Multimessenger Astronomy with Tidal Disruption Events

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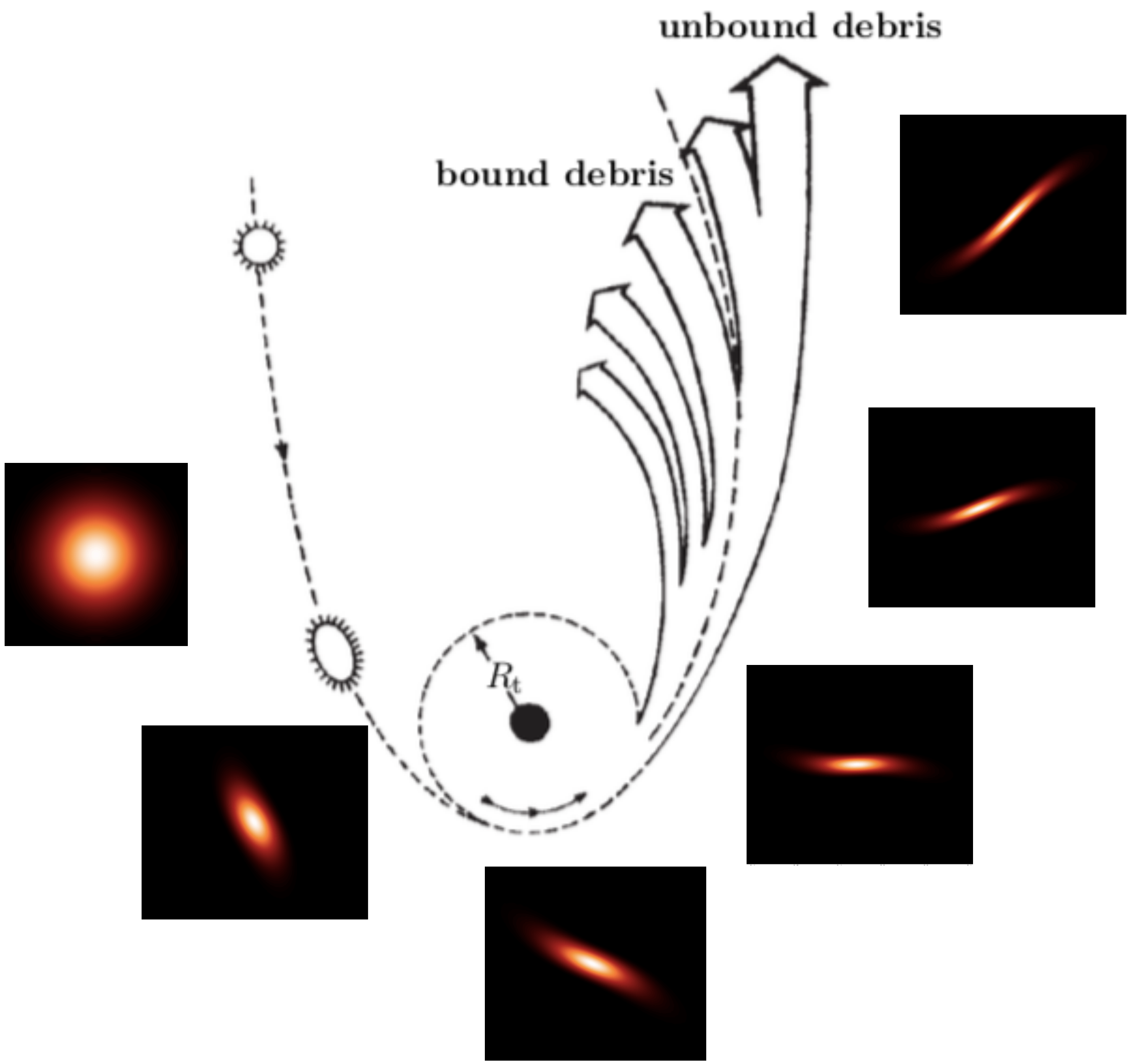
Basics of TDE physics

Tidal Disruption Events (TDEs) ⟷ stars disrupted by black hole (BH) tides



Star on a Keplerian parabolic orbit around a massive BH

While approaching the pericenter, it gets deformed by BH tides

At the pericenter it gets disrupted

After the disruption, roughly half of the stellar debris circularize

Image from Rees (1988). Snapshots by **Toscani M.** Simulation done with GRPHANTOM (Price and Liptai 2019) and visualized with SPLASH (Price 2017)

Basics of TDE physics

$$R_t \approx R_* \left(\frac{M_h}{M_*}\right)^{1/3} \approx 7 \times 10^{12} \mathrm{cm} \times \mathrm{r}_* \left(\frac{\mathrm{m}_6}{\mathrm{m}_*}\right)^{1/3}$$

$$M_h = 10^6 m_6 \mathrm{M}_\odot$$
$$M_* = m_* \mathrm{M}_\odot$$
$$R_* = r_* \mathrm{R}_\odot$$

$R_p > R_t \rightarrow$ squeezars

$R_p \sim R_t \rightarrow$ partial TDEs (Tiengo A., Esposito P., **Toscani M.** et al., submitted)

