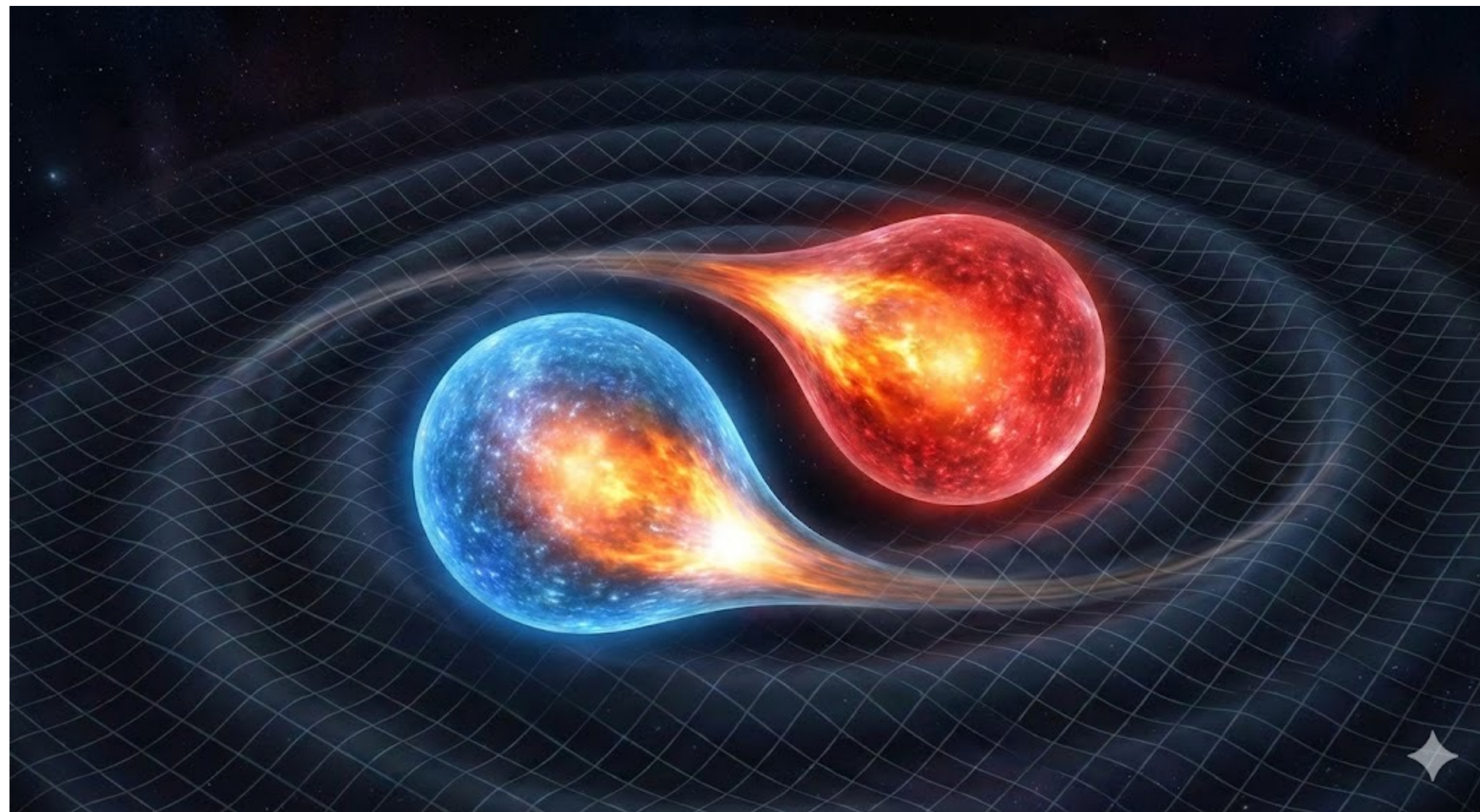


Bulk viscosity effects in compact star mergers: quark matter

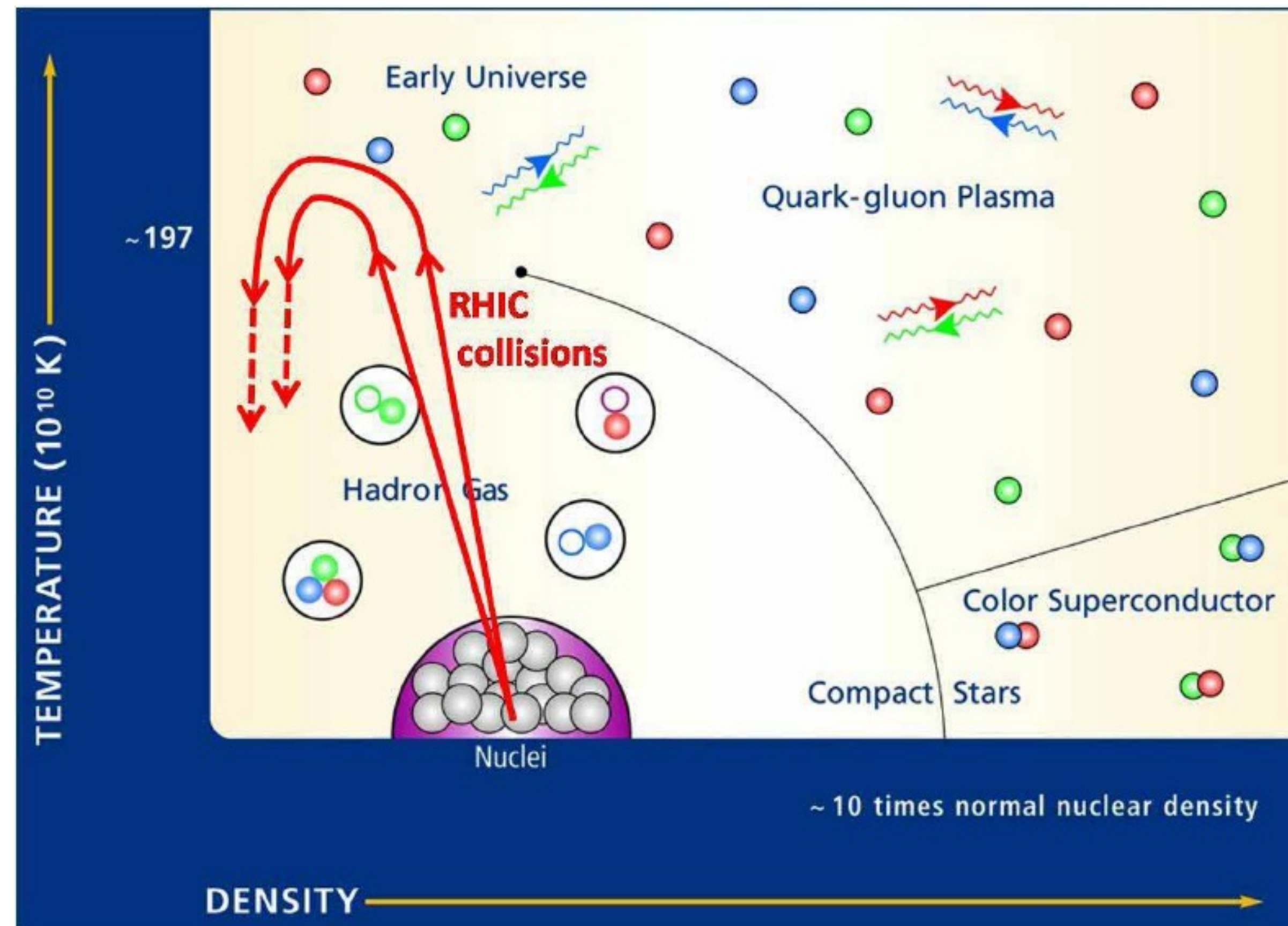


Cristina Manuel



Stony Brook, February 2026





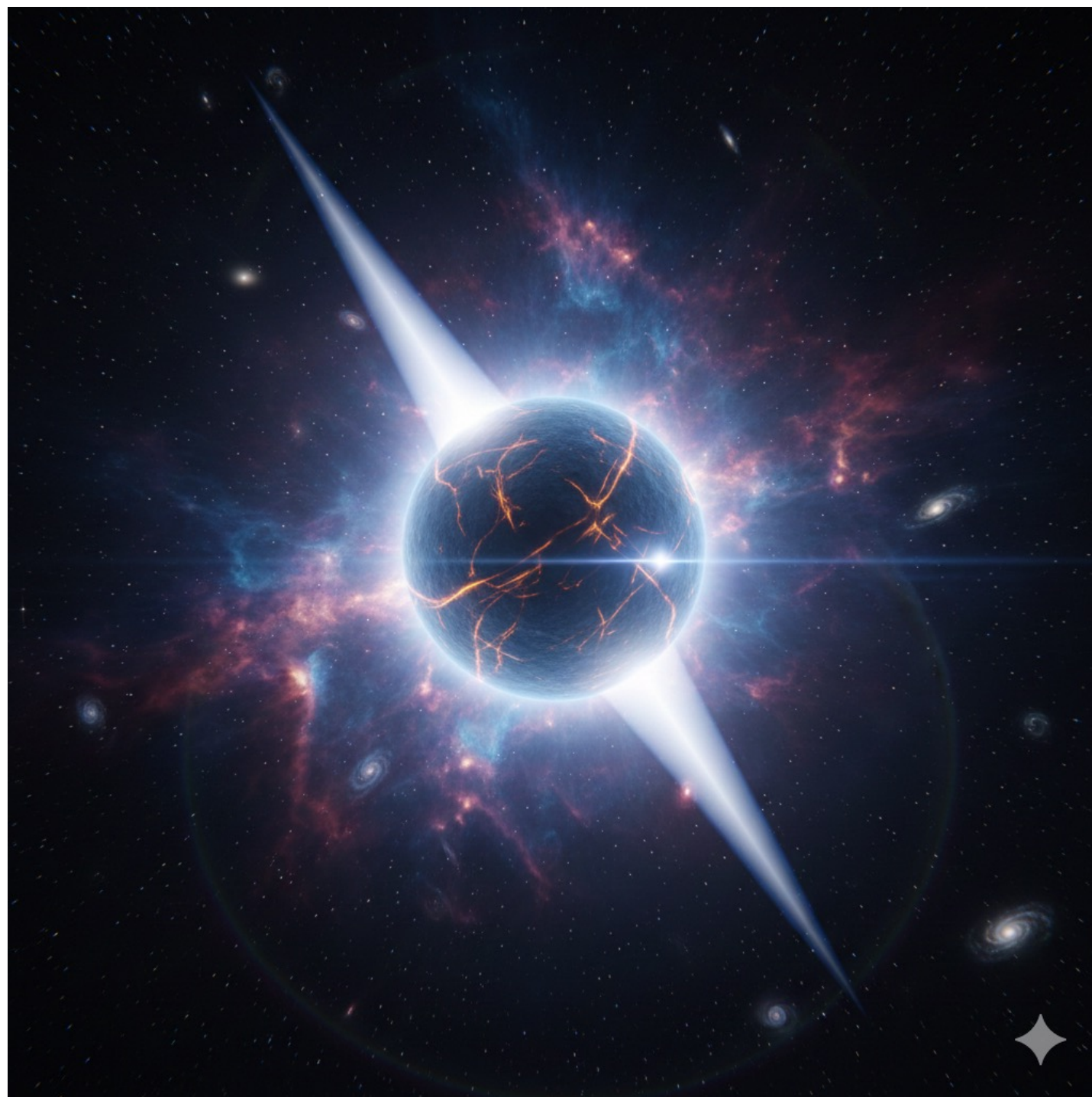
Can we detect deconfined phases at extreme conditions?

OUTLINE

- Introduction and motivation
- Bulk viscosity and nuclear matter
- Bulk viscosity and quark matter

based on work with J. Hernandez, L.Tolos and S. Säppi

ars: remnants of massive stars after supernova ex



Mass:	$M \sim 1-2 M_{\odot},$
Radius:	$R \sim 10-12 \text{ km}$
Density:	$n \sim 10^{14}-10^{15} \text{ g/cm}^3$
Magnetic field:	$B \sim 10^8...10^{16} \text{ G}$
Temperature:	$T \sim 10^6...10^{11} \text{ K}$
Rotational periods:	$P \sim \text{ms} \dots \text{s}$

Observed as: magnetars, radio pulsars, x-ray pulsars, magnetar+pulsar,

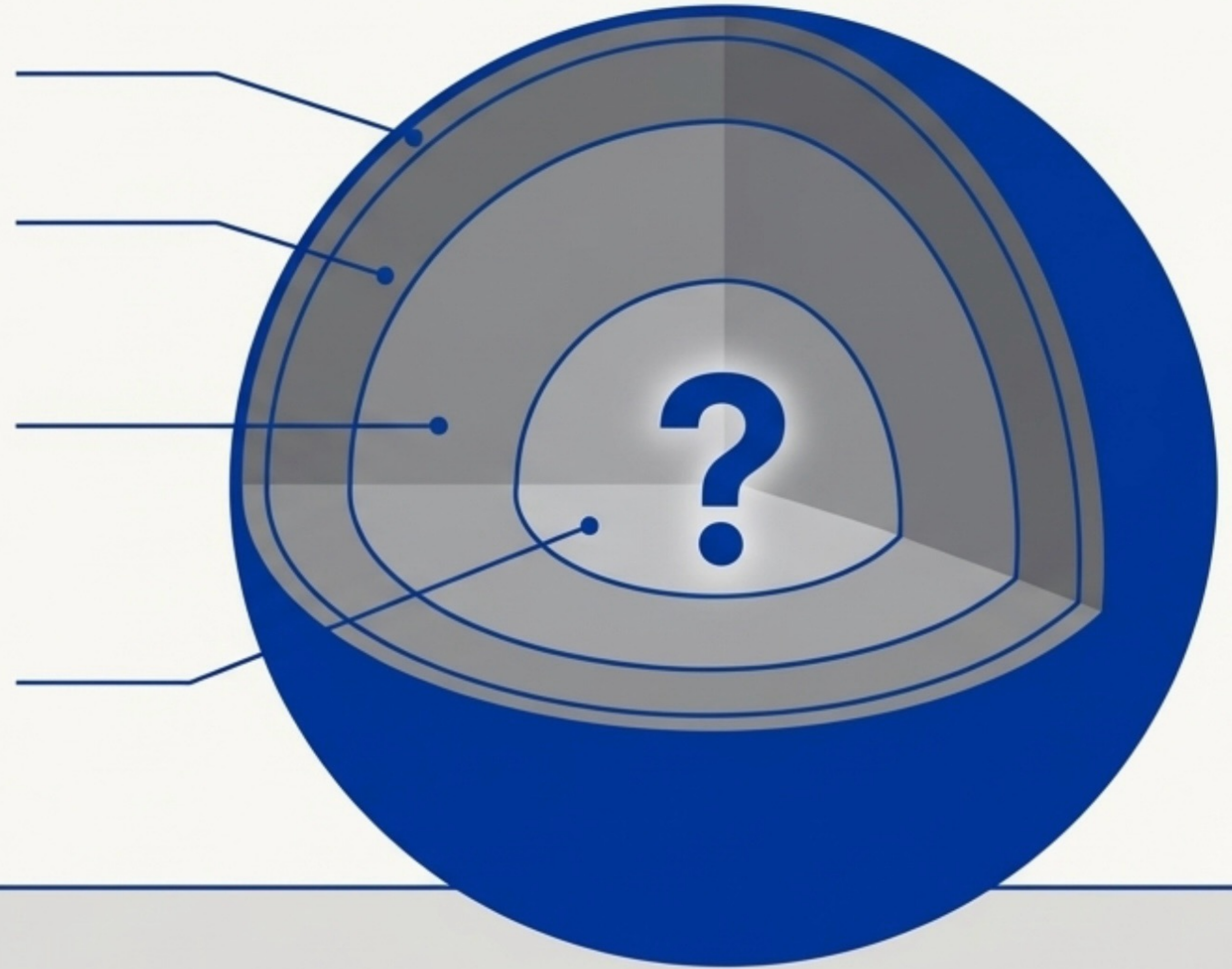
Structure of a Neutron Star

Outer Crust: A solid lattice of atomic nuclei and a sea of free electrons.

