Modeling the light curves of re-brightening TDEs

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Transient Phenomena and Physical Processes Around Supermassive Black Holes
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Tidal Disruption Event (TDE)

- What is TDE?

A star approaching to an MBH is torn apart and accreted, producing a luminous flare that can last for months to years.

- Observation

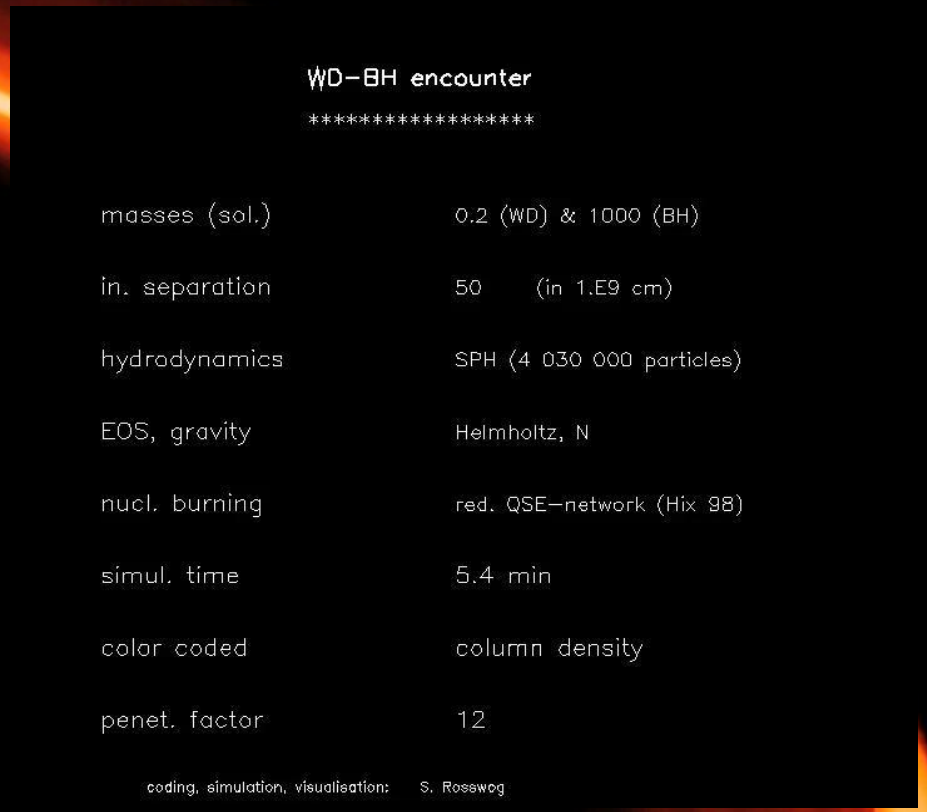
Multi-band: X-ray, UV/Optical, IR, radio

Number of detection: more than 100, will be boosted in the coming decade

- Application of TDE

Light curve: detect dormant MBH and measure its mass; study accretion physics & radiation mechanism

Event rate: stellar dynamics in galactic center



http://compact-merger.astro.su.se/Movies/IMBH1000_WD02_4e6parts_P12_N.mov

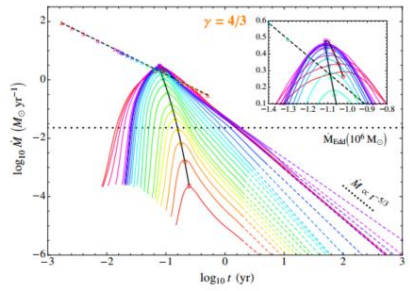
Image Credit: NASA, S. Gezari, J. Guillochon

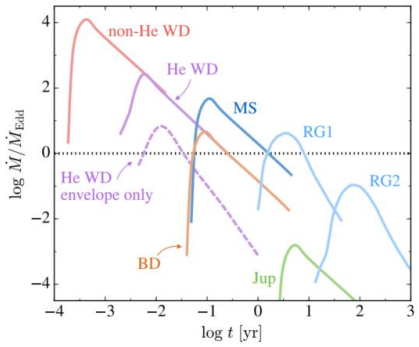
Flow chart of UV/Optical light curve modeling

- BH mass
- Stellar mass/structure
- Orbital eccentricity
- Penetration factor β

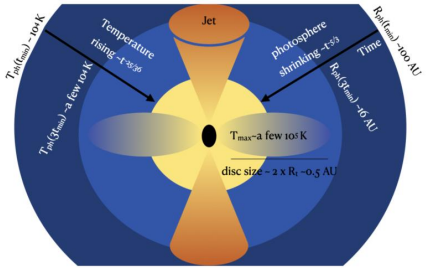
$$\beta = \frac{r_t}{r_p}$$

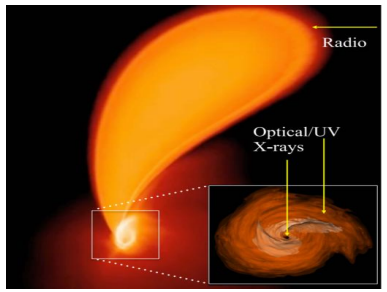
Mass fallback rate

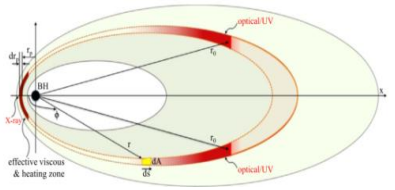


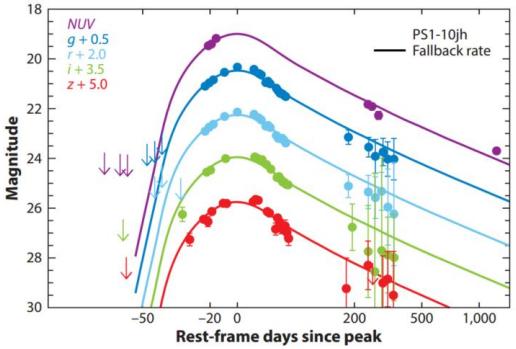


Radiation Model









Physical quantities extracted from light curve

Physical model	Open source software	Input	Output	reference
Dynamical Blackbody Photosphere	MOSFiT	Multiband light curve	M_{BH}, m_*, β, etc.	Mockler et al., 2019, ApJ, 872, 151
Classic Accretion Disk + Reprocessing Layer	TiDE	Multiband light curve	M_{BH}, m_*, β, etc.	Kovács-Stermeczky & Vinkó, 2023, PASP, 135, 034102
Stream-stream collision	TDEMASS	L_p, T_p	M_{BH}, m_*	Ryu et al., 2020, ApJ, 904, 73 Krolik et al. arXiv:2409.02894
Eccentric Accretion Disk	--	L_p, $E_{rad,tot}$	M_{BH}, m_*	Zhou et al., 2021, ApJ, 907, 77

