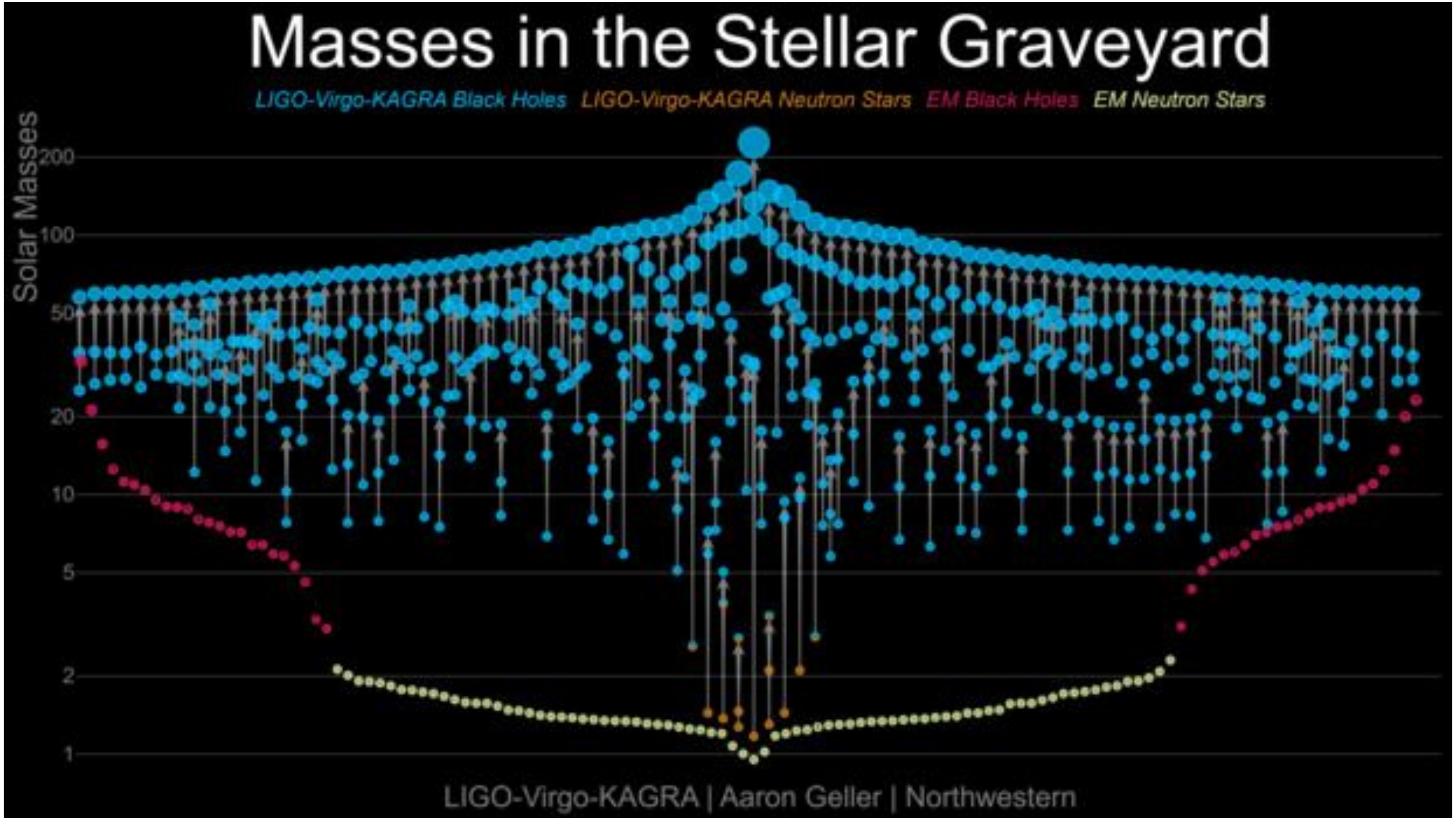
The mode-sum approach to neutron star dynamical tides: The multi-faceted impact of dissipation

Suprovo Ghosh

In collaboration with Nils Andersson (Southampton) and Fabian Gittins (Utrecht)

