# Self-energy of pion and its impact on equation of state and binary neutron star merger

Ninoy Rahman

Vimal Vijayan, Andreas Bauswein, Pok Man Lo, Gabriel Martínez-Pinedo
GSI Helmholtzzentrum für Schwerionenforschung

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# Outline

- Motivation.
- Pionic equation of state.
- Impact on binary neutron star merger simulations.

# Motivation

- Nuclear equation of state (EOS) impacts the outcomes of binary neutron star merger (BNS) simulations.
- EOS impacts threshold mass, ejecta properties, gravitational wave properties.
- Nucleosynthesis yield depends on ejecta properties such as neutron to proton ratio, entropy, and expansion timescale.
- Kilonova light curve and spectrum depend on the nucleosynthesis yield.

# Chemical potential

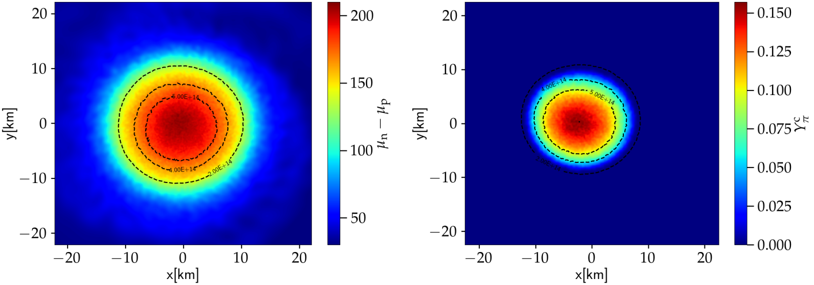



Figure 1: Vijayan et. al. 2023

# Pionic EOS

- We studied both free pions and interacting pions at BNS merger conditions.
- Pions are treated as Bose gas $f(p) = (1 + \exp((E(p) - \mu_\pi)/T))^{-1}$.
- We introduced pions to existing non-pionic EOSs such as SFHo and DD2 EOSs.
- Condensed negatively charged pions $\pi^-$ are considered.
- In BNS merger, the $\pi^+$ and $\pi^0$ productions are supressed.

# Pionic EOS

- Interactions modify the relativistic pionic energy-momentum relation: $E^2(p) = m_\pi^2 + p^2 + \mathrm{Re}\Sigma_{\pi\mathrm{N}}(p) + \mathrm{Re}\Sigma_{\pi\pi}(p)$ and the effective mass $m_{\mathrm{eff}}^2(p) = m_\pi^2 + \mathrm{Re}\Sigma_{\pi\mathrm{N}}(p) + \mathrm{Re}\Sigma_{\pi\pi}(p)$.
- Attractive interaction leads to $m_{\mathrm{eff}}(p) < m_\pi$ and repulsive interaction results in $m_{\mathrm{eff}}(p) > m_\pi$.
- Pionic self-energy $\Sigma$ is evaluated using the phase shift data $\delta$ from pion-pion and pion-nucleon scattering experiments.

$$\Sigma_{\pi\mathrm{N}/\pi}(p) = \int \frac{\mathrm{d}^3 q}{(2\pi)^3} \frac{f_{\mathrm{N}/\pi}(q)}{2\epsilon(q)} T(s)\,,$$

$$T(s) = -8\pi\sqrt{s} P_{\mathrm{cm}}^{-1} (2l+1) \exp\left(i\delta(s)\right) \sin\left(\delta(s)\right) \quad (1)$$

# Phase shifts

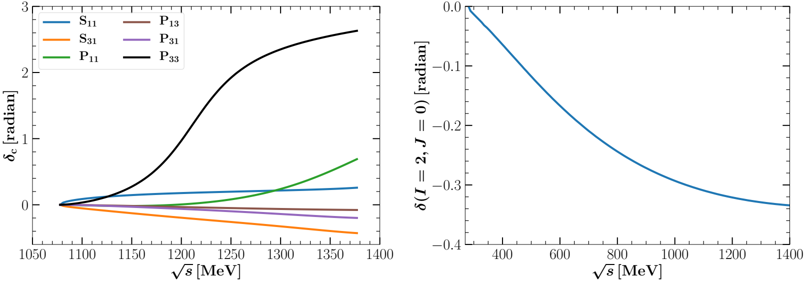



Figure 2: The pion-nucleon phase shifts (left panel) are from Hoferichter et al. 2016 and the pion-pion phase shifts (right panel) are Protopopescu et al. 1973, Estabrooks and Martin 1974, Froggatt and Petersen 1977.

# EOS and Tolman–Oppenheimer–Volkoff solutions

- Pion interactions modify the energy-momentum relation by $\sim$5%.

