# Transport and dissipation in neutron star mergers

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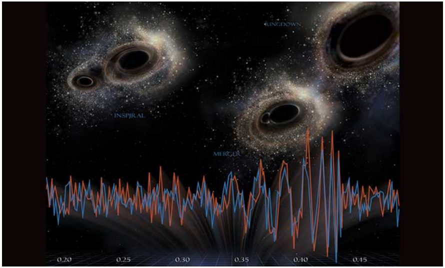
# Outline

- Neutron star mergers
- Thermal conductivity
- Bulk viscosity
- Conclusions

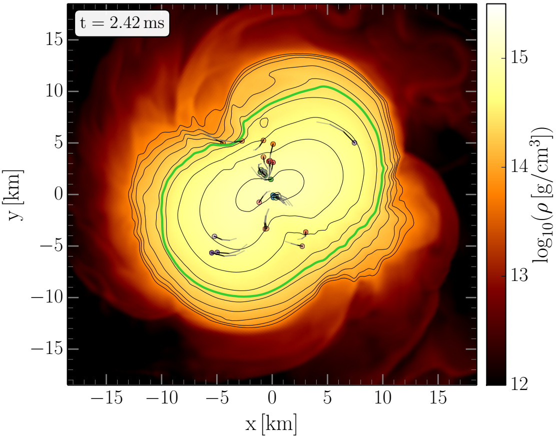
# Neutron star mergers




LIGO has seen black hole mergers
And one neutron star merger.

- Neutron star mergers are believed to be an important site for nucleosynthsis of heavy elements (e.g Gold), so they should occur often enough to account for the observed abundances.
- If we can achieve a quantitative understanding of neutron star mergers, perhaps we could use their gravitational wave, electromagentic, and neutrino signals to learn about properties of nuclear matter under extreme conditions

# Nuclear material in a neutron star merger




Density:
up to 4 $n_{\rm sat}$

Temperature:
5 to 20 MeV

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

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

# Summary

- It is useful to have estimates of the equilibration times for various forms of dissipation, to decide which is the most important.
- Thermal equilibration: If neutrinos are trapped, and there are short-distance temperature gradients then thermal transport might be fast enough to play a role.

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

- Shear viscosity: similar conclusion.
- Bulk viscosity: If Direct Urca processes remain suppressed at the relevant densities and temperatures, bulk viscosity will quickly damp density oscillations

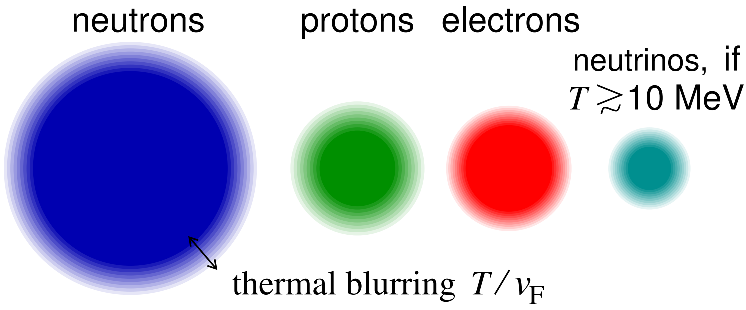
$$\tau_\zeta^{\rm min} \approx 3\,\text{ms} \left(\frac{t_{\rm comp}}{1\,\rm ms}\right) \left(\frac{K}{250\,\text{MeV}}\right) \left(\frac{0.25\,\rm MeV}{Y_\zeta}\right)$$

# Nuclear material constituents

Temperature: 5 to 20 MeV

Density: up to 4 $n_{\mathrm{sat}}$

Fermi surfaces:

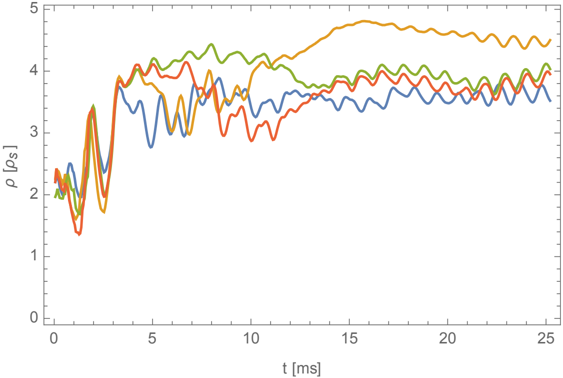



| | | |
|---|---|---|
| neutrons: | $\sim 90\%$ of baryons | $p_{Fn} \sim 350\,\mathrm{MeV}$ |
| protons: | $\sim 10\%$ of baryons | $p_{Fp} \sim 150\,\mathrm{MeV}$ |
| electrons: | same density as protons | $p_{Fe} = p_{Fp}$ |
| neutrinos: | only present if mfp $\lesssim 1\,\mathrm{km}$ | $p_{F\nu} \sim \frac{1}{2} p_{Fe}$ |

# Bulk viscosity: compression dissipation

Bulk viscosity turns compression energy of density oscillations into heat.

