Impact of pions on binary neutron star mergers

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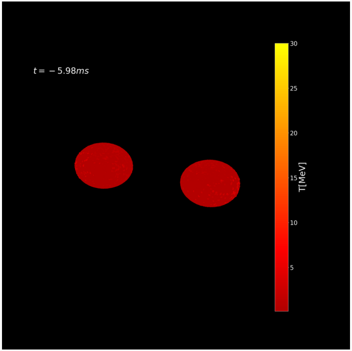
BNS mergers

- To probe physics of matter at extreme densities and temperatures ($\sim$ order of nuclear saturation density and several 10 MeV).
- Neutron star (NS) interior : n, p, ${}^{A}_{Z}X$, e^-, e^+, γ, Quarks? Hyperons? **Pions**? etc.
- Incompletely known equation of state (EoS) and not precisely known NS stellar structure.
- **Approach**: Compute observables from simulations and compare to observations.

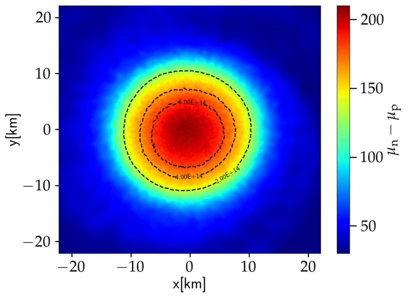


BNS merger

NS EoS

- Theoretically constructed candidate EoSs in merger simulations. E.g. SFHo and DD2 (includes n, p, ${}^{A}_{Z}X$, e^-, e^+, γ)
- Neutron-proton chemical potential difference is large enough for the presence of pions, π^-, π^+ and π^0, since $m_{\pi^\pm}$ =139.6 MeV and m_{π^0} =134.9 MeV.
- **Drawback:** All currently used EoS tables for BNS mergers neglect pions!

(a) Base DD2

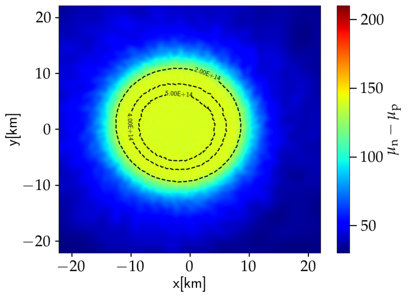


- What is the impact of pions on observables?
- Is inference of observables (GW, kilonova) biased by neglecting pions (in currently employed empirical relation for observables)?

NS EoS + Pions

- Pions included as non-interacting boson gas (a first simple approach). In thermal and chemical equilibrium with nucleons through the strong interaction.
- $\mu_{\pi^\pm} = \mp(\mu_n - \mu_p)$ and $\mu_{\pi^0} = 0$
- Charge neutrality :
  $Y_p = Y_e + Y_\pi = Y_e + Y_{\pi^-} - Y_{\pi^+}$
- Pions can exist as condensate and thermal pions, i.e.
  $Y_\pi = Y_{\pi^{\text{condensate}}} + Y_{\pi^{\text{thermal}}}$.

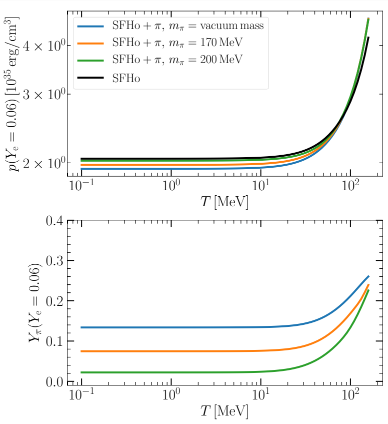
(b) DD2 + π, m_π = Vac. mass



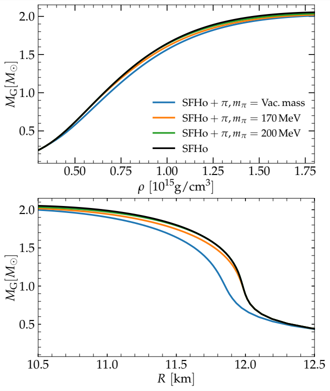
- Chosen effective mass of the pions: Vaccuum mass, 170MeV and 200MeV (as first approximation).

NS EoS + Pions

- Overall reduction of the pressure, softening of the EoS.
- Impact on the properties of isolated NS, BNS dynamics/observables.

