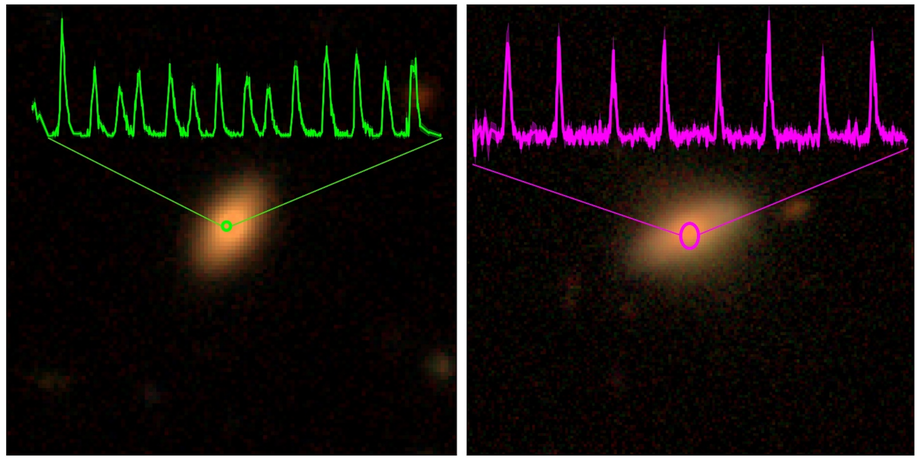


EMRI+TDE=QPE: QPEs, TDEs and Star-Disk Interaction

Itai Linial
THEA, Columbia University, New York
Institute for Advanced Study, Princeton

with **Brian Metzger, Eliot Quataert, Indrek Vurm, Re'em Sari, Xiaoshan Huang, Philippe Yao, Riccardo Arcodia**

INSTITUTE FOR ADVANCED STUDY

THEORETICAL HIGH ENERGY ASTROPHYSICS

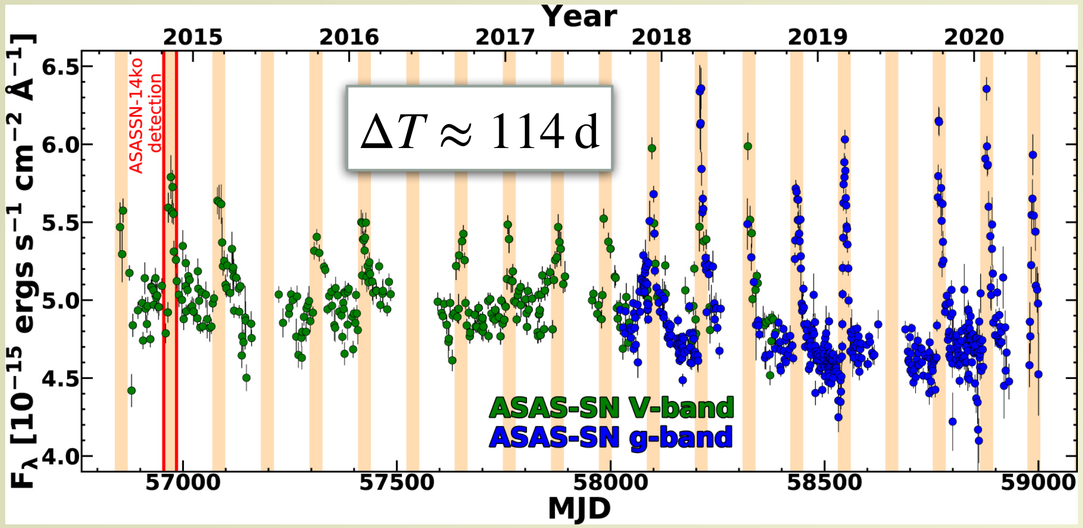
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Yad Hanadiv יד הנדיב يَاد هَنَديف

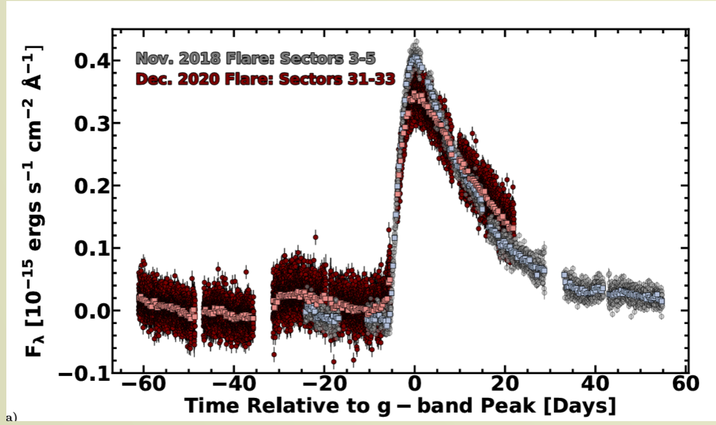
GRUBER FOUNDATION

Repeating TDEs vs. QPEs

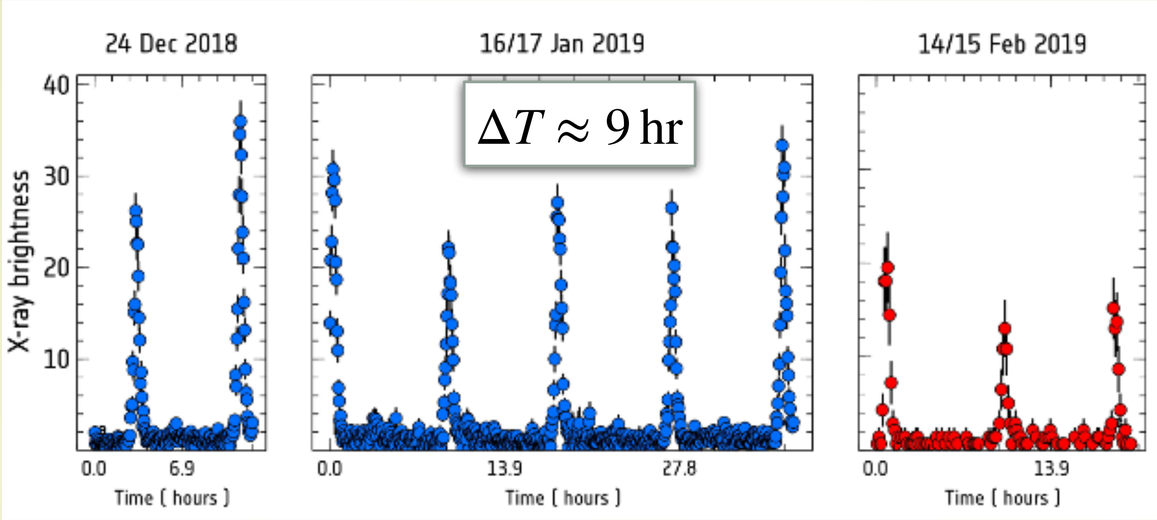
ASASSN-14ko (Payne+21)



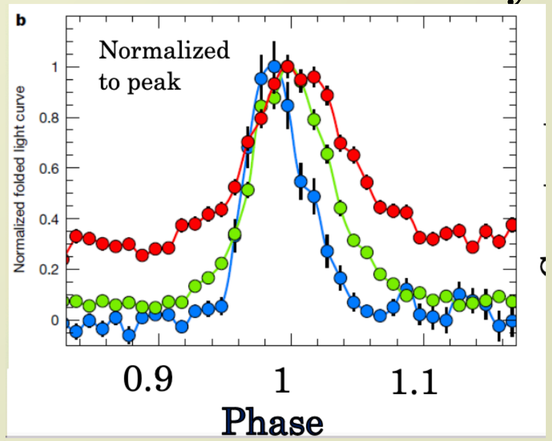
Optical/UV/X-ray
TDE-like flares
Period: Months-years



GSN 069 (Miniutti+19)



Soft X-ray only
Unlike any known AGN variability
Period: Hours-Day

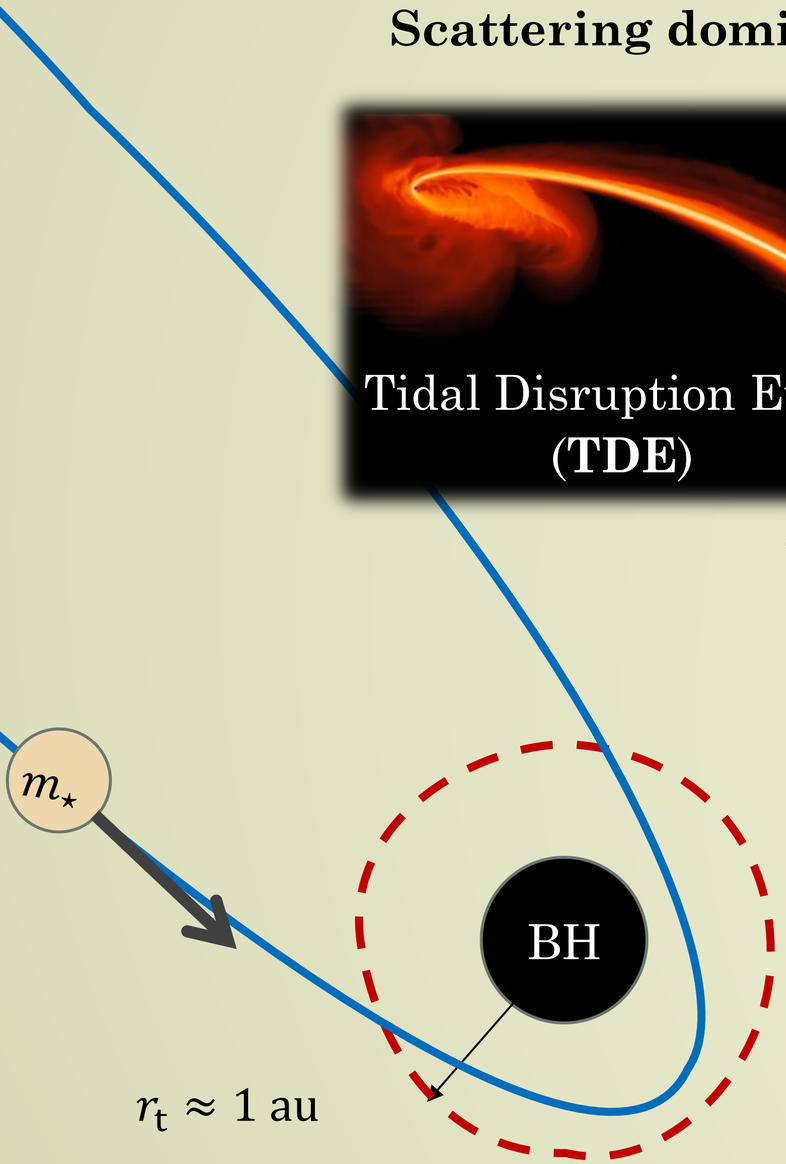


[See further discussion in Guolo+24]

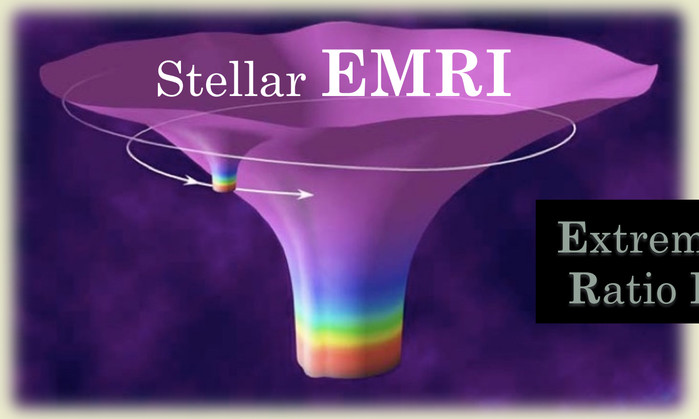
Two Flavors of Stellar Destruction

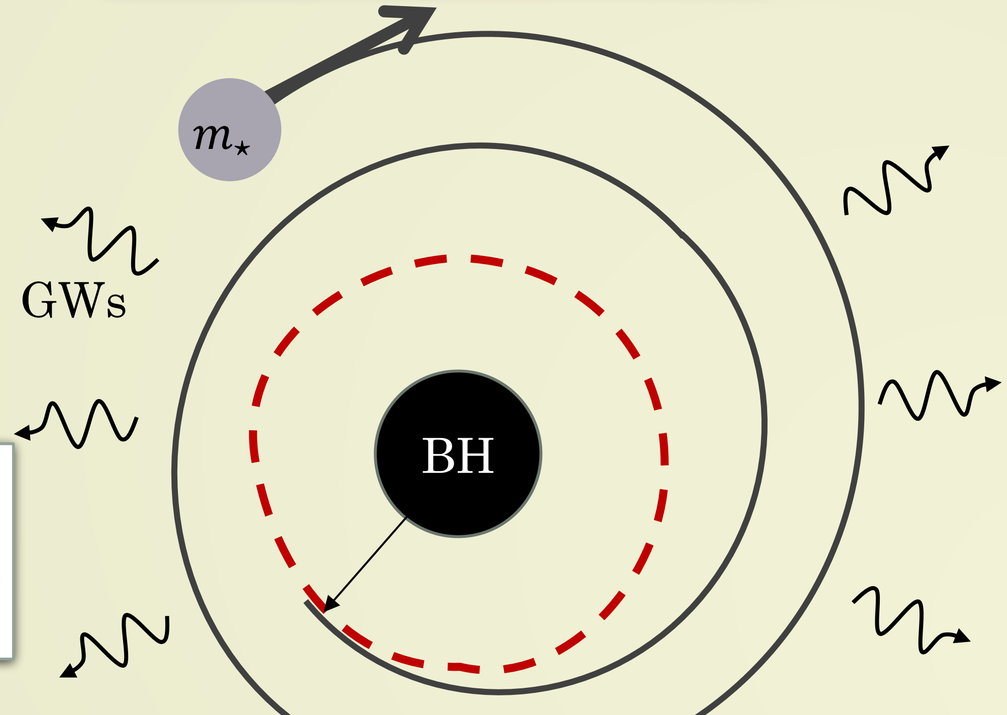
Scattering dominated:

"Plunges"



Gravitational Wave (GW) dominated:



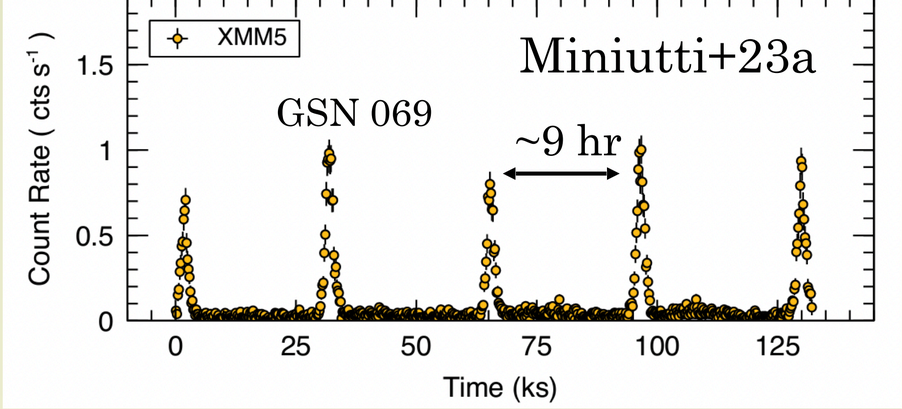


See:
Dai & Blandford (2013)
Linial & Sari (2017,2023)
Linial & Metzger (2023)

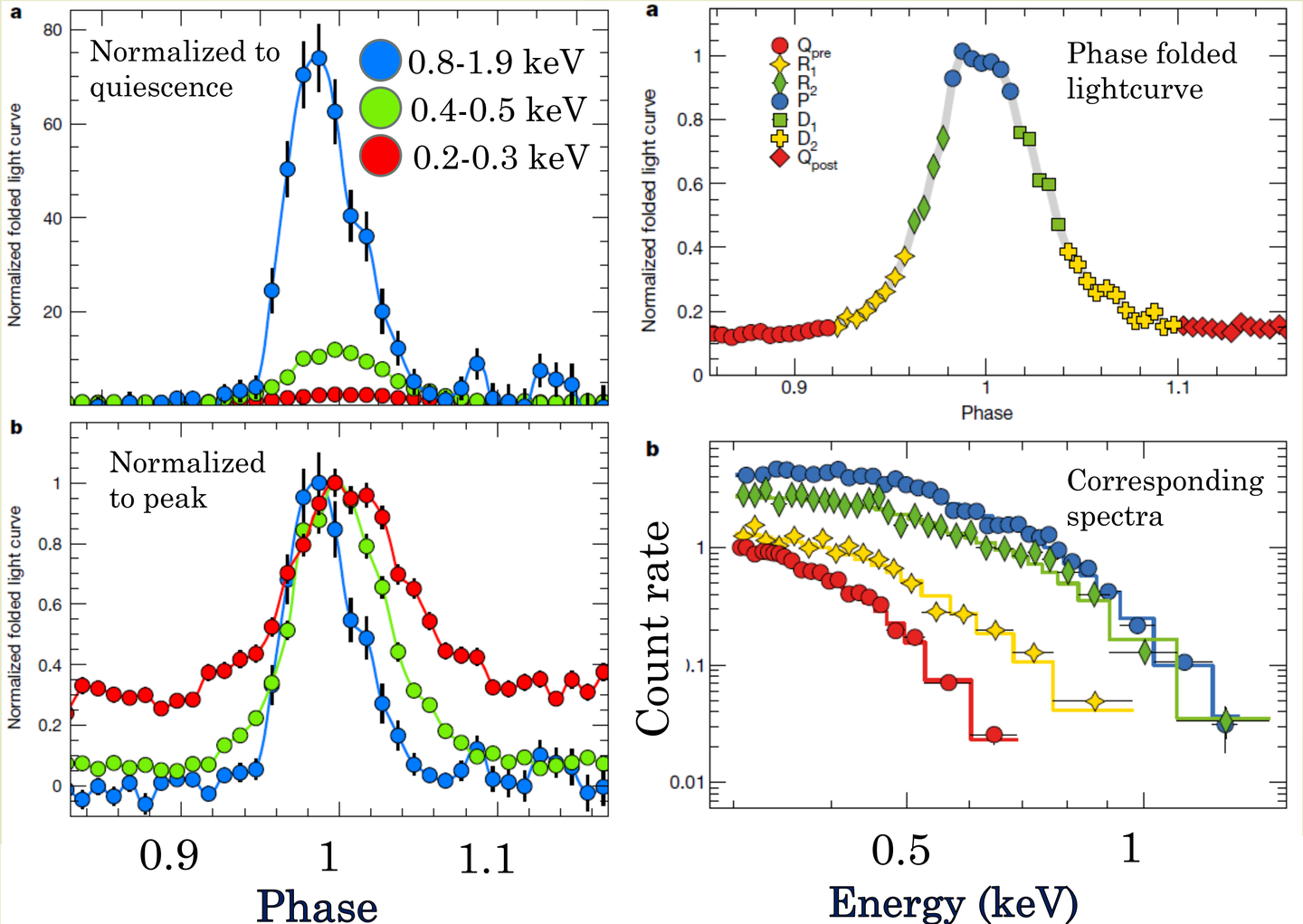
Quasi-Periodic Eruptions

- 6 confirmed systems to date (+2 candidates)
- (Quasi)-Periodic: ~**2.5-20 hr**
- Duty cycle ~ **10-30%**
- Peak luminosities
  $L_{peak} \approx 10^{42}$ **erg s^{-1}**
  $k_B T_{pk} \approx 150 - 200$ eV
- $M_\bullet \approx$ **few** $\times 10^5$ – **few** $\times 10^6$ $M_\odot$

[Miniutti et al., *Nature*, 2019
Giustini et al., *A&A*, 2019
Arcodia et al., *Nature*, 2021
Chakraborty et al., *ApJL*, 2021]

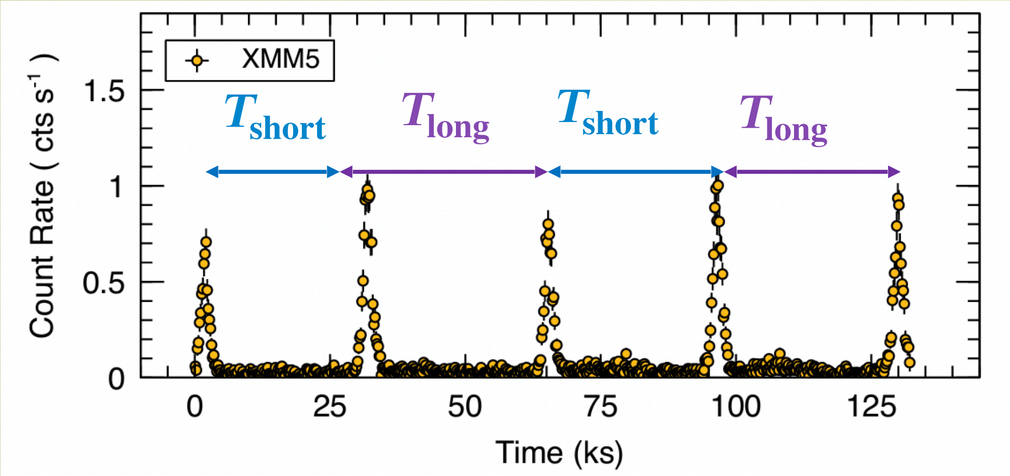


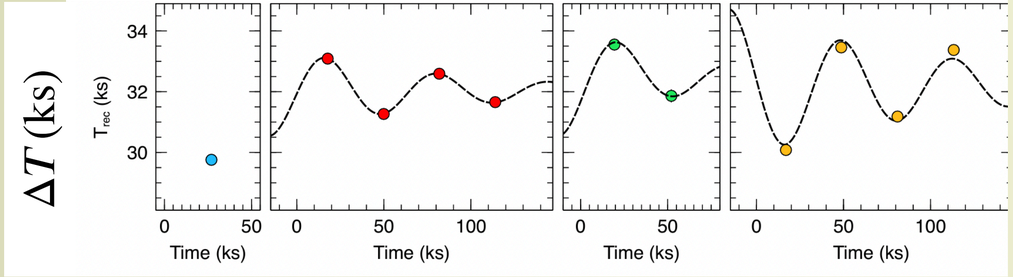
[GSN-069: Miniutti+19]



