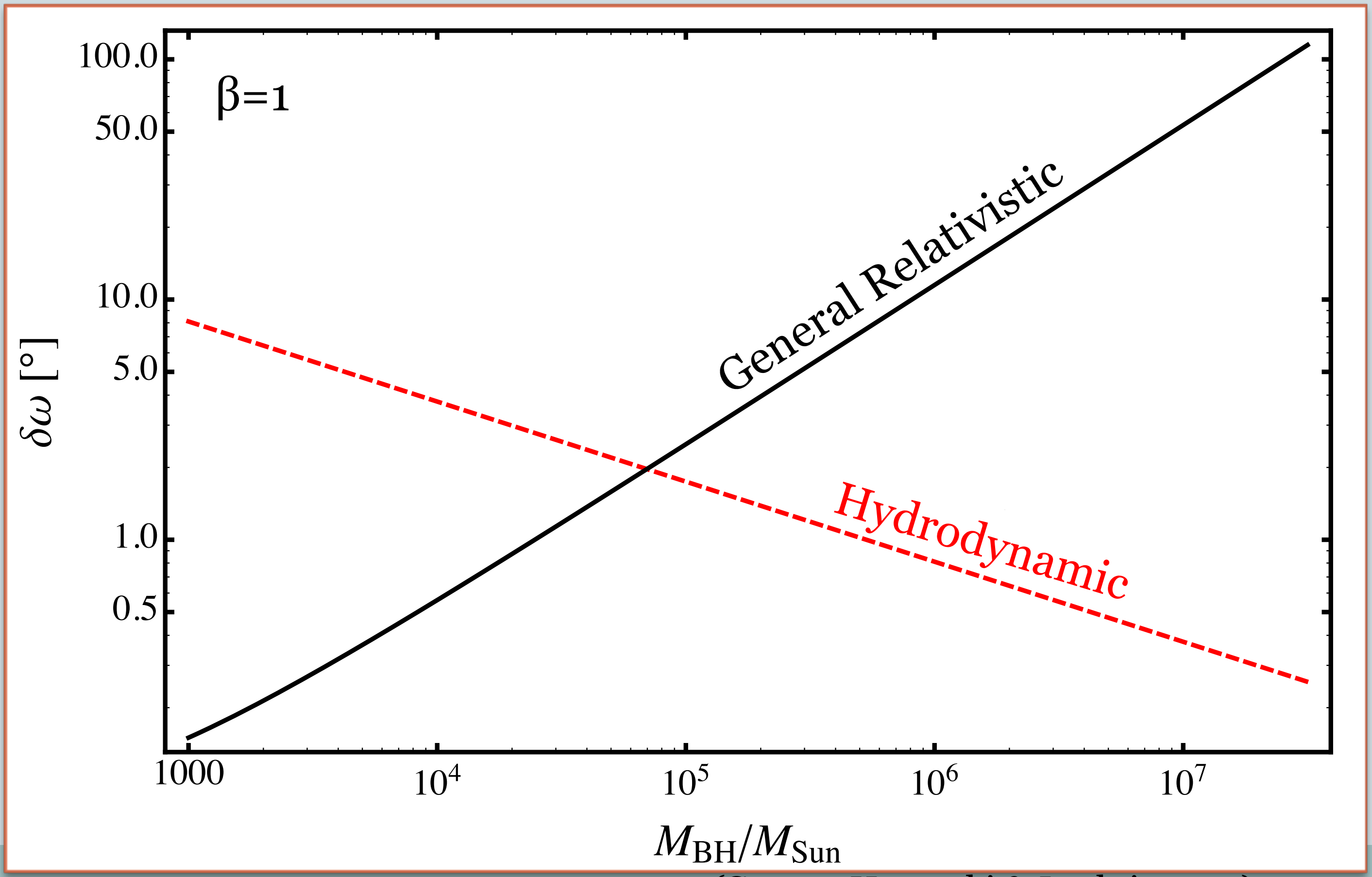
- Self-intersection occurs at $\pi \pm \delta\omega/2$

(**Stone**, Hayasaki & Loeb *in prep*)



