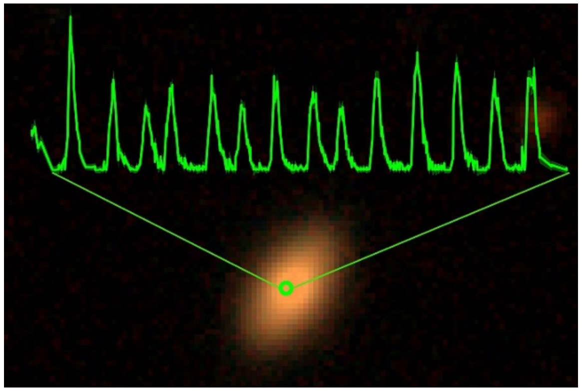
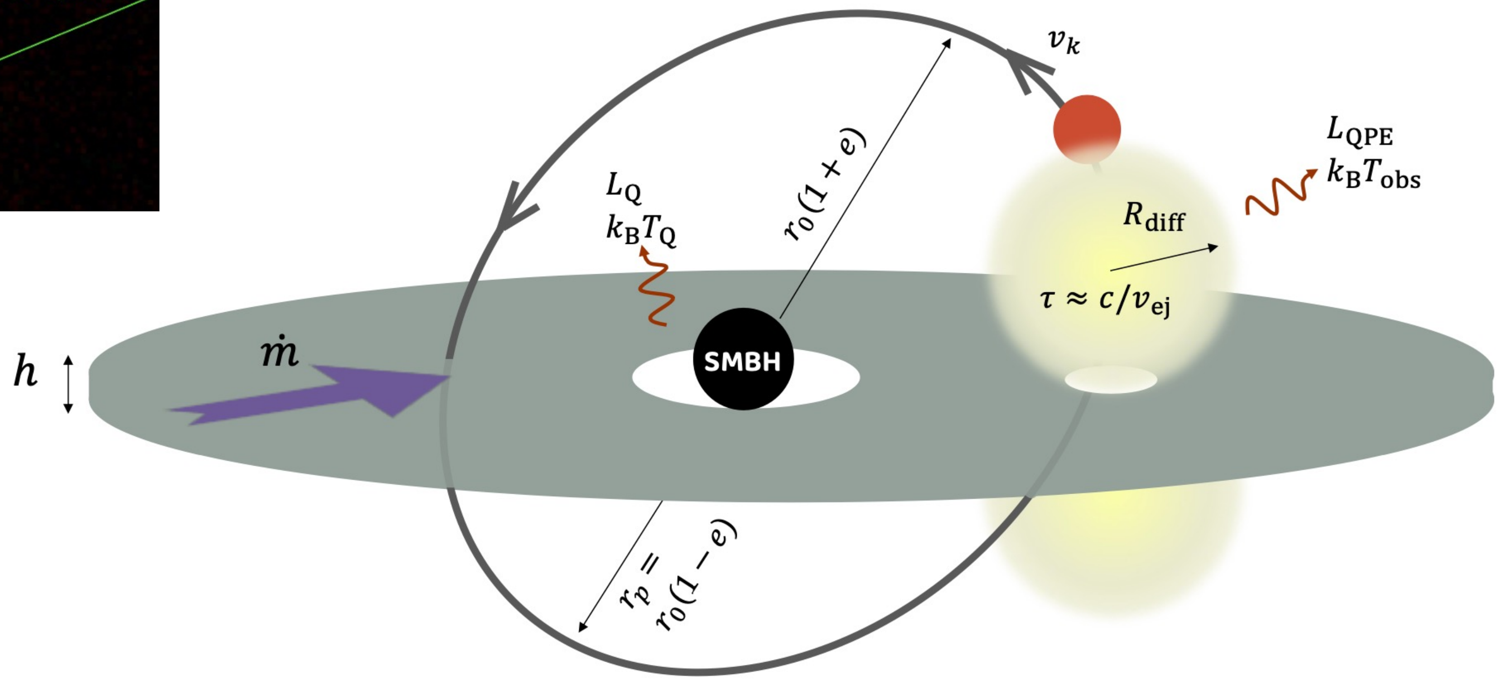
Quasi-Periodic Eruptions from Star-Disk Collisions in Galactic Nuclei





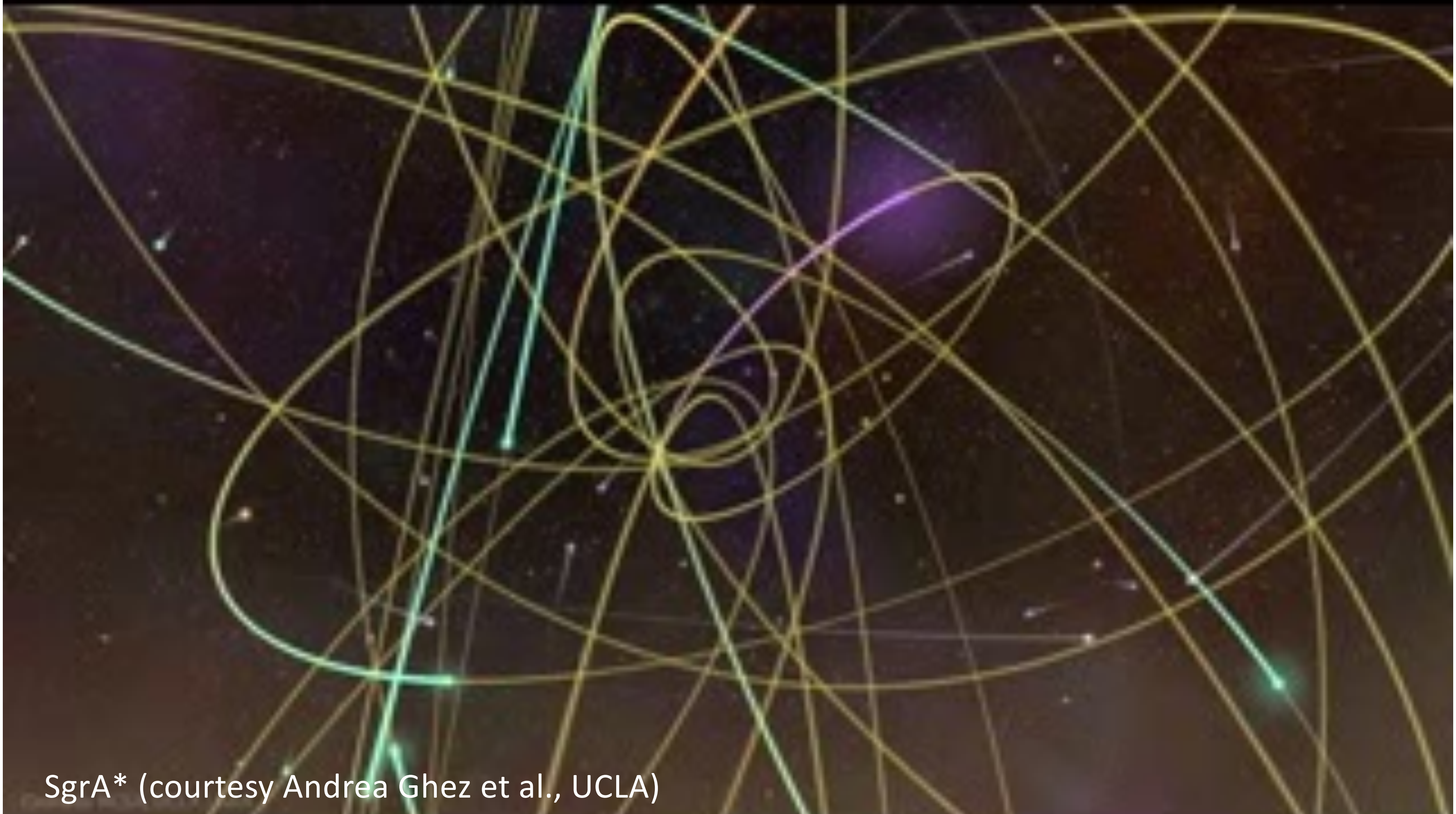
FLATIRON INSTITUTE

Brian Metzger

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

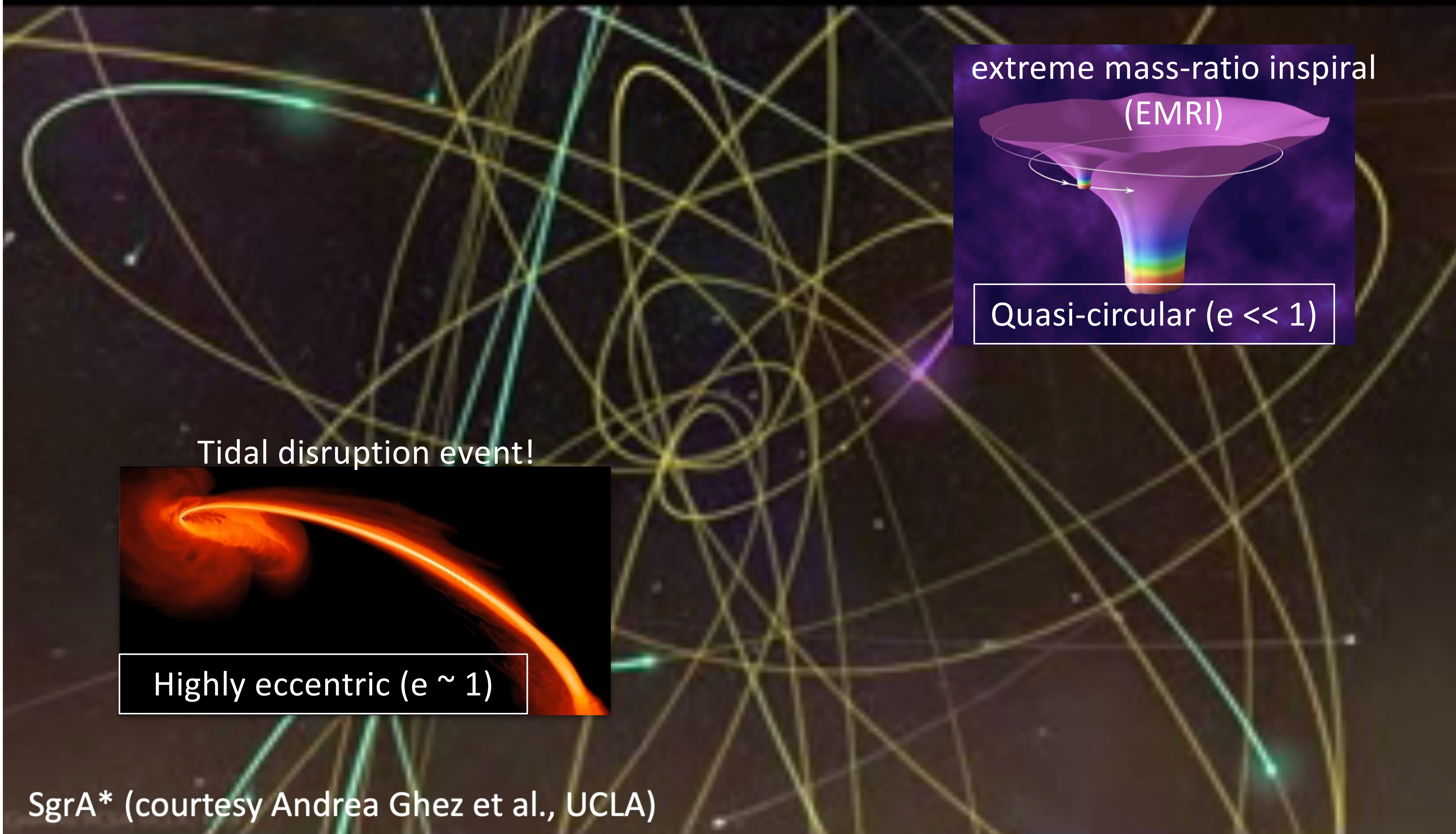
with **Itai Linial** (Columbia/IAS), Nick Stone (Wisconsin), Shmuel Gilbaum (HUJI)

Happenings around massive black holes



SgrA* (courtesy Andrea Ghez et al., UCLA)

Happenings around massive black holes



Quasi-Periodic Eruptions from Galactic Nuclei

- 7 systems known (maybe +2)

  4 eROSITA sources

- (quasi)period: **2.5-20 hr**

- Duty cycle ~ 10-30%

  durations: **0.2-3 hr**

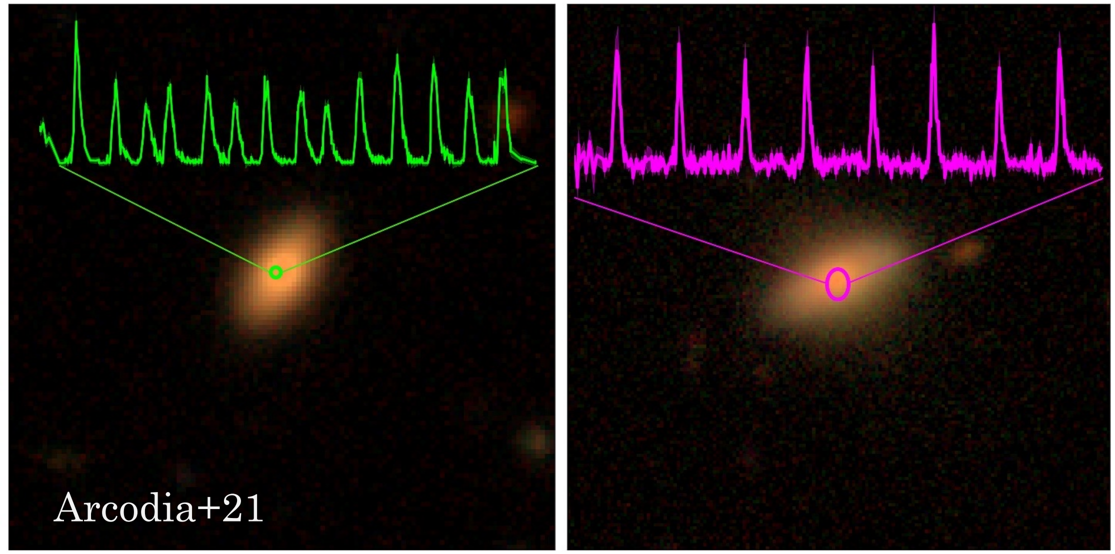
- Peak luminosities:

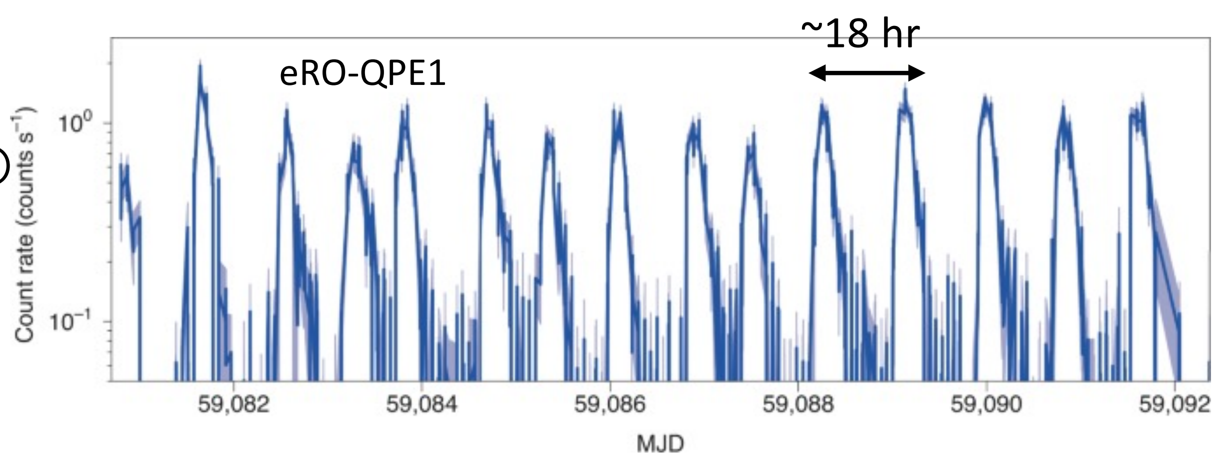
  $\mathrm{L}_{\mathbf{peak}} \sim \mathbf{10^{42}\ erg\ s^{-1}}$

  $kT_{\mathrm{pk}} \approx 100 - 200\ \mathrm{eV}$

- $M_{\bullet} \approx \mathbf{3{\times}10^{5} - 5{\times}10^{6}}\ \boldsymbol{M_{\odot}}$

