Quasi-Periodic Eruptions

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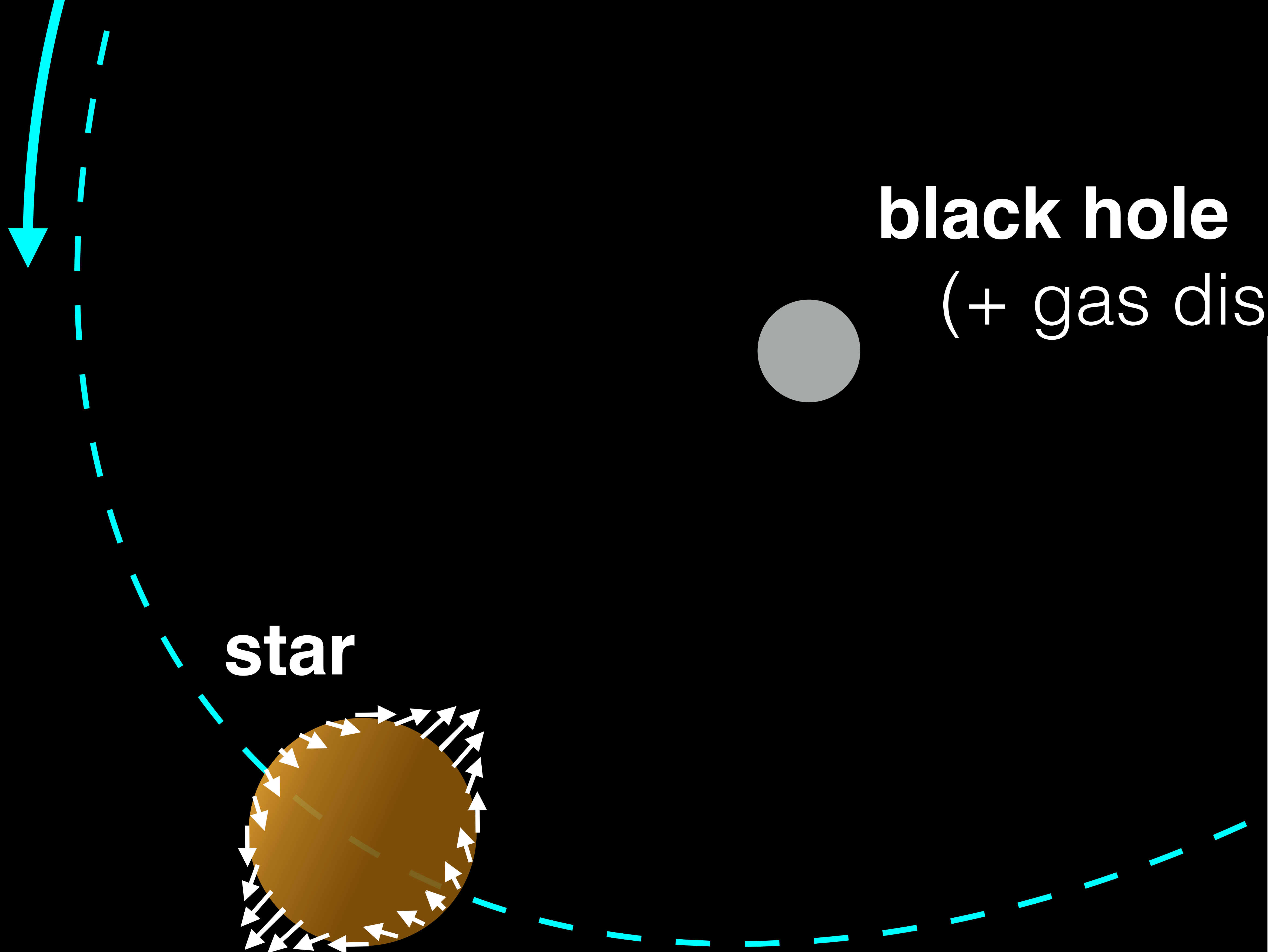
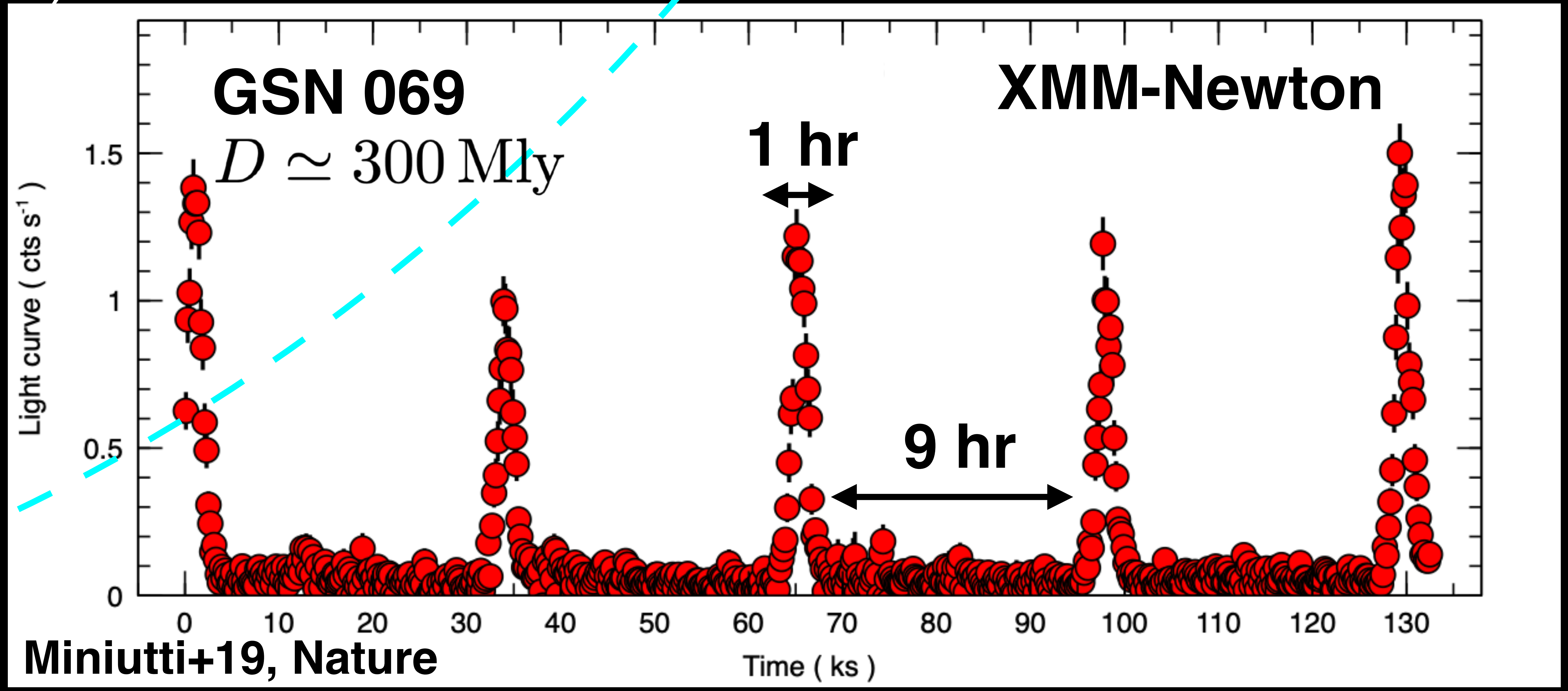
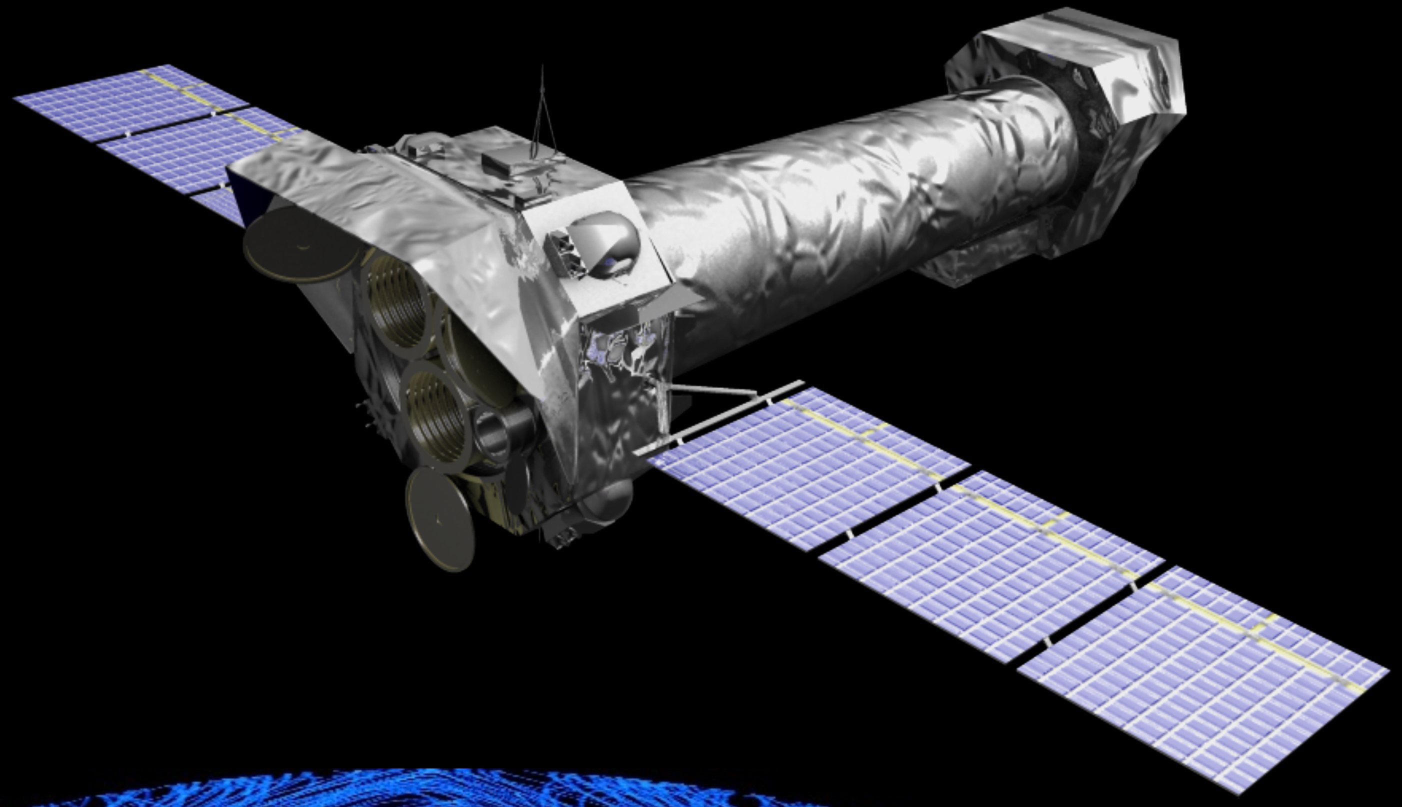
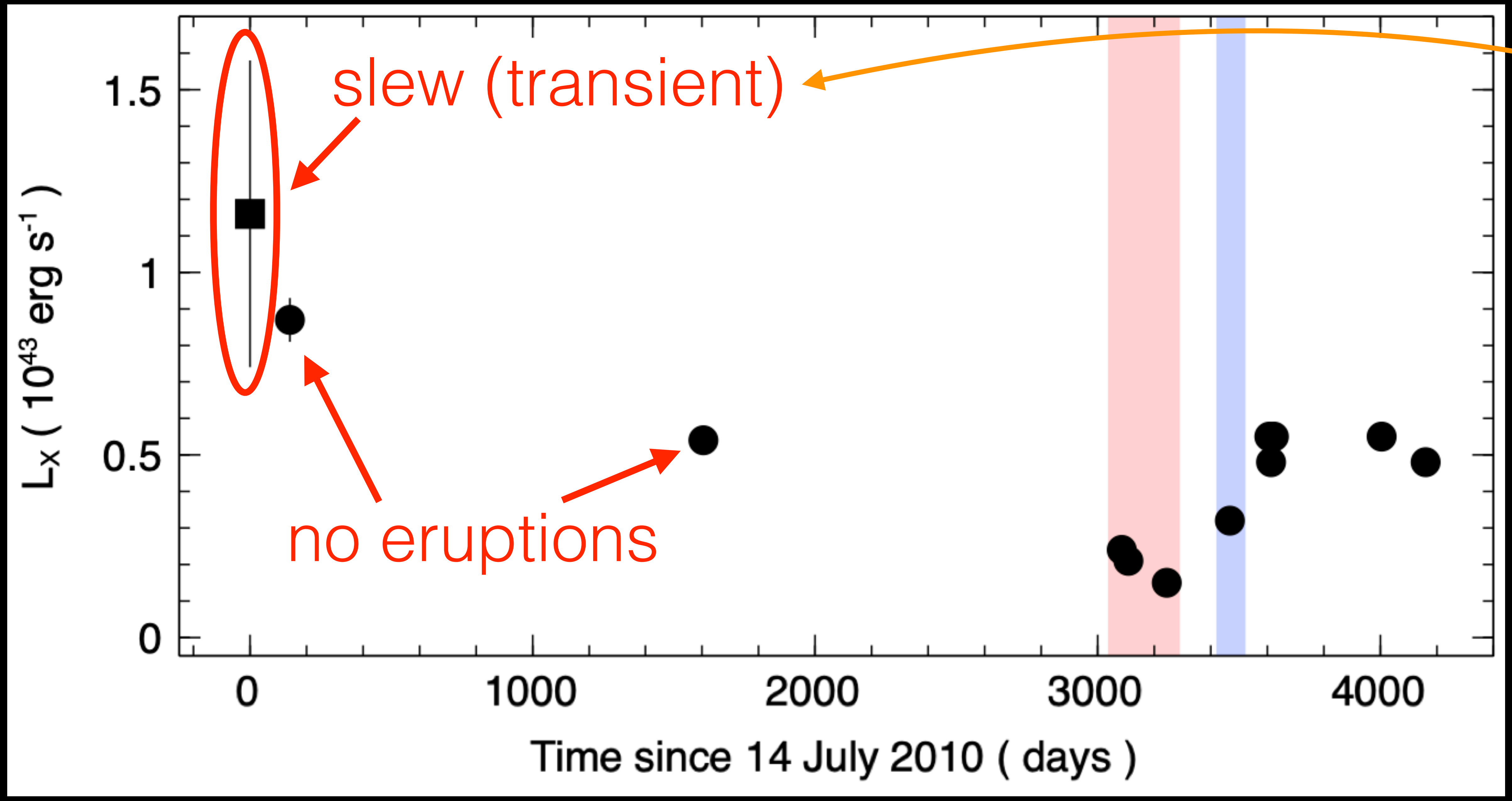
LU & Quataert 2023, MNRAS



