Neutron star mergers as materials science experiments

Prof. Mark Alford
Washington University in St. Louis



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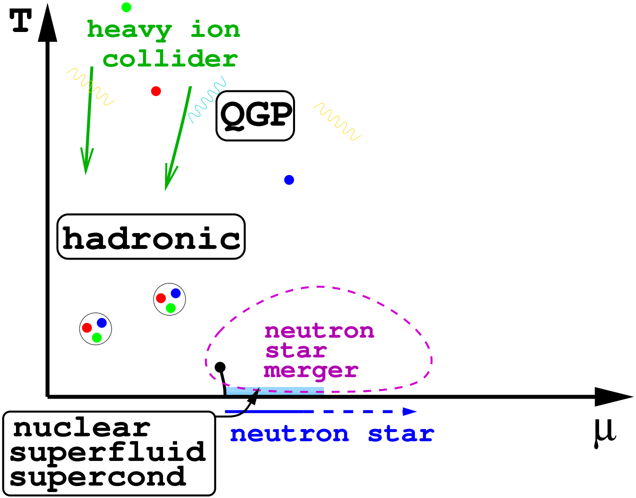
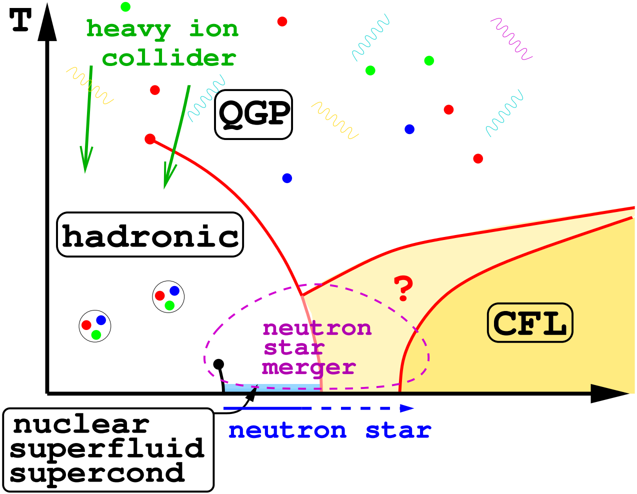
QCD Phase diagram



Conjectured QCD Phase diagram



heavy ion collisions: deconfinement crossover and chiral critical point

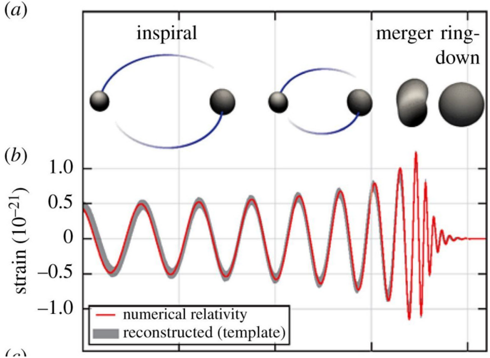
neutron stars: quark matter core?

neutron star mergers: dynamics of warm and dense matter

Observing mergers: prediction

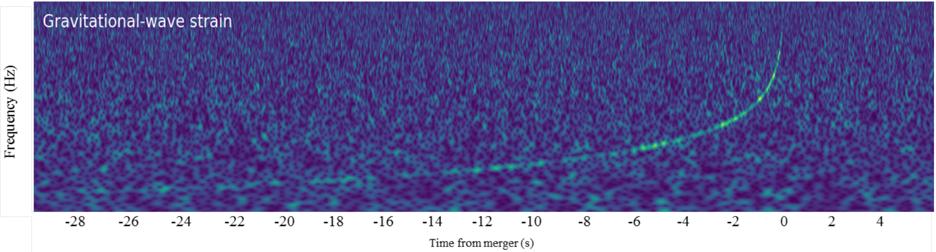
To use mergers as a probe of dense matter we need to perform simulations that incorporate the relevant microscopic physics.

E.g. to predict the gravitational wave signal



Observing mergers: data

LIGO Data from the event GW170817



Omega Scan of LIGO's First Neutron Star Merger Detection

With LIGO we only see the inspiral, not the merger itself.

We hope that future gravitational wave detectors such as Einstein Telescope or Cosmic Explorer will "hear" the merger.