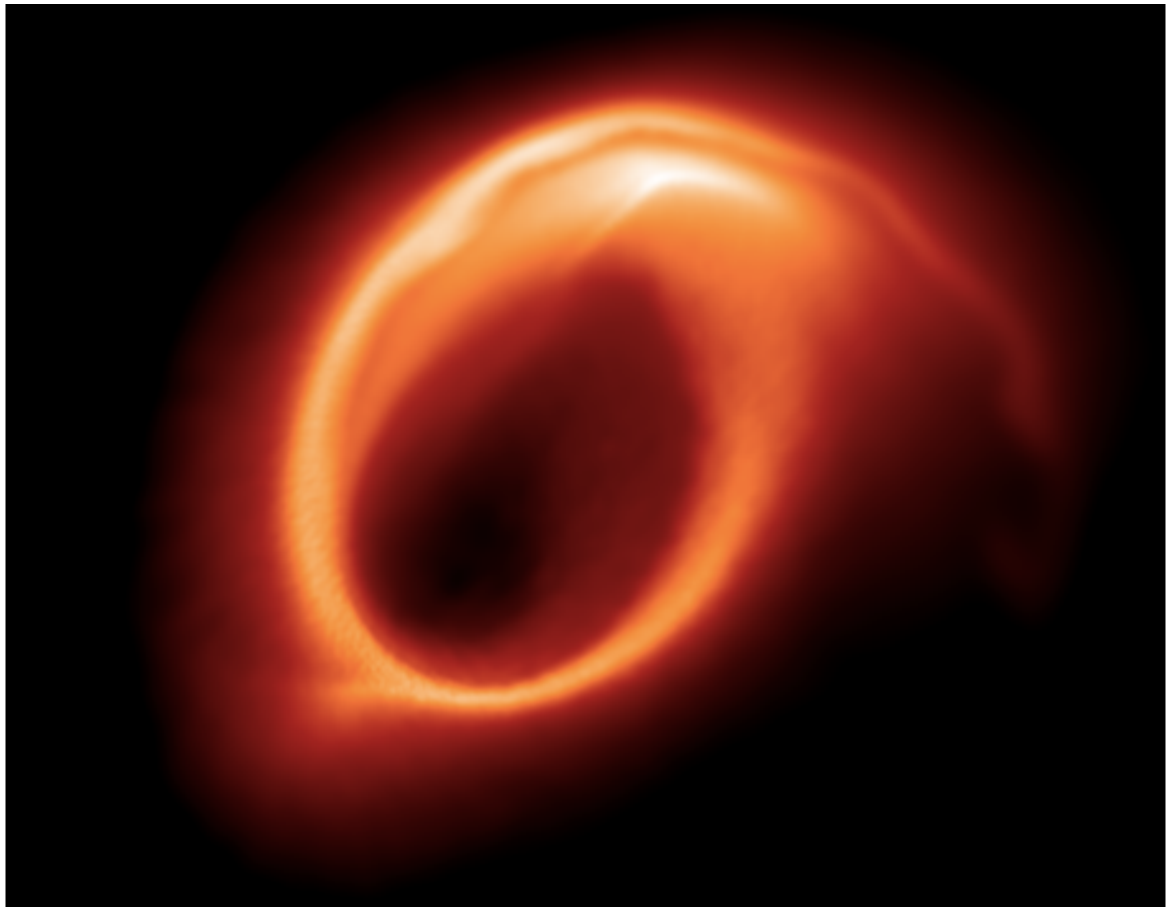
$R_p < R_t \rightarrow$ full TDEs

$$\beta = \frac{R_t}{R_p}$$

→ $\beta_{min} = \beta_{cr}$ → partial vs full

→ β_{max} → Hills mass upper limit for BH

Basics of TDE physics



Snapshot by Toscani M.
Simulation done with GRPHANTOM (Price and Liptai 2019) and visualized with SPLASH (Price 2017)

$$t_{\mathrm{min}} \sim 40\,\mathrm{days} \times \mathrm{m}_6^{1/2} \mathrm{m}_*^{-1} \mathrm{r}_*^{3/2}$$

$$\dot{M} \propto t^{-5/3}$$

Rees 1988
Phinney 1989

Luminous electromagnetic (EM) flares produced

Peak luminosities can be super Eddington

See reviews: Rossi et al. 2020, Lodato et al. 2020, Stone et al. 2020

Emission from TDEs

EM radiation

optical
~30 events

reprocessing of X-ray

soft X-ray
~20 events

inner parts accretion disc

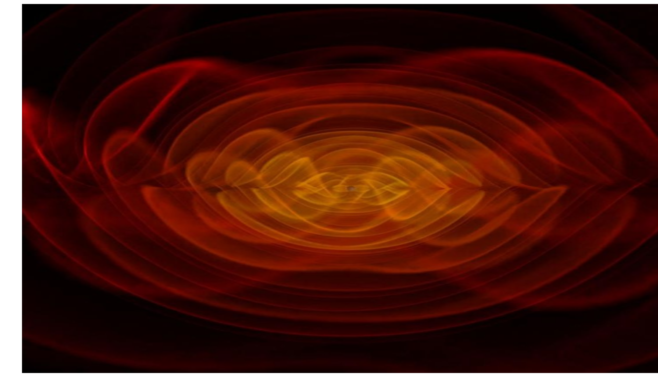
See reviews: van Velzen et al. 2020, Saxton et al. 2020, Alexander et al 2020

high energy neutrinos

a few potential candidates

internal shock in relativistic jets

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



GW emission

no detection so far

why?

GWs from TDEs

1 variation internal quadrupole of the star

(e.g. Guillochon et al. 2009, Stone et al. 2013)

↓

the star is approaching the pericenter

2 variation quadrupole star - BH

(Kobayashi et al. 2004, **Toscani et al. 2020, Toscani et al. 2021**)

↓

the star is disrupted

3 variation quadrupole debris-BH

(Kiuchi et al. 2004, **Toscani et al. 2019**)

↓

circularization process

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circularization process

GWs from TDEs

$$h \approx \beta \times 2 \times 10^{-22} \times m_*^{4/3} m_6^{2/3} r_*^{-1} d_{20}^{-1}$$

$$f \approx 10^{-4}\, Hz \times m_*^{1/2} r_*^{-3/2}$$

Point particle approximation on a Keplerian orbit

$$d_{20} = \frac{d}{20\, Mpc}$$

For a Sun-like star disrupted by a BH of $M_\mathrm{h} = 10^6 \mathrm{M}_\odot$

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

For a white dwarf (WD) of $M_* = 0.5\mathrm{M}_\odot$ and radius $R_* = 0.01\mathrm{R}_\odot$disrupted by a BH of $M_\mathrm{h} = 10^4 \mathrm{M}_\odot$

