Quasi-Periodic Eruption の早期段階進化

Matsumoto workshop

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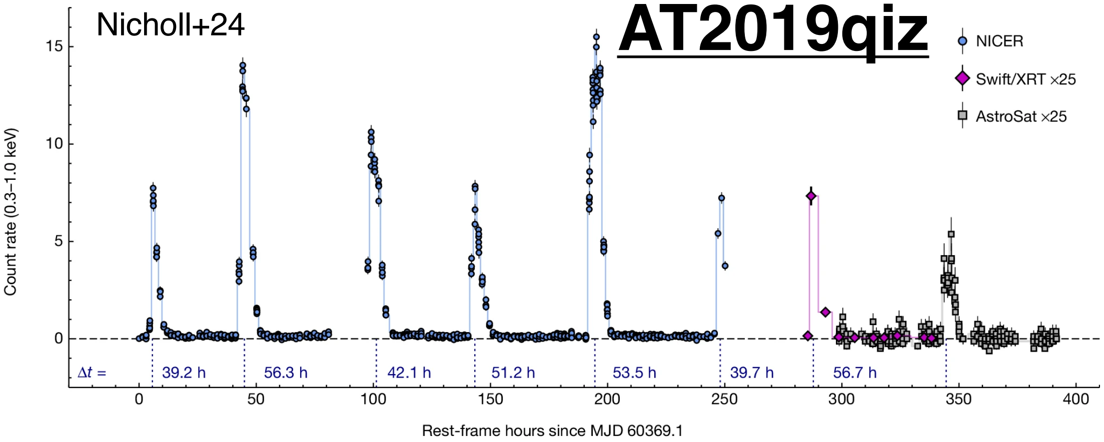
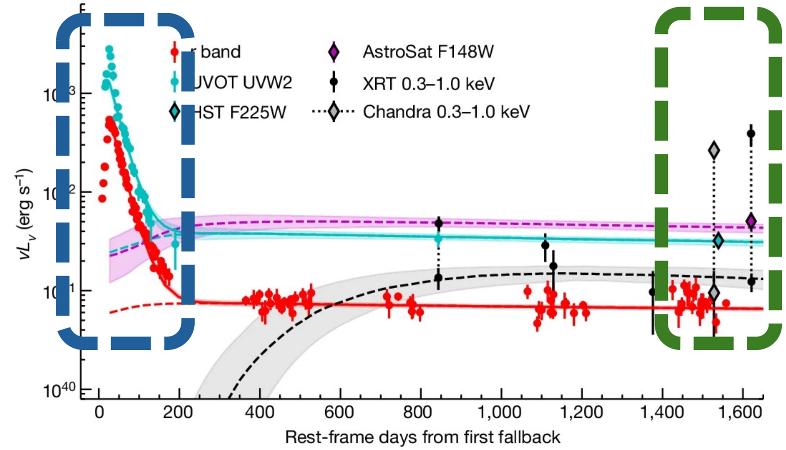
UTokyo

Quasi-periodic Eruption(QPE)

銀河中心核の(準)周期的なX線バースト現象





+ バースト間隔: **数時間 – 数日**
+ ピーク光度: $\mathbf{10^{41-43}\ erg\ s^{-1}}$
+ duty cycle: ~ $\mathbf{10\%}$
+ ピーク温度: $\mathbf{100-200\ eV}$

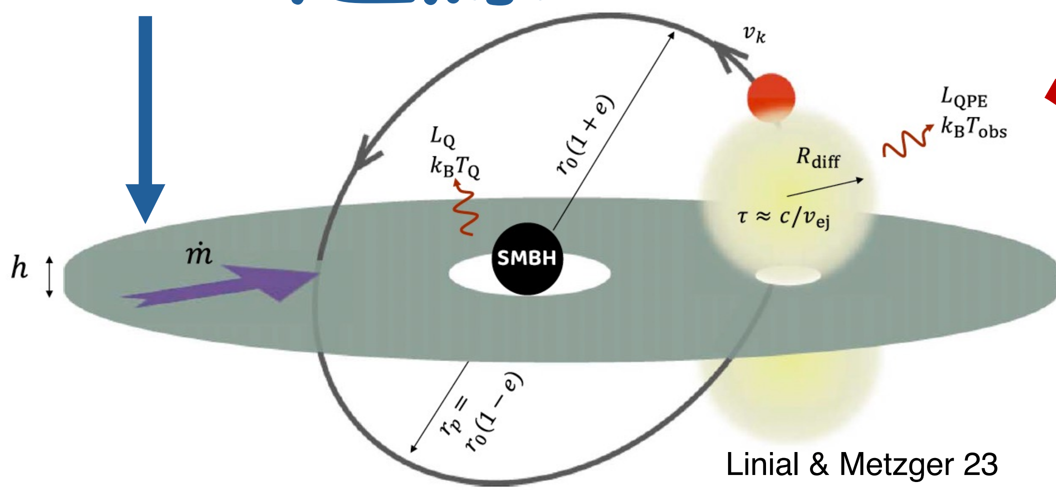
+ **Tidal Disruption Event(TDE)との関連が示唆**

“EMRI + TDE = QPE”

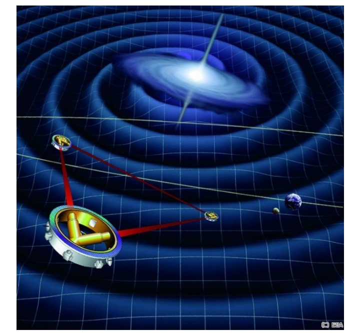
SMBHの周りを回る星と円盤との衝突起源説

TDE起源!?

