How important is bulk viscosity in neutron star mergers?

Prof. Mark Alford
Washington University in St. Louis

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

Alford, Harutyunyan, Sedrakian, arXiv:1907.04192

Alford and Harris, arXiv:1907.03795

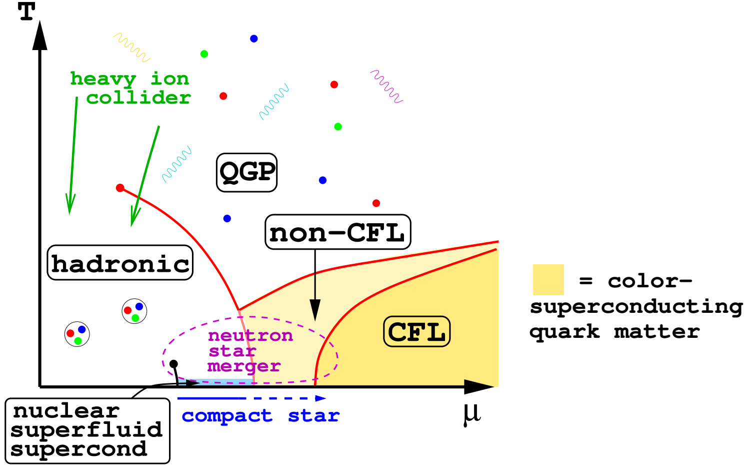
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Neutron star mergers
- Beta equilibration in nuclear matter
  Urca processes
  The neutrino-transparent regime: $T \lesssim 5\,\mathrm{MeV}$
- Damping time for density oscillations
  Bulk viscosity
  Resonance between equilibration and oscillation
- Summary and future prospects

Conjectured QCD Phase diagram

We want to know the properties of matter under extreme conditions



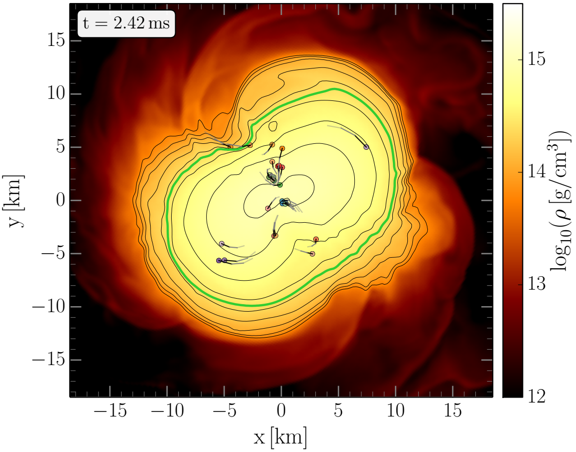
heavy ion collisions: deconfinement crossover and chiral critical point

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 $\sim 60\,\text{MeV}$)

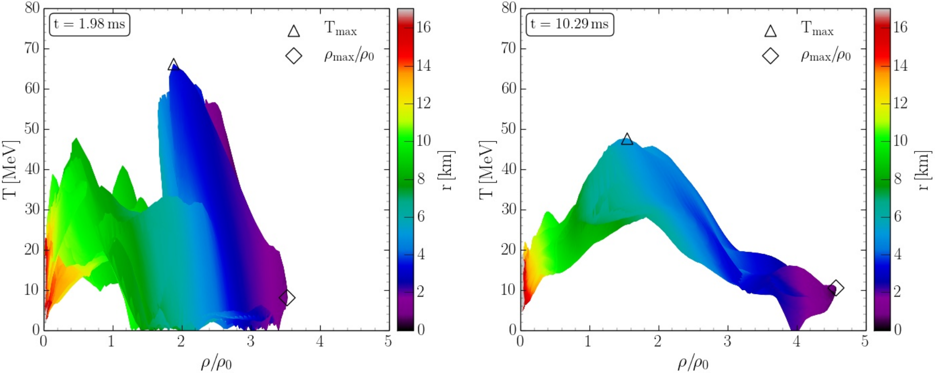


We need to include all the relevant physics in our simulations.

