

Tidal Heating in Binary Neutron Star Inspiral: A Novel Probe of Exotic Matter at Neutron Star Cores

Suprovo Ghosh

Based on

Phys.Rev.D 112 (2025) 8, 084072, *Phys.Rev.D* 109 (2024) 10, 103036

INT Workshop

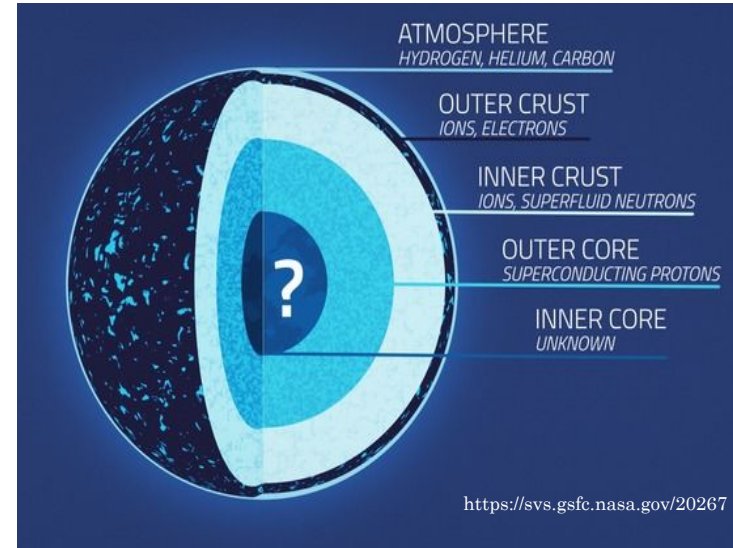
Finite-Temperature Effects in Multi-Messenger Astrophysics

15th June, 2026



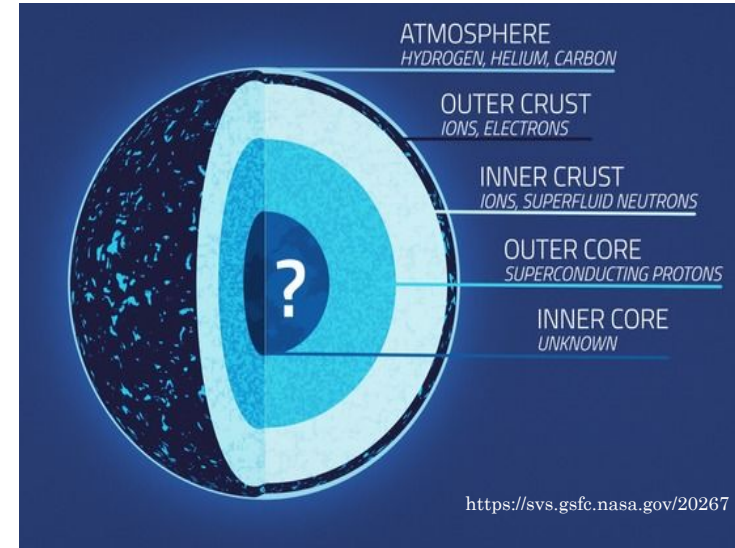
Neutron star : Astrophysical Laboratory to study Dense Matter

- Neutron stars : Endpoint of stellar evolution of massive stars ($> 8M_{\odot}$)
- One of the densest objects in the Universe
 $M \sim 1-2 M_{\odot}$, $R \sim 10-14$ km , $\rho \sim 2-10 n_0$
- Composition of the NS core still unknown - quarks, hyperons, kaon condensate...??
- Strange Quark stars: Star made up entirely of quarks.
- Equation of State (EoS) : Pressure-density relation.
Uncertain because of the extrapolation to higher density, finite temperature, and isospin asymmetry



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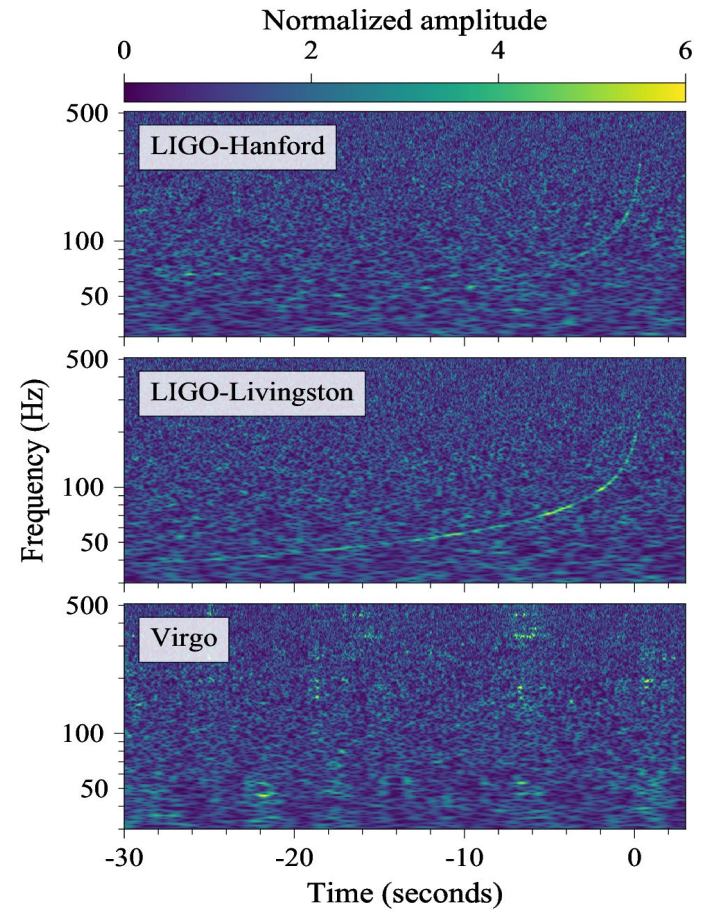