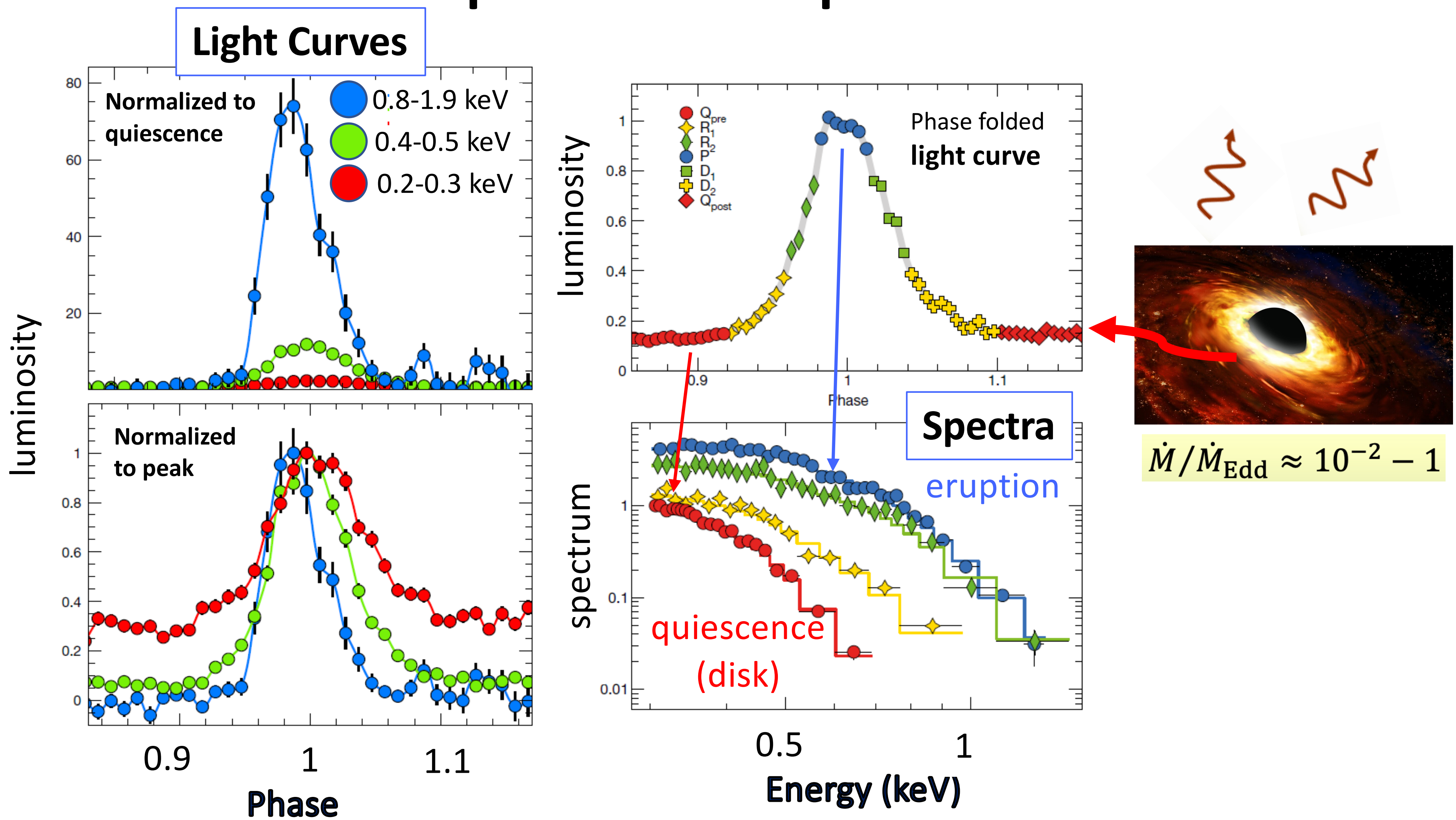
gal. occupation fraction ~10^{-5}





Miniutti et al., *Nature,* 2019
Giustini et al., *A&A*, 2019
Arcodia et al., *Nature,* 2021
Chakraborty et al., *ApJL,* 2021
Miniutti et al., *ApJ*, 2023

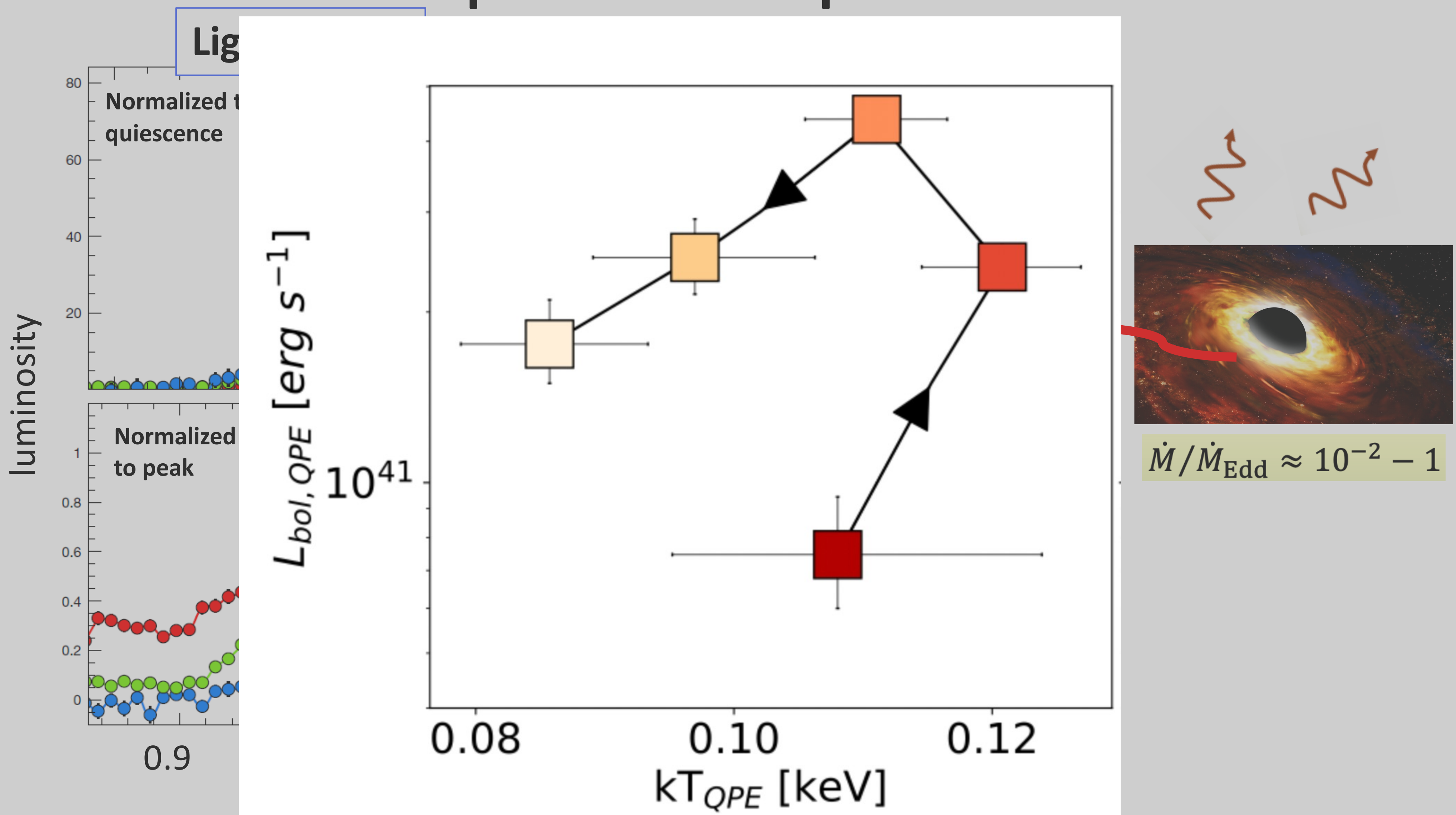
Eruption Properties



GSN-069: Miniutti+19

- Light curves narrower & peak faster at higher photon energies
- “hard” thermal eruptions on top of softer thermal (disk) emission

Eruption Properties



GSN-069: Miniutti+19

- Light curves narrower & peak faster at higher photon energies
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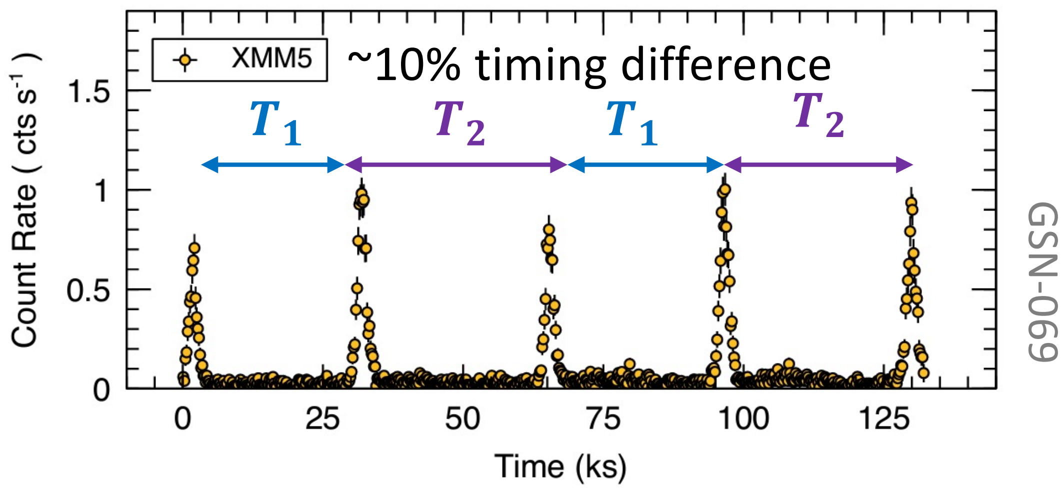
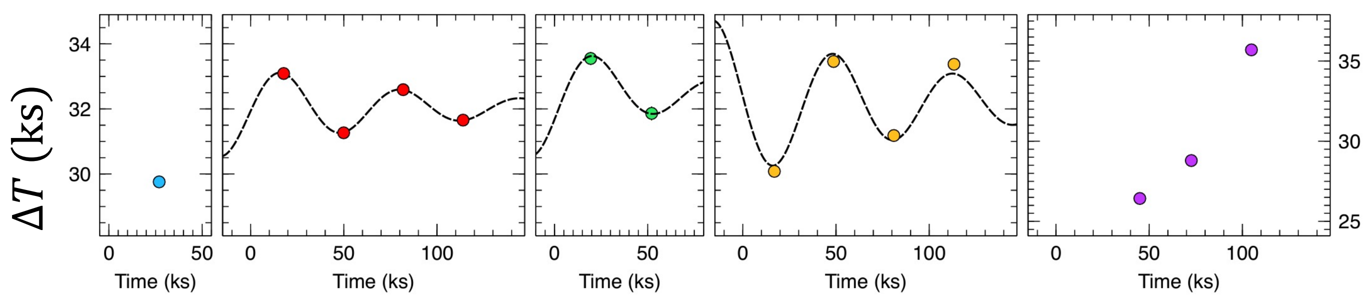
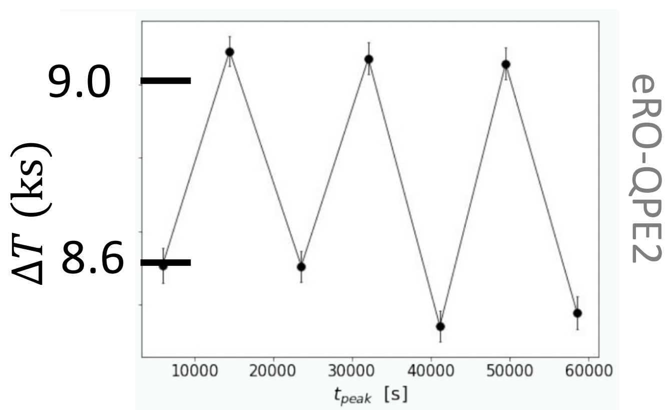
QPEs are not strictly periodic, but their arrival times can exhibit regularities…

Long-Short Arrival Time Oscillations

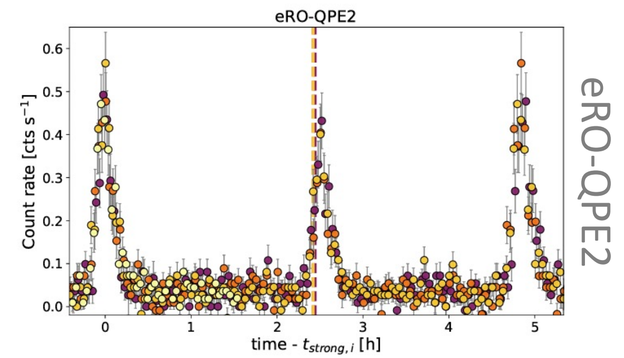


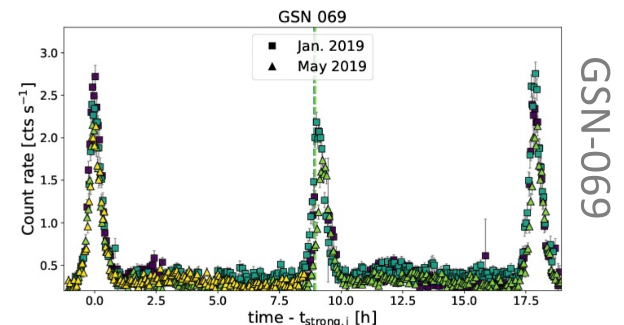


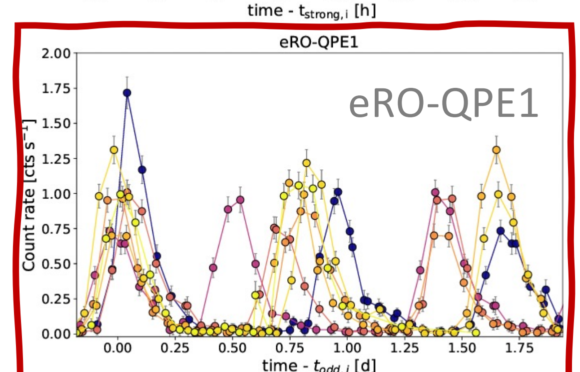
[Miniutti+23]



[Arcodia 2022]







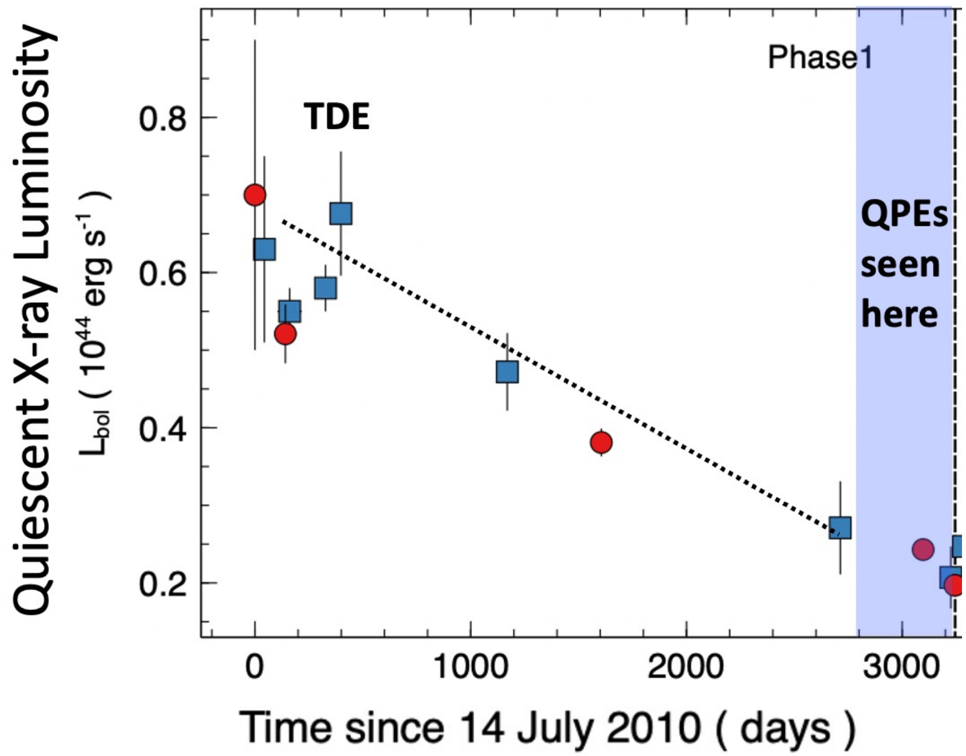
others more irregular

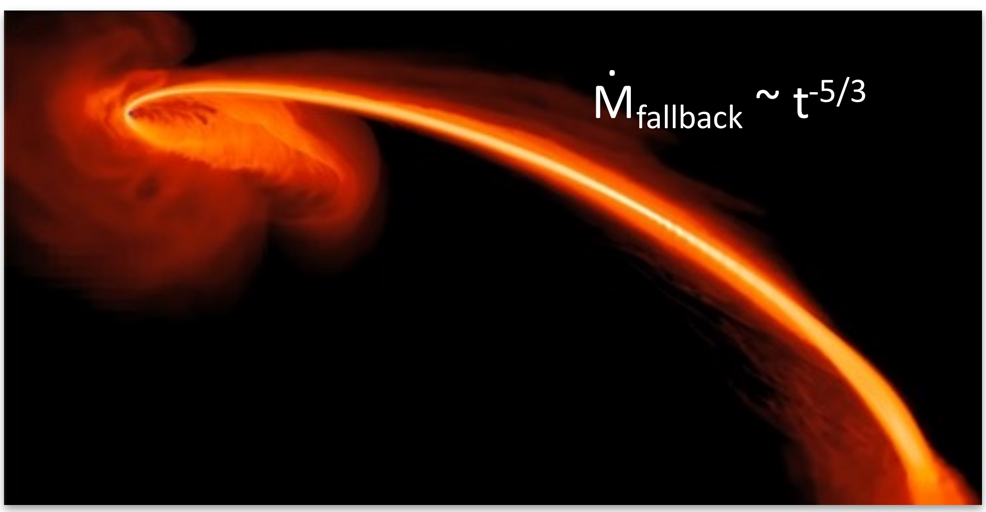
QPE-TDE association?