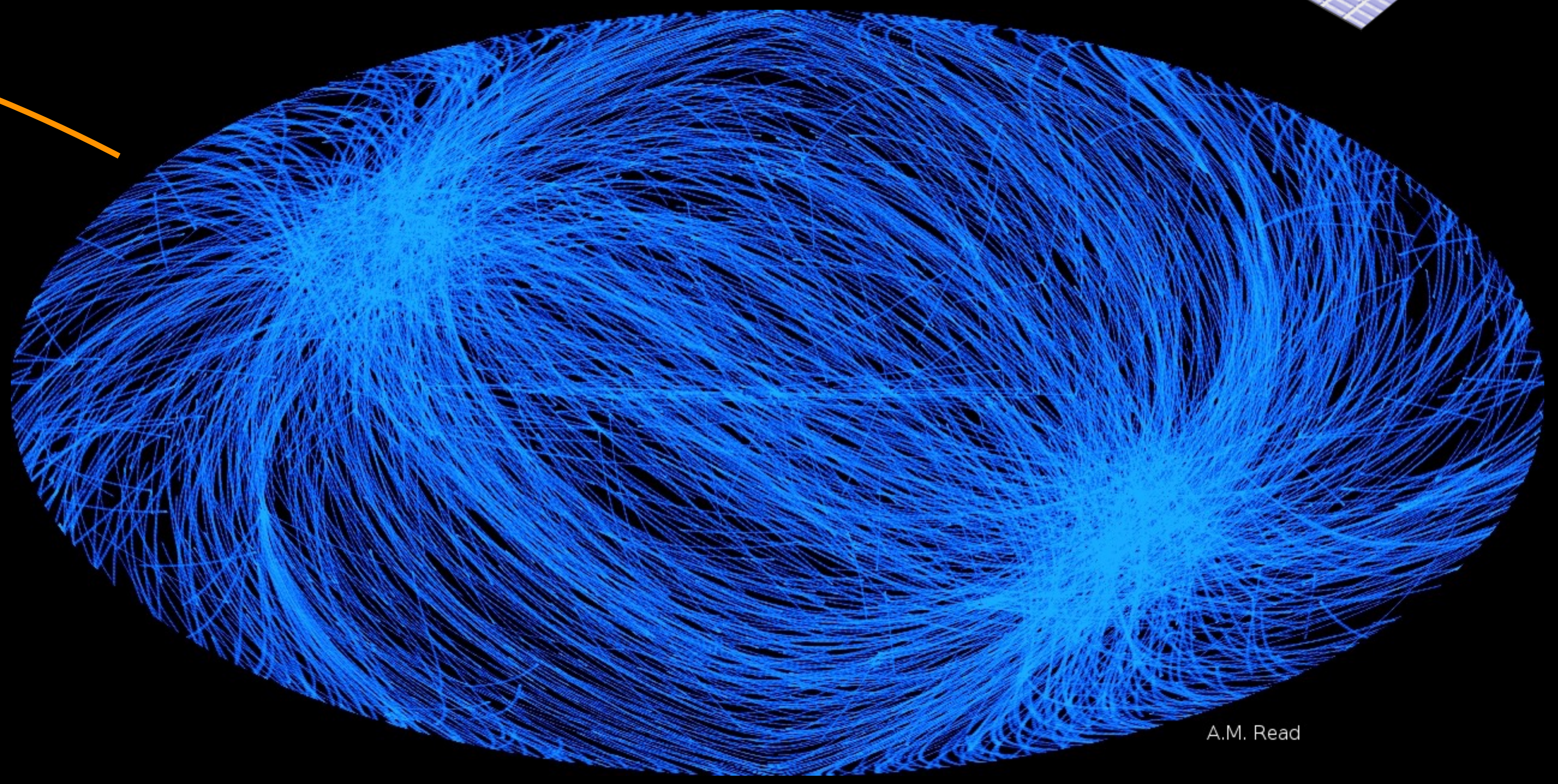


Discovery of GSN 069





Miniutti+22



XMM-Newton Slew Tracks
(short exposures of >80% of the sky)

Long-term Evolution of GSN 069

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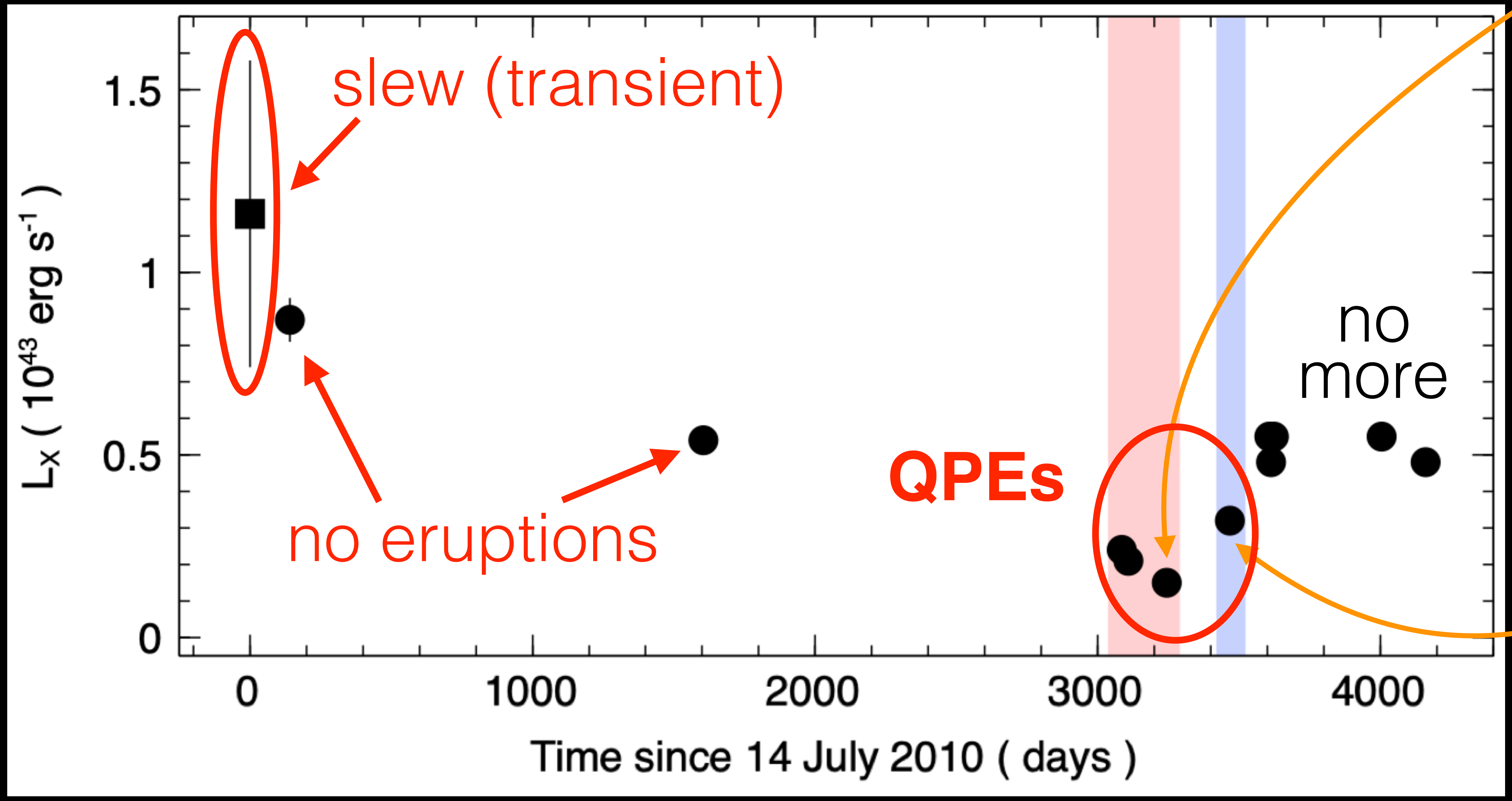

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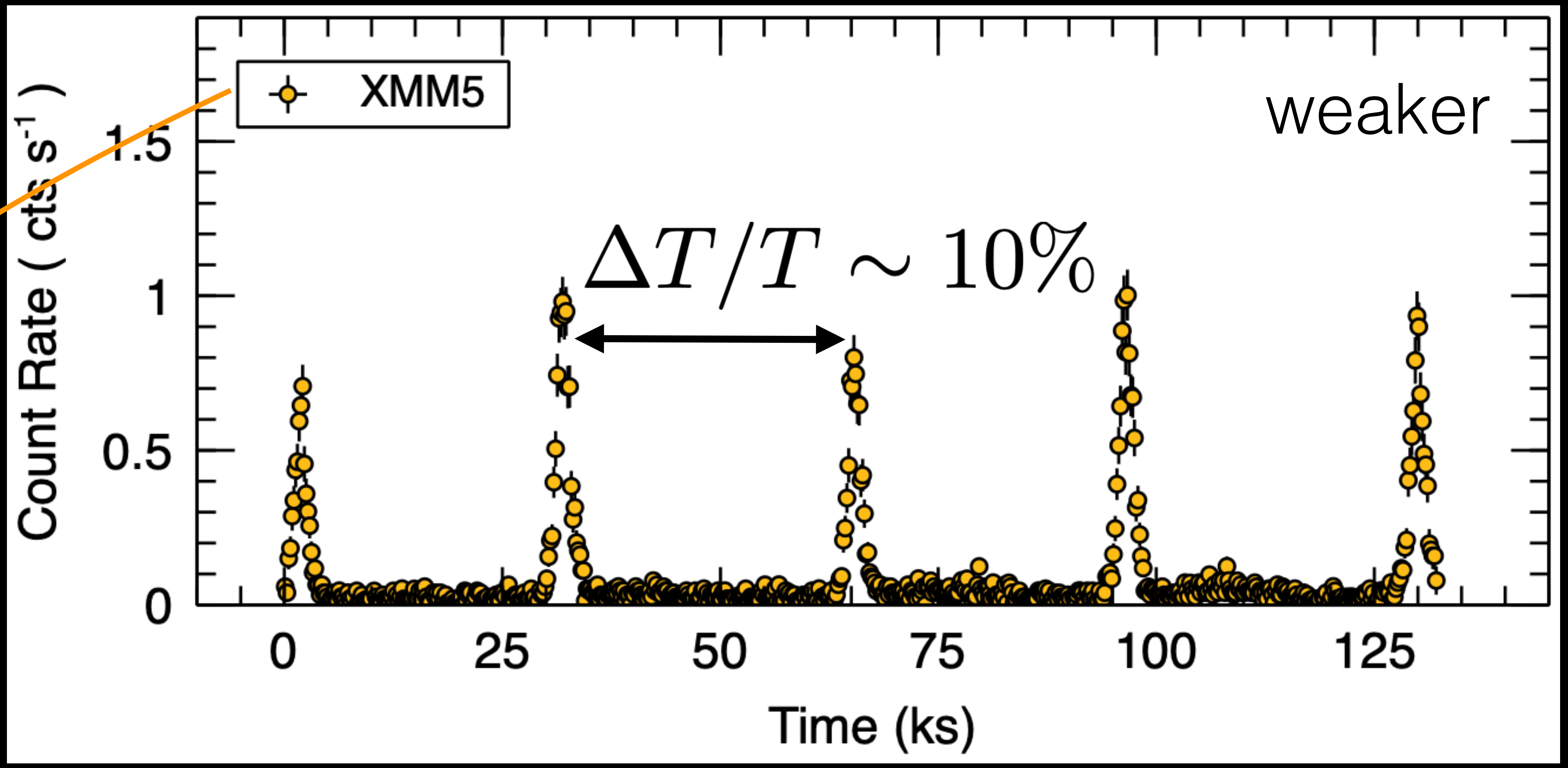
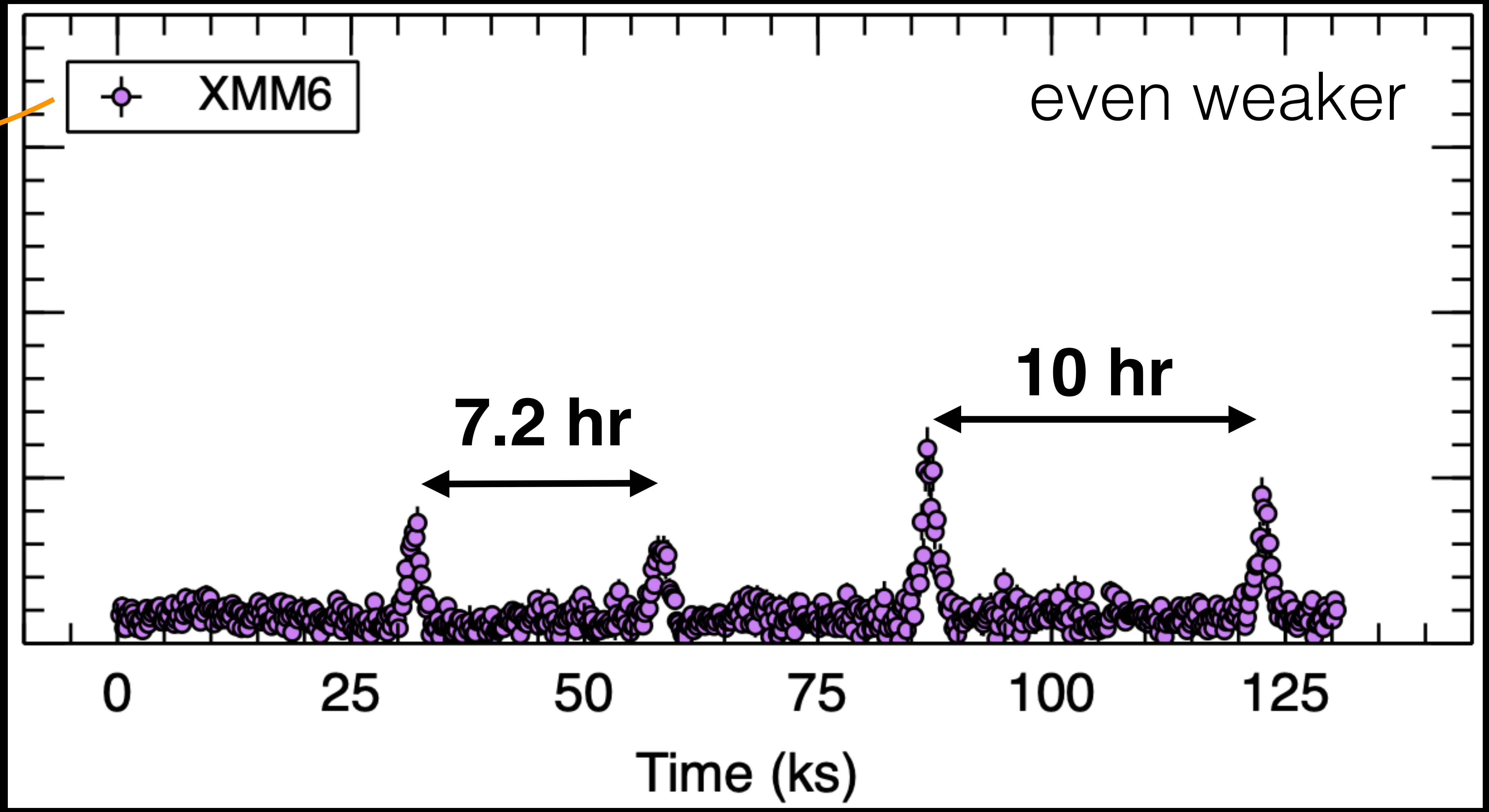
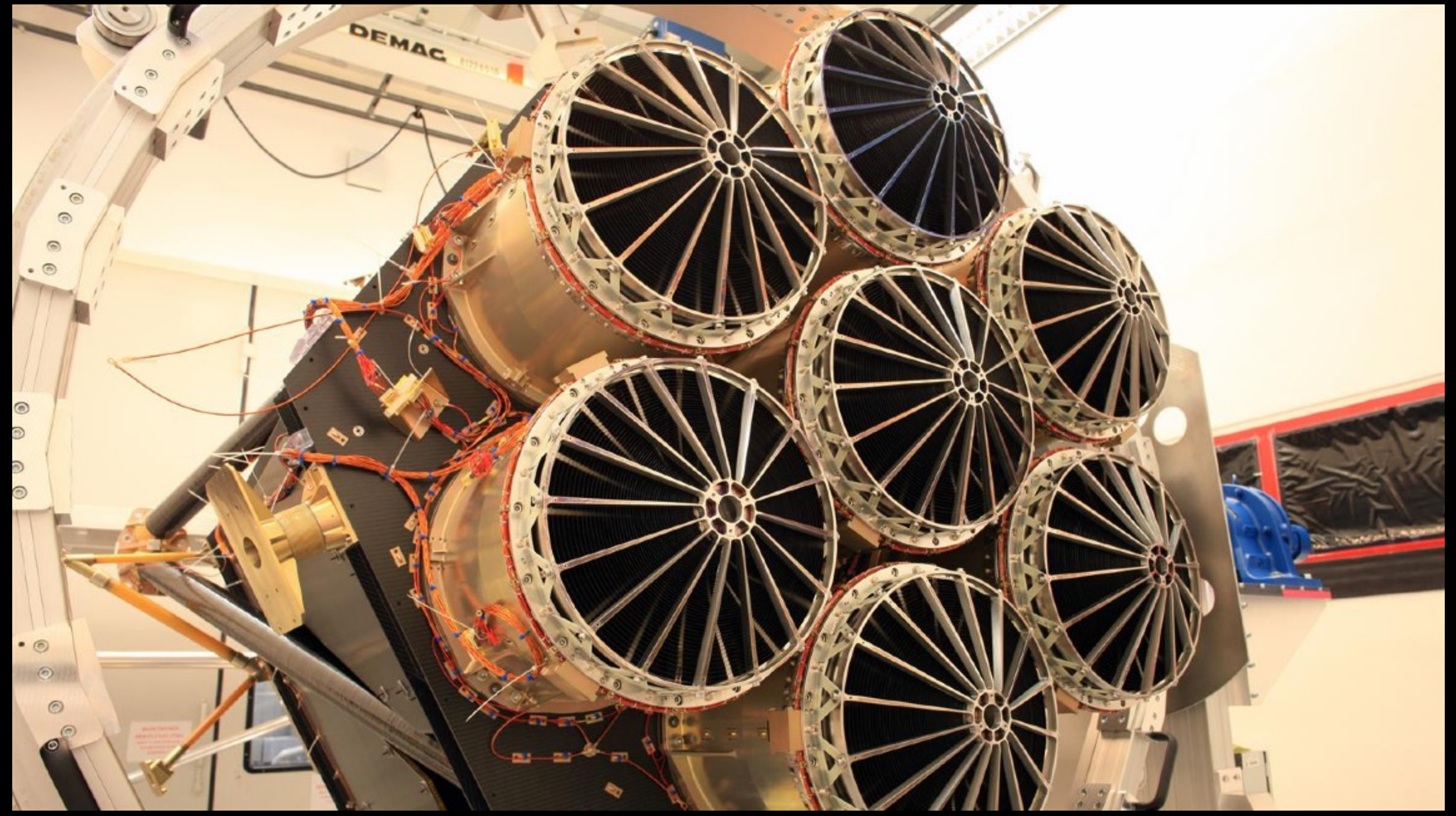






