32nd Texas Symposium on Relativistic Astrophysics
Dec 11–15, 2023

Distortion of GW signals by astrophysical environments

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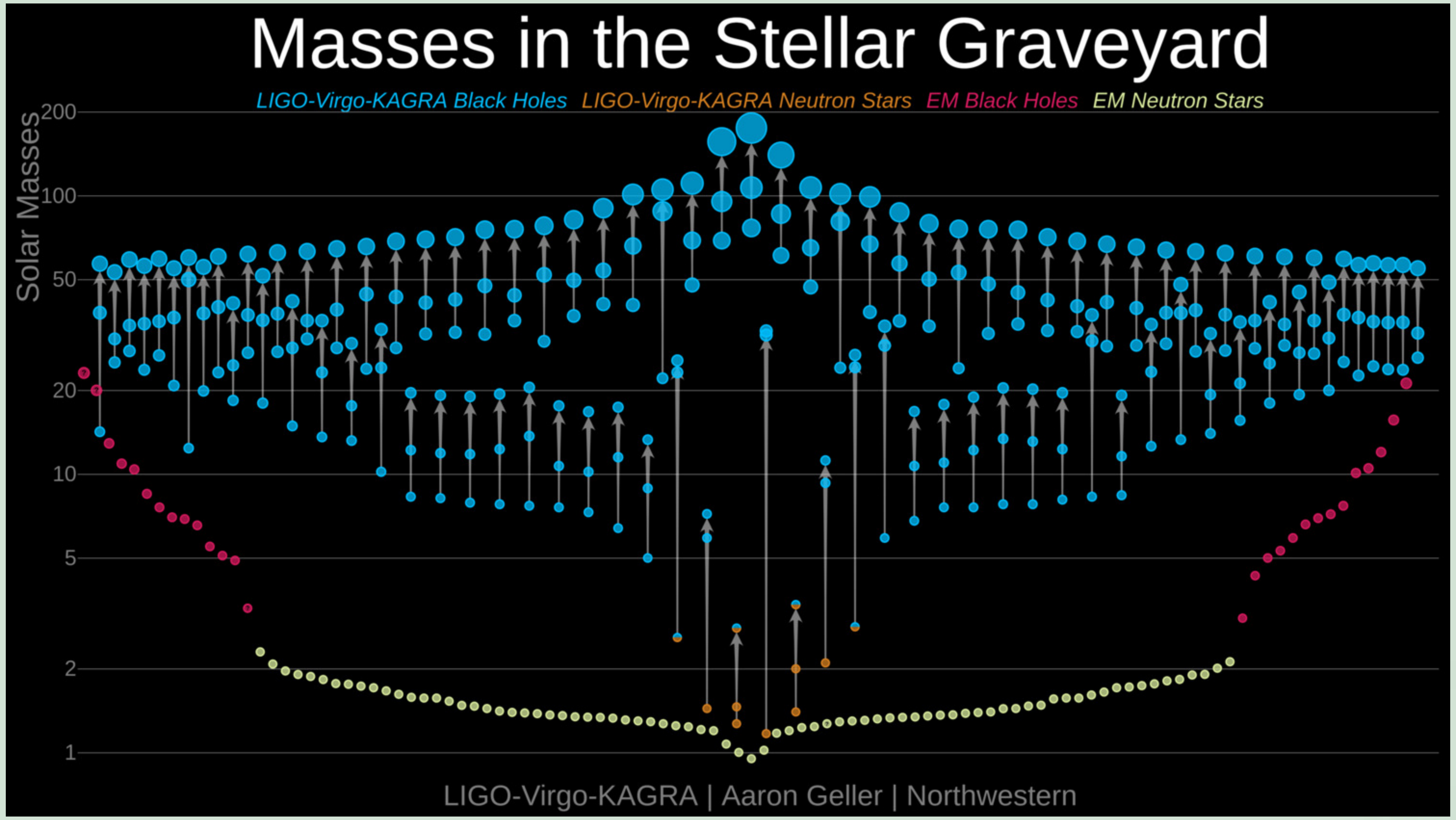
Massive black holes detected by LIGO/Virgo

～90 GW BBHs 3-10 times more massive than X-ray BHs



(See arXiv:1602.03846; 1811.12940; 2009.01190 from LIGO/Virgo collaboration for reviews of formation channels)

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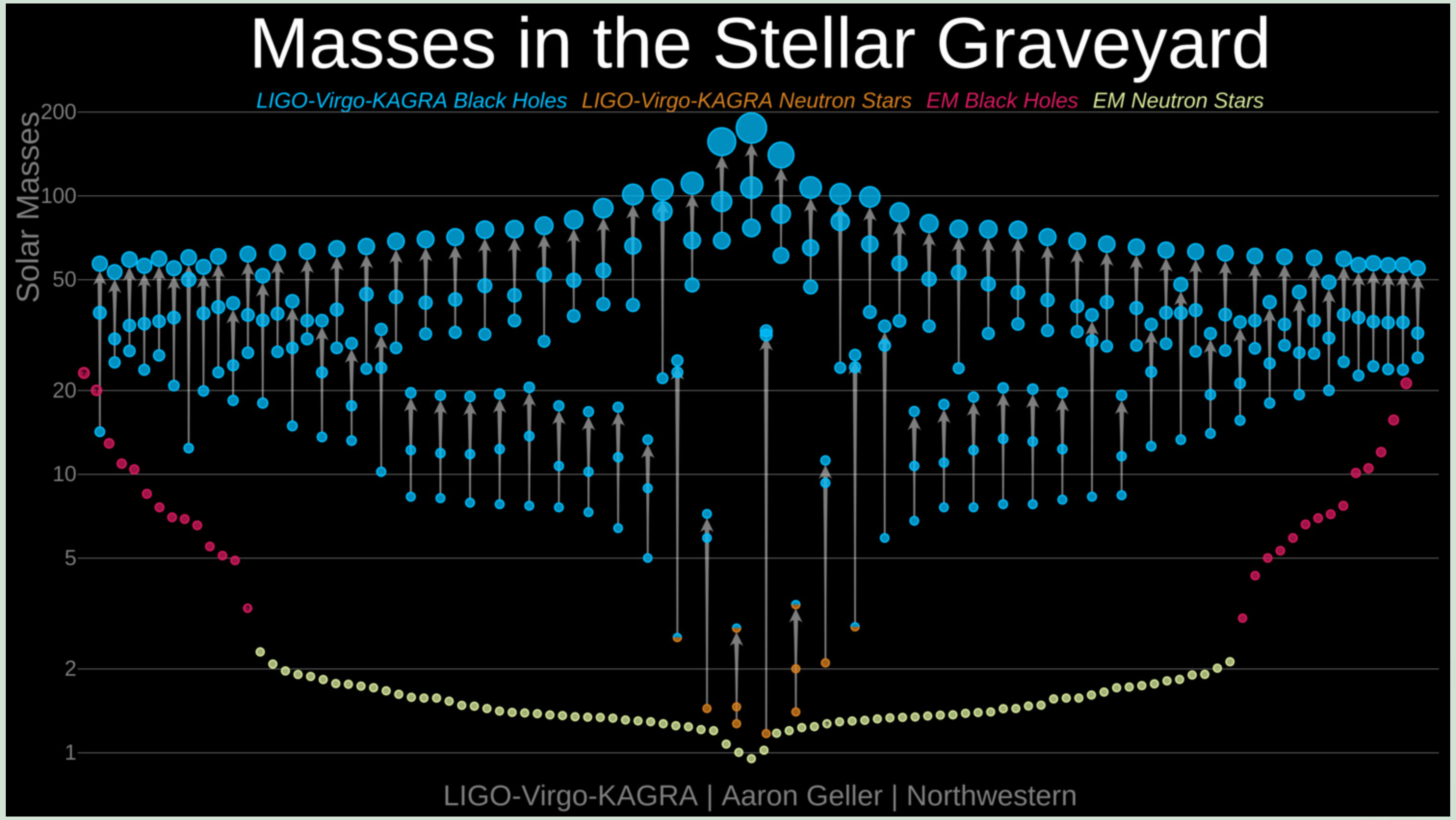

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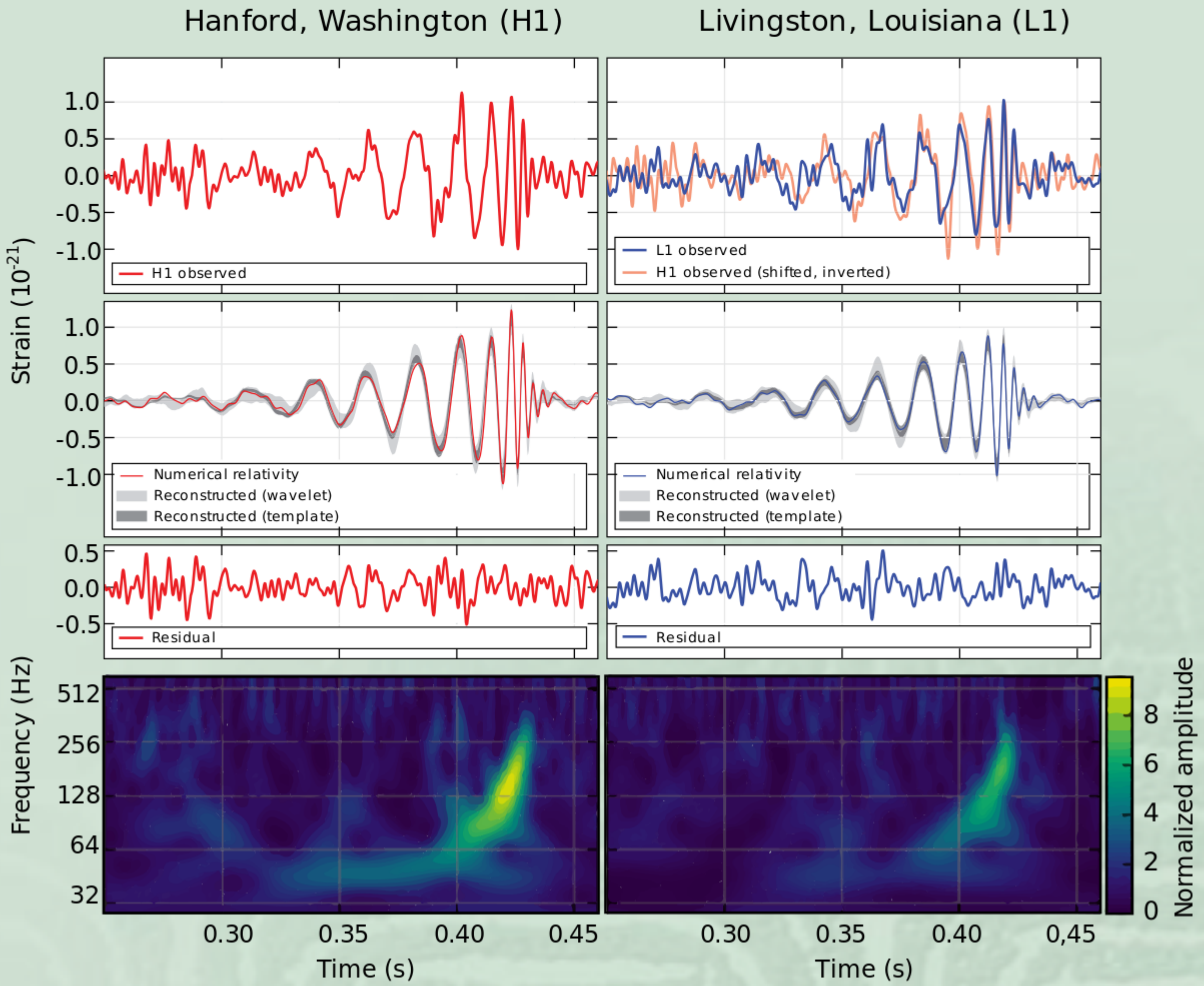

How is mass mesasured: Observe the chirp

(Abbott et al. 2016 PRL)

- $h(m1, m2, a)$
- $f(m1, m2, a)$
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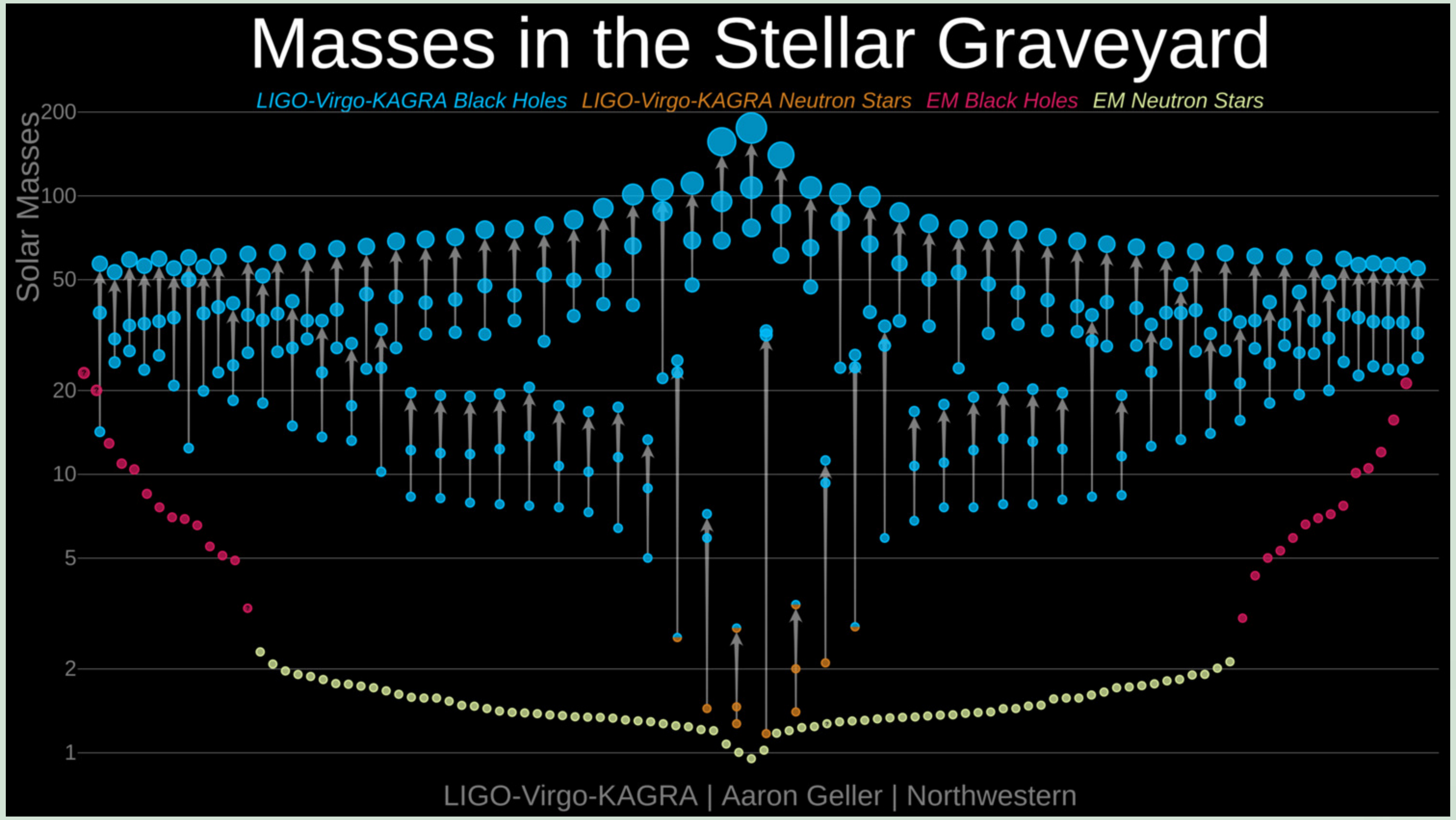

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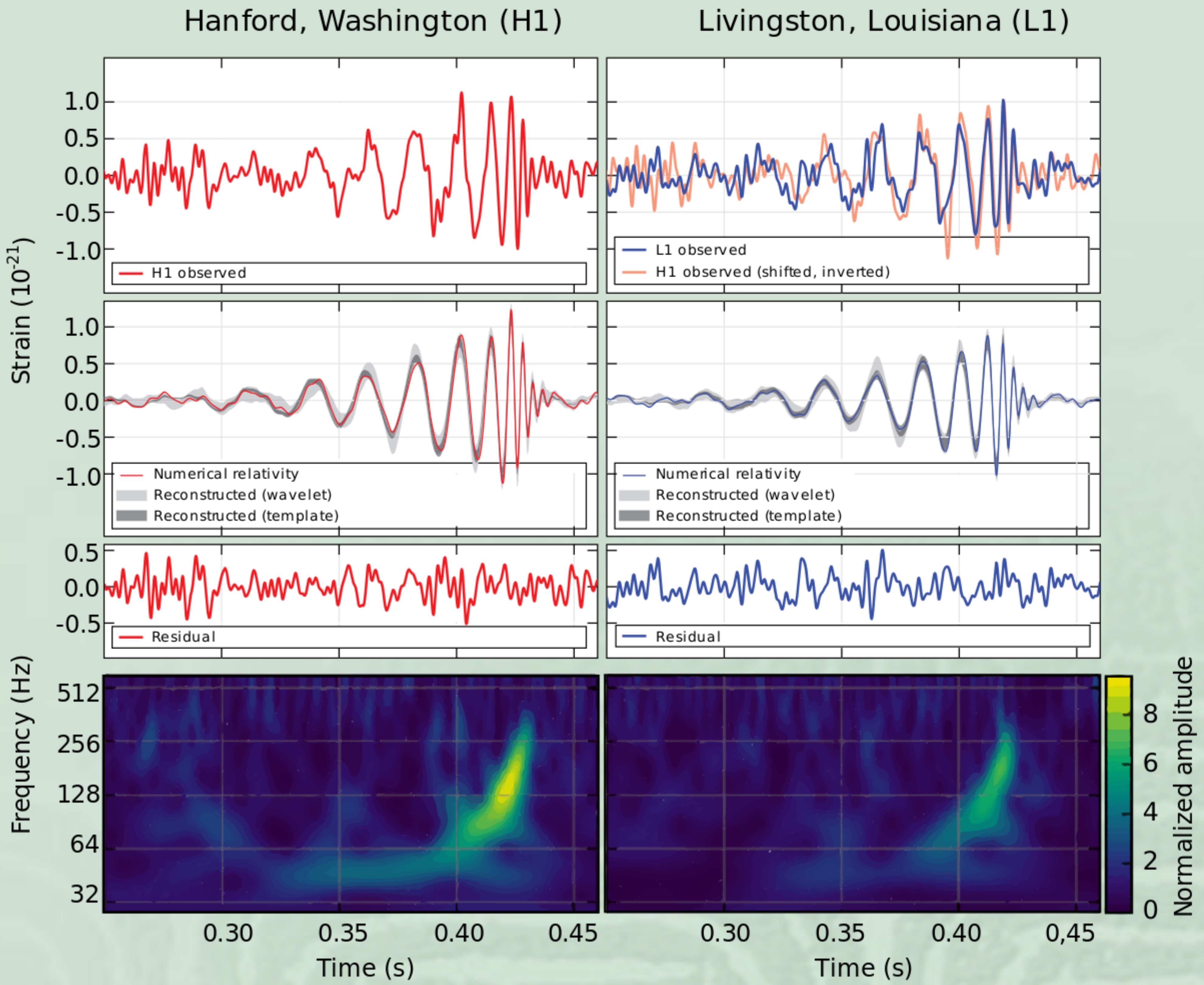

