Tidal Disruptions:
Dynamics, Light, and ~~Relics~~

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Blender visualization: 1602.03178

Outline of today's talk

- **I. Hydrodynamics of tidal disruptions**
  Bound and unbound debris.

- **II. An observational signature of the bound debris:**
  Luminous flares from accretion.

- III. (Skipping) Observational signatures of the unbound debris:
  See the ArXiv tonight! (Girma + Guillochon)

I: Hydrodynamics

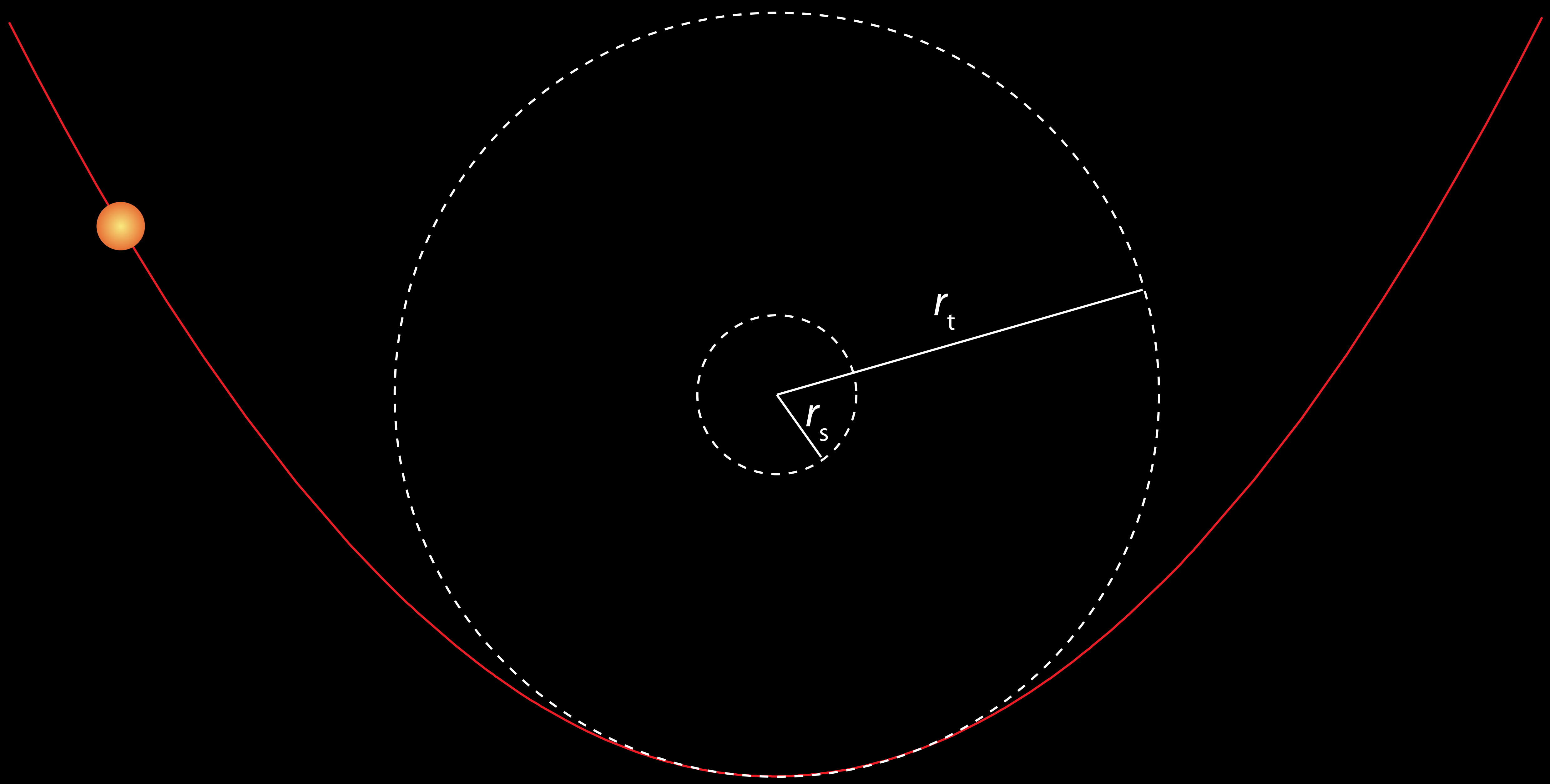
How do tidal disruptions work?

Schwarzschild Radius

$$r_\mathrm{s} = 3 \times 10^{11} M_6 \ \mathrm{cm}$$

Tidal Radius

$$r_\mathrm{t} = 7 \times 10^{12} \left(\frac{r_*}{r_\odot}\right) \left(\frac{M_*}{M_\odot}\right)^{-1/3} M_6^{1/3} \ \mathrm{cm}$$



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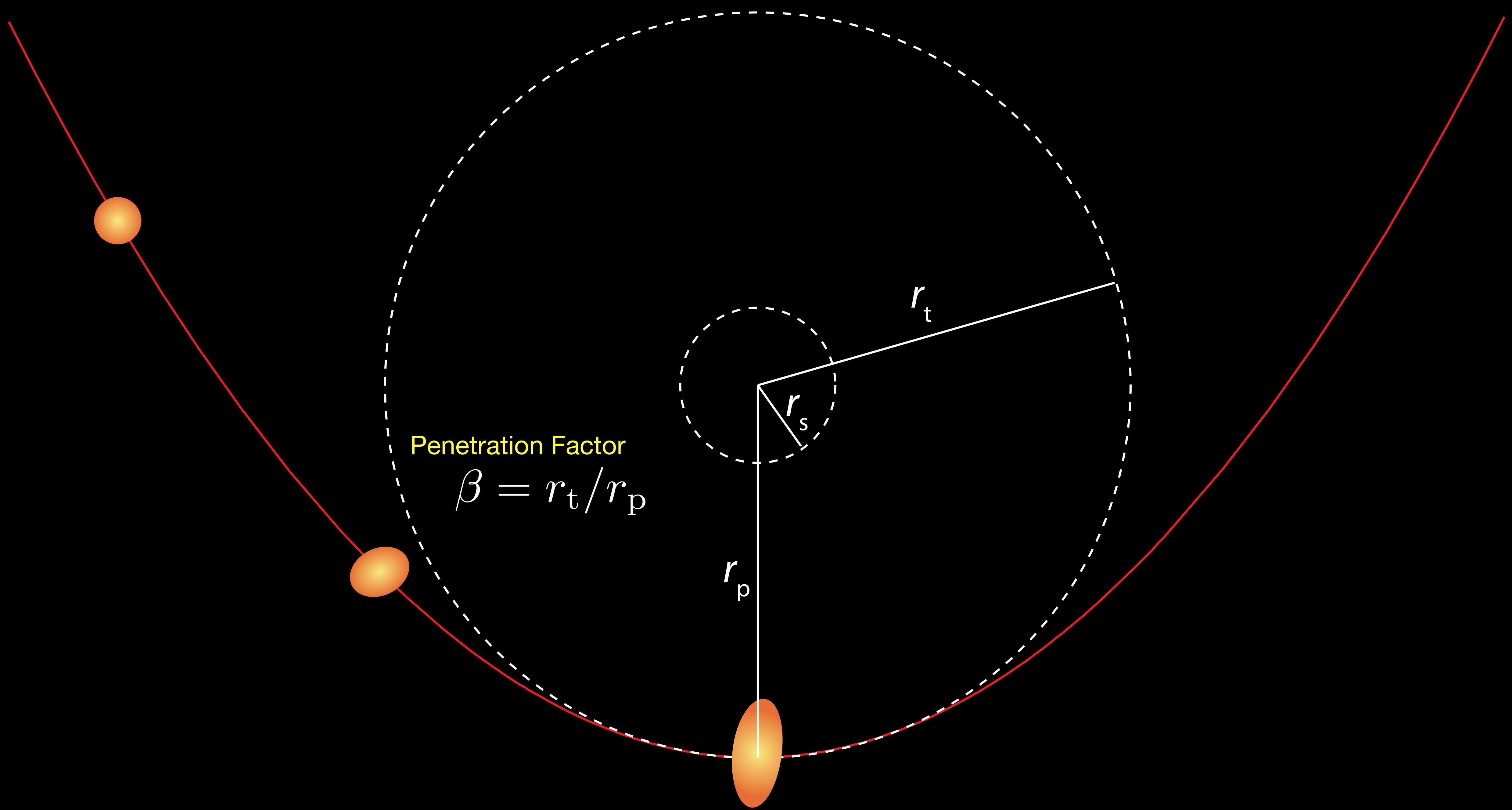

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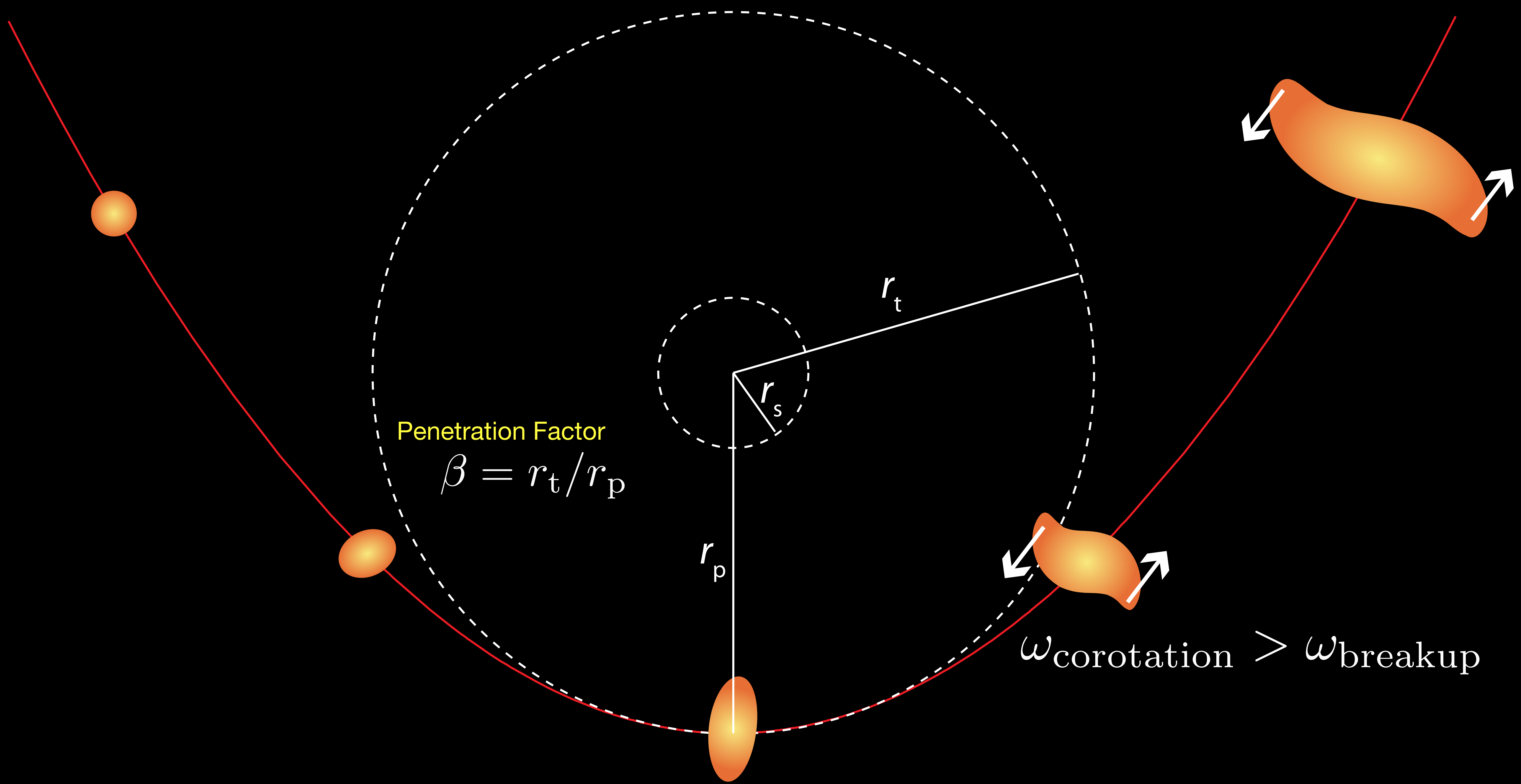