CSQCD 2026
May 18 – 23, 2026

GWTC: Gravitational-Wave Transient Catalog



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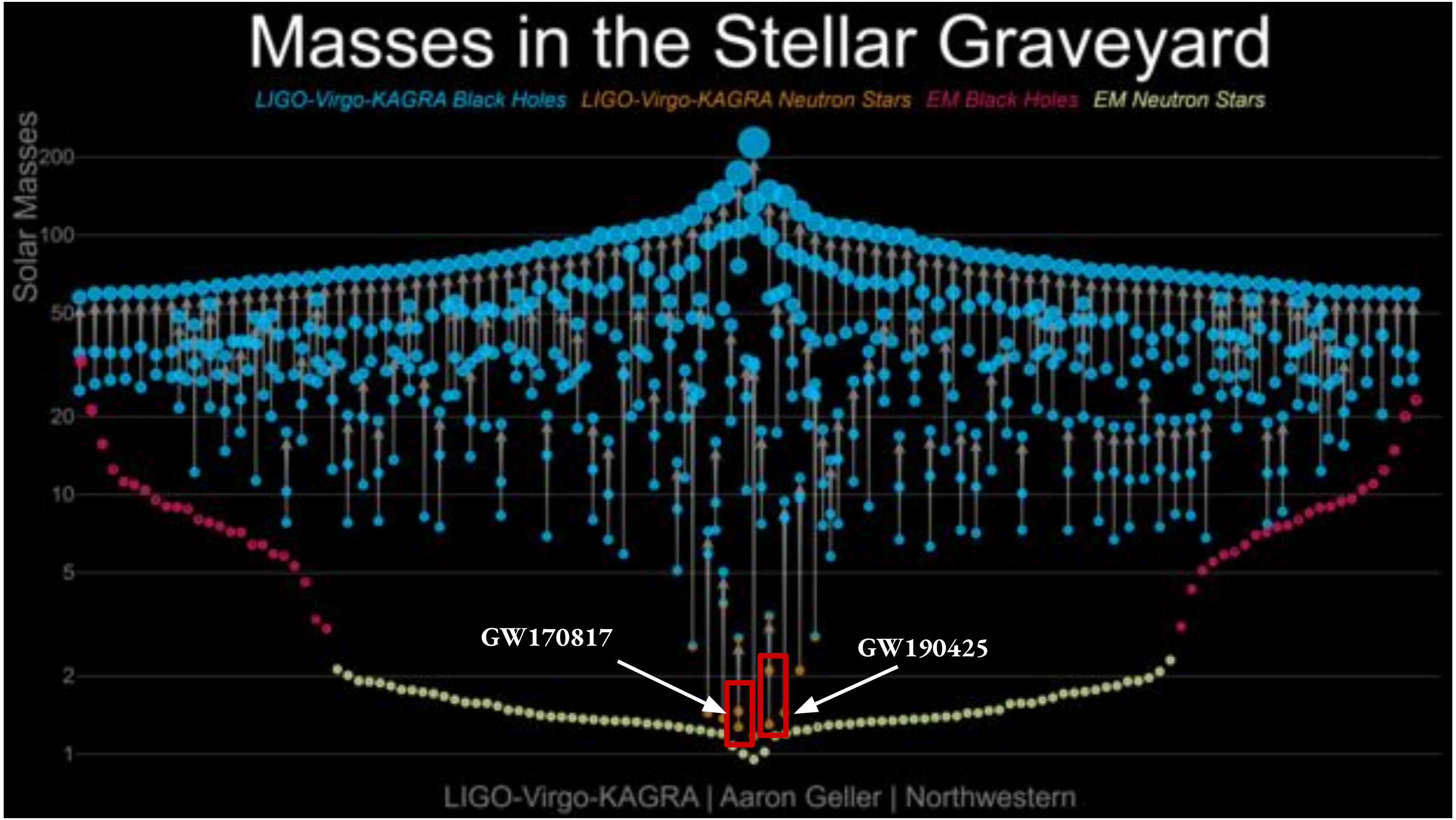
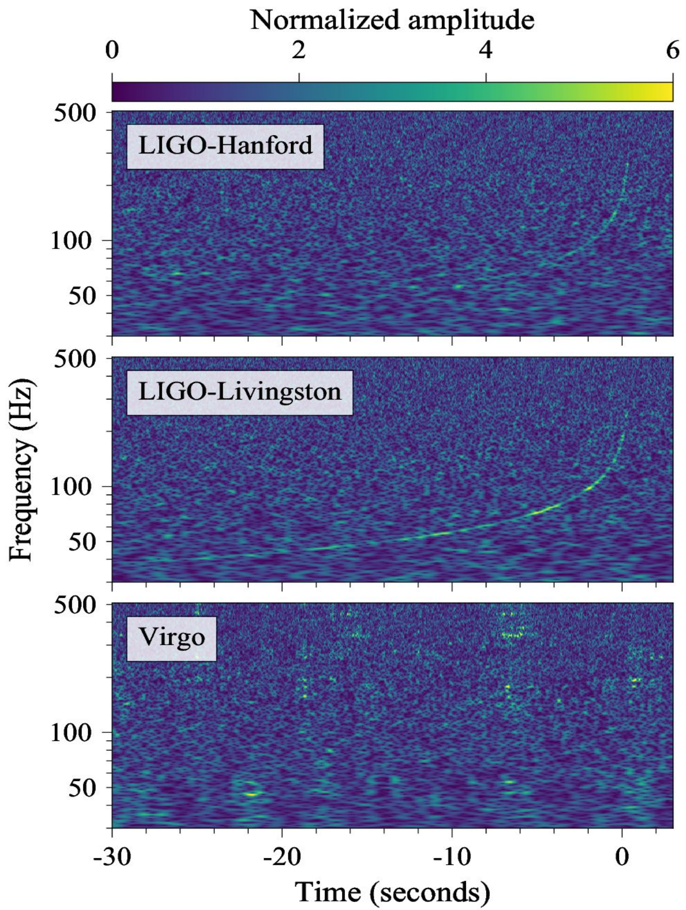


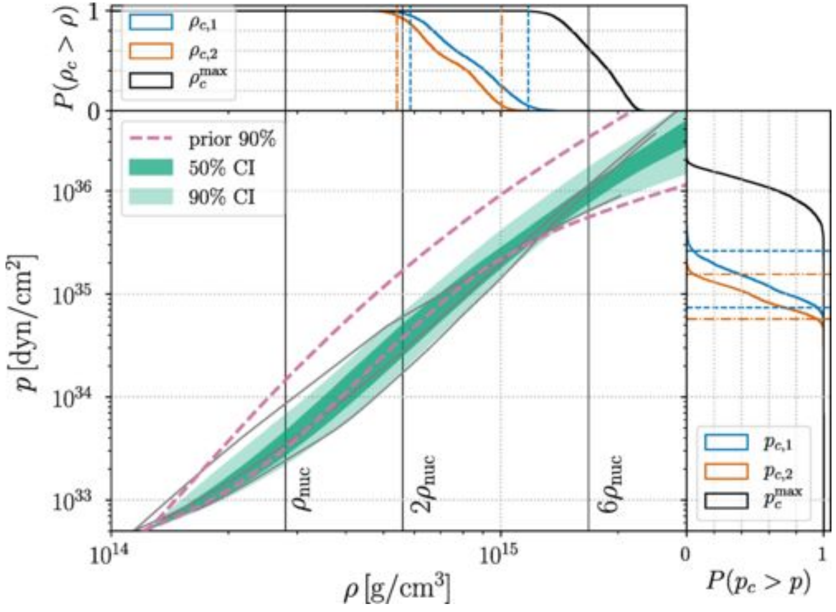
GW170817 - The 'Golden' Event



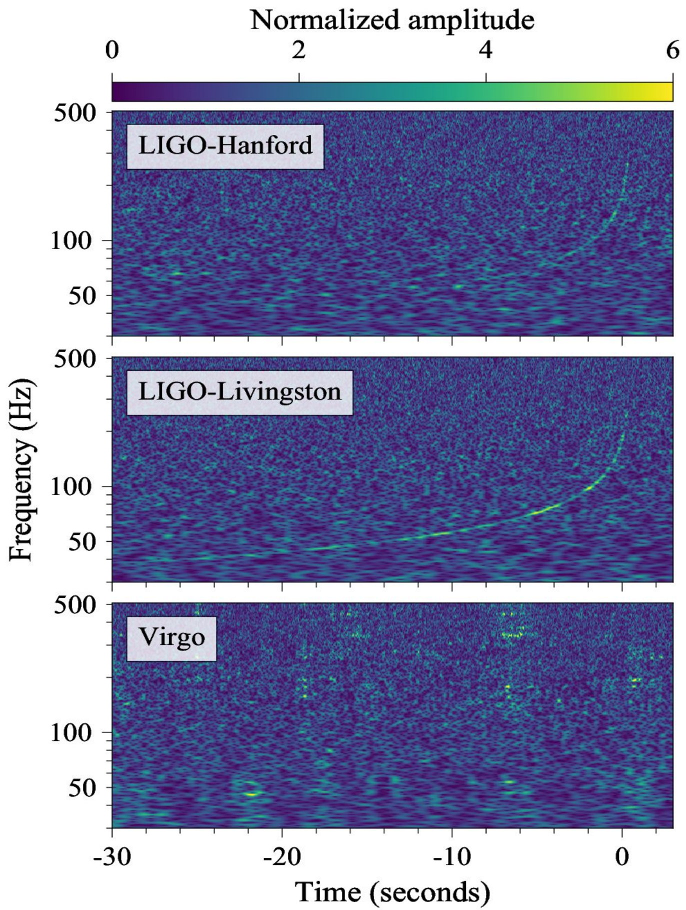
Abbott *et al, PRL 119 161101 (2017)*

GW170817 - The 'Golden' Event

EoS constraints from GW170817



Abbott *et al, PRL* 121, 161101 (2018)