Density vs time for tracers in merger




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

Amplitude: up to 50%
Period: $\sim 2\,\mathrm{ms}$

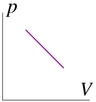
- What is the largest bulk viscosity $\zeta_{\max}$ we could expect?
- What is the equilibration time $\tau_\zeta$?
  Ie how long does it take for bulk viscosity to dissipate a good fraction of the energy of a density oscillation?

# Bulk viscosity: phase lag in system response

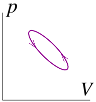
Some component in the material is equilibrating slowly.
Baryon density $n$ and hence fluid element volume $V$ gets out of phase with applied pressure $p$:

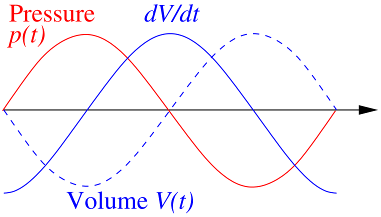
$$\text{Dissipation} = -\int p\, dV = -\int p \frac{dV}{dt} dt$$

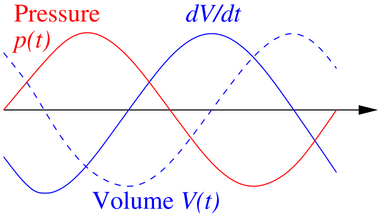
No phase lag.
Dissipation $= 0$




Some phase lag.
Dissipation $> 0$



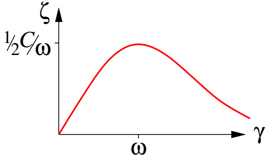
# Bulk viscosity: a resonant phenomenon

Bulk viscosity is maximum when

(internal equilibration rate) $\sim$ (freq of density oscillation)

$\gamma$ $\qquad\qquad$ $\omega$

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




What quantity would equilibrate on the timescale of the density oscillations in neutron star mergers (milliseconds)?

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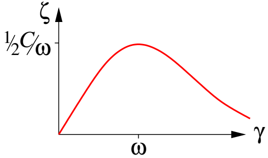



What quantity would equilibrate on the timescale of the density oscillations in neutron star mergers (milliseconds)?

Flavor, via weak interactions

# Bulk viscosity and flavor equilibration

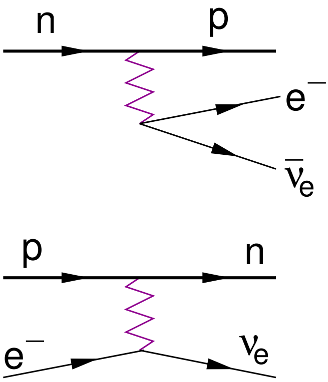
When you compress nuclear matter, the proton fraction wants to change.

Weak interactions convert $n \leftrightarrow p$

But exactly what is the timescale?
Is it similar to the millisecond timescale of density oscillations in neutron star mergers?

