High-Frequency Gravitational Waves from Phase Transitions in Nascent Neutron Stars

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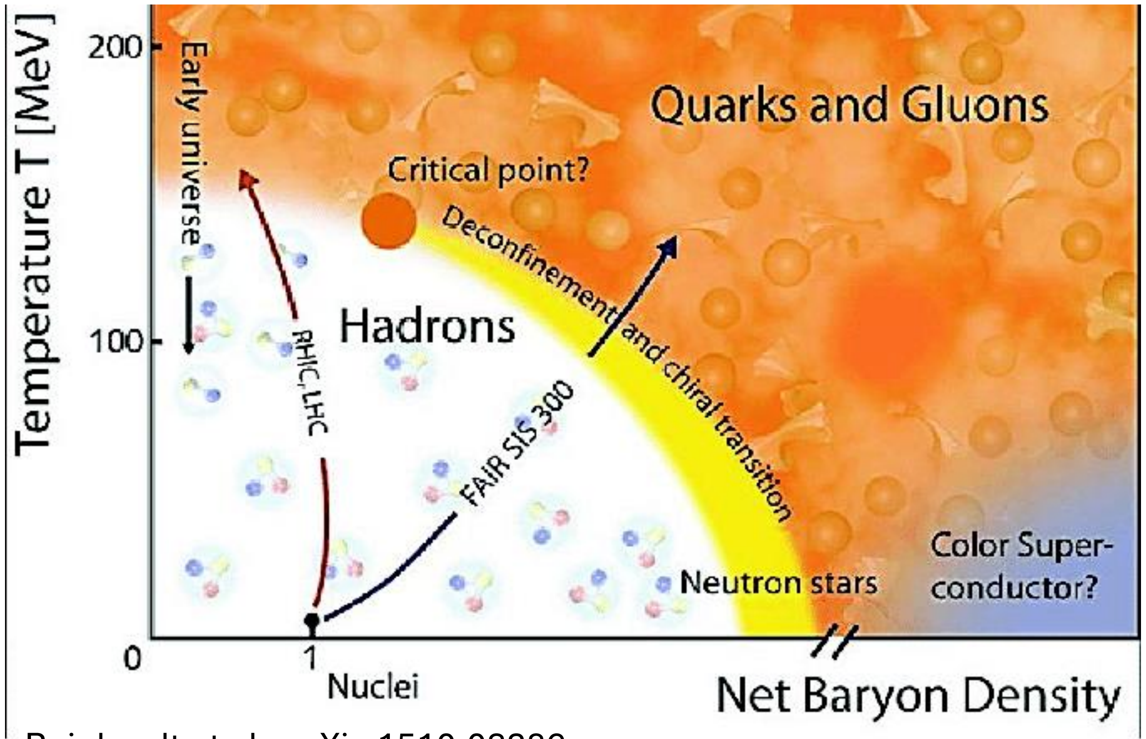
In collaboration with Joachim Kopp (CERN, JGU), Jiheon Lee (KAIST) and Jorinde van de Vis (CERN)

Coming soon to arxiv!

