Class 19 :
Tidal Disruption Events

ASTR350 Black Holes (Spring 2022)

Cole Miller

RECAP

- So far in our discussion of supermassive BHs…
  - Discovery of quasars...
    - First realization that there are accreting supermassive BHs
  - Optical properties of AGN
    - Accretion disk thermal emissions
  - X-ray properties of AGN
    - Role of the disk corona
  - Jets and radio-loud AGN
    - Powerful directed outflows from AGN
    - Relativistic (one sided; superluminal motion)
  - The center of our galaxy
    - Evidence for the 4 million solar mass BH in our Galaxy
    - Past activity in our Galactic Center

This class

- How to find and measure distant SMBHs
- Supermassive black holes eating stars!
  - Tides and Tidal Disruption Events (TDEs)
  - Theoretical arguments
  - Searching for TDEs
- The tidal disruption of stars is an inevitable consequence of the presence of supermassive black holes (SMBHs)in the cores of galaxies.
  - Stars in close approach can be ripped apart by the tidal forces of the SMBH.
  - A significant fraction of the stellar material will subsequently be accreted, producing a luminous flare of radiation.

What is a TDE ?

- Models predict every $10^3 - 10^5$ yr a star in a galaxy will pass within the tidal disruption radius of the central BH,
- $R_{disr} < R_{Tidal} = R_\star(M_{BH}/M_\star)^{1/3}$, and *will be torn apart by tidal forces.*

- After the star is disrupted, ~1/2 of the debris is ejected from the system, and some fraction remains bound to the BH and is accreted.
- The fallback of debris onto the BH produces a luminous electromagnetic flare that peaks in the UV/X-rays and radiates close to the Eddington luminosity.

- The detection of a tidal disruption event (TDE) is unambiguous evidence for the presence of a central BH, and enables the detection of quiescent SMBHs – those not accreting, or at such low rates as to be undetectable.

Why Study TDEs?

- Direct detection of SMBHs in the centers of quiescent galaxies via stellar and gas dynamics is severely limited by our ability to spatially resolve the sphere of influence of the central BH, $R_{sph} \sim GM_{BH}/\sigma^2$ (where σ is is the velocity of the stars due to the galaxy)- this is the distance at which the motion of stars is controlled by the BH rather than the galaxy potential
- Even with today's best telescopes we can only measure stellar or gas velocities over the relevant scales at D<100Mpc and only for the most massive BHs
- **Need some other way to find 'non-active' BHs !**

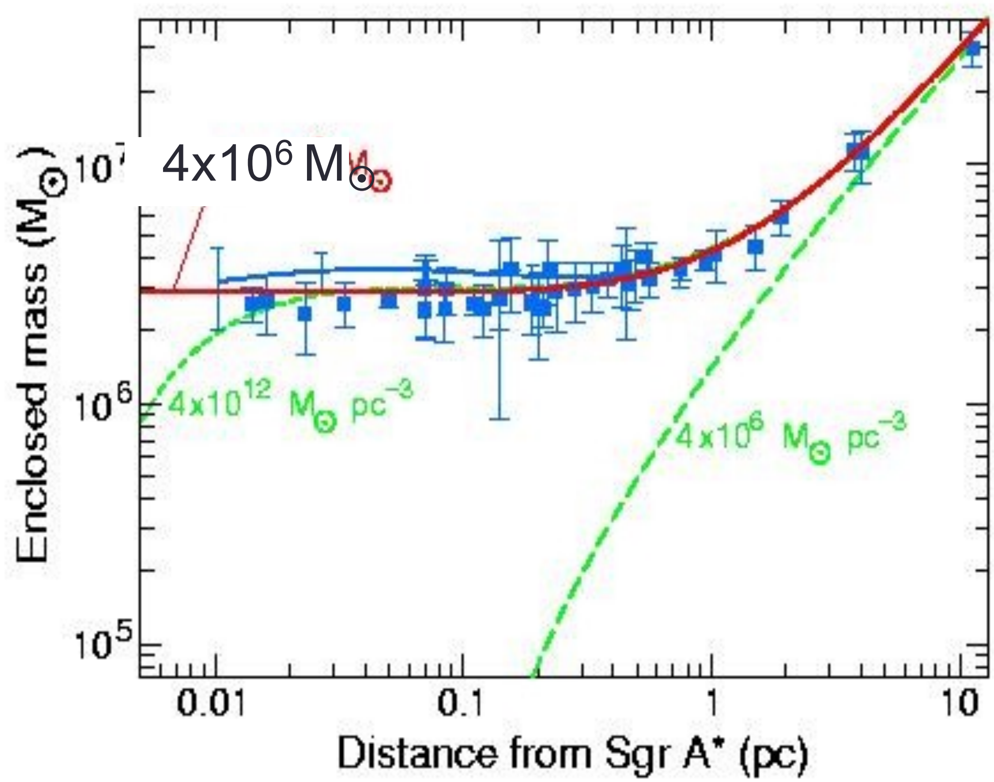
Why Study TDEs?

- TDEs also provide a laboratory for studying the detailed physics of accretion onto BHs.
    - The properties of the flare from the accreting stellar debris (luminosity, light curve, and spectral energy distribution) are dependent on the mass and spin of the BH +physics of accretion.
    - Detailed observations of tidal disruption flares provides an independent means of measuring the masses and spins of dormant BHs in distant galaxies as well as how gas can be accreted and "digested"

How to Measure the Mass of a Supermassive Black hole

- As we discussed last time the most definitive way to indicate the existence and mass of a SMBH in a galaxy is to measure the velocity field of the gas and stars and show that a SMBH is required using Newton's Laws
- **This requires high angular resolution to measure the places where the stars motions are controlled by the black hole (call this the sphere of influence)**
- For the MW this occurs at ~1 pc

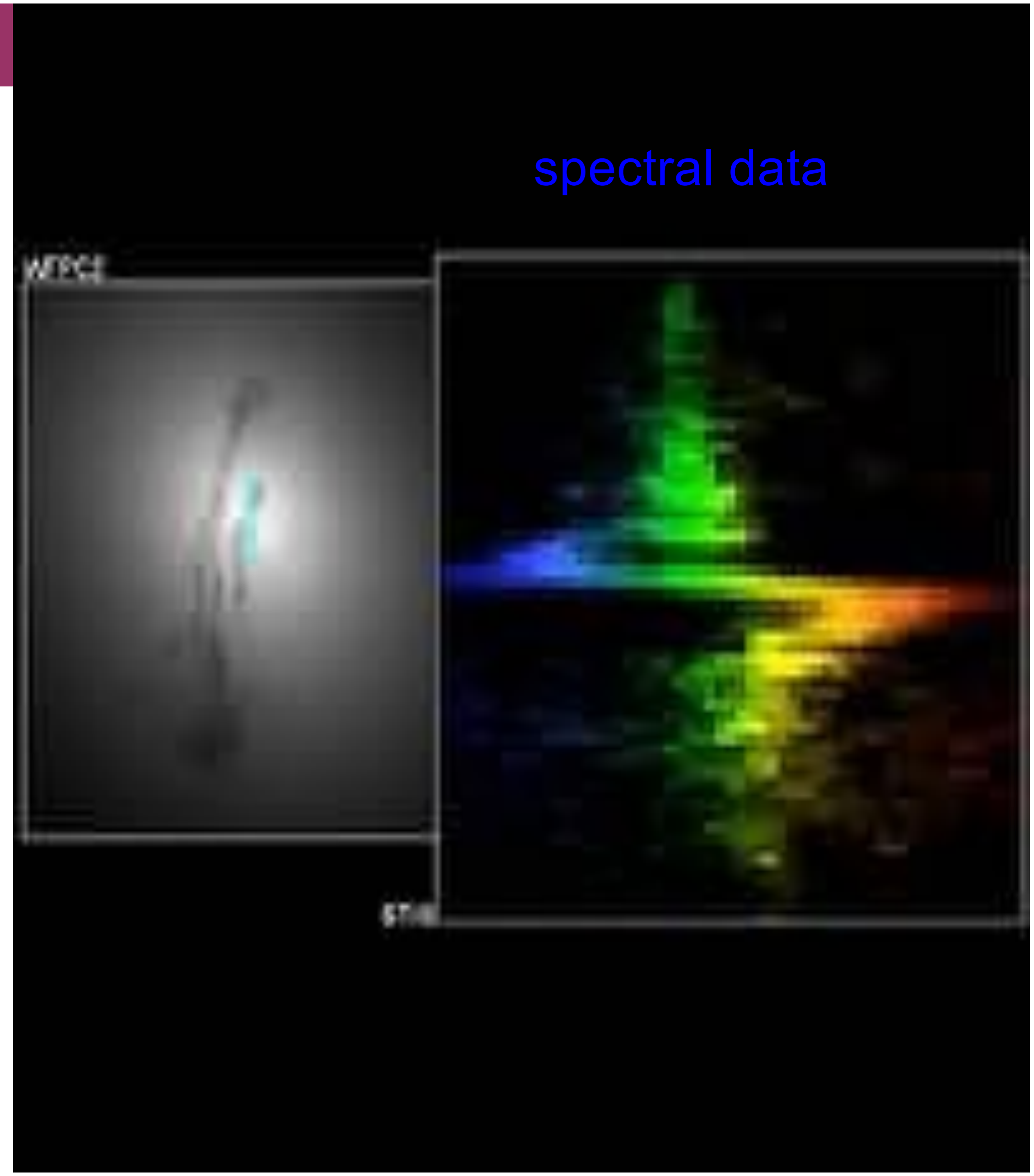
(or .015" at 16 Mpc, distance of Virgo cluster- this angular resolution is difficult to achieve in optical, IR, or X-rays-more later)



