ANDREJA GOMBOC
CENTER FOR ASTROPHYSICS AND COSMOLOGY
UNIVERSITY OF NOVA GORICA
SLOVENIA

# TIDAL DISRUPTION EVENTS

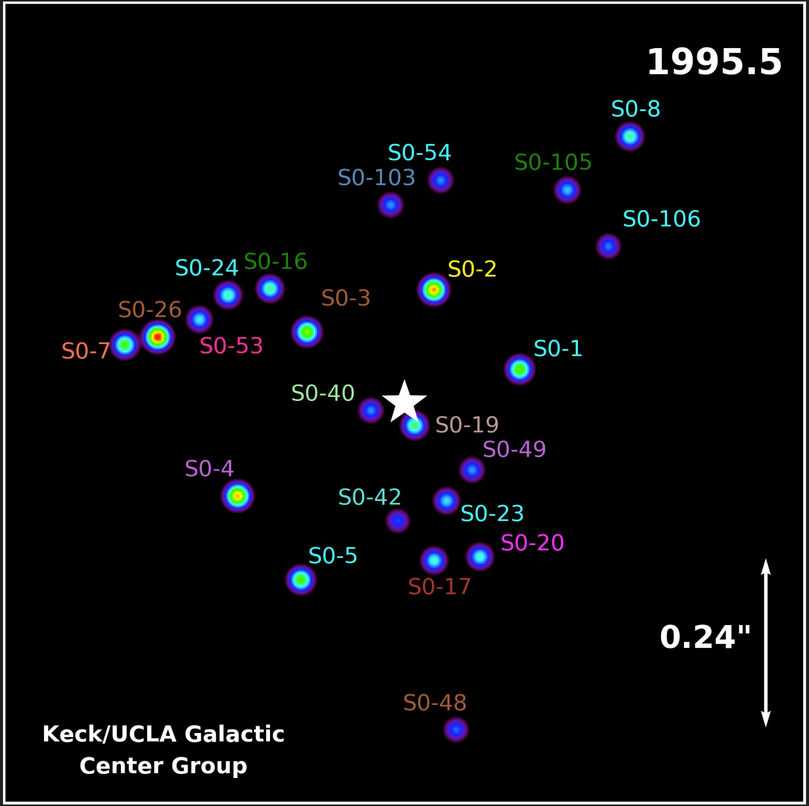
The Restless Nature of AGN: 10 years later

Naples, June 29th, 2023

# TIDAL BREAK-UP OF STARS

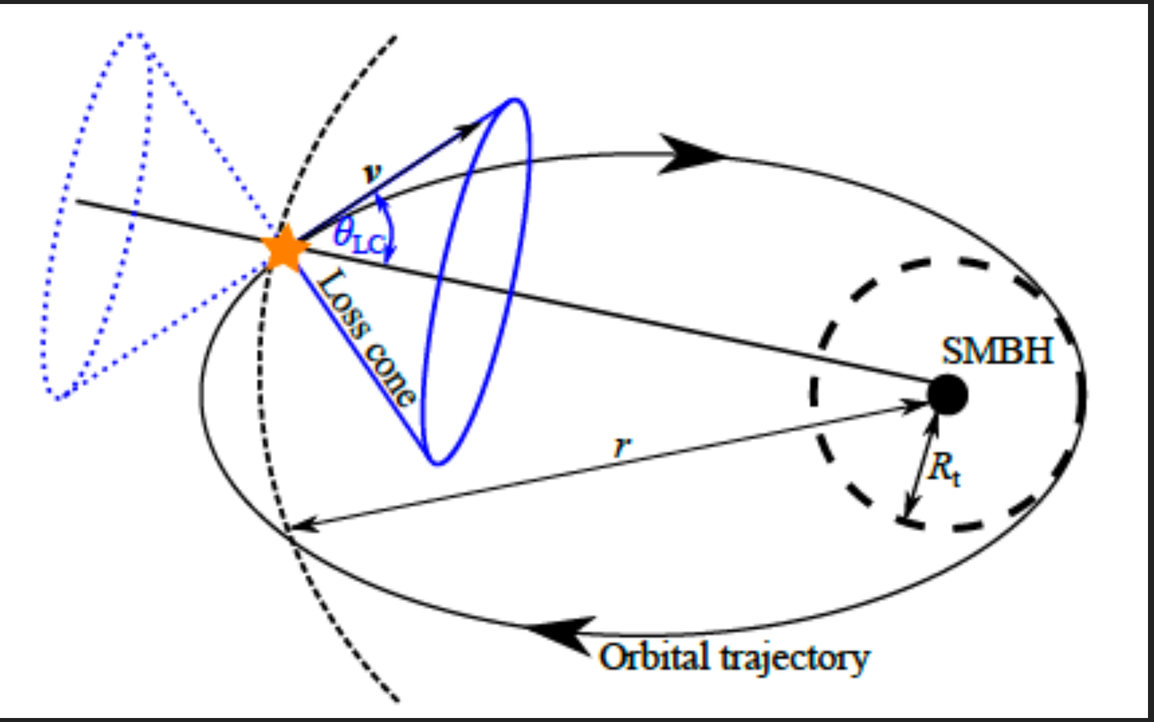
- Hills 1975, 1978:*"tidal breakup of stars…may explain… QSOs and the nuclei of Seyfert galaxies."*
- Frank&Rees 1976, Frank 1978
- Young, Shields, Wheeler 1977: **rate too low**
- Rees 1988 - TDE flares: reveal non-active MBH?

our Galactic center



# UNFORTUNATE STARS

- orbits shaped by: BH gravitational potential, stellar population, dynamical scattering due to interactions with other stellar mass objects
- lose cone
- repopulation
- different effects:
  - two-body relaxation
  - resonant relaxation
  - non-spherical galactic nuclei
  - nuclear stellar disc
  - nuclear bars
  - binary MBHs
  - stellar binary TDEs
  - …




Jankovič 2023, Merritt 2013

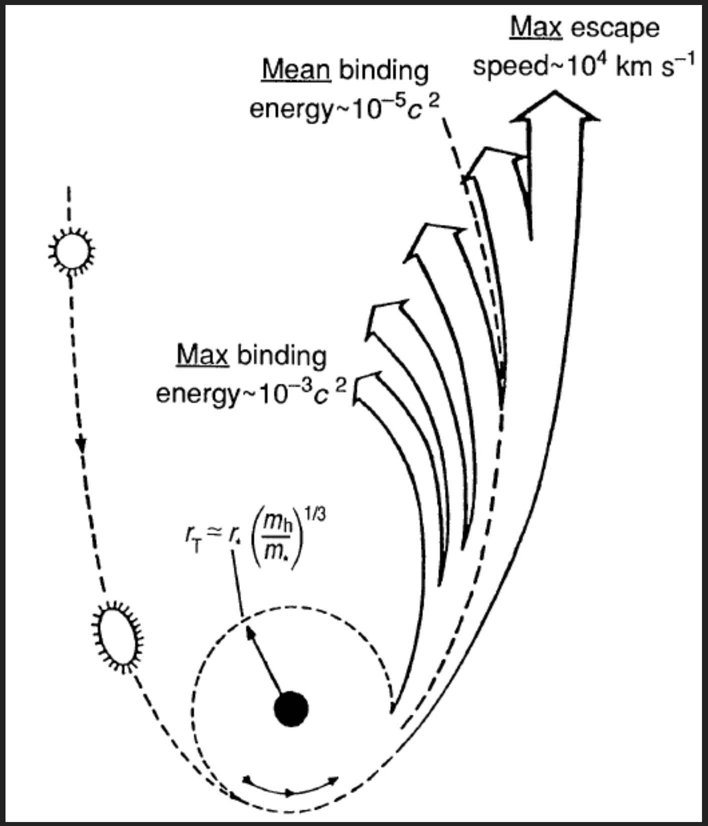
# BASIC PICTURE

- tidal radius: $r_t = R_* \left(\frac{M_{BH}}{M_*}\right)^{1/3}$
- "strength" of encounter - impact parameter

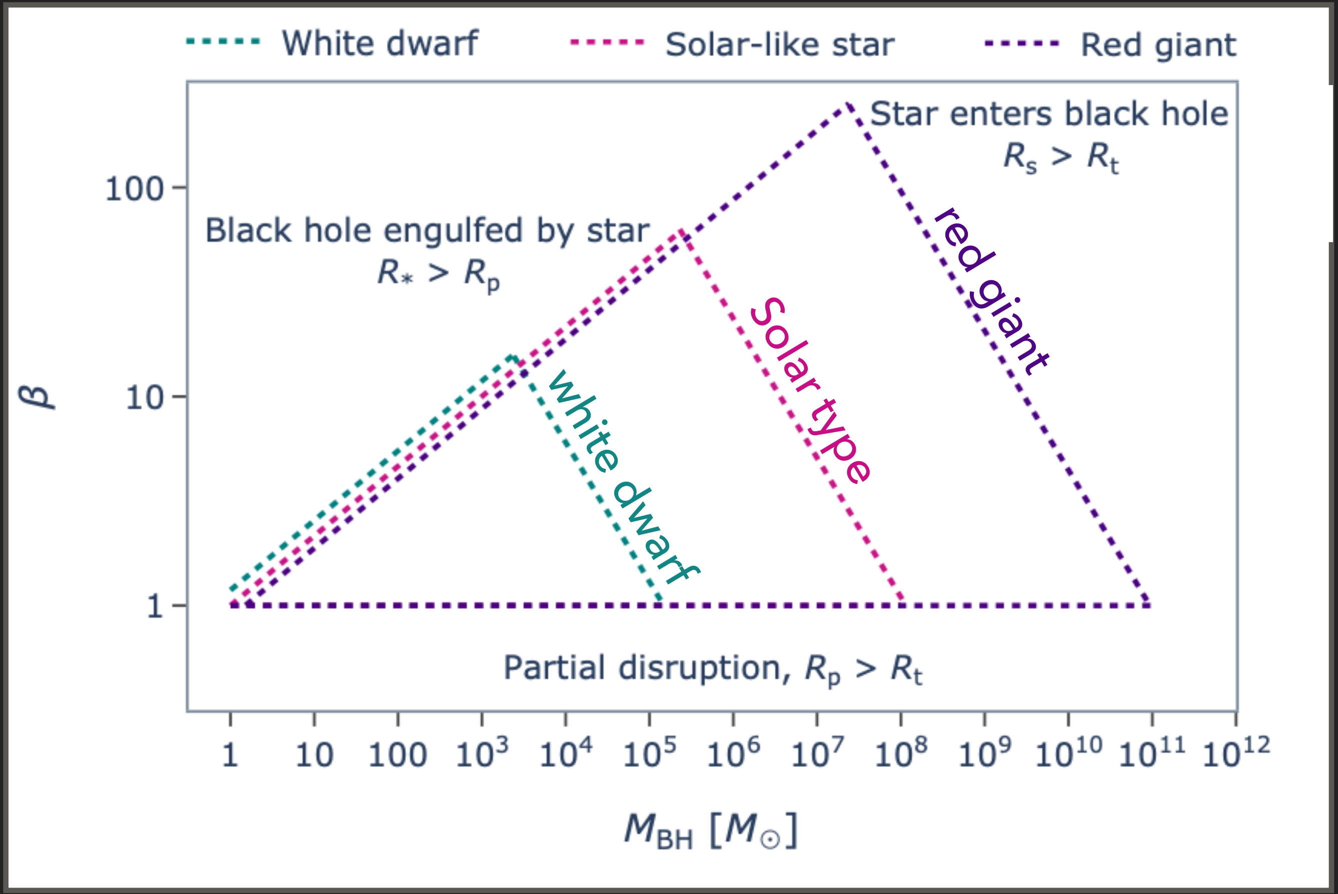
$$\beta = \frac{r_t}{r_p}$$

- $r_p <= r_t$
- $r_p > R_*$
- $r_t > r_{Sch}$

$$r_{Sch} = \frac{2GM_{BH}}{c^2}$$




Rees, 1990




from Bučar Bricman 2021

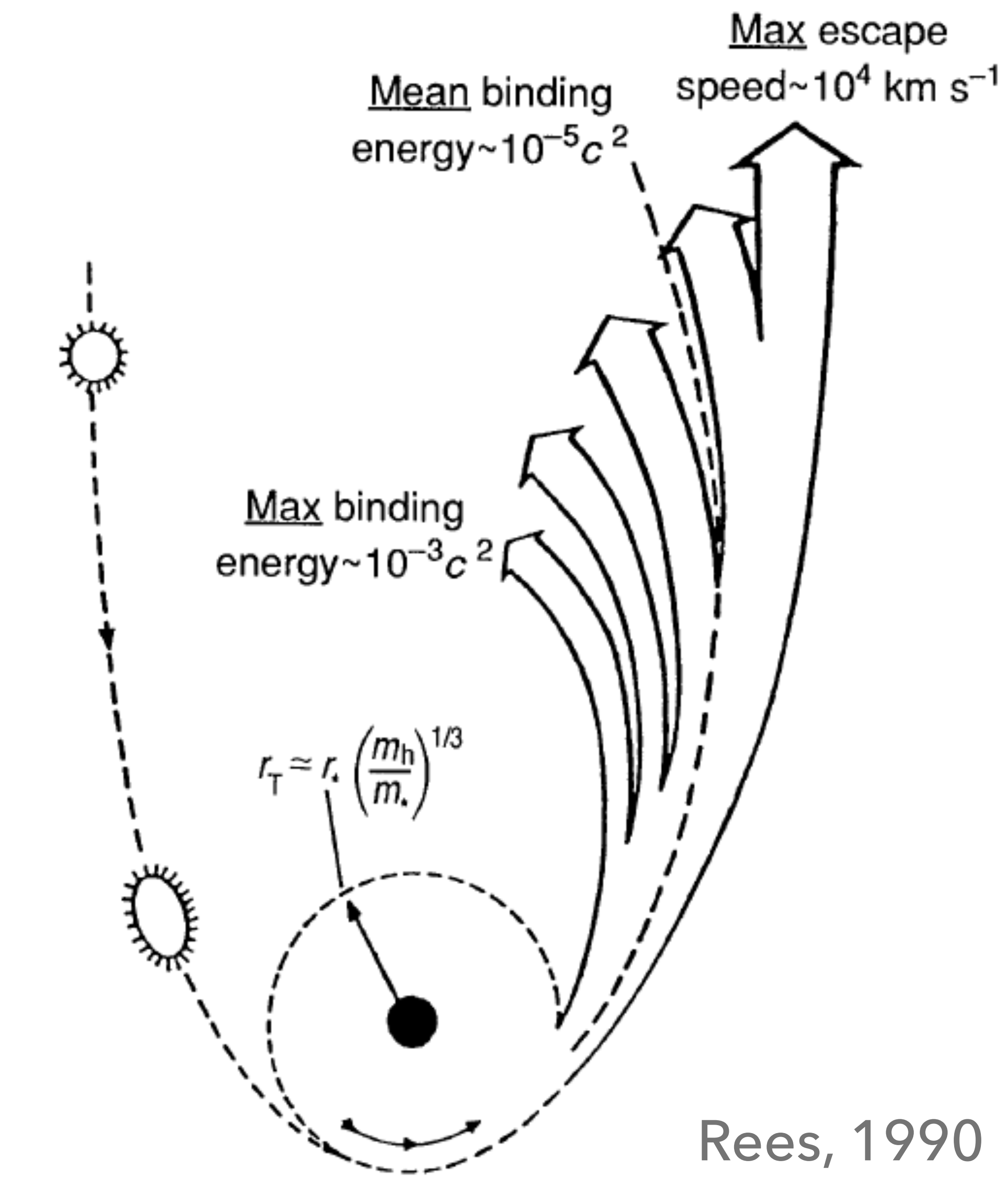
# FALLBACK RATE

- Rees 1988
- parabolic orbit, non-rotating BH
- 3rd Kepler's law $\epsilon = -\frac{1}{2}\left(\frac{2\pi G M_{\rm BH}}{t}\right)^{2/3}$
- flat E distribution
- fallback rate:

$$\frac{{\rm d}m}{{\rm d}t} = \boxed{\frac{{\rm d}m}{{\rm d}\epsilon}}\frac{{\rm d}\epsilon}{{\rm d}t} = \frac{1}{3}(2\pi G M_{\rm BH})^{2/3}\frac{{\rm d}m}{{\rm d}\epsilon}t^{-5/3}$$