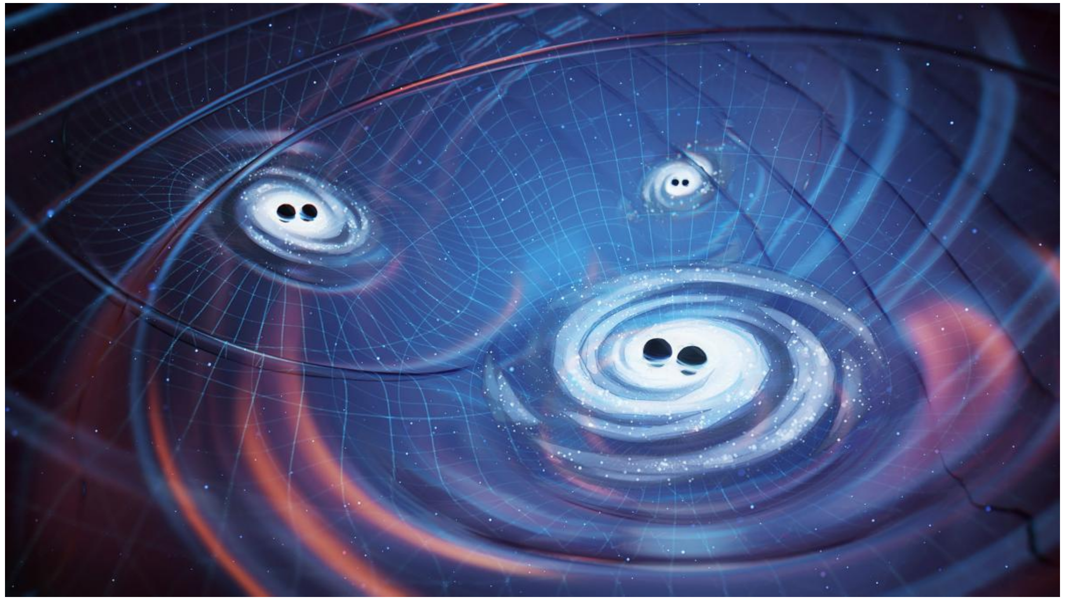
Introduction

QCD phase diagram mostly unknown

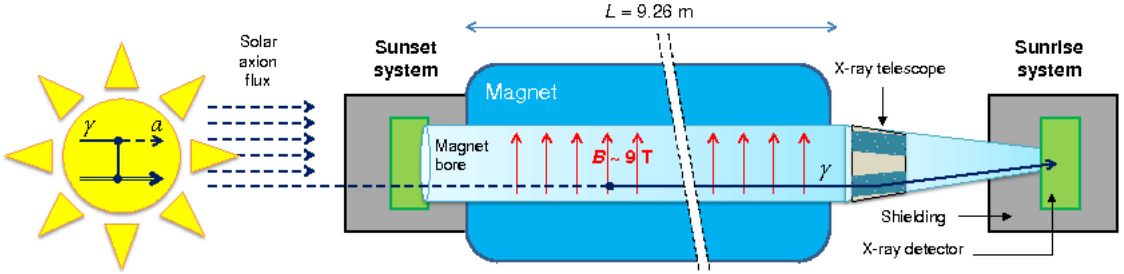


Reinhardt et al., arXiv:1510.03286

Progress in gravitational wave detection



nanograv.org



Anastassopoulos et al., arXiv:1705.02290

Overview

Birth of neutron star from core-collapse supernova

I.
1st order phase transition from hadronic matter to quark-gluon plasma in core

II. Bubble nucleation and collisions

III.
Gravitational wave signal with O(MHz) frequency

Unique opportunity for high-frequency GW detectors to probe extreme regime of QCD

Dynamics of the Phase Transition

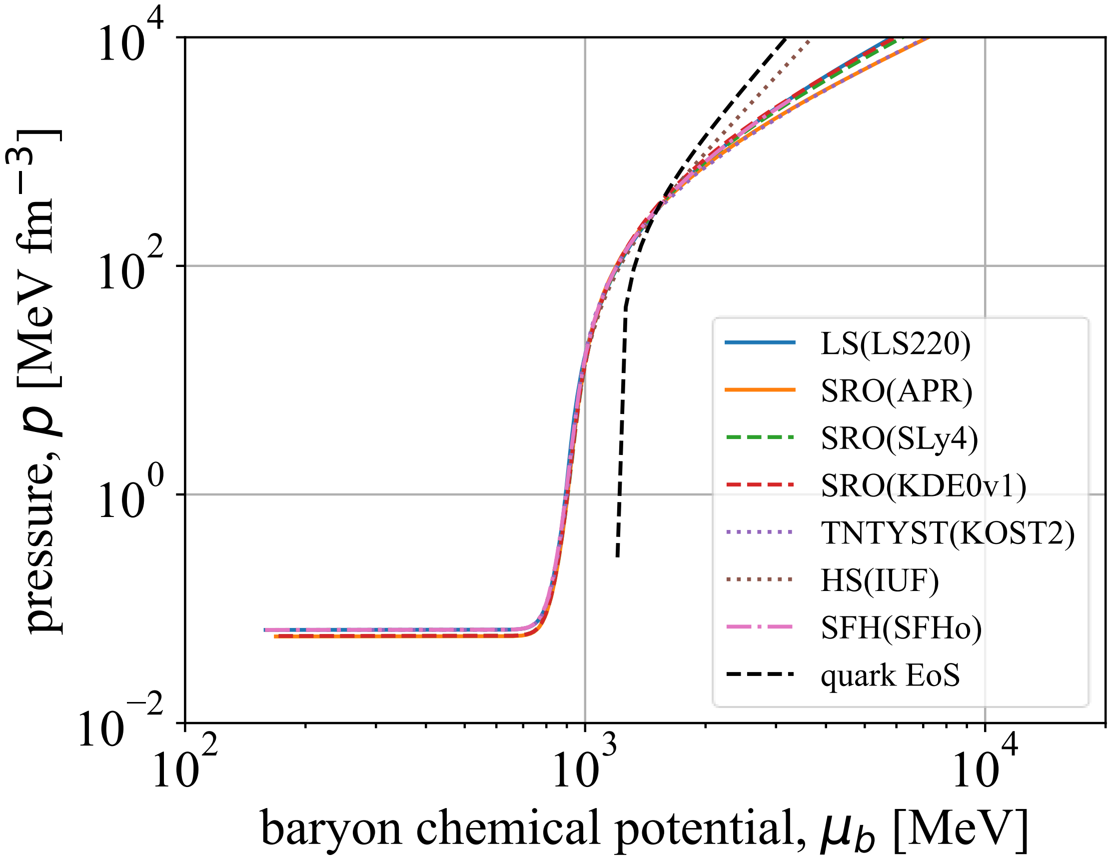
- Uninterrupted transition
  - Quark matter bubbles expand and coalesce until transition is complete
  - Strongest GW signal
  - Need pressure to remain high enough as volume transitions to quark phase
- Stalled transition
  - Expansion of quark matter bubbles stops before transition is complete
  - GW signal is suppressed
- Smooth formation of mixed phase
  - Quarks and hadrons co-exist as unordered mixture or as ‘pasta’
  - Slow and smooth process produces no GW signal

GW signal depends strongly on high-density QCD dynamics!