For now: work on making *accurate* predictions

Outline

- Neutron star mergers are like experiments that probe the properties of dense matter. People mostly talk about the *Equation of State*.
- Also potentially important: **Out-of-equilibrium phenomena**
  - Flavor equilibration — bulk viscosity
  - Thermal equilibration — thermal conductivity
  - Shear flow equilibration — shear viscosity

  etc

  Better than the equation of state for probing phase structure!

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  • Flavor equilibration — bulk viscosity
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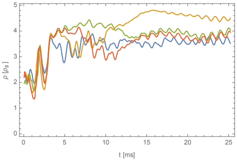
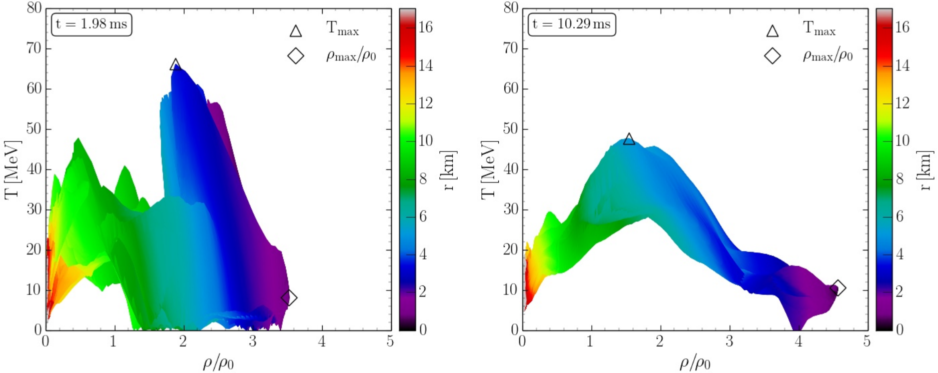
  • Shear flow equilibration — shear viscosity
  etc
  Better than the equation of state for probing phase structure!
- Flavor equilibration: is it important in mergers?
  • relaxation time for the proton fraction
  • *Critical equilibration*: when relaxation should be included in the dynamics
  • physical manifestations: bulk viscosity and sound attenuation



Nuclear material in a neutron star merger

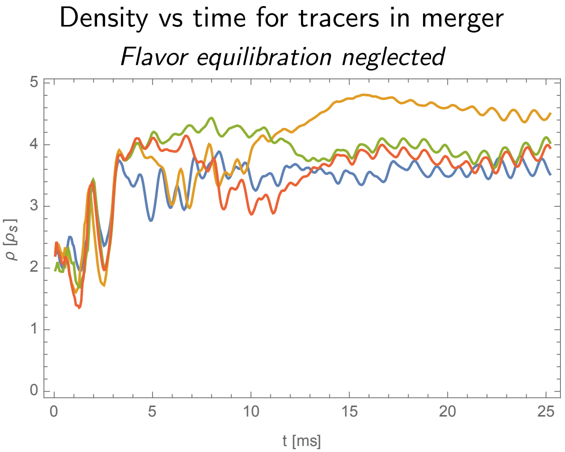


M. Hanauske, Rezzolla group, Frankfurt

Significant spatial/temporal variation in:
- temperature
- fluid flow velocity
- density ⇒ flavor content

so we need to allow for
- thermal conductivity
- shear viscosity
- bulk viscosity

Density oscillations in mergers



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

Amplitude: up to 50%
Period: 1–2 ms
Freq: ~ 1 kHz

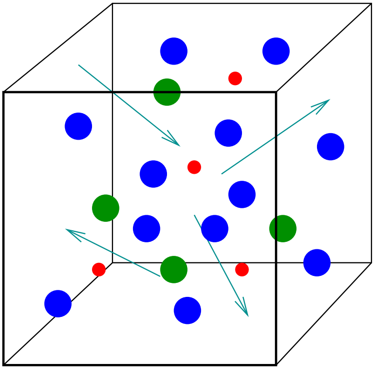
Do density oscillations drive the system out of flavor equilibrium?

Does flavor equilibration affect the oscillations?

