Tidal heating as a direct probe of strangeness inside neutron stars

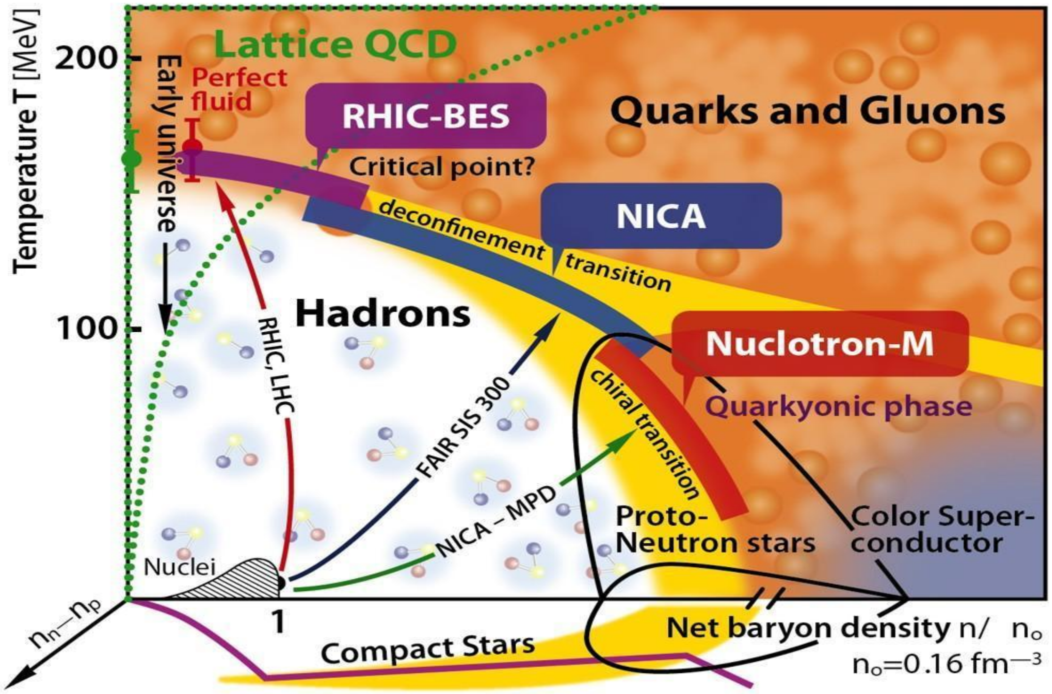
Suprovo Ghosh

Based on Phys. Rev. D 109,103036 (2024)

In collaboration with Bikram Pradhan and Debarati Chatterjee.

Workshop on
Anti-matter, Hyper-matter and Exotica Production
13 November, 2025

QCD Phase Diagram



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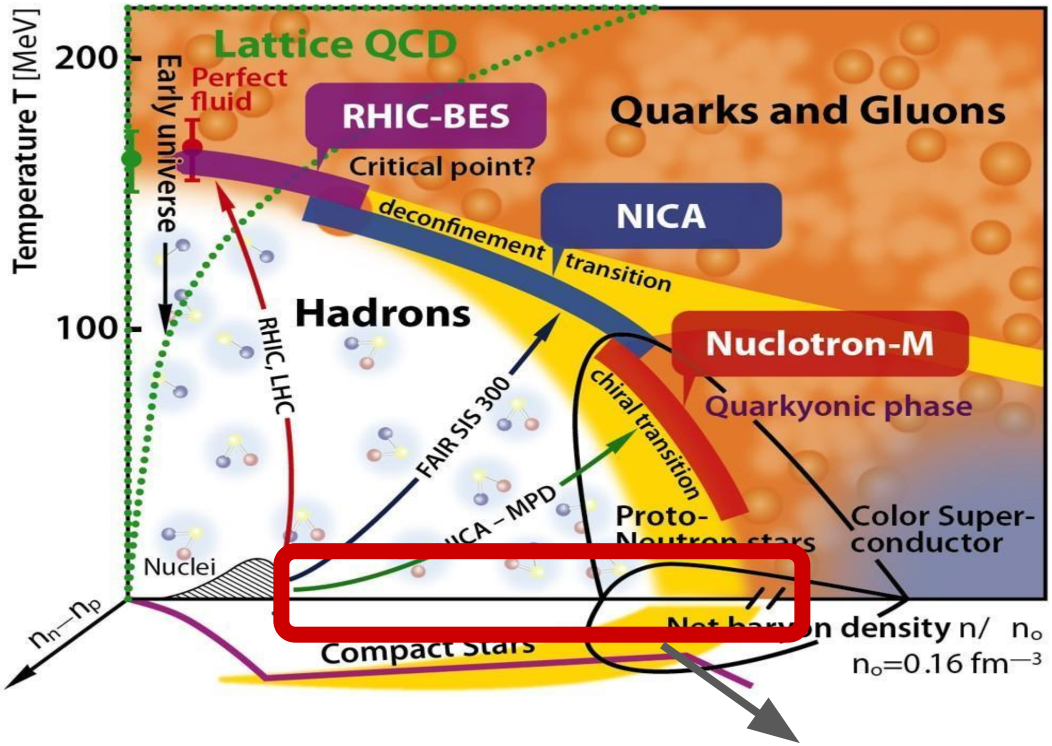
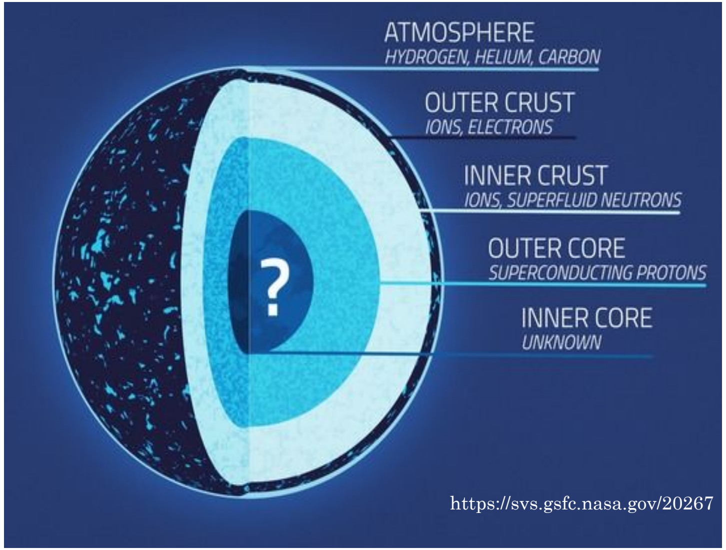


