Tidal disruption events for the LGWA

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

erc

LISA CONSORTIUM

EPTA

ET EINSTEIN TELESCOPE

Elisa Bortolas

Main collaborators: A. Sesana, L. Broggi, M. Bonetti, M. Toscani, T. Ryu,...

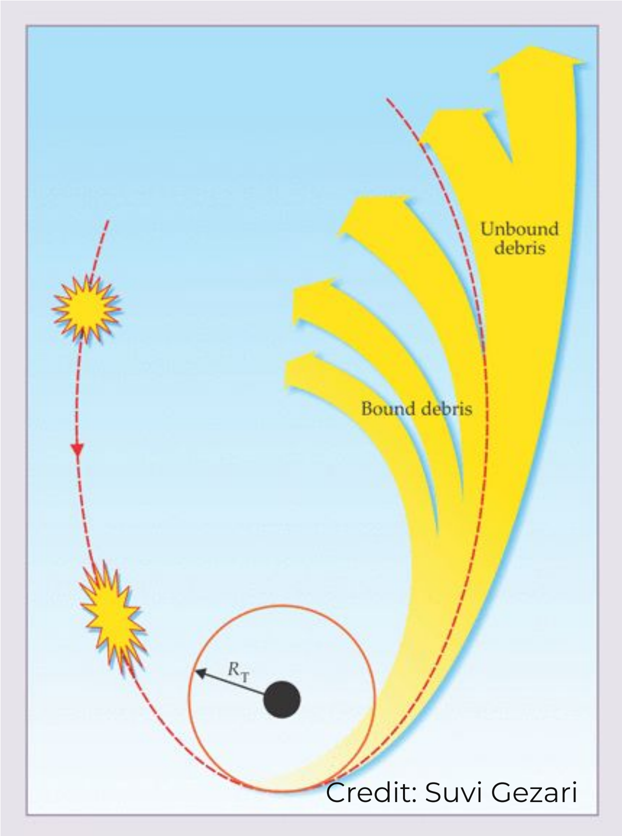
**LUNAR GRAVITATIONAL WAVE ANTENNA –
WHITE PAPER KICK-OFF**

L'Aquila, February 9th, 2023

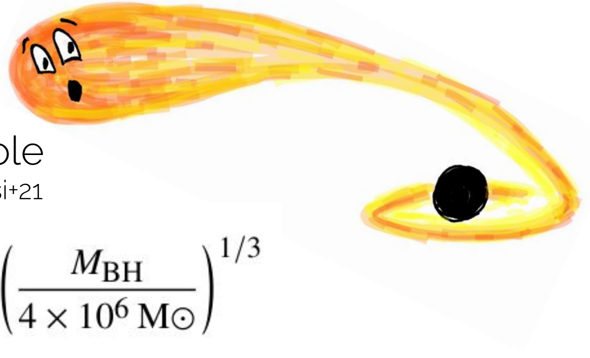
Tidal disruption events

Disruption of a star when it gets too close to a supermassive black hole

Rees88, Phinney89, Lodato&Rossi11, Rossi+21



$$R_{\rm TDE} \approx \left(\frac{M_{\rm BH}}{m_\star}\right)^{1/3} R_\star = 3.6\times10^{-6}\ {\rm pc}\left(\frac{M_{\rm BH}}{4\times10^6\,{\rm M}\odot}\right)^{1/3}$$



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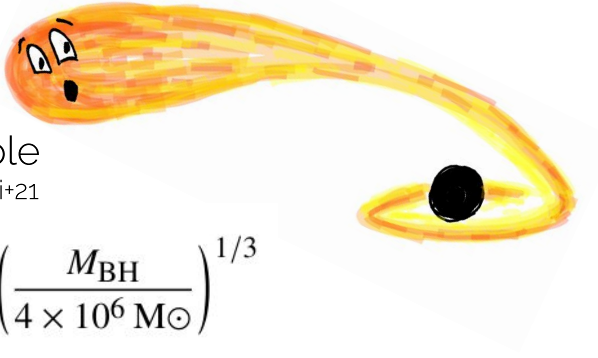

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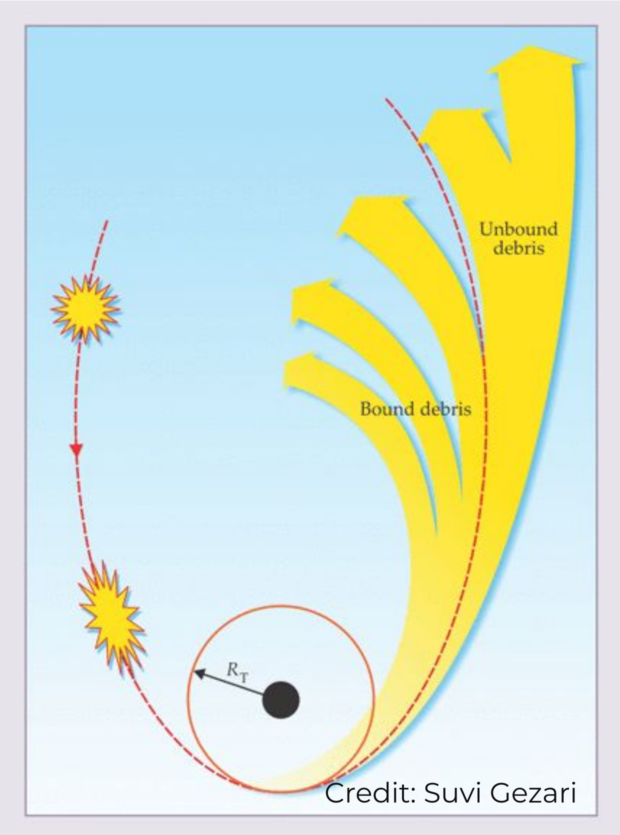

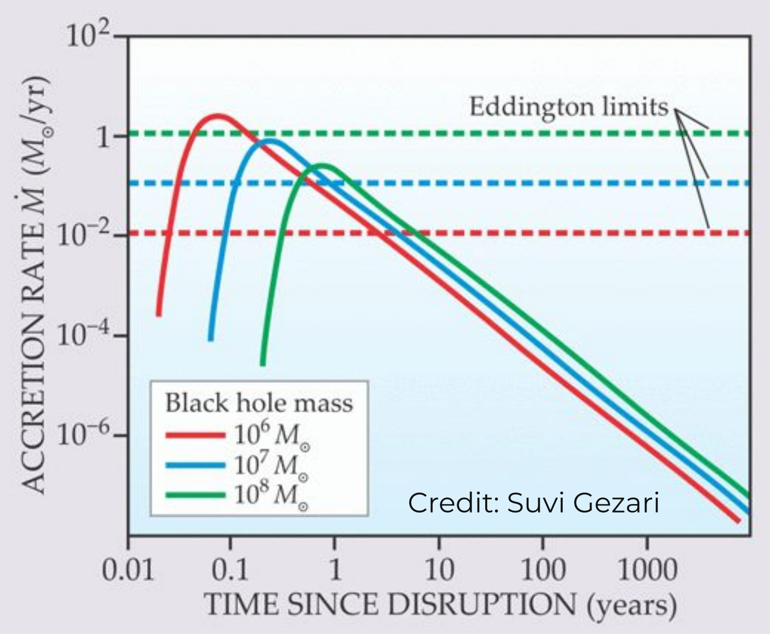

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– Multi-wavelenght emission
– Can be significantly super-Eddington

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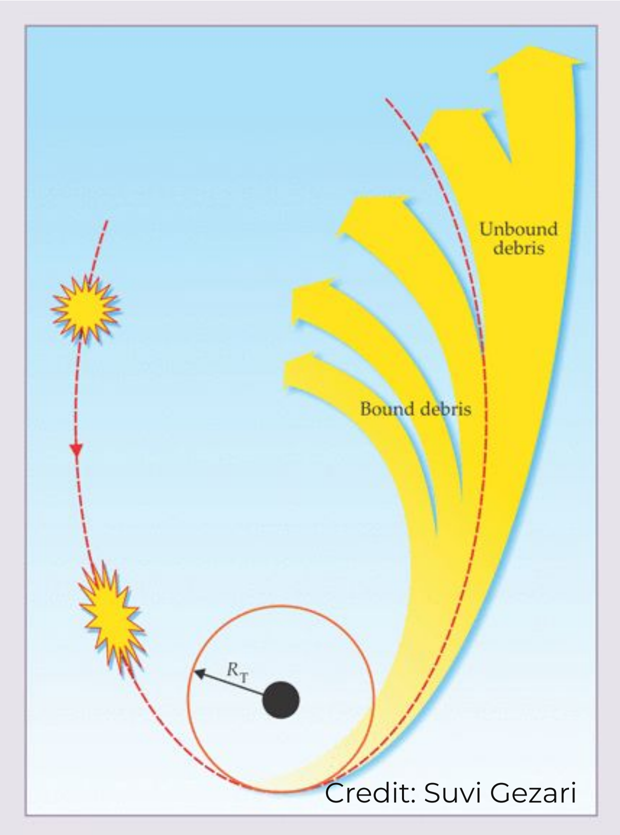

