The Evolution of Accretion Disk in Tidal Disruption Events (TDEs)

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(in prep.)

ESAC Workshop of TDEs, Madrid, June 25, 2012

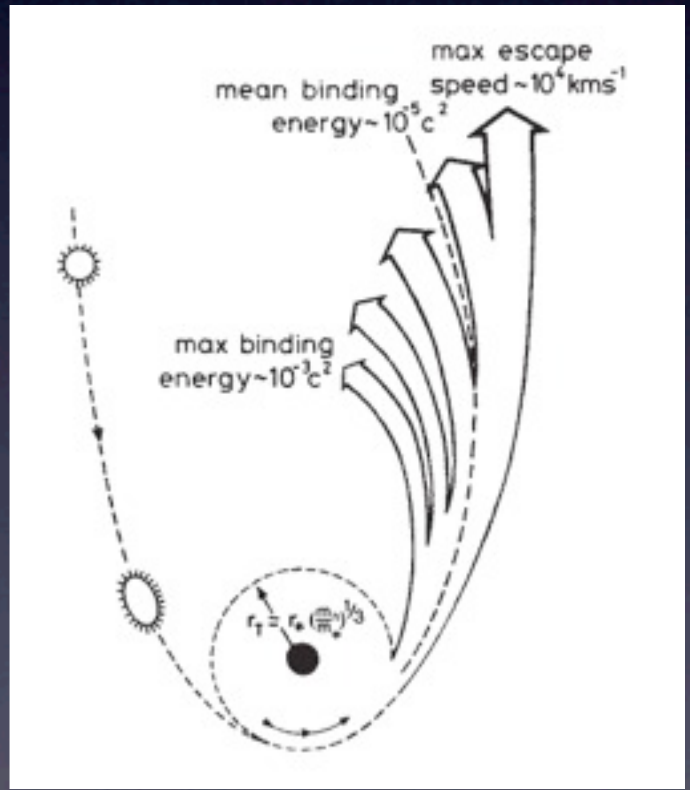
TDE model predictions

- (Rees 88; Evans & Kochanek 89; Li et al. 02; Strubbe & Quataert 09; Lodato et al. 09; ...)
- $R_T = R_* \, (M/M_*)^{1/3} \sim 20 \, M_6^{-2/3} r_* \, m_*^{-1/3}$ R_S.

  $\beta = R_T \, / \, R_p$.
- $t_f \sim 3.3{\times}10^6 \, \beta^{-3} \, M_6^{1/2} \, r_*^{2/3} \, m_*^{-1}$ s.
- Peak fallback rate $\sim 0.5 M_*/t_f$

  $\sim 10^{-7} \, \beta^3 \, M_6^{-1/2} \, r_*^{-2/3} \, m_*^2 \, M_\odot \, s^{-1}$

  $\sim 10^2 \, \beta^3 \, M_6^{-3/2} \, r_*^{-2/3} \, m_*^2$ × Eddington accretion rate (10% efficiency)!



(Rees 1988)

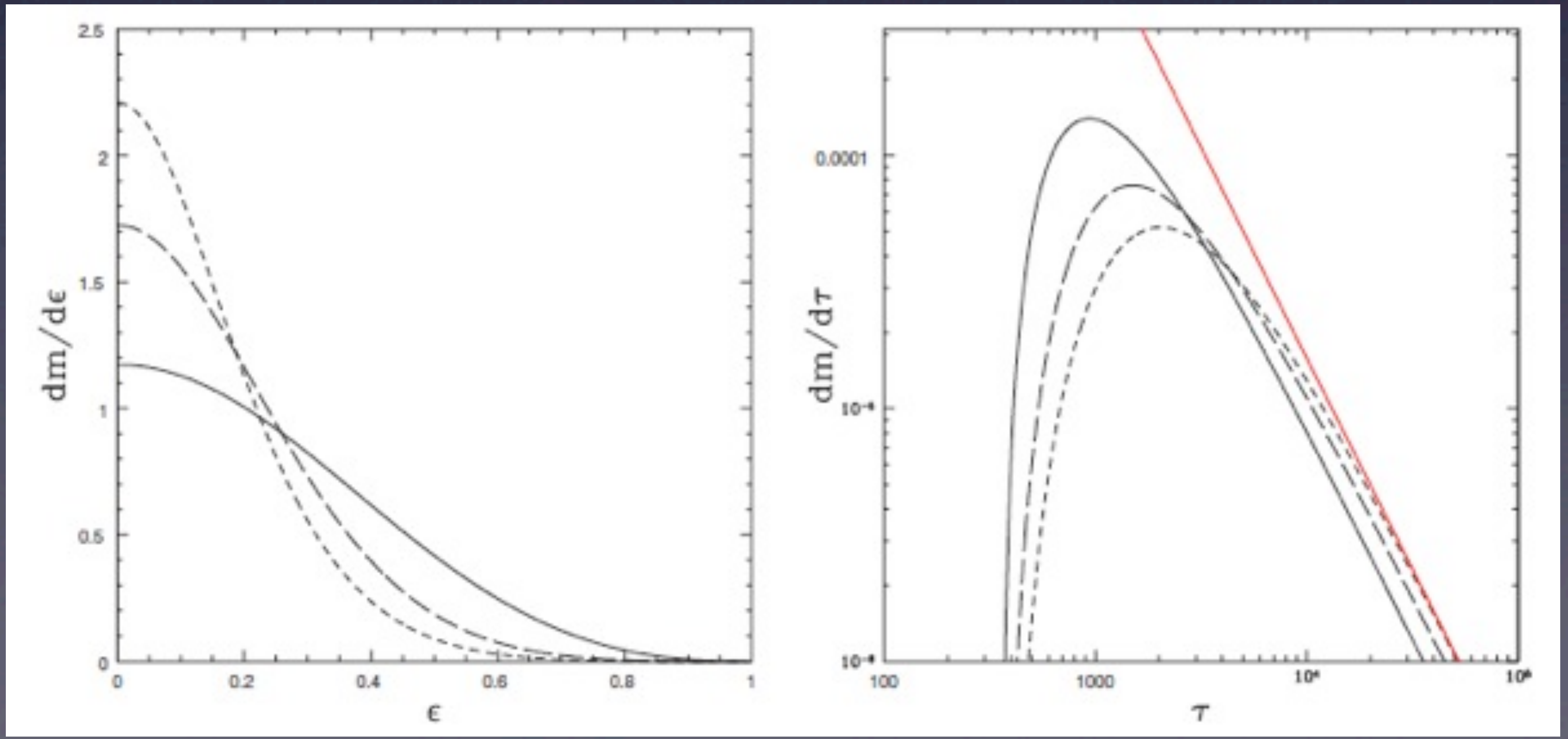
Debris mass fallback rate

- Fallback rate is determined by stellar mass distribution over specific energy.
- For constant distribution (e.g., Rees 1988),

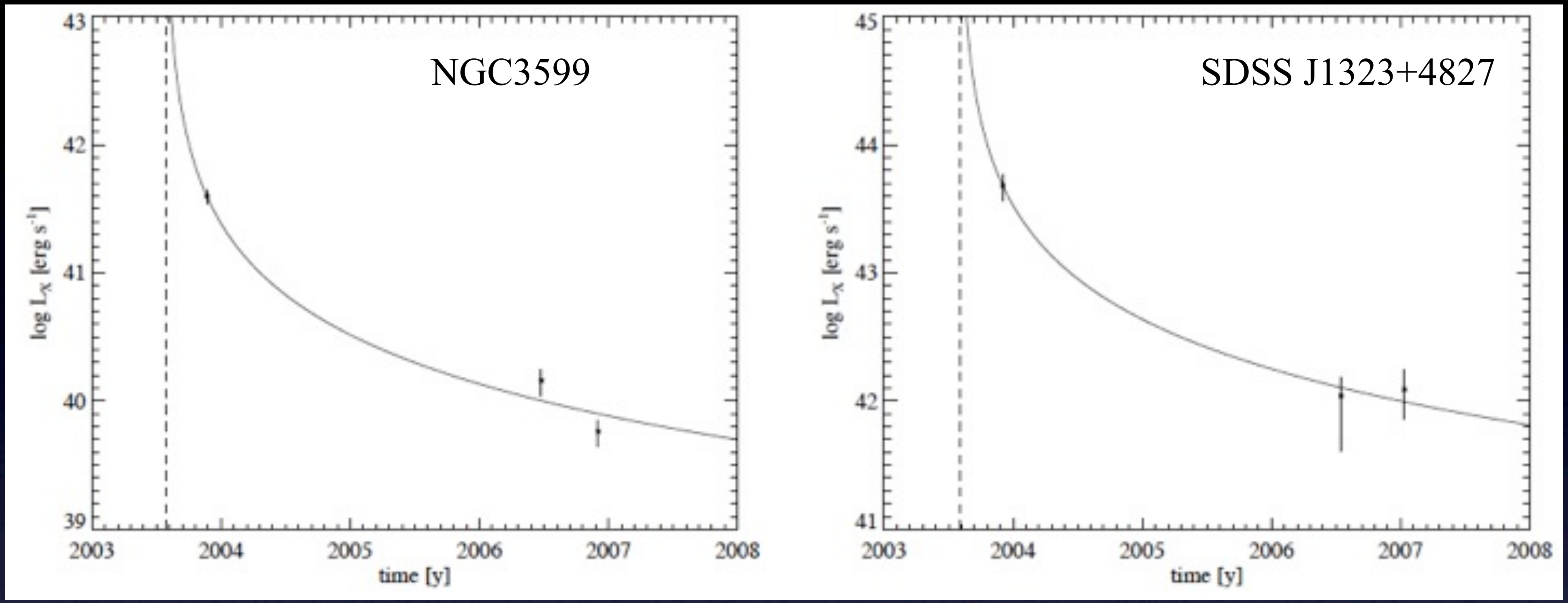
$$\dot{M}_{\rm fb} \propto (t/t_f)^{-\frac{5}{3}}$$

- Early fallback rate depends on stellar structure.