Neutron stars

Low T, High ρ, neutron-proton asymmetric

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 - $M \sim 1\text{-}2\ M_\odot$, $R \sim 10\text{-}14$ km , $\varrho \sim 2\text{-}10\ n_0$
- Composition of the NS core still unknown.
- Theoretical models to describe the dense matter behaviour.
- Equation of State (EoS) : Pressure-density relation. Uncertain because of the extrapolation to higher density, finite temperature, and isospin asymmetry



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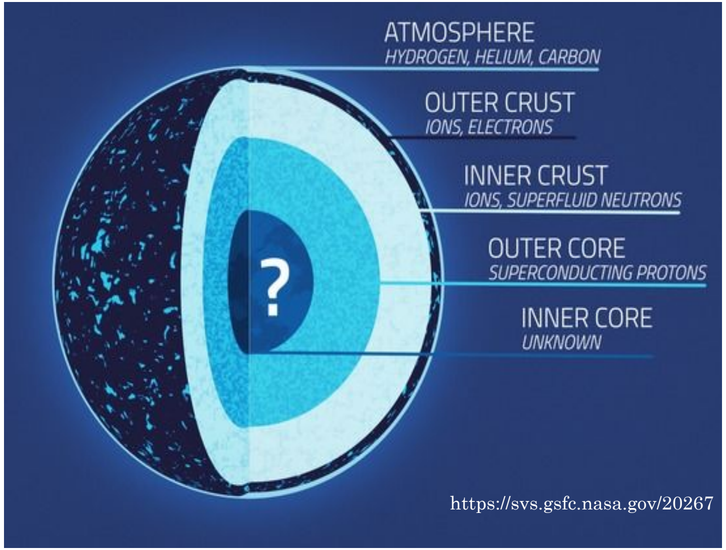
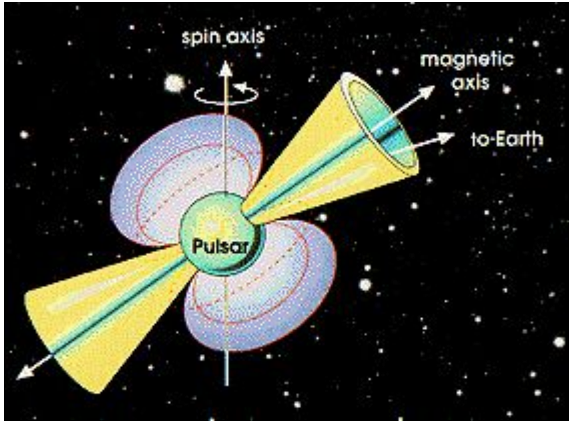


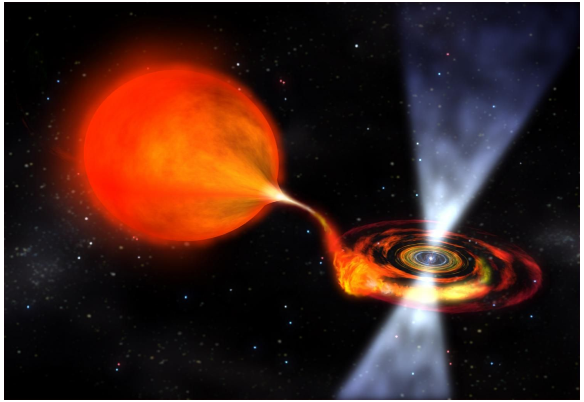
Multi-messenger observations of neutron stars → *Equation of state, Composition of neutron star core*

