Transport in Neutron Star Mergers

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Alford, A.H., Harris, Zhang, arXiv:2108.03324
Alford, A.H., arXiv:2009.05181,
Alford et.al., 1707.09475

N3AS seminar September 21st, 2021

Topic of this Talk

Question of the day:

How can we use transport in neutron star mergers to study the QCD phase diagram ?

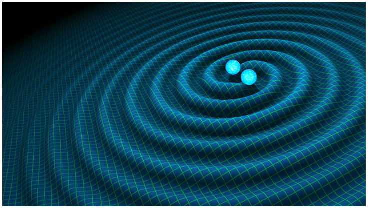
Answer:

- Build better gravitational wave detectors
- Improve microscopic physics in merger simulations
- Need to re-evaluate our $T = 0$ wisdom

Outline

Introduction & Motivation

1. Neutron star merger and the study of dense matter
2. Gravitational waves: simulations and measurement
3. Thermodynamics of neutron star merger
4. Relevant transport properties ?



R. HURT/CALTECH-JPL

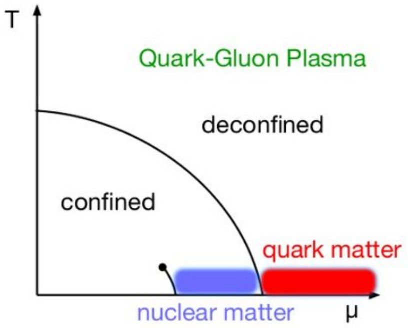
Results

1. Bulk viscosity
2. **Chemical equilibrium in mergers**

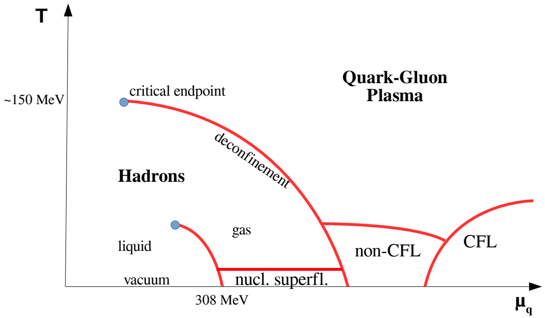
Summary & Outlook

- Ultimate goal: understanding the phase diagram of fundamental matter as described by quantum chromodynamics (QCD)
- Various features and regions

conservative version



"bolder" version

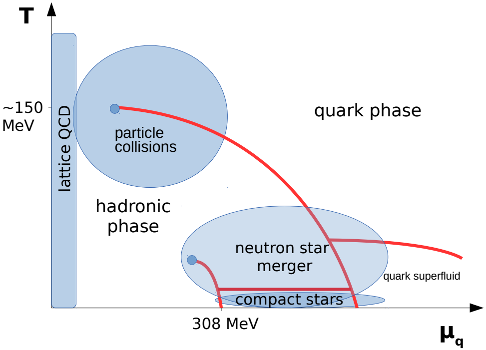


$$T = 1\ \text{MeV} \approx 10^{10}\text{K}$$

QCD Phase Diagram II

How can we attack the QCD phase diagram

- Investigation of the phase diagram can be experimental or theoretical (in reality always a mix)
- Huge range of thermodynamic parameters (T, n_B, x_n, B, particle content) ...

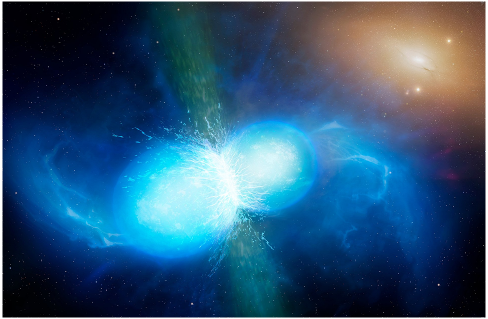


- Perturbative QCD at high densities/temperatures (μ, $T \gg \Lambda_{\mathrm{QCD}}$)
- Lattice QCD at low densities ($\mu \ll T$ - "sign problem")
- Nuclear theory at liquid-gas transition
- Experiments for nuclear and hyperonic matter
- Collider experiments (RHIC, LHC, PANDA, NICA)
- Neutron stars (NS) and binary NS merger

