The nuclear materials science of neutron star mergers

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

Alford and Harris, arXiv:1907.03795

Alford, Harutyunyan, Sedrakian, arXiv:2006.07975, 2108.07523

Alford and Haber, arXiv:2009.05181

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Outline

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  - Thermal equilibration — thermal conductivity
  - Shear flow equilibration — shear viscosity

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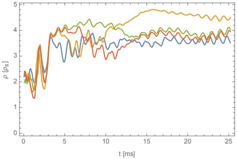
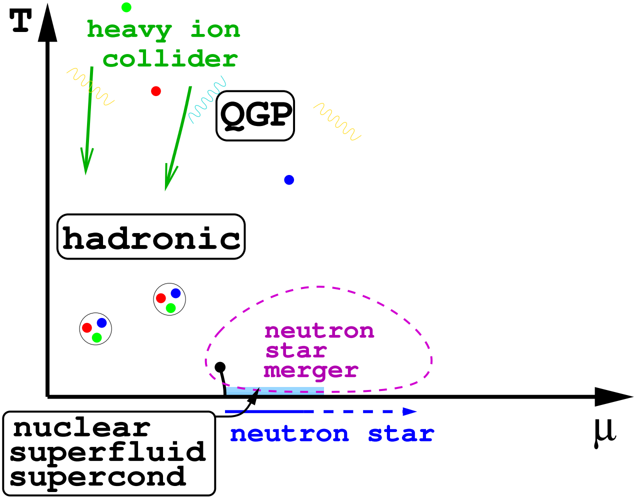
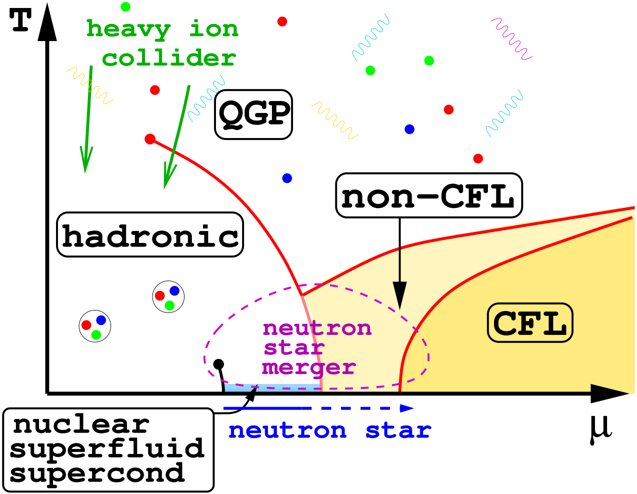
  Better than the equation of state for probing phase structure!
- Flavor equilibration: is it important in mergers?
  - How bulk viscosity arises from flavor equilibration
  - Interesting features, e.g.: bulk viscosity is a resonance
  - One manifestation: Damping time for density oscillations



QCD Phase diagram



Conjectured QCD Phase diagram



heavy ion collisions: deconfinement crossover and chiral critical point

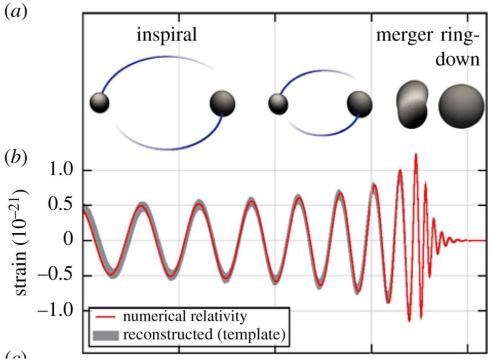
neutron stars: quark matter core?

neutron star mergers: dynamics of warm and dense matter

Observing mergers: prediction

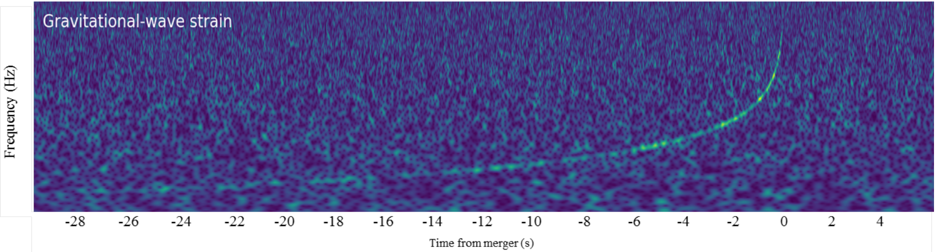
To use mergers as a probe of dense matter we need to perform simulations that incorporate the microscopic physics.