- luminosity follows the fallback rate:

$$L \propto \dot{M}_{\rm fallback} \propto t^{-5/3}$$

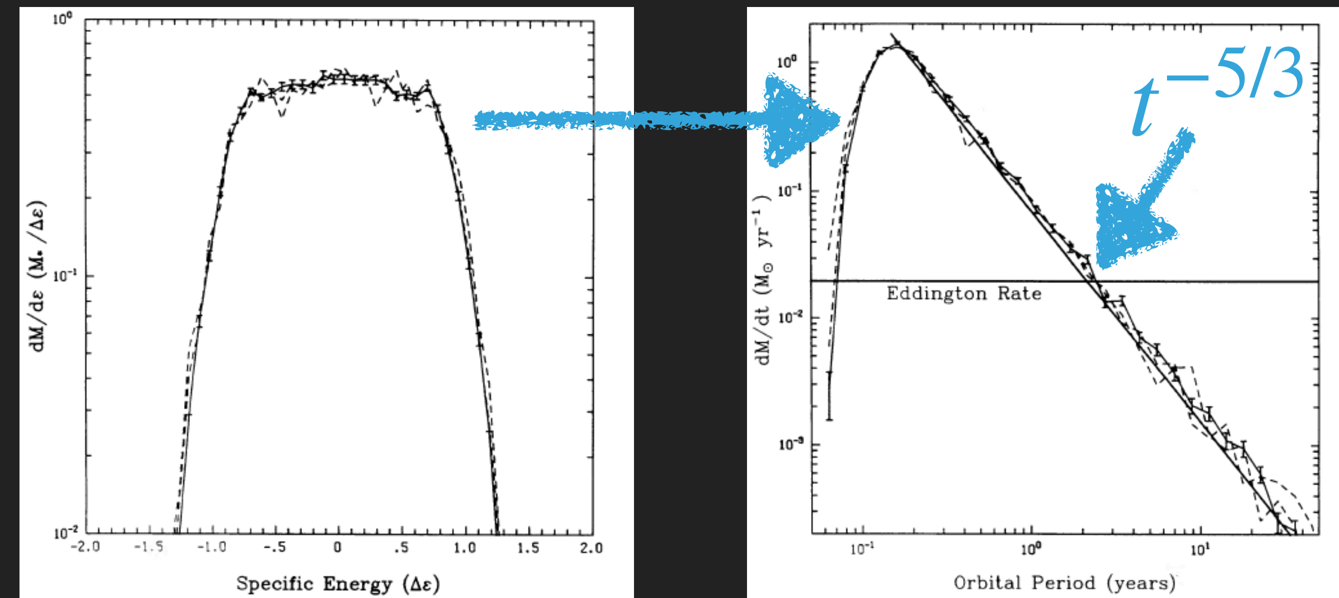



Rees, 1990

# MASS FALLBACK RATE

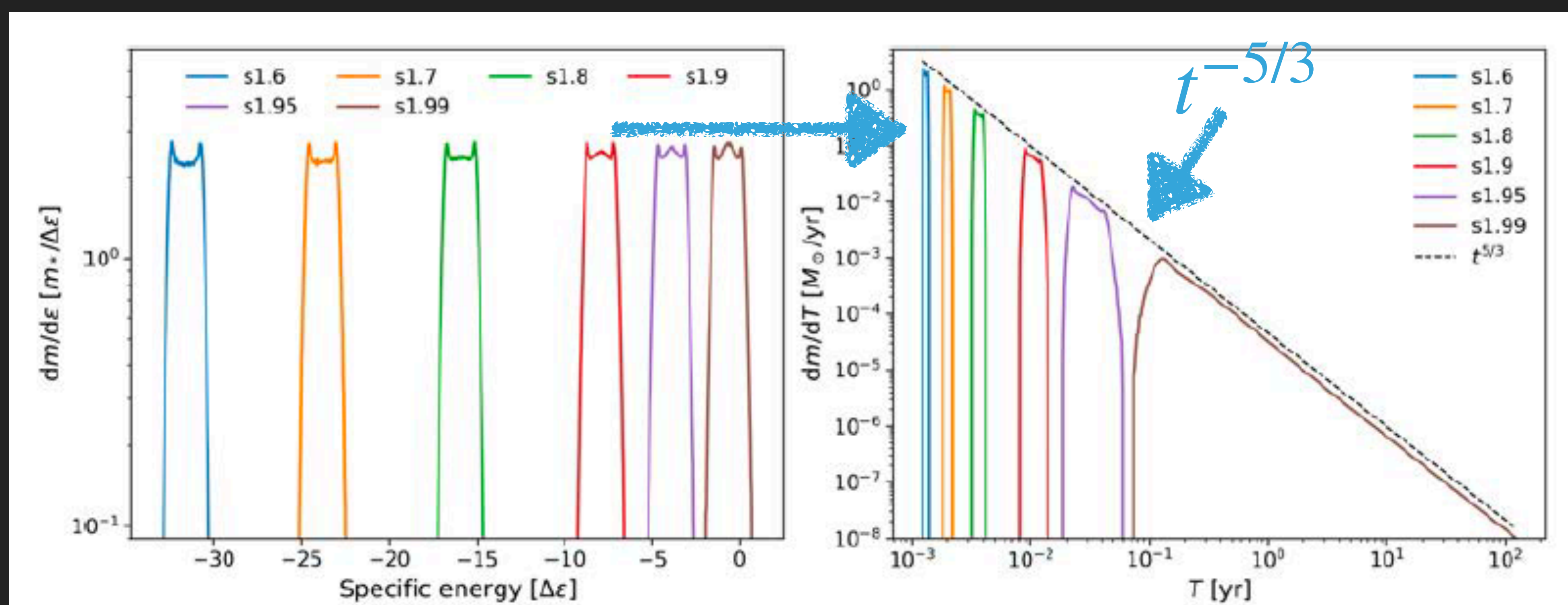
- mass fallback rate set by dM/dE (frozen in approximation)

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \boxed{\frac{\mathrm{d}m}{\mathrm{d}\epsilon}}\frac{\mathrm{d}\epsilon}{\mathrm{d}t} = \frac{1}{3}(2\pi G M_{\mathrm{BH}})^{2/3}\frac{\mathrm{d}m}{\mathrm{d}\epsilon}t^{-5/3}$$




Evans & Kochanek 1989

PHANTOM, generalized post-Newtonian potential, polytrope 5/3, Solar type star, beta=1, varying e