Quasi-Periodicity - Regular vs. Irregular

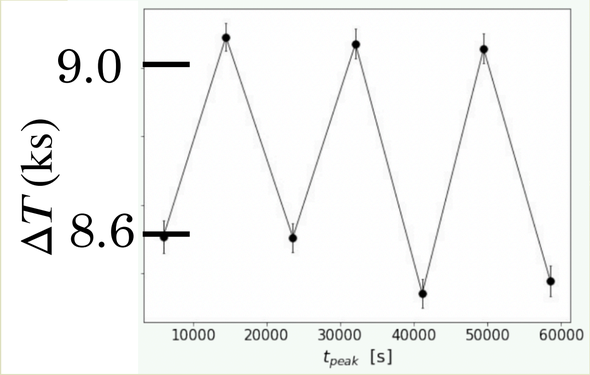
~10% timing diff





GSN-069

[Miniutti+23]

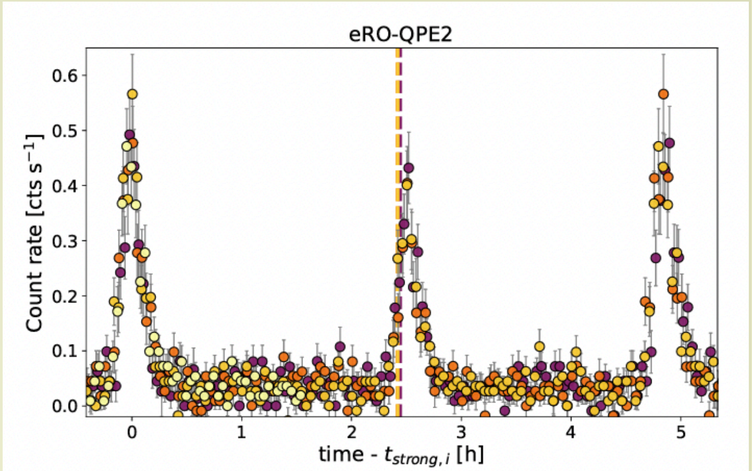


eRO-QPE2

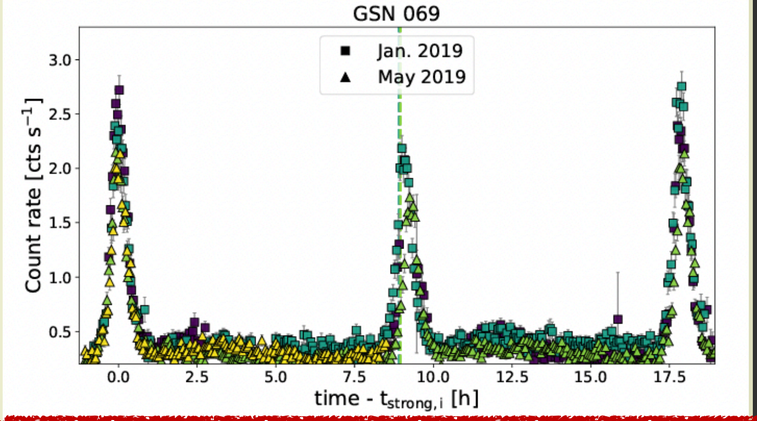
~5-10% alternation

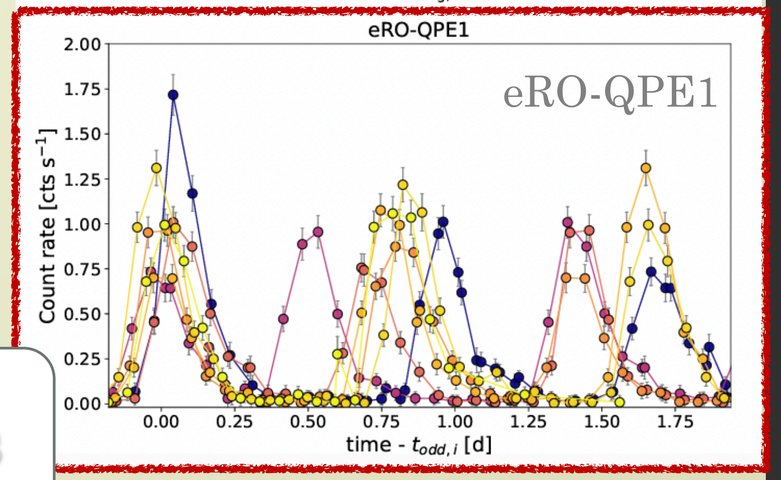
Alternating long/short pattern

eRO-QPE2



GSN-069





Erratic flares

[Arcodia 2022]

Proposed Interpretations

1. Disk instabilities

   [Miniutti+21, Arcodia+21, Raj&Nixon 21, Pan+22, Kaur+22, Sniegowska+22]

2. Lensing by a massive companion

   [Ingram+22]

3. Clumpy debris stream

   [Nixon & Coughlin 22]

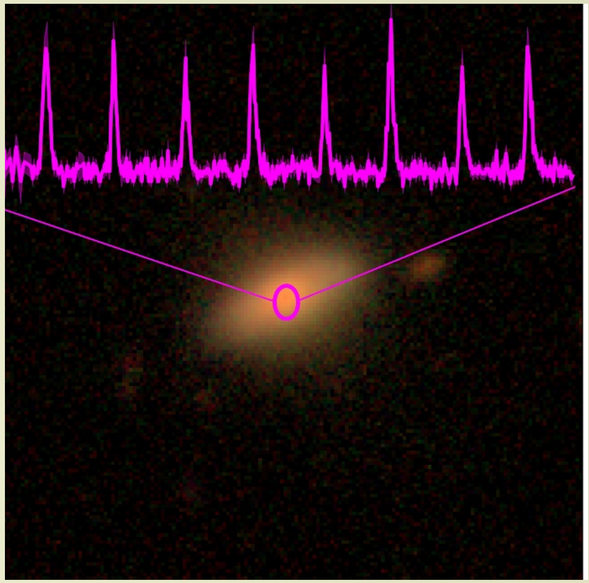
4. Mass Transferring Companion(s) "EMRI"

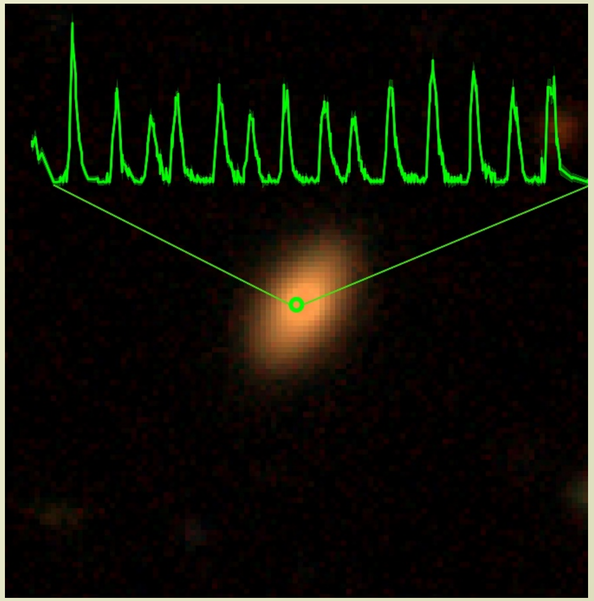
   1. Compact companion (White Dwarf, He core)

      [King 20,22,23, Zhao+22, Chen+22, Wang+22, Xian+22]

   2. Low-mass Main-Sequence star

      [Metzger+22, Krolik & **Linial** 22, **Linial** & Sari 23, Lu & Quataert 23]





Over the course of one week...

arXiv > astro-ph > arXiv:2303.16231

Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 28 Mar 2023 (v1), last revised 2 Sep 2023 (this version, v4)]

EMRI + TDE = QPE: Periodic X-ray Flares from Star-Disk Collisions in Galactic Nuclei

Itai Linial, Brian D. Metzger

arXiv > astro-ph > arXiv:2304.00775

Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 3 Apr 2023 (v1), last revised 14 Jun 2023 (this version, v2)]

Quasi-periodic eruptions from impacts between the secondary and a rigidly precessing accretion disc in an extreme mass-ratio inspiral system

Alessia Franchini, Matteo Bonetti, Alessandro Lupi, Giovanni Miniutti, Elisa Bortolas, Margherita Giustini, Massimo Dotti, Alberto Sesana, Riccardo Arcodia, Taeho Ryu

arXiv > astro-ph > arXiv:2304.03670

Astrophysics > High Energy Astrophysical Phenomena

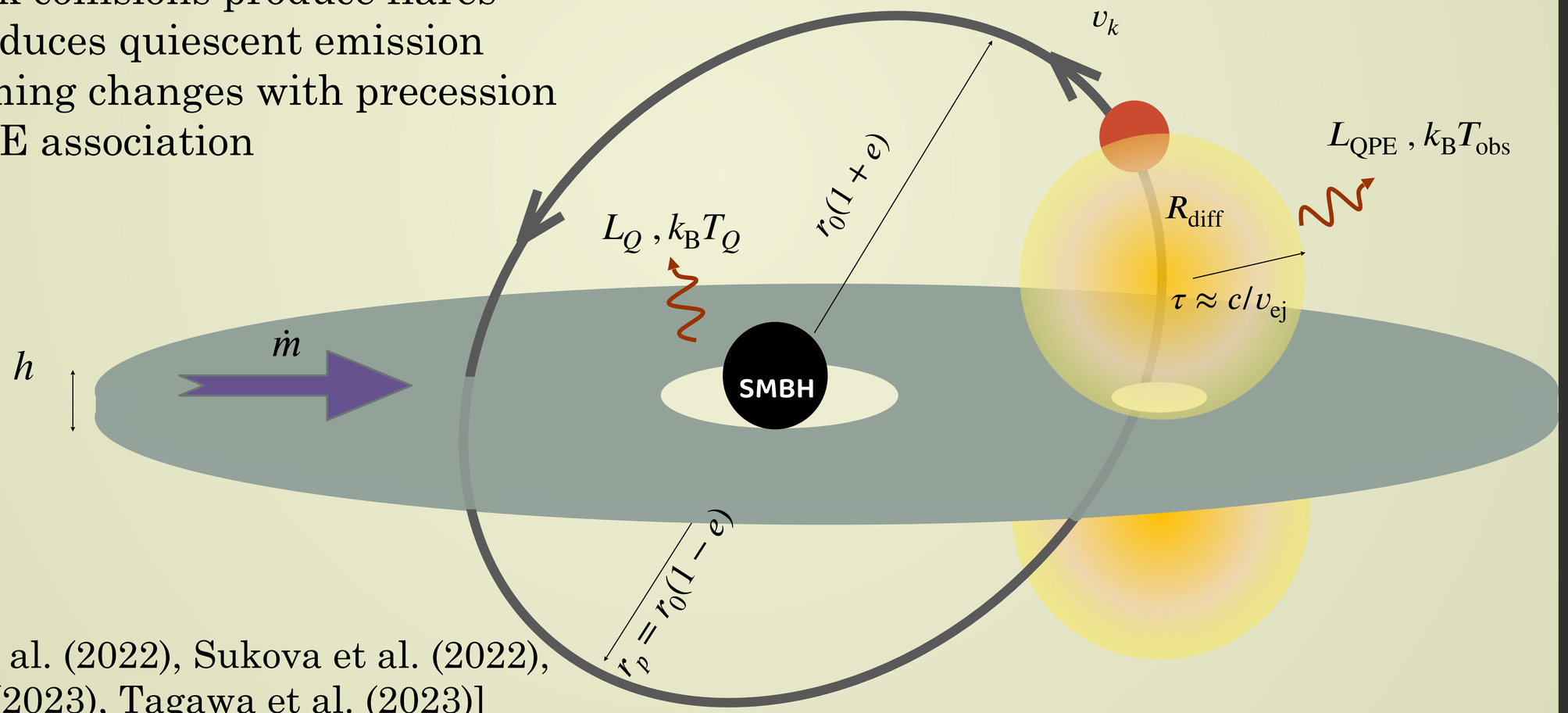
[Submitted on 7 Apr 2023 (v1), last revised 29 Aug 2023 (this version, v2)]

Flares from stars crossing active galactic nuclei disks on low-inclination orbits

Hiromichi Tagawa, Zoltán Haiman

QPEs from Star-Disk Collisions [Linial & Metzger 2023]

- Accretion disk + **Main-Sequence** stellar-EMRI
- Star-Disk collisions produce flares
- Disk produces quiescent emission
- Flare timing changes with precession
- TDE-QPE association



[See also Xian et al. (2022), Sukova et al. (2022), Franchini et al. (2023), Tagawa et al. (2023)]

Flare Timing

$$P_{\rm orb} = T_{\rm short} + T_{\rm long} = 2\langle T\rangle \approx 5 - 18\ {\rm hr}$$

$$\frac{T_2 - T_1}{\langle T\rangle} = F(e, I, \varpi) \sim O(e)$$

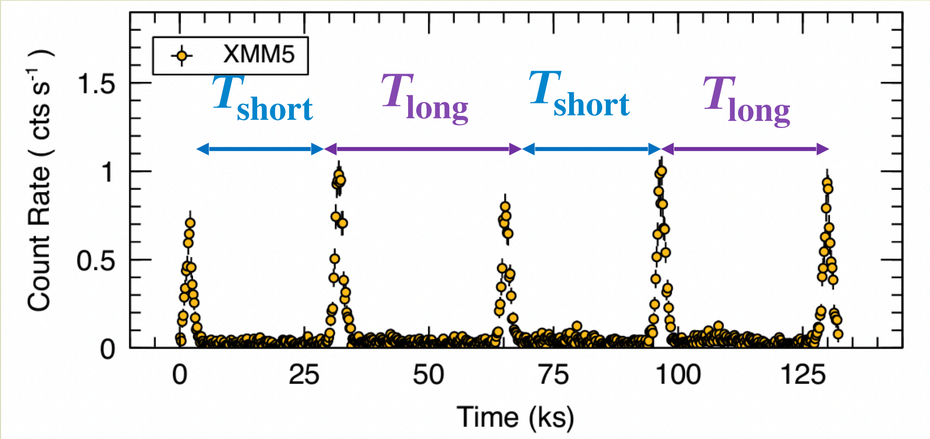
$$e \approx 0.1$$

* See dynamical formation

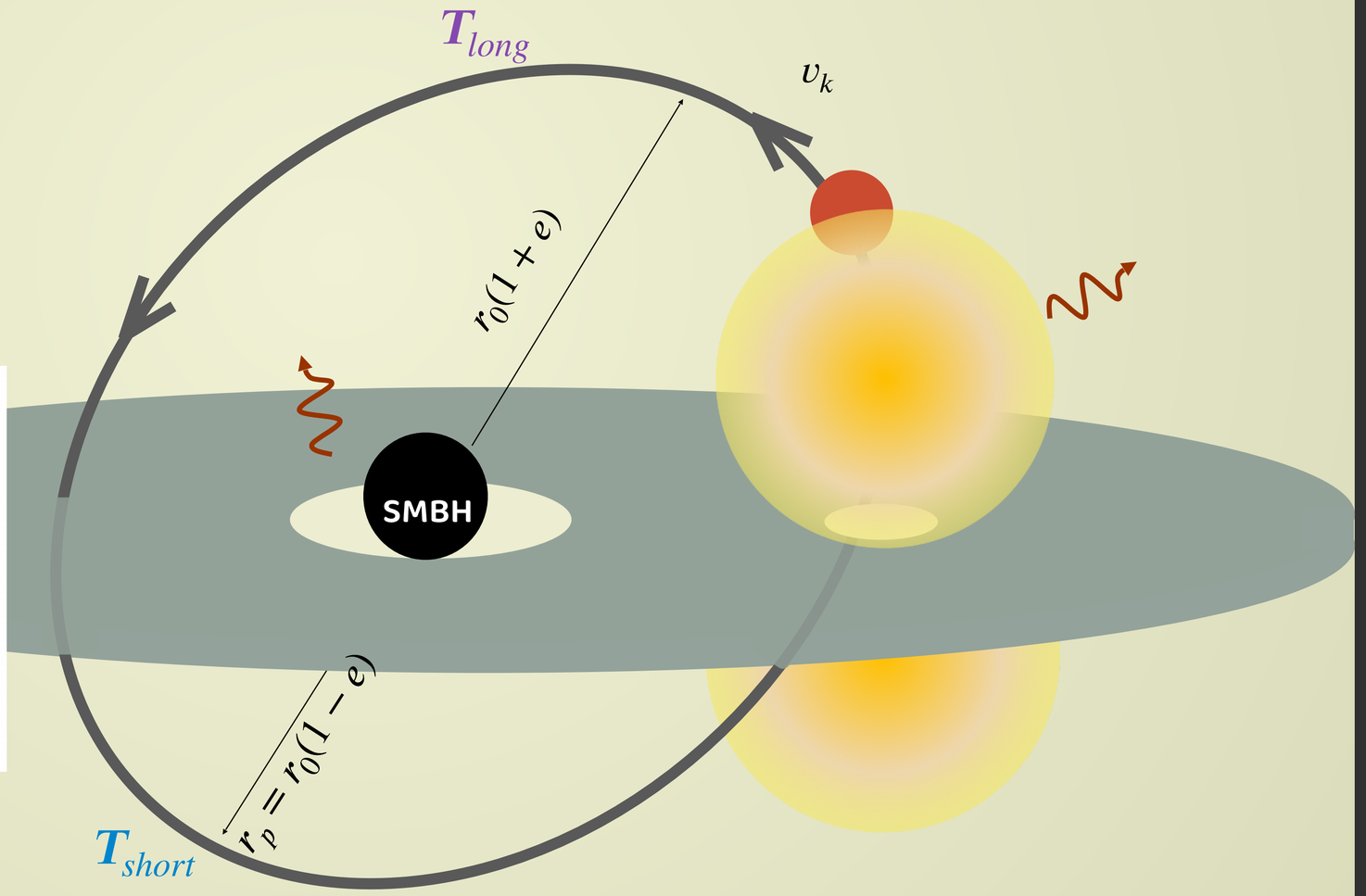
Light travel time

$$\delta t_{\rm lt} \leq \frac{2a}{c} \approx 5\%\ \langle T\rangle$$

(Observer angle dependent)



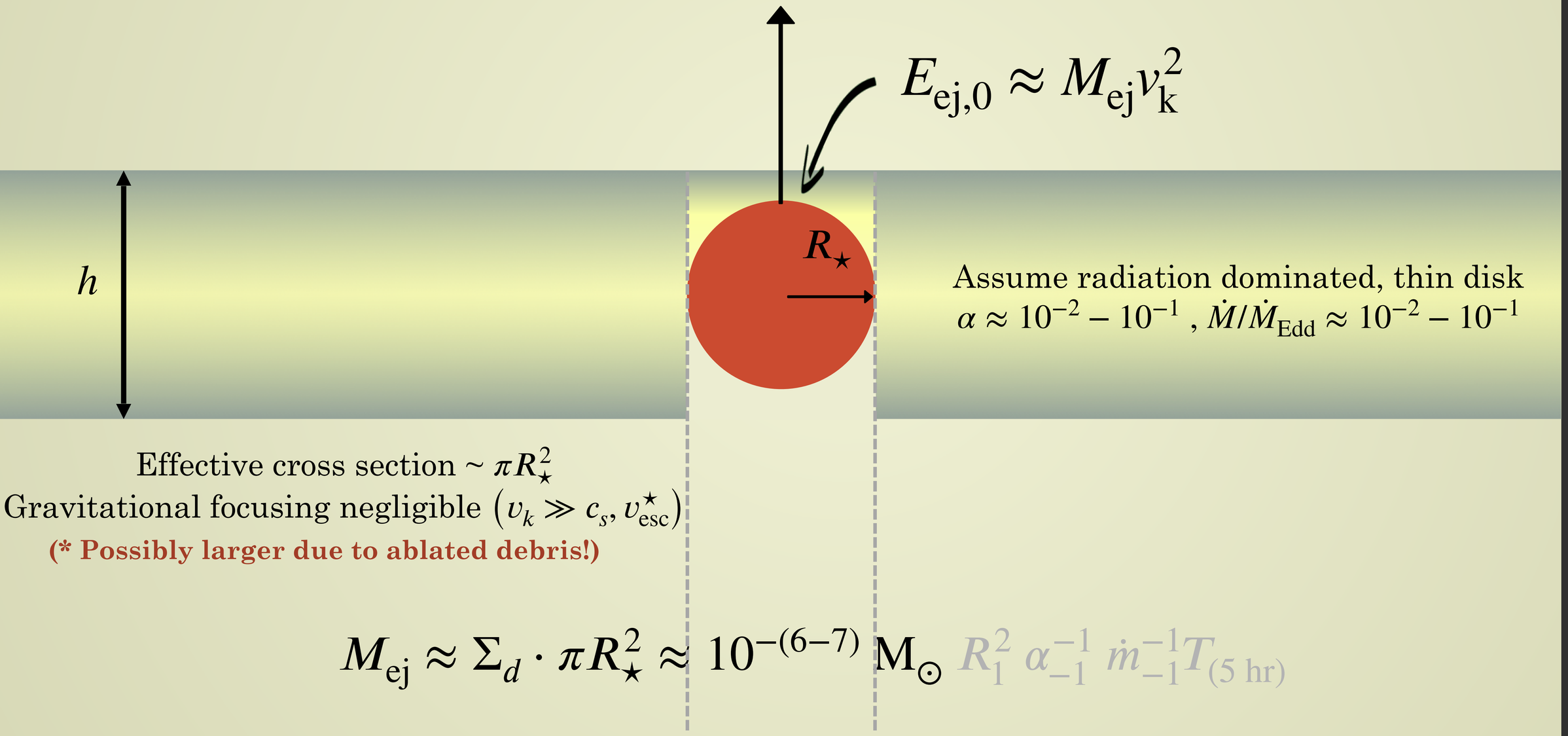
[Miniutti 2023]