Penetration Factor

$$\beta = r_\mathrm{t}/r_\mathrm{p}$$

$$\omega_\mathrm{corotation} > \omega_\mathrm{breakup}$$

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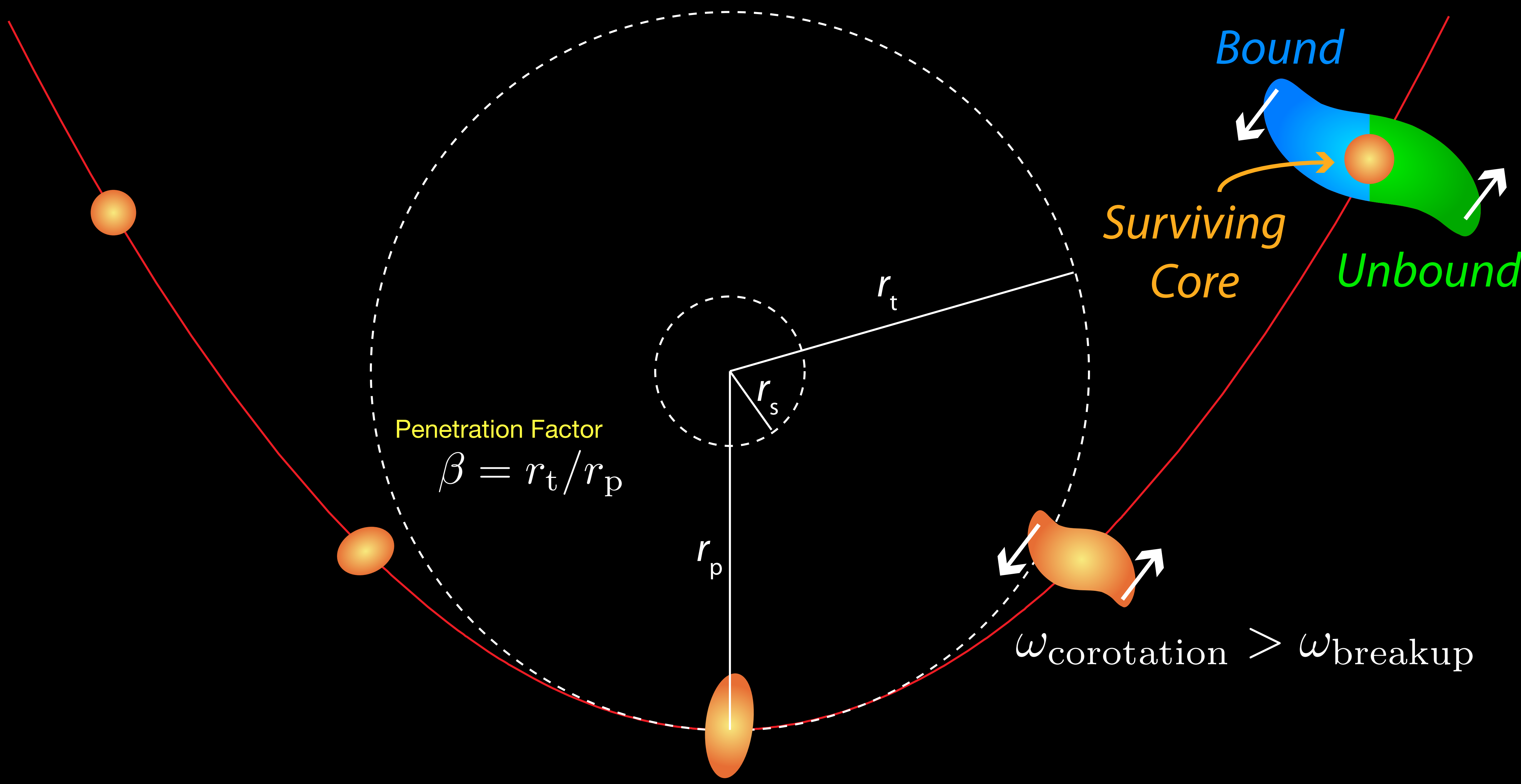
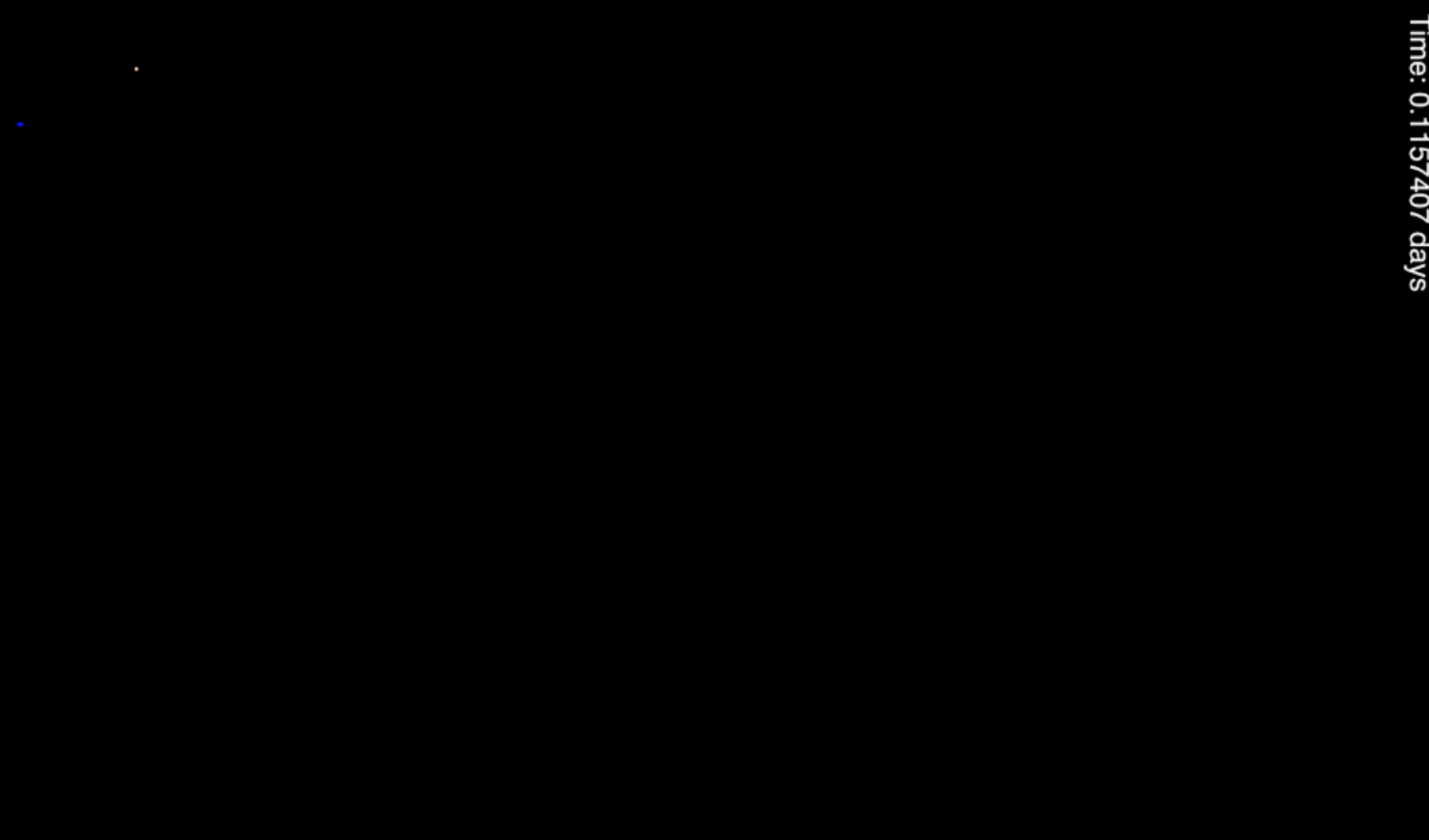


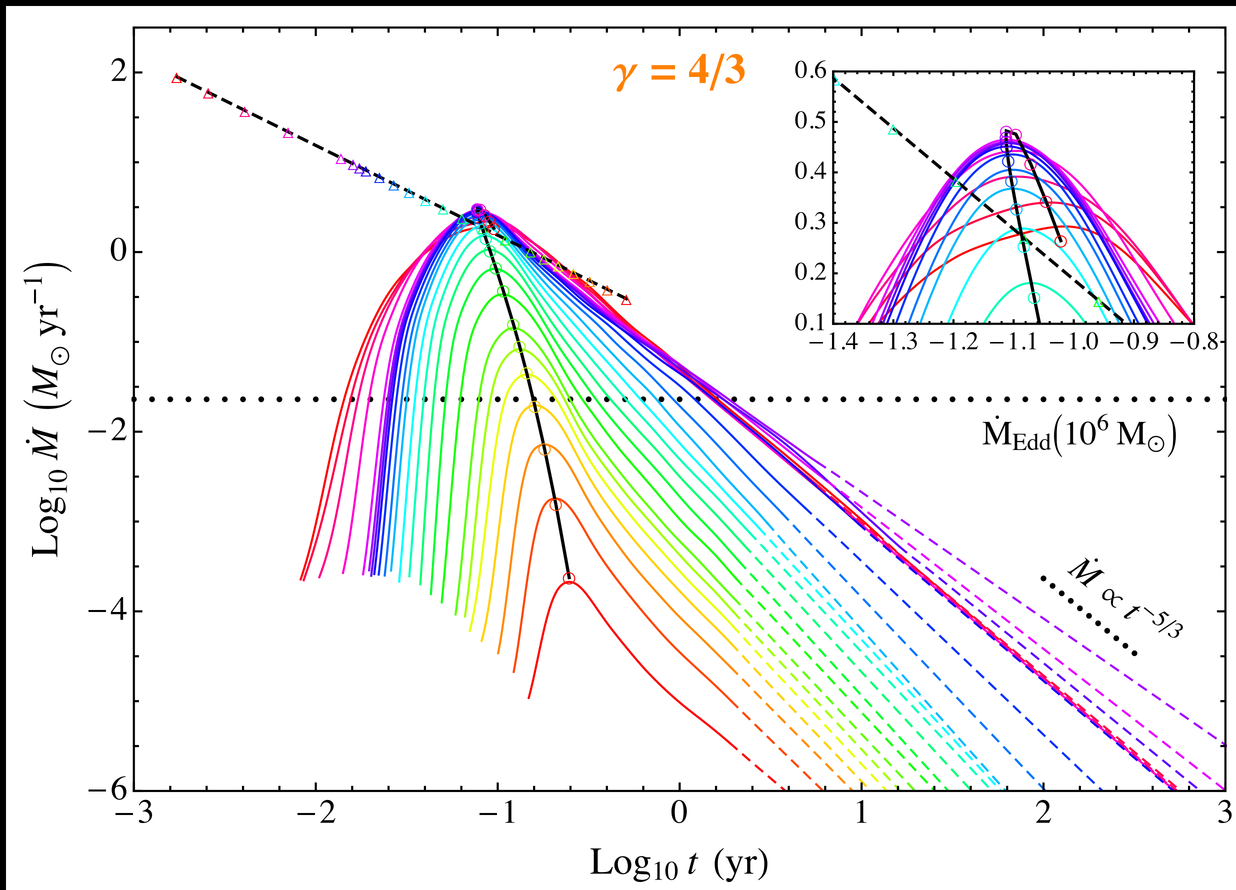
Tidal disruption of a star by a black hole

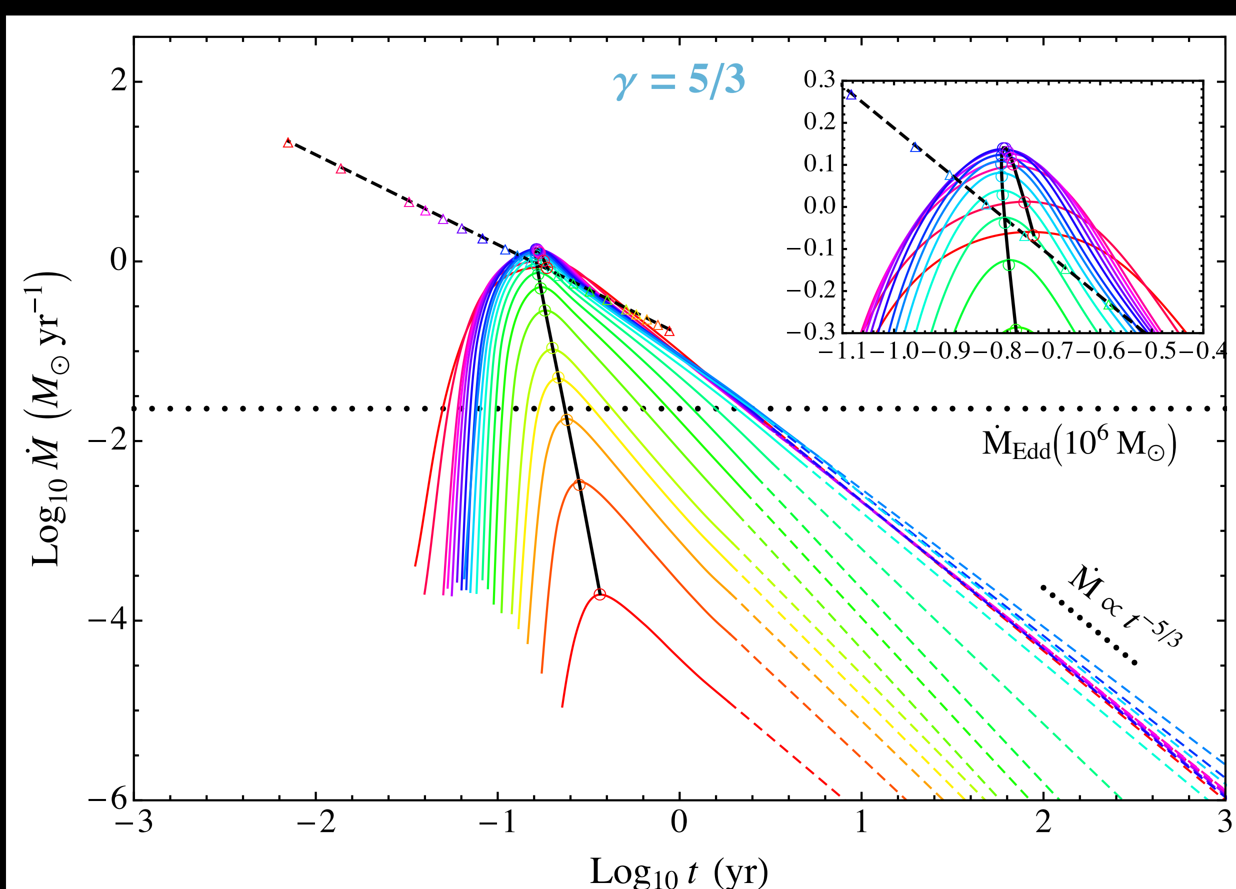
Mass ratio: 10^3



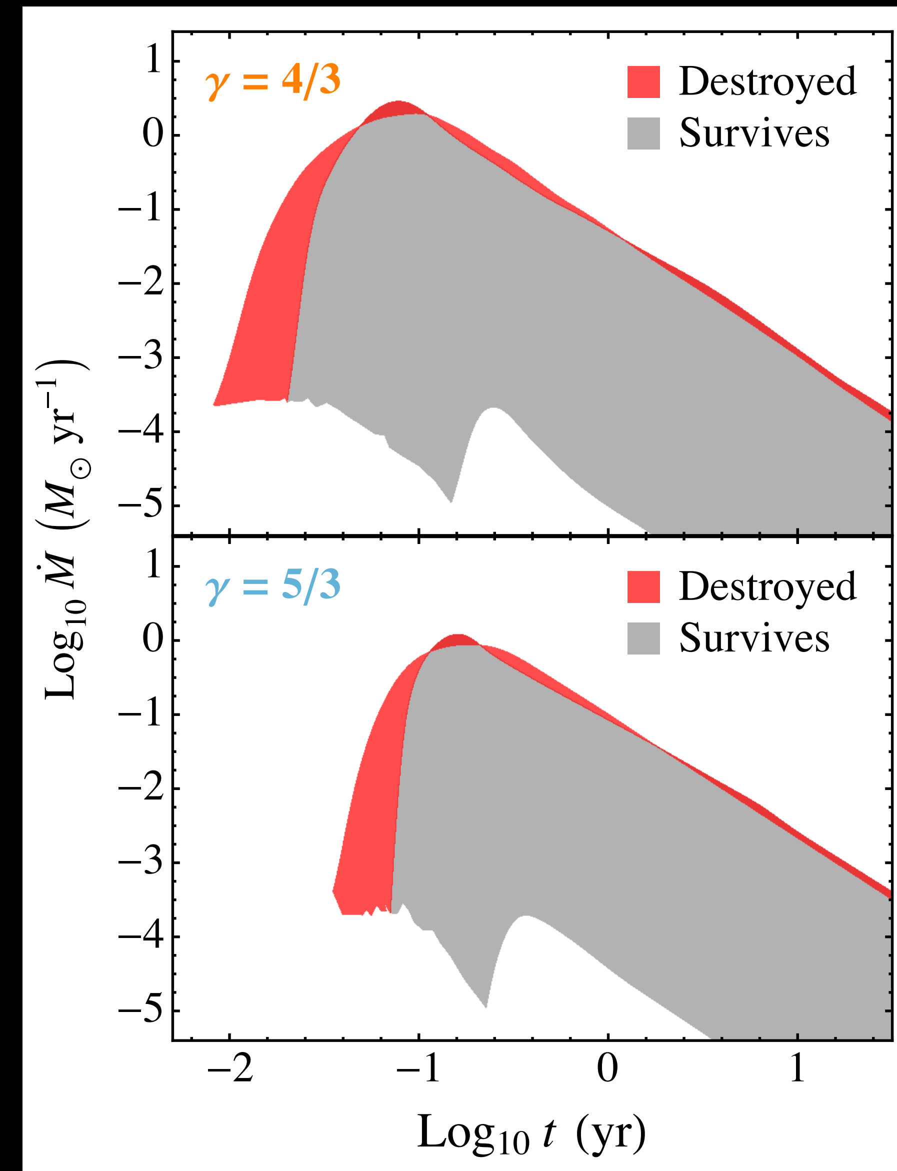
Half of the debris is bound, half is unbound.
Width of stream comparable to original star.

