Quasi-Periodic Eruptions as a Probe of TDE Disks

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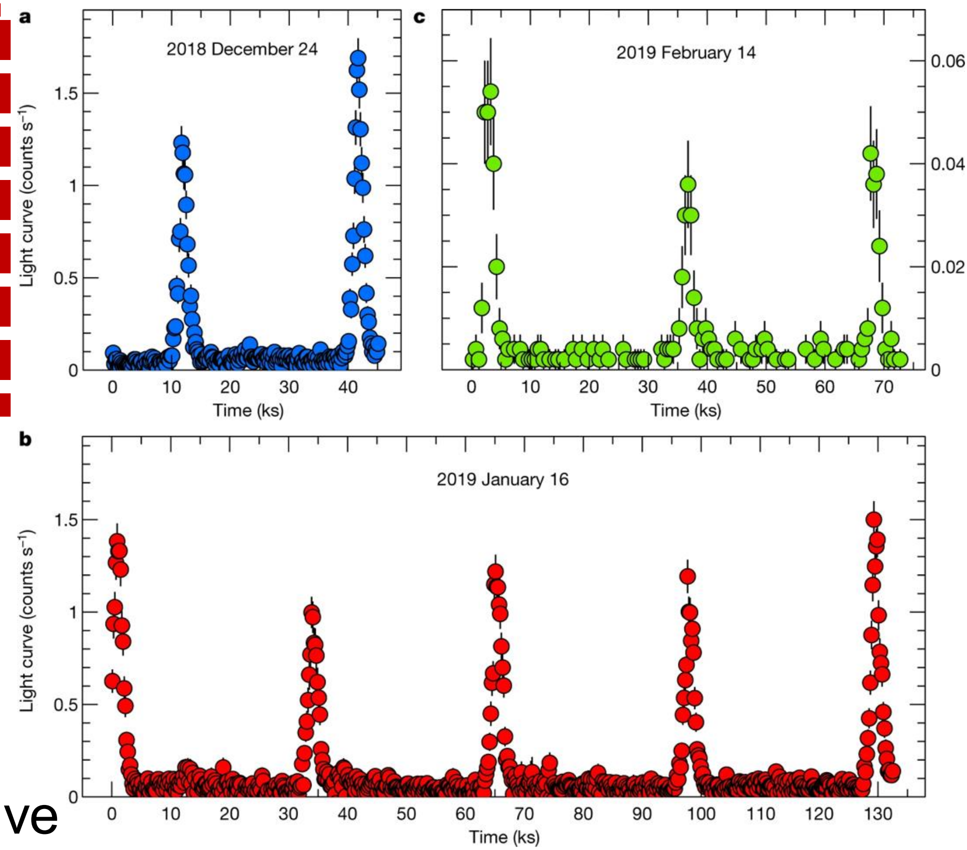
TS & Matsumoto (arXiv: 2509.01663)

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: $\mathbf{100 - 200\ eV}$

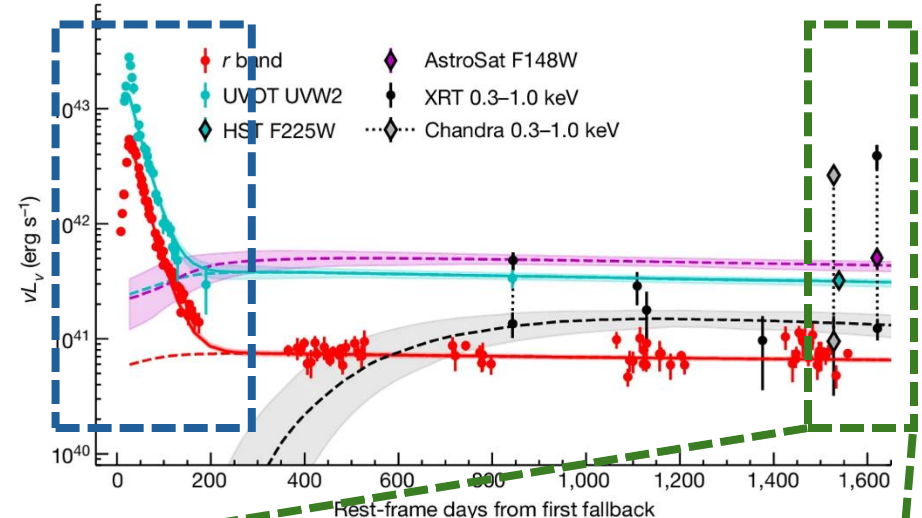


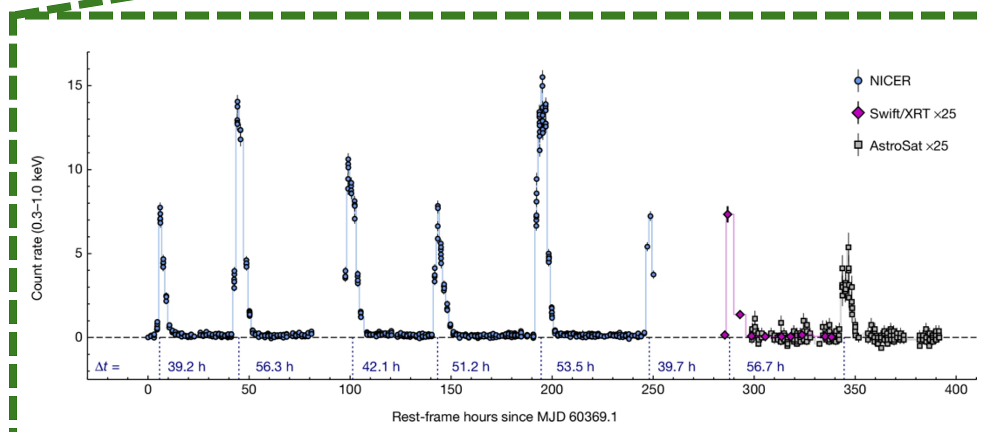
+ Quasi-periodicity
  - long/short oscillation ($\sim 10\ \%$) in the recurrence time
+ Host galaxies
  - low mass ($M_{\rm BH} \sim 10^{5-7} M_{\odot}$) & inactive
+ No similar bursts at other wavelengths