Star Disk Collisions

$v_k \approx 0.1\mathrm{c}$ $M_{\bullet,6}^{1/3}\, T_{(5\ \mathrm{hr})}^{-1/3}$

$E_{\mathrm{ej},0} \approx M_{\mathrm{ej}} v_{\mathrm{k}}^2$



Assume radiation dominated, thin disk
$\alpha \approx 10^{-2} - 10^{-1}$, $\dot{M}/\dot{M}_{\mathrm{Edd}} \approx 10^{-2} - 10^{-1}$

Effective cross section ~ $\pi R_\star^2$
Gravitational focusing negligible $\left(v_k \gg c_s, v_{\mathrm{esc}}^\star\right)$
(* Possibly larger due to ablated debris!)

$$M_{\mathrm{ej}} \approx \Sigma_d \cdot \pi R_\star^2 \approx 10^{-(6-7)}\,\mathrm{M}_\odot\; R_1^2\, \alpha_{-1}^{-1}\, \dot{m}_{-1}^{-1} T_{(5\ \mathrm{hr})}$$

Radiation escape condition

$t_{\rm diff} \approx t_{\rm dyn} \rightarrow \tau_{\rm peak} \approx \frac{c}{v_k} = 10$ *

$$\tau(t) \approx \frac{\kappa_{\rm es} M_{\rm ej}}{4\pi (v_k t)^2}$$

$$t_{\rm peak} \approx \sqrt{\frac{\kappa_{\rm es} M_{\rm ej}}{4\pi v_k c}} \approx 0.3\ {\rm hr}$$

$$L_{\rm peak} \approx L_{\rm Edd} \left(\frac{R_\star}{a}\right) \approx 10^{42}\ {\rm erg/s}$$

R

$$R_{\rm peak} \approx v_k t_{\rm peak} \sim 10^{12}\ {\rm cm}$$

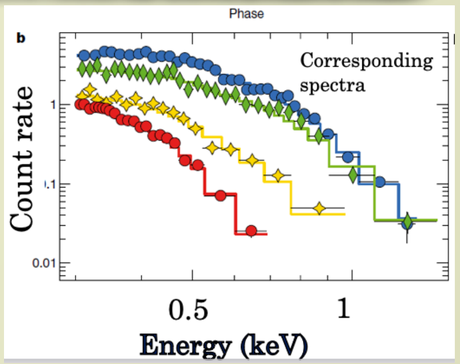
Internal energy degraded by adiabatic expansion

$PV^\gamma = {\rm const}$

$$E_{\rm int}(t) \approx M_{\rm ej} v_k^2 \left(\frac{V_0}{(v_k t)^3}\right)^{\gamma-1}$$

Temperature:
Photon starved ejecta - Comptonized free-free

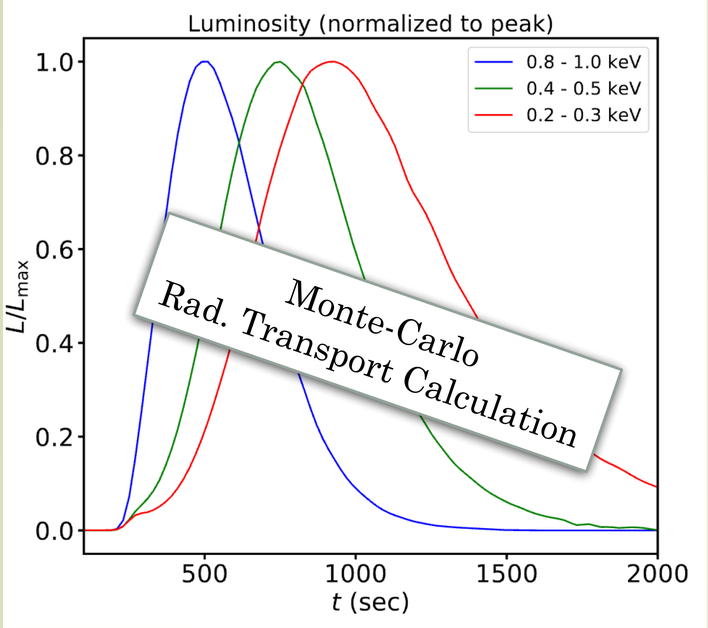
~Thermal Wien-tail of kT~100eV

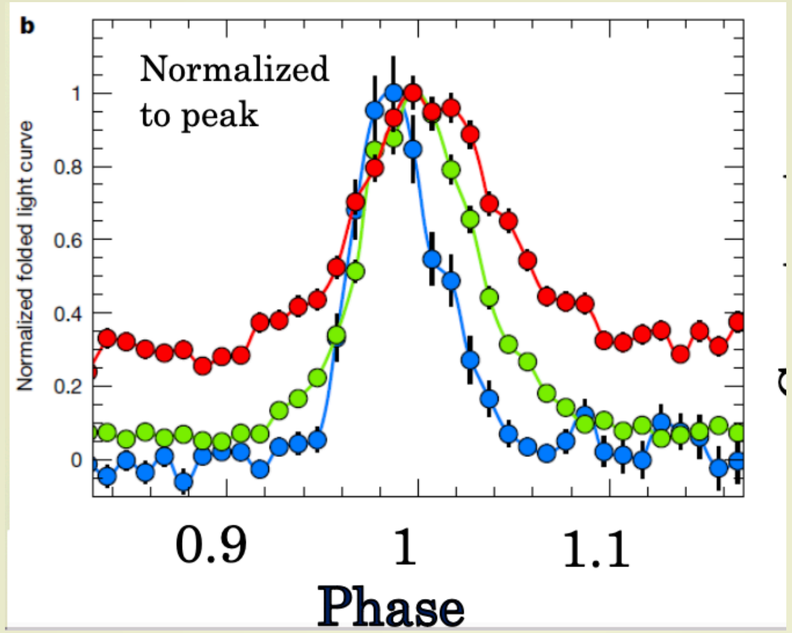


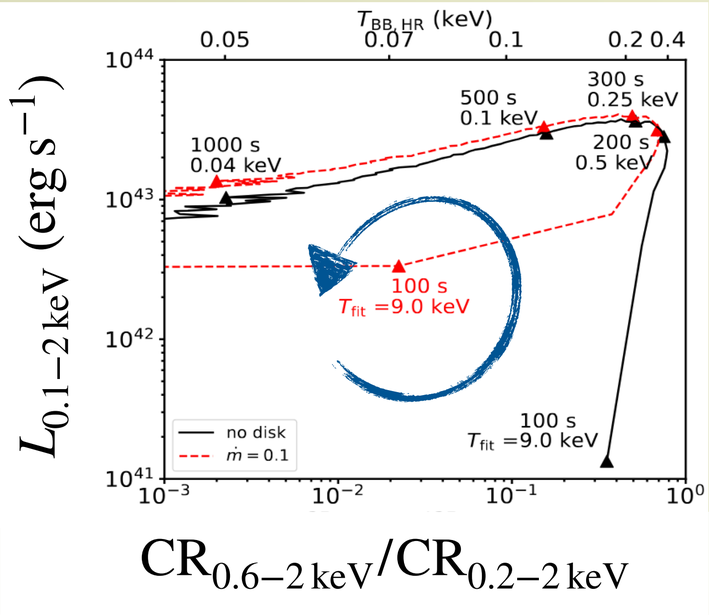
* Nayakshin et al. (2004) use $\tau \approx 1$ - resulting in flares dimmer by 2 orders of mag.

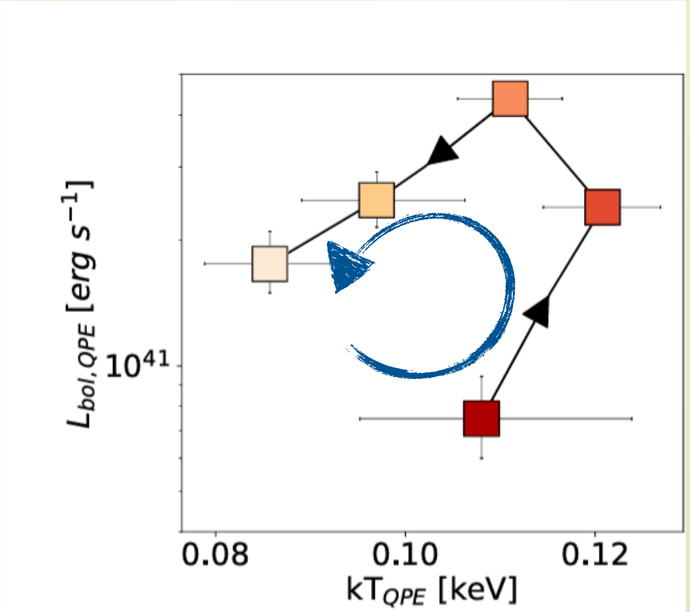
Star Disk Collisions - Numerical Calculation

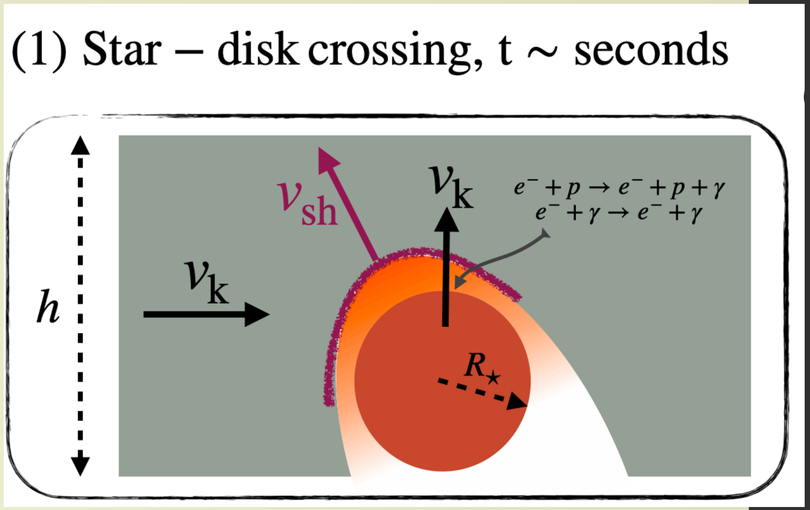
Vurm, **Linial**, Metzger (2024)

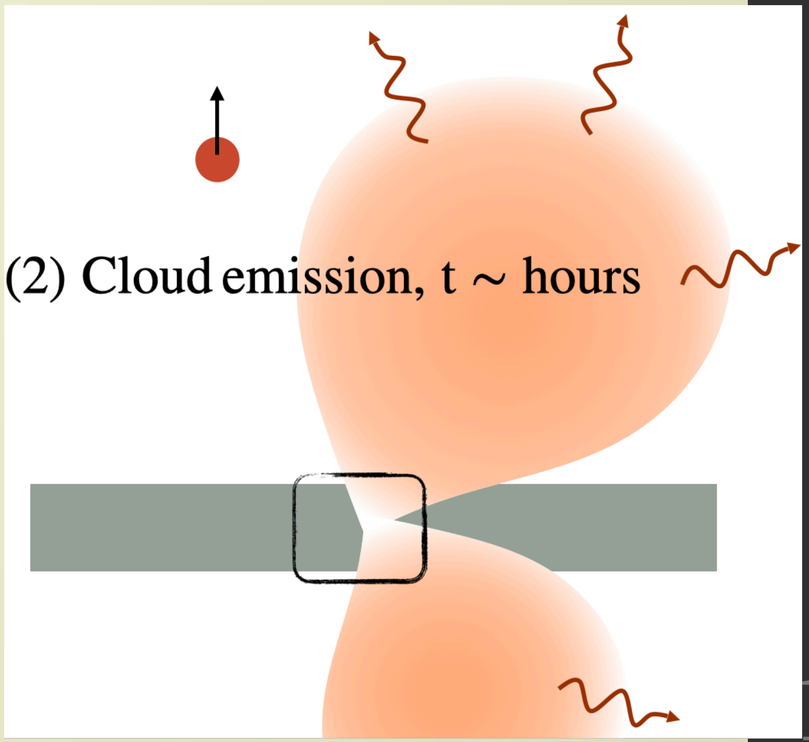










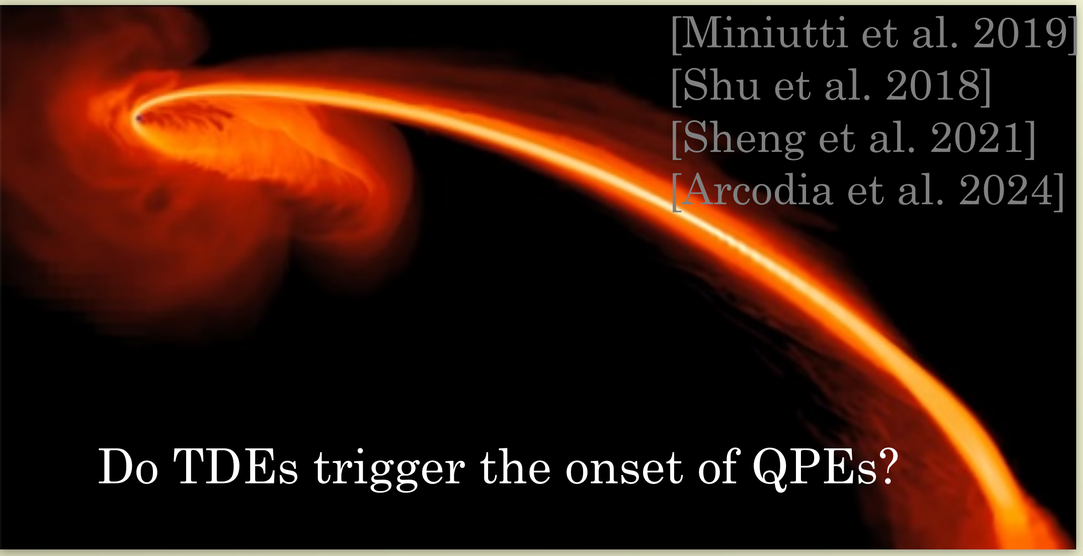


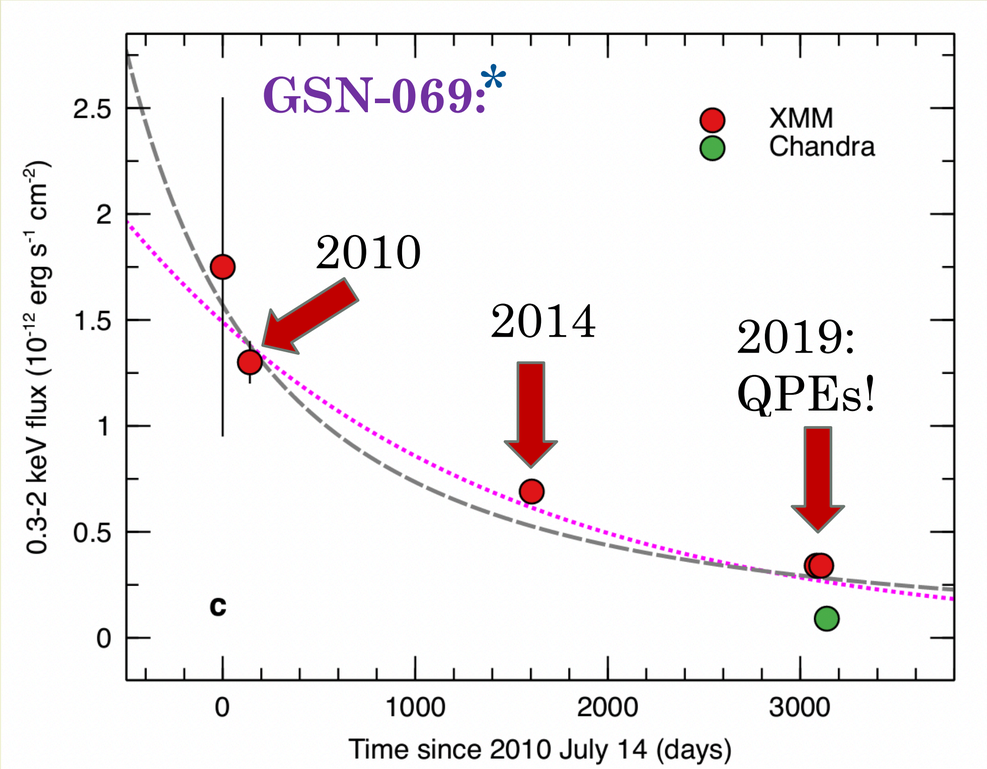
QPE-TDE association

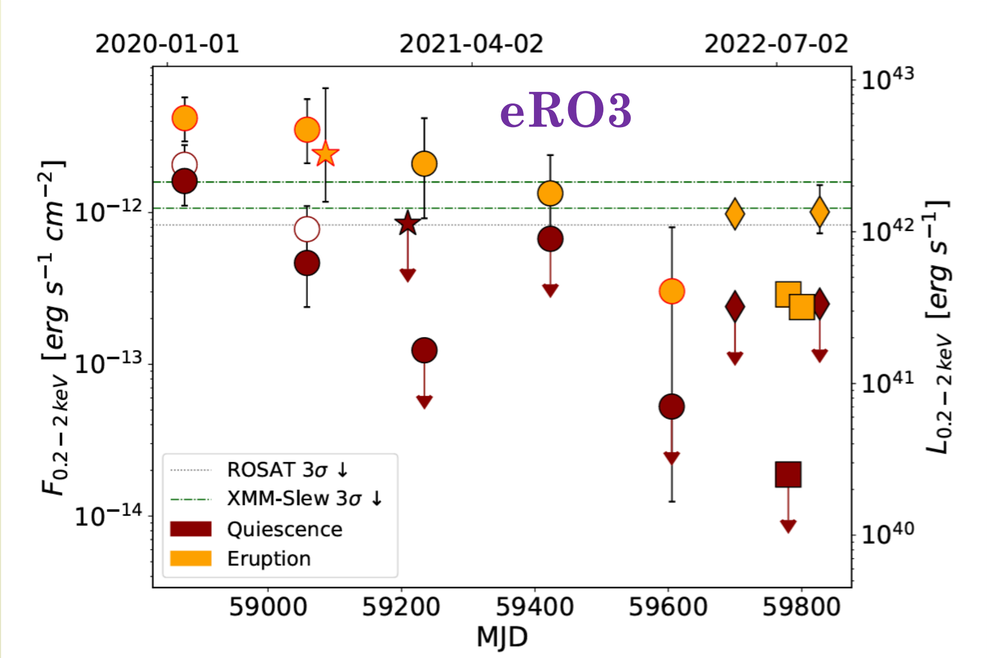
- Gradual **X-ray decay** preceding QPE appearance
  (seen in GSN-069, eRO-QPE3, AT2019vcb, +1 candidate)

- QPE hosts generally consistent with TDE hosts
  [Wevers+22,24, Gilbert+24]

* TDE? Surprisingly slow decay? See [Linial&Metzger 24b]





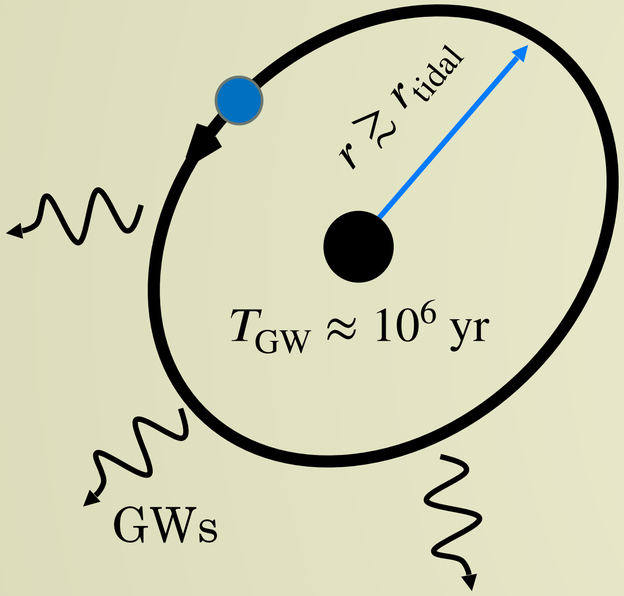


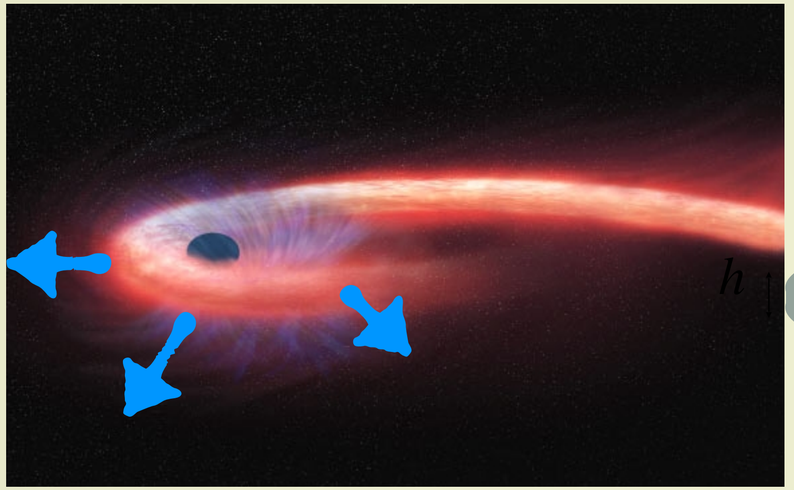
EMRI + TDE = QPE: Periodic X-Ray Flares from Star–Disk Collisions in Galactic Nuclei

Itai Linial[1] and Brian D. Metzger[2,3]

