Some Recent Topics on Quasi-Periodic Eruptions

Keihan Astrophysics Meeting 2025 fall

Octorber 1, 2025

Tomoya Suzuguchi (Kyoto Univ.)

Contents

1. **Introduction of QPEs**
2. **Early time evolution**
3. **More recent topics (biased)**
   - Observation; discovery of the strange QPEs
   - Theoretical challenges
   - Formation mechanisms

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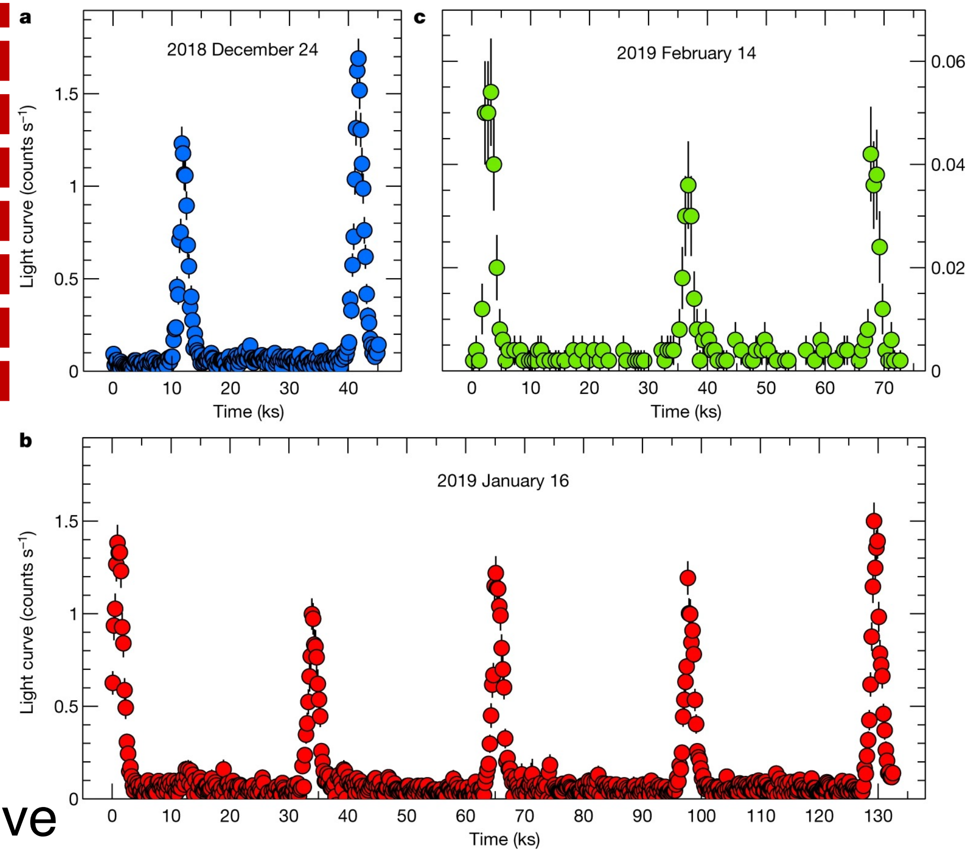
   - Observation; discovery of the strange QPEs
   - Theoretical challenges
   - Formation mechanisms

Quasi-Periodic Eruption (QPE)

Recurring X-ray nuclear transients

Miniutti+19, Giustini+20, Arcodia+21,24,25, Chakraborty+21, Quintin+23, Bykov+24, Chakraborty+25, Hernandez-Garcia+25

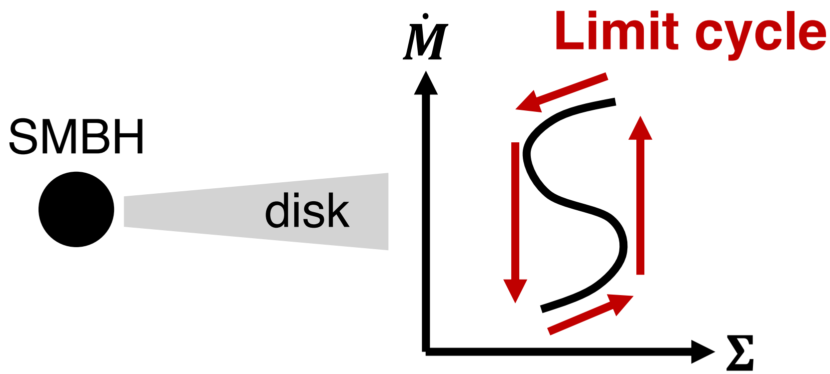
- Recurrence time: **hours - days**
- Peak luminosity: $\mathbf{10^{41-43}\ erg\ s^{-1}}$
- Duty cycle: $\sim \mathbf{10\ \%}$
- Peak temperature: $\mathbf{100 - 200\ eV}$



+ Quasi-periodicity
  - long/short oscillation ($\sim 10\ \%$) in the recurrence time
+ Host galaxies
  - low mass ($M_{\rm BH} \sim 10^{5-7} M_{\odot}$) & inactive
+ No similar bursts at other wavelengths

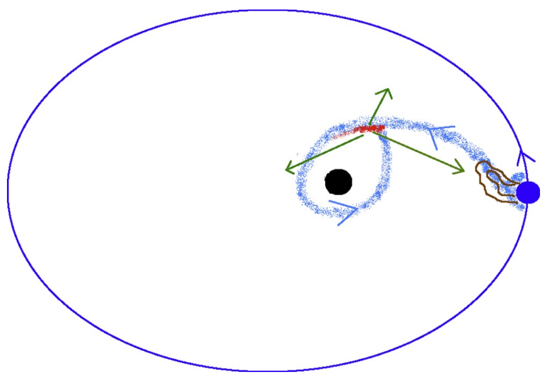
Scenarios

1. Disk instability



Raj & Nixon 21, Pan+22,23,25, Kaur+23, Sciegowska+23

2. Mass transfer

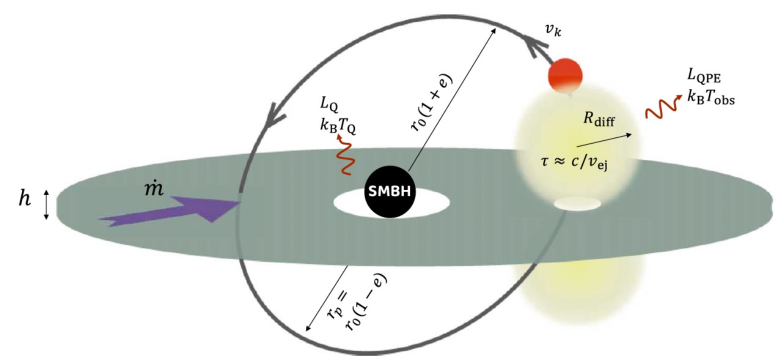


Krolik & Linial 22, Metzger+22, Linial & Sari 23, Lu & Quataert 23, Olejak+25

3. Star-disk collision

Interaction between the disk and the orbiting star makes QPE signals

- Low-eccentricity & inclined orbit naturally explains quasi-periodicity



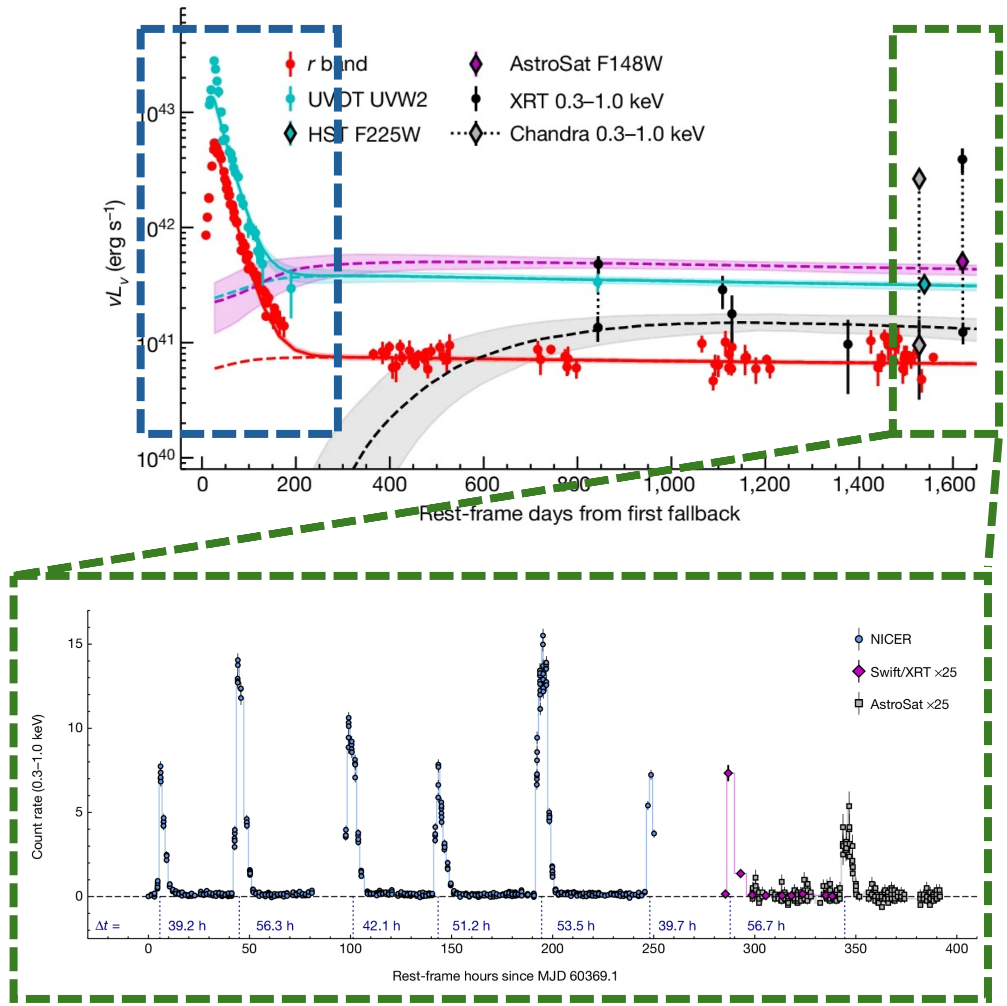
Dai+10, Xian+21, Sukova+21, Linial & Metzger 23, Franchini+23, Tagawa & Haiman 23, Linial & Metzger 24, Zhou+24a,b,25, Linial+25, Tsz-Lok Lam+25, Vurm+25, Yao+25, Huang+25