GR versus Hydrodynamic Effective Precession

- Hydrodynamic "precession" competitive for IMBHs



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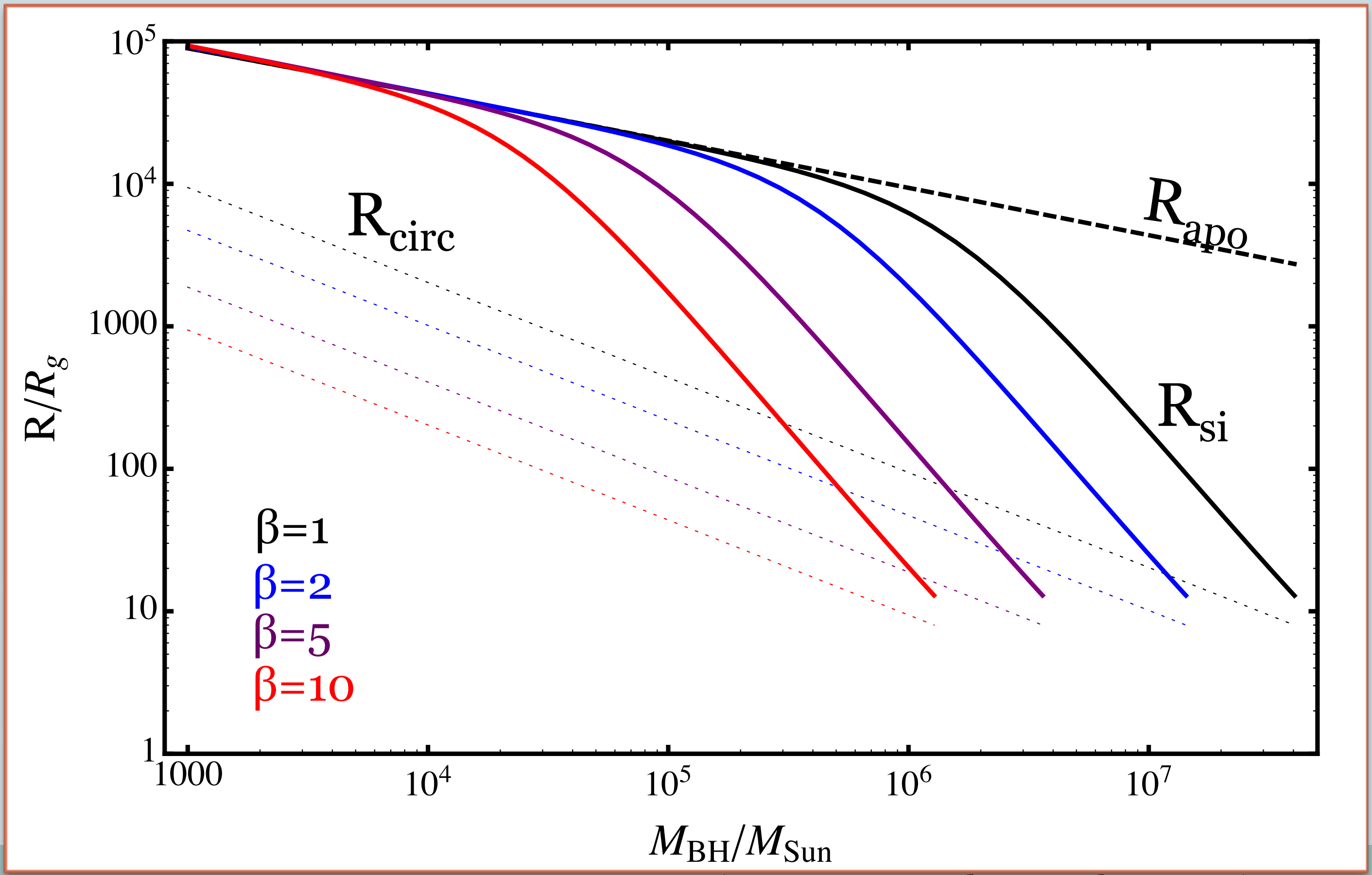
Incomplete Circularization via GR?