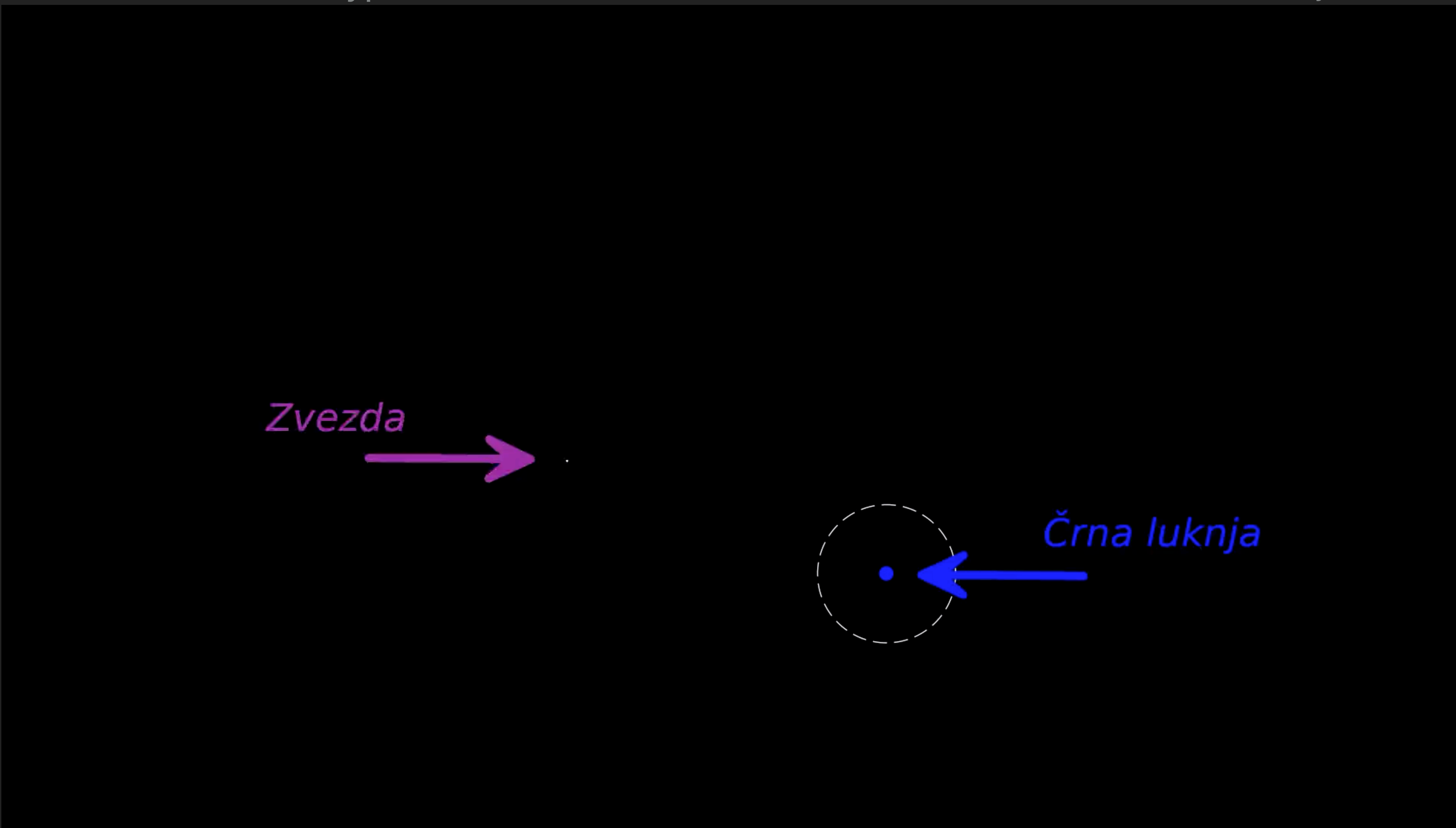



Clerici 2020

- late-time fallback rate $t^{-5/3}$ for full disruptions, but not partial

PHANTOM, Solar type star, e=1, beta=7

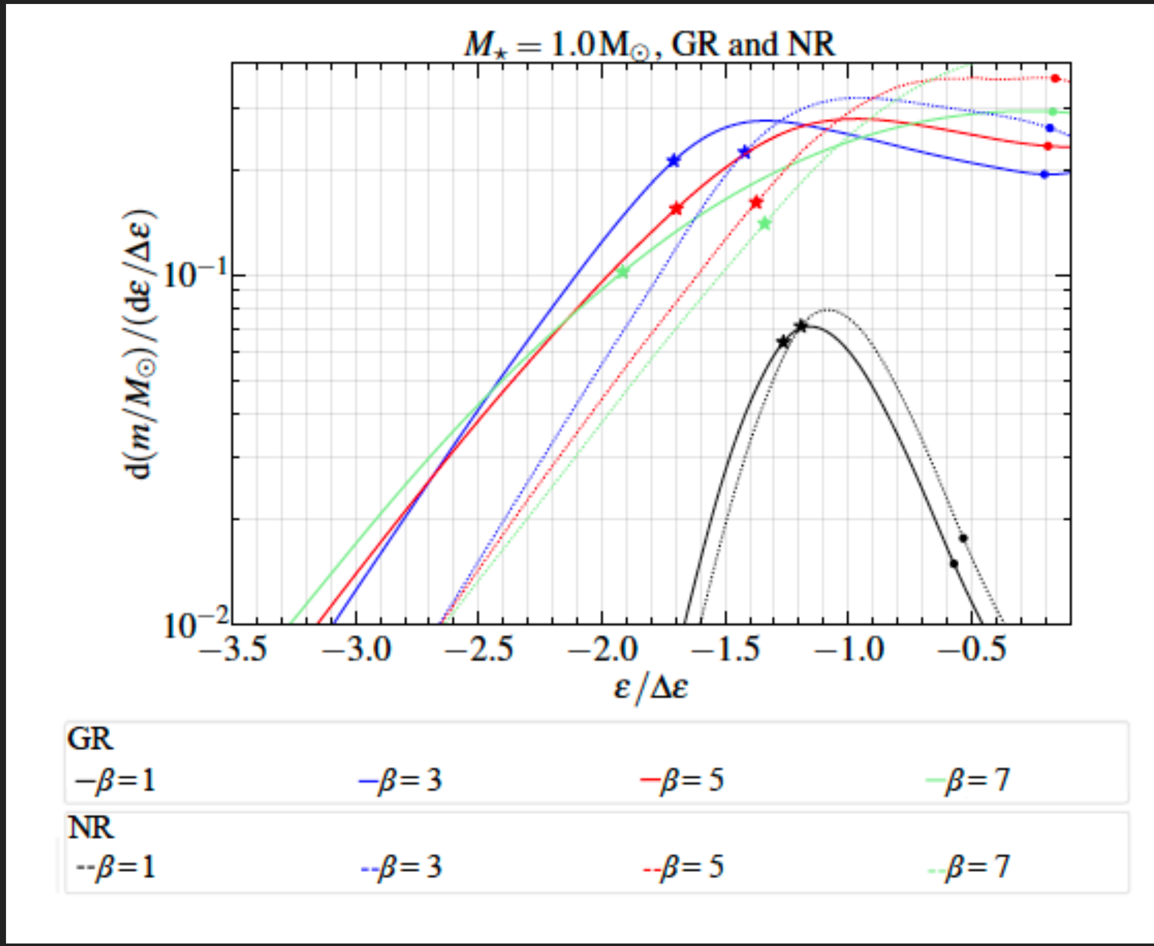
Taj Jankovič

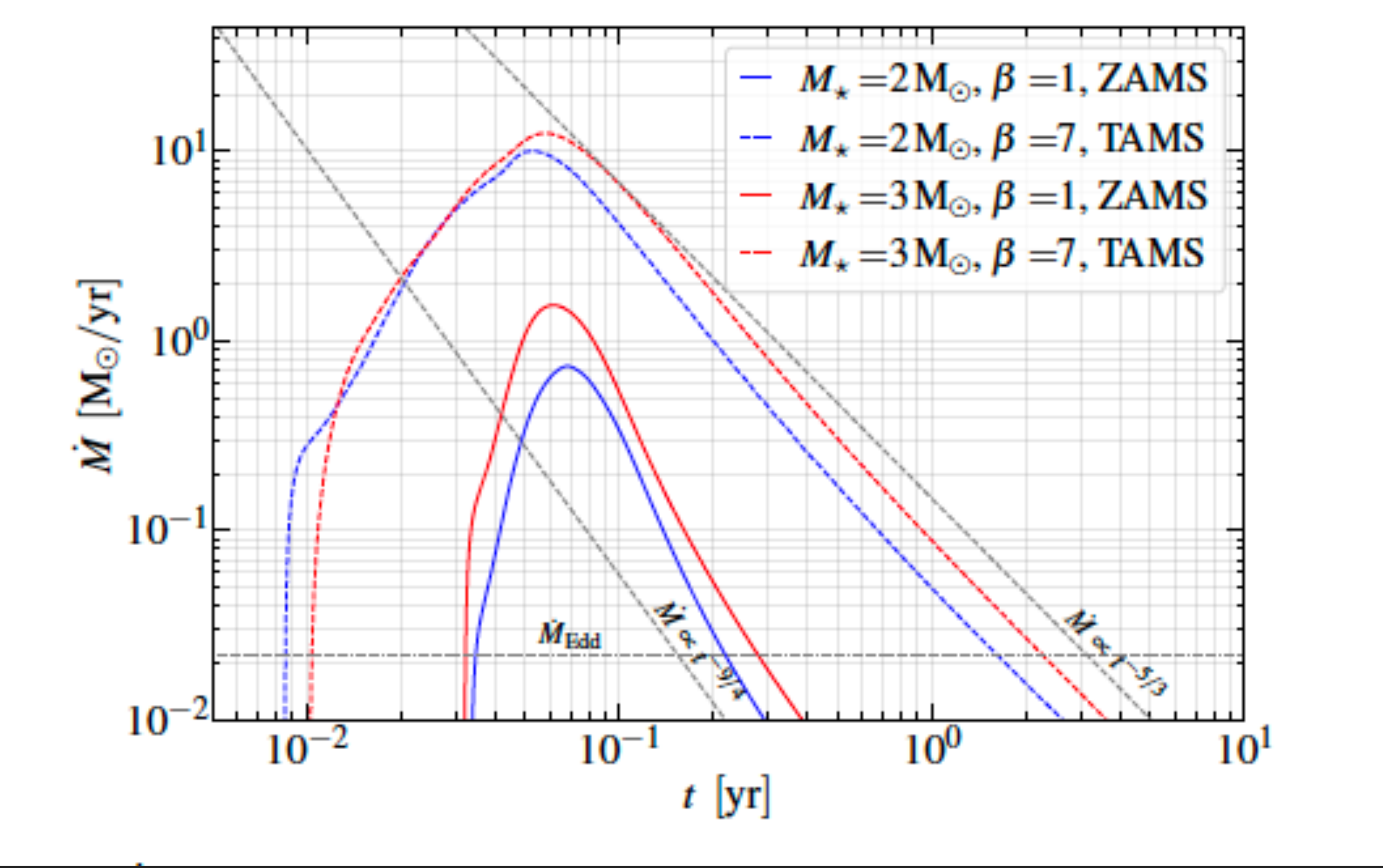


# FALL BACK RATE

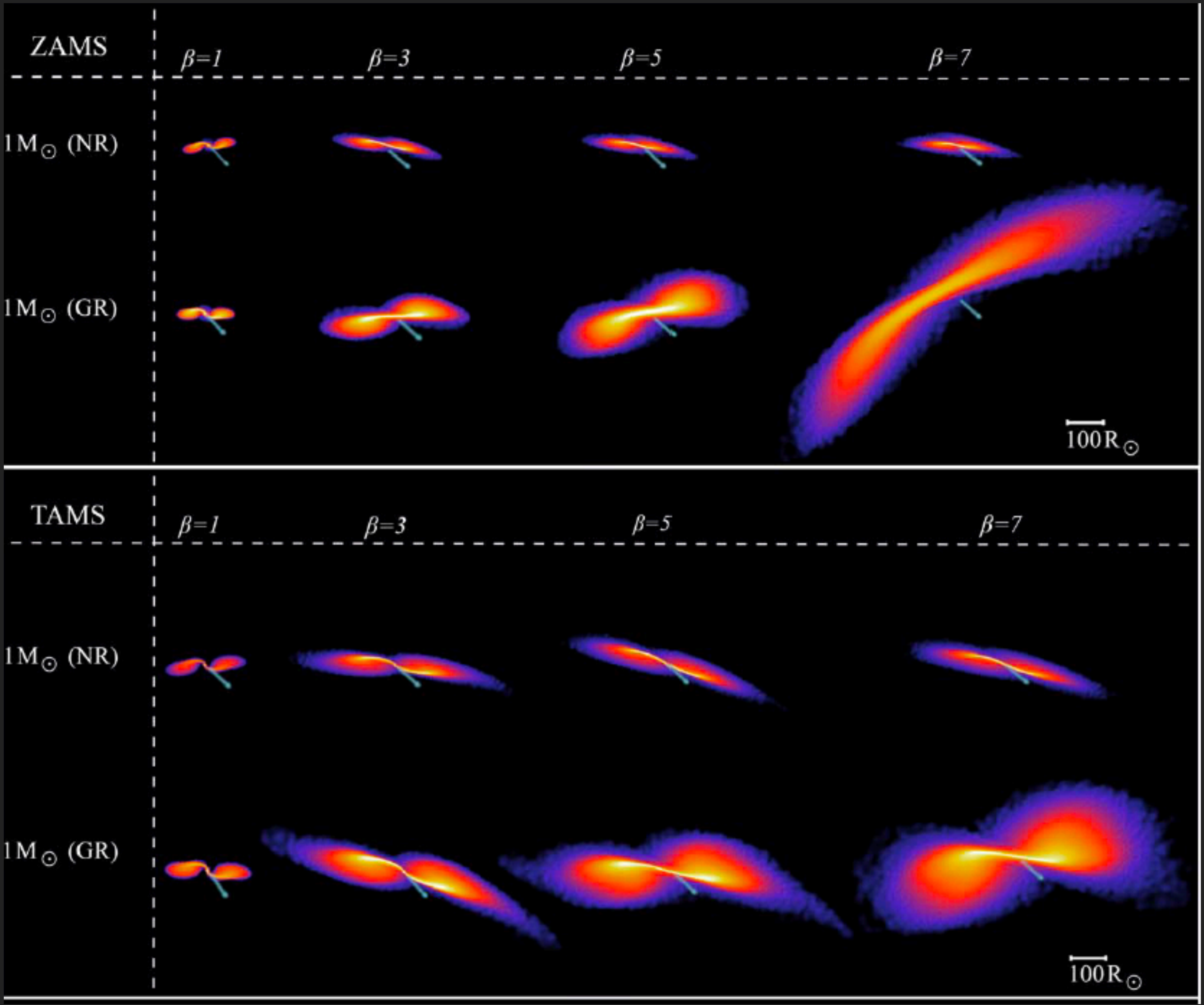

Taj Jankovič

- Jankovič & Gomboc, 2023
- SPH code PHANTOM (Price)
- stellar type, age - MESA (Paxton et al. 2011)
- GR, BH spin, varying mass & age, parabolic orbit, beta