TDE-QPE Association

Some observations imply that QPEs are associated with TDEs

+ **Direct:**
  Some QPEs are discovered after TDEs occur
  Nicholl+24, Chakraborty+25

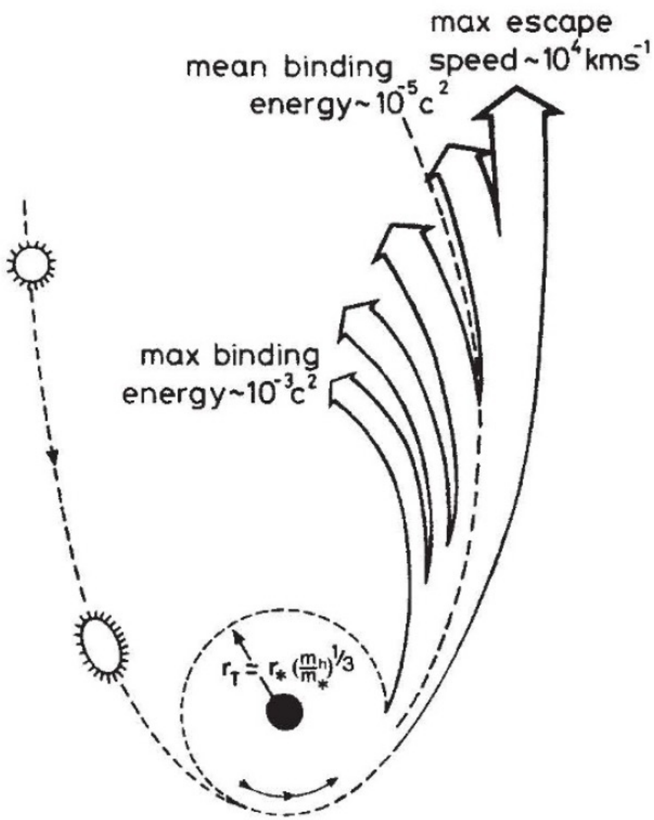
+ **Indirect:**
  Some properties of host galaxies are similar Wevers+22,24
  - low-mass & inactive
  - prefer post-starburst galaxies



Tidal Disruption Event (TDE)

Stars are disrupted by the tidal force if passing near the SMBHs

c.f., Keihan 2024spring



Rees 88, Phinney 89

+ Tidal force $\geq$ Self-gravity of the star

$$\Leftrightarrow \quad r \leq R_{\mathrm{T}} := R_\star \left(\frac{M_\cdot}{M_\star}\right)^{1/3}$$

$$\simeq 47 R_{\mathrm{g}} \frac{r_\star}{M_{\cdot,6}^{2/3}\, m_\star^{1/3}}$$

+ Half of the stellar component is bound, forming a <u>compact</u> disk!

$$R_{\mathrm{c}} \simeq 2 R_{\mathrm{T}}$$

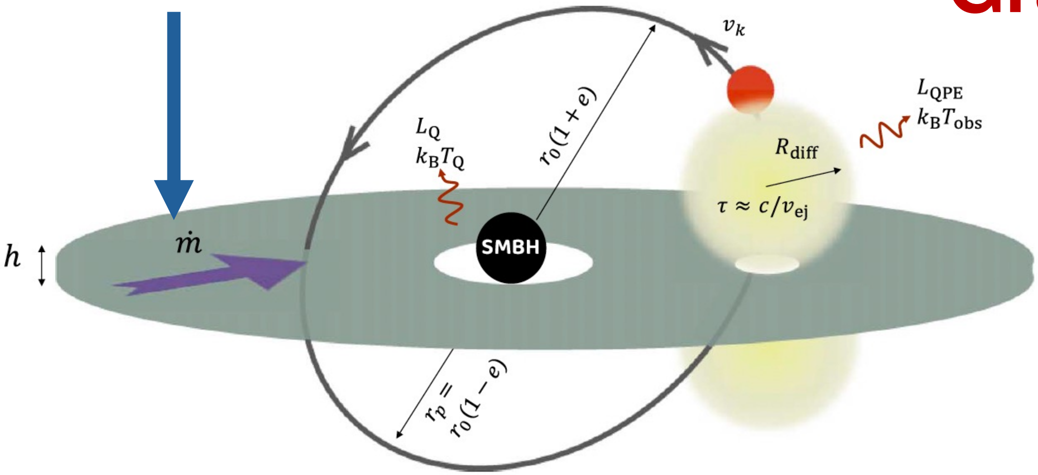
Circularization radius (= initial disk size)

+ Viscous expansion of the disk

“EMRI + TDE = QPE”

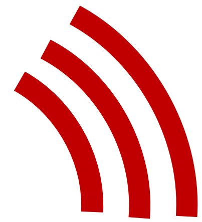
Extreme Mass Ratio Inspiral

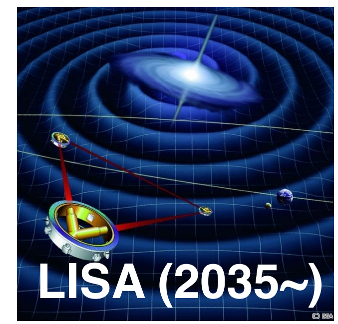
from TDE!?



Linial & Metzger 23, Franchini+23, Tagawa & Haiman 23

Gravitational Wave





$$P_{\mathrm{QPE}} \sim 4\ \mathrm{hr}\ M_{\mathrm{BH},6}^{-1/2}\ a_2^{3/2}$$

$$a = 10^2 R_g a_2$$

QPE may be a **multi-messenger** source!

Chen+22, Kejriwal+24, Lyu+24, Duque+25, Olejak+25, Lui+25

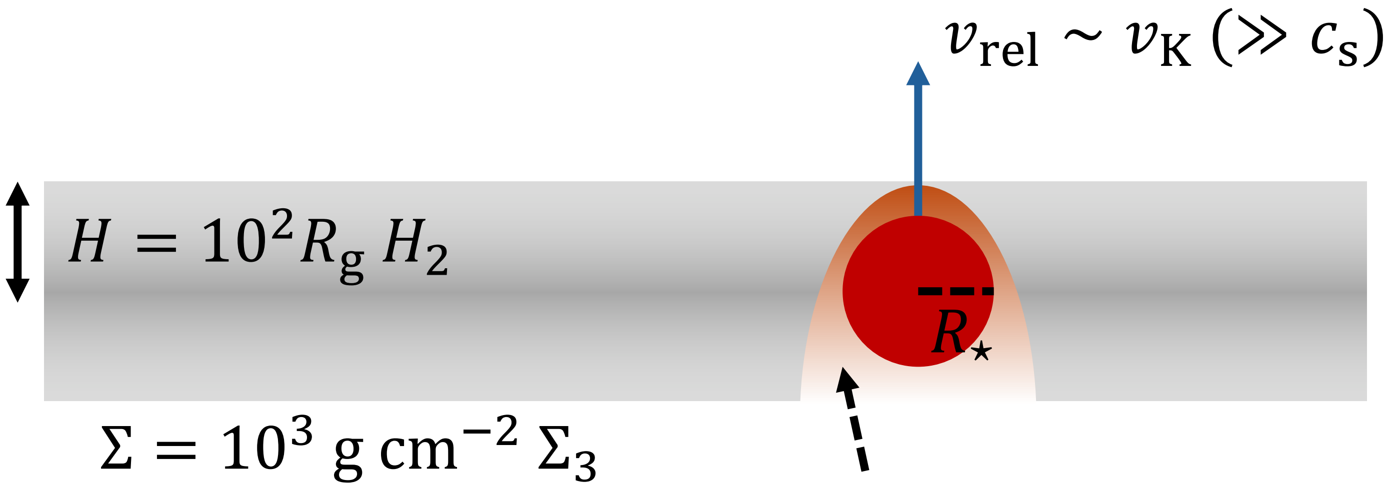
See also TS, Omiya & Takeda 25 (arXiv: 2505.10488)

Emission mechanism

"EMRI + TDE = QPE" model

Linial & Metzger 23

Gaseous medium in the disk is compressed by the passing star



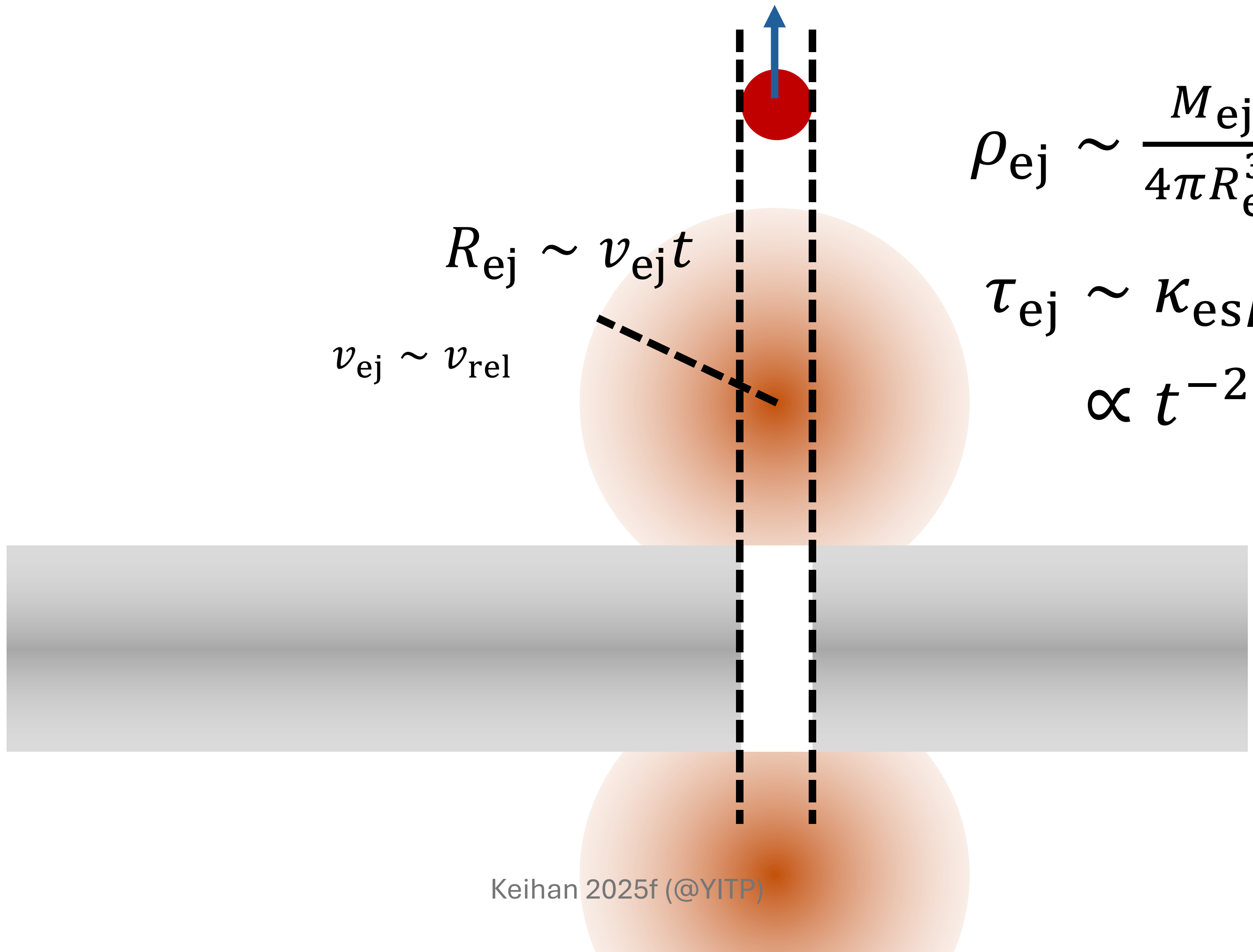
$$M_{\rm ej} \sim \pi R_\star^2 \Sigma$$