dM/dt as a function of β and γ





Guillochon+ 2013

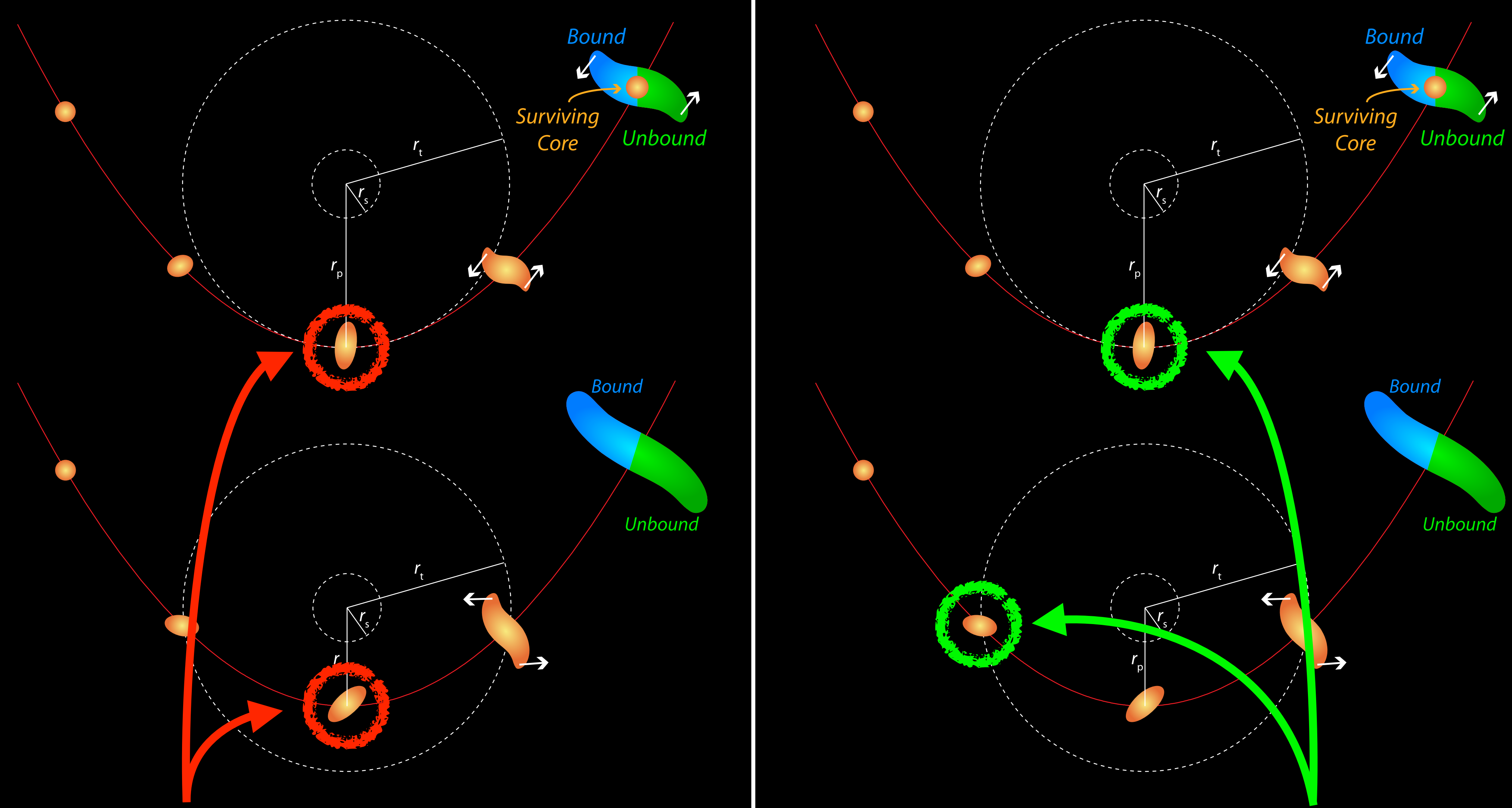


At a glance:

- dM/dt looks nearly identical for $\beta > \beta_{\rm destroy}$, aside from the earliest times.
- $t_{\rm peak}$ is fairly similar for all disruptions, both full and partial, and for both values of γ.

The appropriate freezing approximation presumes that the gas behaves as a collection of free-streaming particles once the tidal force dominates the star's self-gravity.

Incorrect: | **(More) Correct:**



Freeze the binding energy at pericenter

Freeze the binding energy at the tidal radius

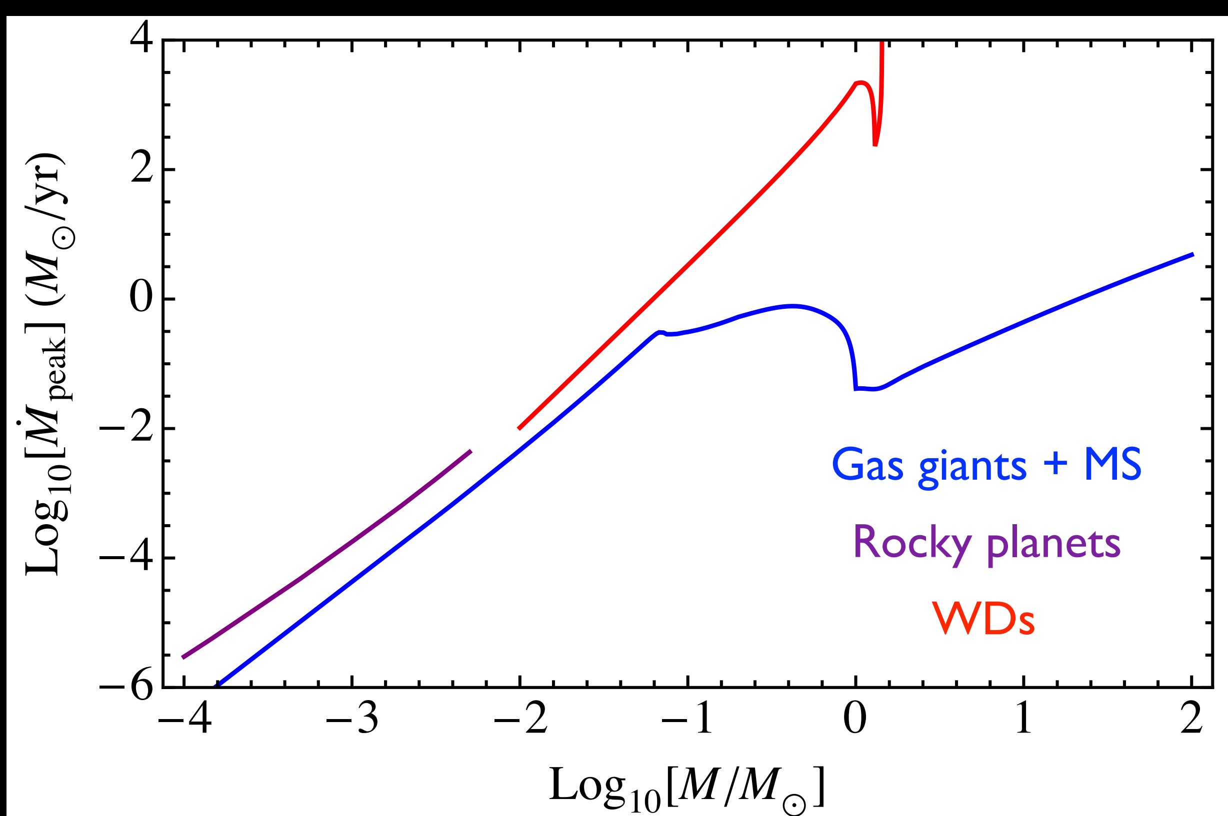
This is why dM/dt resulting from complete disruptions look nearly the same, independent of β (see Stone+ 2013, Guillochon+ 2013).

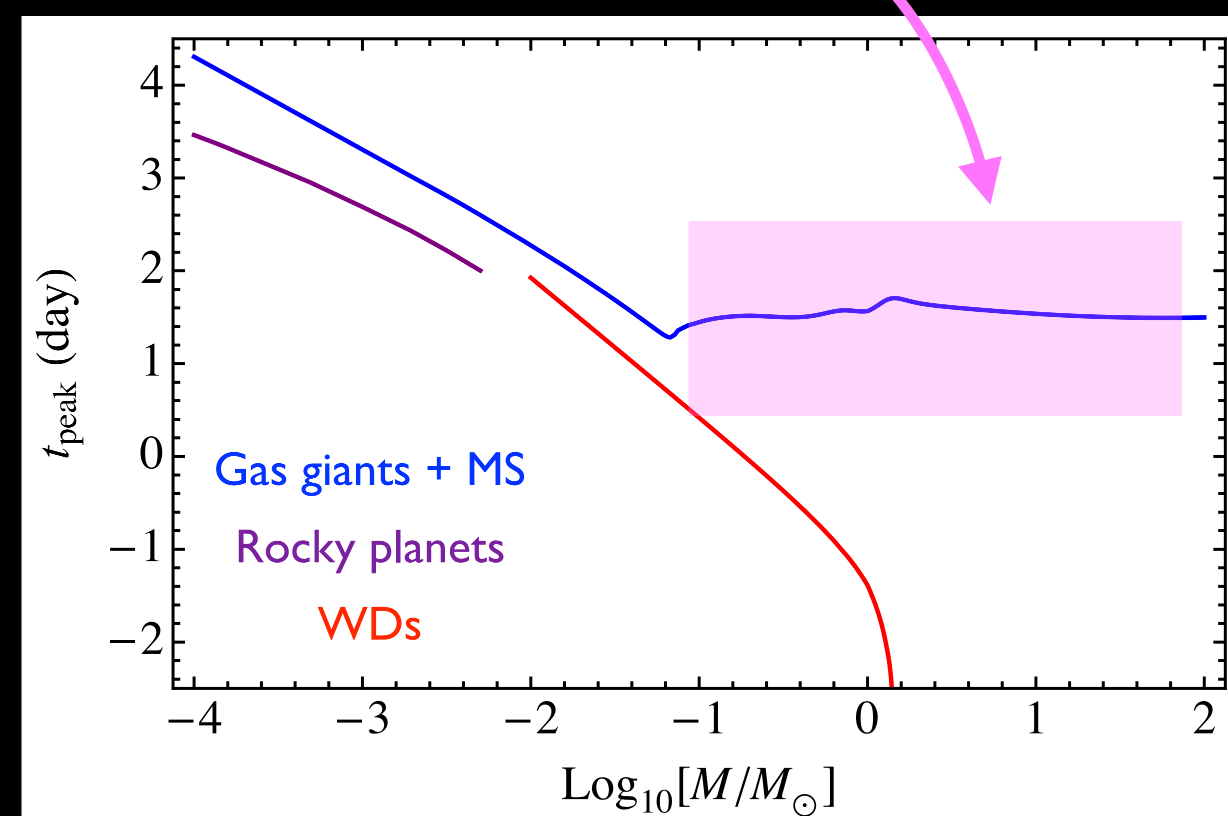
The dream: Tidal disruptions as a measure of black hole mass?

$$\dot{M}_{\rm peak} = g(\beta,\gamma)\left(\frac{M_{\rm h}}{10^6 M_\odot}\right)^{-1/2}\left(\frac{M_*}{M_\odot}\right)^{2}\left(\frac{R_*}{R_\odot}\right)^{-3/2}$$

$$t_{\rm peak} = f(\beta,\gamma)\left(\frac{M_{\rm h}}{10^6 M_\odot}\right)^{1/2}\left(\frac{M_*}{M_\odot}\right)^{-1}\left(\frac{R_*}{R_\odot}\right)^{3/2}$$

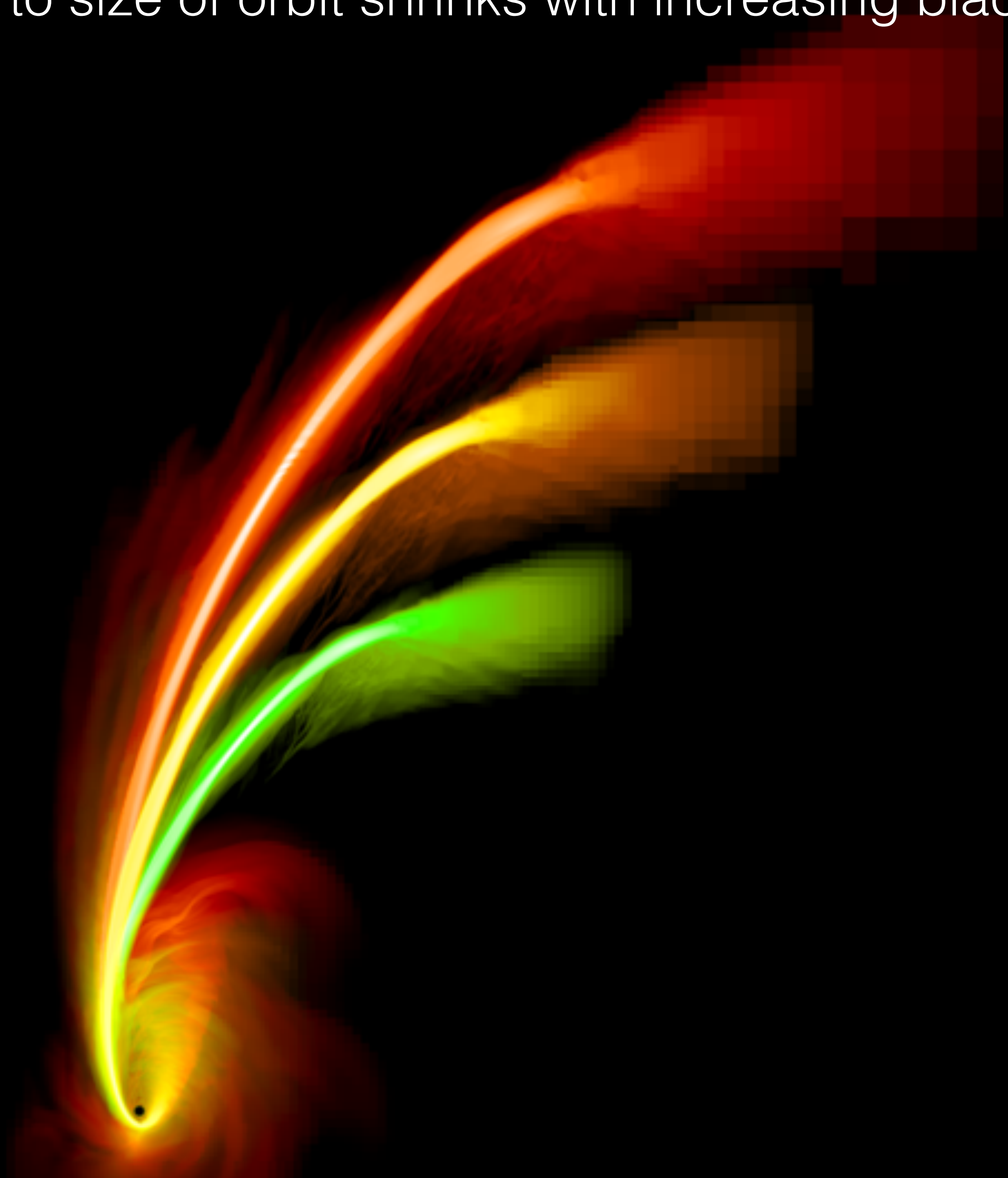
MS stars have very similar timescales



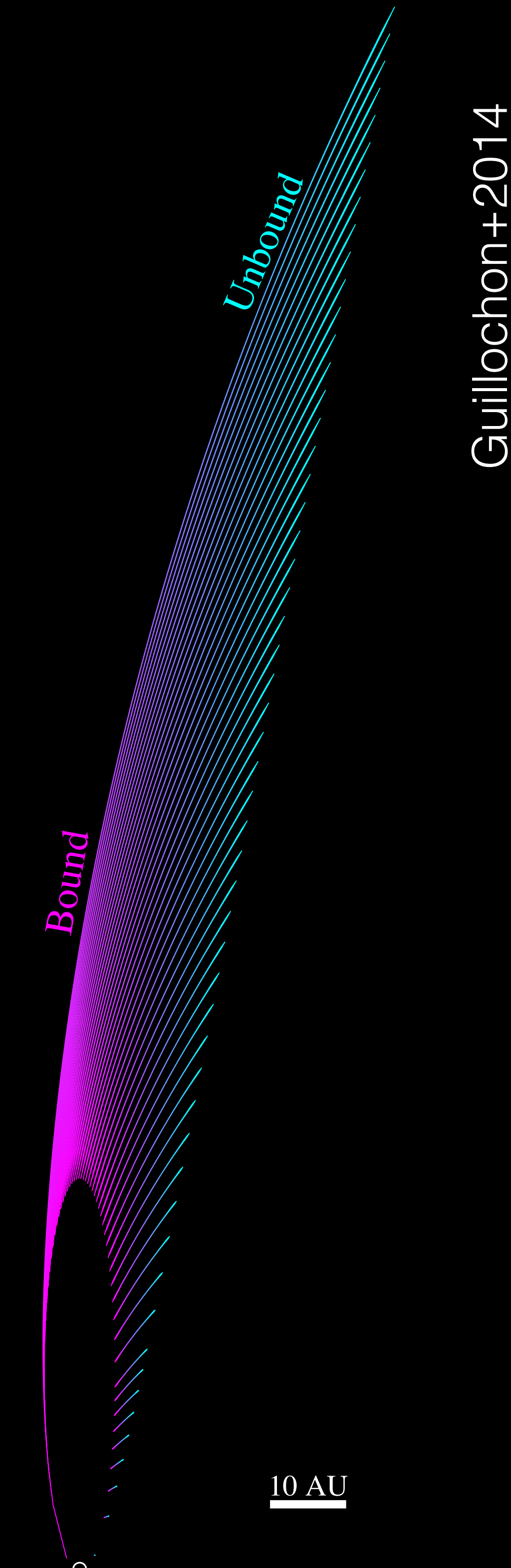


(for $M_h = 10^6$)

Because tidal radius grows with mass, width of stream compared to size of orbit shrinks with increasing black hole mass.