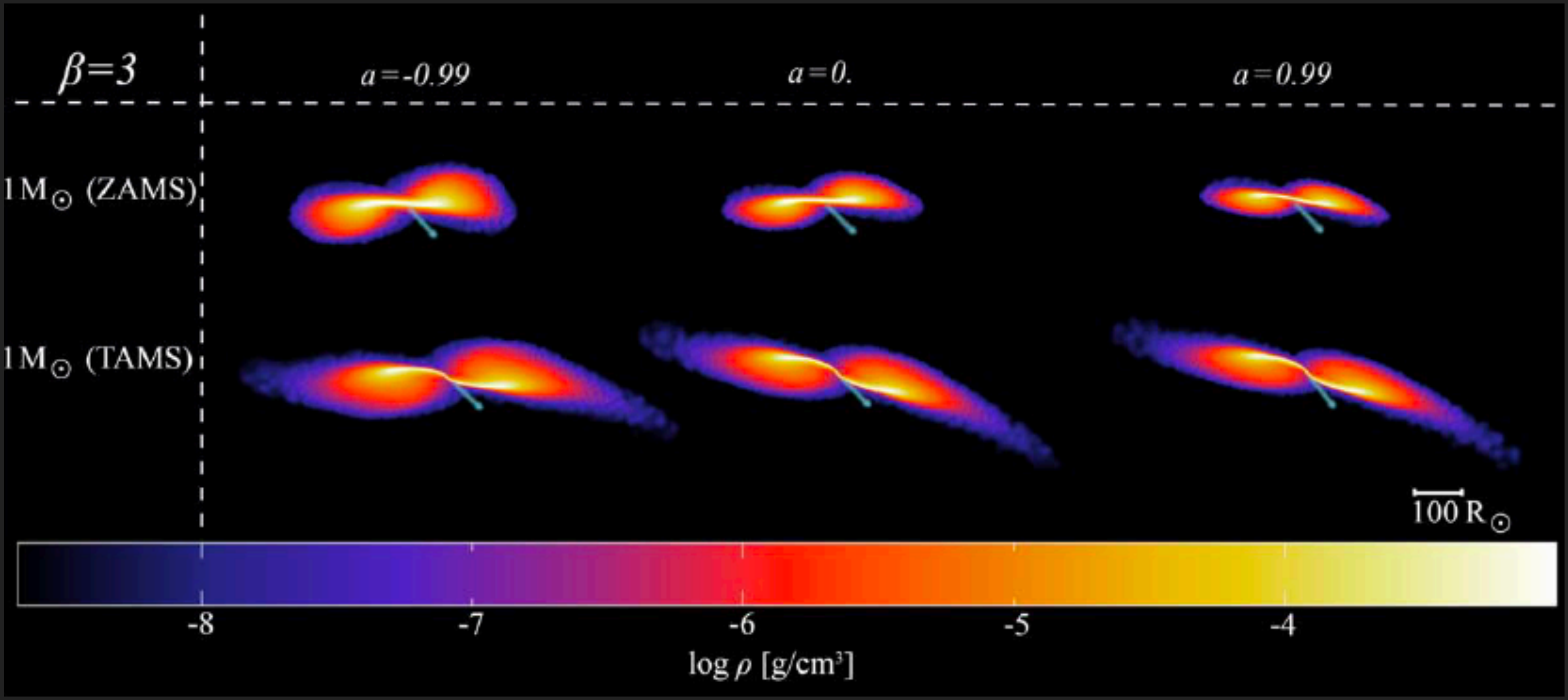


# GR VS. NEWTONIAN

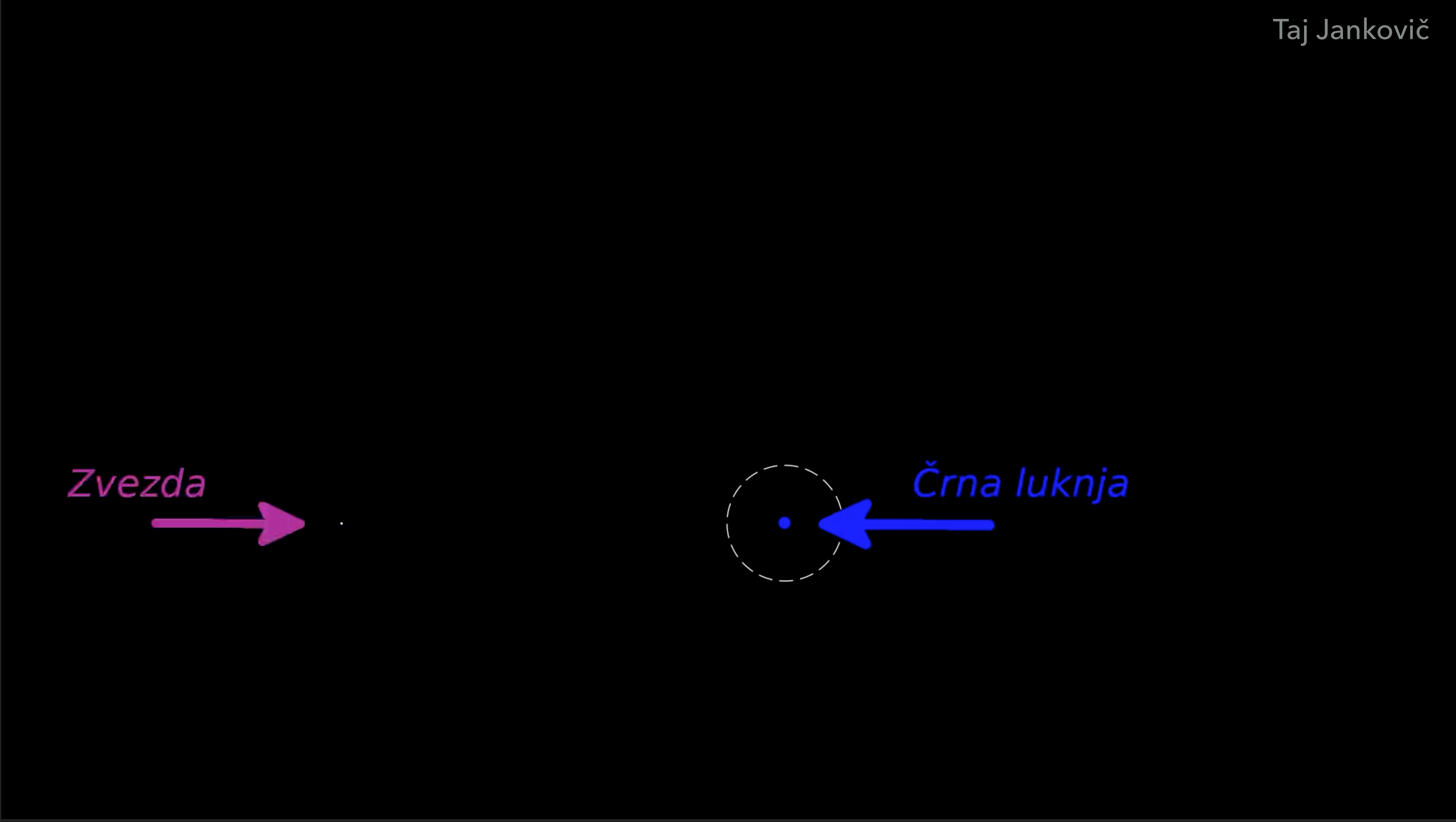


# BLACK HOLE SPIN

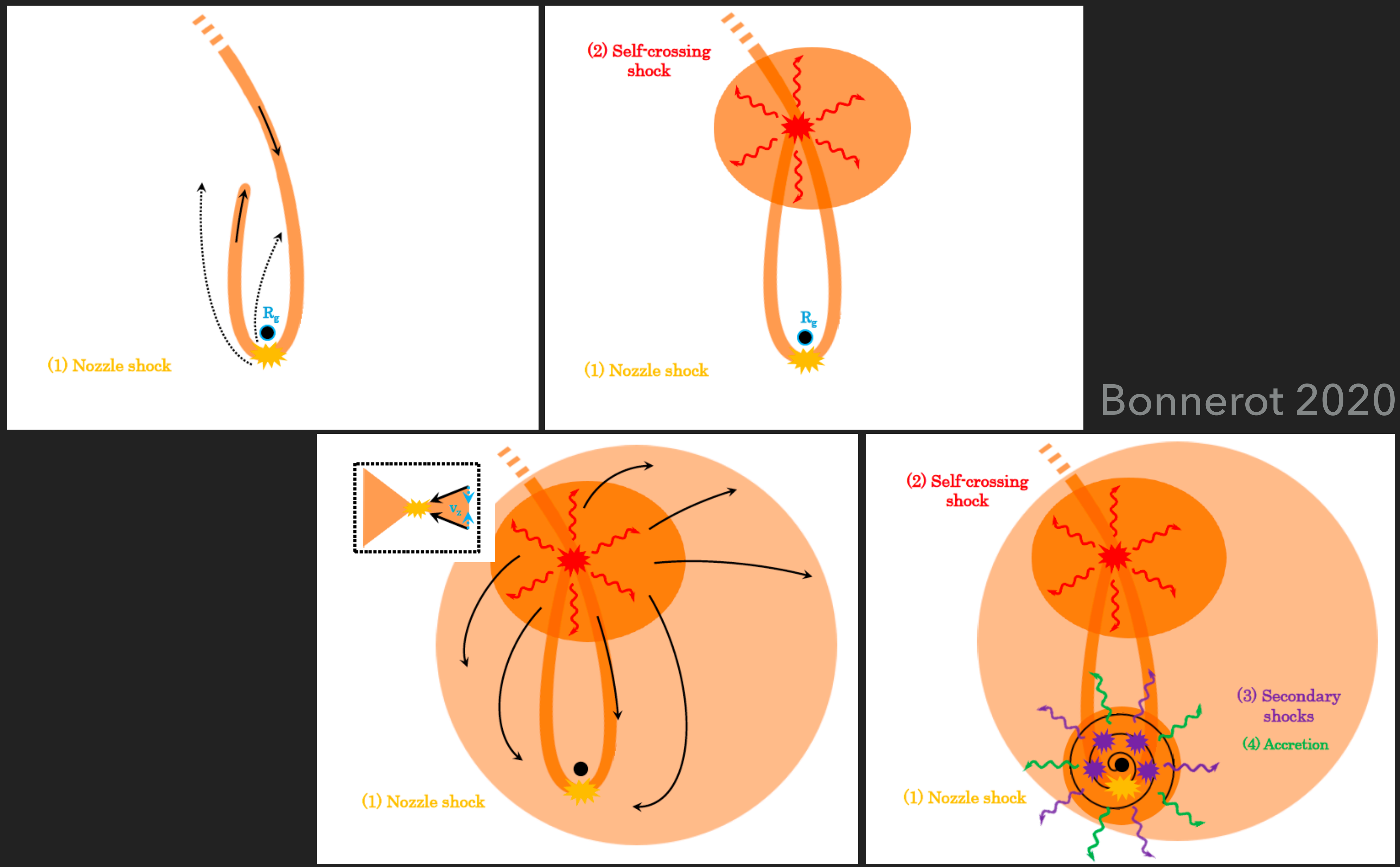


# SELF-CROSSING AND DEBRIS CIRCULARIZATION

PHANTOM, Solar type star, e=0.95, beta=5



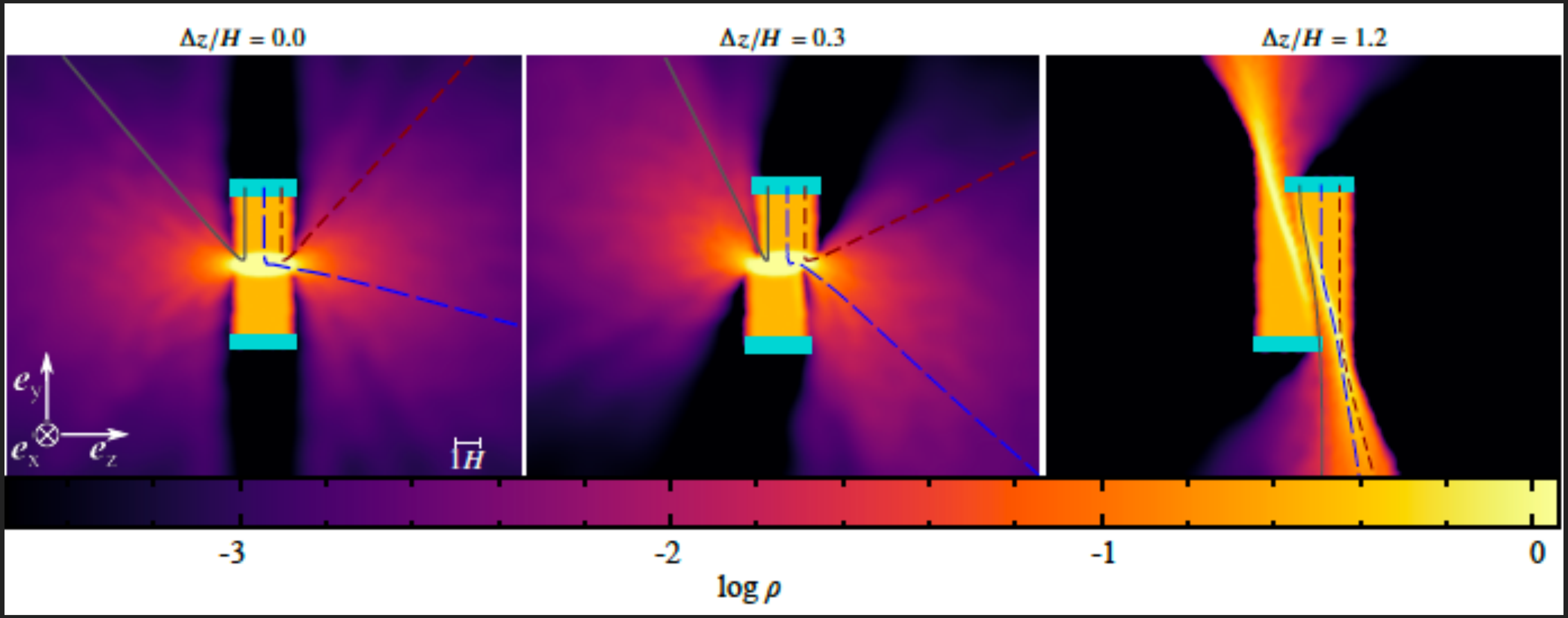
# DEBRIS CIRCULARIZATION




Bonnerot 2020

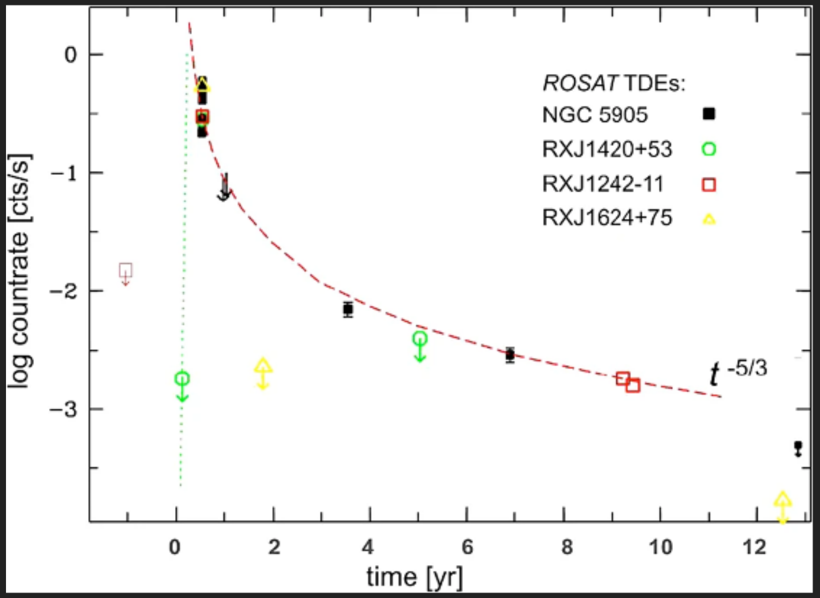
# SPIN AND SELF CROSSING

Jankovič, Bonnerot, Gomboc: arXiv 2303.16230

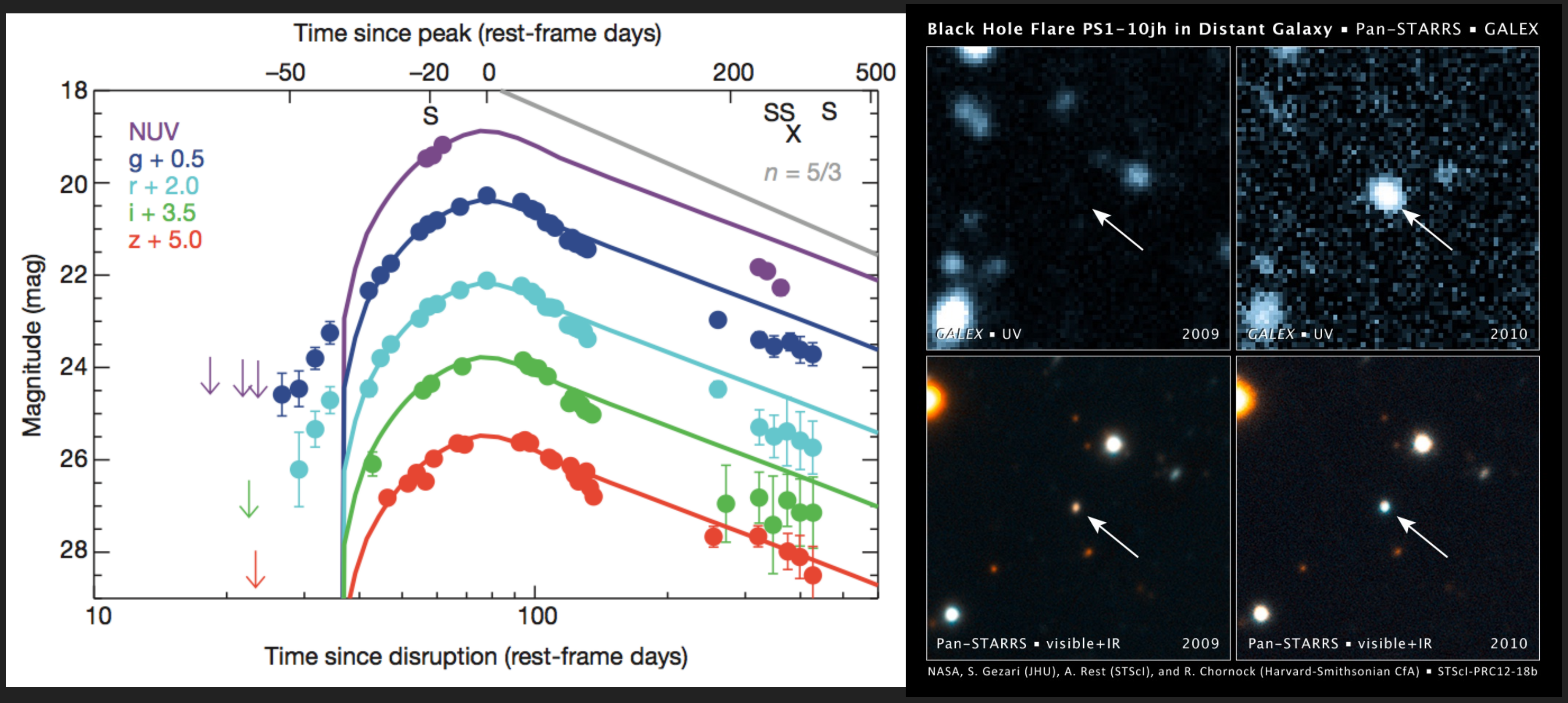


# OBSERVATIONS

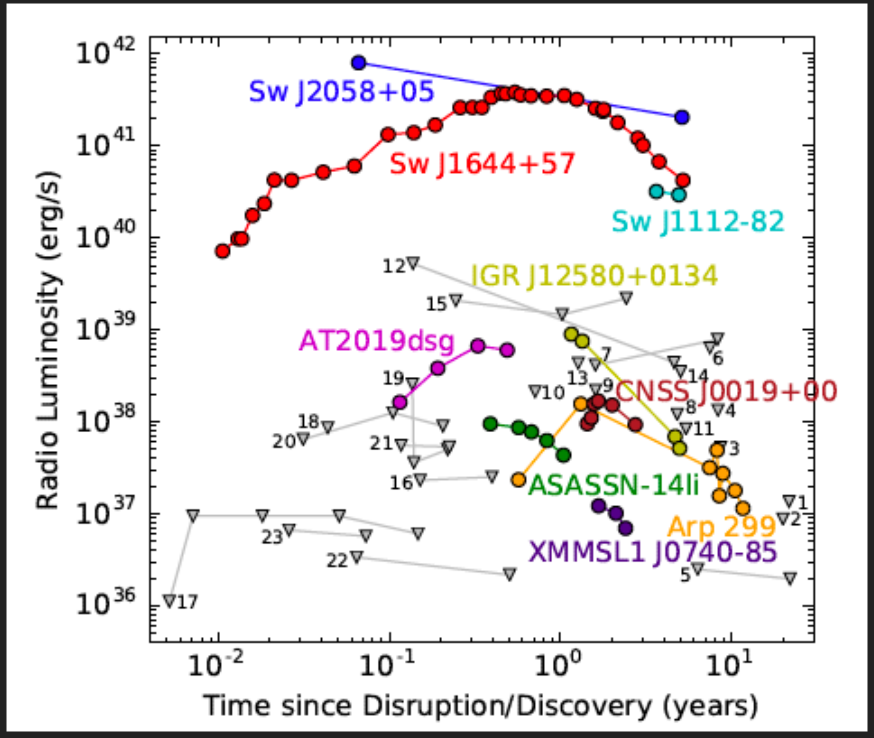
Komossa 2004




- X-ray flares - ROSAT all-sky survey in 1990s
- UV/optical
- radio
- jets




Gezari et al. 2012




Alexander et al. 2020

Hammerstein et al. 2023

# OBSERVATIONS

- nuclear transients, rate ~ 100 $Gpc^{-3}\,yr^{-1}$,

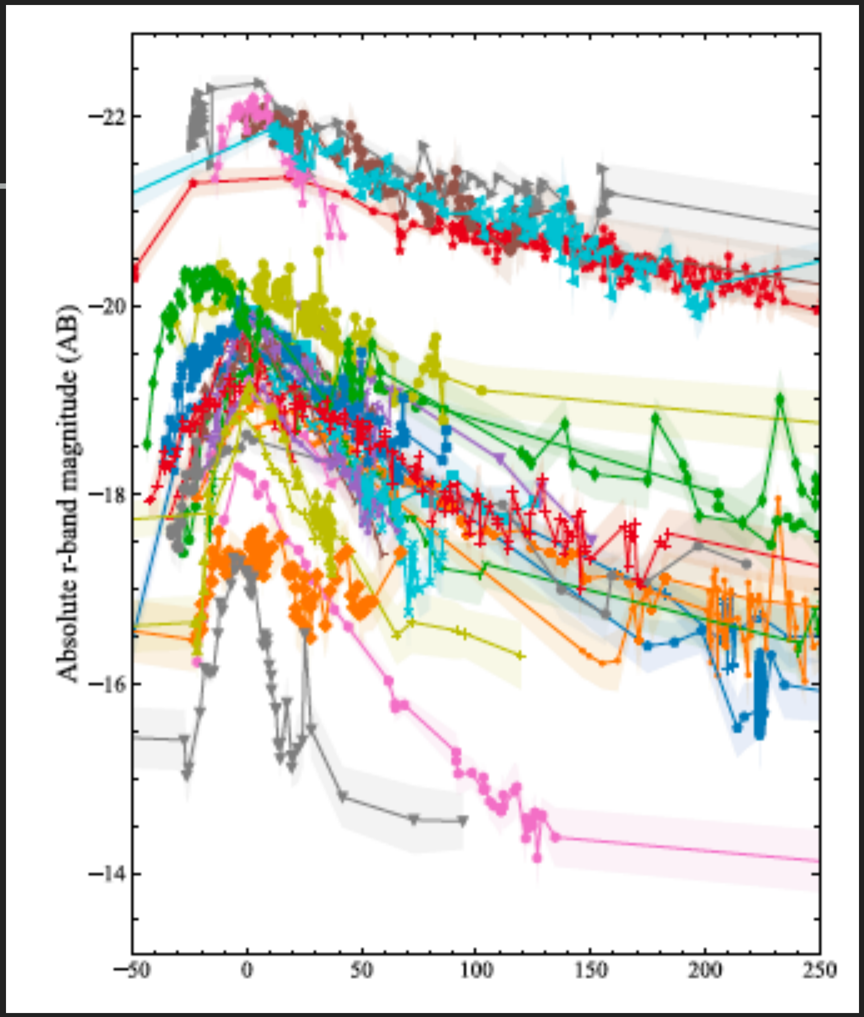
  $10^{-4}$ $galaxy^{-1}\,yr^{-1}$

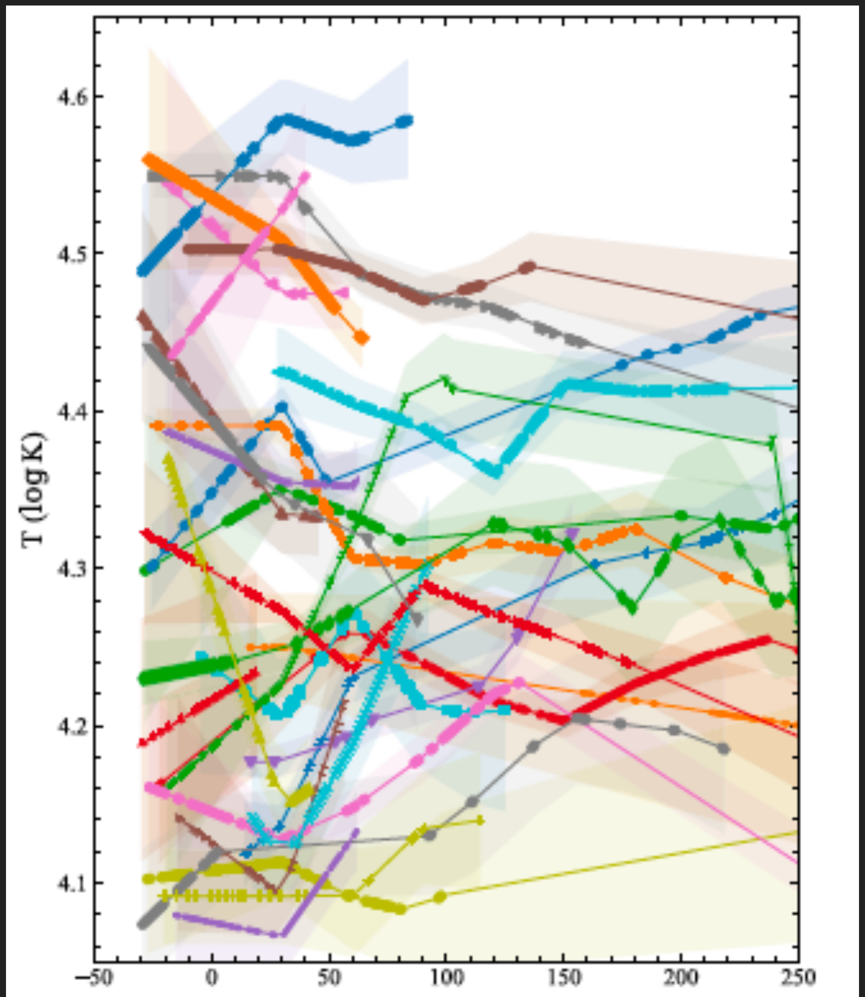
- about 100 TDE candidates (review: van Velzen et al. 2020, Hammerstein et al 2023)

- rise ~month, decay $t^{-5/3}$, UV/opt peak ~ -20 mag