The nuclear matter fluid

neutrons: dominant constituent
protons: small fraction
electrons: maintaining local neutrality
neutrinos: *thermally equilibrated?*

Generic fluid element



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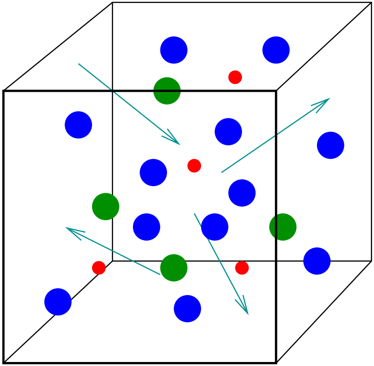

Fluid is described by 3-4 parameters:

$\boxed{n_B} = n_\mathsf{n} + n_\mathsf{p}$	baryon density
$\boxed{T}$	temperature
$\boxed{x_p} = n_\mathsf{p}/n_B$	proton fraction
($\boxed{x_L} = n_L/n_B$ [if neutrinos are trapped]	lepton fraction)

The nuclear matter fluid

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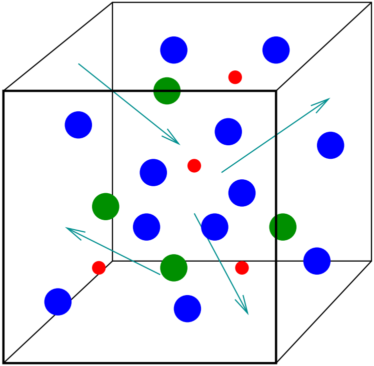

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$\boxed{T}$ temperature

$\boxed{x_p} = n_\mathrm{p}/n_B$ proton fraction

$\left(\boxed{x_L} = n_L/n_B \right.$ lepton fraction $\left. \right)$
[if neutrinos are trapped]

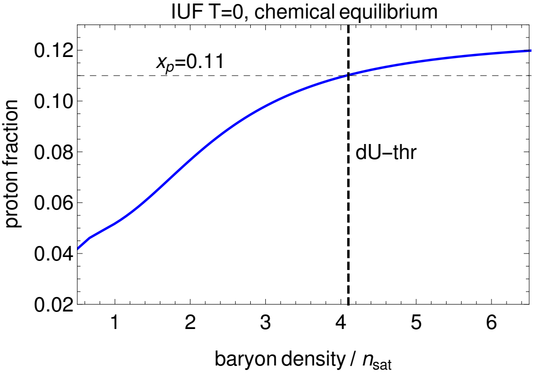
Equation of state relates these to relevant quantities: pressure, energy density etc,

$$p(n_B, T, x_p, x_L)$$
$$\varepsilon(n_B, T, x_p, x_L)$$
$$\dots$$

Density oscillations and beta equilibration

Each fluid element relaxes to the *equilibrium proton fraction* $x_p^{\text{eq}}(n_B, T)$ via weak interactions.

$x_p^{\text{eq}}(n_B, T)$ is determined by properties of the strong interaction (nuclear symmetry energy) and the requirement of electrical neutrality.



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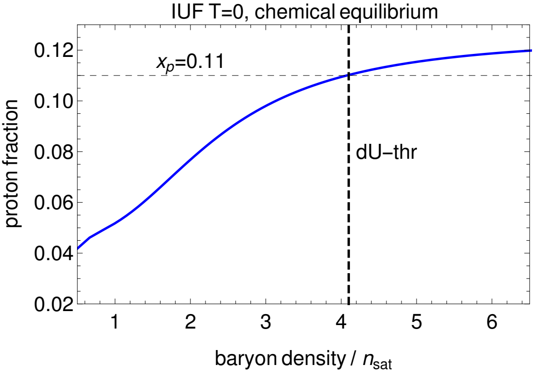

So when you compress nuclear matter, the proton fraction wants to change.

But this doesn't happen instantaneously!

Density oscillations can drive the system away from flavor ("beta", "chemical", "isospin") equilibrium.

Fast and slow equilibration

- Fluid element undergoes density oscillation of angular frequency ω

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

- Proton fraction relaxes to equilibrium at *relaxation rate* $\gamma(n_B,T)$

$$\partial_t x_p = -\gamma\big(x_p - x_p^{\text{eq}}(n_B,T)\big)$$

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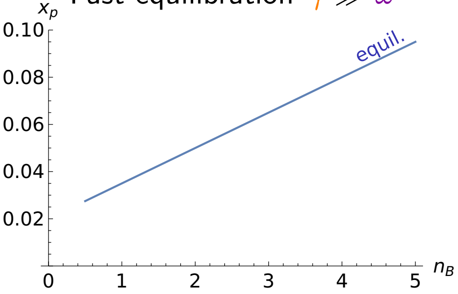

