Outflows in Tidal Disruption Events

Julian Krolik, JHU
with Roseanne Cheng, Tsvi Piran, Hotaka Shiokawa, Gilad Svirski

What Are Tidal Disruption Events?

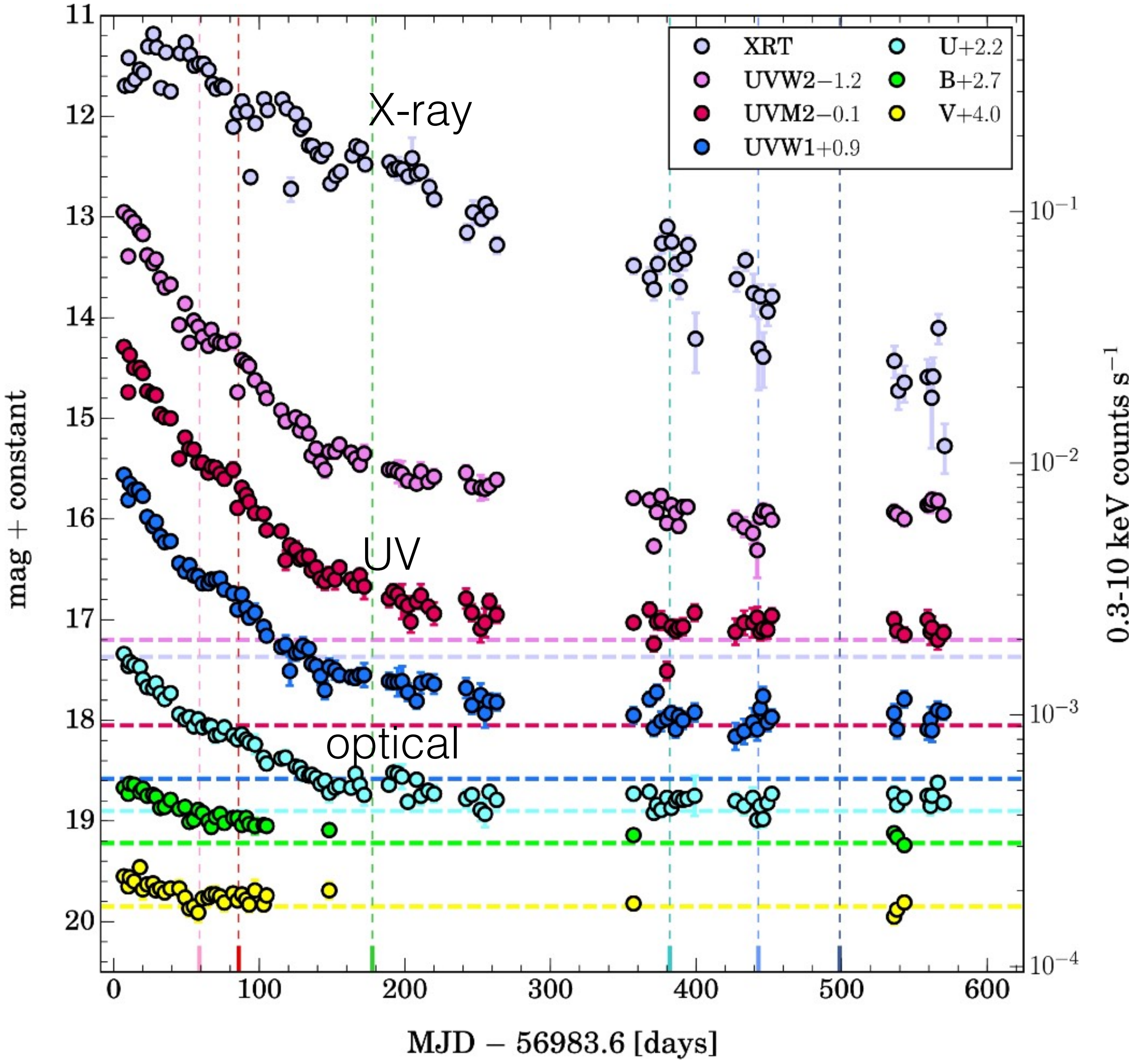
Conceptual definition:

Star passes within tidal radius of
a supermassive black hole;
Much of its material eventually
accreted onto the black hole

Operational definition:

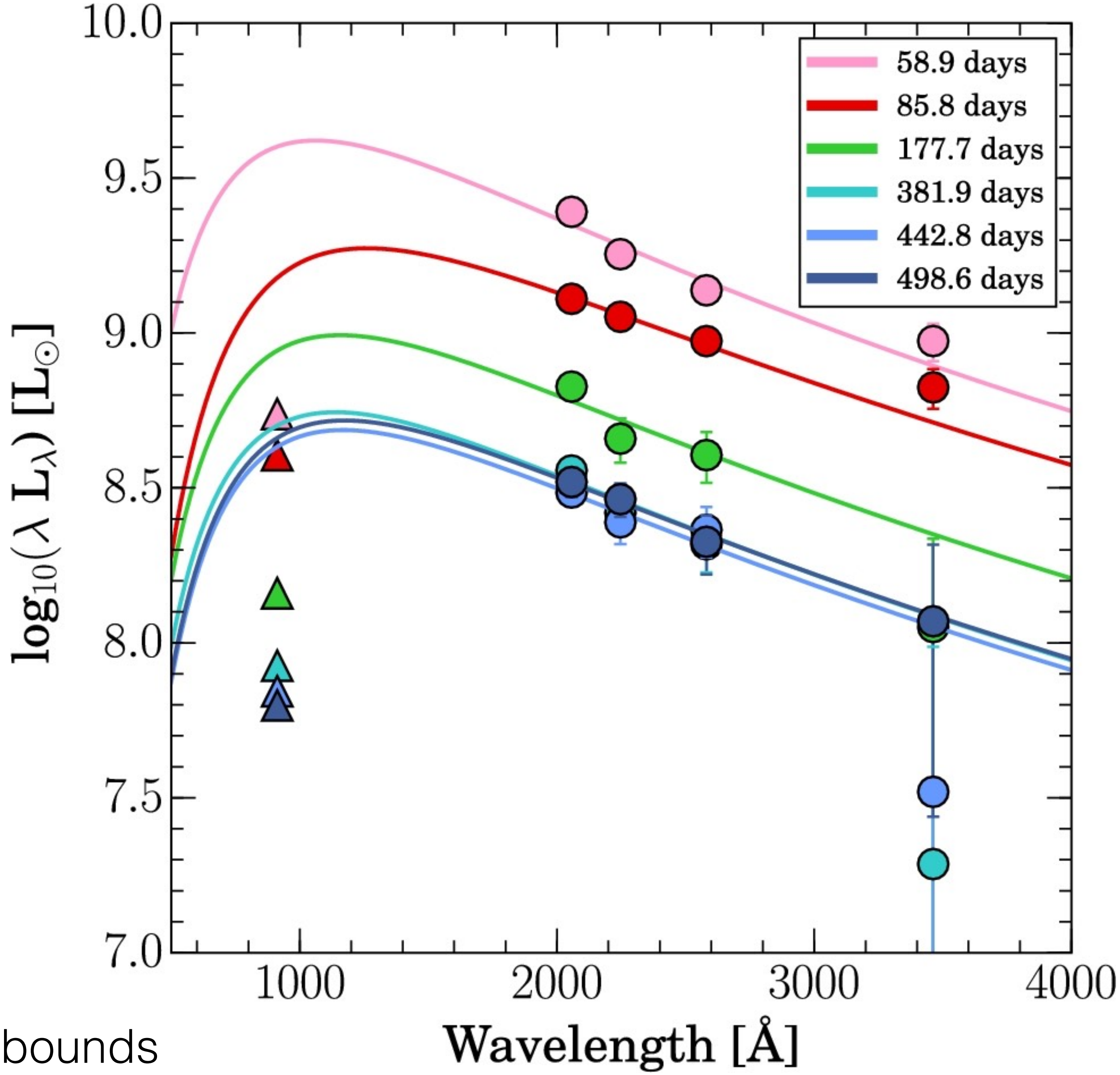
Optical or UV or X-ray flare;
Generally caught while declining;
Detectable ~few weeks — ~year;
In a galactic center;
Distinguishable from a supernova