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Isolated in vacuum

- *h*(*m*1, *m*2, *a*)
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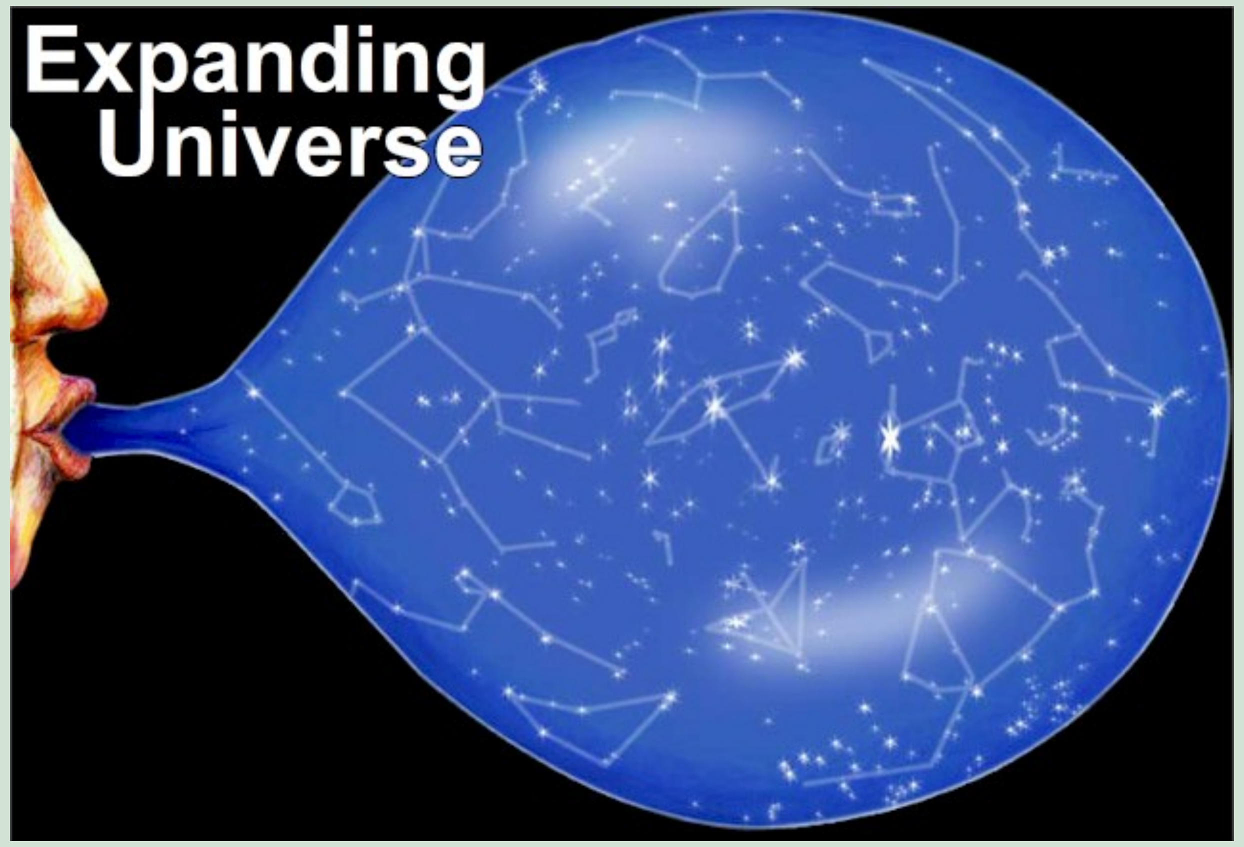
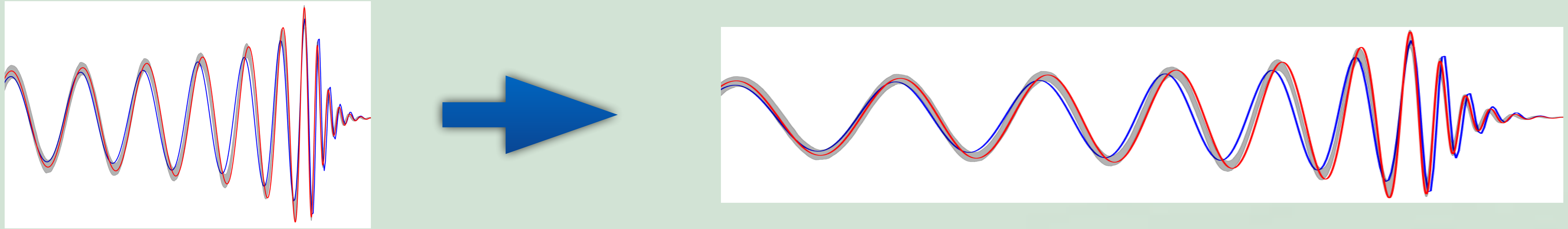
- *df*/*dt* (m1, m2, a)

Mass-redshift degeneracy





Cosmological redshift

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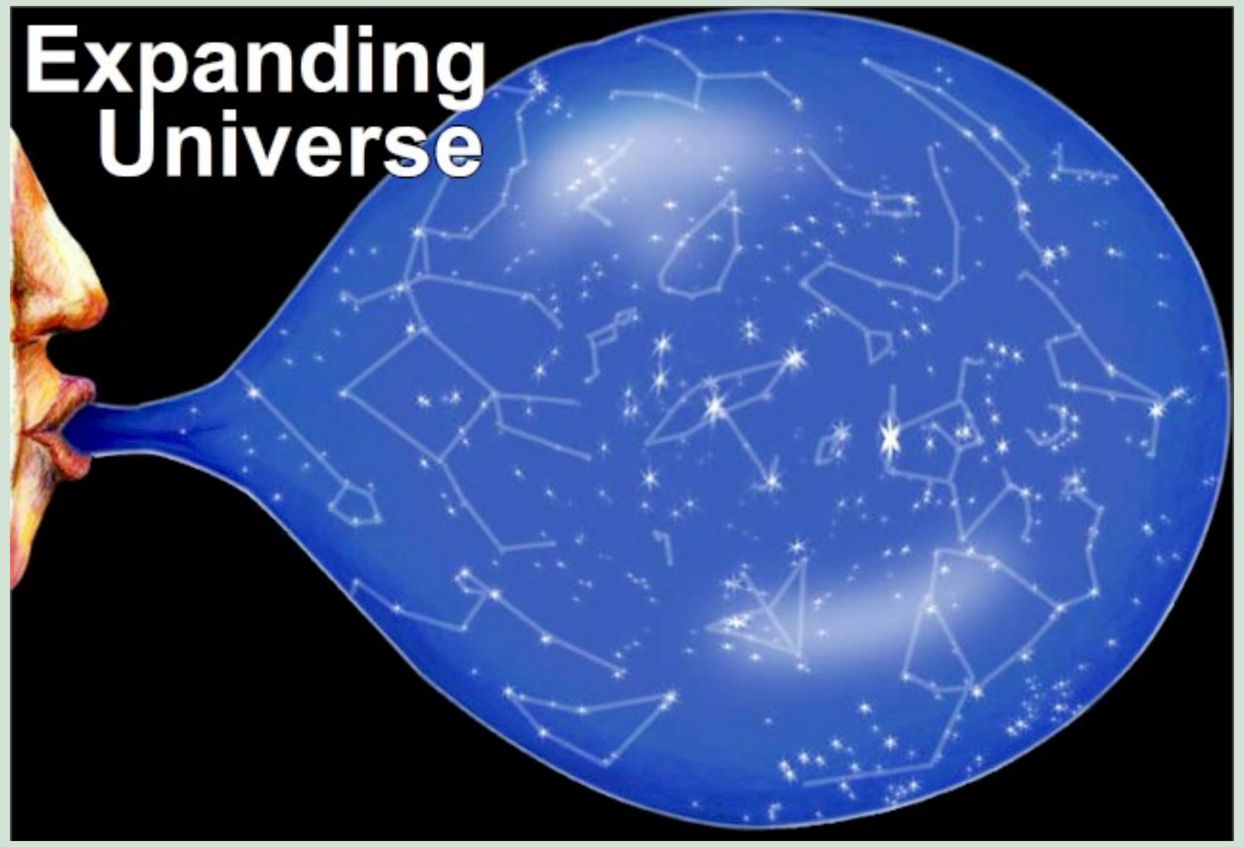

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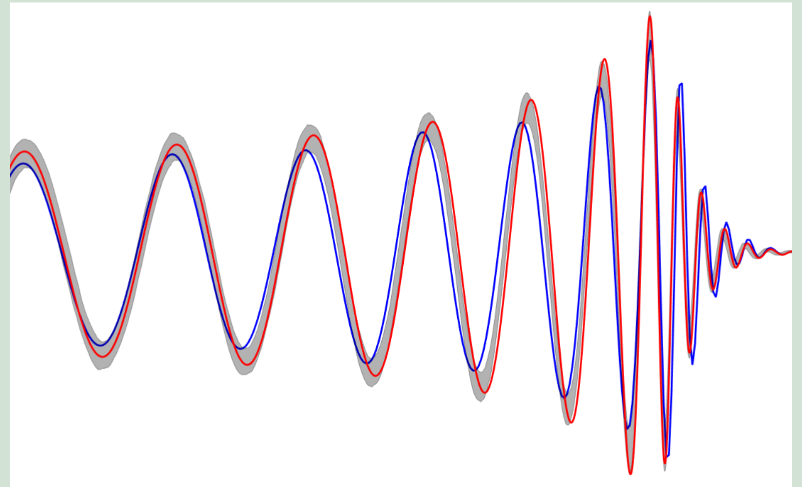

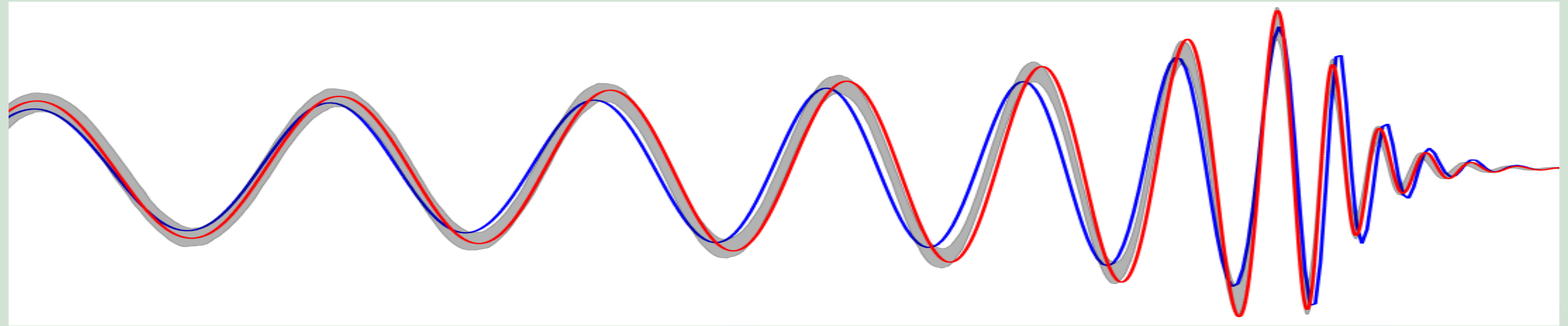

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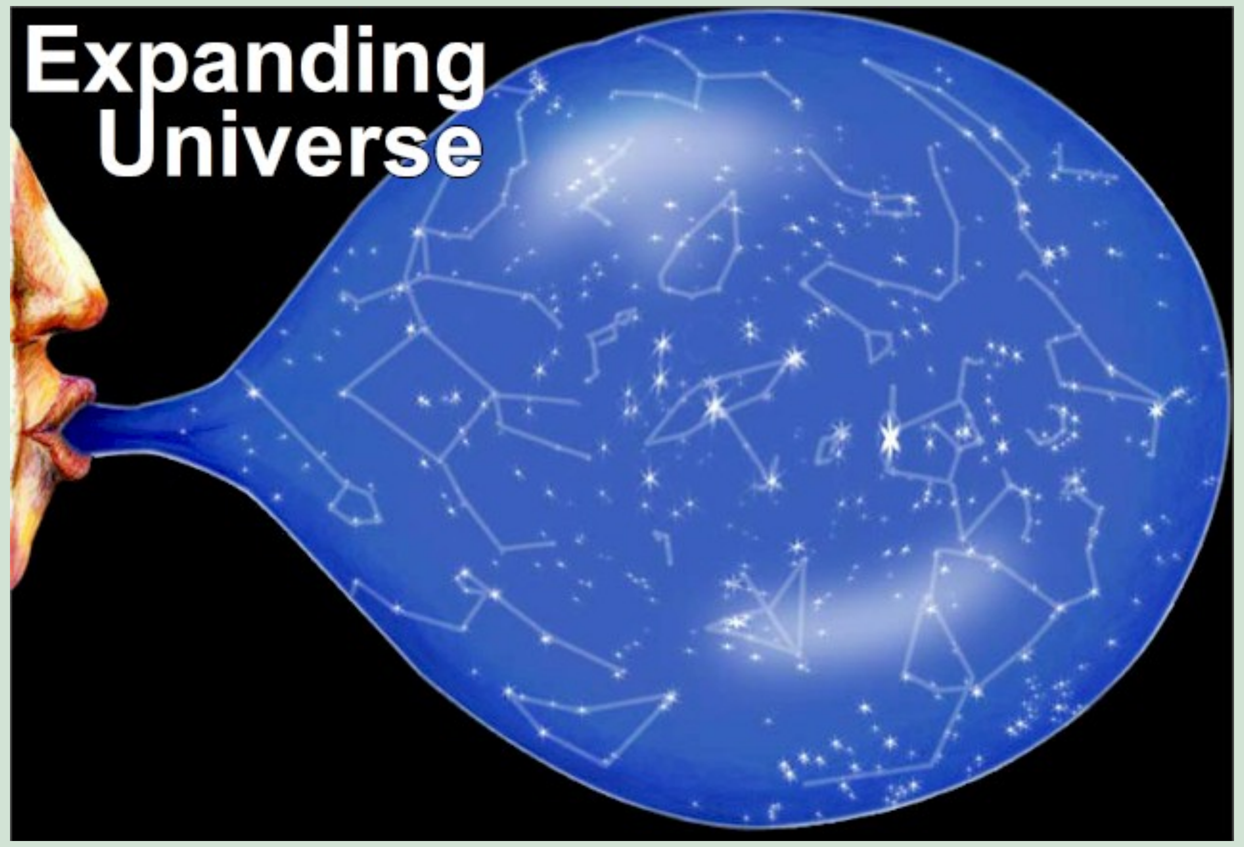

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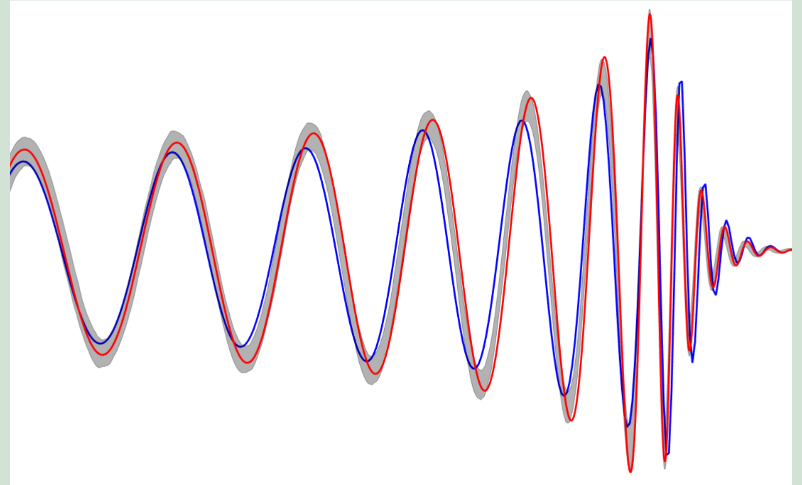

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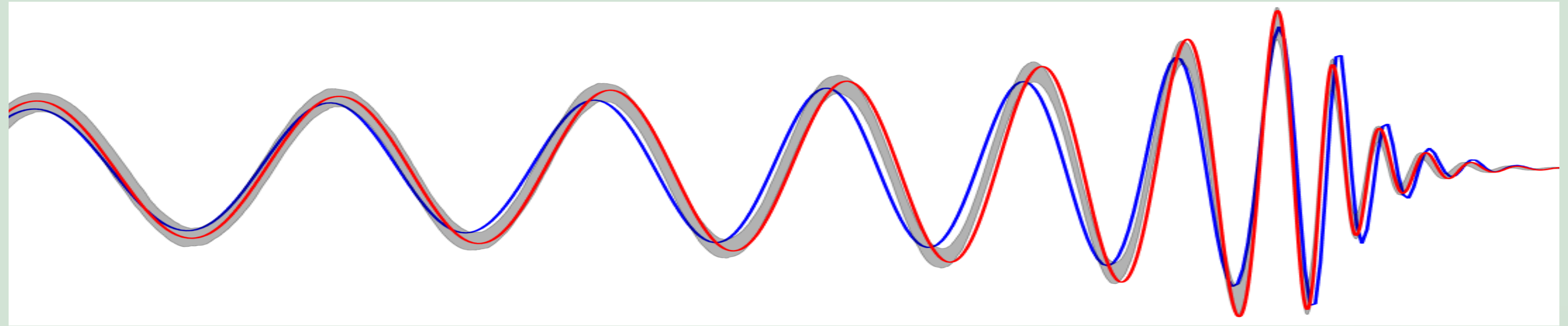