$$E_{\rm ej} \sim \frac{1}{2} M_{\rm ej} v_{\rm rel}^2$$

Emission mechanism

‘’EMRI + TDE = QPE” model

Compressed material expands adiabatically



$$\rho_{\rm ej} \sim \frac{M_{\rm ej}}{4\pi R_{\rm ej}^3}$$

$$\tau_{\rm ej} \sim \kappa_{\rm es} \rho_{\rm ej} R_{\rm ej}$$

$$\propto t^{-2}$$

Keihan 2025f (@YITP)

Emission mechanism

"EMRI + TDE = QPE" model

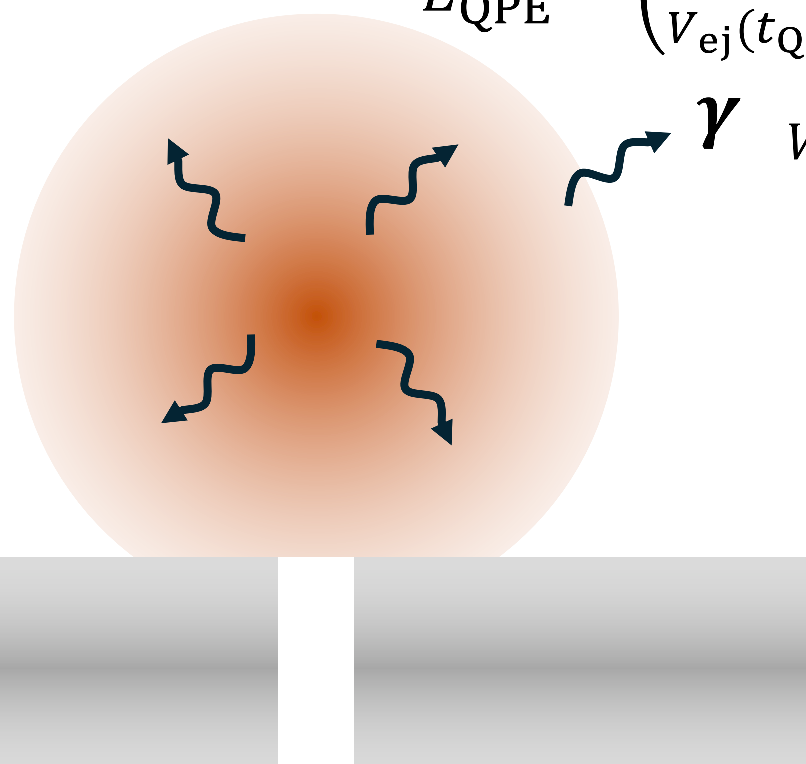
When the ejecta becomes optically thin, QPE appears

$$\tau_{\mathrm{ej}} \sim \frac{c}{v_{\mathrm{ej}}}$$

$$\Leftrightarrow \quad t_{\mathrm{QPE}} \sim \left(\frac{\kappa_{\mathrm{es}} M_{\mathrm{ej}}}{4\pi c v_{\mathrm{ej}}}\right)^{1/2}$$

$$L_{\mathrm{QPE}} \sim \frac{E_{\mathrm{QPE}}}{t_{\mathrm{QPE}}}$$

$$E_{\mathrm{QPE}} \sim \left(\frac{V_{\mathrm{sh}}}{V_{\mathrm{ej}}(t_{\mathrm{QPE}})}\right)^{1/3} E_{\mathrm{ej}}$$



$$V_{\mathrm{sh}} \sim \pi R_\star^2 H$$

Keihan 2025f (@YITP)

Emission mechanism

"EMRI + TDE = QPE" model

QPE temperature is not necessarily equal to blackbody value because of inefficient photon production

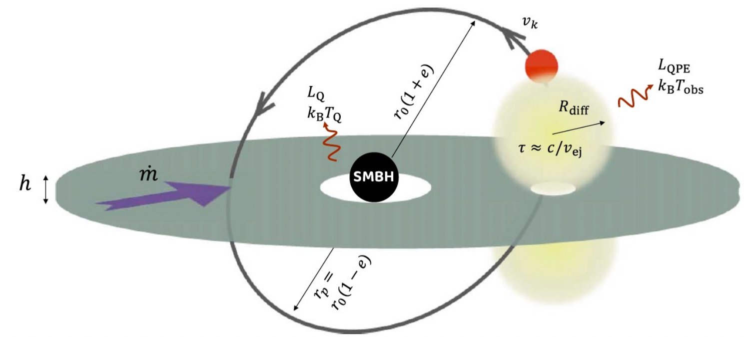
Weaver 76, Katz+10, Nakar & Sari 10

$$\eta := \frac{n_{\mathrm{BB}}(T_{\mathrm{BB}})}{t_{\mathrm{cross}}\,\dot{n}_{\gamma,\mathrm{ff}}(T_{\mathrm{BB}},\rho)}$$

Photon number required to achieve thermal equilibrium

Photon number produced by free-free emission

$$\simeq 15\,\frac{H_2^{1/8}}{\Sigma_3^{9/8}\,a_2^{11/8}} > 1$$



$$\Rightarrow\quad T_{\mathrm{QPE}} \simeq \eta^2 T_{\mathrm{BB}} > T_{\mathrm{BB}}$$

Note: Comptonization becomes important in some cases…

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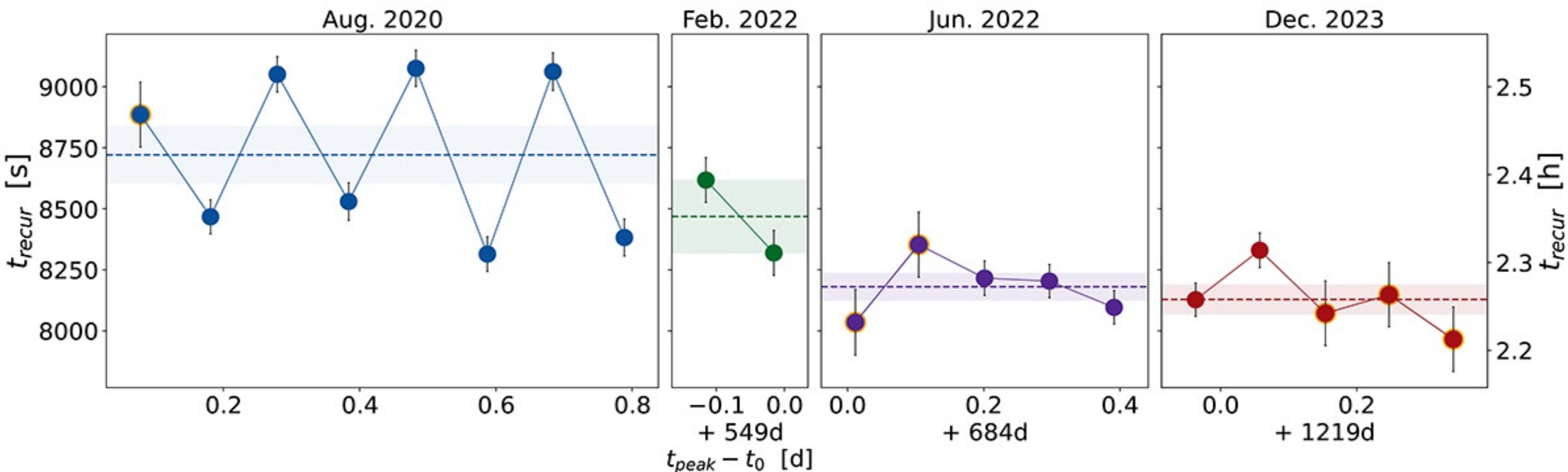
Long-term evolution

Some QPEs have been monitored over long periods



Arcodia+24b

+ Overall recurrence time gradually decreases

- consitent with the orbital decay of a solar-like star due to gas drag…?

