Dynamics and Energetic Transients in Galactic Nuclei

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with
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NASA Hubble Fellowship Program

INSTITUTE FOR ADVANCED STUDY

THEORETICAL HIGH ENERGY ASTROPHYSICS

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

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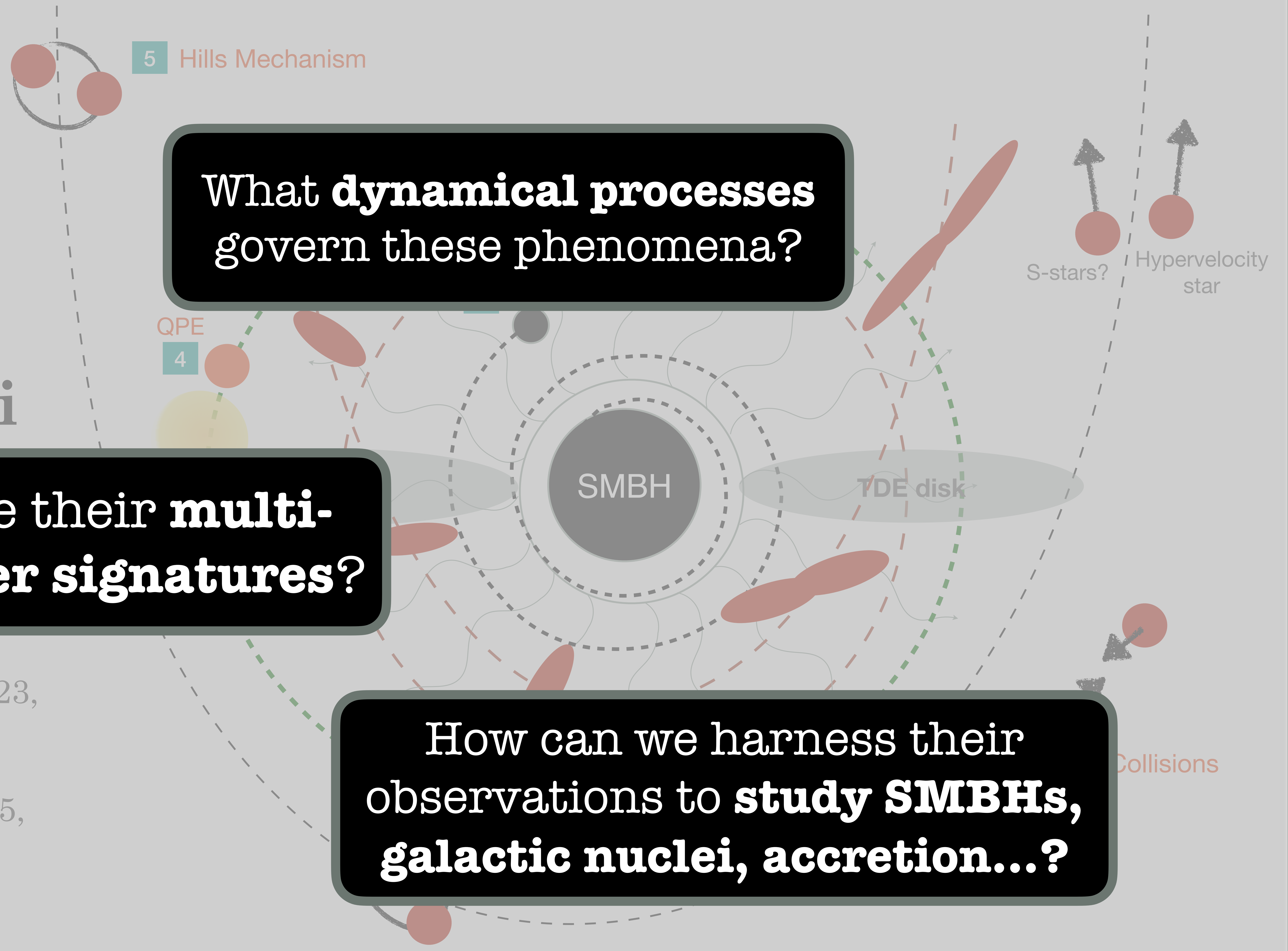
GRUBER FOUNDATION

Outline

- High energy processes in Galactic Nuclei
- Formation channels and rates
- **TAKEAWAY** - Stars on tight orbits around SMBHs are ubiquitous
- Manifestations of a stellar-EMRI near an SMBH
- **TAKEAWAY** - Some observed galactic nuclei transients may be powered by such stellar EMRIs

High-Energy Phenomena in Galactic Nuclei



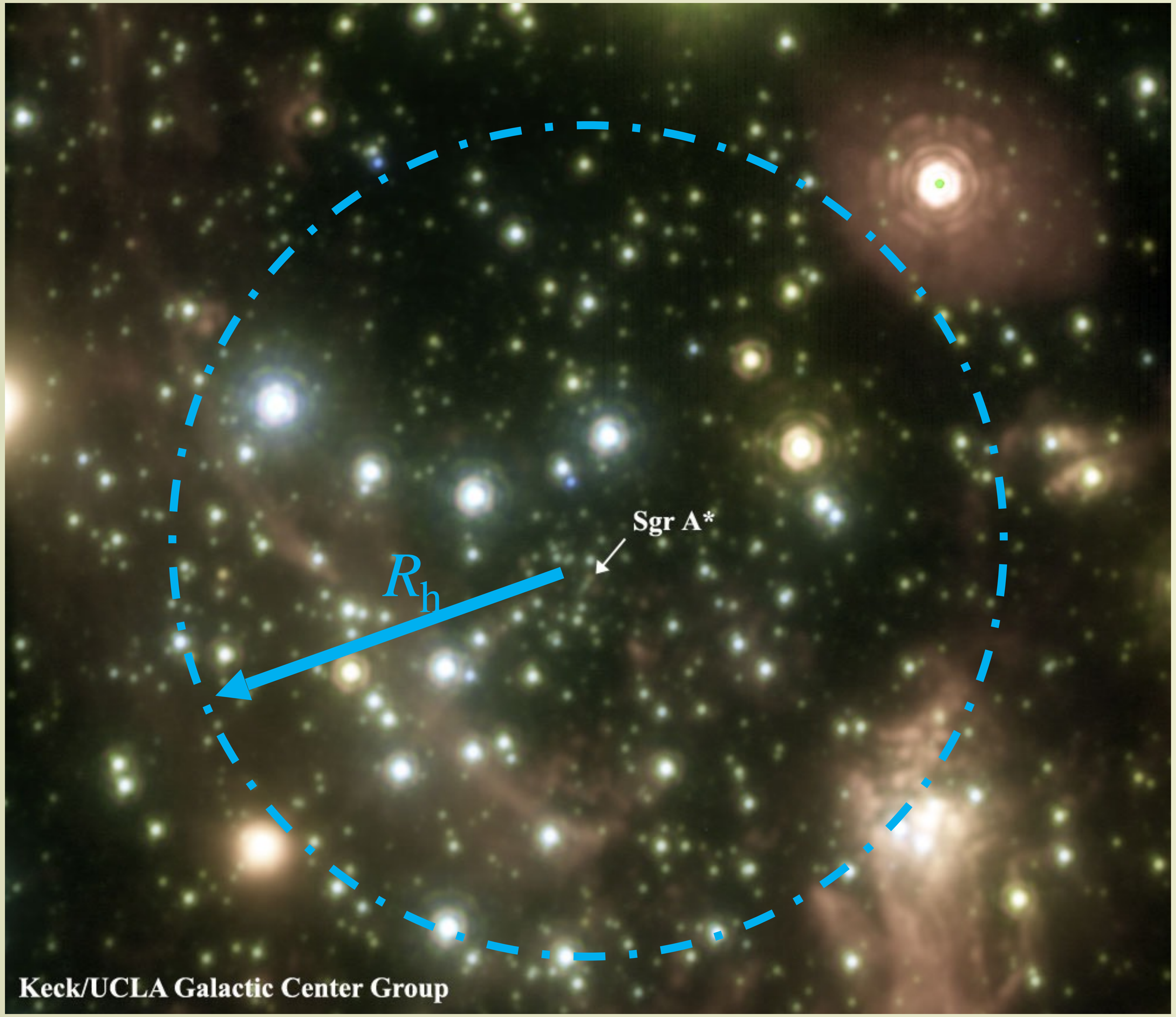
What **dynamical processes** govern these phenomena?

What are their **multi-messenger signatures**?

How can we harness their observations to **study SMBHs, galactic nuclei, accretion…?**

[Linial & Sa
Krolik & Linial 22,
Rose, Naoz, Sari & Linial 22,23,
Linial & Metzger 23,24a,b,
Linial & Quataert 24a,b,
Linial, Metzger & Quataert 25,
Rom, Linial et al. 24,
Huang, Linial et al. 25.
Martire, … Linial 26]

Galactic Nuclei: Millions of stars & one Supermassive Black Hole



Supermassive Black Hole

$$M_{\rm BH} \approx 10^5 - 10^9\ \mathrm{M}_\odot$$

Radius of Influence:

$$R_{\rm h} \approx \mathcal{O}(1) \times \mathrm{pc}$$

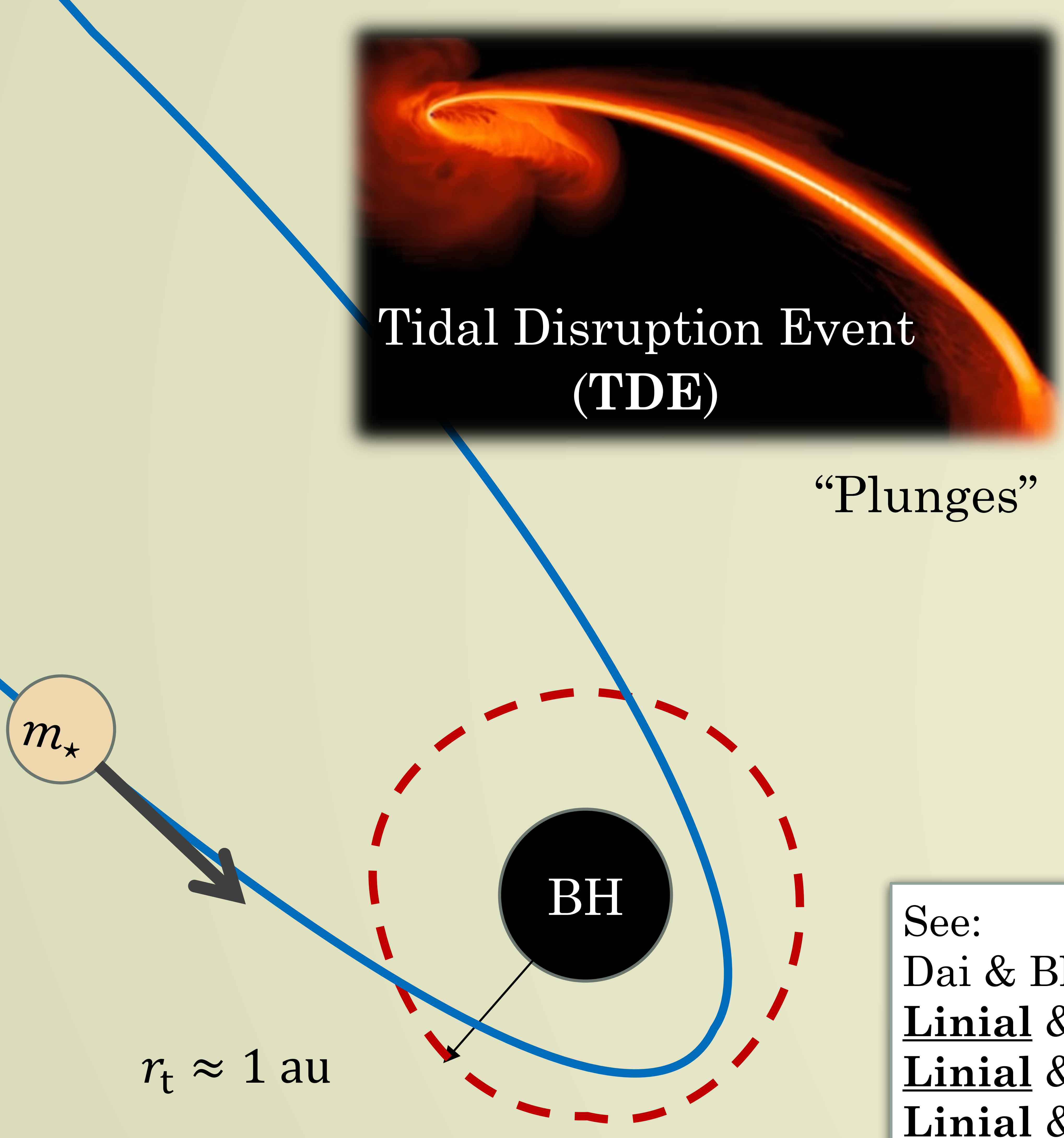
$$M_{\rm tot}(r \le r_{\rm h}) = 2\, M_{\rm BH}$$

Stars & Stellar remnants

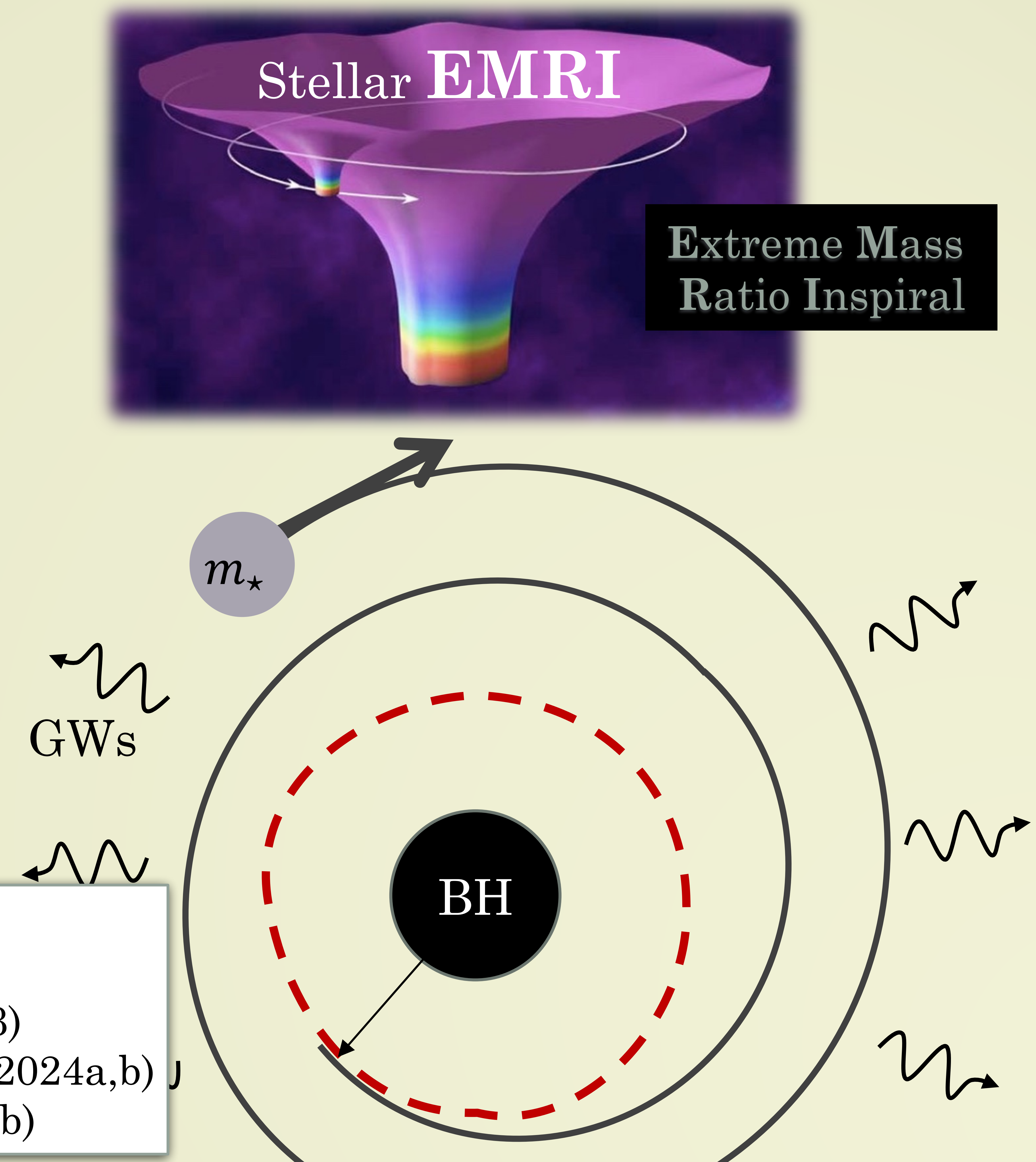
$$N_\star \approx M_{\rm BH} / \langle m_\star \rangle \approx 10^{5-9}$$

Two Flavors of Stellar Destruction

Scattering dominated:



Gravitational Wave (GW) dominated:



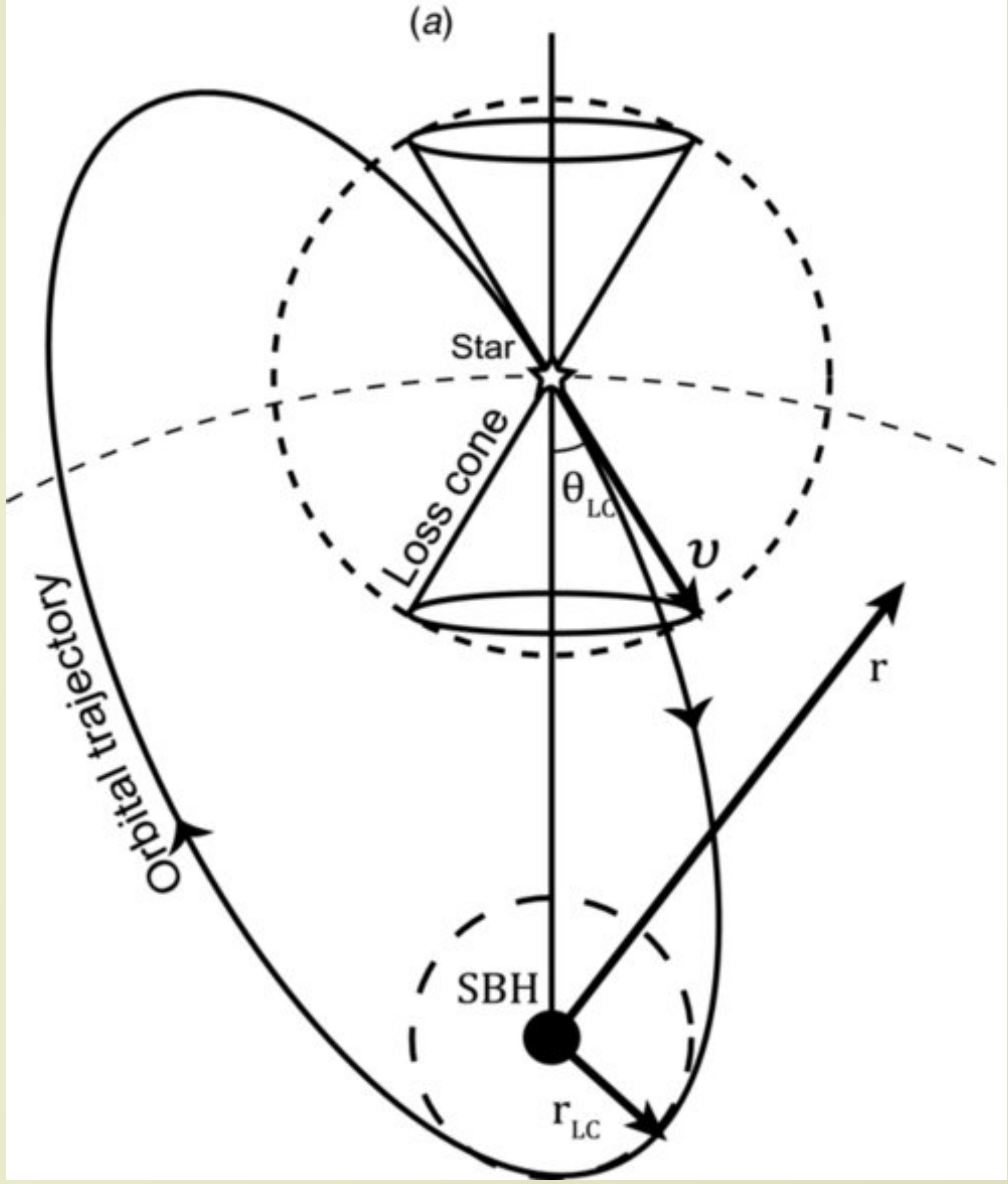
See:
Dai & Blandford (2013)
Linial & Sari (2017,2023)
Linial & Metzger (2023,2024a,b)
Linial & Quataert (2024b)

The Loss Cone Problem in Galactic Nuclei

- **<u>Critical radius</u>** (e.g., tidal disruption): $r_{\rm lc}$

  $r_{\rm p} \lesssim r_{\rm lc} \rightarrow J \lesssim \sqrt{2GM_{\bullet} r_{\rm lc}}$

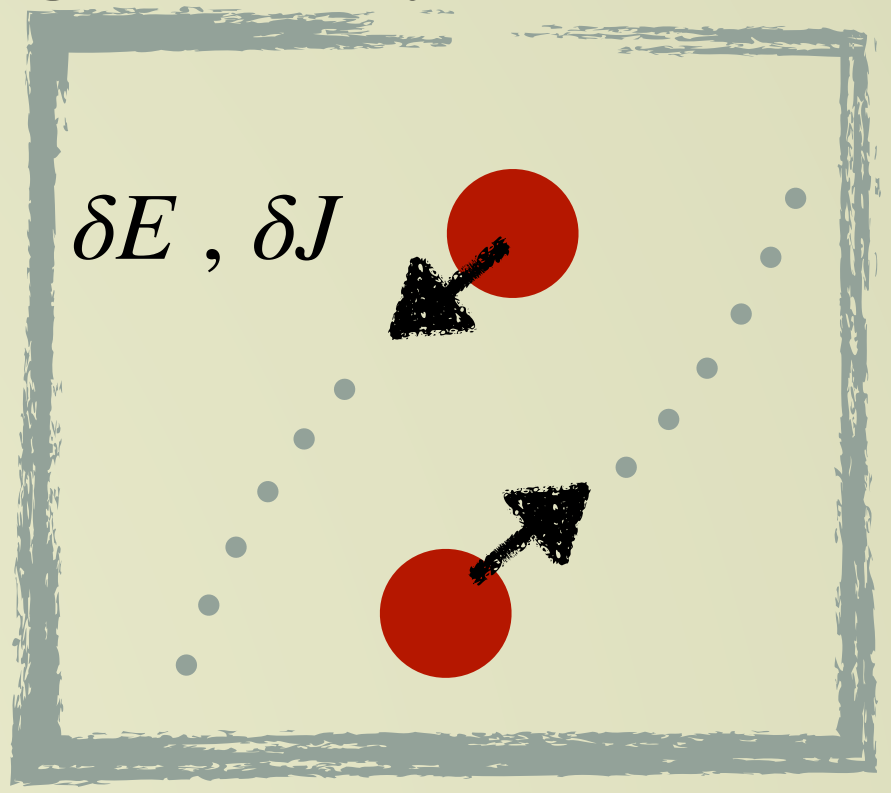
- **<u>Spherical symmetry: *J* conserved</u>**
  <u>Angular Momentum Relaxation</u>
  - Stochastic, 2-body scattering [Cohn & Kulsrud 78']
  - Resonant interaction [Rauch & Tremaine 96']
    (coherence time — long apsidal/nodal precession)
- **<u>Full vs. Empty Loss Cone (Rapid vs. Slow *J* Relaxation)</u>**
- **<u>Additional Processes:</u>**
  - Non-spherical potential due to stellar cluster:
    Orbits torqued to low *J* "collisionlessly"
    [Tremaine & Magorrian 99', Vasiliev & Merritt 13', Kaur & Stone 24']
  - Dissipation due to GWs, gas drag [Bar-Or & Alexander 15']
  - Direct collisions [Rose, **<u>Linial</u>** et al. 22', Balberg & Yasur 24']
  - Mass segregation [**<u>Linial</u>** & Sari 22', Rom & Sari 24']



Adapted From Merritt (2013)

Diffusion in Integrals of Motion

e.g., 2-body relaxation



(Orbit-Averaged) Fokker-Planck Equation

$$\frac{df}{dt} = \Gamma\left[f\right]$$

"Collisions"

$$\frac{\partial f(E,J,t)}{\partial t} + \frac{\partial}{\partial E}\left(D_E\, f - D_{EJ}\frac{\partial f}{\partial J} - D_{EE}\frac{\partial f}{\partial E}\right) + \frac{\partial}{\partial J}\left(D_J f - D_{JE}\frac{\partial f}{\partial E} - D_{JJ}\frac{\partial f}{\partial J}\right) = 0$$

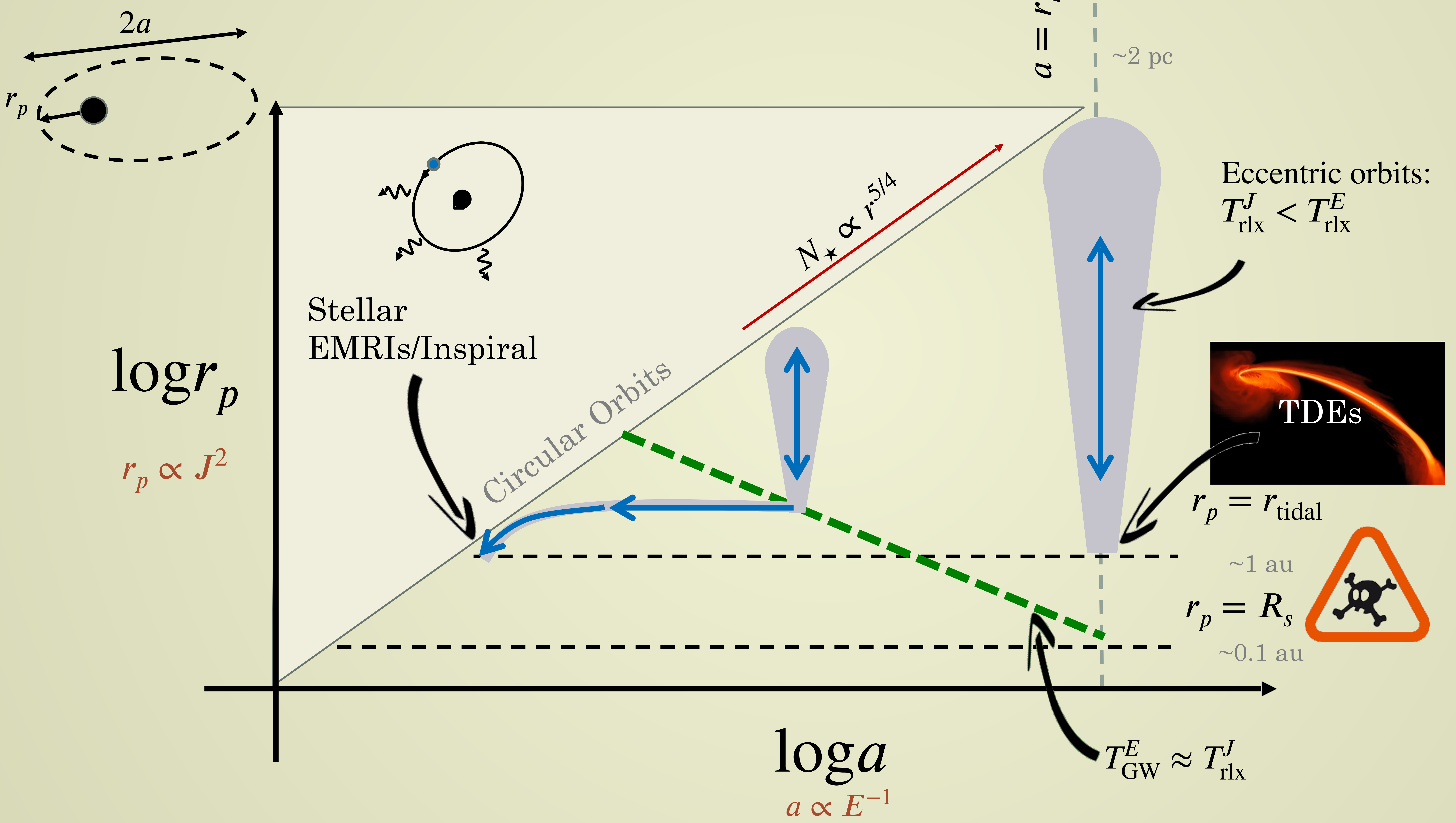
E, J Current densities:
Advection (drift) + diffusion

$D_E, D_J, D_{EE}, \; D_{JJ}, D_{EJ}, \; D_{JE}$ - 1st/2nd order Diffusion coefficients

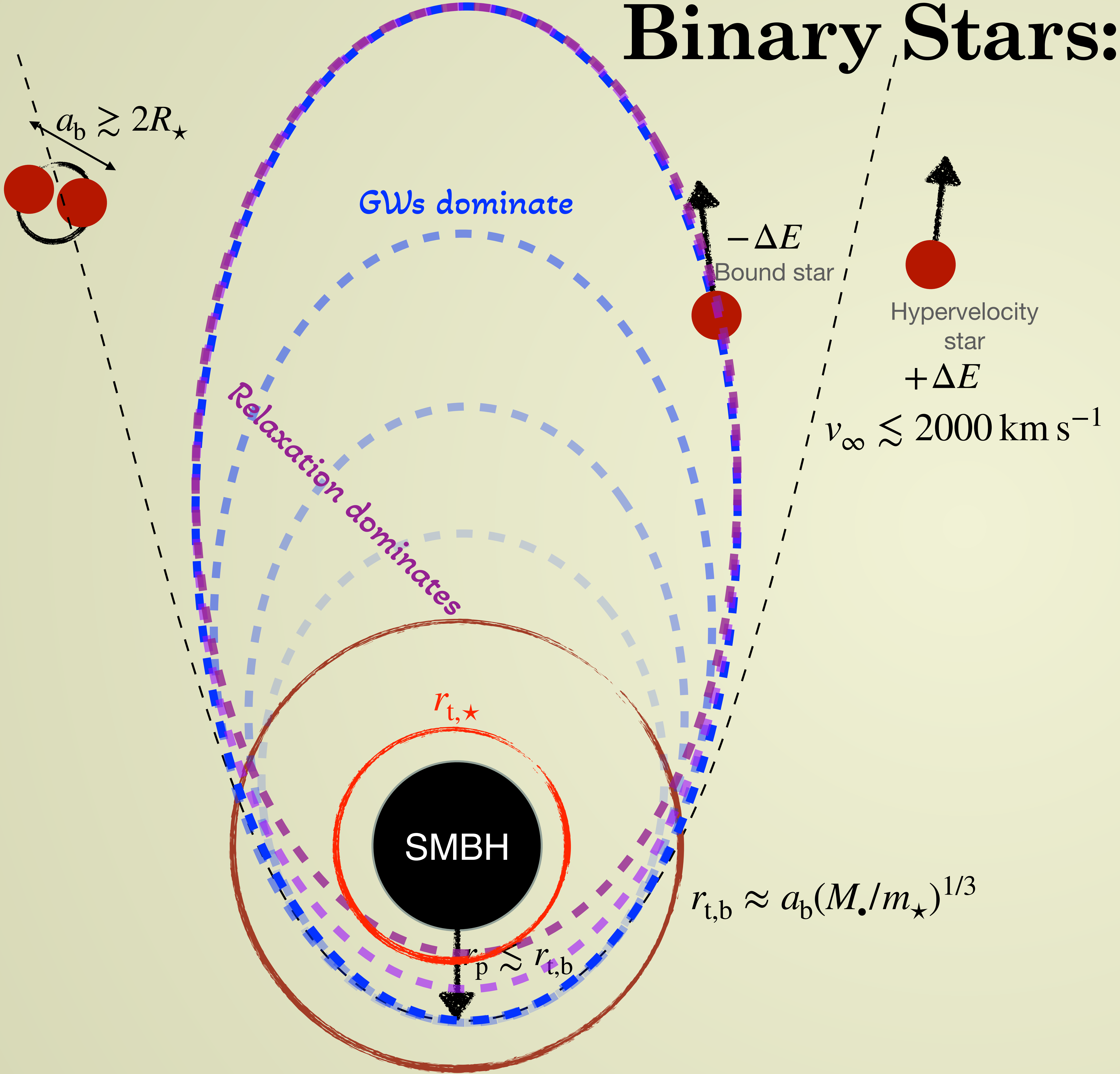
In the context of galactic nuclei:
[Cohn & Kulsrud (1978), Magorrian & Tremaine (1999), Hopman & Alexander (2005), Merritt (2013), Bar-Or & Alexander (2016), Vasiliev (2019), Broggi et al. (2022),…]

Phase Space Trajectories

[**Linial** & Sari 22,23,
Rose, **Linial** + 21,22,
Rom, **Linial** & Sari 24]



Binary Stars: Hills' Mechanism



$$|\Delta E| \approx (Gm_\star^2/a_b)\left(\frac{M_\bullet}{m_\star}\right)^{1/3}$$

Bound star:

$$r_p \approx r_{t,b} \quad , \quad a = r_{t,b}(M_\bullet/m_\star)^{1/3}$$

$$e \approx 0.99$$

$$P_{orb} \approx 10^2\,\mathrm{d}\,(a_b/2R_\odot)^{3/2}$$

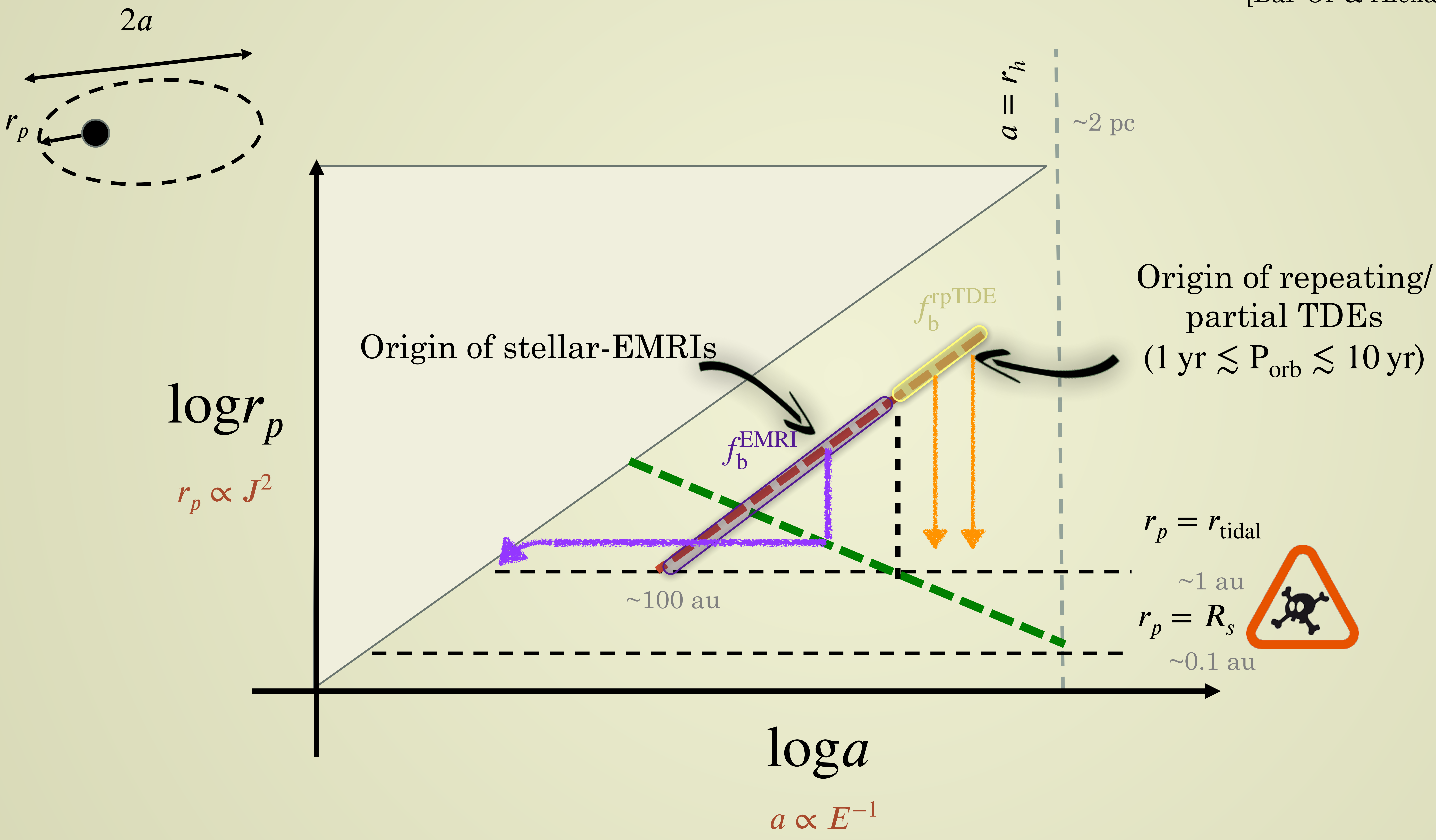
$\mathscr{R}_{Hills} \approx f_b \times \mathscr{R}_{TDE}$ (empty l.c.)

$f_b \sim 0.1$

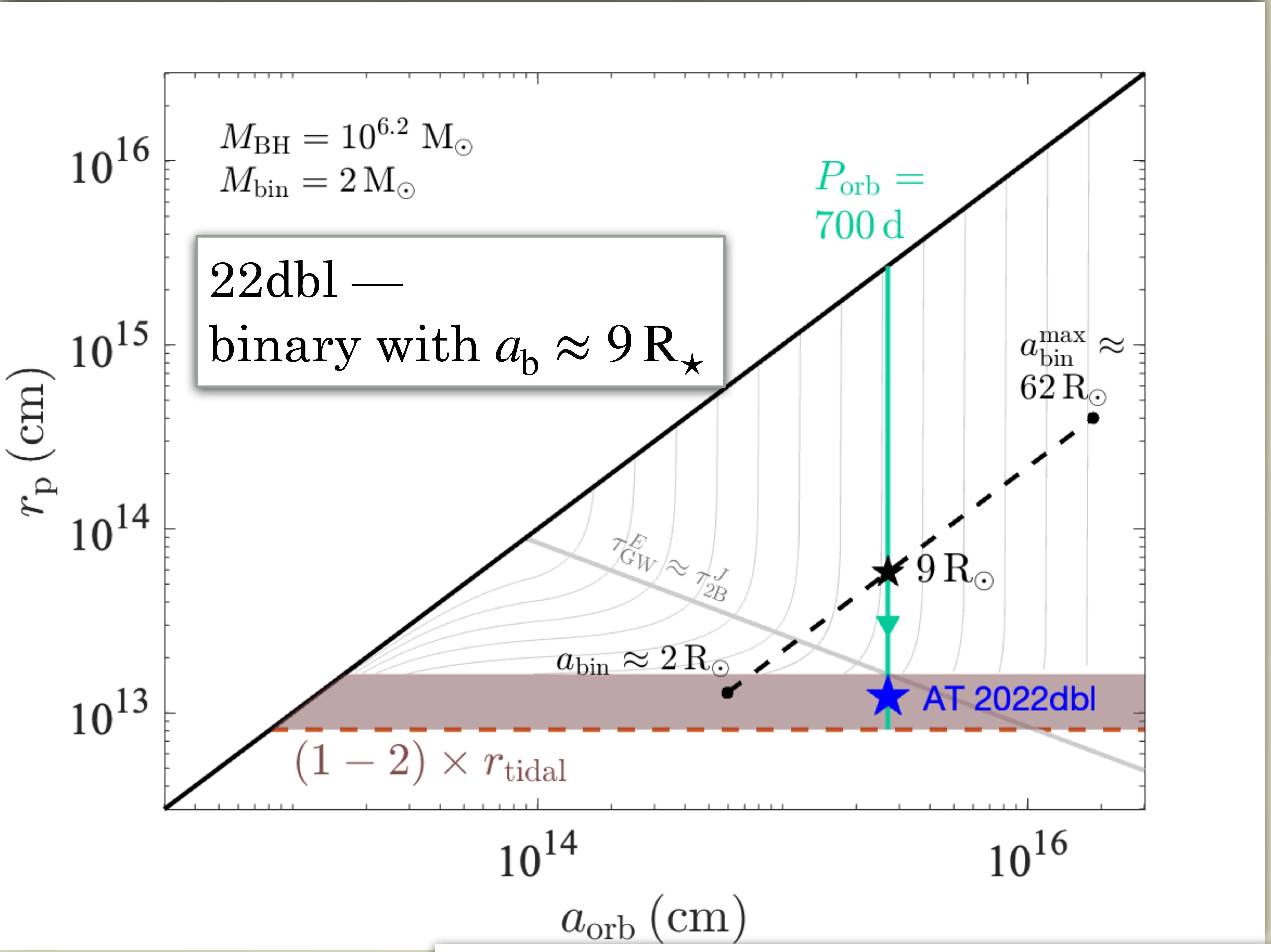
Observational constraints on binaries in Galactic Center
[Gautam+24]

EMRIs vs. rpTDEs

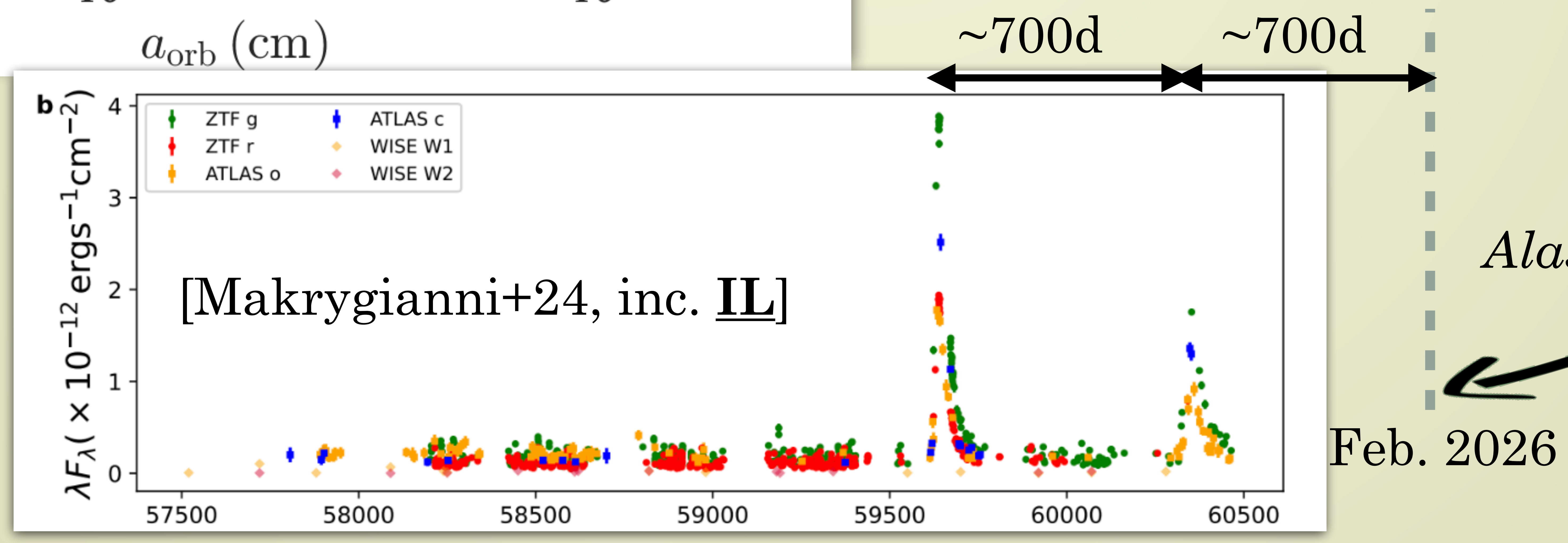
[**Linial** & Sari 2023]
[Sari & Fragione 2019]
[Miller (2005)]
[Bar-Or & Alexander (2016)]



The “dbl” TDE (AT 2022dbl) [See Iair’s talk]



- Two nearly identical flares, 700d apart
- 1st flare declines faster than 2nd (possibly partial and full disruption?)
- Possible formation through Hills’ mechanism



Alas, no 3rd flare (yet?)