Best Observed Example:
ASASSN 14li



Brown et al. 2017

Best Observed Example:
ASASSN 14li



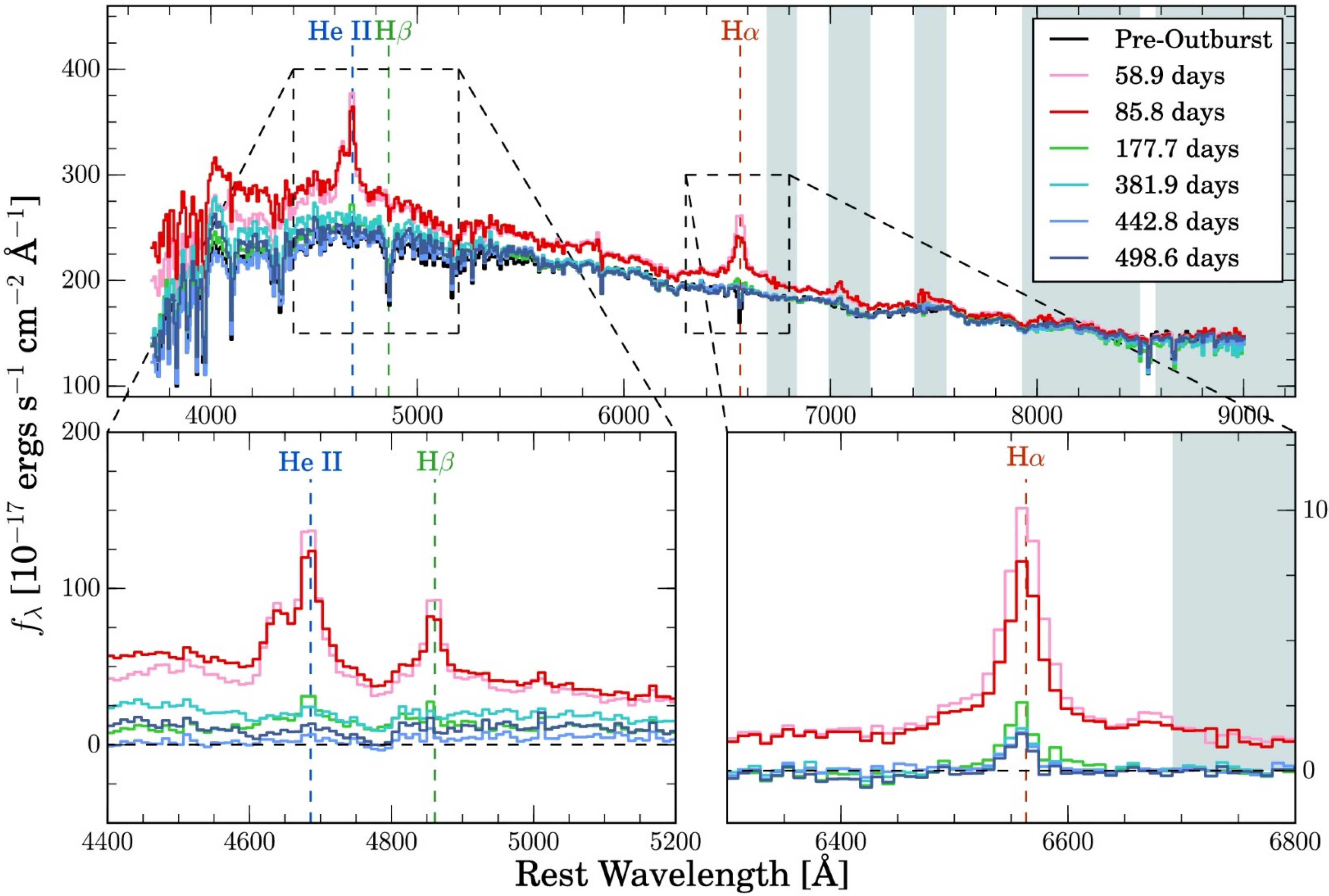
$T_X \sim 50$ eV

$T_{opt} \sim 2 \times 10^4$ K

Triangles: lower bounds for Hα production

Brown et al. 2017

Best Observed Example:
ASASSN 14li



Brown et al. 2017

TDEs Are Just Like AGN

- Accretion onto a supermassive black hole is the basic engine
- Expect T ~ few x 10^4 — few x 10^5 K
- If black hole rotates, why not a jet?

TDEs Are **NOT** Like AGN

- Accretion **non**-steady, possibly **super**-Eddington, **non**-circular, fed relatively close to the black hole

- Missing much of the usual phenomenology: **no** NLR, obscuring torus, coronal X-rays; no broad CIII], MgII, sometimes no Balmer lines; line widths few x AGN widths, and change over time

- Indications that much of the visible light **not** from local turbulent dissipation

Basic Mechanics

- Tidal radius from density/frequency matching

$$R_T \simeq R_*(M_{\rm BH}/M_*)^{1/3}$$

$$R_T \simeq 15[(k/f)/0.08]^{1/6}(M_*/M_\odot)^{2/3-\xi}M_{\rm BH,6.5}^{-2/3}R_g$$ (main sequence)

- Number of stars with <R> this small << 1 —> stars come from far out on nearly-parabolic orbits

- Within R$_T$, “independent fluid elements”

Half stellar mass bound, half unbound

$$\max|E| \sim GM_{\rm BH|}R_*/R_T^2$$

Basic Mechanics

- Most-bound energy implies

$$a_{\rm min} \sim R_T (M_{\rm BH}/M_*)^{1/3} \sim 2000[(k/f)/0.08]^{1/6} (M_*/M_\odot)^{1/3-\xi} M_{\rm BH,6.5}^{-1/3} R_g$$

$$t_0 \equiv P_{\rm min} \simeq 20[(k/f)/0.08]^{1/2} (M_*/M_\odot)^{(1-3\xi)/2} M_{\rm BH,6.5}^{1/2} \ {\rm d}$$

$$e_{\rm min} \simeq 1 - 2(M_{\rm BH}/M_*)^{1/3}$$

- Most-unbound energy implies

$$v_\infty \simeq 11,000[(k/f)/0.08]^{-1/6} (M_*/M_\odot)^{-1/6+\xi/2} M_{\rm BH,6.5}^{1/6} \ {\rm km/s}$$

- Lack of another energy scale implies

$$dM/dE \simeq const. \ {\rm for} \ -\max|E| \leq E \leq +\max|E|$$

Consequences for Stellar Debris

Mass-return rate rises to ~$M_*/(3t_0)$ at $t \sim t_0$

$$\max\left(\dot{M}_{\rm return}\right) \simeq 60(\eta/0.1)[(k/f)/0.08]^{-1/2}(M_*/M_\odot)^{(1+3\xi)/2}M_{\rm BH,6.5}^{-3/2}$$