Neutron Star Model I

I.
1st order phase transition from hadronic matter to quark-gluon plasma in core

The neutron star is characterized by an equation of state (EoS).



p-vs-μ_b plane:

- Critical pressure p_c = intersection point of the hadron EoS and the quark EoS
- Bubble nucleation starts at the nucleation pressure $p_n \geq p_c$

→ **pressure, energy density, phase transition strength**

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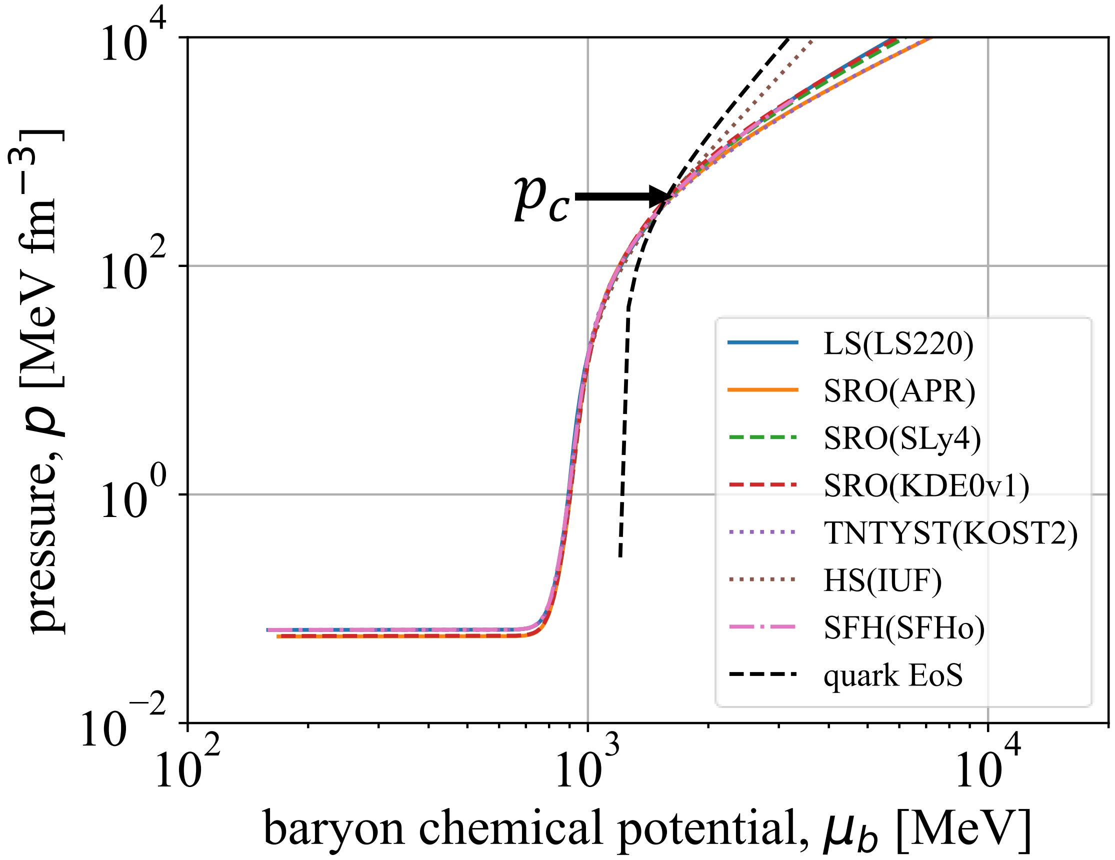

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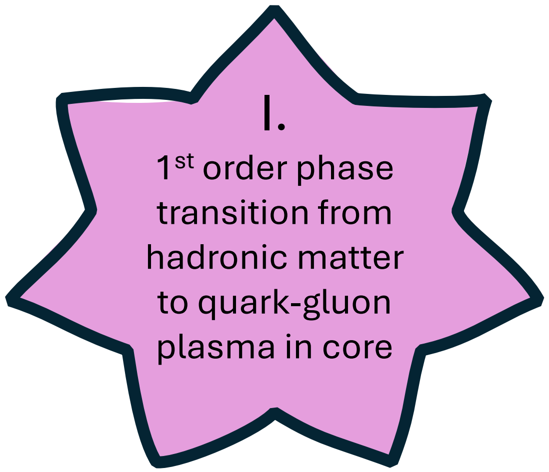