Neutron star : Multi-messenger observations



Pulsars : Radio Emission from Magnetised rotating neutron stars

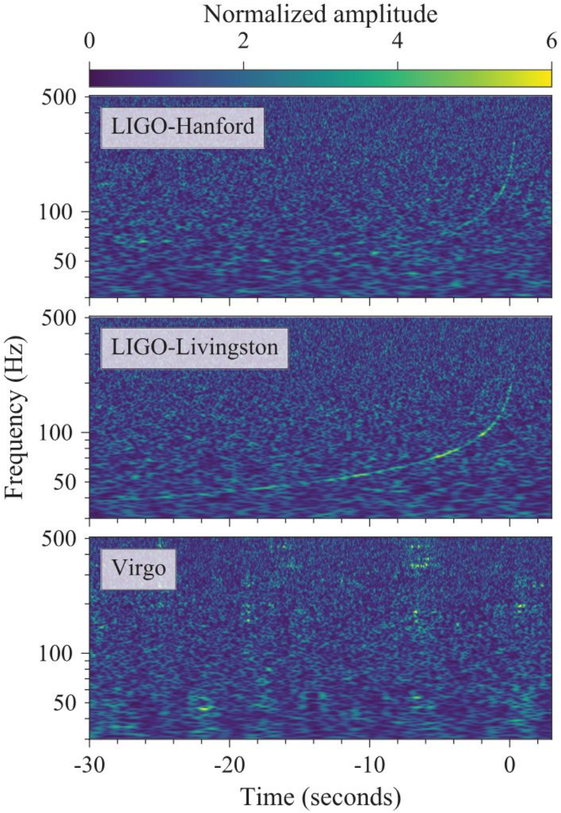
Magnetars : Giant magnetic flares



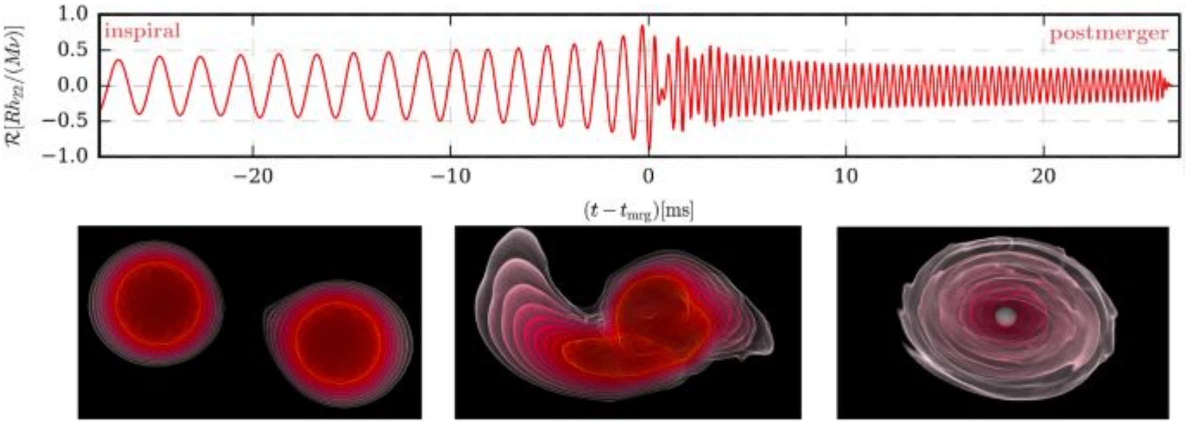
Low mass X-ray Binaries : Thermal emission from Accretion powered NSs

Gravitational wave as a probe of neutron star interior

BNS merger event GW170817



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



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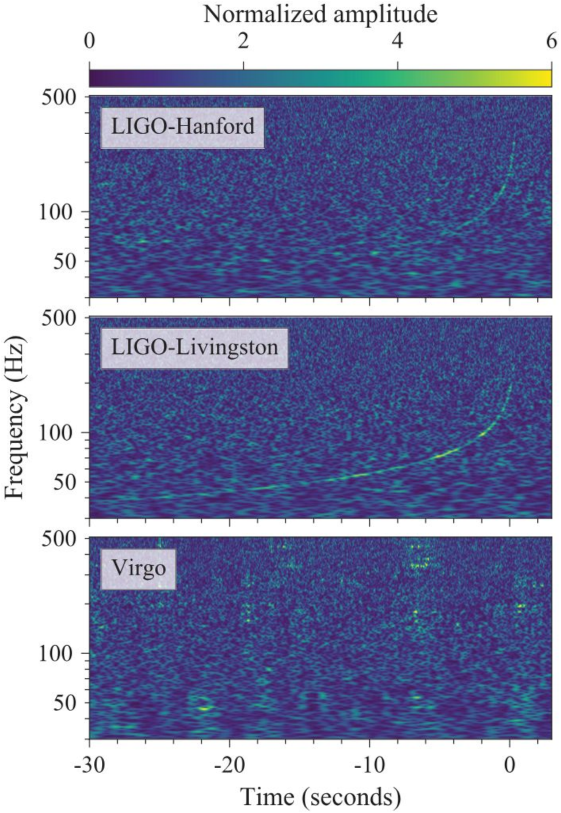

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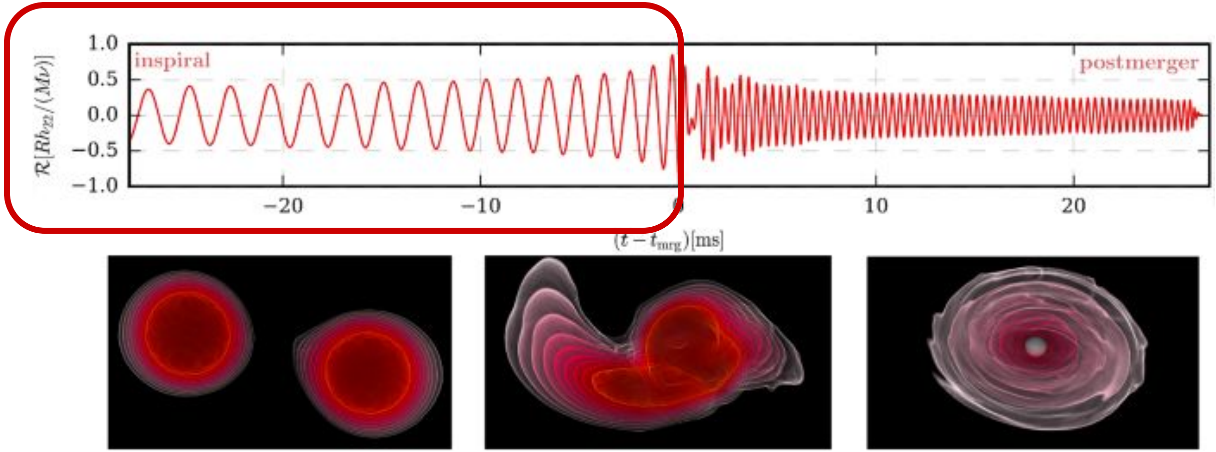


Dietrich *et al*, *Gen Relativ Gravit* 53, 27 (2021).