Mass-return rate then falls ~ $(t/t_0)^{-5/3}$

But mass-return rate is **NOT** the same as mass-accretion rate

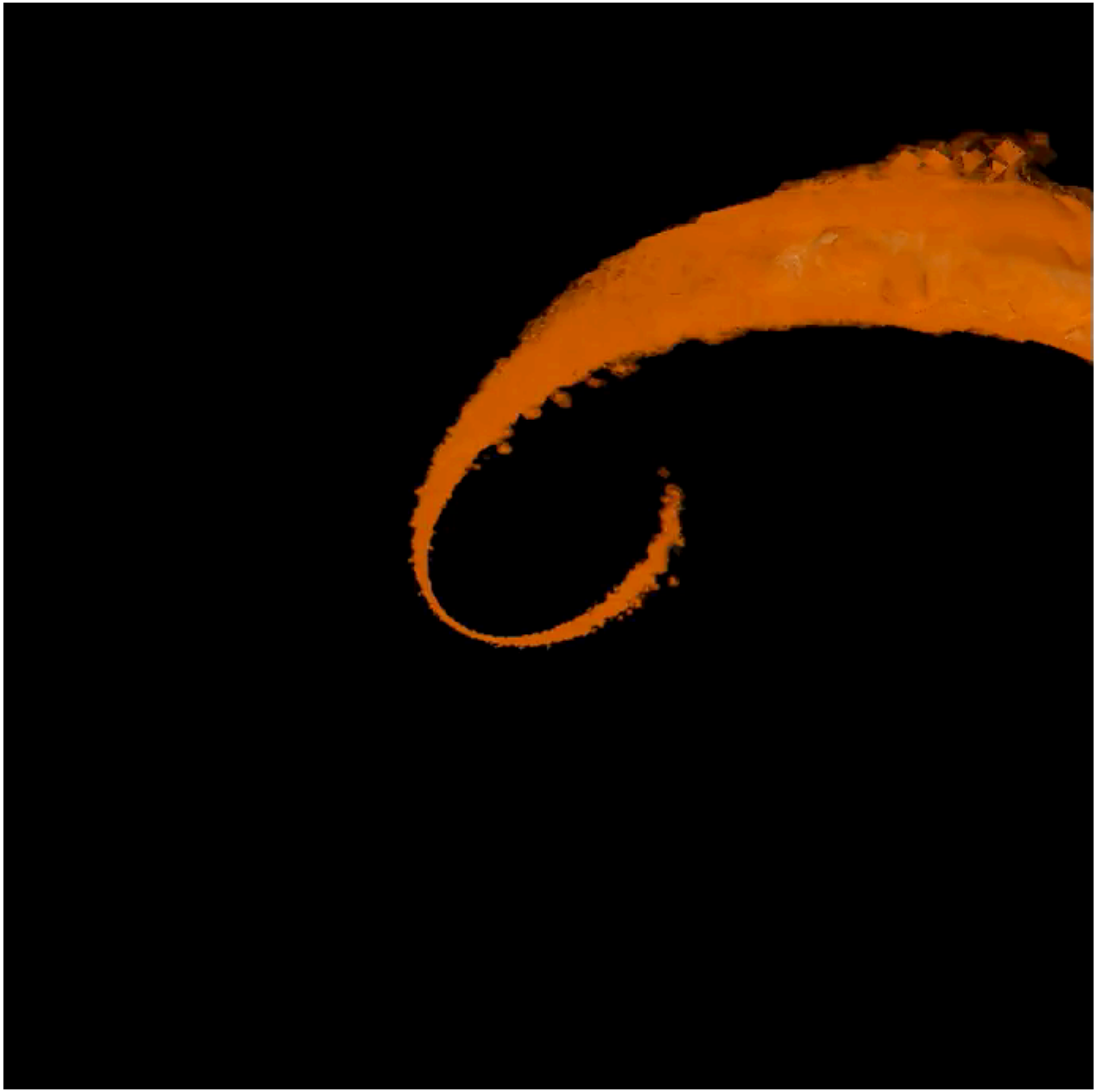
$E_B(a_{min})$ << E_B (R_T) and orbital energy-loss is slow:

Glancing convergence makes pericenter shocks weak;
small velocities make apocenter shocks weak;

Orbital plane oblique to black hole spin can precess.

Putting It All Together

Shiokawa, K, Cheng, Piran & Noble 2015



Immediate Result

- ~1/3 bound mass deflected inward near R_T by t ~ $10t_0$
- Most bound mass in an extended, messy elliptical flow
- Unbound mass coasts outward, slowing from ~c/4 to ~ ~c/30

Varieties of Outflows

Radiation-driven Winds

(Strubbe & Quataert 2009, 2011; Metzger & Stone 2016)

If mass-return rate super-Eddington, maybe $L_{acc} > L_E$?

Assume luminosity ~ $(R_{ISCO}/2R_T)L_{acc}$ from fallback shock at ~$2R_T$;
Guess fraction of returning mass to expel;
Guess fraction of $v_{ff}(R_T)$ for terminal speed.