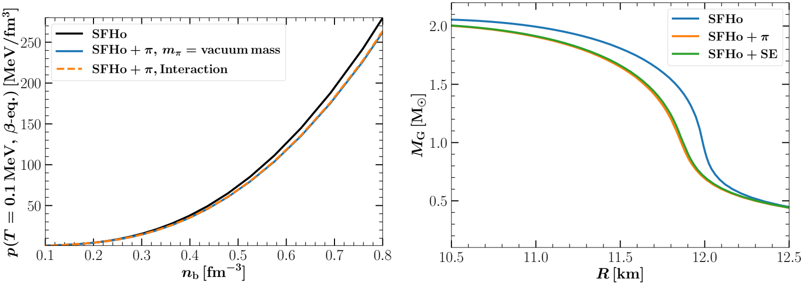



Figure 3: Pressure vs number density (left panel) and Tolman–Oppenheimer–Volkoff solutions (right panel) at $\beta$-equilibrium.

# BNS merger simulations: setup

- We conducted general relativistic BNS merger simulations with our pionic EOSs.
- Pionic effective mass is treated as a free parameter with values equal to 139.57, 170, 200 MeV.

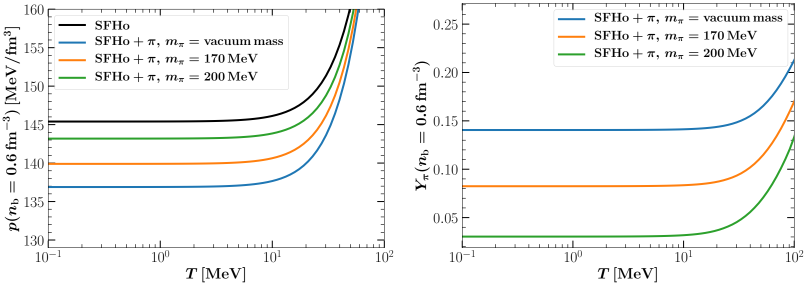
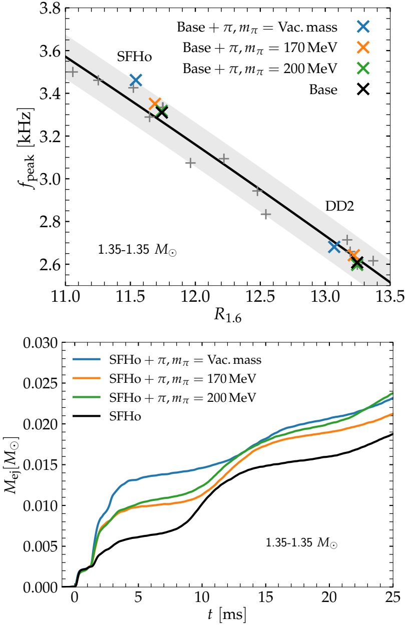



Figure 4: Pressure (left panel) and pion fraction (right panel) vs temperature.

# BNS merger simulations: results



# BNS merger simulations: ejecta properties

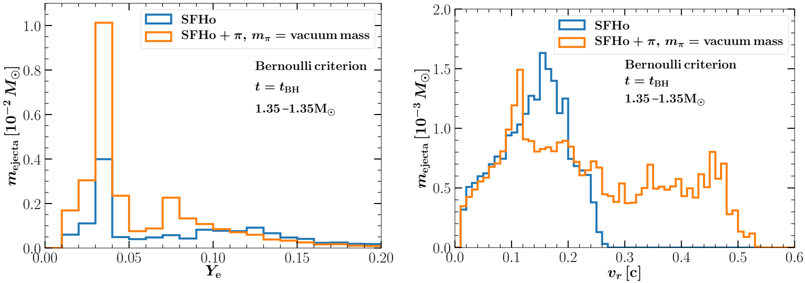



Figure 5: ejecta histograms against electron fraction (left panel) and radial velocity (right panel).