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

GWs from TDEs

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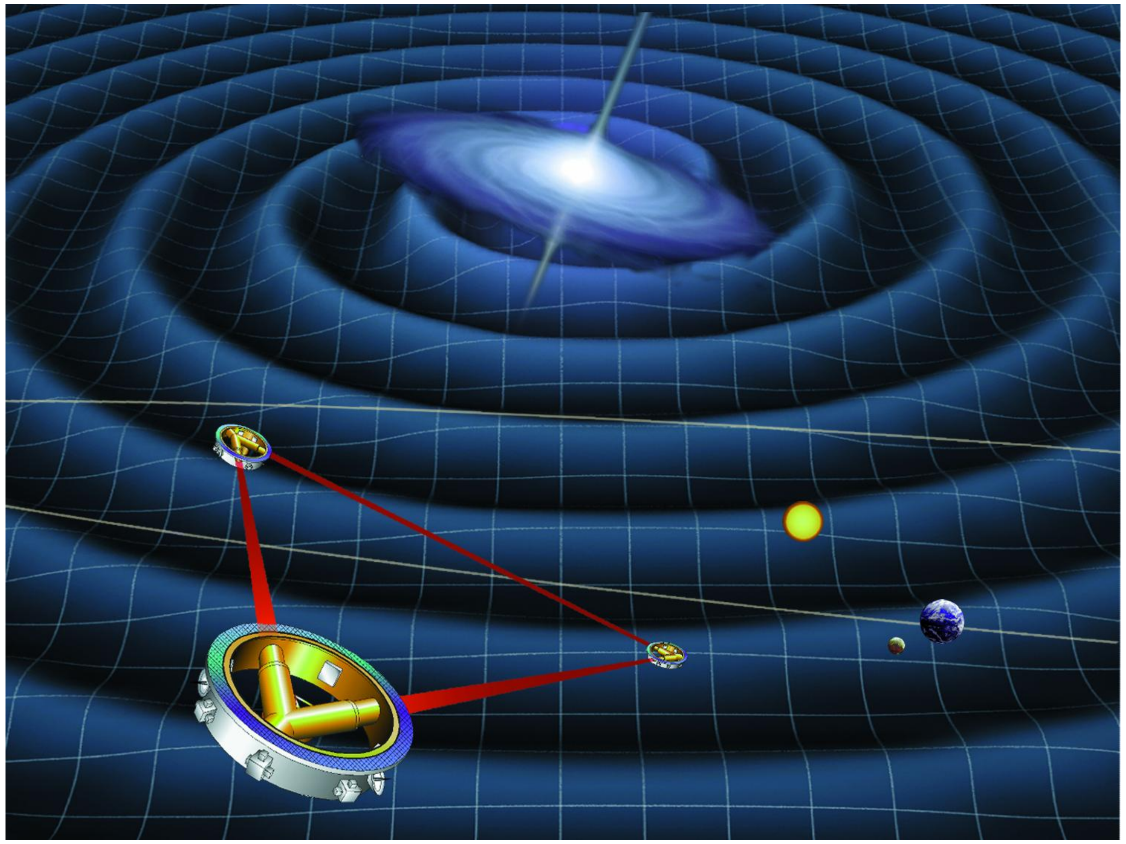
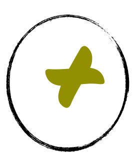
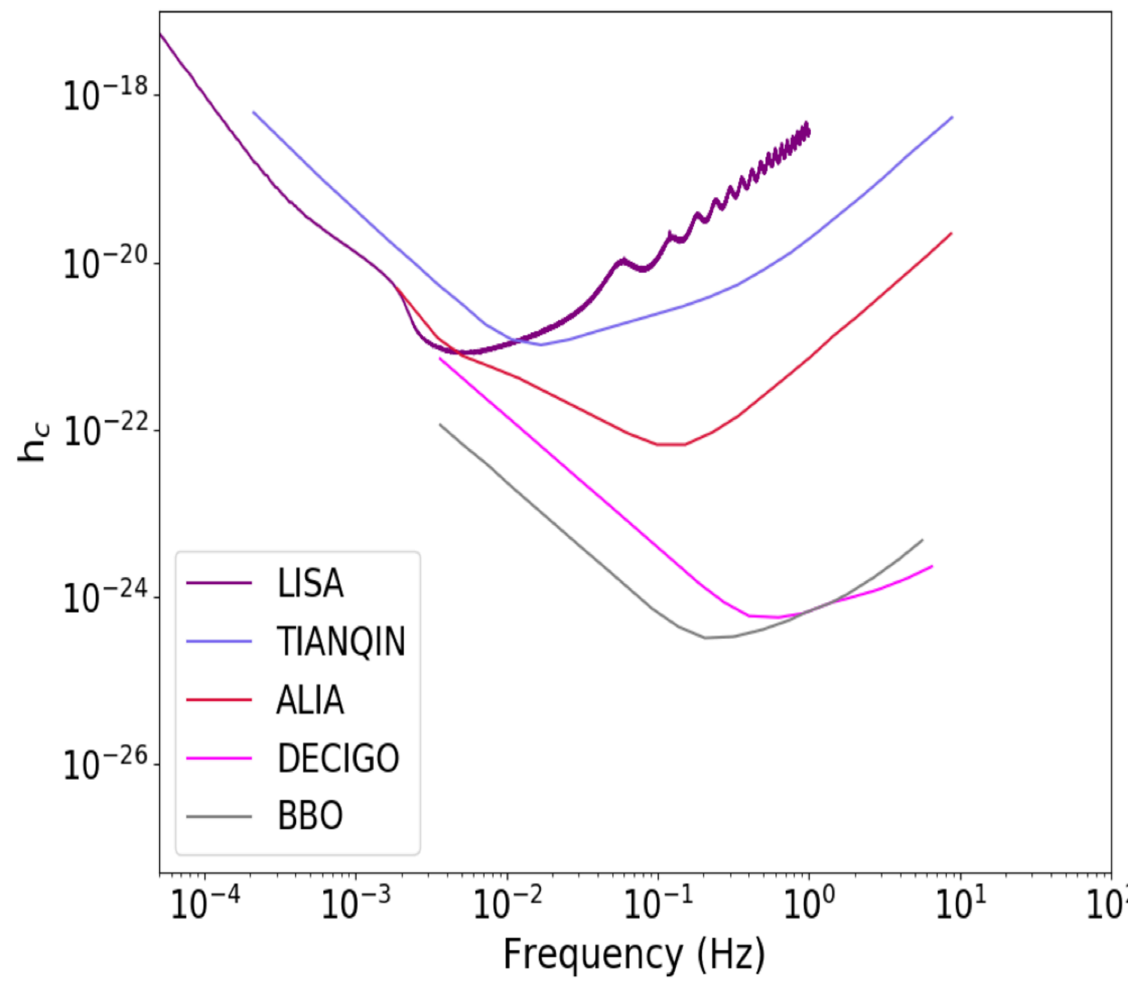