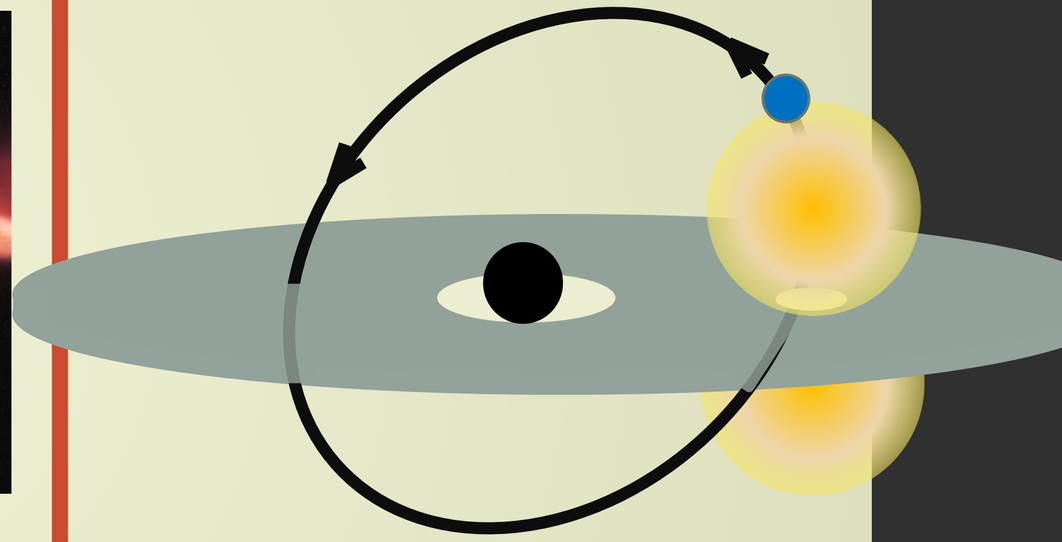
[Linial & Metzger 23]

"EMRI + TDE = QPE"





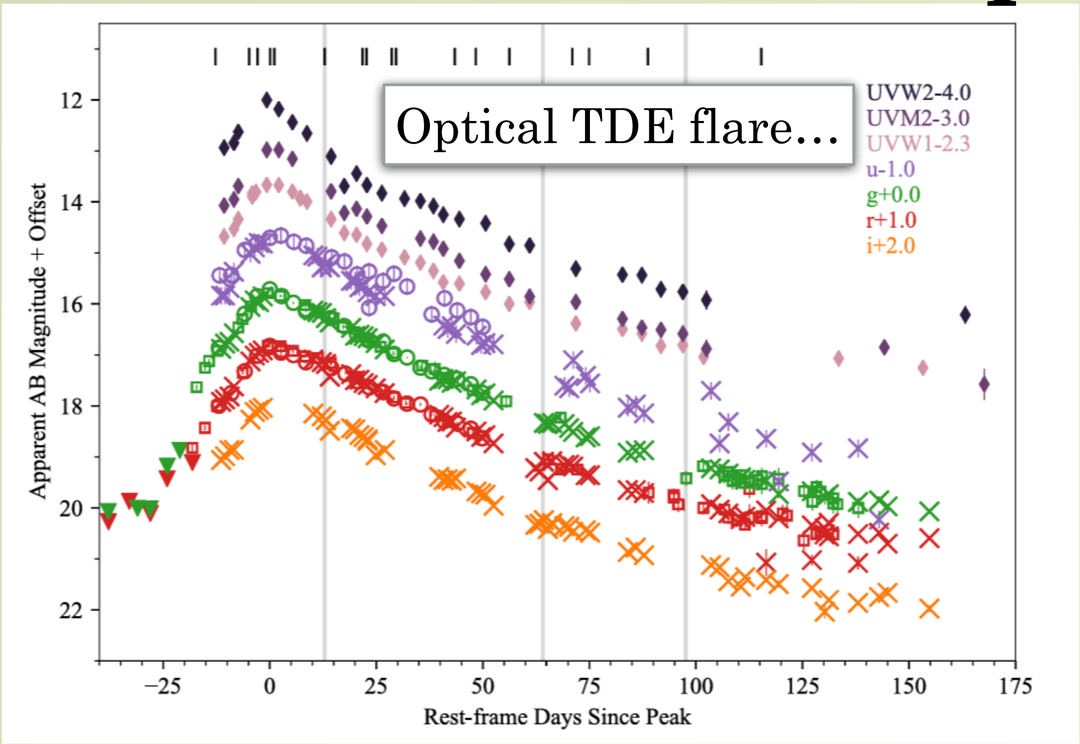
$\mathscr{R}_{\rm TDE} \approx 10^{-5} - 10^{-4}\ {\rm yr}^{-1}\ {\rm gal}^{-1}$

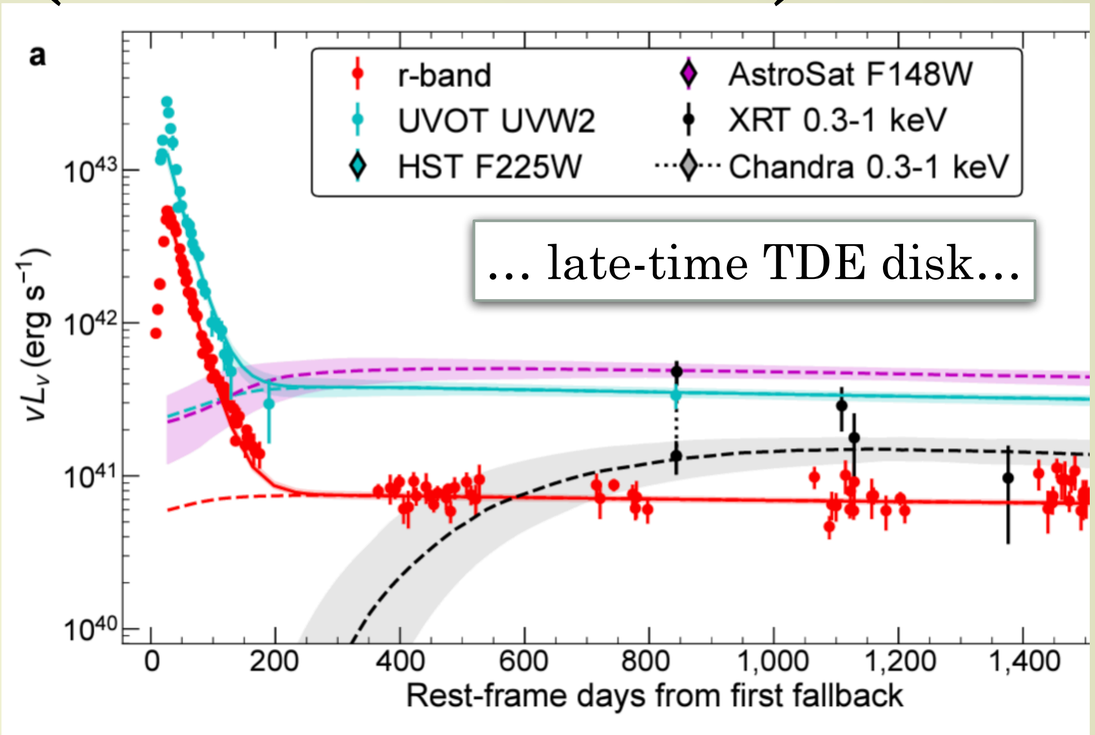


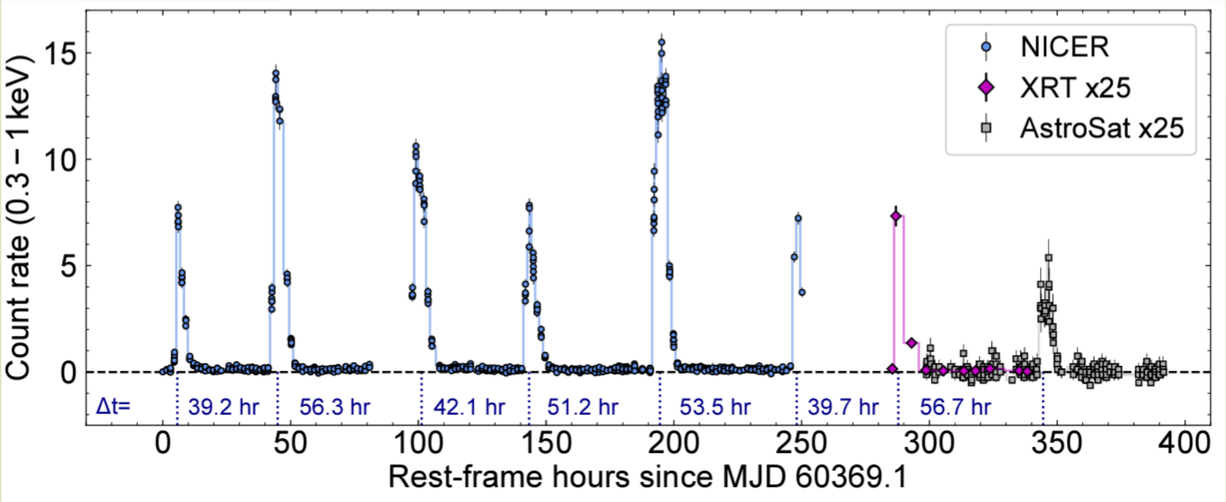
* **QPE-TDE association**
* **Delay time** between TDE and QPE (settle to thin disc)
* Typically **high inclination**
* Reproduces **QPE periodicity** ($r_{\rm disc} \approx 2r_{\rm tidal}$)
* Delayed onset due to **disk spreading** and/or $\dot{M}_{\rm d}$ **evolution**

The relative rates of TDEs and stellar EMRIs are such that a significant fraction ~1%–10% of TDE flares should host a QPE, depending in the details on the EMRI rate and number of TDE flares a given EMRI can survive (Section 3.3). Within large theoretical and observational uncertainties, the occurrence rate of EMRI-TDE

The Case of AT 2019qiz (see Matt's talk)





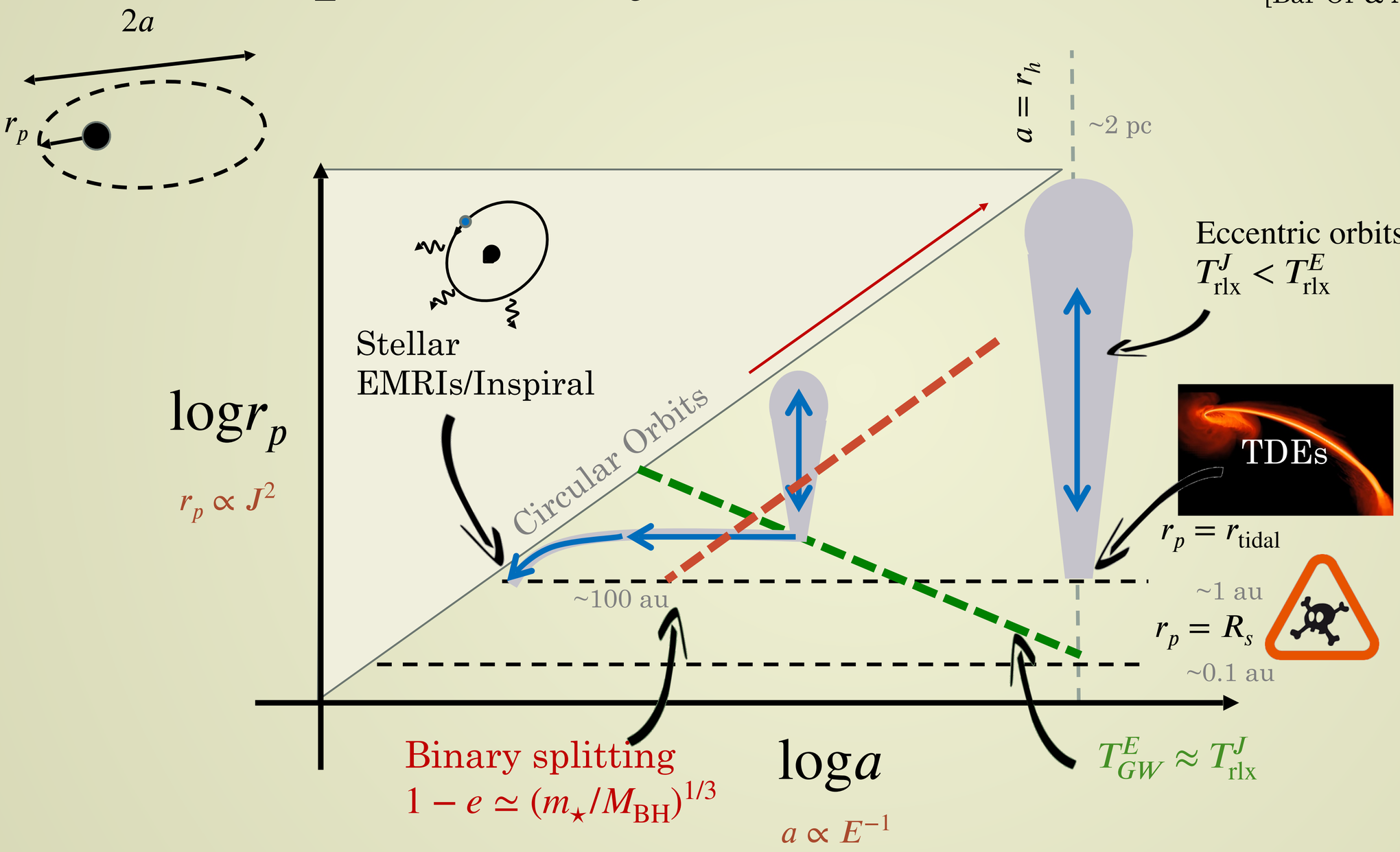


…X-ray QPEs!

[Nicholl+24]

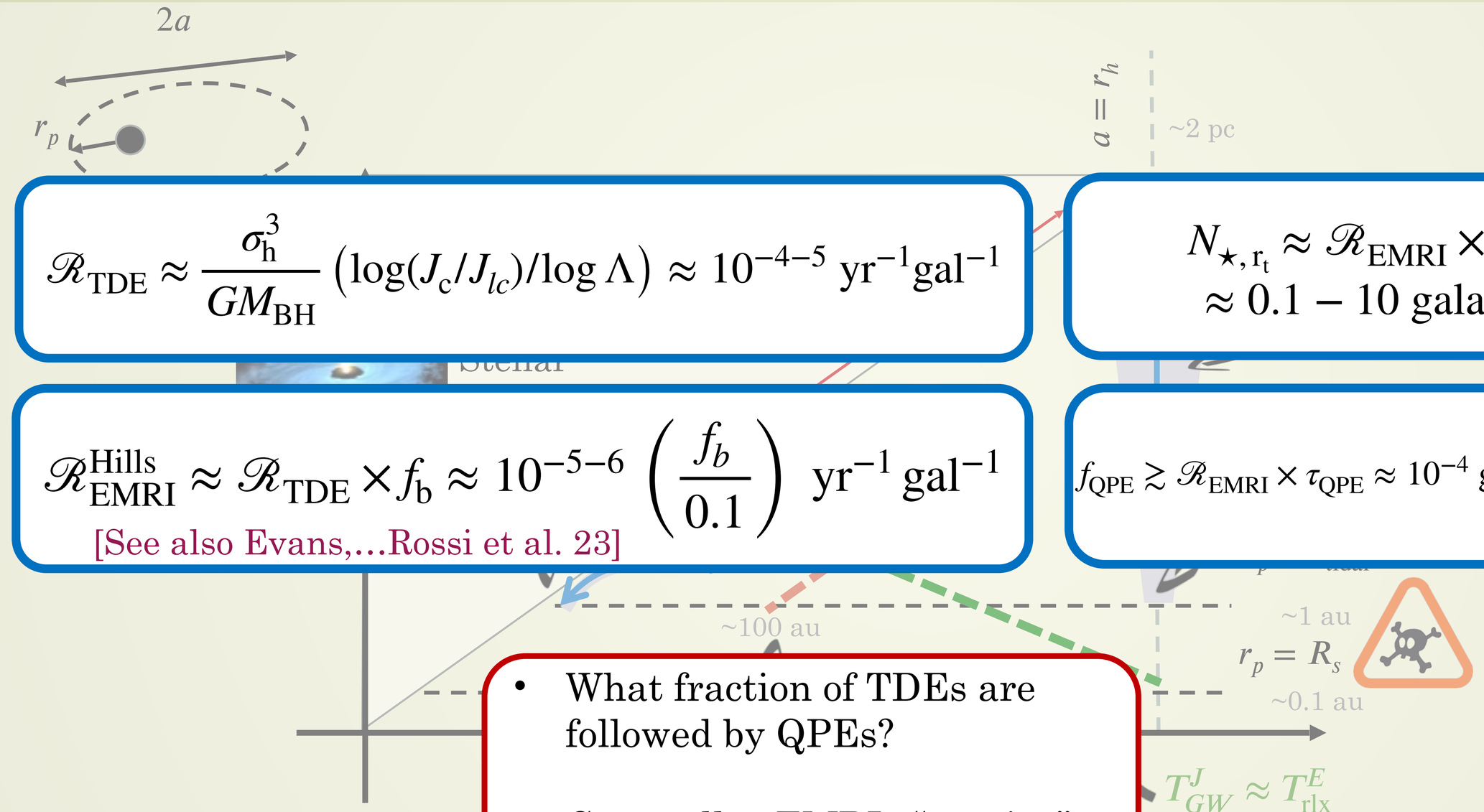
Phase Space Trajectories

[**Linial** & Sari 2023]
[Sari & Fragione 2019]
[Miller (2005)]
[Bar-Or & Alexander (2016)]



Phase Space Trajectories

[Linial & Sari 2022]
[Sari & Fragione 2019]



$$\mathscr{R}_{\rm TDE} \approx \frac{\sigma_{\rm h}^3}{GM_{\rm BH}} \left(\log(J_{\rm c}/J_{lc})/\log\Lambda\right) \approx 10^{-4-5}\ {\rm yr}^{-1}{\rm gal}^{-1}$$

$$N_{\star,\,{\rm r_t}} \approx \mathscr{R}_{\rm EMRI} \times T_{\rm GW} \approx 0.1 - 10\ {\rm galaxy}^{-1}$$

$$\mathscr{R}^{\rm Hills}_{\rm EMRI} \approx \mathscr{R}_{\rm TDE} \times f_{\rm b} \approx 10^{-5-6} \left(\frac{f_b}{0.1}\right)\ {\rm yr}^{-1}\ {\rm gal}^{-1}$$

[See also Evans,…Rossi et al. 23]

$$f_{\rm QPE} \gtrsim \mathscr{R}_{\rm EMRI} \times \tau_{\rm QPE} \approx 10^{-4}\ {\rm gal}^{-1} \left(\frac{\tau_{\rm QPE}}{10\ {\rm yr}}\right)$$

- What fraction of TDEs are followed by QPEs?
- Can stellar EMRIs "survive" multiple TDEs?

QPEs are Rare

4 eROSITA QPEs
Per-Galaxy abundance:

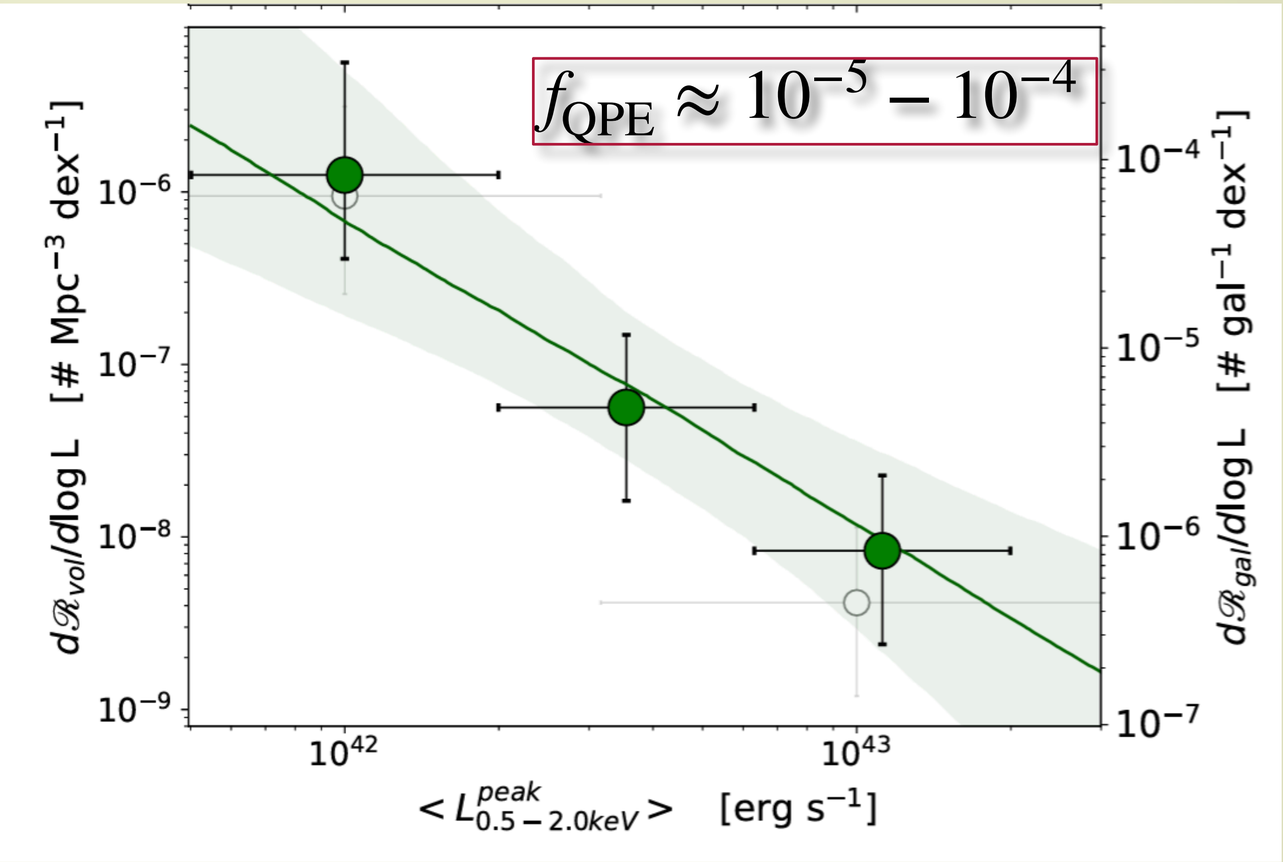
$$f_{\rm QPE} \approx \frac{\mathcal{O}(1)\ \text{QPEs}}{N_{\rm gal}(d)} \approx 10^{-4}$$