Fallback shock photons diffuse out through outflow;
Disk radiation (filtered by outflow?) reprocessed by unbound matter

Transfer through radiation-driven outflow + unbound matter
makes optical/UV continuum + emission lines;
a very extended stellar atmosphere! (Roth et al. 2016)

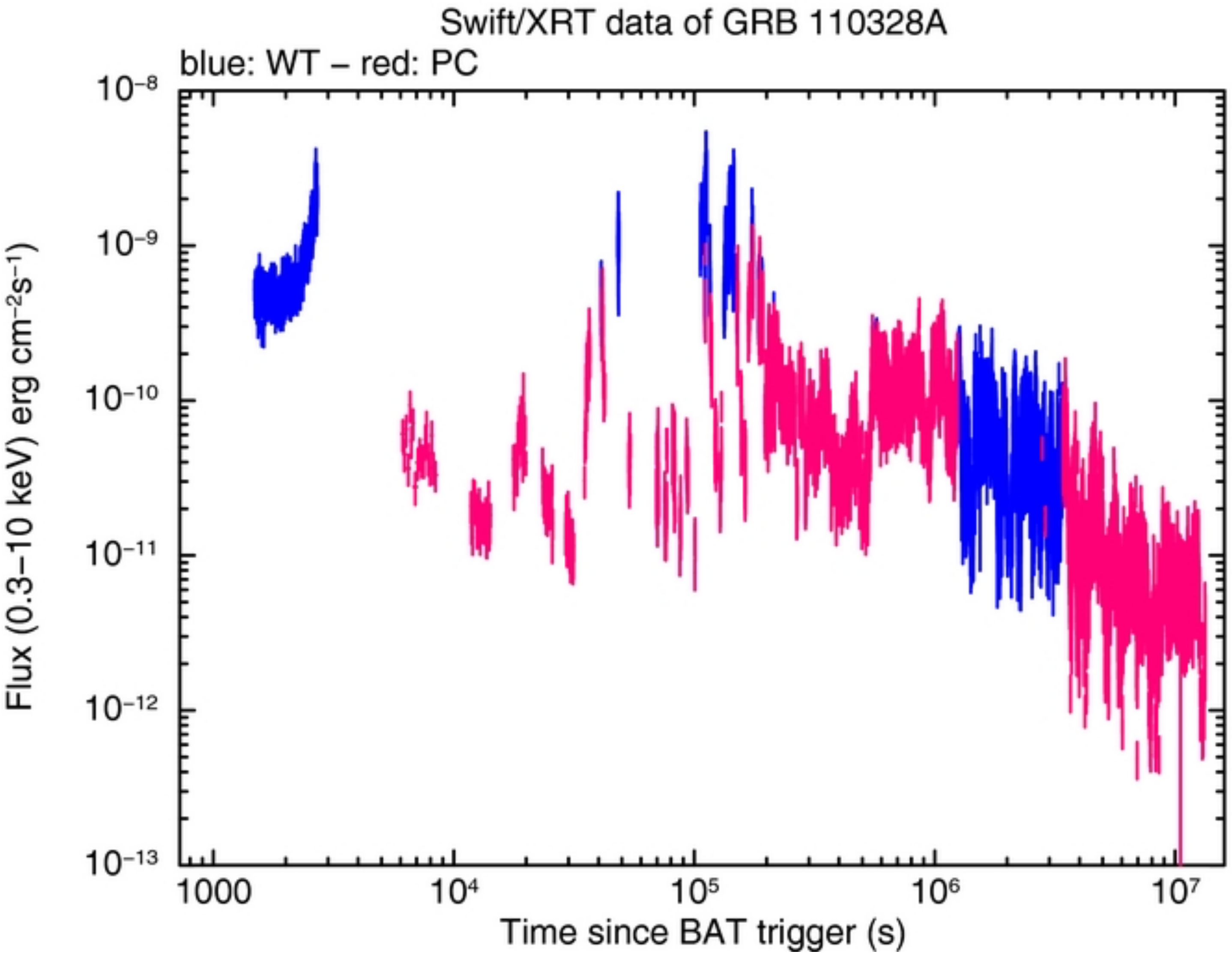
Problems:

So much put in by hand;
Shock near R_T usually weak;
Asymmetry of unbound matter + optical
depth of outflow lead to shifted lines