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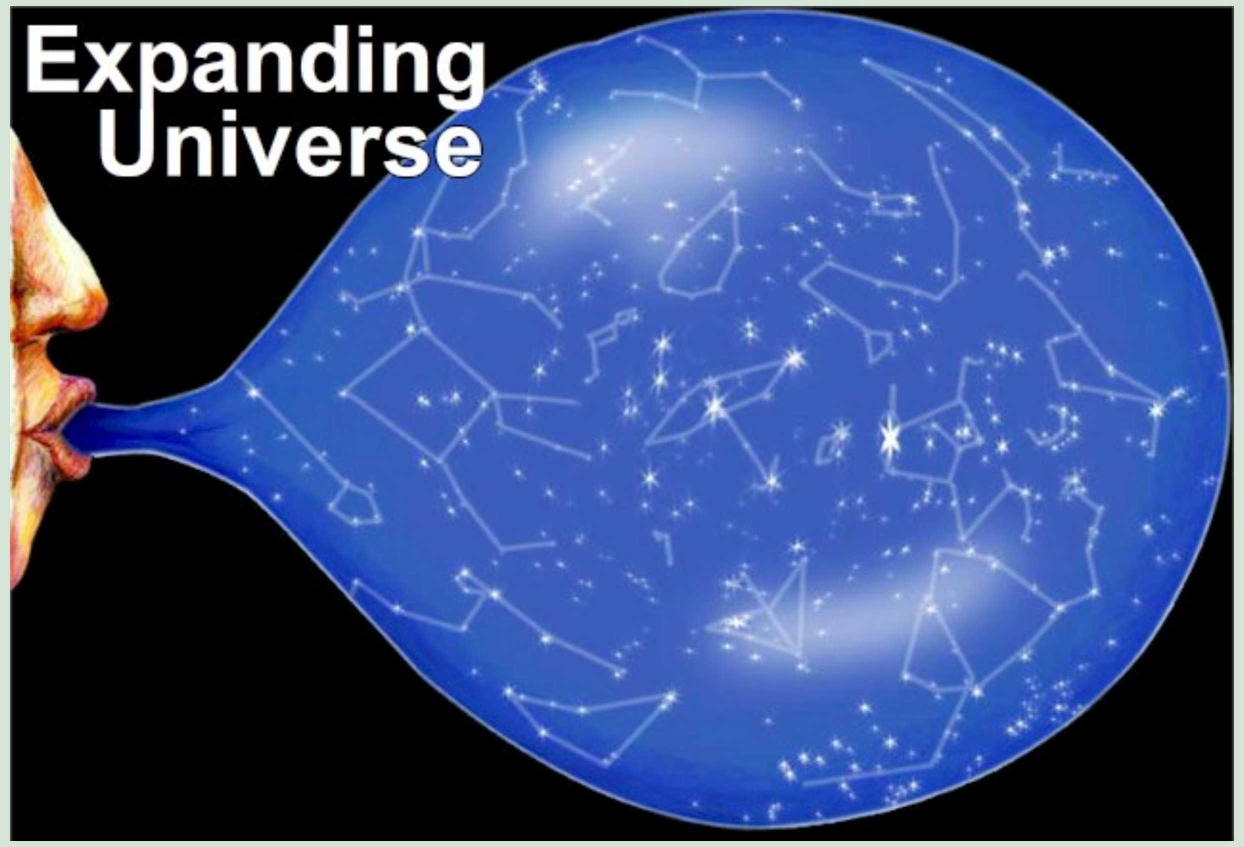

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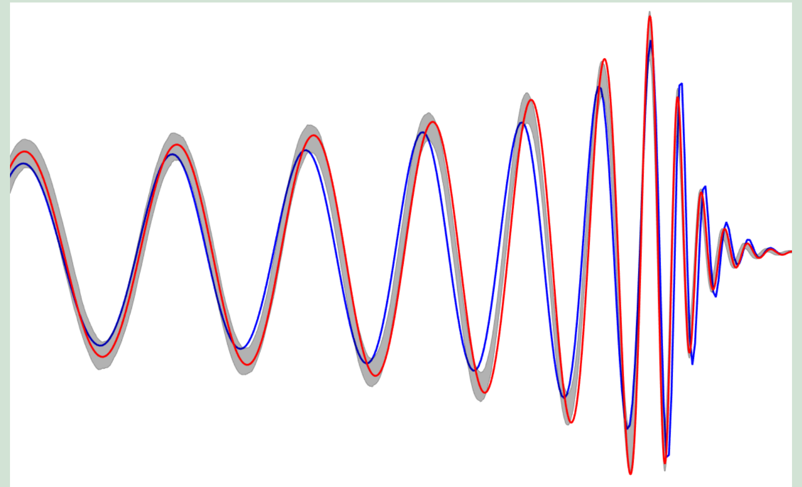

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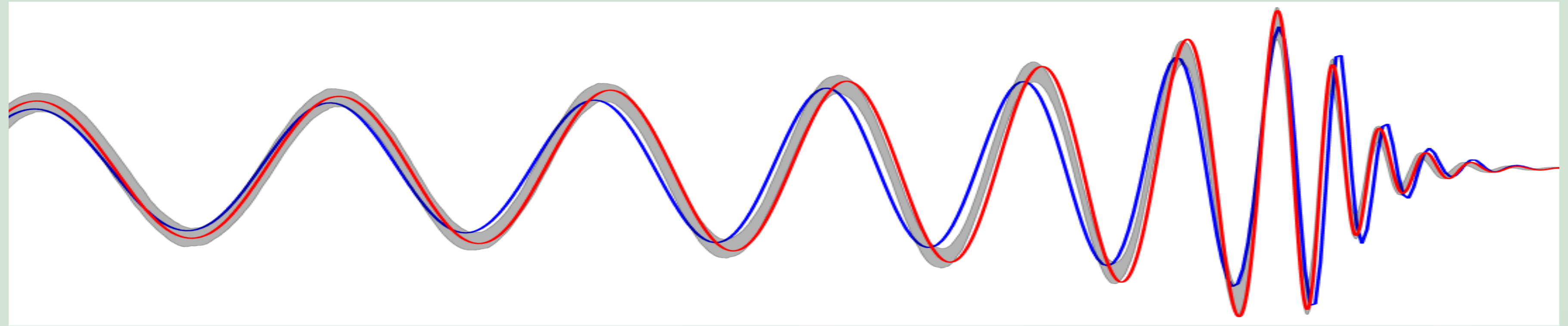

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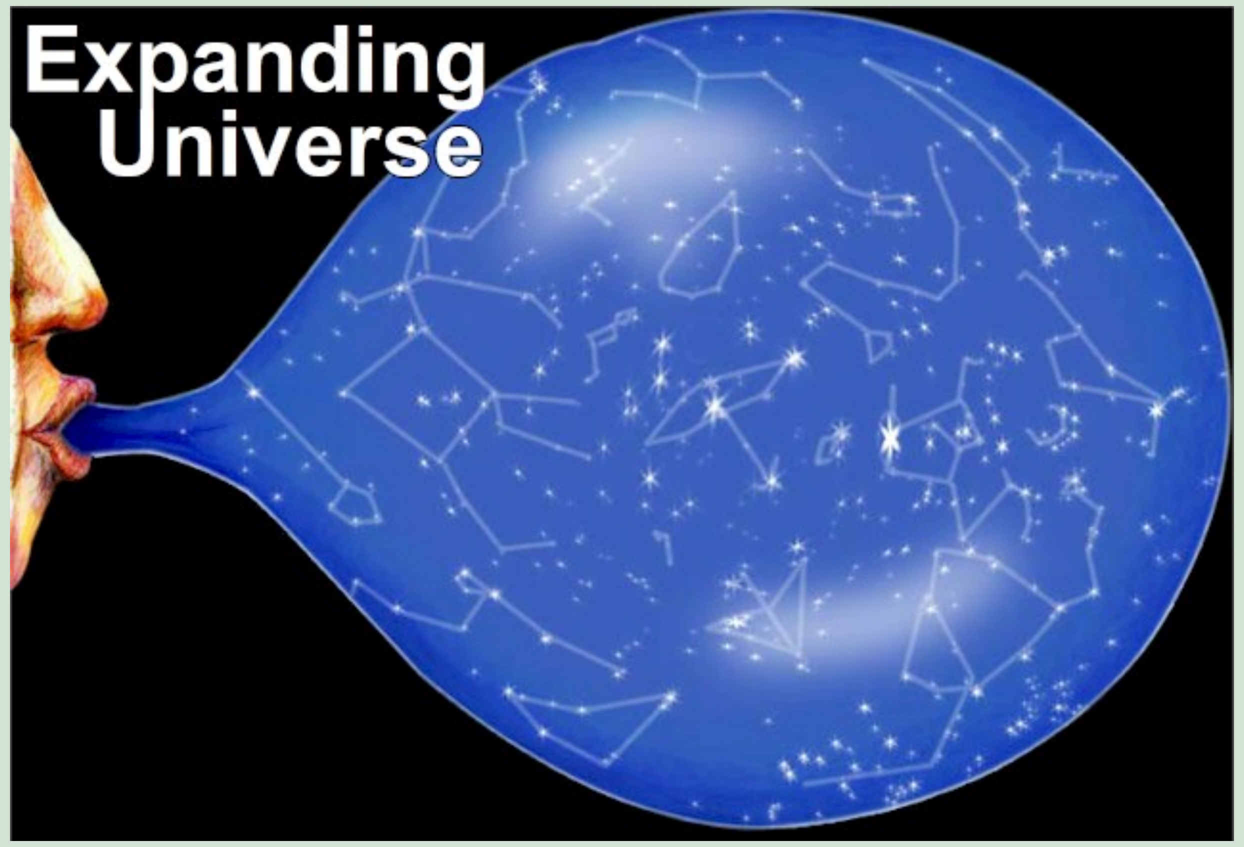

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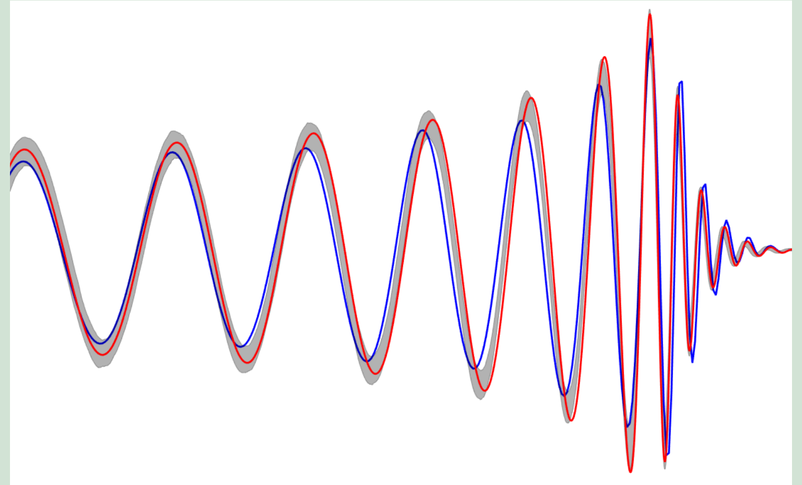

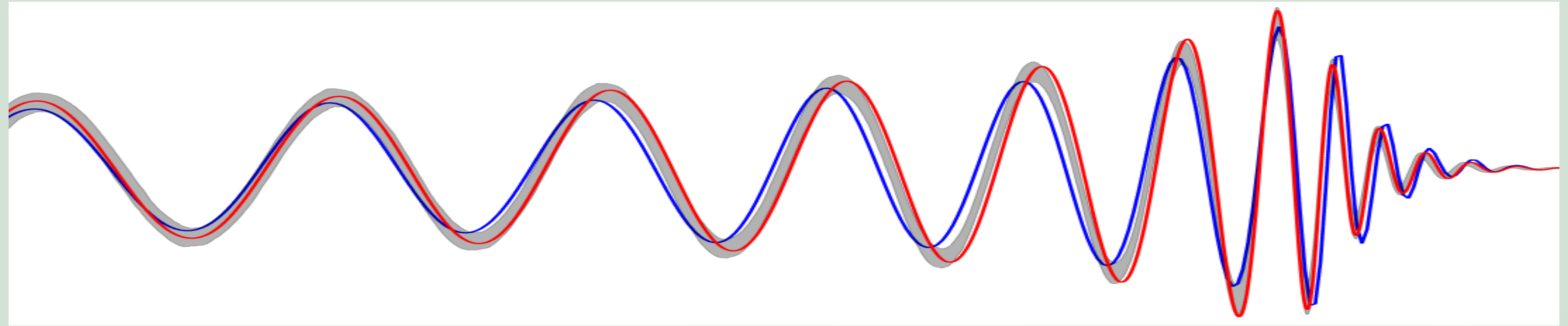

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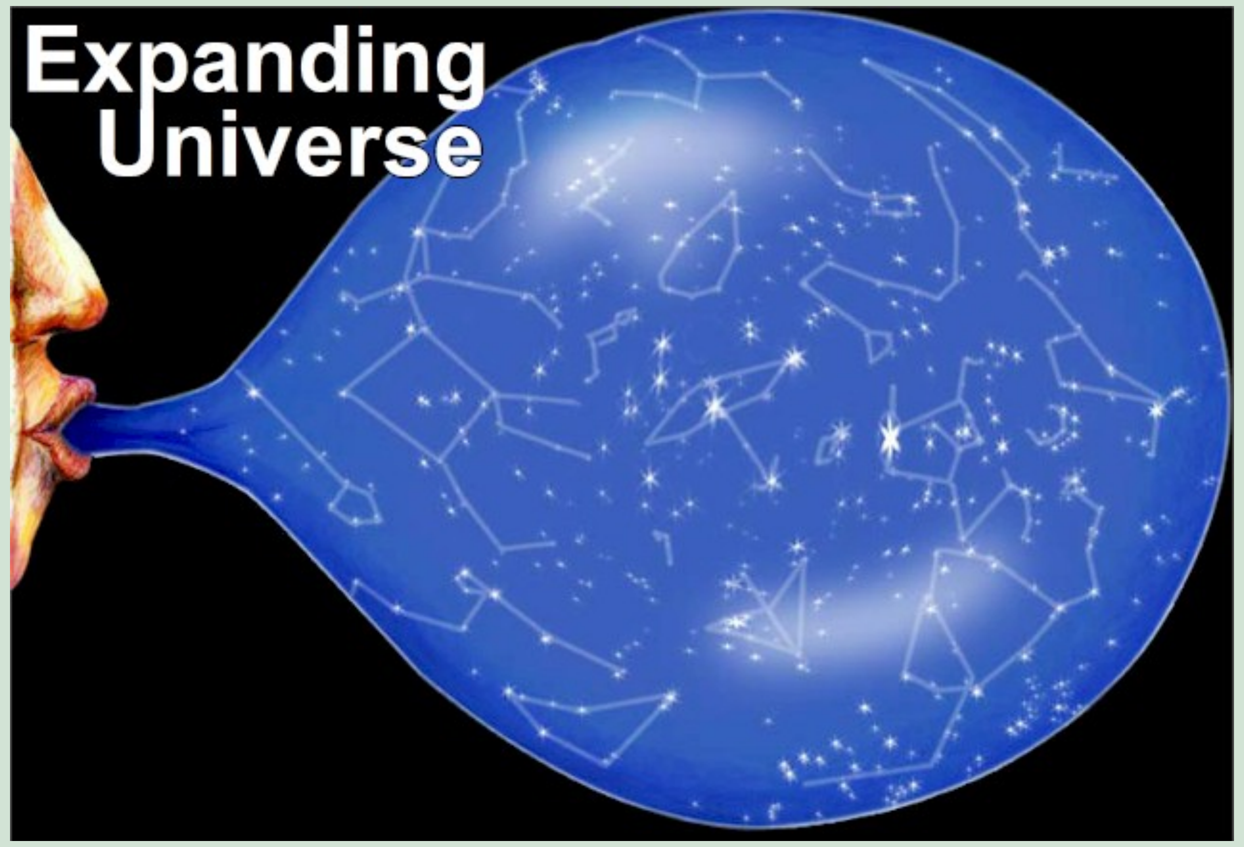
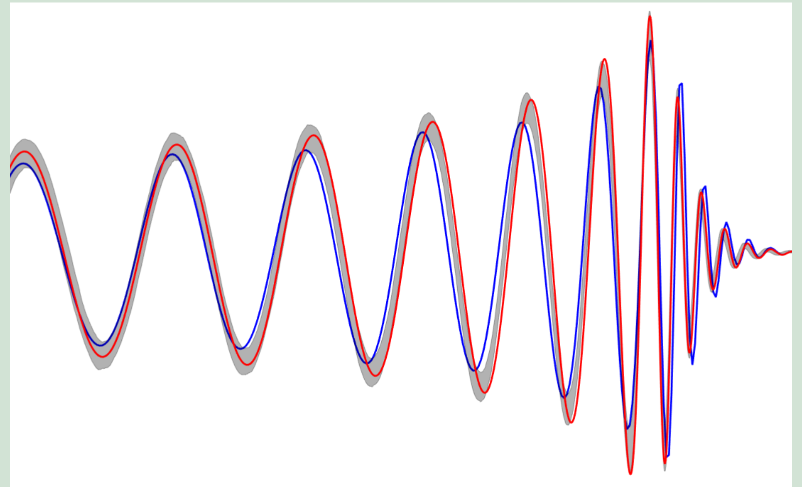
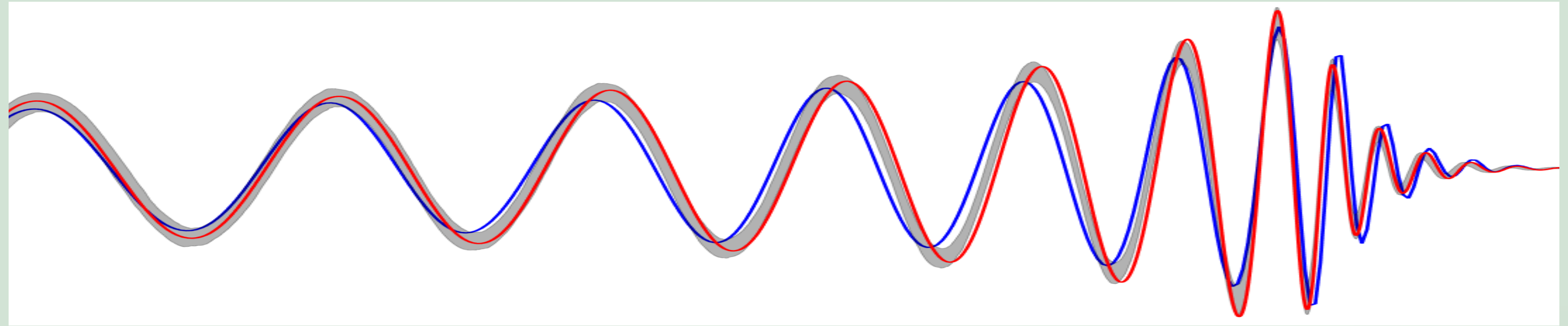


Cosmological redshift

Doppler redshift?
Gravitational redshift?