Rezzolla group, Frankfurt

Video

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 in mergers

The important dissipation mechanisms are the ones whose equilibration time is in the 10-30 ms range

- Thermal equilibration: If neutrinos are trapped, and there are short-distance temperature gradients then thermal transport might be fast enough to play a role.

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

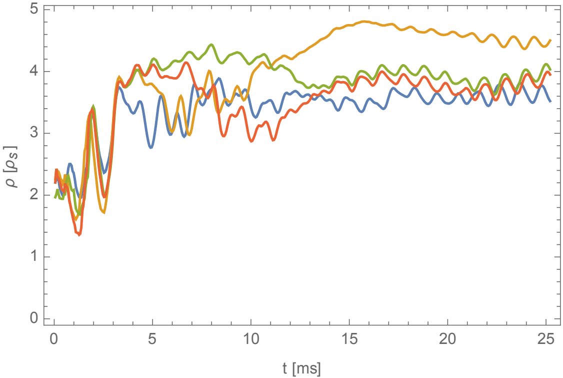
- Shear viscosity: similar conclusion.
- Bulk viscosity: could damp density oscillations on the same timescale as the merger!

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

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?

Density oscillation damping time τ_ζ

Density oscillation of amplitude Δn at angular freq ω:

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

Energy of density oscillation:
(K = nuclear incompressibility)

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

Compression dissipation rate:

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

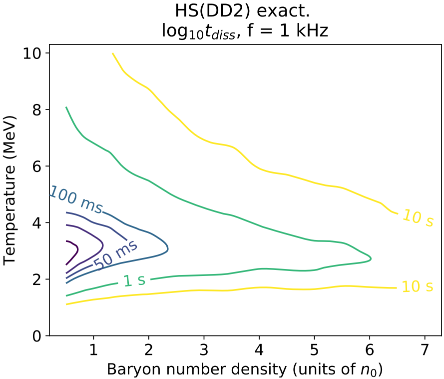
Damping Time: $\tau_\zeta = \dfrac{E_{\rm comp}}{W_{\rm comp}} = \dfrac{K\bar{n}}{9\omega^2\,\zeta}$

Bulk visc is important if $\tau_\zeta \lesssim 20\,\mathrm{ms}$

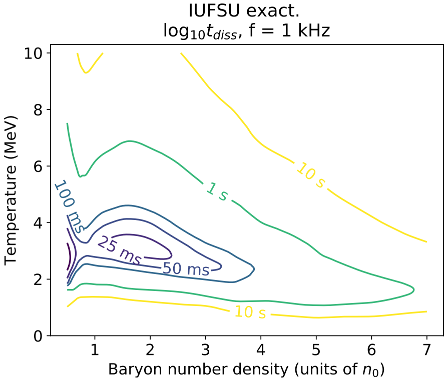
Damping time results

We studied two eqns of state:

name	type	$M_{\max}$	$R_{1.4\,M_\odot}$	d-Urca threshold
HS(DD2)	stiffer	$2.42\,M_\odot$	$13.3\,\text{km}$	none
IUFSU	softer	$1.96\,M_\odot$	$12.8\,\text{km}$	$4n_{\text{sat}}$



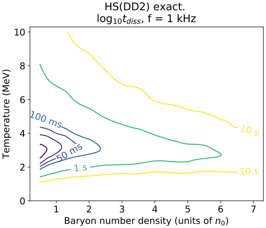
No direct Urca



d-Urca threshold at $4n_{\text{sat}}$

At $T \sim 3\,\text{MeV}$, some EoS give $\tau_\zeta \lesssim 20\,\text{ms}$

Damping time behavior



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

Characteristics of the damping time plot:

- Non-monotonic T-dependence: damping is fastest at $T \sim 3\,\text{MeV}$. Damping is slow at very low or very high temperature.