Rates of TDEs/Inspirals

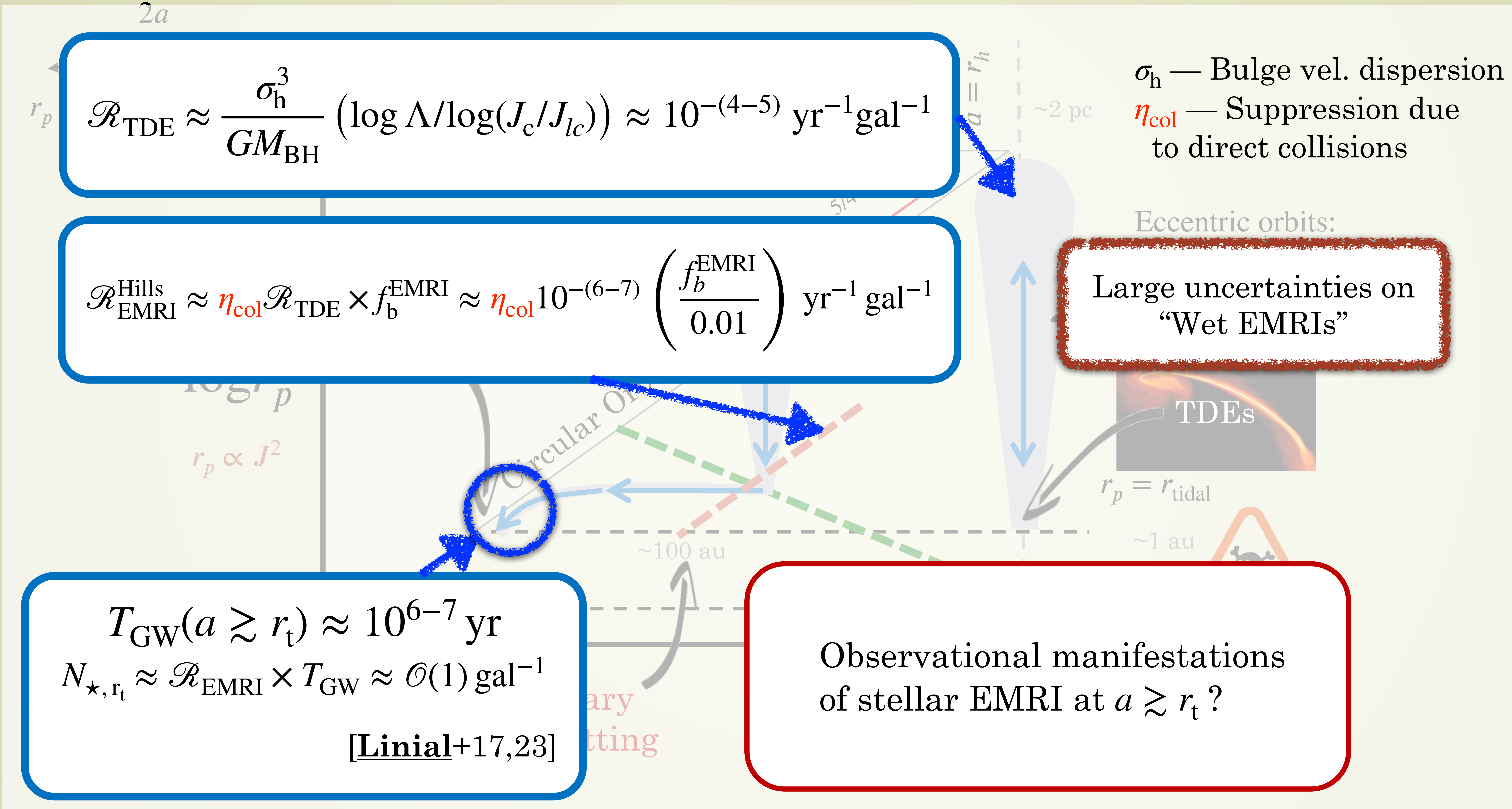
[**Linial** & Sari 2022]
[Sari & Fragione 2019]

$$\mathscr{R}_{\rm TDE} \approx \frac{\sigma_{\rm h}^3}{GM_{\rm BH}} \left(\log \Lambda / \log(J_{\rm c}/J_{lc})\right) \approx 10^{-(4-5)}\ {\rm yr}^{-1}{\rm gal}^{-1}$$

$\sigma_{\rm h}$ — Bulge vel. dispersion
$\eta_{\rm col}$ — Suppression due to direct collisions

$$\mathscr{R}^{\rm Hills}_{\rm EMRI} \approx \eta_{\rm col} \mathscr{R}_{\rm TDE} \times f_{\rm b}^{\rm EMRI} \approx \eta_{\rm col} 10^{-(6-7)} \left(\frac{f_b^{\rm EMRI}}{0.01}\right)\ {\rm yr}^{-1}\ {\rm gal}^{-1}$$

Large uncertainties on "Wet EMRIs"



$$T_{\rm GW}(a \gtrsim r_{\rm t}) \approx 10^{6-7}\ {\rm yr}$$
$$N_{\star, r_{\rm t}} \approx \mathscr{R}_{\rm EMRI} \times T_{\rm GW} \approx \mathscr{O}(1)\ {\rm gal}^{-1}$$

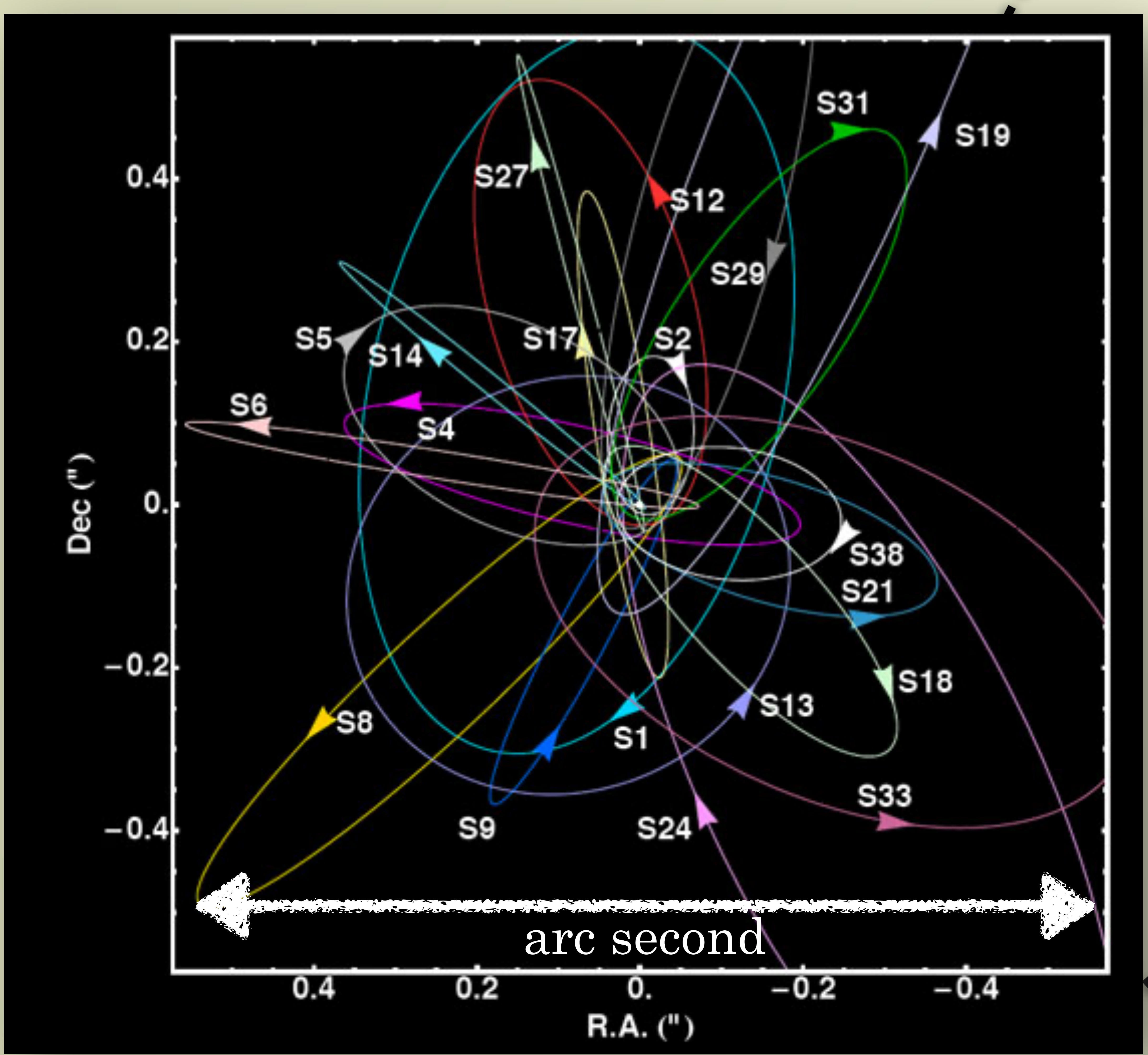
[**Linial**+17,23]

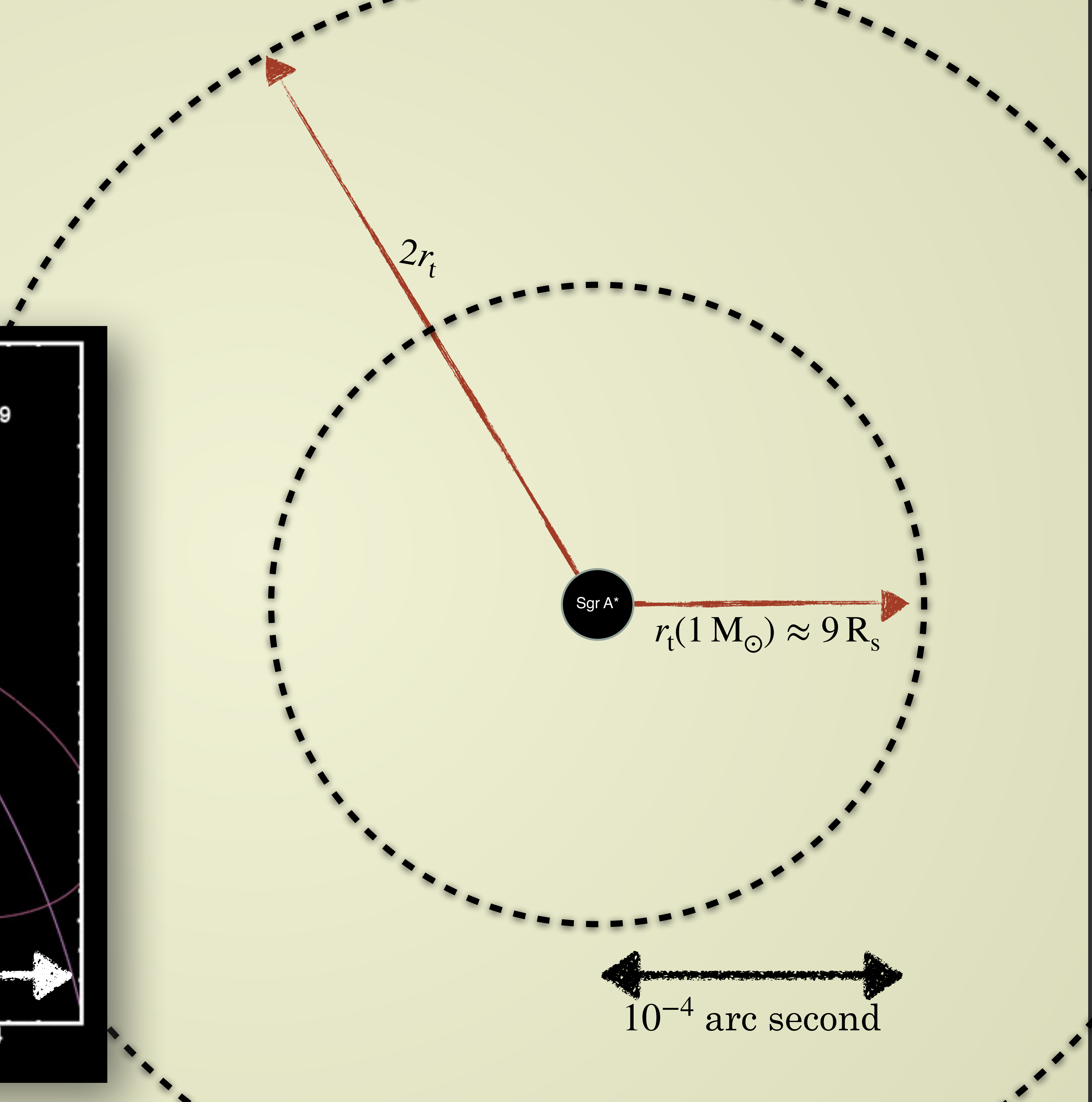
Observational manifestations of stellar EMRI at $a \gtrsim r_{\rm t}$?

In Milky Way

Pericenter of S4714 ~ 320 R_g

Tidal radius of 1 $M_\odot$ ~ 19 R_g





Manifestations of stellar-EMRI at $a \gtrsim r_t$

Inspiral $a \to 2r_t$, Roche lobe overflow

Stable → Power Low-luminosity AGN?

[**Linial** & Sari 17, Olajeck+25, Yao+25]

Unstable → Runaway mass transfer, **"Circular TDE"**

[**Linial** & Sari 23, Lu & Quataert 23, **Linial** & Quataert 24b]

High velocity collisions w/ star/sBH

[Rose, **Linial** et al. 23, Rom+26 (in prep.)]

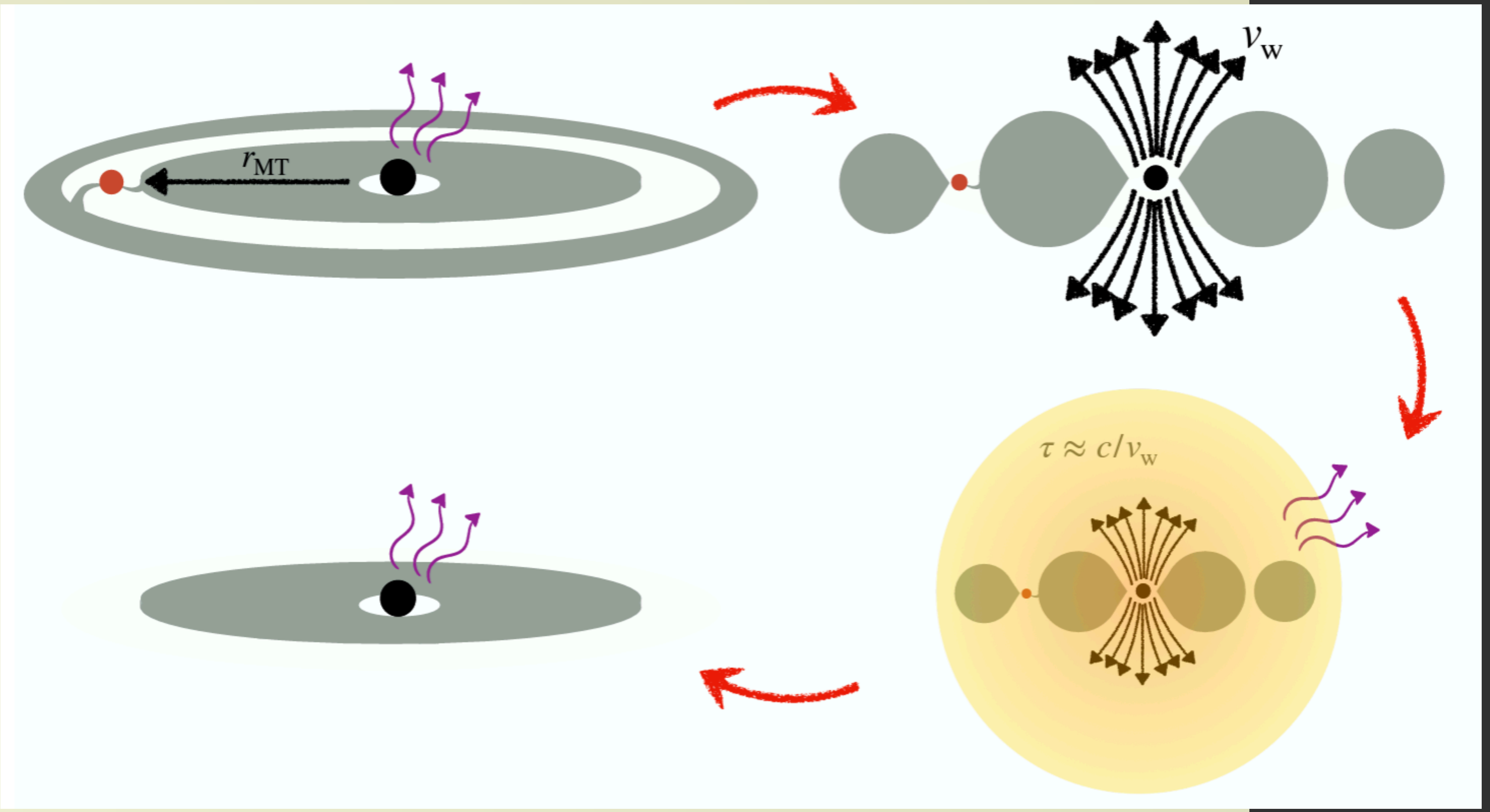
Interaction w/ BH accretion flow

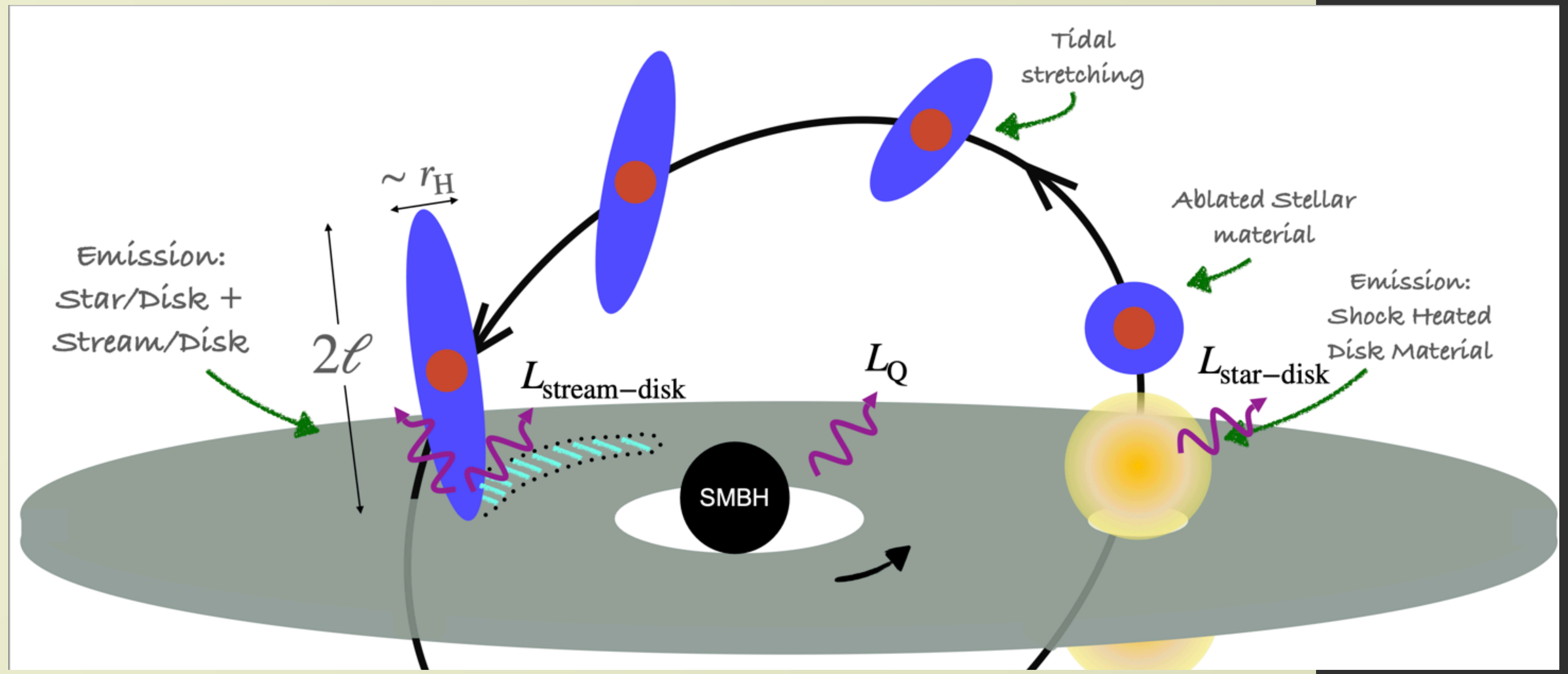
e.g., "EMRI+TDE"

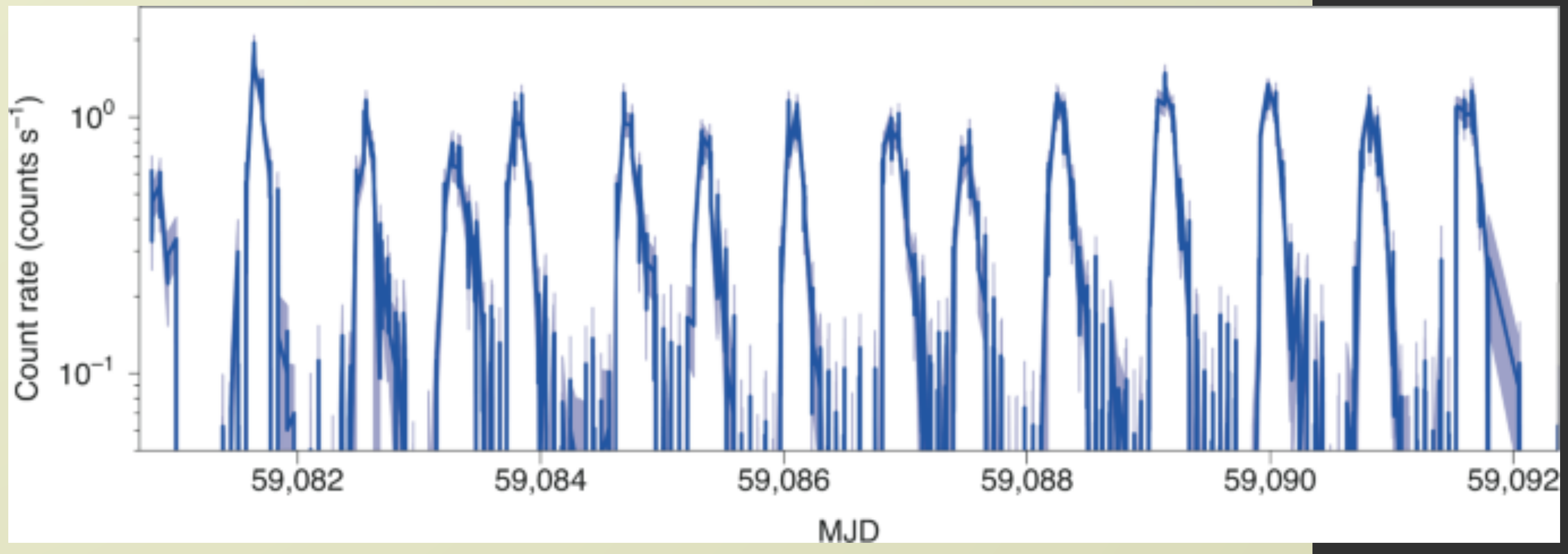
→ Repeated energetic flares, QPEs?

[**Linial** & Metzger, 23, 24a,b, Vurm+25, **Linial**+25]

→ Drive energetic outflows





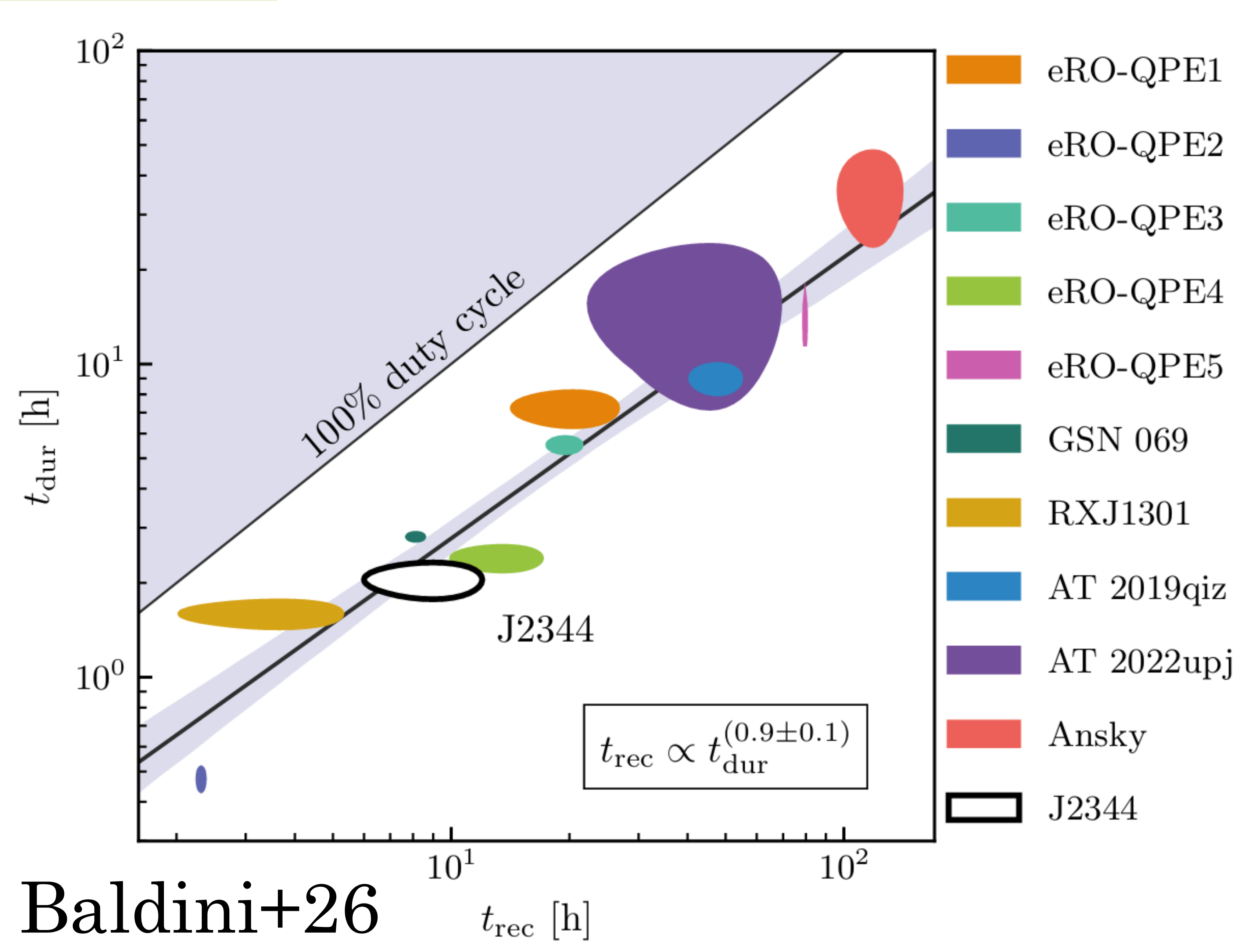


Quasi-Periodic X-Ray Eruptions (aka QPEs)

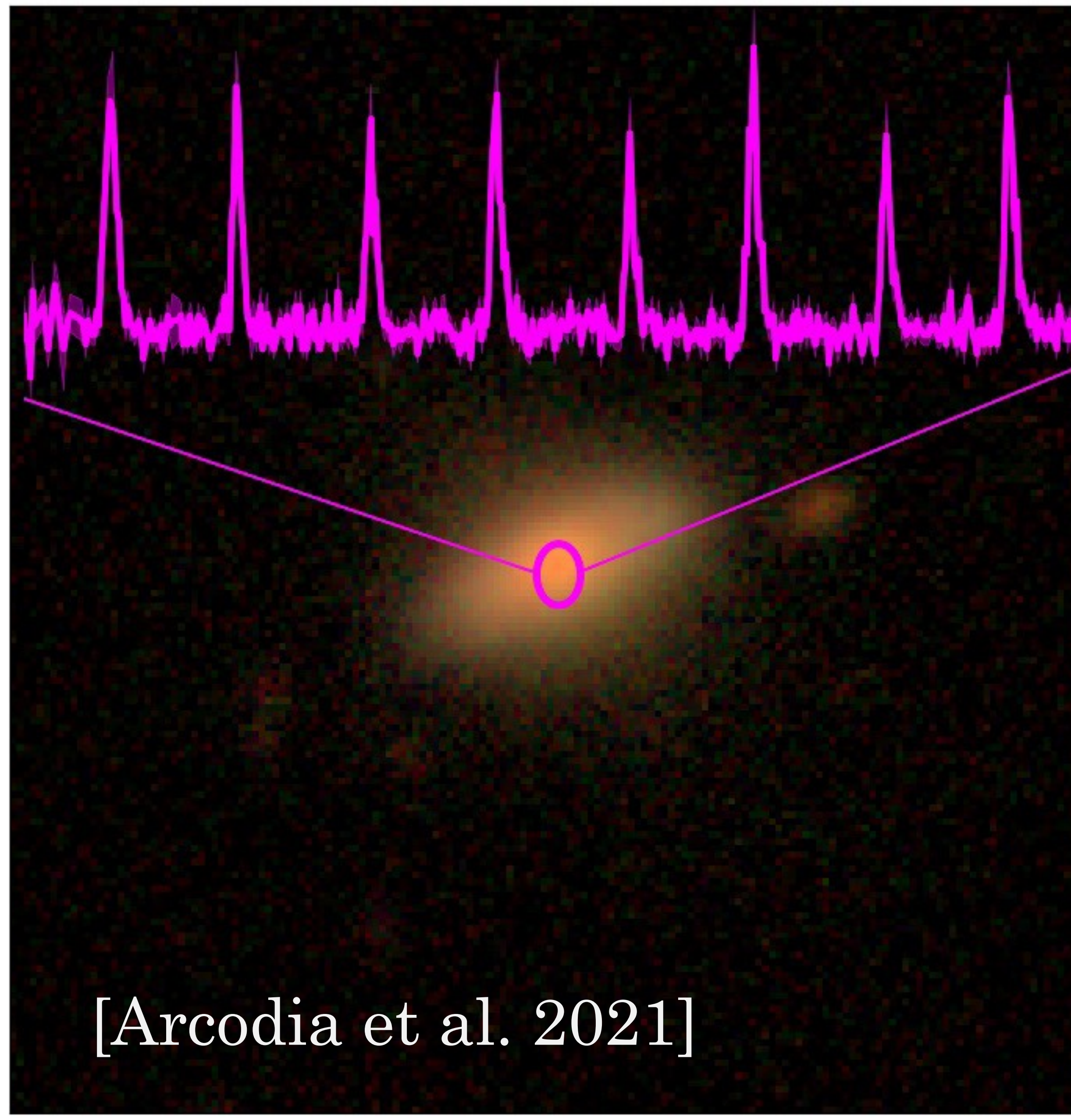
- **~11 confirmed sources** (+2/3?)
- (Quasi)-Period: **2.5 hr - few days**
- Duty cycle ~ **10-30%**
- Peak luminosities
  $L_{\rm pk} \approx 10^{42-43}\,{\rm erg\,s^{-1}}$
  $k_B T_{\rm pk} \approx 150 - 200$ eV
- $M_{\rm BH} \approx {\rm few} \times 10^5 - {\rm few} \times 10^6$

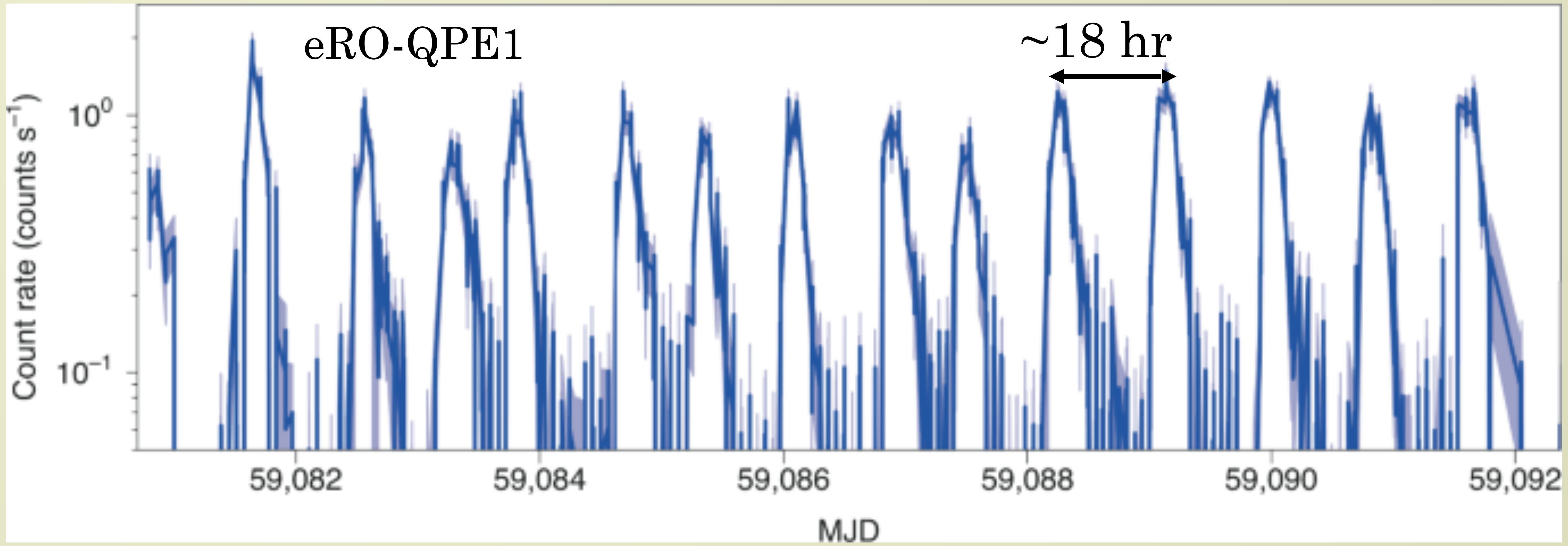
(Wevers+22, from host galaxy scaling relations)

[Miniutti et al., *Nature*, 2019
Giustini et al., *A&A*, 2019
Arcodia et al., *Nature*, 2021
Chakraborty et al., *ApJL*, 2021]