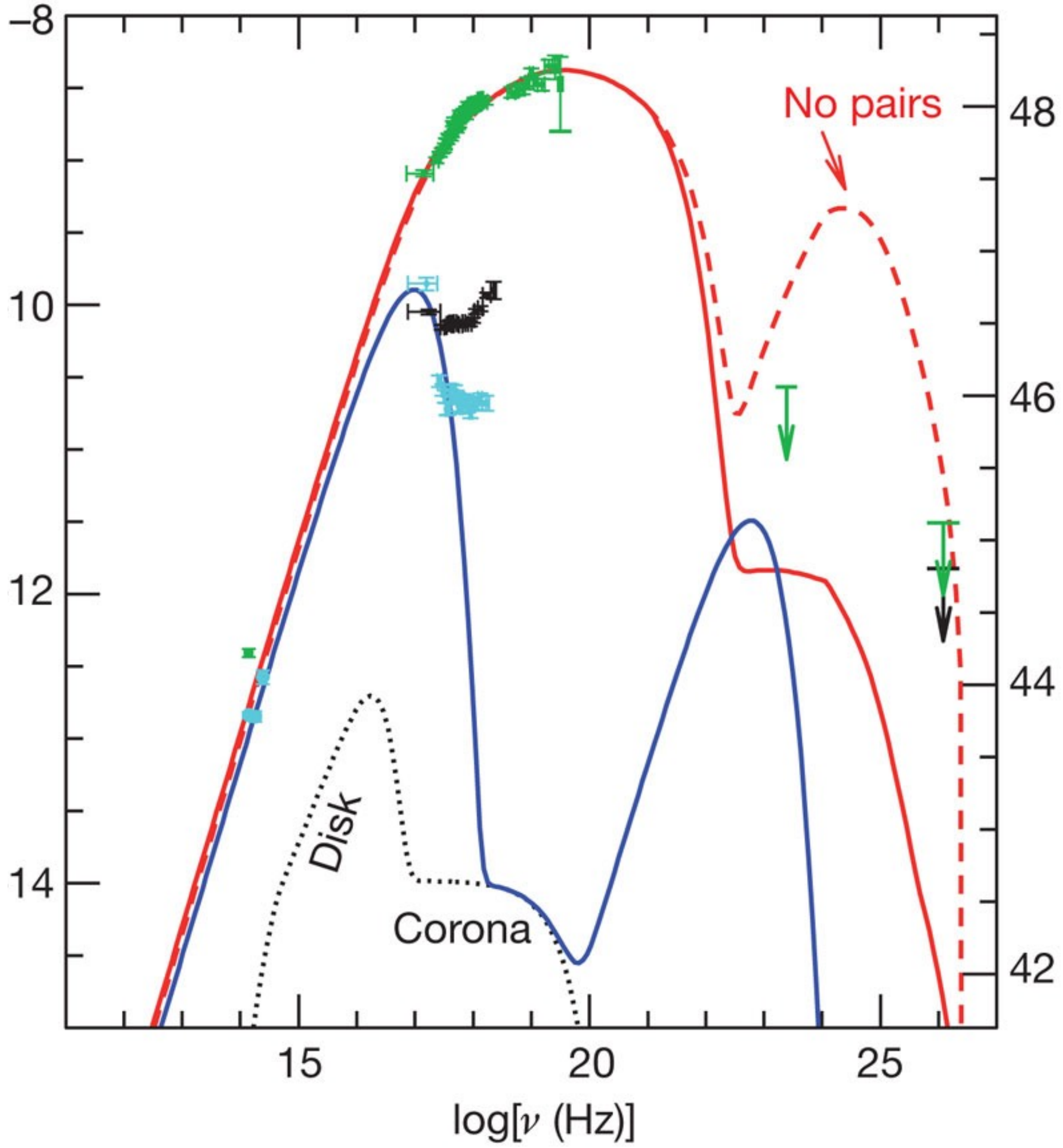
There Are Jets!