Credit: Suvi Gezari

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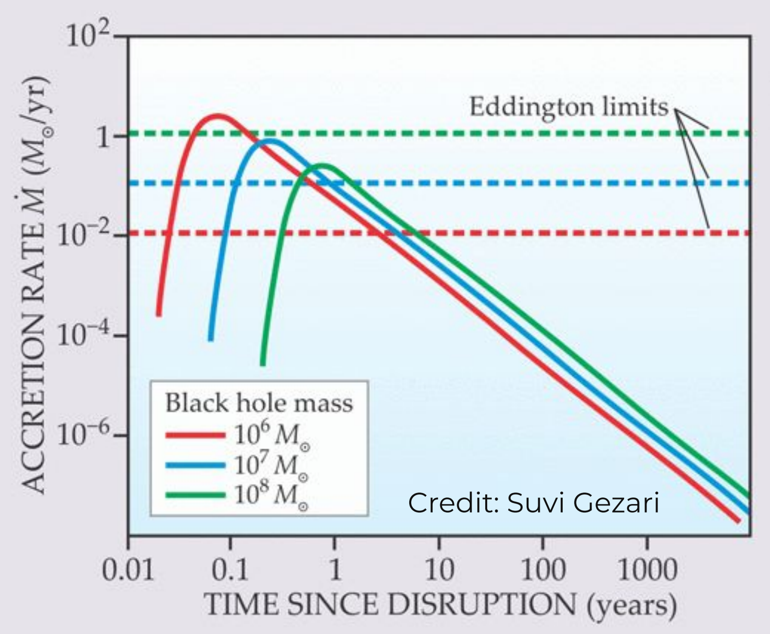

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– Characteristic decline in the light-curve $\propto t^{-5/3}$
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– Can be significantly super-Eddington

Ideal to unveil otherwise quiescent MBHs!

Tidal disruption events for the LGWA

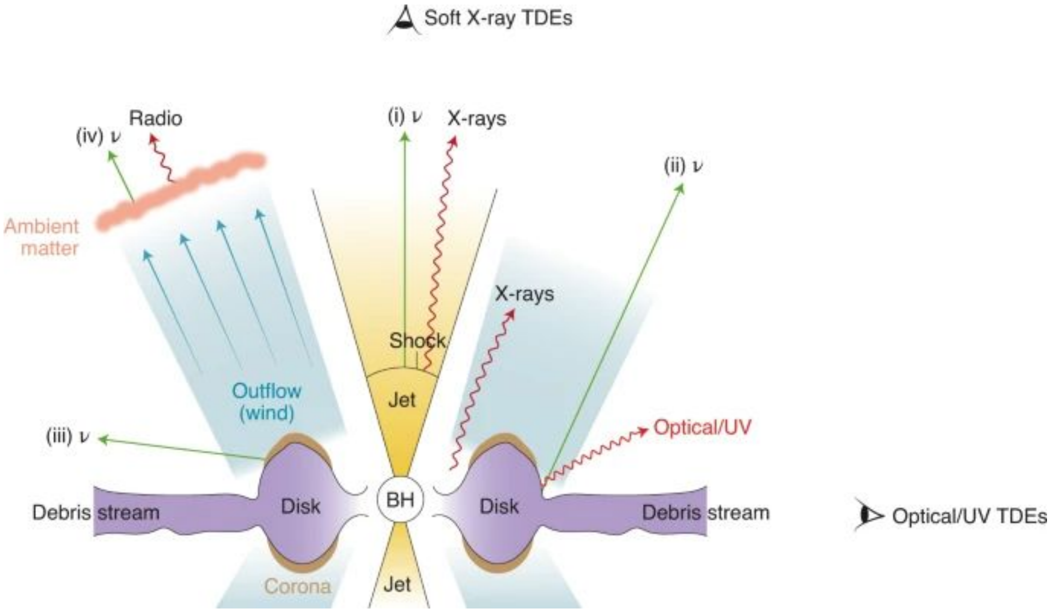
Multi-messenger sources

TDEs as multi-messenger sources

Gravitational waves

Cosmic neutrinos

Neutrino emission (Stein+21) possibly accelerated through a central engine powering a synchrotron-emitting outflow



TDEs as multi-messenger sources

Gravitational waves

Either as single sources or as GW background (Toscani+19,20,21,22) mHz to dHz lasting for a few ks.

Measurements of H_0! (Wong23)

$$h \sim \frac{GM_* R_g}{c^2 D R_p} \sim 2 \times 10^{-22} \beta_p \left(\frac{D}{10Mpc}\right)^{-1} \left(\frac{R_*}{R_\odot}\right)^{-1} \left(\frac{M_*}{M_\odot}\right)^{4/3} \left(\frac{M_h}{10^6 M_\odot}\right)^{2/3}$$

$$f \sim \left(\frac{GM_h}{R_p^3}\right)^{1/2} \sim 6 \times 10^{-4} \beta_p^{3/2} \left(\frac{M_*}{M_\odot}\right)^{1/2} \left(\frac{R_*}{R_\odot}\right)^{-3/2} \mathrm{Hz}.$$

Kobayashi+04

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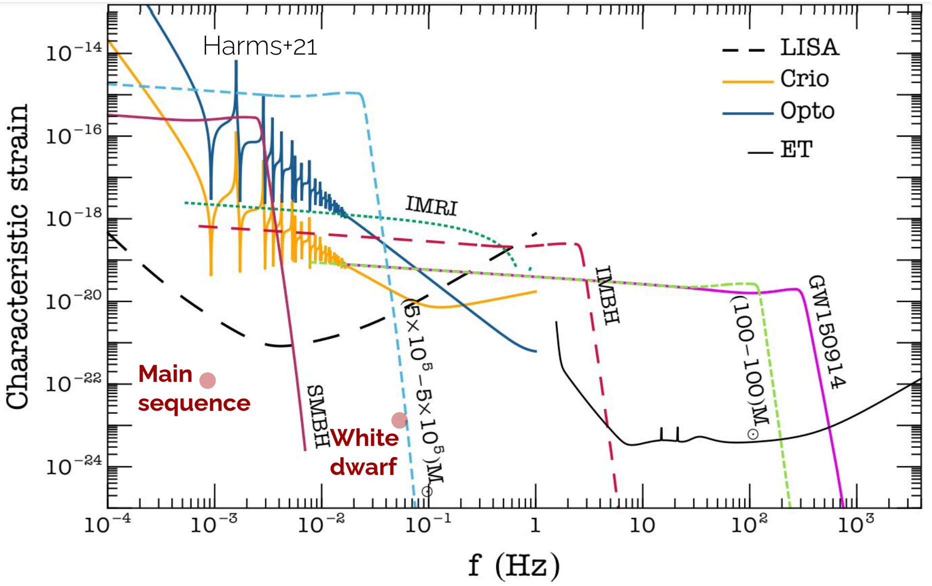