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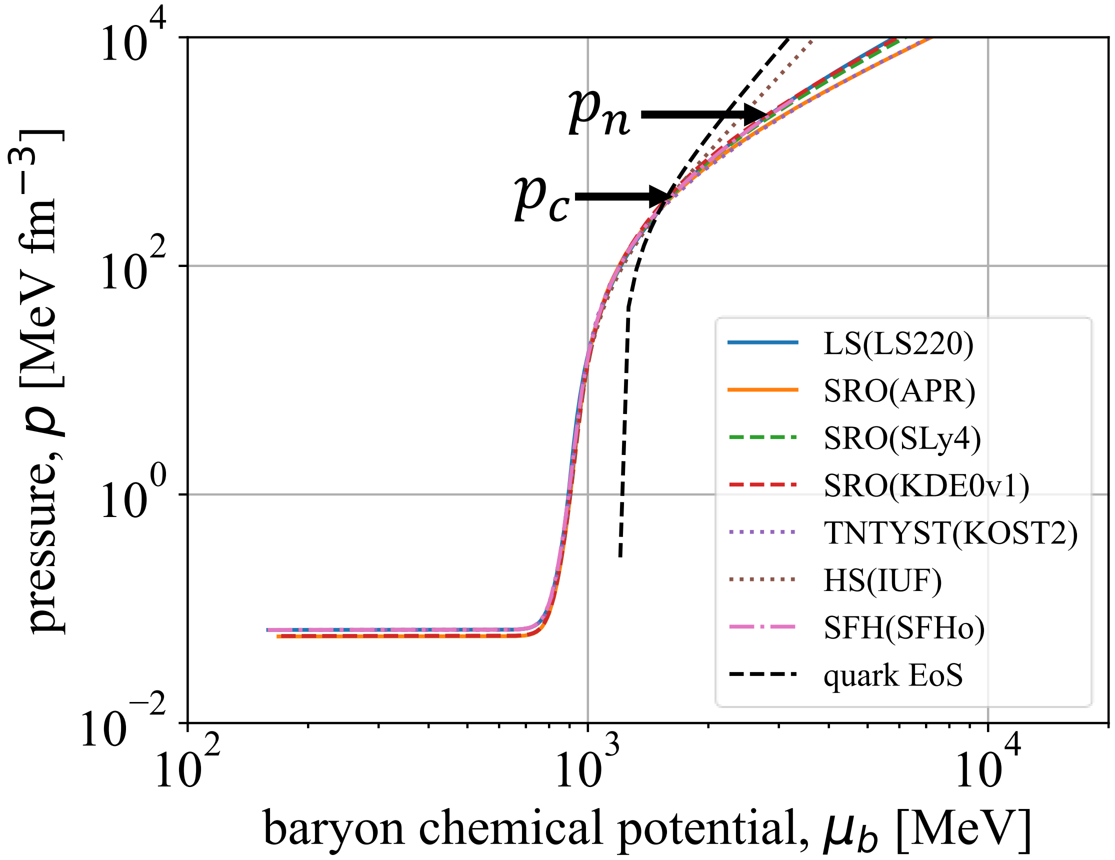

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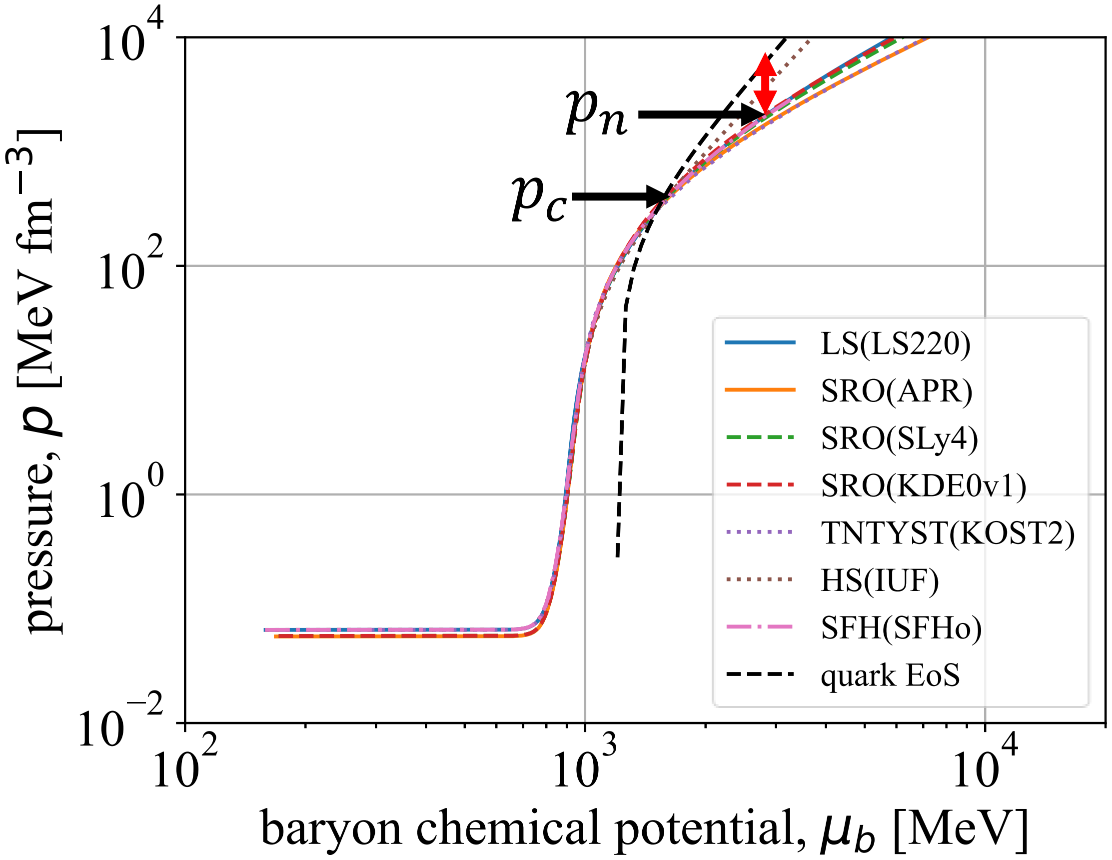

