Transport and equation of state for neutron stars and mergers

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Outline

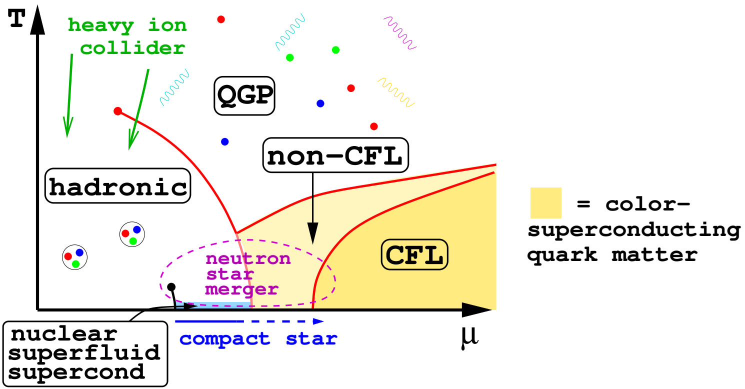
I Phase diagram of dense matter
Using neutron stars to probe the states of dense matter
Quark matter phases

II The equation of state
Do exotic phases show up in the Equation of State?

III Transport/dissipation in mergers
Transport and dissipation properties of dense matter
Do they affect mergers?

IV Future directions

I. The phases of dense matter (conjectured)



heavy ion collisions: deconfinement crossover and chiral critical point

neutron stars: color superconducting quark matter core?

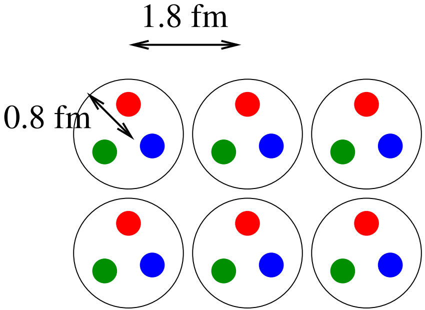
neutron star mergers: dynamics of warm matter, heavy remnant

Quark matter at high density

Nuclear density

$$n_B \approx \frac{1}{(1.8\,\mathrm{fm})^3} = 0.17\,\mathrm{fm}^{-3}$$

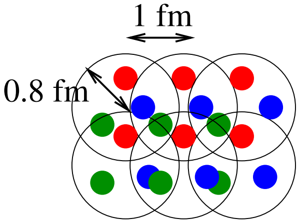
Nucleons are distinguishable:
Nuclear Matter



6 × **Nuclear density**

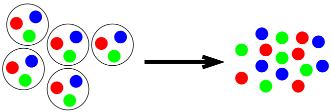
$$n_B \approx \frac{1}{(1.0\,\mathrm{fm})^3} = 1.0\,\mathrm{fm}^{-3}$$

Not clear which nucleon
a given quark "belongs" to:
Quark Matter



Phases of (cool) quark matter

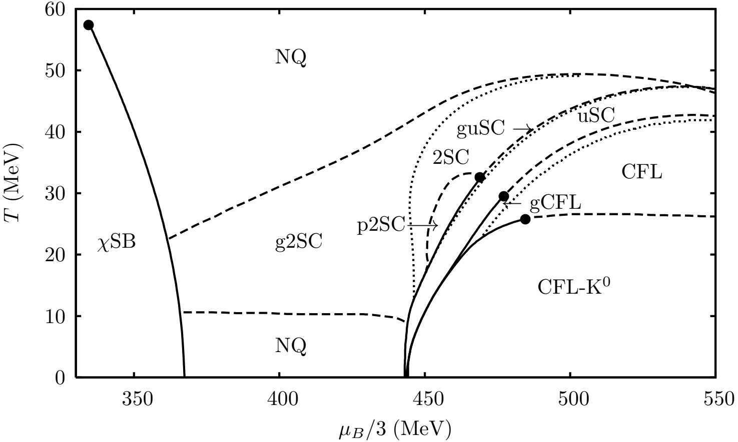
- Quark matter is "Unconfined"
  Spatially localized baryonic bags
  are not the relevant degrees of freedom.
  But confinement is not an observable.
  E.g., excited states are still created by
  gauge-invariant *baryonic* operators



- Color superconductivity
  In the ultra-high density limit, we expect the ground state to be a condensate of Cooper pairs of quarks. Many pairing patterns with different transport properties
  - Color-Flavor-Locked (CFL): superfluid; all colors and flavors pair
  - 2SC: only u,d,u,d undergo pairing
  - LOFF: spatially modulated condensate, forming a crystal
  - Color-Spin-Locked (CSL): pairing of all 3 colors of a single flavor
  - ...

