# Tidal Disruption Events

## Relativistic spectral line reverberation


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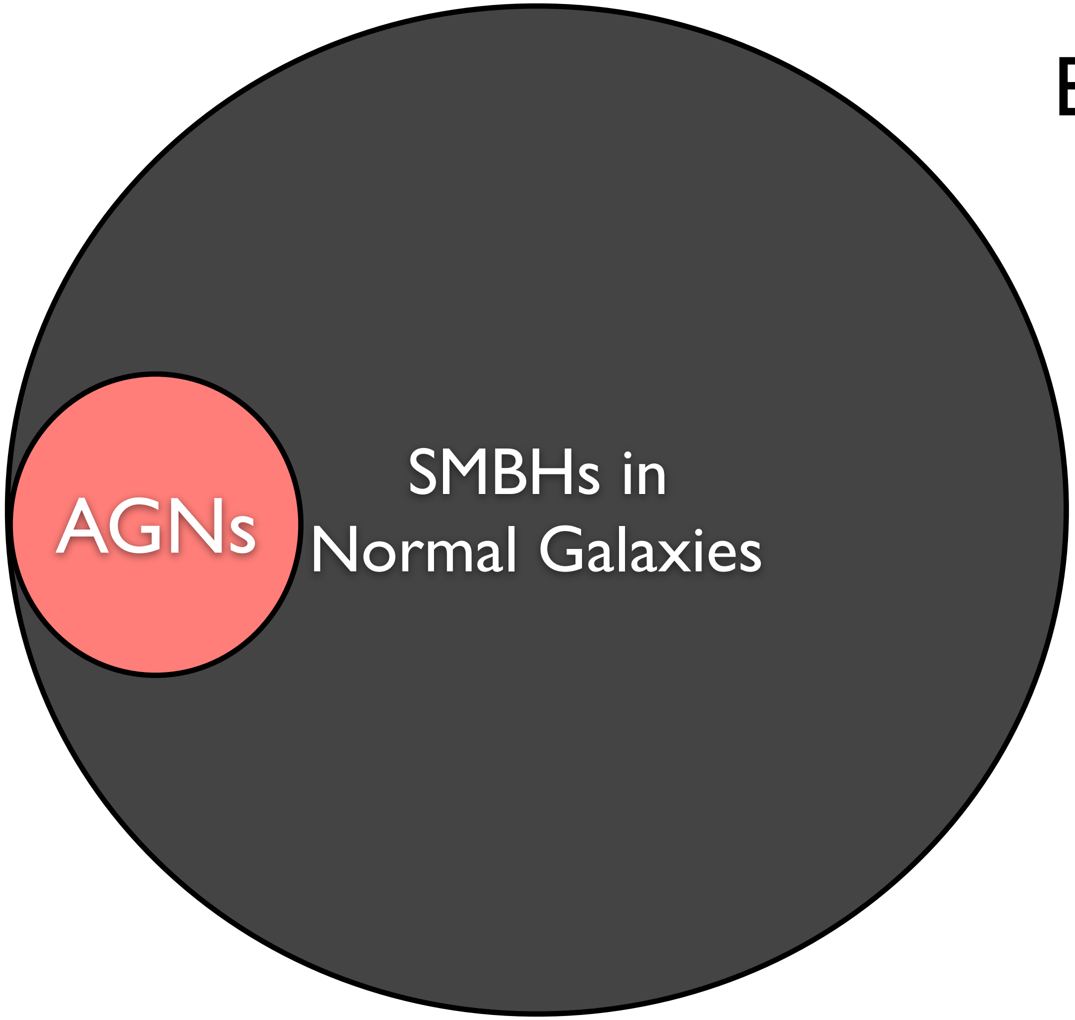
# Supermassive Black Holes in the Universe




BHs and Galaxies co-evolution

↓

Growth of BHs

SMBH mass ?

SMBH spin ?

**TDEs: Critical probe of more than 90% SMBHs in the Universe**

# Tidal Disruption Events (TDEs): Theory

When a star is passing too close to a SMBH, it can be shredded by strong tidal forces partially or entirely, producing optical, UV, and X-ray flares due to accretion of the debris of the star.

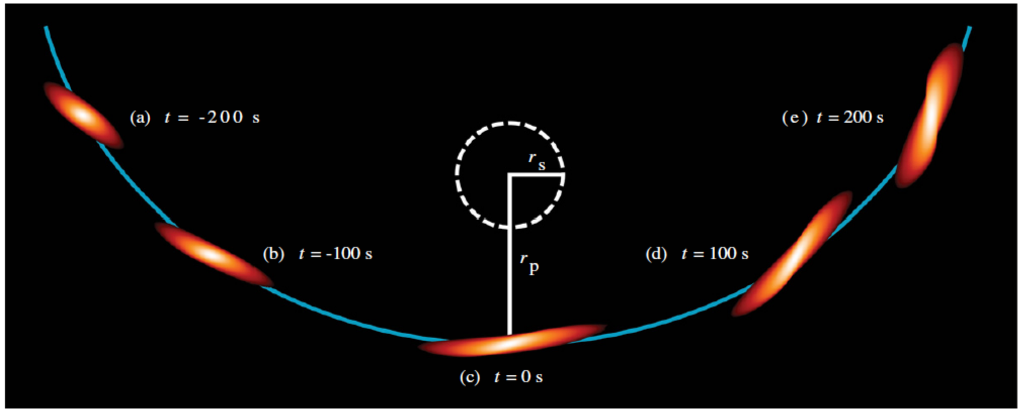
Some pioneer works:

Hills, 1975, Nautre, 254, 295:
"Possible power source of Seyfert galaxies and QSOs'

Carter & Luminet, 1982, Nature, 296, 211:
"Pancake detonation of stars by black holes in galactic nuclei"

Rees, 1988, Nature, 333, 523:
"Tidal disruption of stars by black holes of 10^6 - 10^8 solar masses in nearby galaxies

Rees, 1990, Science, 247, 817:
"Dead Quasars" in Nearby Galaxies ?




TDEs were initially associated with bright SMBHs...

But they are different from flares in AGNs !

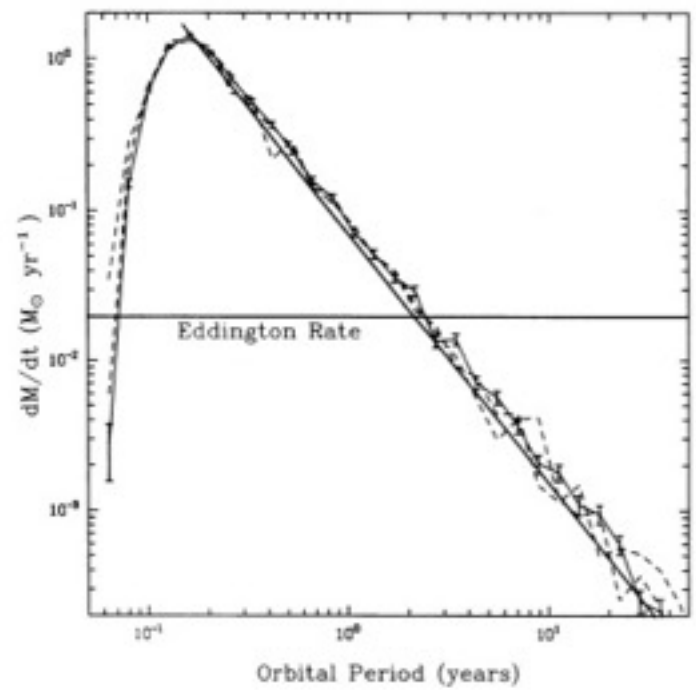
# Tidal Disruption Events (TDEs): Theory

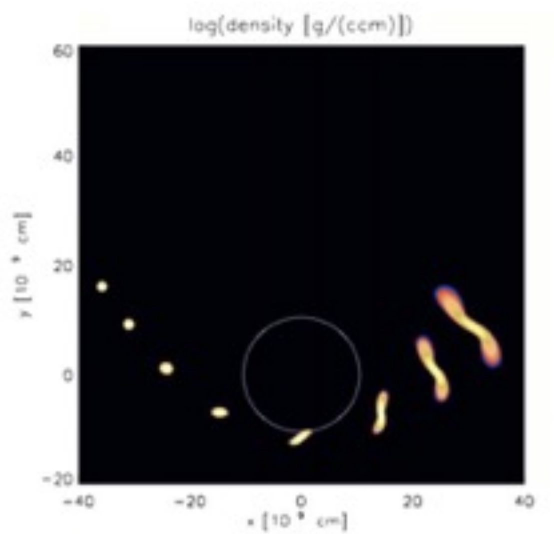
*Evans & Kochanek (1989)*

A star will be disrupted by a central supermassive black hole when $R_p < R_T \approx R_\star (M_\bullet / M_\star)^{1/3}$.

A fraction of the stellar debris falls back onto the black hole and is accreted, resulting in a luminous flare.

For $M_\bullet > 10^8 M_\odot$, $R_T < R_{Sch}$, and the star is swallowed whole.