重力波



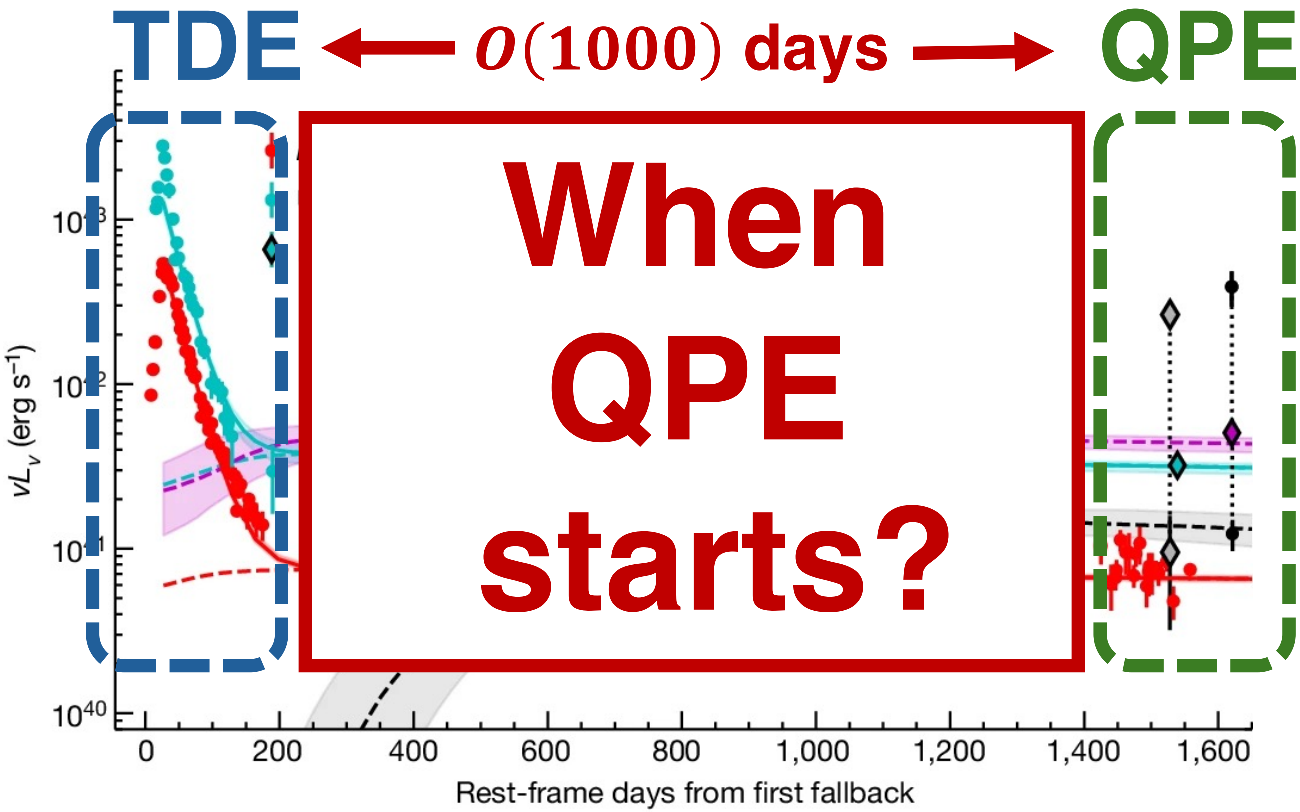
Linial & Metzger 23



QPEはマルチメッセンジャー源になるかも

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

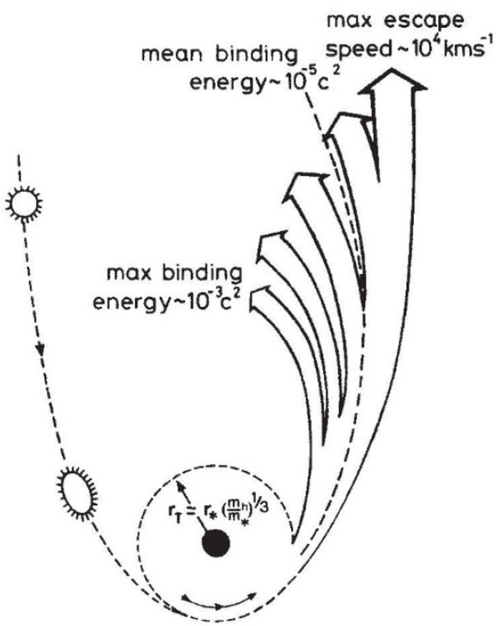
QPEの発生時期



TDE発生後 $\underline{O(100)}$ 日の銀河でQPEは観測できるか？

TDE円盤

降着率が時間依存性をもつ



Rees 88, Phinney 89

+ 束縛物質のfallback rate:

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

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

$$\beta = R_{\rm p}/R_{\rm T} \qquad m_\star = M_\star/M_\odot \qquad r_\star = R_\star/R_\odot$$

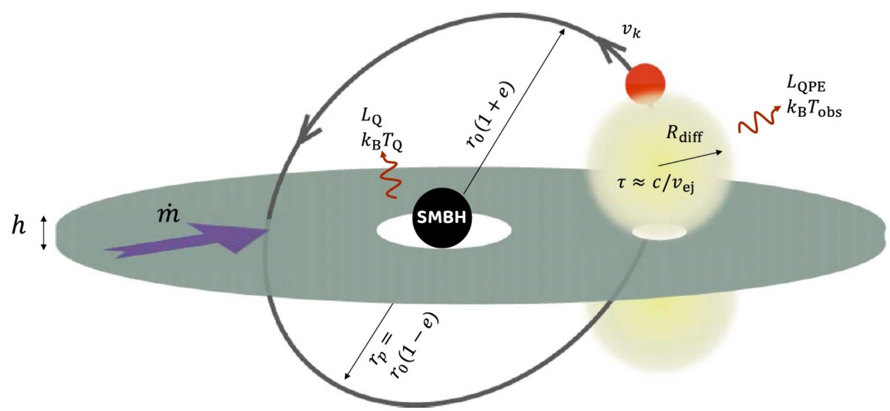
スリム円盤!

