# Transient formation in interactions of stars and black holes


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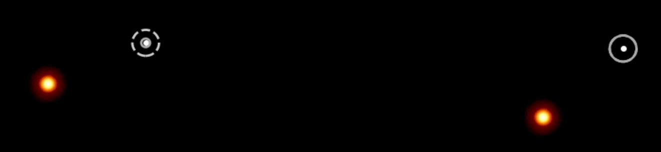
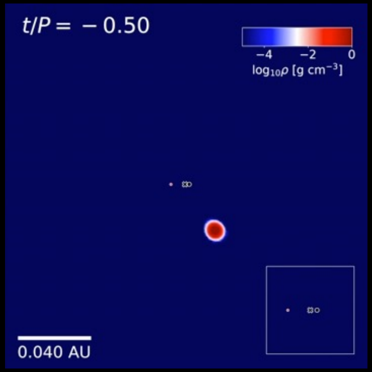
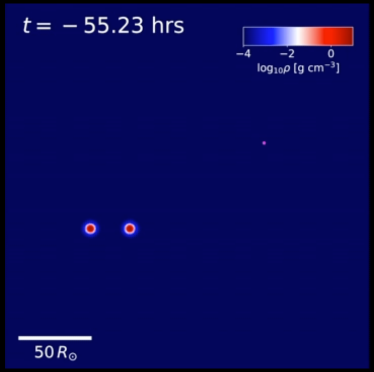
MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

LAGRANGE

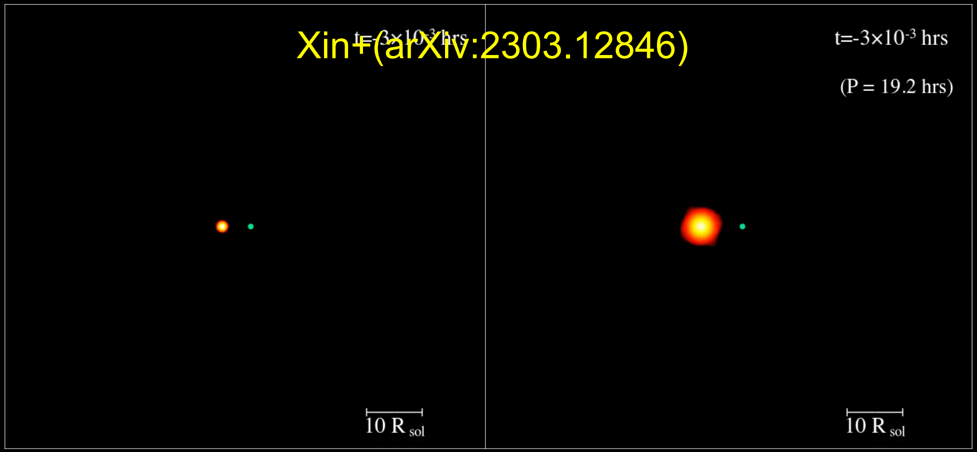
Vynatheya+(in prep)





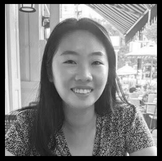




Xin+(arXiv:2303.12846)





Pavan Vynatheya (MPA)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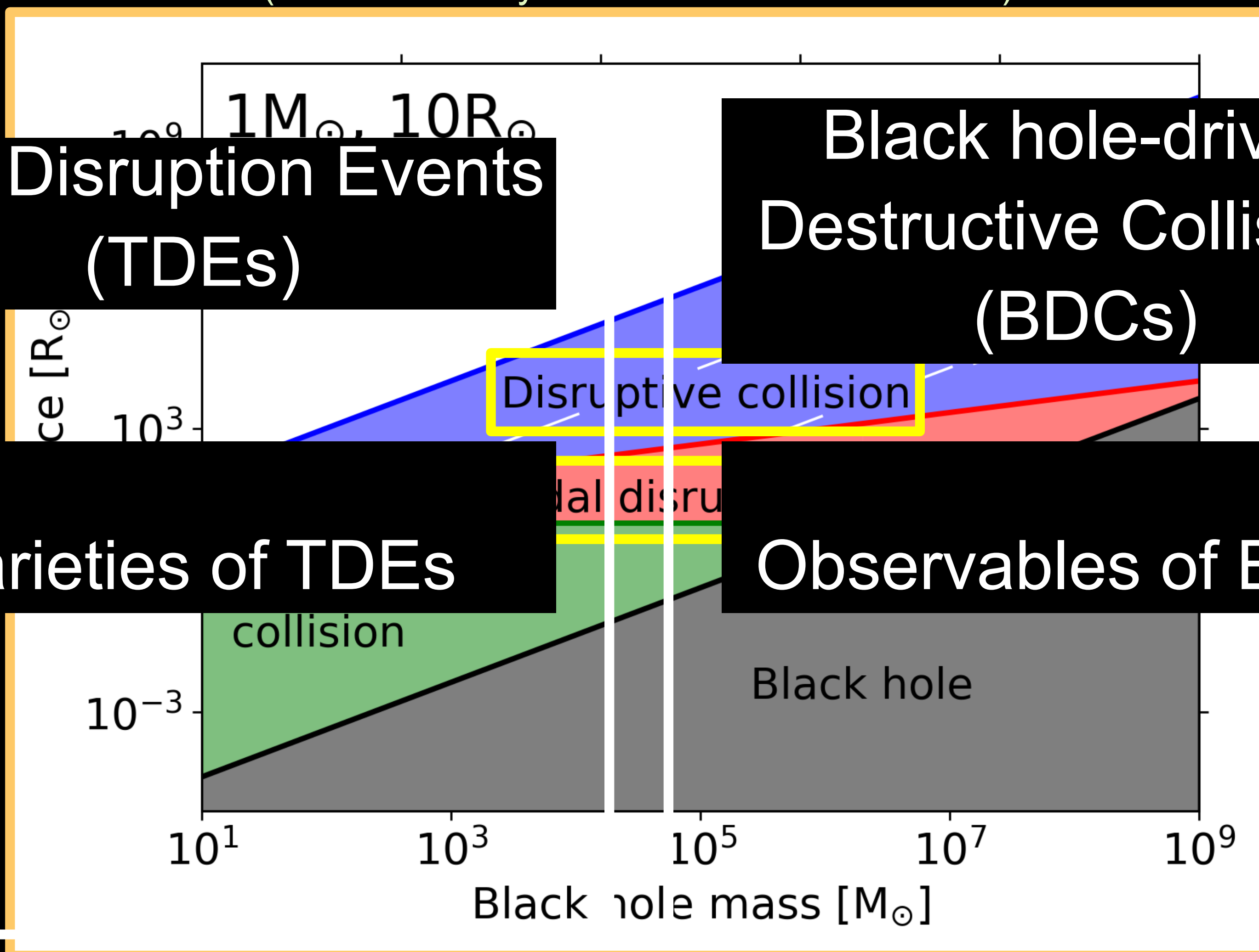
# Nuclear transients

✓ Nuclear transients are astronomical phenomena lasting as long as human lifetime that are observed at galactic nuclei, likely involved with supermassive black holes (not necessarily related to nuclear reaction)




**Tidal Disruption Events (TDEs)**

**Black hole-driven Destructive Collisions (BDCs)**

**Varieties of TDEs**

**Observables of BDCs**

# Supermassive black hole

- Almost every nearby massive galaxy harbors a supermassive black hole (Kormendy&Ho2013)

- Many questions yet to be answered
  - e.g., How such massive black holes formed?
    - Massive black holes at high redshifts (Goudling+2023,Bogdan+2023,Ding+2023)
    - Super-Eddington accretion vs massive star vs runaway merger/tidal disruption vs etc?
  - e.g., What is the physics of accretion?
    - Angular momentum transport, jet, magnetic field..
    - Circular disk vs eccentric disk..
    - Outflow, galaxy evolution – AGN activity..
  - e.g., How many (active and inactive) black holes are out there?
    - How many black holes we are missing?
    - Black hole – galaxy scaling relations at lower-mass end..

- Understanding nuclear transients would help us answer many of questions

e.g., Sagittarius A*

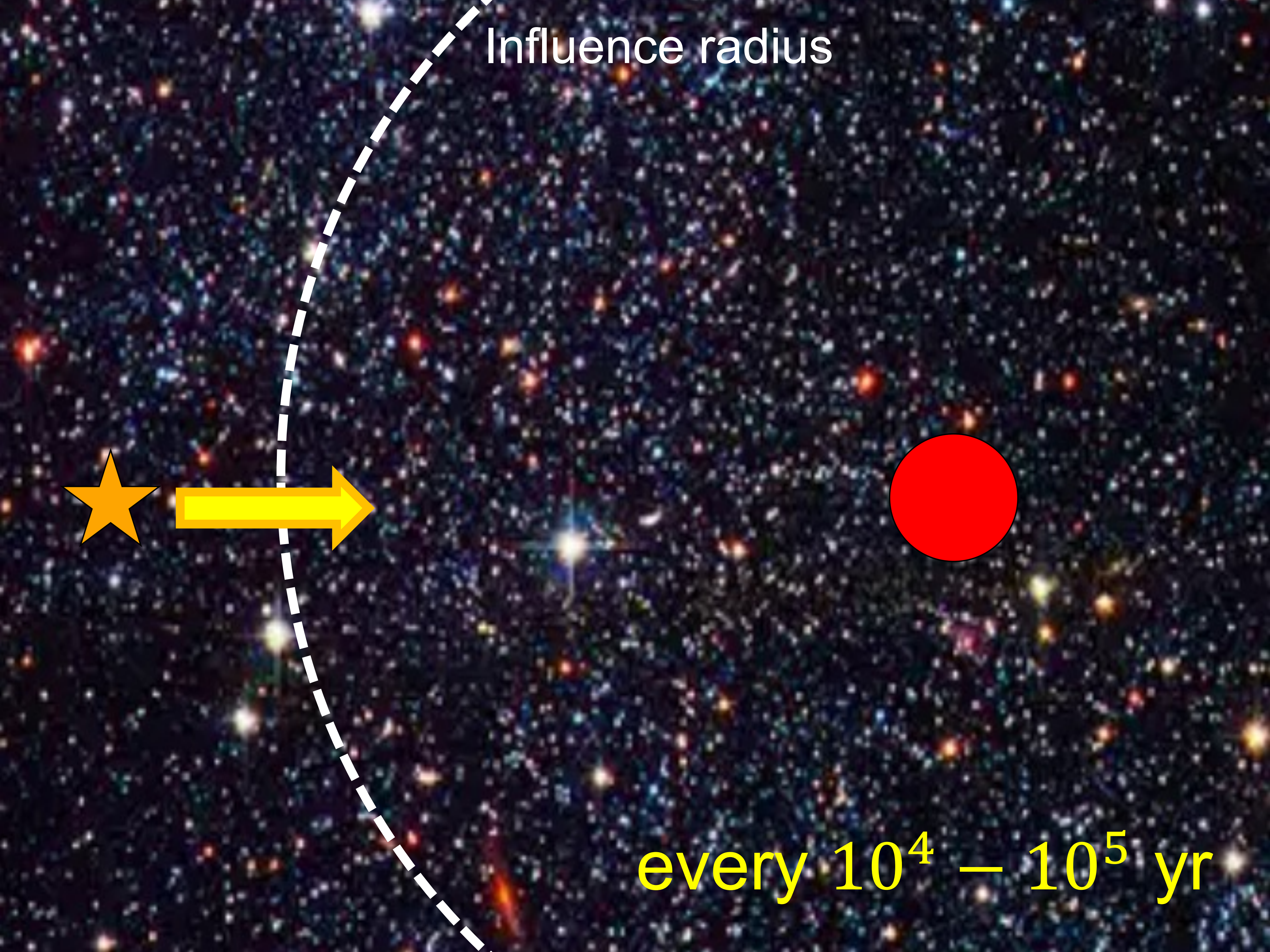
GRAVITY collaboration

# Tidal Disruption Event (TDE)

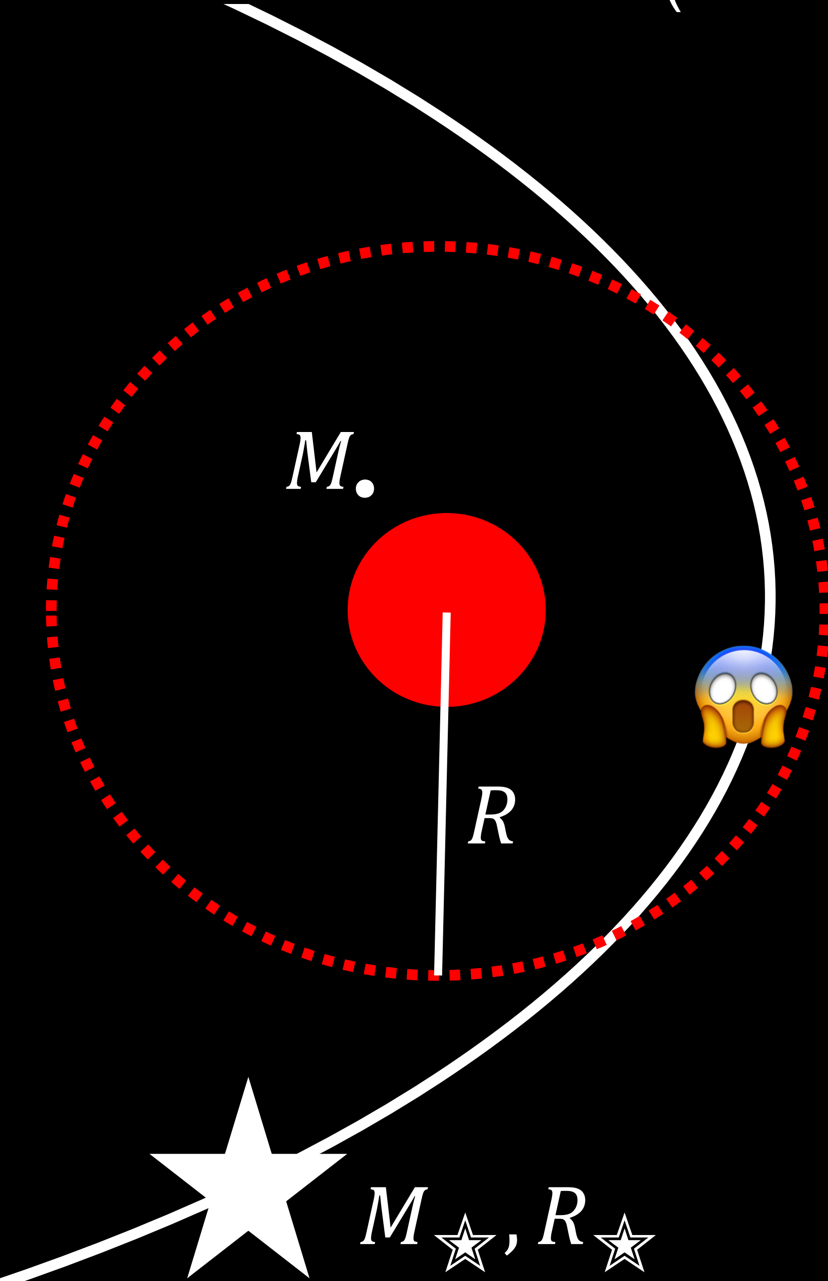
One of the most dramatic transients where stars on a nearly radial orbit are tidally torn apart by black holes

(theoretically proposed in 1980s)

Lacy+1982, Hills 1988, Rees 1988 and more


Influence radius
every $10^4 - 10^5$ yr

# Tidal radius (Newtonian, order-of-magnitude estimate)




Tidal force = Stellar self gravity

$$\frac{GM_\bullet}{R^3} R_\star = \frac{GM_\star}{R_\star^2}$$

$$r_t = \left(\frac{M_\bullet}{M_\star}\right)^{1/3} R_\star \sim \left(\frac{M_\bullet}{\rho_\star}\right)^{1/3}$$

$=50 r_{\rm g}$ for Sun-like star and $M_\bullet = 10^6 M_\odot$

✓ Tidal radius $\propto \rho_c^{-1/3}$ (Ryu+2020)