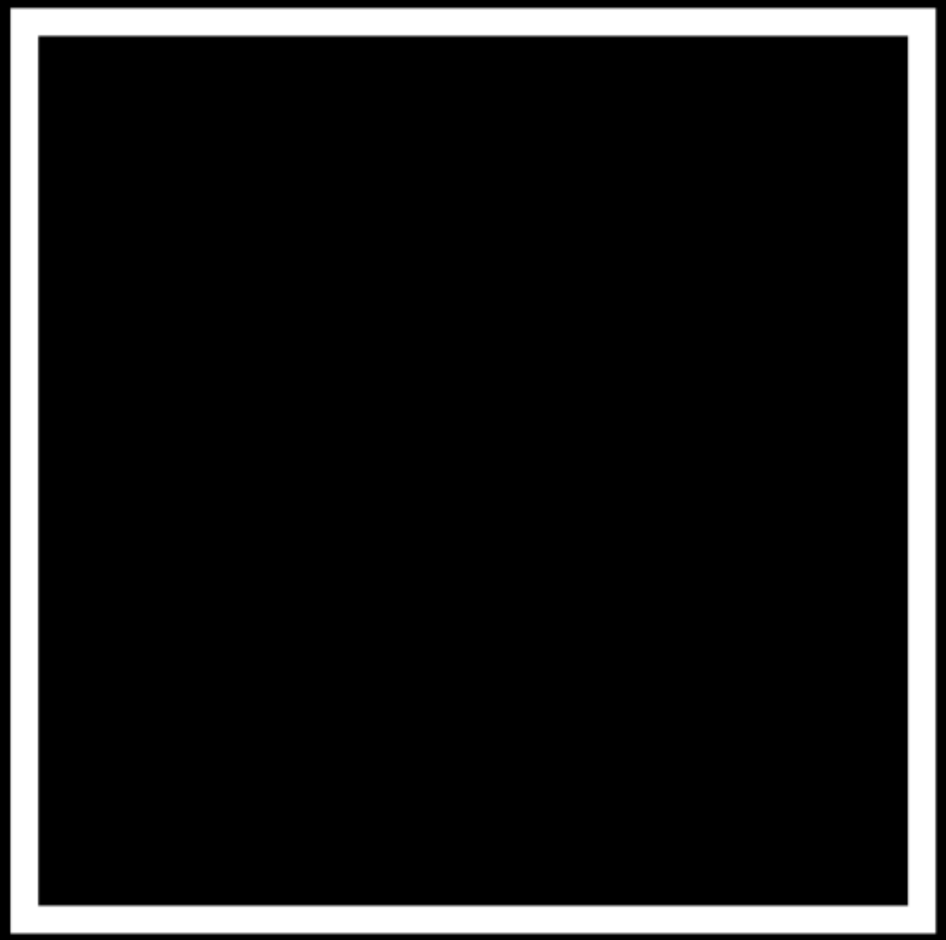
eROSITA All-Sky Survey

survey speed:

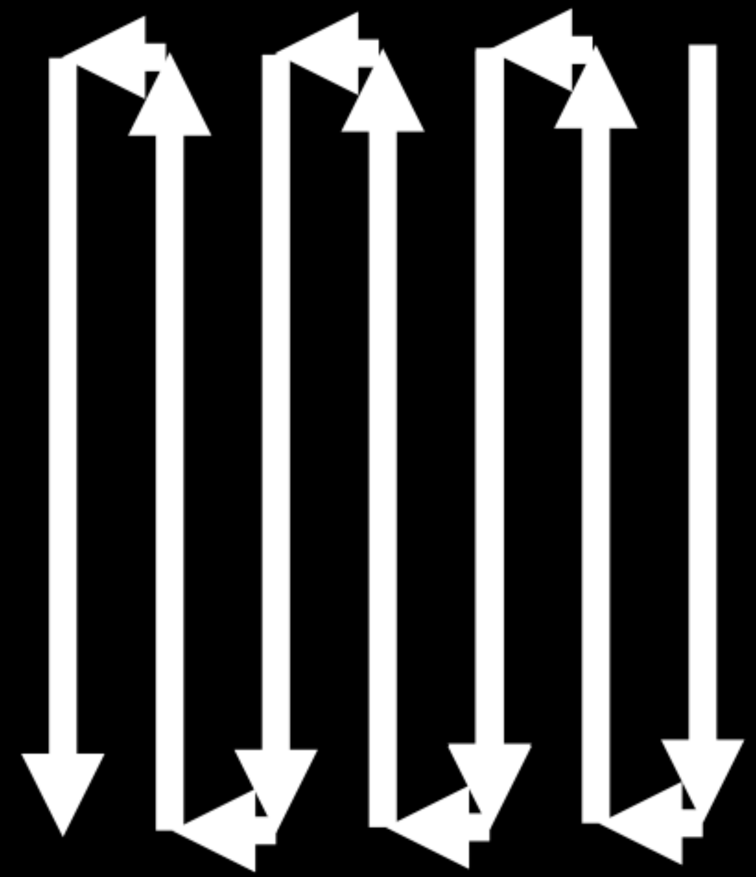
- 5×XMM-Newton
- 100×Chandra
- 30 x ROSAT
- 4 years = 8 all-sky scans

Moon diameter
30 arcmin

eROSITA
Field of view ~ 62 arcmin

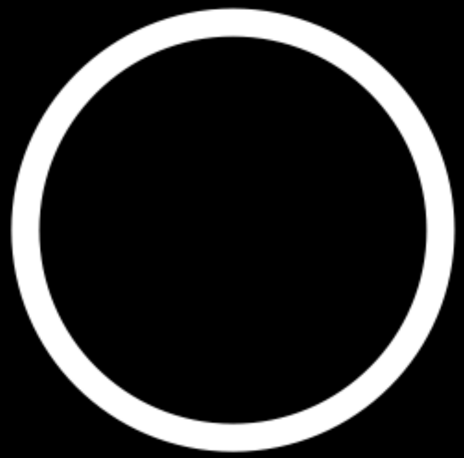


+

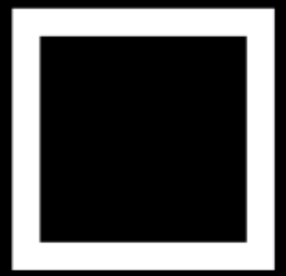


Scanning feature

XMM-Newton
Field of view ~ 30 arcmin



Chandra
Field of view ~ 17 arcmin

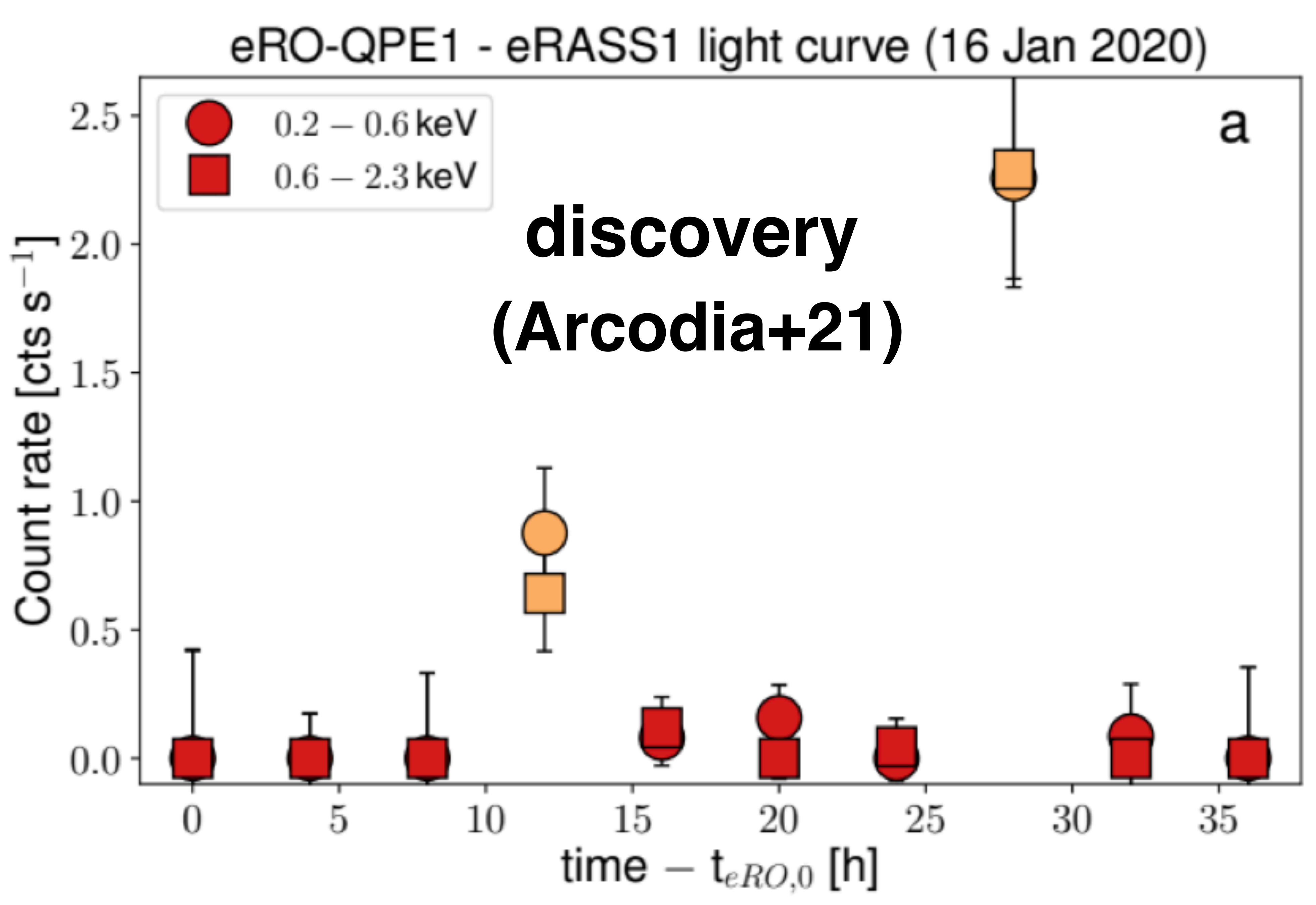


Slide from P. Predehl (PI of eROSITA)