(Lodato et al. 2009; most recently Guillochon & Ramirez-Ruiz 2012)

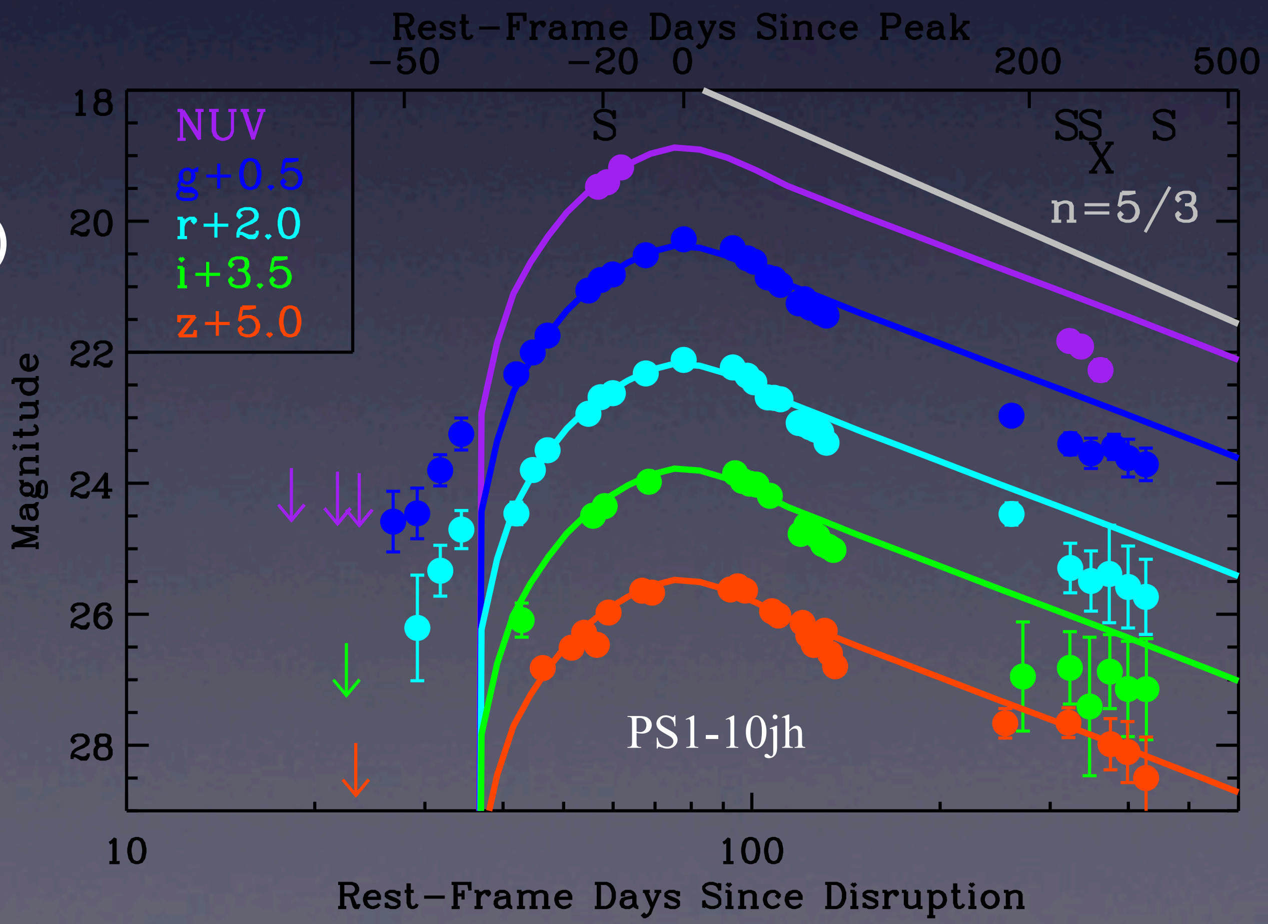


TDE observations



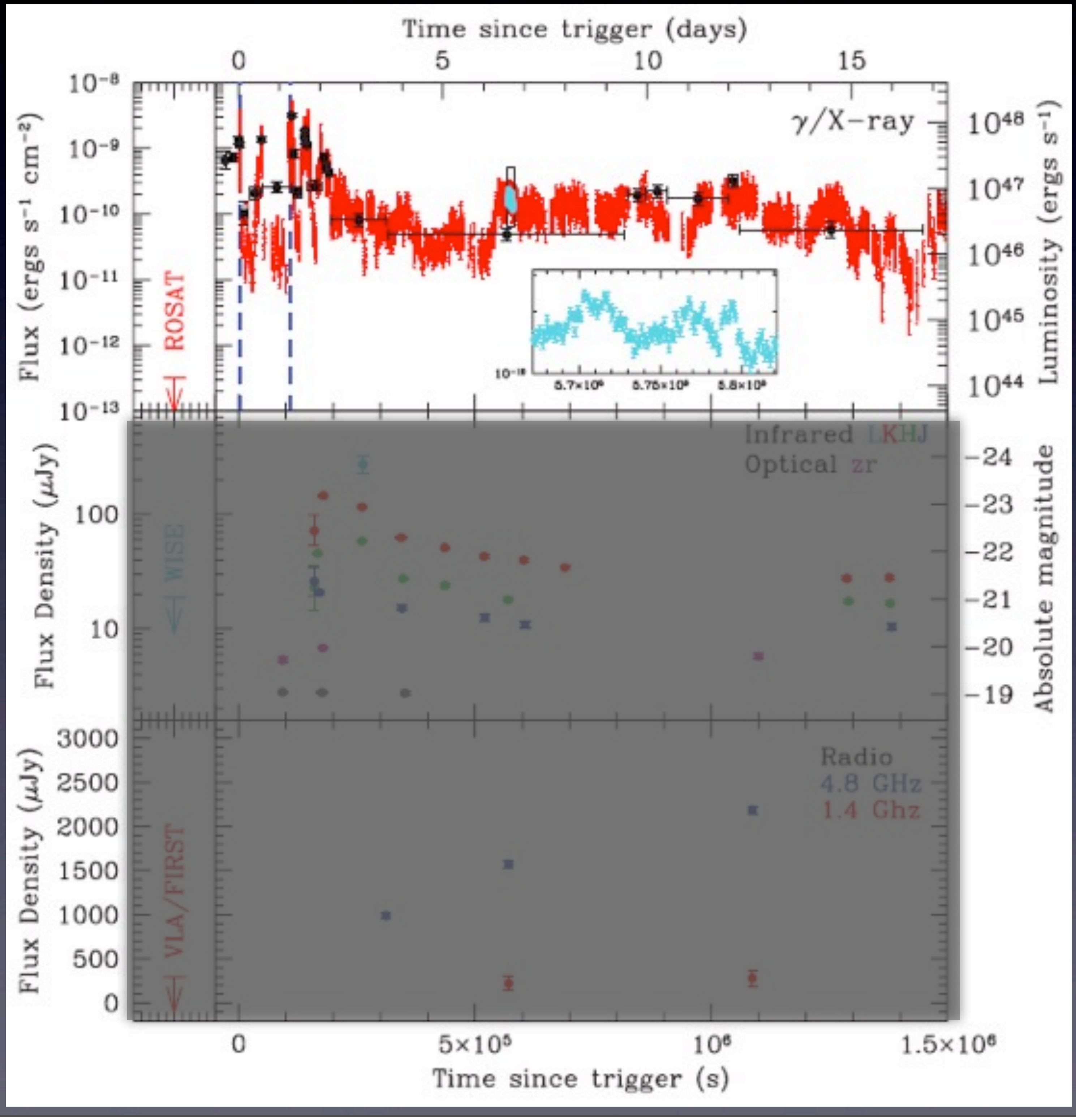
(Esquej et al. 2008)

(Gezari et al. 2012)



- Targets of transient surveys (Pan-STARRS, PTF, LSST, LOFAR, SARSIR, EXIST, …)

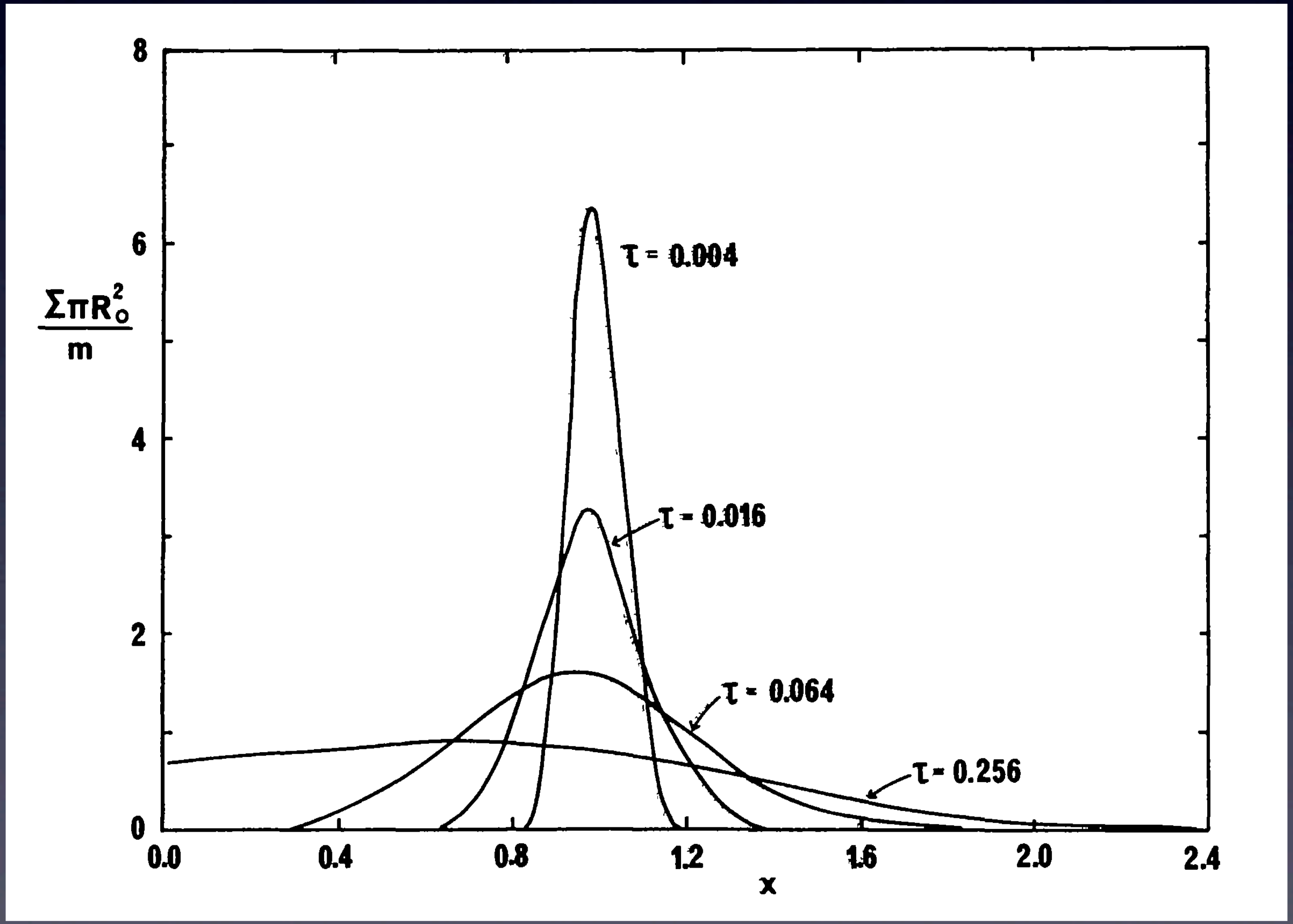
Swift J1644-57: a jetted TDE



(Levan et al. 2011)

