

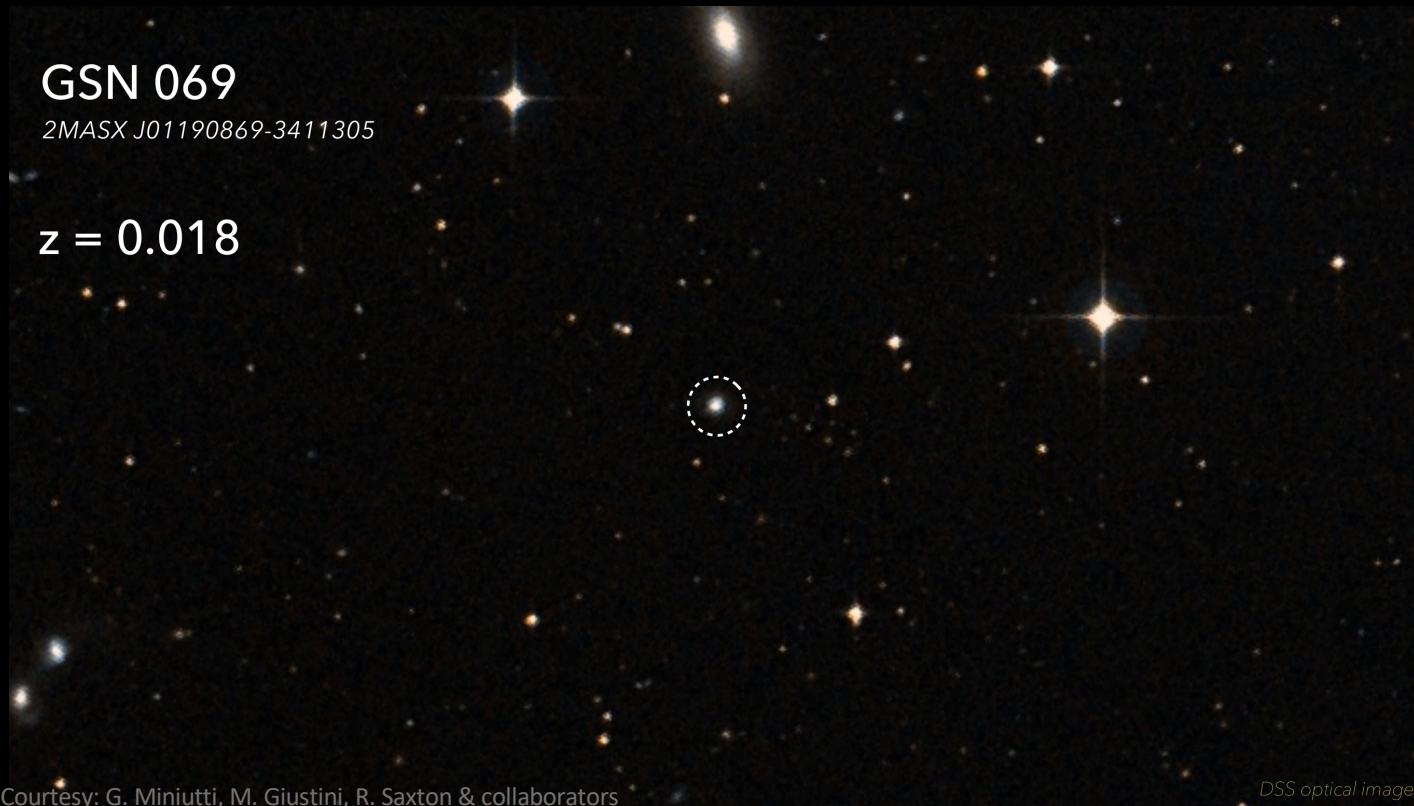


Repeating X-ray flares as probes for galactic nuclei dynamics

Riccardo Arcodia
NASA Einstein Fellow at the MIT Kavli Institute

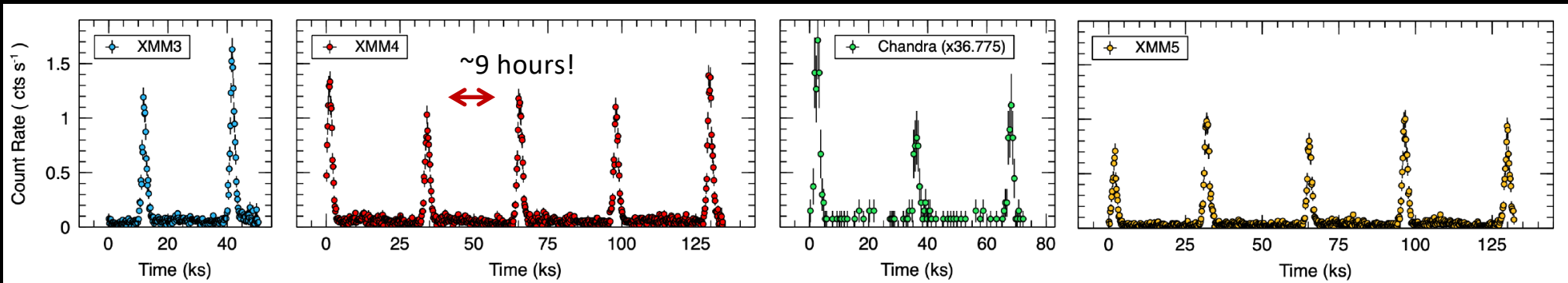
Not too long ago in a galaxy not that far away..

- At the end of 2018 this galaxy was being monitored in X-rays



X-ray quasi-periodic eruptions

- At the end of 2018 this galaxy was being monitored in X-rays



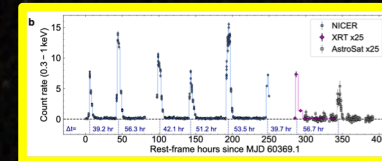
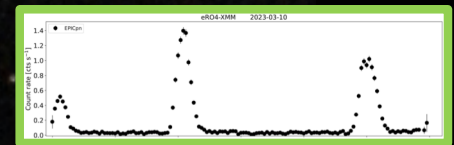
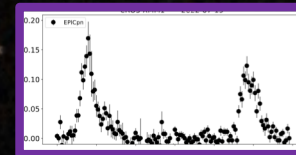
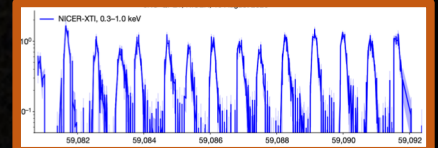
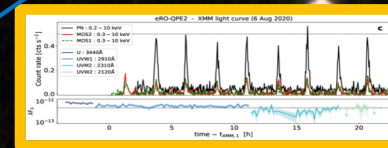
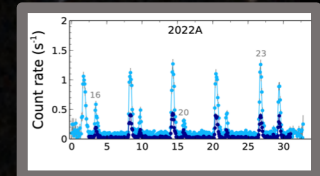
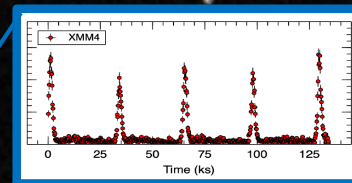
Courtesy: G. Miniutti, M. Giustini, R. Saxton & collaborators

→ This new exotic phenomenon was called “Quasi-Periodic Eruptions (QPEs)”

X-ray quasi-periodic eruptions

Seen in ~10 galaxies now!

X-ray light curves



Miniutti+19; Giustini+20; Arcodia+21;24a; Nicholl+24

Courtesy: G. Miniutti, M. Giustini, R. Saxton & collaborators

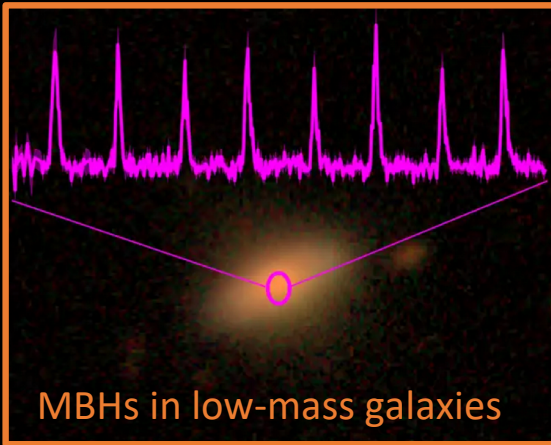
DSS optical image

Riccardo Arcodia

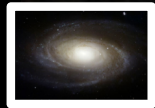
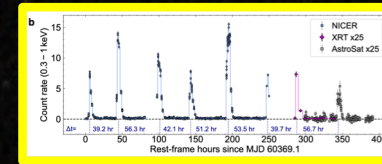
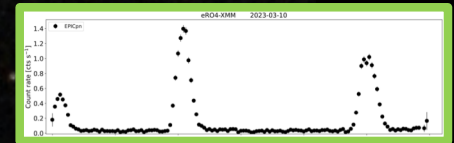
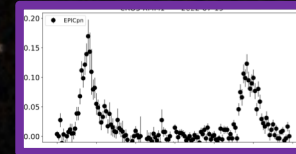
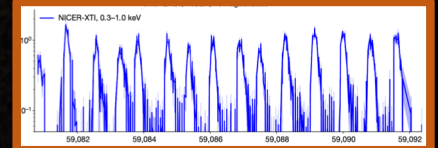
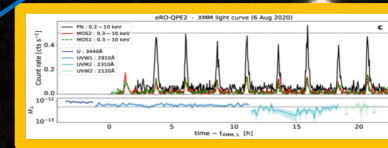
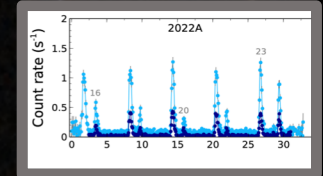
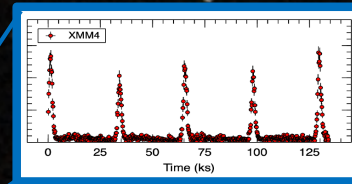
@NHFP24 Sept. 20th 2024

X-ray quasi-periodic eruptions

Seen in ~10 galaxies now!