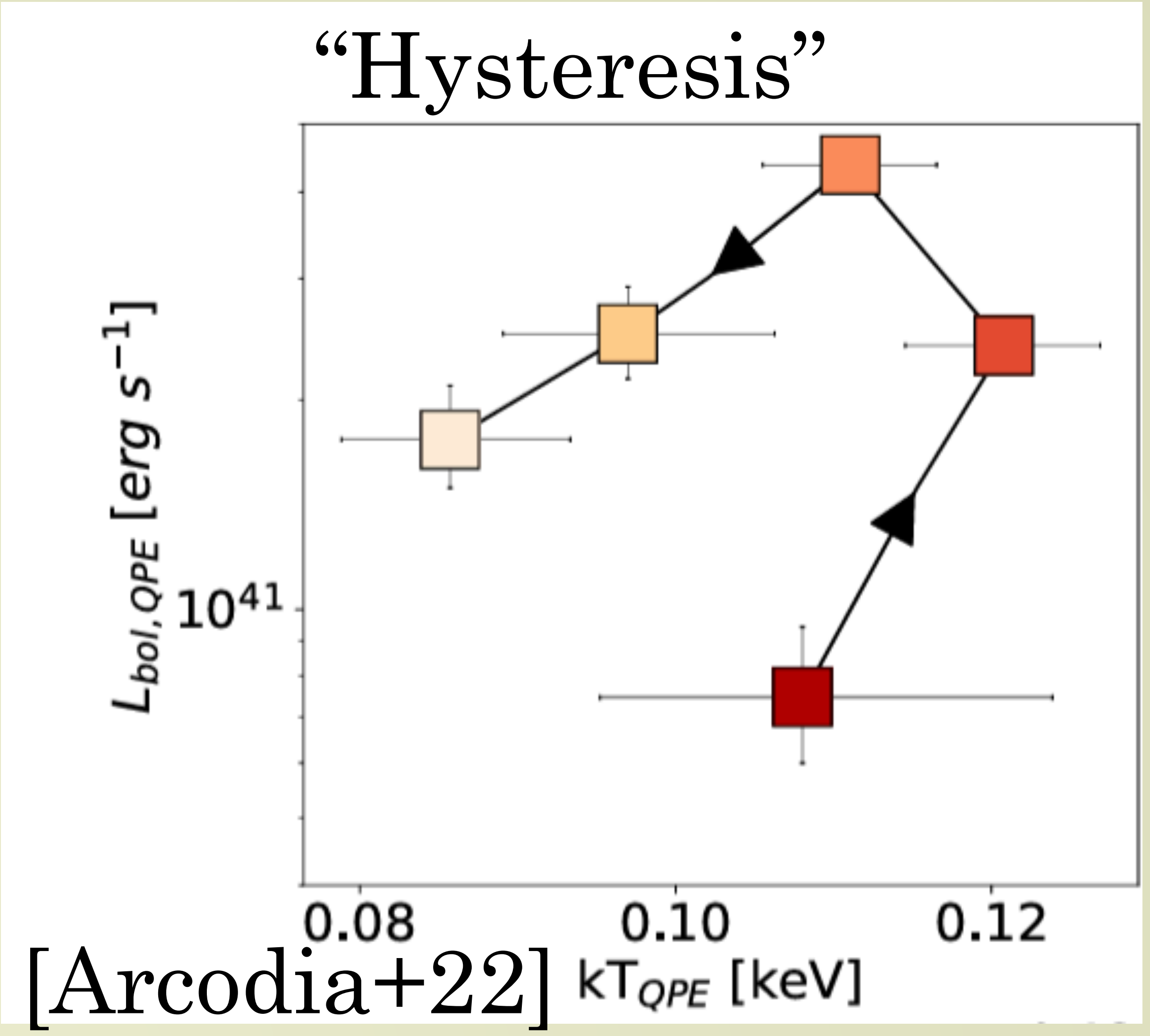


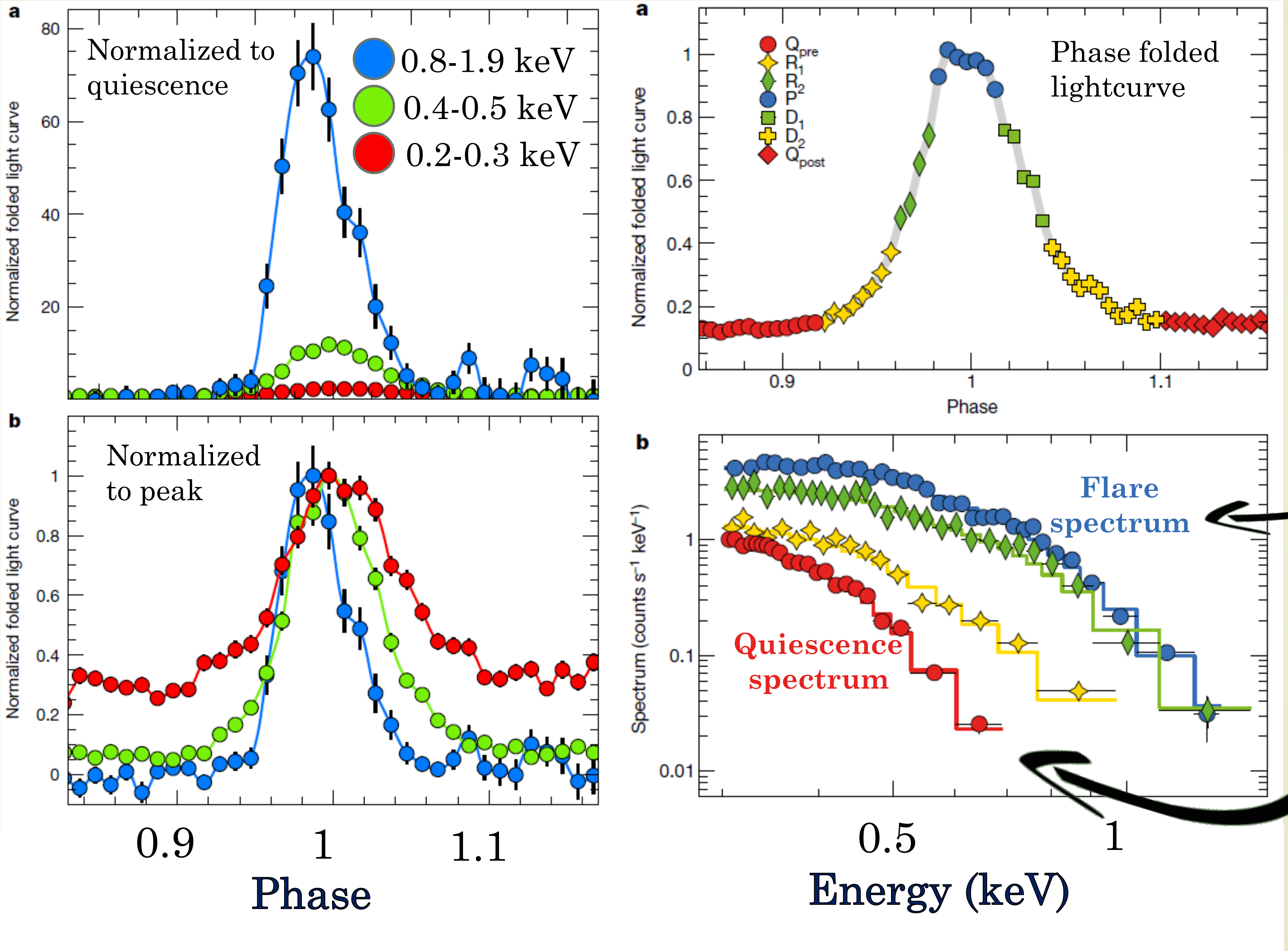
Baldini+26


[Arcodia et al. 2021]



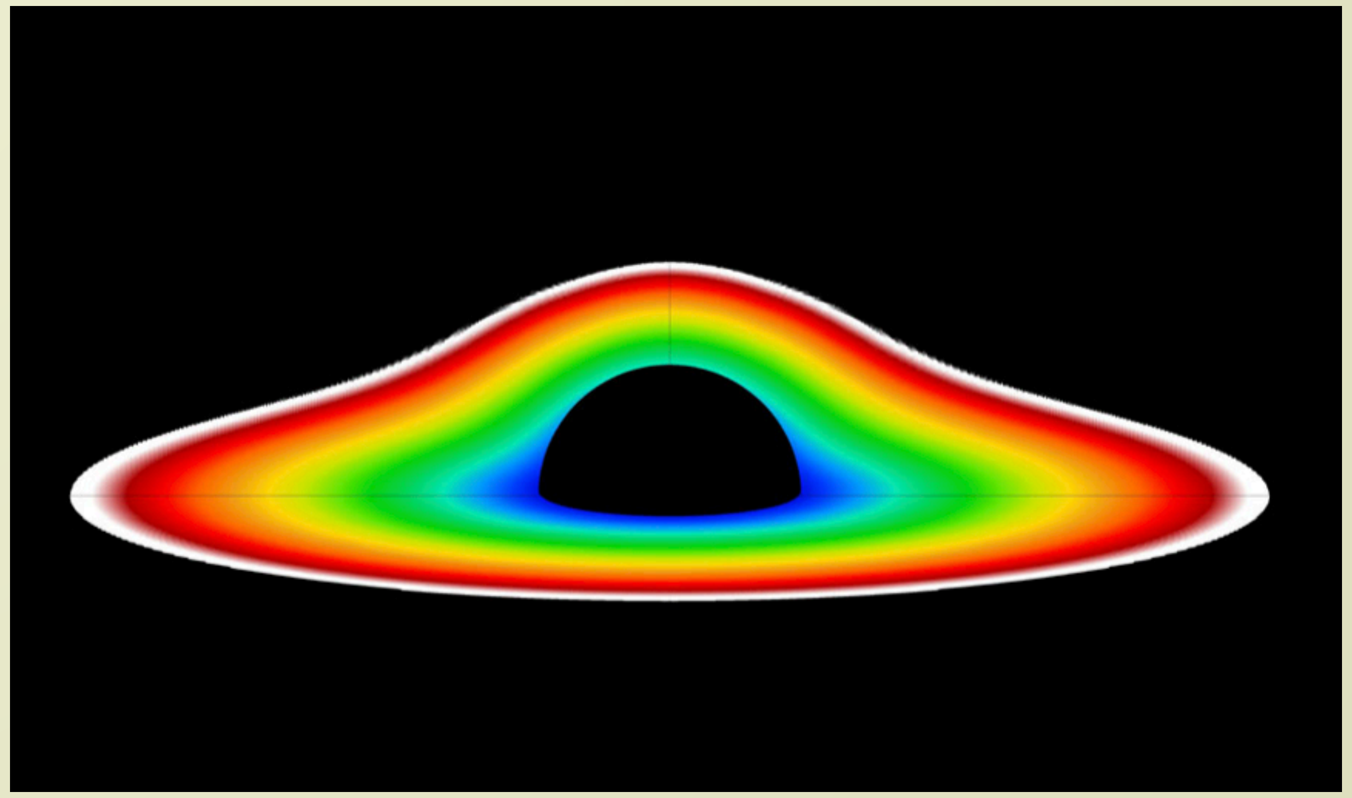
Lightcurve and spectral evolution





(Semi-) Blackbody Wien tail

$$B_\nu(\epsilon) \propto \frac{\epsilon^3}{\exp\left(\frac{\epsilon}{k_B T}\right) - 1}$$



[GSN-069: Miniutti 2019]

[Wilkins 2018]

$N_{Models} \gtrsim N_{Sources}$

Accretion Disk Instabilities

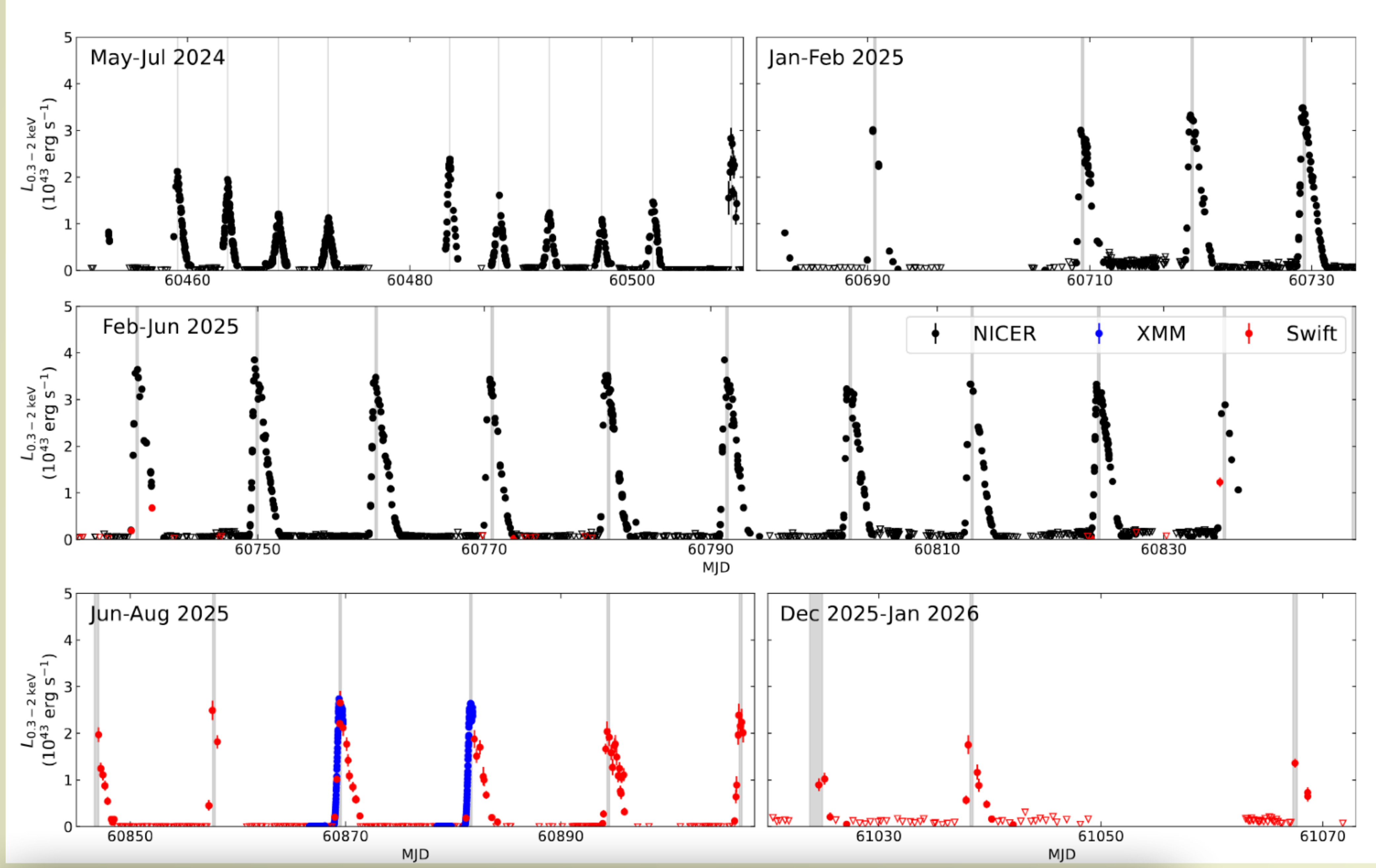
SMBH + Orbiter

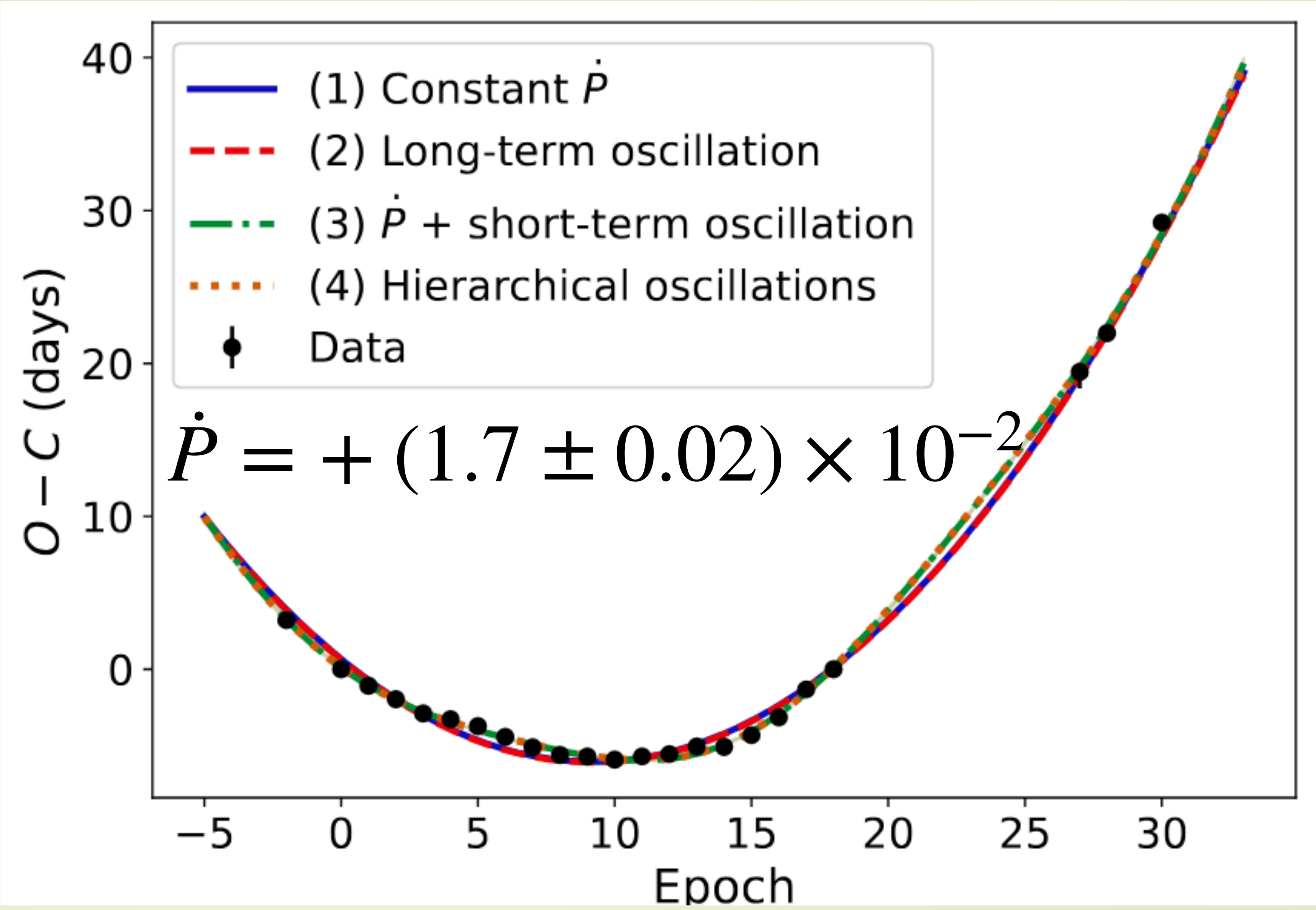
"Accretion Powered" — "Shock Powered"

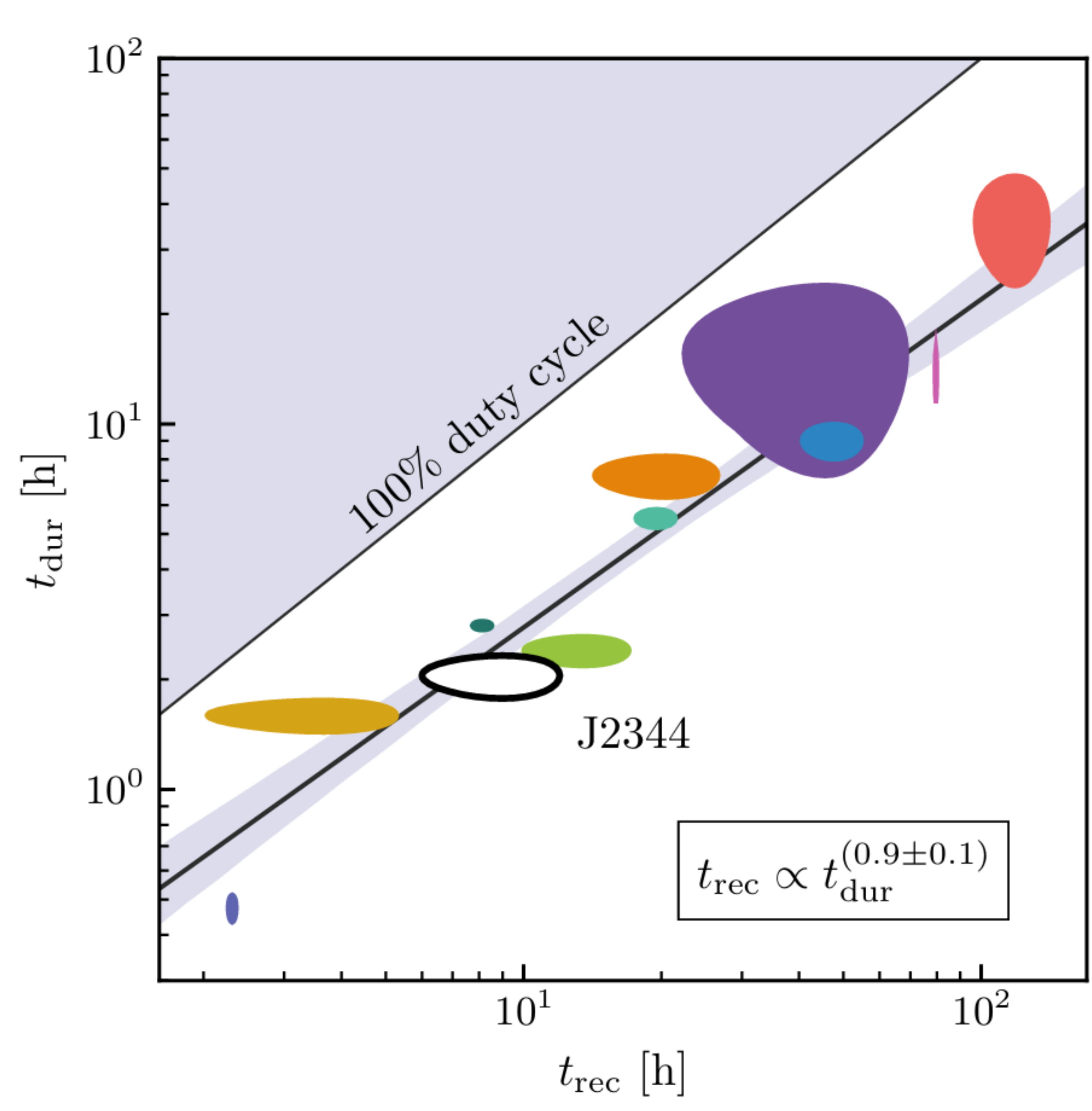
Thermo-viscous instability	Tearing of misaligned disk	TDE + Clumpy stream	Dual AGN + self lensing	Tidal stripping of companion	Orbiter + Disk interaction
Miniutti+21 Arcodia+21 Pan+22,23 Kaur+22 Sniegowska+22	Raj+21a,b	Coughlin+15,20 Nixon+22	Ingram+21	Zalamea+10 King 20,22 Zhao+22 Wang+22 Metzger+21 Krolik+**Linial** 22 **Linial**+Sari 23 Lu+23	Xian+21 **Linial**+Metzger 23 Franchini+23 Tagawa+23 **Linial+**Metzger 24a,b Vurm,**Linial**+ 25 Huang, Jiang,**IL** 25 Lam+25 Linial+25

Middleton+25
(Lense-Thirring Precessing outflow)

ZTF19acnskyy ("*Ansky*")







[Chakraborty,…,**IL**+26, *under review*]

Advance Access publication 2023 November 9

Period evolution of repeating transients in galactic nuclei

Itai Linial [1,2★] and Eliot Quataert [3]

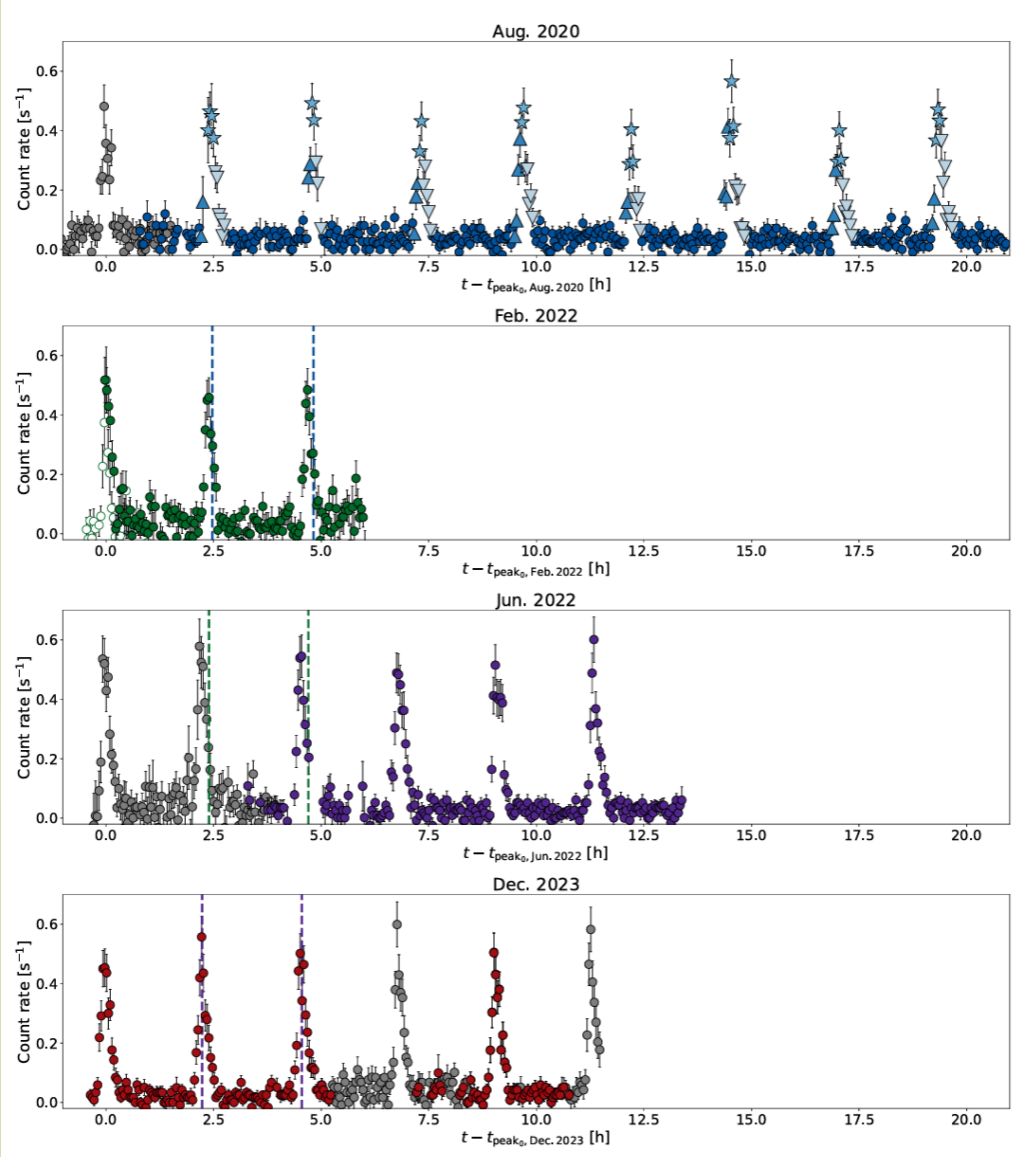
Some proposed ideas: [see also **Linial** & Quataert 24a]

- Orbital evolution due to mass transfer
- Velocity kicks due to tidal interaction at pericenter
- Geometrical modulation of timing due to apsidal precession

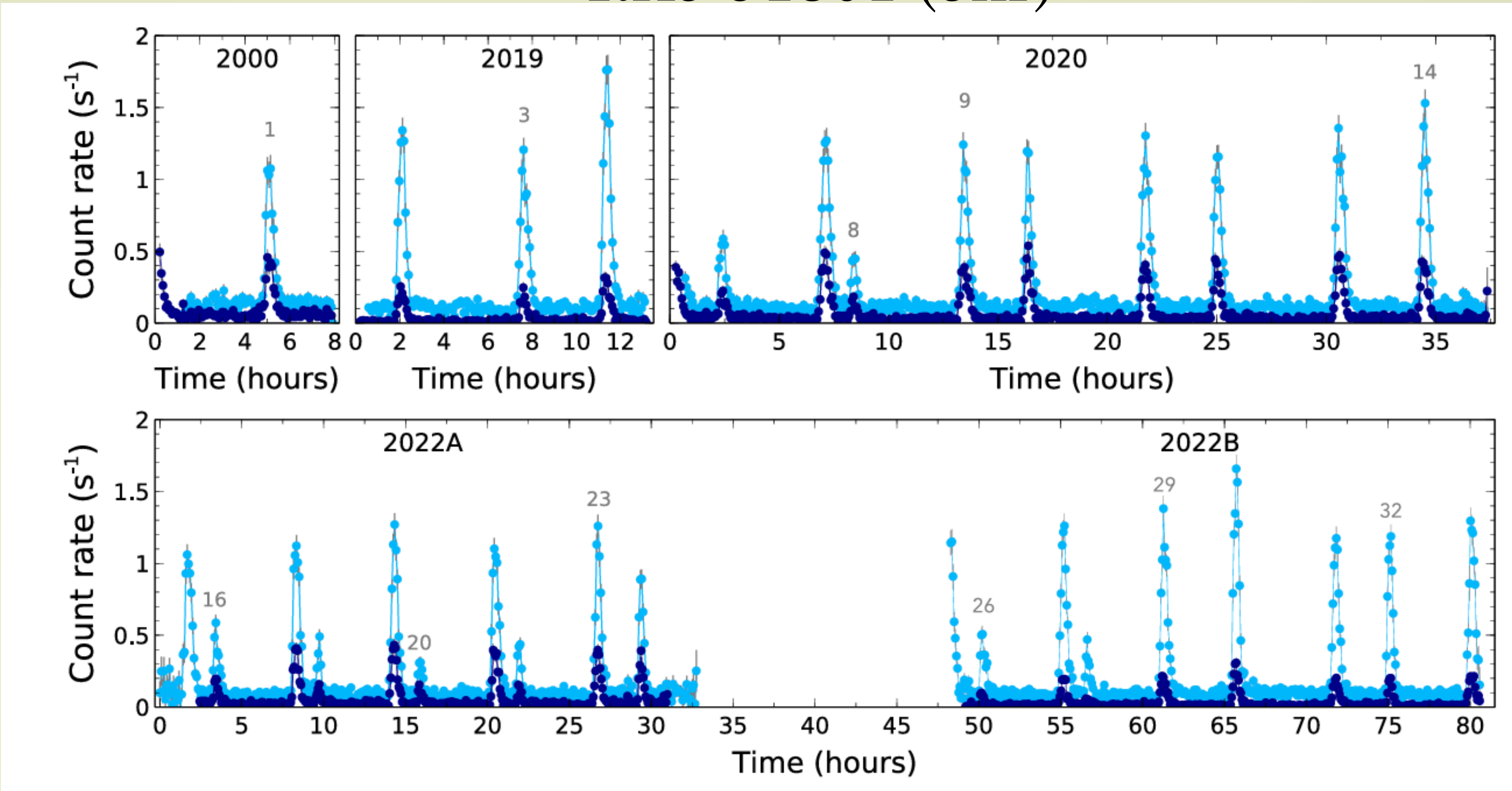
Longer Baseline would determine periodic modulation vs. $\dot{P} \simeq$ const

Search for positive Pdot in other QPEs? Other none-orbital behavior?

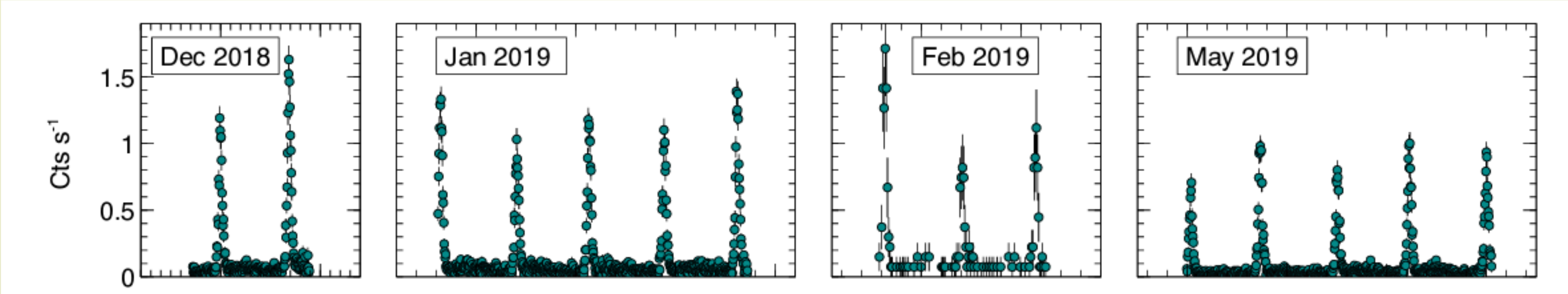
eRO-QPE2 (2.5hr)



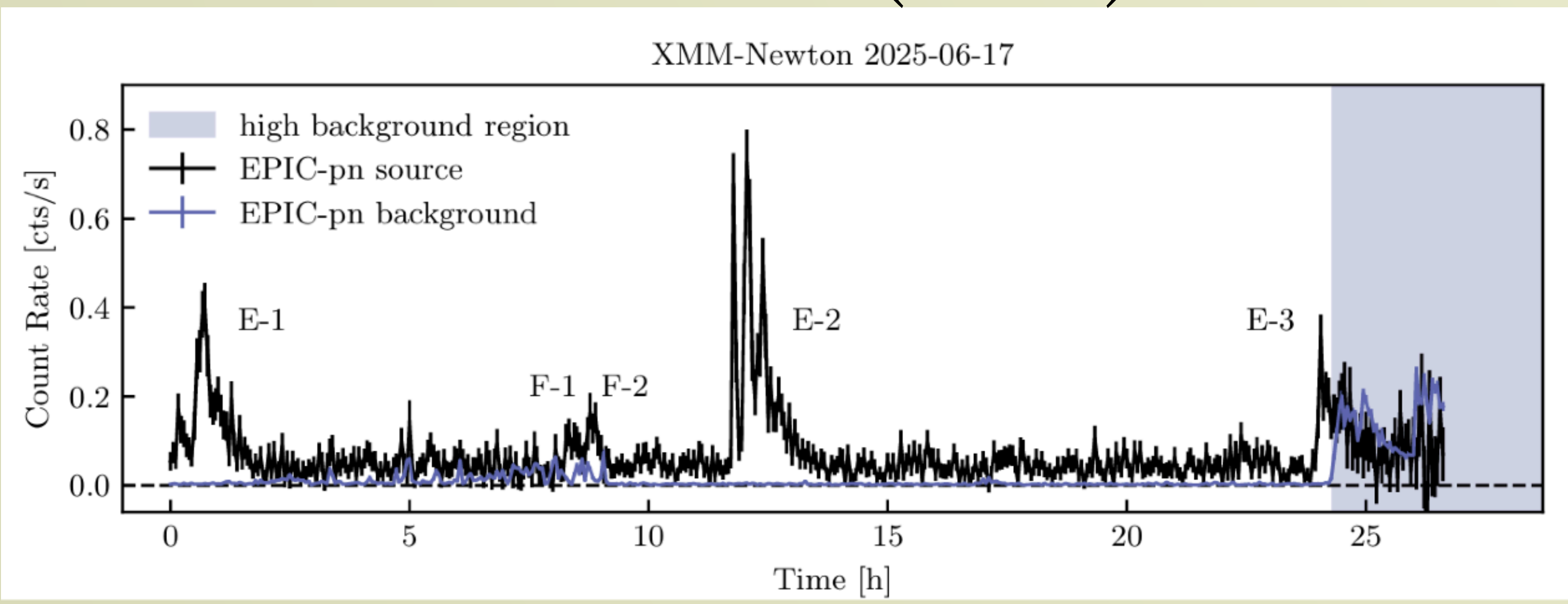
RXJ J1301 (5hr)



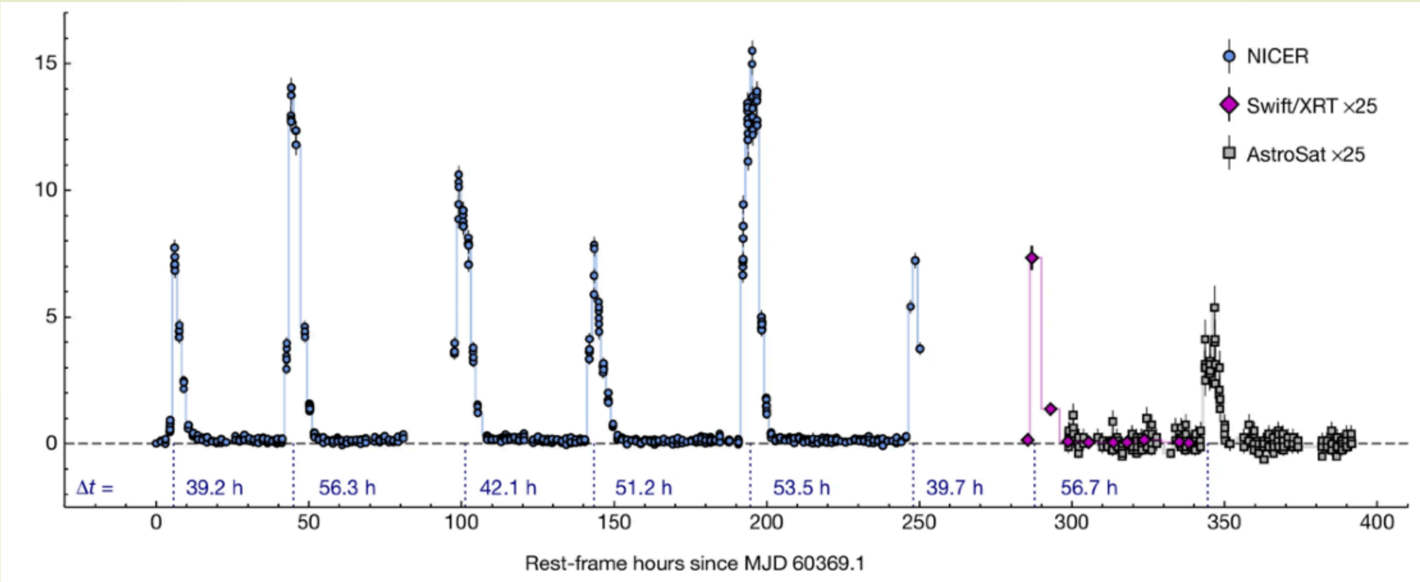
GSN 069 (9hr)



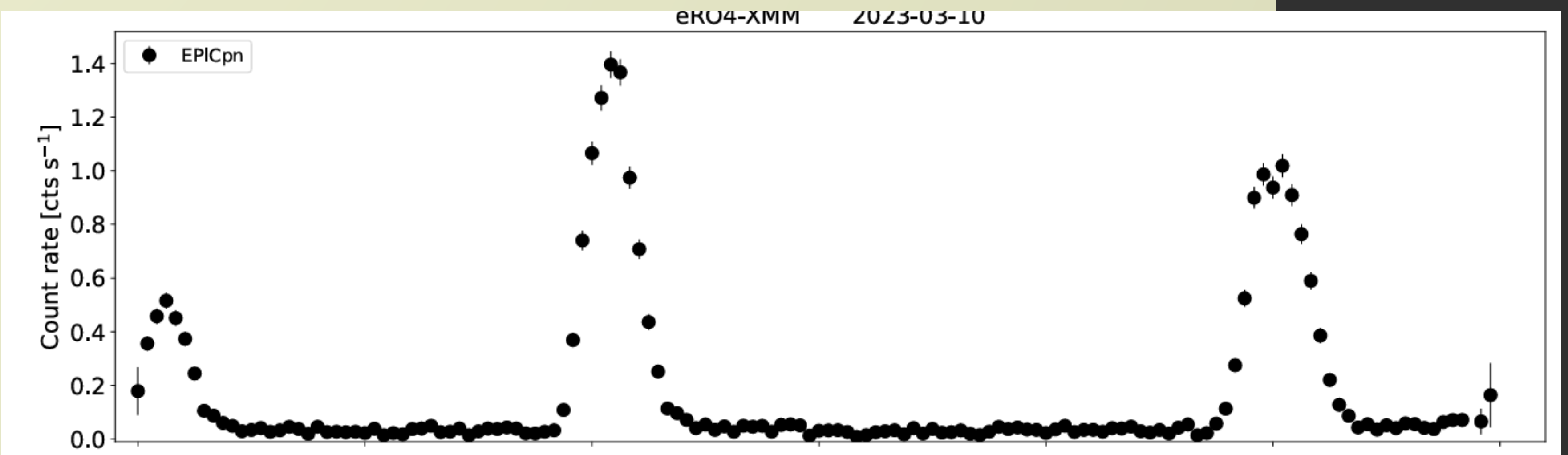
J2344 (12hr)



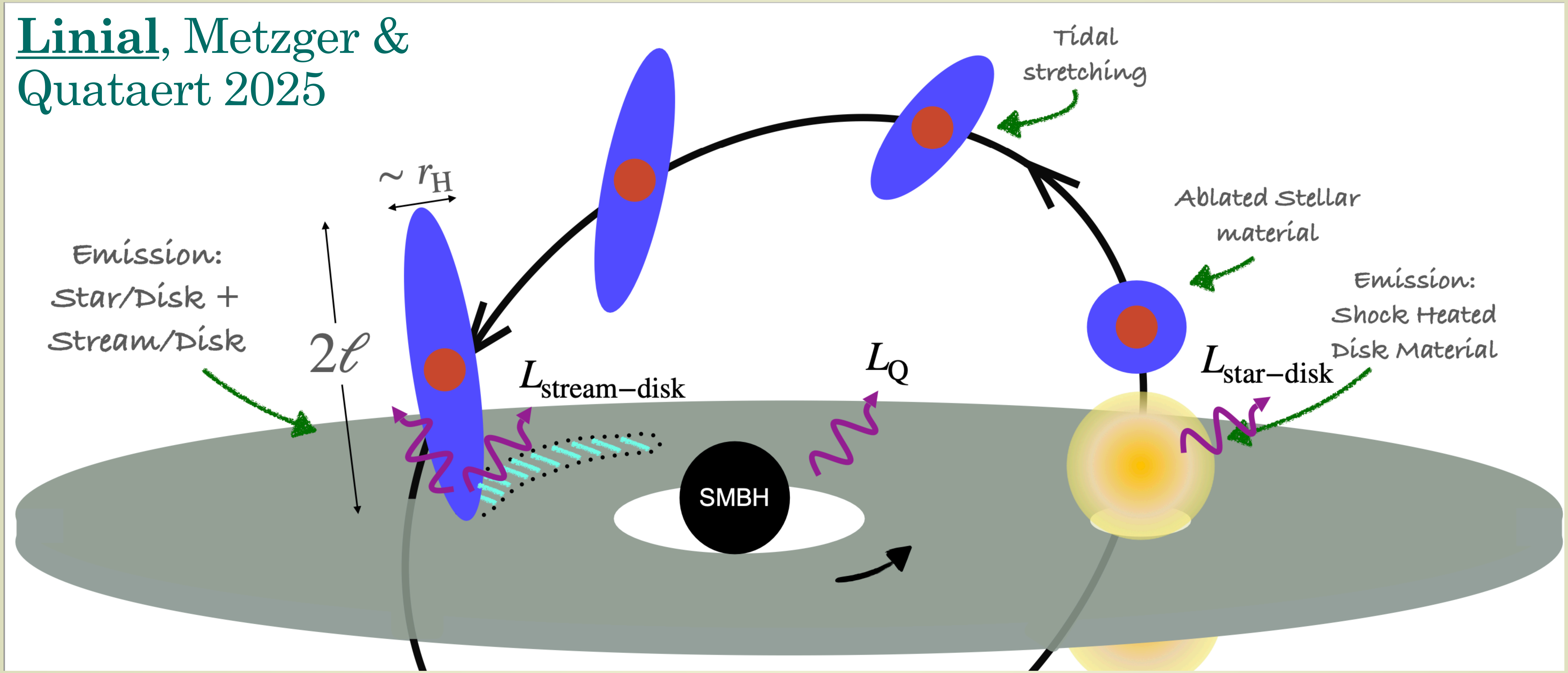
AT 2019qiz (2d)



eRO-QPE5 (3.7d)