This region depends on how massive the BH is and how much mass is in normal matter (stars) near the BH

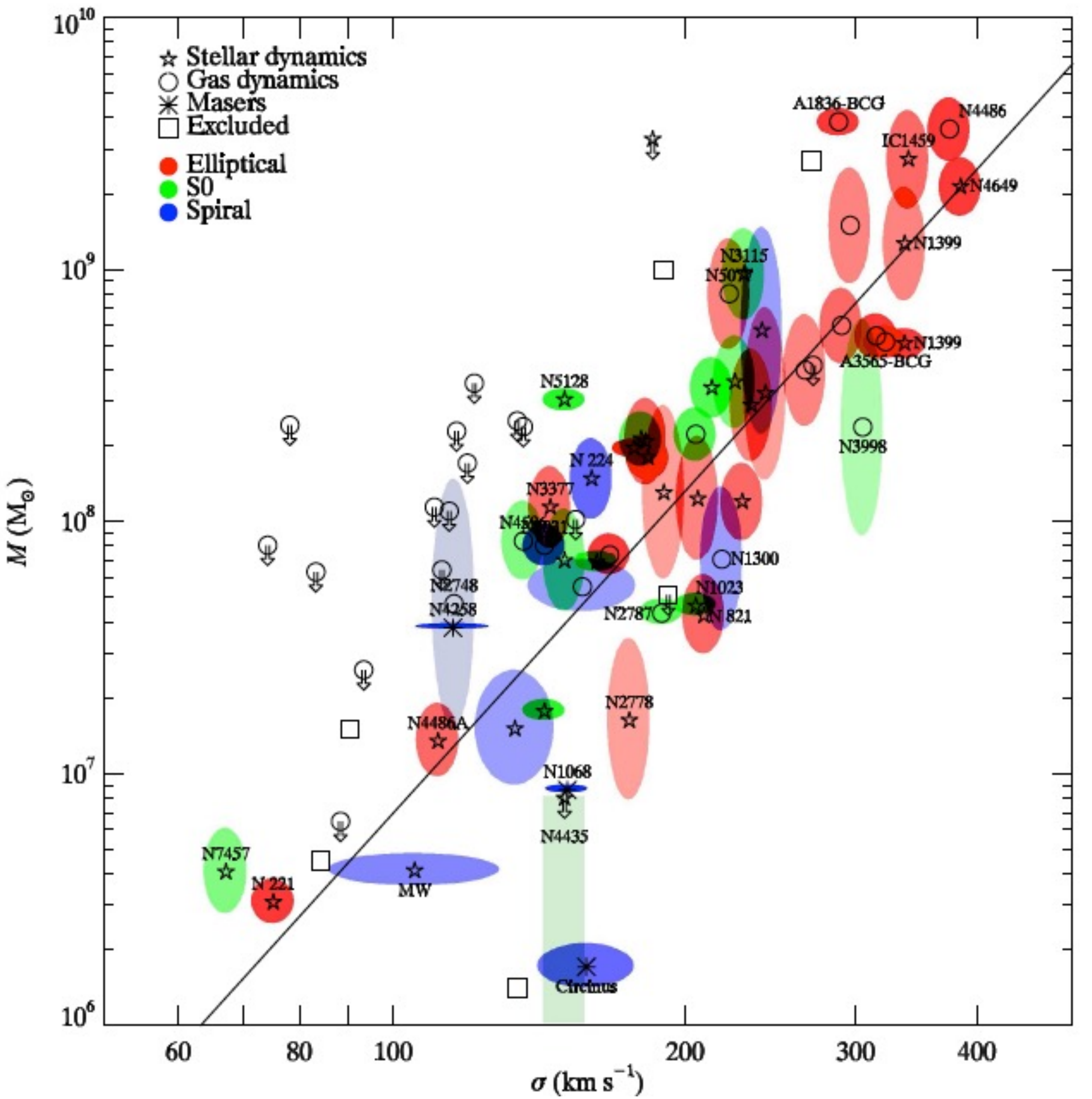
How to measure the mass of a distant quiescent supermassive black hole

- Image of central regions and velocity of gas near the center of **M84** a nearby galaxy (Bower et al 1998) -
  - The color scale maps the range of velocity along the slit, with blue and red color representing velocities that are blueshifted and redshifted, respectively.
  - The dispersion axis (horizontal) covers a velocity interval of 1445 km s^{-1}, while the spatial axis (vertical) covers the central 3 arcsec;.
- **The large change in velocity over the center of this galaxy indicates a black hole!**



