Neutron star mergers as materials science

Prof. Mark Alford
Washington University in St. Louis

Alford, Bovard, Hanauske, Rezzolla, Schwenzer, arXiv:1707.09475

Alford, Harutyunyan, Sedrakian, arXiv:1907.04192, 2006.07975

Alford and Harris, arXiv:1803.00662, arXiv:1907.03795

Alford and Haber, arXiv:2009.05181

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

I Neutron star mergers as a probe of dense matter:
Different phases with similar equation of state may be distinguishable by their Transport Properties

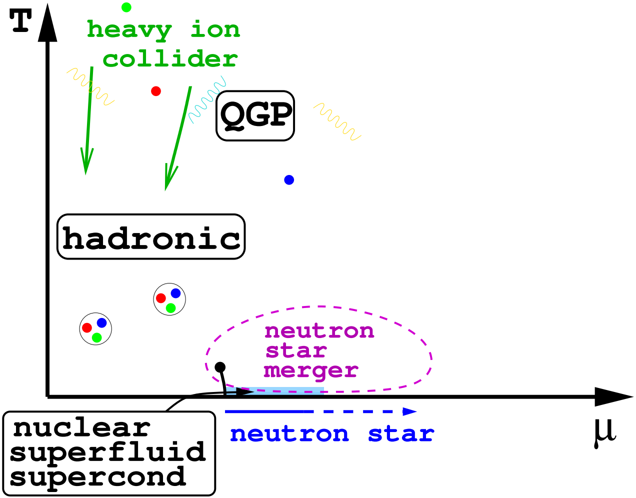
II Thermal conductivity in mergers
Damping time for temperature inhomogeneities: is it fast enough to affect mergers?

III Bulk viscosity in mergers
Damping time for density oscillations: is it fast enough to affect mergers?

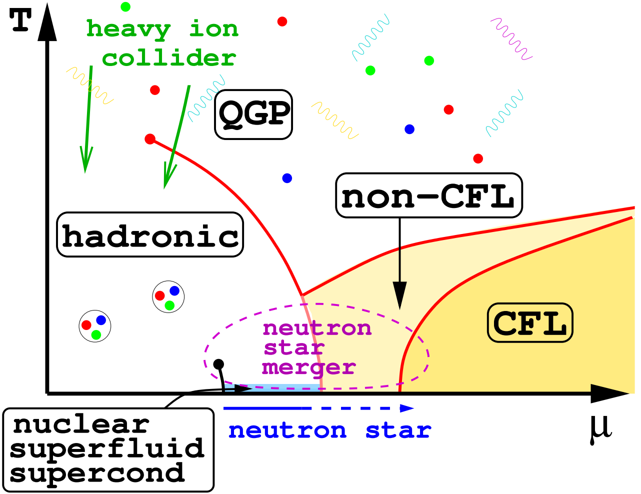
IV Summary and Prospects

I. Mergers as a probe of dense matter

Observed QCD Phase diagram



Conjectured QCD Phase diagram



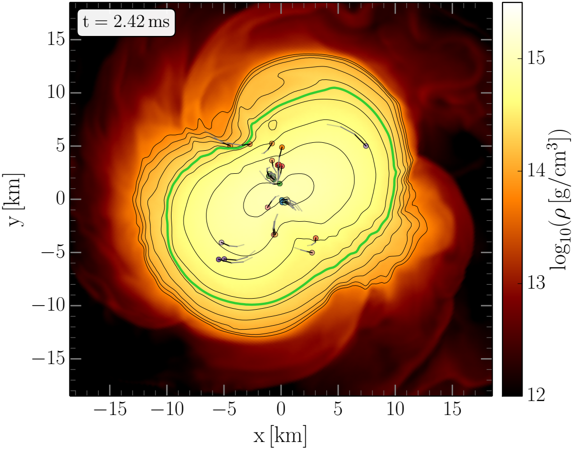
heavy ion collisions: deconfinement crossover and chiral critical point

neutron stars: quark matter core?

neutron star mergers: dynamics of warm and dense matter

Neutron star mergers

Mergers probe the properties of nuclear/quark matter
at high density (up to $\sim 4n_{\text{sat}}$) and temperature (up to $\sim 80\,\text{MeV}$)