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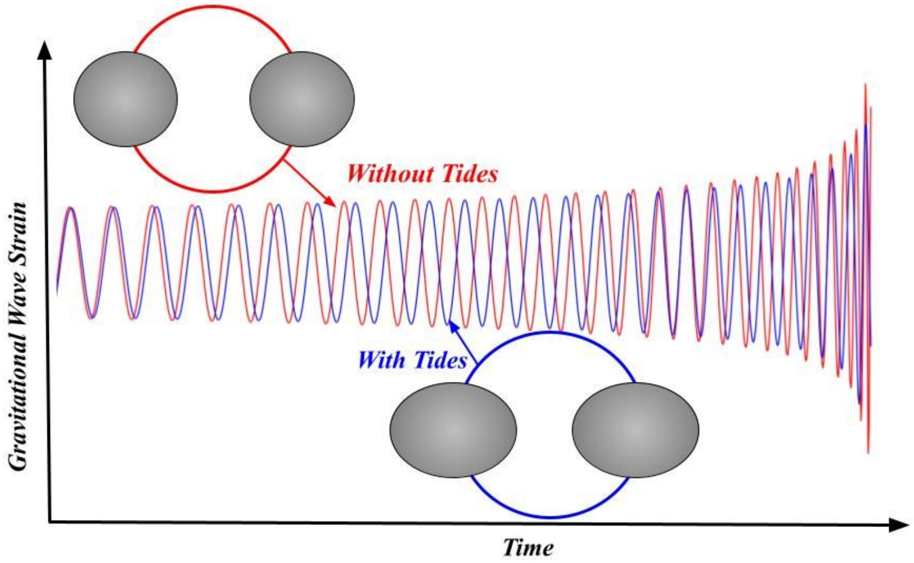
Tidal Effects in binary inspiral

➢ Two body orbiting will tidally deform each other that impacts gravitational waveform.

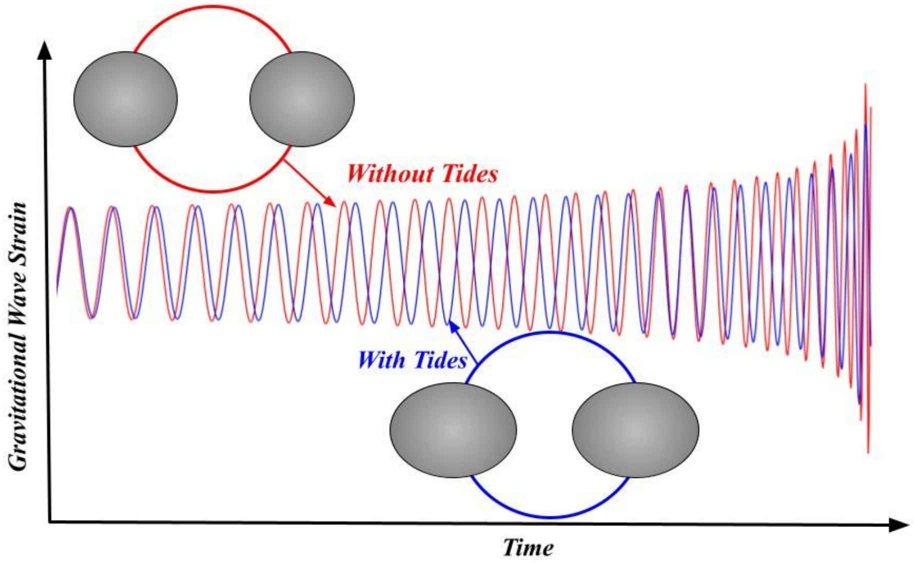


Tidal Effects in binary inspiral

- Two body orbiting will tidally deform each other that impacts gravitational waveform.
- The static tidal deformations are quantified via the tidal love numbers (k_l)

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

Hinderer et al., PRD 81, 123016 (2010)



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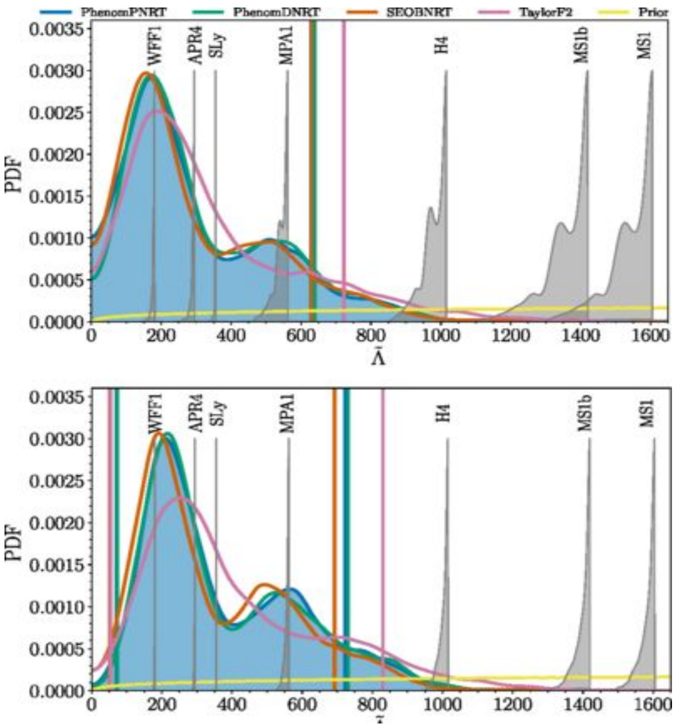
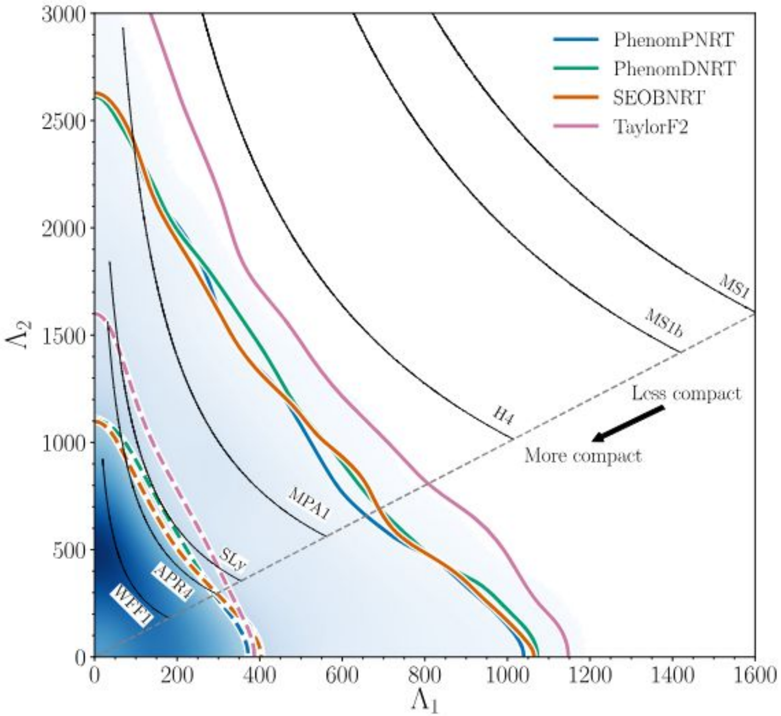
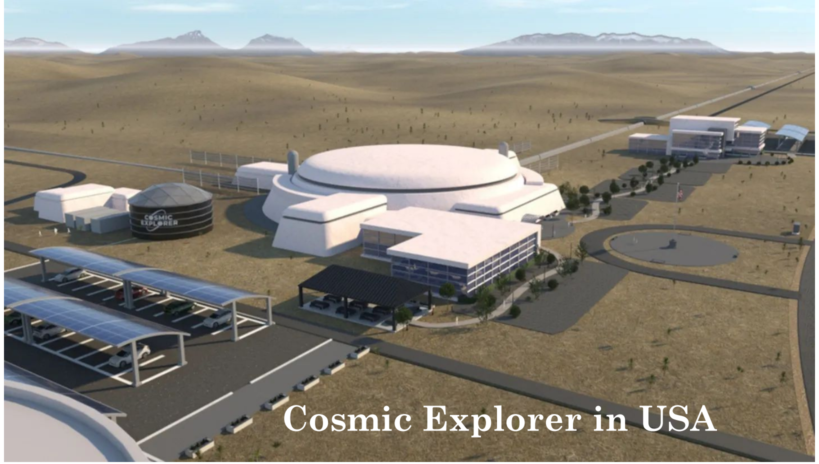
$$\Psi_{\text{tidal}}(f) = -\frac{3}{128\eta v^5}\left[-\frac{39}{2}\tilde{\Lambda}v^{10} + \left(-\frac{3115}{64}\tilde{\Lambda} + \frac{6595}{364}\delta\tilde{\Lambda}\right)v^{12}\right]$$