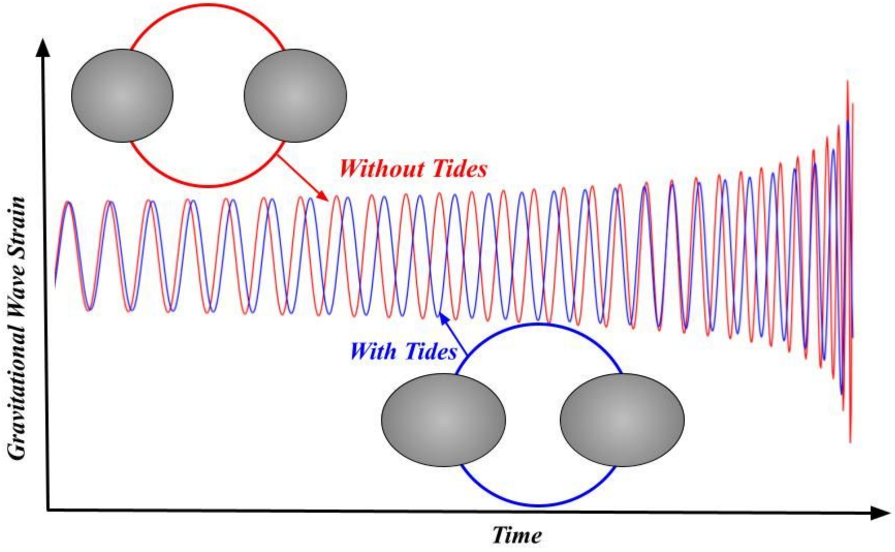
Gravitational wave as a probe of neutron star interior

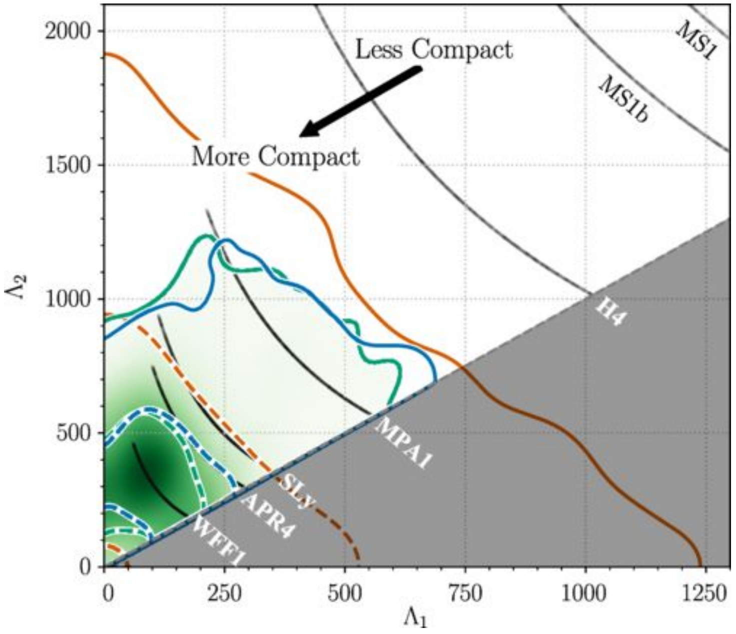
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

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

BNS merger event GW170817

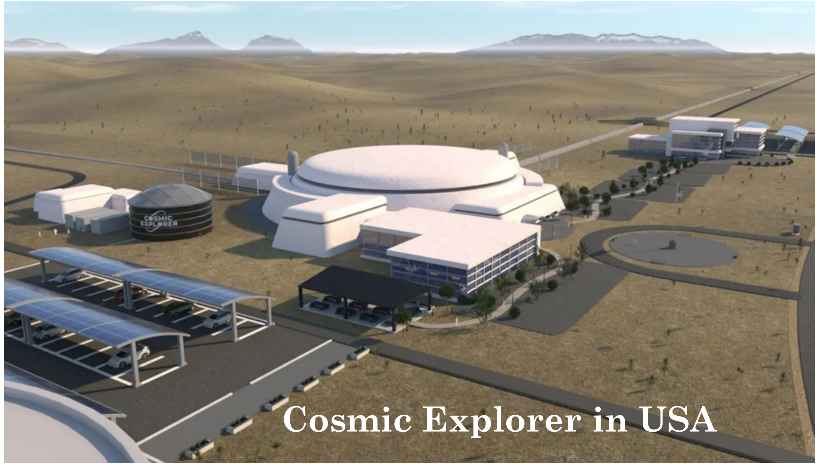
Constraint on dense matter EOS from mass & tidal deformability posterior.