These tools only handle single flare

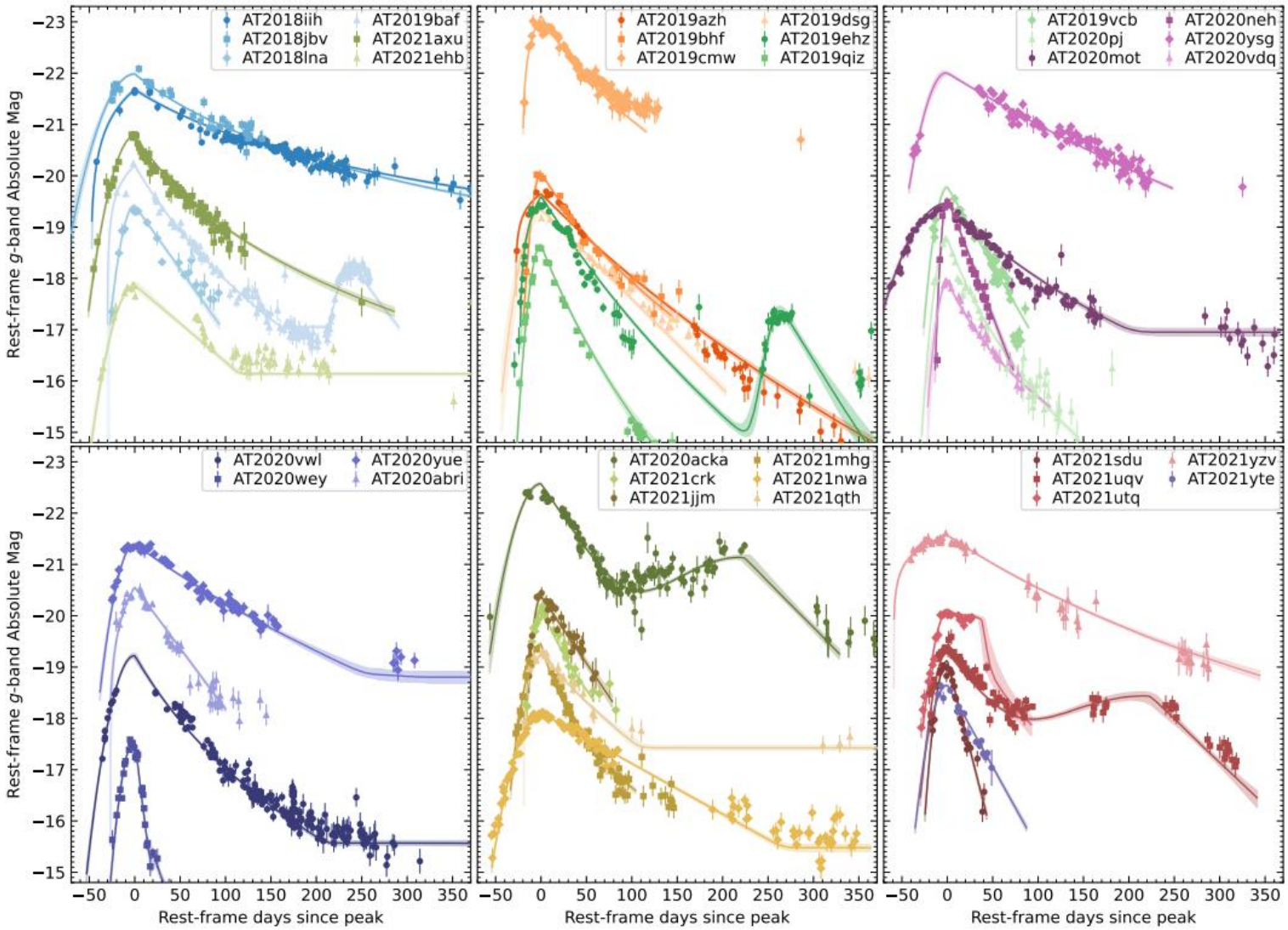
Re-brightening TDEs

- Yao et al. (2023) published 30+ new TDEs, among which
  - 5 show re-brighten feature: **2019baf, 2019ehz, 2020acka, 2021uqv, 2020vdq(#)**
- Other examples:
  - AT2018fyk (Wevers+2023; Pasham+2024)
  - AT2019aalc (Veres+2024)
  - AT2021aeuk (Bao+2024)
  - AT2022dbl (Lin+2024)
  - AT2023adr (AstroNote 2024-178)
  - and more shall show up…

Somalwar et al (2023), the second flare is brighter

Tidal Disruption Event Demographics with the Zwicky Transient Facility: Volumetric Rates, Luminosity Function, and Implications for the Local Black Hole Mass Function

Yuhan Yao [1], Vikram Ravi [1], Suvi Gezari [2,3], Sjoert van Velzen [4], Wenbin Lu [5], Steve Schulze [6]



Possible Origins

- Repeated partial TDEs (PTDEs) by a single star
  - AT 2020vdq (Somalwar et al. 2023)
  - AT 2022dbl (Lin et al. 2024)
  - ASASSN-14ko (Payne et al. 2021)

