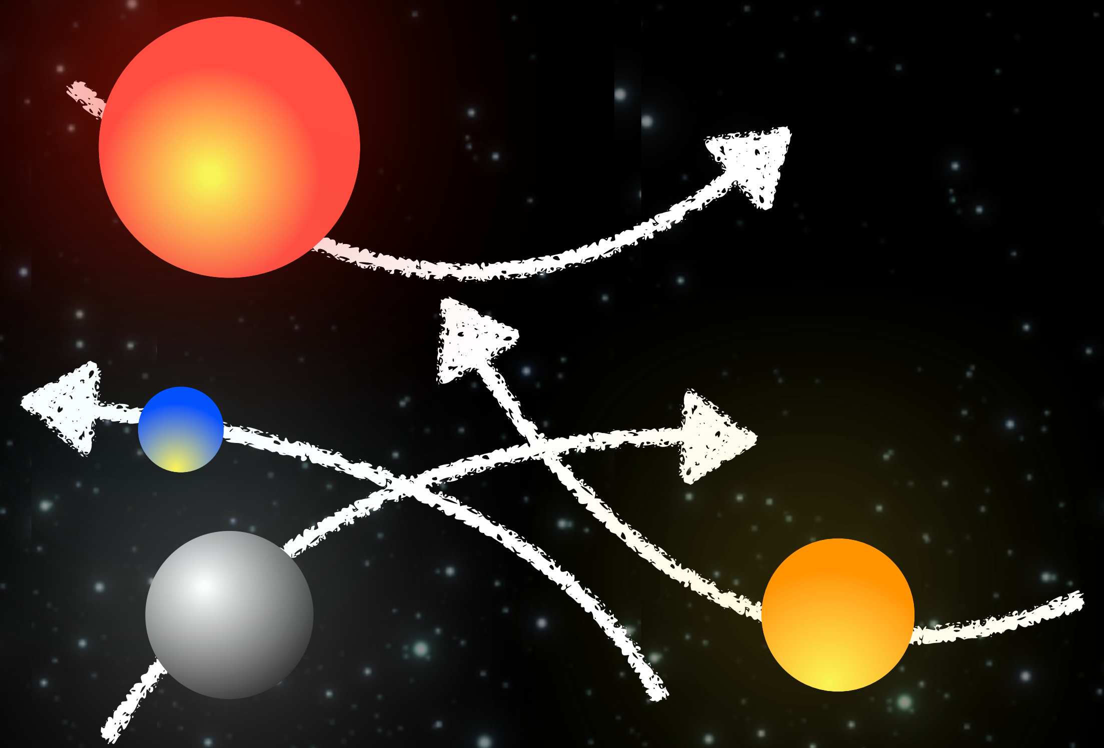
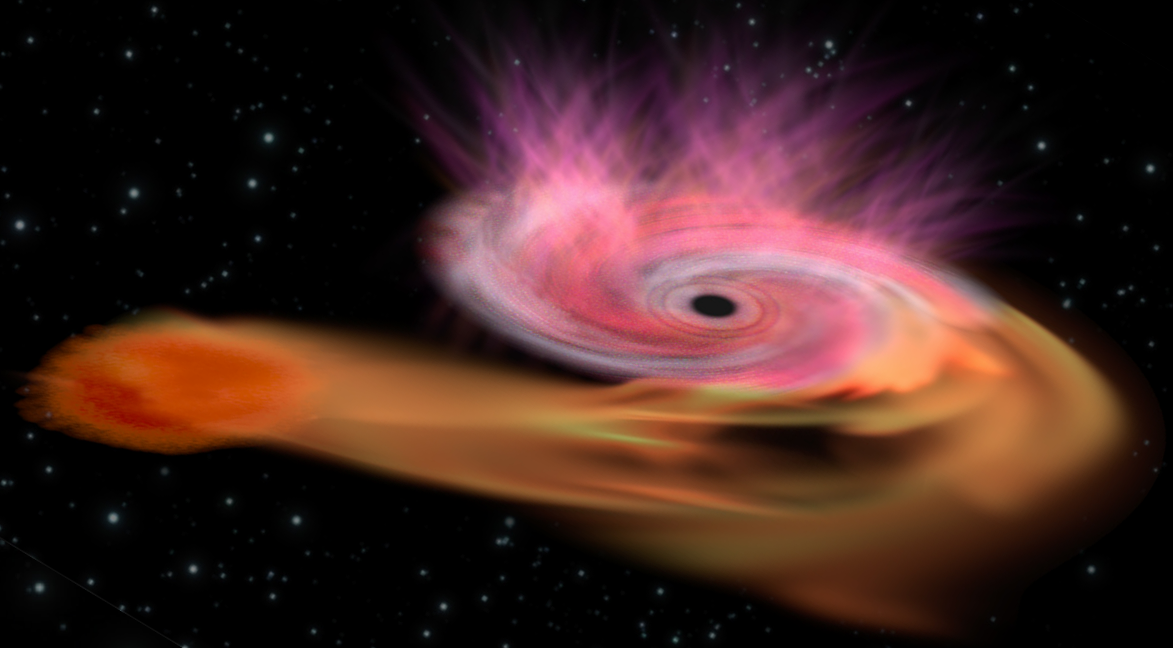
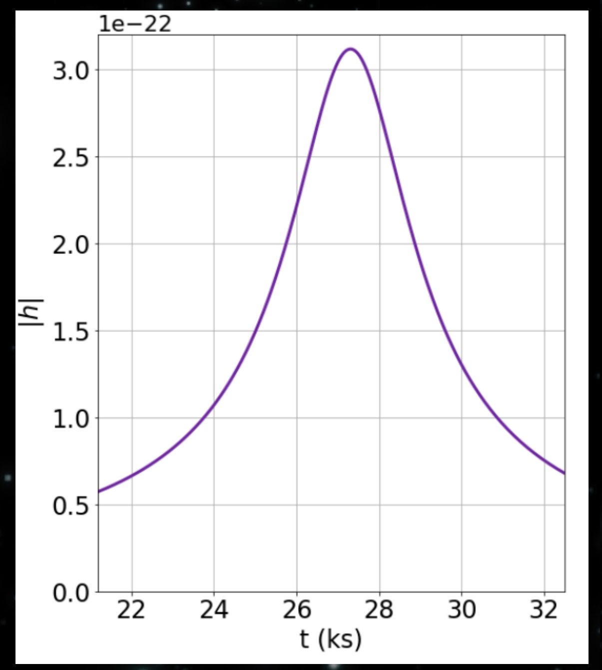
Stars & Black Holes Encounters in Young Star Clusters







Sara Rastello

In coll. with : **Giuliano Iorio, Long Wang, Mark Gieles**

Universitat de Barcelona

Institut de Ciències del Cosmos, Universitat de Barcelona (ICCUB) — Excelencia María de Maeztu 2020–2023

beatriu de pinós

1st TEONGRAV workshop, La Sapienza, September 19th 2024

Tidal Disruption Events (Macro-TDEs)

A star orbiting around a SMBH is disrupted during the first pericenter passage once the tidal forces of the SMBH exceed the self-gravity of the star

Hills 1975, Rees 1988

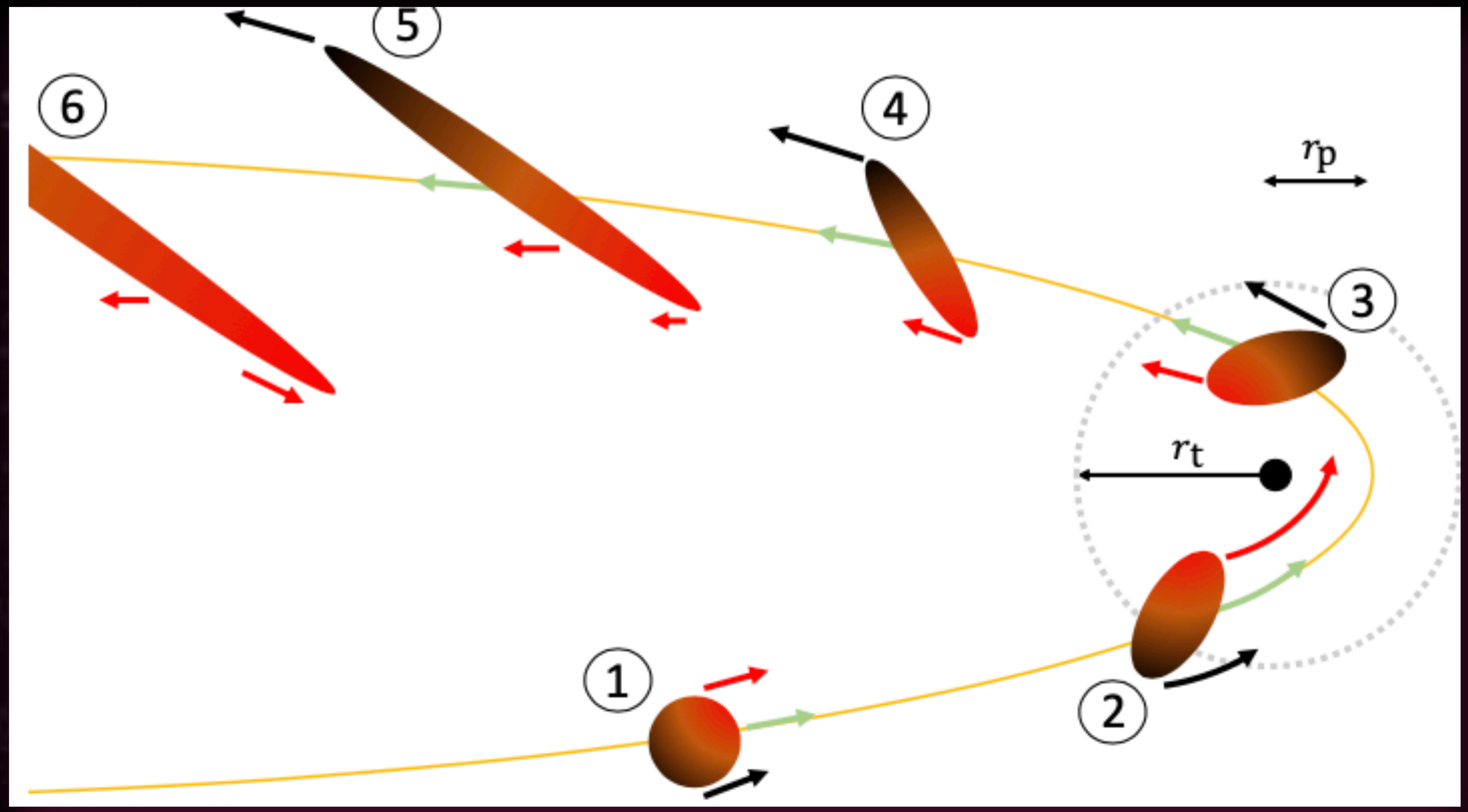
Tidal Radius R_t

$$R_{\rm t} = R_* \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3} \approx 7 \times 10^{12} \left(\frac{R_*}{R_\odot}\right) \left(\frac{M_*}{M_\odot}\right)^{-1/3} \left(\frac{M_{\rm BH}}{10^6 M_\odot}\right)^{1/3} \mathrm{cm}$$

Kobayashi 2004

Komossa 2015

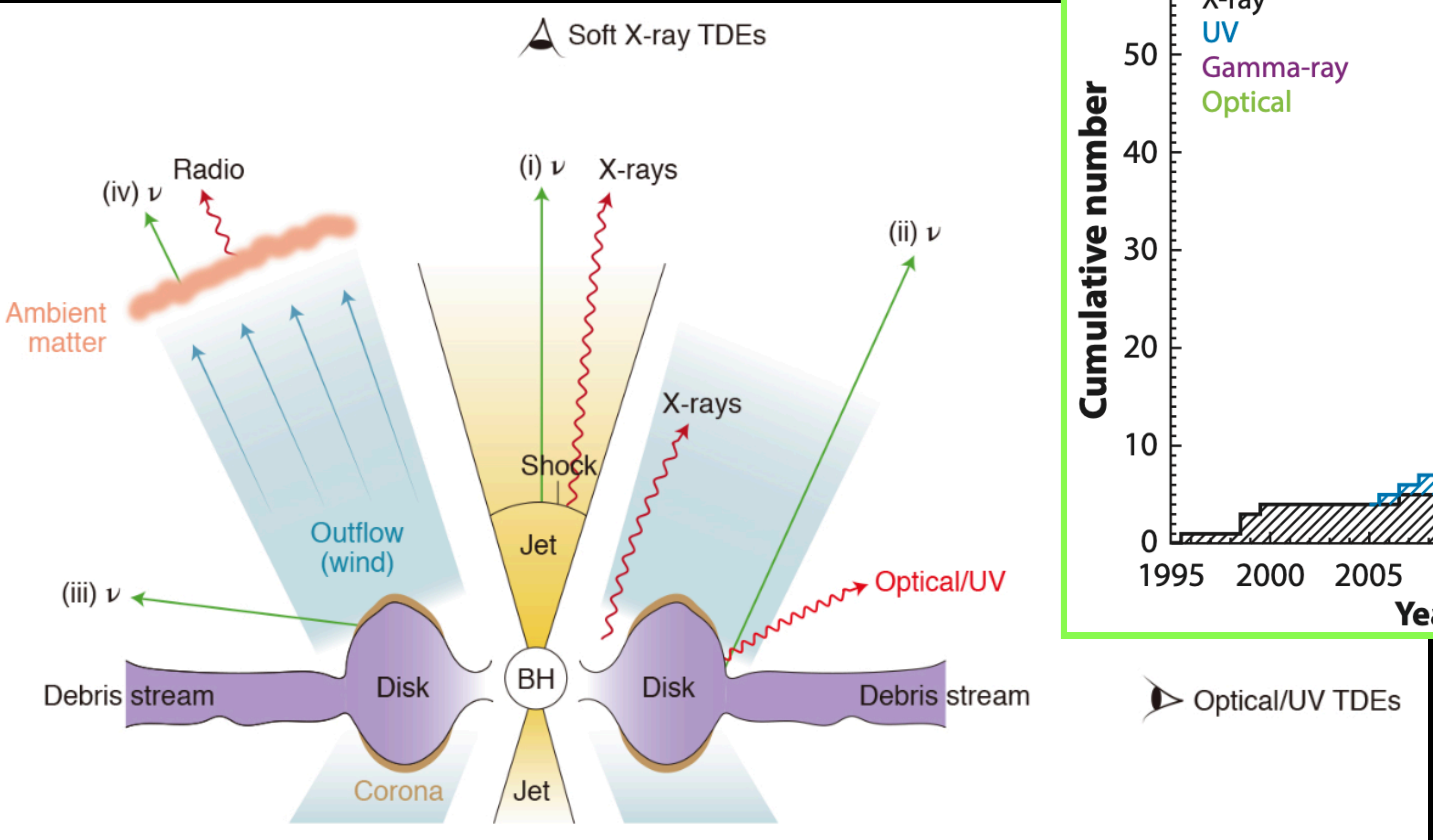
$M_{SMBH} = 1e6\ M_\odot$ $M_s^* = 1 M_\odot$ $R_s^* = 1 R_\odot$ $R_t \sim 100\ R_\odot$