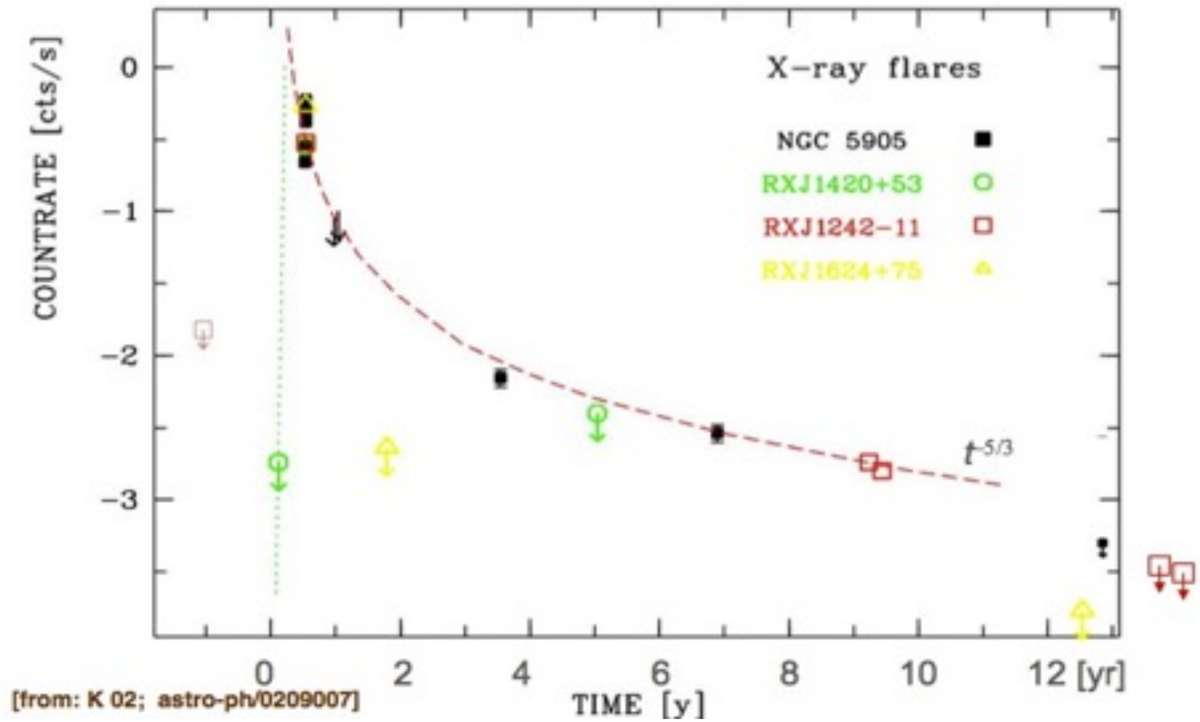




Predictions for the disruption of normal stars like our Sun by SMBHs of ~ M=10^7 solar masses (Based on fall-back mass rate only):

Luminosity: L ~ L_Edd = 1.3 x 10^45 $M_7$ erg $s^{-1}$
Temperature: $T_{eff}$ ~ 3 x 10^5 $M_7$ ^-1/12
Light curve: L(t) ~ ($t-t_0$)^(-5/3)

# Tidal Disruption Flares: the Rise

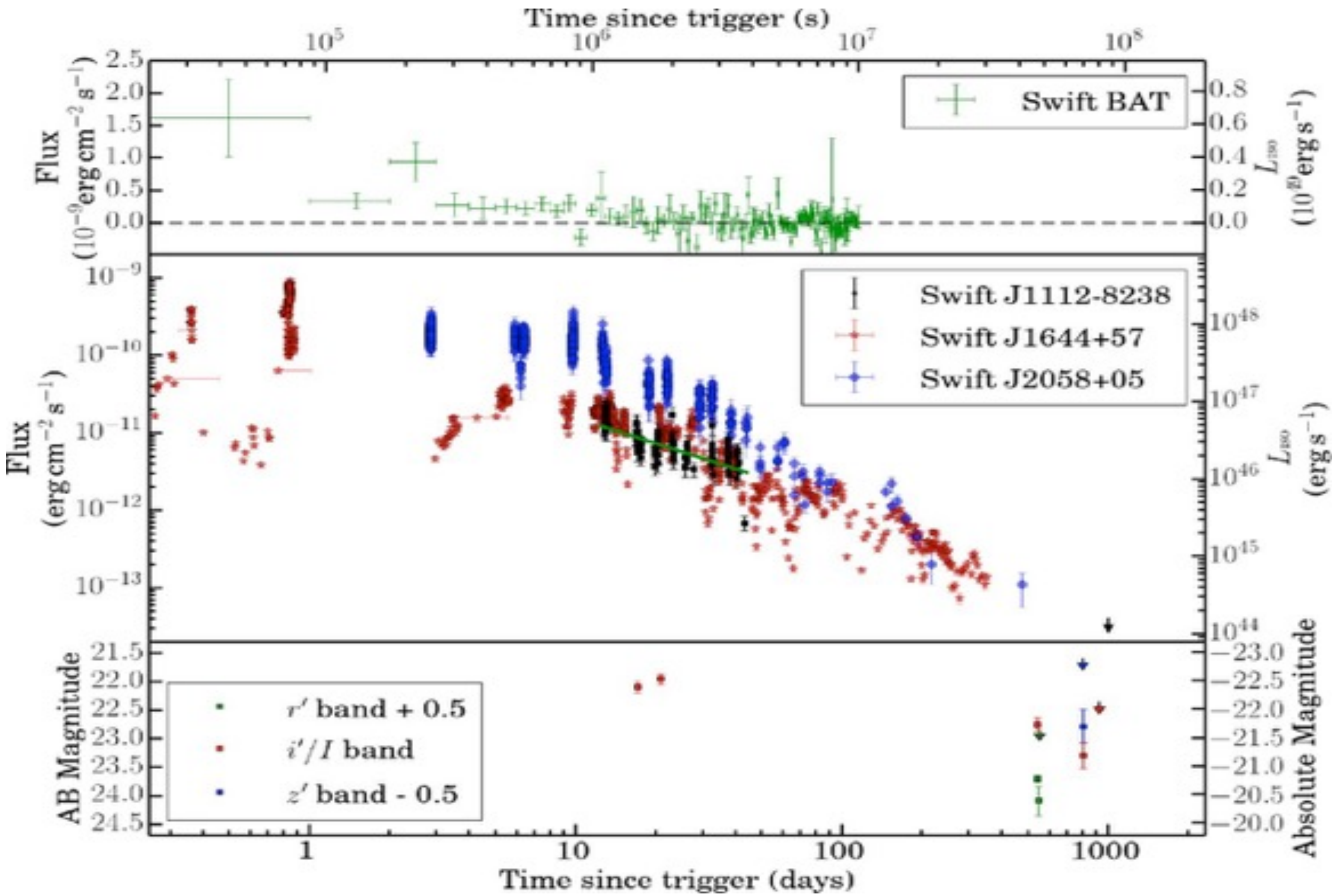
The rise is not well known but can be fast - a few weeks or less !!




TDE flares seen with the ROSAT (Kommosa et al. 2002)

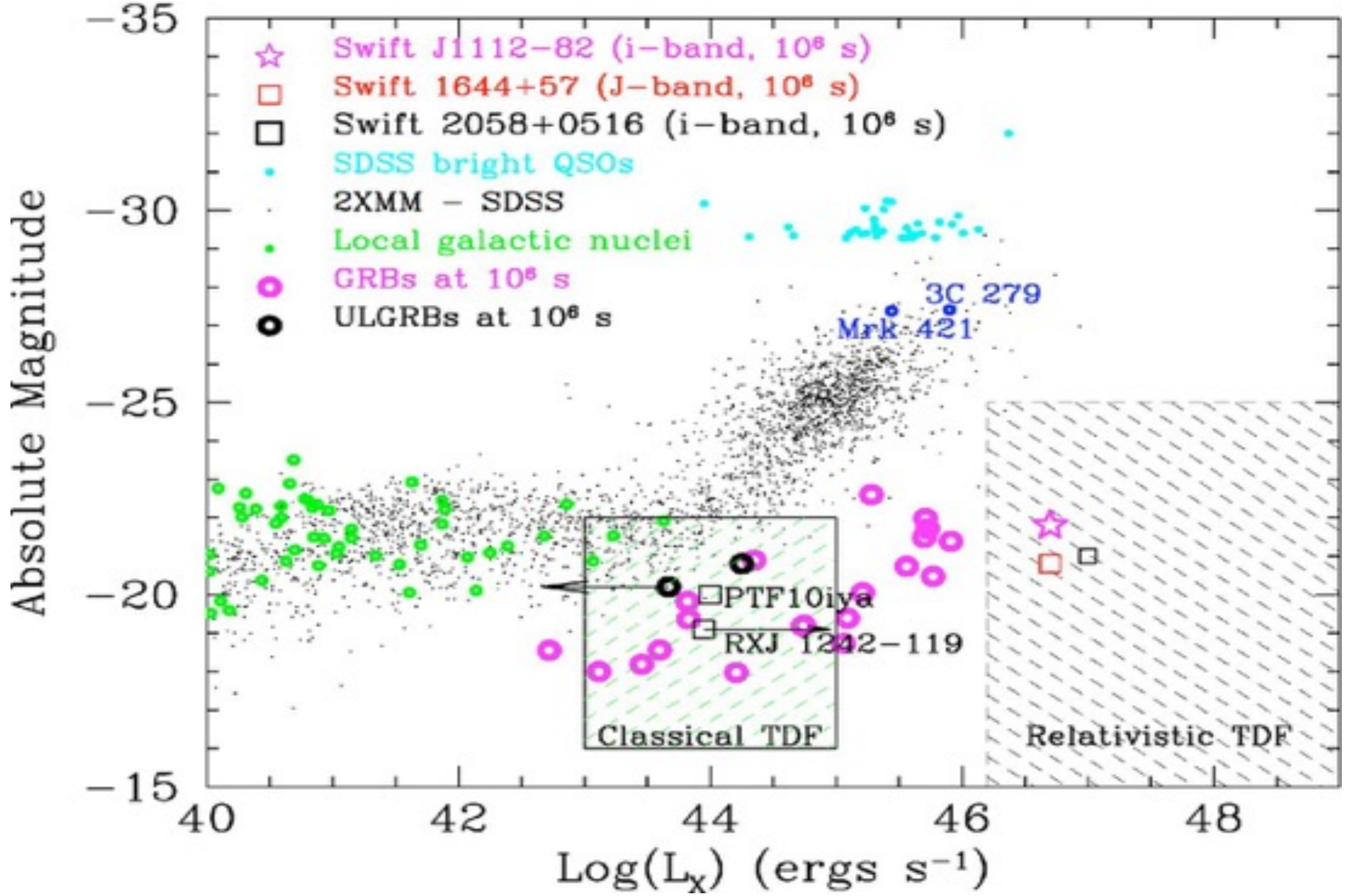
# Observations of X-ray Flares of Three Relativistic TDEs