Inner Crust: Heavier nuclei, free electrons, and a superfluid of “dripped” neutrons. Exotic “pasta” phases may exist here.

Outer Core: A quantum liquid of superfluid neutrons, superconducting protons, and electrons. Densities are several times that of an atomic nucleus ($\sim 0.5 - 2 \rho_0$).

Inner Core: The ultimate unknown. Densities may reach $10-15 \rho_0$. Is it hyperons? A quark-gluon plasma? A color superconductor?



Central Challenge

- The main puzzle: strong nuclear interactions (QCD) have never been tested at so high densities.
- Most of our predictions are based on models.

Einstein equations + Relativistic Hydrodynamics

M/R in the range 0.1 - 0.3

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - g^{\mu\nu}$$

} EOS allows to fix M/R (TOV equations)

$$\delta(G_{\mu\nu} - 8\pi T_{\mu\nu}) = 0$$

$$\delta[u^\mu \nabla_\alpha T_\mu^\alpha] = 0$$

$$\delta[P_\rho^\mu \nabla_\alpha T_\mu^\alpha] = 0$$

$$\delta(\nabla_\mu (n u^\mu)) = 0$$

} Oscillation hydrodynamical modes

(p, f, g, r modes)

} Frequency fixed by EOS, lifetime by
transport coefficients

GRAVITATIONAL WAVE ASTRONOMY

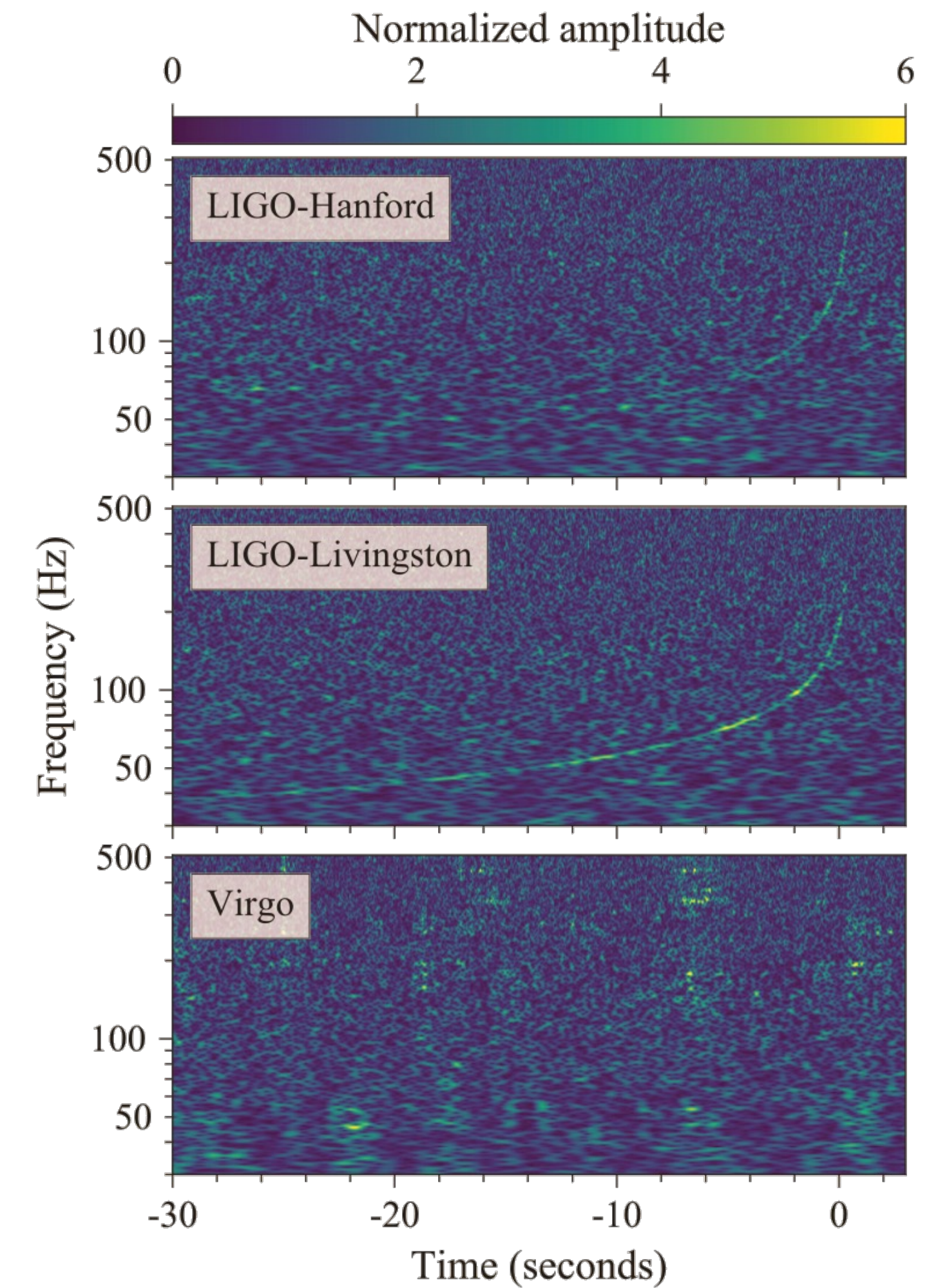
It can provide information on the M/R ratio (and thus EOS) and tidal deformability



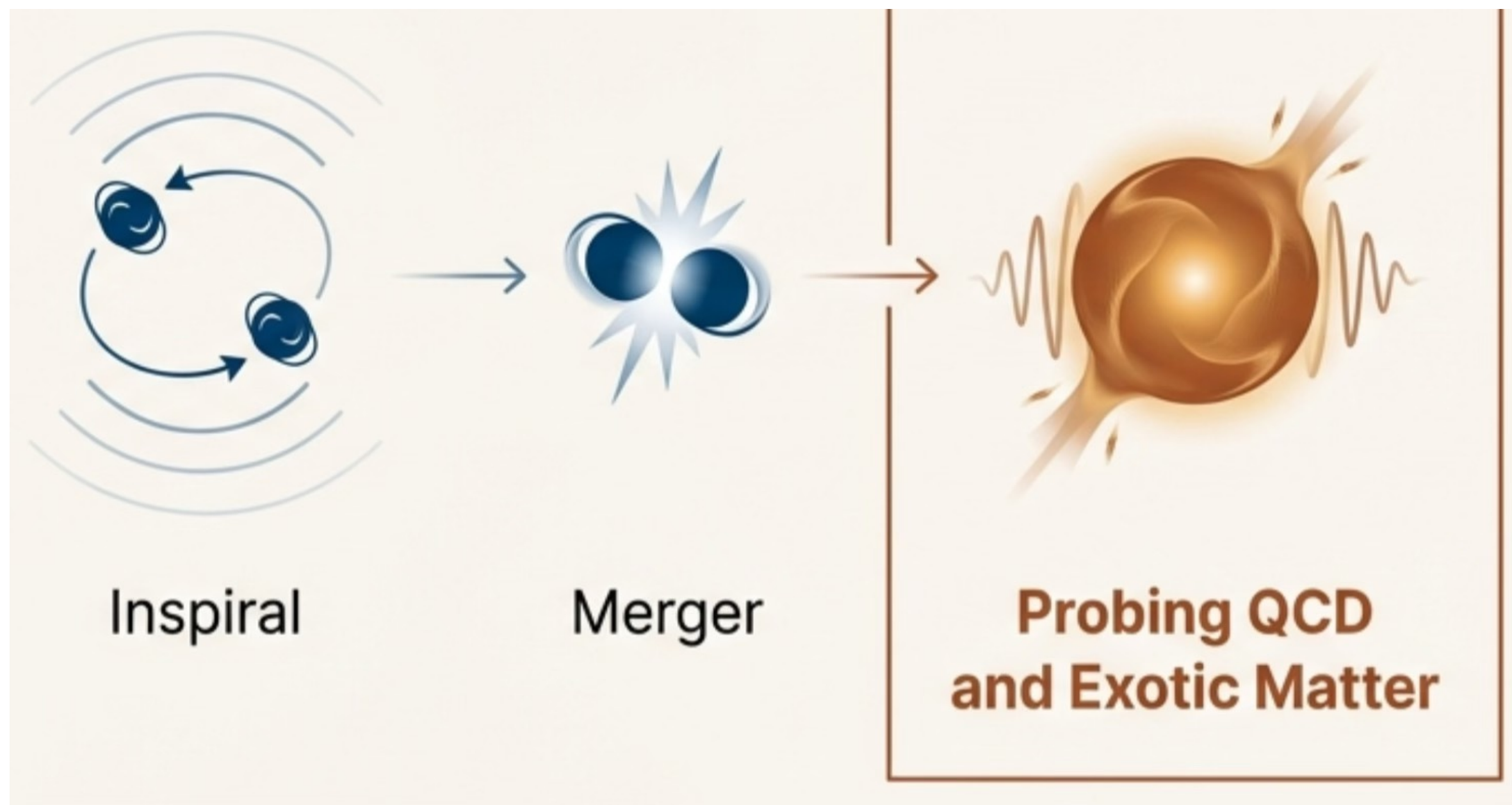
LIGO Scientific Collaboration and Virgo Collaboration

GW170817 first detection of a neutron
star merger

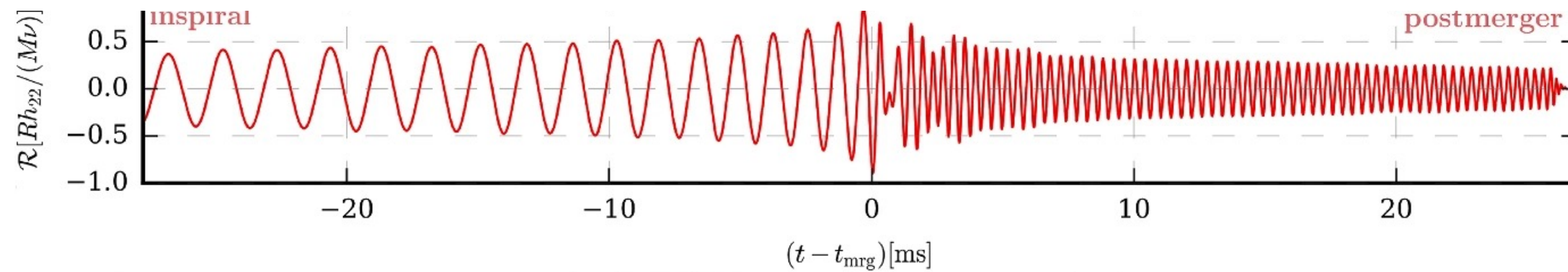
GW190425



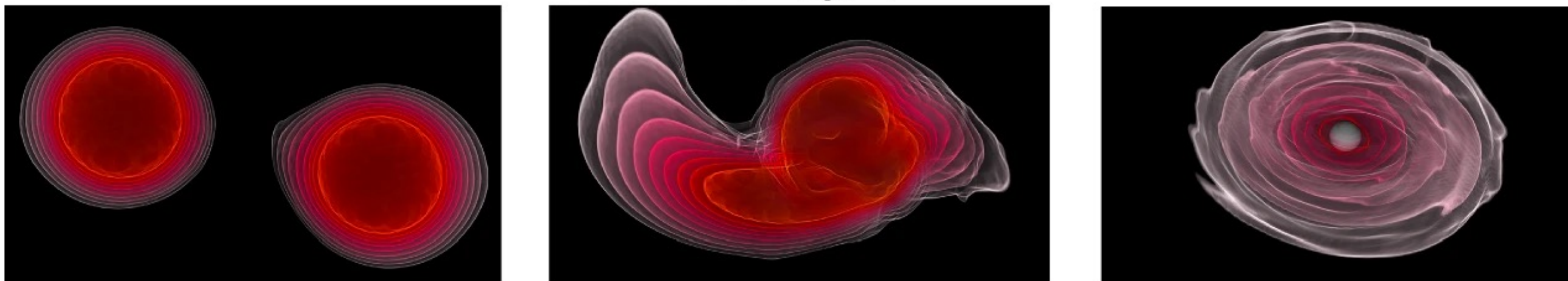
Can it provide information on transport properties of NS?



Numerical simulations GW emitted



Relevant times scales



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

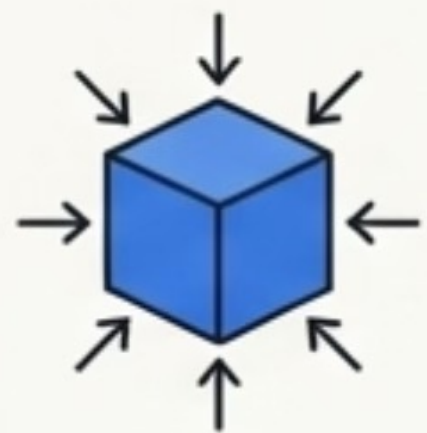
Estimates associated to shear viscosity, thermal conductivity and bulk viscosity for nuclear matter

Alford et al, Phys. Rev. Lett. **120**, 041101

$$\tau_{\eta}^e \approx 1.6 \cdot 10^8 \text{s} \left(\frac{z_{\text{typ}}}{1 \text{ km}} \right)^2 \left(\frac{T}{1 \text{ MeV}} \right)^{5/3} \left(\frac{0.1}{x_p} \right)^{14/9} \left(\frac{n_0}{n_B} \right)^{5/9}$$

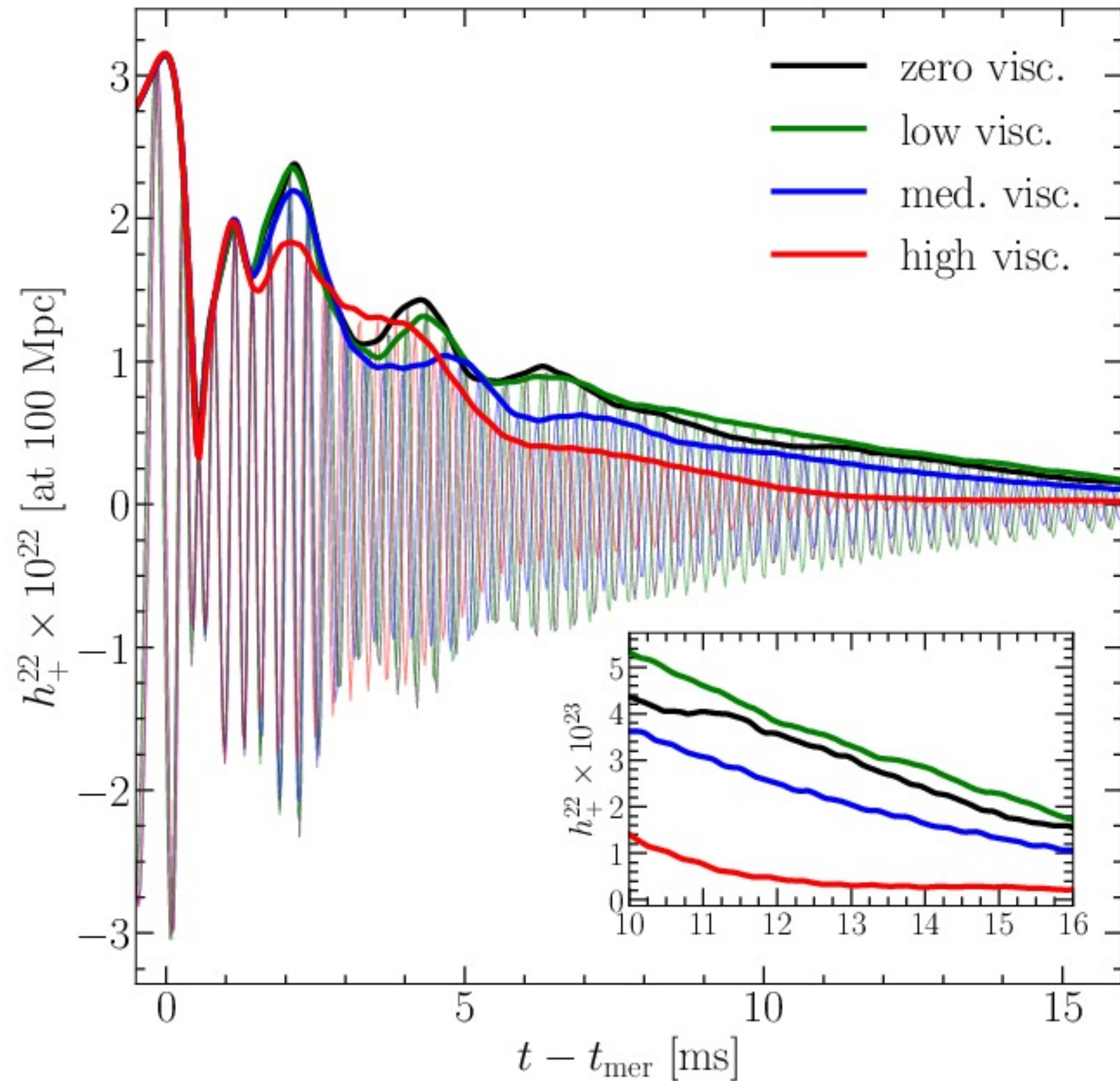
$$\tau_{\kappa}^e \approx 5 \cdot 10^8 \text{s} \left(\frac{0.1}{x_p} \right)^{2/3} \left(\frac{m_n^*}{m_n} \right) \left(\frac{n_0}{n_B} \right)^{1/3} \left(\frac{z_{\text{typ}}}{1 \text{ km}} \right) \left(\frac{T}{1 \text{ MeV}} \right)$$

$$\tau_{\zeta}^m \approx 3 \text{ ms} \left(\frac{\tau_{\text{dens}}}{1 \text{ ms}} \right) \left(\frac{K}{250 \text{ MeV}} \right) \left(\frac{0.25 \text{ MeV}}{Y_{\zeta}} \right)$$



Bulk Viscosity (ζ): The fluid's resistance to compression or expansion. It's crucial during the violent oscillations of a merger.