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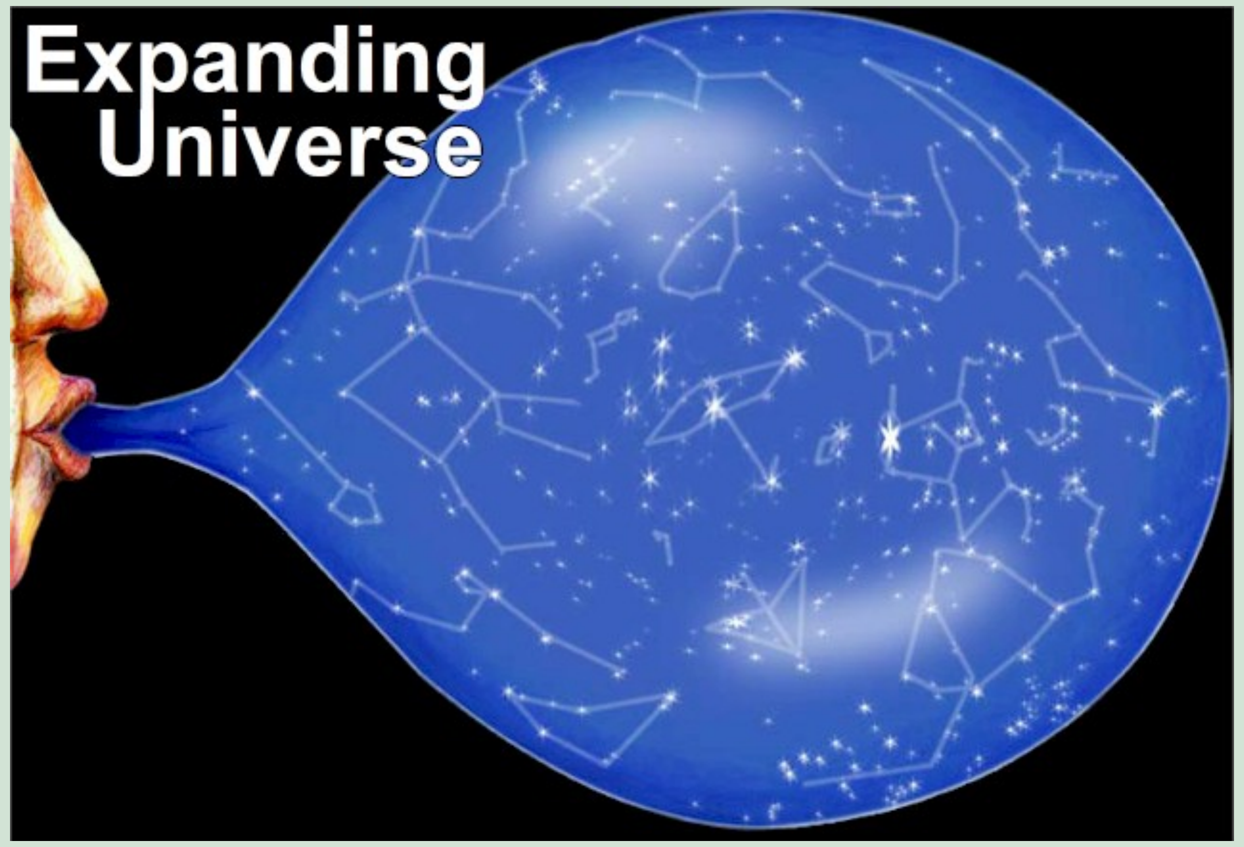

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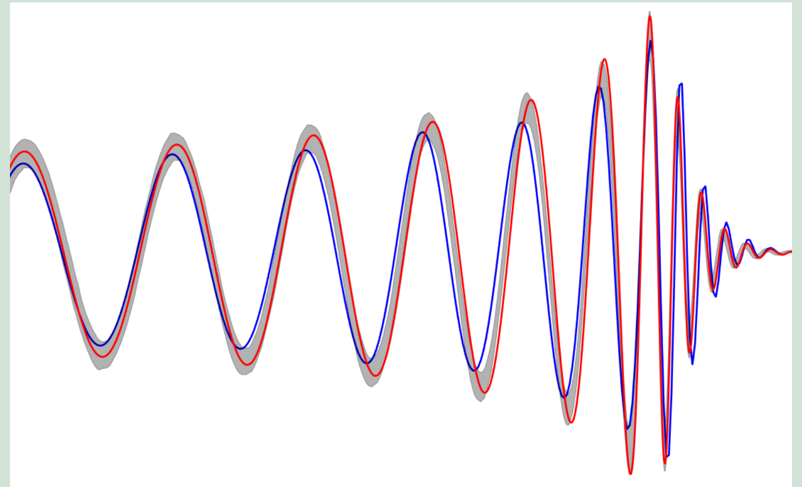

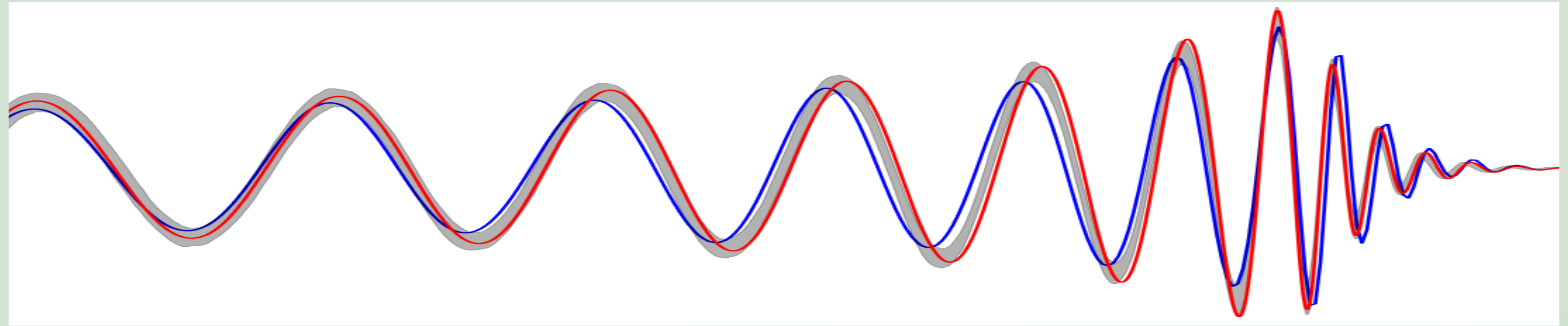

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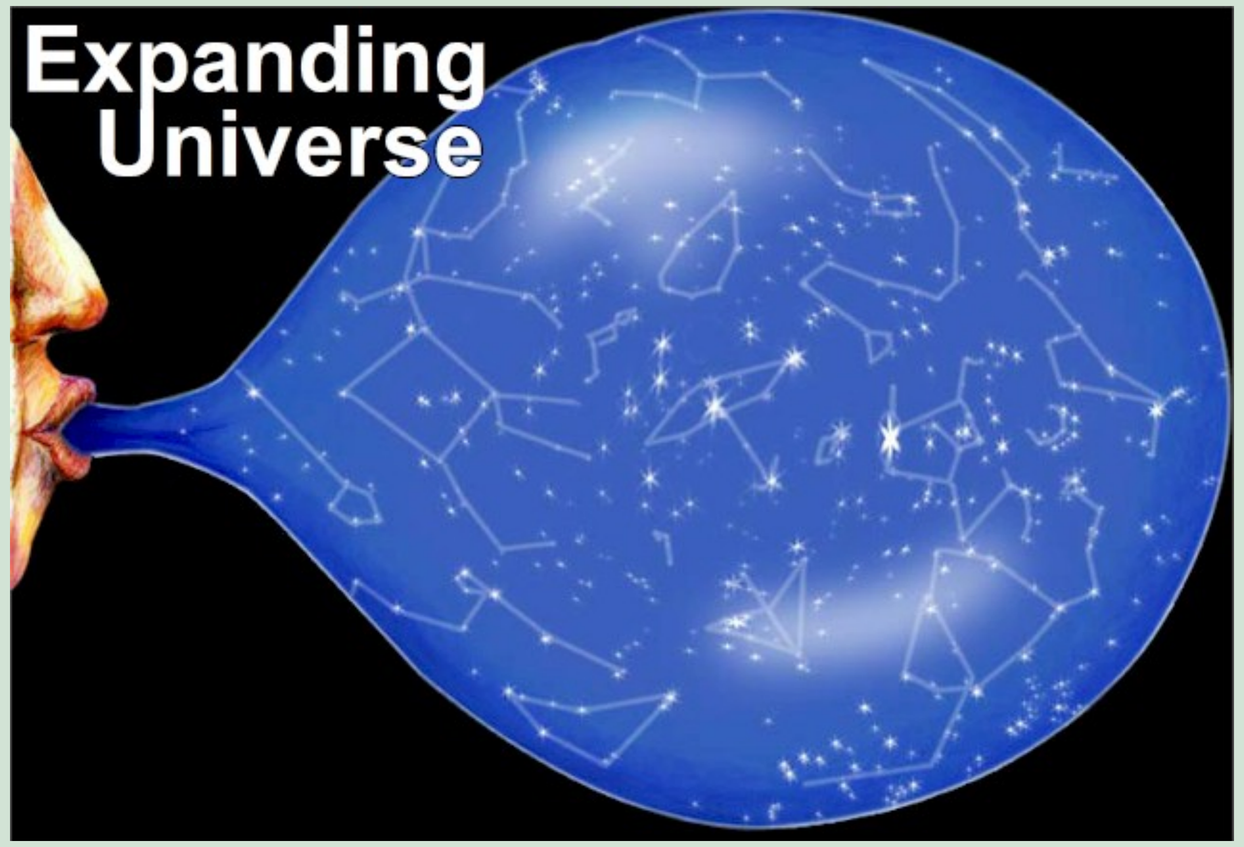

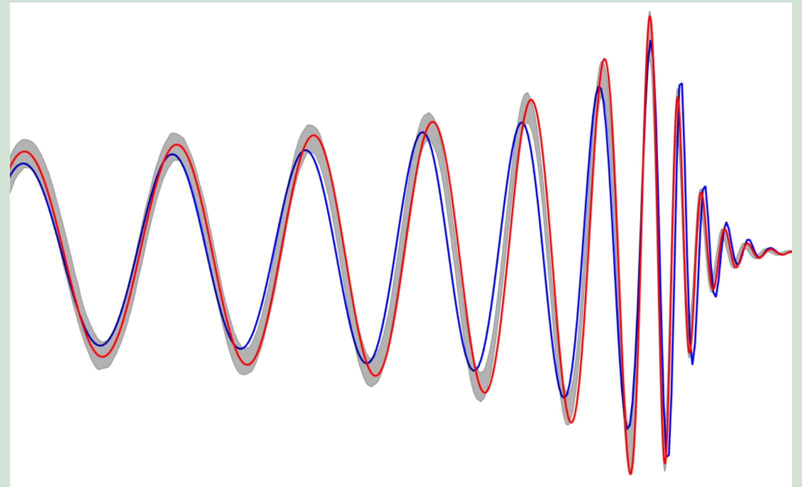

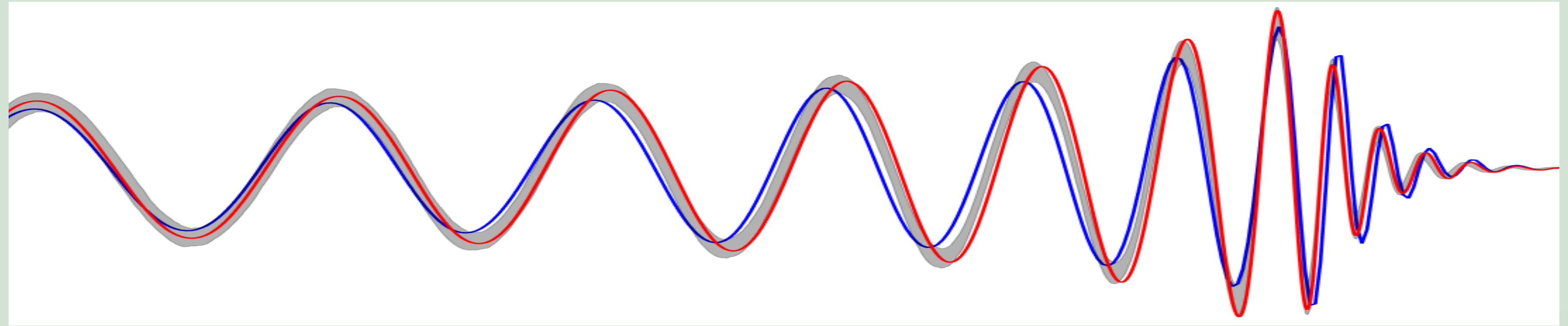

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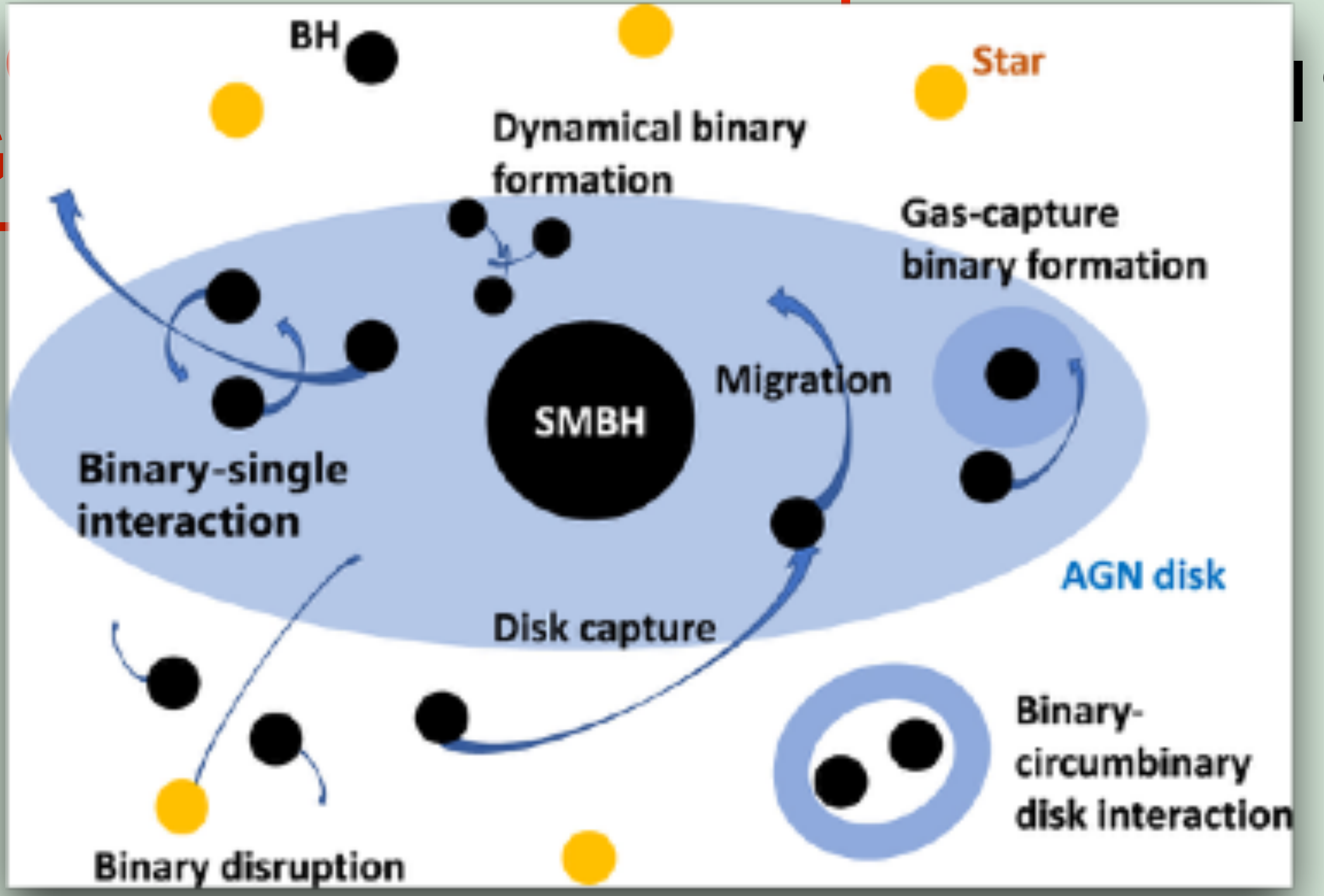

Sketch from Tagawa et al. 2020

- Conventional formation channels:
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- Recent view: Enhancement of mergers close to a supermassive black hole (>10^6 Msun) because
  - Large escape velocity for compact objects
  - Mass segregation effect
  - Tidal perturbation of binaries by surrounding objects
  - Hydrodynamical drag if inside an active galactic nucleus (AGN)
  - (See Arca-Sedda, Naoz, Kocsis 2023 for a recent review)

Fake massive black holes around a SMBH

- $M_o = M(1+z_{cos})(1+z_{dop})(1+z_{gra})$
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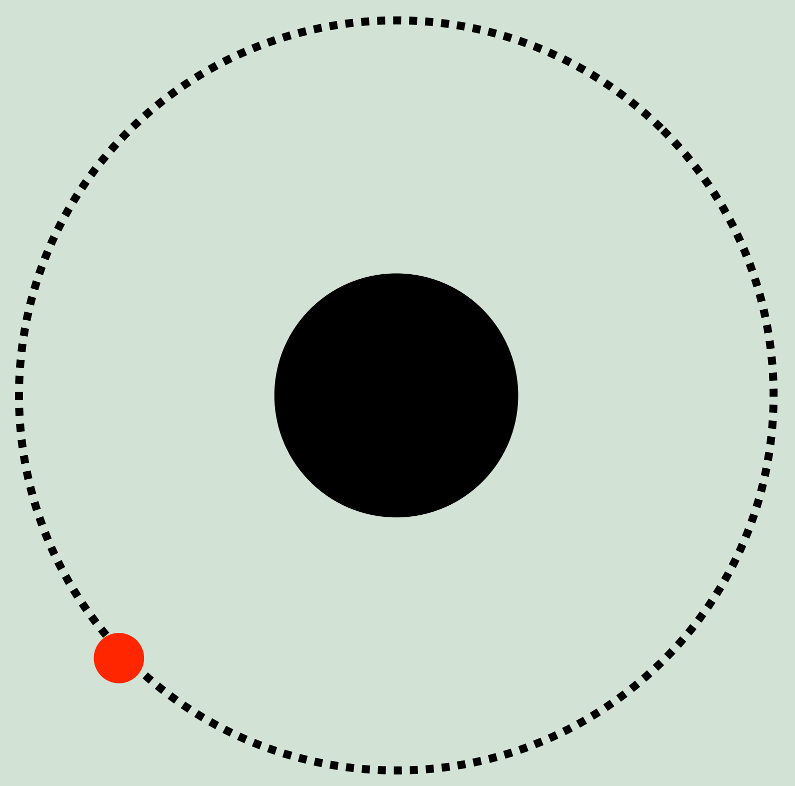