Multi-messenger observations of neutron stars



Equation of state, Composition of neutron star core

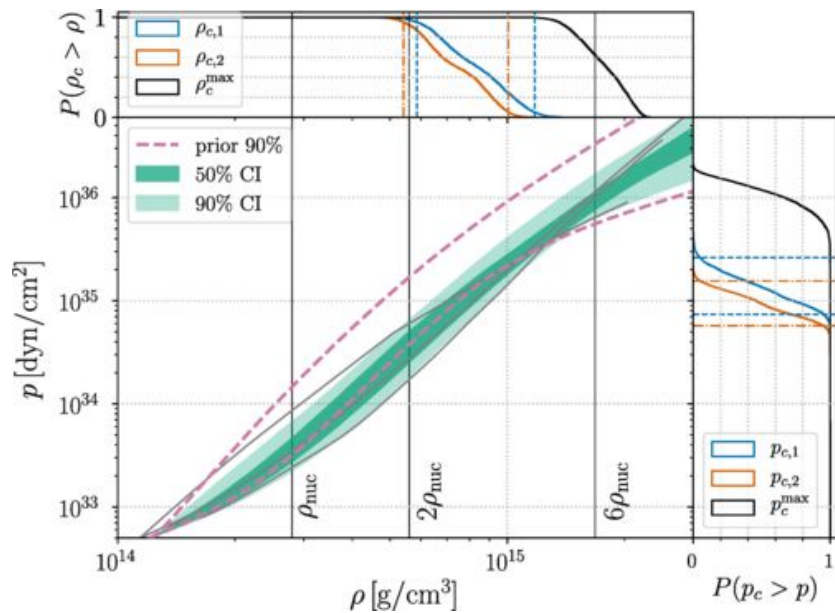
GW170817 - The 'Golden' Event



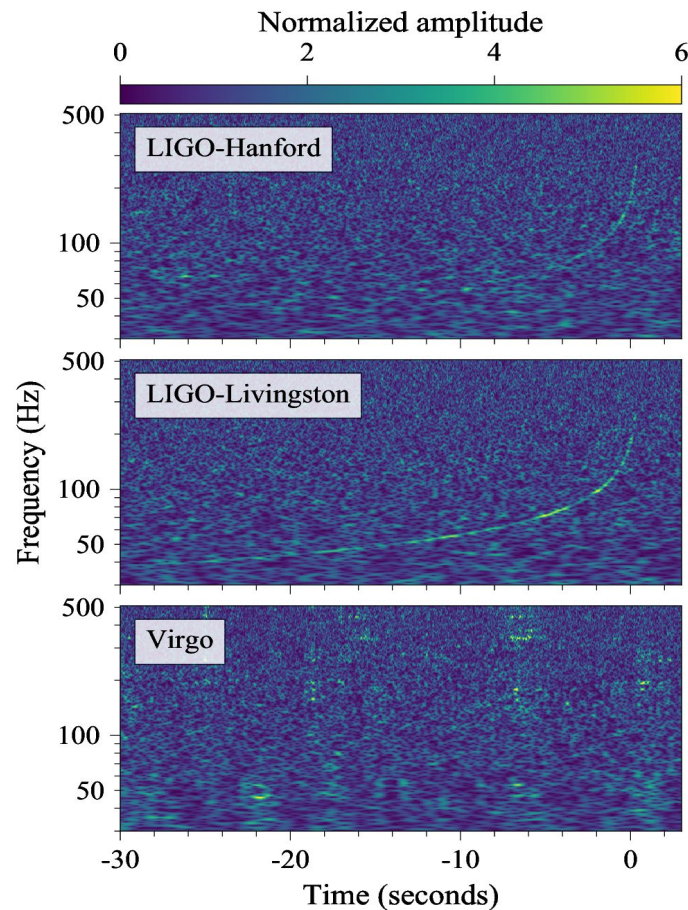
Abbott et al, PRL 119 161101 (2017)

GW170817 - The 'Golden' Event

EoS constraints from GW170817



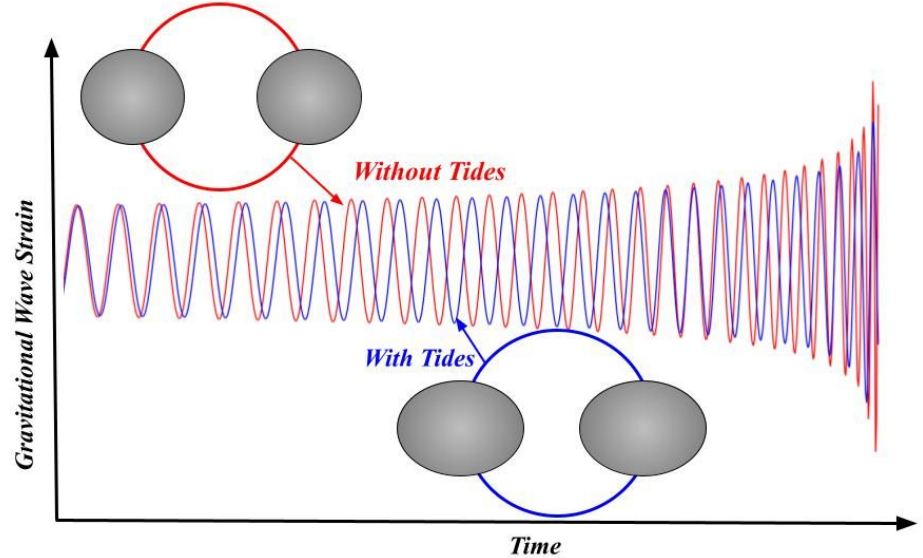
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Tidal Effects in binary inspiral