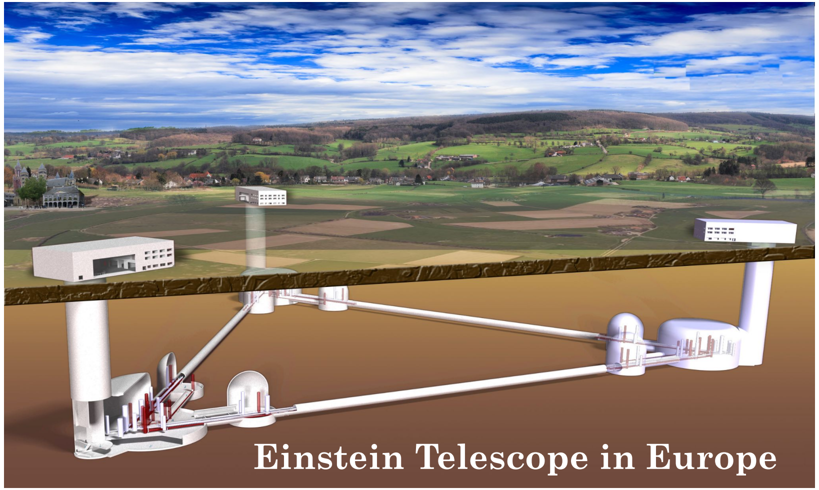


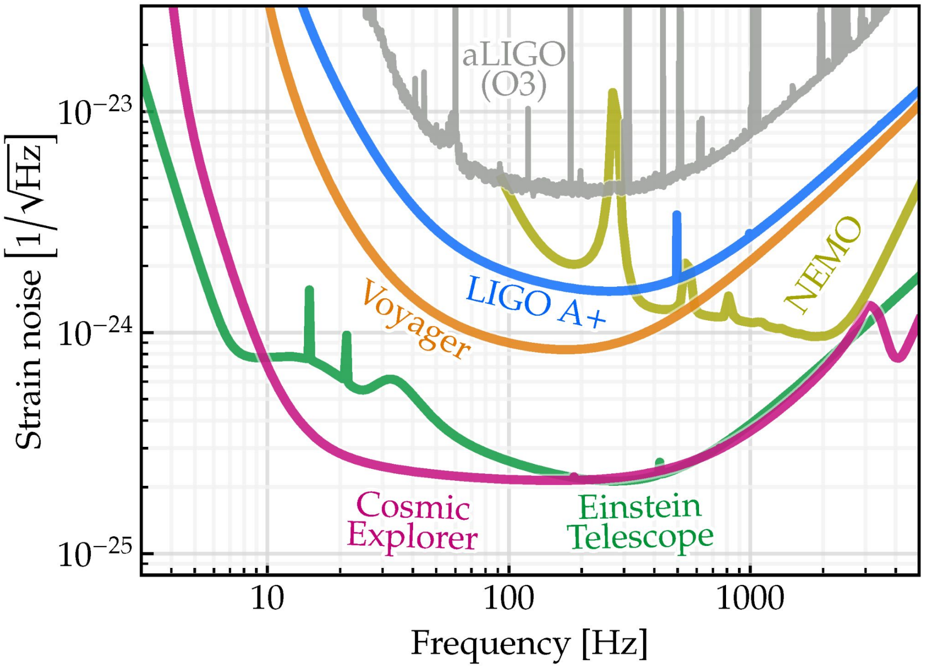


Abbott *et al, PRL* 121, 161101 (2018)

Next -generation GW detectors and BNS mergers







Evan D. Hall, Galaxies 2022, 10, 90

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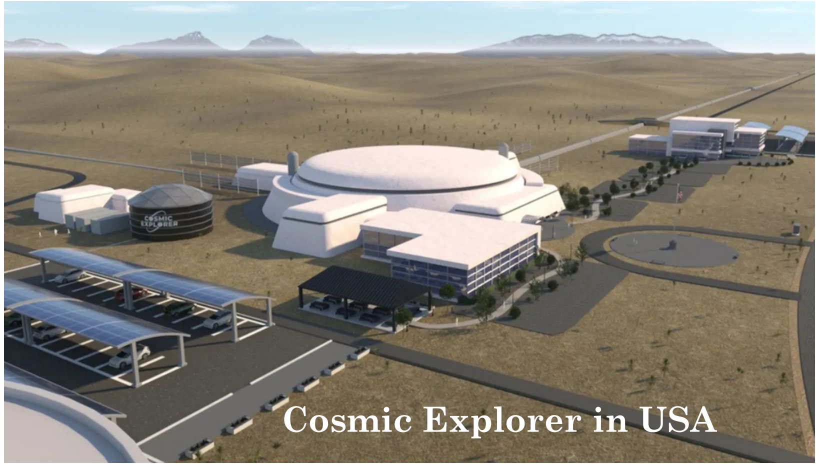