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

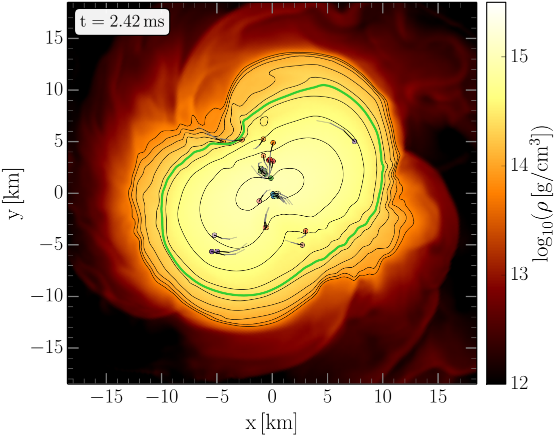
With LIGO we only see the inspiral, not the merger itself.

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

Neutron star mergers

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

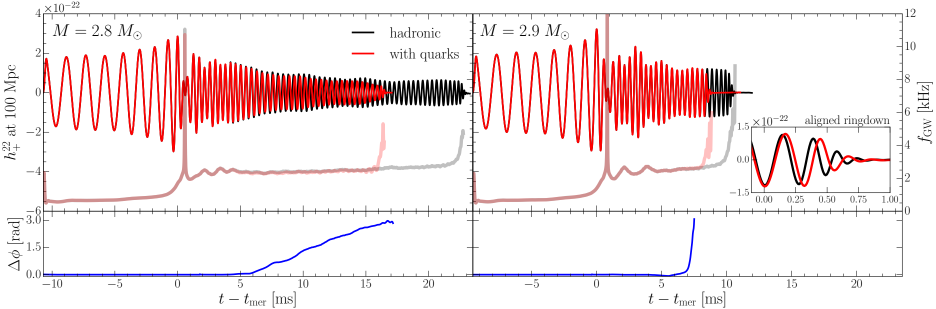


Rezzolla group, Frankfurt [Video]

If we want to use mergers to learn about nuclear matter, we need to **include all the relevant physics in our simulations.**

Using grav waves to probe equilibrium properties of dense matter

Equation of State: Try to see GW signatures of EoS features like a first-order phase transition:



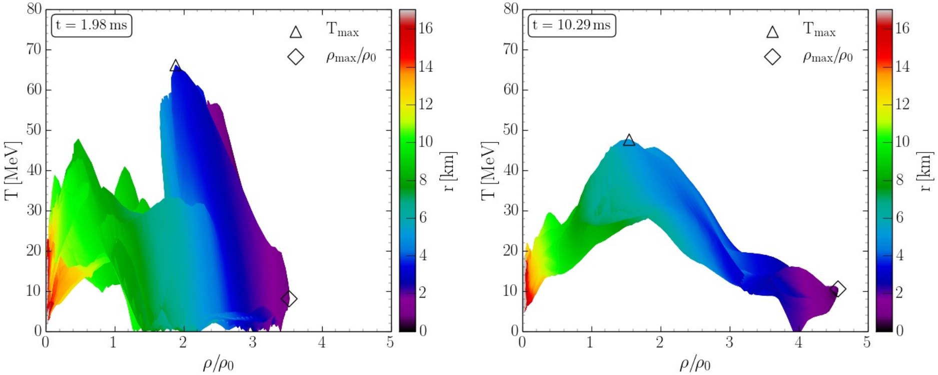
Most et. al., `arXiv:1807.03684`

solid lines: grav wave strain; translucent lines: instantaneous freq

What about out-of-equilibrium properties of dense matter?

The important properties are the ones whose equilibration time is $\lesssim 20\,\mathrm{ms}$

Nuclear material in a neutron star merger



M. Hanauske, Rezzolla group, Frankfurt

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

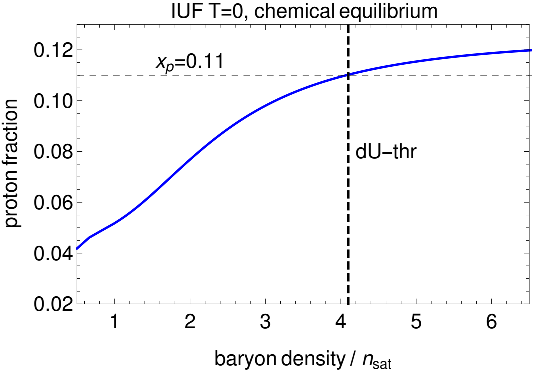
so we need to allow for
- thermal conductivity
- shear viscosity
- bulk viscosity

Density oscillations and beta equilibration

Departures from flavor equilibrium will be created by density oscillations.