The Laser Interferometer Space Antenna (LISA) Amaro-Seoane et al. 2017

- space based
- monitoring distance between free falling test masses
- arms ~ 2.5 million of km
- 4 year duration (minimum)
- frequency range: 10^{-4}Hz – 10^{-1}Hz





Deci-Hertz observatories

天琴计划（TianQin)
DECIGO
ALIA
BBO

GWs from TDEs

Toscani et al. 2021

Smoothed particle hydrodynamic (SPH) code general relativistic fluid-dynamics (Price et al 2018, Liptai and Price 2019)

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

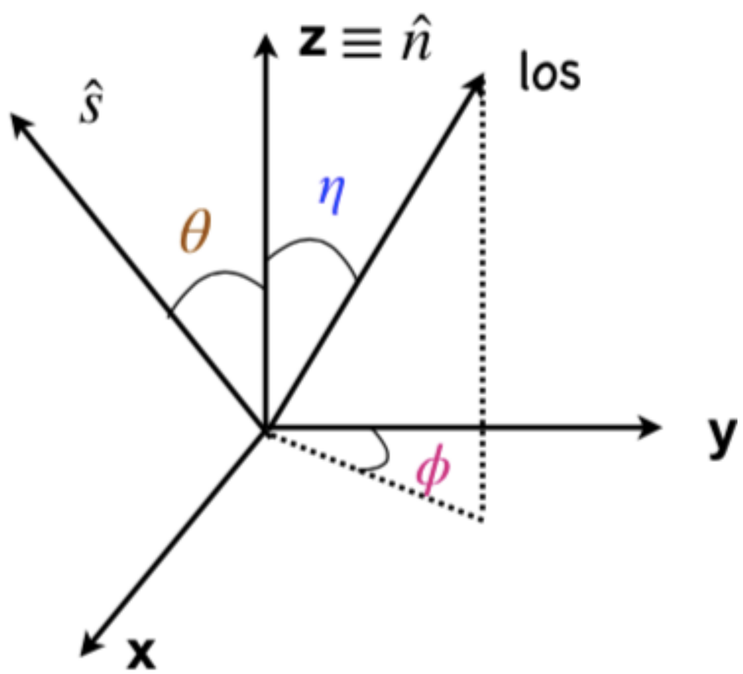
M: inertia moment of the system

$$M^{\mathrm{kl}} = \frac{1}{c^2} \int d\mathbf{x} T_{00} x^{\mathrm{k}} x^{\mathrm{l}} \Rightarrow M^{\mathrm{kl}} = \sum_{\mathrm{a}} m_{\mathrm{a}} x_{\mathrm{a}}^{\mathrm{k}} x_{\mathrm{a}}^{\mathrm{l}},$$

a: index that runs over the number of particles

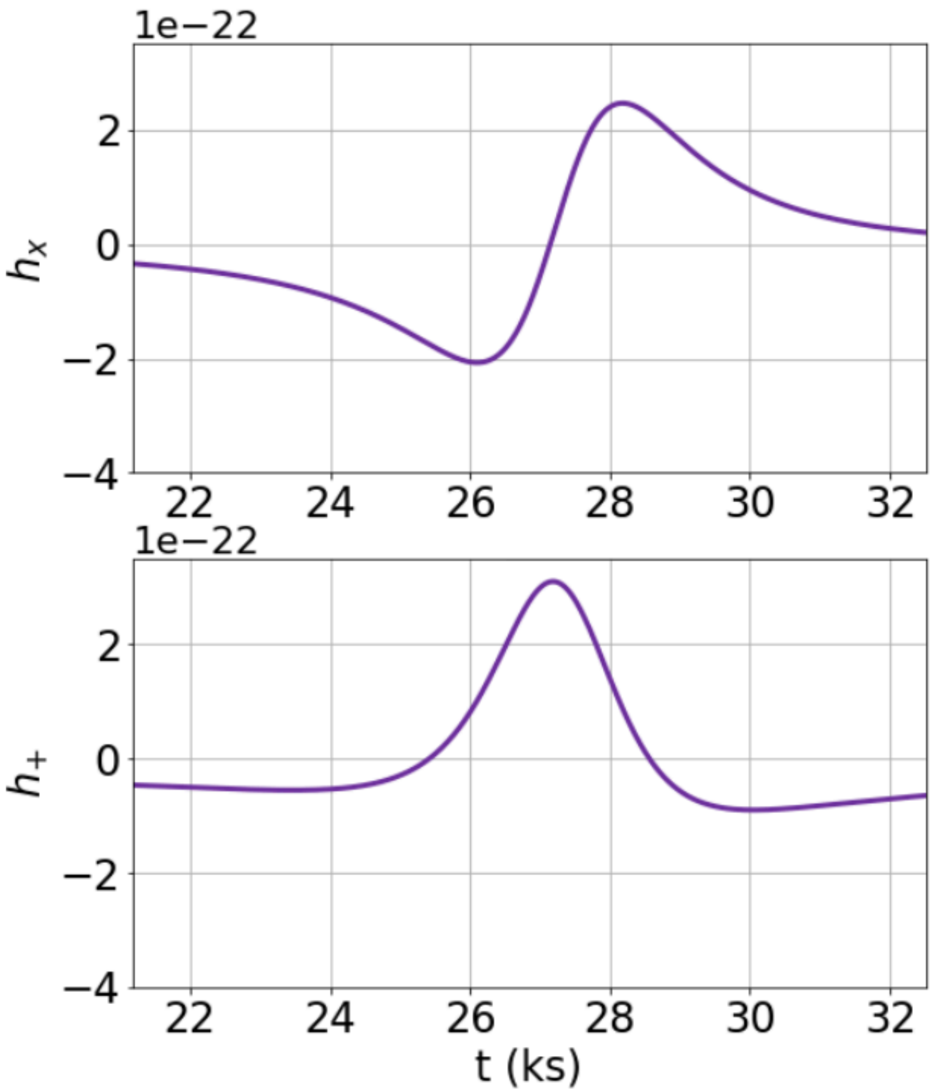
$$\ddot{M}^{\mathrm{kl}} = \sum_{\mathrm{a}} m_{\mathrm{a}} (\ddot{x}^{\mathrm{l}} x^{\mathrm{k}} + 2\dot{x}^{\mathrm{k}} \dot{x}^{\mathrm{l}} + x^{\mathrm{l}} \ddot{x}^{\mathrm{k}})_{\mathrm{a}}$$