$d_{\rm QPE} \approx 100\,{\rm Mpc}$

$N_{\rm gal}(< d_{\rm QPE}, M_{\rm BH} \approx 10^6\,{\rm M}_\odot) \approx 10^4$

Per-Galaxy Formation Rate

$$\mathscr{R}_{\rm QPE} \approx f_{\rm QPE}/\tau_{\rm life} \approx 10^{-(5-6)}\ {\rm yr}^{-1} \left(\frac{\tau_{\rm life}}{10\,{\rm yr}}\right)^{-1}$$



[Arcodia+24b]

Additional Topics

Long term evolution of Repeating Nuclear Transients
* **Linial**&Quataert 24a , Arcodia, **Linial** et al. 24, Pasham+24

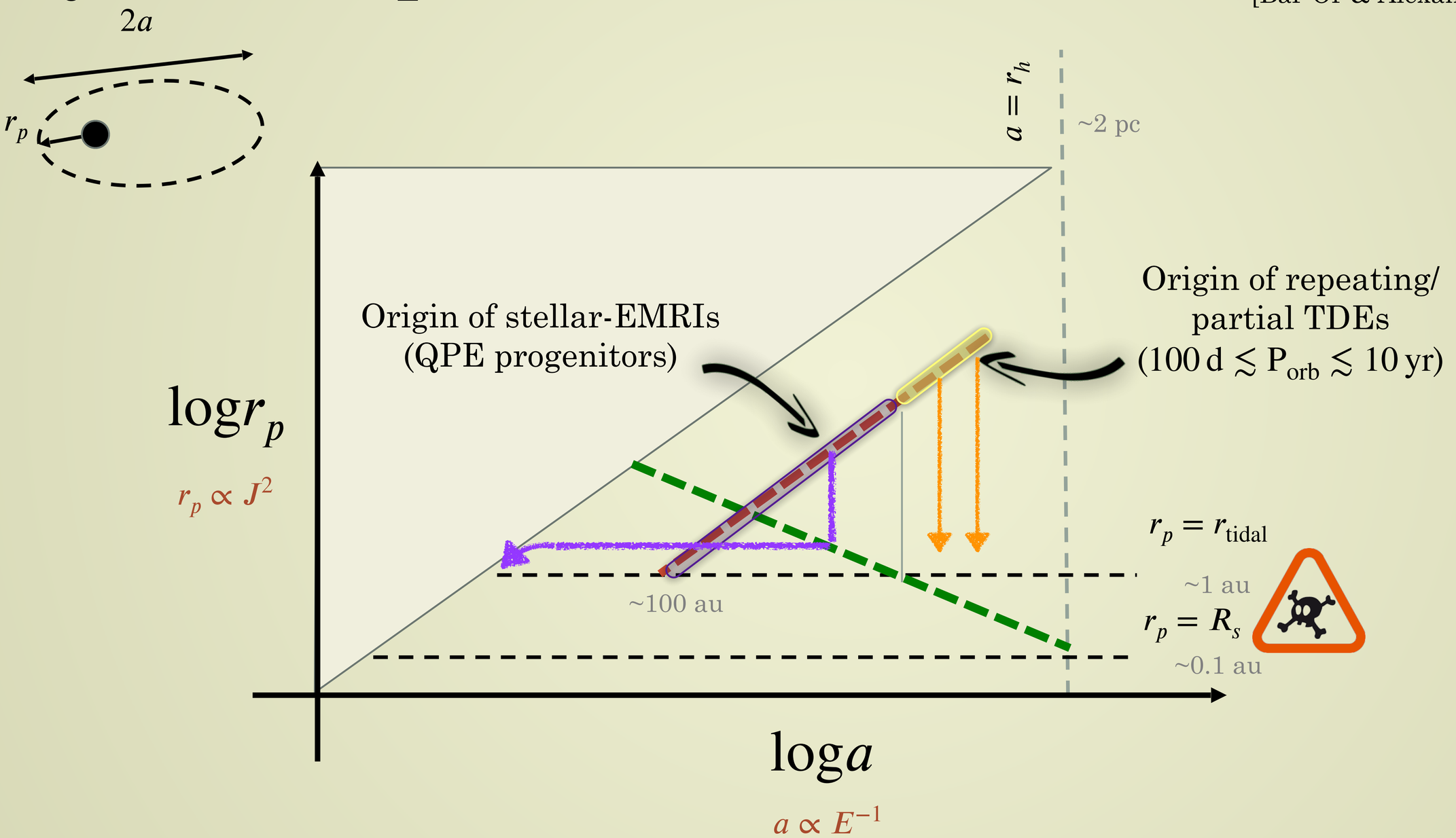
Lifetime of QPEs
* **Linial**&Metzger 23, 24a , Yao+24

Mass transfer from stellar-EMRIs
* **Linial**&Sari 17, 23 , **Linial**&Quataert 24b

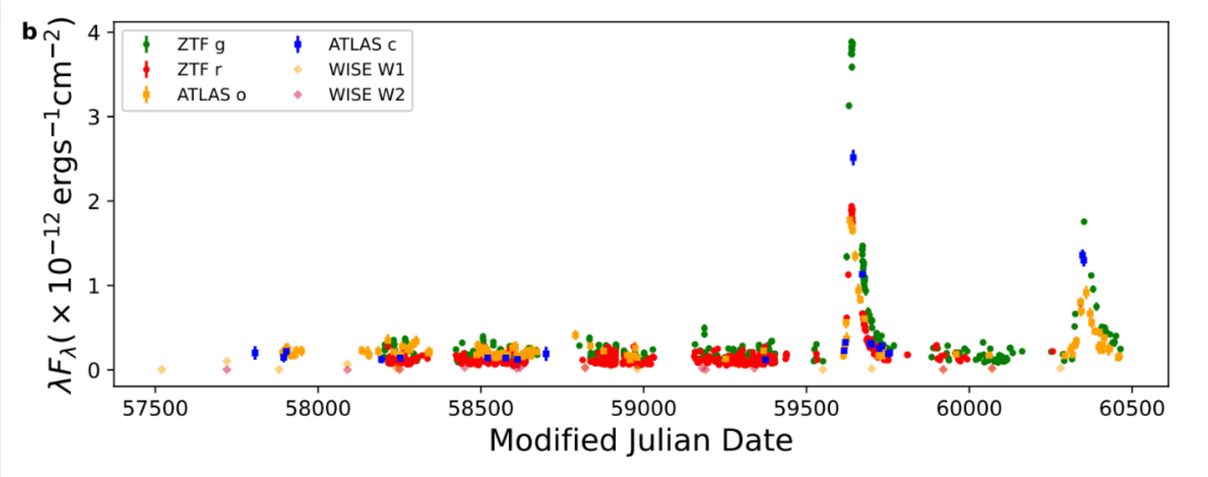
Repeating TDEs vs. QPEs
* **Linial**&Quataert 24a, Makrygianni+24

QPEs vs. rpTDEs

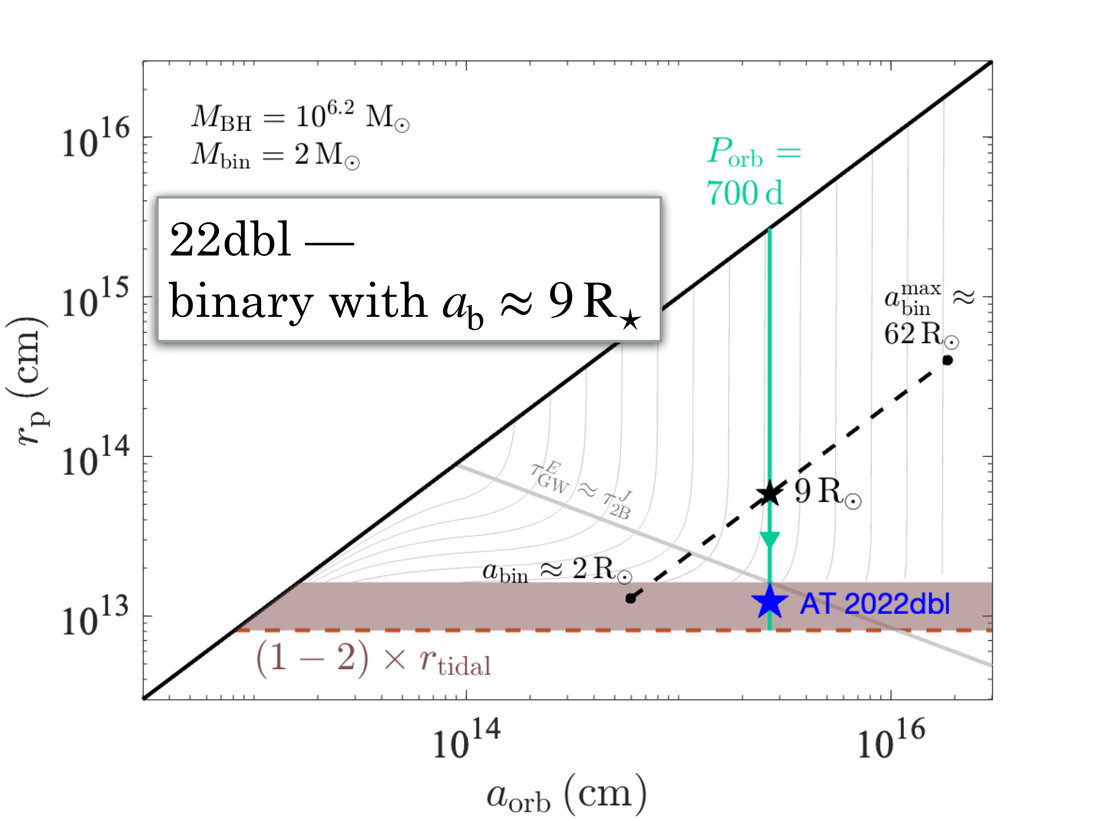
[**Linial** & Sari 2023]
[Sari & Fragione 2019]
[Miller (2005)]
[Bar-Or & Alexander (2016)]

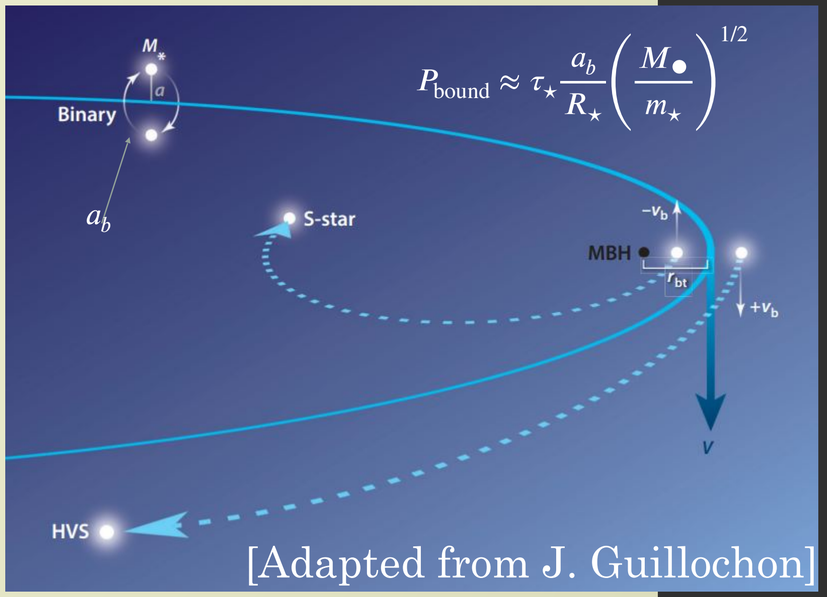


The “dbl” TDE (AT 2022dbl) [See Iair’s talk]



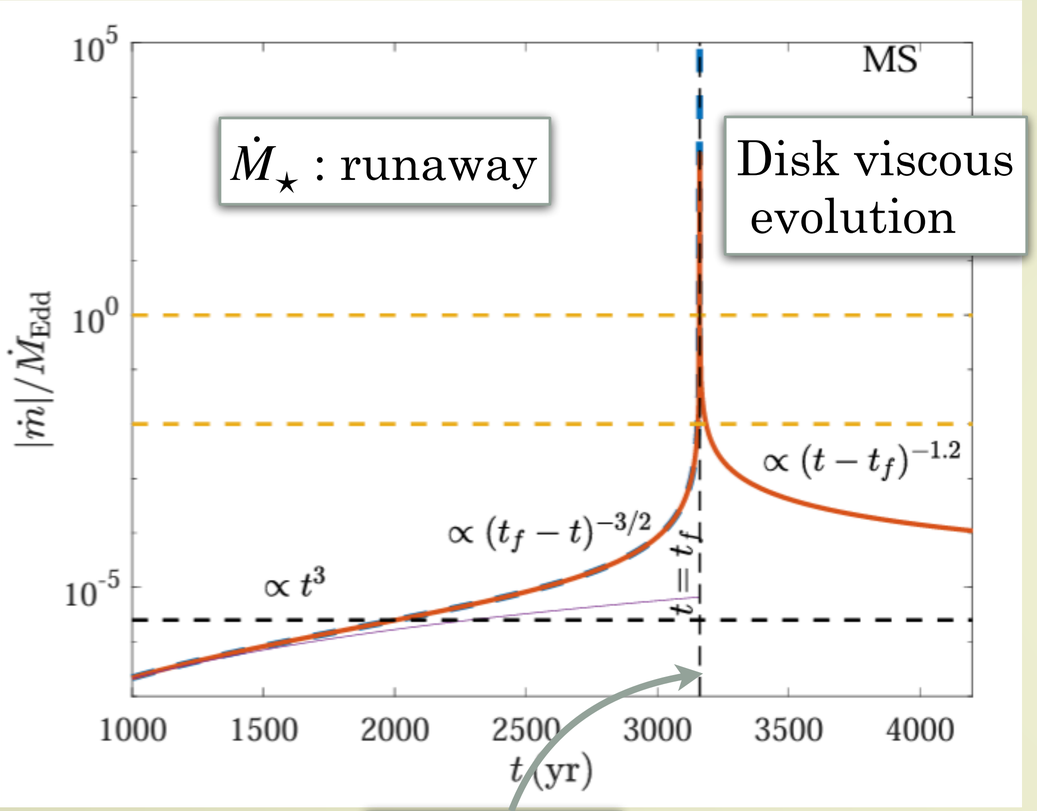
[Makrygianni+24 (submitted)]



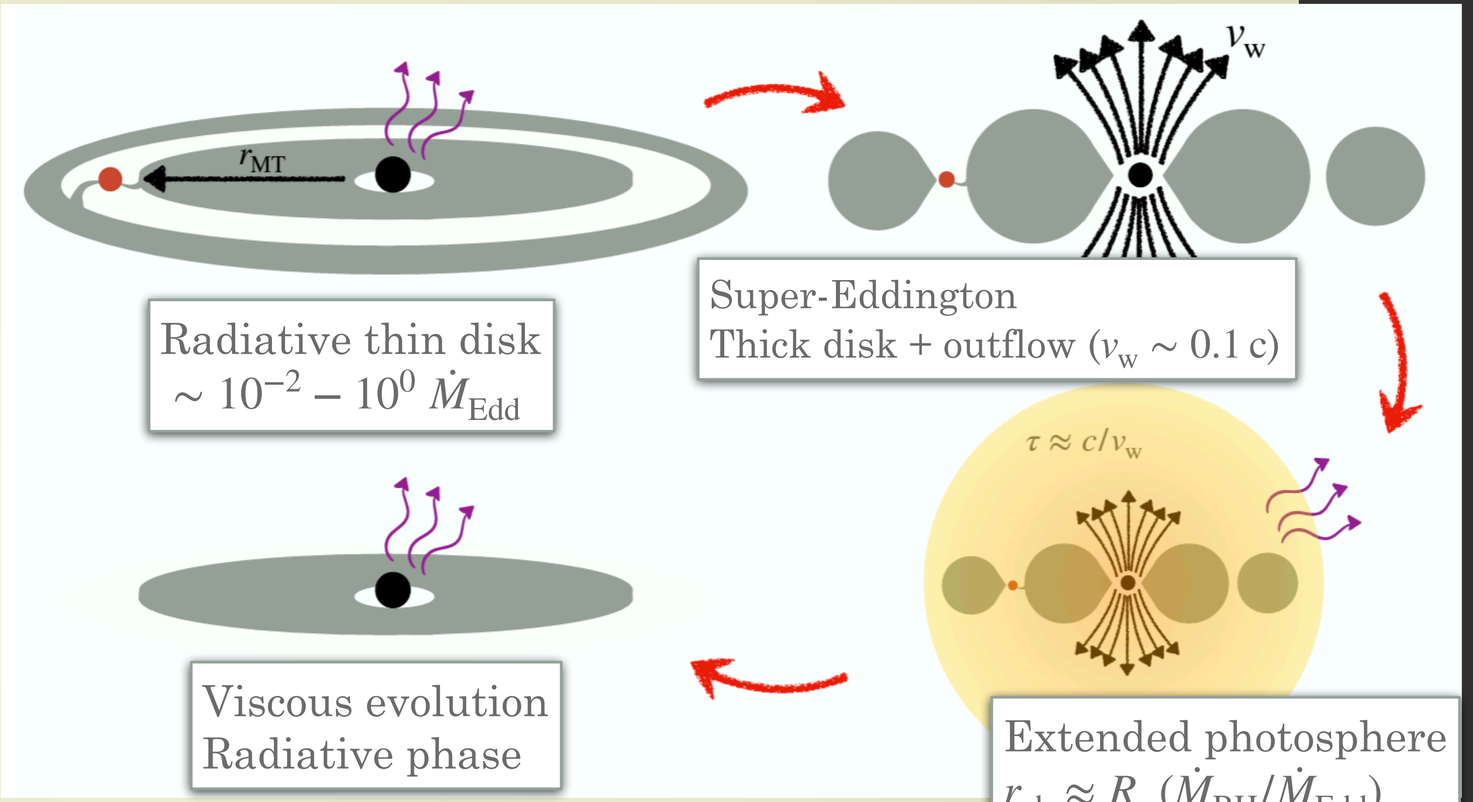


Circular TDEs (Linial & Quataert 24b)

Orbit shrink to $r \to \sim r_t$: Roche Lobe Overflow , **UNSTABLE** mass transfer [e.g., Linial & Sari 23]

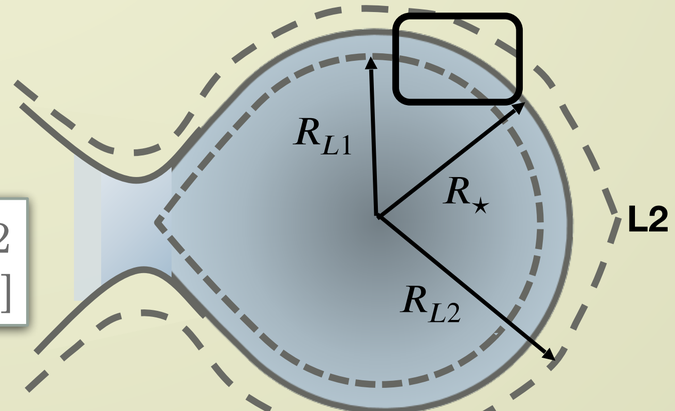


Final disruption



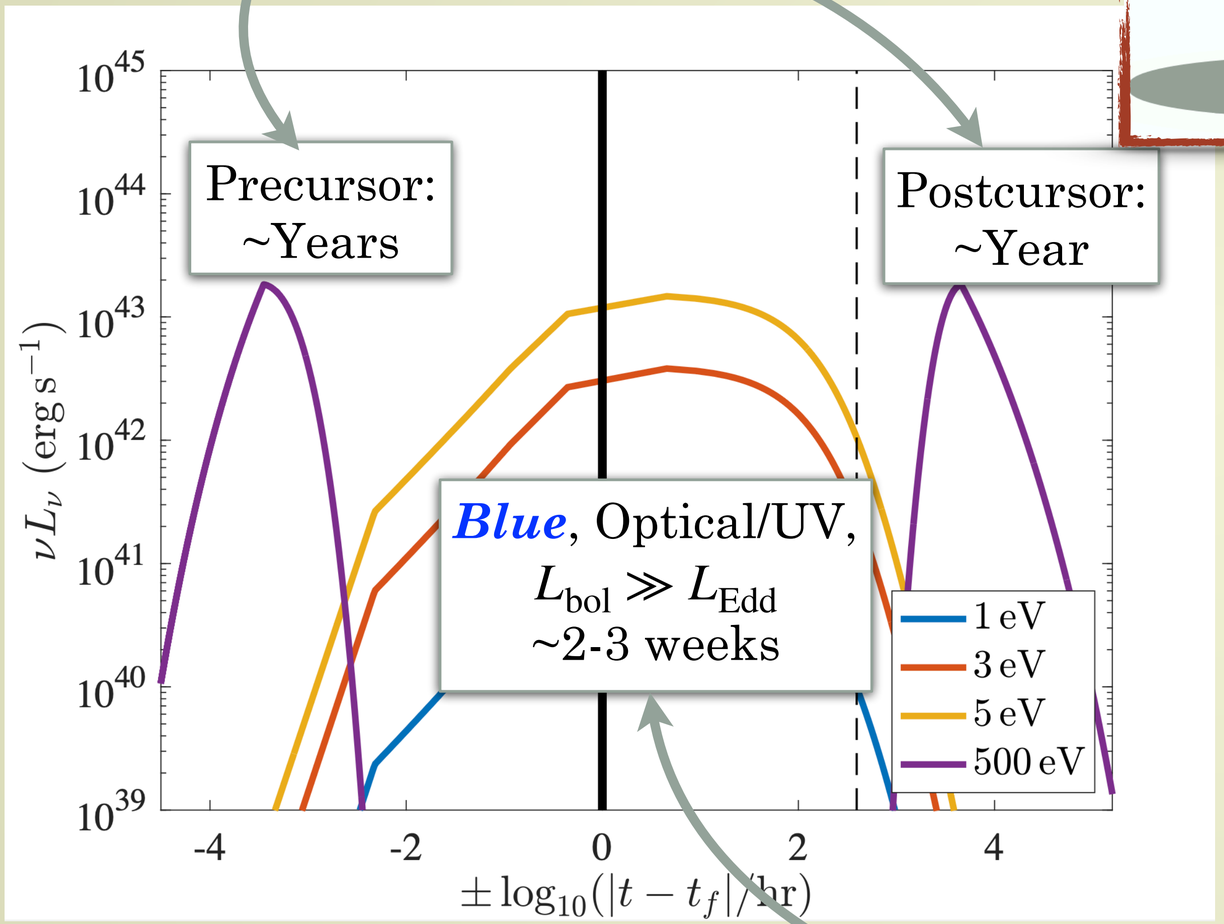
$$\dot{M}_\star \approx \frac{M_\star}{t_{\rm dyn}} \left(\frac{R_\star - R_{\rm L1}}{R_\star} \right)^3$$

