Gravitational wave signal from mass transferring star-supermassive black hole systems

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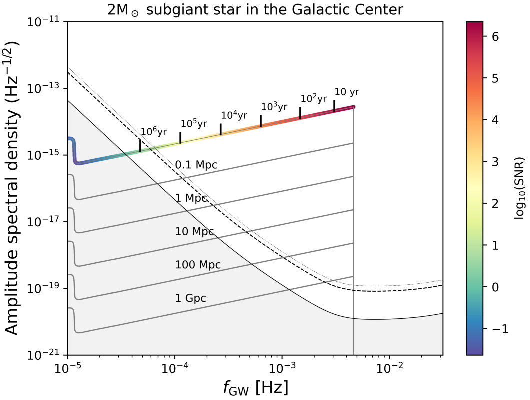
Motivation

Possible long-lasting, bright GW sources in the LISA band!

Local Universe: $\approx$ 10 events; **Galactic Center:** $\approx$ 0.1%



Olejak et al. in prep.

System formation. Rate $\approx 10^{-6}\text{yr}^{-1}$ per galaxy

Galactic center → very dense stellar environment (10^7 stars per cubic parsec!) → dynamical interactions are important. As well as GWs...

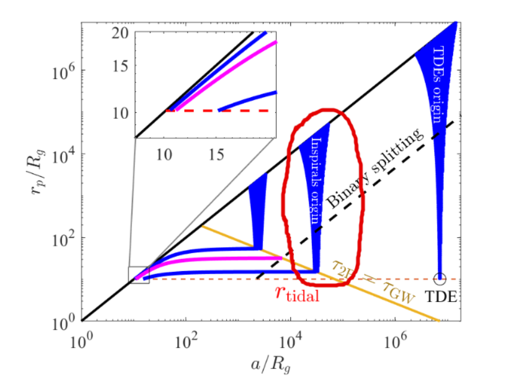


Fig: Linial, I. & Sari, R. 2023

Stable or unstable mass transfer?

Stability of mass transfer (MT) is determined by:

- **orbital evolution due to MT and GW:**
  MT conservative (mass + AM) → orbital widening due to MT + shrink due to GW → more stable MT (rather unrealistic assumption).

$$\dot{a} = \dot{a}_{\rm MT} + \dot{a}_{\rm GW} = 2a\dot{M}_{\rm don}\left(\frac{M_{\rm don} - M_{\rm acc}}{M_{\rm acc}M_{\rm don}}\right) - \frac{64}{5}\frac{G^3\mu M^2}{c^5 a^3}$$

  Probably more realistic: AM doesn't go back to the orbit → orbit only shrinks due to GW → makes MT more unstable

- **stellar structure and radius response to mass transfer**:
  strongly depends on the mass and evolutionary stage (convective, non-convective but also expansion → distance to SMBH).

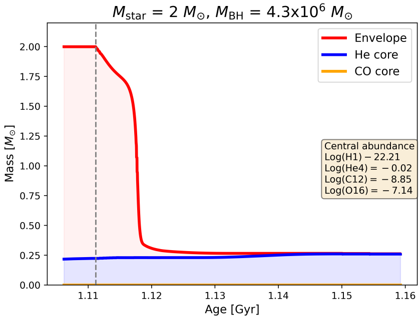
Motivation: stable or unstable mass transfer?

- **Unstable mass transfer:**
  possible candidate for QPEs - high MT rates required (see e.g. Linial & Sari 2023 or Linial & Quataert 2024, Wang et al. 2024, and others)
- **Stable mass transfer:**
  fuel to the AGN central engine - each star $\sim 10^{-7} - 10^{-4} M_{\odot}/yr$ (e.g. Hameury et al. 1994) . Possibly a powerful and long-lasting source of GW emission in the LISA band. The main interest of this talk!

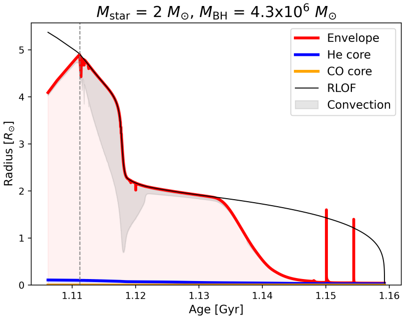
MESA

Paxton et al. 2011, 2013, 2015, 2018, 2019, Jermyn et al. 2023

Subgiant - long stable mass transfer case



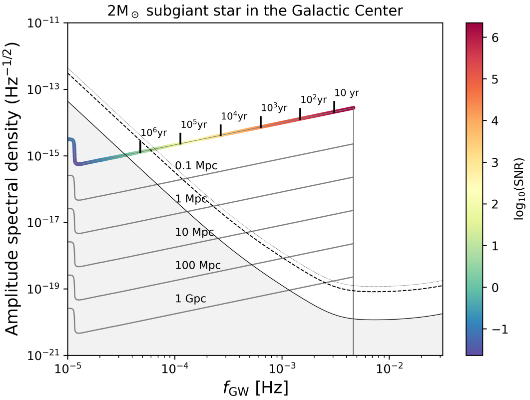
Mass evolution - a case of $2M_\odot$ subgiant (using MESA). Olejak et al. in prep.