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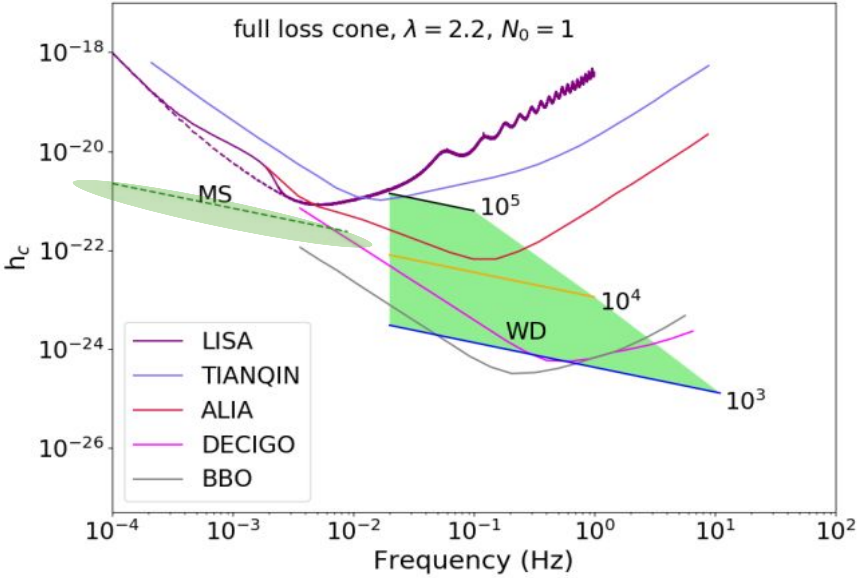
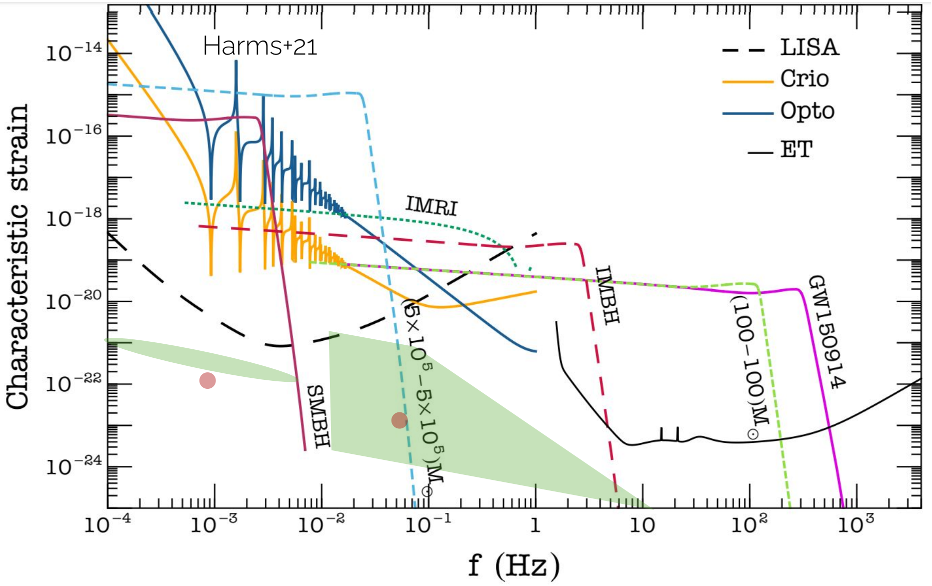
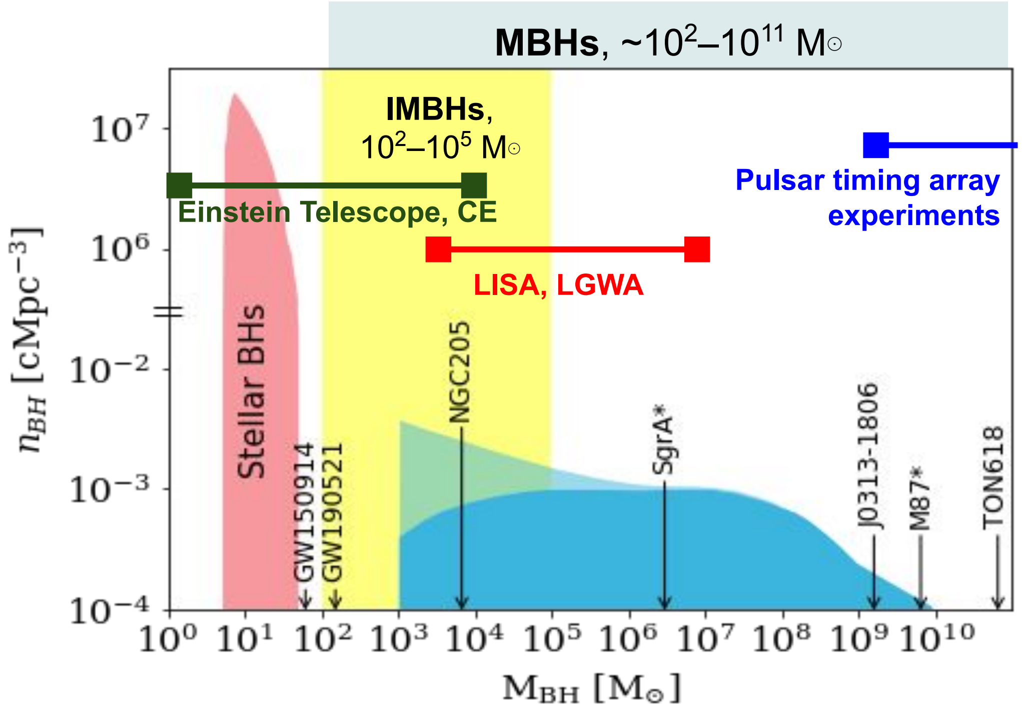




Tidal disruption events for the LGWA

Predicting the population of MBH mergers

Shedding light on the BH mass function



Greene+20, Volonteri+21

TDEs as probes for low-mass MBHs

TDEs

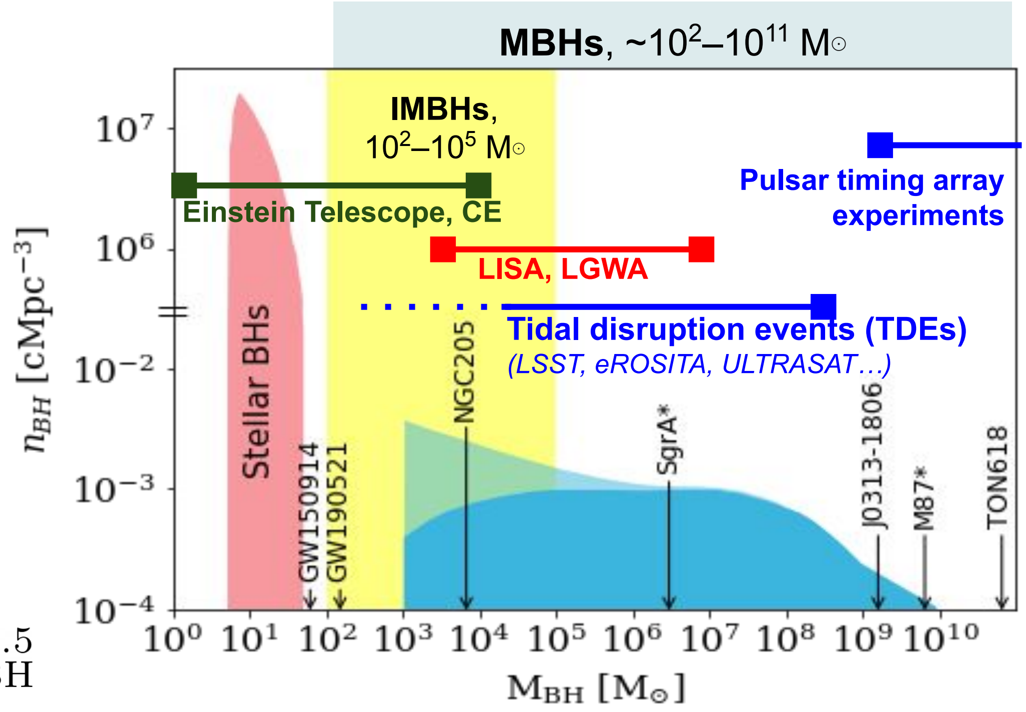
- Can only occur about low mass MBHs ($<\sim 10^8$ Msun)
- Can be significantly **super-Eddington** for low MBH masses (Rossi+21)

$$\frac{\dot{M}}{\dot{M}_{\rm Edd}} \sim 100 \left(\frac{M_{\rm BH}}{10^6\, M_\odot} \right)^{-1.5}$$

- TDE **rates** may be **larger about low-mass MBHs** (Stone&Metzger16)
- The fallback timescale can be used to **measure the MBH mass**

$$t_{\rm fallback} \propto M_{\rm BH}^{0.5}\, m_\star^{-1}\, R_\star^{1.5} \sim M_{\rm BH}^{0.5}$$

(*MoSFIT* – Guillochon+17, Mockler+19; *TDEMass* – Ryu+20)
ASSUMPTIONS on the EMISSION!



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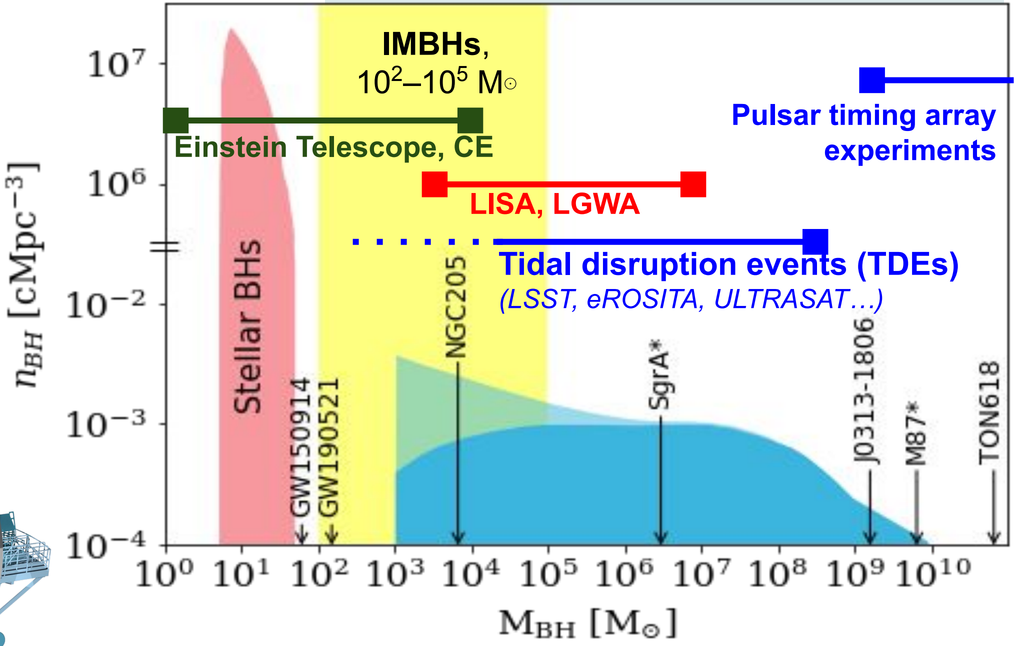
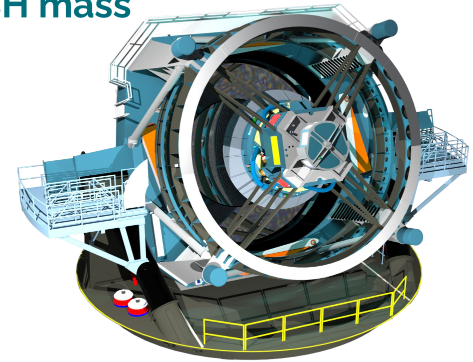
MBHs, ~10^2–10^{11} M⊙