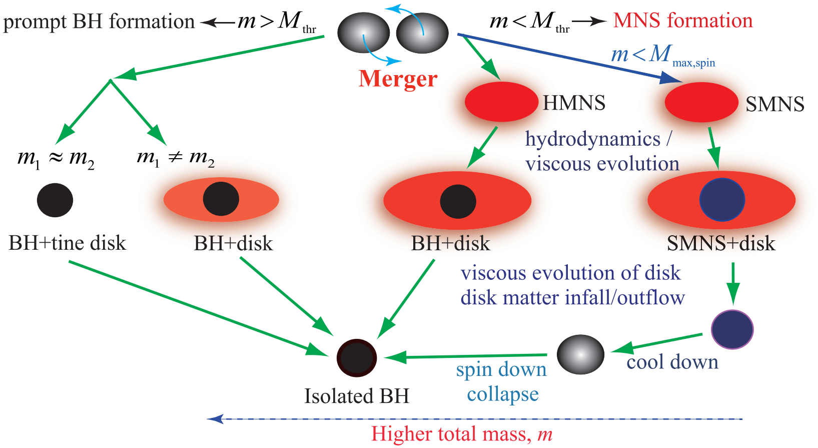
# Summary and conclusion

- We studied pionic EOS with and without interactions.
- Pion-pion and pion-nucleon two-body interactions show minute influence on the EOS and the TOV solutions.
- BNS merger simulations are conducted employing pionic EOS with parametric pion mass.
- GW peak frequency can shift upto $\sim$150Hz.
- Noticeable increase in ejecta mass with the inclusion of pions.
- Threshold mass of the prompt black hole formation reduces by $0.07\mathrm{M}_\odot$.

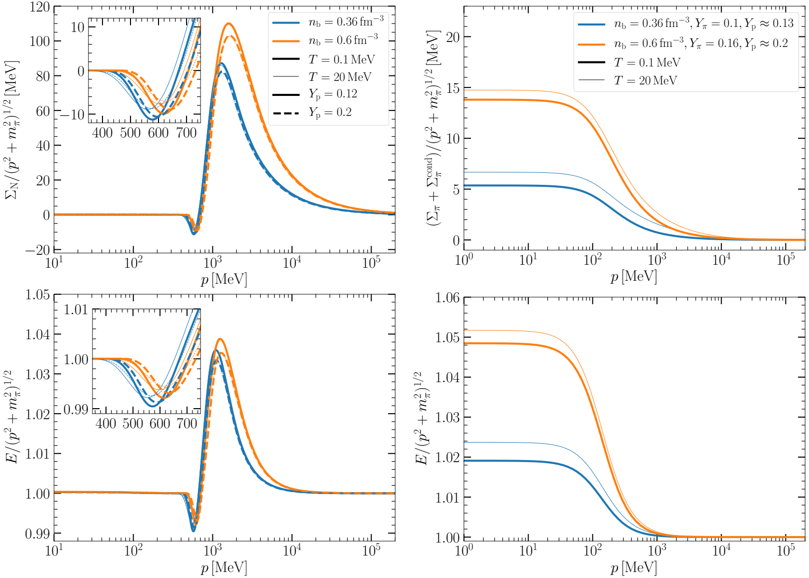
# Key questions and future developments

- Inclusion of the three body pion-nucleon/pion-pion interactions and their impact on EOS.
- In future simulations, muons and neutrinos need to be included and pion decay to muon should be considered.

# Backup


prompt BH formation ⟵ $m > M_{thr}$
$m < M_{thr}$ ⟶ MNS formation
Merger
$m < M_{max,spin}$
HMNS
SMNS
hydrodynamics /
viscous evolution
$m_1 \approx m_2$
$m_1 \neq m_2$
BH+tine disk
BH+disk
BH+disk
SMNS+disk
viscous evolution of disk
disk matter infall/outflow
cool down
spin down
collapse
Isolated BH
Higher total mass, $m$

# Backup



$n_\mathrm{b} = 0.36\,\mathrm{fm}^{-3}$
$n_\mathrm{b} = 0.6\,\mathrm{fm}^{-3}$
$T = 0.1\,\mathrm{MeV}$
$T = 20\,\mathrm{MeV}$
$Y_\mathrm{p} = 0.12$
$Y_\mathrm{p} = 0.2$
$\Sigma_\mathrm{N}/(p^2 + m_\pi^2)^{1/2}\,[\mathrm{MeV}]$
$p\,[\mathrm{MeV}]$
$n_\mathrm{b} = 0.36\,\mathrm{fm}^{-3}, Y_\pi = 0.1, Y_\mathrm{p} \approx 0.13$
$n_\mathrm{b} = 0.6\,\mathrm{fm}^{-3}, Y_\pi = 0.16, Y_\mathrm{p} \approx 0.2$
$T = 0.1\,\mathrm{MeV}$
$T = 20\,\mathrm{MeV}$
$(\Sigma_\pi + \Sigma_\pi^\mathrm{cond})/(p^2 + m_\pi^2)^{1/2}\,[\mathrm{MeV}]$
$p\,[\mathrm{MeV}]$
$E/(p^2 + m_\pi^2)^{1/2}$
$p\,[\mathrm{MeV}]$
$E/(p^2 + m_\pi^2)^{1/2}$
$p\,[\mathrm{MeV}]$