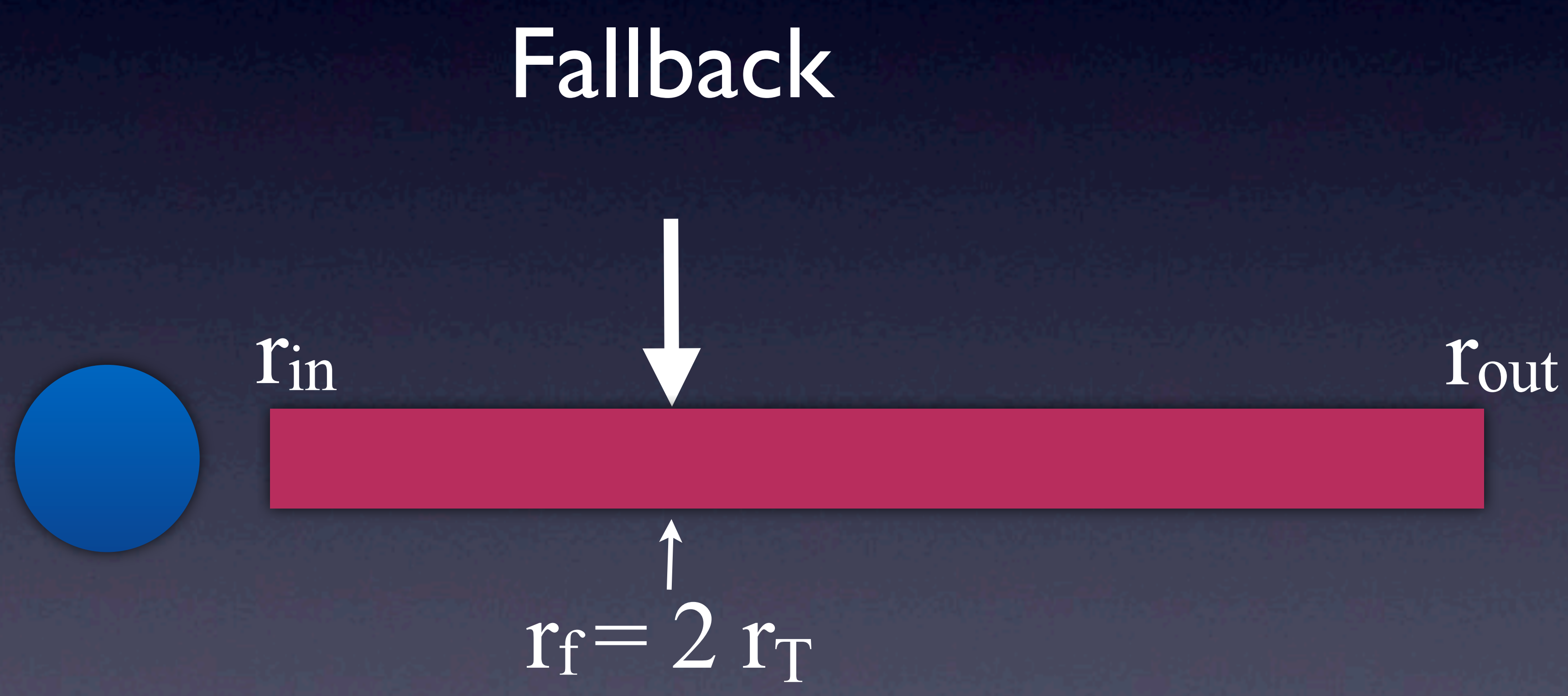
Accretion rate = fallback rate?

- Accretion (viscosity) timescale << fallback time scale.
- Accretion rate evolution is driven by viscous spreading.
- And is affected by wind loss for an ADAF (advection dominated accretion flow) disk.



Viscous spreading of a ring of mass (Pringle 1981).

TDE: Accretion disk with fallback



r — Schwarzschild-normalized radius

Viscous evolution of accretion disk

- Viscous spreading of a Keplerian disk with an infall (Lightman 74; Cannizzo et al. 90; Pringle 91; Tanaka 11; …)

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}(R^{1/2}\nu\Sigma)\right] + S(R,t)$$

$$\nu = \frac{2\alpha P}{3\Omega_k \rho}$$

- Σ - surface density; α - Shakura & Sunyaev viscosity parameter.
- For the case of $\nu \propto R^n$ and $S(R,t)=0$:
  - $\Sigma \propto R^{-n}$
  - $R_{out} \propto t^{1/[2(2-n)]}$
  - $\dot{M}_{\rm vis} \propto t^{-\frac{5-2n}{4-2n}}$

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- For $S(R,t)=\mathrm{const.}$:

$$\dot{M}_{\mathrm{BH}} \approx \dot{M}_{\mathrm{fb}}(t)$$

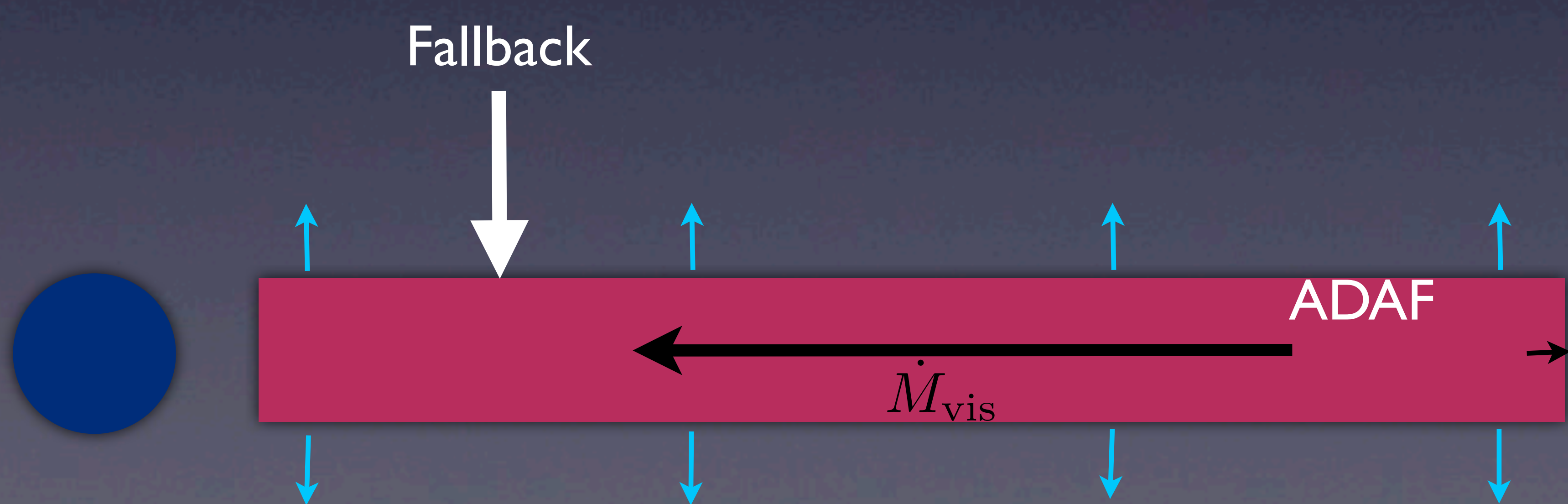
(Metzger et al. 12)

A spreading disk with fallback

(without fallback)

$$\dot{M}_{\rm BH}(t) = \dot{M}_{\rm vis}(t) + \dot{M}_{\rm fb}(t)$$

(Impact of wind loss to be included)



Outline

- Is accretion rate equal to fallback rate?
- Accretion is driven by viscous spreading.
- What is the long-term evolution history of $\dot{M}_{\rm BH}(t)$?
  - What is n ($\nu \sim R^n$) ?
  - Impacts of wind loss and fallback on $\dot{M}_{\rm BH}(t)$
- Application to Swift J164449.3+573451.
- Precession of disk misaligned with BH spin.

Steady state disk equations

- Energy equation:
  local heating = advective cooling + radiative cooling.

$$Q^+_{\rm vis}(\nu,\Sigma) = Q^-_{\rm adv}(\nu,\Sigma,P/\rho) + Q^-_{\rm rad}(\Sigma,T)$$

- If $Q_{\rm adv}^- \gg Q_{\rm rad}^-$ (ADAF), $\nu \propto R^{1/2}$, $\longrightarrow$ n= 1/2. $\longrightarrow \dot{M}_{\rm vis} \propto t^{-\frac{4}{3}}$
- If $Q_{\rm adv}^- \ll Q_{\rm rad}^-$ (Radiative),
  - when $P \simeq P_{\rm rad}$, $\nu \propto R^{-3/2}$, $\longrightarrow$ n= -3/2; $\longrightarrow \dot{M}_{\rm vis} \propto t^{-\frac{8}{7}}$
  - when $P \simeq P_{\rm gas}$, $\nu \propto R^{3/5}$, $\longrightarrow$ n= 3/5. $\longrightarrow \dot{M}_{\rm vis} \propto t^{-\frac{19}{14}}$

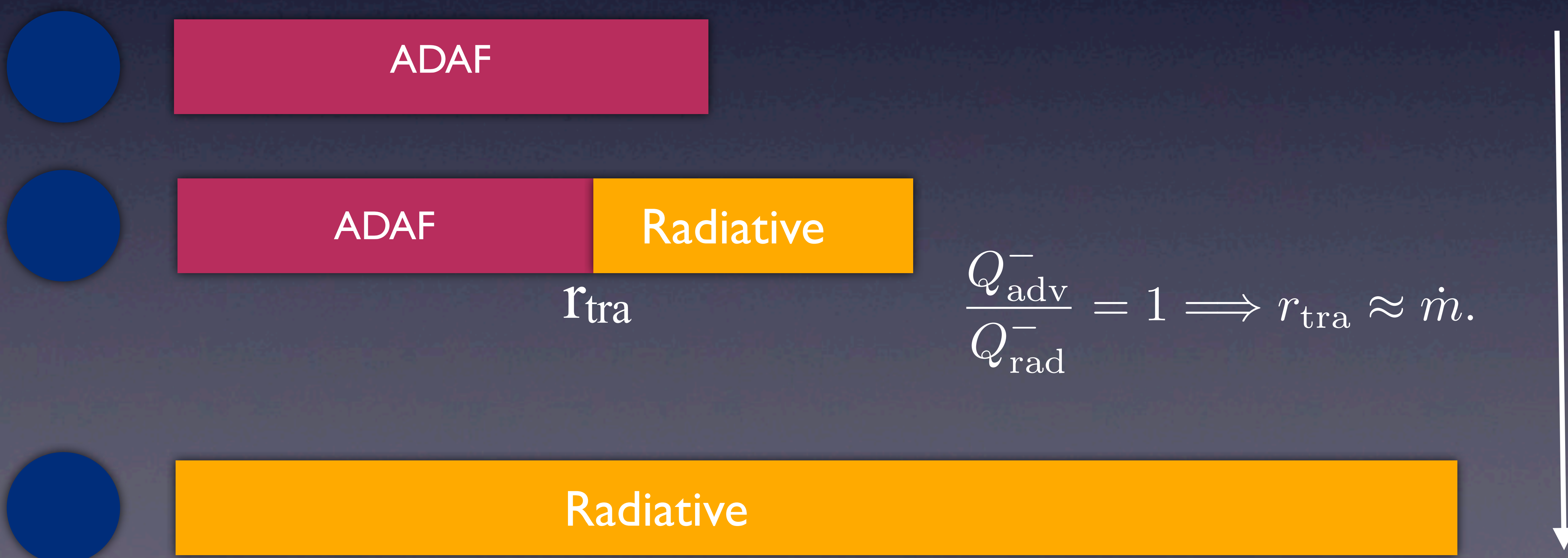
Phase changes of disk

- Assuming $P \simeq P_{\rm rad} \gg P_{\rm gas}$,

Eddington-normalized accretion rate

$$\frac{H}{R} = \frac{\sqrt{P/\rho}}{\Omega_k R} \approx \min\left(1, \frac{\dot{m}}{r}\right), \qquad \frac{Q^-_{\rm adv}}{Q^-_{\rm rad}} = \frac{5}{4}\left(\frac{\dot{m}}{r}\right)\left(\frac{H}{R}\right).$$

- As accretion rate drops:



$$\frac{Q^-_{\rm adv}}{Q^-_{\rm rad}} = 1 \Longrightarrow r_{\rm tra} \approx \dot{m}.$$