Transient surveys are observing TDEs at unprecedented rates

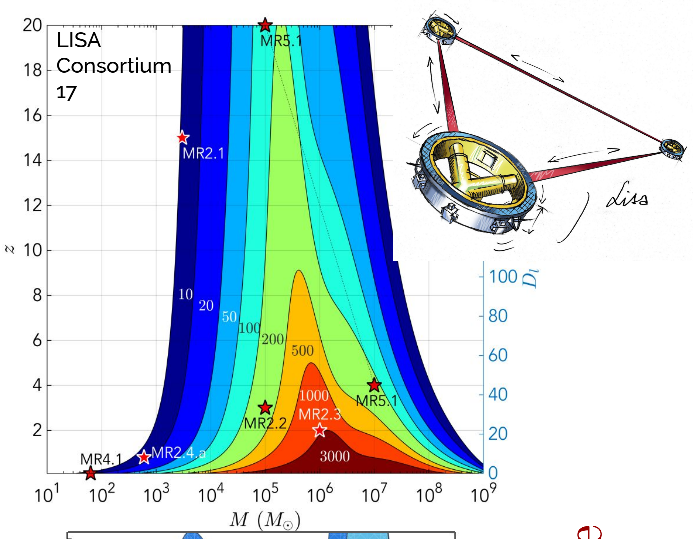


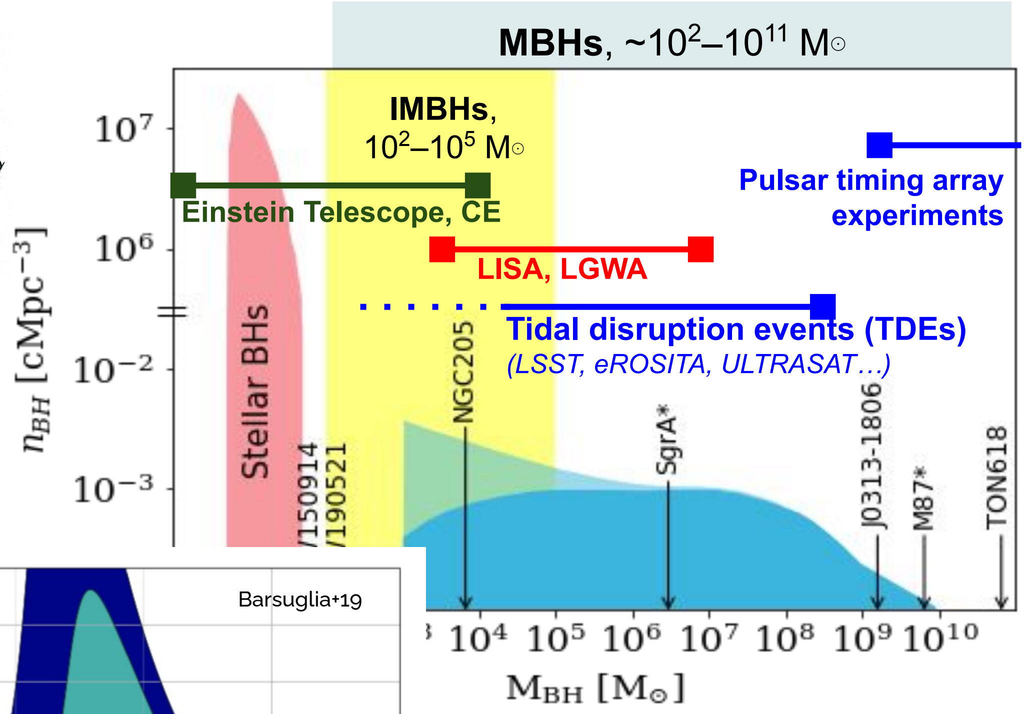
(ZTF, ~20/yr, VanVelzen+20; eROSITA, ~50/yr, Sazonov+21)

Upcoming surveys as LSST/VRO, ULTRASAT (*Roman?*) may detect thousands of TDEs per year!

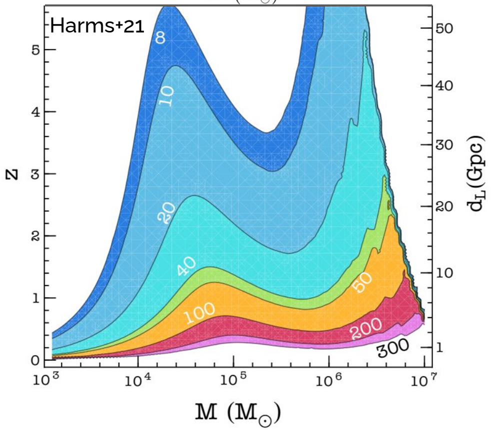
TDEs can anticipate the population of merging MBHs

LISA observatory

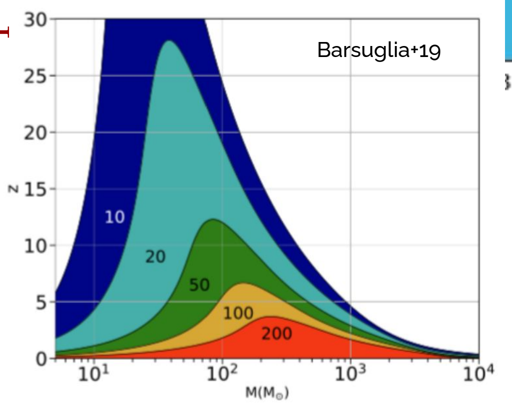




LGWA



Einstein Telescope



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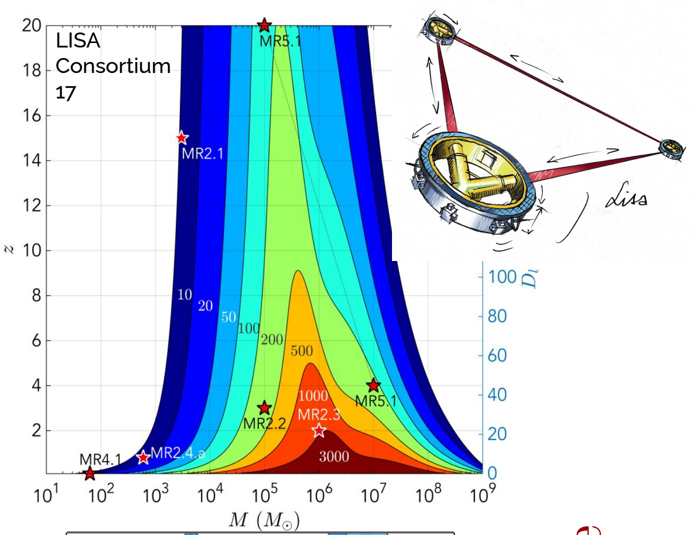