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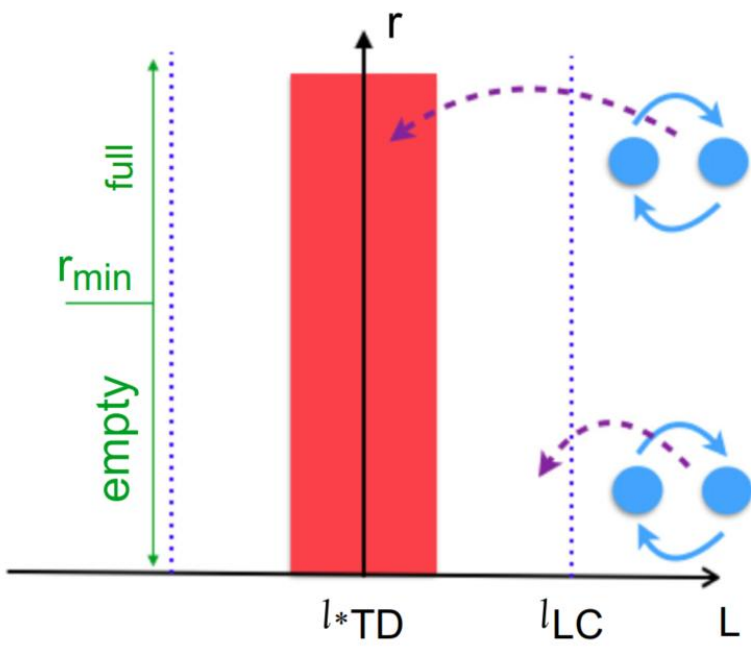
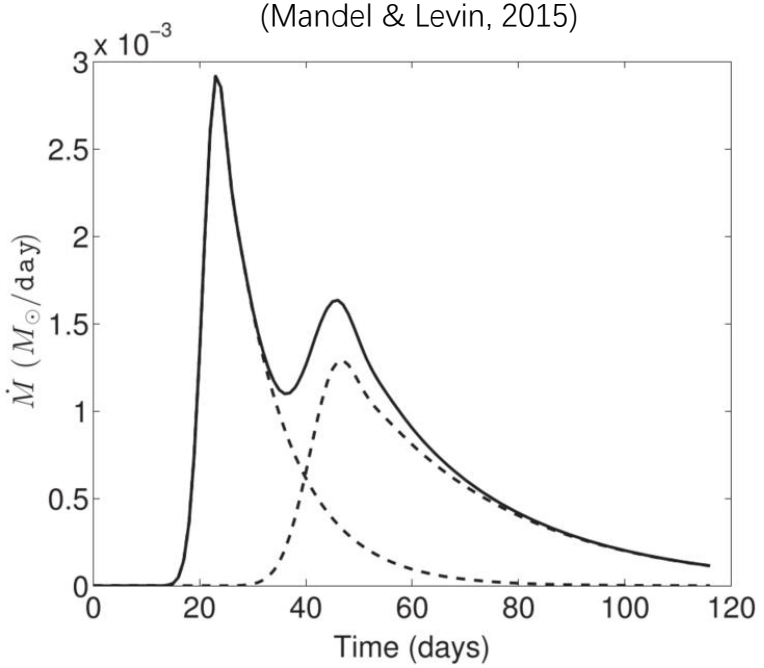
- Double TDEs following the tidal break up of binary stars (Mandel & Levin, 2015)



(Mandel & Levin, 2015)



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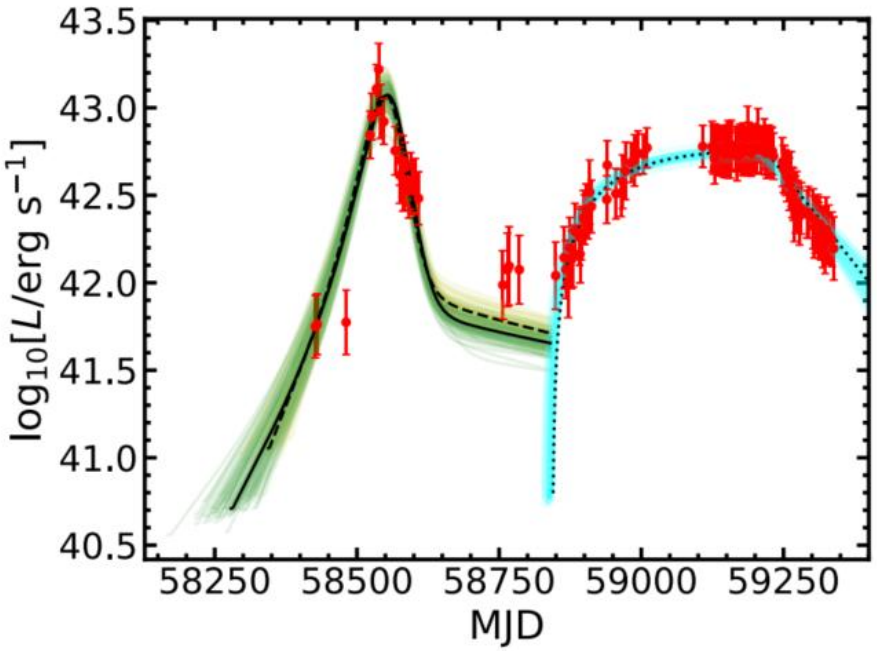
  - AT 2022dbl (Lin et al. 2024)
  - ASASSN-14ko (Payne et al. 2021, 2023)
- Double TDEs followed by tidal break up of binary stars (Mandel & Levin, 2015)
- Single TDE with two-phase evolution (Chen+2022)
  - 1st flare powered by shocks: self-intersection & stream-disk (see also Bonnerot+2017)
  - 2nd flare powered by a delayed accretion

AT 2019avd (Chen et al. 2022)

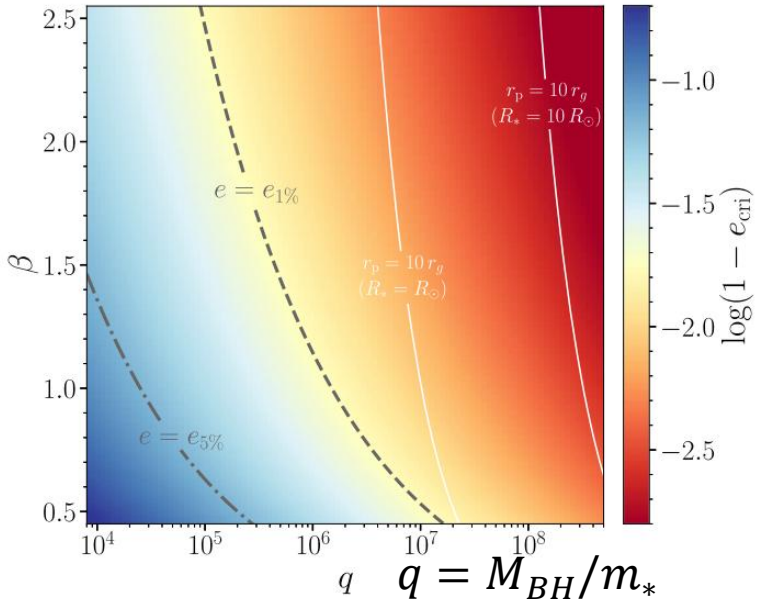


Issues of the existing fitting tools

- Assumes the star moves on parabolic orbit ($e = 1$)
- In the case of repeated PTDEs, $e < 1$
  - The debris mass distribution shall be modified (so do the fallback rate),

$$\frac{dm}{d\epsilon}(\epsilon) = \left(\frac{dm}{d\epsilon}\right)_{e=1}(\epsilon - \epsilon_{\rm orb}). \qquad \epsilon_{\rm orb} = -\frac{\beta(1-e)}{2}q^{1/3}\Delta\epsilon,$$