eRO-QPE1

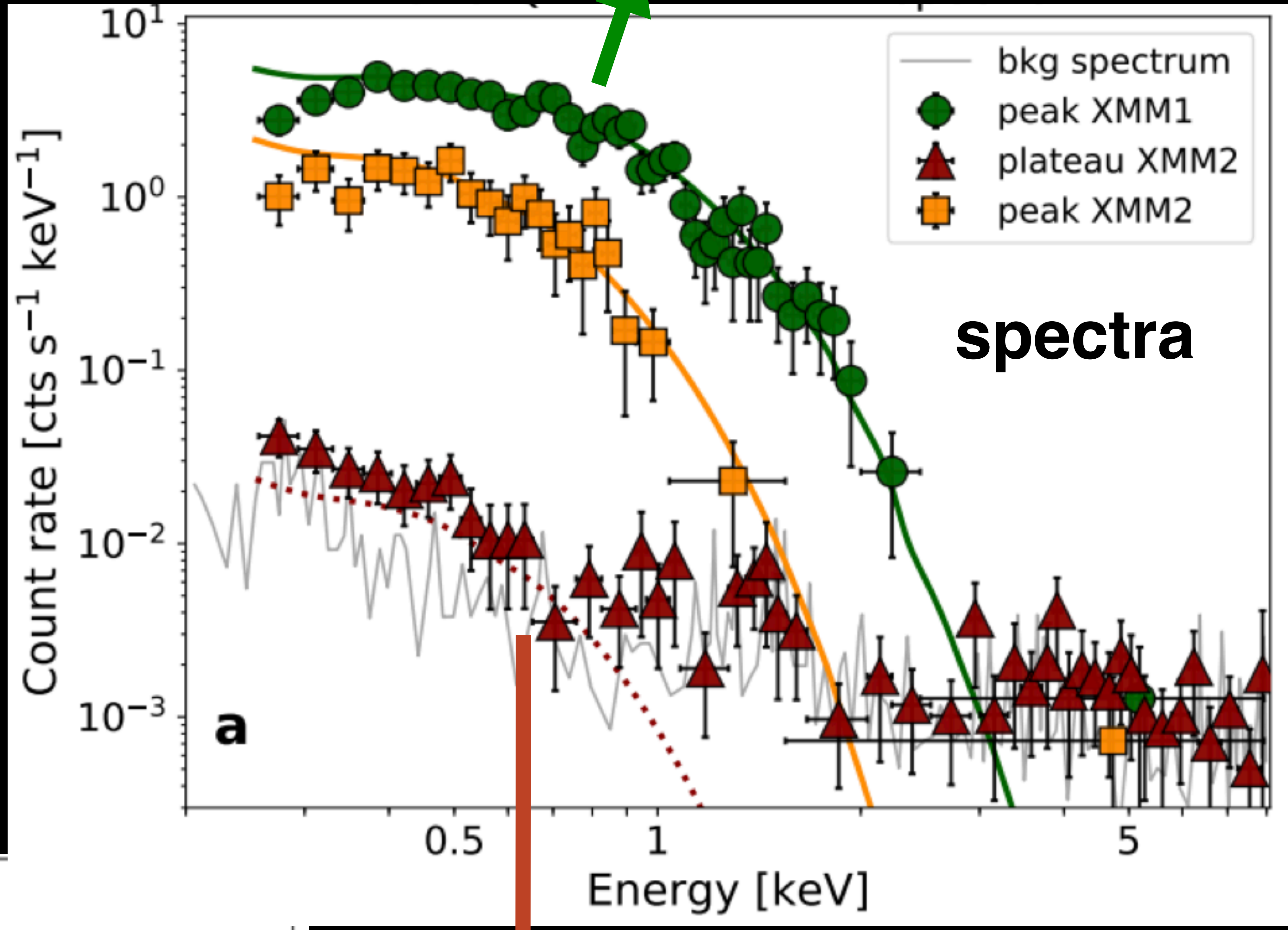
$D \simeq 700\mathrm{Mly}$

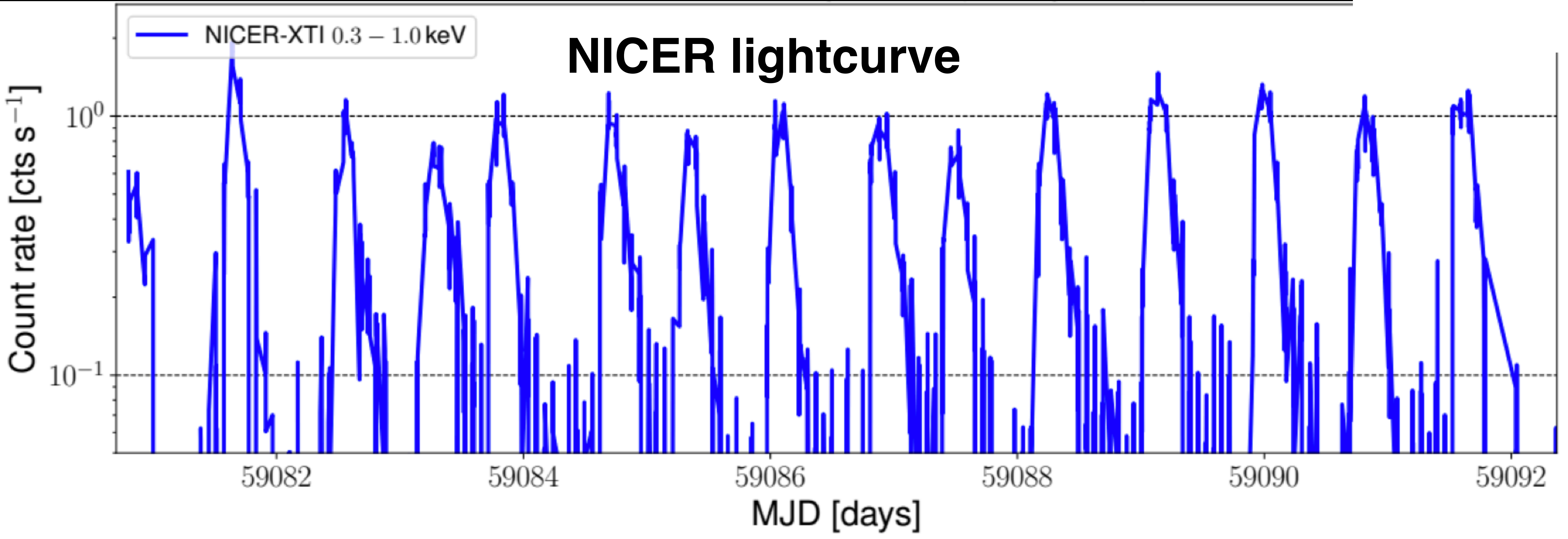
$P \simeq 18.5\,\mathrm{hr}$



$kT_{\mathrm{fit}} \simeq 0.2\,\mathrm{keV}$

in burst



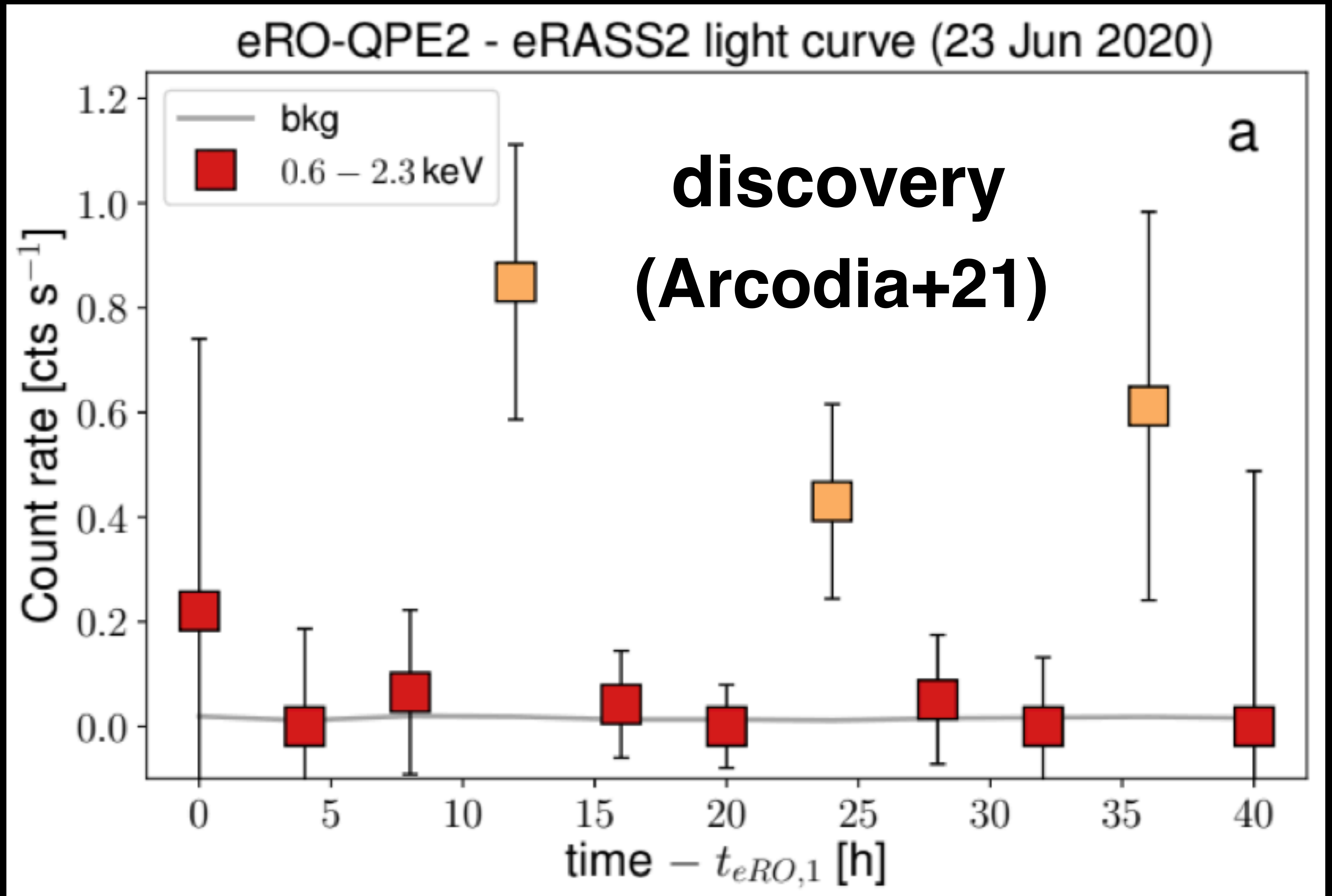


Quiescent emission
not detected

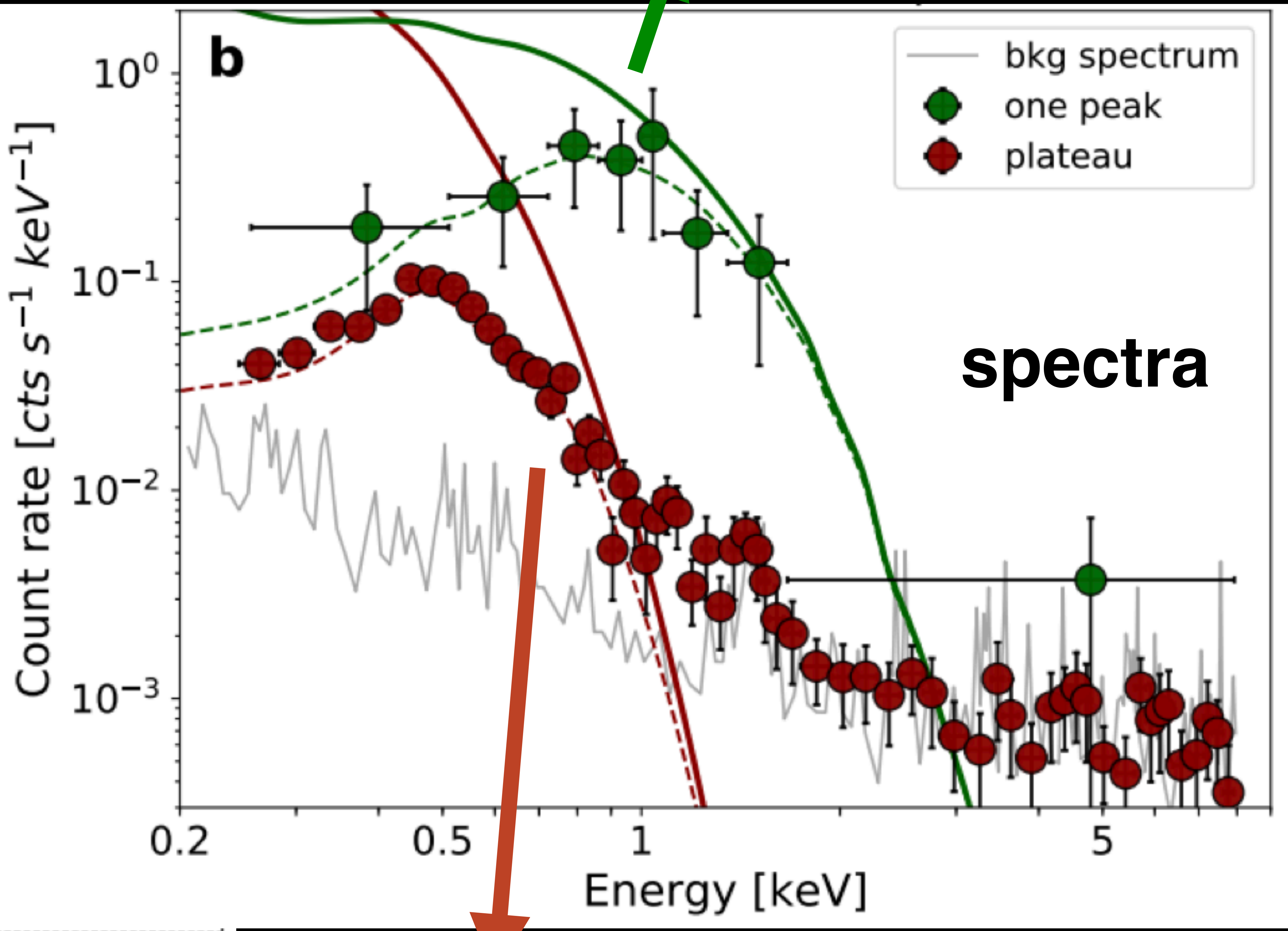
eRO-QPE2

$D \simeq 300\mathrm{Mly}$

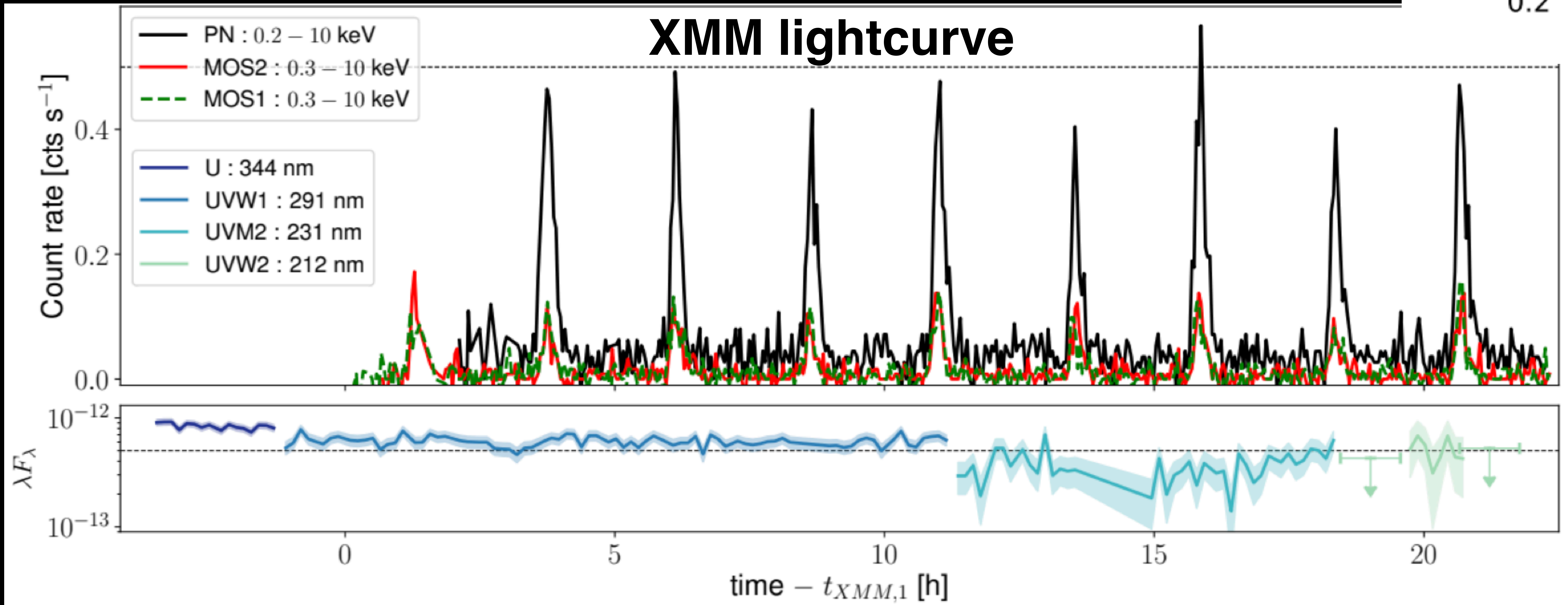
$P \simeq 2.4\,\mathrm{hr}$



$kT_{\mathrm{fit}} \simeq 0.2\,\mathrm{keV}$
in burst



$kT_{\mathrm{fit}} \simeq 0.1\,\mathrm{keV}$
in quiescence



No significant UV variability

Summary of Observations

- ⋆ Luminosity $\langle L_{\rm QPE}\rangle \sim 10^{42}\,{\rm erg\,s^{-1}}$ (wide range)
- ⋆ Powered by supermassive BHs (low-mass?)
- ⋆ Energy per flare $\sim 10^{46}\,{\rm erg}$
- ⋆ Quiescent emission (colder) + Eruptions (hotter)
- ⋆ (Quasi-)Period $P \sim 10\,{\rm hr}$
- ⋆ Duty cycle ~10%
- ⋆ Volume density $\sim 10^3\,{\rm Gpc^{-3}}$
- ⋆ Secular evolution 1 to 10 yrs

Many Models

- ★ **Instability in Gas Accretion Disk**
  - **thermo-viscous instability**
  - **tearing of misaligned disk**

  Miniutti+19; Sniegowska+20;
  Pan+21; Raj & Nixon 21

- ★ **Star Orbiting SMBH**
  - **main-sequence star**
    - **one**
    - **two**
  - **evolved star (He core)**
  - **dead star (white dwarf or even BH)**

King 20, 22, 23; Xian+21; Sukova+21
Wang+22; Zhao+22; Metzger+22;
Krolik & Linial 22; Linial & Sari 22;
Lu & Quataert 23; Linial & Metzger 23;
Tagawa & Haiman 23; etc.