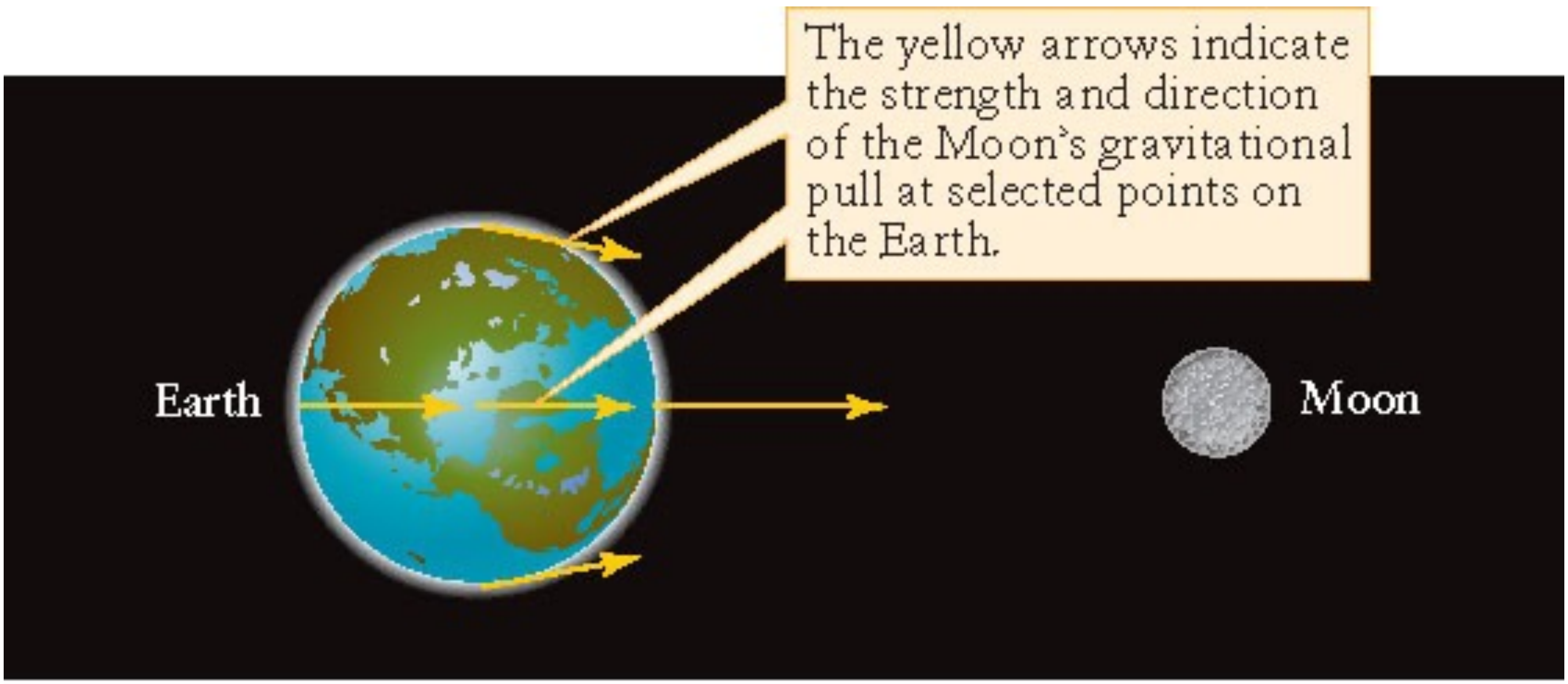
HST imaging and spectral data

- All the nearby galaxies with dynamical masses for their central black holes (Gultekin+ 2009) [my first Ph.D. student!]
- There is a scaling of the mass of the black hole with the velocity dispersion (random motion) of the stars of the galaxy
- $M_{BH} \sim 10^{-3} M_{bulge}$
- **Galaxies know about their BH and vice versa- more later**



I : Introduction to Tides

- Let's talk about tides…
  - The most familiar tides are those experienced by the Earth due to the Moon
  - "There is a tide in the affairs of men. Which, taken at the flood, leads on to fortune..."



(a)

I : Introduction to Tides

- The basic idea is simple: consider 2 bodies, the side of them closest to the other experiences more gravitational force (because it is closer) than the other side.

- In other words, tides occur because the object is a body of finite extent and the forces are not uniform:
  - some parts of the Earth are closer to the Moon than other parts, and since the gravitational force is weaker with increasing distance the parts that are closer experience a larger gravitational tug from the Moon than parts that are further away.

I : Introduction to Tides

- *So what*: well there is a force that is pulling the bodies *apart*. In the Earth-Moon system this force is felt strongest in water because the cohesion of water is much less than that of rock.

- In other words: differential forces act on the body (the Earth in this example). The effect of differential forces on a body is to distort the body.
  - The body of the Earth is rather rigid, so such distortion effects are small. However, the fluid in the Earth's oceans is much more easily deformed and this leads to significant tidal effects

I : Introduction to Tides

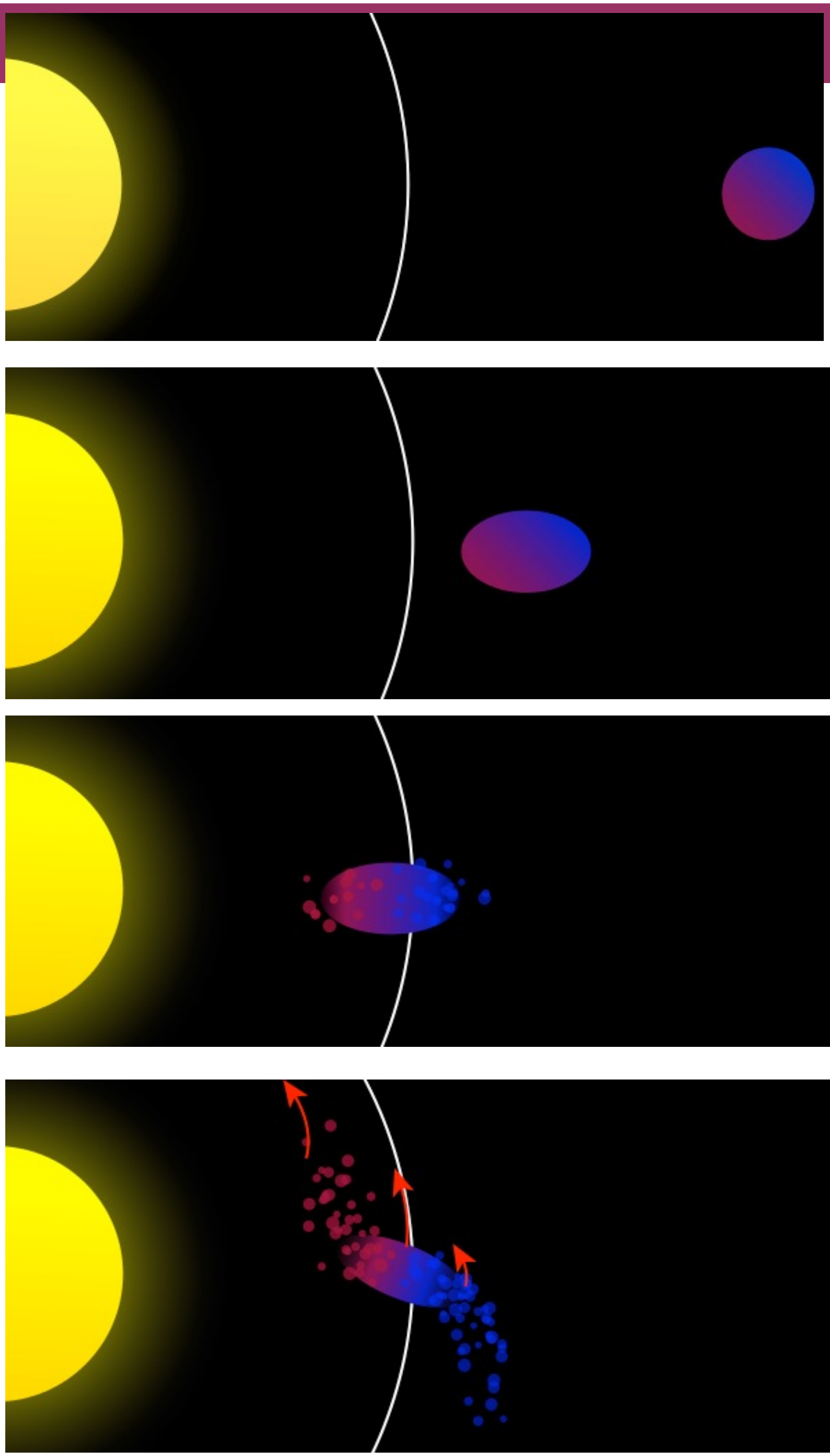
- Using Newtonian gravity for the Earth-Moon system
- The side of the Earth facing the moon is 12800km closer than the side away.
  - The differential forces are 3% of the moon's total gravitational force, and that is enough to create the tides.

II Tidal disruption…

- What happens when “tidal” forces on an object overwhelm the gravitational forces holding the object today?

  the object will be pulled apart!
- This happens when the object is inside its Roche* radius
- this happens occasionally in our solar system when an asteroid or comet passes too close to a planet.