First attempts to include the effects of the bulk viscosity

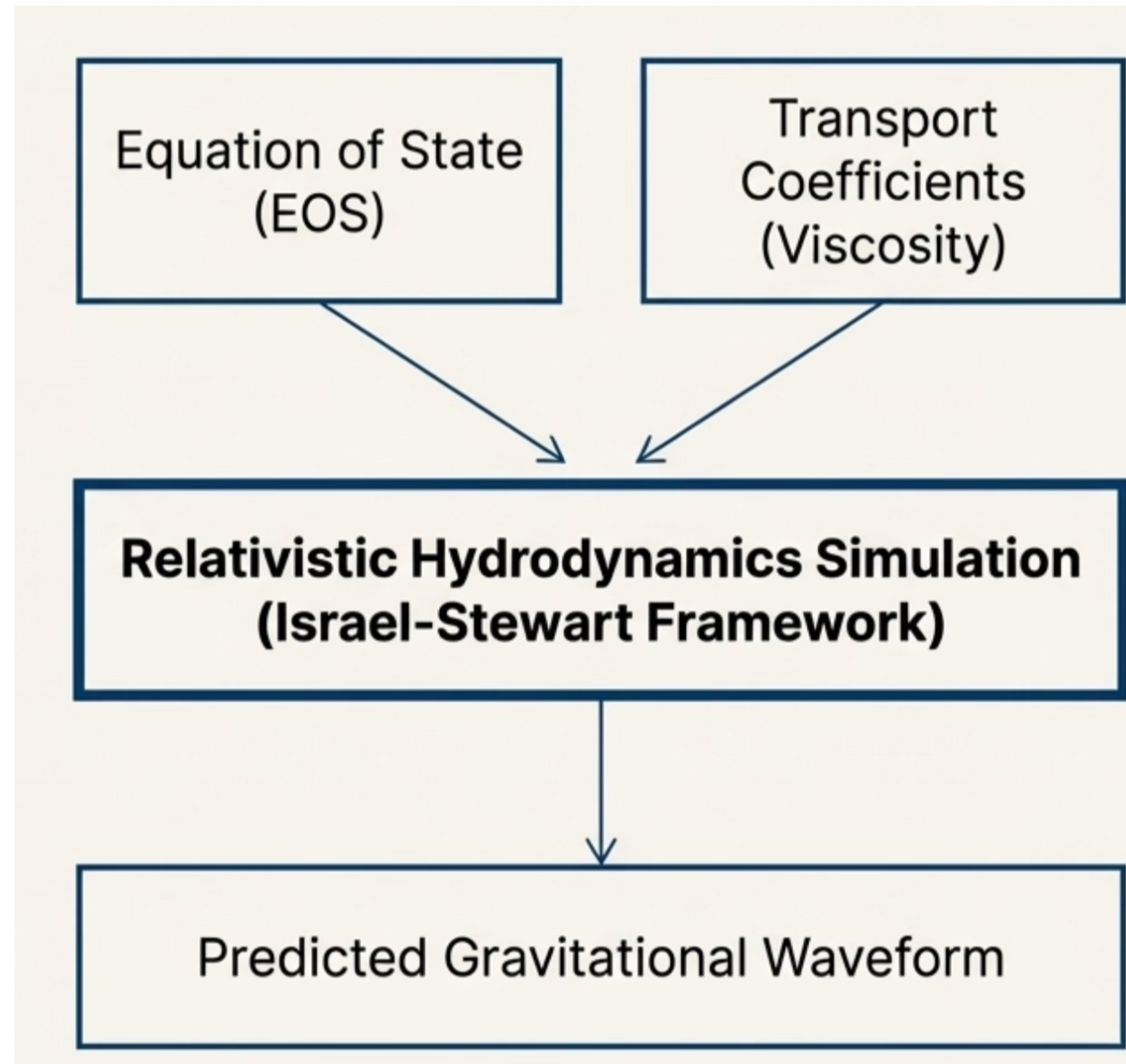


$$\zeta \in \zeta_0 [10^{-4}, 0.4, 0.1, 2.4]$$

$$\zeta_0 = 10^{30} \text{gcm}^{-1} \text{s}^{-1}$$

Viscosity would provide a quickly damped signal

From microphysics to GW



NUCLEAR MATTER

Matter composed by neutrons, protons and electrons - only neutrinos if $T > 5 \text{ MeV}$
(muons can as well appear if the density is high enough, depends on the EoS)

In beta equilibrium

$$\mu_n = \mu_p + \mu_e$$

Direct Urca processes

$$n \rightarrow p + e + \bar{\nu}_e$$

$$p + e \rightarrow n + \nu_e$$

Most available EoS don't allow these processes unless the density is very high

Modified Urca processes

$$n + N \rightarrow p + N + e + \bar{\nu}_e$$

$$p + N + e \rightarrow n + N + \nu_e,$$

D-Urca Rates

$$\lambda_e \approx \frac{17}{480\pi} G^2 T^4 \mu_n^* \Theta(p_{F,e} + p_{F,p} - p_{F,n}) (p_{F,p}^2 + p_{F,e}^2 + 2\mu_e \mu_p^* - p_{F,n}^2)$$

M-Urca rates

$$\begin{aligned} \lambda_{ne} &\approx \frac{367}{1152\pi^3} G_F^2 \cos^2 \Theta_C g_A^2 f_{\pi NN}^4 \\ &\times \frac{m_n^{*3} m_p^*}{m_\pi^4} \frac{p_{Fn}^4 p_{Fp}}{(p_{Fn}^2 + m_\pi^2)^2} \vartheta_{ne} T^6, \\ \lambda_{pe} &\approx \frac{367}{8064\pi^3} G_F^2 \cos^2 \Theta_C g_A^2 f_{\pi NN}^4 \\ &\times \frac{m_n^* m_p^{*3}}{m_\pi^4} \frac{p_{Fn} (p_{Fn} - p_{Fp})^4}{[(p_{Fn} - p_{Fp})^2 + m_\pi^2]^2} \vartheta_{pe} T^6, \end{aligned}$$

RELATIVISTIC VISCOUS HYDRODYNAMICS

$$\Pi = P - P_0$$

Bulk viscous pressure

Second order transport hydrodynamics

$$\tau D_u \Pi + \Pi = -\zeta_0 \vartheta$$

$$D_u \equiv u^\mu \nabla_\mu$$

$$\vartheta \equiv \nabla_\mu u^\mu$$

Israel-Stewart (IS) equation

For harmonic oscillations, it is equivalent to consider a frequency-dependent bulk viscosity

$$\Pi \propto e^{-i\omega t}$$

$$\zeta(\omega) = -\frac{\text{Re}\Pi}{v\vartheta}$$

Effective frequency-dependent viscosity

Resonant behaviour

$$\zeta(\omega) = \frac{\zeta_0}{1 + \tau^2 \omega^2}$$

$$\omega\tau \ll 1$$

Navier-Stokes regime recovered

$$\omega\tau \sim 1$$

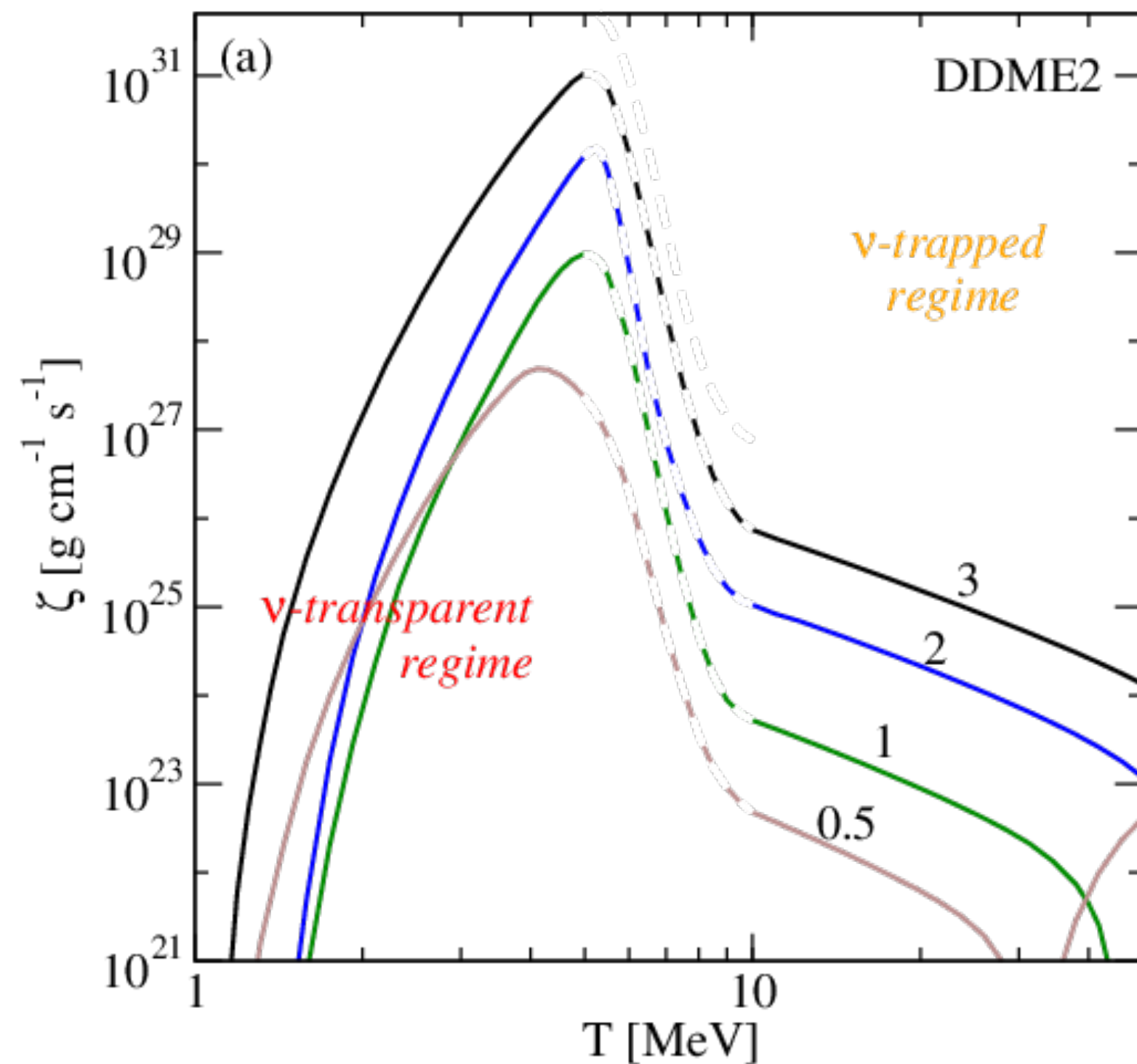
Maximum dissipation

$$\omega\tau \gg 1$$

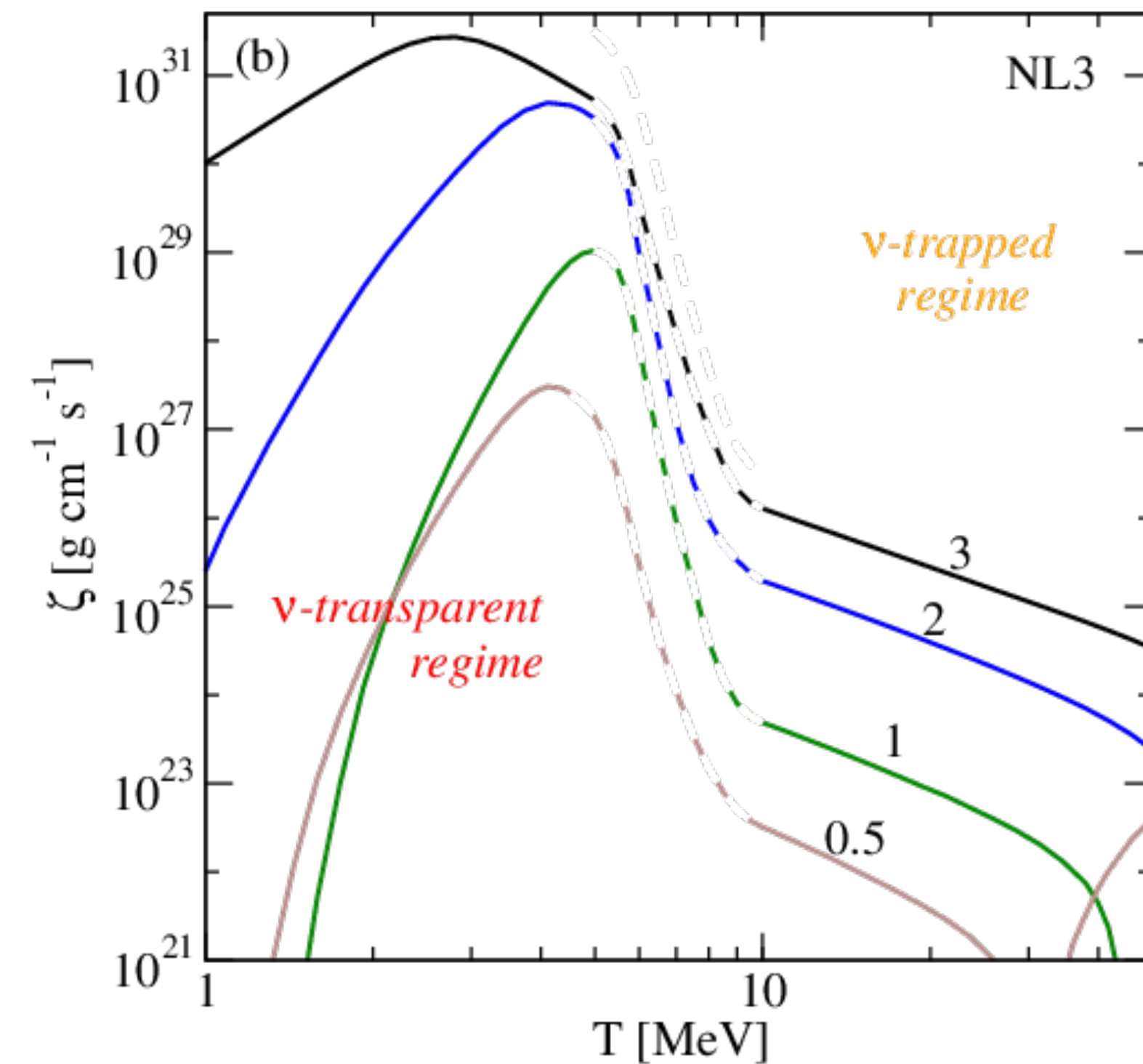
Frozen: no dissipation

Bulk viscosity in nuclear matter

For two different models



Frequency 1 kHz



Alford, Harutyunyan, and Sedrakian, 2006.07975

Differences critical values of density for the opening of dURCA (5 n_0 vs 2.5 n_0)

