Gravitational waves with PHANTOM: the case of *Tidal Disruption Events*

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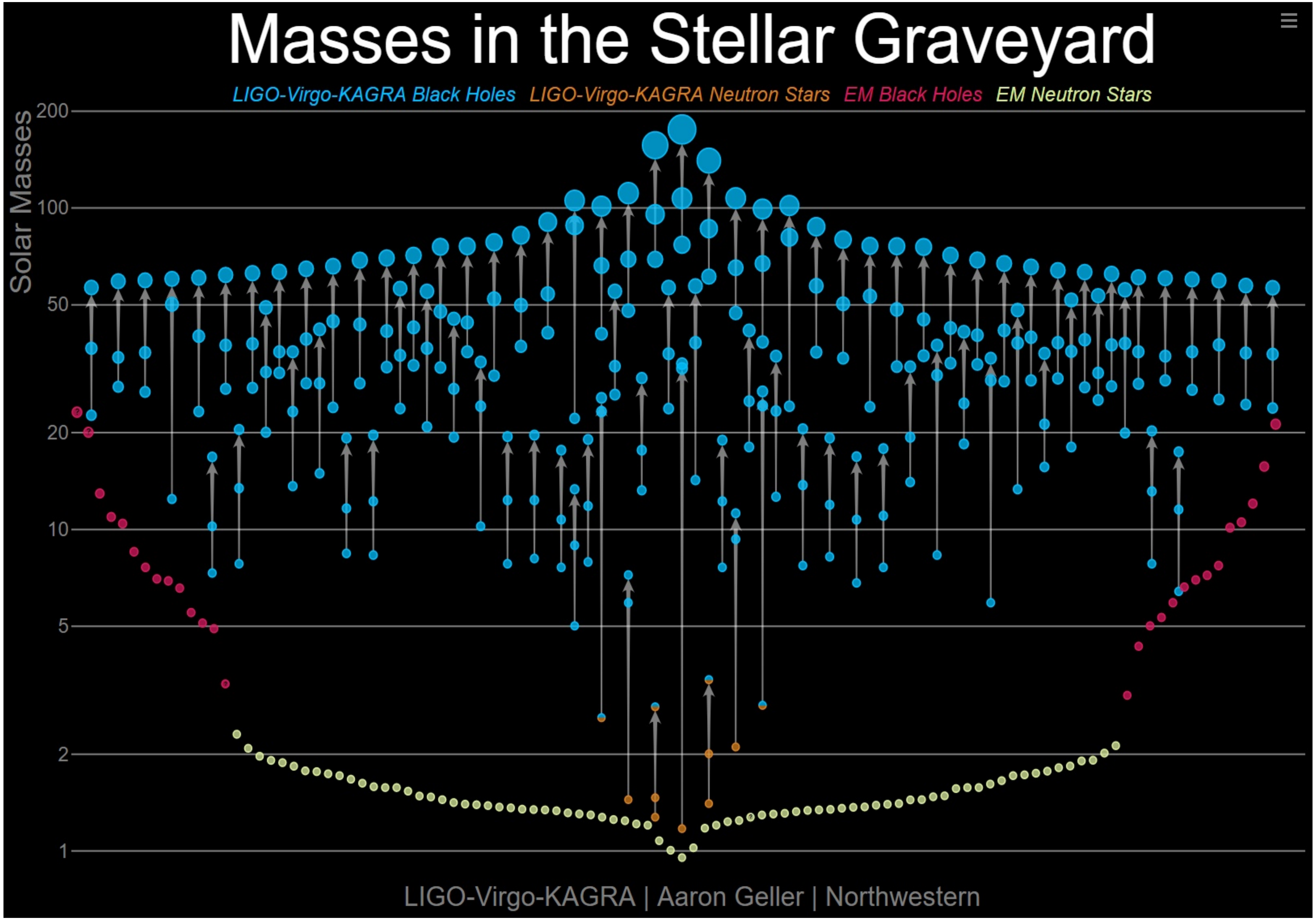
CREDIT image: NRAO/AUI/NSF/NASA



Since 2015,
90ish gravitational wave (GW) events detected!