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  - 3 Schwarzschild radii
  - $v \sim 0.408c$
  - 1+z in total:1.89
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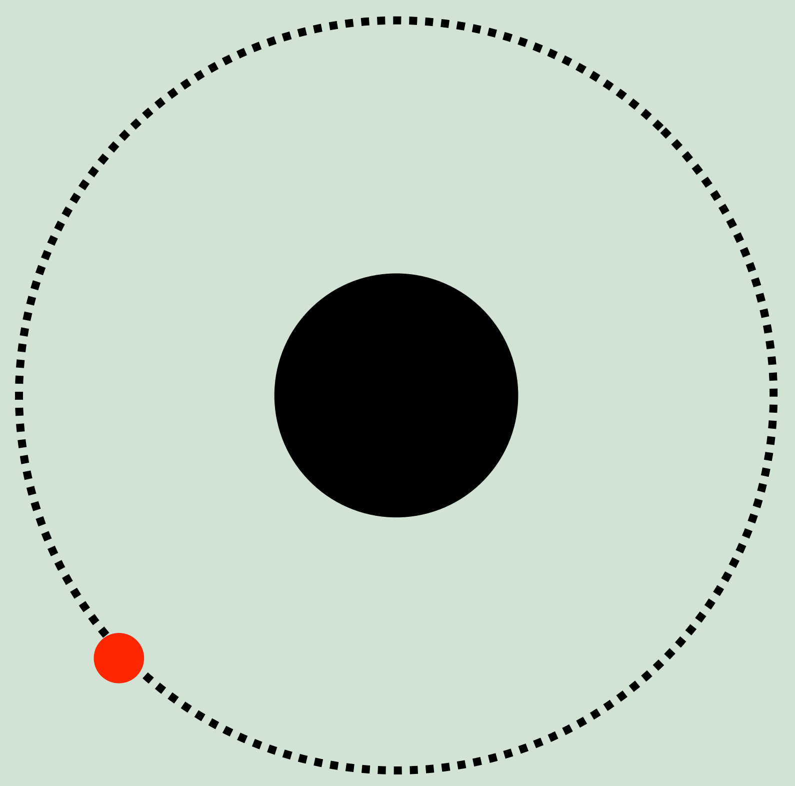
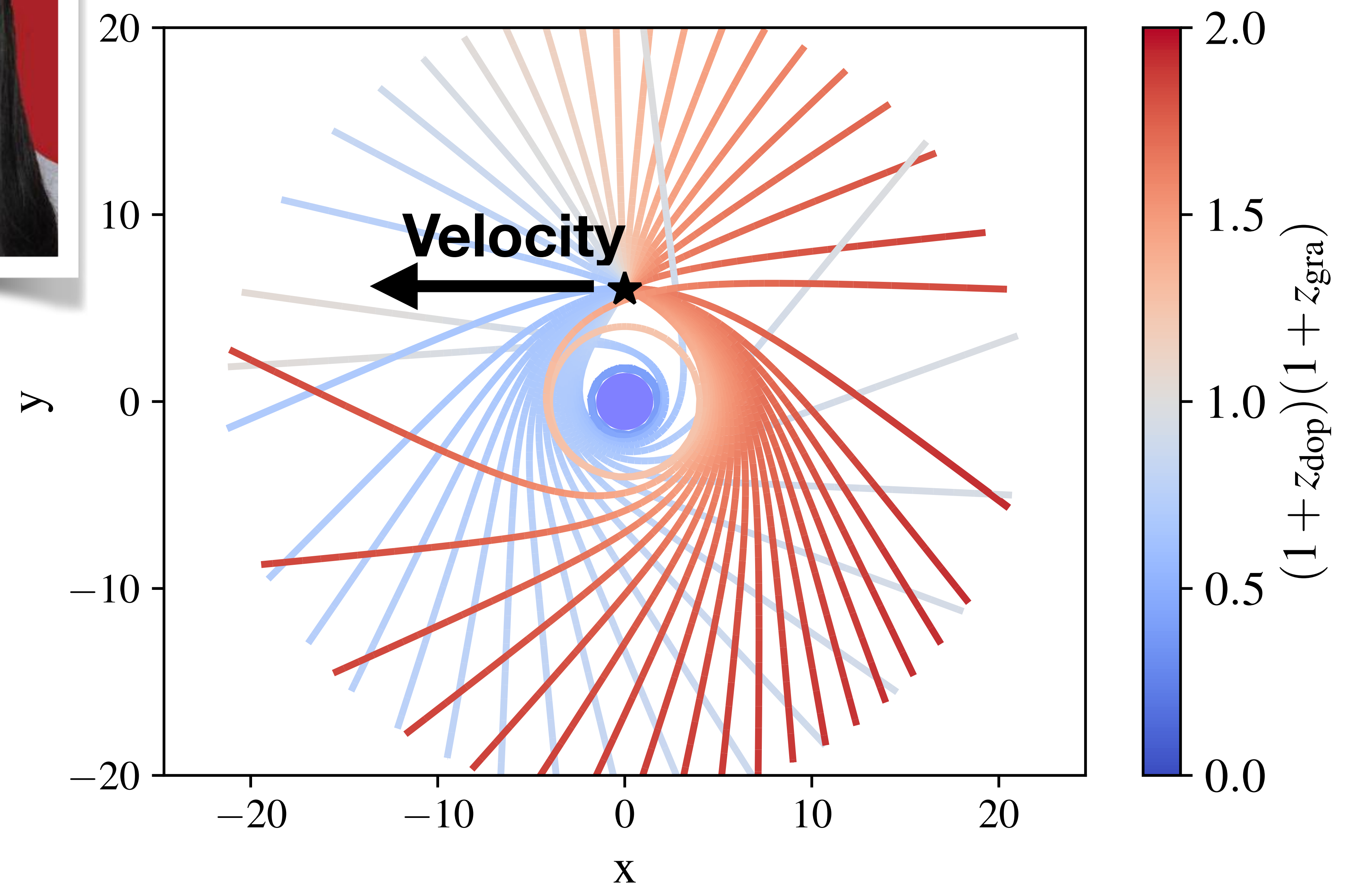


Kerr SMBH *a*=0.9

(Zhang & Chen 2023 MNRAS)



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- Both blueshift and redshift: both heavy and light BHs
- Asymmetric: dark red v.s. light blue
- Light bending: focused and de-focused rays
- Affect amplitude and distance measurement

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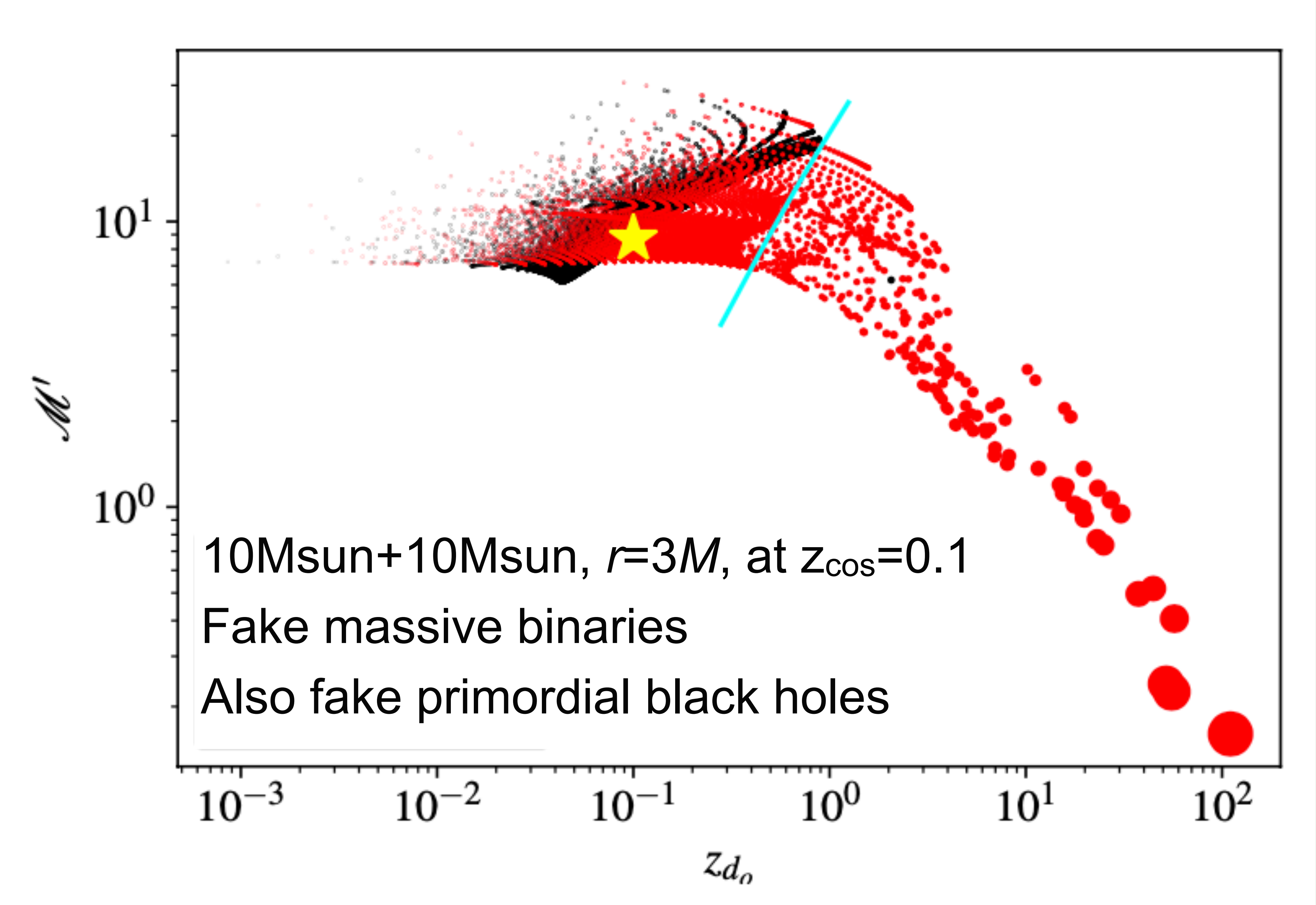

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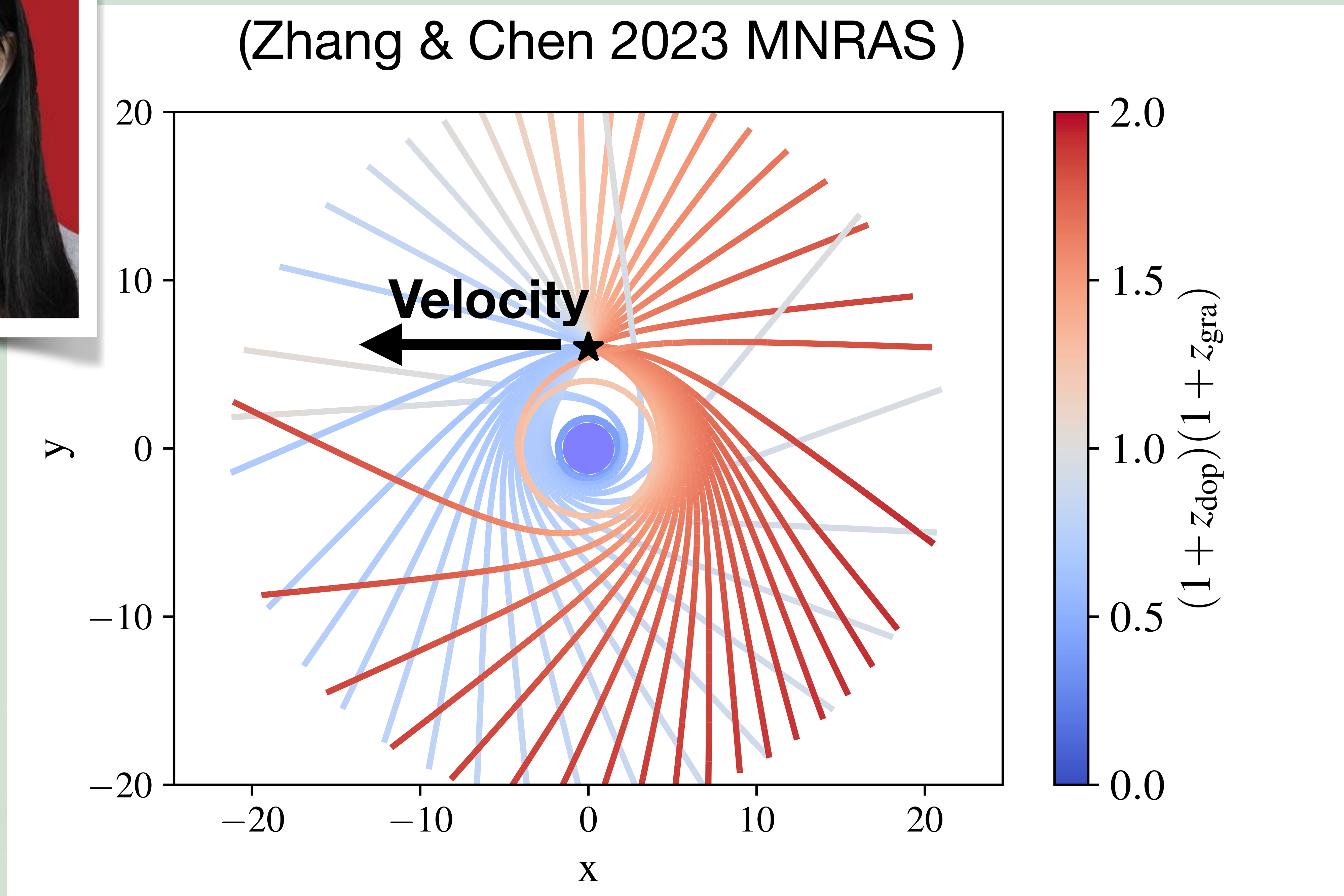

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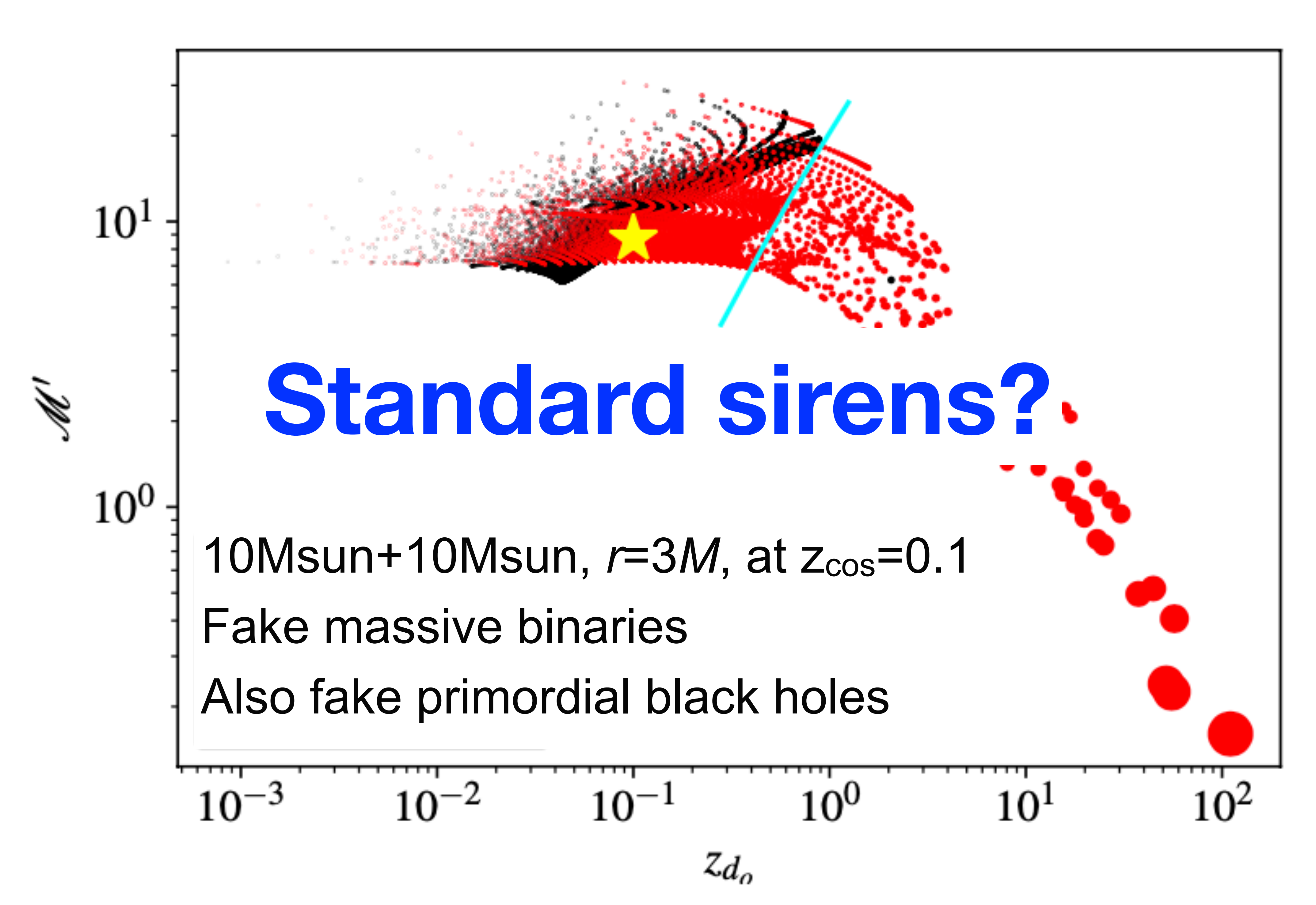

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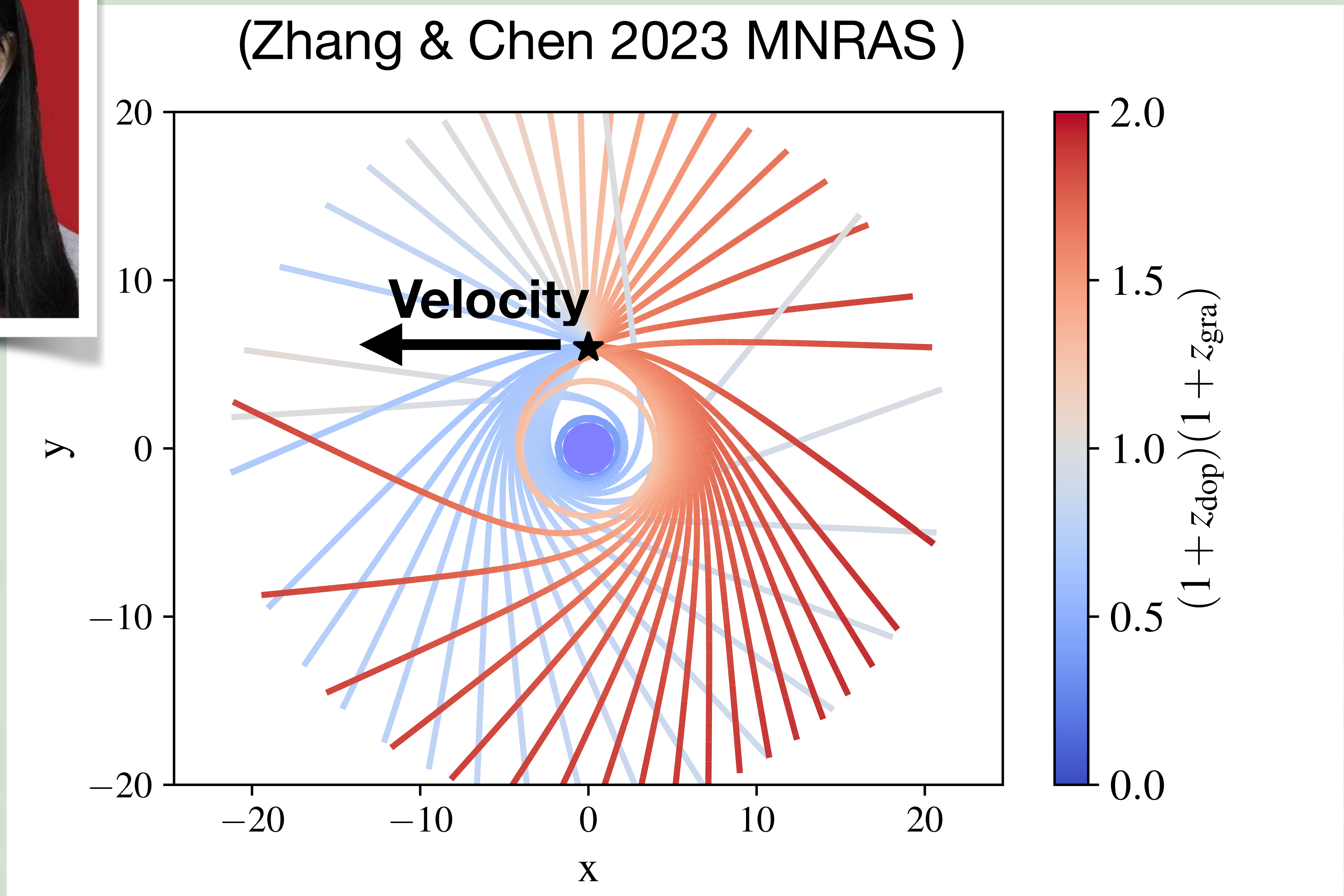