X-ray light curves



$$M_* \sim 10^9 - 10^{10.5} M_\odot$$



$$M_{\text{BH}} \sim 10^{5-7.5} M_\odot$$

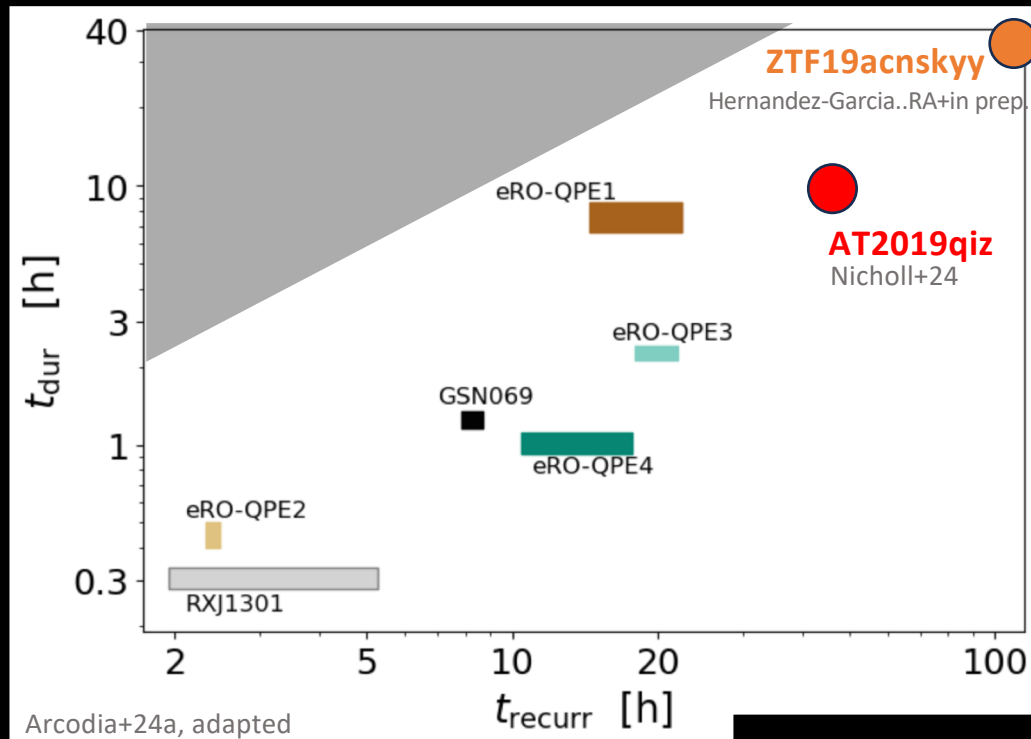
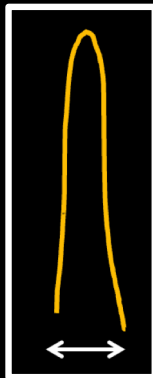
Miniutti+19; Giustini+20; Arcodia+21;24a; Nicholl+24