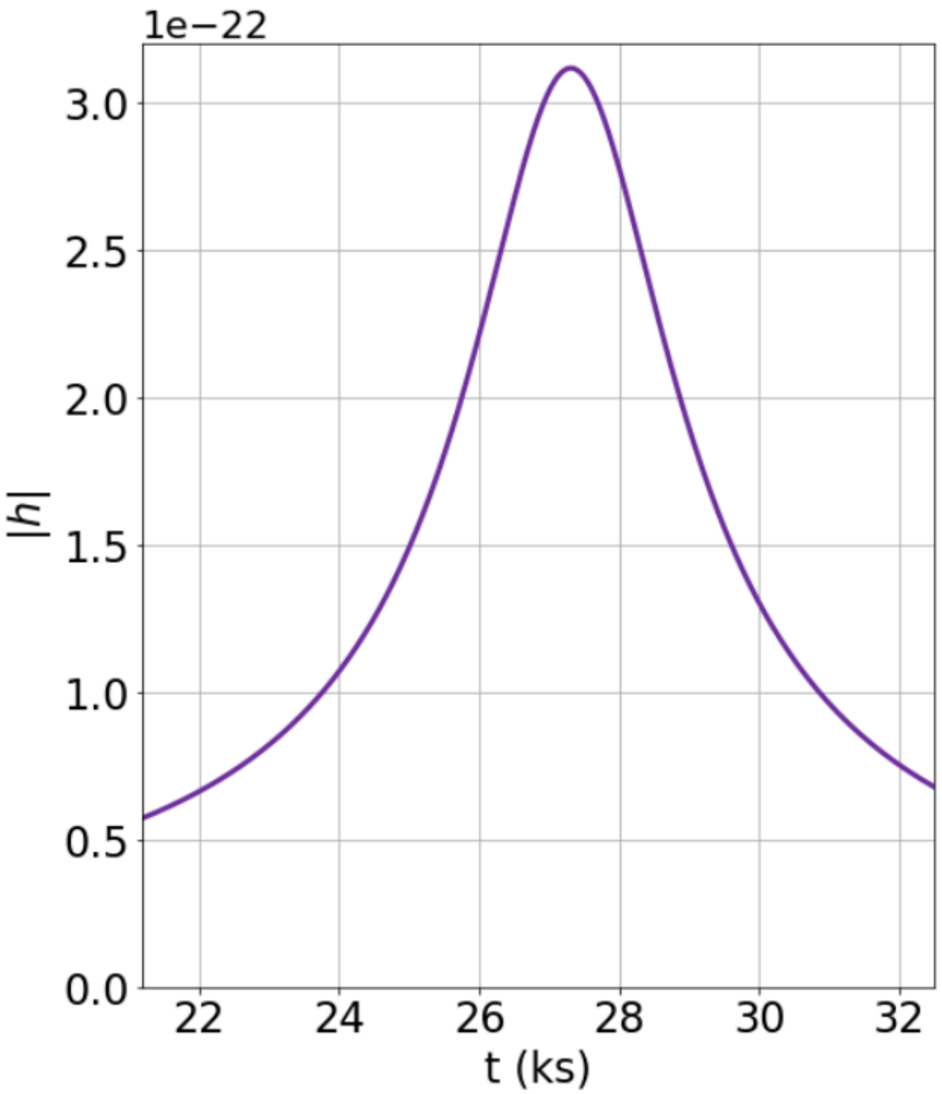
$$h_+ \, h_\times$$



GWs from TDEs

Toscani et al. 2021





Standard TDE at 20 Mpc

Kerr metric

Face-on signals

$$h \approx 10^{-22}$$

$$\tau \approx 10^4 \text{ks}$$

cf. Kobayashi et al. 2004

243 simulations

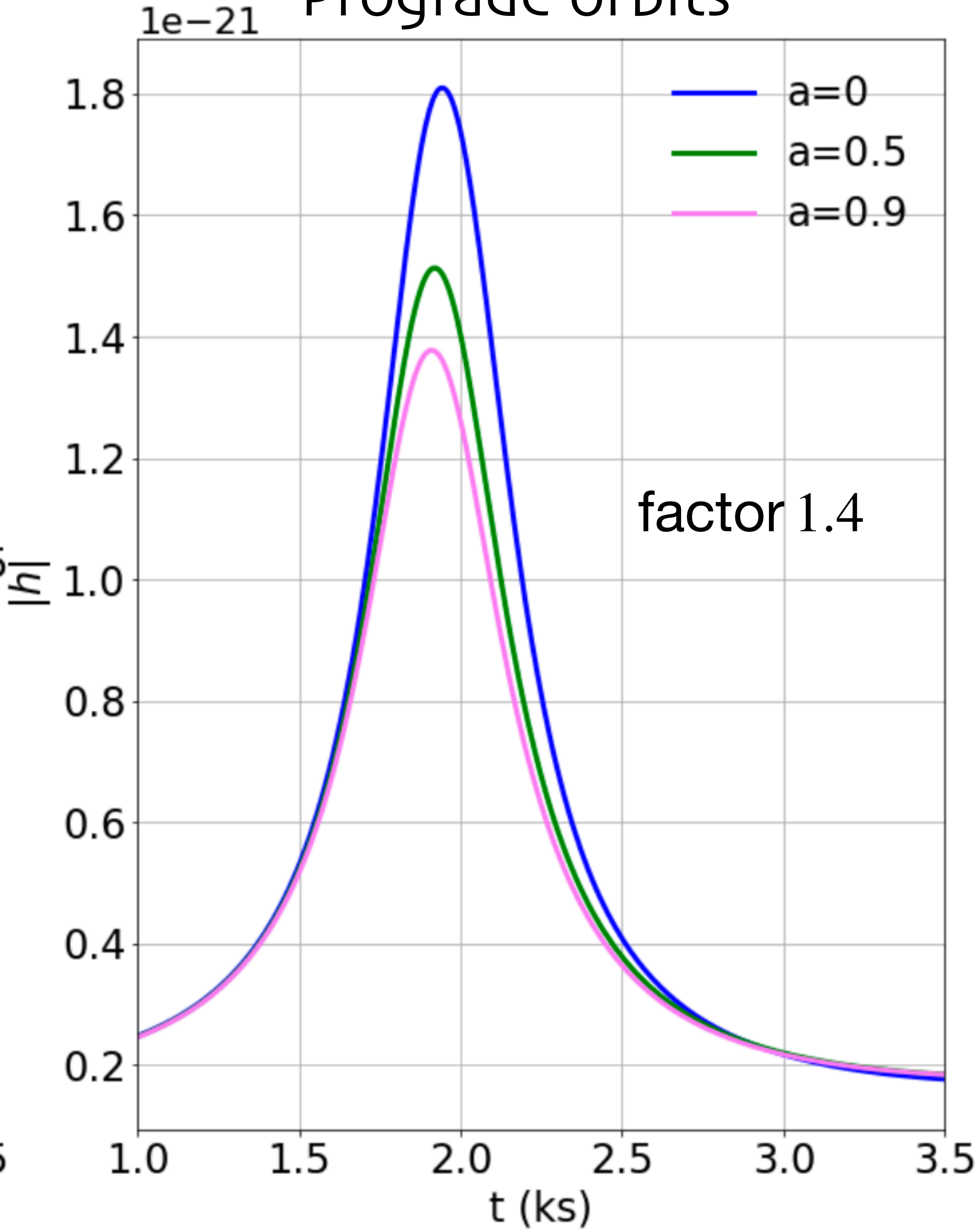
Eccentricity e, BH spin a, penetration factor β, orbital inclination θ