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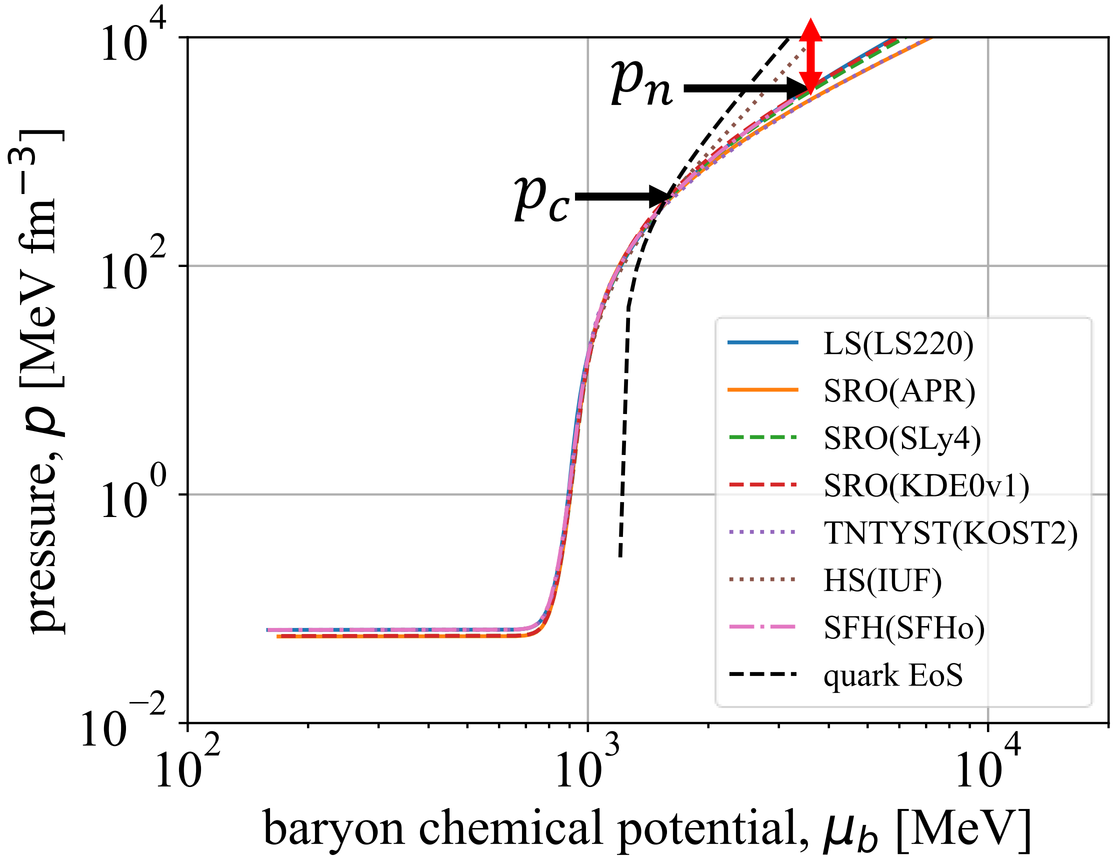

p-vs-μ_b plane:

- Critical pressure p_c = intersection point of the hadron EoS and the quark EoS
- Bubble nucleation starts at the nucleation pressure $p_n \geq p_c$