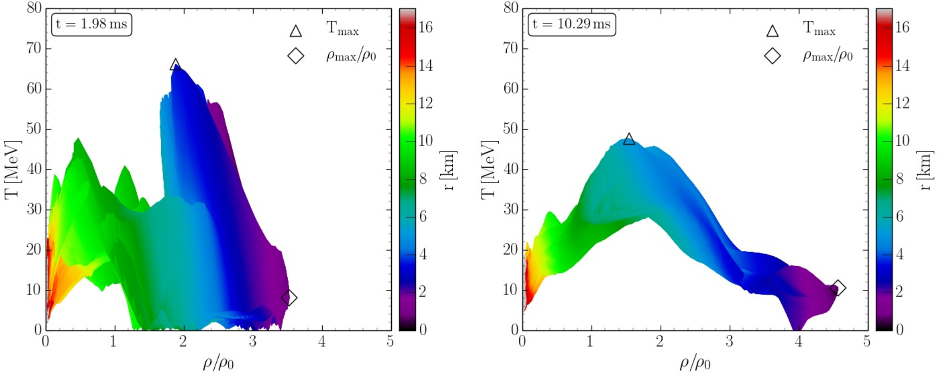
Rezzolla group, Frankfurt

Video

Which
material properties
are relevant?

- Equation of state $\rho(p)$
- And...?

Nuclear material in a neutron star merger



M. Hanauske, Rezzolla group, Frankfurt

Significant spatial/temporal variation in:

- temperature
- fluid flow velocity
- density

so we need to allow for

- thermal conductivity
- shear viscosity
- bulk viscosity

Role of transport/dissipation in mergers

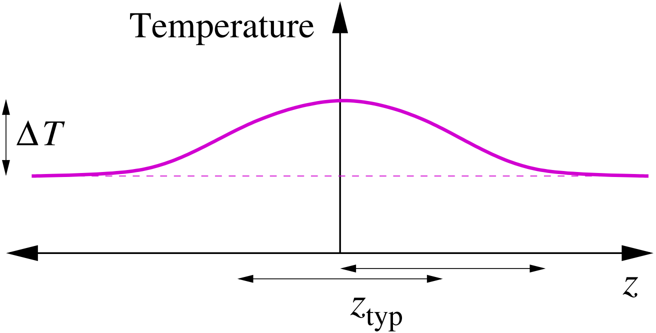
The important dissipation mechanisms are the ones whose equilibration time is $\lesssim 20\,\text{ms}$

Executive Summary:

Thermal conductivity:	Might play a role, if • neutrinos are trapped • there are short-distance temperature gradients
Shear viscosity:	Similar conclusion.
Bulk viscosity:	Could damp density oscillations on the same timescale as the merger. Include bulk viscosity in merger simulations.

II. Thermal equilibration under merger conditions

Thermal equilibration time



Volume
$V \sim z_{\rm typ}^3$

Surface area
$A \sim 6 z_{\rm typ}^2$

Time to equilibrate: $\tau_\kappa = \dfrac{\text{extra heat in region}}{\text{rate of heat outflow}} = \dfrac{E_{\rm therm}}{W_{\rm therm}}$

Thermal diffusion is important if $\tau_\kappa \lesssim 20\,\mathrm{ms}$

Estimating thermal equilibration time

Extra heat in region: $E_{\text{therm}} = c_V V \Delta T \approx c_V z_{\text{typ}}^3 \Delta T$

Rate of heat outflow: $W_{\text{therm}} = \kappa \frac{dT}{dz} A \approx \kappa \frac{\Delta T}{z_{\text{typ}}} 6 z_{\text{typ}}^2$

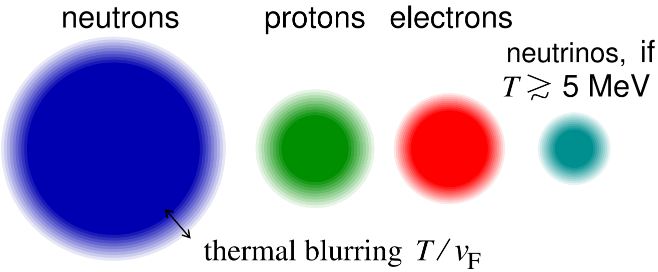
$$\boxed{\text{Time to equilibrate:} \quad \tau_\kappa = \frac{E_{\text{therm}}}{W_{\text{therm}}} \approx \frac{c_V z_{\text{typ}}^2}{6\kappa}}$$