*Roche radius: is the distance within which a body, held together only by its own force of gravity, will **disintegrate** due to a second celestial body's tidal forces exceeding the first body's gravitational self-attraction



Progression of tidal disruption

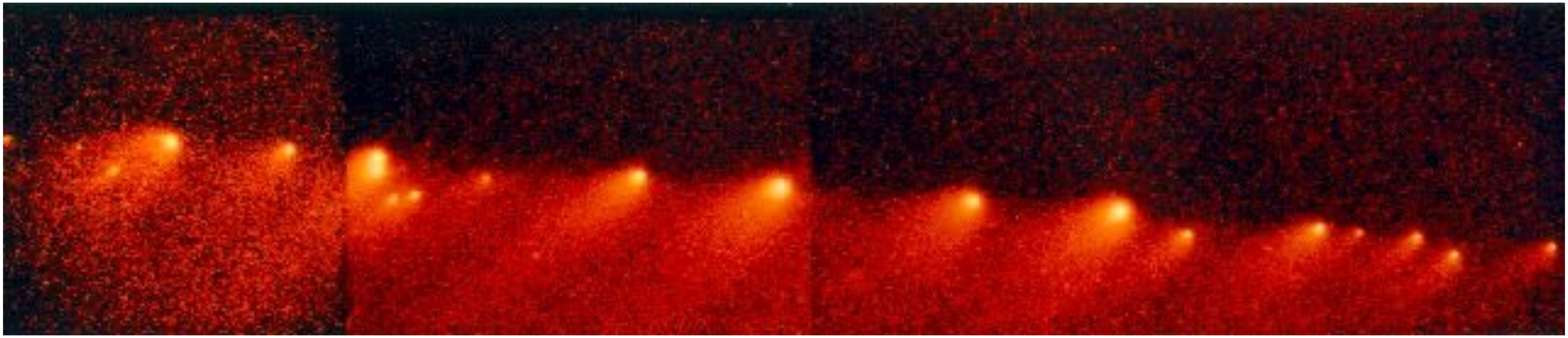
Roche limit is proportional to $R_{small}(M_{big}/M_{small})^{1/3}$

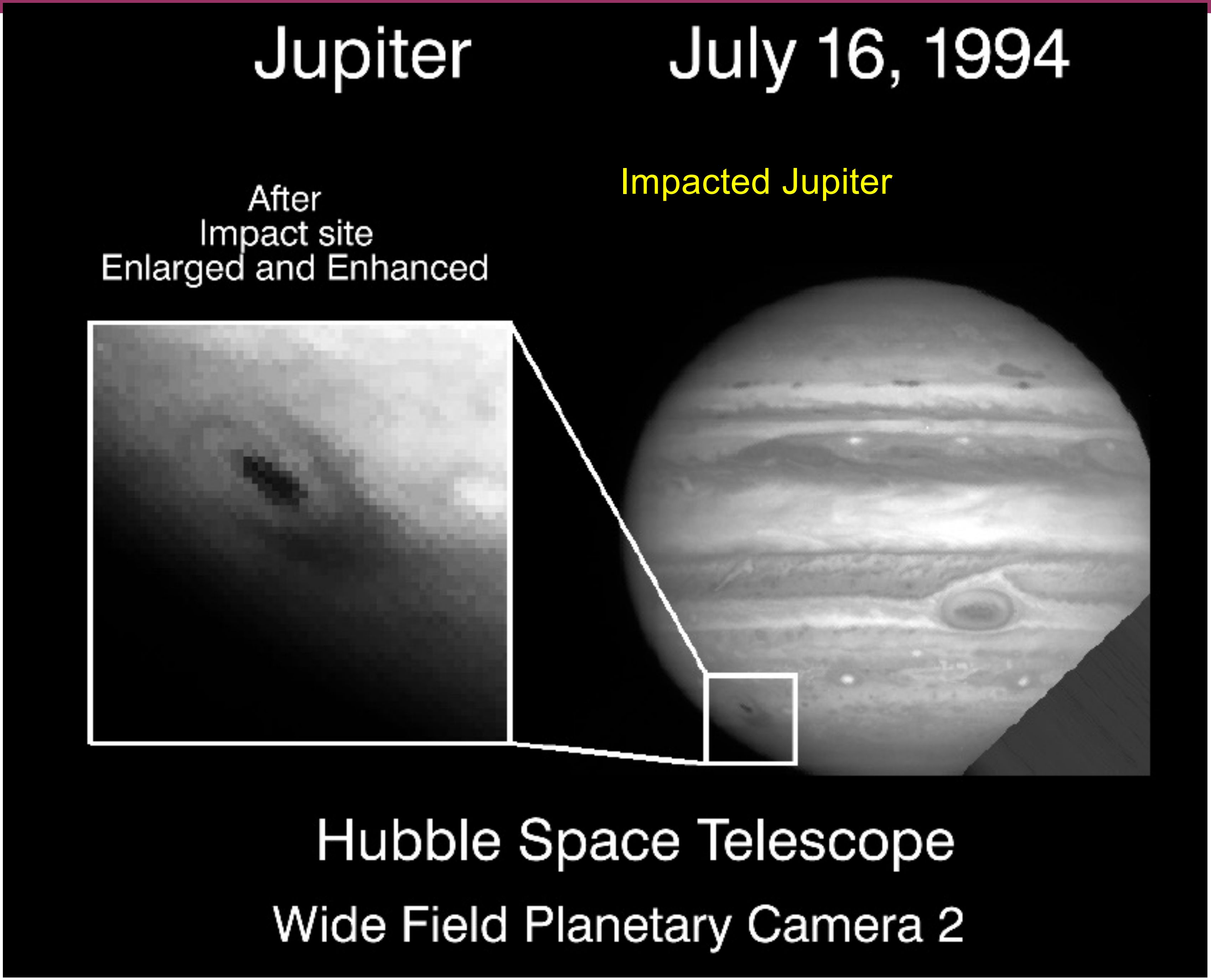
where small refers to the object being torn apart and big to the one doing the disruption.

Figure from Wikipedia

Comet Shoemaker-Levy 9 Disrupted by Jupiter

- Discovered by Carolyn/Eugene Shoemaker and David Levy on 24th March 1993
- Unusual comet – a whole string of nuclei
  - **a comet torn apart by tidal forces**




Jupiter
July 16, 1994
Impacted Jupiter
After
Impact site
Enlarged and Enhanced
Hubble Space Telescope
Wide Field Planetary Camera 2

III : Tidal Disruption of Stars by Supermassive Black Holes

NATURE VOL. 333 9 JUNE 1988 ARTICLES 523

Tidal disruption of stars by black holes of 10^6–10^8 solar masses in nearby galaxies

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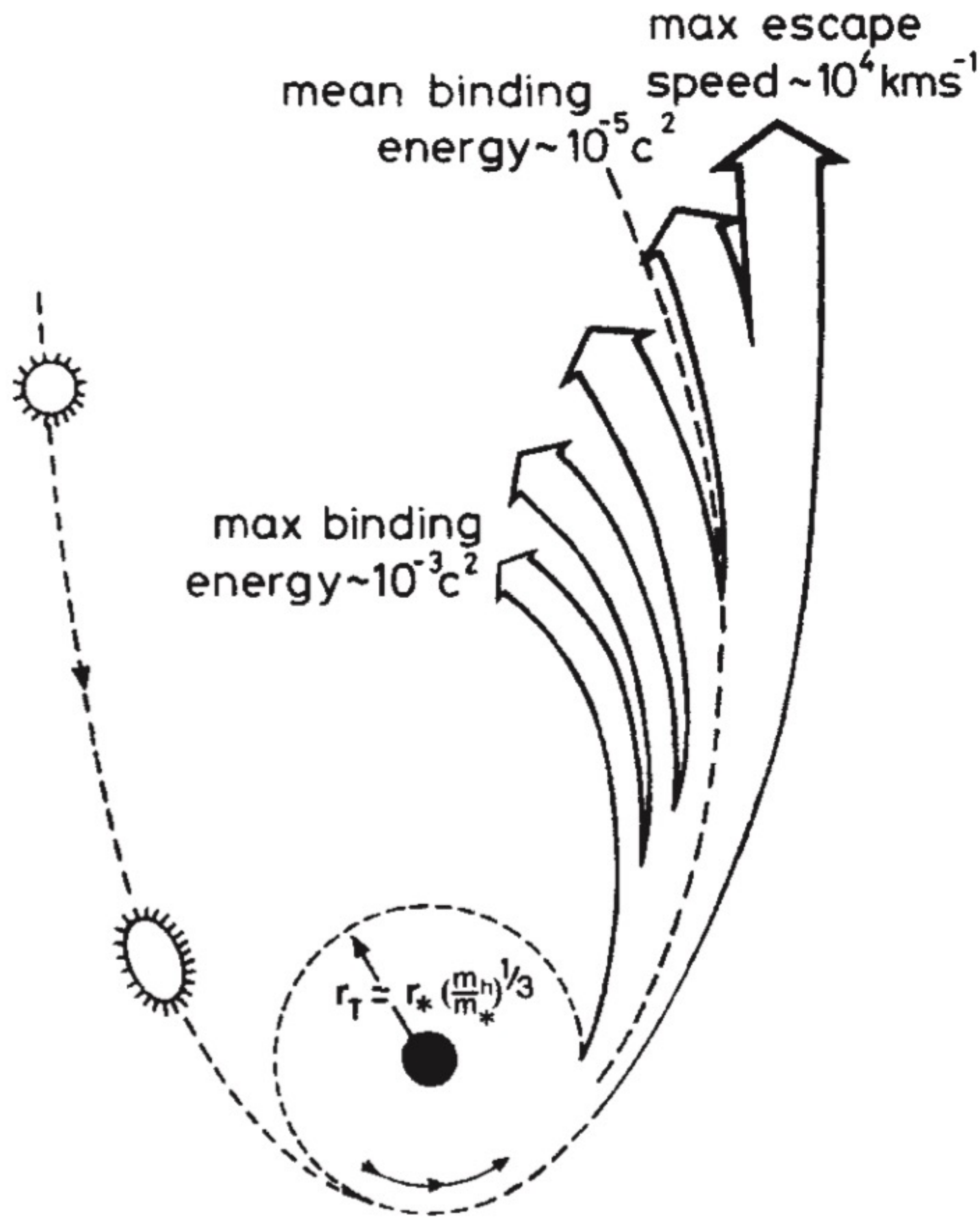
My grand-advisor! And my advisor corrected him on a detail...