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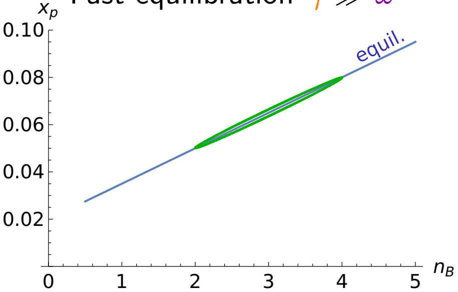

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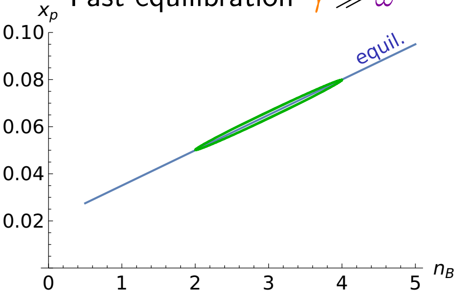

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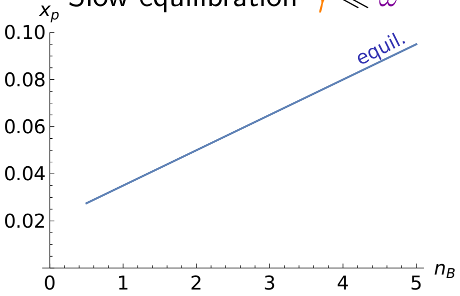

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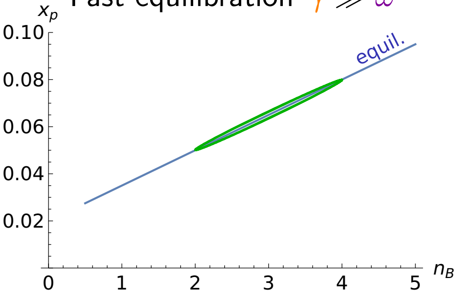

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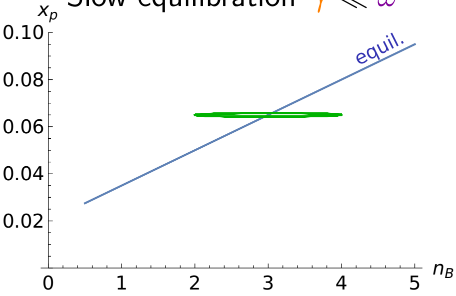

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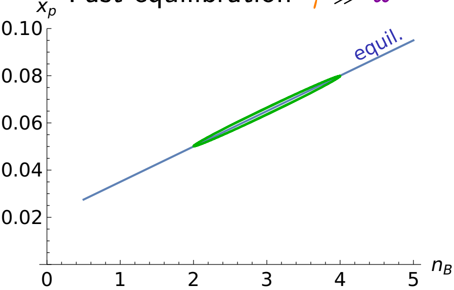

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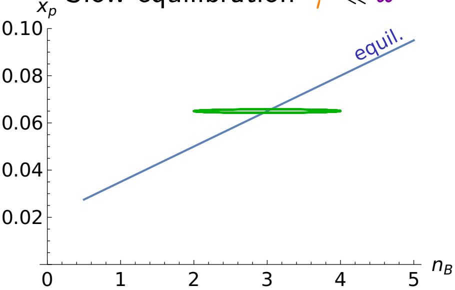

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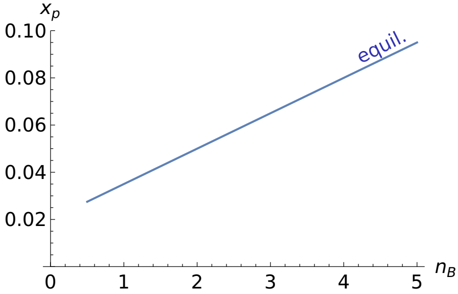
What happens if $\gamma \sim \omega$?