Neutron Star Merger

A new way to tackle the QCD phase diagram

- Binary neutron star merger can be observed via electromagnetic and gravitational waves
- Offer a new way to study dense matter (nuclear, quark, exotic)

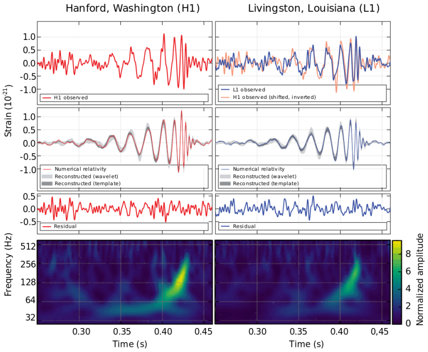


- Merger test matter at densities up to several times saturation density and tens of MeV of temperature
- Inferring properties of dense matter from gravitational waves is challenging
- Unique opportunity to test matter in one of the most extreme environments imaginable

Gravitational Waves

Detection requires simulations

- BNS (inspiral) can be detected with current detectors (GW170817 and GW190425)
- Signal can be **very noisy** - requires simulation of wave form
- Simulations provide us thermodynamic input and allow us to extract microscopic properties of matter



B. P. Abbott et al. (LIGO and Virgo Collaboration)

Simulations take into account (most) of the following:

- General Relativity: Basis of simulations is evolving spacetime metric throughout the merger using Einstein's equations of GR
- Relativistic Hydrodynamics: Matter compromising the stars is modeled as "perfect fluid" (no true viscosity, numerical viscosity can be a problem)
- Equation of state $P(\varepsilon)$: Equation of state describes behavior and composition of matter, often simple model equations, not fundamental
- Electrodynamics: Magnetic fields can influence the development of the merger
- Neutrino transport: Behavior of neutrinos depends on temperature

Merger Simulations II
What next?

- Simulations = numerical (general) relativity + relativistic hydrodynamics

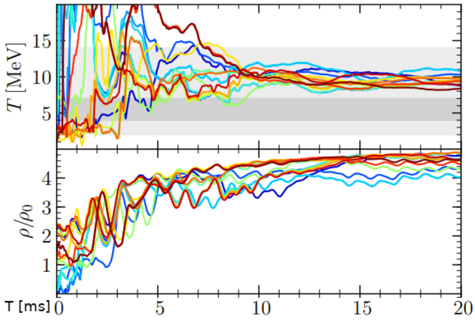
→ Simulations = technically hard + sophisticated . . .

. . . but necessarily neglect a lot of physics

- Improvements necessary, especially if we want to learn as much as possible from post-merger phase

But where to start?

Neutron Star Merger
Thermodynamic environment



Alford, Bovard et.al., PRL 120 (2018)

- Significant spatial and temporal variation in
  - temperature $\rightarrow$ thermal conductivity
  - fluid flow velocity $\rightarrow$ shear viscosity
  - density $\rightarrow$ bulk viscosity
- (Strong) density fluctuations with
  - $\omega \approx 2\pi \times 1$ kHz frequency
  - especially in the first 5 ms
  - up to 50% amplitude
  - largely die down after 20 ms

? Which processes operate on merger time scales (ms range)?

Transport Properties in Mergers

Better discriminator of different phases than EOS

Premise

The important dissipation mechanisms are the ones whose equilibration time is $\lesssim$ 20ms

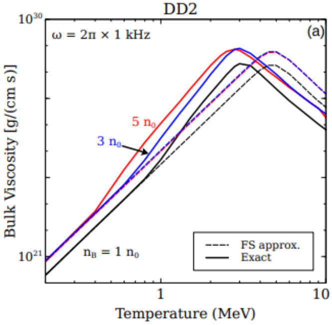
Estimates for transport properties: **Alford, Bovard, et.al. PRL 120 (2018)**