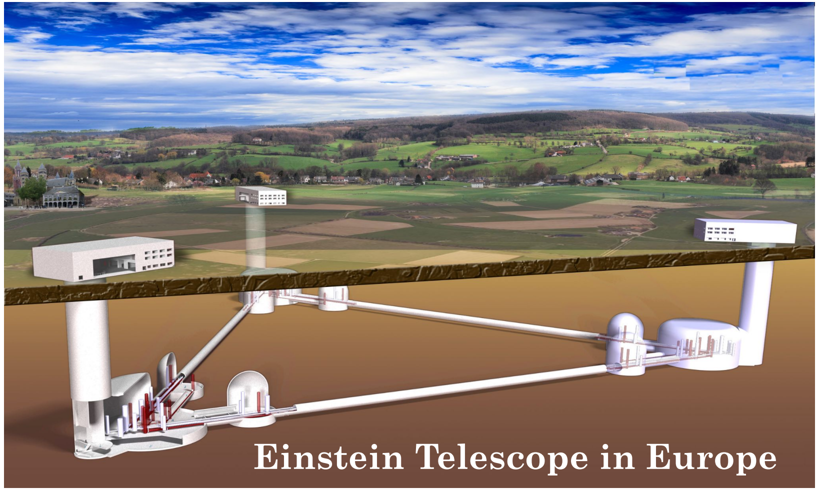


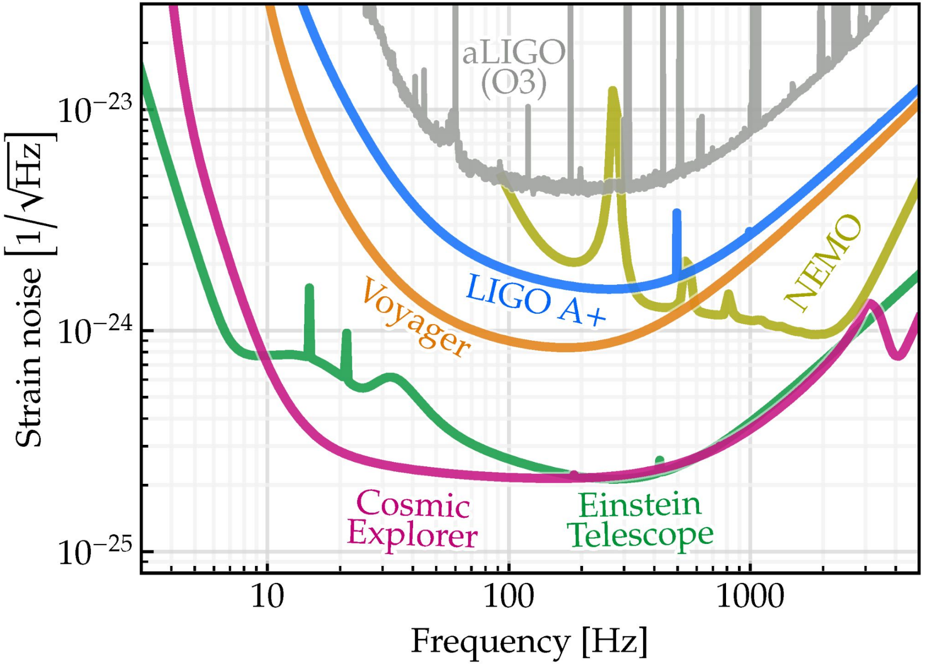


Abbott *et al*, *PRX* 9, 011001 (2019)

Next -generation GW detectors and BNS mergers







Evan D. Hall, Galaxies 2022, 10, 90

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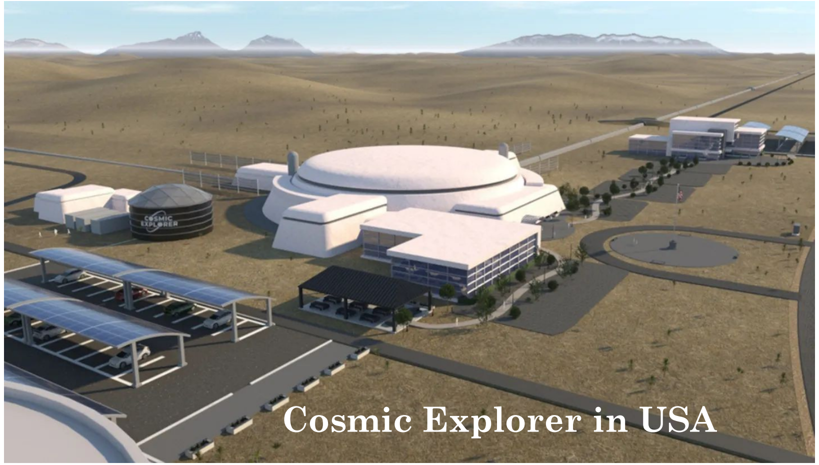