- high black body temperatures (T ~$2.10^4$ K, persists): blue colors

constant blue colors for months after peak are typical for TDEs

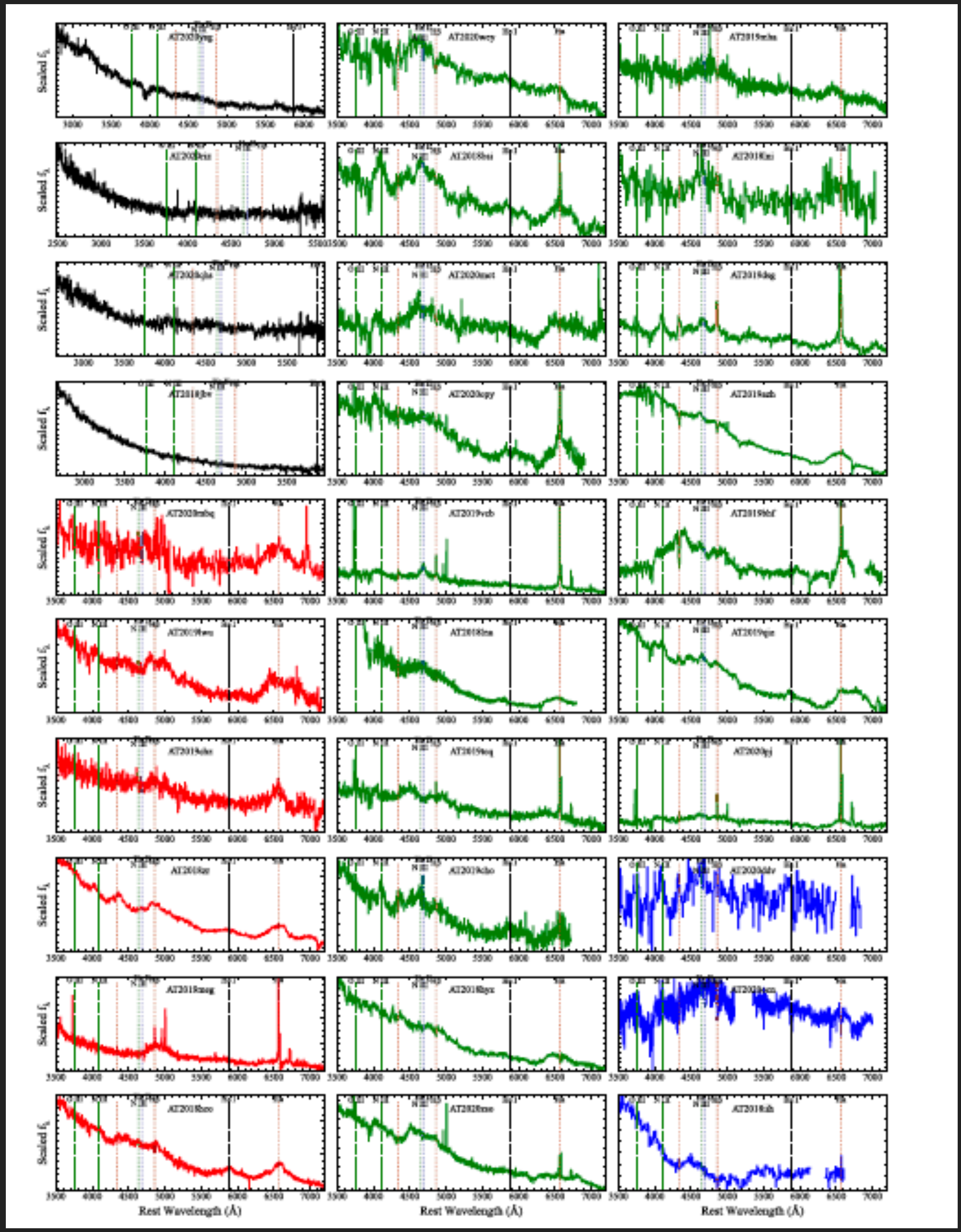


# OPTICAL SPECTRA

- broad emission lines superimposed on a strong and consistent blue continuum
- TDE-H, TDE-He, TDE-H+He, TDE featureless classes
- majority of H+He TDEs show Bowen fluorescence lines

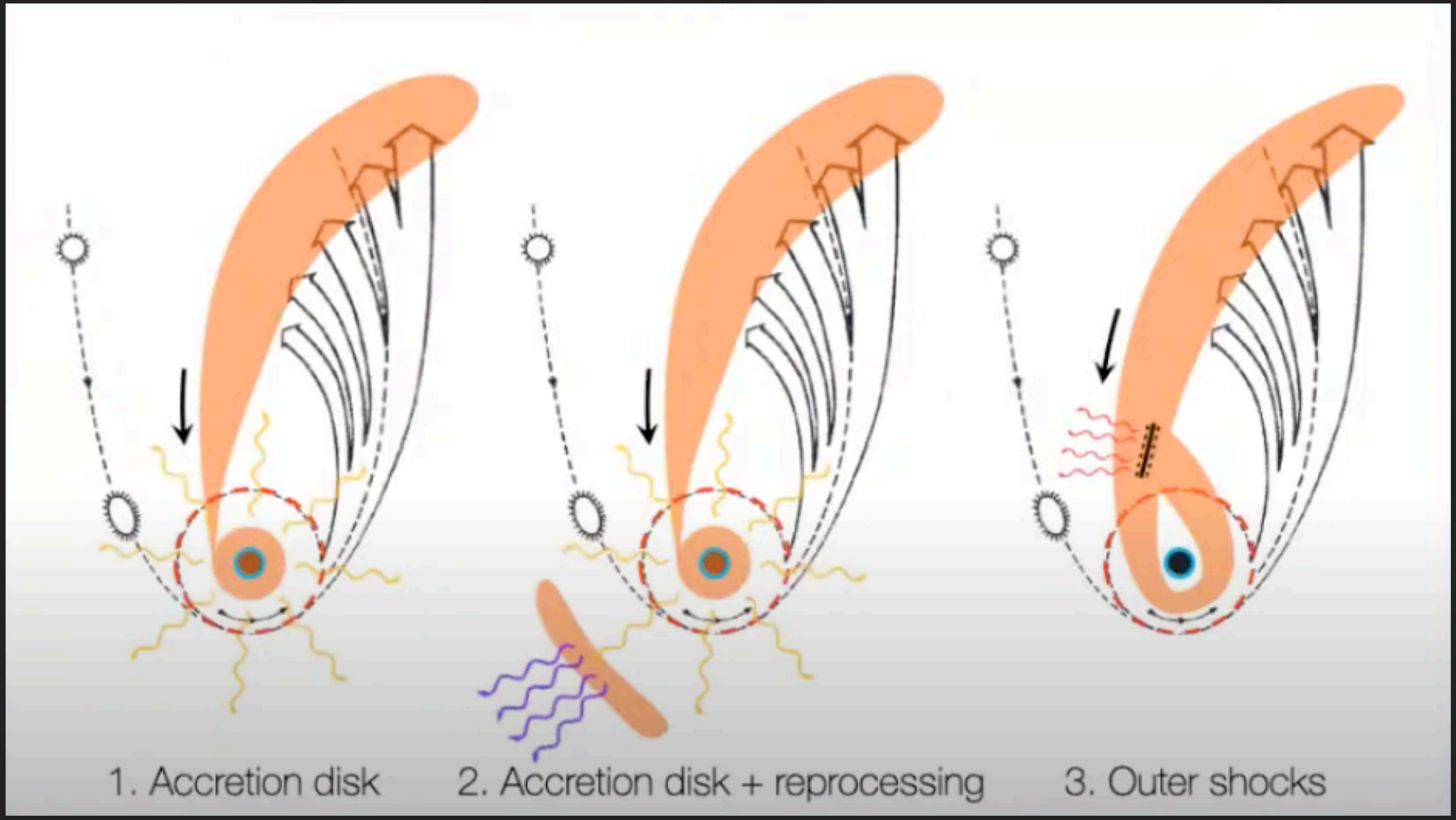
spectra are very important for classification.



Hammerstein et al 2023

# ORIGIN OF THE EMISSION?

- X-ray - disk
- UV/optical?
- reprocessing envelope
- shocks
- outflow



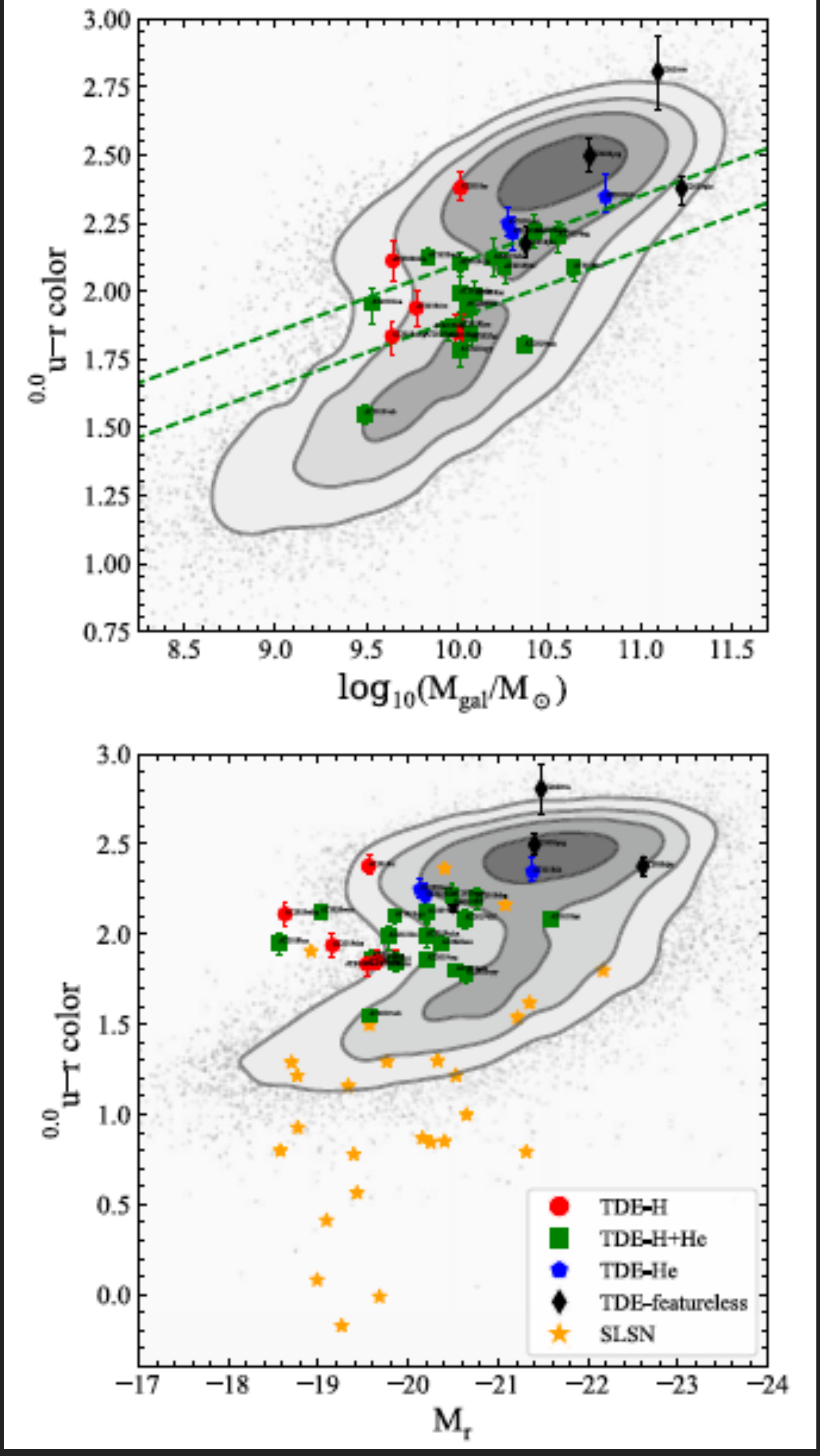

Bonnerot

- some TDEs are bright in UV/optical and not in X-rays (and vice versa)
- some are bright in UV/optical and in X-rays
- some TDEs show variability in X-rays and a smooth power-law in UV/optical

Hammerstein et al 2023

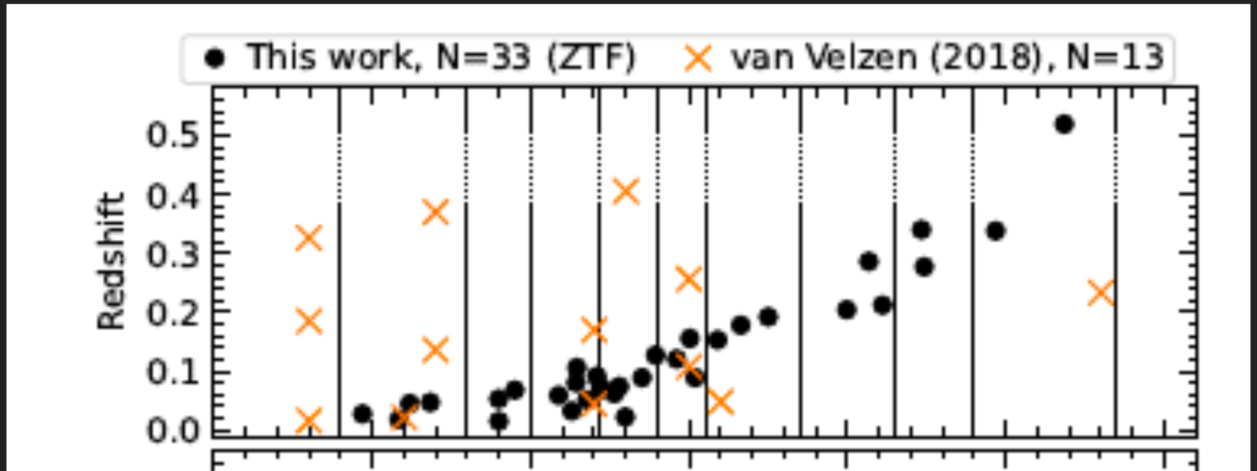
# HOST GALAXIES

- preference for Quiescent Balmer Strong (QBS) galaxies and their subset of post-starburst E+A galaxies
- located in the green-valley
- TDEs occur in other galaxies as well




redshift:

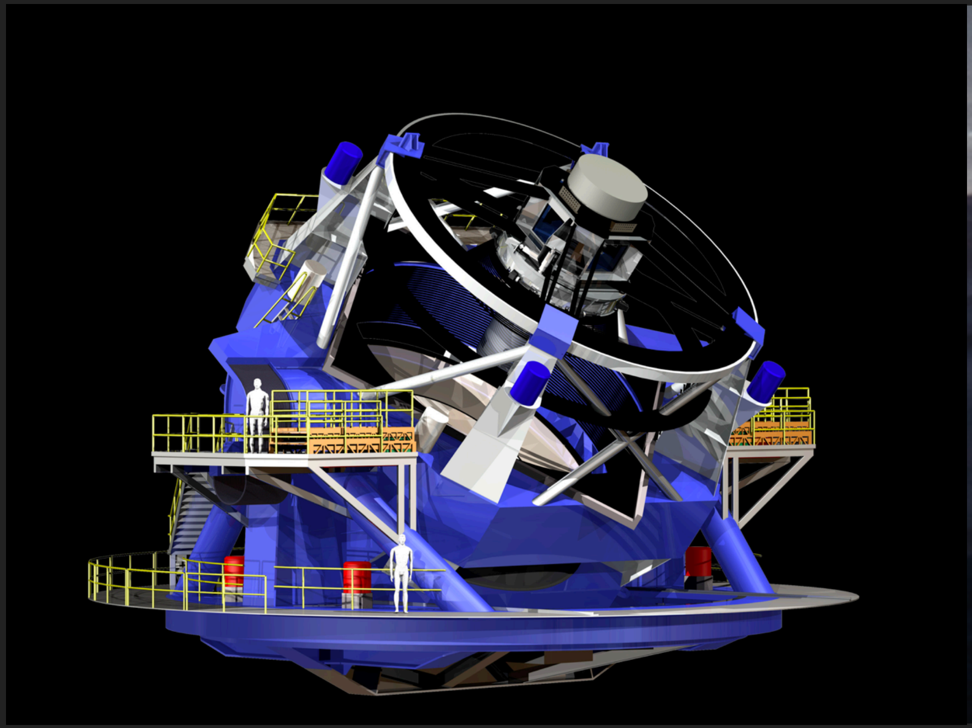
Yao et al 2023

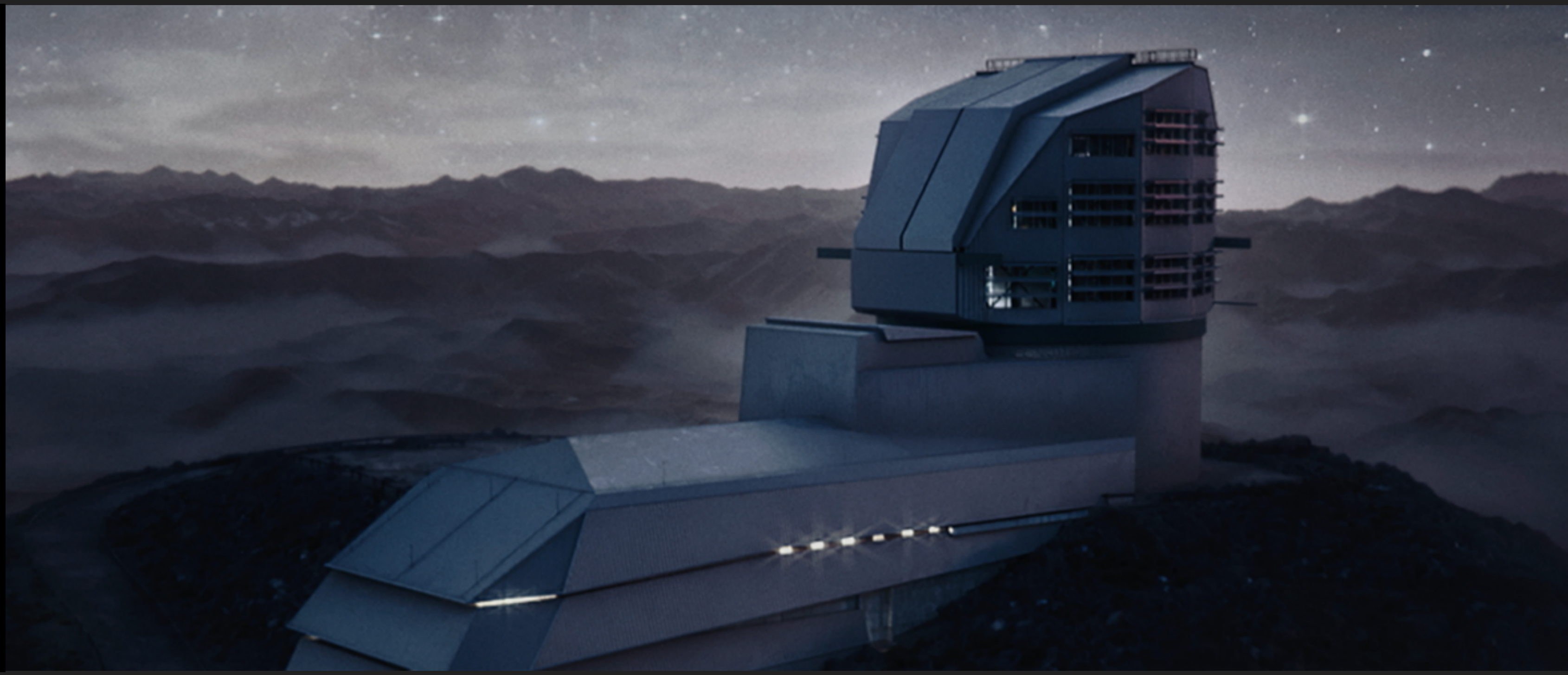


# VERA C. RUBIN OBSERVATORY LEGACY SURVEY OF SPACE AND TIME - RUBIN LSST

Cerro Pachon, Chile,
8,4-m telescope
10-year survey
u, g, r, i, z, y
limiting magnitude r~24.5 in a single exposure
r~27.5 coadded

Vera Rubin
(1928-2016)





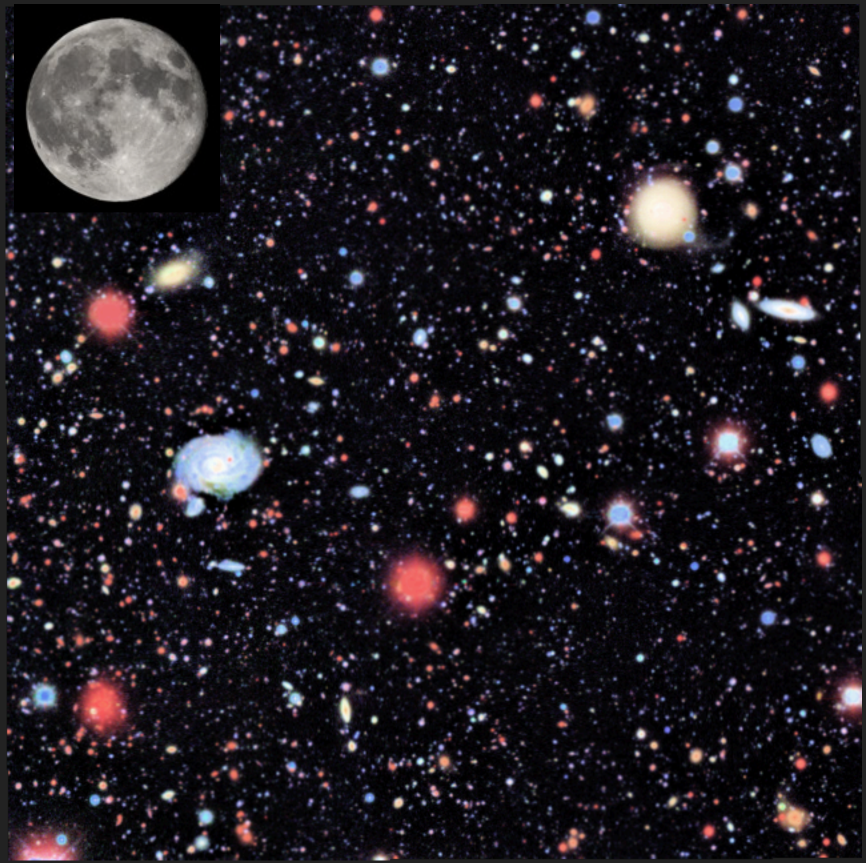
Simonyi Survey Telescope

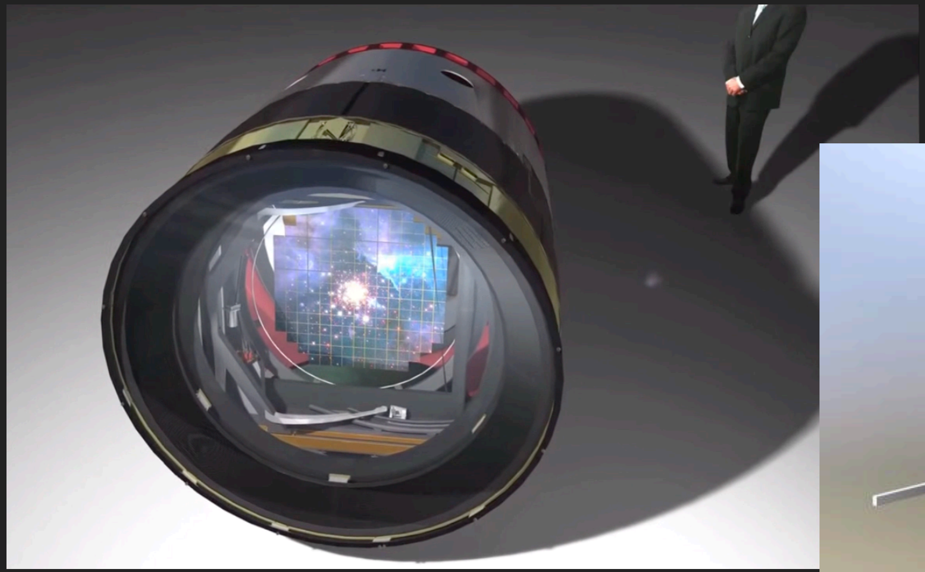
## WIDE-FAST-DEEP

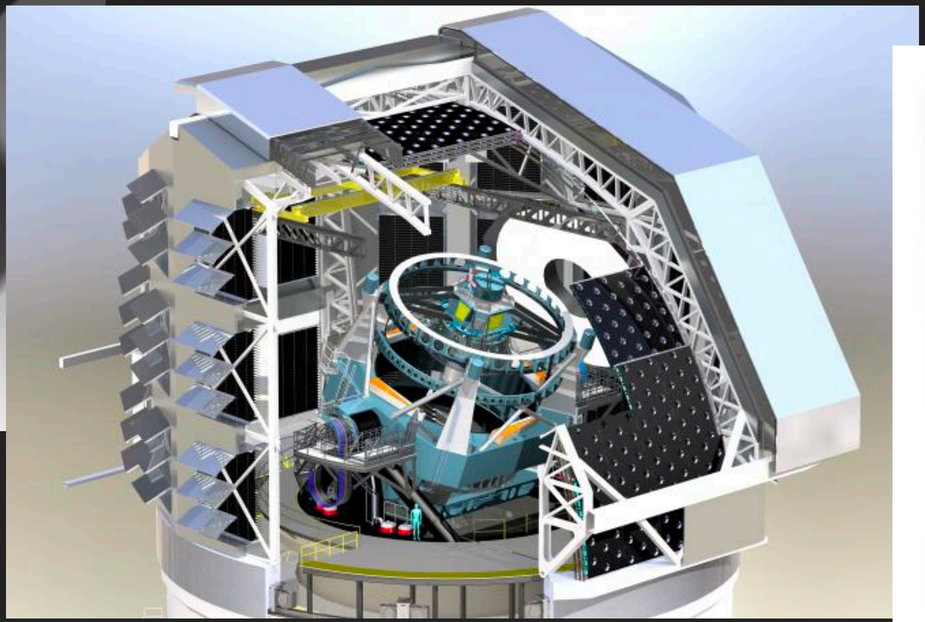
FoV 9.6 deg$^2$ - to cover large areas of sky to faint magnitudes in a short amount of time