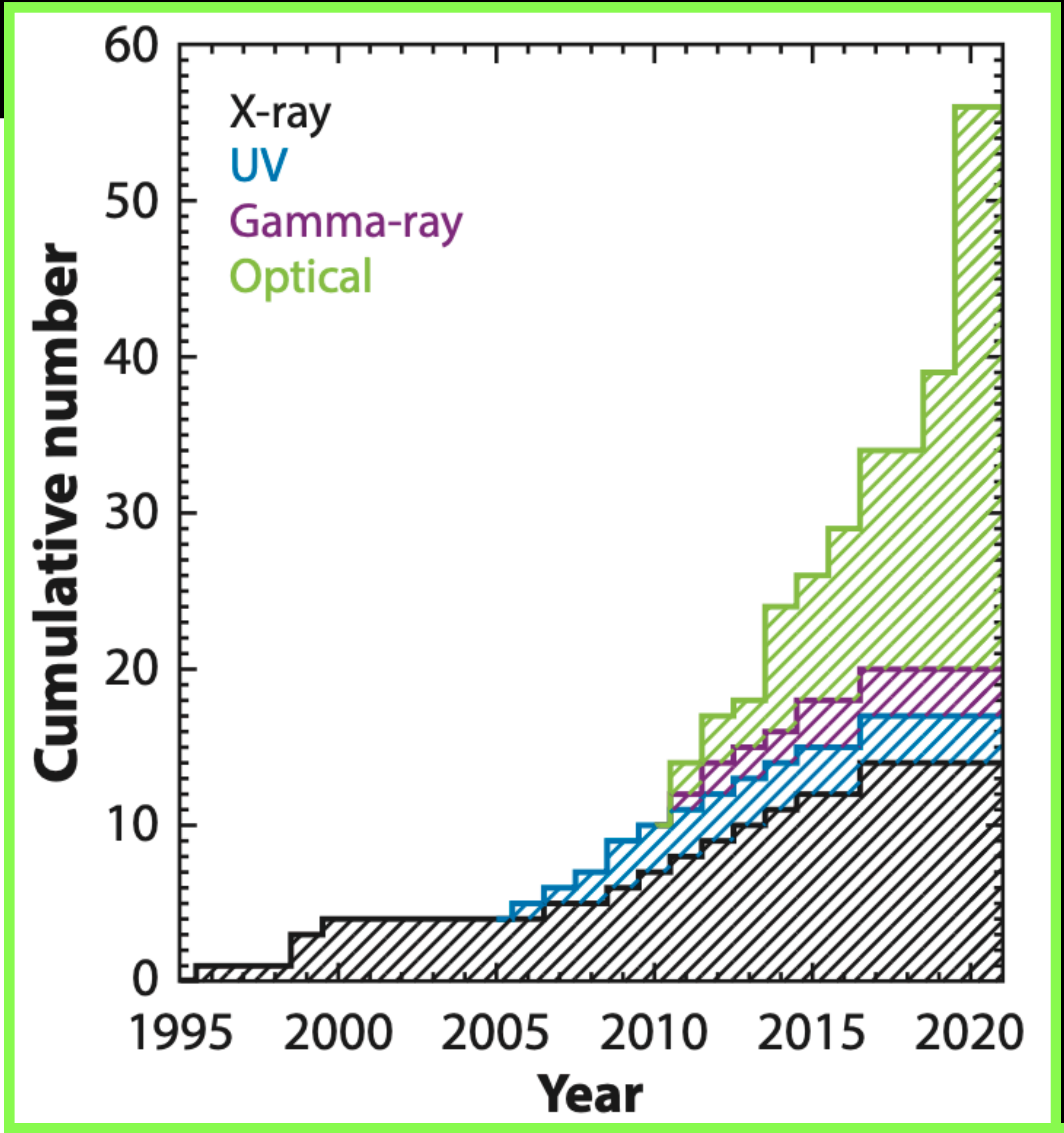


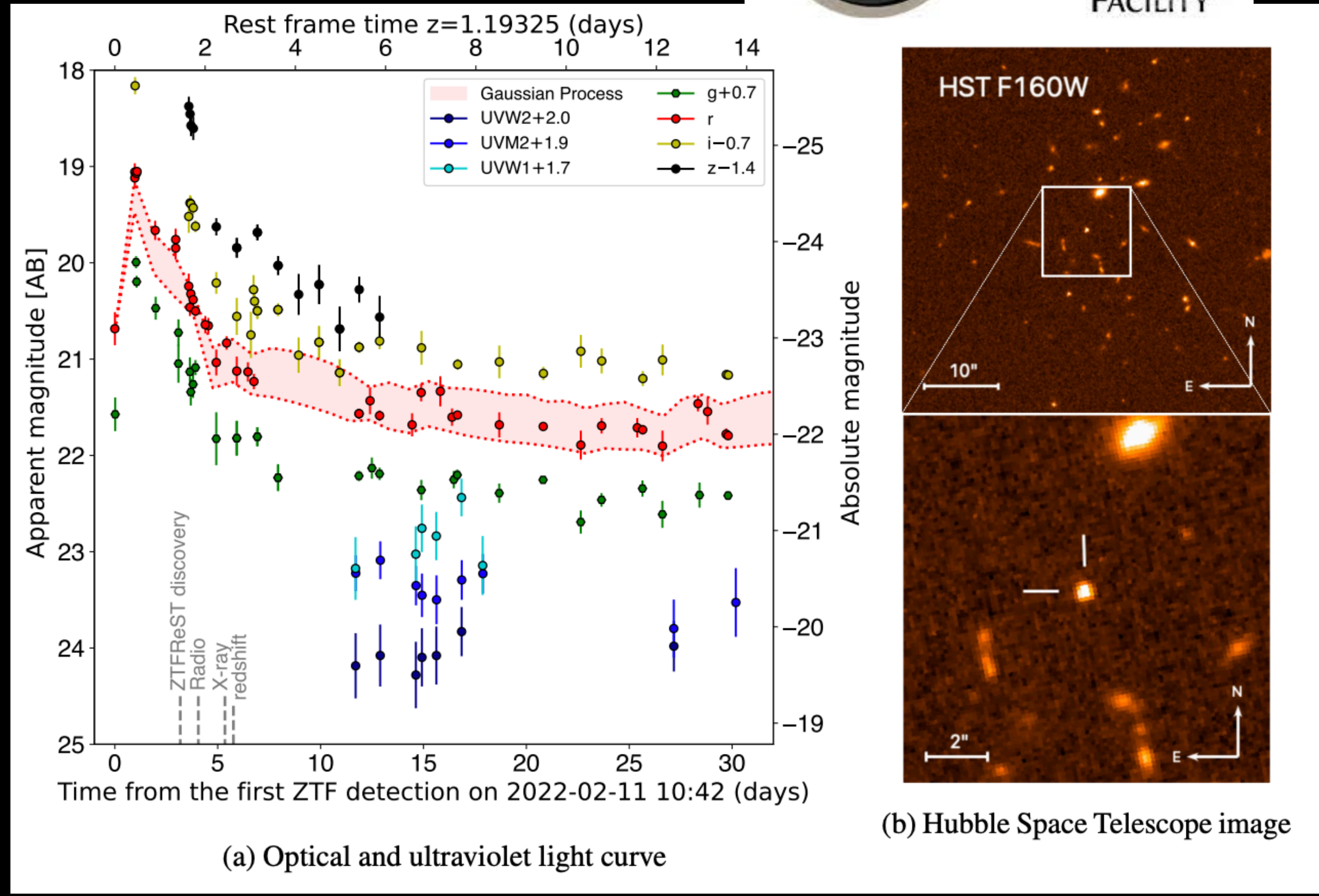
Wever & Ryu, 2023

TDEs as Multi-Messenger Sources I

Electro Magnetic (EM) emission







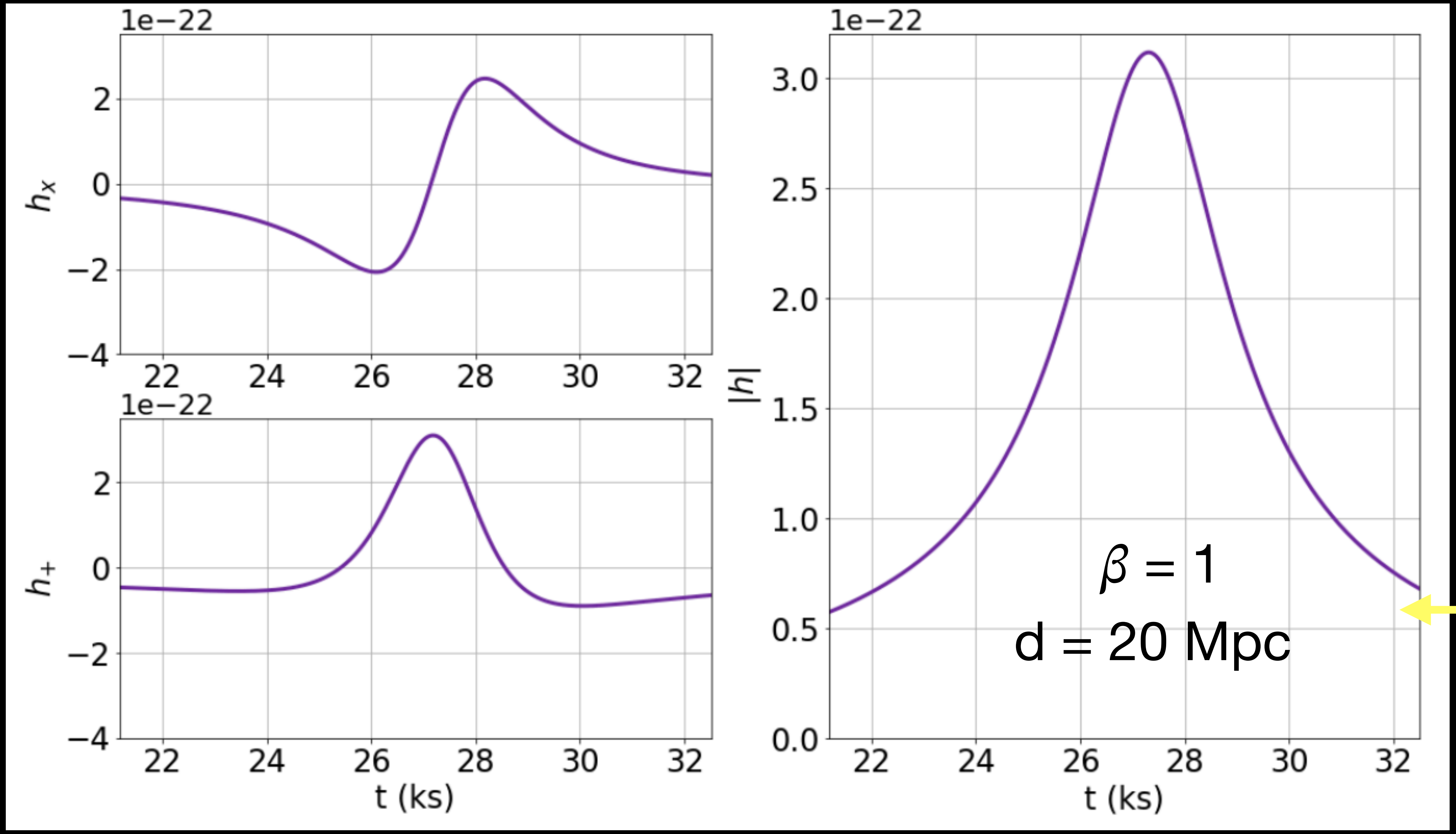
Andreoni et al., 2022

~ hundred of TDEs detected with EM

Gezari 2021

TDEs as Multi-Messenger Sources II

Gravitational wave (GW) signals



Sun-like star on a parabolic orbit around a SMBH 1e6 $M_\odot$

Guillochon et al. 2009; Stone et al. 2013; Toscani et al., 2019,2022

GW burst emitted when the star is torn apart [variation of the quadrupole mass of the BH-star system.]

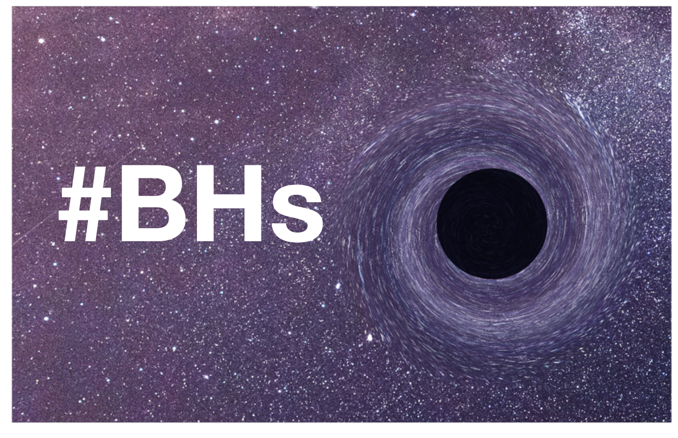
Kobayashi et al. 2004

Free online catalog

https://gwcataloguetdes.fisica.unimi.it/

Toscani et al., 2022

GW frequency in the LISA band



micro-TDEs (μ-TDEs)

A star is destroyed in a close encounter with a compact object (CO) as **stellar mass BH, NS** or **WD**