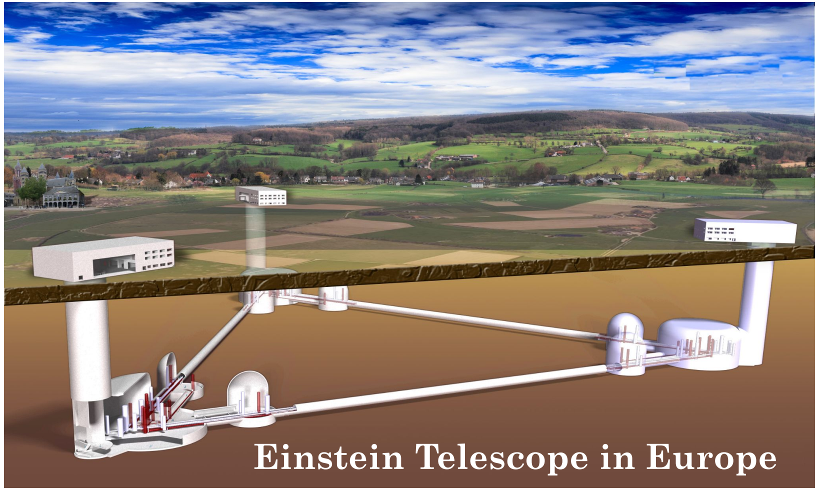

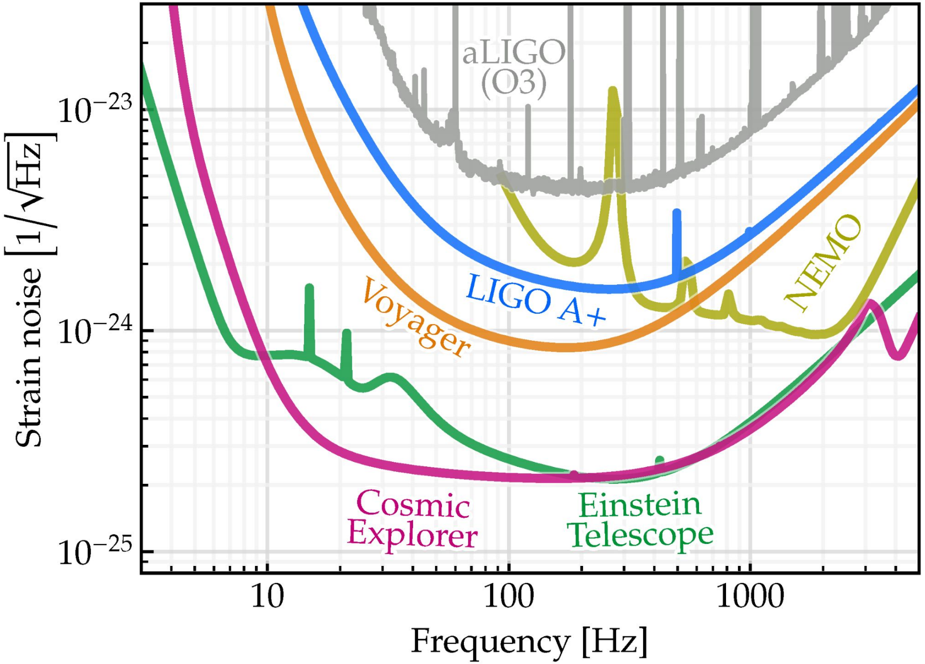

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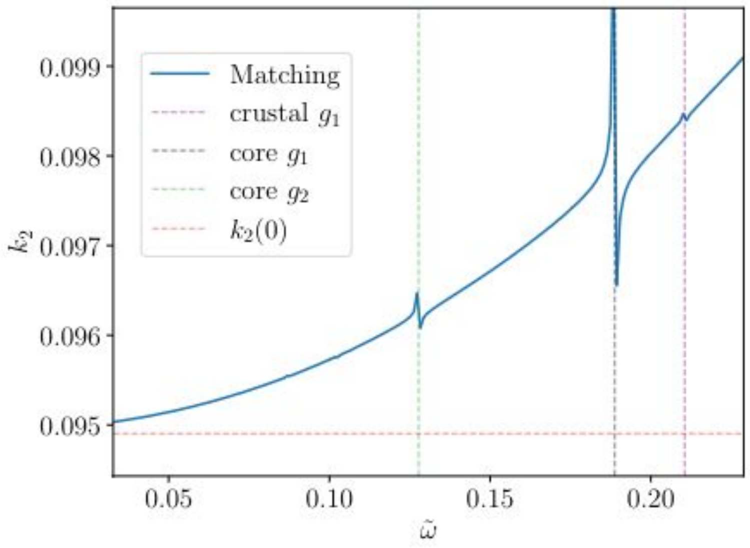
Signature of neutron star interior on gravitational wave data beyond adiabatic tidal effects within the reach of next-gen GW detectors?

Dynamical tides

- The static approximation inevitably breaks down close to the merger.
- Rich mode-spectrum of neutron stars.



Andersson *et al*, *PRD 113, 064051 (2026)*

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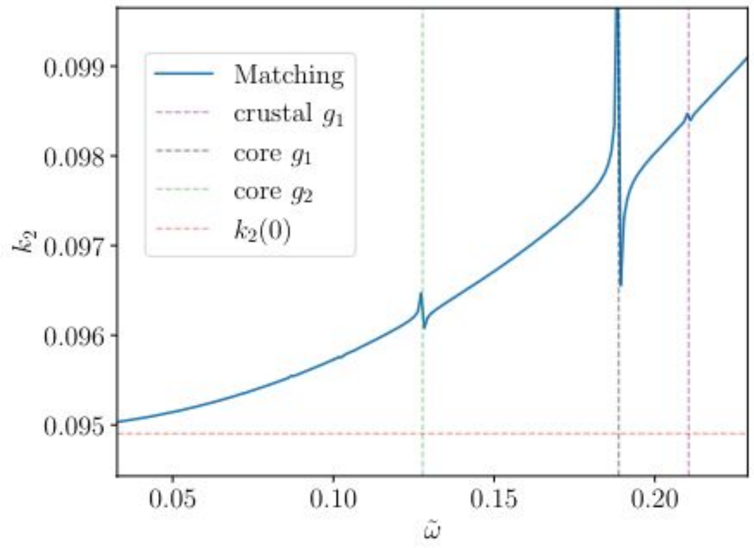
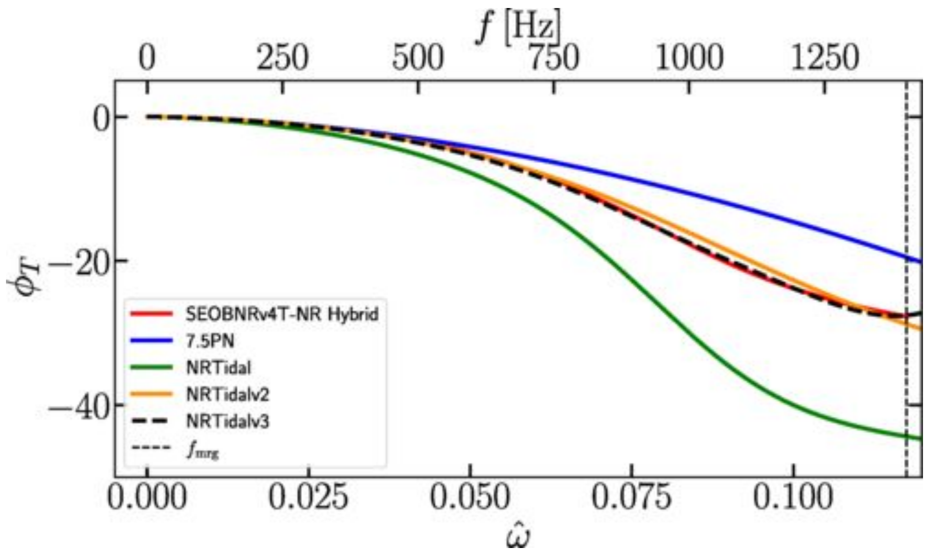