→ **pressure, energy density, phase transition strength**

Neutron Star Model II

I.
1^{st} order phase transition from hadronic matter to quark-gluon plasma in core

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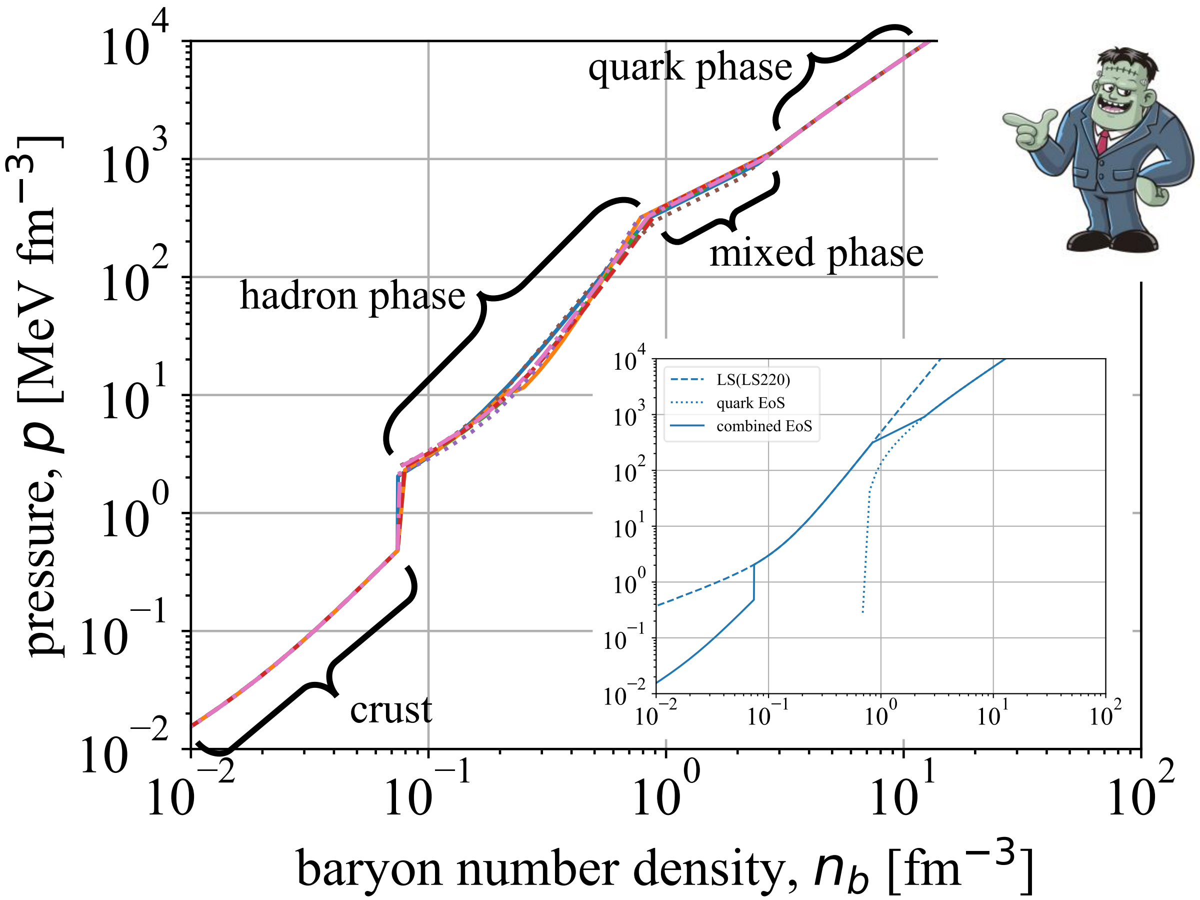


p-vs-n_b plane:

- Discontinuity at p_c smoothed out by the mixed phase EoS
- A mixed phase where hadrons and quarks co-exist typically exists in neutron star models
- $p = \kappa n_b^{\Gamma}$ (slope parametrized by Γ)

➔ **input for TOV equations**

Neutron Star Model III

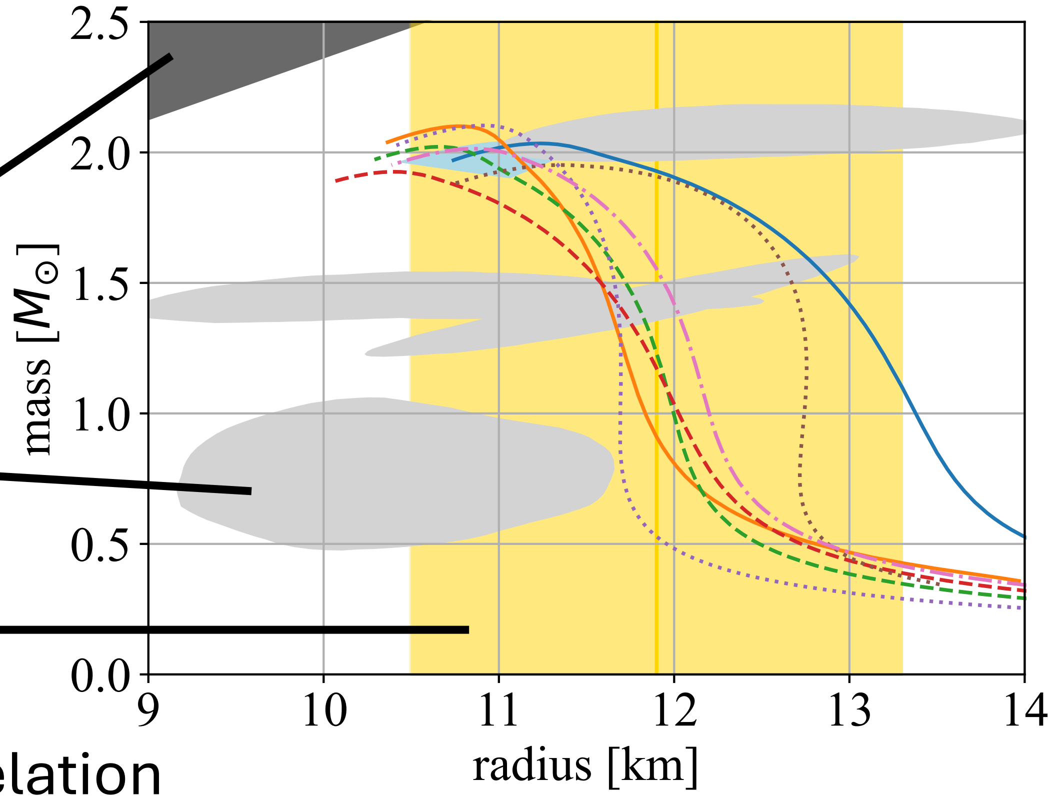
I.
1^{st} order phase transition from hadronic matter to quark-gluon plasma in core