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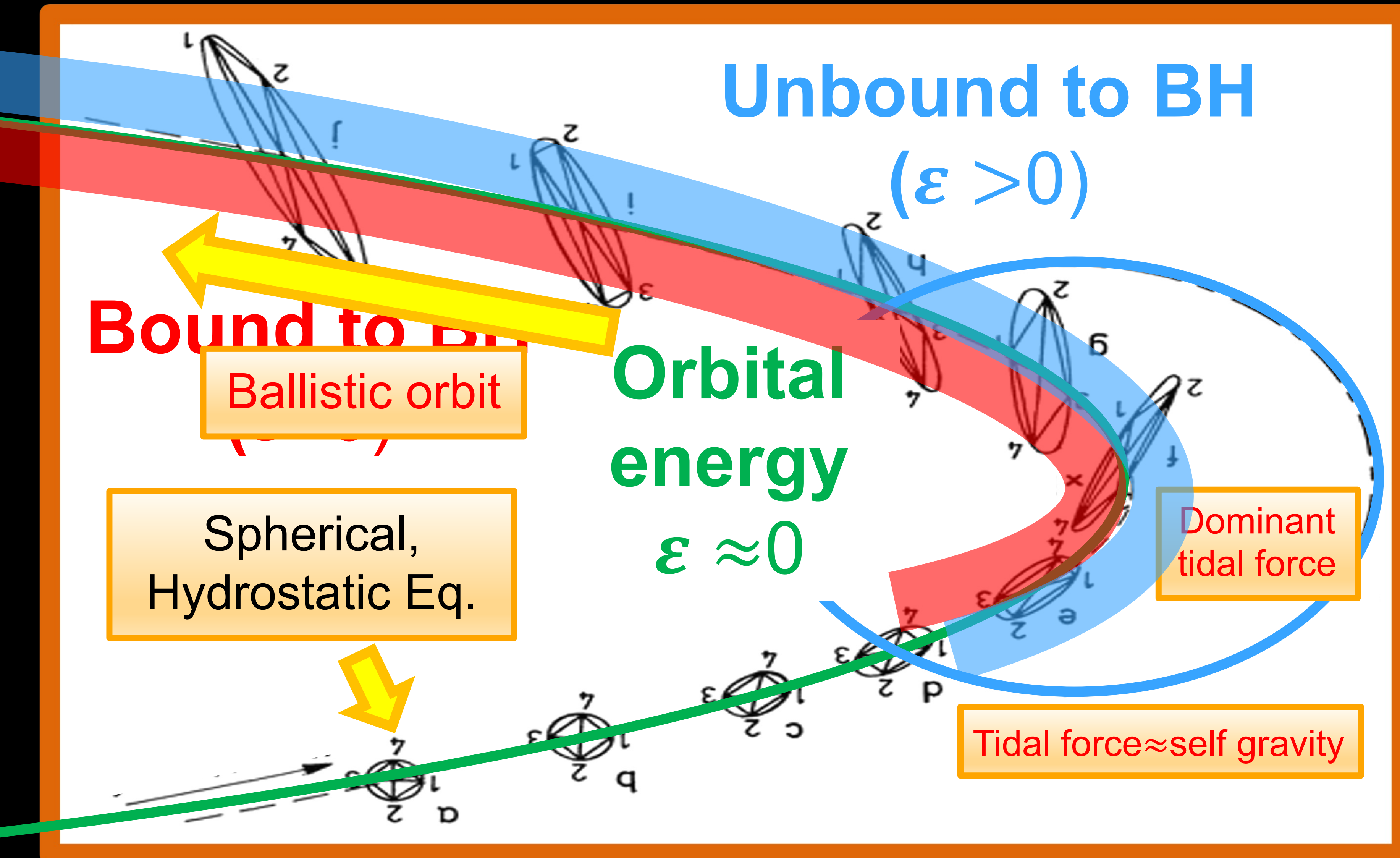
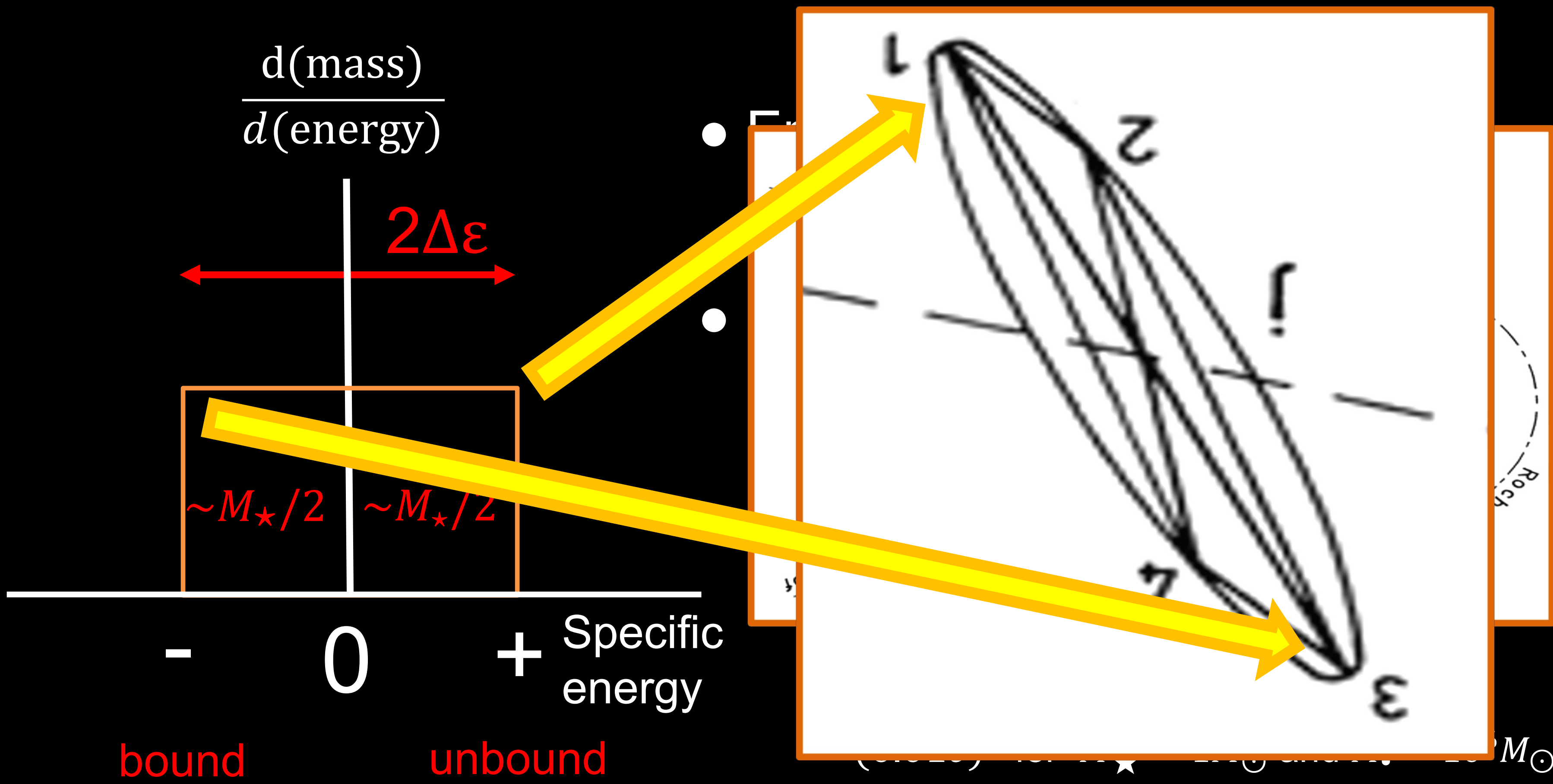
# Standard Picture



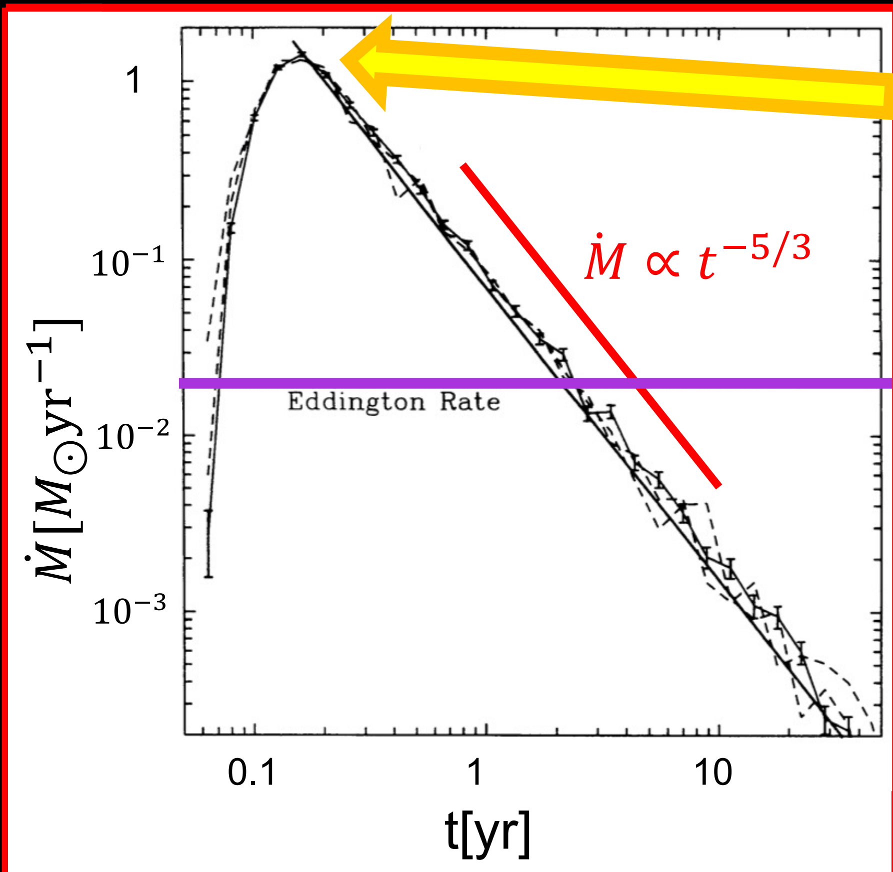

Evans & Kochanek (1989)

# Standard Picture (Energy distribution)



# Standard Picture

Top hat + Ballistic + Kepler's law ⇒ Mass return rate (not accretion rate!)

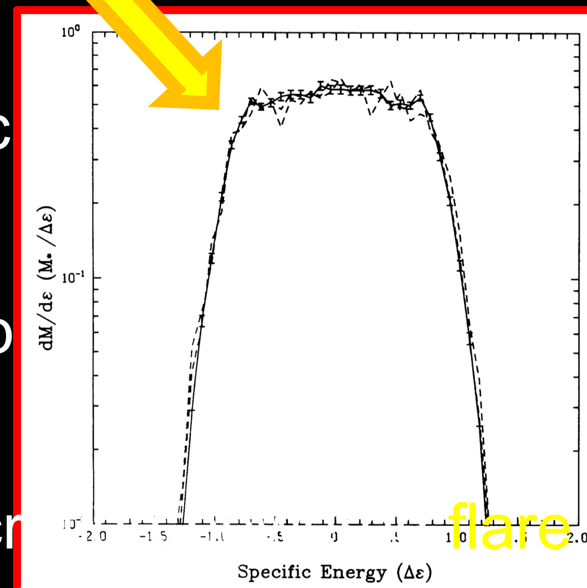



$M_\bullet = 10^6\ M_\odot,\ M_\star = 1\ M_\odot$

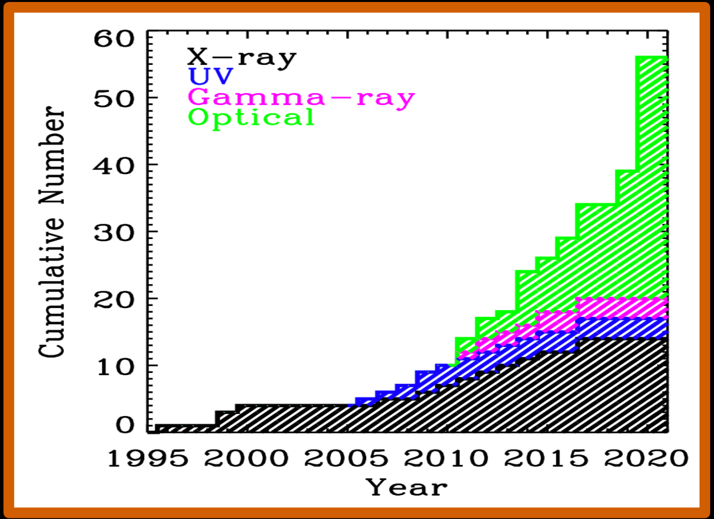
Evans & Kochanek (1989)

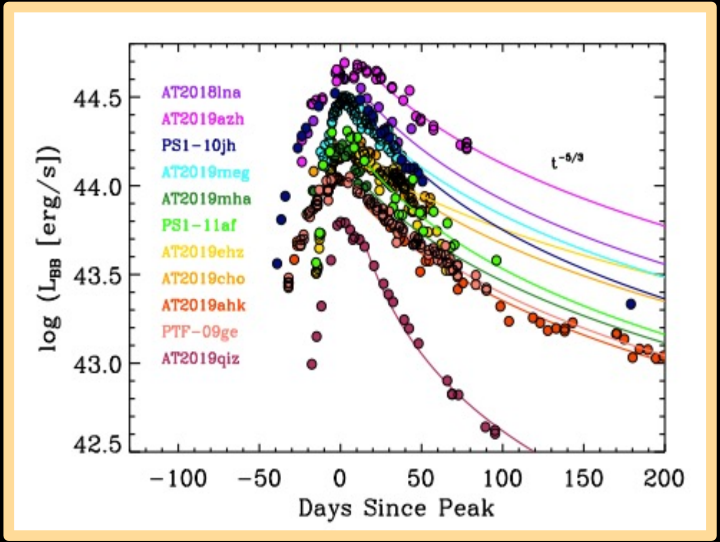
- Peak : $|\varepsilon| \sim \Delta\varepsilon$
- Dec
- Rap … nation
- Acc … flare

(expected to be bright in X-ray band)



# Tsunami of TDE candidates coming!




Gezari 2021 (review)

- First discovered in 1990s
  (ROSAT all-sky survey)
- so far ~100 events (mostly optical/UV)
  (ZTF: ~10 / yr)
- Ongoing / future surveys
  - eROSITA (X-ray, 4 years) : a few 100 / yr
    (Sazanov+2021)

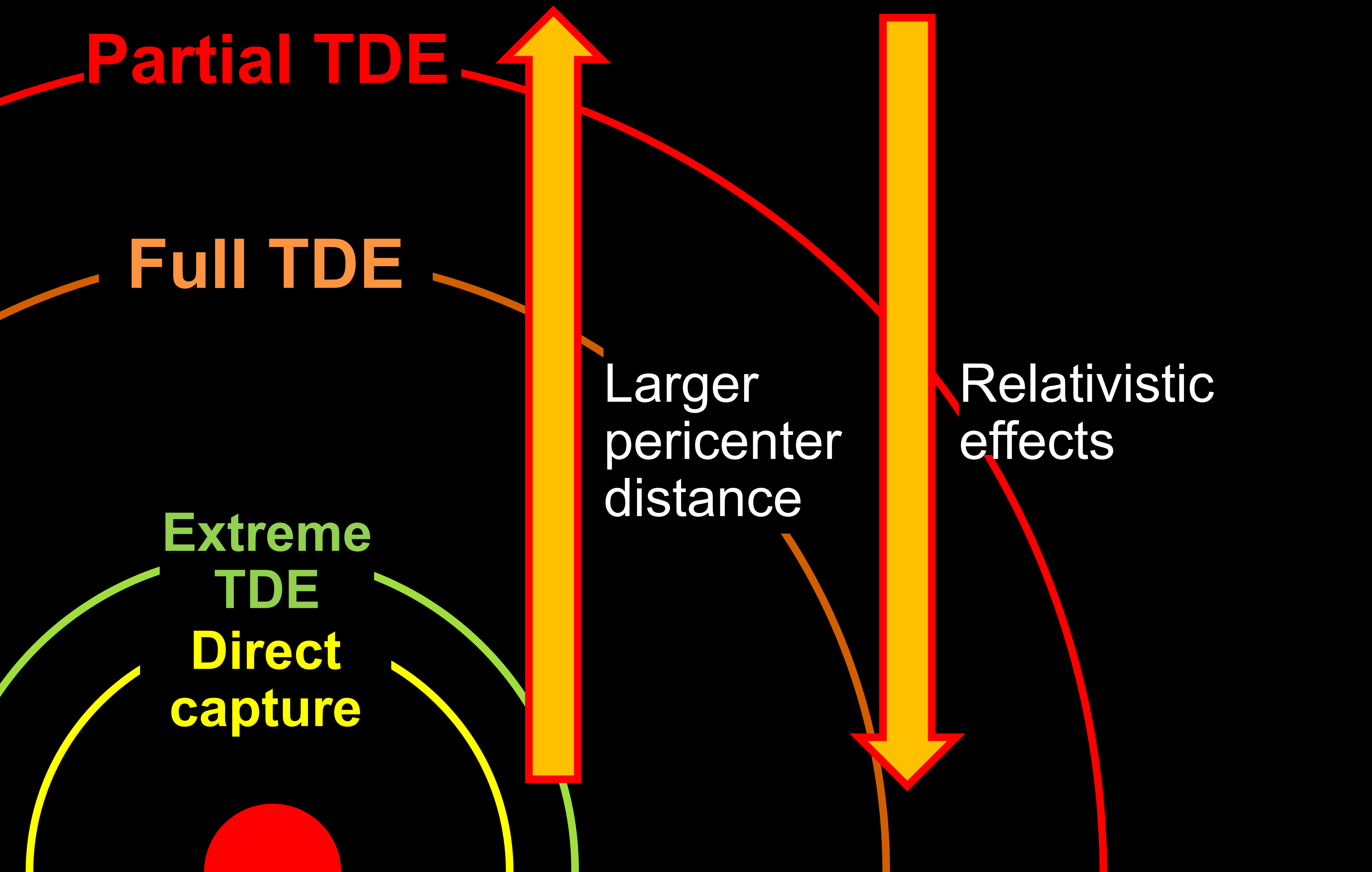
    ~20 eROSITA TDE candidates
    (e.g., Liu+2023, Wevers+2023, Malyali+2023)
  - ULTRASAT (UV, 3 years) : a few 100 / yr
    (Ben-Ami+2022)
  - LSST (Optical, 10 years) : a few 1000 / yr
    (Bricman&Gomboc2020)
- Population study is possible

⇨ Need to know different types!