Revolution in astronomy

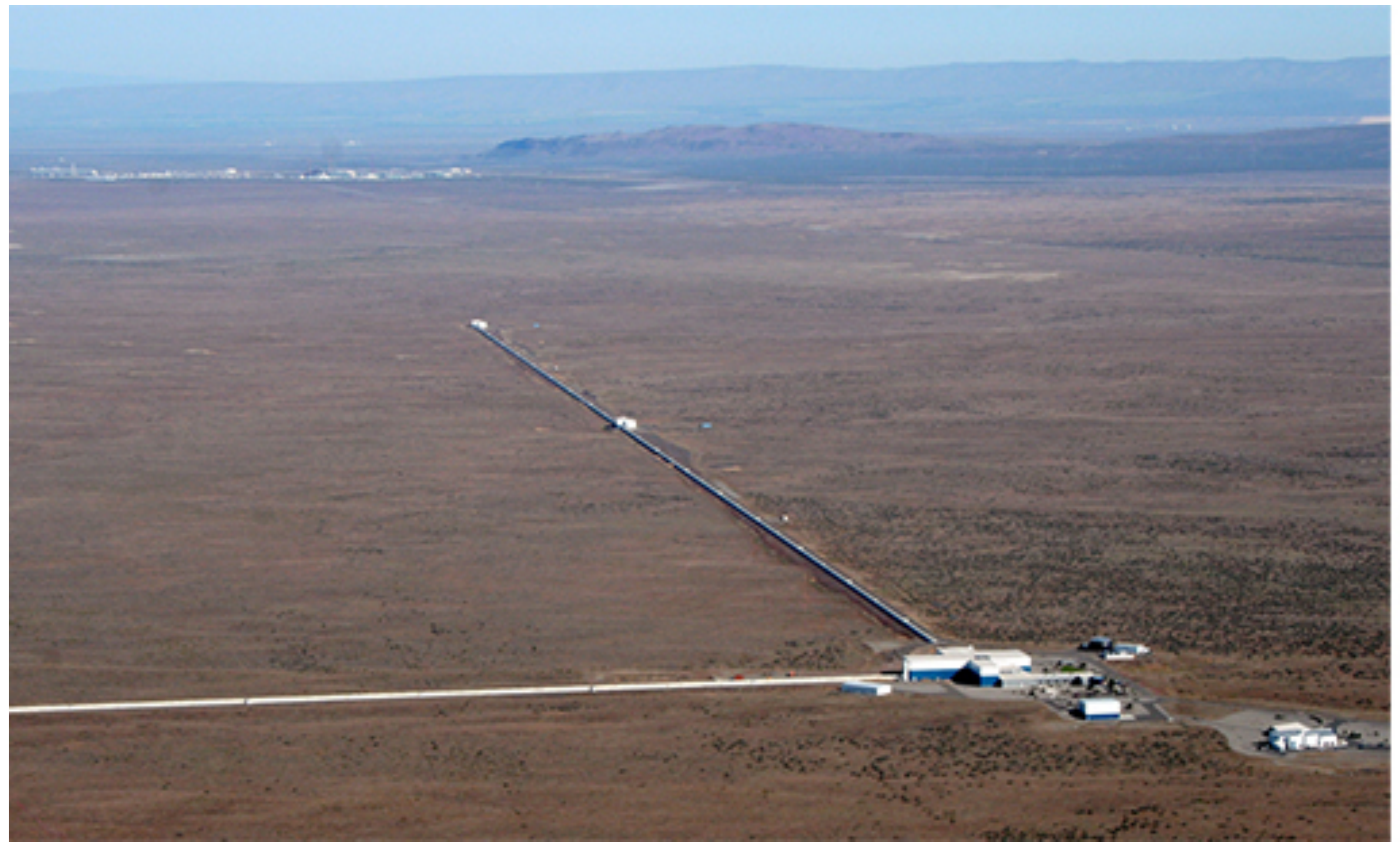
Ground based laser interferometers

Most sensitive instrument on Earth

1000 times smaller than an atom

10 ~1000 Hz

LIGO | Handford



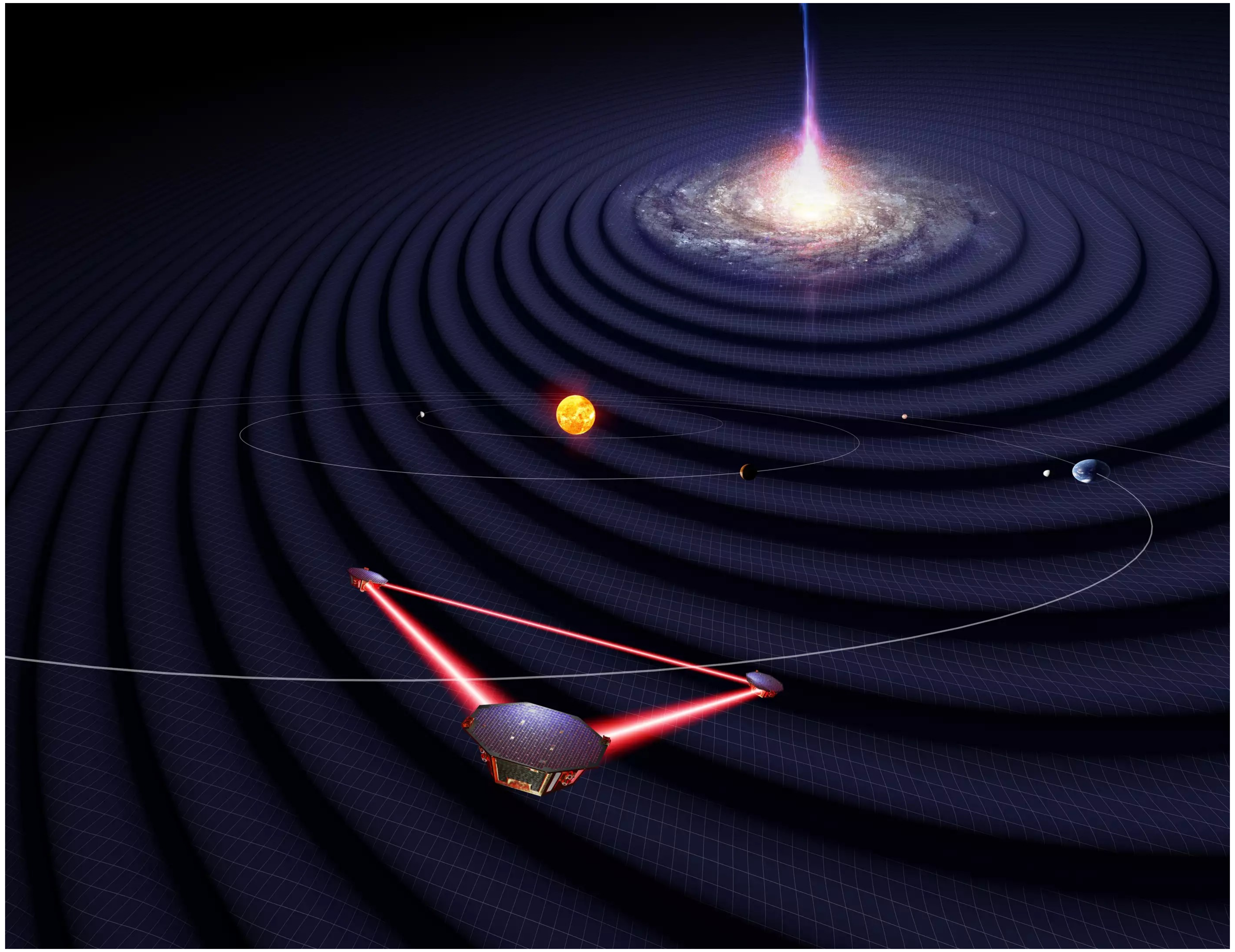
LIGO |Livingston

Virgo

Credits: LIGO Laboratory (first two images) and Virgo / Nicola Baldocchi 2015

+ KAGRA

Space based laser interferometers

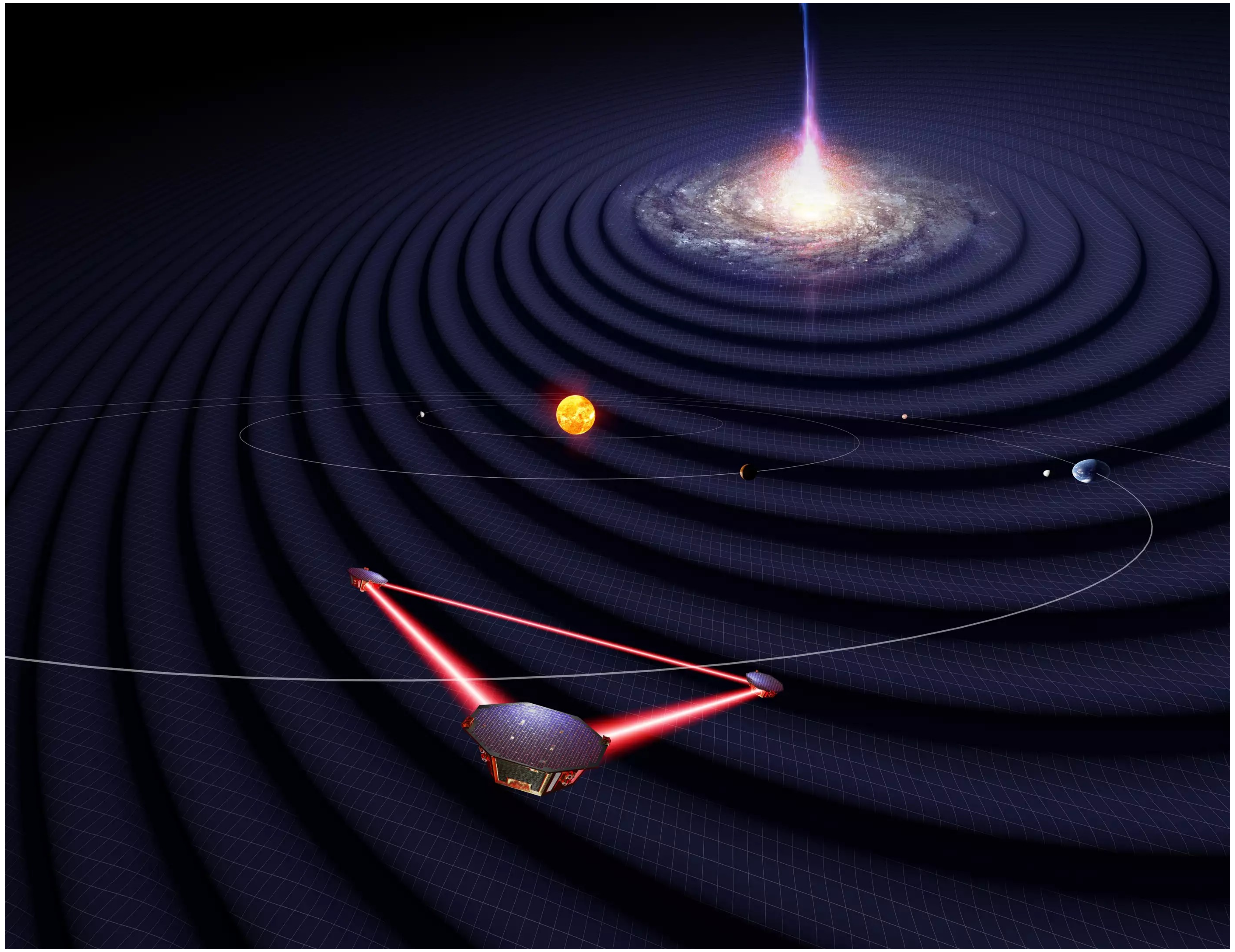


Credits: University of Florida / Simon Barke (CC BY 4.0)

LISA is the future! ~2037 (Amaro-Seoane+ 2017, 2022)

0.0001 ~ 0.1Hz

Space based laser interferometers



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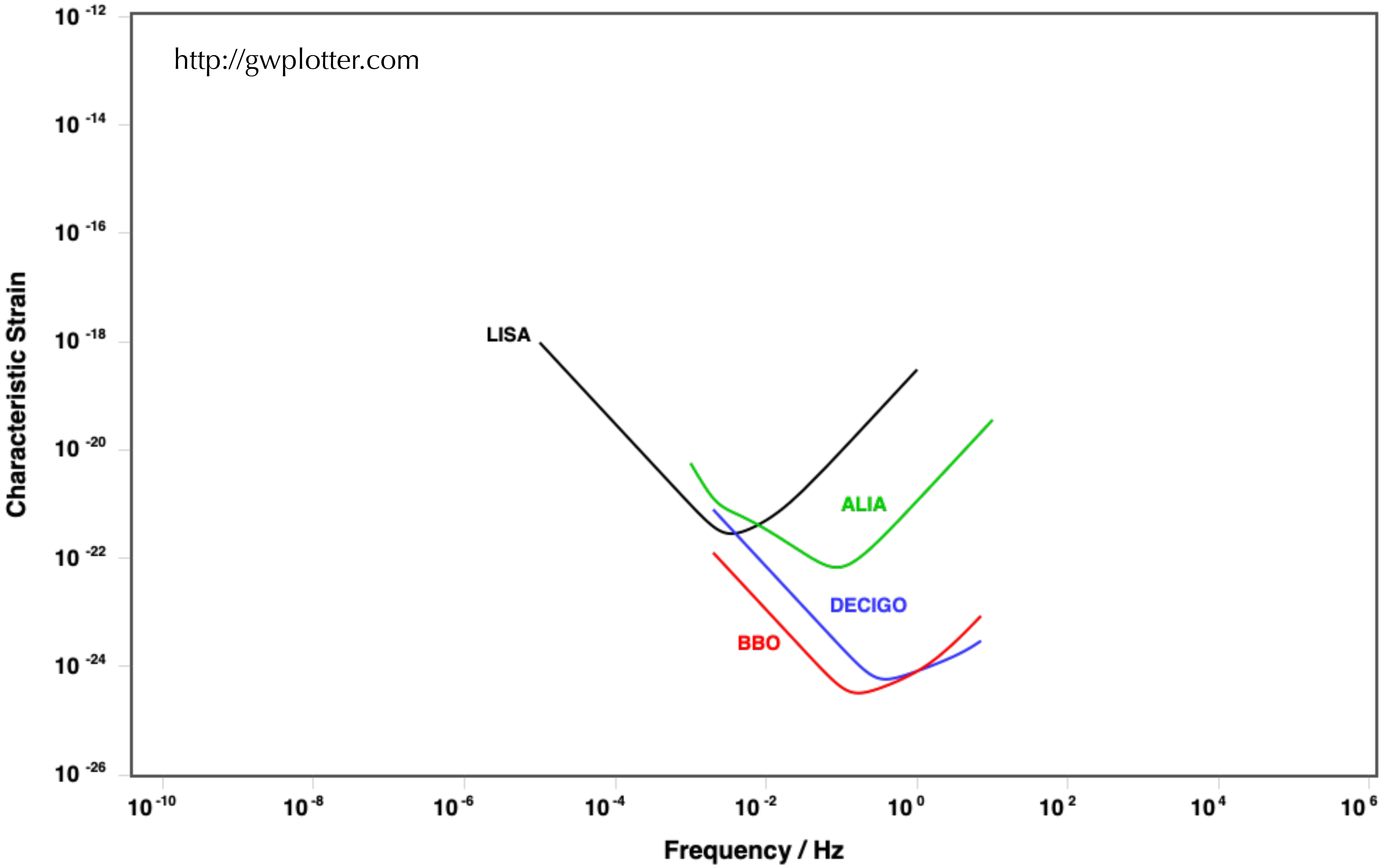

General Relativity in a nutshell

Einstein field equations

$$\underset{\text{curvature}}{G_{\mu\nu}} \propto \underset{\text{mass and energy}}{T_{\mu\nu}}$$