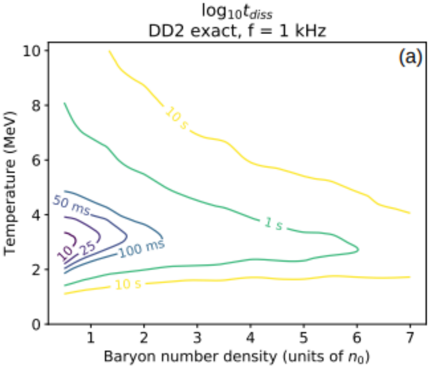
- Thermal transport: $\tau^{\nu}_{\kappa} \approx 0.7\,\mathrm{s} \times \left(\frac{0.1}{x_p}\right)^{1/3} \left(\frac{m_n^*}{0.8 m_n}\right)^3 \left(\frac{\mu_e}{2\mu_\nu}\right)^2 \left(\frac{z_{\mathrm{typ}}}{1\,\mathrm{km}}\right)^2 \left(\frac{T}{10\,\mathrm{MeV}}\right)^2$

  $\rightarrow$ might be fast enough if
  - neutrinos are trapped ($T > 5$ MeV)
  - there are short-distance temperature gradients on $\approx$ 0.1 km scale
- Shear viscosity similar conclusion
- Bulk viscosity potentially important: large enough for significant damping of oscillations in millisecond time-range?

Nuclear Bulk Viscosity
neutrino trapped vs. free-streeming

- Nuclear bulk viscosity in neutrino-transparent matter ($T \lesssim 5$ MeV):
  Alford, Harris, Phys.Rev. C100 (2019): millisecond damping times
- Nuclear bulk viscosity in neutrino-trapped matter ($T \gtrsim 10$ MeV):
  Alford, Harutyunyan, Sedrakian Phys.Rev.D100 (2019): rates too fast $\rightarrow$ low bulk viscosity

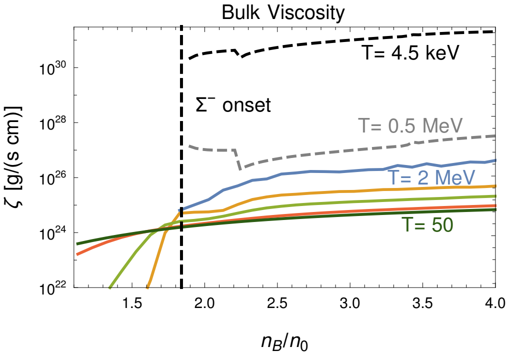


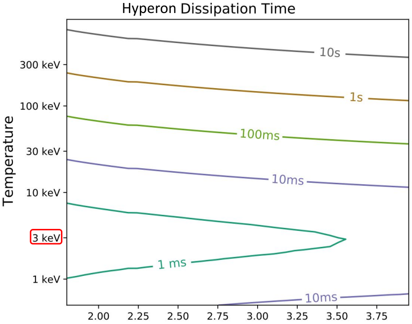


Hyperonic Bulk Viscosity

non-leptonic

- Hyperon bulk viscosity for non-leptonic processes :
  Alford, A.H. 2009.05181: millisecond damping times only at keV temperatures
- Hyperonic rates at higher temperatures too fast for sizeable bulk-viscosity





Beta Equilibrium

Cold vs warm beta equilibrium

- Beta-equilibrium = chemical equilibrium: composition of matter (e.g. proton fraction) stays constant with time
- "Chemical composition" (particle fractions) change via weak interactions

beta equilibrium: neutron decay and electron capture balance

$$n + \cdots \rightarrow p + e^- + \ldots \qquad p + e^- + \cdots \rightarrow n + \cdots$$

- Above $T \gtrsim 10\,\mathrm{MeV}$, neutrinos are trapped
- In this talk: work in neutrino free-streaming regime: $\mu_\nu = \mu_{\bar{\nu}} = 0$

If rates balance and are inverse to each other:

cold beta equilibrium: correct at $T = 0$

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

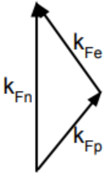
? Still valid at moderate, **finite temperatures** ?