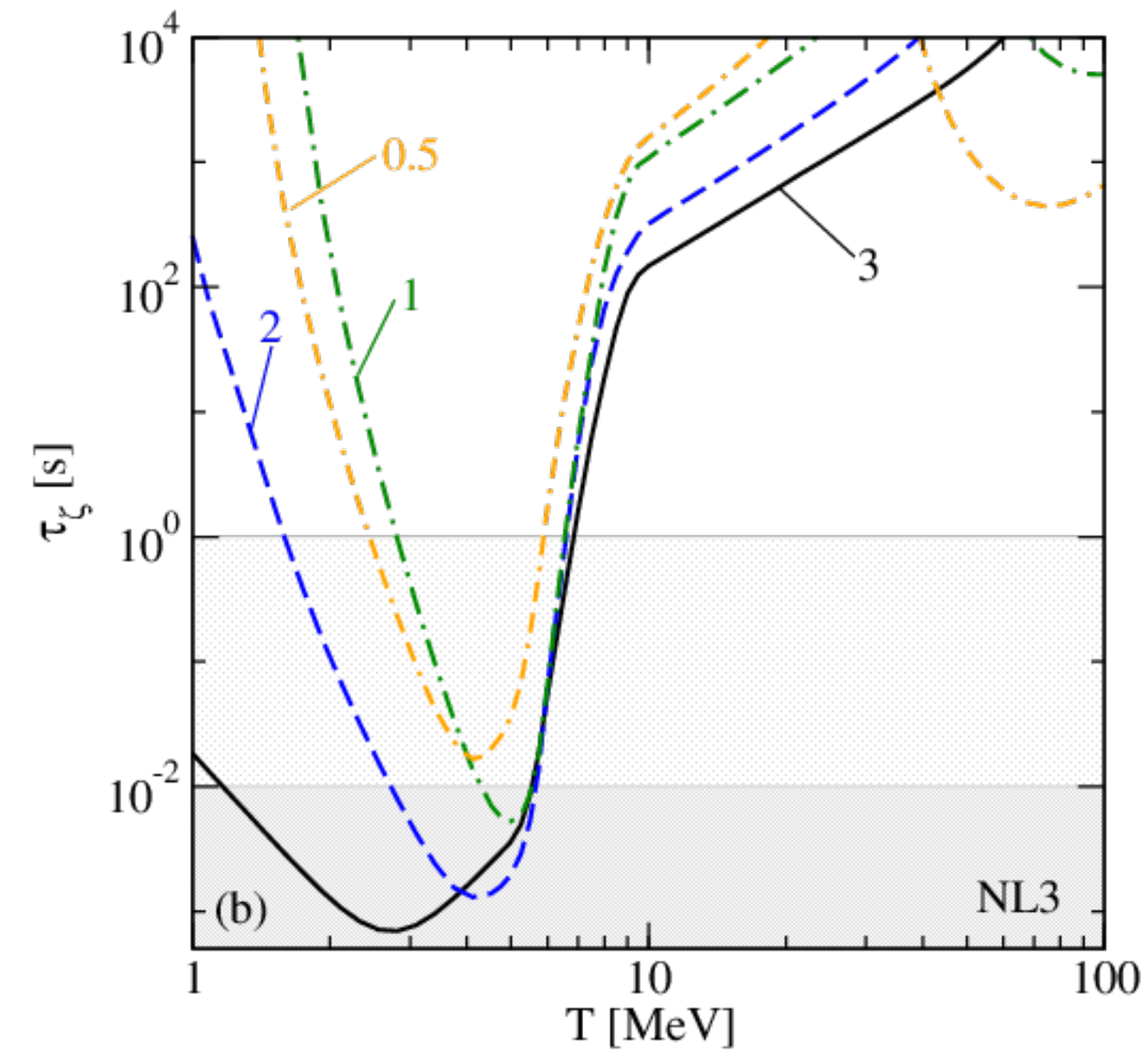
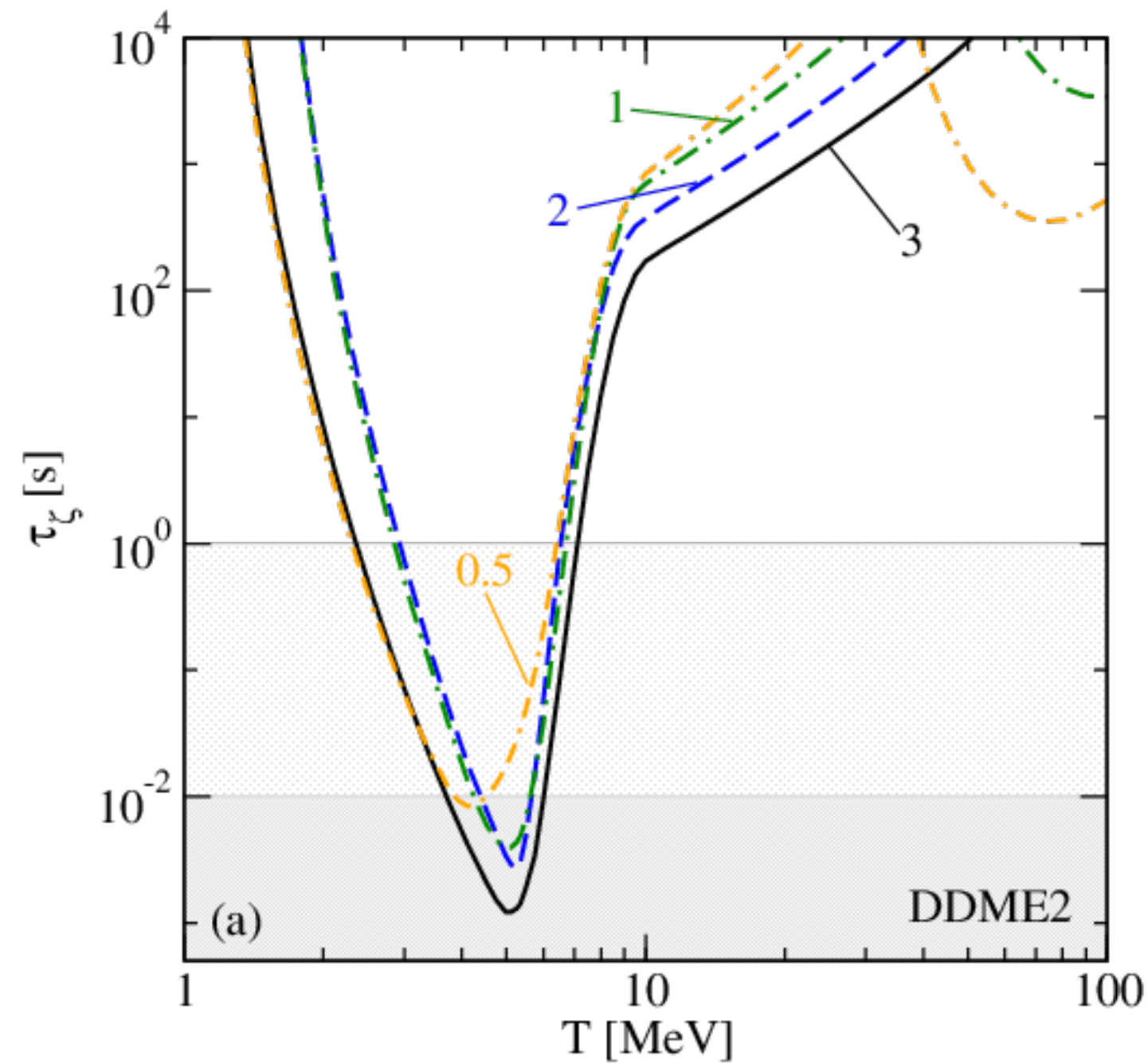
Damping of density oscillations

$$n(t) = \bar{n} + \Delta n \cos(\omega t)$$

Damping time of density oscillations

$$\tau_{\zeta} = \frac{E}{dE/dt} = \frac{K\bar{n}}{9\omega^2\zeta(\omega)}$$

K nuclear compressibility

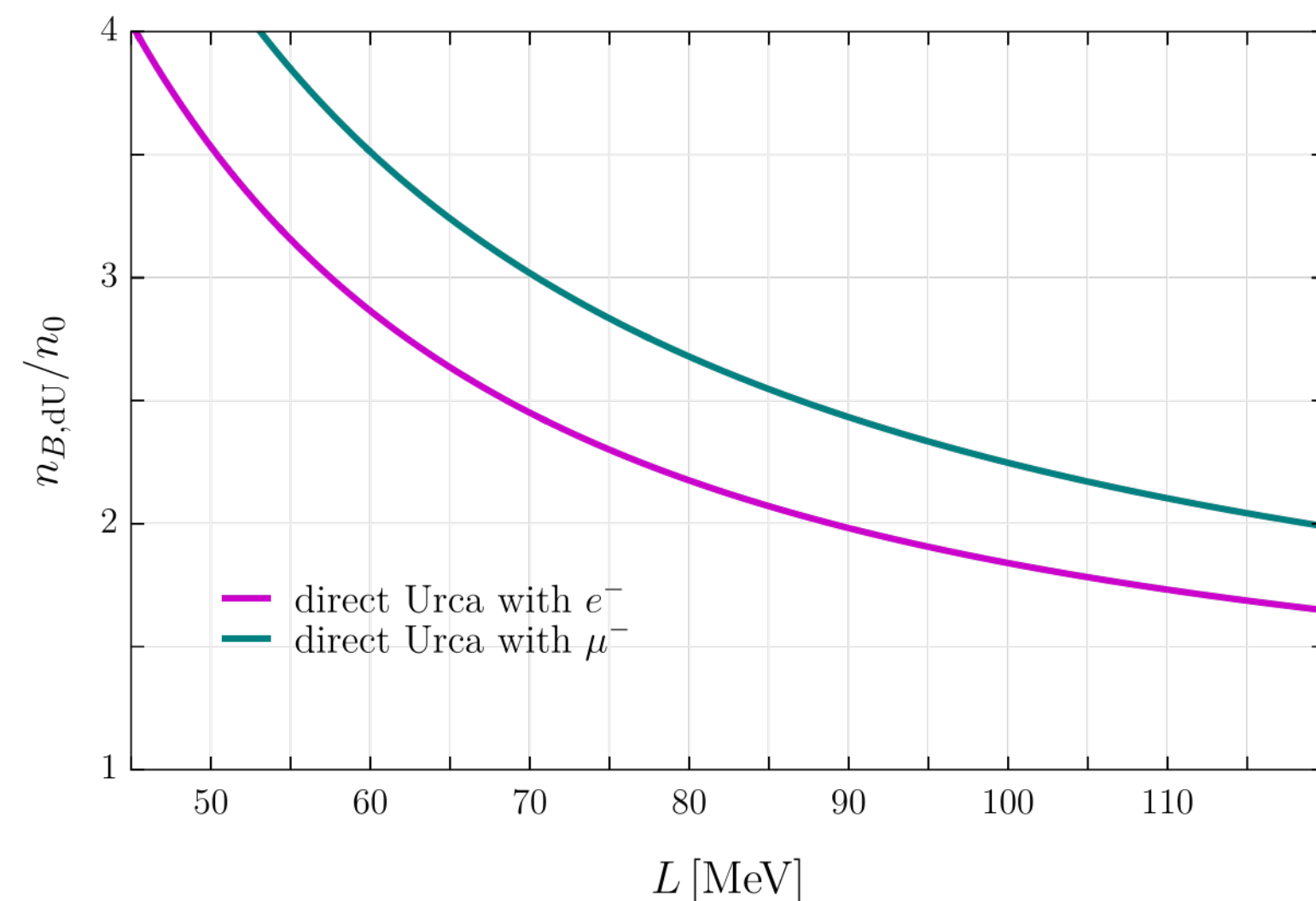


Recent claims that the bulk viscosity of nuclear matter may change by several orders of magnitude

if the parameter that controls the so called symmetry energy

Yang, Hippert, Speranza, Noronha, 2504.07895

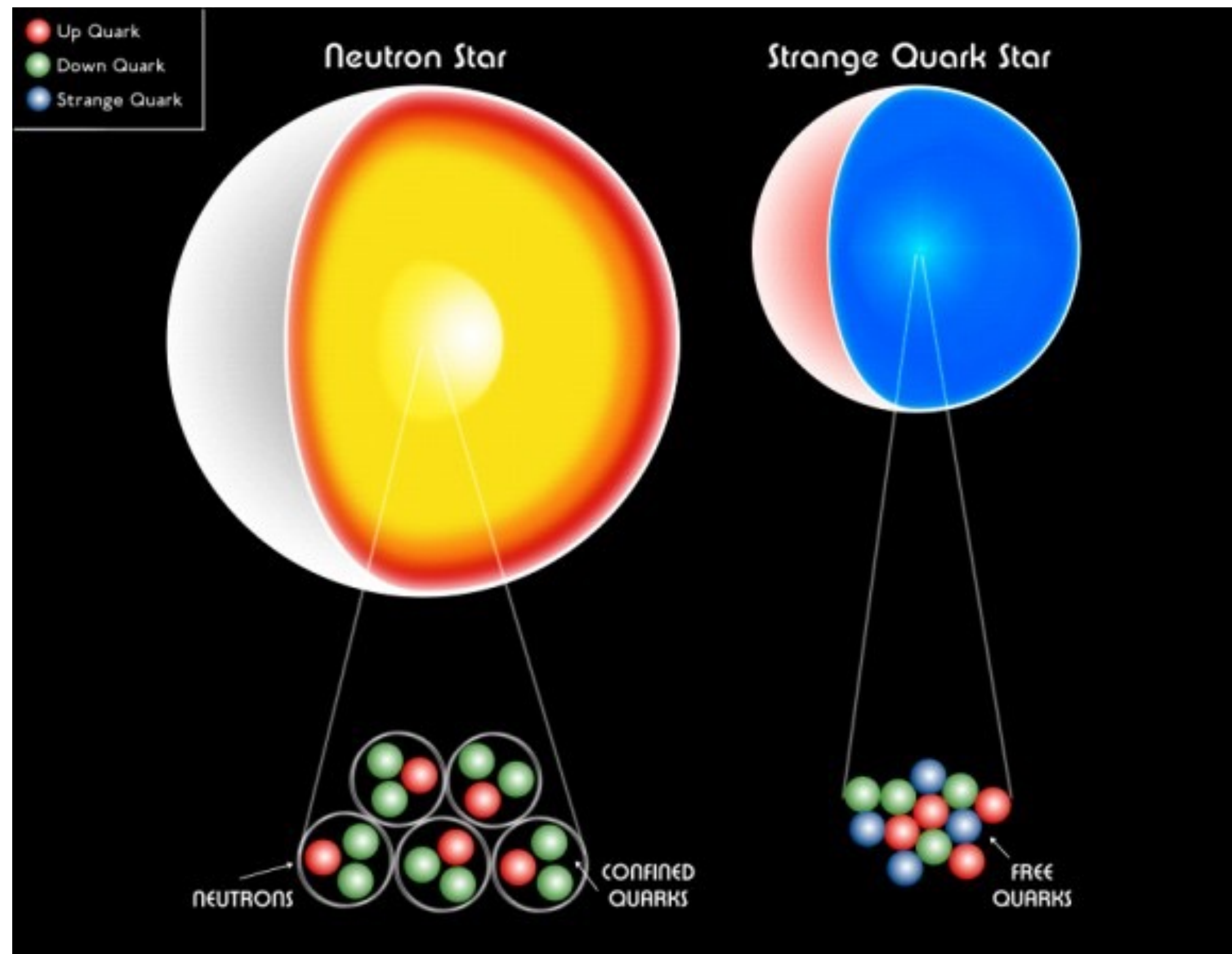
Large values of the so called L allow for the opening of direct Urca processes at smaller densities