Radius evolution - a case of $2M_\odot$ subgiant (using MESA). Olejak et al. in prep.

Gravitational wave signal in the LISA band

$$h = \frac{8T^{1/2}(GM_c/c^3)^{5/3}\pi^{2/3}f^{2/3}}{5^{1/2}D_L/c} \propto M_c^{5/3}f^{2/3}{D_L}^{-1} \text{ (Robson et al. 2019)}$$



Olejak et al. in prep.

$\sim 10^4$ galaxies per 100 Mpc^{-3}, $\sim 10^7 - 10^8$ galaxies per 1 Gpc^{-3}

Event rates:

- formation rate per galaxy: $\sim 10^{-6}$-10^{-5} yr^{-1} $\times 1/R_*$
- duration few $\times\ 10^5$ yr^{-1} with evolving SNR(t)
- detectable from distance up to ~ 100 Mpc - 1 Gpc
- fraction of subgiants $\approx 3\%$

$$R_{\text{event}} \approx N_{\text{gal}} \times t_{\text{dur}} \times R_{\text{form}} \times f_{\text{sub}}$$

Number of LISA sources (optimistic):

Local Universe: 10^8 x 10 yr x 10^{-7} yr^{-1} x $f_{\text{sub}} \approx$ 1-10

Galactic Center: 2×10^5 yr x 10^{-7} yr^{-1} x $f_{\text{sub}} \approx$ 0.001

QPEs vs EMRIs?

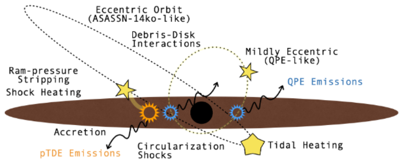
Quasi-periodic eruptions (QPE):

TDE + star-disk interactions

Article | Open access | Published: 09 October 2024

Quasi-periodic X-ray eruptions years after a nearby tidal disruption event

M. Nicholl, D. R. Pasham, A. Mummery, M. Guolo, K. Gendreau, G. C. Dewangan, E. C. Ferrara, R. Remillard, C. Bonnerot, J. Chakraborty, A. Hajela, V. S. Dhillon, A. F. Gillan, J. Greenwood, M. E. Huber, A. Janiuk, G. Salvesen, S. van Velzen, A. Aamer, K. D. Alexander, C. R. Angus, Z. Arzoumanian, K. Auchettl, E. Berger, … D. R. Young + Show authors



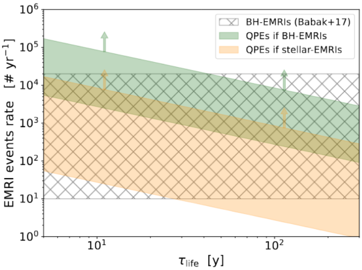
Possible QPE schema. Yao, P. et al. 2024

If QPEs = EMRIs

The first lower limit on QPE rate:

$R_{\rm vol} = 0.60^{+4.73}_{-0.43} \times 10^{-6}$ Mpc^{-3}

by Arcodia, R. et al 2024



EMRI rates ($z = 1$) based on QPEs volumetric rate. Arcodia, R. et al 2024.

Conclusions

- Stars transferring mass on SMBH could be stable for a long time $\sim 10^6$ yr.
- Such systems could be very bright and long-lasting LISA sources.
- In optimistic estimates, 1–10 events caused only by subgiants will be detectable by LISA.
- 0.1 % chance of having it in our Galactic Center.
- Stars near SMBH can be multimessenger sources: EM+GW.

Some characteristic values:

The case of main sequence, $M_\star = 1 M_\odot$, $M_{\rm SMBH} = 4.3 \cdot 10^6 M_\odot$:

- Separation: $a_{\rm RLOF} = R_\star [\frac{0.49 \cdot q^{2/3}}{0.6 \cdot q^{2/3} + \log(1+q^{1/3})}]^{-1} \approx 330 R_\odot$.
- $R_g = 2GM/c^2 \approx 18 R_\odot$. So $a_{\rm RLOF}/R_g \approx 18$.
- Orbital period: $P \approx 0.34$ days. Corresponding to $f_{\rm GW} \approx 10^{-5}$Hz (LISA)