早期段階(~ 1 yr)ではsuper-Eddington降着!

e.g., Ulmer 99

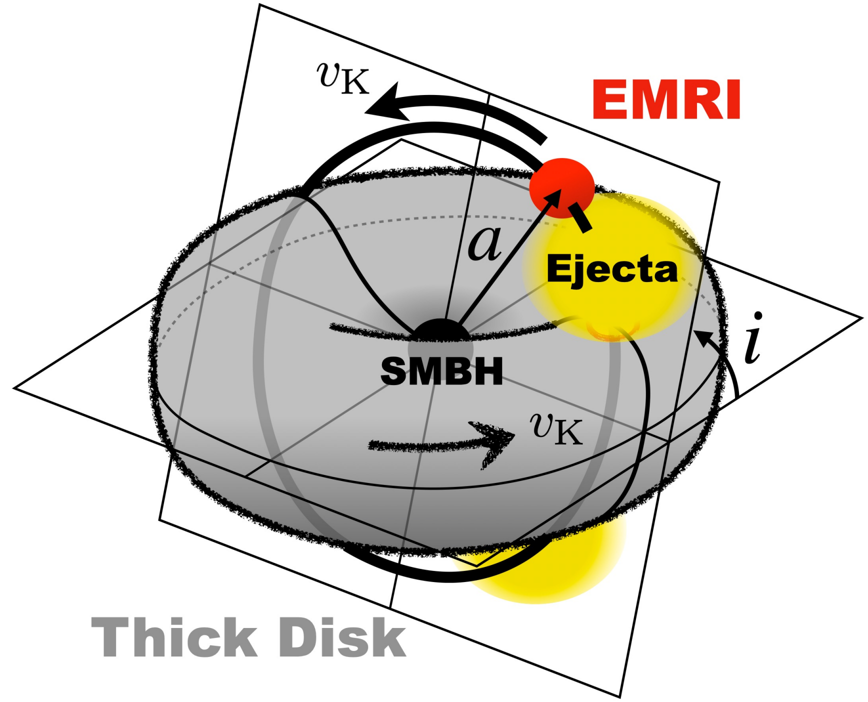
研究の動機

Previous work



Linial & Metzger 23

Our work



標準円盤

スリム円盤

時間依存性も議論したい

TDE円盤モデル

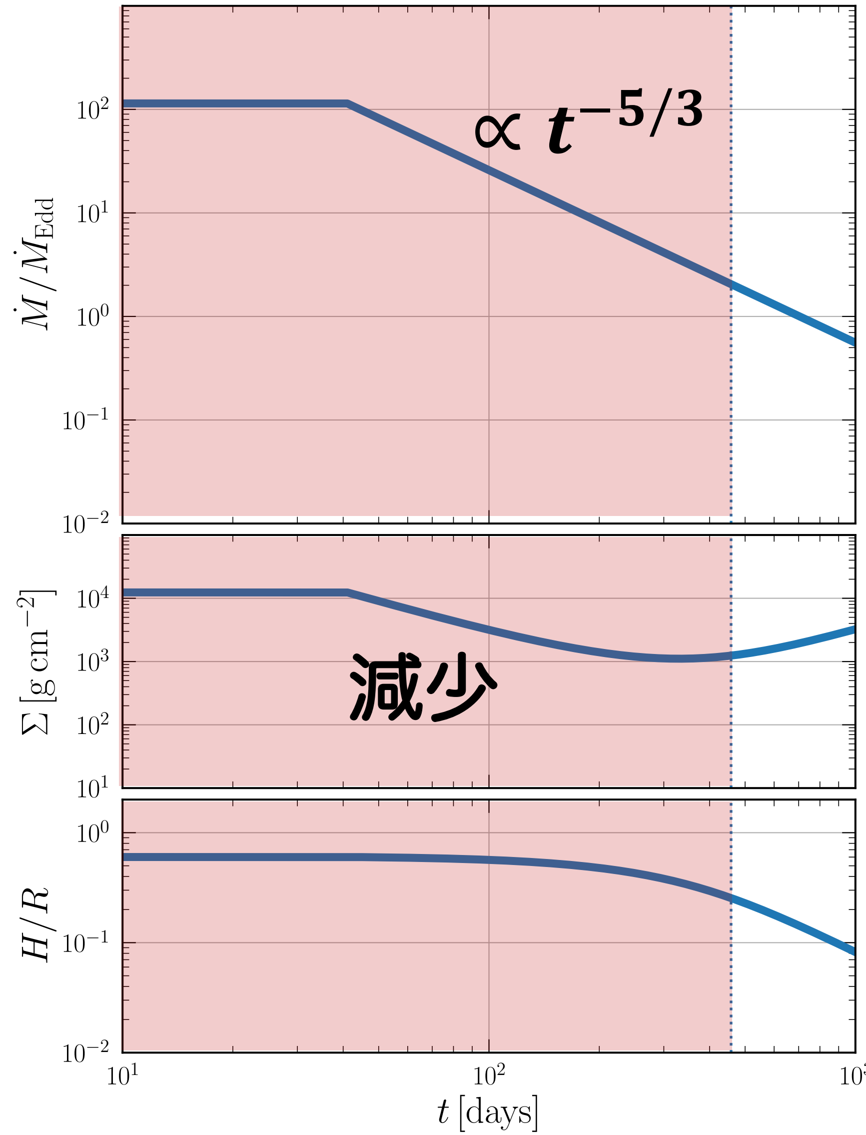
定常解

+ 輻射冷却と移流冷却を共に含んだ定常解

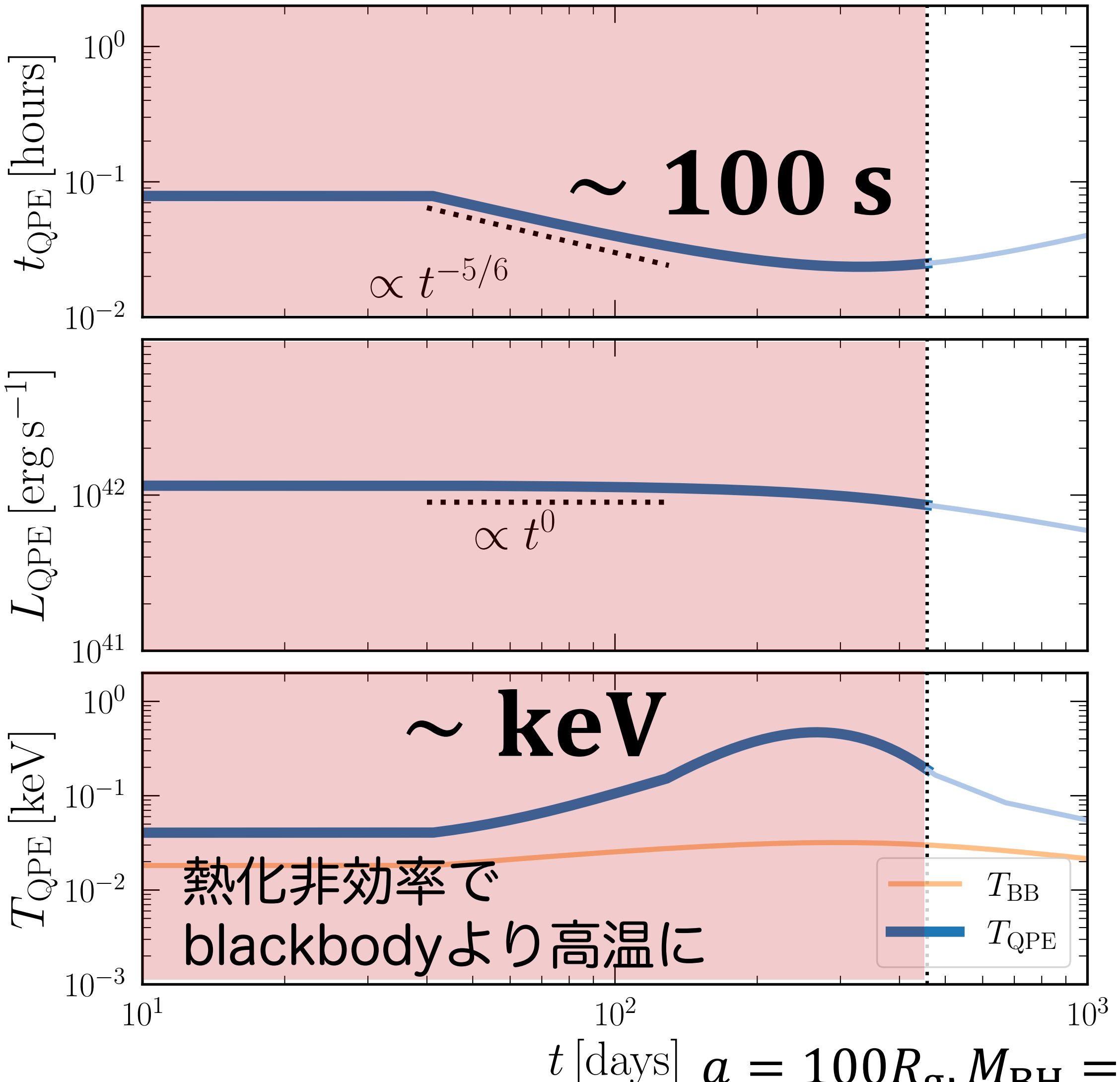
時間依存する降着率

+ 降着率＝fallback rateを仮定

Strubbe & Quataert 09



観測量の時間発展