Ablation

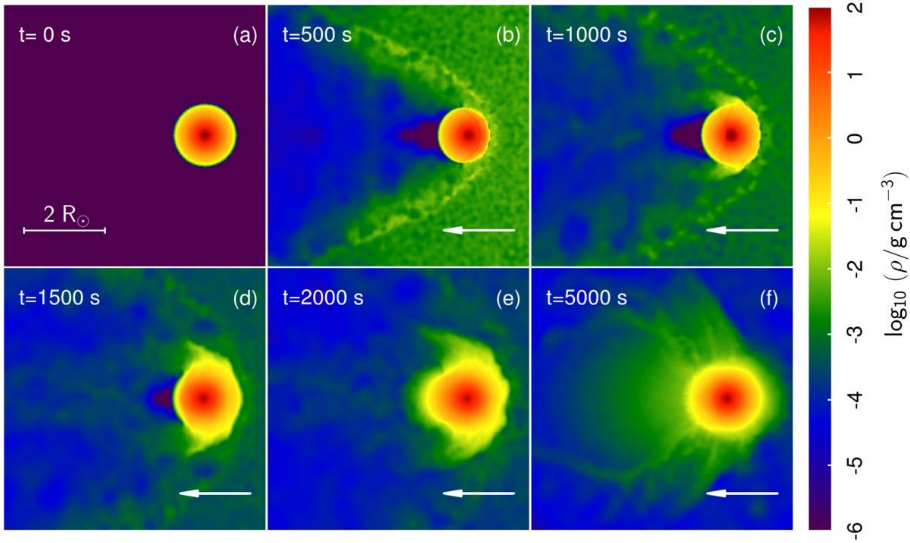
At the disk crossing, supersonic motion of the star causes the ablation by the ram pressure

$$\frac{\Delta m_\star}{m_\star} \sim 10^{-3} \left(\frac{p_{\rm ram}}{p_\star}\right)$$

Liu+15 (ablation by the SN ejecta)

$$p_{\rm ram} \sim \frac{1}{2}\rho v_{\rm rel}^2$$

$$p_\star \sim \frac{Gm_\star}{4\pi R_\star^4}$$



$$\tau_{\rm abl} \sim \frac{m_\star}{P_{\rm QPE}\Delta m_\star} \sim 880\,{\rm yr}\,\alpha_{-1}\,M_{\rm BH,6}^{4/3}\,\dot{m}_{-1}^2\,P_{\rm QPE,4}^{2/3}\,m_\star^2\,R_\star^{-4}$$

$$(\ll \tau_{\rm decay})$$

Mass loss due to the ablation may determine the QPE lifetime

Linial & Metzger 23, 24b

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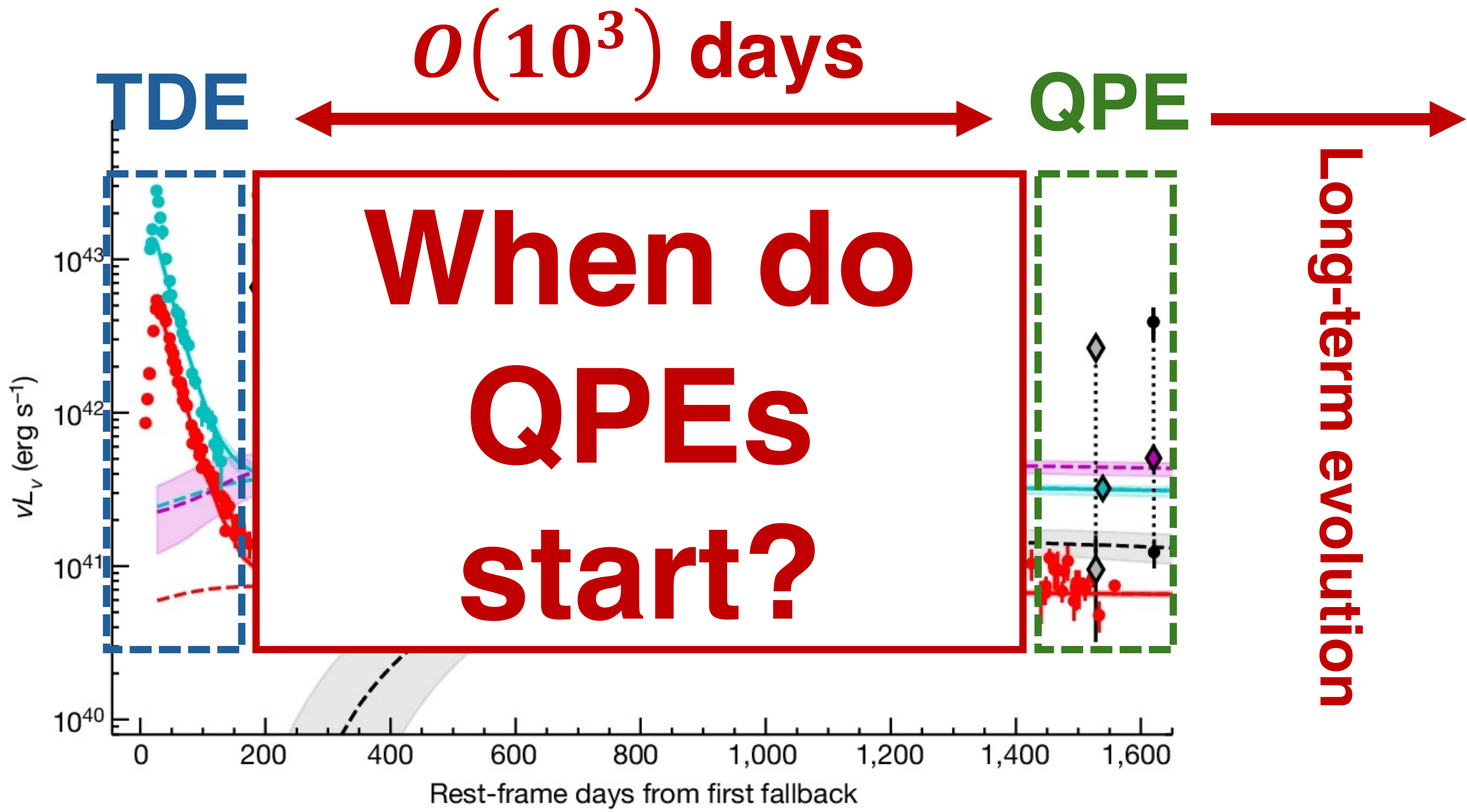
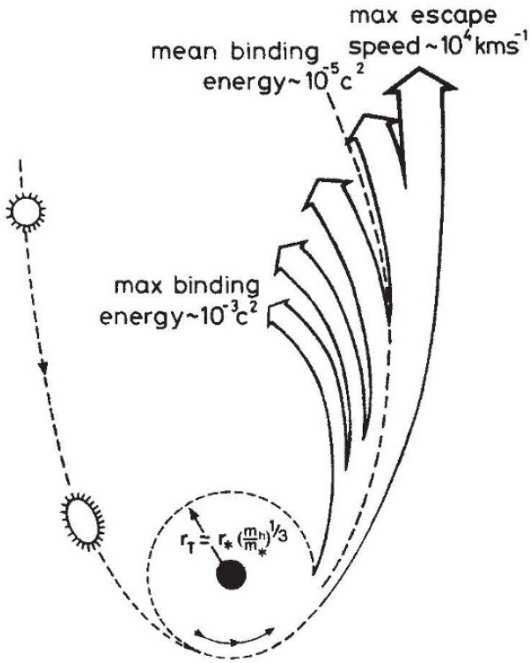
Early-time evolution



Discuss whether QPEs can be observed in the TDE host $\mathcal{O}(10^2)$ **days** after TDEs

TDE disk

Accretion rate is ***t*-dependent**!



+ fallback rate of the bound material:

$$\dot{M}_{\rm fb} \simeq 133\,\dot{M}_{\rm Edd}\frac{m_\star^2\,\beta^3}{r_\star^{3/2}\,M_{\bullet,6}^{3/2}}\left(\frac{t}{t_{\rm fb}}\right)^{-5/3}$$

$$t_{\rm fb} \simeq 0.11\,{\rm yr}\,\frac{M_{\bullet,6}^{1/2}\,r_\star^{3/2}}{m_\star\,\beta^3}$$

$$\beta = R_{\rm p}/R_{\rm T}$$

Slim disk!

Super-Eddington accretion accomplishes in the early phase ($\sim$ 1 yr)

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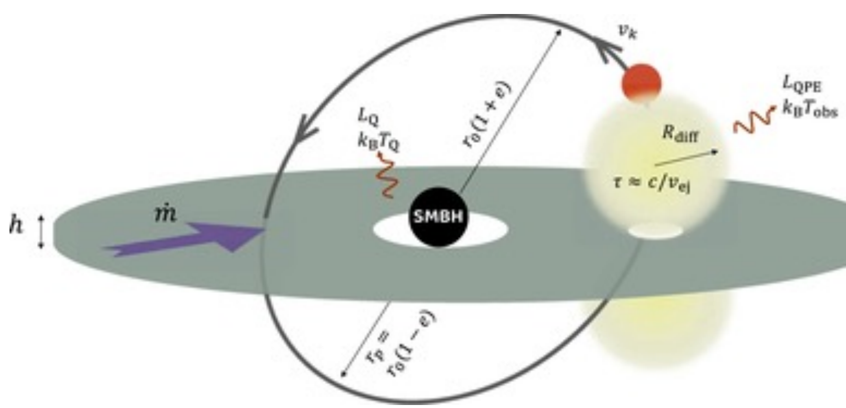
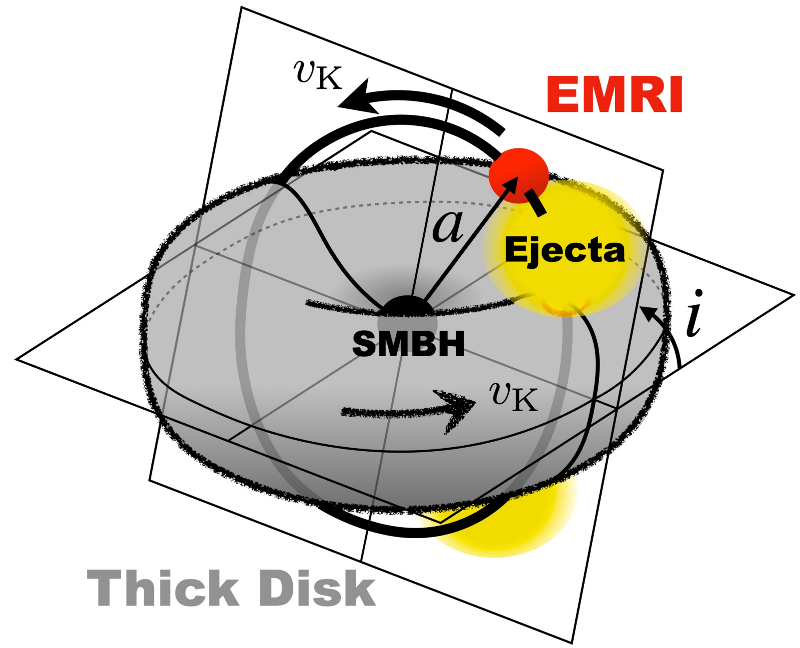
Motivation of our work

Previous work



Standard Disk

Our work



Slim Disk

We also discuss the time evolution of the QPE observables

QPE can be a probe of the TDE disk formation!