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

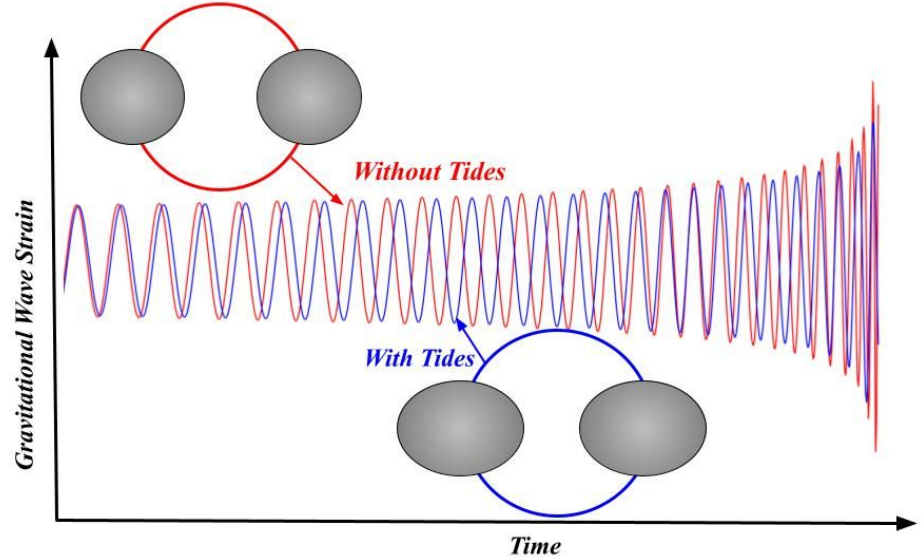


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- The static tidal deformations are quantified via the tidal love numbers (k_1)

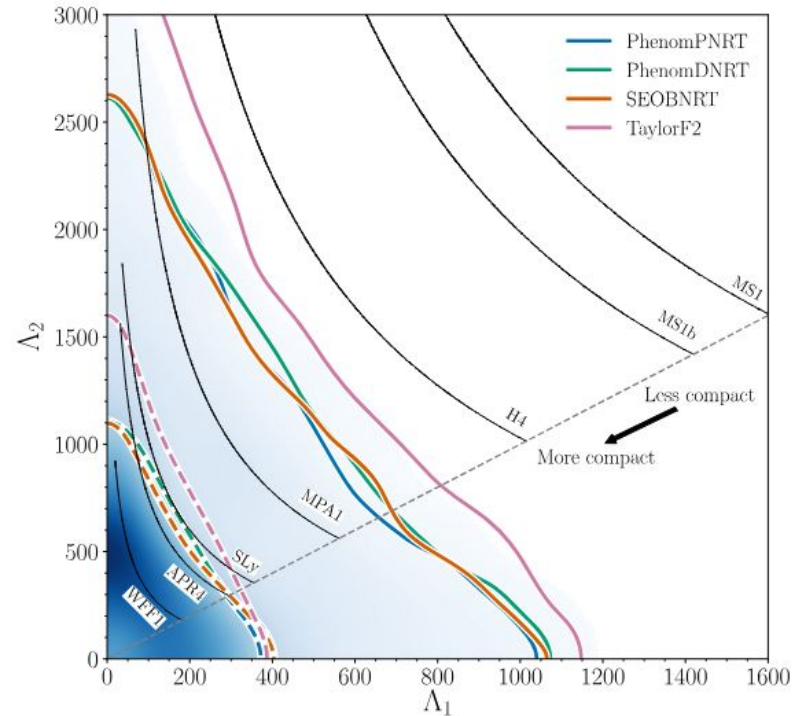
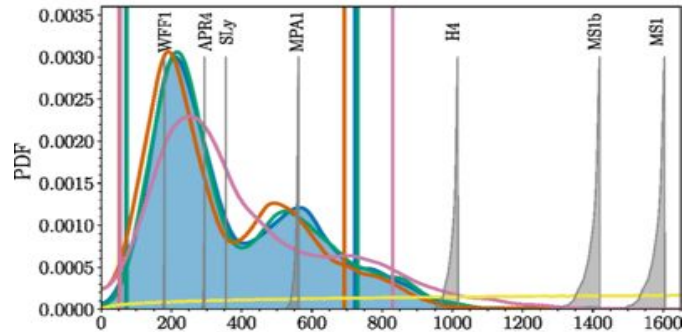
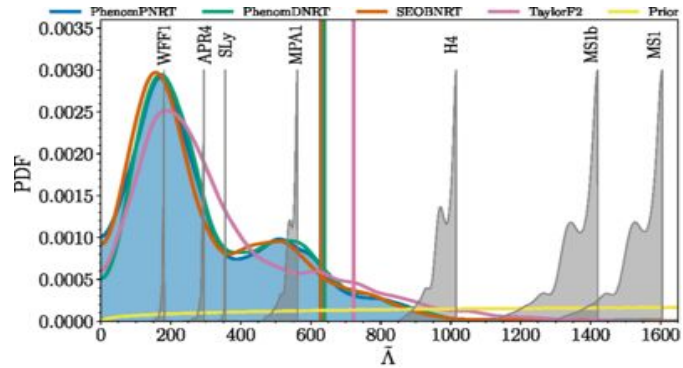
$$\Lambda = \frac{2}{3}k_2 \left(\frac{R}{M} \right)^5$$