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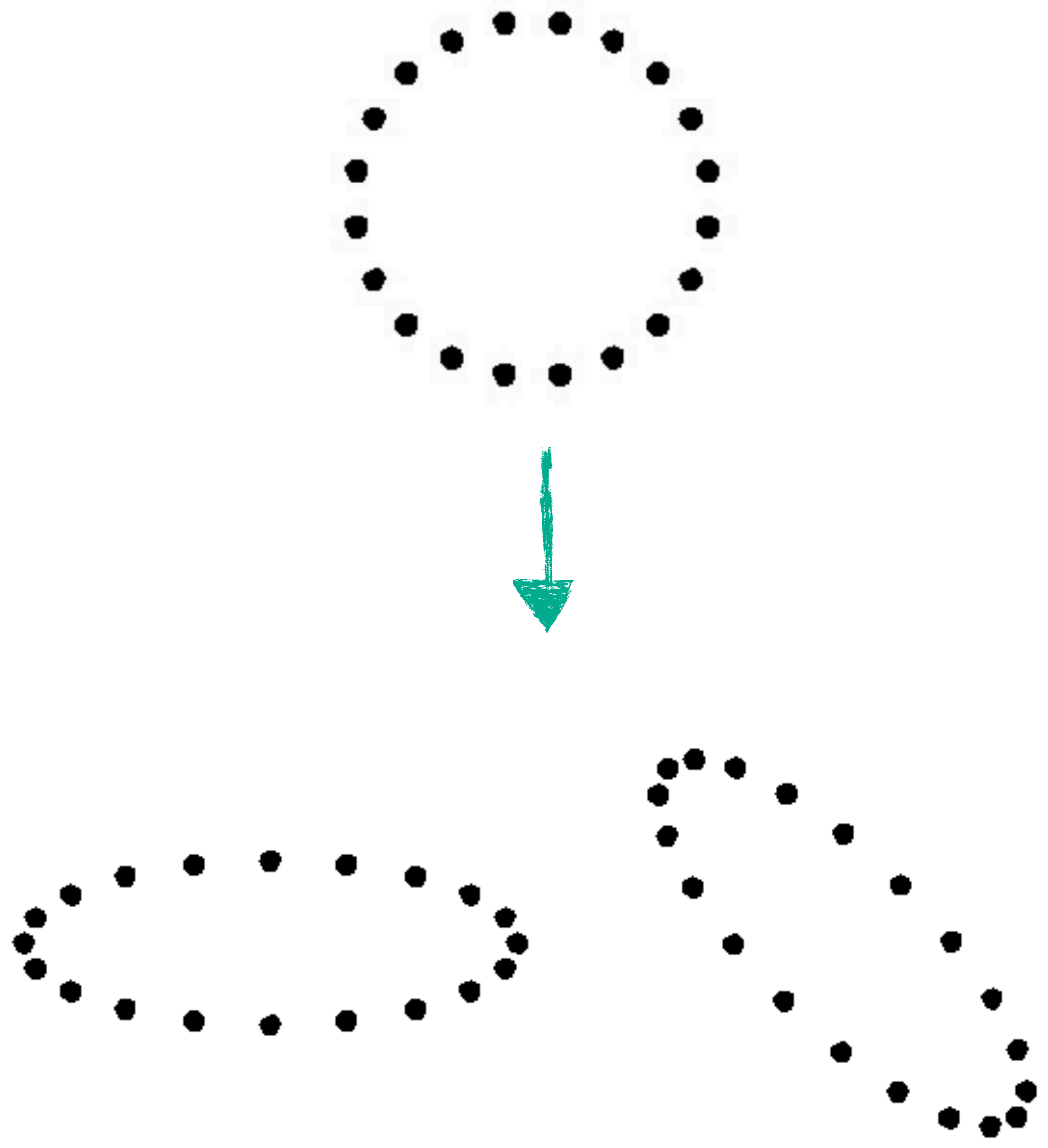
Accelerated, asymmetric mass distribution perturbs spacetime

↓

Gravitational waves

$$h \sim \frac{\Delta L}{L}$$



In General Relativity, two polarisations

$$h_+,\ h_\times$$

Steps to implement GWs in PHANTOM

Price et al. 2018:

- low-memory, fast, high-efficient
- widely tested for accretion physics
- we love PHANTOM

Liptai and Price 2019:

- able to capture relativistic shocks
- precise and accurate treatment of orbital dynamics
- ability to work in Kerr geometry

Steps to implement GWs in PHANTOM

Toscani, Lodato, Nealon 2019
- in post process

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$$h^{TT}(t, \mathbf{n}) \propto \ddot{M}^{kl}$$

$$M^{kl} = \frac{1}{c^2}\int d\mathbf{x} T_{00} x^k x^l \Rightarrow M^{kl} = \sum_a m_a x_a^k x_a^l,$$

On the fly!

$$\ddot{M}^{kl} = \sum_a m_a (\ddot{x}^l x^k + 2\dot{x}^k \dot{x}^l + x^l \ddot{x}^k)_a$$

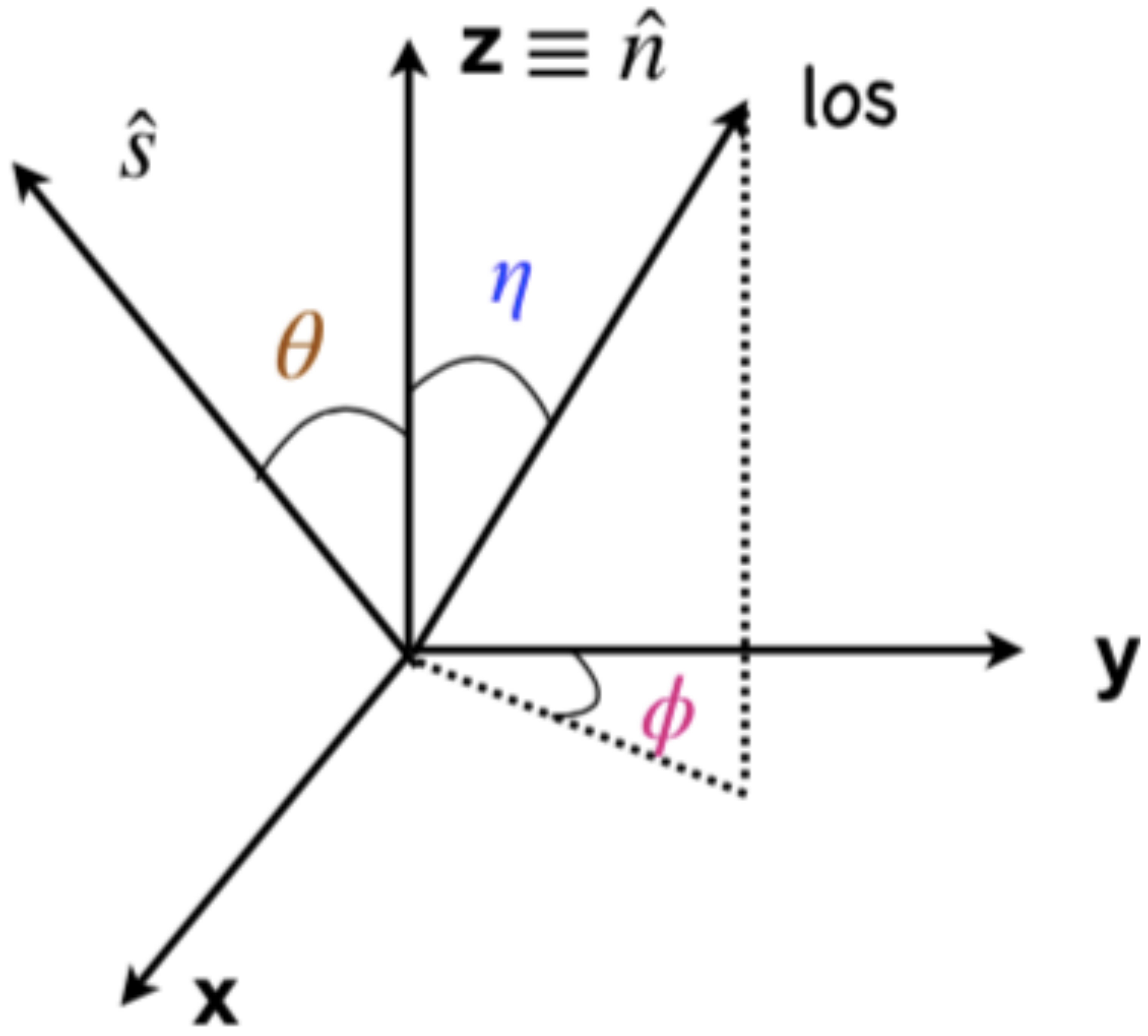
M: inertia moment of the system

a: index that runs over the number of particles

$$h_+ \, h_\times$$

Toscani, Lodato, Price, Liptai 2022

Steps to implement GWs in PHANTOM



η : angle between the line of sight and the normal to the orbit

θ : rotation of xy plane

ϕ : angle between the projection between line of sight and y axis

Toscani, Lodato, Price, Liptai 2022

Tidal Disruption Events (TDEs)

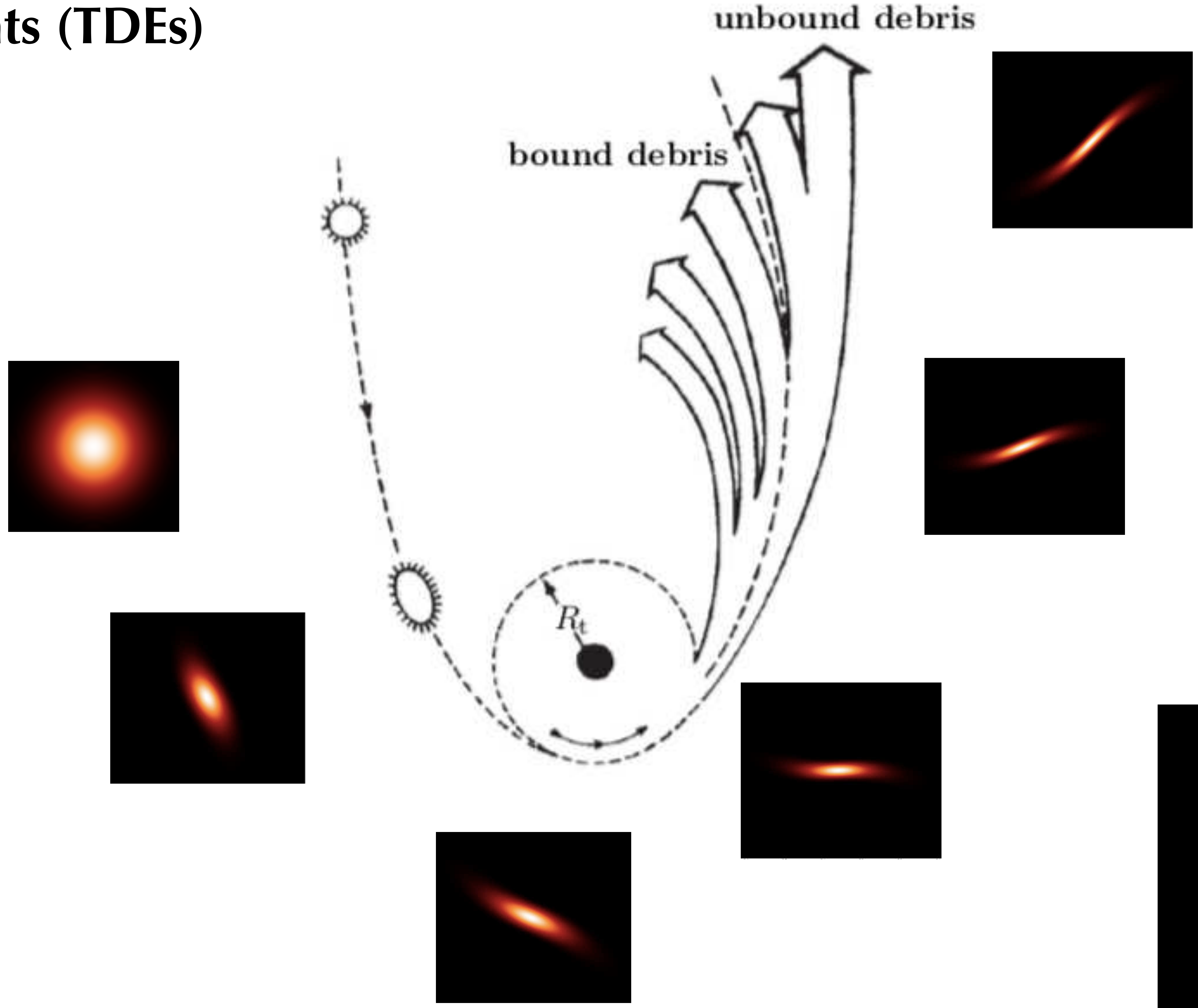


Image from Rees (1988). Snapshots by M. Toscani.
Simulation done with GRPHANTOM (Price and Liptai 2019)
and visualized with SPLASH (Price 2018).