Swift discovered two, both in 2011

Dramatically variable



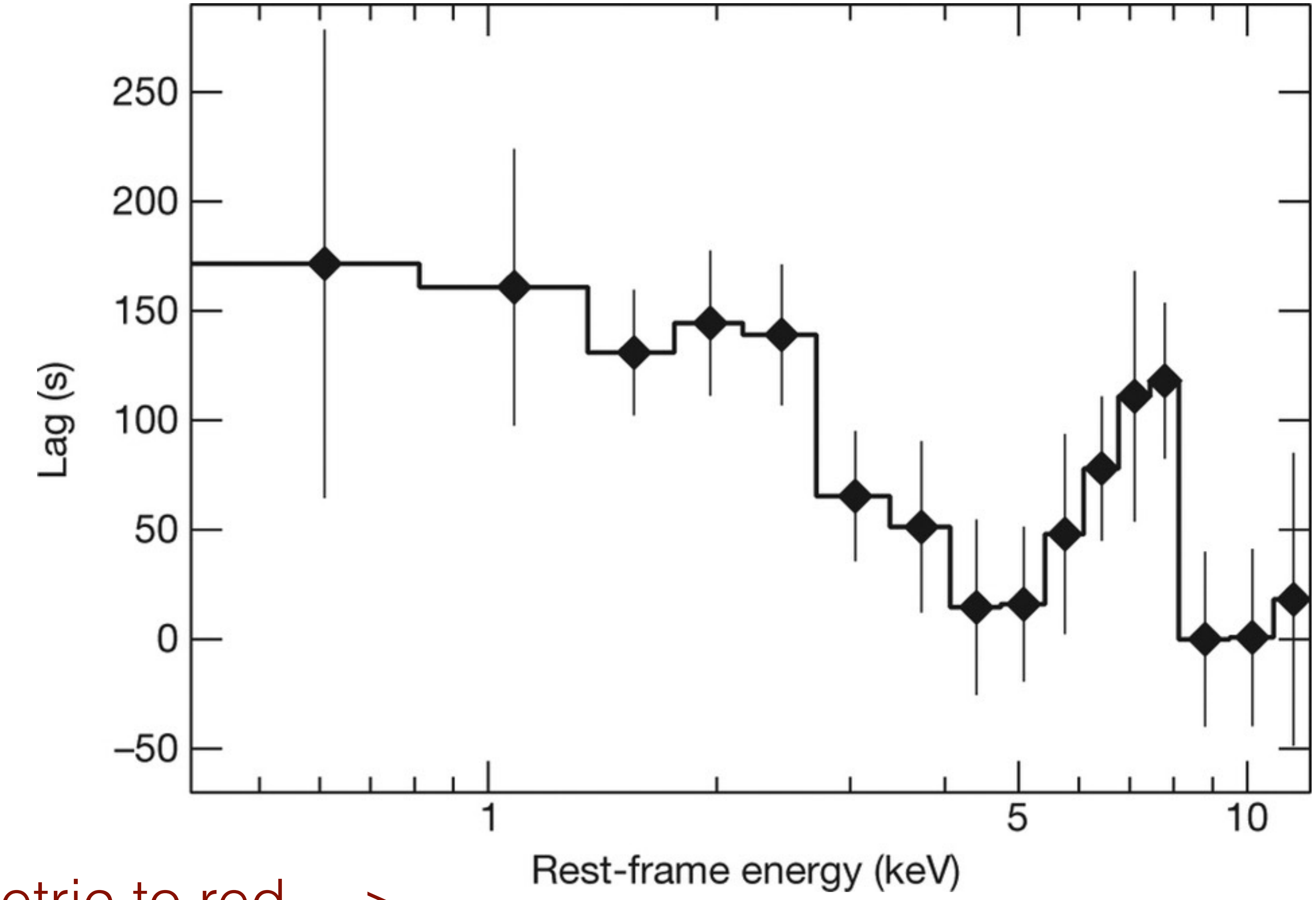
Very hard spectrum



SwJ1644+57: left (K & Piran 2011); right (Burrows et al. 2011)

Maybe There Aren't Jets, After all

- VLBI —> v < 0.3c (Yang et al. 2016)
- Fe Kα lags continuum by ~ 100 s ~ 10 r_g (Kara et al. 2016)

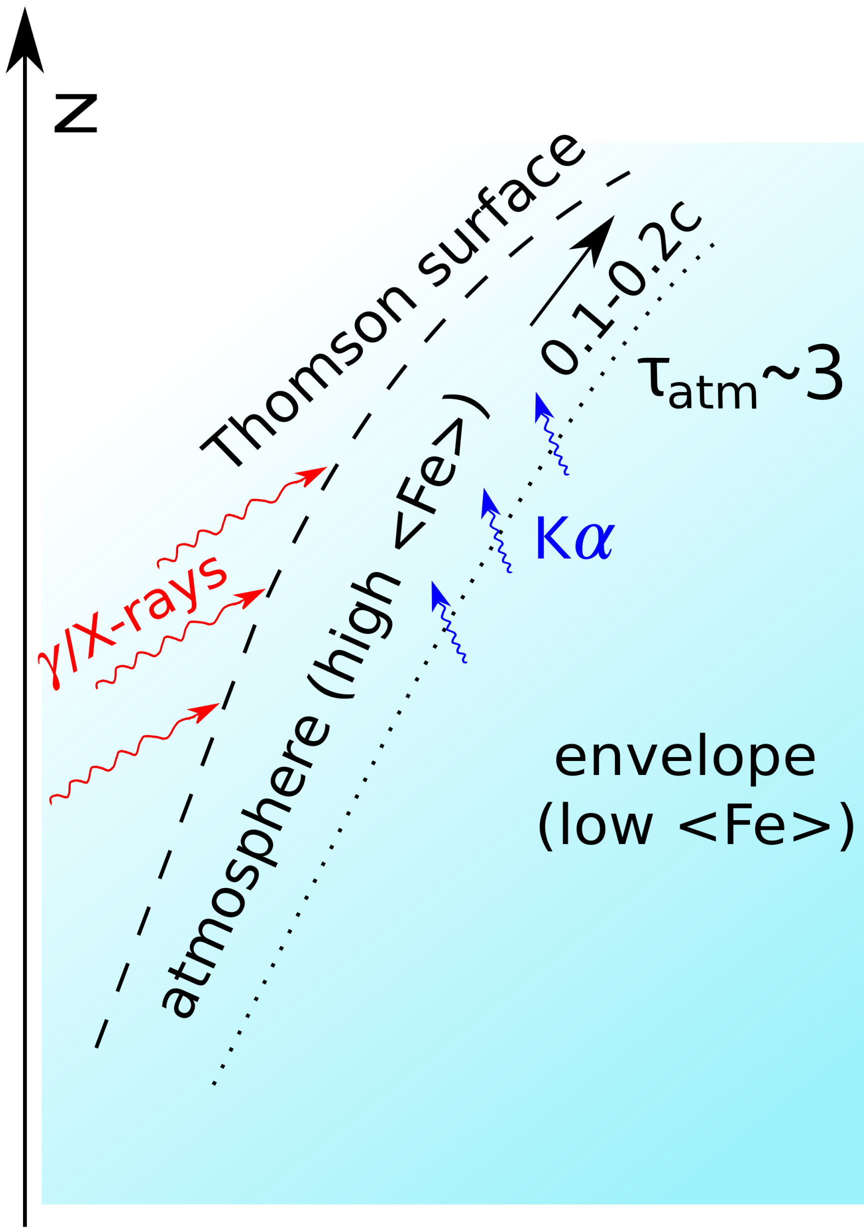


Lag profile asymmetric to red —>
gravitational redshift, small kinematic boost

Maybe There Are Jets, After All

(Lu, K, Kumar & Crumley 2017)