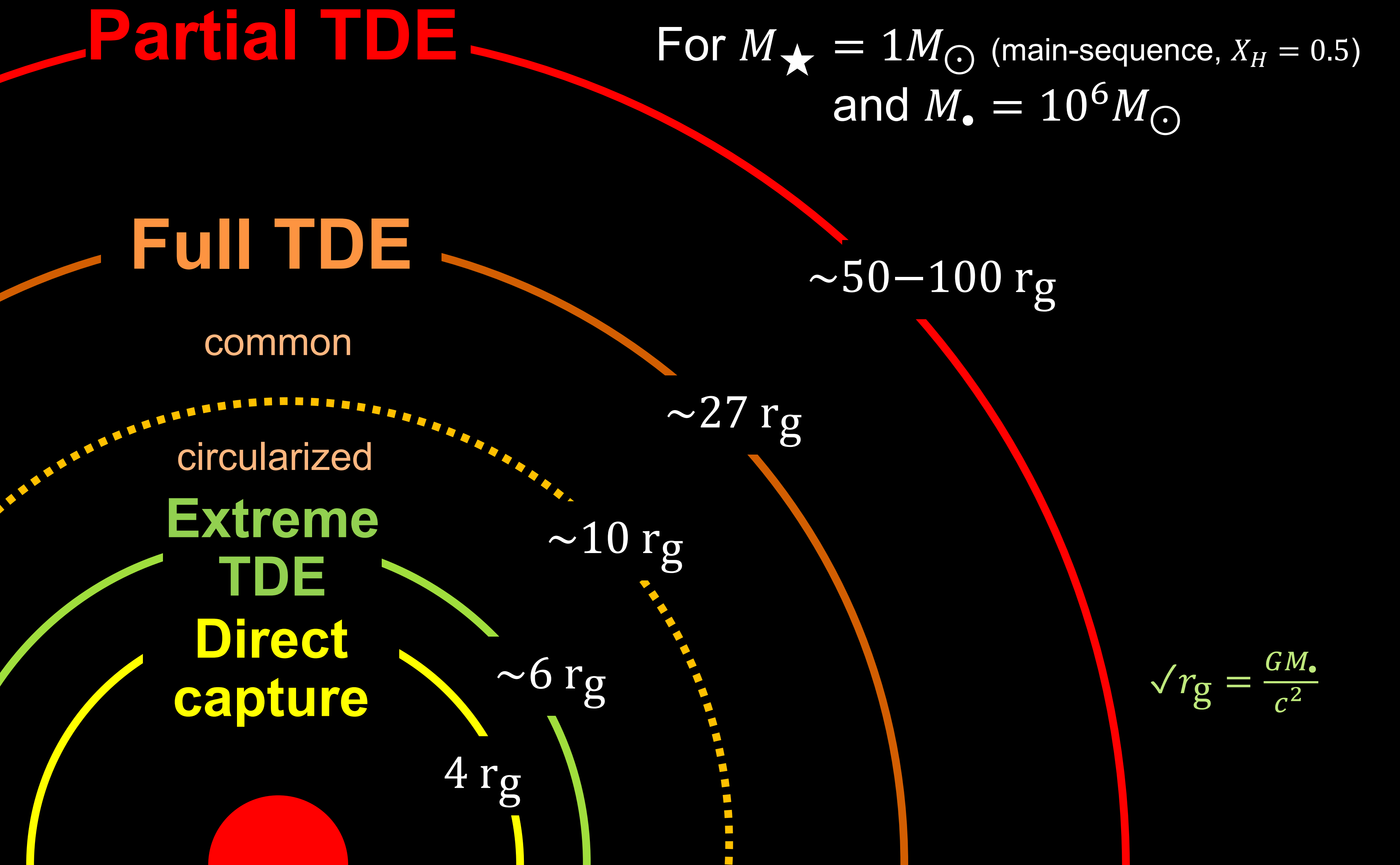
# Varieties of TDEs

- depending on the structure of debris and its evolution, closely related to observational features

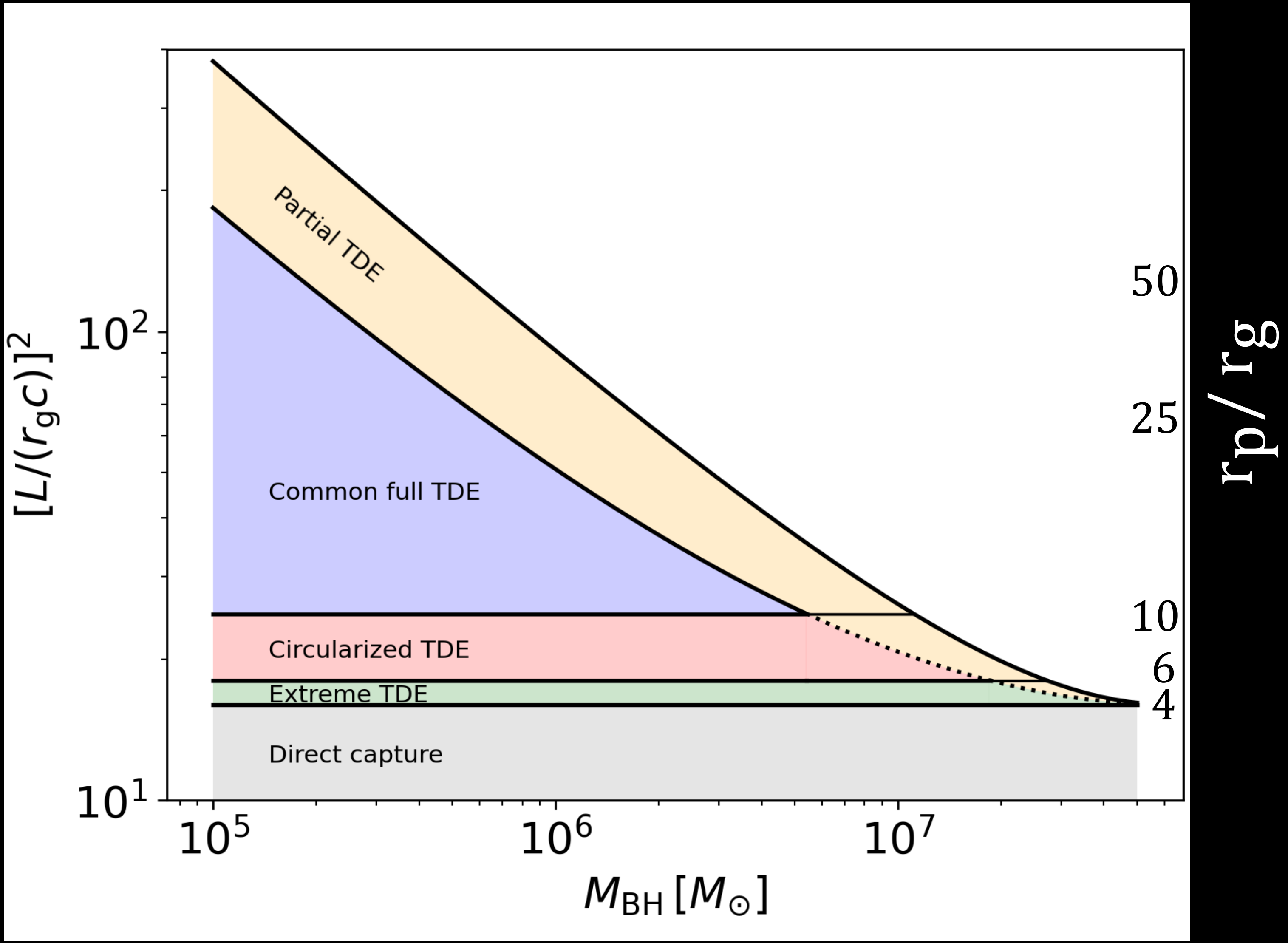
# Varieties of TDEs



# Varieties of TDEs



# Varieties of TDEs




Ryu, Krolik and Piran (2023)

TDEs by more massive black holes are more relativistic!


**Partial TDE**

**Full TDE**

common

circularized

**Extreme**

**Direct capture**

# Partial
# Tidal Disruption Events
## (Least relativistic observable events)

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# Partial Tidal Disruption Events

Small pericenter

**Partial TDE**

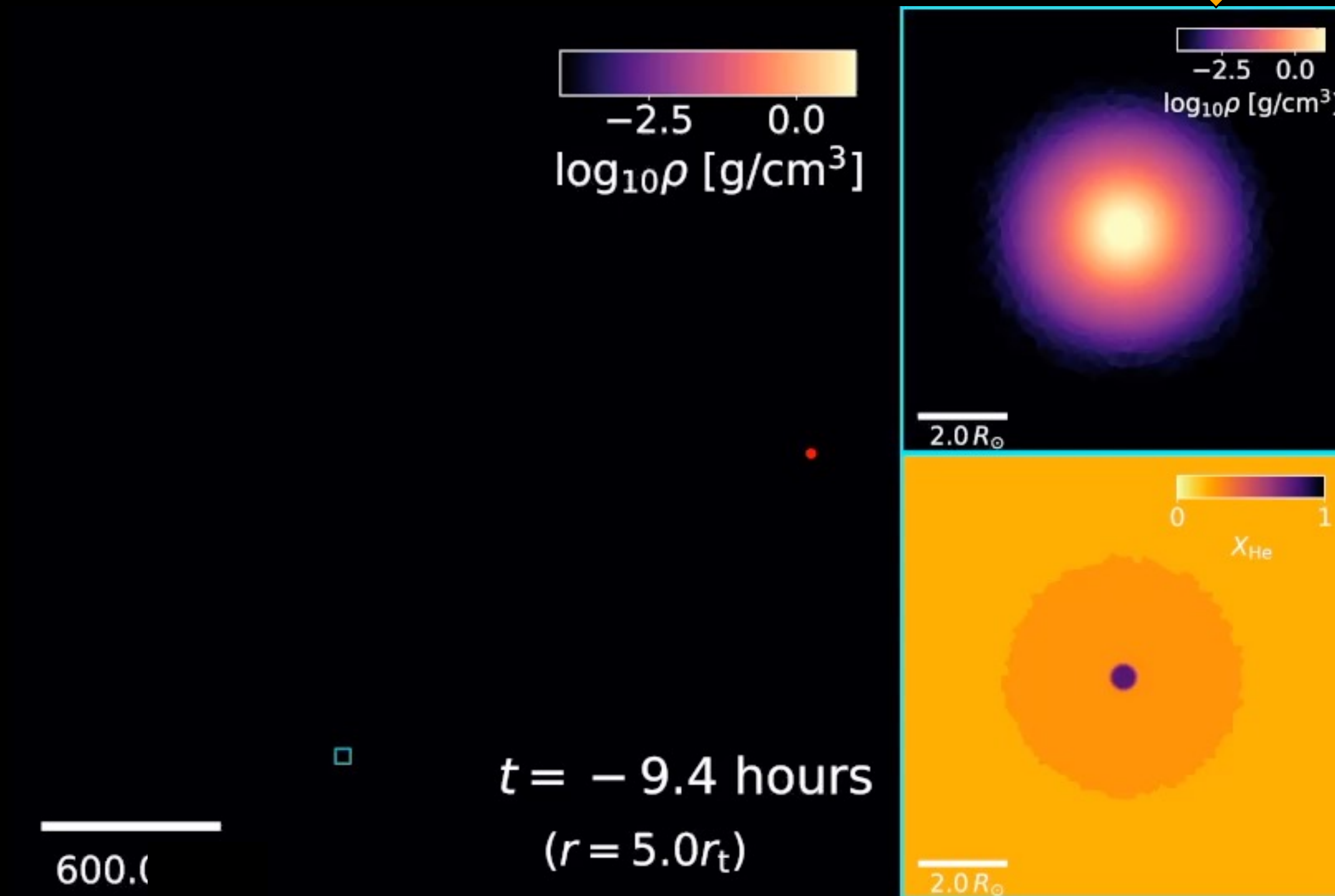
**Full TDE**

common

circularized

**Extreme**

**Direct capture**

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# Partial Tidal Disruption Events

Small pericenter

**Partial TDE**
**Full TDE**
common
circularized
**Extreme**
**Direct capture**

- Outcome : surviving remnant + debris
  - Hotter than ordinary star of the same mass
  - Sp (di
  - Po
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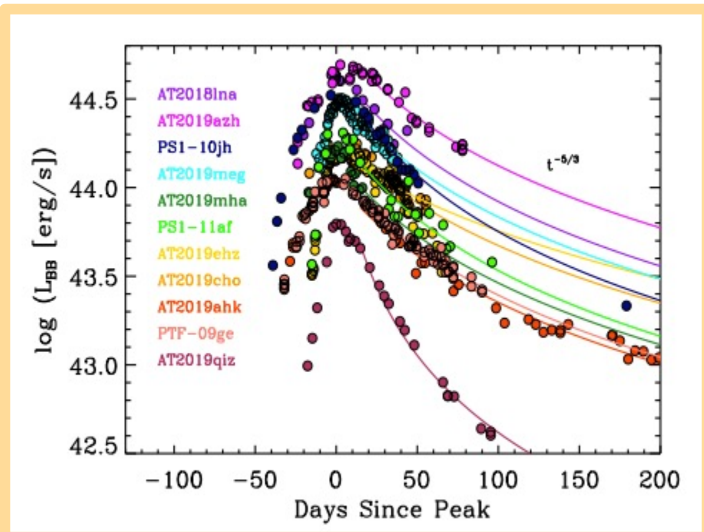
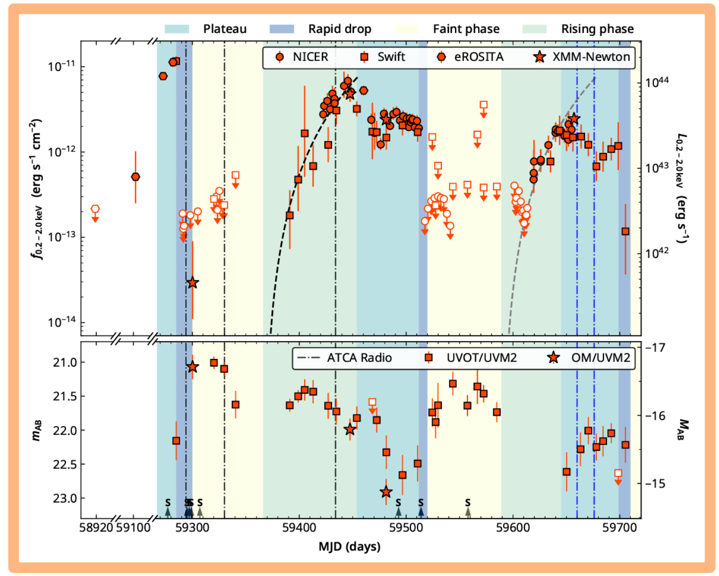
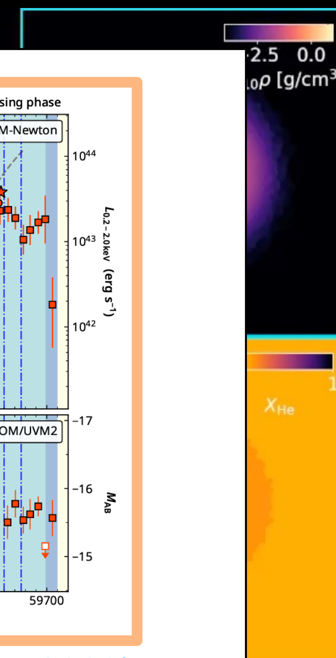
  e.g.,
  - Po
  e.g.,




Gezari 2021 (review)