Courtesy: G. Miniutti, M. Giustini, R. Saxton & collaborators

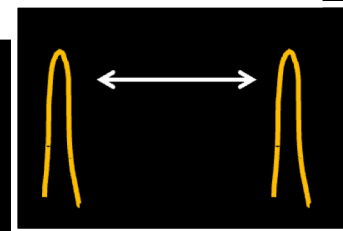
DSS optical image

X-ray quasi-periodic eruptions

Duration



Recurrence time



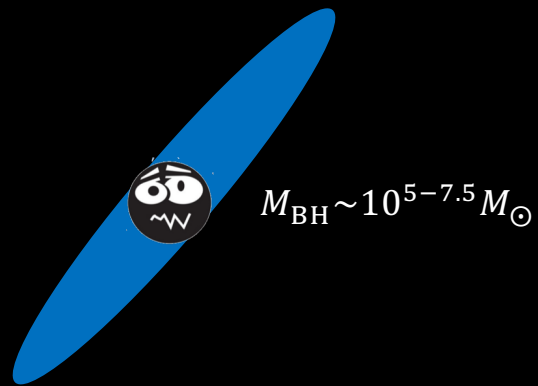
X-ray quasi-periodic eruptions



$$M_{\text{BH}} \sim 10^{5-7.5} M_{\odot}$$

Positions
Luminosity

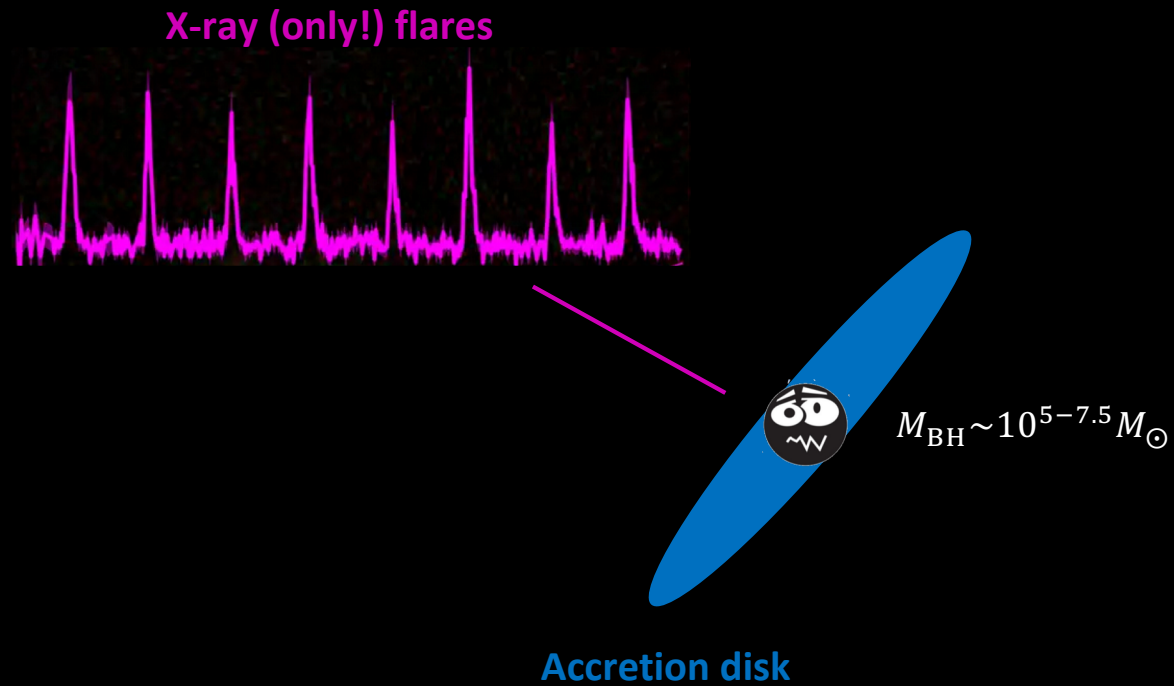
X-ray quasi-periodic eruptions



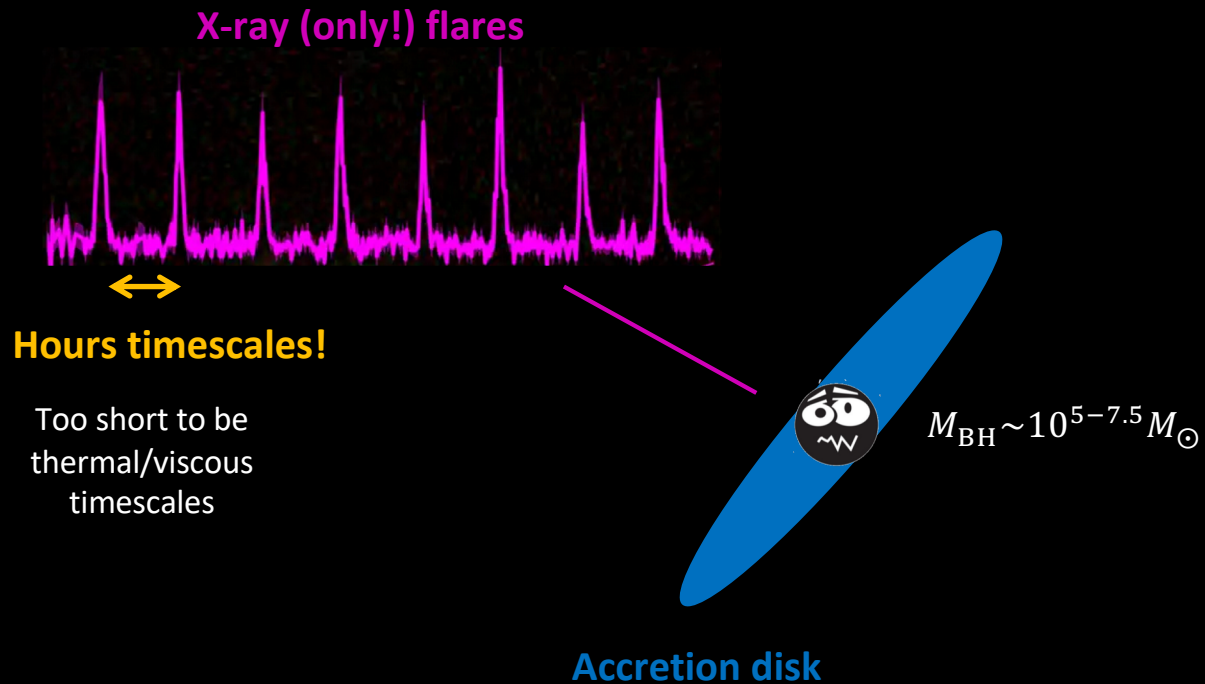
Accretion disk

Soft X-rays, UV

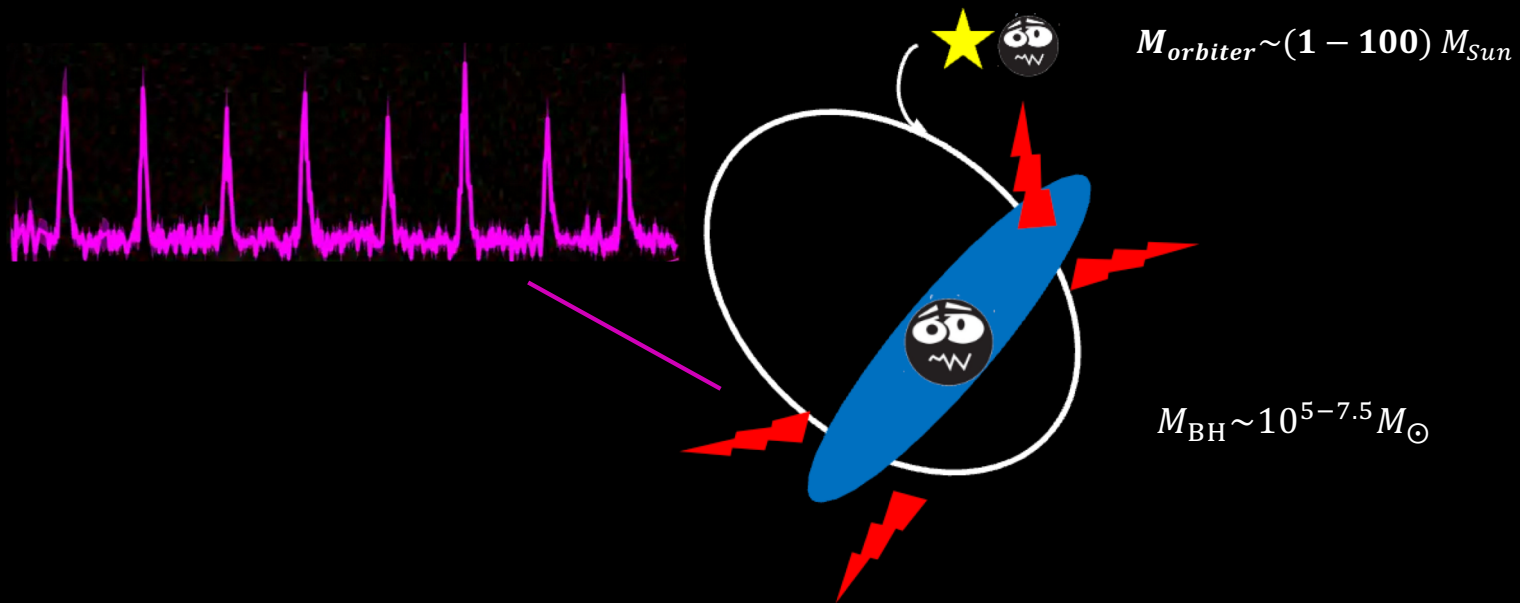
X-ray quasi-periodic eruptions



X-ray quasi-periodic eruptions



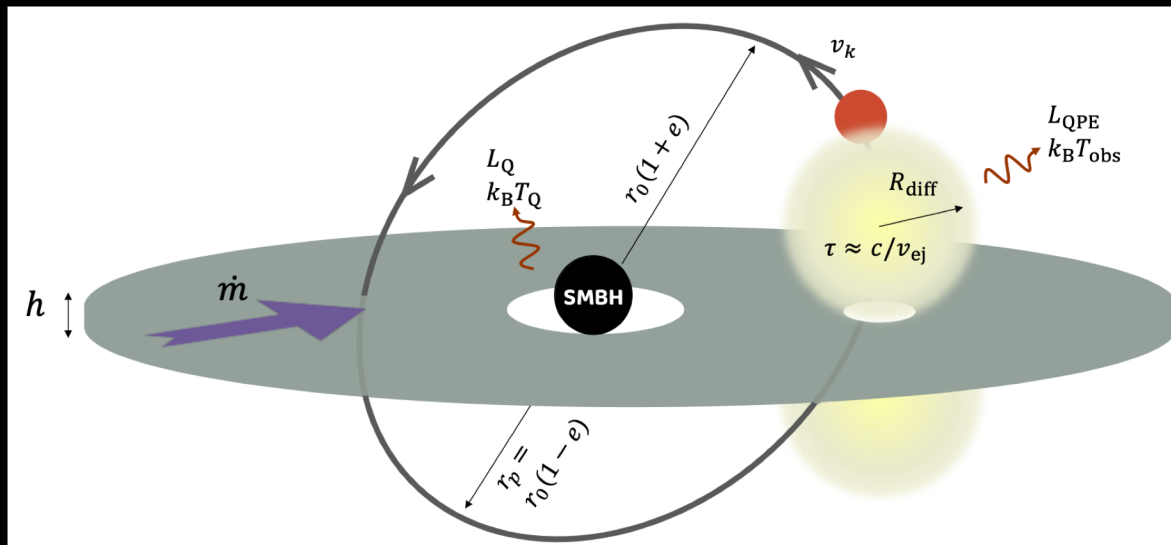
X-ray quasi-periodic eruptions



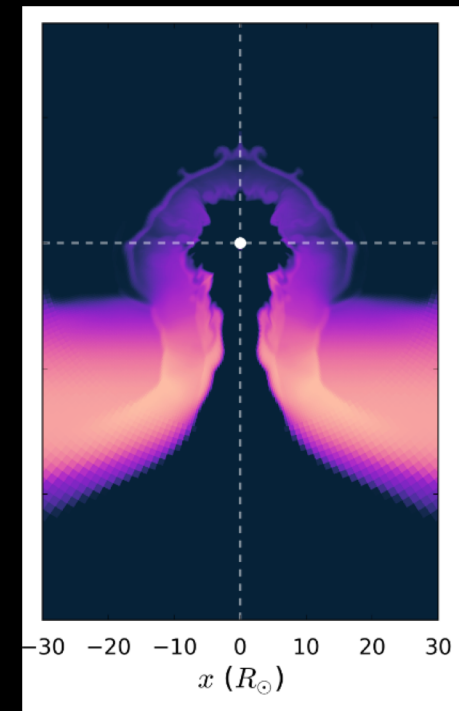
X-ray quasi-periodic eruptions

- QPEs = collisions of a stellar-mass orbiter with the accretion disk

Xian+21; Linial&Metzger23; Franchini,Bonetti+23; Tagawa&Haiman23; Zhou+24; Yao+24