J.L. Hernandez, unpublished

Strange quark matter

assuming ungapped phase



$$n = \frac{1}{3} (n_u + n_d + n_s)$$

u, d, s quarks - need of e for charge neutrality

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0$$

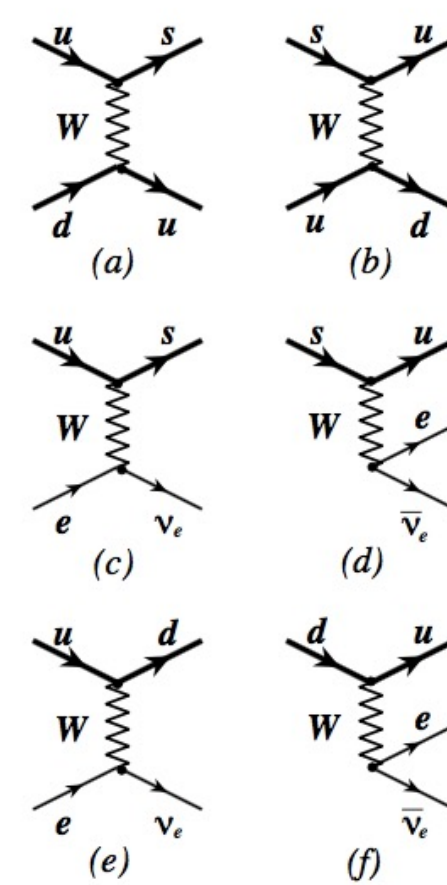
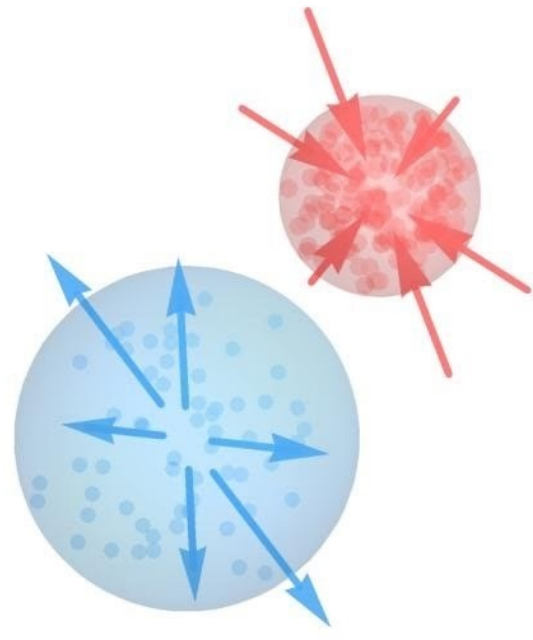
Beta equilibrium conditions

$$\mu_s = \mu_d = \mu_u + \mu_e$$

At very low temperatures, system characterised by different (constrained)

quark chemical potential -assumed massless, except for the strange quark

Out-of equilibrium: electroweak interactions restore the equilibrium



$$\mu_s \neq \mu_d, \quad \mu_s \neq \mu_u + \mu_e$$

$$\mu_1 \equiv \mu_s - \mu_d,$$

$$\mu_2 \equiv \mu_u - \mu_d + \mu_e$$

Nonleptonic

$$u + s \leftrightarrow u + d$$

$$\mu_1 \lambda_1 = \Gamma_{u+s \rightarrow u+d} - \Gamma_{u+d \rightarrow u+s}$$

$$(\mu_2 - \mu_1) \lambda_3 = \Gamma_{s \rightarrow u+e+\bar{\nu}_e} - \Gamma_{u+e \rightarrow s+\nu_e}$$

$$-\mu_2 \lambda_2 = \Gamma_{d \rightarrow u+e+\bar{\nu}_e} - \Gamma_{u+e \rightarrow d+\nu_e}$$

SemiLeptonic

$$u + e^- \rightarrow d + \nu_e$$

$$d \rightarrow u + e^- + \bar{\nu}_e$$

$$u + e^- \rightarrow s + \nu_e$$

$$s \rightarrow u + e^- + \bar{\nu}_e$$

$$\lambda_1 \approx \frac{64}{5\pi^3} G_F^2 \sin^2 \Theta_C \cos^2 \Theta_C \mu_d^5 T^2$$

$$\lambda_2 \approx \frac{17}{40\pi} G_F^2 \sin^2 \Theta_C \mu_s m_s^2 T^4$$

$$\lambda_3 \approx \frac{17}{15\pi^2} G_F^2 \cos^2 \Theta_C \alpha_s \mu_d \mu_u \mu_e T^4$$

Bulk viscosity in strange quark matter

Frequency dependent oscillations

$$\Pi \propto e^{-i\omega t}$$

$$\frac{dn_s}{dt} \approx -\mu_1 \lambda_1 - (\mu_2 - \mu_1) \lambda_3$$

$$\frac{dn_e}{dt} \approx -\mu_2 \lambda_2 + (\mu_2 - \mu_1) \lambda_3$$

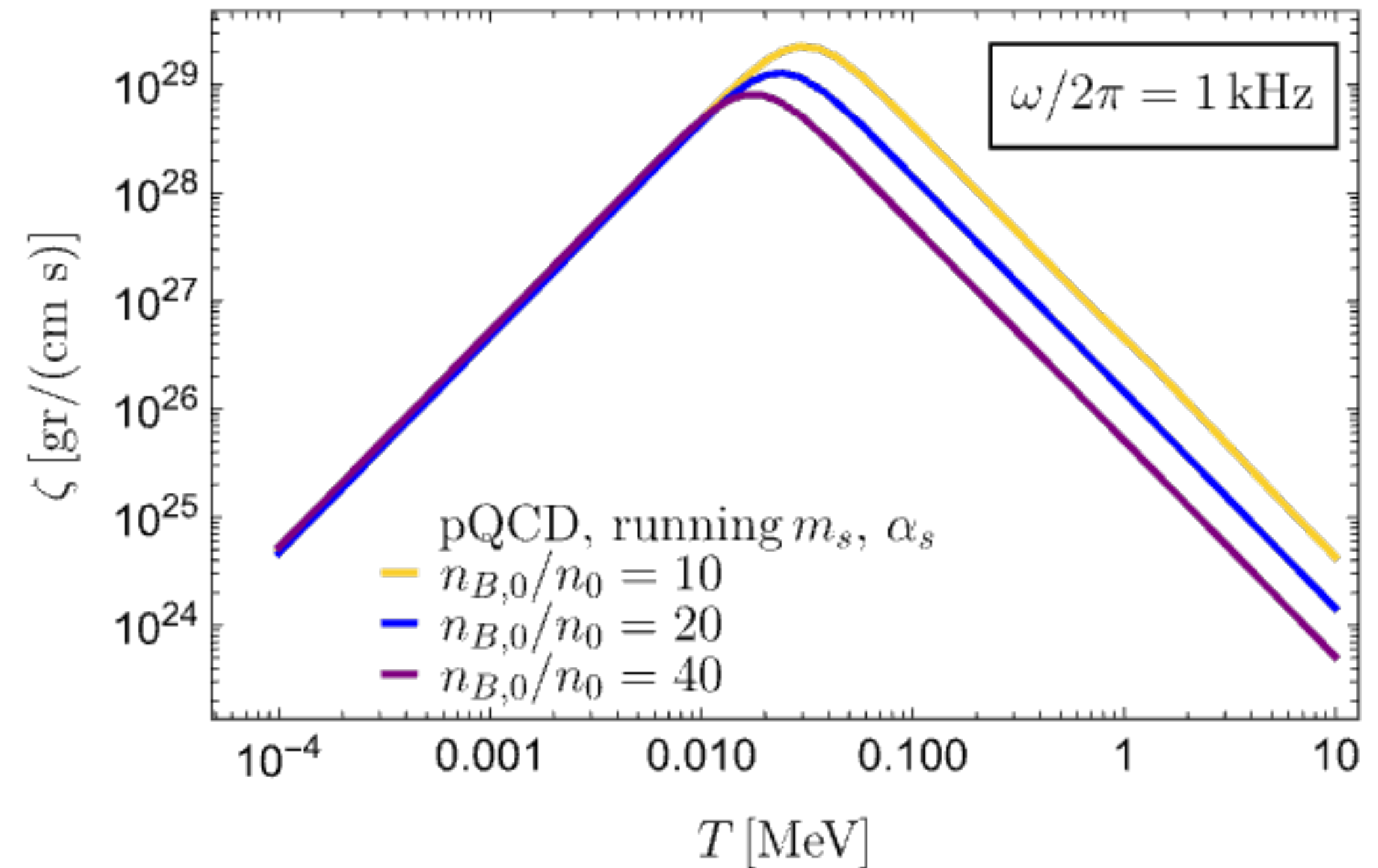
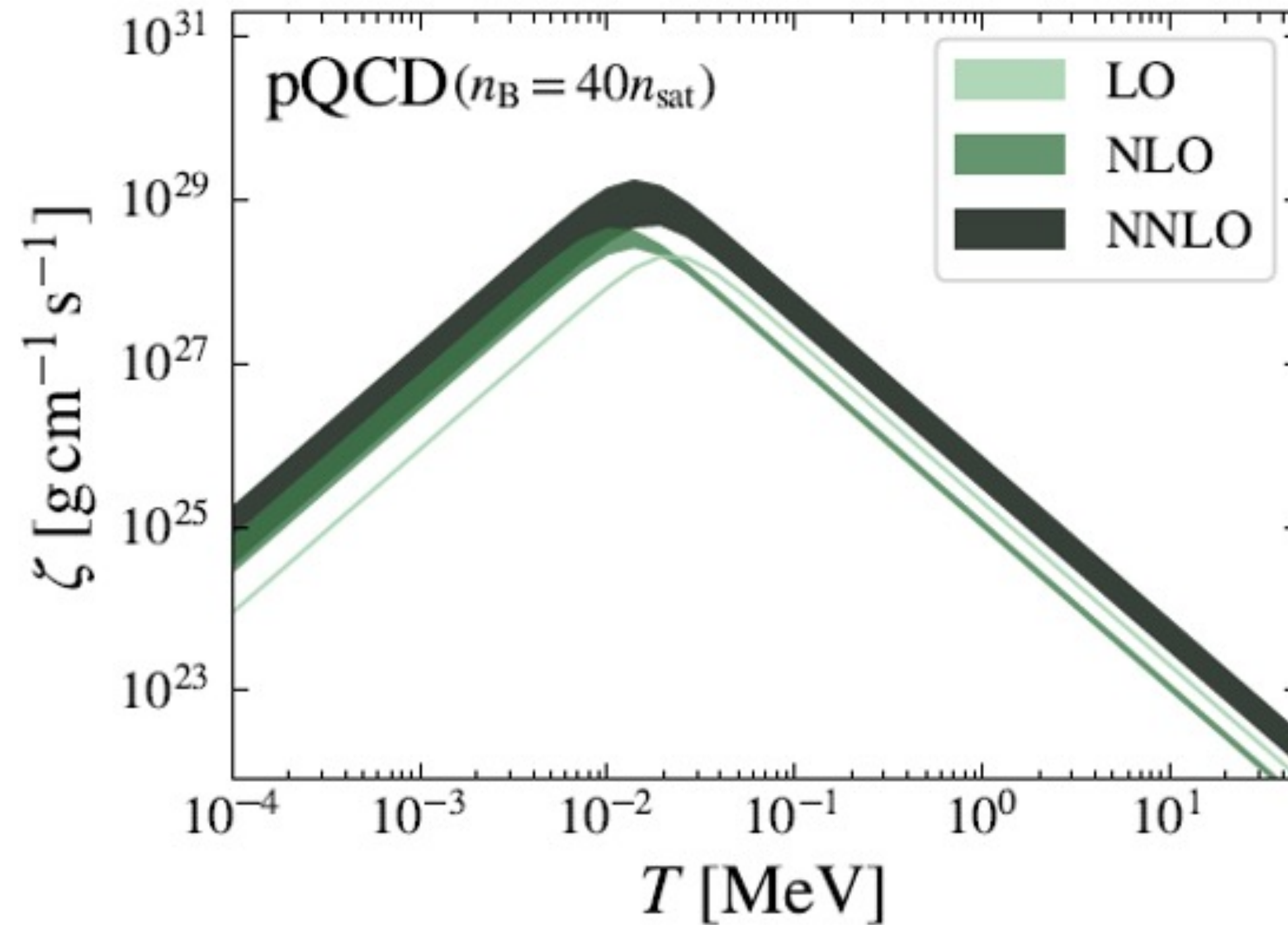
$$\Pi \equiv P - P_{\text{eq}}$$

$$\zeta = \frac{\kappa_1 + \kappa_2 \omega^2}{\kappa_3 + \kappa_4 \omega^2 + \omega^4}$$

$$\kappa_i = \kappa_i \left(\mu_a, n_B, \lambda_1(T), \lambda_2(T), \lambda_3(T), (\chi^{-1})_a^a \right)$$

$$(\chi^{-1})_a^b = (\partial \mu_a / \partial n_b)_{n_{c \neq b}, T}$$

Bulk viscosity in perturbative QCD

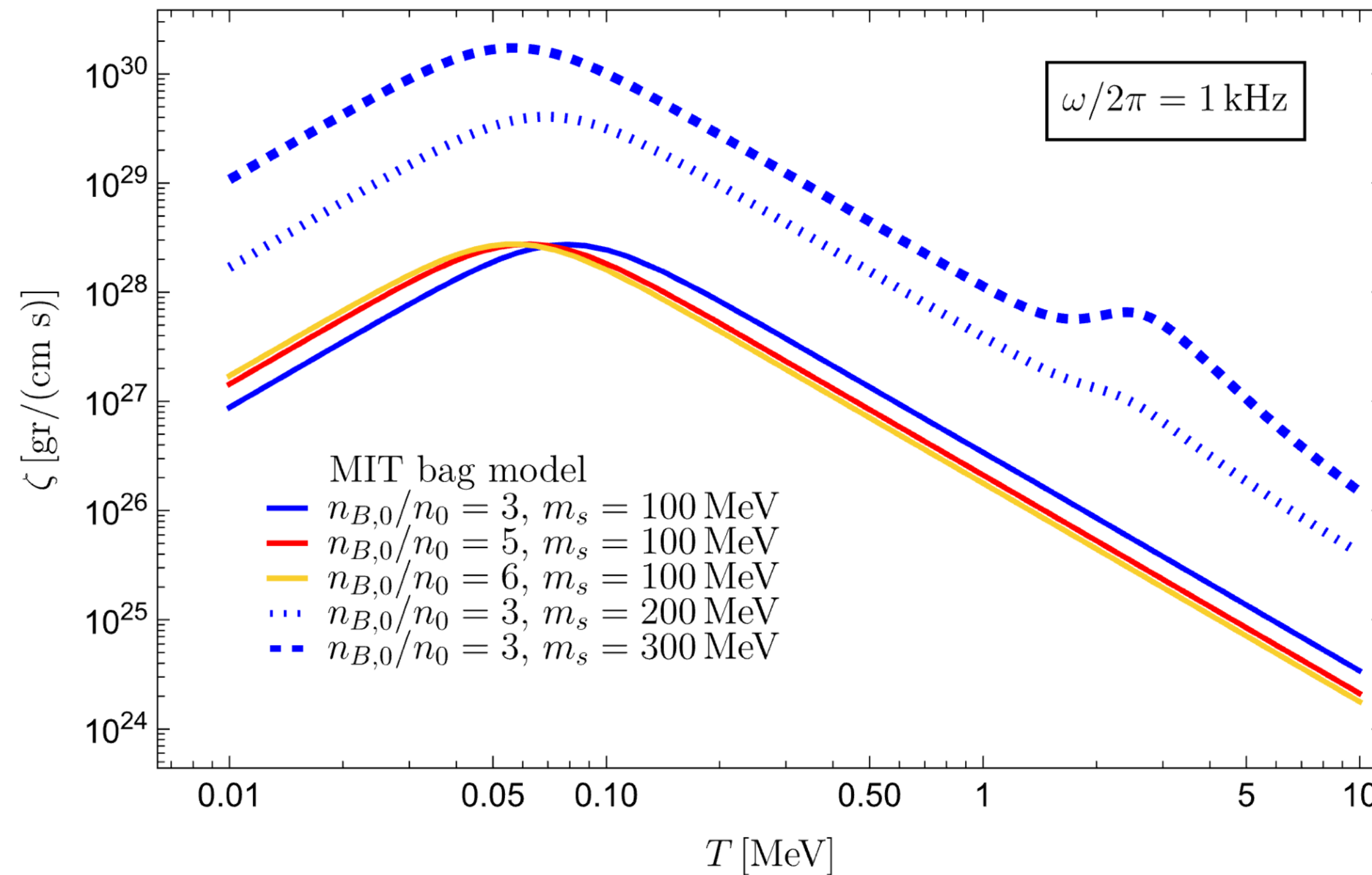


¹Rojas, Gorda, Hoyos, Jokela, Järvinen, Kurkela, Paatelainen, Säppi, Vuorinen, 2024, arXiv:2402.00621
Hernandez, Manuel, Tolos, arXiv: 2402.06595