# Flavor equilibration processes

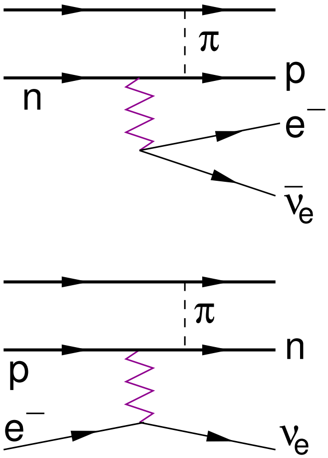
Direct Urca




Only occurs if proton density is high enough: $p_{Fn} < p_{Fe} + p_{Fp}$

Rate $\gamma_D \sim T^4$

Modified Urca



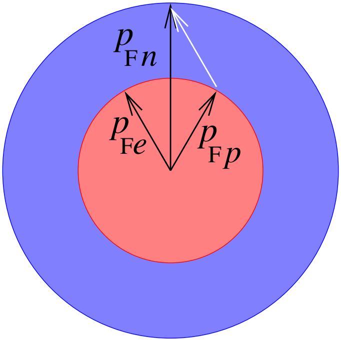

$\gamma_M \sim T^6$

# When can Direct Urca happen?

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

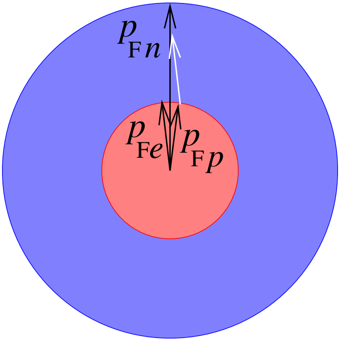
For $T = 0$ and the case of no neutrino trapping ($\mu_\nu = 0$)

High proton fraction:
Direct Urca open




$\vec{p}_n = \vec{p}_p + \vec{p}_e$ is possible
because $p_{Fn} < p_{Fp} + p_{Fe}$

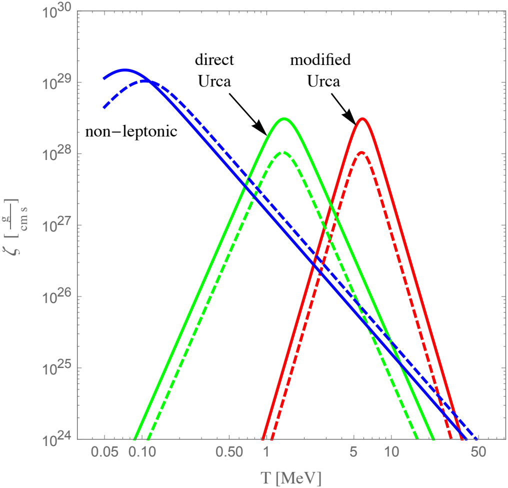
Low proton fraction:
Direct Urca closed




$\vec{p}_n = \vec{p}_p + \vec{p}_e$ is impossible
because $p_{Fn} > p_{Fp} + p_{Fe}$

# Bulk viscosity: resonant peak

For oscillations of freq $\omega = 2\pi \times 1\,\text{kHz}$




Bulk visc reaches maximum when flavor equilibration rate $\gamma(T) = \omega$.

Direct Urca is faster, so $\gamma_D(T) = \omega$ at $T \sim 1\,\text{MeV}$
$\zeta$ suppressed at $T \gtrsim 5\,\text{MeV}$

Modified Urca is slower, so $\gamma_M(T) = \omega$ at $T \sim 7\,\text{MeV}$

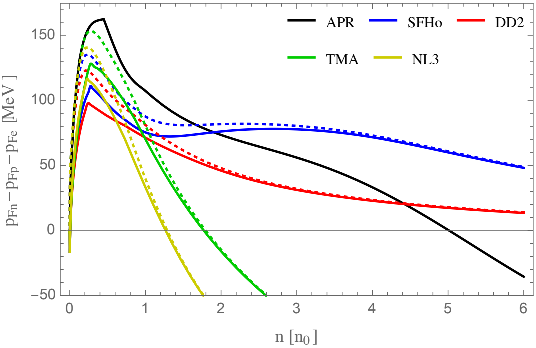
$\zeta_{\text{max}}$ is determined by EoS, indp of equilibration rate

Typical temperature in first 5ms of post-merger (where density oscillations are large) is 5-20 MeV, so we expect strong bulk viscosity if the Direct Urca channel is suppressed (proton density low).

# Does Direct Urca occur?

Direct Urca happens when $p_{Fn} < p_{Fe} + p_{Fp}$

i.e. when $p_{Fn} - p_{Fe} - p_{Fp} < 0$




At $T = 0$, there is no consensus among candidate nuclear matter equations of state about the threshold density for Direct Urca.

Need to consider:

- Thermal effects
- Interaction effects
- Gradual opening of Direct Urca phase space
- Effects of $\nu_e$ trapping

The amount of bulk visc dissipation is a probe of the nuclear EoS

# Bulk viscosity equilibration time

Density oscillation of amplitude $\Delta n$ on timescale $t_{\rm comp}$:

$$n(t) = \bar{n} + \Delta n \cos(2\pi t / t_{\rm comp})$$

Energy of density oscillation: $\mathcal{E}_{\rm comp} = \dfrac{K}{18}\bar{n}\left(\dfrac{\Delta n}{\bar{n}}\right)^2$