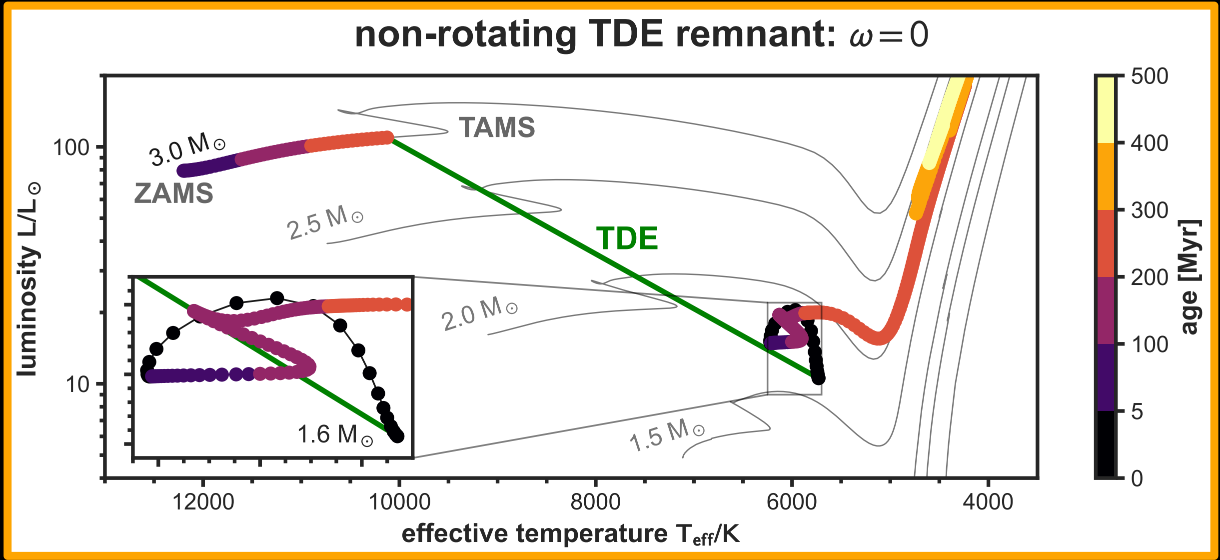

eRASStJ045650.3−203750 (Liu+2023)

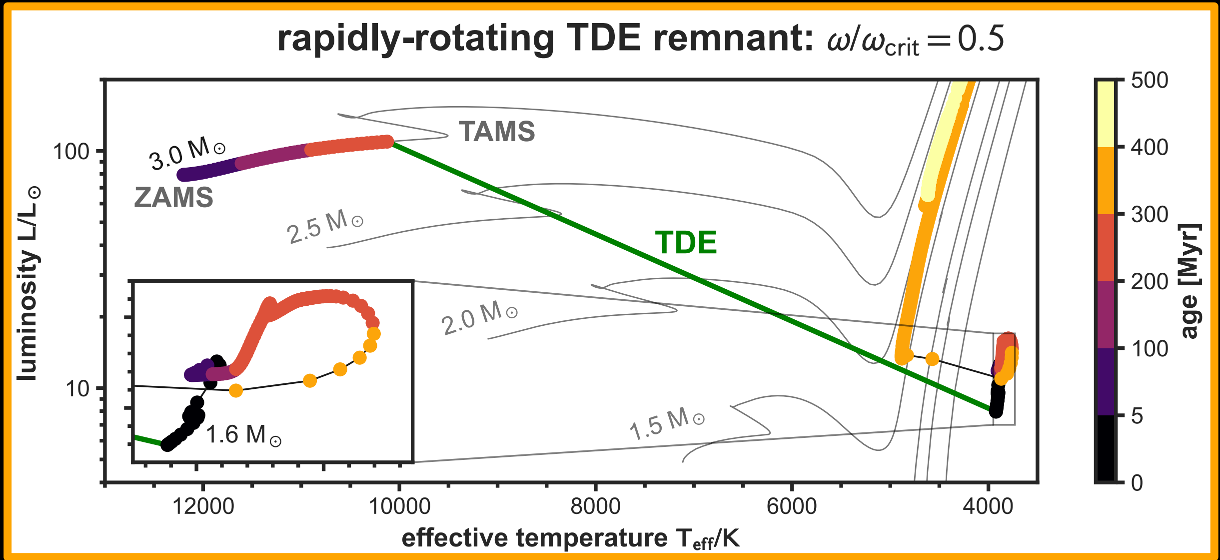



- Rate is comparable to or higher than full TDEs (Krolik+2020,Zhong+2022,Bortolas,Ryu+2023)

# Properties and evolution of remnants

Long-term evolution using MESA (preliminary result) Bellinger & Ryu(in prep)



Small pericenter

**Partial TDE**

**Full TDE**

common

circularized

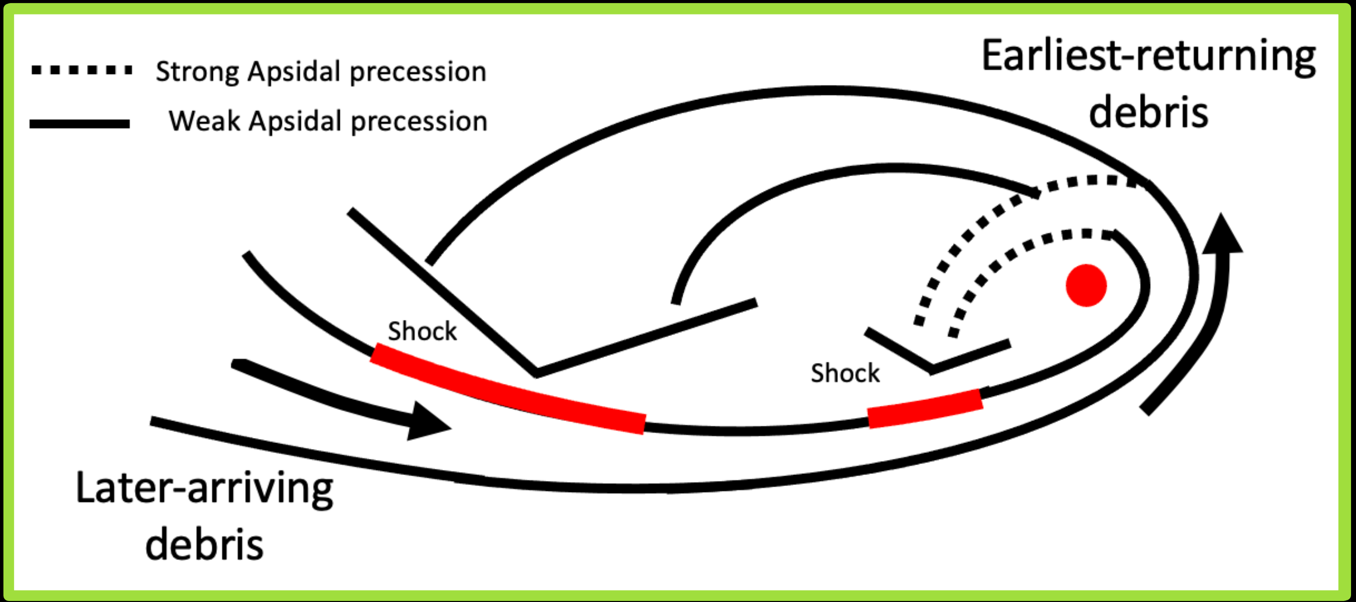
**Extreme**

**Direct capture**

# Full
# Tidal Disruption Events
## (Still controversial observable events)

Emission mechanism for optical/UV is not fully understood…

# Emission mechanism - Circularized vs Common




Steinberg&Stone2022

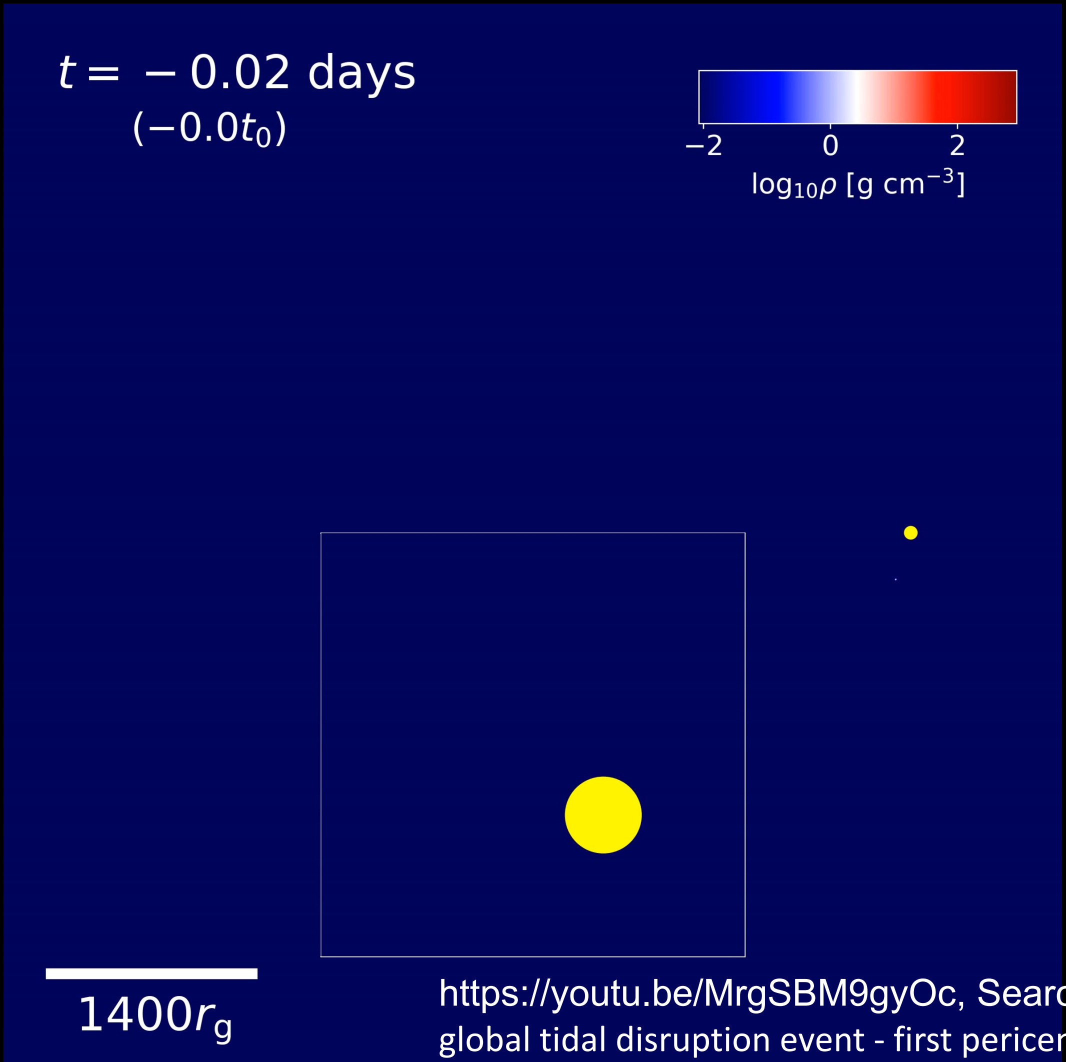
| | Circularized (e.g., Rees 1988, Sadowski+2016, Bonnerot&Lu2020, Andalman+2022) | Common (e.g., Piran+2015, Shiokawa+2015, Bonnerot&Lu2016, Ryu+2023) |
|---|---|---|
| Apsidal precession | Strong ($r_p \lesssim 10\, r_g$ ) | Weak ($r_p \gtrsim 10\, r_g$ ) |
| Energy dissipation | Shocks near pericenter | Shocks near apocenter |
| Outcome | Compact circular disk (~period of the most bound debris) | Extended elliptical disk (> period of the most bound debris) |
| Energy source | Accretion (X-ray) | Shock-driven dissipation (Optical/UV) |

# Common TDE

- Fully relativistic global hydrodynamics simulation (Ryu+2023)
- $M_\star = 3M_\odot$(MESA) , $M_\bullet = 10^5 M_\odot$, $r_p \sim 100\ r_g$
- Evolve up to 3 (peak mass return time)

Partial TDE
Full TDE
common
circularized
Extreme
Direct capture

Small pericenter

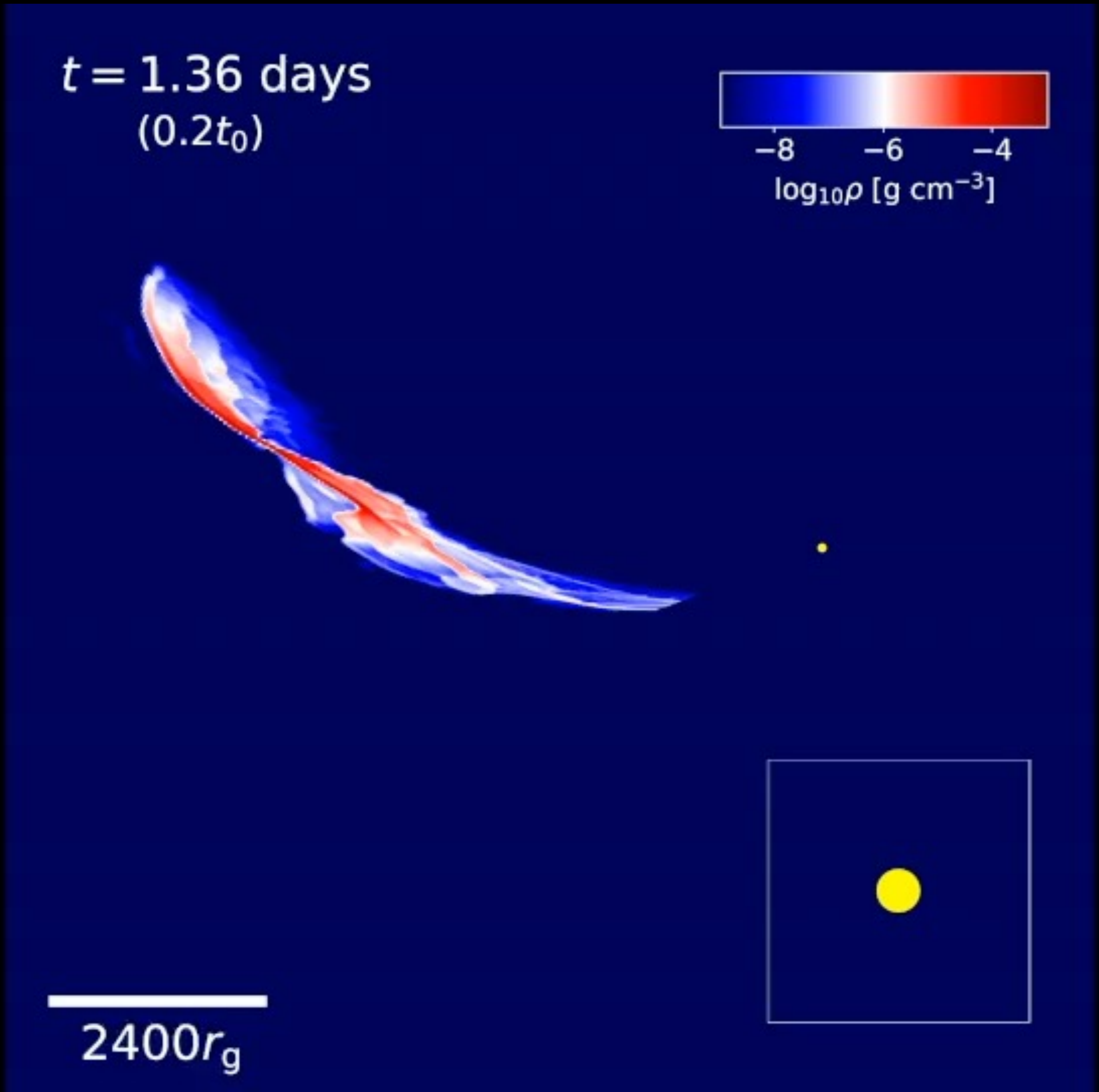



√ $r_g = \frac{GM_\bullet}{c^2}$

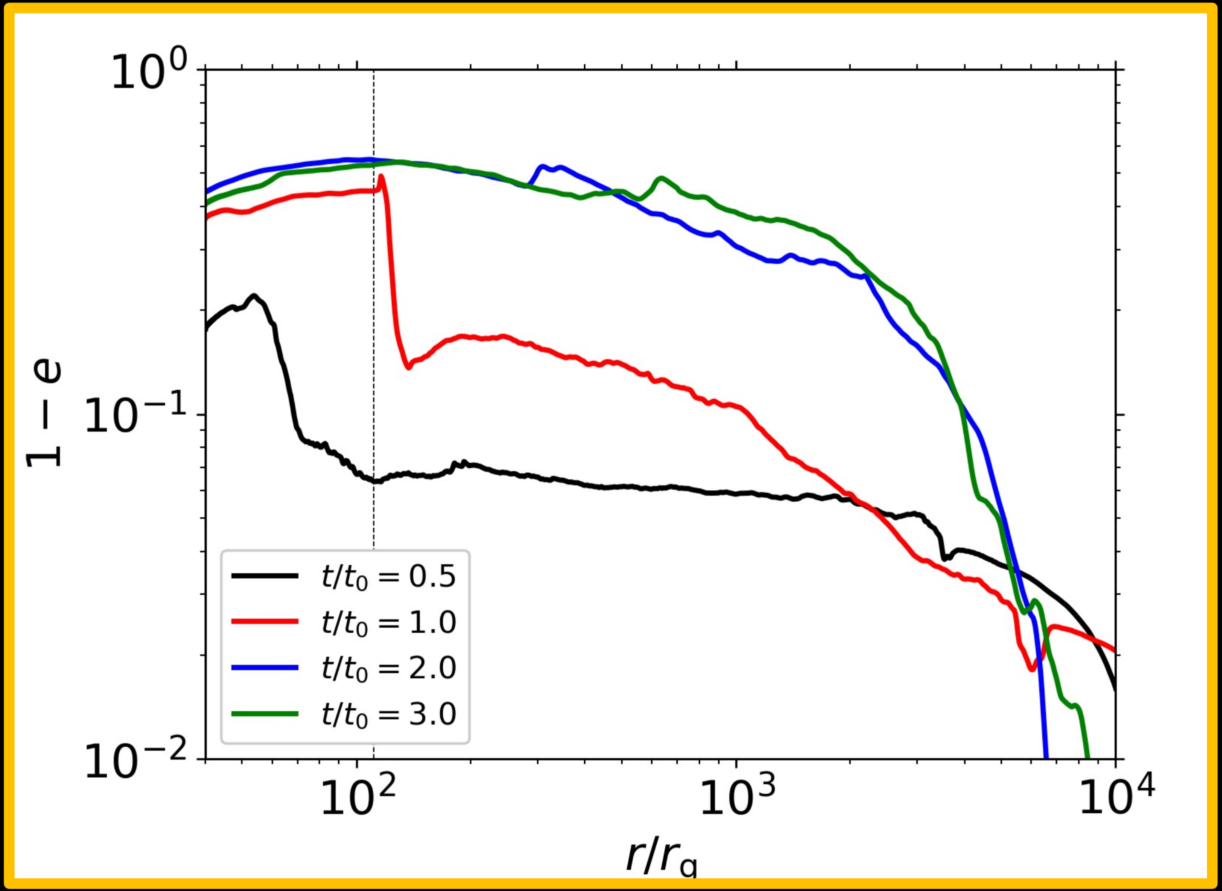
https://youtu.be/MrgSBM9gyOc, Search for "Fully relativistic global tidal disruption event - first pericenter passage" on Youtube