Strange quark mass is not a free parameter

Bulk viscosity using the MIT bag model

$\zeta(T)$ varying $n_{B,0}$ and m_s
 $\zeta_{\max}$ increases with $n_{B,0}$
Strong dependence on m_s

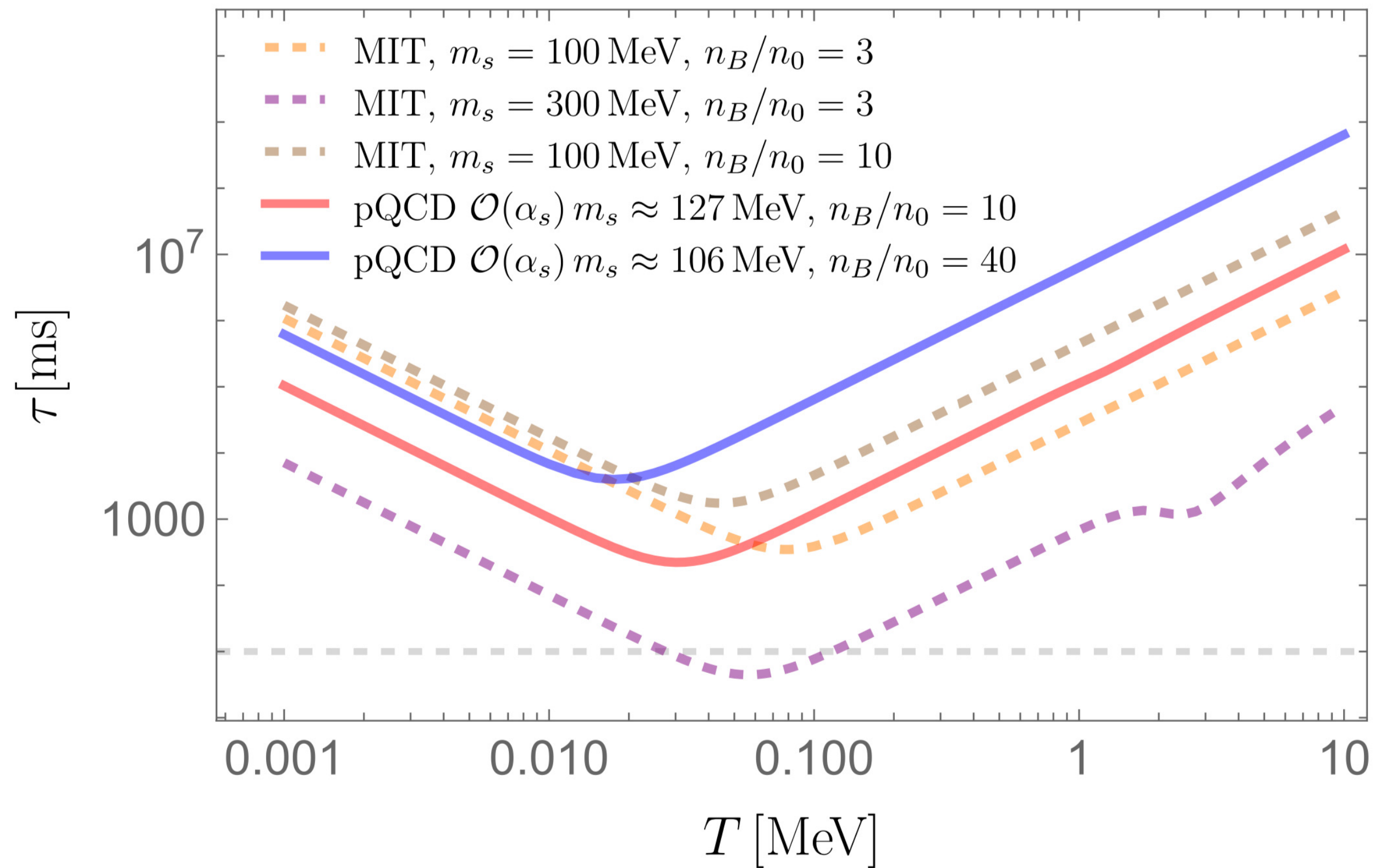


Strange quark mass
as a free parameter

$\zeta_{\max} \in [10^{28}, 2 \times 10^{30}] \text{ gr}/(\text{cm} \cdot \text{s})$ at $T \in [0.01, 0.1] \text{ MeV}$

$1 \text{ MeV} \sim 10^{10} \text{ K}$ and $n_0 = 0.15 \text{ fm}^{-3}$

Damping of density oscillations



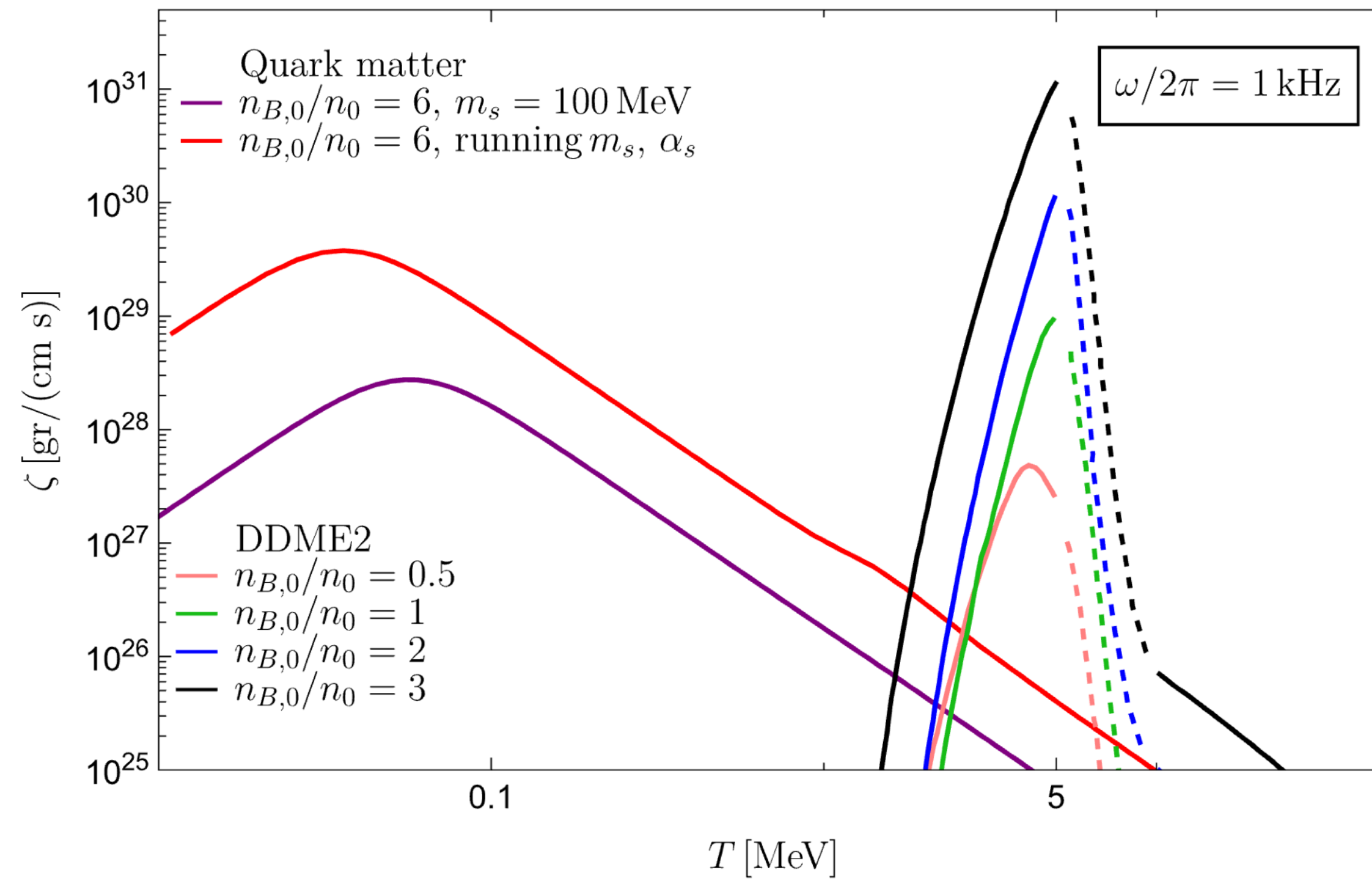
$$\tau = \frac{n_B^2}{\omega^2 \zeta} \left. \frac{\partial^2 \varepsilon}{\partial n_B^2} \right|_{n_s, n_e}$$

$\tau_{\min}$ reaching few ms at $T \in [0.01, 0.1]$ MeV

$n_{B,0}/n_0$	T_m [MeV]	$\zeta_{\max}$ [gr/(cm·s)]	$\tau_{\min}$ [ms]	m_s [MeV]
3	7.9×10^{-2}	2.73×10^{27}	213.24	100
3	6.9×10^{-2}	4.05×10^{29}	13.93	200
3	5.7×10^{-2}	1.73×10^{30}	3.19	300
5	6.2×10^{-2}	2.75×10^{28}	420.14	100
6	5.7×10^{-2}	2.76×10^{28}	535.37	100

Bulk viscosity in nuclear matter

Bulk viscosity in quark matter differs from the one in hadronic matter

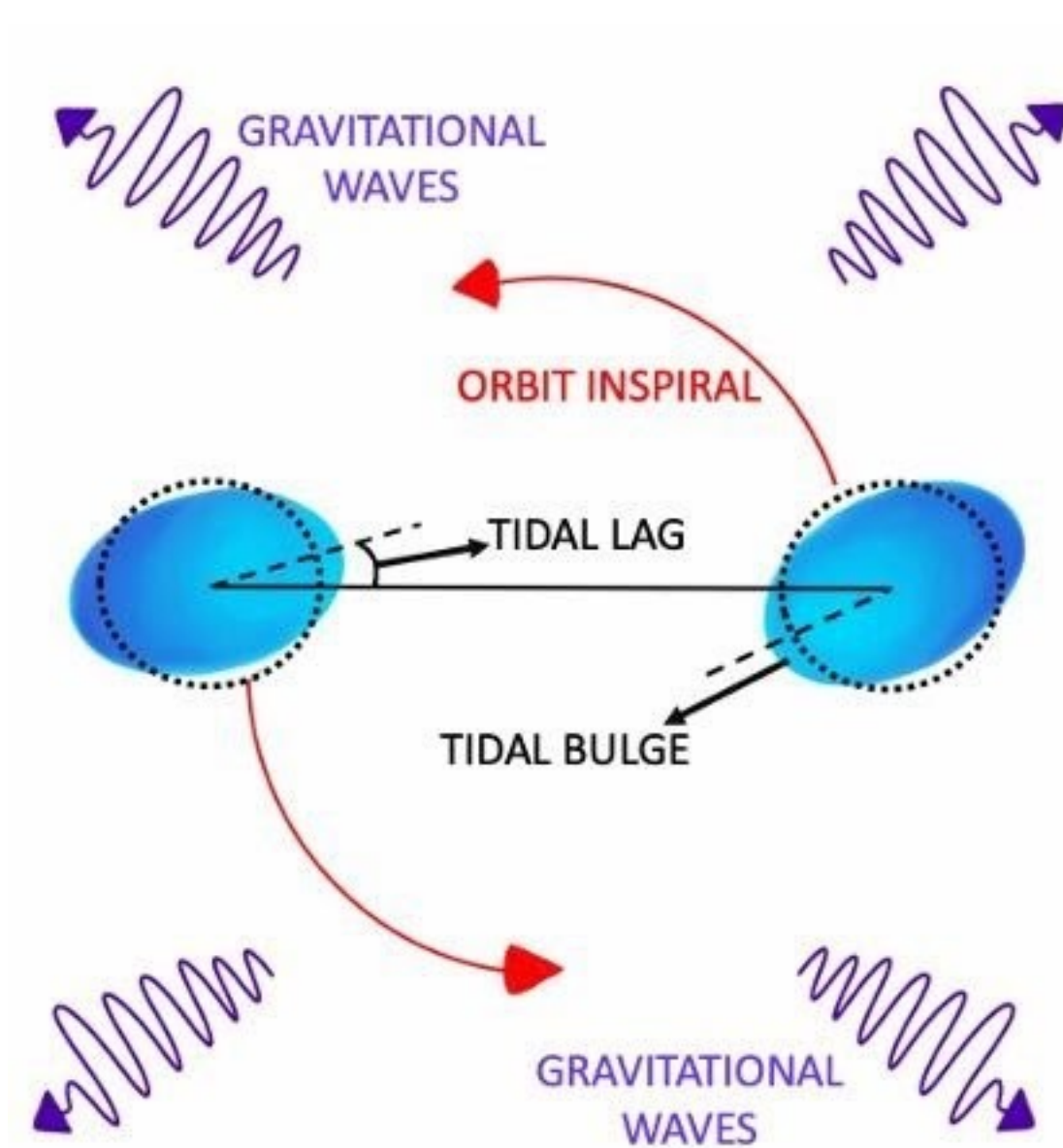


Comparison of the bulk viscosity in quark matter with the one predicted using the DDME2 model¹

¹Alford, Harutyunyan and Sedrakian, 2020, *arXiv:2006.07975*

TIDAL HEATING IN THE INSPIRAL PHASE

Dynamical tidal forces drive the system out of equilibrium



f-mode (and other) hydrodynamical modes are excited

Energy dissipation due to viscosities

Dissipation of the tidal deformation heats

up the star

Ripley, Hegade, Chandramouli, Yunes, Nature Astronomy 8, 1277-1283 (2024)

Effect negligible for nuclear matter, unless it contains hyperons

A constraint on the dissipative tidal deformability of neutron stars

Received: 12 January 2024

Accepted: 21 June 2024

Published online: 19 July 2024

 Check for updates

Justin L. Ripley  , Abhishek Hegade K R  , Rohit S. Chandramouli  & Nicolás Yunes 

The gravitational waves emitted by neutron star binaries probe the physics of matter at supranuclear densities. During the late inspiral, tidal deformations raised on each star by the gravitational field of its companion depend crucially on the star’s internal properties. The misalignment of a star’s tidal bulge with its companion’s gravitational field encodes the strength of internal dissipative processes, which imprint onto the phase of the gravitational waves emitted. Here, we analyse gravitational wave data from the GW170817 (binary neutron star) event detected by LIGO and Virgo and find a constraint on the dissipative tidal deformability of a neutron star. From this constraint, assuming a temperature profile for each star in the binary, we obtain an order of magnitude bound on the averaged bulk (ζ) and shear (η) viscosity of each star during the inspiral: $\zeta \lesssim 10^{31} \text{ g cm}^{-1} \text{ s}^{-1}$ and $\eta \lesssim 10^{28} \text{ g cm}^{-1} \text{ s}^{-1}$. We forecast that these bounds could be improved by two orders of magnitude with third-generation detectors, like Cosmic Explorer, using inspiral data. These constraints already inform nuclear physics models and motivate further theoretical work to better understand the interplay between viscosity and temperature in the late inspiral of neutron stars.