Phases of quark matter

Prediction of an NJL model, uniform phases only



Warringa, `hep-ph/0606063`

Signatures of quark matter in compact stars

Observable $\leftarrow$ Microphysical properties (and neutron star structure) $\leftarrow$ Phases of dense matter

	Property	Nuclear phase	Quark phase
mass distribution (mass, radius, Λ)	eqn of state $\varepsilon(p)$	known up to $\sim n_{\rm sat}$	unknown; many models

Signatures of quark matter in compact stars

Observable ← Microphysical properties (and neutron star structure) ← Phases of dense matter

	Property	Nuclear phase	Quark phase
mass distribution (mass, radius, Λ)	eqn of state $\varepsilon(p)$	known up to $\sim n_{\text{sat}}$	unknown; many models
spindown (spin freq, age)	bulk viscosity shear viscosity	Depends on phase:	Depends on phase:
cooling (temp, age)	heat capacity neutrino emissivity thermal cond.	$n\,p\,e$ $n\,p\,e,\mu$ $n\,p\,e,\Lambda,\Sigma^-$	unpaired CFL CFL-K^0
glitches (superfluid, crystal)	shear modulus vortex pinning energy	n superfluid p supercond π condensate K condensate	2SC CSL LOFF 1SC
merger dynamics (grav waves)	eqn of state bulk viscosity		...

II. Quark Matter and the Equation of State

✗ "Masquerade effect"

EoS may be very similar in different phases
(e.g. in metals: superconducting vs. "normal").

Uncertainty about quark matter EoS allows tuning its parameters to match hadronic EoS.

✓ Sharp 1st-order phase transition

This *could* indicate nuclear to quark matter transition

How would a strong first-order transition in the EoS manifest itself in observations?

✓ Conformal speed of sound c_s

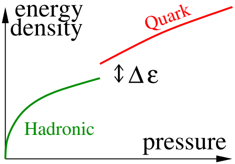
Quark matter: massless *weakly-interacting* fermions have $c_s^2 \approx 1/3$
Hadronic matter: relativistic mean field models can give $c_s^2 \approx 1$

Manifestation of 1^{st} order PT: twin stars

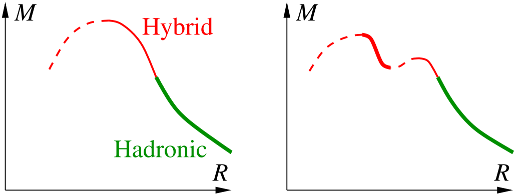
equation of state

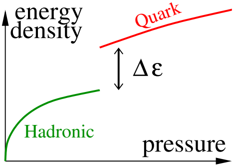
$c_s^2 \lesssim 1/2$
no twin

$c_s^2 \gtrsim 1/2$
Twin Branch

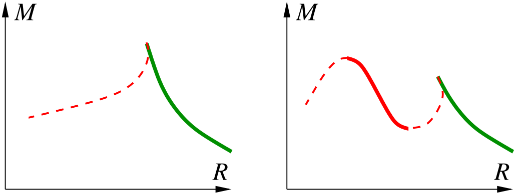


weakly first-order transition



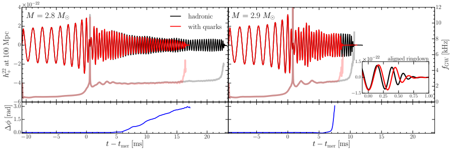


strongly first-order transition

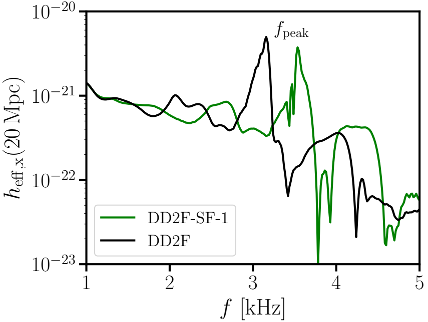


Alford, Han, Prakash, `arXiv:1302.4732`; Montana, Tolós, Hanauske, Rezzolla, `arXiv:1811.10929`

1^{st} order PT: grav waves from mergers



Most et. al., `arXiv:1807.03684`



Bauswein et. al., `arXiv:1809.01116`

See other talks and panels in this workshop!

III. Transport/dissipation in Mergers

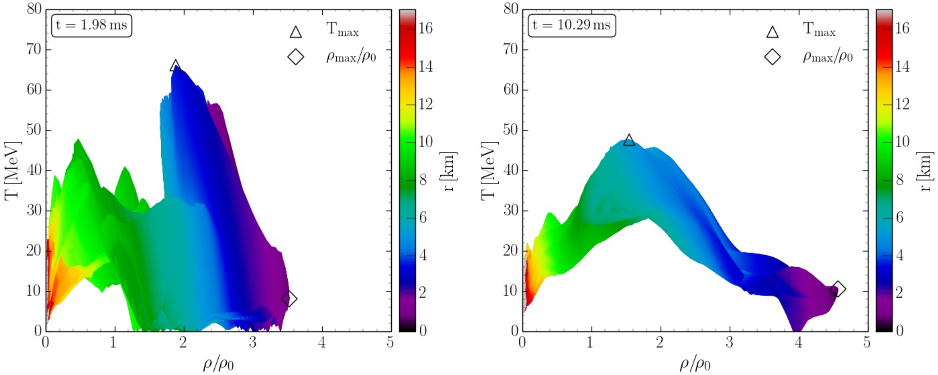
Transport properties are a better discriminator of different phases than the Equation of State

Neutron star mergers provide data on the behavior of dense matter, including the dynamics on millisecond timescales

Estimate transport/dissipation in:

- ordinary *npe* nuclear matter
- other nuclear phases (trapped neutrinos, muons, thermal pions...)
- other hadronic phases (e.g. hyperonic matter)
- quark matter (unpaired, CFL, 2SC, LOFF, ...)