# Common TDE

https://youtu.be/BerBVHa42Fo, Search for "Fully relativistic global tidal disruption event – after first pericenter passage" on Youtube



# Common TDE – eccentricity of debris



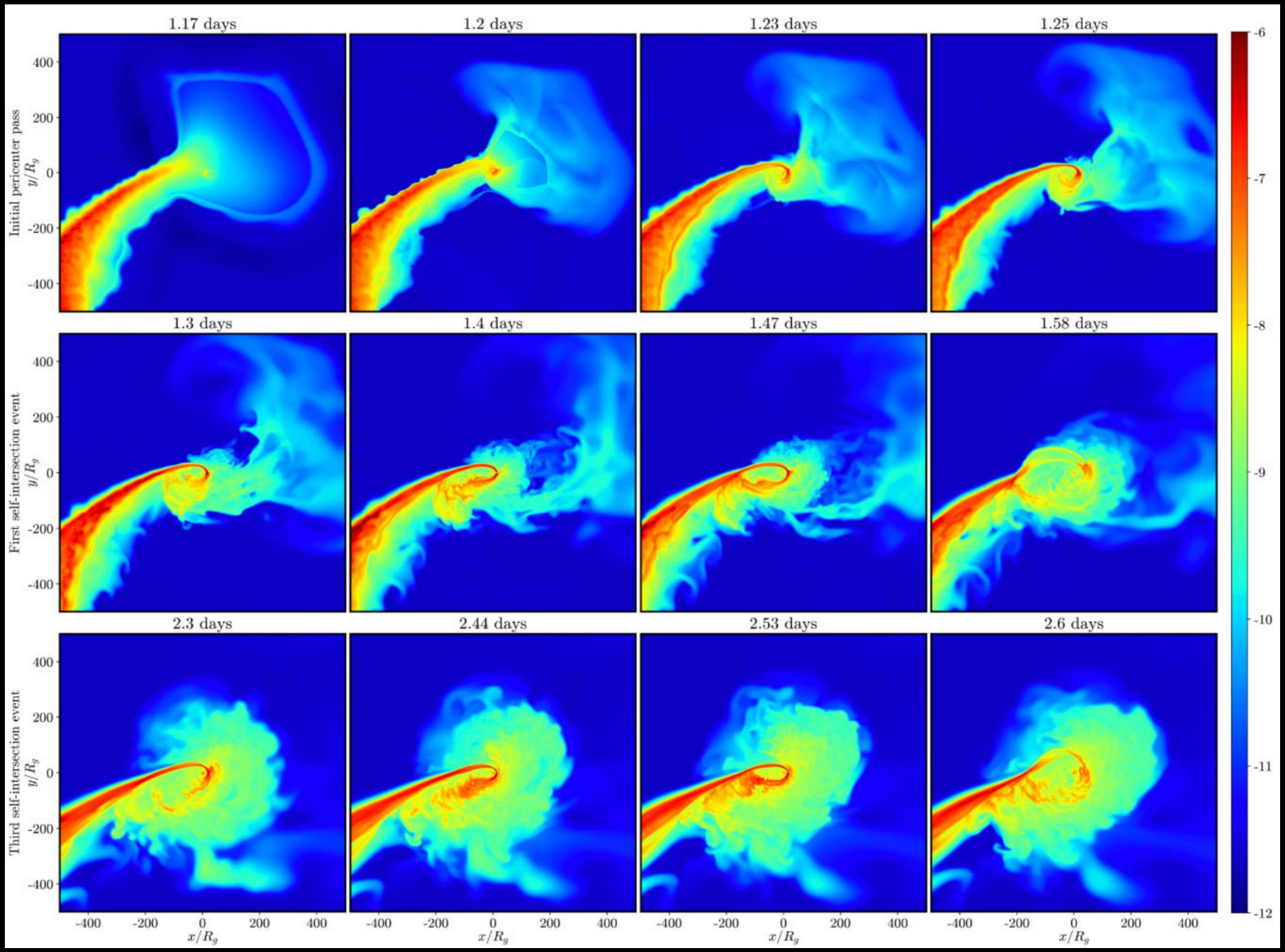

- ~30 characteristic times for full circularization!

cf. one characteristic time in the tranditional picture

- Shock-driven luminosity is enough to explain observed luminosity!

# Circularized TDE

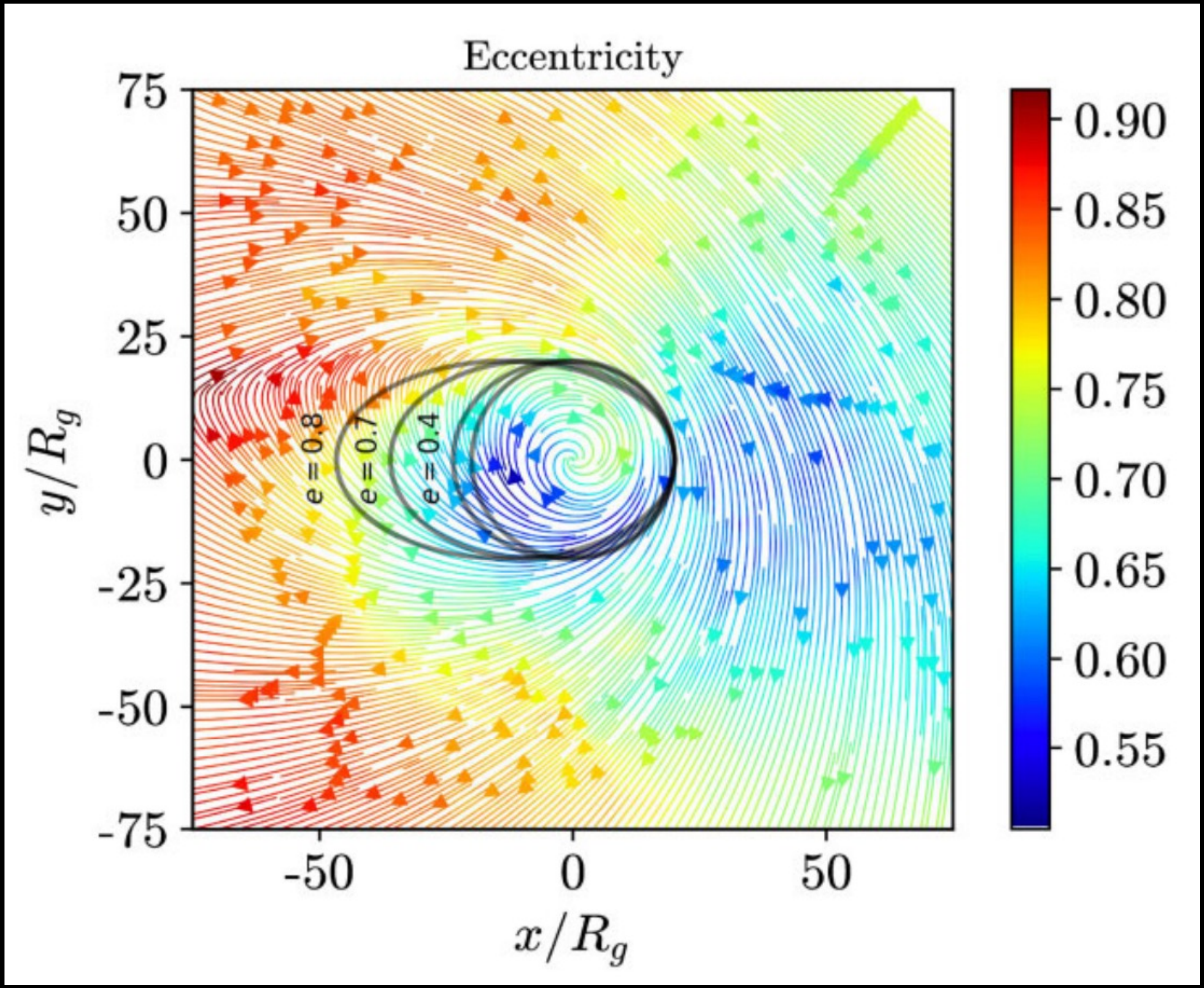




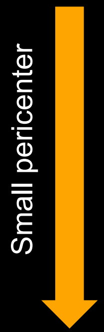

Andalman+2022

- Phantom (Price+2018) + GPU-accelerated GRMHD code H-ARM (Liska+2019)
- $M_\star = 1M_\odot, M_\bullet = 10^6 M_\odot$, $r_p = 7\ r_g$
- Evolve up to 7 days ~ 0.2 (peak mass return time)

# Circularized TDE




Andalman+2022




**Partial TDE**

**Full TDE**

common

circularized

**Extreme**

**Direct capture**

Small pericenter

**Partial TDE**

**Full TDE**

common

circularized

**Extreme**

**Direct capture**

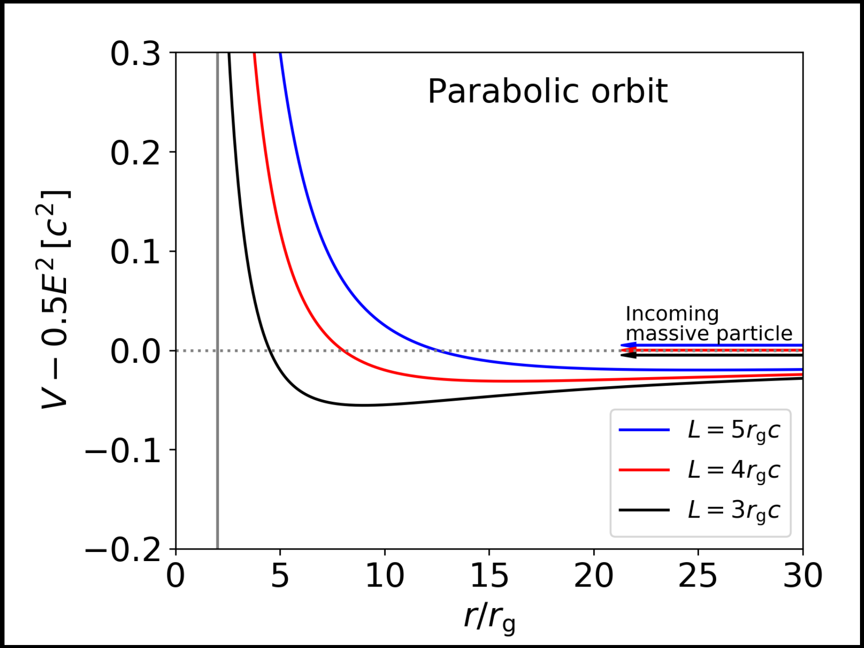
# Extreme
# Tidal Disruption Events
## (most relativistic observable event)

# Relativistic geodesic

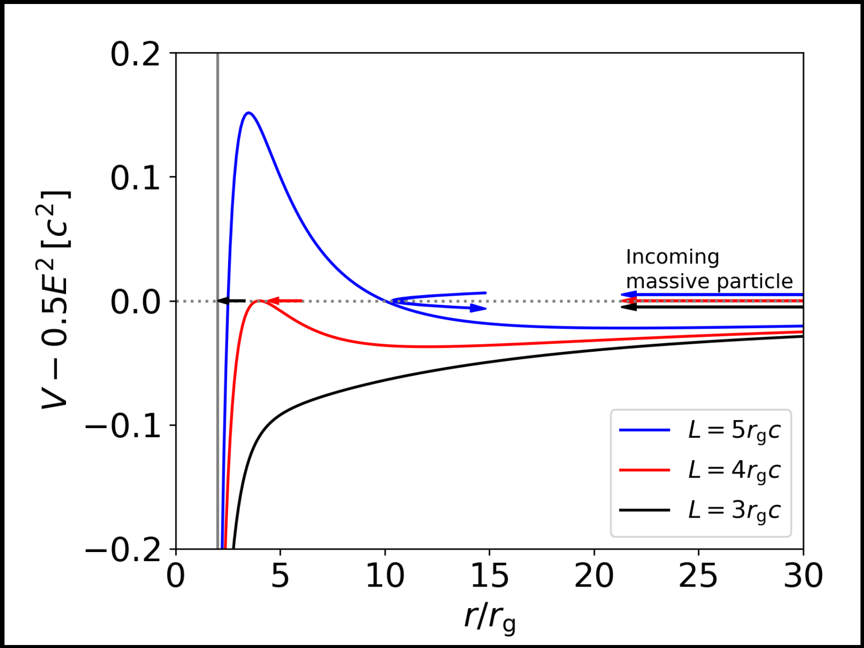
$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2 = -V(r) + \frac{1}{2}E^2$$

$$V(r) = \alpha - \frac{GM_\bullet}{r} + \frac{L^2}{2r^2} - \frac{GM_\bullet L^2}{r^3}$$

Newtonian



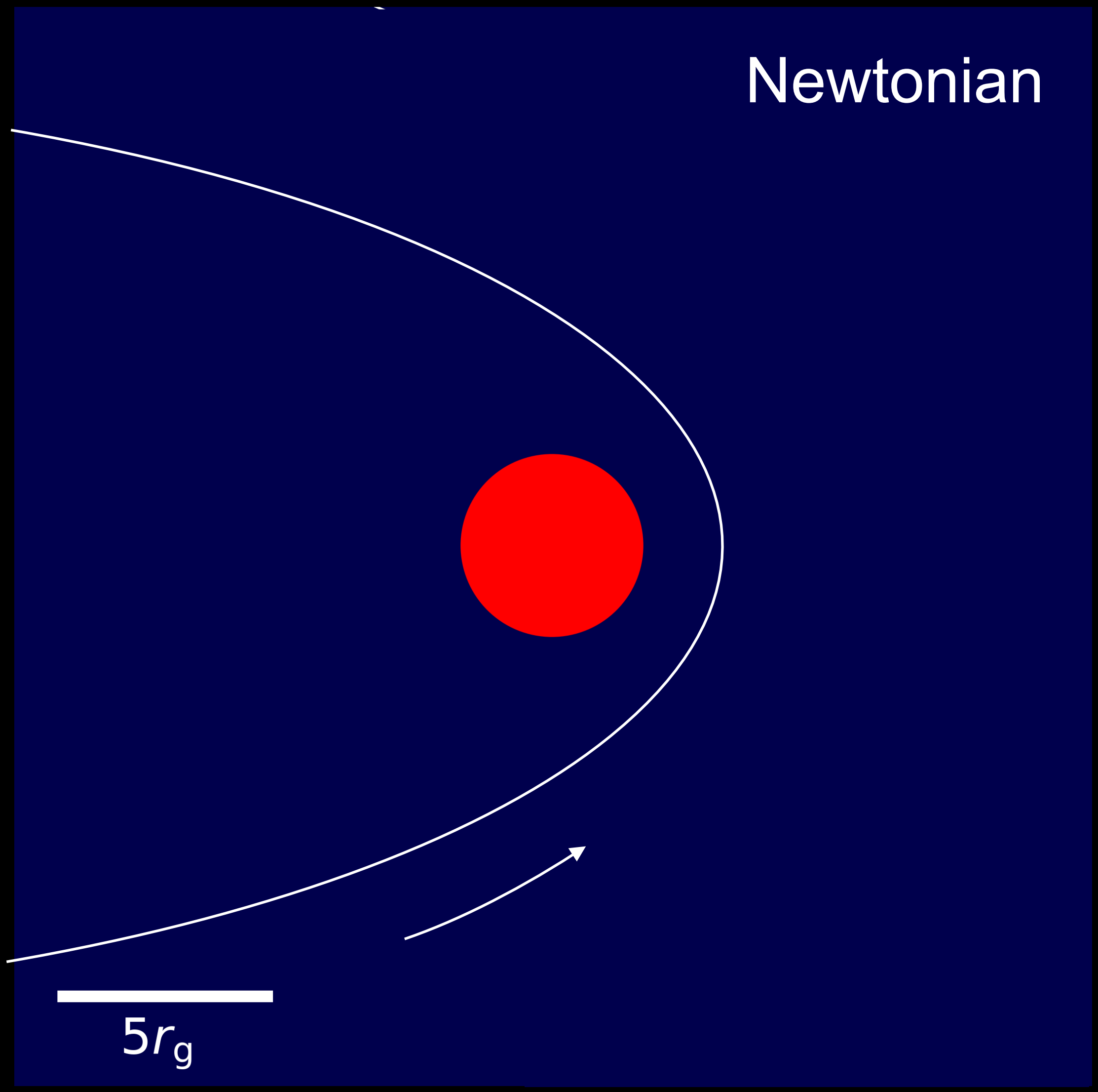

Relativistic (Schwarzschild)