Outline

- General constraints on current orbit
- What powers the emission in low/high states?
- What's causing stellar mass loss?
- Origin of the stellar orbit

General Constraints

Assumptions: SMBH + star, $P \sim 10\,\mathrm{hr}$, tidal force $\lesssim$ self-gravity at r_p

$(M_* \sim 0.5 M_\odot)$

1) semimajor axis $a/r_\mathrm{g} \simeq 100\, P_{10\mathrm{hr}}^{-2/3} M_6^{-2/3}$

2) pericenter $r_\mathrm{p}/r_\mathrm{g} \lesssim 50 M_6^{-2/3}$

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$\Rightarrow$ $e \lesssim 0.5$

$\boxed{\text{Mildly eccentric orbit!}}$

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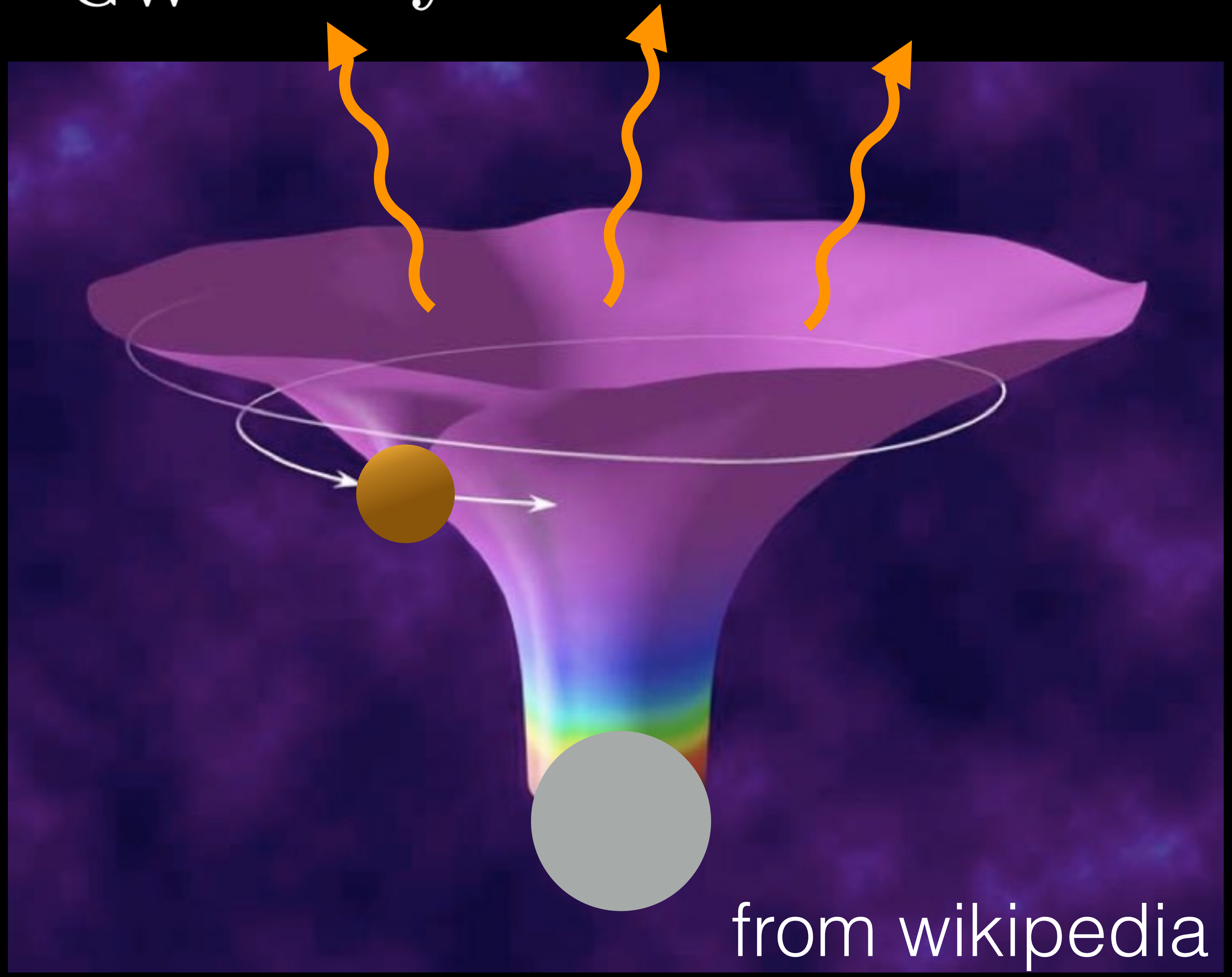
$e \lesssim 0.5$ **Mildly eccentric orbit!**

$t_\mathrm{GW} \sim \mathrm{Myr}$ **Gravitational Waves**



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Mildly eccentric orbit!

$t_\mathrm{GW} \sim \mathrm{Myr}$

3) lifetime $t_\mathrm{life} \lesssim \dfrac{0.1 M_* c^2}{\langle L_\mathrm{QPE} \rangle} \sim 10^3\,\mathrm{yr}$

Star is losing mass, but not driven by GW

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$\Rightarrow$ $e \lesssim 0.5$ **Mildly eccentric orbit!**

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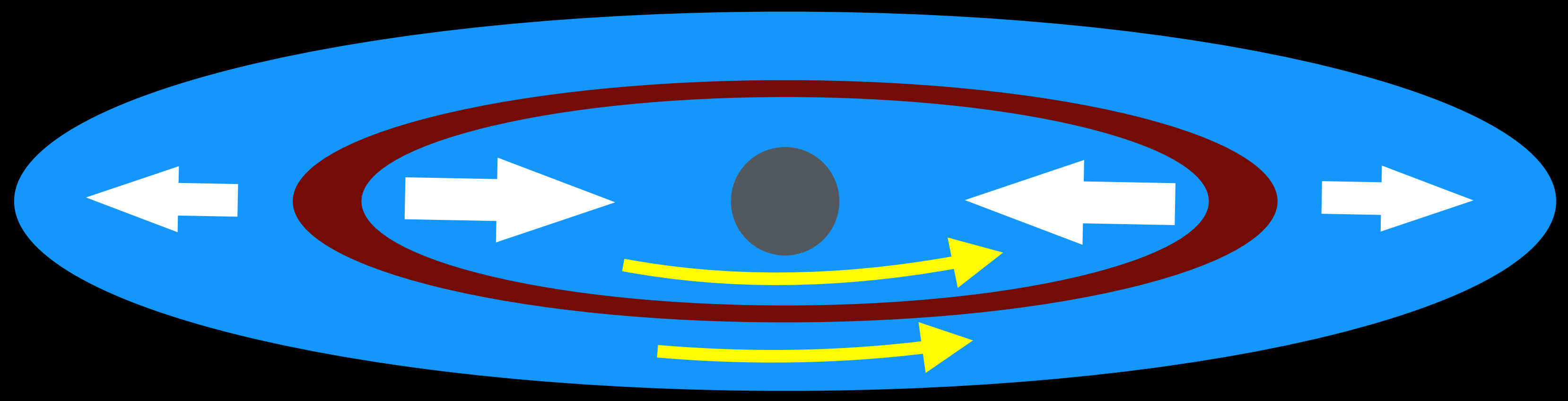
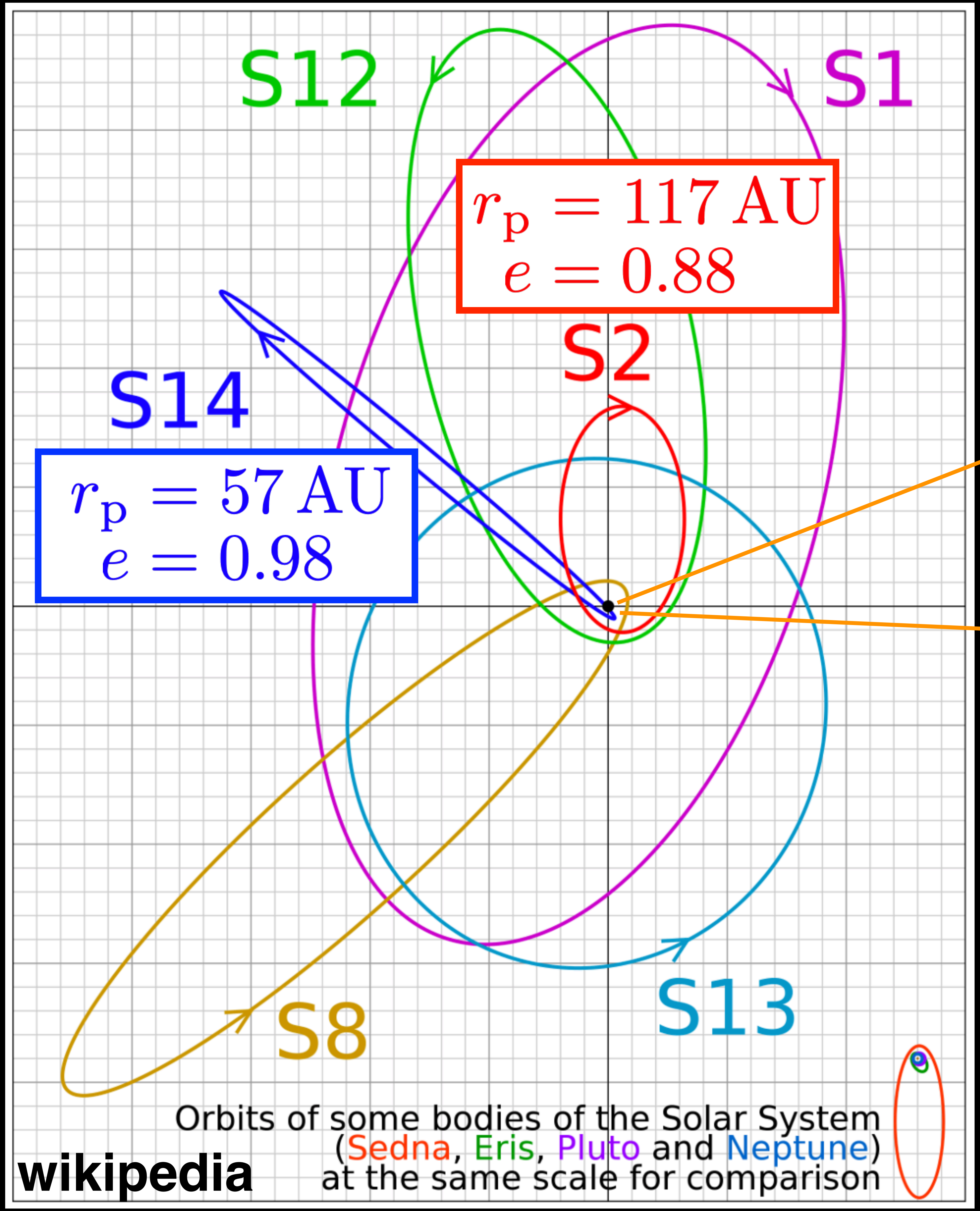
$\Rightarrow$ **Star is losing mass, but not driven by GW**

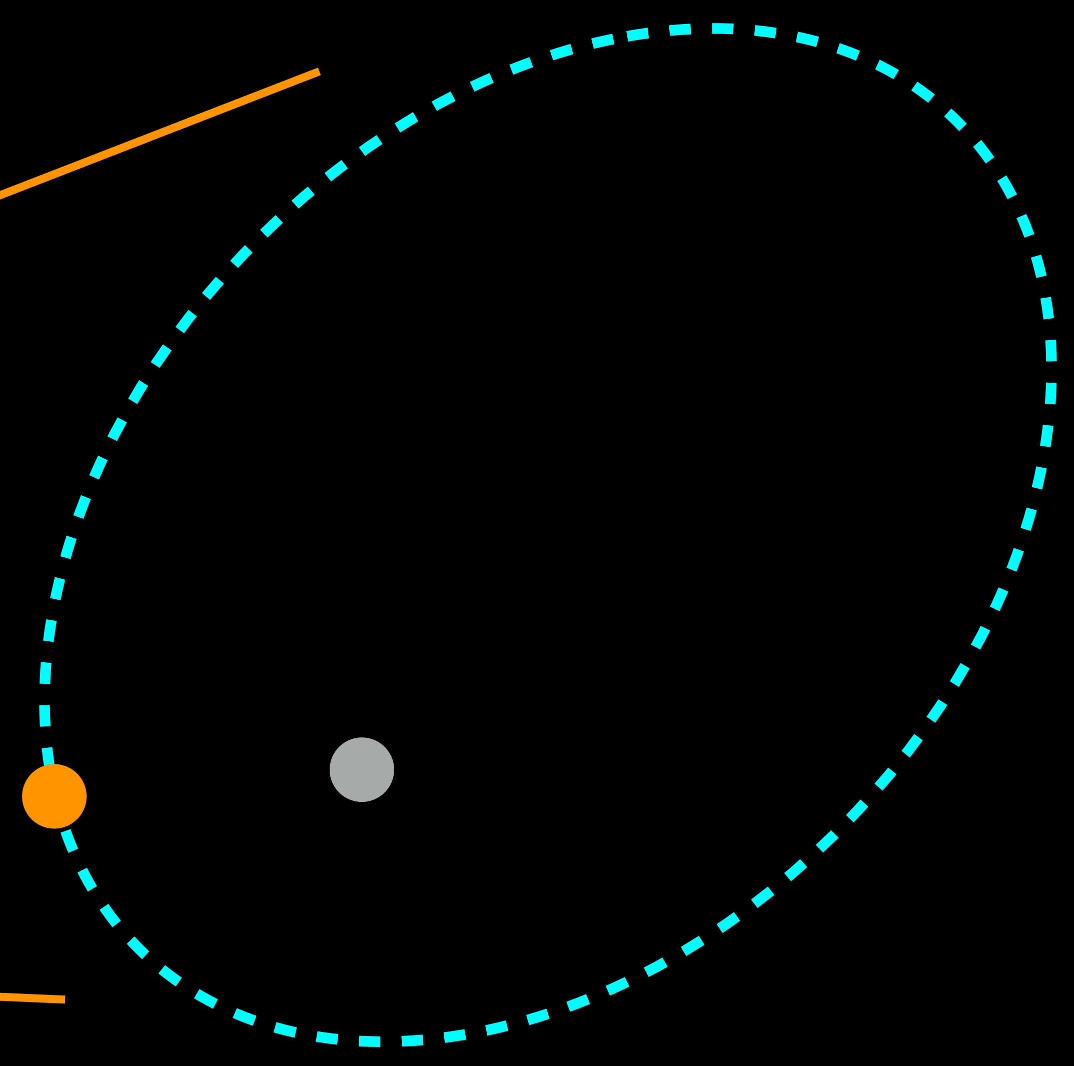
4) **accretion time >> orbital period** $t_\mathrm{acc}(r_\mathrm{p}) \gg P$