  - Liu et al. (2023): the above treatment is valid, as long as $e > e_{1\%}$ (or even $e > e_{5\%}$ (≈ 0.95))



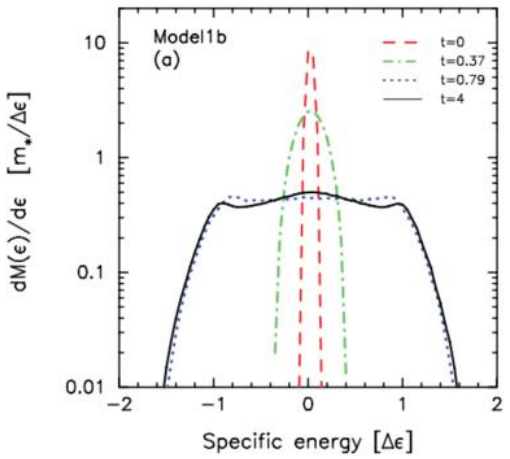
$$e = 1 - \left(\frac{2\pi t_{*,\rm dyn}}{P_{\rm orb}}\right)^{2/3}\beta^{-1}$$

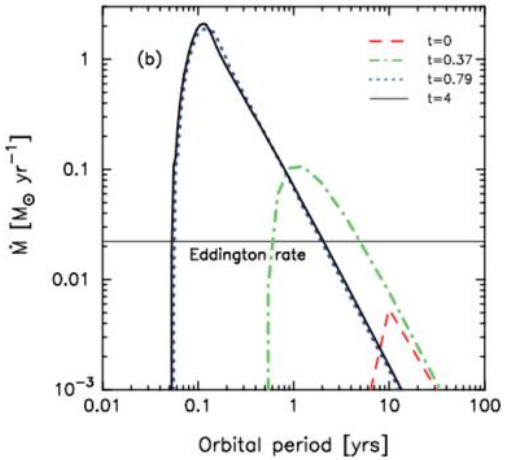
Typically, $e \approx 0.989$

$q = M_{BH}/m_*$

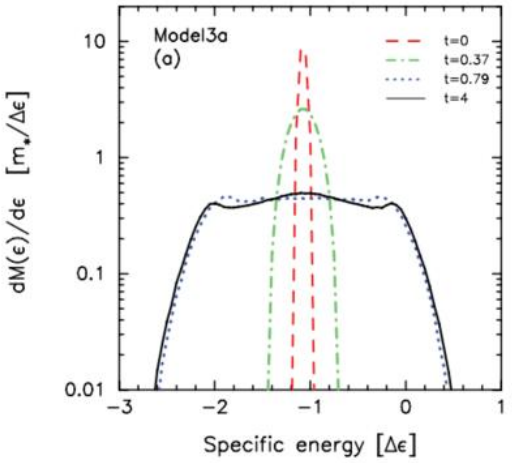
Liu+2023: https://doi.org/10.3847/1538-4357/acafe1