Tidal Disruption Events (TDEs)

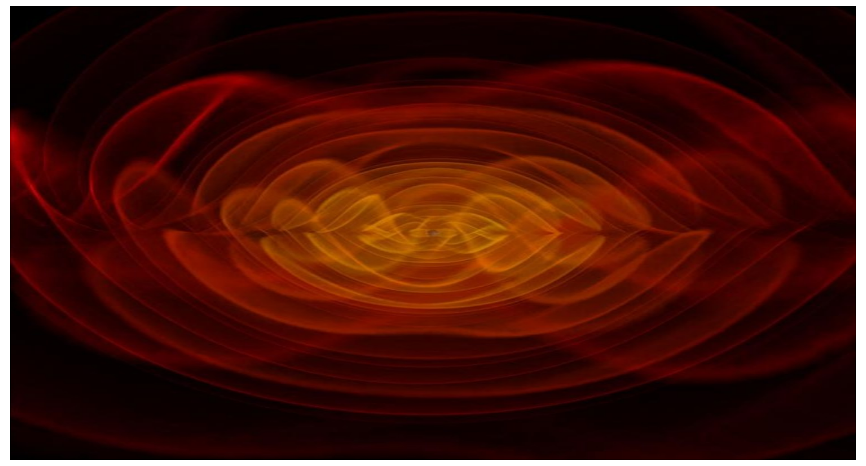
electromagnetic (EM) sources
accretion
100 events
optical, X-rays, radio

see reviews: vanVelzen et al 2020, Saxton et al. 2020, Alexander et al. 2020

neutrino sources

few potential candidates

Stein et al. 2021, Hayasaki 2021, Reusch et al. 2021



GW sources
disruption

Guillochon & Ramirez-Ruiz 2009, Stone et al. 2013, Kobayashi et al. 2004, **Toscani et al. 2019**, **Toscani et al. 2021**

GWs from TDEs

<u>monochromatic GW burst</u>

Sun-like star disrupted by a BH

$M_{\rm h} = 10^6 {\rm M}_\odot$

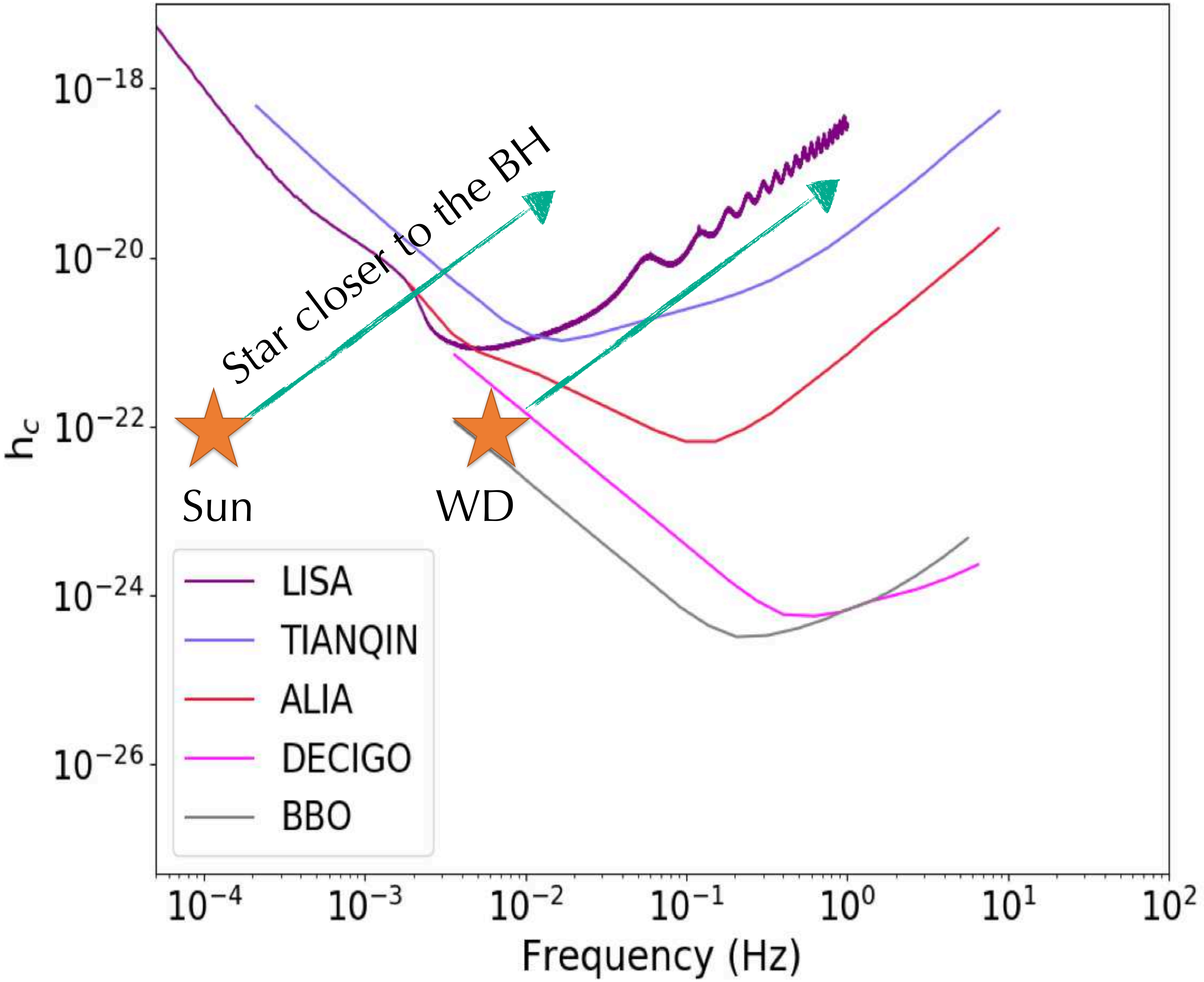
$$h \approx 10^{-22}, \quad f \approx 10^{-4}{\rm Hz}$$

White dwarf (WD)

$M_* = 0.5{\rm M}_\odot, {\rm R}_* = 0.01{\rm R}_\odot$

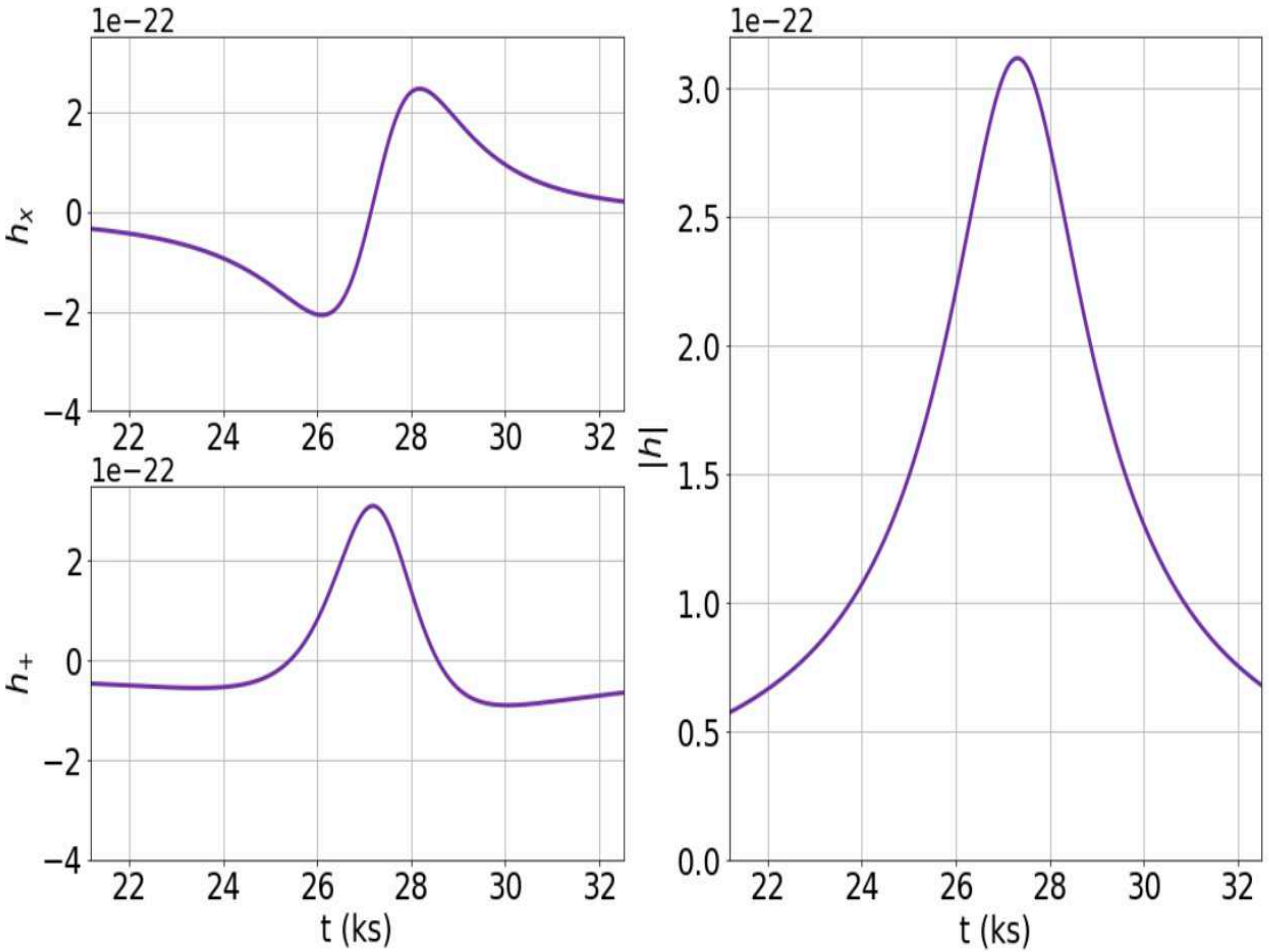
disrupted by a BH $\quad M_{\rm h} = 10^4 {\rm M}_\odot$