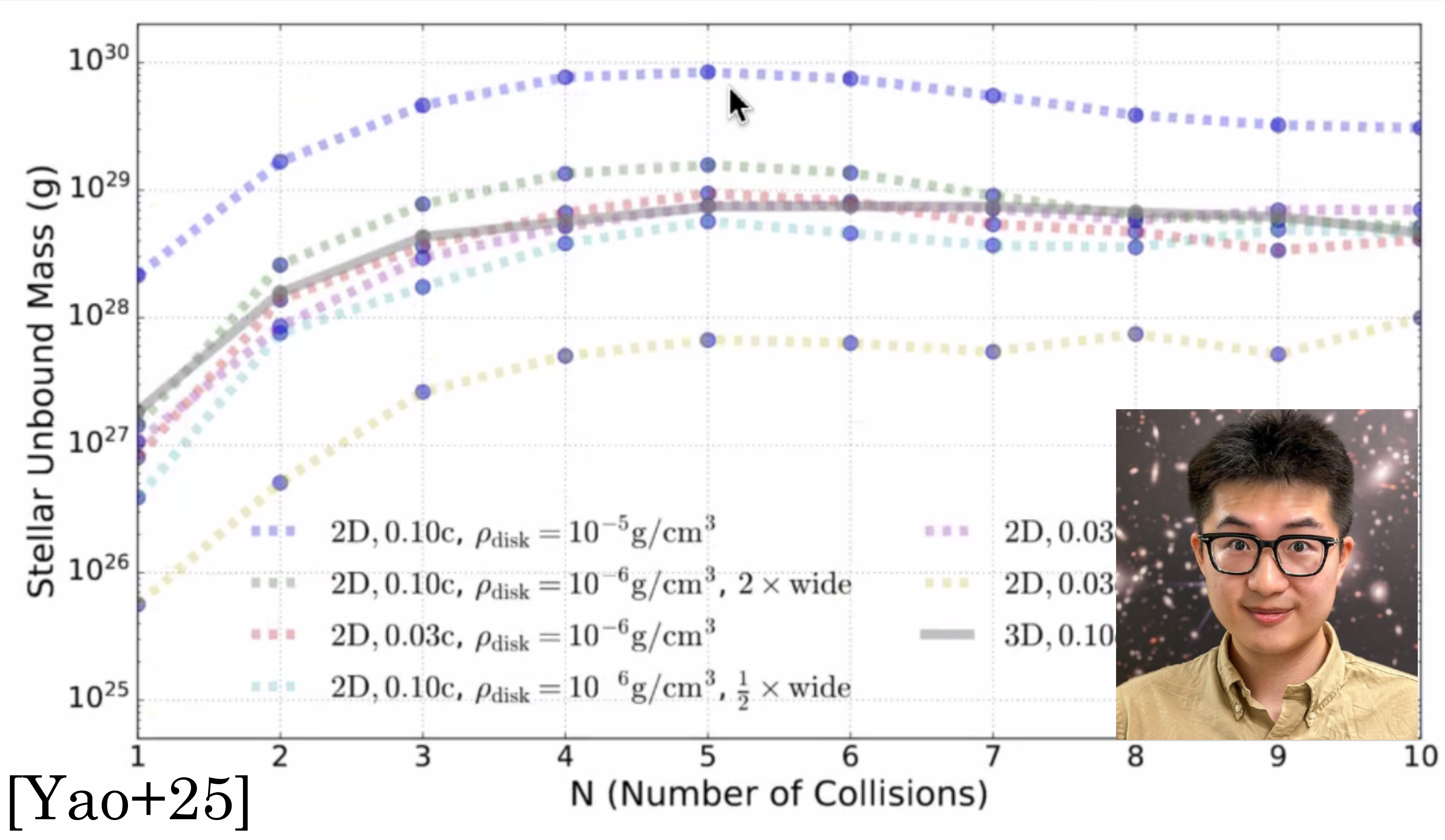
EMRI+Disk: Flares from ***Streams of Ablated Stellar Debris***

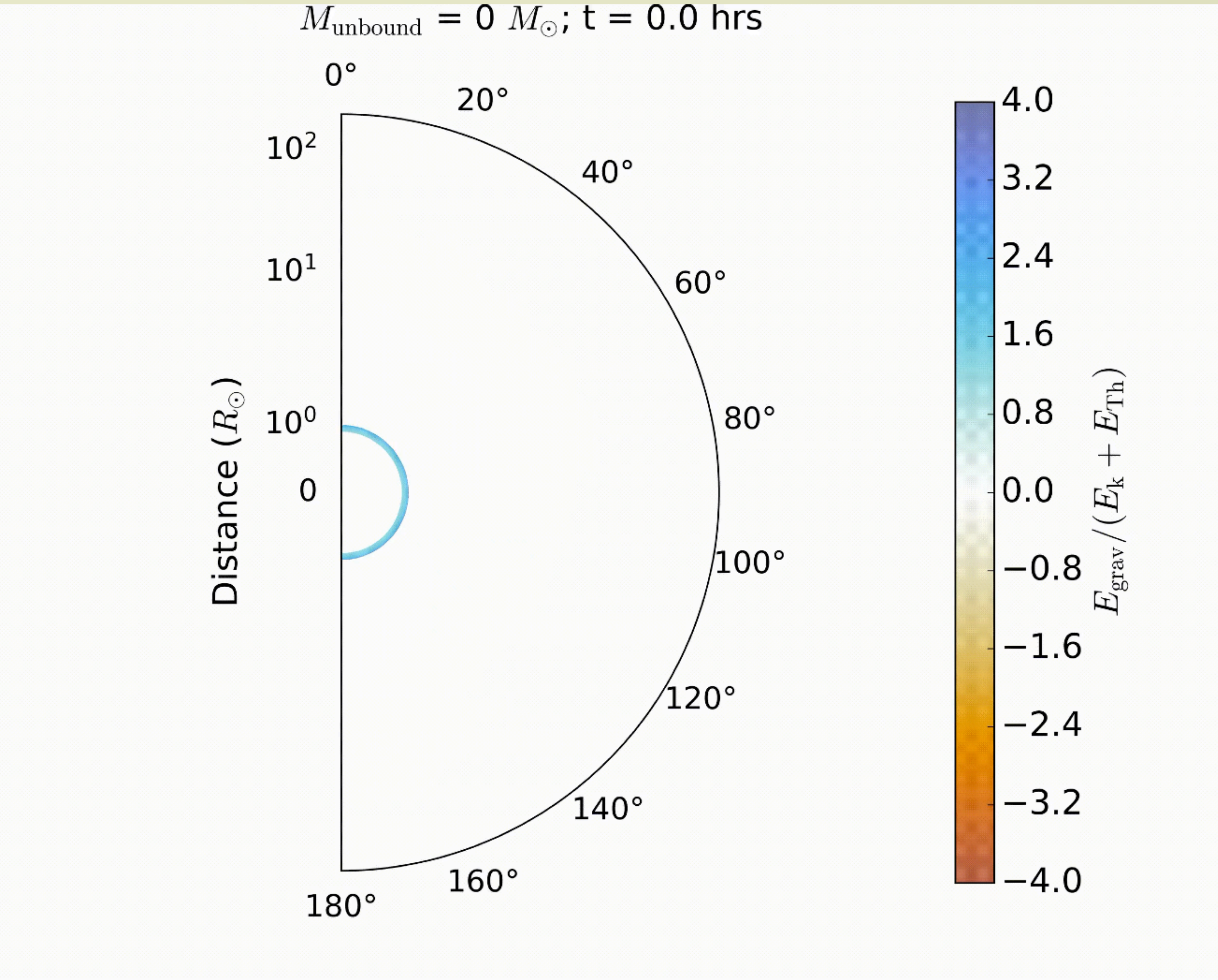


- Accretion disk + **Main-Sequence** stellar-EMRI
- Stream-Disk collisions produce bright flares
- Disk produces quiescent emission
- Flare duration set by stream geometry
- TDE-QPE association
- Flare timing changes with precession

Ablation from Star-Disk Collisions

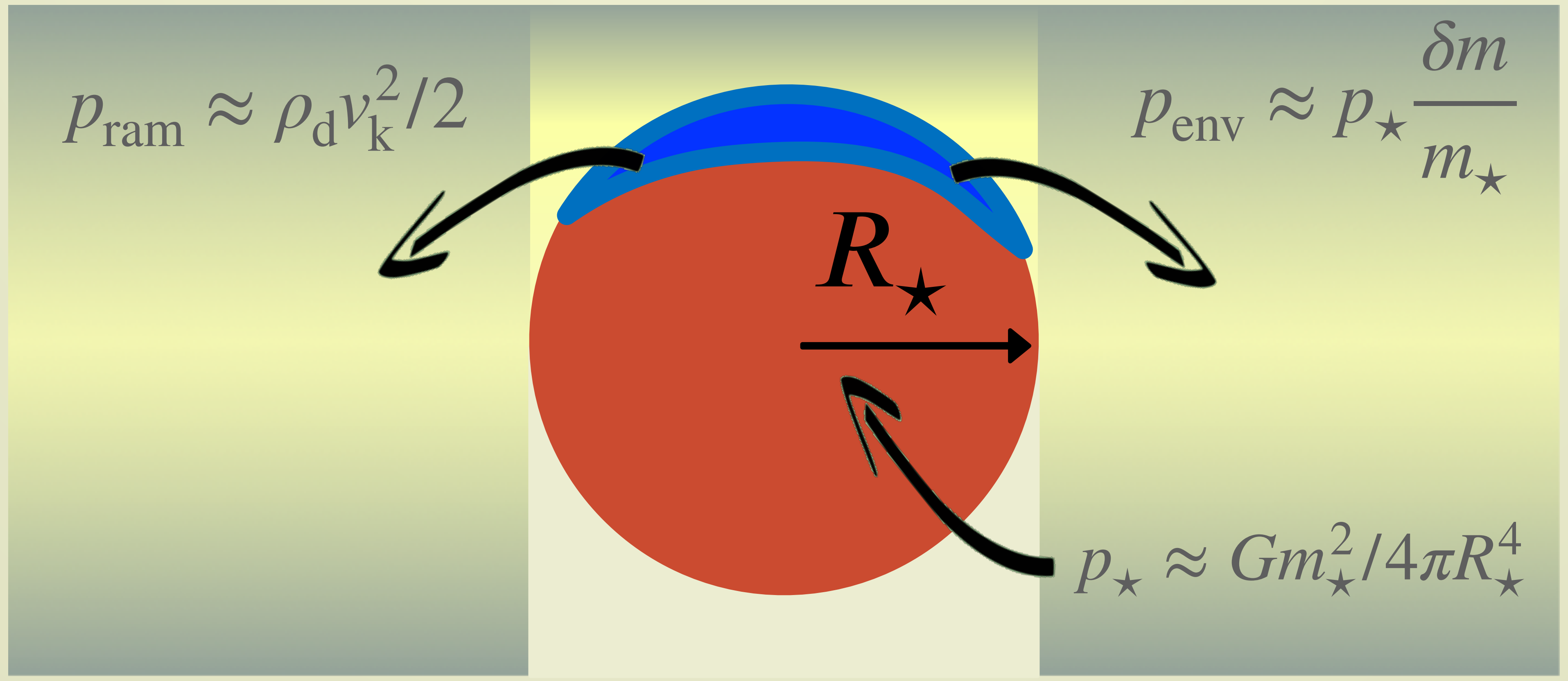
- Limited QPE lifetime?
- Disk fed by stellar material?





$$\frac{\delta m}{m_\star} \approx \eta \times \frac{p_{ram}}{p_\star}$$

$\eta \approx 3\,\%$ for n = 3/2 polytrope

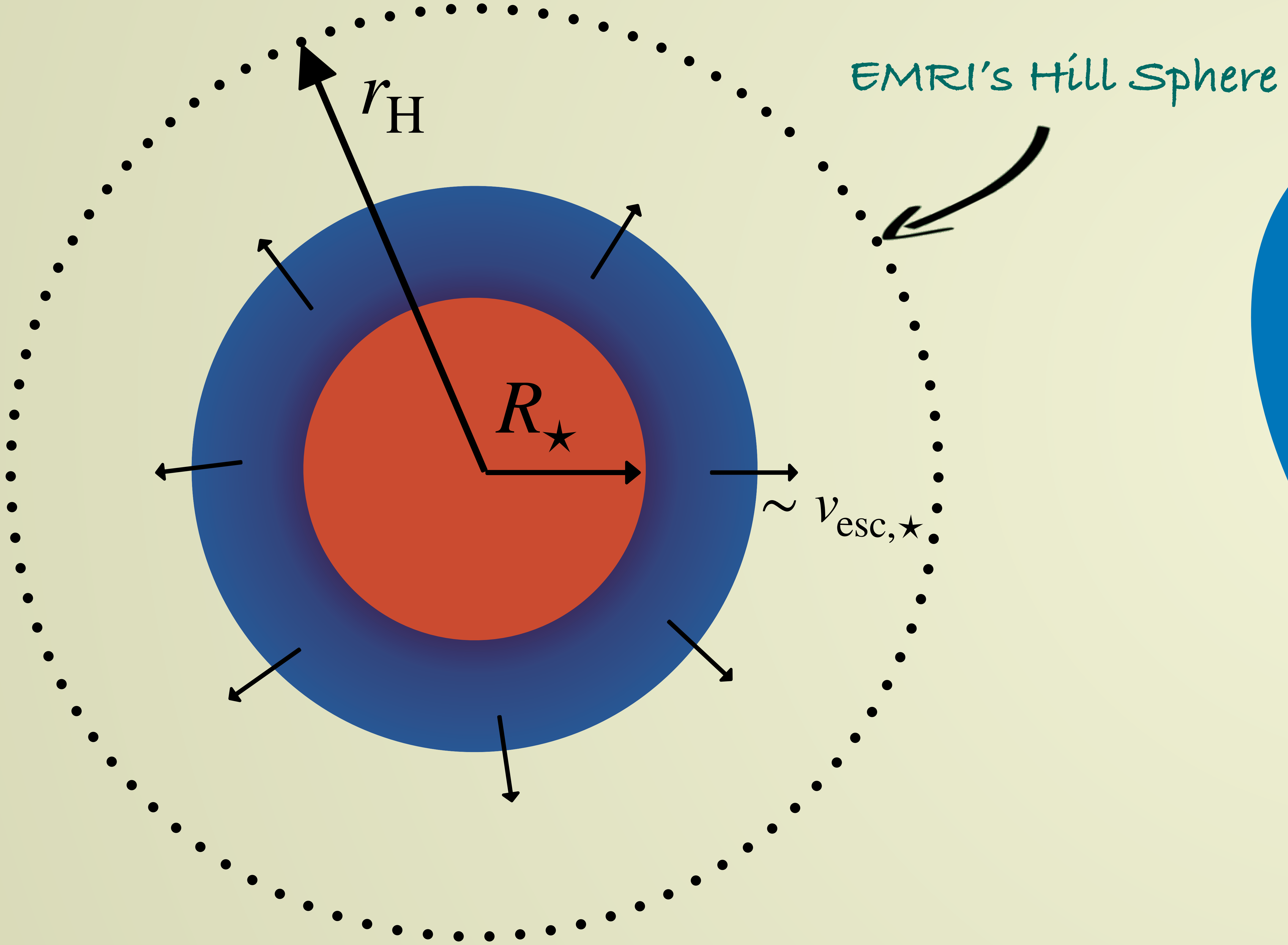


[Co-evolution of star and disk? See - **Linial** & Metzger 24b]

See also:
[Liu+15]
[Lu&Quataert 23]

Evolution of Ablated Debris (Linial+25)

Ejecta fills Hill sphere within $\ll 0.1\, P_{\rm orb}$



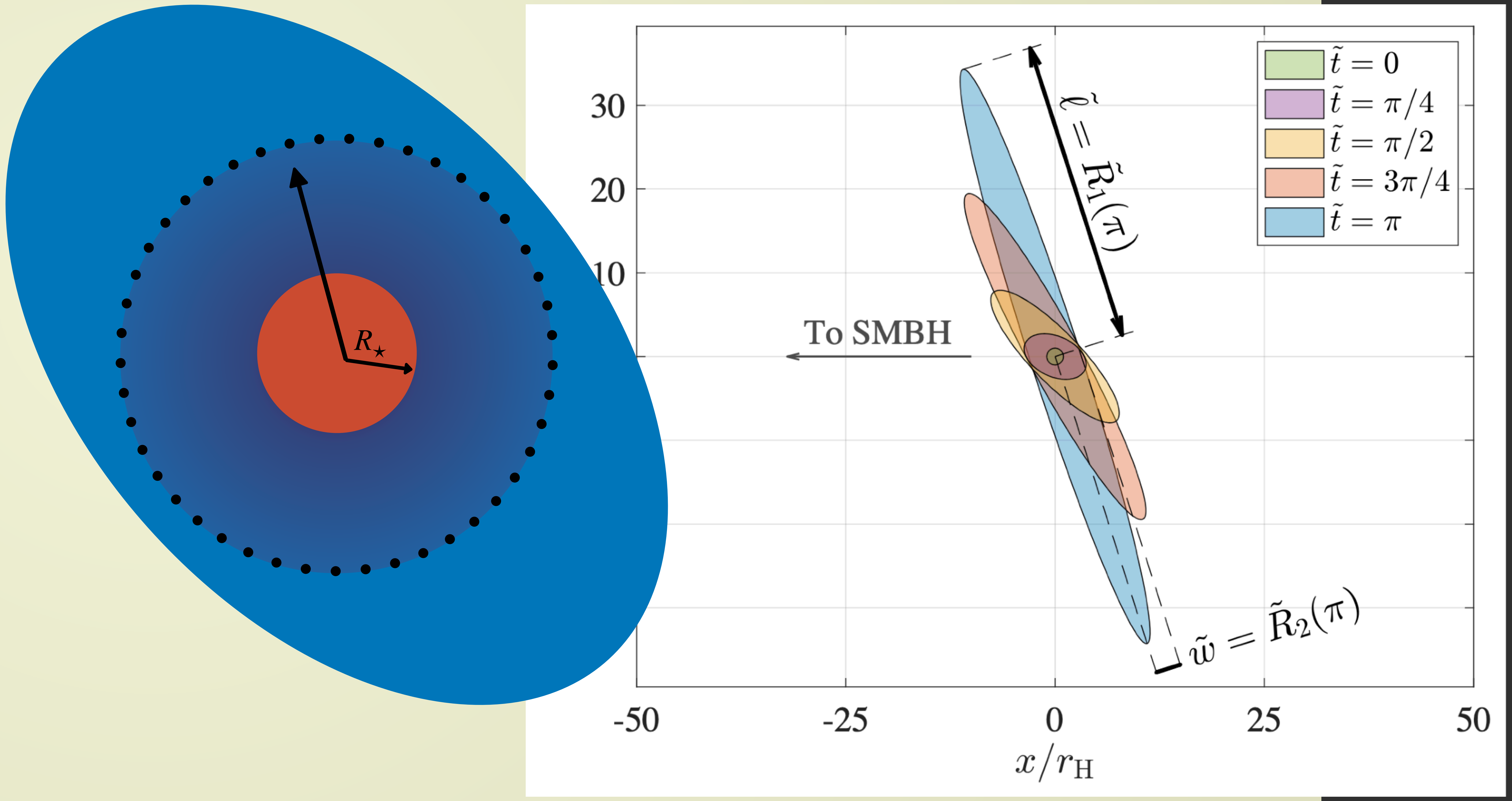
$r_{\rm H} \approx a_0 (m_\star / M_\bullet)^{1/3} = R_\star (a_0 / r_{\rm t})$

$v_{{\rm esc},\star} / \Omega_0 r_{\rm H} \approx \sqrt{a_0 / r_{\rm t}} \gg 1$

Outside Hill Sphere: Dominated by **TIDES**

Hill's Equations (1878)

$$\ddot{x} = 3\Omega_0^2 x + 2\Omega_0 \dot{z}\,,$$
$$\ddot{y} = -2\Omega_0 \dot{x}\,,$$
$$\ddot{z} = -\Omega_0^2 z\,.$$

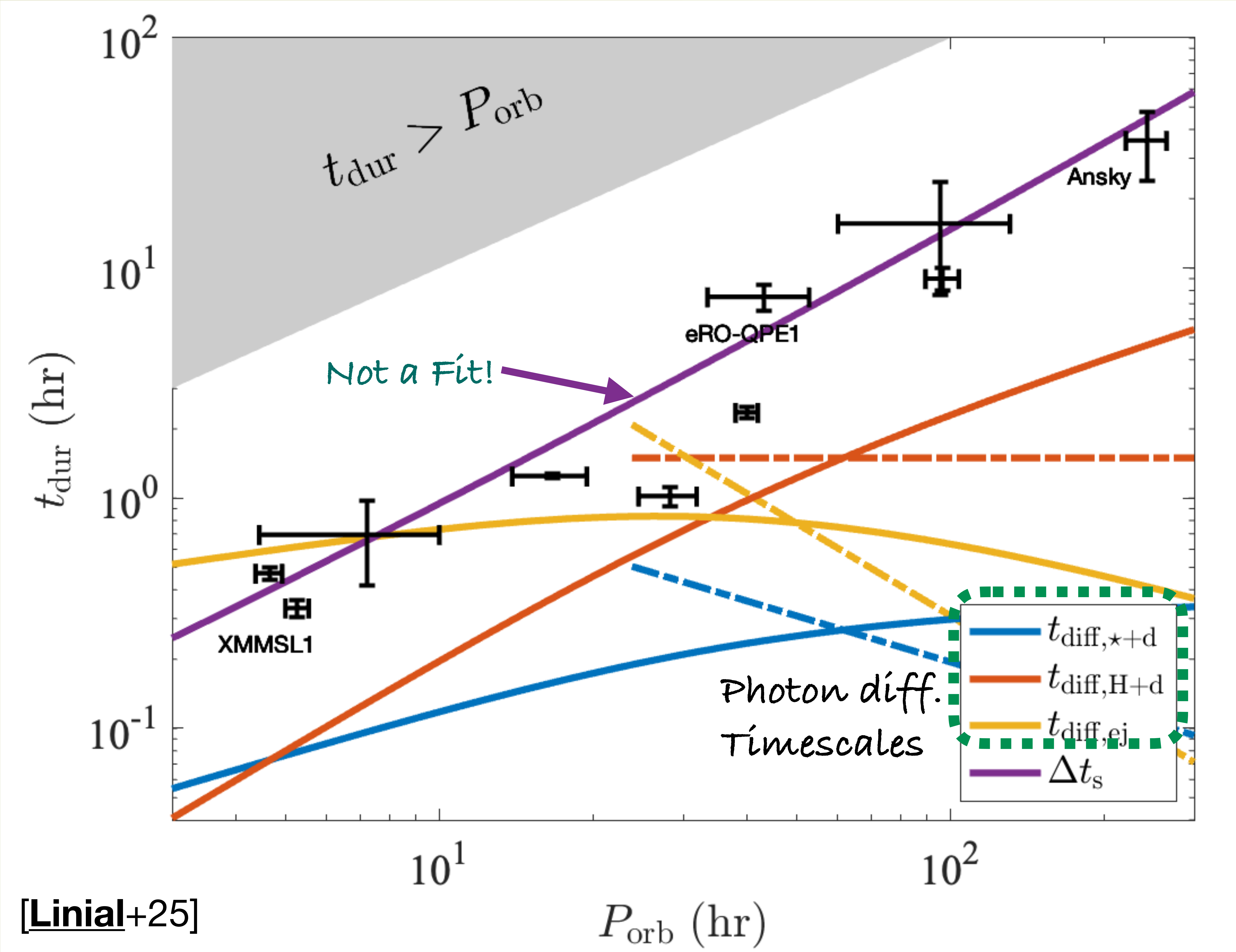


Debris Evolves to a an elongated Ellipsoid

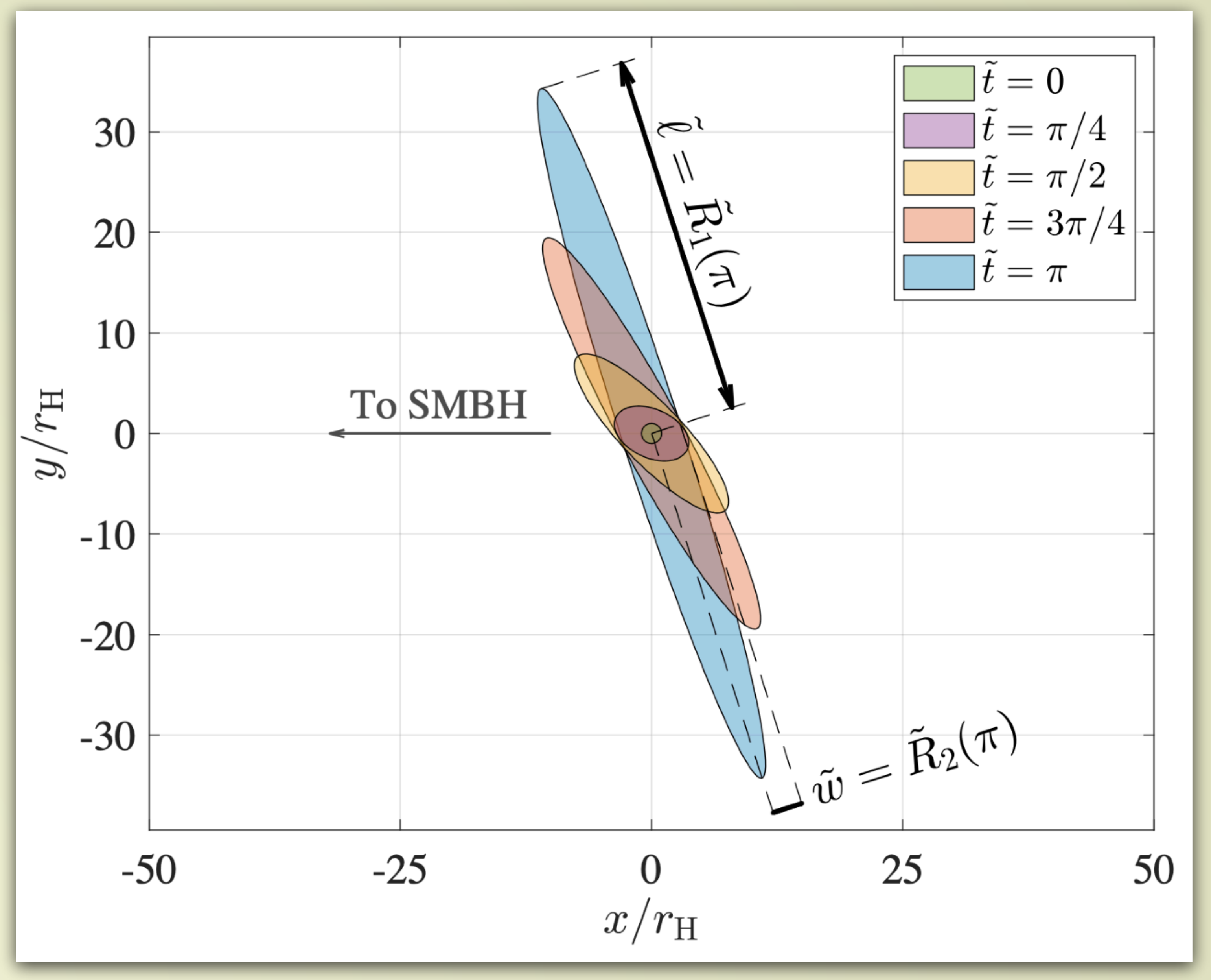
Flare Duration Set by Collision Duration

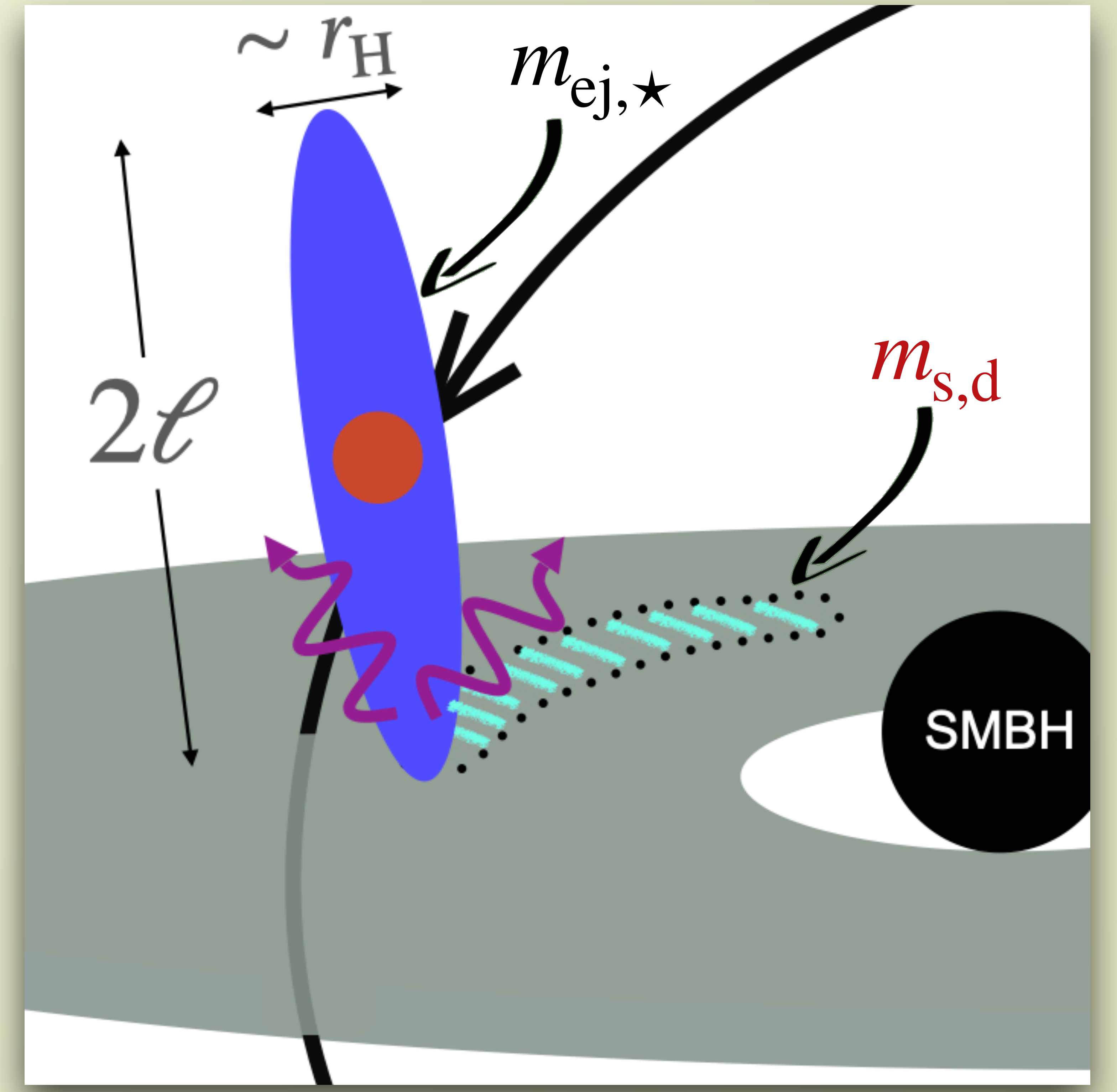
Stream-Disk Collision Time

$$\Delta t_{\rm flare} \approx 2\ell / v_{\rm k} \approx 0.1\, P_{\rm orb}$$

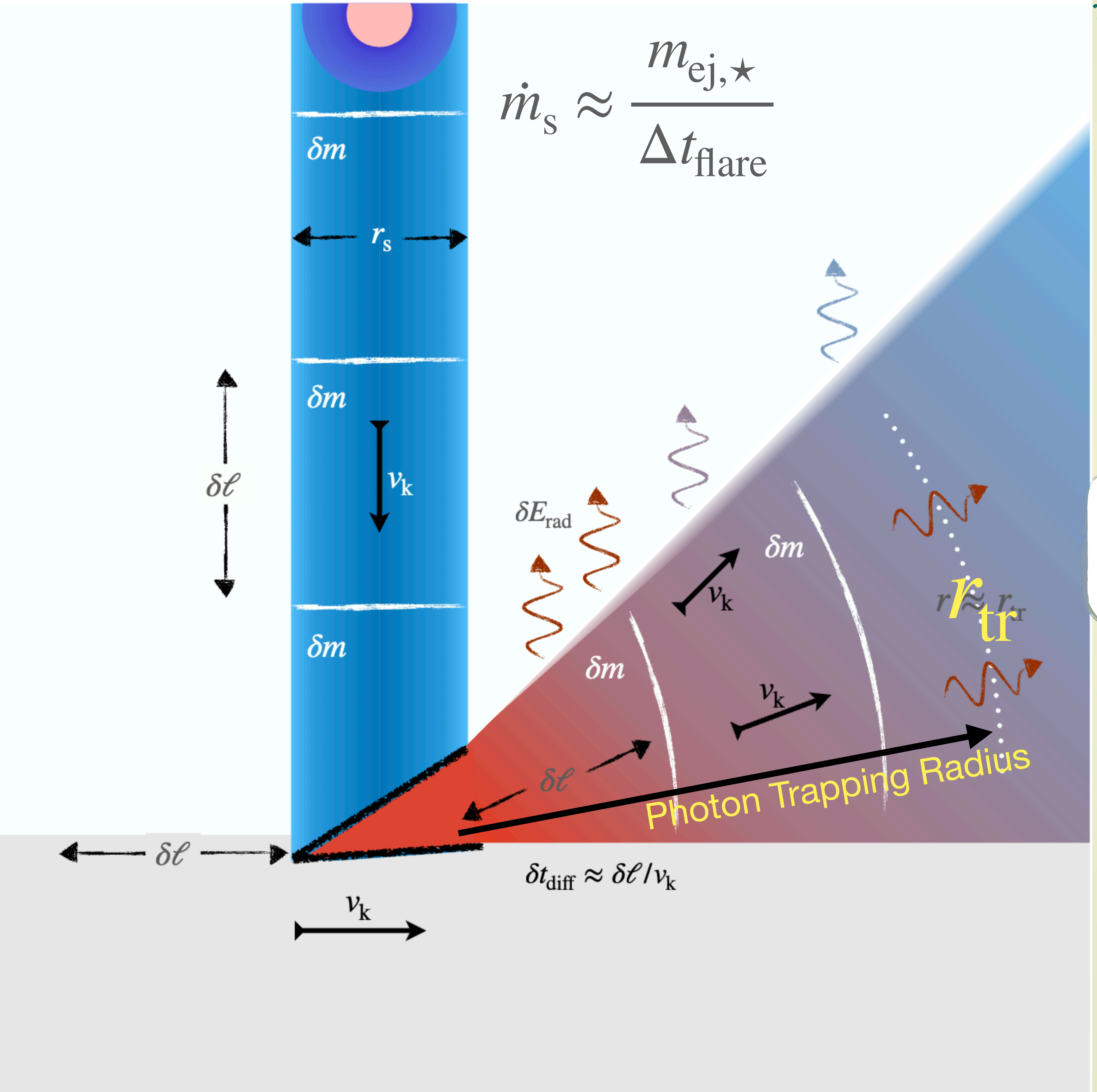


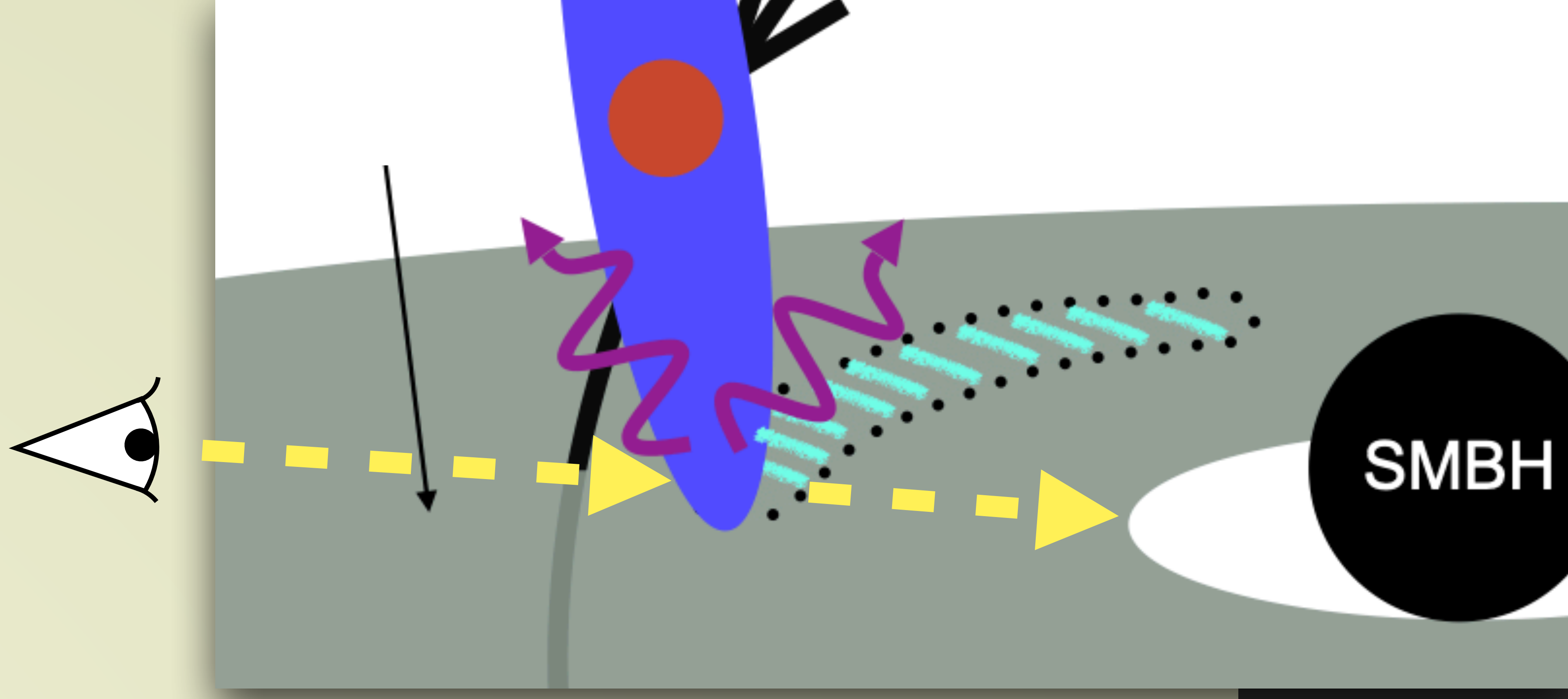
[Linial+25]





Stream-Disk Collision [Linial+25]