direct Urca (dU)

neutron decay: $n \rightarrow p + e^- + \bar{\nu}_e$ electron capture: $p + e^- \rightarrow n + \nu_e$

$$\Gamma_{\mathrm{dU,nd}} \propto \int d^{12}p \, |M|^2 \, f_n(1 - f_e)(1 - f_p) \, \delta^4(4 - \mathrm{mom\,cons.})$$

- Dominated by particles on their Fermi surface (FS)
- Momentum conservation on FS demands $\vec{k}_{Fn} \leq \vec{k}_{Fp} + \vec{k}_{Fe}$
- If momentum cons. on FS not possible: rate heavily suppressed
- Momentum conservation can be achieved via spectator nucleon N



modified Urca (mU)

neutron decay: $n + N \rightarrow p + e^- + \bar{\nu}_e + N$ electron capture $p + e^- + N \rightarrow n + \nu_e + N$

Direct Urca Threshold

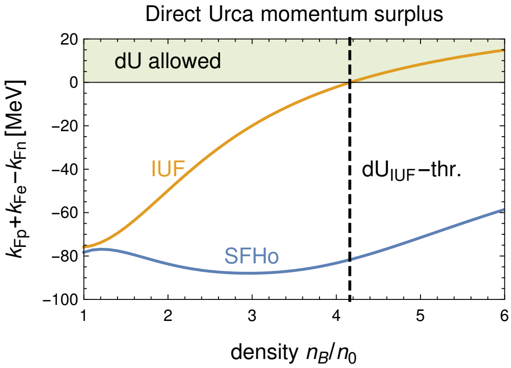
Property of the equation of state

charge neutrality requires $n_e = n_p$ so at $T = 0$: $k_{Fp} = k_{Fe}$

direct Urca threshold:

$$k_{Fn} = k_{Fp} + k_{Fe}$$

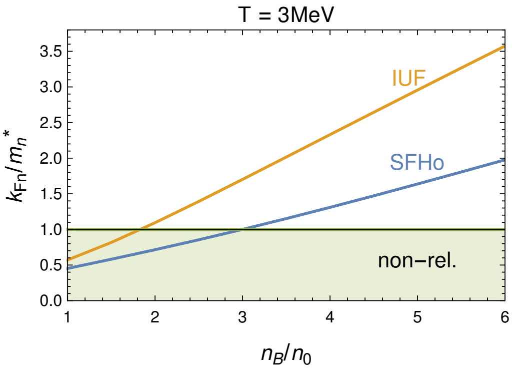
- dU requires higher proton fraction
- Nearly all equation of states (EOS) have monotonically rising proton fraction with n_B
- Compare two different EOS (relativistic mean field models-RMF): IUF and SFHo
- IUF: direct Urca threshold at $n_B \approx 4.1 n_0$



Relativistic vs Non-Relativistic

Non-relativistic expansion

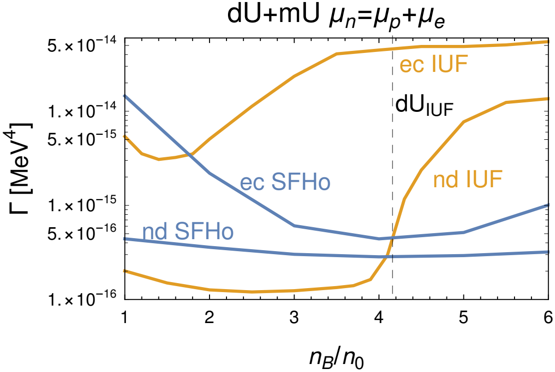
$$\sqrt{k^2 + m_n^{*2}} \approx m_n^* + k^2/(2m_n^*) + \ldots \text{ requires } k_{Fn}/m_n^* \ll 1$$



- In-medium nucleon mass drops quickly with density in RMFs (however:PRC 100, 065807 (2019))
- Neutrons become fully relativistic between $2 - 3\ n_0$
- Protons become fully relativistic between $3 - 6\ n_0$

Total Urca in Cold Beta-Equilibrium

$T = 3\,\text{MeV}$ - neutrino transparent



- IUF-results show clear dU threshold
- Electron-capture and neutron-decay differ by $1-2$ **orders of magnitude**
- Cold beta-equlibrium clearly violated

Reason:

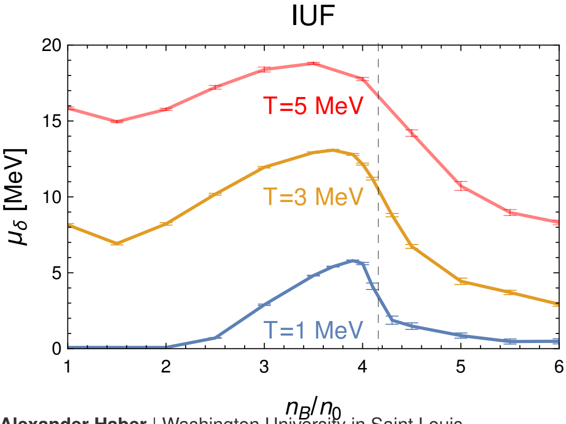
electron-capture and neutron-decay are **not** inverse processes: neutrino switches side

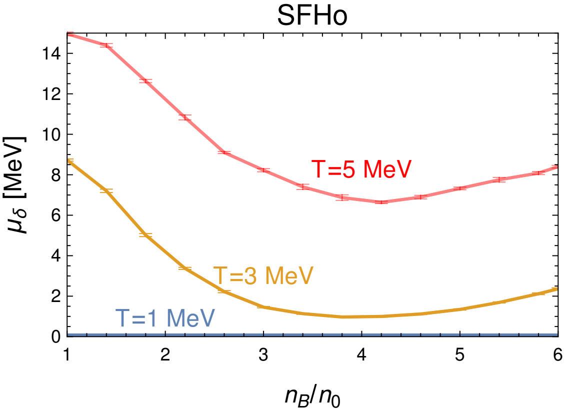
Warm Beta Equilibrium

Alford, Harris PRC 98 (2018), **Alford, A.H., Harris, Zhang, arXiv:2108.03324**

Warm Beta Equilibrium

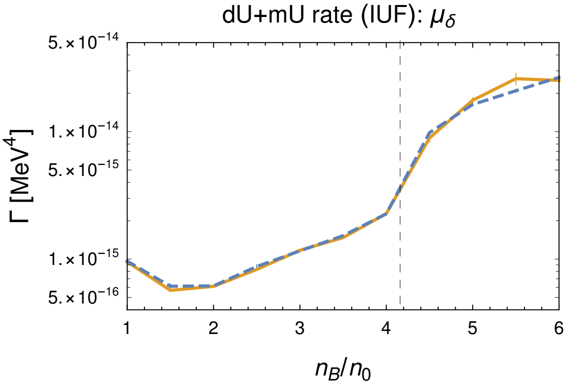
$\mu_n = \mu_p + \mu_e + \mu_\delta$ where μ_δ is choosen s.t. $\Gamma_{nd} = \Gamma_{ec}$

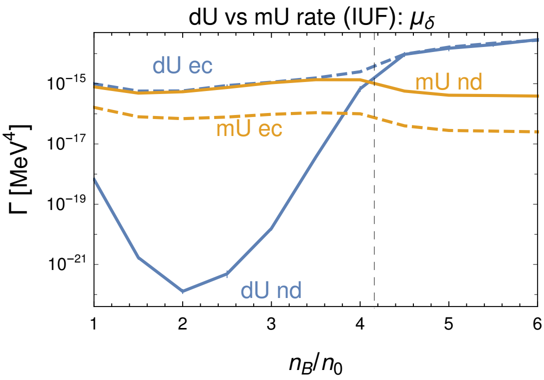




Corrected Rates

for IUF EOS at $T = 3\,\text{MeV}$





direct Urca electron capture dominates over modified Urca

Summary & Outlook

Summary

- Need to improve microphysics in simulations
- Bulk viscosity might play an important role in BNS merger
- Traditional beta-equilibrium is violated for temperatures in the few MeV range
- μ_δ reaches up to 15 MeV
- Direct Urca can dominate over modified Urca even below threshold

Outlook

- Incorporate viscosity in merger simulations
- Effect of μ_δ on cooling?
- Effect of μ_δ on bulk viscosity?
- ...

Thank you for your attention!