TDE disk model

Strubbe & Quataert 09

+ Steady-state solution

- Radiative & advection cooling

+ t-dep. accretion rate

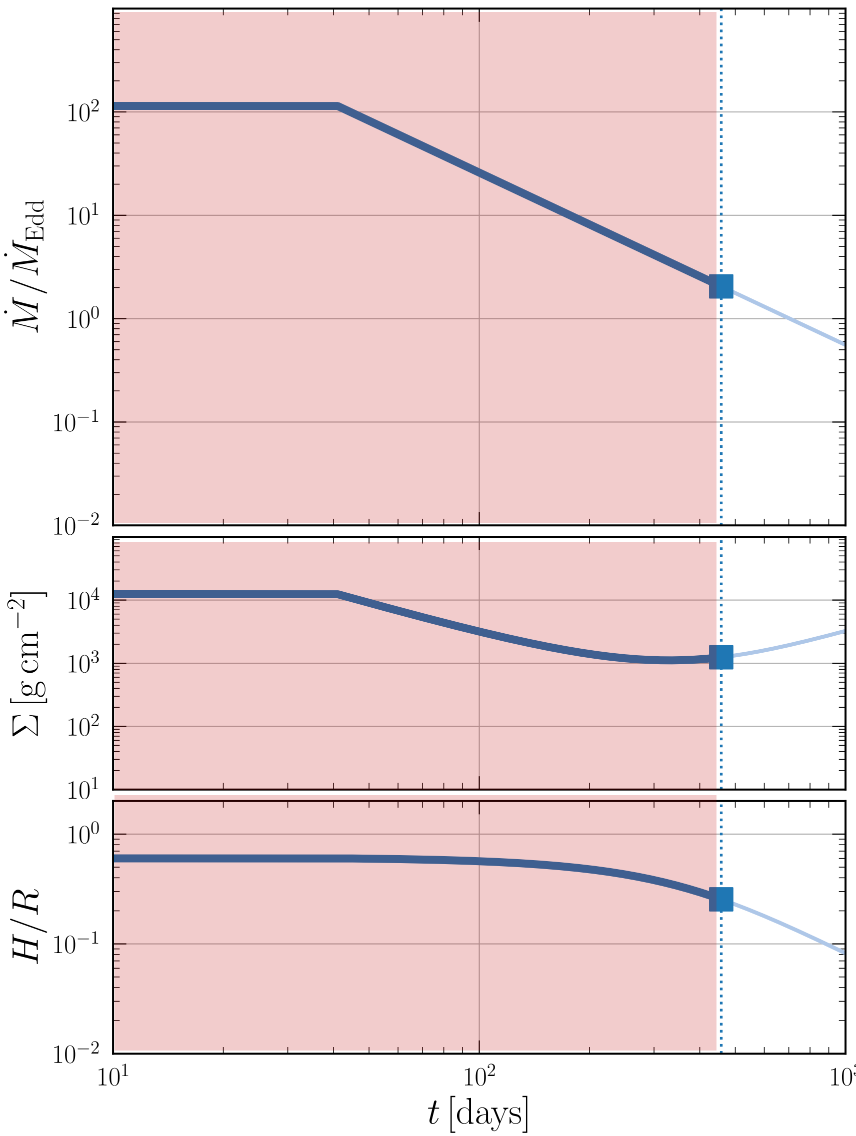
- Assume that accretion rate = fallback rate

+ Fiducial parameter

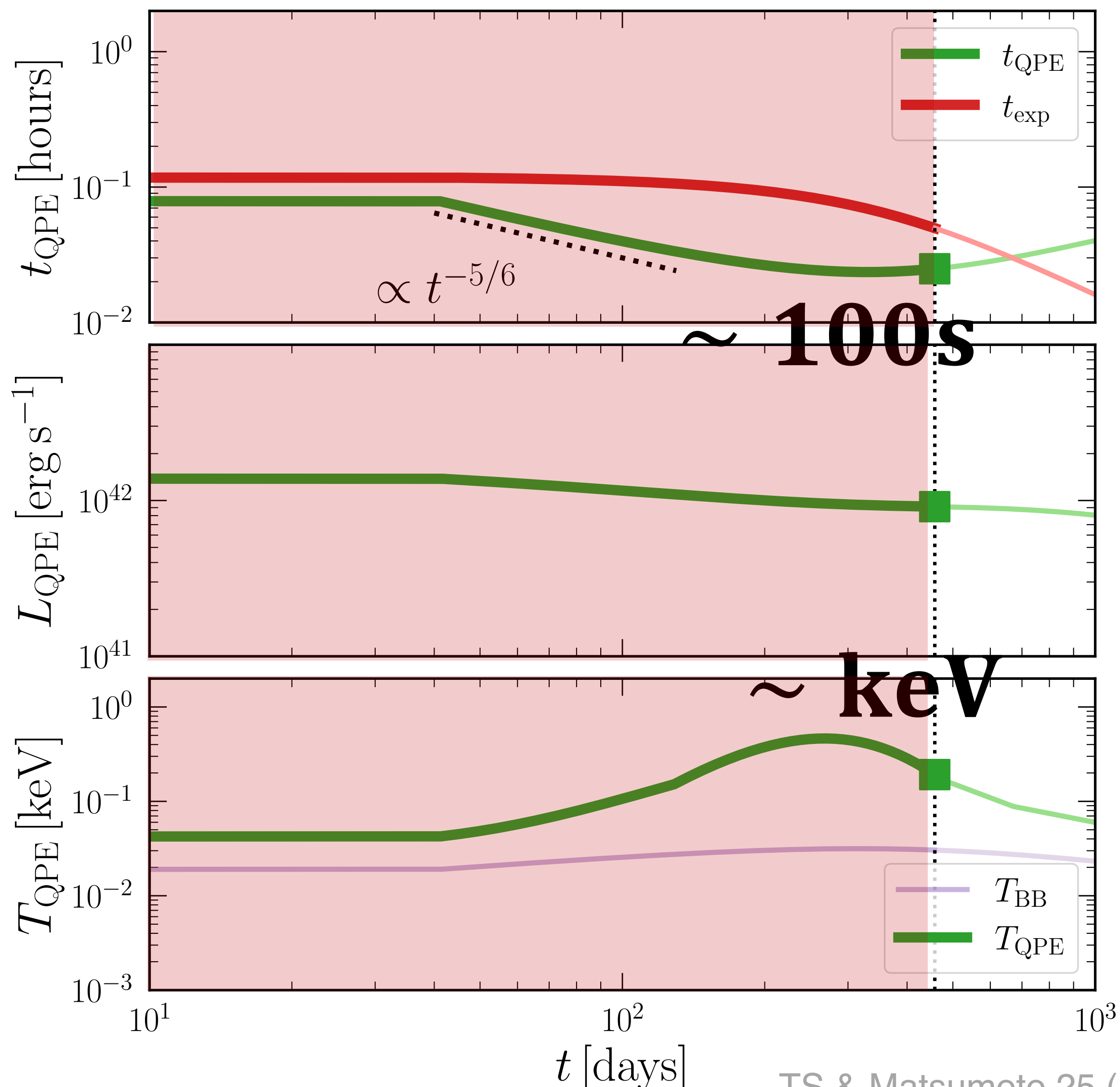
$$M_{\rm BH} = 10^6 M_\odot$$

$$\alpha = 0.1$$

$$a = 100 R_{\rm g}$$



Evolution of observables



TS & Matsumoto 25 (arXiv: 2509.01663)

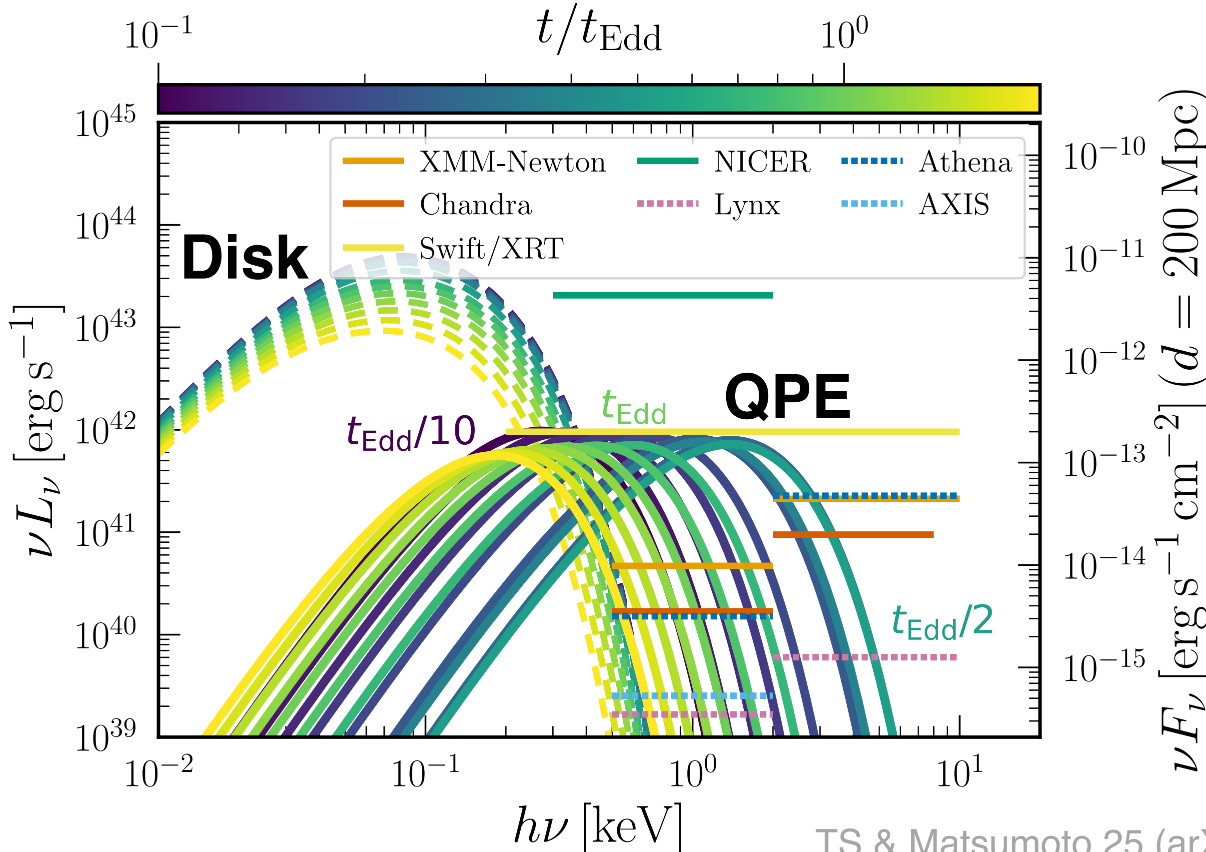
Comparison

Standard disk	Slim disk
$\Sigma \sim 10^4\ \mathrm{g\ cm^{-2}}$	$\Sigma \sim 10^3\ \mathrm{g\ cm^{-2}}$
$t_{\mathrm{QPE}} \sim 500\ \mathrm{s}$	$t_{\mathrm{QPE}} \sim 100\ \mathrm{s}$ Lower surface density causes shorter diffusion time
$T_{\mathrm{QPE}} \sim 100\ \mathrm{eV}$	$T_{\mathrm{QPE}} \sim \mathrm{keV}$ Lower density leads to inefficient thermalization