Radiative Efficiency

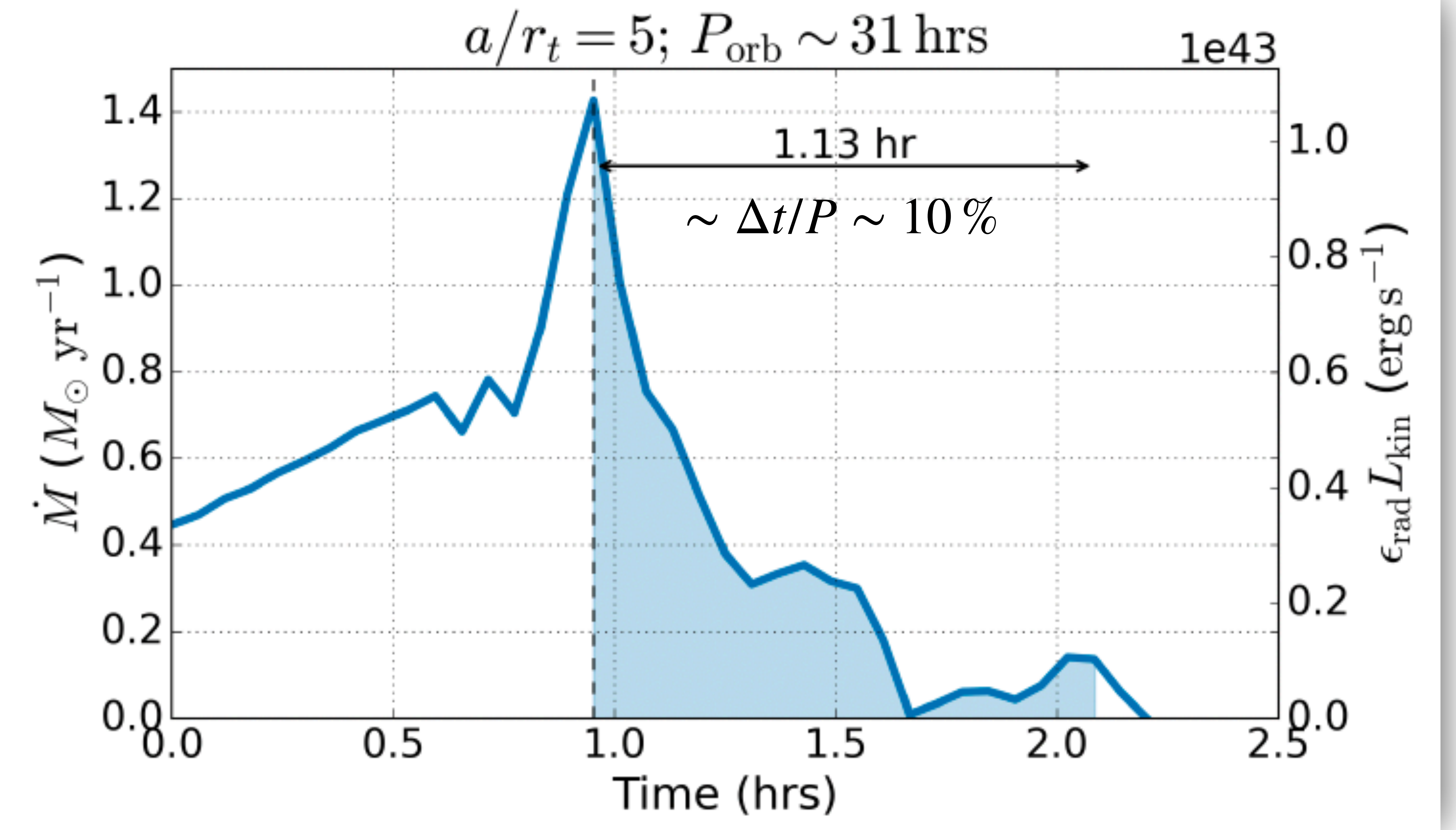
$$\varepsilon_{rad} \sim (r_{tr}/r_s) \propto (\dot{m}_s v_k^2)^{-1} \lesssim 1$$

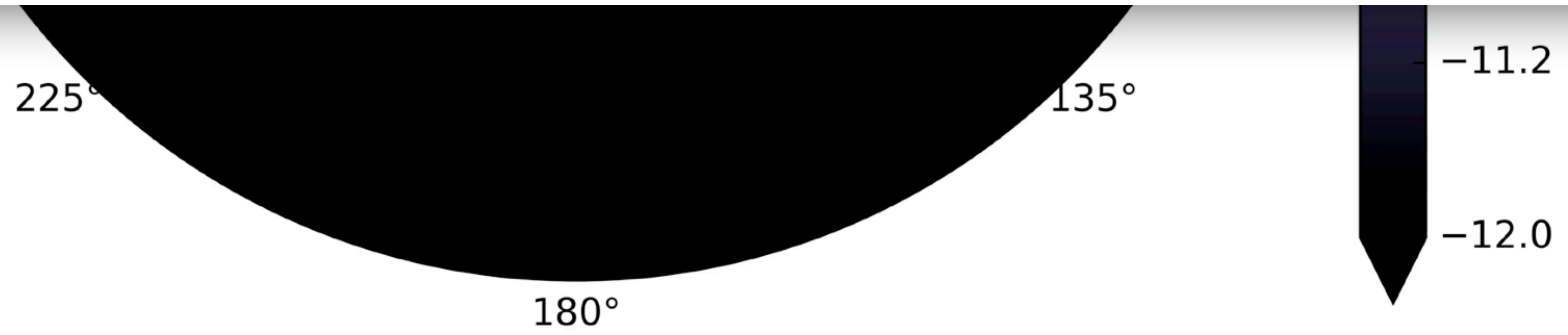
$$L_{bol} \approx \varepsilon_{rad} \dot{m}_s v_k^2 \approx 10^{43}\,\mathrm{erg\,s^{-1}}$$

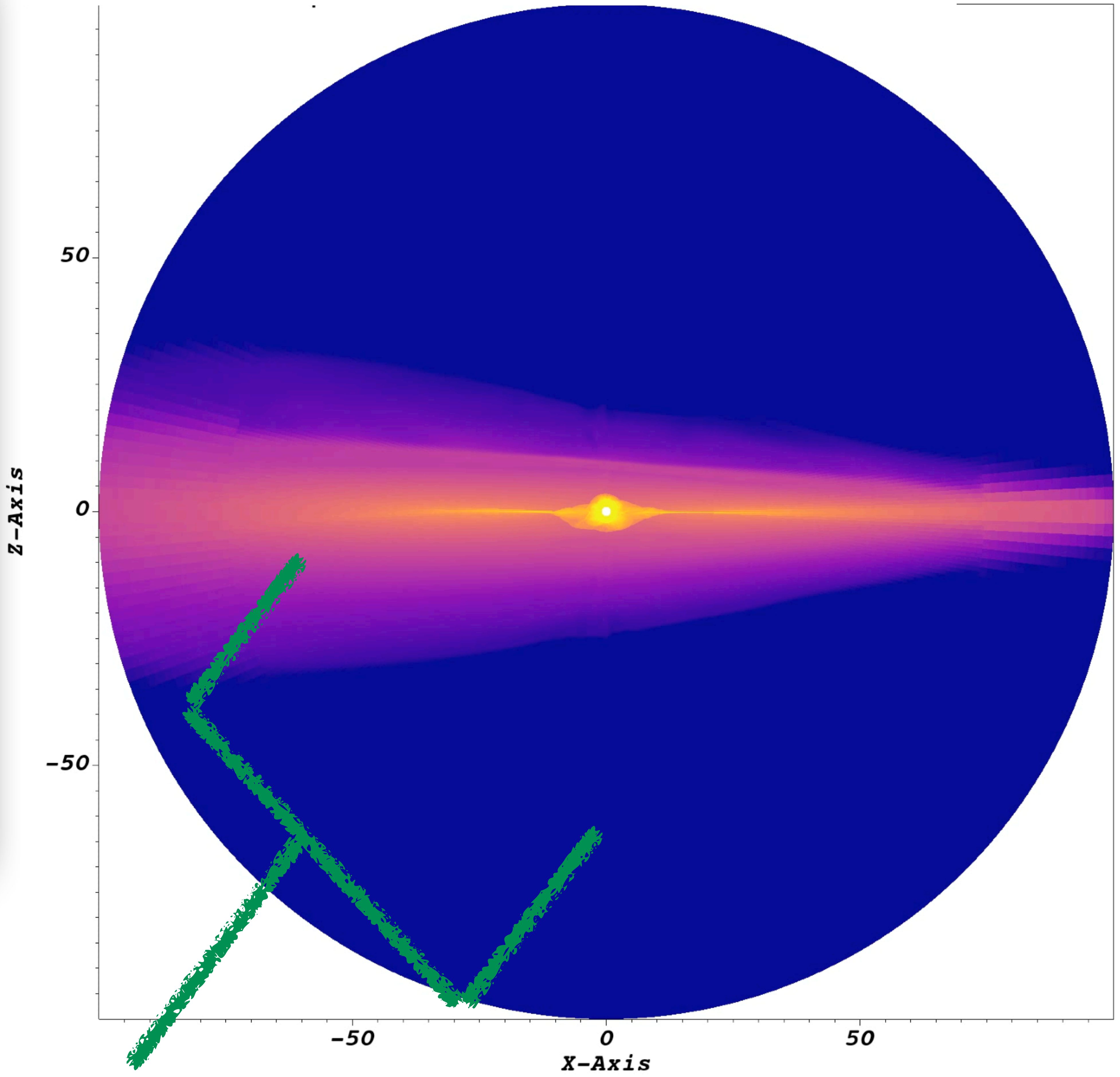
$$E_{rad} \approx L_{rad} P_{orb} \mathscr{D} \approx 10^{47}\,\mathrm{erg}\,(P_{orb}/1\,\mathrm{d})$$

$$T_{BB} \approx \varepsilon_{rad} (\rho_s v_k^2 / a_{rad})^{1/4} \approx (100 - 200\,\mathrm{eV}/k_B)\varepsilon_{rad}^{1/2}$$

Star/Stream/Disk Interaction (Yao+26 in prep., inc. Linial)







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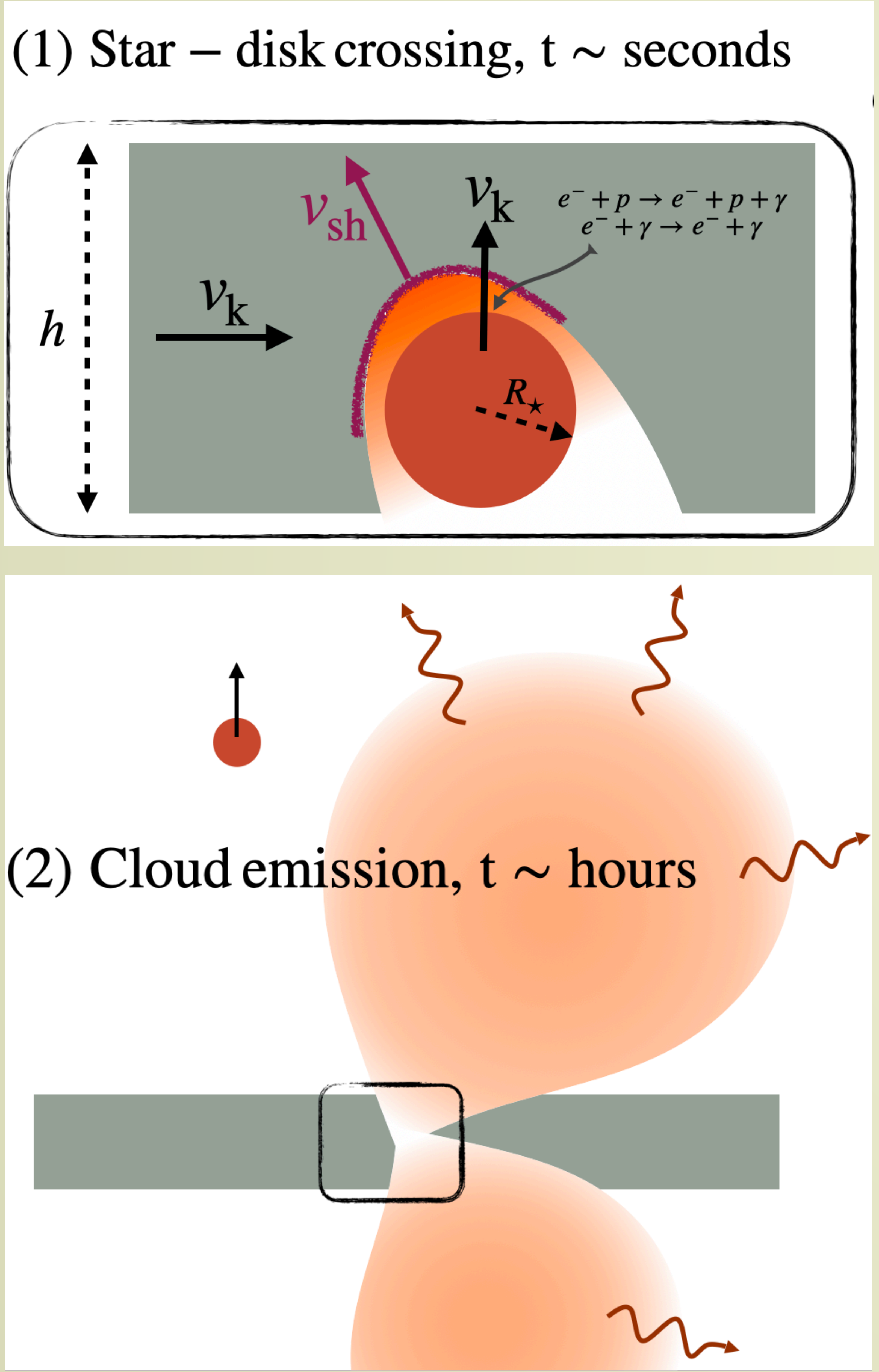
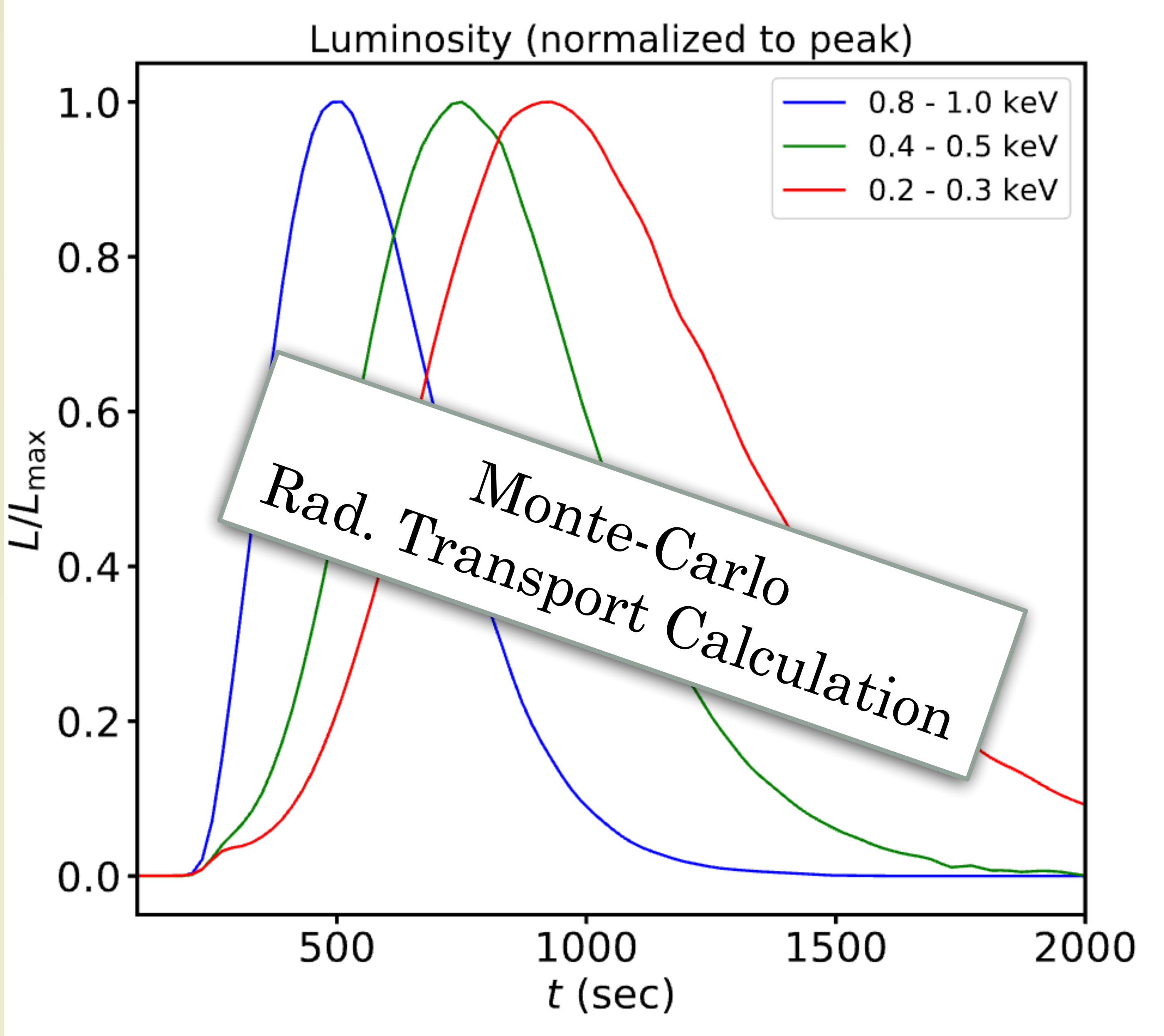
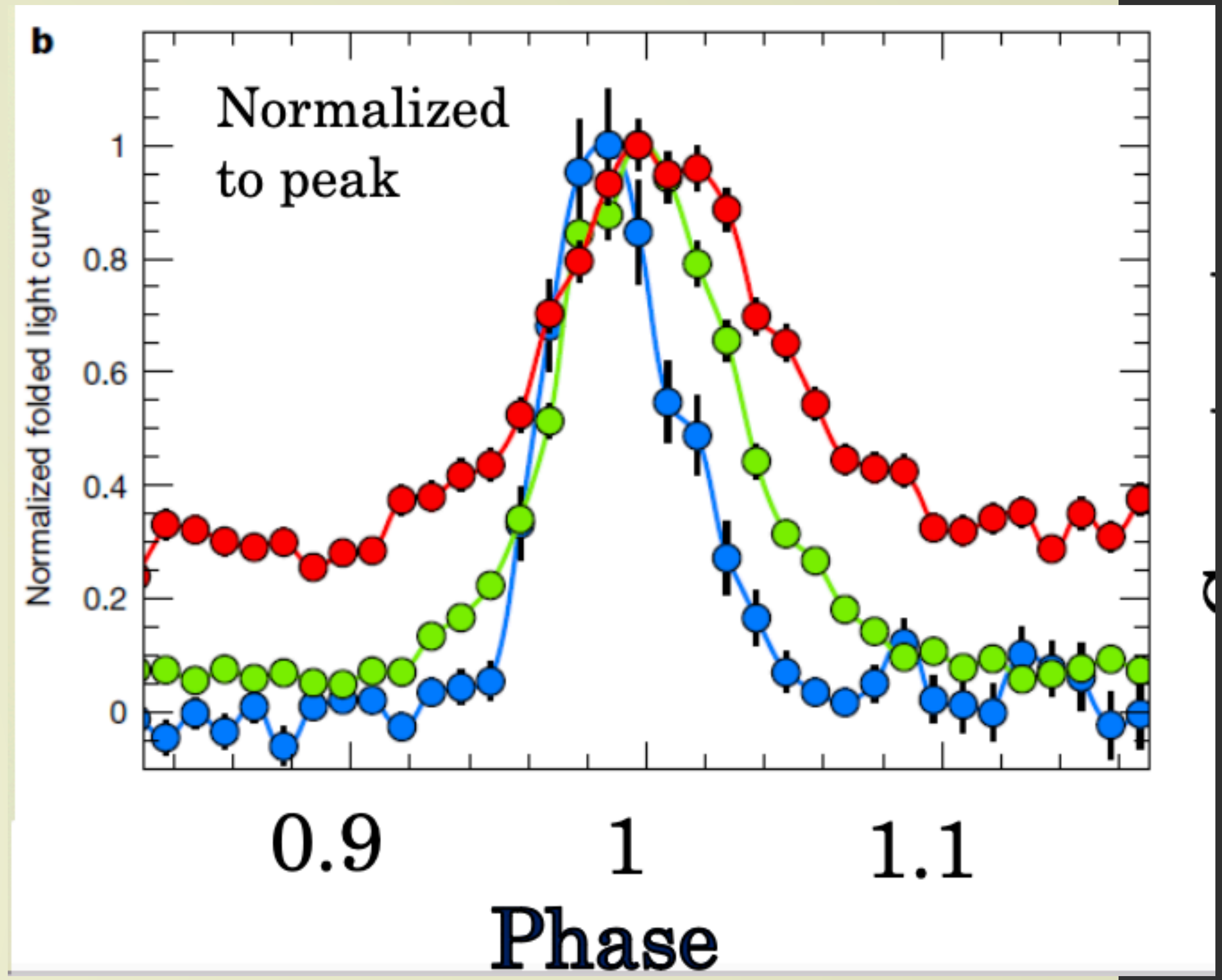
$$L(t) \approx \epsilon_{\rm rad}\, \dot{M}_{\rm stream} v_{\rm k}^2$$

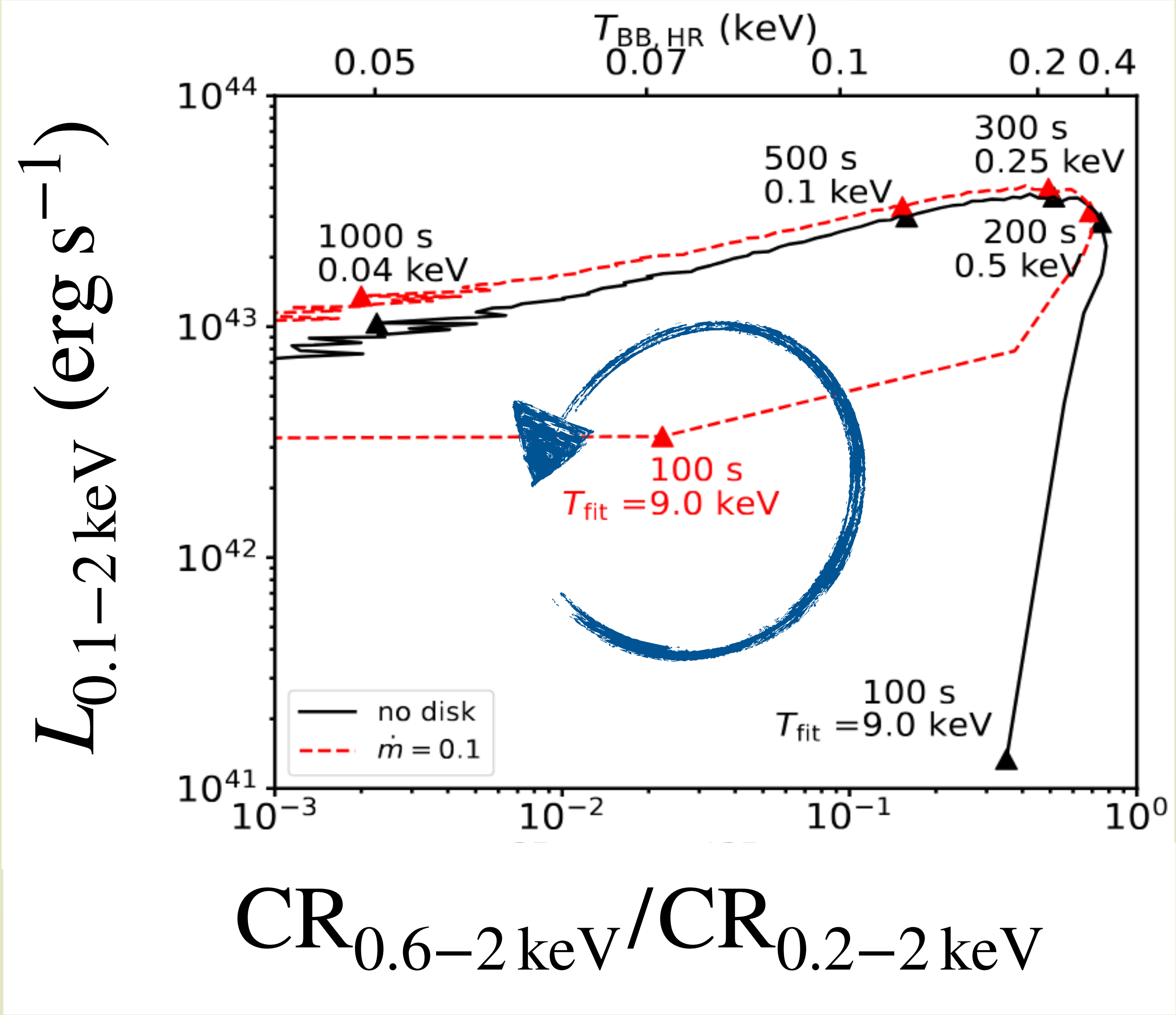
Star Disk Collisions - Numerical Calculation

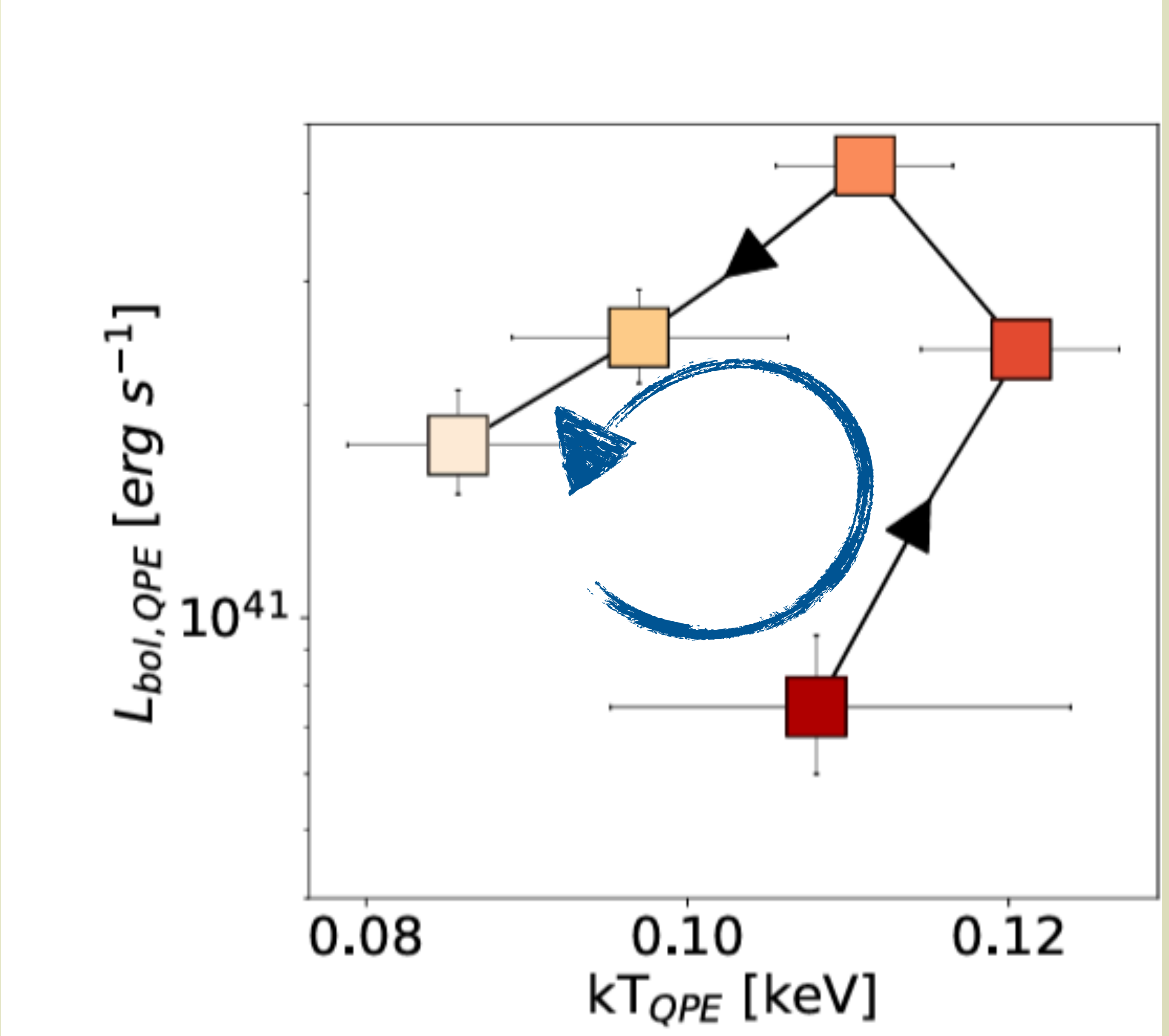
Vurm, **Linial**, Metzger (2025)