Some systems show long term **<u>decay of quiescent X-ray</u>** emission before QPEs

⇒ TDEs precede QPE activity?

A recent **very** convincing case (Nicholl et al., in prep)





[Miniutti et al. 2019, 23]
[Shu et al. 2018]
[Sheng et al. 2021]
[Chakraborti et al. 2021]

Theoretical Models

1. Disk instabilities

   [Miniutti+21, Arcodia+21, Raj & Nixon 21, Pan+22, Kaur+22, Sniegowska+22]

2. Lensing by a massive companion

   [Ingram+22]

3. Mass Transferring Companion(s) “EMRI”

   1. Compact companion (White Dwarf, He core)

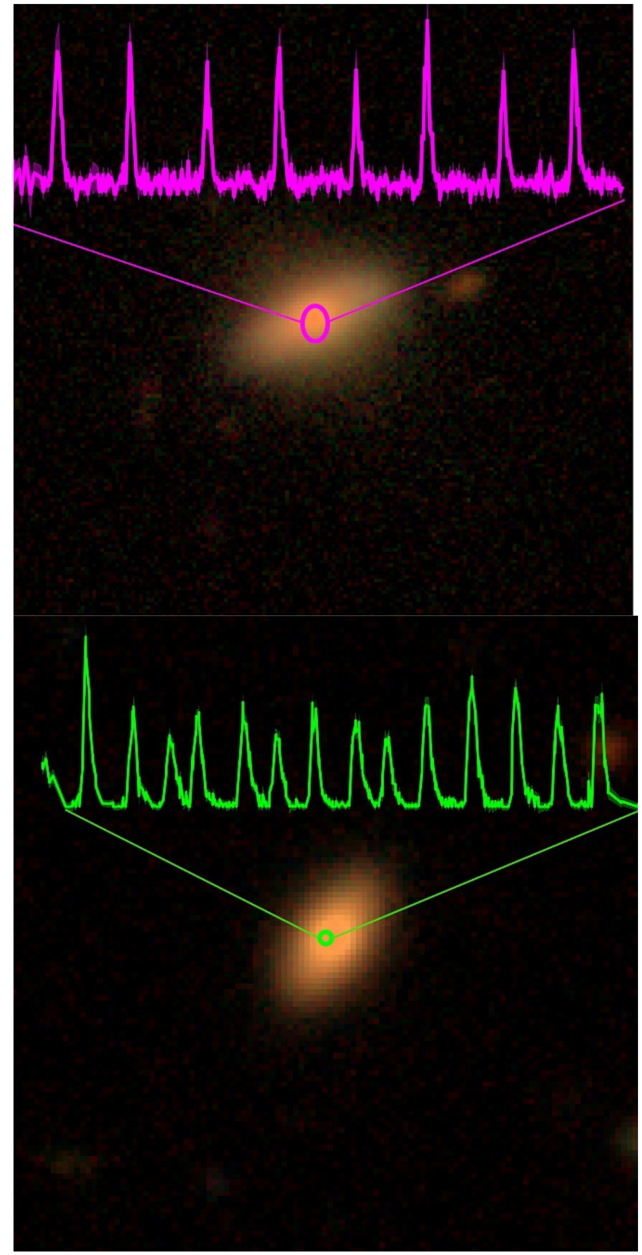
      [King 20,22,23, Zhao+22, Chen+22, Wang+22, Xian+22]

   2. Main-Sequence star on quasi-circular orbit

      [**Metzger+22**, Krolik & **Linial** 22, **Linial** & Sari 23, Lu & Quataert 23]

~hours period => main-sequence stars

$$P_{QPE} \sim P_{orb} \sim 8\ \mathrm{hr}\ (\rho/\rho_{\odot})^{-1/2}$$



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   1. Compac

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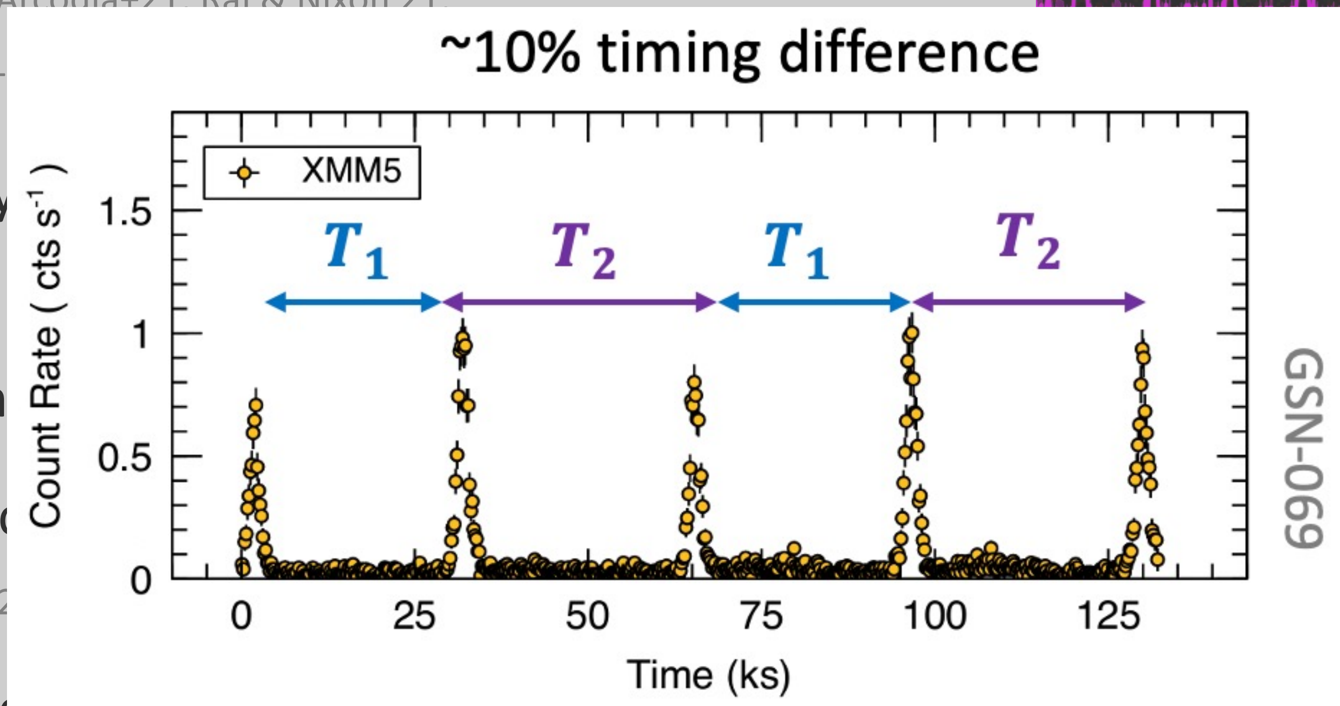
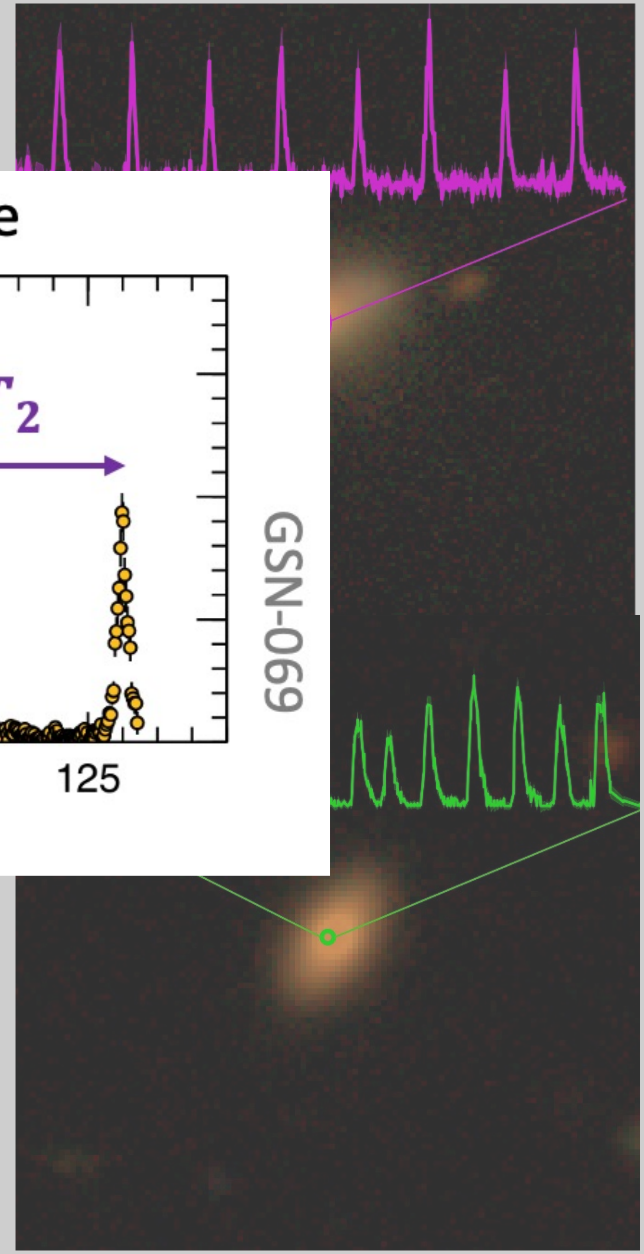
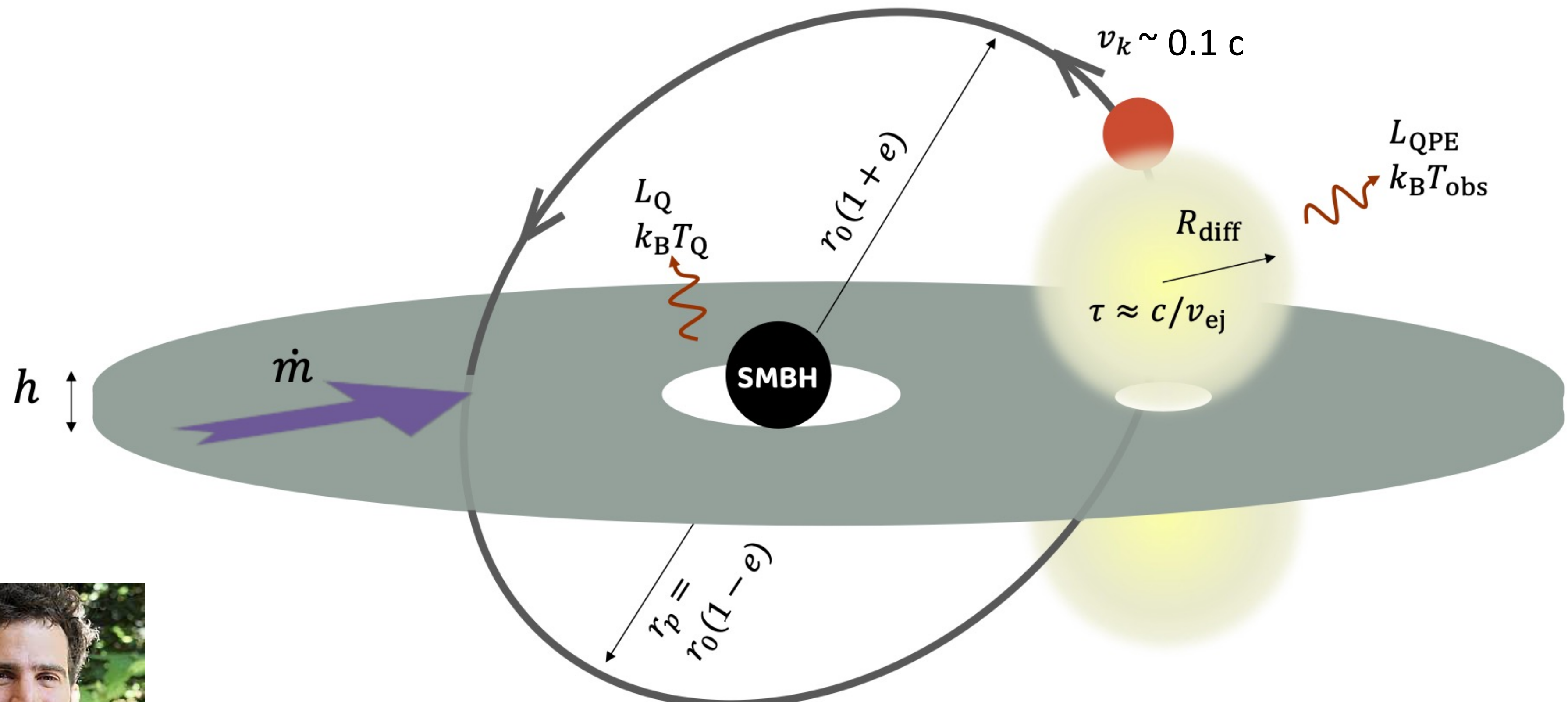




QPEs from Star-Disk Collisions

- Stellar EMRI + accretion disk
- Star-Disk collisions produce flares
- Disk produces quiescent emission
- TDE-QPE association

Linial & BDM (2023)



[See also Xian+22, Sukova+22, Franchini+23, Tagawa & Haiman 23]