$a = 100 R_{\mathrm{g}}, M_{\mathrm{BH}} = 10^6 M_{\odot}, R_{\star} = R_{\odot}$

Spectrum & Observability

Early QPE can be observed by ongoing X-ray observatories



TS & Matsumoto 25 (arXiv: 2509.01663)

Smaller duty cycle / X-ray obscuration leads to non-detection…?

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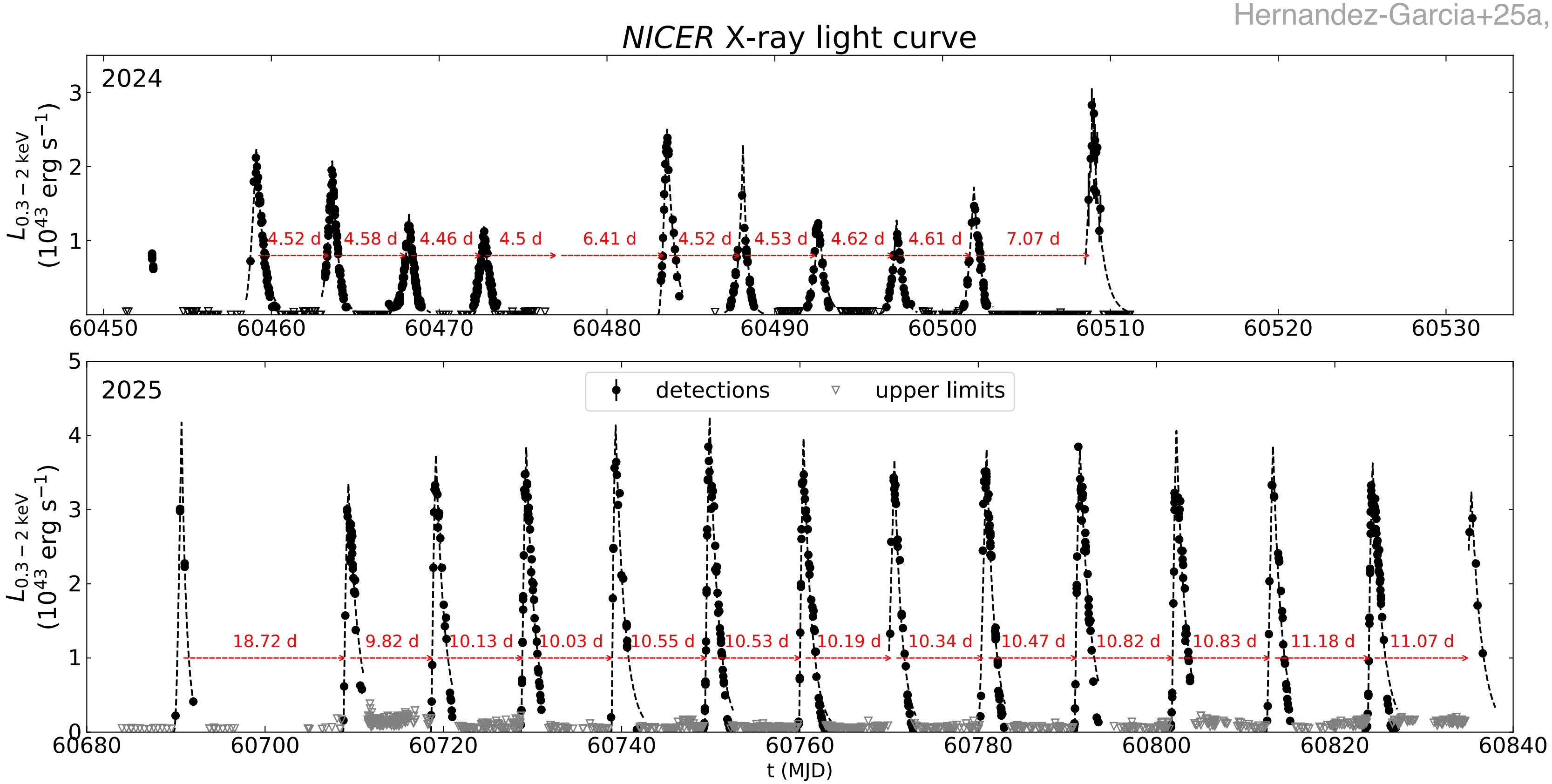
Ansky: strange QPE

Ansky: Newly discovered QPE in ‘turning on’ AGN (not TDE)

Hernandez-Garcia+25a,b



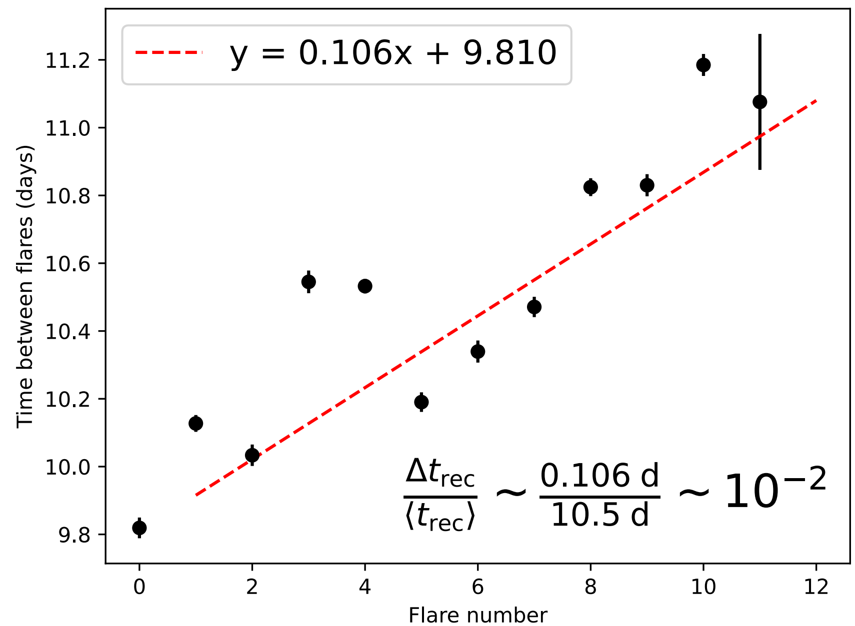
Increasing recurrence time!

Ansky: strange QPE

Ansky: Newly discovered QPE in 'turning on' AGN (not TDE)

Hernandez-Garcia+25a,b

+ Recurrence time increases linearly
  - doubling within one year
+ But why? Nobody knows…
  - Three body effect?
  - Disk instability?



Challenges in EMRI model

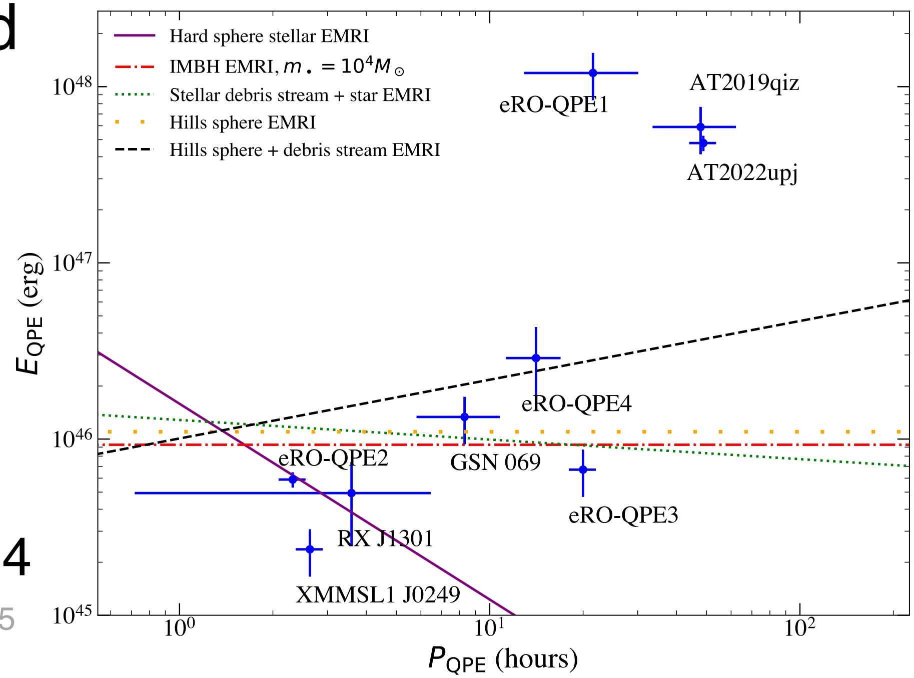
Testing the EMRI model reveals its difficulty in explaining QPEs

+ Larger stellar radius is required to explain the peak luminosity
  - Tidal disruption of the ejecta?