Critical equilibration

Critical equilibration $\gamma = \omega$



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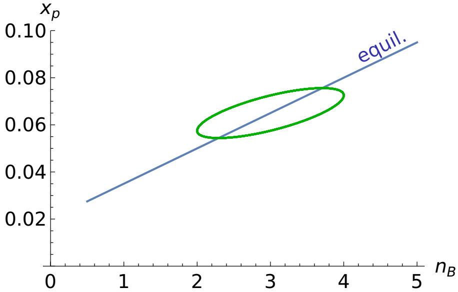

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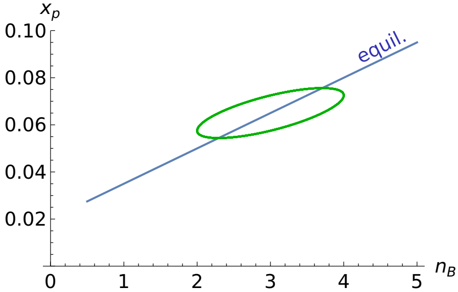

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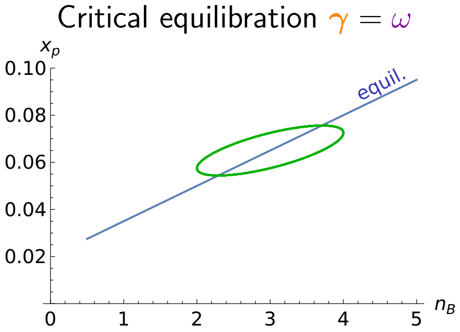

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Other features of critical equilibration:

- Maximal phase lag between density and proton fraction
- Maximal bulk viscosity $\Rightarrow$ Maximal damping of density oscillations

Is there critical equilibration in mergers?

Critical equilibration ($\gamma = \omega$) in mergers?

Frequency for typical density oscillations in a merger: $\boxed{\omega \approx 2\pi \times 1\,\text{kHz}}$

Relaxation rate $\gamma(n_B,T)$ for proton fraction: determined by weak interaction "Urca processes" in which neutrinos play an essential role.

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We can calculate the relaxation rate in two limiting cases:

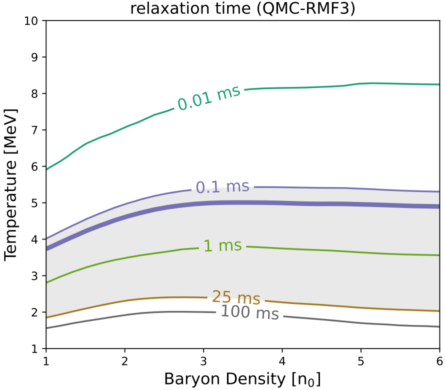
Urca process	neutrino-transparent	neutrino-trapped
neutron decay	$\text{n} \rightarrow \text{p} + \text{e}^- + \bar{\nu}_e$	$\nu_e + \text{n} \rightarrow \text{p} + \text{e}^-$
electron capture	$\text{p} + \text{e}^- \rightarrow \text{n} + \nu_e$	$\text{p} + \text{e}^- \rightarrow \text{n} + \nu_e$

When is $\gamma(n_B, T)$ comparable to the $2\pi \times 1\,\text{kHz}$ timescale?

At what density and temperature?

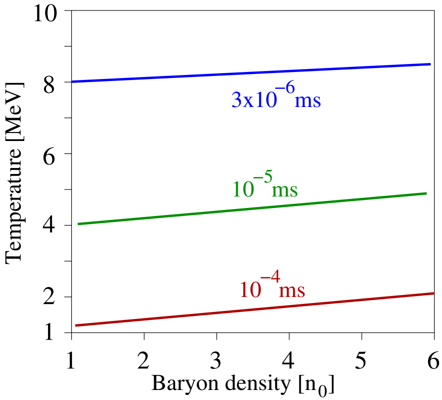
Proton fraction relaxation time $\tau = 1/\gamma$,

neutrino-transparent



Alford, Haber, Zhang `arXiv:2306.06180`

neutrino-trapped



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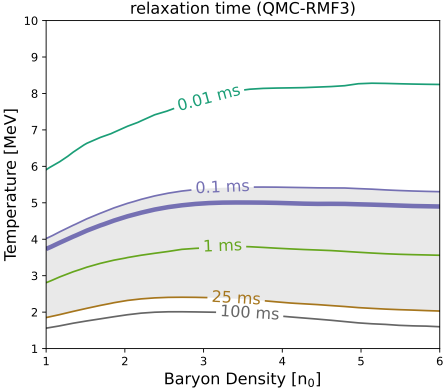

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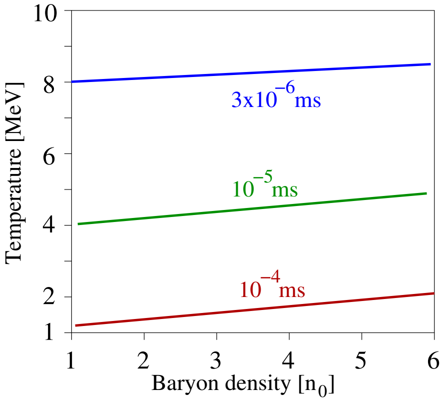