TDE-QPE Association

Some observations imply that QPEs are associated with TDEs

+ **Direct:**
  Some QPEs are discovered after TDEs occur
  - Two events are confirmed
    Nicholl+24, Chakraborty+25
  - Some (maybe three) candidates
    Miniutti+19, Chakraborty+21, Quintin+23, Bykov+25

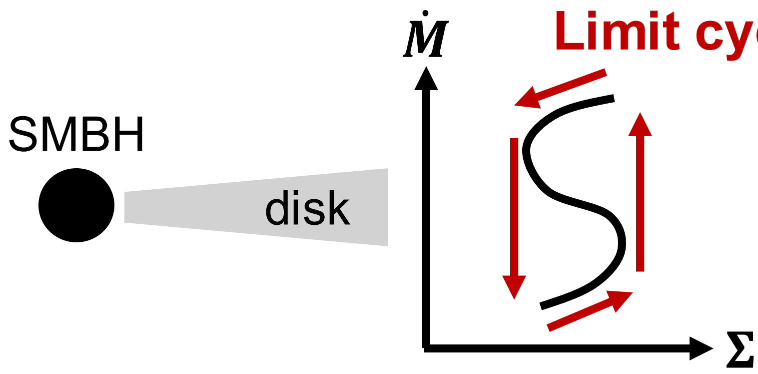




+ **Indirect:**
  Some properties of host galaxies are similar Wevers+22,24
  - low-mass & inactive
  - prefer <u>post-starburst galaxies</u>

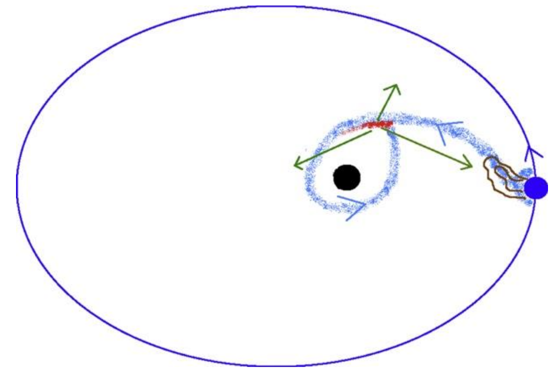
Scenarios

1. Disk instability



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

2. Mass transfer

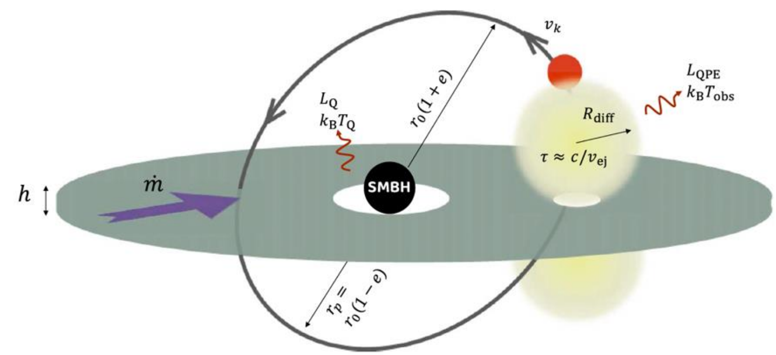


Krolik & Linial 22, Metzger+22, Linial & Sari 23,
Lu & Quataert 23, Olejak+25

3. Star-disk collision

Interaction between the disk and the orbiting star makes QPE signals

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

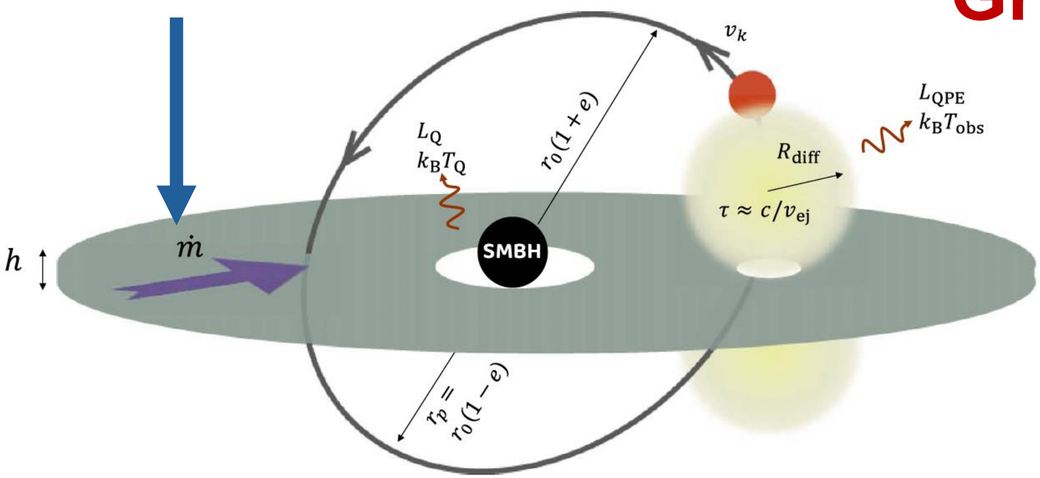


Dai+10, Xian+21, Sukova+21, Linial & Metzger 23, Franchini+23, Tagawa & Haiman 23, Linial & Metzger 24, Zhou+24a,b,25,
Linial+25, Tsz-Lok Lam+25, Vurm+25, Yao+25, Huang+25