- Large-angle collisions only out to $R_{si} >> R_{circ}=2R_p$



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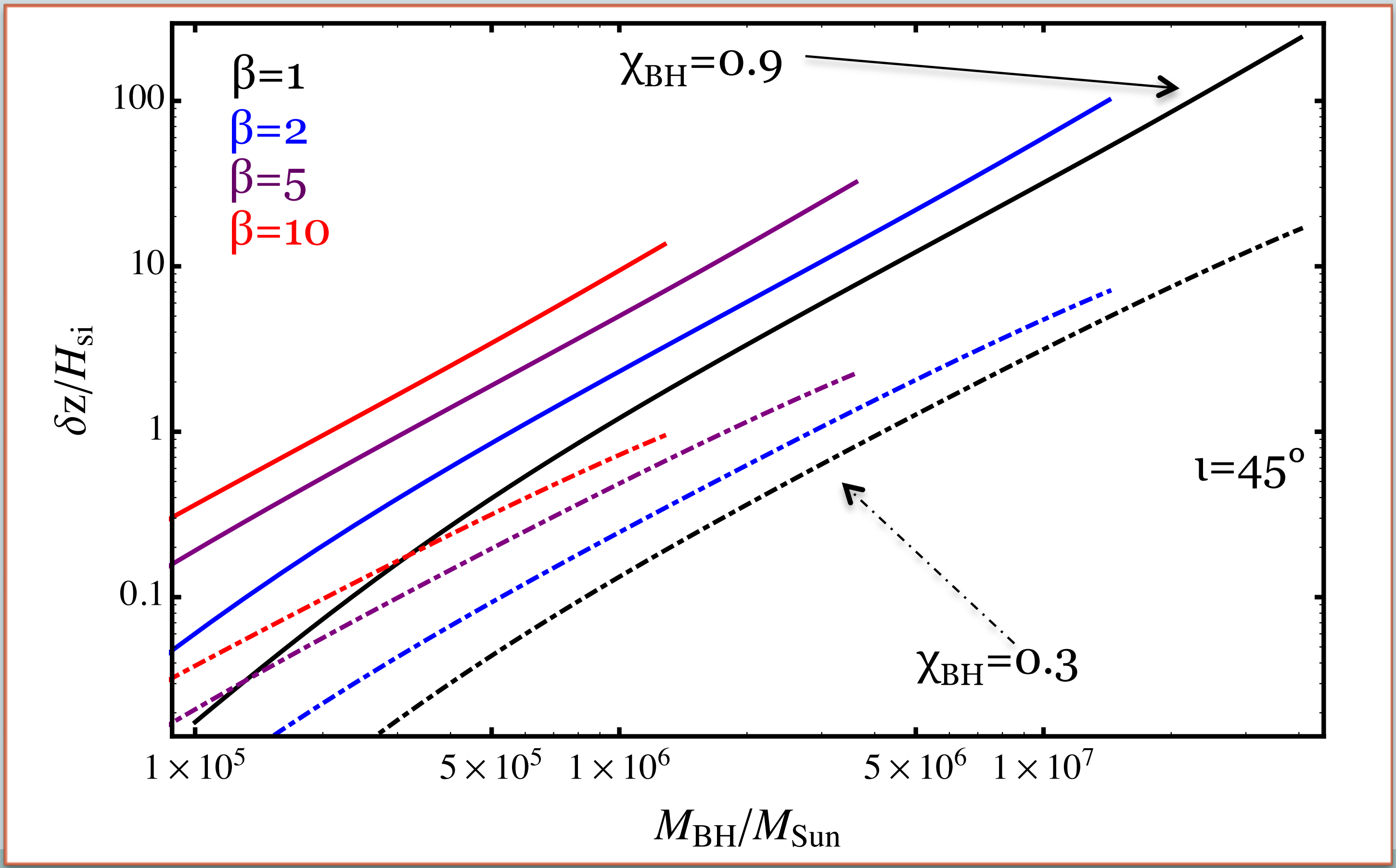
Delays Due to Lense-Thirring Precession

- Height-normalized misalignment δz: sensitive to β



(**Stone**, Hayasaki & Loeb *in prep*)

Conclusions

- Rising phase of light curve controlled by both dM/dt *and* circularization
  - Complicates extraction of stellar structure parameters
- GR precession may produce eccentric disks
  - $\beta=1$, $M_{BH}<10^6 M_\odot$ unlikely to efficiently circularize
- GR precession dominates hydrodynamic "precession" for $M_{BH}>10^5 M_\odot$
- Both R_{si} and $\delta z/H$ strong function of β
- If streams remain vertically self-gravitating, serious delay in circularization for $\chi_{BH}>0.75$ (0.3) when $M_{BH}=10^6\ M_\odot$ ($10^7\ M_\odot$)

Questions?