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

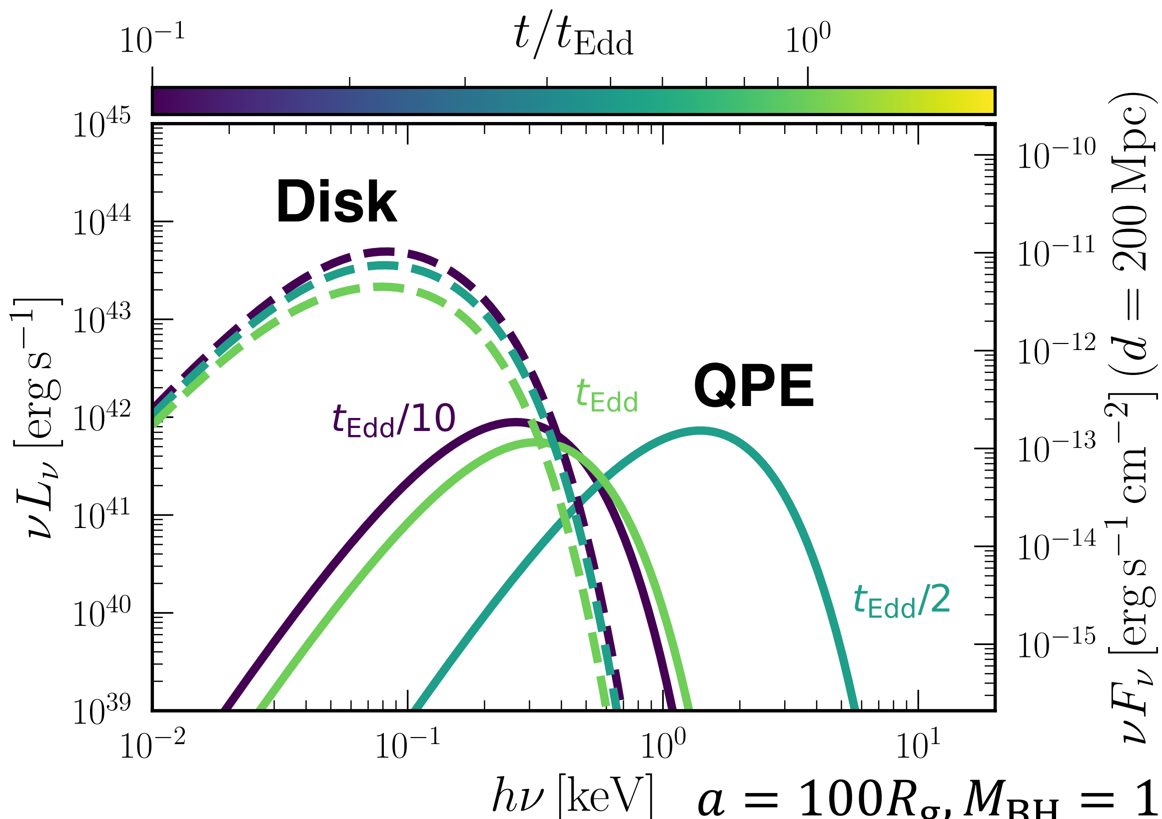
比較

標準円盤	スリム円盤
$\Sigma \sim 10^4 \ \mathrm{g\ cm^{-2}}$	$\Sigma \sim 10^3 \ \mathrm{g\ cm^{-2}}$
$t_{\mathrm{QPE}} \sim 500 \ \mathrm{s}$	$t_{\mathrm{QPE}} \sim 100 \ \mathrm{s}$ 光子の拡散時間が短い
$T_{\mathrm{QPE}} \sim 100 \ \mathrm{eV}$	$T_{\mathrm{QPE}} \sim \mathrm{keV}$ 熱化非効率