“EMRI + TDE = QPE”

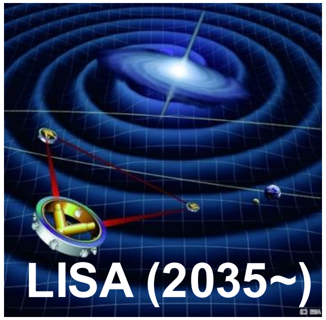
Extreme Mass Ratio Inspiral

from TDE!?



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

Gravitational Wave



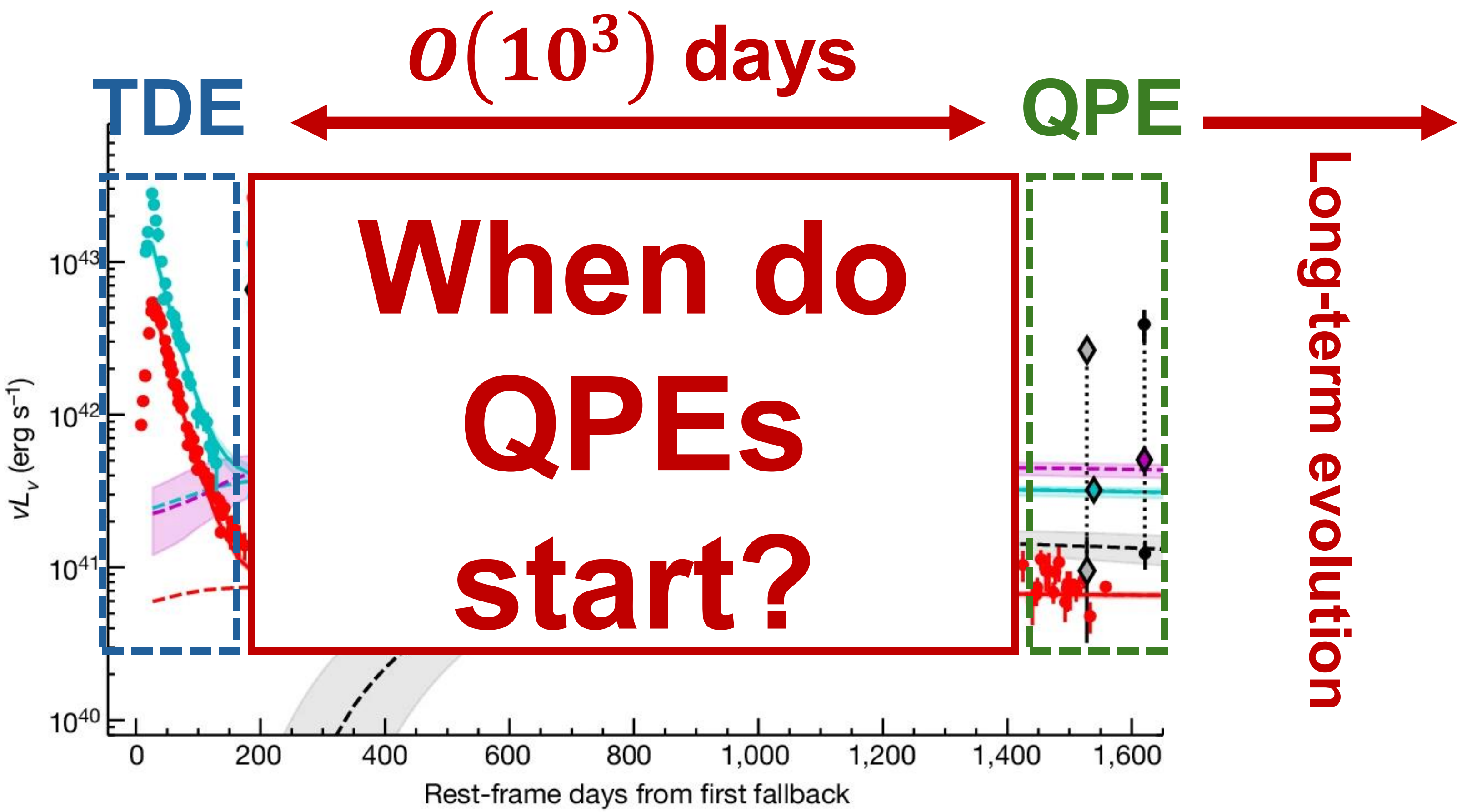
$$P_{\mathrm{QPE}} \sim 4\,\mathrm{hr}\, M_{\mathrm{BH},6}^{-1/2}\, a_2^{3/2}$$