  Non-monotonic dependence of bulk viscosity on temperature

- Damping gets slower at higher density.

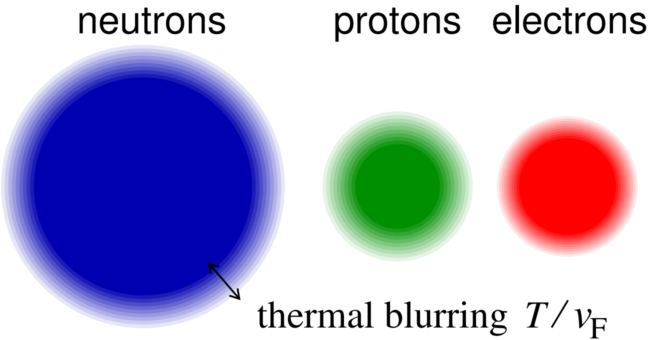
  Baryon density $\bar{n}$ and incompressibility K are both increasing.

  Oscillations carry more energy ⇒ slower to damp

Nuclear material constituents

We will focus on the neutrino-transparent regime, $T \lesssim 5\,\mathrm{MeV}$

Fermi surfaces:



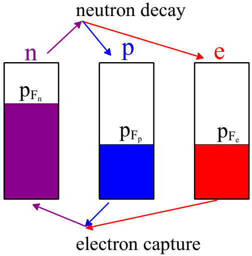
thermal blurring T/v_{F}

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 $\lesssim 1\,\mathrm{km}$	i.e. when $T \gtrsim 5\,\mathrm{MeV}$

Bulk viscosity and beta equilibration

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

Weak interactions convert $n \leftrightarrow p$ to establish the new proton fraction



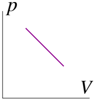
Beta equilibration is slow
Delayed response to compression $\Rightarrow$ bulk viscosity

Bulk viscosity: phase lag in system response

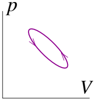
Proton fraction takes time to equilibrate.
Baryon density n and hence fluid element volume V gets out of phase with applied pressure p:

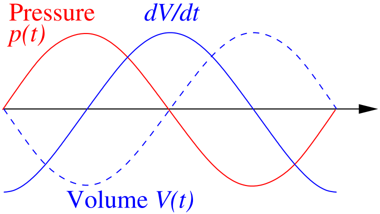
$$\text{Dissipation} = -\int p\, dV = -\int p\, \frac{dV}{dt}\, dt$$

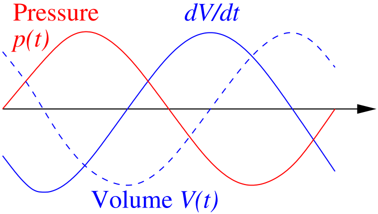
No phase lag.
Dissipation $= 0$



Some phase lag.
Dissipation > 0







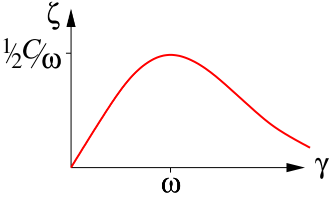
Bulk viscosity: a resonant phenomenon

Bulk viscosity is maximum when

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

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

C is a combination of susceptibilities

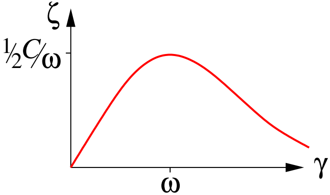


- **Fast equilibration:** $\gamma \to \infty$, $\zeta \to 0$
  System is always in equilibrium. No pressure-density phase lag.
- **Slow equilibration:** $\gamma \to 0$, $\zeta \to 0$.
  System does not try to equilibrate: proton number and neutron number are both conserved. Proton fraction fixed.
- **Maximum**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

Resonant peak in bulk viscosity

So now we see why bulk viscosity has a non-monotonic dependence on temperature.