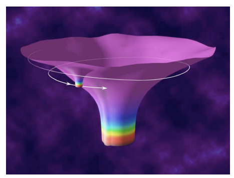
Flare Timing

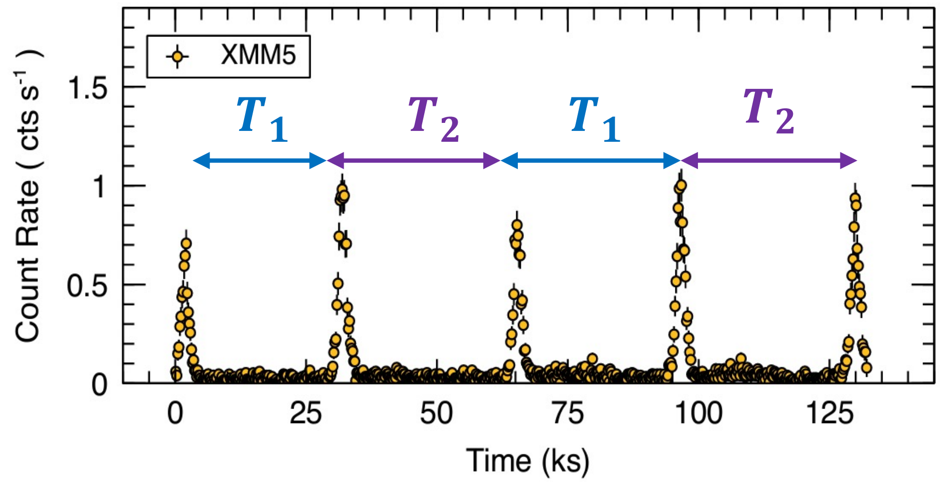
$$P_{\rm orb} = T_1 + T_2 = 2\langle T\rangle \approx 5 - 18\ \text{hr}$$ ✓

$$\frac{T_2 - T_1}{\langle T\rangle} \sim O(e)$$

$$e \approx 0.1$$

Consistent with EMRI





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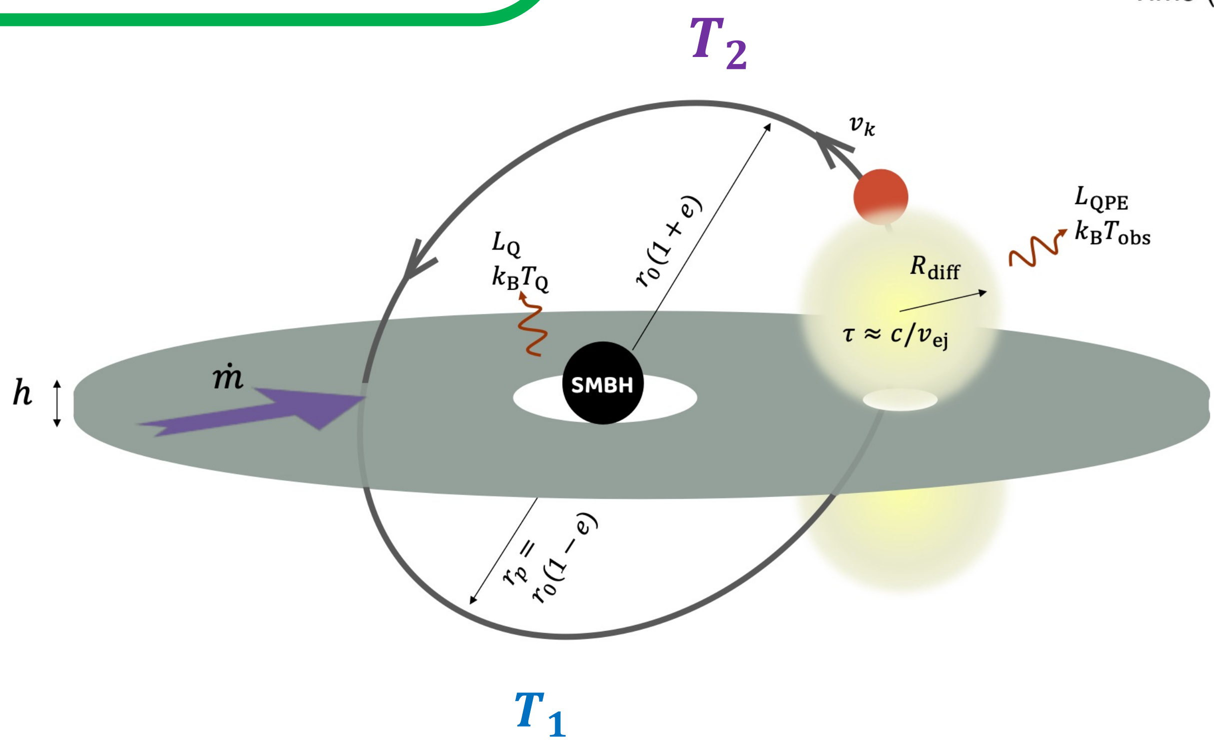
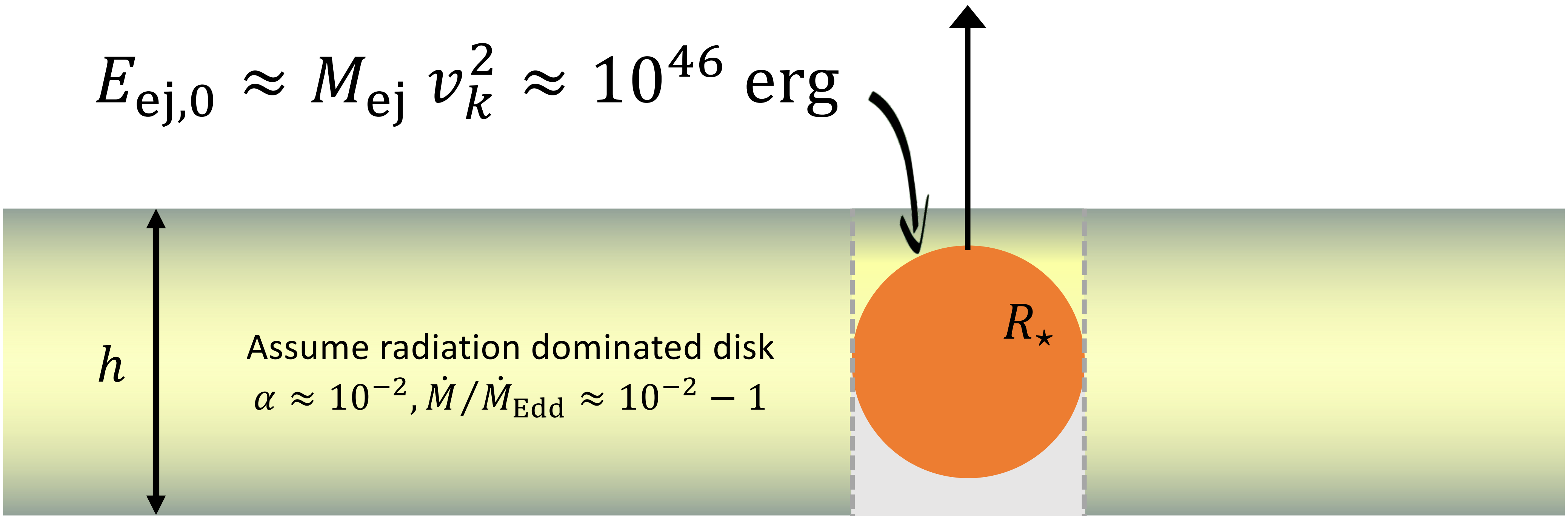


Star Disk Collisions

$$v_k \approx 0.1\mathrm{c}\ M_{\bullet,6}^{1/3}\ T_{(5\,\mathrm{hr})}^{-1/3}$$

$$E_{\mathrm{ej},0} \approx M_{\mathrm{ej}}\, v_k^2 \approx 10^{46}\ \mathrm{erg}$$



Effective cross section ~ $\pi R_\star^2$

Gravitational focusing negligible ($v_k \gg c_s, v_{\mathrm{esc}}^\star$)

$$M_{\mathrm{ej}} \approx \Sigma_d \cdot \pi R_\star^2 \approx 10^{-6}\ \mathrm{M}_\odot\ R_1^2\ \alpha_{-2}^{-1}\ \dot{m}_{-1}^{-1} T_{(5\,\mathrm{hr})}$$

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h

Assume radiation dominated disk

$\alpha \approx 10^{-2}, \dot{M}/\dot{M}_{\mathrm{Edd}} \approx 10^{-2} - 1$

Effective cross section ~ $\pi R_\star^2$

Gravitational focusing negligible ($v_k \gg c_s, v_{\mathrm{esc}}^\star$

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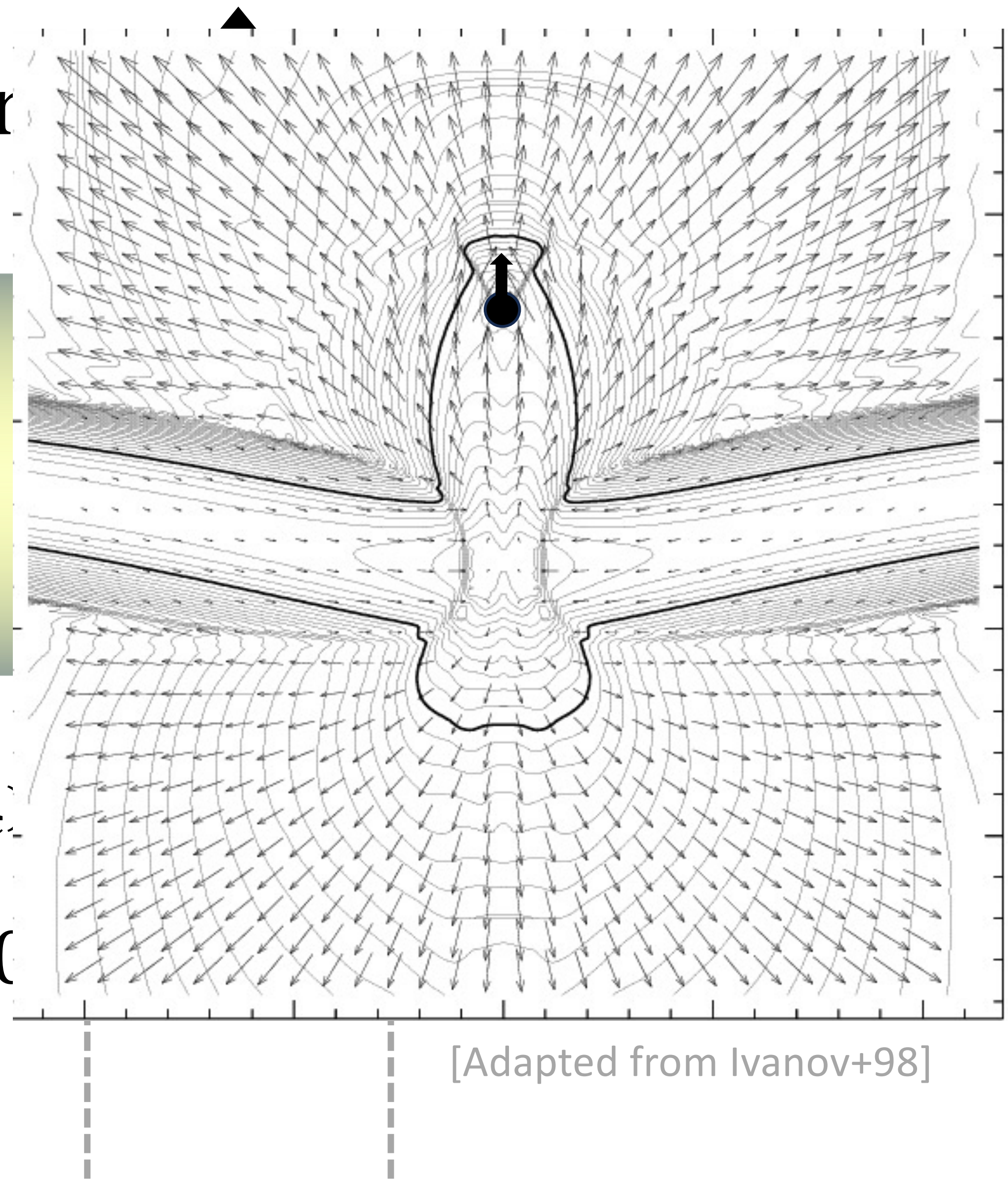

[Adapted from Ivanov+98]

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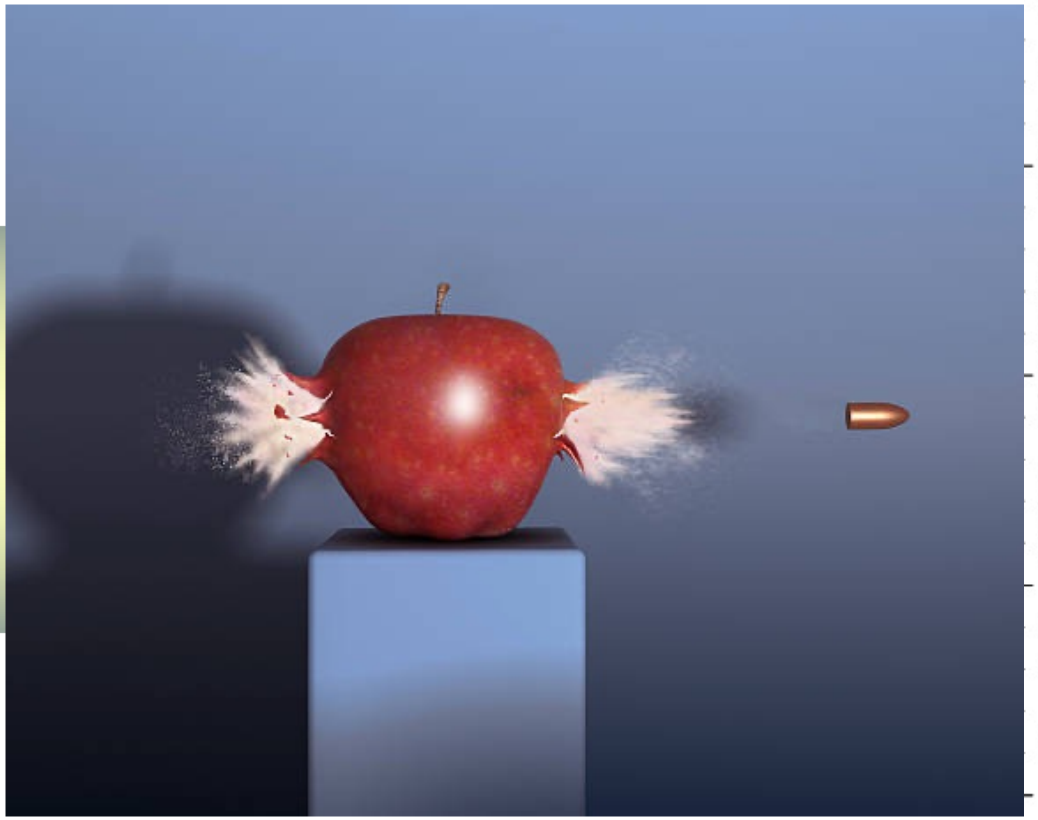

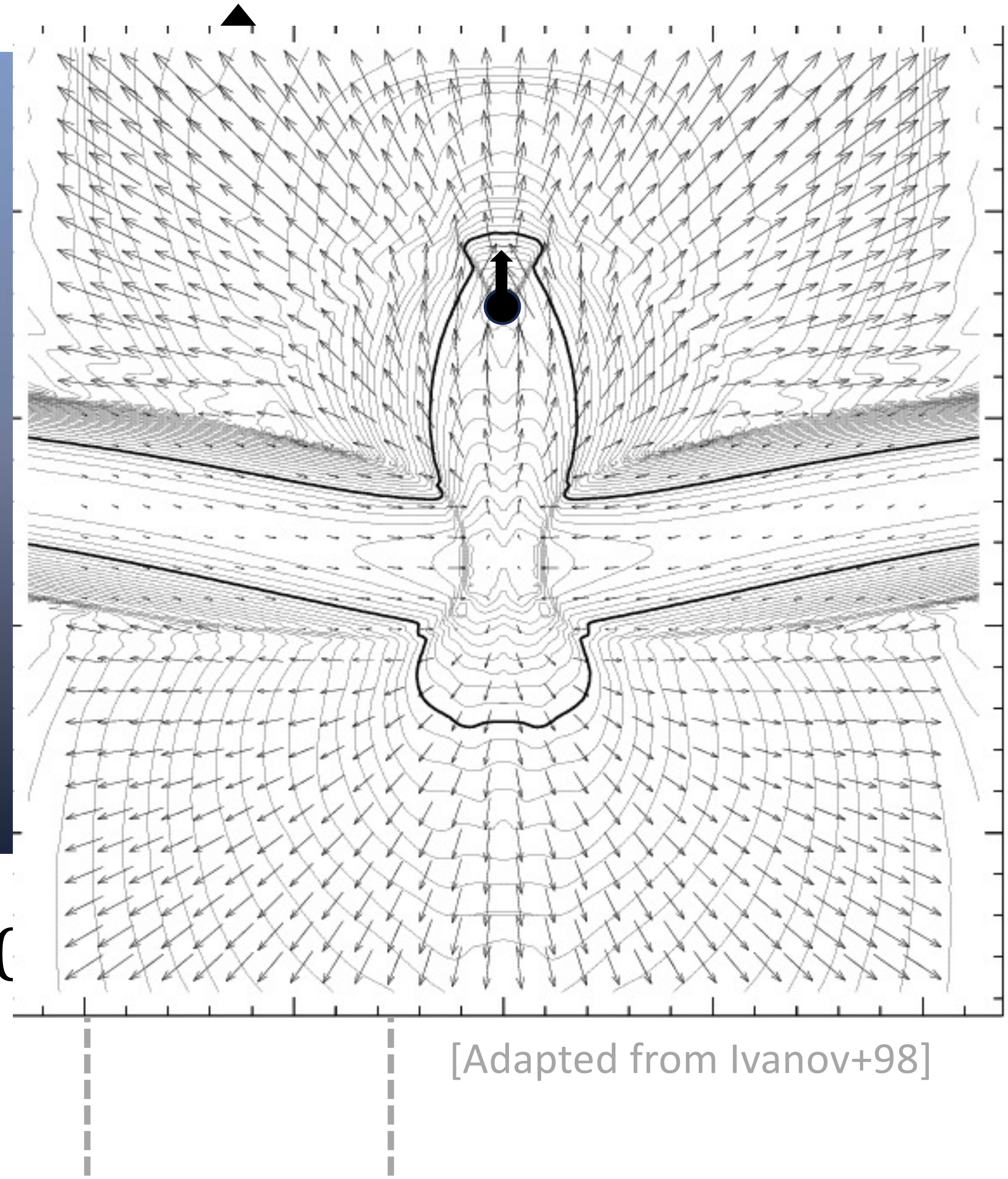

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[Adapted from Ivanov+98]