# Stellar orbit in Extreme TDEs $(4\, r_g < r_p < 6\, r_g)$

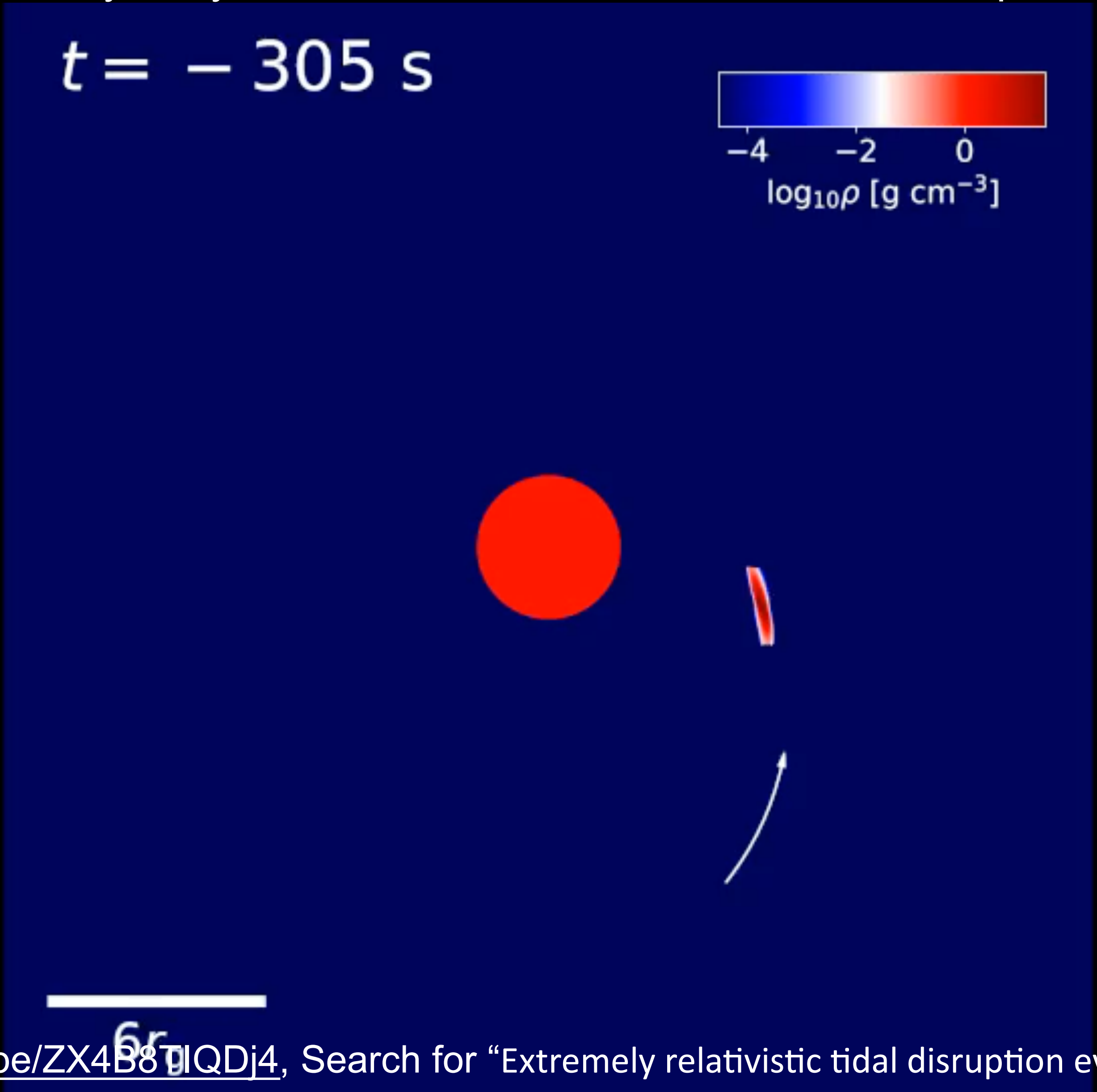
- Extremely large apsidal precession

$r_p \sim 4.02 r_g$



# Extreme TDEs ($4\,r_g < r_p < 6\,r_g$)

Fully relativistic hydrodynamics simulation with realistic main-sequence star (MESA)




(Ryu+2023)

https://youtu.be/ZX4B8TIQDj4, Search for “Extremely relativistic tidal disruption event“ on Youtube

# Extreme TDEs ($4\,r_g < r_p < 6\,r_g$)

Extreme

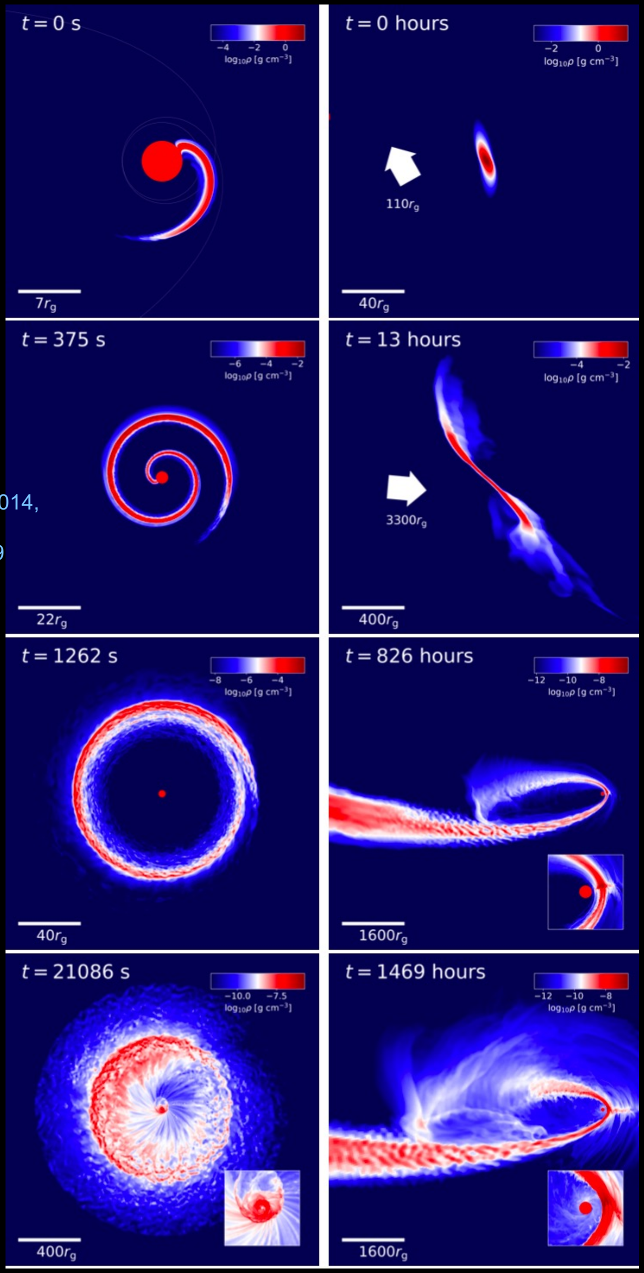
Crescent

Spirals

Laguna+1993,
Kobayashi+2004,
Cheng&Bogdanovic 2014,
Tejeda+2017,
Gafton&Rosswog2019

Expanding ring

Expanding ring +
hot accretion flow

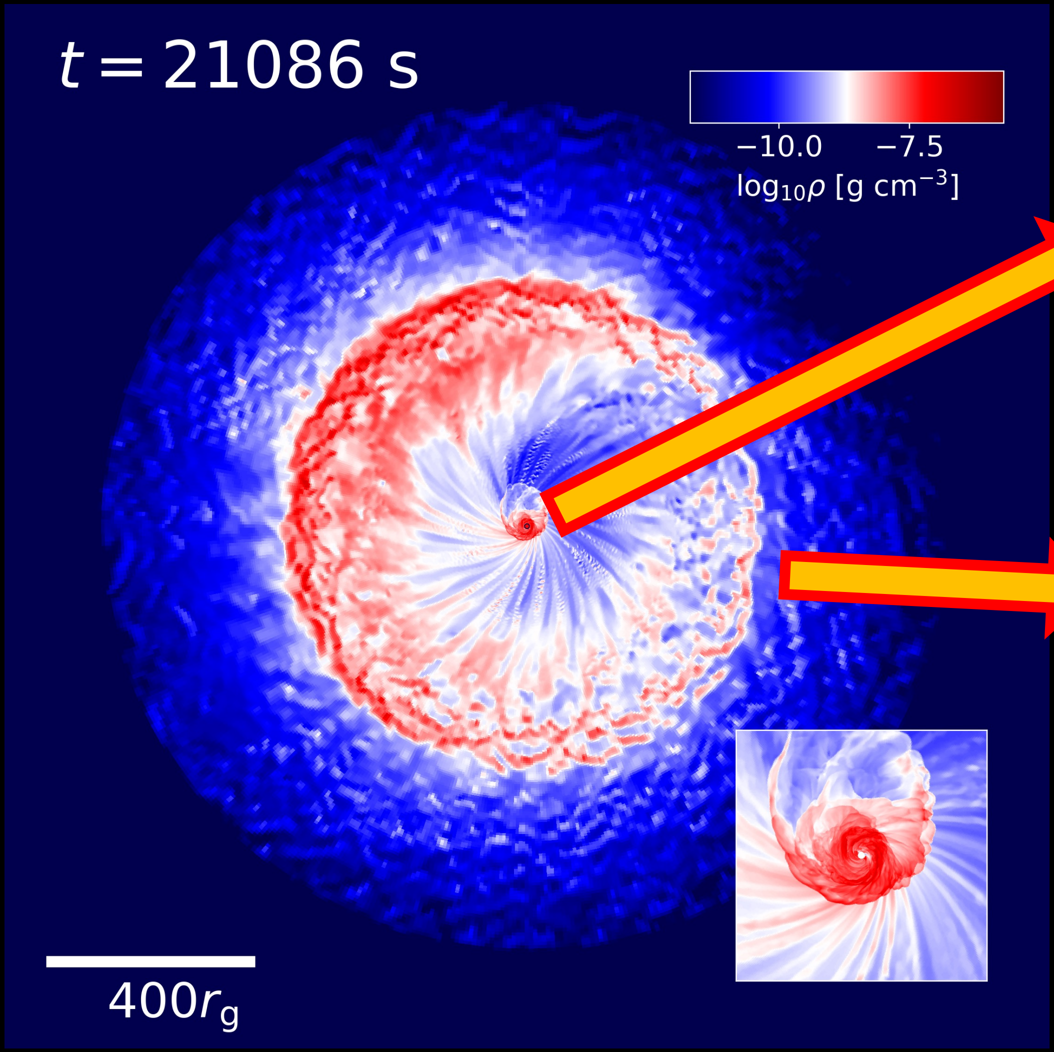



Common

Ellipsoid

Elliptical disk

# Observational signature from extreme TDEs




Hot compact accretion flow

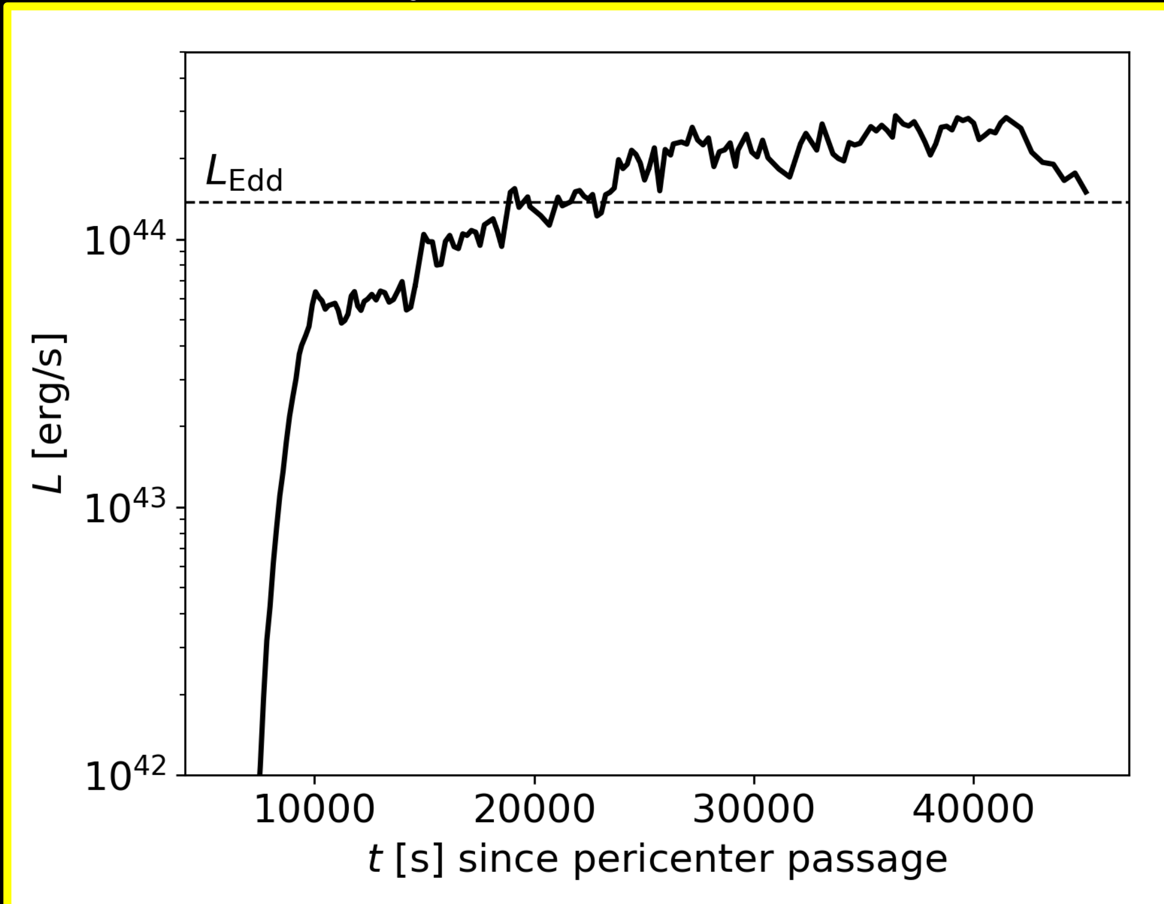
X-rays (~0.1-0.2keV)

Expanding ring
(unbound ejecta)

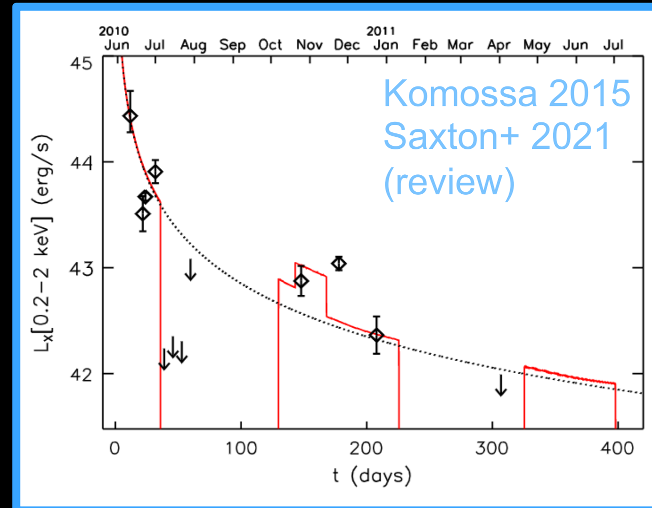
Radio signal

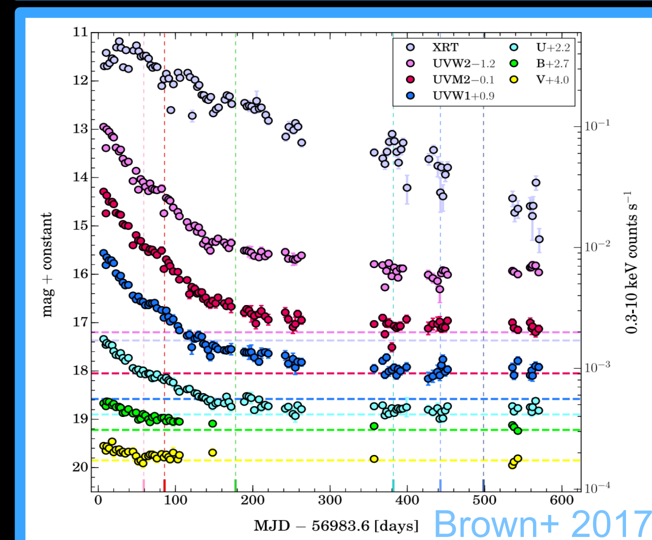
# Observational signature from extreme TDEs