Impact of wind loss

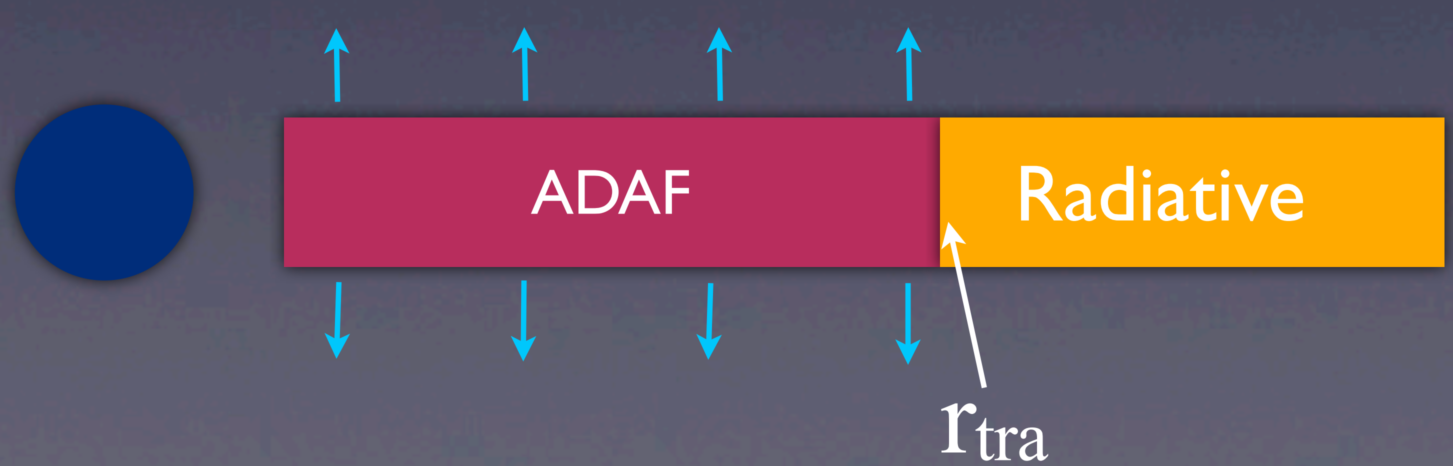
- ADAF launches outflow (wind) up to $\min(r_{tra}, r_{out})$ (Blandford & Begelman 99; Narayan et al. 00;...).

$$\dot{m}(r) \propto r^s, \text{ with } 0 \leq s \leq 1.$$

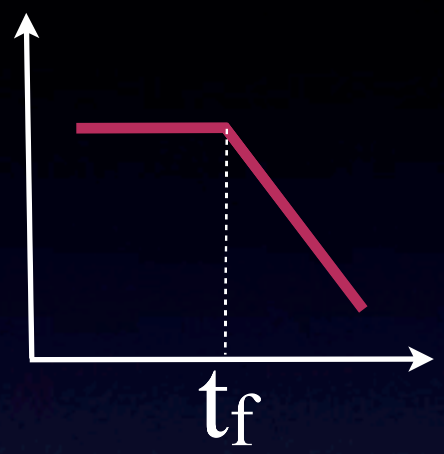
$$\Sigma \propto r^{-n+s}, \quad \dot{m}(r,t) = \dot{m}(r_{\rm out},t)\left[\frac{r}{r_{\rm out}(t)}\right]^s.$$

- For a complete ADAF disk ($n=1/2$; without fallback):

loss of disk angular mom. via wind $\Longrightarrow \dot{m}_{\rm vis}(r_{\rm out},t) = t^{-\frac{4+2s}{3}}.$



Impact of fallback

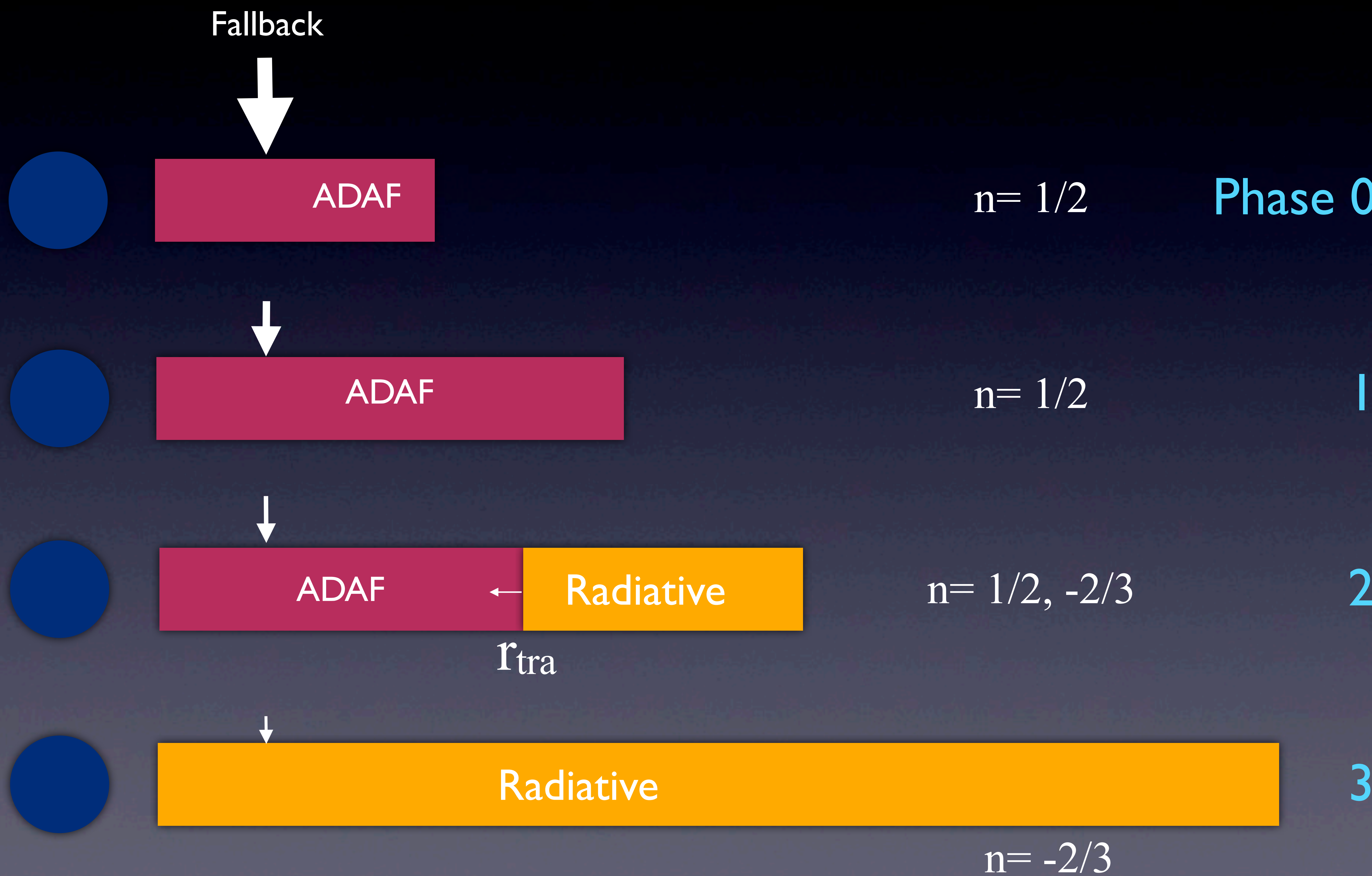


- $\dot{m}_{\rm fb}(t)$~ constant up to t_f; drops as $t^{-5/3}$ afterwards.
- During $t \le t_f$, disk builds up and is in ADAF; all infall mass at r_f accretes inward and has wind:

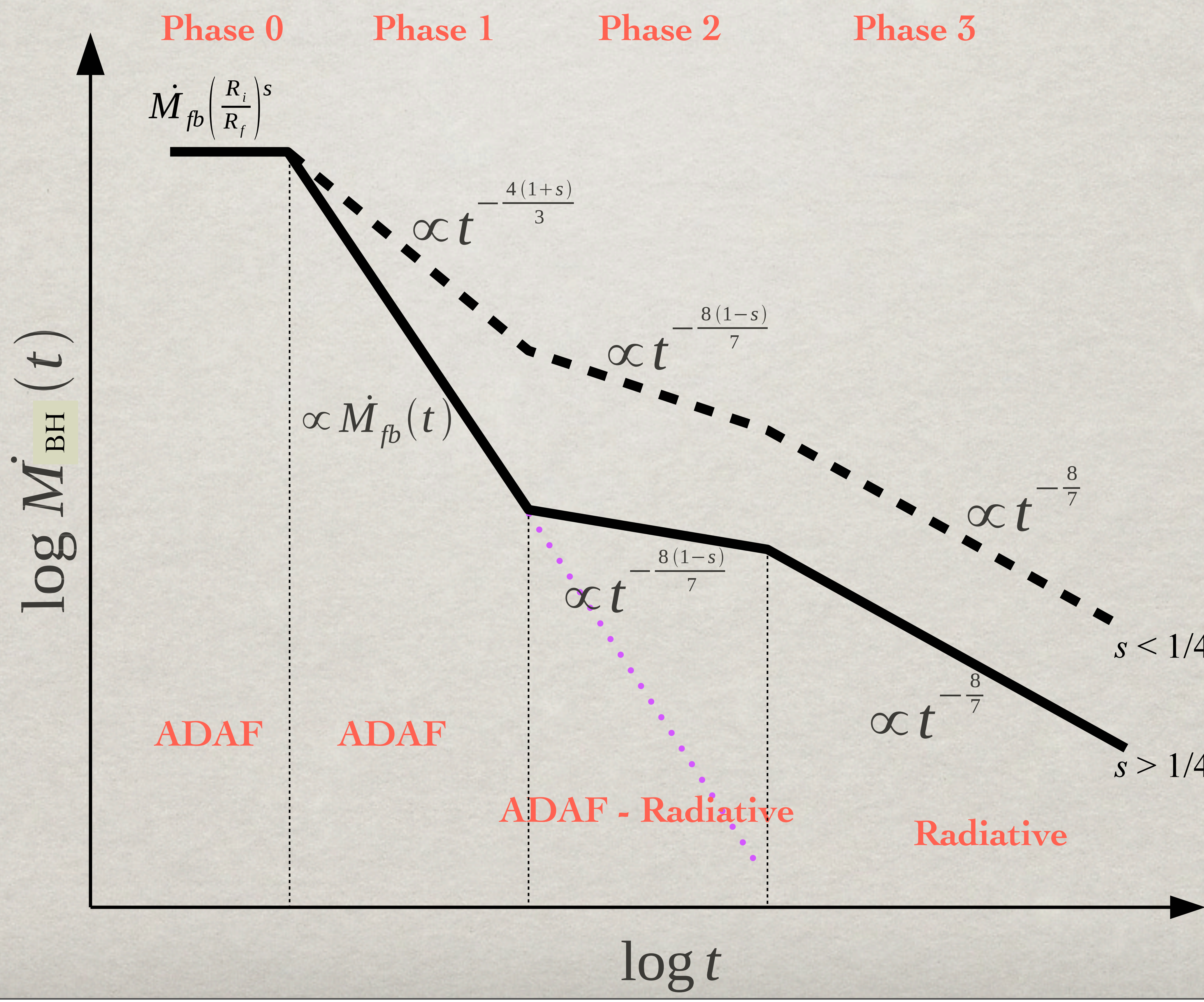
$$\dot{m}_{\rm BH} = \dot{m}_{\rm fb}(t)(r_{\rm in}/r_f)^s$$

- After t_f, fallback is important only when accretion rate drops faster than fallback rate ($t^{-5/3}$).
  - when s < 1/4, $\dot{m}_{BH} \propto t^{-4(1+s)/3}$;
  - when s > 1/4, $\dot{m}_{BH} \propto \dot{m}_{\rm fb}(t)$.