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

スペクトル

円盤：multi-color blackbody & QPE: Wien

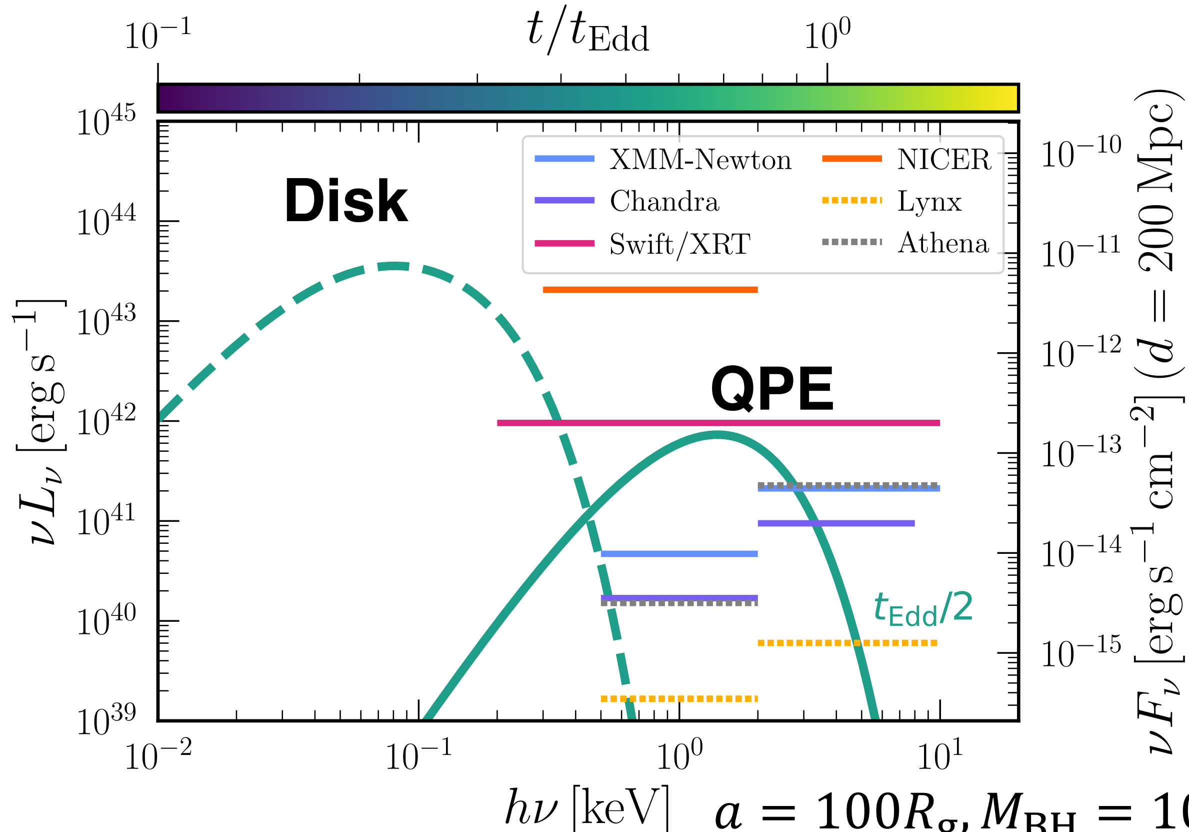


$a = 100R_{\rm g}, M_{\rm BH} = 10^6 M_\odot, R_\star = R_\odot$

QPEは円盤放射に埋もれることなく観測可能

観測可能性

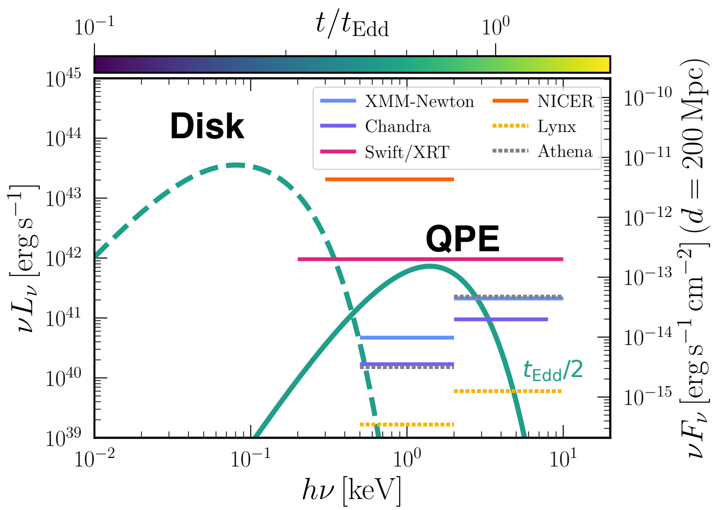
現行のX線観測で検出可能