Radiation escape condition

$$t_{\rm diff} \approx t_{\rm dyn} \rightarrow \tau_{\rm peak} \approx \frac{c}{v_k} \sim 10$$

$$\tau(t) \approx \frac{\kappa_{\rm es} M_{\rm ej}}{4\pi (v_k t)^2}$$

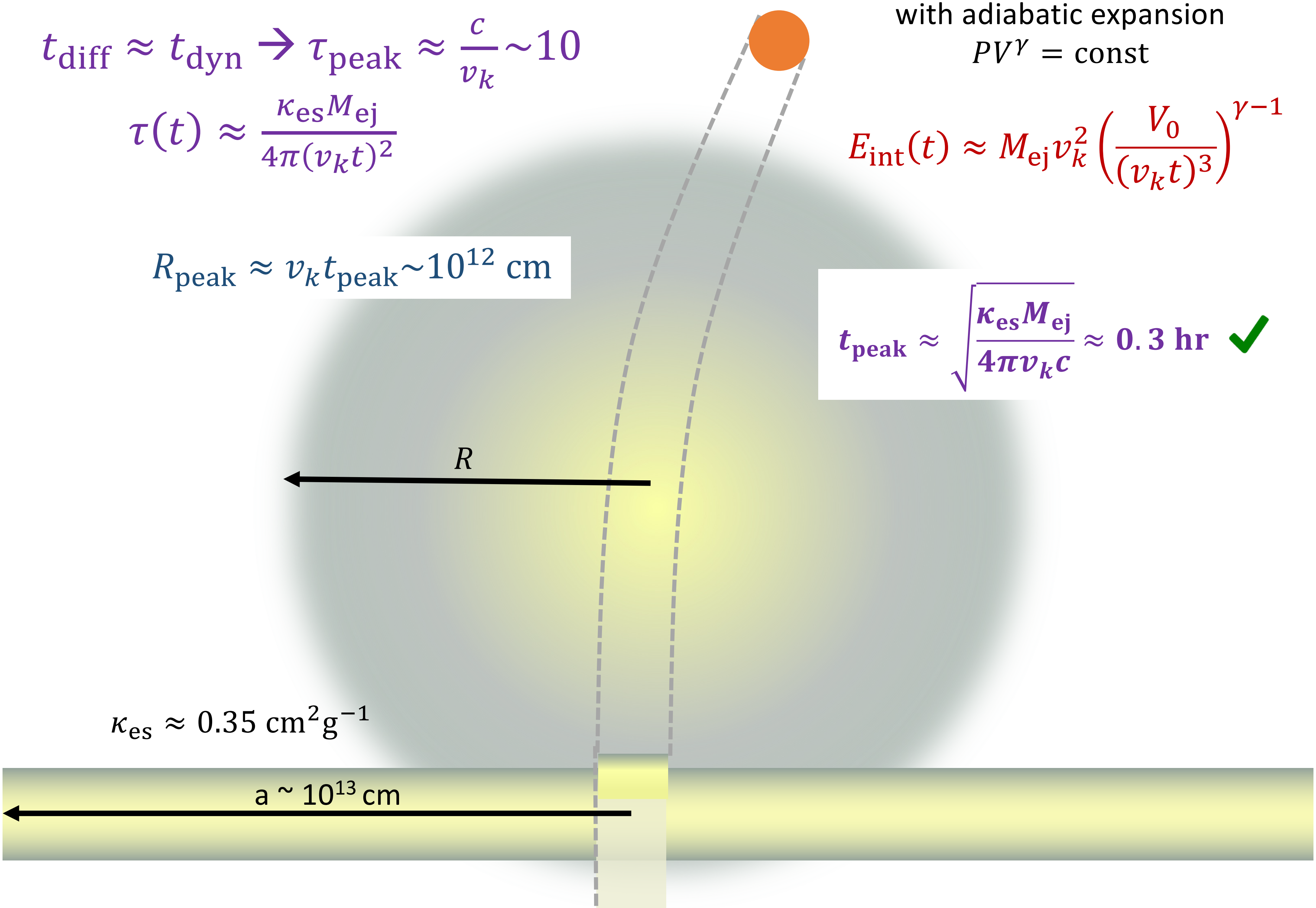
$$R_{\rm peak} \approx v_k t_{\rm peak} \sim 10^{12}\ {\rm cm}$$

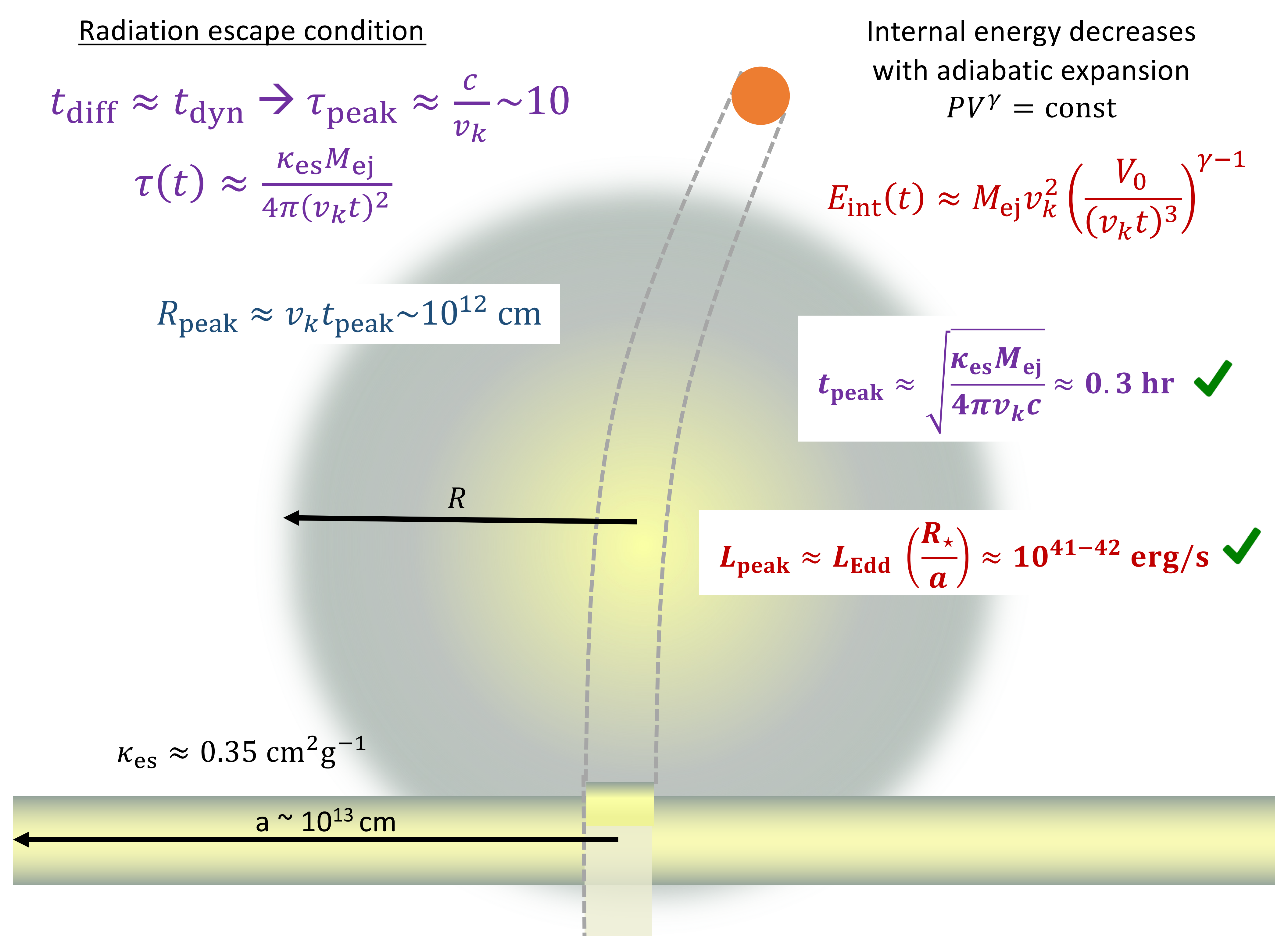
$$\kappa_{\rm es} \approx 0.35\ {\rm cm^2 g^{-1}}$$

Internal energy decreases
with adiabatic expansion
$PV^{\gamma} = {\rm const}$

$$E_{\rm int}(t) \approx M_{\rm ej} v_k^2 \left(\frac{V_0}{(v_k t)^3}\right)^{\gamma - 1}$$

$$t_{\rm peak} \approx \sqrt{\frac{\kappa_{\rm es} M_{\rm ej}}{4\pi v_k c}} \approx 0.3\ {\rm hr}\ ✓$$





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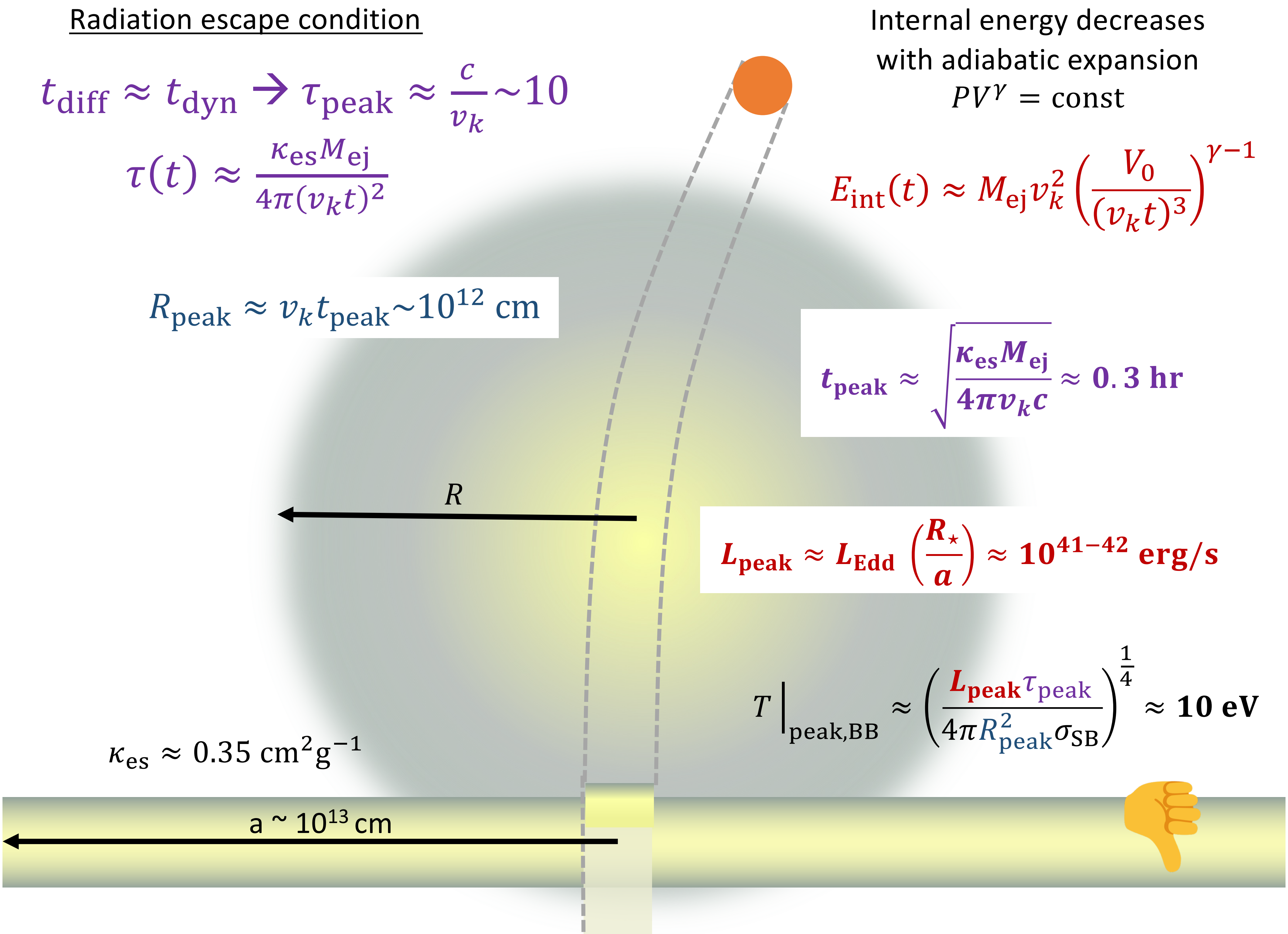
$\kappa_{\rm es} \approx 0.35\ \rm cm^2 g^{-1}$
a ~ 10^{13} cm



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$T\big|_{\rm peak,BB} \approx \left(\frac{L_{\rm peak} \tau_{\rm peak}}{4\pi R_{\rm peak}^2 \sigma_{\rm SB}}\right)^{\frac{1}{4}} \approx 10$ eV
$\kappa_{\rm es} \approx 0.35\ {\rm cm^2 g^{-1}}$
a ~ 10^{13} cm

Photon starved ejecta

[Weaver 76, Katz+09, Nakar & Sari 10]

Black body -- Thermal equilibrium -- Efficient photon production

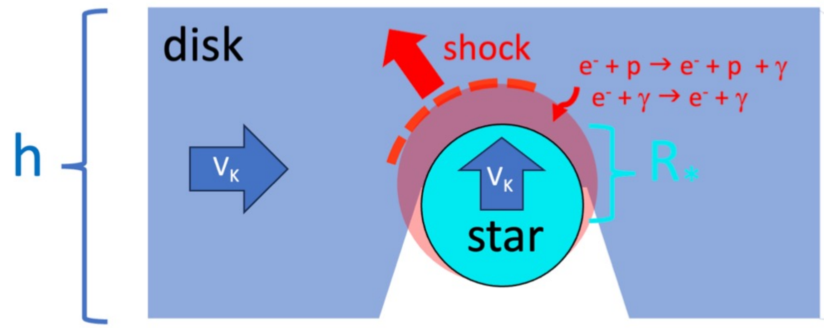
Number density of photons at equilibrium

$$n_{\rm BB} = aT_{\rm BB}^4 / k_{\rm B} T_{\rm BB}$$

$$\eta = \frac{n_{\rm BB}}{\dot{n}_{\rm ff}(T_{\rm BB}, \rho_{sh}) \times t_{\rm exp}} \gg 1$$

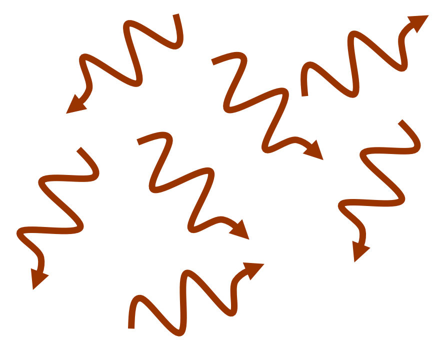
Photon production rate through Bremsstrahlung

star-disk passage (t ~ seconds)



Out of thermal equilibrium

Fewer photons share the same energy density



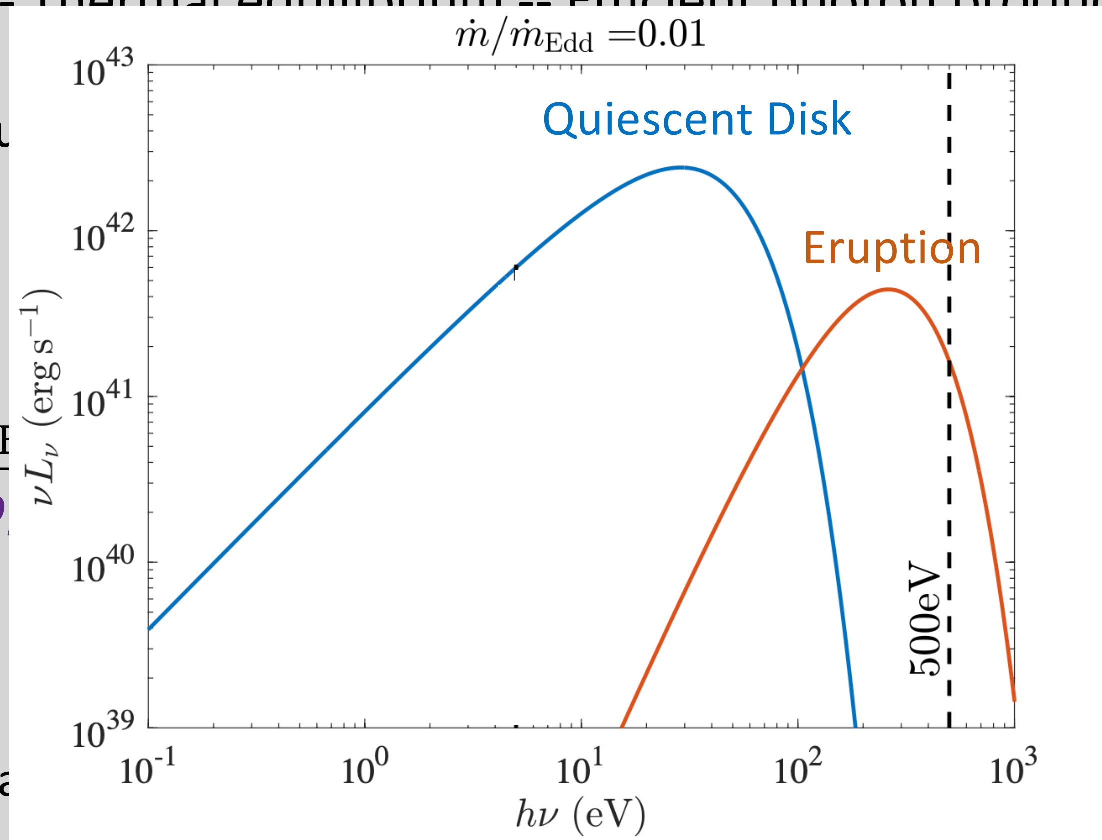
✔ $k_{\rm B} T_{\rm obs} \approx k_{\rm B} T_{\rm BB} \times \eta^2 > 100 \text{ eV}$