$$a = 10^2 R_{\mathrm{g}} a_2$$

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

Chen+22, Kejriwal+24, Lyu+24, Duque+25, Olejak+25, Lui+25, TS, Omiya & Takeda 25

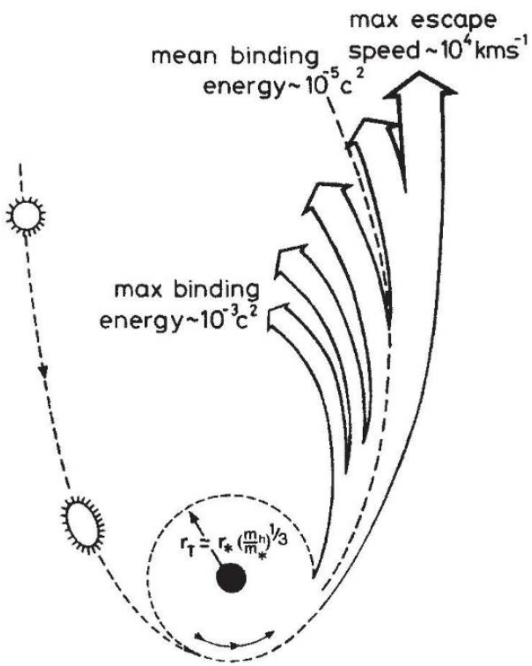
Early-time evolution



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

TDE disk

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



\+ fallback rate of the bound material:

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

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

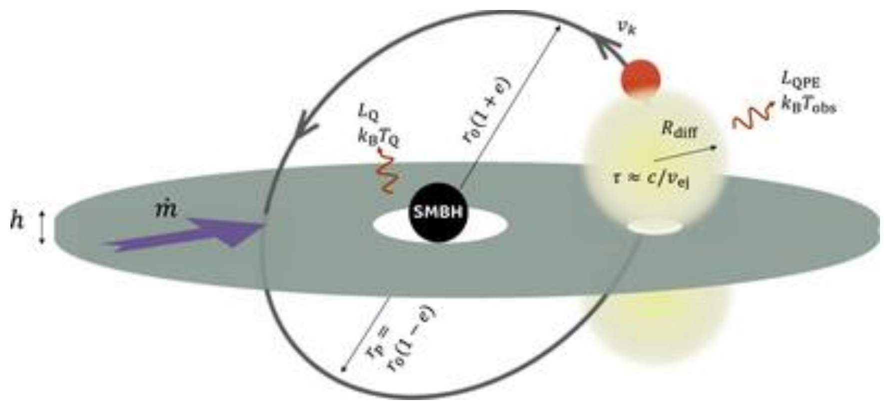
$$\beta = R_{\mathrm{p}}/R_{\mathrm{T}}$$

Slim disk!