- Luminosity rises rapidly to Eddington in a few hours, remains at that level for weeks – a year



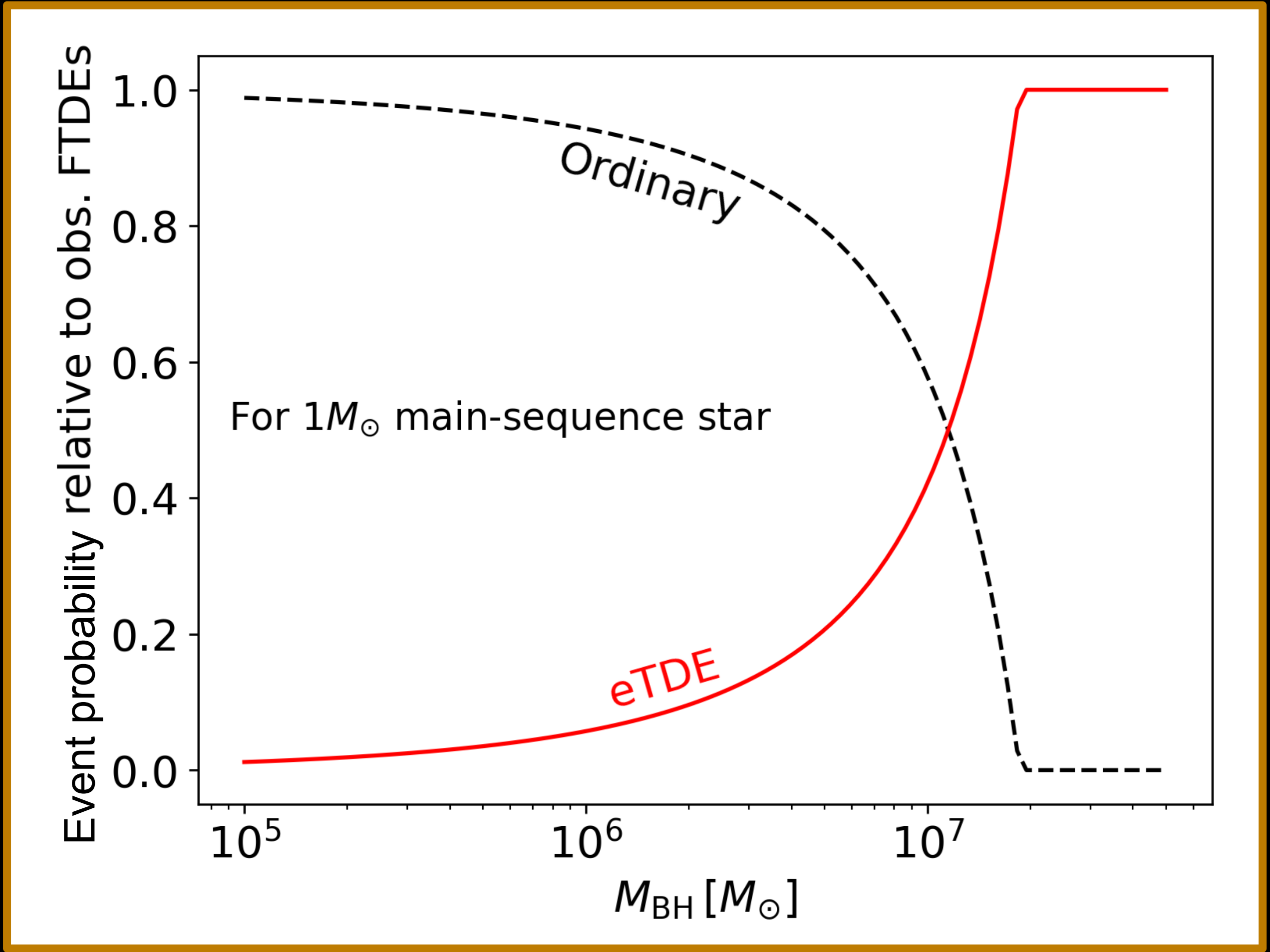

Extreme TDEs

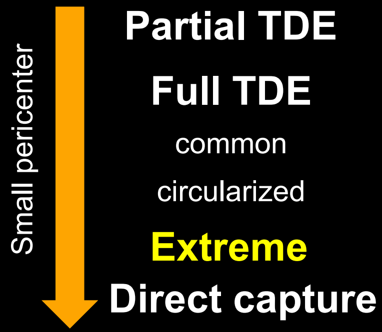



Observed TDEs

# Minor channel? Not necessarily!




- Minor for low-mass BH : $\lesssim 6\%$ of all observable events for $M_\bullet \lesssim 10^6 M_\odot$
- Major for high-mass BH: $\gtrsim 40-50\%$ for $M_\bullet \gtrsim (1-3)\times 10^7 M_\odot$
- Peak rate ~ $6\times10^{-5}\mathrm{yr}^{-1}\mathrm{galaxy}^{-1}$ (assuming $1M_\odot$ main-sequence stars)

Small pericenter

**Partial TDE**

**Full TDE**

common

circularized

**Extreme**

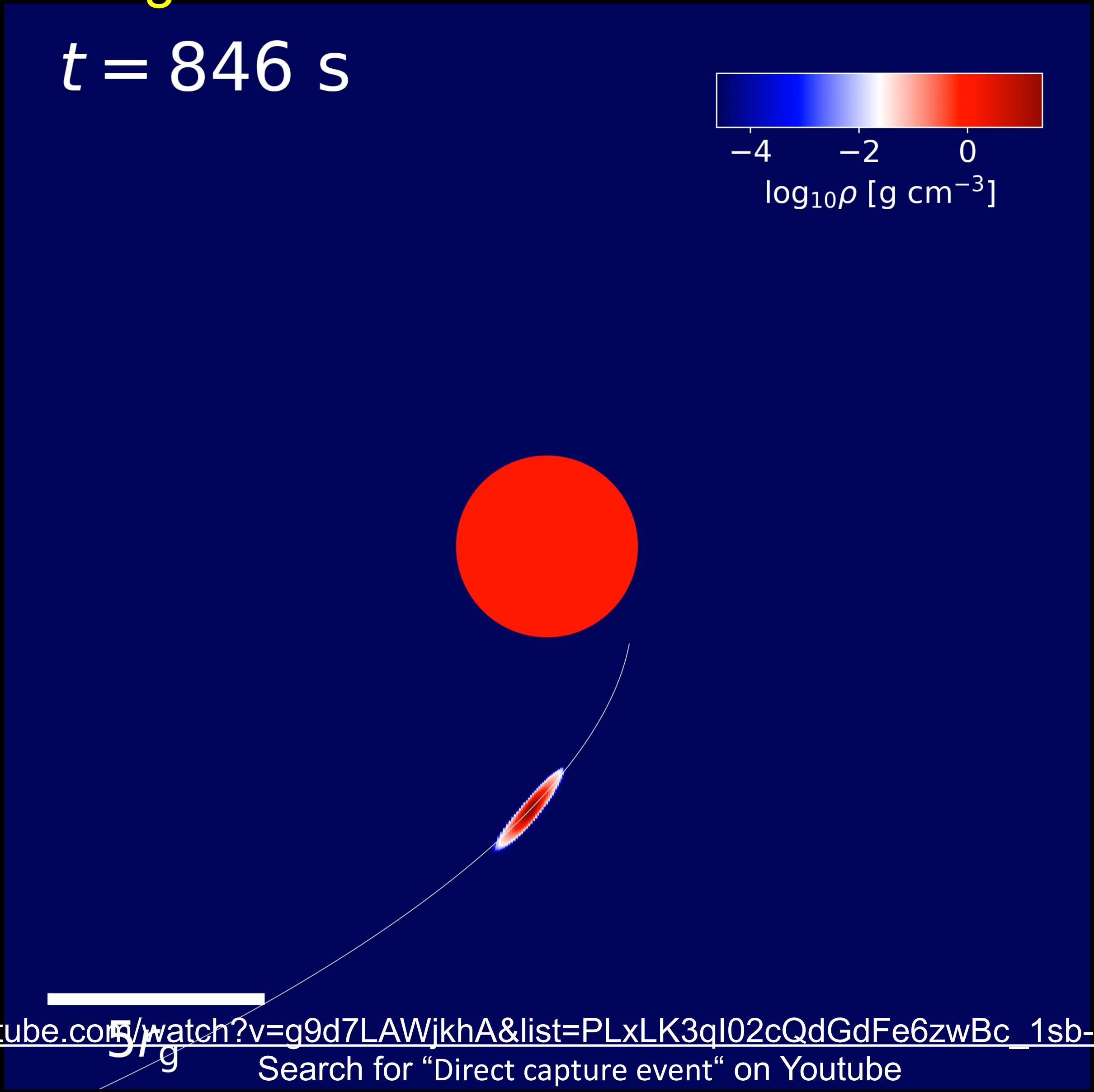
**Direct capture**

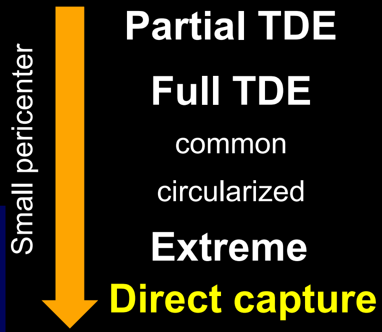
# Direct capture

**(most relativistic unobservable events)**

# Direct capture ($r_p < 4\, r_g$)

- No electromagnetic emission




https://www.youtube.com/watch?v=g9d7LAWjkhA&list=PLxLK3qI02cQdGdFe6zwBc_1sb-XDW-mPk&index=2

Search for "Direct capture event" on Youtube

# Black hole-driven Disruptive Collision

## (BDC, most powerful stellar collision)

Taeho Ryu, 26th Sep. 2023, Lagrange Laboratoire

# Dynamical Stellar collisions at galactic centers

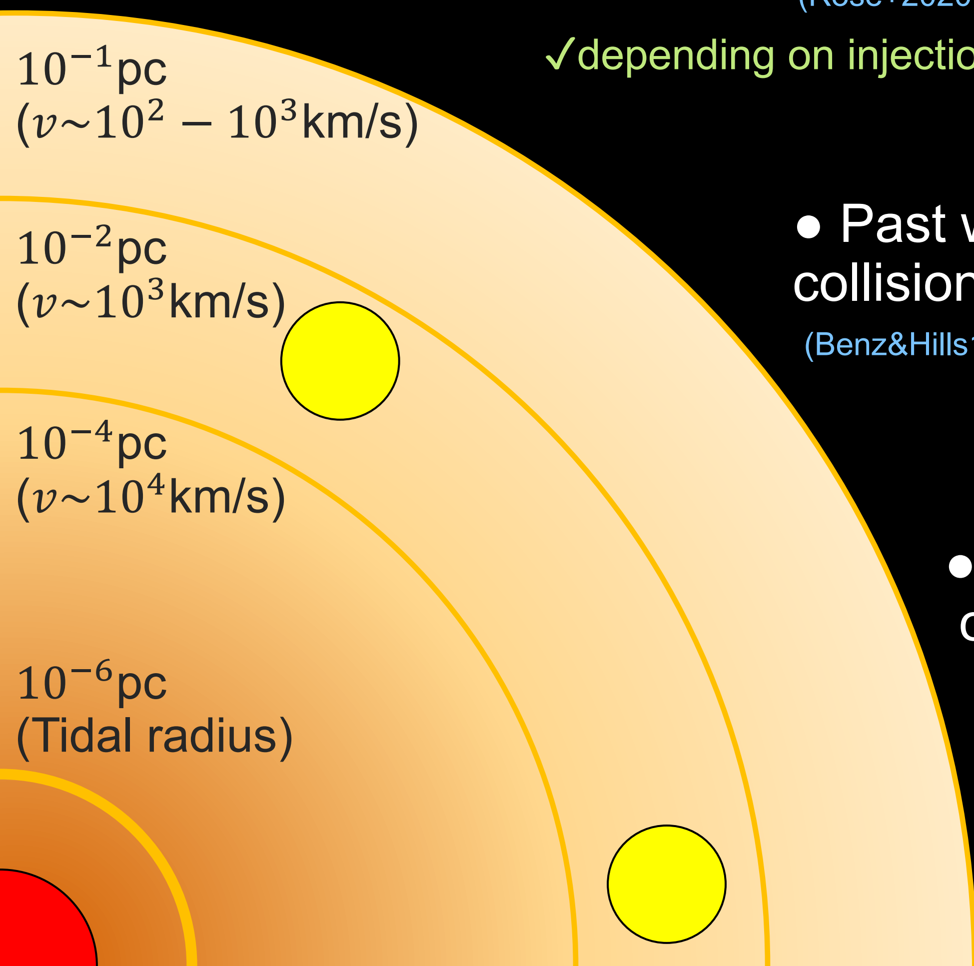
- Kinetic energy > stellar binding energy

  e.g., for $1M_\odot$ stars colliding at $\mathrm{v} \gtrsim 1000$km/s
  $\gtrsim 10^{49}$ erg vs $\lesssim 10^{48}$erg

  ➡ Bright flare can be generated

- $10^{-4} - 10^{-9} \mathrm{yr}^{-1} \mathrm{galaxy}^{-1}$ for main-sequence stars
  (Rose+2020, Amaro Seoane 2023, Rose+2023)

  ✓depending on injection and depletion rate (Balberg&Yassur2023)

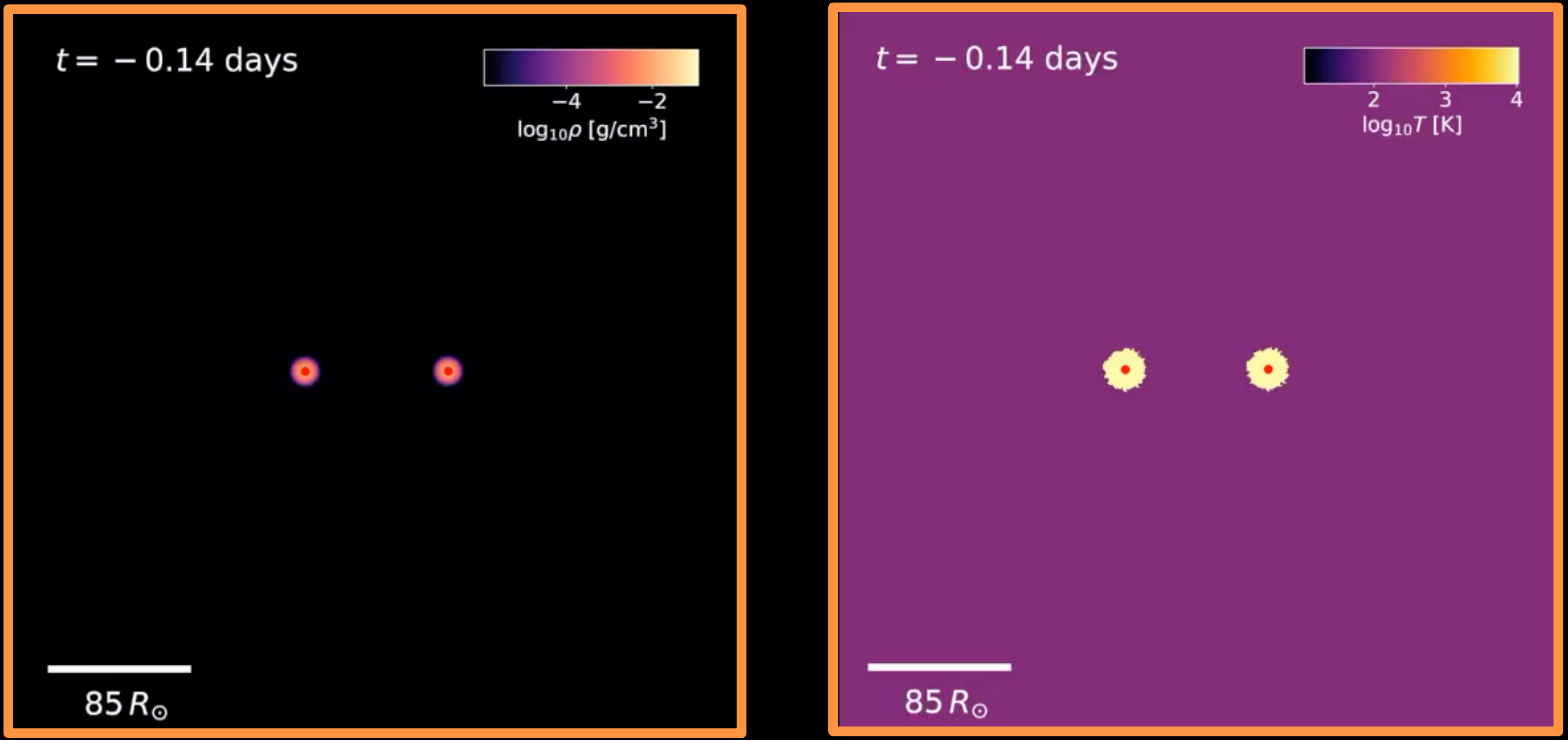



- Past work mostly on destructive collisions between main-sequence stars
  (Benz&Hills1987,1992, Lai+1993, Rauch1999, Freitag&Benz2005)