Photon starved ejecta

[Weaver 76, Katz+09, Nakar & Sari 10]

Black body -- Thermal equilibrium -- Efficient photon production

Nu

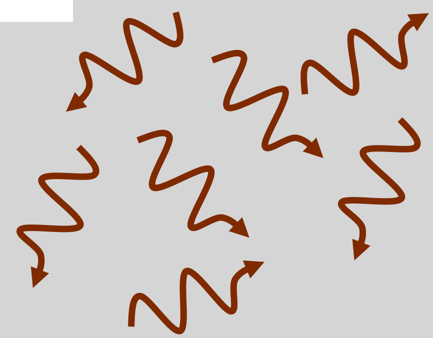


$\eta = \frac{n_{\rm BB}}{\dot{n}_{\rm ff}(T_{\rm BB}, \rho}$

Photon production ra

photons share the

e energy density



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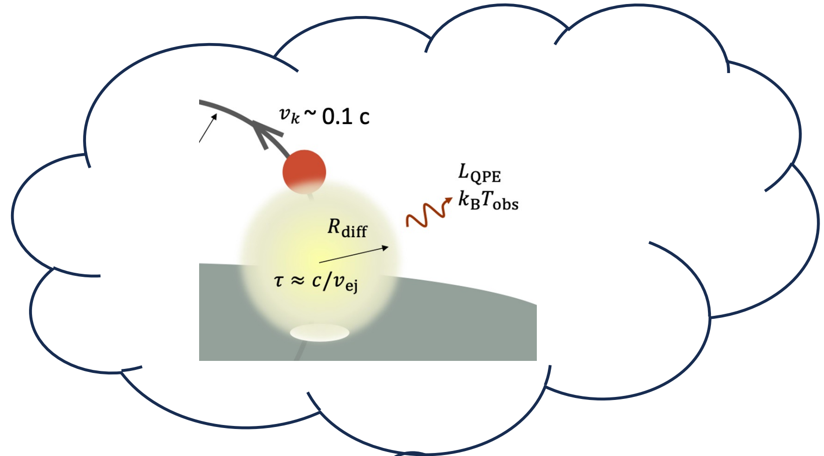
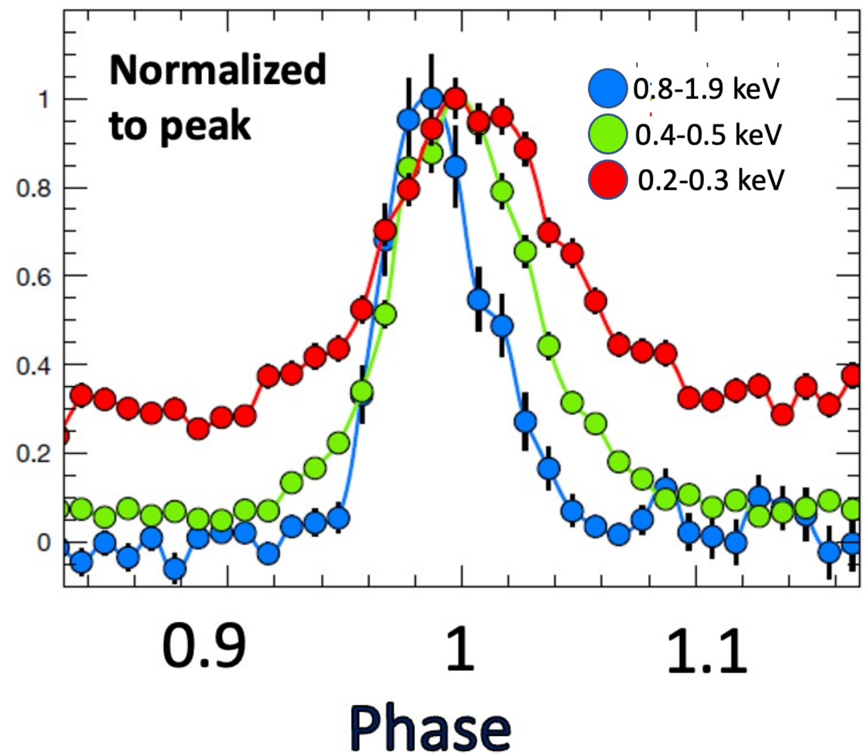
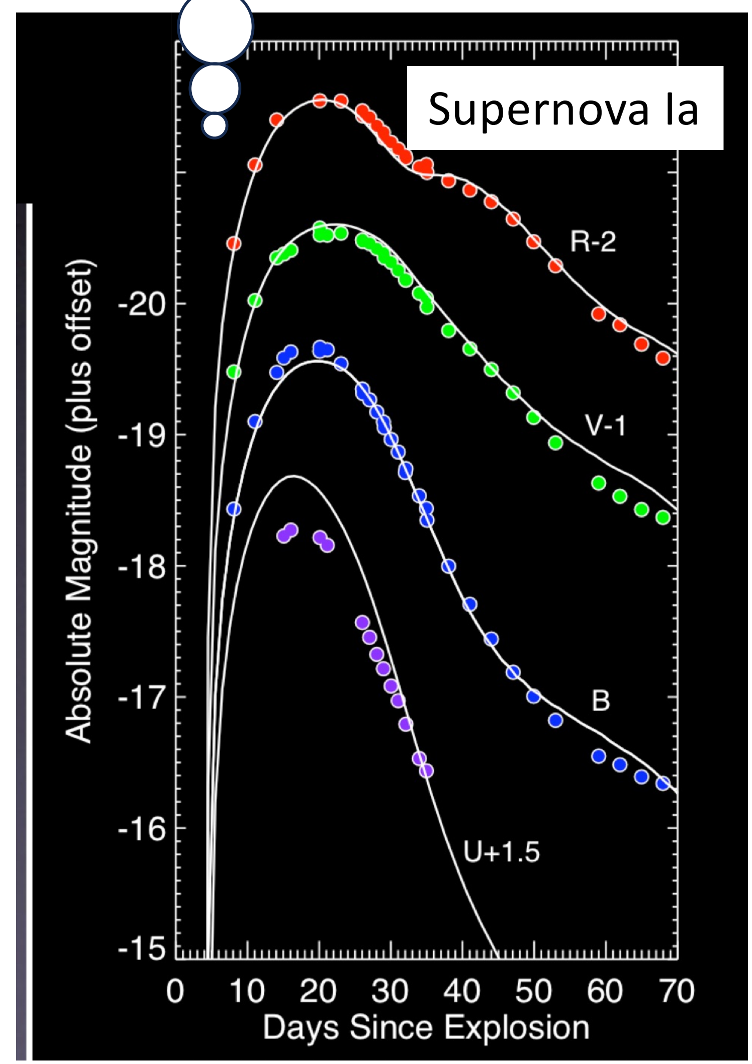
“X-ray supernovae”



Harder bands:

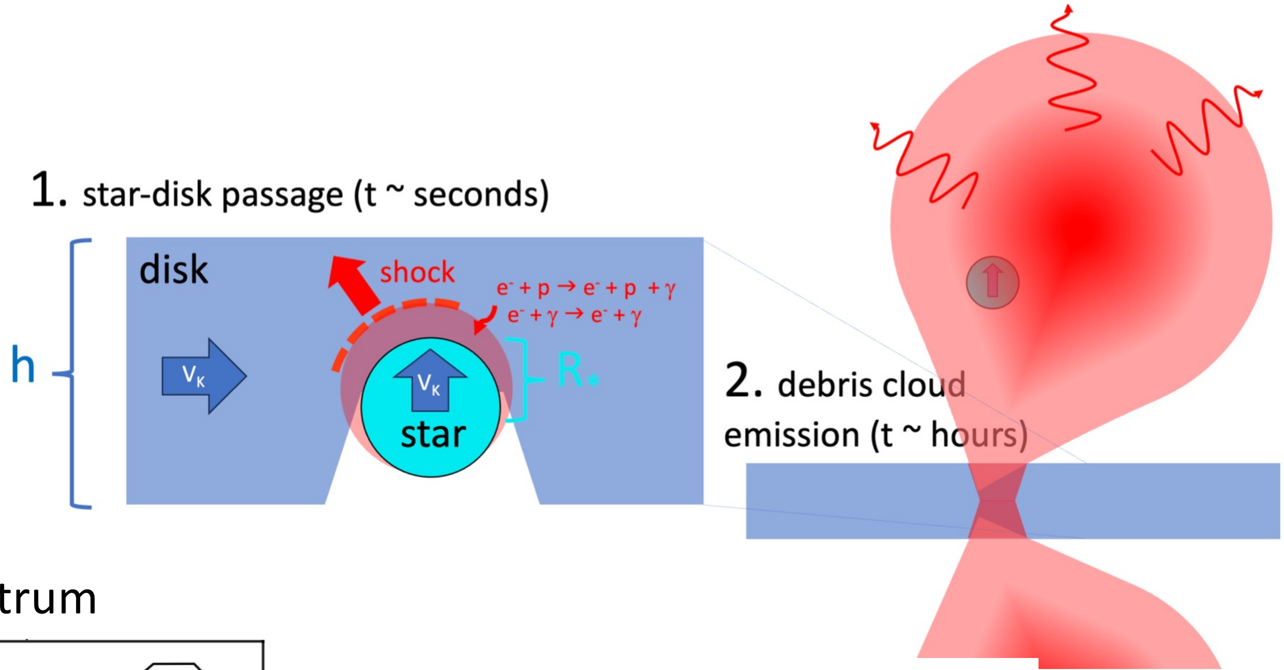
- peak earlier,
- decay faster



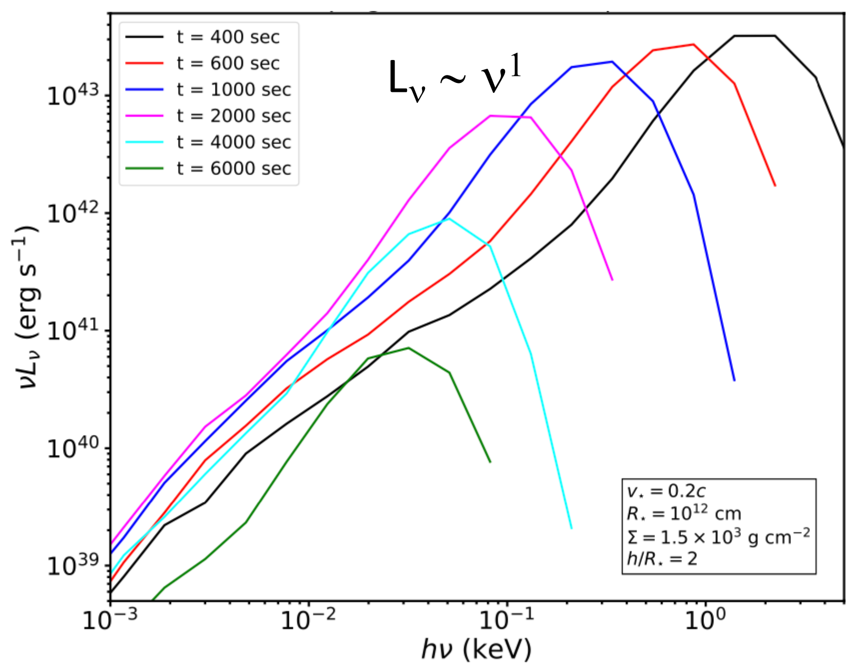


MC Radiation-hydrodynamic simulations

(photon production, diffusion, Comptonization, etc.)