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



Beta equilibration rate γ is sensitive to temperature (phase space at Fermi surface)

Maximum bulk viscosity in a neutron star merger will be when beta equilibration rate $\gamma \sim 2\pi \times 1\,\mathrm{kHz}$

- Do we get $\gamma(n_B, T) \sim 2\pi\,\mathrm{kHz}$ at the densities and temperatures of a neutron star merger?
- Is the prefactor C big enough to yield damping on the timescale of a merger, $\tau_\eta \lesssim 20\,\mathrm{ms}$?

Subtleties in beta equilibration

Beta equilibration in neutrino-transparent matter is via "Urca" processes

$$\begin{aligned} \text{neutron decay:} \quad & n \to p + e^- + \bar{\nu}_e \ , \\ \text{electron capture:} \quad & p + e^- \to n + \nu_e \ . \end{aligned}$$

Standard calculations use the "Fermi Surface approximation": rate is dominated by particles close to their Fermi surfaces (except ν).

At $T \gtrsim 1\,\text{MeV}$, Fermi Surface approximation breaks down.

(Proton Fermi energy is $E_F \sim 10\,\text{MeV}$).

1. In FS approx there is a sharp distinction between "direct Urca" and "modified Urca". At $T \gtrsim 1\,\text{MeV}$ this distinction breaks down.
2. In the FS approx, neutrino energy is negligible and beta process is in equilibrium when
$$\mu_n = \mu_p + \mu_e$$
but at $T \gtrsim 1\,\text{MeV}$ this is no longer valid.

   But what about detailed balance? The two processes that equilibrate are not inverses of each other so detailed balance need not hold.

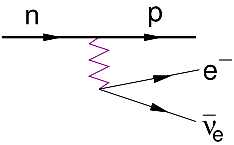
Beta equilibration: Urca processes

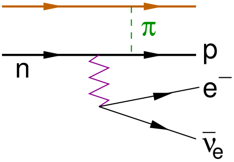
Traditionally, sharp separation between *direct* and *modified* Urca

Direct Urca

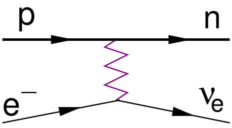
Modified Urca

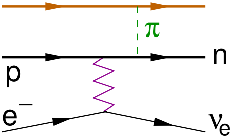
n decay





p capture

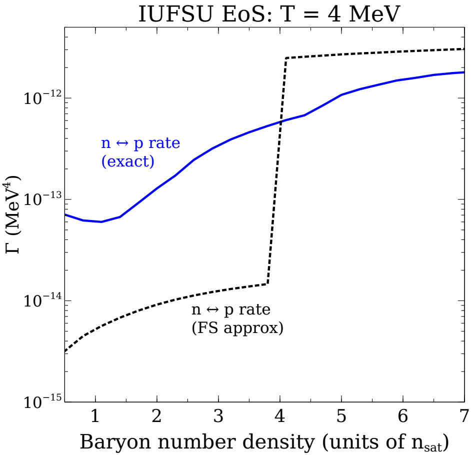




d-Urca only occurs above
"direct Urca threshold" density

But at $T \gtrsim 1\,\mathrm{MeV}$, d-Urca and m-Urca blur together

Beyond the Fermi Surface approx



Fermi Surface Approximation

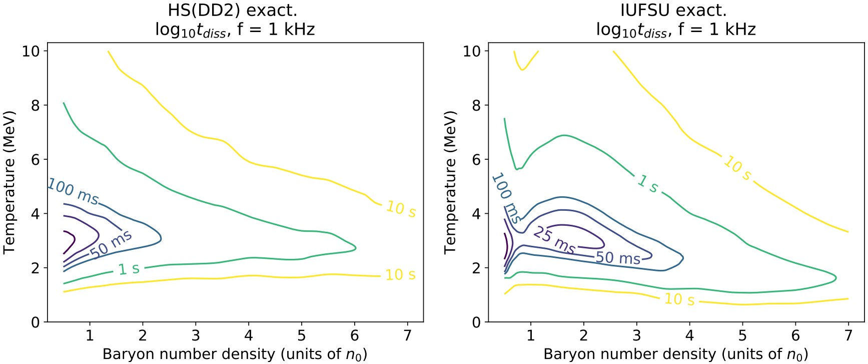
Standard calculations assume only states close to the Fermi surface contribute ($T \ll E_F$).