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- Relaxation is faster at higher temperatures, insensitive to density
- neutrino-trapped matter: relaxation is very fast
- neutrino-transparent matter: relaxation on merger timescales!
- Thick contour shows critical equilibration, where $\tau = 1\,\text{ms}/2\pi$

Summary

- Neutrino-trapped matter:
  proton fraction relaxes *quickly*, in microseconds at $T \geqslant 1\,\text{MeV}$.
  Only merger simulations with very short timesteps would need to include this process.
- Neutrino-transparent matter:
  at $T \sim 2$ to $5\,\text{MeV}$, proton fraction relaxes on the same timescale as the merger dynamics. Critical equilibration!
  Proton fraction equilibration is part of the dynamics.

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In reality, neutrinos in mergers have some non-thermal distribution with an energy-dependent mean free path.
Need to develop tools to deal with this.

If critical equilibration (relaxation time $\approx$ oscillation period) occurs in mergers, are there physical consequences?

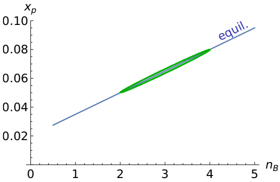
Bulk viscosity: phase lag in system response

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

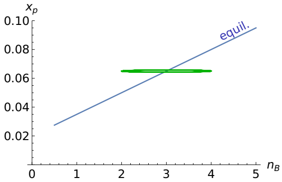
Baryon density n and hence fluid element volume V go out of phase with applied pressure P

$$\text{Dissipation} = -\int P\,dV$$

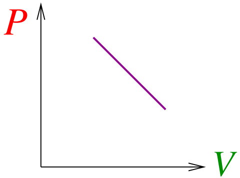
Fast equilibration



Slow equilibration



No dissipation



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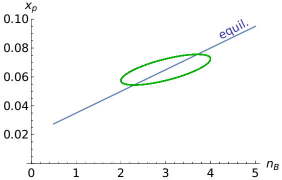
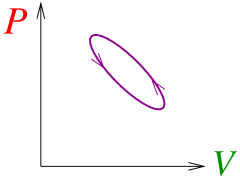
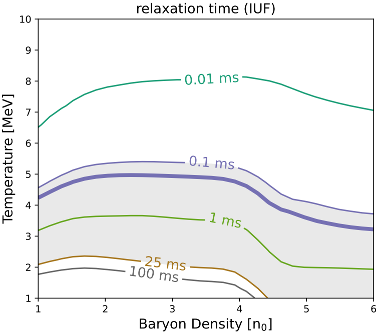


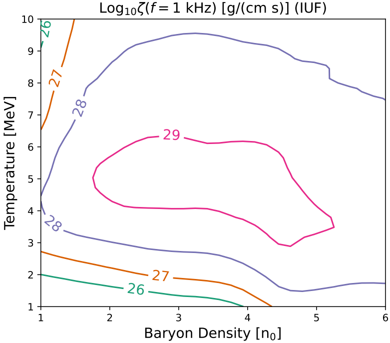
Max dissipation



Resonant peak in bulk viscosity
(neutrino-transparent)

Critical equilibration ($\gamma = \omega$) $\Rightarrow$ Maximum bulk viscosity





- *Non-monotonic T-dependence:* bulk viscosity reaches a maximum at $T \sim 5\,\mathrm{MeV}$
- Not very sensitive to density

Bulk viscosity: a resonant phenomenon

Bulk viscosity is **maximum** at critical equilibration, when

$$\underset{\gamma}{\text{(flavor relaxation rate)}} = \underset{\omega}{\text{(freq of density oscillation)}}$$

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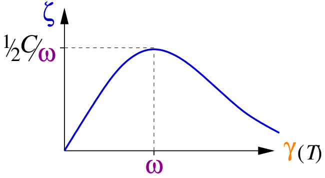
$\gamma \qquad\qquad \omega$

$$\zeta = C \frac{\gamma}{\gamma^2 + \omega^2}$$



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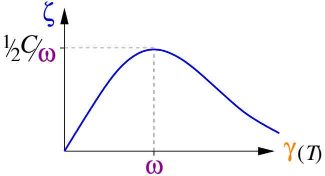

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  System is always in equilibrium. No pressure-density phase lag.