- Close in and without relativistic motion, thermal photons from disk keep electrons too cool to produce hard spectrum
- Continuum dilution —> true Kα lag ~1000 s
- Relativistic beaming, larger lengthscale needed for low enough ionization to permit Kα emission
- Beamed X-rays accelerate disk atmosphere
- Multiple Compton scatters in cool medium create red tail; continuum dilution shortens the apparent lag



Unbound Matter

(Guillochon et al. 2016; K, Piran, Svirski & Cheng 2016)

Unbound mass carries as much energy as a supernova

$$E_{\rm unbound} \simeq 6 \times 10^{50}[(k/f)/0.08]^{-1/3}(M_*/M_\odot)^{-1/3+\xi} M_{BH,6.5}^{1/3}\ {\rm erg}$$

Spherically-expanding ejecta slow down only after

$$10(n_{\rm ext}/10^4{\rm cm}^{-3})^{-1/3}[(k/f)/0.08]^{1/6}(M_*/M_\odot)^{1/6-\xi/2} M_{\rm BH,6.5}^{-1/6}\ {\rm yr}$$

Actual unbound ejecta form a thin wedge, ~1 rad in azimuthal extent; drive a wider wedge-shaped bow shock:

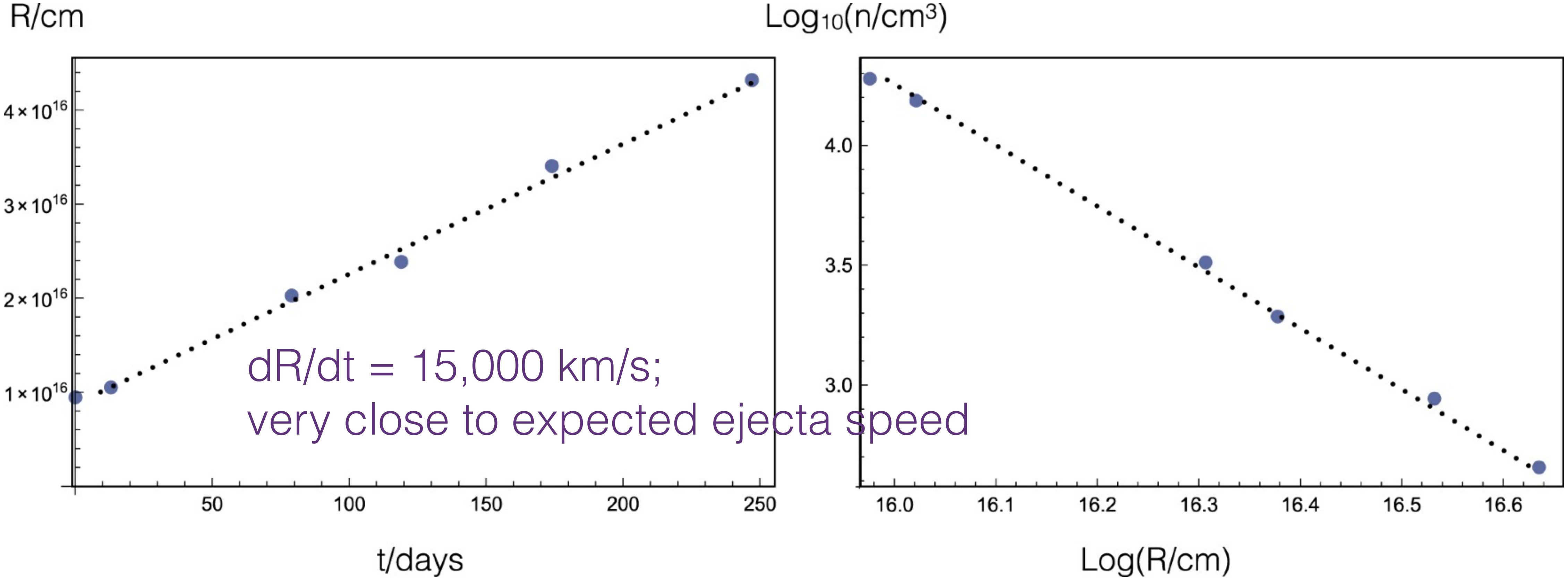
$$\Delta\theta \sim 0.2[R_s/R_s(\Delta\theta)]^{2/3}\,[1 - R_s(\Delta\theta)/R_s]^{1/3}\,(M_*/M_\odot)^{1/9} M_{BH,6.5}^{-1/9}$$

If external density moderately high and bow shock leads to equipartition magnetic field and relativistic electrons, detectable synchrotron emission

Example: ASASSN 14li

Observed multiple times at several radio frequencies

Each spectrum —> peak frequency, flux at peak frequency; self-absorbed synchrotron model determined by R, n_e, and B; energy minimization fixes all three.



dR/dt = 15,000 km/s;
very close to expected ejecta speed

Summary

- Outflows in TDEs can be rather different from AGN outflows

- Best evidence for jets (in some instances) and the unbound debris

- Winds due to super-Eddington luminosity much discussed and plausible, but luminosity may not reach those levels, and not observationally supported