This gives a sharp "switch-on" of direct Urca at a threshold density..

But for protons, $E_F \sim 10\,\text{MeV}$ so at $T \gtrsim 1\,\text{MeV}$ the proton Fermi surface is thermally blurred, smoothing out the appearance of direct Urca.

Alford & Harris, `arXiv:1803.00662`

Damping time



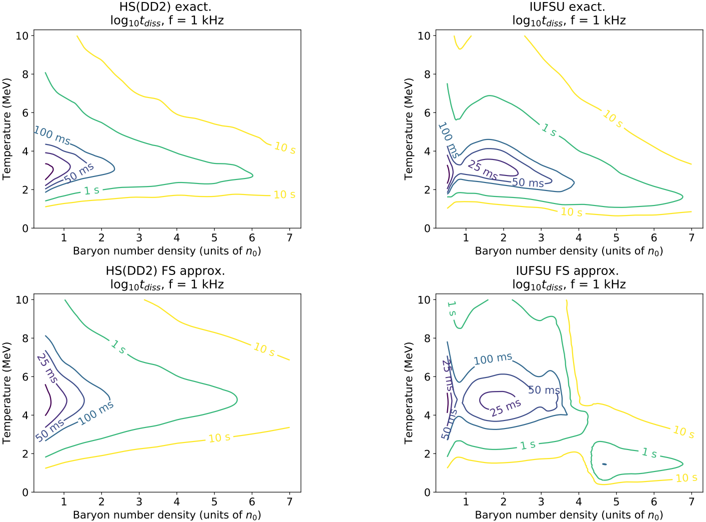
The damping time for density oscillations is shortest around $T \sim 3\,\mathrm{MeV}$, independent of the EoS.

It is short enough to be relevant for neutron star mergers, especially at low density $n \sim 0.5 n_{\mathrm{sat}}$, or at $n \sim 2 n_{\mathrm{sat}}$ for the softer IUFSU EoS.

Fermi Surface Approx

Exact:

FS approx:



HS(DD2) exact.
$\log_{10} t_{diss}$, f = 1 kHz

IUFSU exact.
$\log_{10} t_{diss}$, f = 1 kHz

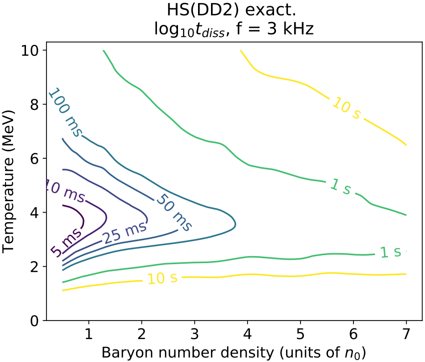
HS(DD2) FS approx.
$\log_{10} t_{diss}$, f = 1 kHz

IUFSU FS approx.
$\log_{10} t_{diss}$, f = 1 kHz

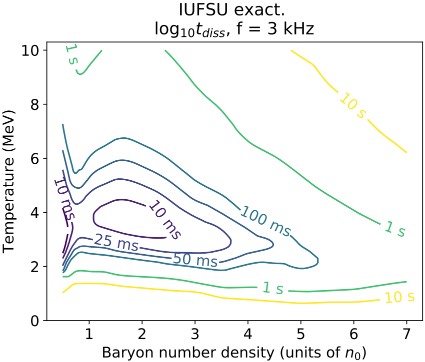
FS approx exaggerates the sharpness of the onset of direct Urca (IUFSU, at $n = 4n_{\mathrm{sat}}$)

Higher frequency oscillations

If 3 kHz oscillations occur then they would be damped even faster.