We need to know

- specific heat capacity c_V
- thermal conductivity κ

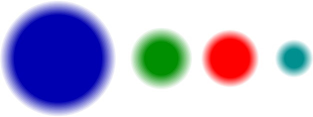
Nuclear material constituents

<u>Fermi surfaces</u>:



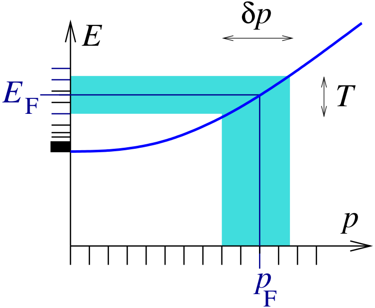
neutrons:	$\sim$ 90% of baryons	$p_{Fn} \sim 350\,\text{MeV}$
protons:	$\sim$ 10% of baryons	$p_{Fp} \sim 150\,\text{MeV}$
electrons:	same density as protons	$p_{Fe} = p_{Fp}$
neutrinos:	only present if mfp $\ll 10\,\text{km}$	i.e. when $T \gtrsim 5\,\text{MeV}$

Specific heat capacity



Dominated by neutrons

$$\begin{aligned} c_V &\sim \text{number of states available} \\ &\ \text{to carry energy} \lesssim T \\ &\sim \text{vol of mom space with states available to carry energy} \lesssim T \\ &\sim {p_{Fn}}^2 \delta p \end{aligned}$$



$$\delta p = \frac{T}{v_{Fn}} = T \times \frac{m_n^*}{p_{Fn}}$$

$$c_V \sim {p_{Fn}}^2 \delta p \sim {p_{Fn}}^2 \frac{m_n^*}{p_{Fn}} T \sim m_n^* p_{Fn} T$$

(Note: neutron density $n_n \sim {p_{Fn}}^3$)

$$\boxed{c_V \approx 1.0\, m_n^*\, {n_n}^{1/3}\, T}$$

Thermal conductivity

Thermal conductivity $\kappa \propto n\, v\, \lambda$

Dominated by the species with the right combination of
- high density
- weak interactions $\Rightarrow$ long mean free path (mfp) λ

neutrons: high density, but strongly interacting (short mfp) ✗

protons: low density, strongly interacting (short mfp) ✗

electrons: low density, only EM interactions (long mfp) ✓

neutrinos:
- $T \lesssim 5\,\text{MeV}$: $\lambda >$ size of merged stars, so they all escape, density $= 0$ ✗
- $T \gtrsim 5\,\text{MeV}$: $\lambda <$ size of merged stars, but still very long mfp! ✓✓

Neutrino-dominated thermal equilibration

Neutrino-trapped regime, $T \gtrsim 5\,\mathrm{MeV}$

equilibration time $\tau_\kappa \approx \dfrac{c_V z_{\rm typ}^2}{6\kappa}$ $\kappa^{(\nu)} \approx 0.33 \dfrac{n_\nu^{2/3}}{G_F^2 m_n^{*2} n_e^{1/3} T}$

$$\tau_\kappa^{(\nu)} \approx \boxed{700\,\mathrm{ms}} \left(\frac{z_{\rm typ}}{1\,\mathrm{km}}\right)^2 \left(\frac{T}{10\,\mathrm{MeV}}\right)^2 \left(\frac{\mu_e}{2\mu_\nu}\right)^2 \left(\frac{0.1}{x_p}\right)^{1/3} \left(\frac{m_n^*}{0.8\,m_n}\right)^3$$

Neutrino thermal transport may be important if there are thermal gradients on $\lesssim 0.1\,\mathrm{km}$ scale