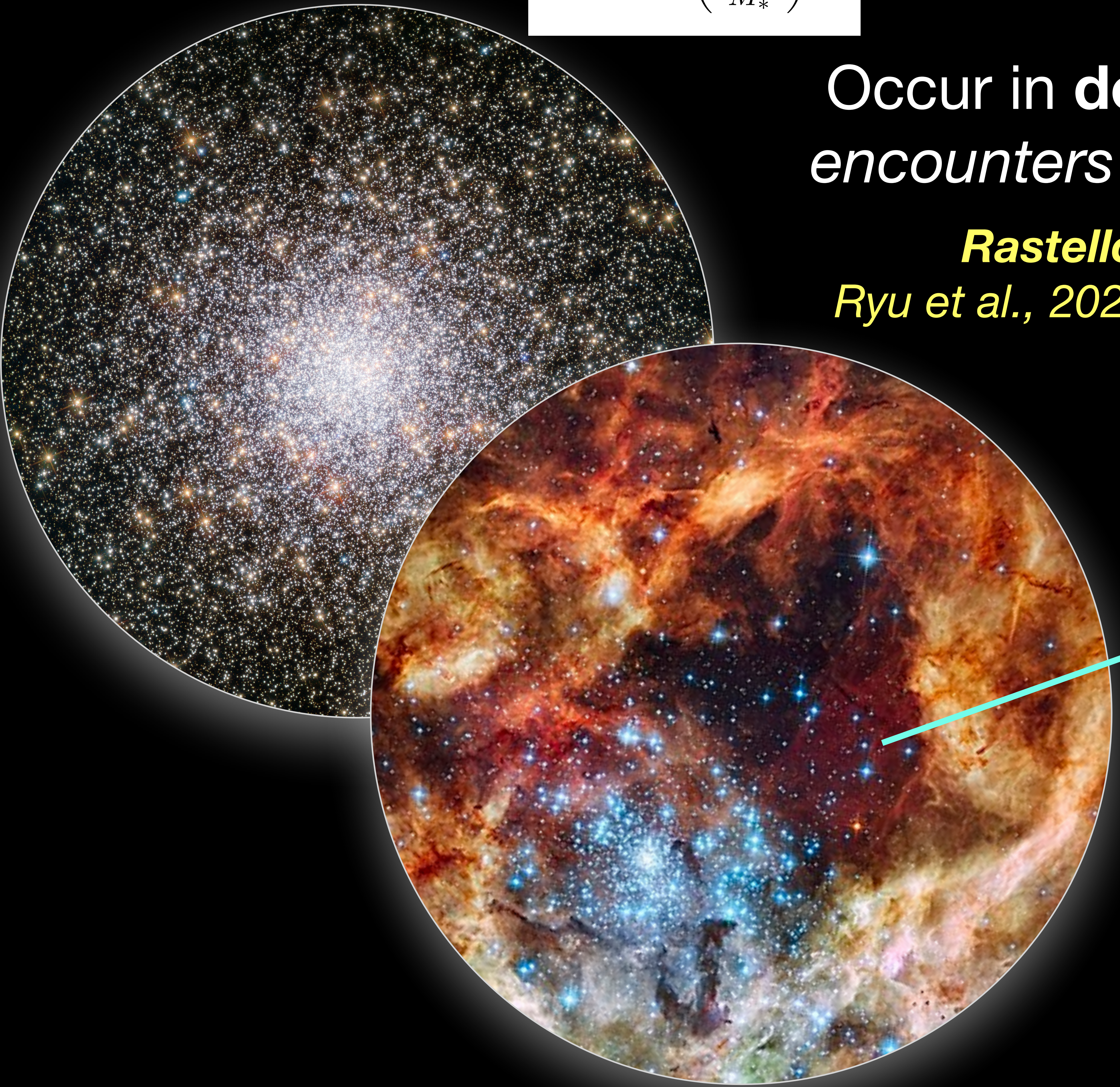
Hills 1975; Rees 1988

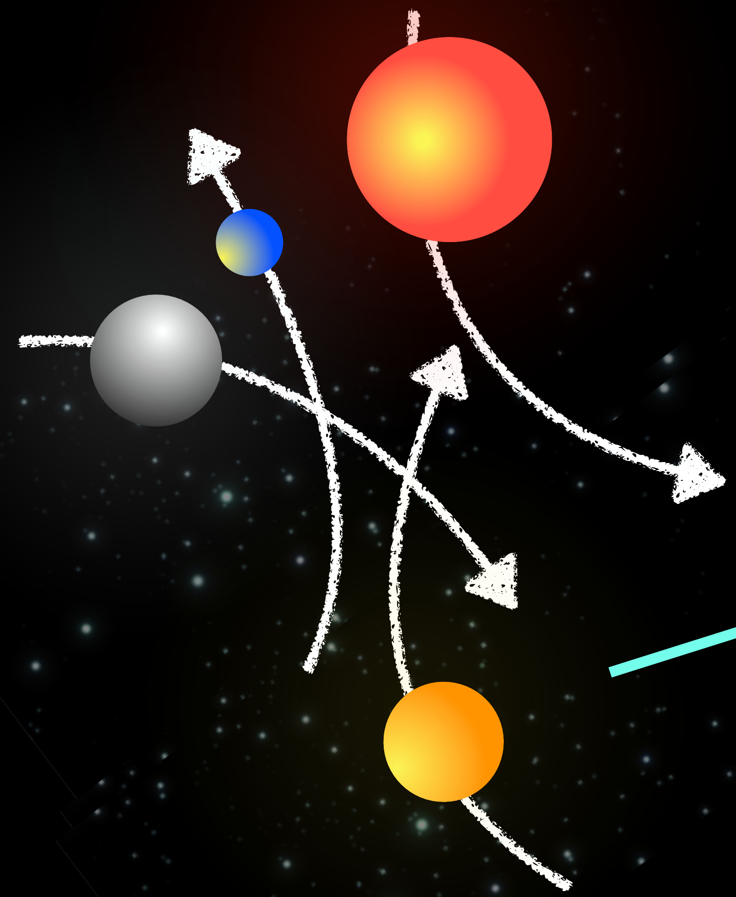
$$R_{\rm t} = R_* \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3}$$

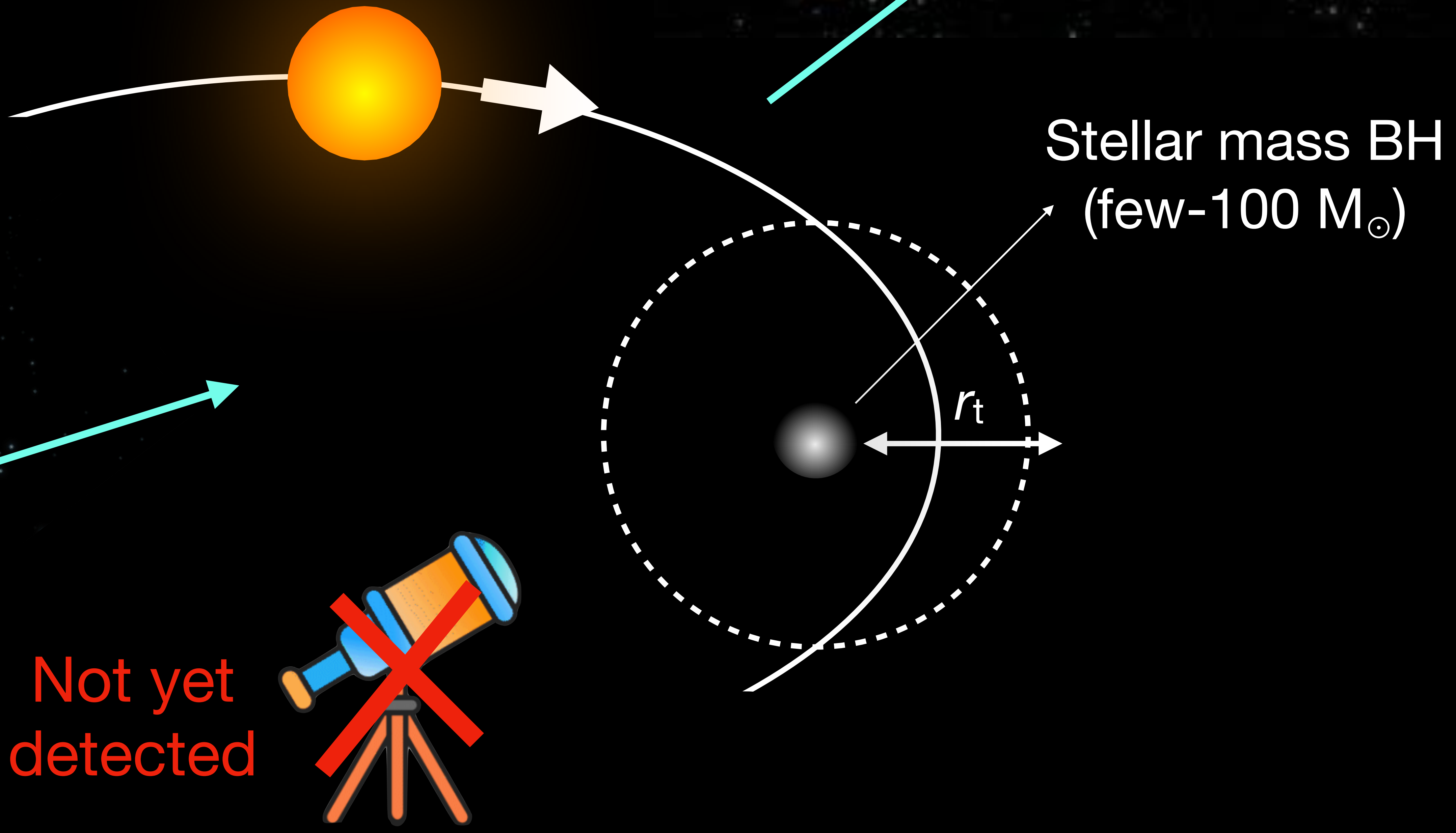
Perets et al., 2016

Occur in **dense star clusters** where *dynamical encounters* between stars and COs are frequent

Rastello et al., 2019; *Kremer et al., 2019,2021,2023; Ryu et al., 2022,2023a,c,d; Vynatheya et al., 2024; Xin et al., 2024*







Not yet detected

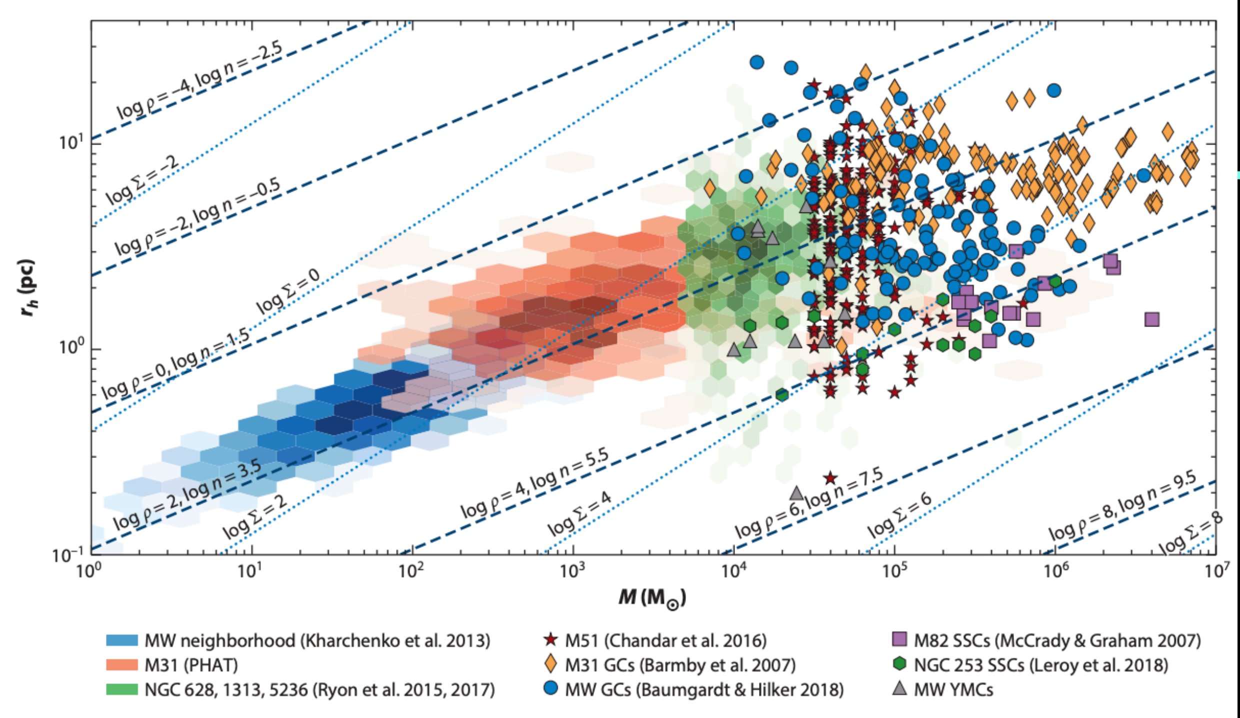
YSCs models: SCs prop.

Suite of numerical high-precision direct *N*-body simulations of massive collisional realistic **Young Star Clusters** with the state-of-the-art *N*-body code PETAR *Wang et al., 2020*

Customized Code Version

- 5e4 < M_{SC} ($M_\odot$) < 5e5
- *King (1966)* Density profile (r_h & ρ) with *limepy* lib. (*Gieles & Zocchi 2015*)
- Z = 0.0002-0.02
- MW2014 tidal field (Galpy, *Bovy 2014*)
- YSCs on a Sun-like circular orbit
- BSE as in PeTar (*Banerjee et al. 2020*)
- Delayed SN model
- Mass dependent binary fraction (*Moe & Di Stefano 2017*)

Milky Way-like YSCs



Krumholz et al., 2019

PI: S. Rastello
~2 M at RES

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

RES
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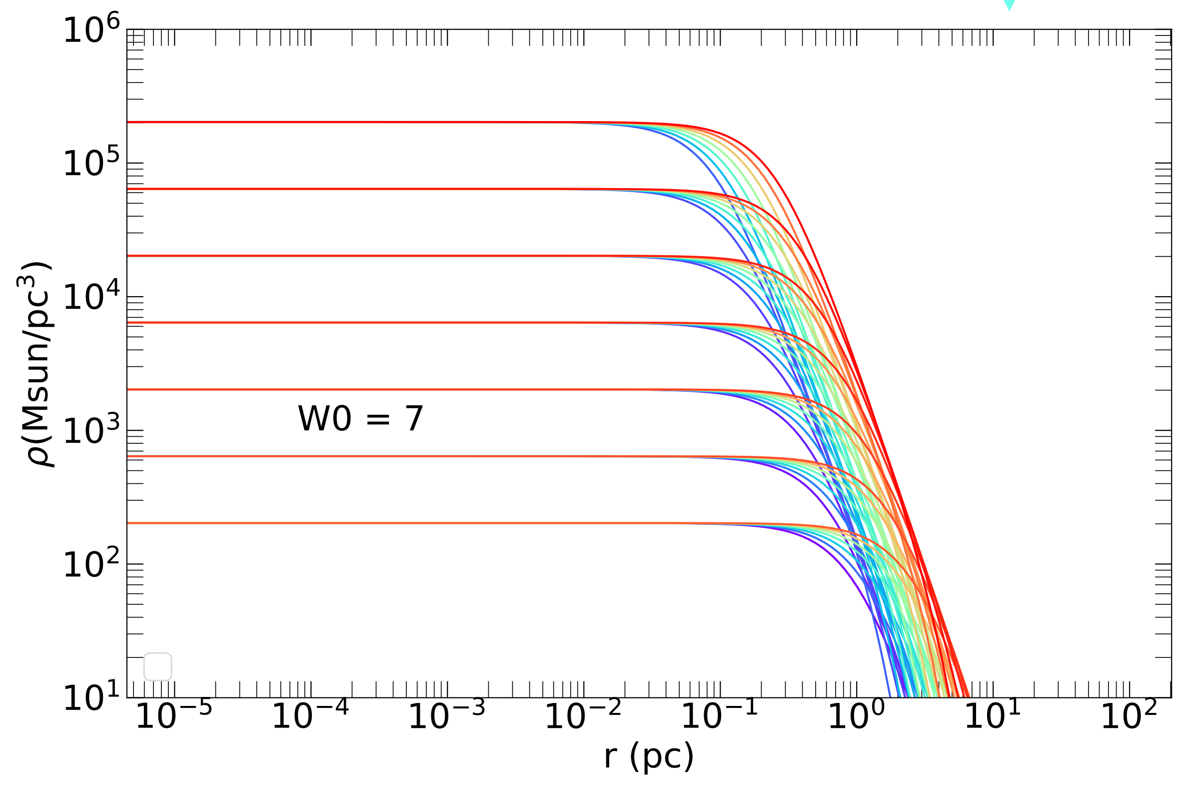
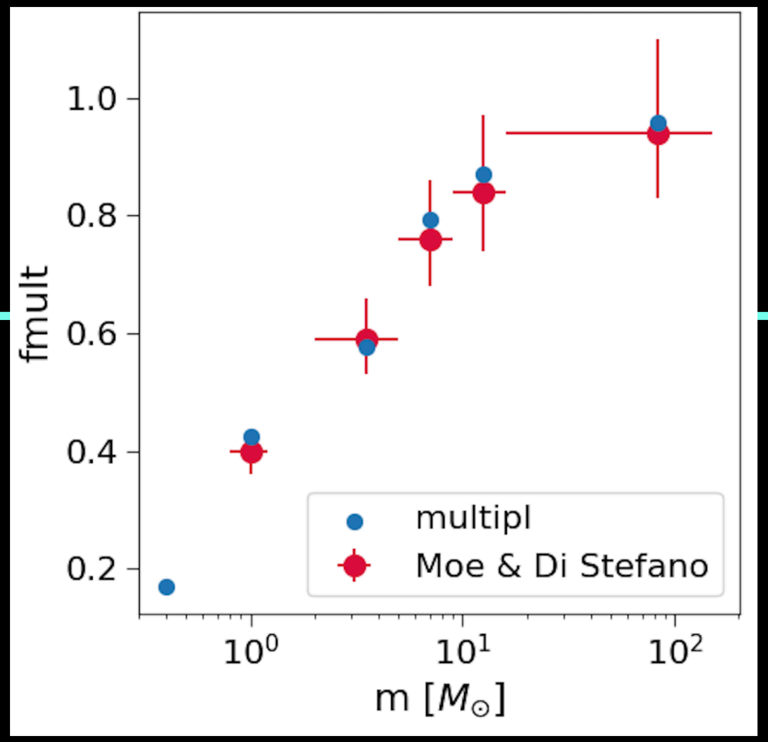
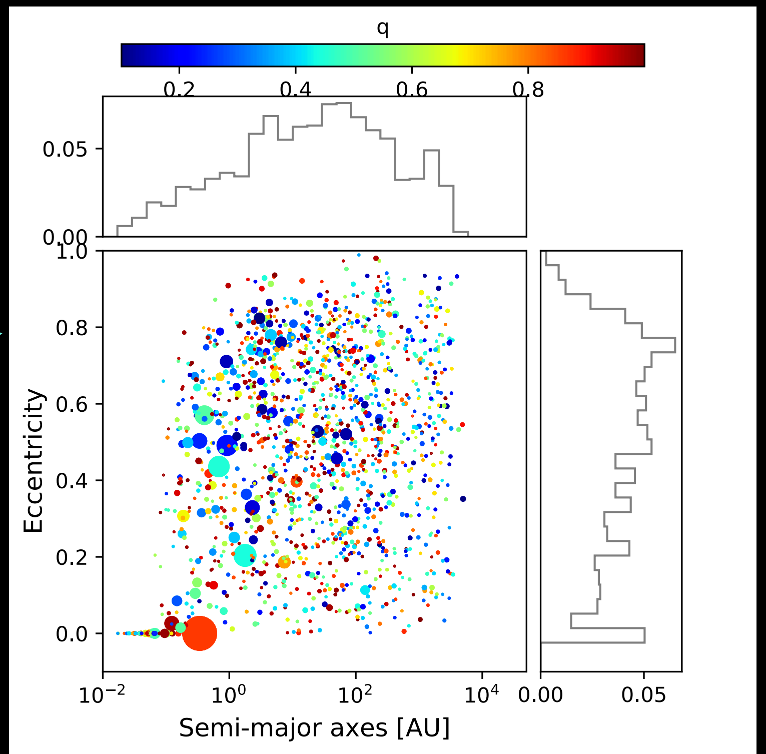