When you compress nuclear matter, the proton fraction wants to change.
(beta equilibrium, electrical neutrality, nuclear "symmetry energy")

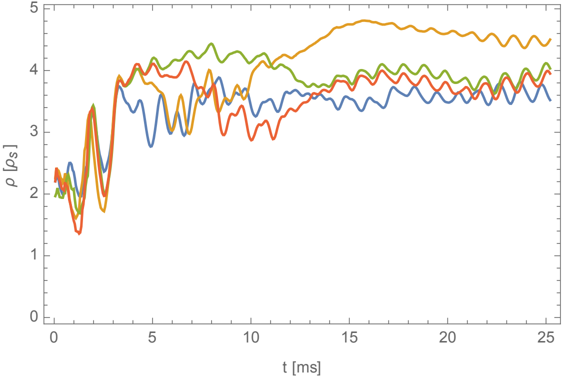
But this doesn't happen instantaneously!



Density oscillations in mergers

Density vs time for tracers in merger

Flavor equilibration neglected



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

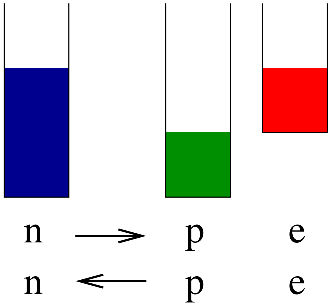
Amplitude: up to 50%
Period: 1–2 ms

Do oscillations drive the system out of flavor equilibrium?

Does flavor equilibration affect the oscillations?

Flavor equilibration and bulk viscosity

Only the weak interaction can change proton fraction;



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If so, simulators should include it.

(2) Estimate the effects, e.g dissipation via bulk viscosity

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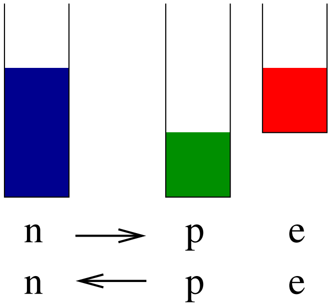

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(2) Estimate the effects, e.g dissipation via bulk viscosity

Let's estimate the damping time τ_ζ
for density oscillations

Density oscillation damping time τ_ζ

Density oscillation of amplitude Δn at angular freq ω:

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

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(K = nuclear incompressibility)

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

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Damping Time: $\tau_\zeta = \dfrac{E_{\rm comp}}{W_{\rm comp}} = \dfrac{K\bar{n}}{9\omega^2\zeta}$

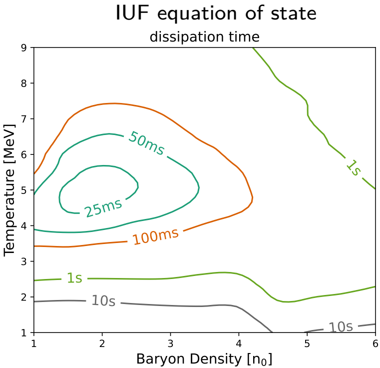
Bulk viscosity due to flavor equilibration
is important in mergers if $\tau_\zeta \lesssim 20\,\text{ms}$

Damping time calculation (ν-transparent)

Damping time:

$$\tau_\zeta = \frac{K\bar{n}}{9\omega^2\zeta}$$

Damping can be fast enough to affect merger dynamics!



talk by Z. Zhang, Session V15.00005

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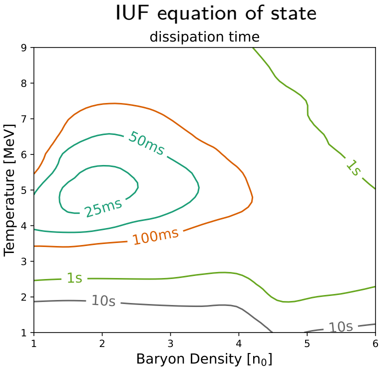

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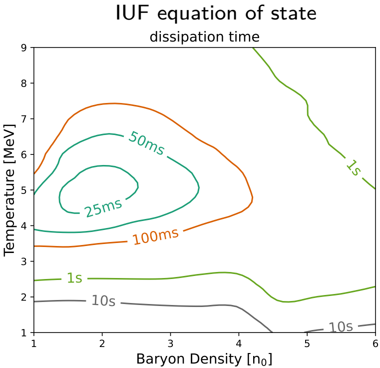

talk by Z. Zhang, Session V15.00005

- 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 $T \sim 5\,\text{MeV}$.
  Damping is slow at very low or very high temperature.
  Non-monotonic dependence of bulk viscosity on temperature