Mass ratio: 10^3



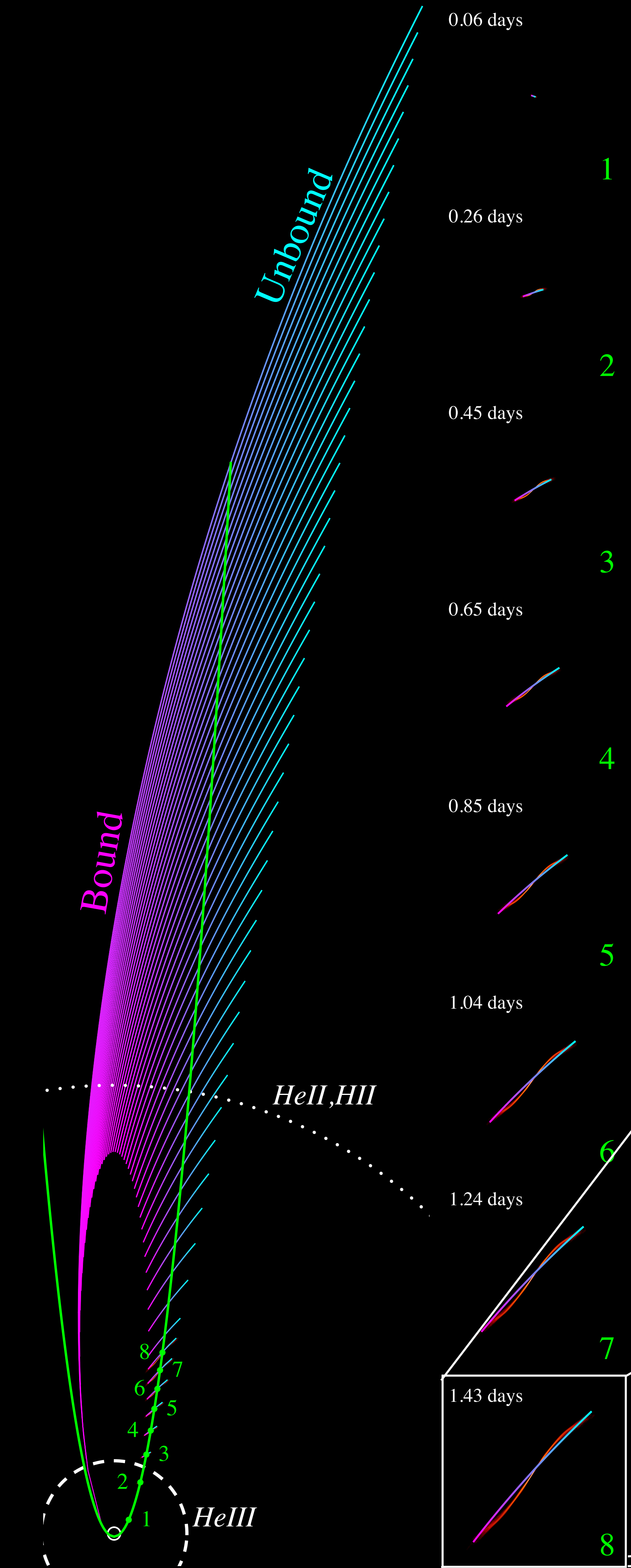
Mass ratio: 10^6

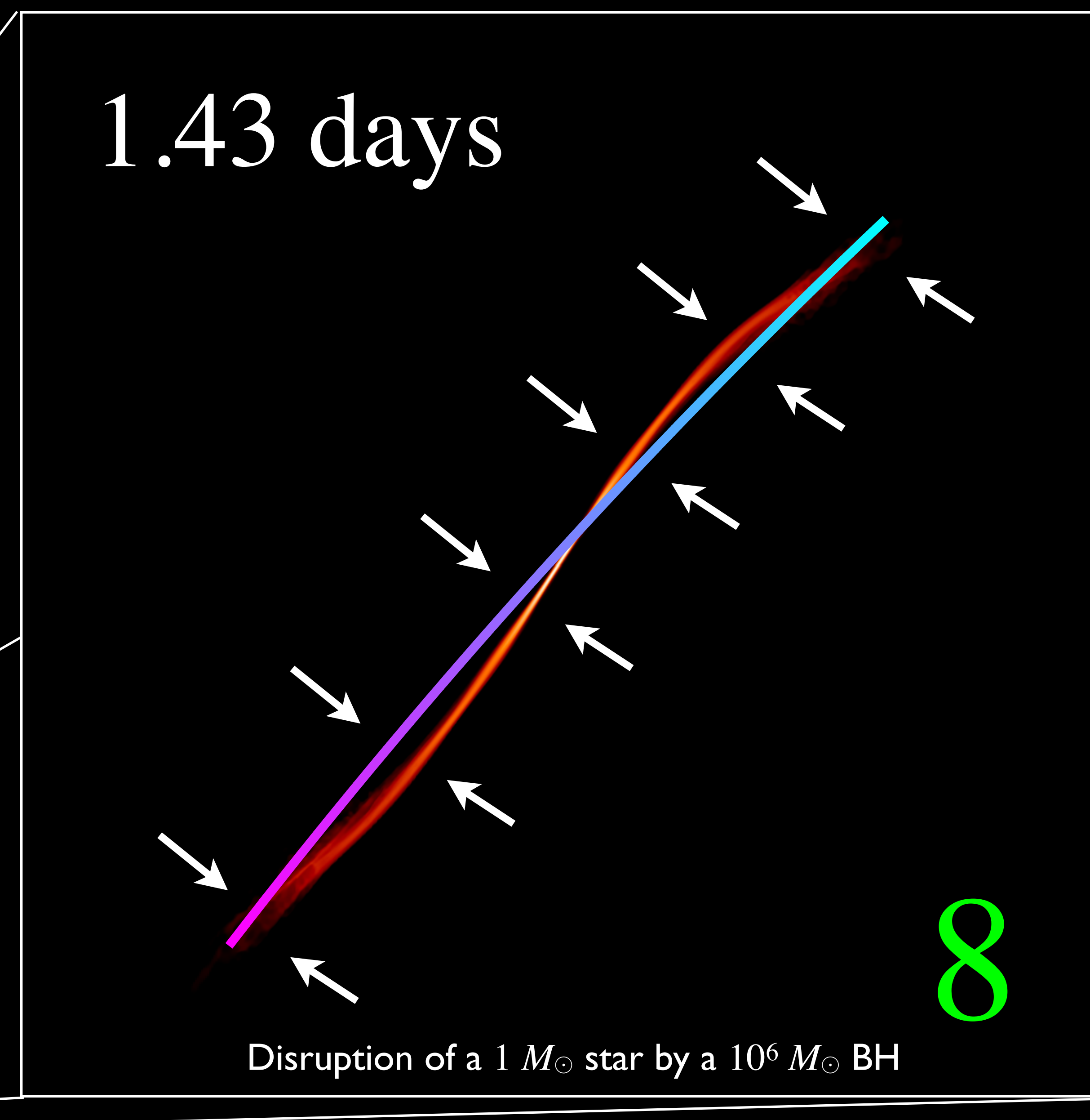
$$r_{\rm t} = 7 \times 10^{12} \left(\frac{r_*}{r_\odot}\right) \left(\frac{M_*}{M_\odot}\right)^{-1/3} M_6^{1/3} \text{ cm} \quad \Rightarrow \quad r_{\rm t}/r_* = 300 M_6^{1/3}$$

The usual phases of gravitational collapse
(planar → cylindrical → spherical)
are happening in reverse!

In a tidal disruption, a star regresses back into a self-gravitating cylinder, this makes them remain narrow:

$$H \propto r^{1/4}$$

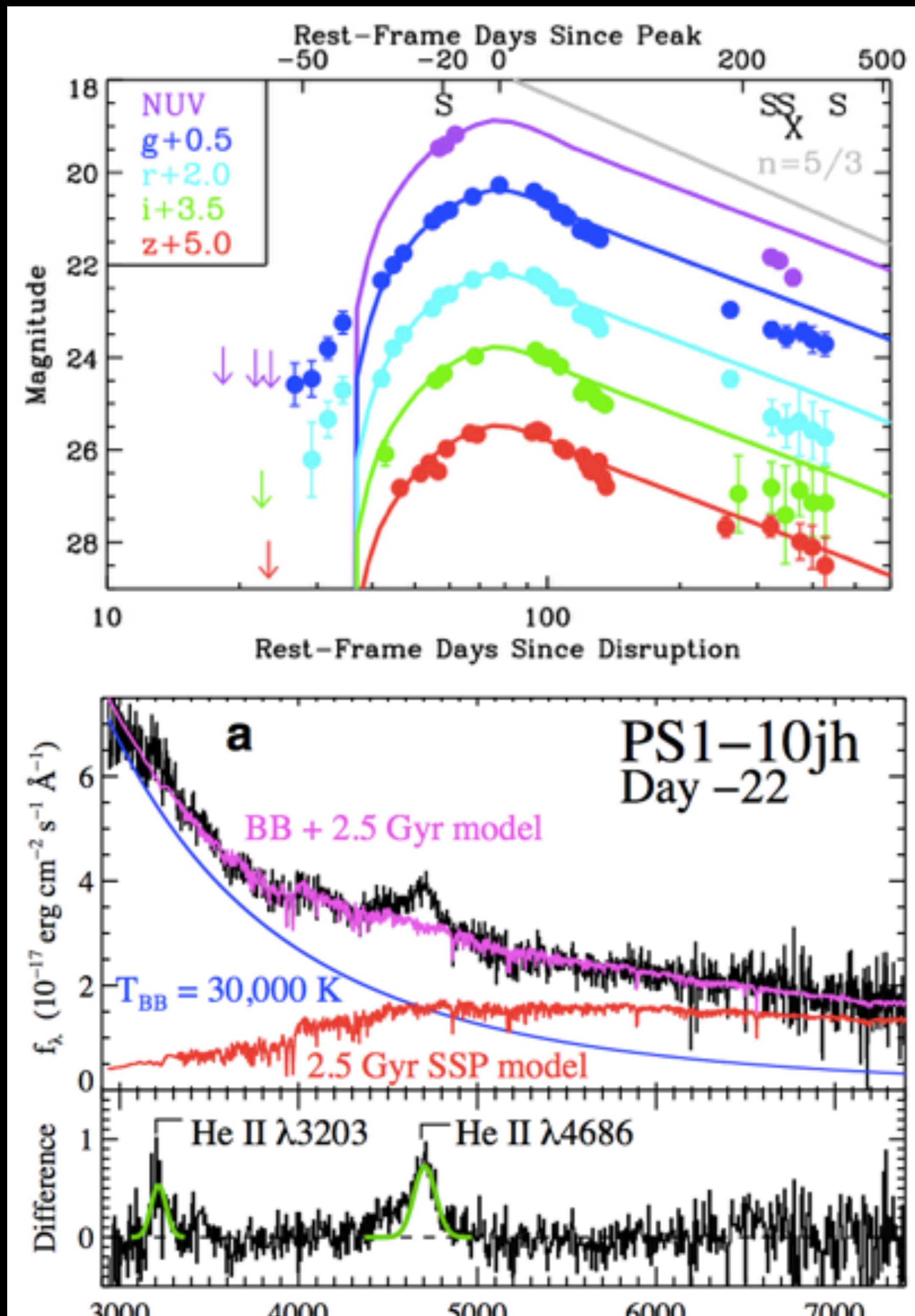




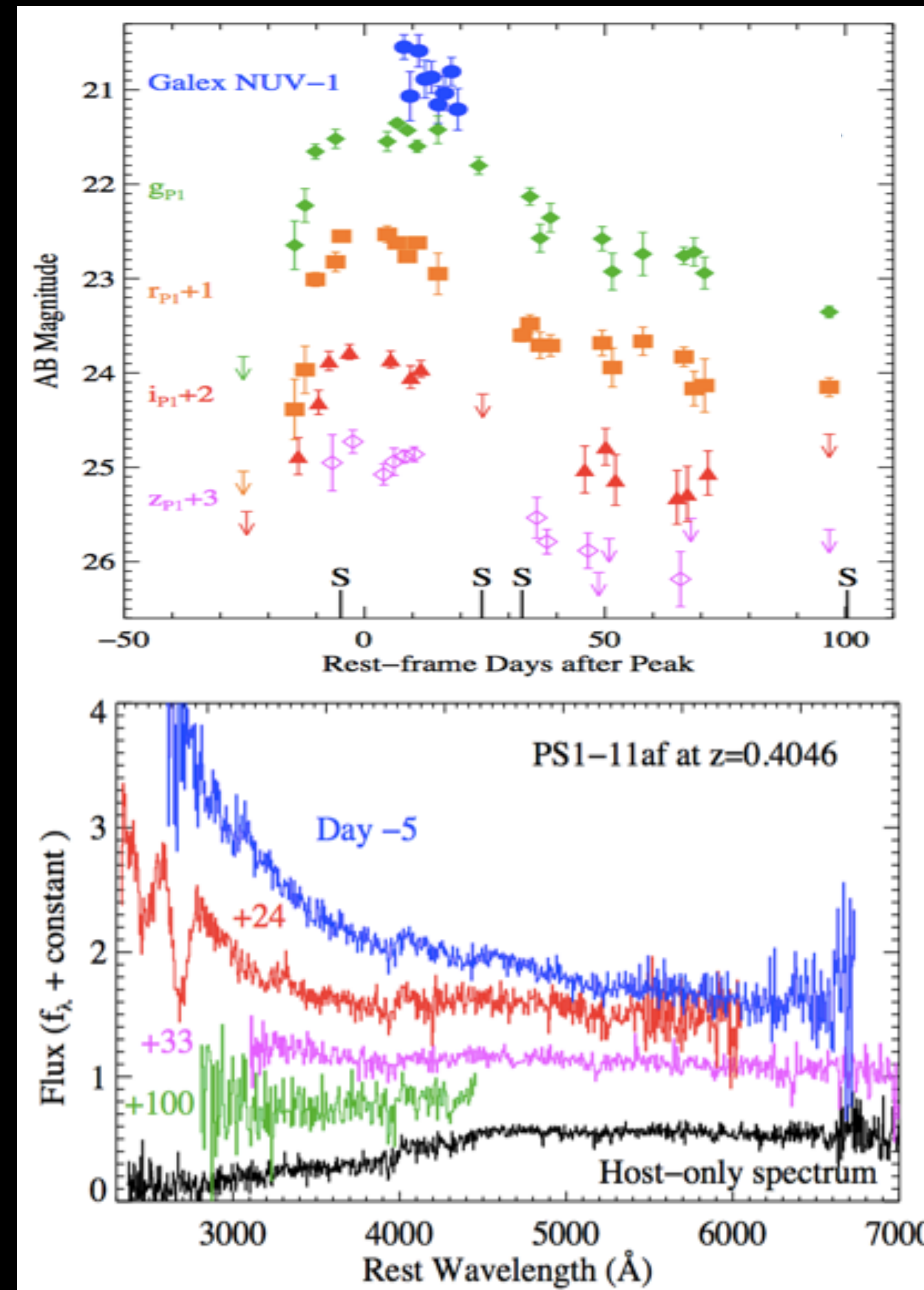
Disruption of a 1 $M_\odot$ star by a 10^6 $M_\odot$ BH

II: An Observational Signature of the Bound Debris

The TDEs of today:
Black hole mass measurements possible?