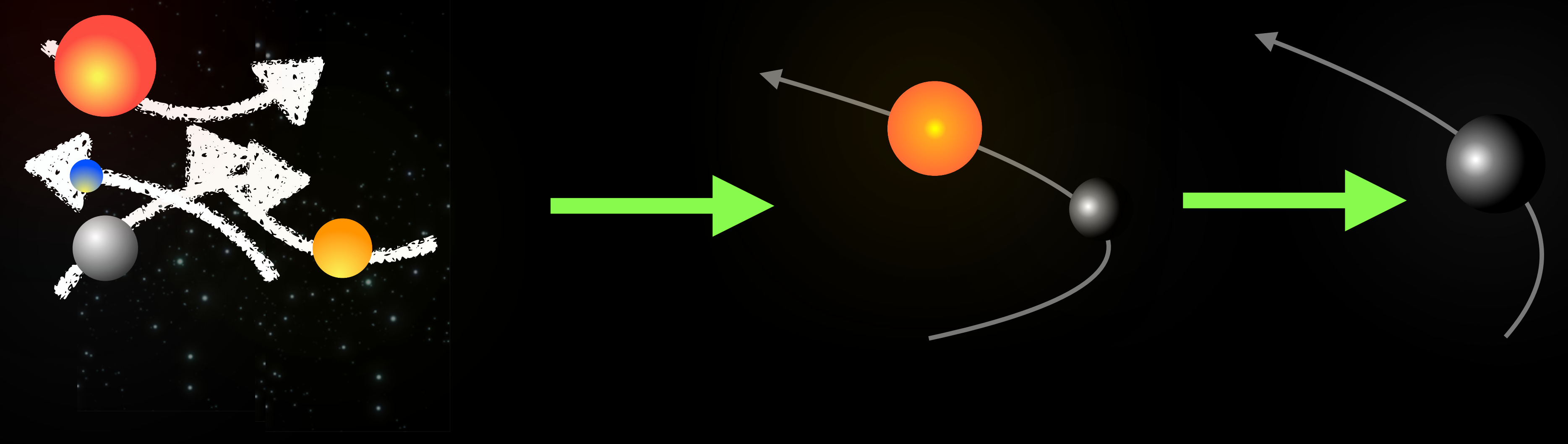
Rastello et al., in prep.



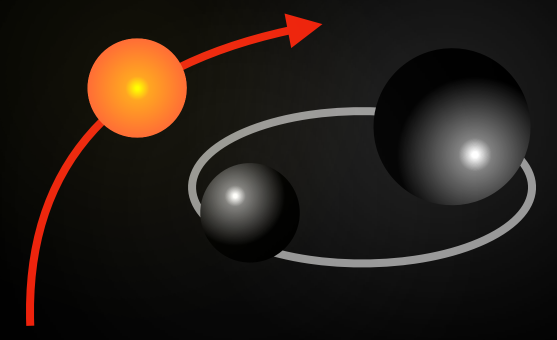


How can we model μ-TDEs in SCs?

1. Close interactions between single stars and single COs



$$R_{\rm t} = R_* \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3}$$

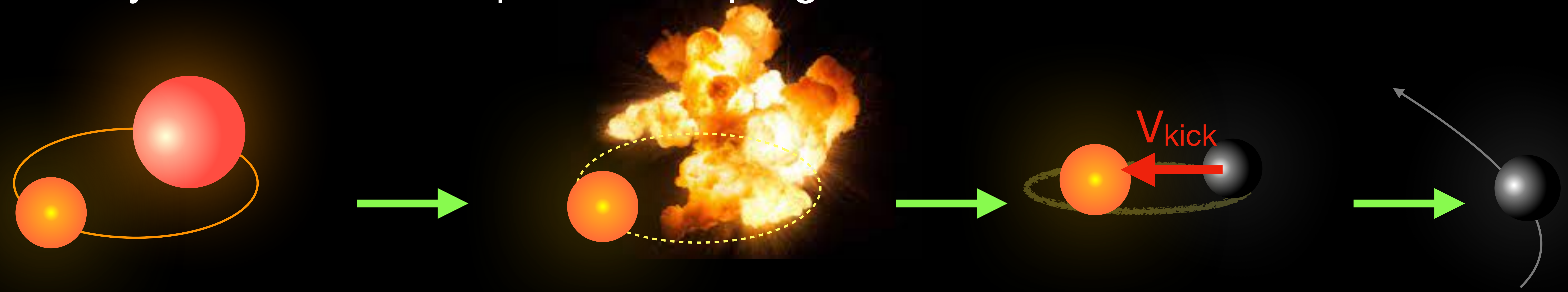


2. Close encounters involving binaries

i.e. Star-Star+ CO, CO-CO+Star, Star-CO + star, Star-CO +CO

Perets et al., 2016;
Michaely et al., 2016;
Hirai & Podsiadlowski 2022;

3. Stars destroyed when the companion CO-progenitor receives a natal kick



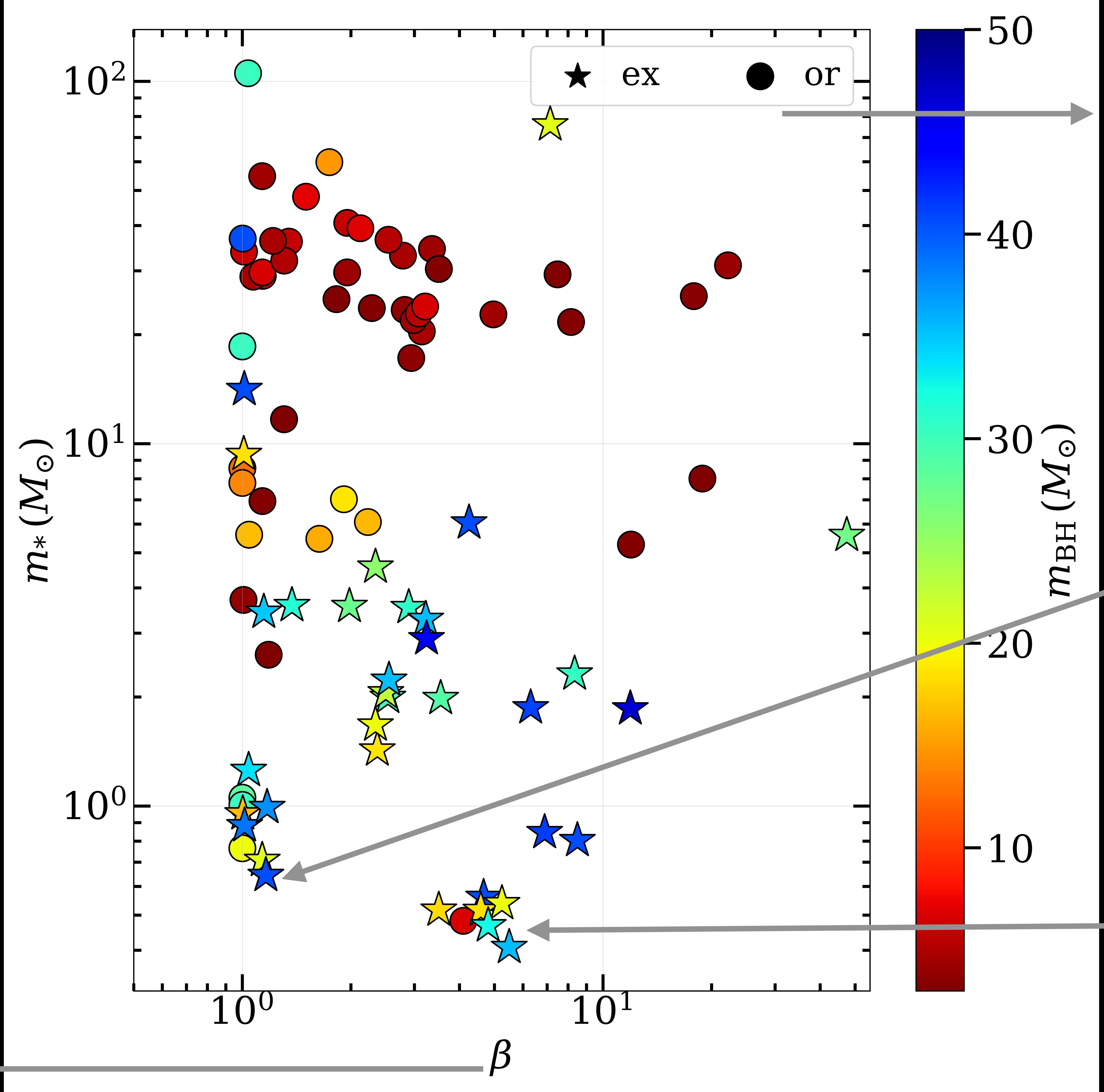
Stellar disruptions : all candidates*

* Satisfy the disruption condition $r_p \leq r_t$

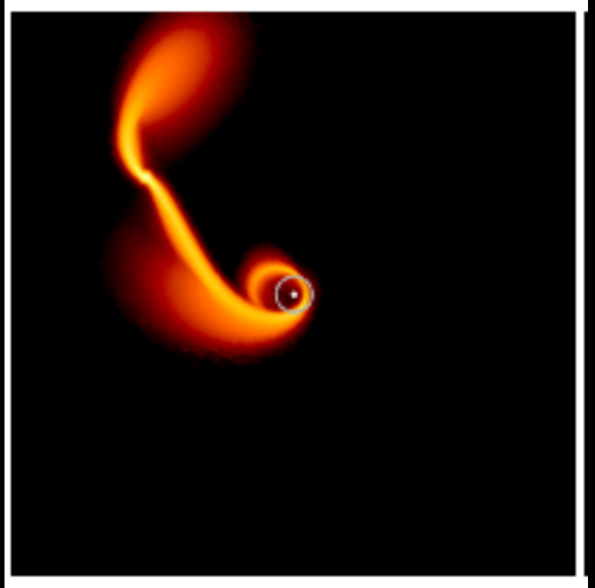
$$R_p \leq R_t = R_* \left(\frac{M_{BH}}{M_*}\right)^{1/3}$$

55 % or. t <100 Myr

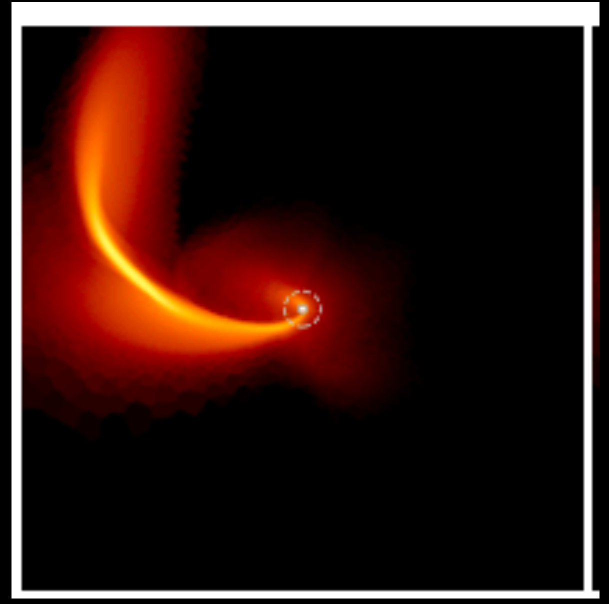
45 % ex. t >100 Myr



Original binaries: paired since t=0 Myr
Exchanged binaries: paired through dynamics