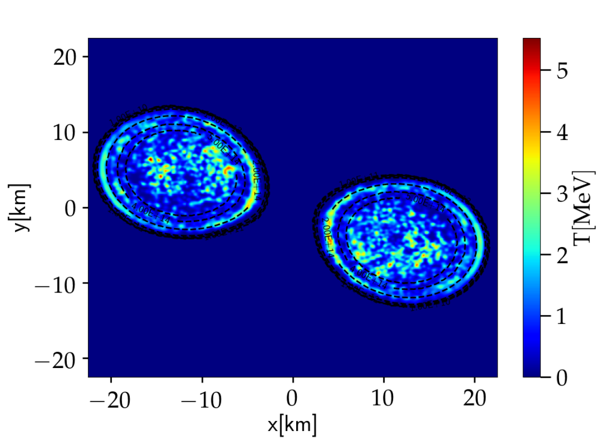


Pressure and Y_π versus temperature



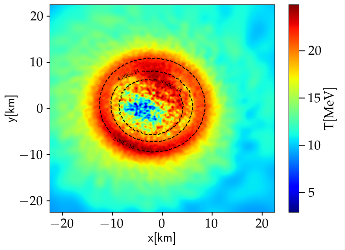
Gravitational mass versus NS central density and radius

BNS merger simulations with Pions

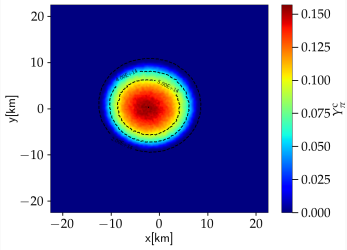


Simulations with Pions

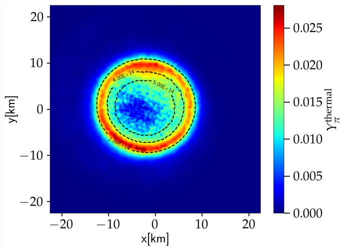
(c) T [MeV]



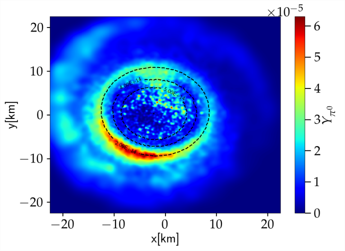
(d) Y_π^c



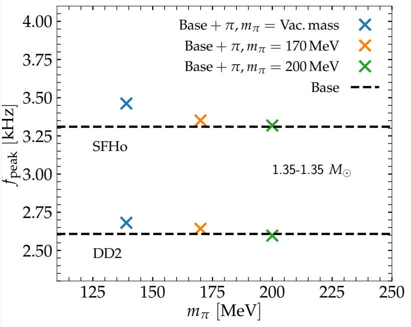
(e) $Y_\pi^{\rm thermal}$

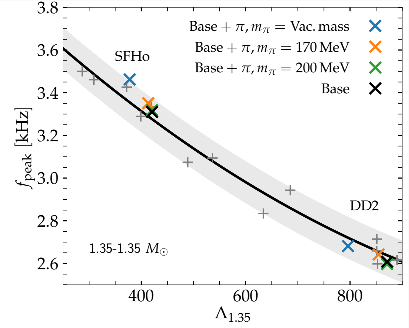


(f) Y_{π^0}



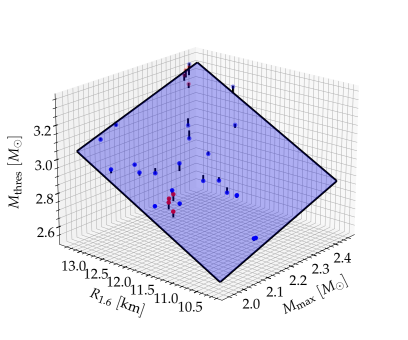
Results

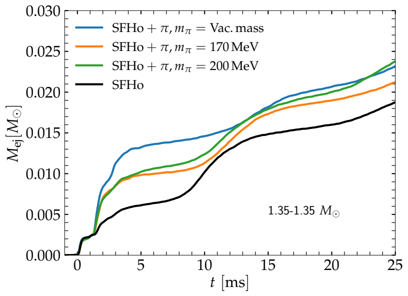




- Shift of the dominant postmerger gravitational-wave frequency by up to 150Hz to higher frequencies (stronger for smaller effective pion masses).
- Empirical relations between the threshold mass or the f_{peak} and stellar parameters of nonrotating neutron stars remain valid to good accuracy (cancellation effect).

Results





- Reduction of the threshold binary mass for prompt black-hole formation by up to $0.07 M_\odot$ (stronger for smaller effective pion masses).
- Pronounced increase of ejecta mass by the inclusion of pions.