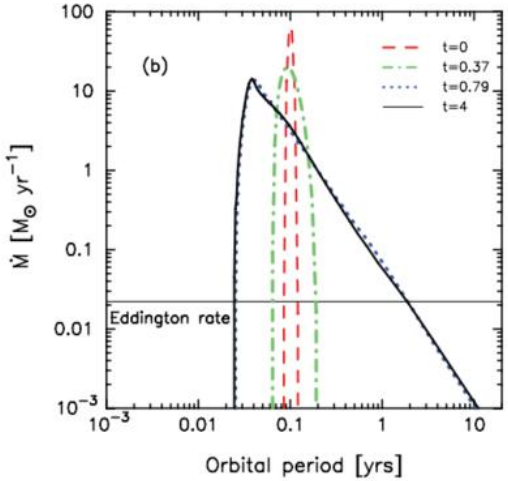
$e = 1$





$e = 0.98$

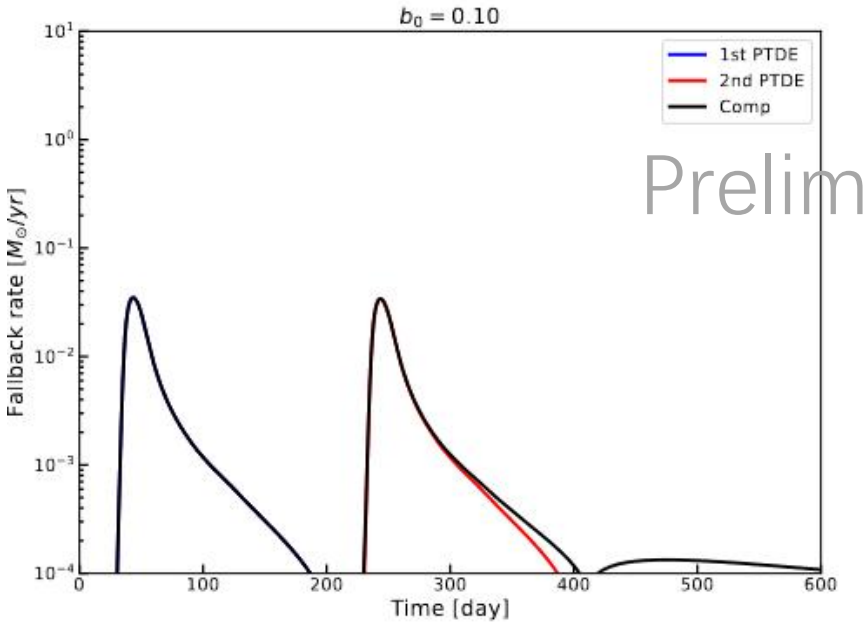


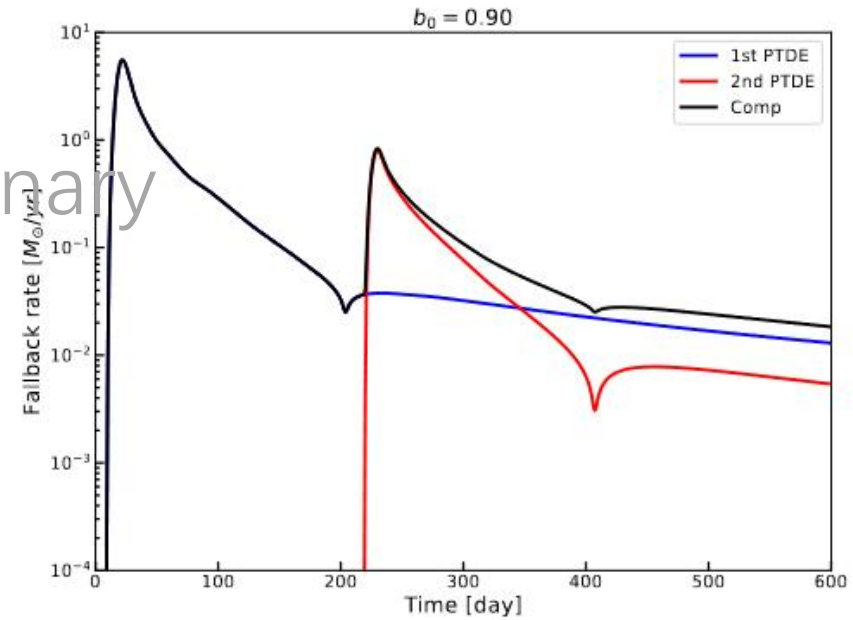


Hayasaki et al., 2013, MNRAS, 434, 909

Issues of the existing fitting tools

- One could try fitting the two flares separately, with MOSFiT or TiDE.
- Can not accurately model the flare of the second PTDE
  - The second flare declines slower, due to the contribution from the first PTDE





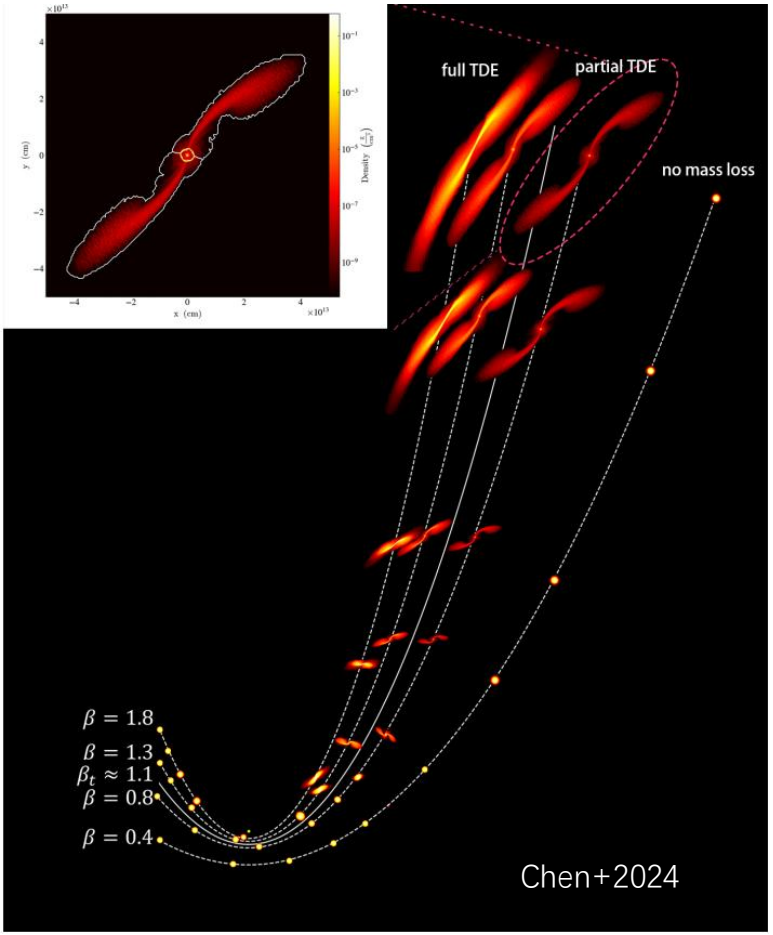
$b_0 = 0$, no disruption
$b_0 = 1$, full disruption

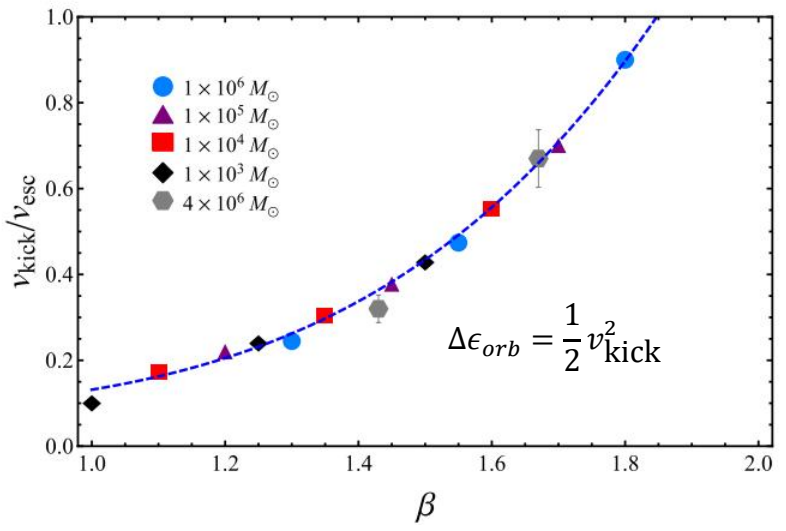
Example: fallback rates with different initial scaled penetration factor b_0. (Zhong et al. *in prep*)

- $M_{BH} = 10^6 M_\odot$, $m_{star} = 1 M_\odot$, initial $P_{orb} = 200$ days.
- ZAMS mass-radius relation

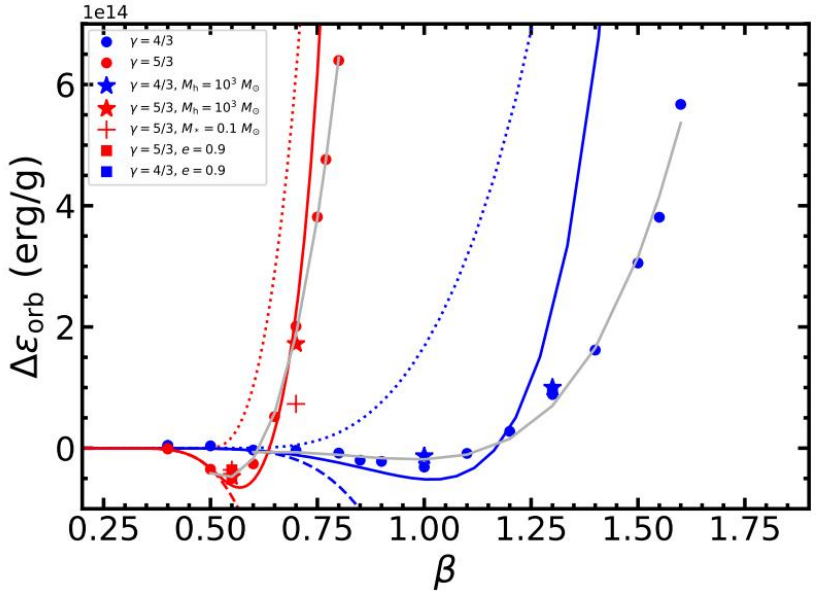
Orbital period and energy variation after PTDE