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:

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

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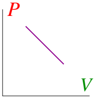

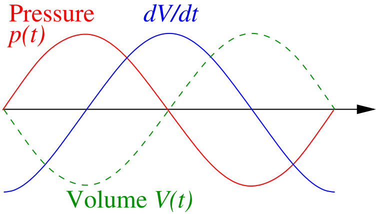

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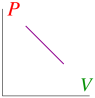
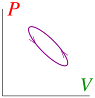
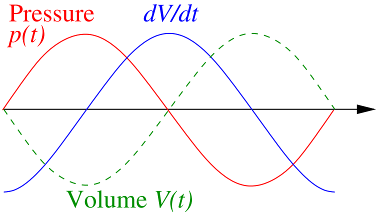
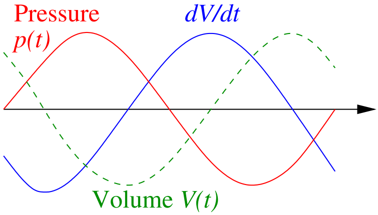


Some phase lag.
Dissipation > 0





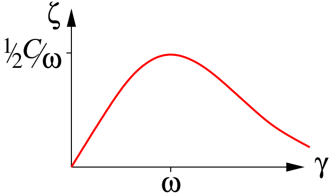


Bulk viscosity: a resonant phenomenon

Bulk viscosity is **maximum** when

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

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



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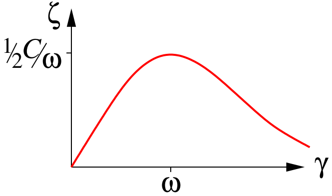

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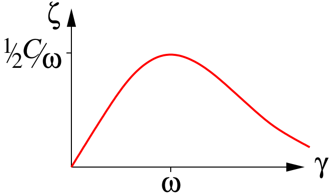

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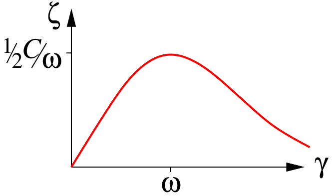

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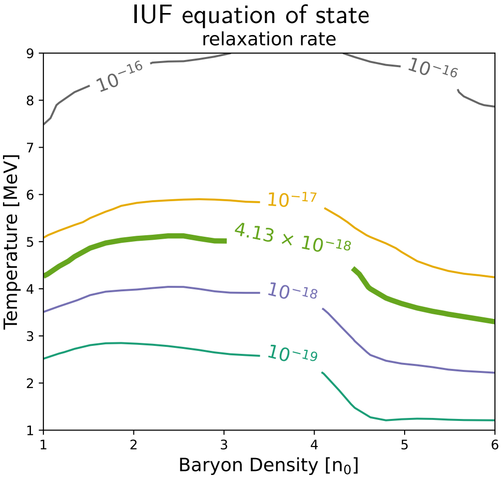
  System is always in equilibrium. No pressure-density phase lag.
- Slow equilibration: $\gamma \to 0 \;\Rightarrow\; \zeta \to 0$.
  System does not try to equilibrate: proton number and neutron number are both conserved. Proton fraction fixed.
- Maximum phase lag when $\omega = \gamma$.

Can the relaxation rate be $\sim$kHz?

Can the relaxation rate be ~kHz?



- Assumes ν-transparent matter

$$n \to p\ e^-\ \bar{\nu}_e$$
$$p\ e^- \to n\ \nu_e$$

- Relaxation rate γ is mainly determined by temperature
- It crosses through $2\pi\,\mathrm{kHz} \approx 4\times 10^{-18}\,\mathrm{MeV}$ at $T \sim 4$ to $5\,\mathrm{MeV}$

Flavor relaxation resonates with expected oscillation timescale for mergers at $T \sim 5\,\mathrm{MeV}$

This will produce maximum bulk viscosity

Resonant peak in bulk viscosity

We now see why bulk visc is a non-monotonic function of temperature: it goes through a resonance

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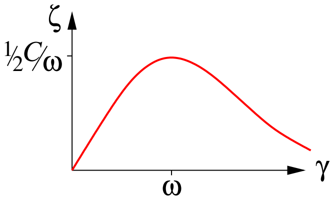
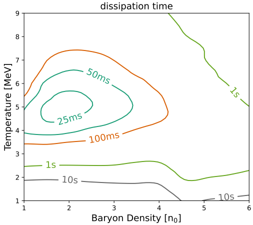
$$\zeta(T) = C\frac{\gamma(T)}{\gamma(T)^2 + \omega^2}$$