Analytic Treatment: Kerr

- Nodal precession also impulsive to high accuracy

$$\delta\Omega = \frac{4\pi\chi_{BH}}{c^3}\left(\frac{GM_{BH}}{a(1-e^2)}\right)^{3/2} - \frac{3\pi\chi_{BH}^2}{c^4}\left(\frac{GM_{BH}}{a(1-e^2)}\right)^2 \cos\iota$$

Lense-Thirring

Quadrupole Moment

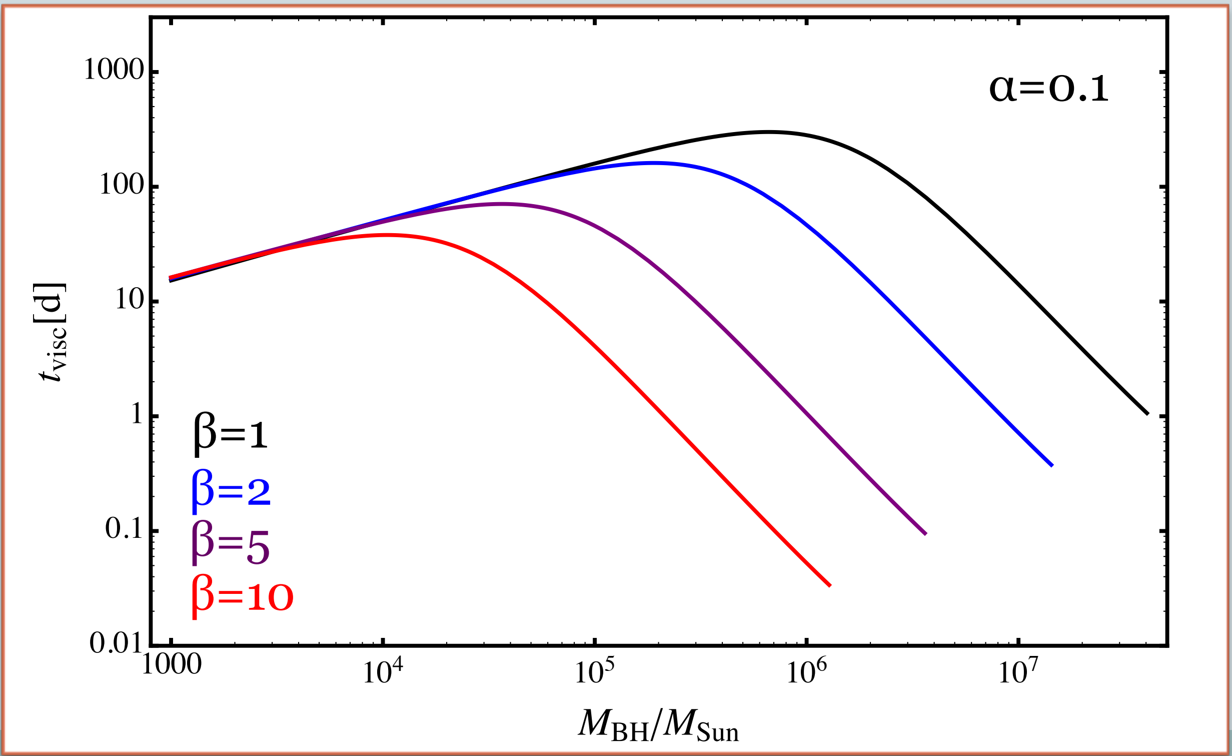
$$\approx 0.79^\circ\left(\frac{\tilde{R}_p}{47}\right)^{-3/2}\chi_{BH} - 0.0706^\circ\left(\frac{\tilde{R}_p}{47}\right)^{-2}\chi_{BH}^2\cos\iota$$

- In impulsive limit, streams miss each other by:

$$\frac{\delta z}{R_{si}} = \left(2\cos\iota\sin\frac{\delta\omega}{2}\sin^2\frac{\delta\Omega}{2} + \cos\frac{\delta\omega}{2}\sin\delta\Omega\right)^2 + \left(\cos\frac{\delta\omega}{2}(\cos\delta\Omega - 1) - \cos\iota\sin\frac{\delta\omega}{2}\sin\delta\Omega\right)^2$$