Phases of disk evolution



Complete Accretion Rate History

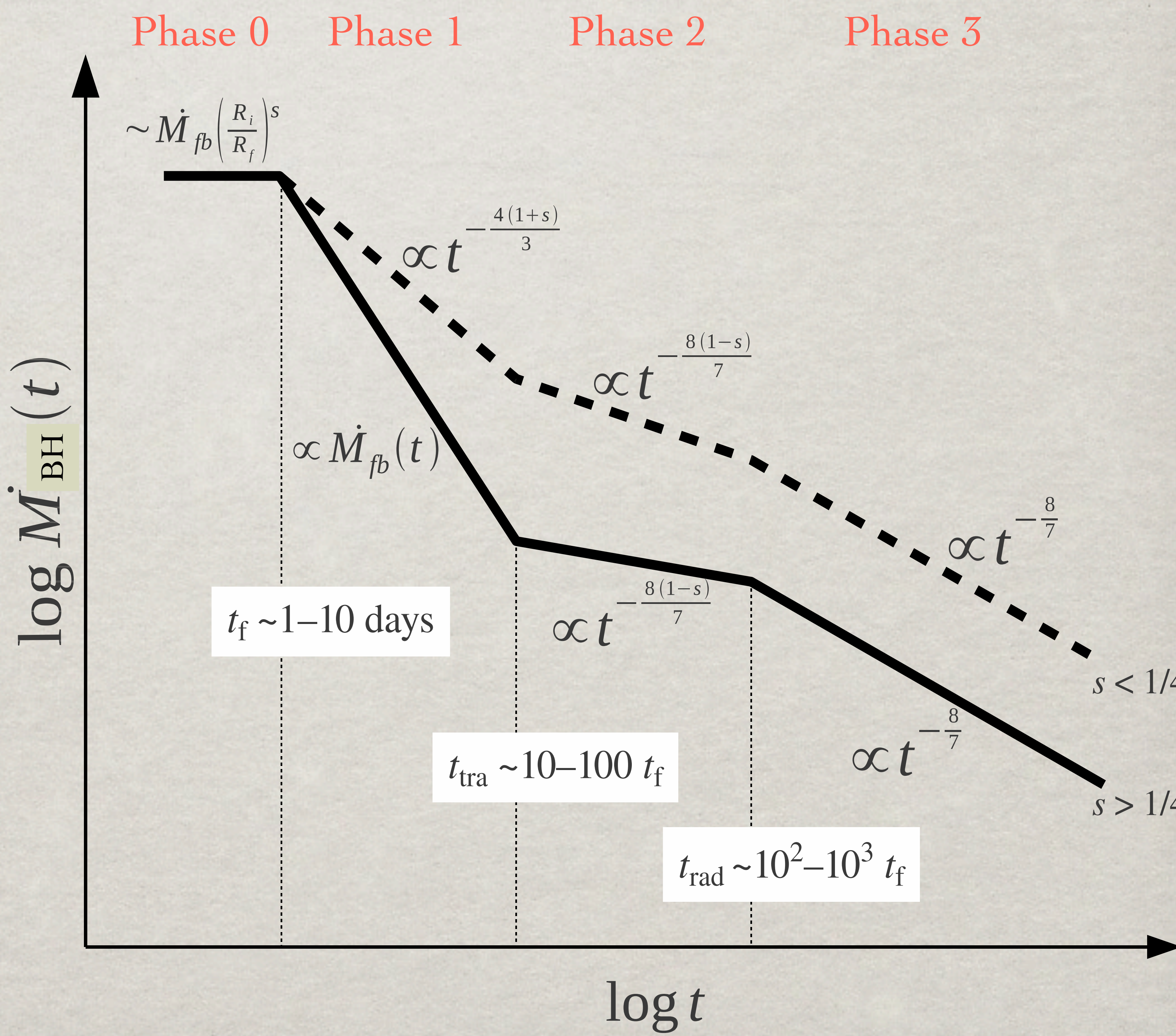


Time scales

- $r_{tra}(t) = r_{out}(t) \Longrightarrow t_{tra}$
- $r_{tra}(t) = r_{in} \Longrightarrow t_{rad}$
- Uncertainties are due to:

  β — "penetration" parameter;

  r_*, m_*, α, M_6

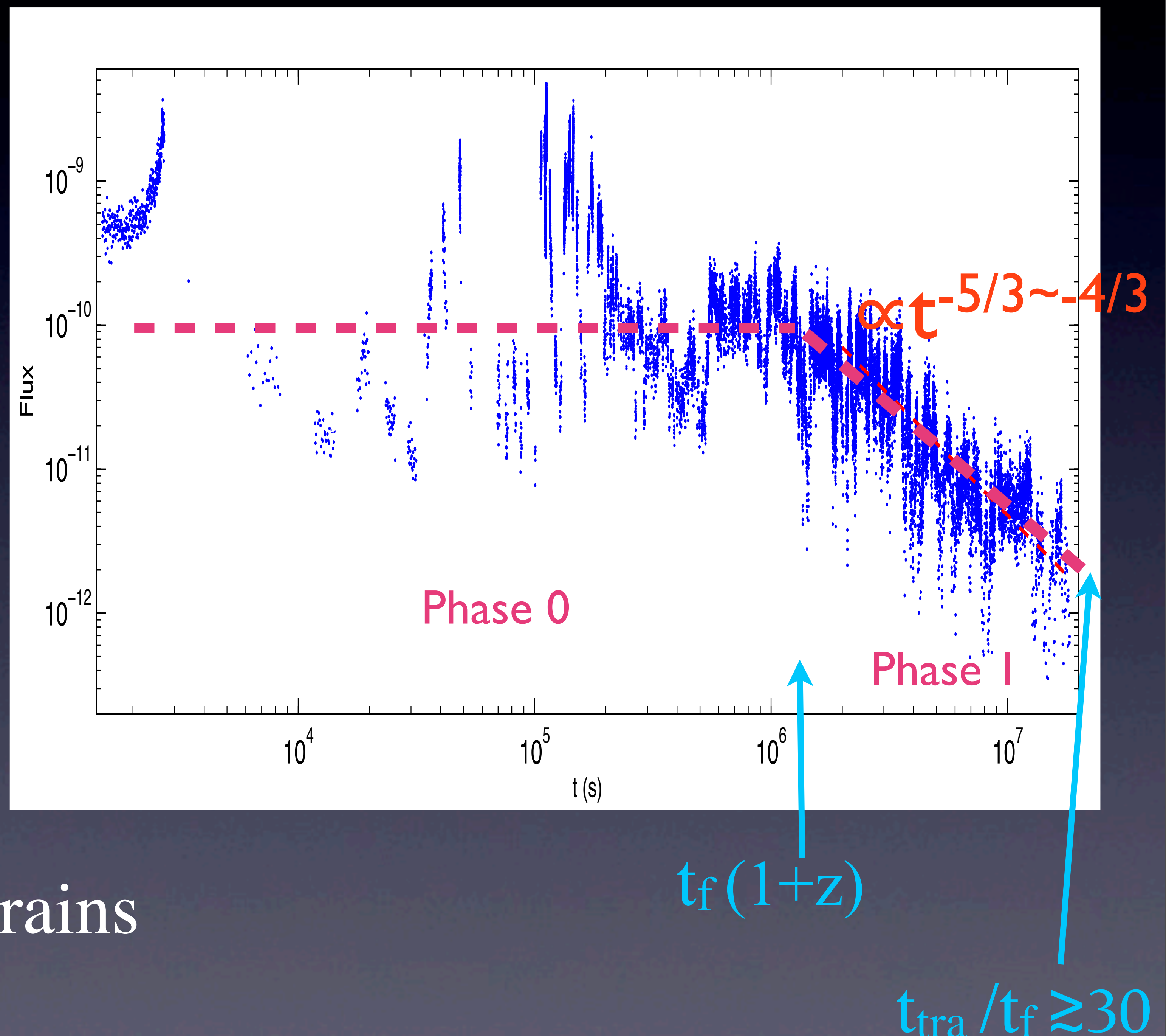


Application to Sw J1644+57

- Suggests accretion started as being ADAF and stays up to now with s > 1/4.
- $t_f\,(1+z) = 10^6$ s $\Longrightarrow$

$$\dot{m}_{\rm fb}(t_f) = 386\ m_* M_6^{-1}.$$

- $t_{tra}/t_f \simeq 0.5\ \ \alpha^{-1/3}\ M_6^{-1/6}\ m_*^{1/2}$ s.



- Observed $t_{tra}/t_f \gtrsim 30$ constrains $\alpha \lesssim 3\times10^{-5}\ M_6^{-1/2}\ m_*^{1/2}$.

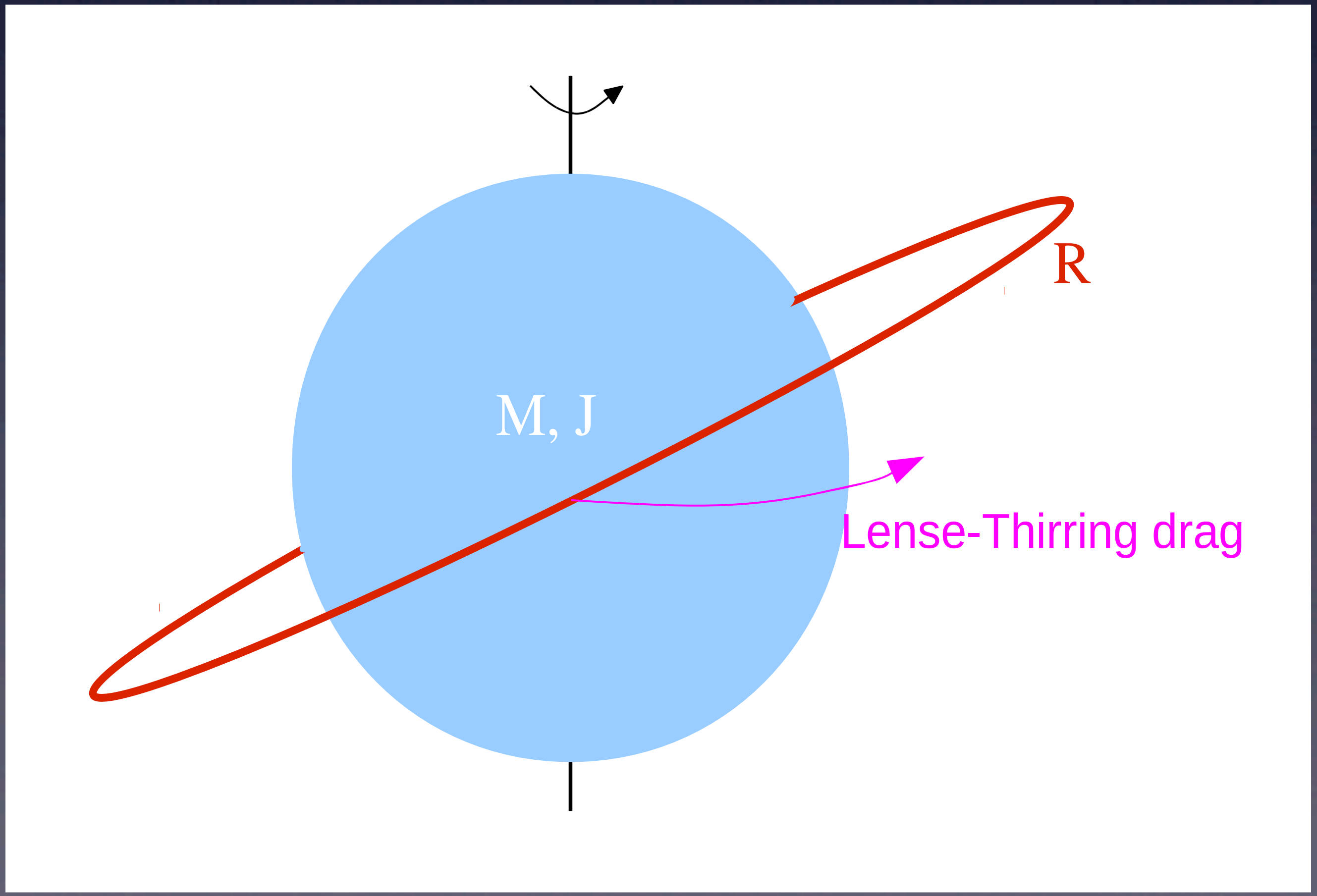
Conclusions

- Accretion rate in TDE is governed by viscous spreading.
- Our simple analytical model describes accretion rate history across four phases of disk evolution.
- Accretion rate can decline as steeply as $t^{-5/3}$ only if disk losses mass in copious wind (s>1/4) in early ADAF phase.
- Later, accretion rate history is $t^{-8/7}$ or shallower.
- Application to Sw J1644+57 constrains $\alpha \lesssim 3\times10^{-5} M_6^{-1/2} m_*^{1/2}$.