That can lead to $\tau_\kappa \lesssim 20\,\mathrm{ms}$

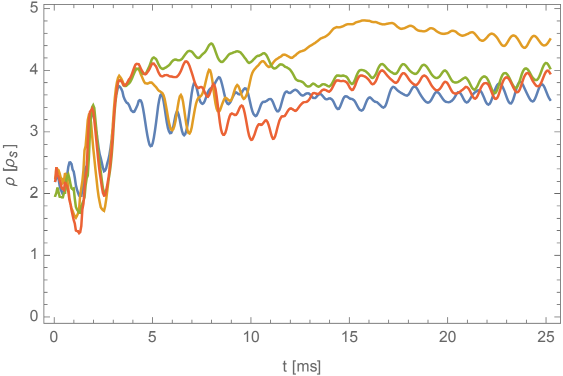
III. Damping of density oscillations in mergers

Equivalently: sound attenuation via bulk viscosity

Density oscillations in mergers

Density vs time for tracers in merger

(Bulk viscosity neglected)



Tracers (co-moving fluid elements) show dramatic density oscillations, especially in the first 5 ms.

Amplitude: up to 50%

Period: 1–2 ms

How long does it take for bulk viscosity to dissipate a sizeable fraction of the energy of a density oscillation?

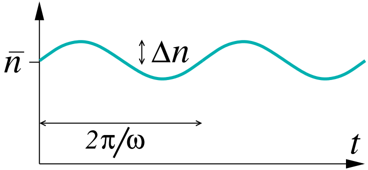
What is the damping time τ_ζ?

Can we get $\tau_\zeta \lesssim 20\,\text{ms}$?

Density oscillation damping time τ_ζ

Density oscillation of amplitude Δn at angular freq ω:

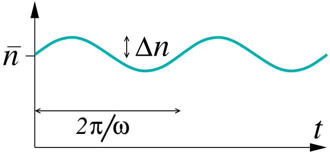
$$n(t) = \bar{n} + \Delta n \cos(\omega t)$$



Damping Time: $\tau_\zeta = \dfrac{\text{energy stored in oscillation}}{\text{rate of energy loss}} = \dfrac{E_{\rm comp}}{W_{\rm comp}}$

Bulk viscous damping is important if $\tau_\zeta \lesssim 20\,\text{ms}$

Calculating damping time



Energy of density oscillation:
(K = nuclear incompressibility)

$$E_{\mathrm{comp}} = \frac{K}{18}\bar{n}\left(\frac{\Delta n}{\bar{n}}\right)^2$$

Compression dissipation rate:
(ζ = bulk viscosity)

$$W_{\mathrm{comp}} = \zeta\frac{\omega^2}{2}\left(\frac{\Delta n}{\bar{n}}\right)^2$$

$$\boxed{\text{Damping Time:}\quad \tau_\zeta = \frac{E_{\mathrm{comp}}}{W_{\mathrm{comp}}} = \frac{K\bar{n}}{9\omega^2\,\zeta}}$$

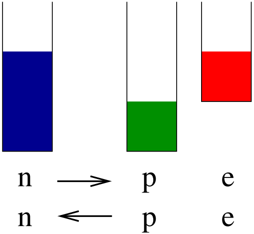
We need:

- nuclear incompressibility K (from EoS)
- bulk viscosity ζ (from beta-equilibration of proton fraction)

Bulk viscosity and beta equilibration

When you compress nuclear matter, the proton fraction wants to change.

Only weak interactions can change proton fraction, and they are rather slow. . .



	neutrino-transparent $(T \lesssim 5\,\mathrm{MeV})^*$	neutrino-trapped $(T \gtrsim 5\,\mathrm{MeV})^*$
neutron decay	$n \rightarrow p + e^- + \bar{\nu}_e$	$\nu_e + n \rightarrow p + e^-$
electron capture	$p + e^- \rightarrow n + \nu_e$	$p + e^- \rightarrow n + \nu_e$
	forward $\neq$ backward	$A + B \leftrightarrow C + D$

---

* Neutrino transparency is a finite volume effect, which occurs when the neutrino mean free path is greater than the size of the system. Our system is a neutron star, $R \sim 10\,\mathrm{km}$

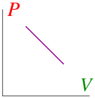
Bulk viscosity: phase lag in system response

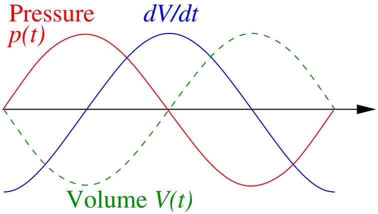
Some property of the material (proton fraction) takes time to equilibrate.