Swift J1644+57, Swift J2058+05, and Swift J1112-8238




Brown et al. MNRAS 2015;452:4297-4306

# X-ray Flares of TDEs: Relativistic Events and Classical TDE

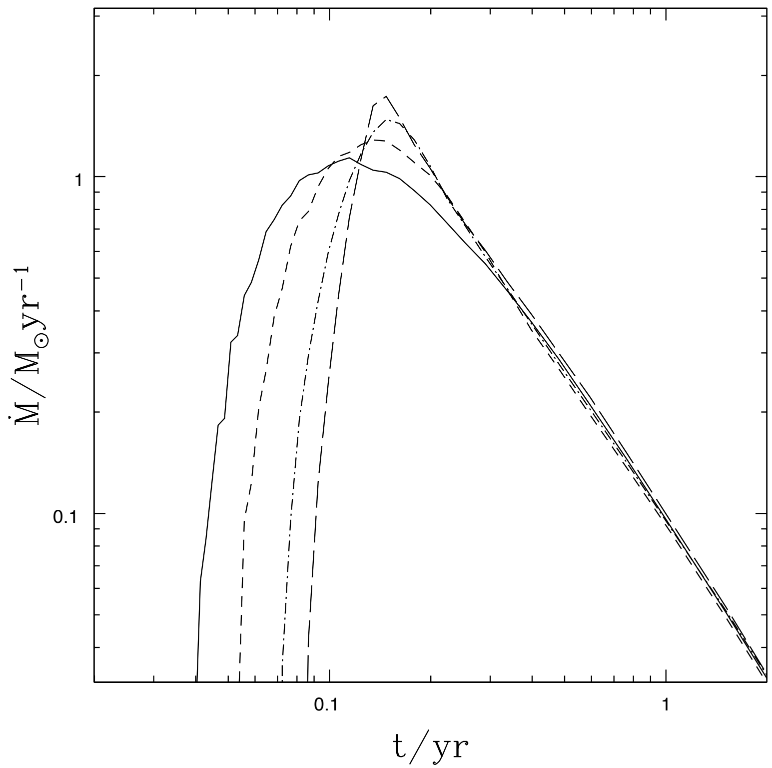



From Brown et al. MNRAS 2015;452:4297-4306

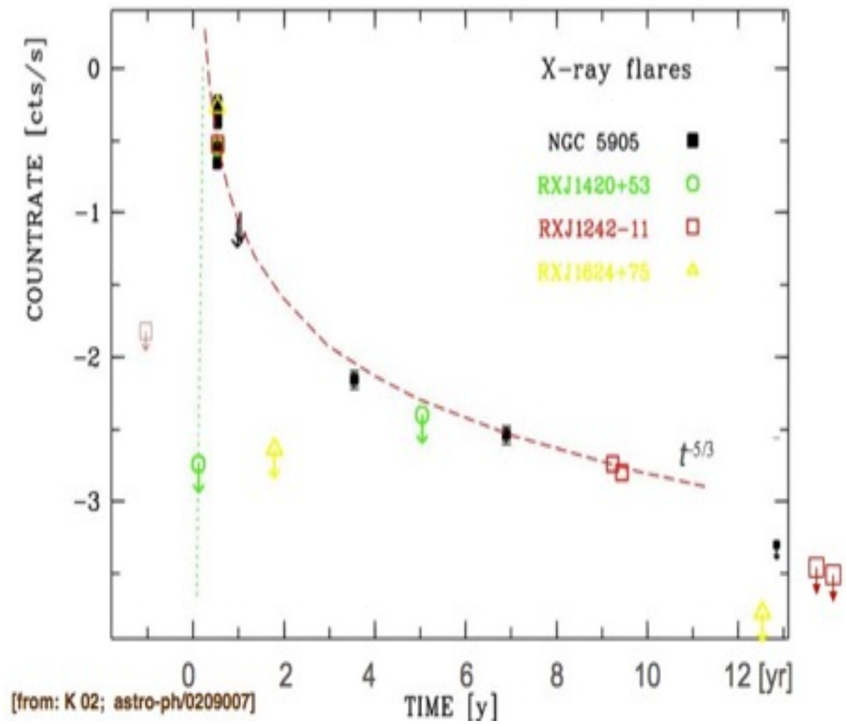
# Tidal Disruption Flares: the Rise

The rise is not well known but can be fast - a few weeks or less !!

## Theory: Fallback Rate




## Observations: X-ray Flux




RISE: corresponds to an extremely large range of mass accretion rate:

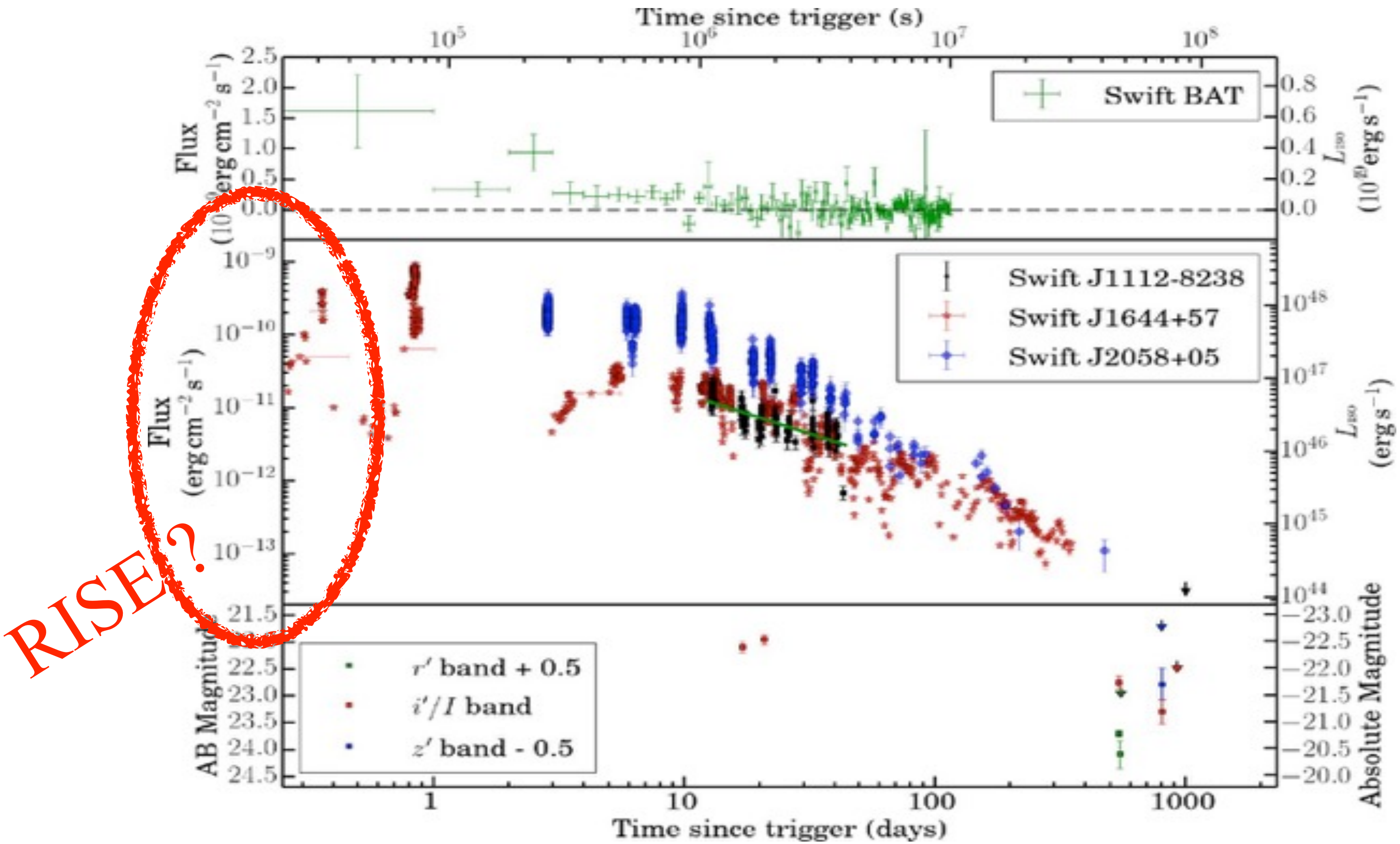
- observed luminosity range: 10^35 ergs/s – 10^47 ergs/s