Andersson *et al, PRD 113, 064051 (2026)*

Impact on the waveform



Abac *et al, PRD* 109, 024062 *(2024)*

Tidal interaction during binary neutron star inspiral

- **Adiabatic Tides : Parameterized as 'Tidal deformability'; has the dominant contribution towards the late inspiral**
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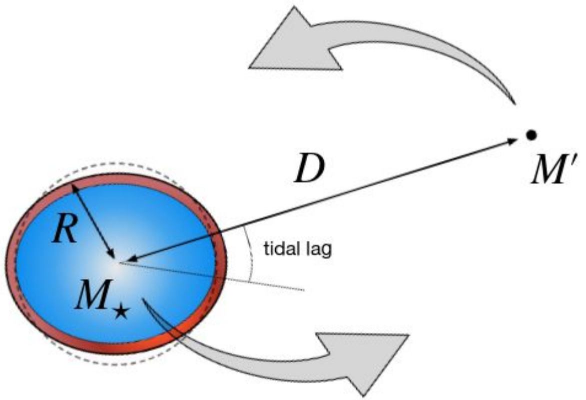
    - *Tidal torquing for spinning NS(tidal spin)*



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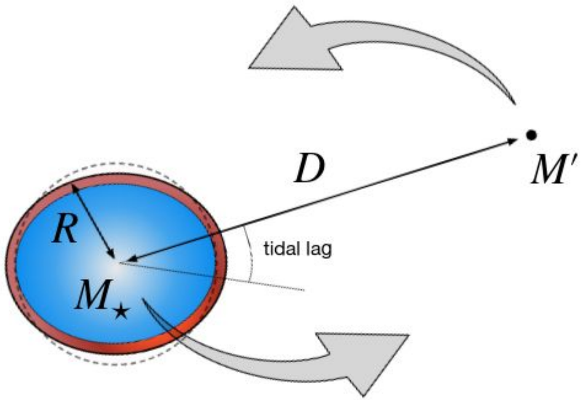
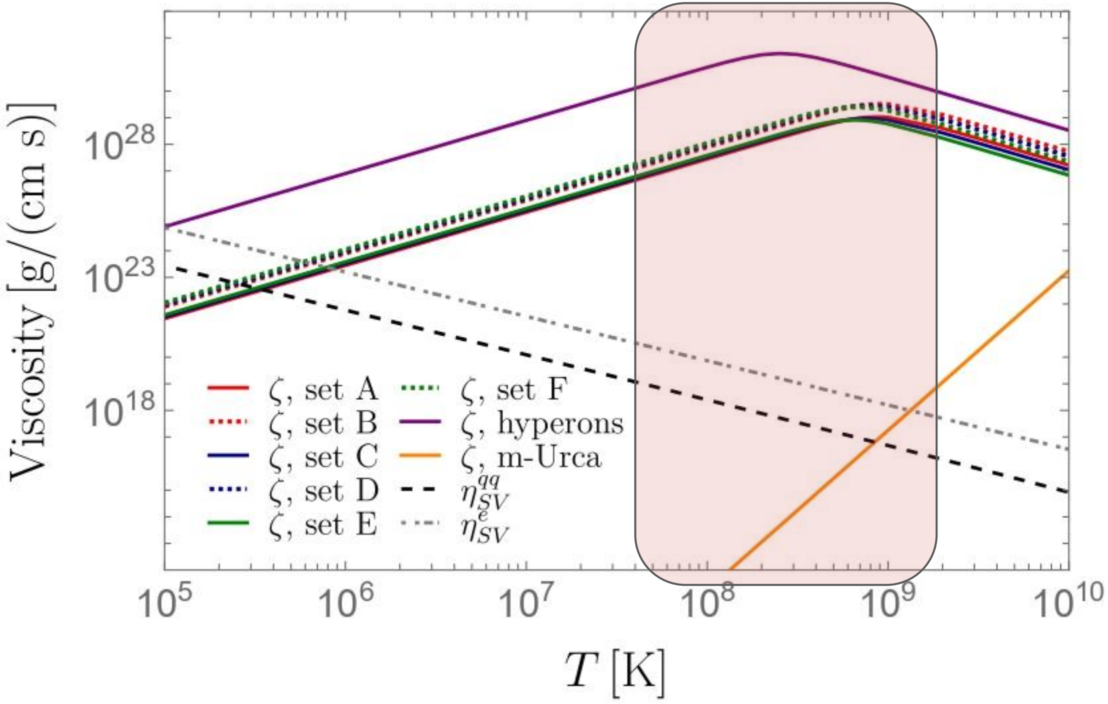
- **Dominant source at low temperature (T<< 1 MeV): Shear viscosity from n-n/e-e scattering (Bildsten & Cutler, ApJ 400(1992))**