Linial&Metzger23

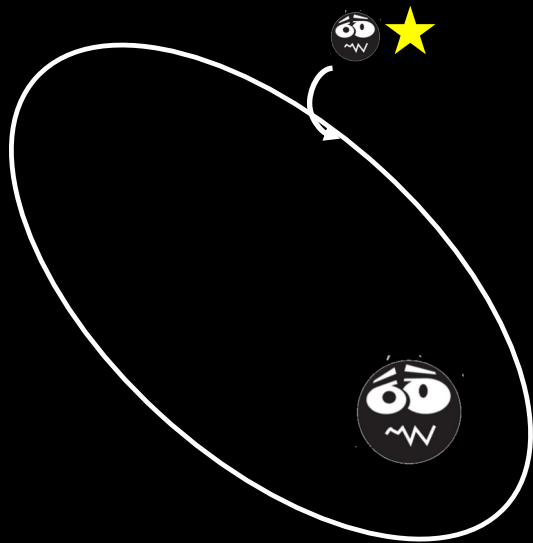


Yao+24

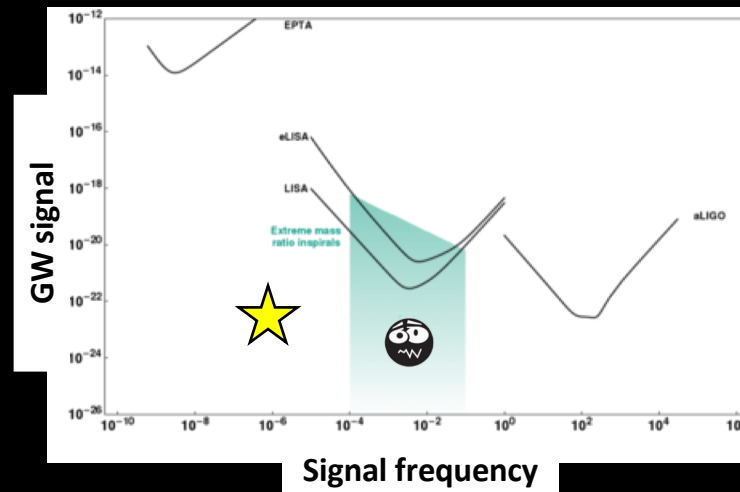
X-ray quasi-periodic eruptions

- QPEs = collisions of a stellar-mass orbiter with the accretion disk

Xian+21; Linial&Metzger23; Franchini,Bonetti+23; Tagawa&Haiman23; Zhou+24; Yao+24



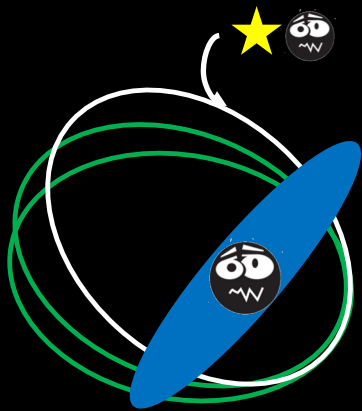
→ These extreme-mass ratio inspirals (EMRIs) emit GWs!



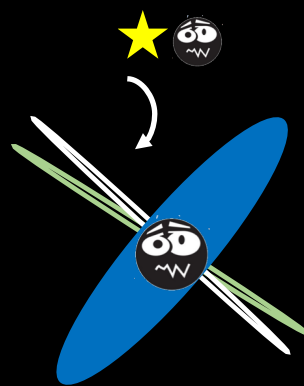
If confirmed, huge implications and synergies between future X-ray/GW missions

Testing orbital models

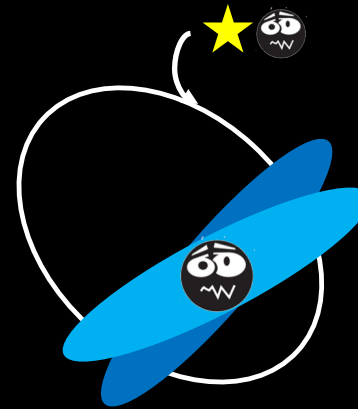
- What effects do we expect to be at play? e.g. Liniat&Metzger23;Franchini+(RA)23



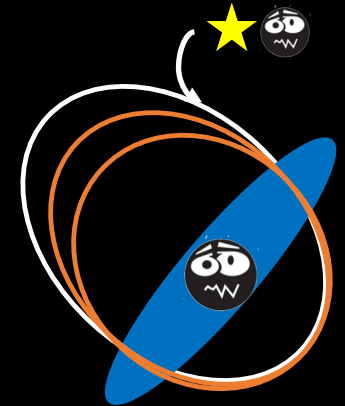
EMRI apsidal
(tens of days+)



EMRI nodal
(~1-few years+)



Disk nodal
(?? days to years ??)

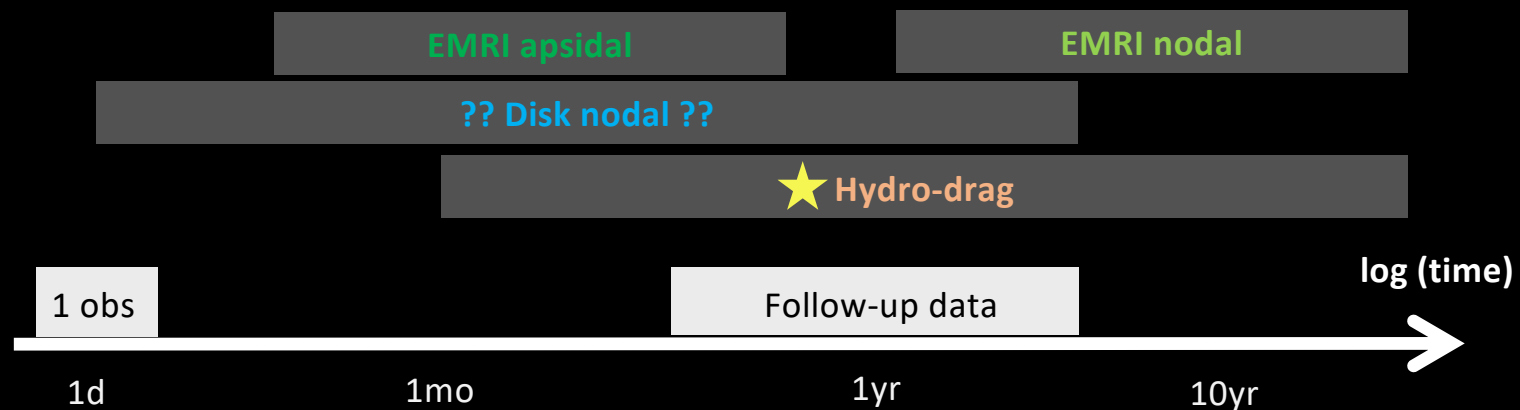


★  GW
(<<1s - <1s per year)

★ Hydro-drag
(10-100s seconds per year)

Testing orbital models

- We can divide these effects in fast acting and slow acting (cf our observations)



Single observations are barely sensitive to constrain some effects

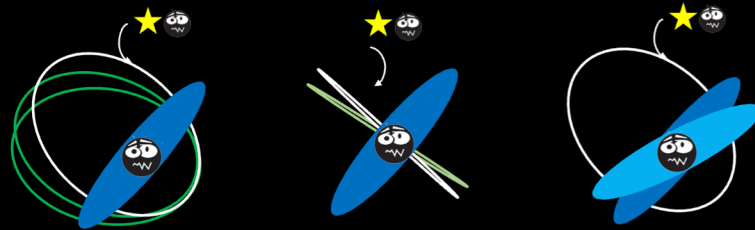
Multiple observations have gaps so long that one loses track of what happened (N_{QPE} is lost)

Testing orbital models

- What can we do now? Per-epoch constraints; model-dependent assumptions to fill the gaps

e.g. Xian+21; Franchini+23; Zhou+24a,b

↙ Test short-term and long-term super-orbital modulation



Chakraborty, RA+24; Arcodia+24c; Miniutti..RA+ in prep. & others



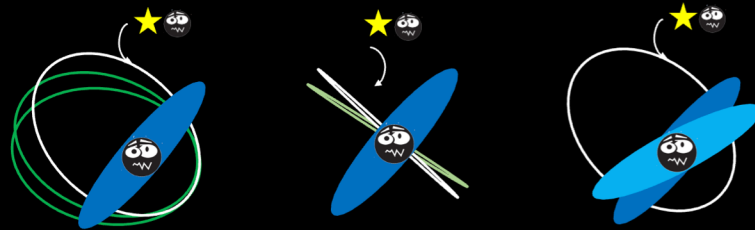
Joheen Chakraborty, MIT

Testing orbital models

- What can we do now? Per-epoch constraints; model-dependent assumptions to fill the gaps