$$h \approx 10^{-22}, \quad f \approx 10^{-2}{\rm Hz}$$



GWs from TDEs

Toscani, Lodato, Price, Liptai 2022



Standard TDE at 20 Mpc

Face-on signals

243 simulations

'Living' catalogue

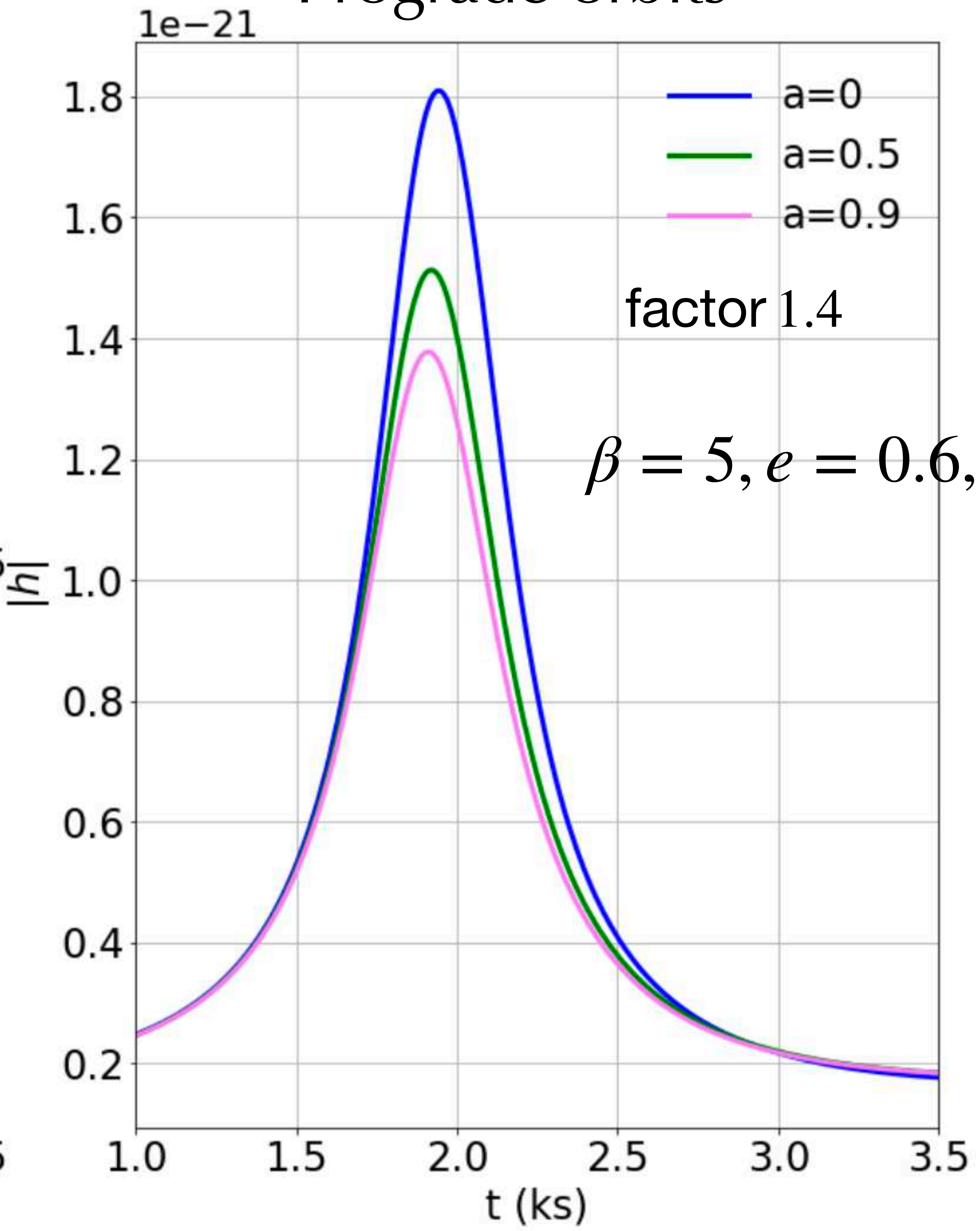
ONLINE OPEN CATALOGUE

https://gwcataloguetdes.fisica.unimi.it

GWs from TDEs

Toscani, Lodato, Price, Liptai 2022

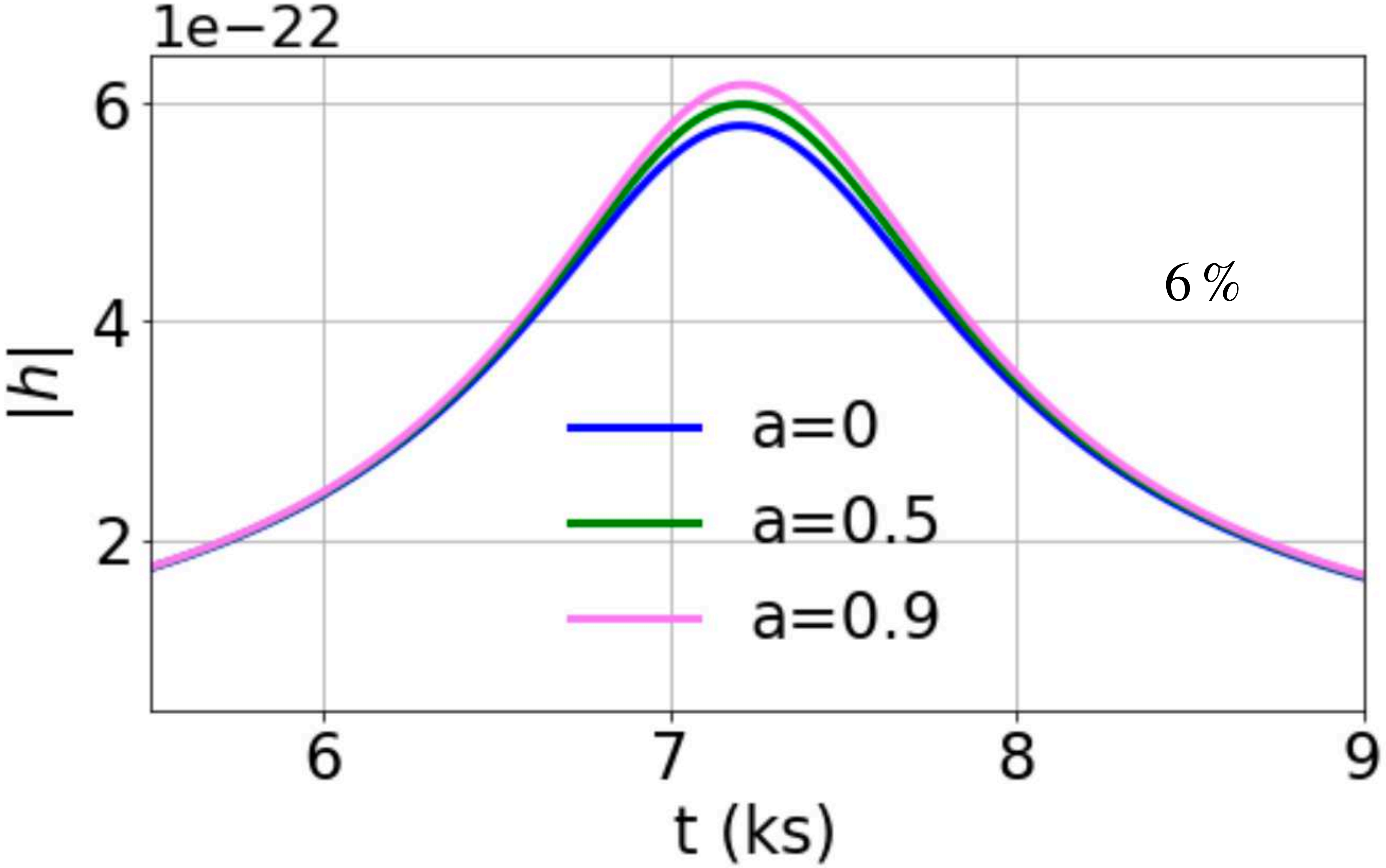
Prograde orbits



$\beta = 5, e = 0.6, \theta = 0$

Retrograde orbits

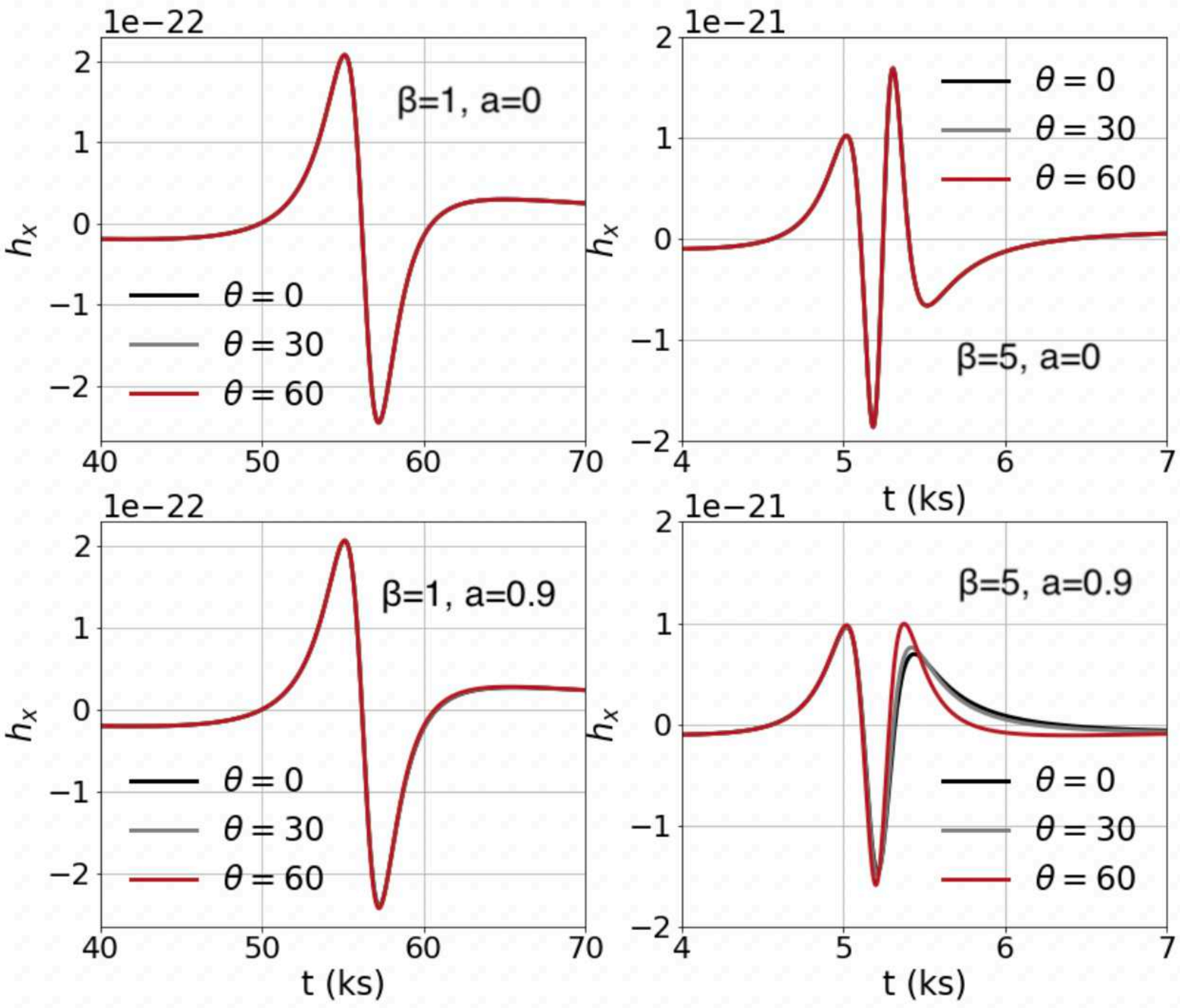
$\beta = 2, e = 0.6, \theta = 0$



GW signal increases for high retrograde orbits, decreases for high prograde orbits