$m_{BH} = 40.0\ M_\odot$
$m_* = 0.5\ M_\odot$



Vynatheya et al., 2024

$$\beta = \frac{r_t}{r_p}$$

Penetration factor

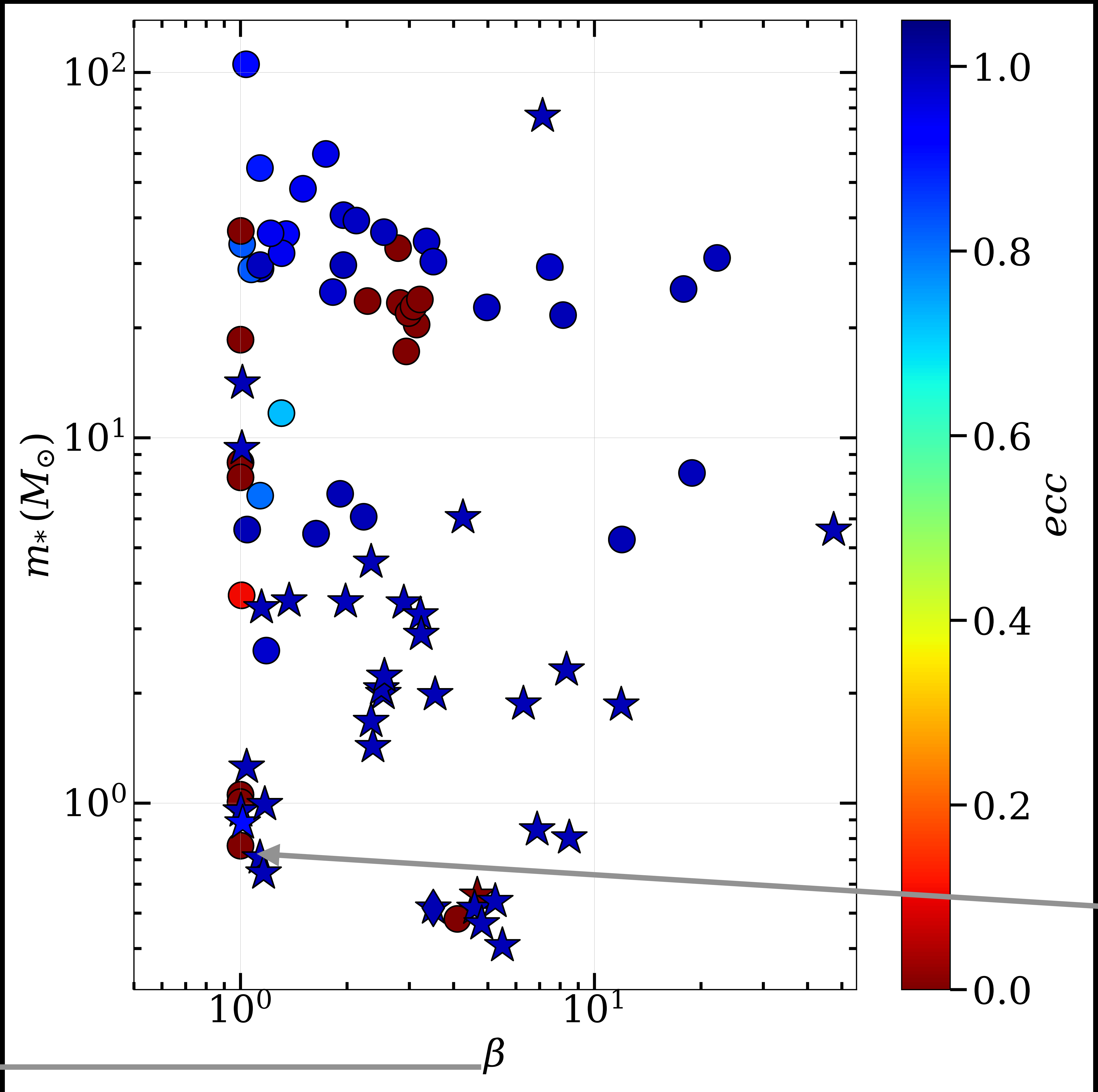
83 % MS, 9 % HG, 7% naked He, 1% WD

Stellar disruptions : eccentricity

Most (%) events occur on almost parabolic orbits

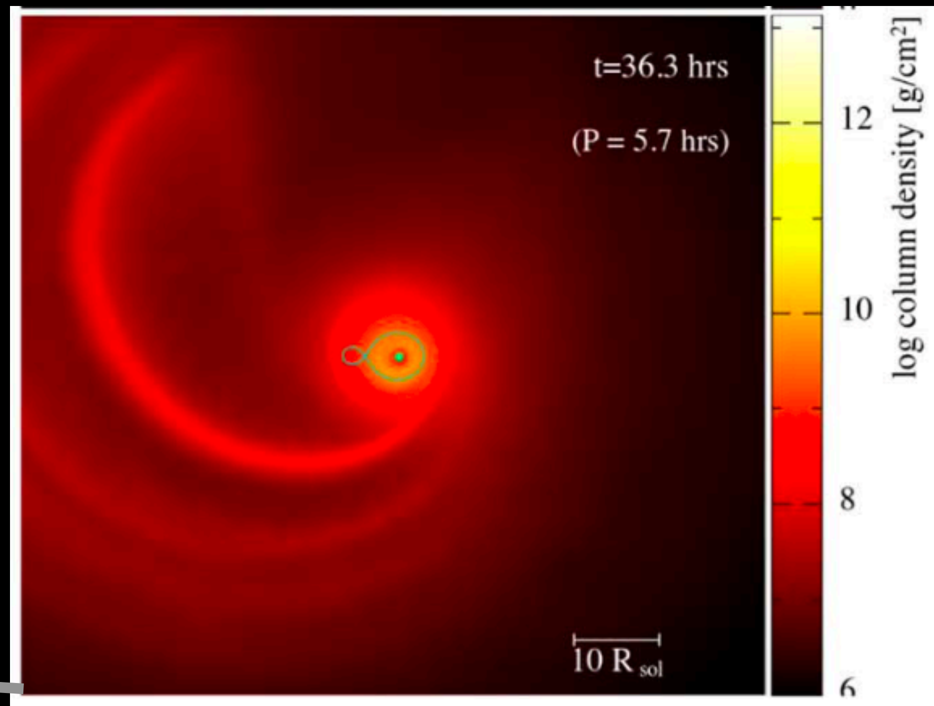
85 % 0.99 < ecc < 1.1

$$\beta = \frac{r_t}{r_p}$$



TPE (tidal peeling events) candidates?