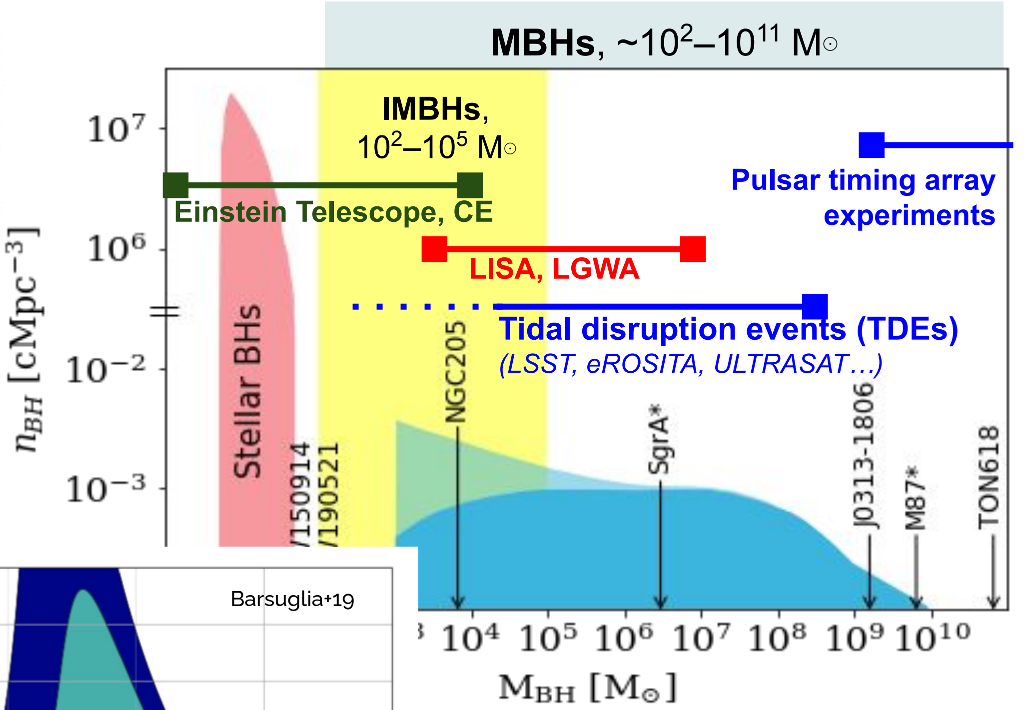

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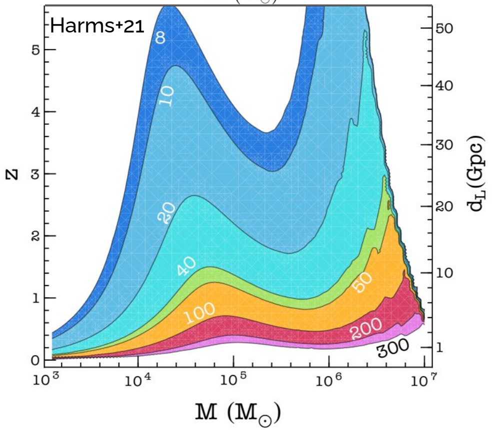

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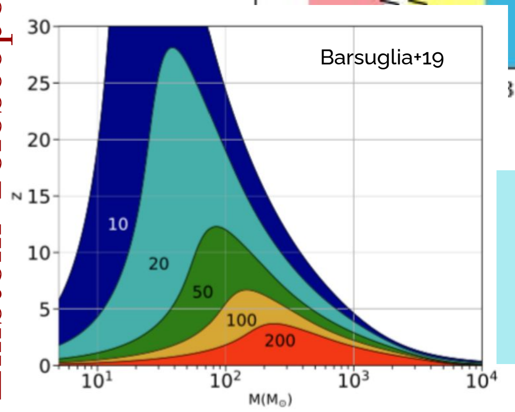

TDEs can be used to anticipate the population of merging MBHs that will be probed by future GW missions

How to properly constrain the MBH mass function?

Collection of thousands of future **TDE observations** from new facilities *(LSST/ULTRASAT/eROSITA…)*

“bias corrector machine”

Complete MBH mass function

Predictions for future GW detectors (to be tested!)

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Assessment of the observability of TDEs
(obs. bias + emission processes)

Collection of thousands of future **TDE observations** from new facilities *(LSST/ULTRASAT/eROSITA...)*

Properties of a galactic nucleus
(MBH mass, density...)

TDE rates

Assessment of the observability of TDEs
(obs. bias + emission processes)

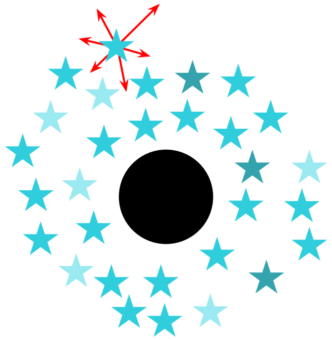
"bias corrector machine"

Complete MBH mass function

Predictions for future GW detectors (to be tested!)

Predicting TDE rates

Ubiquitous production mechanism: two-body relaxation

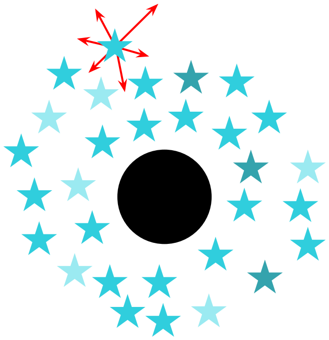


Two-body relaxation between stellar objects slowly perturbs stellar orbits → statistically, at some point, a star can reach a *deadly* orbit and get disrupted

NOTE: this is the same main generation mechanism as for extreme-mass-ratio inspirals (EMRIs)

Predicting TDE rates

Ubiquitous production mechanism: two-body relaxation



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OPEN PROBLEMS:

Predicted TDE rates ~ a few x 10^{-4} /galaxy/year

Observed TDE rates ~ 10^{-5} galaxy/year

Rare post-starburst galaxies are overrepresented in the sample of TDE hosts

Predicting TDE rates

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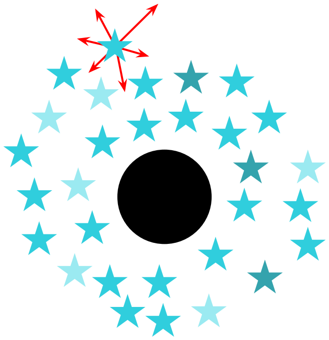

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Missing ingredients in the computation of the event rates!

- Knowledge about the density profile within the MBH influence radius (ELTs?)
- Time-dependent events rates
- Single-mass versus complete stellar mass function
- Partial tidal disruption events

Time-dependent rates

Modelling of the host

MBH mass	NSC mass	NSC eff. radius	$\varrho(r) \propto r^{-\gamma}$
$M_\bullet/\mathrm{M}_\odot$	$M_n/\mathrm{M}_\odot$	$R_{e,n}/\mathrm{pc}$	γ
$10^{7.5}$	5.462×10^7	9.353	1.751
10^7	2.789×10^7	7.602	1.882
$10^{6.5}$	1.424×10^7	6.178	2.012
10^6	7.271×10^6	5.021	2.143
$10^{5.5}$	3.712×10^6	4.081	2.273
10^5	1.896×10^6	3.316	2.404

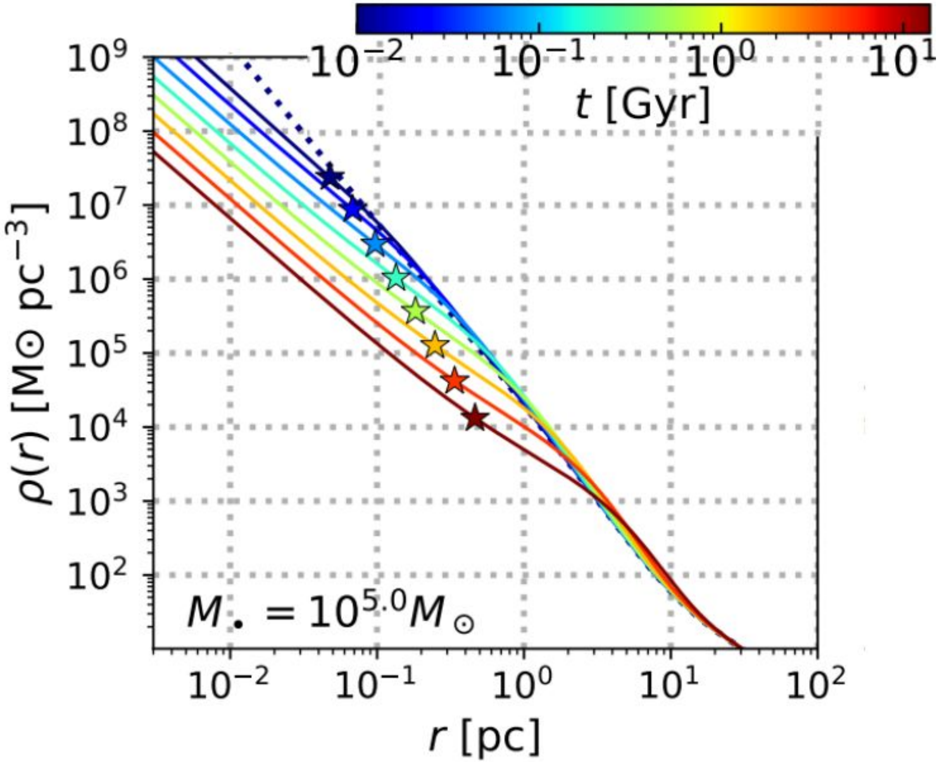
All above Bahacall-Wolf cusp (1.75)