- <u>Input</u>: Combined EoS
- <u>Solve</u> Tolman–Oppenheimer–Volkoff (TOV) equations
- <u>Output</u>:
  - Mass-radius relation (compare to observations)
  - Pressure profiles (**radius of the quark core**)

Theoretical limit (causality)

NICER data contours

GW170817 radius measurement

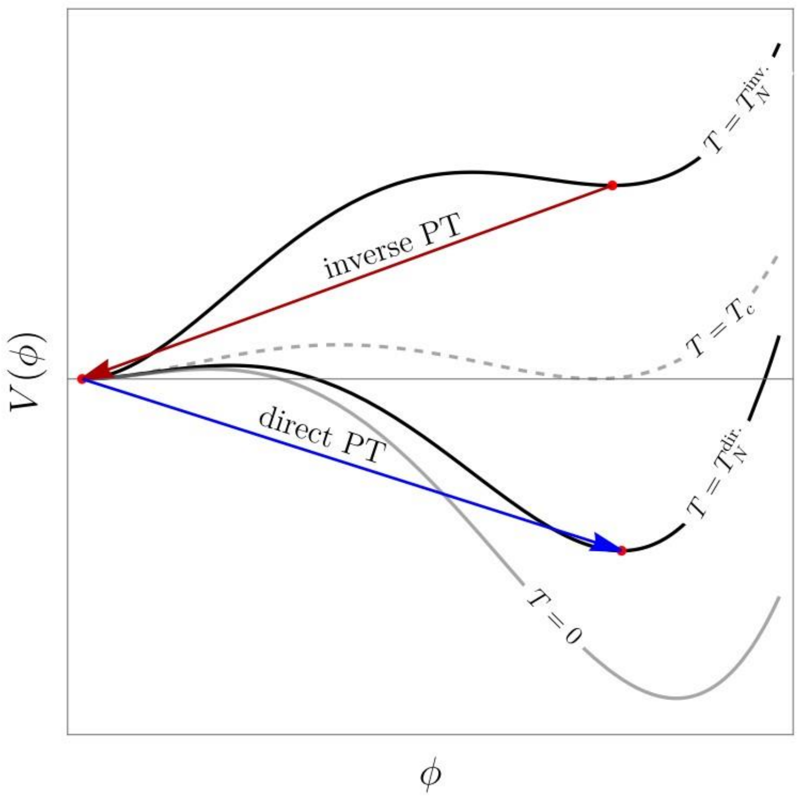


- Note: choice of Γ (mixed EoS) affects M-R relation

Hydrodynamics

- Source of gravitational wave signal = **sound waves produced by bubble collisions**
- Goal of hydrodynamics code: compute **bubble wall velocity**
  - Size of bubbles
  - Efficiency factor
- Need Local Thermal Equilibrium approximation (accounts for vacuum energy and fluid effects, w/o dissipative friction forces) + entropy conservation
- Note: fluid velocity and enthalpy profiles are determined for an ***inverse* phase transition**.

II. Bubble nucleation and collisions



Barni, Blasi, Vanvlasselaer, arXiv:2406.01596v2

I.
1^{st} order phase transition from hadronic matter to quark-gluon plasma in core

II.
Bubble nucleation and collisions

Neutron Star Model:

- Pressure & energy density before and after PT
- Phase transition strength
- Radius of quark core

Hydrodynamics:

- Bubble wall velocity
- Size of bubbles
- Efficiency factor

III.
Gravitational wave signal with O(MHz) frequency

Frequency of Gravitational Wave Signal

arxiv: 2210.03171

- Peak frequency ≈ 1/(size of quark bubbles)
- Rate of bubble nucleation per volume element:

$$\frac{dP_{\rm nuc}(t)}{dt\, d^3x} = \Lambda^4 e^{-S(t)}$$

- Number density of bubbles at time *t*:

$$n_{\rm bubbles}(t) = \int_{t_c}^{t} dt' \left[1 - x_q(t')\right] \frac{dP_{\rm nuc}(t')}{dt'\, d^3x}$$

where x_q is the fraction of the core that has transitioned

- Define timescale of phase transition: $\beta \equiv -\frac{dS}{dt}$
- Taylor expanding the exponent *S(t)*:

$$n_{\rm bubbles}(t) \simeq \frac{x_q \beta^3}{8\pi v_w^3}$$

where (size of quark bubbles) = $(n_{bubbles})^{-1/3}$

Characteristic Strain

$$h_c^2 = \frac{8\pi G}{2\pi^2}\frac{\rho_{GW}}{f_p^2}$$

III. Gravitational wave signal with O(MHz) frequency

$$\rho_{\rm GW} = 8\pi G (e+p)^2 \left(\frac{3}{4}|\alpha_N|\kappa\right)^2 (\tau R_*) \tilde{\Omega}_{\rm GW}$$