RISE: barely known (in both theory and observation aspects)

- the start of the flare would occur weeks before its peak

# Observations of X-ray Flares of Three Relativistic TDEs

Swift J1644+57, Swift J2058+05, and Swift J1112-8238




**Brown et al. MNRAS 2015;452:4297-4306**

# Iron Line Reverberation in AGN Cases

## Reverberation mapping with the iron lines due to illuminating X-ray flares

- proposed for the study of the iron line response to the illuminating flares in AGNs (before the Chandra era)
- model based on hard X-ray irradiation of cold, dense matter in the innermost disk inside ~ 100 Rg
- broad, relativistic iron lines to probe black hole mass and spin

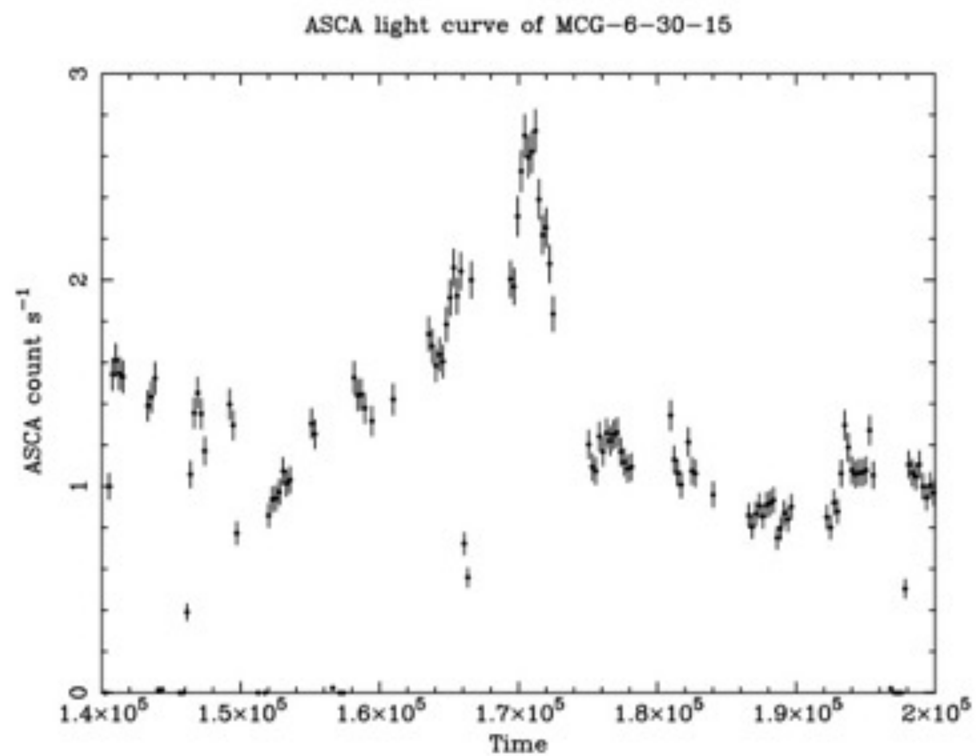


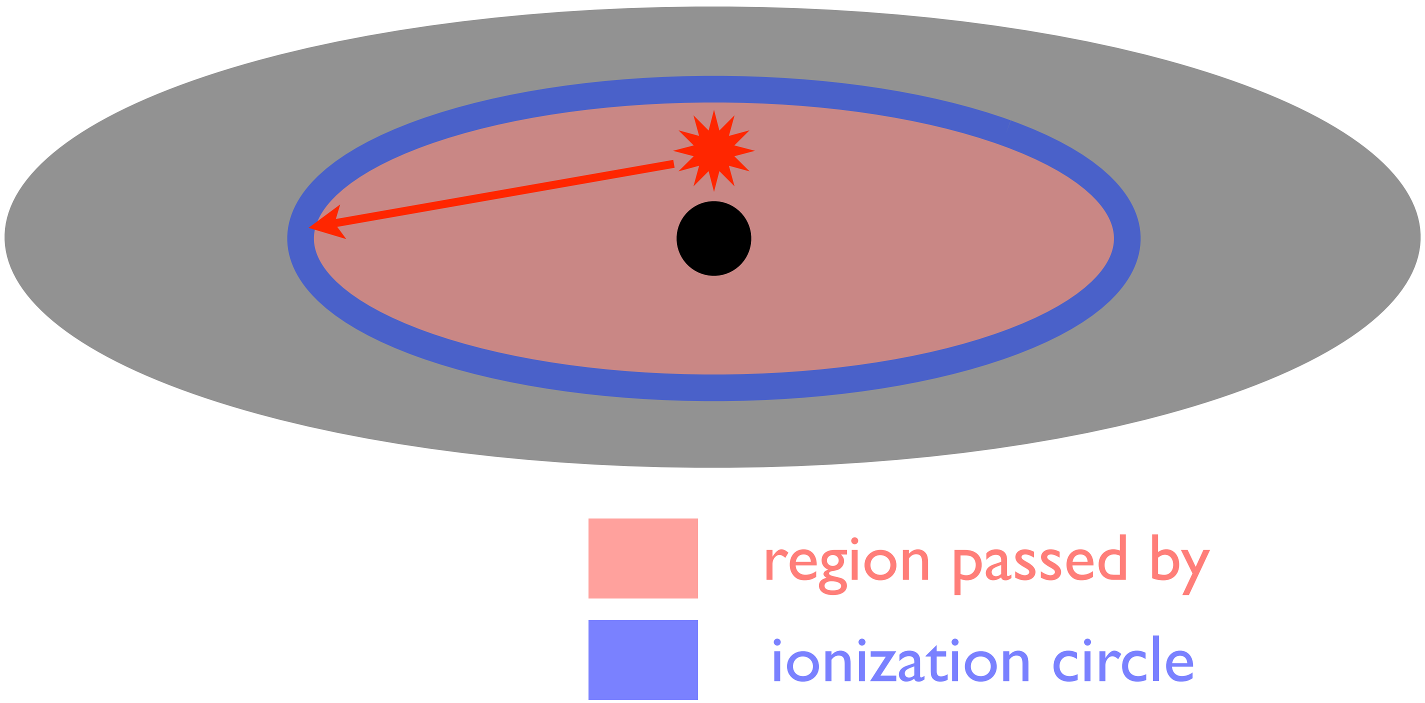

FIG. 1.—The 60,000 s *ASCA* light curve of MCG −6-30-15 showing two "flares" lasting a few thousand seconds each (Lee et al. 1999).