e.g. Xian+21; Franchini+23; Zhou+24a,b

↙ Test short-term and long-term super-orbital modulation



Chakraborty, RA+24; Arcodia+24c; Miniutti..RA+ in prep. & others

↙ Plan dedicated campaigns to test for orbital decay

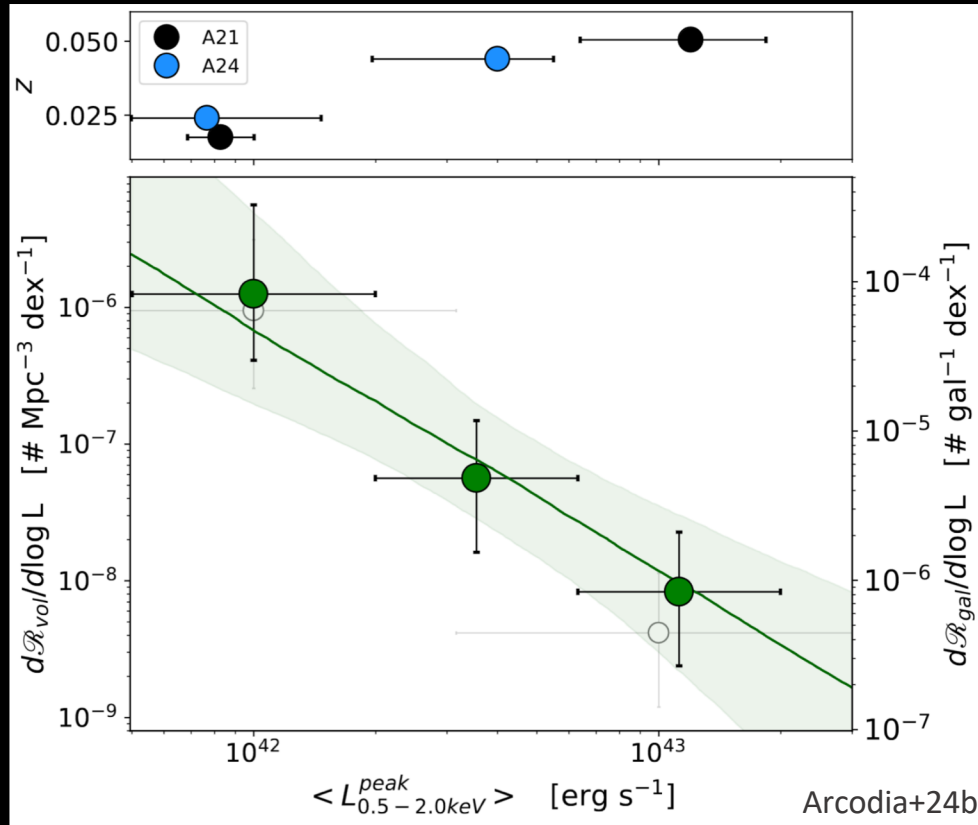


Arcodia+ in prep

Intrinsic rates

- QPEs luminosity function, corrected for detection efficiency

Number density of QPEs

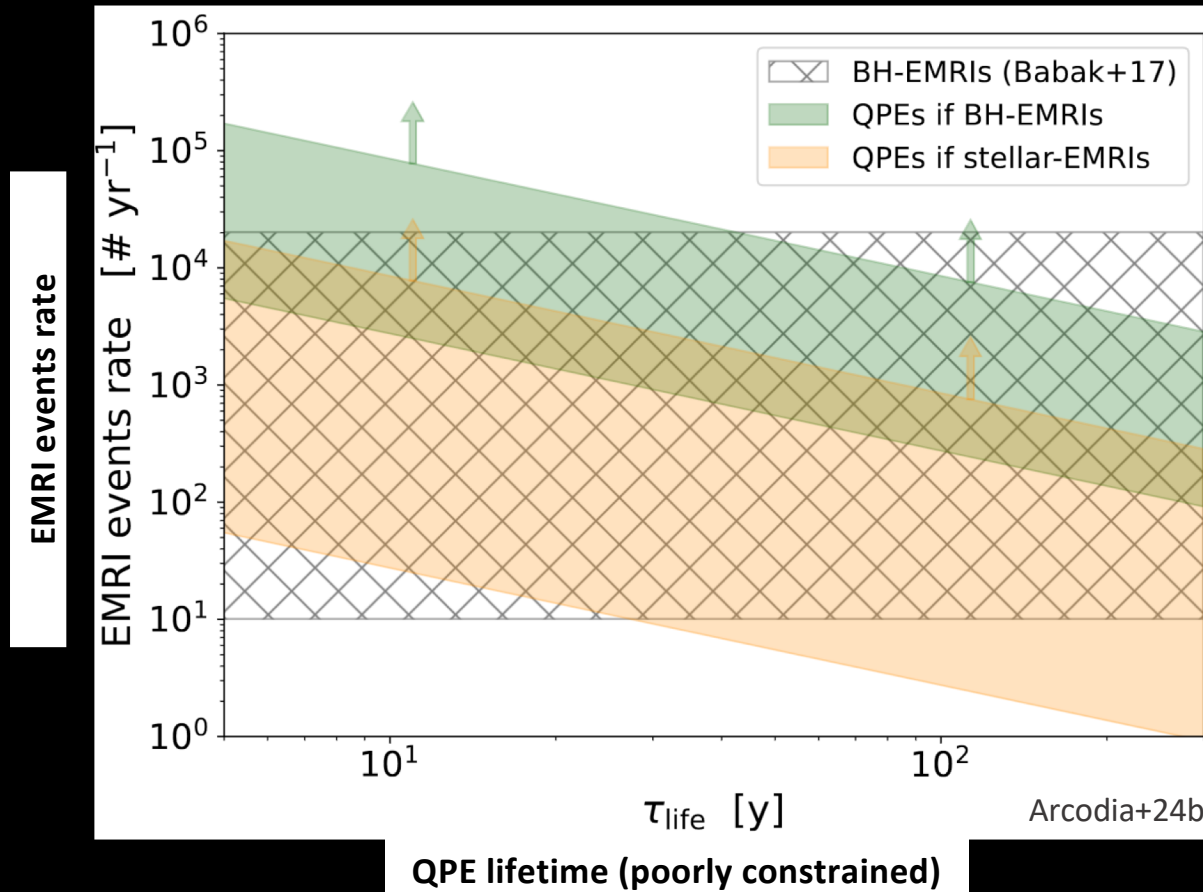


Assuming gal $\sim 10^{8.5-10.5} M_*$

Abundance rate:
 $\approx 10^{-6} \text{ Mpc}^{-3}$
 ≈ 1 every 10^4 gal is emitting QPEs
 $(\log L_X > 41.7)$

Intrinsic rates

- If QPE = EMRI: first ever observational constraint to the EMRI rates for LISA!

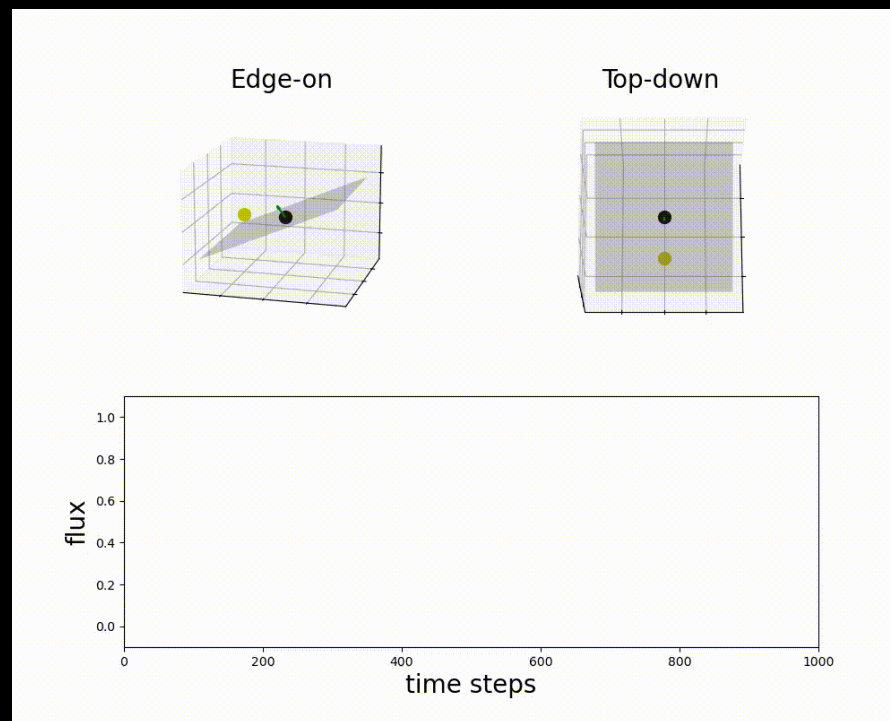


Thank you!