Stars in galactic nuclei can be captured or tidally disrupted by a central black hole. Some debris would be ejected at high speed; the remainder would be swallowed by the hole, causing a bright flare lasting at most a few years. Such phenomena are compatible with the presence of 10^6–10^8 $M_\odot$ holes in the nuclei of many nearby galaxies. Stellar disruption may have interesting consequences in our own Galactic Centre if a $\sim 10^6$ $M_\odot$ hole lurks there.

TDEs are fundamentally general-relativistic events, in that GR is not a first- or second-order correction to basically Newtonian physics

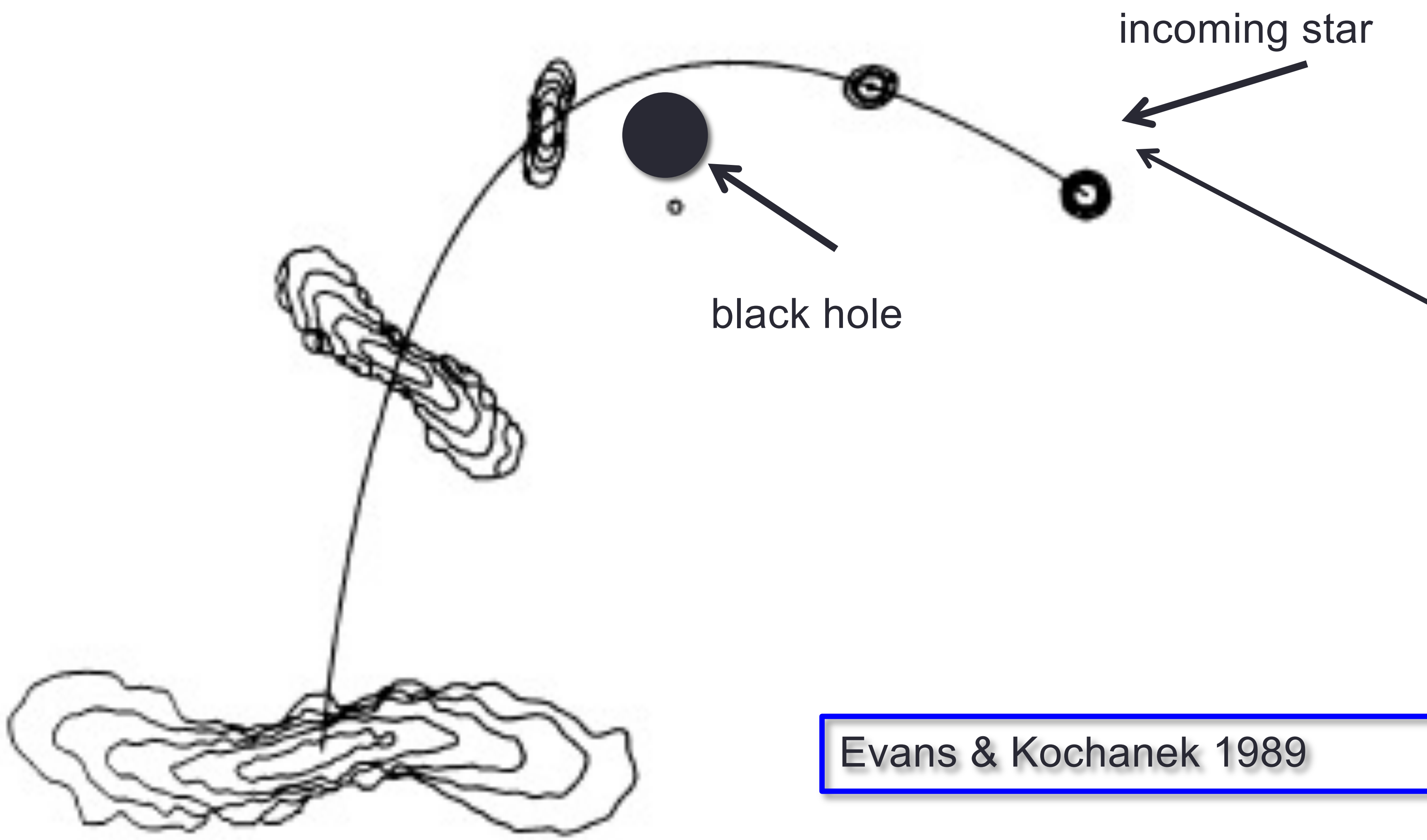
How the Star Falls Apart Predicted in 1988



Events were discovered in the nineties in form of luminous, soft X-ray outbursts from otherwise quiescent, normal galaxies that matched this model

This sort of event occurs at ~10^{-4} /galaxy/year, i.e., once every 10,000 years in an average galaxy

What happens when a star ventures too close to a black hole?



Evans & Kochanek 1989

It gets ripped apart!

Slide courtesy of Prof. Suvi Gezari

Why TDEs are Interesting

- TDEs probe relativistic effects and the extremes of accretion physics at high rates and near the last stable orbit, and provide a way of measuring BH spin.
- Current and upcoming surveys, such as LSST in the optical and e-ROSITA in the X-ray, are expected to detect hundreds to thousands of TDEs each year.
- Jetted TDEs provide new insight into the formation and early evolution of radio jets.
- TDEs, now being detected frequently, will unveil the population of moderate-mass BHs (10^3-10^5 M_{sun}) in the universe.
- The TDE rates are strongly enhanced by binary SMBHs: these are the origin of gravitational waves to be detected by LISA

Tidal Disruption of a Star

The star is ripped apart when tidal forces overcome the self gravity of the star:

$$\frac{GM_{BH}R_{\star}}{r^3} \geq \frac{Gm_{\star}}{R_{\star}^2}$$

Tidal Force Self-Gravity

$$r_{\mathrm{T}} \approx R_{\star}(M_{\mathrm{BH}}/m_{\star})^{1/3}$$

r_T-Tidal Disruption Radius- the distance from the black hole where the star gets disrupted

R_* is size of star

m_* is mass of star

Slide courtesy of Prof. Suvi Gezari

Tidal Disruption of a Star

The radius where a sun-like star is ripped apart is

$$r_t \simeq 7 \times 10^{12} \left(\frac{M_{\rm BH}}{10^6 M_\odot}\right)^{\frac{1}{3}} \left(\frac{M_*}{M_\odot}\right)^{-\frac{1}{3}} \frac{r_*}{r_\odot} {\rm cm}\,.$$

r_T-Tidal Disruption Radius- the distance from the black hole where the star gets disrupted

Schwarschild radius of $10^6 M_\odot$ BH is 3×10^{11}cm

Notice r_t proportional to $M^{1/3}$, R_{sch} to M so at large M what happens?

r_* is size of star M_* is mass of star

Tidal Disruption of a Star

For a BH of mass $10^6 M_{sun}$ the Schwarzschild radius is $\sim 3 \times 10^{11}$ cm – so disruption is occurring at ~25 R_s

Because r_t and R_s depend differently on BH mass, solar type stars are swallowed whole for SMBH masses exceeding ~ $10^8 M_{sun}$