Eccentric Disks

- Eccentric disks unstable on a viscous timescale to shock/turbulent dissipation (Papaloizou 05)
  - Caveat: simulations in different regime (e~0.25, H/R~0.1)
  - Viscous spreading also reignites GR-driven shocks



(**Stone**, Hayasaki & Loeb *in prep*)

TDEs as Stellar Dynamical Probes

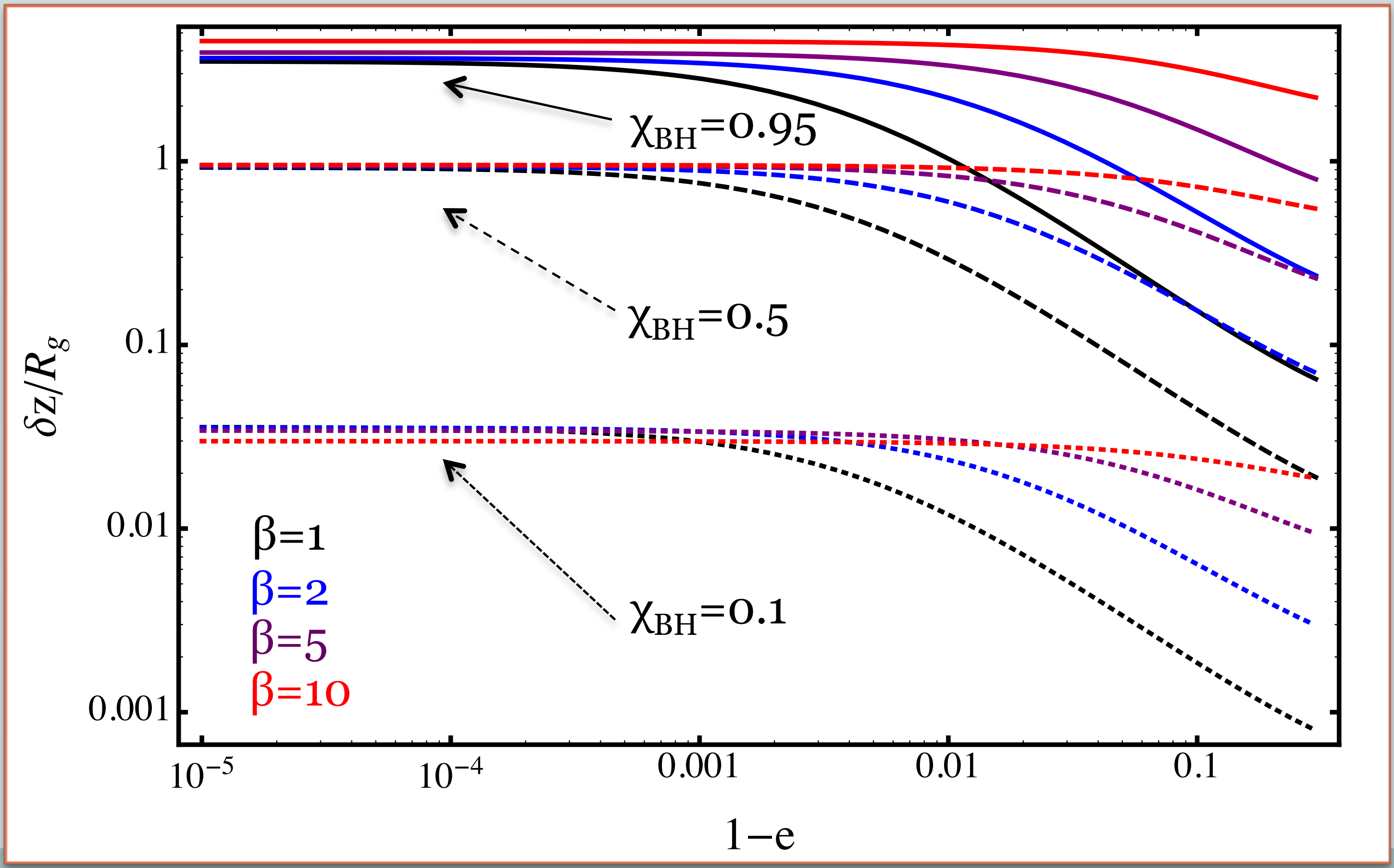
- TDEs offer indirect clues of extragalactic stellar dynamics
    - Rate, $\beta = R_t / R_p$