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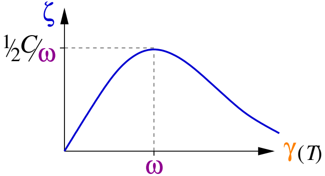

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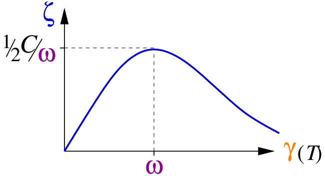

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- **Slow equilibration:** $\gamma \to 0 \Rightarrow \zeta \to 0$.
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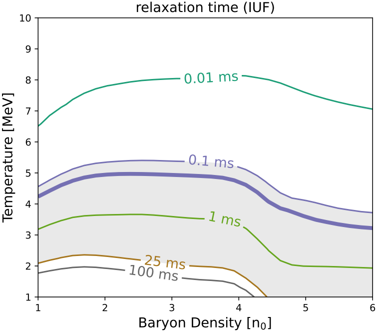
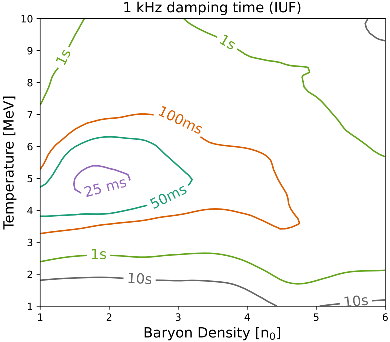
  No pressure-density phase lag.
- **Critical equilibration:** $\omega = \gamma \Rightarrow$ maximum phase lag between pressure and density $\Rightarrow$ maximum dissipation

Damping time for oscillations
(neutrino-transparent)

Critical equilibration ($\gamma = \omega$) $\Rightarrow$ Maximum bulk viscosity $\Rightarrow$ Fastest damping of density oscillations



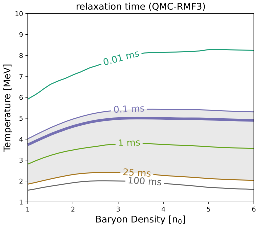


Summary

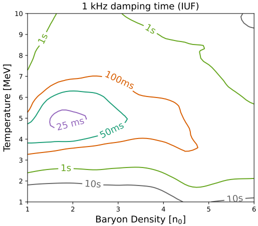
- Neutron star mergers probe the dynamical response of high-density matter on the millisecond timescale.
- In neutrino-transparent nuclear matter at $T \sim 2$ to $5\,\mathrm{MeV}$: *critical equilibration*.

  Proton fraction relaxes in milliseconds.

  We should include flavor relaxation via Urca processes in merger simulations.



- Resultant bulk viscosity damps density oscillations in 20 to 100 ms

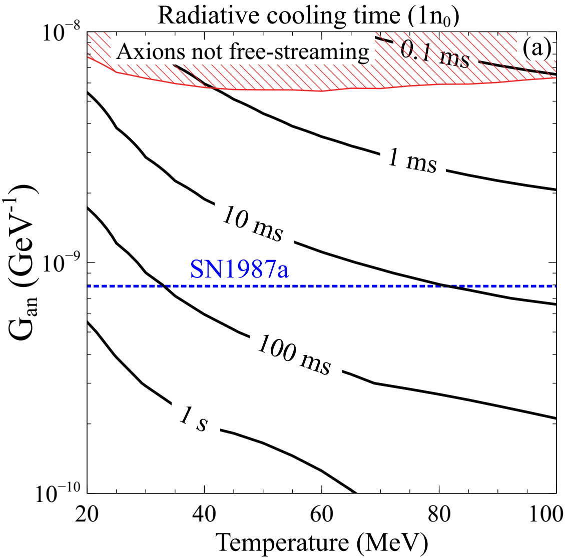


Next steps

- Beyond neutrino transparent/trapped:
  Flavor equilibration rates for arbitrary neutrino distributions
- Beyond npe:
  Flavor equilibration rates for other forms of matter.
  - Hyperonic: fast relaxation
  - Pion condensed, nuclear pasta, quark matter, etc
- Beyond bulk viscous damping:
  Other manifestations of flavor equilibration:
  - Heating
  - neutrino emission
- Beyond flavor equilibration:
  Thermal conductivity and shear viscosity may become significant in the neutrino-trapped regime if there are gradients of scale $\lesssim 100\,\mathrm{m}$.
- 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