Testing orbital models

- In absence of eccentricity, and precession:

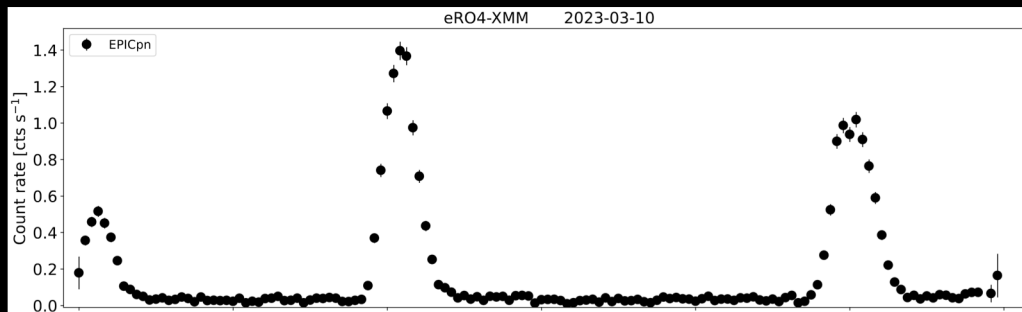


Joheen Chakraborty, MIT

Testing orbital models

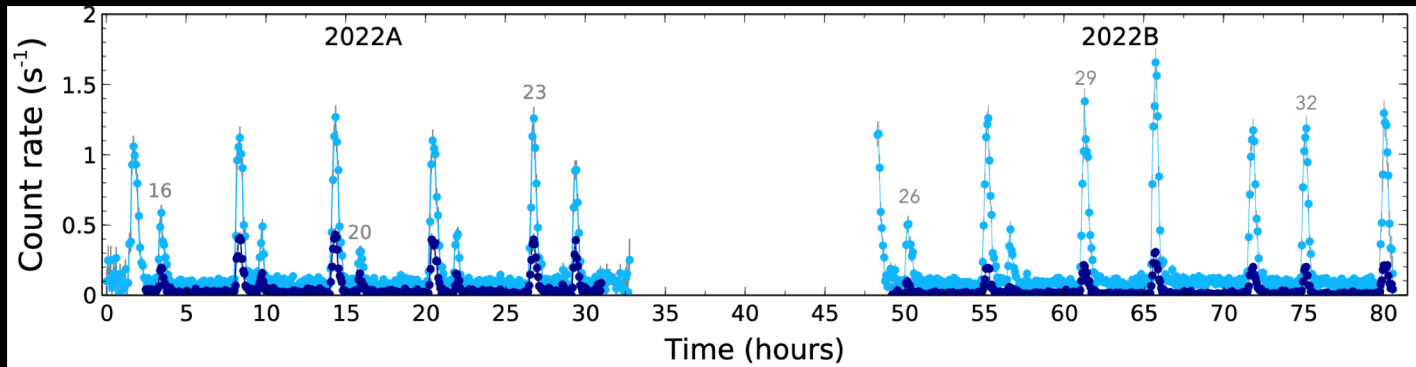
- In absence of eccentricity, and precession: not quite what we see

eRO-QPE4



Arcodia+24a

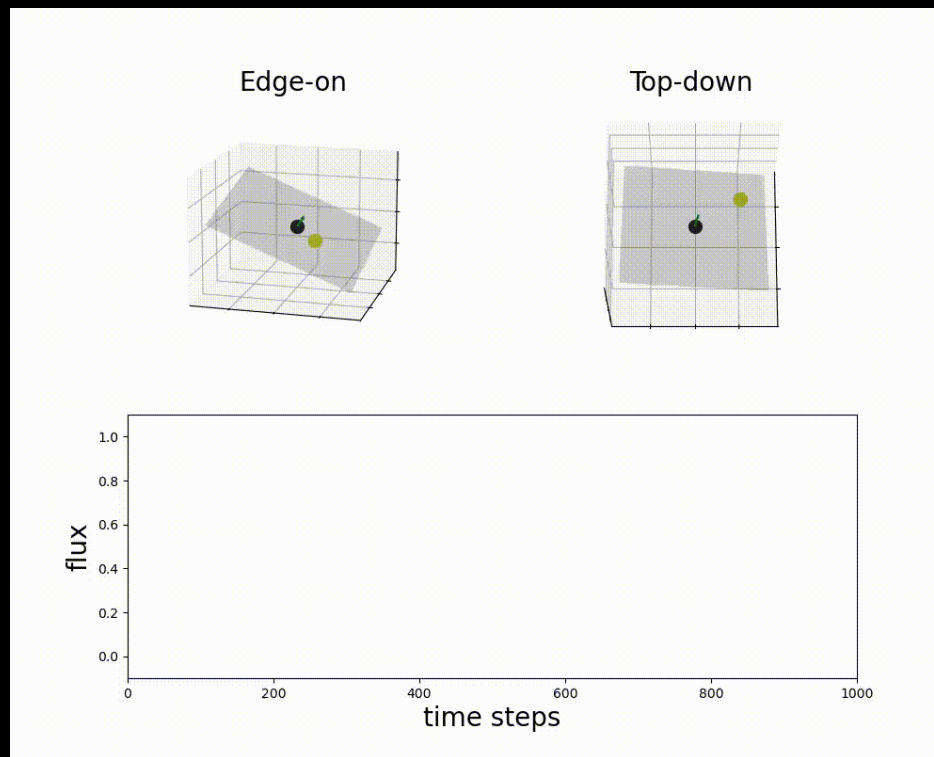
RX J1301.9+2747



Giustini+(RA)24

Testing orbital models

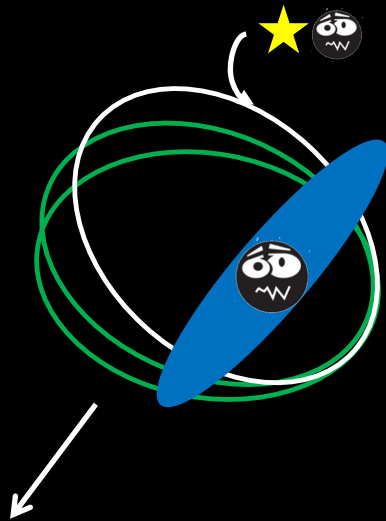
- What effects do we expect to be at play? e.g. Linial&Metzger23;Franchini+(RA)23



Joheen Chakraborty, MIT

Testing orbital models

- What effects do we expect to be at play? e.g. [Linial&Metzger23](#); [Franchini+\(RA\)23](#)

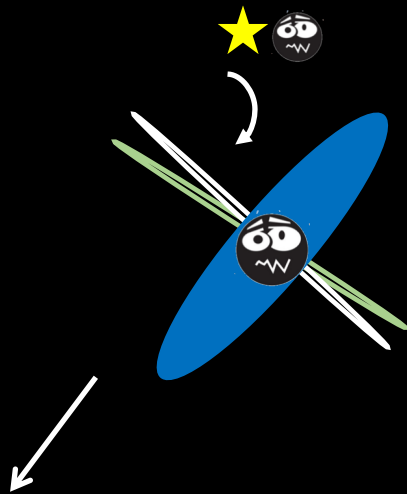


EMRI apsidal

$$T_\epsilon \sim \frac{\Delta\epsilon}{\delta\epsilon} P_{\text{orb}} \simeq \frac{P_{\text{orb}}}{3} \frac{r_0}{R_g} \approx 10.6 \text{ d } M_{\bullet,6}^{-2/3} \mathcal{P}_{\text{QPE},4}^{5/3}$$

Testing orbital models

- What effects do we expect to be at play? e.g. Linnell&Metzger23; Franchini+(RA)23



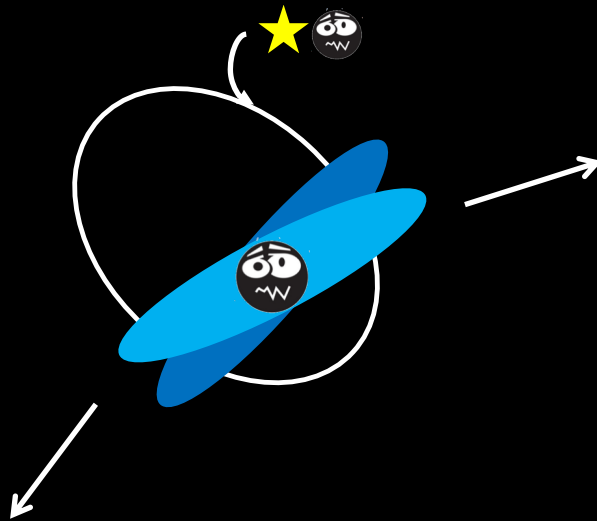
EMRI apsidal (~10s days)

EMRI nodal

$$T_{\Omega} \sim \frac{\Delta\Omega}{\delta\Omega} P_{\text{orb}} \simeq \frac{P_{\text{orb}}}{2a_{\bullet}} \left(\frac{r_0}{R_g} \right)^{3/2} \approx 155 \text{ d} \frac{\mathcal{P}_{\text{QPE},4}^2}{a_{\bullet} M_{\bullet,6}}, \quad (11)$$

Testing orbital models

- What effects do we expect to be at play? e.g. Linal&Metzger23;Franchini+(RA)23



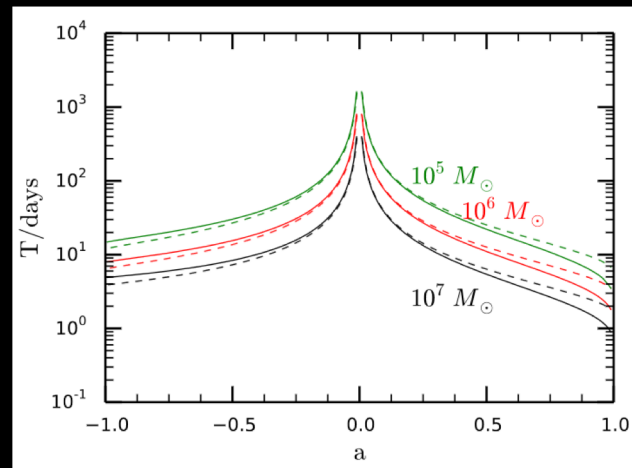
EMRI apsidal (~10s days)

EMRI nodal (~1-few years)

Disk nodal (days to years ??)