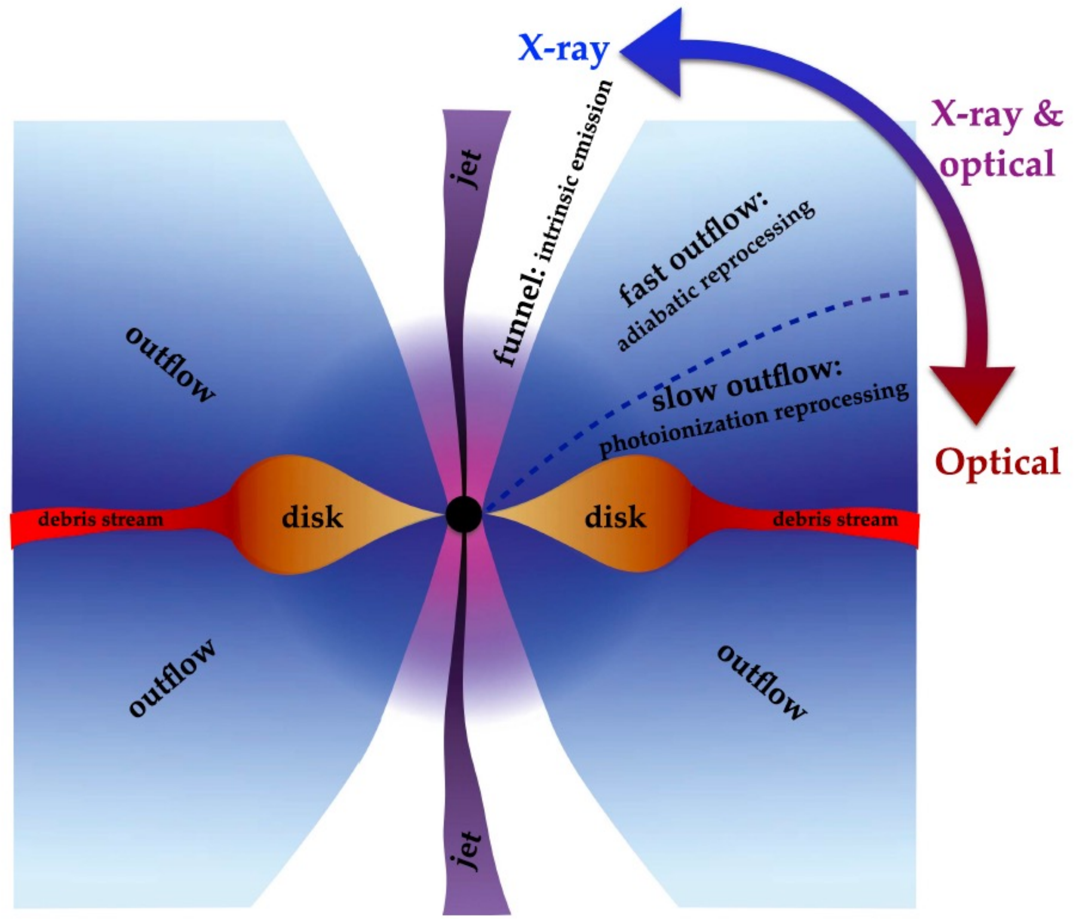


$a = 100R_{\rm g}, M_{\rm BH} = 10^6 M_\odot, R_\star = R_\odot$

duty cycleが小さい or X線の吸収により未検出?

観測可能性





Dai+18

duty cycleが小さい or X線の吸収により未検出?

まとめと展望

+ TDEが起きて1年以内の、super-Eddington降着が実現している段階におけるQPEの観測可能性を調べた
+ このような早期段階では、QPEは現在の観測に比べて
  - 高温: 円盤放射に隠されない
  - 短継続: それでも現行のX線観測で検出可能