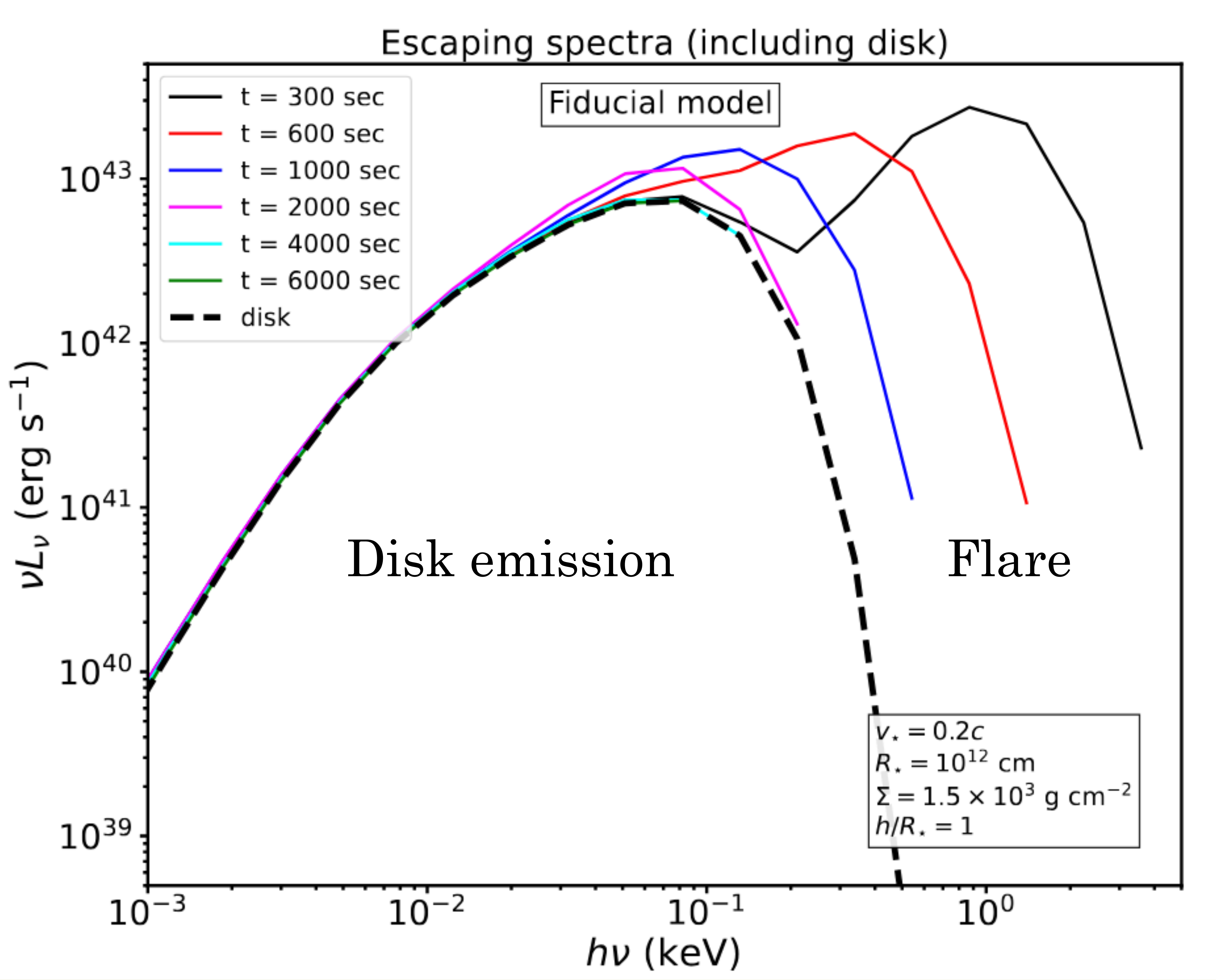


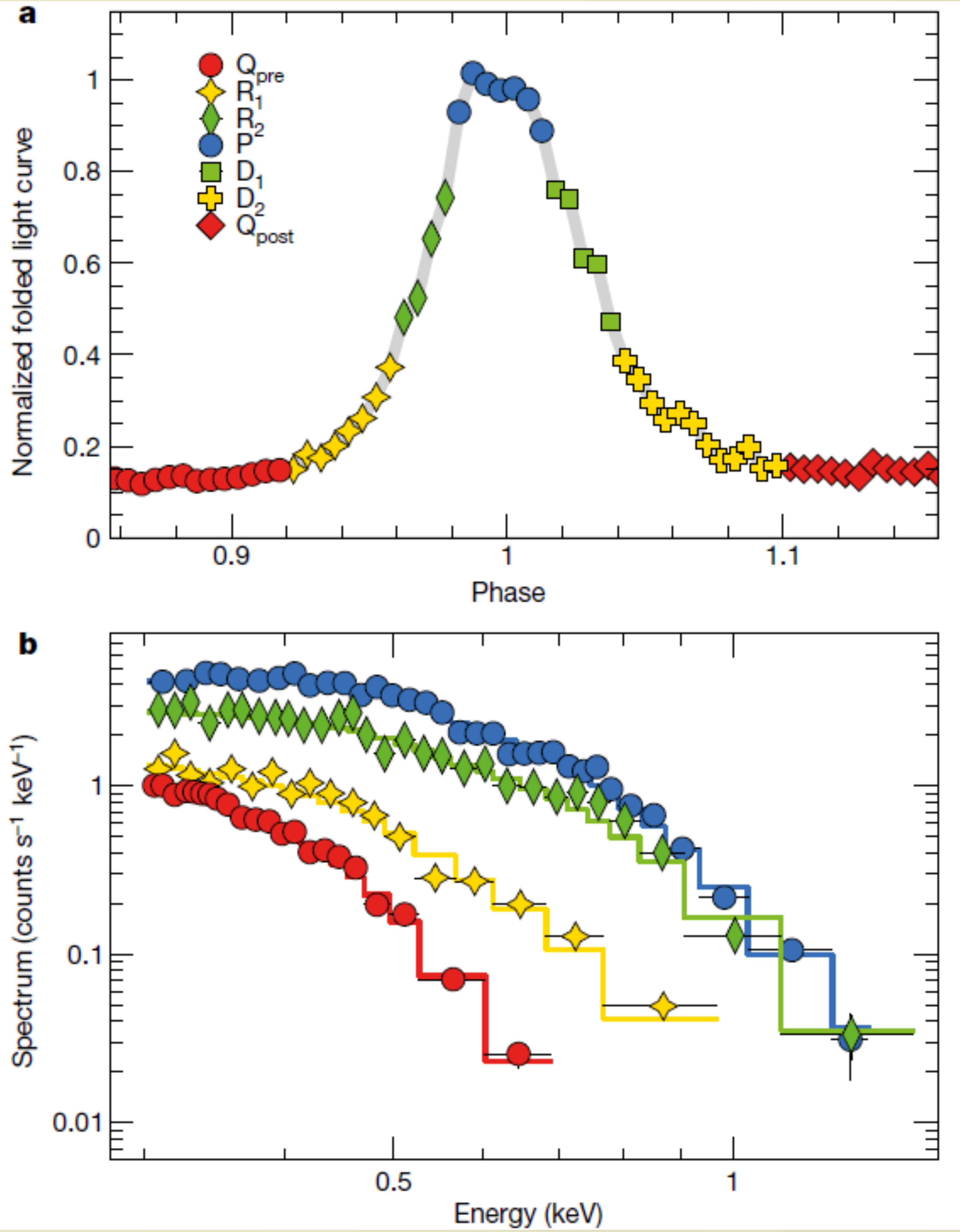




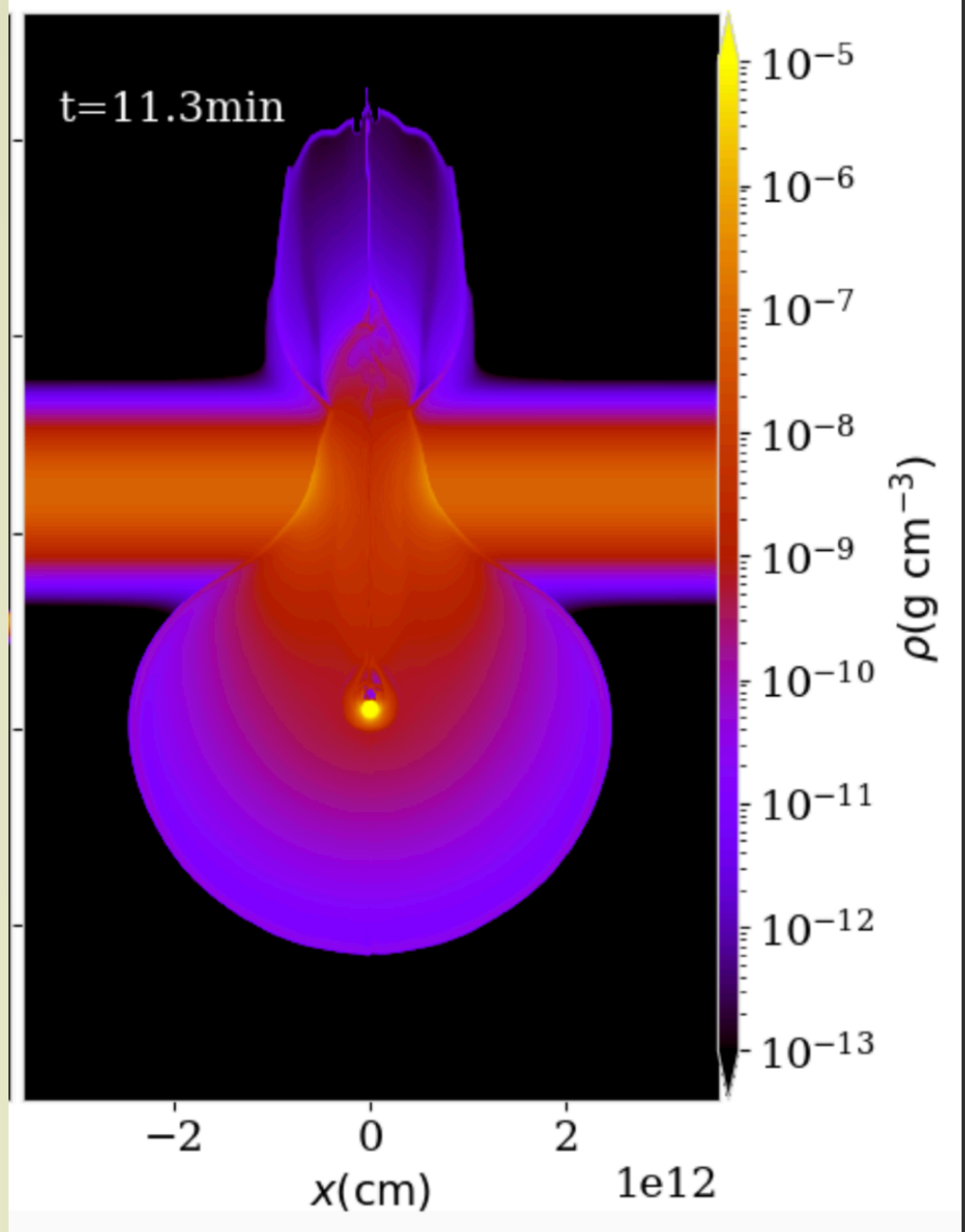


Flare + Disk Emission

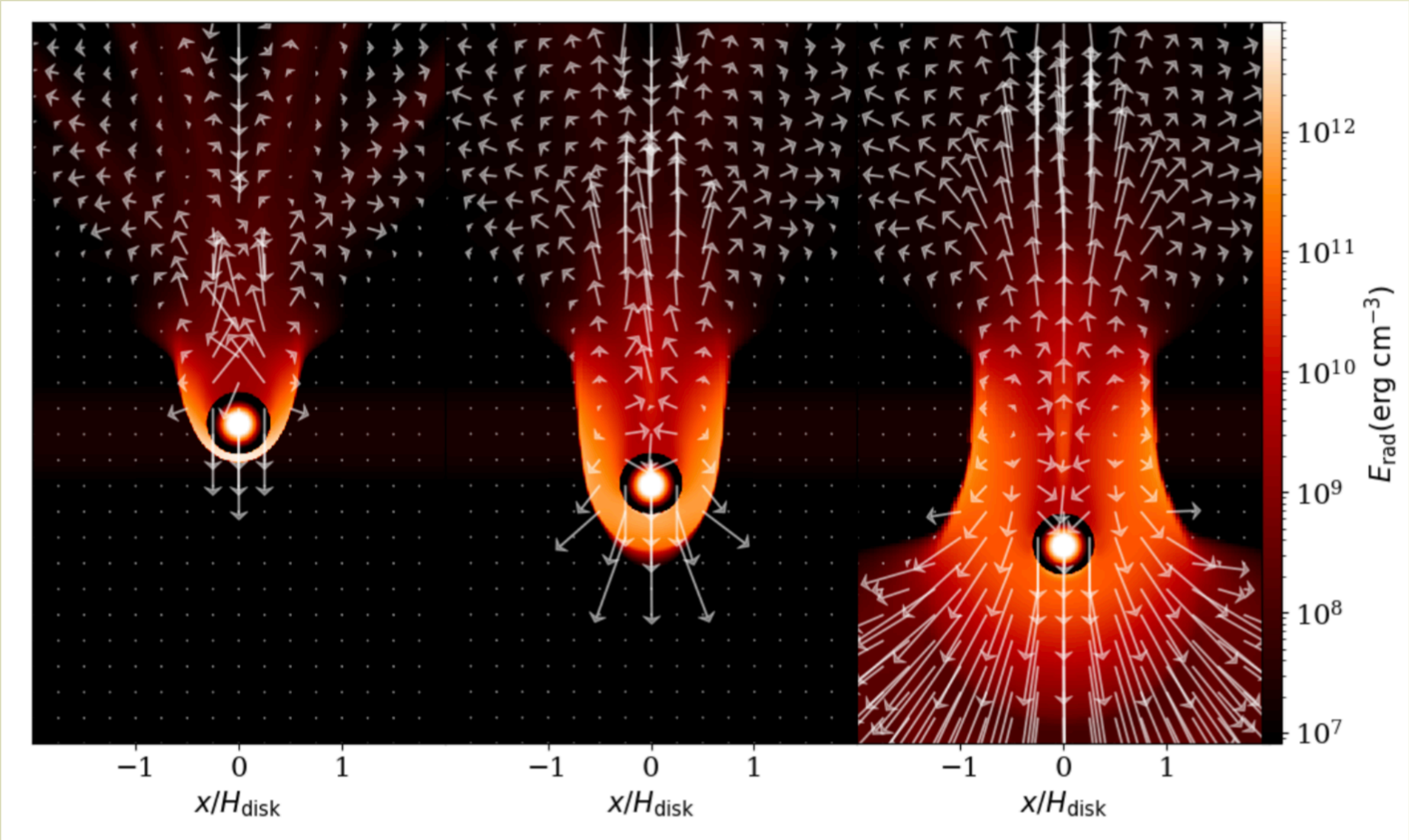


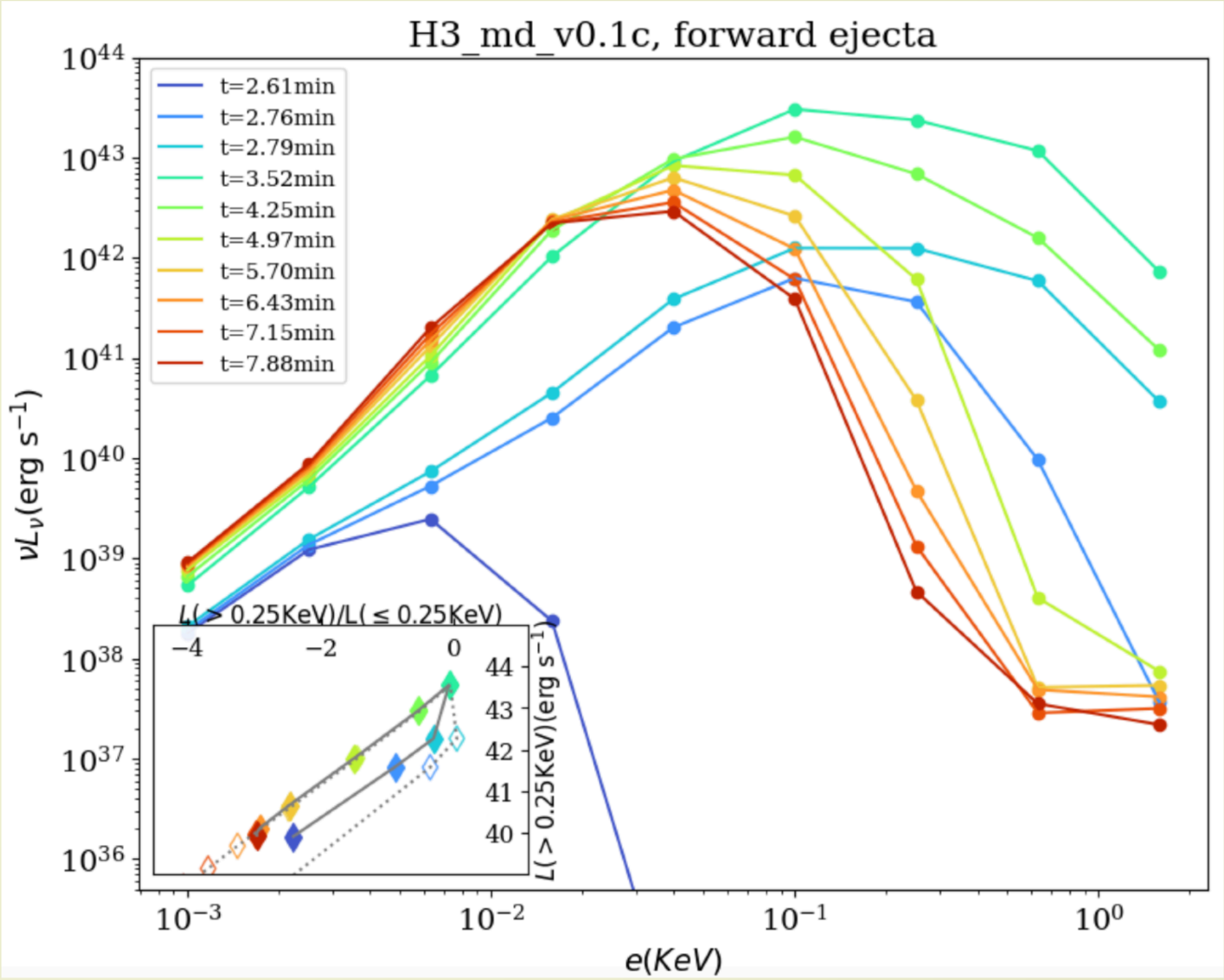


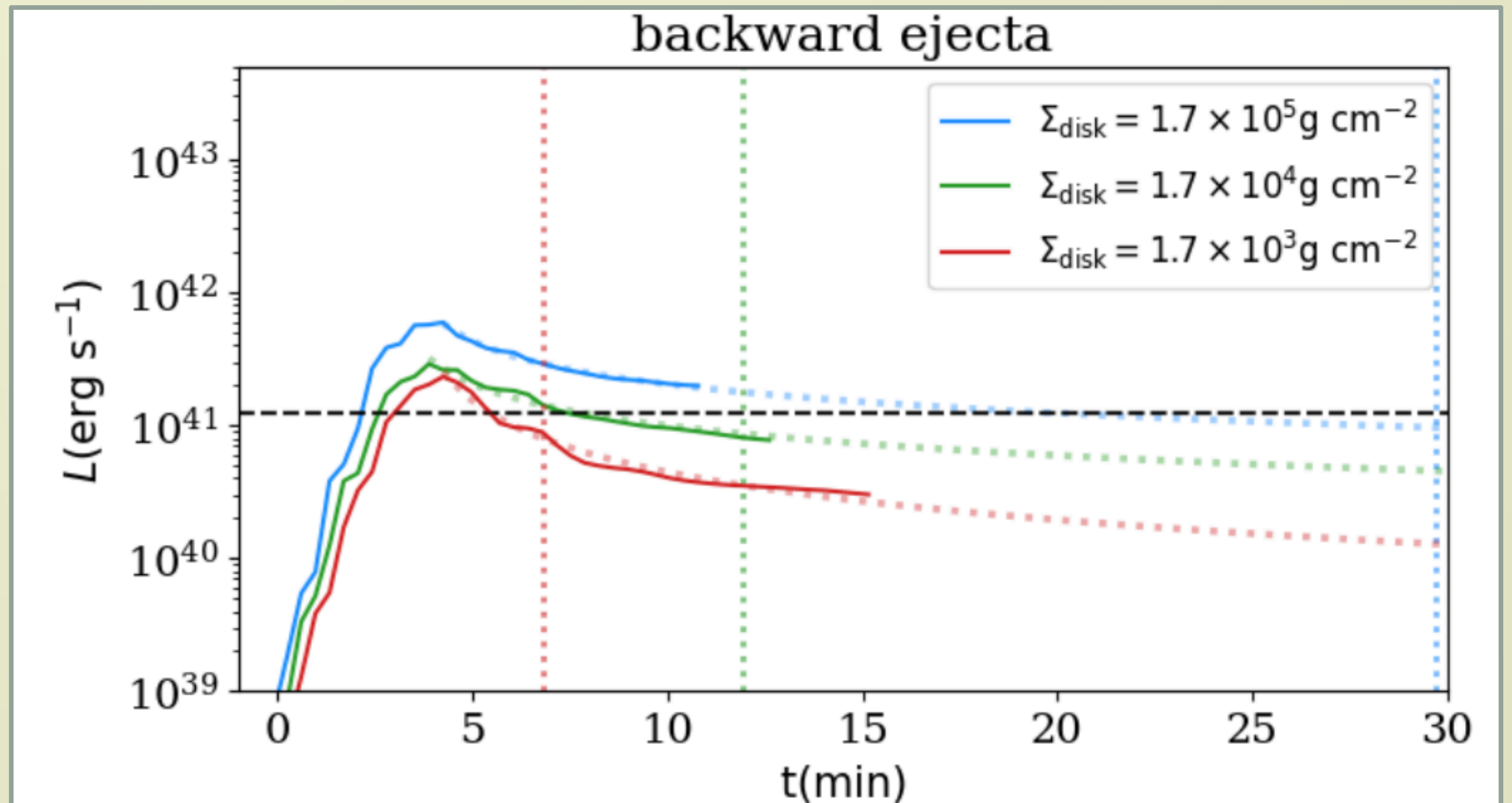
Star-Disk Collision Simulations:
Huang, Jiang & **Linial** (2025)



- Athena++
  2D, Multi-group, Rad-Hydro Simulations, TOPS opacity







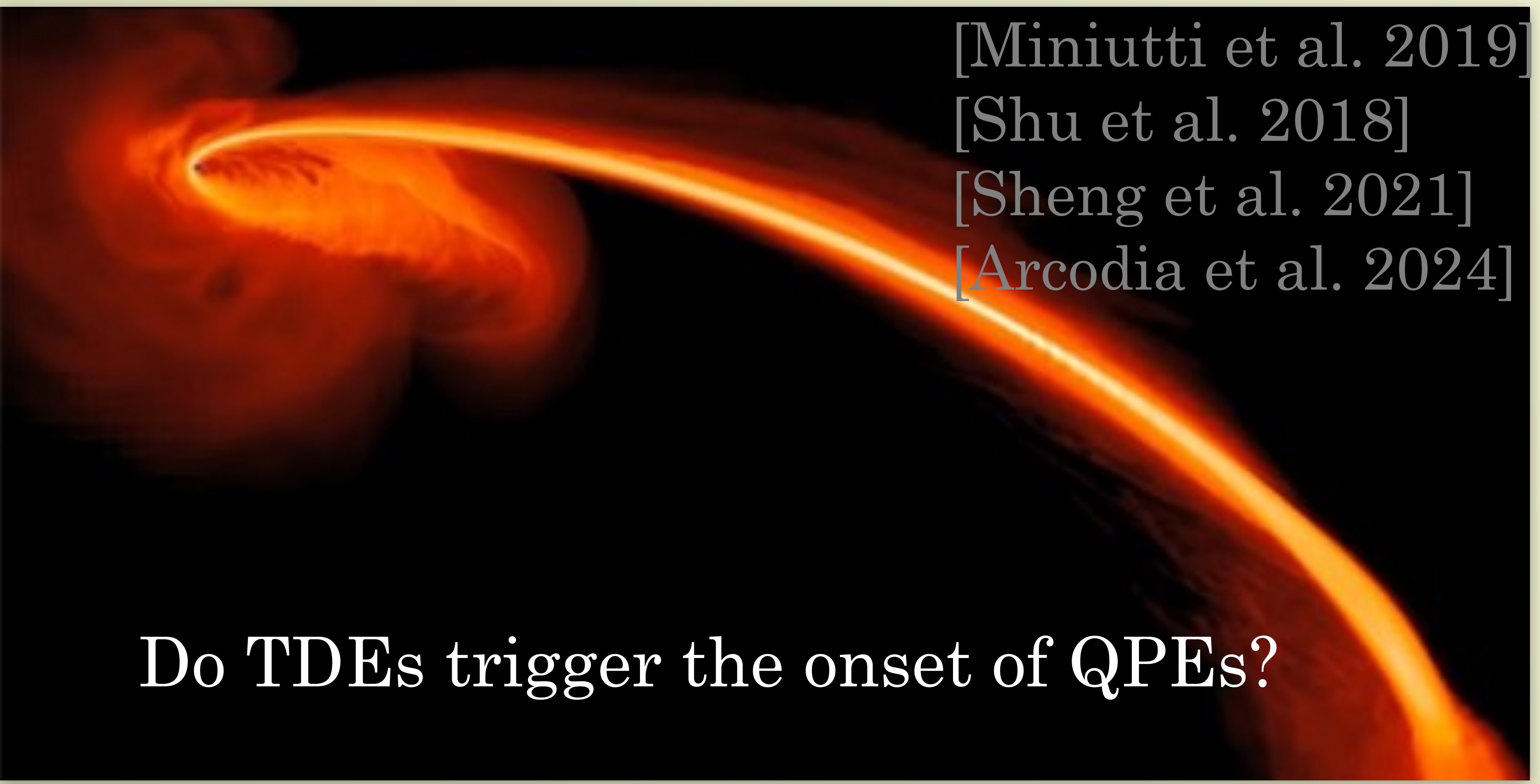
* Forward/backward ejecta asymmetries
* Less asymmetry when $H_{\rm d}/R_\star \gtrsim 7$
* Flare energetics and temperature consistent with systems of $P_{\rm QPE} \approx \mathcal{O}(\rm hrs)$

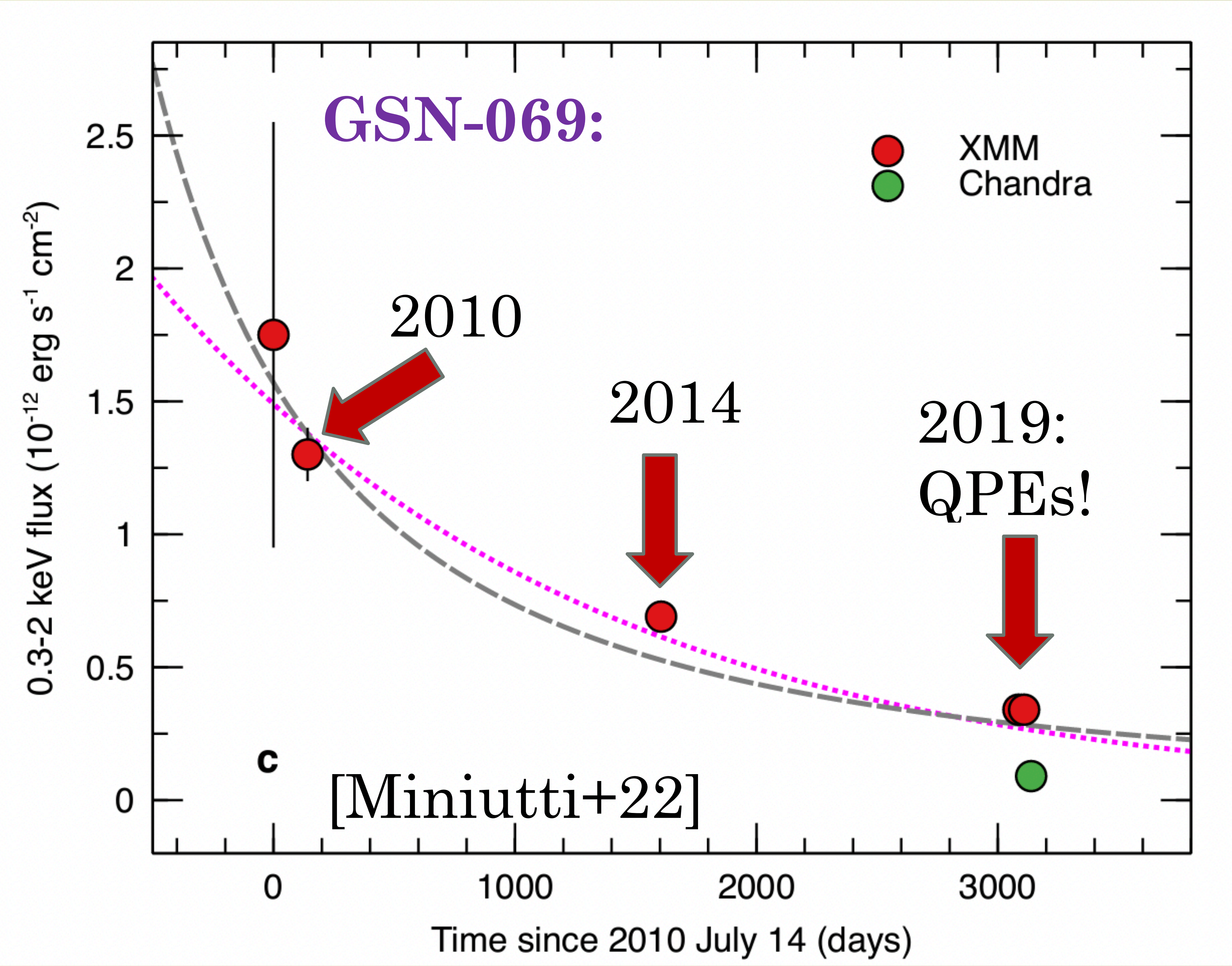
(Pre 2024:) Tentative QPE-TDE association

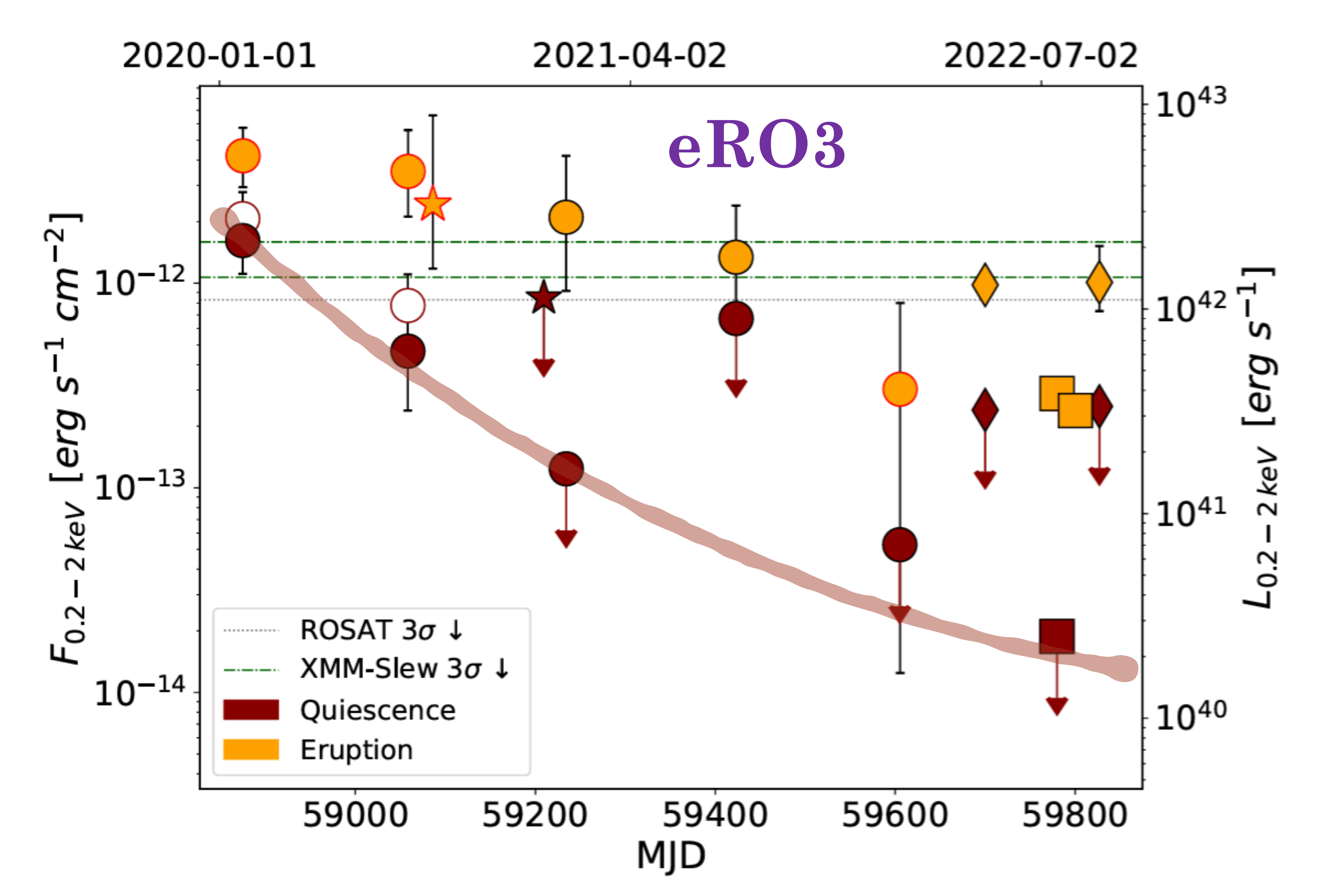
- Gradual **X-ray decay** of quiescence prior to onset of QPE flares
  (seen in GSN-069, eRO-QPE3 + two candidates)

- QPE hosts generally consistent with TDE hosts
  [Wevers+22]

- Narrow lines, phases of nuclear activity
  [Ionized outflow: Kosec+24]





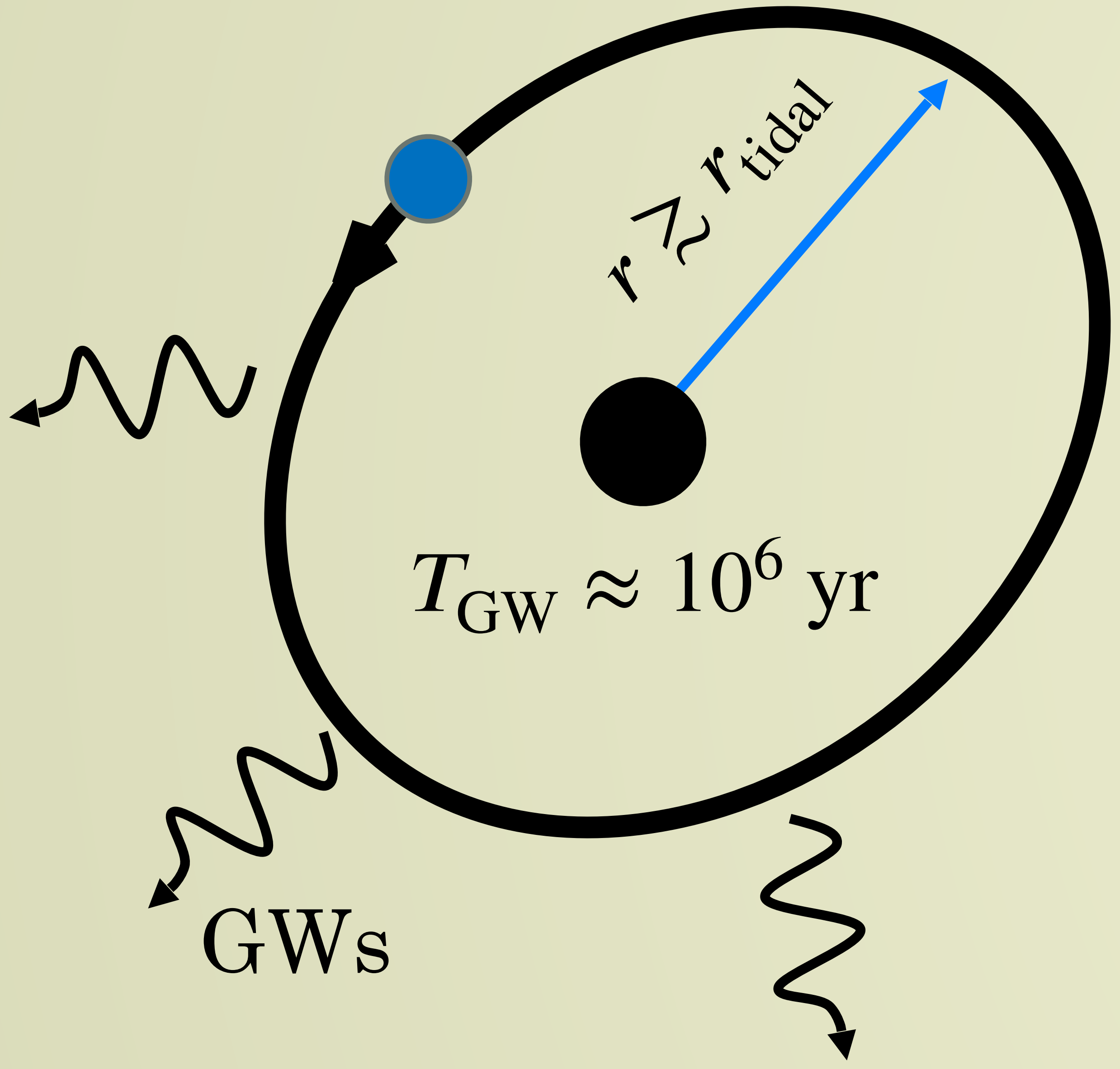


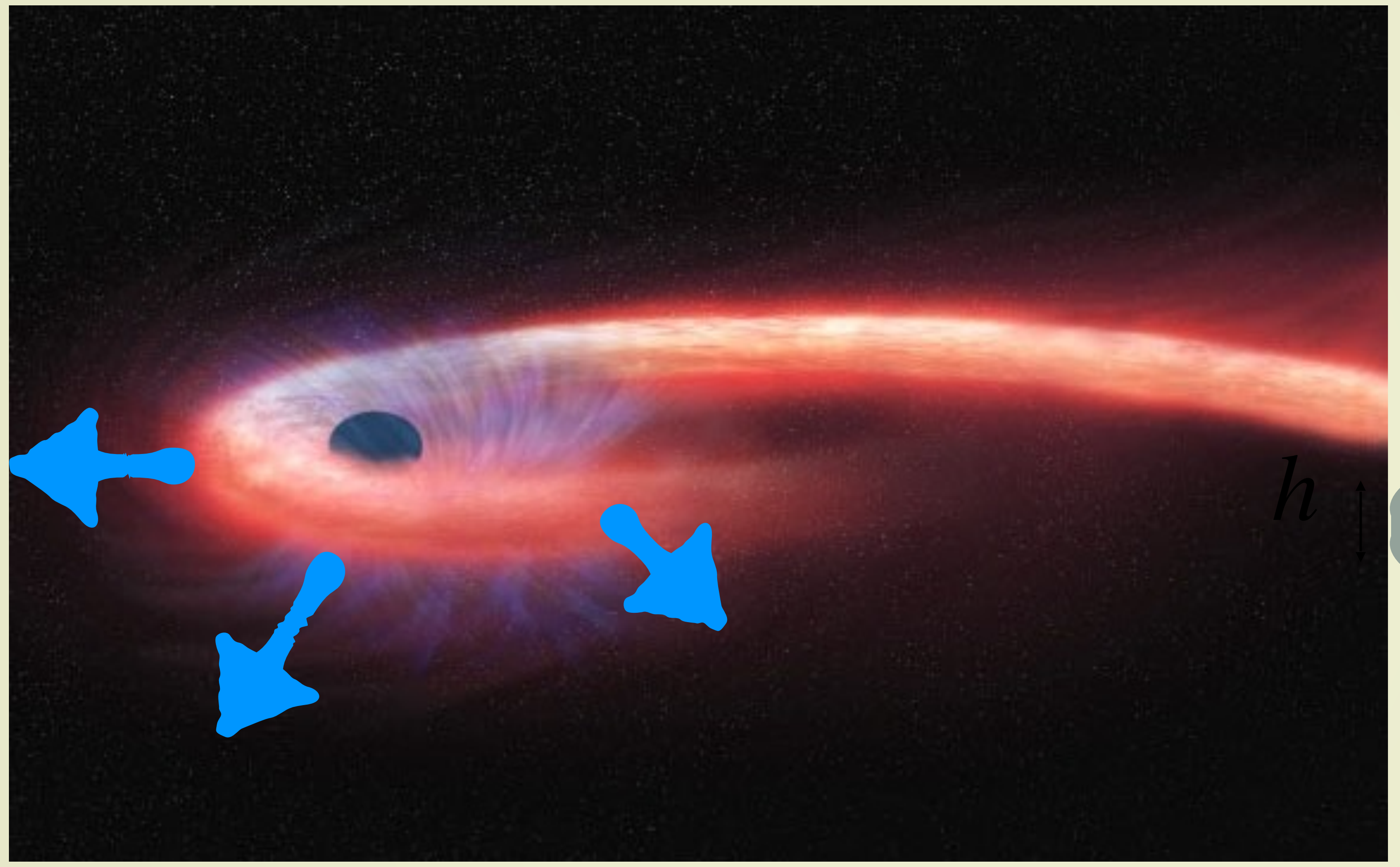
EMRI + TDE = QPE: Periodic X-Ray Flares from Star–Disk Collisions in Galactic Nuclei

Itai Linial[1] and Brian D. Metzger[2,3]

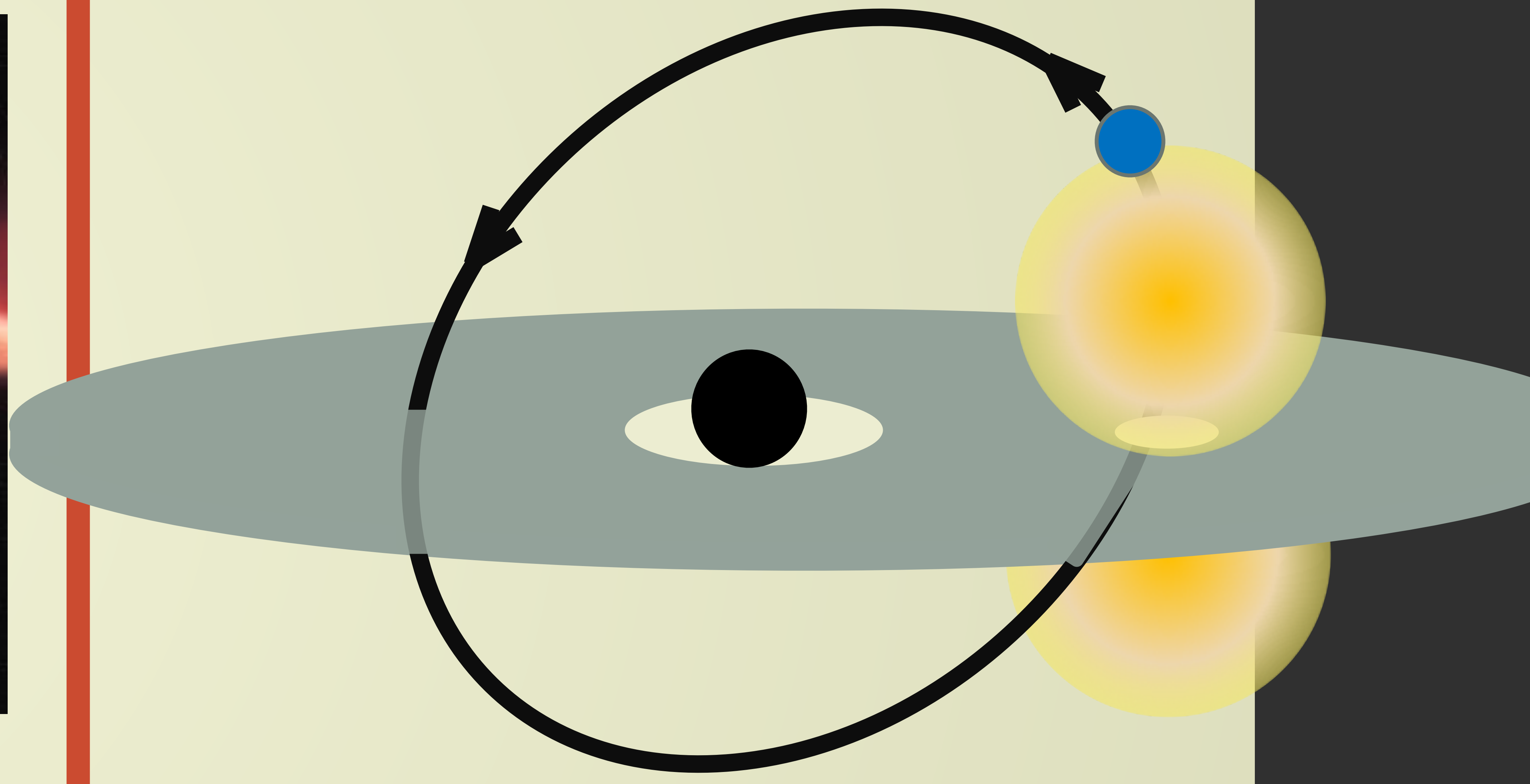
[Linial & Metzger 23]

"EMRI + TDE = QPE"





$\mathscr{R}_{\rm TDE} \approx 10^{-5} - 10^{-4}\ {\rm yr^{-1}\ gal^{-1}}$



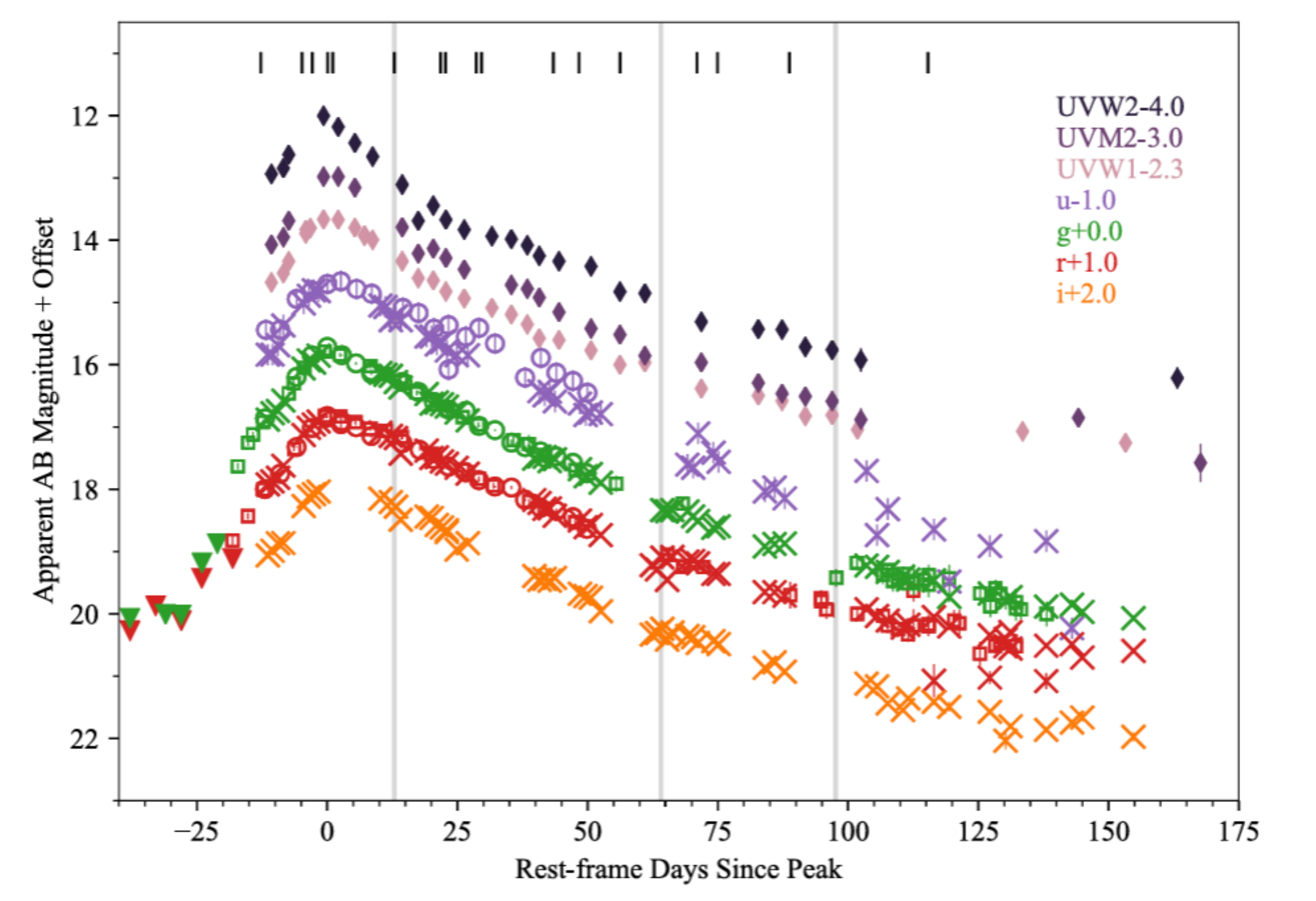
* **QPE-TDE association**
* **Delay time** between TDE and QPE (settle to cold disk)
* Delayed onset due to **disk spreading** and/or $\dot{M}_{\rm d}$ **evolution**
* Typically **high inclination**
* Reproduces **QPE periodicity** ($r_{\rm disc} \approx 2 r_{\rm tidal}$)

The relative rates of TDEs and stellar EMRIs are such that a significant fraction ∼1%–10% of TDE flares should host a QPE, depending in the details on the EMRI rate and number of TDE flares a given EMRI can survive (Section 3.3). Within large theoretical and observational uncertainties, the occurrence rate of EMRI-TDE

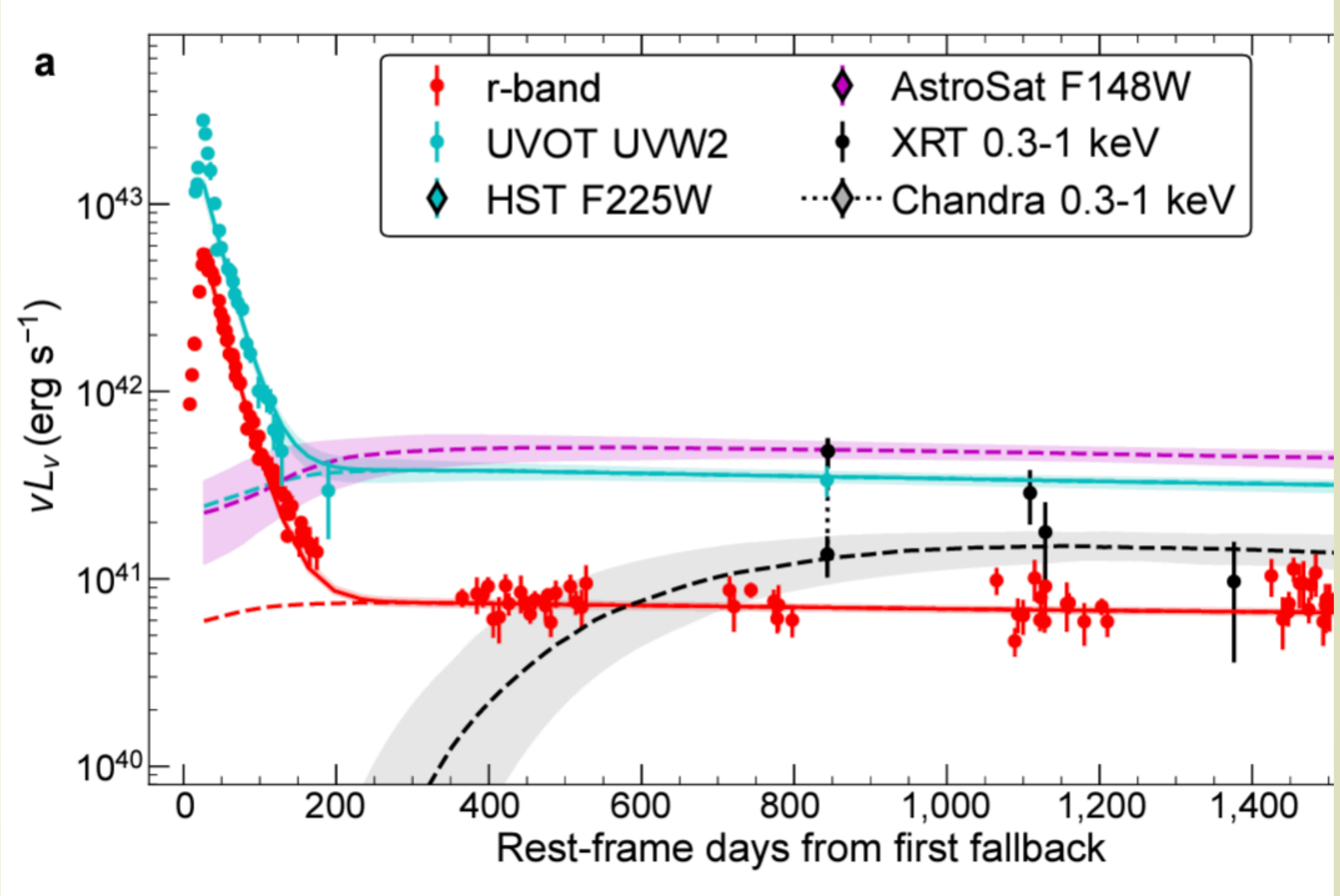
The Case of AT 2019qiz

April 2024 (Nicholl+24)

AT 2019qiz (detected 09/19/19)