GWs from TDEs

Toscani, Lodato, Price, Liptai 2022

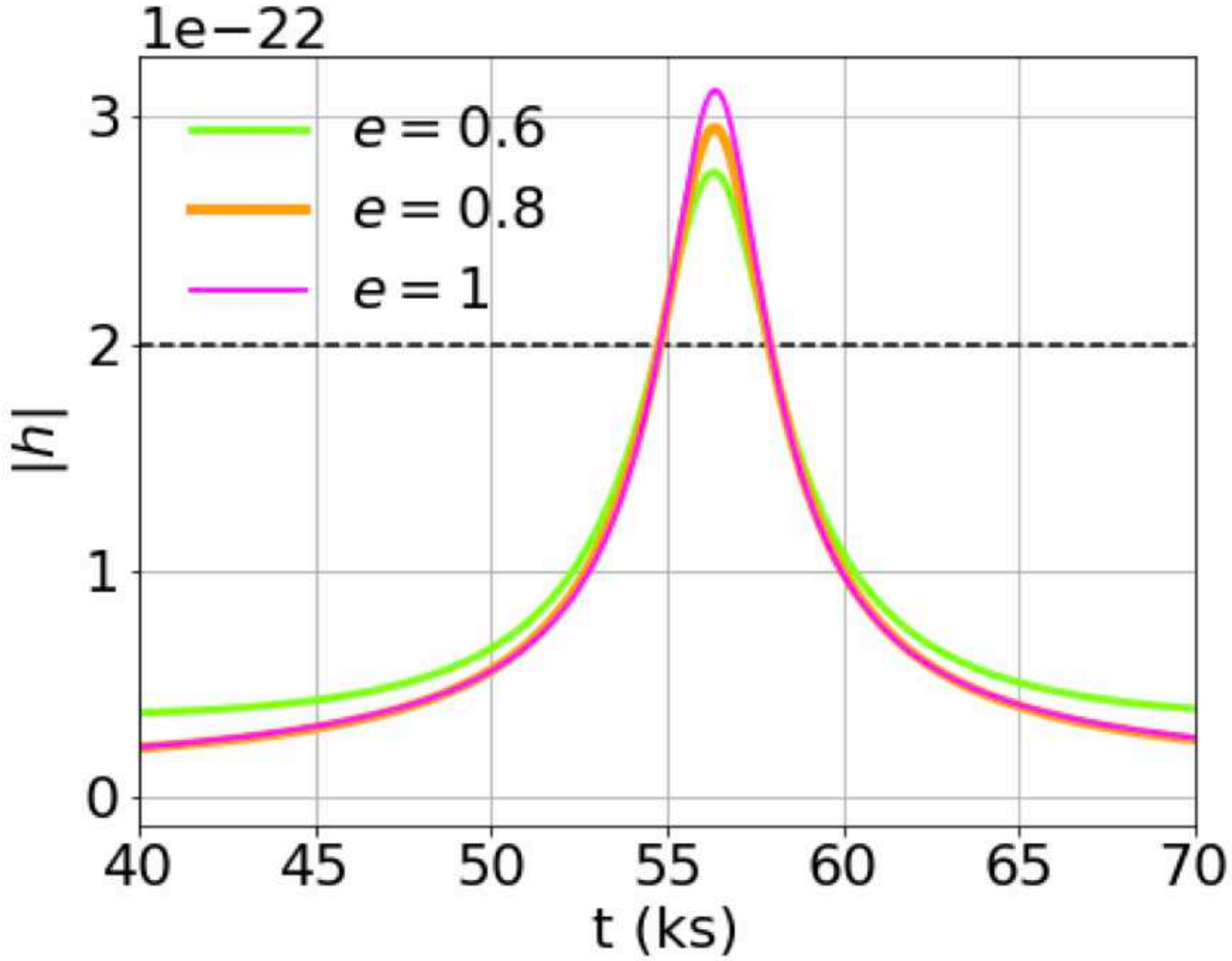


$e = 0.8$

Inclination angles affect signal only with spin AND penetrating events

GWs from TDEs

Toscani, Lodato, Price, Liptai 2022

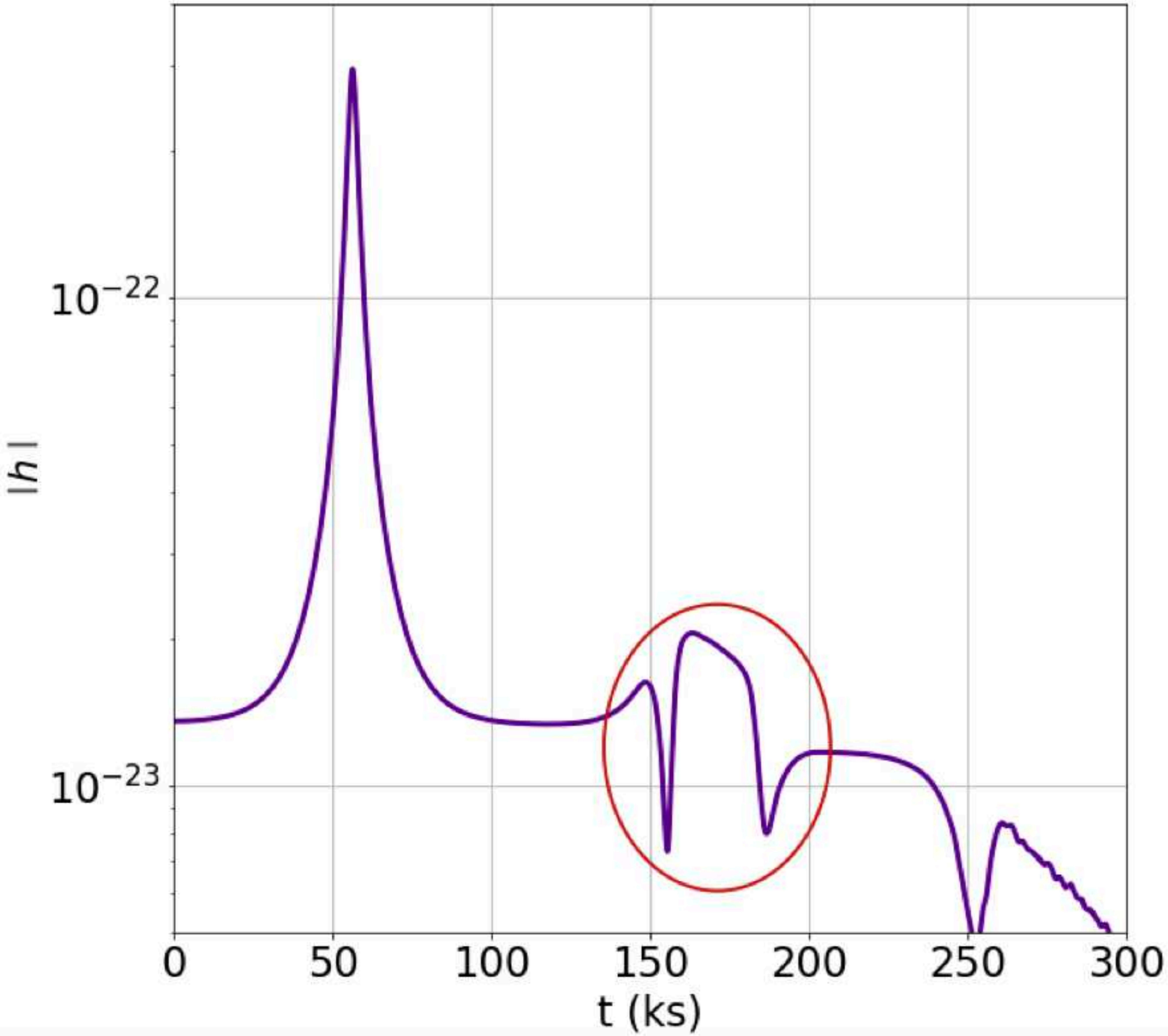


$\beta = 1, \theta = 0$

GW signal increases for higher eccentricities

GWs from TDEs

Toscani, Lodato, Price, Liptai 2022



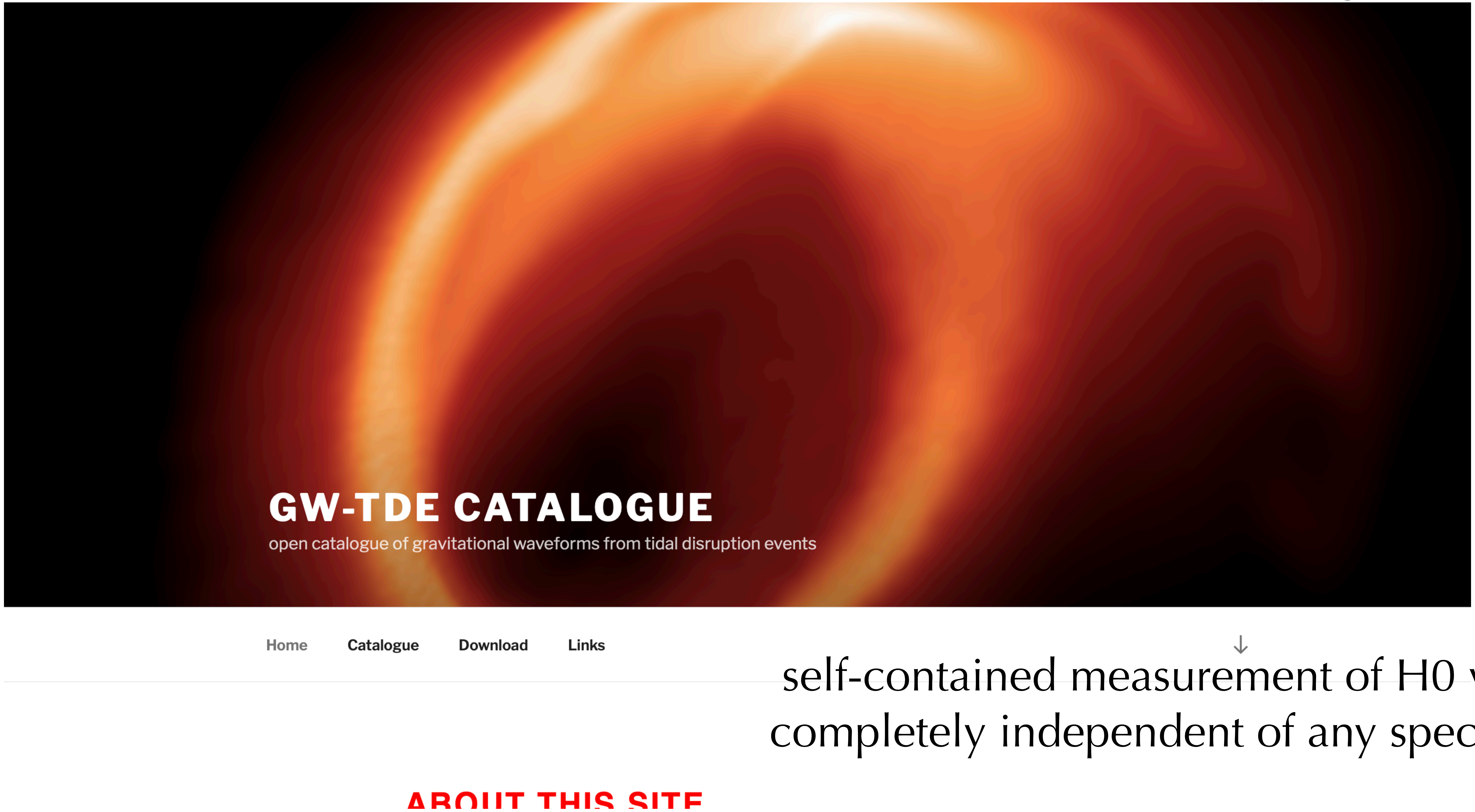
$\beta = 1, e = 0.8$

With interferometers sensitive enough, combined detection of GWs and EM

What’s next

1) catalogue needs to be enlarged (maintained by myself)