Young & Reynolds 2000

# The idea: a δ-function illumination flare

generating an expanding ionization circle

- A circle of illumination in the rest frame
- expanding with light speed



# Reverberation mapping: Schwarzschild BHs

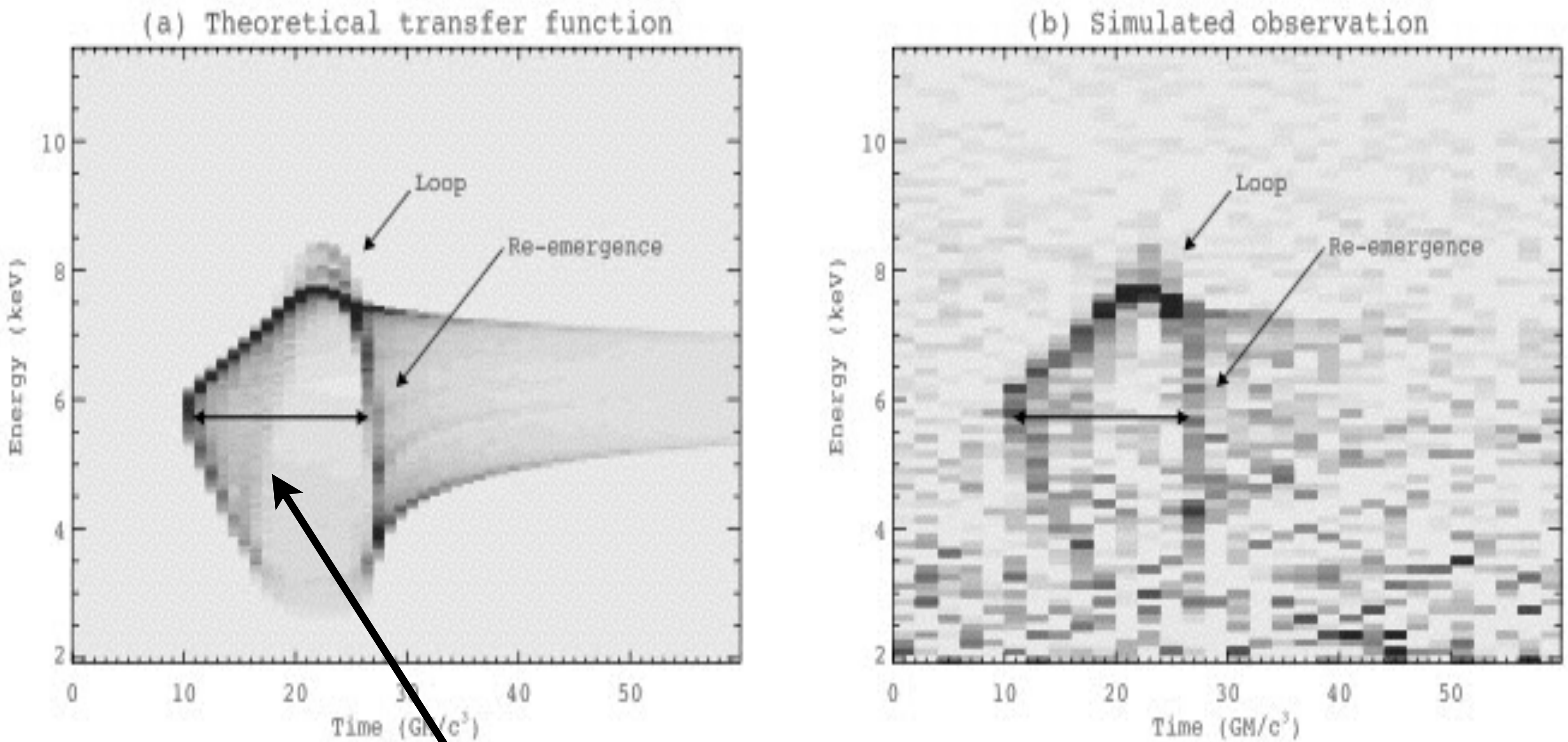



FIG. 6.—Panel *a* shows the theoretical transfer function for a Schwarzschild case with an inclination of 60° and an on-axis flare at a height of $10GM/c^2$. Note the "loops" in the transfer function corresponding to fluorescence from the ionized regions of the disk within the innermost stable orbit. The horizontal line shows the time delay between the initial response and the "reemergence" which may be used to estimate the black hole mass. Panel *b* shows the simulated observed transfer function. The loops are still visible. The data have been rebinned to produce these figures with improved signal-to-noise ratio.

Young & Reynolds 2000

part of the ionization circle is seen because of significant light travel effect

Separation between the double line peaks become narrower with time due to 1) reduced gravitational redshift 2) reduced Doppler effect

# Reverberation mapping: case of Kerr BHs

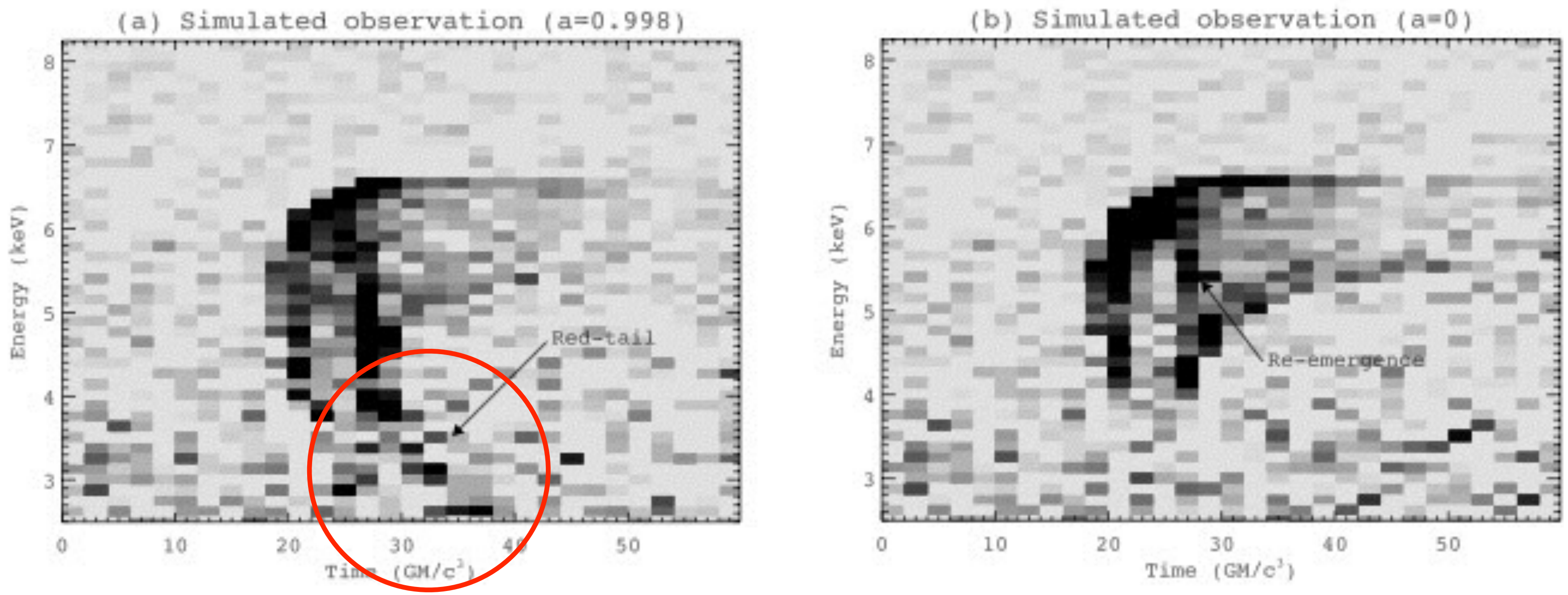



FIG. 4.—Simulated transfer function for (*a*) an extremal Kerr hole and (*b*) a Schwarzschild hole. In both cases, the flare has been placed on the symmetry axis at a height of $10GM/c^2$ above the disk plane, and an observer inclination of 30° has been assumed. The data have been rebinned to produce these figures with improved signal-to-noise ratio.

different from the Schwartzchild BH case:

*A "red-ward moving bump" - signature of a Kerr SMBH*

Young & Reynolds 2000

# Iron line reverberation mapping of the innermost disks
## AGNs vs. Previously dormant SMBHs (TD flares)

### AGN

- Coupling between the iron line and the ionization flux
- Illuminations by both persistent flux and flares exist !
- Only recently results are achieved from averaging flares

### TD flares

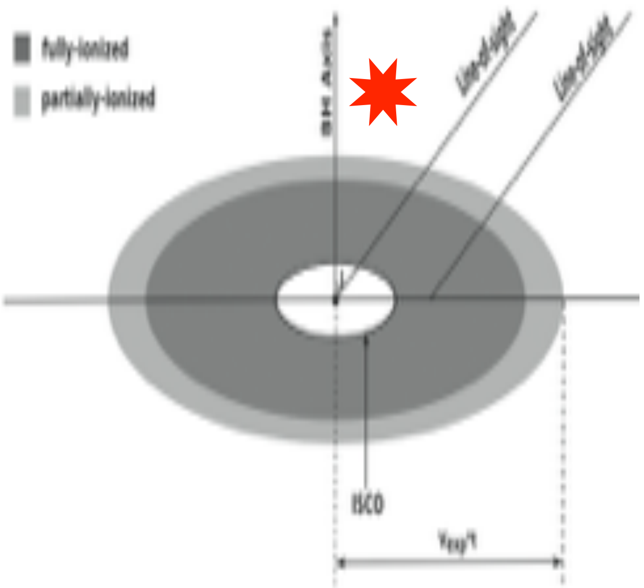
- a newly formed disk has not been ionized
- X-ray flare illuminates and ionized the fresh disk
- Rising edge of the luminous TD (X-ray) flare serves as the "δ-function" illumination