- Different TDE production mechanisms:
    - 2-body relaxation (full loss cone): low rate, $N(\beta) \alpha \beta^{-1}$
    - 2-body relaxation (empty loss cone): low rate, $\beta = 1$
    - Triaxial/axisymmetric orbits: high rate, $N(\beta) \alpha \beta^{-1}$

- Other mechanisms unlikely to dominate event rate

Delays Due to Lense-Thirring Precession

- Absolute value of misalignment δz: insensitive to β



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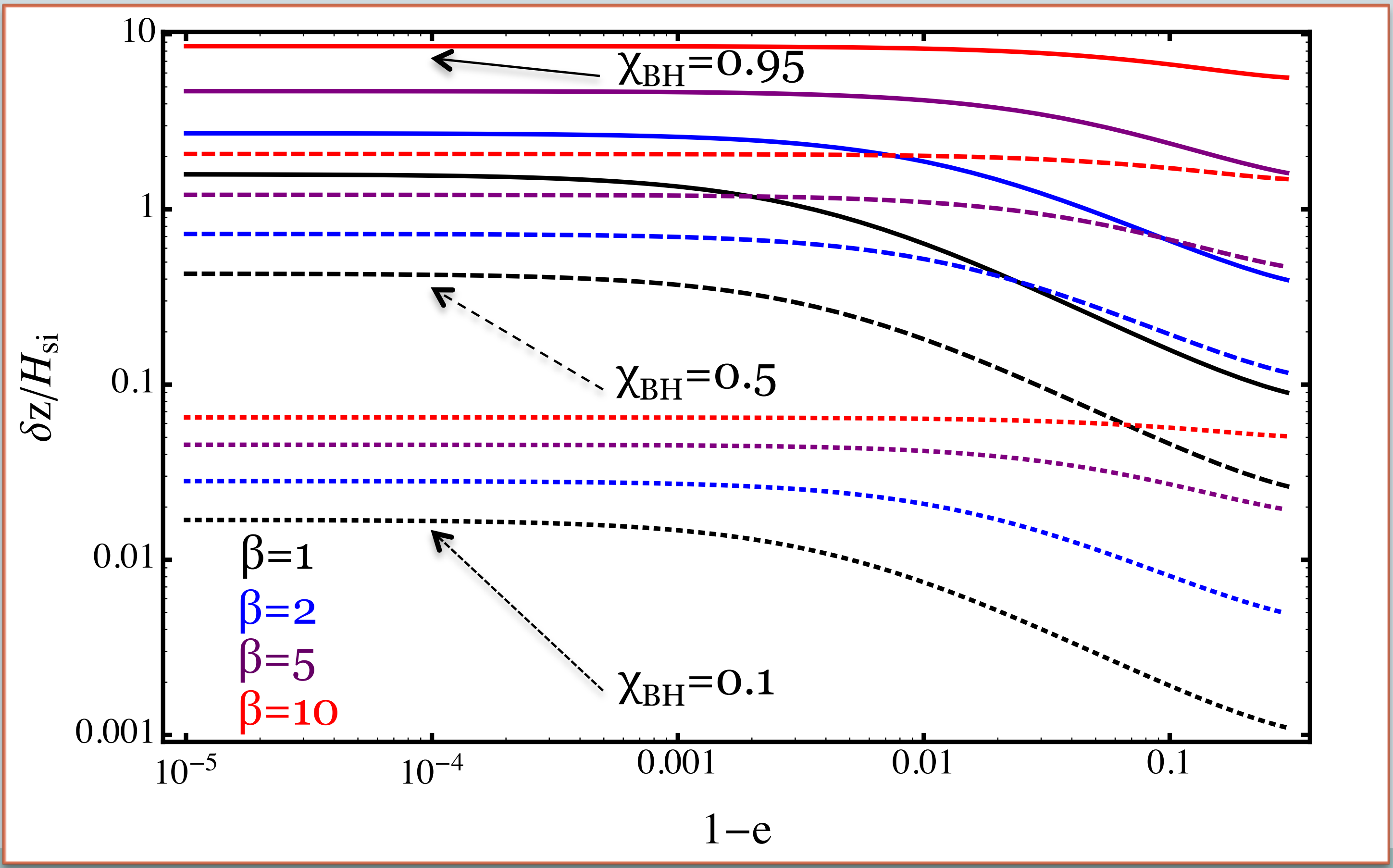
Delays Due to Lense-Thirring Precession