0 < ecc <0.6



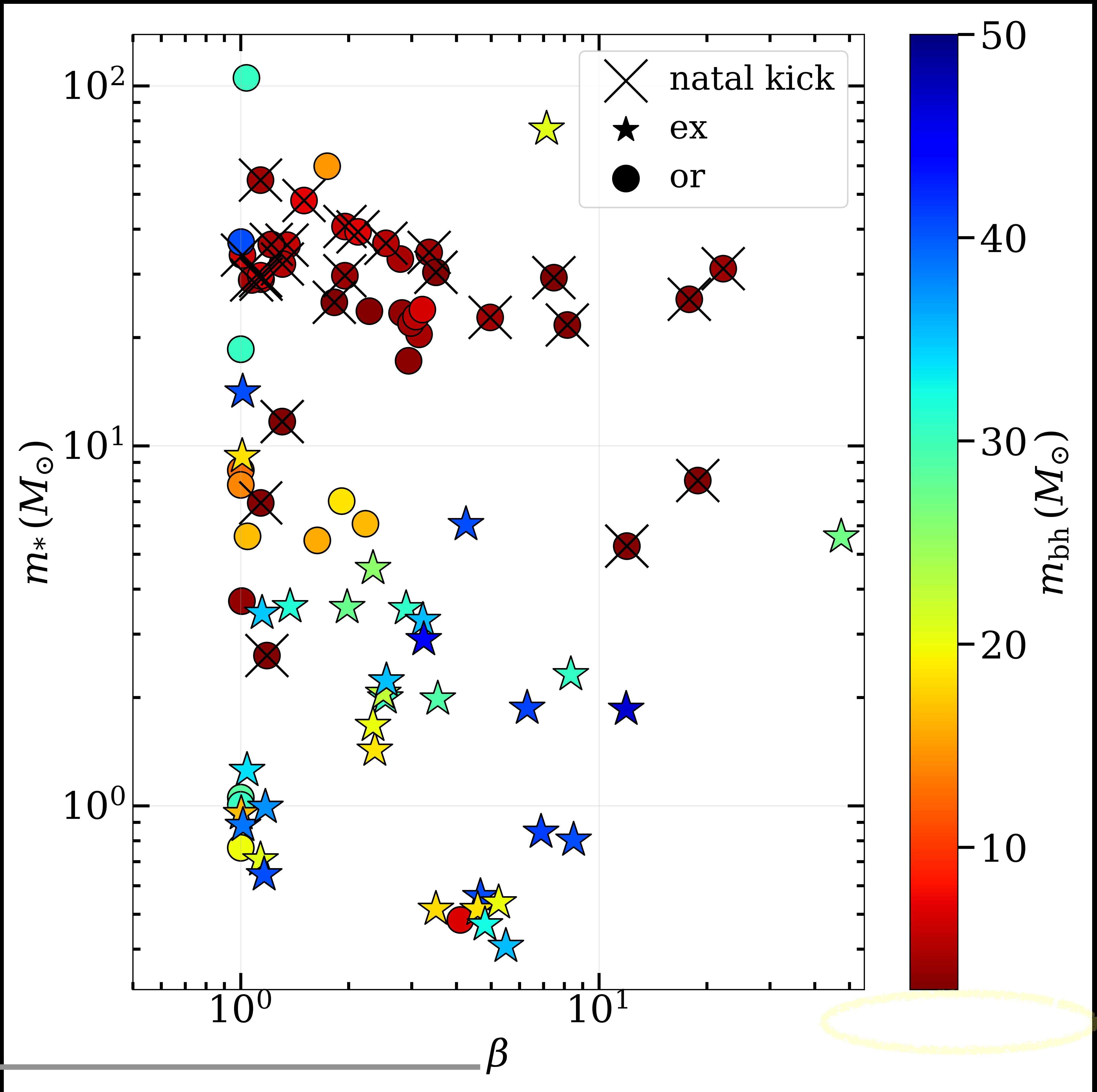
Xin et al., 2024

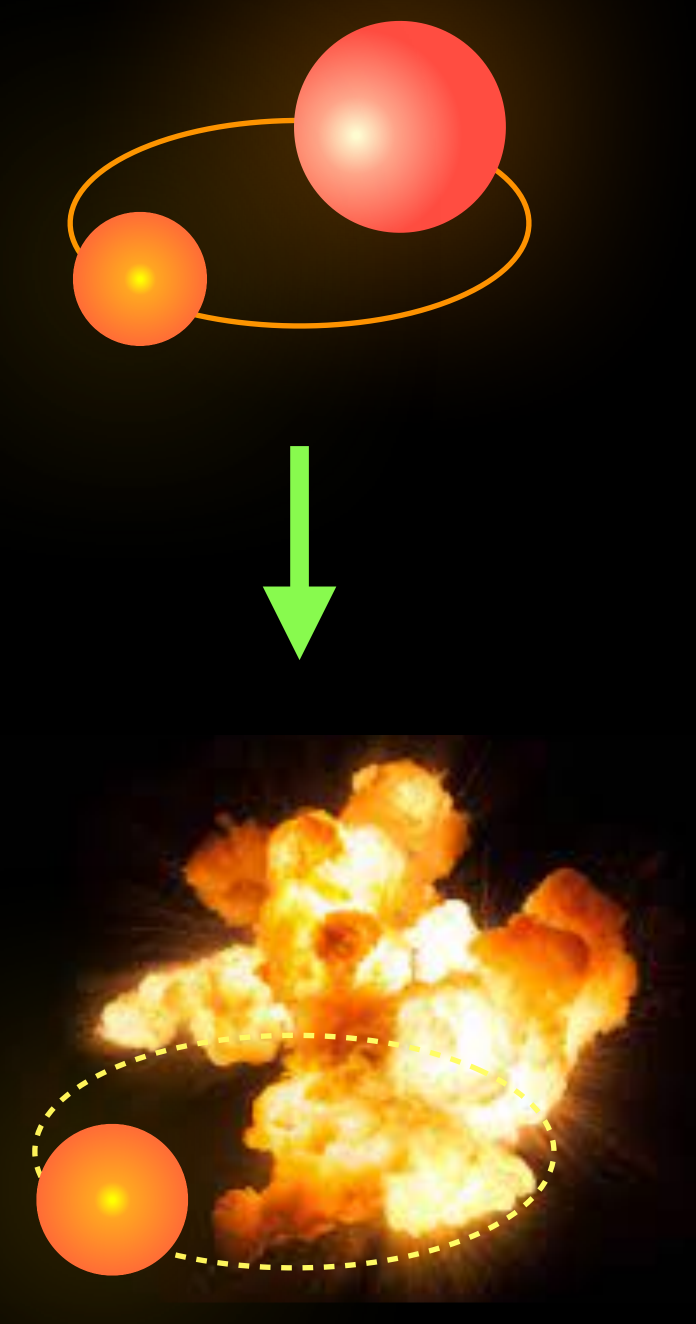
Stellar disruptions : BH natal kick

Stars disruption induced by orbital change at BH formation

~ 30 %

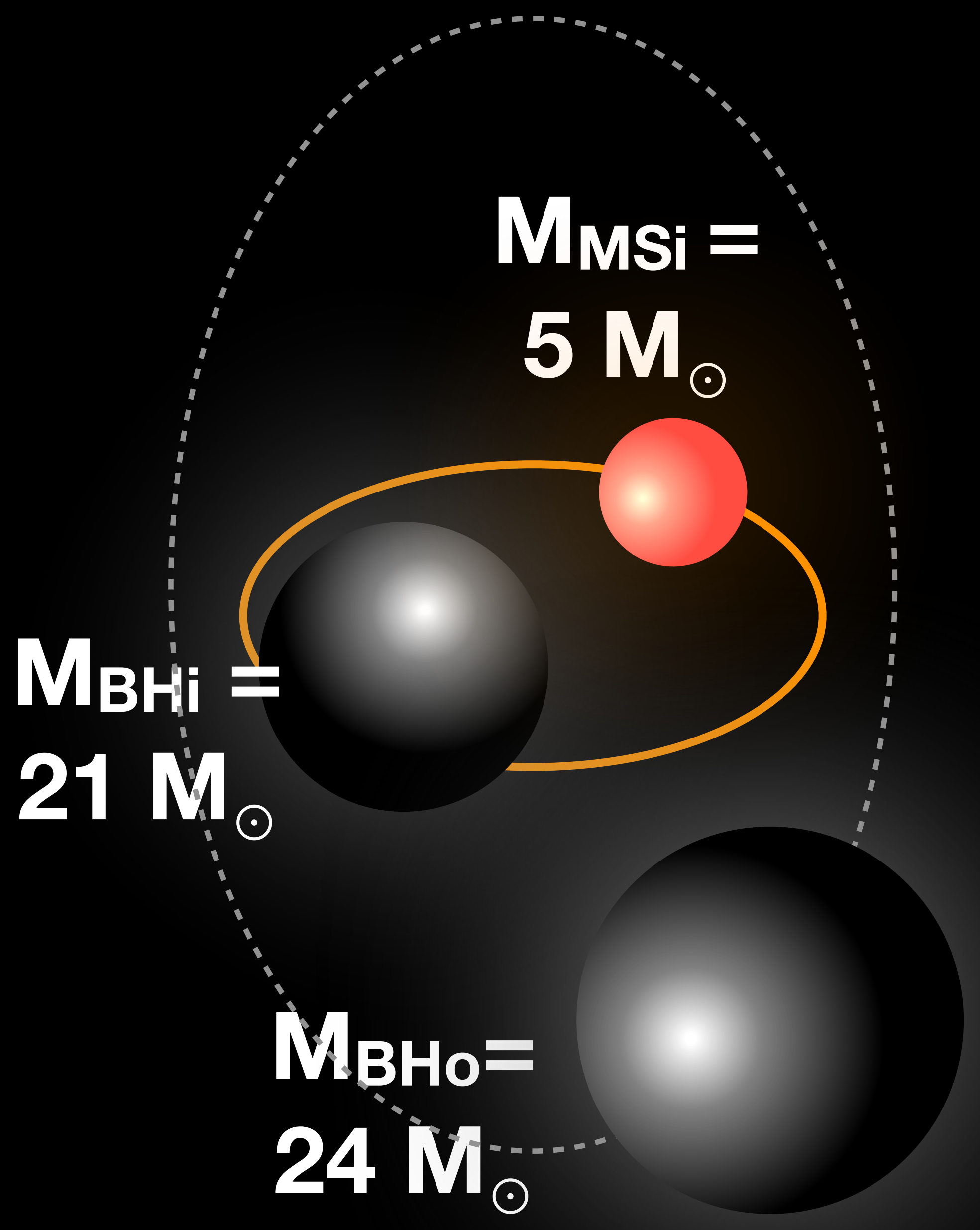
$$\beta = \frac{r_t}{r_p}$$





Stellar disruptions : an example of a triple

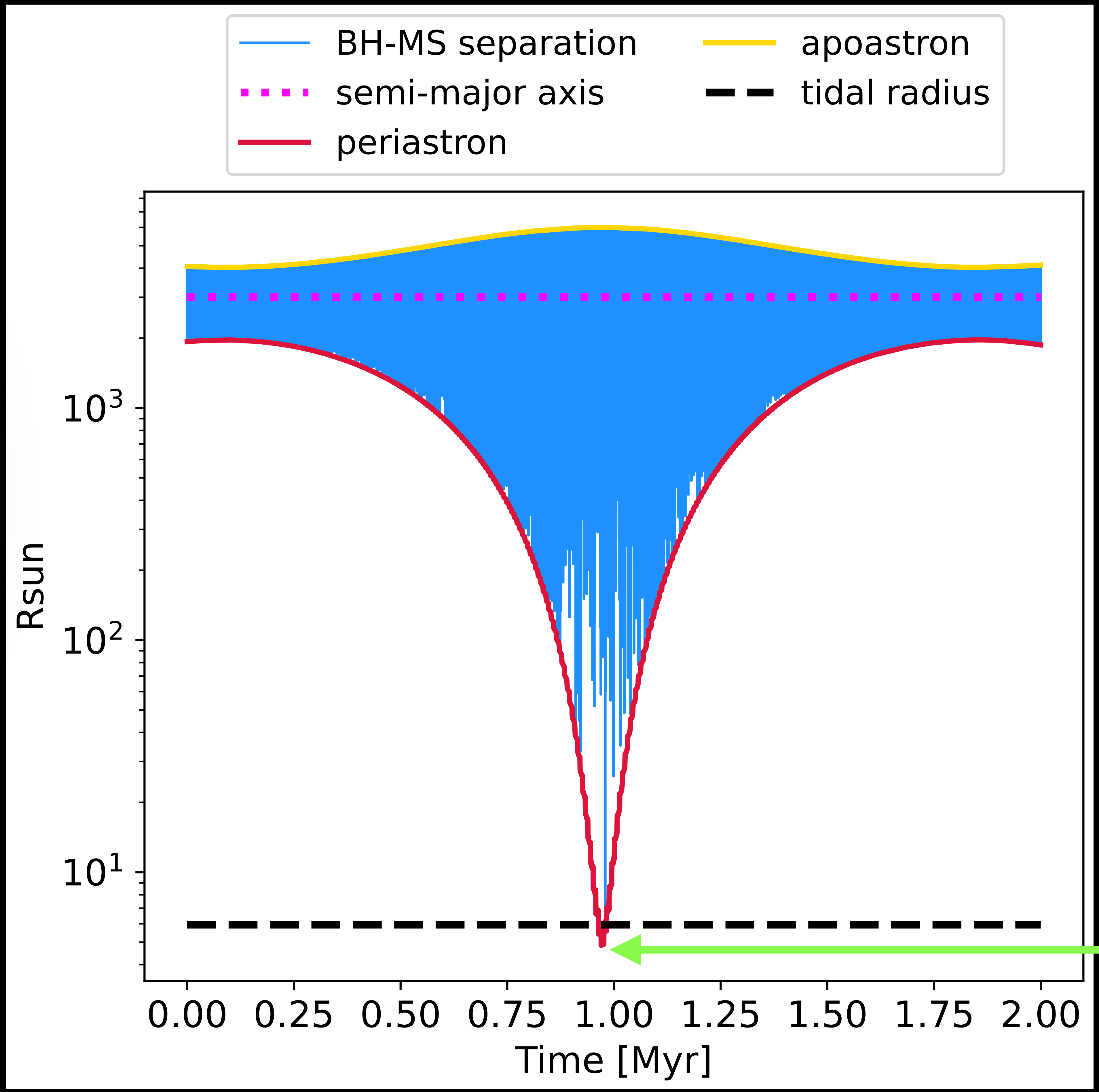
TSUNAMI code *(Trani & Spera 2022)*



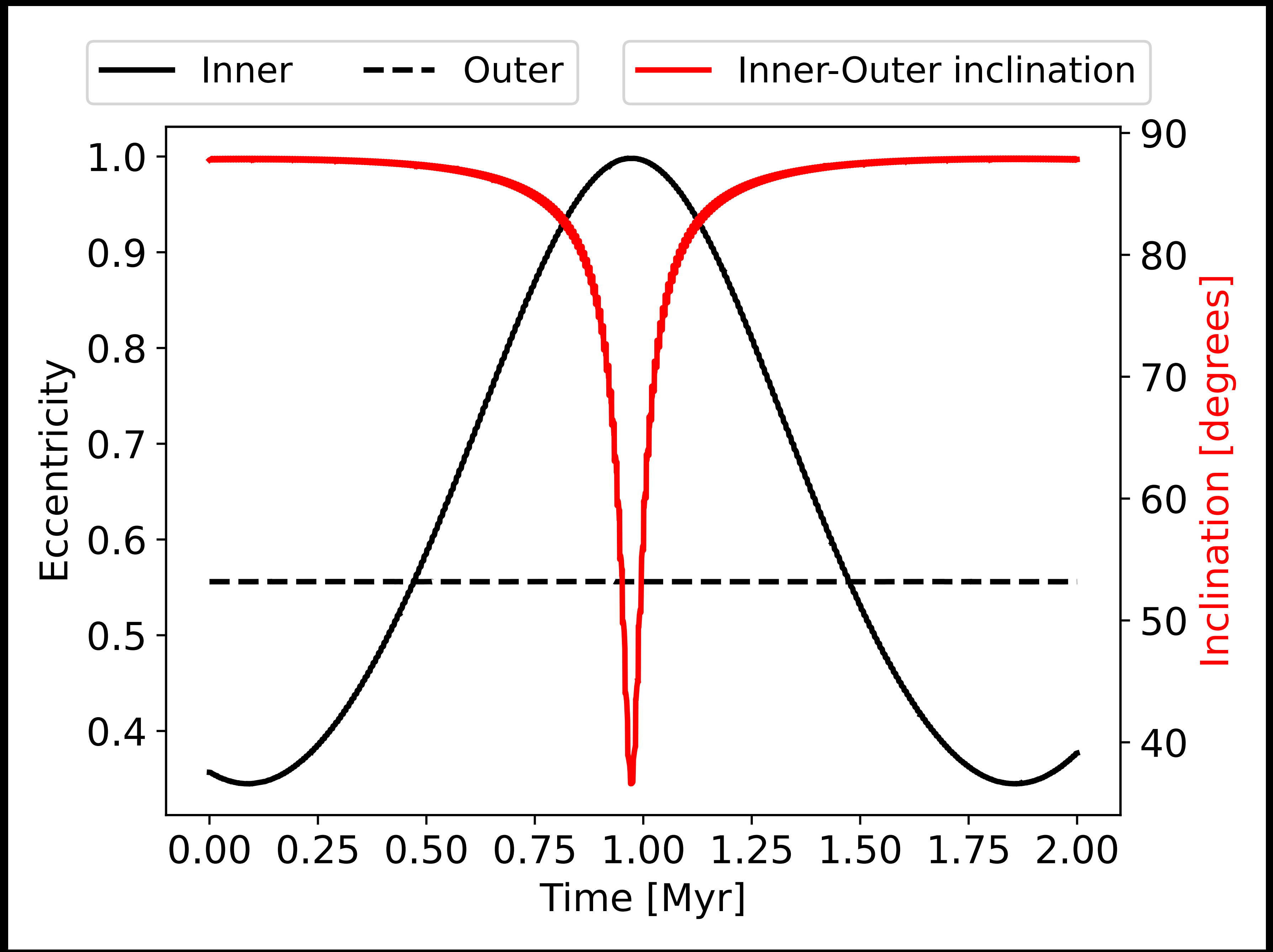
$ecc_i = 0.35$

$a_i = 3000\ R_\odot$

KZL effect



Ecc$_i$ & *i* variation on a period of ~ 2 Myr



$$R_p \le R_t = R_* \left(\frac{M_{BH}}{M_*}\right)^{1/3}$$

Implications: Multi-Messenger Astronomy I

#BHs

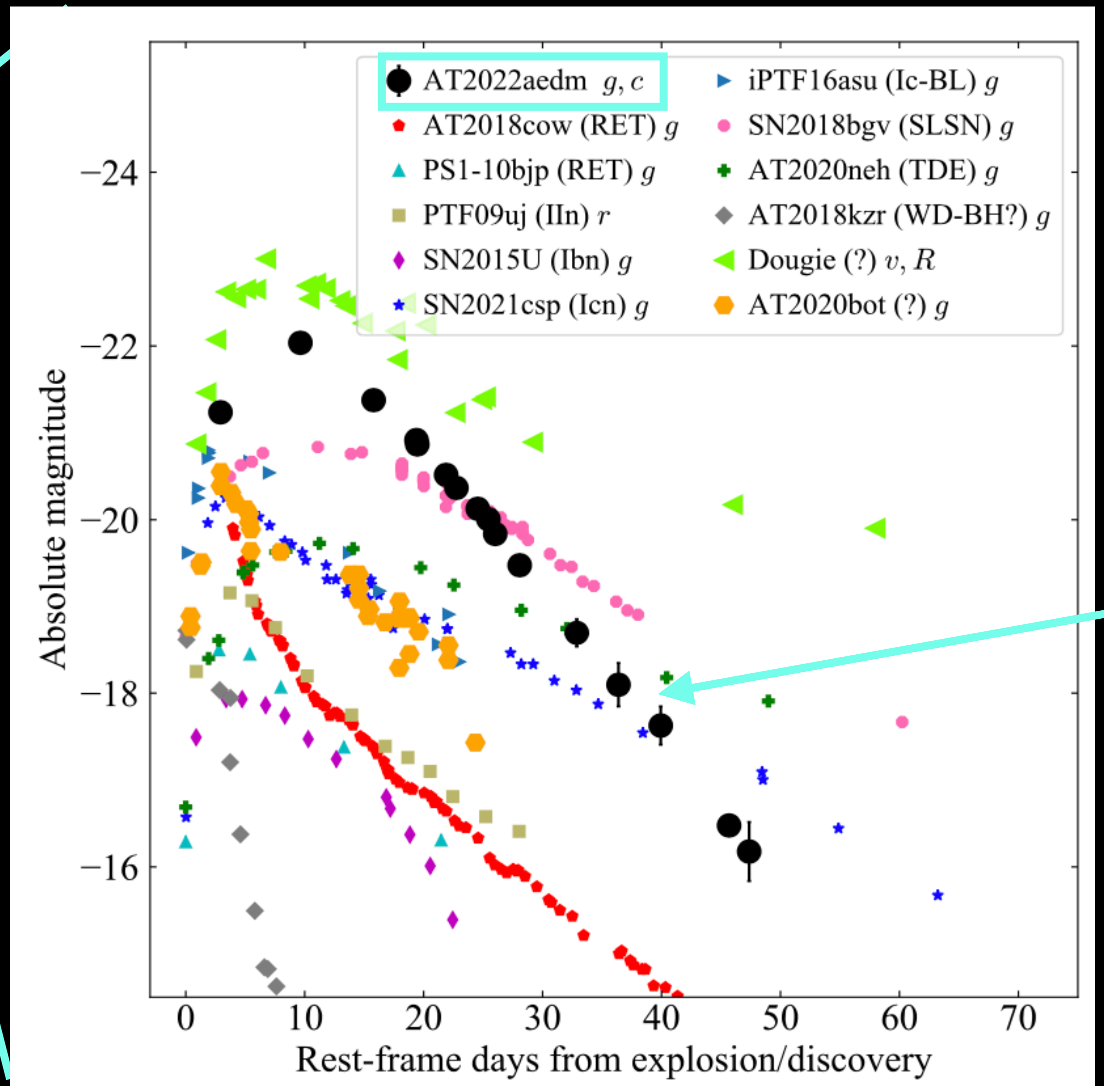
EM: ~Fast Blue Optical Transients (FBOT)

LSST	**ZTF**	**ULTRASAT**
exp. 2025	ongoing	exp. 2026

Optical transients
UV transients

Detection rate estimate:
$10\text{–}10^5\ \mathrm{yr}^{-1}$ (Rubin), $1 - 50\ \mathrm{yr}^{-1}$ (ZTF), and $0.3\text{–}10^3\ \mathrm{yr}^{-1}$ (ULTRASAT)

Kremer et al., 2023



Maybe the first "candidate" μ-TDE ?

Nicholl et al., 2023

Not yet confirmed

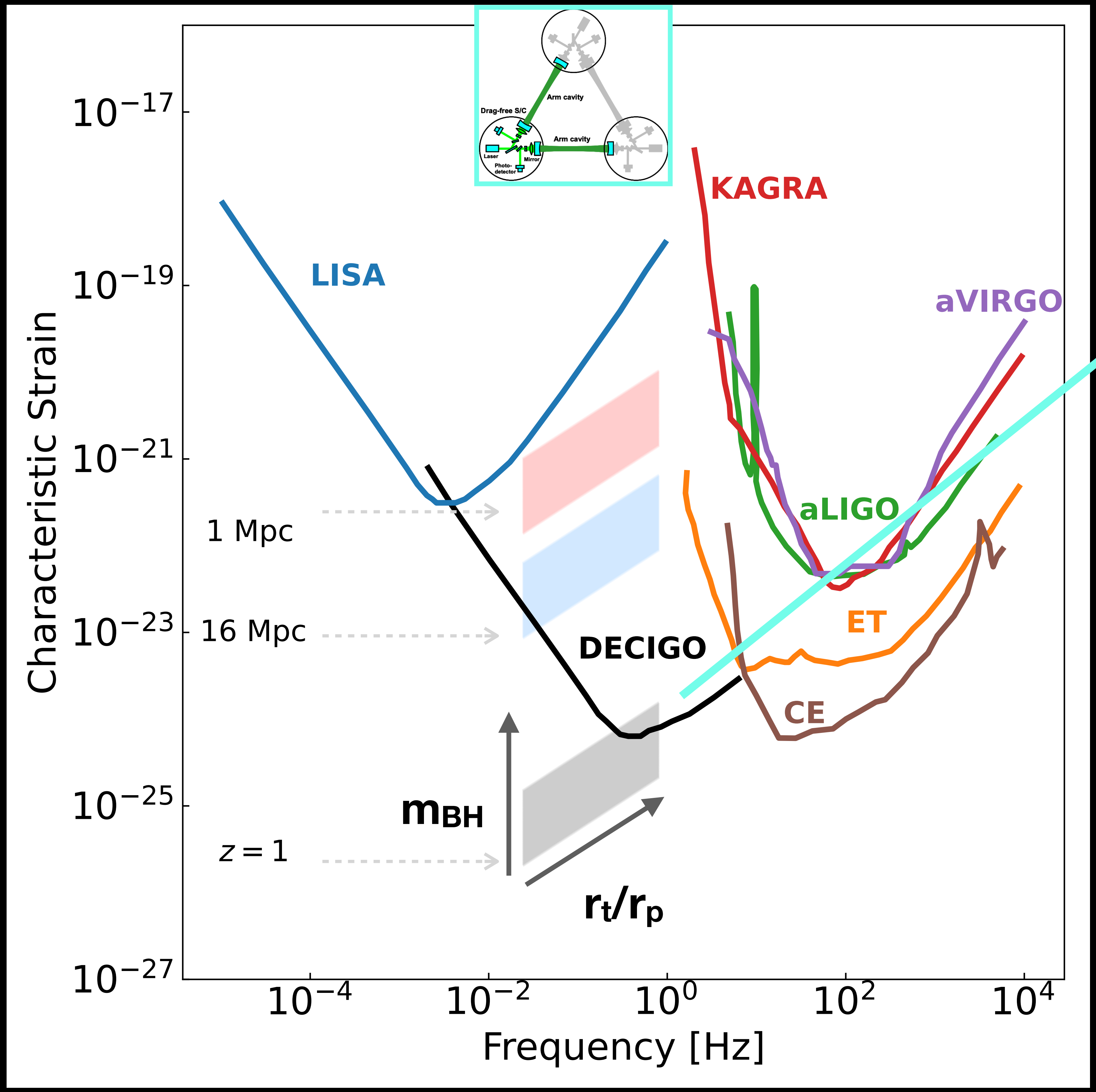
Implications: Multi-Messenger Astronomy II