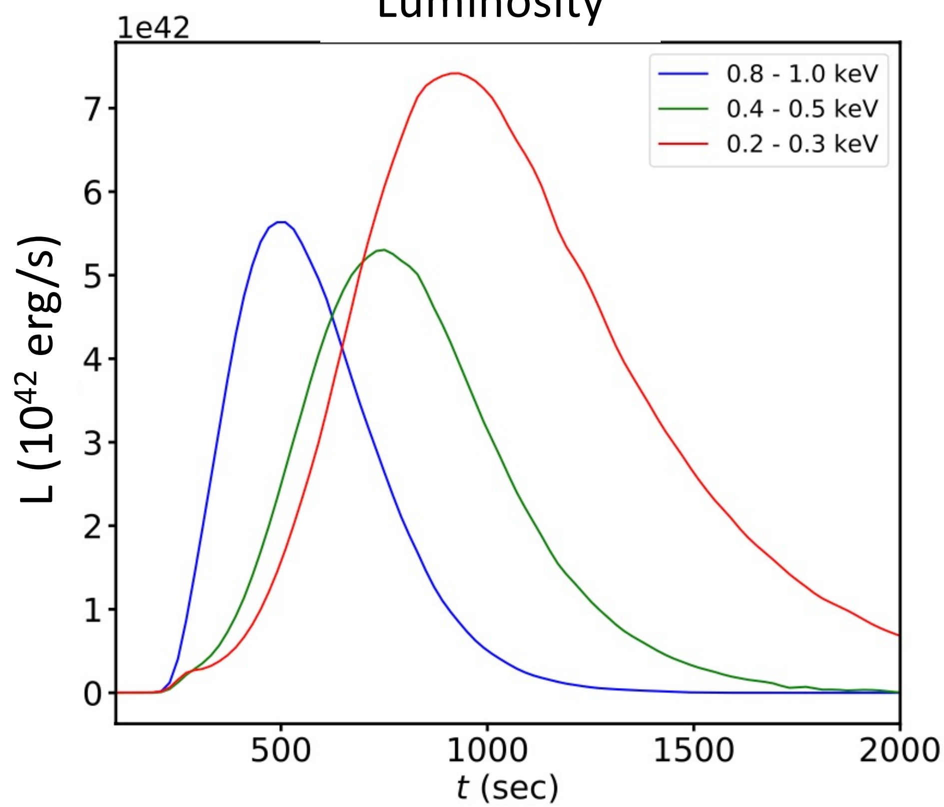


Escaping Spectrum



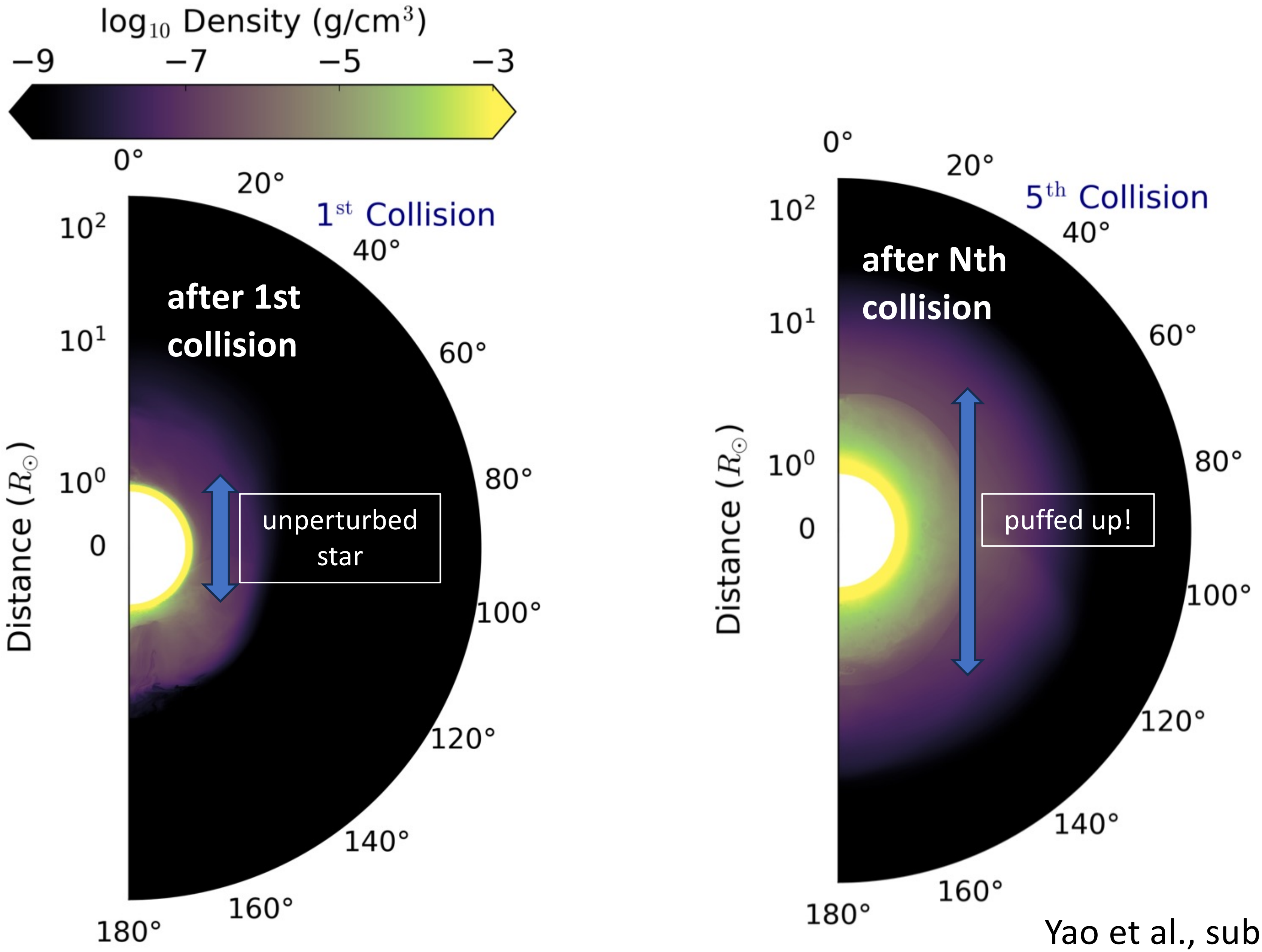
$R_* \sim 10 R_\odot$!

Luminosity



Vurm, Linial, BDM, in prep

Star is perturbed + inflated!

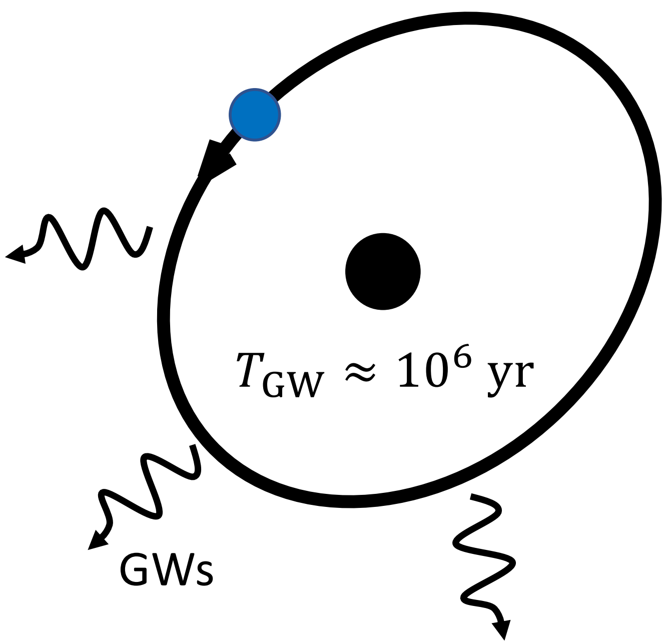


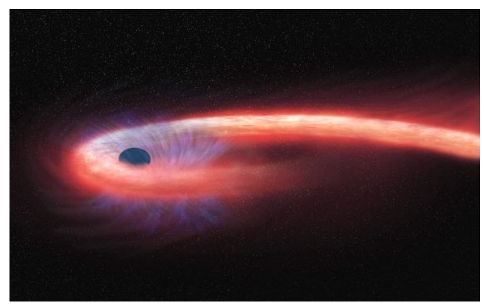
Yao et al., submitted

QPE-TDE Association

“EMRI + TDE = QPE”

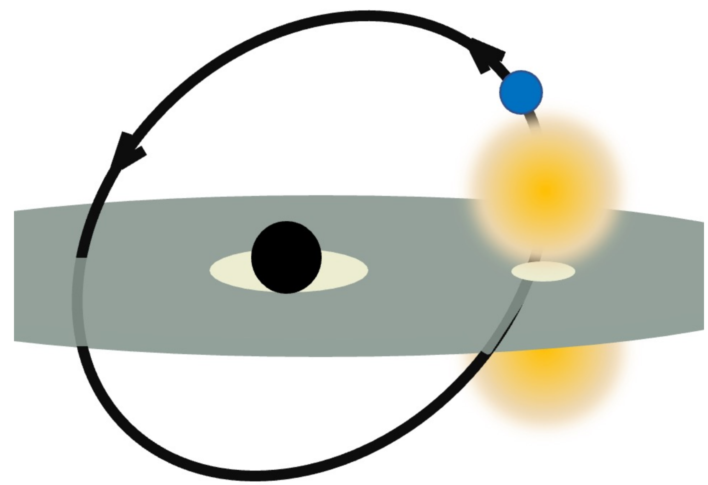
(Linial & BDM 23)





$R_{TDE} \approx 10^{-4}\ \mathrm{yr}^{-1}$

“every EMRI experiences at least one TDE”



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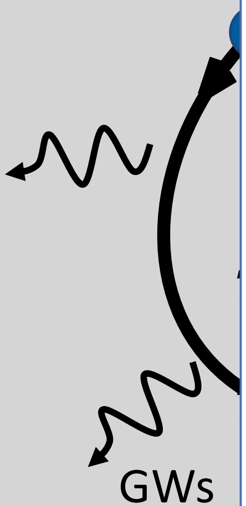
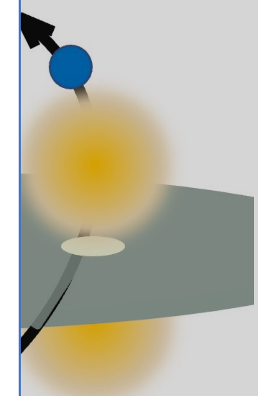
"EMRI + TDE = QPE"

(Linial & BDM 23)





TDE rate $\dot{N}_{\rm TDE} \sim 10^{-4}\,{\rm yr}^{-1}$

EMRI rate (Hills) $\dot{N}_{\rm EMRI} \sim 10^{-5}\left(\frac{f_{\rm bin}}{0.1}\right)\,{\rm yr}^{-1}$

Fraction of TDE with QPE:

$$f_{\rm TDE} \sim \frac{\dot{N}_{\rm EMRI}}{\dot{N}_{\rm TDE}} N_{\rm TDE} \sim 0.1 N_{\rm TDE}$$

TDEs an EMRI survives

$\Rightarrow$ QPE-TDE associations should be common!

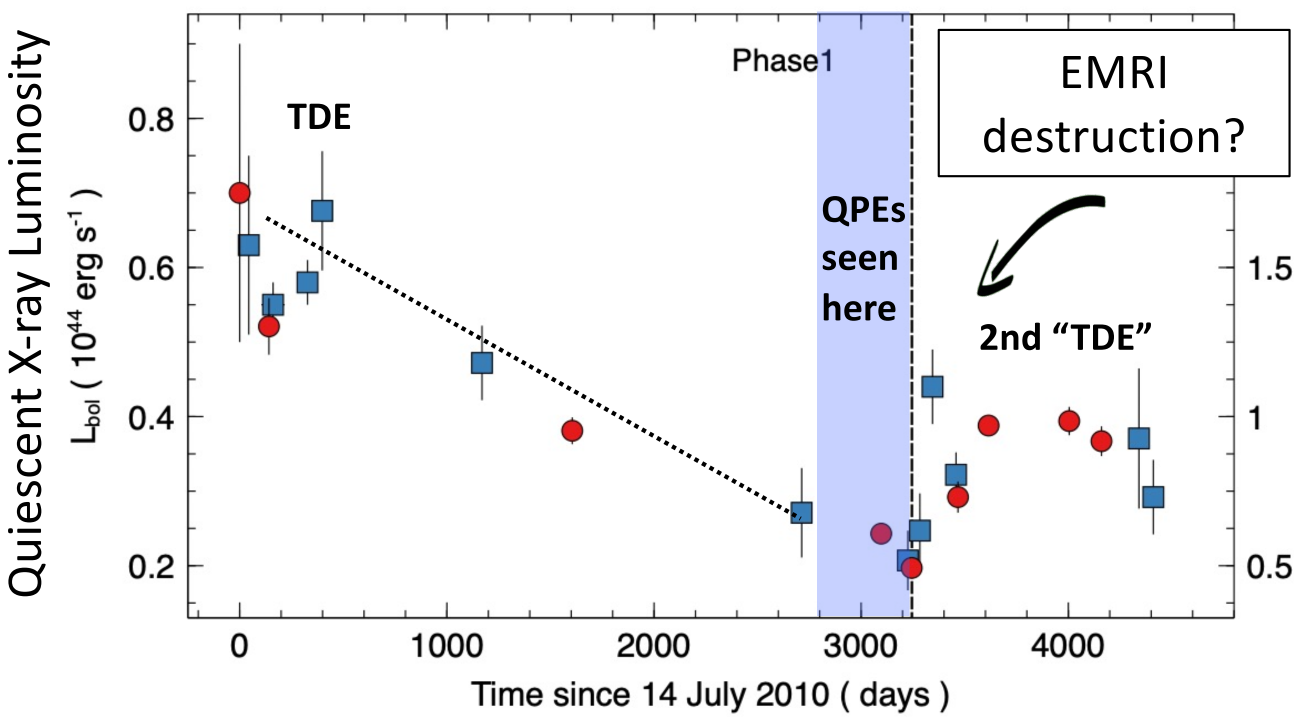
(confirmed! Nicholl et al., in prep)

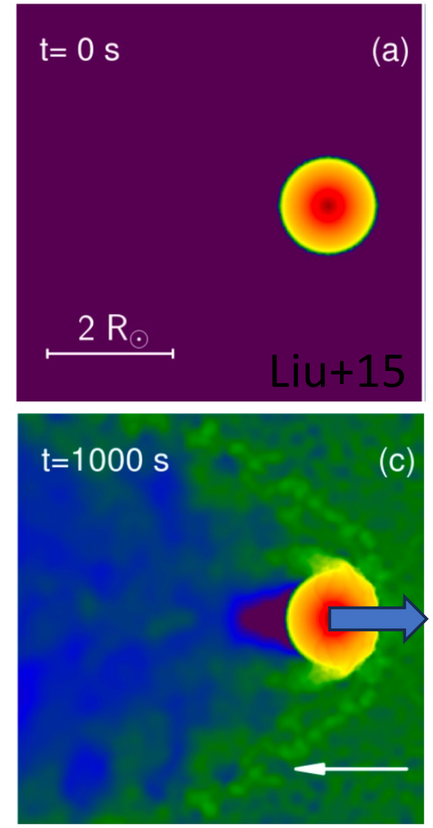
EMRI destruction by ram-pressure stripping

Mass-loss per collision $$\frac{\Delta M_\star}{M_\star} \sim 10^{-3}\left(\frac{p_{\rm ram}}{p_\star}\right) \approx 5\times10^{-7}\frac{\mathcal{R}_\star^4 \mathcal{T}_{\rm QPE,4}^{1/3}}{\alpha_{-1}\mathcal{M}_\star^2 M_{\bullet,6}^{4/3}\dot{m}_{-1}^2}$$

After TDE: $\dot{m} \propto t^{-5/3}$

Destruction time $$\tau_{\rm dest} \approx 24.7\,{\rm yr}\,\frac{\alpha_{-1}^{3/13}(\mathcal{M}_\star^{\rm 2nd})^{34/65}\mathcal{M}_\star^{6/13}\mathcal{T}_{\rm QPE,4}^{2/13}}{\mathcal{R}_\star^{12/13}}$$



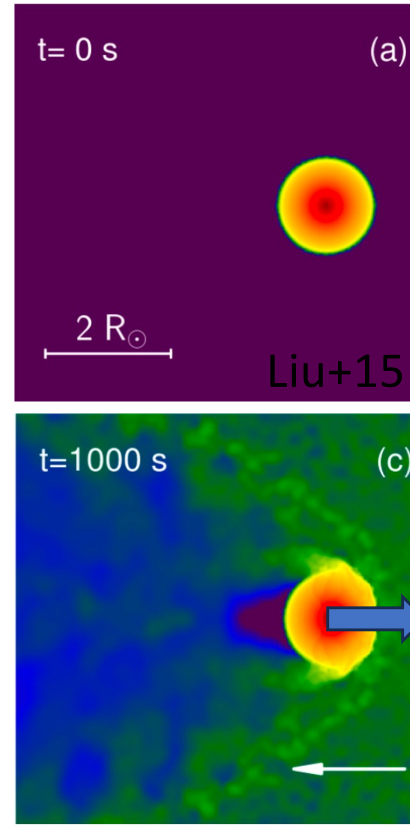


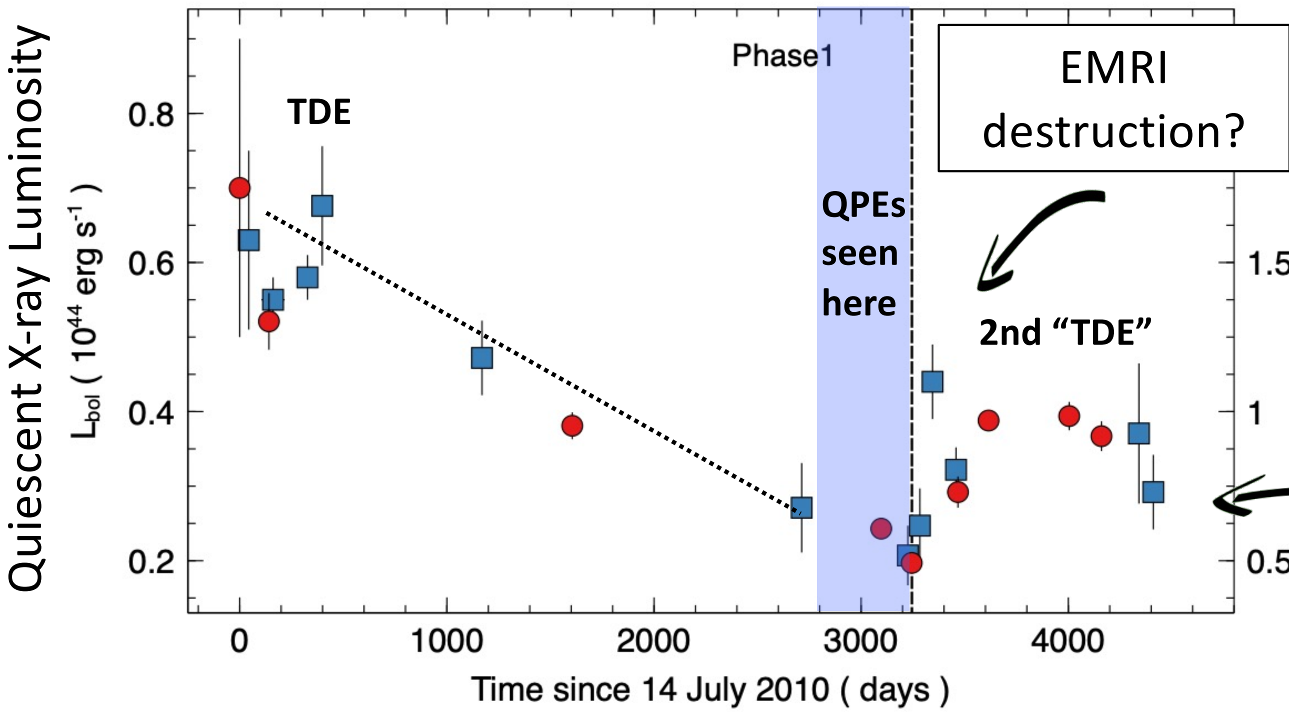
EMRI destruction by ram-pressure stripping