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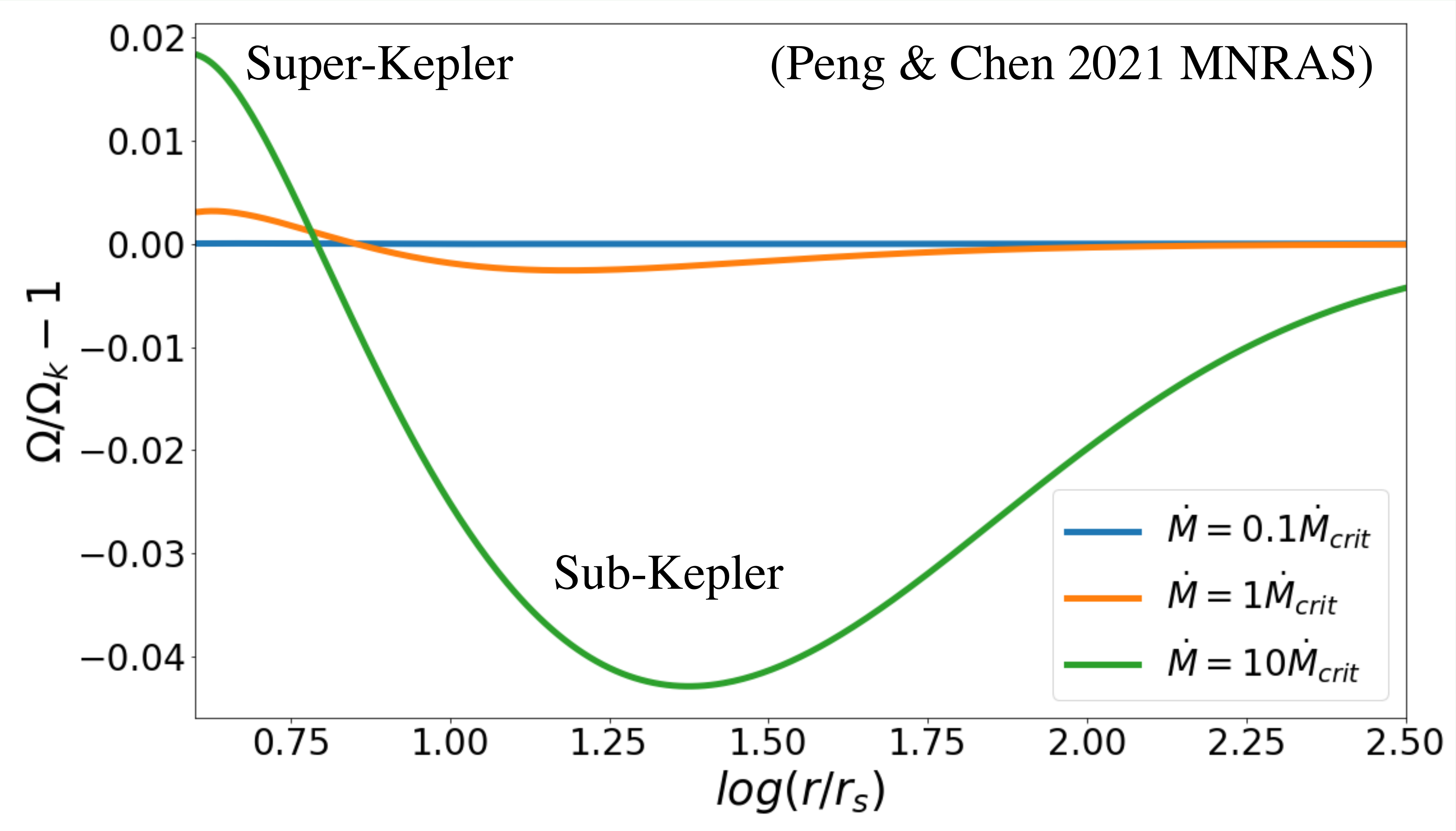

QSO disk has a super- to sub-Keplerian transition region

(Early works by Abramowicz et al. 1978; Chakrabarti et al. 93-96; Kocsis et al. 2011)

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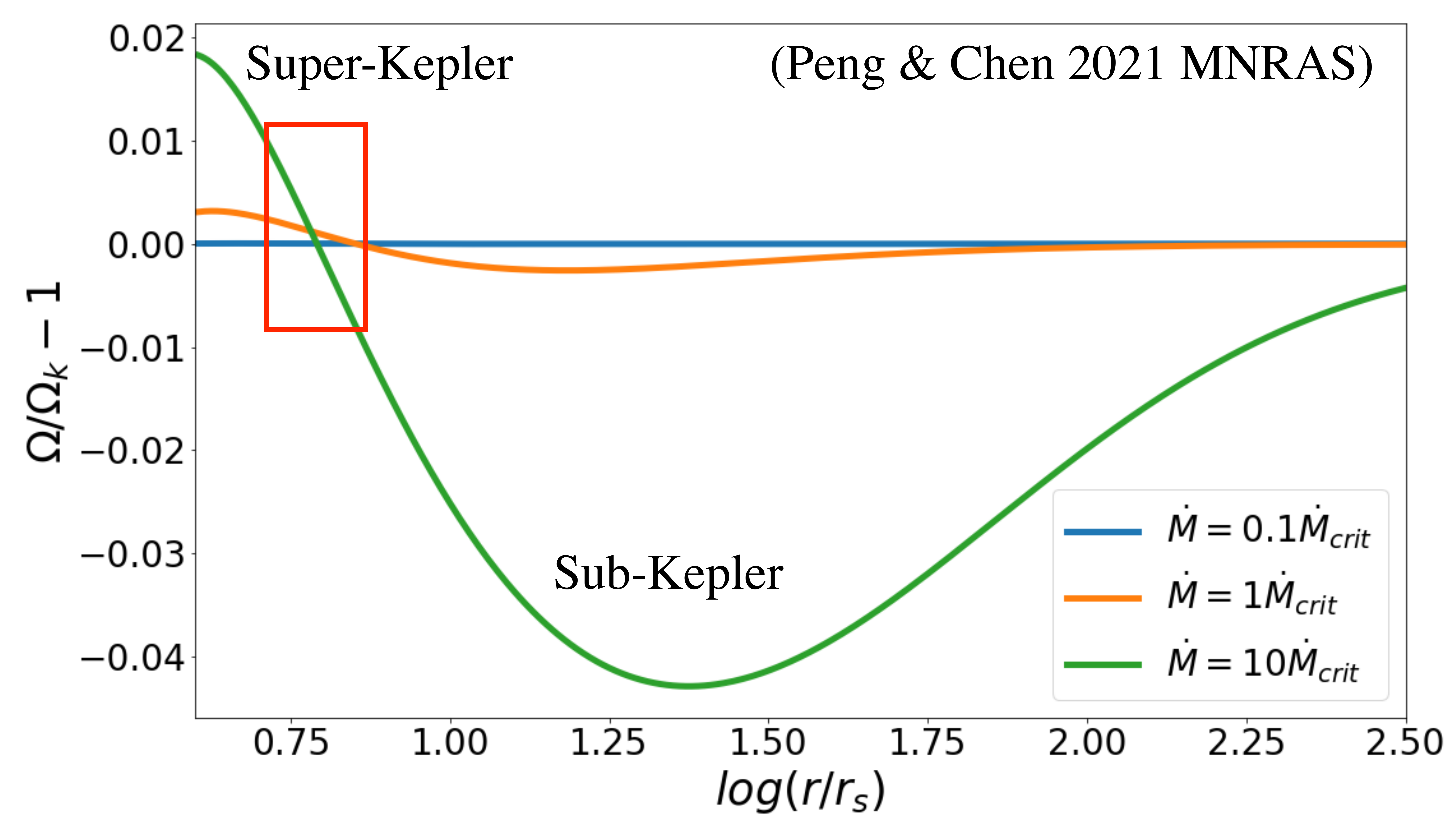

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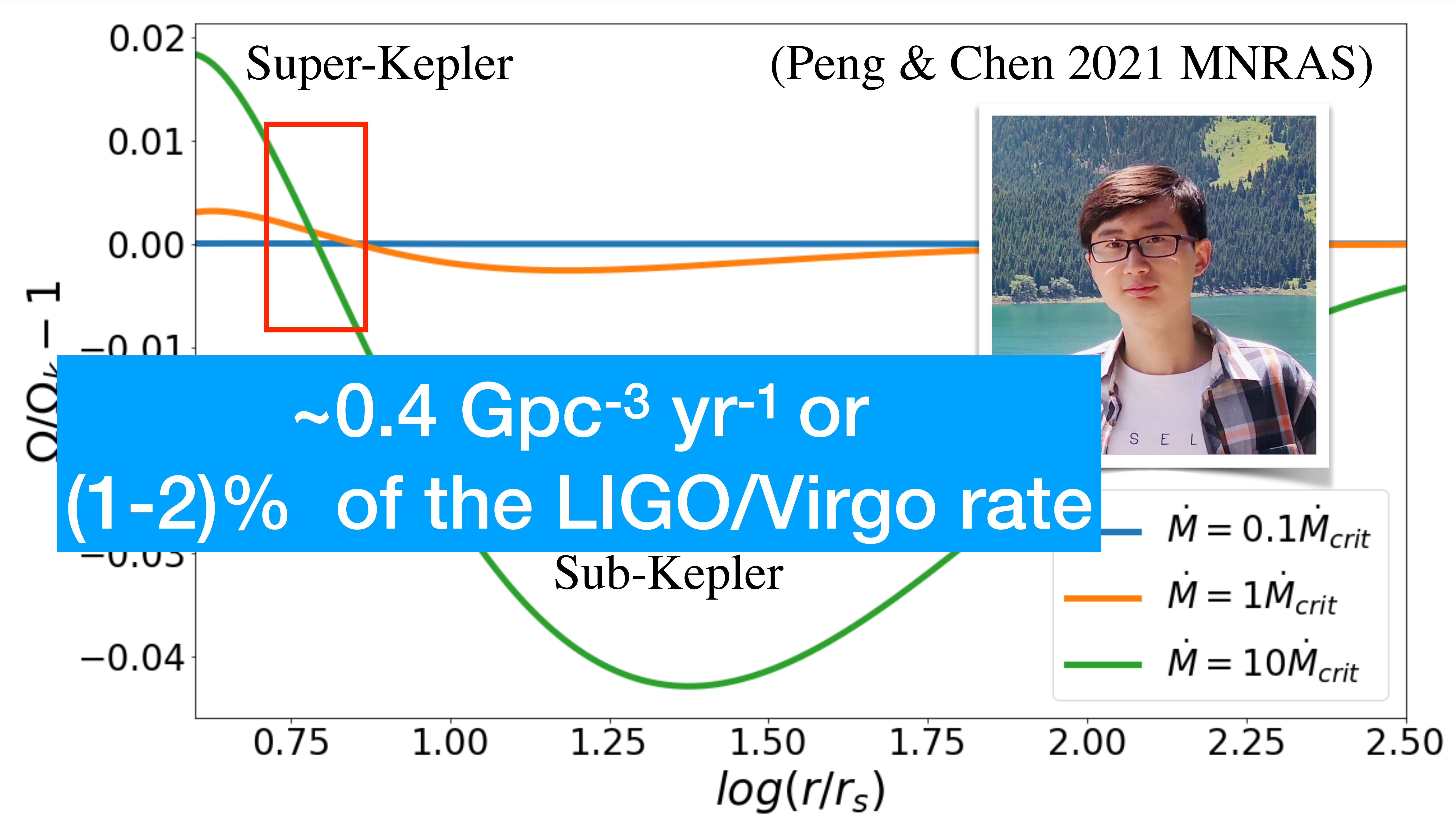

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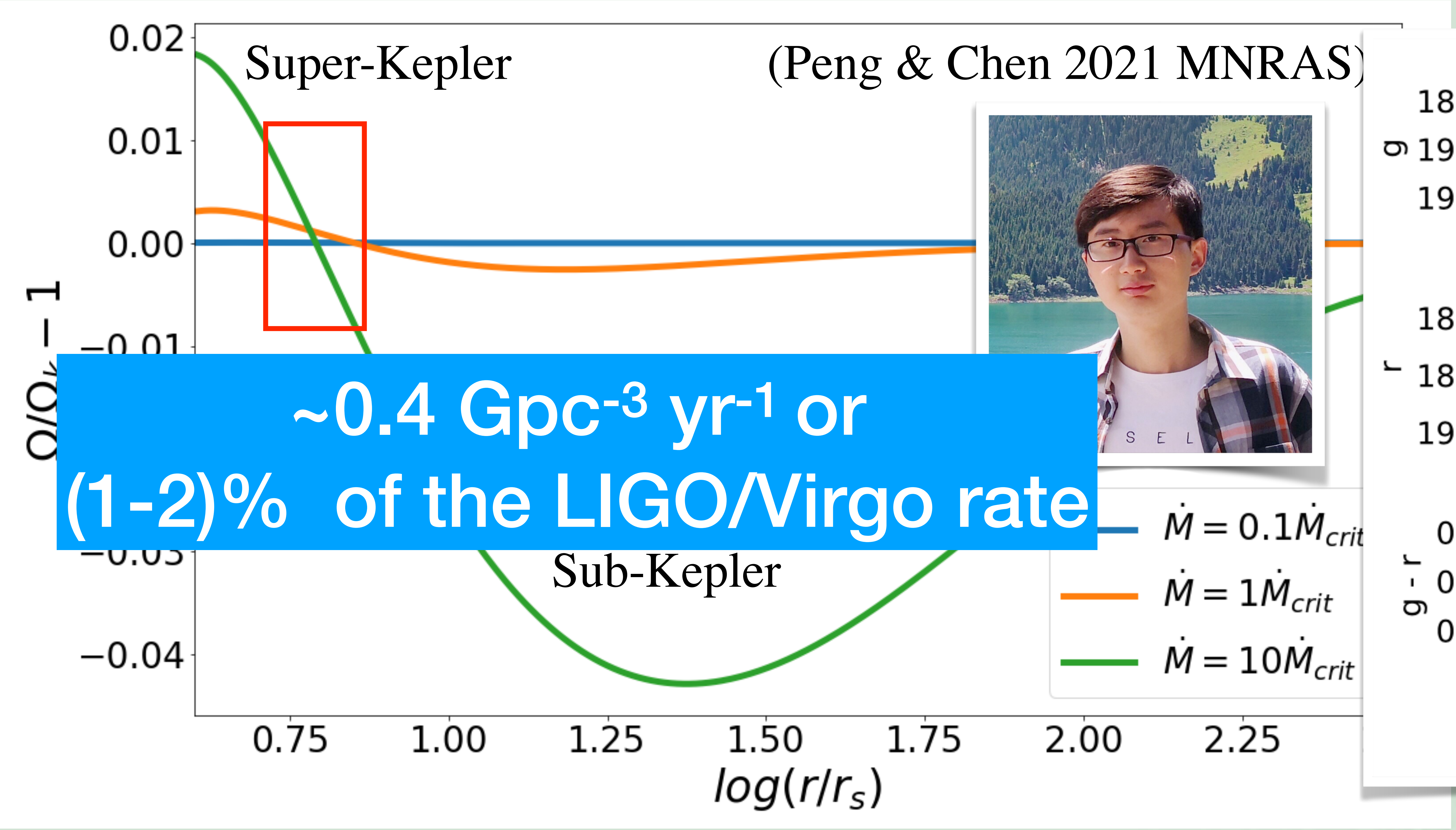

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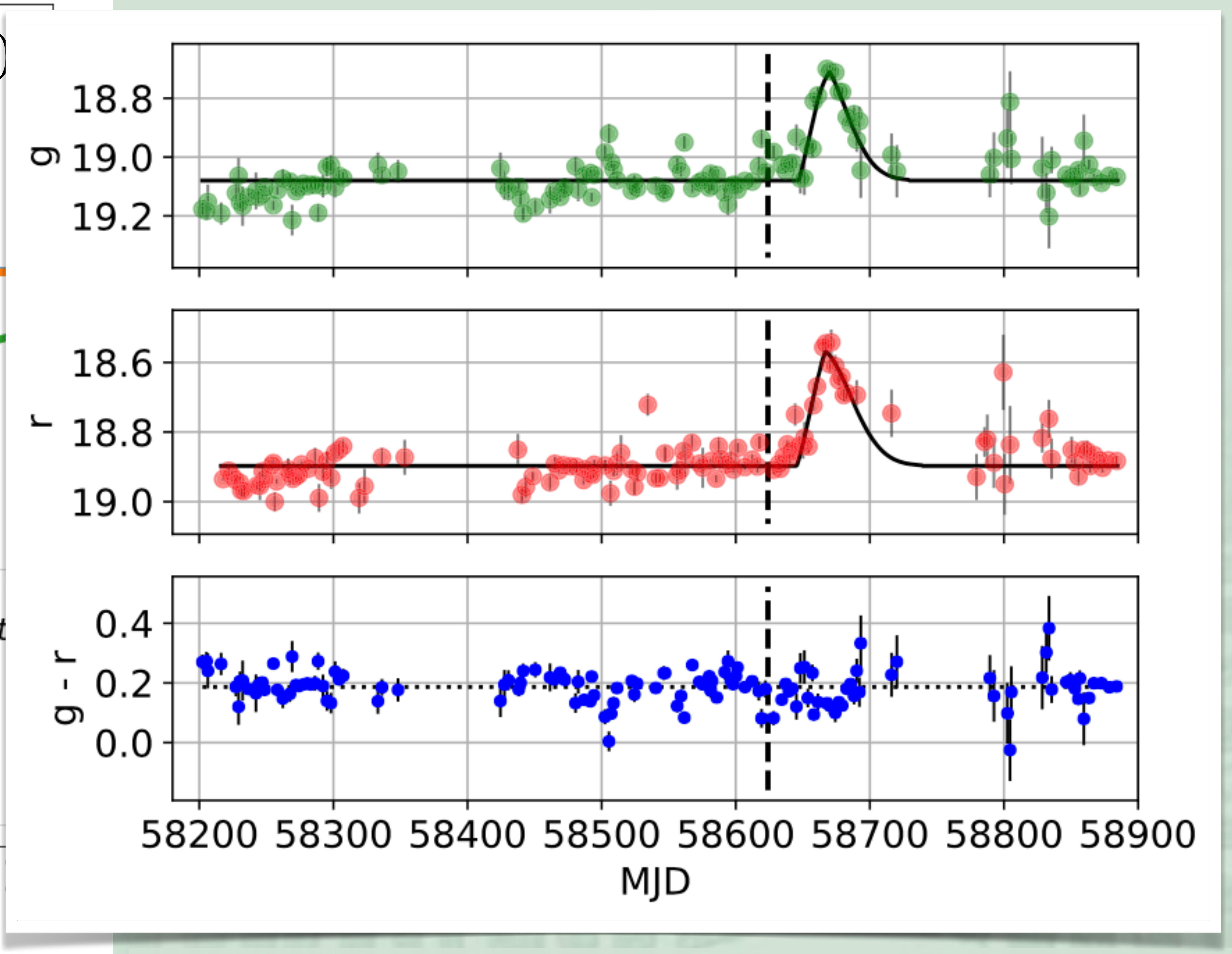