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

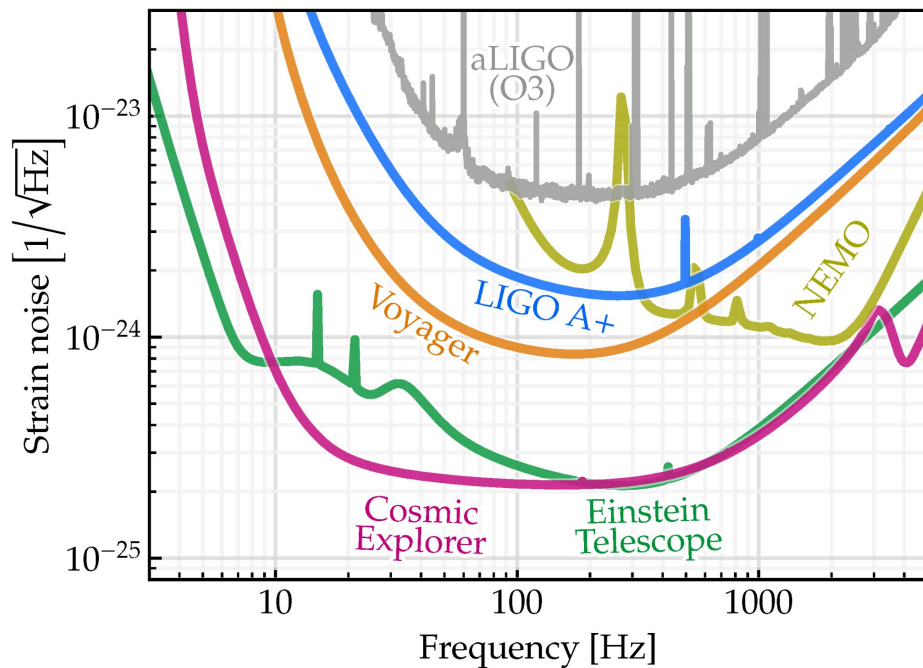
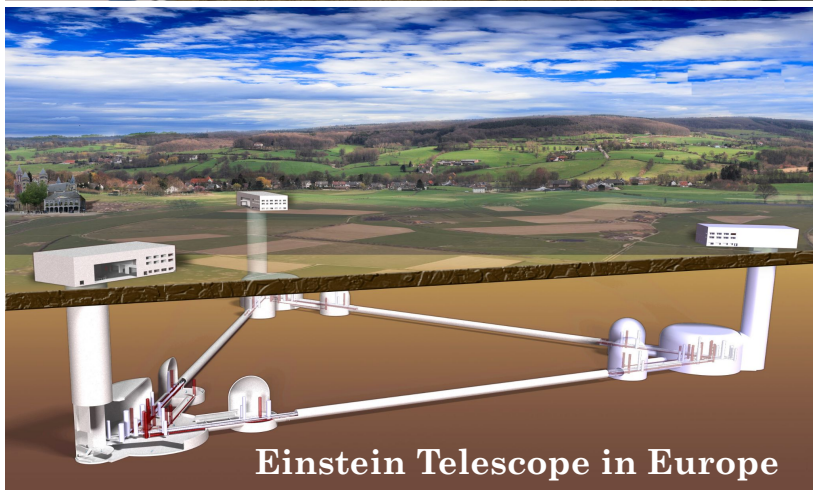


Tidal Effects in binary inspiral

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

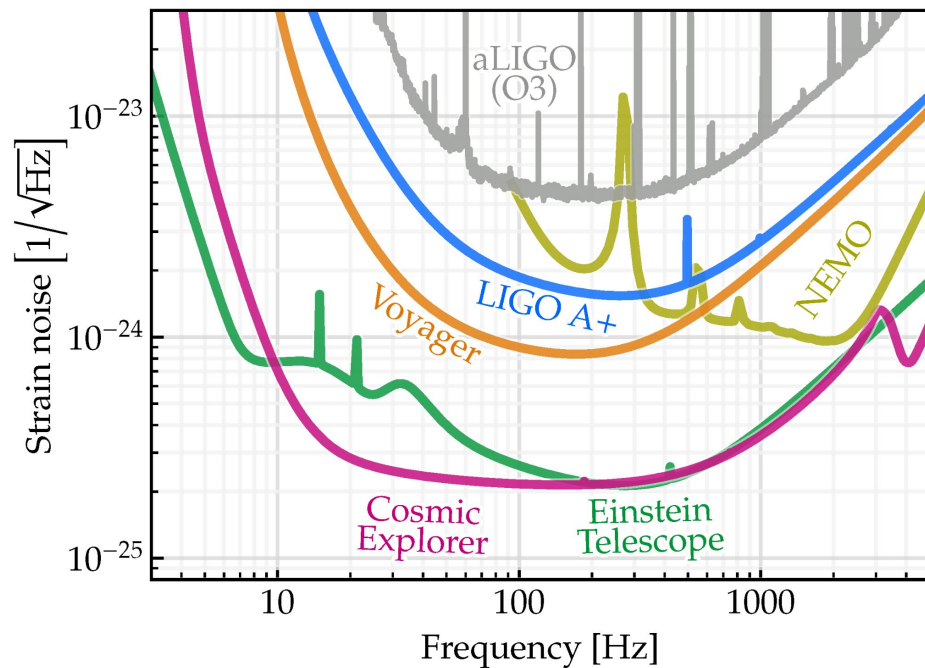
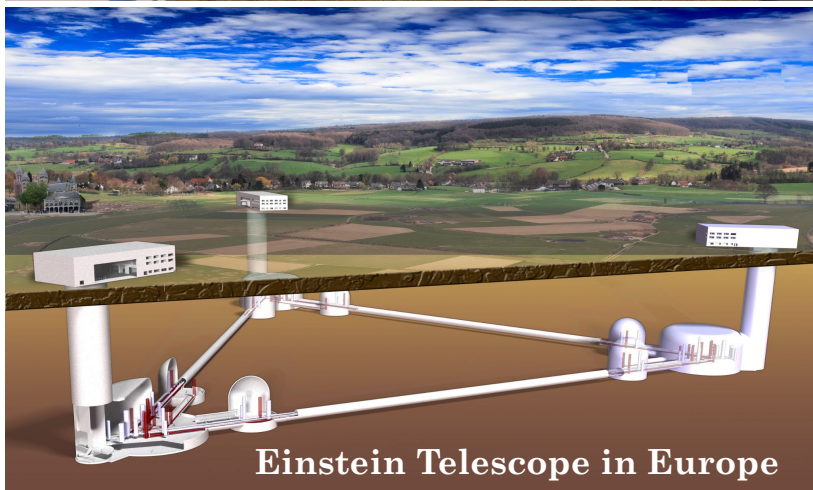