Largely uncertain and model dependent:

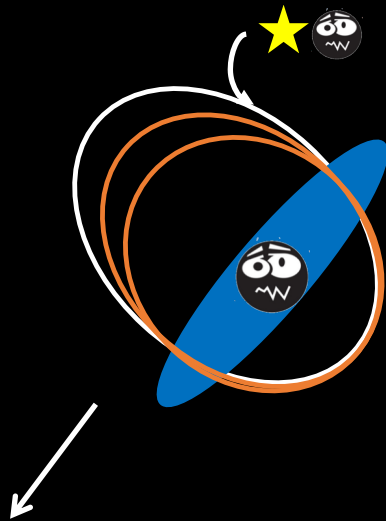
e.g if TDE compact disk



Franchini+16

Testing orbital models

- What effects do we expect to be at play? e.g. Liniat&Metzger23;Franchini+(RA)23



Disk nodal (days to years ??)

Orbital energy loss

EMRI apsidal (~10s days)

EMRI nodal (~1-few years)



GW

$$\dot{P}_{\text{QPE}}|_{\text{GW}} \approx -6 \times 10^{-10} \left(\frac{P_{\text{QPE}}}{4 \text{ hr}} \right)^{-5/3} \left(\frac{m_{\star}}{M_{\odot}} \right) M_{\bullet,6}^{2/3}$$

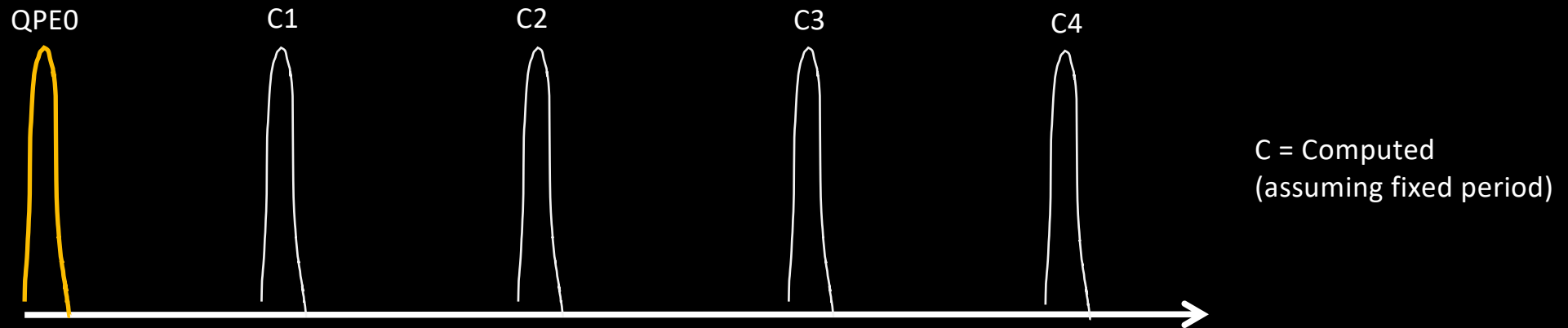


Hydro-drag

$$\langle \dot{P}_{\text{drag}} \rangle \approx -2 \times 10^{-6} \left(\frac{m_{\star}}{M_{\odot}} \right)^{-1} \left(\frac{R_{\star}}{R_{\odot}} \right)^2 \left(\frac{\Sigma}{10^5 \text{ g cm}^{-2}} \right)$$