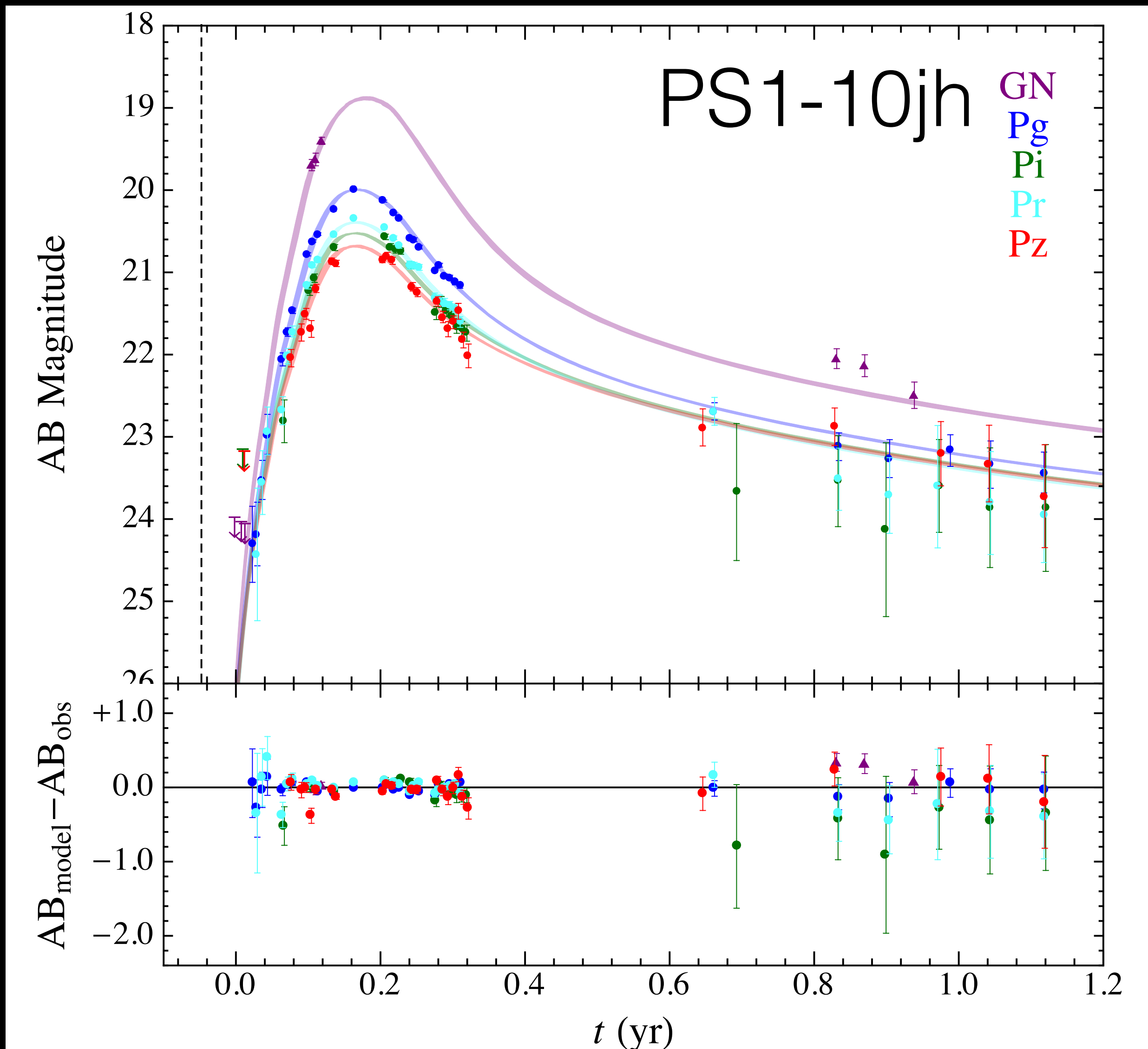


Gezari+ 2012

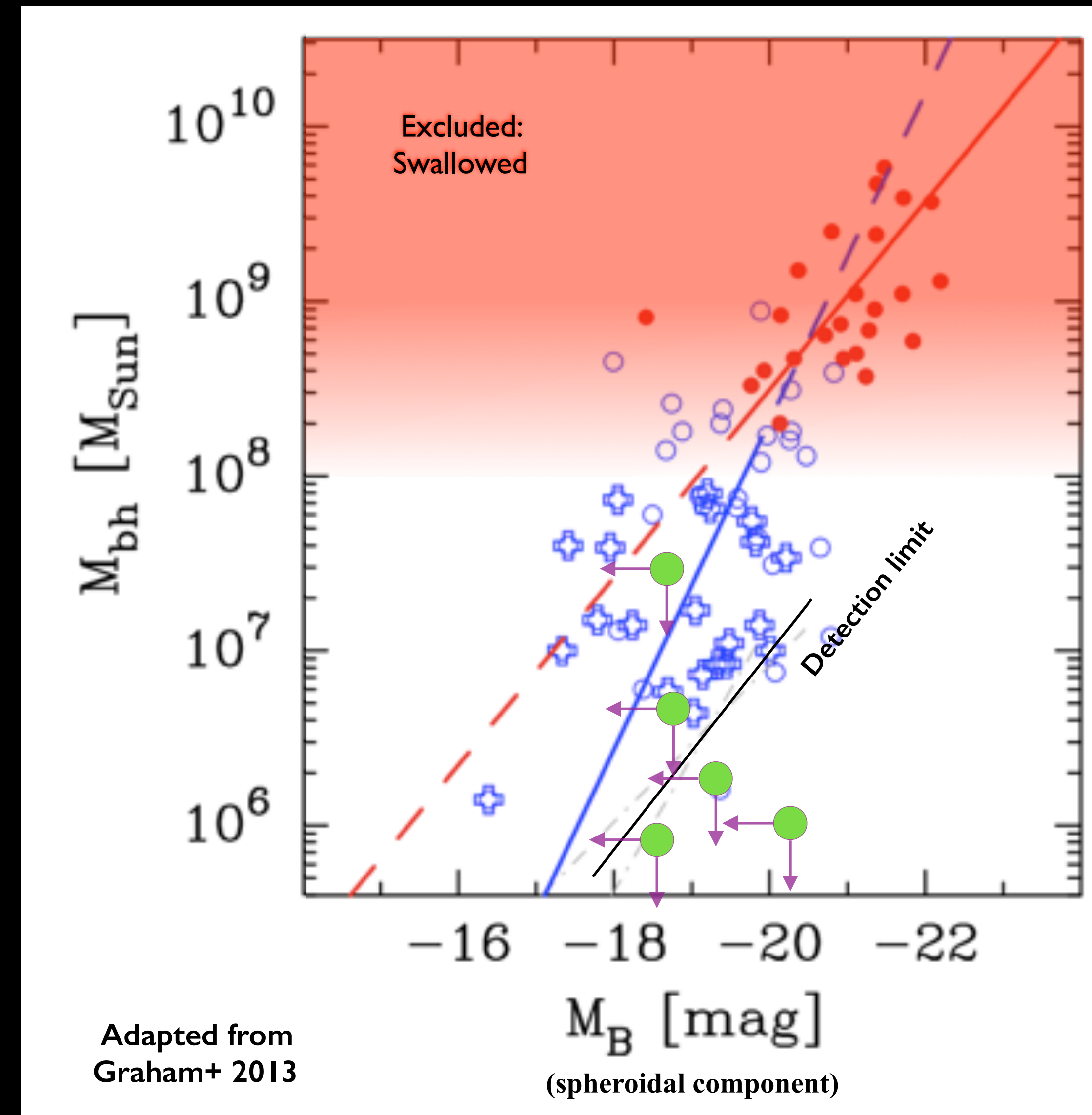


Chornock+ 2013

Derived Black Hole Masses: A first attempt



Guillochon+2014



Photometry calculated using **TDEFit**, a piece of software we developed to determine the most-likely physical parameters to match observed flares.

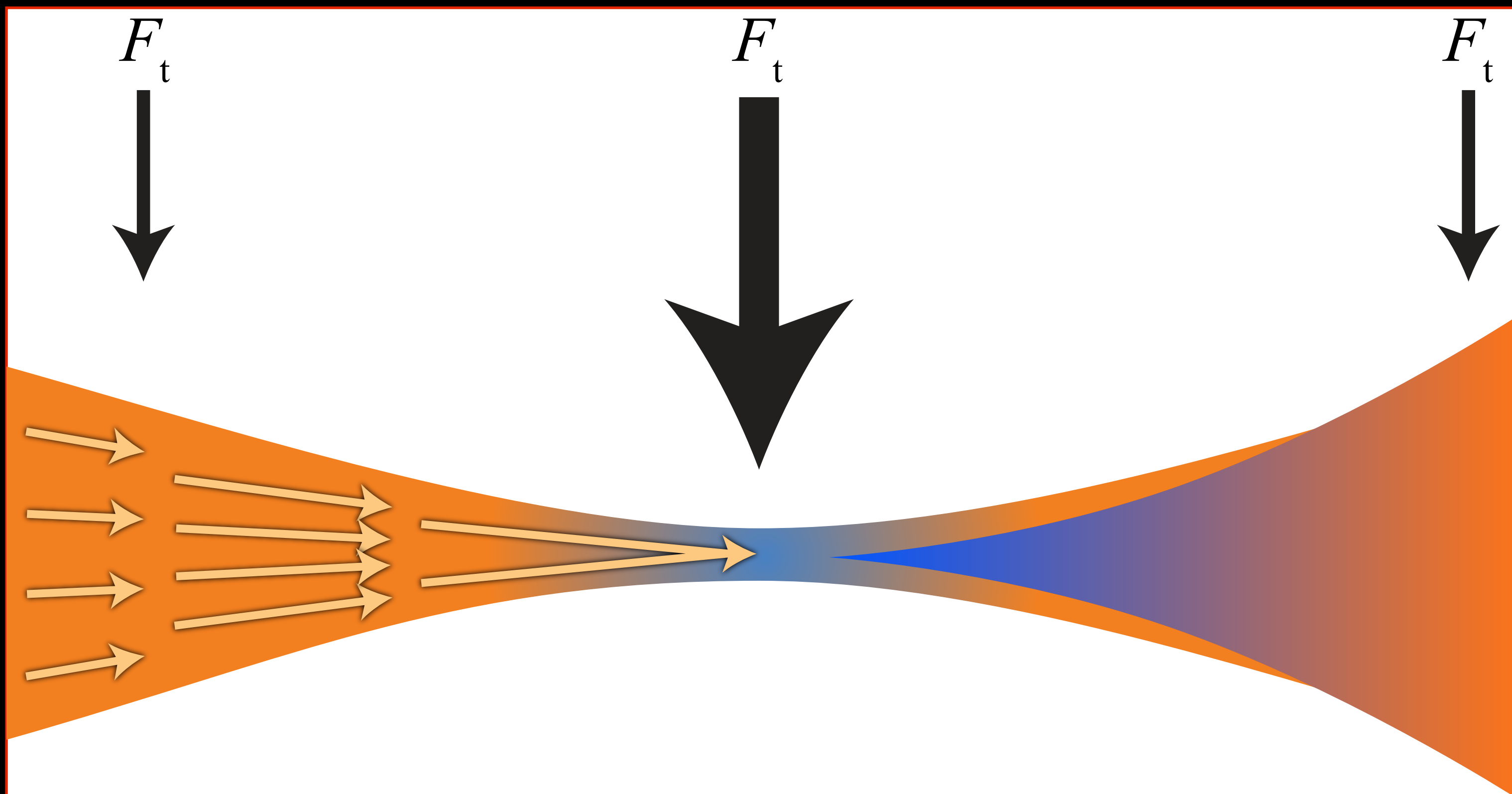
Not only can the software determine black hole mass, it can also determine other interesting parameters of the disruption (stellar mass, black hole spin, accretion disk properties, etc.).

Mission accomplished…?

A closer look: Are we *actually* tapping into the fallback accretion immediately?

NO! Material does *not* accrete onto the black hole right away!

Shocks as the stream returns to pericenter (the "nozzle")