Next-generation GW detectors and BNS mergers



Evan D. Hall, Galaxies 2022, 10, 90

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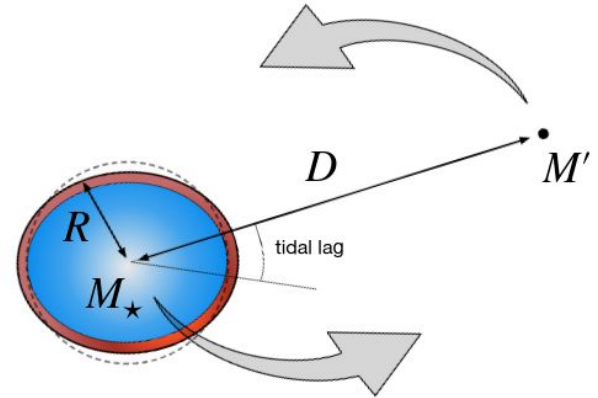
Signature of neutron star interior on gravitational wave data beyond adiabatic tidal effects within the reach of next-gen GW detectors?

Tidal interaction during binary neutron star inspiral

- **Adiabatic Tides** : Parameterized as ‘Tidal deformability’; has the dominant contribution towards the late inspiral
- **Dynamical Tides** : Associated with individual mode (e.g., f,g-mode) resonances

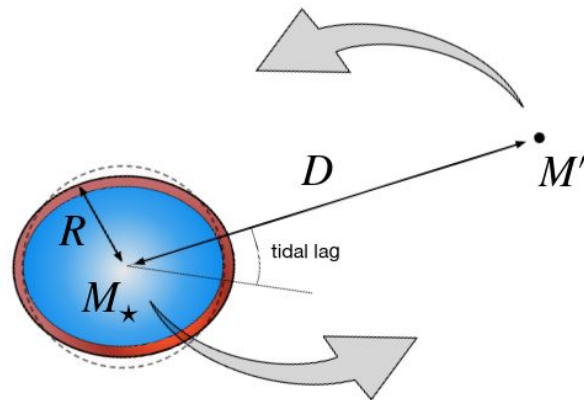
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- *Viscous effects in inspiral :*
- *Tidal Lag or dissipation*
 - *Tidal torquing for spinning NS(tidal spin)*



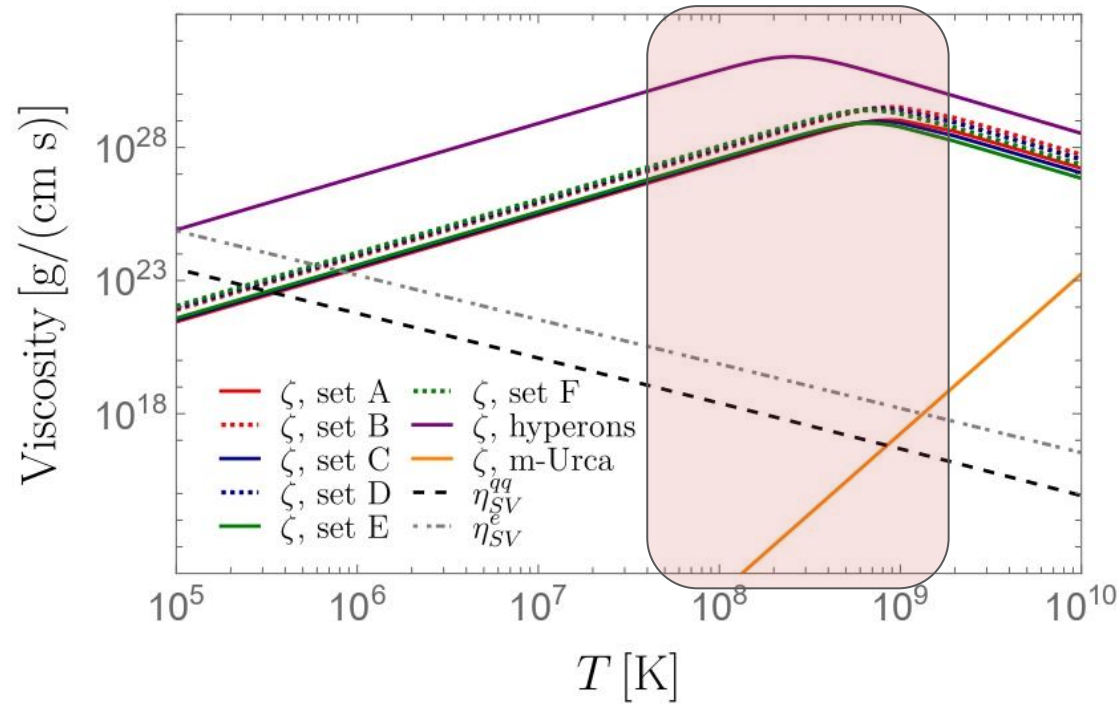
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- Dominant source at low temperature ($T \ll 1$ MeV): Shear viscosity from n-n/e-e scattering (**Bildsten & Cutler, ApJ 400(1992)**)



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

Bulk viscosity of exotic matter



Bulk viscosity during binary inspiral

Quark matter (unpaired u, d and s quarks) with electrons,
 ν -transparent regime, low T (neutrinos escape the star)

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Weak interactions
try to restore balance

Phase lag creates dissipation.