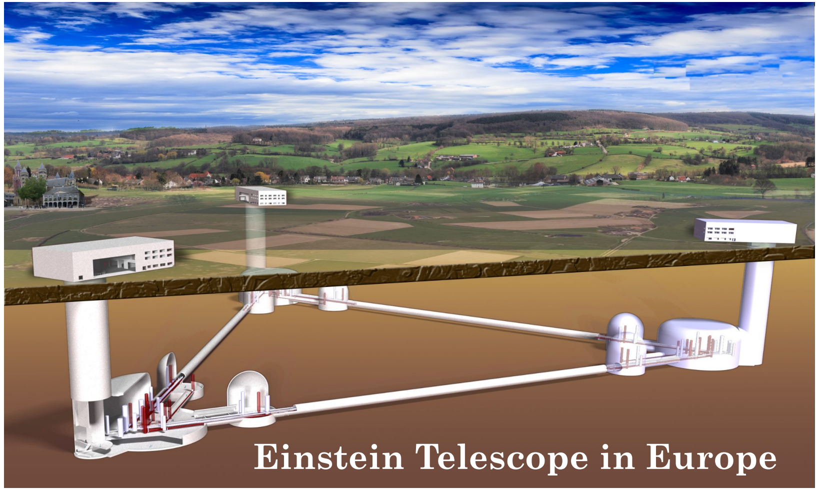

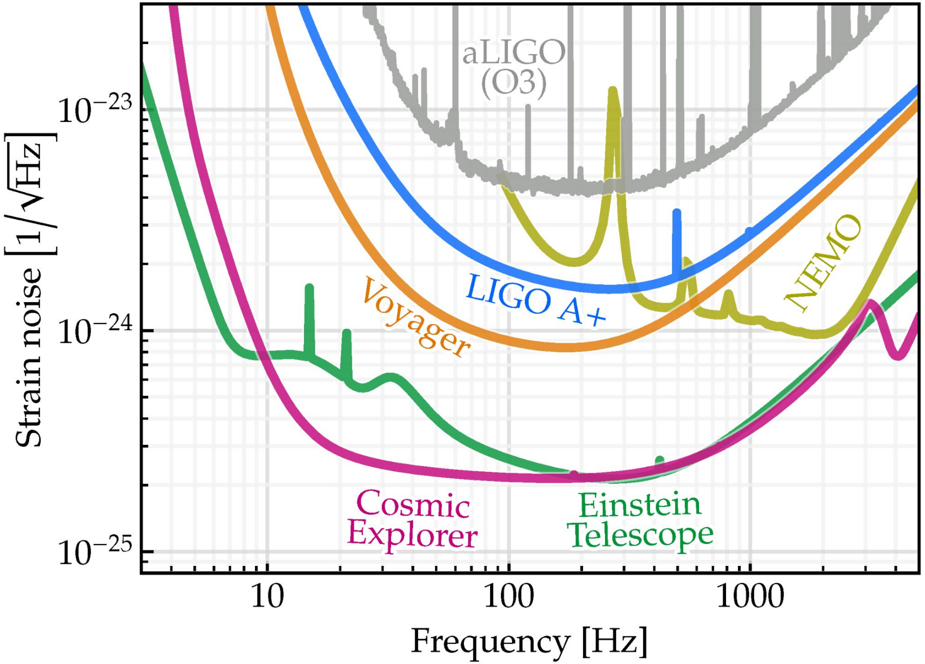

Evan D. Hall, Galaxies 2022, 10, 90

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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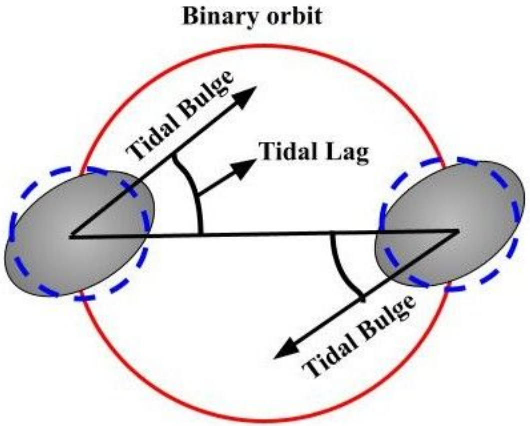
  - *Dissipative effects in inspiral :*
    - *Tidal Lag or dissipation*
    - *Tidal torquing for spinning NS (tidal spin)*
  - Dominant source at low temperature (T<< 1 MeV): Shear viscosity from n-n/e-e scattering (Bildsten & Cutler, ApJ 400(1992))

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



Bulk viscosity during binary inspiral

Nuclear matter with hyperons
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Dominant contribution to the viscosity at low temperatures (**Lindblom & Own, PRD 65,063006 (2002)**)

Bulk viscosity from hyperons

- Relaxation rates are expressed as

$$\frac{1}{\tau} = \frac{\Gamma_\Lambda}{\delta\mu}\frac{\delta\mu}{\delta n_n}$$

- For harmonic oscillations

$$\zeta = n_B \frac{\partial P}{\partial n_n}\frac{dn_n}{dn_B}\frac{\tau}{1+(\omega\tau)^2}$$

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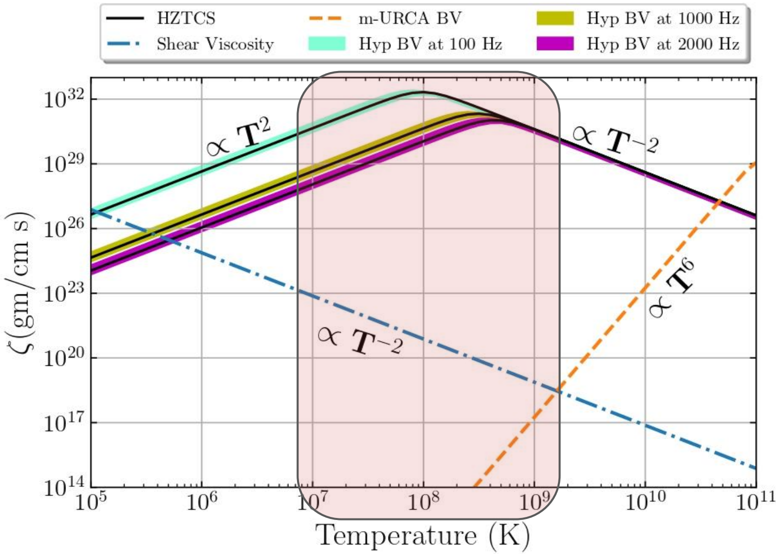


Ghosh *et al*, PRD 109, 103036(2024)

Equation of State Framework

Microscopic description:

Ghosh, Pradhan, Chatterjee, Schaffner-Bielich, Front. Astron. Space Sci. 9:864294 (2022)

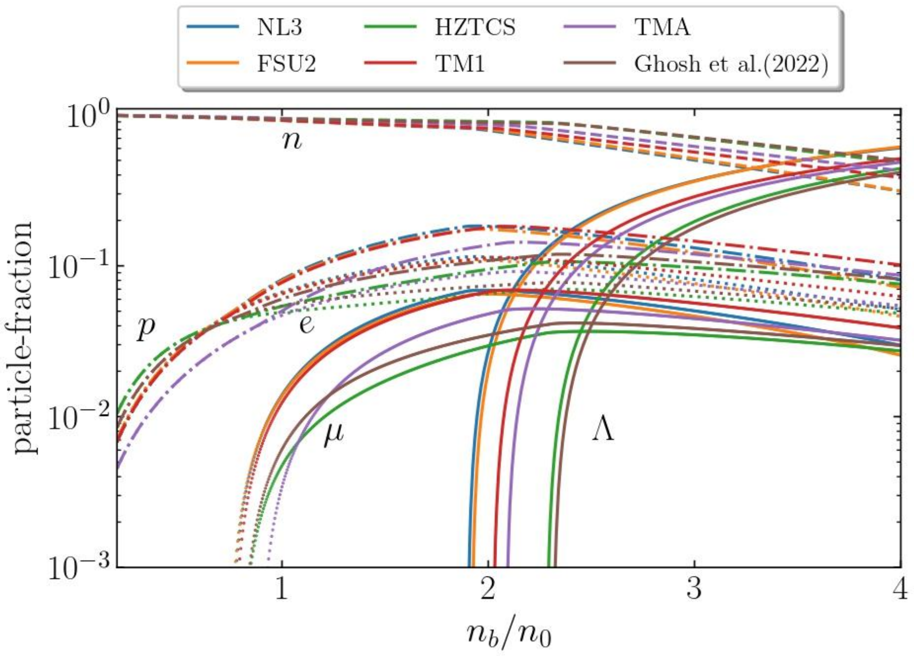
- Phenomenological Relativistic Mean Field (RMF) model.
- Strong interaction mediated by scalar(σ), vector(ω) & isovector(ρ) mesons.
- Interaction among hyperons is mediated by the exchange of strange vector (ϕ) meson.
- Coupling constants are determined by fitting them to the nuclear saturation properties.