GWs from TDEs

Toscani et al. 2021

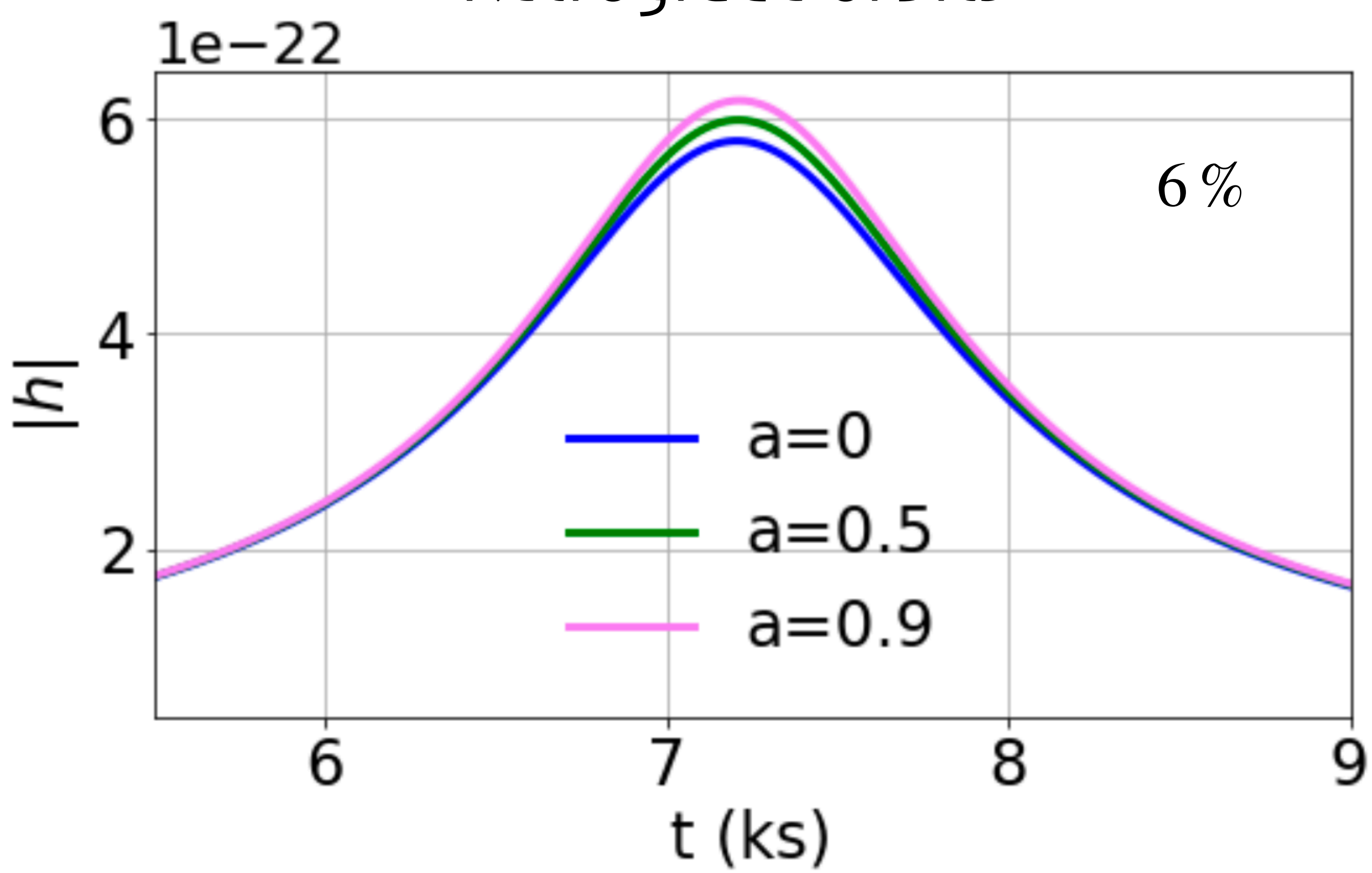
$\beta = 5, e = 0.6, \theta = 0$

Prograde orbits



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

Retrograde orbits

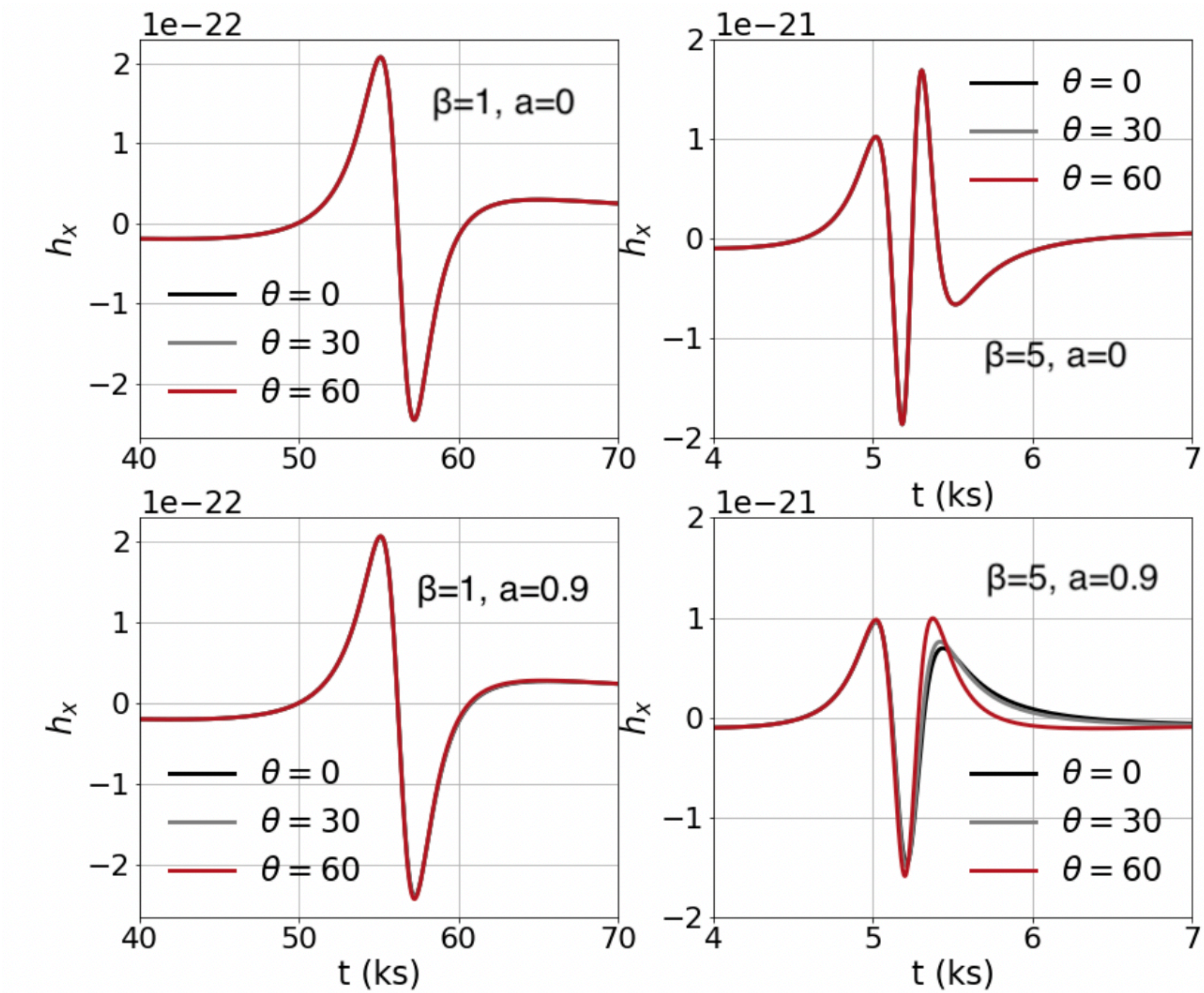


GW signal increases for high retrograde orbits, decreases for high prograde orbits