Baryon density n and hence fluid element volume V gets out of phase with applied pressure p:

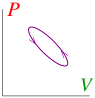
$$\text{Dissipation} = -\int p\, dV = -\int p\, \frac{dV}{dt} dt$$

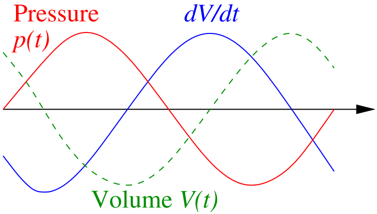
No phase lag.
Dissipation $= 0$



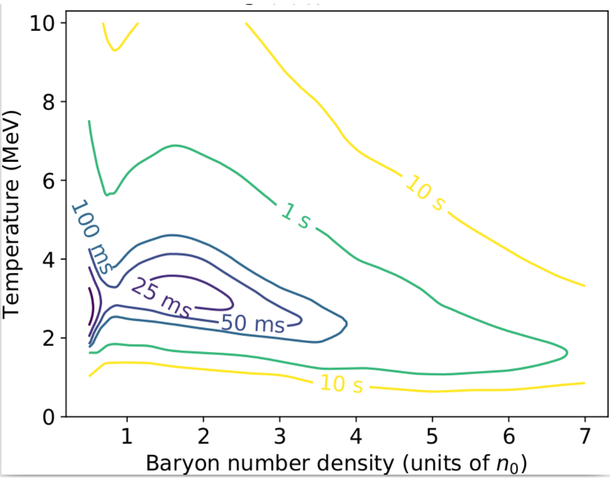


Some phase lag.
Dissipation > 0





Damping time results (ν-transparent)



EoS: IUFSU
$M_{\max}$: $1.96\,M_\odot$
$R_{1.4\,M_\odot}$: $12.8\,\mathrm{km}$

Oscillation freq:
$f = 1\,\mathrm{kHz}$

Fast damping at $T \sim 3\,\mathrm{MeV}$, $n \lesssim 2n_{\mathrm{sat}}$

IV. Summary and Prospects

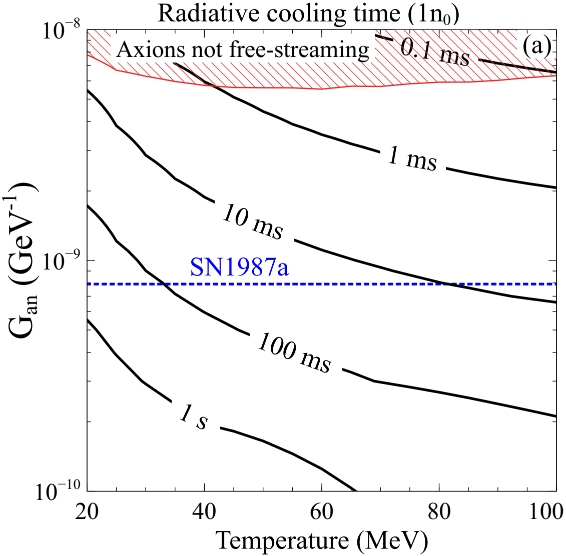
- Some forms of dissipation are probably physically important for neutron star mergers.
- Thermal conductivity and shear viscosity may become significant in the neutrino-trapped regime ($T \gtrsim 5\,\mathrm{MeV}$) if there are fine-scale gradients ($z \lesssim 100\,\mathrm{m}$).
- Bulk viscosity quickly damps density oscillations in neutrino-transparent nuclear matter (at low density and $T \sim 3\,\mathrm{MeV}$).

Prospects:

- Include bulk viscosity in merger simulations.
- Calculate bulk viscous damping for other forms of matter: hyperonic, muonic, pion condensed, nuclear pasta, quark matter, etc
- Beyond Standard Model physics...?

Cooling by axion emission

Time for a hot region to cool to half its original temperature



Harris, Fortin, Sinha, Alford
`arXiv:2003.09768`