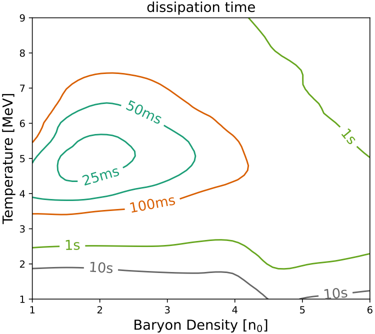
Flavor (beta) relaxation rate γ rises with temperature (phase space at Fermi surface)

Maximum bulk viscosity in a neutron star merger will be when relaxation rate γ matches typical oscillation frequency $\omega \approx 2\pi \times 1\,\mathrm{kHz}$

In ν-transparent matter this occurs at $T \sim 5\,\mathrm{MeV}$

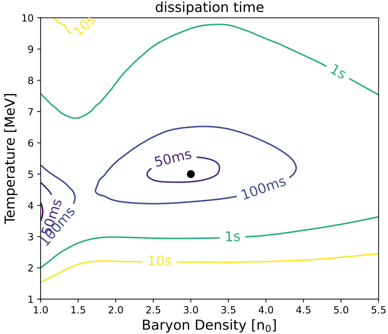
Two different EoSes

IUF equation of state



QMC-RMF3 equation of state

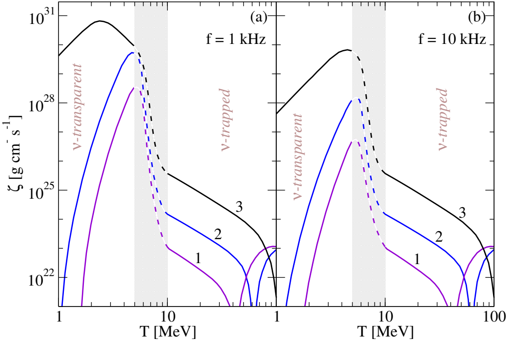
Talk by L. Brodie, session V15.00004



The damping time for density oscillations is shortest around $T \sim 5, \mathrm{MeV}$, independent of the EoS.

Damping time is short enough to be relevant for mergers, especially at low density.

The "hot" (neutrino-trapped) regime



Beta equilibration now includes neutrinos in the initial state too:

$\nu_e + n \leftrightarrow p + e^-$

Bulk viscosity is *lower* in hot matter ($T \gtrsim 5\,\mathrm{MeV}$).

- Beta equilibration is too fast, above resonant temperature, because there so much phase space at the Fermi surfaces
- The relevant susceptibilities are smaller, so the peak bulk visc is smaller

Summary

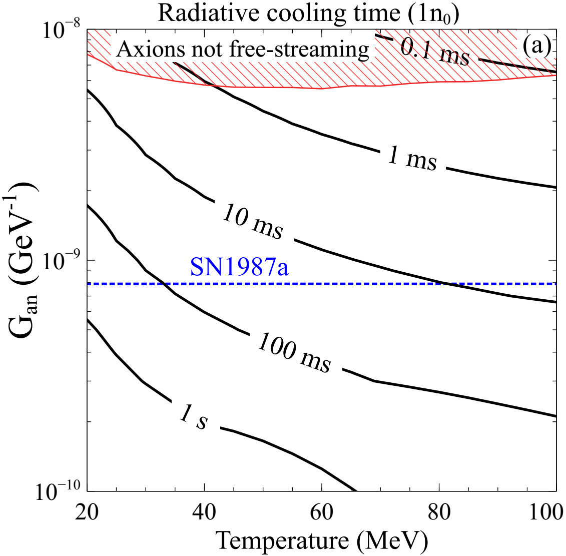
- Neutron star mergers probe the dynamical response of high-density matter on the millisecond timescale.
- In neutrino-transparent nuclear matter (at moderate density and $T \sim 4\,\mathrm{MeV}$) flavor ("beta") equilibration occurs on the timescale of the merger, and cannot be neglected.
- We expect that the resultant bulk viscosity will damp density oscillations.
- Under these conditions, rates must be integrated over the whole phase space: the Fermi Surface approximation and detailed balance are not valid.

Next steps

- Include flavor equilibration in merger simulations.
  talk by A. Haber, session U15.00002
- Beyond neutrino transparent/trapped: calculate flavor equilibration rates for arbitrary neutrino distributions
- Beyond *npe*: calculate flavor equilibration rates for other forms of matter: hyperonic, 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 ($T \gtrsim 5\,\text{MeV}$) if there are fine-scale gradients ($z \lesssim 100\,\text{m}$).
- 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`