$$T_{Visc} \gg T_{inspiral}$$



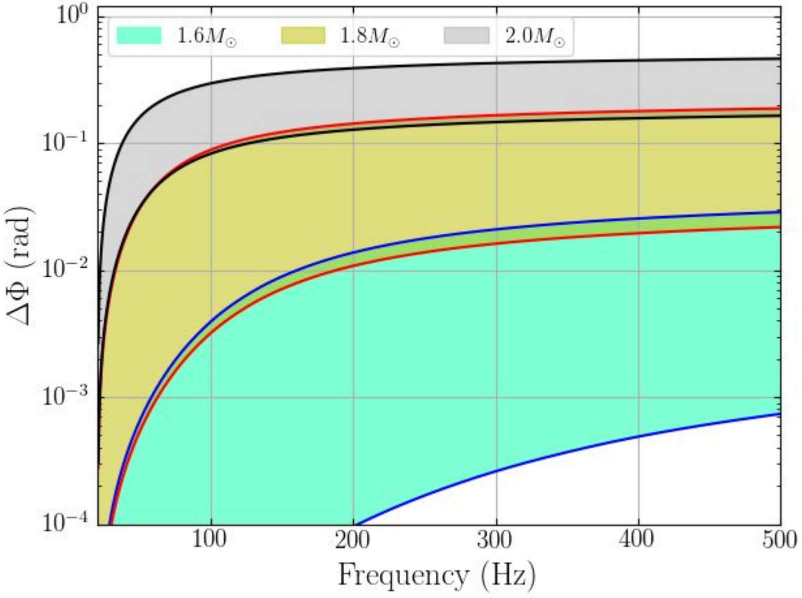
Bulk viscosity of exotic matter



Ghosh et al., PRD 112 (2025) 8, 084072

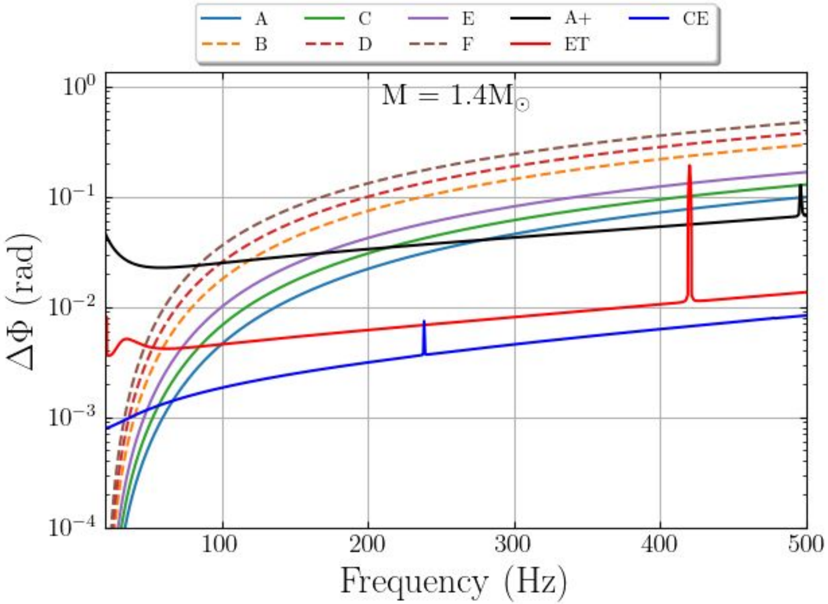
Detectability of fluid dissipation

Hyperons



Ghosh et al., PRD 109, 103036(2024)

Quarks



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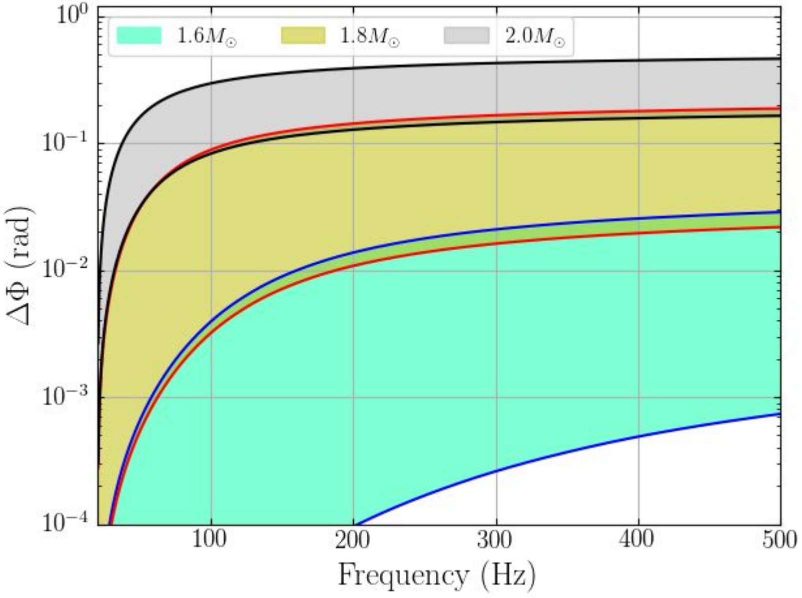

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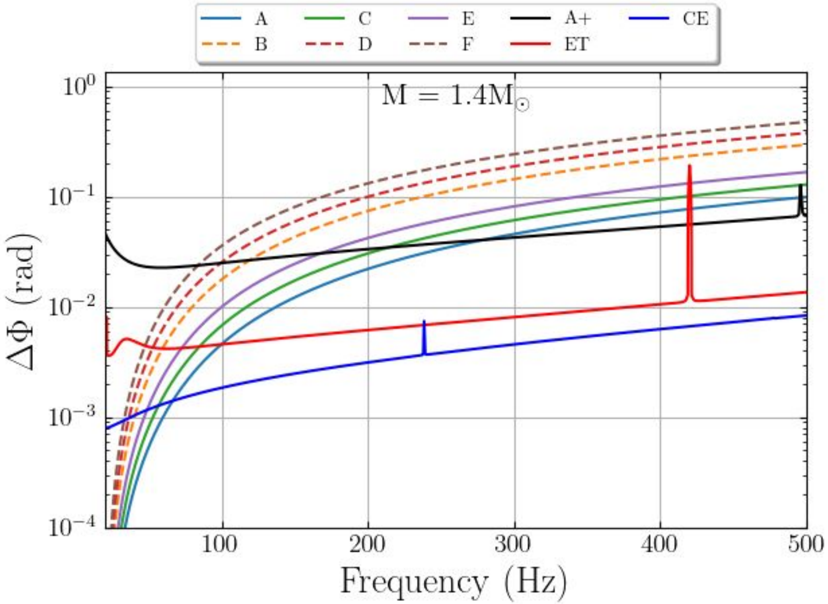

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Fluid dissipation can be smoking gun signature for exotic matter!

Tidal lag : modelling dissipation in binary neutron stars mergers

Tidal lag: The moments induced by slowly varying tidal fields experience a lag with the tidal fields, which is parametrized as

$$Q_2 = \frac{2}{3} R^5 k_2 (\chi - \tau \dot{\chi})$$

k_2 is the love number and τ is the tidal lag. The latter is non zero for neutron stars when there is fluid-viscosity.

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Recent attempts to calculate tidal lag :

- Based on scaling relation from Newtonian viscous fluid
  - Poisson *PRD* 80 (2009) 064029; *Ripley et al, PRD 108, 103037 (2023)*
- Fluid perturbation in low frequency, low viscosity limit
  - Hegade et al, PRD 109, 104064 (2024)
- Using Gravitational Scattering
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Computation of tidal lag based on microphysical viscosity is still lacking!