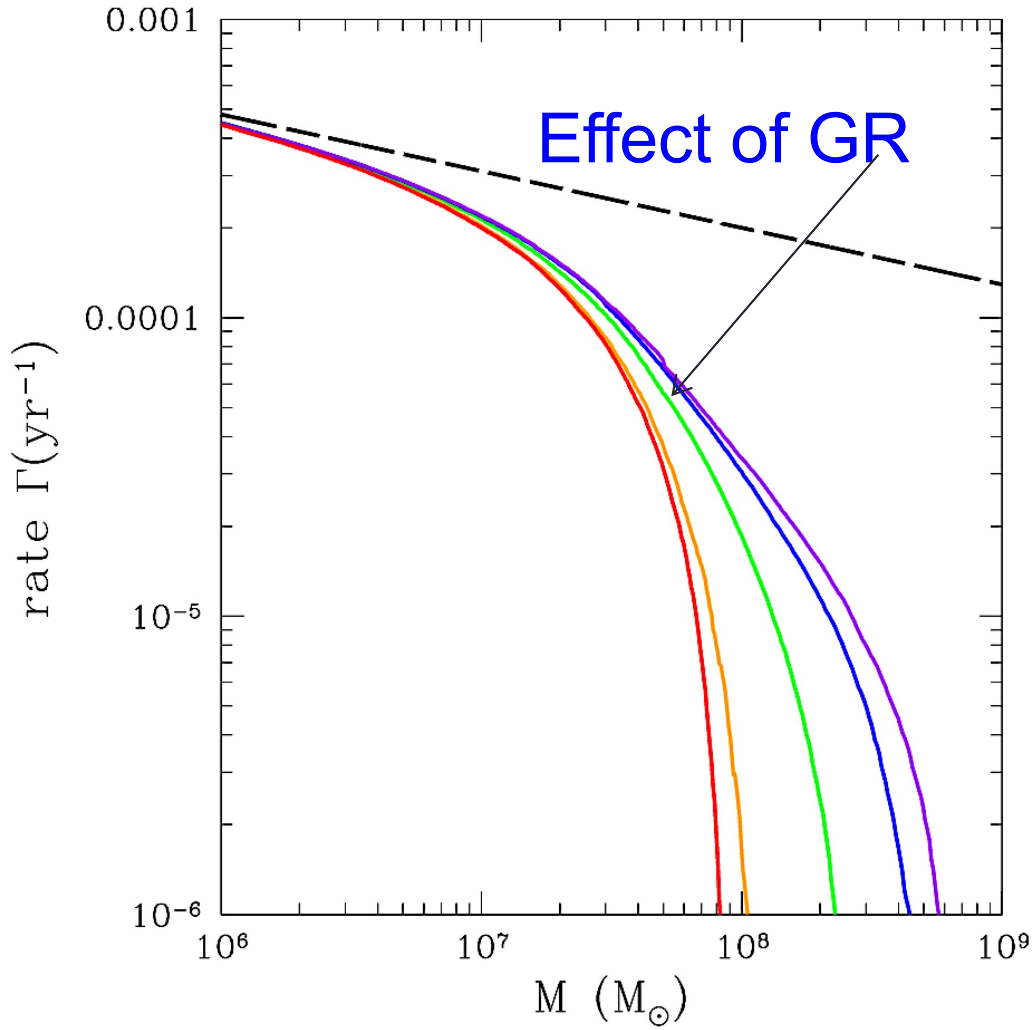
Tidal Disruption of a Star

- For SMBHs with masses above $\sim 10^7 M_\odot$, the tidal disruption of solar-type stars occurs within 10 gravitational radii of the SMBH, thus **general relativity (GR) is needed.**
- Tides are 'different' in GR and even more different in Kerr BHs.

Stars experience stronger tides at pericenter in GR than they do in Newtonian gravity and disruption at larger radii.
This affects the rate of TDEs
GR also strongly affects how the gas moves after the star is disrupted and thus how/if an accretion disk forms.

Effect of GR on Rates of TDEs

As spin increases there are more TDEs at high ($M>10^7 M_\odot$) BH masses (x axis is mass of BH, y axis is number of TDEs per year per galaxy)

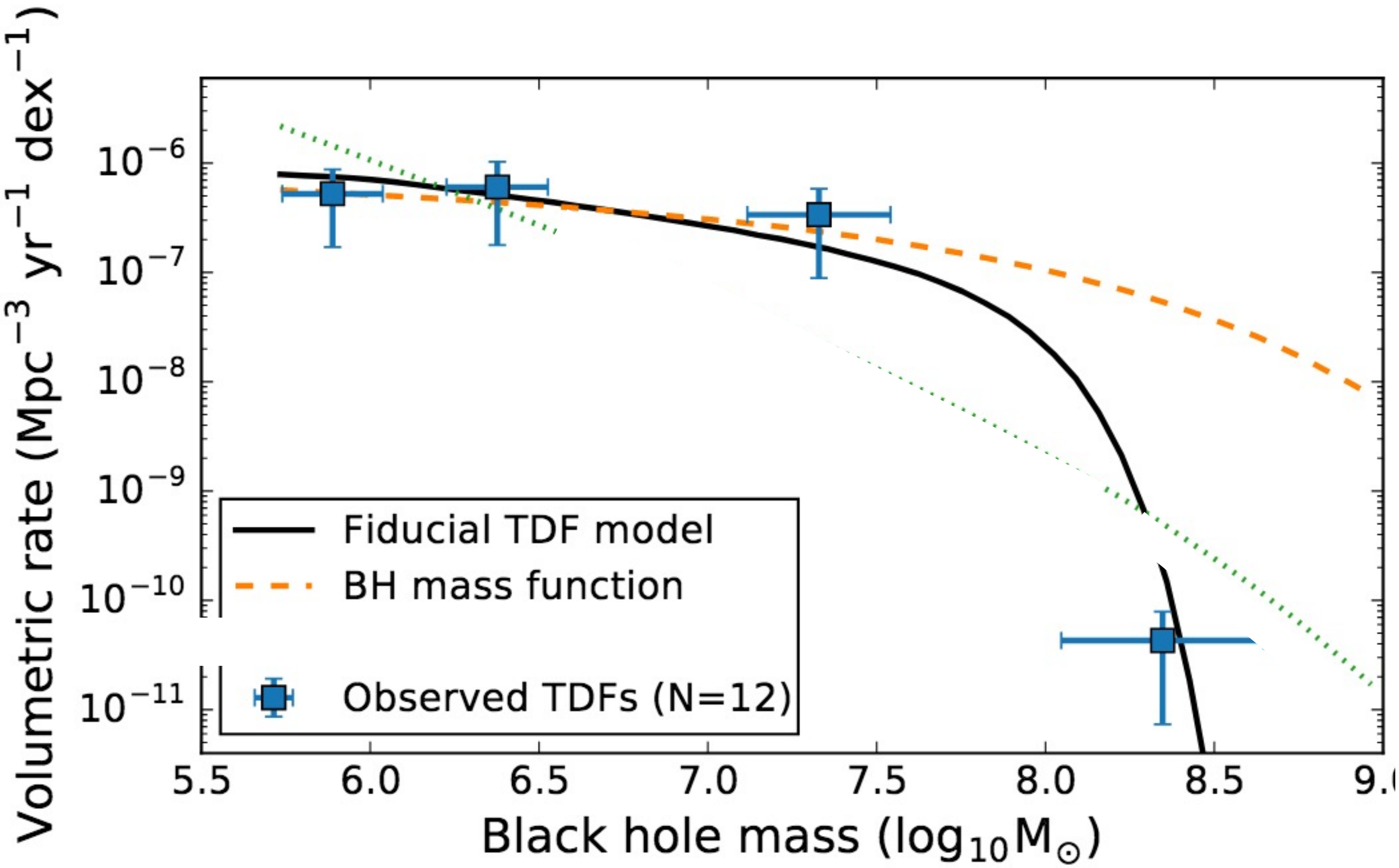


Black line is 'Newtonian' BH,
red line is Schwarzschild,
Purple is maximal Kerr

Where Do They Occur?

Measured rate of TDEs vs BH mass
Notice that there are no BH masses above $10^{8.5}$ M- the value at which stars get swallowed no matter what the spin.