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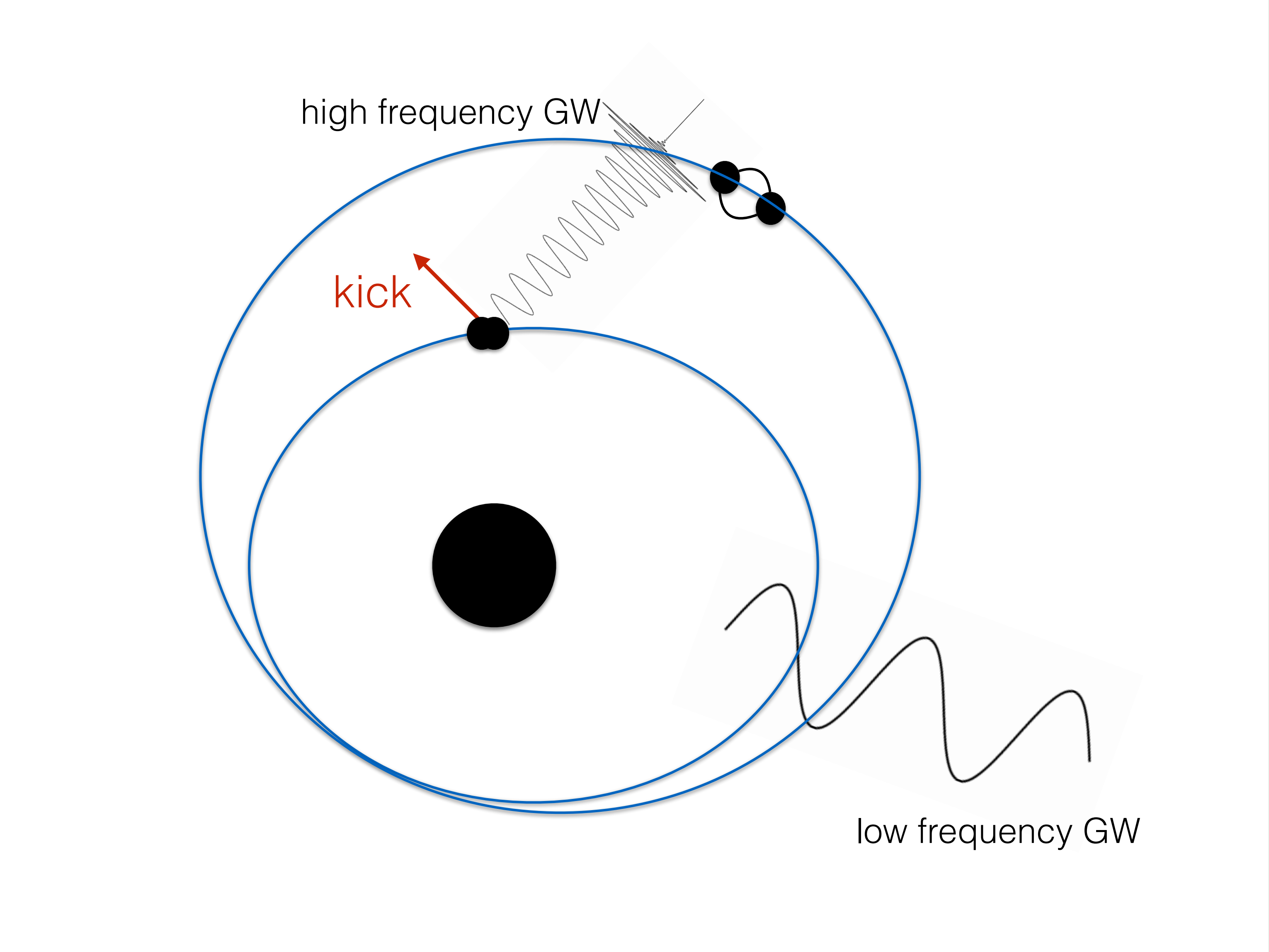
GW190521: 91+67 Msun

- d_{GW}=4.5 Gpc (Abbott+20)
- d_{EM}=2.2 Gpc (S190521g, Graham+20)
- $(1+z_{dop})(1+z_{gra})=2$
- See Graham+22 for more candidates

Signatures from relativistic three-body dynamics

- ~~Post-Newtonian formalism~~ (high velocities)
- ~~Full numerical relativity~~ (dynamical range: $M/m \sim 10^{6-7}$)



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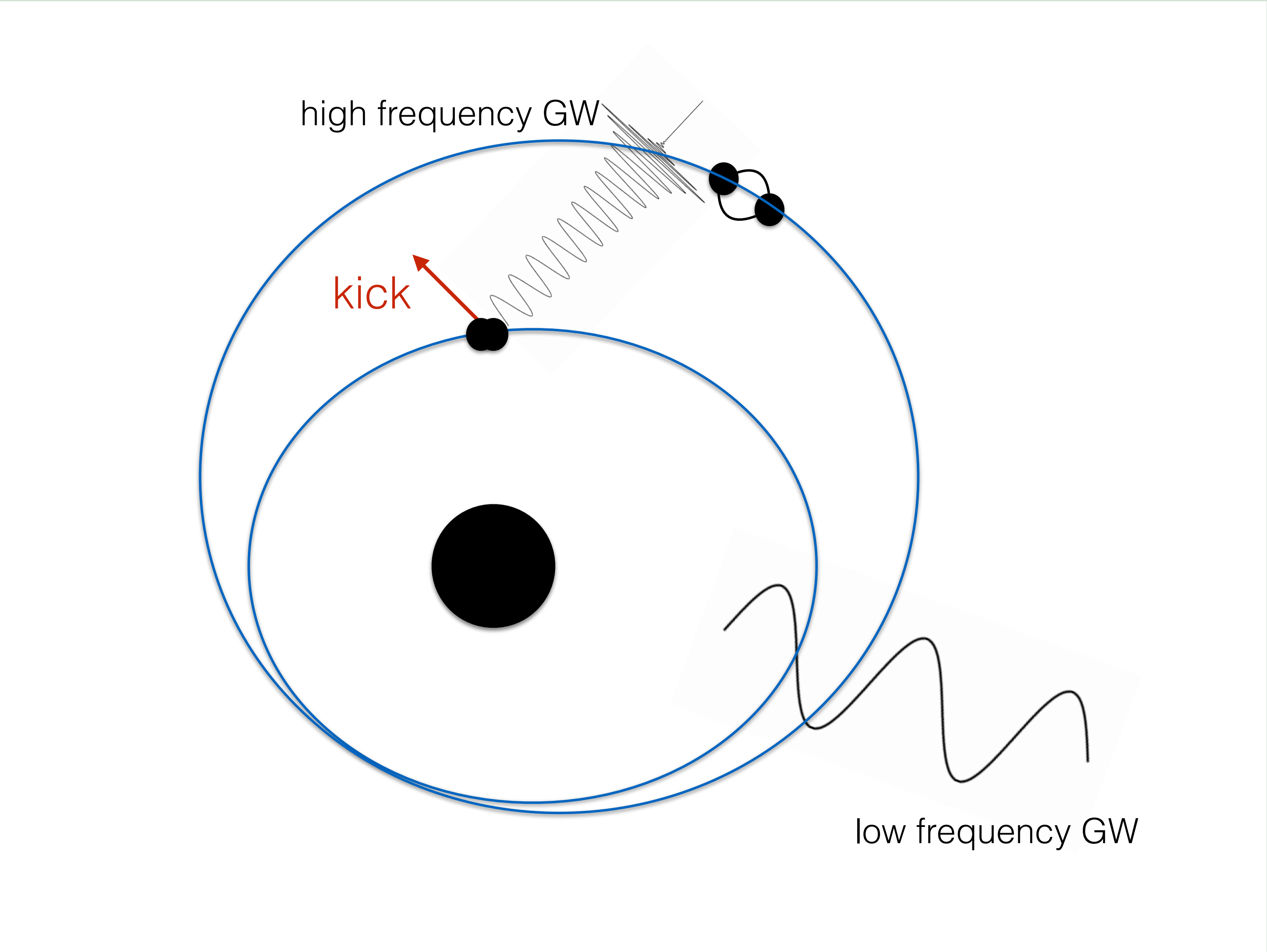

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  - Gravity of the SMBH almost "disappears"
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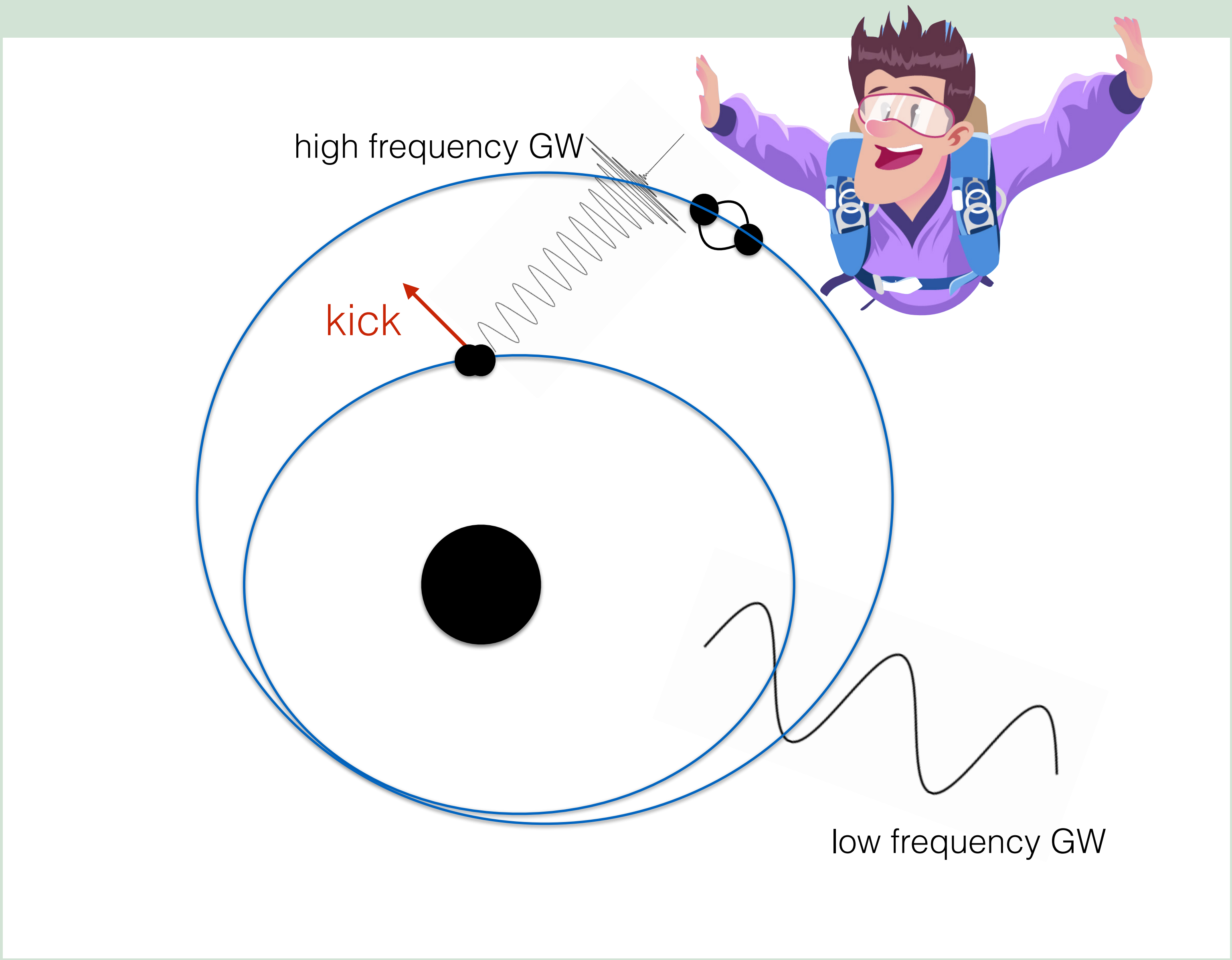

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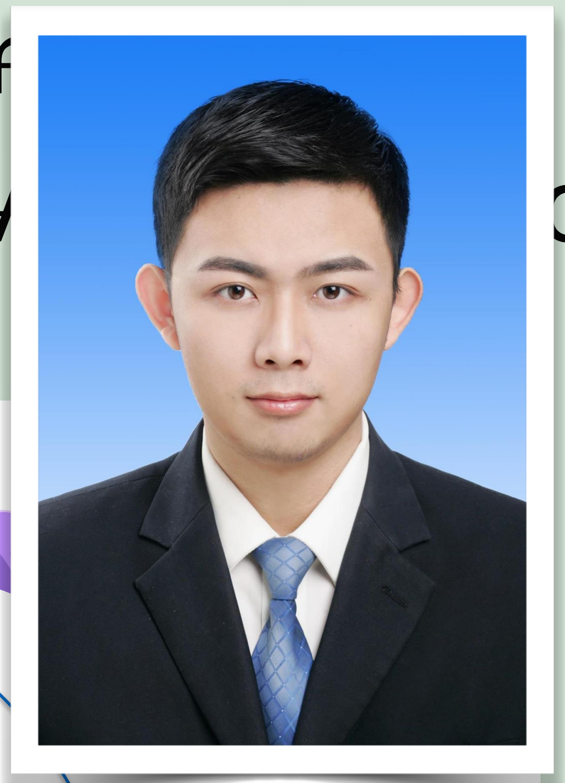