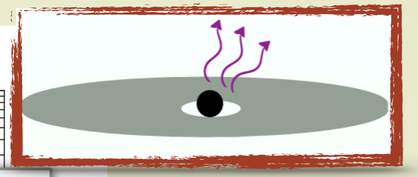
Mass loss from L2
[Linial & Sari 17]



Circular TDEs - Unique Observable Predictions

Inner radiative disk
Soft X-rays

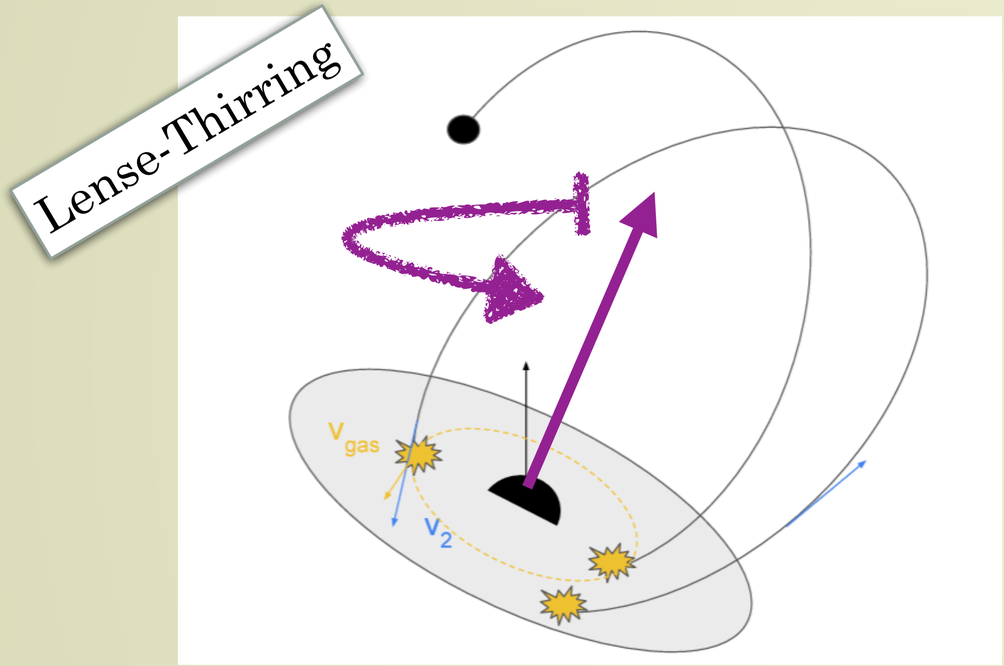




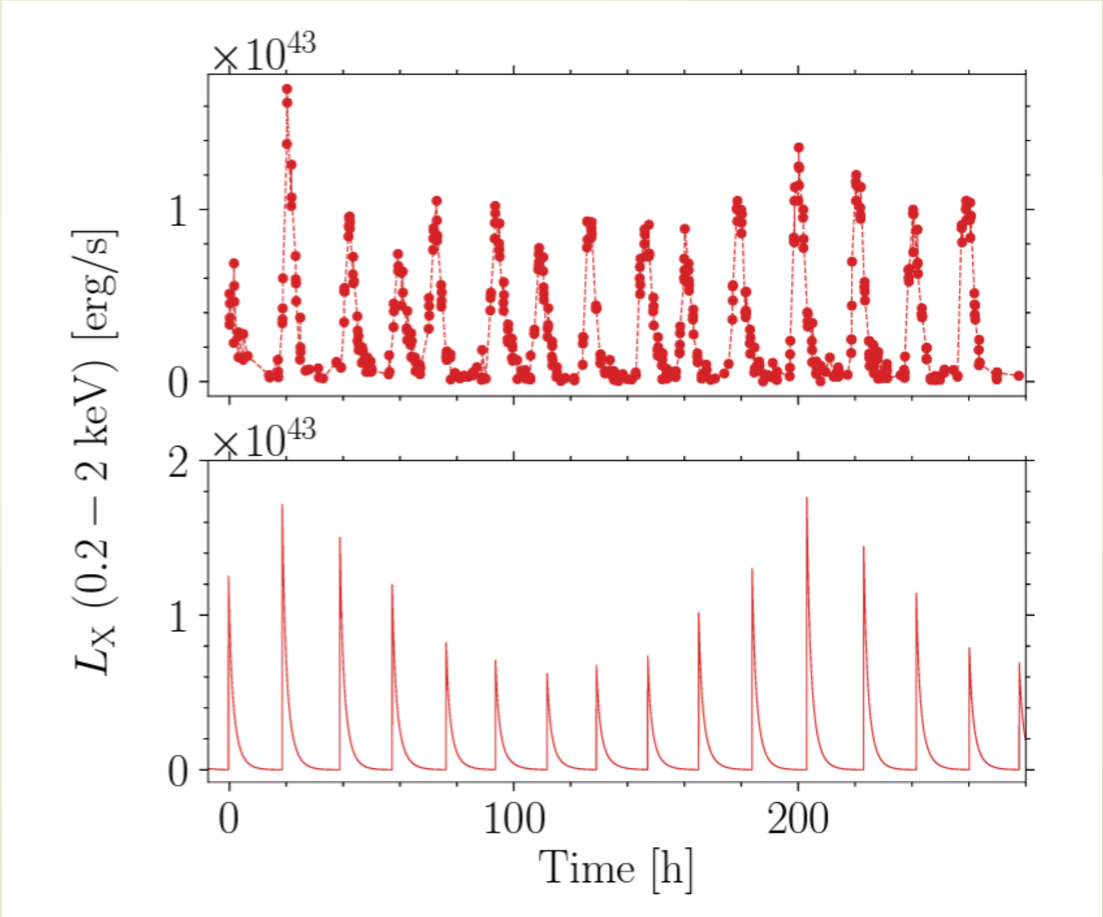
- TDEs in AGN
- **L**uminous **F**ast **B**lue **O**ptical **T**ransients (**LFBOT**s)
- Connection to jetted TDEs

Extended super-Eddington outflow

Complex timing patterns - disk precession [Franchini et al. (2023)]



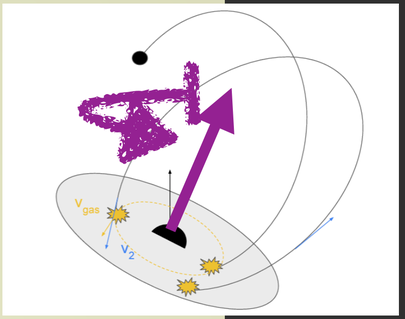
QPE timing probes BH spin



[Franchini et al. (2023)]

[Pasham+24,Chakraborty+24]

eRO-QPE1



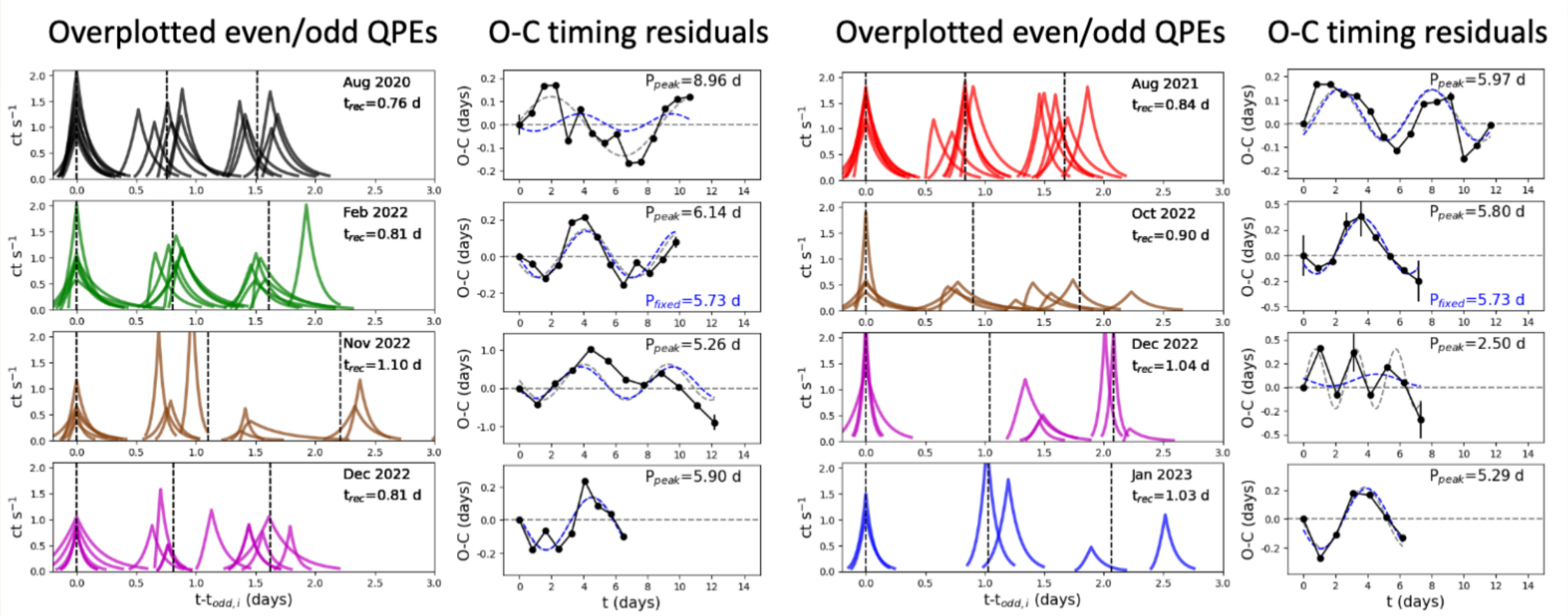
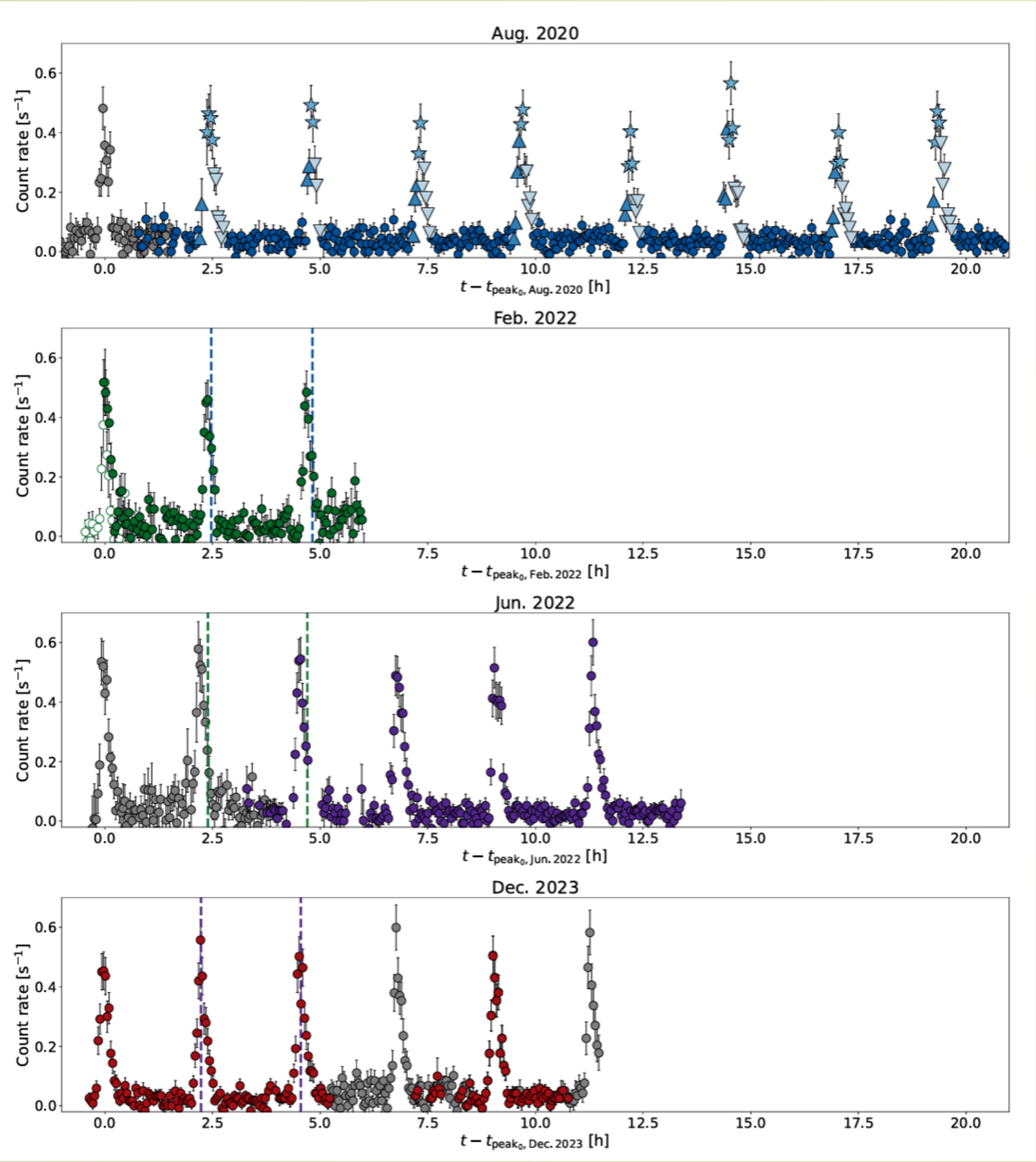
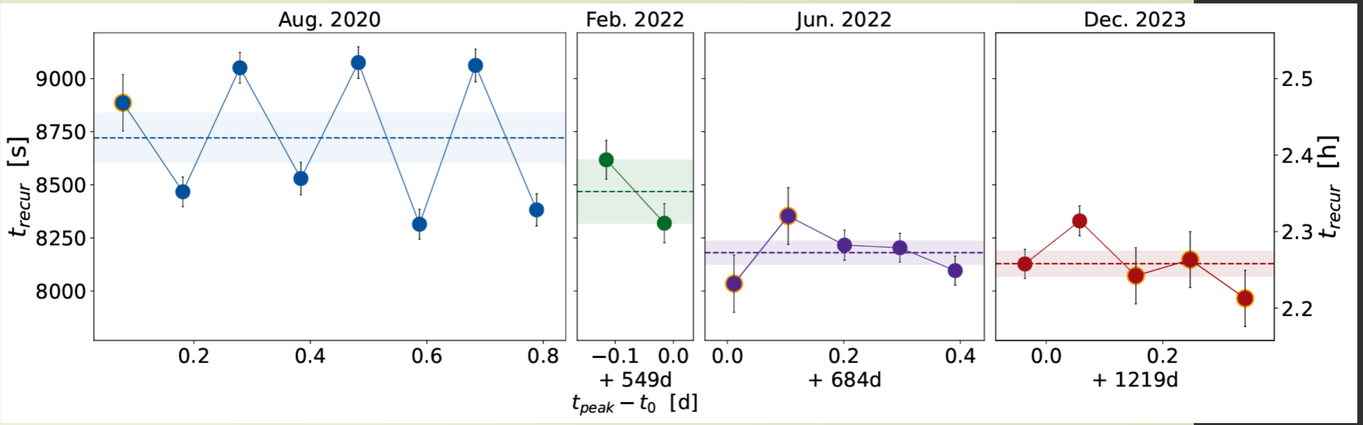


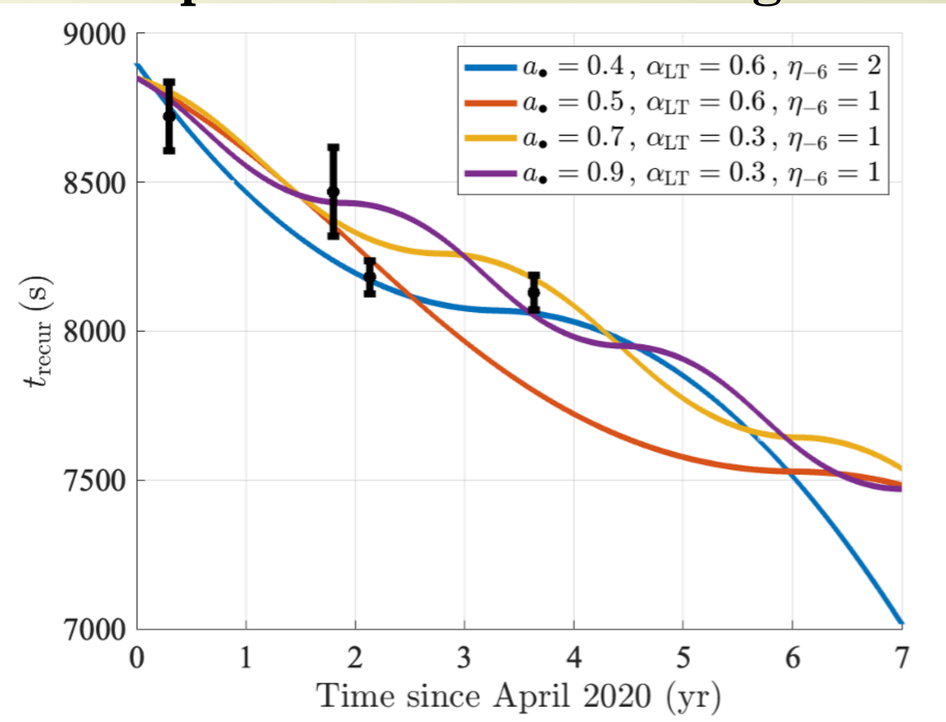
Figure 6. Overplotted even/odd burst sequences (demonstrating the high scatter and lack of any long/short recurrence pattern), and the corresponding O-C timing residuals (i.e. whether each burst arrives early/late compared to the average t_{rec} within the epoch, Section 2.3). As noted in Arcodia et al. 2022, the scatter in recurrence time ($\sim 50\%$) is significantly higher than other QPE sources. The O-C plots are overplotted with best-fit periods per-epoch (gray dashed line) and overall (blue dashed). The Aug 2020 epoch ($P_{peak} = 8.96$ days) and first Dec 2022 epoch ($P_{peak} = 2.5$ days) are significant outliers from the 5.73 average period. The first Dec 2022 epoch briefly shows the long-short recurrence pattern seen in other QPEs.