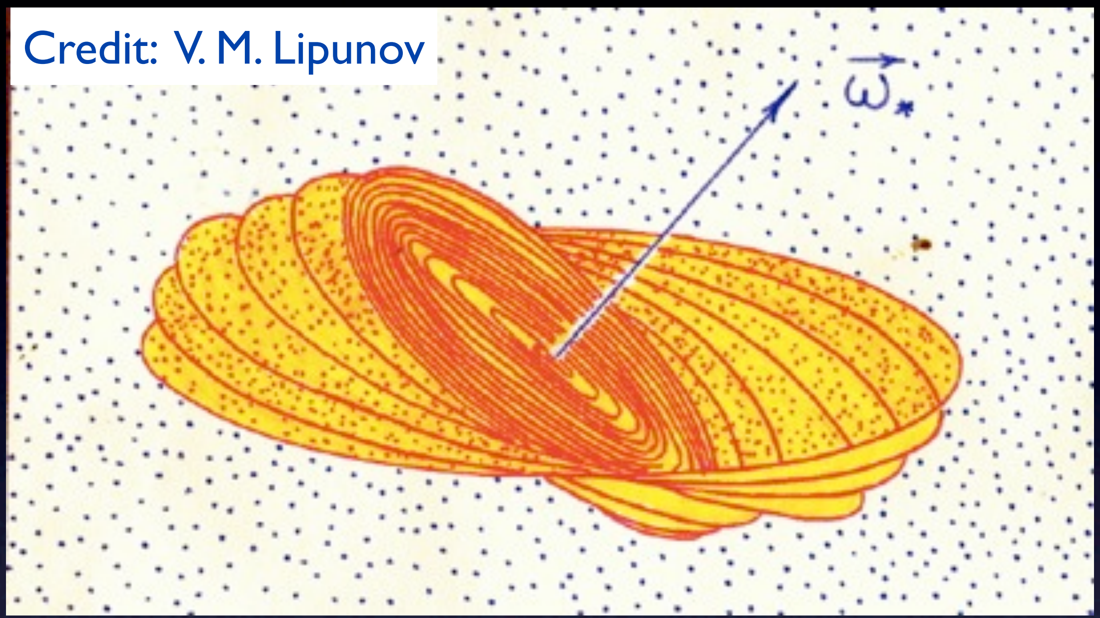
Disk precession in TDE

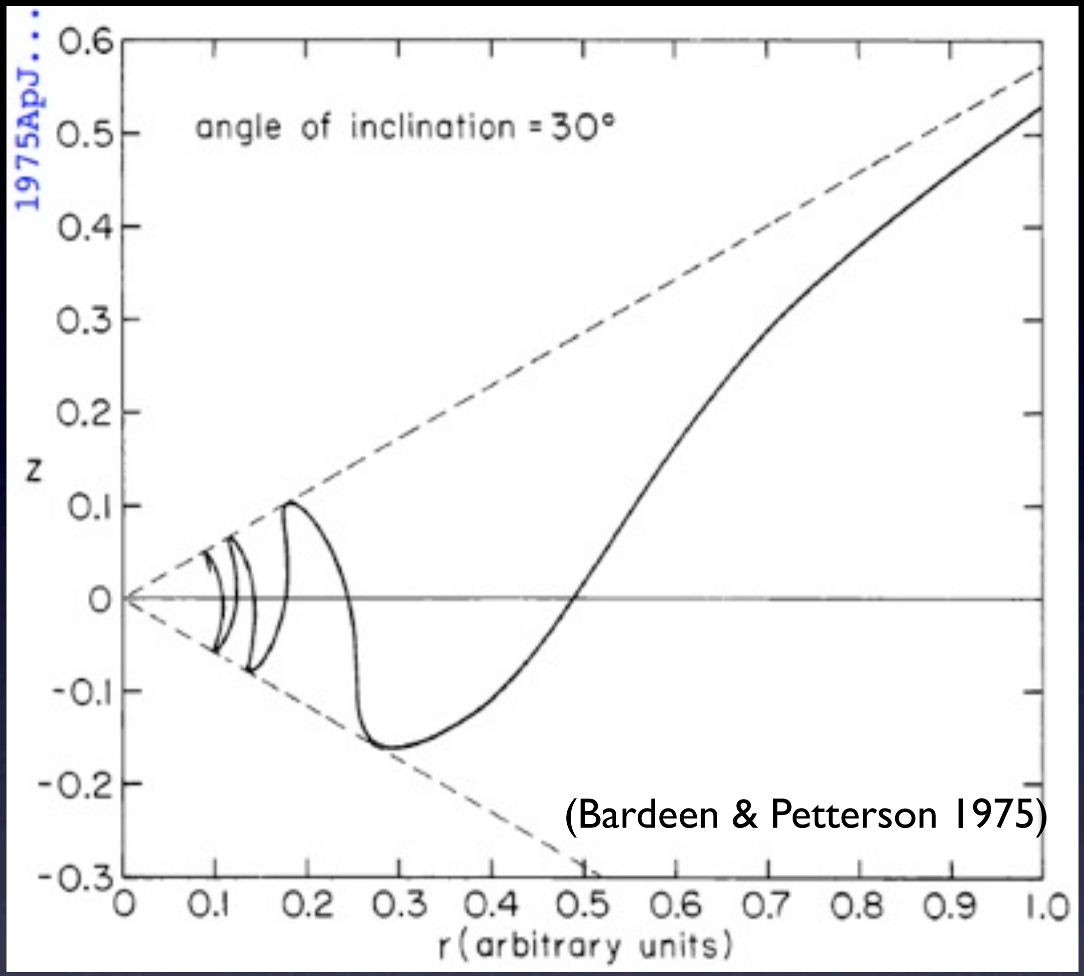
- A spinning BH: accretion disk is most likely mis-aligned with BH equator.
- General relativity for a spinning massive object ➔ frame dragging.
- A tilted orbit of test particle precesses.
- $t_{LT} \sim R^3/ J = R^3/(a\ M^2)$. Lense-Thirring effect.

  a — BH spin



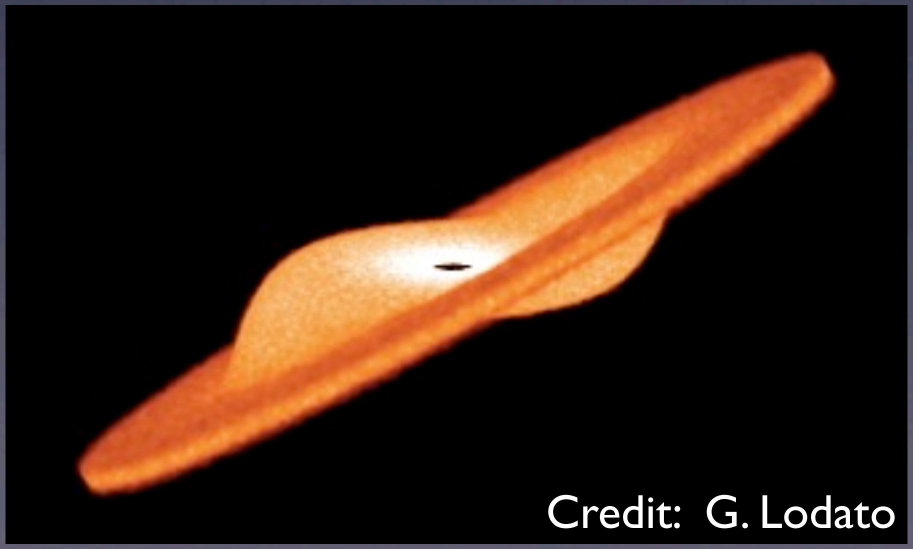
Twisted accretion disk





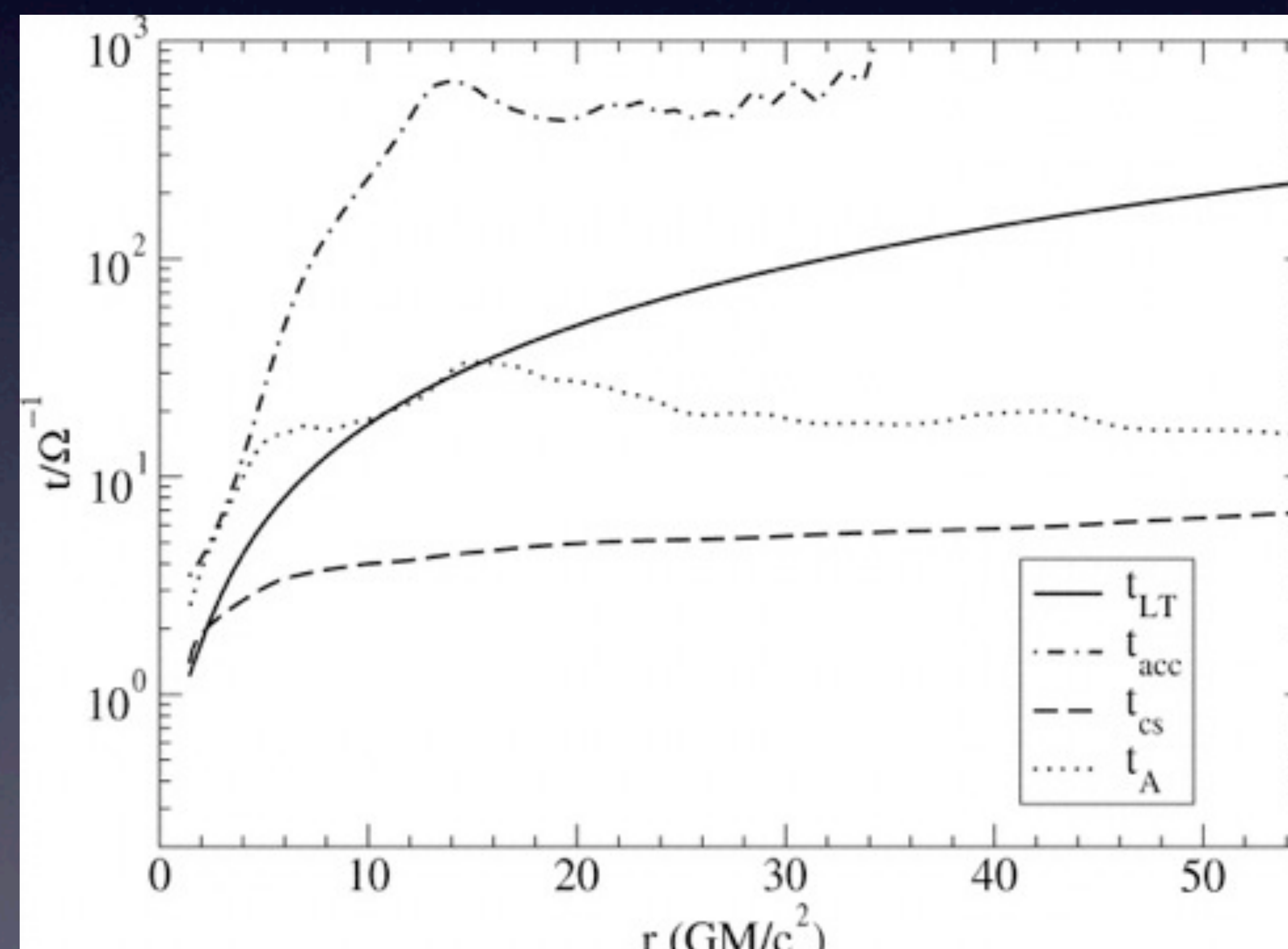
(Bardeen & Petterson 1975)

- L-T differential precession ➔ warps in inner disk.
- Viscosity due to vertical shear straightens out warps ➔ inner disk aligns with BH equator.
- Outer region: L-T effects drop rapidly outward, so it remains in original orbital plane ➔ Bardeen-Petterson configuration.
- Picture changes if considering propagation of warps.