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 $\lesssim 20\,\text{ms}$

Thermal equilibration: might be fast enough to 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.

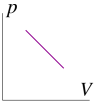
(Alford, Bovard, Hanauske, Rezzolla, Schwenzer, arXiv:1707.09475)

Bulk viscosity: phase lag in system response

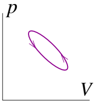
Some property of the material (proton fraction) takes time to equilibrate.
Baryon density n and hence fluid element volume V gets out of phase with applied pressure p:

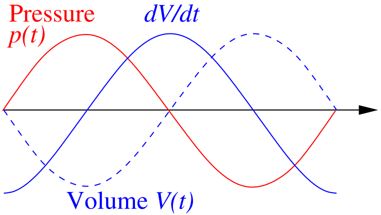
$$\text{Dissipation} = -\int p\, dV = -\int p\, \frac{dV}{dt} dt$$

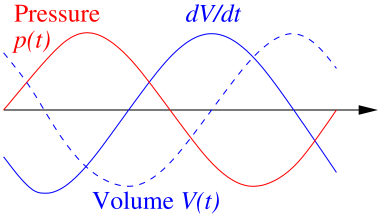
No phase lag.
Dissipation $= 0$



Some phase lag.
Dissipation > 0

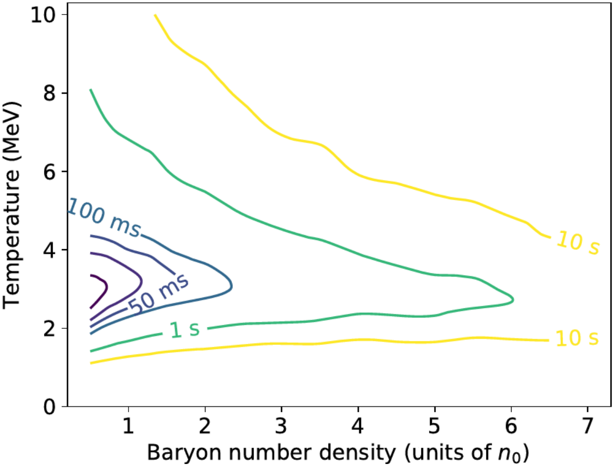






Bulk viscous damping time results
(ν-transparent)

Damping time for density oscillations in nuclear matter



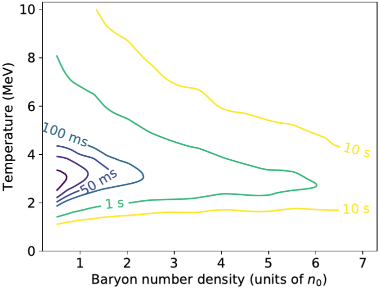
EoS: HS(DD2)
$M_{\rm max}$: 2.42 $M_\odot$
$R_{1.4\,M_\odot}$: 13.3 km

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

Alford and Harris,
`arXiv:1907.03795`

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

Damping time behavior



Damping Time $\quad \tau_\zeta = \dfrac{K\bar{n}}{9\omega^2\,\zeta}$

Characteristics of the damping time plot:

- Damping gets slower at higher density.
  Baryon density $\bar{n}$ and incompressibility K are both increasing.
  Oscillations carry more energy $\Rightarrow$ slower to damp
- Non-monotonic T-dependence: damping is fastest at $T \sim 3\,\text{MeV}$.
  Damping is slow at very low or very high temperature.
  Bulk viscosity has resonant maximum at $T \sim 3\,\text{MeV}$

IV. Looking to the Future

How can we detect exotic phases in neutron star cores?

- **Data** on observable properties of neutron stars
  Isolated stars: mass, radius, spindown (spin and age),
  cooling (temperature, age, mass)
  grav waves from elliptical deformation
  Mergers: grav waves, E-M counterparts
- **Astro theory:** better modelling of neutron stars and mergers
  Isolated stars: damping and saturation mechanisms for r-modes,
  mechanism of glitches; effects of magnetic fields
  Mergers: include dissipation; finer resolution; magnetic fields
- **Particle/nuclear theory:** understand high-density matter
  Nuclear matter: systematic analysis beyond chiral effective theory?
  Quark matter beyond pert theory: Functional RG, Schwinger-Dyson, . . .
  Ultimately: solve the sign problem and do lattice QCD at high density.