  であることがわかった

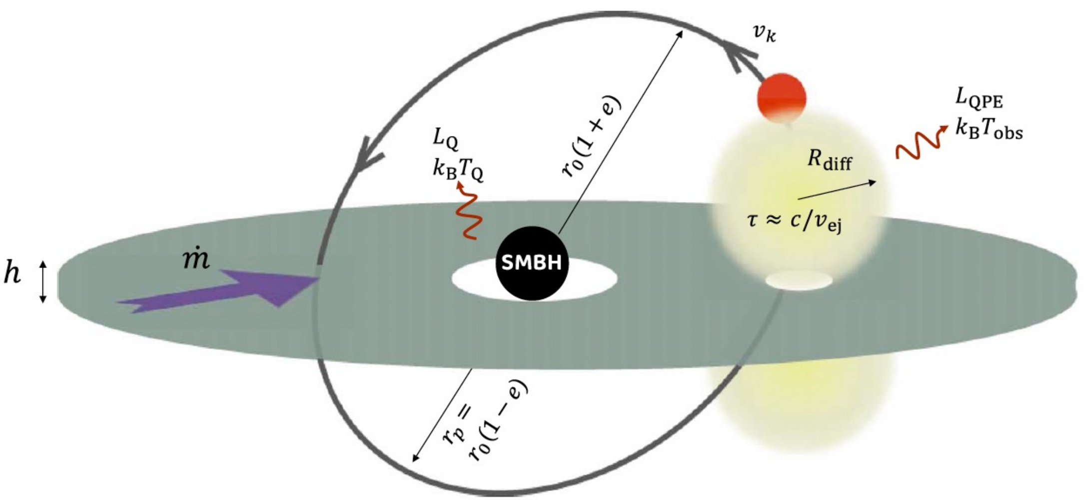
＊emission model？

＊長期の時間進化？

+ One-zone → 1D
+ 円盤不安定性

＊形成メカニズム？

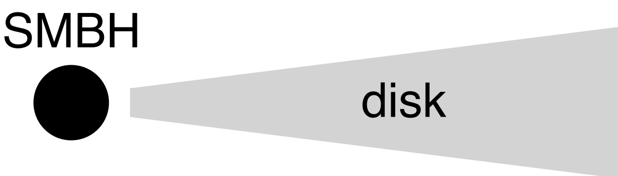
+ low eccentricity?



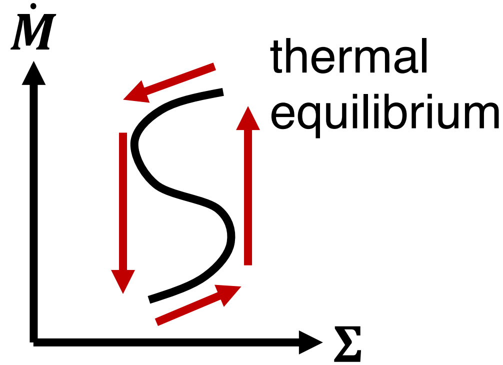
Back Up

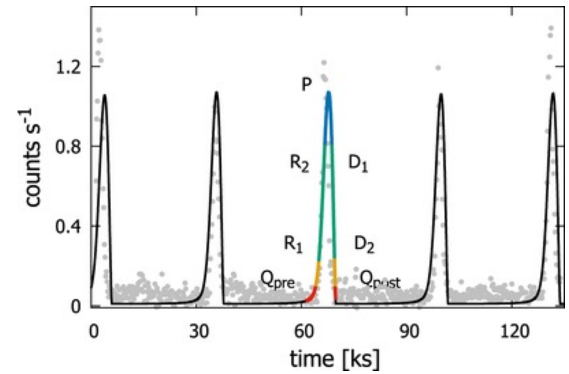
Origin Candidates

1. Limit cycle due to the disk instability



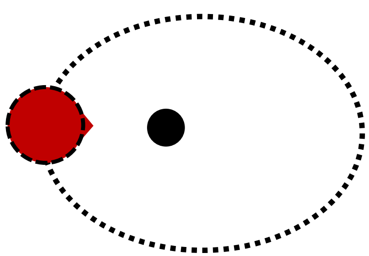
Raj & Nixon 21, Pan+22, Kaur+23, Sniegowska+23



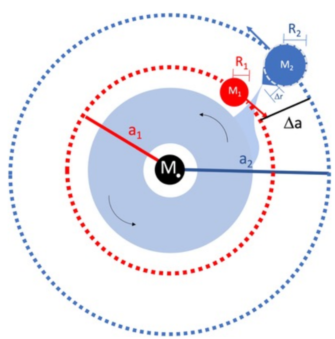


2. Mass transfer

e.g., low-eccentricity orbit

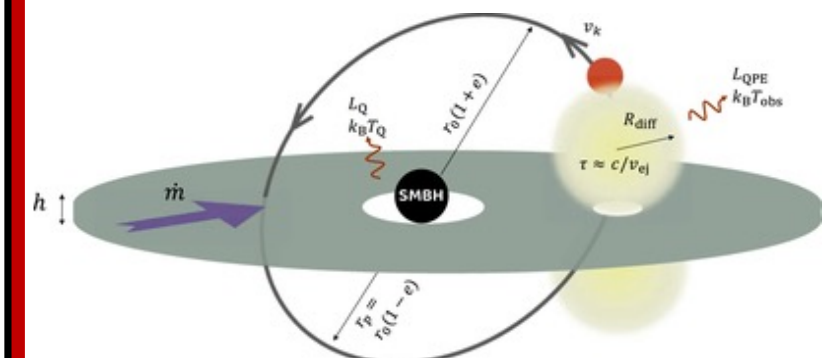


e.g., counter-rotating binary



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

3. Disk+EMRI



Linial&Metzger23, Franchini+23, Tagawa & Haiman 23

TDE disk model

Steady solution + t-dep. fallback rate

+ Steady solution both with radiative and advection cooling

+ Assume that accretion rate = fallback rate

Strubbe & Quataert 09

Scale height: $h \simeq 2.1\times10^{12}\ \mathrm{cm}\ \boldsymbol{g}^{-1}\ \dot{\boldsymbol{m}}(\boldsymbol{t})\ M_{\bullet,6}$

Surface density: $\Sigma \simeq 1.7\times10^{3}\ \mathrm{g\ cm}^{-2}\ \dfrac{\boldsymbol{g}^2\ a_2^{3/2}}{\alpha_{-1}\ \dot{\boldsymbol{m}}(\boldsymbol{t})}$

$\dot{m} = \dot{M}/\dot{M}_{\mathrm{Edd}}$

$$\boldsymbol{g} := \frac{1}{2} + \left[\frac{1}{4} + 150\,\dot{m}^2\left(\frac{a}{R_{\mathrm{g}}}\right)^{-2}\right]^{1/2}$$