Propagation of warps

- (Pringle 99; Nelson & Papaloizou 99, 00; Fragile et al. 05, 07; …)
- Propagation of warps: in thick disk (α < H/R), $t_{prop} \sim t_{cs} < t_{LT}$ everywhere ➔ warps are communicated through the disk ➔ solid-body precession.
- Probably applies to TDE disk.



(Fragile et al. 2007)

Rigid-body precession of disk

- For $\Sigma \propto r^{-\zeta}$,

$$t_{\rm prec,disk} \simeq \frac{8\pi}{a}\frac{GM}{c^3} \times r_{\rm out}^{5/2-\zeta} r_{\rm in}^{1/2+\zeta}$$

- For an ADAF disk, $\zeta = 1/2-s$; and for $a=0.9$, $s=1/2$, $r_{in}=3$, $r_{out}=20$:

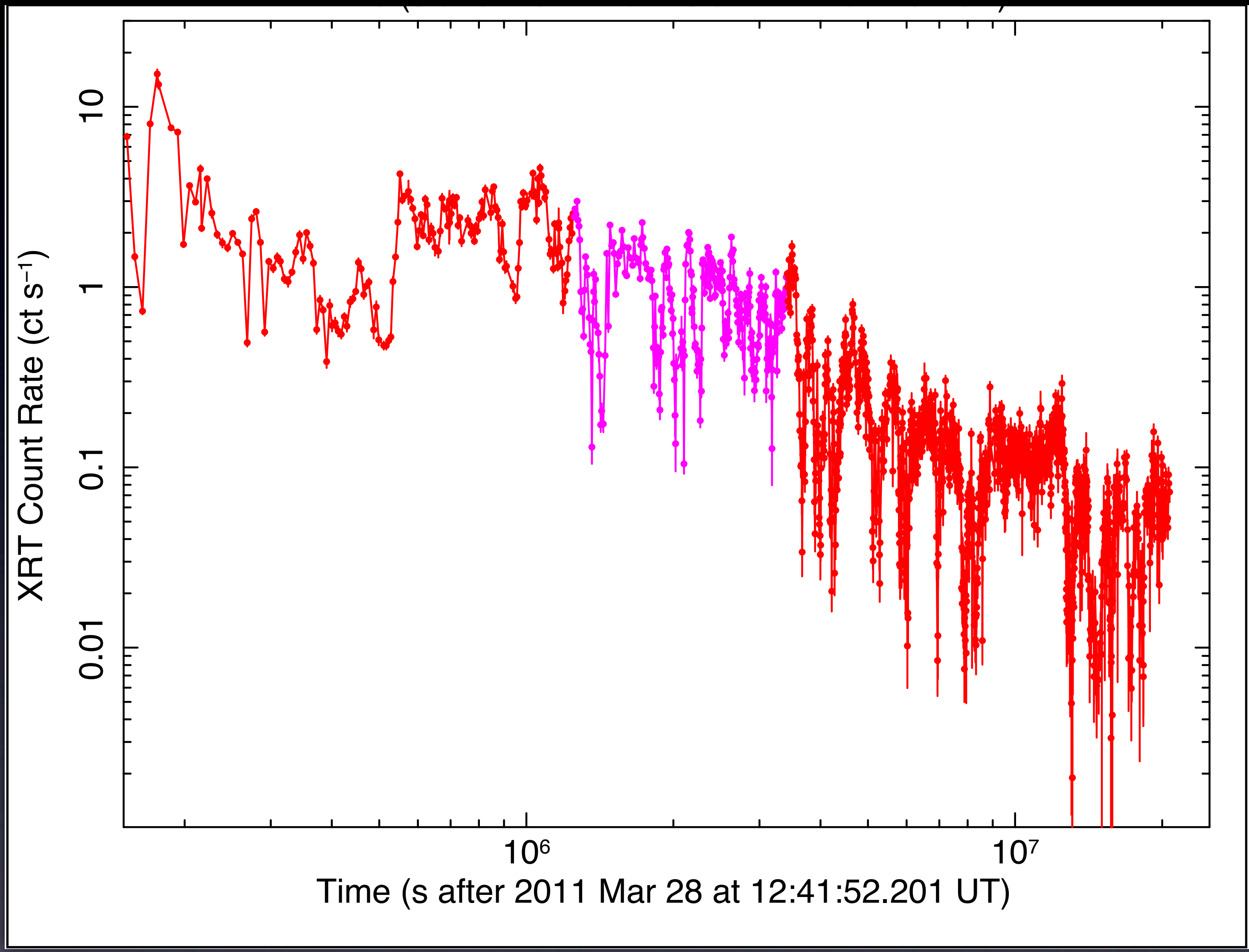
$$t_{prec,disk} \approx 10^5\ M_6\ s.$$

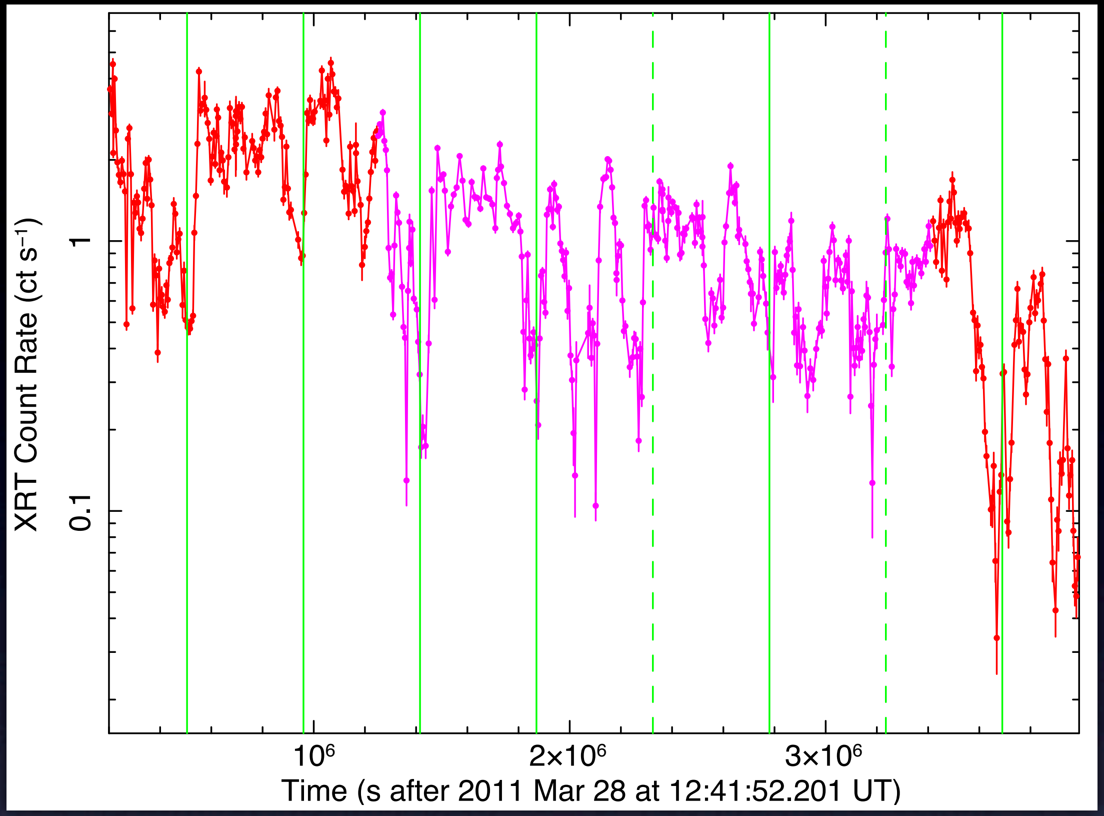
Evolution of precession period

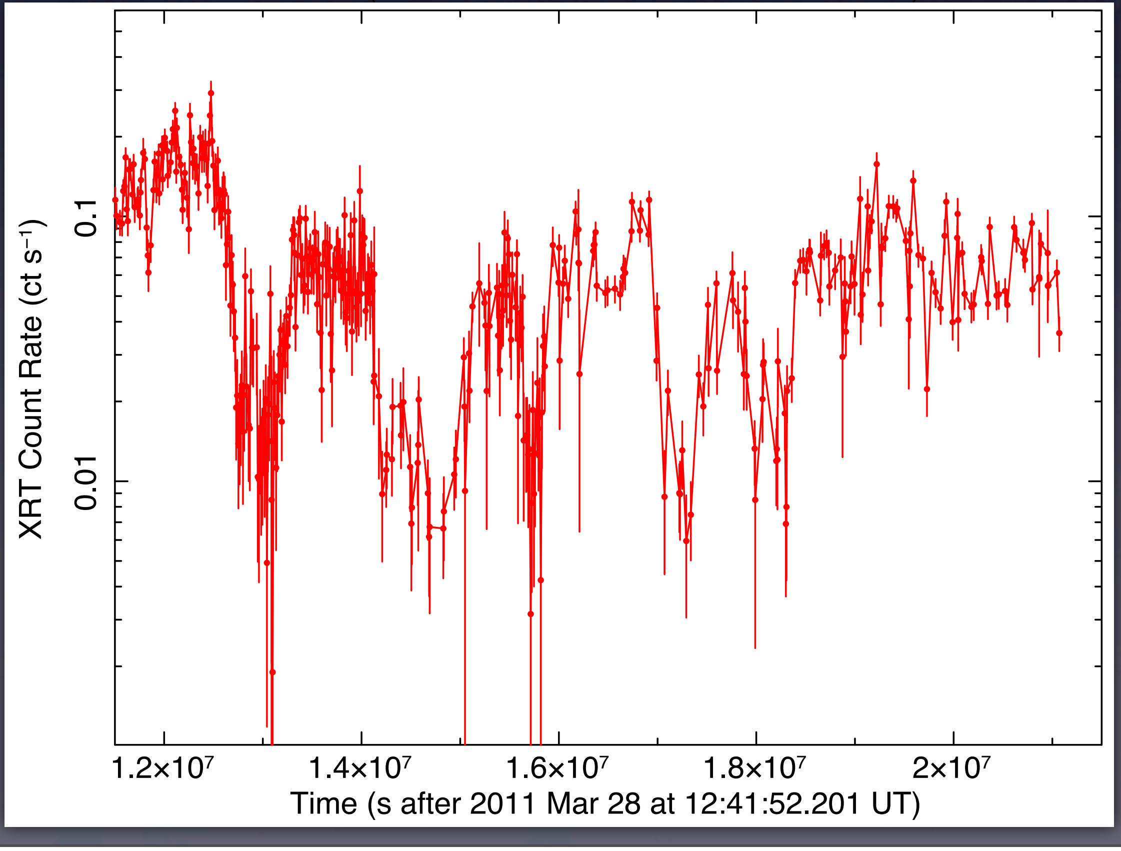
	Phase 0	Phase 1	Phase 2	Phase 3
$r_{out}(t)$	$\propto t^{2/3}$	$\propto t^{2/3}$	$\propto t^{2/7}$	$\propto t^{2/7}$
ζ	1	$= \begin{cases} 1/2 - s, & \text{if } s < 1/4, \\ 1, & \text{if } s > 1/4. \end{cases}$	-3/2	-3/2
$t_{prec,disk}$	$\propto t$	$\propto \begin{cases} t^{\frac{2}{3}(2+s)}, & \text{if } s < 1/4, \\ t, & \text{if } s > 1/4. \end{cases}$	$\propto t^{6/7}$	$\propto t^{6/7}$