TD flares from previously dormant SMBHs are perfect targets

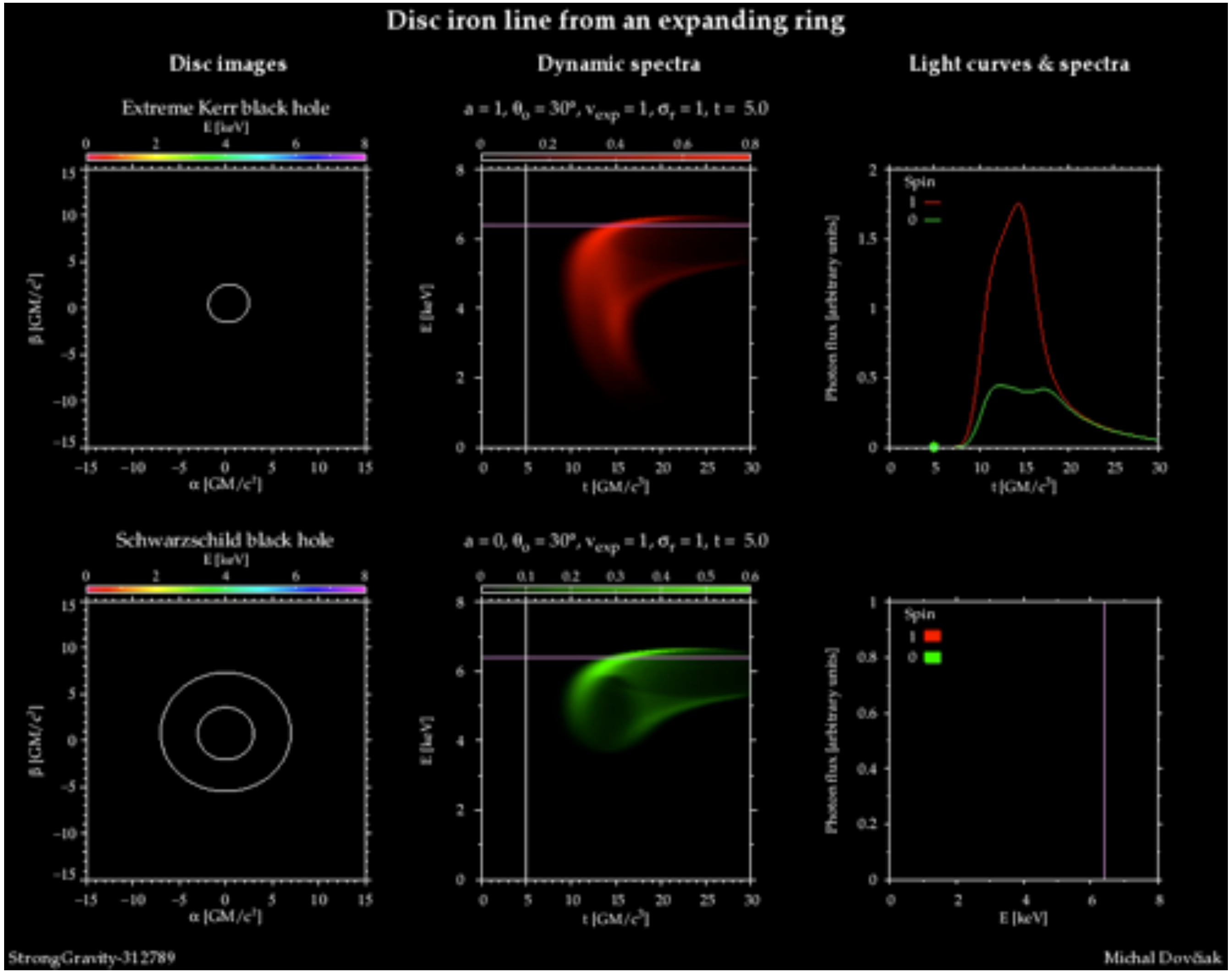
Potential application in the spectral lines in the UV band