Modelling based on Pechetti+2020

They provide a relation between the MBH mass and the properties of the nuclear star cluster (NSC)

29 objects <10 Mpc from us

Resolution ~1 pc



The density profile changes very quickly and becomes **much less dense in the centre**

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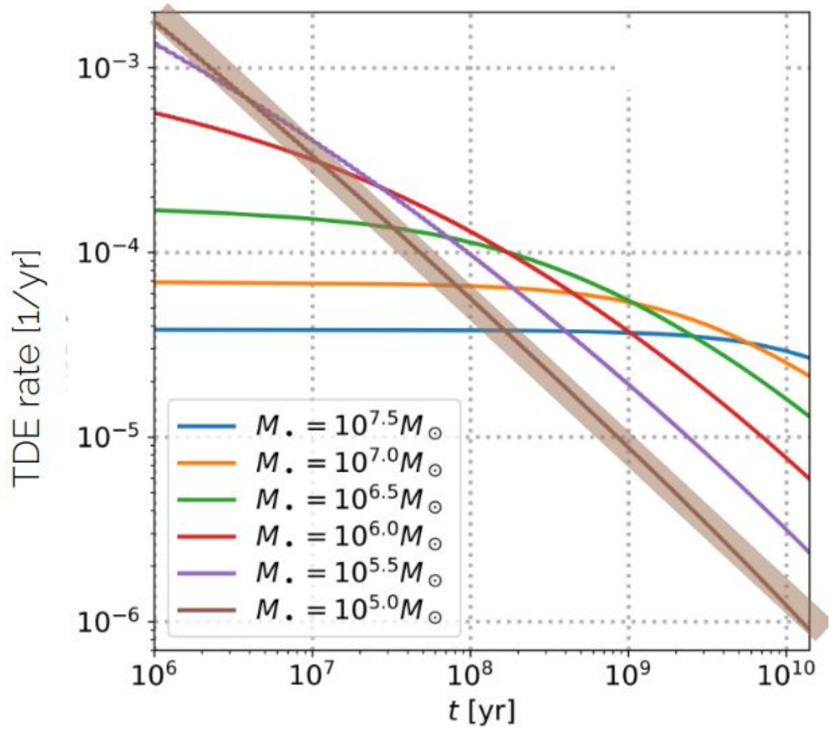
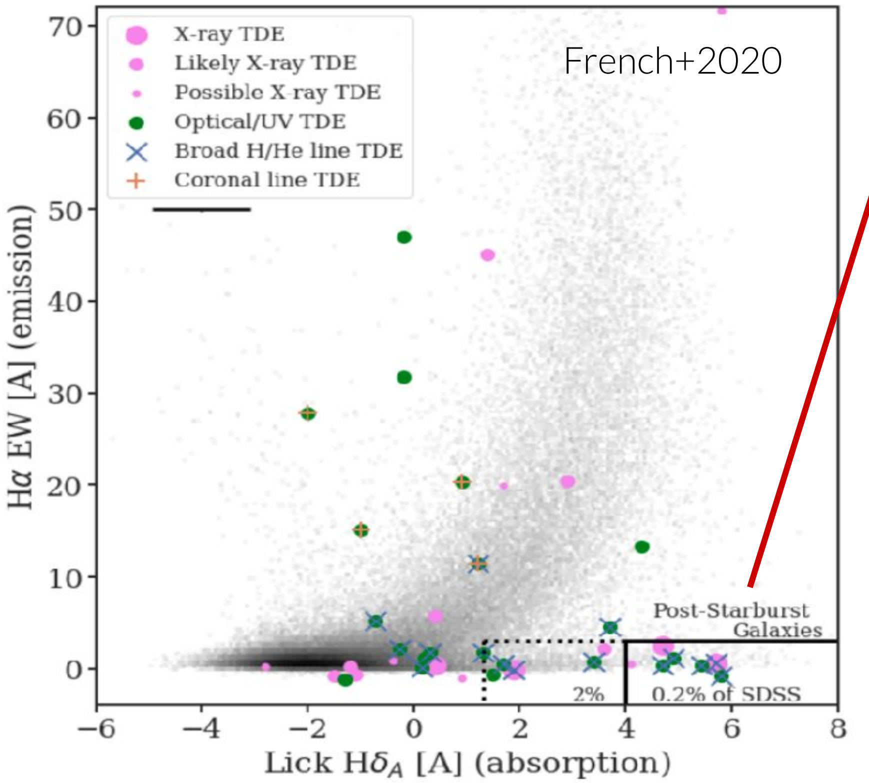


The event rate drops very quickly in time and very large event rates cannot be sustained for long

See Broggi, EB+2020 for time dependent rates of TDEs and EMRIs

Time-dependent rates & complete stellar mass function

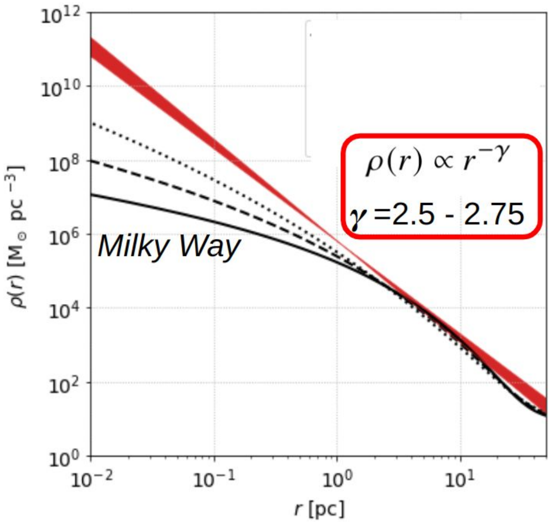
Time-dependent rates and post-starburst galaxies



TDEs are substantially overrepresented (~factor 20) in **post-starburst galaxies**: those have experienced a recent starburst (<1 Gyr old) that created >3% of their current stellar mass over 25-200 Myr

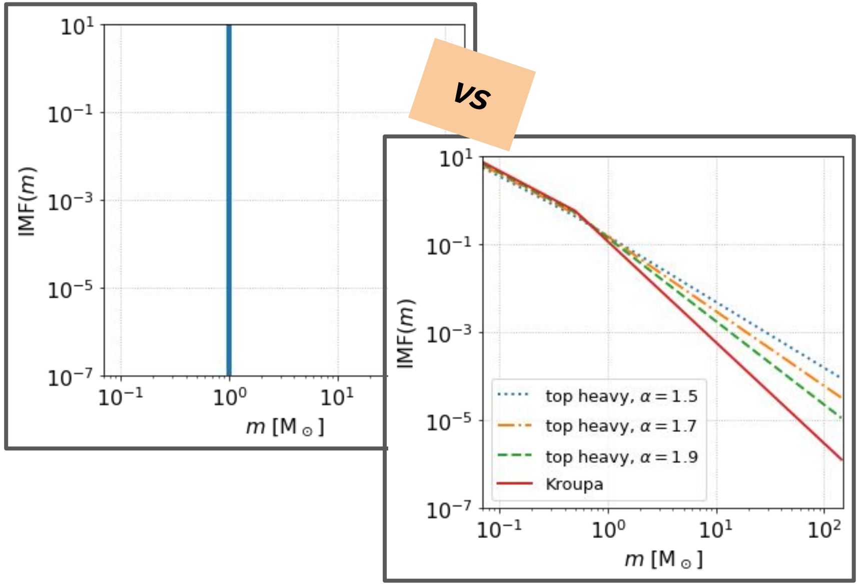
If starbursting galaxies yield very large central stellar densities *the poststarburst preference can be explained*

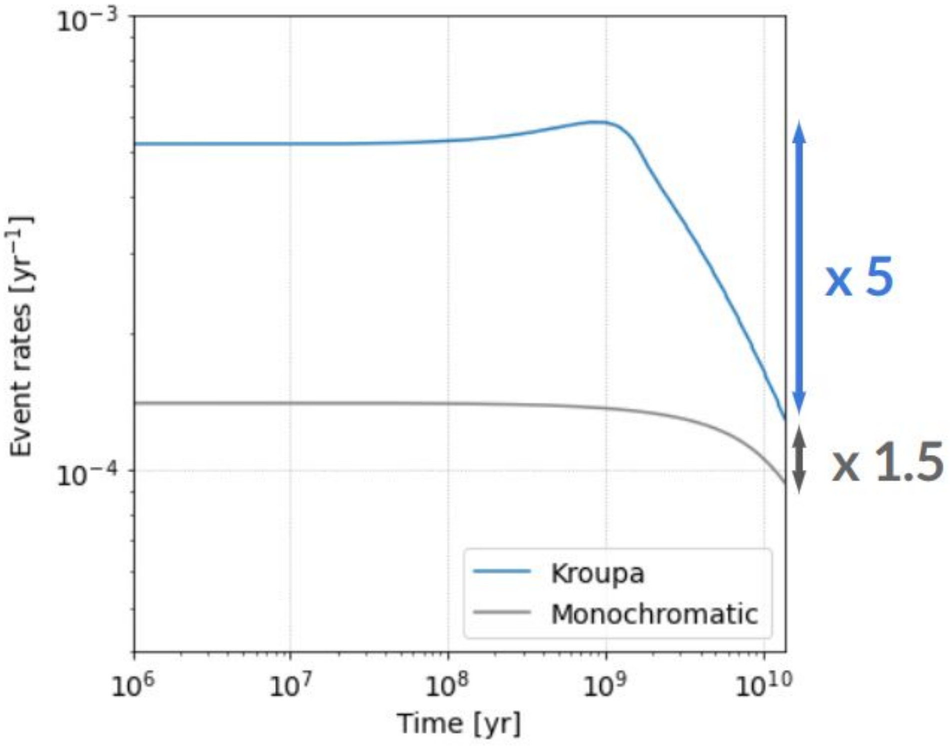
(Stone+17, Stone & Van Velzen16)