Dissipation per orbit ~ v_*^2

10% per orbit for $M_h = 10^3$

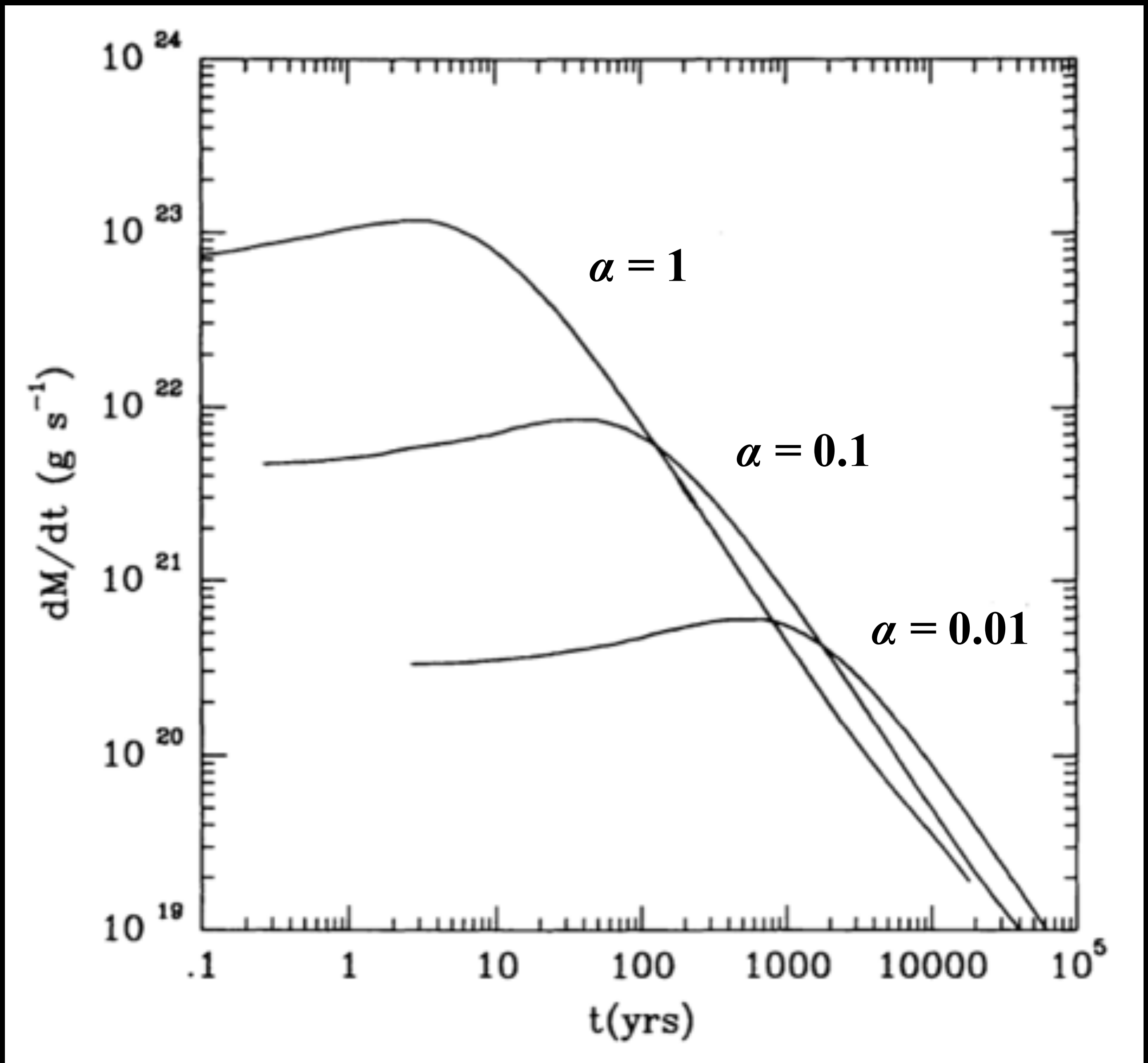
1% per orbit for $M_h = 10^6$

T

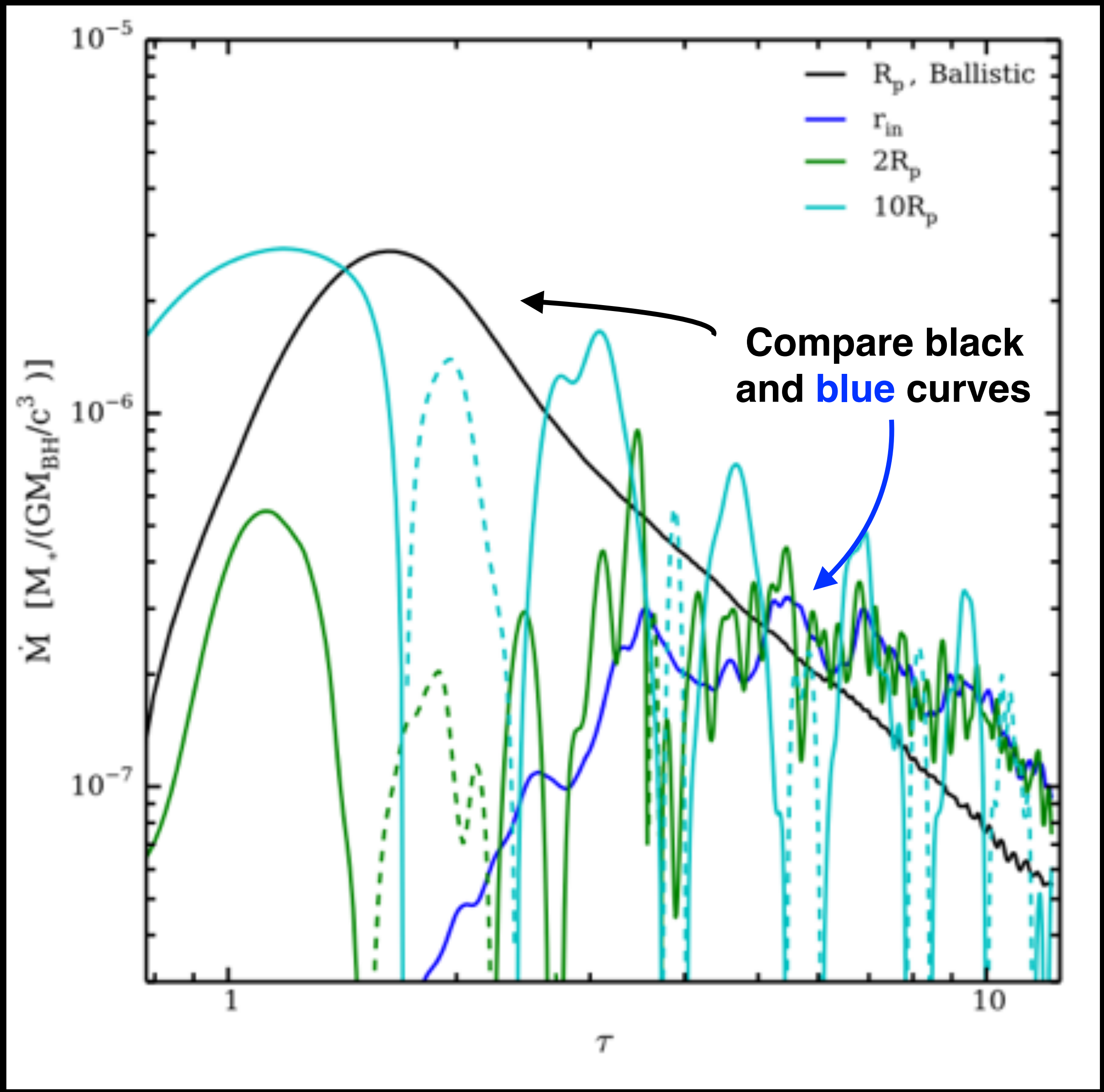
v_z

TDEs should be *slooooooooow!*

(many graduate student lifetimes)



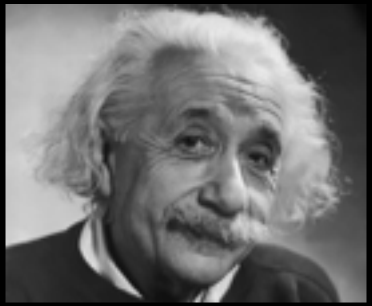
Cannizzo+ 1990

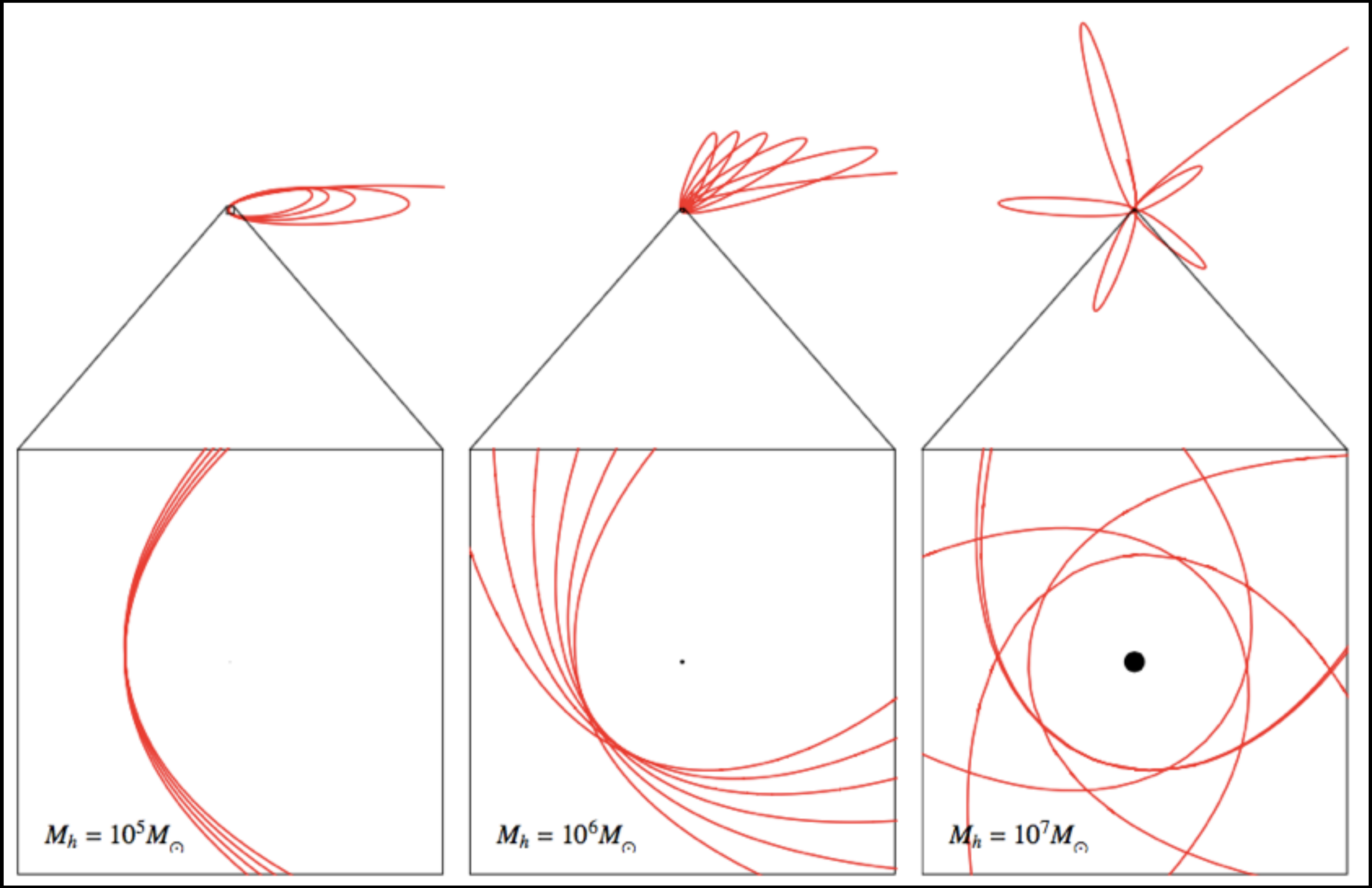


Shiokawa+ 2015

But, the observed flares *are* fast. **What gives?**

One option: **Relativity!**
Precession from relativity will cause the stream to collide much closer to the black hole.





Guillochon & Ramirez-Ruiz 2015

GR effects stronger for higher black hole mass as Schwarzschild radius scales with M and tidal radius scales with $M^{1/3}$.

Dissipation for Schwarzschild black holes (no spin)

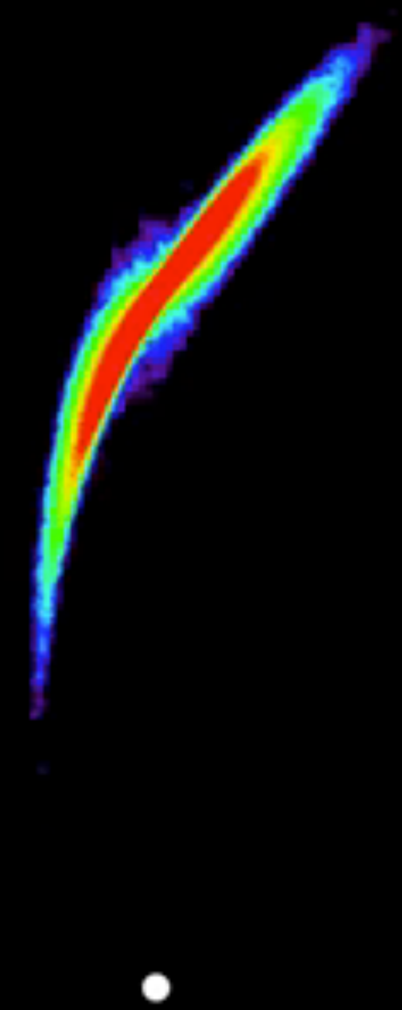
Dissipation at the nozzle is **weaker**
for higher-mass black holes

$$\mathcal{V}_{\rm nozzle} = \beta q^{-1/3}$$

$$\mathcal{V}_{\rm GR} \propto \beta q^{2/3}$$

Dissipation from stream-stream collisions
due to GR precession is **stronger**
for higher-mass black holes

(See Dai+2015 for details)



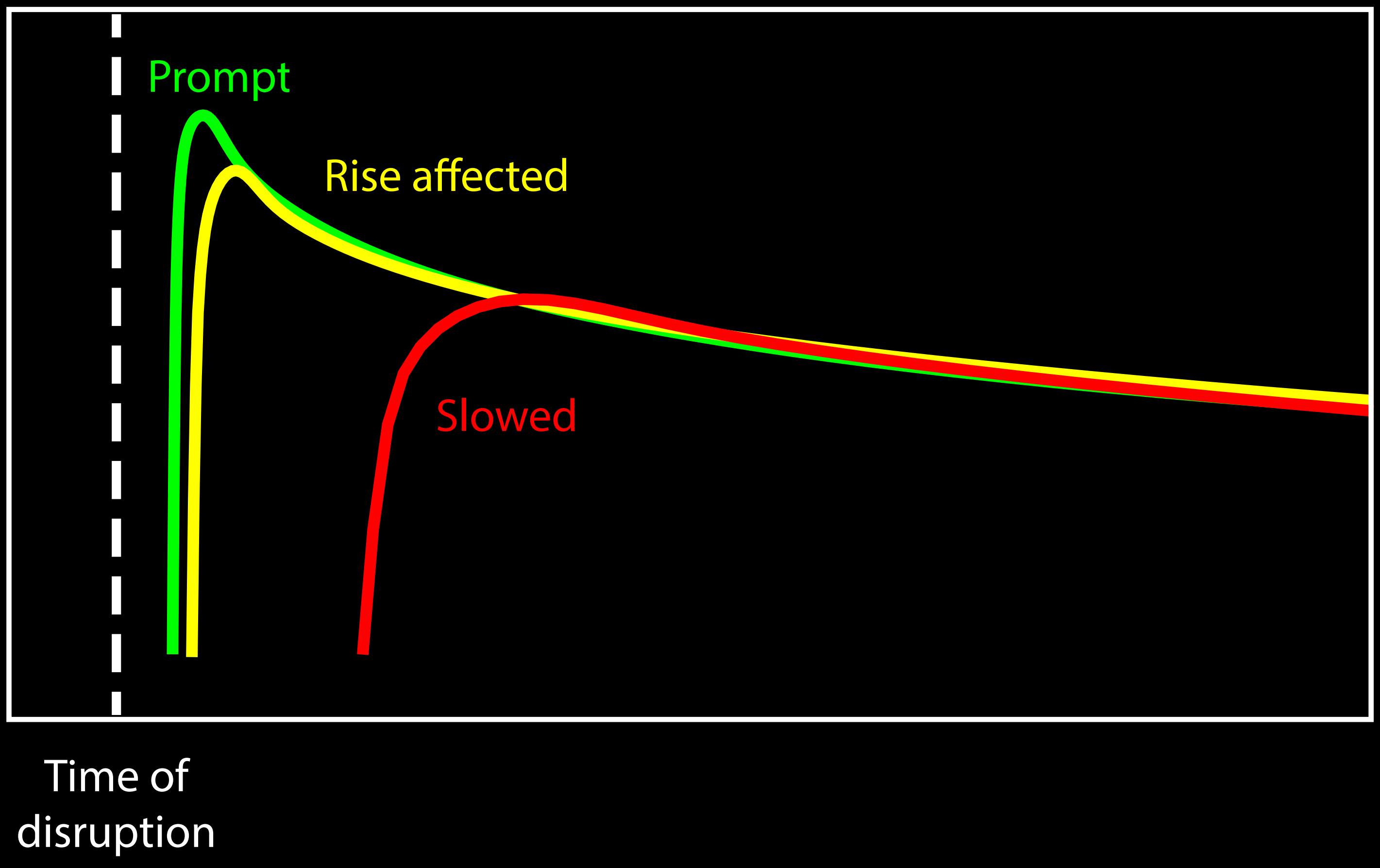
Disruption of a $1\ M_{\odot}$ star by a
$10^6\ M_{\odot}$ BH (Bonnerot+2015)