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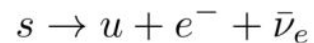
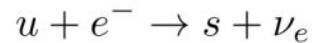
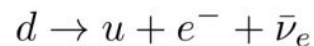
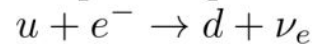
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Nonleptonic processes



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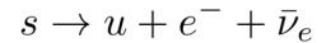
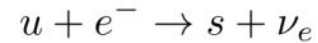
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Dominant contribution to the
viscosity at low temperatures

(Luis *et al*, *PRD* 109, 123022 (2024))

Impact of dissipation in the binary inspiral

➤ **Mode-sum approach (Newtonian)** : Tidal response of a neutron star as a sum of contributions associated with the star's free oscillation modes (D.Lai, 1994, MNRAS, 270, 611; N. Andersson et al, PRD 101, 083001 (2020)).

- Viscous dissipation modify the neutron star fluid response under tidal perturbations

$$\ddot{a}_\alpha + \boxed{\gamma_\alpha} \dot{a}_\alpha + \omega_\alpha^2 a_\alpha^2 = - \frac{M' W_{lm} Q_{nl}}{D^{l+1}} e^{i\Phi(t)}$$

viscous dissipation rate

Ghosh et al. arxiv:2504.07659

Energy dissipated and thermal evolution

- The leading order (Newtonian) energy dissipation rate from the dominant f-mode oscillations

$$\dot{E}_{\text{visc}} = \frac{24\pi}{5} \frac{M^2}{R} \omega_0^{-4} Q_0^2 \left(\frac{R}{D} \right)^9 \gamma_{\text{bulk}}$$

- The heating rate is given by

$$\frac{dU}{dt} = \dot{E}_{\text{visc}} + \dot{E}_{\text{cool}},$$

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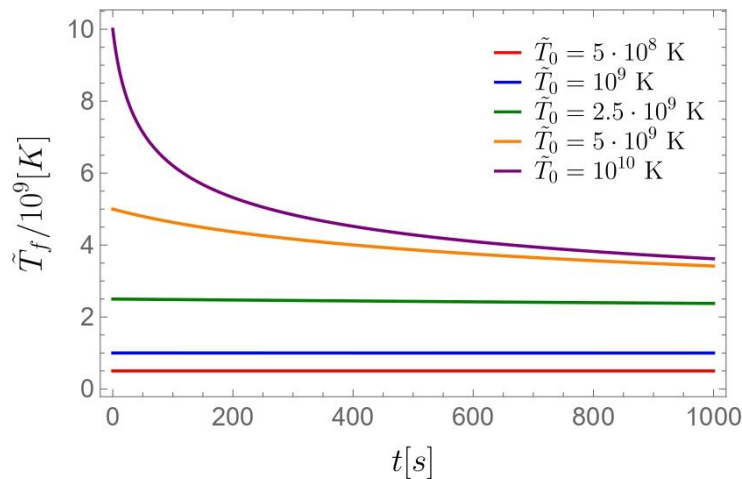
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Cooling timescales are much longer than the inspiral, so ignored.

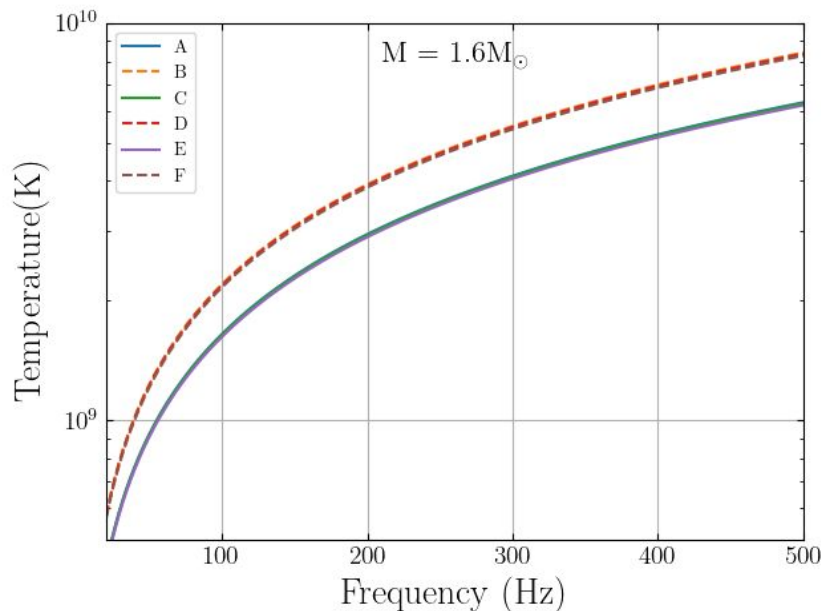
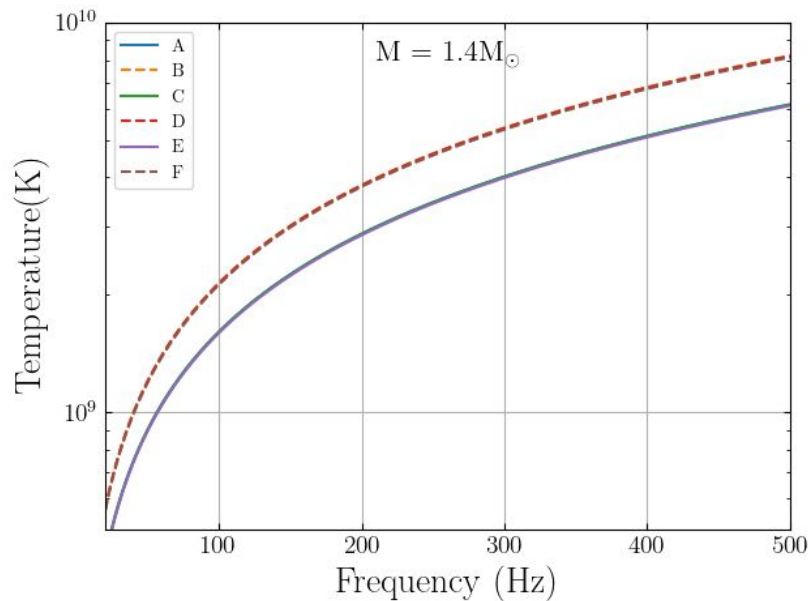