Guo & Shen 25

+ Long-term evolution check
  - HST UV/optical data implies that one QPE, GSN 069, could be discovered by the observation in 2014

Guolo+25

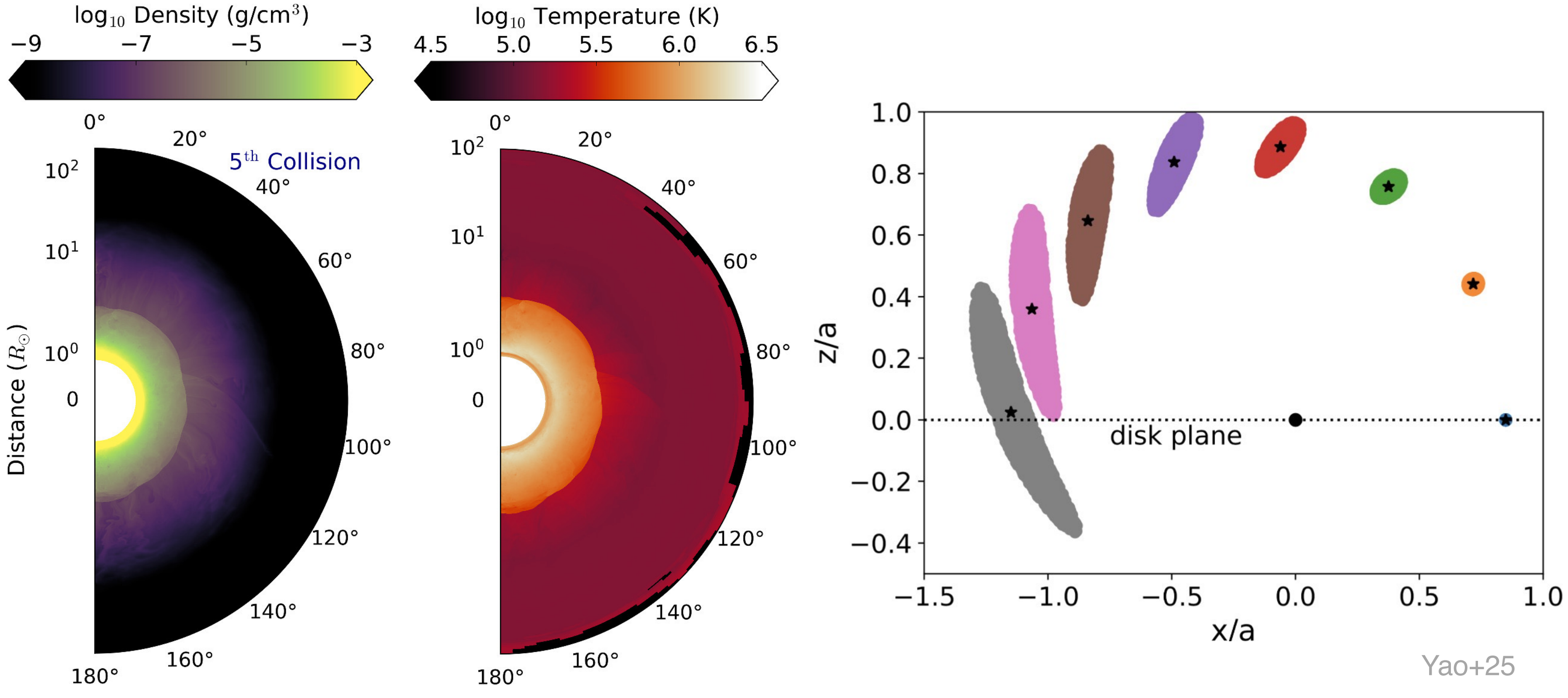


+ $P_{\rm QPE}$-$E_{\rm QPE}$ observationally has a positive correlation, contradicting the theoretical prediction…
  - Longer $P_{\rm QPE}$ means smaller kinetic energy

Mummery 25

Debris-disk collision

Hydrodynamical simulations of the star-disk collision reveal that multiple collisions cause the expansion of the stellar envelope

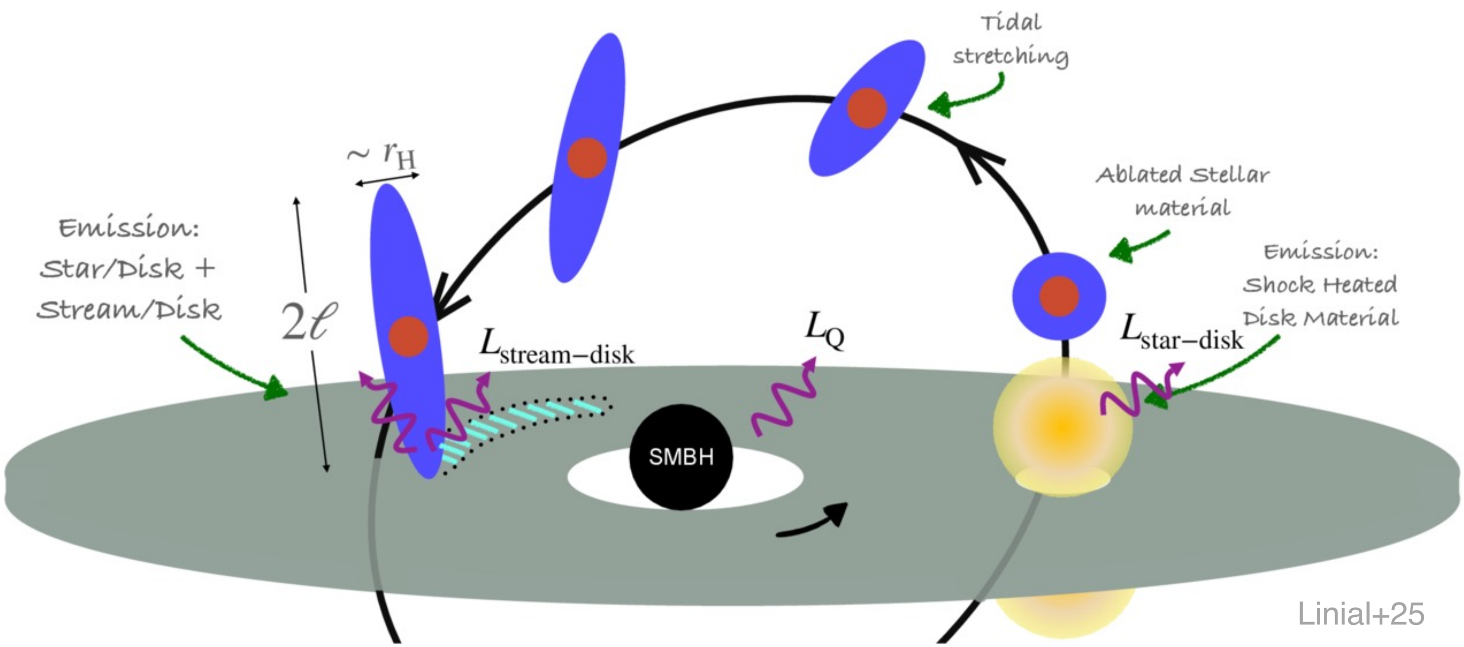


Expanding envelope fills the Hill radius of the star

Debris-disk collision

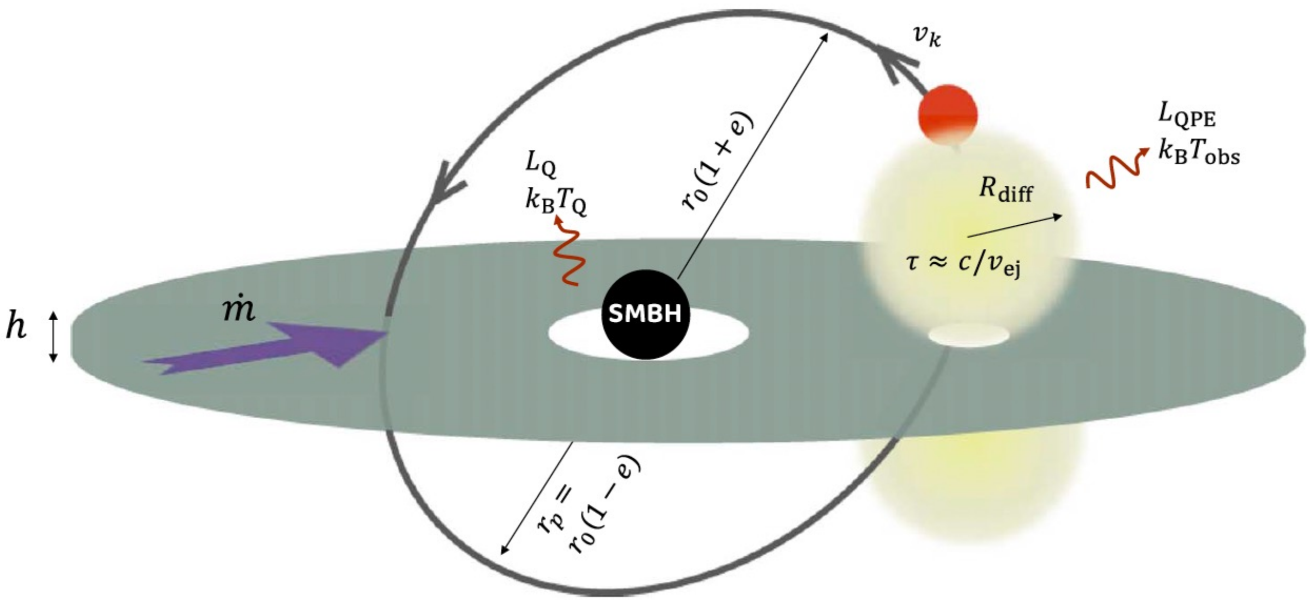
Effective cross section is determined by **Hill radius**

$$R_{\mathrm{Hill}} \simeq \left(\frac{m_\star}{M_{\mathrm{BH}}}\right)^{1/3} a$$



QPE formation

Nearly circular orbit!