Recurrence Time Evolution - [Arcodia, Linial+24]



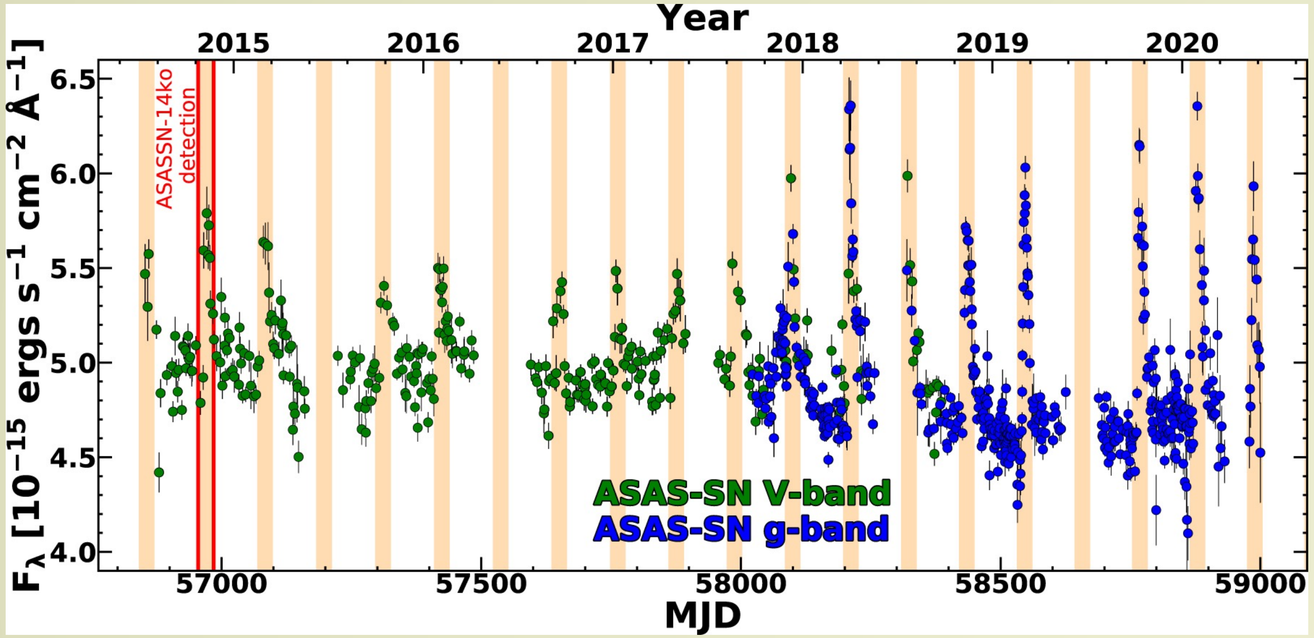


Nodal precession + disc drag



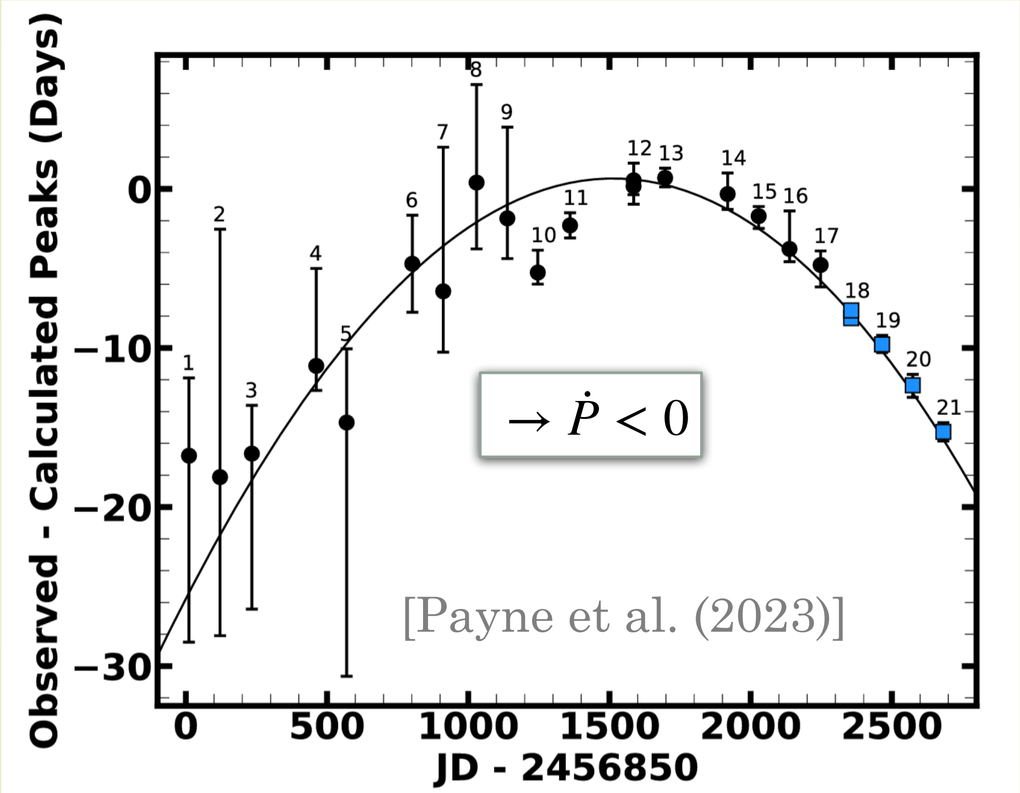
Other Repeating Nuclear Transients

- ASASSN-14ko - 115 days



[Payne et al. (2021)]

$$\text{Measured } \dot{P} \approx -2.7\times10^{-3}$$
$$\frac{P}{|\dot{P}|} \sim 100 \text{ yr}$$



Not a QPE:
(Detected in optical, Period ~100 day >> few hours)

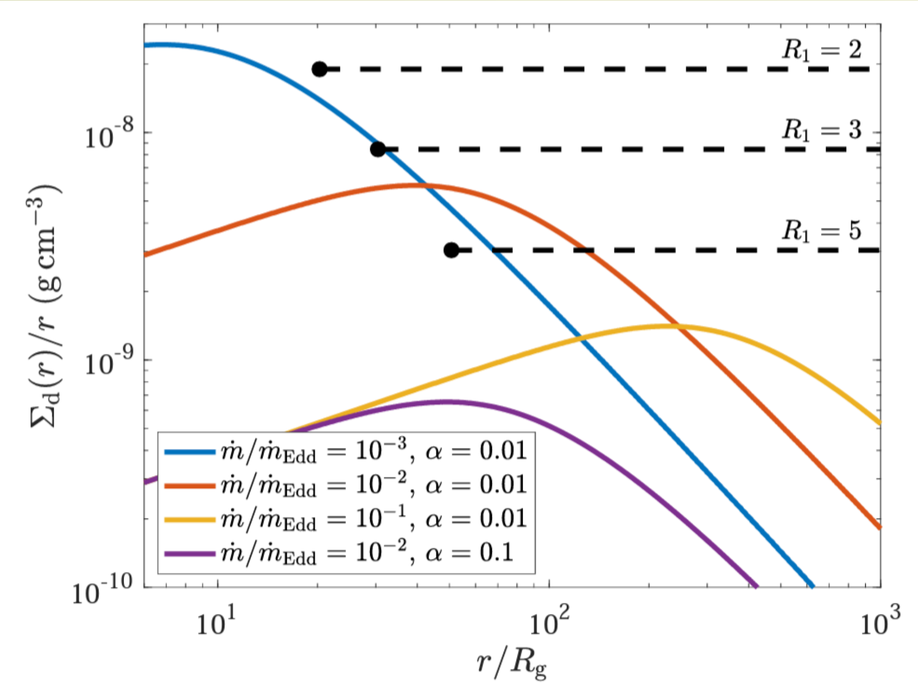
Repeating partial-TDE candidate?

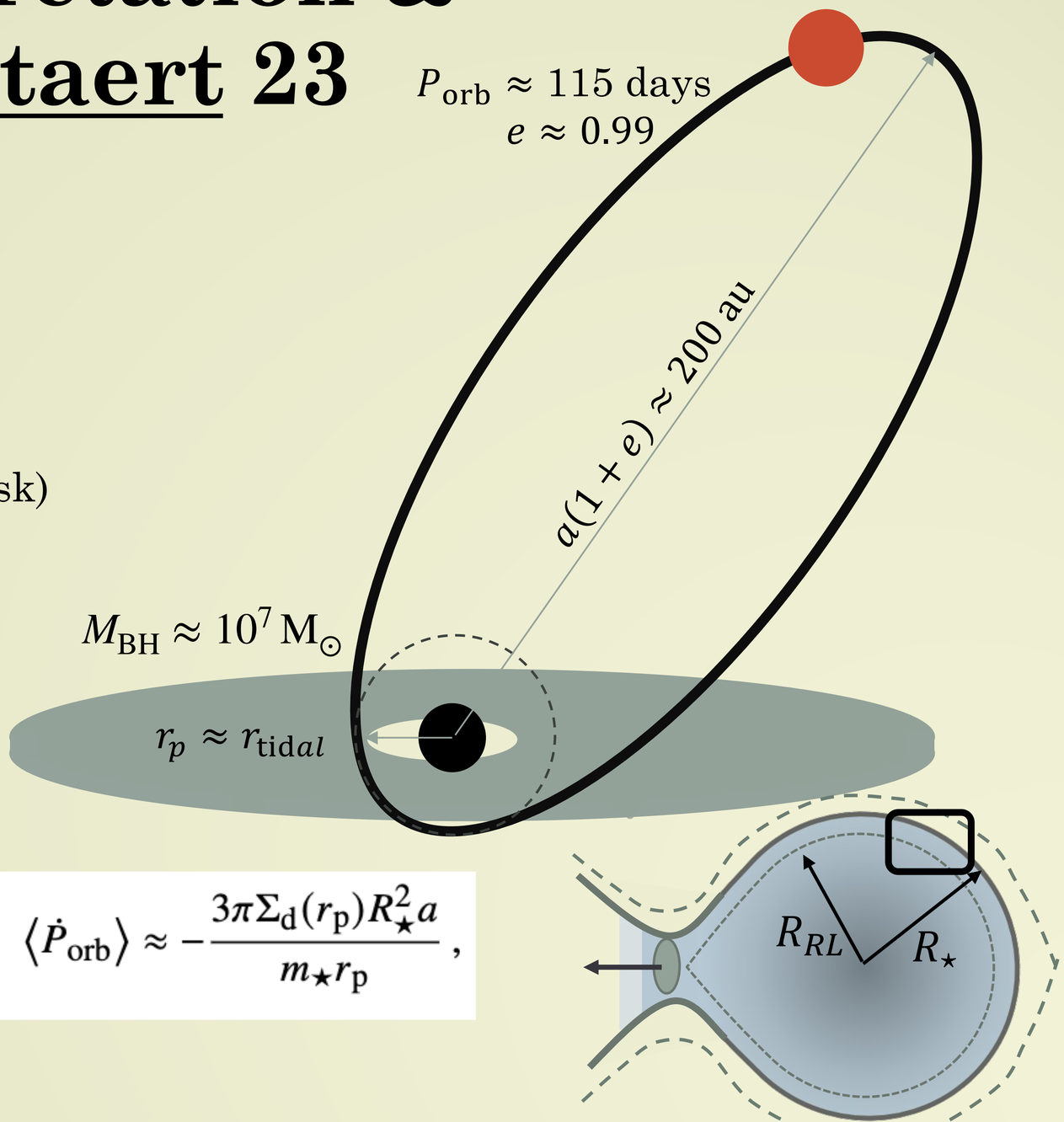
Partial TDE Interpretation & Pdot - Linial & Quataert 23

See also discussion in. [Liu+23, Cufari+22]

- $\delta m \approx \left(\frac{E_{\rm rad}}{\eta_{\rm eff} c^2}\right) \approx 0.02\, M_\odot$

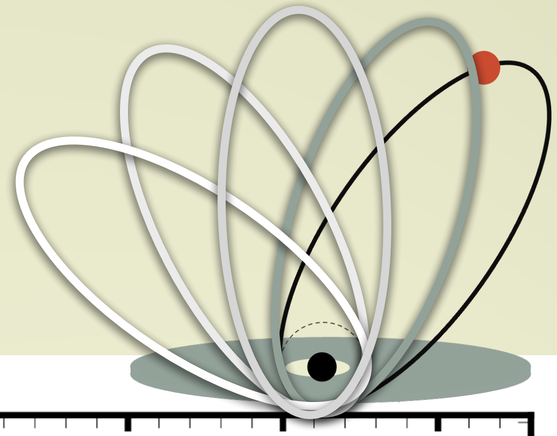
- Origin of Pdot?
  - ~~GWs~~
  - ~~Mass transfer~~
  - ~~Light travel (precession)~~
  - Hydrodynamic disk drag (AGN disk)



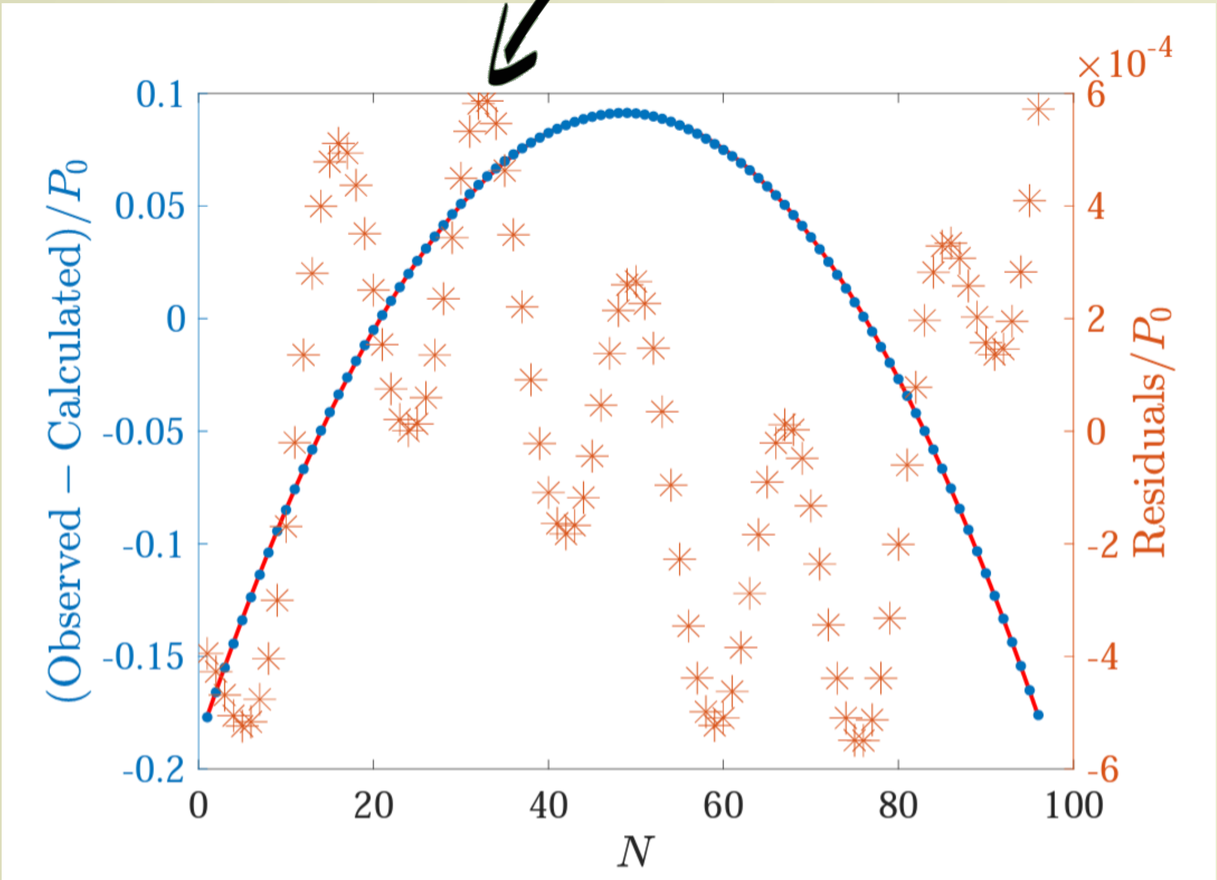


$$\langle \dot{P}_{\rm orb} \rangle \approx -\frac{3\pi \Sigma_{\rm d}(r_{\rm p}) R_\star^2 a}{m_\star r_{\rm p}},$$

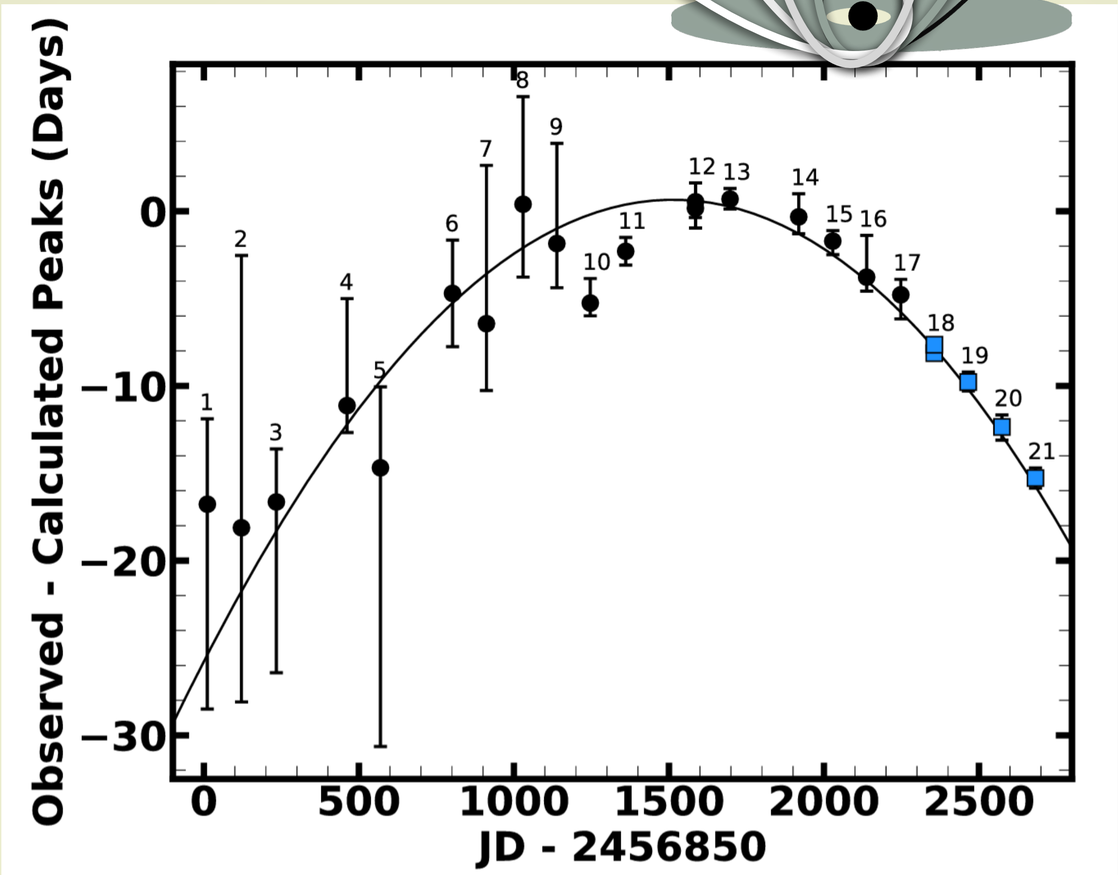
Apsidal Precession + Disk Drag



Residuals from quadratic fit

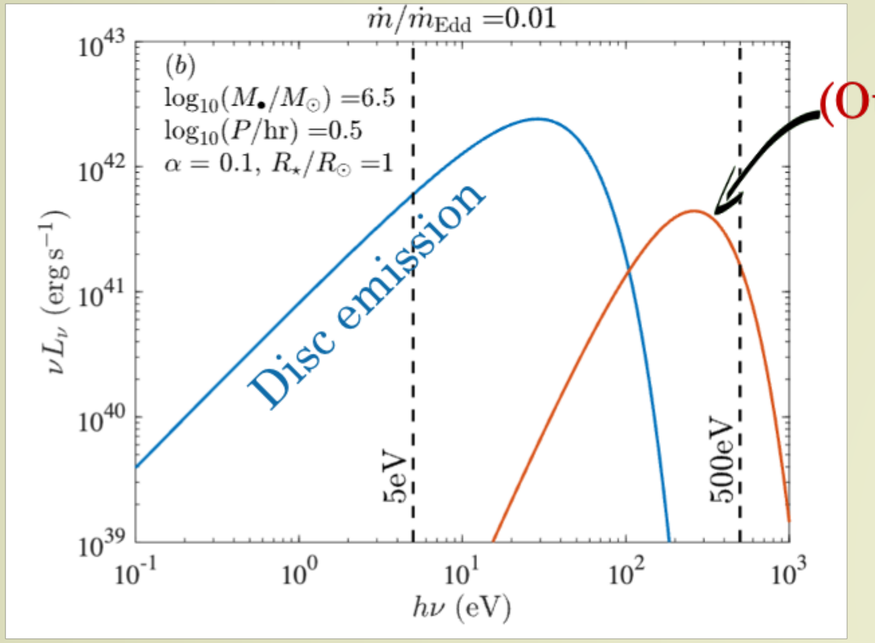


[**Linial** & Quataert (2023)]

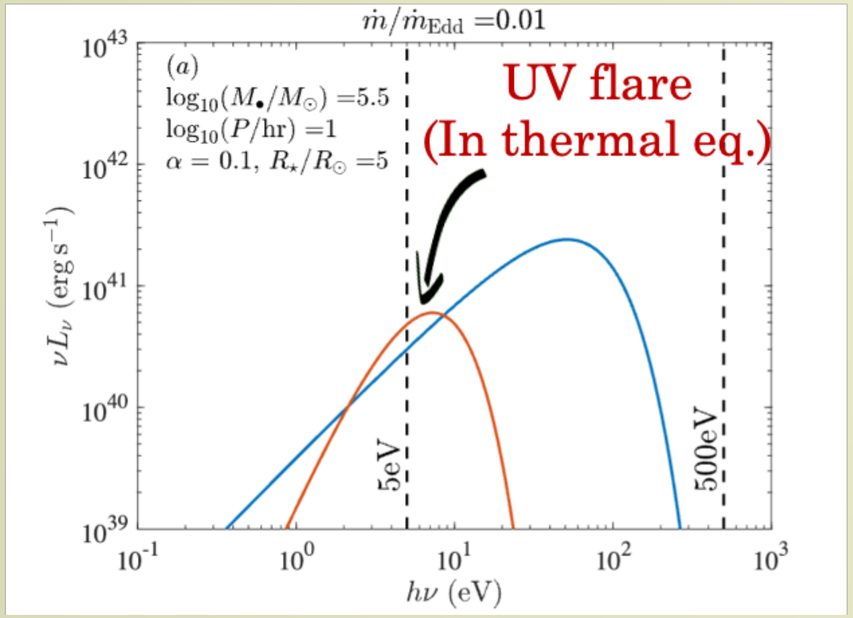


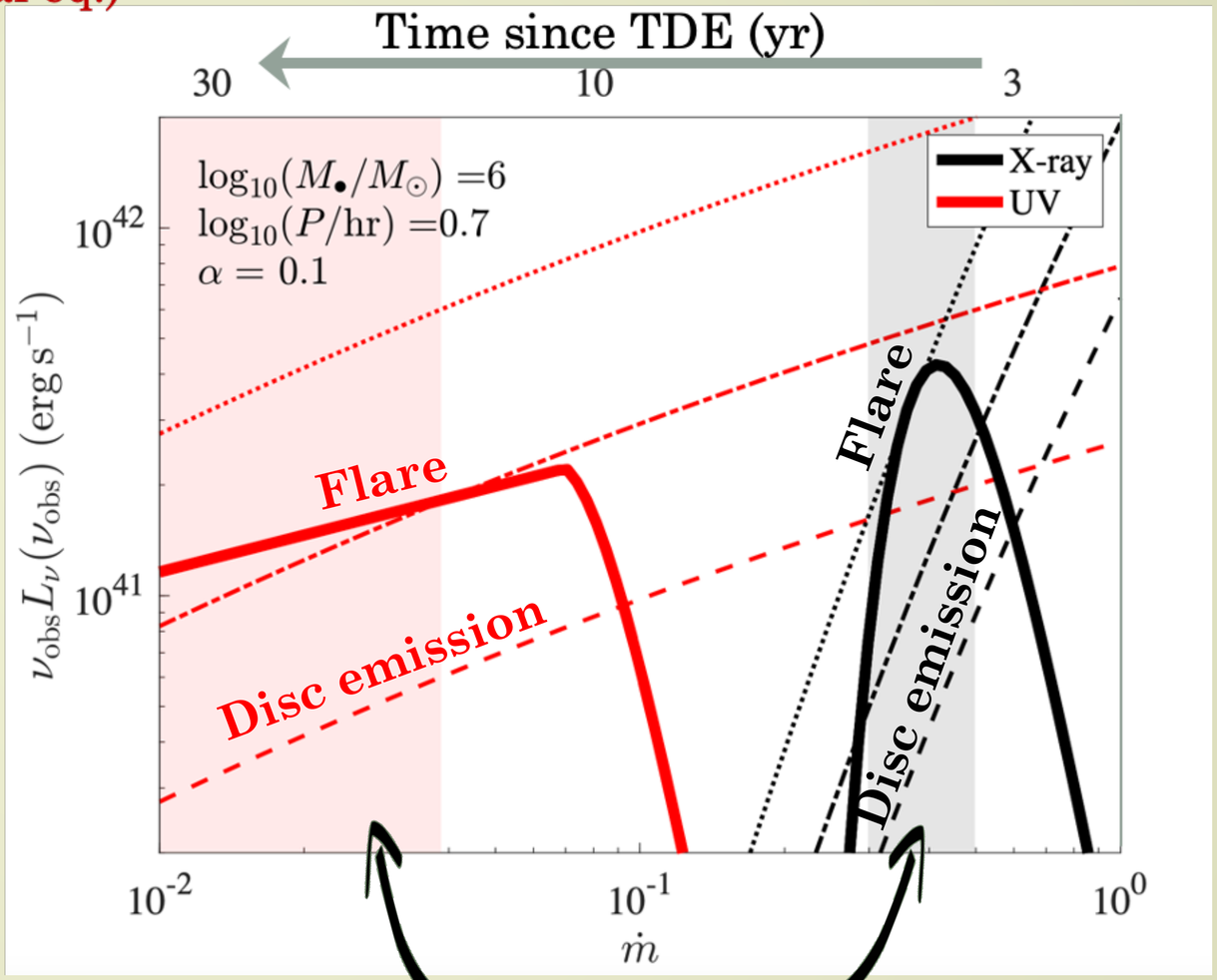
[Payne et al. (2023)]

"UV-QPEs" - Linial & Metzger (2024)



X-Ray flare
(Out of thermal eq.)