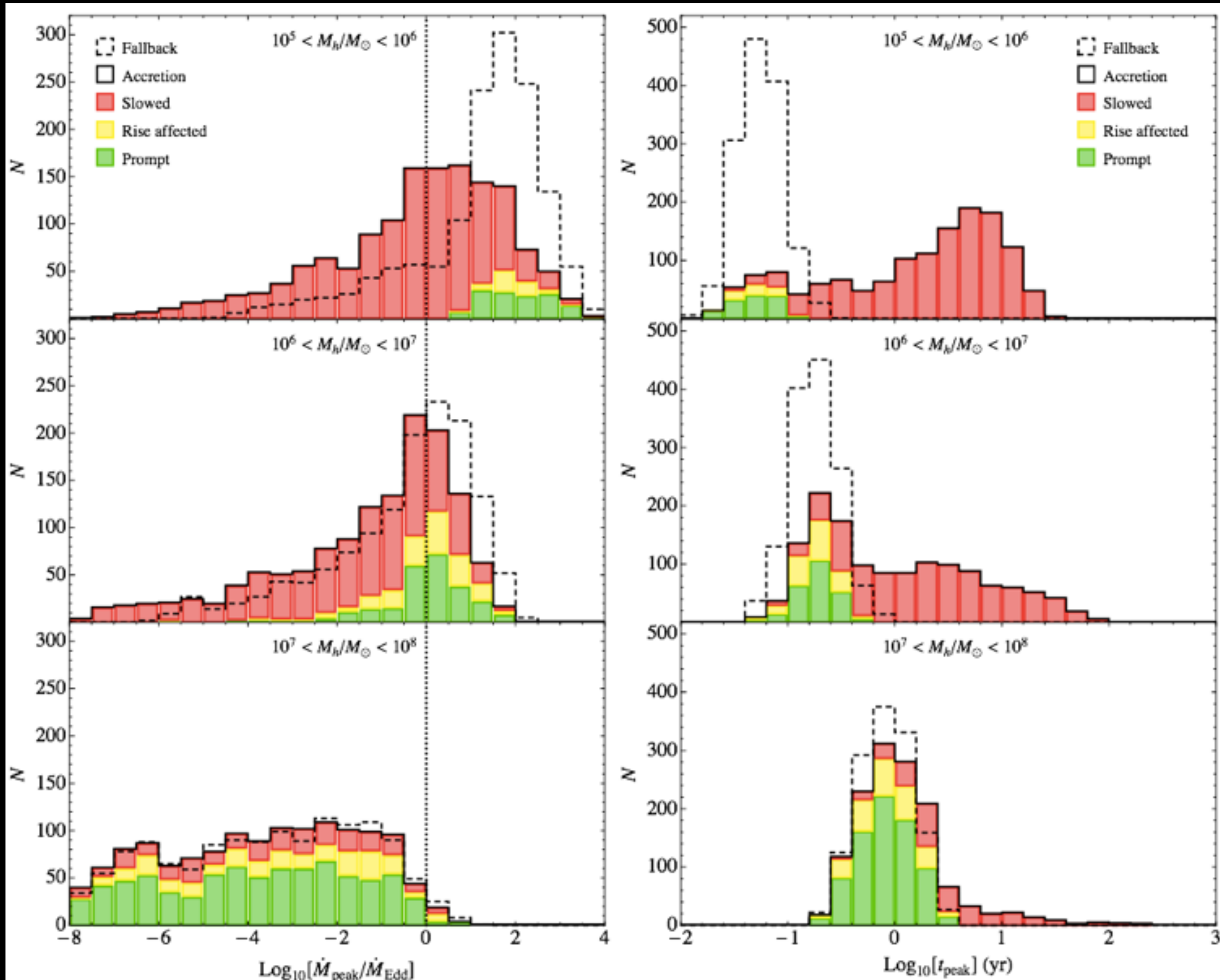
A dichotomy: Slowed vs. prompt TDEs

★ The angle of the stream intersection, and where it occurs, determines the viscous timescale.

★ If the viscous timescale is long the thermal flare will be "slowed," if it's comparable to the time of peak accretion it will only have its "rise affected," and if it's shorter than this timescale it will be "prompt," closely following $\mathrm{d}m/\mathrm{d}t$.

★ Slowed events will likely not look like TDEs!

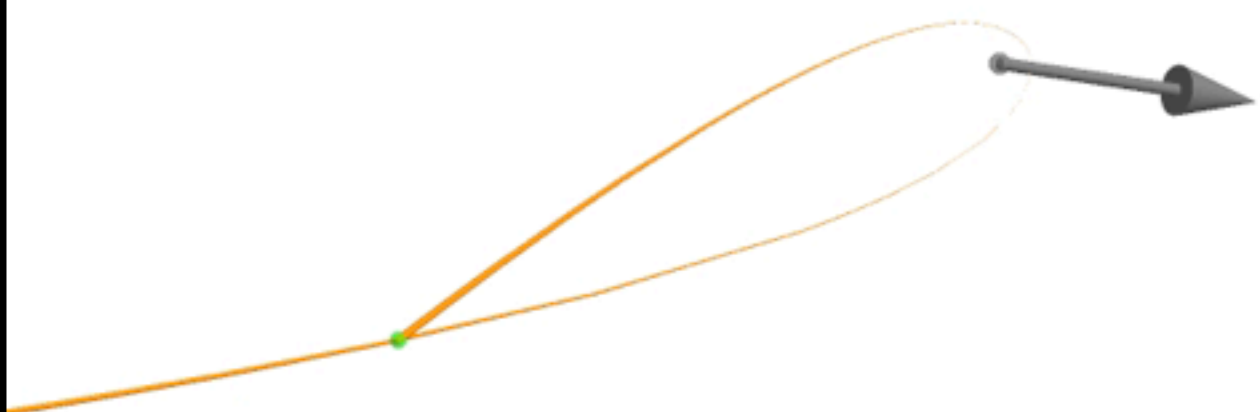




Guillochon & Ramirez-Ruiz 2015

- ★ 10% of events prompt for low-mass black holes, 50% prompt for high-mass.
- ★ Only deep encounters are prompt around low-mass black holes.
- ★ Less than half are super-Eddington at peak (required to produce jets).
- ★ Some flares take **decades** to peak!

A "dark year" for tidal disruptions.

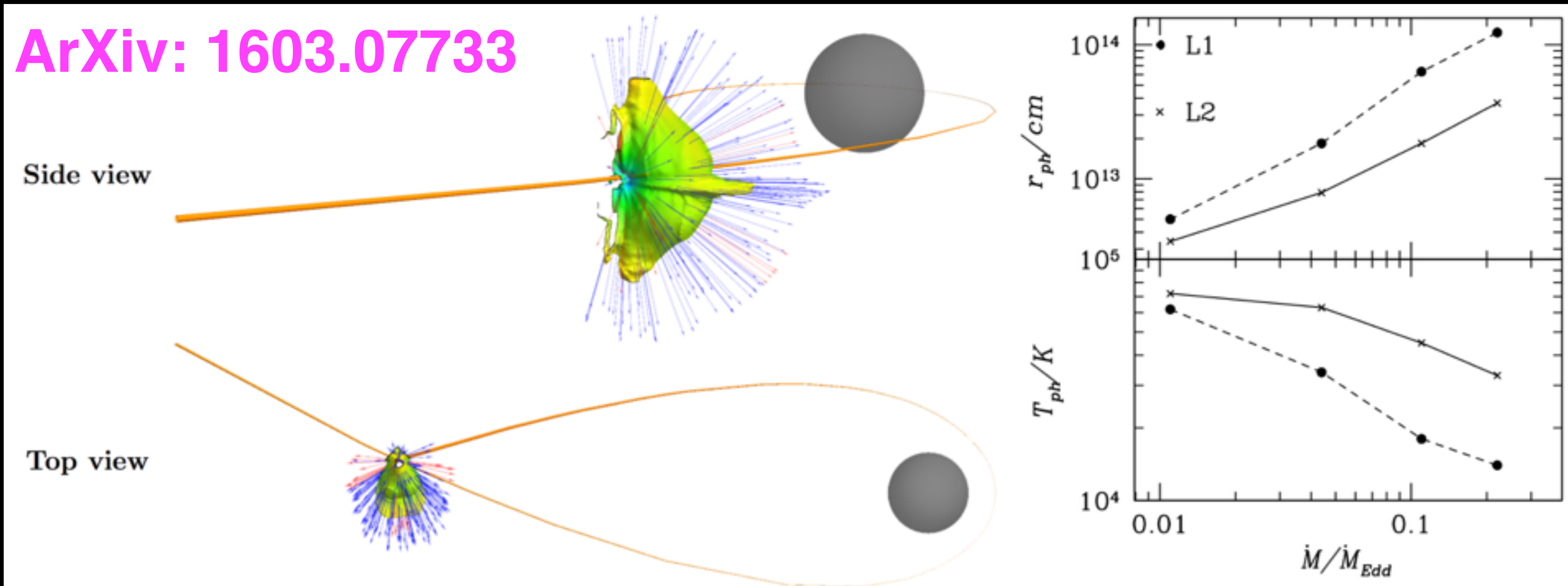


Guillochon & Ramirez-Ruiz 2015

Out of plane precession (due to black hole spin) can delay the flare by **months** to **decades**.

A second option:
Stream-stream collisions

Jiang, Guillochon, & Loeb 2016



- ★ Found prompt optical radiation with the right luminosities and temperatures from stream-stream collisions.
- ★ ~10% of the mass ejected via radiation pressure for Eddington accretion rates.
- ★ Definitely an important component to consider when modeling TDEs.

Open Transient Modeling with MOSFiT

Modular **O**pen-**S**ource **Fi**tter for **T**ransients

http://mosfit.readthedocs.io

- **MOSFiT** downloads any dataset from one of the open catalogs (e.g. Open Supernova and Tidal Disruption catalogs) and fits against a user-specified model.
- Many semi-analytical models employ similar physics with slightly different assumptions. This redundancy motivates a **modular** design, which is what MOSFiT implements.
- Can utilize photometry, radio observations, X-ray observations, and spectra when model matching.
- Performs minimization and sampling of the maximum likelihood via a combination of MCMC and global optimization.
- Can be run in parallel and/or on a list of events and/or models.
- Written in Python, **available now**, paper soon. **Intended for use by both observers and theorists.**

```
pip install mosfit
```

A minimal model for optical tidal disruption flares

Assumptions

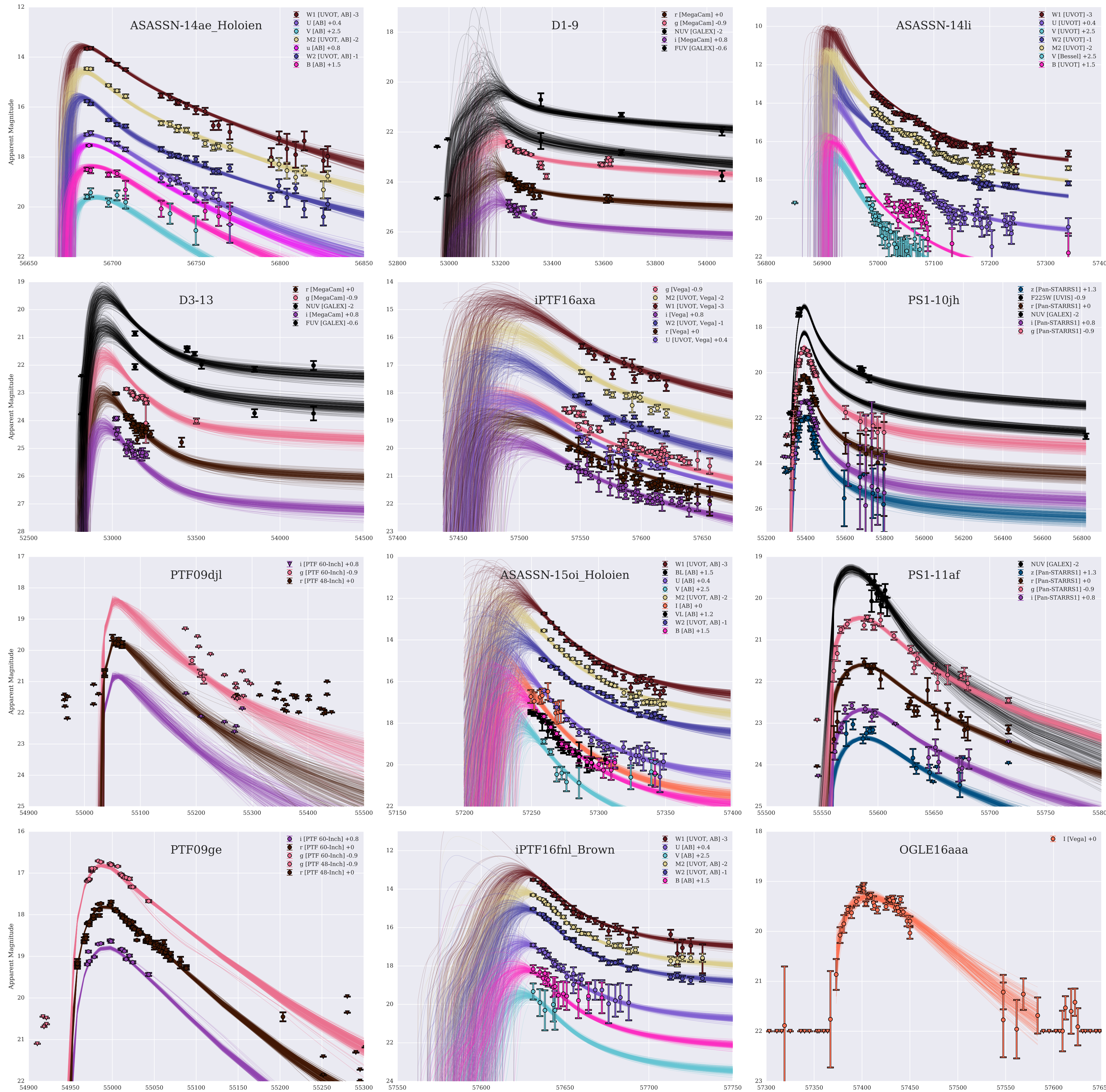
- Either the bolometric luminosity follows the fallback rate directly, or it follows a transformed, delayed accretion rate that is derived by "time filtering" through a disk.

$$\dot{M}_{\rm d}(t) = \dot{M}_{\rm fb}(t) - M_{\rm d}(t)/\tau_{\rm visc}$$

$$\dot{M}_{\rm d}(t) = \frac{1}{\tau_{\rm visc}} \left(e^{-t/\tau_{\rm visc}} \int_0^t e^{t'/\tau_{\rm visc}} \dot{M}_{\rm fb}(t') dt' \right)$$