Mode sum approach to tidal dissipation

- **In Newtonian gravity, tidal perturbations can be expressed as a sum of contributions associated with the star's free oscillation modes.**

$$\ddot{a}_n(t) + \omega_n^2 a_n(t) = \frac{v_{lm}(t) Q_n}{M_\star R^2} e^{-im\Phi(t)}$$

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- There are two sources of dissipation in the binary inspiral problem -

1. Emission of gravitational waves and orbital shrinking

$$\frac{\dot{\Omega}}{\Omega} \approx \frac{96}{5c^5} (G\mathcal{M})^{5/3} \Omega^{8/3}$$

2. Damping of oscillation modes from gravitational radiation and fluid viscosity

$$\ddot{a}_n(t) + 2\gamma_n \dot{a}_n + \omega_n^2 a_n(t) = \frac{v_{lm}(t) Q_n}{M_\star R^2} e^{-im\Phi(t)}$$

Phenomenological dissipative timescale

Effective Love number

➢ **The general solution to the mode amplitude, beyond the equilibrium tide is given by**

$$b_n = \frac{GM'W_{lm}Q_n}{\mathcal{A}_n^2 D^{l+1}} \left(\omega_n^2 - m^2\Omega^2\right) \left\{ (\omega_n^2 - m^2\Omega^2)^2 - 2im\gamma_n\Omega(\omega_n^2 - m^2\Omega^2) - im\dot{\Omega}\left[\frac{(4l+7)}{3}\left(\omega_n^2 - m^2\Omega^2\right) + 4m^2\Omega^2\right]\right\}^{-1}$$

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Orbital decay

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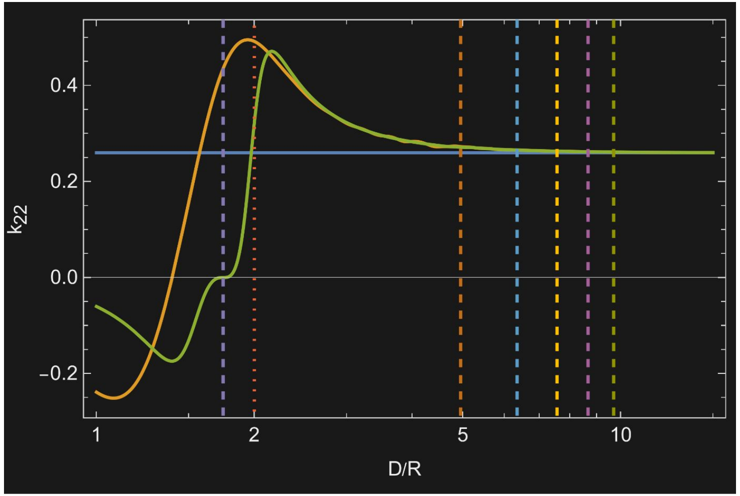
Viscous

Orbital decay

- Effective Love number obtained as

$$k_{lm} \approx \frac{2\pi}{2l+1}\sum_{n'}\frac{\tilde{Q}_n^2}{\tilde{\omega}_n^2}\kappa_n(\Omega)$$

$$\kappa_n(\Omega) = \omega_n^2\left(\omega_n^2 - m^2\Omega^2\right)\left\{\left(\omega_n^2 - m^2\Omega^2\right)^2 - im\left[\left(\frac{4l+7}{3}\dot{\Omega} + 2\gamma_n\Omega\right)\left(\omega_n^2 - m^2\Omega^2\right) + 4m^2\Omega^2\dot{\Omega}\right]\right\}^{-1}$$



Credit: Pantelis Pnigouras

Tidal lag

- **For the multipole moments, we can have**

$$GI^{\langle L\rangle} = \frac{8\pi l! R^{2l+1}}{(2l+1)!!} \sum_{m=-l}^{l} \mathcal{Y}_{lm}^{*\langle L\rangle} (\mathrm{Re}\, k_{lm}) d_{lm}(t - \tau_{lm})$$

- **Effective love number, including the lag depends on the m-multipoles explicitly.**

Tidal lag

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$$GI^{\langle L\rangle} = \frac{8\pi l! R^{2l+1}}{(2l+1)!!} \sum_{m=-l}^{l} \mathcal{Y}^{*\langle L\rangle}_{lm} (\mathrm{Re}\, k_{lm}) d_{lm}(t - \tau_{lm})$$

- Effective love number, including the lag depends on the m-multipoles explicitly.

- If we consider the tidal response is dominated by f-mode and away from resonance,

$$GI_{\langle L\rangle} = -\frac{2k_l}{(2l-1)!!} R^{2l+1} \mathcal{E}_L(t-\tau)$$

- where we can define the tidal lag as

$$\tau_l = \frac{1}{\omega_{n'}^2} \left(2\gamma_{n'} + \frac{\dot{\Omega}}{\Omega} \frac{4l+7}{3} \right).$$

This expression is particularly useful to calculate tidal lags from microphysics.

Takeaways and next steps

- **Dissipation effects on dynamical tides '*might not be negligible*' if exotic particles like hyperons or quarks are present in neutron star cores.**

- **With next generation GW detectors, with increased sensitivity, detecting this effect is possible for high SNR events. Can be smoking gun evidence for exotic matter.**

- **Gravitational wave modelling via introducing tidal lag. Need to be careful about defining a single 'tidal dissipation number' as observable.**

Future goals : Developing a relativistic waveform model incorporating fluid and gravitation radiation reaction dissipation accurately and constraining fluid viscosity (out-of-equilibrium behaviour of dense matter) from GW merger events.

CoCoNuT Meeting 2026

8–11 Sept 2026
University of Southampton
Europe/London timezone

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Contact

m.miravet-tenes@soton....
s.ghosh@soton.ac.uk

The CoCoNuT Meeting is a series of workshops aimed at fostering collaboration among **relativistic astrophysics** groups, especially within Europe. The series has been taking place yearly since 2009, and this edition will be hosted at the **University of Southampton (United Kingdom)**.

This edition will focus on **Magnetohydrodynamics,** particularly in the context of core-collapse supernovae, neutron star mergers, and magnetars. The different topics will be introduced by the invited speakers, followed by contributed talks.

There will also be a **day-0 Workshop** on the 8th of September about **machine learning applications in numerical relativity,** jointly organised with members of the CPP-UKNR community. During registration, please mention if you want to attend only the workshop or the CoCoNuT meeting, or both.

The meeting will take place at the Mathematical Sciences Student Centre **(Building 56)** of the University of Southampton.

Confirmed Invited Speakers

- **Anna Neuweiler,** Universität Potsdam, Germany
- **Martin Obergaulinger,** Universitat de València, Spain
- **Daniel Siegel,** Universität Greifswald, Germany

Important dates:

• Registration opening	13 May, 2026
• Abstract submission deadline	1 July, 2026
• Communication of Abstract Acceptances	15 July, 2026
• Registration deadline	31 August, 2026