$\dot{m} \ll 1\ (\Leftrightarrow Q^-_{\mathrm{rad}} \gg Q^-_{\mathrm{adv}}) \Rightarrow g \to 1$

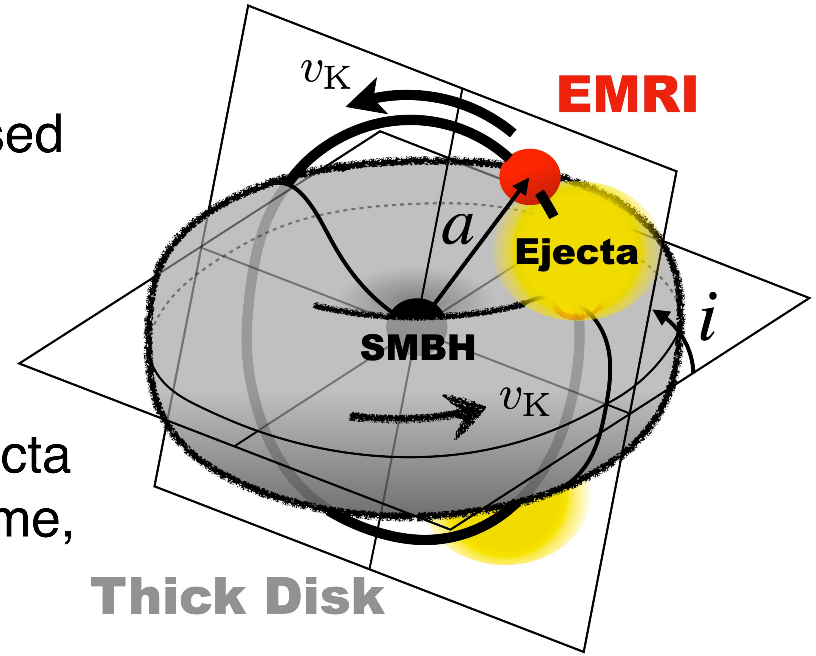
Standard disk !

+ $\dot{\boldsymbol{m}}(\boldsymbol{t}) = \dot{\boldsymbol{m}}_{\mathbf{fb}} \propto \boldsymbol{t}^{-5/3}$

Emission mechanism

"Disk+EMRI" model

1. Gaseous medium in the disk is compressed by the passing star.
2. Compressed material expands adiabatically.
3. When the photon diffusion time of the ejecta becomes comparable to the dynamical time, QPE appears.



duration: $$t_{\rm QPE} \simeq 2.7\times10^{-2}\ {\rm hr}\,\frac{r_\star\,\Sigma_3^{1/2}\,a_2^{1/4}}{\sin i\,\sin^{1/2}(i/2)}$$

luminosity: $$L_{\rm QPE} \simeq 6.8\times10^{41}{\rm erg s}^{-1}\,\frac{\sin^2(i/2)}{\sin^{2/3} i}\,\frac{r_\star^{2/3}\,H_2^{1/3}\,M_{\rm BH,6}^{1/3}}{a_2}$$

$\Sigma = 10^3\ {\rm g\ cm}^{-2}\ \Sigma_3 \qquad H = 10^2 R_{\rm g}\ H_2$

Emission mechanism

"Disk+EMRI" model

4. Free-free emission can not produce sufficient photons to accomplish thermal equilibrium

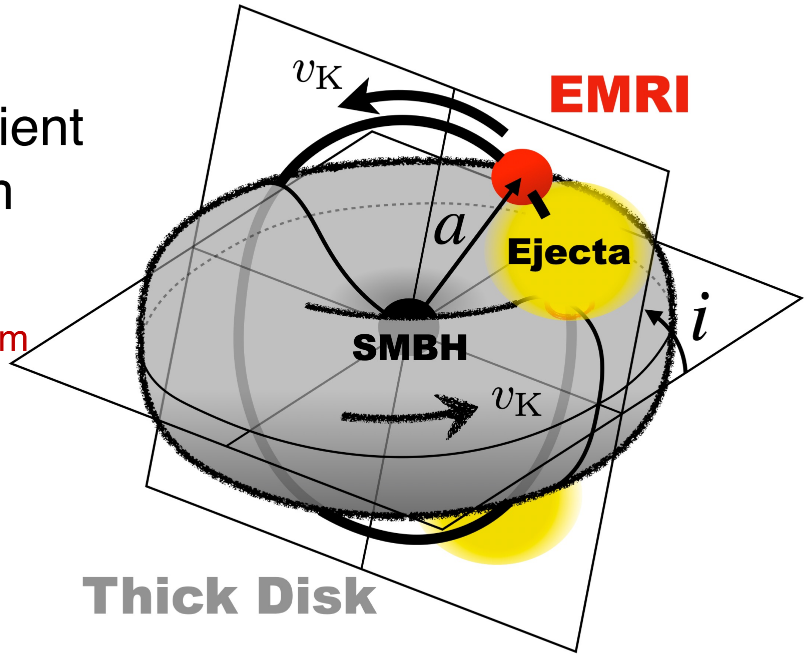
Weaver 76, Katz+10, Nakar & Sari 10

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

Photon number required to accomplish thermal equilibrium

Photon number produced by free-free emission

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



$$\Rightarrow \quad T_{\rm QPE} \simeq \eta^2 T_{\rm BB} \simeq 7.1\,\mathrm{keV}\,\frac{H_2^{1/3}}{r_\star^{1/3}\,\Sigma_3^{5/2}\,a_2^{11/4}}$$

Hard X-ray QPE!

Comptonization

+ free-free absorption
+ dynamical time以内のComptonization