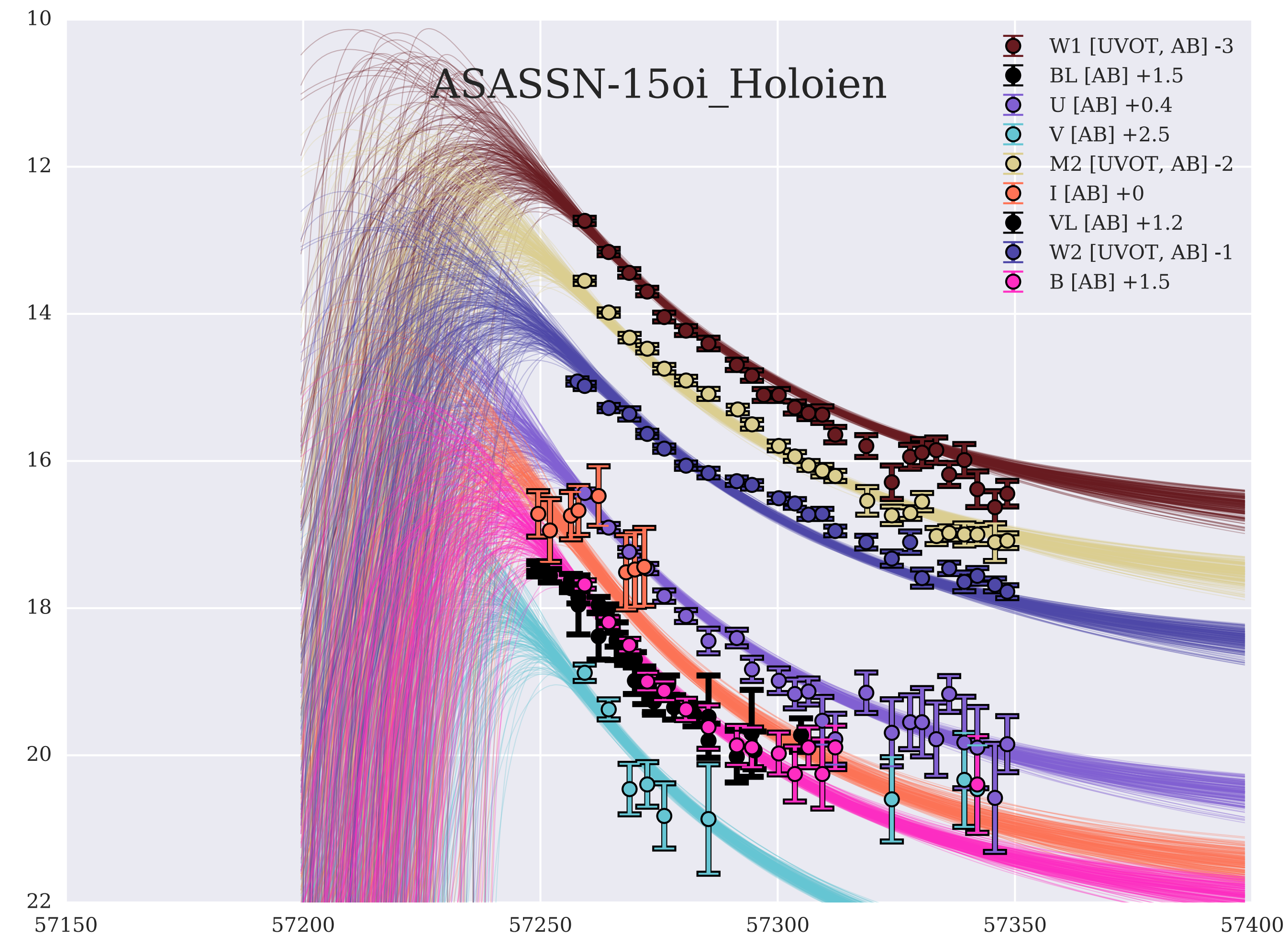
- All optical radiation is coming from a single blackbody that intercepts some fraction of the light produced by *either* the disk *or* circularization (we are agnostic). Efficiencies are allowed to be very low, as they could be if light leaves unreprocessed or is produced w/ circularization (<1% — 40%).

- Cannot model complicated flares like 15lh which clearly have two separate optical components (but only 1 out of ~dozen flares).

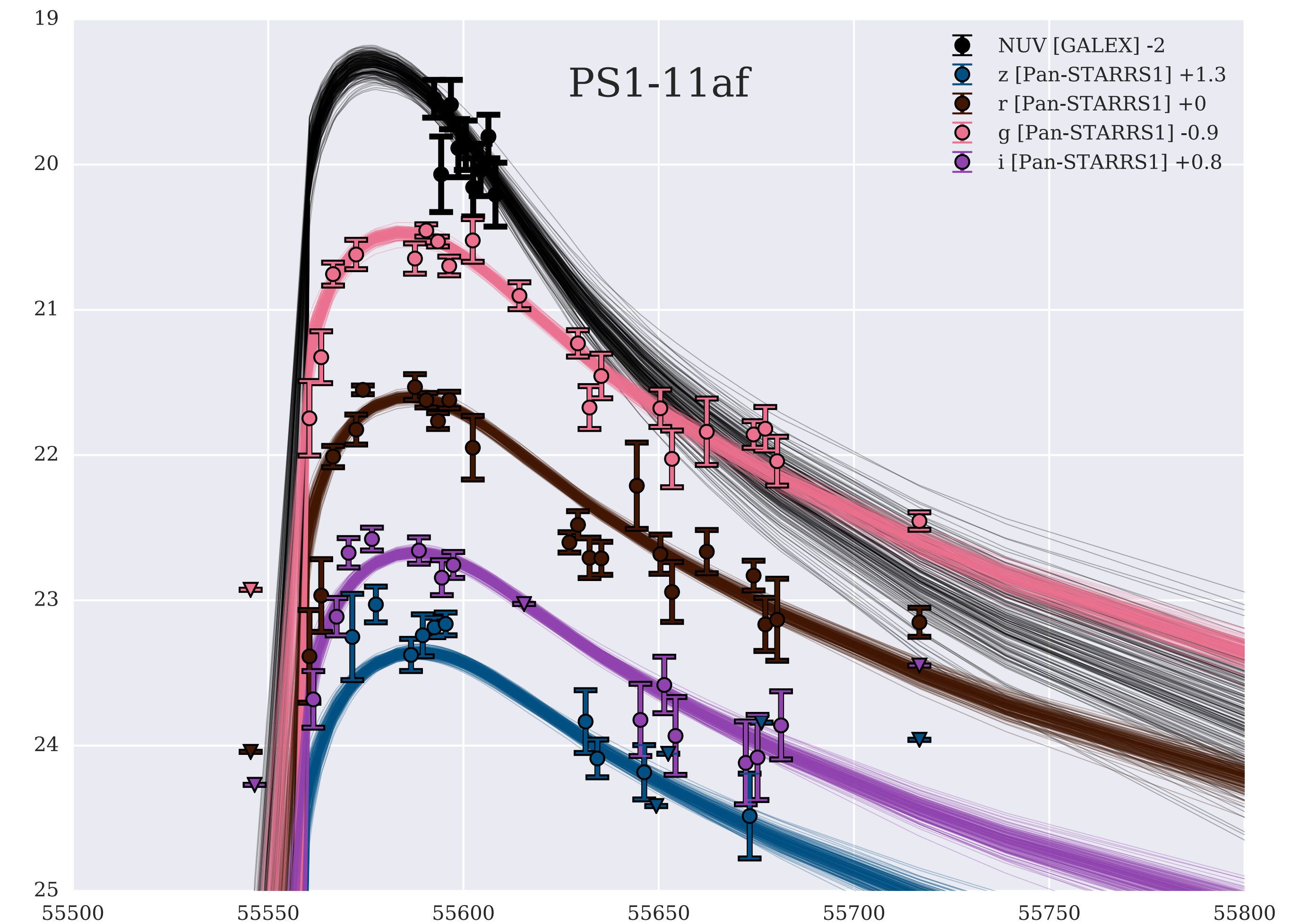


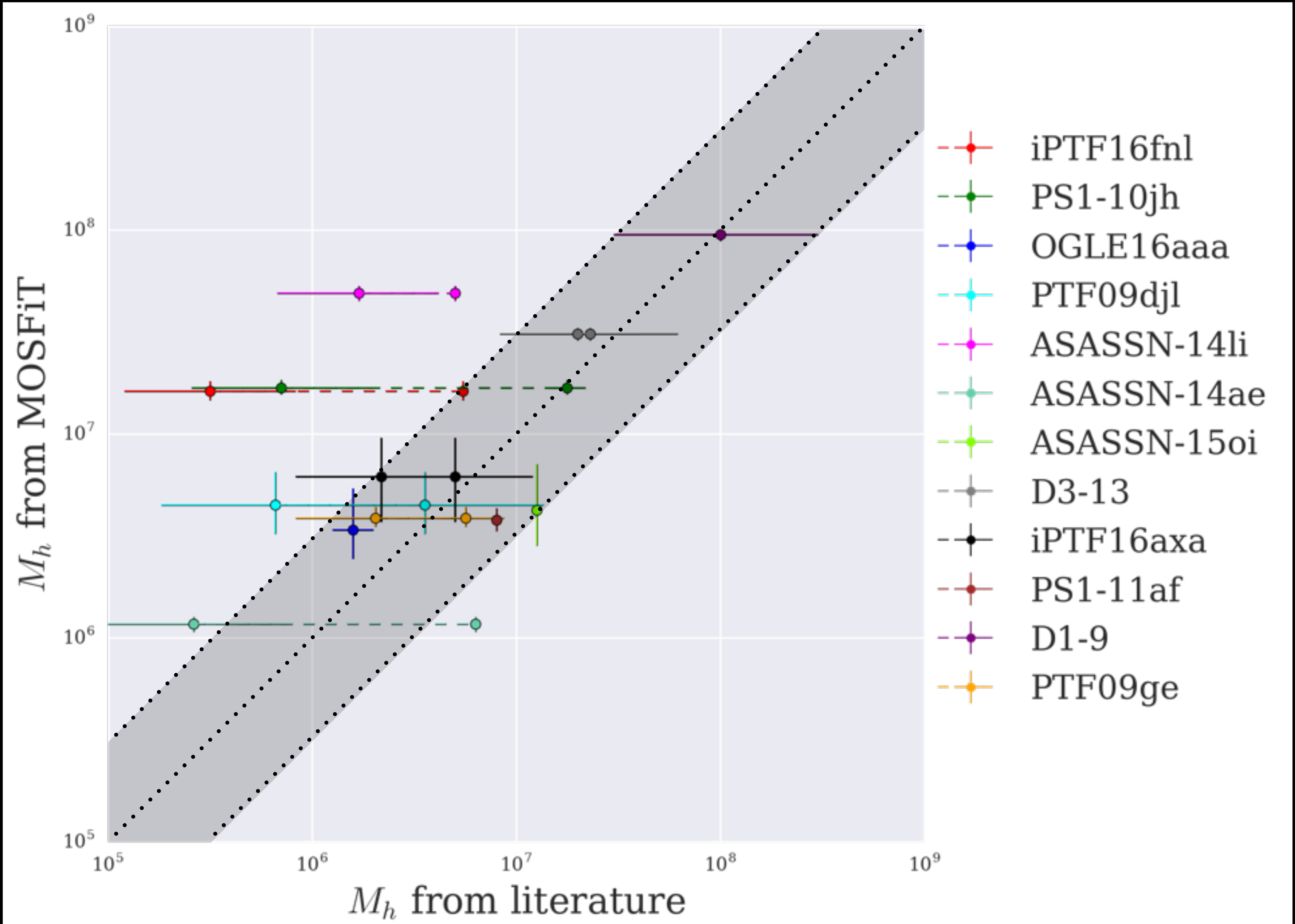
ASASSN-14ae_Holoien
D1-9
ASASSN-14li
D3-13
iPTF16axa
PS1-10jh
PTF09djl
ASASSN-15oi_Holoien
PS1-11af
PTF09ge
iPTF16fnl_Brown
OGLE16aaa
Apparent Magnitude
MJD

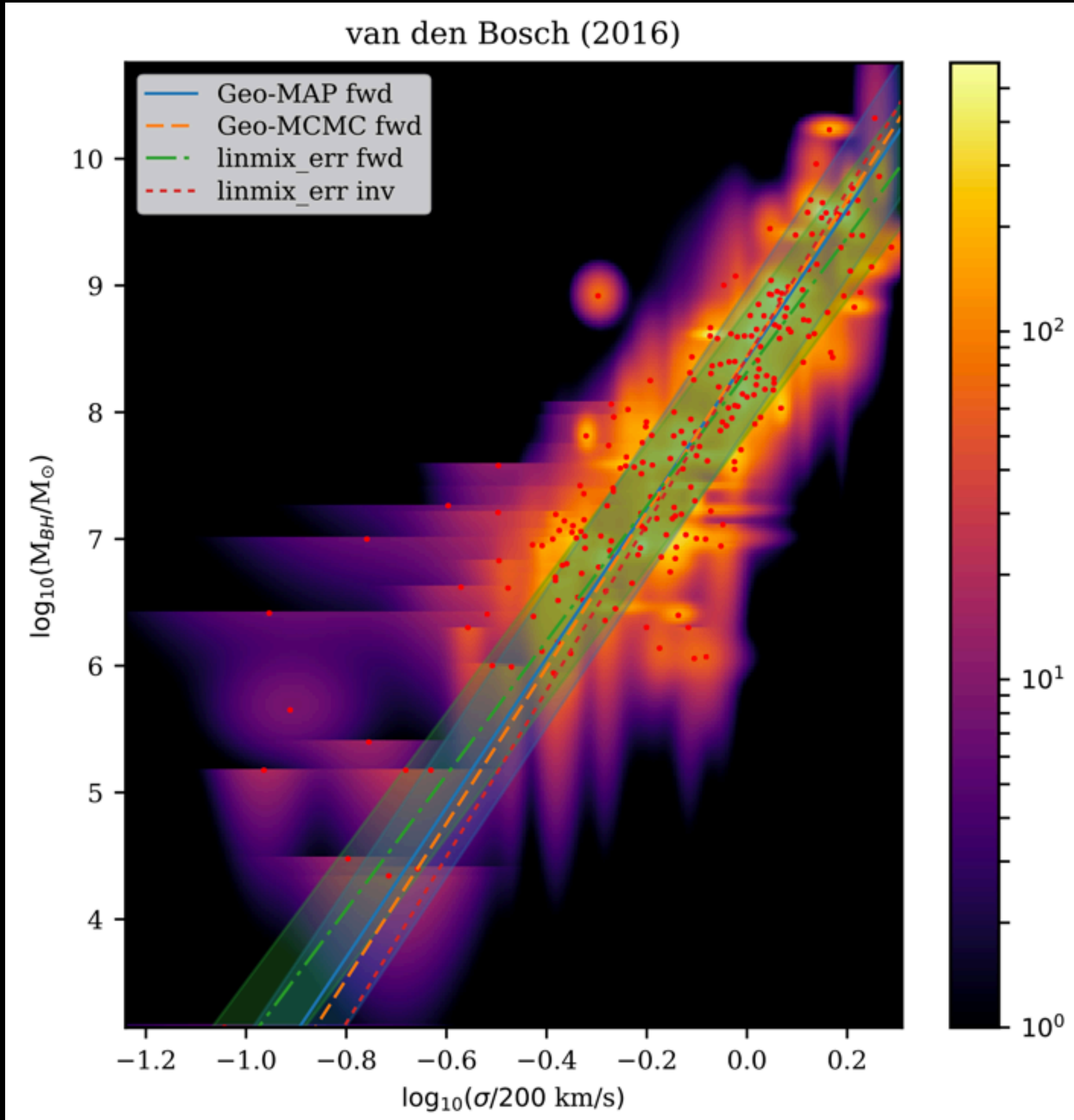
Peak not observed



Peak observed




M_h from MOSFiT
M_h from literature
10^5
10^6
10^7
10^8
10^9
iPTF16fnl
PS1-10jh
OGLE16aaa
PTF09djl
ASASSN-14li
ASASSN-14ae
ASASSN-15oi
D3-13
iPTF16axa
PS1-11af
D1-9
PTF09ge



Pihajoki 2017

Final thoughts

- Despite their active past, most massive black holes are quiet today, and difficult to see beyond the local Universe.
- Tidal disruptions of stars light up black holes in various ways, with detected signatures ranging from days to potentially millennia after disruptions.
- If we could just use the fallback rate, our lives would be simple, and tidal disruptions would give us interesting numbers like black hole masses.
- But luckily, tidal disruptions are ***NOT*** simple, they involve a lot of complicated topics that are inter-related: Hydrodynamics, relativity, conduction, cooling, nuclear reactions, stellar structure, accretion disks, jets, stellar rotation, SMBH environments, radiative transfer, magnetic fields, stellar dynamics, fluid instabilities, particle acceleration, stellar evolution.
- While extracting numbers from each event is appealing, by modeling tidal disruptions in detail, **from start to finish**, we can learn more about physics.