- The P_{orb} and ϵ_{orb} are crucial in determining the time of the second PTDE and its fallback rate.
- Variation of ϵ_{orb} is caused by the asymmetric mass loss through the two tidal tails:
  - Remnant star always gain orbital energy (Manukian+2013; Gafton+2015)
  - Remnant star may gain or lose orbital energy, depending on stellar structure and β (Ryu+2020; Chen+2024)





Manukian et al. (2013)



$$\Delta\epsilon_{\rm orb} = \begin{cases} 7.9\beta^4 - 19.2\beta^3 + 15.1\beta^2 - 3.94\beta + 0.0035, \gamma = 4/3 \\ 121\beta^3 - 128\beta^2 + 32.8\beta + 0.0011, \gamma = 5/3 \end{cases} \times 10^{14} \text{erg g}^{-1},$$

Chen+2024, arXiv:2408.10925

Goal: fit the two flares simultaneously

- Currently, the model only consists of two consecutive partial TDEs
- 1st step: construct composite mass fallback rate dM/dt
  - ✓ Based on Guillochon & Ramirez-Ruiz (2013) fallback rates ($e = 1$), modified for $e < 1$ case
  - ✓ Variation of P_{orb} and ϵ_{orb} after every PTDE
- 2nd step: convert dM/dt to multiband light curves in optical bands
  - ✓ dynamical photosphere model and black body SED (same as MOSFiT)

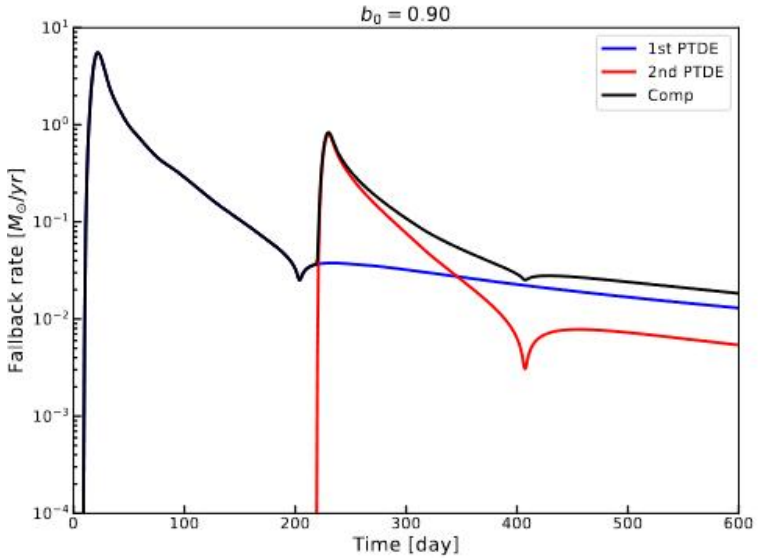
$$L_{bol} = \eta \dot{M} c^2$$

$$R_{ph} = R_{ph0} a_{peak} (L_{bol}/L_{Edd})^{l}$$

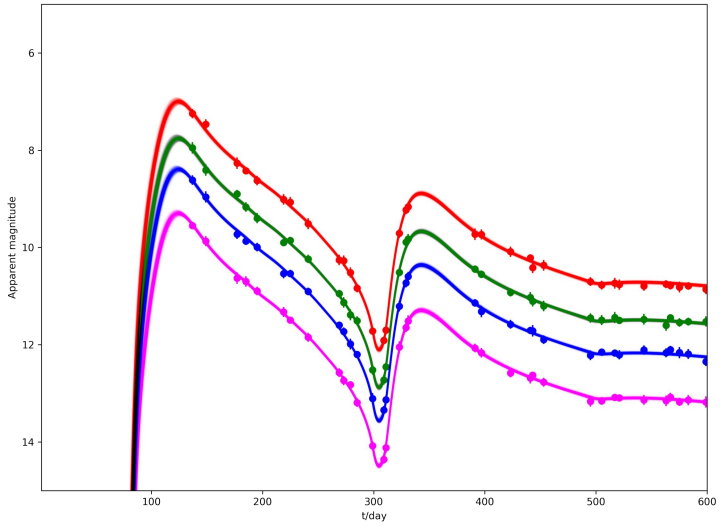
$$T_{eff} = \left(\frac{L_{bol}}{4\pi\sigma R_{ph}^2} \right)^{1/4}$$