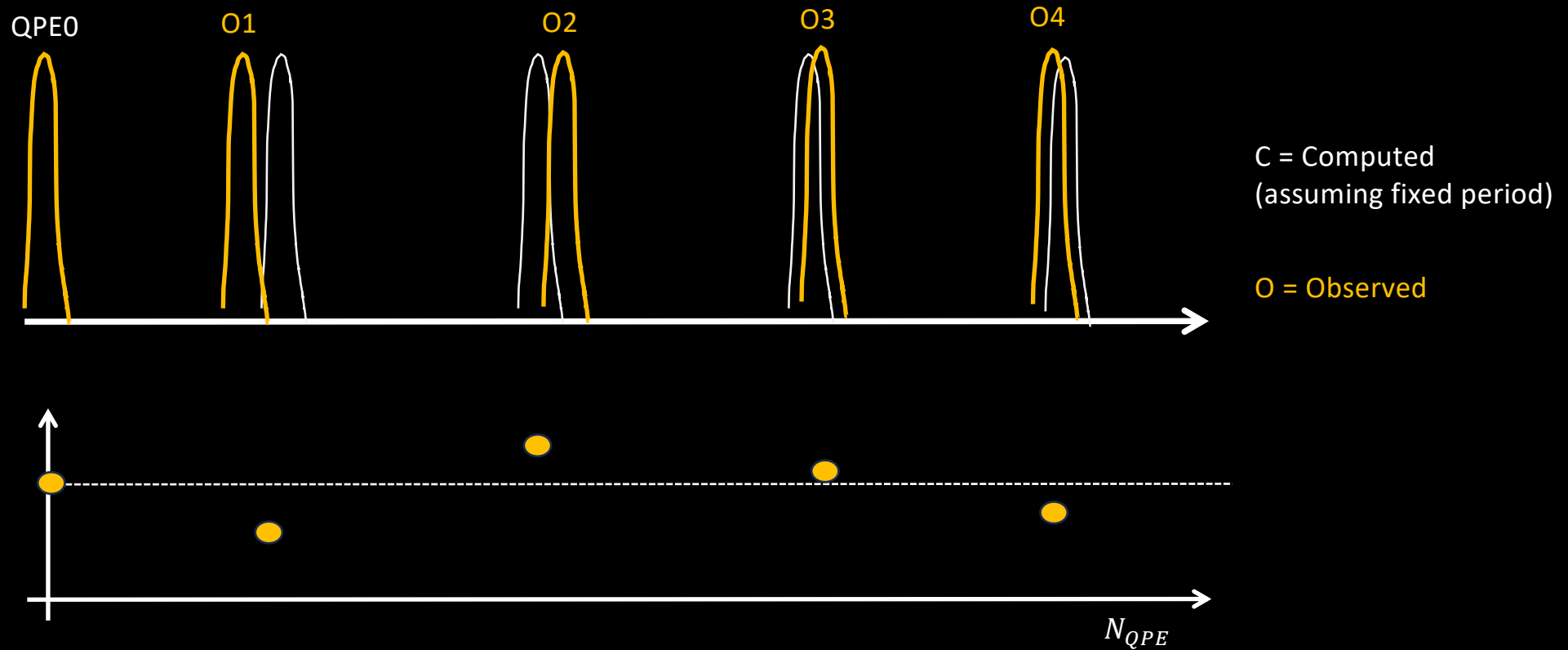
Testing orbital models

- How can we test these effects? “O-C” (“Observed-computed”)
e.g. Sterken05



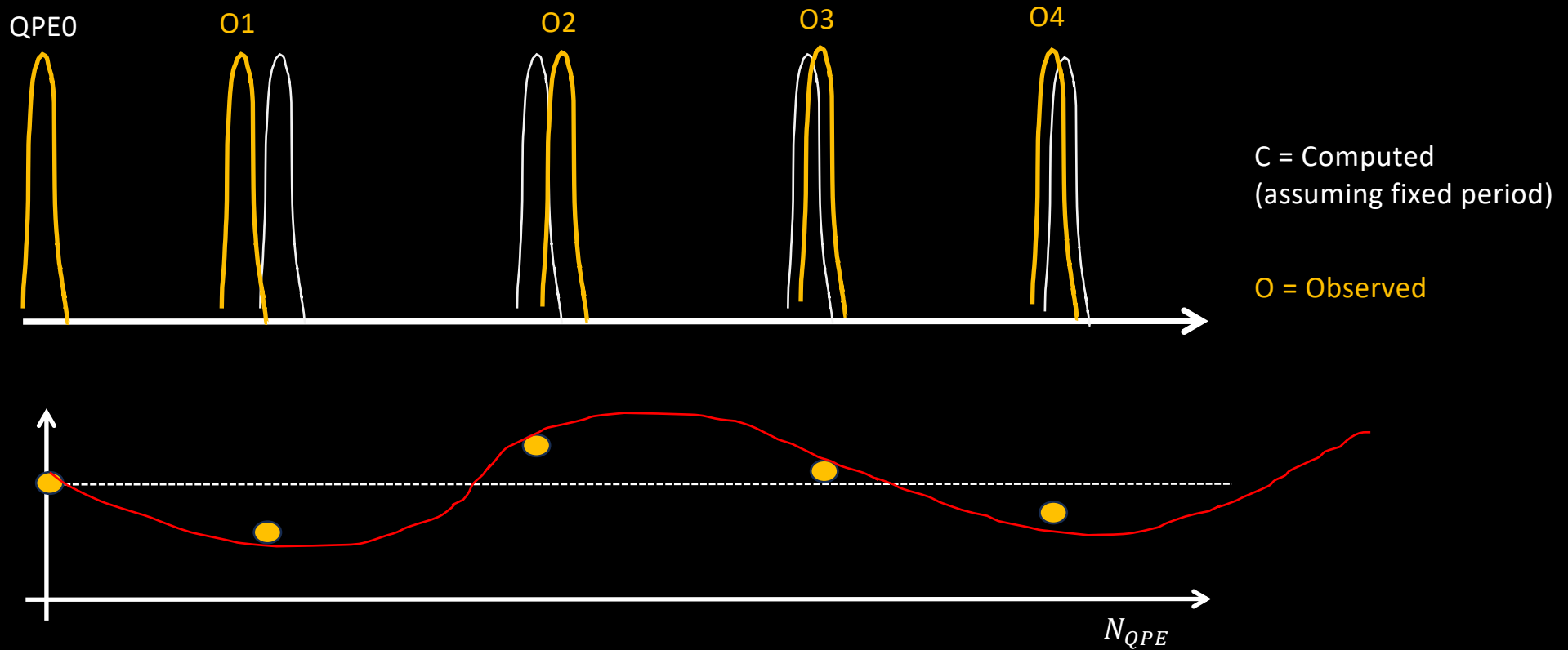
Testing orbital models

- How can we test these effects? “O-C” (“Observed-computed”)
e.g. Sterken05



Testing orbital models

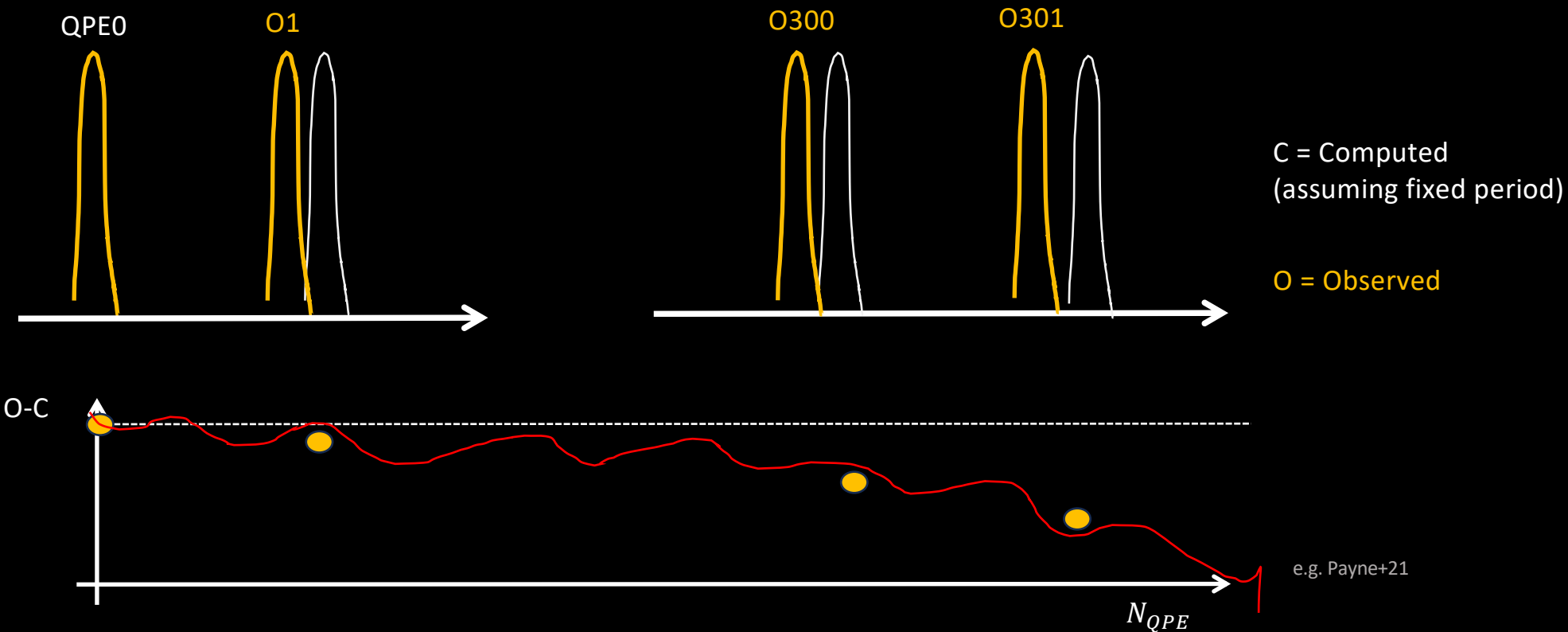
- How can we test these effects? "O-C" ("Observed-computed")
e.g. Sterken05



Testing orbital models

- How can we test these effects? “O-C” (“Observed-computed”)

e.g. Sterken05



Testing orbital models

- What can we do now? Per-epoch constraints; model-dependent assumptions to fill the gaps

e.g. Xian+21; Franchini+23; Zhou+24a,b



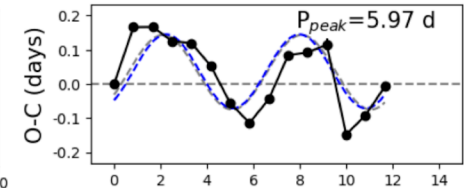
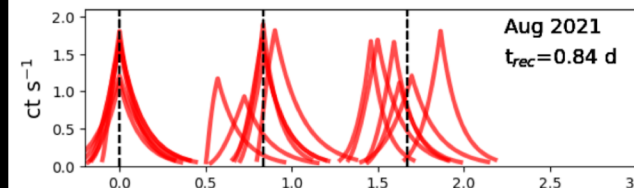
Testing short-term (intra-observation) super-orbital modulation

Disk nodal ??

eRO-QPE1

Overplotted even/odd QPEs

O-C timing residuals



Chakraborty, RA+24

Testing orbital models

- What can we do now? Per-epoch constraints; model-dependent assumptions to fill the gaps

e.g. Xian+21; Franchini+23; Zhou+24a,b

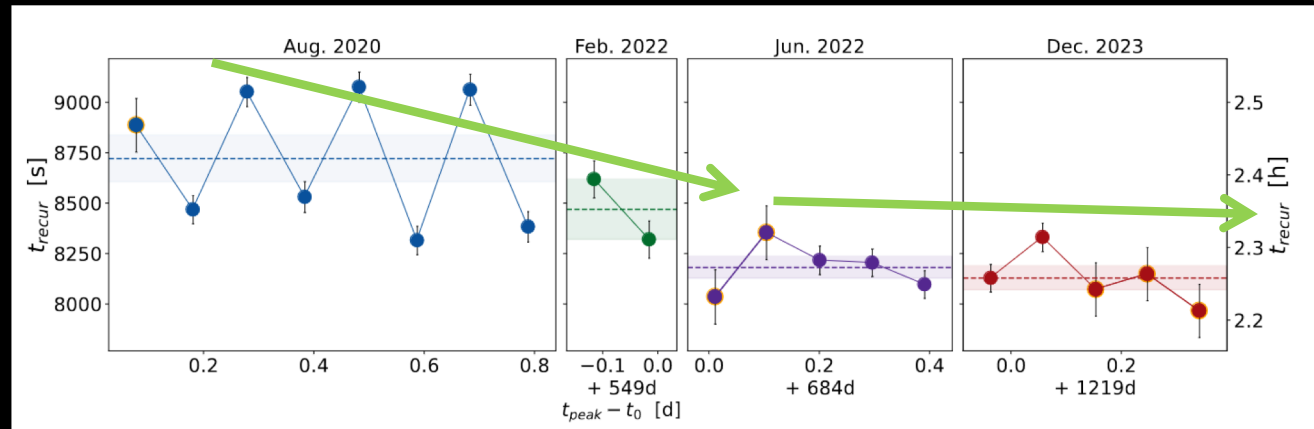


Testing short-term (intra-observation) super-orbital modulation

Testing long-term (inter-observation) super-orbital modulation

EMRI nodal?

eRO-QPE2



RA+24

Average recurrence time decreased (~few % in 3.3y), but **not uniformly**