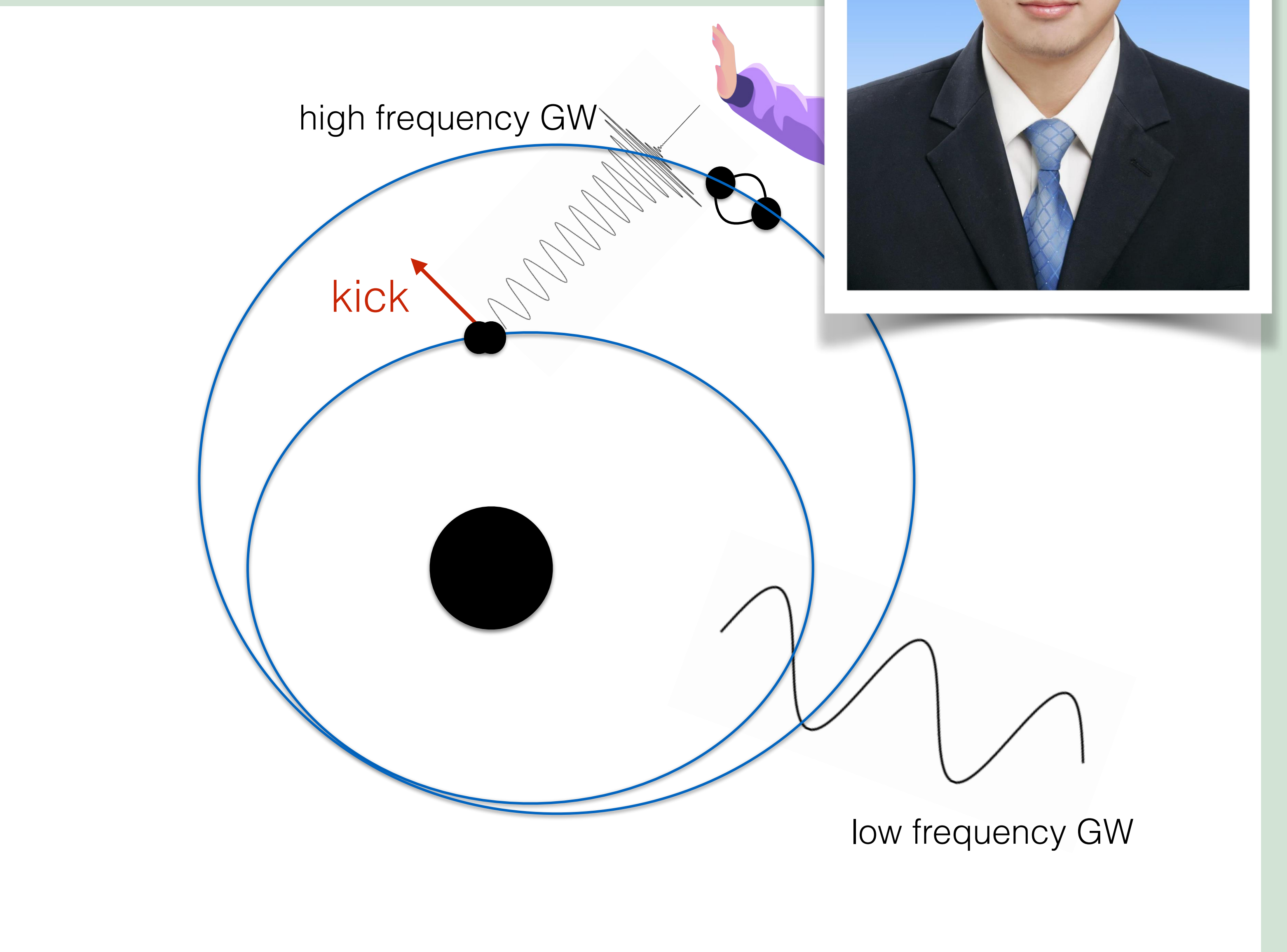

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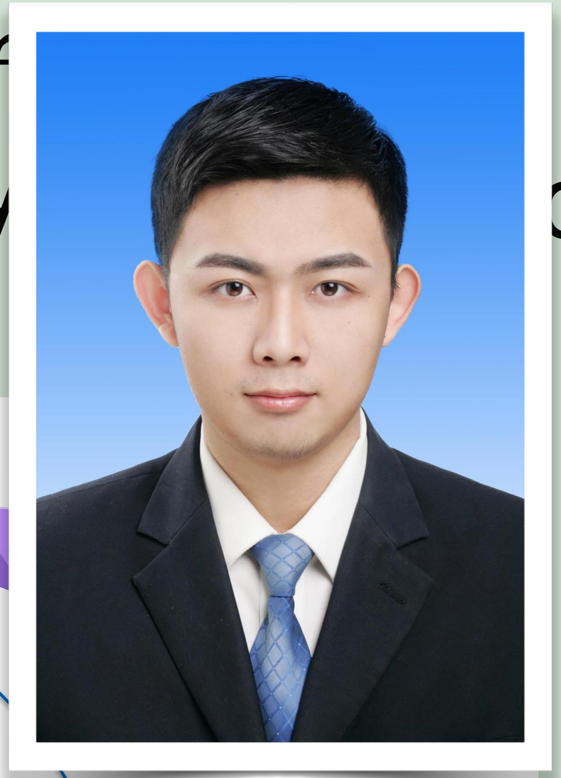
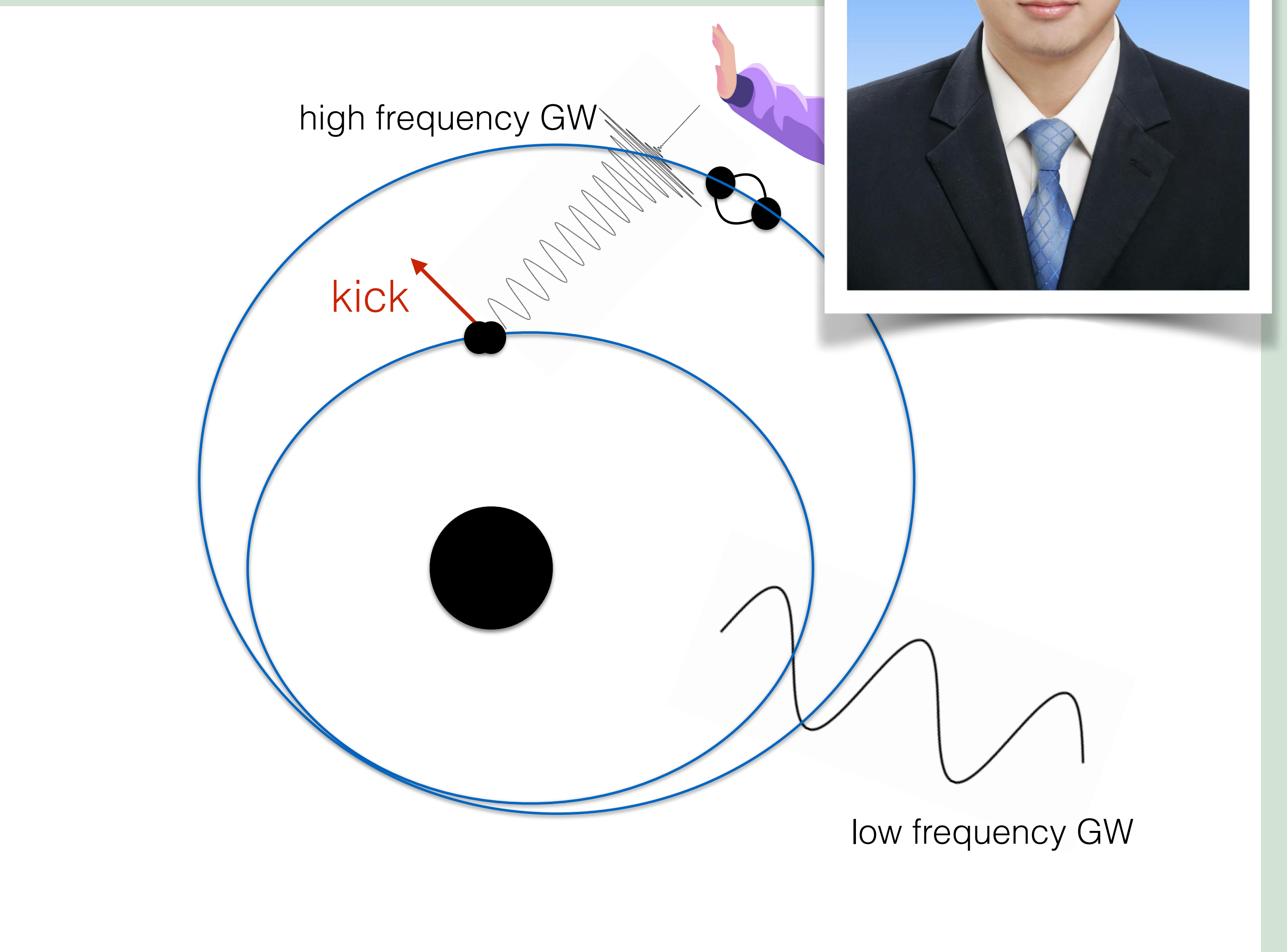
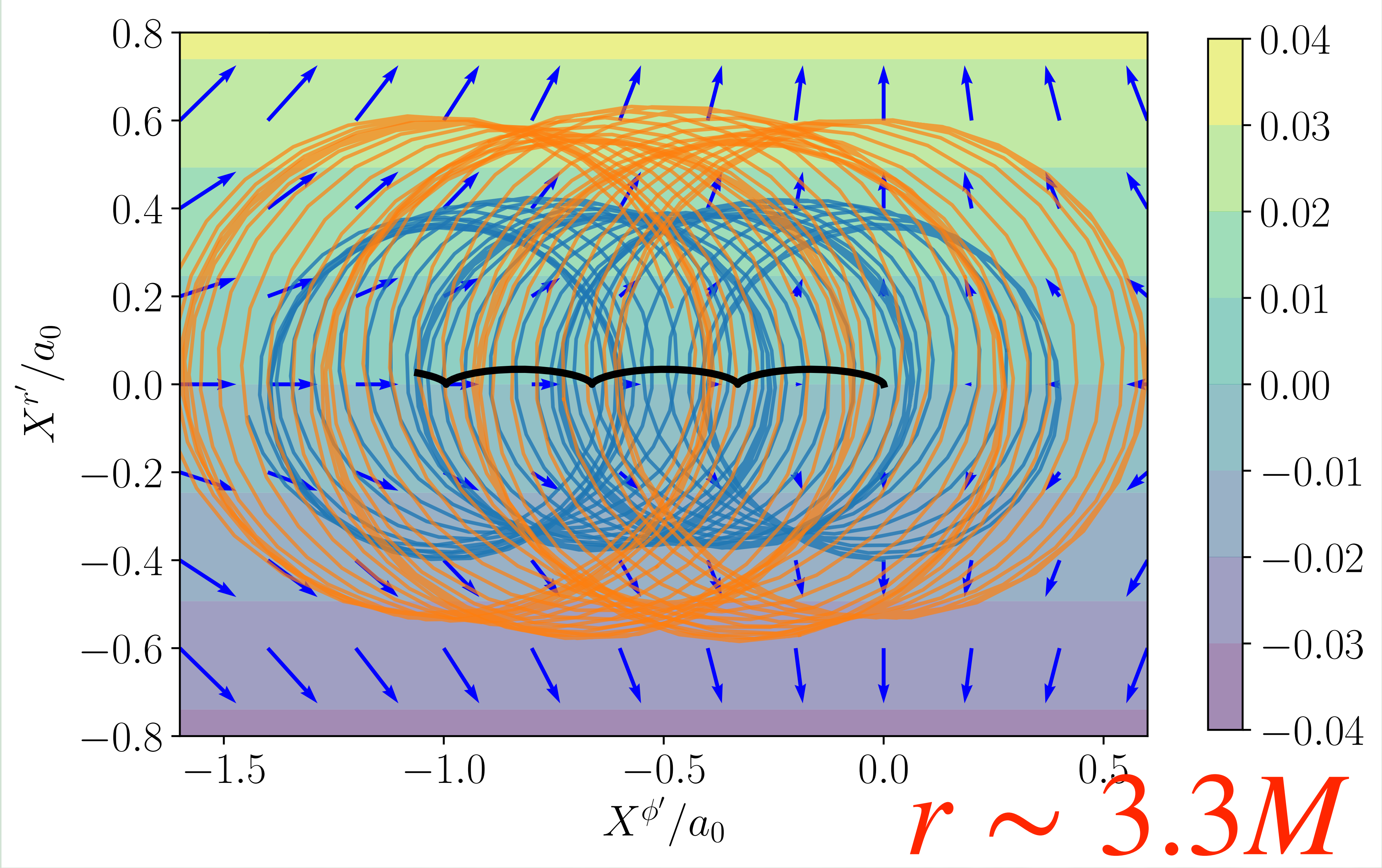




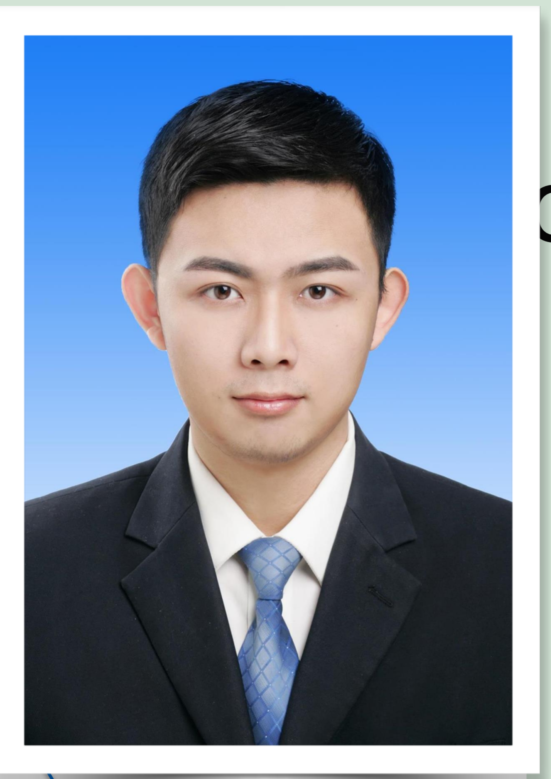


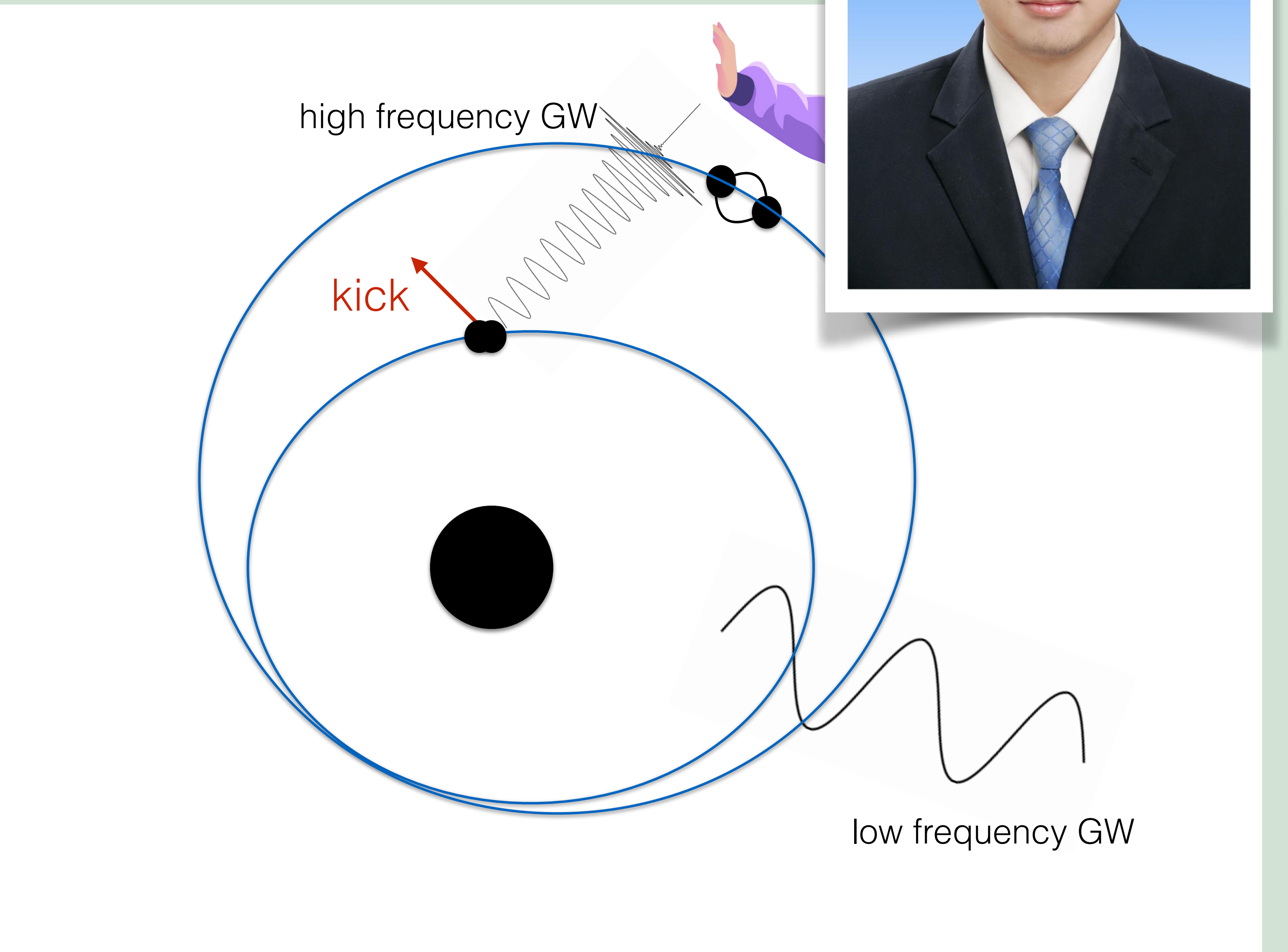
- Concentric circles in previous works
- *r*-oscillation and theta-drift due to metric perturbation

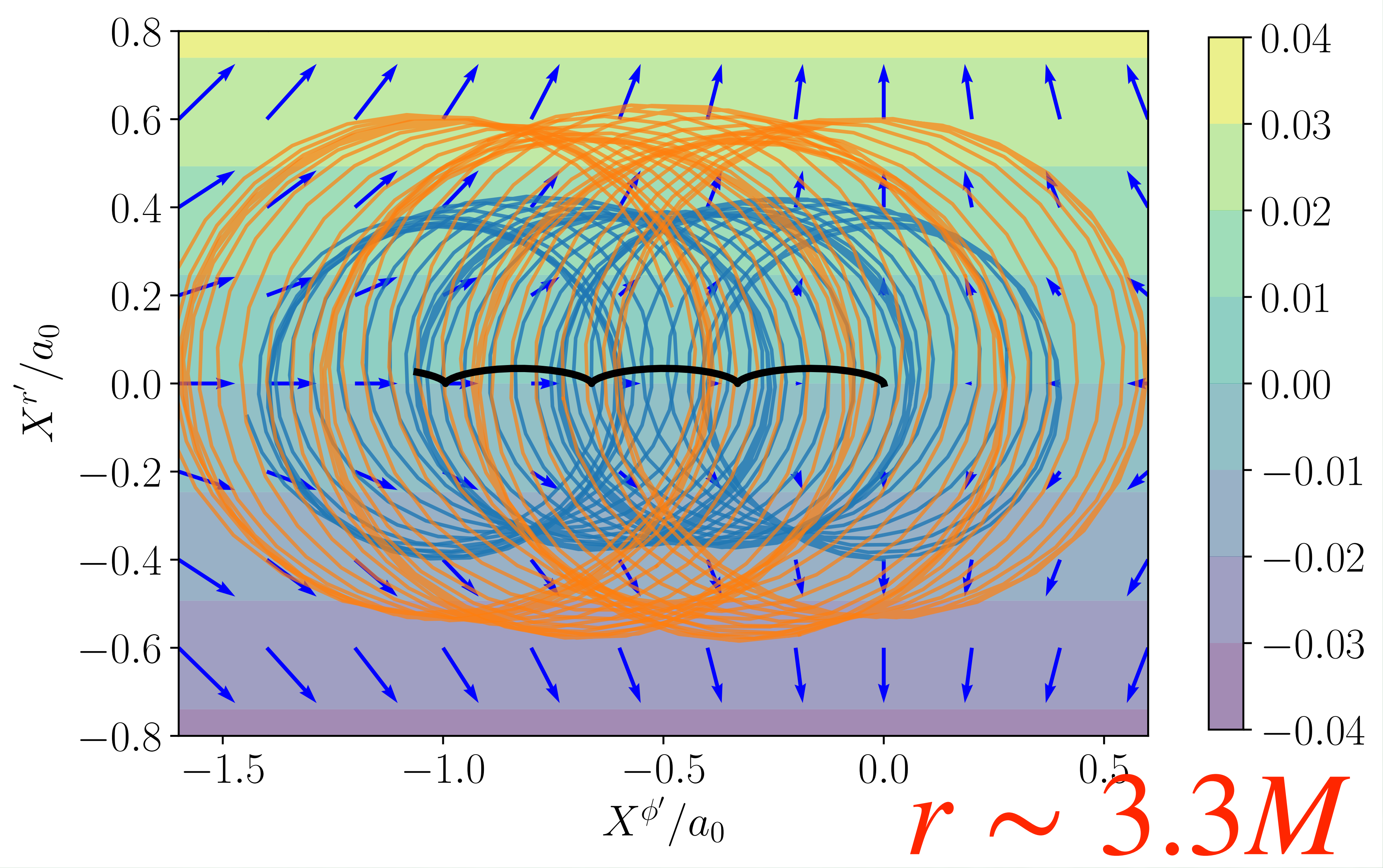
- Simple dynamics in the free-fall frame:
  - Gravity of the SMBH almost “disappears”
  - Binary (10$^{4-5}$ km) feels small curvature (gravity-electromagnetic forces)
  - Chen & Zhang 2022 PRD, also see Camilloni+2023; Maeda+23

Signatures from relativistic three-body dynamics

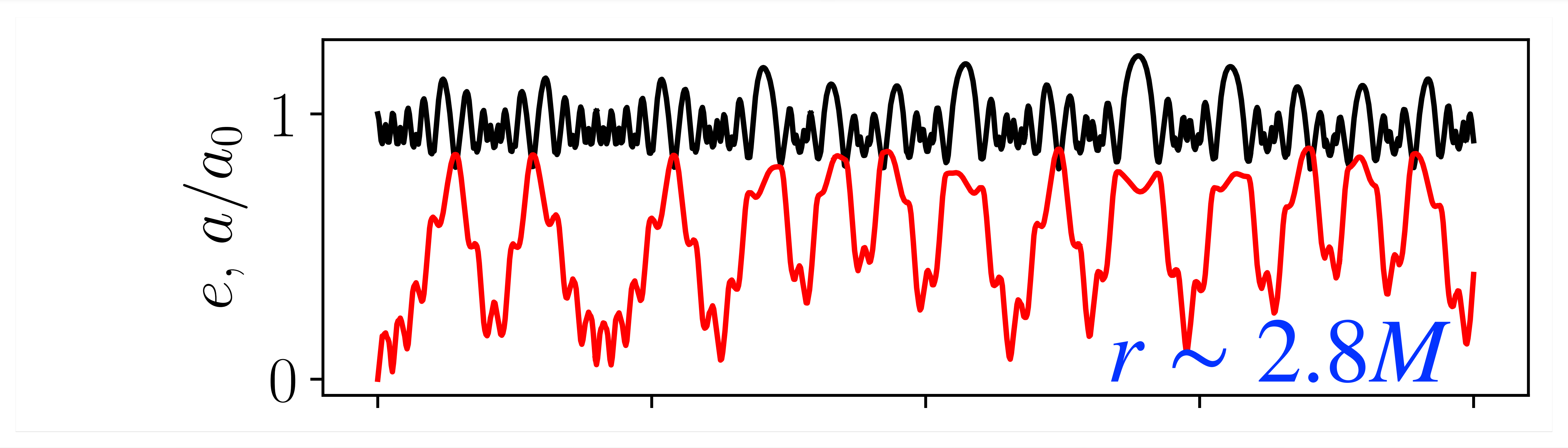
- ~~Post-Newtonian form~~ velocities)
- ~~Full numerical relativ~~ cal range: $M/m \sim 10^{6\text{-}7}$)







- Concentric circles in previous works



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- Significant eccentricity evolution
- Why BBHs merge only at small distances.

Summary

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- Astrophysical environments (like a nearby SMBH) affect GW signals

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- Change apparent mass and distance
  - Mislead our understanding of the origin of BHs
  - Wrong cosmology
  - Distinguish environmental effects using GWs? (e.g. Kocsis 2013; Barausse+2014; Bonvin+2017; Inayoshi+2017; Meiron+2017; Fedrow+2017; Derdzinski+2019; Liu+2019; Fang, XC, Huang 2019; Torres-Orjuela, XC, et al. 2019, 2020; D'Orazio & Loeb 2020; Yu & Chen 2021; Gondán & Kocsis 2022; Oancea+2022; Zwick+2023…)