Dips in Sw J1644+57

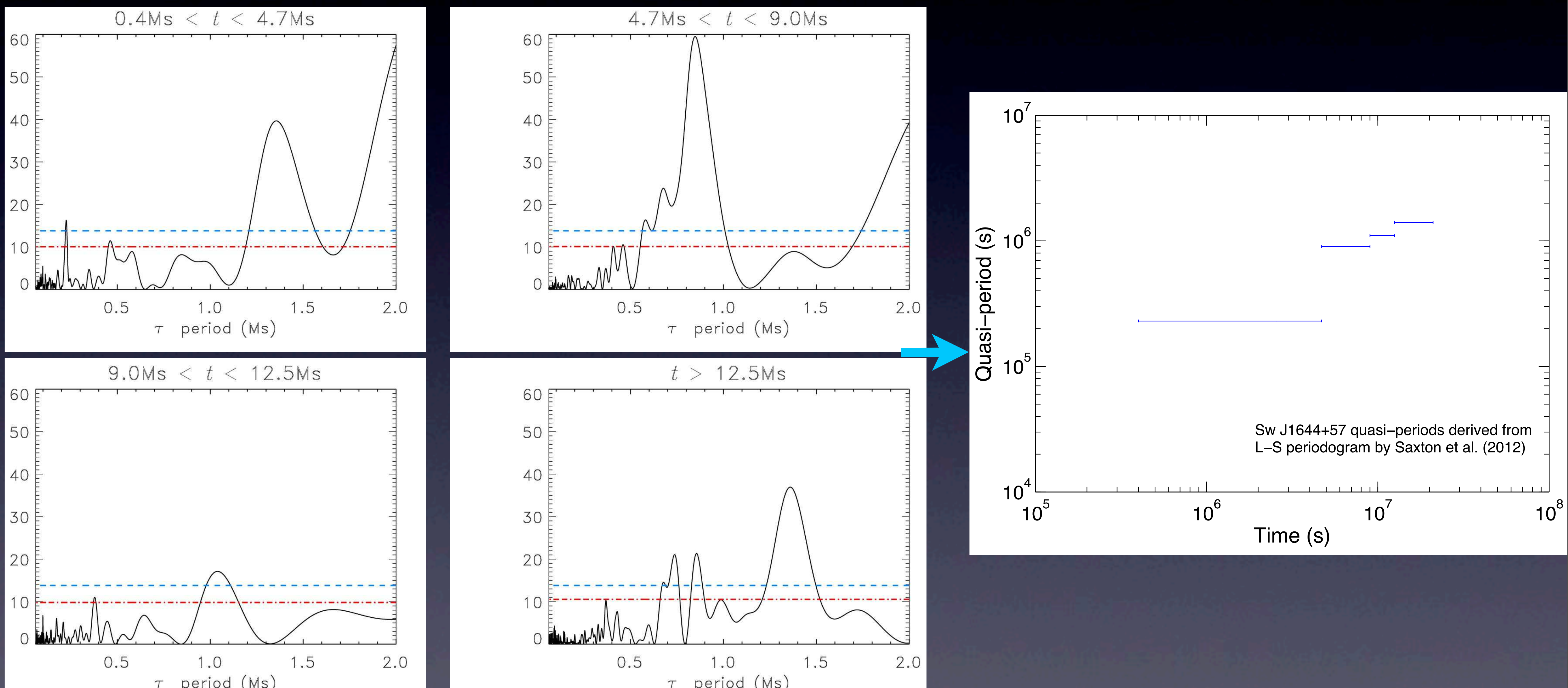
(C. J. Saxton et al. 2011)





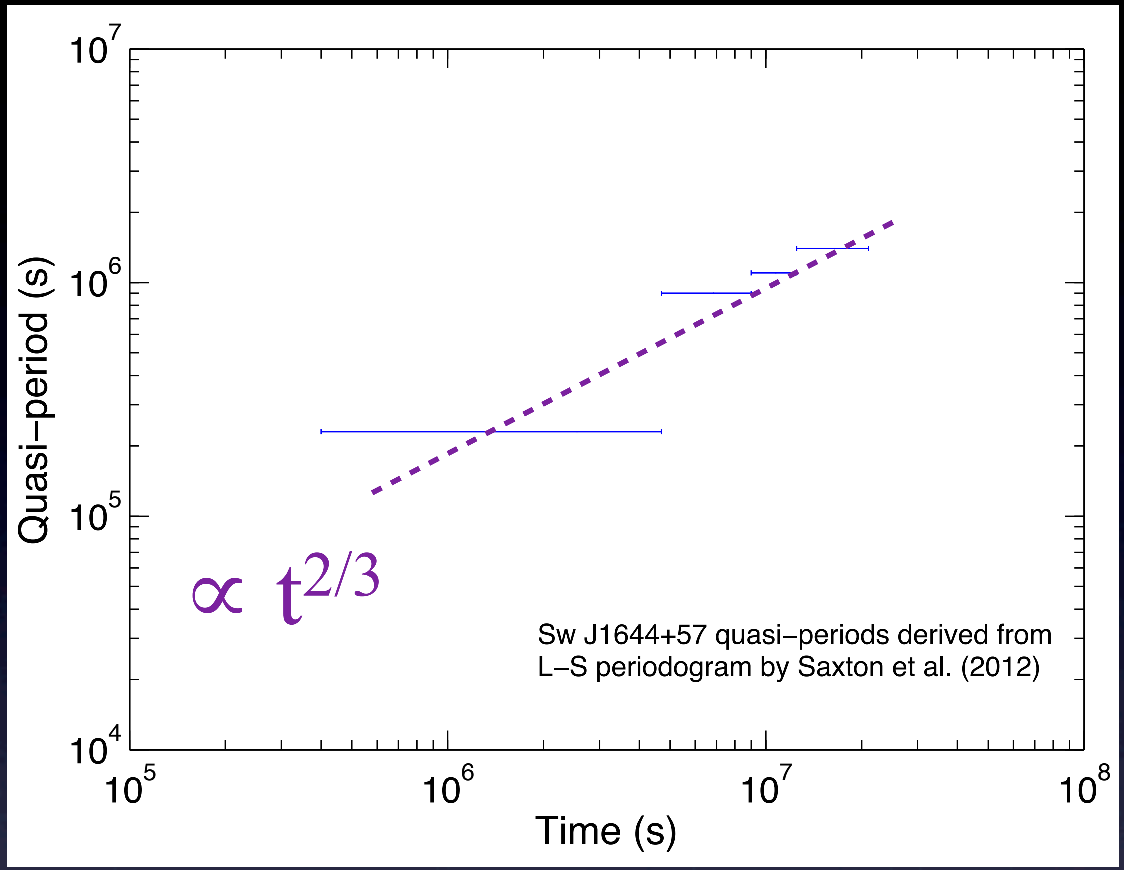


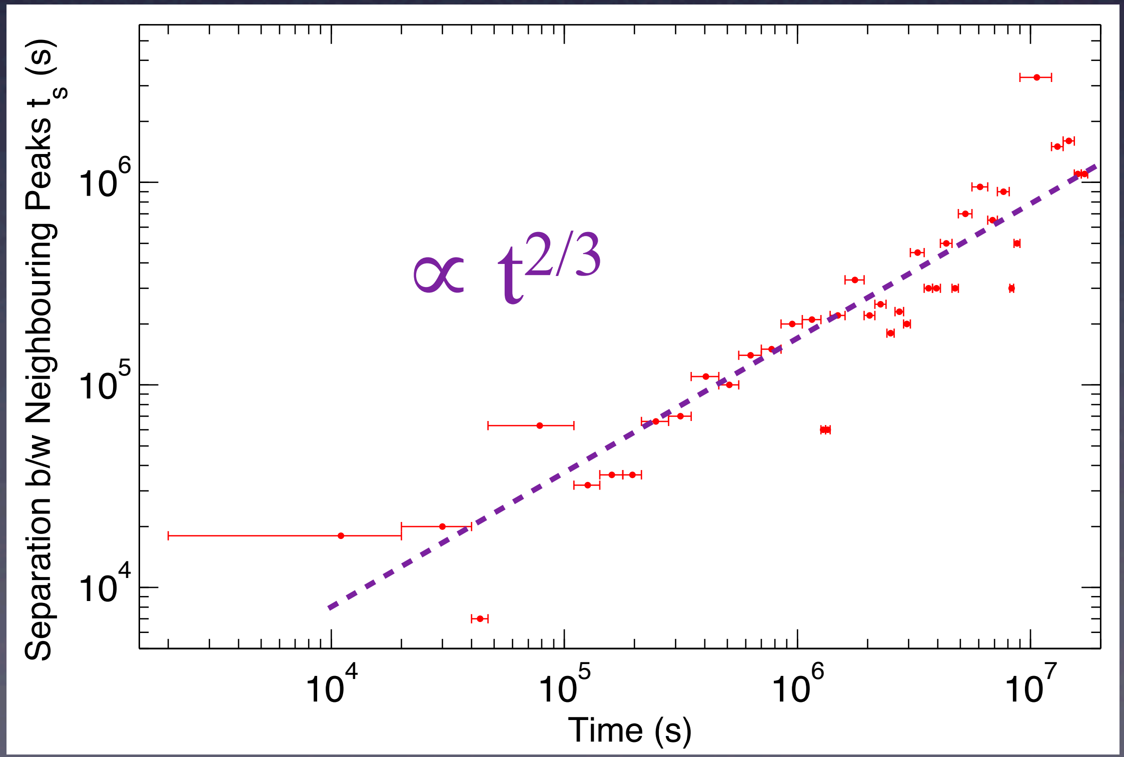
Quasi-periodicity in light curve
(Saxton et al. 2011)



Comparing prediction with data

- Observed dipping period evolution is slower than predicted $t_{prec,disk}$ evolution.
- Suggests the rigid body assumption may not be valid.
- Calls for a thorough investigation of disk precession in TDEs.





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