https://gwcataloguetdes.fisica.unimi.it



↓

self-contained measurement of H0 via Hubble’s law, completely independent of any specific cosmological models

(idea suggested by Wong 2023)

What's next

2) Explore other systems or variations of TDEs

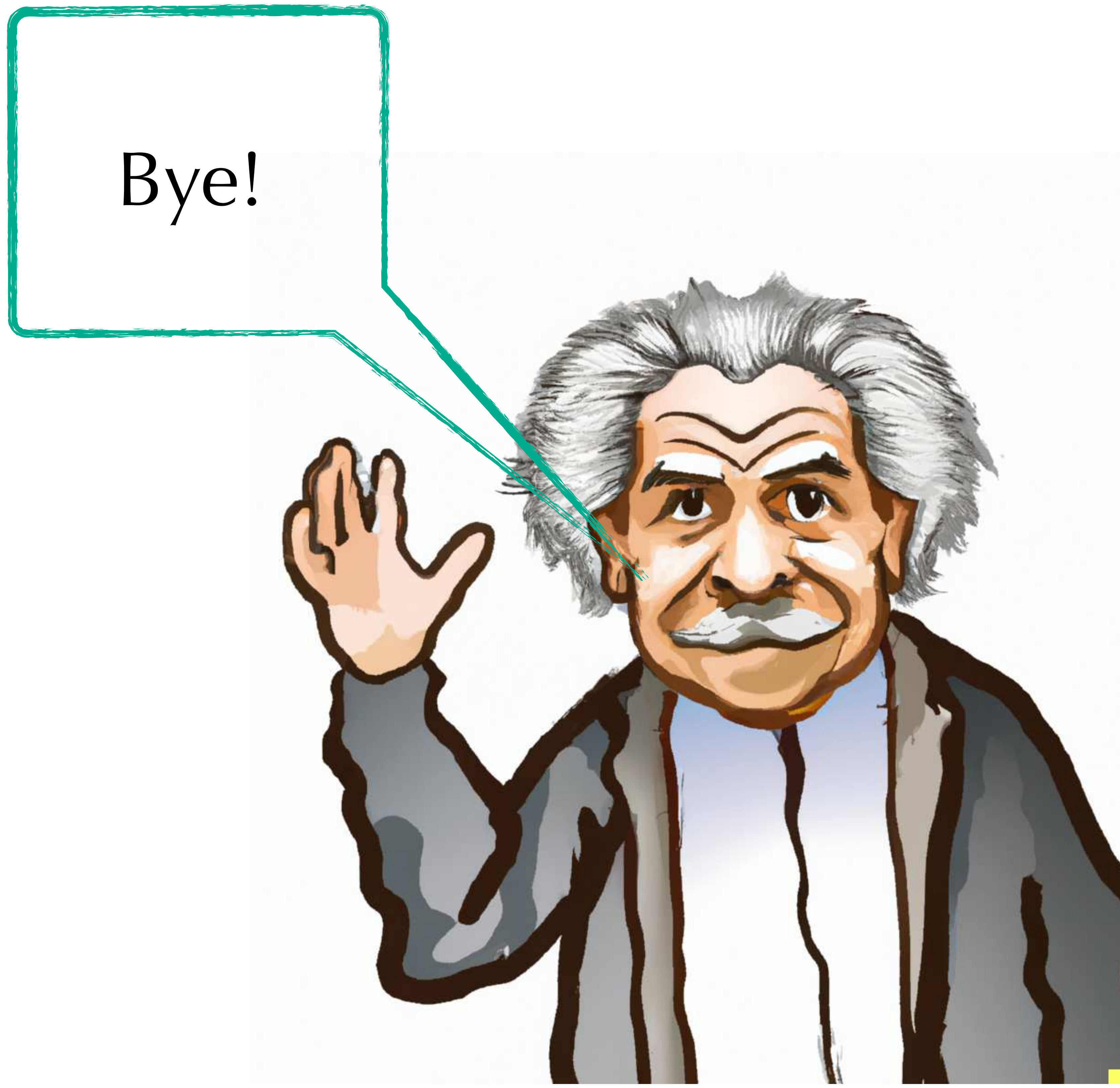
- Partial TDE
- TDE around a BH binary
- Binary stars tidally disrupted
- GW signal emitted by BH binary surrounded by a disc with some particular stuff going on
- Planet disruption