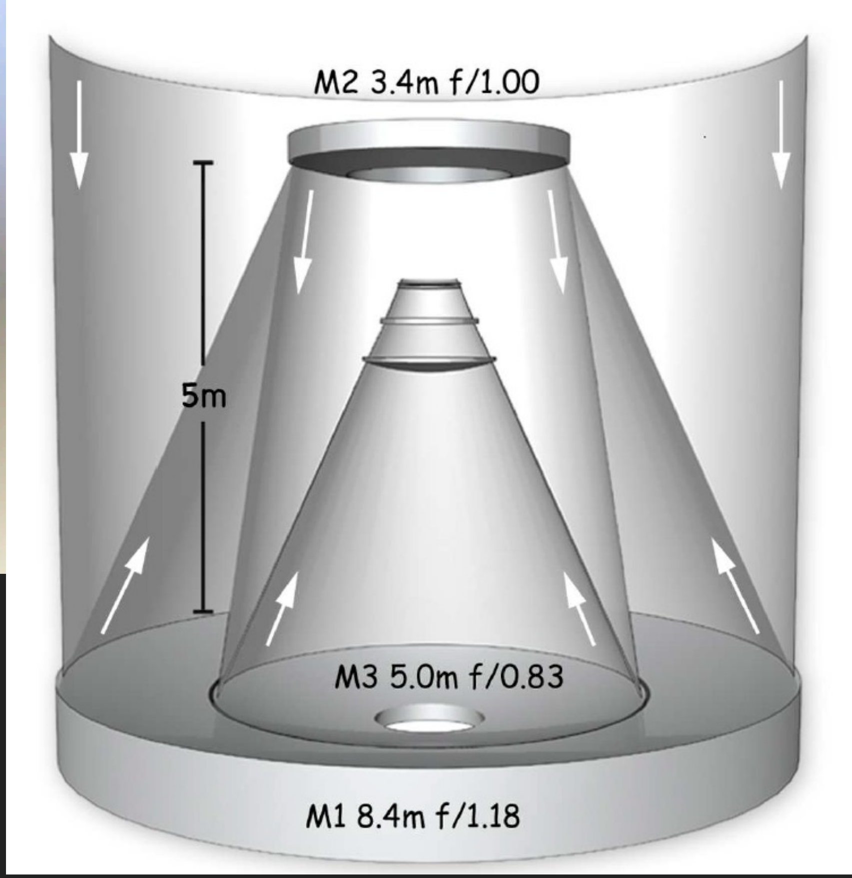
10.000 deg$^2$ /night

3.2 Gigapixels camera









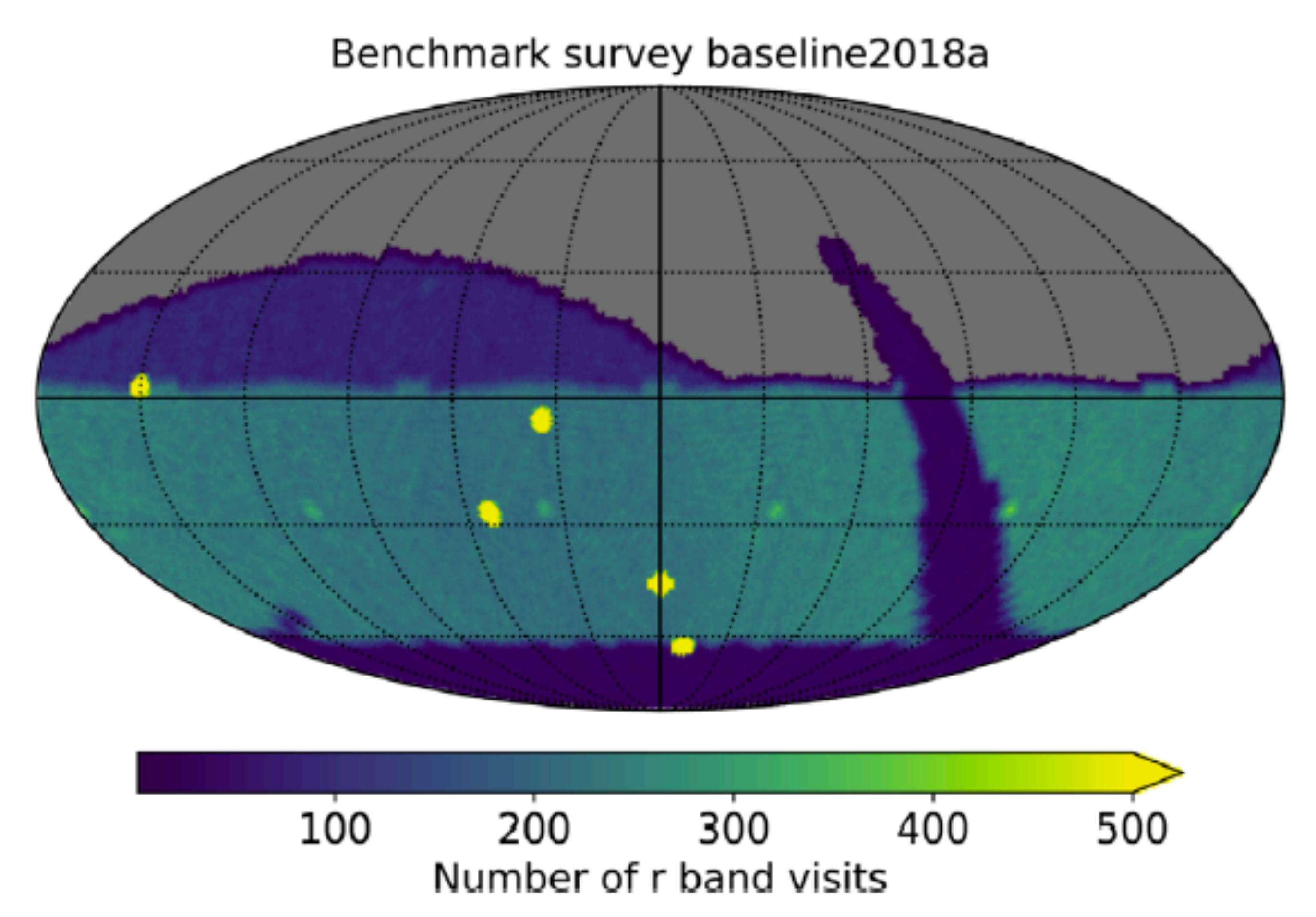

1000 frames/night

about 30-40 TB data/night

in total 500 PB data and data products

# BASELINE OBSERVING STRATEGY

- main "Wide-Fast-Deep" (WFD) survey
- 5 Deep Drilling Field candidate mini surveys
- Galactic Plane candidate mini survey
- North Ecliptic Spur candidate mini survey
- South Celestial Pole candidate mini survey




The LSST Baseline Design and Survey Parameters

| Quantity | Baseline Design Specification |
|---|---|
| Optical config. | Three-mirror modified Paul-Baker |
| Mount config. | Alt-azimuth |
| Final *f*-ratio, aperture | $f/1.234$, 8.4 m |
| Field of view, étendue | 9.6 $deg^2$, 319 $m^2 deg^2$ |
| Plate scale | 50.9 $\mu$m/arcsec (0.″2 pix) |
| Pixel count | 3.2 gigapixels |
| Wavelength coverage | 320–1050 nm, *ugrizy* |
| Single-visit depths, design[a] | 23.9, 25.0, 24.7, 24.0, 23.3, 22.1 |
| Single-visit depths, min.[b] | 23.4, 24.6, 24.3, 23.6, 22.9, 21.7 |
| Mean number of visits[c] | 56, 80, 184, 184, 160, 160 |
| Final (co-added) depths[d] | 26.1, 27.4, 27.5, 26.8, 26.1, 24.9 |

Ivezić et al 2019

~ 825 visits/field

1-10 million time-domain alerts/night

# PROSPECTS OF OBSERVING TDES WITH THE RUBIN LSST?

- LSST Software Stack - minion_1016 cadence
- added TDEs in Catalog Simulator - using MOSFiT (Guillochon et al. 2018) to calculate SED
- 1 $M_S$, parabolic orbit
- varied impact parameter and BH mass

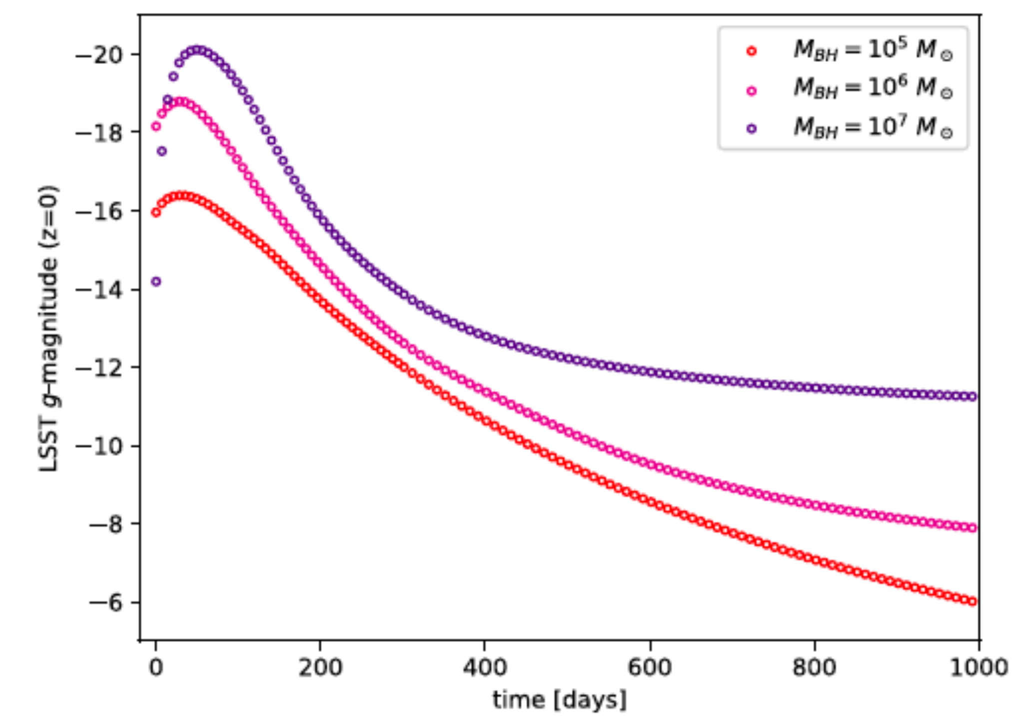
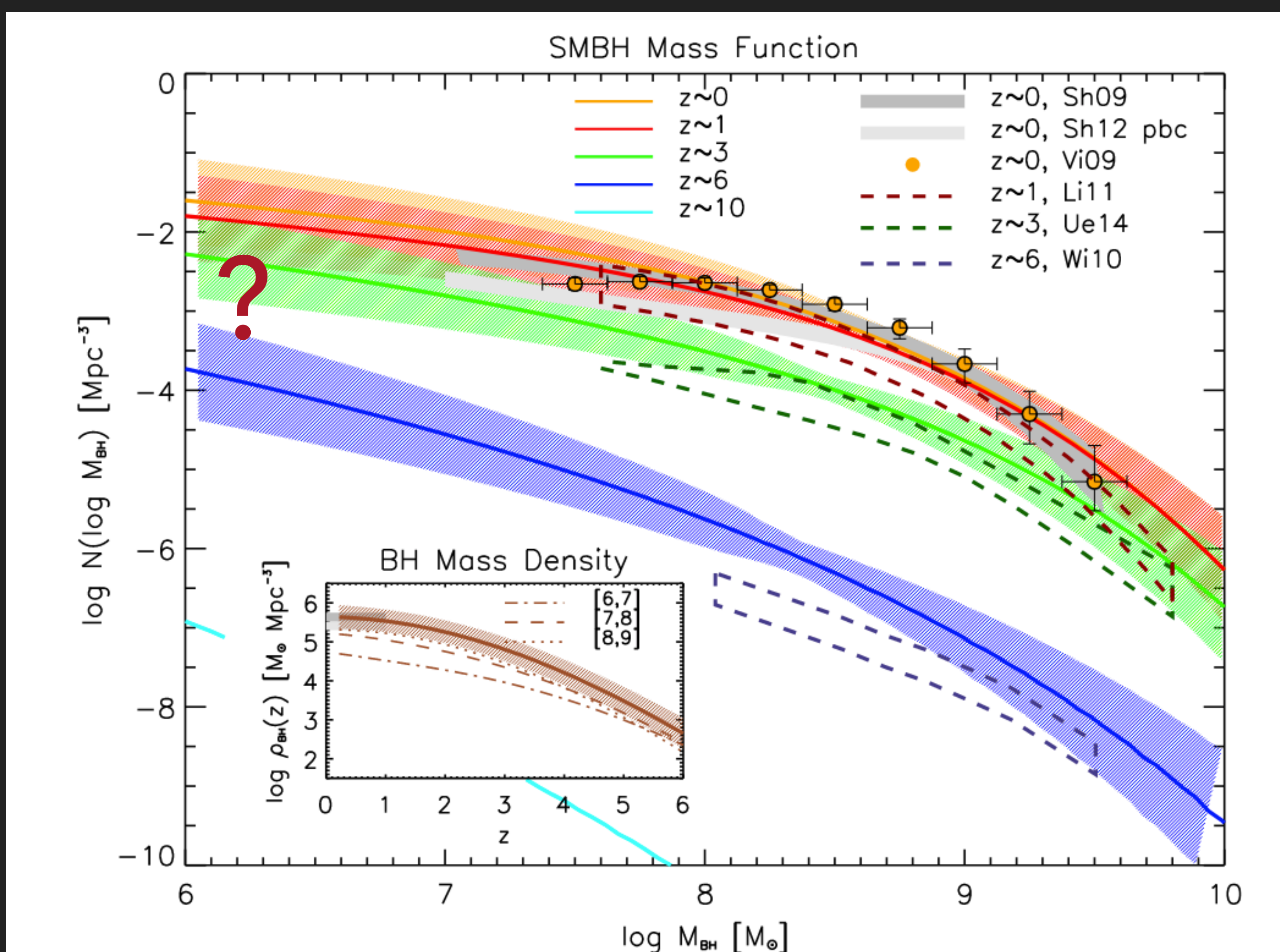



**Figure 1.** MOSFiT-generated light curves of three TDEs with black hole masses: $10^5\ M_\odot$ (red), $10^6\ M_\odot$ (pink), and $10^7\ M_\odot$ (violet). In all three events a solar-type star disruption with $\beta = 1$ was assumed. The absolute magnitudes were calculated in the LSST $g$ band.