#BHs

GW: Burst emitted when the star is torn apart

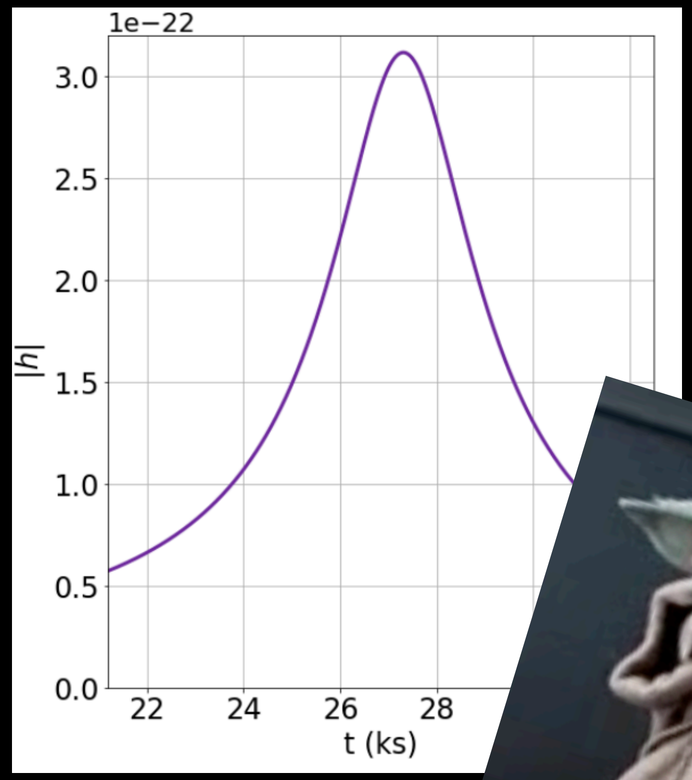
Sensitivity Curves:
Amaro-Seoane et al., 2017;
Sato et al., 2017;
Abbott et al., 2020a;
Maggiore et al., 2021;
Ng et al., 2021

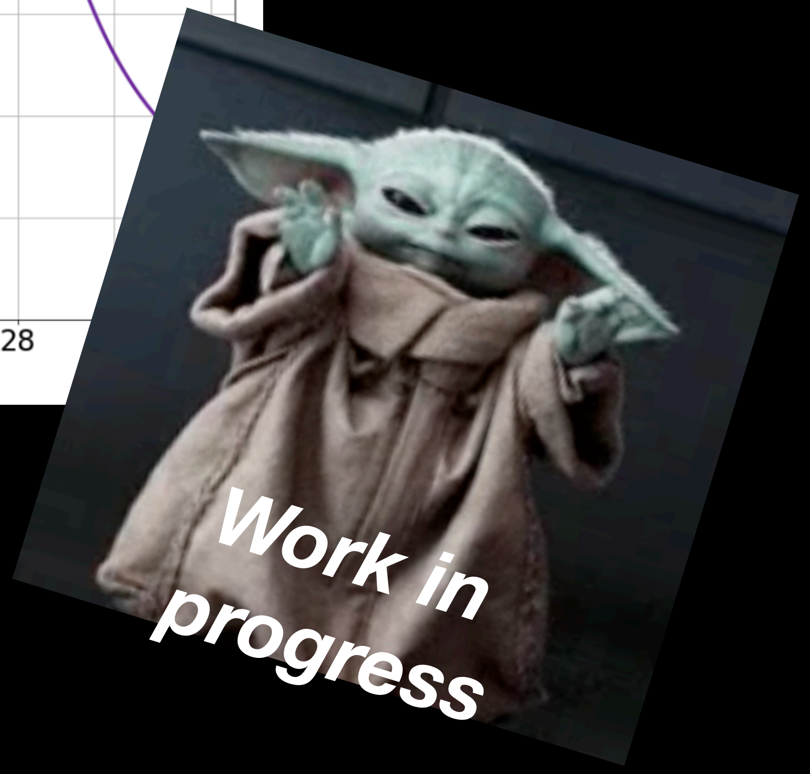
$m_{BH} = 5\text{-}100\ M_\odot$



1 $M_\odot$ Stars destroyed
*by **stellar mass BHs***

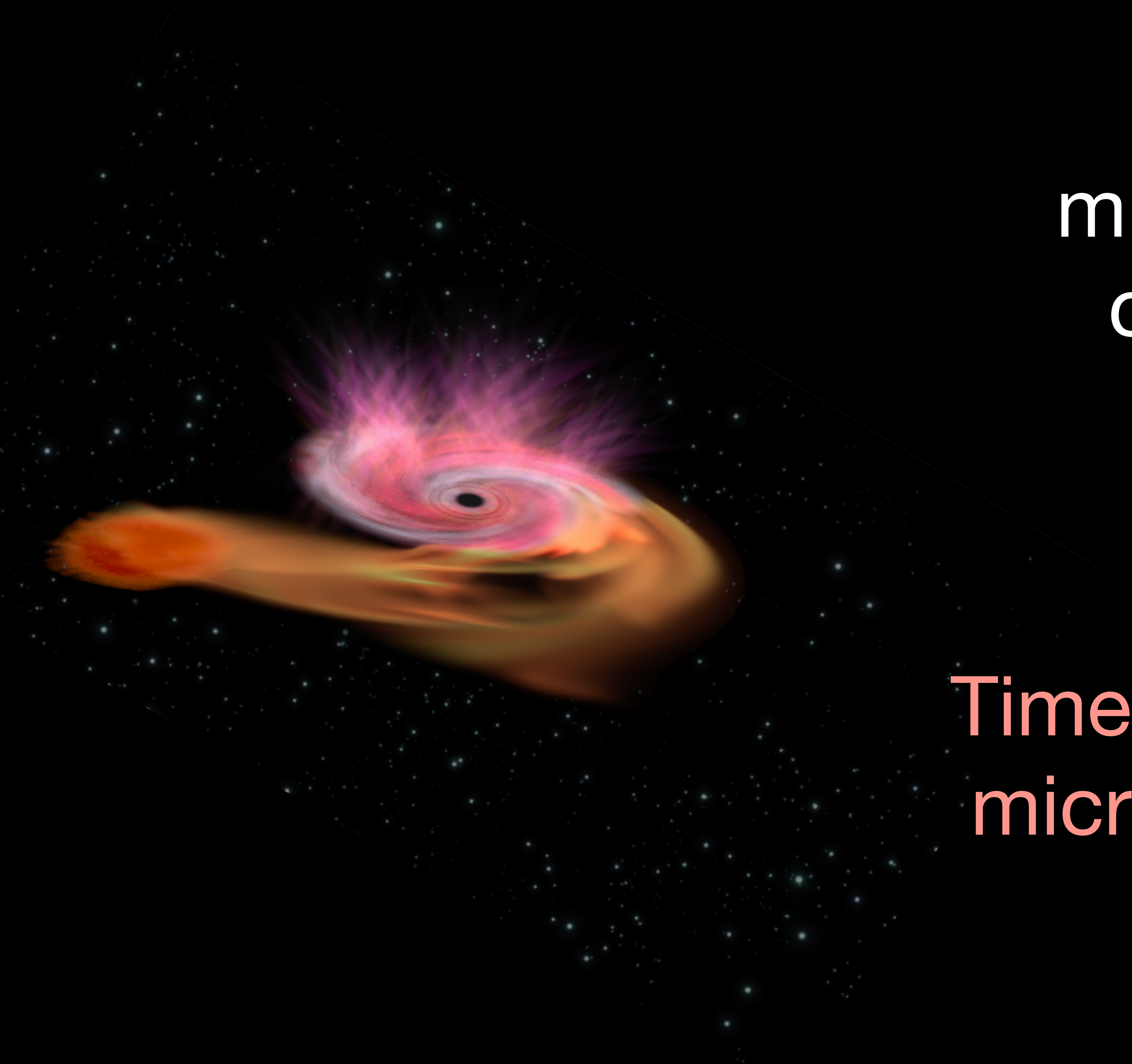
Catalogue of GW waveforms
from micro-TDEs





Take home message

Macro-micro TDEs are promising multi-messenger sources expected to be detected soon (EM+GW)



micro-TDEs involve a large variety of configurations (BCOs+star, binary stars+COs etc)

Timely need for a catalogue of template of micro-TDEs waveforms in preparation for next GW data

GW SCHOOL

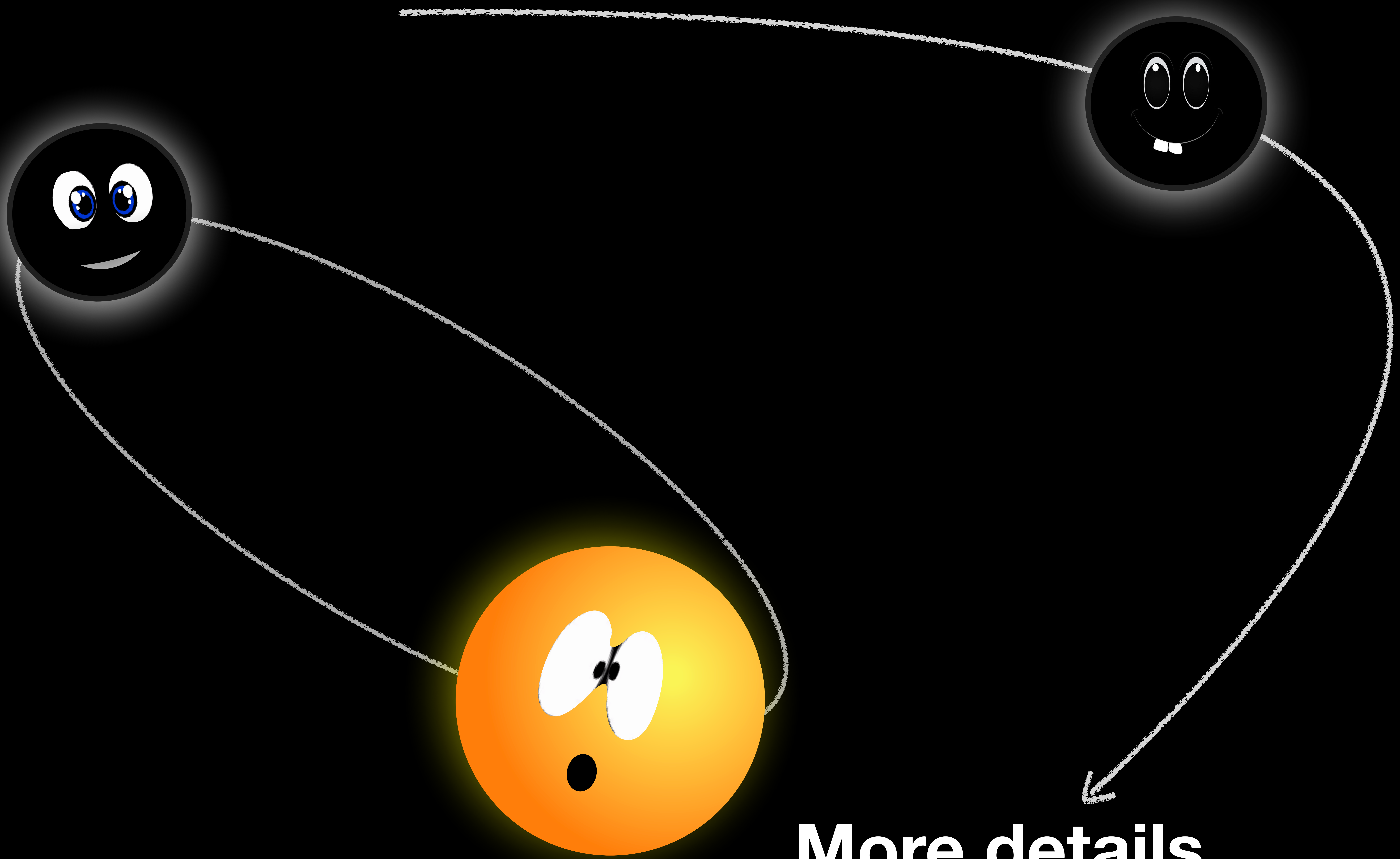
Center for Mathematical Modeling (CMM), Universidad de Chile, **from Monday, November 18 to Friday, November 22, 2024**.

https://eventos.cmm.uchile.cl/waves2024/

Apply / Register

Apply now to participate in the School if you are a master's or doctoral student, or register to attend as a postdoc, researcher, or other professional.

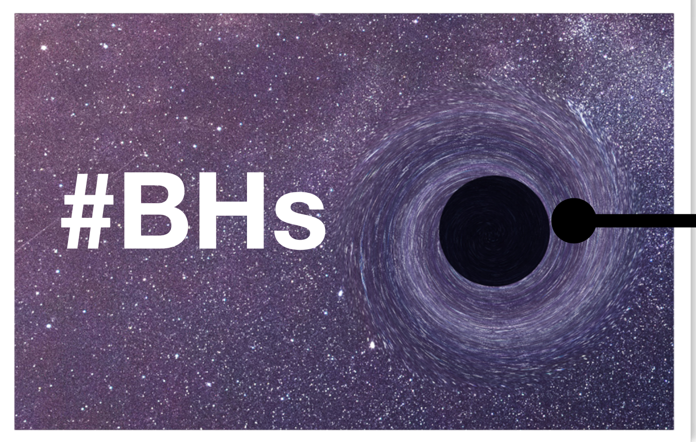
The registration deadline is **September 22nd**, with results announced during the **second week of October.**