# Prediction of Line Reverberation in TDEs

Zhang, Yu et al. 2015, ApJ

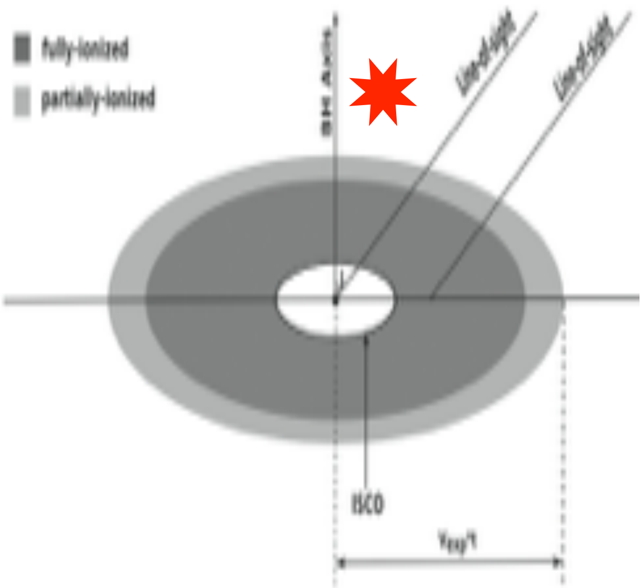



ionization circle

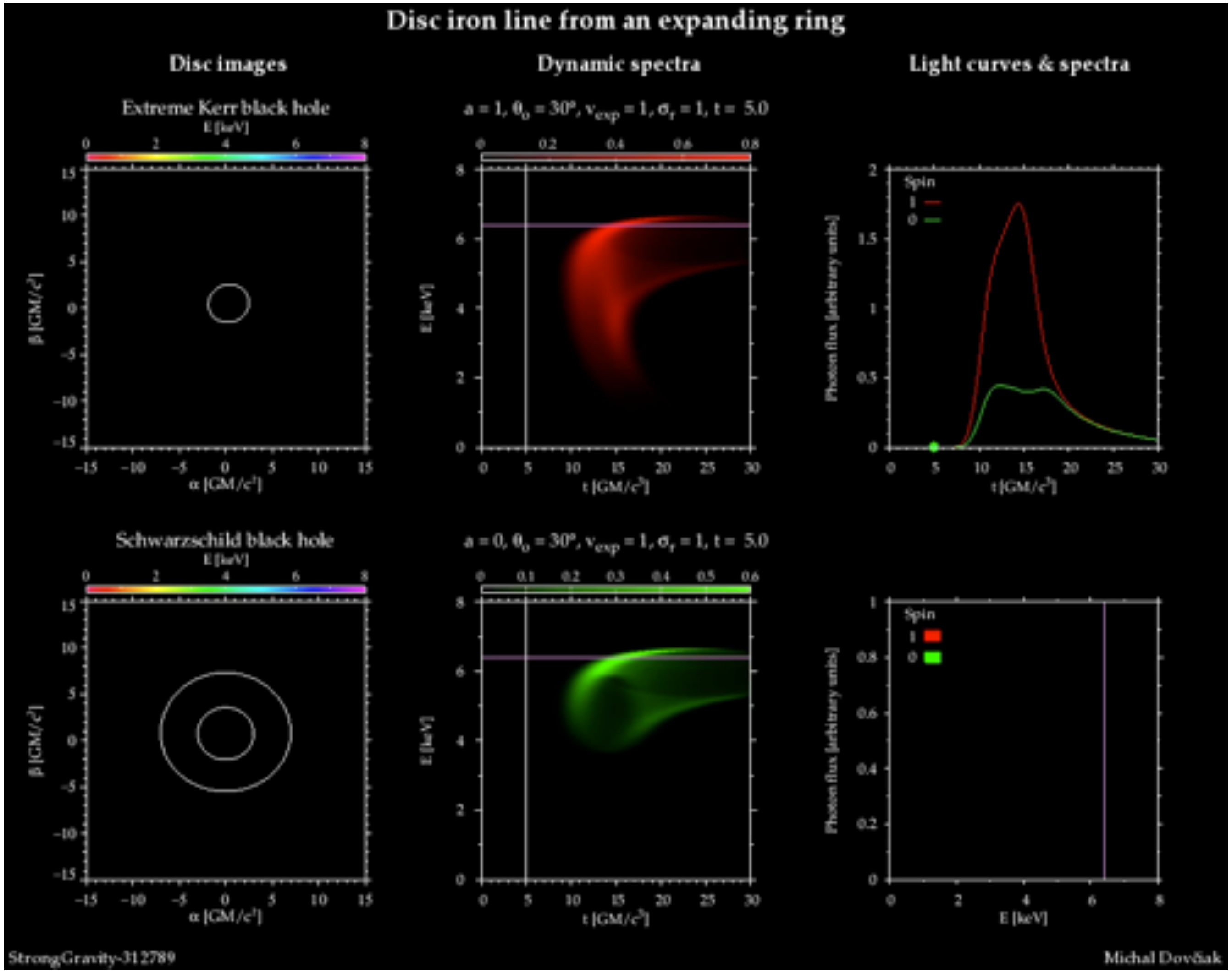


# Prediction of Line Reverberation in TDEs

Zhang, Yu et al. 2015, ApJ

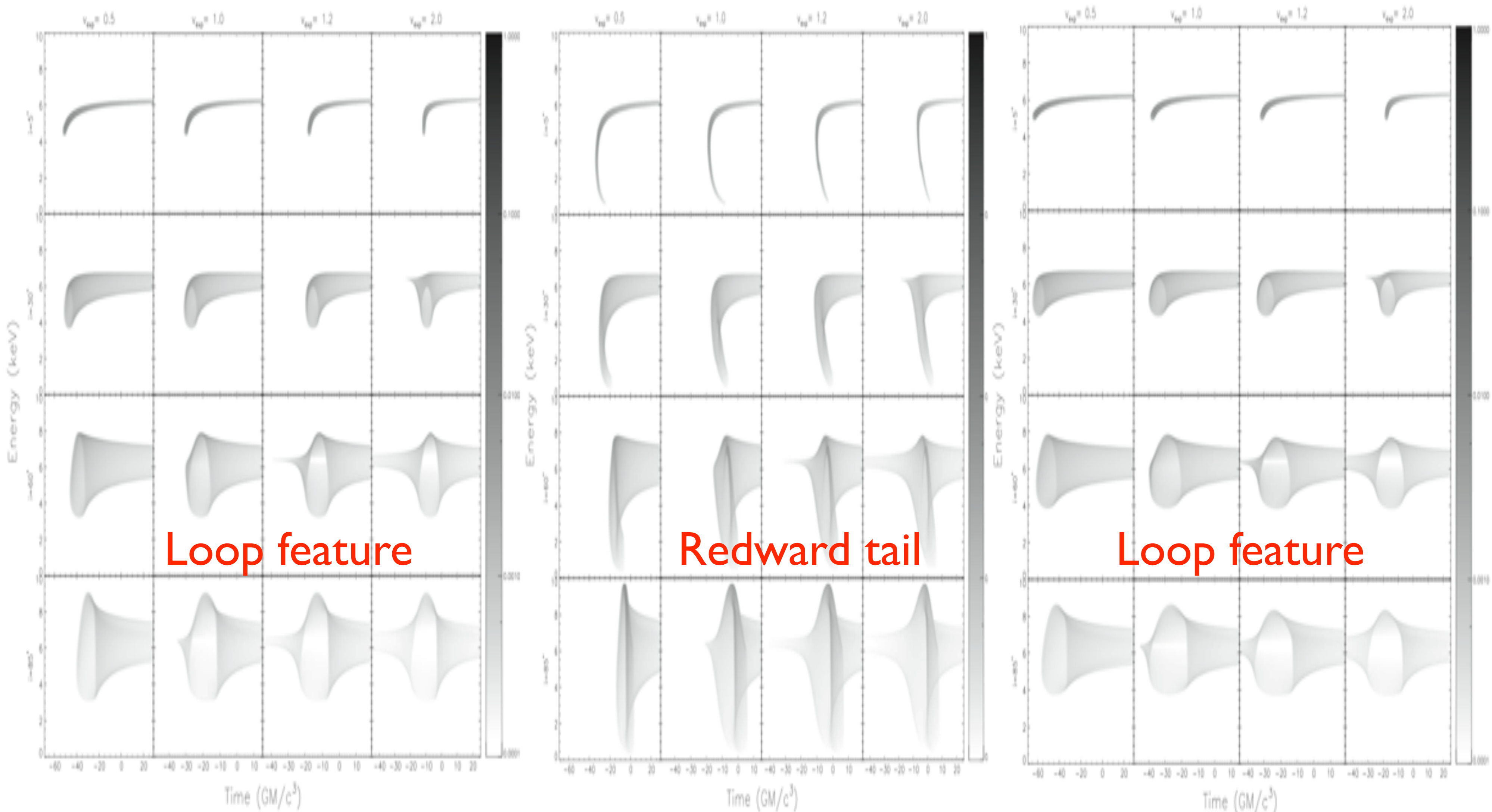



ionization circle



# Predictions of Line Profiles in the TDE cases

Zhang et al. 2015, ApJ, 807, 89




Schwarzschild BH Case

Kerr BH case

# The Maximum Mass of SMBHs in TDEs: Kerr BHs

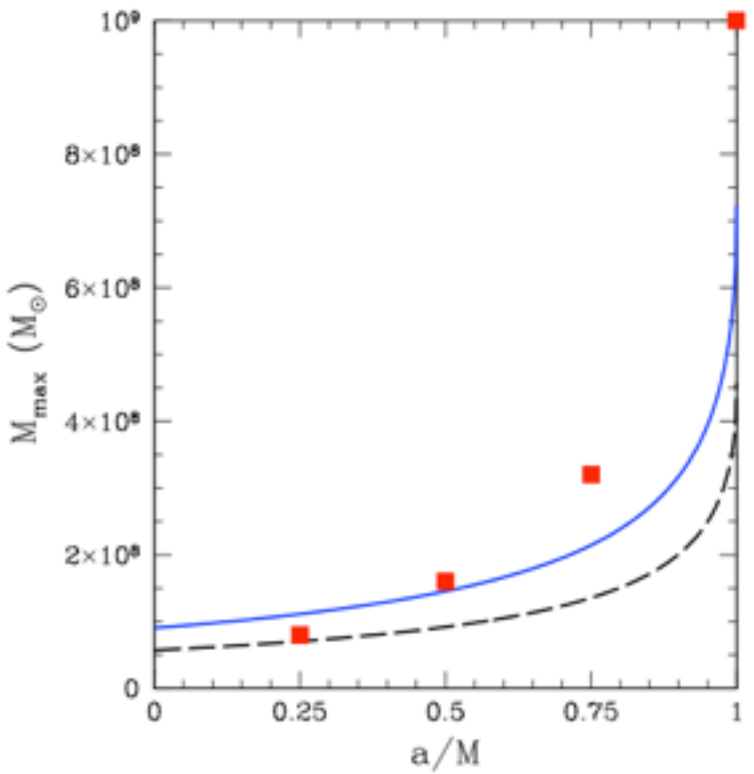



FIG. 1: The mass $M_{max}$ of the heaviest SBH capable of disrupting a star of solar mass and radius as a function of SBH spin $a/M$. The red squares show the values listed in Table 2 of [27] derived using a simple hydrodynamical model. The solid blue curve shows our prediction according to the relativistic criterion (11), while the dashed black curve shows the Newtonian prediction (12).

**Kesden 2012, PhRvD, 85, 4037**

For Kerr SMBHs, the ISCO radius is much smaller than that of Schwartzchild SMBHs:

- The disruption radius can be:

~ 5 time smaller

- For the disruption of sun-like stars, the maximum mass of the SMBHs can be:

~ 7 x 10^8 solar masses

Cases of the disruption of giant stars or stars less compact, or cases of partial disruptions would point to more massive SMBHs in TDEs

# The Maximum Mass of SMBHs in TDEs

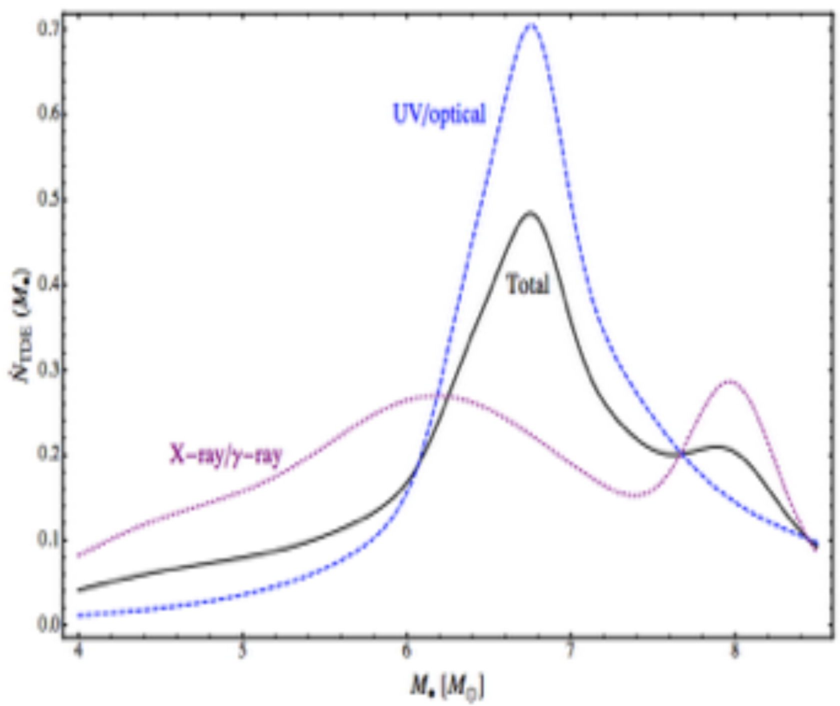
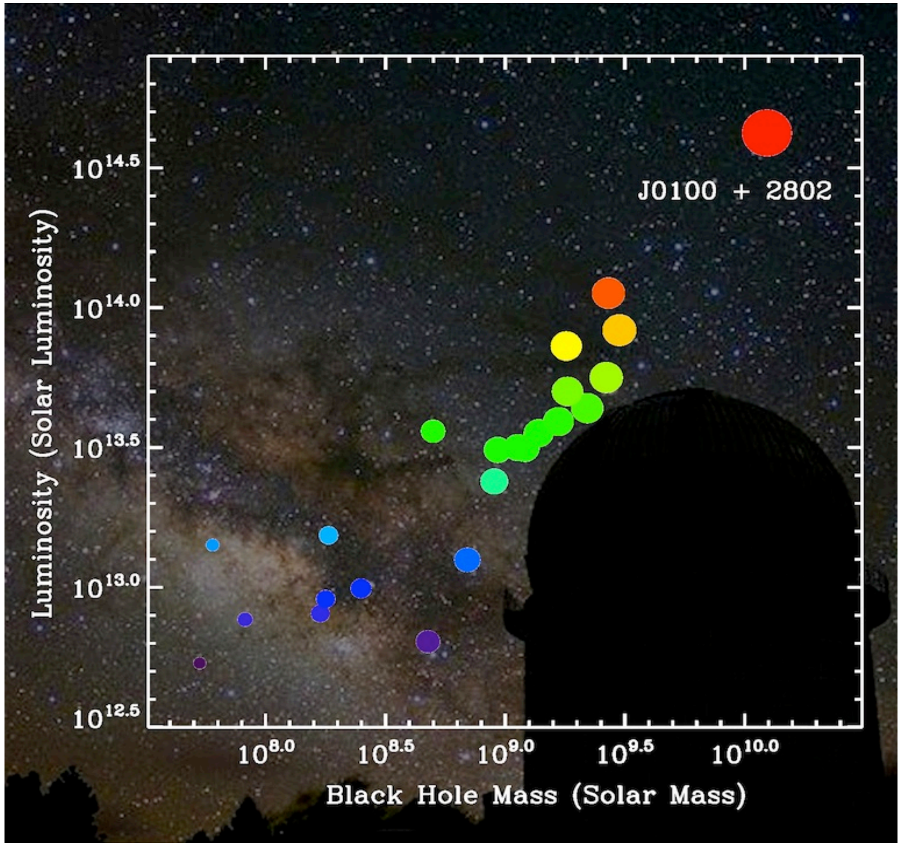