- Height-normalized misalignment δz: sensitive to β



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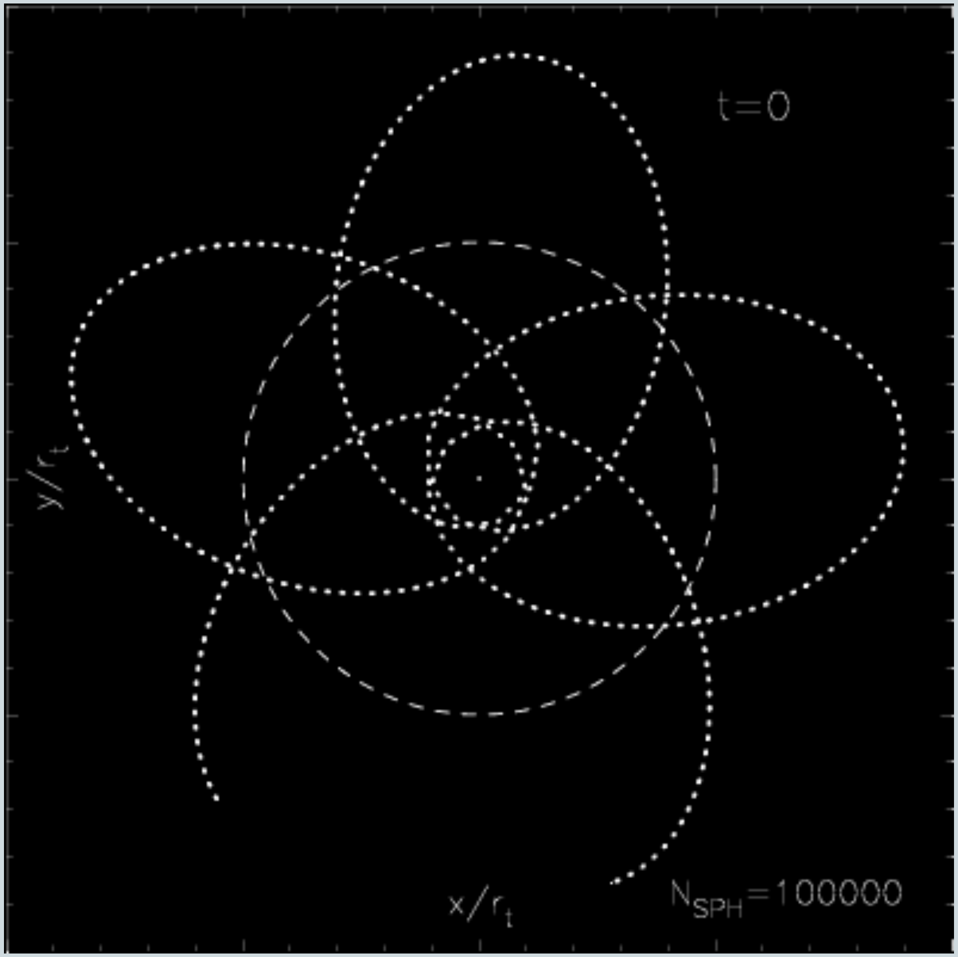
- Only SMBHs with $M_{BH} < 10^8\ M_\odot$ can disrupt solar-type stars
  - Unless the SMBH is spinning rapidly (Kesden 11)

- Spread in debris energy: $\Delta\varepsilon \sim GM_{BH} R_* / R_t^2$
  - Independent of R_p (**Stone**+13, Guillochon & Ramirez-Ruiz 13)
- Lightcurve often assumed to follow: $L \propto \dot{M} \propto t^{-5/3}$
  - At early times, numerical models for dM/dt necessary (Lodato+09, Guillochon & Ramirez-Ruiz 13)