$\Downarrow$ **Eruptions are not accretion powered!**



THE Closest Stars to Supermassive BHs





$a \sim 1\,\mathrm{AU}$

$e \sim 0.5$

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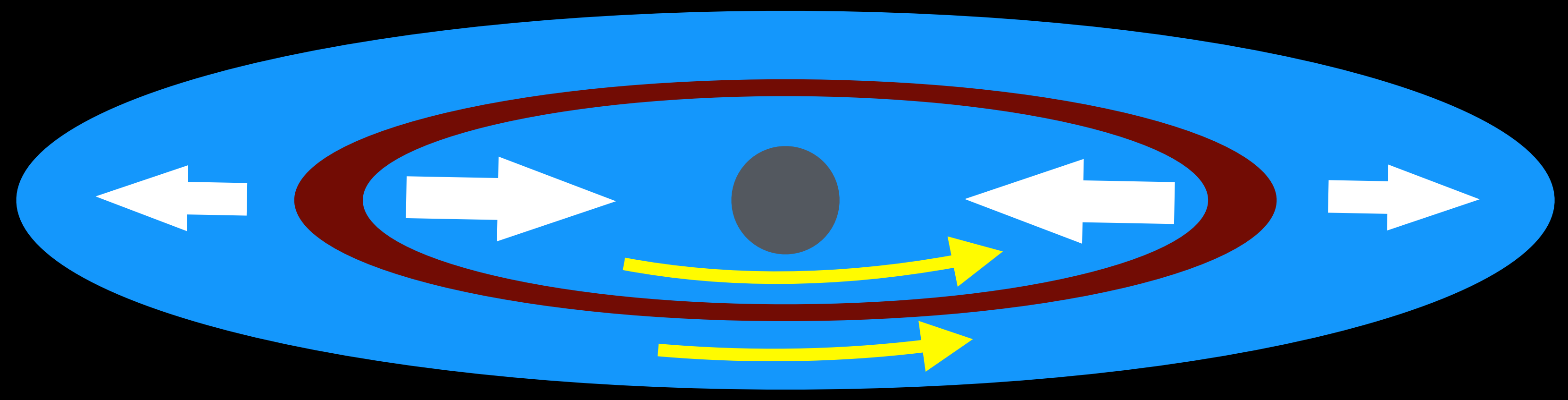
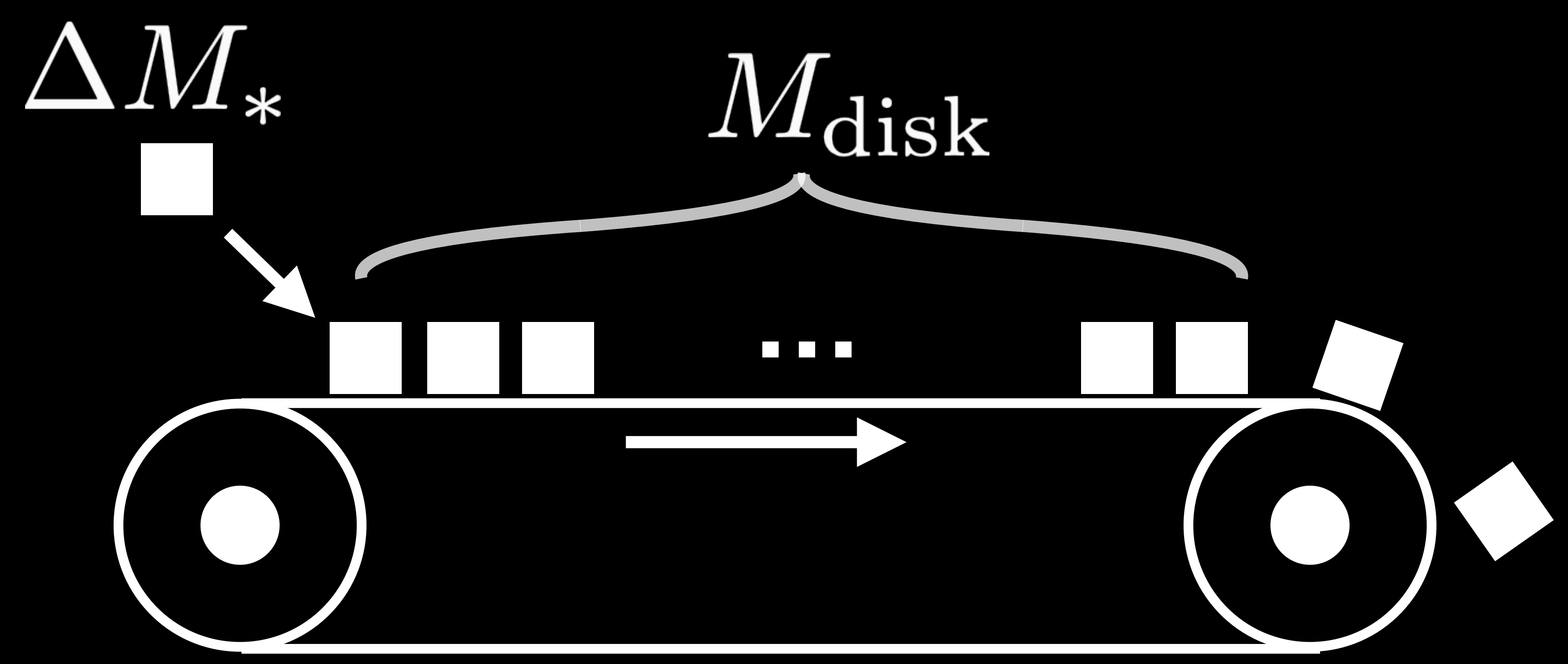
Quiescent Emission from Disk Accretion

$$\frac{M_{\rm disk}}{\Delta M_*} = \frac{t_{\rm acc}}{P} \sim 10^2 (H/0.1r)^{-2} \left(\frac{1-e}{0.5}\right)^{-3/2}$$

disk mass accumulates over time

mass loss per orbit





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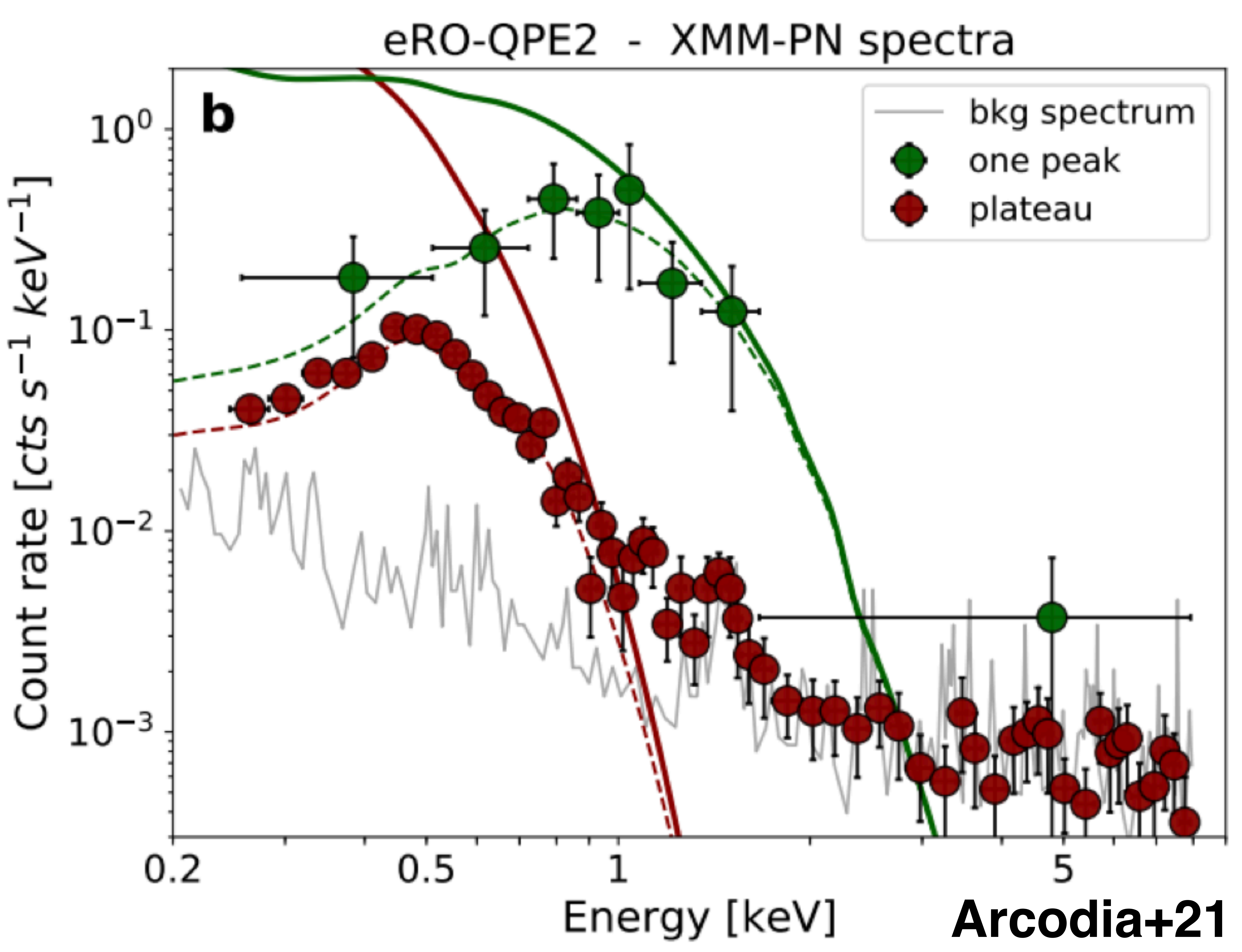
Quiescent emission powered by accretion



Arcodia+21

What Powers the Eruptions?

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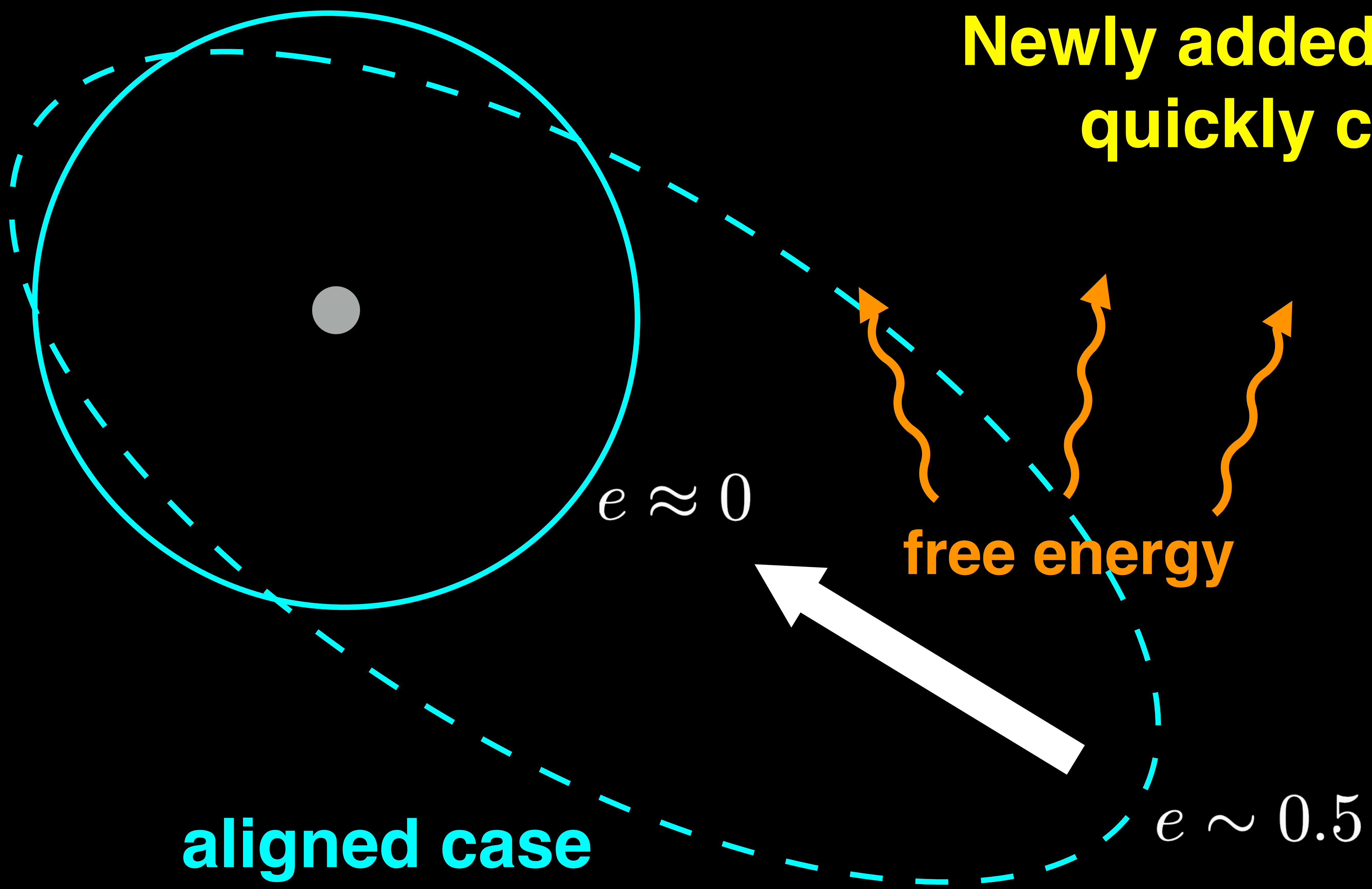
mass loss per orbit

$$\boxed{M_{\rm disk} \gg \Delta M_*}$$

Newly added mass should quickly circularize!



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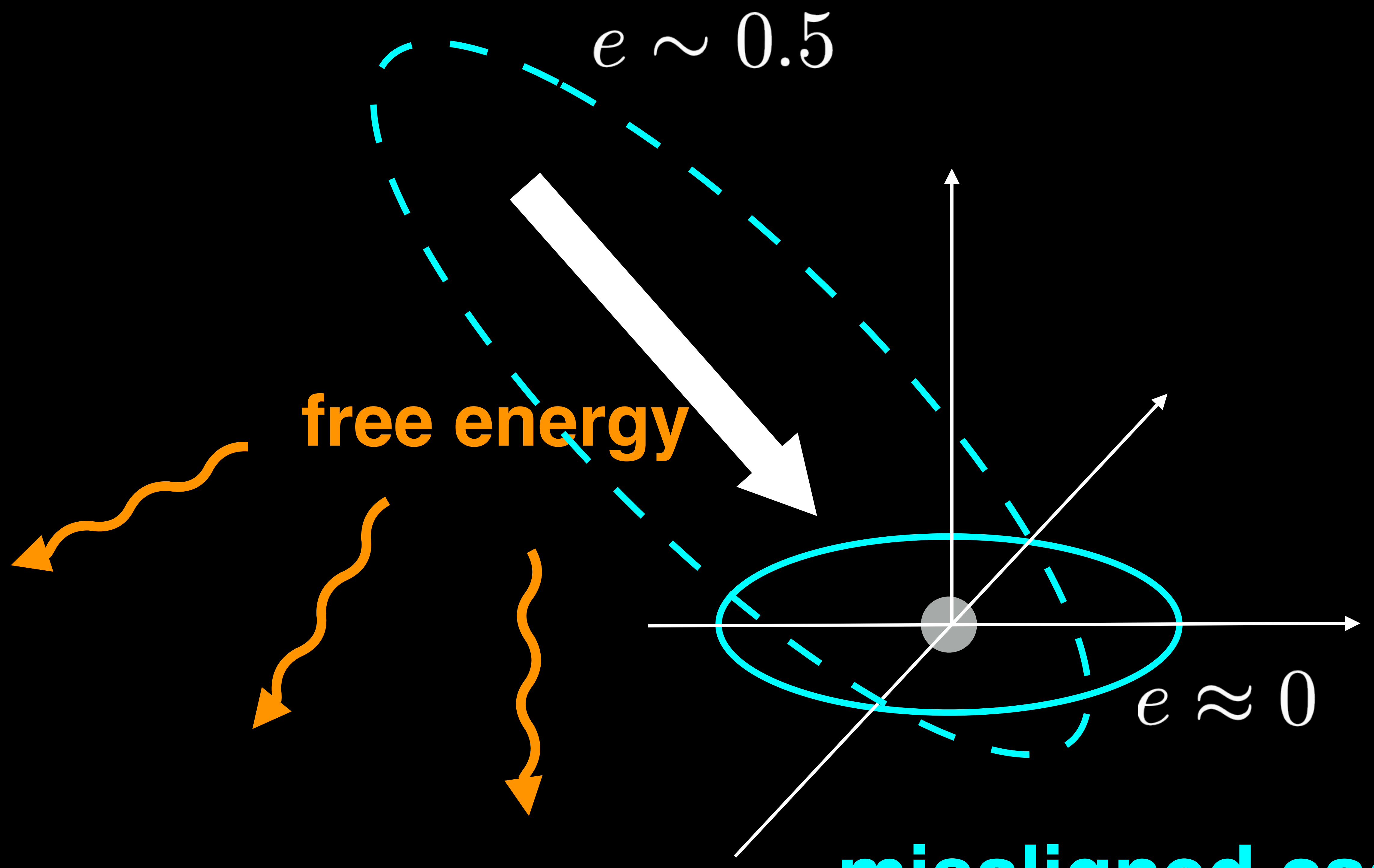

misaligned case

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mass loss per orbit

$$\boxed{M_{\rm disk} \gg \Delta M_*}$$

Newly added mass should quickly circularize!