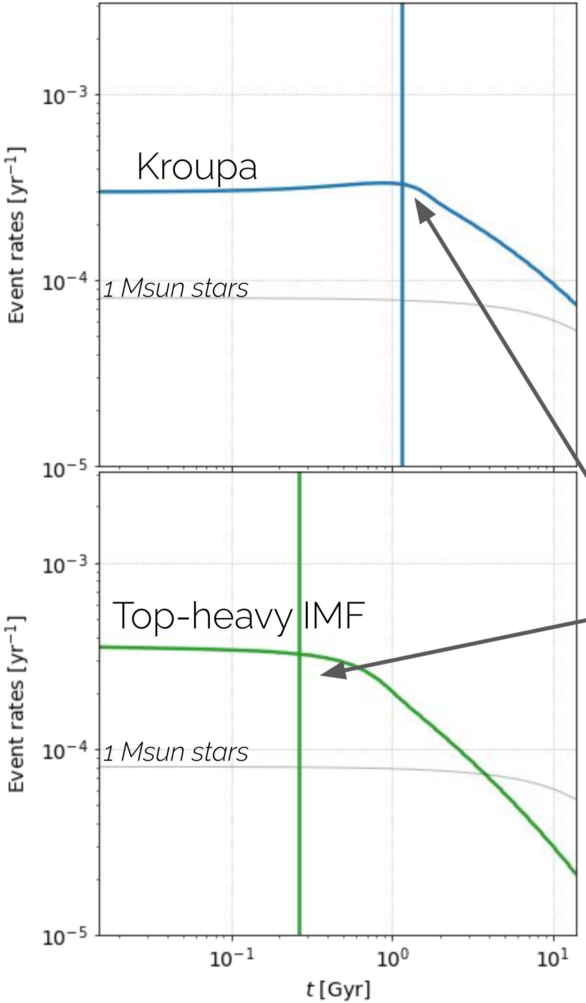
Time-dependent rates and post-starburst galaxies

The importance of time evolution and of **accounting for a complete stellar mass function**





Bortolas 2022, MNRAS 511, 2885

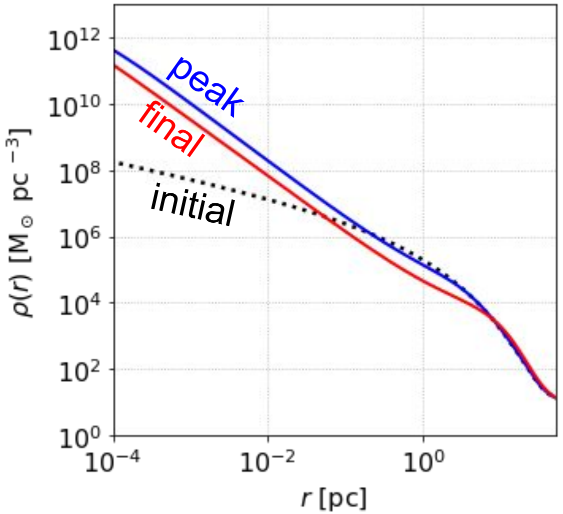


Time-dependent rates and post-starburst galaxies

Mass segregation and the related efficient relaxation **is the driver for the initial TDE burst**

At later times, **the system reaches an equilibrium and relaxes (expands) in time** → rate drop

$$t_{\text{mass segr.}} \approx \frac{0.0814 v_{\text{rms}}^3}{G^2 \tilde{m}_\star \rho_\star \ln \Lambda}$$



General and more realistic explanation of the post-starburst galaxies

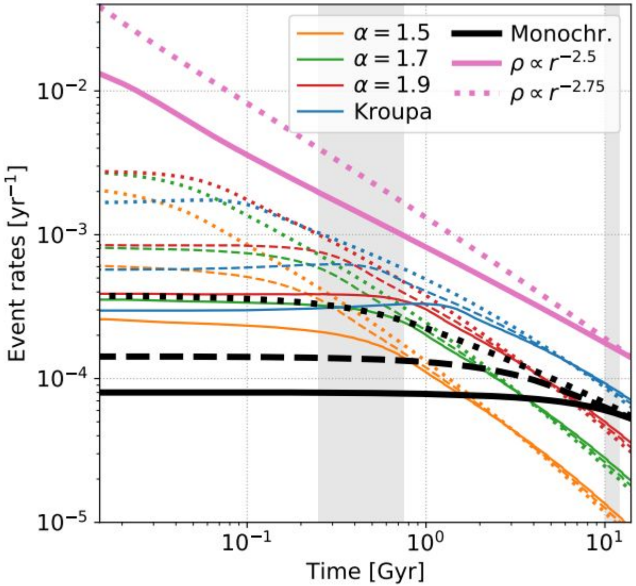
Bortolas 2022, MNRAS 511, 2885

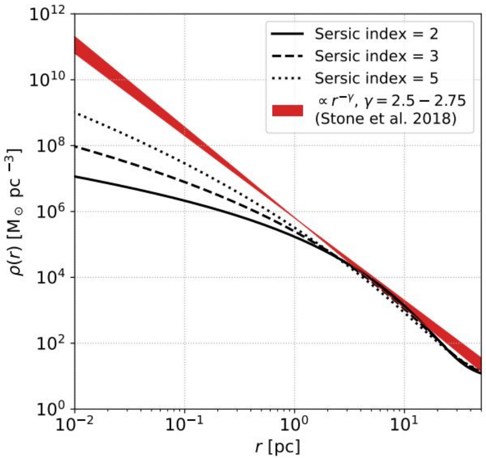
Time-dependent rates and post-starburst galaxies

Rate drop

- beginning to end is ~10–300
- between 250 Myr and 10 Gyr is 5–25

Rate drop in the equivalent ultrasteep cusp proposed by Stone+18 is about 8 – 14



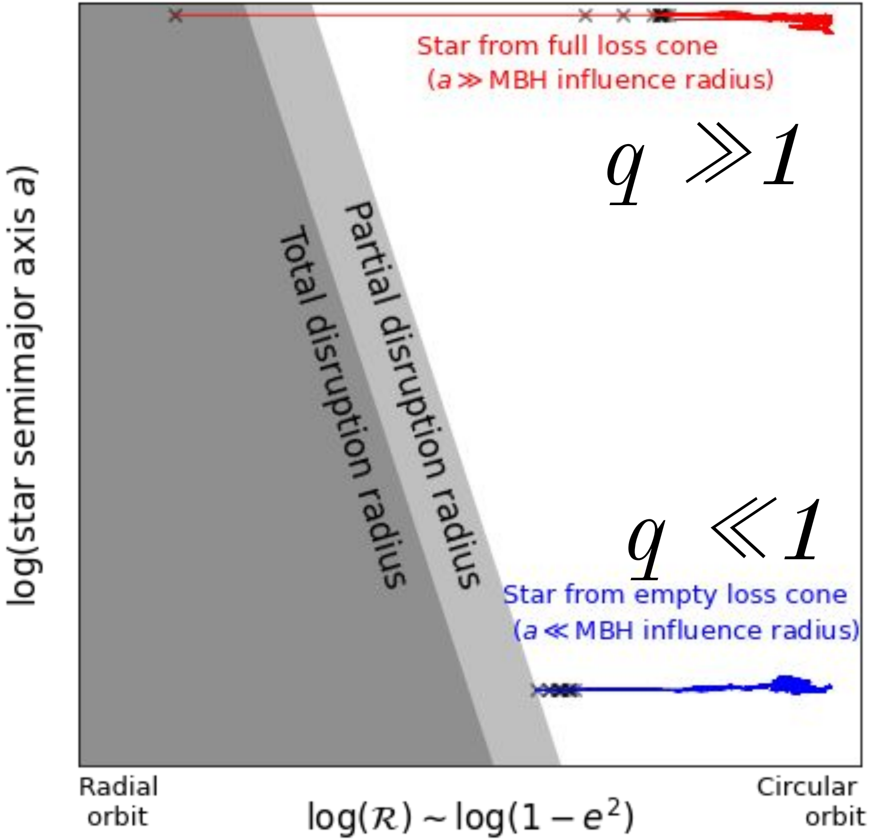


Adopting a complete stellar mass function and evolving TDE rates in time can reconcile predicted and observed rates