GWs from TDEs

Toscani et al. 2021

$e = 0.8$

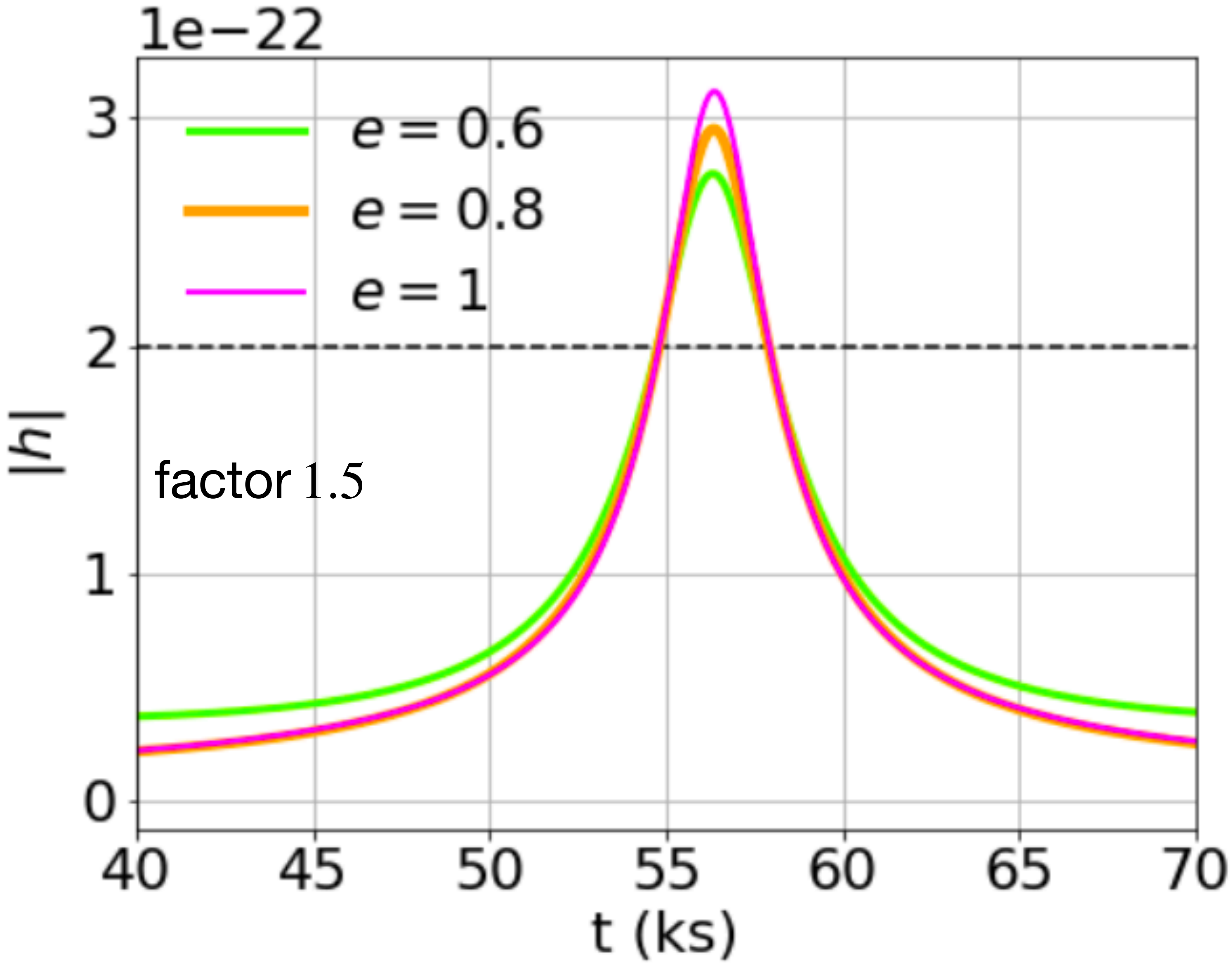


Inclination angles affect signal only with spin AND penetrating events

GWs from TDEs

Toscani et al. 2021

$\beta = 1, \theta = 0$



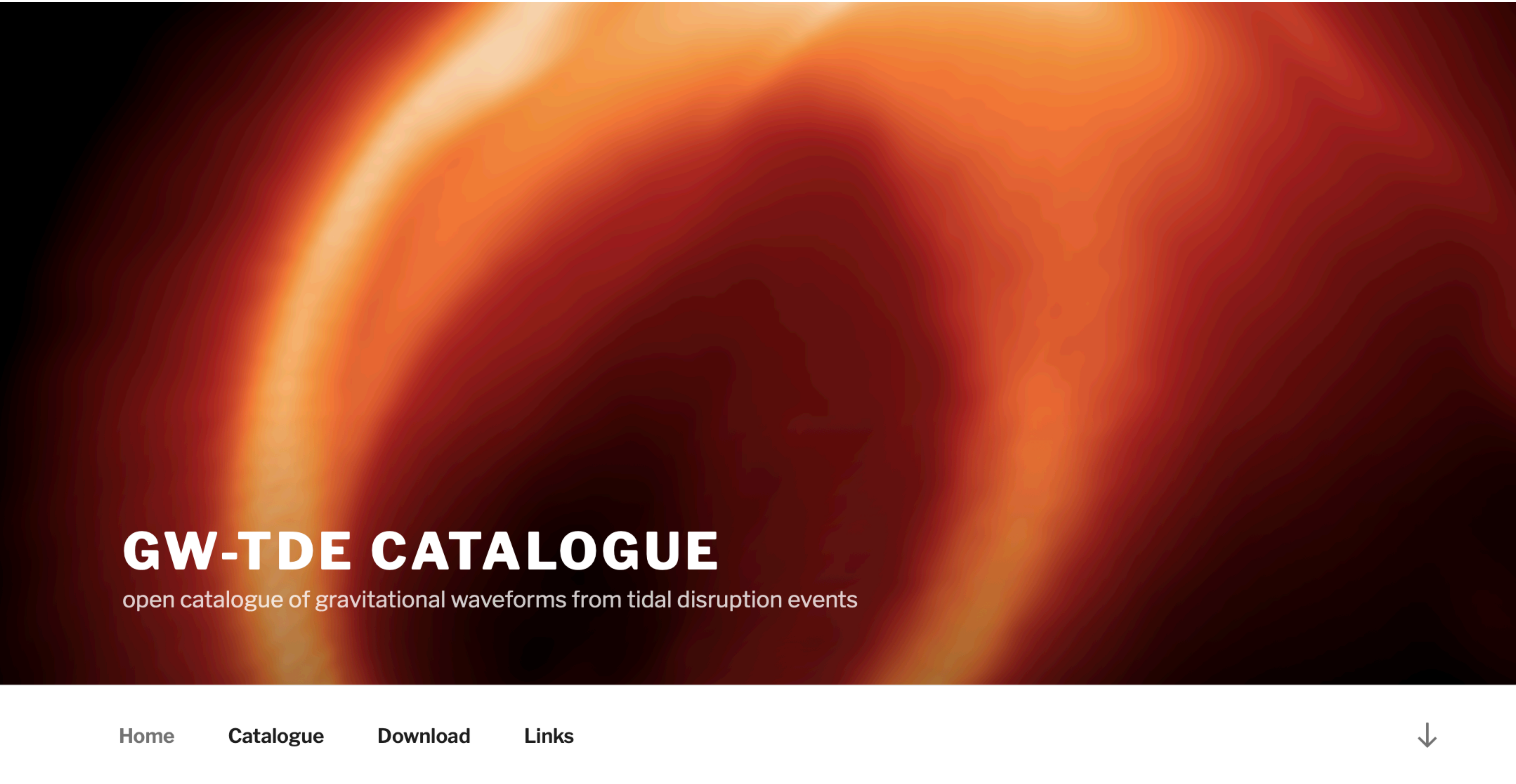
GW amplitude increases for higher eccentricities

GWs from TDEs

Toscani et al. 2021

ONLINE OPEN CATALOGUE

https://gwcataloguetdes.fisica.unimi.it



'Living' catalogue

Possible bridges with Nuclear Physics

1. more realistic EOS change the GW signal?

2. WD and pTDE: how the surviving core is deformed bu BH tides and how this affects the GWs?

3. Same with neutron stars?

4. Same with neutron stars?

5. Runaway fusion in compressed WDs: what are the exact parameters?

Conclusions

In the next future → GW detections of TDEs

In the next future → Multi-messenger observations of TDEs

The GW signal from the disruption phase is stronger

Be ready for the first detections —> GW catalogue

https://gwcataloguetdes.fisica.unimi.it

Many interesting connection points with Astronuclear Physics

→ Ideas?

Merci pour vôtre attention
Questions?

Fin