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

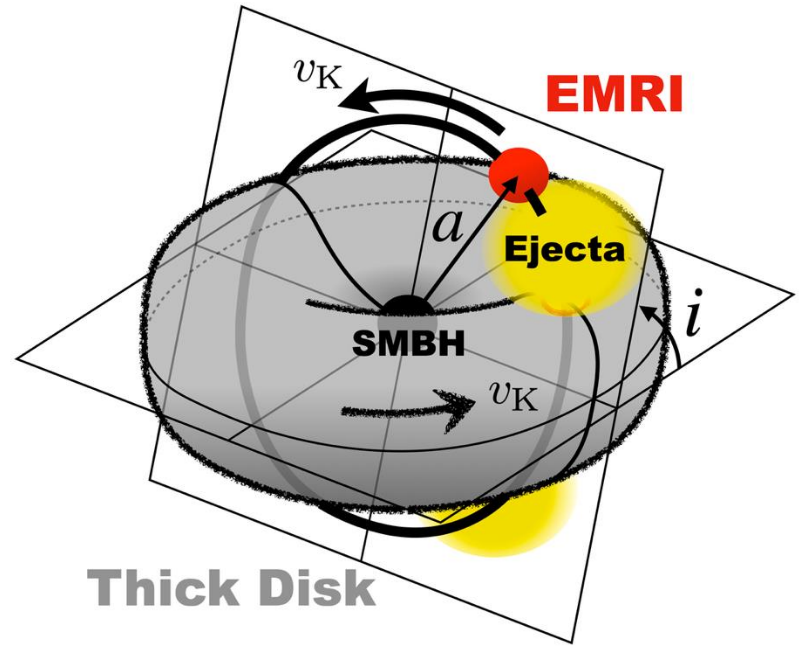
Motivation of our work

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

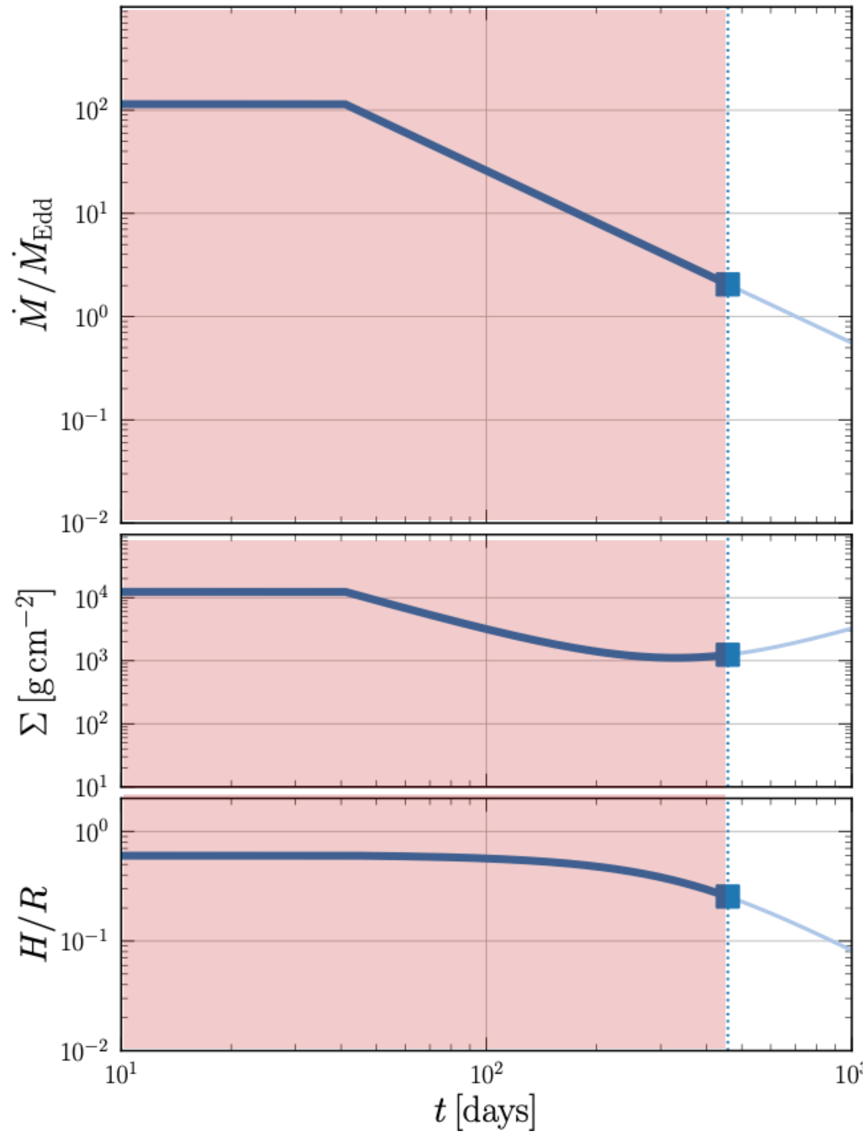
- Assume that accretion rate = fallback rate