HS(DD2) exact.
$\log_{10} t_{diss}$, f = 3 kHz



IUFSU exact.
$\log_{10} t_{diss}$, f = 3 kHz

Note that max damping occurs at a slightly higher temperature, to get the beta equilibration rate to match the higher oscillation frequency.

Summary

- Bulk viscosity may be physically important for neutron star mergers.
- At millisecond time scales, bulk viscosity arises from equilibration of the proton fraction via weak interactions.
- In non-ν-trapped nuclear matter ($T \lesssim 5\,\mathrm{MeV}$) the damping time for density oscillations is shortest around $T \sim 3\,\mathrm{MeV}$, independent of the EoS
- To do the calculation properly we have to do the full phase space integral for the weak interactions that equilibrate proton fraction. The Fermi Surface approximation is not valid.

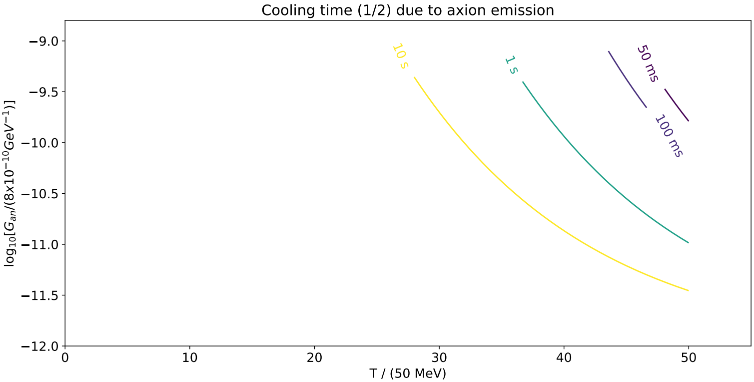
The Future

- Calculate bulk visc in the neutrino trapped regime
  Alford, Harutyunyan, Sedrakian, `arXiv:1907.04192`
- Understand neutrino trapping:
  At what temp/densities can we treat neutrinos as free-streaming?
  At what temp/densities can we treat neutrinos as trapped?
  What should we do in between?
- Bulk visc in hyperonic matter, nuclear pasta, quark matter, etc
- Suprathermal (high-amplitude) bulk viscosity
- Numerical simulations incorporating bulk viscosity
- Are there short-range gradients ($z_{\rm typ} \sim 0.1\,\text{km}$) 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
- Could axions play a role in mergers?

Cooling by axion emission

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

PRELIMINARY



Alford, Fortin, Harris, Kuver, `work in progress`

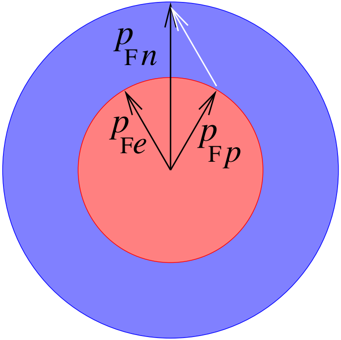
Extra slides

When can Direct Urca happen?

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

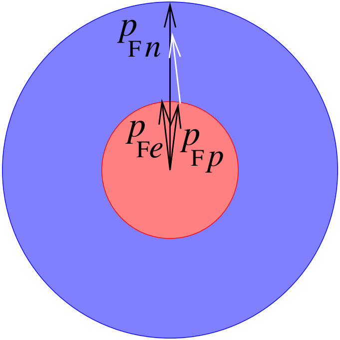
For $T = 0$ and the case of no neutrino trapping ($\mu_\nu = 0$)

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 $p_{Fn} > p_{Fp} + p_{Fe}$