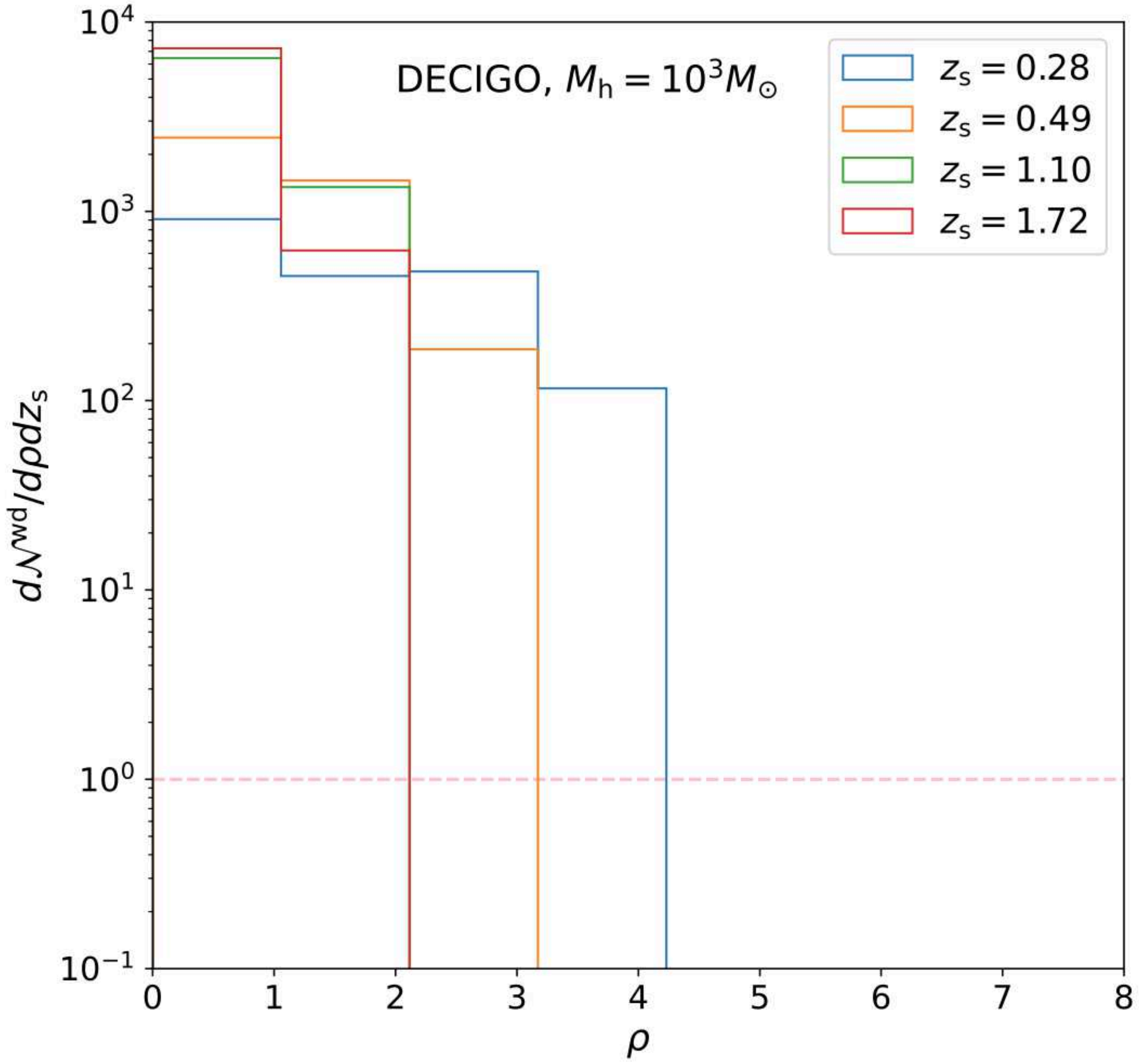
3) PostNewtonian formalism

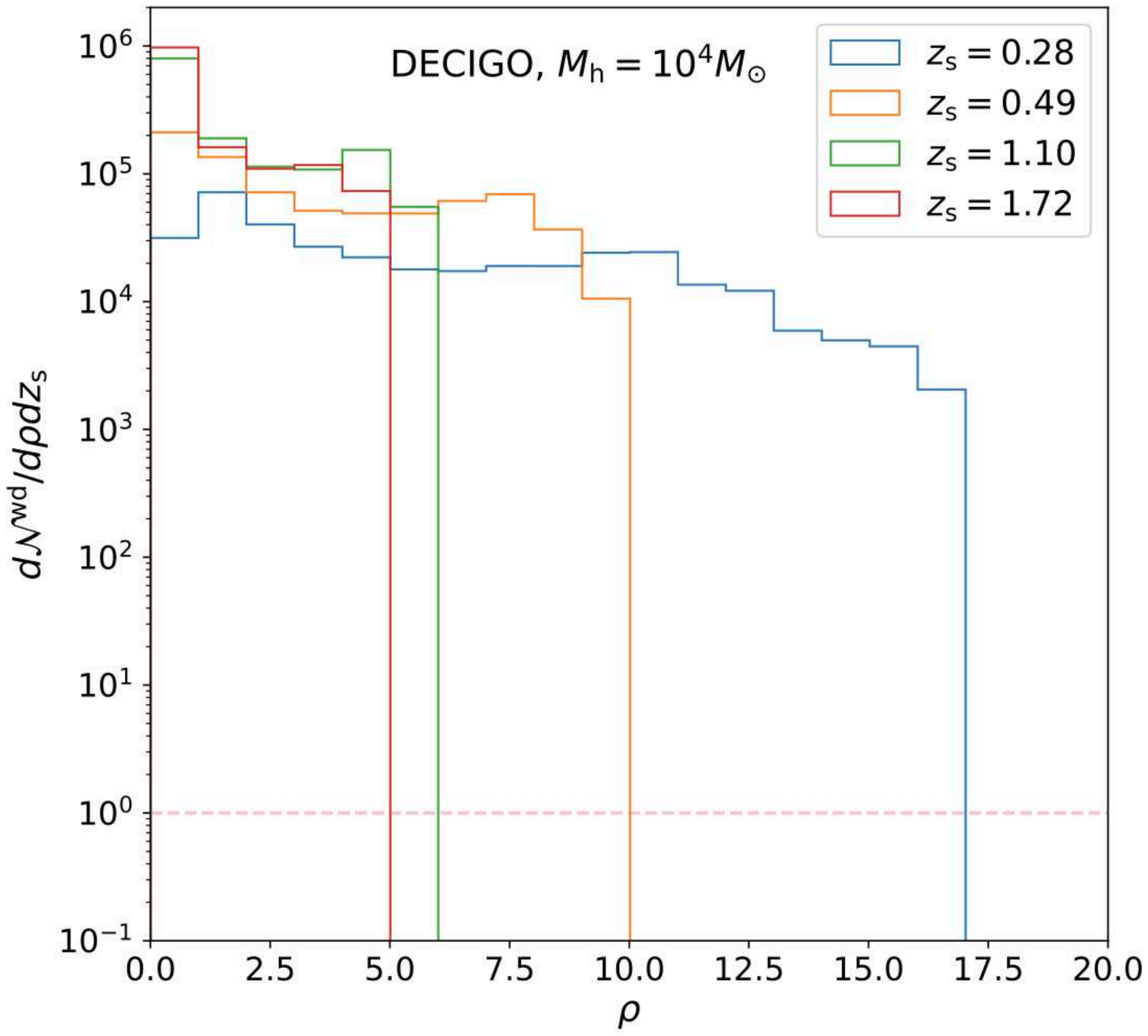
Fin

Thanks for your attention!

Questions?




DECIGO, $M_h = 10^3 M_\odot$
$z_s = 0.28$
$z_s = 0.49$
$z_s = 1.10$
$z_s = 1.72$
$d\mathcal{N}^{wd}/d\rho dz_s$
ρ


DECIGO, $M_h = 10^4 M_\odot$
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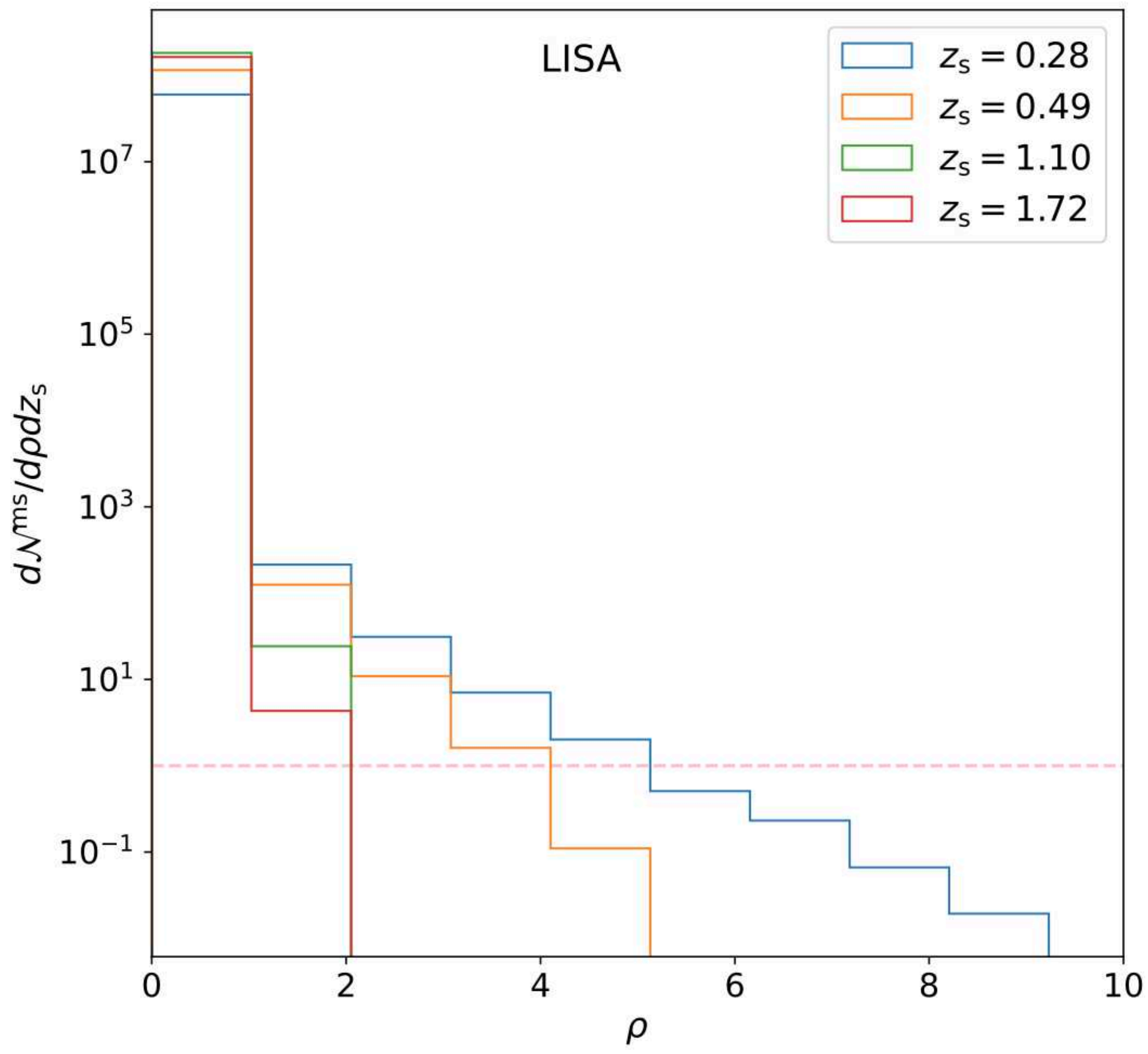
LISA
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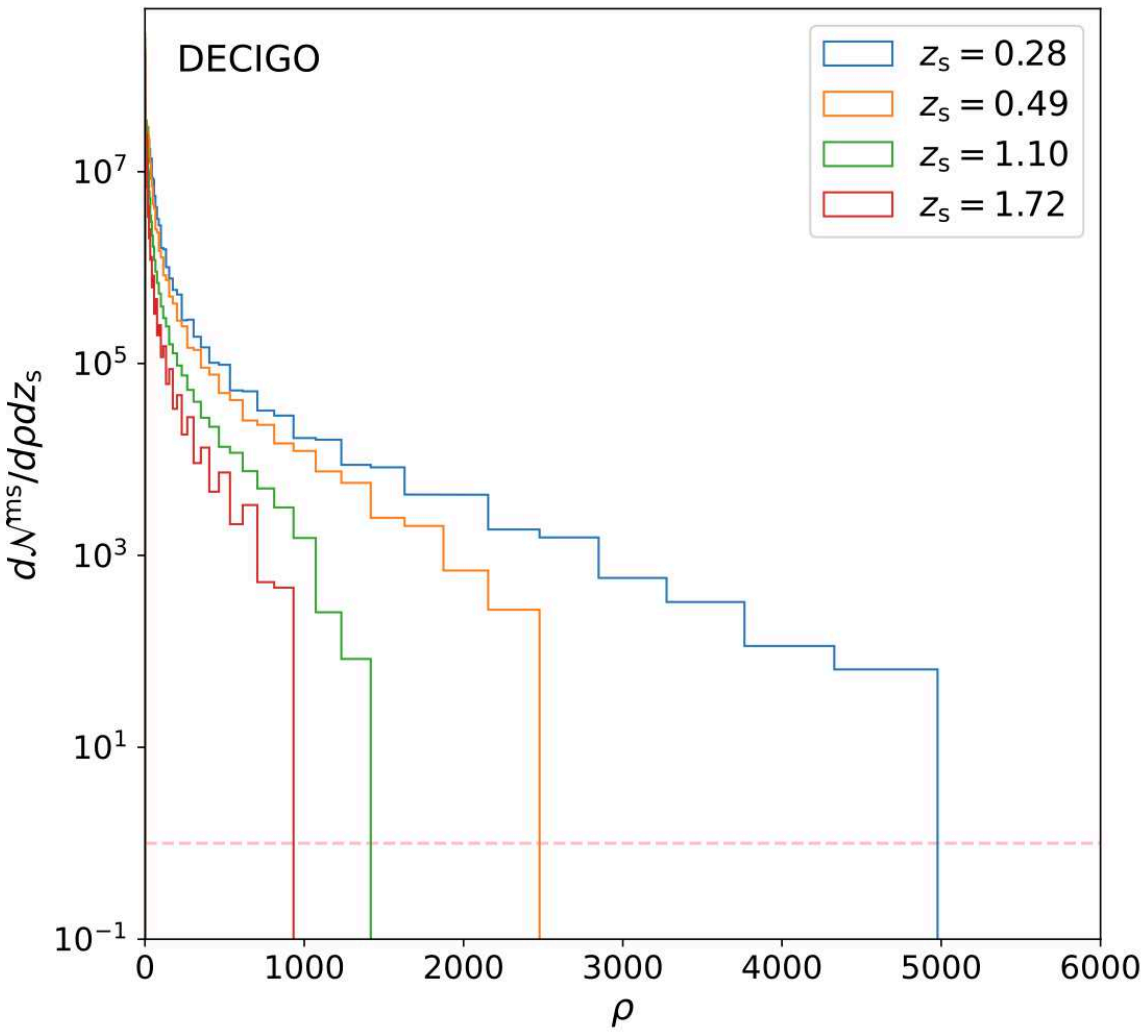
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ρ

$$|v_\phi| = \frac{c^3}{2\pi G M_\mathrm{h}} \left| \frac{1}{(2r/r_\mathrm{g})^{3/2} \pm a} \right|$$

$$v_\mathrm{kepl} = \left[\frac{G M_\mathrm{h}}{r_\mathrm{p}} (1+e) \right]^{1/2} \propto (1+e)^{1/2}$$