- Light curve fitting: python package **emcee**

Composite fallback rate

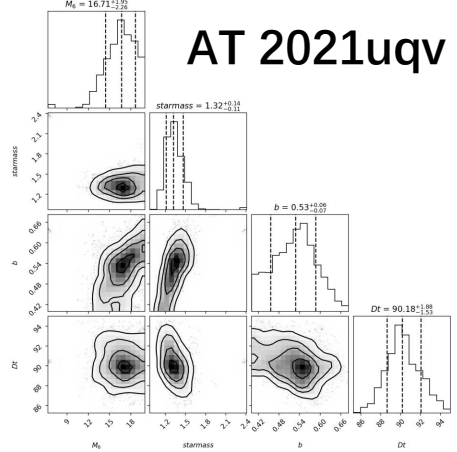


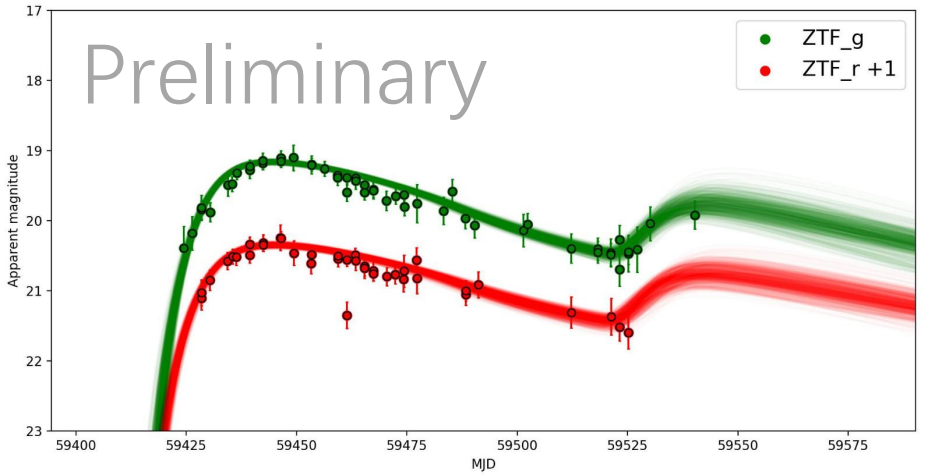
Fitting test on a mock light curve

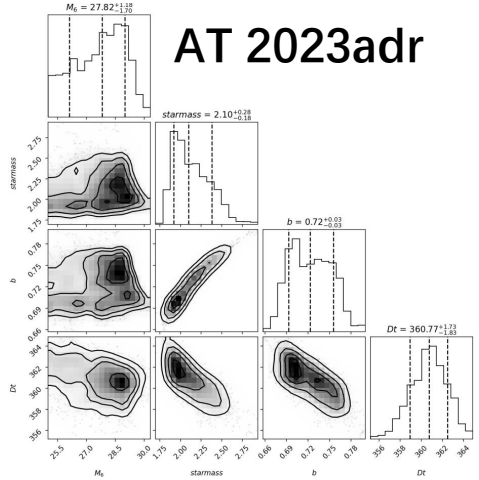


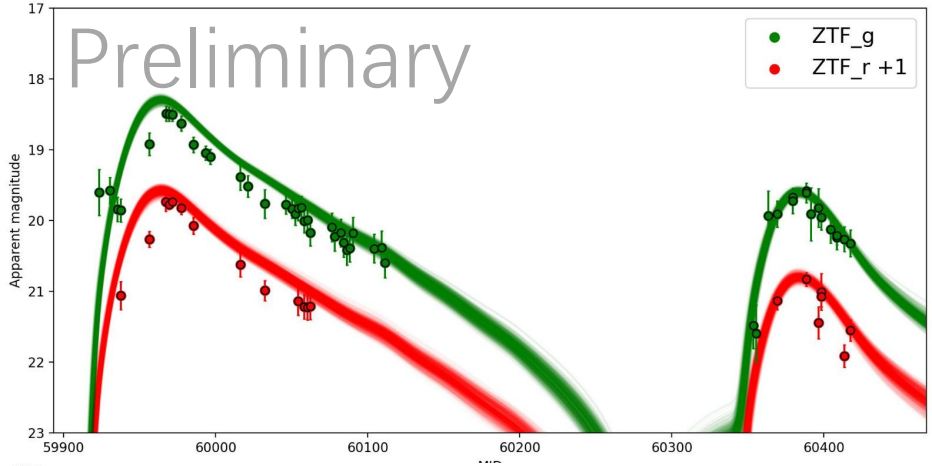
Apply to the rebrightening TDEs

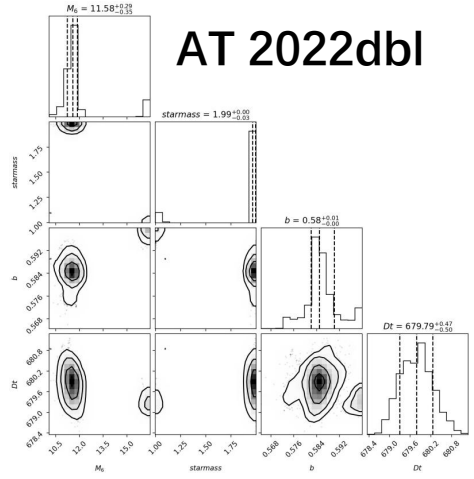
- Example light curves retrieved from ALeRCE (https://alerce.online/), to test our model and fitting code.