Neutron stars are the densest material objects in the Universe. Their interiors reach densities many times that of atomic nuclei at temperatures well below those probed by heavy-ion collisions. Determining the physical properties of neutron star matter, therefore, has remained an outstanding problem in astrophysics, gravitational physics and nuclear physics for almost a century¹. Gravitational waves (GWs) from neutron star binaries encode the tidal deformations that neutron stars experience during their late inspiral before merger. These tidal deformations are in turn affected by the material properties of the stars. The prompt, conservative, relativistic, tidal response is described by the tidal deformability λ (refs. 2–4), which encodes aspects of the equilibrium properties of neutron star matter through the neutron star equation of state (EOS)¹. The GWs from the binary neutron star event GW170817 have been used to constrain the tidal deformability of these two neutron stars and, thus, their EOS^{5,6}.

The tidal response of a star can be visualized as a ‘tidal bulge’ that is sourced but not aligned with the time-varying, externally imposed, gravitational field of its companion (Fig. 1). Nonequilibrium dissipative

effects within the star force the bulge to trail the orbit, inducing a tidal lag angle between the direction of the bulge and the orbital separation. The extent to which the tidal multipolar moments are misaligned with the external gravitational multipolar moments is, to a first approximation, described by the tidal lag time τ_d . The tidal lag time is a universal feature for self-gravitating astrophysical objects, from planets⁷ to black holes^{8,9}, and it has been observed in many planetary systems^{7,10}. This tidal misalignment torques the two stars and heats them up through tidal, viscous heating (for example, refs. 11,12).

Since the 1990s, it had been thought that the magnitude of these effects on the dynamics of neutron star binaries is too small to measure with GWs. Indeed, unphysically large values of viscosity are required to tidally lock the spins of the two stars to their orbit before merger¹³. Recent work in nuclear physics, however, suggests that weak-force processes can induce an effective bulk viscosity^{14–16}, which, although not large enough to tidally lock the spins of the two stars, may still have a measurable effect in the GWs emitted during the late inspiral¹⁷. This has motivated different numerical groups to model out-of-equilibrium

$$\eta \leq 10^{28} \text{ g cm}^{-1} \text{ s}^{-1}$$
$$\zeta \leq 10^{31} \text{ g cm}^{-1} \text{ s}^{-1}$$

Illinois Center for Advanced Studies of the Universe & Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL, USA.

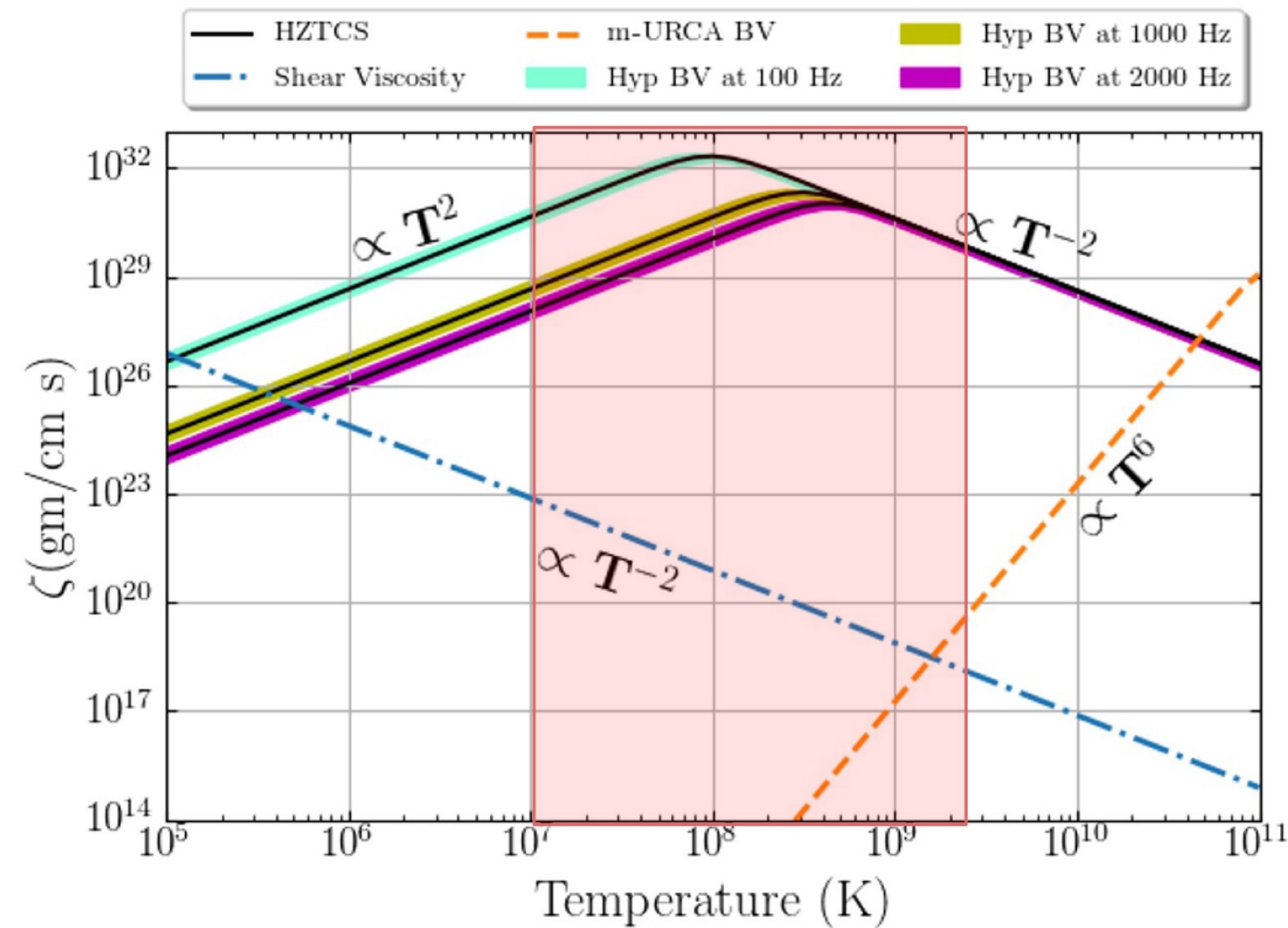
 e-mail: lloydripley@gmail.com; ah30@illinois.edu



High bulk viscosity from exotic phases in NS core

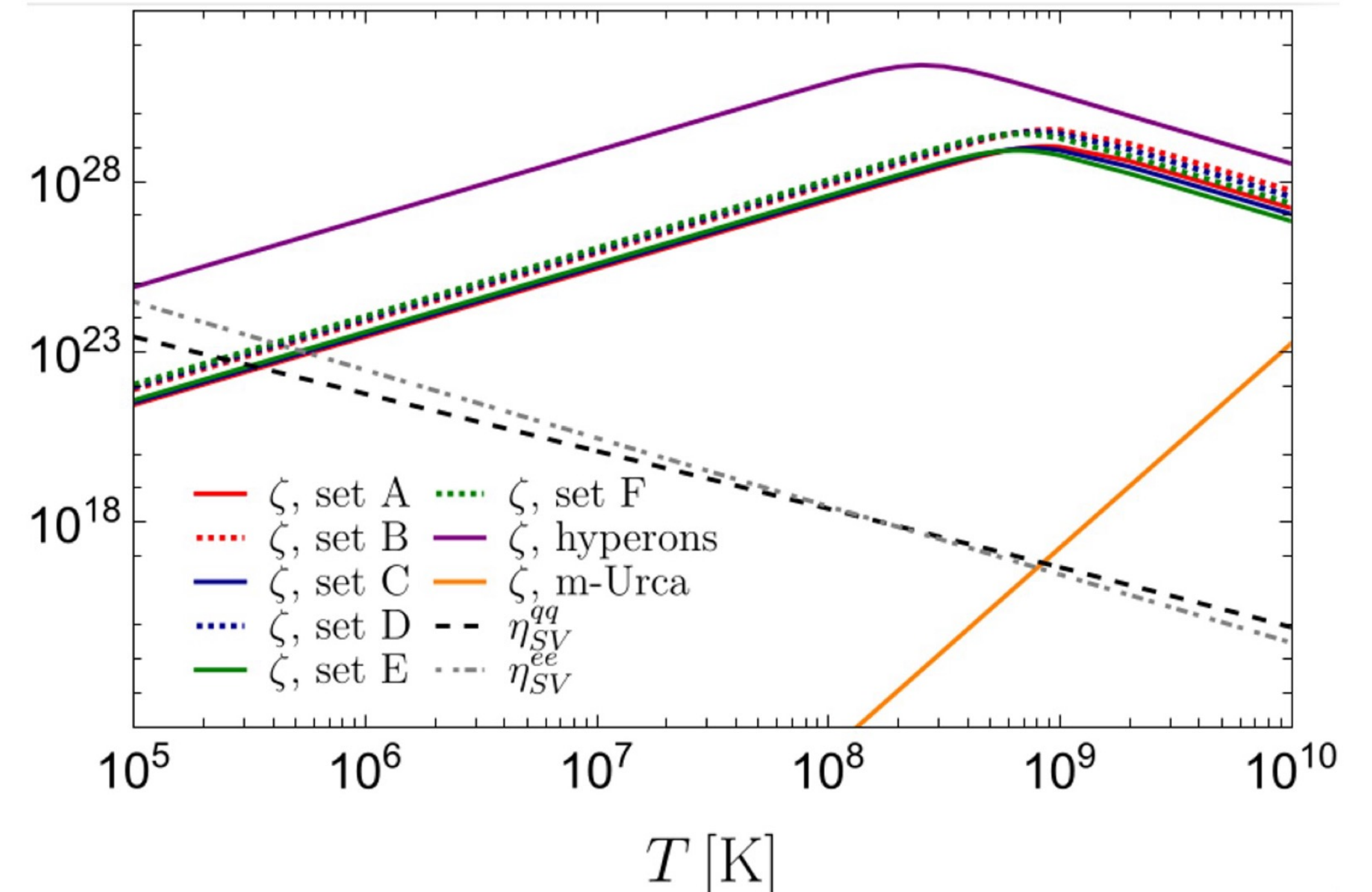
- Bulk viscosity arises due to the pressure and density variations associated with the dynamical tidal excitation of NS oscillation modes that drive the system out of chemical equilibrium.

Dominant channel from hyperons



Ghosh et al, PRD 109, 103036(2024)

Dominant channel from quarks



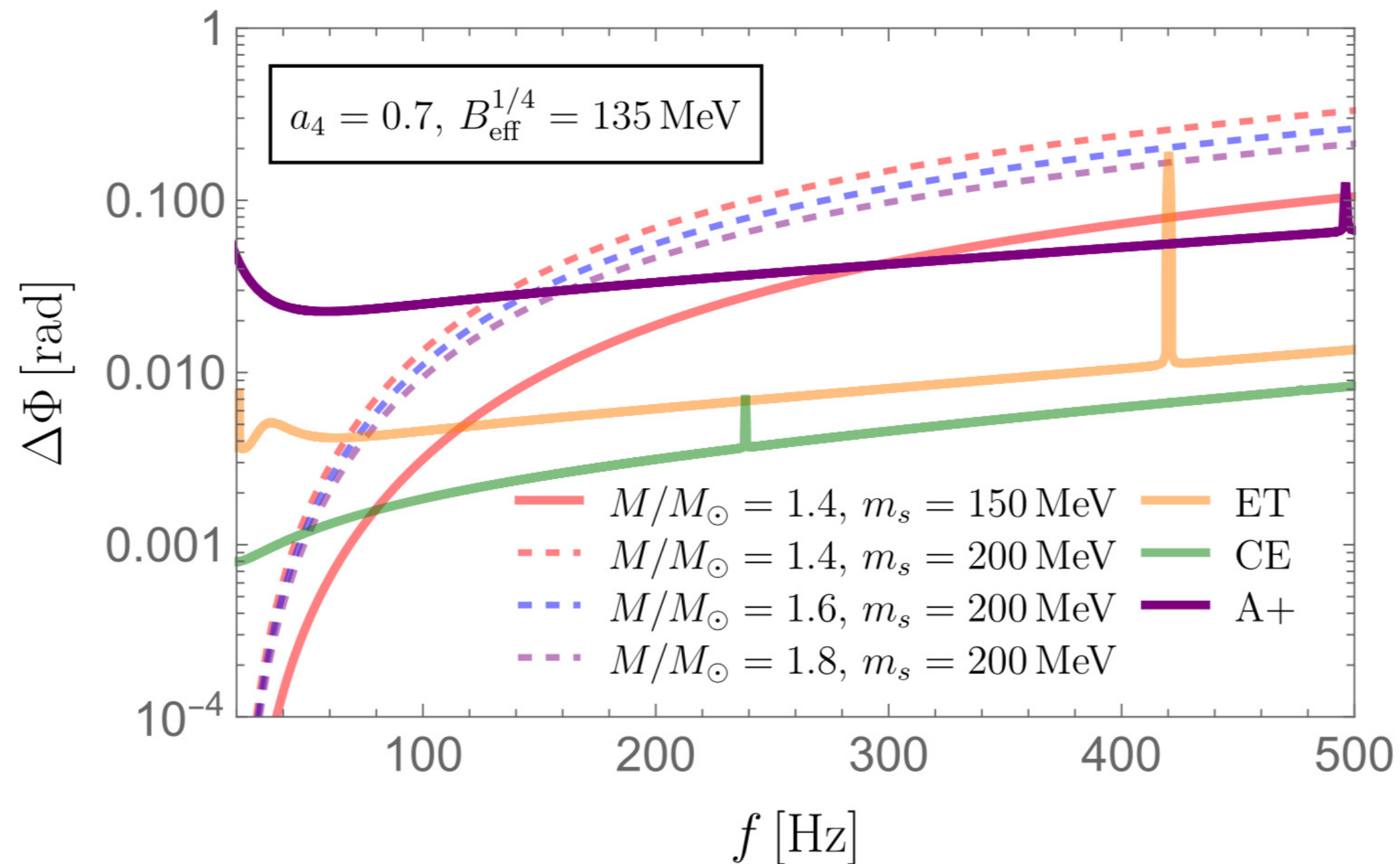
Ghosh et al, arxiv: 2504.07659(2025)

Phase shift to the gravitational waveform

Bulk-viscous dissipation might induce a phase shift in the gravitational waveform

$$\tilde{h}(v) = \tilde{A}(v)e^{-i\Phi(v)}, \quad v = (\pi M f)^{1/3}$$

M the total mass of the binary and f the GW frequency



$\Delta\Phi$ difference between the phase with and w/o energy dissipation

For nuclear matter, the effect on the phase is not significant [1]

Burgers equation for the quark viscous pressure

$$\Pi \equiv P - P_{\text{eq}}$$

In nuclear matter the bulk viscous pressure obeys a IS equation

$$\tau D_u \Pi + \Pi = -\zeta_0 \vartheta \qquad D_u \equiv u^\mu \nabla_\mu$$

Quark matter obeys a Burgers type equation

$$\Pi = \Pi_1 \mu_1 + \Pi_2 \mu_2 \qquad \mu_1 \equiv \mu_s - \mu_d, \qquad \mu_2 \equiv \mu_u - \mu_d + \mu_e$$