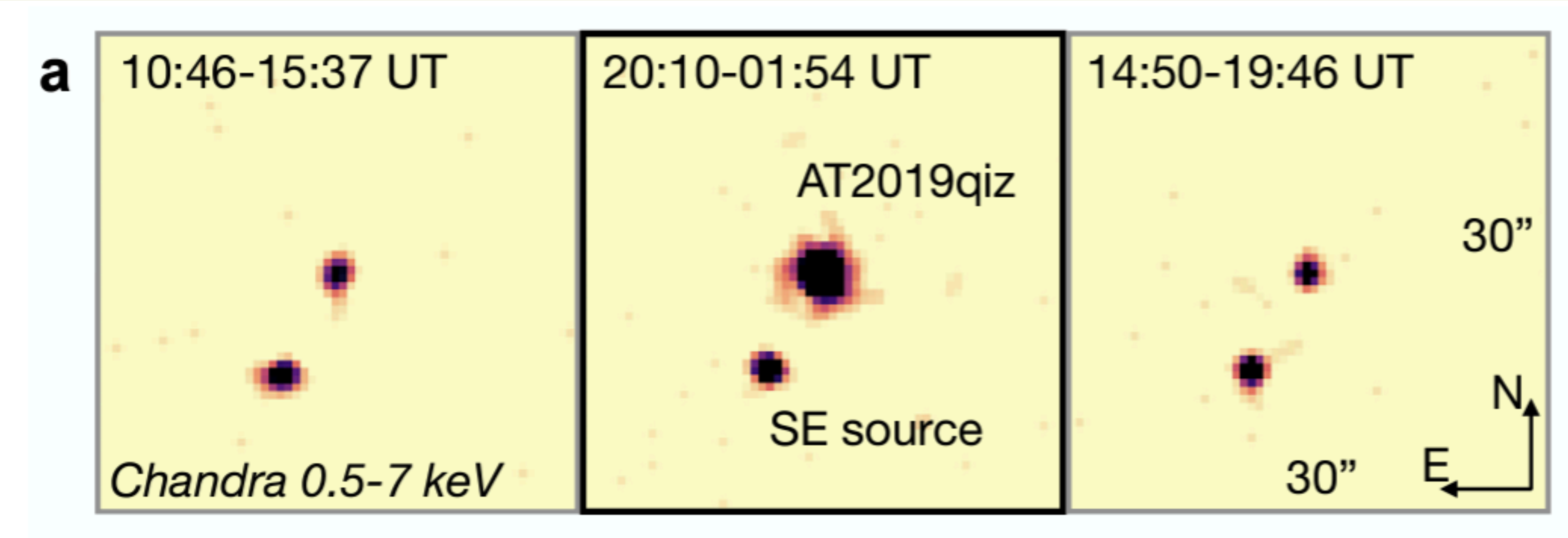


Late time disk-like emission

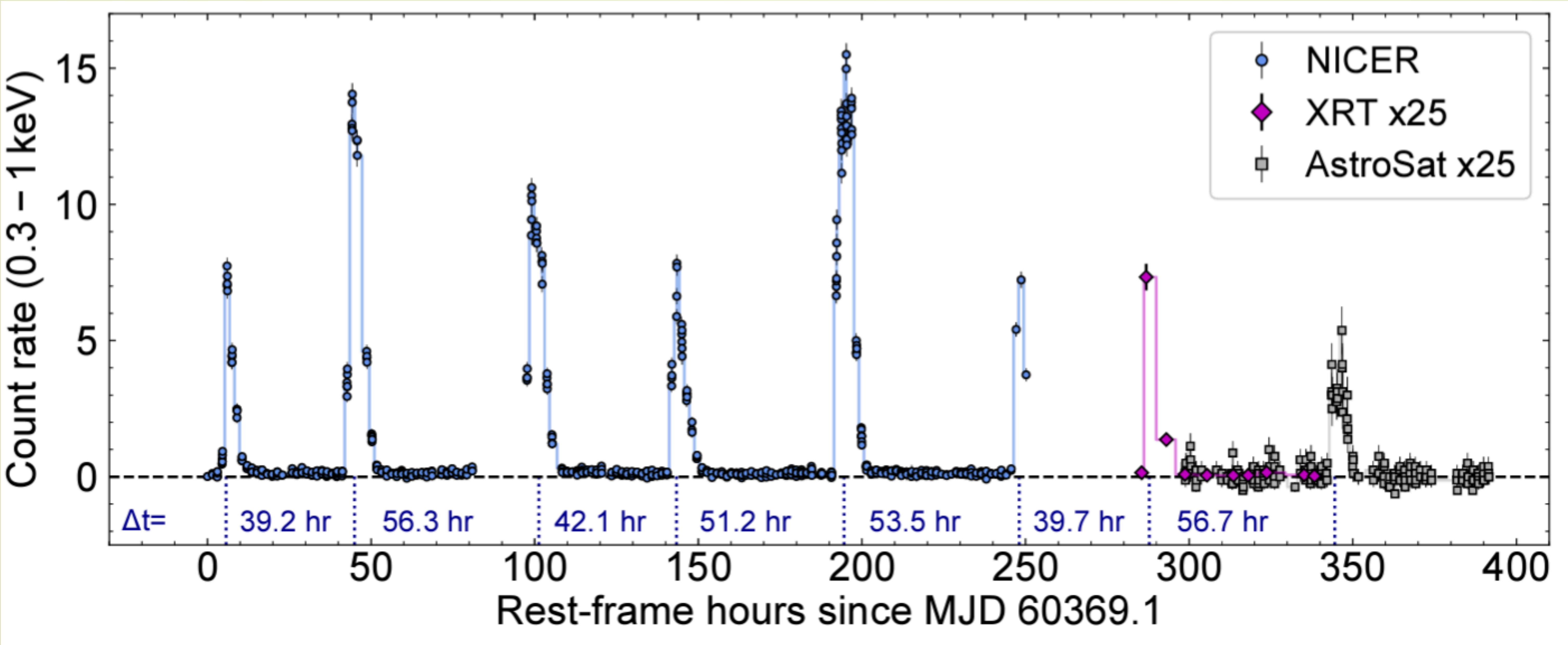


* Typical optical TDE light curve + spectra
* Nearby TDE ($z = 0.0151$, $\sim 65\,\mathrm{Mpc}$)
* Typical late time **UV/optical plateau**, characteristic of radiatively efficient time-evolving disk [Mummery+21]

Followup observations for studying TDE disks…



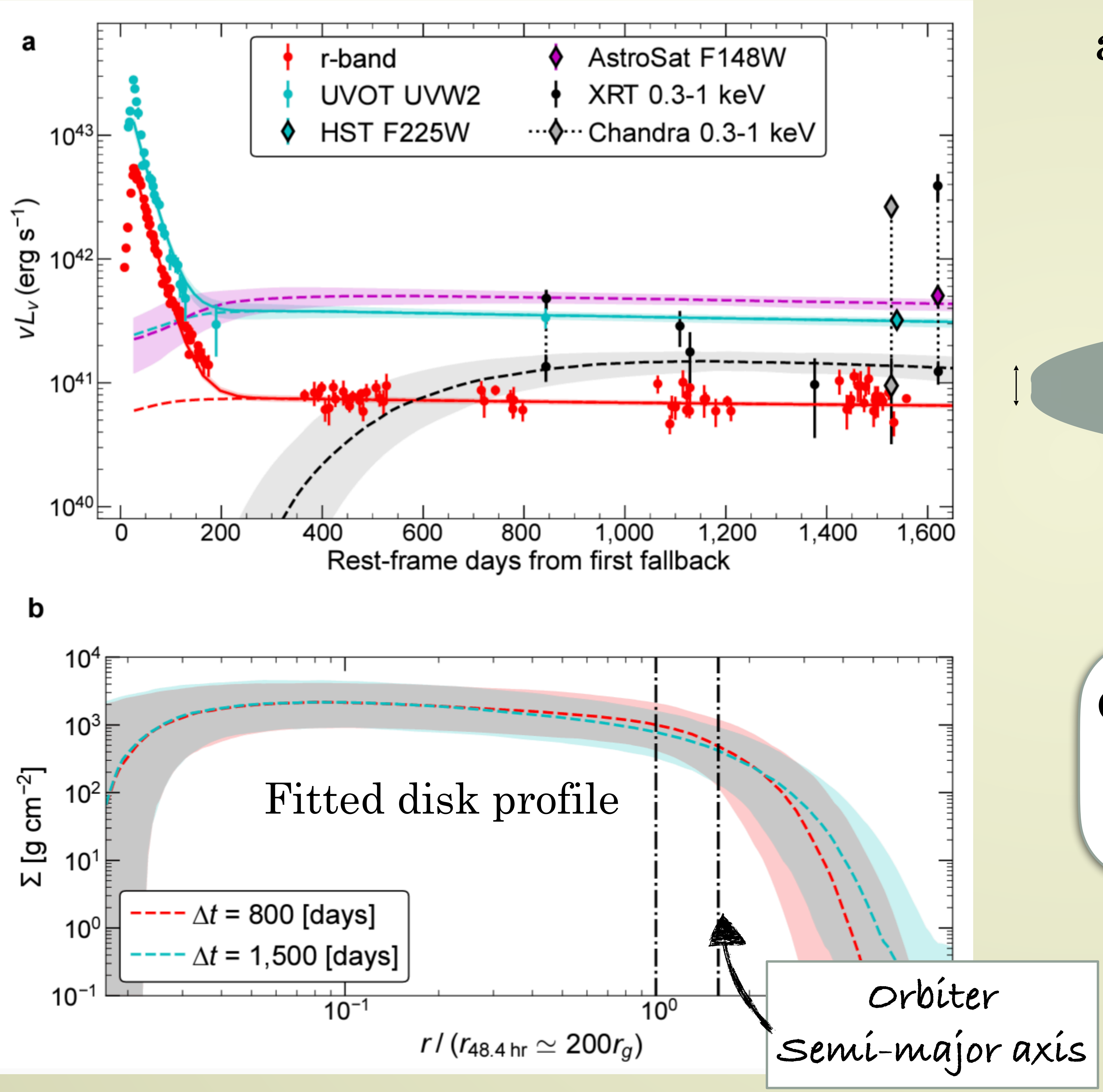
… additional X-ray observations (10d *NICER*):



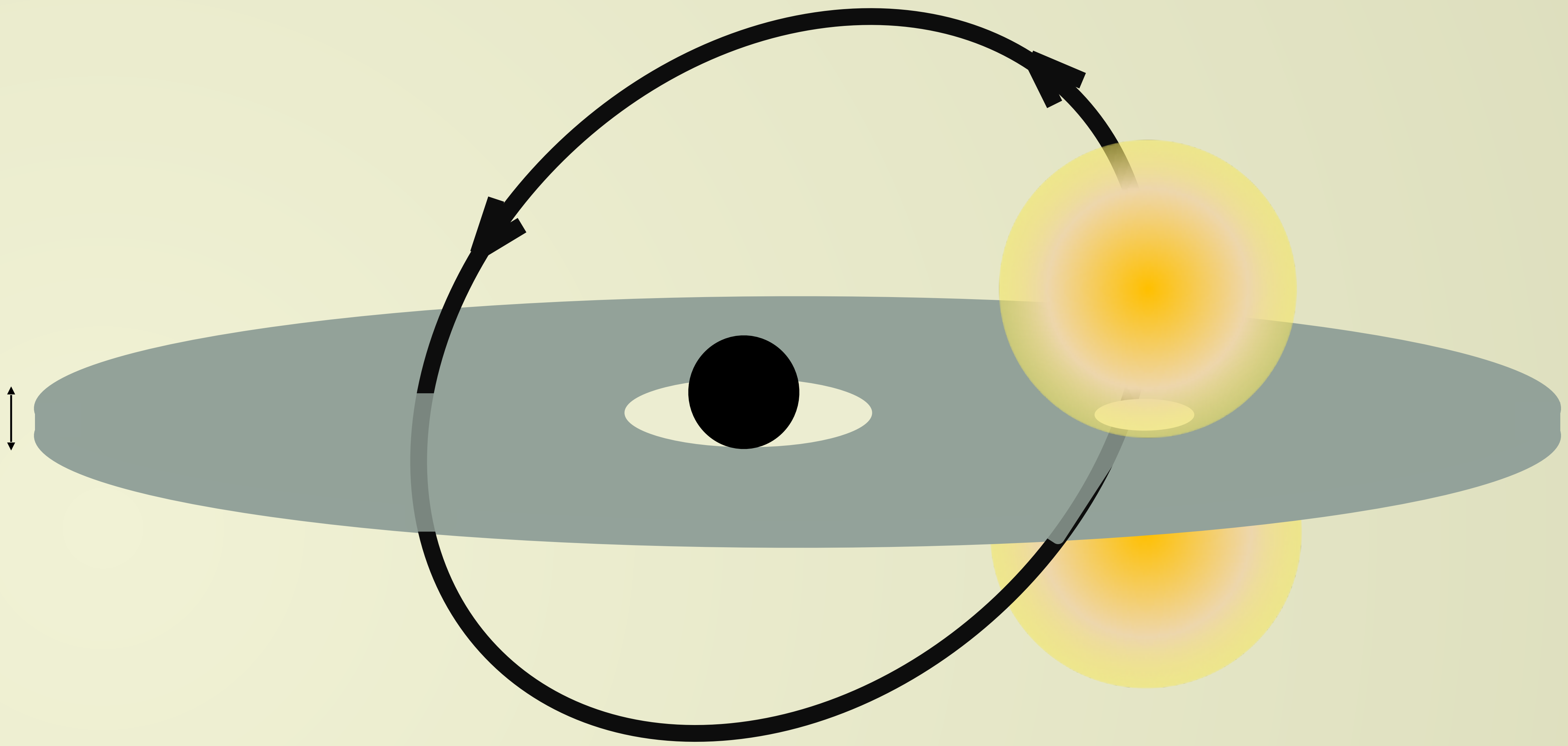
$$\langle P_{\rm QPE} \rangle \approx 2\,{\rm day}$$

$$\rightarrow P_{\rm orb} \approx 2 \text{ or } 4\,{\rm day}$$

Extent of TDE disk



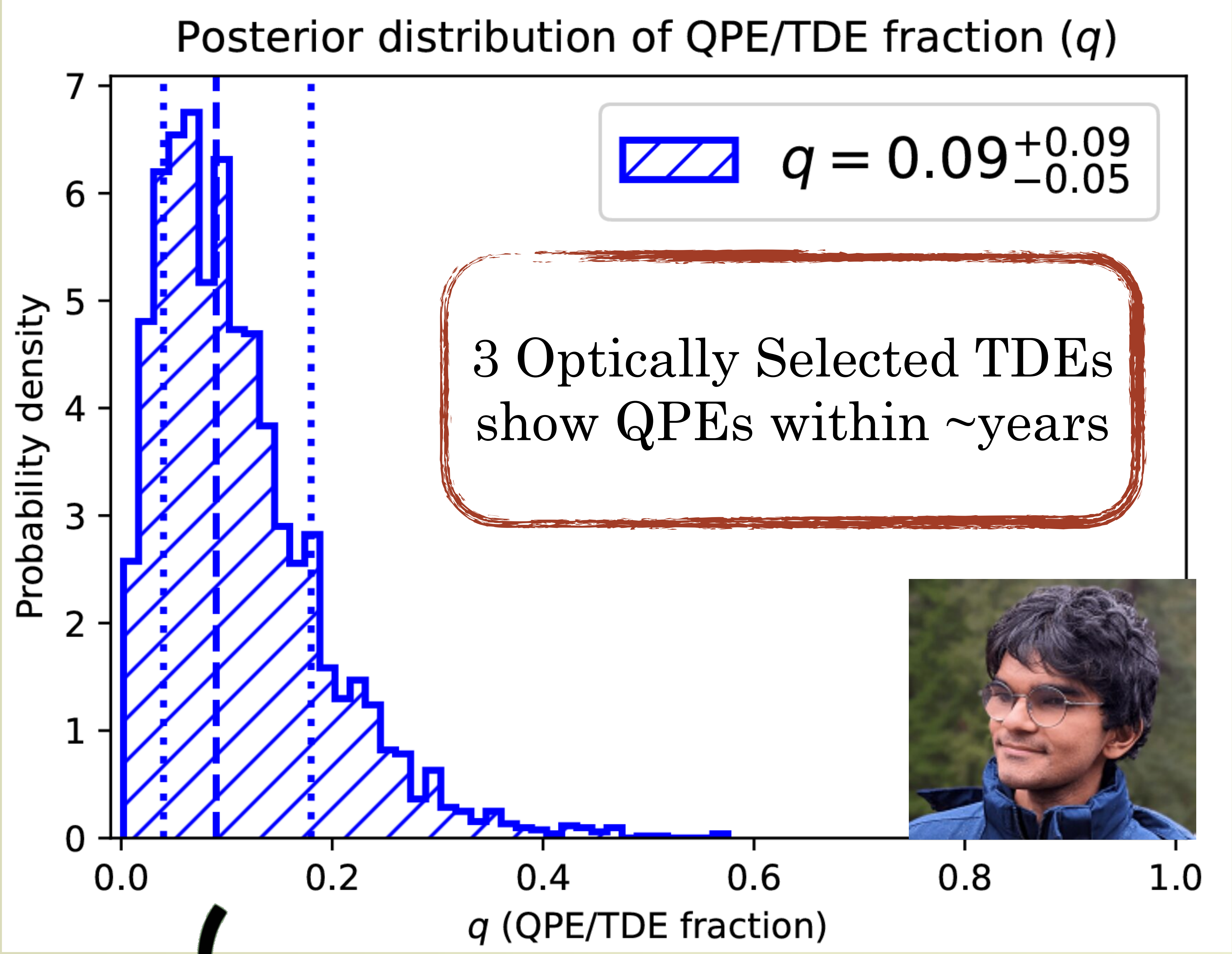
* QPEs appeared around the time $\Sigma_d(r_{EMRI}, t)$ approached maximum



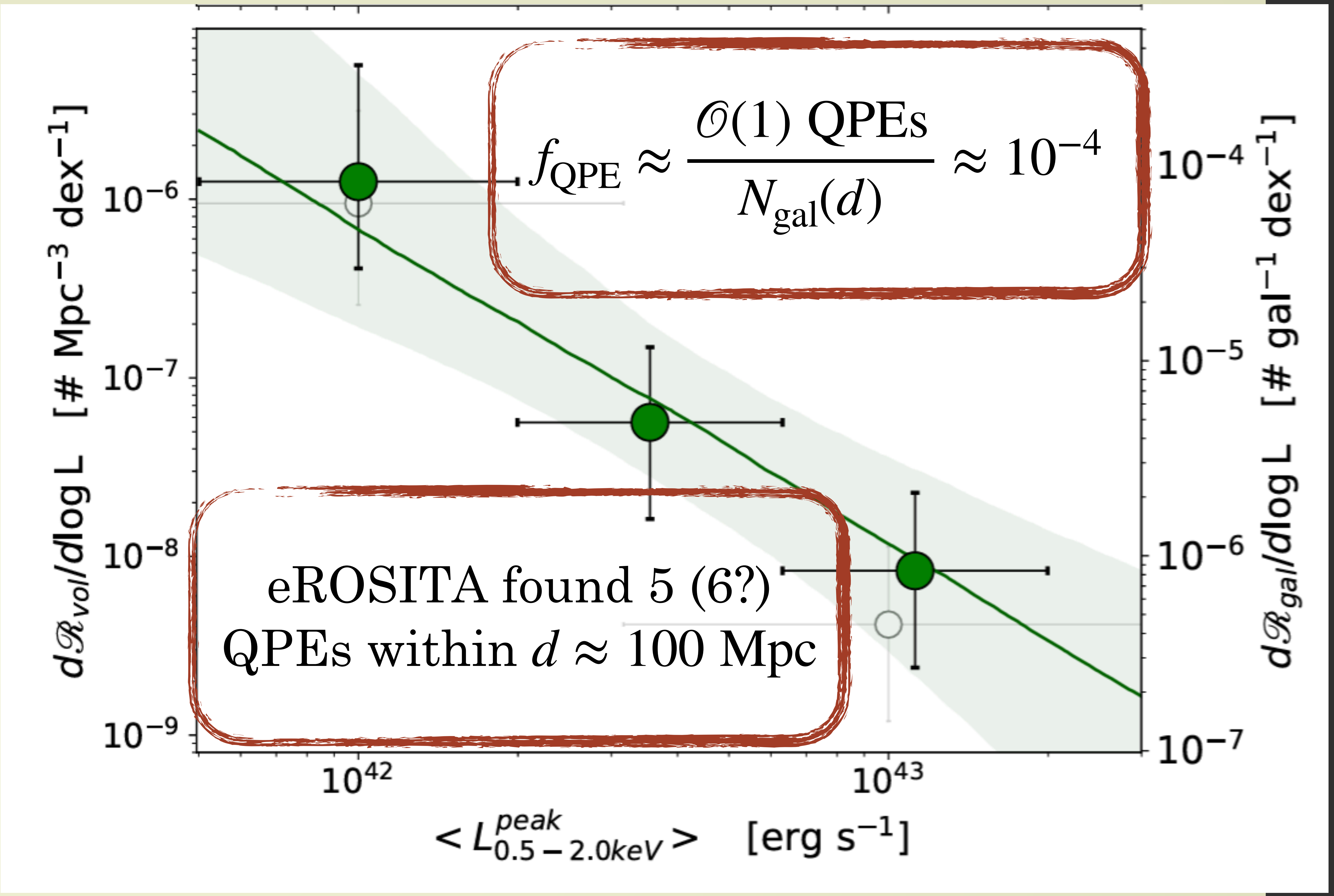
QPE Detection in Late Time TDEs

- Previously - X-ray surveys - eROSITA
- Now - **dedicated X-ray followup** of TDEs

TDEs Hosting QPEs:



[Chakraborty+25 (inc. **Linial**)]



[Arcodia+24b]

~10% of Optically Selected TDEs Show X-ray QPEs

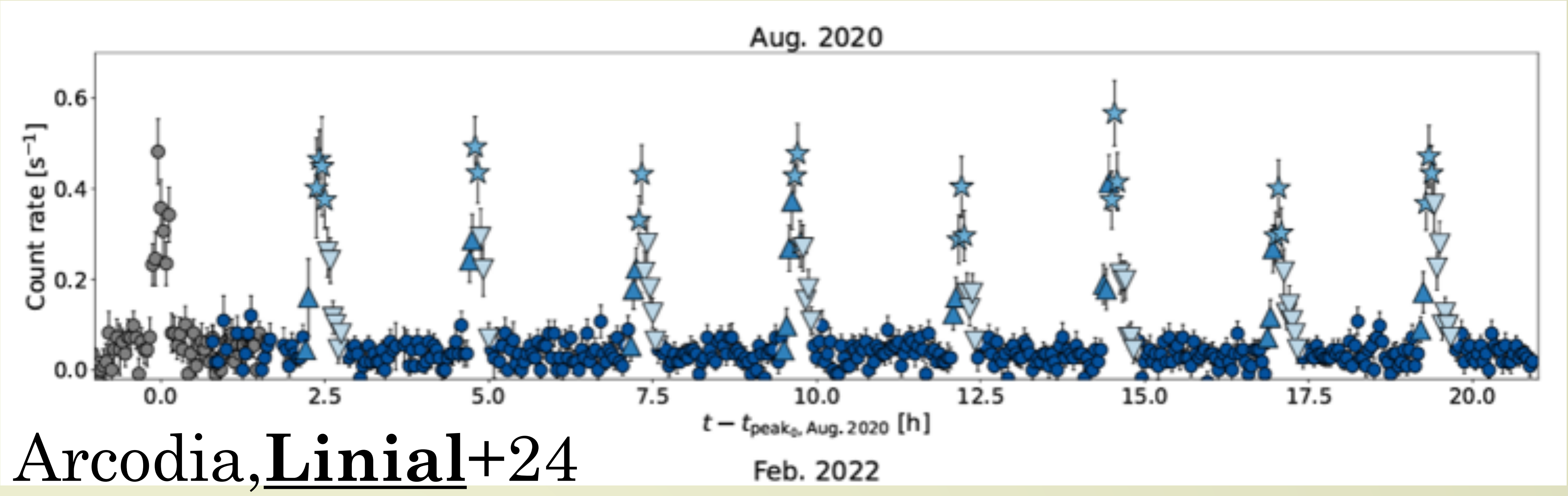
$$\frac{\mathcal{R}_{\rm EMRI}}{\mathcal{R}_{\rm TDE}} \approx 0.1 \left(\frac{\tau_{\rm life}}{10\,\rm yr}\right)^{-1}$$

QPEs/RNTs as probes

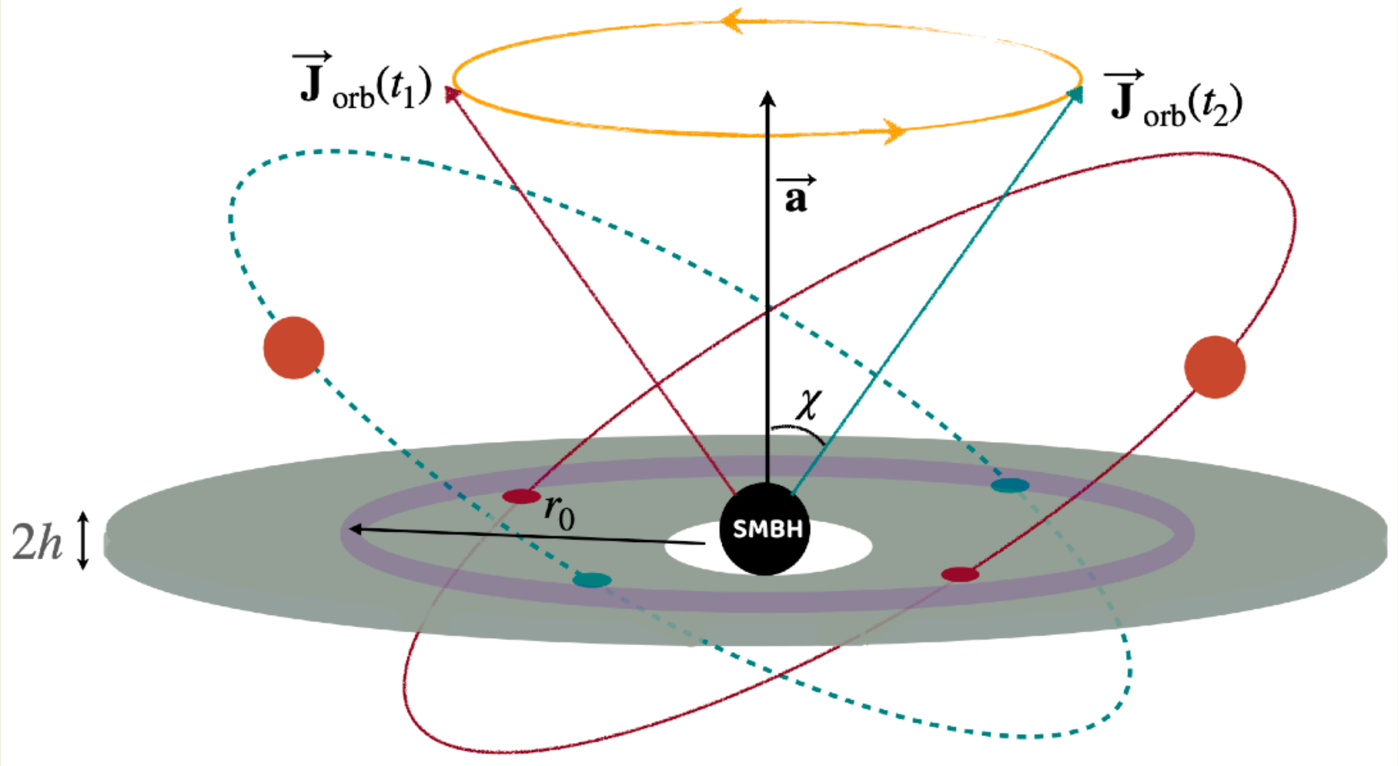
Long Baseline Flare Timing:

- Orbital parameters (inclination, ecc.)
- SMBH Mass + Spin

[See e.g., Xian+21, Zhou+24a,b,Pan+24]



Arcodia,**Linial**+24

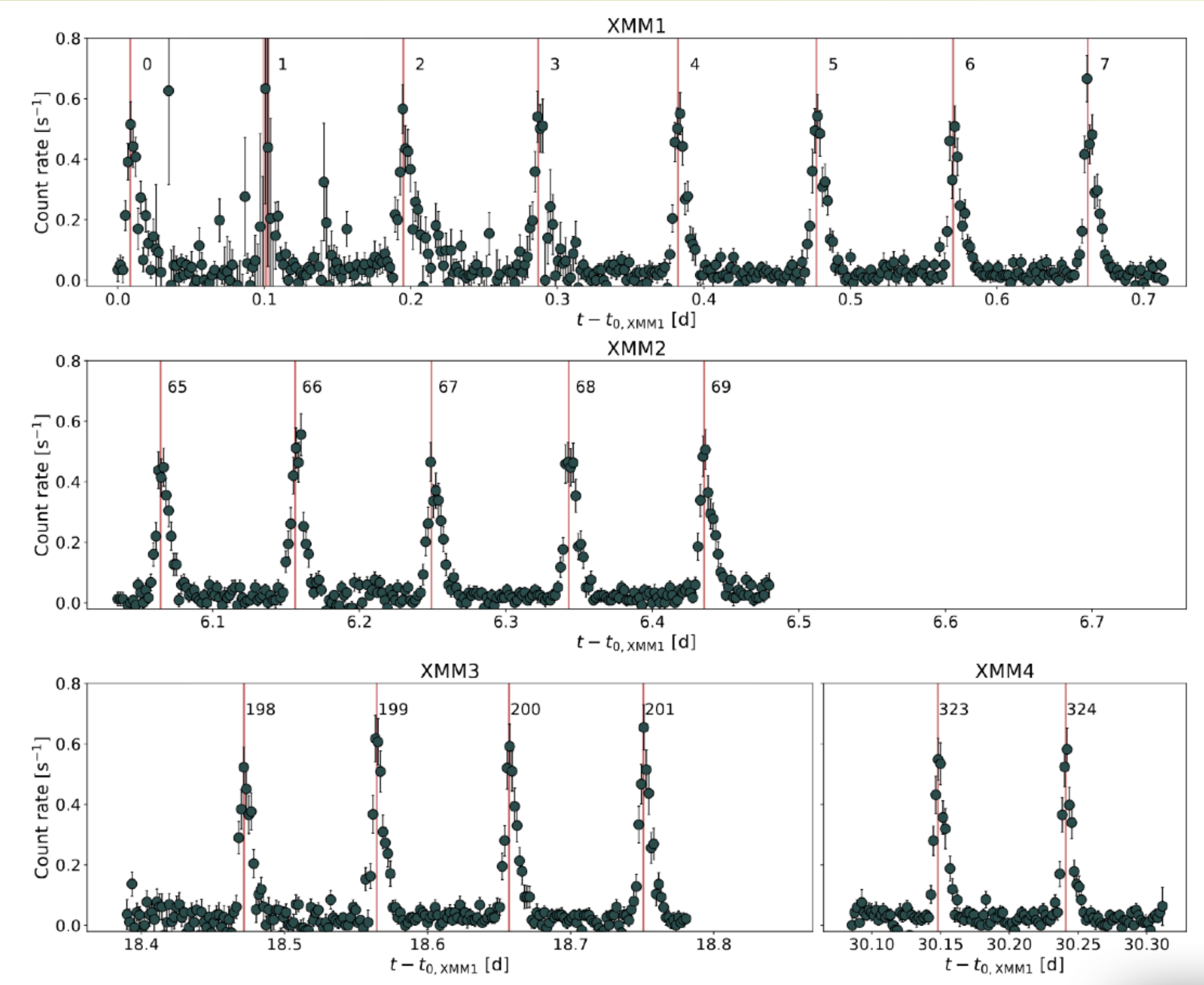


[**Linial** & Metzger 24b]

$$\tau_{\rm ap} \approx P_{\rm orb}(a/3R_{\rm g})(1-e^2) \propto M_{\rm BH}^{-2/3} P_{\rm orb}^{5/3}$$

$$\tau_{\rm nod} \approx \frac{P_{\rm orb}}{2a_{\rm BH}}\left(\frac{a}{R_{\rm g}}\right)^{3/2} \propto a_{\rm BH}^{-1} M_{\rm BH}^{-1} P_{\rm orb}^{2}$$

$$[\tau_{\rm ap} \approx 10\,{\rm d} \ll \tau_{\rm nod} \approx {\rm a}_{\rm BH}^{-1}\ 10^2\,{\rm d}]$$



[Arcodia+ (inc. **IL**) in review]

~Month long monitoring of eRO-QPE2 w/ XMM:

Modulation w/ $\tau \approx 4.4\,{\rm d} \;\rightarrow\; M_\bullet \approx 1.5 \times 10^5\,{\rm M}_\odot$

$|\dot{P}| \lesssim 2 \times 10^{-6}$

- Disfavors eccentric ~0.99 orbiter [King 20]
- Disfavors low-e IMBH with $m_{\rm IMBH} > 500\,{\rm M}_\odot$ [Franchini+23]

Additional unexplained **high-amplitude** modulation, $\tau \approx 10^2\,{\rm d}$

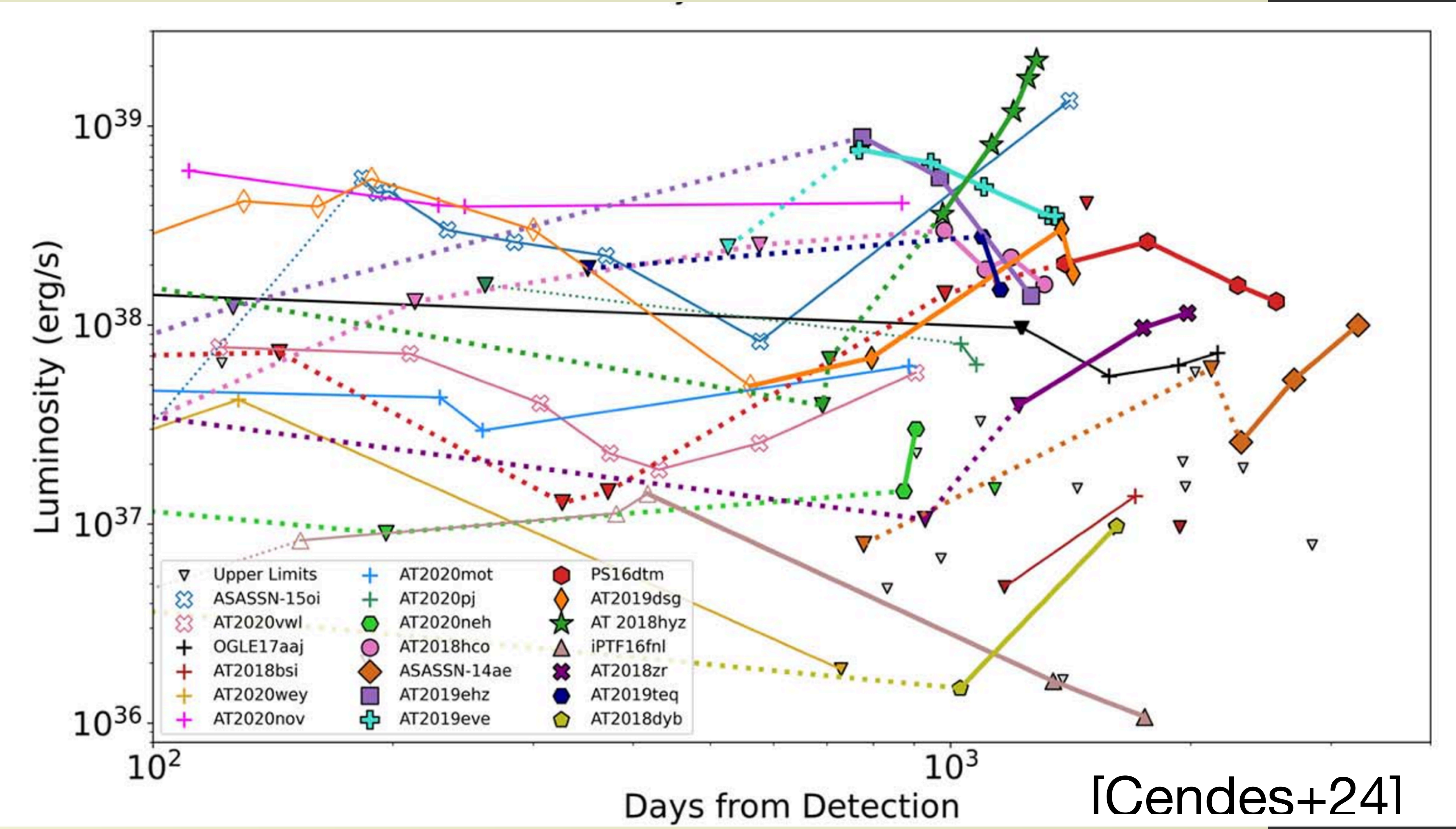
Delayed Radio Flares in TDEs

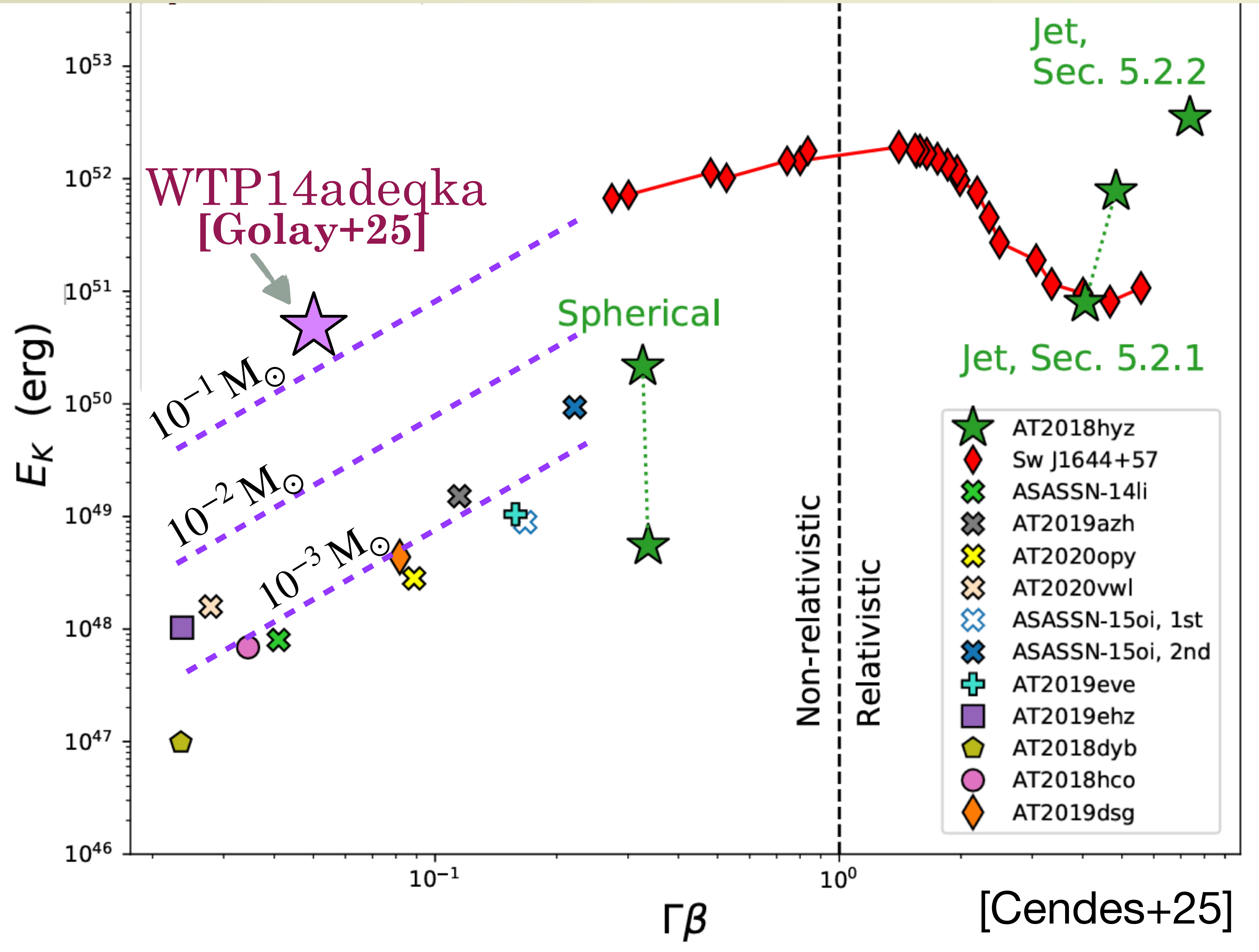
See talks by Kate, Adelle, Andy

Delayed Radio Flares are Ubiquitous

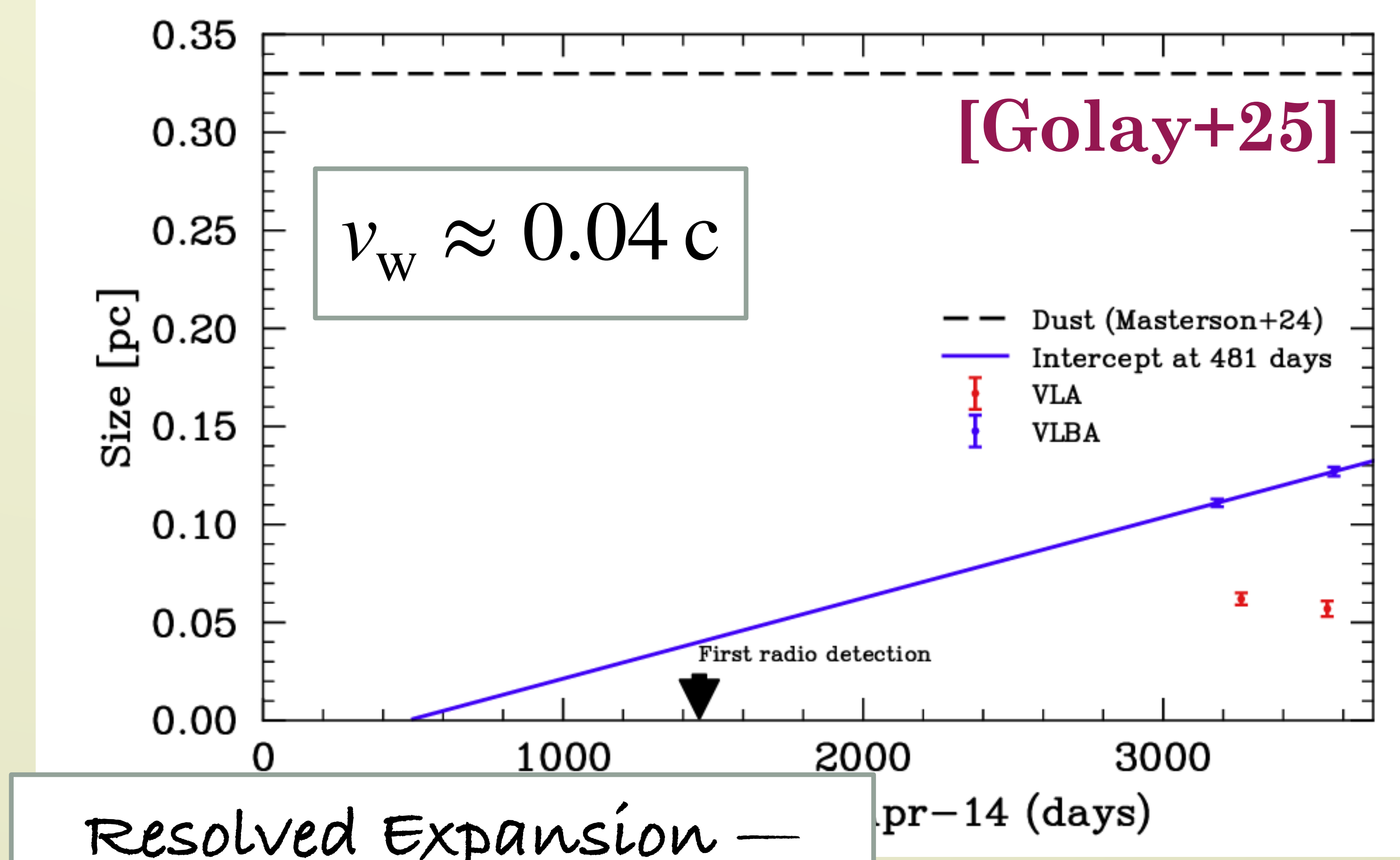
Early ($t \lesssim 100\,\mathrm{d}$) Radio Flares: >30%
Powerful Relativistic Jets: <1% (intrinsic)