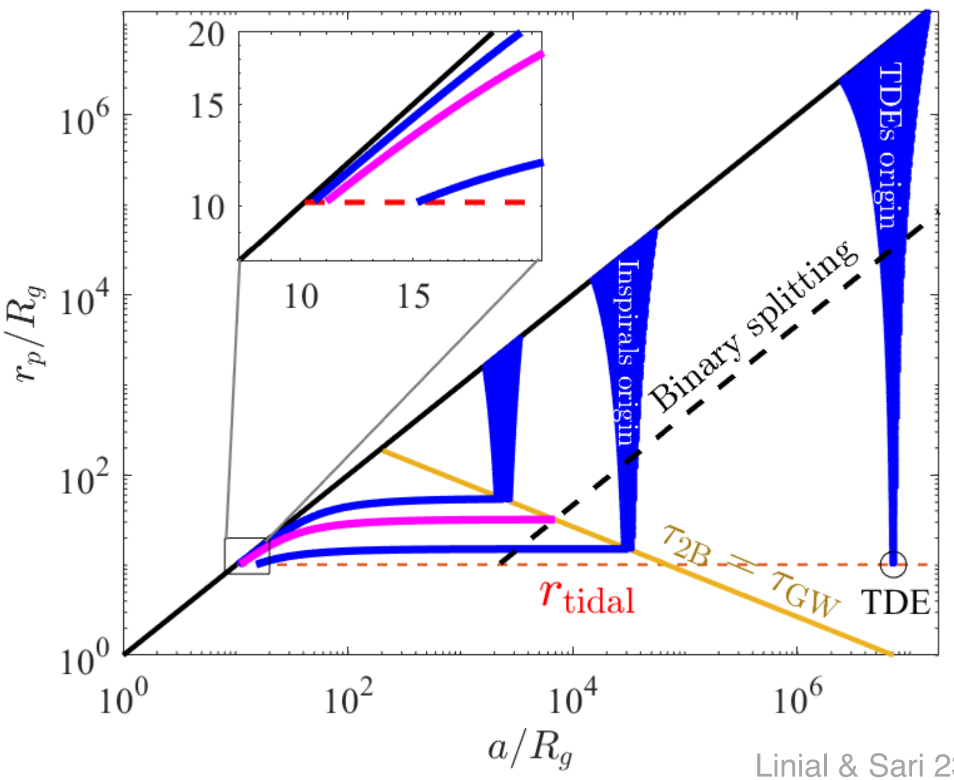


Producing circular orbit near the SMBH is nontrivial…

Dry-EMRI channel

Two-body scattering / Hills mechanism + **GW emission**

Circularization!



Linial & Sari 23, Zhou+24a,b

Extended Emission Line Region

The Astrophysical Journal, 989:49 (14pp), 2025 August 10 https://doi.org/10.3847/1538-4357/ade2d7

CrossMark

Extended Emission-line Region in a Poststarburst Galaxy Hosting Tidal Disruption Event AT2019qiz and Quasiperiodic Eruptions

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Abstract

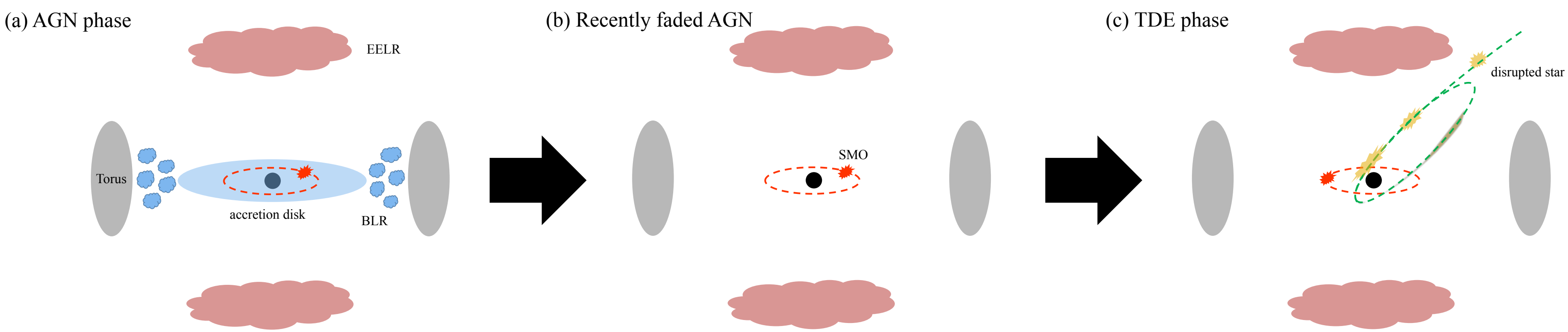
We present a comprehensive analysis of the extended emission-line region (EELR) in the host galaxy of the tidal disruption event (TDE) AT2019qiz, utilizing Very Large Telescope (VLT)/MUSE integral-field spectroscopy. The high spatial-resolution data reveal a biconical emission structure approximately 3.7 kpc in scale within the galactic center, characterized by a prominent [O III] line in the nucleus and significant [N II] line emission extending into the EELR. Spectral analysis of the EELR indicates line ratios consistent with Seyfert ionization in the center and LINER-type ionization in the outer diffuse region, suggesting ionization from galactic nuclear activity. The required ionizing luminosity, estimated from the Hα and Hβ luminosities based on the photoionization and recombination balance assumption, is $10^{41.8}$ erg s^{-1} for all spaxels classified as active galactic nucleus (AGN), and $10^{40.7}$ erg s^{-1} for spaxels in the central 0.9 kpc Seyfert region. However, the current bolometric luminosity of the nucleus $L_{\rm bol} \leqslant 10^{40.8}$ erg s^{-1}, estimated from quiescent-state soft X-ray observations, is insufficient to ionize the entire EELR, implying a recently faded AGN or a delayed response to historical activity. Stellar population analysis reveals a poststarburst characteristic in the EELR, and the gas kinematics show disturbances and noncircular components compared to the stellar kinematics. Notably, the recent detection of quasiperiodic eruptions (QPEs) in the X-ray light curve of AT2019qiz confirms the TDE–QPE association. Our findings provide direct evidence for an AGN-like EELR in the host galaxy of the nearest TDE with QPE detection, offering new insights into the complex interplay between TDEs, QPEs, AGN activity, and host-galaxy evolution.

Unified Astronomy Thesaurus concepts: Tidal disruption (1696); Supermassive black holes (1663); Active galactic nuclei (16); AGN host galaxies (2017); Photoionization (2060)

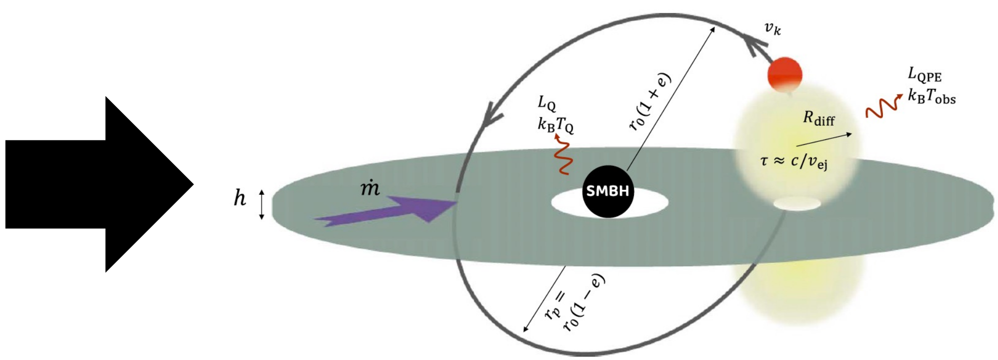
Circularization by the interaction with AGN disk may be important

Unified Model

Circularization & orbital decay by the AGN disk produces QPEs



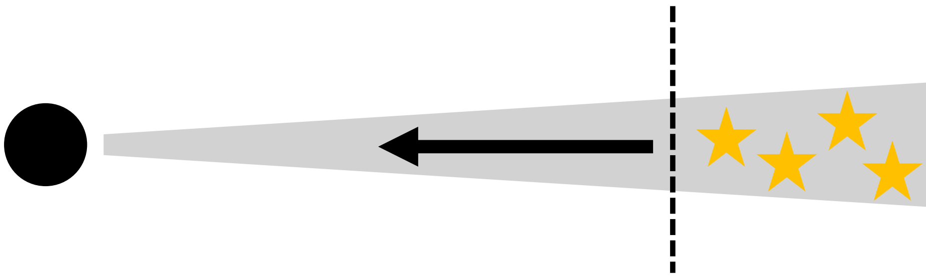
Xiong+25



Q. Where do these stars come from?

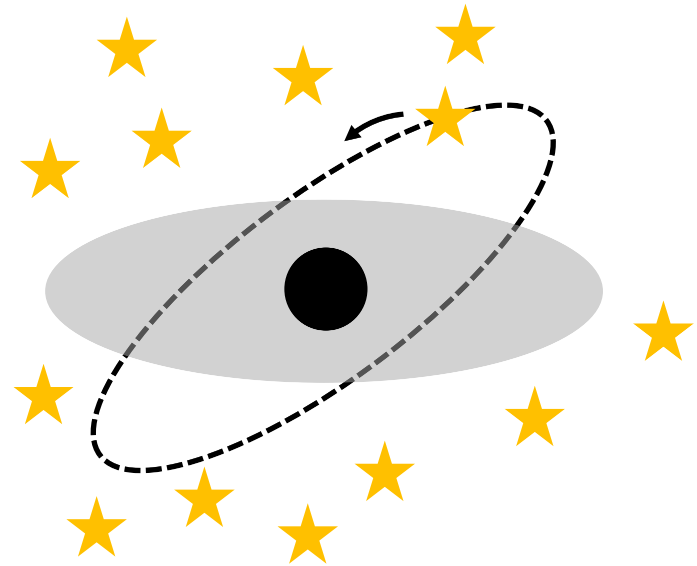
Disk-embedded stars

I. in-situ



Fragmentation by gravitational instability
& migration of the fragment

II. capture



Capture by the interaction with
the disk & migration

Quantitative checks are my ongoing work (but limited by thesis…)

<u>Take home messeages</u>

+ **<u>Quasi-periodic eruptions (QPEs)</u>** are recurring nuclear X-ray transients, and the promising origin is **<u>star-disk collision</u>**
+ Recent observations imply that QPEs are associated with tidal disruption events (TDEs), suggesting that the disk originates from TDEs
+ Long-term observations have been carried out vigorously, which may constrain the QPE (emission) model
+ There is no observation of QPEs 100 days after TDEs, but if these QPEs are discovered in the future,
  - their durations may be shorter than those detected so far
  - their spectra may be harder than those detected so far
  - they may be served as a probe of the initial evolution of the TDE disk
+ Discovery of the strange QPEs, theoretical challenges on the emission mechanism, non-trivial formation mechanism…

QPEs should remain interesting for a while!!