Dense Nuclear Matter in the Multi-Messenger Era

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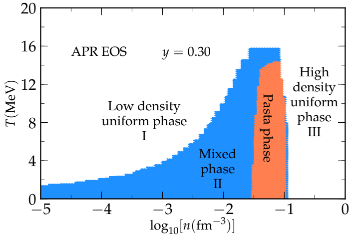
Matter in Astrophysical Phenomena

	Core-collapse supernovae	Proto-neutron stars	Mergers of compact binary stars
Baryon Density(n_0)	$10^{-8} - 10$	$10^{-8} - 10$	$10^{-8} - 10$
Temperature(MeV)	$0 - 30$	$0 - 50$	$0 - 100$
Entropy(k_B)	$0.5 - 10$	$0 - 10$	$0 - 100$
Proton Fraction	$0.35 - 0.45$	$0.01 - 0.3$	$0.01 - 0.6$



- Not shown above: Deconfined quark phase

Goals

- Pions: thermally-excited and collective modes.
- Quarks: Identify binary-neutron-star-merger observables that can establish the presence of deconfined quarks in neutron star interiors.
- Beyond mean-field: Needed for the study of phase transitions, quantum fluctuations at lower densities, and the transport properties of hot and dense matter.
- Phase-equivalent potentials: to address the limitations of the virial expansion and the excluded volume approximation.
- Relax single-nucleus approximation: so that processes requiring a full nuclear ensemble can be accommodated.
- Astrophysical applications.

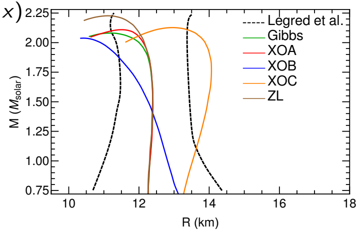
- Global, long-lived, nonradial fluid oscillations resulting from fluid-element perturbations in a stratified environment.
- Slow chemical equilibration generates buoyancy forces to oppose dispacement; strong dependence on compositional gradients.
- In stably-stratified systems the opposing force sets up oscillations with a characteristic frequency (Brunt-Väisälä) which depends on both the equilibrium and the adiabatic sound speeds.
- g-mode oscillations couple to tidal forces; they can be excited in a NS merger and provide information on the interior composition.
- Detection remains a challenge; but within sensitivity of 3rd generation detectors.
- Calculation of properties via linearized GR (4 ODEs) or the Cowling approximation (2 ODEs).

Equation of State

- Nucleons: Zhao - Lattimer

$$\epsilon_B = \sum_{h=n,p} \frac{1}{\pi^2} \int_0^{k_{Fh}} k^2 \sqrt{M_B^2 + k^2}\, dk + n_B V(u,x)$$

$$V = 4x(1-x)(a_0 u + b_0 u^\gamma) + (1-2x)^2 (a_1 u + b_1 u^{\gamma_1})$$

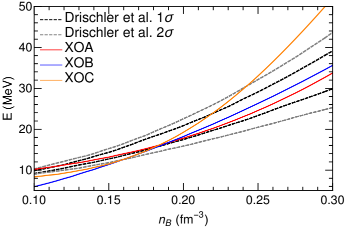


- Quarks: vMIT

$$\mathcal{L} = \sum_{q=u,d,s} \left[\bar{\psi}_q \left(i\partial\!\!\!/ - m_q - B\right)\psi_i + \mathcal{L}_{\rm int}\right]\Theta$$

$$\mathcal{L}_{\rm int} = -G_v \sum_q \bar{\psi}\gamma_\mu V^\mu \psi + \left(m_V^2/2\right) V_\mu V^\mu$$

$$\epsilon_Q = \sum_q \epsilon_{\rm FG,q} + \frac{1}{2}\left(\frac{G_v}{m_V}\right)^2 n_Q^2 + B$$



- Leptons: noninteracting, relativistic fermions

$$\epsilon_L = \sum_{l=e,\mu} \frac{1}{\pi^2} \int_0^{k_{Fh}} k^2 \sqrt{m_L^2 + k^2}\, dk$$

Hybrid Matter in Neutron Stars

- Gibbs
  - Mechanical equilibrium: $P_Q = P_H$
  - Strong equilibrium: $\mu_n = 2\mu_d + \mu_u \;\; ; \;\; \mu_p = 2\mu_u + \mu_d$
  - Weak equilibrium: $\mu_n = \mu_p + \mu_e \;\; ; \;\; \mu_e = \mu_\mu \;\; ; \;\; \mu_d = \mu_s$
  - Charge neutrality: $f \; n_p + (1-f)(2n_u - n_d - n_s)/3 - (n_e + n_\mu) = 0$
  - Baryon number conservation: $f(n_n + n_p) + (1-f)(n_u + n_d + n_s)/3 - n_B = 0$