Delayed ($t \gtrsim 10^3\,\mathrm{d}$) Radio Flares: ~40%

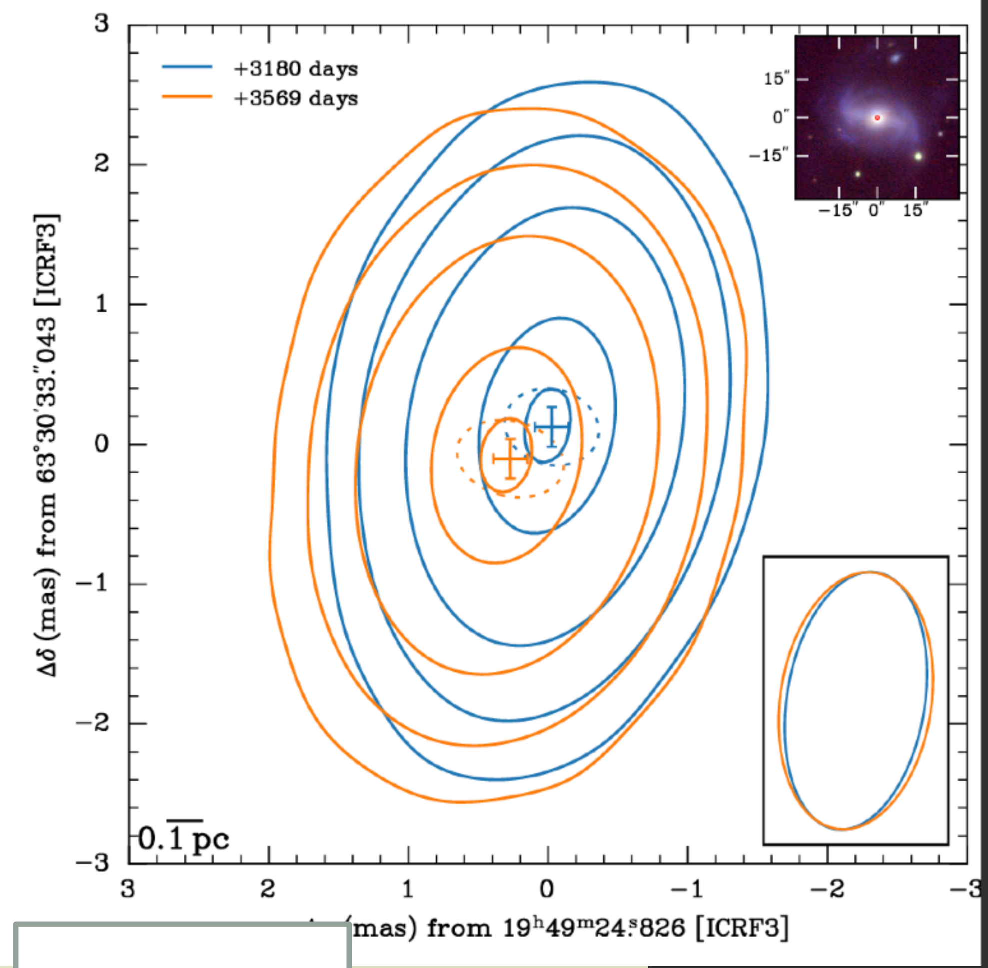




WTP14ADEQKA: FIRST RESOLVED DELAYED OUTFLOW



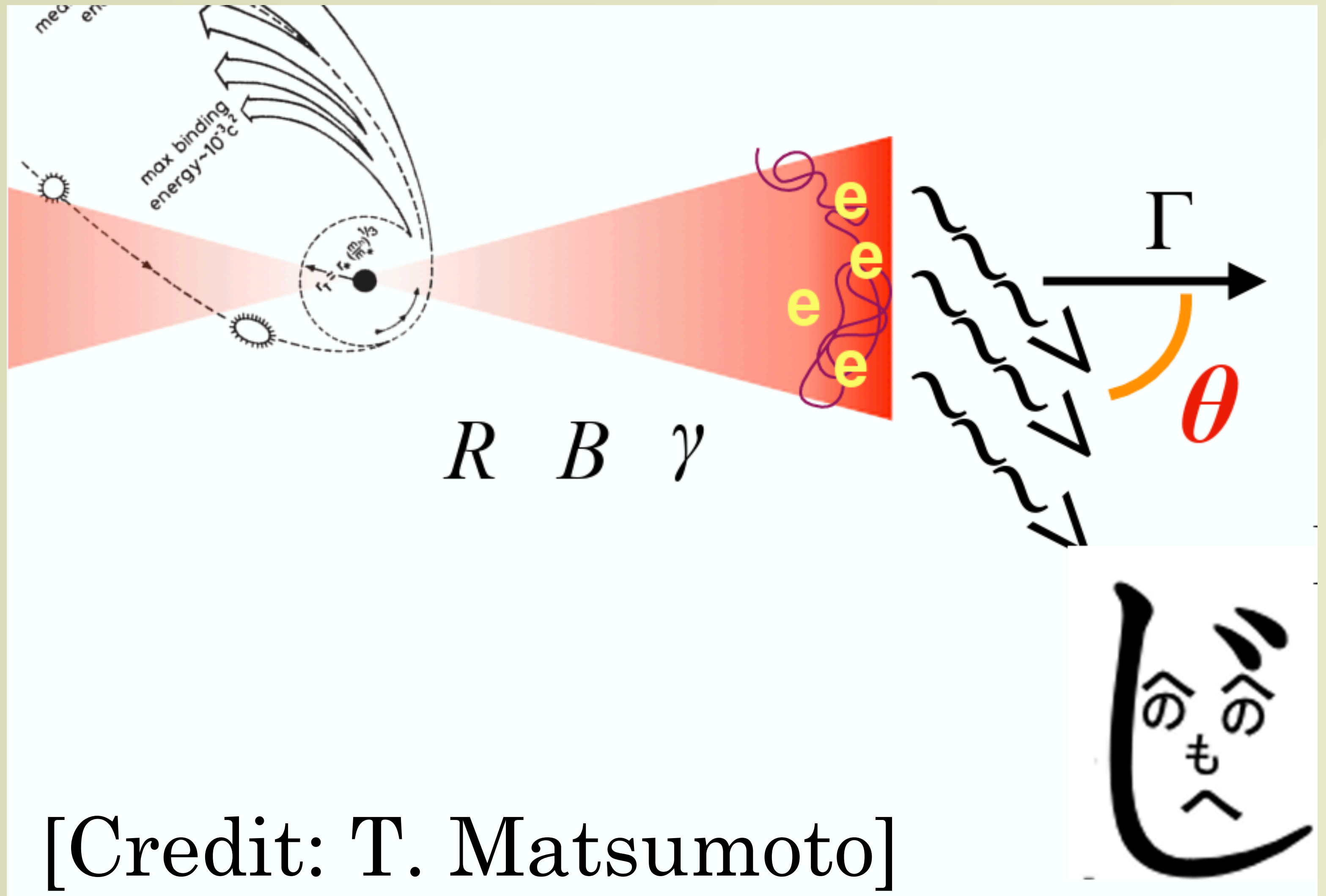
Resolved Expansion — Delayed launch ~500d



VLBA

Promptly launched relativistic jet, viewed off-axis, brightens as $\Gamma \lesssim 1/\theta_{\rm obs}$

[Matsumoto+23]



[Credit: T. Matsumoto]

- Jetted TDEs are **rare** (<1%)
- Most flares **too dim, slow**
- May explain some sources? (e.g., AT 2018hyz)[Cendes+24]

Delayed launching of relativistic jets [Teboul+23, Lu+24]

Non-relativistic outflow, **delayed** launch

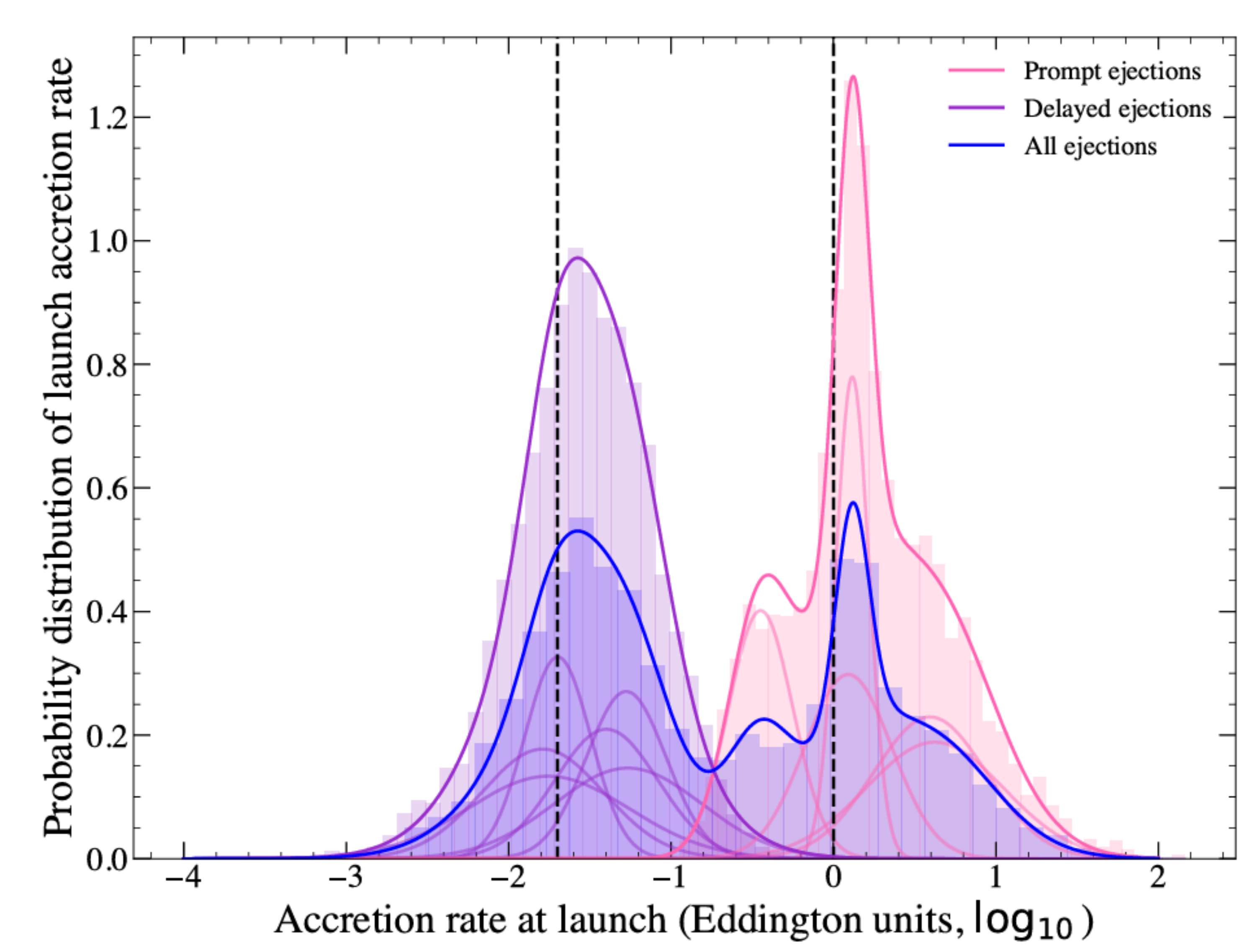
$v_{\rm w} \sim 0.01 - 0.1\,c$
$m_{\rm w} \approx 10^{-3} - 10^{-1}\,{\rm M}_\odot$
$\Delta t_{\rm w} \approx {\rm few} \times 10^2 - 10^3\,{\rm d}$

Outflows from accretion disk in a radiatively inefficient regime
$\dot{M} \gg \dot{M}_{\rm Edd}$, $\dot{M} \ll 0.01\,\dot{M}_{\rm Edd}$

Disk thermal/viscous instability, launching outflows in high $\dot{M}$ state

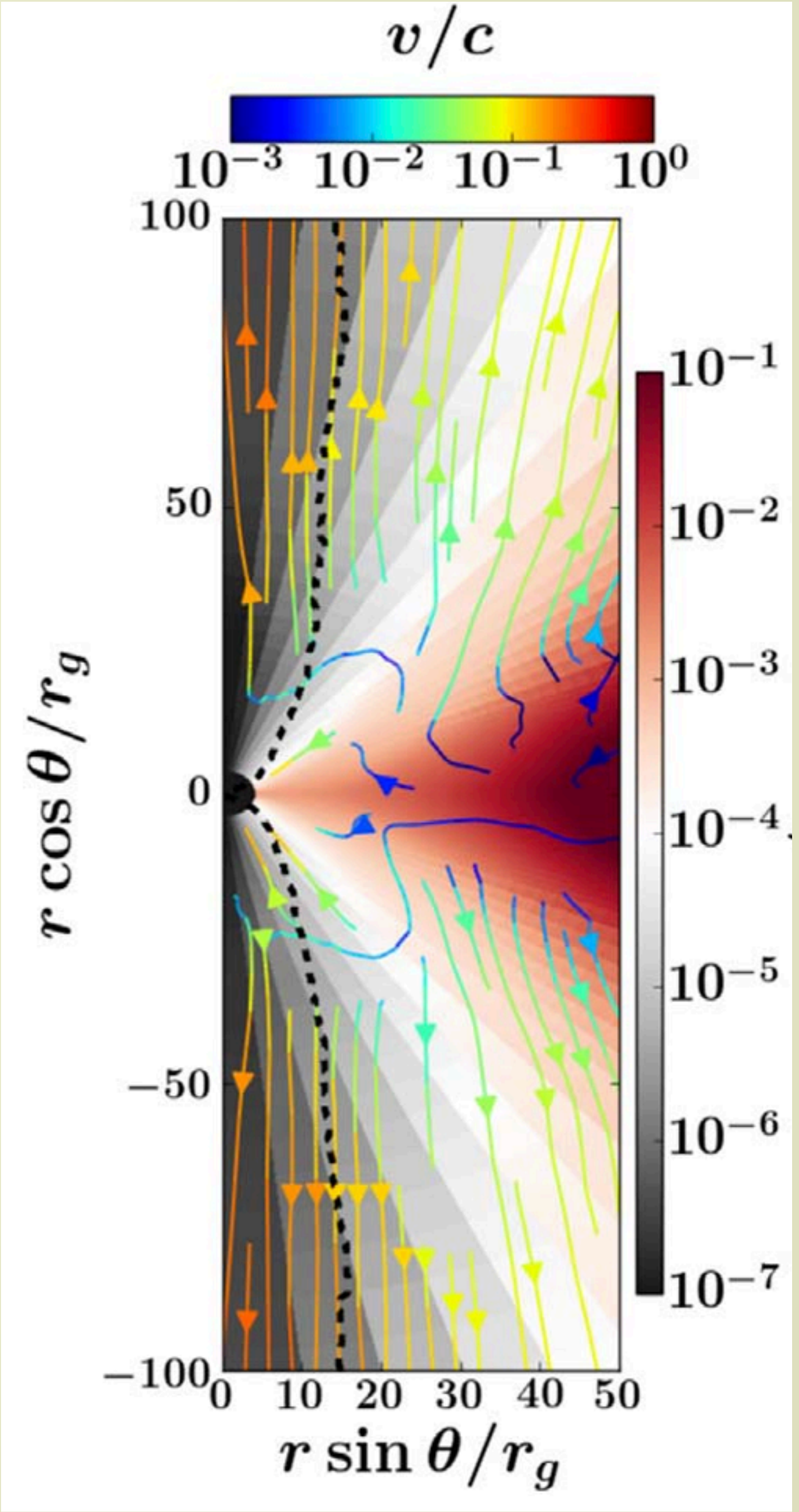
[Piro+25,Wu+25]

Launch times associated with
$\dot{M}_\bullet > \dot{M}_{\rm Edd}$ or $\dot{M}_\bullet < 0.01\,\dot{M}_{\rm Edd}$
[Alexander+25, Goodwin & Mummery 26]



Accretion State Transition Outflows

Super-Eddington outflows [Jiang+19]
GRMHD + Radiation



- If launched from $r \approx r_{\rm ISCO}$, <u>most energy</u> expected in $v_{\rm w} \approx 0.2 - 0.4\,c$ (e.g., Jiang+19)
- Observed range of velocities 0.01 – 0.2 c

$\rightarrow F_\nu^{\rm pk} \propto v_{\rm w}^{3-4}$

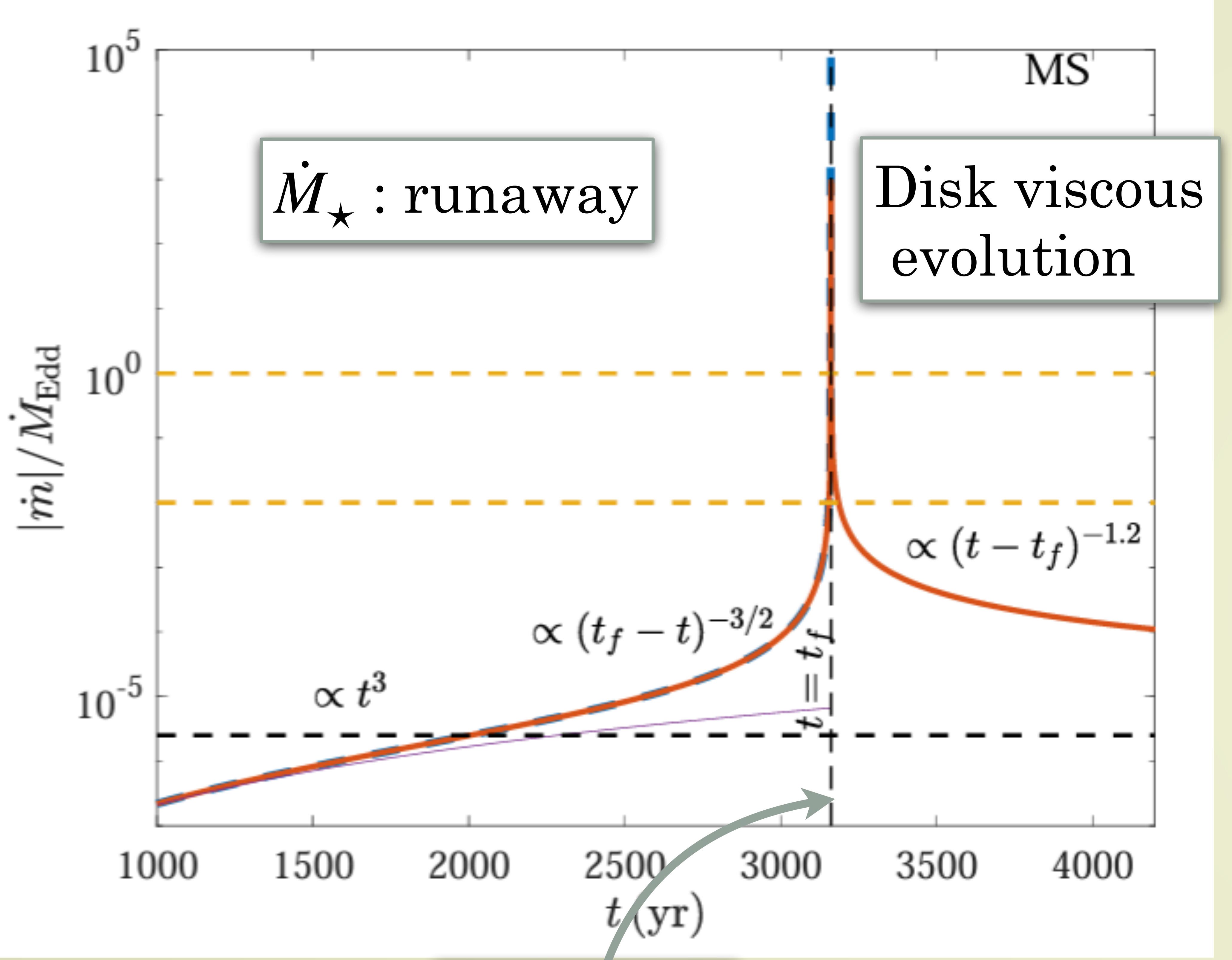
- Challenging to explain up to $0.1\,{\rm M}_\odot$ of ejecta (especially in $10^{-2}\,\dot{M}_{\rm Edd}$)

$$m_{\rm w} \ll m_{\rm d} \approx (10^{-2}\,\dot{M}_{\rm Edd}) \times (10^3\,{\rm d}) \sim 10^{-3}\,{\rm M}_\odot\,(M_{\bullet,6})$$

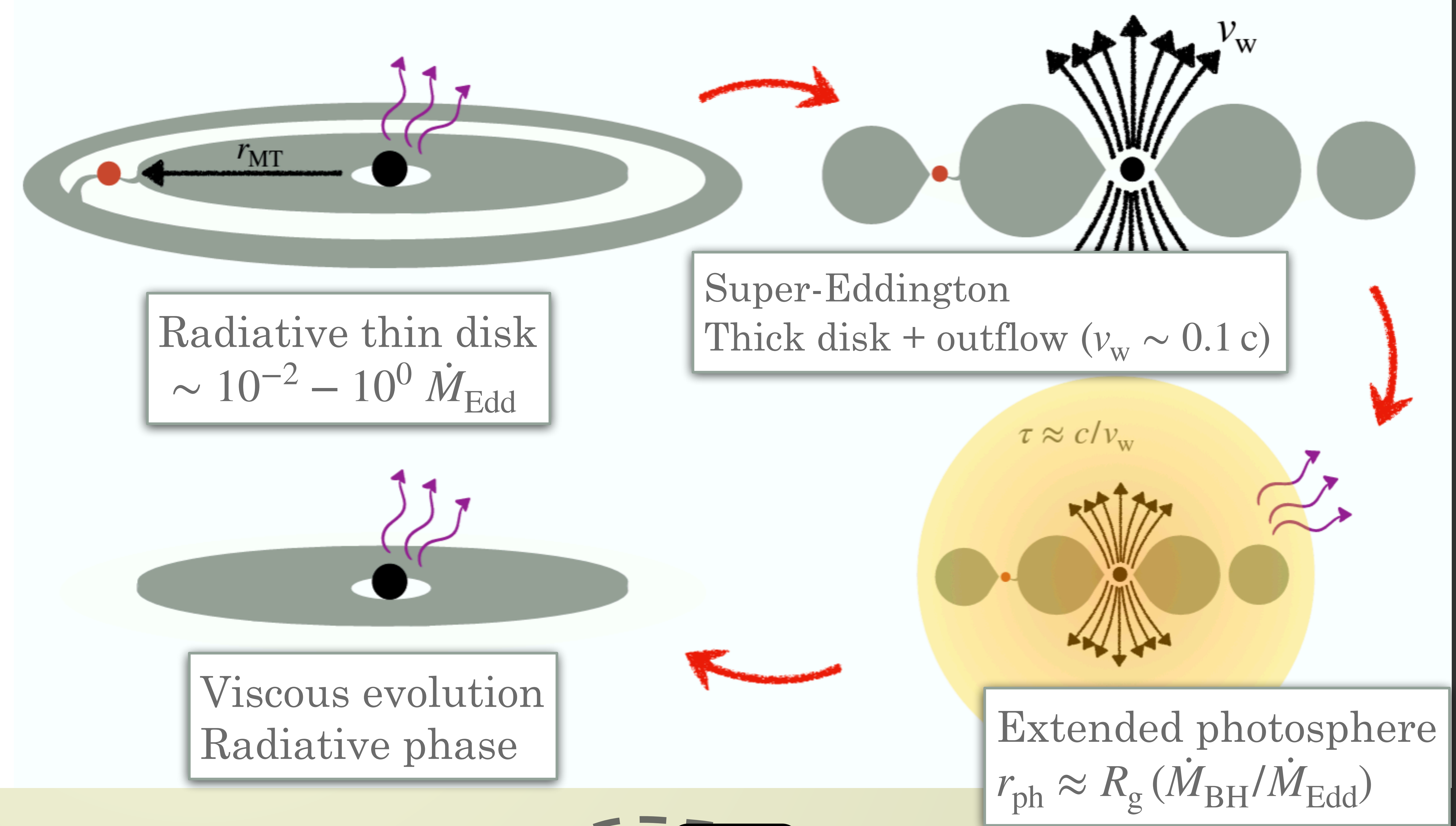
- UV/Optical <u>typically persists after radio flare</u>

Circular TDEs (**Linial** & Quataert 24b)

Orbit shrink to $r \to \sim r_t$: Roche Lobe Overflow , **UNSTABLE** mass transfer [e.g., **Linial** & Sari 23]

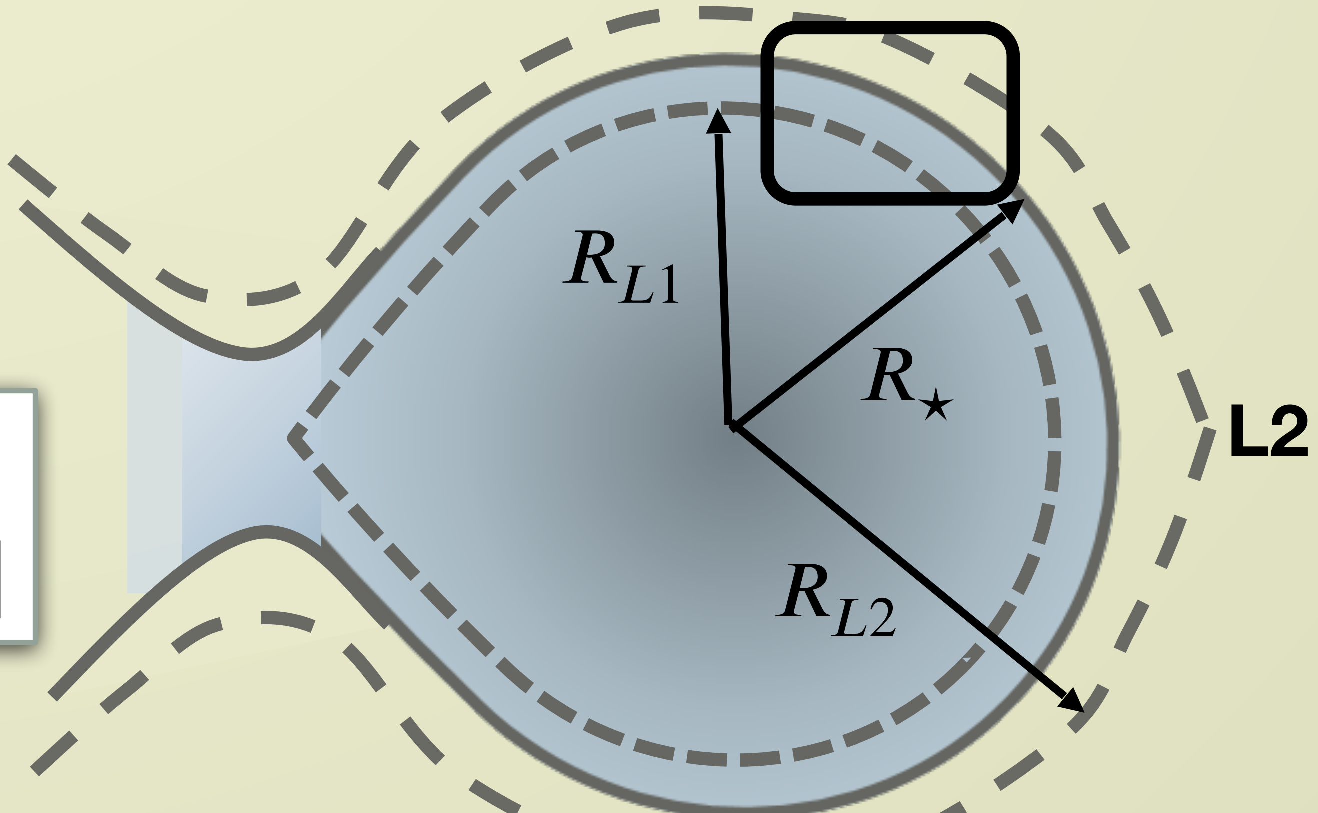


Final disruption



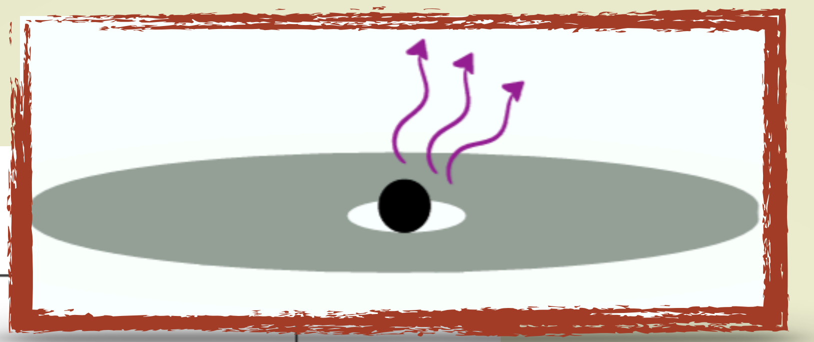
$$\dot{M}_\star \approx \frac{M_\star}{t_{dyn}} \left(\frac{R_\star - R_{L1}}{R_\star} \right)^3$$

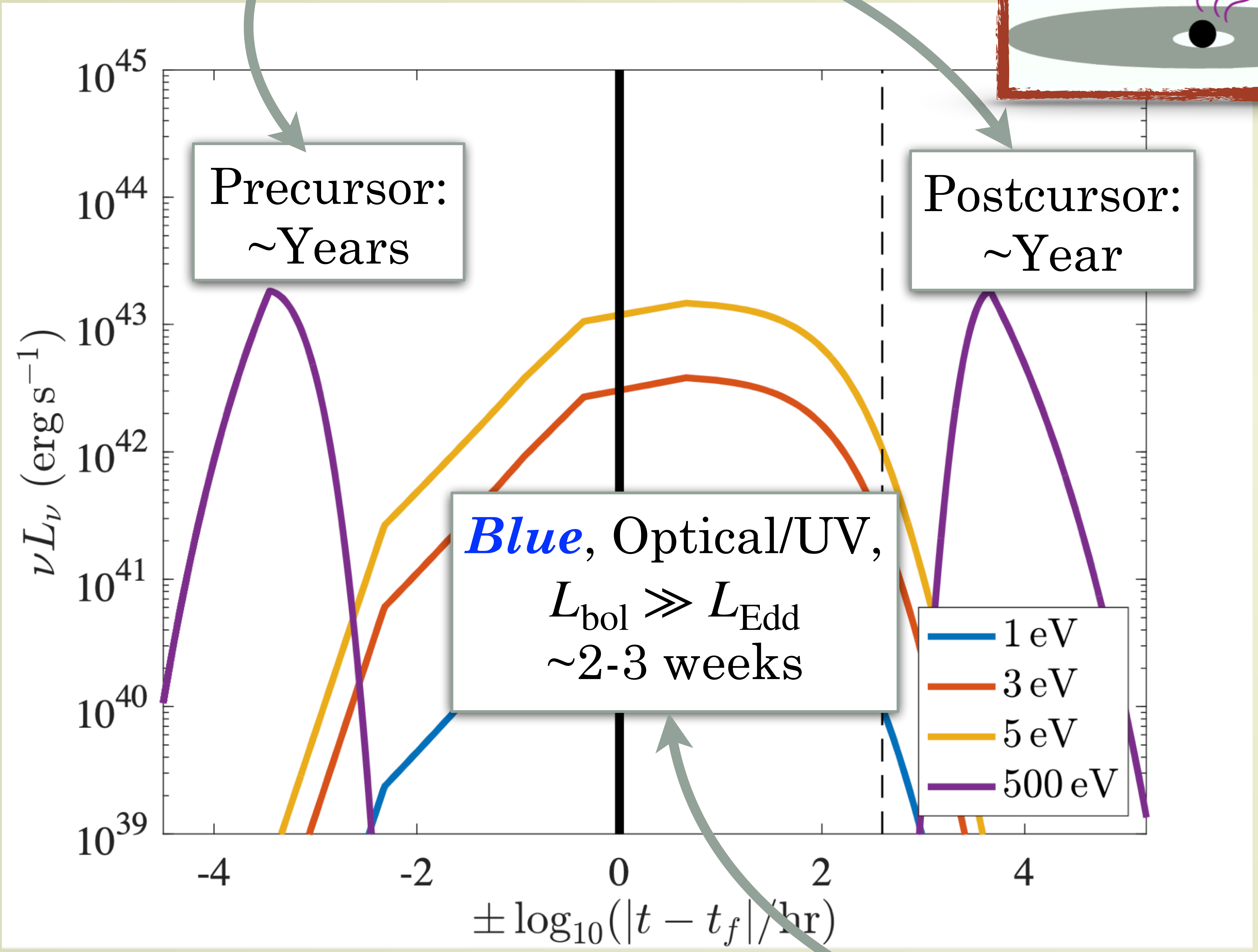
Mass loss from L2
[**Linial** & Sari 17]



Circular TDEs - Unique Observable Predictions

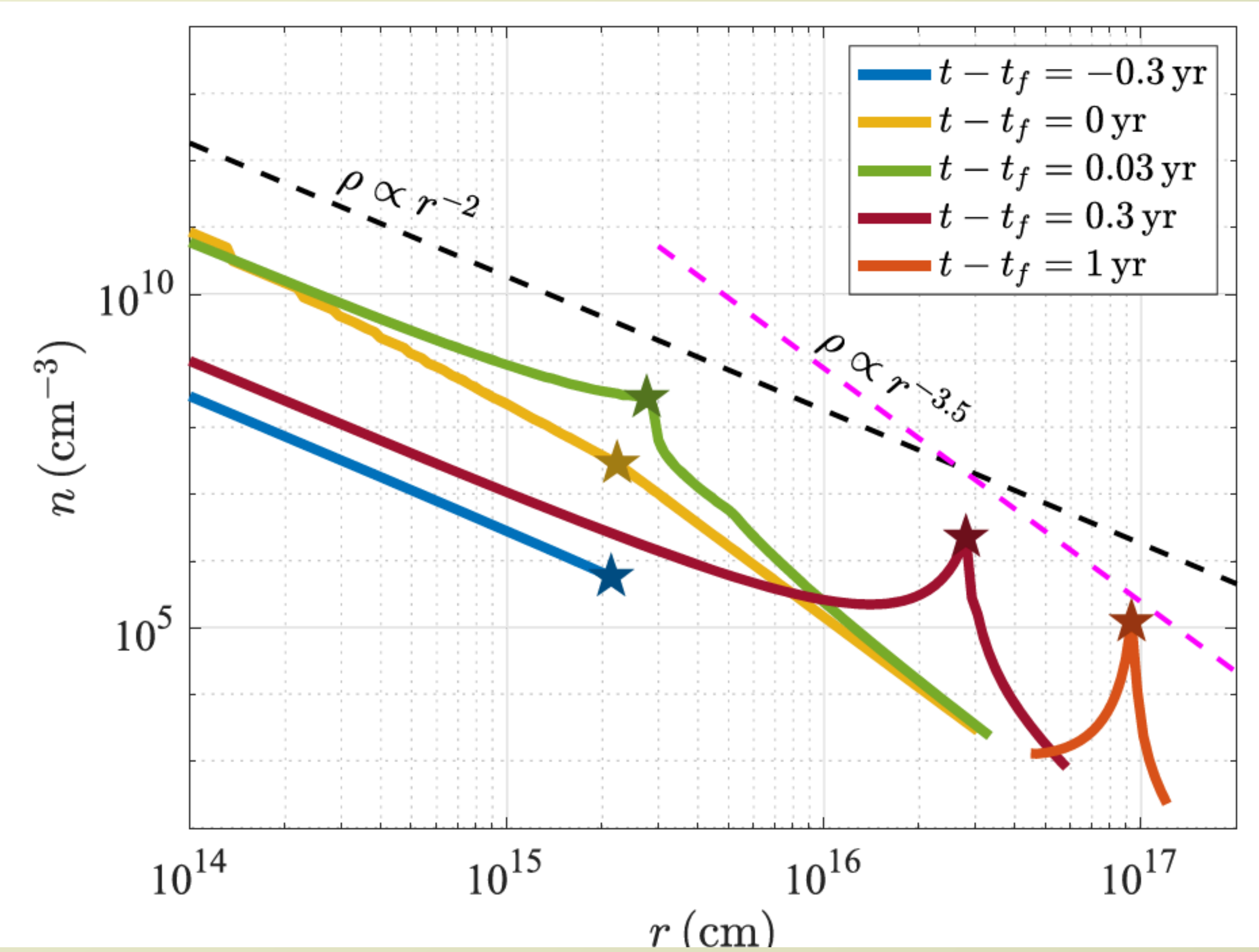
Inner radiative disk
Soft X-rays





Extended super-Eddington outflow

- TDEs in AGN
- Jetted TDEs?
- Self-generate CNM, luminous and blue: Possible connection to **L**uminous **F**ast **B**lue **O**ptical **T**ransients (**LFBOT**s)



Summary

- Stellar EMRIs, on mildly eccentric orbits, commonly occur around SMBHs through GW inspiral of tightly bound stars following binary breakup by Hills Mechanism
- During the long GW inspiral of the stellar EMRI, the tidal disruption of a second star produces an accretion disk with which the EMRI interacts.
- The disk is evolving in time, fed by the fallback of the bound stellar debris and possibly by the stellar ablation
- Interactions between the disk and the stellar EMRI produces flares with similar properties to the observed QPEs
- These interactions may be dominated by interaction of ablated stellar material and the disk
- Further study will constrain EMRI formation channels, with implications to milli-Hz GW sources and SMBH feeding habits
- The possibility of an IMBH instead of a stellar-EMRI may be tested by exploring secular period evolution of QPEs
- Delayed radio flares may naturally arise from star-disk interaction. Future detection of radio flares following QPEs may further constrain theoretical uncertainties

EMRI+TDE=QPE:

QPEs from ablated star

Circular TDE

$\dot{P}$ in repeating TDEs