Bricman & Gomboc, 2020

# SMBH MASS FUNCTION

- uncertainties in distribution over BH mass at low mass end




Aversa et al 2015

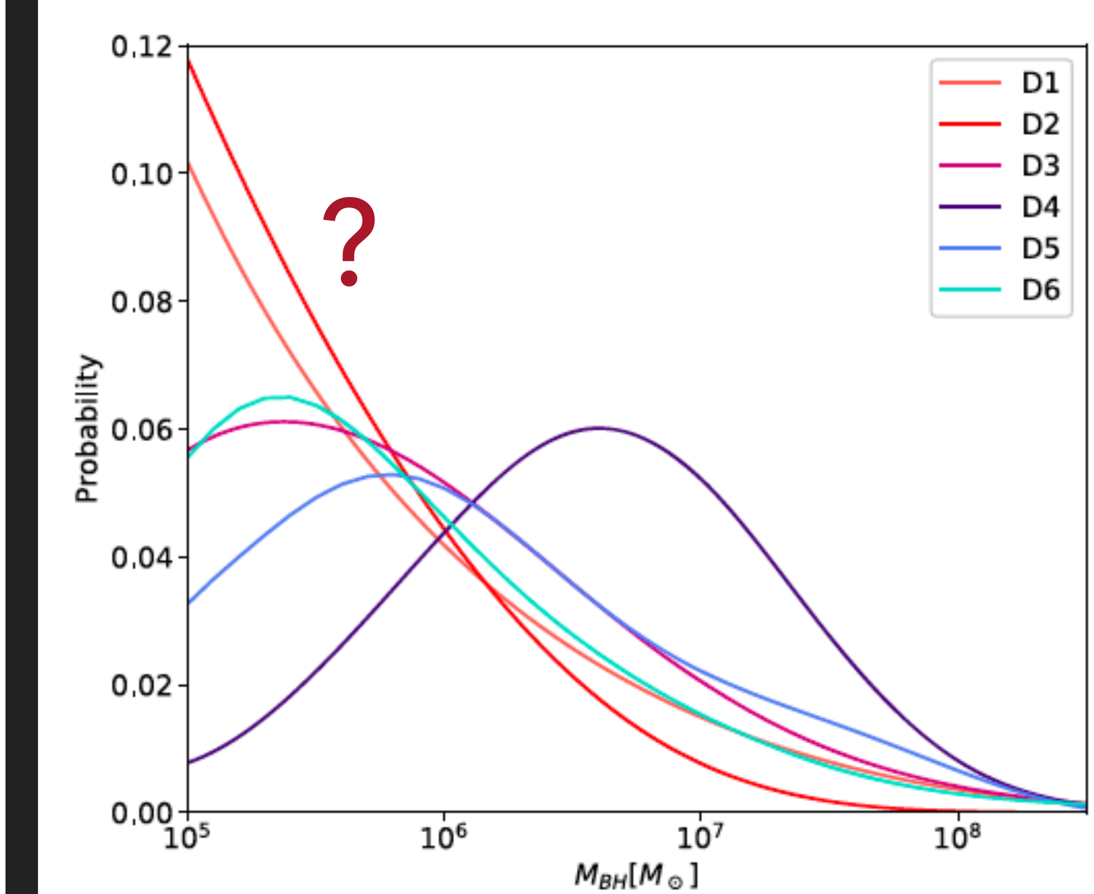



**Figure 2.** Input SMBH mass probability distributions D1–D6.

Bricman & Gomboc, 2020

# DIFFERENT REDSHIFTS & 20 FIELDS IN THE SKY:

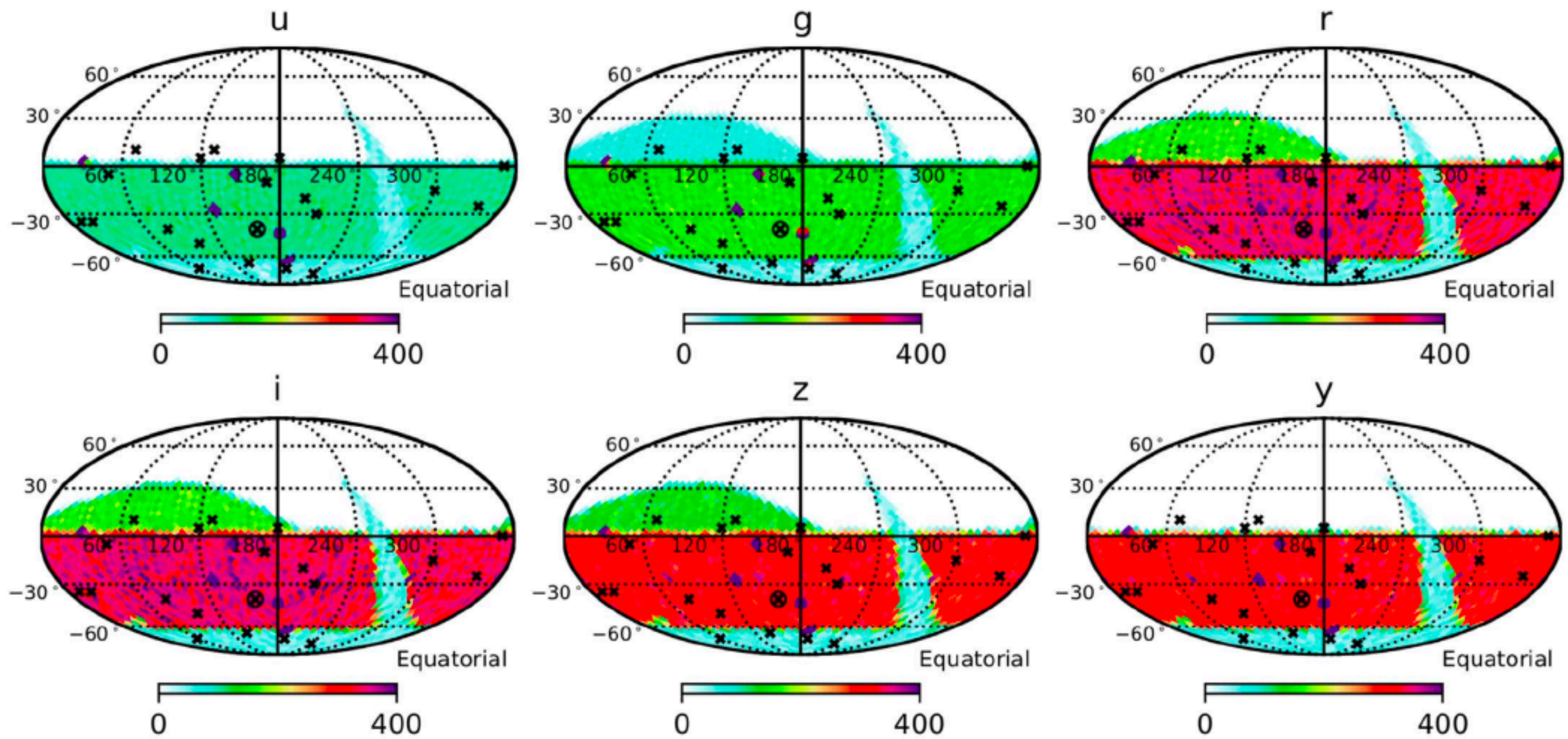



**Figure 3.** Number of visits (where a visit consists of two 15 s exposures) to a given field on the sky over 10 years of LSST observations in all six bands (*u, g, r, i, z,* and *y*) according to the observing strategy `minion_1016`. Observations in the *r, i, z,* and *y* bands will be more common than those in the *u* or *g* band, which is also apparent from the panels corresponding to each of the bands. The distribution of number of visits on the sky is irregular, as the cadence proposed is also irregular. Black crosses mark the locations of fields on which we simulated TDEs.

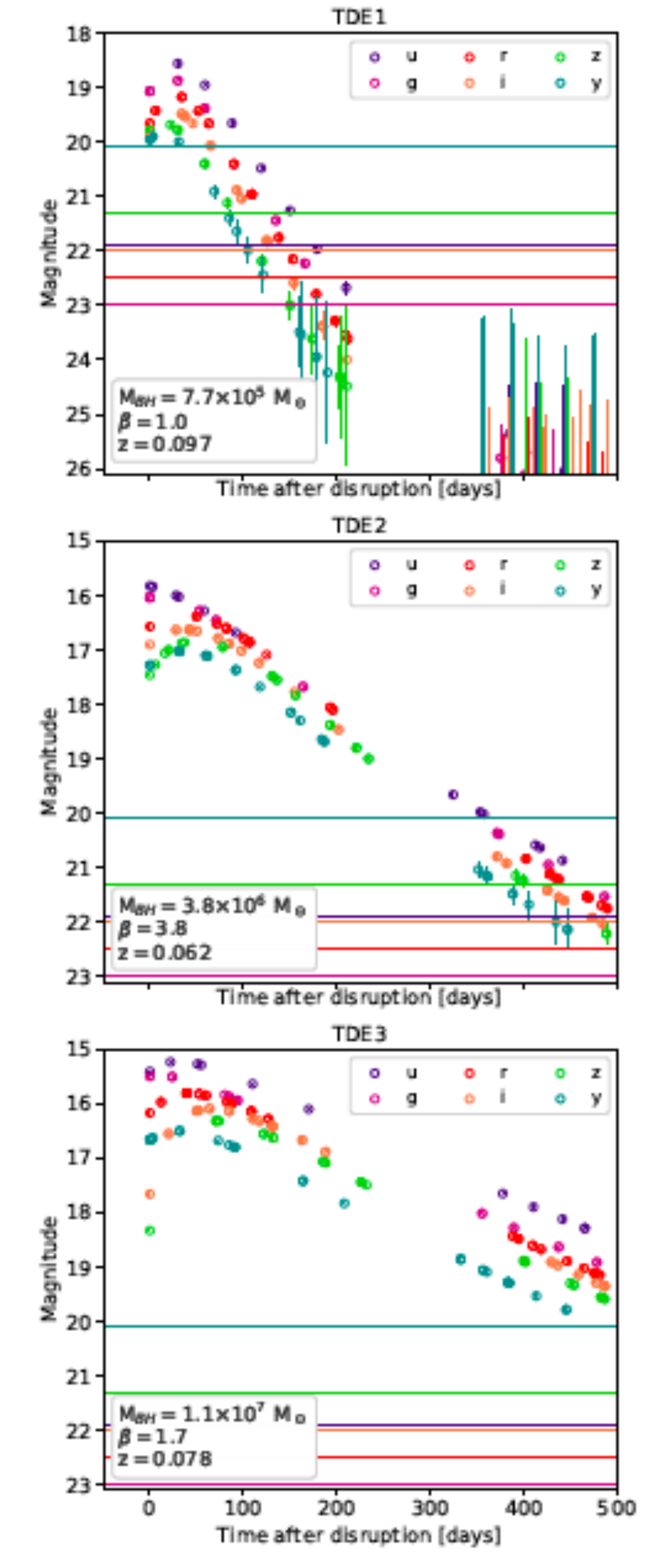
# NUMBER OF TDES DETECTED

10 observations above cutoff magnitude:

$u_c$=21.5, $g_c$=22.8, $r_c$=22.4, $i_c$=21.9, $z_c$=21.3, $y_c$=20.1

~10 - 20 TDEs/night (rate of TDEs: $10^{-5}$ galaxy$^{-1}$ yr$^{-1}$)

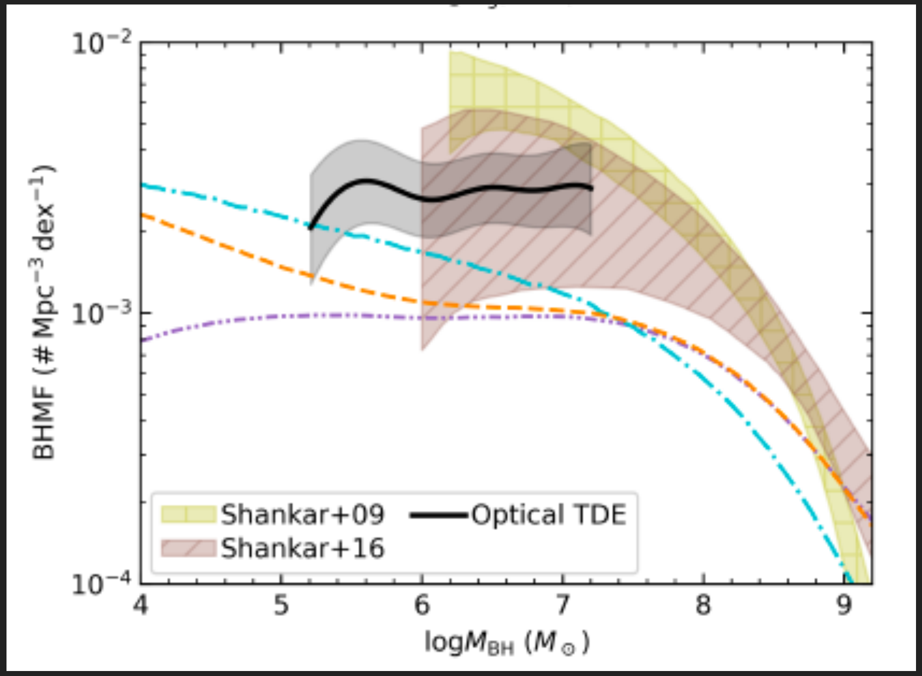
Bricman & Gomboc, 2020



# PROBING THE SMBH MASS FUNCTION

low mass BHs produce fainter and shorter TDEs - easier to miss

BHMF not straightforward :-(




Yao et al 2023

early identification + follow-up!

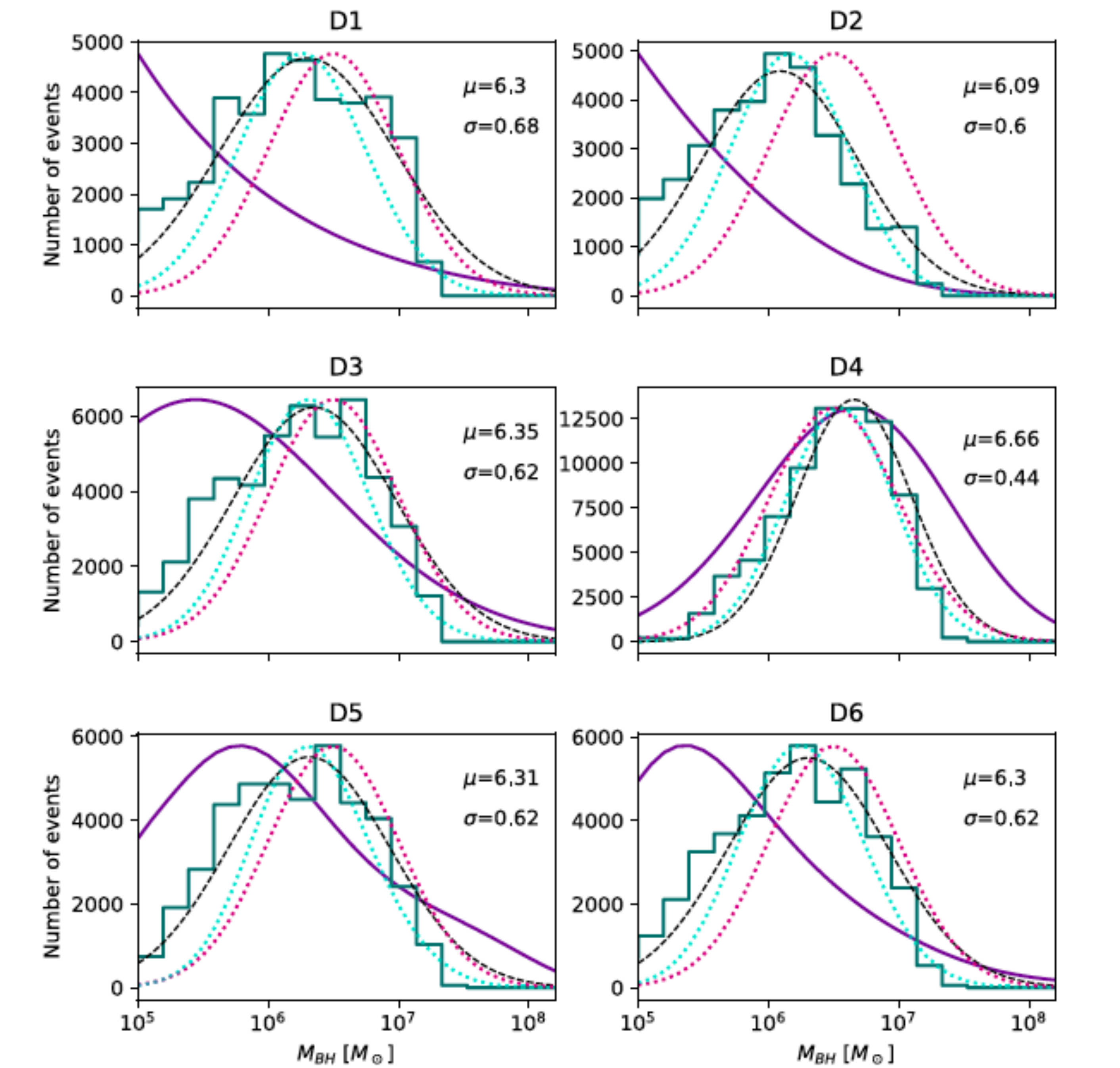



**Figure 7.** Input theoretical SMBH mass distributions D1–D6 (purple lines), the SMBH mass distribution of detected TDEs (green histograms), the Gaussian fit to detected TDEs (black dashed line), and the selection-effects function (pink dotted line). The observed samples consist of all detected TDEs on 20 simulated fields, scaled to the whole observable sky as discussed in 5.2.

Bricman & Gomboc, 2020

# OTHER STRATEGIES PROPOSED

- > 200

7 main survey parameters:

- Survey footprint modifications: WFD area from 18, 000 $deg^2$ to 20, 000 $deg^2$.
- Exposure time per visit: u-band visit - 1x 50 s exposure, retaining the same overall number of visits in u-band
- Allocation of observing time per band: changes in the filter distributions across visits
- Cadence and revisit times variations : visits in a pair in the same or in mixed filter, or adding an additional visit
- Rolling cadence: sky is split into a defined number of declination bands, receiving a higher number of visits during an "on" season followed by a lower number of visits during an "off" season.
- The footprint of mini-surveys : footprints of GP, North Ecliptic Spur, and South Ecliptic Pole mini surveys, DDFs footprint, location and cadence.
- Twilight observations: changing the cadence and filter distribution during twilight observations

# RUBIN LSST TDE FILTERING PLANS

- real-time image difference analysis (in 60 s) → LSST Alerts Stream
- brokers: Alerce, **AMPEL**, ANTARES, BABAMUL, FINK, Lasair, Pitt-Google
- filtering - information included in the LSST Alerts: history, photometric light curve, astrometric data/galaxy cross match, offset from gc, photo-z, galaxy colour/type
- challenge: how to reliably identify a TDE based solely on LSST photometry? before the peak? - to enable follow-up
- TDE filtering based on: nuclear position, light curve features, colour (evolution), absolute peak magnitude (photo-z), galaxy type, machine learning…

# RUBIN & MACHINE LEARNING

- European MSCF Cofund project SMASH
- 50 postdocs in 5 research areas at 5 Slovenian institutions
    - Cosmology and time domain astrophysics with Vera Rubin Observatory
    - Dark matter and gamma-ray astrophysics with the Cherenkov Telescope Array
- new call starting on 15th July
- [smash.ung.si](smash.ung.si)

SMASH

machine learning for science and humanities

## RUBIN FUTURE

- ~10-100 TDEs/night detected with Rubin LSST
- population/statistical studies
- challenge: identification of TDEs! - looking for a postdoc!
- help or bias? - blue colour, nuclear, non-AGN, type of galaxy…
- interesting events

# THANK YOU