The spin distribution of SMBHs in the mass range $10^{7.5}M_{\cdot}$-$10^{8.5}M_{\cdot}$ determines the shape of the cutoff in the observed mass distribution of TDE hosts



How Often do They Occur?

TDE's have up to now been difficult to find – only a few dozen are well studied

The observed rate of TDEs is low ($10^{-5} - 10^{-7}$ yr^{-1} Mpc^{-3}, which is about $10^{-3} - 10^{-5}$ yr^{-1} galaxy^{-1})

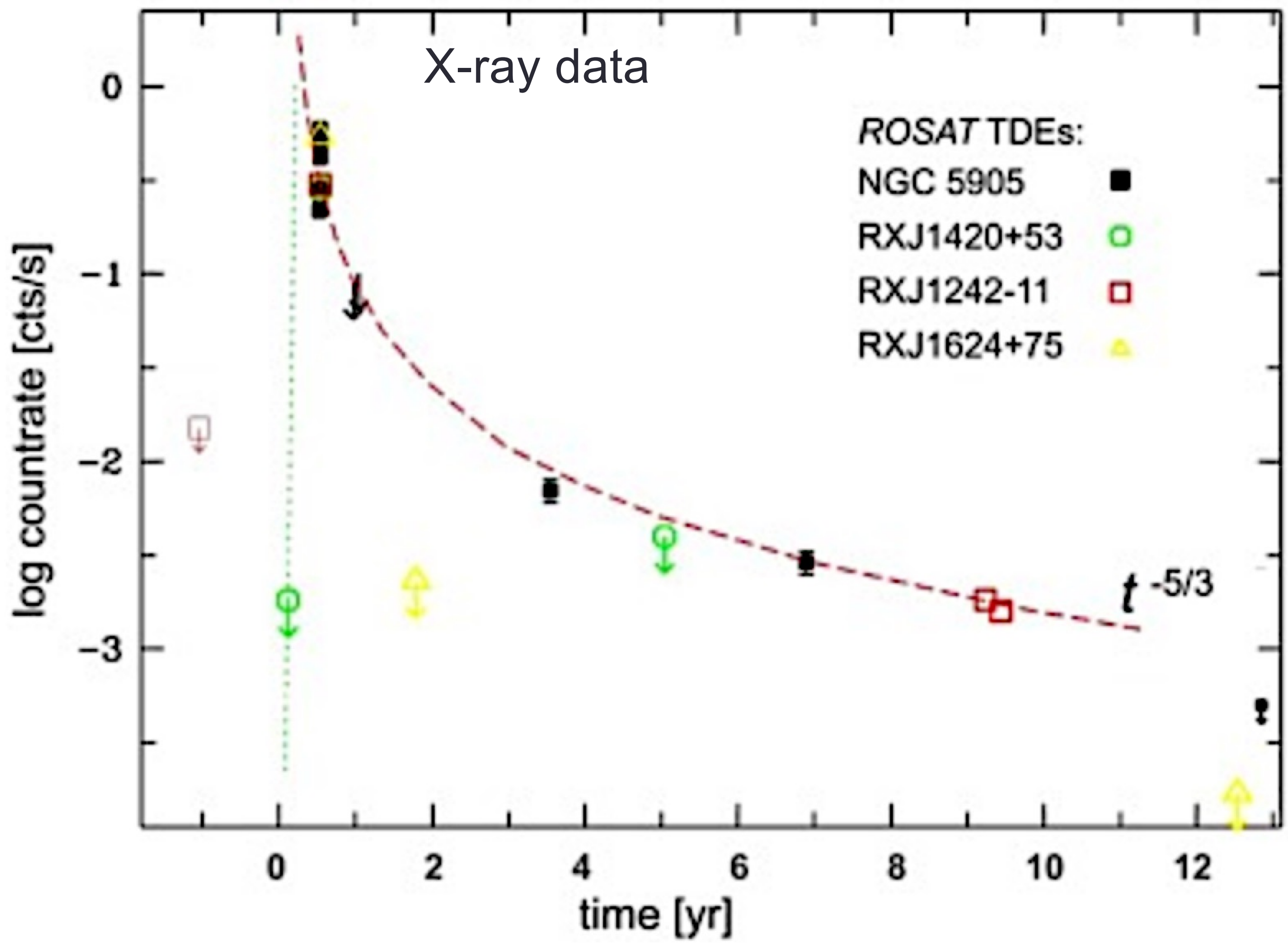
They have been selected for in optical, UV and X-ray surveys, which seem to find different populations.

Advent of new surveys (Zwicky Transient Survey in the optical, eRosita in the X-ray and eventually the Vera Rubin telescope LSST) will dramatically increase their numbers.

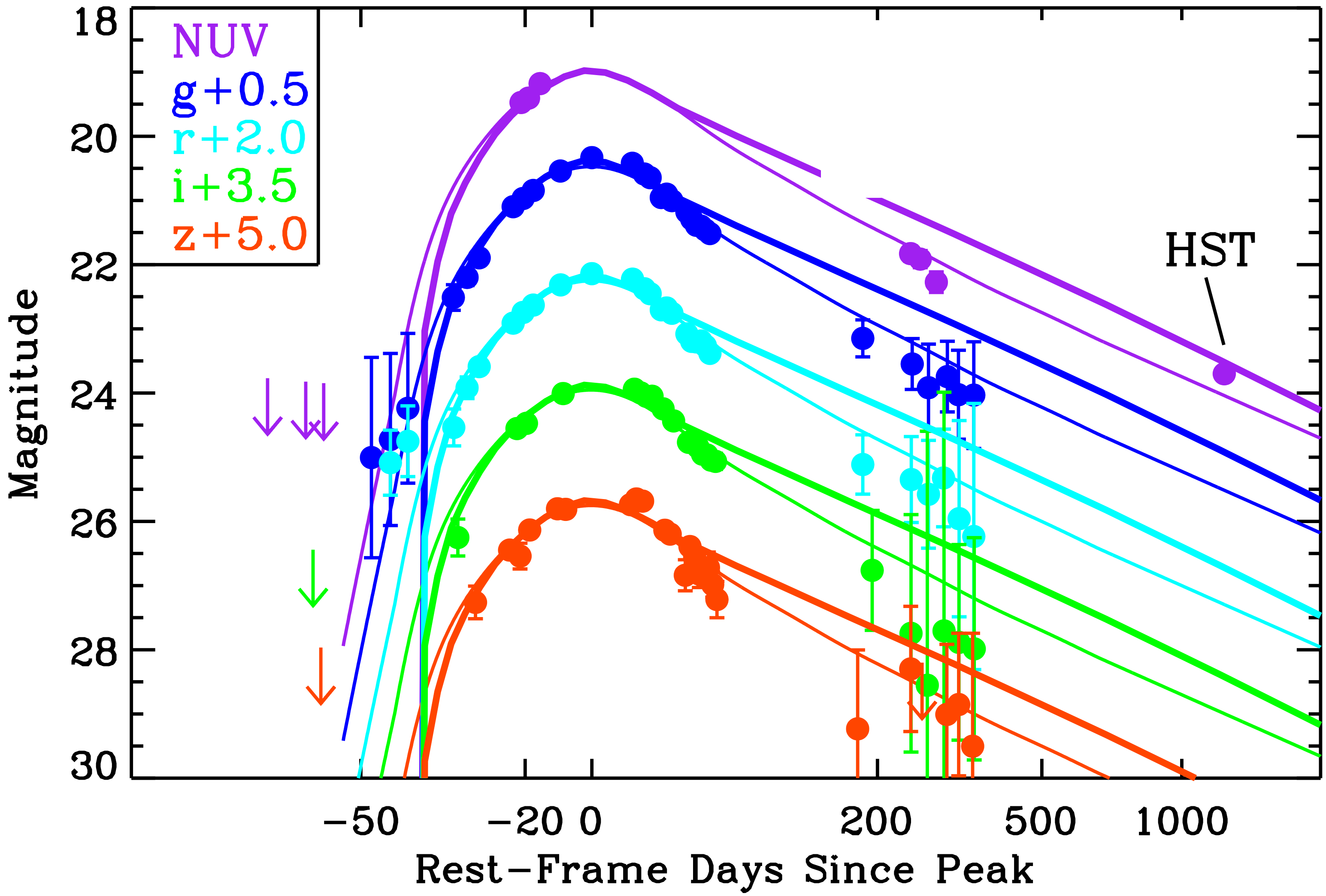
Amplitude of Variability is Very Large

Sharp rise, slow fall over a factor of 1000 in brightness over several years

Very bright at peak total luminosity L~10^{44}ergs/sec- only a small amount of the accreted mass (~$0.1M_{sun}$) is needed to power the observed emission.