+ Fiducial parameter

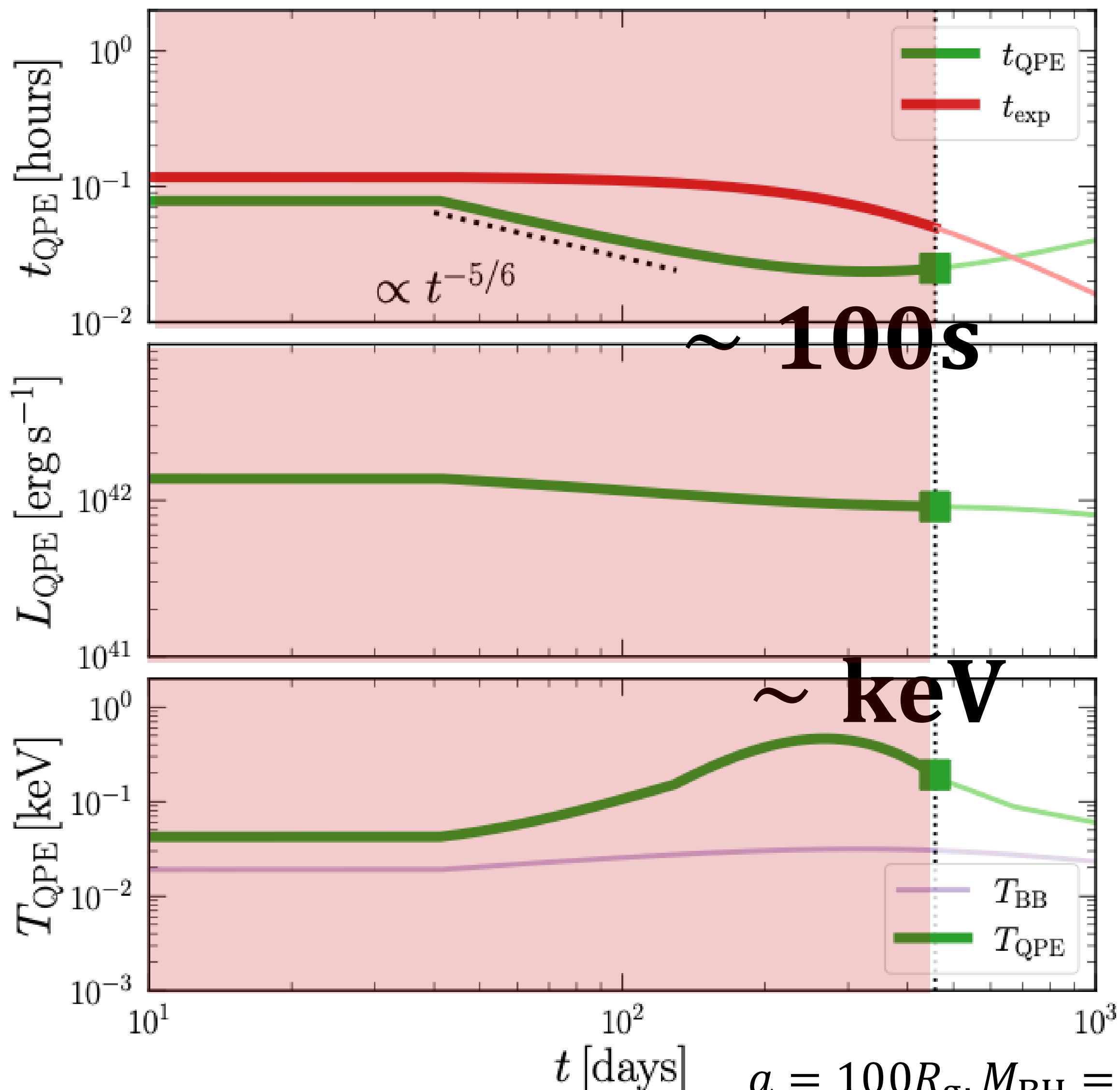
$$M_{\rm BH} = 10^6 M_\odot$$

$$\alpha = 0.1$$

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



Evolution of observables



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

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

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

Emission mechanism

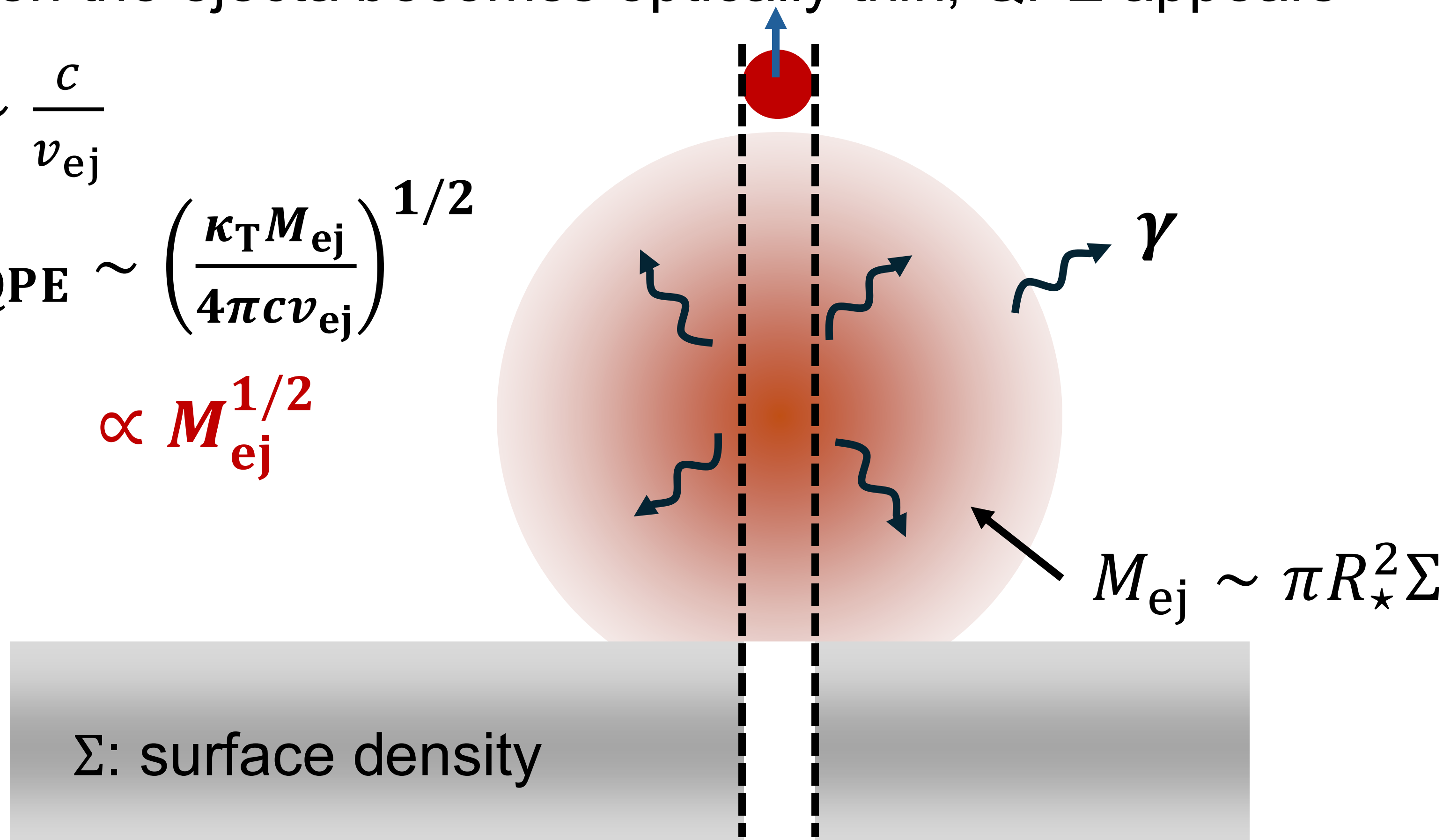
"EMRI + TDE = QPE" model