- Crossover (Kapusta-Welle)

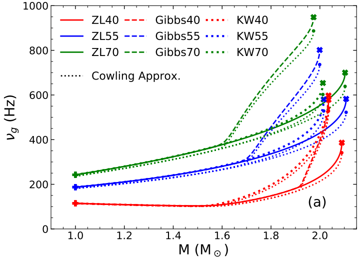
$$P_B = (1-S)P_H + S \; P_Q$$

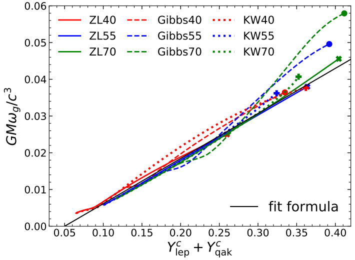
$$S = \exp\left[-\left(\frac{\mu_0}{\mu}\right)^4\right]$$

$$\mu_0 \sim 2 \text{ GeV}$$

g-mode signals

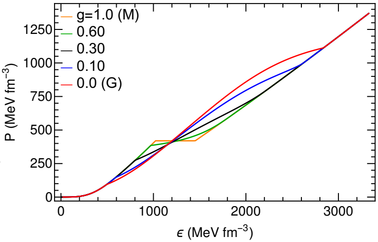
- g-modes in Gibbs hybrid matter have a larger frequency range compared to the pure-nucleon and crossover cases.
- Dramatic changes in ν_g require new particle species not merely a smooth change in composition.
- The Cowling approx. is qualitatively similar to GR but underestimates ν_g by up to 10%; does better for low-mass stars.
- Universal relations depend weakly on the EOS and can be used to break degeneracies and otherwise constrain difficult-to-access observables. $\Omega_g = GM\omega_g/c^3 = 1.228(Y^c - 0.05)$

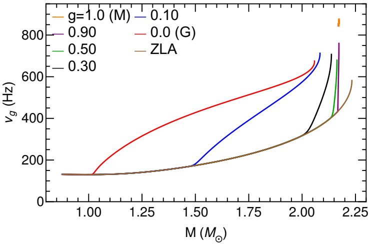




1st-Order Phase Transitions in-between Maxwell and Gibbs

- Maxwell and Gibbs constructions are two extremes of a continuous spectrum of possibilities for first-order phase transitions.
- Allow for charge neutrality to be fulfilled partially locally and partially globally; controlled the ratio g of electrons partaking in LCN to the total number of electrons.
- Modifications to equilibrium equations:
  $\mu_p = 2\mu_u + \mu_d - g(\mu_{eN} - \mu_{eQ})$
  $\mu_p = \mu_n - g\mu_{eN} - (1-g)\mu_{eG}$
  $P_N + gP_{eN} = P_Q + gP_{eQ}$
  $y_p = y_{eN} \;\; ; \;\; y_{eQ} = (2y_u - y_d - y_s)/3$
  $y_e = fgy_{eN} + (1-f)gy_{eQ} + (1-g)y_{eG}$
- For the specific case of g = 1, a gap appears between the quark and hadronic branches of the g-mode frequency.





Summary

- Key Results:
  - First calculation of g-mode properties under Gibbs phase rules and for the KW model (both with the Cowling approximation as well as linearized GR).
  - g-modes can detect nonnucleonic matter in the cores of NS; assuming quark matter (by some other means), g-modes can distinguish between a first-order phase transition and a crossover.
  - Universal relation between Ω_g and Y^c.
  - Construction of a thermodynamically-consistent framework which addresses 1st-order phase transitions of arbitrary surface tension.
  - First demonstration of the compositional g-mode in a hybrid NS reducing to a discontinuity g-mode at the Maxwell limit.
- (Near) Future:
  - Extend KW and framework above to finite T (in progress; specific cases of Gibbs and Maxwell completed).
  - Applications to protoneutron stars (short- and long-term cooling, superfluidity).
  - Construct EOS that uses the same underlying description for quarks and hadrons (QMC - in progress); explore hybrid matter microscopically.
  - Explore the nuclear liquid-gas phase transition in the Lattimer-Swesty scheme with constructions intermediate to the Maxwell and Gibbs extremes.
  - Subnuclear EOS vs. p-mode (pressure-supported vibrational mode; confined to NS surface).