$$\begin{aligned}\mathcal{L} \;=\; & \sum_B \bar{\psi}_B\left(i\gamma^\mu\partial_\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu\omega^\mu - g_{\rho B}\gamma_\mu\vec{I}_B.\vec{\rho}^\mu\right)\psi_B + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - U_\sigma \\ & + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}(\vec{\rho}_{\mu\nu}.\vec{\rho}^{\mu\nu} - 2m_\rho^2\vec{\rho}_\mu.\vec{\rho}^\mu) + \Lambda_\omega(g_{\rho N}^2\vec{\rho}_\mu.\vec{\rho}^\mu)\,(g_{\omega N}^2\omega_\mu\omega^\mu) \\ & + \sum_Y \bar{\psi}_Y(g_{\sigma^* Y}\sigma^* - g_{\phi Y}\gamma_\mu\phi^\mu)\psi_Y + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}(\partial_\mu\sigma^*\partial^\mu\sigma^* - m_{\sigma^*}^2\sigma^{*2}) \\ & + \sum_{\ell=\{e^-,\mu^-\}} \bar{\psi}_\ell(i\gamma^\mu\partial_\mu - m_\ell)\psi_\ell \qquad (1)\end{aligned}$$

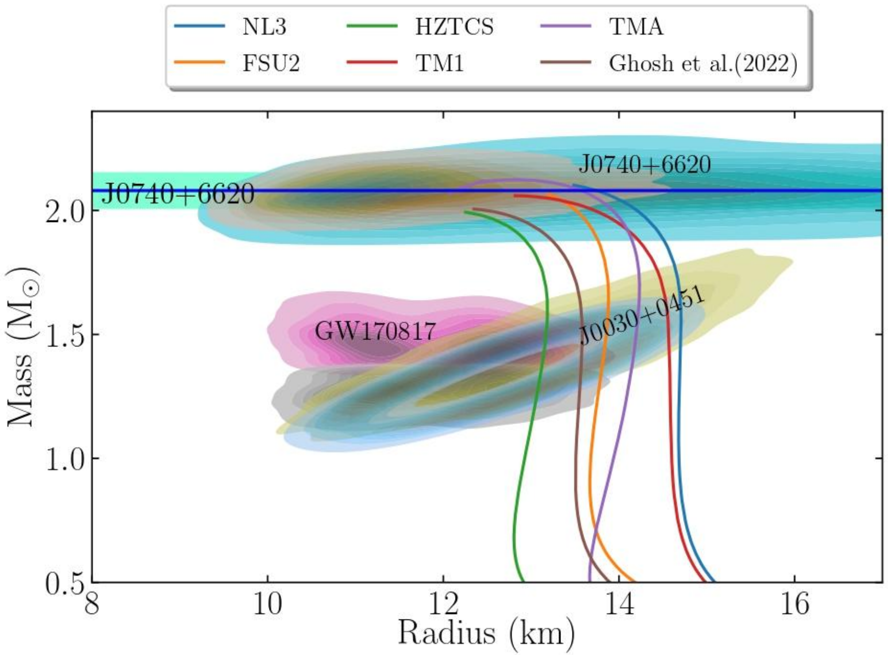
List of EOS

EOS	Max. mass ($M_\odot$)	Λ onset density	Mass($M_\odot$)	Central density	Radius (km)	Hyperon core radius(km)	f-mode Freq.(Hz)	Max. temp(K) at $D/R=3$	$\Delta\Phi = 2\pi\Delta\mathcal{N}$ (rad)
NL3 [47]	2.10	$1.90n_0$	1.6	$2.07n_0$	14.7	3.42	1847	9.7×10^8	0.001
			1.8	$2.48n_0$	14.6	6.19	1909	3.3×10^9	0.08
			2.0	$3.35n_0$	14.2	8.10	2009	6.2×10^9	0.3
TM1 [48]	2.06	$2.02n_0$	1.6	$2.24n_0$	14.55	3.16	1873	8.7×10^8	0.0008
			1.8	$2.77n_0$	14.37	6.18	1947	3.4×10^9	0.09
			2.0	$4.06n_0$	13.6	8.15	2092	6.7×10^9	0.34
TMA [48]	2.12	$2.09n_0$	1.8	$2.54n_0$	14.2	5.13	1948	2.3×10^9	0.02
			2.0	$3.35n_0$	13.89	7.36	1909	5.1×10^9	0.16
HZTCS [49]	2.00	$2.28n_0$	1.6	$2.67n_0$	13.2	4.89	2108	2.3×10^9	0.02
			1.8	$3.32n_0$	13.1	6.82	2171	4.7×10^9	0.16
			2.0	$5.32n_0$	12.25	8.17	2305	7.9×10^9	0.44
FSU2 [47]	2.03	$1.92n_0$	1.6	$2.22n_0$	14.4	4.98	1898	2.1×10^9	0.03
			1.8	$2.72n_0$	14.2	7.07	1968	4.5×10^9	0.19
			2.0	$3.82n_0$	13.6	8.54	2099	7.4×10^9	0.47
Stiffest EOS from Ghosh et al. (2022) [50]	2.01	$2.31n_0$	1.6	$2.71n_0$	13.5	3.88	2047	1.4×10^9	0.004
			1.8	$3.39n_0$	13.4	6.34	2119	4.1×10^9	0.11
			2.0	$5.5n_0$	12.5	8.05	2256	7.2×10^9	0.37