- Peak frequency (~MHz, from size of quark bubbles)
- Energy density and pressure (from equation of state)
- Phase transition strength (from equation of state)
- Efficiency factor (from bubble dynamics)
- Time duration of the source (min. of light crossing time and shock formation time)

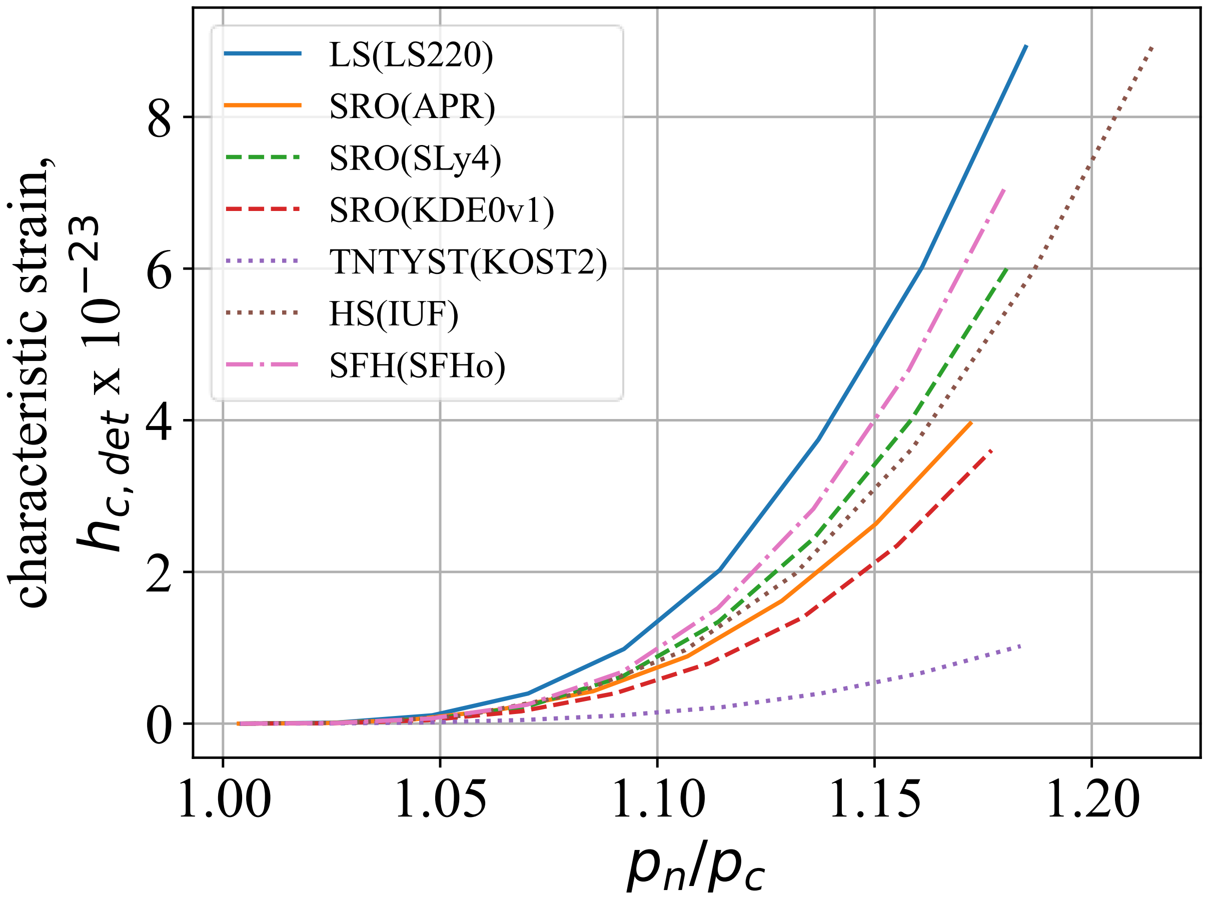
$$\tau = \min(\tau_{\rm lc}, \tau_{\rm sh}) = \min\left(L, \frac{R_*}{\sqrt{\frac{3}{4}\frac{\alpha\,\kappa}{\alpha+1}}}\right)$$

- Size of quark bubbles (from timescale of phase transition and bubble wall velocity)
- Numerical constant (from previous simulations)

- **Characteristic strain suppressed by [volume fraction]$^{9/8}$ for stalled phase transition**

Characteristic Strain

III.
Gravitational
wave signal
with O(MHz)
frequency



- Close to experimental sensitivity of proposed gravitational wave detectors → detectable in the future!
- Unique SM source of high-frequency signal → don't need exotic new physics

1^{st} order phase transition from hadronic matter to quark-gluon plasma in neutron star core

→

Gravitational wave signal with O(MHz) frequency

Thank you!