**Figure 11.** The SMBH mass $M_\bullet$ distribution of observed TDE flares, including 11 optical/UV-selected events (*blue dashed*), 8 X-ray selected events (*purple dotted*), or the full sample (*black solid*). Estimates of the SMBH mass $M_\bullet^{\rm est}$ for each flare are determined using galaxy scaling relations. $M_\bullet - \sigma$ is used when $\sigma$ is available, but other correlations between bulge luminosity and SMBH mass are used otherwise. Measurement errors are combined in quadrature with the intrinsic scatter of the galaxy scaling relations to produce error bars for each $M_\bullet^{\rm est}$; each individual TDE is modeled as a Gaussian probability density function $P(\log_{10} M_\bullet) = \exp(-(\log_{10} M_\bullet - \log_{10} M_\bullet^{\rm est})^2/(2s^2))/(s\sqrt{2\pi})$, where the standard deviation is approximated as $s = \log_{10} M_\bullet^{\rm up} - \log_{10} M_\bullet^{\rm low}$. The X-ray/γ-ray sample consists of NGC5905 (Bade et al. 1996), RXJ1420 (Greiner et al. 2000), SDSS J1323 (Esquej et al. 2007), SDSS J1311 (Maksym et al. 2010), Swift J1644 (Bloom et al. 2011), SDSS J1201 (Saxton et al. 2012), WINGS J1348 (Maksym et al. 2013), and GRB060218 (Shcherbakov et al. 2013). The optical/UV sample consists of D1-9, D3-13 (Gezari et al. 2006, 2008), D23H-1 (Gezari et al. 2009), VV-1, VV-2 (van Velzen et al. 2011), PS1-10jh (Gezari et al. 2012), PS1-11af (Chornock et al. 2014), ASASSN-14ae (Holoien et al. 2014), and PTF09ge, PTF09axc, PTF09djl (Arcavi et al. 2014).

**Stone & Metzger 2015, arXiv: 1410.7772**

**The SMBH mass distribution of observed TDE flares**

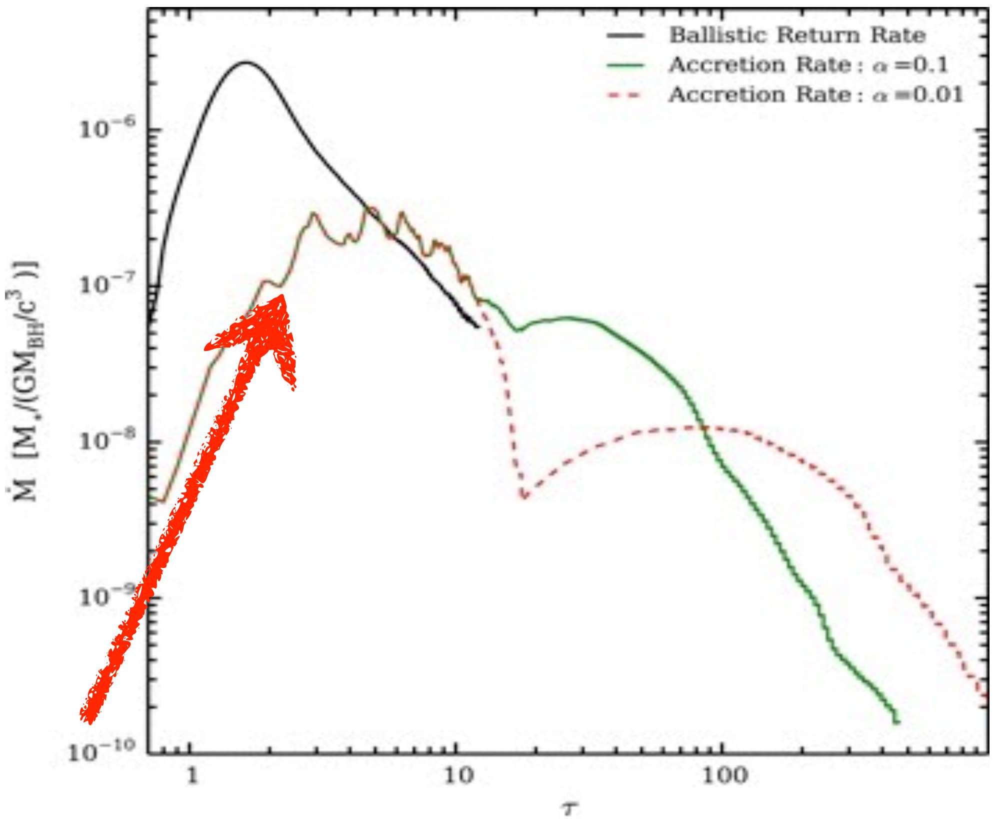



**“An ultraluminous quasar with a twelve-billion solar mass black hole at redshift 6.30 ”**

**M = 1.2 x 10 ^10 solar masses**

**Wu et al. 2015, Nature 518, 512**

# The Classical Fall-back Rate vs. GRHD Simulated Mass Accretion Rate




**Shiokawa et al. 2015, ApJ, 804, 85**

General conclusion:

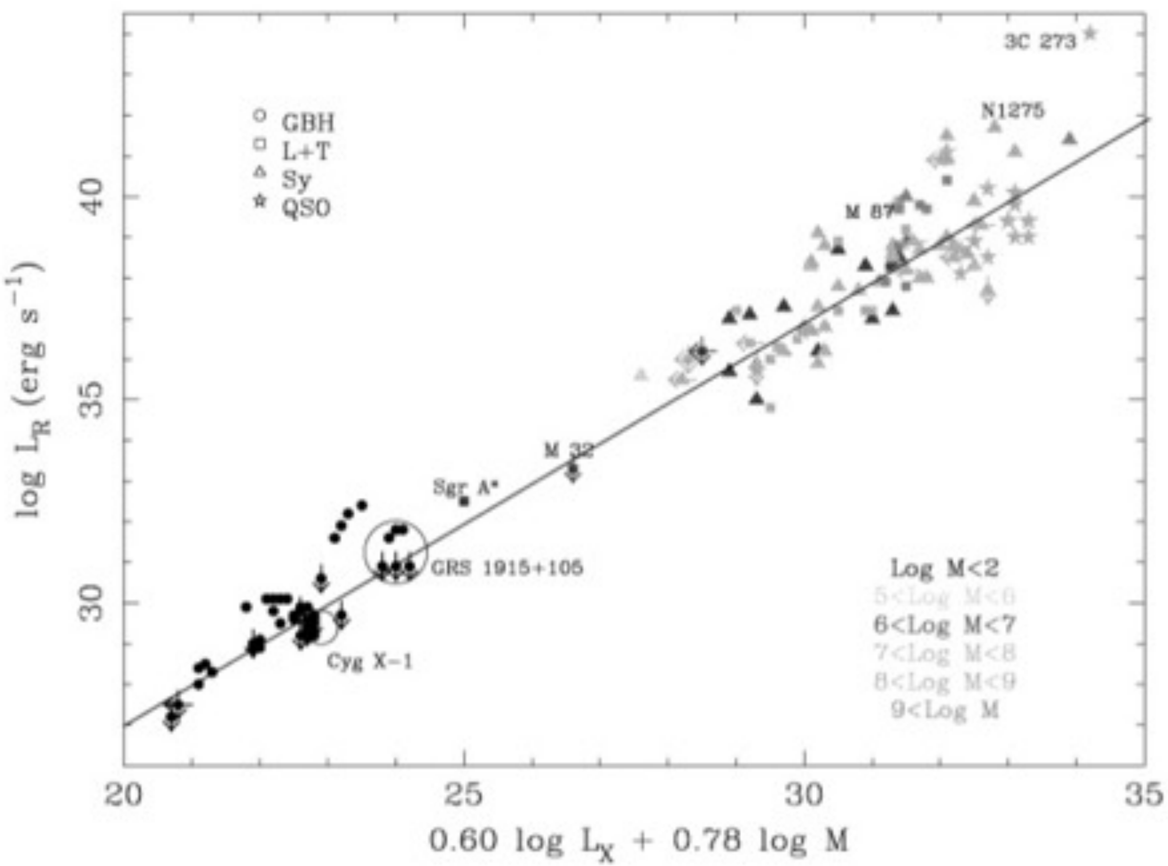
- Peak mass accretion rate is about 10% of the classical expectation

- The mass accretion rate peaks 3-8 times later

# Early Detection of Tidal Disruption Events in Radio

## Multi-wavelength survey and future early alerts from SKA

SMBH fundamental plane for AGNs (Merloni et al. 2005)




SKA Science White book Chapter (Yu et al. 2015):

Due to its large FOV and high sensitivity, SKA has the potential to lead next generation X-ray monitoring of black hole transients

Towards lower accretion rate regimes the radio luminosity decreases slower than the X-ray luminosity

SKA's detection sensitivity corresponds to 1-2 orders of magnitude lower than next generation X-ray all sky monitors = sending out alerts about 1-2 weeks earlier

# Summary

1. X-ray flares of TDEs provide us the opportunity to measure dormant SMBH mass and spin through spectral reverberation, as well as .

2. The early rising phase of the TDE outburst, if our current understanding of black hole accretion applies to TDEs, would be accompanied by radio emission well above the sensitivity of the Square Kilometer Array (SKA) - the future radio wide field telescope.