- Strength of tidal encounter defined by penetration factor $\beta = R_t / R_p$
  - $1 < \beta < 47$ for SMBHs; equivalently $1 < R_p / R_g < 47$

Results: Newtonian



(Hayasaki, **Stone** & Loeb 13)

Numerical Methods

- SPH code developed by Okazaki+ 02, based on Benz 90, Bate+ 95
- Initialize polytropic star ($\gamma=5/3$) at $3R_t$
- Simulate disruption of e=1, e=0.98, e=0.8 orbits with
  - Newtonian potential
  - Pseudo-Newtonian potential (Wegg 12)

Tidal Disruption Physics

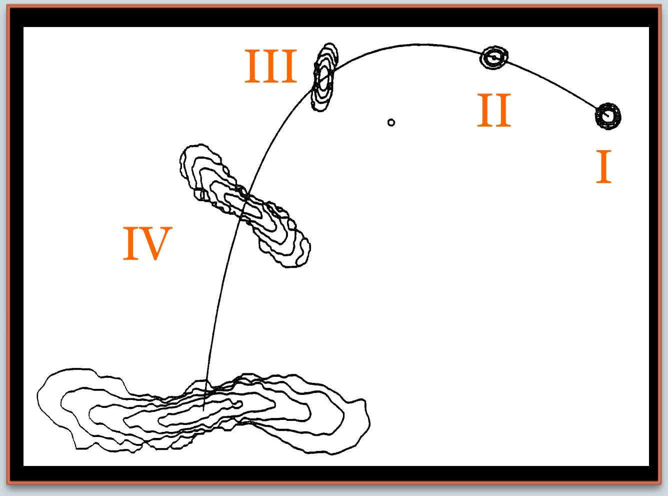
- Tidal radius: $R_t = R_* \sqrt[3]{M_{BH} / M_*}$
- Spread in debris energy: $\Delta\varepsilon \sim \frac{GM_{BH} R_*}{R_p^2}$
- Return time for most tightly bound debris:

$$t_{fall} \sim 20\,\mathrm{min} \left(\frac{M_{BH}}{10^6 M_{sun}} \right)^{5/2} \left(\frac{R_p}{3R_S} \right)^{3} \left(\frac{R_*}{R_{sun}} \right)^{-3/2}$$

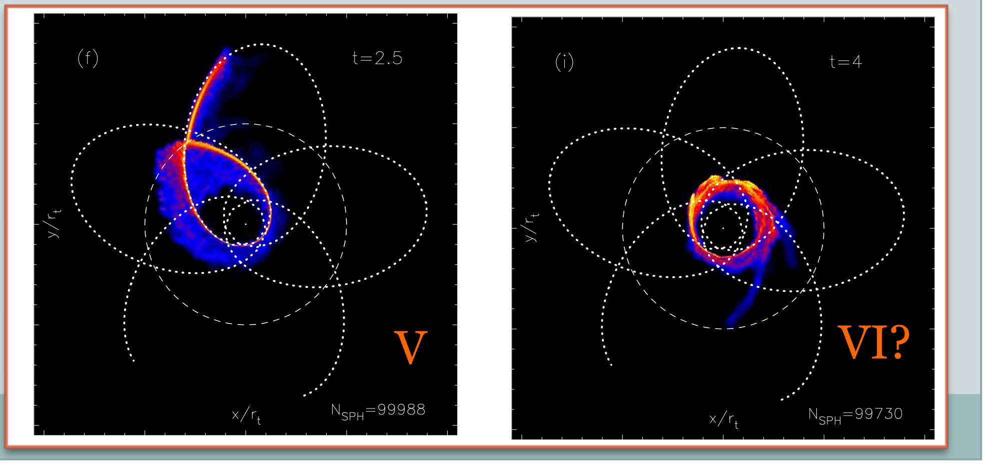
- Lightcurve often assumed to follow: $L \propto \dot{M} \propto t^{-5/3}$
- Disk SED multicolor blackbody, peaked in UV/soft X-ray

Stages of Tidal Disruption

- I: approximate hydrostatic equilibrium
- II: tidal free fall, vertical collapse
- III: maximum compression, bounce
- IV: rebound/expansion
- V: pericenter return, circularization
- VI: accretion



(Evans & Kochanek 89)



(Hayasaki, **Stone** & Loeb 12)