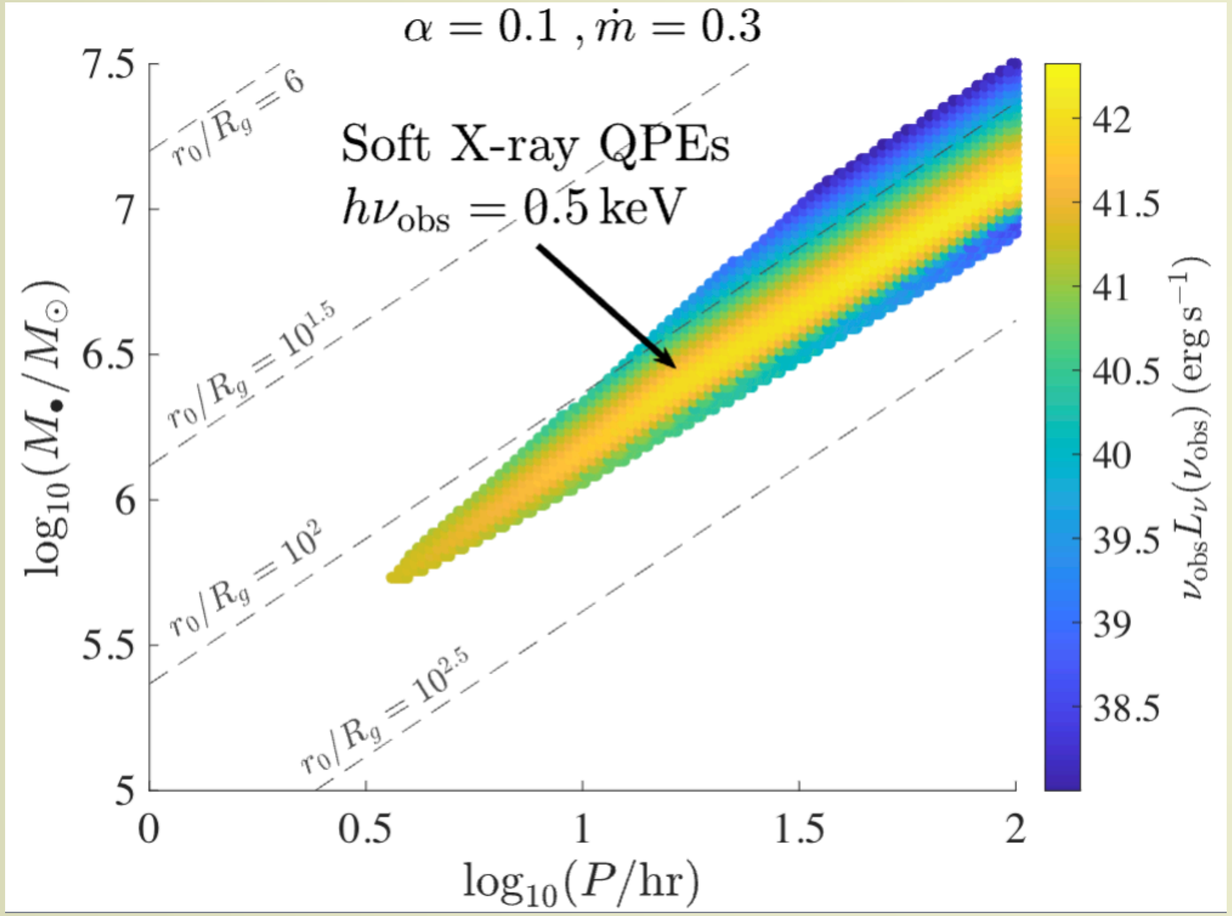


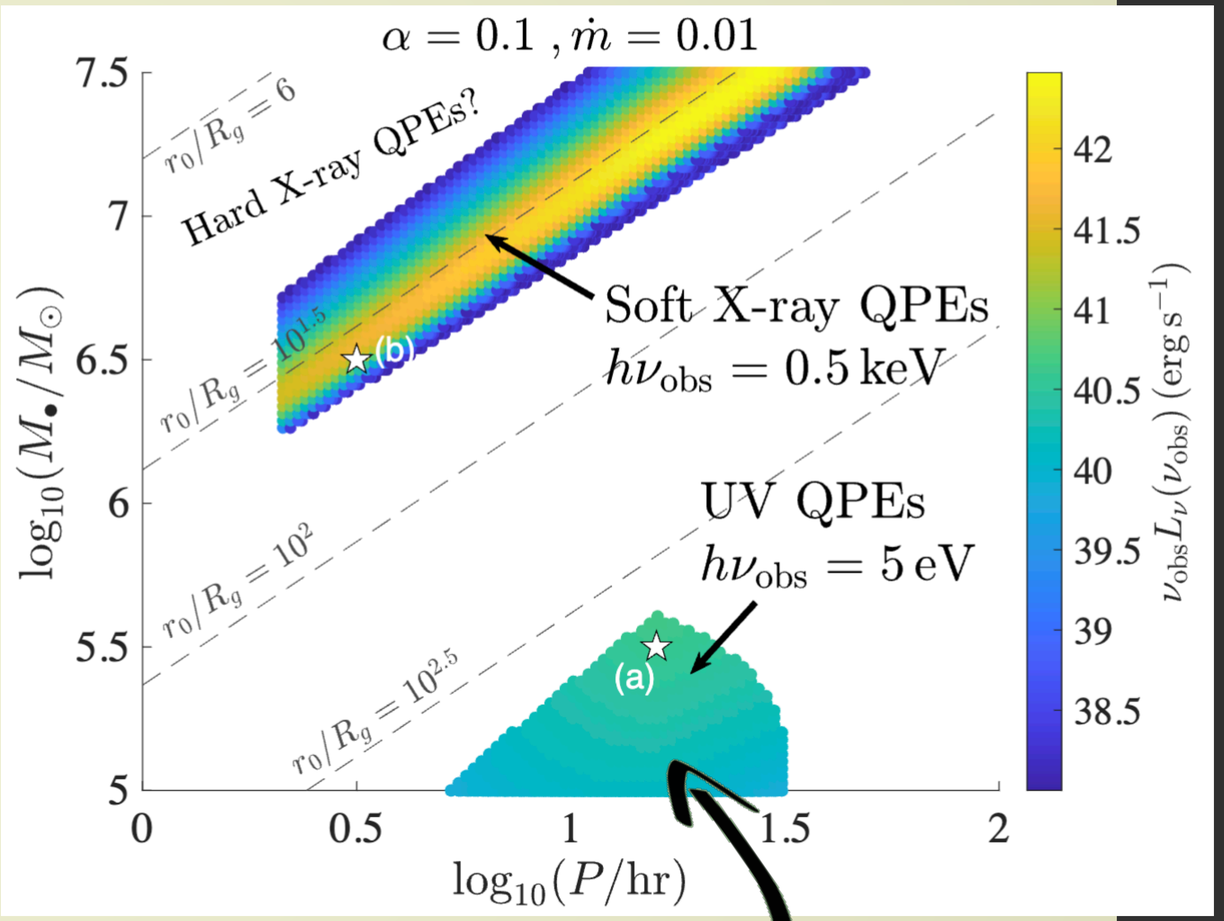


Flares outshine quiescent disk

X-ray & UV QPEs in Parameter Space

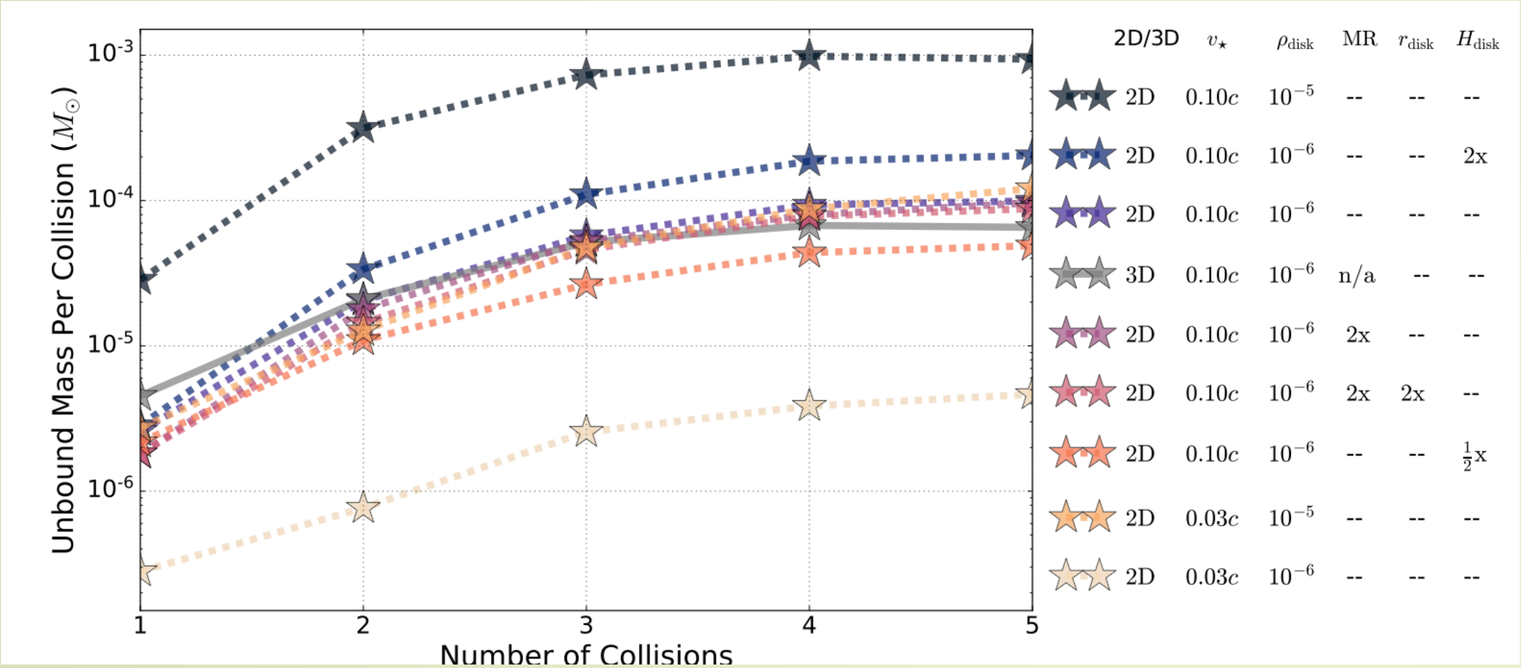
High Eddington Ratio → Low Eddington Ratio



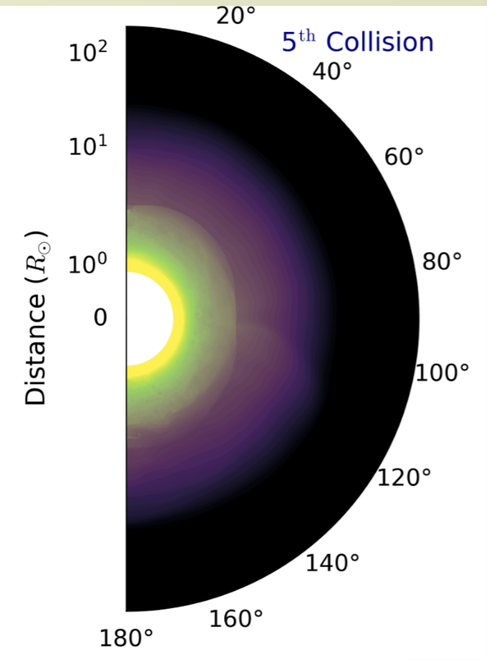


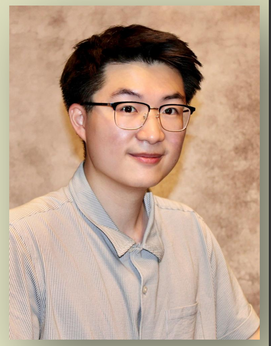
UV Flares to be hosted by **Long period**, **Low-mass SMBHs**

Ablation from Star-Disk Collisions

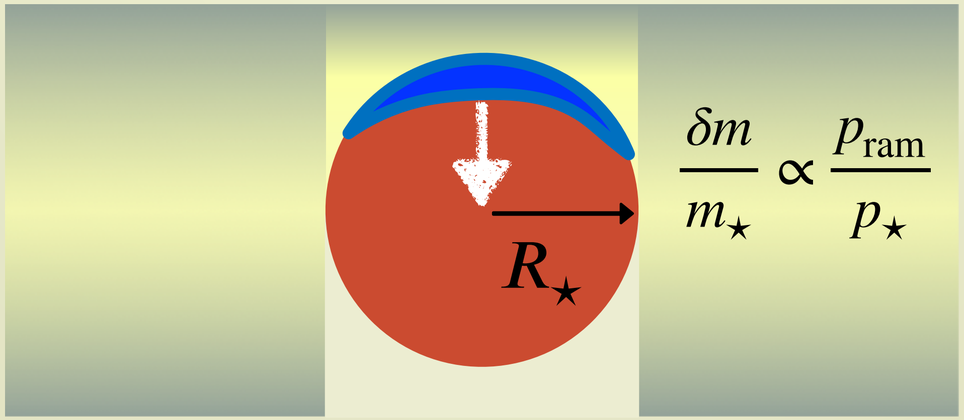


[Yao+24]



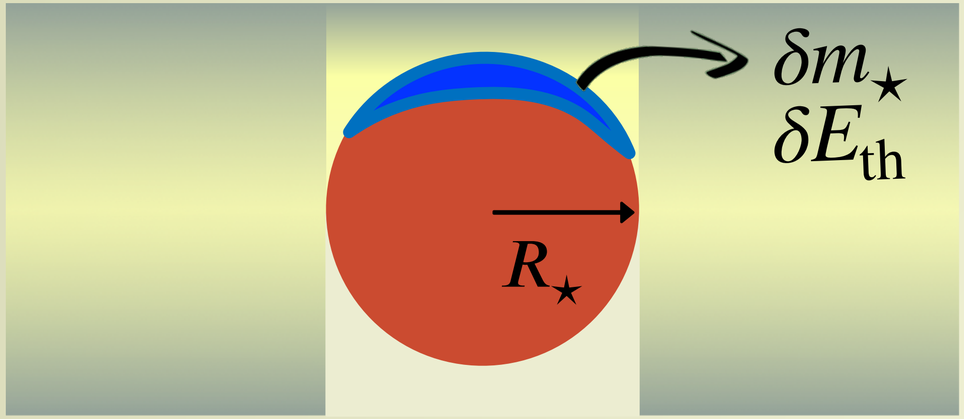


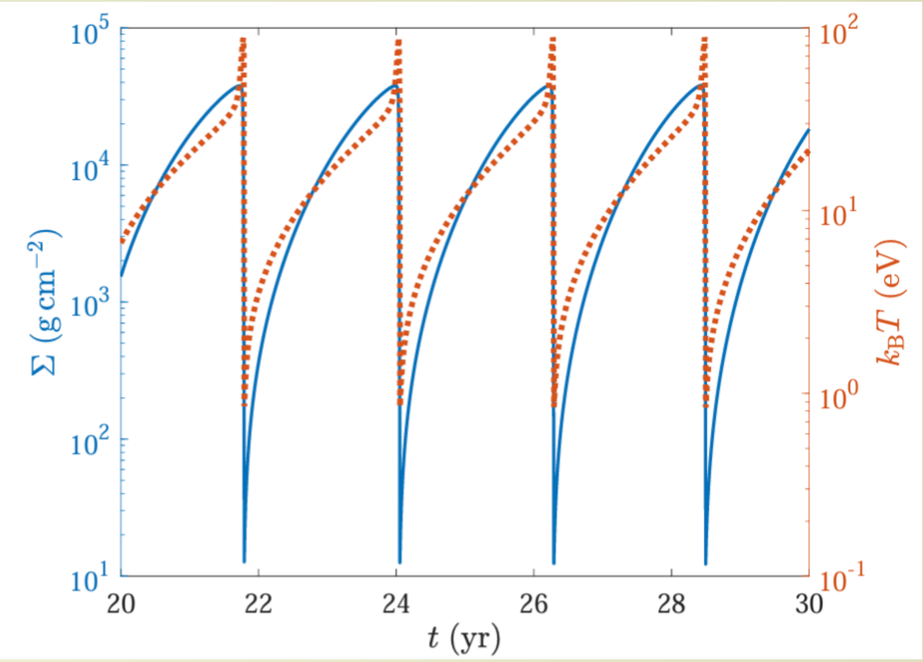
Shock stalls where $p_{\rm ram} \approx p_\star(\delta m)$

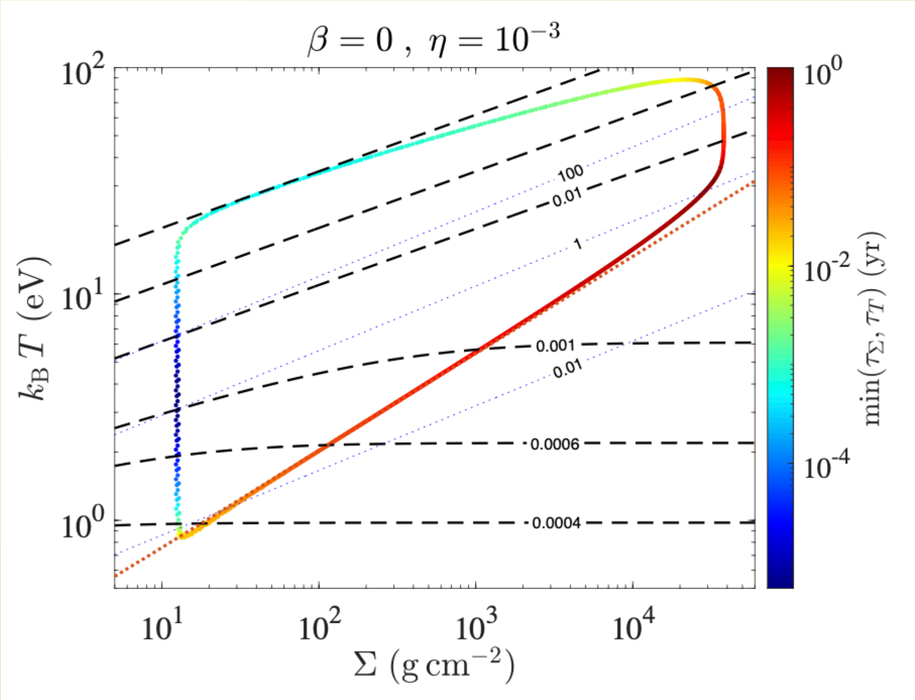


[See Liu+15, Lu&Quataert+23]

Coupled Star-Disk Evolution [Linial & Metzger (2024b)]







* Disk is fed by stellar ablation
* Thermal instability limit cycles
* Outbursts with periodicity ~ $\tau_{\rm cyc} \approx 1 - 10$ yr
* Star is destroyed after $\tau_{\rm dest} \sim$ few $\times\, 10^1 - 10^3$ yr

Summary

- Stellar EMRIs, on mildly eccentric orbits, commonly occur around SMBHs through GW inspiral of tightly bound stars following binary breakup by Hills Mechanism
- During the long GW inspiral of the stellar EMRI, the tidal disruption of a second star produces an accretion disk with which the EMRI interacts.
- The disk is evolving in time, fed by the fallback of the bound stellar debris and possibly by the stellar ablation
- Interactions between the disk and the stellar EMRI produces flares with similar properties to the observed QPEs
- Further study will constrain EMRI formation channels, with implications to milli-Hz GW sources and SMBH feeding habits
- The possibility of an IMBH instead of a stellar-EMRI may be tested by exploring secular period evolution of QPEs
- UV flares may be seen around low-mass SMBH sources, with detection prospects with future UV missions like ULTRASAT and UVEX

EMRI+TDE=QPE:

UV QPEs:

Star-Disk Coevolution:

$\dot{P}$ in repeating TDEs