When the ejecta becomes optically thin, QPE appears

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

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

$$\propto M_{\rm ej}^{1/2}$$



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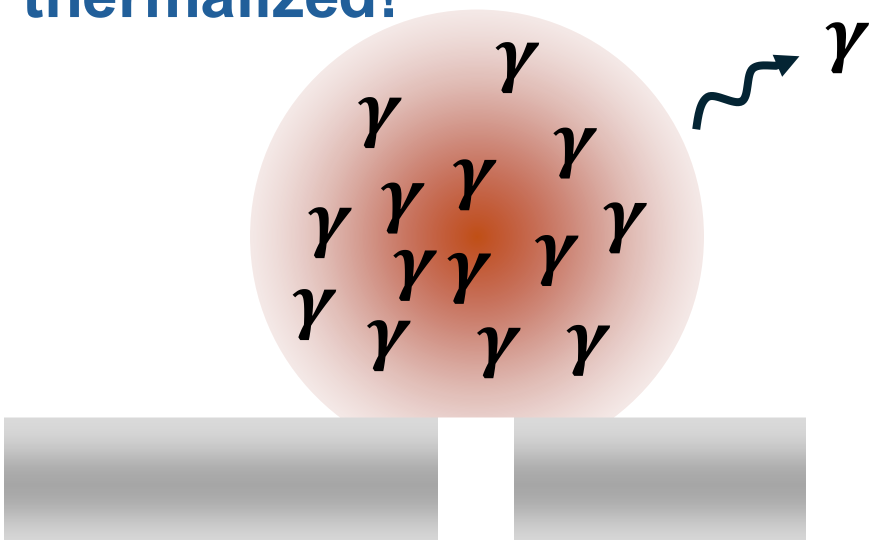
Emission mechanism

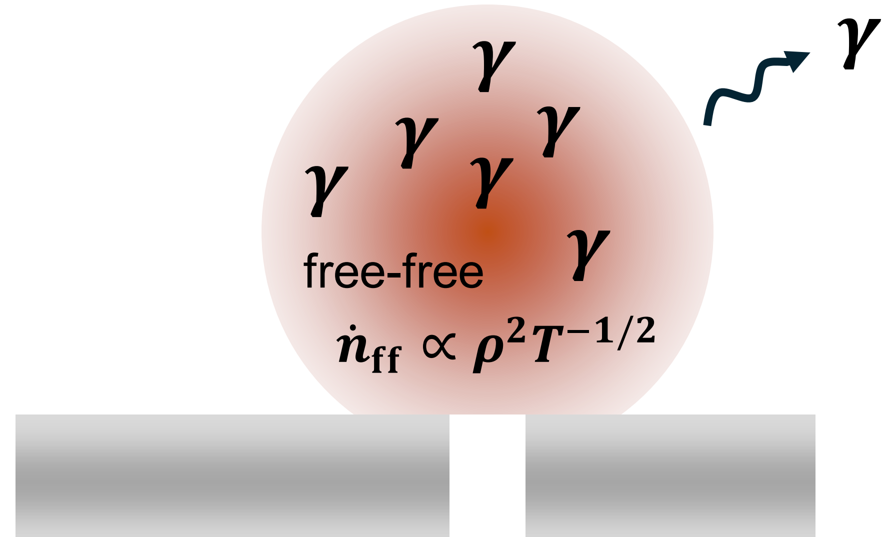
"EMRI + TDE = QPE" model

Inefficient photon production leads to **higher temperature**

Weaver 76, Katz+10, Nakar & Sari 10

thermalized!