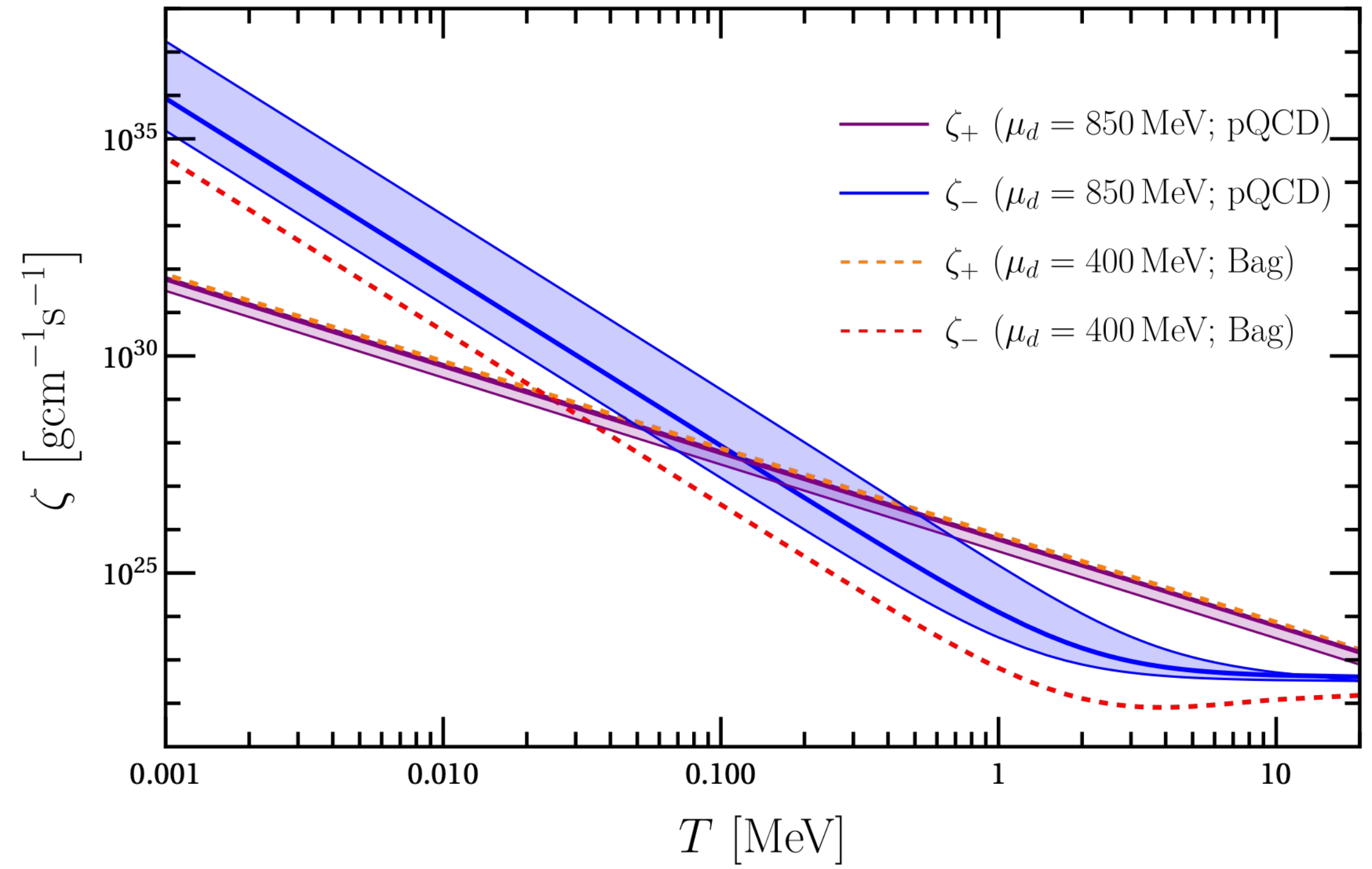
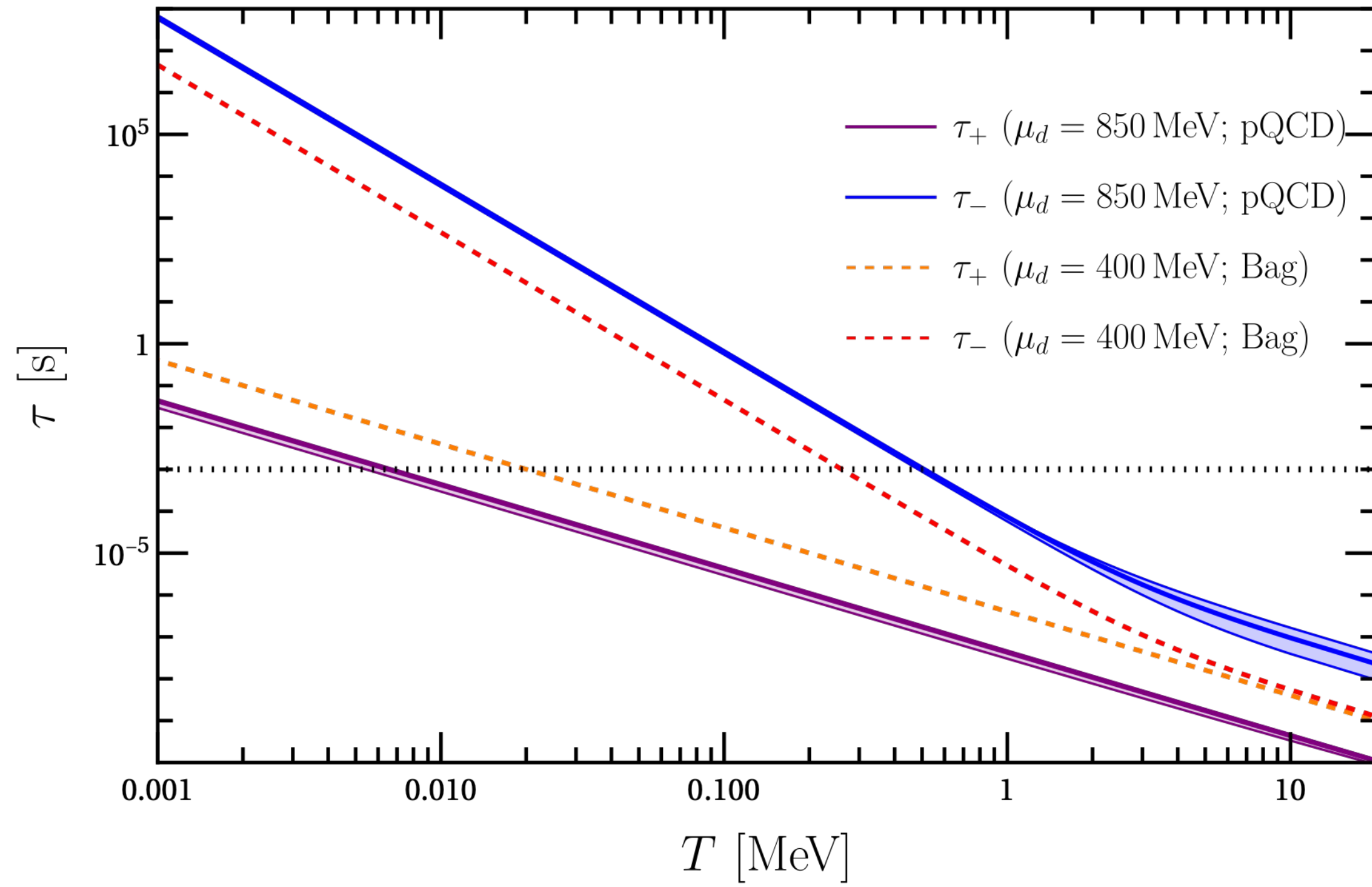
$$\det \tau D_u^2 \Pi + \text{Tr} \tau D_u \Pi + \Pi = -\zeta_0 \theta - \xi D_u \vartheta$$

It is equivalent to two IS equations with partial viscosities

$$(\tau_+, \zeta_+, \tau_-, \zeta_-) \qquad \zeta_+ = \frac{\zeta \tau_+ - \xi}{\tau_+ - \tau_-}, \qquad \zeta_- = \frac{\zeta \tau_- - \xi}{\tau_- - \tau_+}.$$

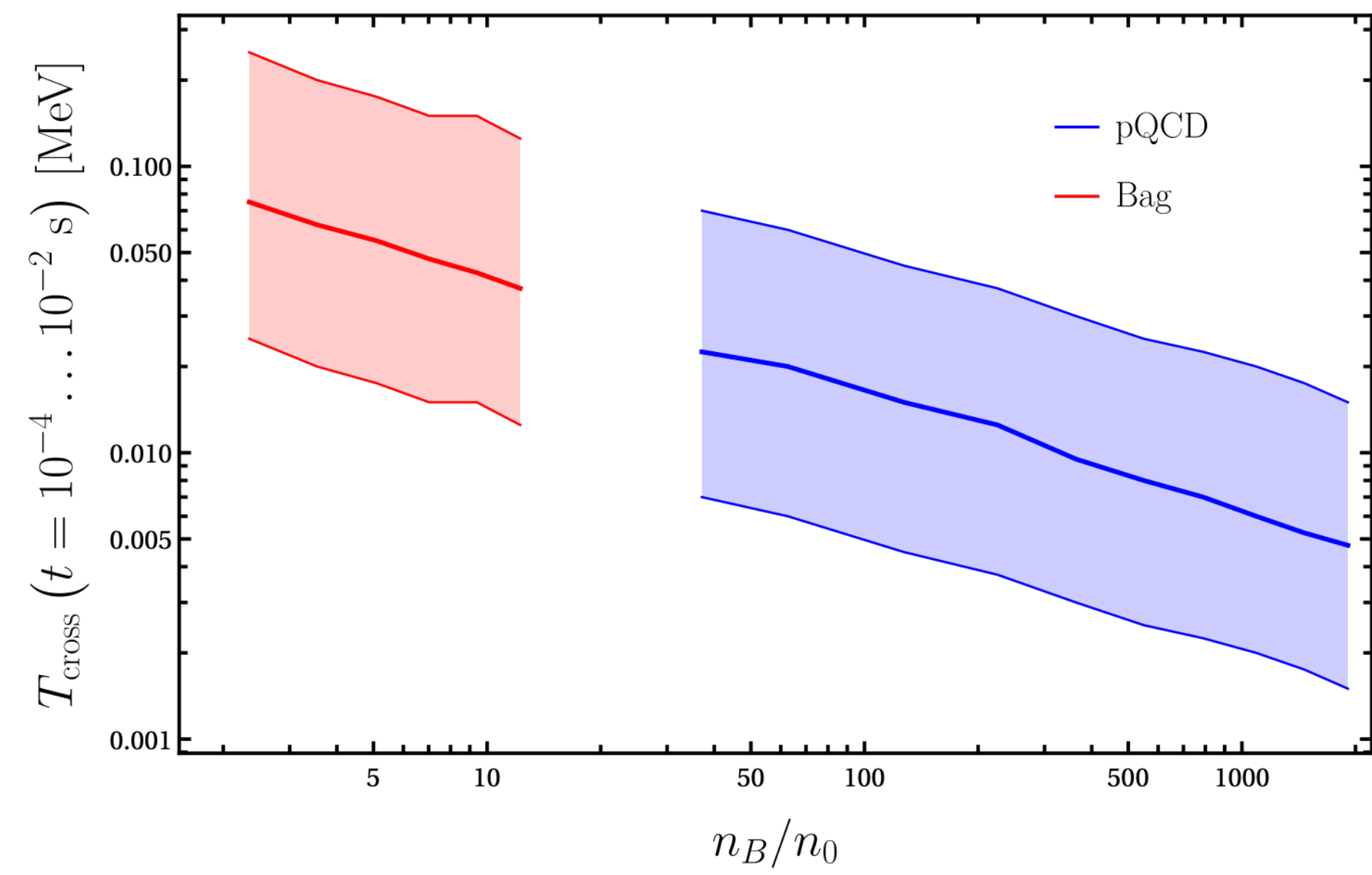
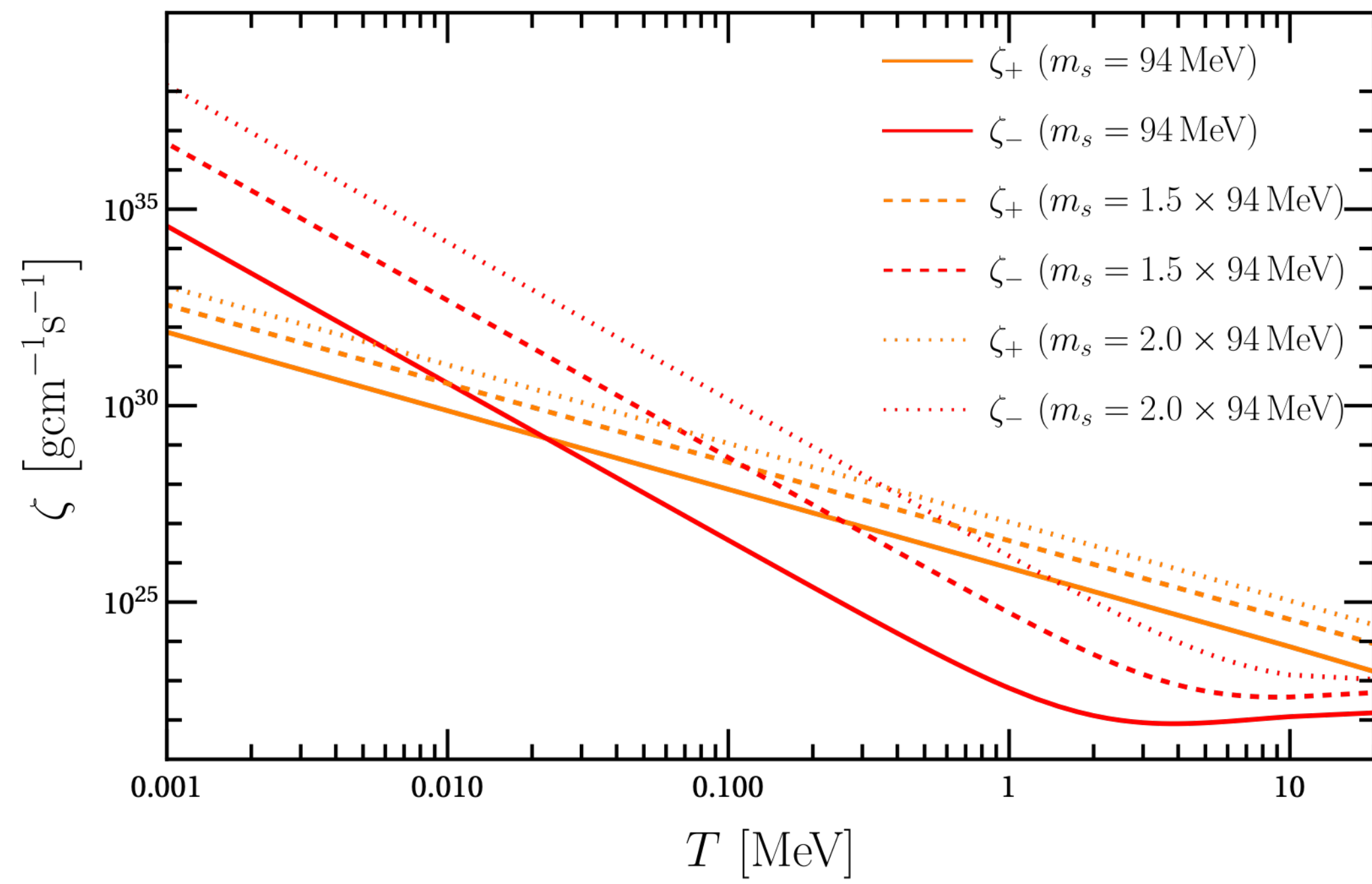
$$\zeta(\omega) = \frac{\zeta_+}{1 + \tau_+^2 \omega^2} + \frac{\zeta_-}{1 + \tau_-^2 \omega^2}$$

Two possible resonant peaks



Our analysis shows that for $T \sim 1$ MeV and above a Burgers equation should be used

Neutrinos trapped around $T \sim 10$ MeV



CONCLUSIONS

- Exciting times ahead for nuclear physics at high density thanks to GW Astronomy
- Realistic possibilities of fixing not only the M and R (and then the EOS) of dense nuclear matter, but also of transport properties

Do you want more? Join us in Barcelona

11th Conference on Compact Stars in the QCD Diagram

18 May -- 23 May 2026

<https://workshops.ice.csic.es/event/6/overview>