UV/Optical Light Curve Follows Fallback Rate



Models for dM/dt, scaled to light curve.

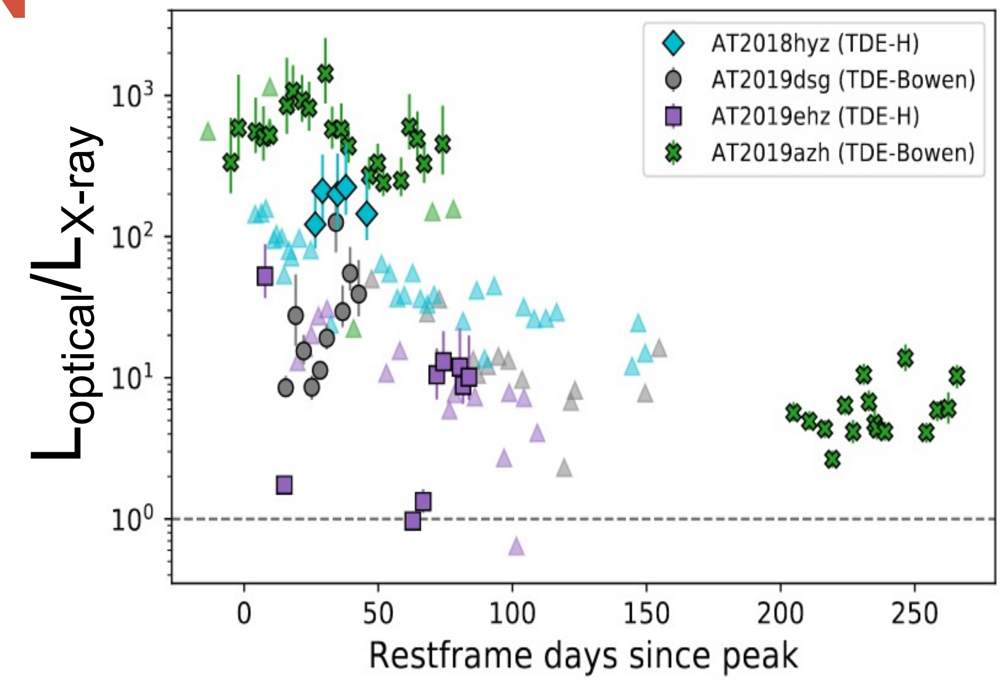
Light curve for one object in 5 optical UV bands

Slide courtesy of Prof. Suvi Gezari

PS1-10jh: Gezari+ 2012, 2015

Differences from AGN

- They have many differences from AGN
  - Surprisingly, TDEs are either optically or X-ray bright: very few are bright in both bands.
    - However some 'change' from being optically to X-ray bright
  - The X-ray and optical spectra have a very different shape than in AGN and the optical lines are different.
  - The peak X-ray luminosities are ~10^{43}erg/s, implying blackbody radii consistent with emission from within a few gravitational radii of the black hole



The UV/optical luminosity has a smooth evolution over time and is well described with a single power-law decline post peak, the soft X-ray component shows variability on several timescales.

Differences from AGN

- TDEs are astrophysically unique since they are tilted accretion systems (since the incoming stars can come in from all directions), e.g., should produce disks with a wide variety of inclination angles.
- Accretion disks around AGN are expected to align with the black hole equatorial plane due to frame-dragging
- However, as short-lived, transient systems, TDE disks may not have time to align themselves with the SMBH.
- This can strongly affect jets, both jets and their parent disks precess about the SMBH spin axis,

Differences from AGN

- We believe that these differences are due to the different way the accretion disk 'operates' depending on the how much mass is deposited where and when and how long it takes to form the x-ray emitting coronae
- However wide variety of behaviors is not understood
- TDE's provide a new and unique look at accretion- the sudden dumping of lots of material on a otherwise quiescent black hole.

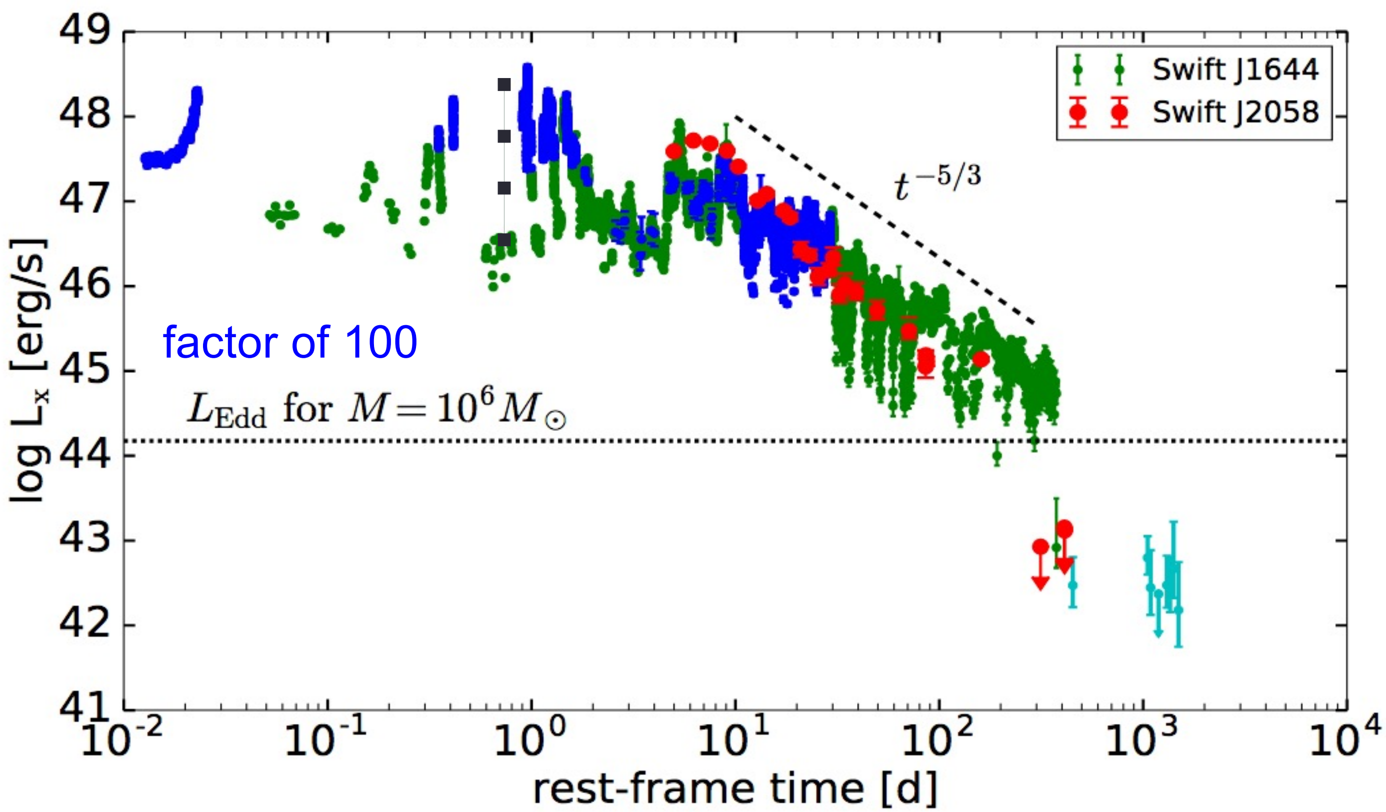
Jets from TDEs

Rarely, relativistic jets have been observed from TDE's

This offers a rare look at the processes that can create jets in a previously quiescent black hole.

X-ray light curves of 2 jetted TDEs

Notice how luminous they are and rapid high amplitude variability (x axis is logarithmic in days, y axis is X-ray luminosity)



Jet launch from a TDE