- Collisions between giants comparable or more frequent (Amaro Seoane 2023)

# Hydrodynamics simulations of BDCs (Ryu+2023, arXiv:2307.07338)

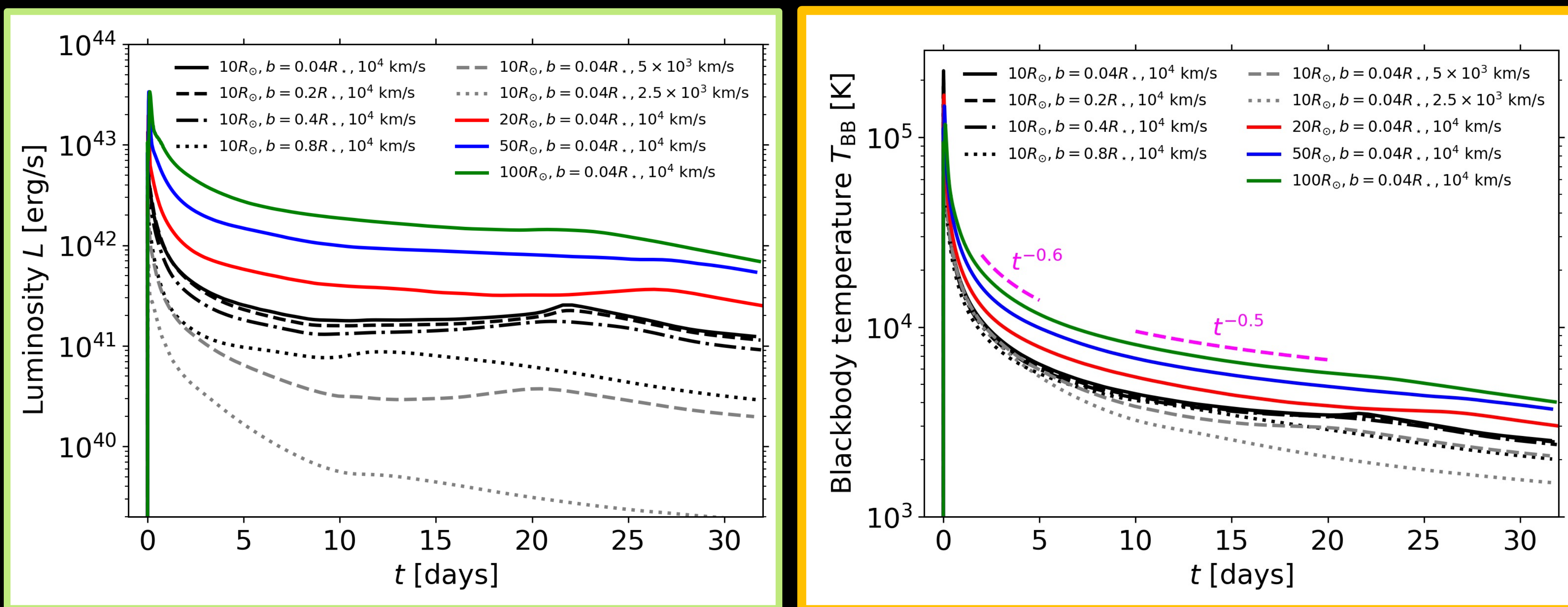
- Primary goal: estimate observables (luminosity, temperature, etc)
- MESA giants $M_\star = 1M_\odot$, $\boldsymbol{R_\star} = 10R_\odot, 20R_\odot, 50R_\odot, 100R_\odot$
- Collisions between giants at v ~ 2500km/s – 10000km/s
- Moving-mesh hydrodynamics code AREPO




Collision between $10R_\odot$ red giants at v ~ 5000km/s

# Collision-driven flare

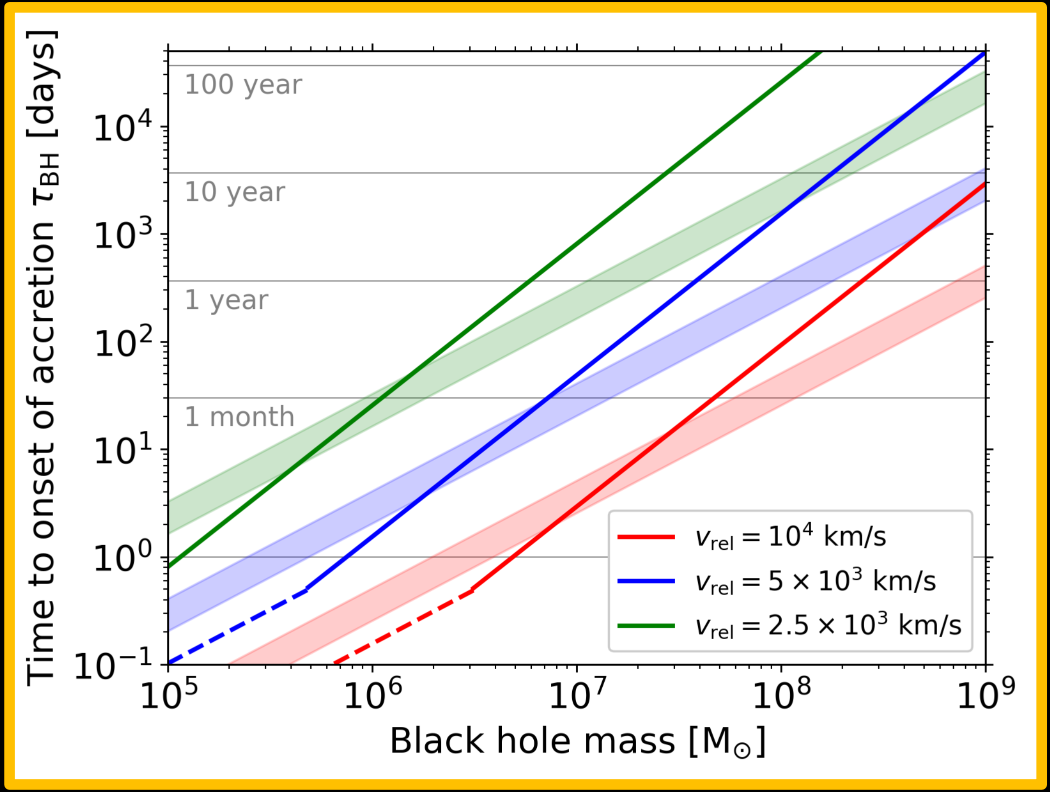
- Peak luminosity ~ $10^{42} - 10^{44} \mathrm{erg}/s$
- Temperature ~ $10^5$K (at peak) - $10^3$K




(Ryu+2023)

✓Detailed non-LTE radiation transfer calculations using CM-FGEN
(Dessart&Ryu, in prep)

# Subsequent accretion-driven flare



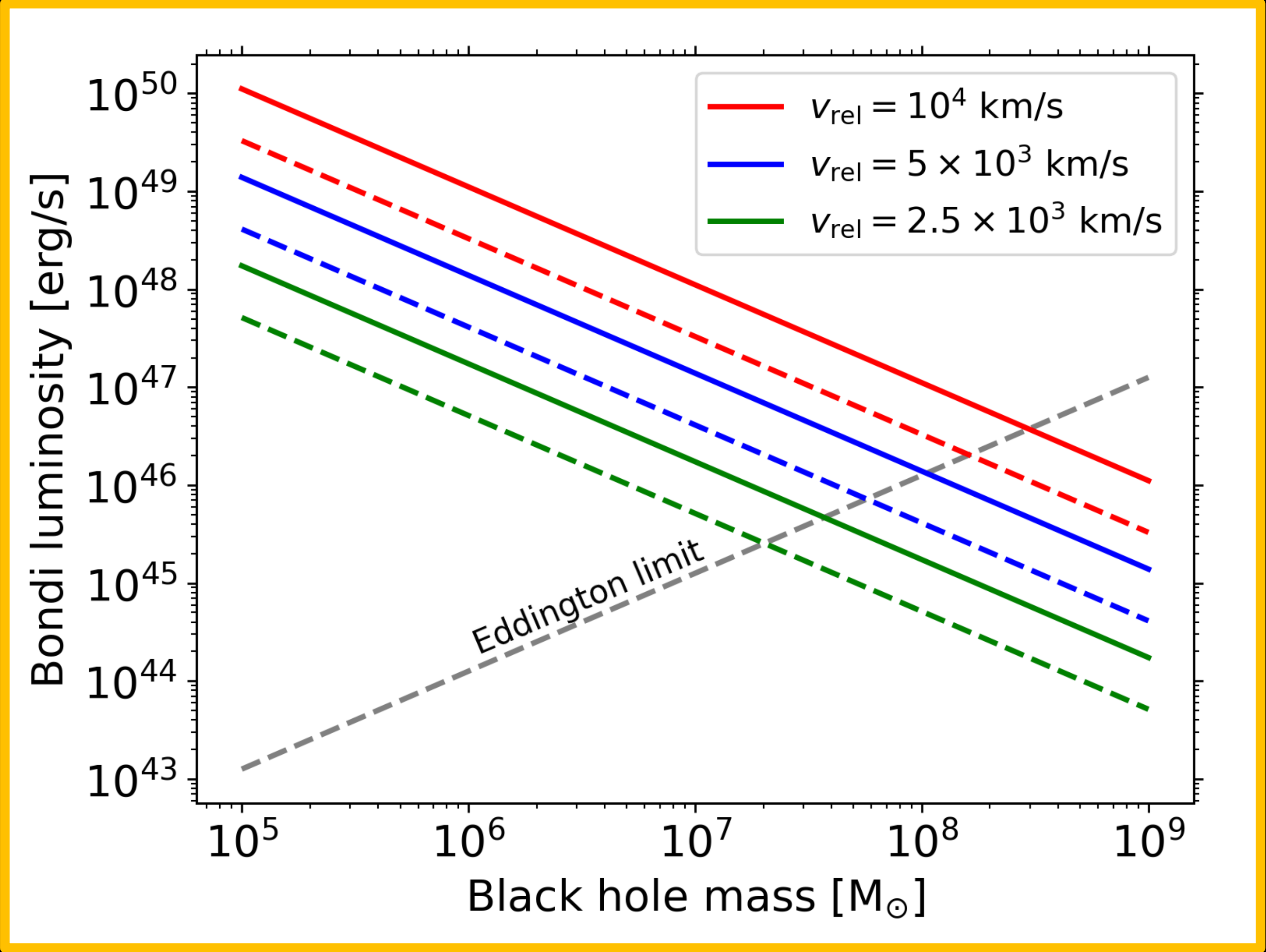

(Ryu+2023)

$r \lesssim 10^{-1}$pc

$v$~$10^3$- $10^4$km/s

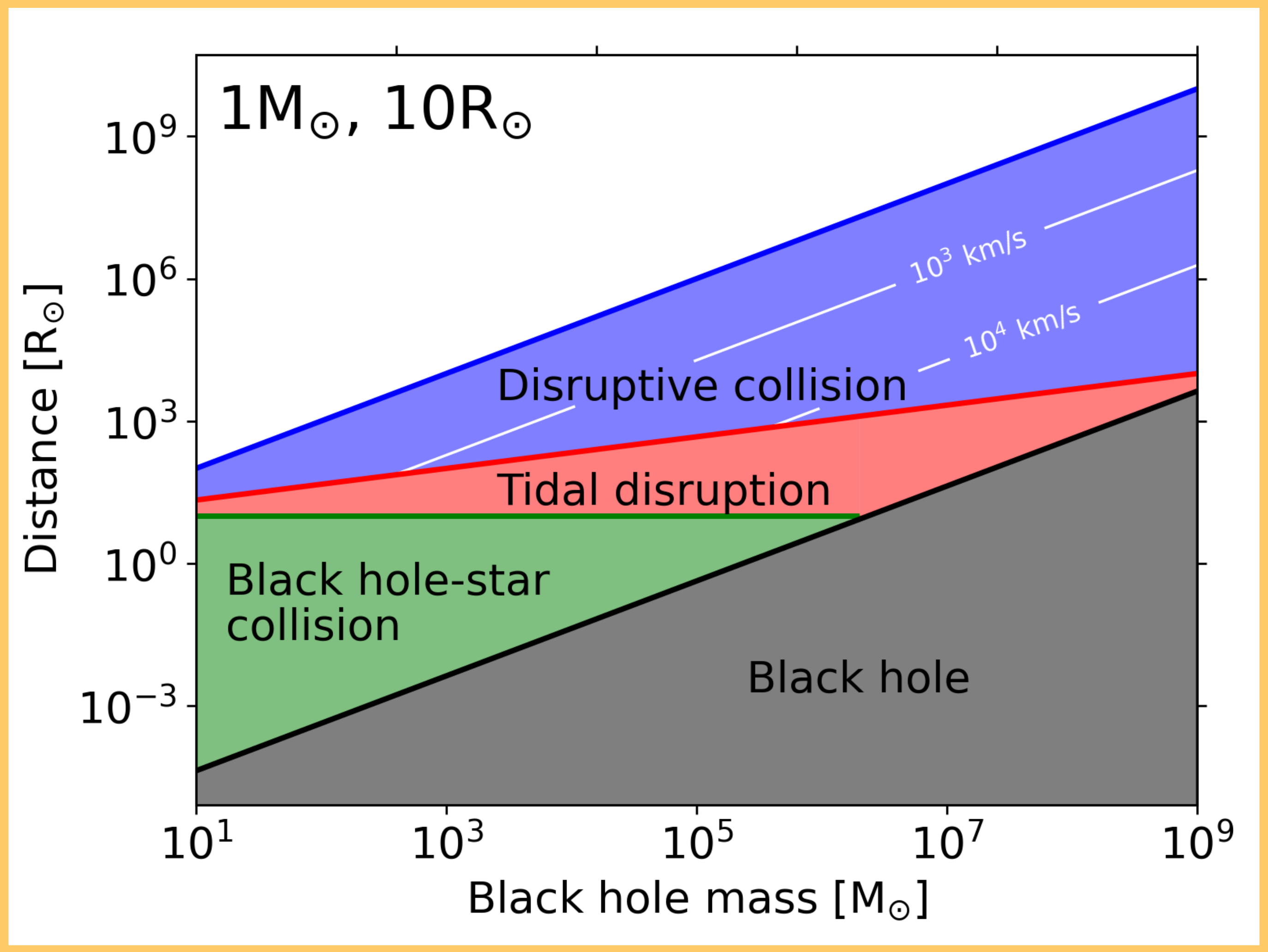
# Subsequent accretion-driven flare

- Possibly brighter than collision-driven flare
- Last up to O(10) years




(Ryu+2023)

# Comparison with other BH-driven transients




(Ryu+2023)

BDCs are

- Possible mechanism for growth of seed black holes at high redshifts
- Possibly used to probe existence of very massive black holes that cannot be by TDEs

# Summary

● Nuclear transients will provide us a better understanding of BH demographics and dynamics in nuclear clusters

● Tidal disruption event (TDE) and black hole-driven disruptive collision (BDC)

● TDE have a variety of types depending on pericenter distance

- Partial TDE : remnants + debris

- Full TDE : only debris, properties of disruption outcome depends on stellar mass, black hole mass. Common and circularized TDEs: depending on pace of circularization.

- Extreme TDE ($4\, r_g \lesssim r_p \lesssim 6\, r_g$) : dominant type for massive BH ($M_{BH} \gtrsim 10^7 M_\odot$), extreme relativistic effects lead to axisymmetric debris, Eddington lumonisity for a week

- Direct capture ($r_p < 4\, r_g$) : no EM signature

● BDC can generate a flare as bright as supernovae in optical/UV

- Peak luminosity: $10^{42} - 10^{44} \mathrm{erg}/s$

- Possibly brighter subsequent accretion-driven flare

- Contribute to the growth of seed black hole

Taeho Ryu