EOS properties



Particle fractions



M-R diagram

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

Binary Inspiral and Tidal Heating

- **Lagrangian fluid displacement vector can be decomposed in terms of normal modes.**

$$\xi_\alpha(r) = \left[\zeta^r_{nl}(r)e_r + r\zeta^{\perp}_{nl}(r)\nabla\right] Y_{lm}(\theta,\phi)$$

- **The energy dissipated due to viscosity is given by (Lai, MNRAS 270(1994))**

$$\dot{E}_{visc} = \int d^3x\sigma_{ij}v_{i,j} \text{ where } \sigma_{ij} = \eta\left(v_{i,j} + v_{i,j} - \frac{2}{3}\delta_{ij}\nabla.v\right) + \zeta\delta_{ij}\nabla.v$$

- **The mode damping rate is given by (Lai, MNRAS 270(1994))**

$$\gamma_{bulk} = \frac{1}{2}\frac{(l+|m|)!}{(l-|m|)!}\int_0^R r^2 dr\zeta\left(\frac{\partial\xi^r}{\partial r} + \frac{2}{r}\xi^r - l(l+1)\frac{\xi^{\perp}}{r}\right)^2$$

- **Leading order gravitational radiation energy**

$$\dot{E}_{gw} = \frac{-32\mathcal{M}\Omega}{5c^5}(G\mathcal{M}\Omega)^{7/3}$$

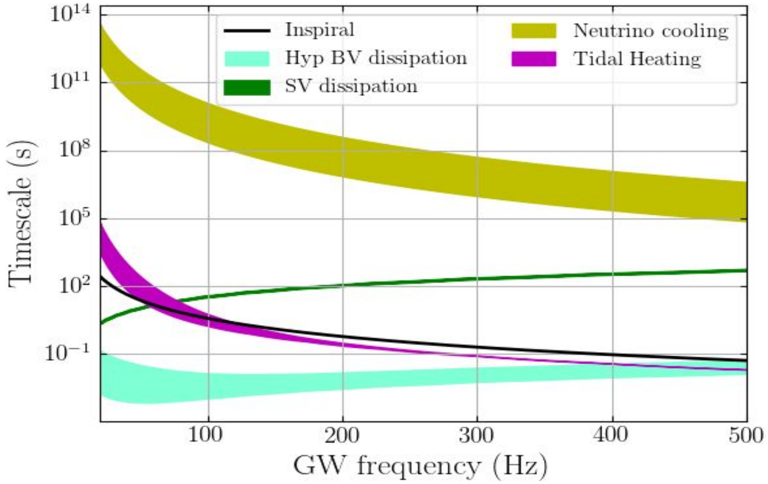
Binary Inspiral and Tidal Heating

- The heating rate is given by

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

- Assuming degenerate Fermi gas, final temperature can be obtained

$$\left[\frac{T^4}{4} + B\ln(T)\right] = \frac{\pi}{21870}\omega_0^{-4}Q_0^2 q\frac{A}{10^{22}} \times \left(\frac{c^2R}{GM}\right)\left(\frac{c^3R^2}{G}\right)\left(\frac{3R}{D}\right)^5, \qquad \gamma_{bulk} = \frac{AT^2}{B+T^4}$$



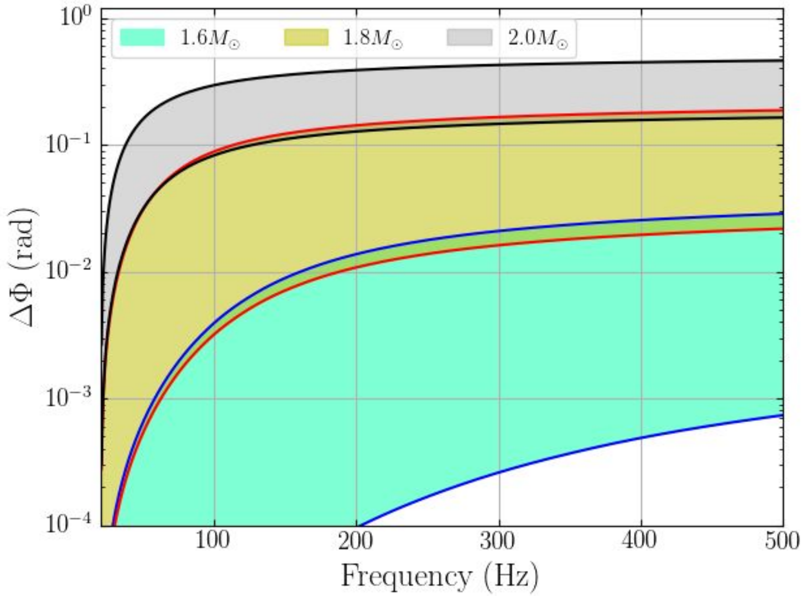
Ghosh *et al*, PRD 109, 103036(2024)

Dissipation and heating happens well within the timescale of inspiral !!

Phase Error Estimation and Detectability

- ➢ **Additional torque to the viscous dissipation of energy will lead to a total change in the number of cycles.**

$$\Delta\mathcal{N} = -\int_{f_a}^{f_b} t_D \left(\frac{\dot{E}_{visc}}{\dot{E}_{gw}}\right) df$$



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

Current phase uncertainty estimates is ~0.02 rad for A+ and 10^{-3} rad for Cosmic Explorer (CE). (Read (2023))

Summary and Future Outlook

- **Tidal dissipation effects in binary neutron stars inspirals '*will not be negligible*' if hyperons are present in neutron star cores.**

- **With next generation GW detectors, with increased sensitivity, detecting this effect is possible for high SNR events.**

- **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.**

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.