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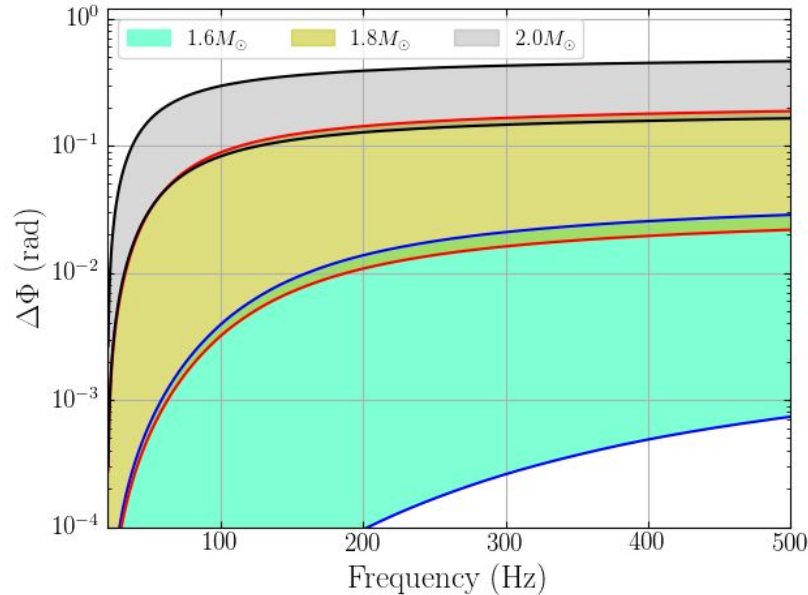


Contribution to the GW phase

➤ In Stationary Phase Approximation (SPA), the frequency domain phase is given as

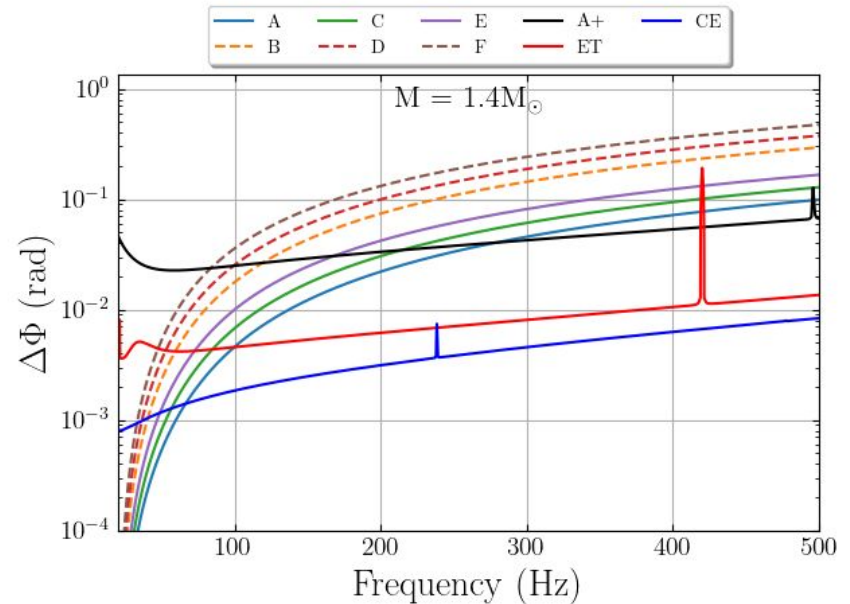
$$\Psi(f) = 2(t_c/M)v^3 - 2\phi_c - \pi/4 - \frac{2}{M} \int (v^3 - \bar{v}^3) \frac{E'(\bar{v})}{\mathcal{F}^\infty(\bar{v}) + \dot{E}_{\text{visc}}(\bar{v})} d\bar{v}$$

Hyperons



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

Quarks



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

Summary

- Tidal dissipation effects in binary neutron stars inspirals '*will not be negligible*' for strange quark stars.
- With next generation GW detectors, with increased sensitivity, detecting this effect is possible for high SNR events.
- Temperature could rise upto 10^9K during the inspiral as well, not required to include thermal effects in the EoS.
- If not accounted for in GW waveform models, this might lead to biased estimation of tidal deformability and thus biased equation of state inference (Ghosh et al., MNARS, 2025).
- A detection would provide “smoking-gun” signature for presence of exotic phases of dense matter inside neutron-star cores since nuclear matter does not have any source of high viscosity at low temperatures.