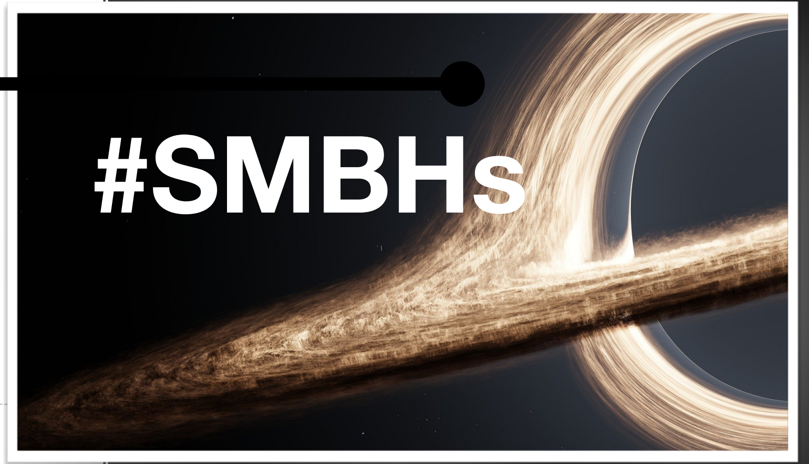


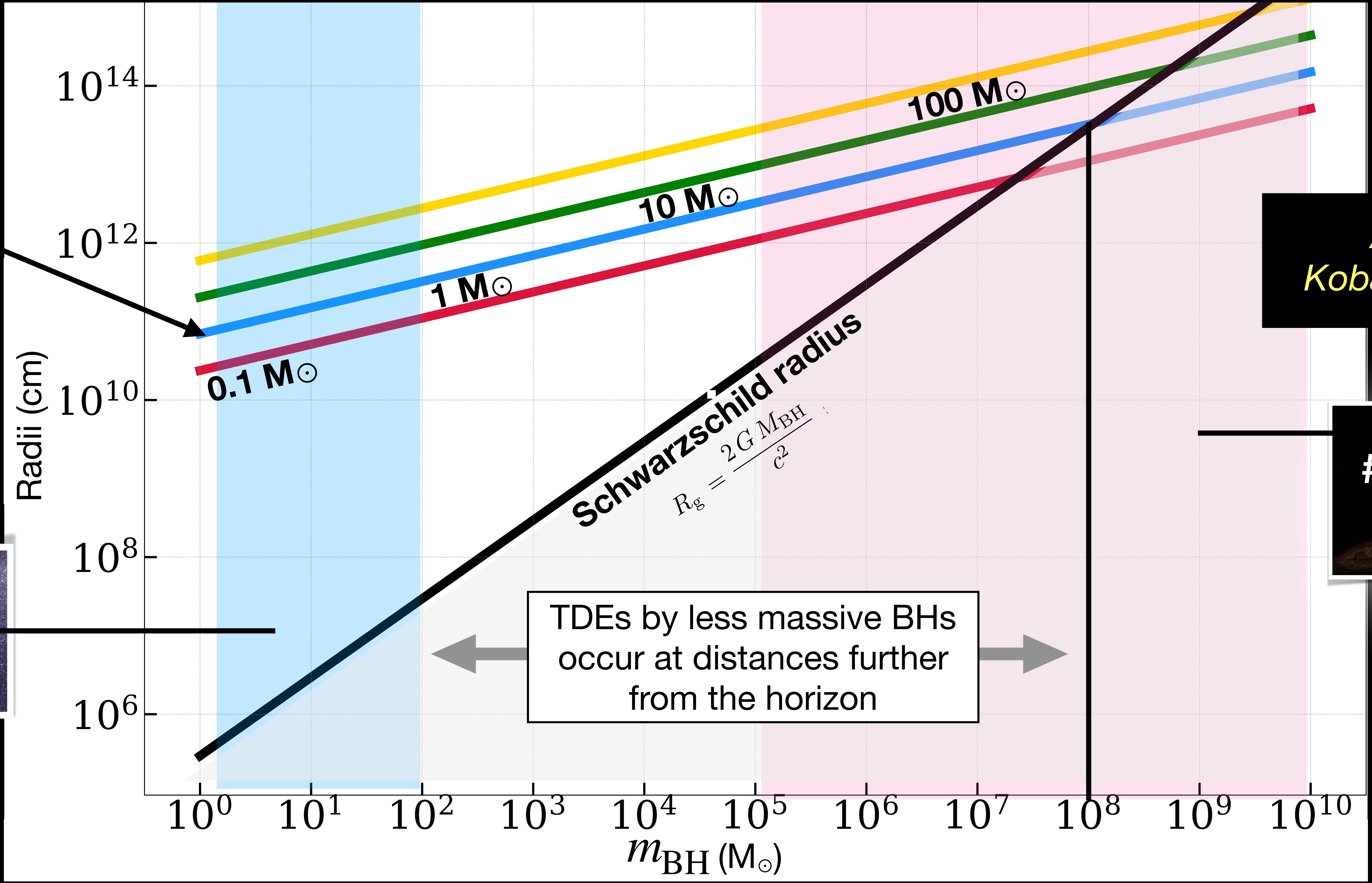
More details...

Radius vs Mass: Macro vs micro-TDEs

MS stars
(r ~ m $^{0.8}$)



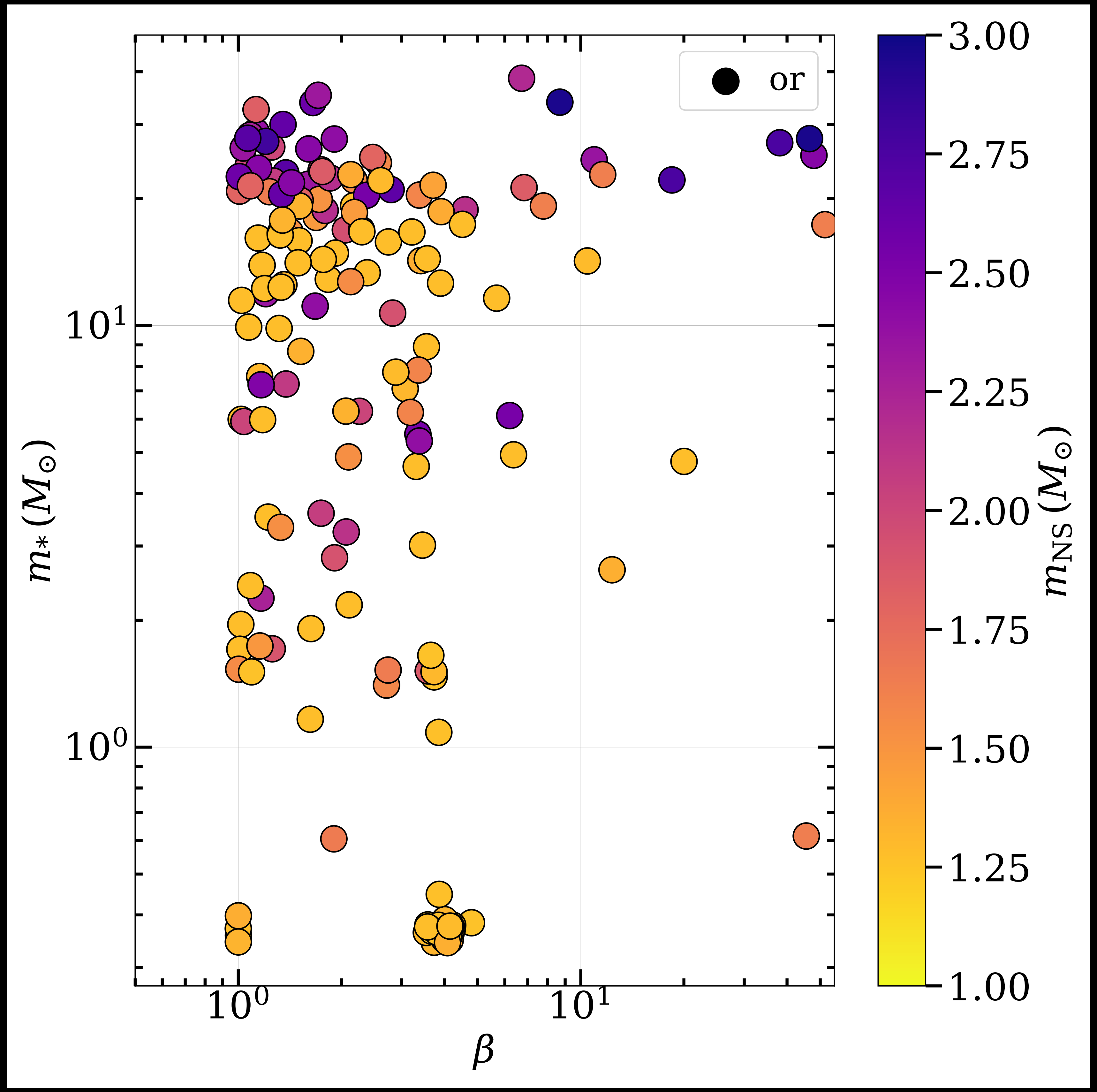




Adapted from
Kobayashi et al., 2004

What about Stars & NS ?

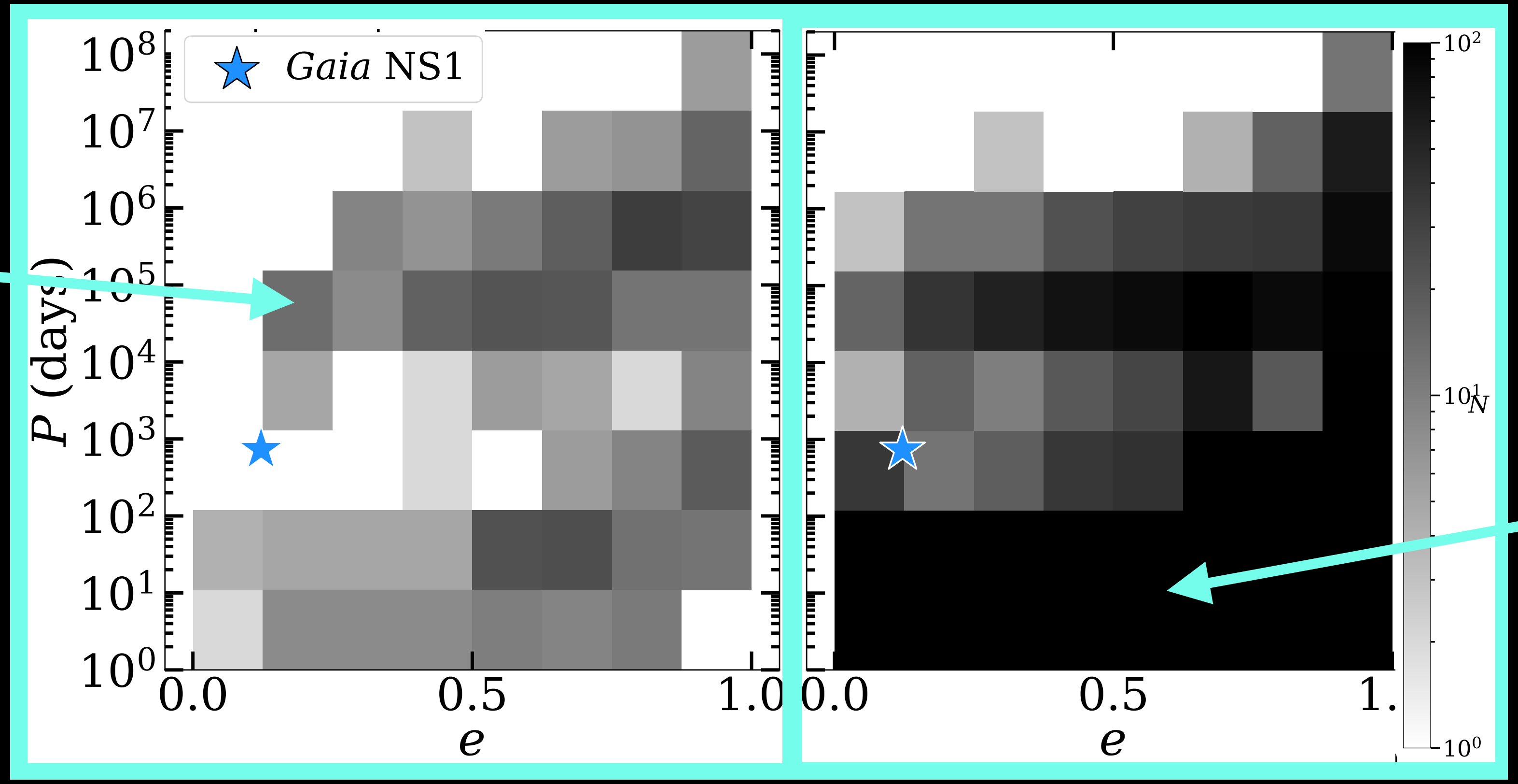
Stars disrupted by NS kicks in YSCs



Dynamical binaries

Gaia **NS1**

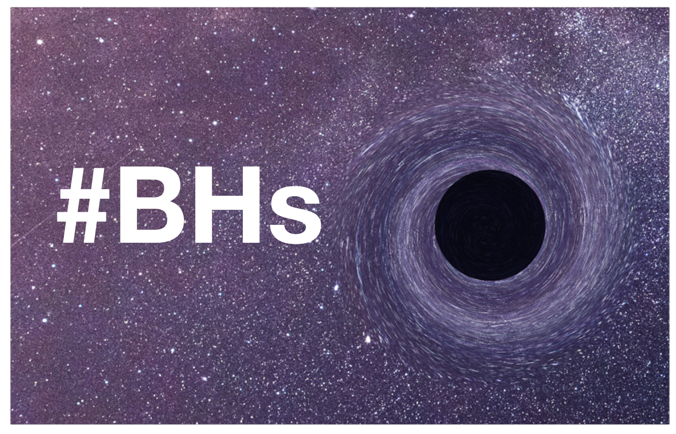
El-Badry et al., 2024



Isolated binaries (Petar.BSE)

Tanikawa et al., 2024

μ-TDEs rate & detectability



Rate in the local Universe:

- 10 Gpc^{-3} yr^{-1} in GCs *(Perets et al. 2016; Kremer et al. 2019d);*
- 20-200 Gpc^{-3} yr^{-1} in YSCs & OCs *(**Rastello et al., 2019**; Kremer et al., 2021)*
- 1-10 Gpc^{-3} yr^{-1} in NSCs *(Fragione et al. 2020)*

LSST
exp. 2025
synoptic astronomical survey

ZTF ongoing
Optical transients

ULTRASAT
exp. 2026
UV transients

Kremer et al., 2023

Environment (1)	Intrinsic rate ($Gpc^{-3}yr^{-1}$) (2)	s (3)	Rubin (g-band) (yr^{-1}) (4)	ZTF (g-band) (yr^{-1}) (5)	ULTRASAT (NUV) (yr^{-1}) (6)
Globular clusters	~10 (Perets et al. 2016; Kremer et al. 2019b)	0.2	6.8×10^3	4.3	133
		0.5	50	0.1	1.2
		0.8	0.9	0.004	0.03
Young massive clusters	~100 (Kremer et al. 2021)	0.2	6.8×10^4	53.9	1.3×10^3
		0.5	490	1.1	12
		0.8	9.1	0.9	0.3

Detection rate estimate: 10–105 yr^{-1} (Rubin), 1 – 50 yr^{-1} (ZTF), and 0.3–10^3 yr^{-1} (ULTRASAT)

1) GW burst from BH-Star

Estimate of the GW strain emitted by the source derived from quadrupole approximation to the Einstein field equations *Toscani et al., 2021, 2022*

M_h mass of the BH

M_* mass of the star

R_* radius of the star

r_s BH Schwarzschild radius

r_t tidal radius

r_p pericenter distance

$$h \approx \frac{1}{d}\frac{4G}{c^2}\frac{E_{\rm kin}}{c^2}$$

d= distance from Earth

$$E_{\rm kin} = M_* \frac{GM_{\rm h}}{r_{\rm p}}$$

kinetic energy

The **GW strain** is thus:

$$h \approx \beta \times \frac{r_{\rm s} r_{\rm s*}}{r_{\rm t} d}$$

$$\approx \beta \times 2 \times 10^{-22} \left(\frac{M_*}{M_\odot}\right)^{4/3} \left(\frac{M_{\rm h}}{10^6\,{\rm M}_\odot}\right)^{2/3} \times \left(\frac{R_*}{R_\odot}\right)^{-1} \left(\frac{d}{16\,{\rm Mpc}}\right)^{-1},$$

The associated **frequency** is thus:

$$f \approx \frac{\beta^{3/2}}{2\pi}\left(\frac{GM_{\rm h}}{r_{\rm t}^3}\right)^{1/2}$$

$$\approx \beta^{3/2} \times 10^{-4}\,{\rm Hz} \times \left(\frac{M_*}{M_\odot}\right)^{1/2} \left(\frac{R_*}{R_\odot}\right)^{-3/2}$$

The dependence on $M_\star$, $R_\star$ and $M_\bullet$ indicates that more compact stars (such as WDs) will produce stronger GW signals.

For β = 1 and a Sun-like star disrupted by a 10^6 $M_\odot$ static BH at ≈ 16 Mpc from us, *h* ≈ 10^{-22} and f ≈ 10^{-4} Hz