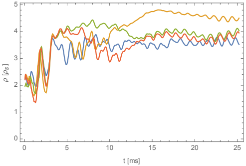
Compression dissipation rate: $W_{\rm comp} = \dfrac{2\pi^2\zeta}{{t_{\rm comp}}^2}\left(\dfrac{\Delta n}{\bar{n}}\right)^2$

Damping Time: $\tau_\zeta = \dfrac{\mathcal{E}_{\rm comp}}{W_{\rm comp}} = \dfrac{K\bar{n}\,{t_{\rm comp}}^2}{36\pi^2\,\zeta}$

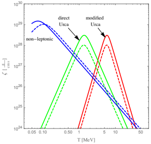
Bulk visc is important if $\tau_\zeta \lesssim 10\,\text{ms}$

# Is bulk visc big enough to matter?

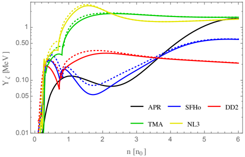
There are high-amplitude density oscillations with $f \sim 1\,\text{kHz}$ in regions at $T \sim 5$ to $10\,\text{MeV}$




Suppose Direct Urca processes are suppressed at those temperatures and densities.
Then flavor equilibration via modified Urca will achieve its maximum value




Max bulk visc from flavor equilibration is
$\zeta_{\max} = Y_\zeta \bar{n}\, t_{\text{comp}}$

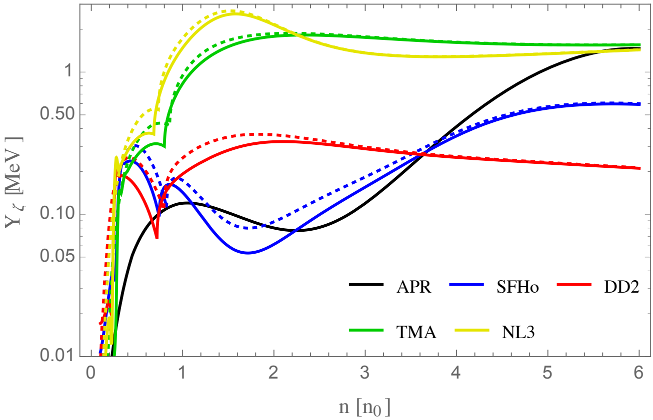



$$\tau_\zeta^{\min} = \left(\frac{K}{36\pi^2\, Y_\zeta}\right) t_{\text{comp}}$$

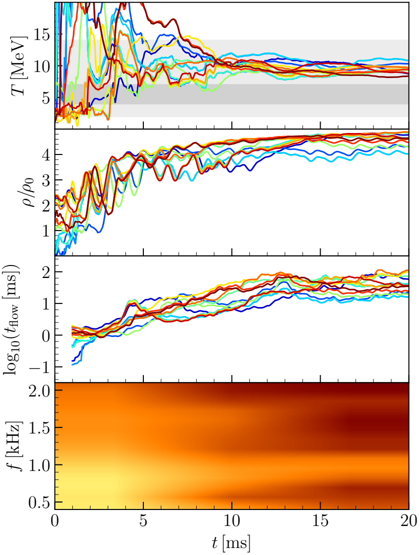
$$\approx \boxed{3\ \text{ms}} \left(\frac{t_{\text{comp}}}{1\,\text{ms}}\right) \left(\frac{K}{250\,\text{MeV}}\right) \left(\frac{0.25\,\text{MeV}}{Y_\zeta}\right)$$

# Max bulk visc "Y" factor

Typical value is in the 0.1 to 1 MeV range



# State of post-merger matter




Temperature is in the range that maximizes bulk viscosity. (assuming Modified Urca only)

Large amplitude $\sim 1\,kHz$ density oscillations during the first 5-10 ms

Density oscillation freq in kHz range

# Summary

- It is useful to have estimates of the equilibration times for various forms of dissipation, to decide which is the most important.
- Thermal equilibration: If neutrinos are trapped, and there are short-distance temp gradients then thermal transport might be fast enough to play a role.

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

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# The Future

- Incorporate bulk viscosity in numerical simulations
- What density and temperature range allows Direct Urca?
- Understand neutrino trapping. At what temp/density is there neutrino-domination of thermal and shear viscous transport?
- Are there short-range gradients ($z_{\rm typ} \sim 0.1\,{\rm km}$) that would lead to rapid shear viscous or thermal equilibration?
- Explore the role of dissipation in the collapse of a single star to a denser "third family" or "twin star" configuration