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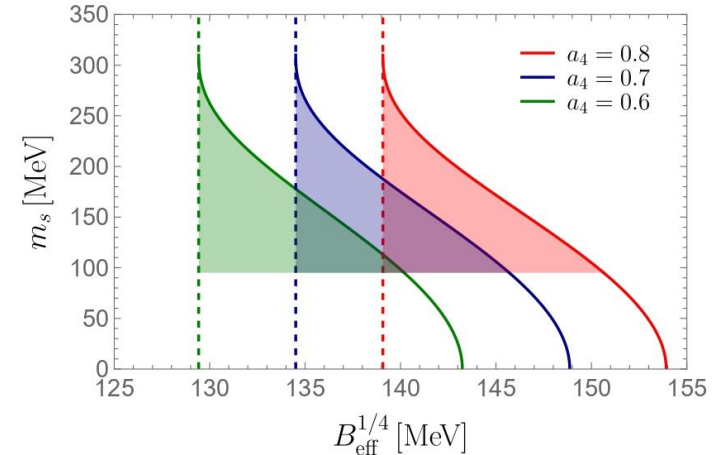
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Future work : Developing a inspiral-merger waveform model **incorporating fluid and gravitation radiation reaction dissipation** accurately and constraining fluid viscosity (out-of-equilibrium behaviour of dense matter) from GW merger events.

EXTRA SLIDES

MIT bag model parameter space

- Parameter space allowed for the bag constant and the strange quark mass by the Bodmer- Witten conjecture, which states that strange quark matter at equal quark chemical potentials might be the true ground state of hadronic matter
- In the zero temperature limit we fix the bag constant so that the binding energy at zero pressure of strange quark matter is less than the energy per baryon of ${}_{56}^{56}\text{Fe}$ (i.e. $\varepsilon/n_B \leq 930$ MeV) and also impose that two-flavour quark matter is not stable (i.e. $\varepsilon/n_B > 930$ MeV), discarding the possibility of neutrons and protons decaying into up and down quarks.
- In this work, we set $a_4 = 0.8, 0.7, 0.6$, which induce small to medium deviations of an ideal free Fermi gas ($a_4 = 1$) and are close to the value reported in . For the non-ideal bag model, we find that $m_{s,\text{max}} \approx 310$ MeV is the maximum value allowed for the strange quark mass.



- The change of internal energy is given by

$$\frac{dU}{dt} = C_V \frac{d\tilde{T}}{dt}$$

- The average heat capacity can be obtained as

$$C_V = \int_0^R c_V(\rho, \tilde{T}) \frac{4\pi r^2 dr}{\sqrt{1 - 2m/r}}$$

where

$$c_V = \tilde{T} e^{-\nu} \left(\frac{\mu_e^2}{3} + a_4 \sum_{f=u,d,s} \mu_f \sqrt{\mu_f^2 - m_f^2} \right)$$

- An analytical integration of the thermal evolution equation leads to

$$\frac{\tilde{T}_f^4}{4} + B \ln \left(\frac{\tilde{T}_f}{\tilde{T}_0} \right) = \frac{\tilde{T}_0^4}{4} + \frac{\pi}{648} \frac{Q^2 q A R^3}{\bar{\omega}^4 \sigma M_1} \left(\frac{3R}{D} \right)^5.$$

where $C_V = \sigma \tilde{T}$ and $\gamma = \frac{A \tilde{T}^2}{B + \tilde{T}^4}$

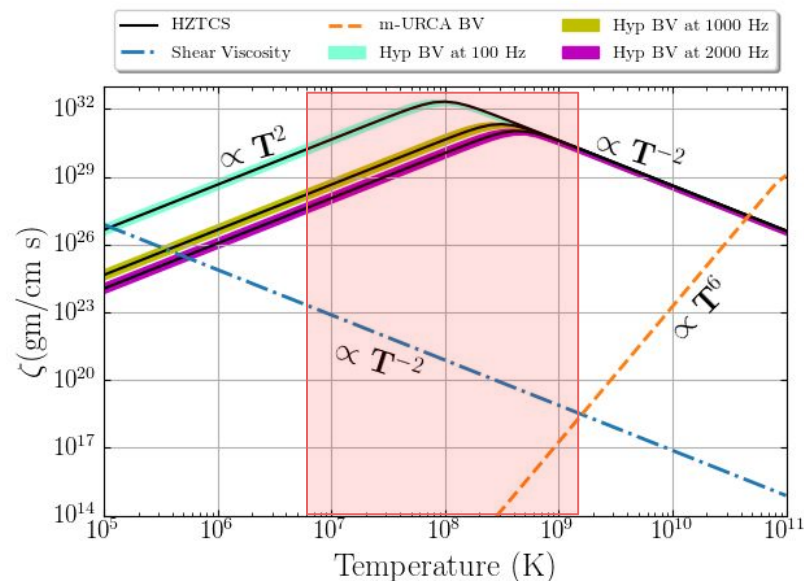
Bulk viscosity due to hyperons

- Bulk viscosity arises due to the pressure and density variations associated with the dynamical tidal excitation of NS oscillation modes that drive the system out of chemical equilibrium.
- Appearance of strangeness containing hyperons at the high-density core

- Dominant non-leptonic channel (**Lindblom and Owen, PRD, 65, 063006(2002)**):



- Hyperon bulk viscosity is higher by 10^8 - 10^{10} times than canonical shear viscosity at low temperatures $\sim 10^8$ K, relevant for the binary inspiral (considering hyperons are not superfluid).



Ghosh et al, PRD 109, 103036(2024)