Bortolas 2022, MNRAS 511, 2885

Accounting for partial TDEs

Estimating the rates of partial TDEs



Stars have a nearly <u>uniform</u> probability of being disrupted at each $r<r_t$ ($N(\beta)d\beta \propto \beta^{-2}d\beta$)

Partial disruptions cannot repeat

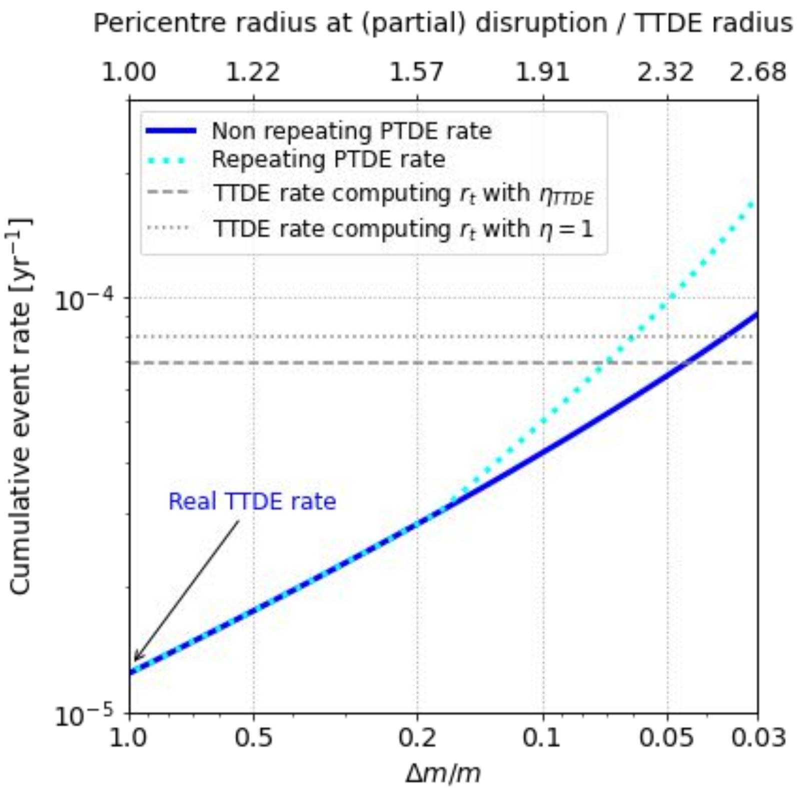
$$q = \frac{\textit{orbital time}}{\textit{relaxation time for an orbit near the loss cone}}$$

Stars can only get disrupted at the largest available r_t ($N(\beta)d\beta \propto \delta(\beta_{MIN})$)

Partial disruptions can repeat

IN THIS LIMIT, ALL TDES ARE PARTIAL!

Estimating the rates of partial TDEs



$$q \ll 1$$

Milky-way like galaxy with a high central density (**features a nuclear star cluster**)

Most of the events come from $q \ll 1$

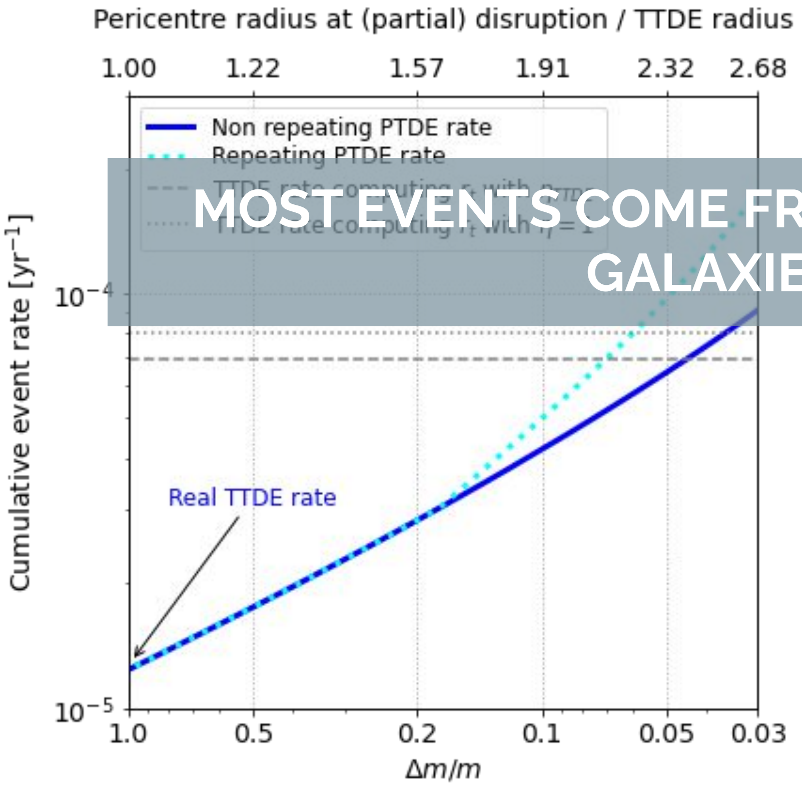
Many repeating partial disruptions (x2)

<u>Standard rates of total TDE rates are severely overestimated</u> (by ~ 1 order of magnitude)

Partial TDEs rates are about 10-20 times more abundant than total TDEs

Bortolas+ to be submitted

Estimating the rates of partial TDEs



$$q \ll 1$$

Milky-way like galaxy with a high central density (**features a nuclear star cluster**)

MOST EVENTS COME FROM THIS KIND OF GALAXIES!

Most of the events come from $q \ll 1$

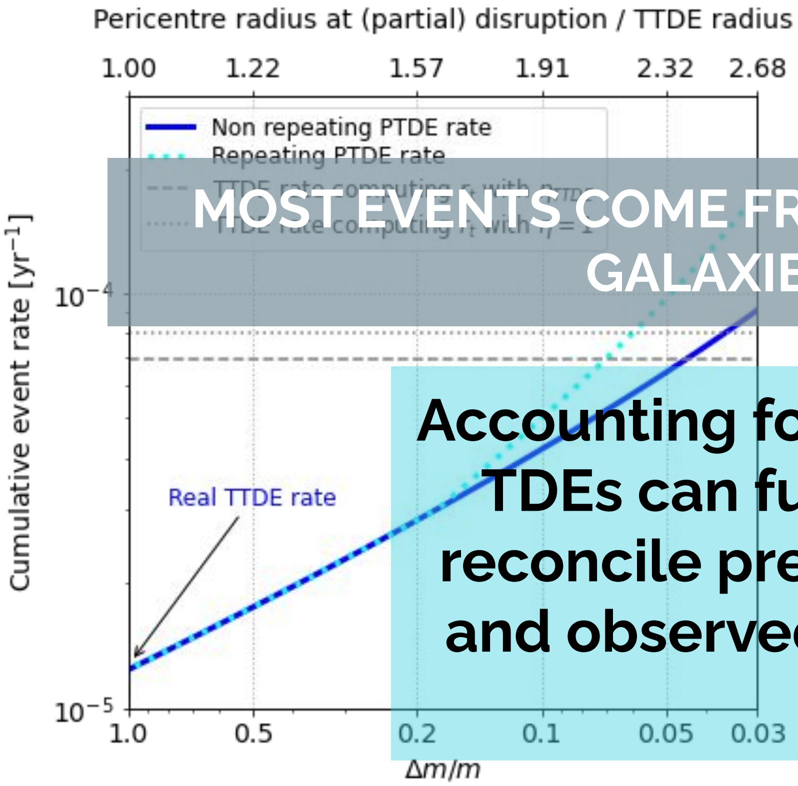
Many repeating partial disruptions (x2)

<u>Standard rates of total TDE rates are severely overestimated</u> (by ~ 1 order of magnitude)

Partial TDEs rates are about 10-20 times more abundant than total TDEs

Bortolas+ to be submitted

Estimating the rates of partial TDEs



$q \ll 1$

Milky-way like galaxy with a high central density (**features a nuclear star cluster**)

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Accounting for partial TDEs can further reconcile predicted and observed rates

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Take-home messages

- TDEs are amazing multimessenger sources (EM, GW, ν)
- TDEs can be used to constrain the low-mass end of the MBH mass function to make solid predictions for LGWA
- Properly assessing TDE rates is fundamental to eventually constrain the MBH mass function; this requires, among others
    - To constrain the stellar density profile within the MBH influence radius
    - To evolve the system in time (non-instantaneous rates)
    - To account for a complete stellar mass function
    - To account for partial TDEs (~neglected so far!)