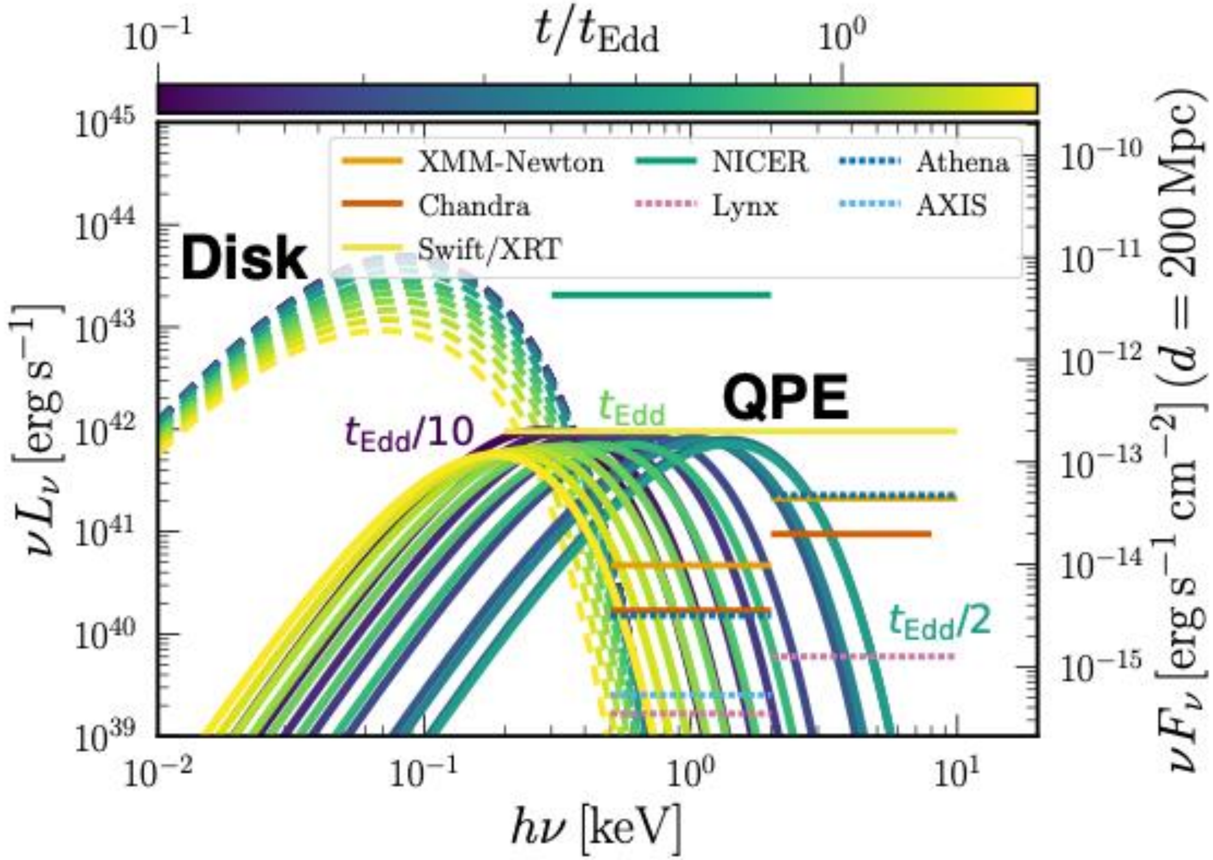
$T_{\rm QPE} = T_{\rm Blackbody}$

$T_{\rm QPE} > T_{\rm Blackbody}$

Note: Comptonization becomes important in some cases…

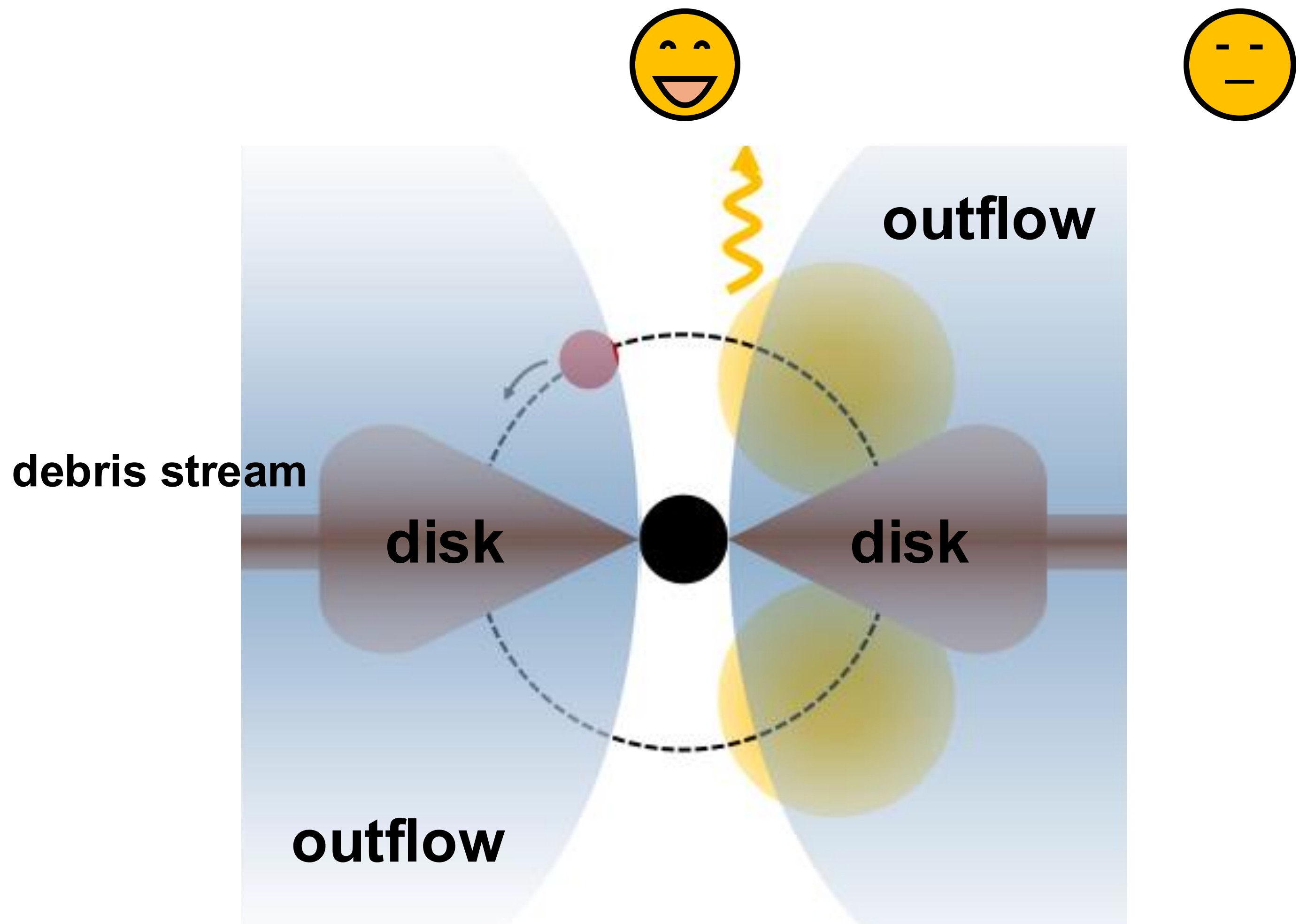
Spectrum & Observability

Temperature evolution: low → high → low



Early QPE can be observed by ongoing X-ray observatories!

Spectrum & Observability



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

Summary

+ **Quasi-periodic eruptions (QPEs)** are recurring nuclear X-ray transients, and the promising origin is **star-disk collision**
+ 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