Mass-loss per collision $\frac{\Delta M_\star}{M_\star} \sim$

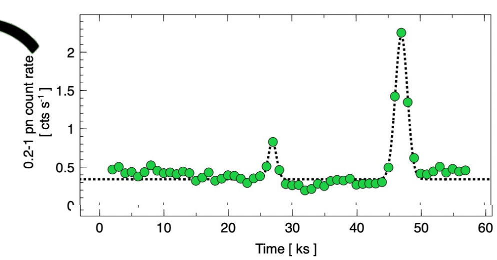
After TDE: r

Destruction time $\tau_{\rm dest} \approx 2$





Miniutti+23



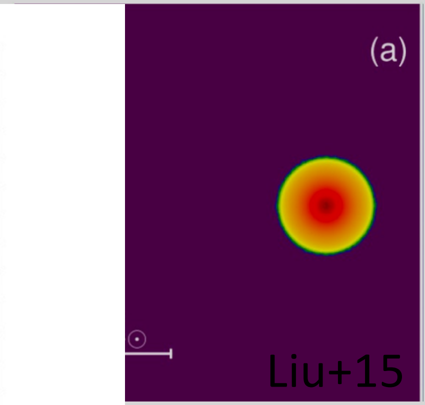
EMRI destruction by ram-pressure stripping

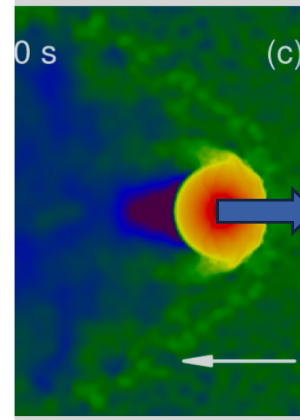
Mass-loss
per collision

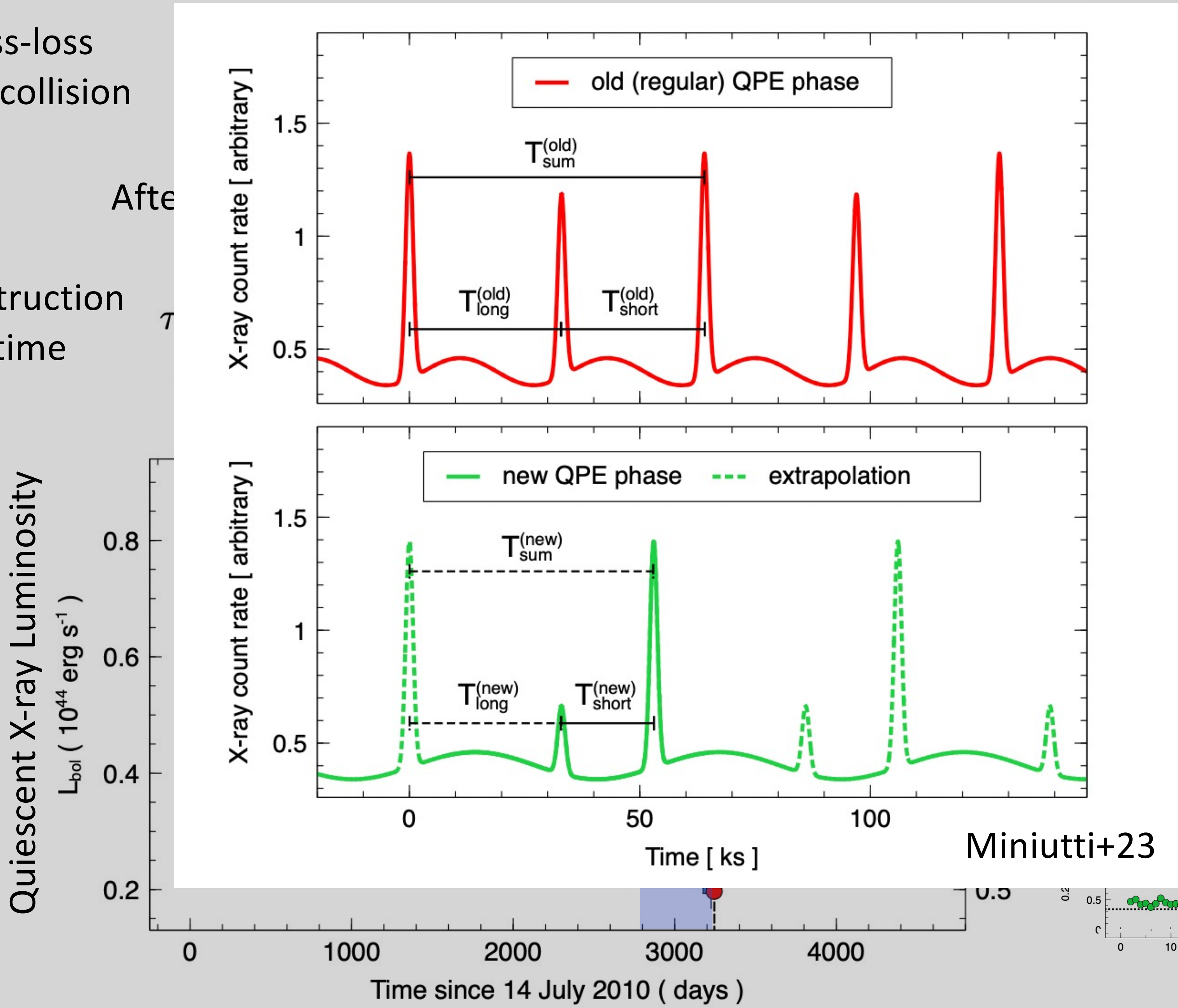
Afte

Destruction
time

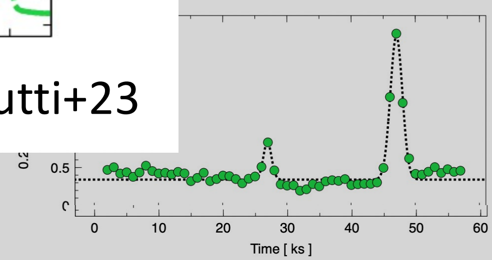
τ







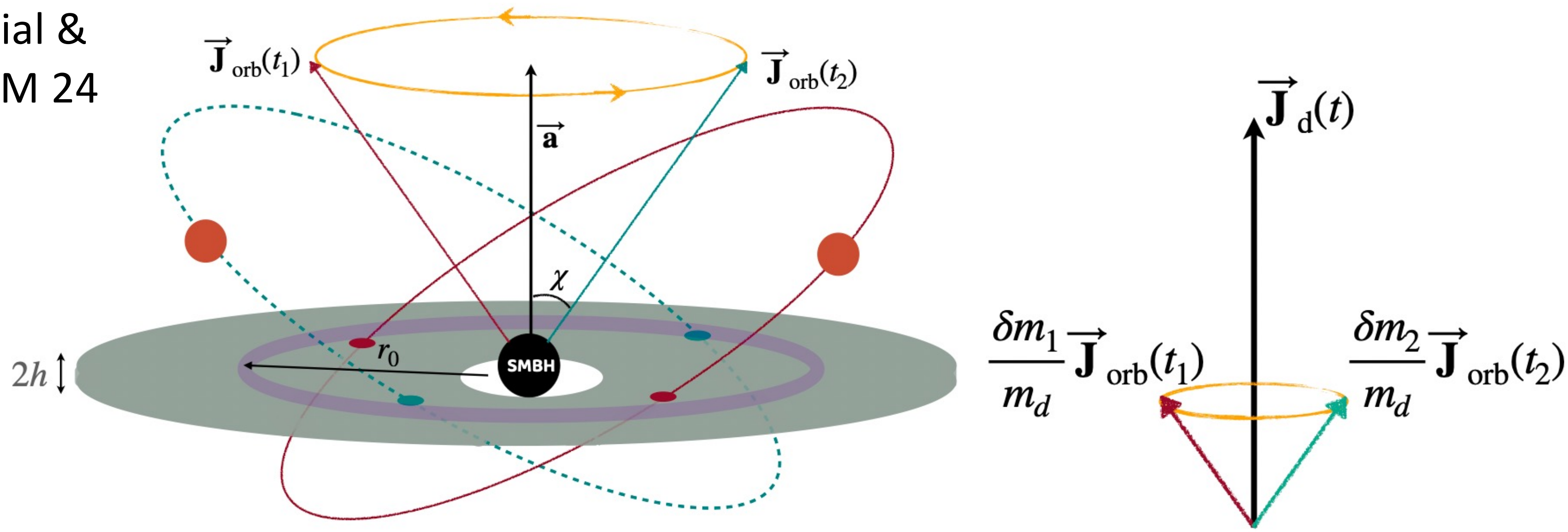
Miniutti+23



Star-collision-fed accretion disks?

Mass-stripping rate comes to exceed $\dot{M}_{TDE}$
=> disk fed by stellar stripping?

Linial & BDM 24

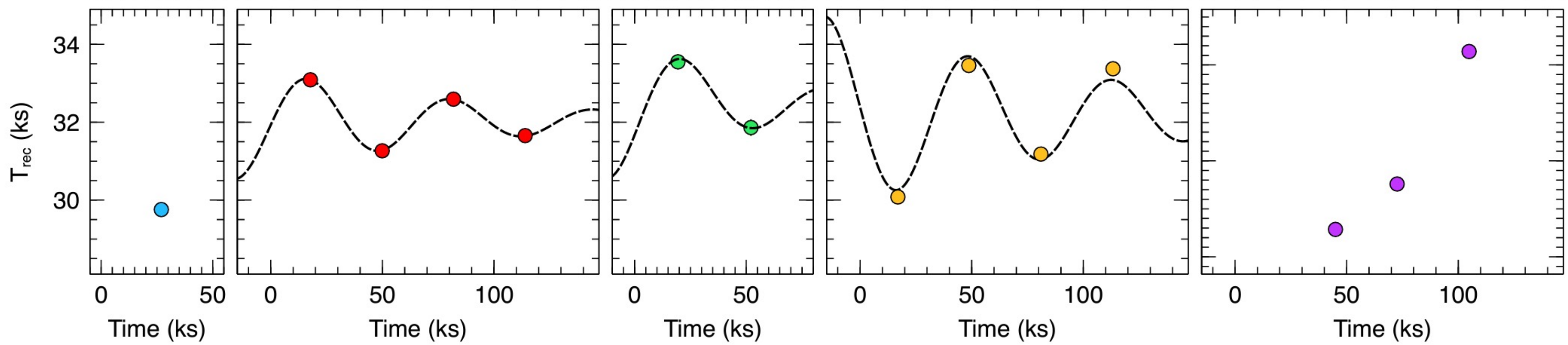


Steady-state accretion rate

$$\frac{\dot{M}_{\rm acc}}{\dot{M}_{\rm Edd}} = \frac{0.07}{1+\frac{8}{3}\beta}\left(\frac{\eta_{-3}\xi_{\rm v}^2}{\alpha_{-1}}\right)^{1/3}\frac{\mathcal{R}_\star^{4/3}}{\mathcal{M}_\star^{1/3}}\mathcal{P}_{\rm QPE,4}^{-2/9}M_{\bullet,6}^{-7/9}$$

$$\tau_{\rm dest} \approx \frac{9}{16}\frac{M_{\star,0}}{\dot{M}_{\rm acc}} \approx 320\,{\rm yr}\left(1+\frac{8}{3}\beta\right)\left(\frac{\alpha_{-1}}{\eta_{-3}\xi_{\rm v}^2}\right)^{1/3}\frac{\mathcal{M}_\star^{4/3}}{\mathcal{R}_\star^{4/3}}\mathcal{P}_{\rm QPE,4}^{2/9}M_{\bullet,6}^{-2/9}$$

Flare timing…



Modulated over the…

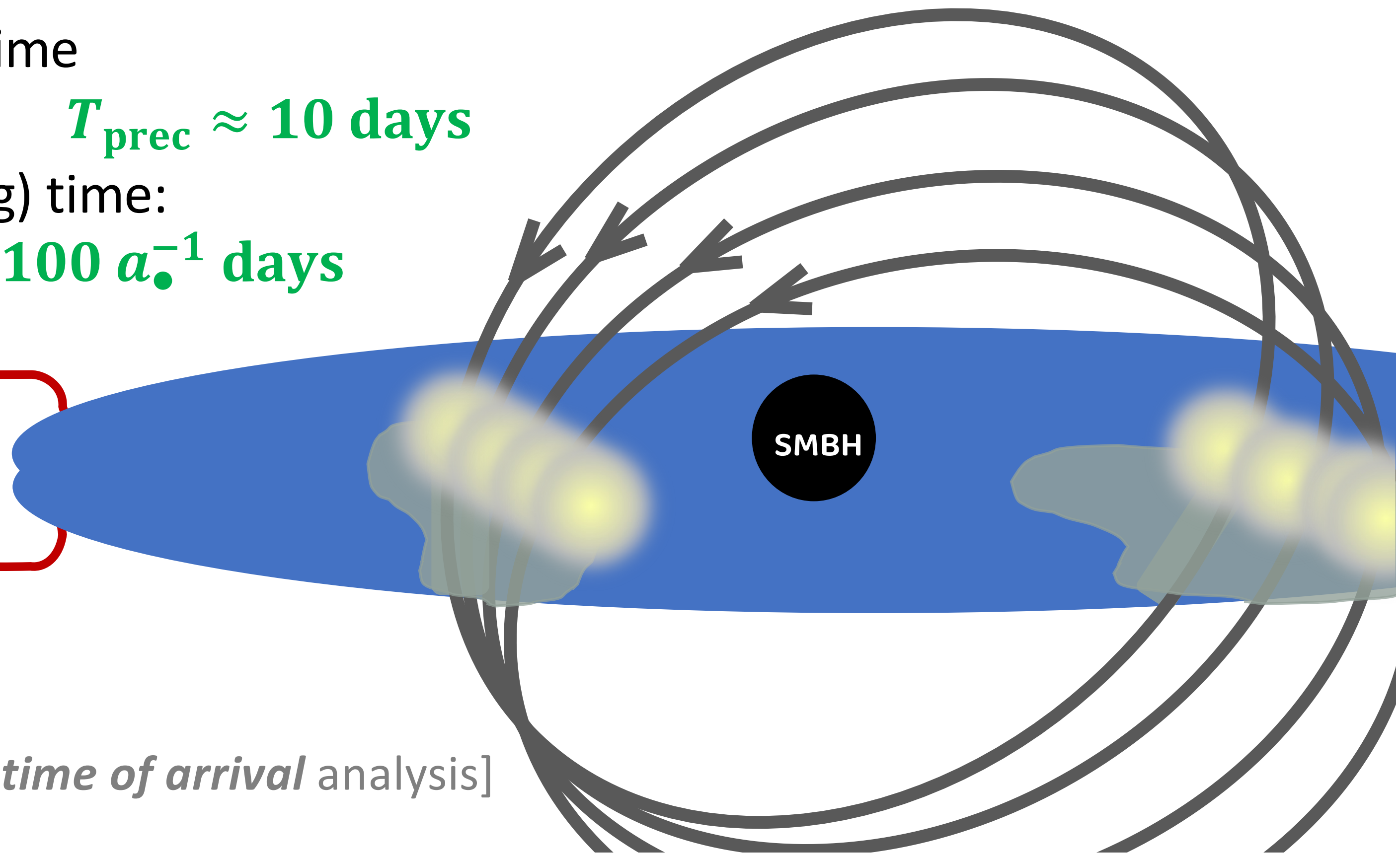
Apsidal precession time

$$T_{\mathrm{prec}} \approx 10 \text{ days}$$

Nodal (Lense-Thirring) time:

$$T_{\mathrm{LT}} \approx 100\, a_\bullet^{-1} \text{ days}$$

Inferring SMBH spin?



[e.g. Xian+21, Franchini+23 for ***time of arrival*** analysis]

Summary

- A star gradually spirals into a galactic nucleus via GW emission
- An independent TDE occurs, creating an accretion disk which radially overlaps but is misaligned with the EMRI orbit
- Twice per-orbit collisions between star and disk generate powers hot ejecta and (quasi-)periodic flares visible over the cooler disk => **X-ray QPEs**
- In some systems the flares can also outshine the disk in the UV, predicting "UV QPEs" (ULTRASAT/UVEX targets?)
- Star is perturbed (puffed up) by repeated collisions and loses substantial mass per orbit, feeding and sustaining the disk longer than an isolated TDE.
- Over decades the star may eventually be destroyed by mass ablation, perhaps giving rise to a luminous final transient (not yet observed).
- Almost all EMRIs should experience a TDE and a sizable fraction of TDEs should host EMRI/QPEs.
- QPEs provide new probes of dynamical processes in galactic nuclei (e.g. LISA GW sources) and potentially strong gravity effects
- Application to BH-disk collisions (e.g. binary AGN candidates like OJ287)