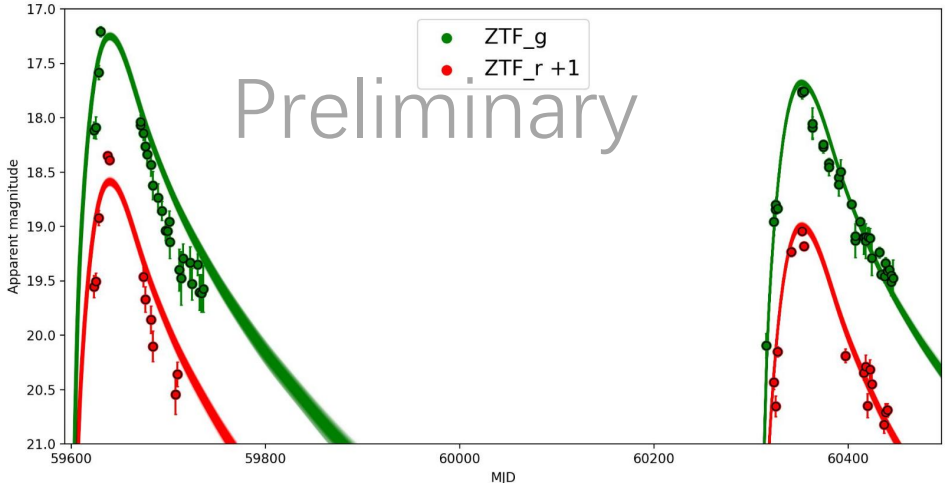






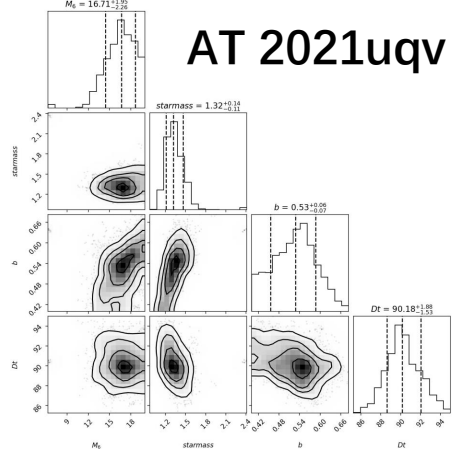


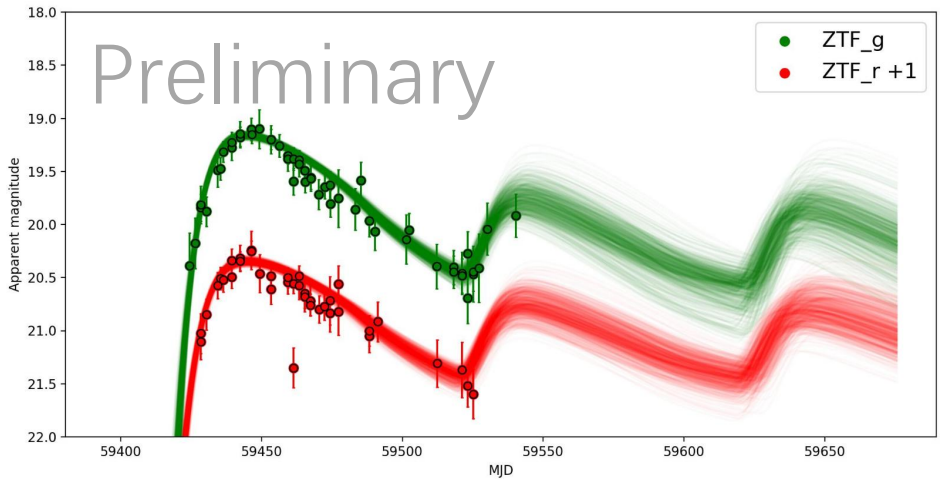


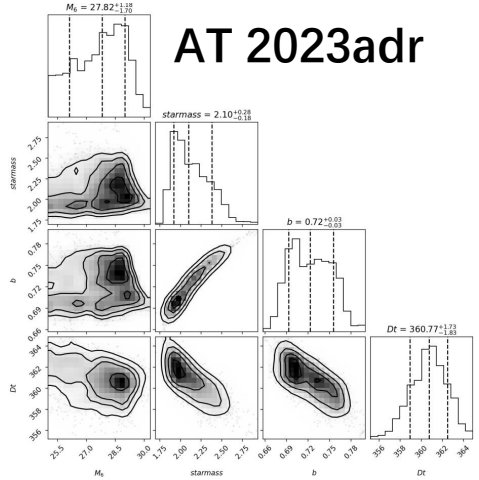


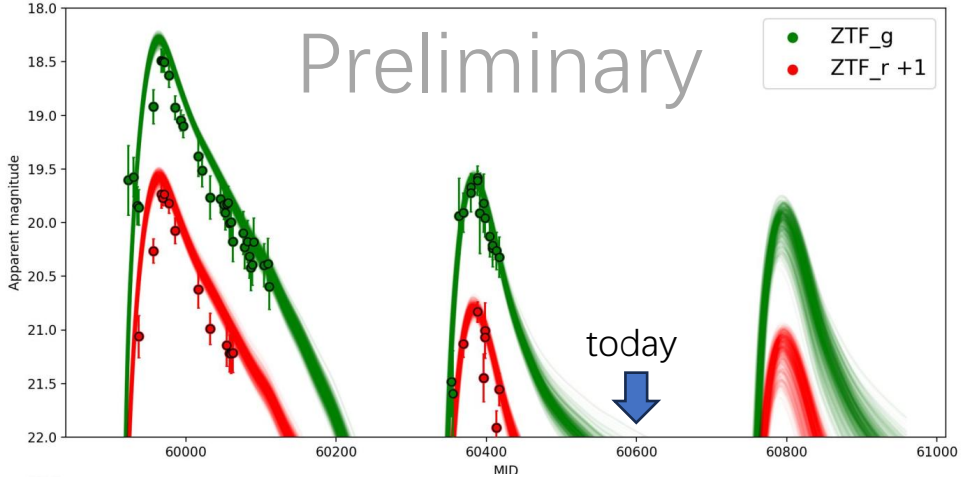
Apply to the rebrightening TDEs

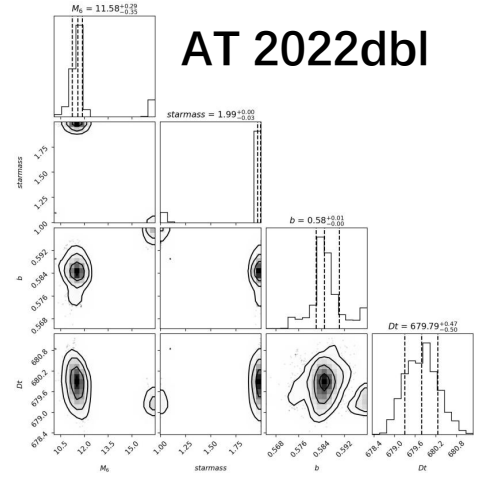
- Forecast the next flare: when and how bright

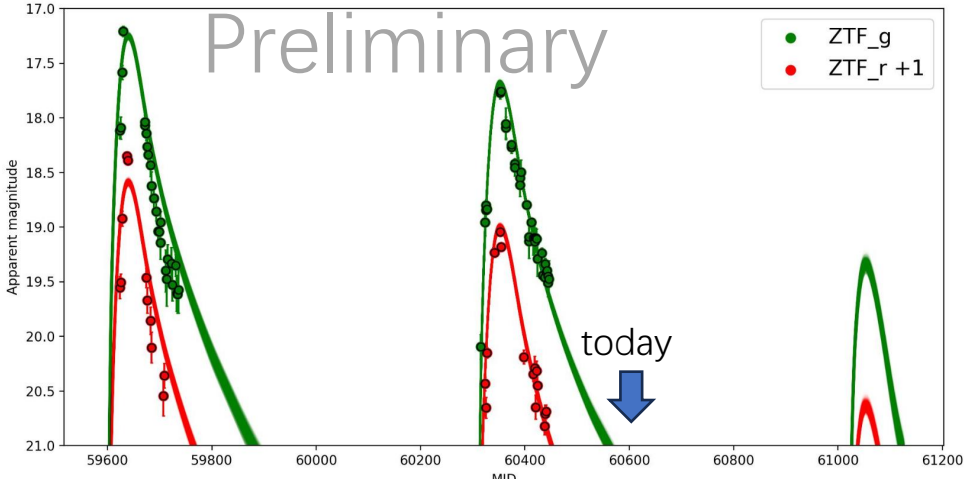












Summary

- Our model (based on repeating PTDEs scenario) could reproduce the light curves of some rebrightening TDEs
  - But not for AT 2020vdq (2nd flare is brighter)
- Aspects to be improved in future
  - Fallback rate: **polytropic** star ⟹ **realistic** star
    - STARS library (Law-Smith et al. 2020)
    - tidally perturbed remnant star: **spin up** (Golightly+2019; Bandopadhyay+2024), **oscillation and radial expansion** (Liu+2024)
  - Add other optical/UV radiation model: disk + reprocessing layer, ⋯
  - Black body SED ⟹ realistic SED with emission lines

Thank you for your attention!