$e \sim 0.5 \to 0$

inclination $\to 0$

QPEs are powered by circularization shocks!

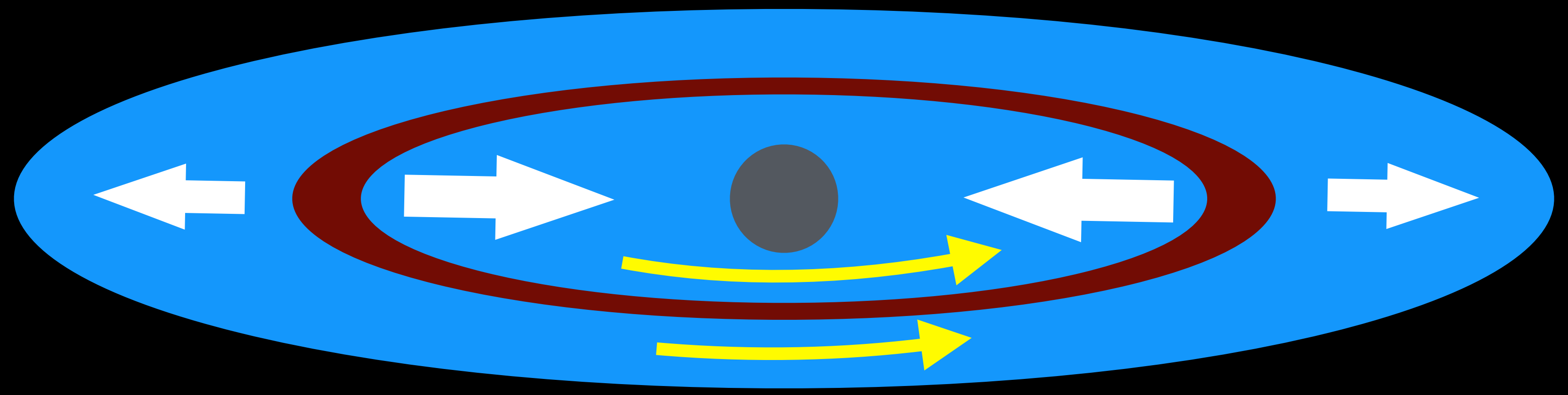
Radiative efficiency $\Delta E \sim 1\% \Delta M_* c^2$

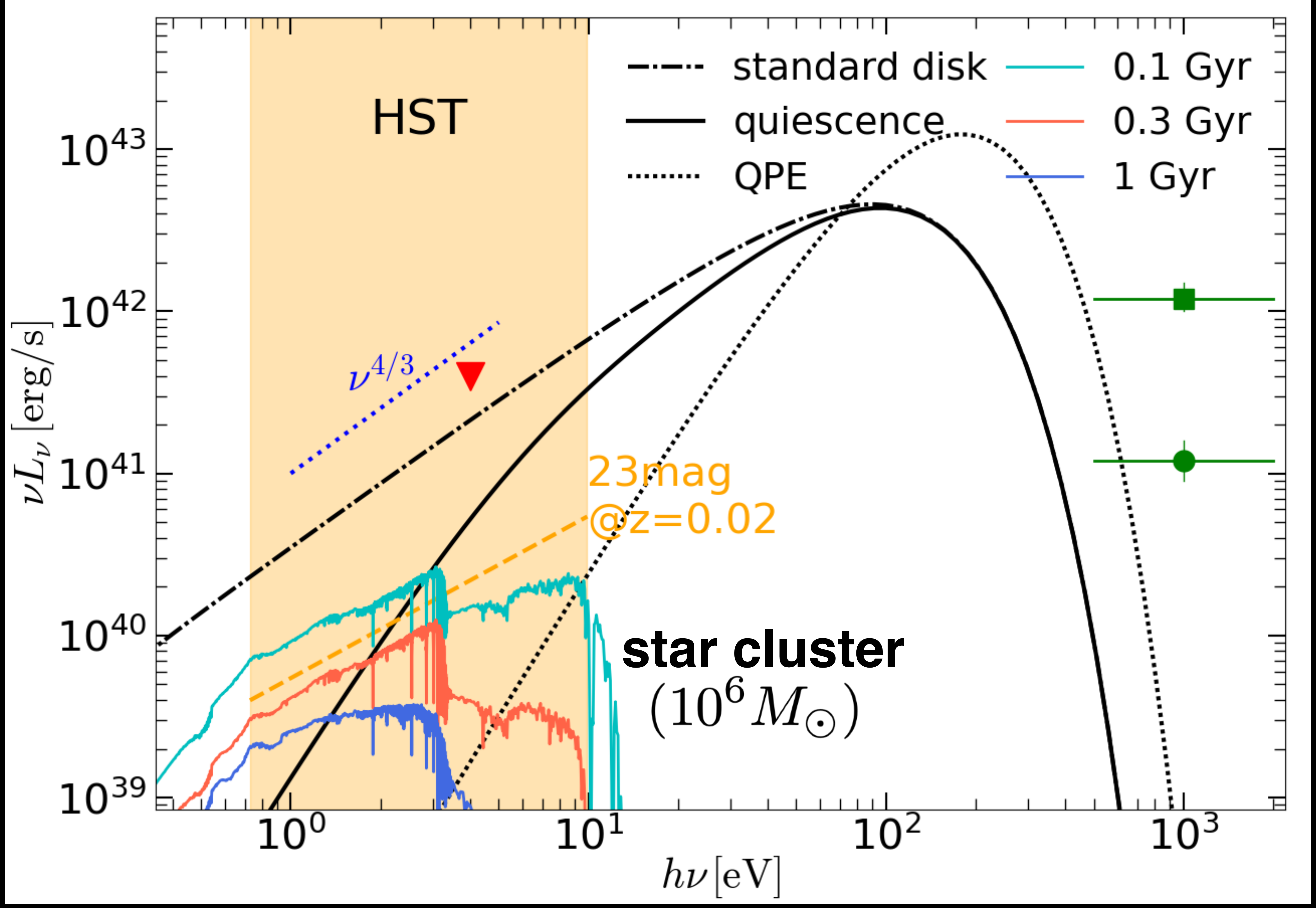
mass budget $\Delta M_* \sim 10^{-6}\, M_\odot \left(\frac{f_{\rm sh}}{1\%}\right)^{-1}$ $\Rightarrow$ $\dot{M}_* = \frac{\Delta M_*}{P} \sim 10^{-3} M_\odot\, {\rm yr}^{-1}$

lifetime $10^2 \sim 10^3\ {\rm yr}$

flare duration $\Delta t \sim 0.1 P$

Broad-band Spectrum





$$M = 3 \times 10^5 M_\odot, \ \dot{M} = 2 \times 10^{-3} M_\odot \, \mathrm{yr}^{-1}$$

Persistent Disk:

1) For $r < r_\mathrm{p}$, $\dot{M}(r) = \mathrm{const}$

➡ $\nu L_\nu \propto \nu^{4/3}$ (standard)

2) For $r > r_\mathrm{p}$, $\dot{J}(r) = \dot{M}\sqrt{GMr} = \mathrm{const}$

➡ $\boxed{\nu L_\nu \propto \nu^{12/7} \text{(steeper)}}$

3) Outer edge (lifetime ~ viscous time)

$r_\mathrm{out} \sim \mathrm{few} \times 100 r_\mathrm{g}$

QPEs:

Rapid circularization (shocks)

➡ Hotter T

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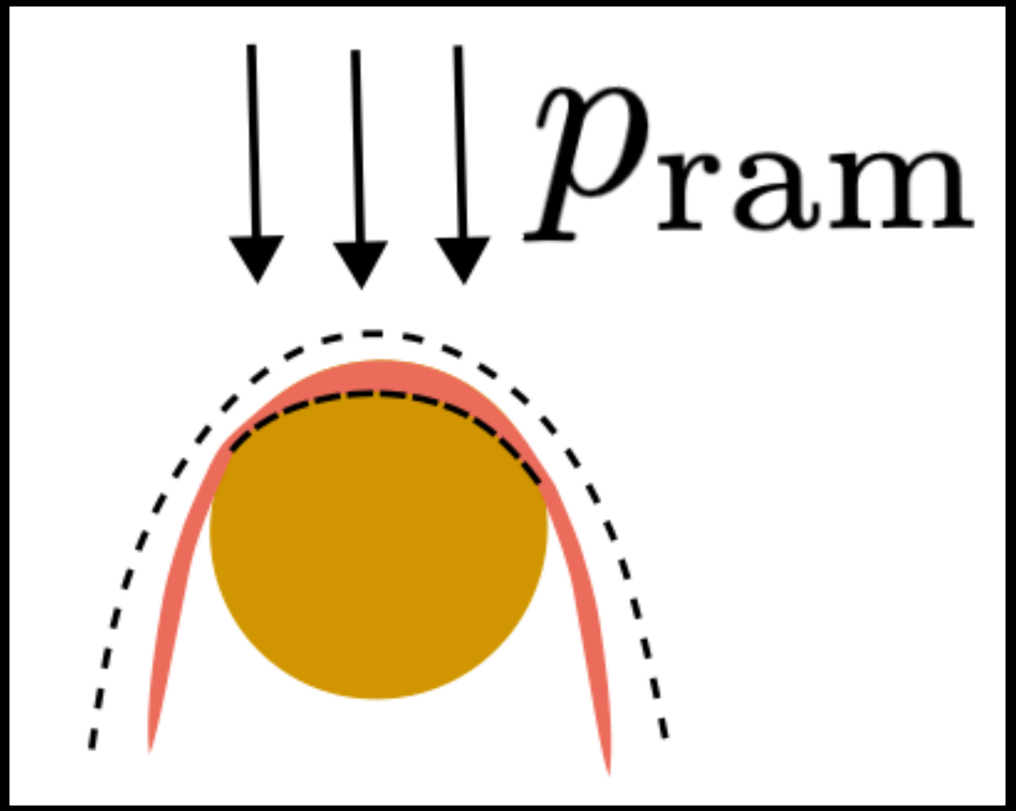
What Causes the Mass Loss?



ram pressure $p_{\rm ram} \sim \rho_{\rm disk} v^2$

$p_{\rm ram} \sim 10^{11}\,{\rm erg\,cm^{-3}}$

$\bar{p} \sim 10^{15}$

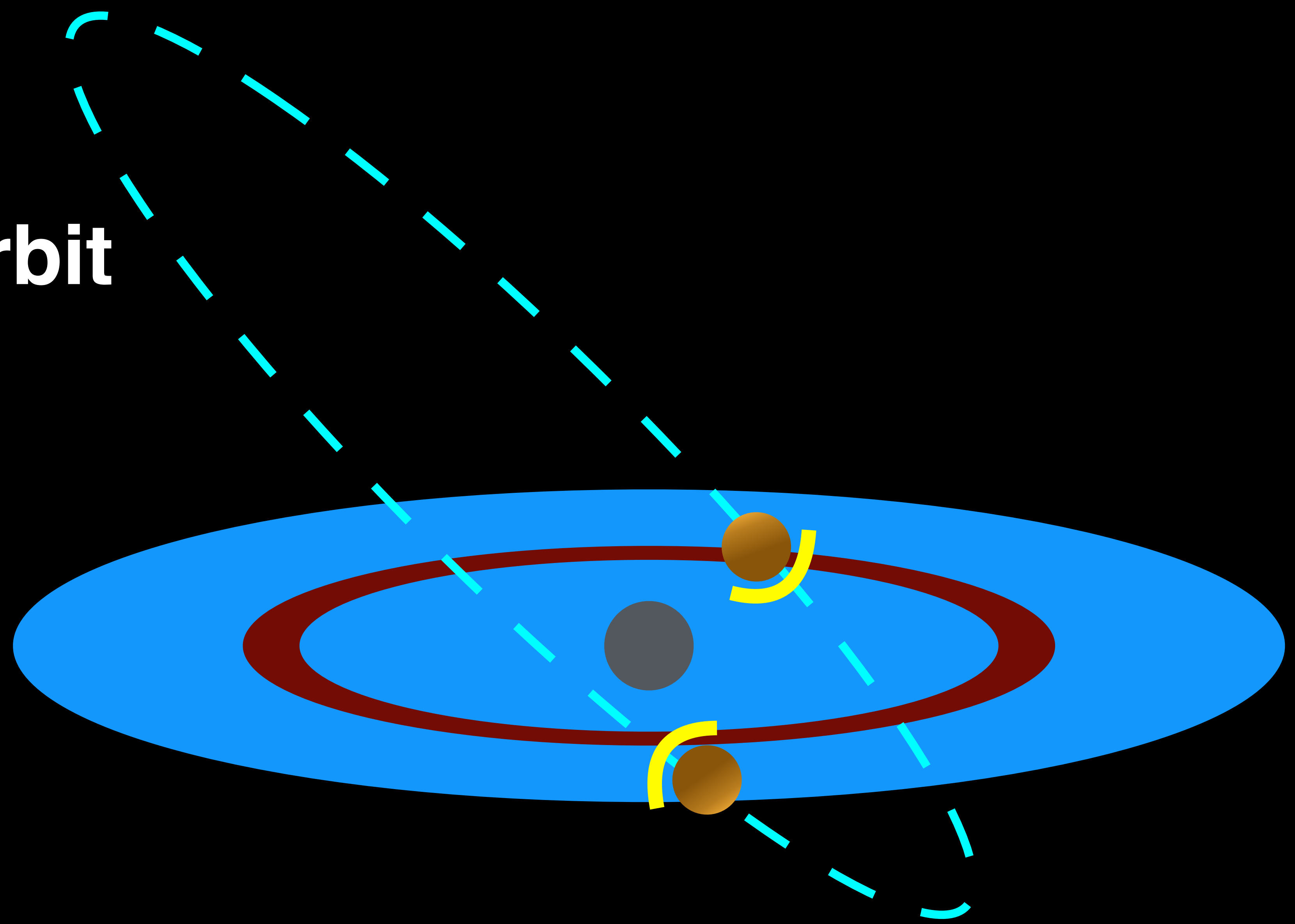
stellar pressure

Ram-pressure effects:

1) Stellar surface layers are *shock heated* to a fractional depth (for polytropic envelope)

$$\frac{\Delta R}{R_*} \sim \left(\frac{p_{\rm ram}}{\bar{p}}\right)^{2/5} \sim {\rm few}\%$$

stellar orbit



disk

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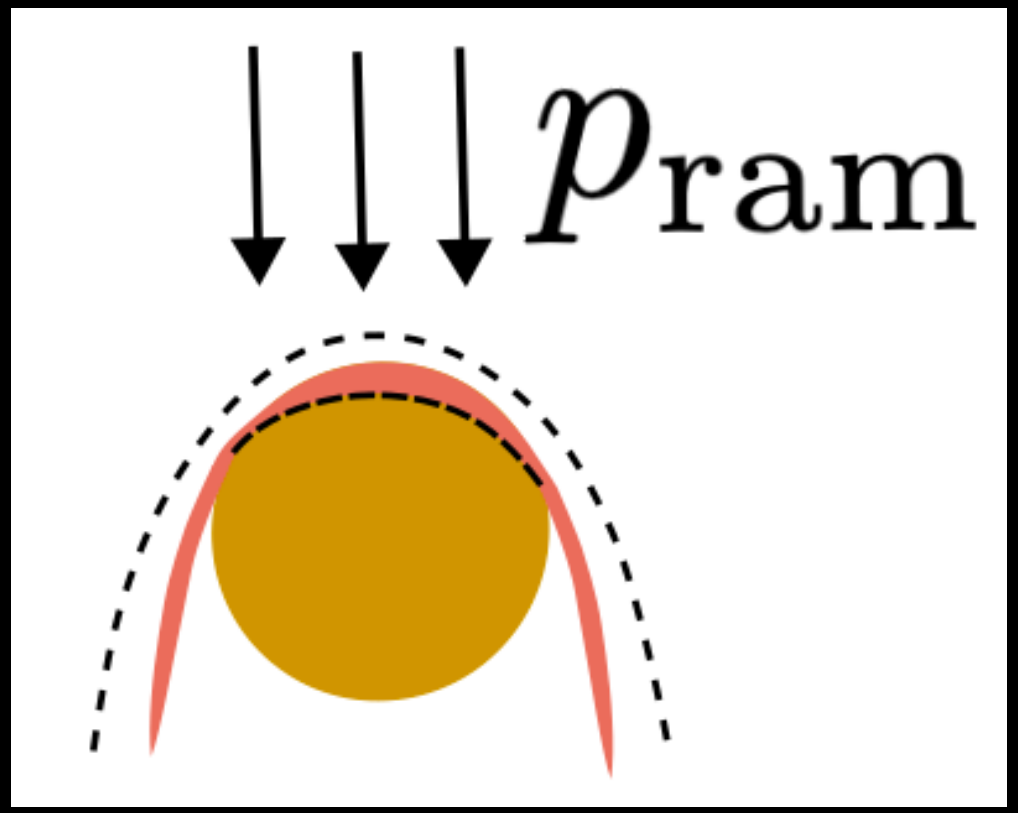

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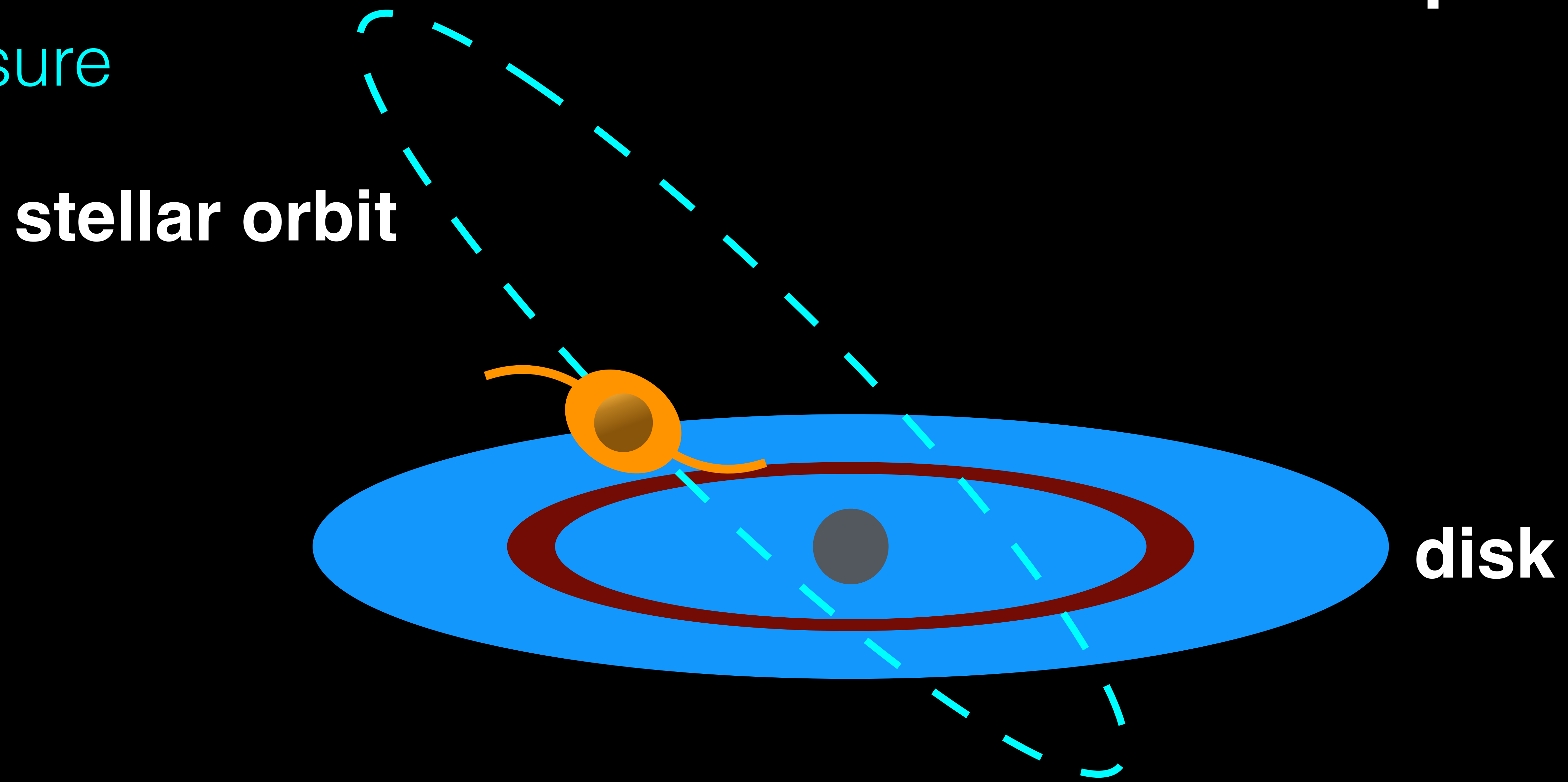
2) Shock-heated layers *expand* to fill up the Roche-lobe, leading to mass loss

HD simulations (on-going)

$$\boxed{\dot{M}_* \sim 10^{-3}\,M_\odot\,{\rm yr}^{-1}}$$



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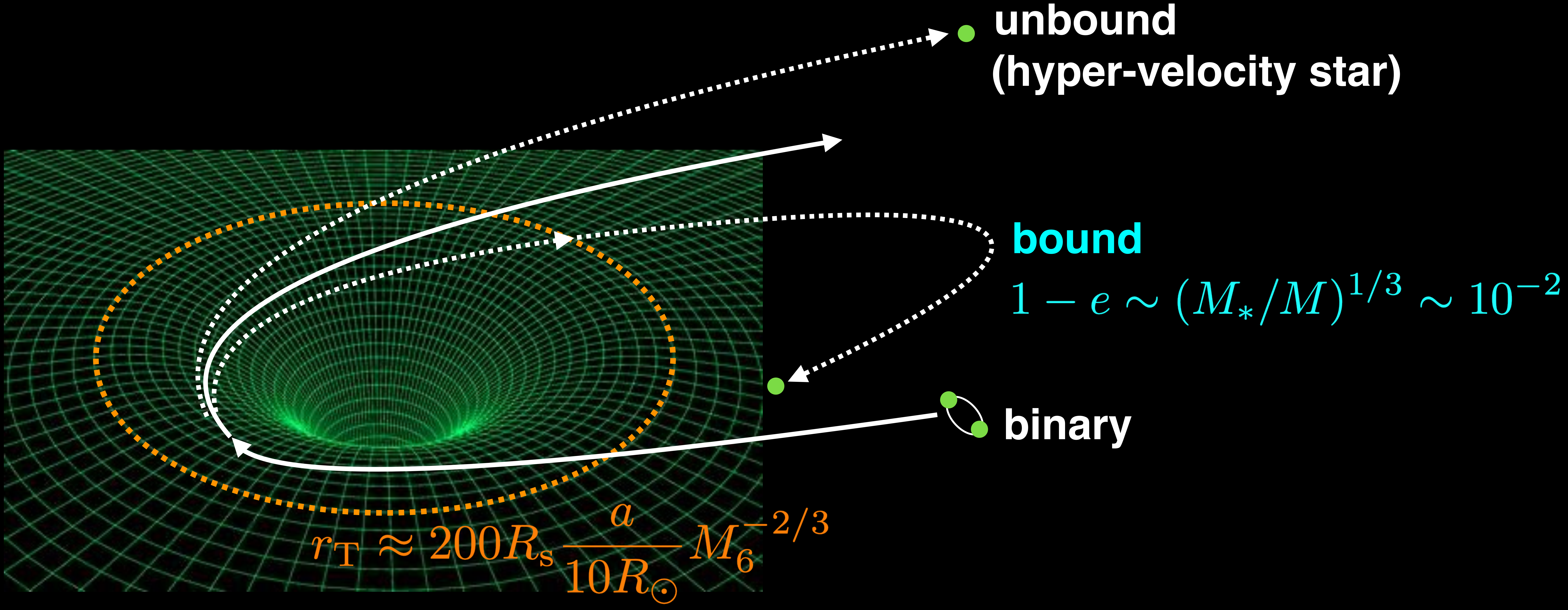
Hills (1988) Mechanism



Summary

Conclusions:

- Quasi-Periodic Eruptions (QPEs) are powered by stars on mildly eccentric orbits
- X-ray eruptions are produced shocks (instead of accretion)
- Quiescent emission have unusual SED
- Star comes from tidal break-up of binary system
- Repeating partial tidal disruptions are linked to QPEs

Predictions:

- QPEs have steep UV/optical spectrum (Hubble Space Telescope)
- Lifetime $10^2 \sim 10^3\,\mathrm{yr}$ (photons ionize gas up to $10^3\,\mathrm{ly}$)
- X-ray timing variations due to orbital precessions

narrow emission lines
e.g., [OIII]

QPE Rate

QPE fraction depends on relaxation time, typically few%

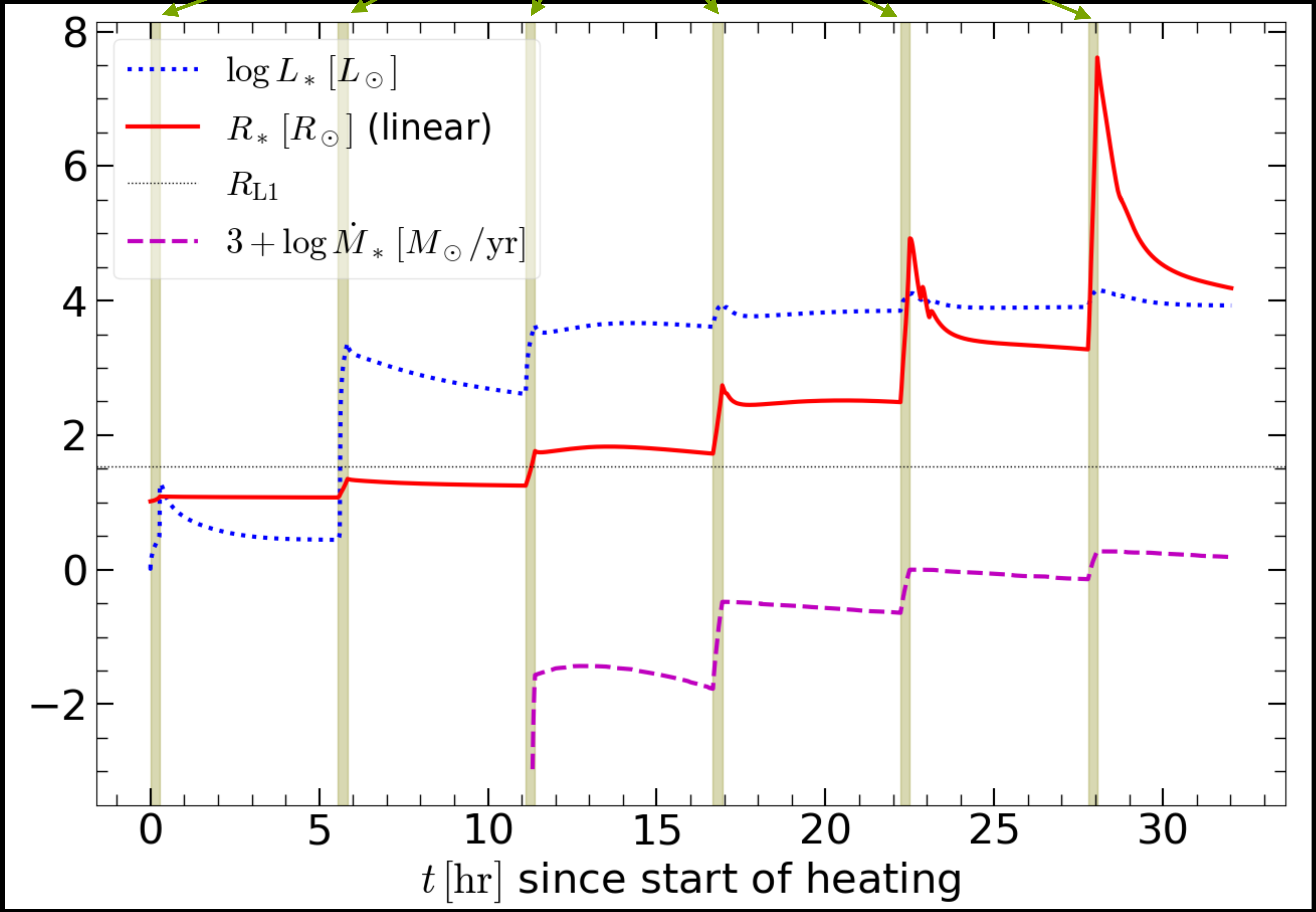
$$\mathcal{R}_{\rm QPE} \sim f_{\rm b} f_{\rm QPE} \mathcal{R}_{\rm TDE} \sim 10\,{\rm Gpc^{-3}\,yr^{-1}}\,\frac{f_{\rm b}}{0.05}\,\frac{f_{\rm QPE}}{0.03}\,\frac{\mathcal{R}_{\rm TDE}}{10^3\,{\rm Gpc^{-3}\,yr^{-1}}}$$

Observed volume density $\sim 10^3\,{\rm Gpc^{-3}}$

Predicted QPE rate consistent with typical lifetime $\sim 10^2\,{\rm yr}$

Ram-Pressure Induced Stellar Expansion

shock heating (entropy injection)



MESA (Paxton+19)

For a single star:

$$M = 1\, M_\odot \text{ @ } 5\,\mathrm{Gyr}$$
$$p_{\rm ram} = 3 \times 10^{11}\,\mathrm{erg\,cm^{-3}}$$
$$P = 5.5\,\mathrm{hr}$$

Rapid expansion => tidal stripping

$$\dot{M} \sim 10^{-3}\, M_\odot\,\mathrm{yr}^{-1}$$